III CPAN Days
Barcelona, November 3rd 2011

Heavy Ions

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Contents:

1. Introduction.

2. Pre-LHC situation:
   - 2.1 Multiplicities.
   - 2.2 Azimuthal asymmetries.
   - 2.3 High-p_T observables.
   - 2.4 Open problems.

Bulk observables: $p \sim \langle p \rangle, T$ (2.1–2.2)

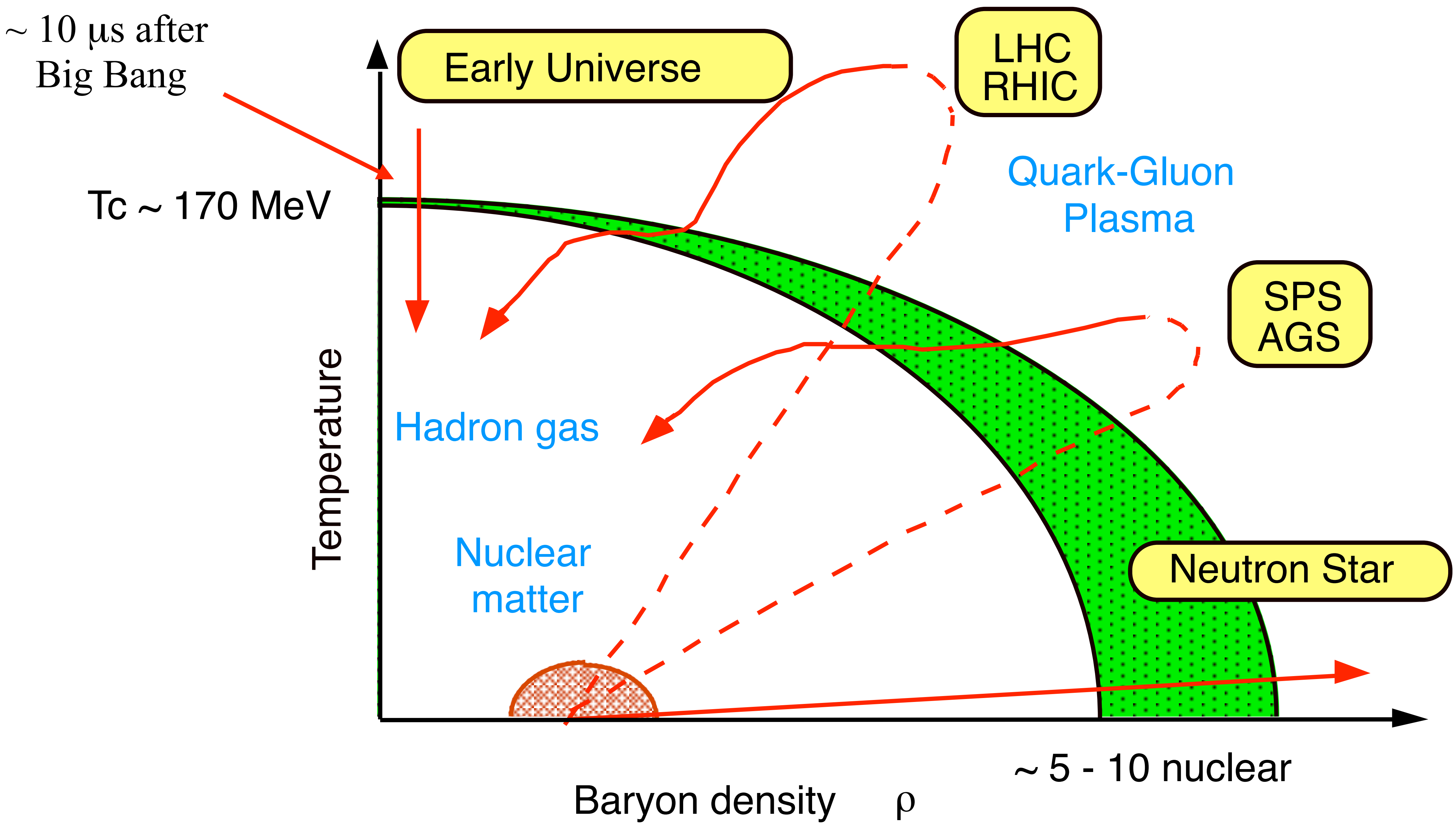
Hard probes: $p \gg \langle p \rangle, T$ (2.3)

3. HIC@LHC:
   - 3.1 Multiplicities.
   - 3.2 Azimuthal asymmetries.
   - 3.3 High-p_T observables and jets.
   - 3.4 Quarkonium.
   - 3.5 Rapidity correlations.
   - 3.6 Femtoscopy.

4. Summary.

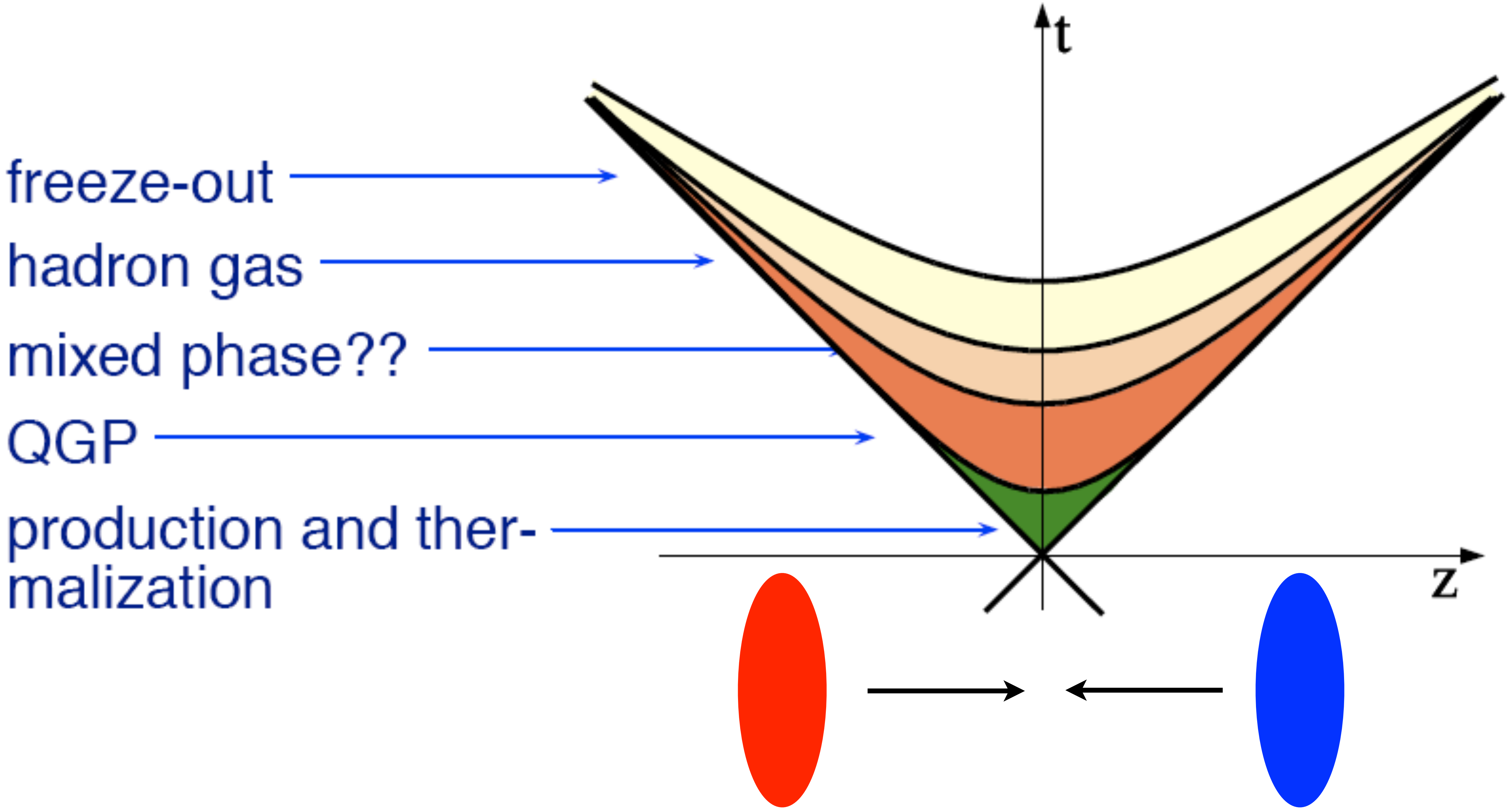
See *Quark-Gluon Plasma 1-4*; NA, arXiv:0903.1330 [hep-ph]; talks at QM2011, http://qm2011.in2p3.fr/.

Phase diagram of QCD:



$$\varepsilon_c \sim 1 \text{ GeV/fm}^3$$

Phase diagram of QCD:



Present status:

Observable at RHIC	Standard interpretation
Low multiplicity (~2/3 expectations $dN_{ch}/d\eta\|_{\eta=0}$~1000 for central collisions)	Strong coherence in particle production: CGC, collectivity, strong gluon shadowing!?
v_2 in agreement with ideal hydro (η/s~a few/(4π))	Almost ideal fluid, very fast thermalization/ isotropization, strongly/weakly coupled!?
Strong jet quenching (R_{AA}(10 GeV) ~0.2 for π^0, disappearance of back-to-back correlations)	Opaque partonic medium, radiative (+elastic) energy loss, weak/strong interaction with the medium!?

scQGP

- **Aim of the talk**: show some new directions in theory and experiment, and confront the standard interpretations with the first LHC data.

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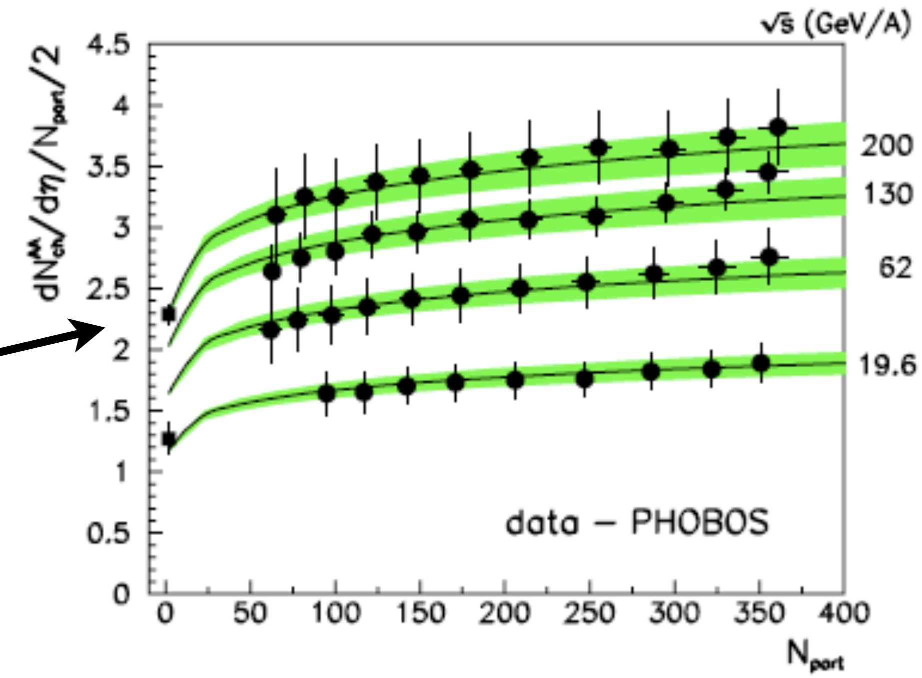
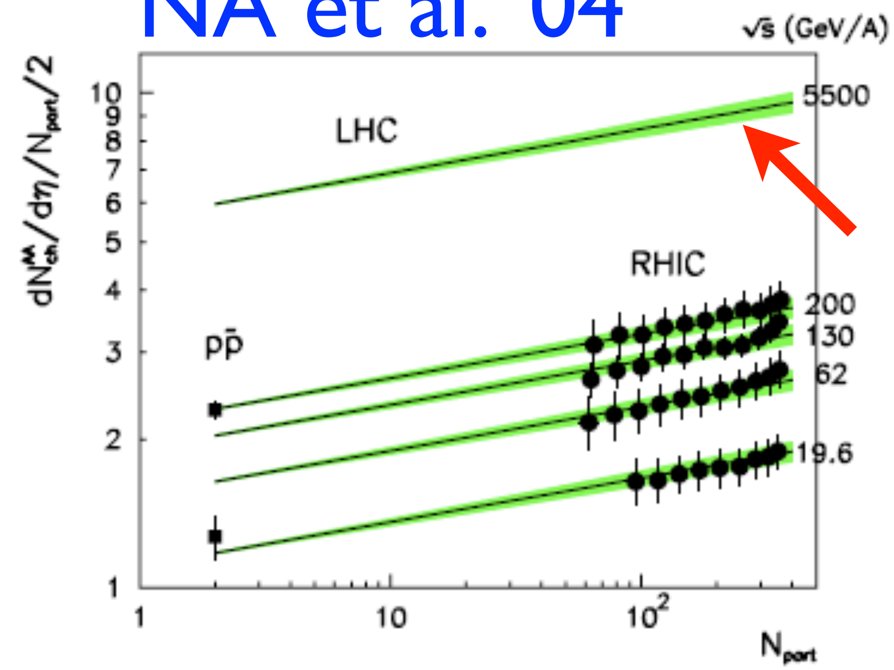
Multiplicities: RHIC

Multiplicity per participant pair measured at $\eta \sim 0$.

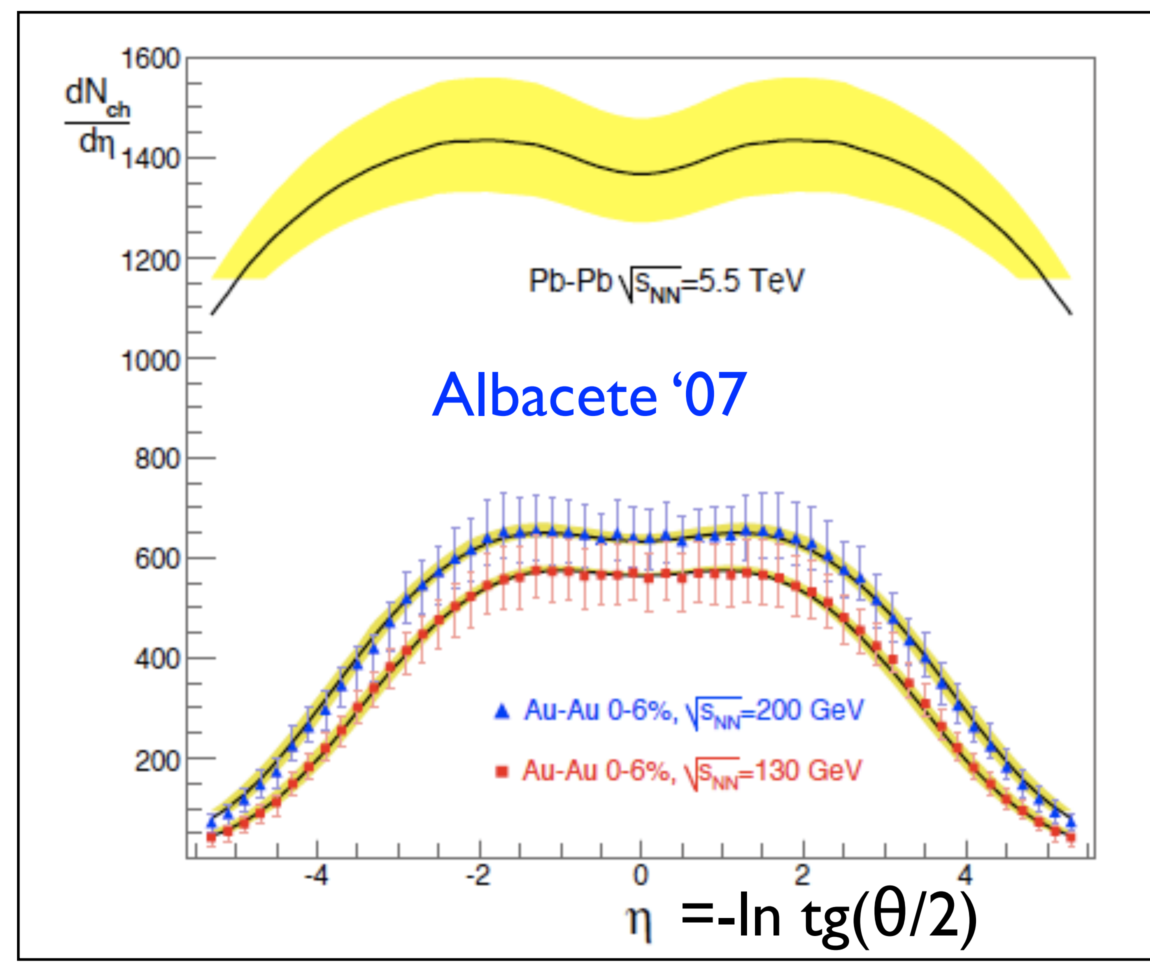


NA et al. '04

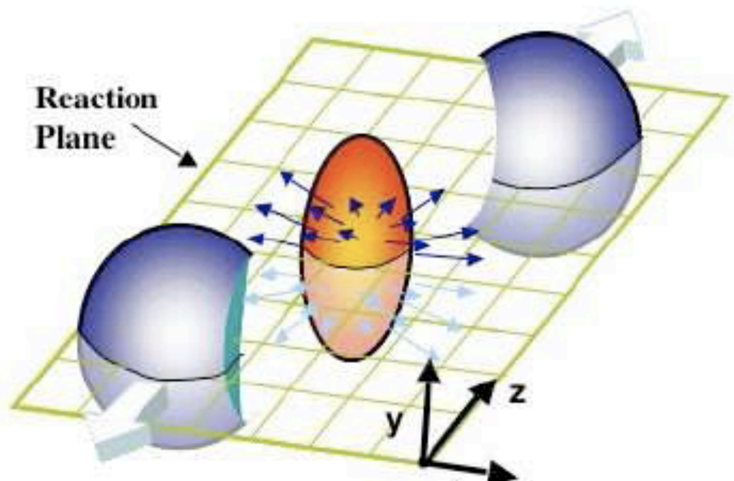


- Multiplicity: 1st-day observable, determines T, ε, backgrounds,...

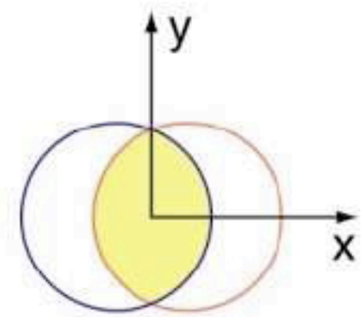
- Pre-RHIC expectations overestimated RHIC data: collectivity far more important than previously assumed → saturation physics, strong gluon shadowing, percolation,...



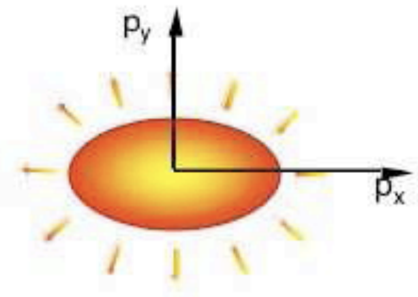
Azimuthal asymmetries:



Tannebaum '06



$$\frac{dN_k}{dy\,dp_T^2\,d\phi} = \frac{dN_k}{dy\,dp_T^2}\frac{1}{2\pi}\left[1 + 2v_1\cos(\phi-\phi_R) + 2v_2\cos 2(\phi-\phi_R) + \ldots\right]$$



$$v_2 = \langle \cos 2(\phi - \phi_R)\rangle = \left\langle \frac{p_x^2 - p_y^2}{p_T^2} \right\rangle$$

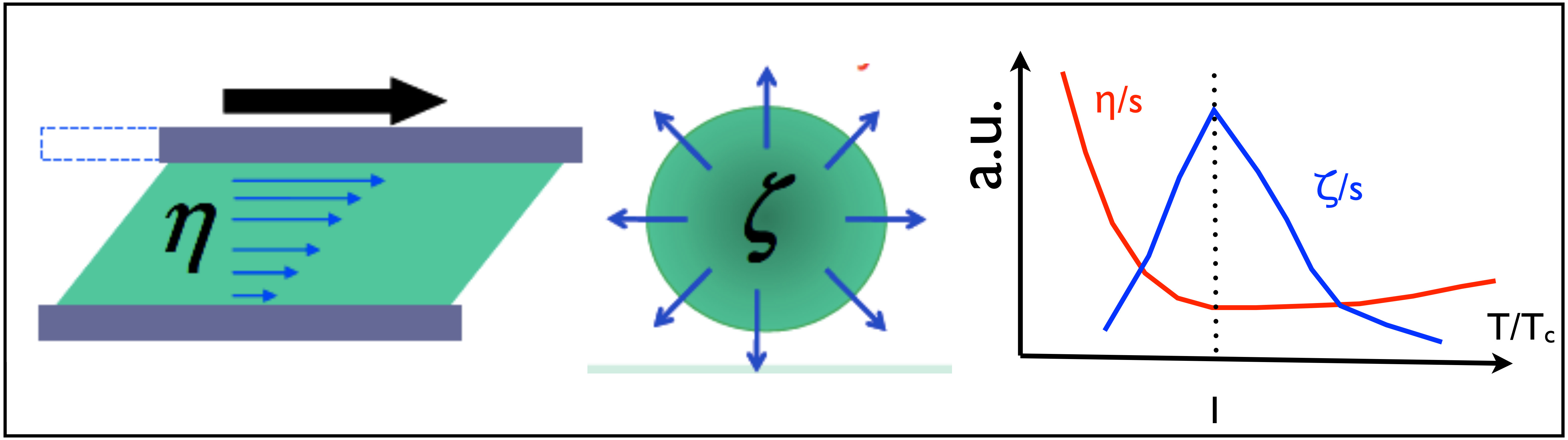
- v_2, also called elliptic flow, is usually interpreted in terms of a final momentum anisotropy dictated by an initial space anisotropy.

