Jets
- experimental aspects

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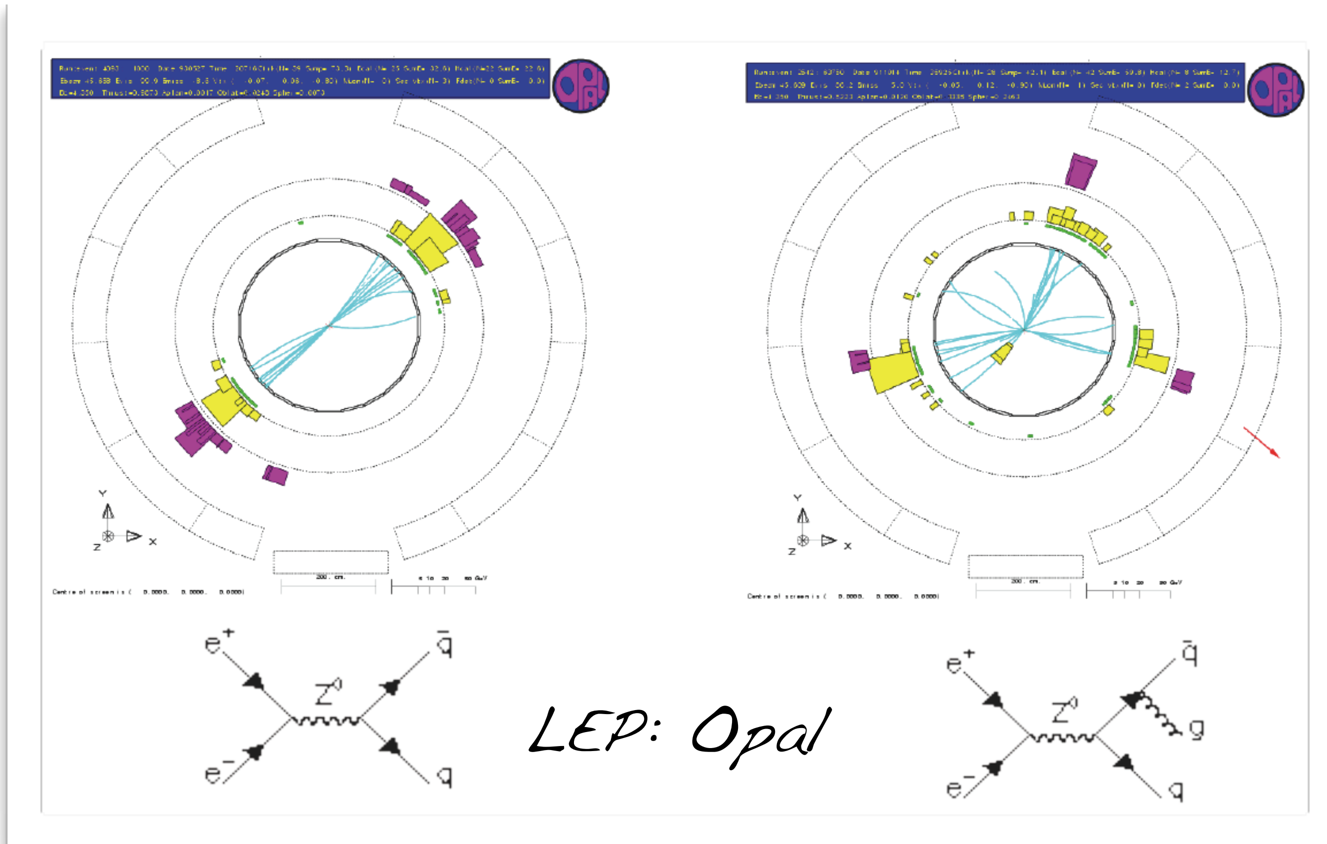
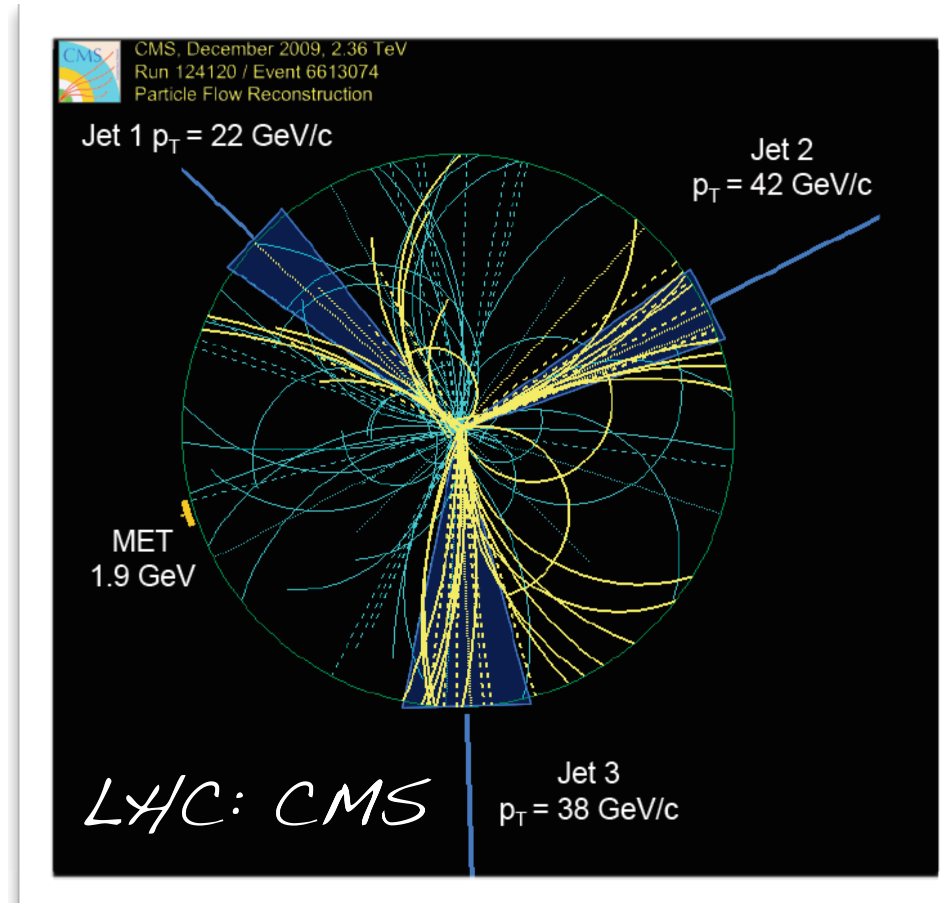
Contents

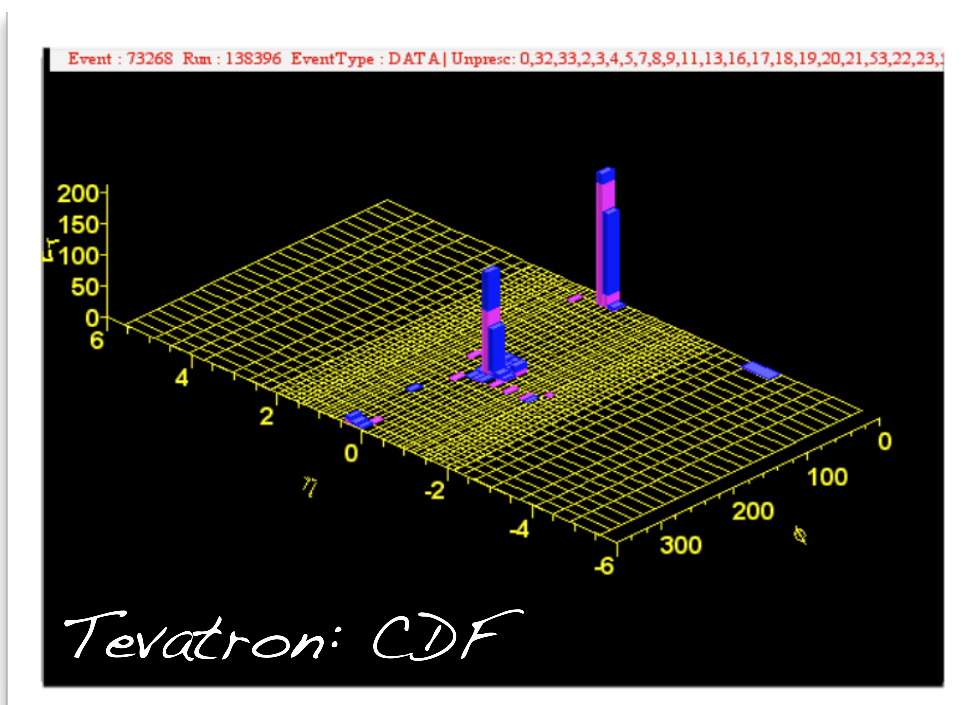
- What is a jet and how to measure it? Relation to theory and partons (1)
- Heavy-ion collisions - experimental controls - some theoretical expectations… (1->2)
- Probing quark-gluon plasma with jets and jet-like observables; jet-medium interactions (2+3)
- All this based on: lessons from RHIC & LHC
  - Note: choice of experiments is randomized - much of what shown measured by multiple experiments…

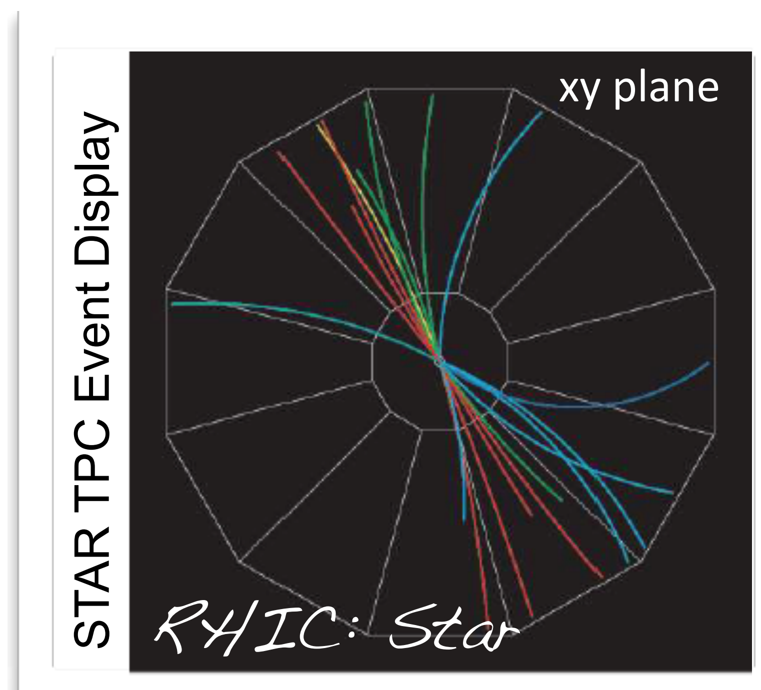
Thanks to all the authors/experiments for the graphics/slides shamelessly stolen for the purpose of this talk

Jets in collider experiments









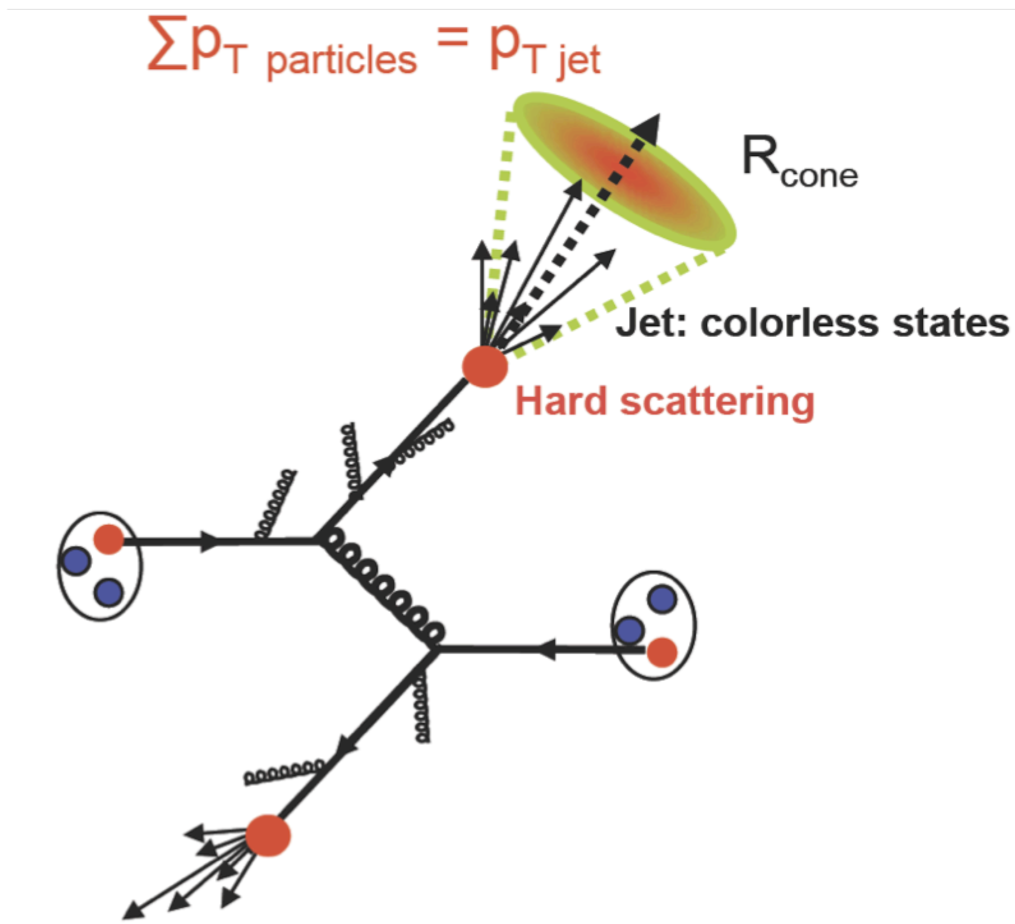
What is a jet?

A spray of collimated showers/particles
- Hardly ever better defined...

Jet = Parton AND its radiation

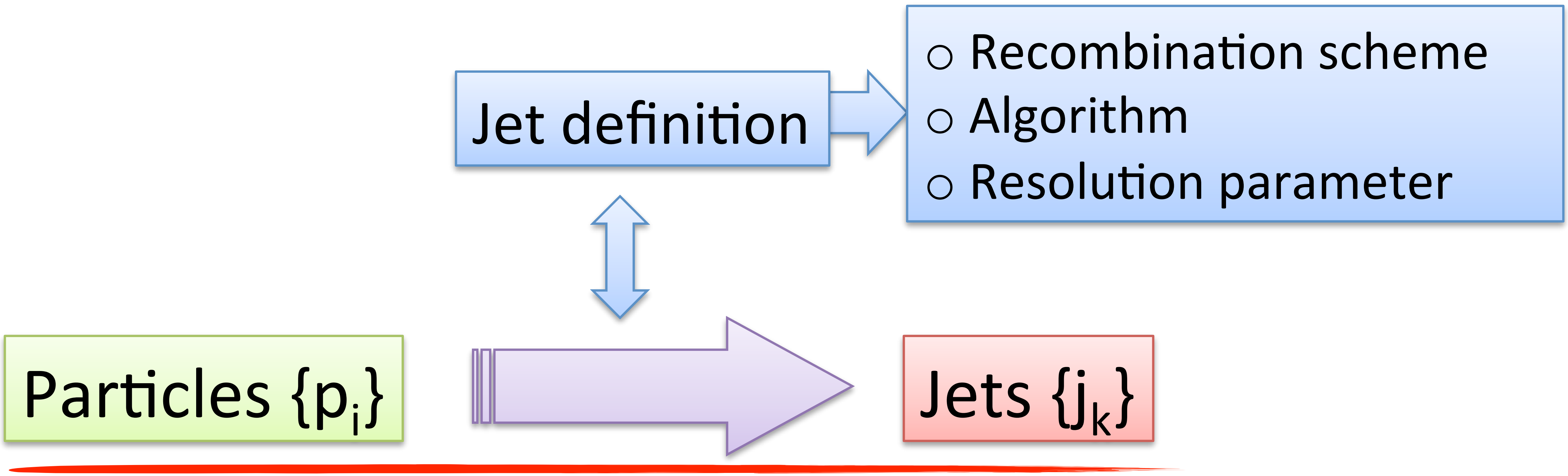
Note: experiment measures spray of particles (~hadrons)

Jets (unlike single hadrons) are objects which are "better" understood/calculable within pQCD



S.D Drell, D.J.Levy and T.M. Yan, Phys. Rev. **187**, 2159 (1969)
N. Cabibbo, G. Parisi and M. Testa, Lett. Nuovo Cimento **4**,35 (1970)
J.D. Bjorken and S.D. Brodsky, Phys. Rev. D 1, 1416 (1970)
Sterman and Weinberg, Phys. Rev. Lett. 39, 1436 (1977) ...

Jet finding



Note: jets originate from hard partons, however definition of a parton in terms of a jet is ambiguous -> multiple jet definitions.

Optimum jet finder algorithm

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

Tevatron 1990

... and infrared safe and colinear safe (~2000)

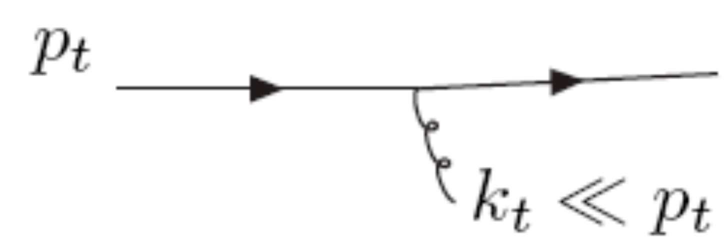
QCD divergencies and jet finders

QCD probability for gluon bremsstrahlung at angle θ and $\perp$-mom. k_t:

$$dP \propto \alpha_s \frac{d\theta}{\theta} \frac{dk_t}{k_t}$$

Two divergences:

Collinear

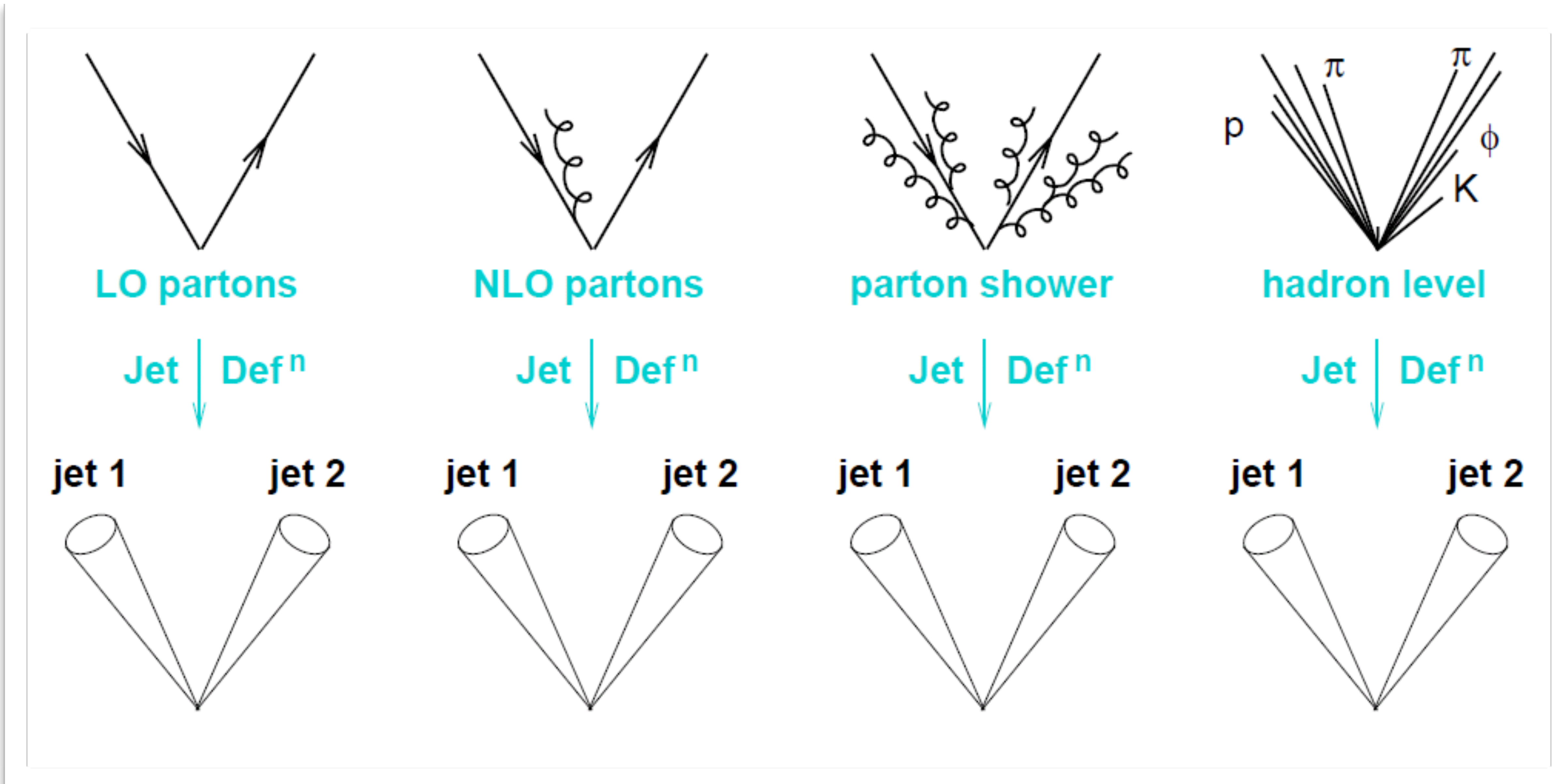


Soft

For pQCD to make sense, the (hard) jets should not change when

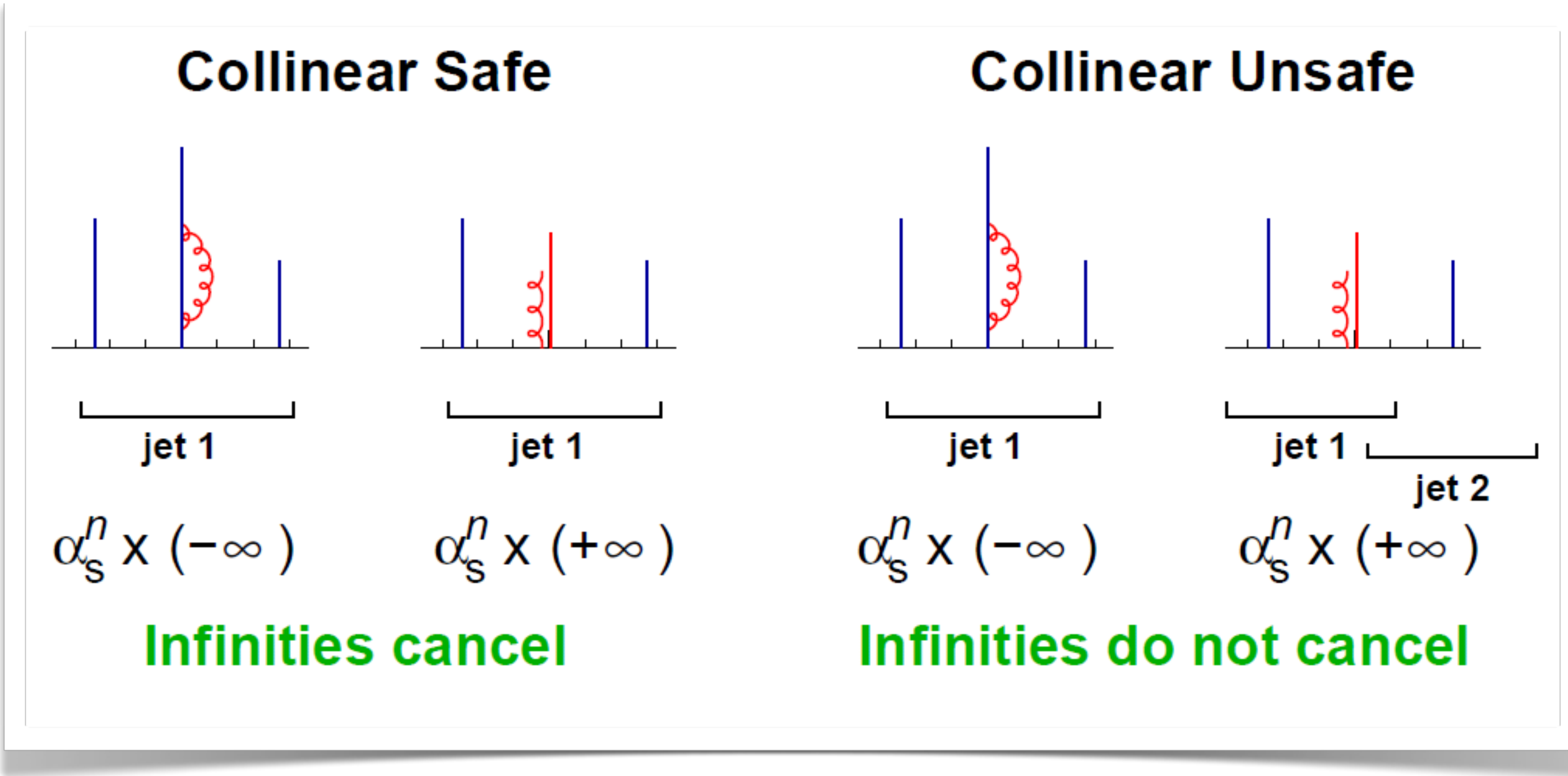
- one has a collinear splitting
  i.e. replaces one parton by two at the same place (η, ϕ)
- one has a soft emission *i.e.* adds a very soft gluon

Jet algorithms: Colinear & infra-red safety



Safety: Results = jets = reconstructed objects - insensitive to modifications at the soft scale of radiation (hadronization, soft colin. radiation)

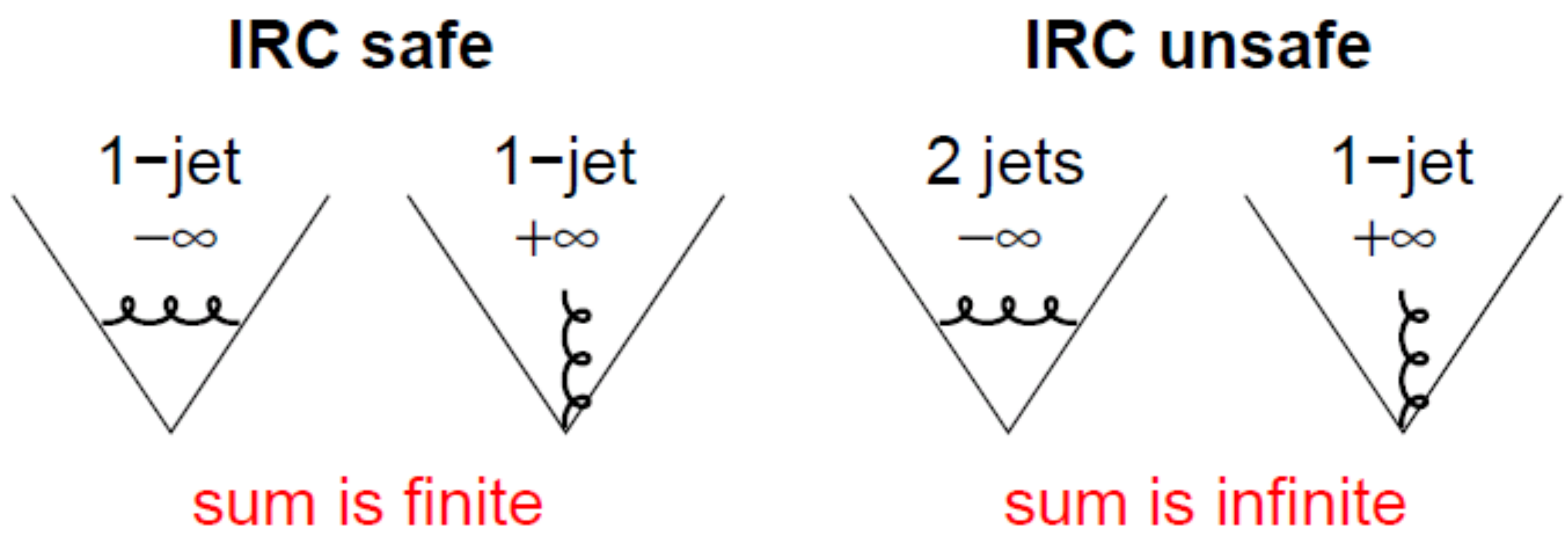
Collinear safety



Infrared safety

Soft emission, collinear splitting are both **infinite** in pert. QCD.

Infinities **cancel** with loop diagrams if jet-alg IRC safe

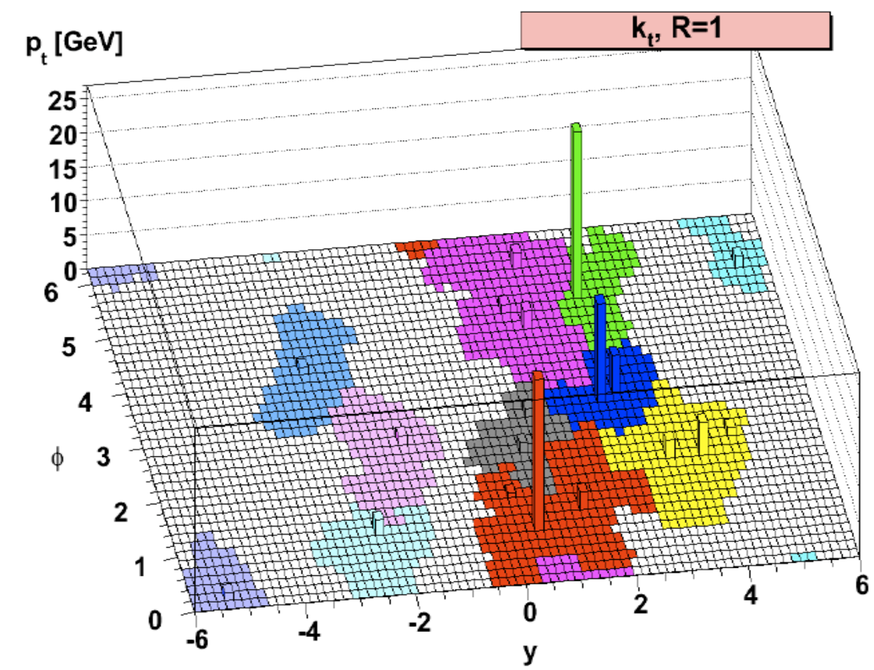


Some calculations simply become **meaningless**

Infrared safety also implies robustness against soft background in heavy ion collisions

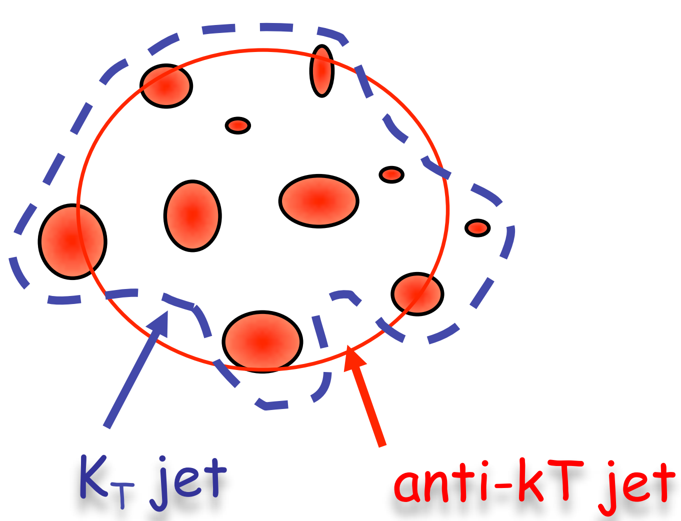
Modern jet algorithms

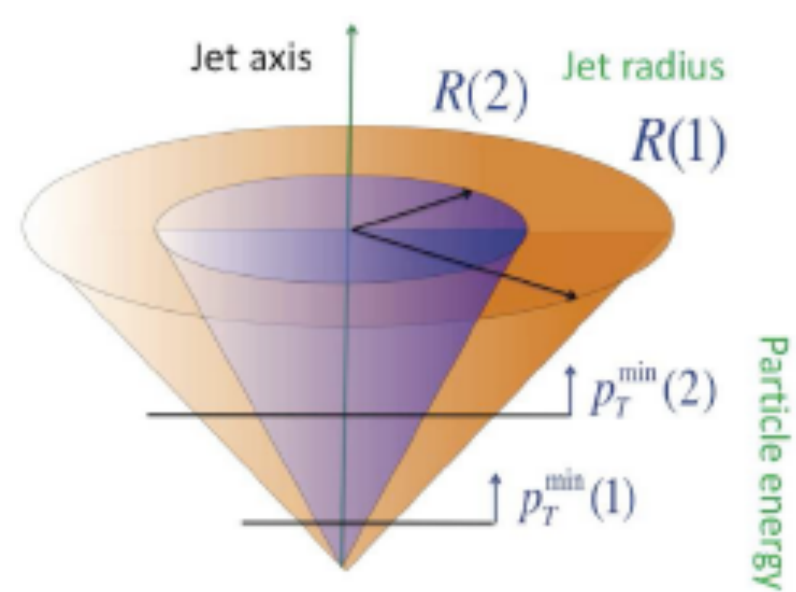
- Colinear and infrared safe
- Improved performance
- Rigorous definition of jet area
- Different algorithms -> different response to the underlying event
  - Developed for uniform bg subtraction (pile-up) at LHC



Two main classes of algorithms:

recombination (kt, Cambridge/Aachen, anti-kt) and cone (Mid point cone, CDF, SIScone)





Sequential recombination (clustering) algorithms

Majority of QCD branching is soft & collinear, with following divergences:

$$[dk_j]|M^2_{g\to g_i g_j}(k_j)| \simeq \frac{2\alpha_s C_A}{\pi} \frac{dE_j}{\min(E_i, E_j)} \frac{d\theta_{ij}}{\theta_{ij}}, \qquad (E_j \ll E_i\,, \;\; \theta_{ij} \ll 1)\,.$$

To invert branching process, take pair with strongest divergence between them — they're the most *likely* to belong together.

This is basis of **k_t/Durham algorithm** (e^+e^-):

1. Calculate (or update) distances between all particles i and j:

$$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{Q^2}$$

NB: relative k_t between particles

2. Find smallest of y_{ij}
   - If $> y_{cut}$, stop clustering
   - Otherwise recombine i and j, and repeat from step 1

Catani, Dokshitzer, Olsson, Turnock & Webber '91

Example: k_T algorithm

1.1 k_t jet algorithm

The definition of the inclusive k_t jet algorithm that is coded is as follows:

1. For each pair of particles i, j work out the k_t distance

$$d_{ij} = \min(k_{ti}^2, k_{tj}^2)\, \Delta R_{ij}^2 / R^2 \tag{1}$$

   with $\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$, where k_{ti}, y_i and ϕ_i are the transverse momentum, rapidity and azimuth of particle i and R is a jet-radius parameter usually taken of order 1; for each parton i also work out the beam distance $d_{iB} = k_{ti}^2$.

2. Find the minimum $d_{\min}$ of all the d_{ij}, d_{iB}. If $d_{\min}$ is a d_{ij} merge particles i and j into a single particle, summing their four-momenta (this is E-scheme recombination); if it is a d_{iB} then declare particle i to be a final jet and remove it from the list.

3. Repeat from step 1 until no particles are left.

Anti-kt: k_t^2 is replaced by k_t^{-1}

M. Cacciari, G. P. Salam, G. Soyez JHEP 0804:063,2008. e-Print: arXiv:0802.1189 [hep-ph]

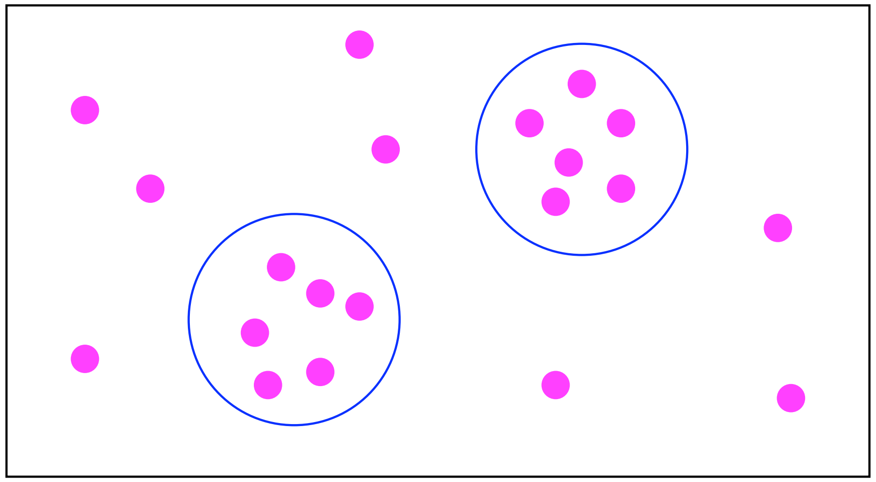
Cone algorithms

Jet Cones

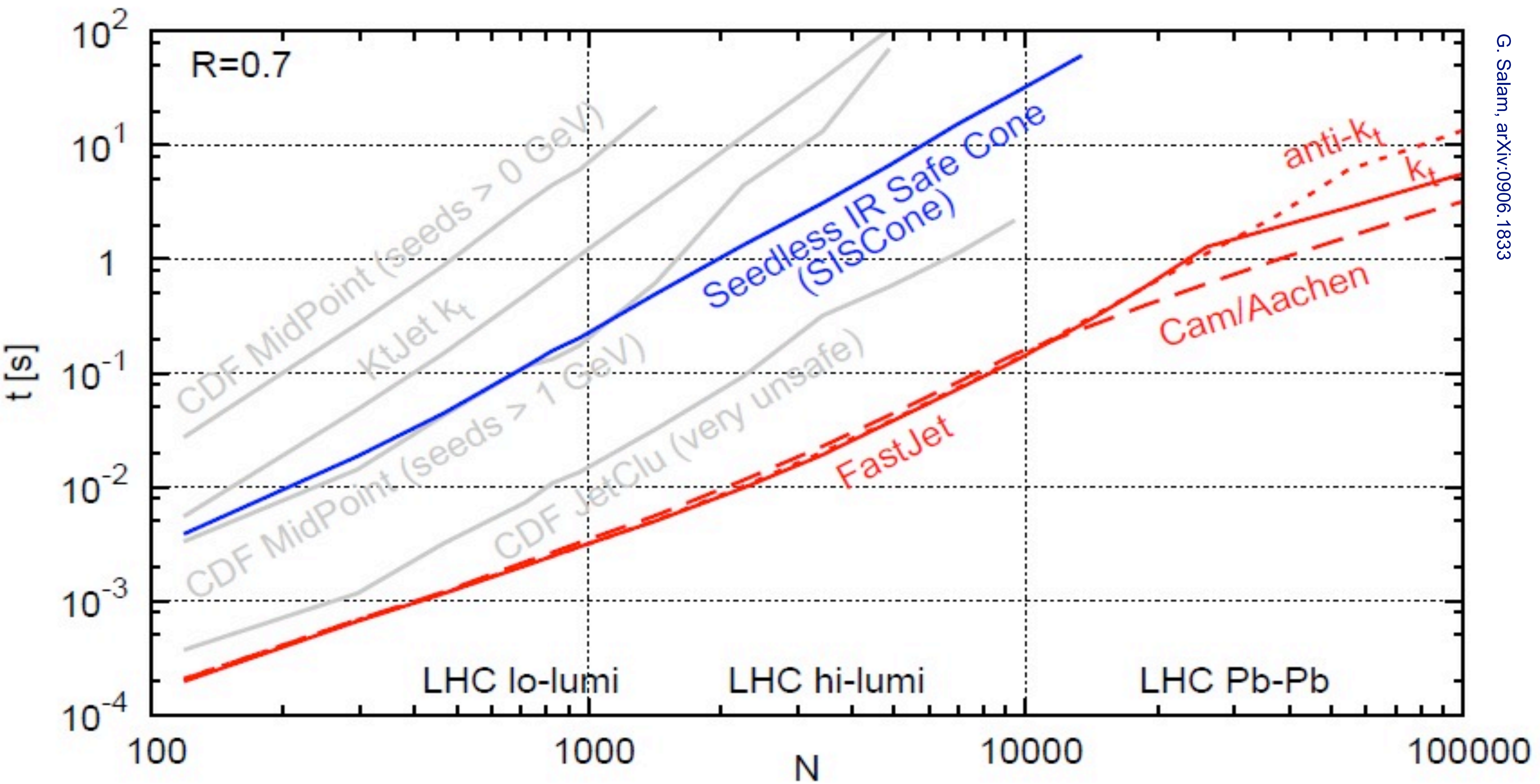
- Cones are always understood as circles in rapidity (y) and azimuth ϕ.
- A particle i is within the cone of radius R around the axis a if
  - $\Delta R^2_{ia} = (y_i - y_a)^2 + (\phi_i - \phi_a)^2 < R^2$
  - ... usual hadron collider variables
- Typical: R = 0.4 - 0.7

Basic Idea:

- Find directions of dominant energy flow " find ALL stable cones
- center of the cone ≡ direction of the total momentum of its particle contents



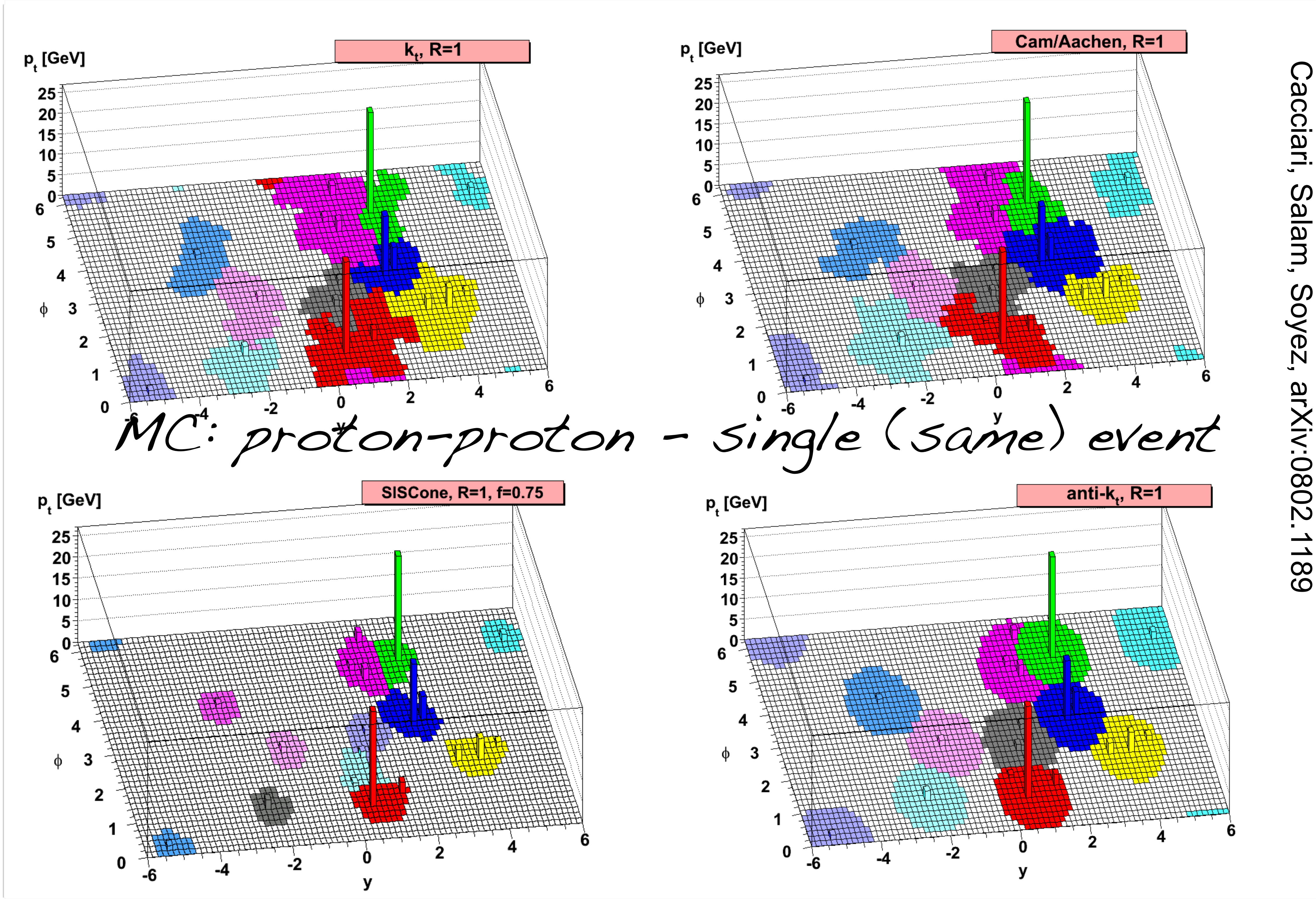
Speed matters!



FJ: Significant gain for high-multiplicities

Jet finding - jet finders

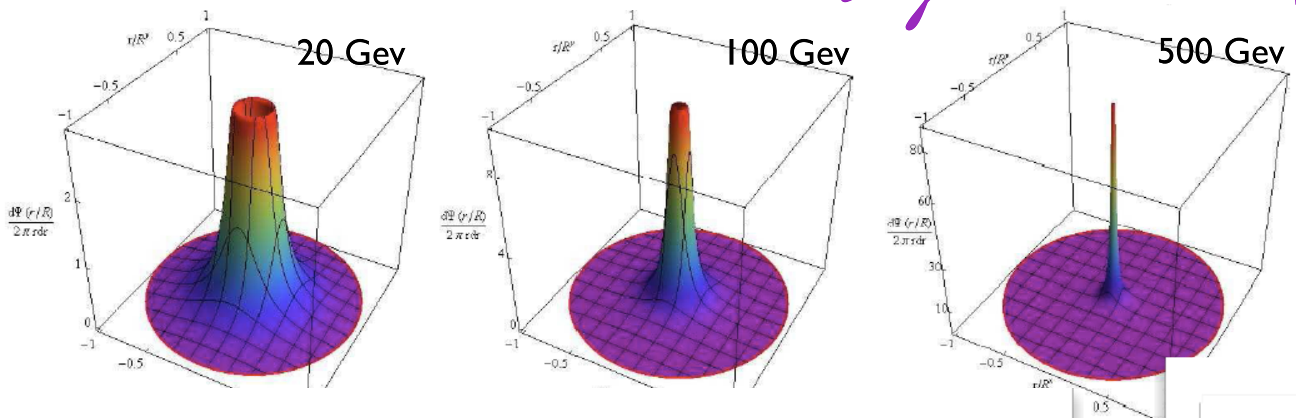
Complete suite of algorithms - FastJet package: http://www.lpthe.jussieu.fr/~salam/fastjet/

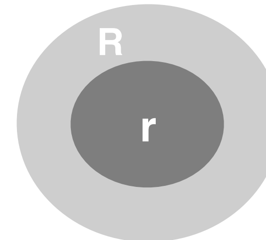


MC: proton-proton - single (same) event

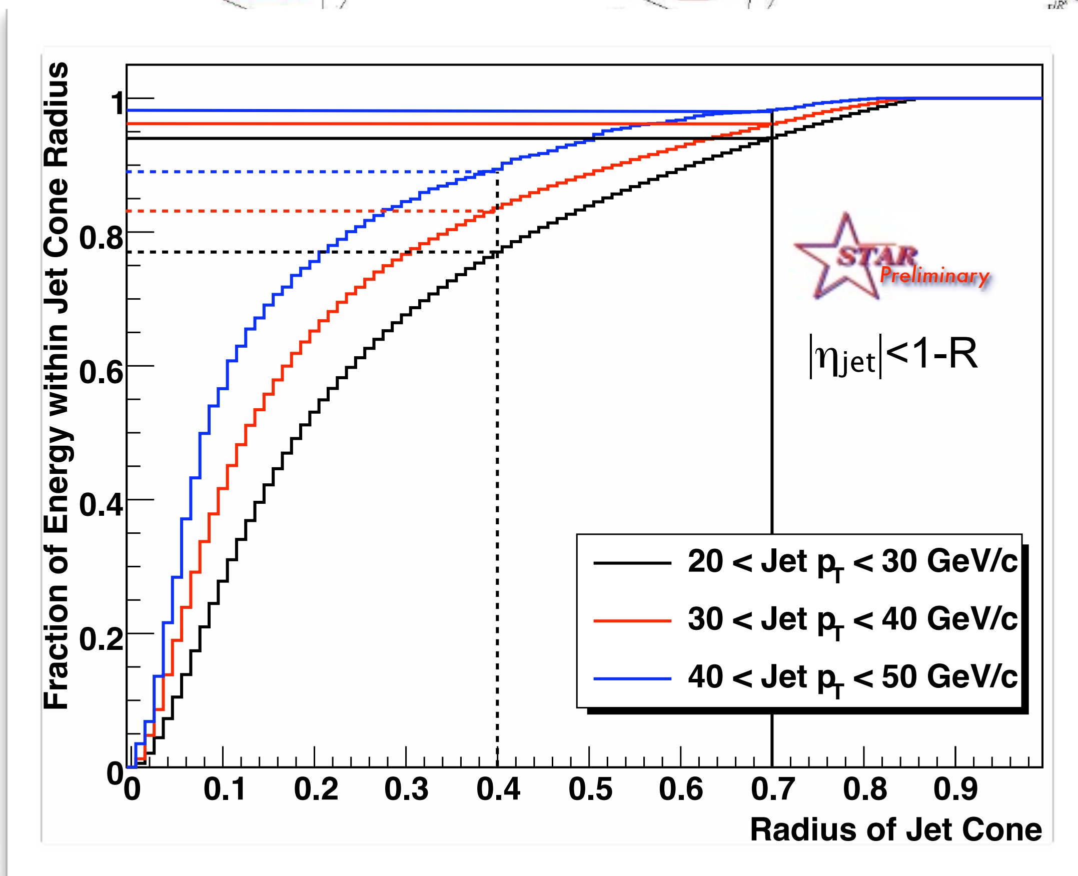
Cacciari, Salam, Soyez, arXiv:0802.1189

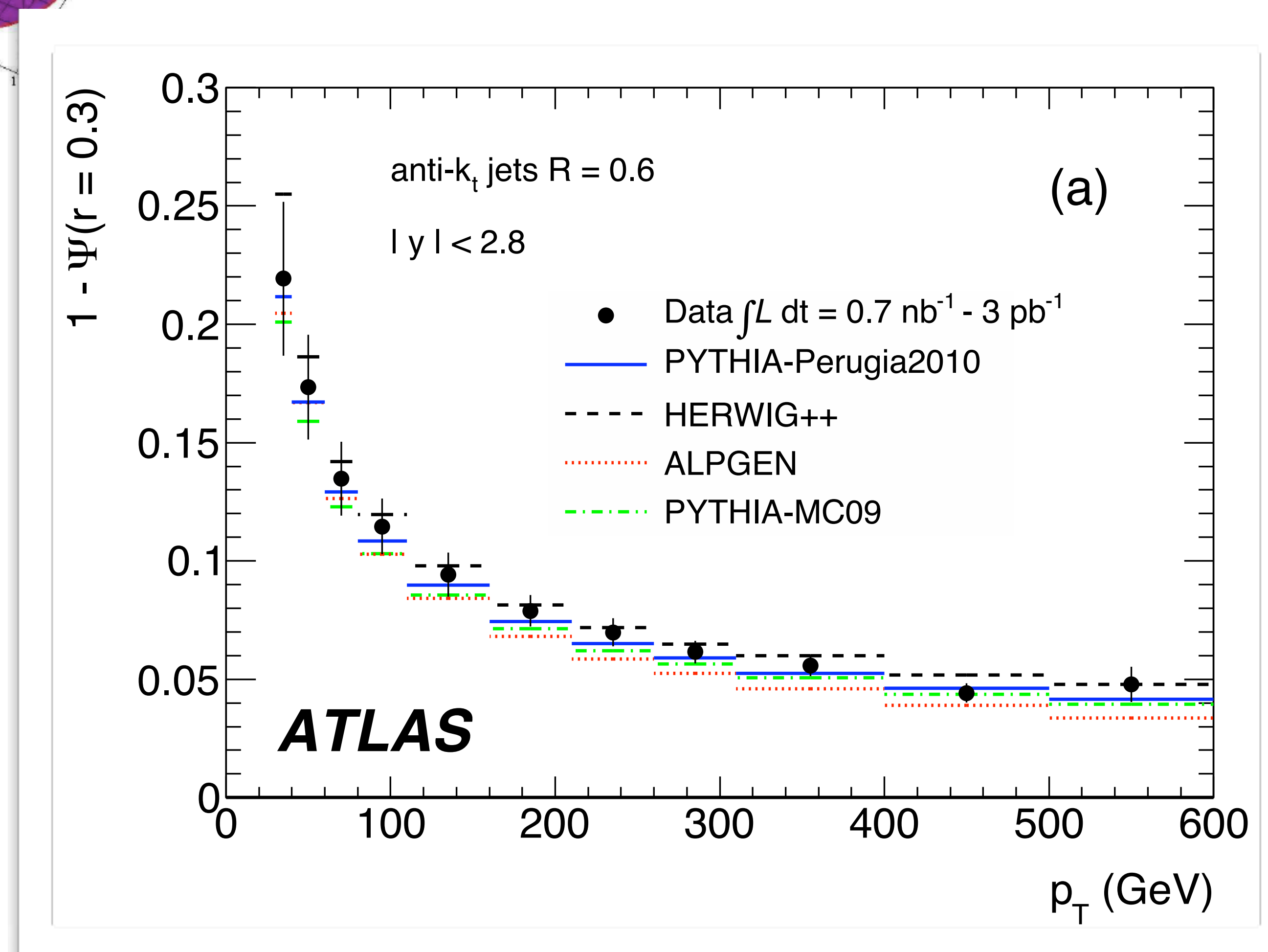
Jet shape - R-dependence





$$\Psi(r) = \frac{1}{N^{\text{jet}}} \sum_{\text{jets}} \frac{p_T(0,r)}{p_T(0,R)}$$





Jets get more collimated/narrower with increasing jet energy

Energy - integrated within a smaller R - depends on R!

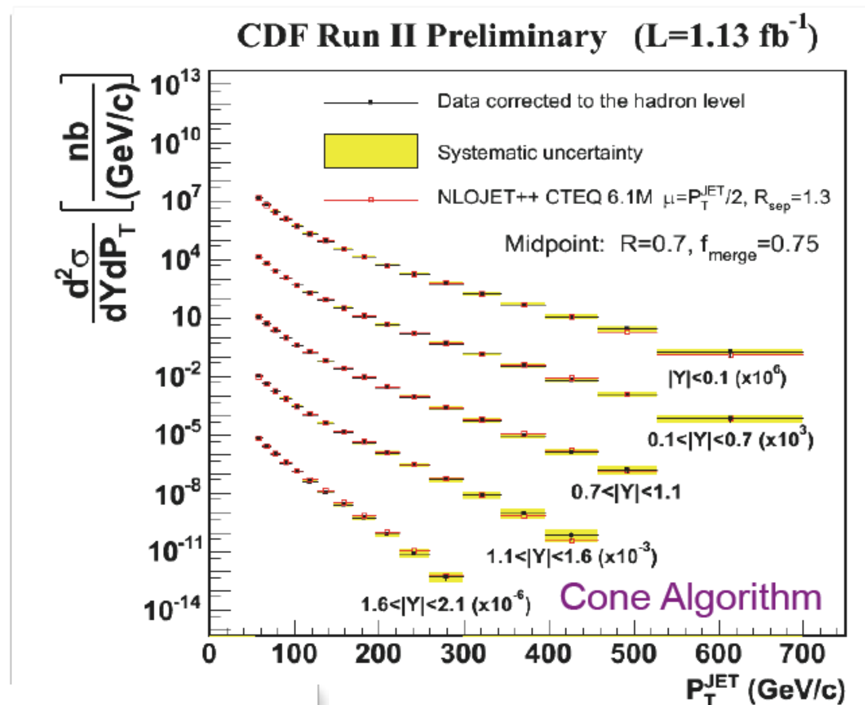
=> importance of the jet definition

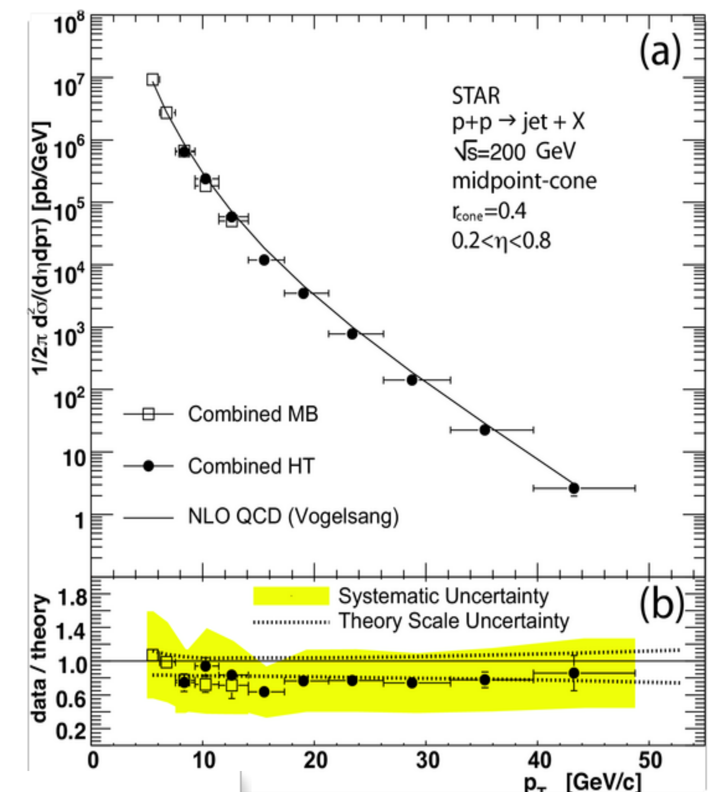
Experiment & Theory must use the same definitions

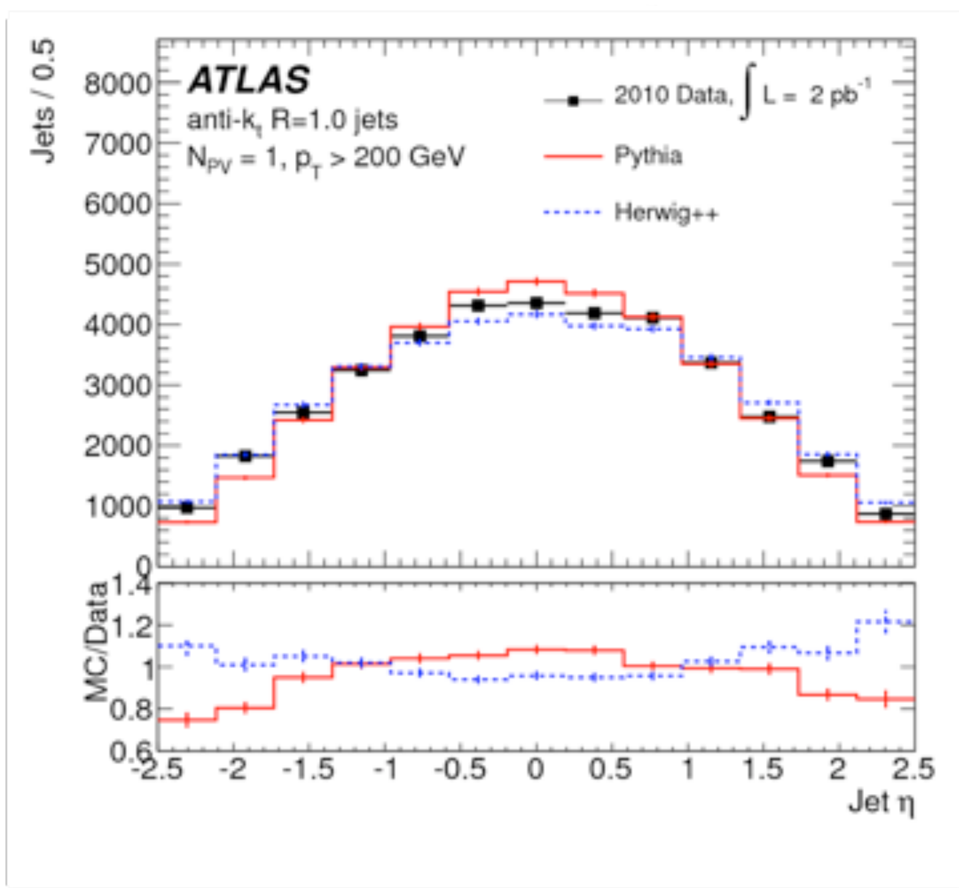
Jets in collider experiments

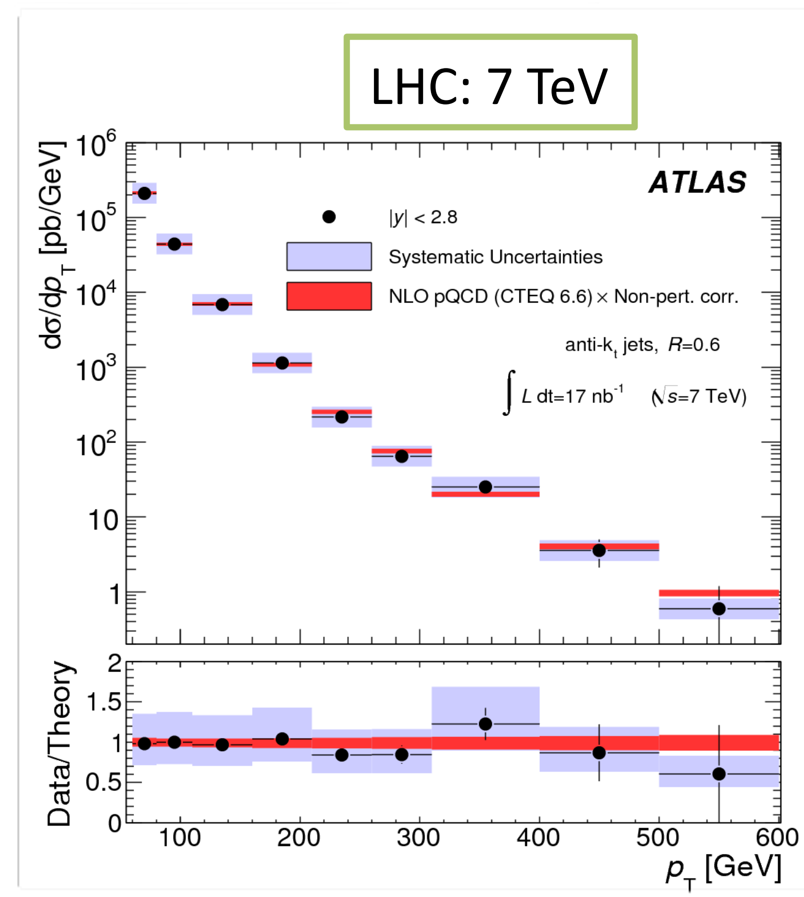
Jets are fairly well known by now... and well described by theory and MC

=> attractive tool for heavy-ions









Hadronic collisions: pQCD and jets

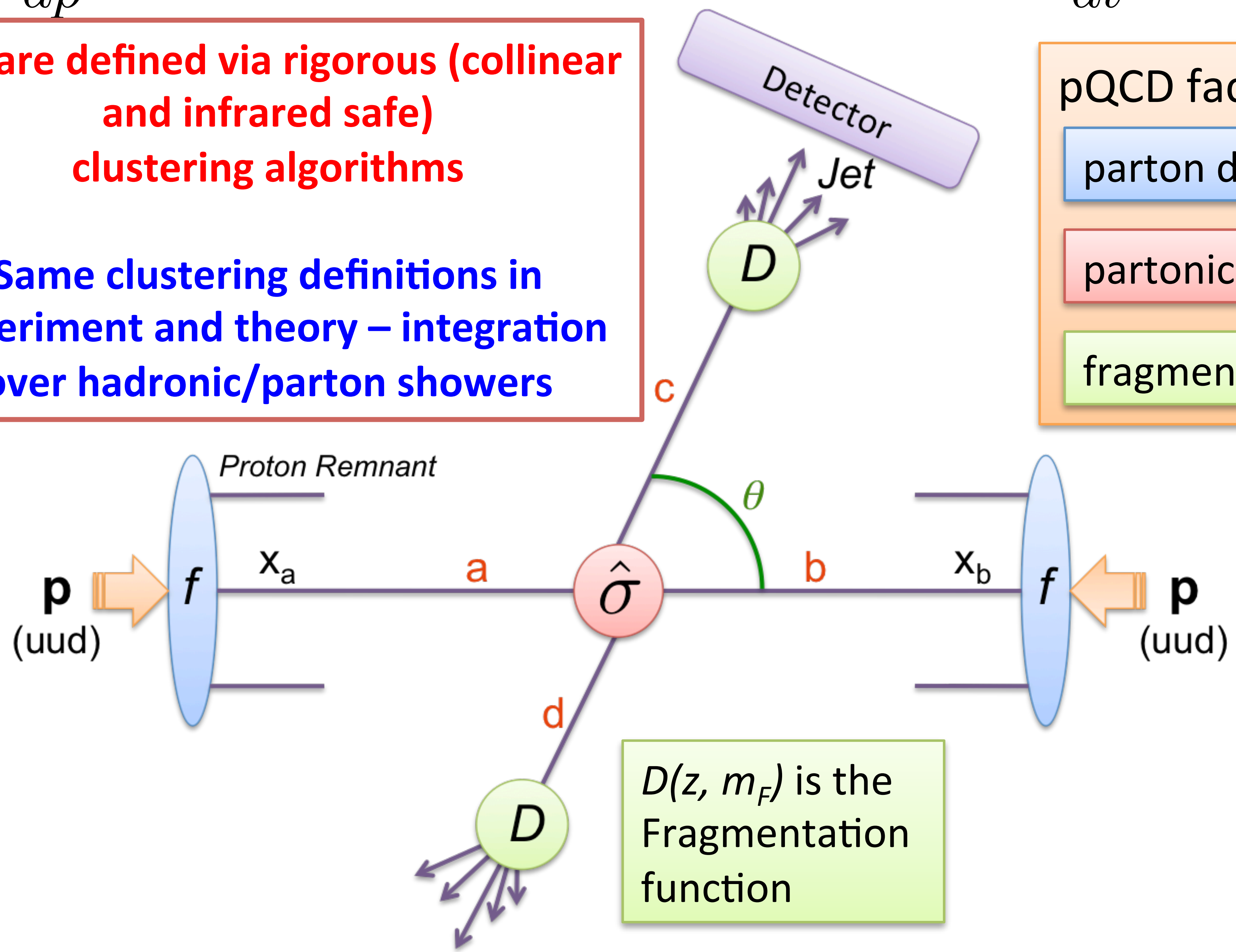
$$E\frac{d^3\sigma}{dp^3} \propto f_{a/A}(x_a, Q^2) \otimes f_{b/B}(x_b, Q^2) \otimes \frac{d\hat{\sigma}^{ab\to cd}}{dt} \otimes D_{h/c}(z_c, Q^2)$$

Jets are defined via rigorous (collinear and infrared safe) clustering algorithms

Same clustering definitions in experiment and theory – integration over hadronic/parton showers

pQCD factorization:

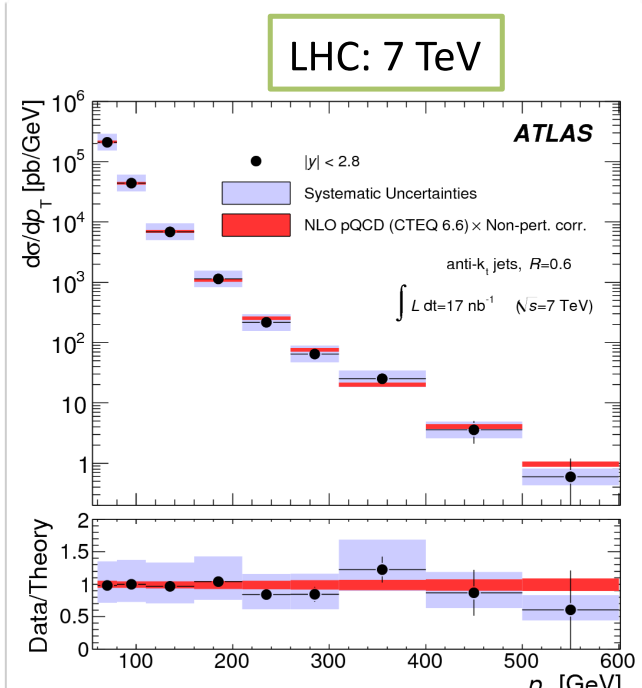
- parton distribution fn $f_{a/A}$
- partonic cross section
- fragmentation fn $D_{h/c}$

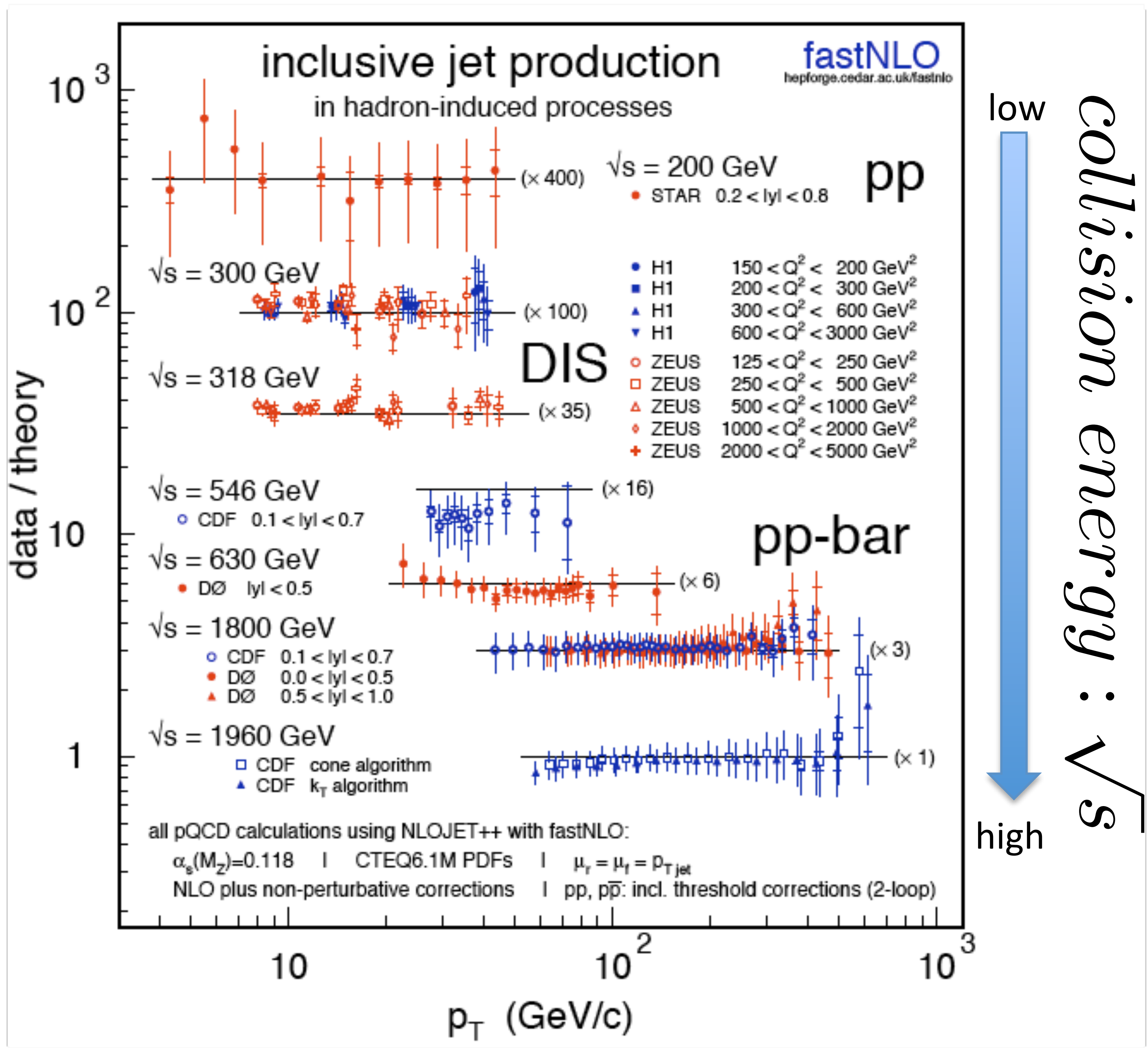


Inclusive jet production: pQCD & data

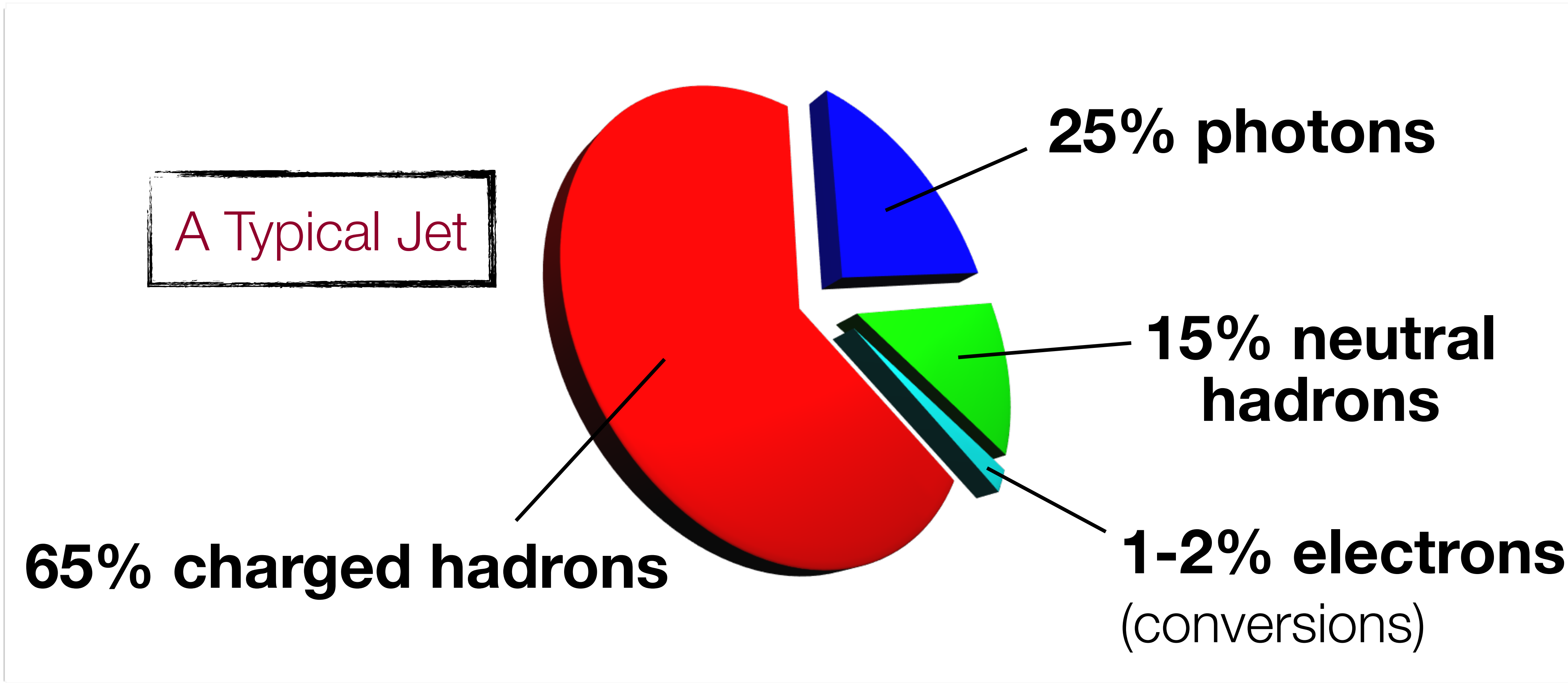
Jets are fairly well known by now... and well described by theory and MC

=> attractive tool for heavy-ions





JET composition



Measure a jet?

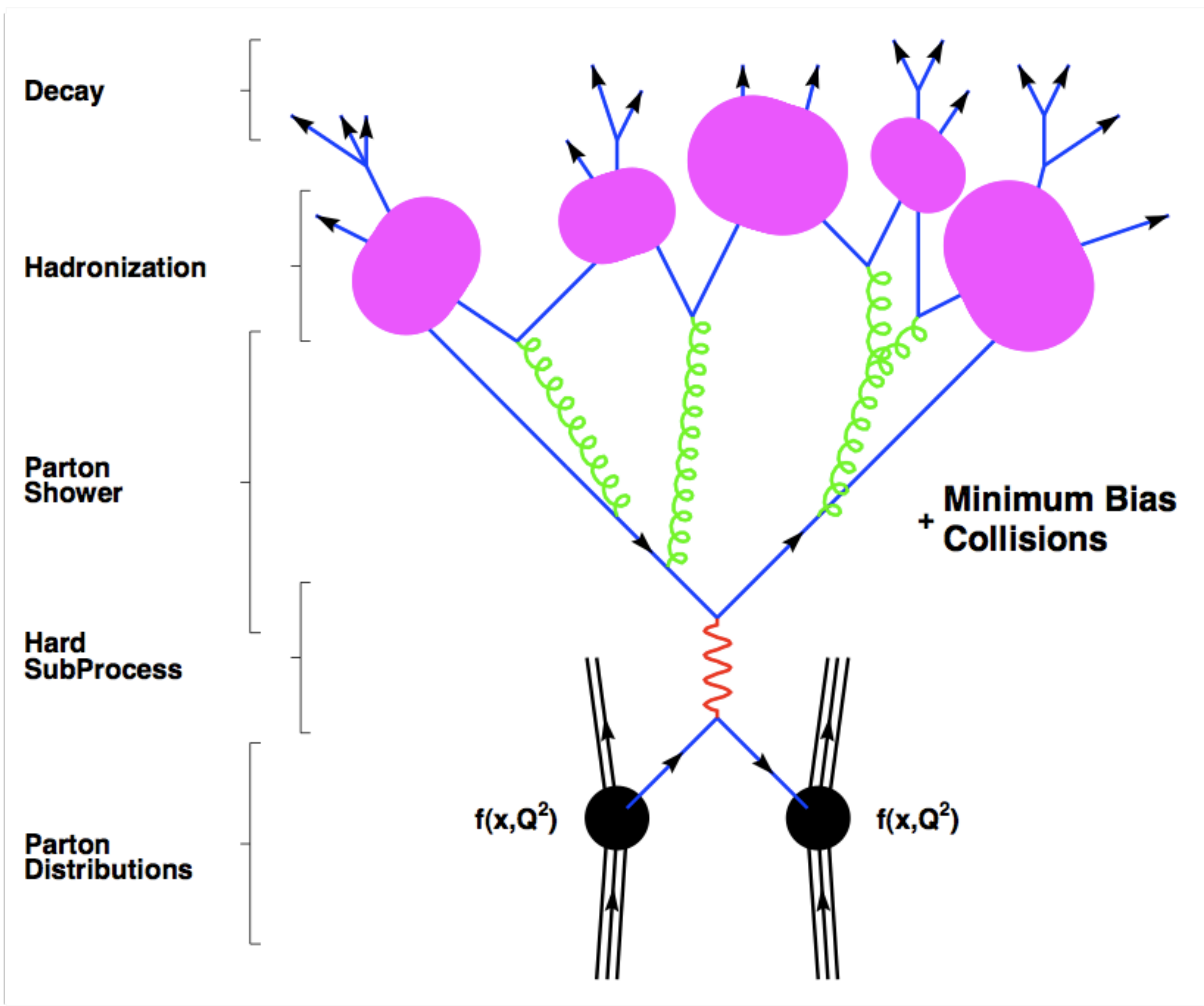
Need to have control over all components...