- Ideal hydro: plus an (lattice) equation of state, <u>initial conditions</u> and a <u>hadronization</u> prescription, reproduces data.

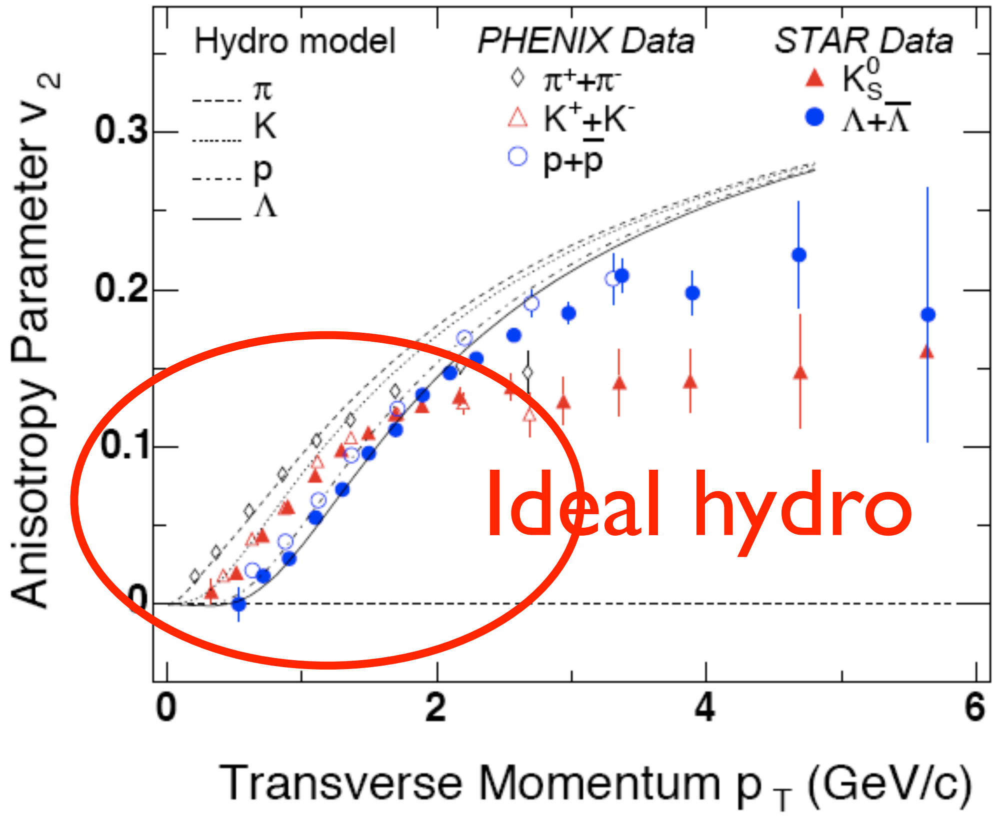
- Non-ideal hydro: dissipative (viscous) corrections. (Bulk and) shear viscosity decrease v_2.

Azimuthal asymmetries:

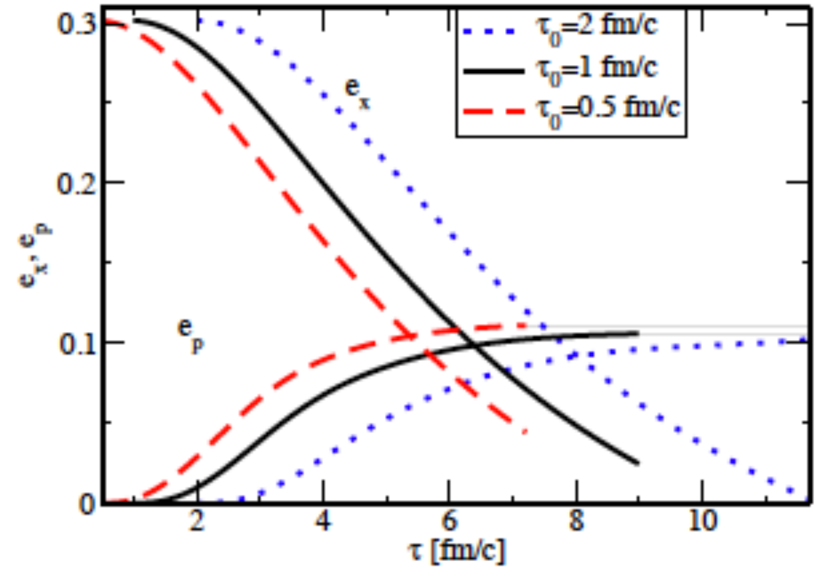
- $\eta/s=1/(4\pi)$ and $\zeta=0$ in CFT: KSS bound.
- $\eta/s=0.1$-1 in pure glue lattice QCD.
- ζ has a peak around T_c in QCD (Dobado et al.).

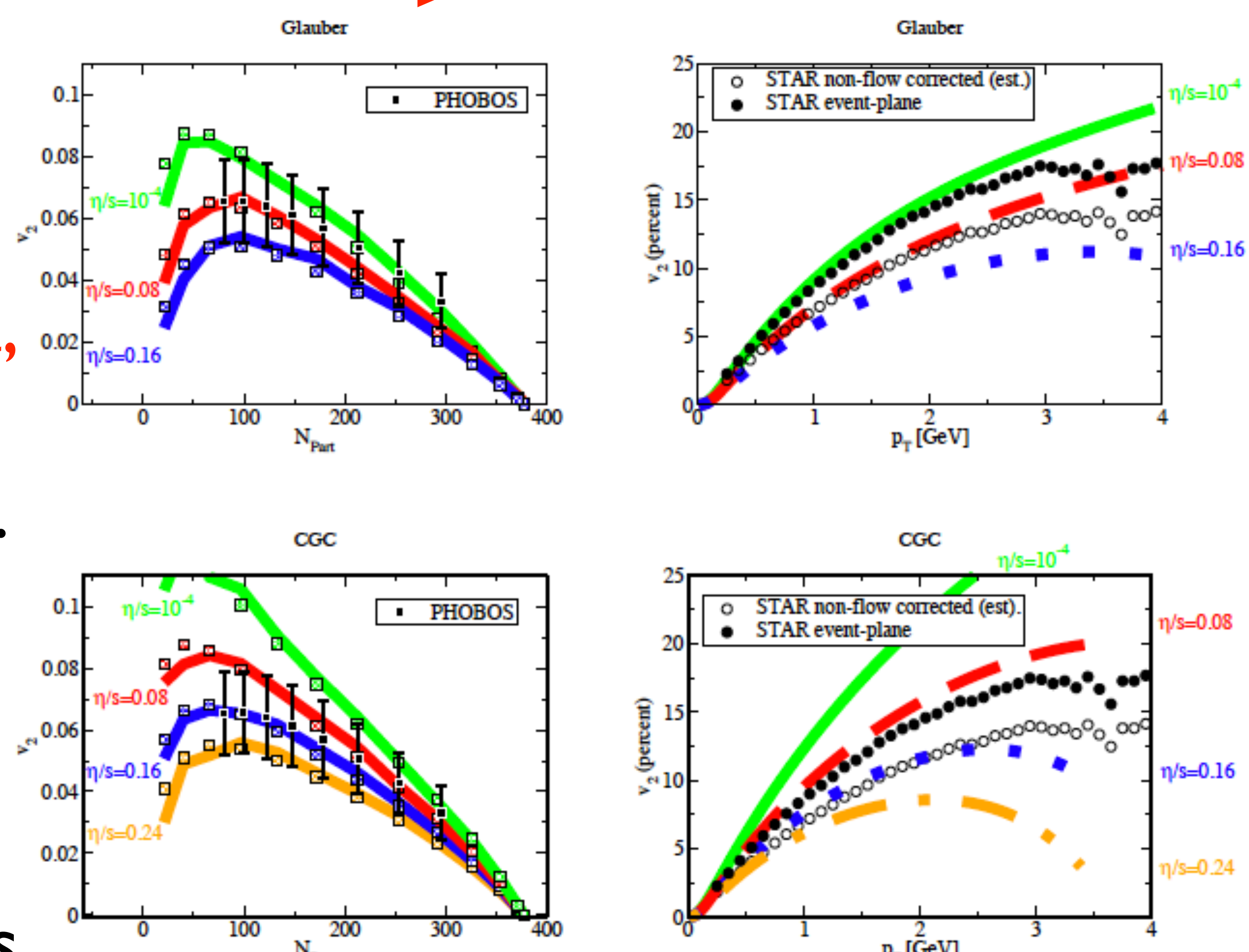


v_2 @ RHIC:



Viscous hydro





Luzum, Romatschke, '08

- Good comparison with data, (τ_0<1 fm/c!) but uncertainties: i.c., hadronization, fluctuations.
- Models with shadowing plus rescattering work (Pajares et al).
- Basis for background subtraction of non-flow effects.

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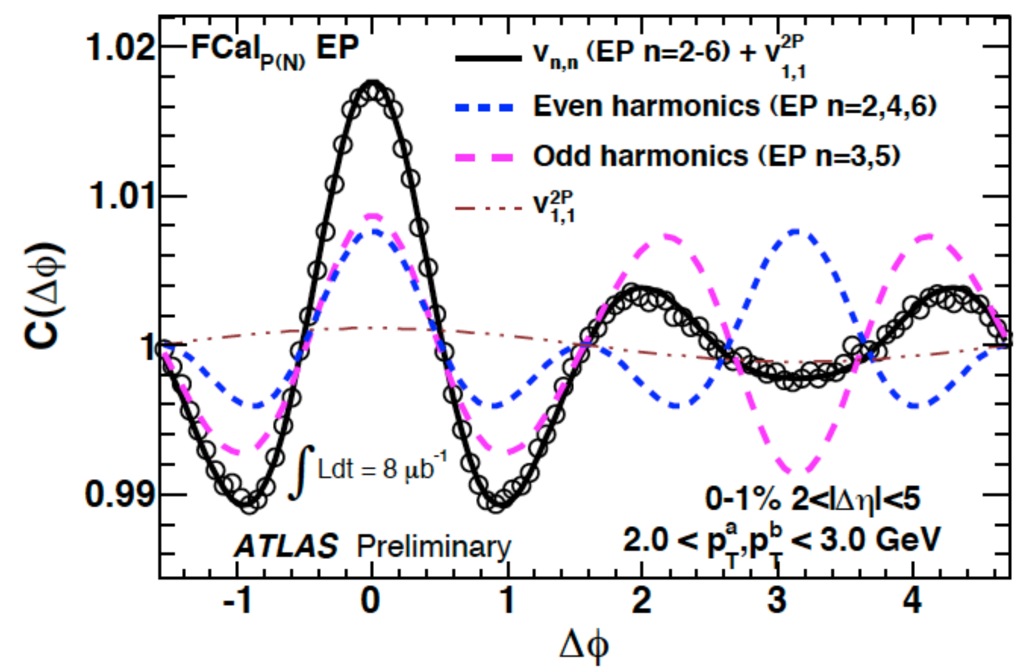

Fourier decomposition shows interplay of even and odd contributions:
"ridge" and "cone" appear as consequences of global event properties

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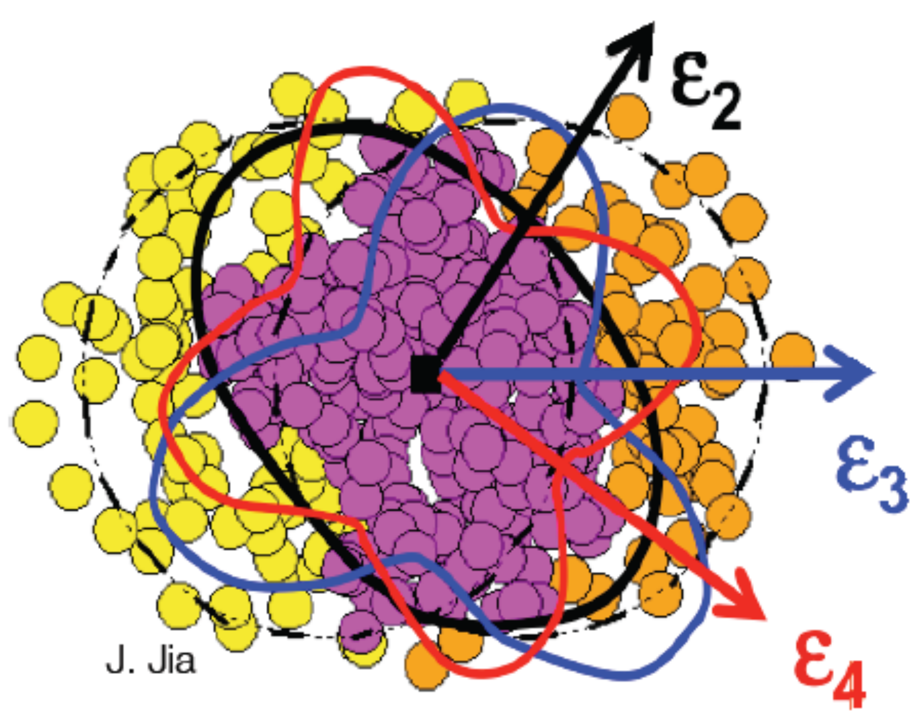

Hard probes:

$$R_{AA}(y, p_T) = \frac{\frac{dN_k^{AA}}{dydp_T}}{\langle N_{coll}\rangle \frac{dN_k^{NN}}{dydp_T}}$$ =1 if no nuclear effects

• Assume collinear factorization works for the reference (pp) and for the probe (in AA):

$$d\sigma[A+B \to h+X] \propto \int [dx] f_{i/A}(x_i) \otimes f_{j/B}(x_j) \otimes d\hat{\sigma}[i+j \to k+X](sx_ix_j) \otimes D[k \to h+X](z)$$

cold nuclear matter effects: nuclear pdf's

cold and hot nuclear matter effects

• pA, eA: check factorization and constrain cold nuclear matter effects.

• AB: (check factorization and) characterize the medium.

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cold nuclea
matter effec
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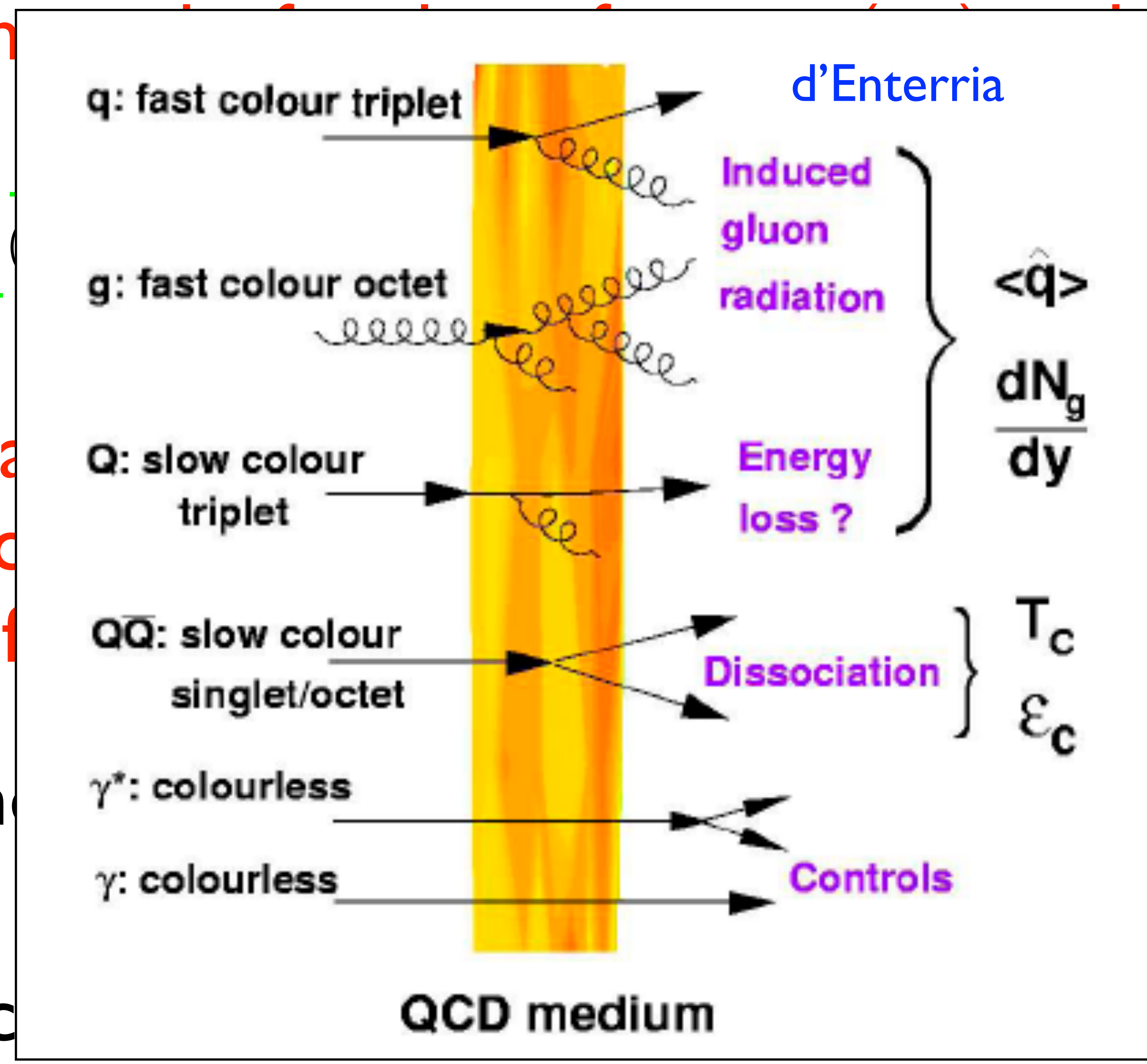
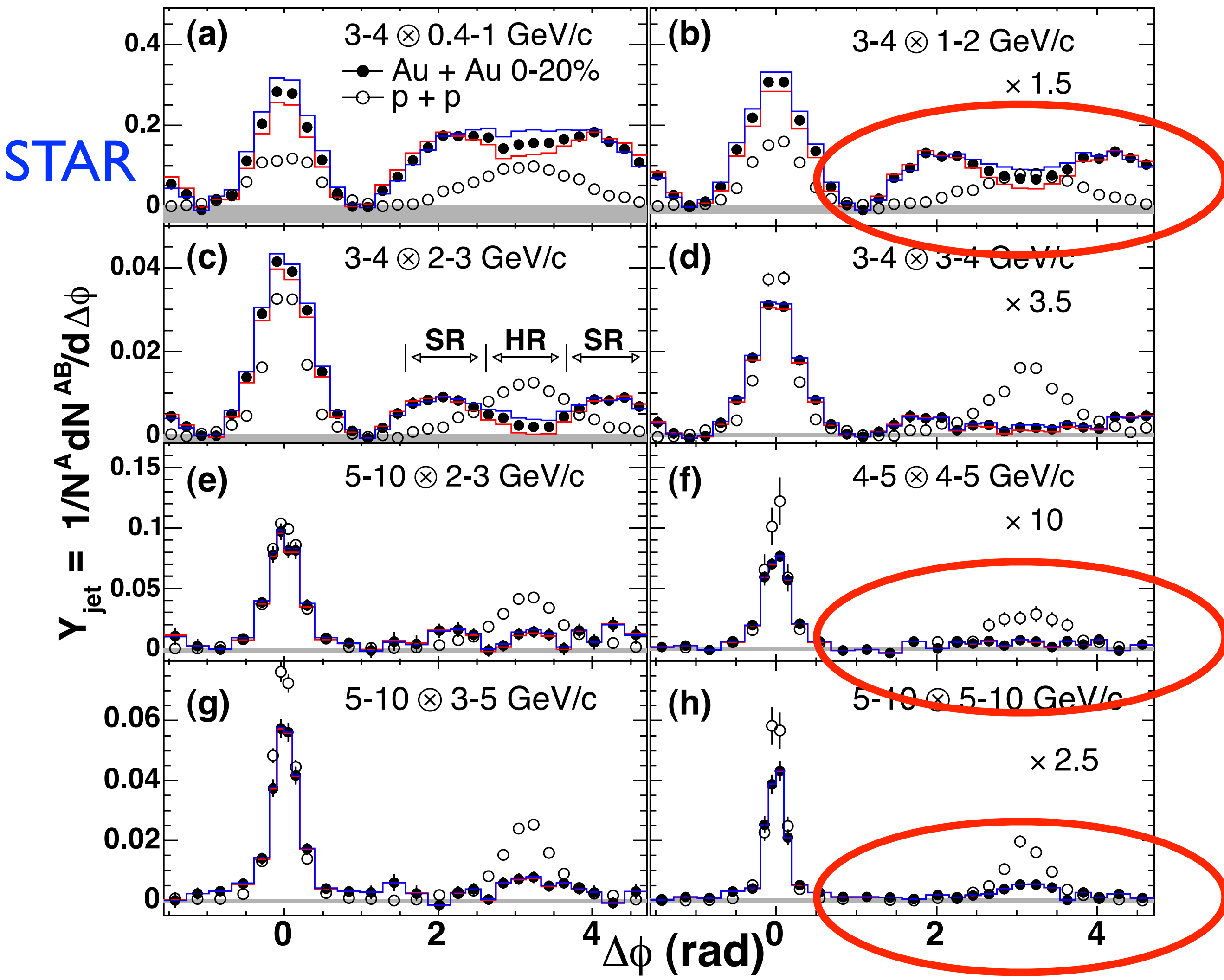
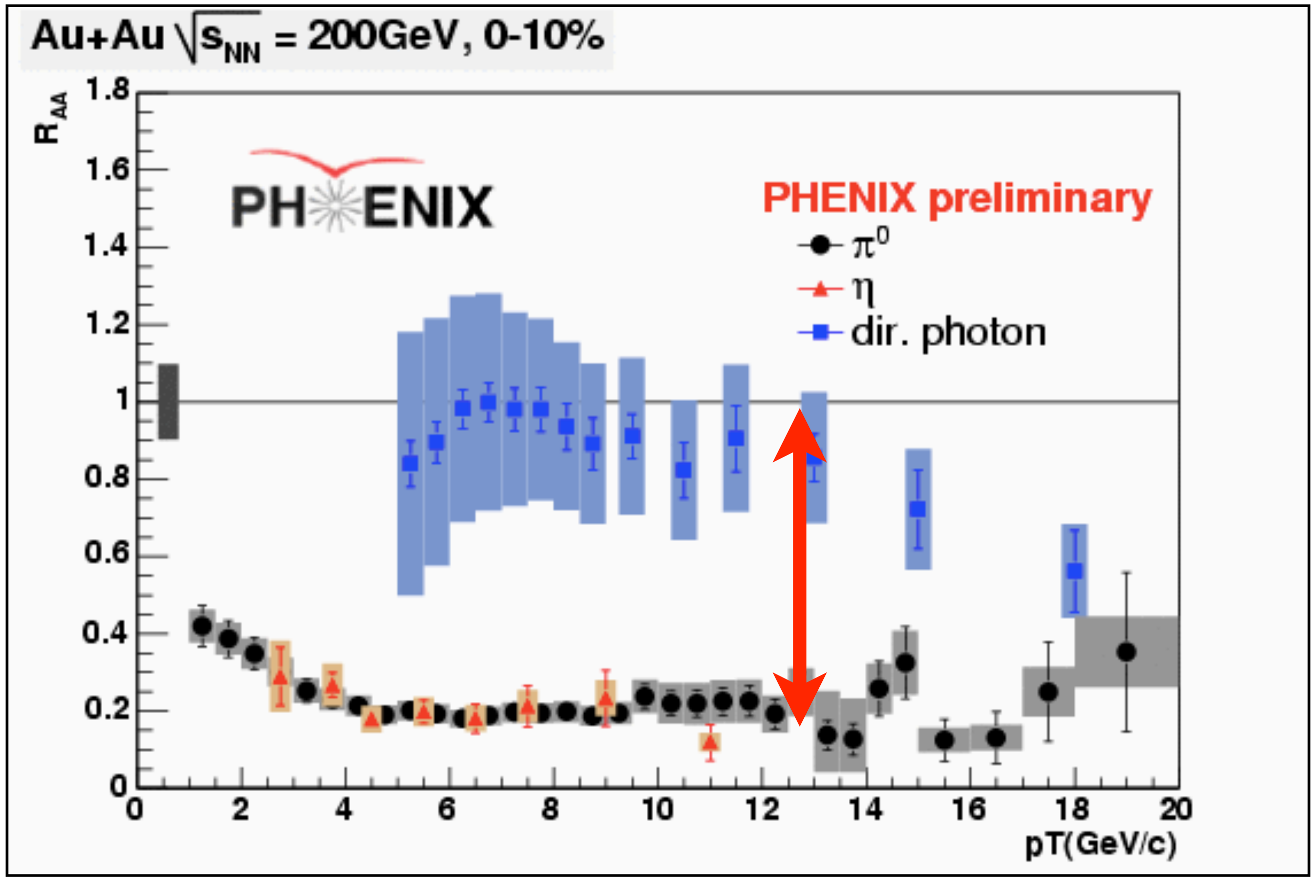
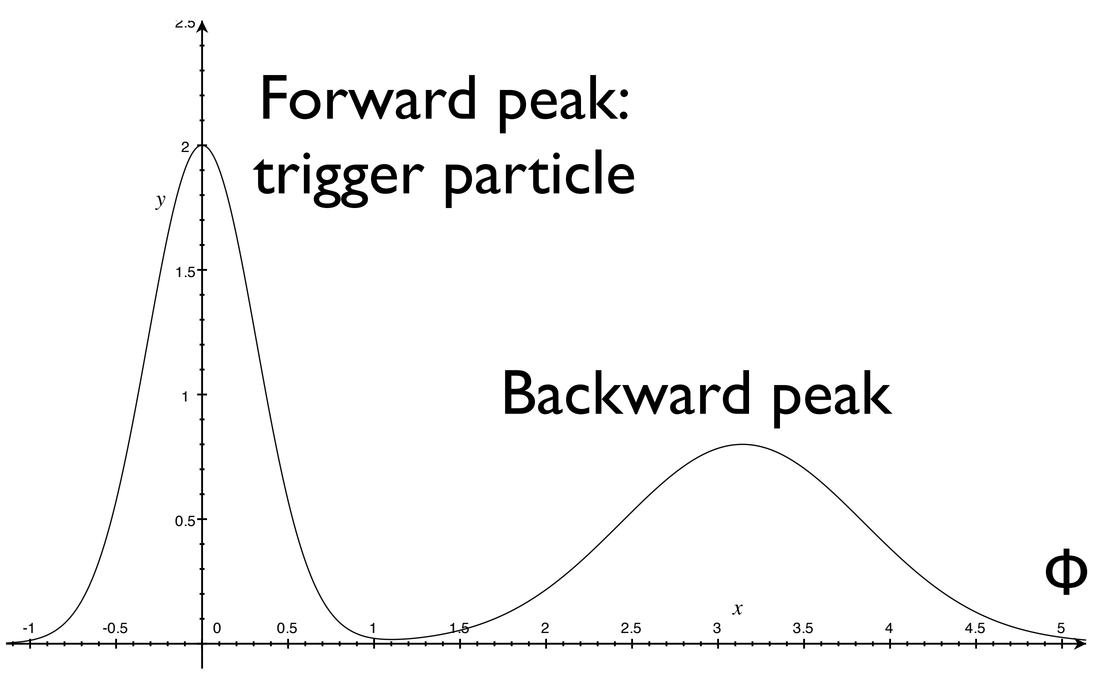


High-pT @ RHIC:







- Data well described by models implementing radiative energy loss.
- Other possibilities: collisional, hadronic rescattering, strong color fields, drag,...
- Jets @ RHIC suffer from huge background: dAu?

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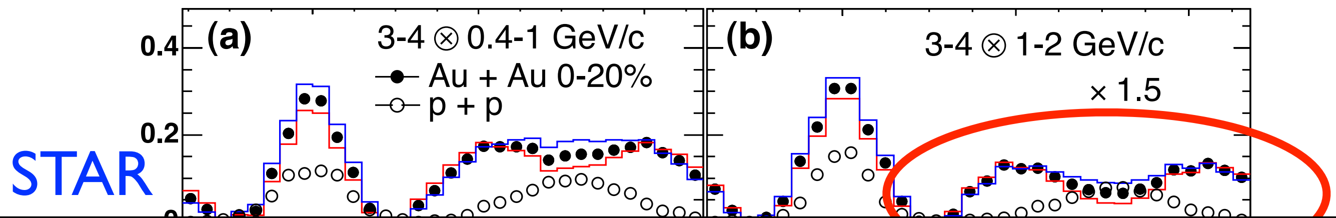

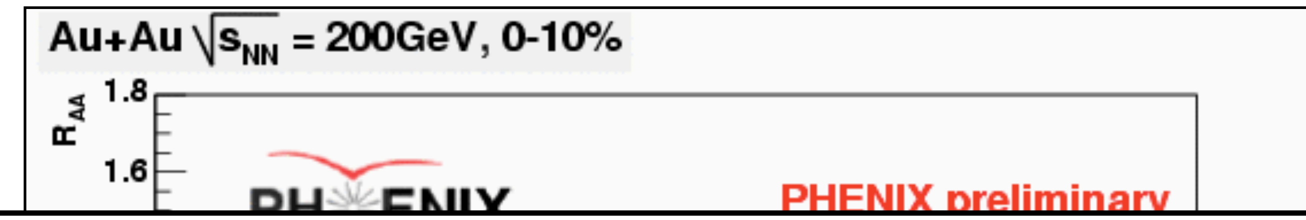

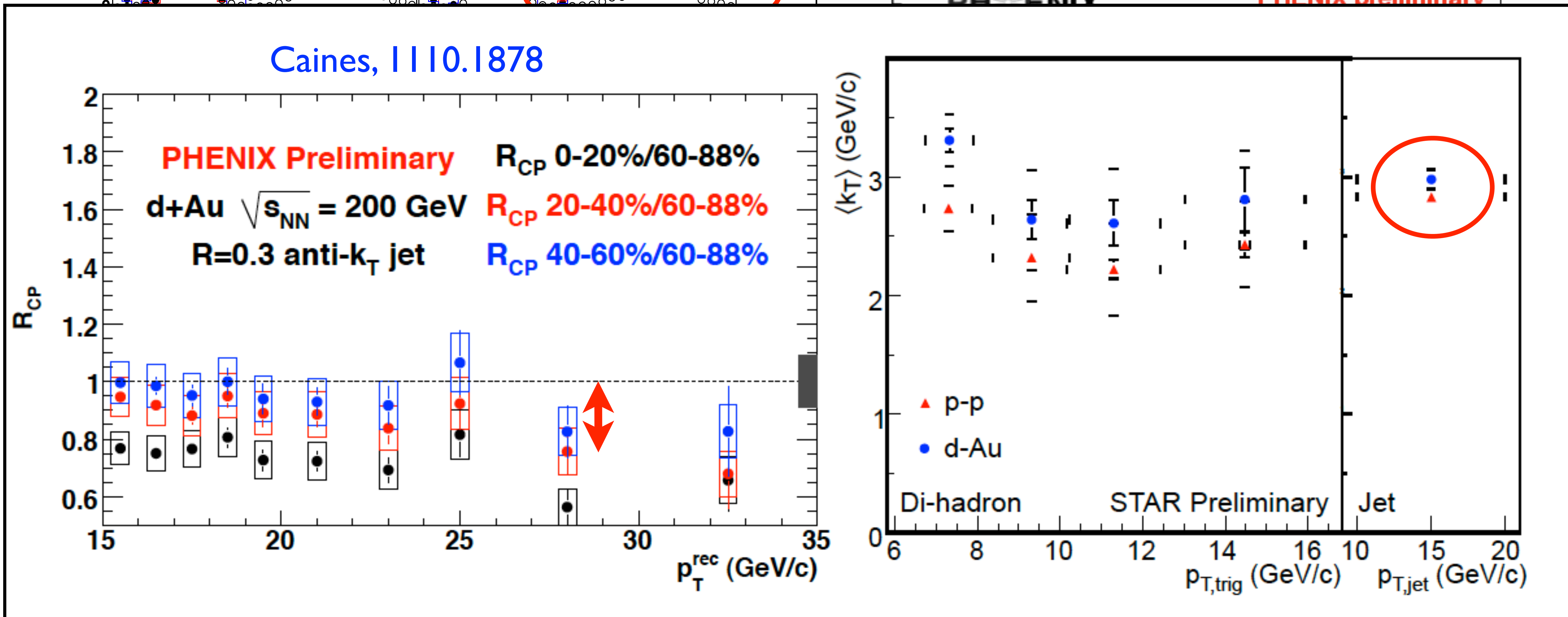

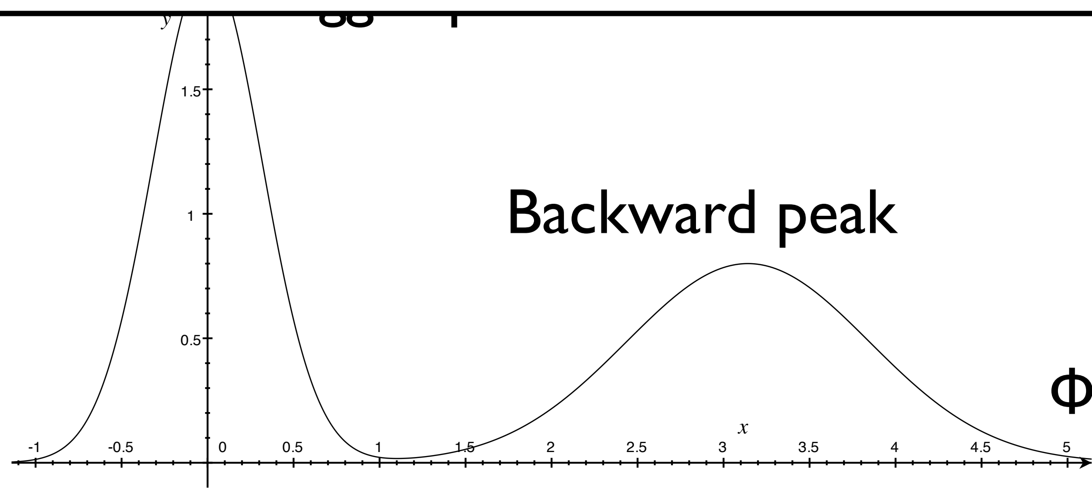

• Other possibilities: collisional, hadronic rescattering, strong color fields, drag,...

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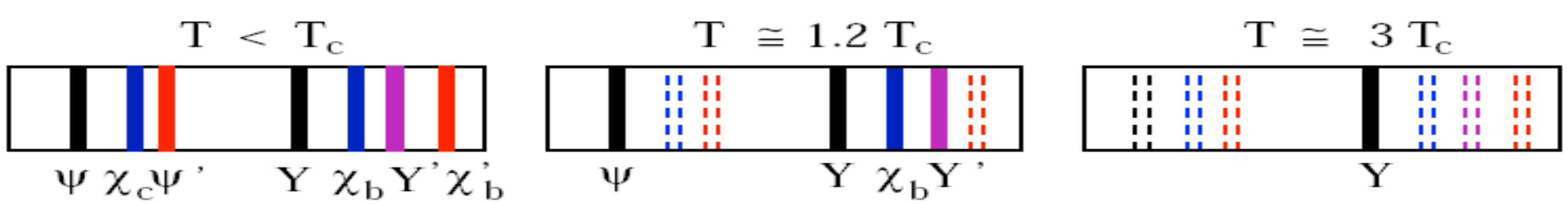
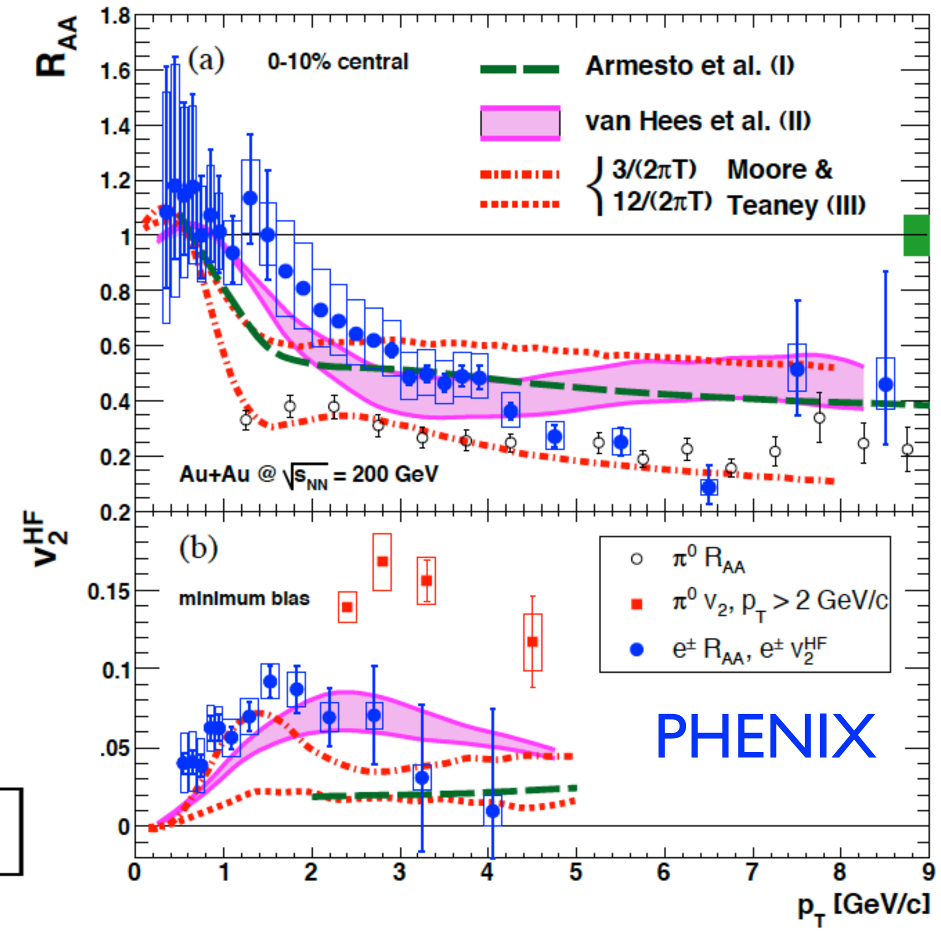
Open problems: HQ and QQbar

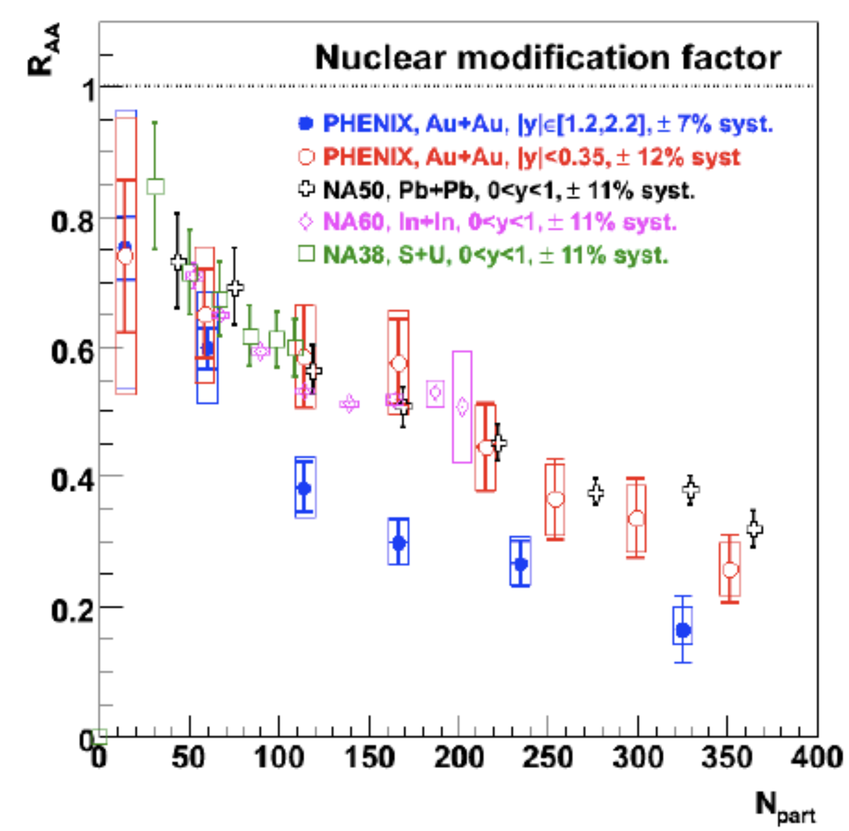
- Heavy quarks: radiative eloss predicts (expansion in m_Q/E) $\Delta E(g) >_{[\text{color charge}]} \Delta E(q) >_{[\text{mass effect}]} \Delta E(Q)$.
- $R_{AA}^{e} \sim R_{AA}^{\pi}$ at RHIC!!! b+c contributions mixed.