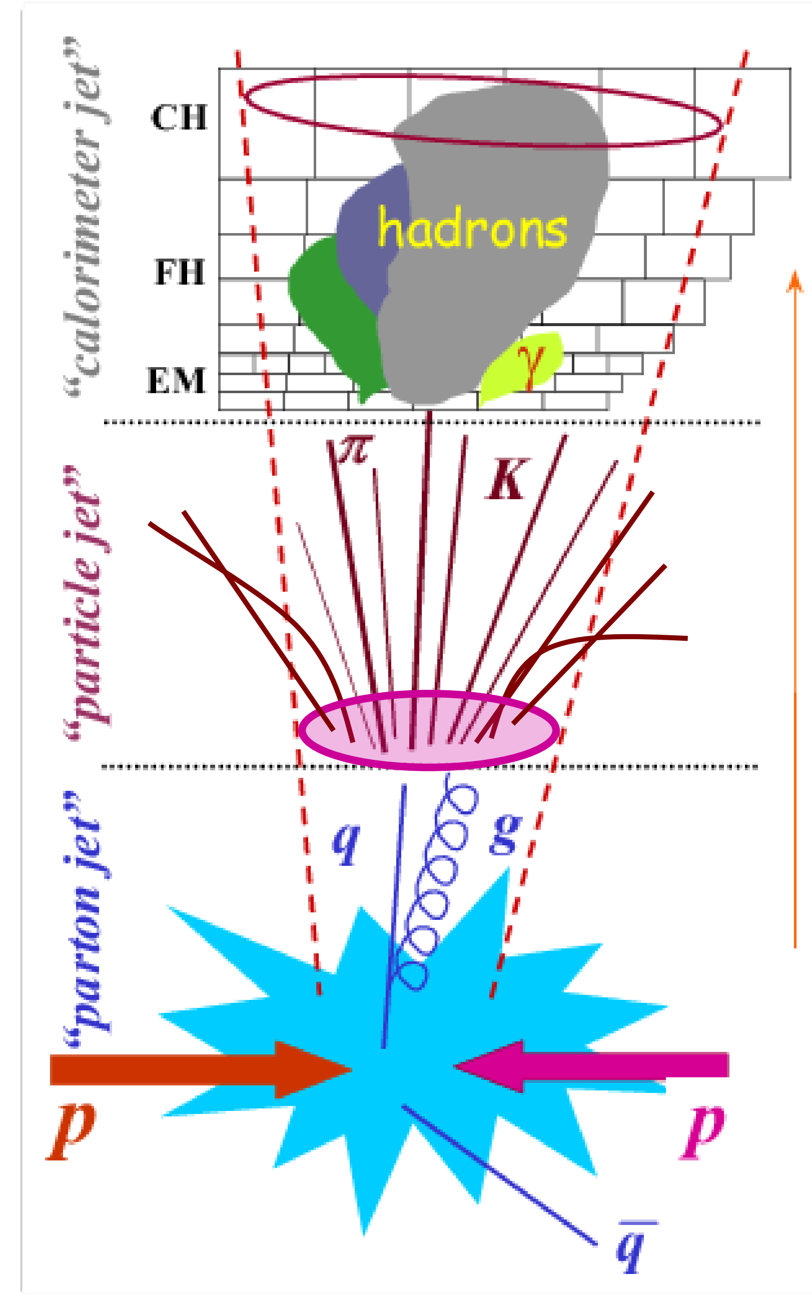
Measure or "know"

the [unknown] rest from DATA + MC

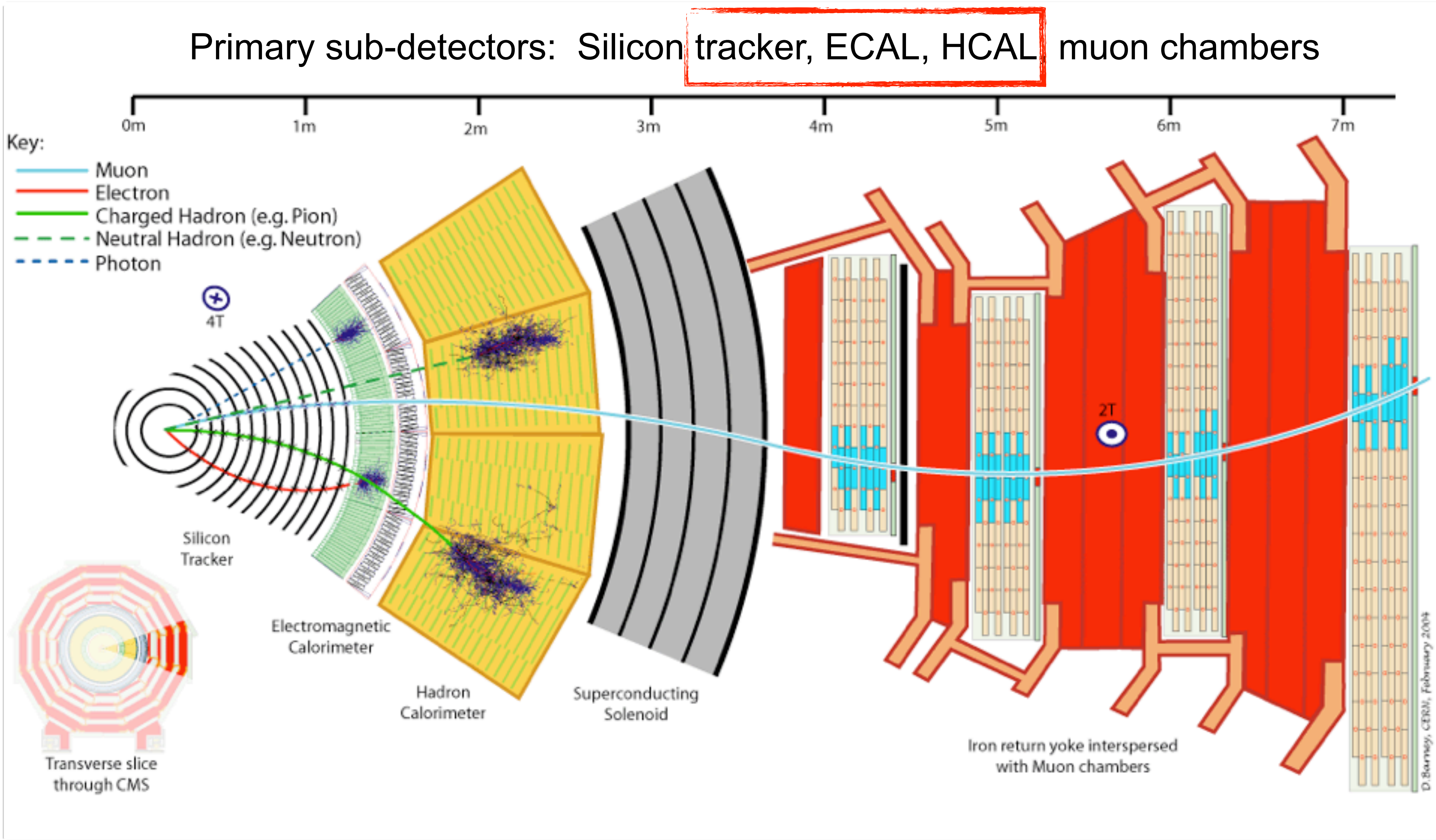
$$J(\overrightarrow{p}_{partons}) \approx J(\overrightarrow{p}_{shower}) \approx J(\overrightarrow{p}_{hadrons}) \approx J(\overrightarrow{p}_{cells/tracks})$$

Jet: from parton to detector

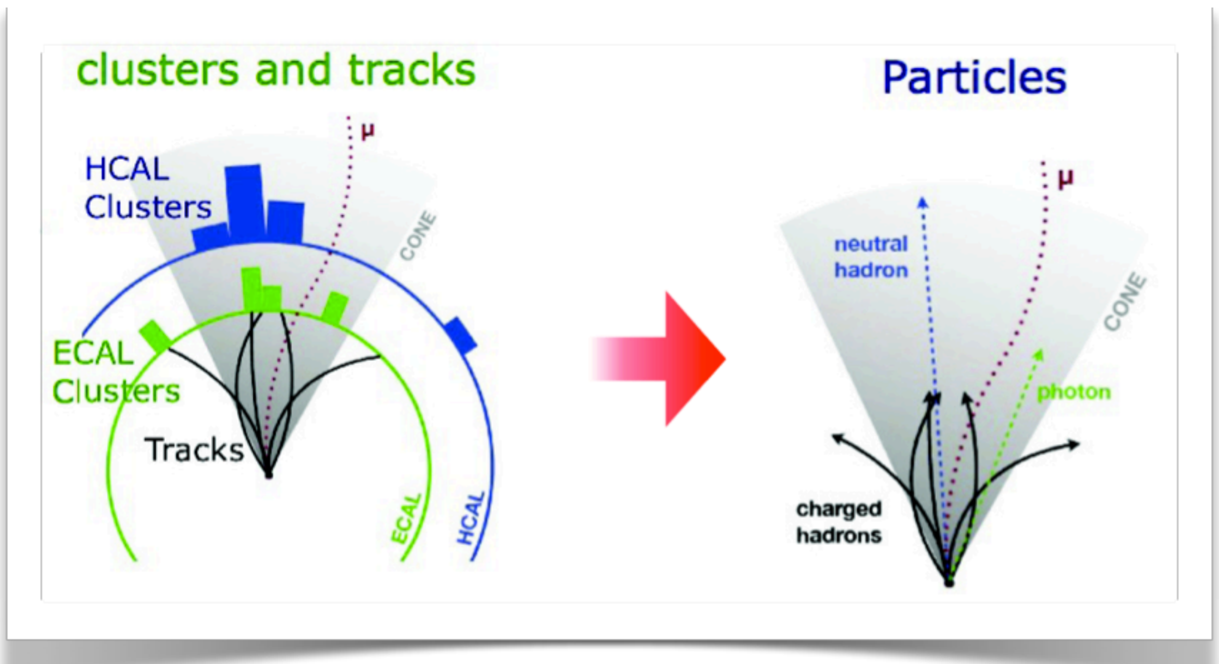




A Jet Detector

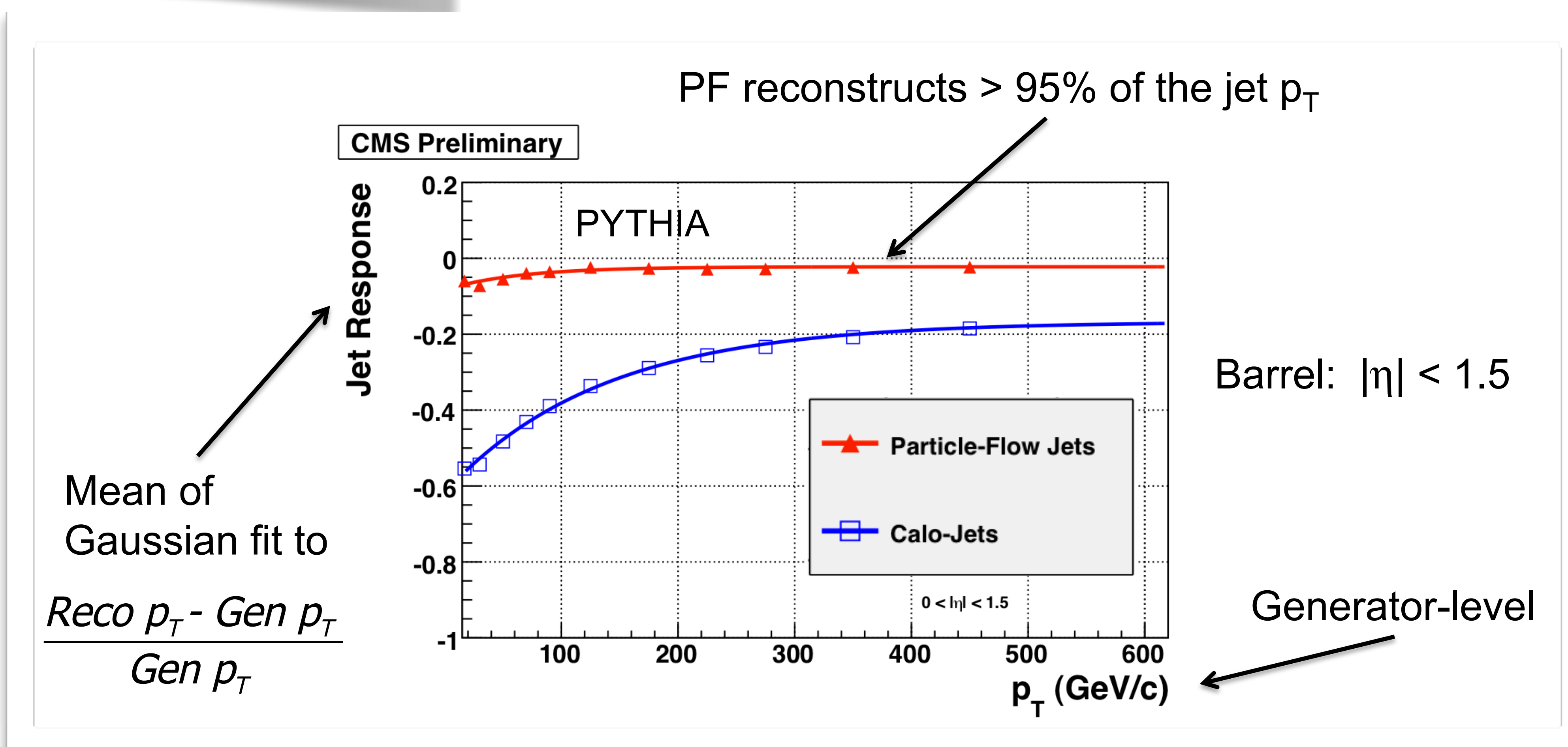


Improvements in jet reconstruction on detector level => Particle flow

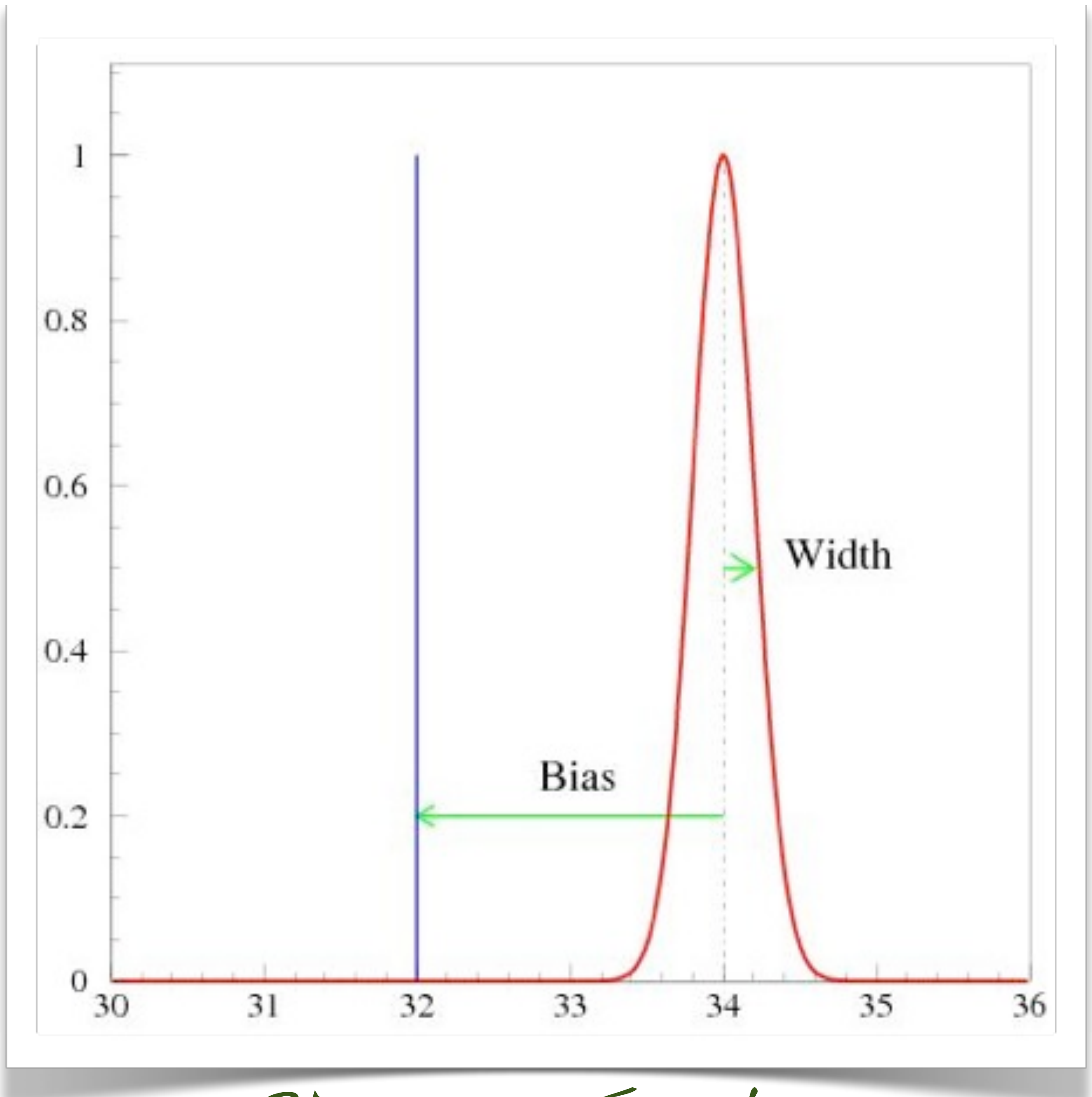


Purely calorimeter jet vs. Particle Flow jet

Better response w.r.t. calorimeter measurement => smaller jet-energy corrections



Jet: energy scale & resolution

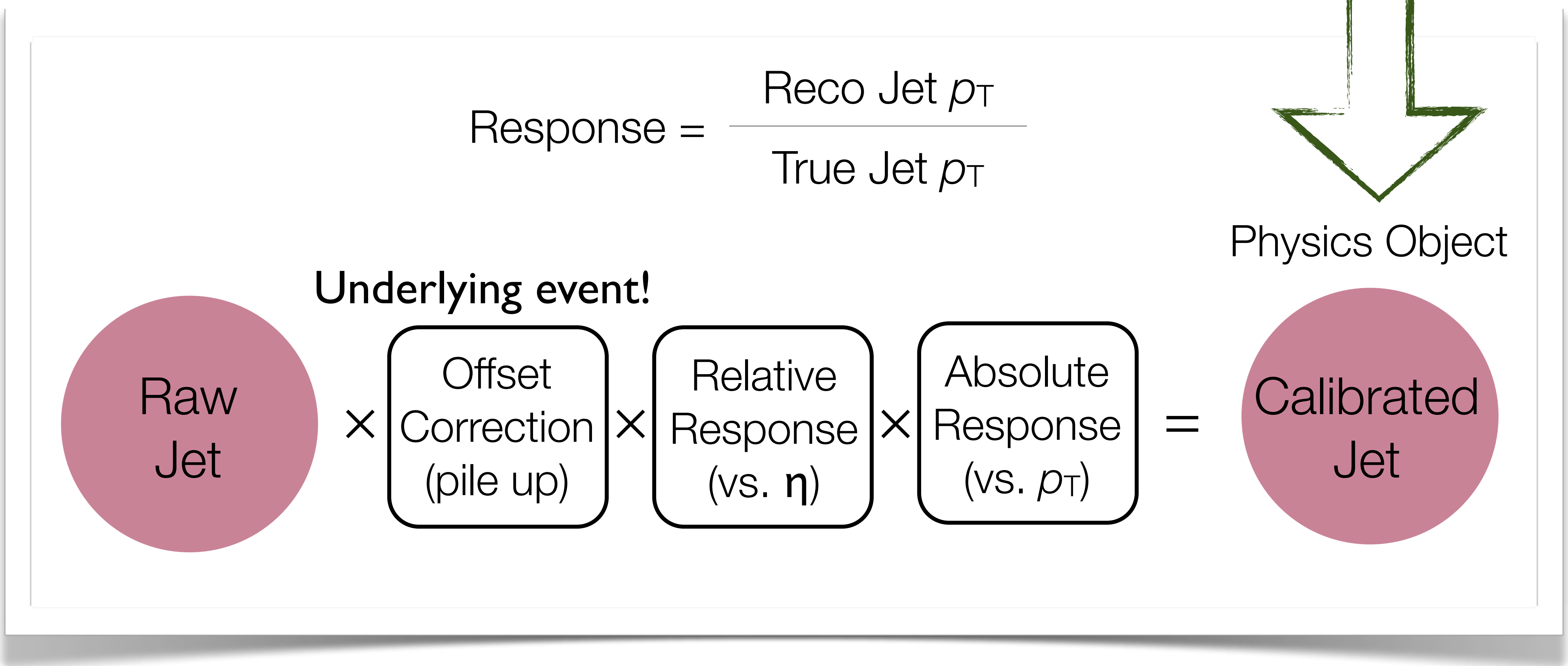


Control over the two crucial in p-p and AA collisions

Bias == Scale

Width == Resolution

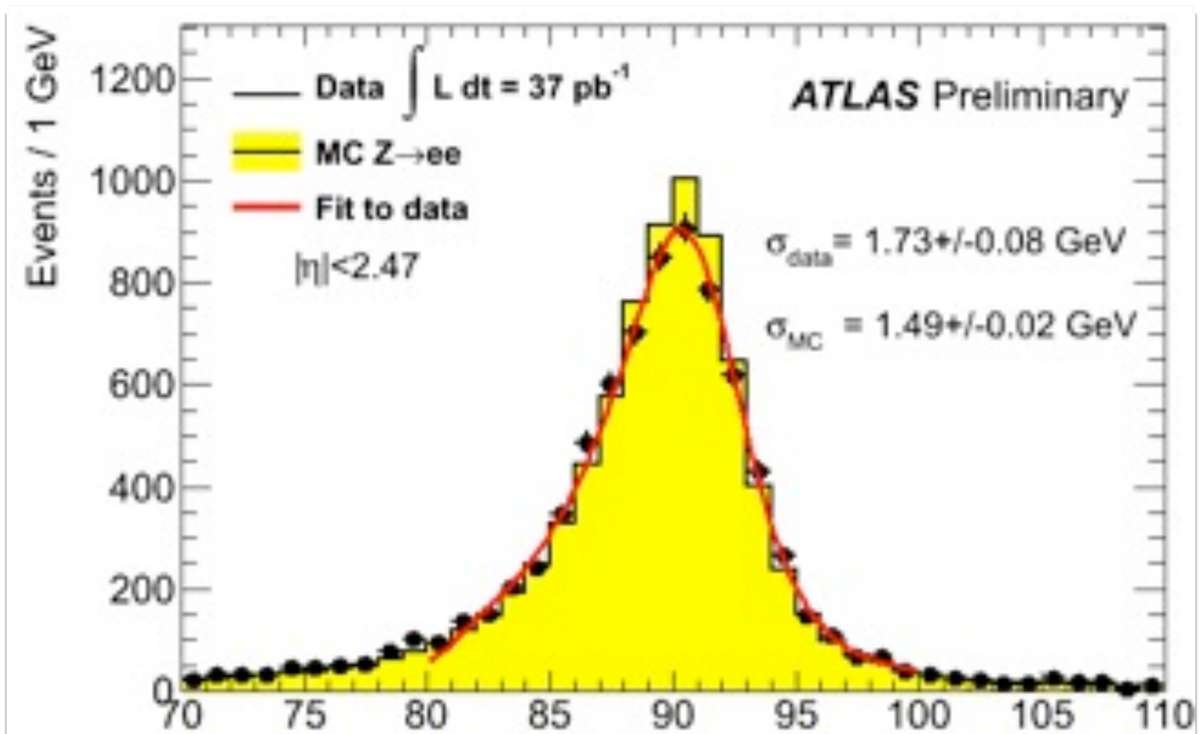
JET: From Measured to meaningful...

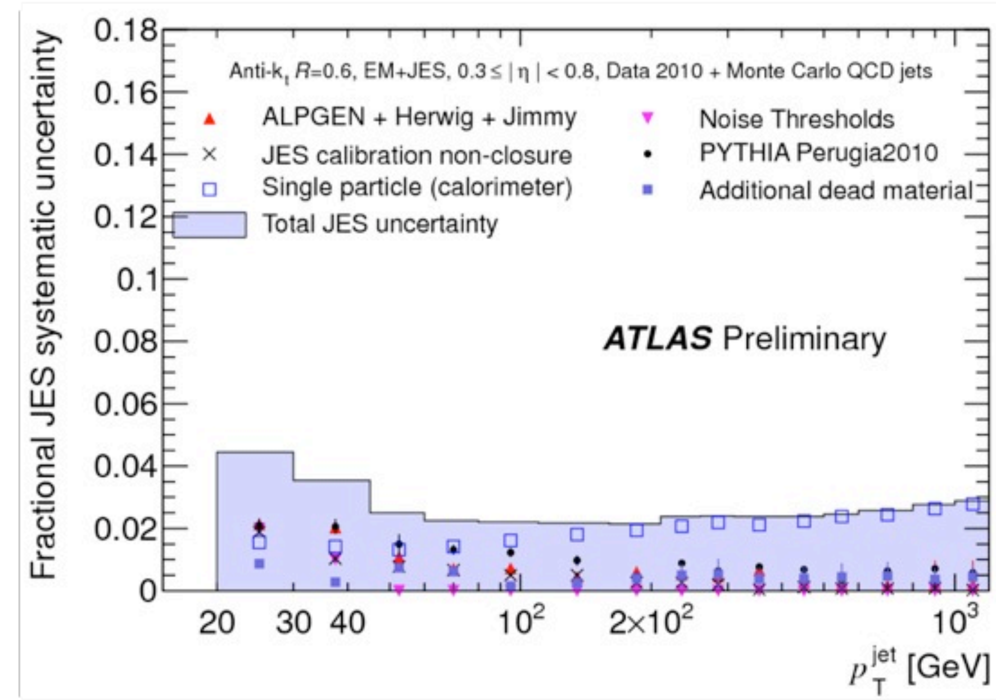


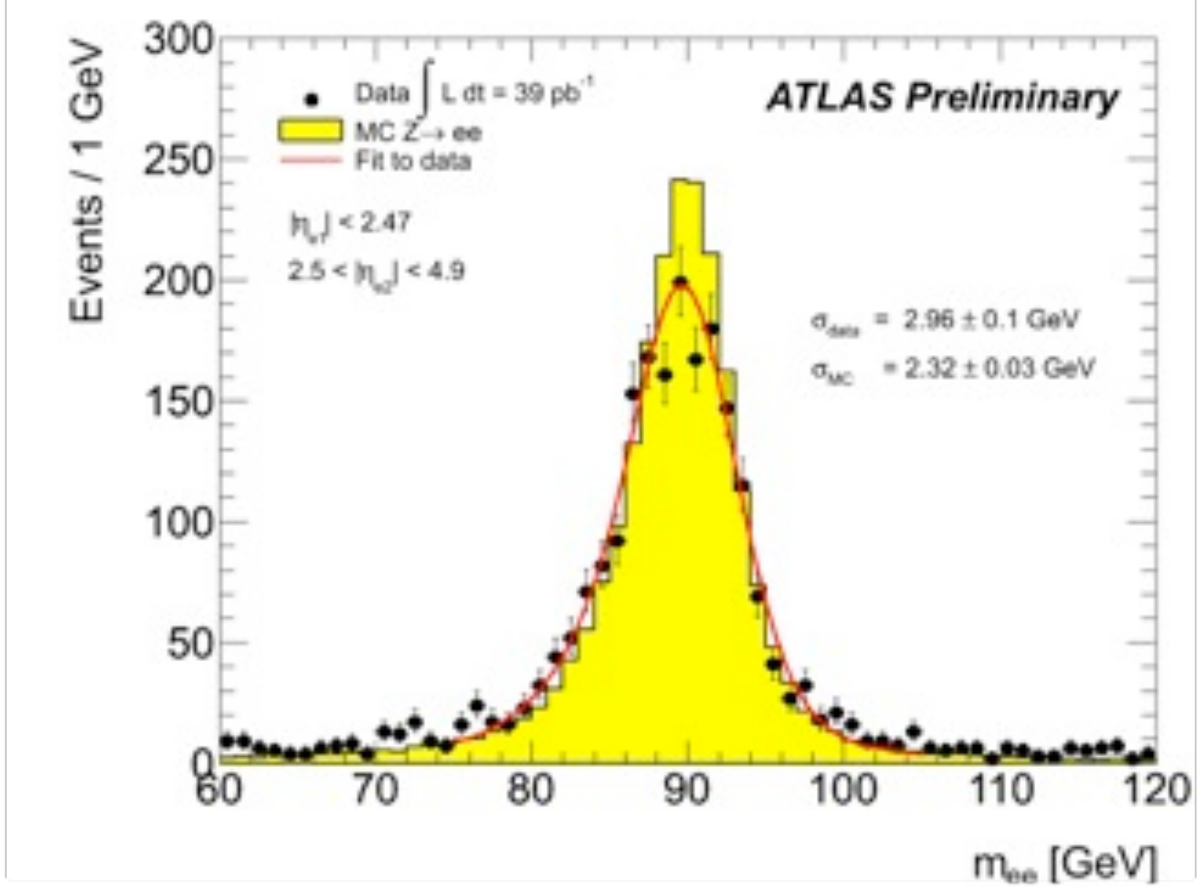
This is an experimental enterprise!

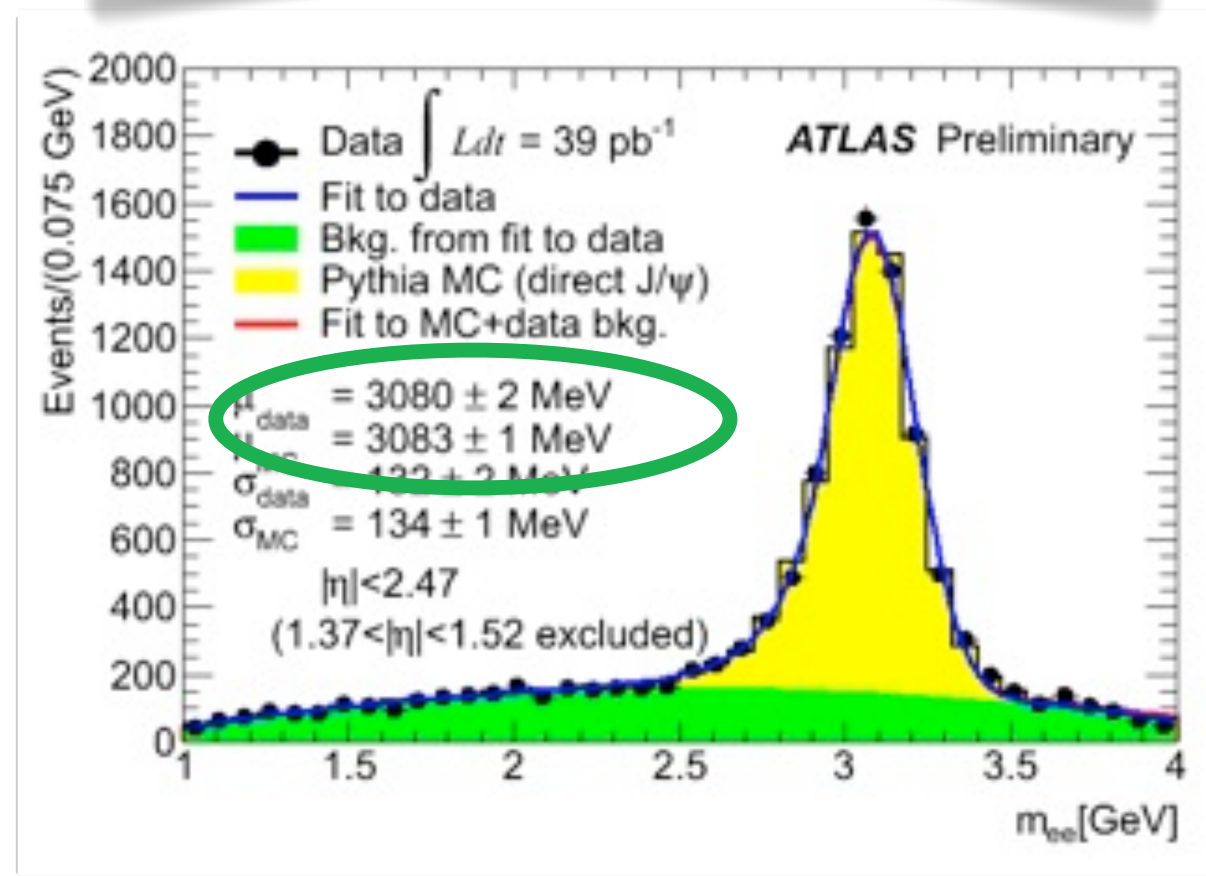
It is a substantial effort...

Control of the energy scale - ATLAS - linearity





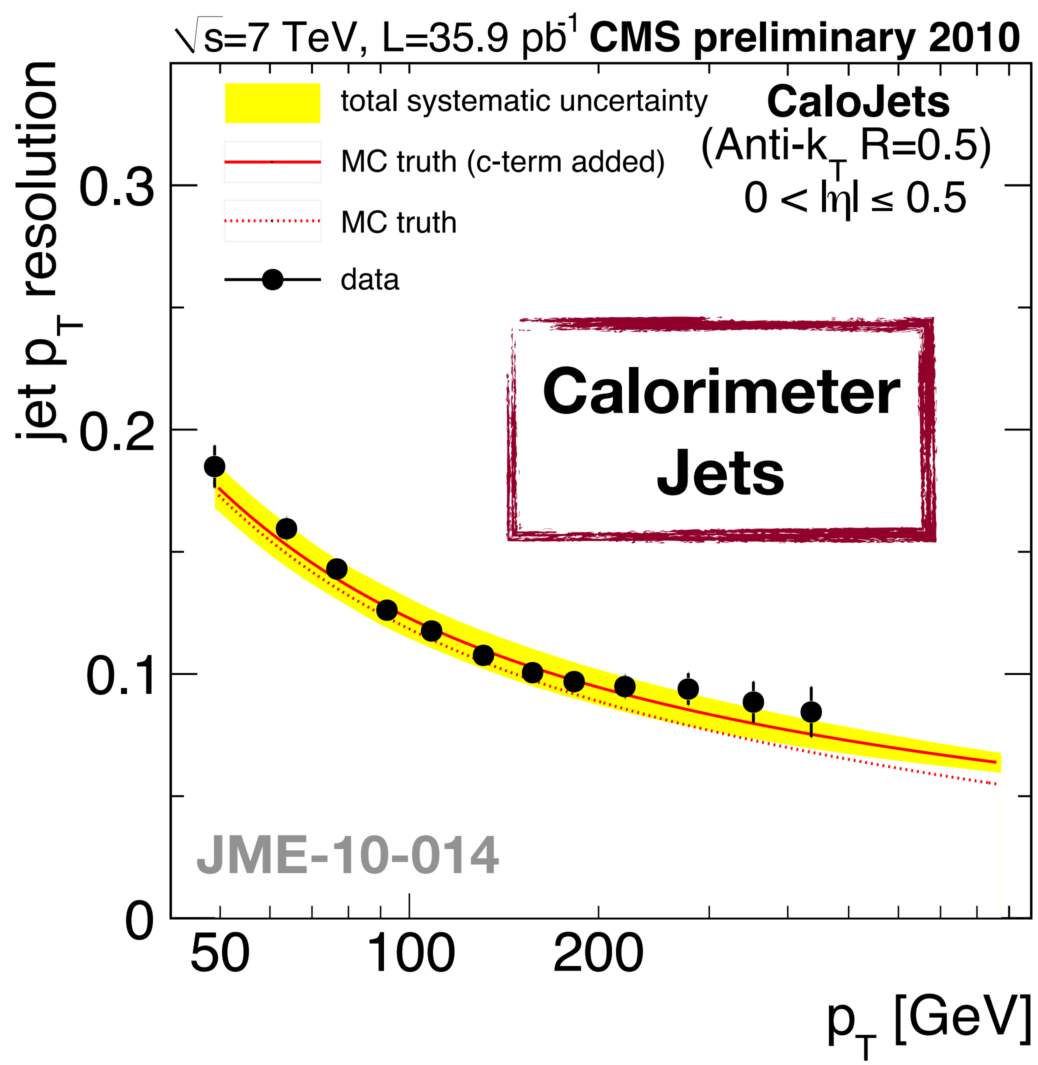


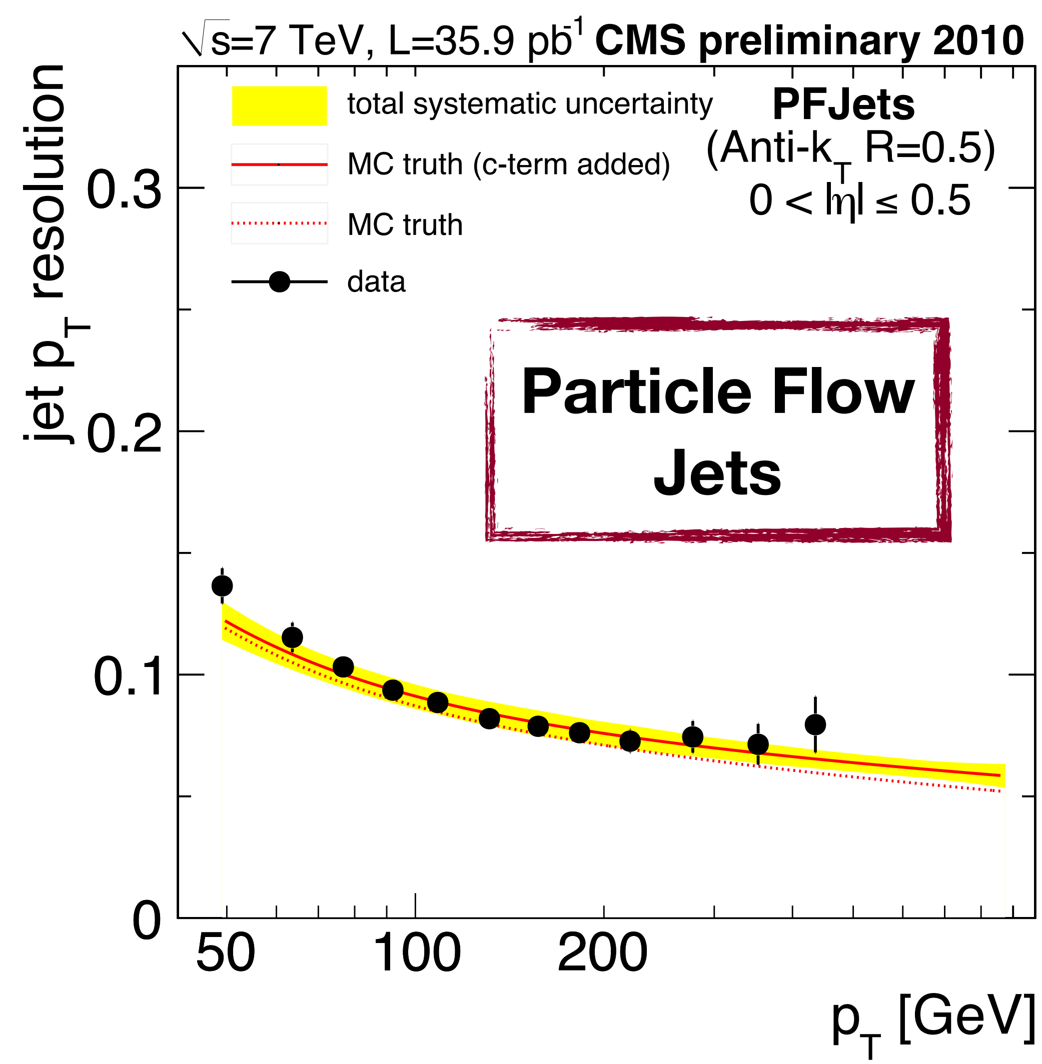


Jet energy resolution

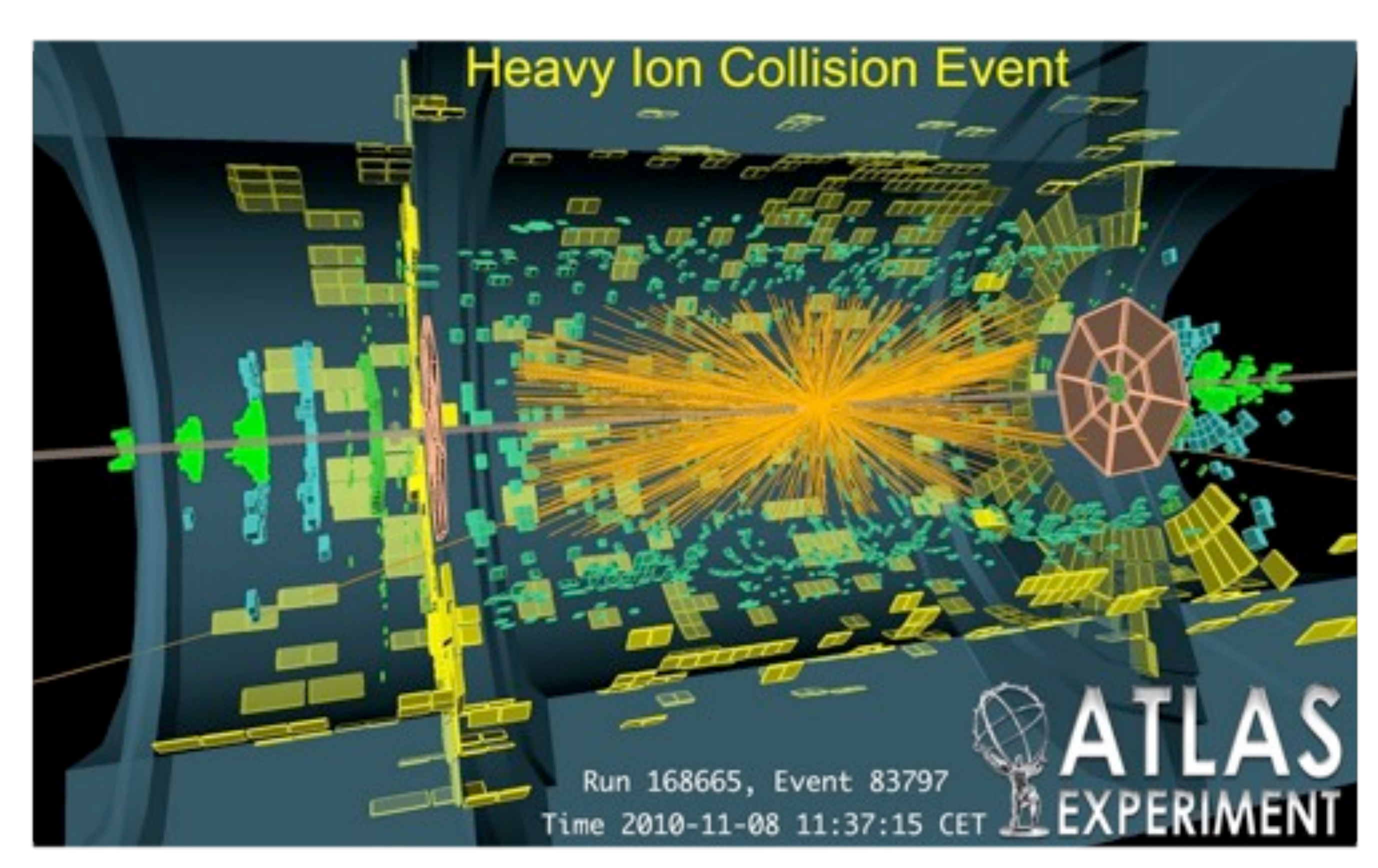
An example: proton-proton collisions

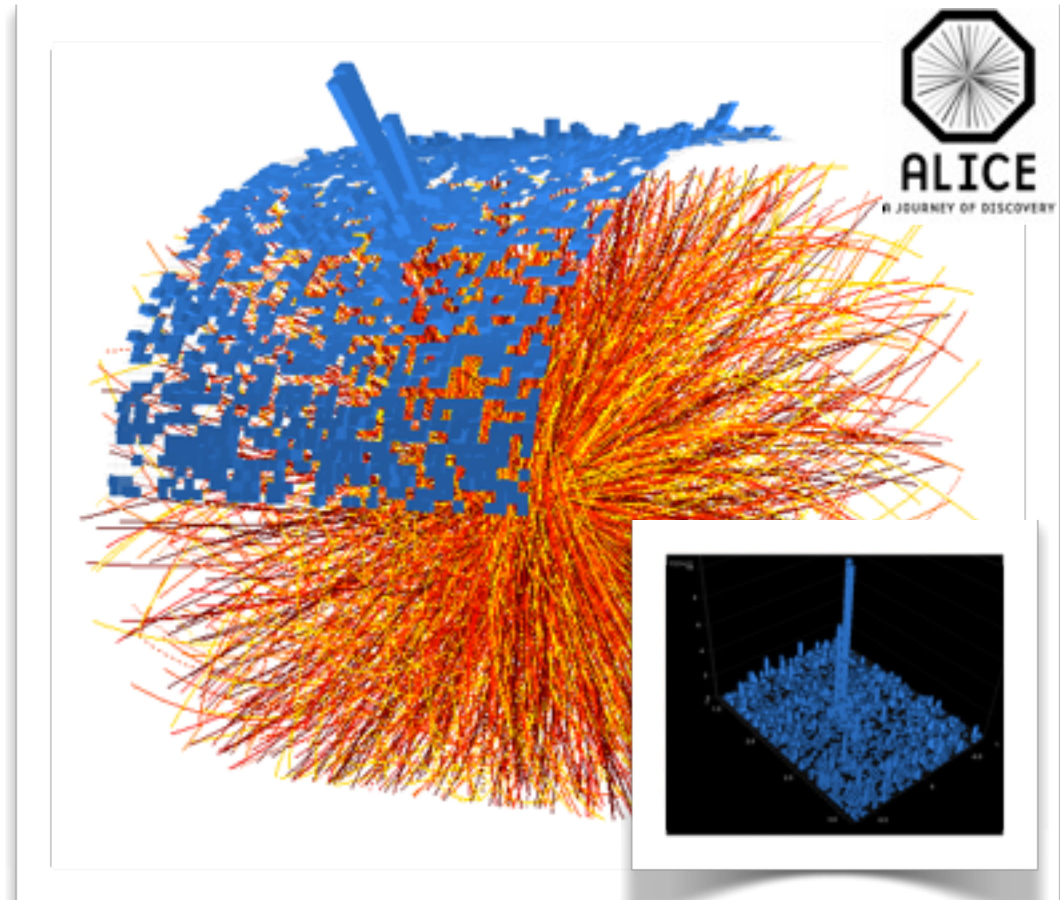
$$\mathcal{A} = \frac{p_T^{\text{Jet1}} - p_T^{\text{Jet2}}}{p_T^{\text{Jet1}} + p_T^{\text{Jet2}}} \rightarrow \frac{\sigma(p_T)}{p_T} = \sqrt{2}\,\sigma_{\mathcal{A}}$$

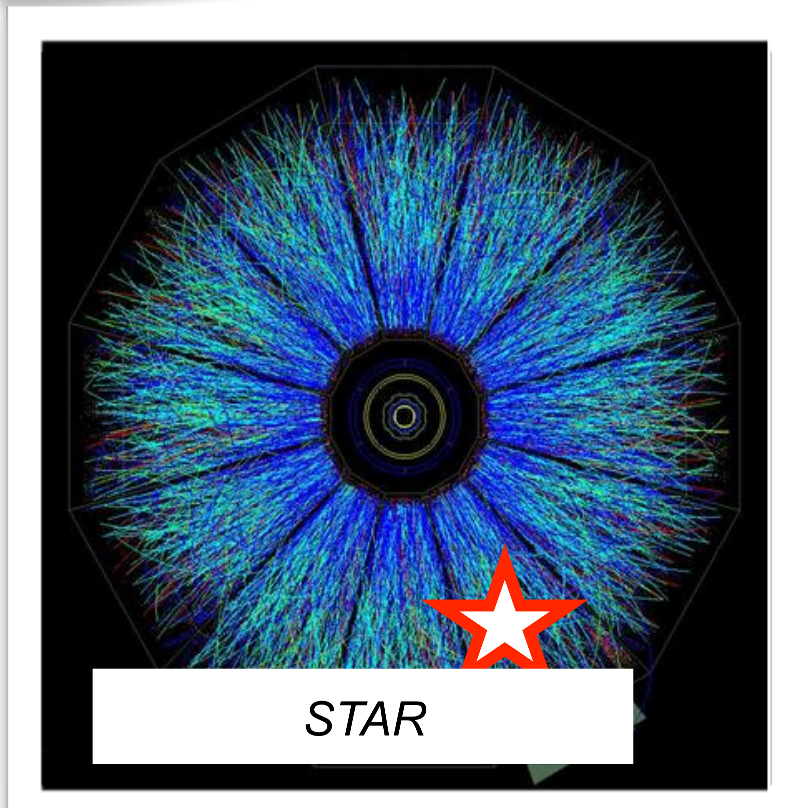


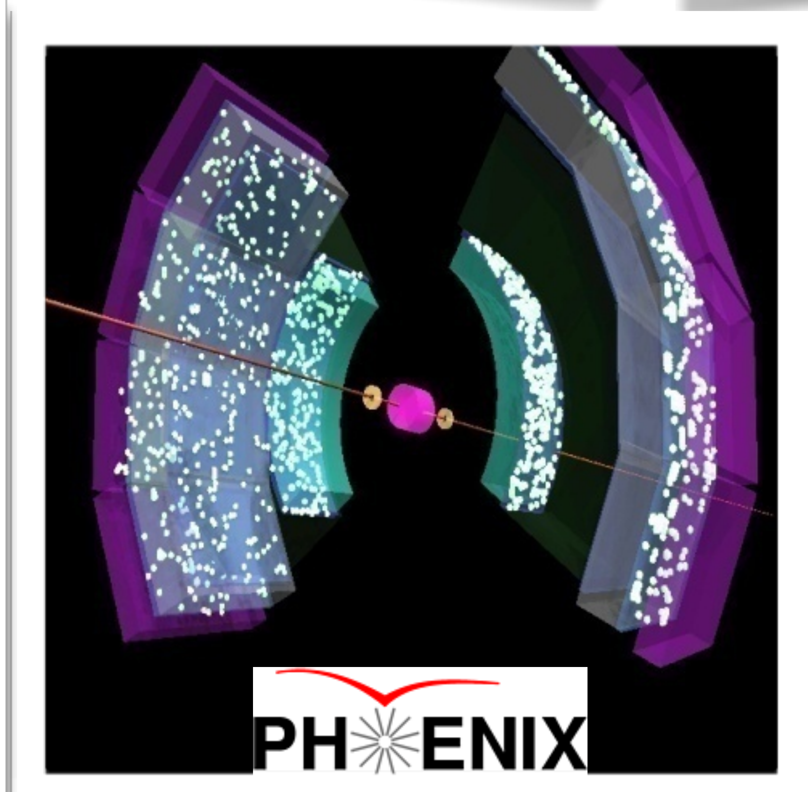


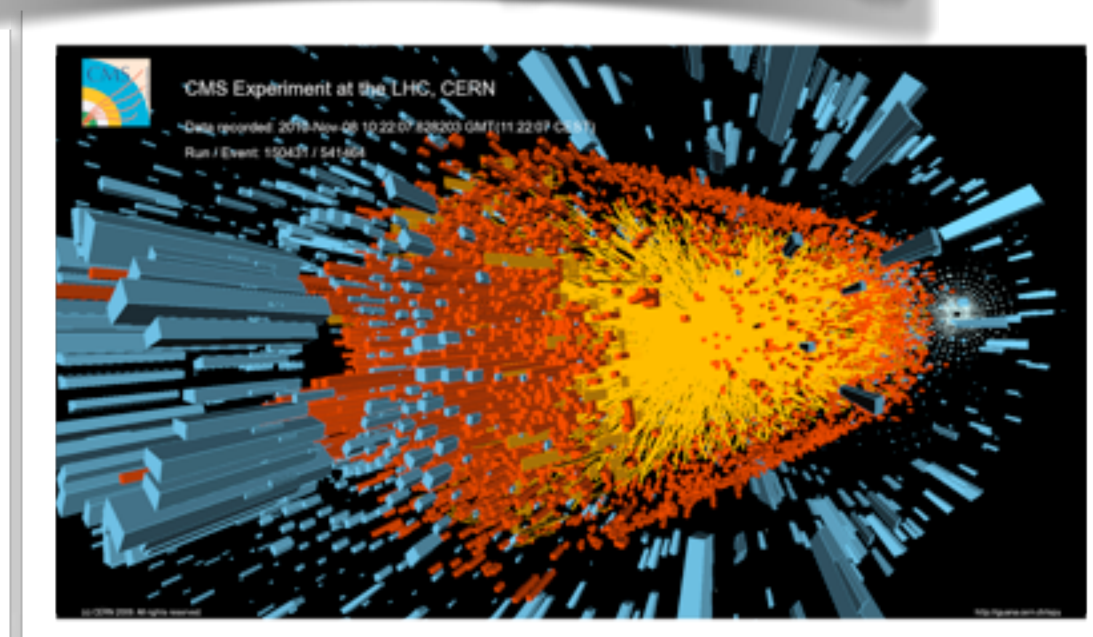
Heavy-ion collisions





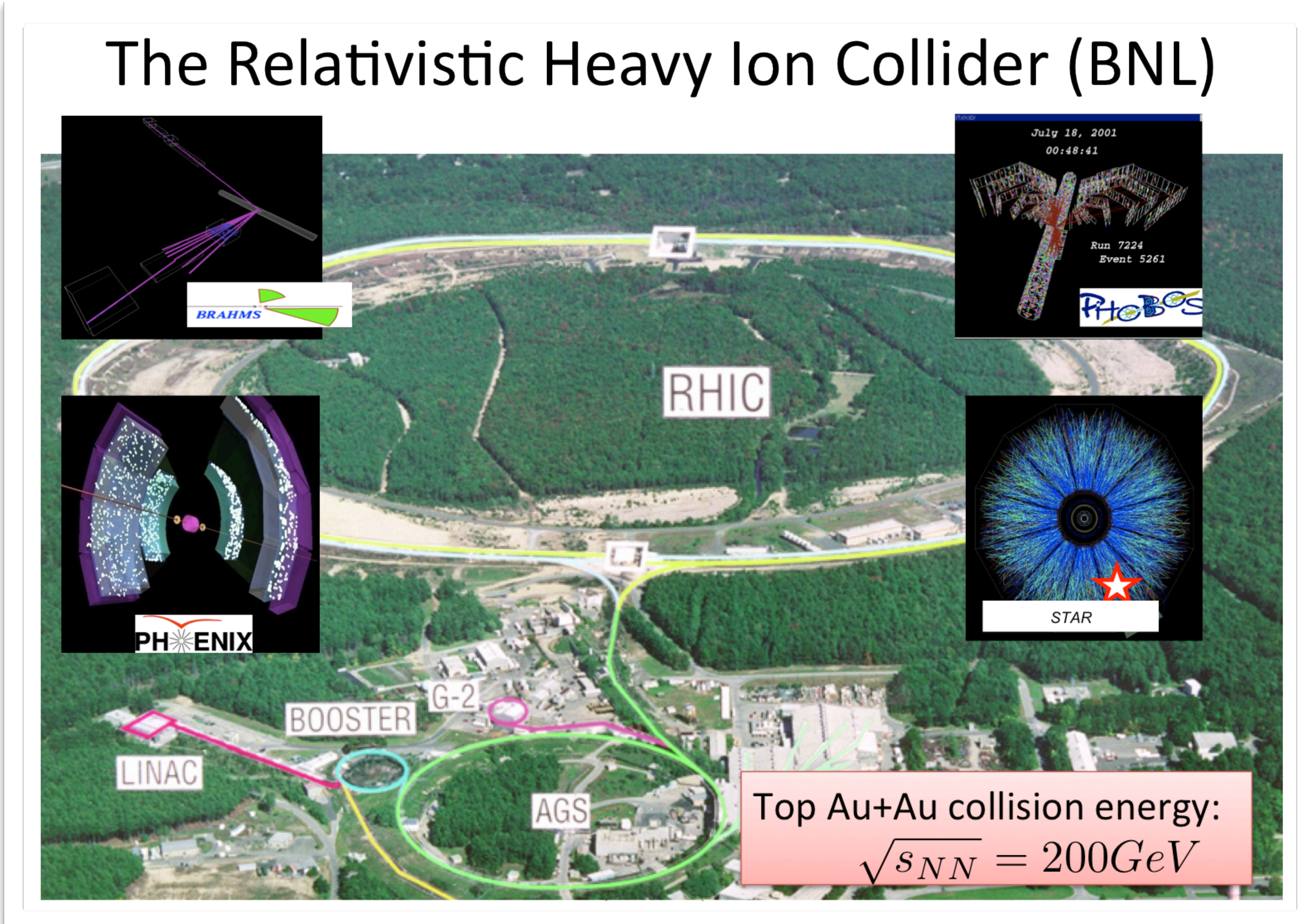


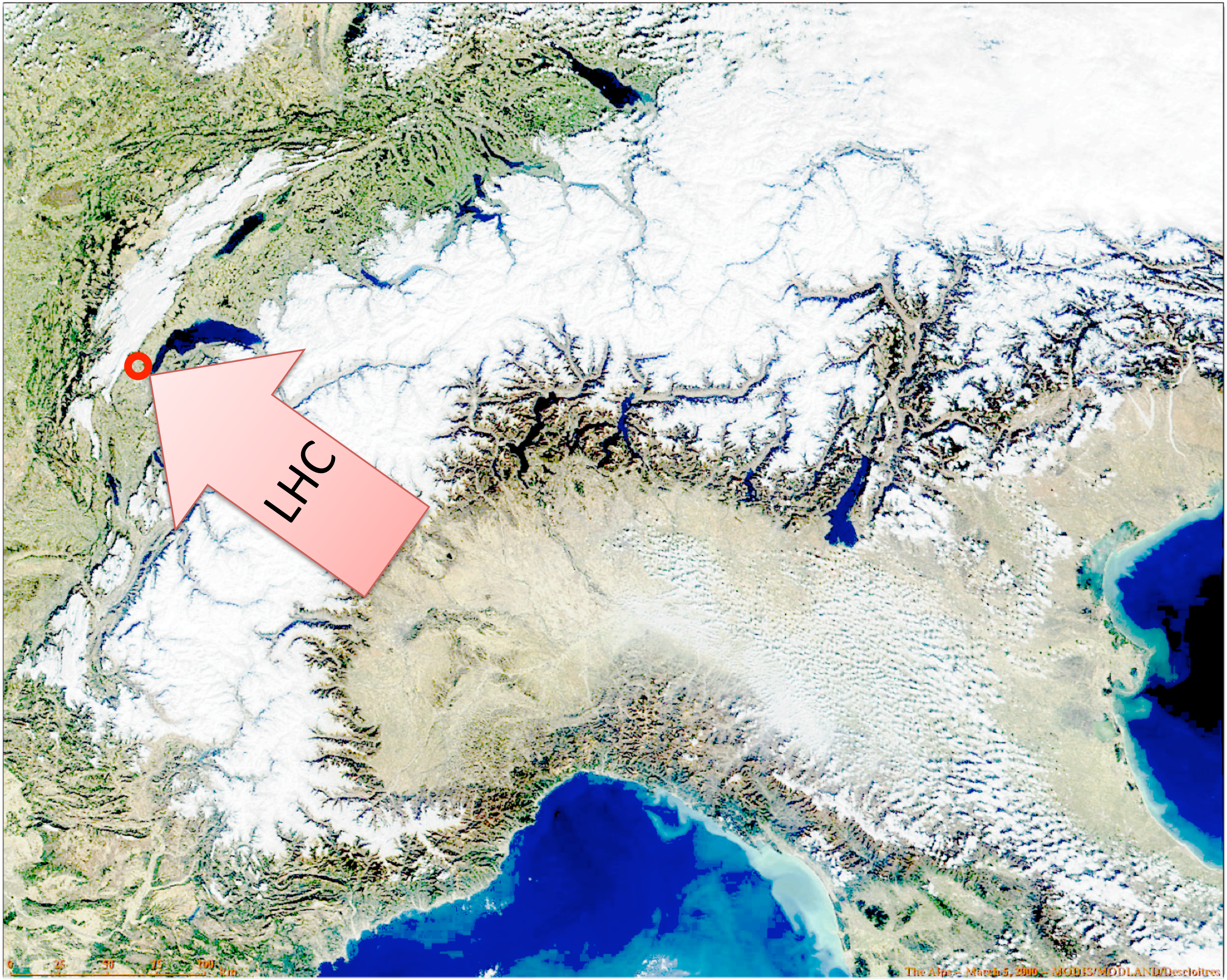




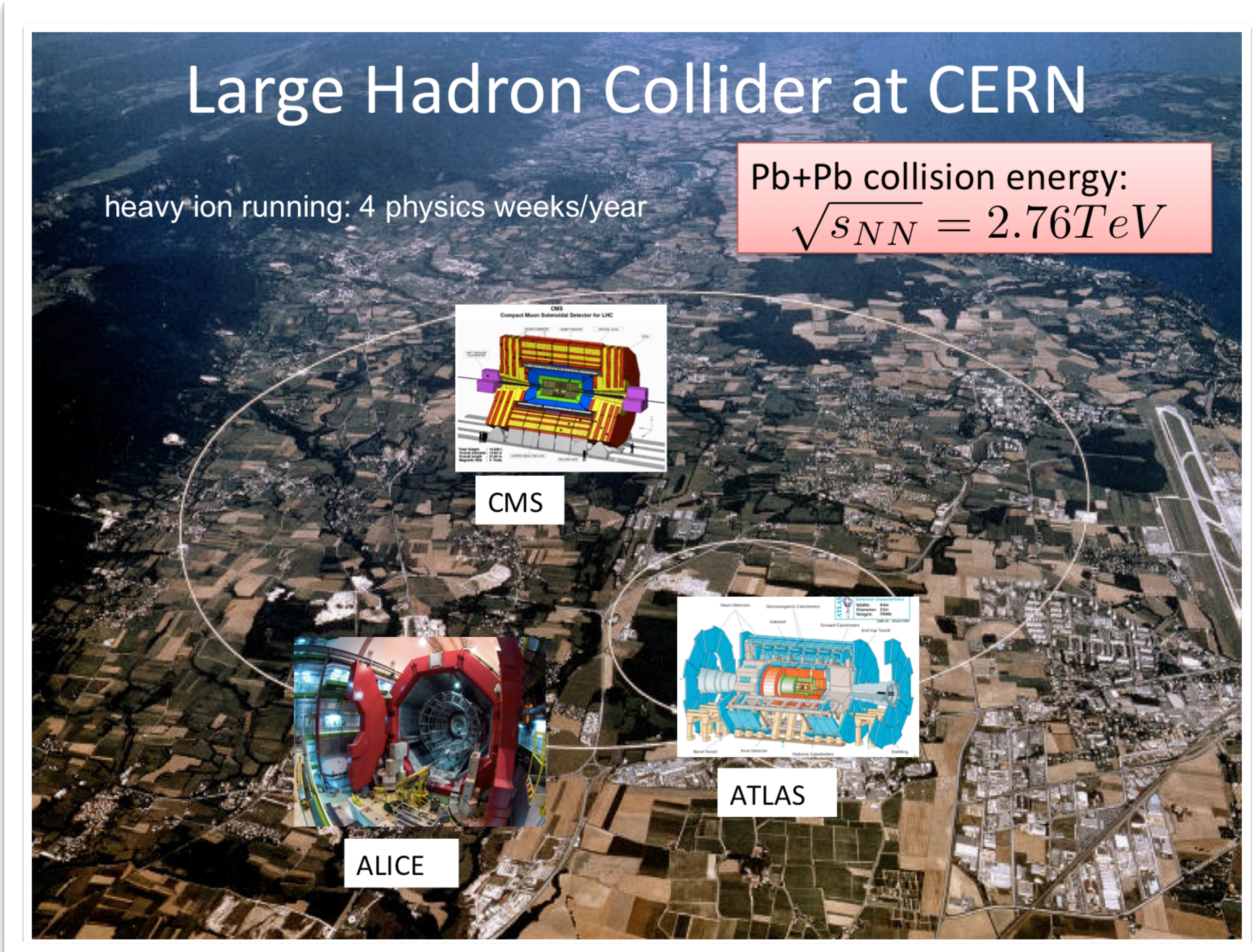
...RHIC to LHC

The hot-QCD laboratories



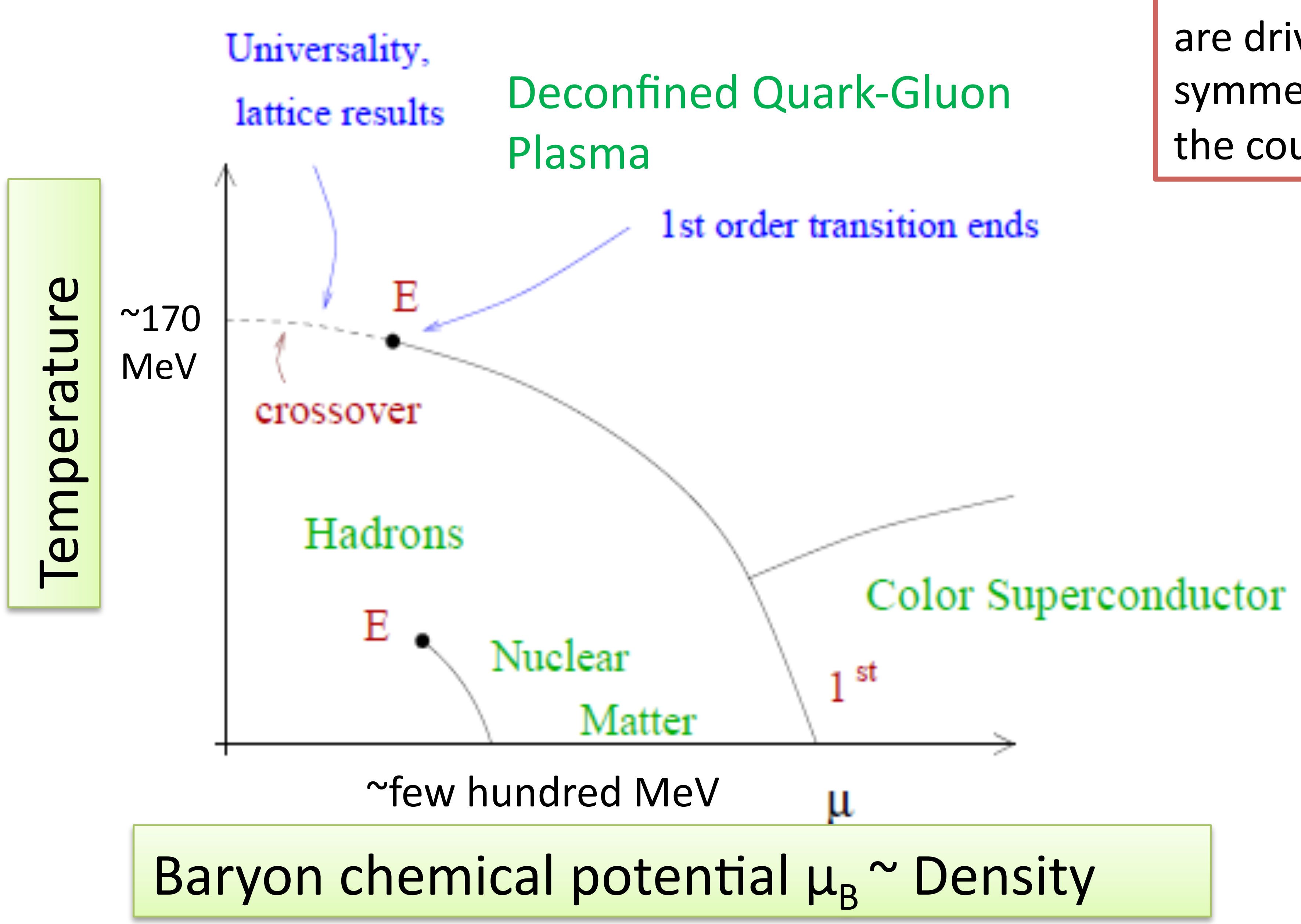

LHC
The Alps – March 5, 2000 – MODIS/MODLAND/Descloitres

The hot-QCD laboratories

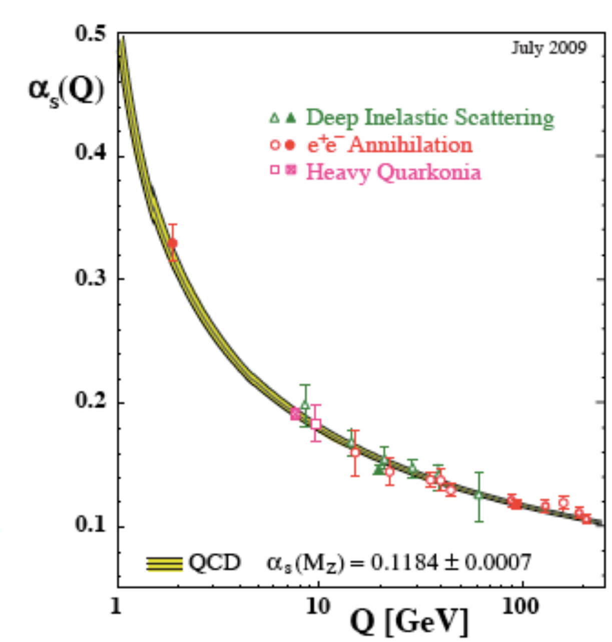


Design -> 5.5 TeV
2.76 at the moment.
Also: p-Pb and other ions planned.

QCD phase diagram – theoretical landscape



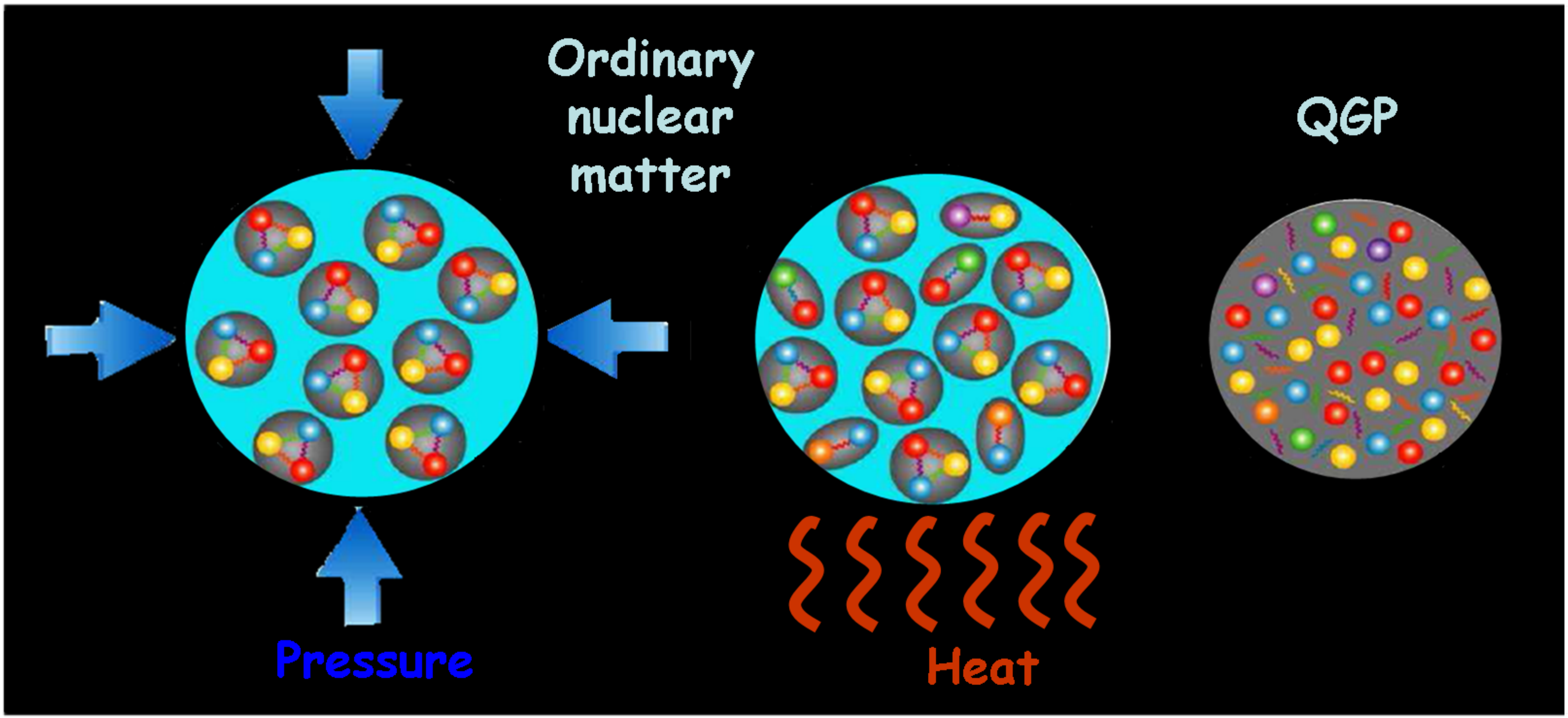
The features of this diagram are driven by QCD symmetries and running of the coupling constant



Create hot & colored medium

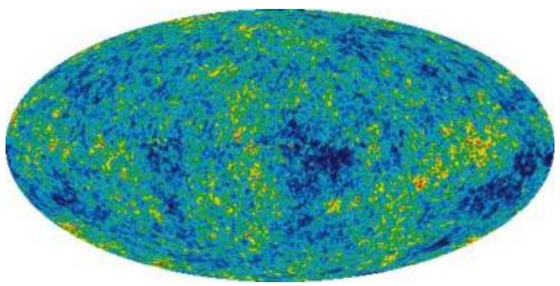
temperatures ~1.5 × 10^{12} K (200 MeV)

far hotter than center of the sun (~2 × 10^7 K)

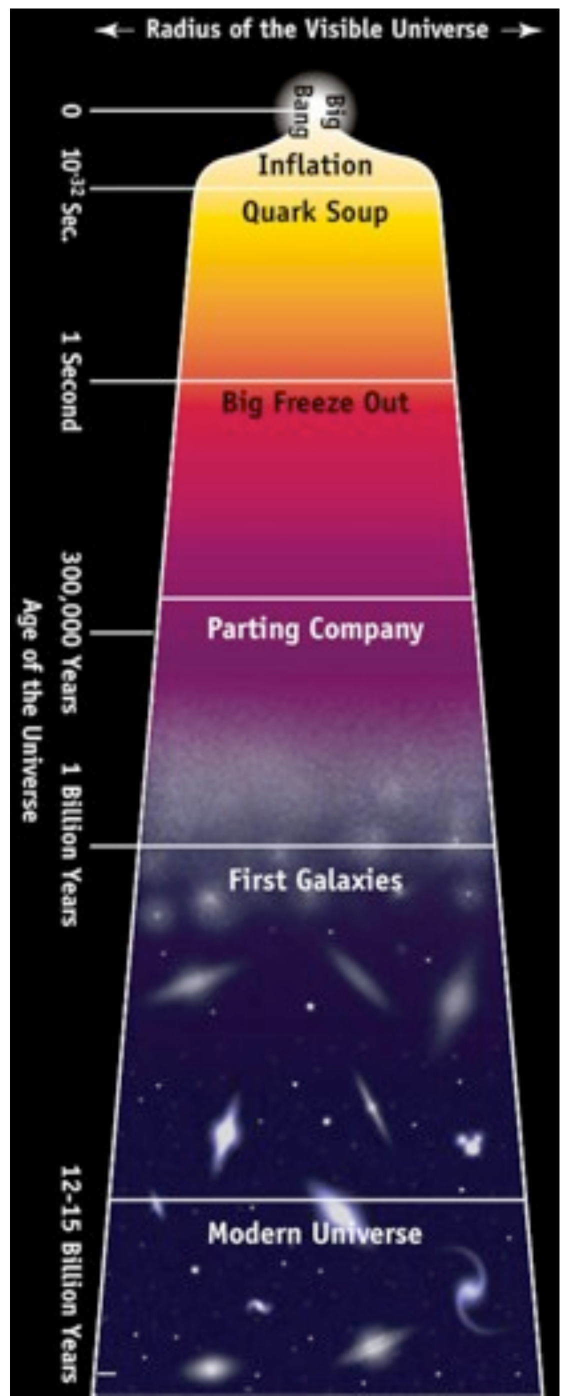


As hot as an early universe? Primodal soup of quarks in the laboratory?

Some history...

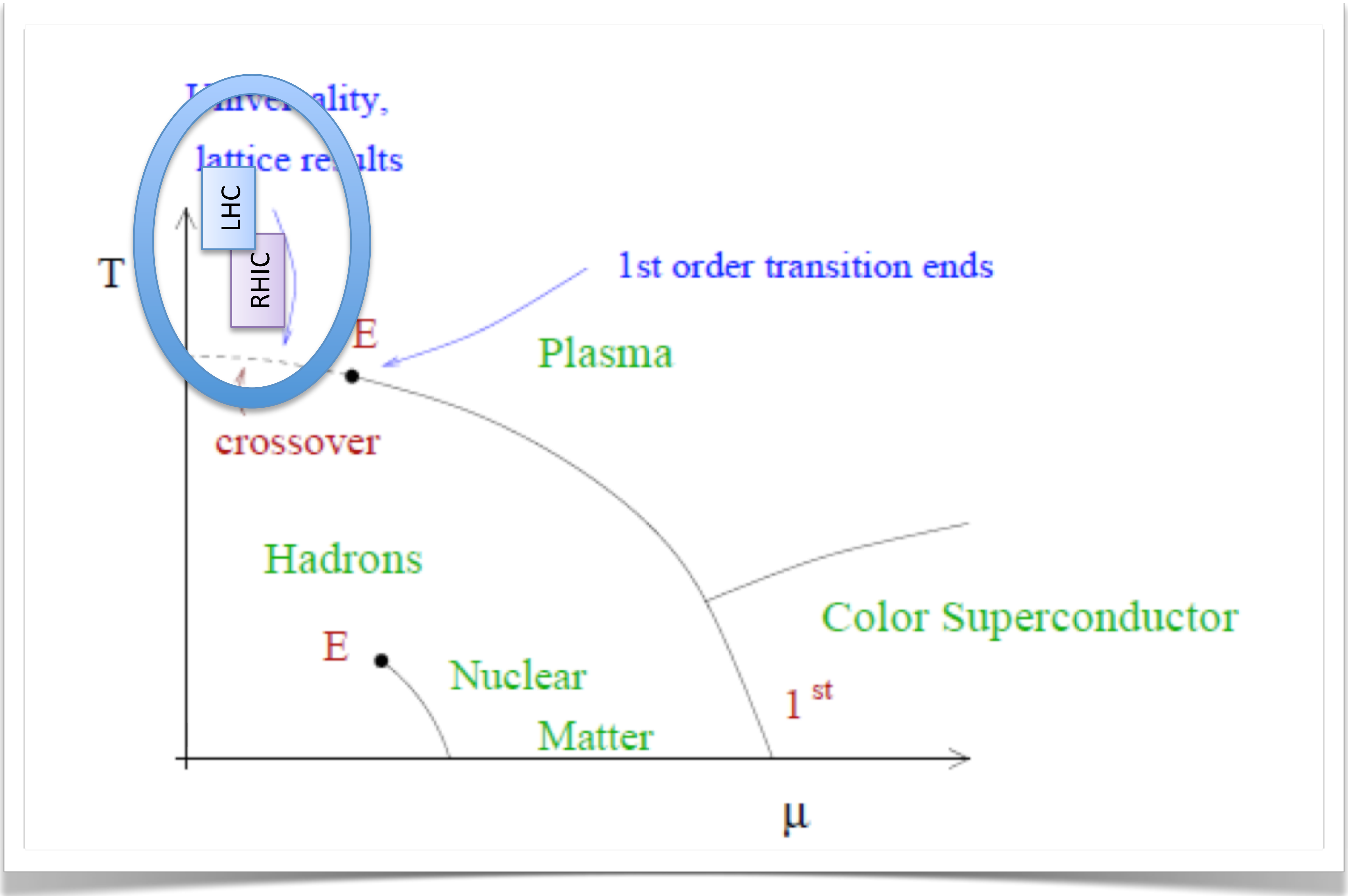


QCD Lab
"few" years later?



10^{-44} sec	Quantum Gravity	Unification of all 4 forces	10^{32} K
10^{-35} sec	Grand Unification	E-M/Weak = Strong forces	10^{27} K
10^{-35} sec?	Inflation	universe exponentially expands by 10^{26}	10^{27} K
2 10^{-10} sec	Electroweak unification	E-M = weak force	10^{15} K
$2 \cdot 10^{-6}$ sec	Proton-Antiproton pairs	creation of nucleons	10^{13} K
6 sec	Electron-Positron pairs	creation of electrons	$6 \cdot 10^{9}$ K
3 min	Nucleosynthesis	light elements formed	10^{9} K
10^{6} yrs	Microwave Background	recombination - transparent to photons	3000 K
10^{9} yrs ?	Galaxy formation	bulges and halos of normal galaxies form	20 K

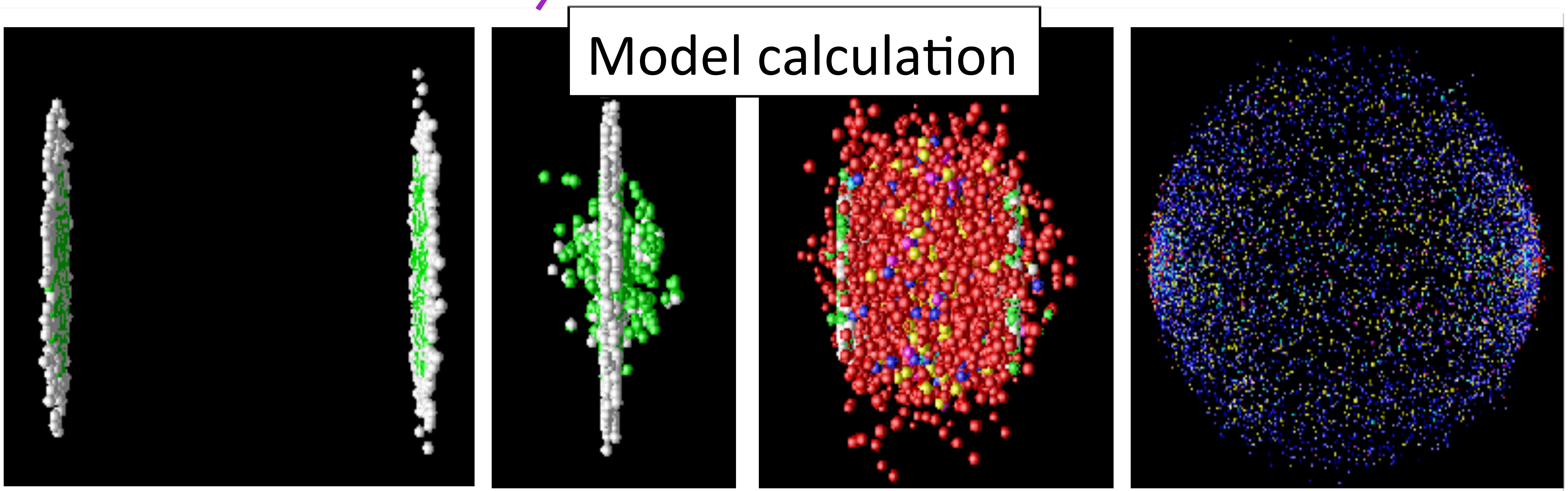
Hot QCD Labs

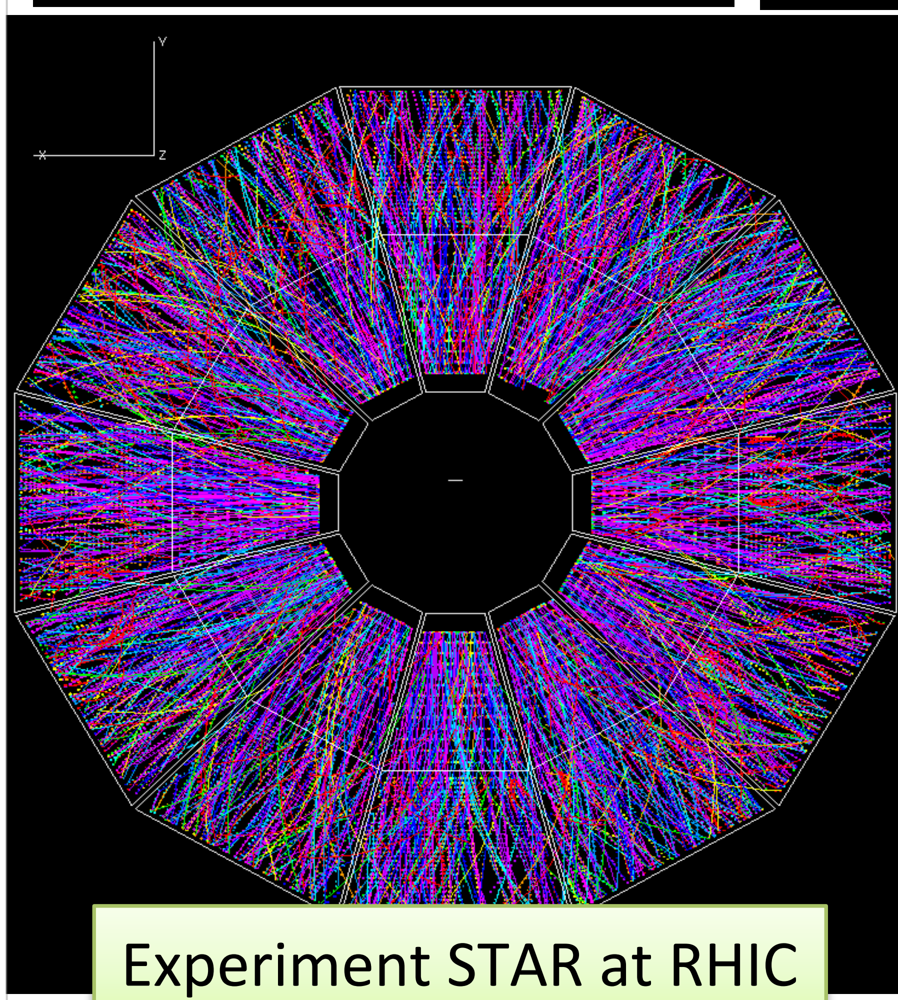

lattice re ults
LHC
RHIC
T
1st order transition ends
E
Plasma
crossover
Hadrons
Color Superconductor
E
Nuclear
Matter
1 st
μ

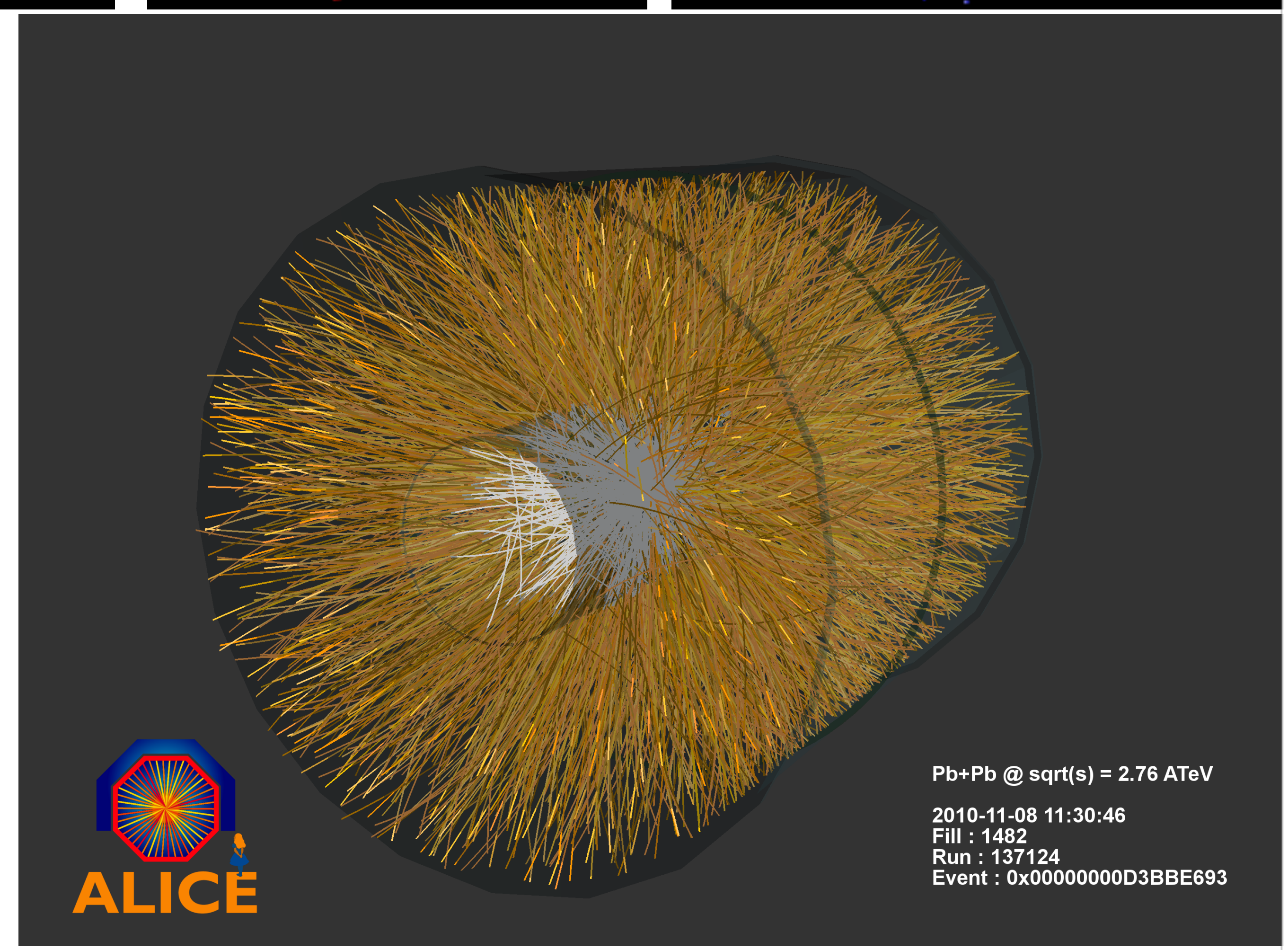
Strategy: how to study QCD matter experimentally?