- Quarkonium:
  * Dissociation by screening in the plasma: thermometer?
  * Dissociation by comovers.
  * Regeneration (c+cbar→J/ψ,...).
  * Scaling with N_{part}.
  * Larger forward suppression?!



Electrons from HQ



J/ψ

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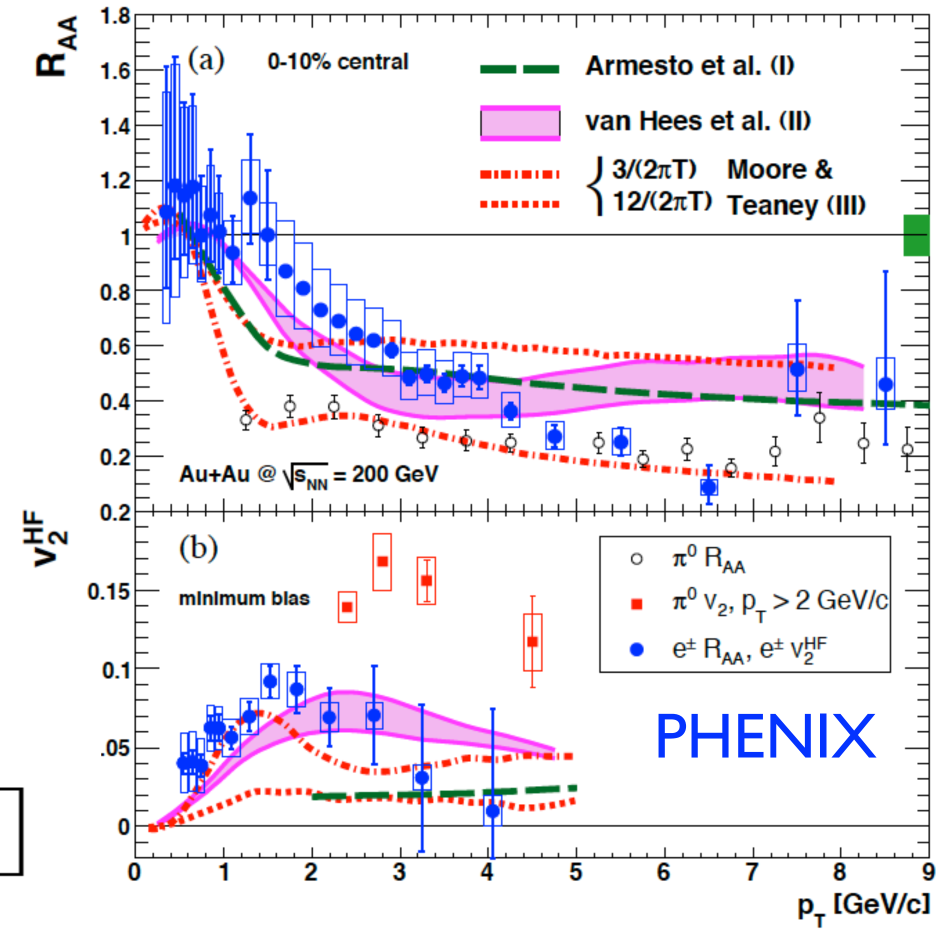

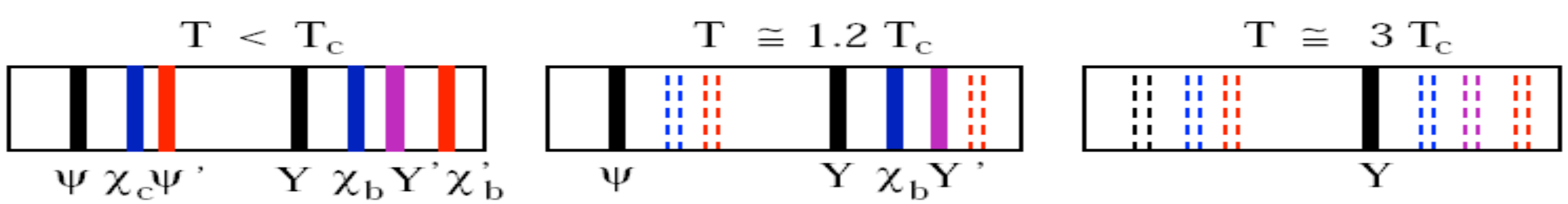

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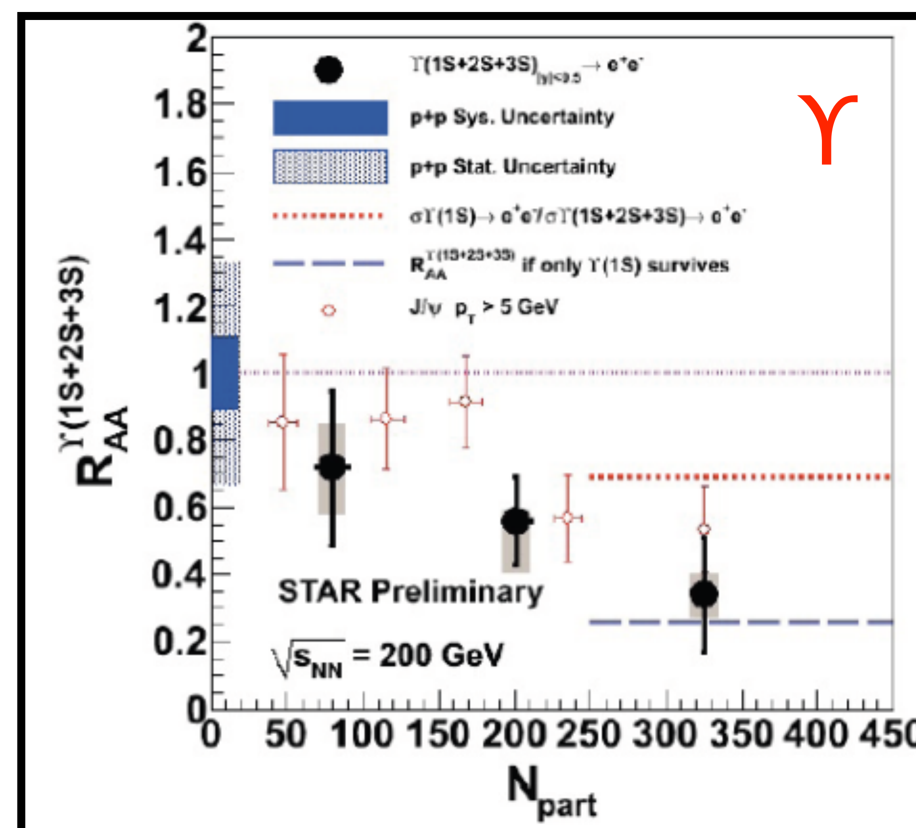

Open problems: theory

- Multiplicities lack of a firm theoretical framework: perturbative techniques?
- Initial conditions for hydro/transport: fast isotropization/ thermalization, transport coefficients, weak or strong coupling.
- Theory developments: CGC, AdS/CFT applied to HIC.
- High p_T: relation density ↔ medium modeling, refine theoretical

tools for radiative eloss (Monte Carlo, coherence - talks by Pérez-Ramos and Casalderrey, in-medium jet calculus), jet reconstruction.

- P and CP violation in the QGP (θ-term): CME → charge asymmetry with respect to the reaction plane.
- P violation in the hadronic phase modifyies $\gamma^{(*)}$ dispersion relations and yields (Andrianov, Espriu, Planells).
- Elongated structures in pseudorapidity: the ridge.

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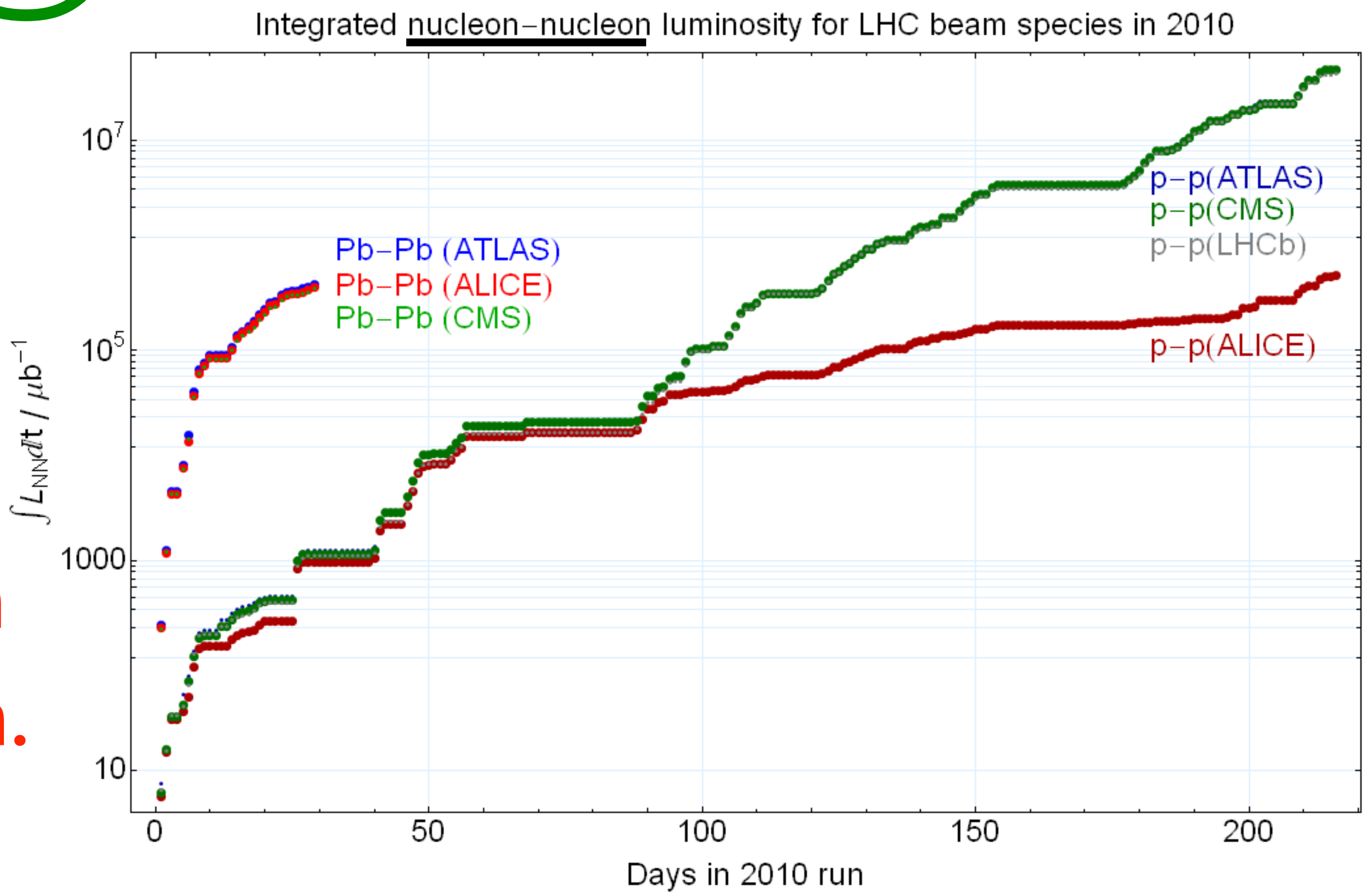


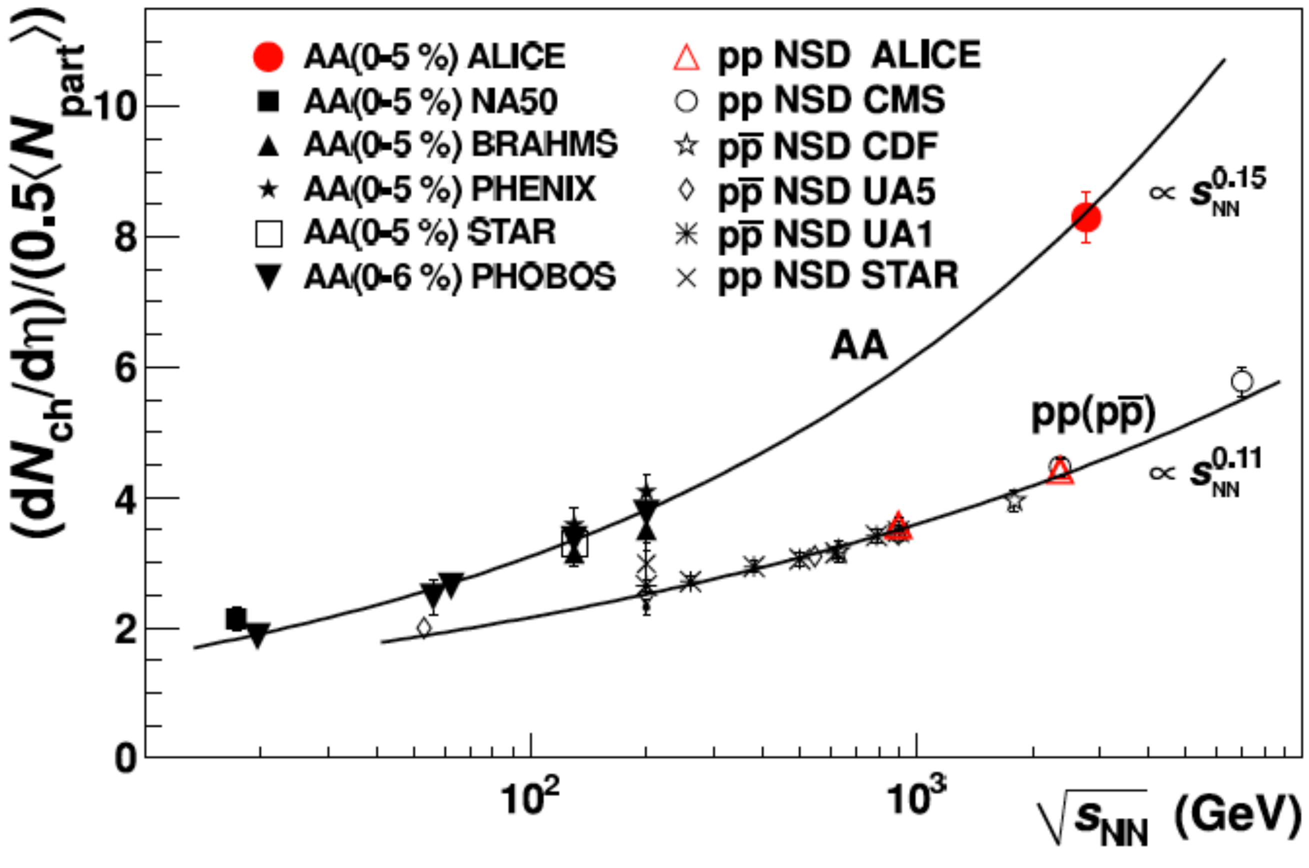
- LHC started accelerating ion beams on 04.11. 2010: $\sqrt{s}$=2.76 TeV/n. 1st collisions in 4 days.

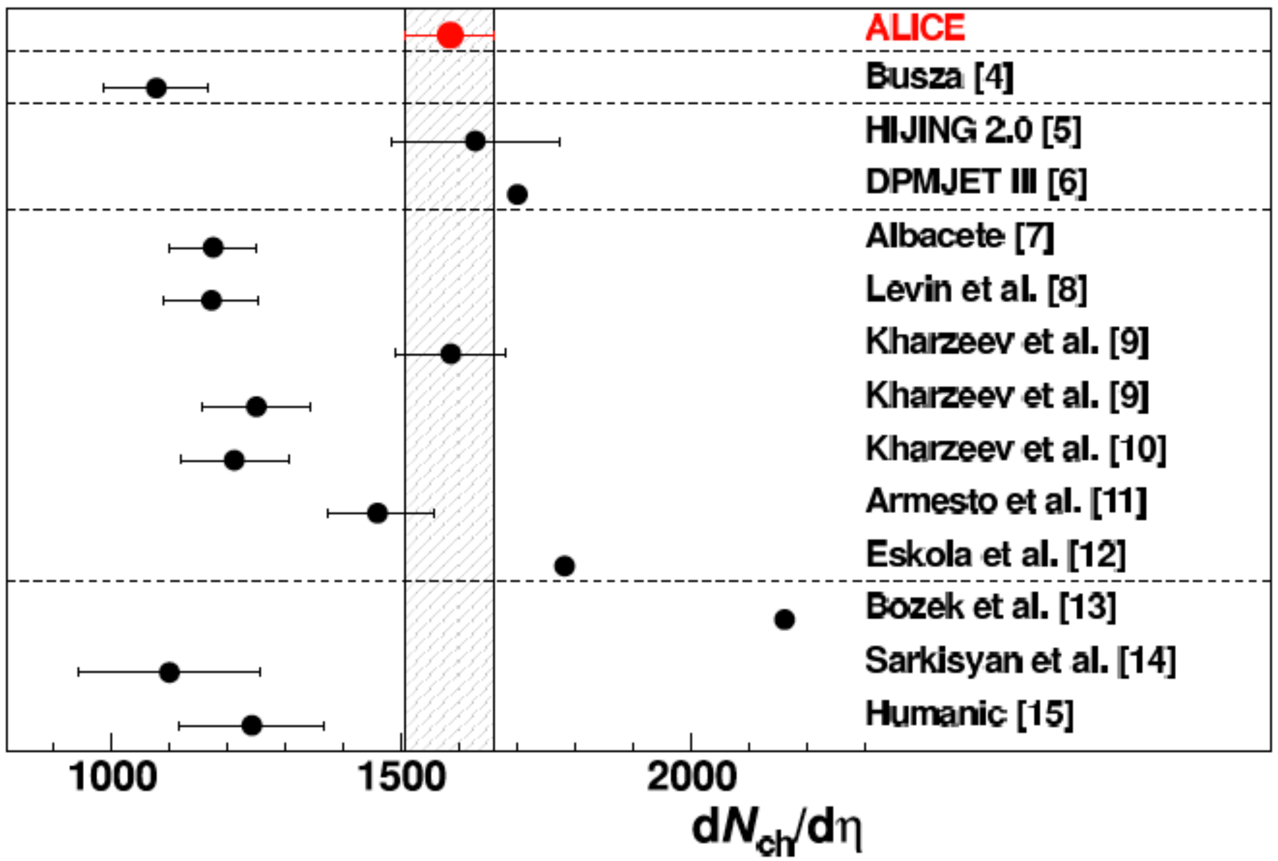
- Now ~ 10^8 recorded events in ALICE+ATLAS+CMS in 1 month.

- 16 papers until now:
  - * ALICE: 7 (2 on multiplicities, 2 on flow, 2 on jet quenching, 1 on interferometry).
  - * ATLAS: 4 (1 on multiplicities, 1 on elliptic flow, 1 on jets, 1 on J/ψ and Z).
  - * CMS: 5 (1 on jets, 1, on W/Z, 1 on correlations, 1 on QQbar, 1 on multiplicities).

+ many new results in QM2011(http://qm2011.in2p3.fr/).