- **Need to find those observables that:**
  - Are sensitive to crucial parameters of hot QCD matter
  - **Can be modeled well – theoretical understanding**
  - **Can be measured well – experimental control**
  - **Can connect theory and data**
- **=> Inclusive measurements; correlations; compare with more elementary collisions (p-p, p-A); compare different energy regimes**

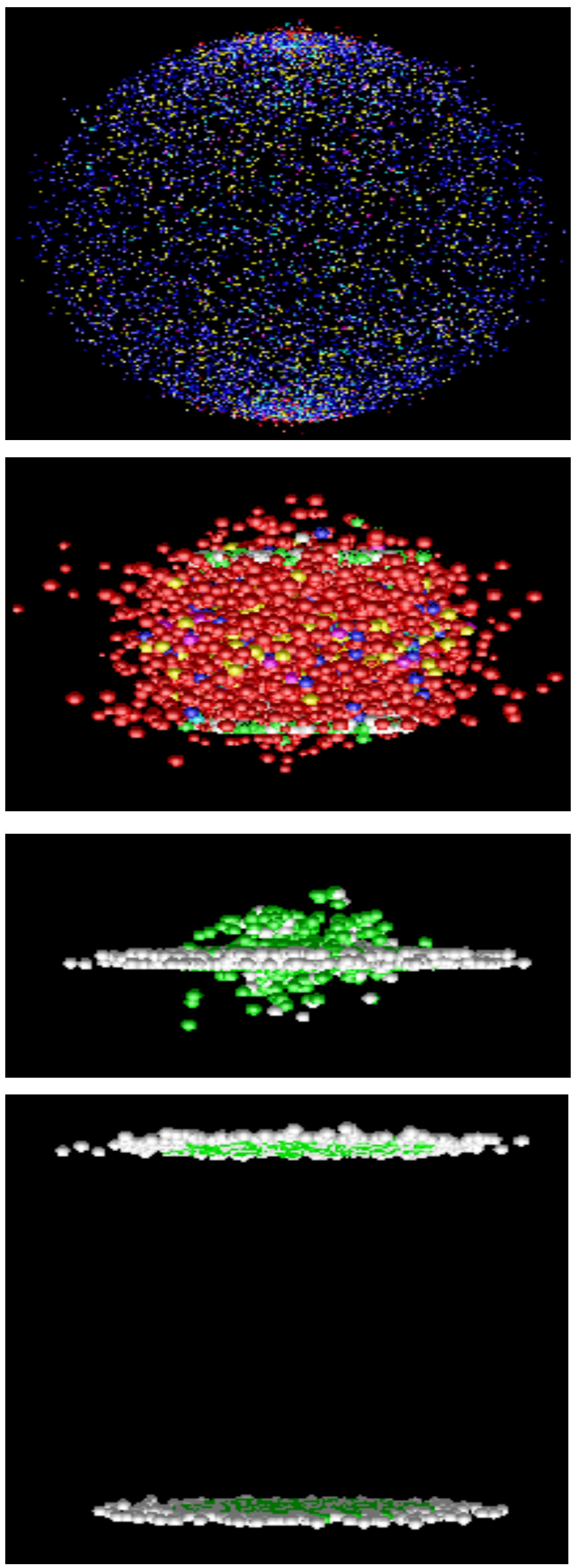
Heavy-ion collisions

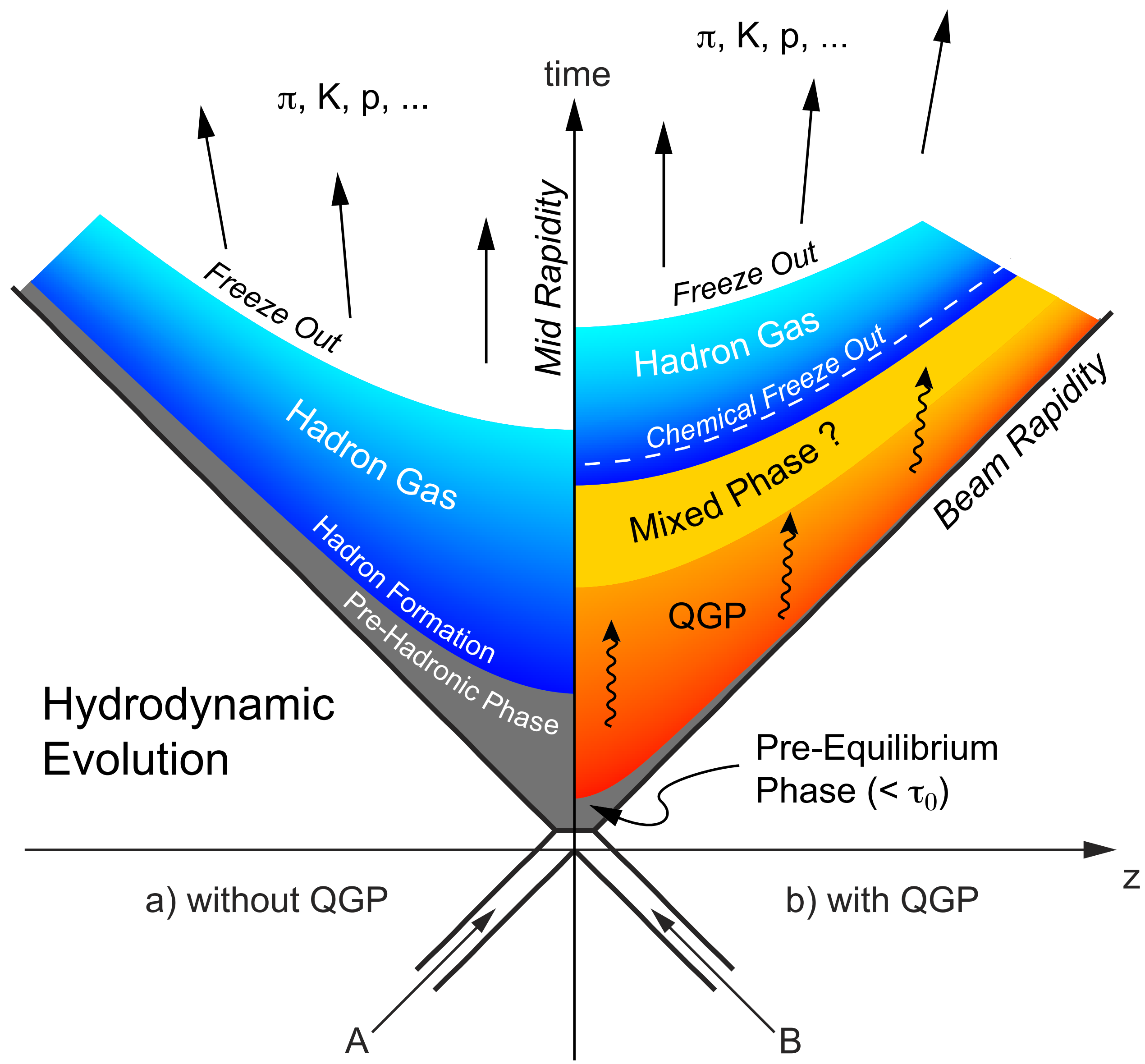




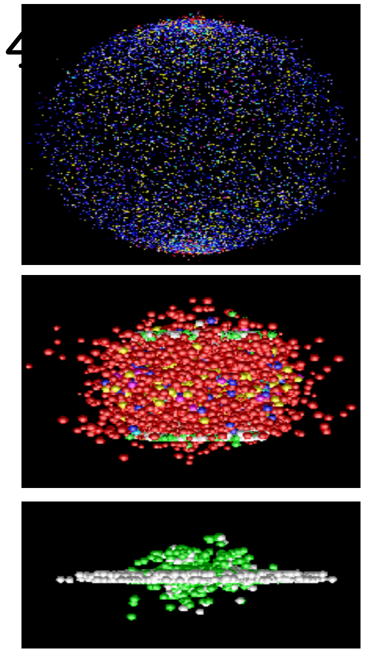


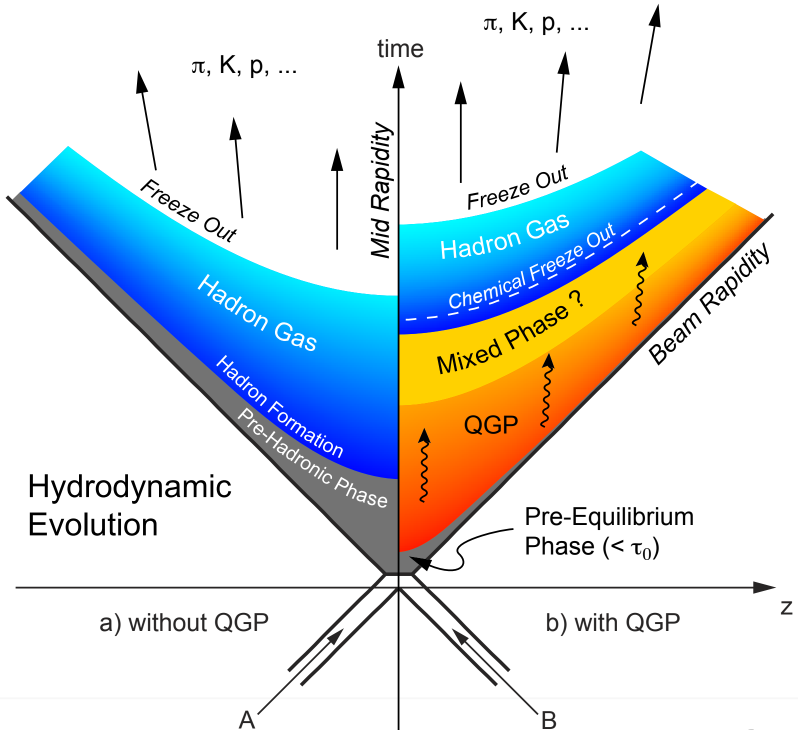
Collision evolution





Note: hard scatterings occur early (at t~0)!
High energy partons "witness" the evolution and jets "testify" about their fate/CV





Collision evolution

Few notes:

We are interested in properties of the QGP phase

Need to disentangle effects from different phases

- not a simple problem by principle: detectors do NOT measure these time-periods/phases separately

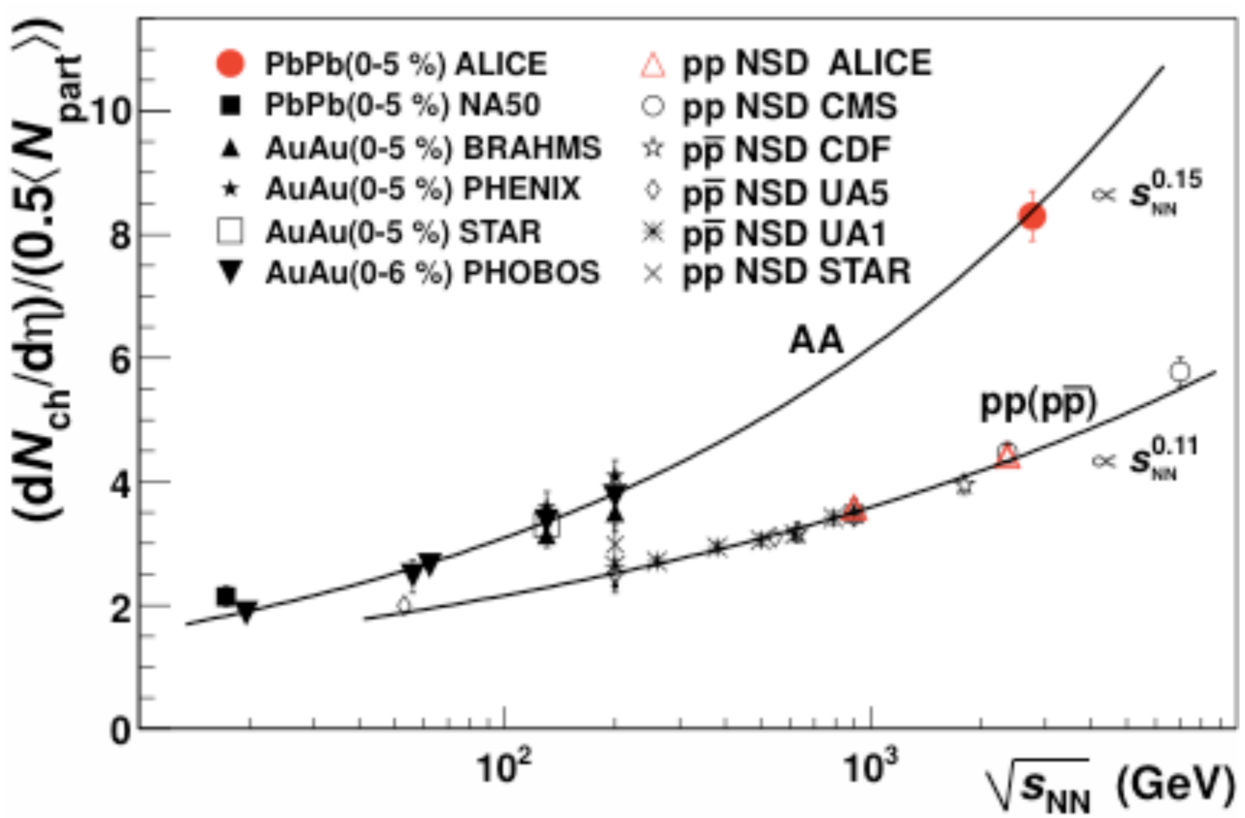
=> need for detail understanding of the physics processes, particle production, dynamics of the system in each phase(!), etc

=> modeling, various assumptions may play an important role in physics interpretation

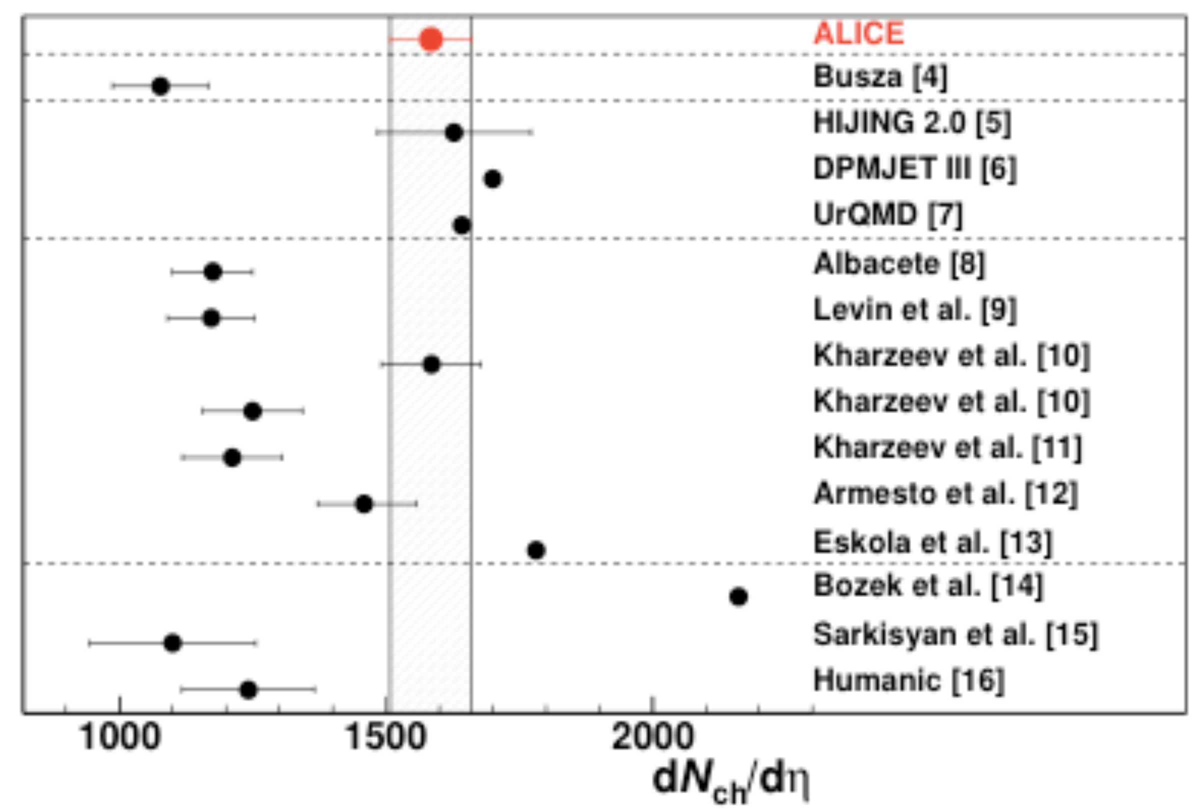
Need for control of the initial conditions, geometry of the collision, the incoming parton distributions (nuclear-PDF vs nucleon-PDF) ...

HI collisions: Particle production

Energy dependence



Comparison to predictions



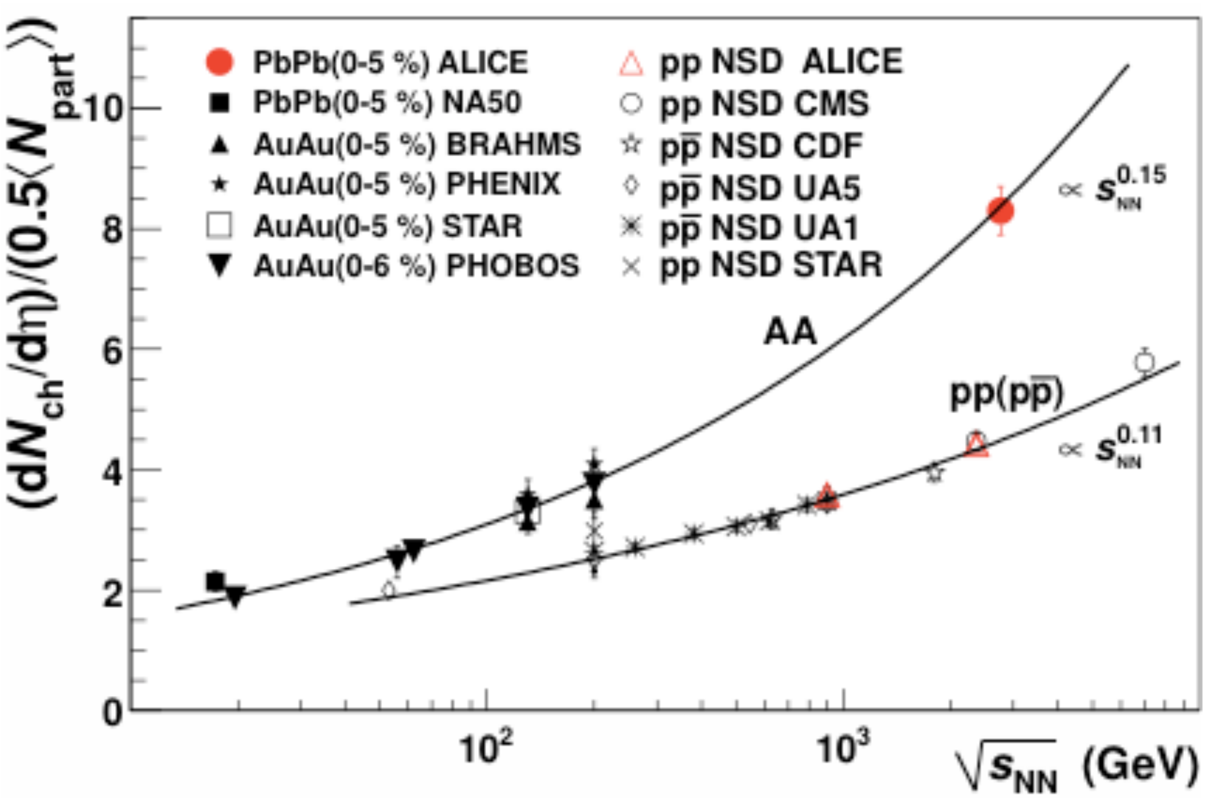
PRL 105, 252301 (2010)

Energy dependence

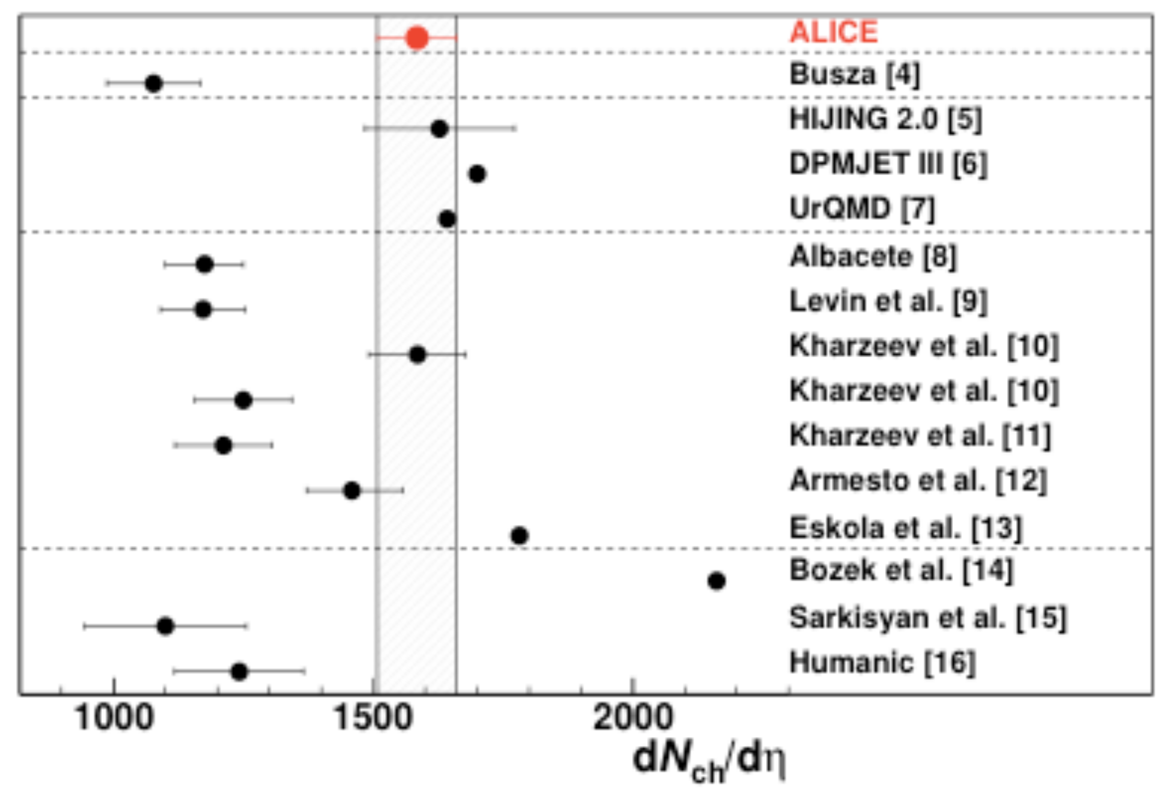
- p-p ~ $s_{NN}^{0.11}$
- A-A ~ $s_{NN}^{0.15}$ (most central - 2x RHIC)
  - – stronger rise than log extrapolation

HI collisions: Particle production

Energy dependence



Comparison to predictions



PRL 105, 252301 (2010)

Feedback within the heavy-ion community:

1. **Multiplicity is crucial [input] for modeling**
2. **Saturation models tend to predict lower multiplicity**
3. **Data driven extrapolations did not seem to anticipate the results**

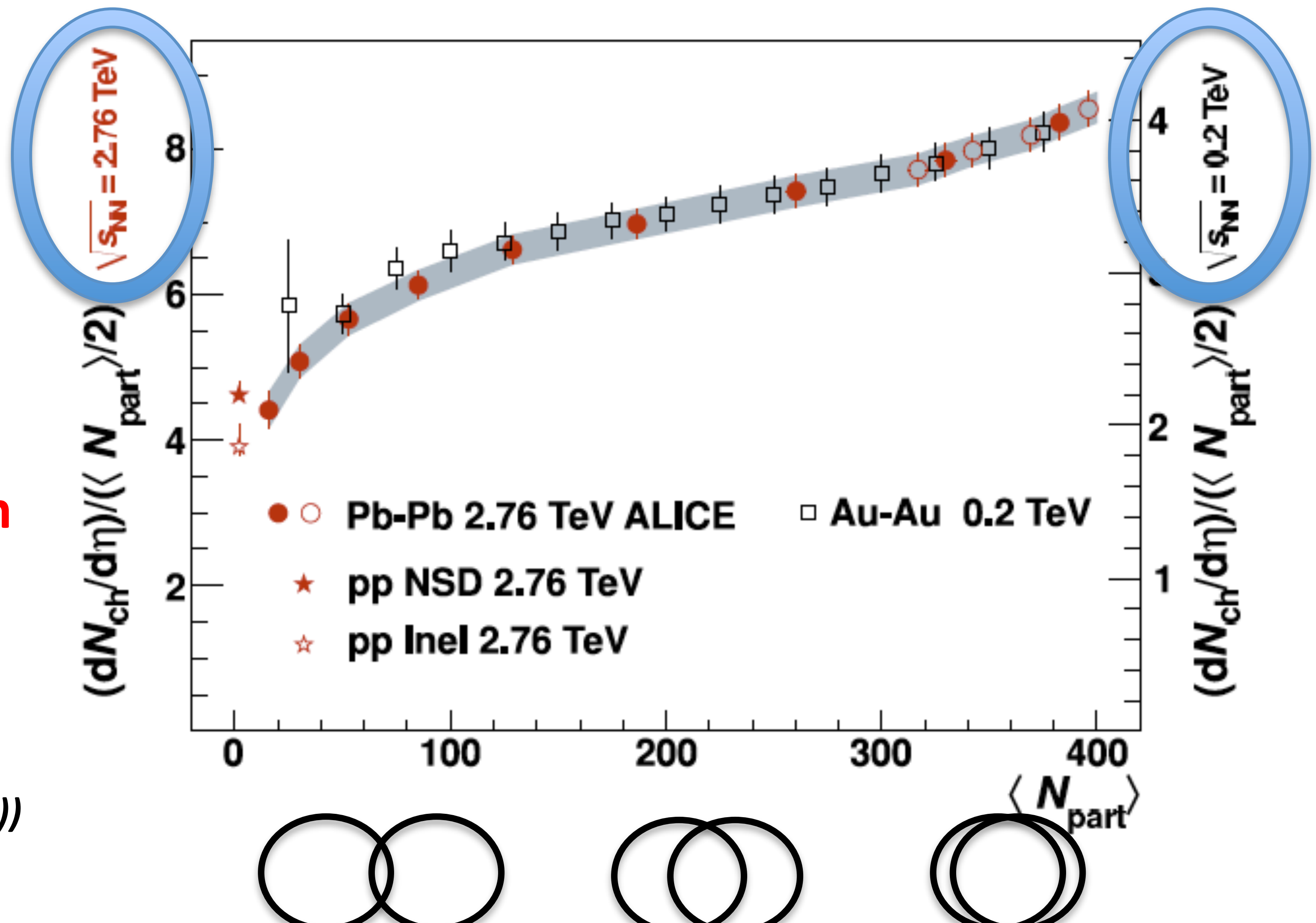
Systematic control: RHIC vs LHC

The same experiment under vastly different conditions!

• Identical variation of particle production with centrality (volume) at RHIC and LHC!
⇒ Global features of the system independent on energy
⇒ Initial conditions!

More on RHIC:
*Phobos (**Phys. Rev. Lett. 102, 142301 (2009)**)*

Centrality dependence of particle production



Centrality of the collisions: peripheral semi-central central

End of 1/3

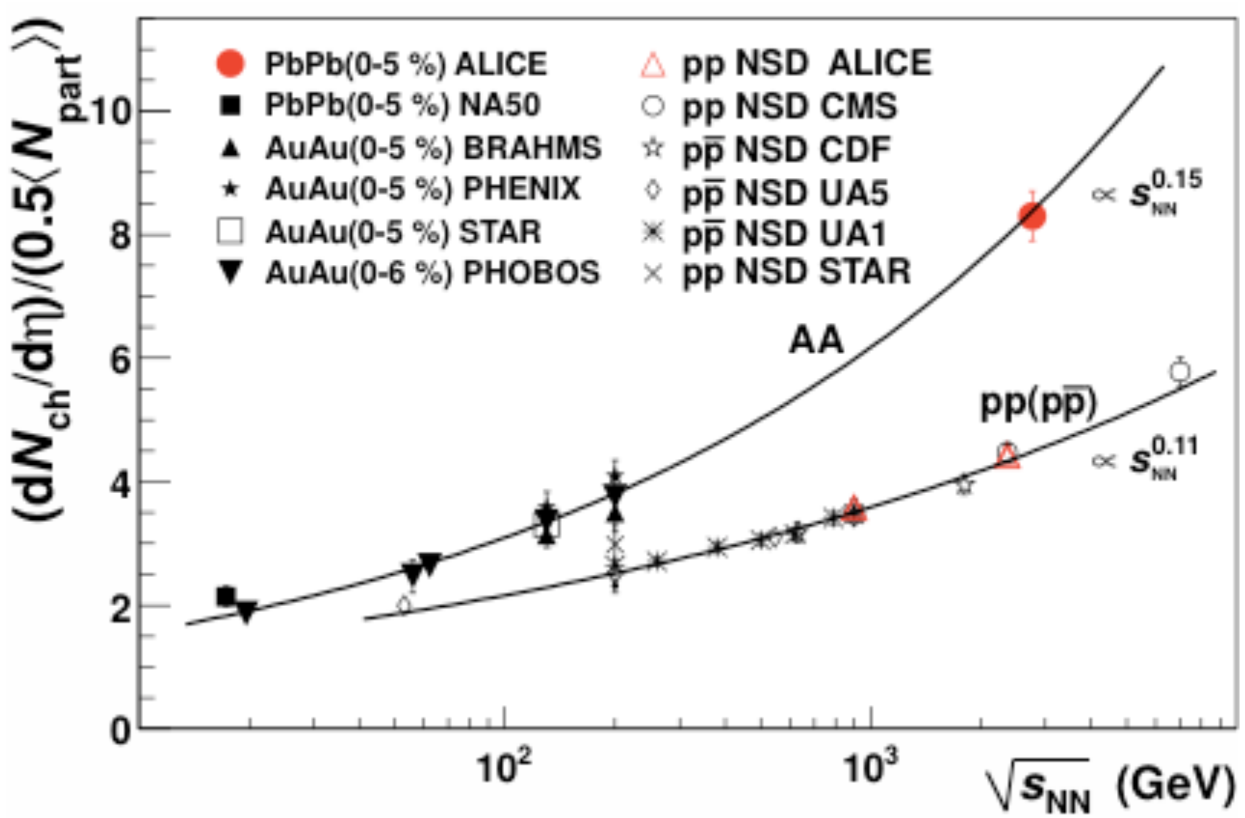
Until now...

- Jets in elementary collisions: must specify an operational definition (algorithm, R, recombination scheme); variety of infrared and collinear safe algorithms
- Jet measurements in e-e and p-p collisions under control - experimental and theoretical understanding - although proper jet reconstruction is an effort even in the "simple" case (vacuum)
- HI collisions: hot QCD matter; large particle (production) densities as compared to vacuum - evolving with centrality

... back to "calibration" measurements

HI collisions: Particle production

Energy dependence



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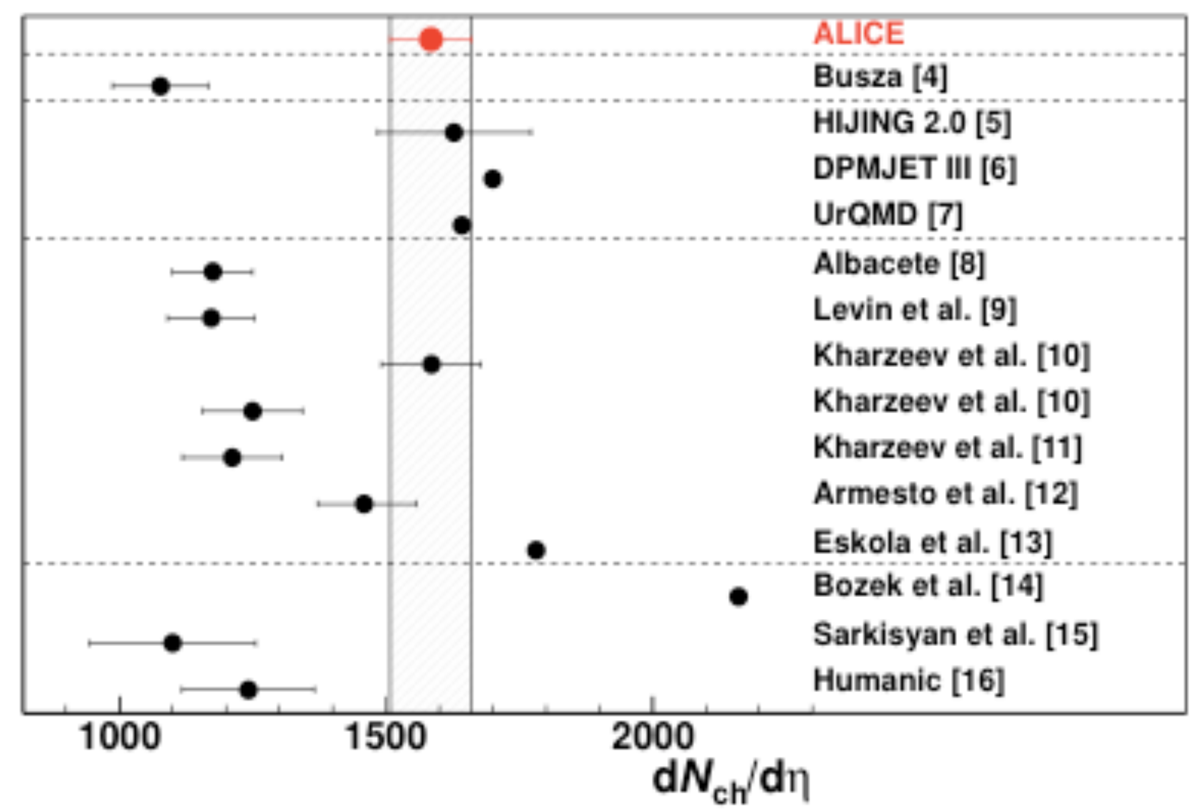

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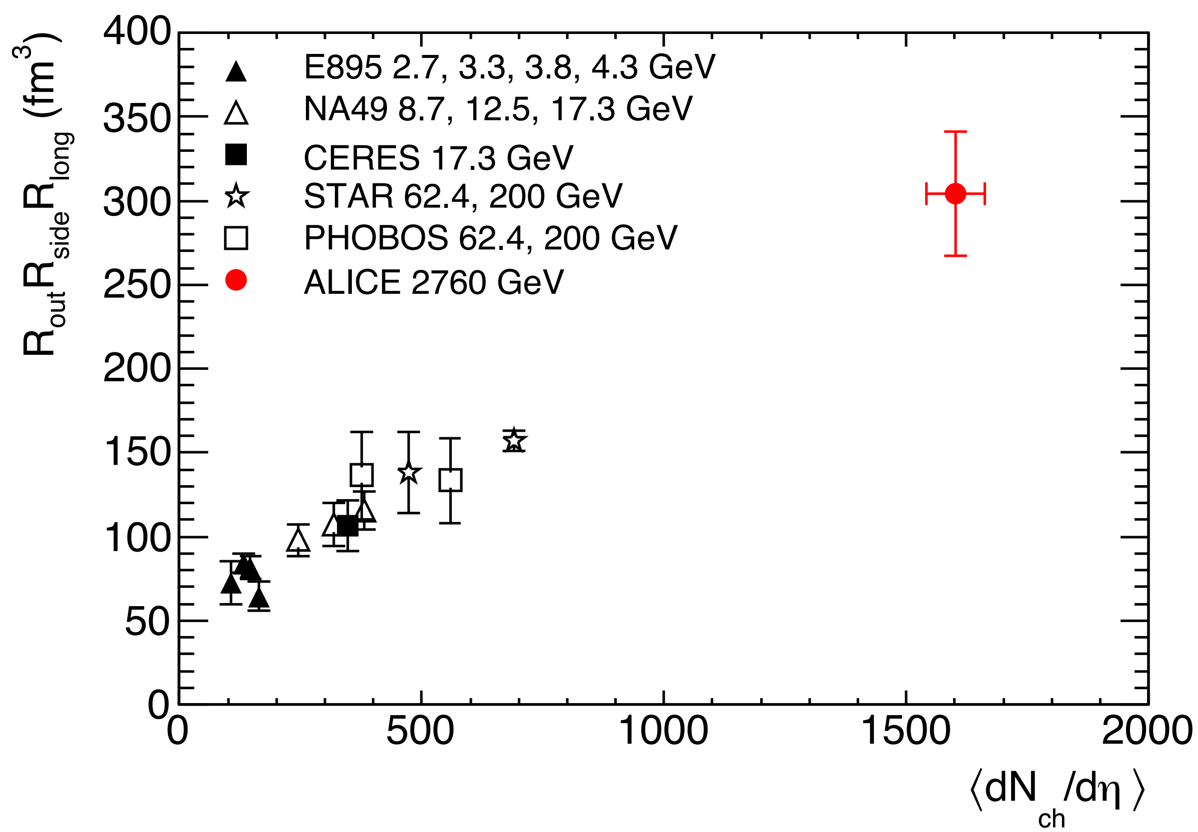
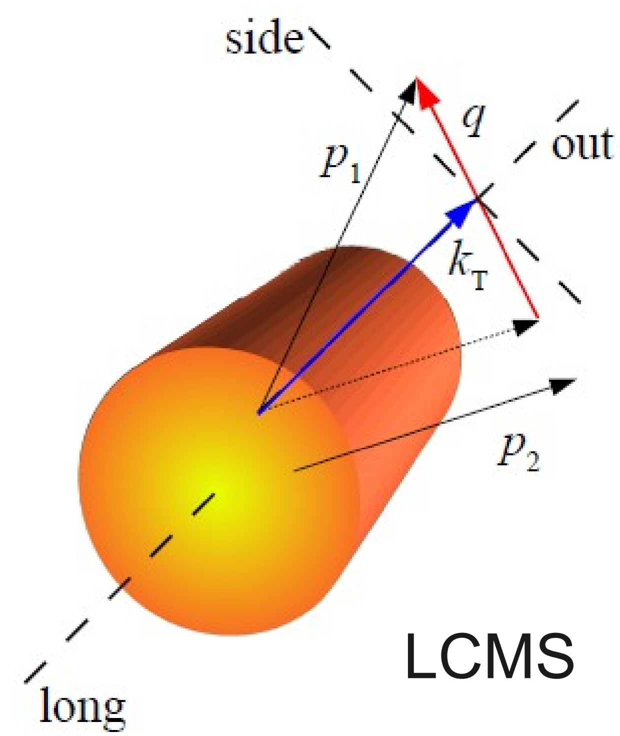
Particle production: source dimensions

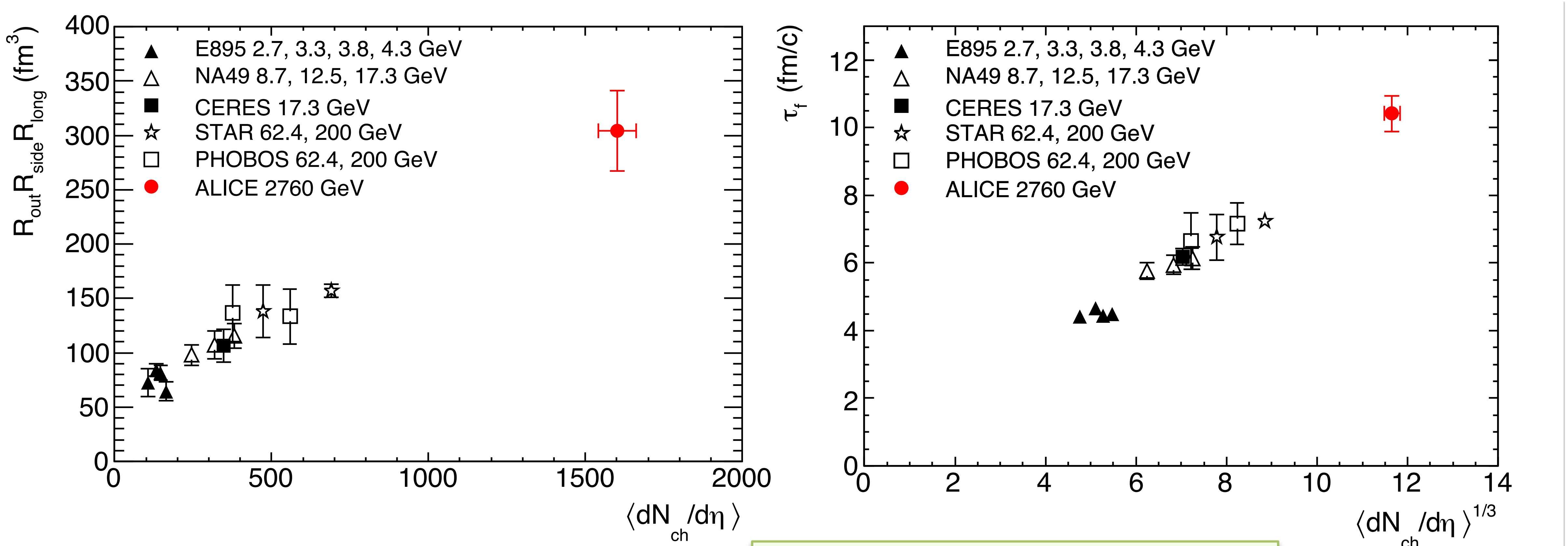




Phys.Lett.B 696:328-337,2011

1. **Energy dependence:**
   - **system with larger (2x) volume and (1.4x) lifetime (w.r.t RHIC); follows the trend of multiplicity; faster expansion <=> larger collective flow**
2. **Pair momentum dependence:**
   - **larger radii, strong dependence on kT; Rout/Rside smaller than at RHIC; overall agreement with extrapolations**
3. **Important constrains to [hydrodynamical] modelling**

Particle production: source dimensions



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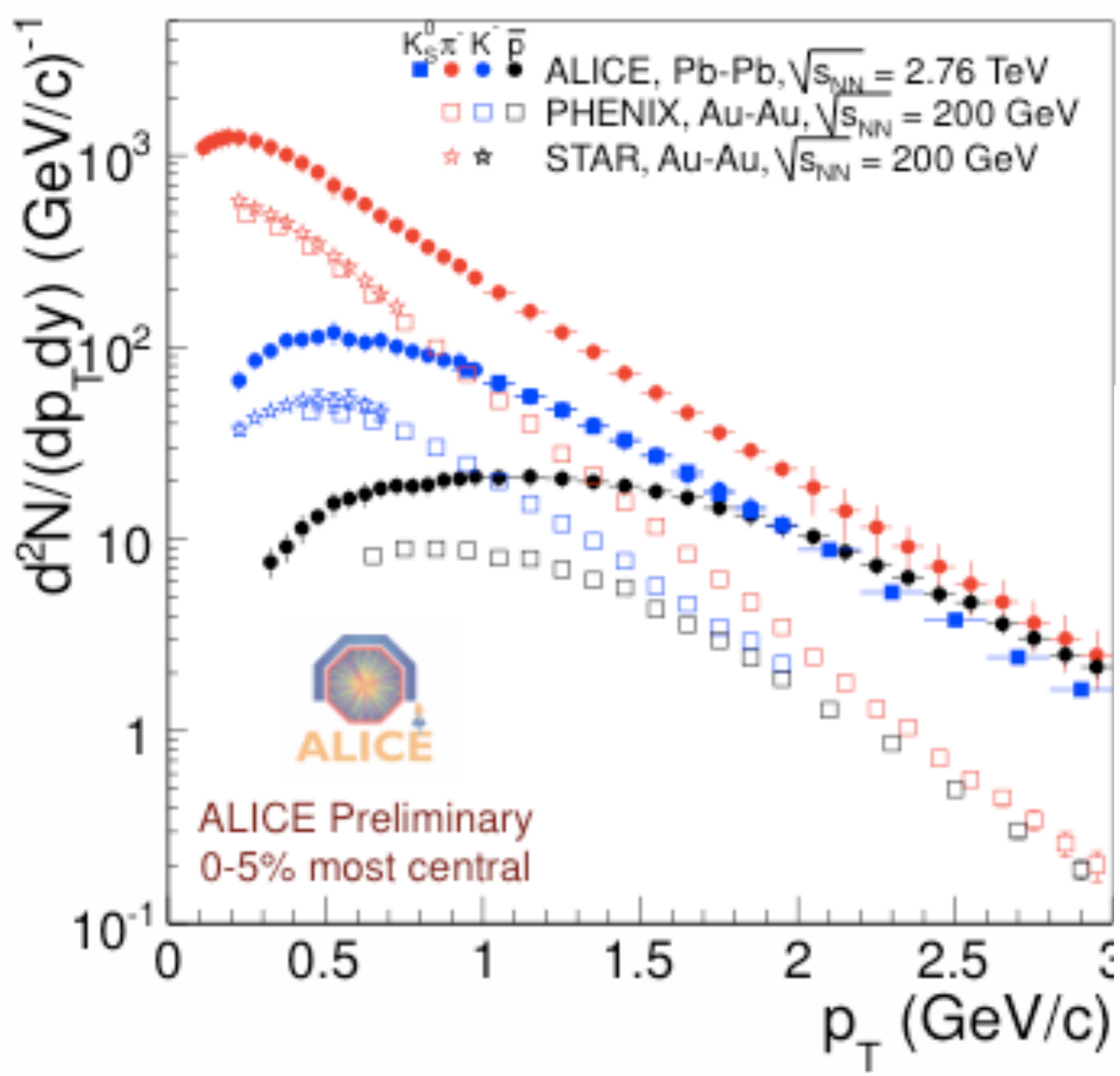
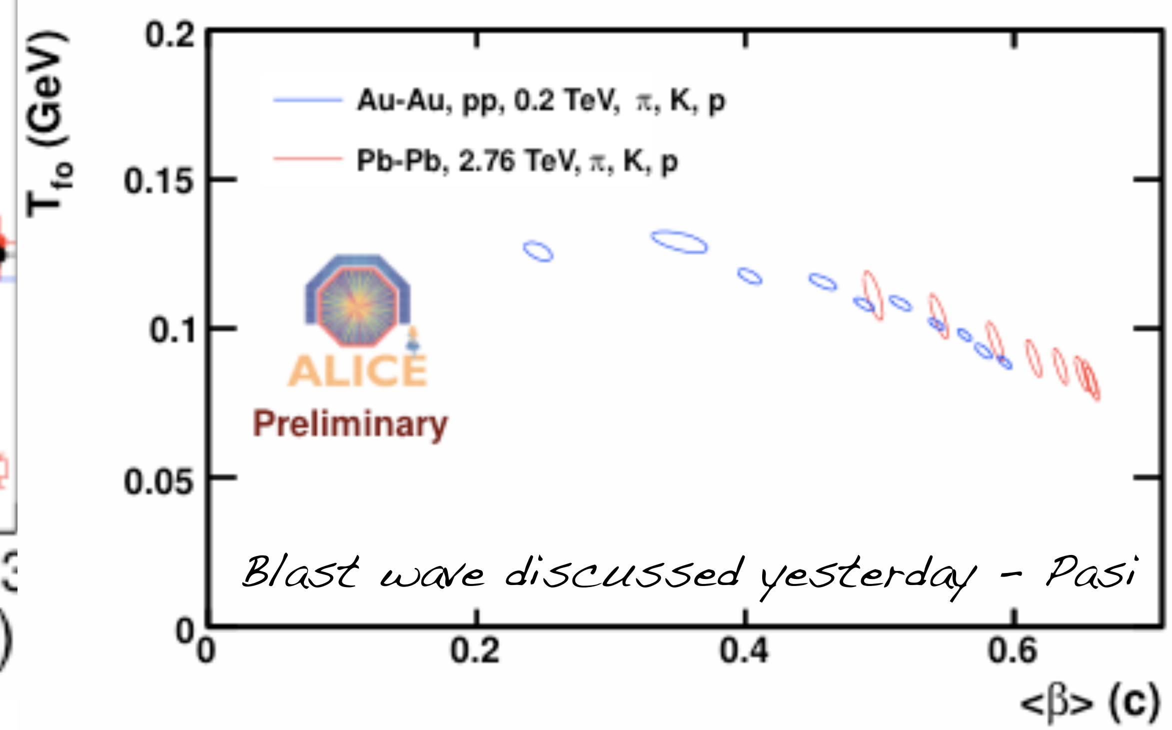
3. Important constrains to [hydrodynamical] modelling

Identified particles & expansion of the system



Stronger radial flow at the LHC.
"Blast wave" fits to spectra indicate an **increase of the average radial boost velocity** up to (2/3)c and a decrease in the kinetic freezeout temperature to just below 100 MeV relative to RHIC



LHC: Large kinematic reach to explore

ALICE: excellent particle identification capabilities at the LHC

Statistical hadronization of the system (thermalized system?)

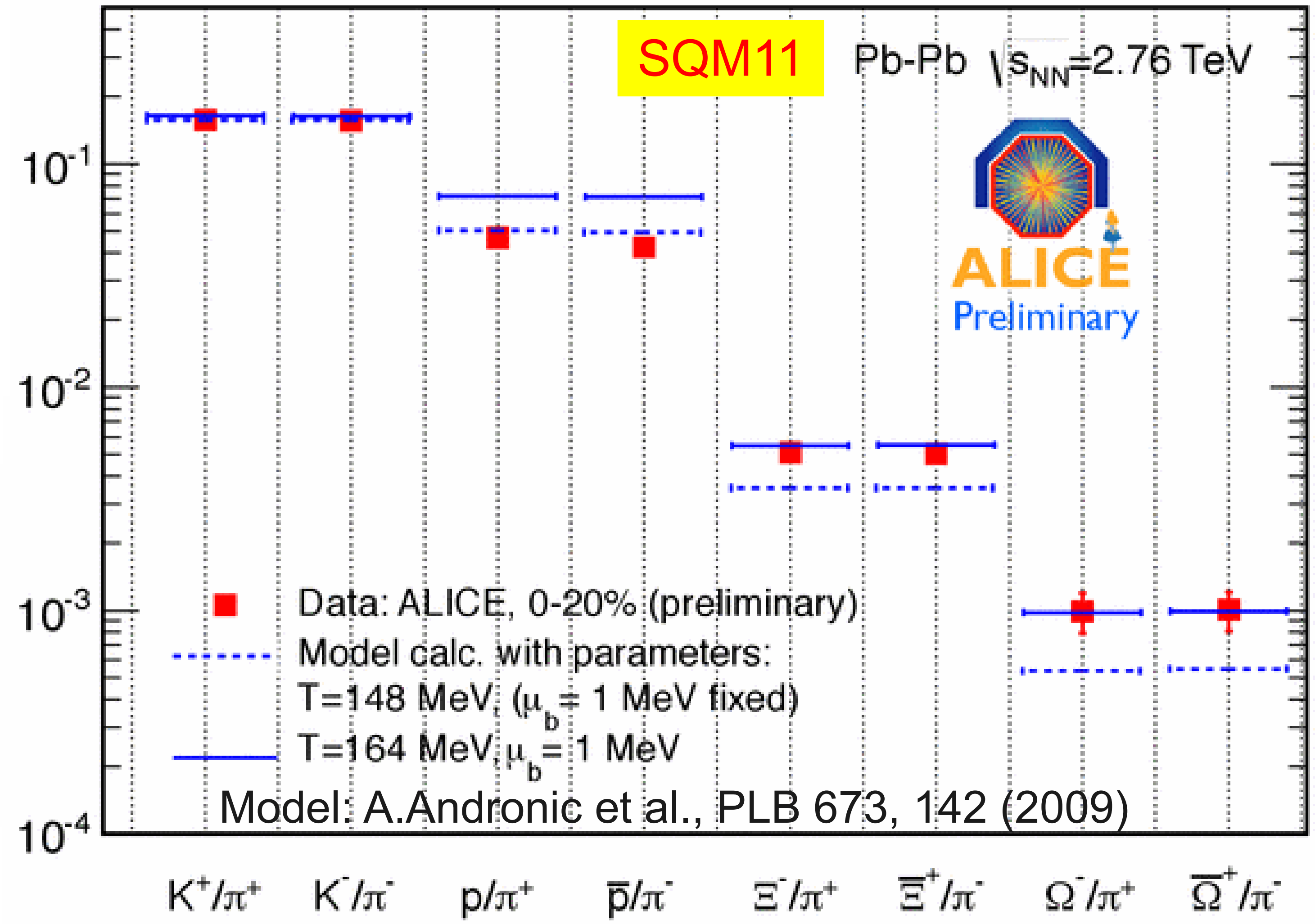
Note: Pasi discussed the RHIC 'version'

Grand-canonical ensemble analysis

$$N_i \propto V \int \frac{d^3 p}{2\pi^3} \frac{1}{e^{(E_i - \mu_B B_i)/Tch} \pm 1}$$

T_{ch} Chemical freeze-out temperature

μ_B Baryochemical potential



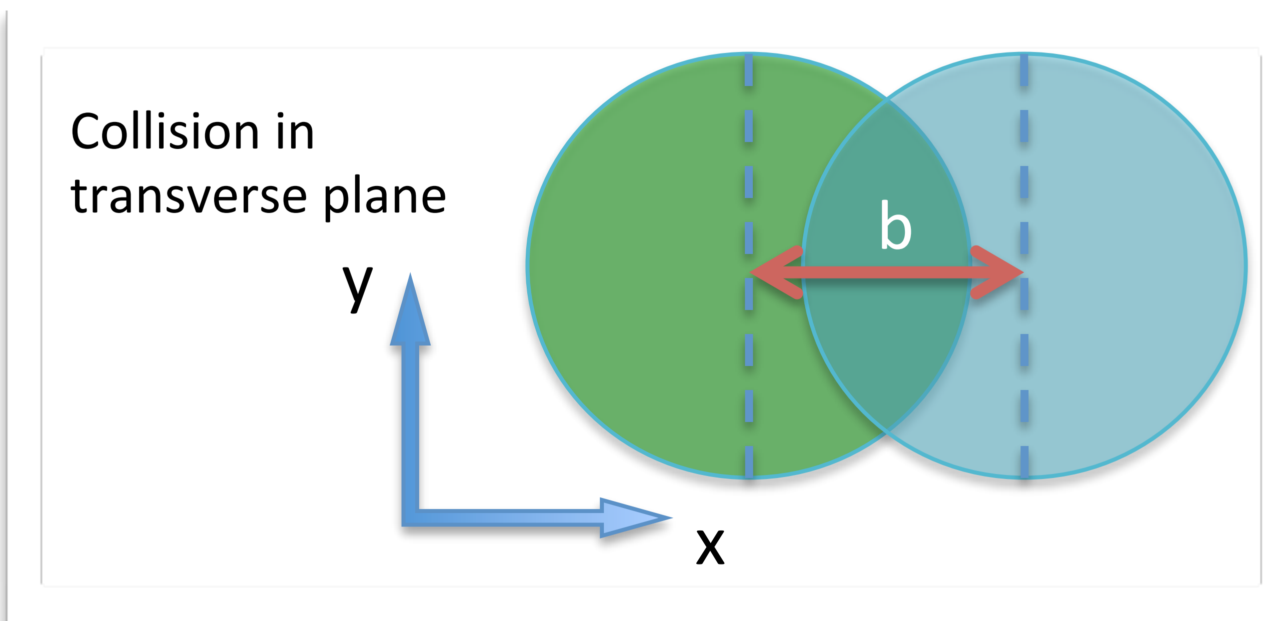
All yields (but protons) described by thermal model with **T_{ch}=164 MeV (and μ_b=1 MeV)**

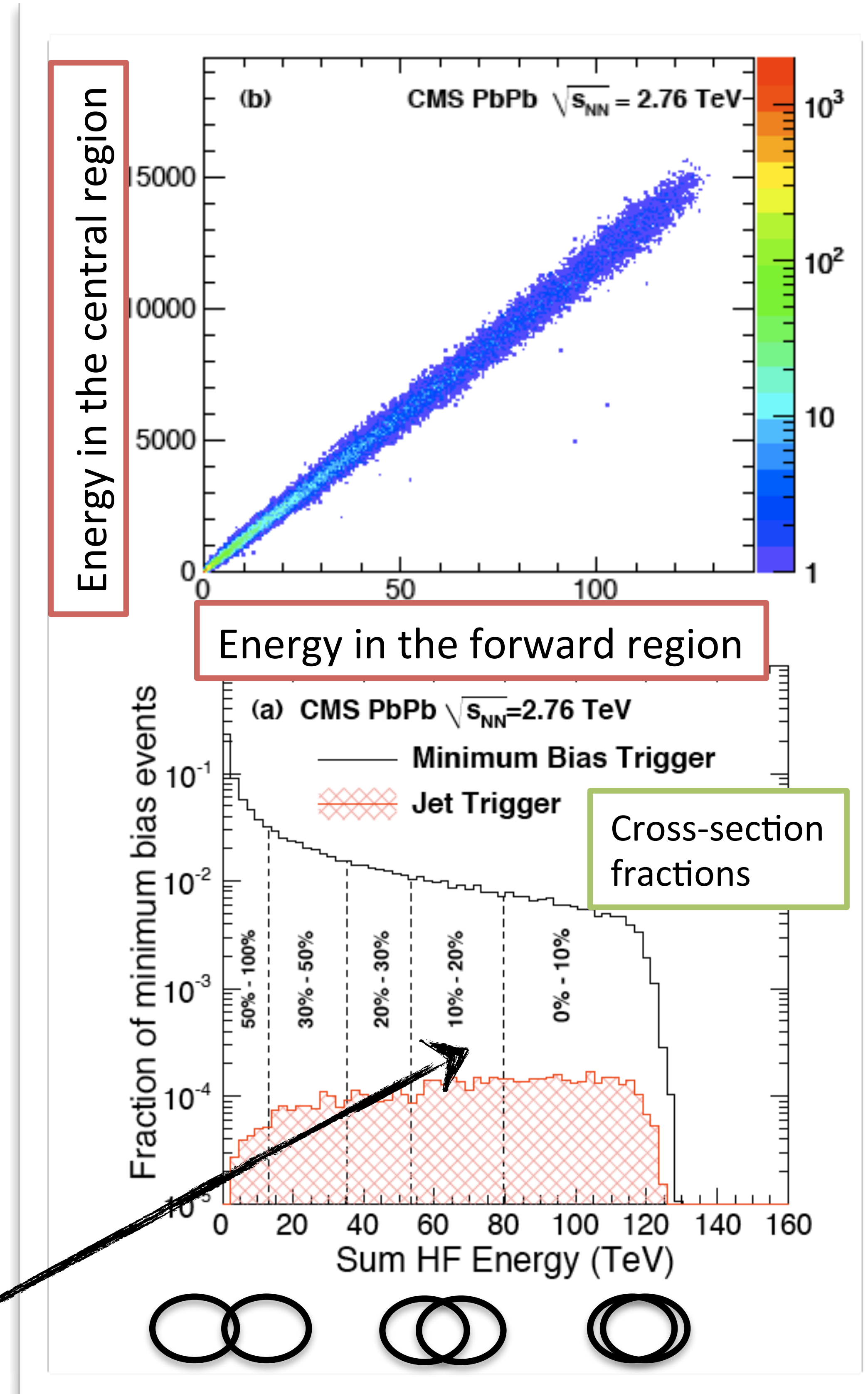
- Similar temperature as at RHIC, however proton/pion below the fit – the tension already present at RHIC
- Strange particles constrain fit
- Conclusions are model independent (confirmed with THERMUS)

Experimental control of collision

How can we measure impact parameter in heavy-ion collisions?

=> Correlate observables connected only by geometry





Characterize events via percentile of inelastic cross section (jargon: "N% most central")

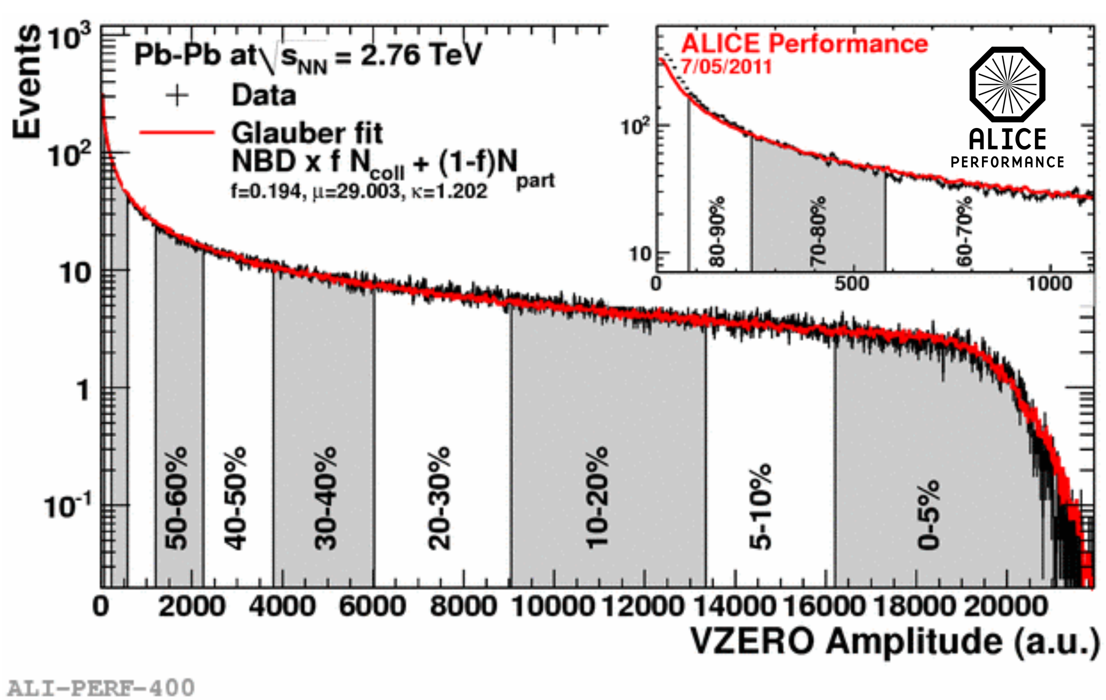
Centrality measurement: use of Glauber in an experiment

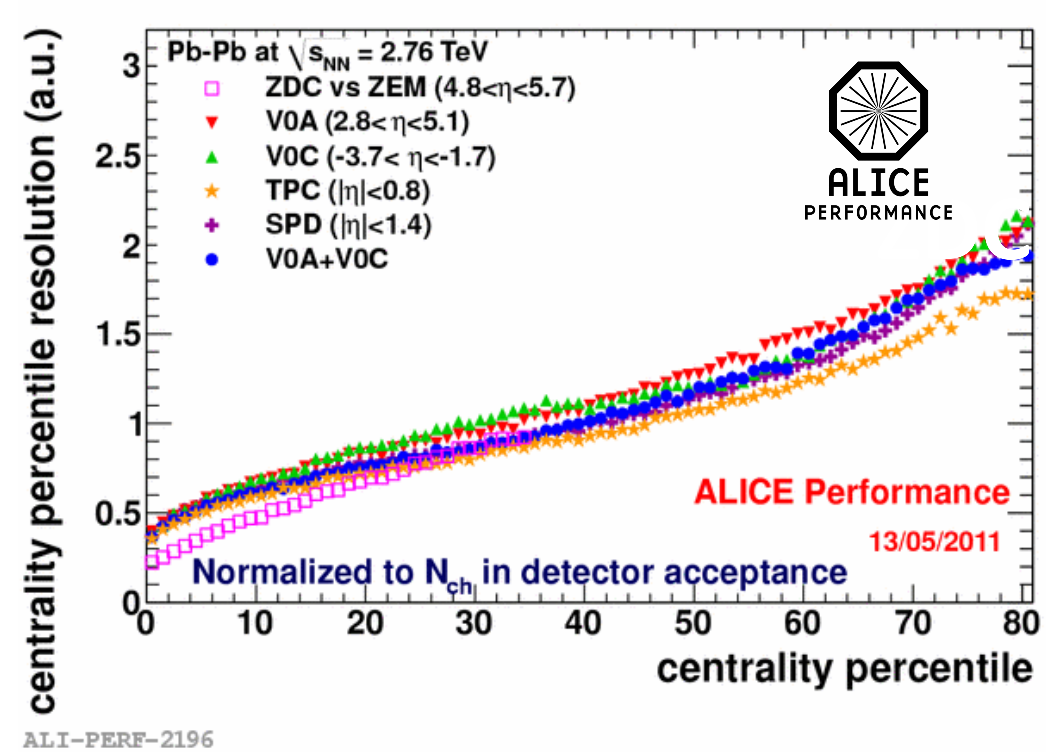
- Fraction of cross section, 2 approaches:
  - Fit with Glauber Monte Carlo
  - Correct: subtract BG, efficiency and integrate multiplicity distributions
- N_{part}, N_{coll}, N_{spect}: require Glauber fit (computed using cuts on impact parameter)
- Estimators:

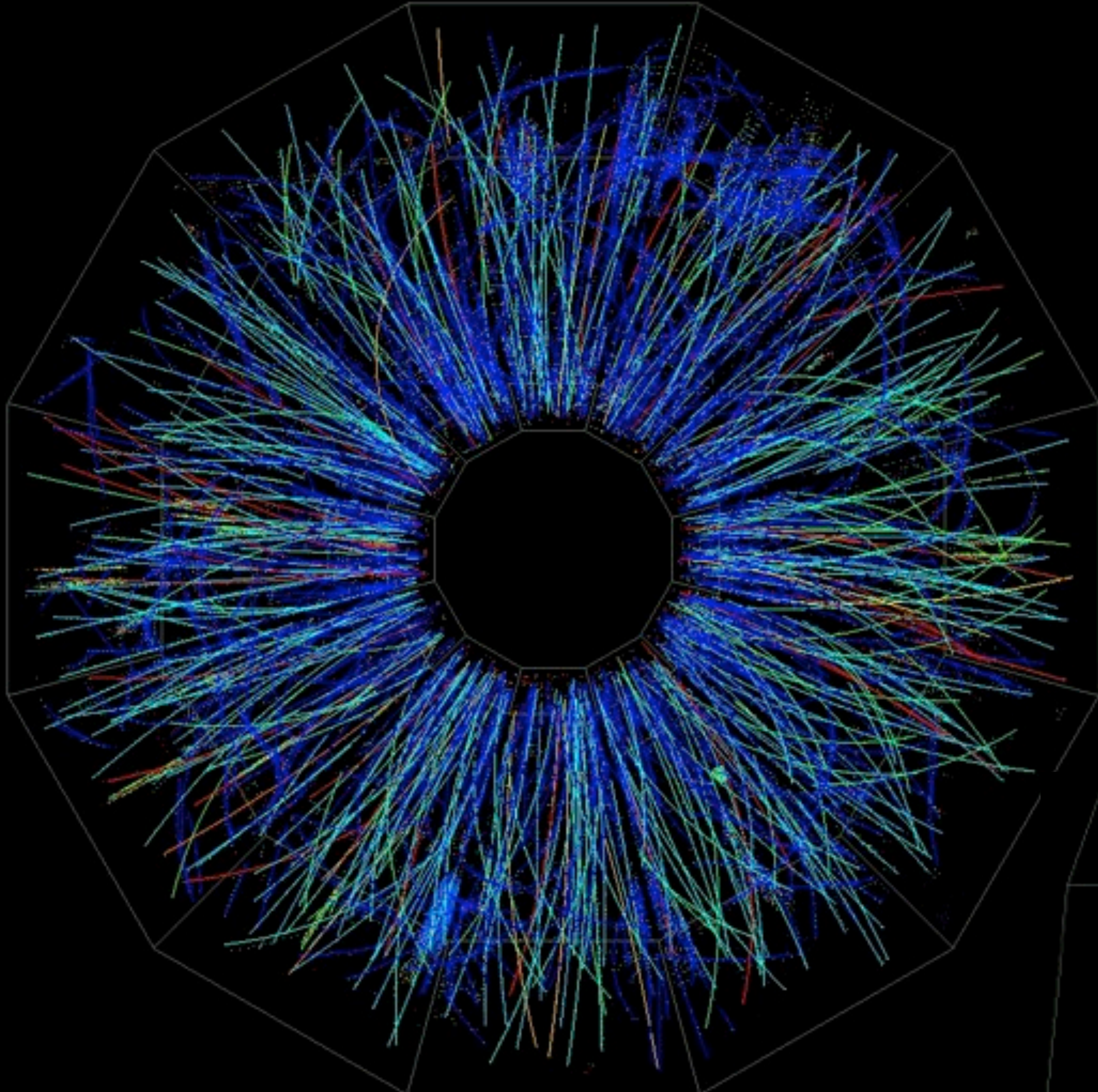
  V0, SPD clusters, TPC tracks, ZDCs, …
- ZDC measures N_{spect}: test of Glauber picture

- Glauber fit ingredients
  - Woods-Saxon (constrained by low energy electron-nucleus scattering)
  - Inelastic pp cross section (measured by ALICE)
  - Nucleons follow straight line trajectories, interact based on their distance
  - Compute (fit) observables assuming:

$$N_{ancestors} = \alpha \cdot N_{part} + (1-\alpha) \cdot N_{coll}$$

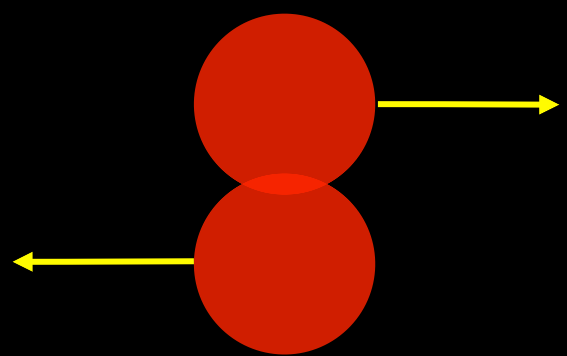


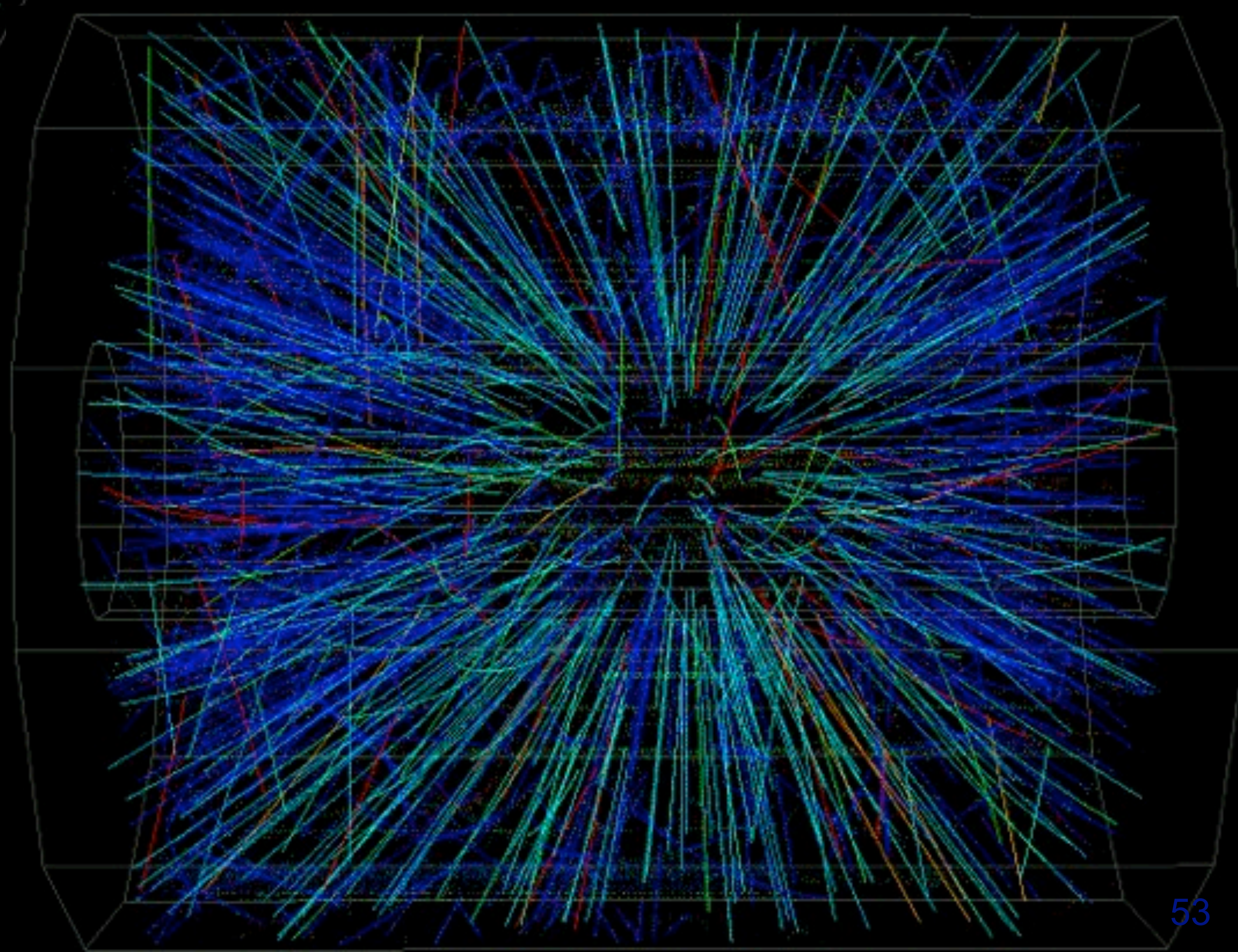




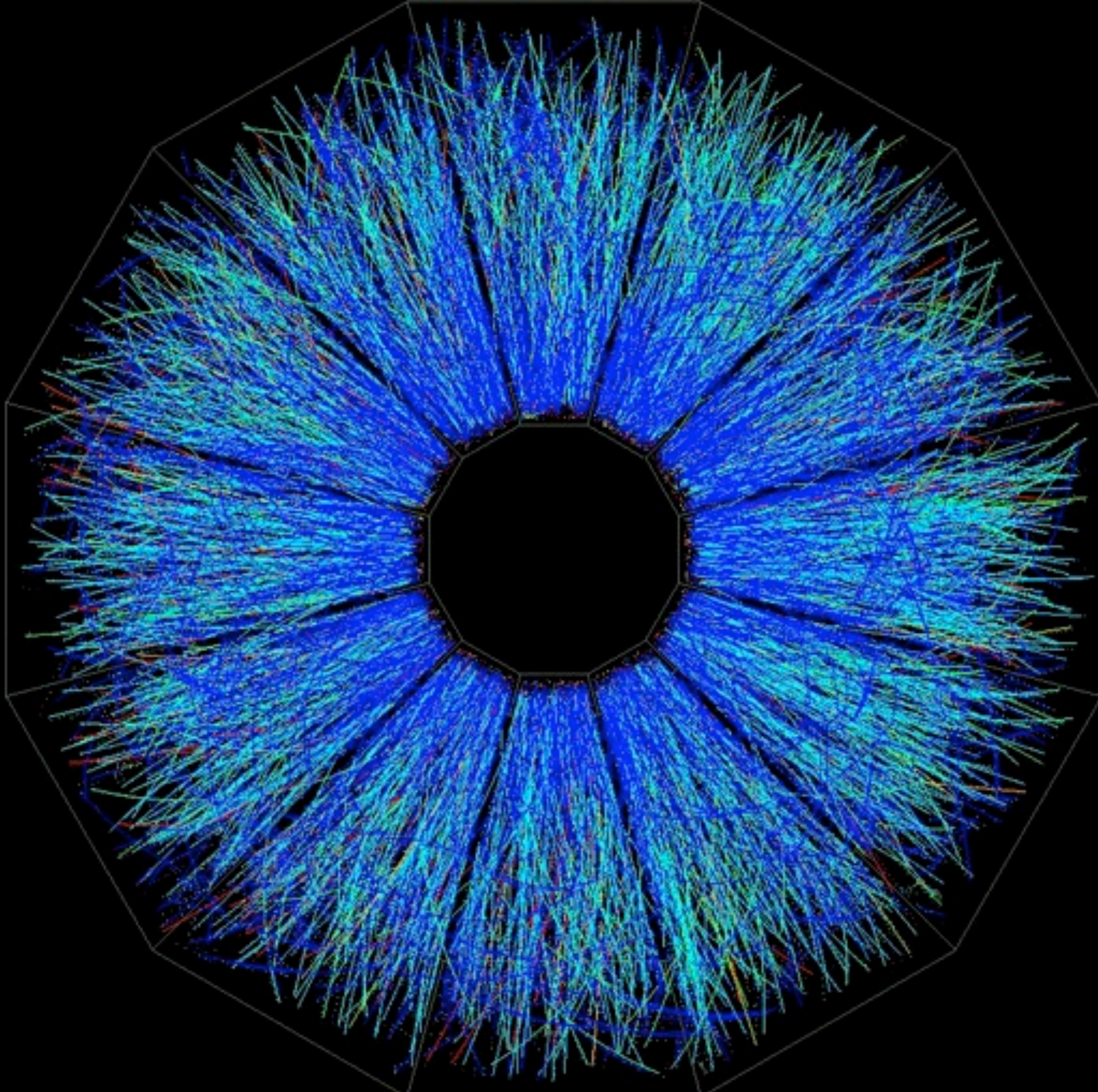
only charged particles visible

Peripheral Collision



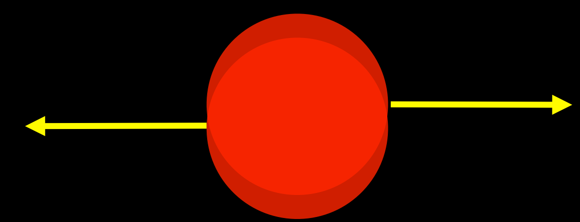


Color ⇒ Energy loss in TPC gas



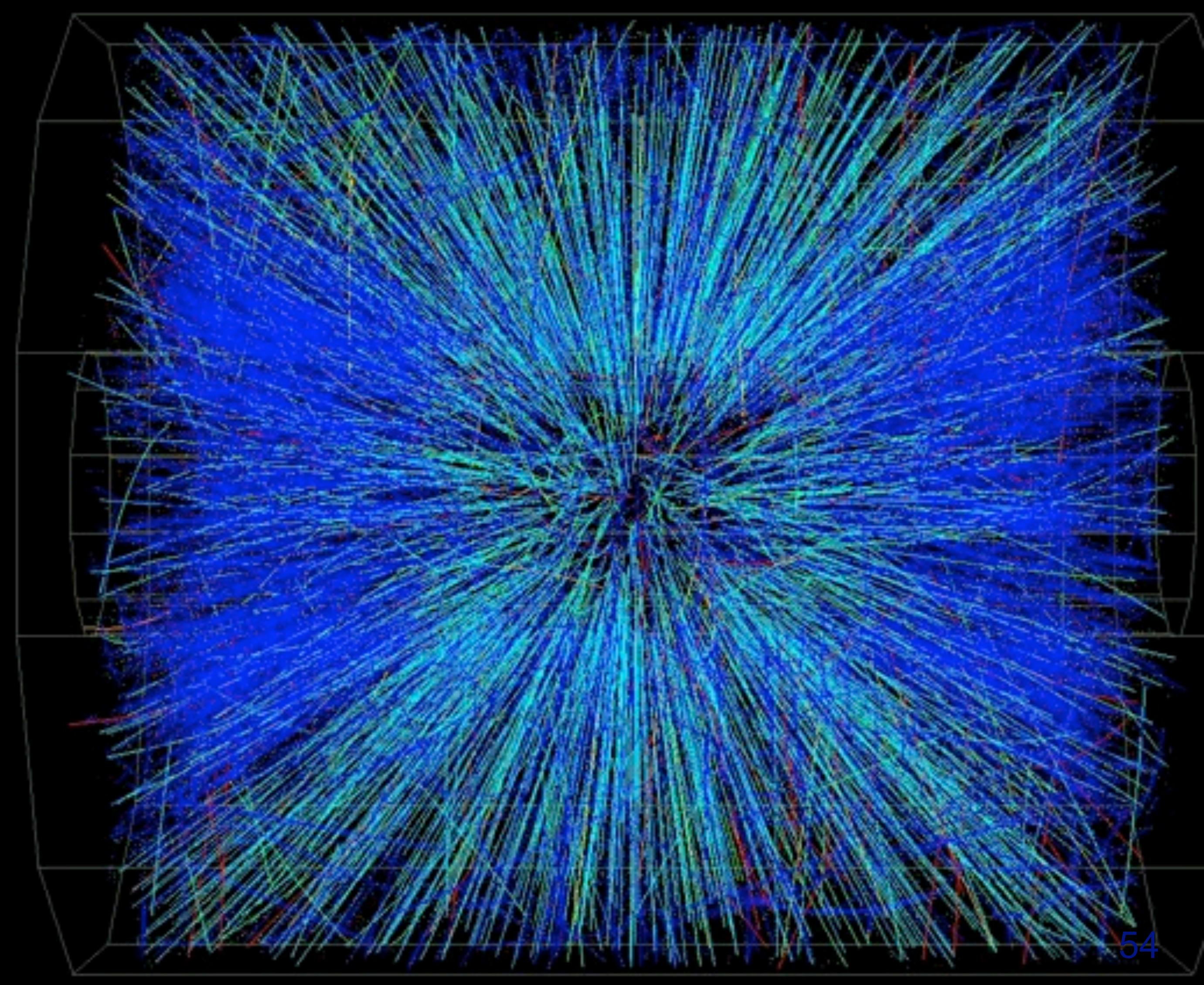
only charged particles visible

Central Collision

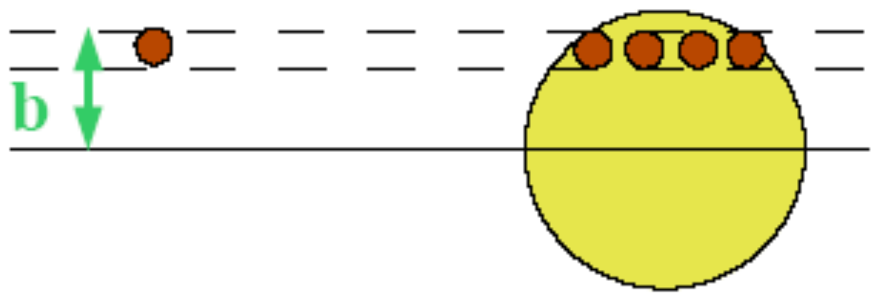


200 GeV Au+Au: $\mathbf{N_{ch}\sim4800}$

STAR



Nuclear geometry - Glauber model



Normalized nuclear density r(*b*,*z*):

$$\int dz\, db\, \rho(b,z) = 1$$

Nuclear thickness function

$$T_A(b) = \int_{-\infty}^{\infty} dz\, \rho(b,z)$$

Inelastic cross section for p+A:

$$\sigma_{pA}^{inel} = \int d\vec{b}\left(1 - \left[1 - T_A(b)\sigma_{NN}^{inel}\right]^A\right)$$

Glauber scaling: hard processes with large momentum transfer

- short coherence length ⇒ successive NN collisions independent
- p+A is incoherent superposition of N+N collisions

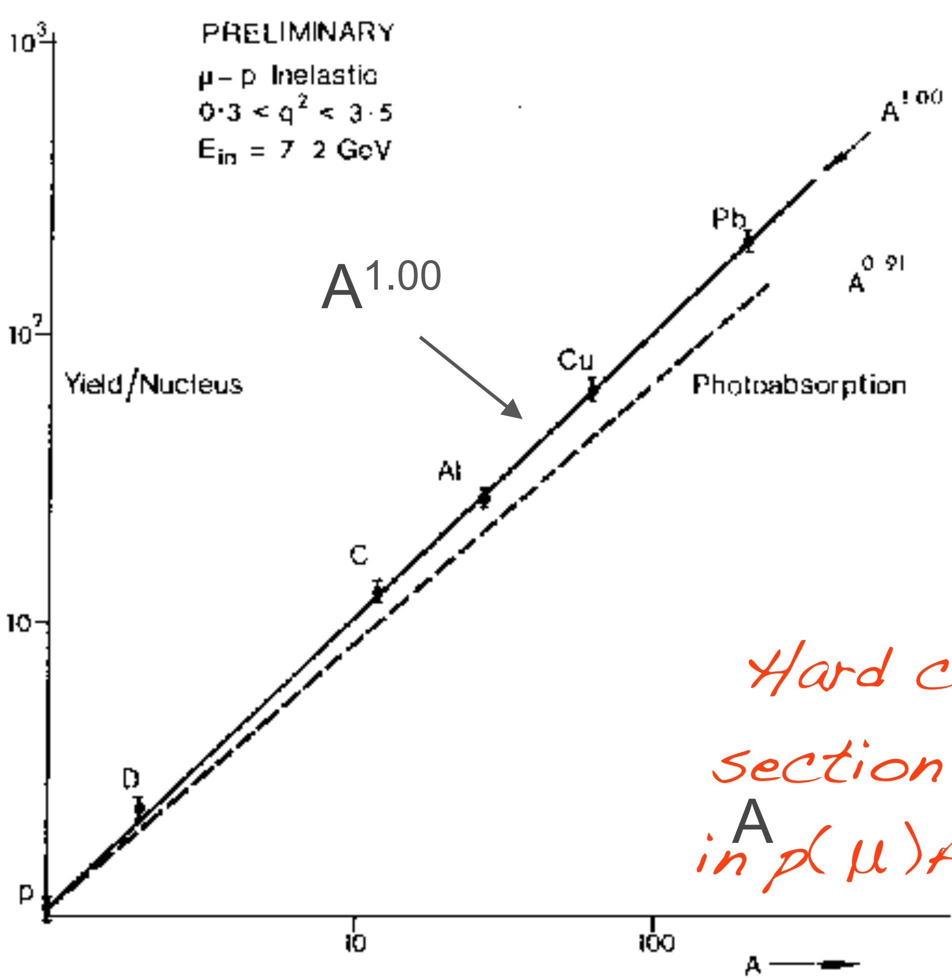
$$\sigma_{pA}^{hard} \approx A\sigma_{NN}^{hard} \int d\vec{b}\, T_A(\vec{b}) = A\sigma_{NN}^{hard}$$

Glauber scaling of hard processes

Glauber scaling: $$\sigma_{pA}^{hard} = A\sigma_{NN}^{hard}$$

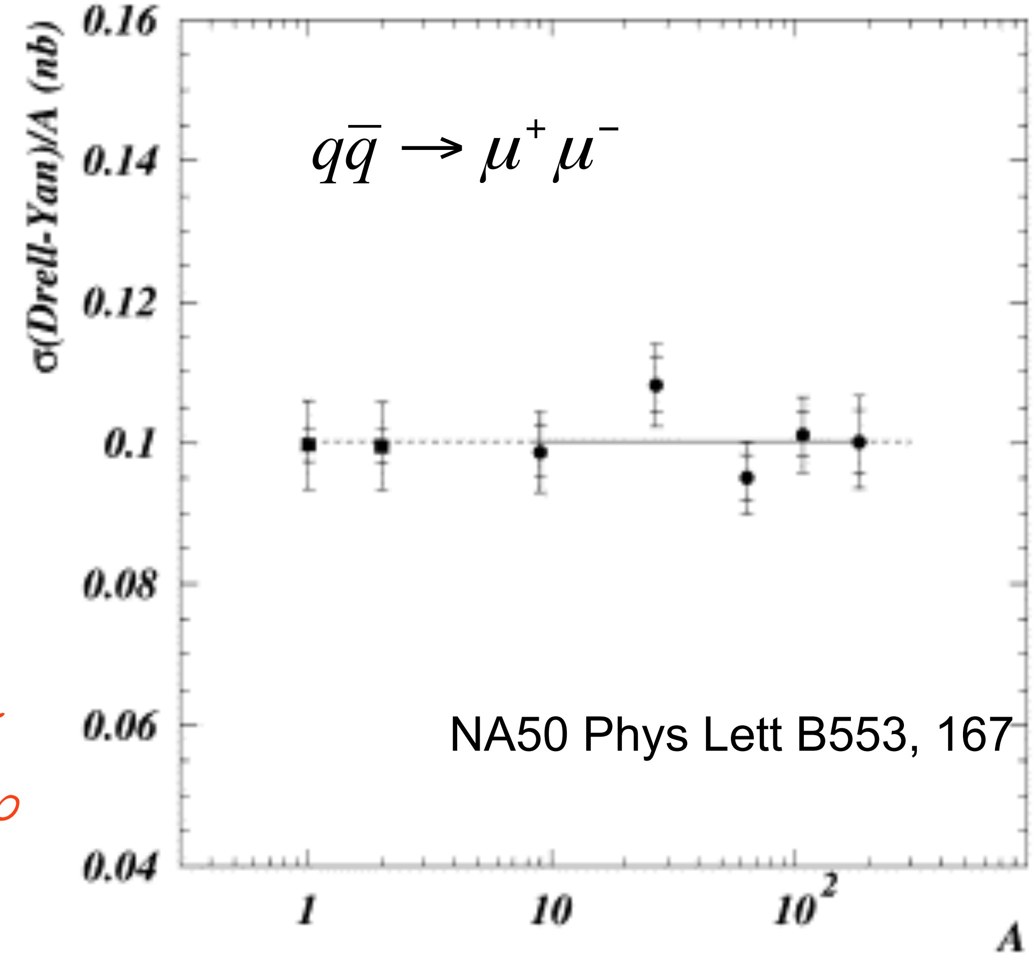
σ_{inel} for 7 GeV muons on nuclei

M.May et al, Phys Rev Lett 35, 407 (1975)



Hard cross-section scales in p(μ)A as $A^{1.0}$

$\sigma_{Drell\text{-}Yan}/A$ in p+A at SPS



Experimental control in heavy-ion collisions?

=> direct photons, Z's (discussed later...)