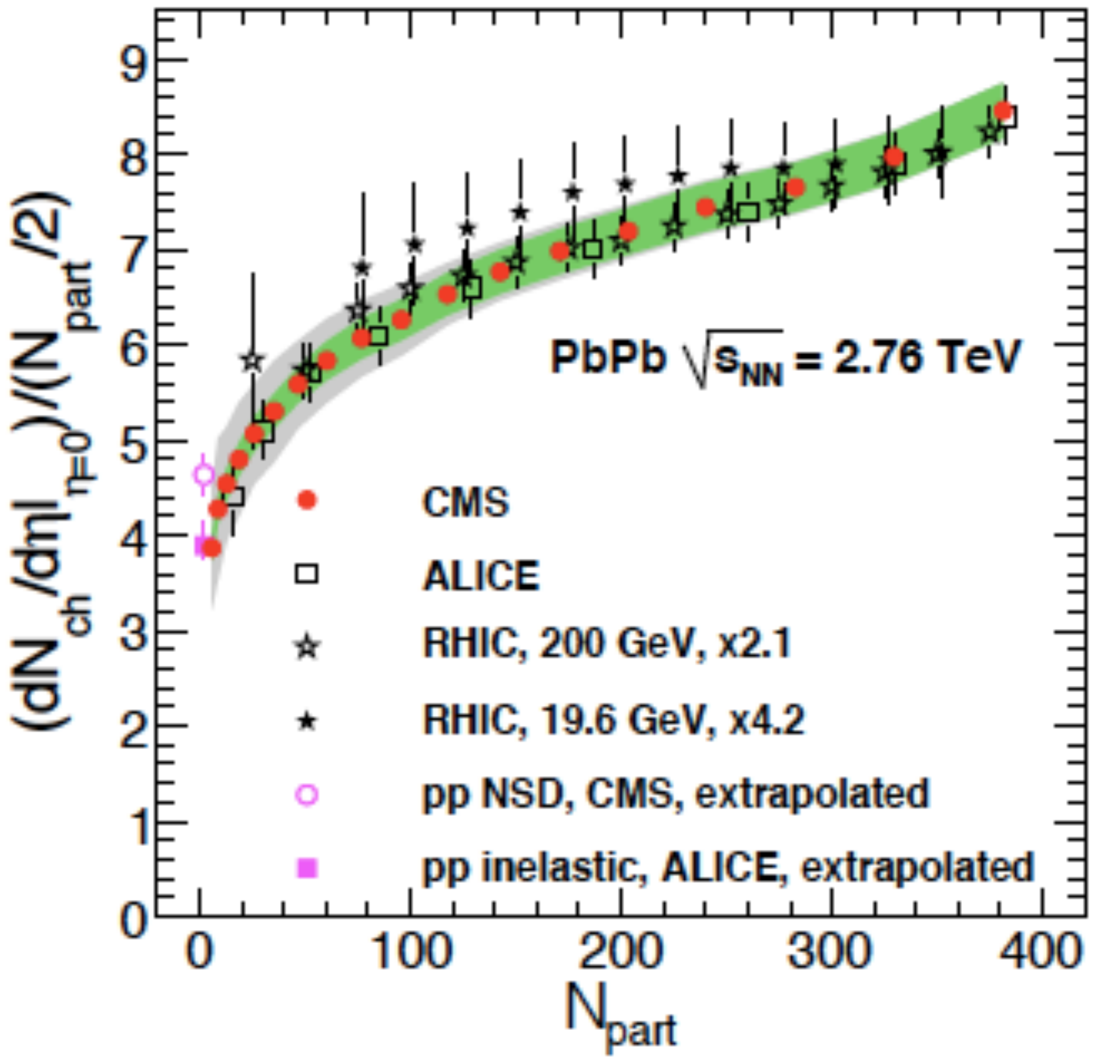
Data on multiplicities:



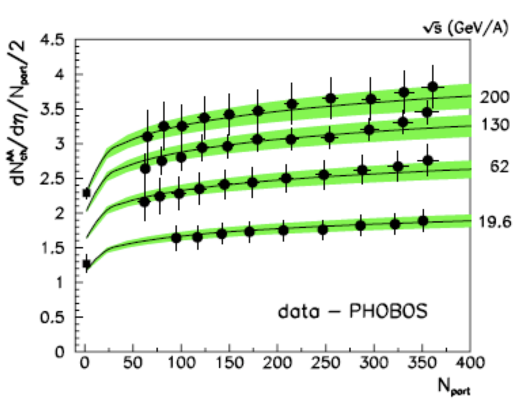


- Multiplicity larger than expected in data-driven extrapolations.
- In agreement with saturation models (based on the behavior of the small-x glue).
- Problems to reconcile the energy behavior of pp and AA (Dias de Deus et al., Capella et al.,...).

Data on centrality dependence:



• Behavior compatible with factorization between energy and centrality dependences, as suggested by saturation.



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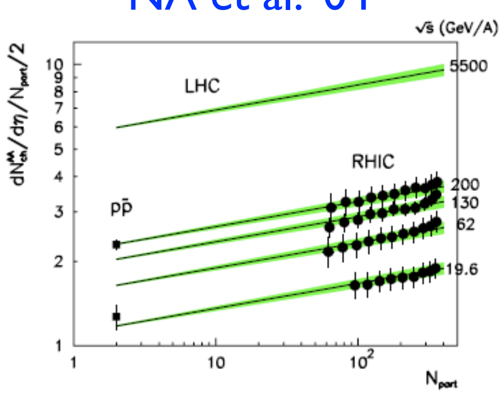
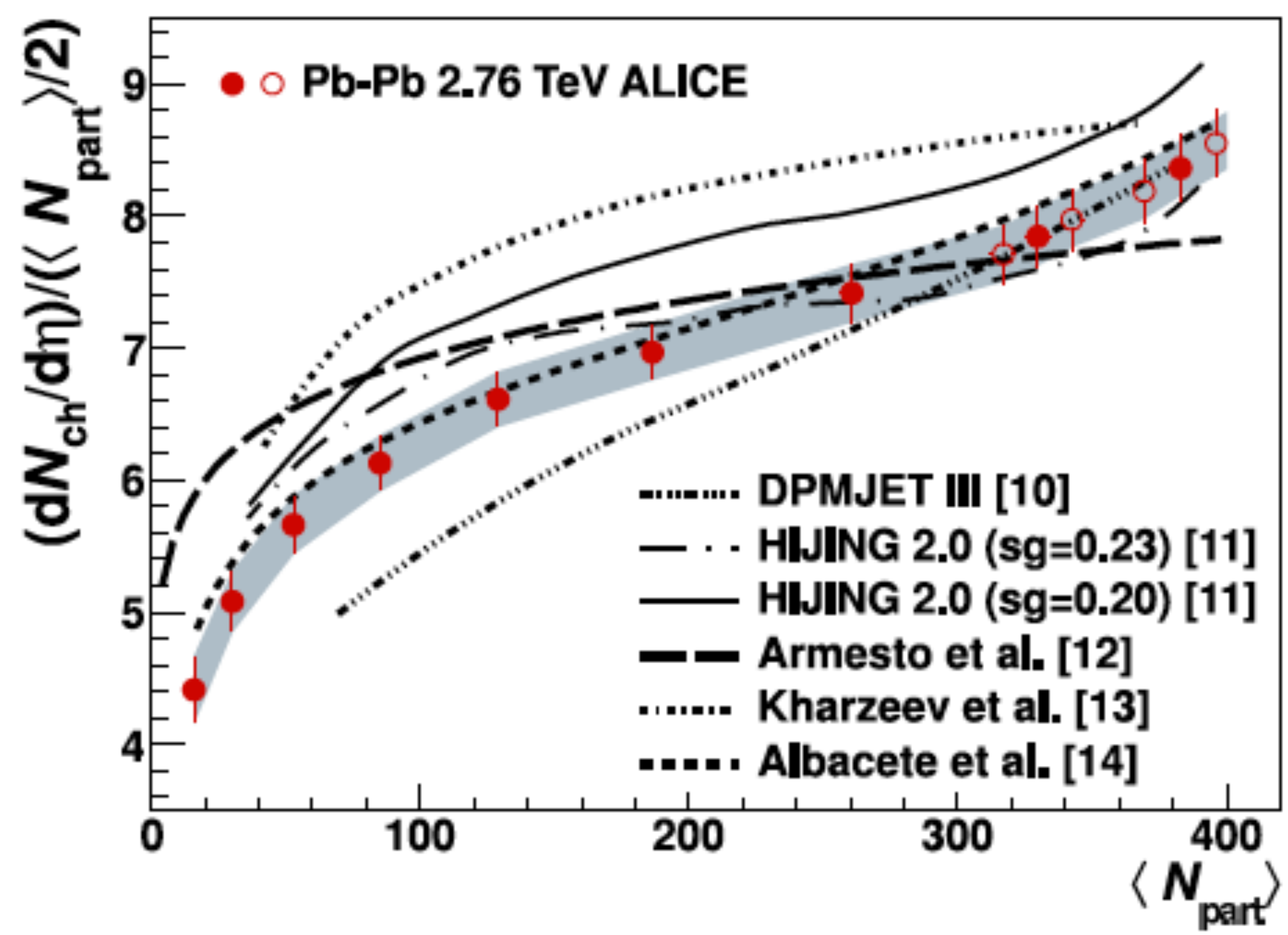
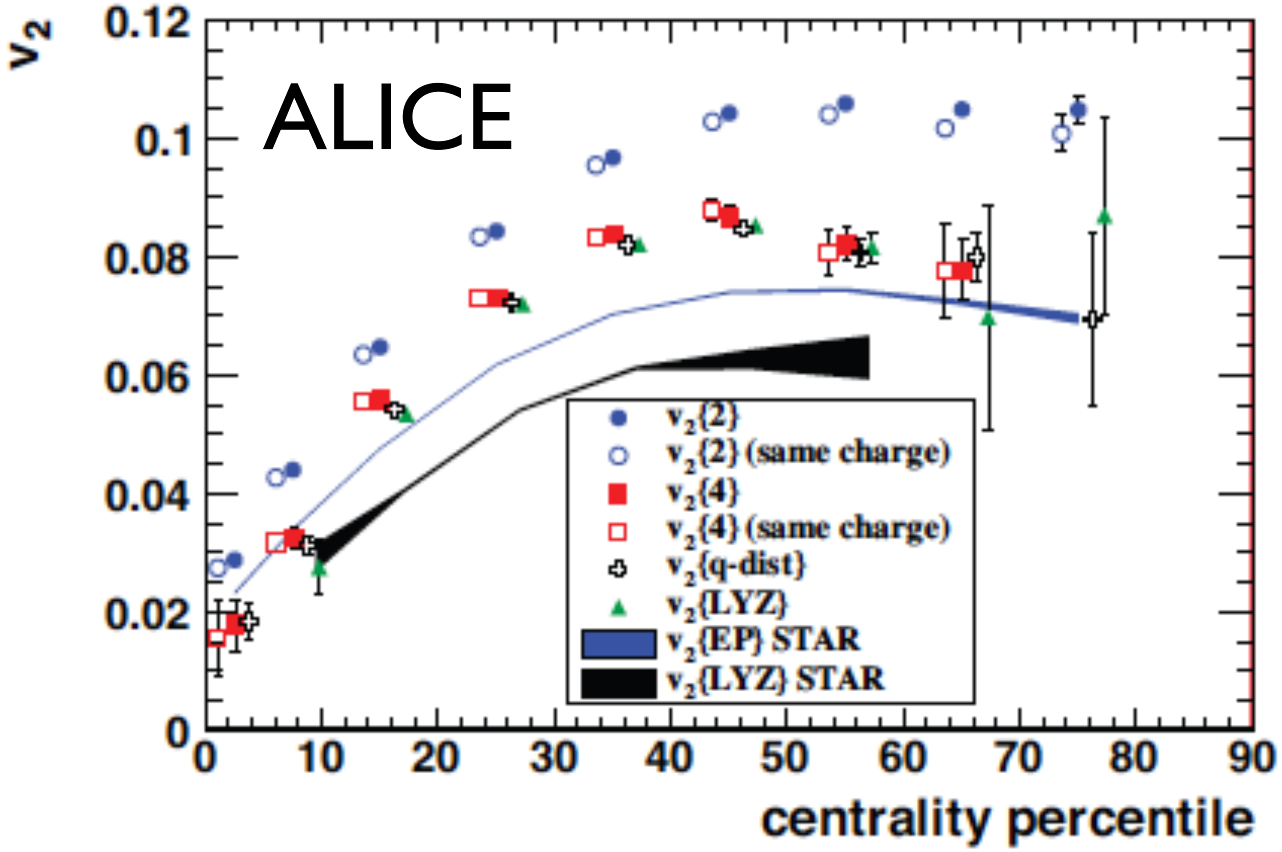
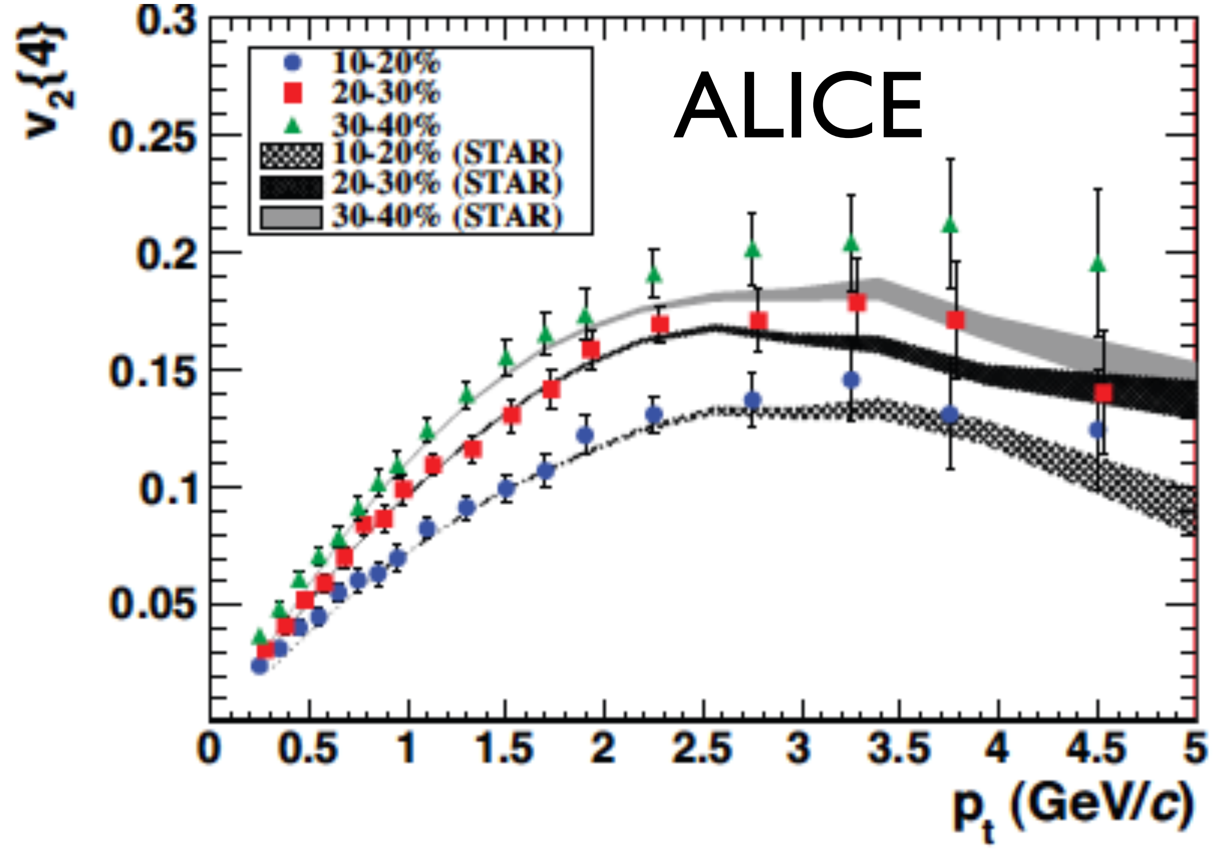


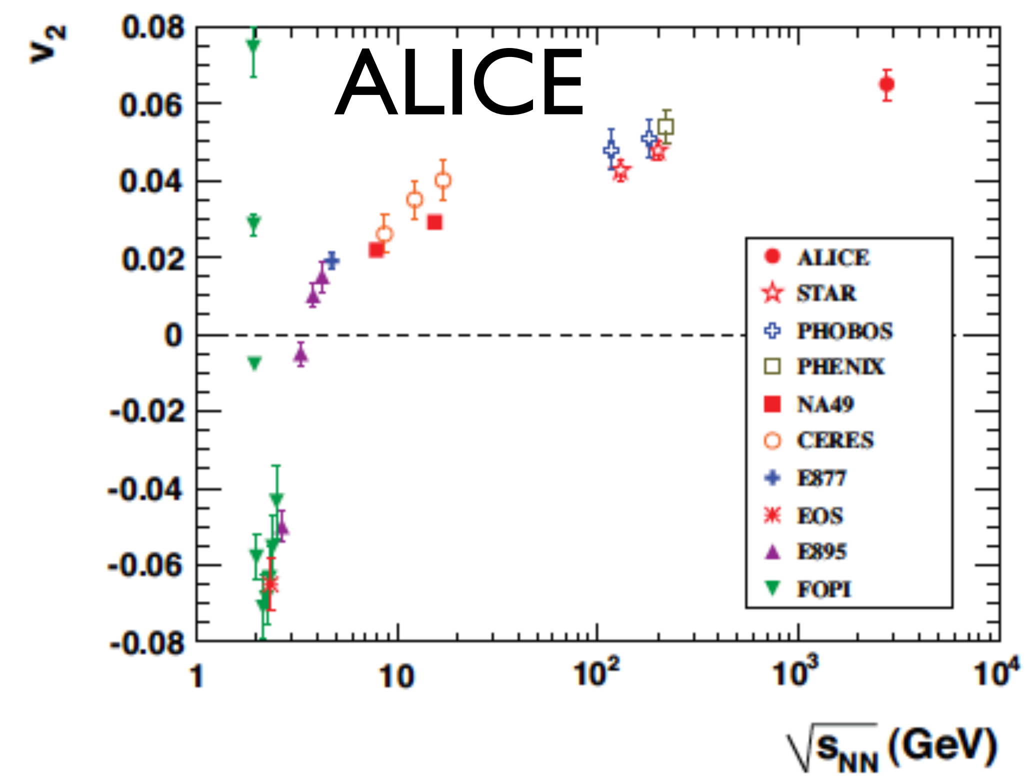


Azimuthal asymmetries:





- Behavior compatible with hydro assuming $\eta_{LHC} \gtrsim \eta_{RHIC}$.
- The scQGP claims remain.
- Many things to be settled; higher harmonics to constrain the initial condition and transport coefficients.