Energy density in AA collisions – RHIC example

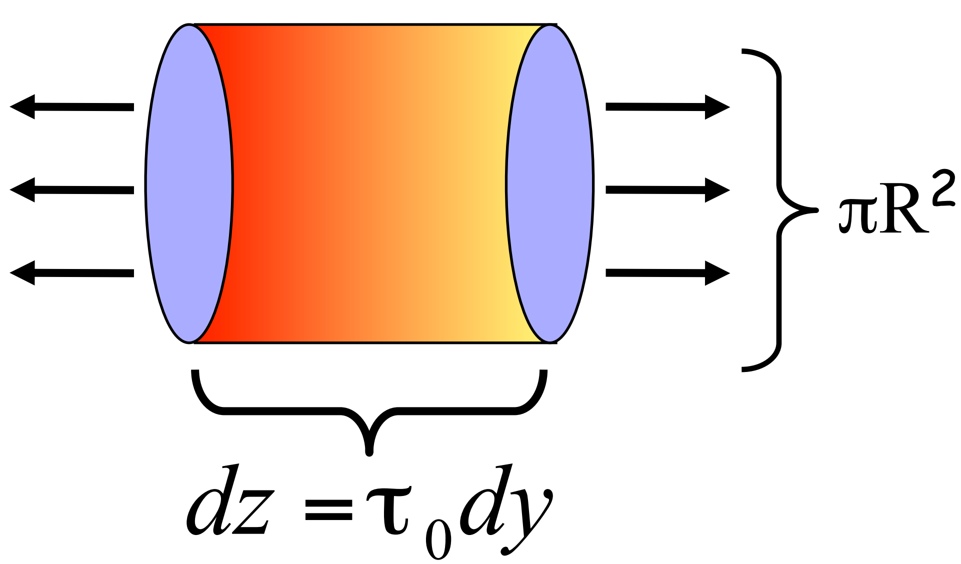
- (calorimeters) measure energy
- estimate volume of collision

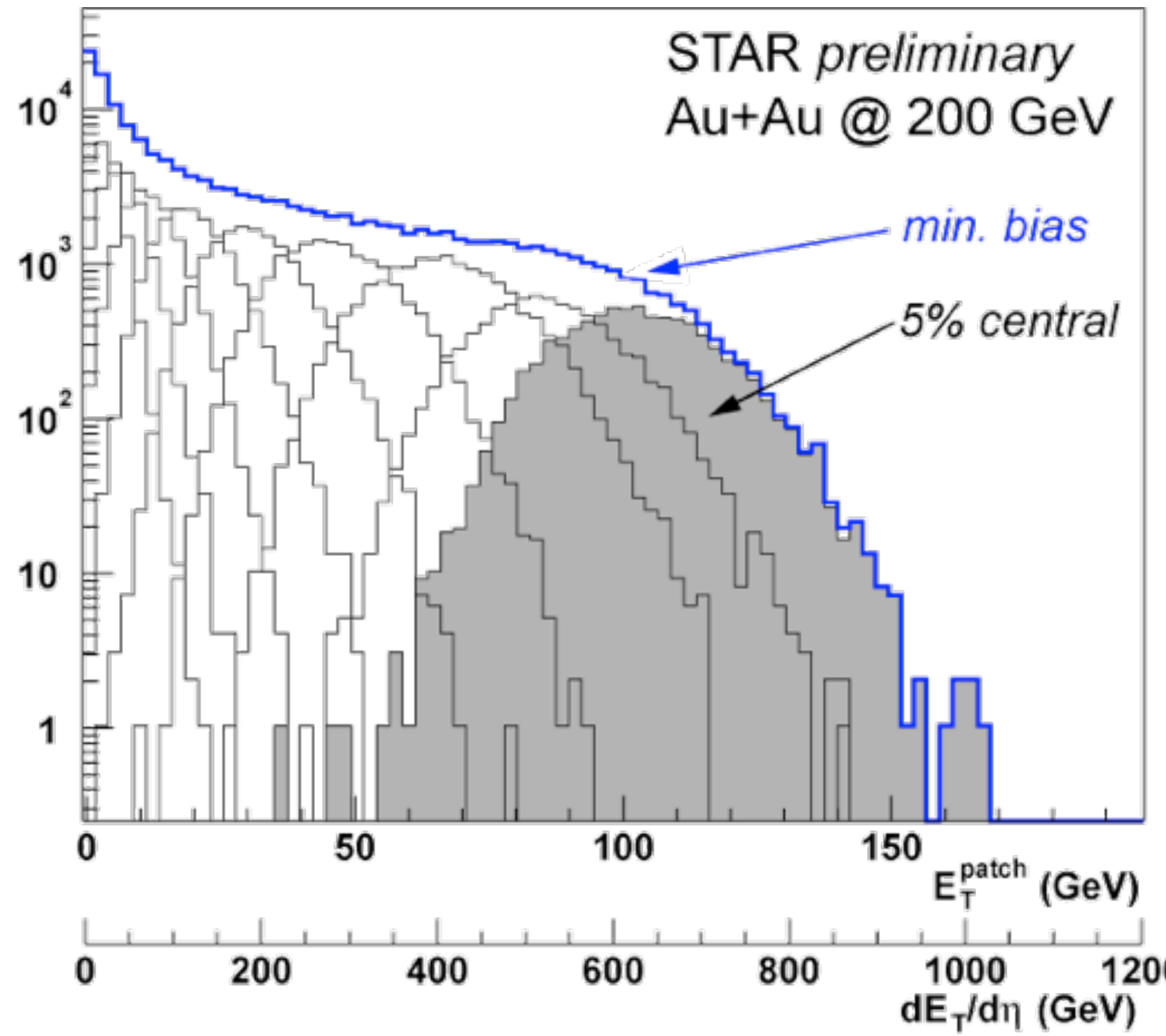
Bjorken energy density:

$$\varepsilon_{Bj} = \frac{\Delta E_T}{\Delta V} = \frac{1}{\pi R^2} \frac{1}{\tau_0} \frac{dE_T}{dy}$$

R~6.5 fm

Time it takes to thermalize system (t_0 ~ 1 fm/c)





$\varepsilon_{BJ} \approx 5.0$ GeV/fm³

RHIC:

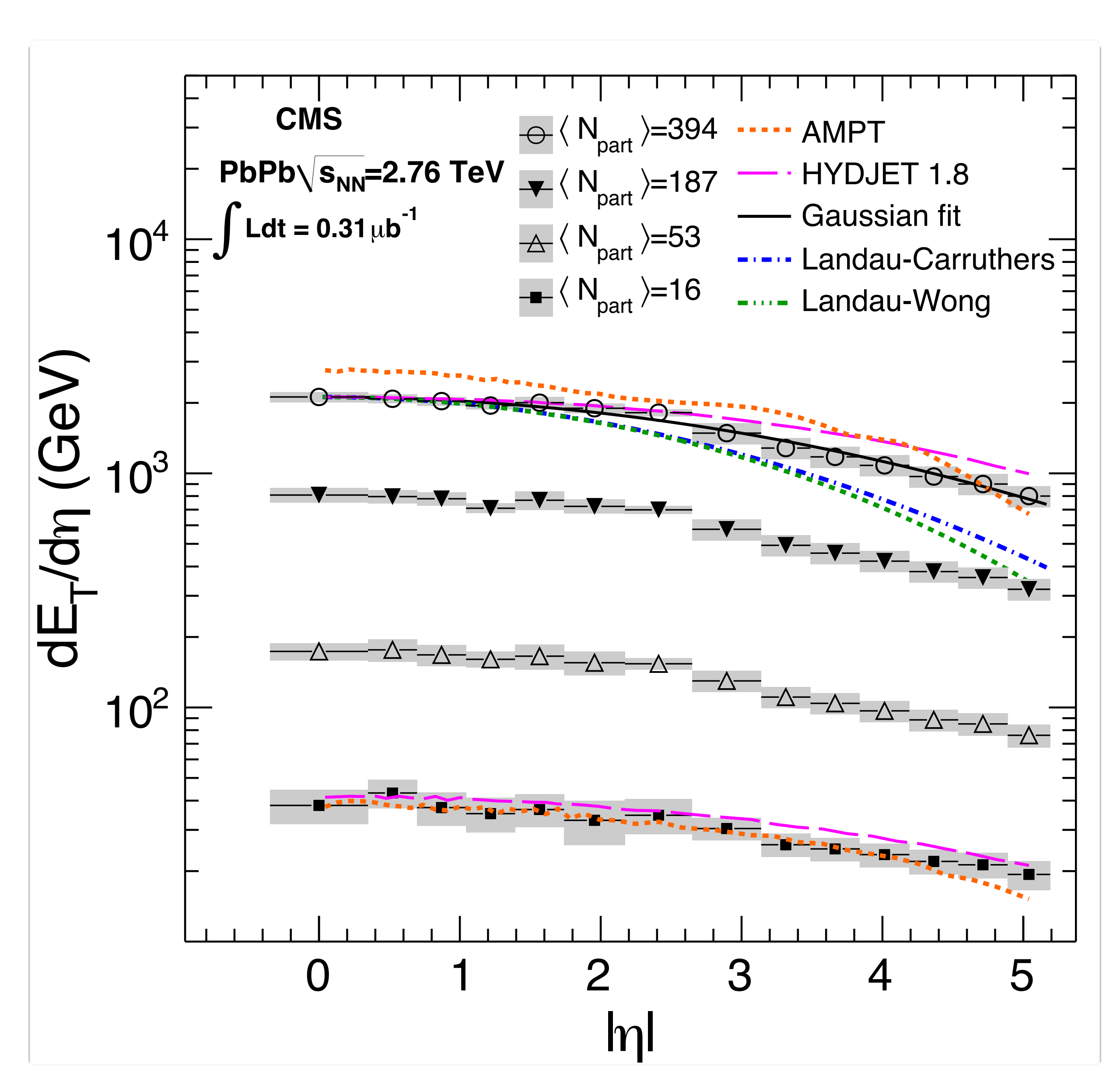
~30 times normal nuclear density

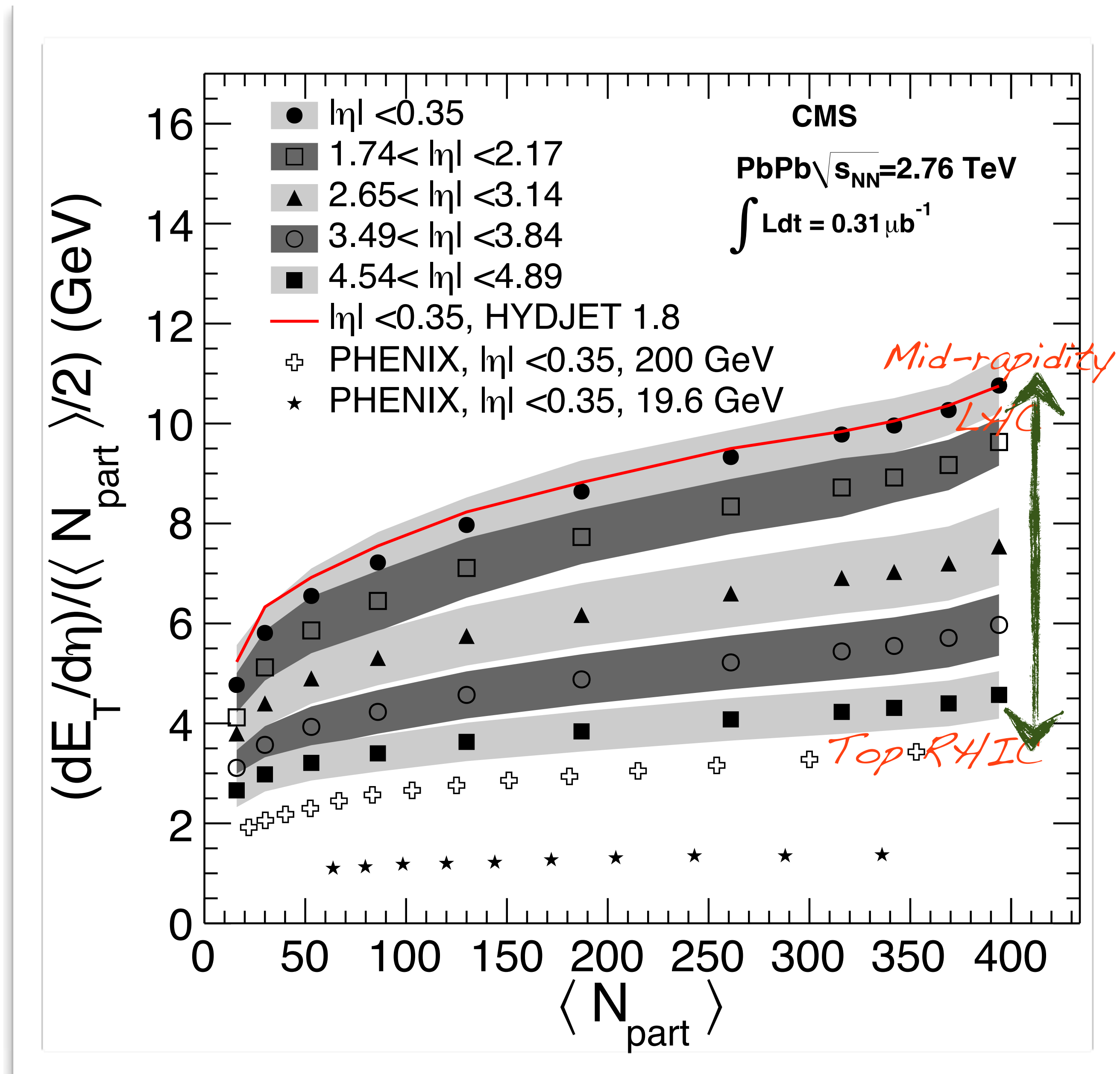
~ 5 times > $\varepsilon_{critical}$ (lattice QCD)

Energy density: RHIC to LHC

LHC > 2.5 × RHIC

... within a volume (per nucleon)



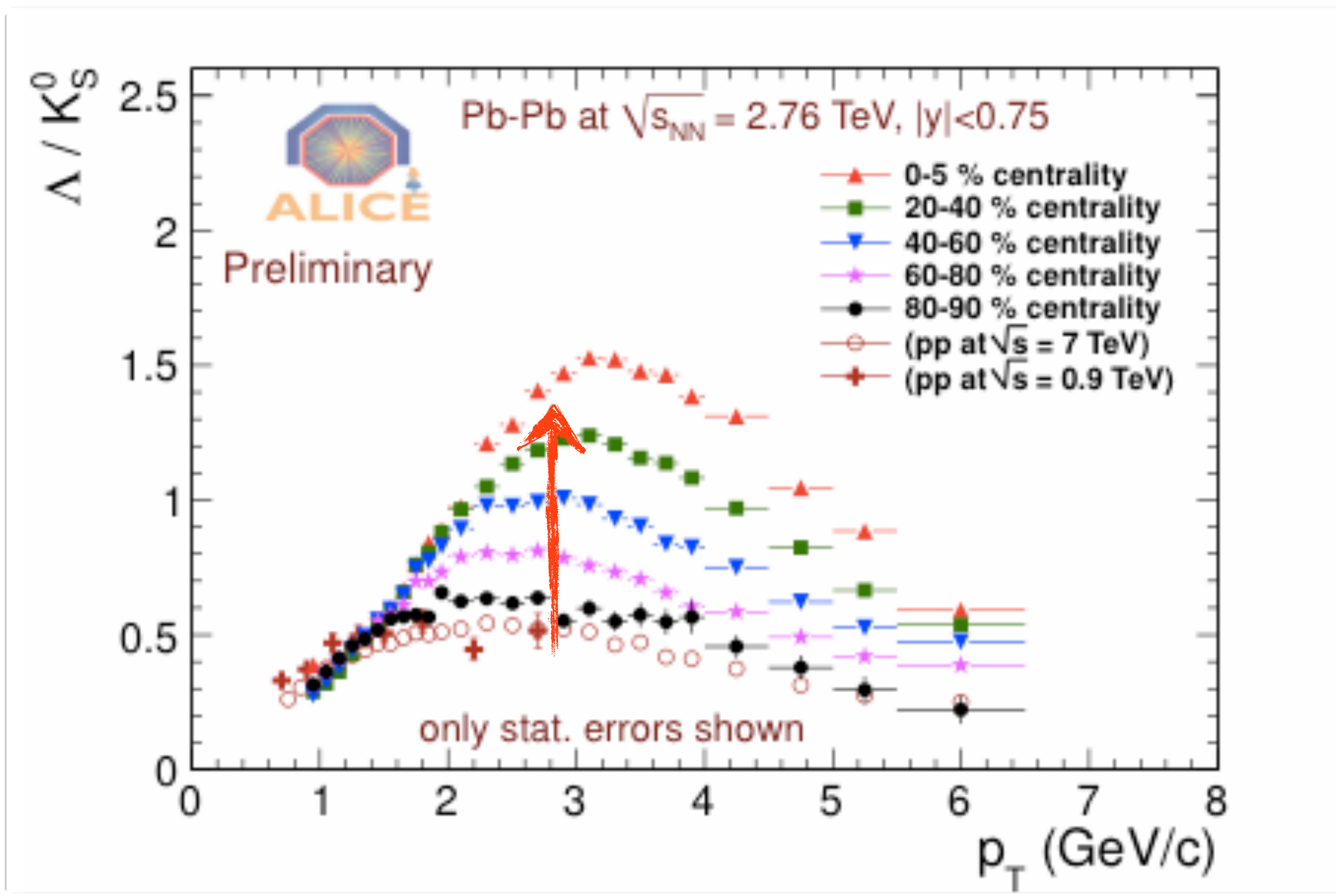


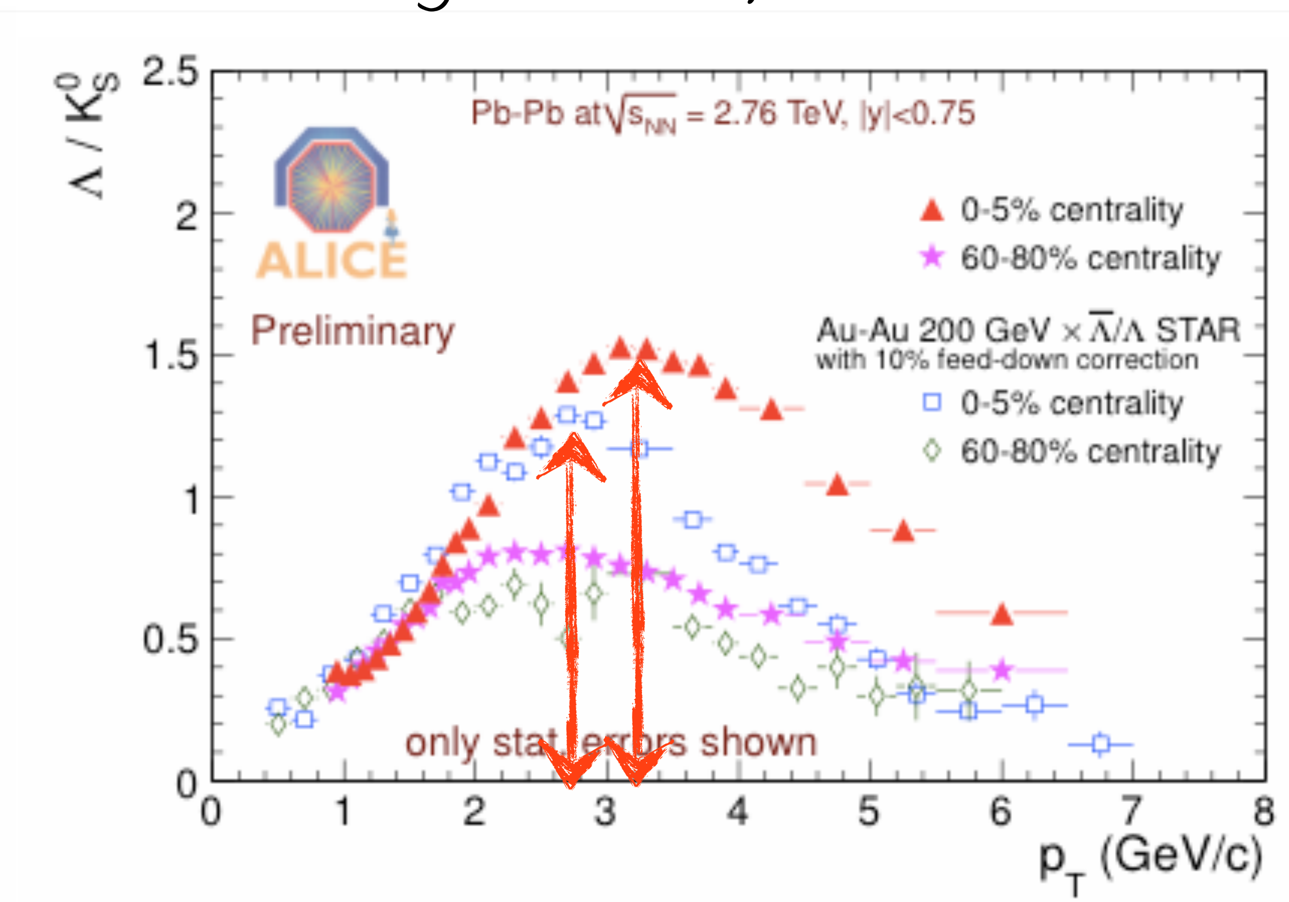
Very hot, super dense(?) -> how dense...?

Hadron production in heavy-ion collisions

A slight digression...

RHIC vs LHC
(LHC: higher mean pT - more flow)

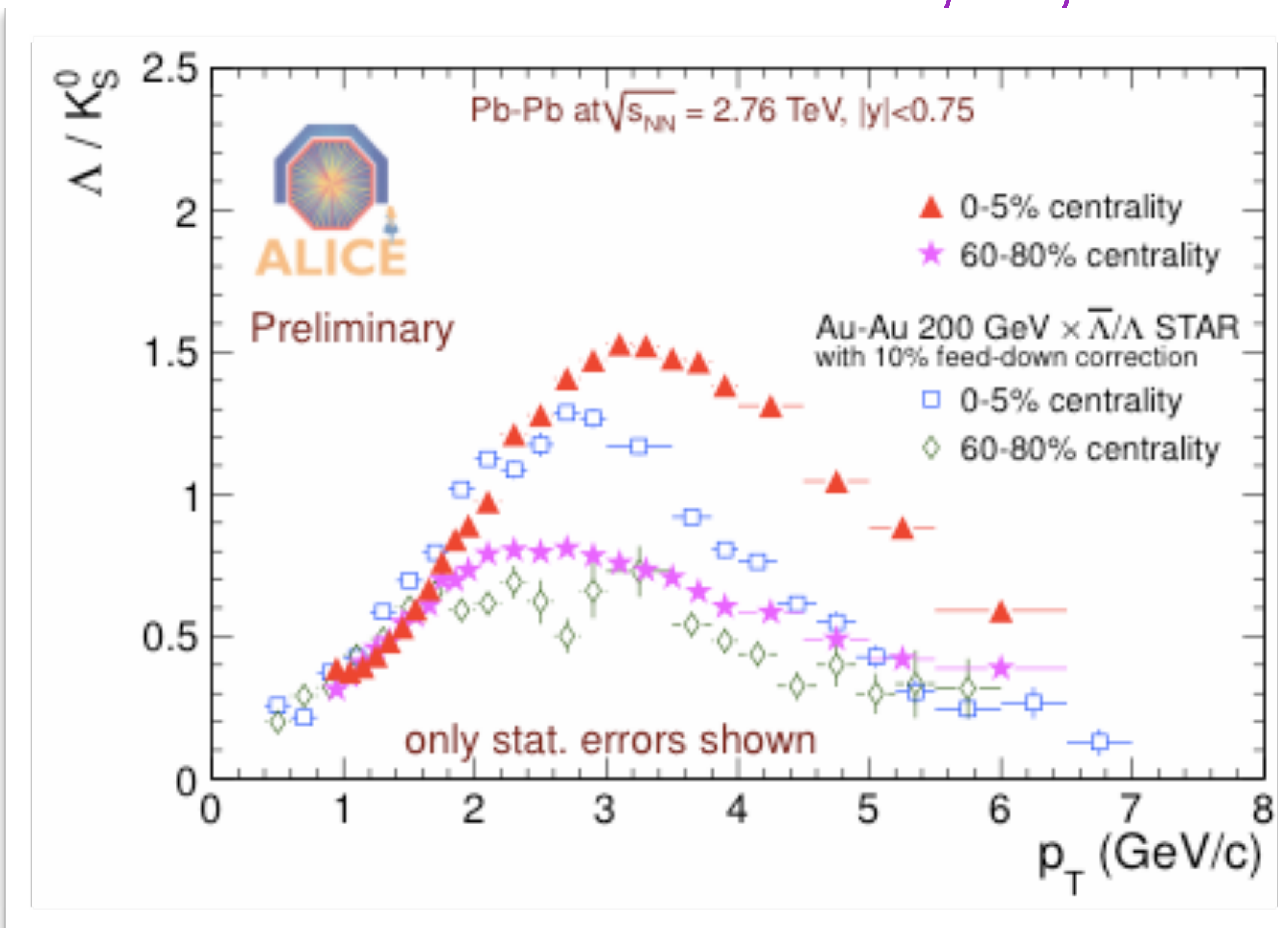




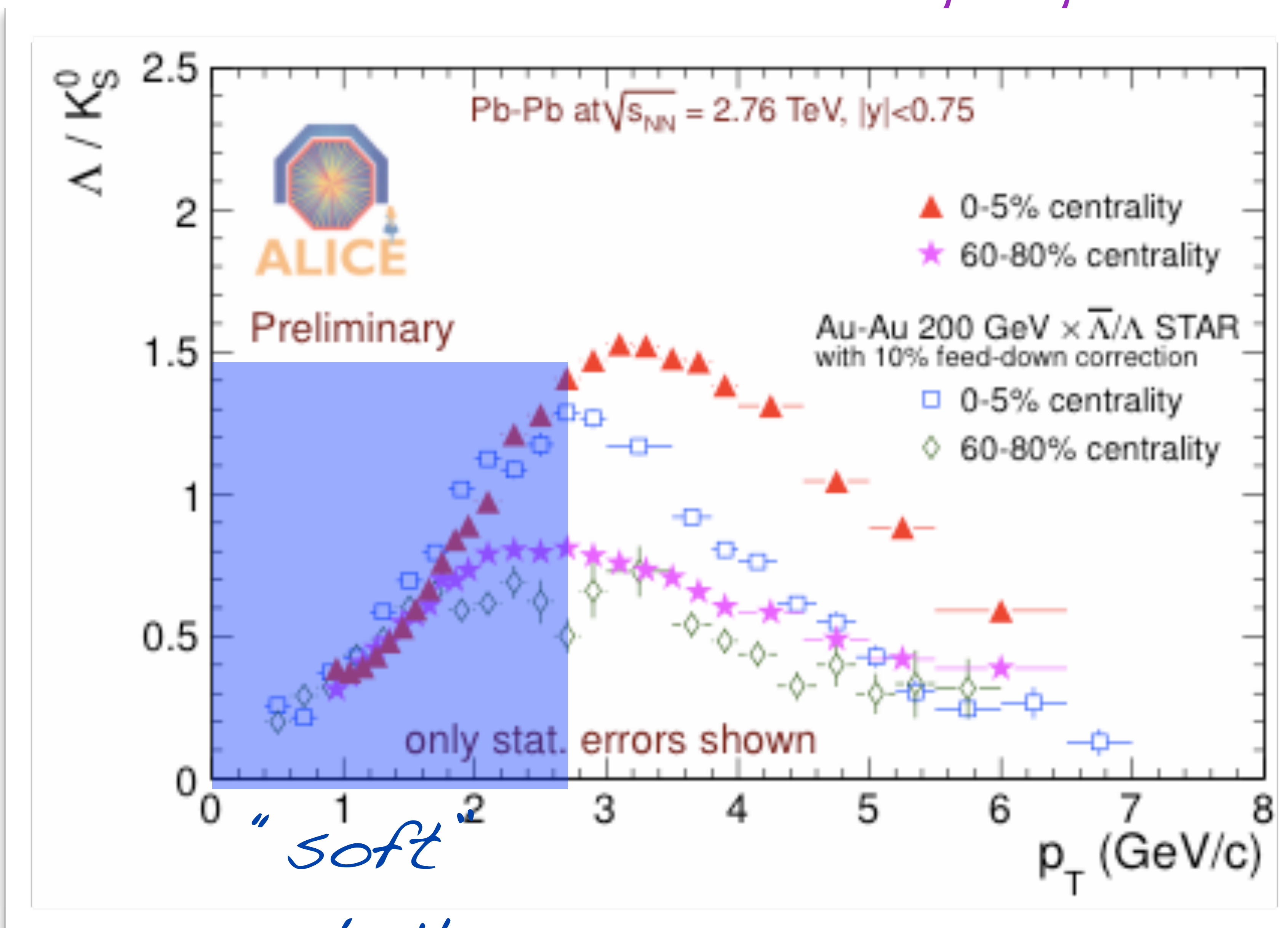
Much more baryons than mesons in central collisions as compared to proton-proton (coalescence/recombination? bulk+jet?)

LHC similar to RHIC
Maximum at slightly higher-pT

bulk, jets, medium and p_T:
arbitrary regions
and INFORMAL Language

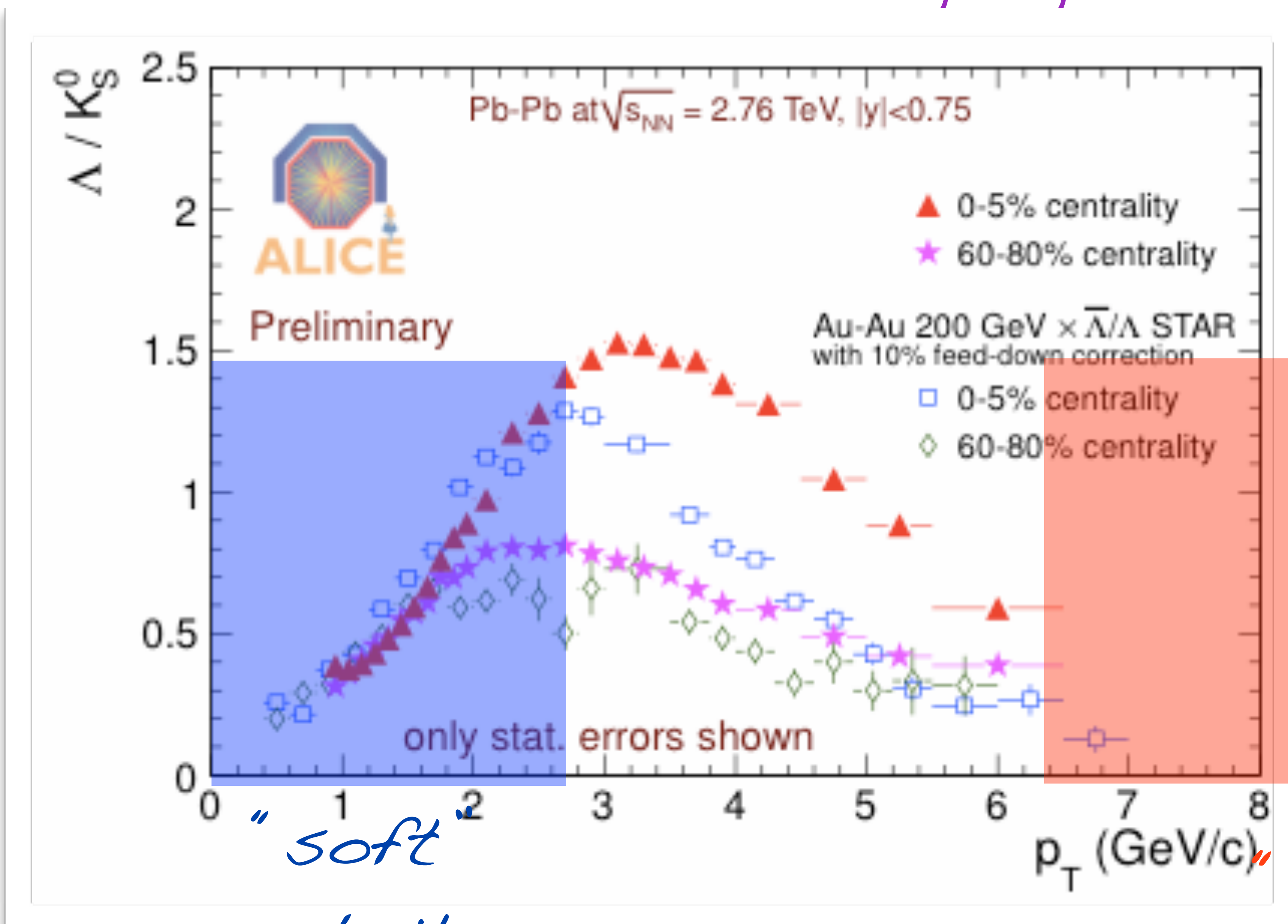


bulk, jets, medium and p_T:
arbitrary regions
and INFORMAL Language



"soft"
-bulk
thermal

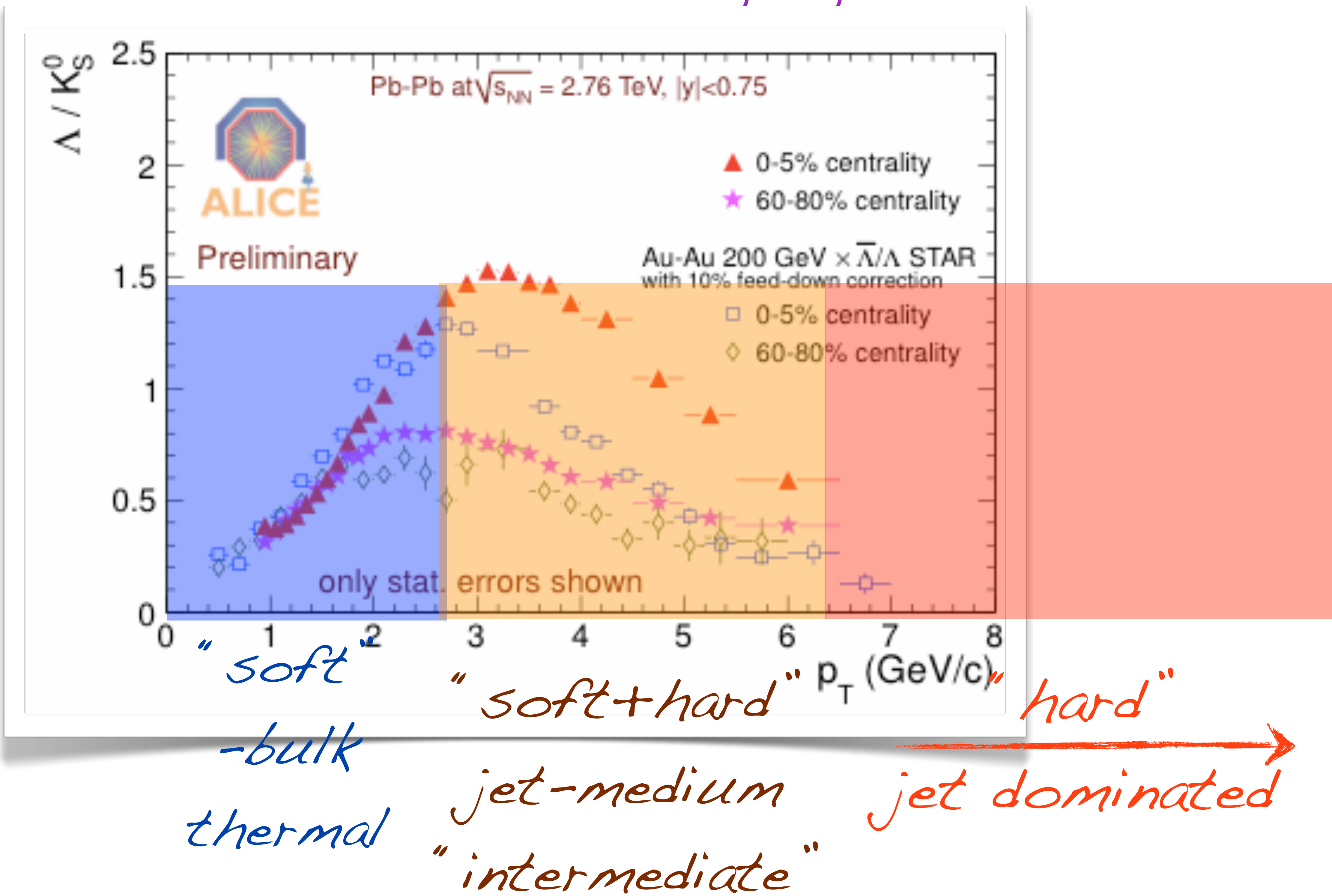
bulk, jets, medium and p_T:
arbitrary regions
and INFORMAL Language



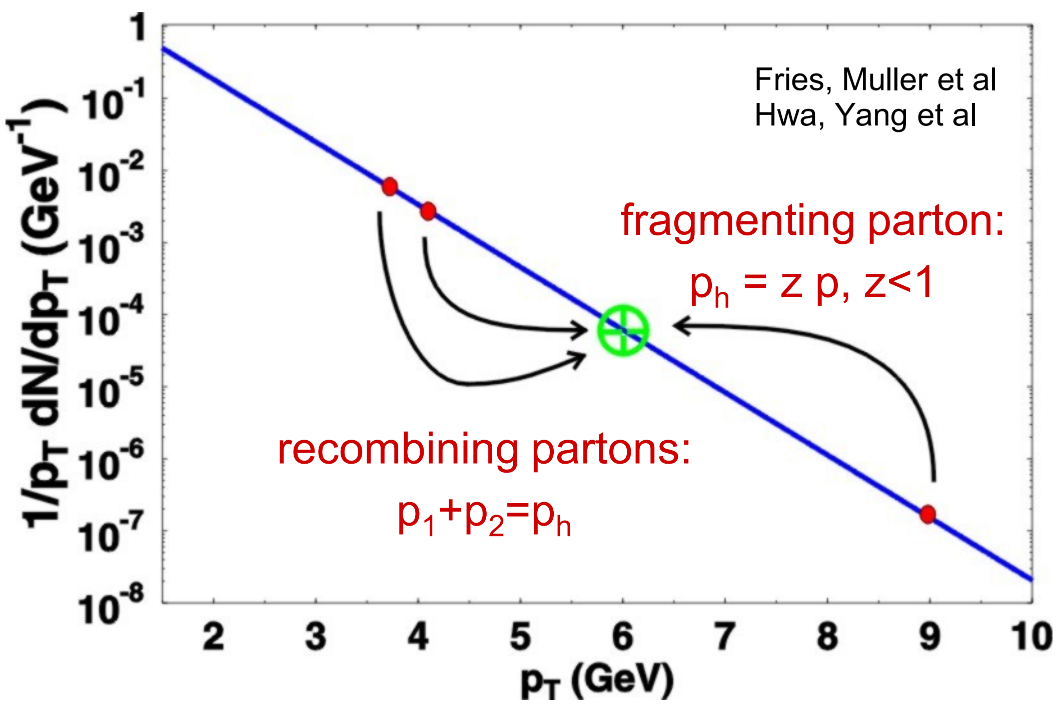
"soft"
-bulk
thermal

"hard"
jet dominated

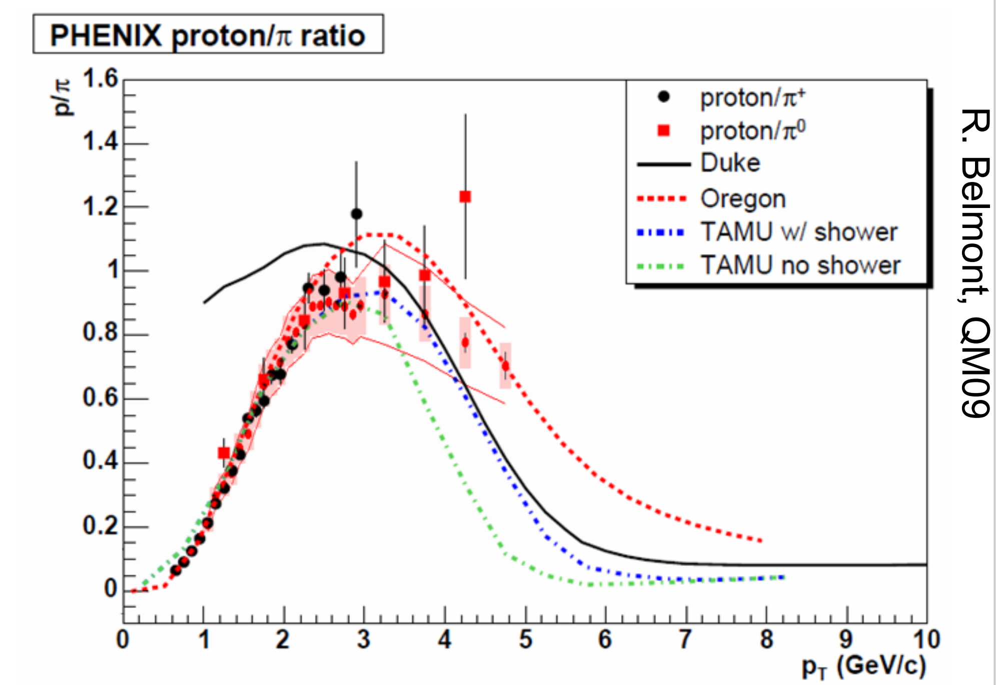
bulk, jets, medium and p_T:
arbitrary regions
and INFORMAL Language



Hadronization of bulk+hard - parton coalescence

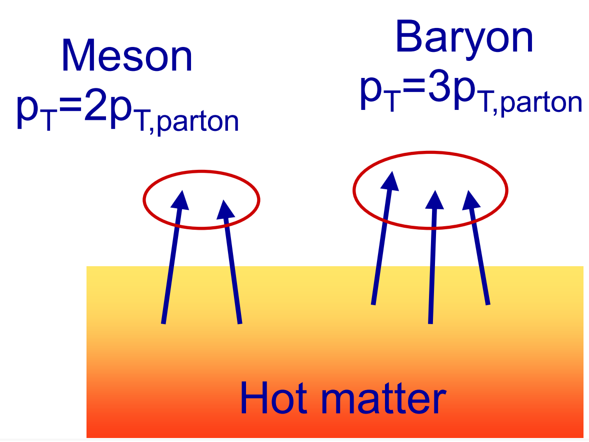


Recombination of thermal ('bulk') partons produces baryons at larger p_T

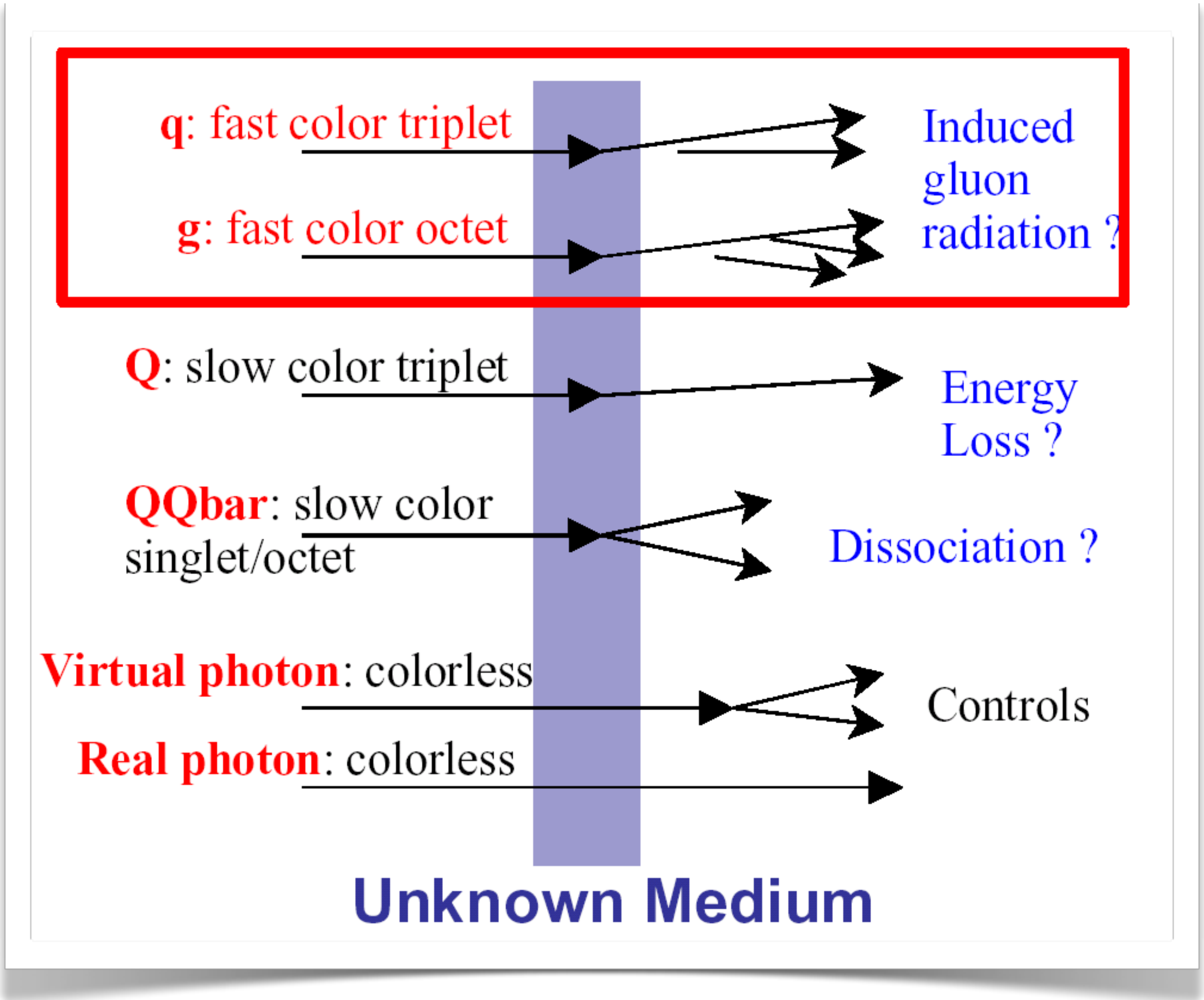


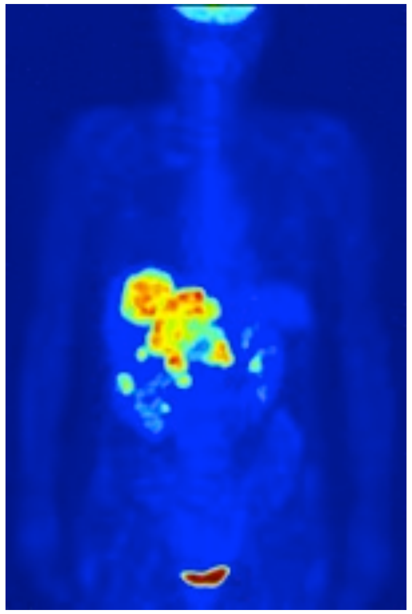
Recombination enhances baryon/meson ratio

Note also: v_2 scaling



Probing the unknown medium...





Human body

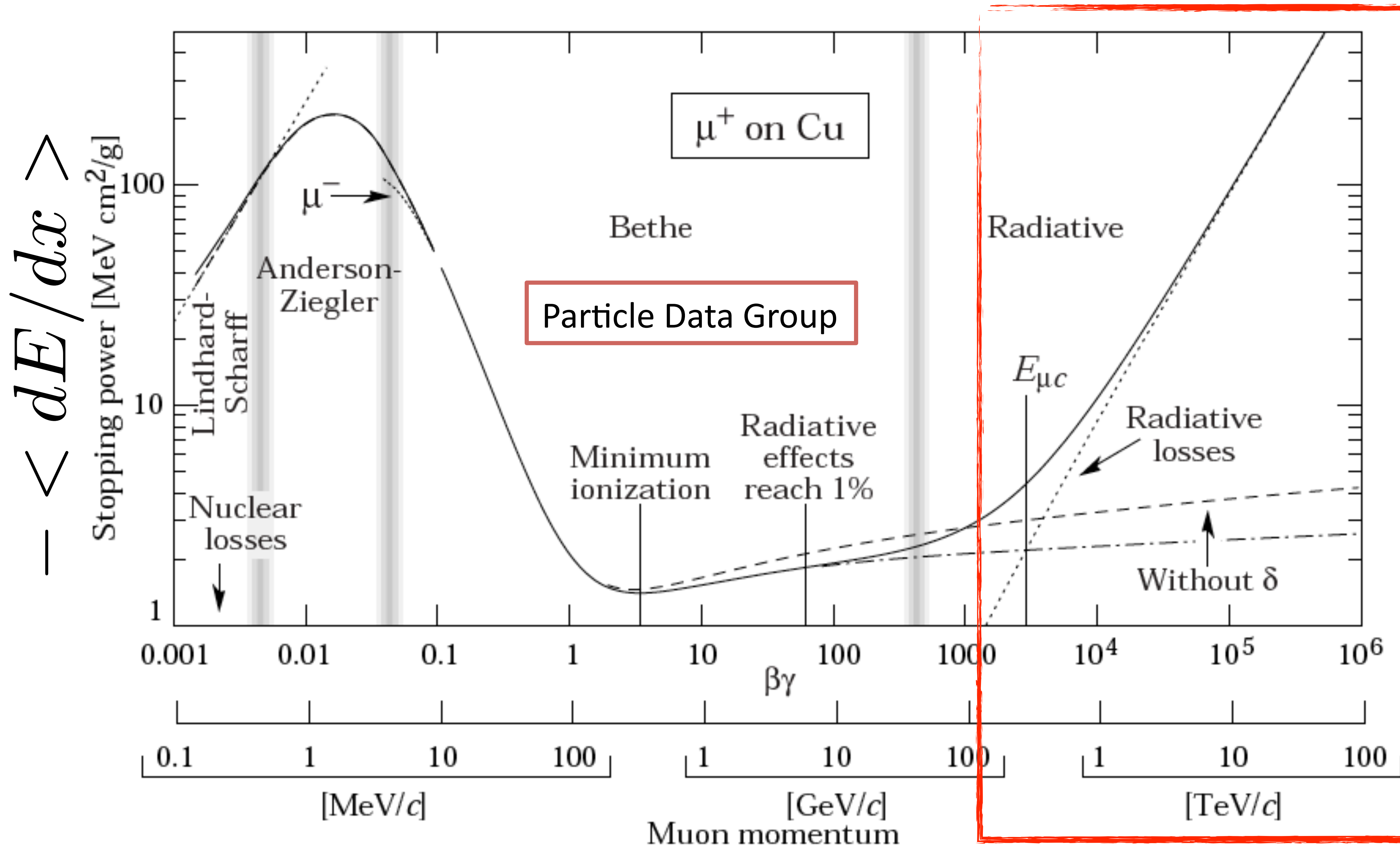
jet suppression (quenching)

charm/bottom dynamics

J/ψ & Υ

color-less particles

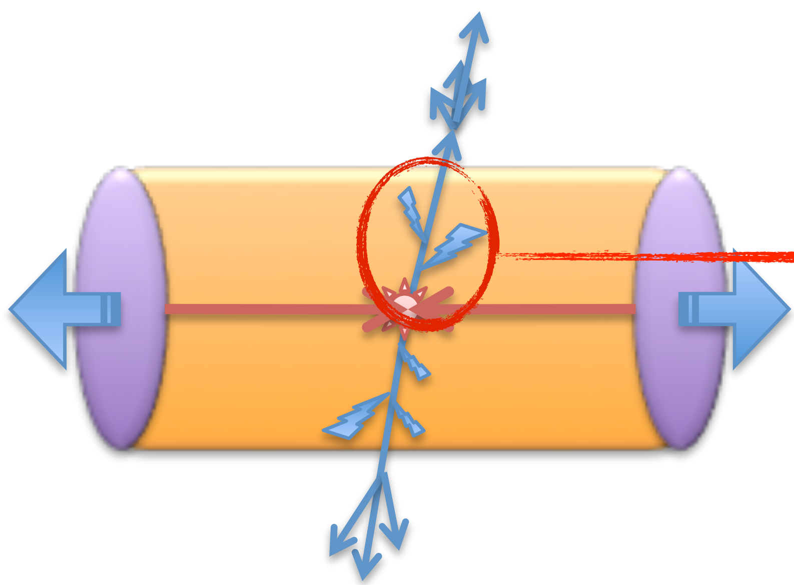
QED: Passage of electrically charged particle through matter

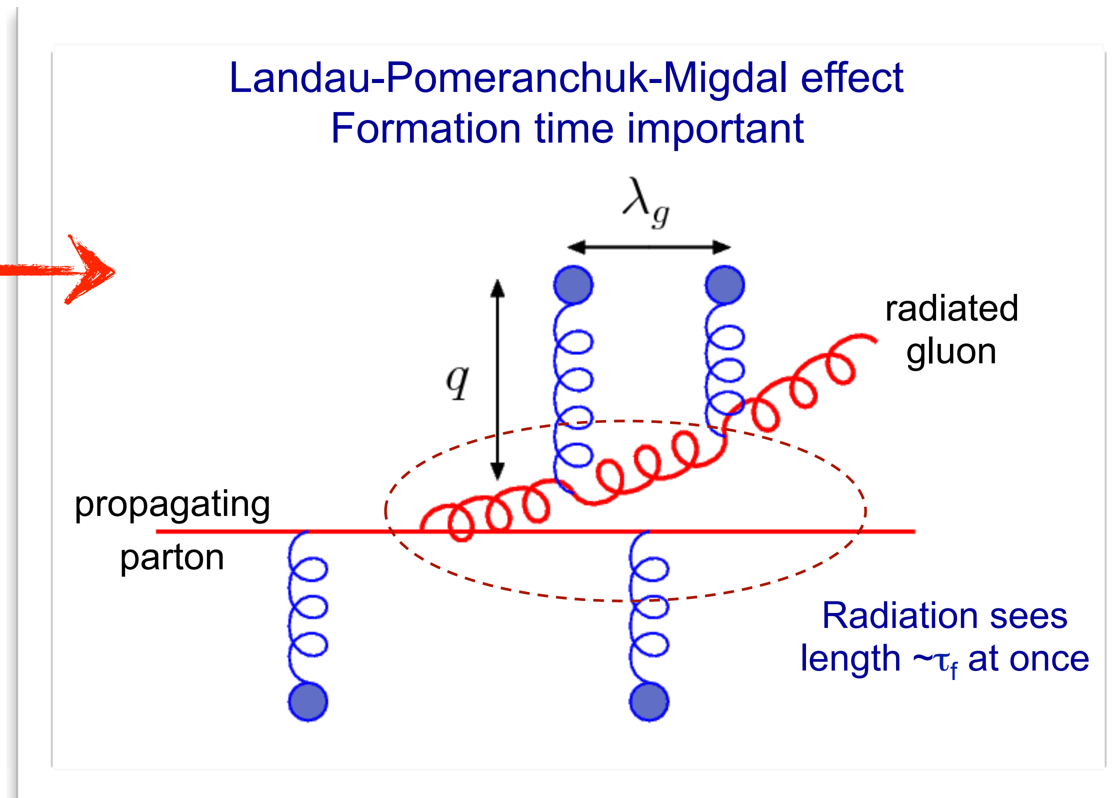


High energy limit: Radiative energy loss

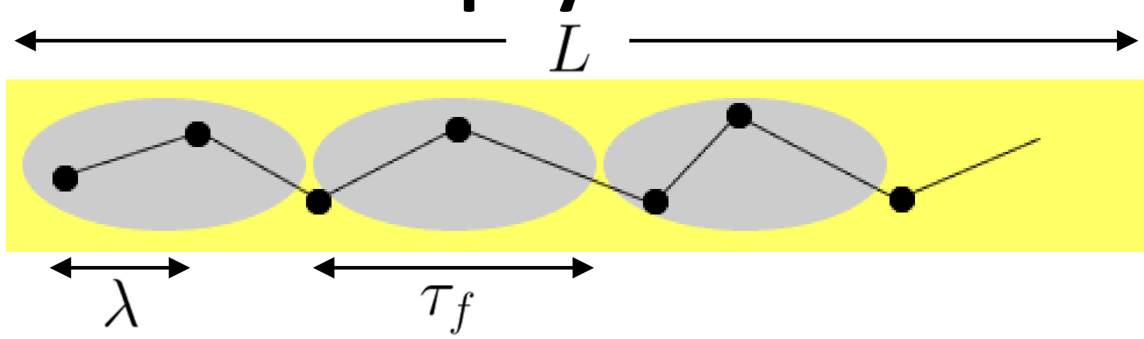
What is the equivalent in QCD?

Brehmsstrahlung in QCD: Formation time -> coherence effects





Formation time physics

- 

  $\tau_f \sim \frac{2\omega}{k_\perp^2}$

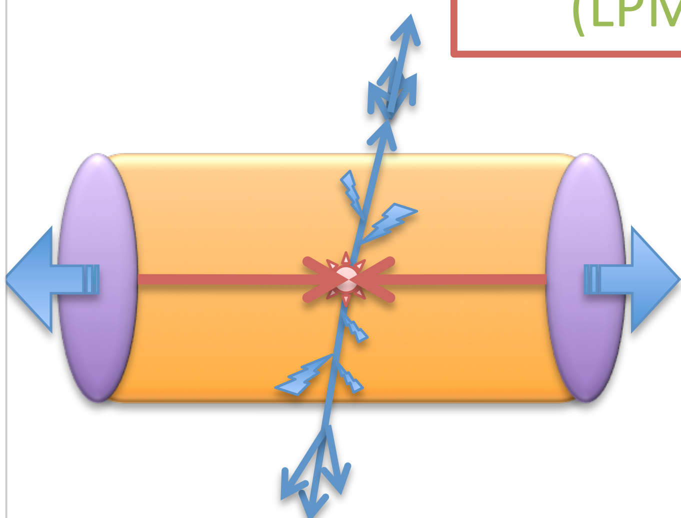
  - $\tau_f < \lambda < L$ Incoherent multiple collisions
  - $\lambda < \tau_f < L$ LPM effect (radiation suppressed by multiple scatterings within one coherence length)
  - $\lambda < L < \tau_f$ Factorization limit (acts as one single scatterer)

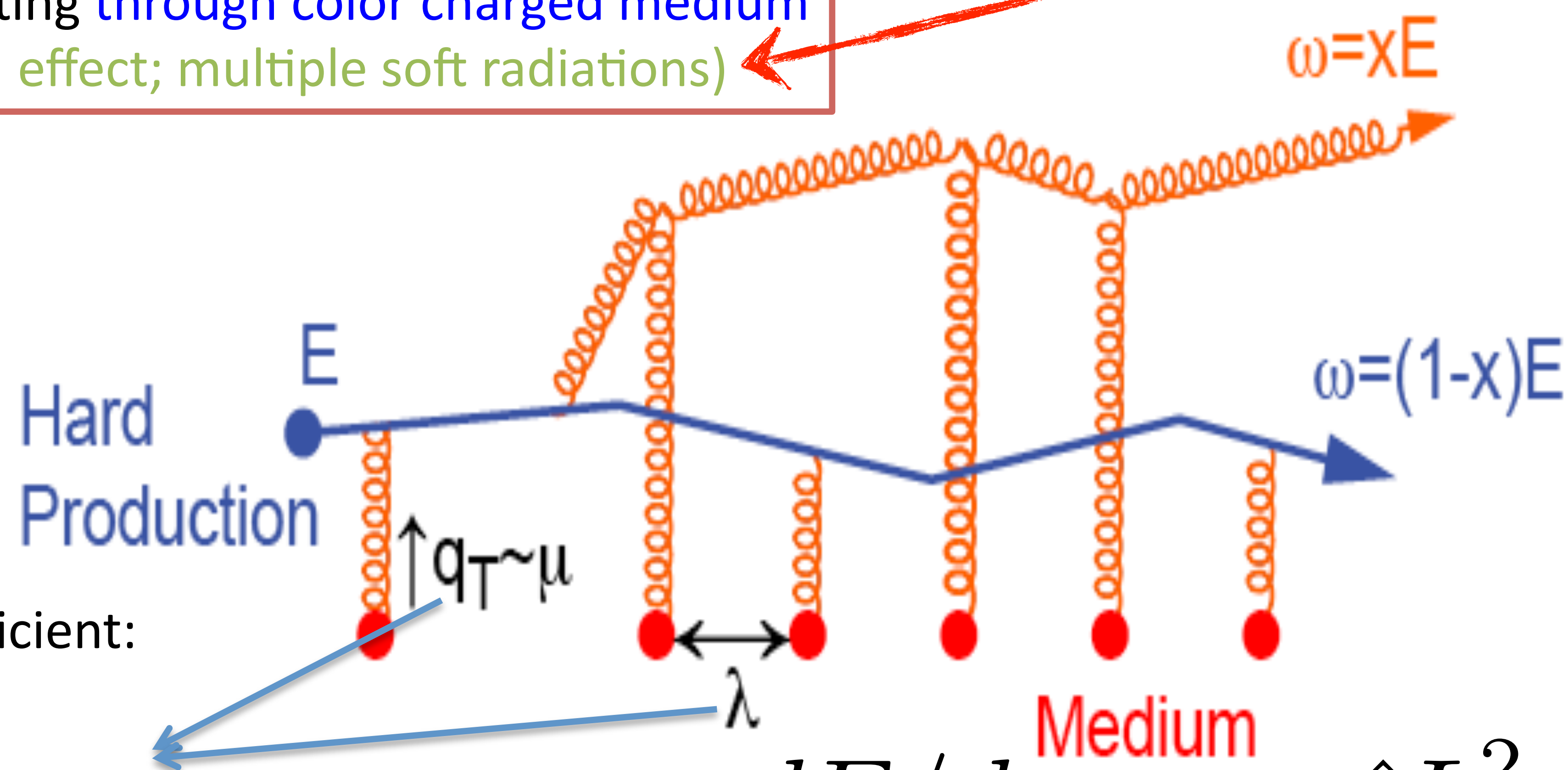
Brehmsstrahlung in QCD

High energy **color charged probe** propagating through color charged medium
(LPM effect; multiple soft radiations)

λ < τ => Multiple scatterings add coherently

$t_{formation} < L \Leftrightarrow \omega < \omega_c$





Define a transport coefficient:

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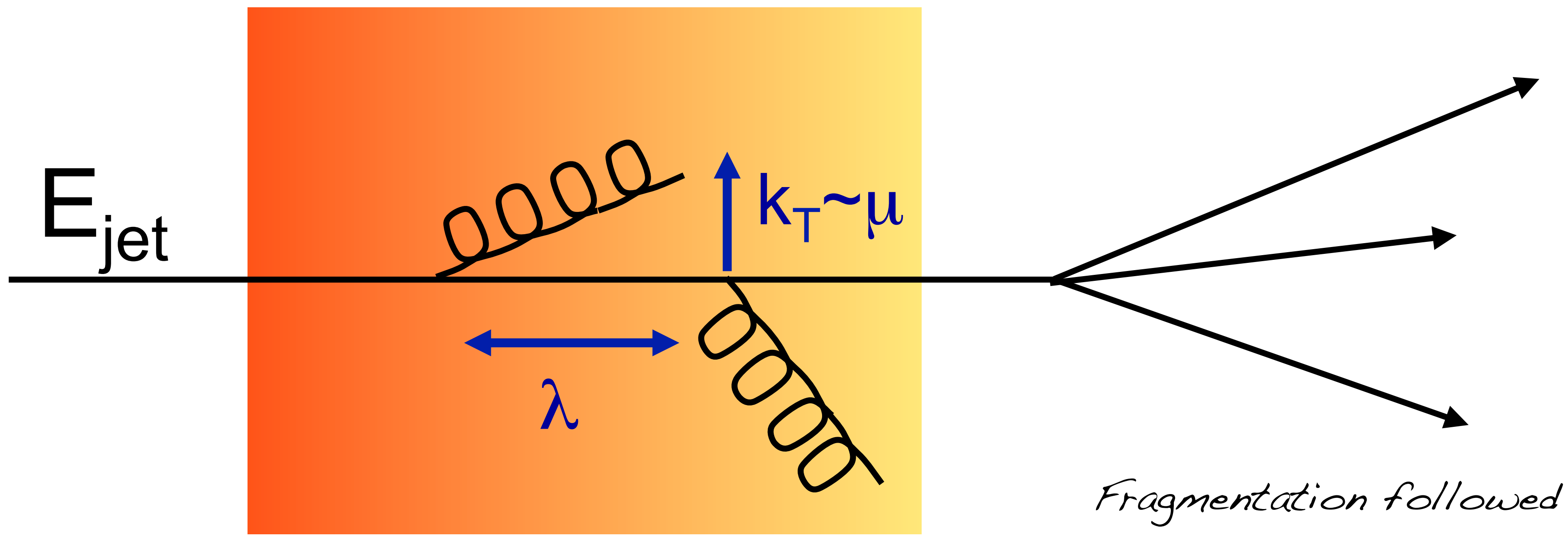
Partonic energy loss in QCD medium is proportional:
- to squared average path length (Note: QED ~ linear)
- to density of the medium

$$\lambda \propto \frac{1}{\rho}$$

⇒ **energy flow (parton+radiation) modified as compared to jet in vacuum**

⇒ **jet "quenched" ("softened" fragmentation)**

Generic expectations from energy loss



Fragmentation followed by E-loss?

Longitudinal modification:

out-of-cone: energy lost, loss of yield, di-jet energy imbalance

in-cone: softening of fragmentation

Transverse modification

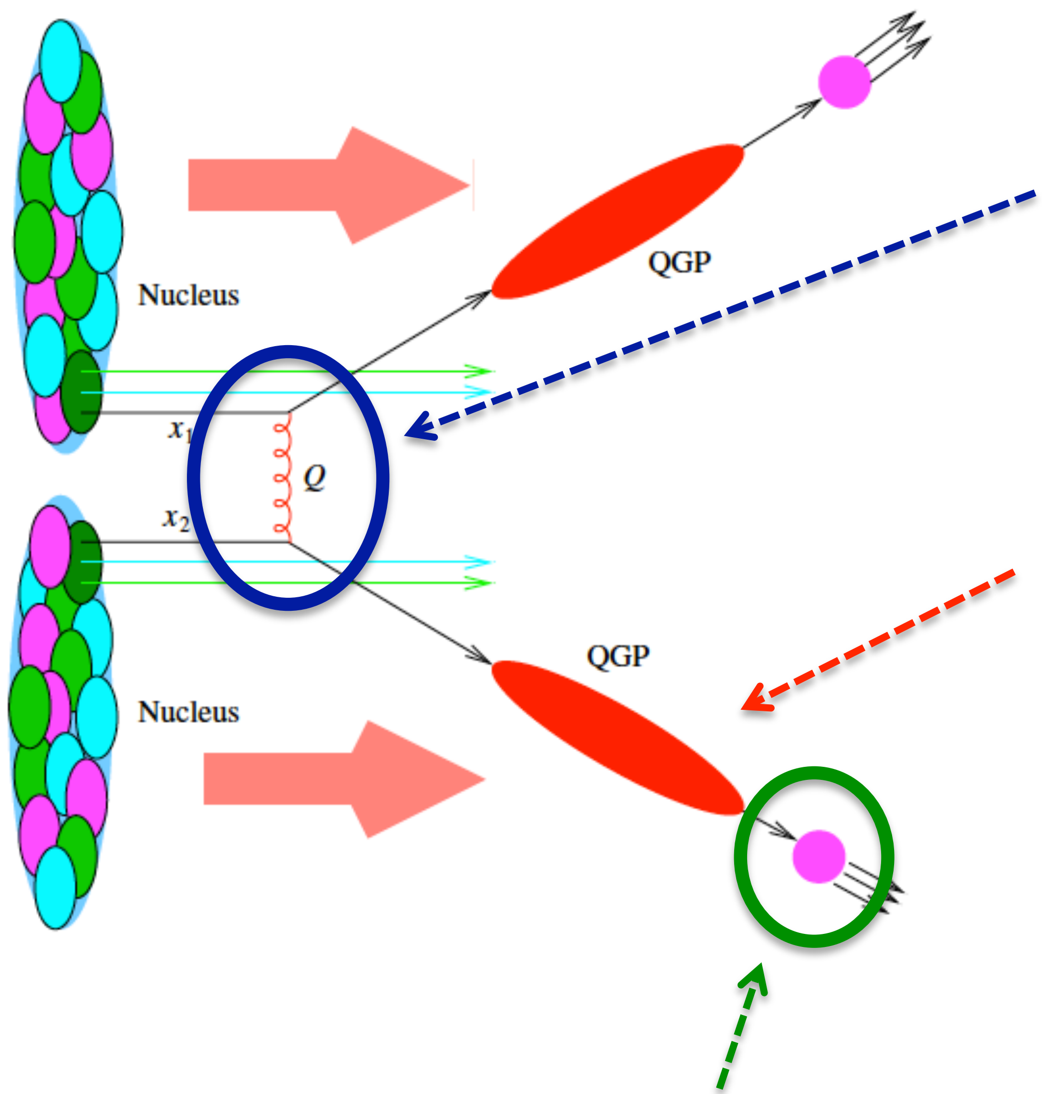
out-of-cone: increase acoplanarity k_T

in-cone: broadening of jet-profile

Jets in heavy-ion collisions - an idealization

=> Factorized picture.

$$\sigma \propto f_a^{PDF} \otimes f_b^{PDF} \otimes \sigma^{hard}$$



production vertex: high Q^2

➔ pQCD

Propagation in strongly coupled Quark Gluon Plasma

➔ pQCD-based jet quenching

➔ hydrodynamics

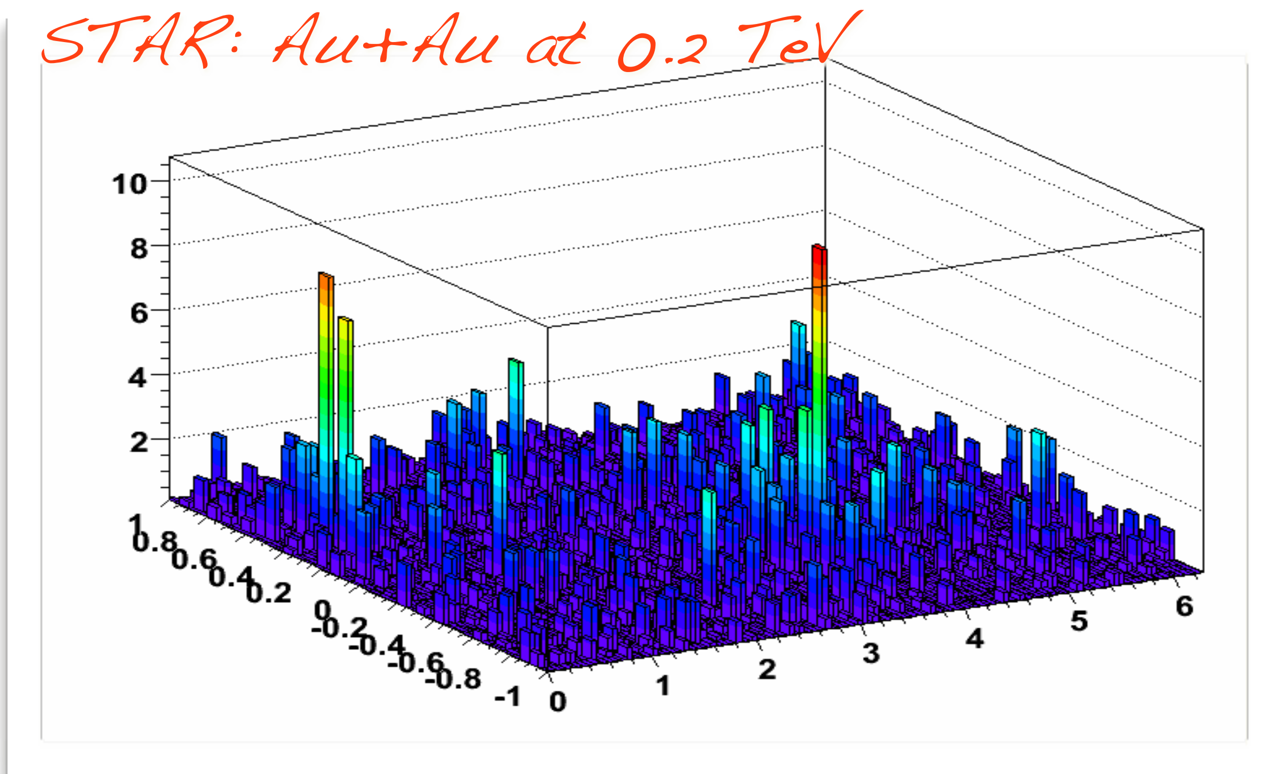
➔ AdS/CFT

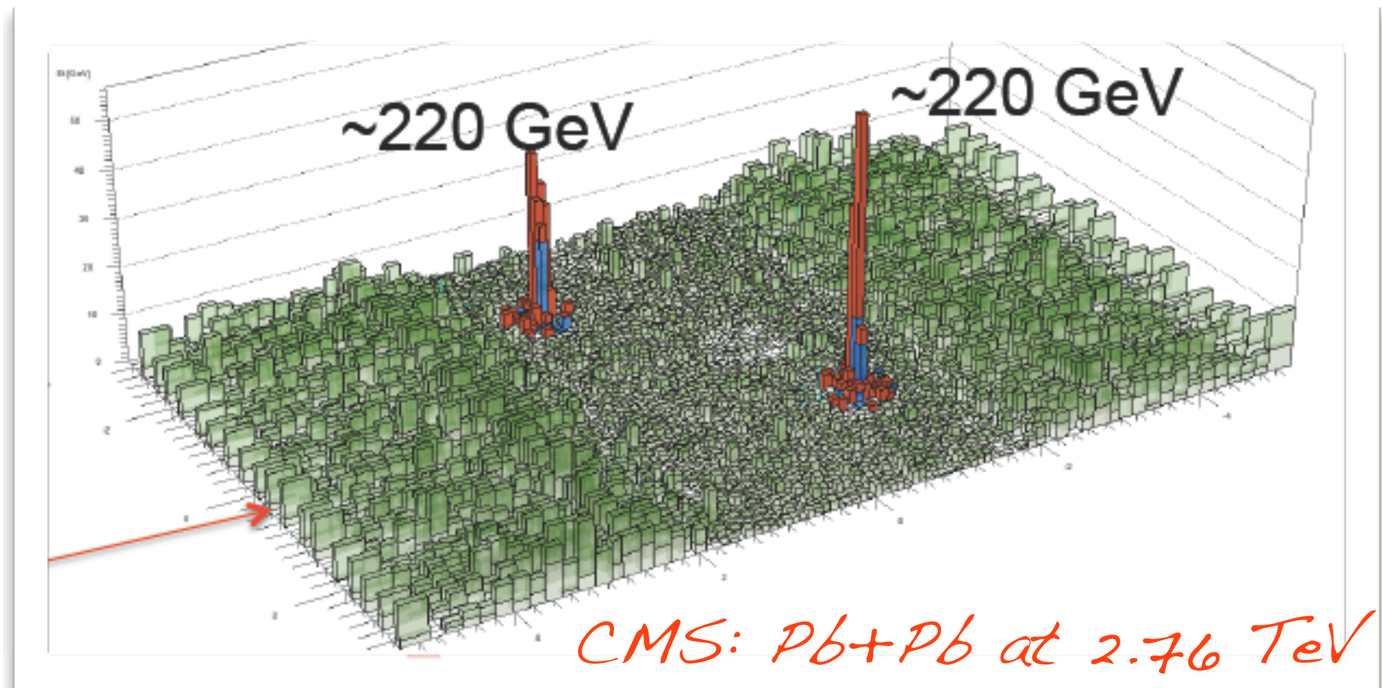
➔ ...

Vacuum fragmentation into hadrons

➔ non-pert. QCD

Jets in heavy-ion collisions
RHIC & LHC





LHC + RHIC: QCD evolution of jet quenching ?

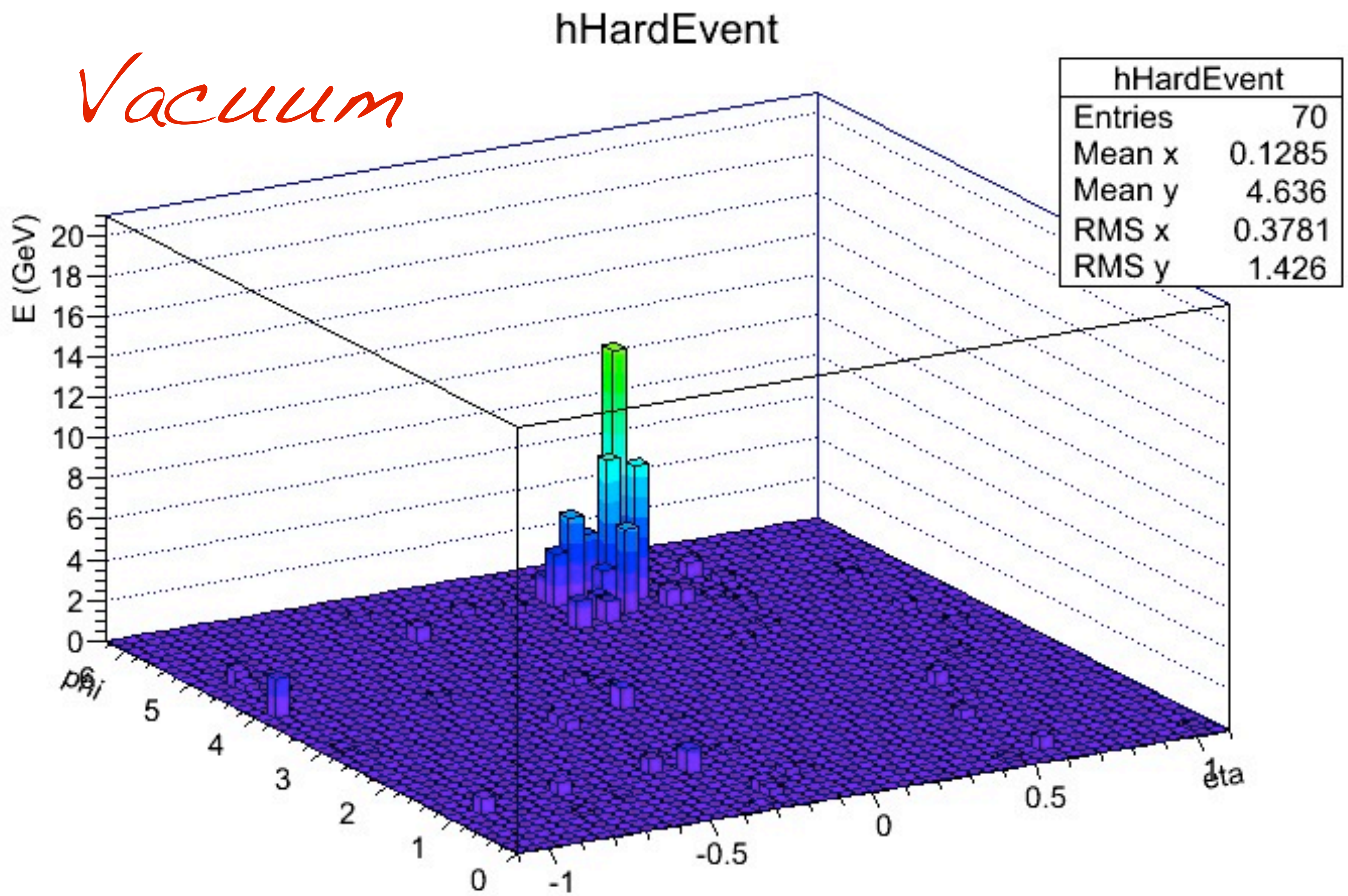
Vary energy of the jet:

LHC: Vary the scale with which QGP is probed (a la DIS)

Compare and contrast RHIC and LHC

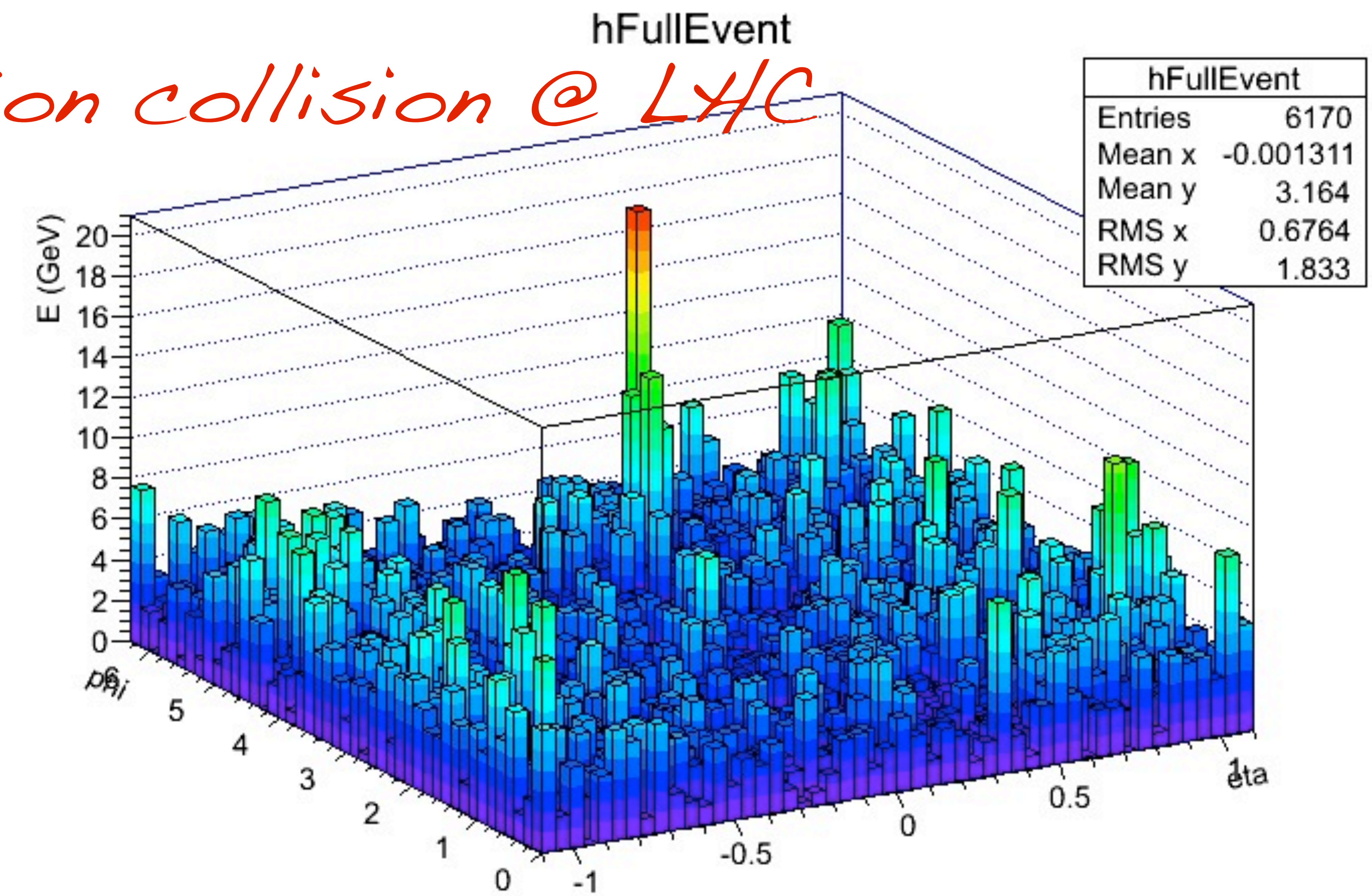
Jets in HI collisions & Experimental difficulties: Vacuum jet vs jet on top of the HI background...

Vacuum

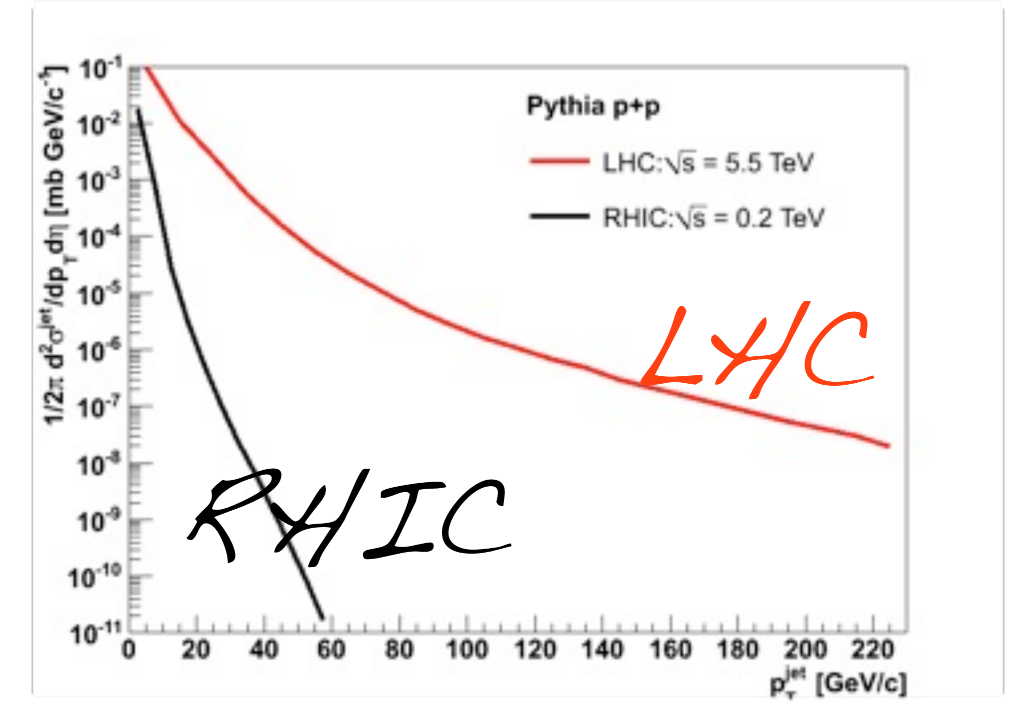


Jets in HI collisions & Experimental difficulties:
Vacuum jet vs jet on top of the HI background...

Heavy-ion collision @ LHC



Jets in heavy-ion collisions RHIC & LHC



Jets in heavy-ion environment - few experimental notes:

- large combinatorial backgrounds (especially at RHIC)
- energy within an event varies from point to point ("fluctuations")
- a plus for LHC is larger kinematic reach - abundance of high-energy jets (higher-pT measurements less affected by backgrounds)

  => various approaches among experiments for background suppression AND/OR jet energy-resolution corrections

- is there an optimal jet definition for heavy-ion collisions (?)

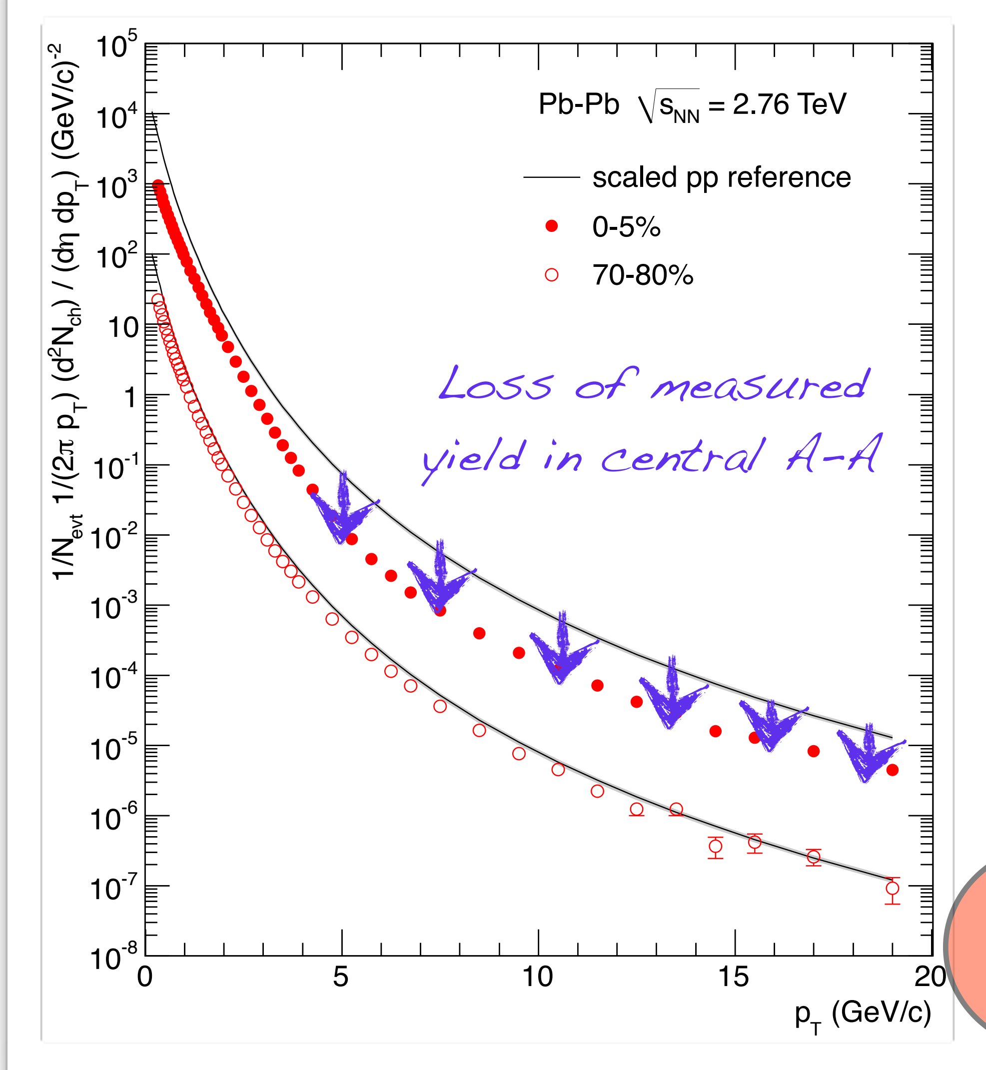
  => use multiple jet algorithms (?); sub-jets (?); filtering (?)