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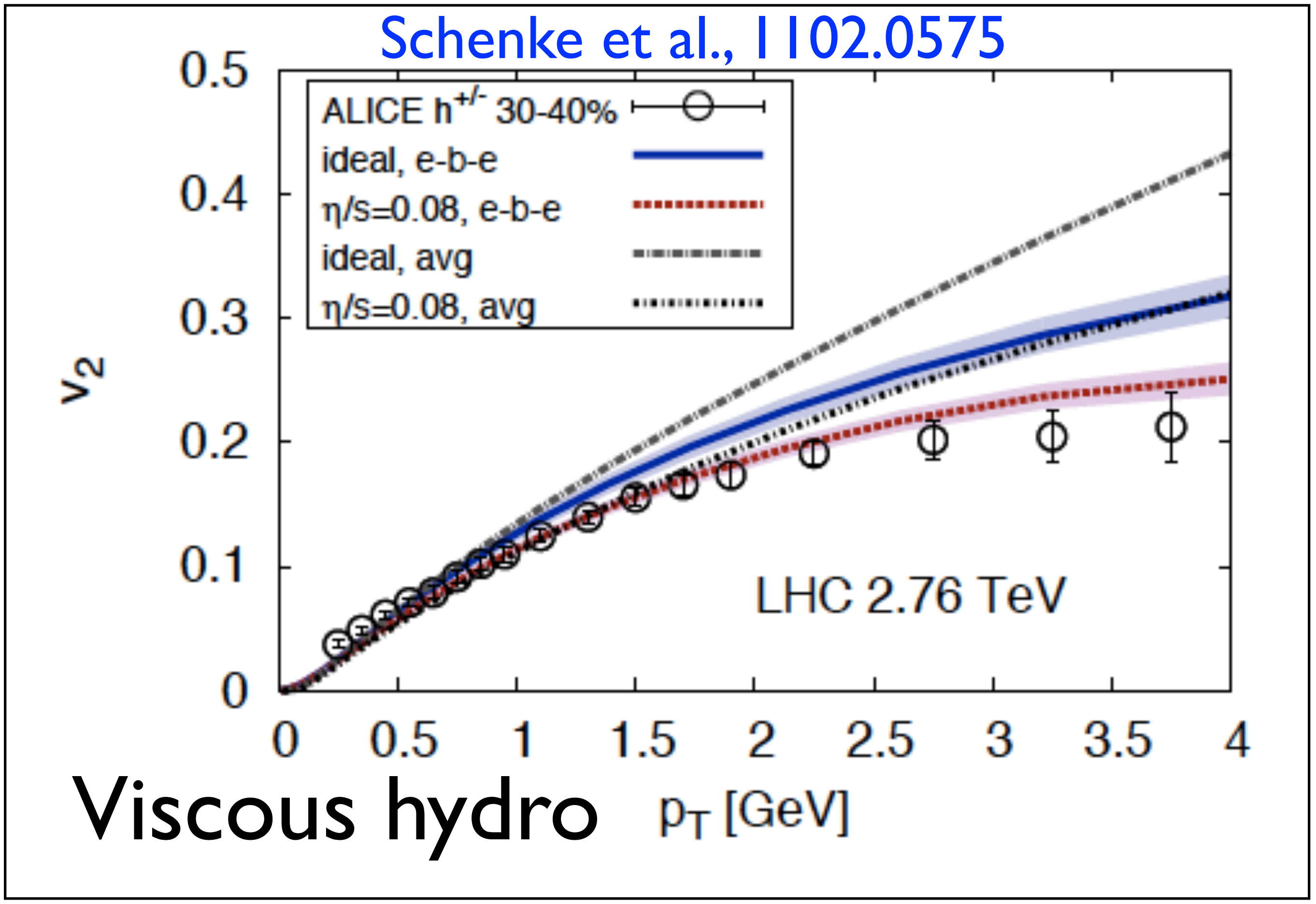

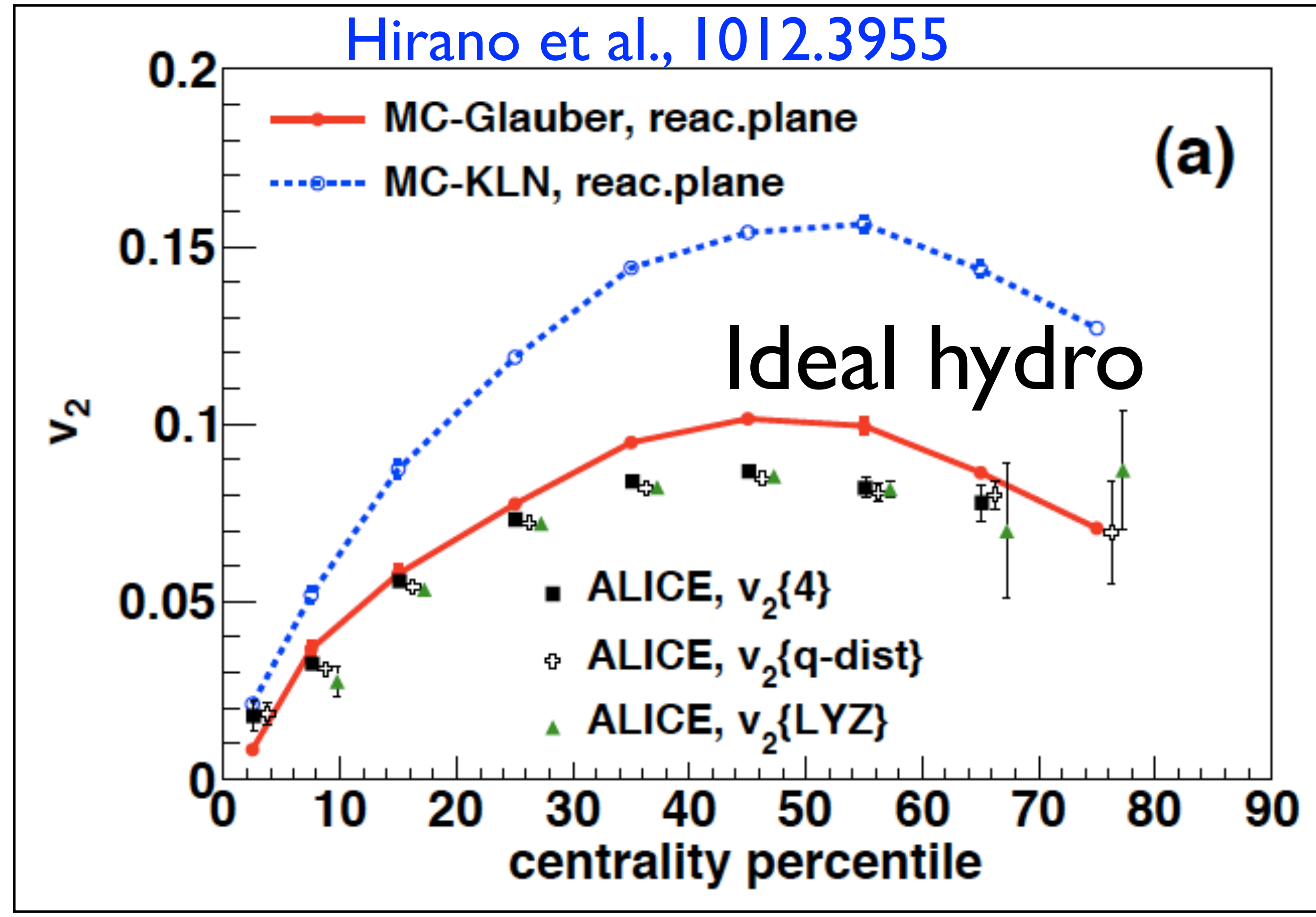

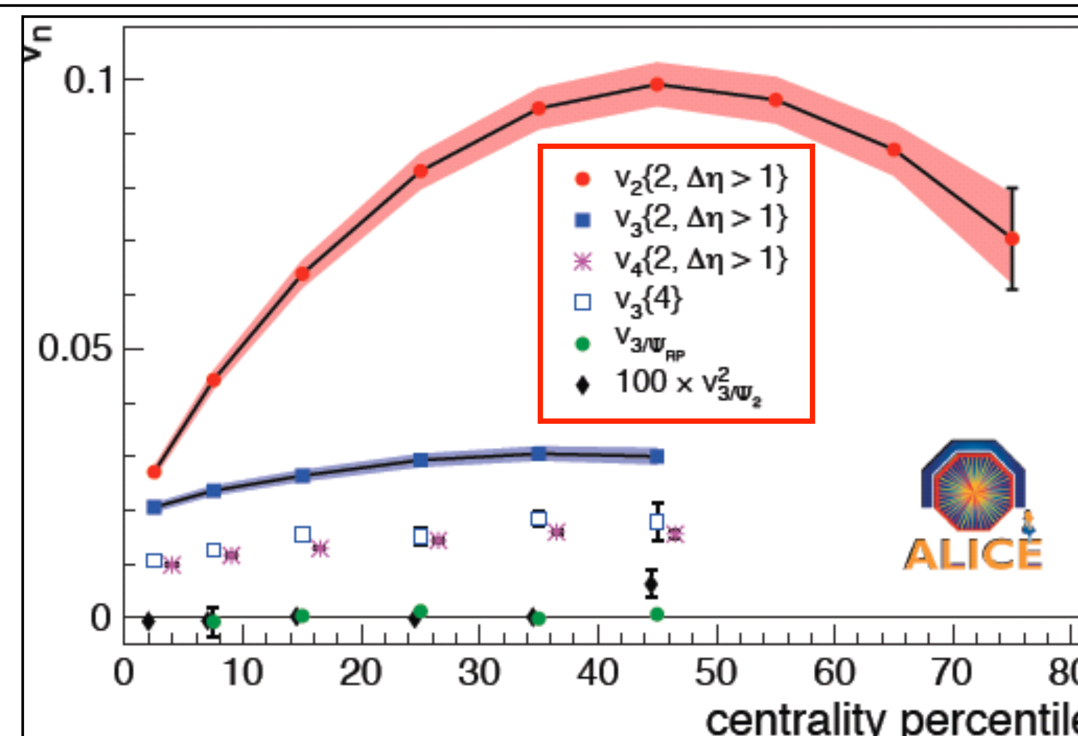

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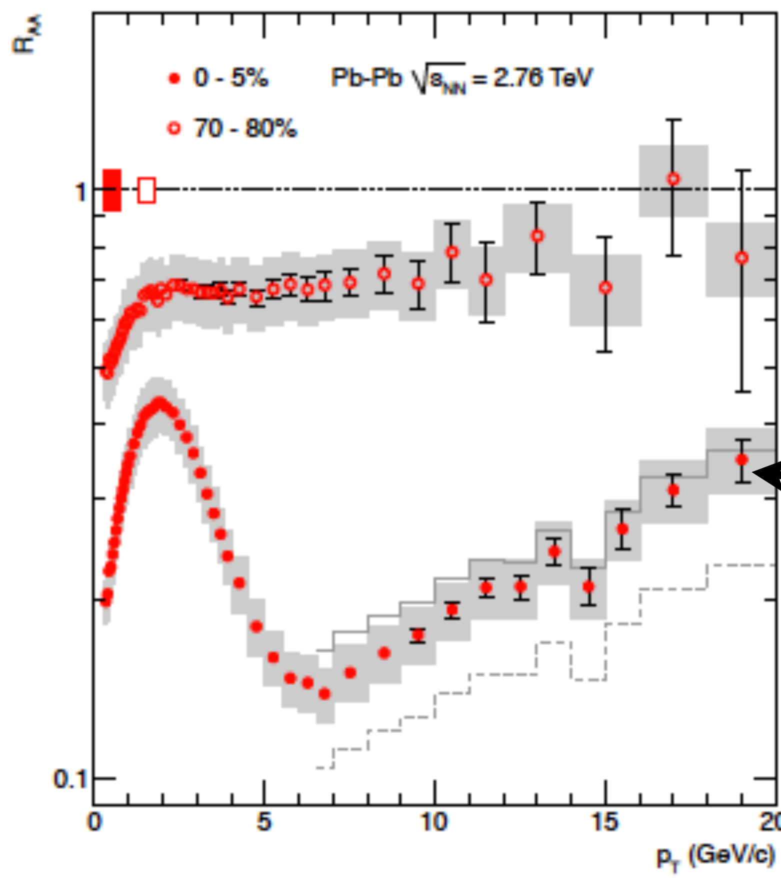
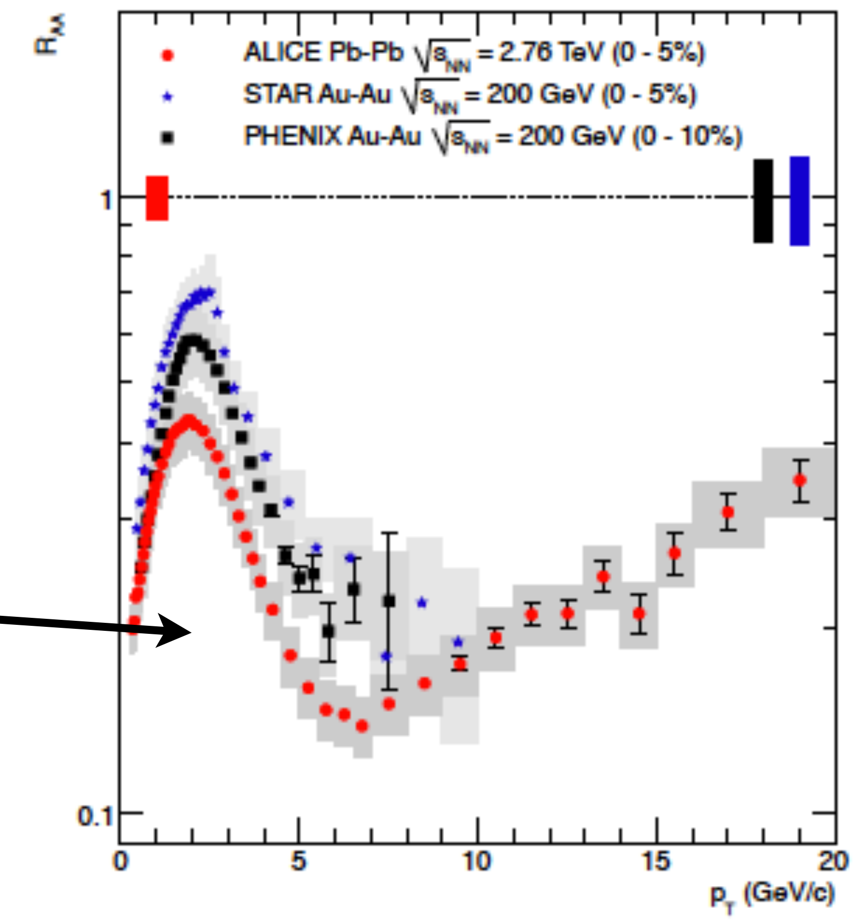
Results for R_{AA}:

$$R_{AA}(y,p_T)=\frac{\frac{dN_k^{AA}}{dydp_T}}{\langle N_{coll}\rangle\frac{dN_k^{NN}}{dydp_T}}$$



Interpolations using:
1.96 to 7
0.9 to 7
NLO QCD



- Behavior compatible with radiative eloss.
- Similar for charged hadrons, for D's, and for jets?!
- Reference crucial!!! (pp@2.76 TeV 03.11, ~10^7 coll/exp, only used till now in QQbar and back-to-back correlations in ALICE).

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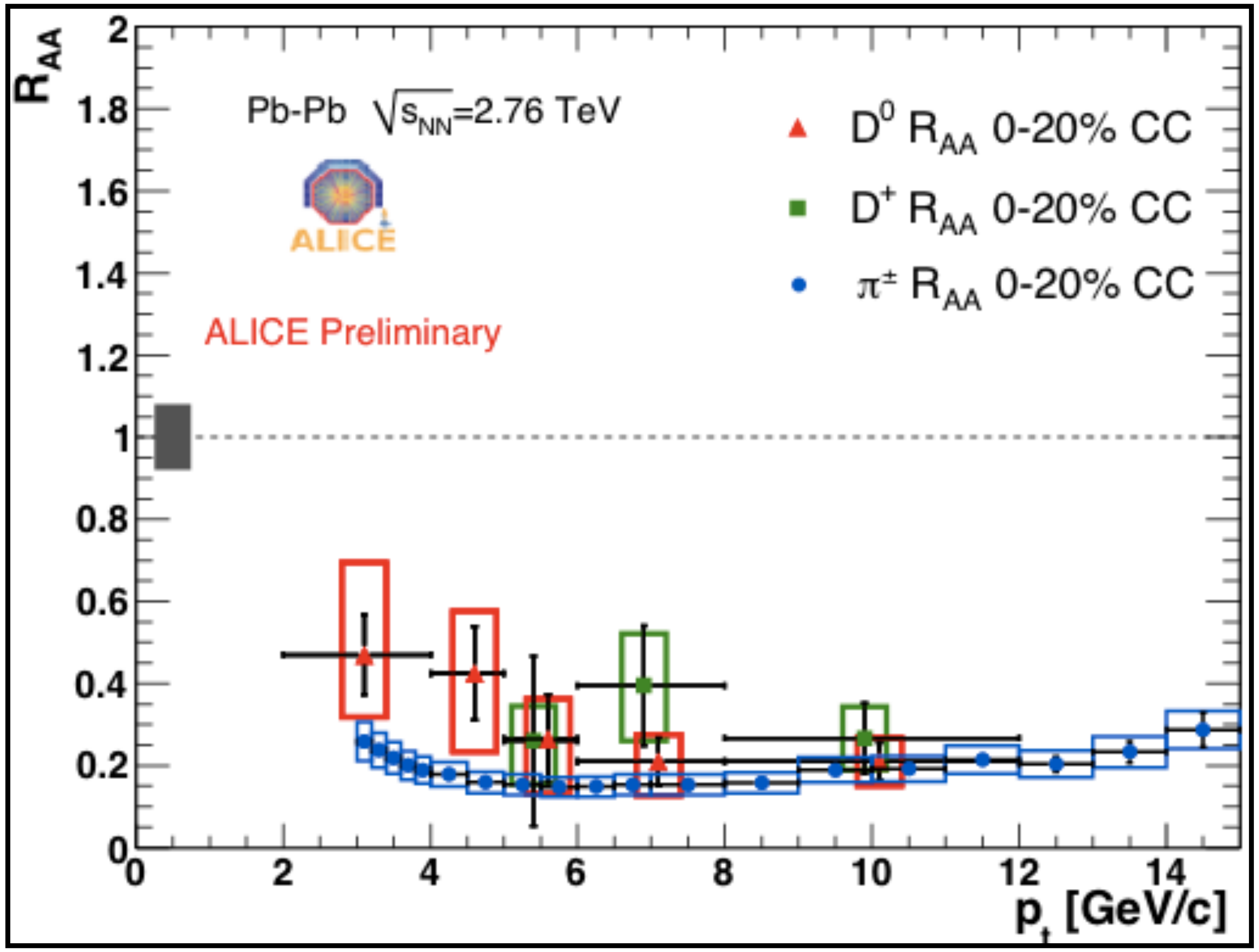