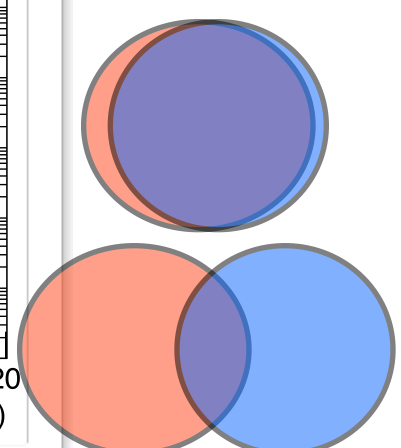
- jets are reported on the particle (generator) level - hadronization corrections (to the "parton" jet) in HI collisions impossible

"Easier" (than full jet reconstruction) exercise: Jet-quenching via leading hadrons

Inclusive hadron production

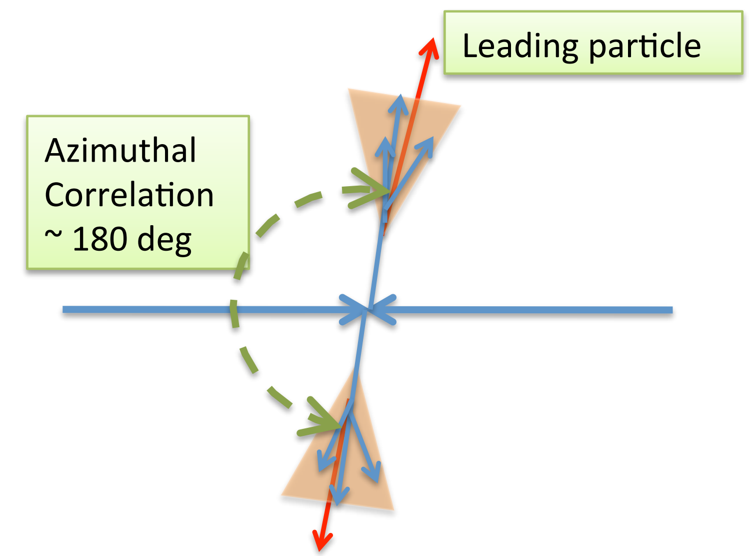
Measured as a function of collision centrality

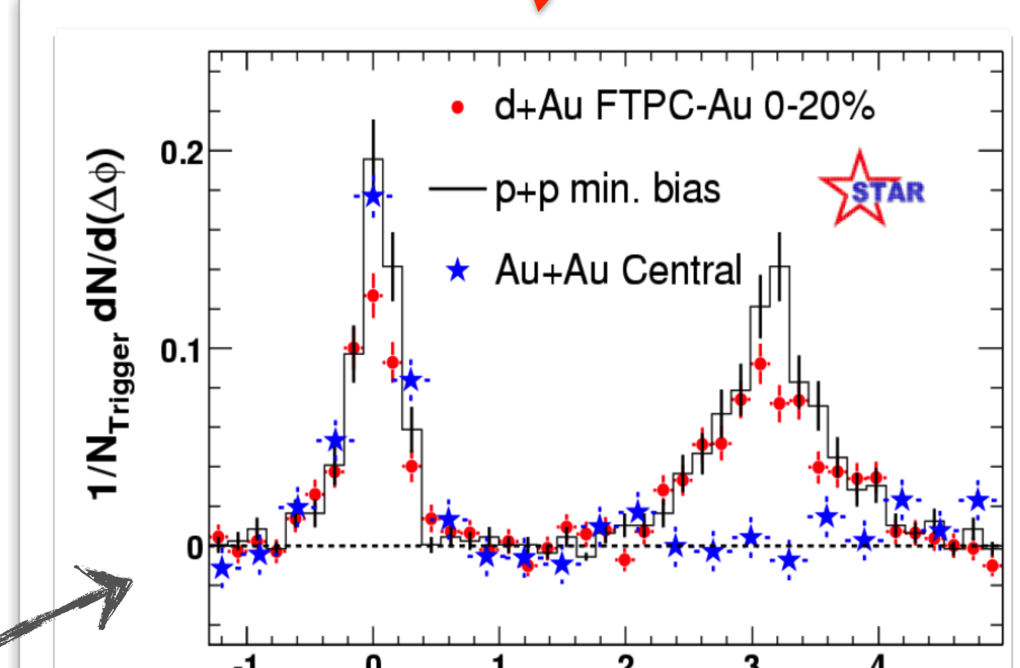




Di-hadron correlations

Rates of recoil ("away-side") hadrons suppressed





Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

Note on correlations: interesting tool to study the "intermediate"-p_T region – jets vs flow and recombination

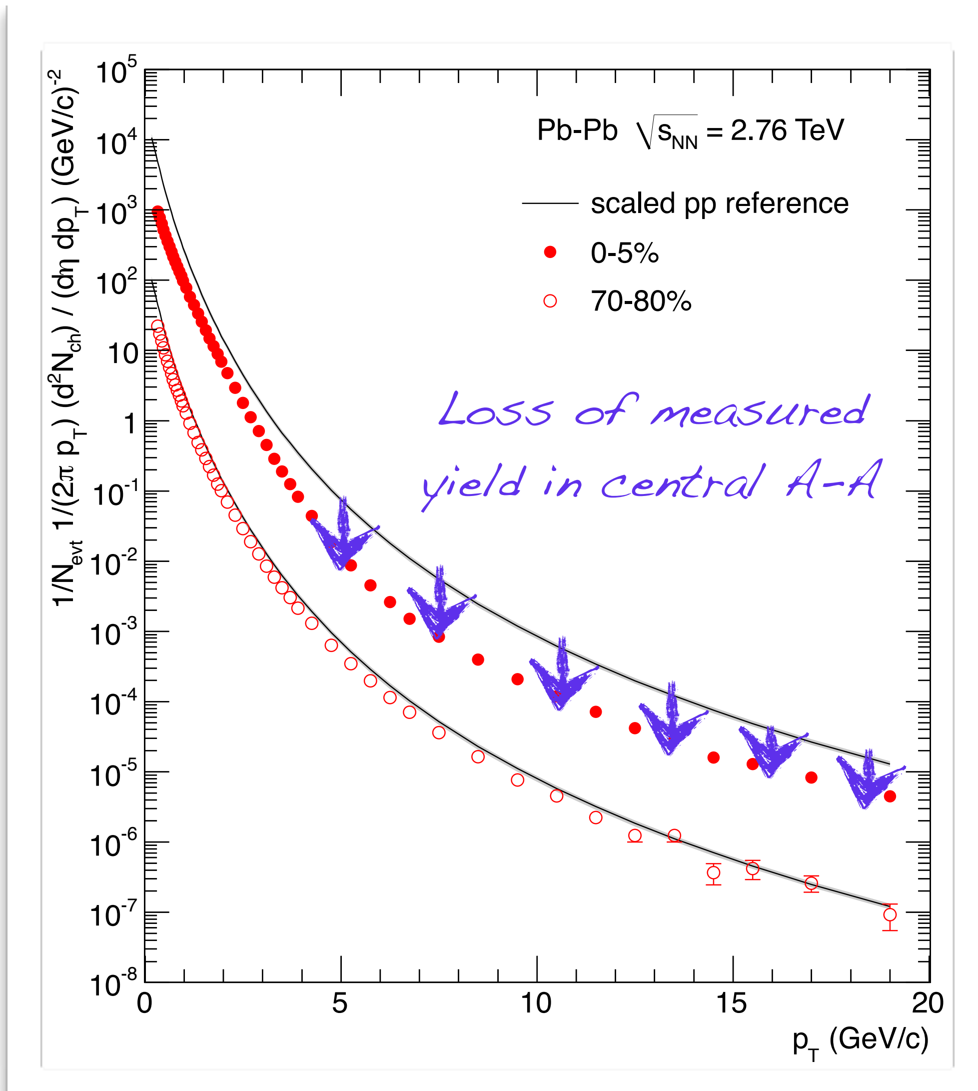
Hadron suppression

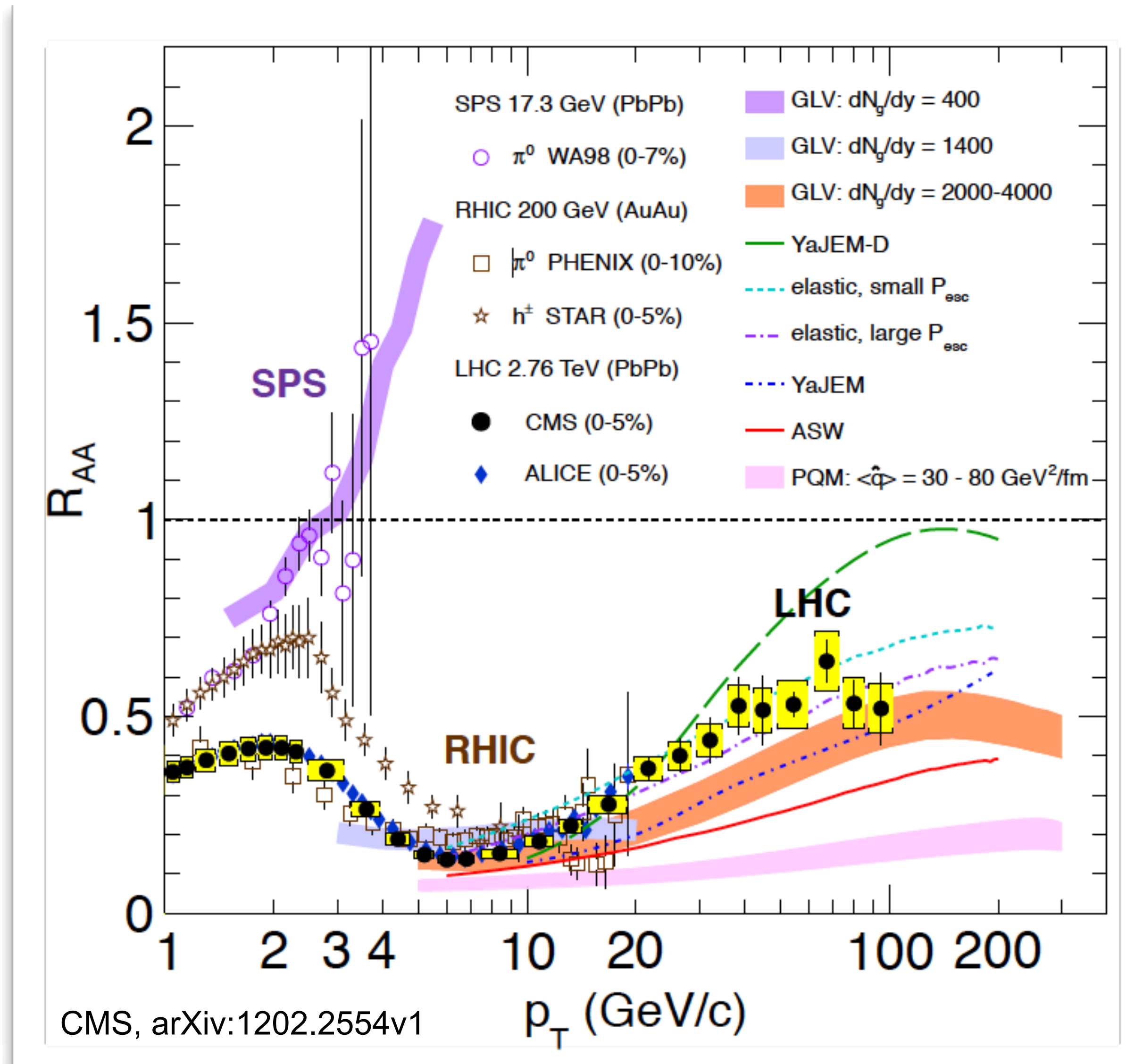
$$R_{AB} = \frac{d^2N/dp_t d\eta}{T_{AB} d^2\sigma^{pp}/dp_t d_\eta}$$

$$T_{AB} = \langle N_{bin} \rangle / \sigma^{pp}_{inel}$$

Nuclear modification factor:

$$R_{AA} = \frac{\#(\text{particles observed in AA collision per N-N (binary) collision})}{\#(\text{particles observed per p-p collision})}$$



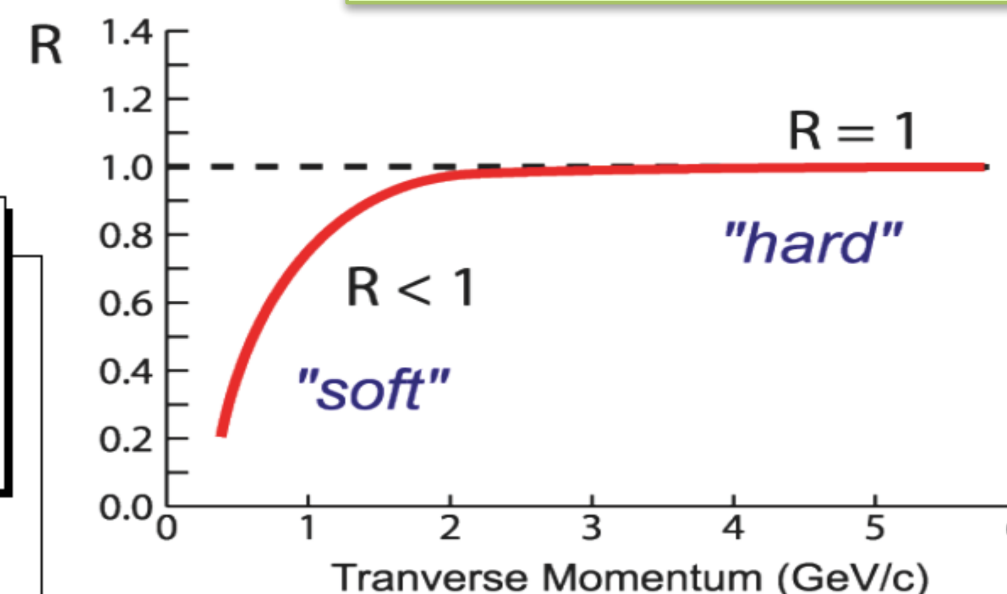


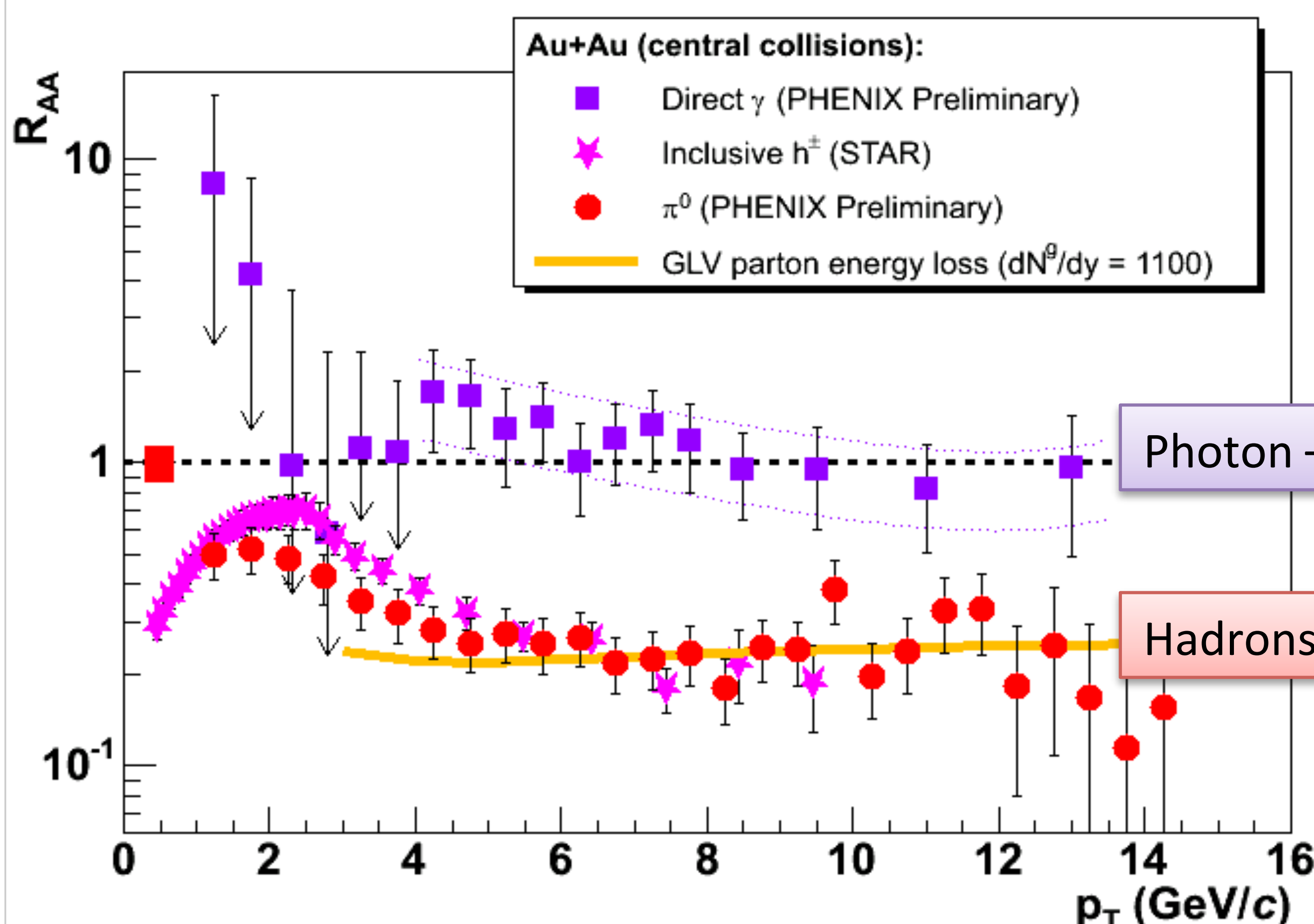
"No effect" case is for RAA = 1 at high pT where hard processes dominate

Jet quenching - RHIC

$$\text{Ratio} = \frac{\#(\text{particles observed in AA collision per binary collision})}{\#(\text{particles observed per p-p collision})}$$

No "effect":
R < 1 at small momenta
R = 1 at higher momenta where hard processes dominate





Photon – color neutral probe => No suppresion

Hadrons from color charged jets => Suppression

RAA: extreme scenarios

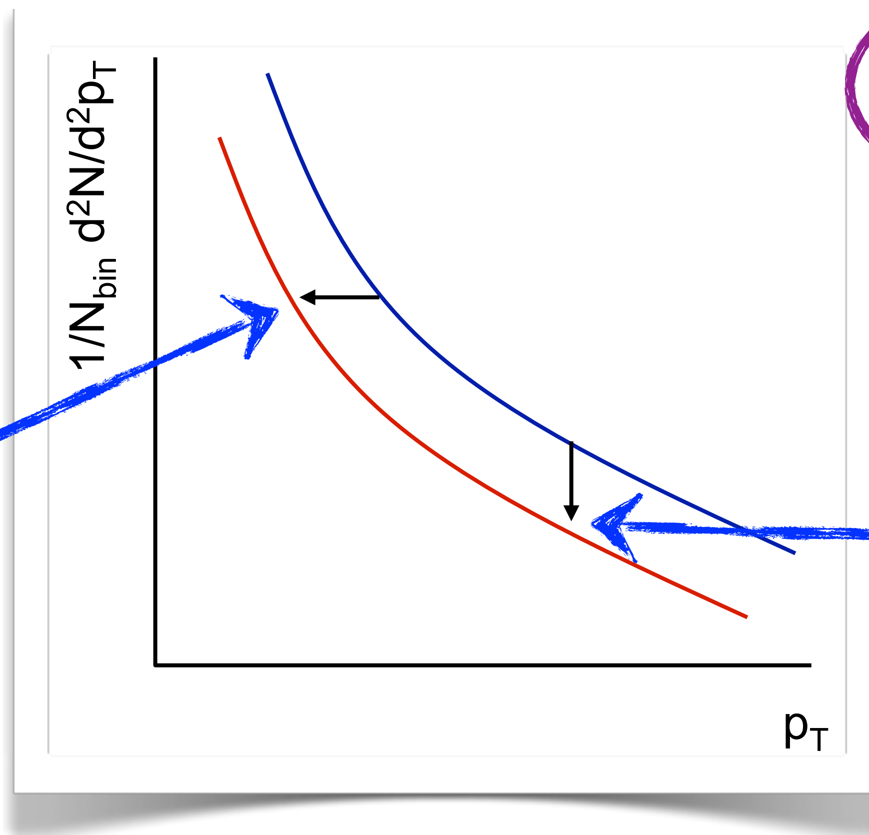
Note: I am not showing you the P(ΔE)

P(ΔE) - probability for parton to loose ΔE

Scenario I
$P(\Delta E) = \delta(\Delta E_0)$

"Energy loss"

"Shift" to lower pT

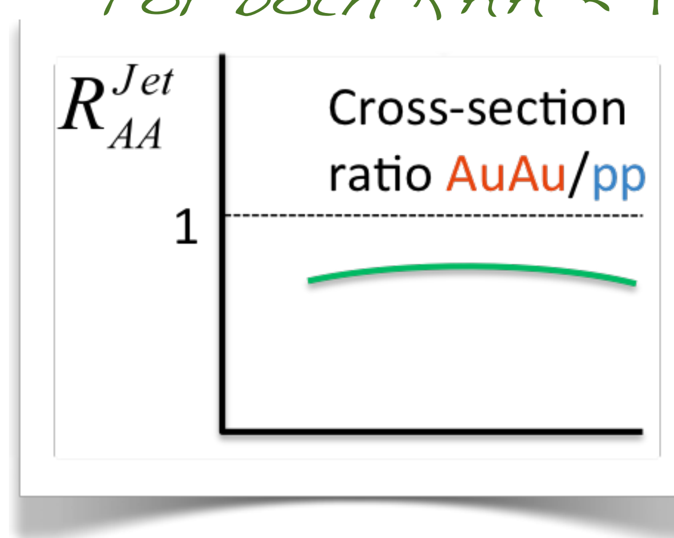


Scenario II
$P(\Delta E) = a\ \delta(0) + b\ \delta(E)$

"Absorption"

"Shift" in yield

For both RAA < 1



P(ΔE) encodes the full energy loss process

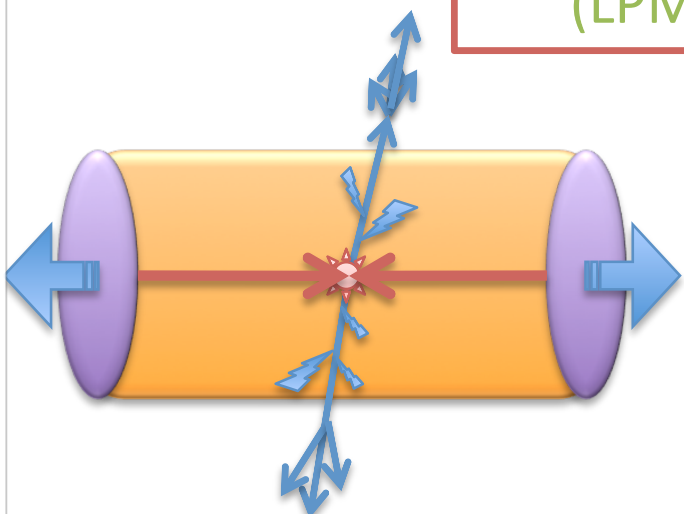
R_{AA} not sensitive to energy loss distribution, details of mechanism...

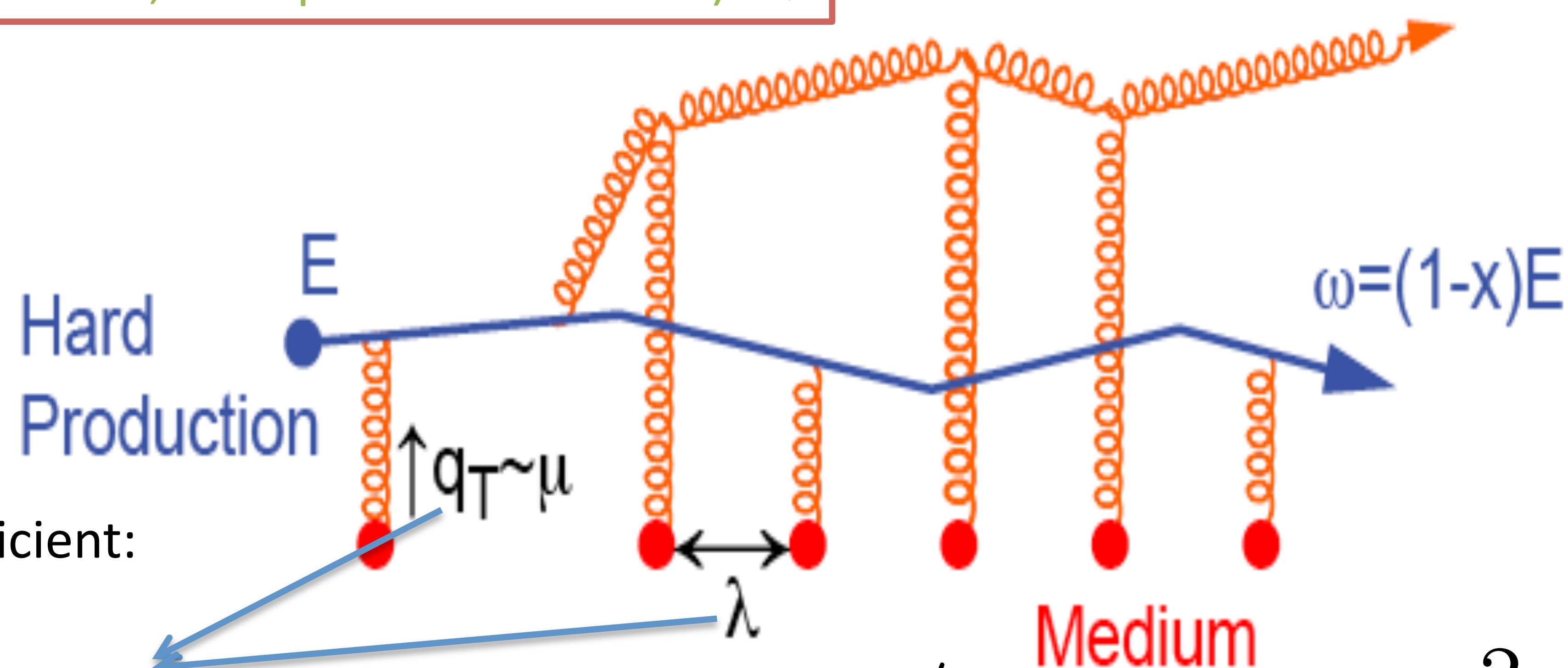
Brehmsstrahlung in QCD

λ < τ => Multiple scatterings add coherently

$t_{formation} < L \Leftrightarrow \omega < \omega_c$

High energy **color charged probe**
propagating through color charged medium
(LPM effect; multiple soft radiations)





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- to squared average path length (Note: QED ~ linear)
- to density of the medium

$$\lambda \propto \frac{1}{\rho}$$

⇒ **energy flow (parton+radiation) modified as compared to jet in vacuum**

⇒ **jet "quenched" ("softened" fragmentation)**

Brehmsstrahlung in QCD

λ < τ => Multiple scatterings add coherently

$t_{formation} < L \Leftrightarrow \omega < \omega_c$

High energy color charged probe propagating through color charged medium (LPM effect; multiple soft radiations)

ω=xE

An idea: vary the path length experimentally?

-> sensitivity to the collision profile

-> different collisions systems?

$-dE/dx \sim \alpha_s \hat{q} L^2$

Partonic energy loss in QCD medium is proportional:

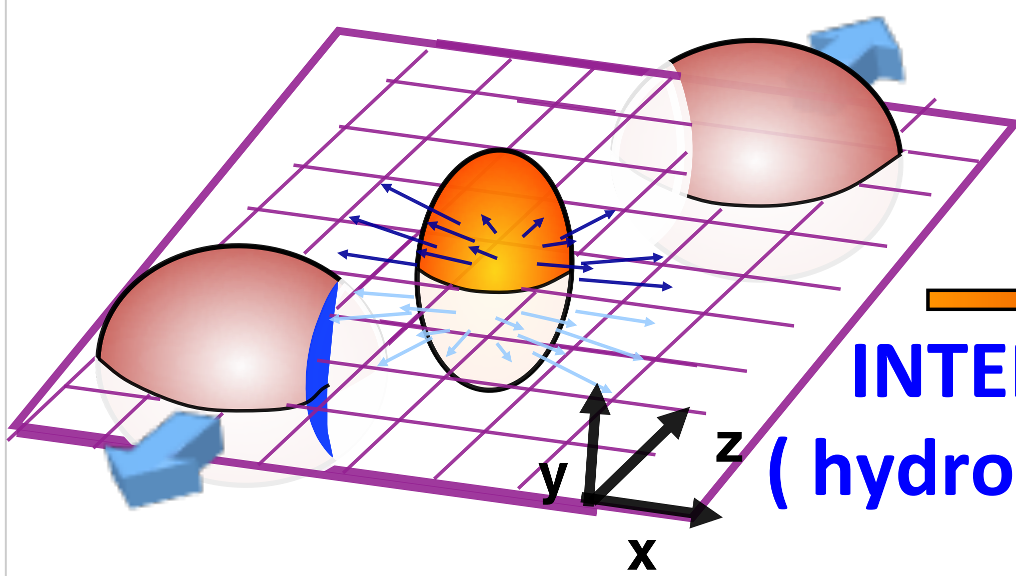
- to squared average path length (Note: QED ~ linear)
- to density of the medium

$$\lambda \propto \frac{1}{\rho}$$

⇒ energy flow (parton+radiation) modified as compared to jet in vacuum

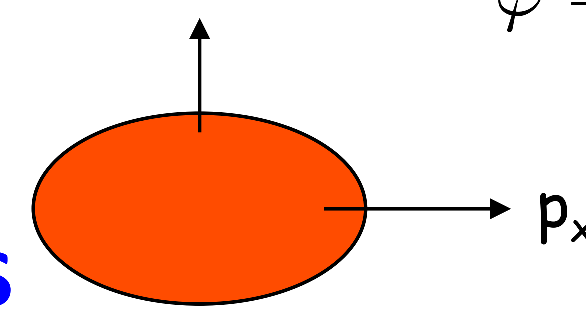
⇒ jet “quenched” (“softened” fragmentation)

Azimuthal angular asymmetry in particle production



INTERATIONS (hydrodynamics?)

$$\varphi = \arctan \frac{p_y}{px}$$



$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

Final momentum anisotropy

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

Initial spatial anisotropy

Reaction plane defined by "soft" (low p_T) particles

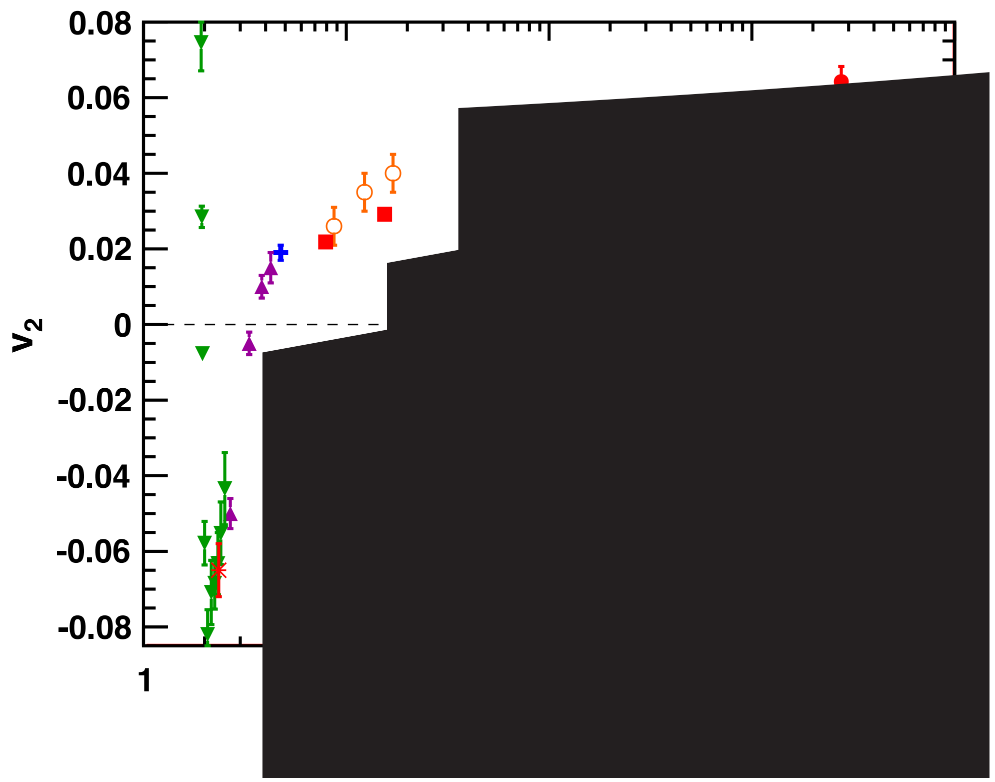
$$\Delta\varphi = \varphi - \varphi^{Reaction\ \ Plane}$$

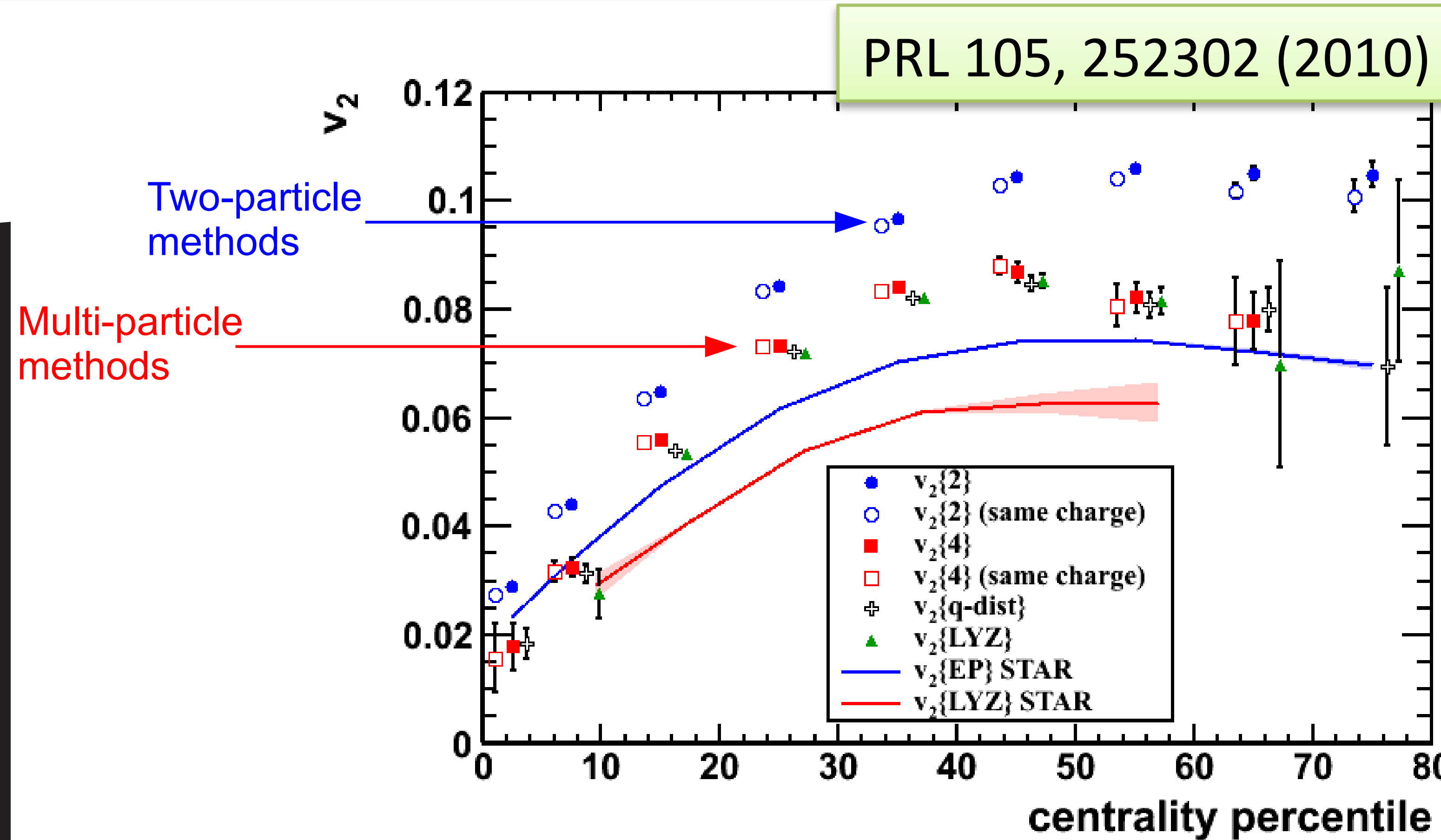
Elliptic flow

$$\frac{dN}{d\Delta\varphi} \propto 1 + 2v_2 \cos(2\Delta\varphi)$$

Azimuthal anisotropy

Energy dependence of v2

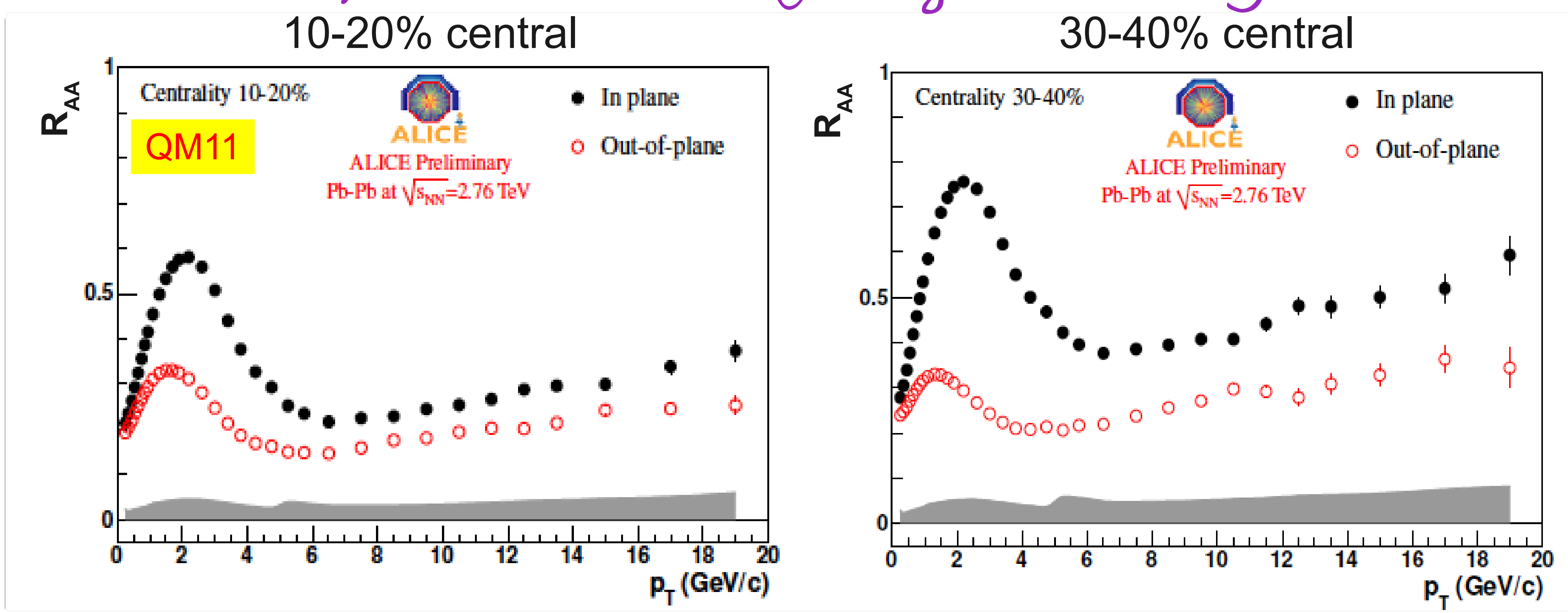


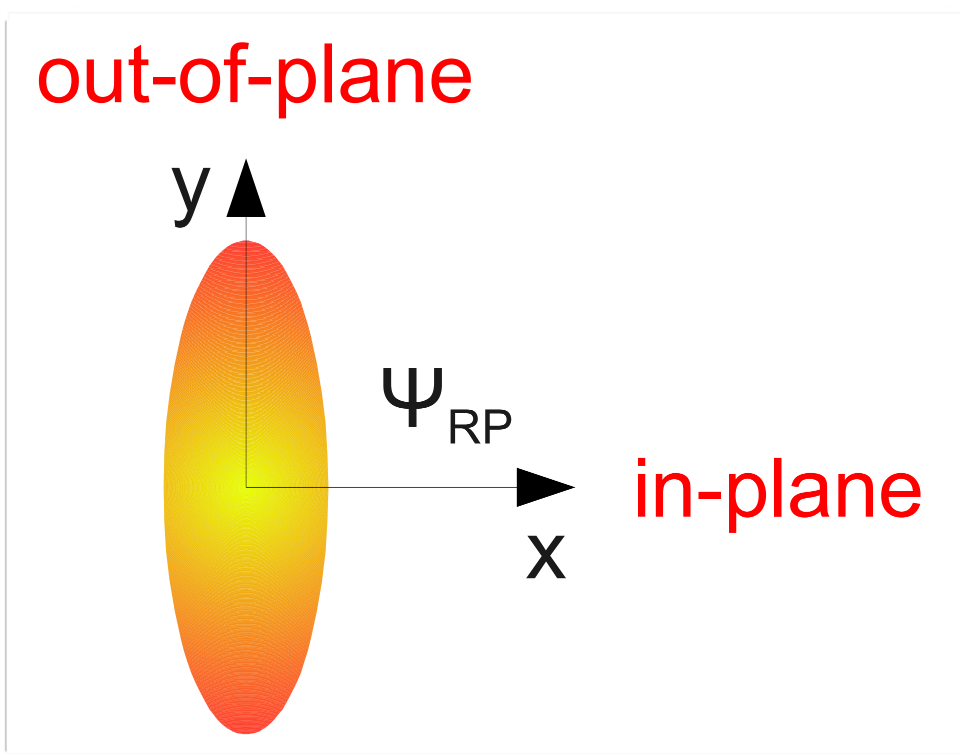


APS Viewpoint: A "Little Bang" arrives at the LHC (E. Shuryak)

1. **Collective behavior observed in Pb-Pb collisions at LHC** (integrated: +0.3 v_2^{RHIC} – consequence of larger $<p_T>$) -> $v_2(p_T)$ similar to RHIC – almost ideal fluid at LHC ? Similar observation down to 39GeV!**
2. **New input to the energy dependence of collective flow**
3. **Additional constraints on Eq-Of-State and transport properties**

RAA wrt reaction plane - path length dependence of jet quenching?





Suppression out-of-plane stronger <= longer in-medium path length - significant effect even at 20 GeV/c

=> Path length dependence of energy loss ?

Additional constraints to energy loss models (?)

- **similar** information from v2 at high p_T

$$R_{AA}(\varphi) = R_{AA}(1 + 2v_2 \cos 2(\varphi - \psi))$$

R_{AA} for different particle type

Is parton energy loss different
for gluons, light-quarks and heavy-quarks?

Expectation: $\Delta E_g > \Delta E_{light\text{-}q} > \Delta E_{heavy\text{-}q}$

$\Delta E \propto \alpha_S C_R q L^2$
CR = 4/3 for quarks,
3 for gluons

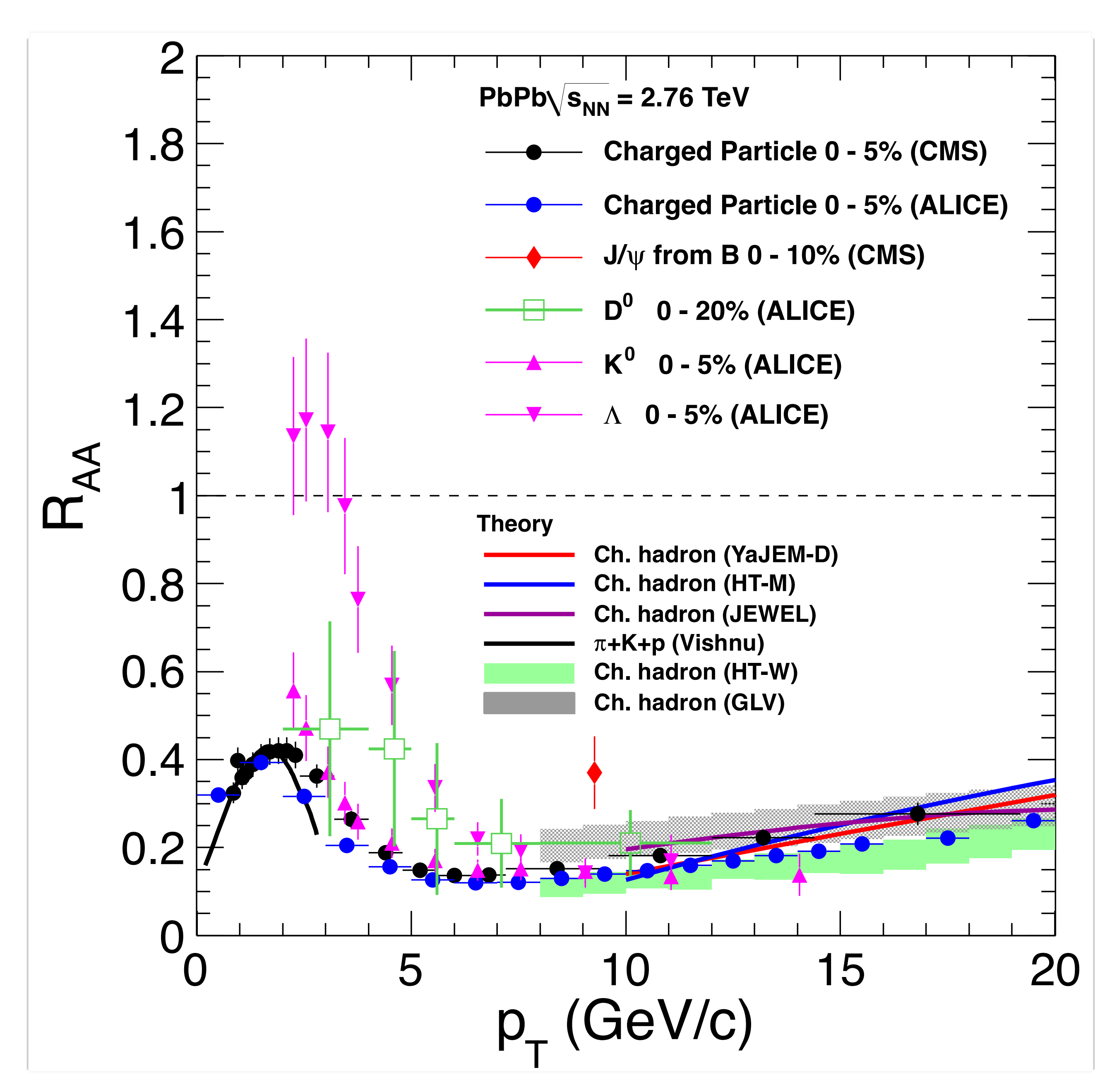
Casimir (color factor)
- gluons "glue" better to
the medium than quarks

"Dead-cone" effect:
mass of the parent quark
=> radiation for angles $\theta < m/E$
is suppressed

=> $R_{AA}^{pions} < R_{AA}^{D\text{-}mesons} < R_{AA}^{B\text{-}mesons}$

RAA for different particle type

Discussion based on LHC results



Similar suppression for heavier-q (strange, charm) and gluons (large elastic e-loss; less dep. on mass?; color factor? - small effect?)

J/ψ from B-decays - dead cone effect?

Lambda vs K0 R_{AA} below 7 GeV - manifestation of flow (?)

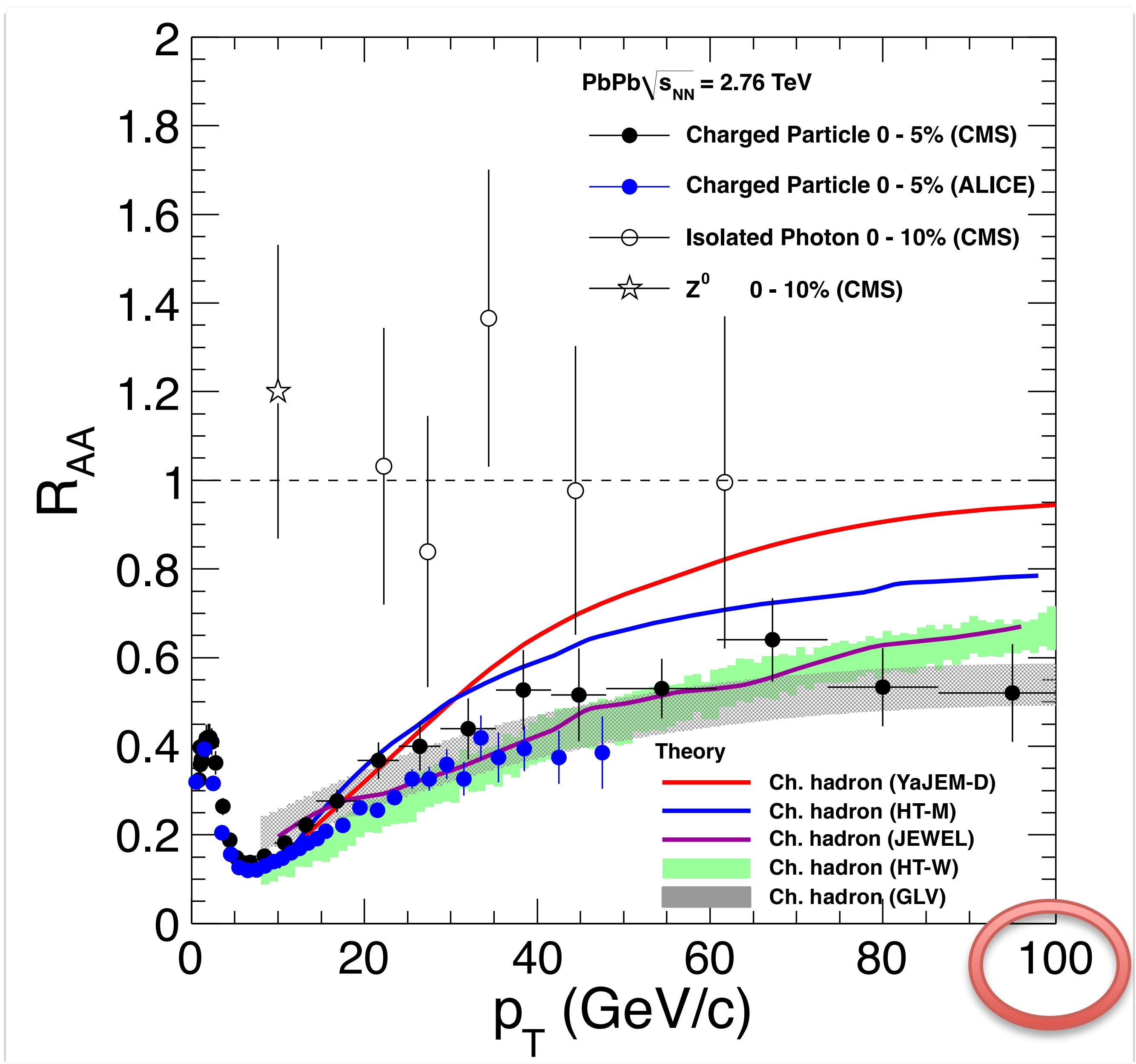
Rise towards higher pT's:

1) Harder partonic spectrum (as compared to RHIC)

2) Weak dependence of [pQCD] e-loss on parton energy

RAA for different particle type

Discussion based on LHC results



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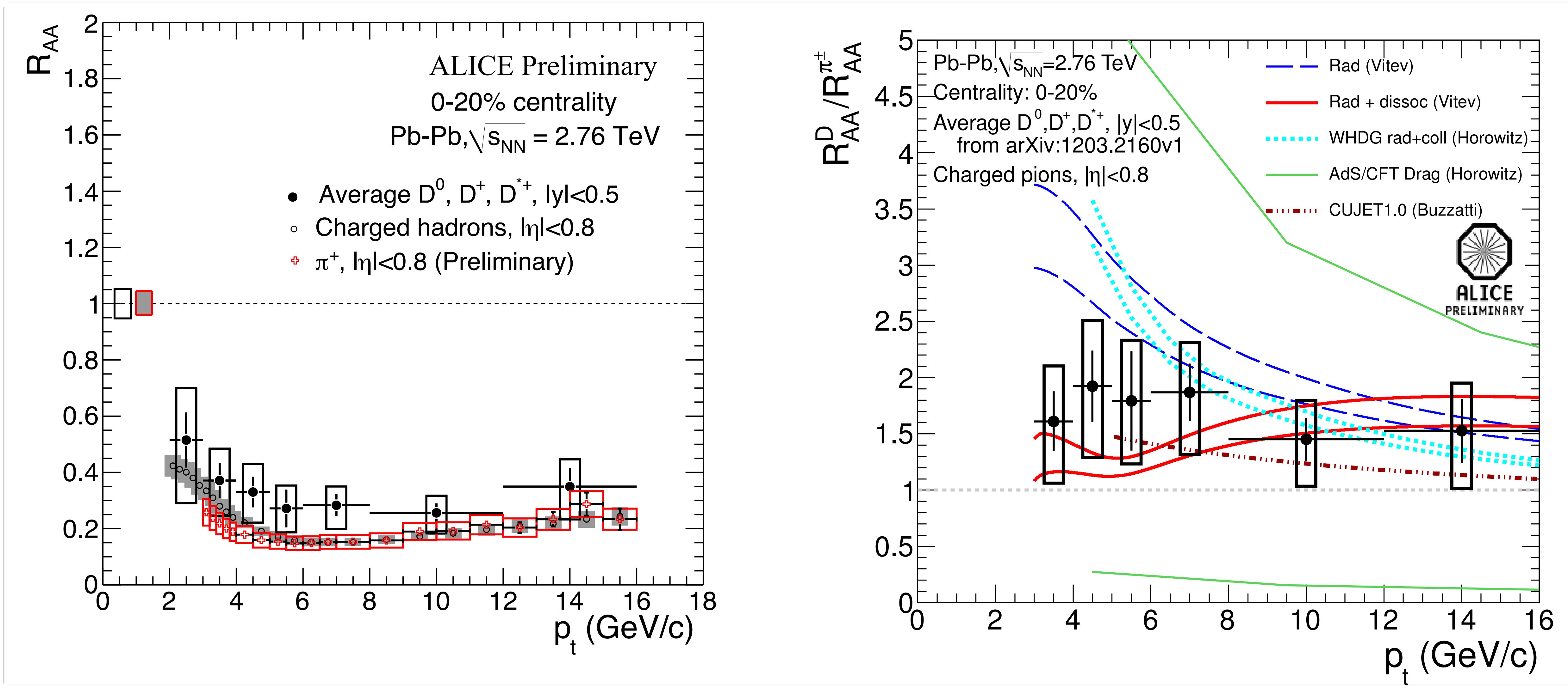
Rise towards higher pT's:

1) Harder partonic spectrum (as compared to RHIC)

2) Weak dependence of [pQCD] e-loss on parton energy

Photons and Z's not suppressed -> quenching is a final state effect

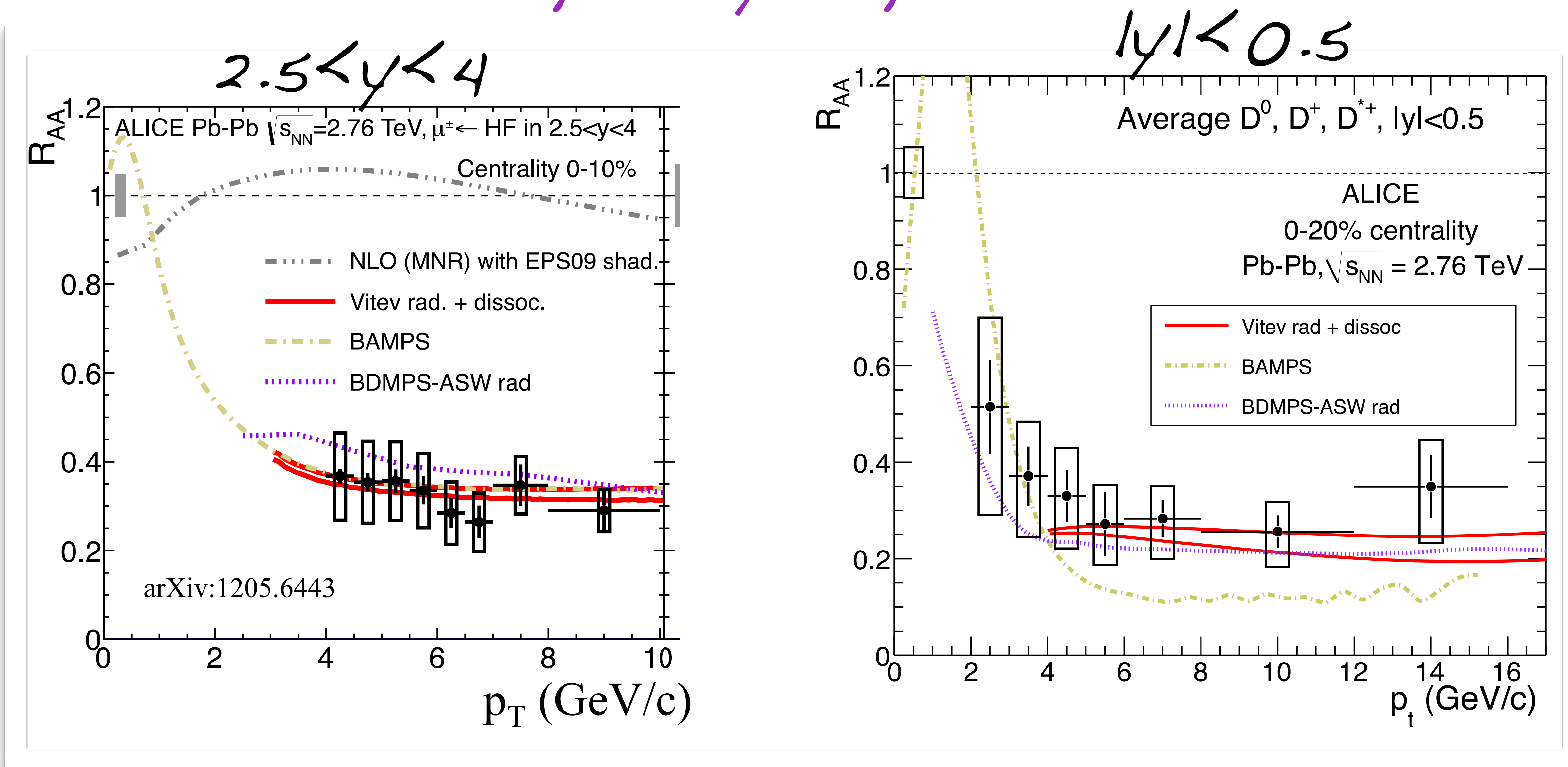
Charm-q energy loss via D-mesons



Hint of larger R_{AA} for D than π

- Color-charge effect?
- No evidence for dead cone effect (p_T dependence)
- Higher precision in progress (Alice)

Heavy-flavor suppression – rapidity dependence



Variants of radiative++ energy loss agree with data

End of 2/3

Until now...

- Jets in elementary collisions: must specify an operational definition (algorithm, R, recombination scheme); variety of infrared and collinear safe algorithms; under control theory/experiment;

- HI collisions: hot QCD matter; large particle (production) densities as compared to vacuum - evolving with centrality; Jet measurements difficult (Today you will see that possible nevertheless)

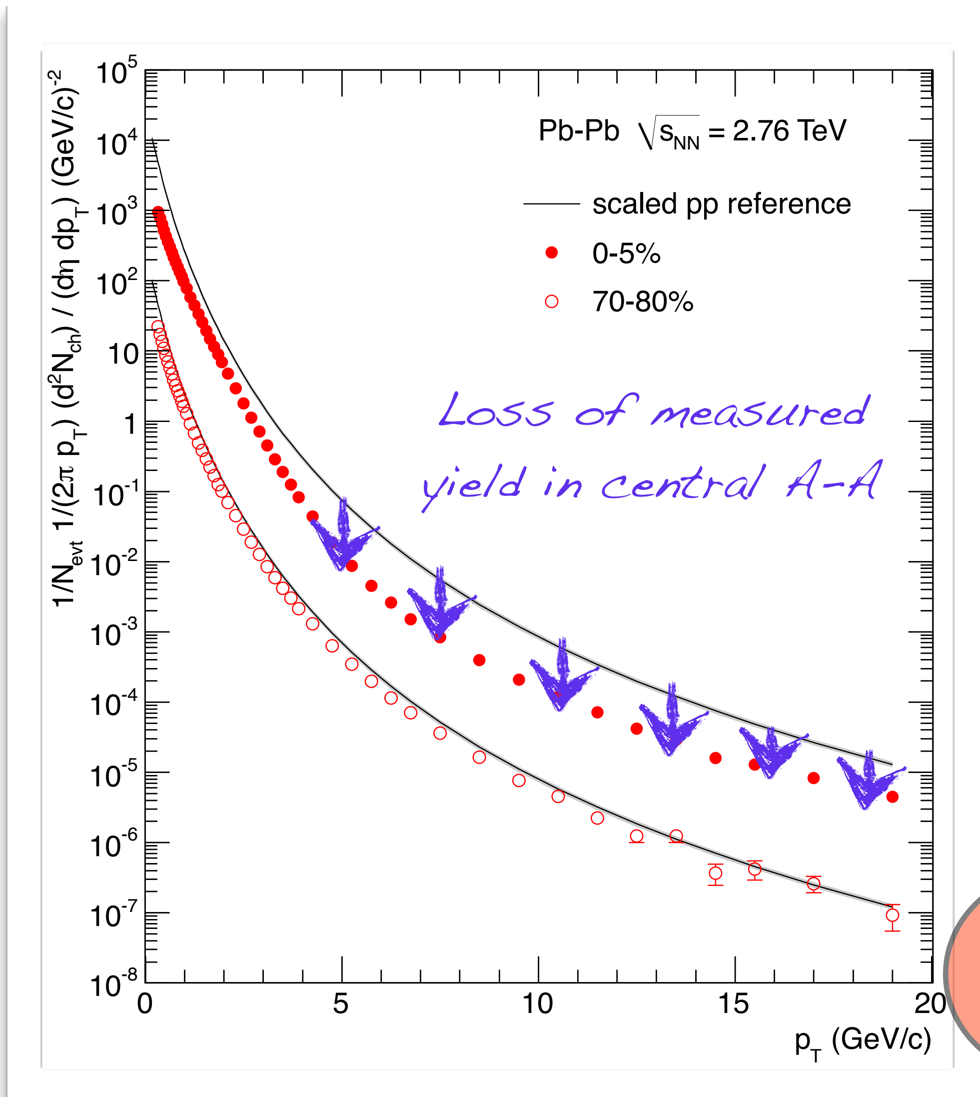
- Leading hadrons suppressed <-> parton energy loss (jet quenching); Hadrons select particular ensemble of jets(!) - fragmentation bias (more Today) - relation of parton vs hadron energy (?)

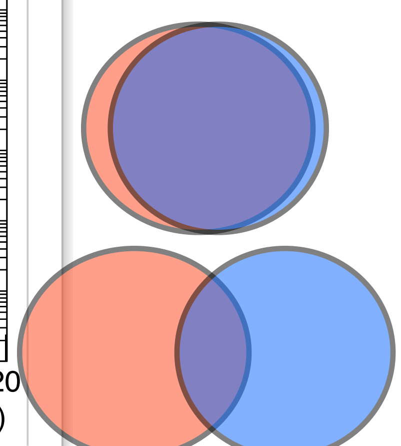
... back to jet quenching measurements

"Easier" (than full jet reconstruction) exercise:
Jet-quenching via leading hadrons

Inclusive hadron production

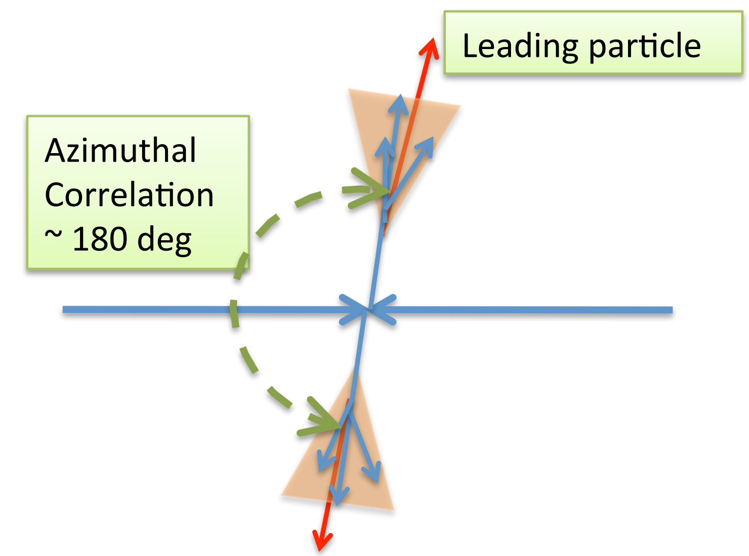
Measured as a function of collision centrality

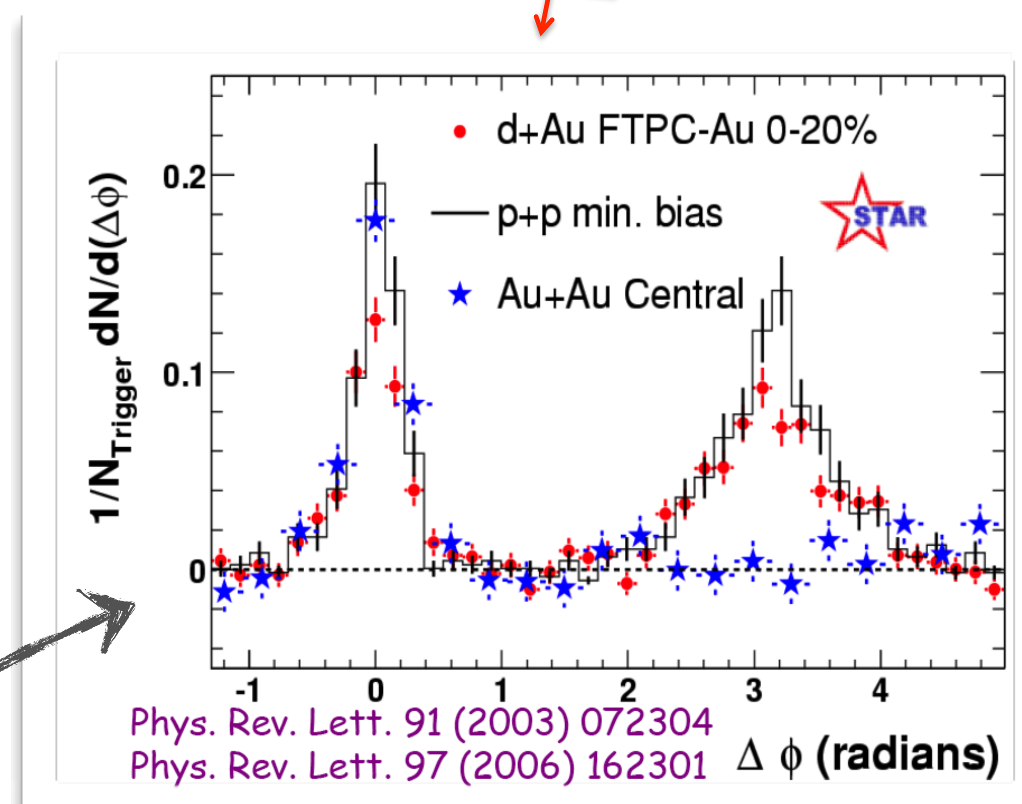




Di-hadron correlations

Rates of recoil ("away-side") hadrons suppressed





Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

Note on correlations: interesting tool to study the "intermediate"-p_T region – jets vs flow and recombination

Sensitivity of particle correlations to different underlying physics

Two-particle correlations

- conditional [per-trigger] yields

$$\frac{1}{N_{trig}}\frac{dN_{assoc}}{d\Delta\varphi} \quad \text{and} \quad \frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\varphi d\Delta\eta}$$

At Low-p_T :

Ridge

Hydrodynamics, flow

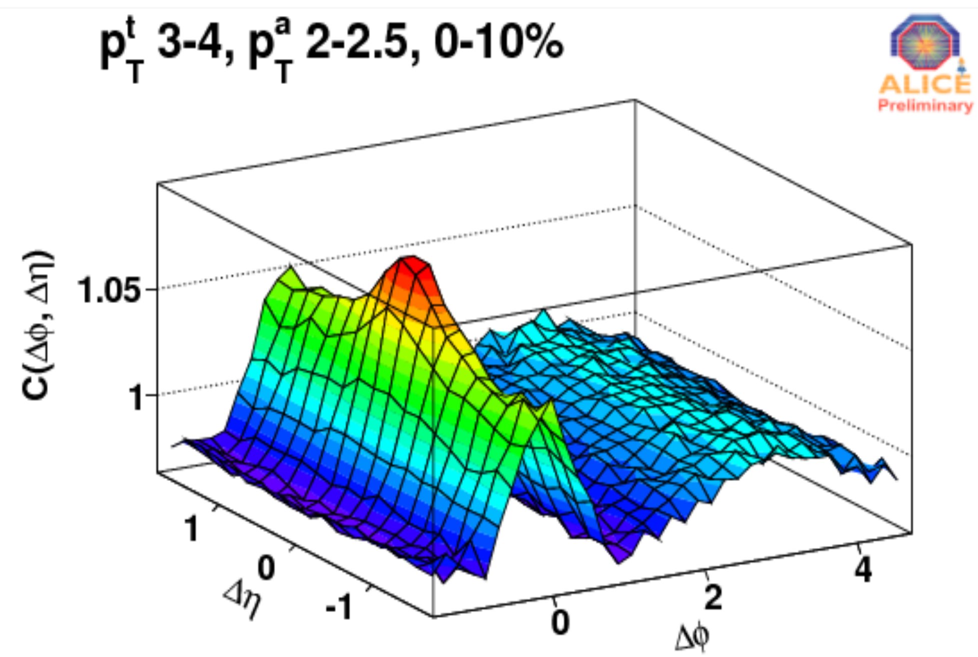
See extra slides for more...

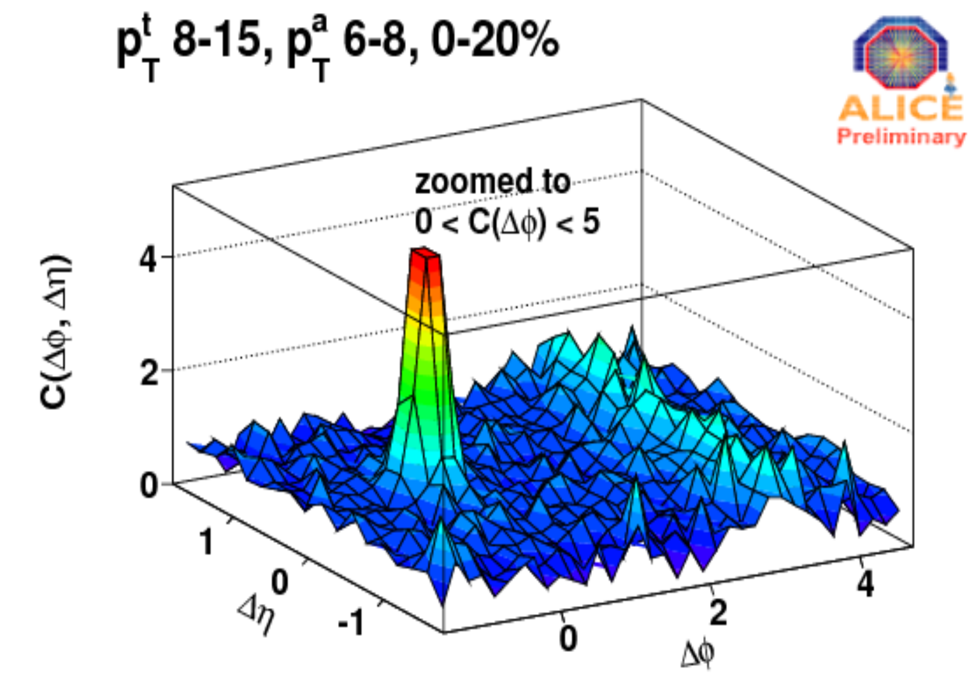
At High-p_T :

Quenching/suppression, broadening

I_{CP}: Yields in central v.s. peripheral collisions

I_{AA}: Yields in A-A compared to p-p

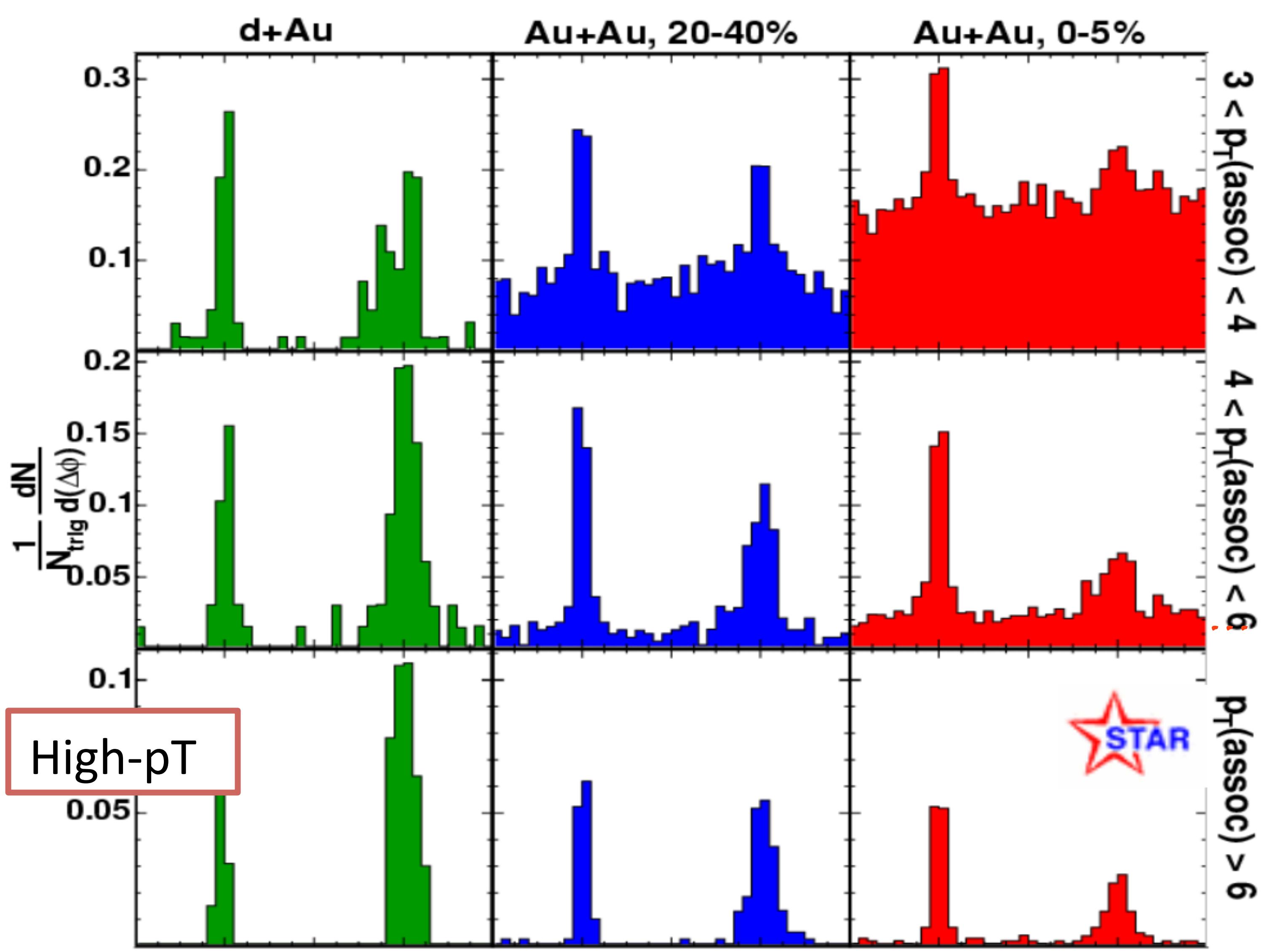




Two-particle correlations

RHIC @ 0.2 TeV

Most central



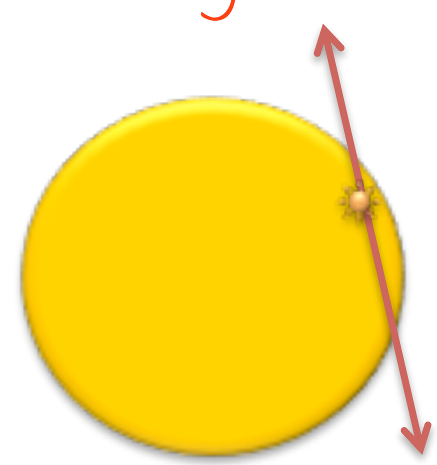
Phys.Rev.Lett.97:162301,2006

Reaperance of the away side peak at high-assoc.-pT:

- ○ similar suppression as in the inclusive spectra
- ○ unmodified shape

Differential measurement of jets w/o interaction

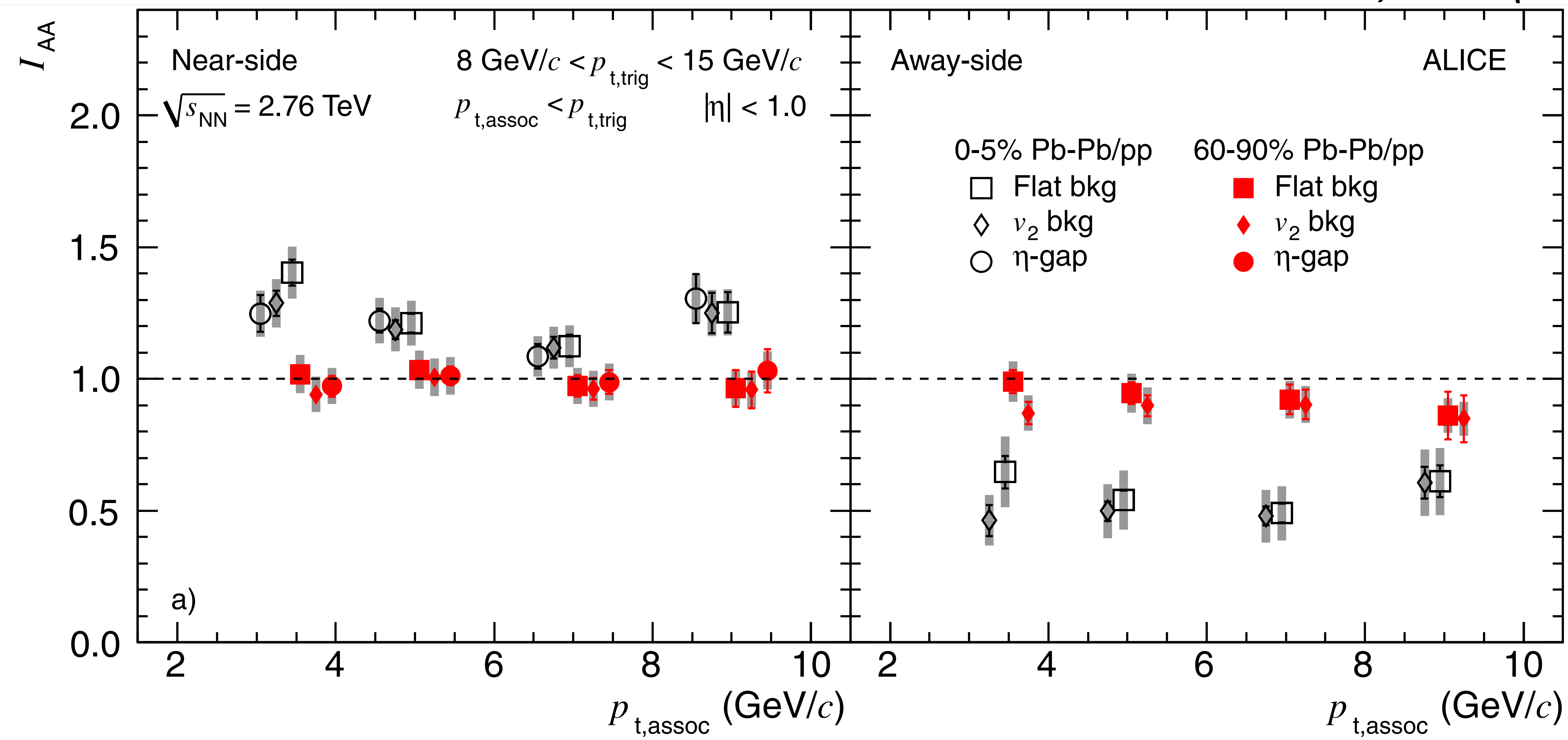
... or jets fragment as in vacuum



Conditional yields - LHC

Yield per trigger particle AA/pp-> I_{AA} (unity==no effect)

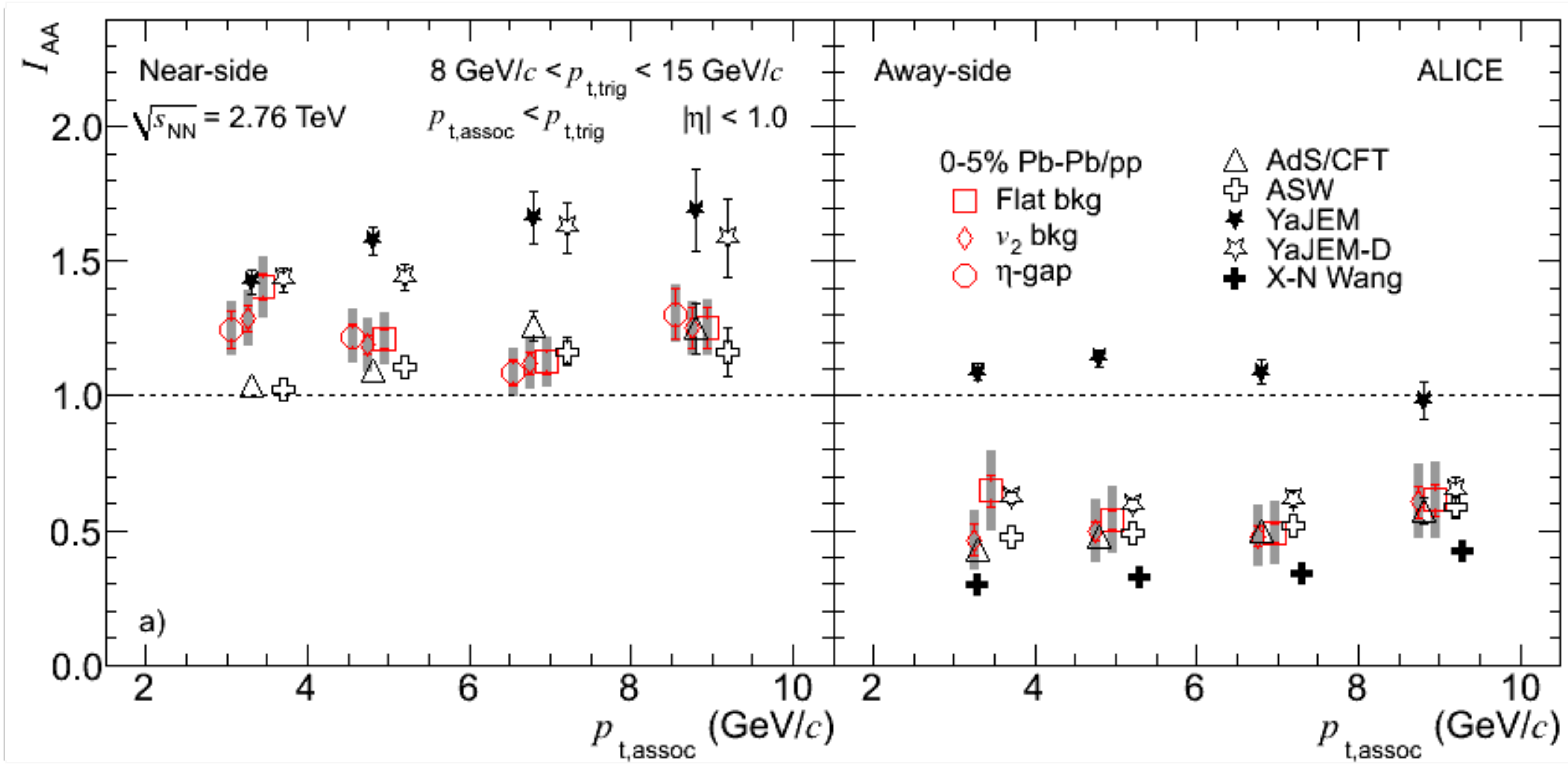
PRL 108, 092301 (2012)



Compare pp and Pb-Pb → $I_{AA} = Y_{AA}/Y_{pp}$

- Central events:
  - near-side enhancement (>1: change in FF? bias on parton spectrum?; q/g-mix different in PbPb as compared to p-p?) - consistent with jet quenching...
  - recoil: suppressed - consistent with quenching

IAA: data & theory description



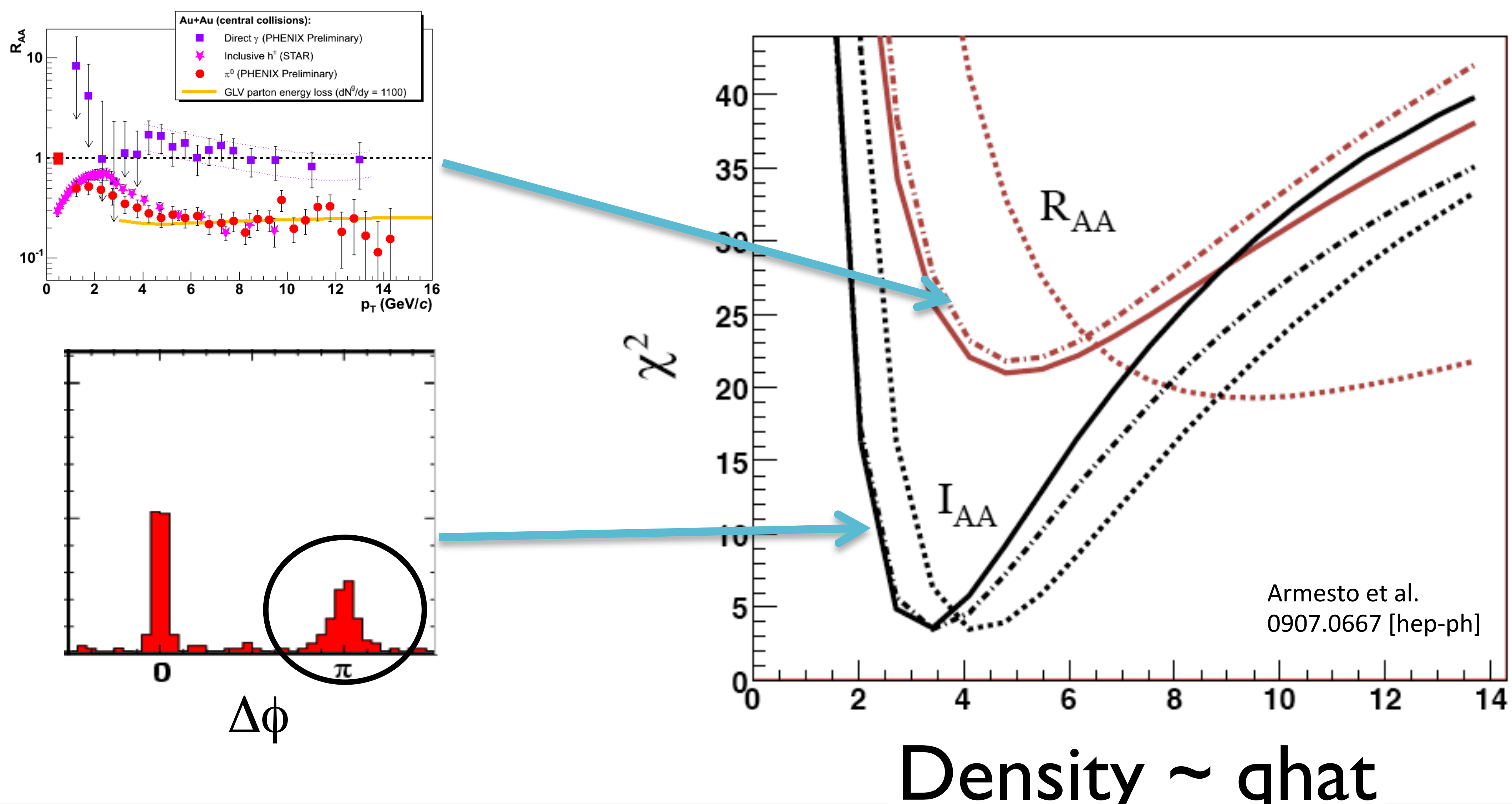
Near-side enhancement:

- Reproduced by AdS/CFT - inspired (L^3 path length dependence) and ASW - inspired (L^2) models
- YaJEM too high (L dependence)

ok, so... compatible with jet quenching...

RHIC Example: High-p_T hadrons - quantitative analysis

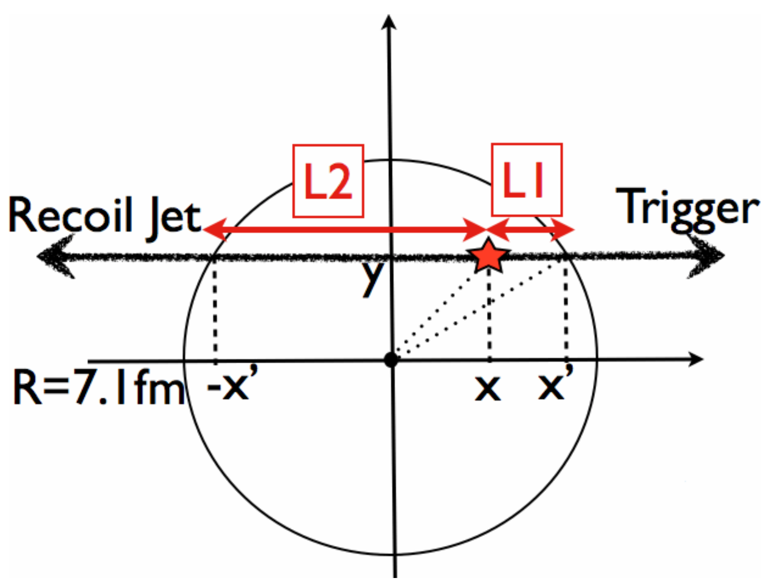
Model calculation: ASW quenching weights, detailed geometry
Simultaneous fit to data.

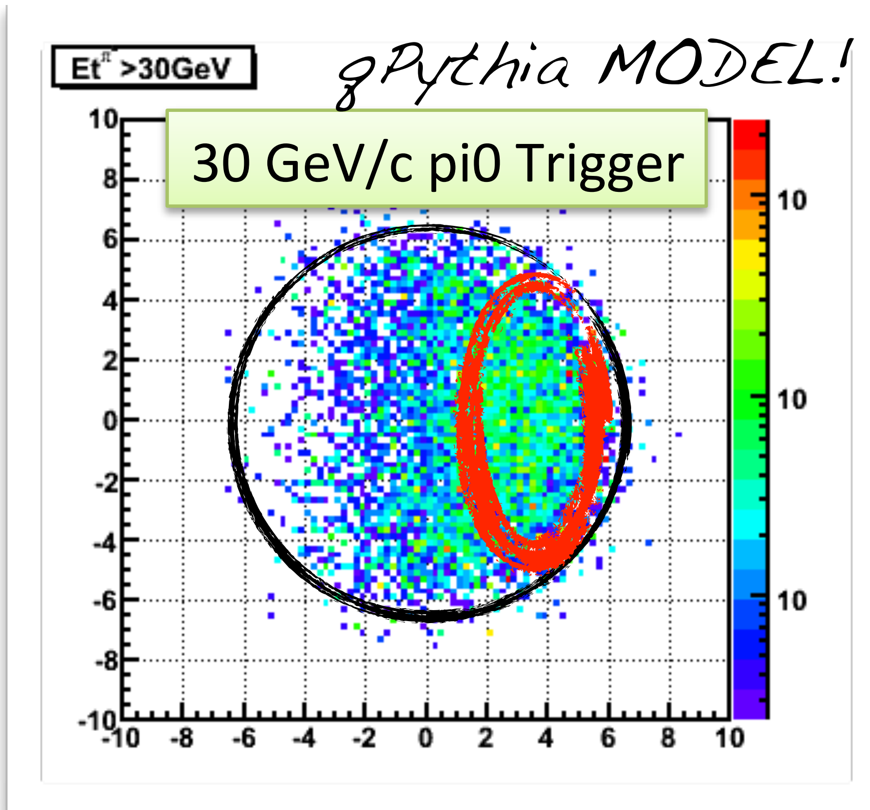


Reasonably self-consistent fit of independent observables
Main limitation is the accuracy of the theory...

So, why bother with full jet reconstruction in heavy-ion collisions?

R_{AA} and correlations of leading hadrons provide constraints on density of the medium (qhat), however do not tell us about the *parton* energy loss and its dynamics; leading hadrons are biased towards jets that interact little or not at all with the medium



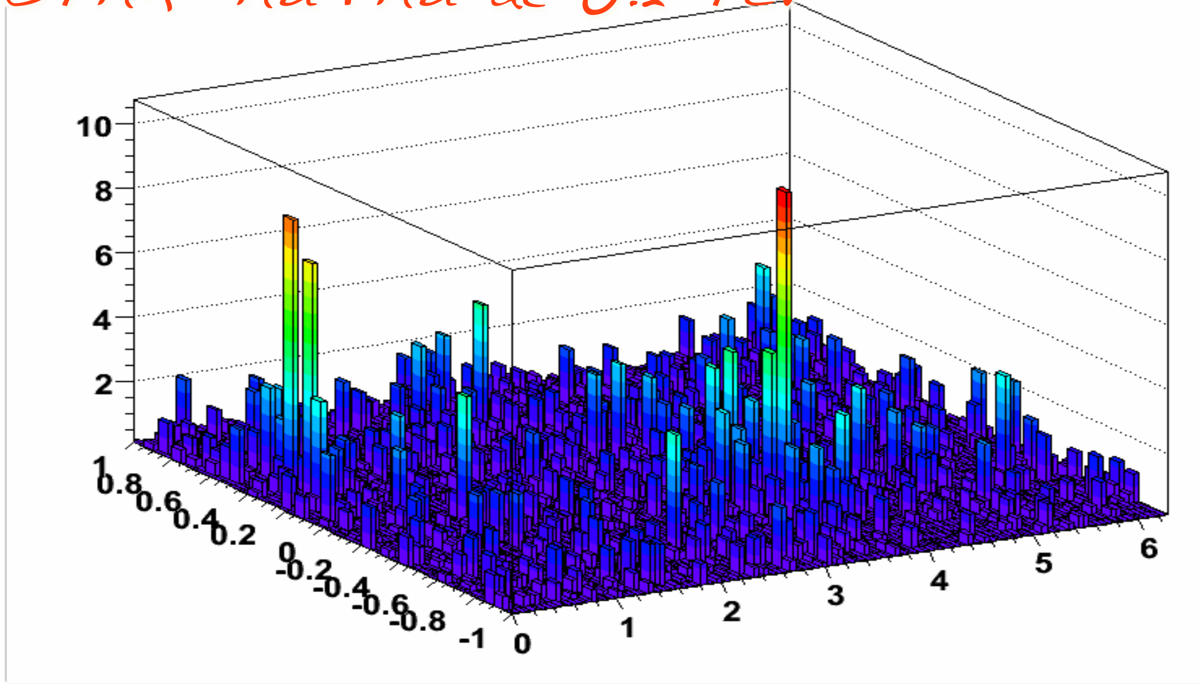


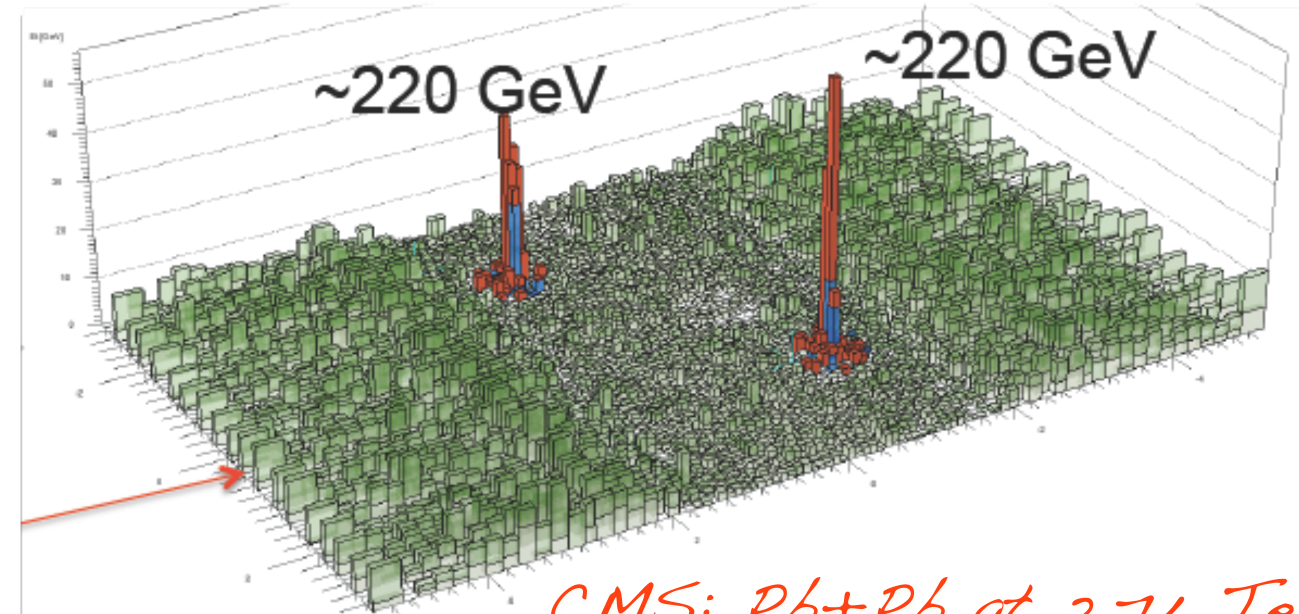
So called surface bias: requesting a high-pT particle selects a population of jets close to surface of the medium - these jets interact only little (or not at all) with the medium

=> full jet reconstruction premise: integrate over the hadronic degrees of freedom; better access to the parton energy scale; dynamics of the jet quenching (?); other promising observables: gamma-jet correlations

Jets in heavy-ion collisions

STAR: Au+Au at 0.2 TeV





CMS: Pb+Pb at 2.76 TeV

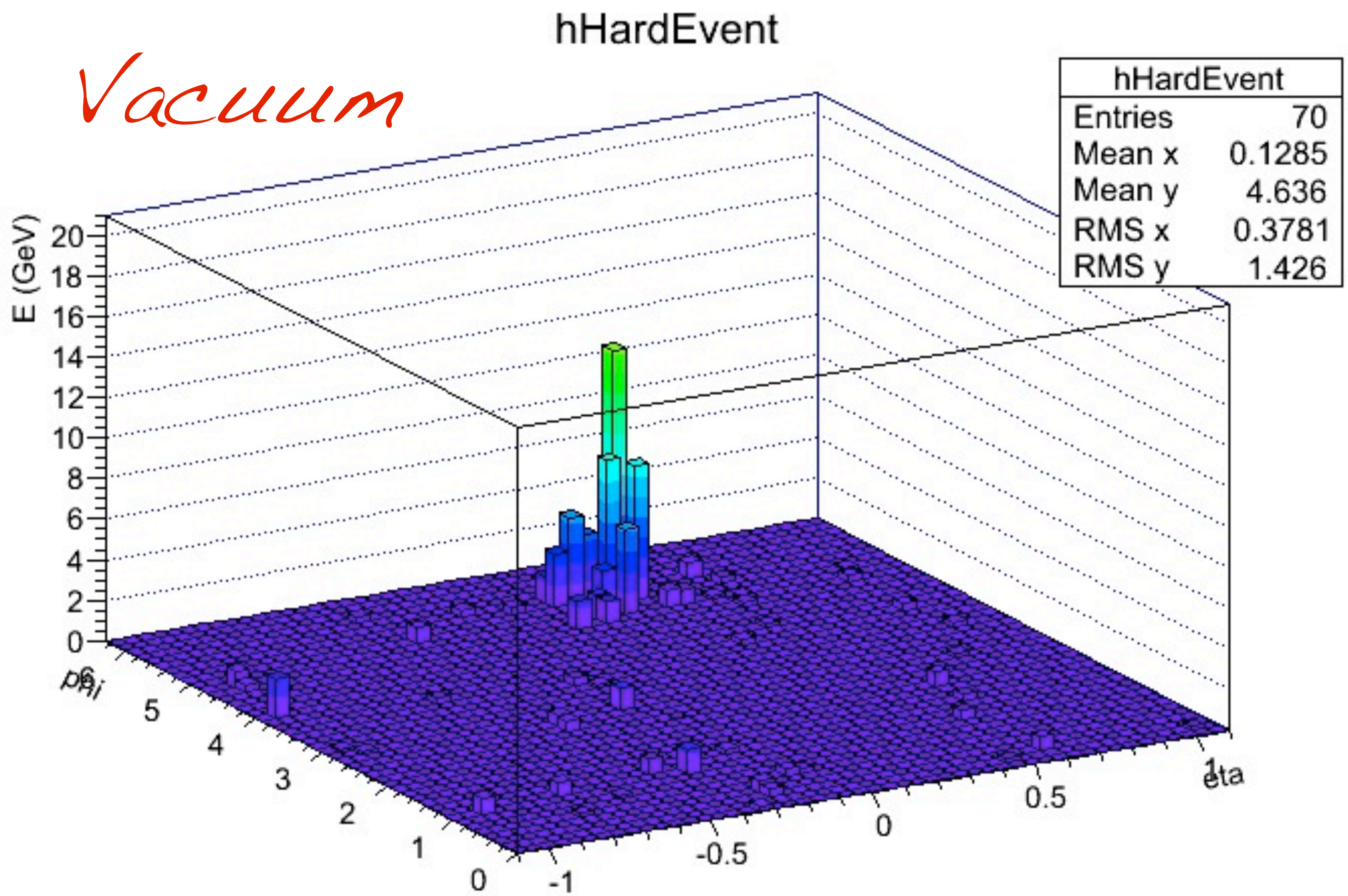
LHC + RHIC: QCD evolution of jet quenching ?

Vary energy of the jet:

LHC: Vary the scale with which QGP is probed (a la DIS)

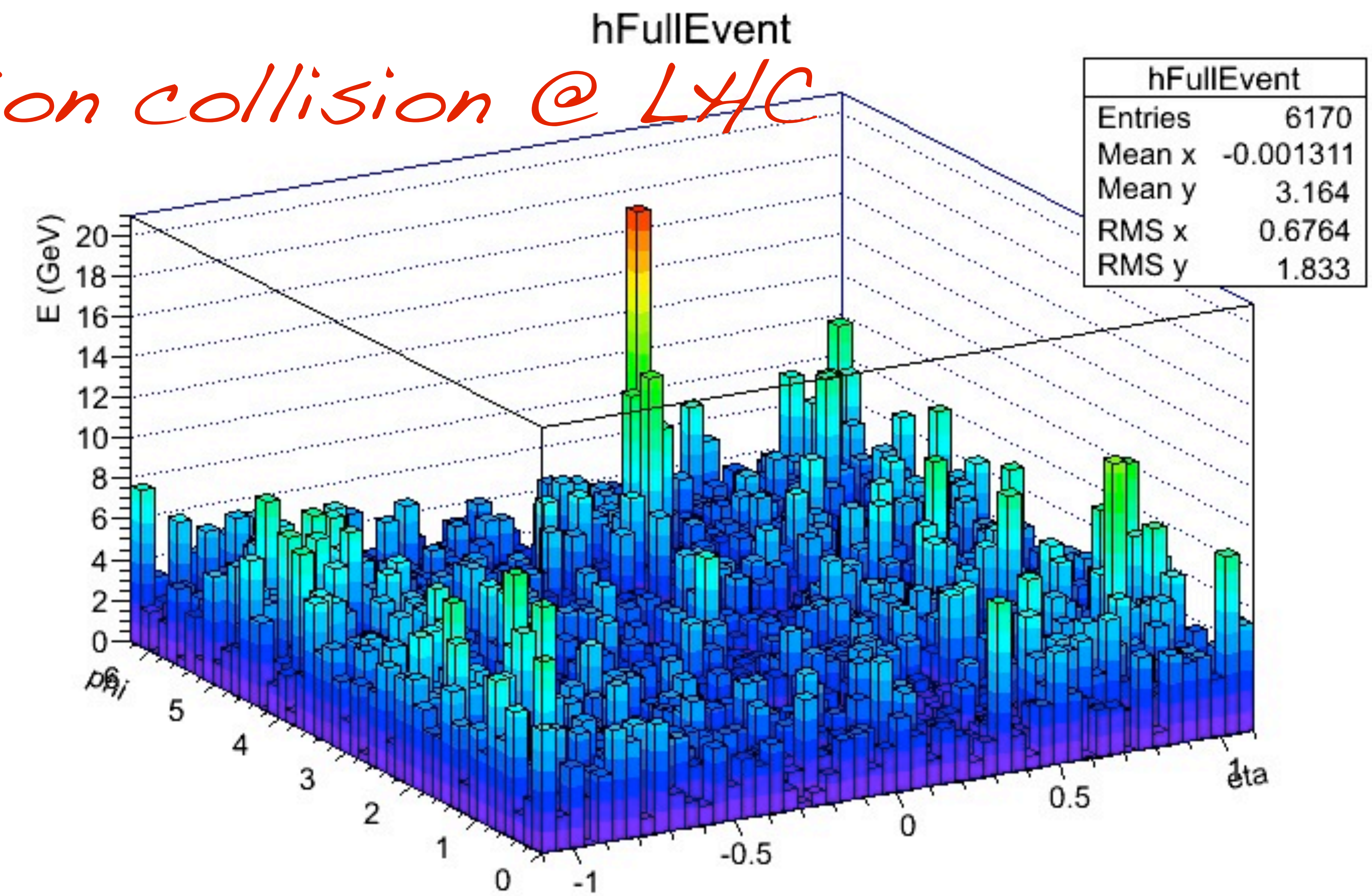
Compare and contrast RHIC and LHC

Jets in HI collisions & Experimental difficulties: Vacuum jet vs jet on top of the HI background...

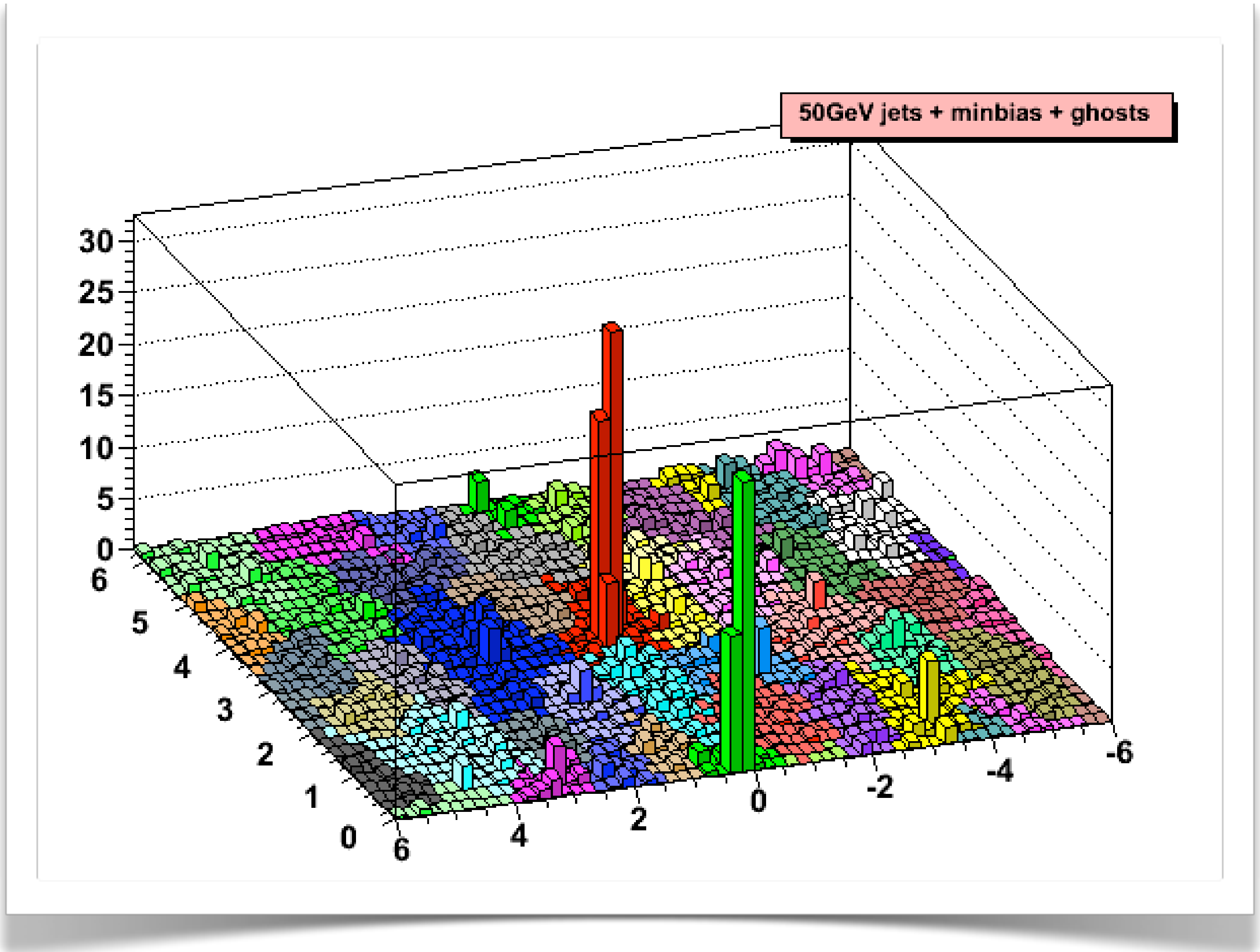


Jets in HI collisions & Experimental difficulties:
Vacuum jet vs jet on top of the HI background...

Heavy-ion collision @ LHC



HI jet finding:



A single event: all particles clustered ("assigned") to a jet

Many of these objects are simply background

Energy of the signal jets overestimated due to background energy

=> several possibilities to subtract the average background and/or suppress the background particles [and background jets]

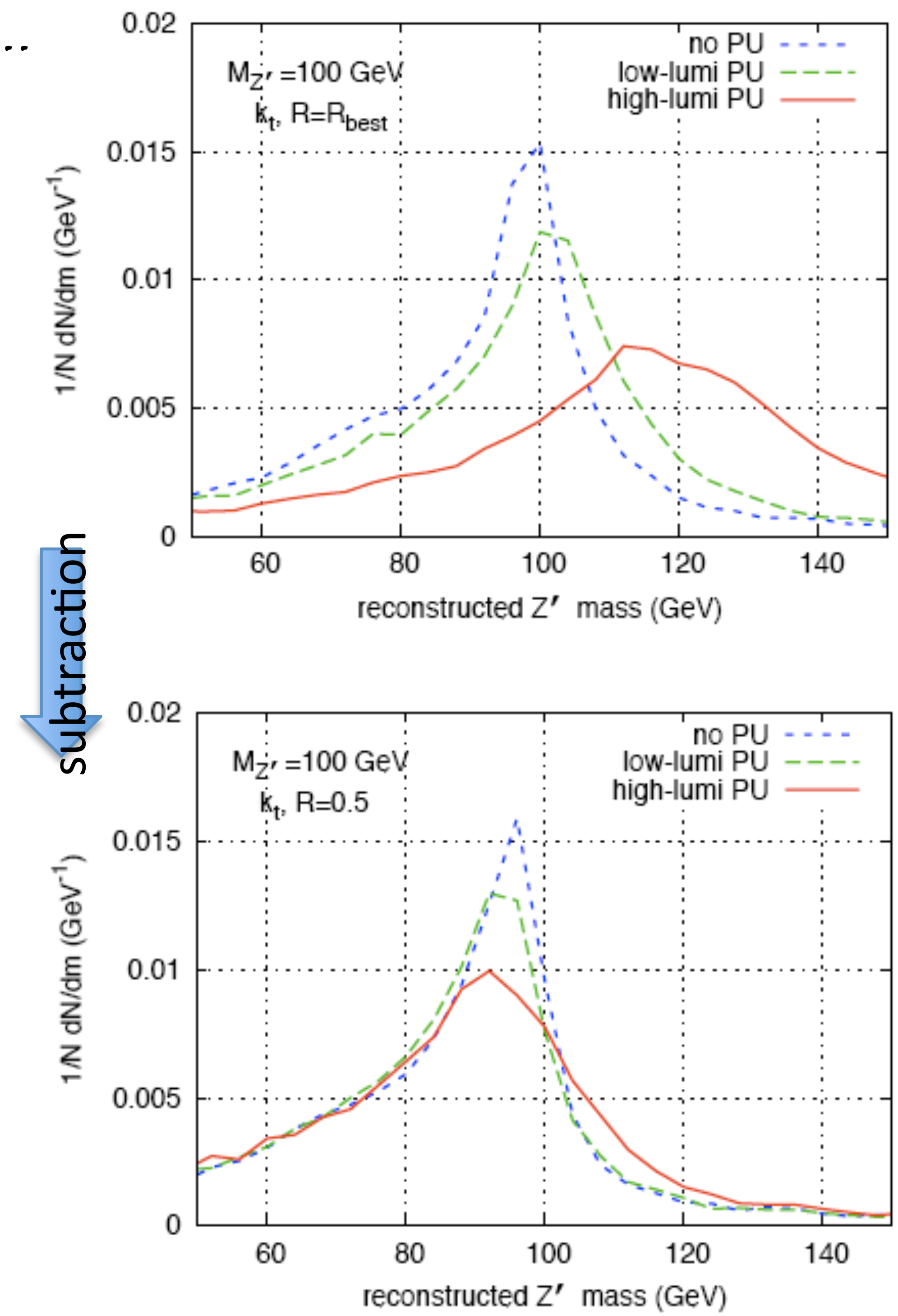
Background subtraction

Developed for pile-up rejection in p-p....

$$p_T^{jet} = p_T^{cluster} - \rho \times Area$$

$$p_T^{jet} = p_T^{true} \otimes \delta\rho$$

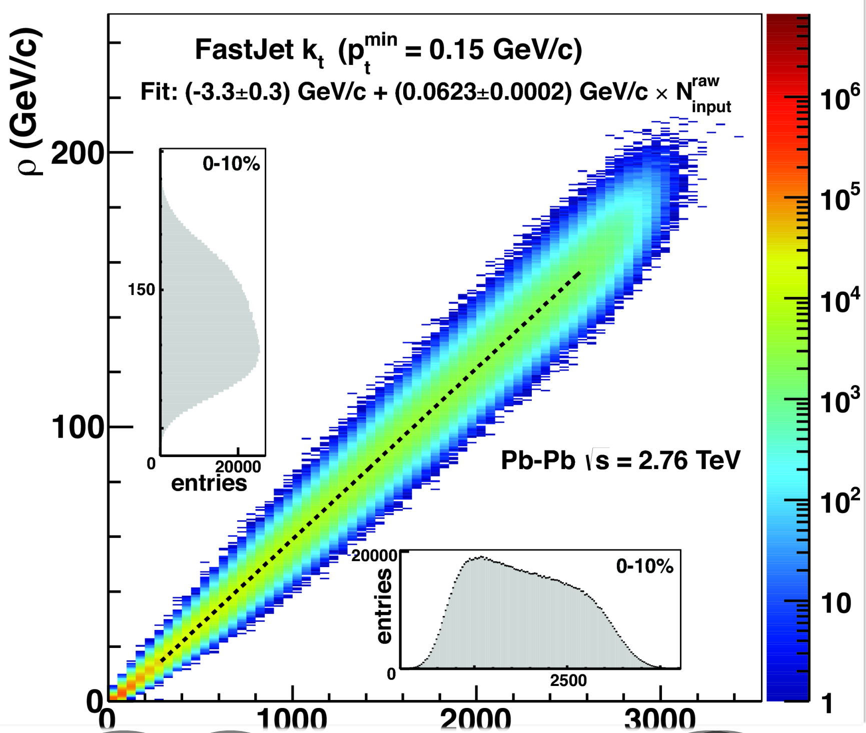
- ρ: median pT per unit area of the diffuse background in an event – measured using background *"jets"* as found by kT algorithm
- A: area of the jet – measured using number of artificially injected infinitely soft particles of finite *"size"* into an event that are clustered into the jet
- δρ: uncertainty due to noise fluctuations – non-uniformity of the event background



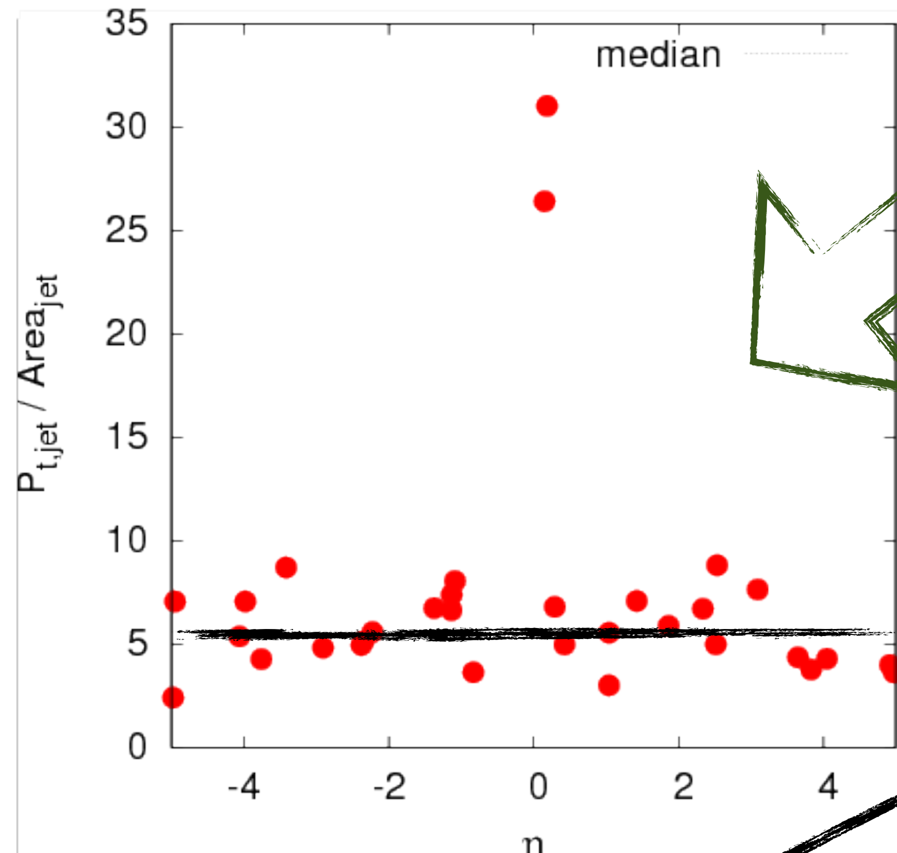
M. Cacciari, G. Salam, G. Soyez JHEP 0804:063,2008. e-Print: arXiv:0802.1189 [hep-ph]
M. Cacciari, G.Salam Phys.Lett.B659:119-126,2008. e-Print: arXiv:0707.1378 [hep-ph]

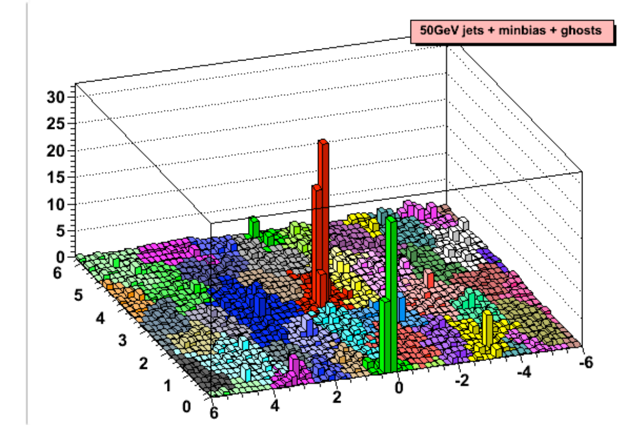
HI jet finding: treatment of the background

$$\rho = median\left(\frac{p_T^{jet,i}}{A_i^{jet}}\right)$$



Method 1





NOT all of the objects returned by jet finder are TRUE jets! (aka - fake/false jets!)

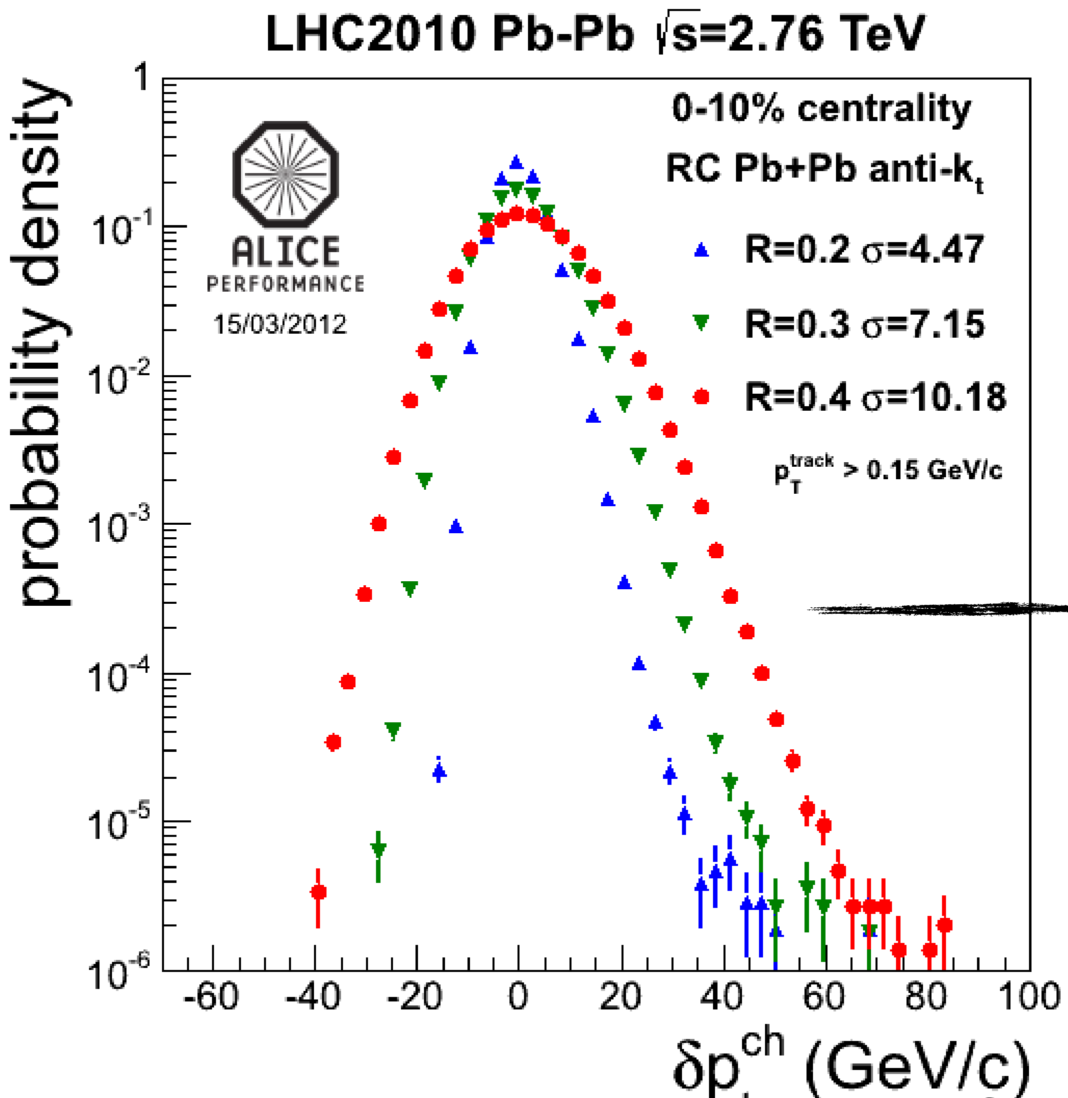
average background energy density

$$p_T = p_T^{raw} - \rho \times Area_{jet}$$

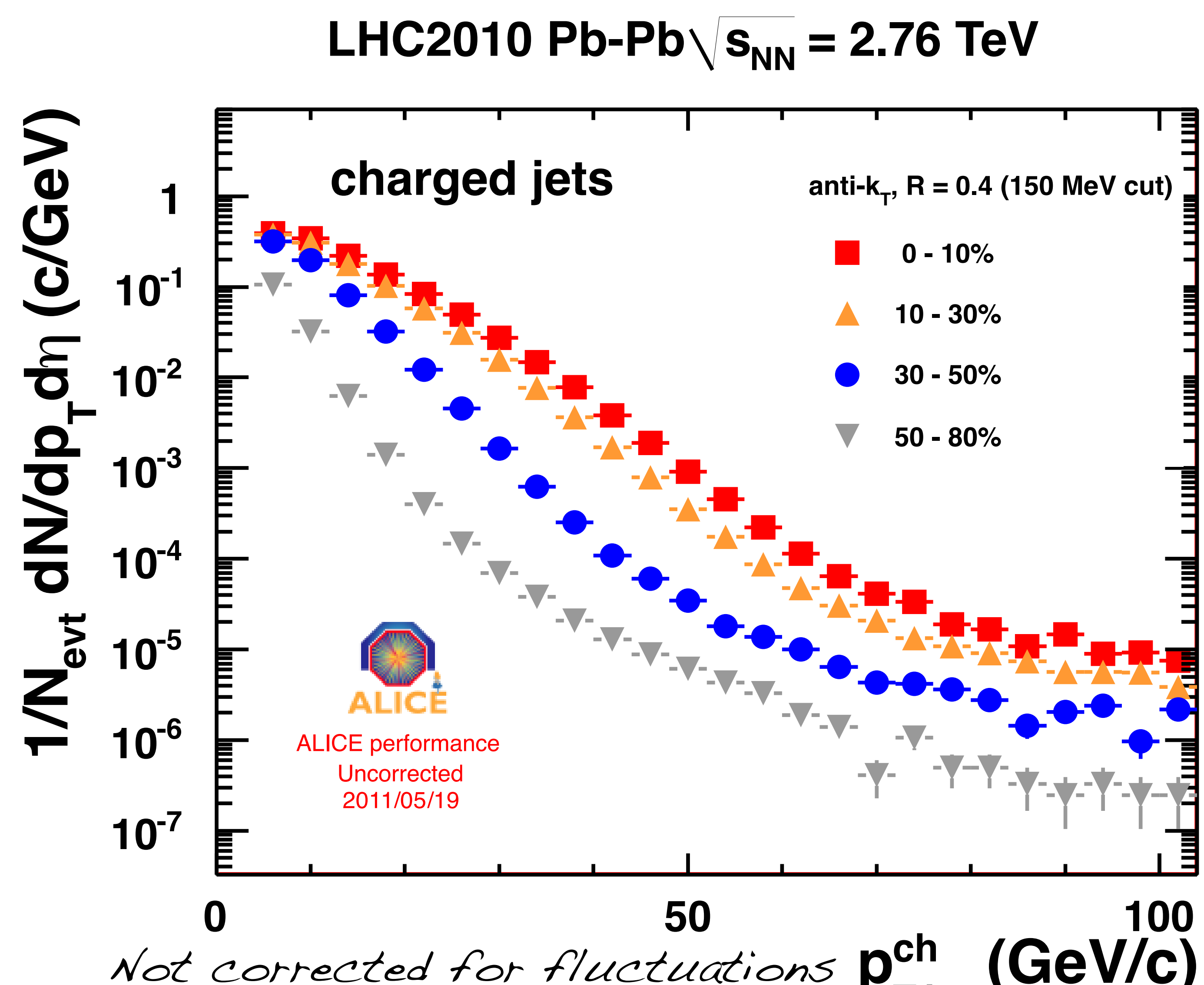
Must correct for remaining residual energy resolution

- magnitude of the correction is related to the background fluctuations
- jet Area : small R (area) - smaller correction

Jet reconstruction in HI collisions: Background fluctuations: characterized by δ pT; spectrum before corrections



Energy resolution function: δp_T



Not corrected for fluctuations

NOT all of the objects returned by jet finder are TRUE jets! (aka - fake/false jets!) - even after background subtraction! <-> fluctuations

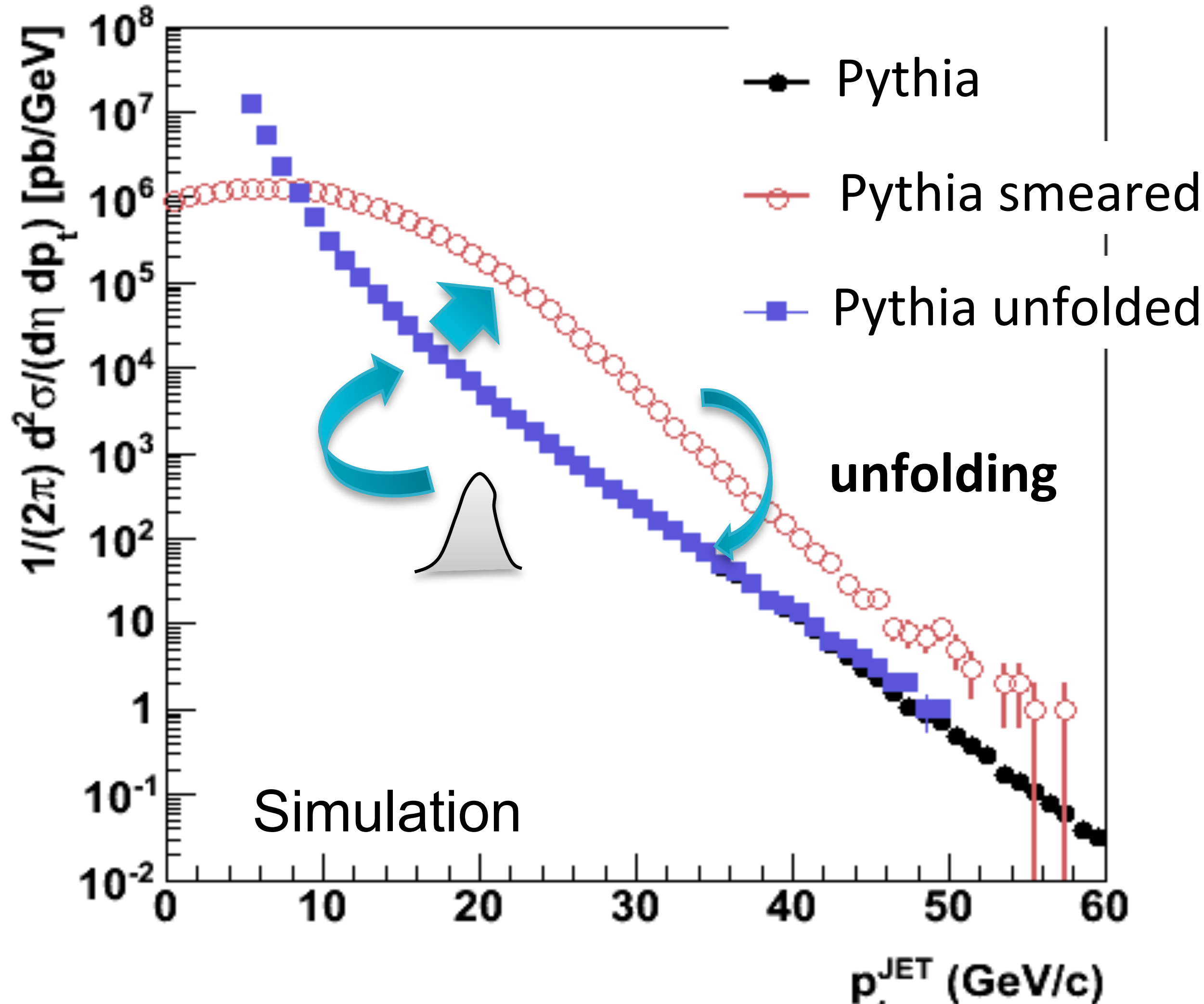
Energy resolution deteriorated due to background energy fluctuations

Model demonstration

$$\frac{dN^{\text{Meas}}}{dp_T} = \frac{dN^{\text{True}}}{dp_T} \otimes f^{\text{Resol}}(\delta\rho)$$

δP_T distribution:
'smearing' of jet spectrum
due to background fluctuations

Large effect on yields
Need to unfold



Background corrections in Atlas

- **UE fluctuations from soft particles can be reconstructed as jets (fakes)**
  - Worse for larger *R*, contribute up to ~80 GeV
  - Require additional signal of **hard particle** production
    - Reject fakes by requiring jet to match:
      - Track jets or EM clusters with $p_T > 7$ GeV
    - Residual fake rate estimated to be ~3% at 50 GeV

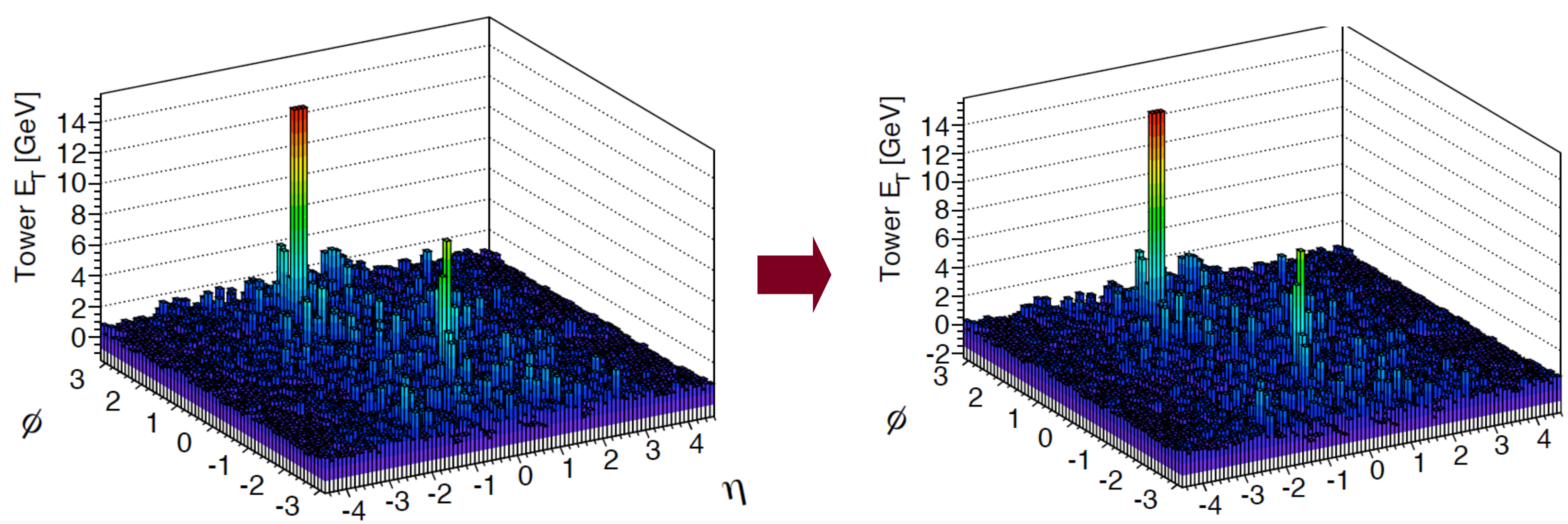
- Reconstruction algorithm anti-k_t (0.2, 0.4).
- Input: calorimeter towers 0.1 x 0.1 (Δη x Δφ).
- Event-by-event background subtraction: $E_{Tsub}^{cell} = E_T^{cell} - \rho^{layer}(\eta) \times A^{cell}$

→ Anti-k_t reconstruction prior to a background subtraction.

→ Underlying event estimated for each longitudinal layer and η slice separately.

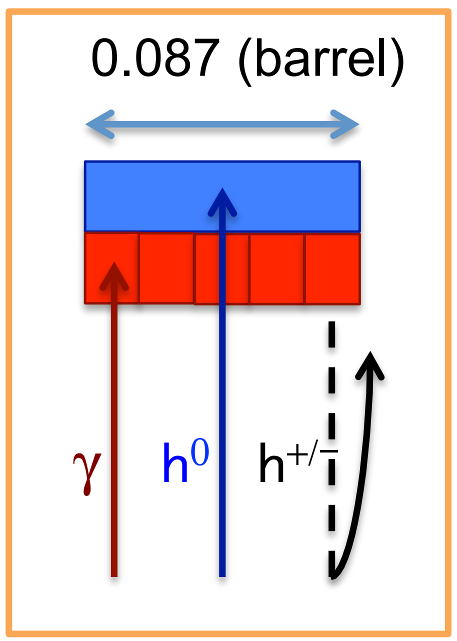
- We exclude jets with $D = E_{T\,tower}^{max} / \langle E_{T\,tower} \rangle > 4$ to avoid biasing subtraction from jets but no jet rejection based on *D*.
- Iteration step to exclude jets with E_T> 50 GeV from background estimation.

  Jets corrected for flow contribution.

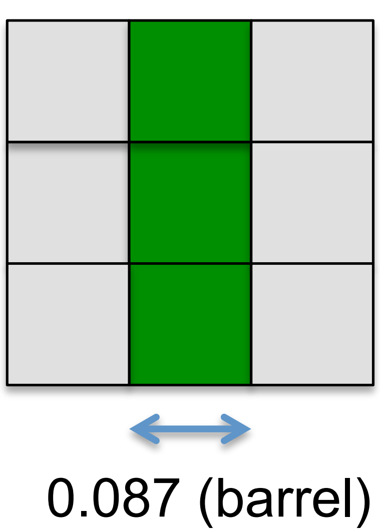


Background subtraction / jet energy corrections (CMS)

PF pseudo-tower



η strip



a) Event-by-event subtraction of the heavy-ion background

- Reconstructed particles towered into an (η,φ) grid according to HCAL cell dimensions

- Mean tower energy and dispersion are calculated for each η strip
- Same iterative background subtraction applied in [0], described in [1]
- Random cone studies: good agreement between background fluctuations in data and HYDJET simulations
- The effect of quenching on the energy scale is constrained using the jet associated charged particle spectra

b) Jet energy corrections (JEC) based on GEANT simulation of PYTHIA jets

c) Validation of the BG subtraction + JEC for PYTHIA jets embedded in HYDJET

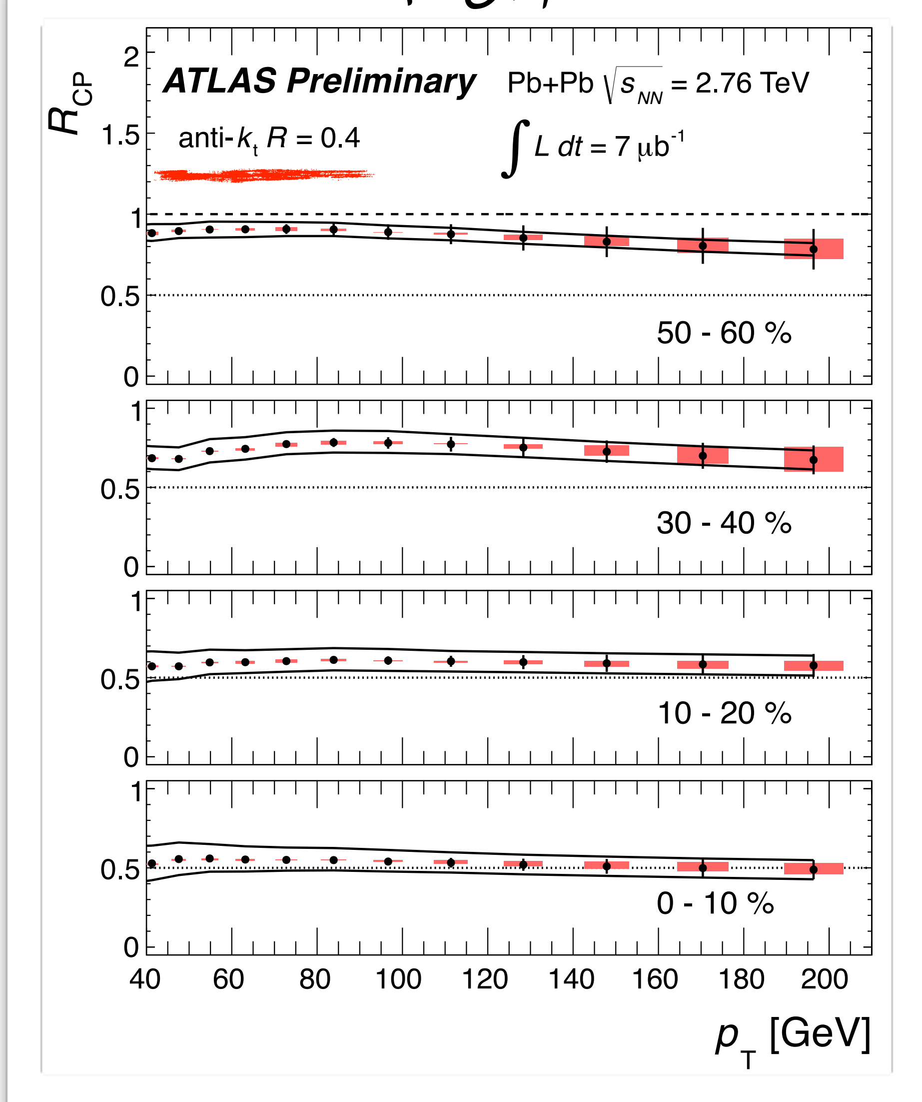
[0] CMS, arXiv:1102.1957
[1] Kodolova et al., EPJC 50 (2007) 117

- Jet quenching measurements with fully reconstructed jets

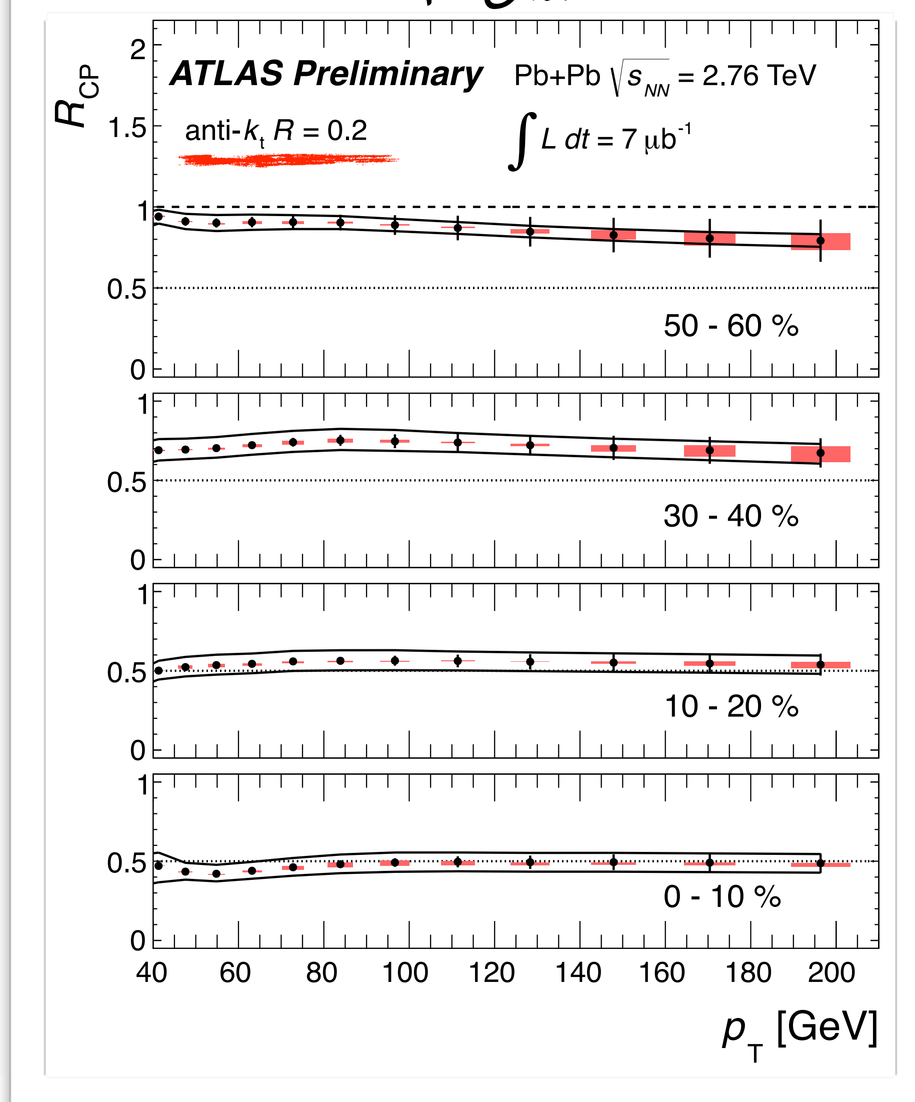
Jet $R_{Central-Peripheral(60-80\%)}$

R_{CP} : similar as R_{AA}, but denominator are not yields from proton-proton but from peripheral heavy-ion collisions

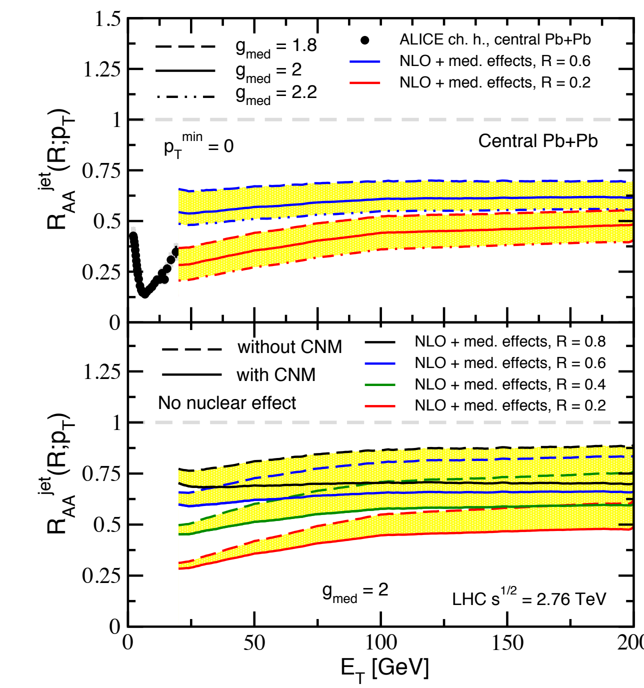
R=0.4



R=0.2



Measure single jet suppression with multiple jet sizes



He, Vitev, and Zhang hep-ph/1105.2566

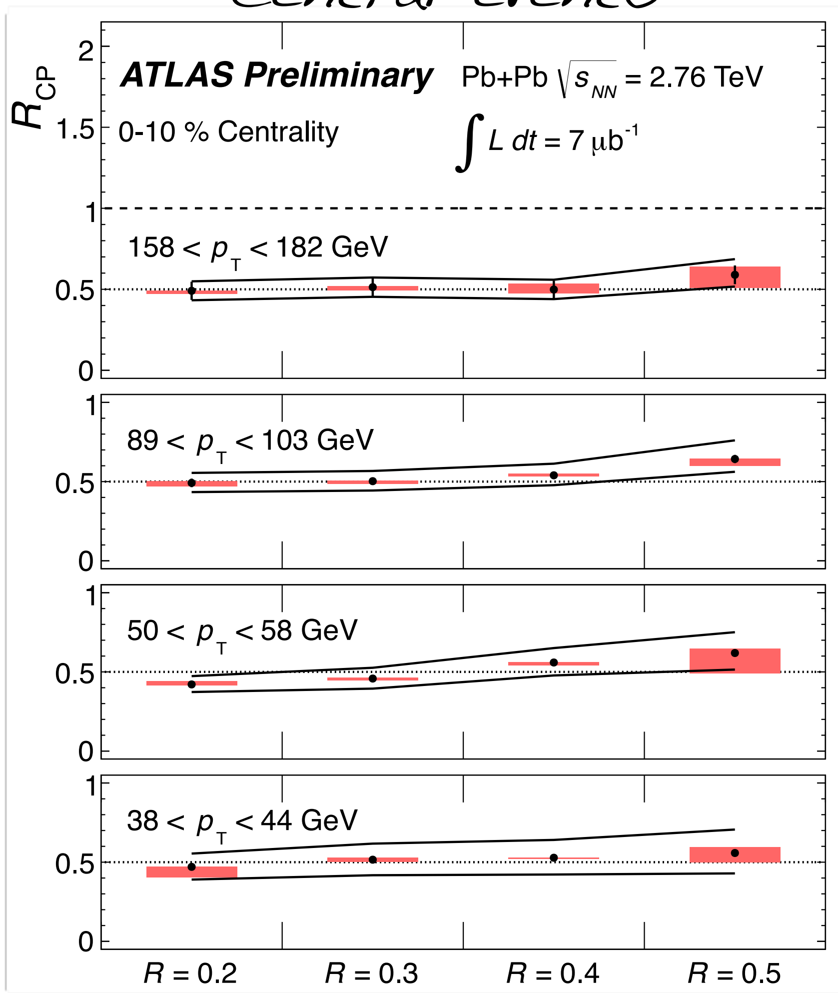
Note: Flat! - in contrast to R_{AA} of hadrons

$R_{CP} \sim 0.5$ => suppression - jets loose energy in most central events - the radiation is not captured within the jet cone (R)

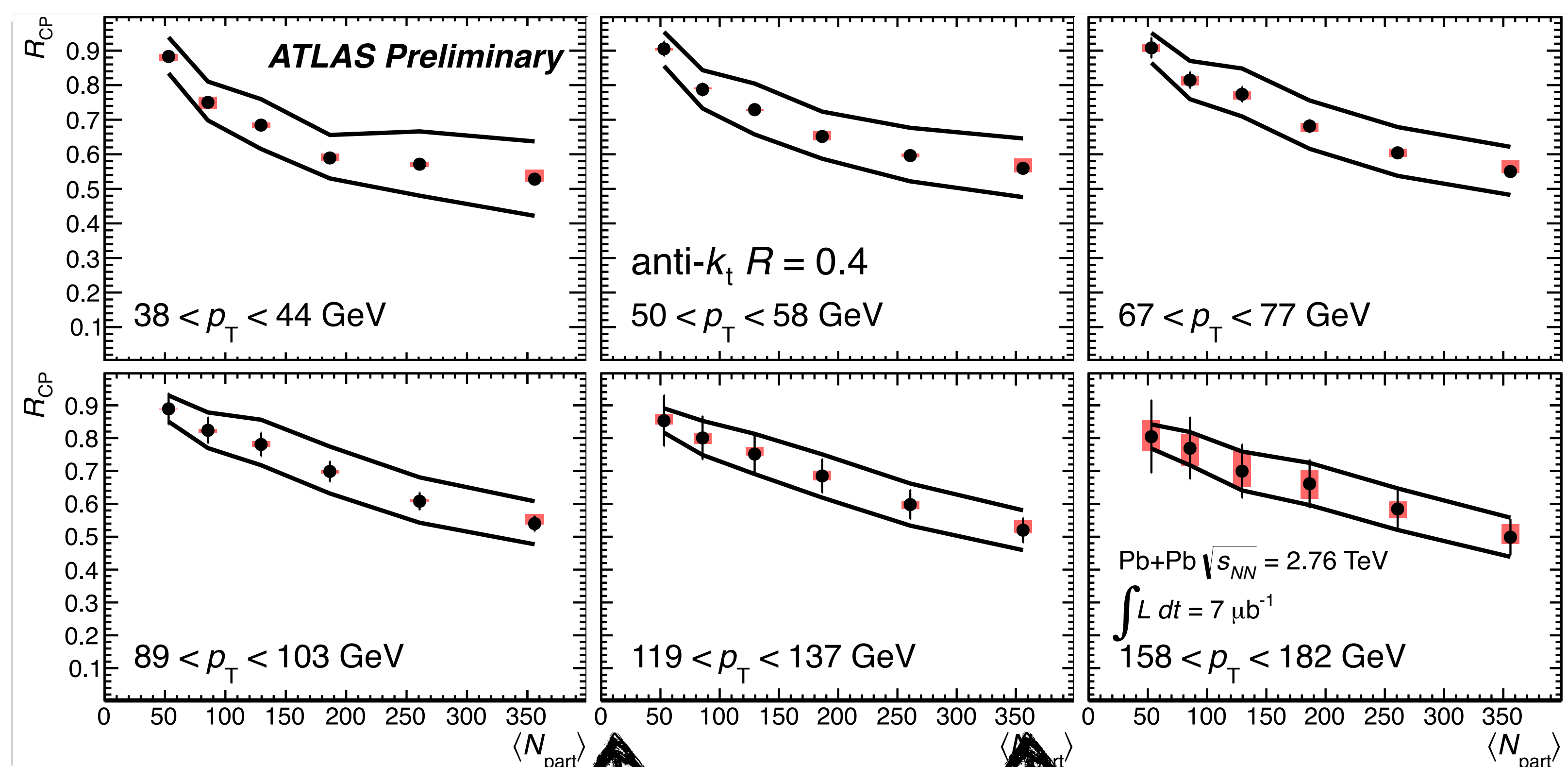
RCP of Jets

Measure single jet suppression with multiple jet sizes

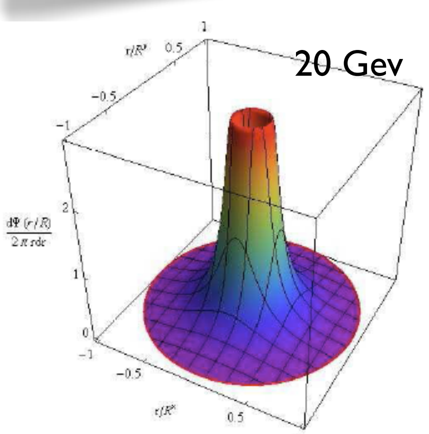
Central events

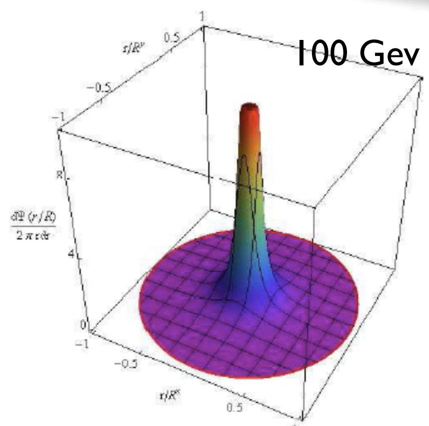


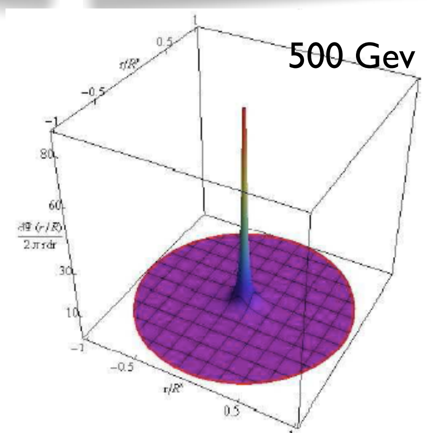
Suppression pattern as a function of centrality



Peripheral   Central

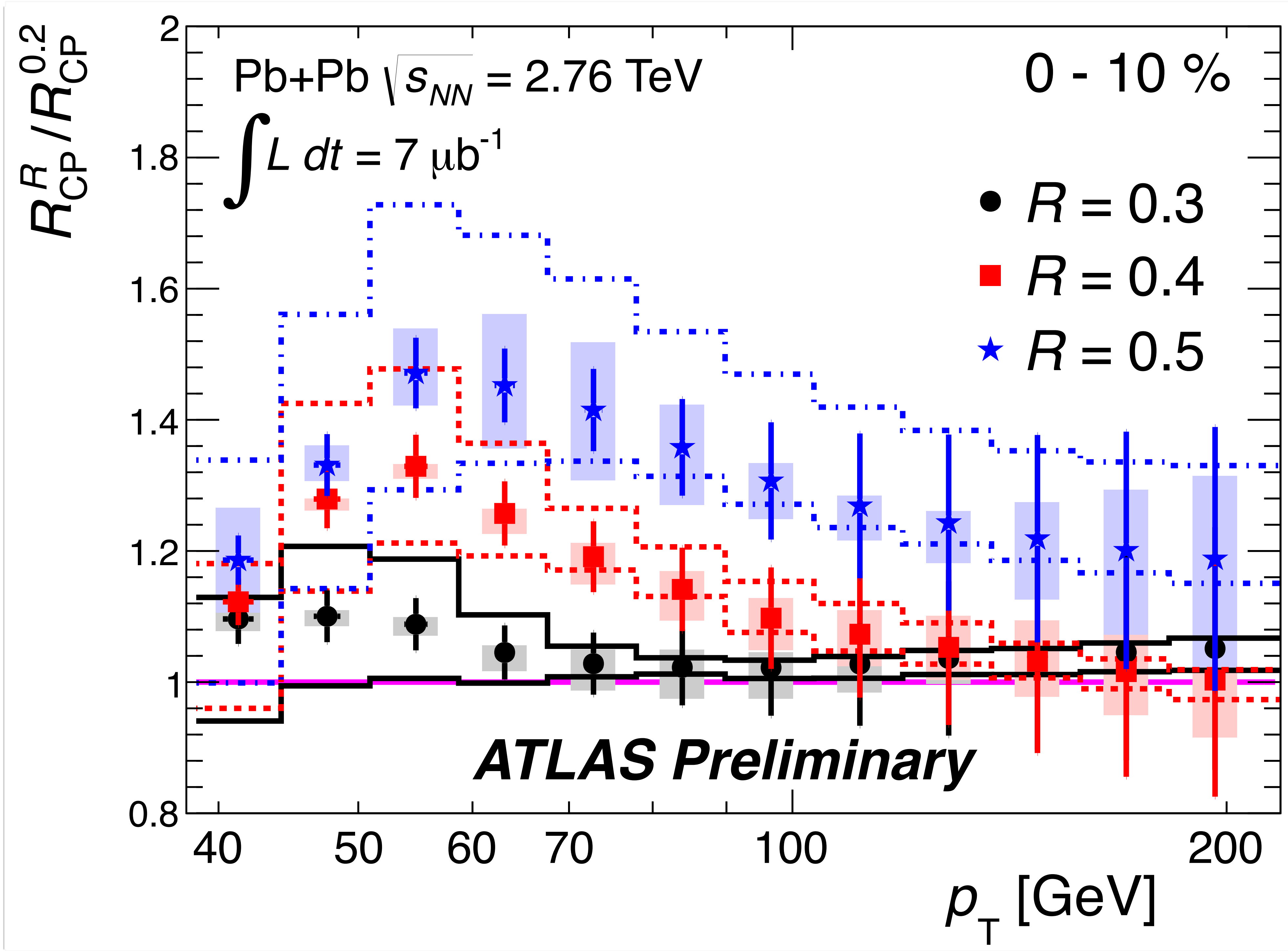




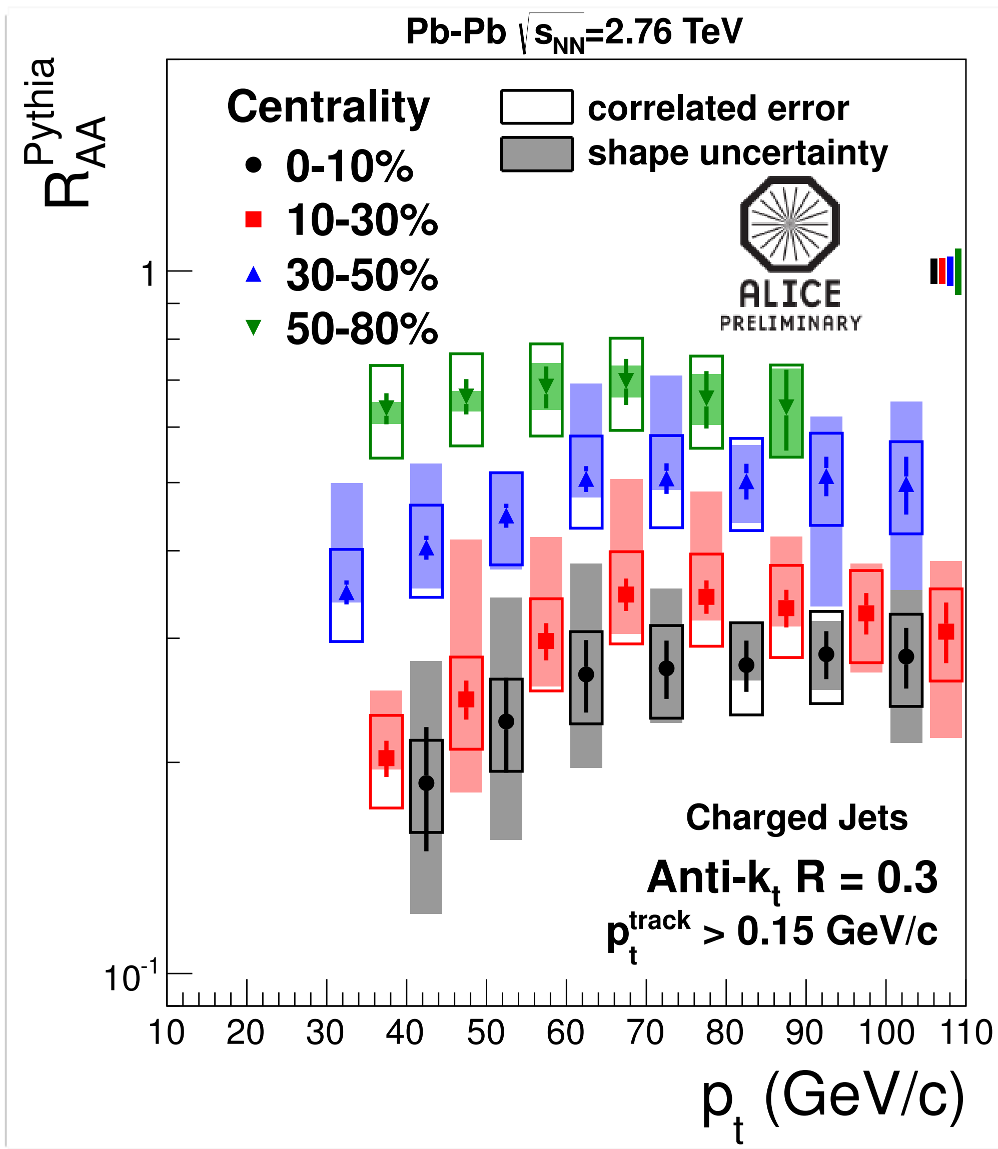


Note: RAA at RHIC also largely below unity...
(see backup)

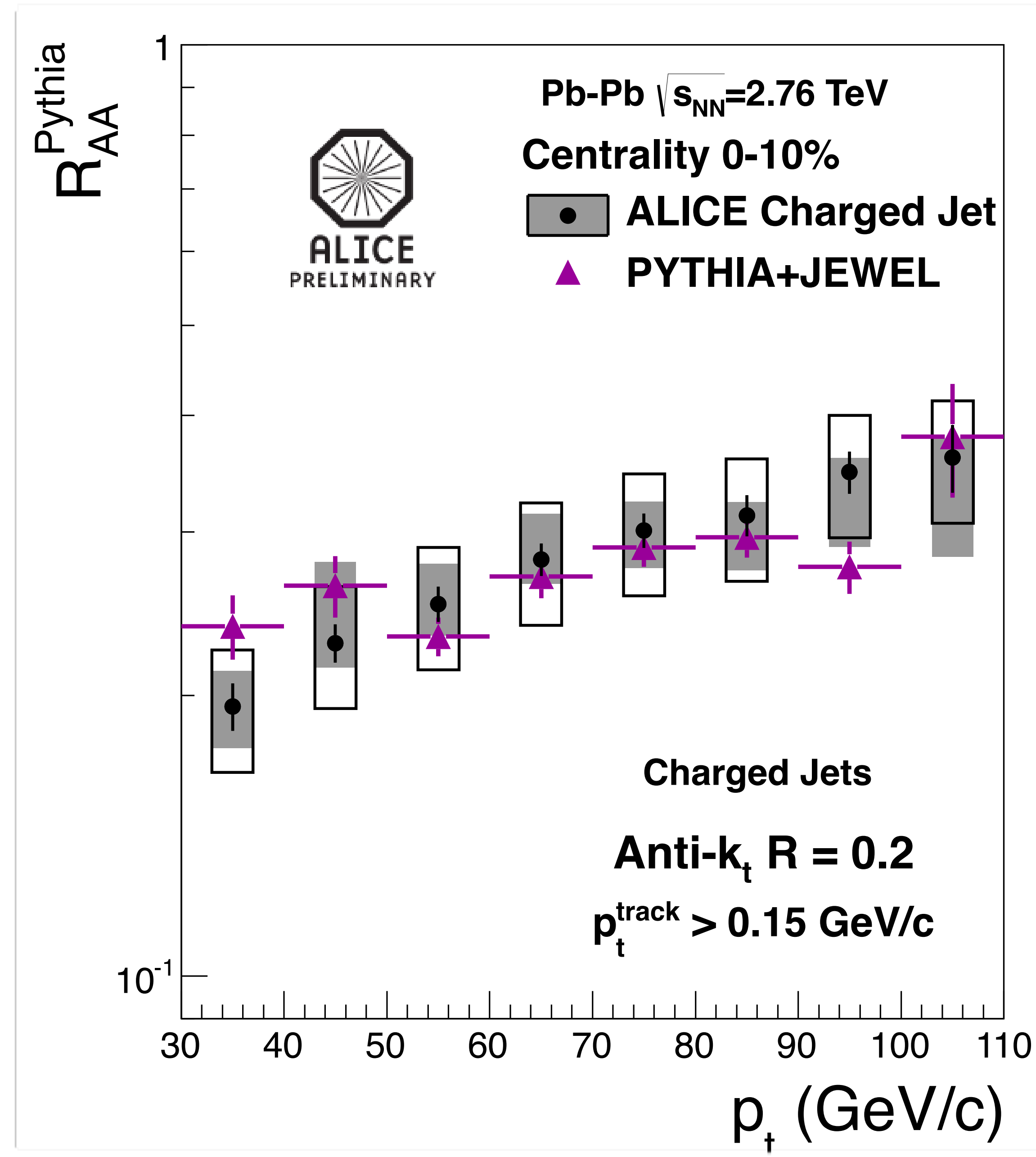
Suppression as a function of R



Jet quenching with charged jets - ALICE

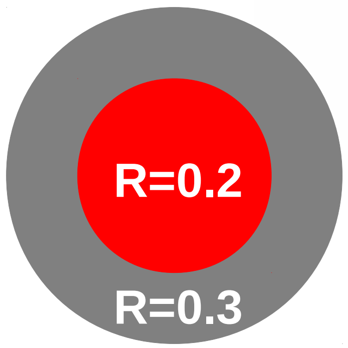


NOTE: Systematically different measurement - same effect found!



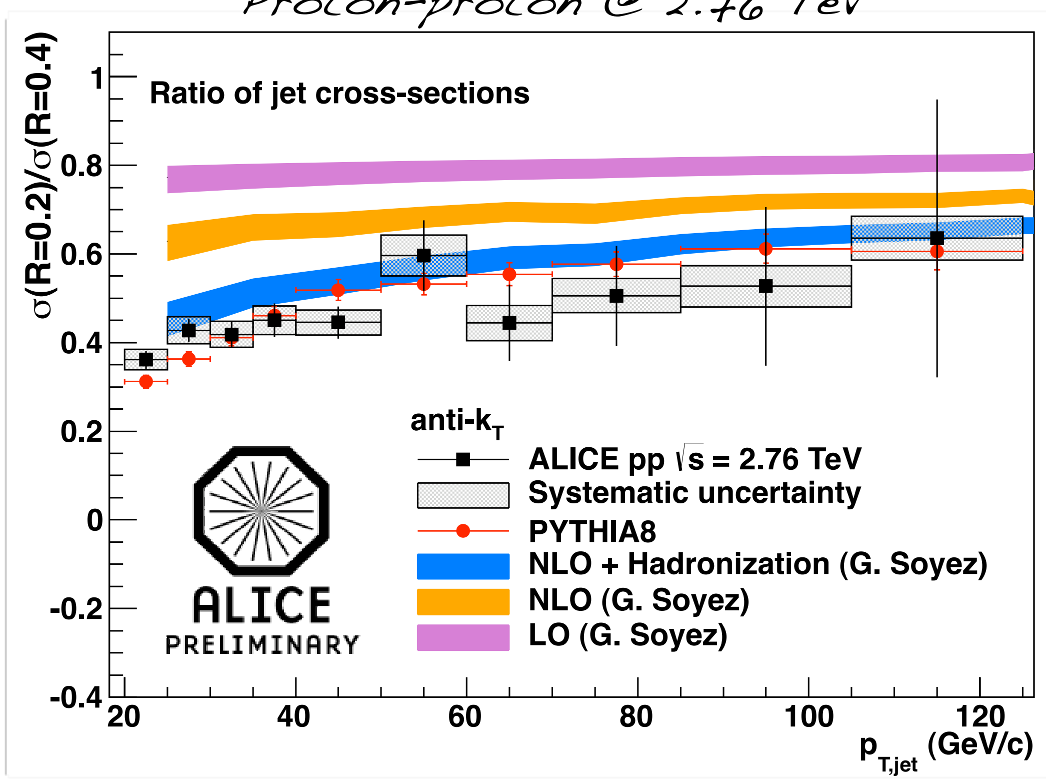
Model tunned on hadron RAA -> reproduces jet RAA

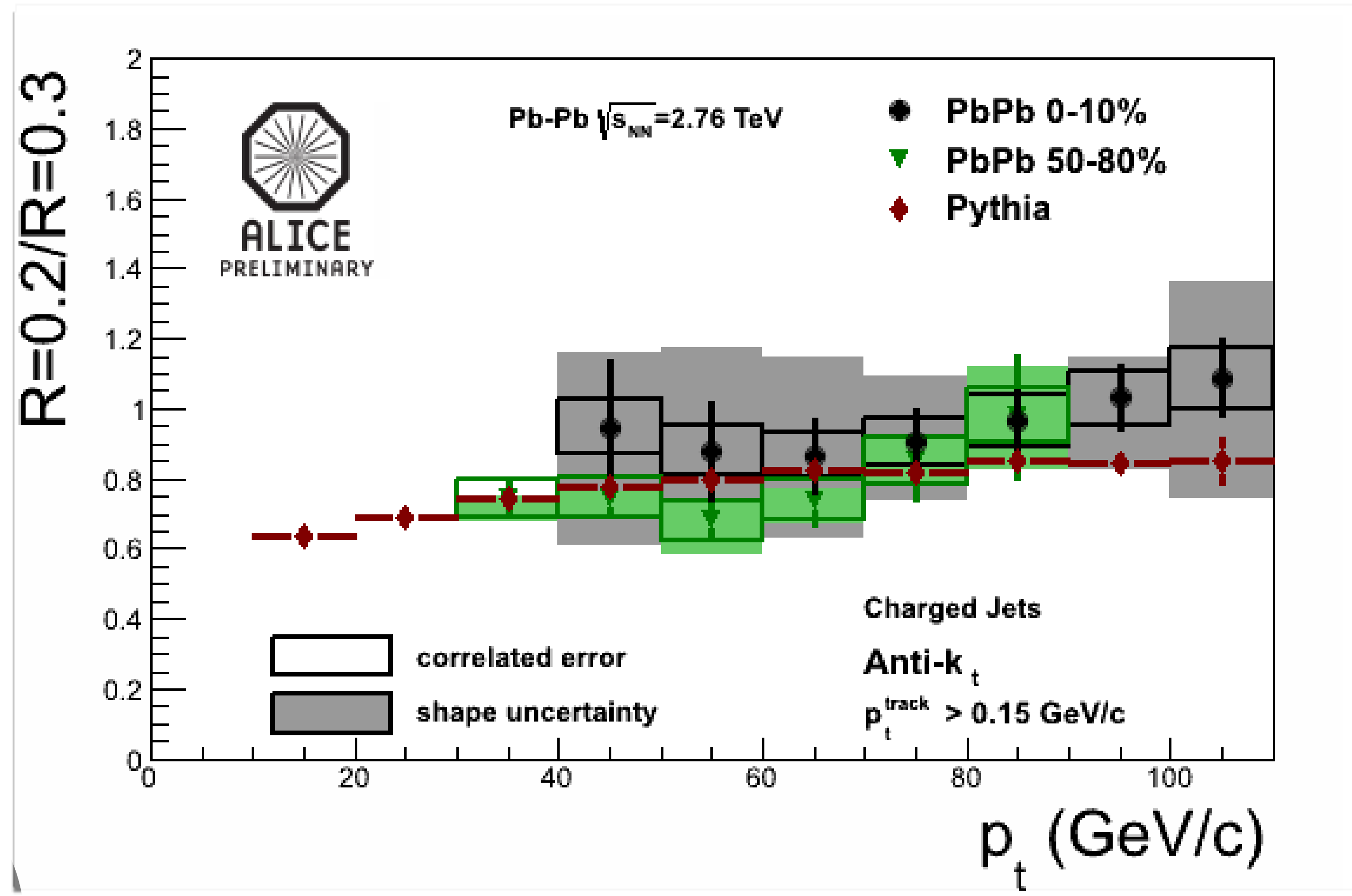
Jet quenching with charged jets - ALICE



Another observable: Ratio of x-sections:
R1/R2 where R1<R2

Proton-proton @ 2.76 TeV

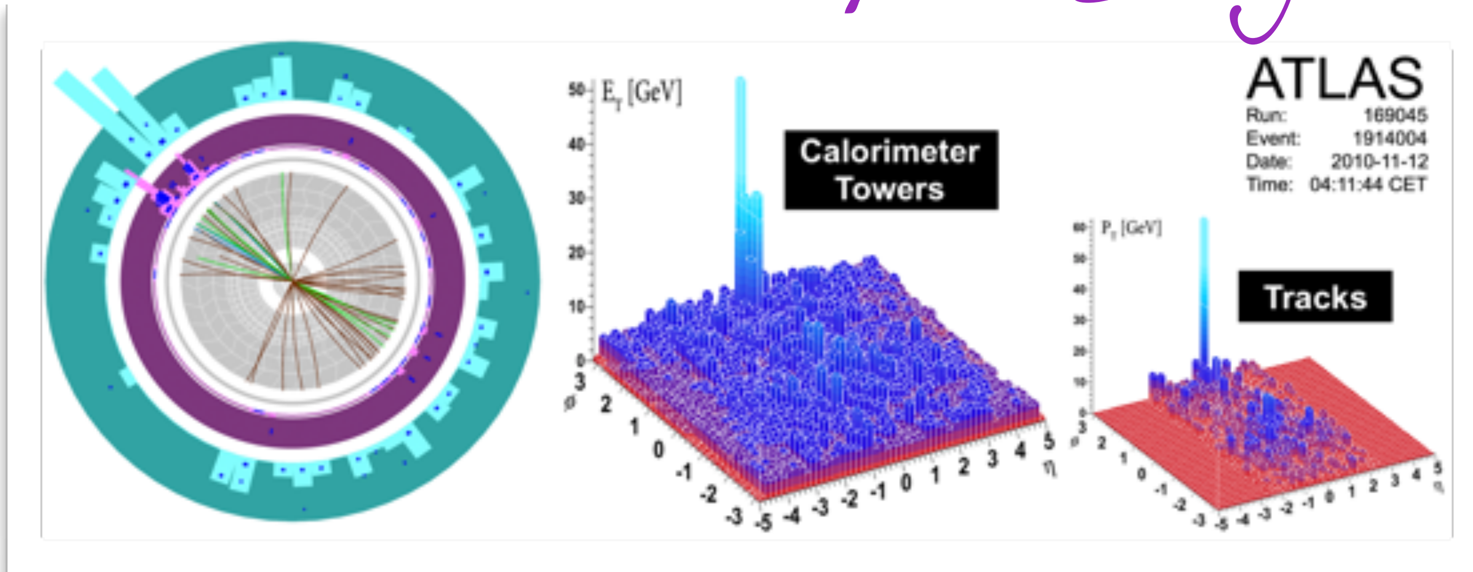




NOTE: Systematically different measurement - same effect found!

Ratio R=0.2/R=0.3 consistent with vacuum jets for peripheral and central collisions

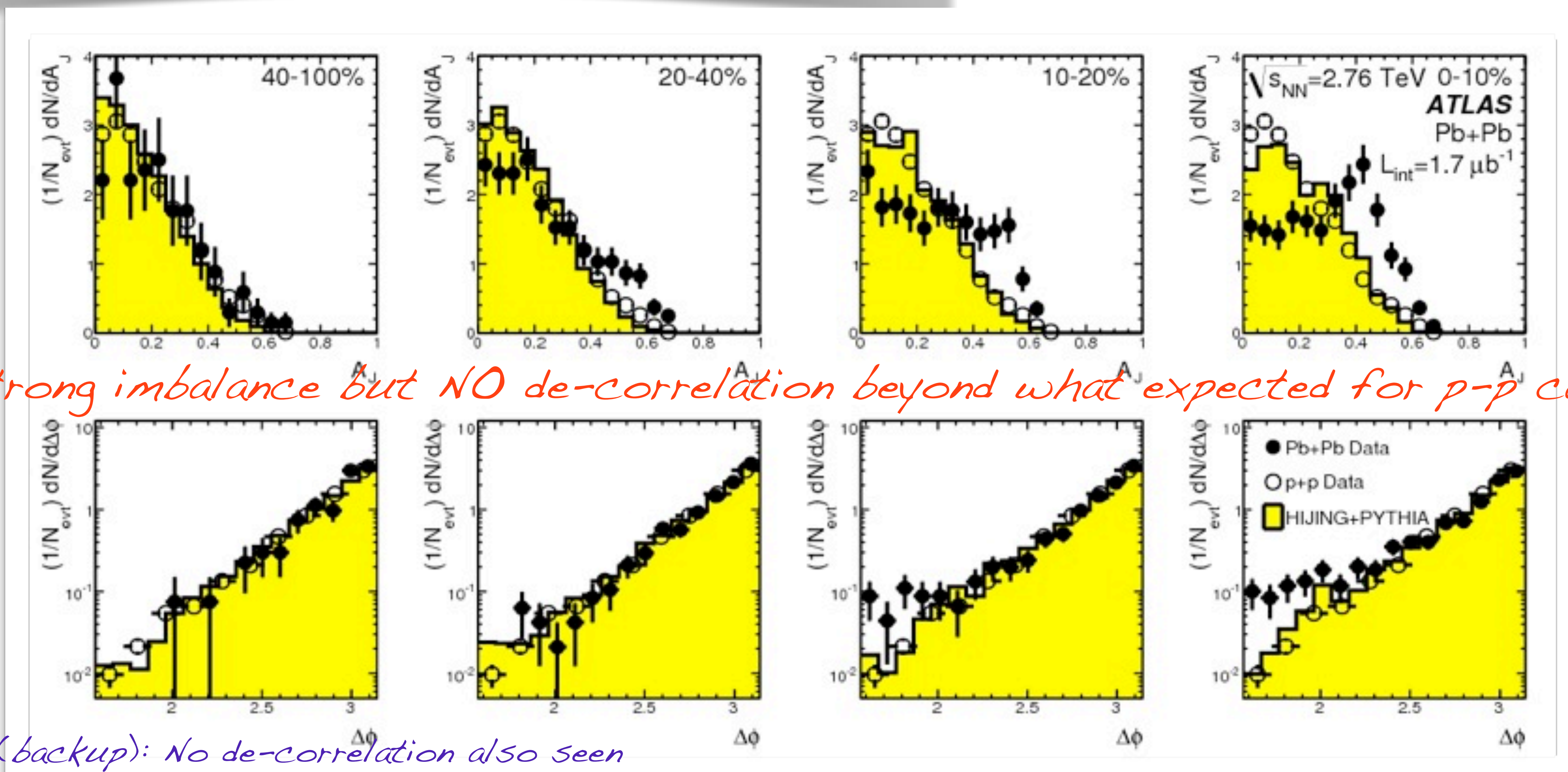
LHC: Di-jet asymmetry



$$A_J \equiv \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

Warning: Aj is sensitive to background fluctuations!

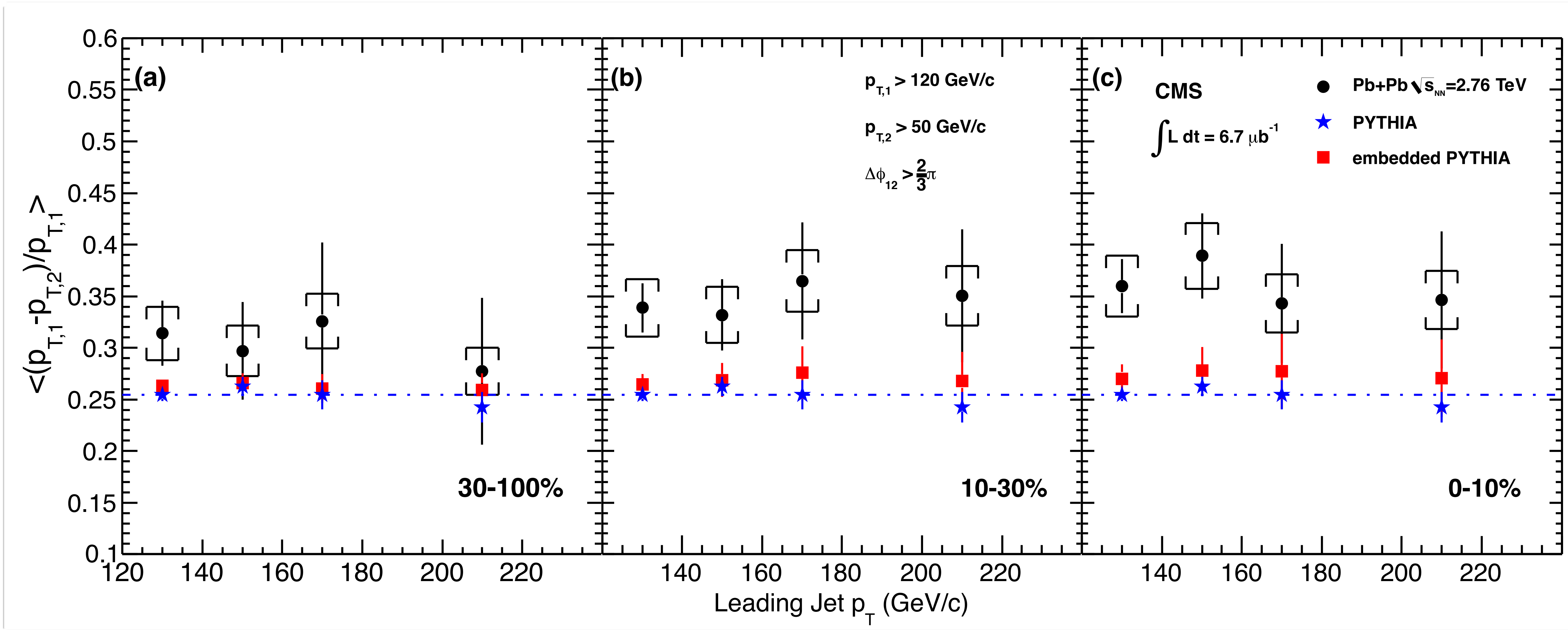
Need proper treatment in the data.