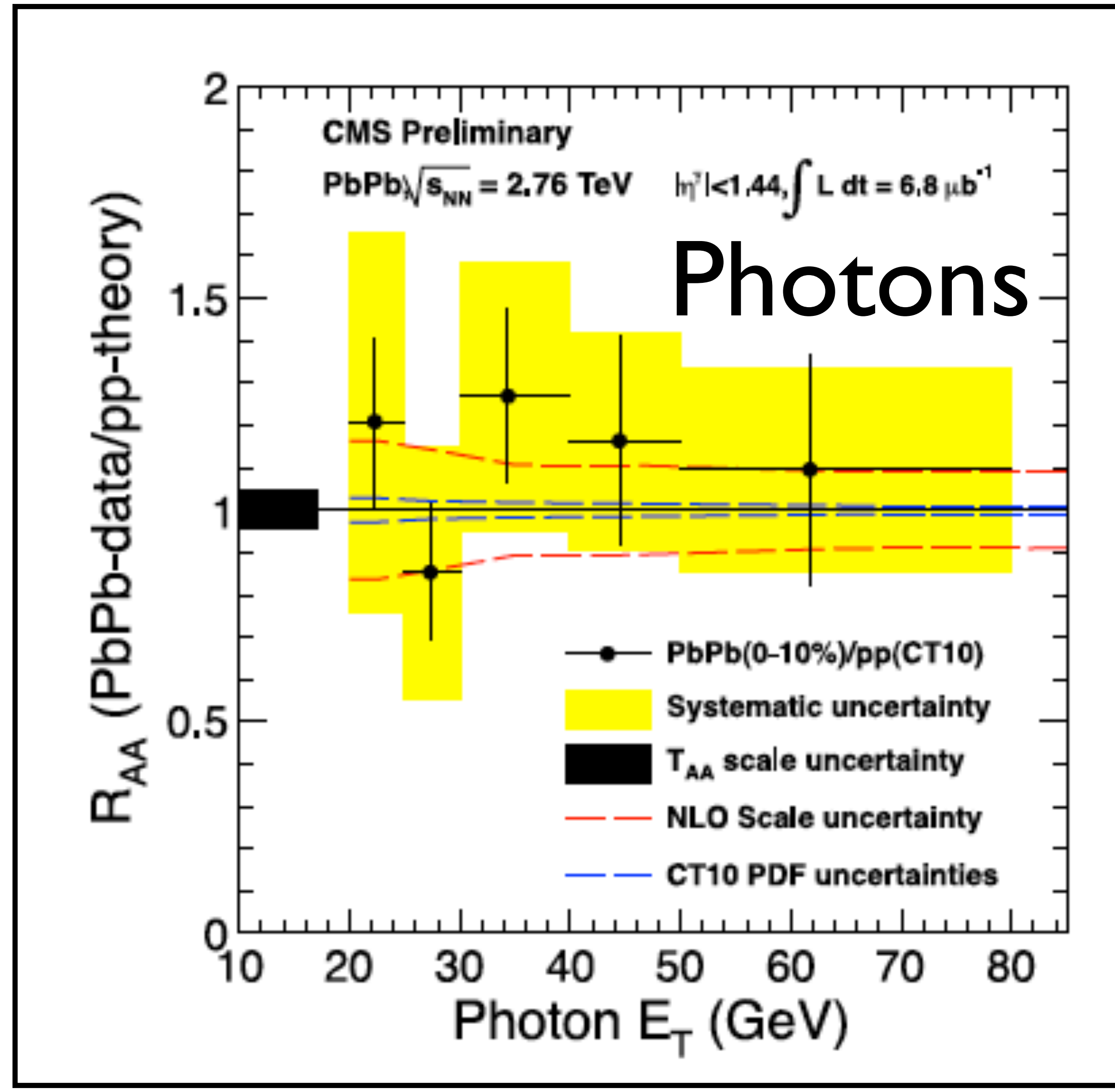

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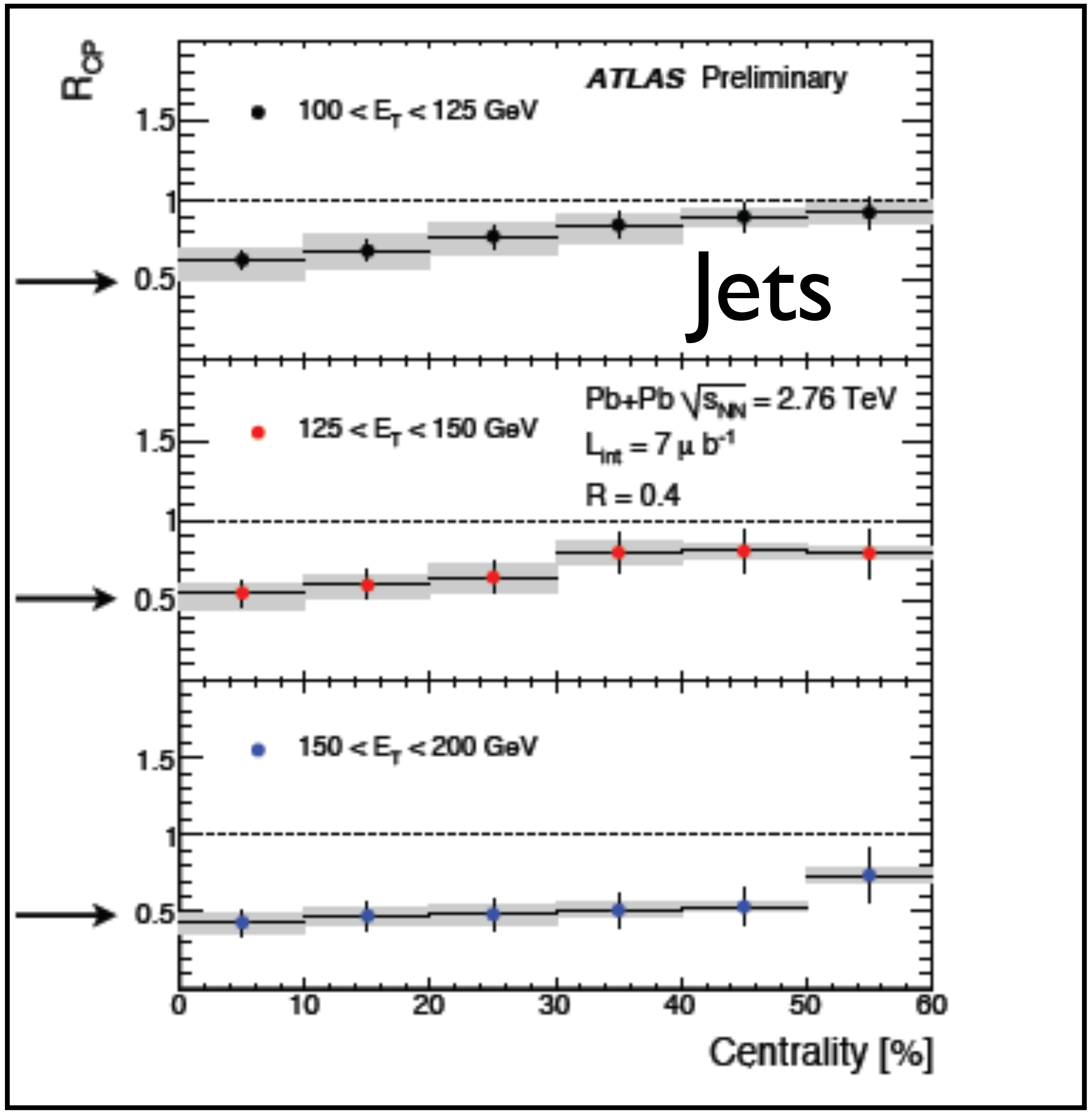

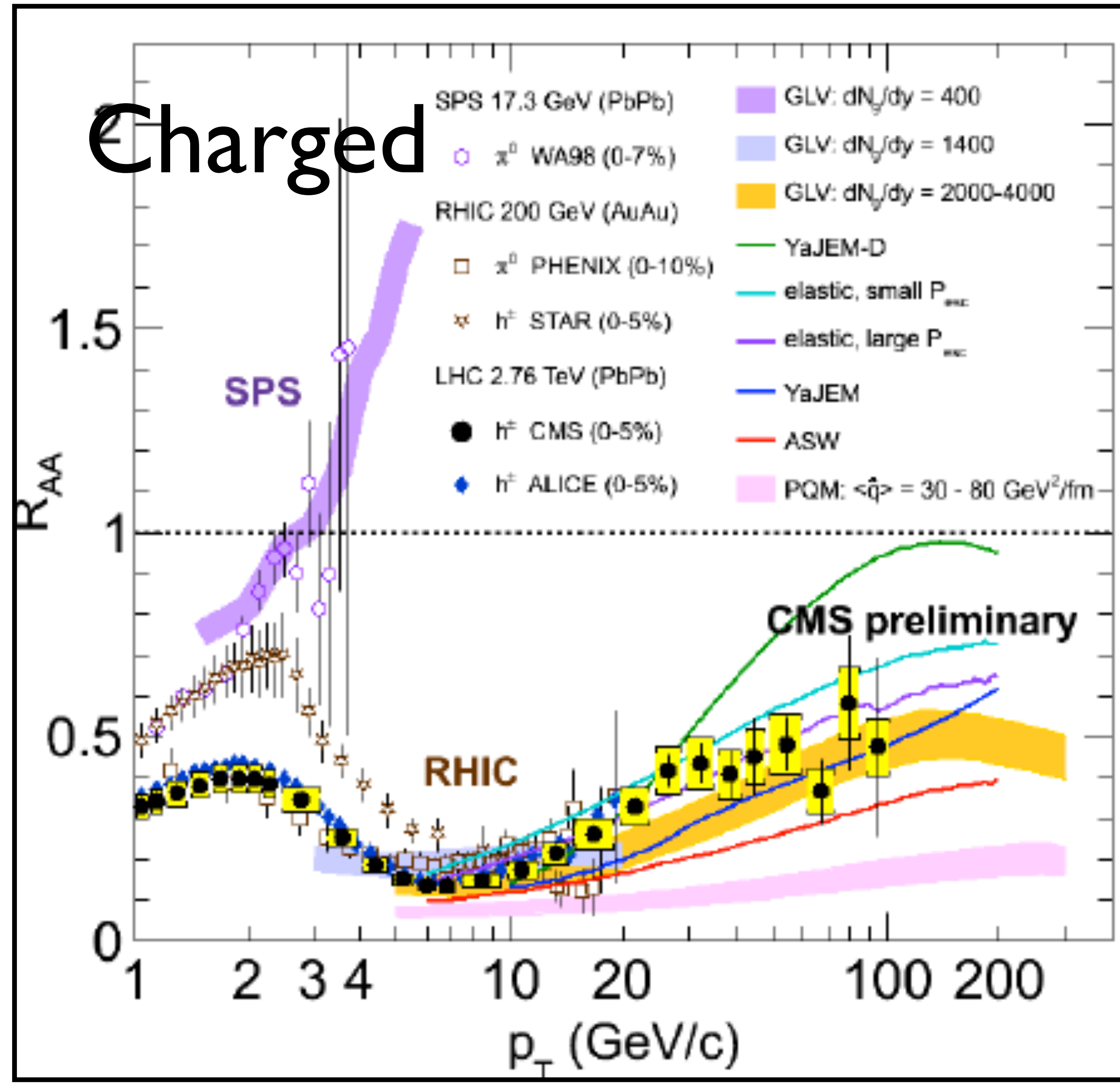

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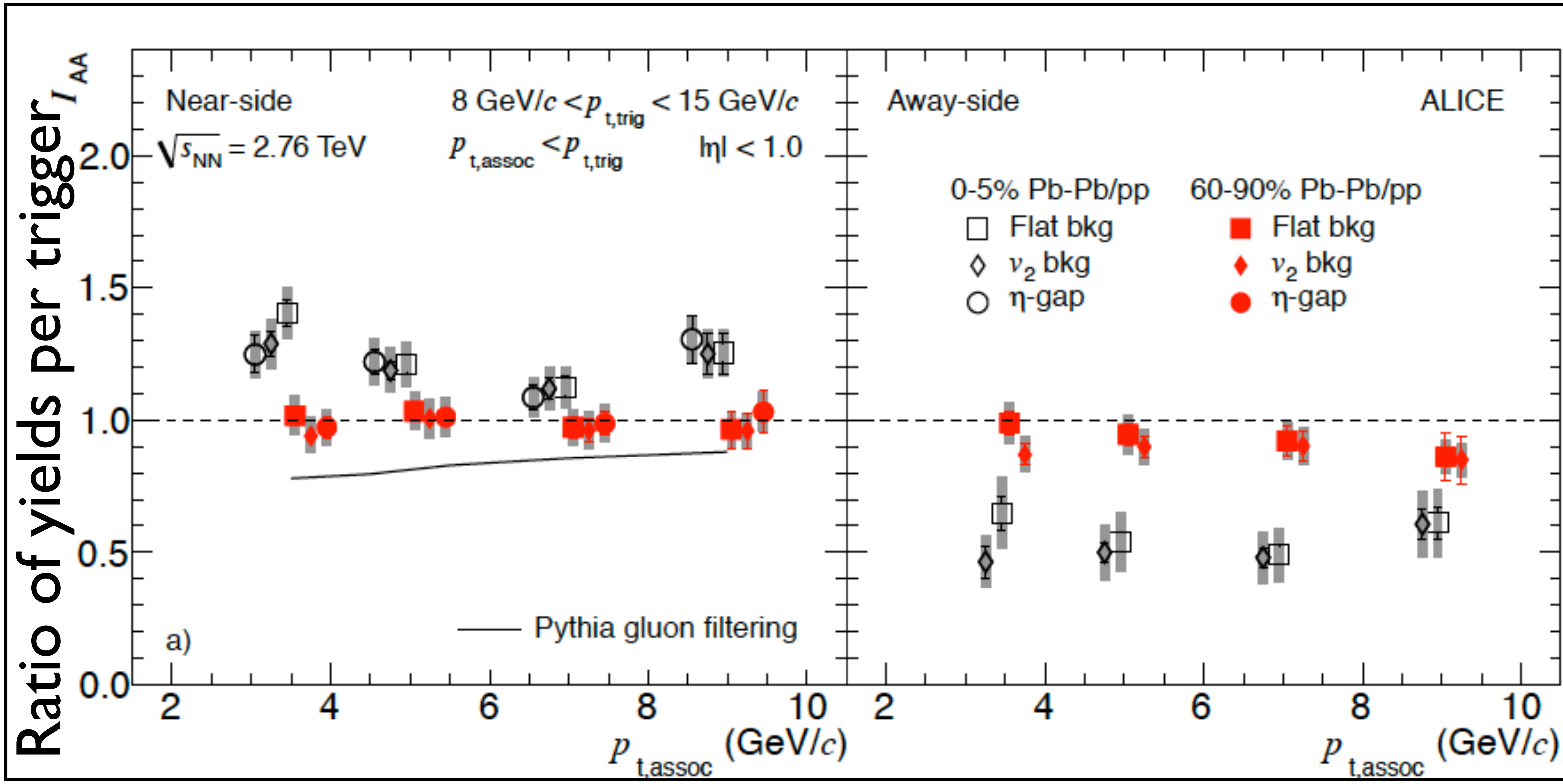
Results for R_{AA}:



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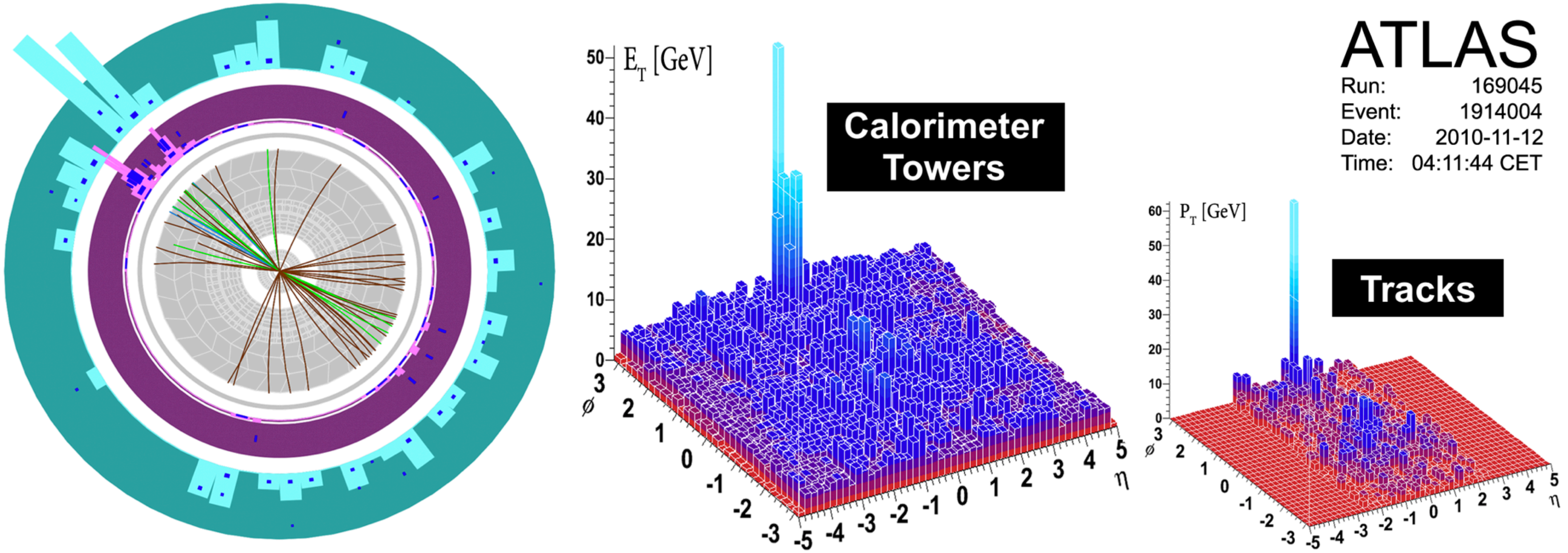
LHC-specific: dijets



anti-k_T, D=0.4

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

$E_{T2} = E_{T1}/2 \Rightarrow$

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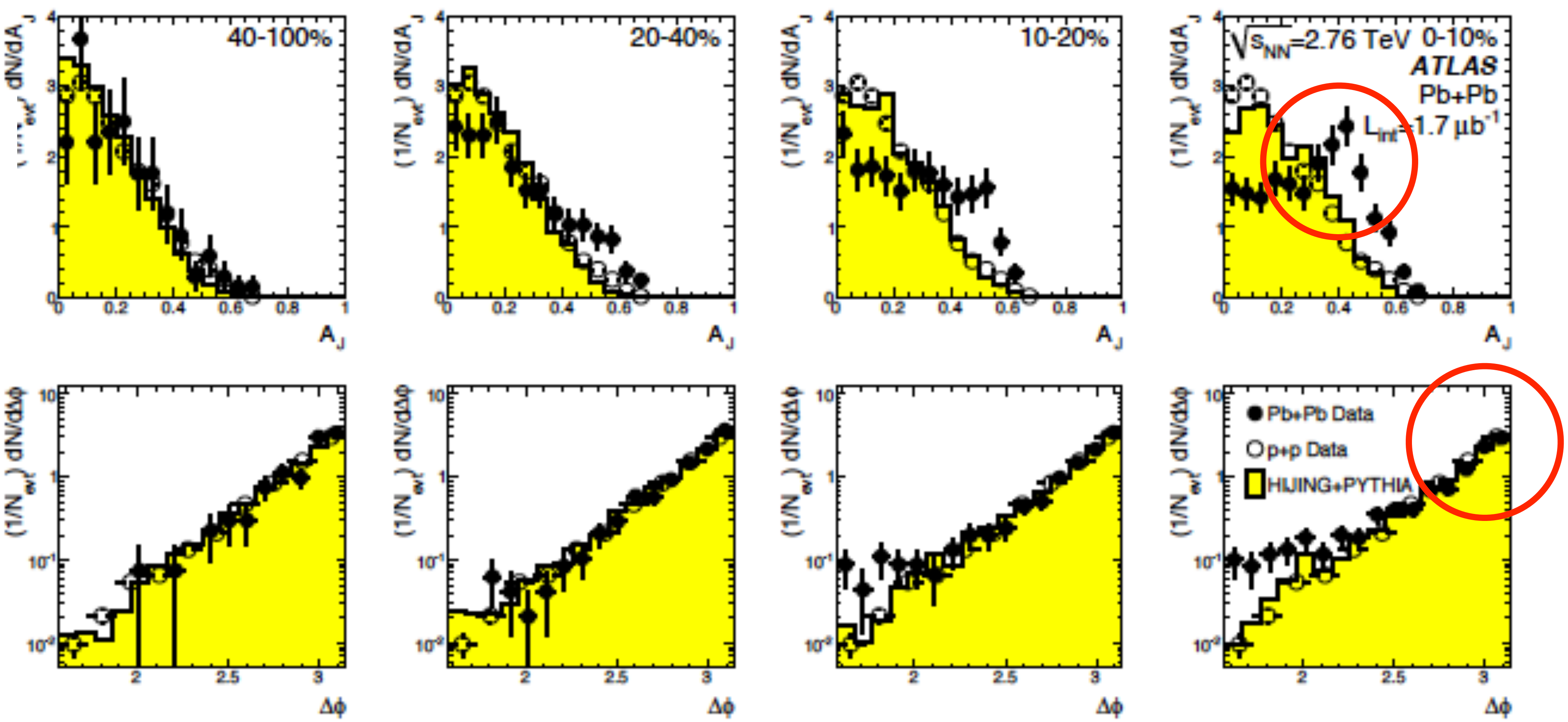

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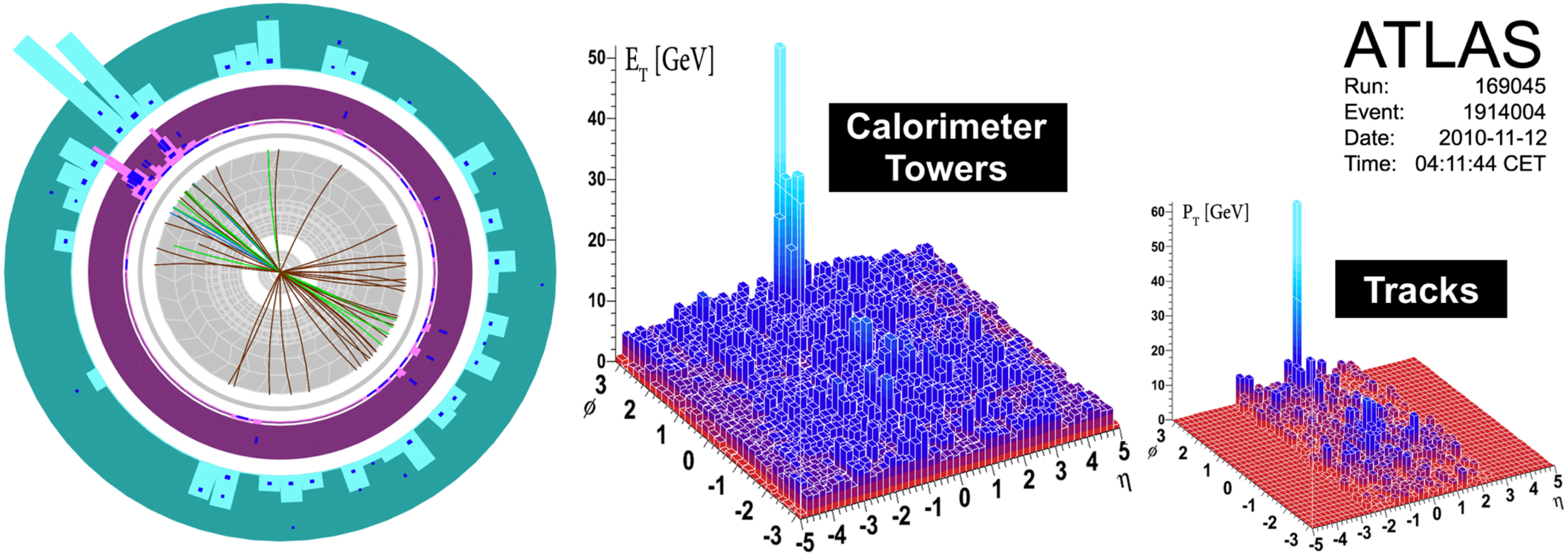