Strong imbalance but NO de-correlation beyond what expected for p-p case(!)

Note (backup): No de-correlation also seen at RHIC: PHENIX in Cu+Cu; also remember the 2-hadron correlations...

CMS - quantifying the di-jet asymmetry



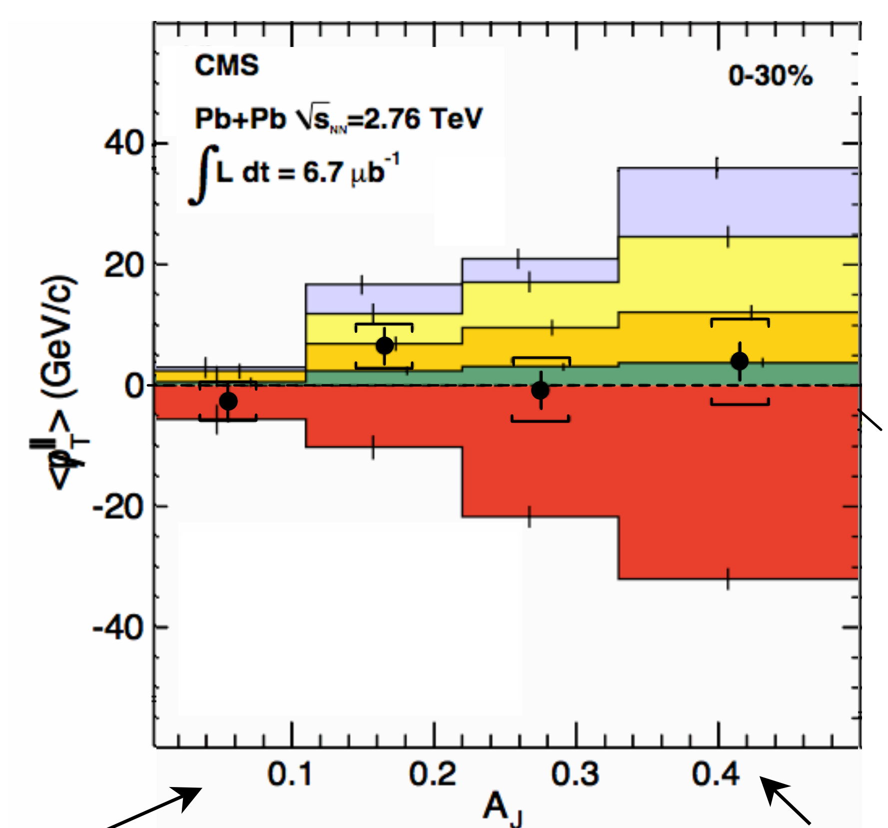
The fractional imbalance:

- grows with collision centrality and reaches a much larger value than in PYTHIA or PYTHIA+DATA
- clearly visible even for the highest-p_T jets observed in the data set
- the $p_{T,1}$ dependence of the excess imbalance is compatible with either a constant difference or a constant fraction of $p_{T,1}$.

di-jet asymmetry: where does the energy go?

Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

0-30% Central PbPb



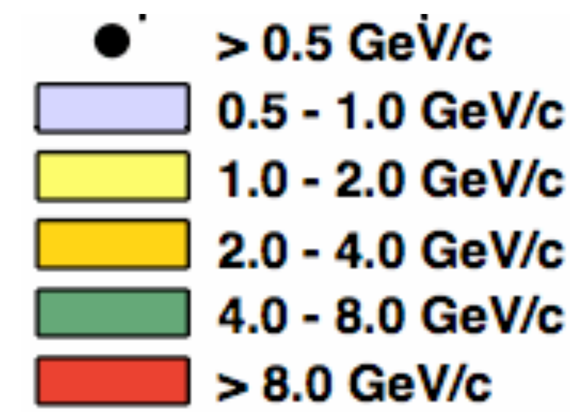
balanced jets

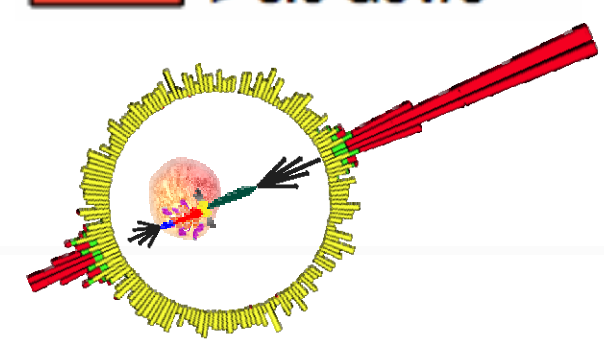
unbalanced jets

excess away from leading jet

excess towards leading jet

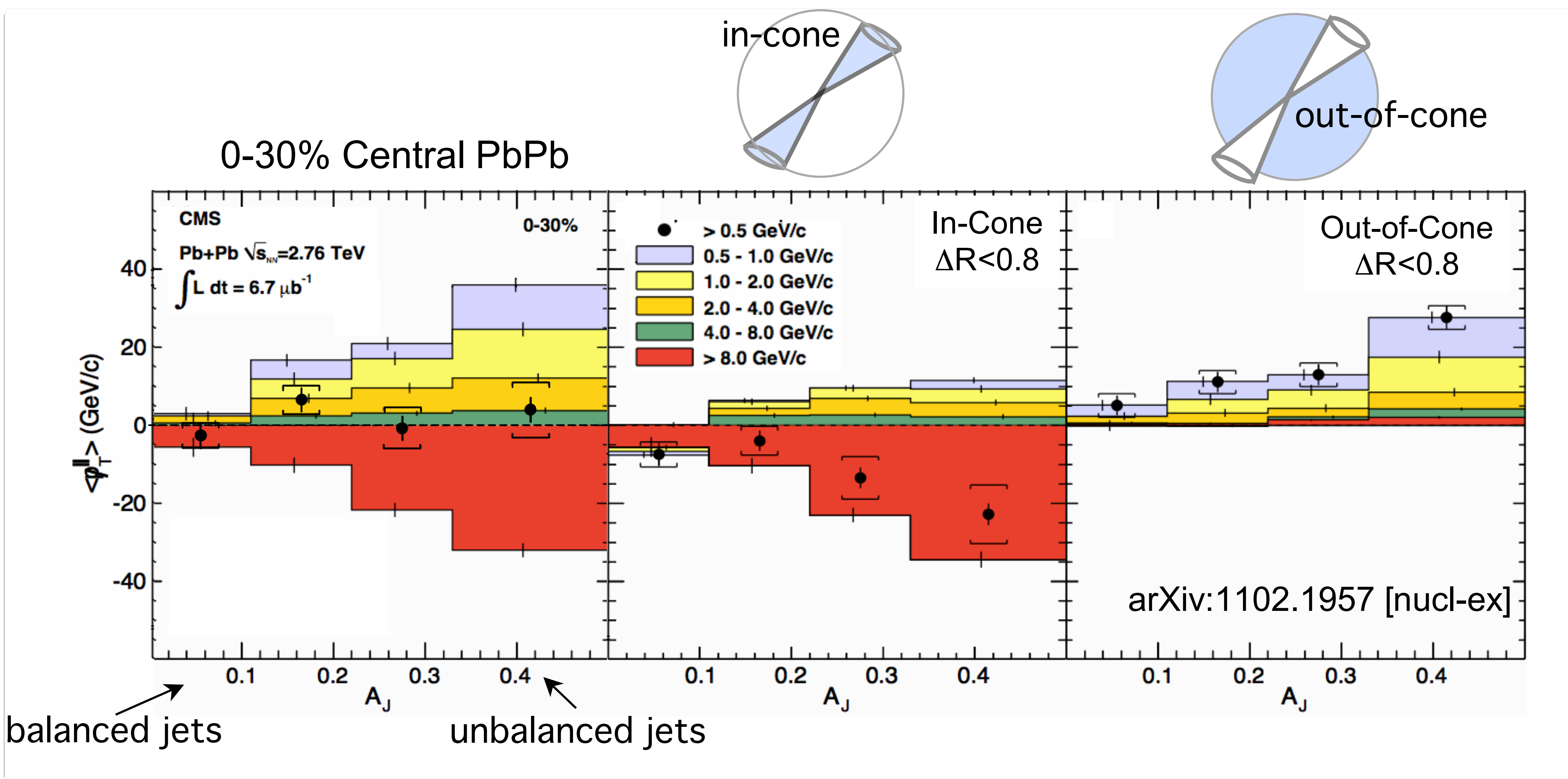
Calculate missing p_T in ranges of track p_T:



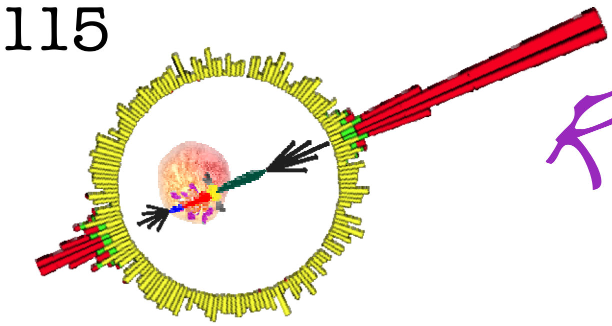


The momentum difference balanced by low-pT particles

di-jet asymmetry: where does the energy go?

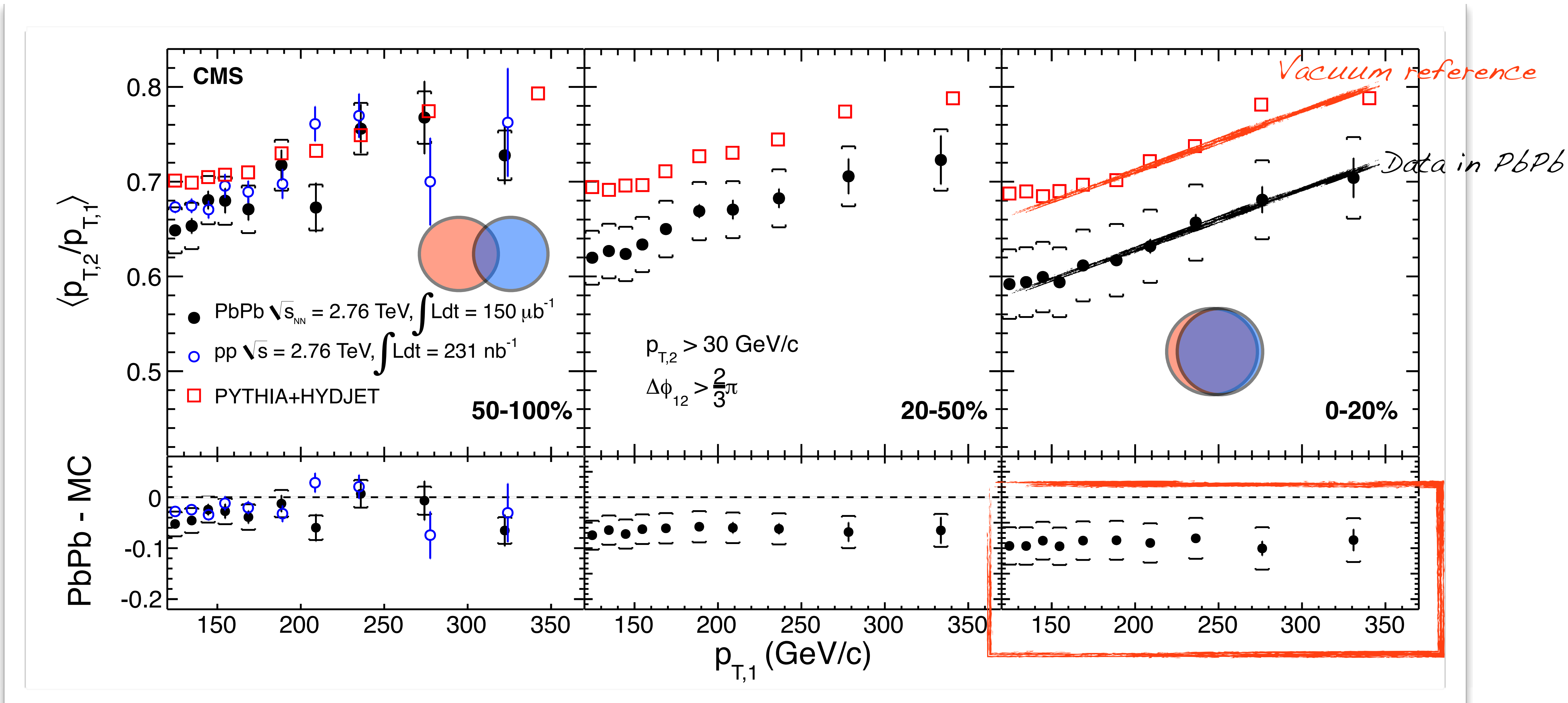


The low-pT particles "balancing" the lost energy appear at large angles wrt recoil jet



$p_{T,2} > 30$ GeV/c

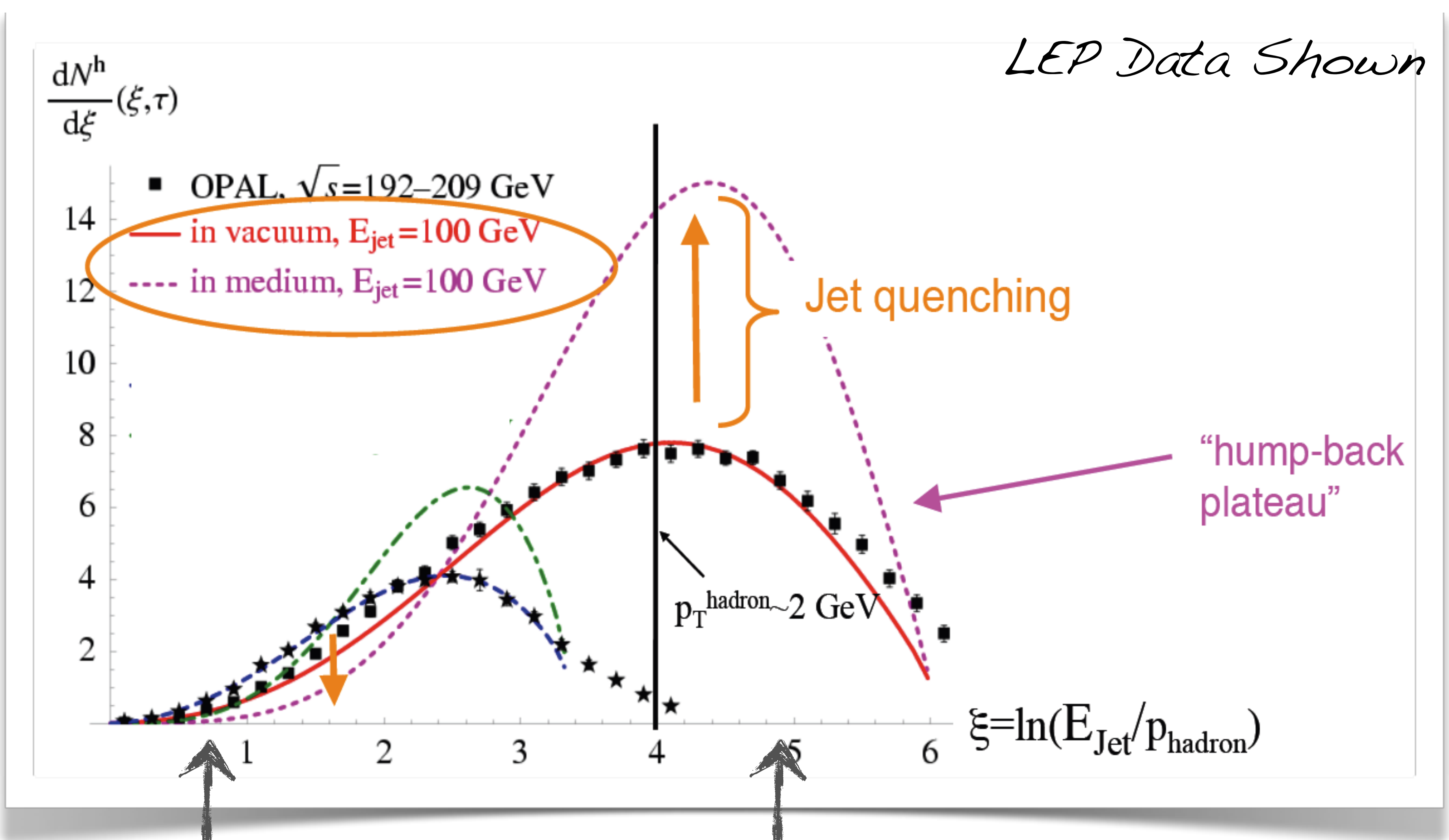
Recoil jet (2) energy-loss as a function of trigger jet (1) p_T

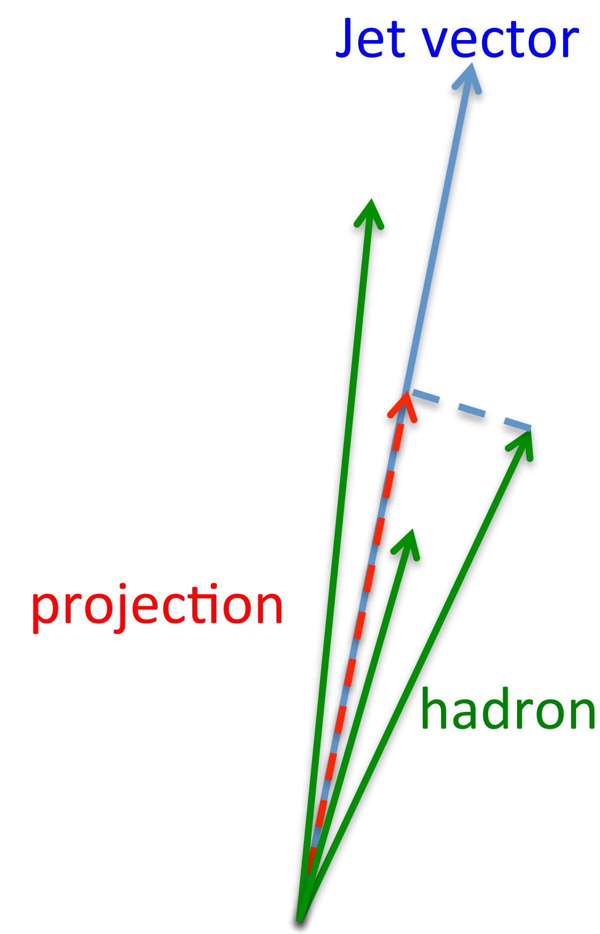


Ratio follows the PYTHIA+HYDJET reference with the same rate - constant offset over 200 GeV in p_T

Modified jet fragmentation
– an expectation from jet quenching

$$\xi = ln(E_{jet}/p_{hadron})$$

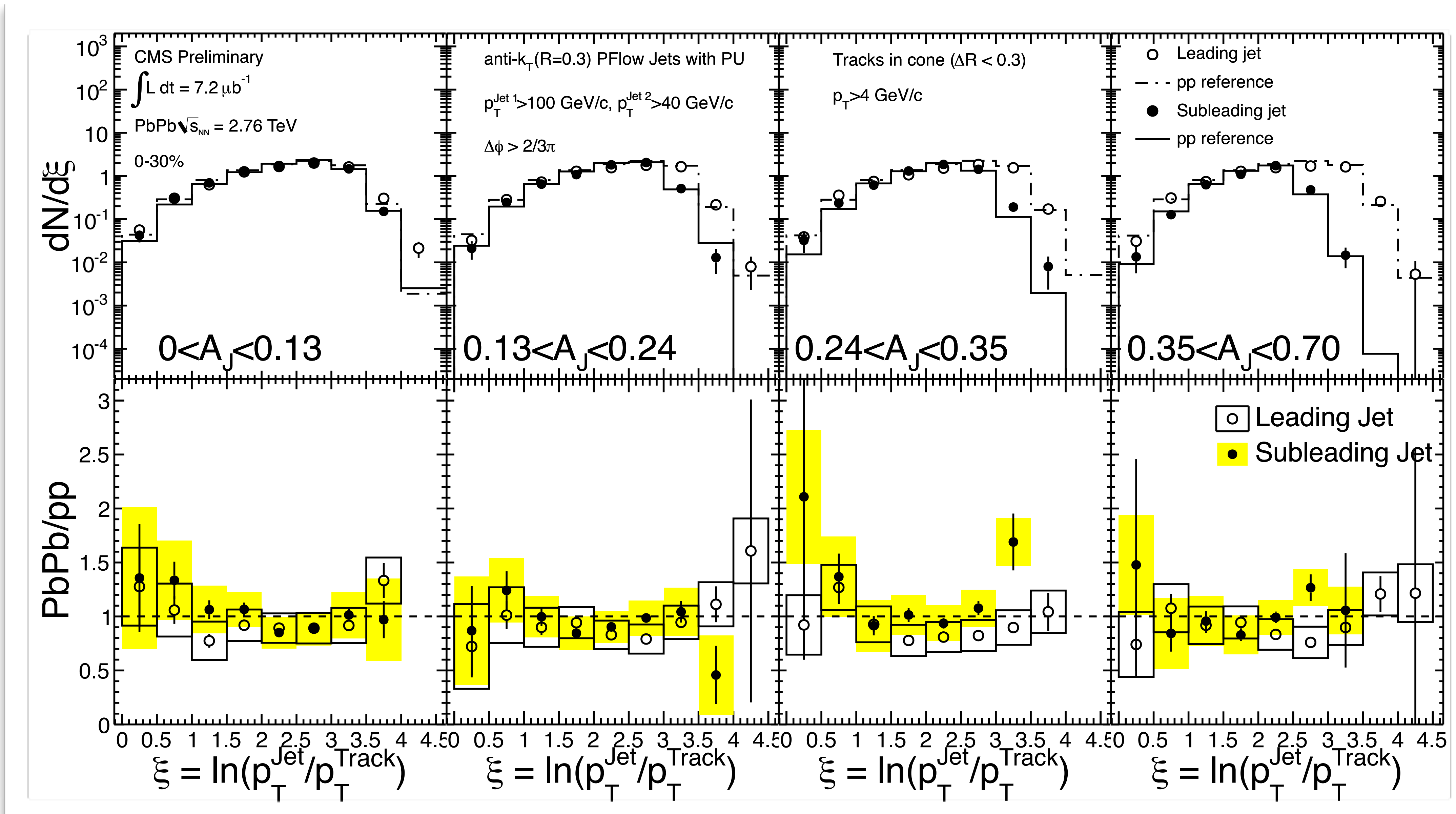




High momentum hadrons

Low momentum hadrons

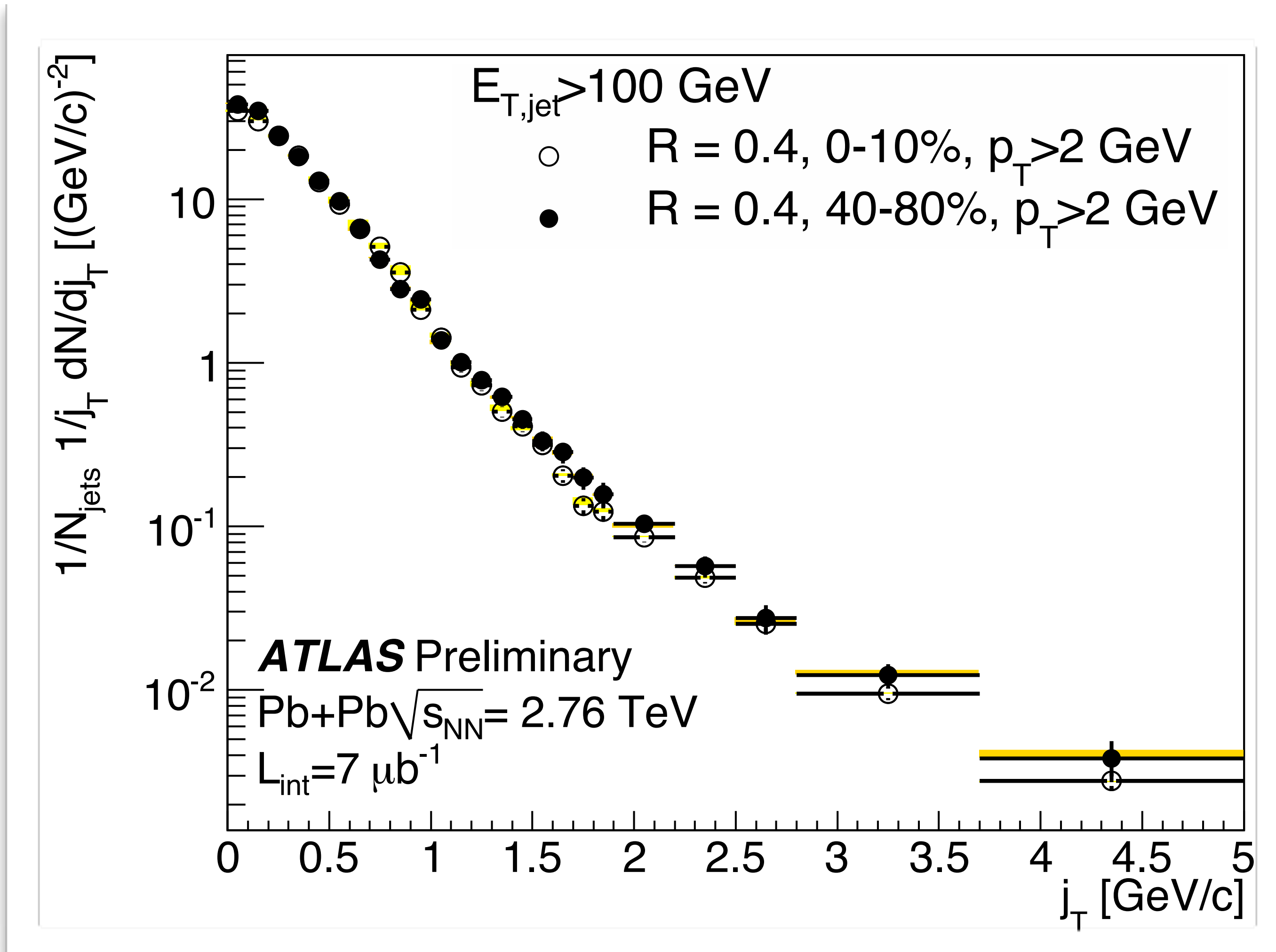
Jet fragmentation in Heavy-ion collisions

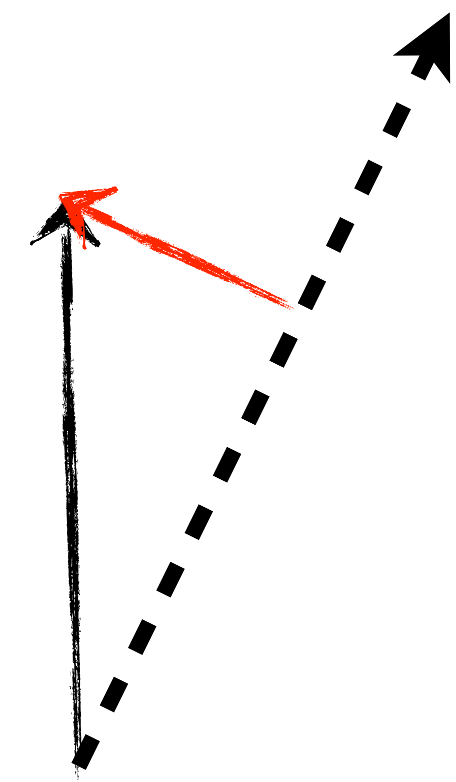


CMS observation: Fragmentation of jets that lost energy consistent with jet fragmentation in proton-proton (vacuum) - similar observations by ATLAS

- a question: is the particle composition of the jet modified?

Transverse jet structure: j_T measurements from Atlas

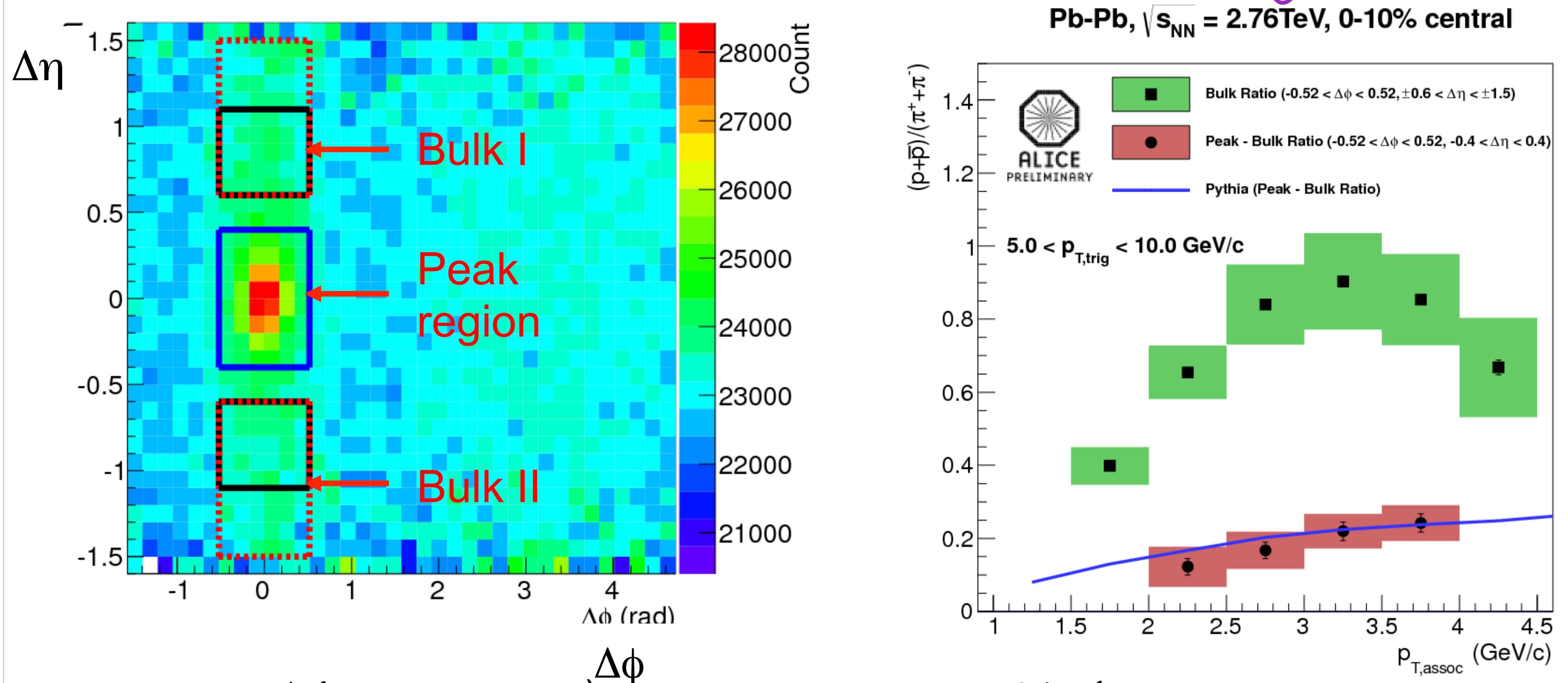




- **Measure distribution of fragment p_T normal to jet axis:** $j_T \equiv p_T^{had} \sin \Delta R = p_T^{had} \sin\left(\sqrt{\Delta\eta^2 + \Delta\phi^2}\right)$
  - **Compare central (0-10%) to peripheral (60-80%)**

    ⇒No substantial broadening observed.

Internal composition of HI jets: proton/pion ratio within a jet



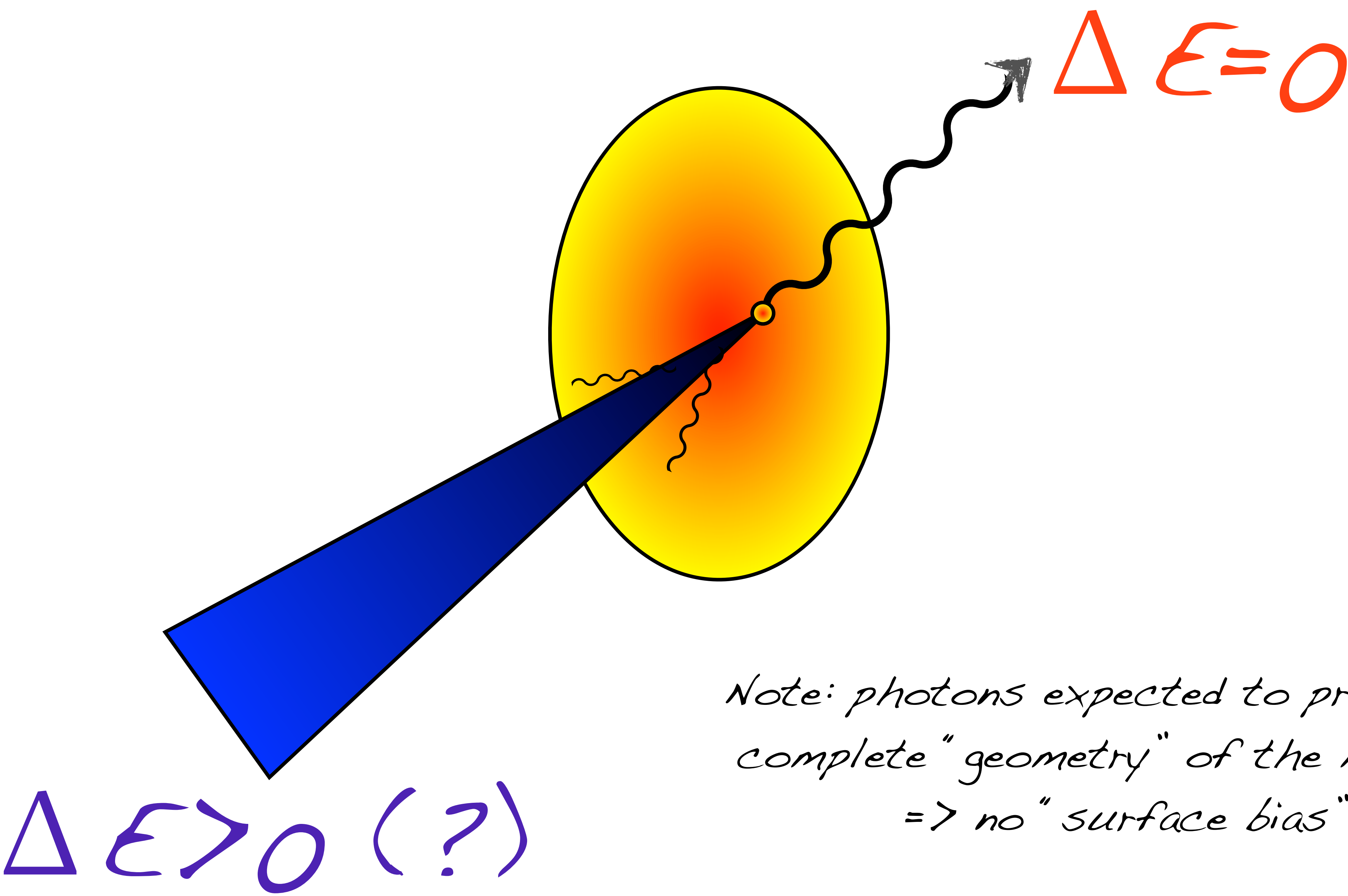
p/π in jet peak (fragmentation) consistent with PYTHIA

- No evidence of medium-induced modification
- Caution: physics evolves rapidly with pT in this region

  p_{Ttrig} :=> fragmentation bias

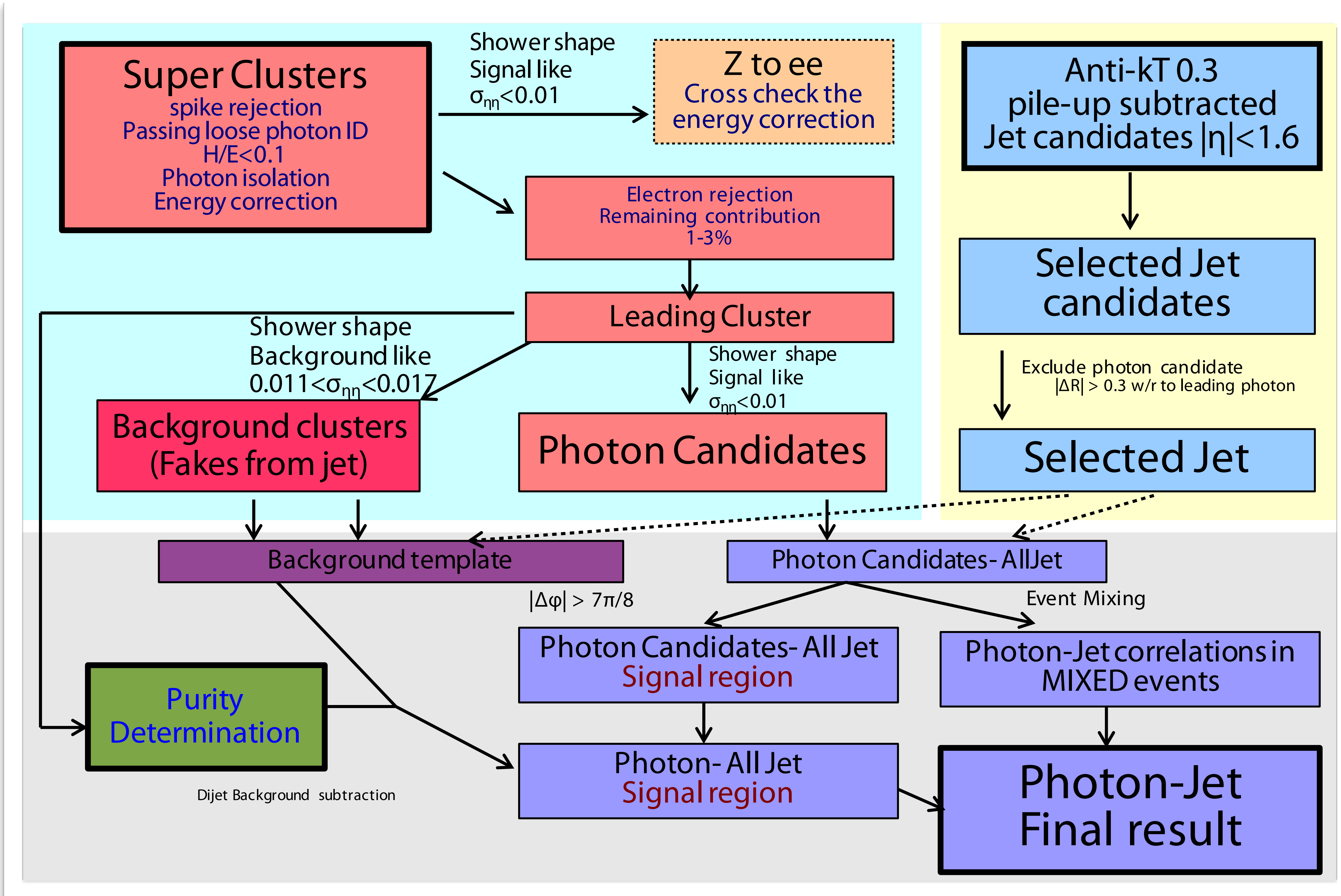
Note: consistent with RAA at high-pT - similar to all species (RHIC&LHC)

Photon-jet



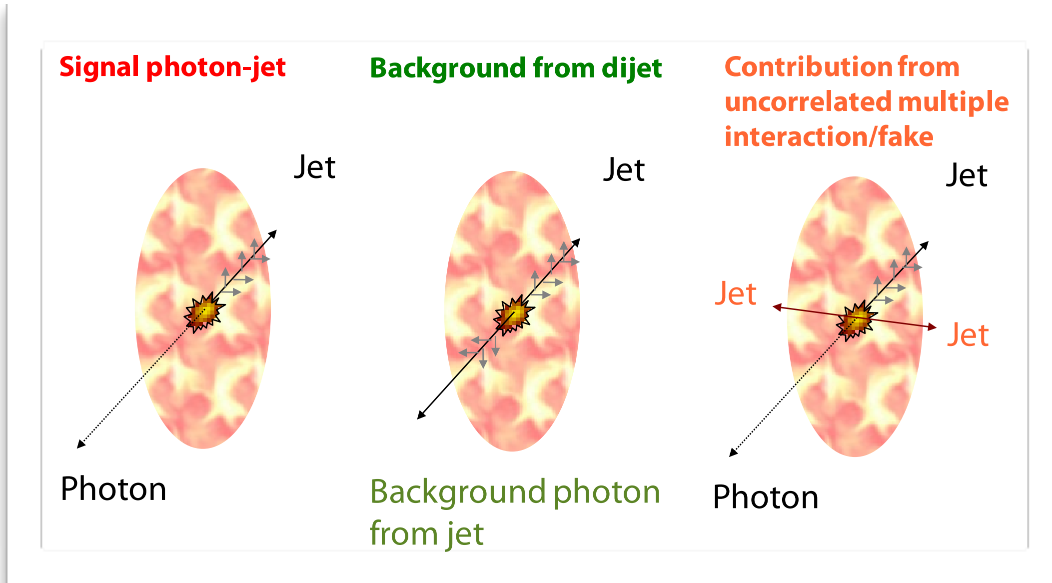
Note: photons expected to probe the complete "geometry" of the medium => no "surface bias"

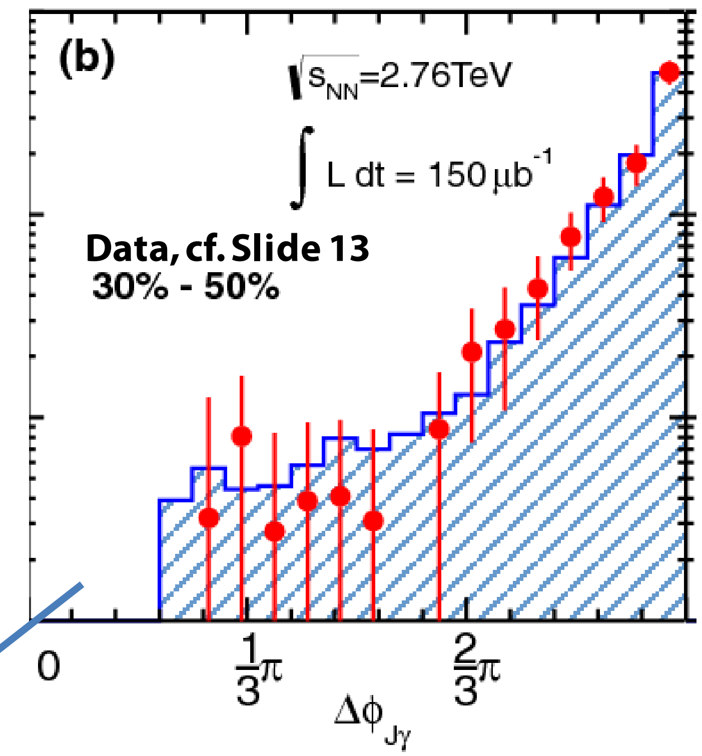
Direct photon(-jet) measurement

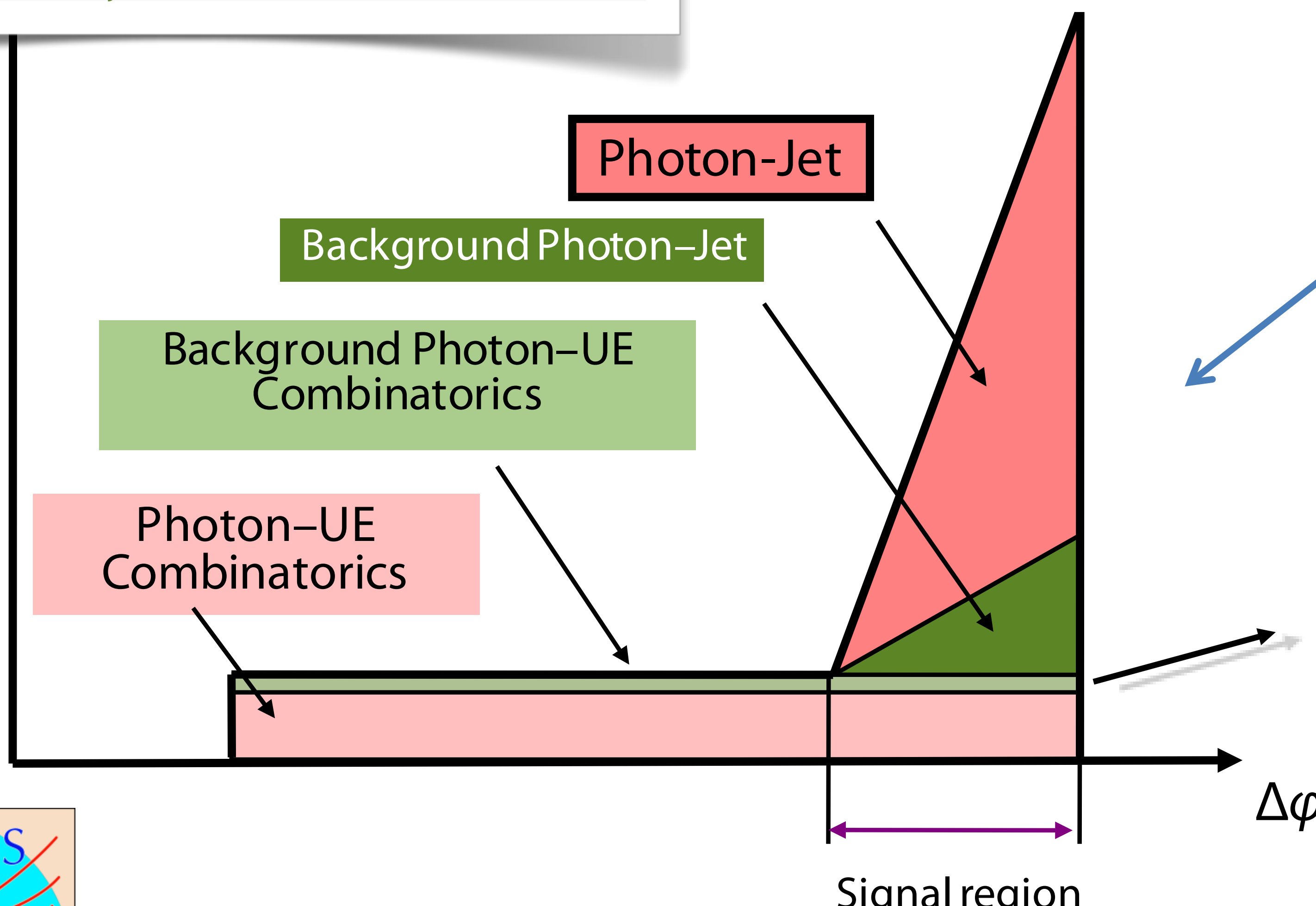


An experimental chart... of the effort(!)

Direct photon(-jet) measurement

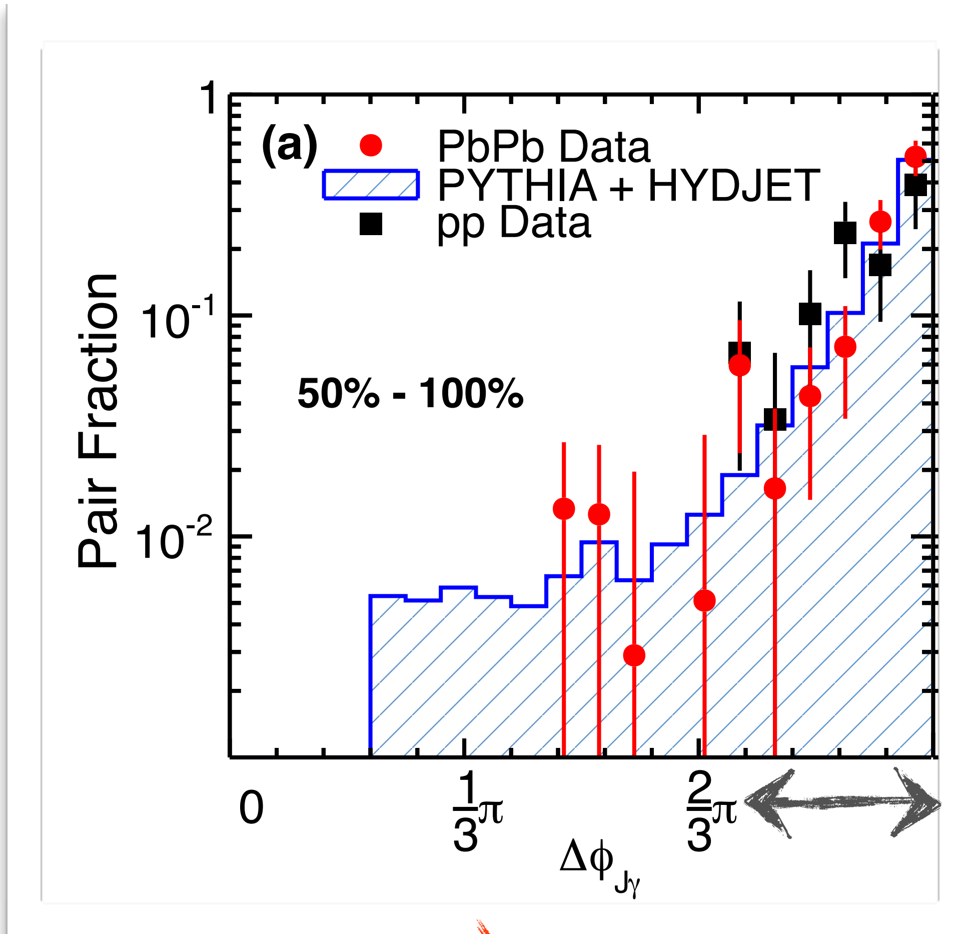


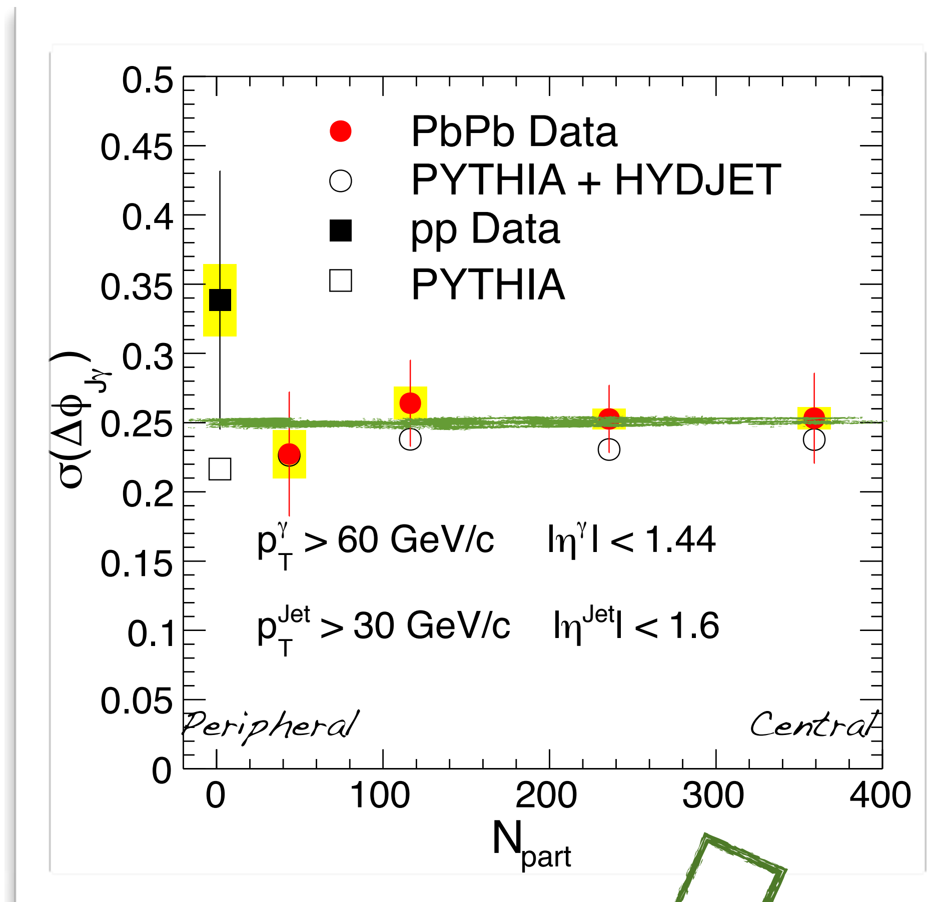




Estimated from event mixing method using minimum-bias data

Result: Photon(ΔE=0)-jet(ΔE>0)





Fit $$\frac{1}{N_{J\gamma}}\frac{dN_{J\gamma}}{d\Delta\phi_{J\gamma}} = \frac{e^{(\Delta\phi-\pi)/\sigma}}{(1-e^{-\pi/\sigma})\,\sigma}$$

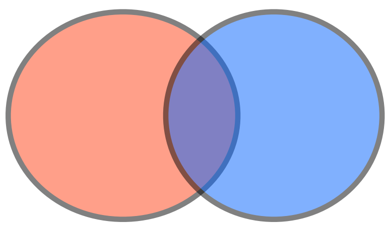
Range: $\Delta\phi > 2\pi/3$

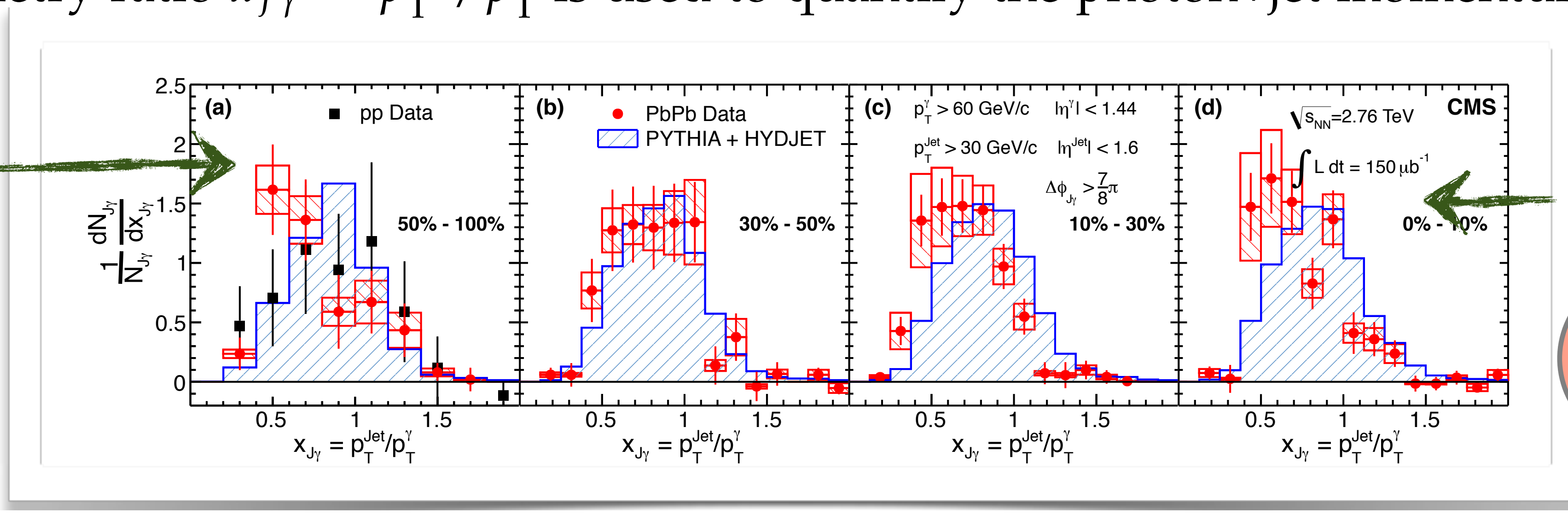
"Width" consistent with vacuum

Photon$_{(\Delta E=0)}$-jet$_{(\Delta E>0)}$

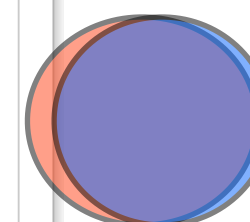
The asymmetry ratio $x_{J\gamma} = p_T^{\text{Jet}} / p_T^{\gamma}$ is used to quantify the photon+jet momentum imbalance.

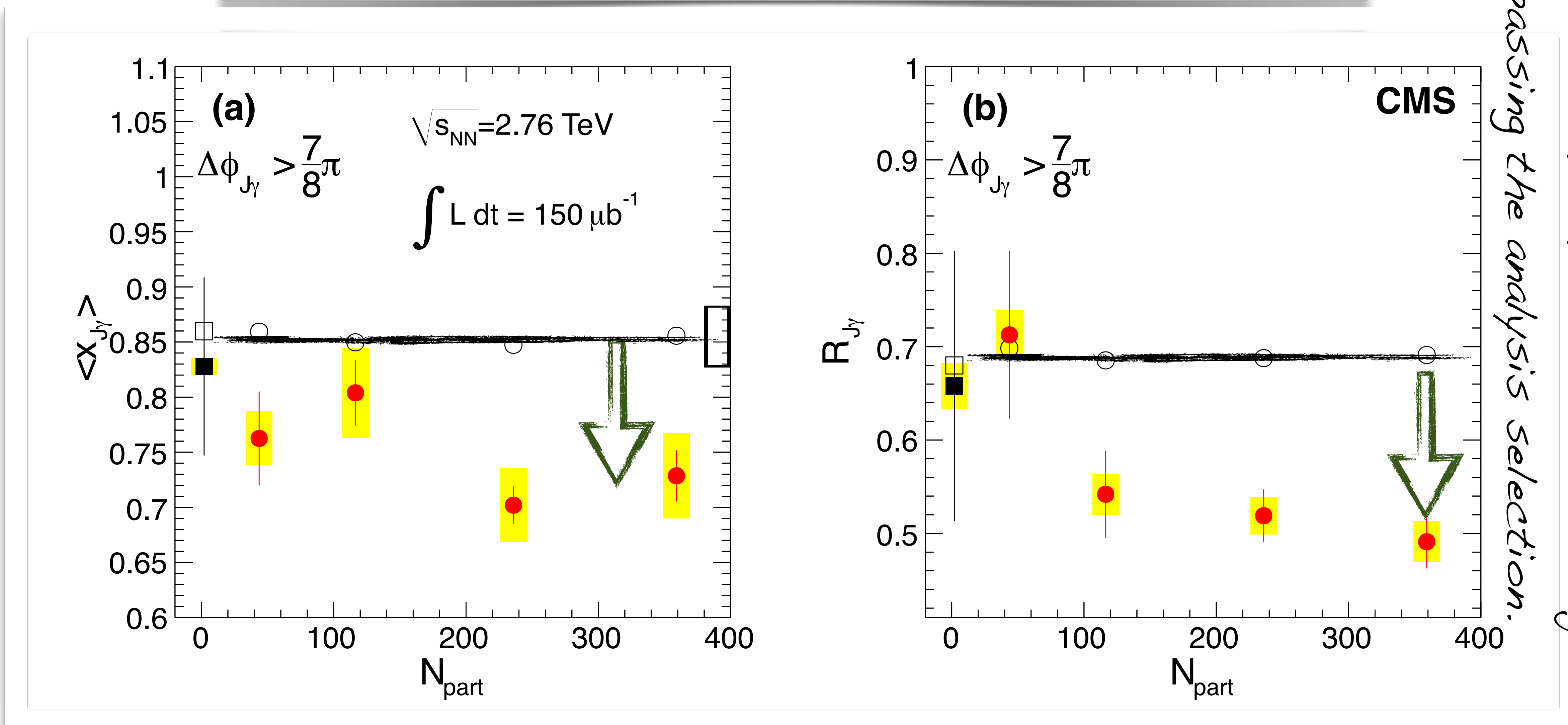
peripheral events





central events

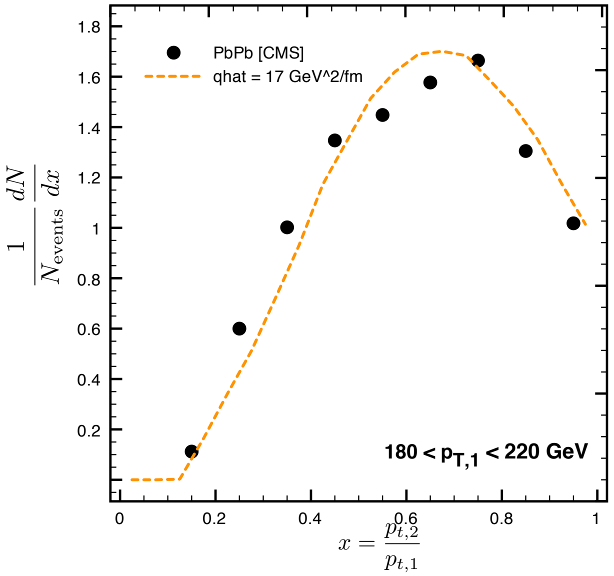


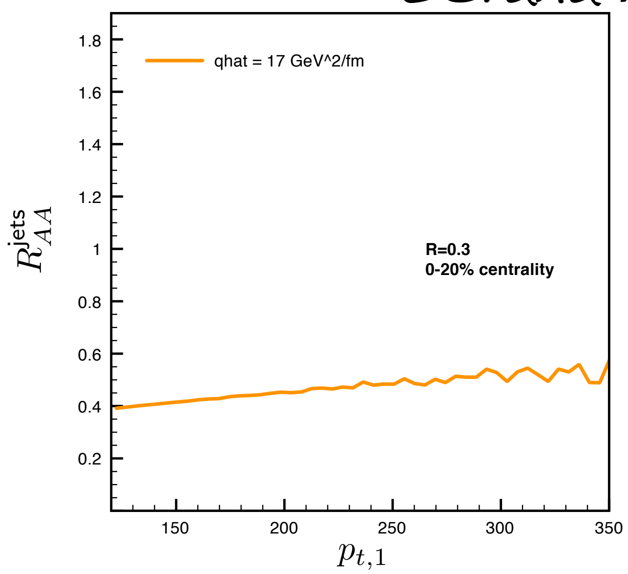


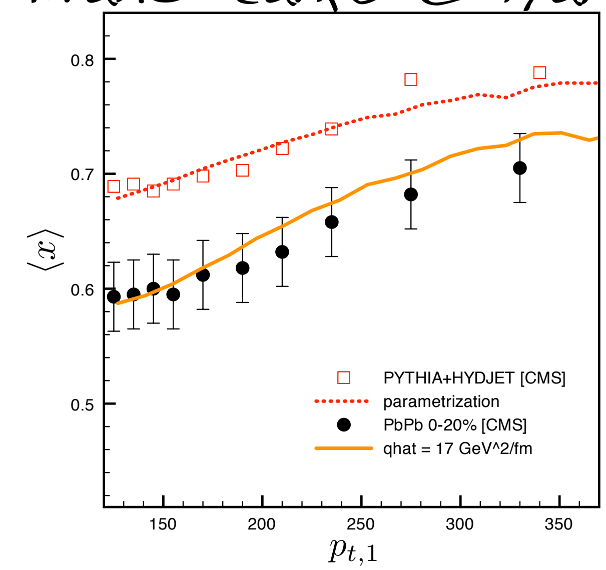
$R_{J\gamma}$ - the fraction of isolated photons that have an associated jet passing the analysis selection.

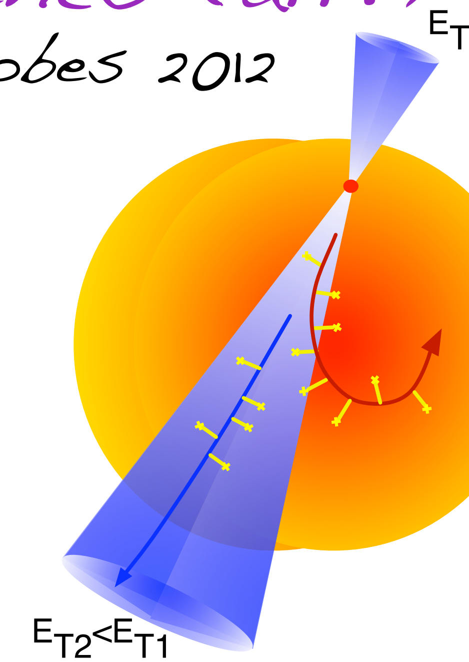
A model describing the first measurements (all!)

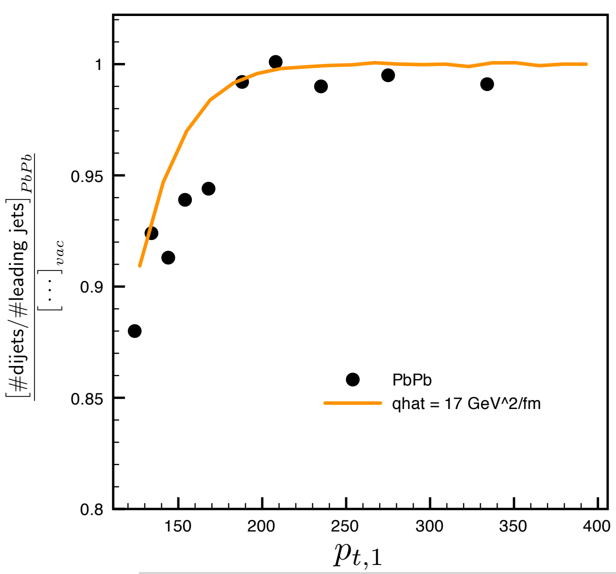
Solana+Milano: talks @ Hard Probes 2012

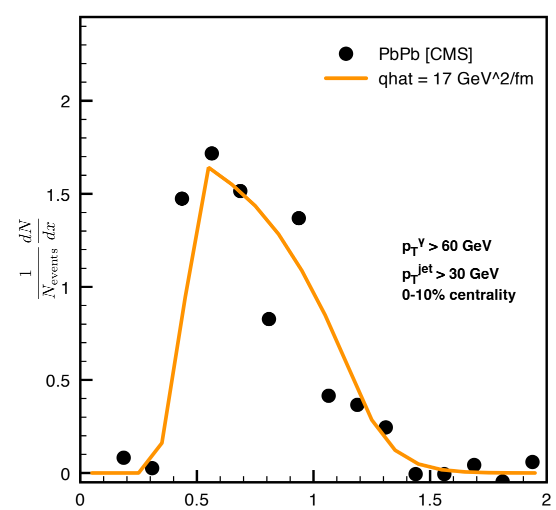






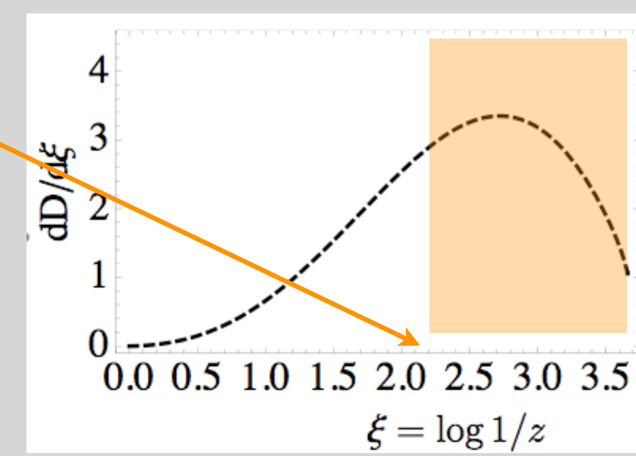


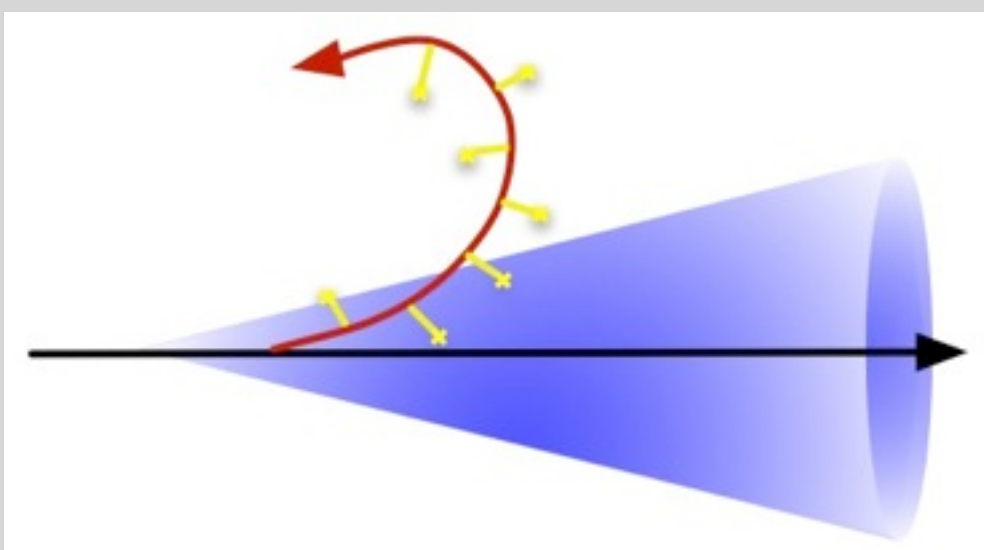




sufficiently soft modes decorrelated [lost] from jet

$\omega \leq \sqrt{\hat{q}L}$





all jet components accumulate transverse momentum

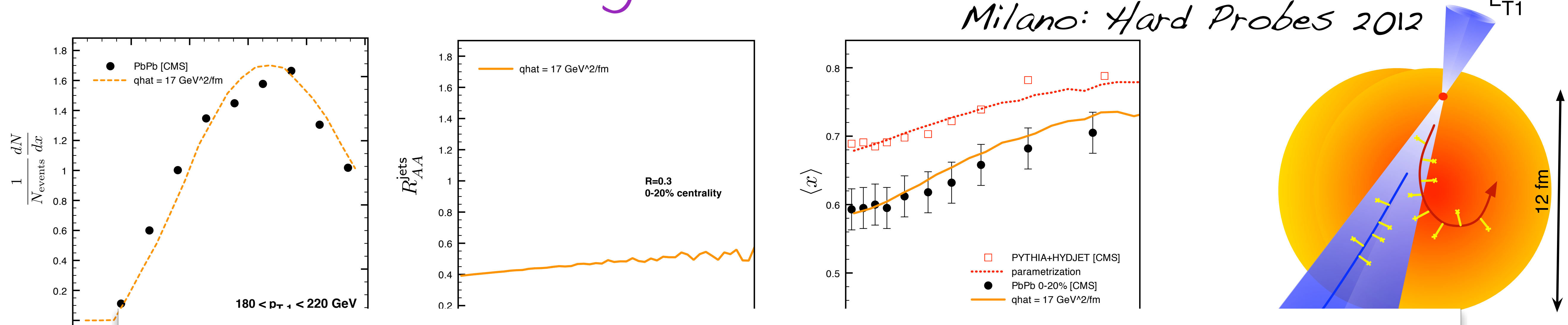
$$\langle k_\perp \rangle \sim \sqrt{\hat{q}L}$$

early availability of soft modes

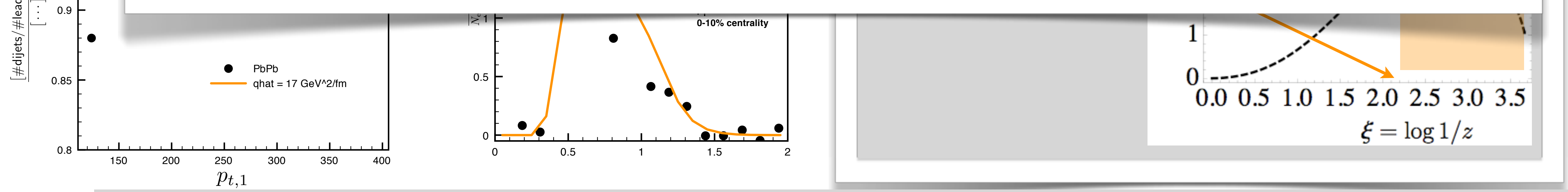
$$\tau \sim \frac{\omega}{k_\perp^2} \xrightarrow[\langle k_\perp^2 \rangle \sim \hat{q}\tau]{} \langle \tau \rangle \sim \sqrt{\frac{\omega}{\hat{q}}}$$

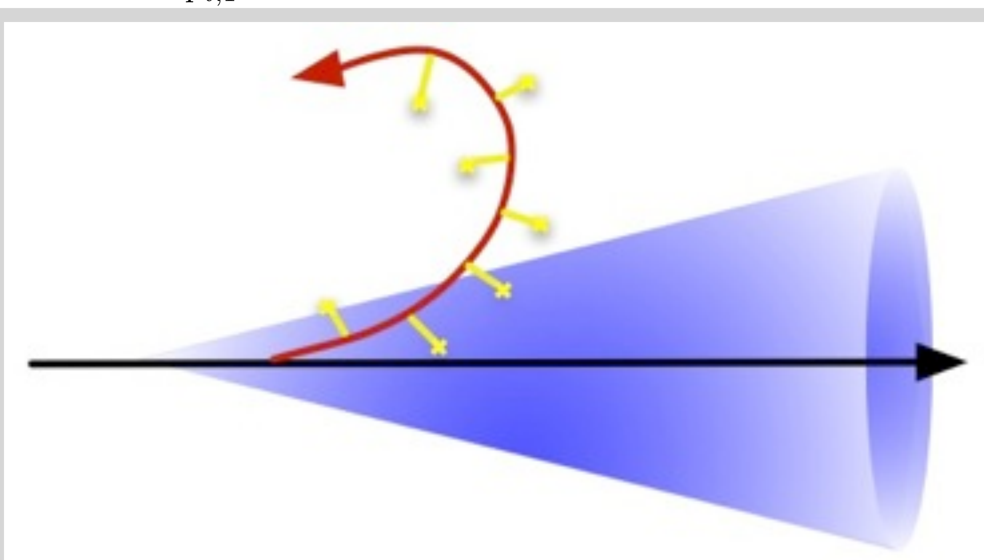
A model describing the first measurements (all!)

Milano: Hard Probes 2012



More in development - this is a representative...
but working extremely well!
...much to learn about jet quenching...





all jet components accumulate transverse momentum

$$\langle k_\perp \rangle \sim \sqrt{\hat{q} L}$$

early availability of soft modes

$$\tau \sim \frac{\omega}{k_\perp^2} \xrightarrow[\langle k_\perp^2 \rangle \sim \hat{q}\tau]{} \langle \tau \rangle \sim \sqrt{\frac{\omega}{\hat{q}}}$$

Summa summarum

- High energy heavy-ion collisions: Hot and dense (opaque to high-energy partons) quark-gluon plasma
- Hadron spectra suppressed (both at RHIC and LHC); Correlations of hadrons (proxies for 2->2 jet process) consistent with jet quenching
- Fully reconstructed jets suppressed (pT dependence of the suppression pattern different than for hadrons) -> constant fractional energy loss (?) -> up to highest jet energies measured (RHIC & LHC)
- The observed jets consistent with unmodified (vacuum?) fragmentation (within the current experimental assessment); The radiated energy "recovered" at large angles wrt jet axis
    - Also: no indication for particle type composition (p/pion etc) modifications of high-pT jets
    - Similar to jet-jet, the photon-jet correlations do NOT show de-correlation beyond p-p case (recoil jet also with unmodified fragmentation)
- Models explaining the phenomena being put forward.

Check the extra slides for more... RHIC jet results and examples of other observables (correlations) from LHC...

Do we understand everything about jet quenching and what fully reconstructed jet observables tell us?
NO! But we learned already a lot... and this is just a good beginning!

Always good to ask: What is next?

- Improved control of the jet reconstruction in HIC - still improvements possible (less biases, other observables) - conceptually different approaches in making...
- New observables? Hadron-jet etc; Rates for 2+1+1 events? Structure of the jet with improved low-pT resolution? (sub-jets ?)
- Correlation of jets with the "soft" background and other observables? (low/intermediate-pT hadron correlations - take a look at the extra slides...)
- Heavy-flavor jets? and their correlations?
- Energy-evolution of jet quenching - more to learn? Higher energy (LHC)... RHIC still working on jets! Various collision systems...

Look at the extra slides!

...worth to look forward to...

Your ideas can make a difference!

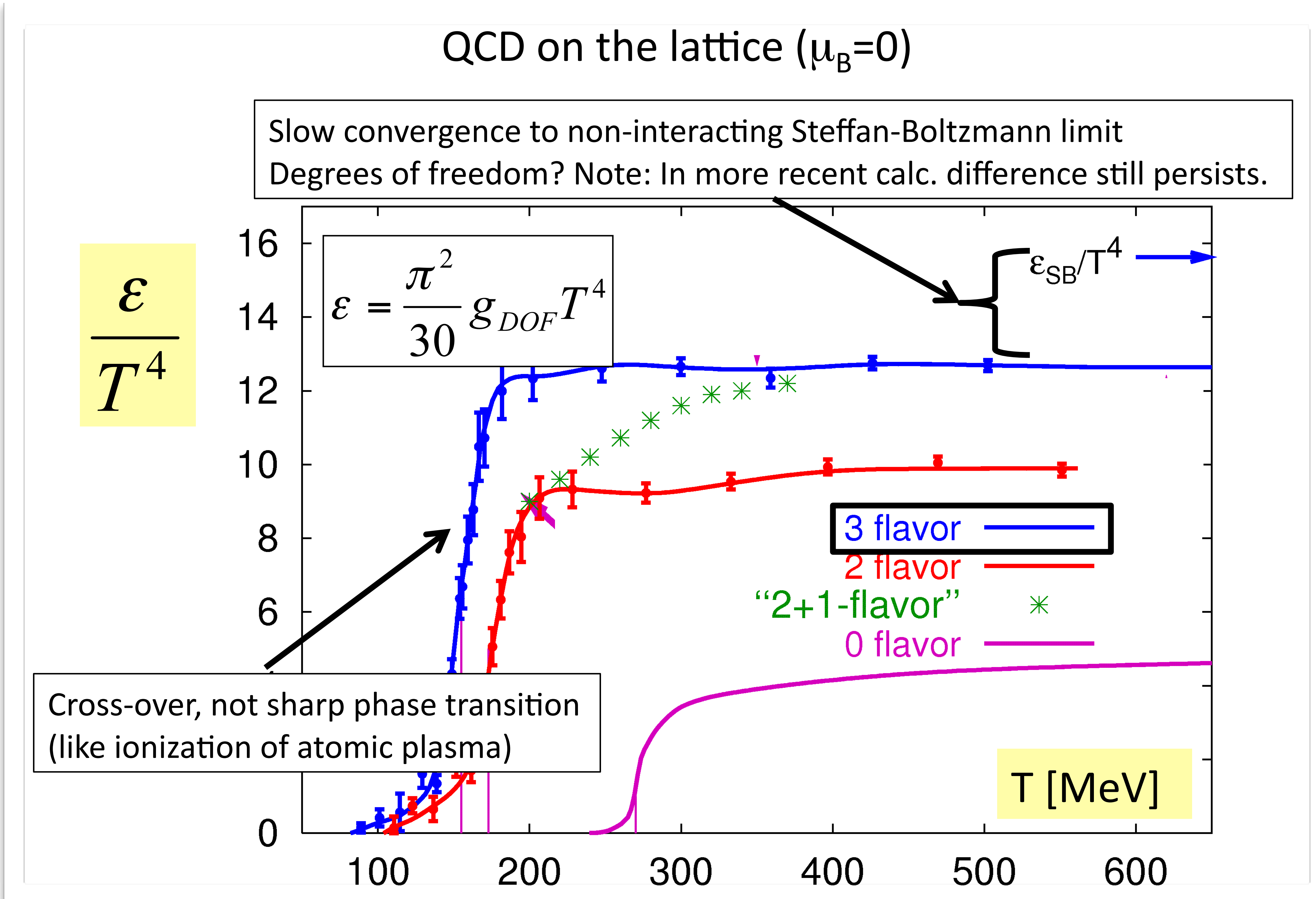
References (and refs therein!)

- Jet reconstruction (p-p and HIC), algorithms etc - FastJet : http://fastjet.fr/about.html
- PHENIX results: http://www.phenix.bnl.gov/results.html
- STAR results: http://drupal.star.bnl.gov/STAR/publications
- ALICE results: http://aliceinfo.cern.ch/ArtSubmission/publications
- ATLAS HI results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
- CMS HI results: http://cms.web.cern.ch/org/cms-papers-and-results
- Overview of first LHC results: Mueller, Wysloluch, Schuckraft: http://arxiv.org/abs/1202.3233
- Hard Probes 2012 conference:
  - http://agenda.infn.it/conferenceOtherViews.py?view=standard&confId=4157

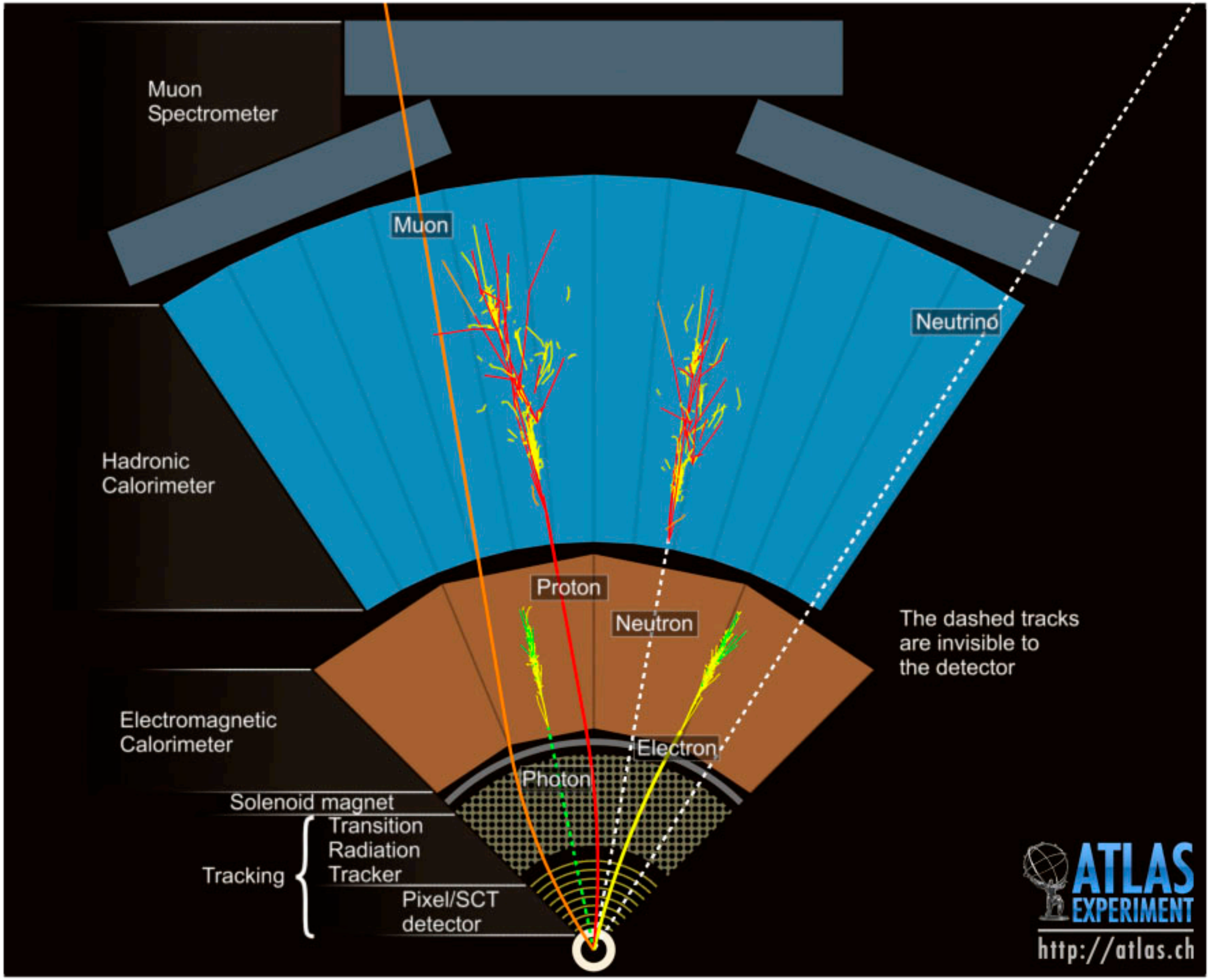
Extra slides

- Did not fit for time reasons but also relevant(!)... make sure you go through these as well.

QCD Thermodynamics - calculation

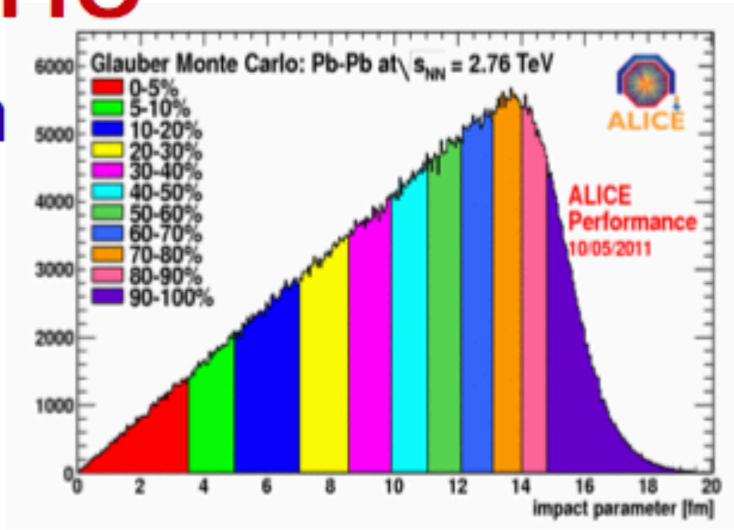


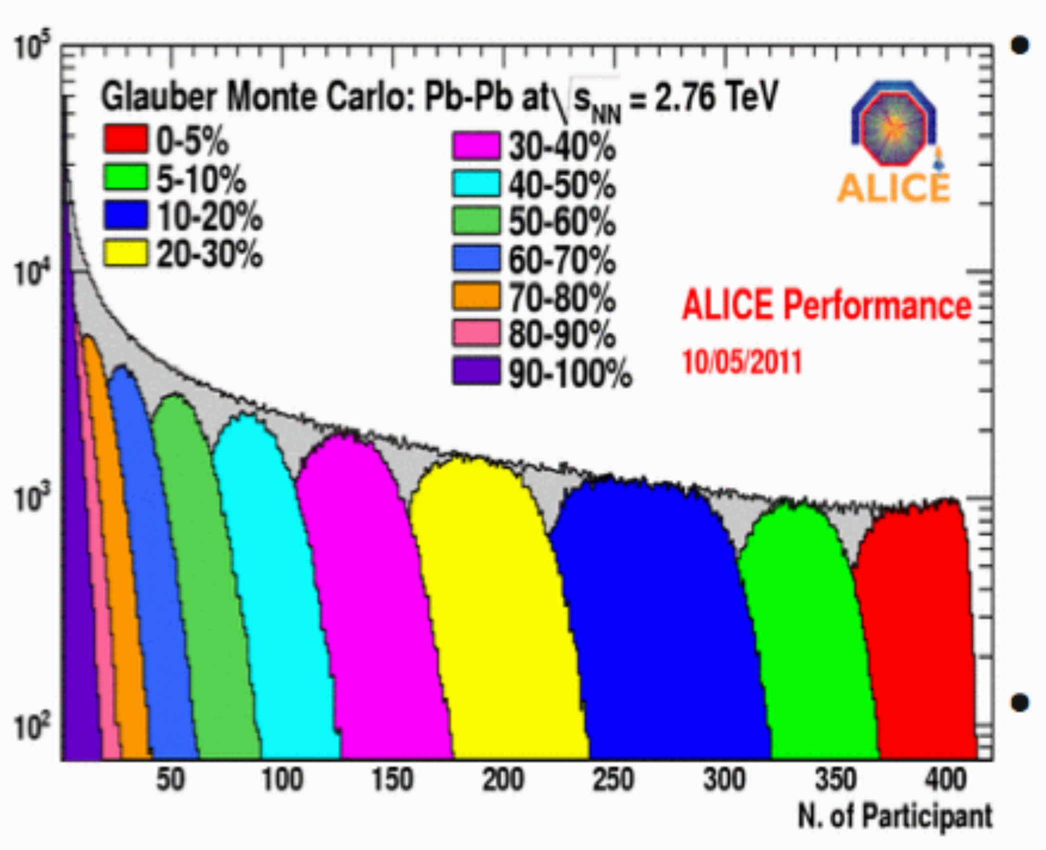
Particle detection



Glauber Monte Carlo

- Glauber model: geometrical picture of AA collision
  - Straight−line nucleon trajectories
  - N-N cross−section independent of the number of collisions the nucleons have undergone before



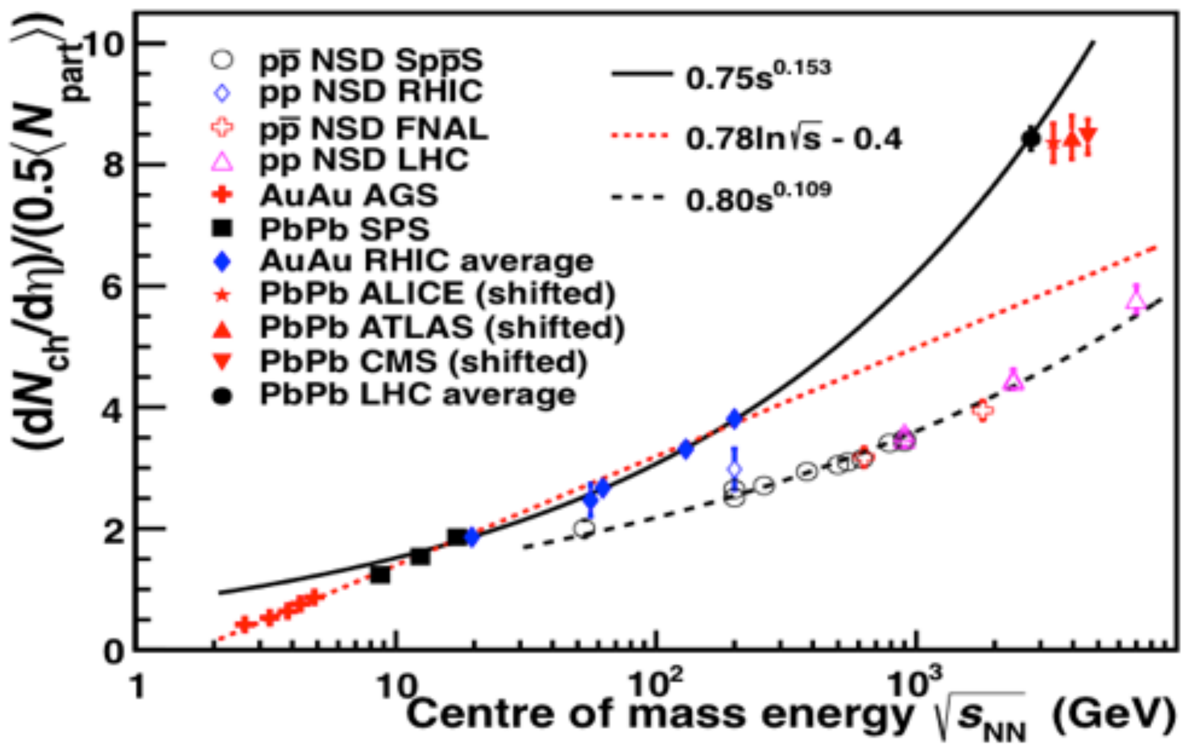


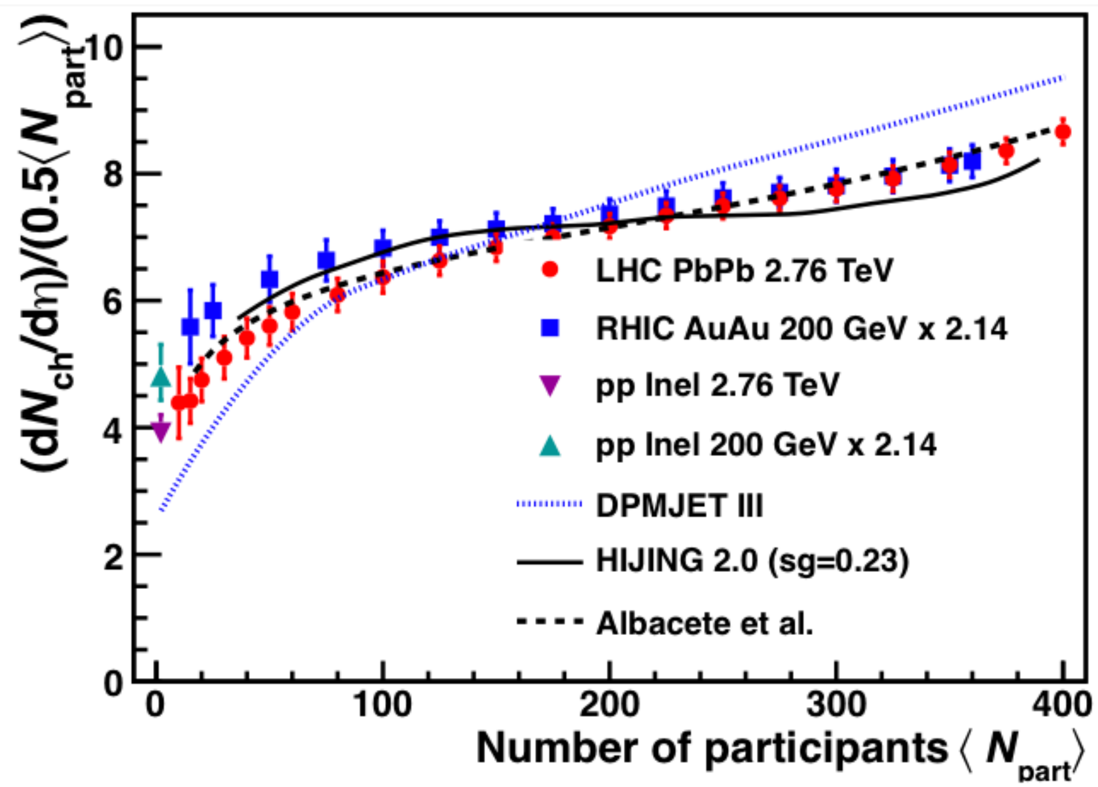
- Nuclear density profile: Woods−Saxon (2pF)

$$\rho(r) = \rho_o \cdot \frac{1}{1 + \exp\left(\frac{r-R}{d}\right)}$$

  - Radius=6.62±0.06fm
  - skin depth=0.546±0.01fm
  - Intra-nucleon distance=0.4±0.4fm
- Nucleon-Nucleon inelastic cross section σ_{NN}=64±5 mb at 2.76 TeV
- Estimate uncertainty by varying model assumptions

Particle multiplicity & centrality





dN/dη scales faster than pp

- Trend predicted by some saturation model
- Excellent agreement with LHC experiments
- Energy density × τ_0 ≈ 3 × RHIC

$$\varepsilon \geq \frac{dE_T/d\eta}{\tau_0\,\pi R^2} = \frac{3}{2}\langle E_T/N\rangle \frac{dN_{ch}/d\eta}{\tau_0\,\pi R^2}$$

Scaling similar to RHIC:

- Contribution of hard processes (N_{coll} scaling)?

Classes of models

- Saturation
- 2 components (hard/soft)

➔models incorporating moderation of multiplicity (shadowing/saturation) favoured

- More on two-particle correlations

Sensitivity of particle correlations to different underlying physics

Two-particle correlations

- conditional [per-trigger] yields

$$\frac{1}{N_{trig}}\frac{dN_{assoc}}{d\Delta\varphi} \quad \text{and} \quad \frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\varphi d\Delta\eta}$$

At Low-p_T :

Ridge

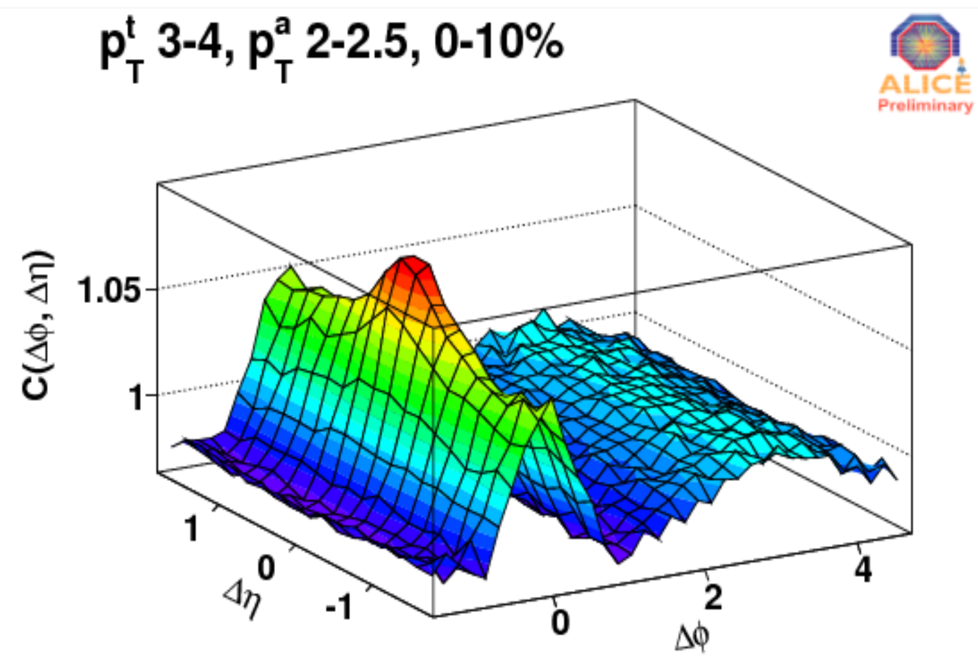
Hydrodynamics, flow

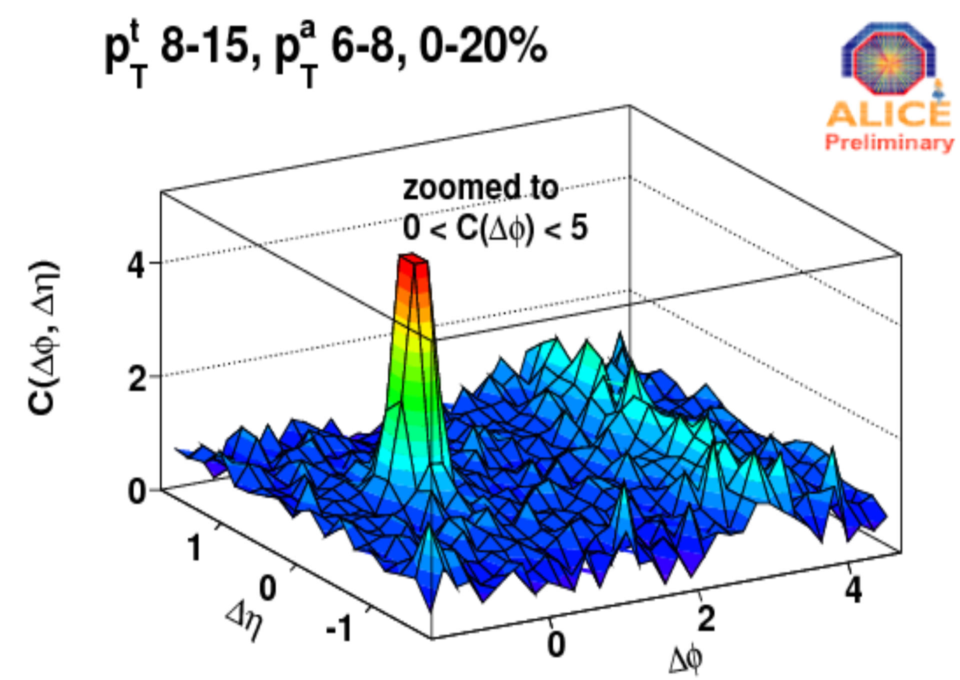
At High-p_T :

Quenching/suppression, broadening

I_{CP}: Yields in central v.s. peripheral collisions

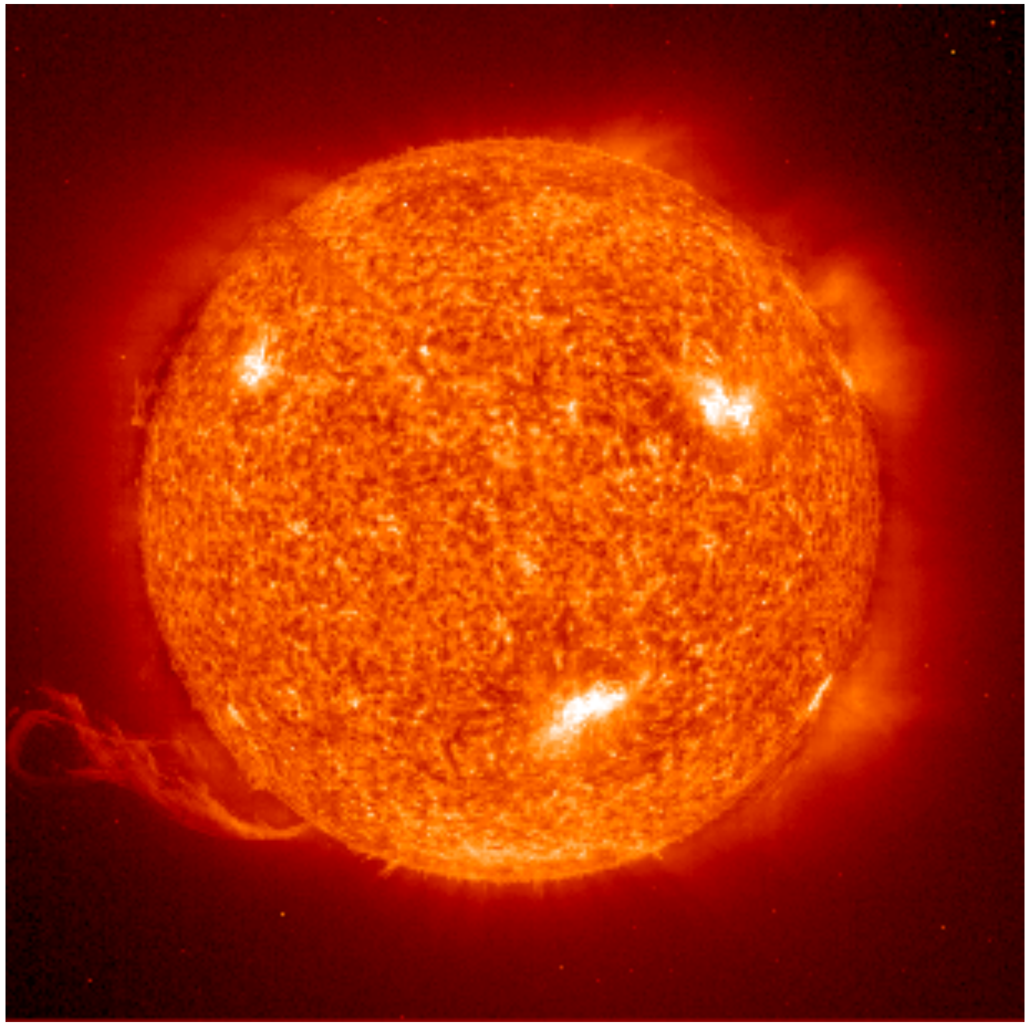
I_{AA}: Yields in A-A compared to p-p

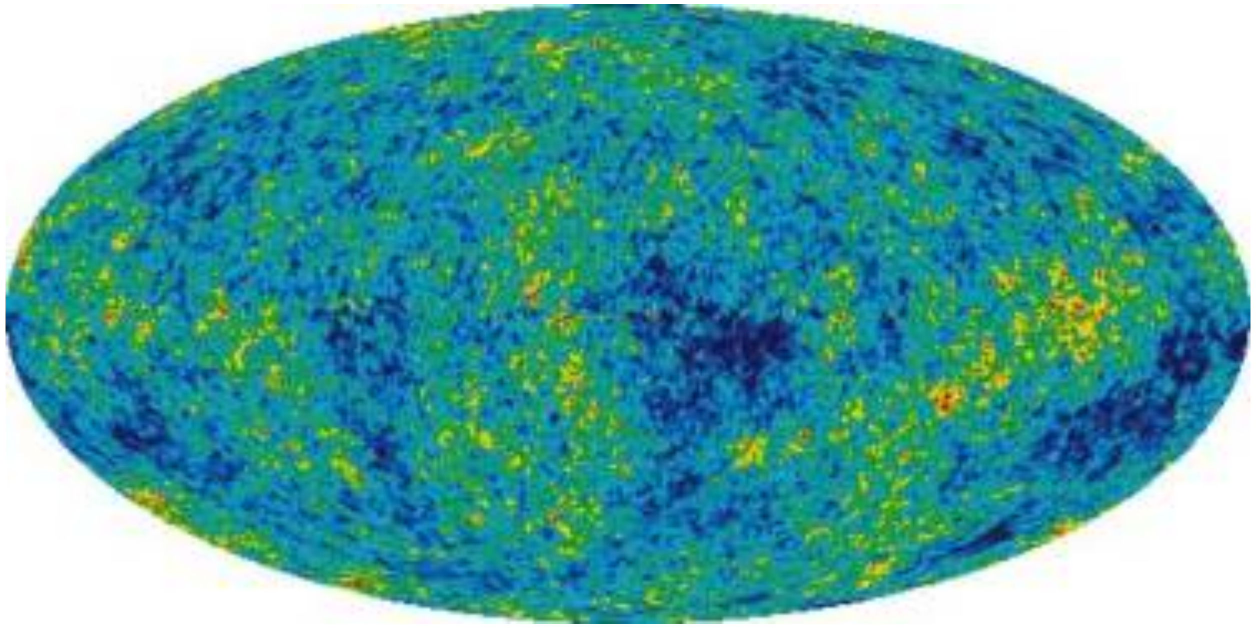




"Beyond" v2

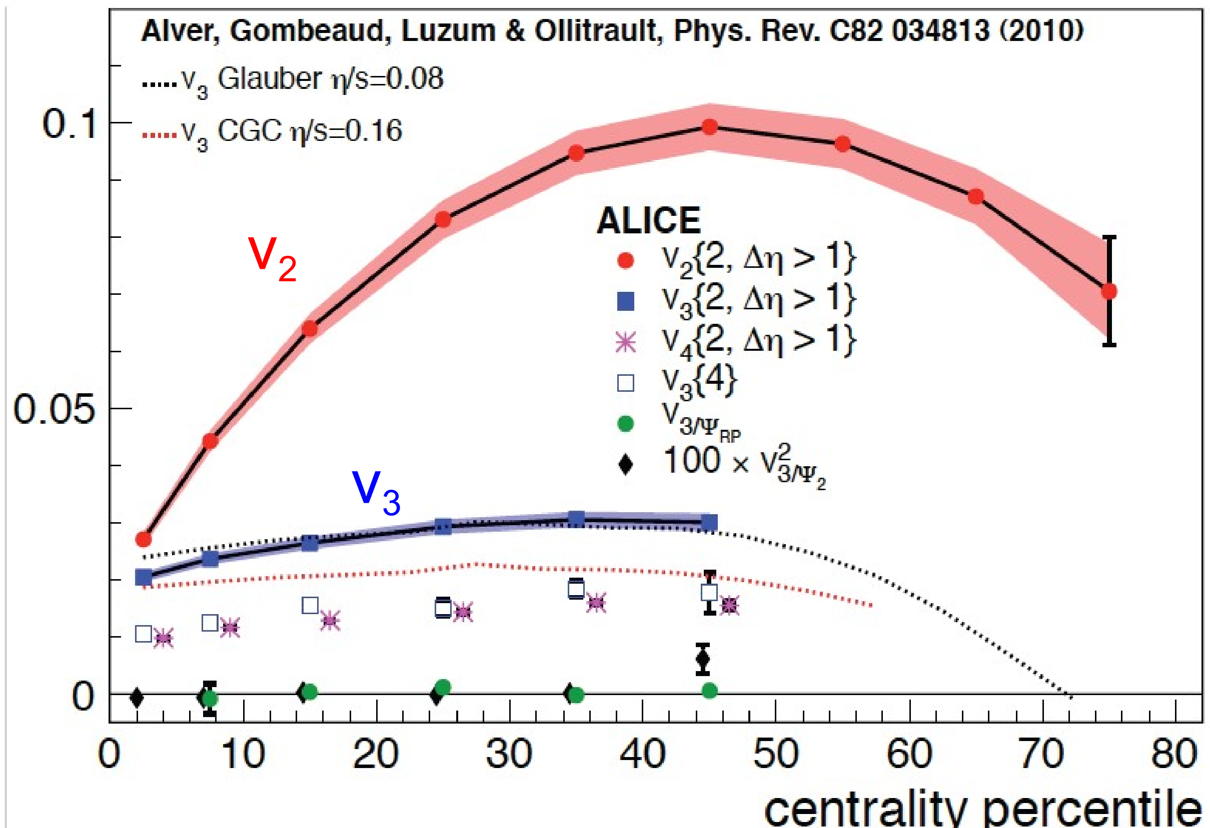
higher moments -> fluctuations / hotspots

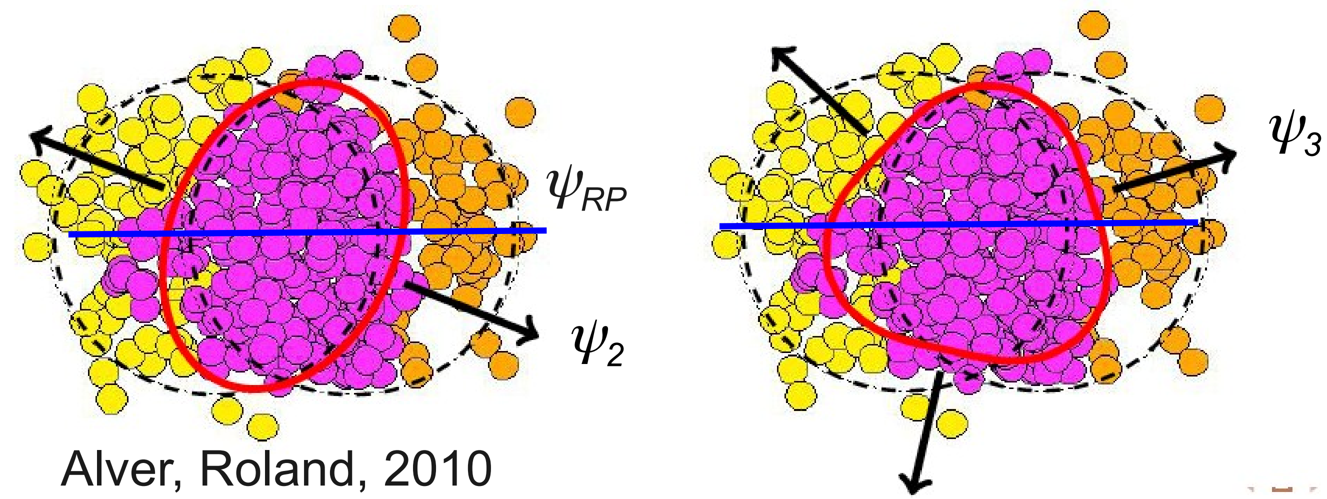


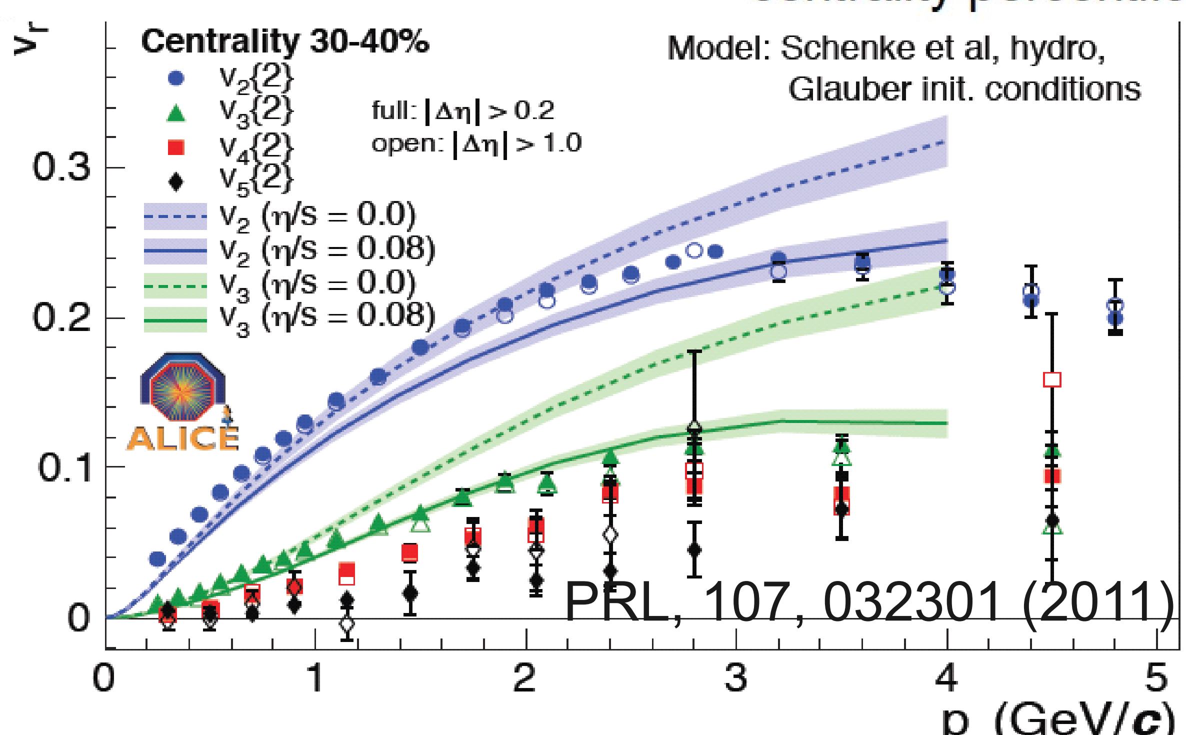


Single event!

Higher harmonics - measured







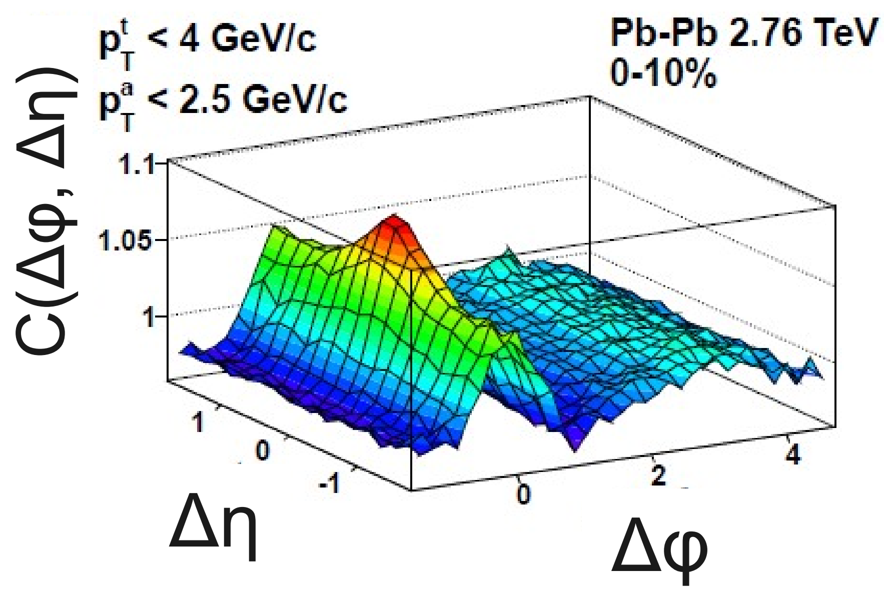
v_3 - triangular flow :
- weak centrality dependence
- vanishes as expected when measured w.r.t. reaction plane

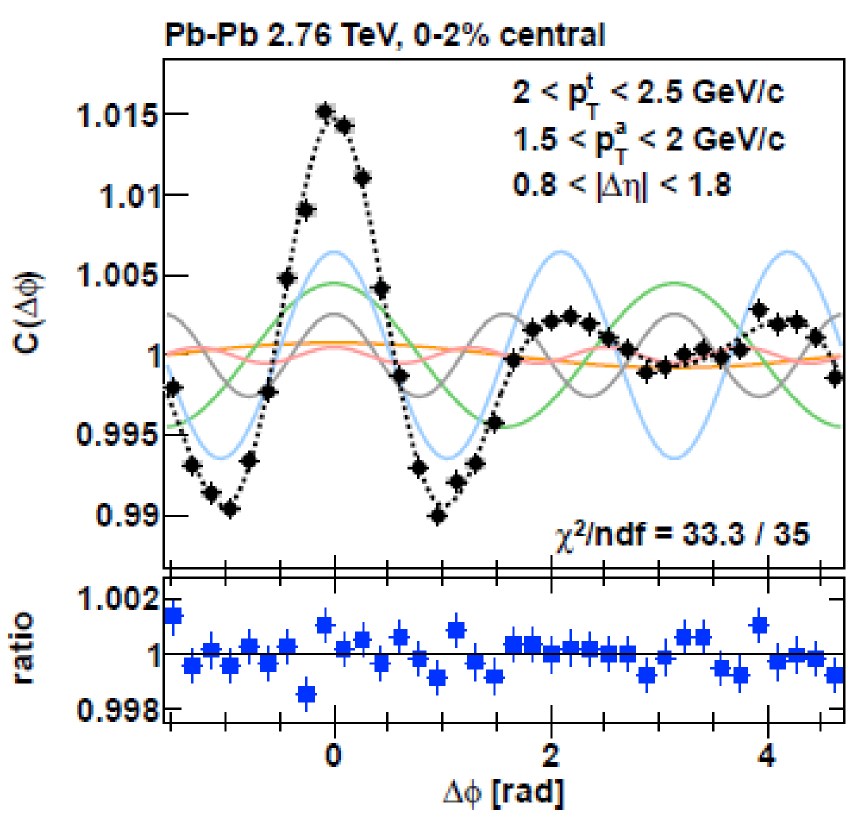
Similar pT dependence for all v_n

Higher harmonics - additional constraints on η/s

η/s small, similar as at RHIC

Two-particle correlations – Fourier decomposition

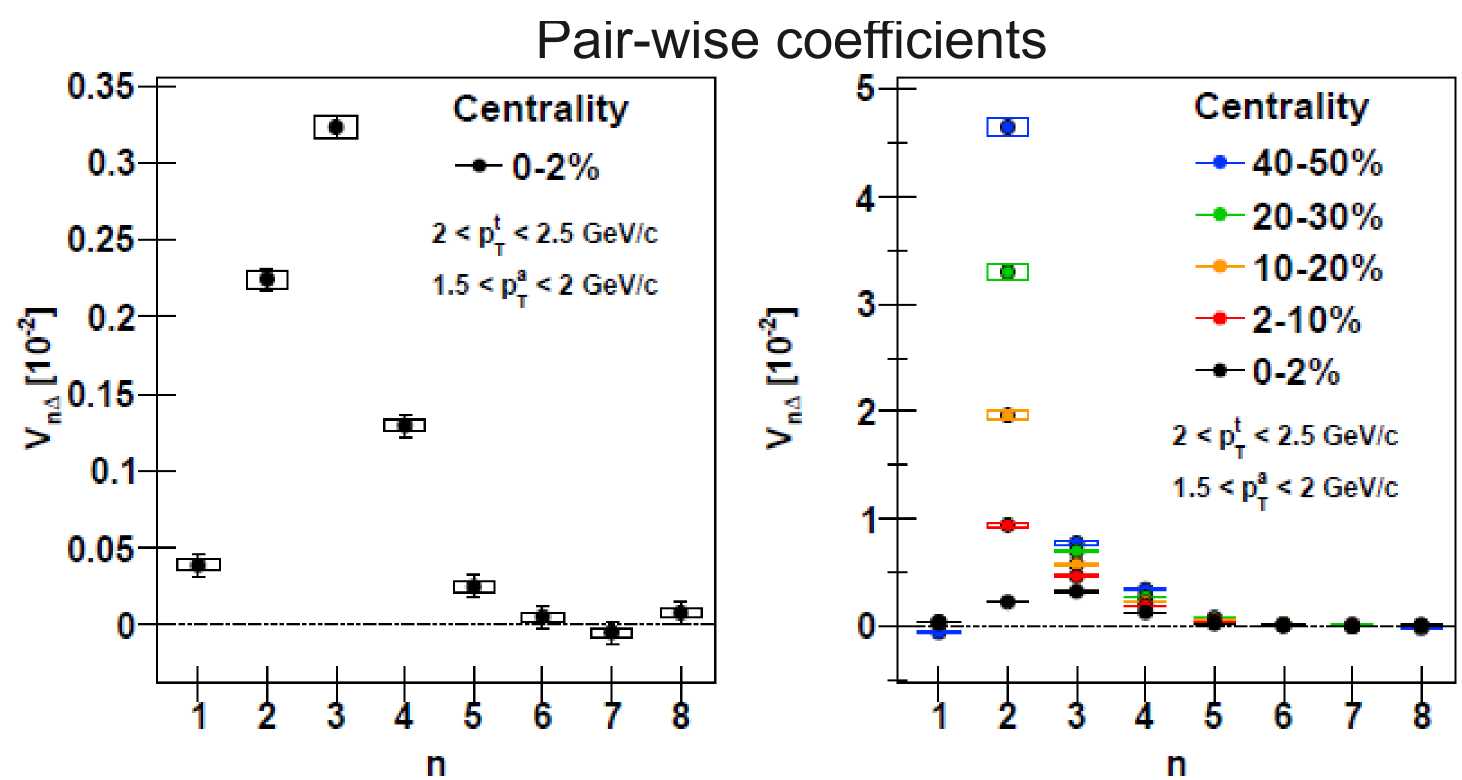




Integration of the correlation function in 0.8 < |Δη| < 1.8 (long) and Fourier decomposition

Collective flow: the coefficients factorize $V_{n\Delta}=v_n(p_T^{T})v_n(p_T^{A})$

$$C(\Delta\phi)=\frac{1}{\Delta\eta_{max}-\Delta\eta_{min}}\int_{\Delta\eta_{min}}^{\Delta\eta_{max}} C(\Delta\eta,\Delta\phi)\sim 1+2\sum_{n=1} V_{n\Delta}\cos(n\Delta\phi)$$



Few components describe the low-pT correlations

⇔ Strong near side ridge and double-peak on the away

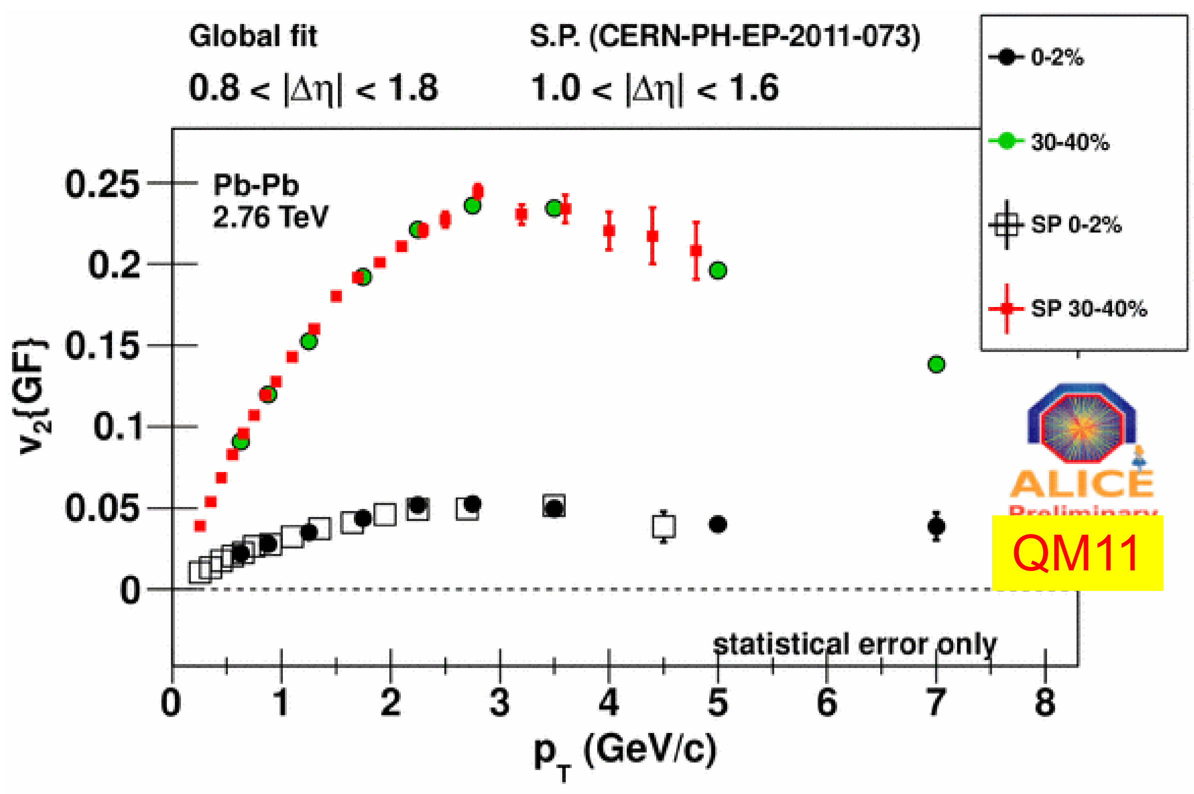
⇔ Also recoil jet up to p_T^{trig}>8 & p_T^{assoc} 6-8 in central

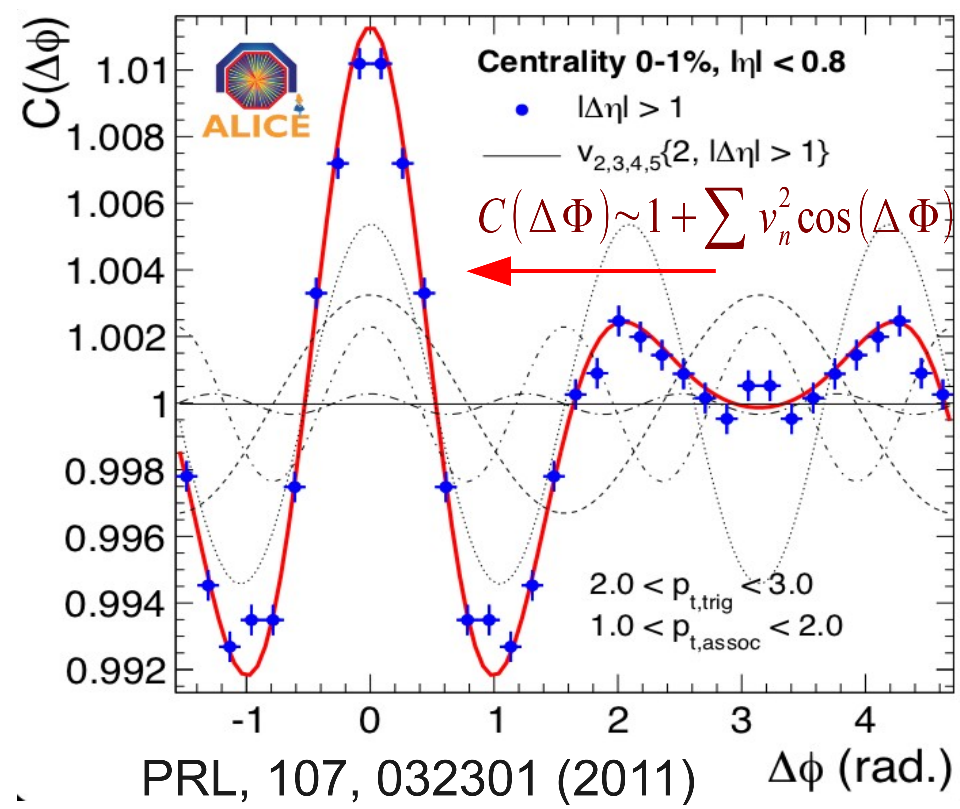
Correlations & hydrodynamics...

Long range correlations – collective flow: the coefficients must factorize such that:

$$V_{n\Delta}=\langle\cos\left[n\left(\phi_{trig}-\phi_{assoc}\right)\right]\rangle=\langle\cos\left[n\left(\phi_{trig}-\Psi_{n}\right)\right]\rangle\langle\cos\left[n\left(\phi_{assoc}-\Psi_{n}\right)\right]\rangle=v_n\left(p_t^{trig}\right)\cdot v_n\left(p_t^{assoc}\right)$$

arXiv:1109.2501

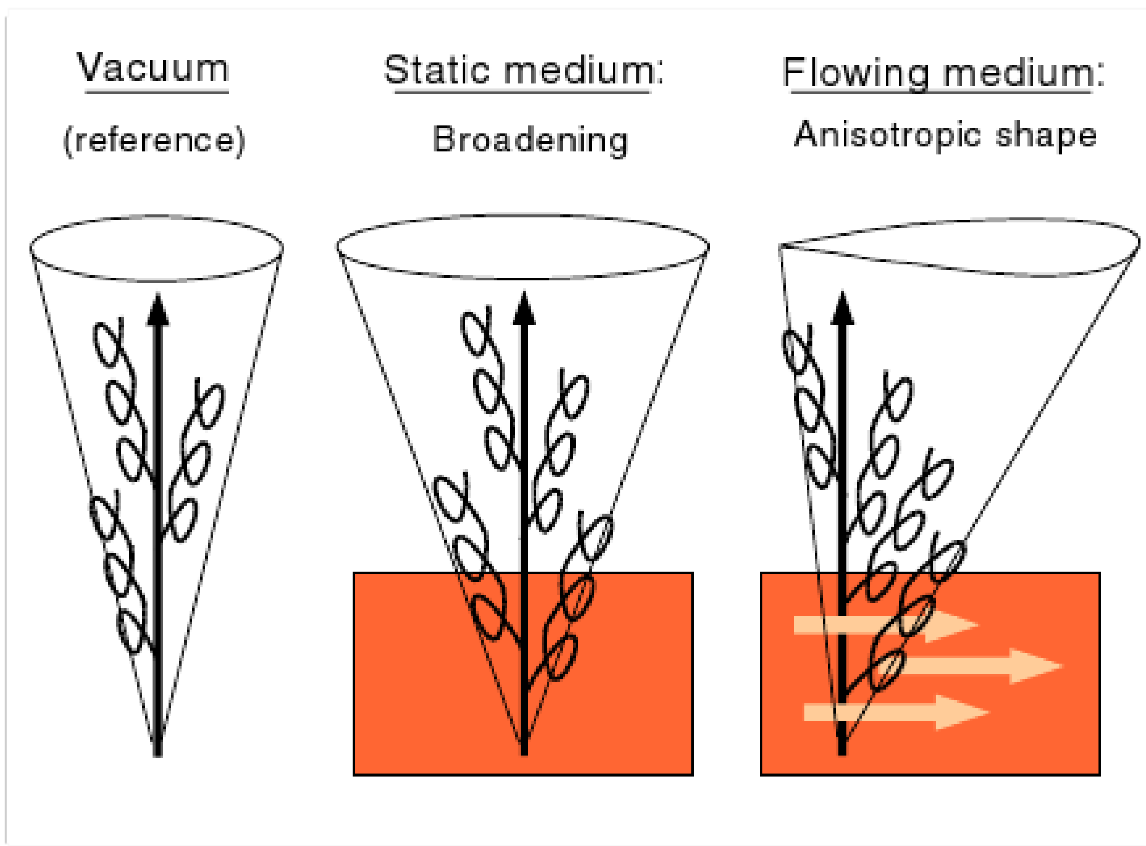




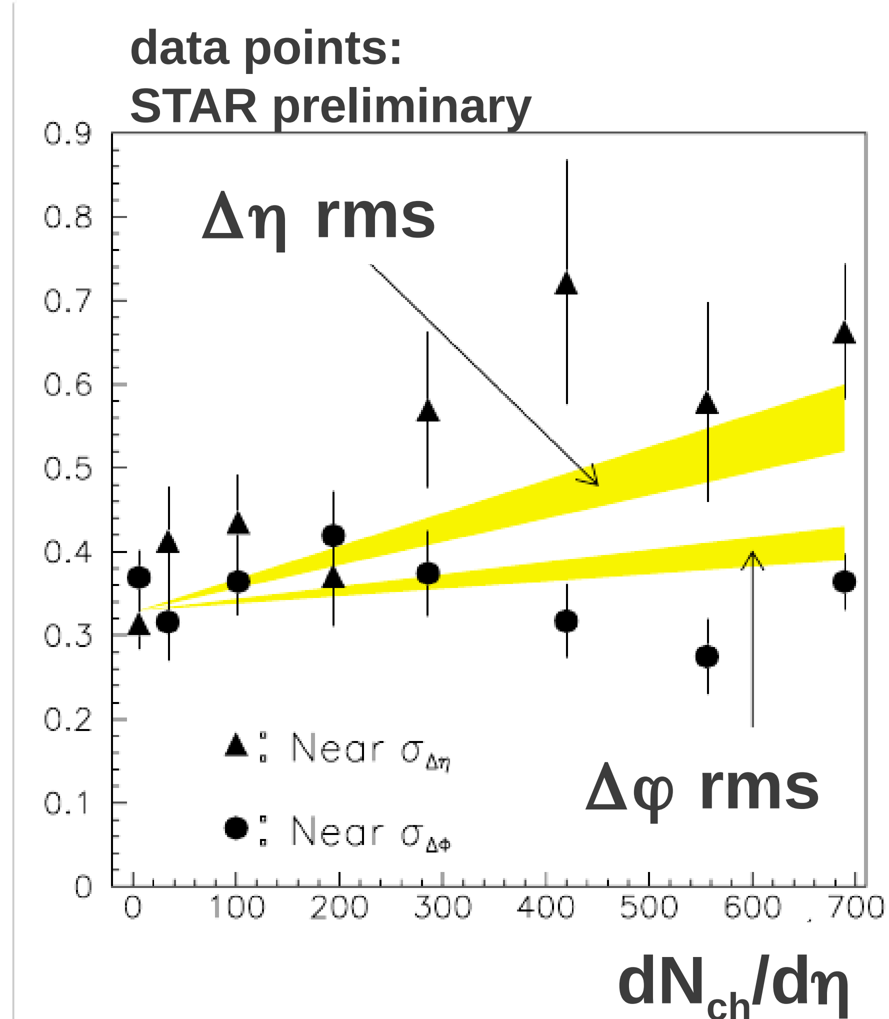
Global fits show:

- Collective flow dominates to about 3-4 GeV/c for all n>1
- Description breaks for high pT or peripheral collisions
- For low pT: double peak and ridge structures seen in two particle correlations are naturally explained by measured anisotropic flow coefficients

Jet-medium-flow coupling via two particle correlations?



N. Armesto, C. Salgado, U. Wiedemann:
Measuring the Collective Flow with Jets
[PRL 93,242301 (2004)]

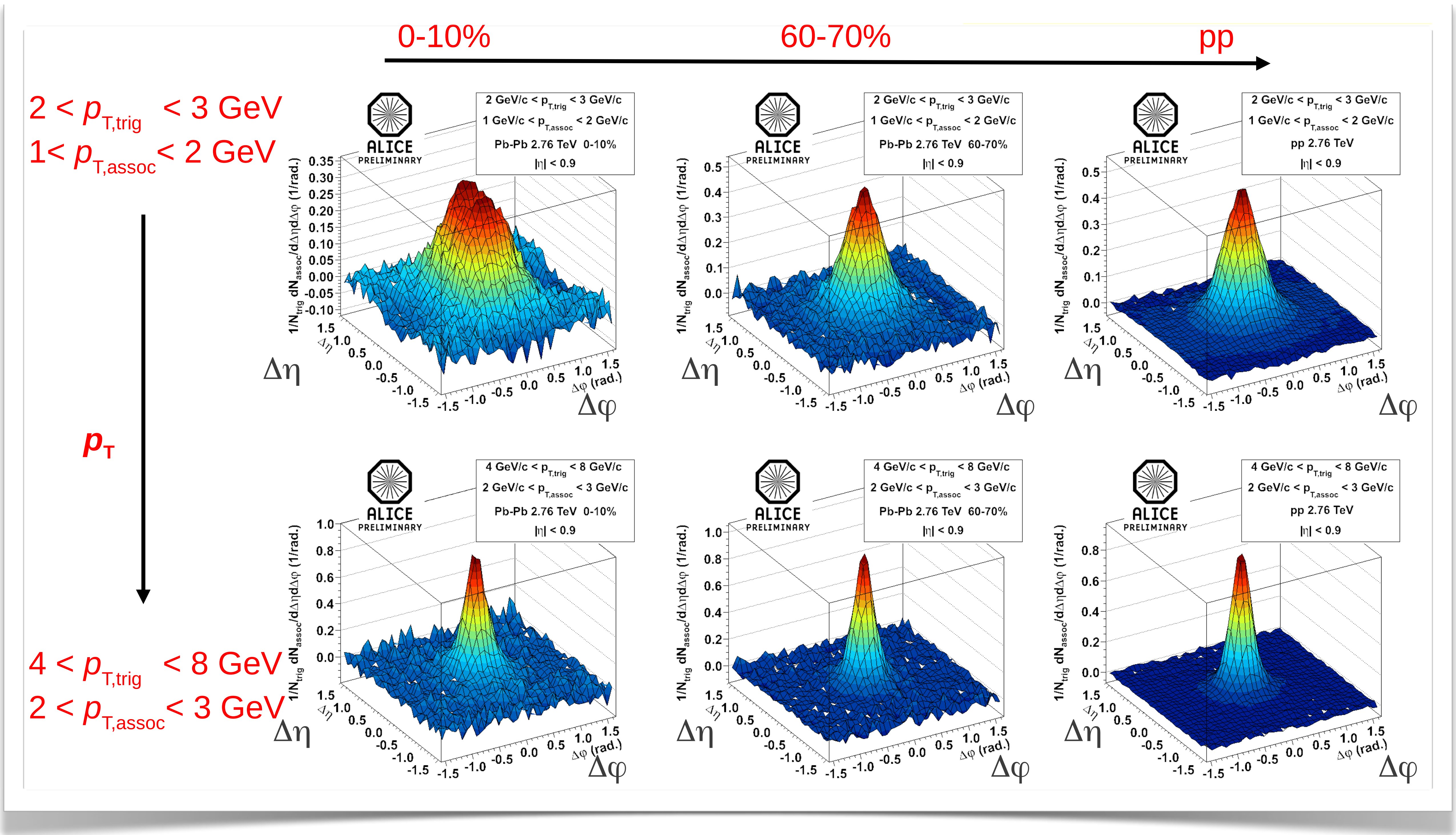


PRL 93,242301 (2004)

=> LHC? - more jets + somewhat more flow...

Jet-peak shape evolution - intermediate pT

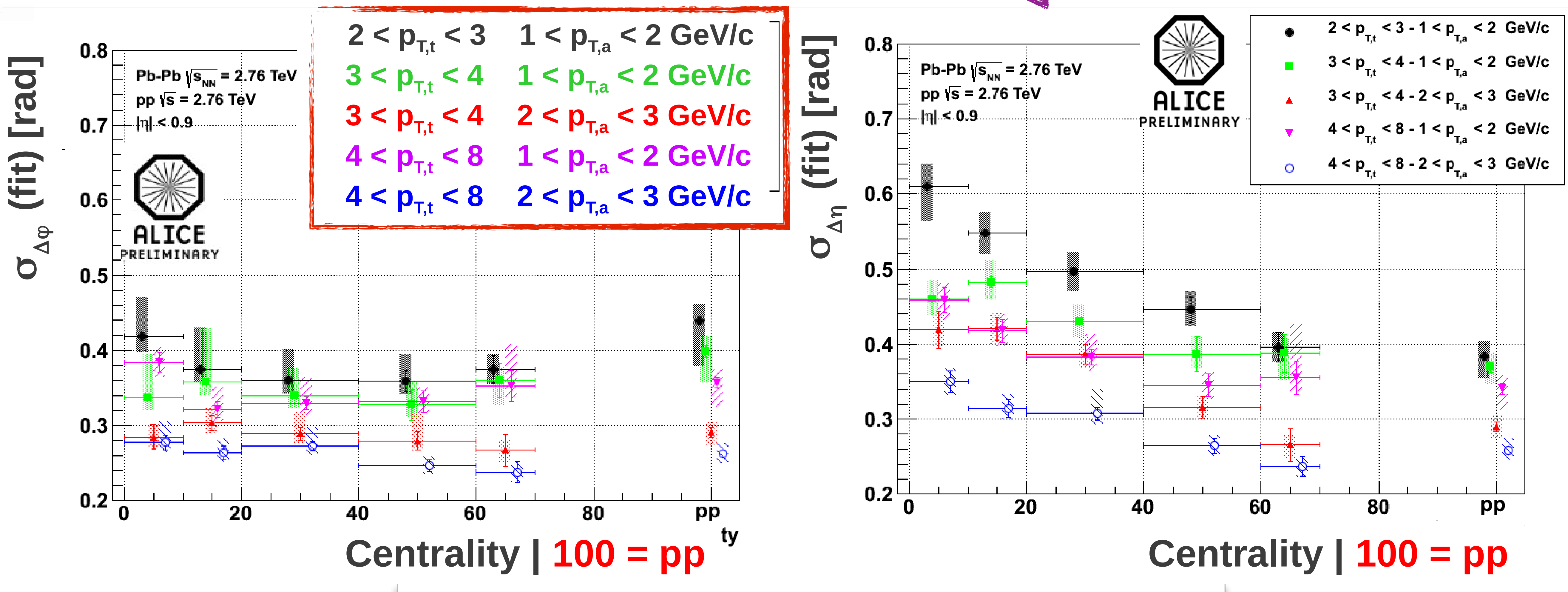
Wider peak in central collisions
Peripheral and p-p similar shape
Strong pT dependence
=> Characterize the peak



Measuring widths of the correlations in azimuth and pseudo-rapidity

Scan in kinematics

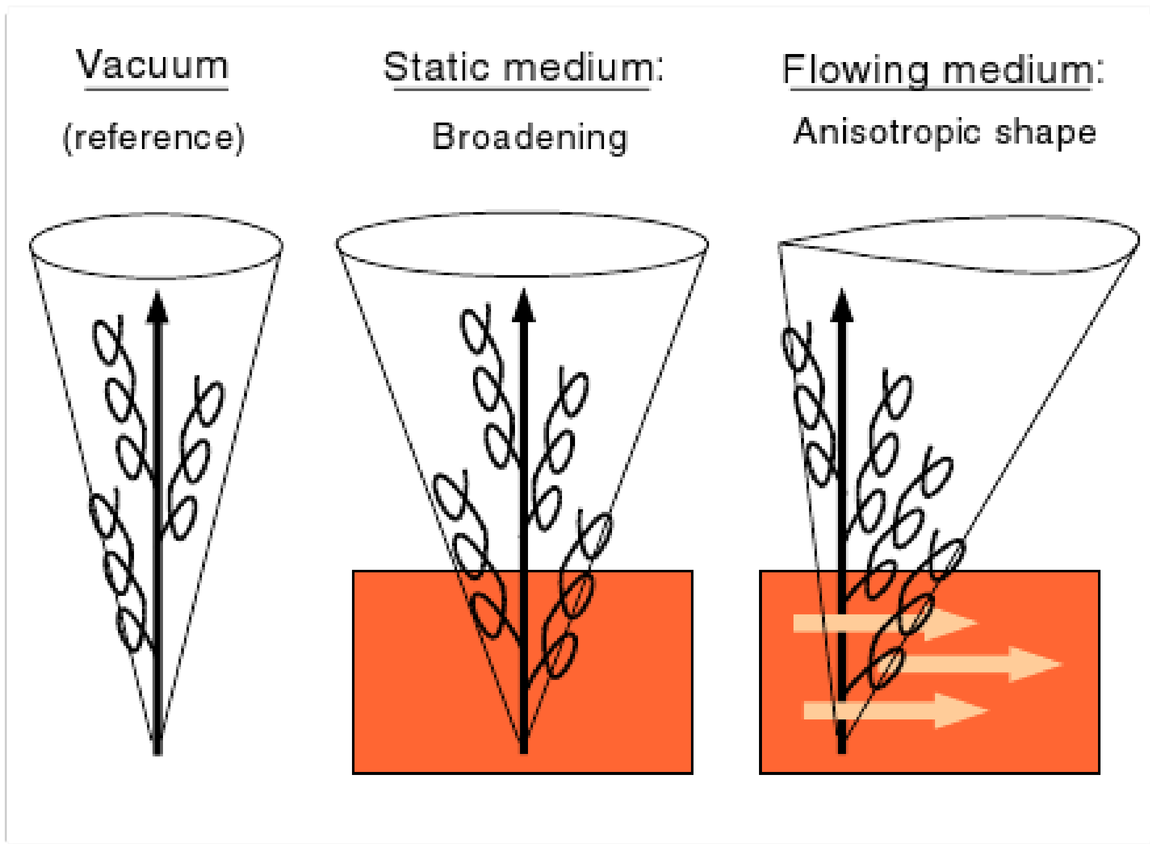
$\sigma_{\Delta\phi}, \sigma_{\Delta\eta}$ from Fit

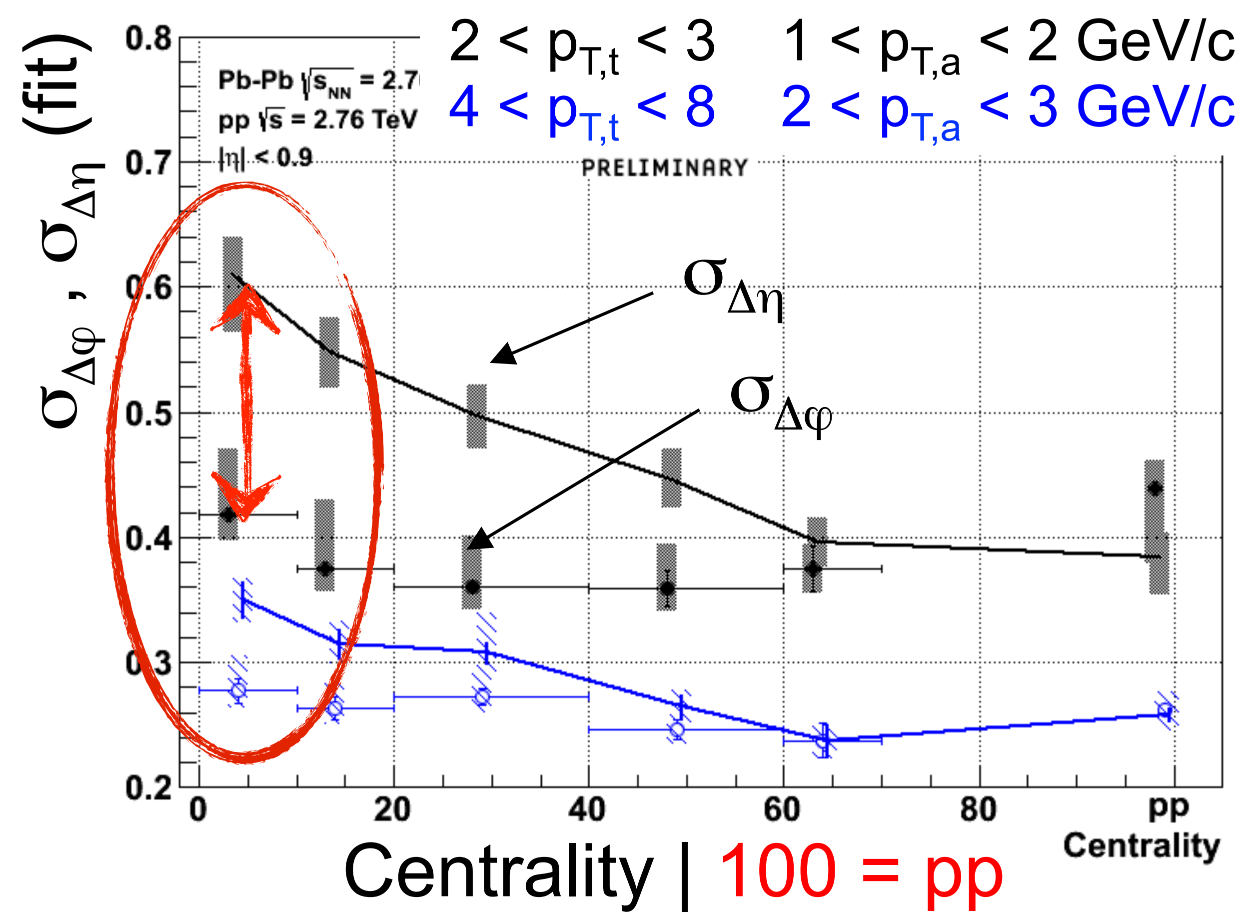


Note: Higher trigger pT -> higher av. parton pT

- No centrality dependence of σ_ϕ
  - $p_{T,assoc}$ dependence governed by $j_T \sim p_{T,assoc}\, \sigma_\phi$ = const.
  - Same for σ_η in peripheral collisions
- Significant increase of σ_η towards central events
  - For the lowest p_T bin, eccentricity $(\sigma_\eta - \sigma_\phi) / (\sigma_\eta + \sigma_\phi)$ increases from 0 to 0.2
- Smooth continuation from peripheral to pp

Measuring widths of the correlations in azimuth and pseudo-rapidity





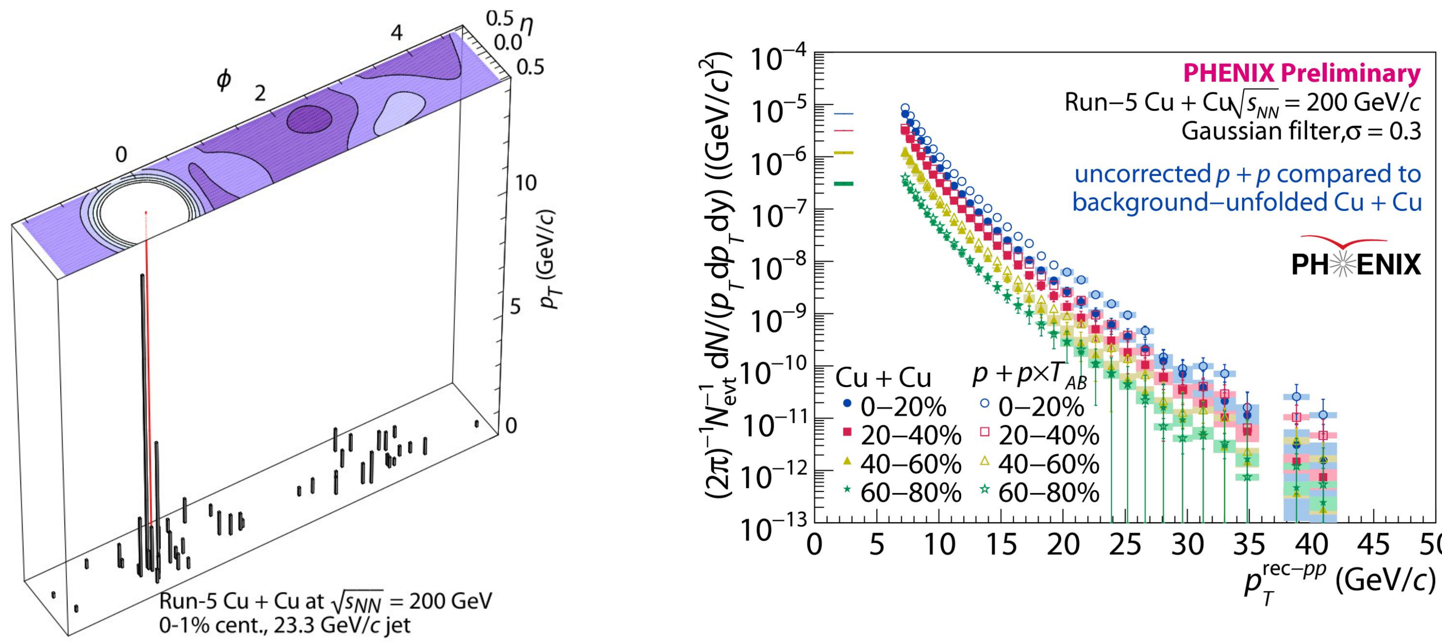
Measure of jets interactions with longitudinal flow (?)

- AMPT (**A** **M**ulti**P**hase **T**ransport Code)
  - Initial conditions simulated using HIJING
  - Parton scattering
  - Hadronization: Lund model + coalescence
  - Hadron scattering
- AMPT describes the main features of the near-side shape evolution observed in data

- Jets at RHIC...

Jets at RHIC in HIC

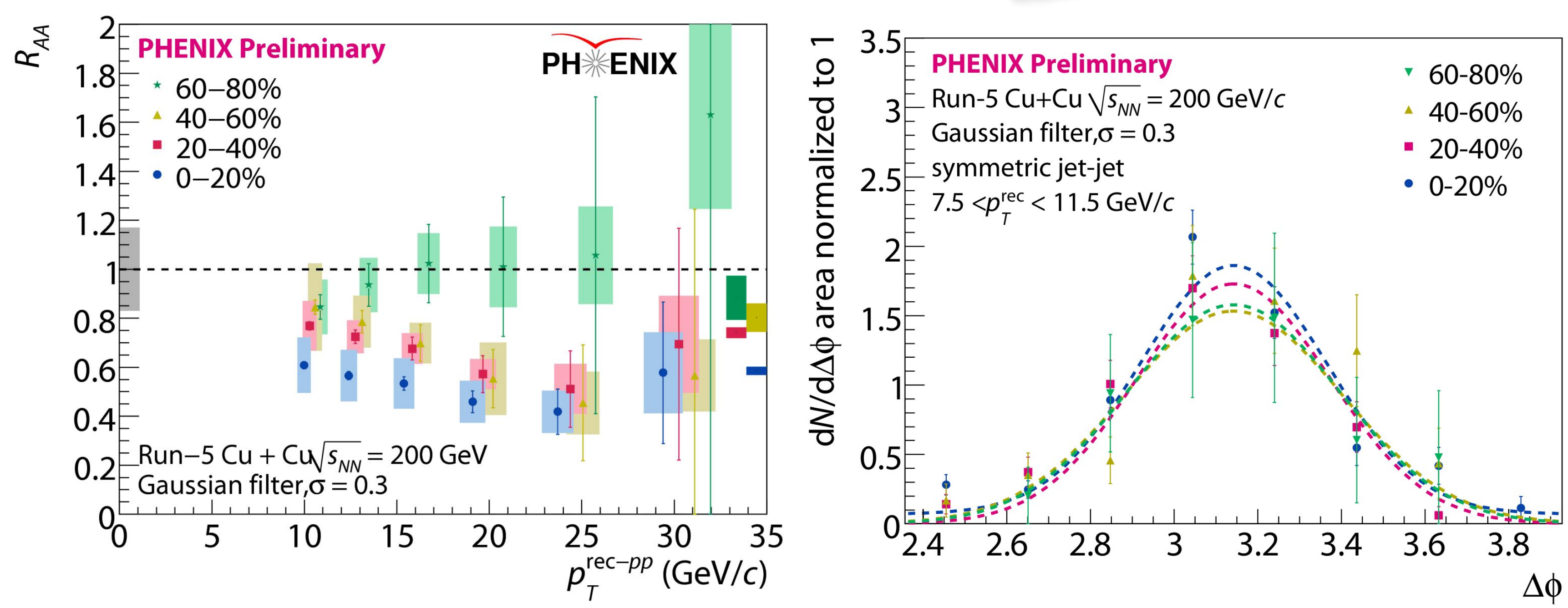
Jets in $Cu+Cu$ at $\sqrt{s} = 200$ GeV



Custom jet finder (Gaussian Filtering) tunned to reject combinatorial jets

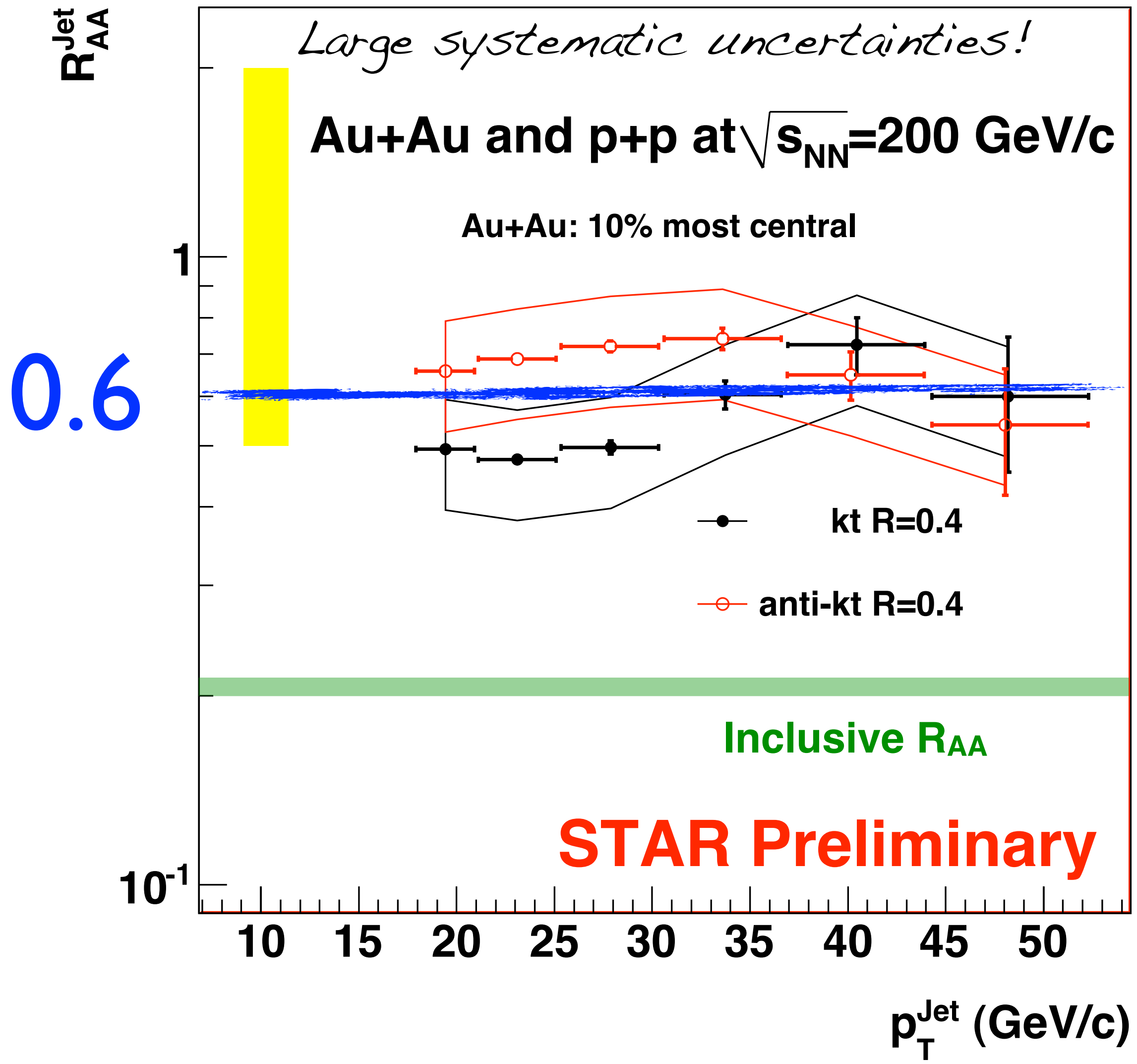
- tune based on vacuum fragmentation

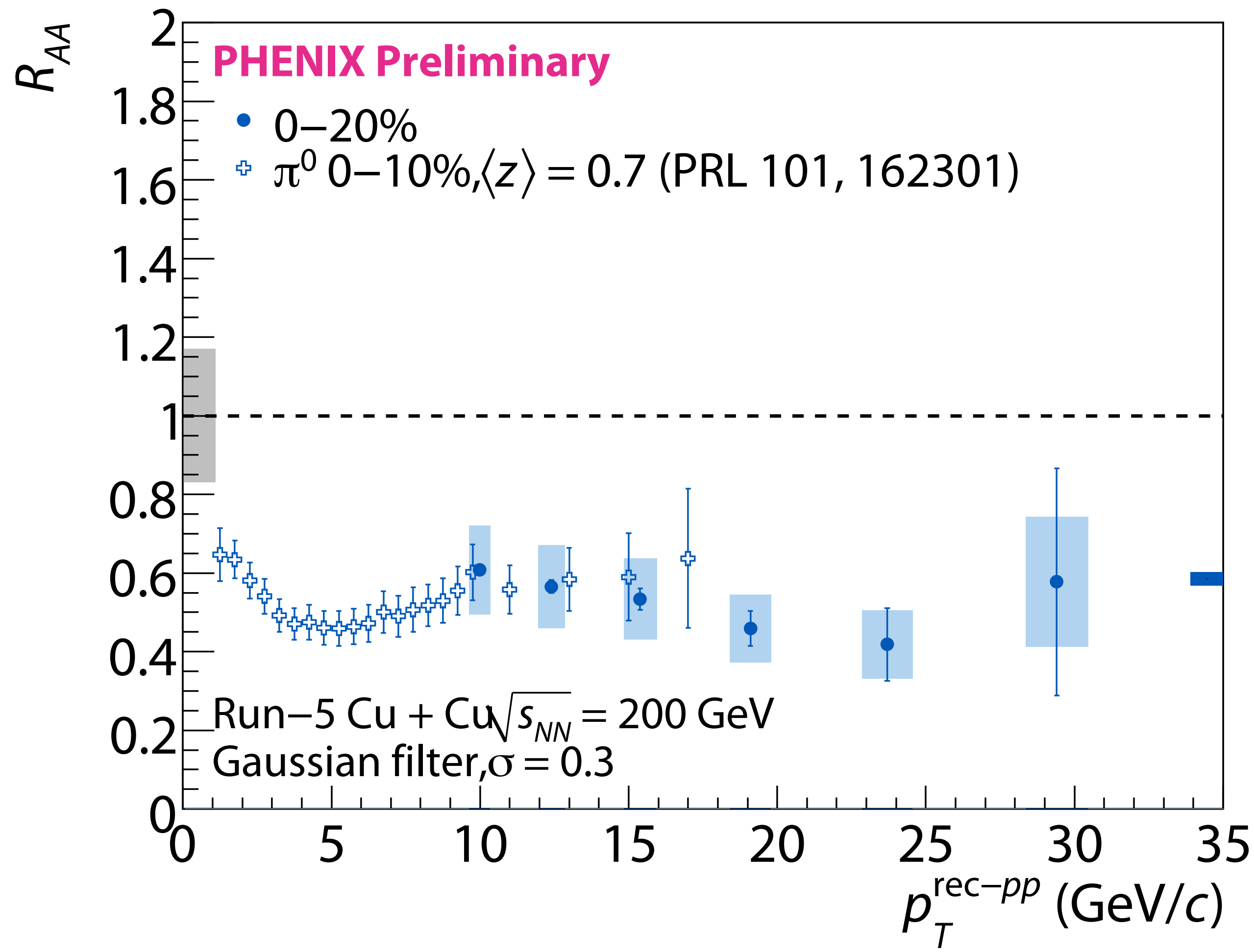
- Suppression of reconstructed jet R_{AA}:
  - $\Rightarrow$ over a wide p_T range
  - $\Rightarrow$ increasing suppression in more central collisions
- Reconstructed di-jet $\Delta\phi$ distributions unmodified:
  - $\Rightarrow$ no angular de-correlation in central collisions!



Jets at RHIC in HIC

Work on final results in progress...





STAR Au+Au: R_{AA}^{JETS} > R_{AA} single particle

=> part of the parton energy recovered

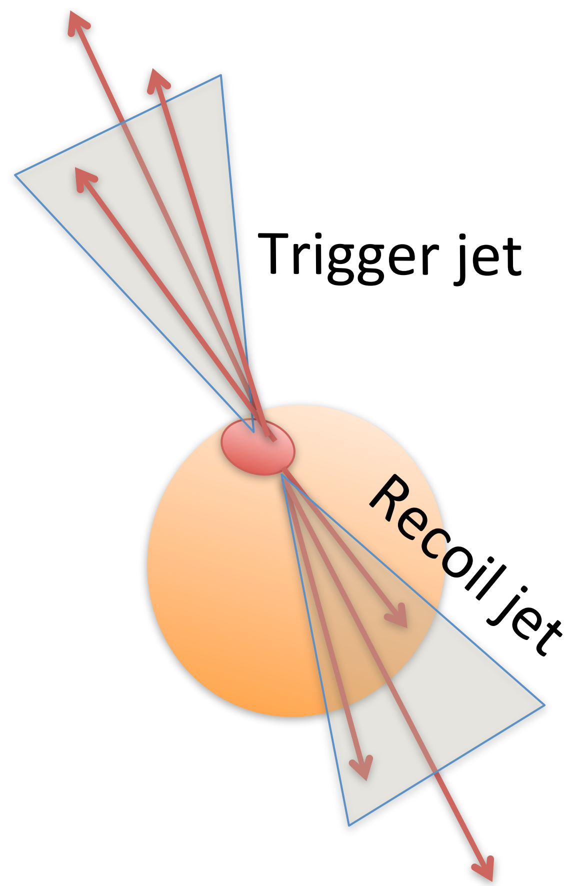
PHENIX Cu+Cu: R_{AA}^{JETS} ~ R_{AA} hadrons

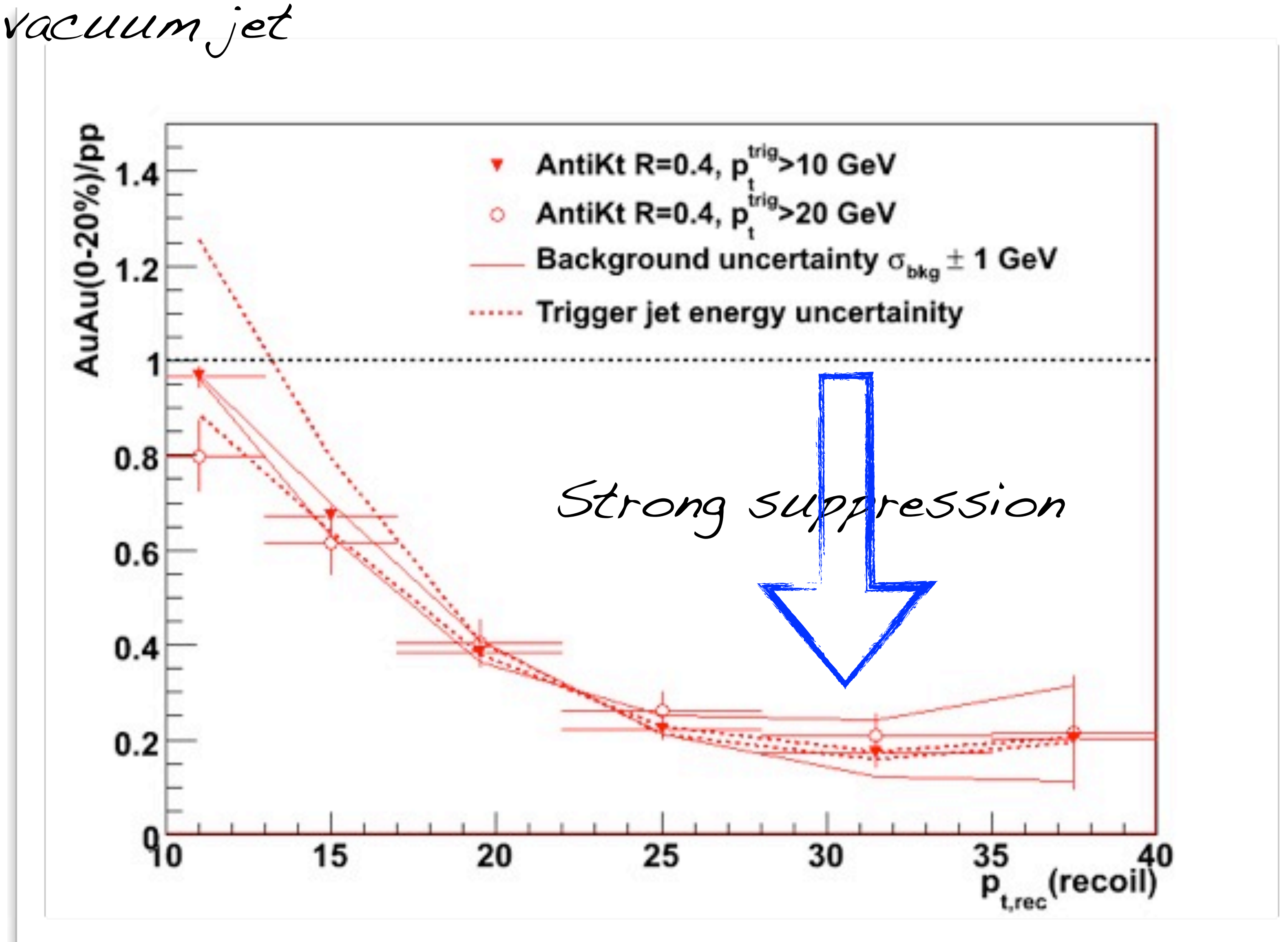
=> measure of vacuum fragmentation

Recoil jet spectrum at RHIC

Trigger-jet: biased towards surface

- strong fragmentation bias ~ vacuum jet





- Selecting biased trigger jet maximizes path length for the recoil (b-2-b) jets: extreme selection of jet population
- Significant suppression in di-jet coincidence measurements!

RHIC: Jet-hadron coincidences

Broadening & softening of the recoil jet at RHIC? -> but v3 component NOT negligible

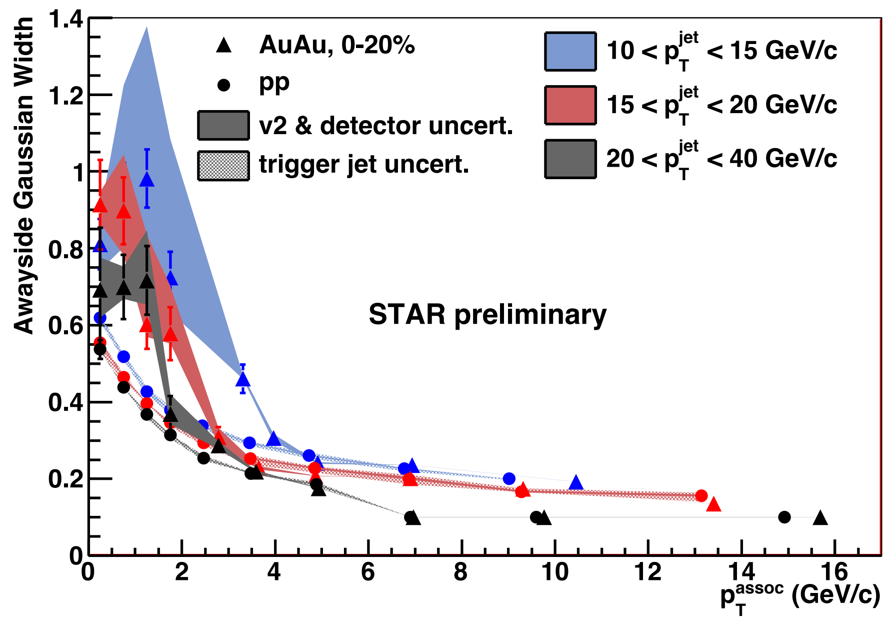
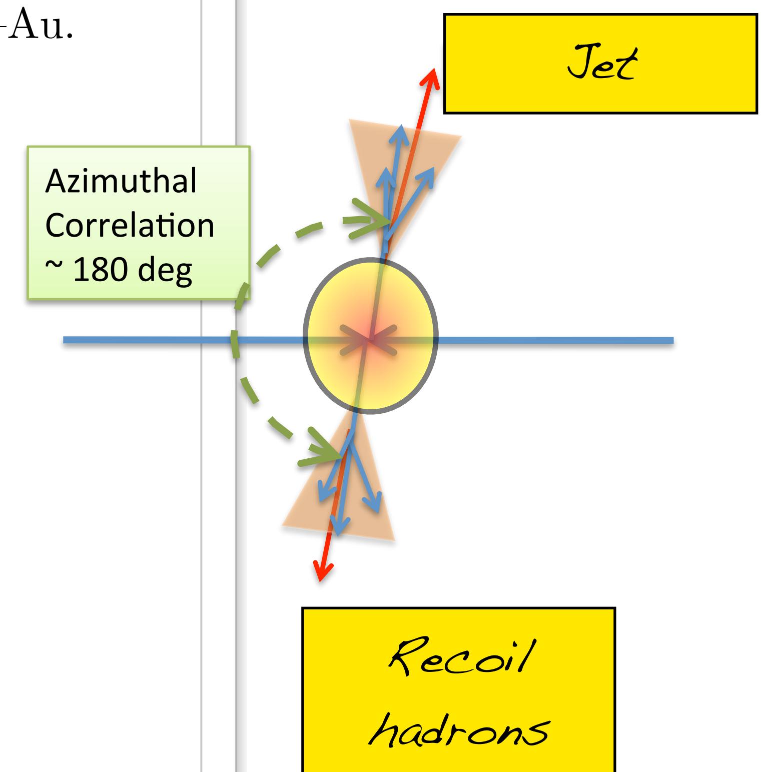


Figure 1. The Gaussian widths of the awayside jet peaks in Au–Au (triangles) and p–p (circles) indicate broadening of the awayside jet in Au–Au.

STAR @ RHIC



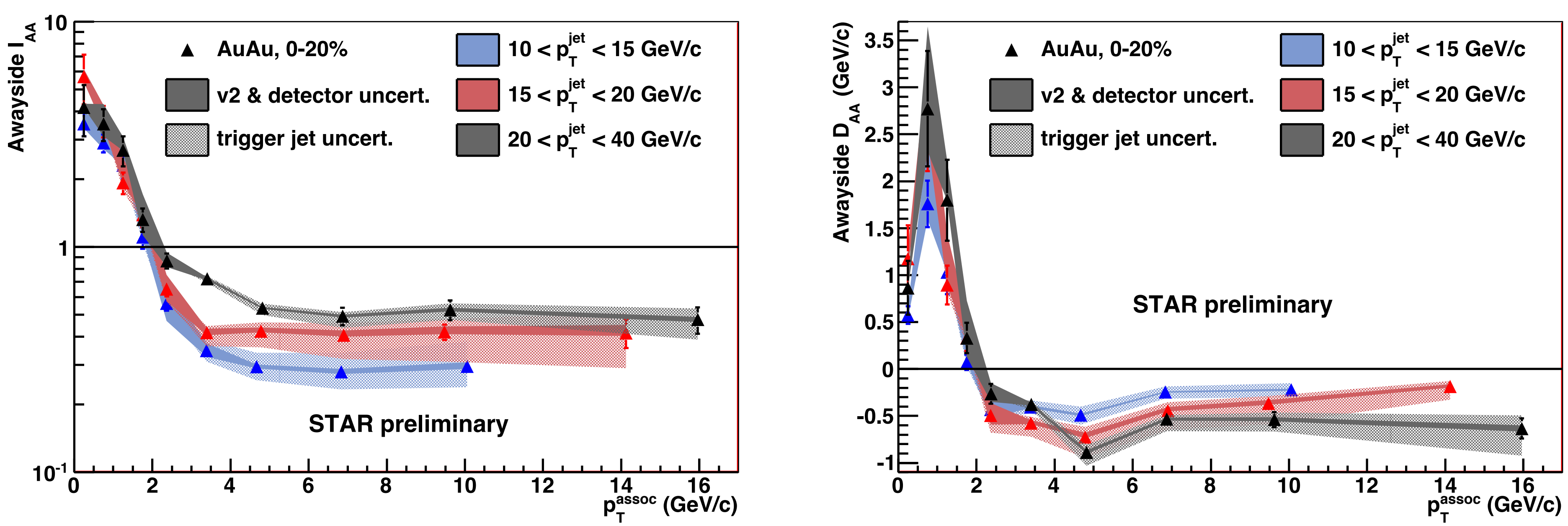


Figure 2. The awayside I_{AA} (left) and D_{AA} (right) indicate a softening of the awayside jet for three reconstructed jet energy ranges. The awayside D_{AA} shows that high-p_T^{assoc} suppression is compensated for by low-p_T^{assoc} enhancement.

Reminder on fragmentation bias...

- Fragmentation bias! - nature is kind and (in most cases) will give you what you ask for - perhaps NOT what you WANT

Thank you!

- For graphics/slides from: B. Cole, P. Govoni, M. Nguyen, T. Hemmick, P. Jacobs, M. Floris, M. van Leeuwen, C. Loizides, A. Morsch, J. Putschke, C. Roland, M. Rybář, G. Salam, Y. Shi Lai, G. Soyez, I. Wingerter
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