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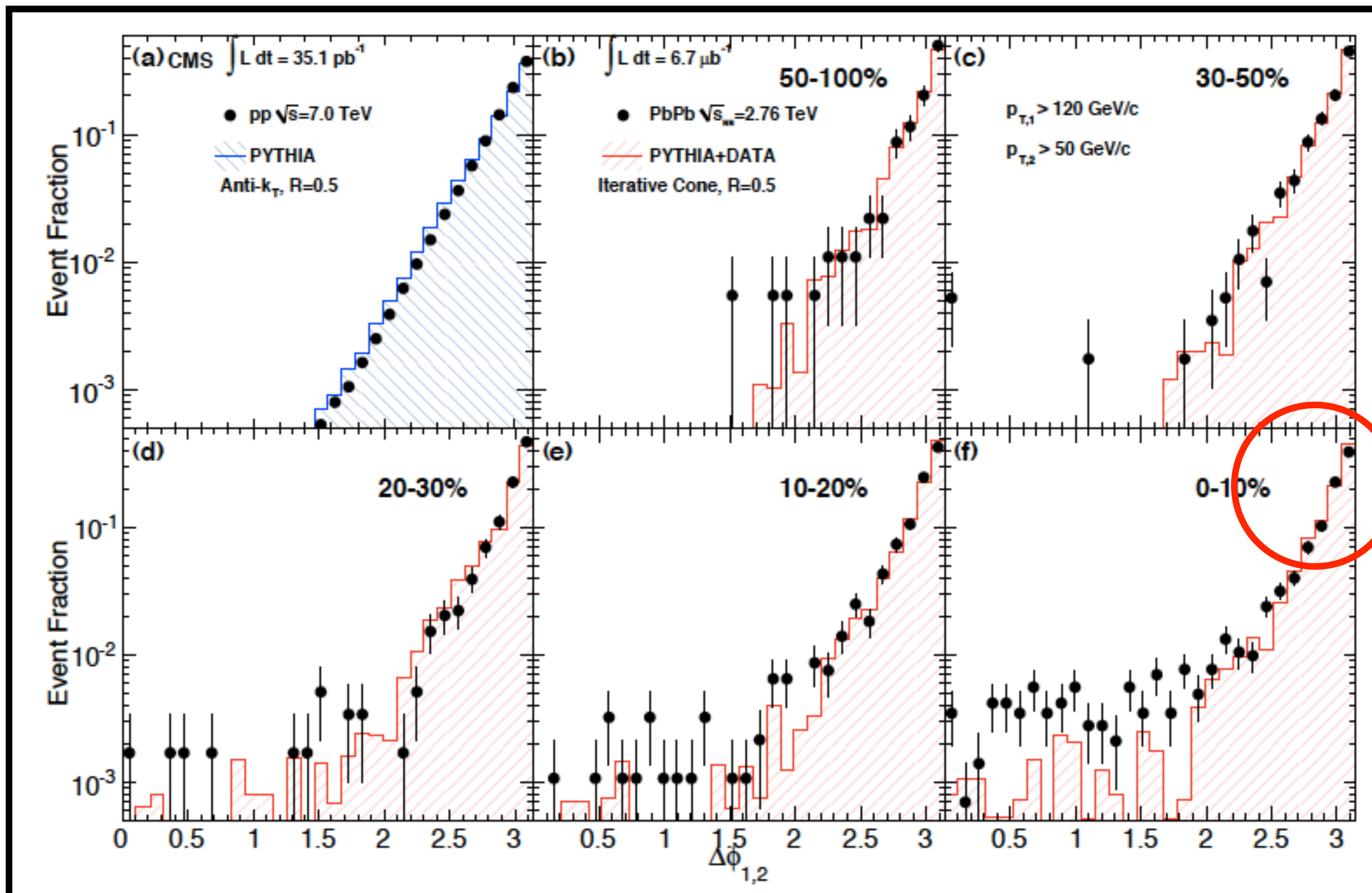

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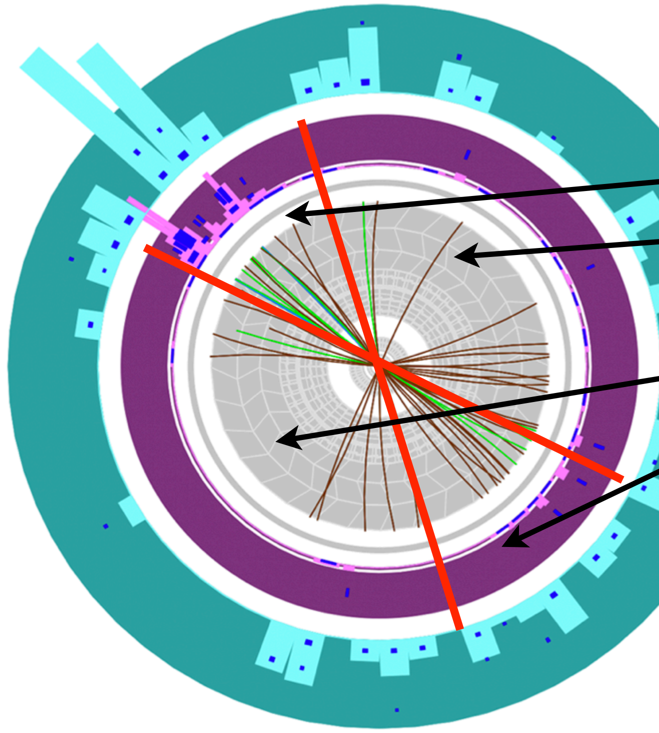

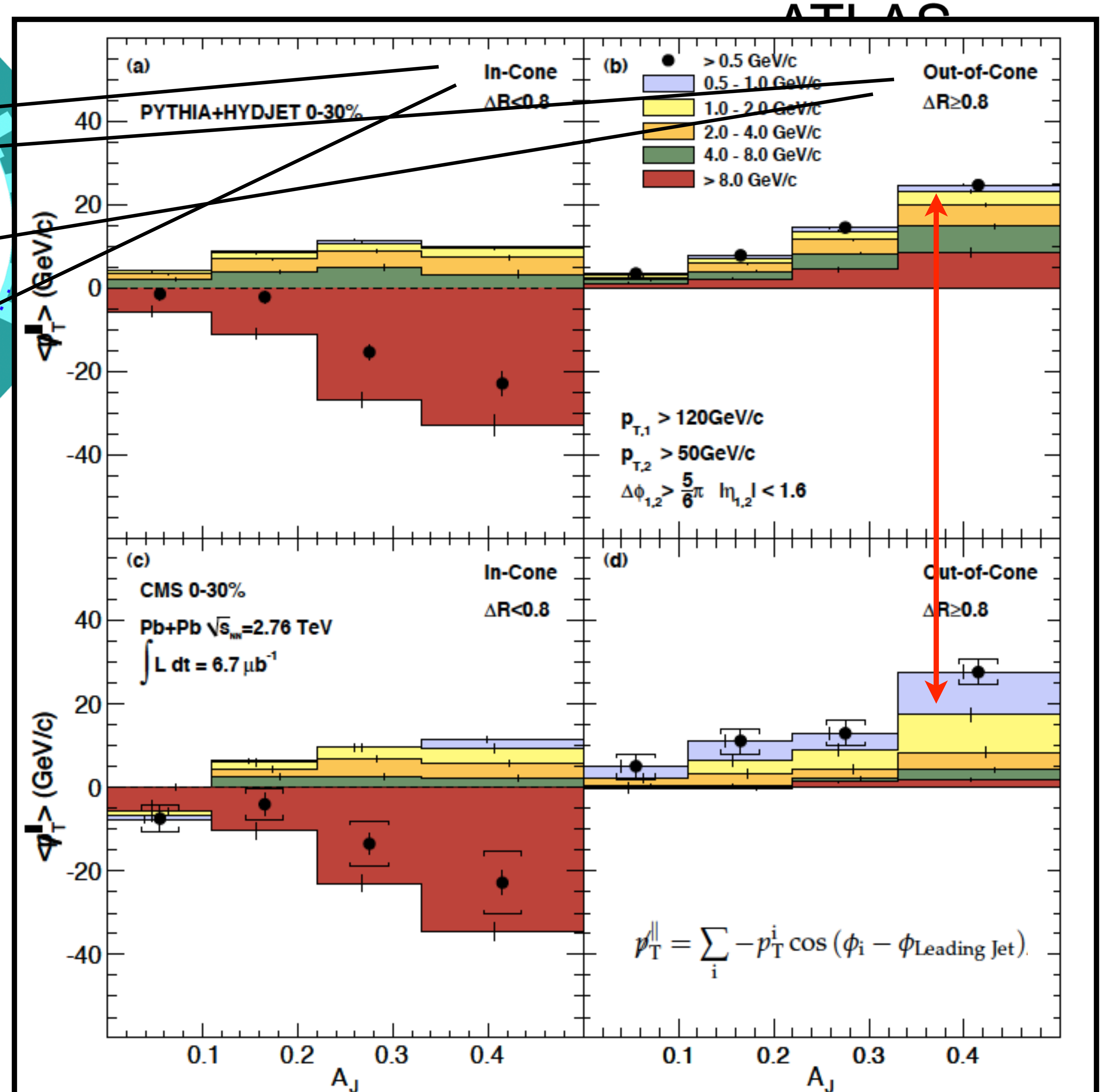

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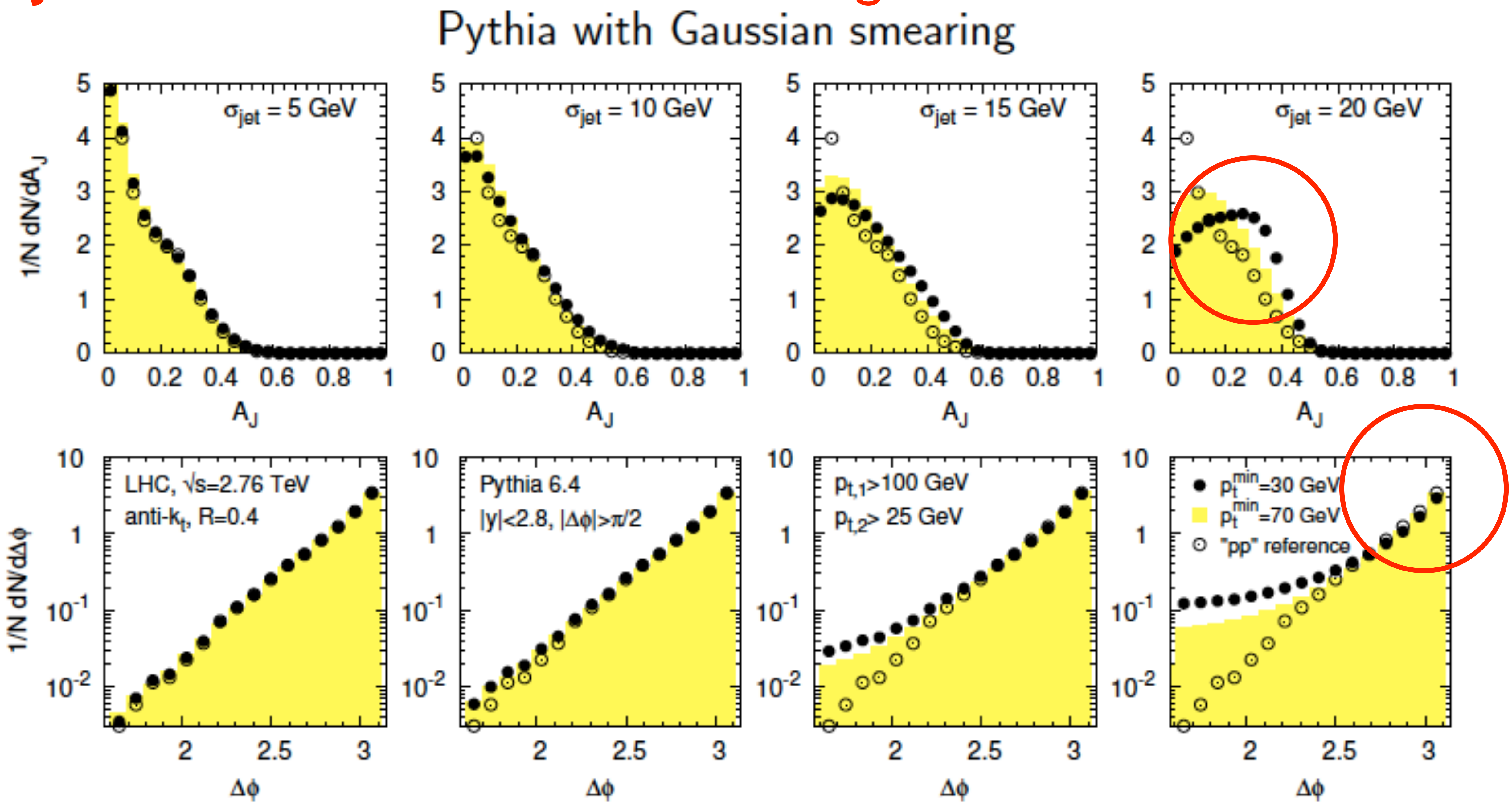
Dijets (II):

Jets are involved observables: background subtraction!



Cacciari et al., 1101.2878

Dijets (II):

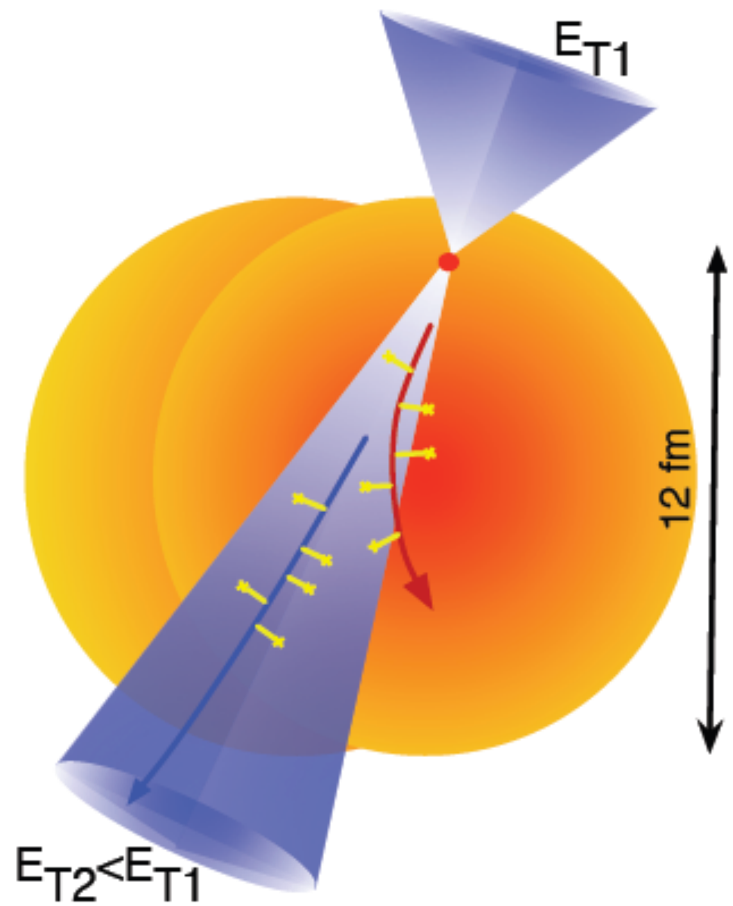
- All in all, it looks as if you have energy loss (degradation) with no broadening, and the energy has been carried away by soft particles.

- Several explanations: radiative (+collisional) eloss (Vitev et al., Lokhtin et al., Qin et al., Gale et al.), collimation (Casalderrey et al.),...

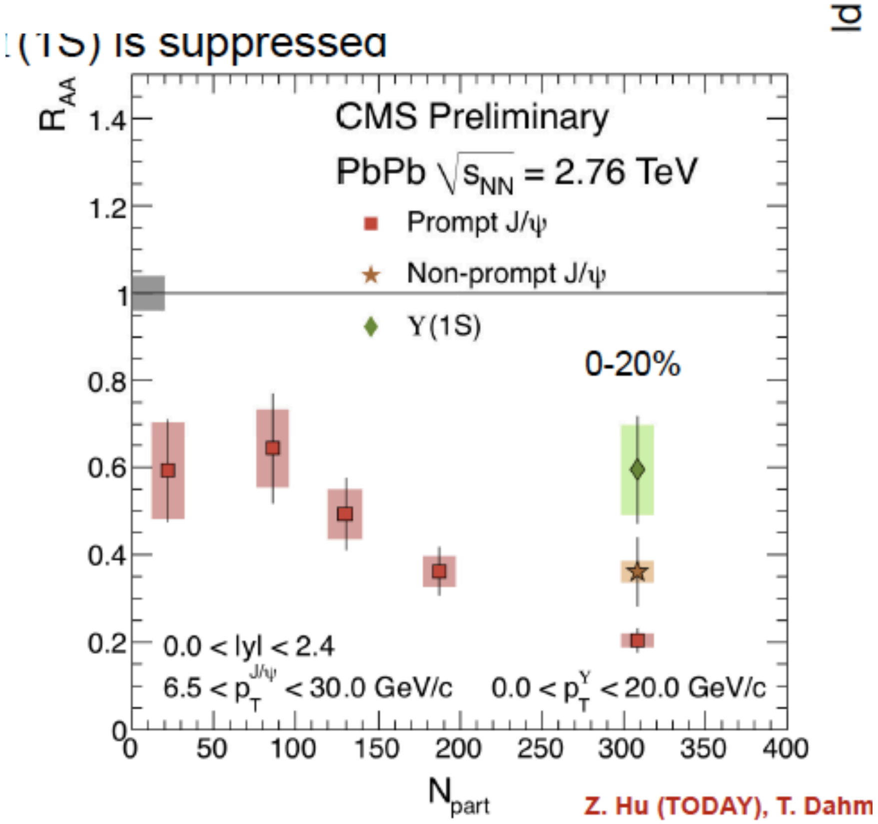
- Conceptual problems for models of radiative eloss which go through large angle, semihard emissions.

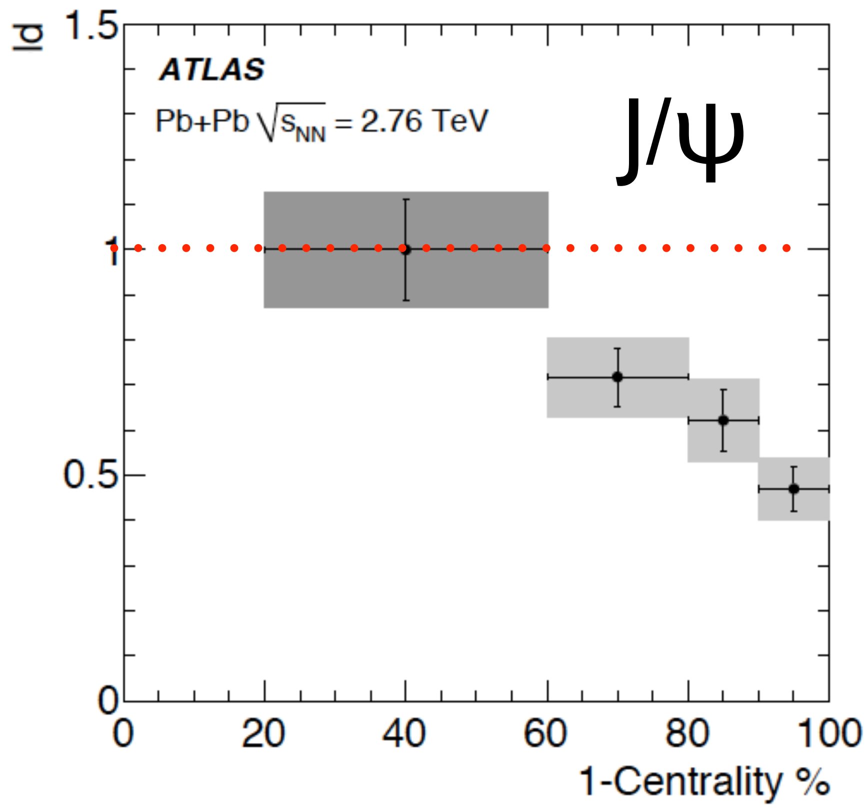
- Still a long way to become quantitative! Background subtraction crucial.

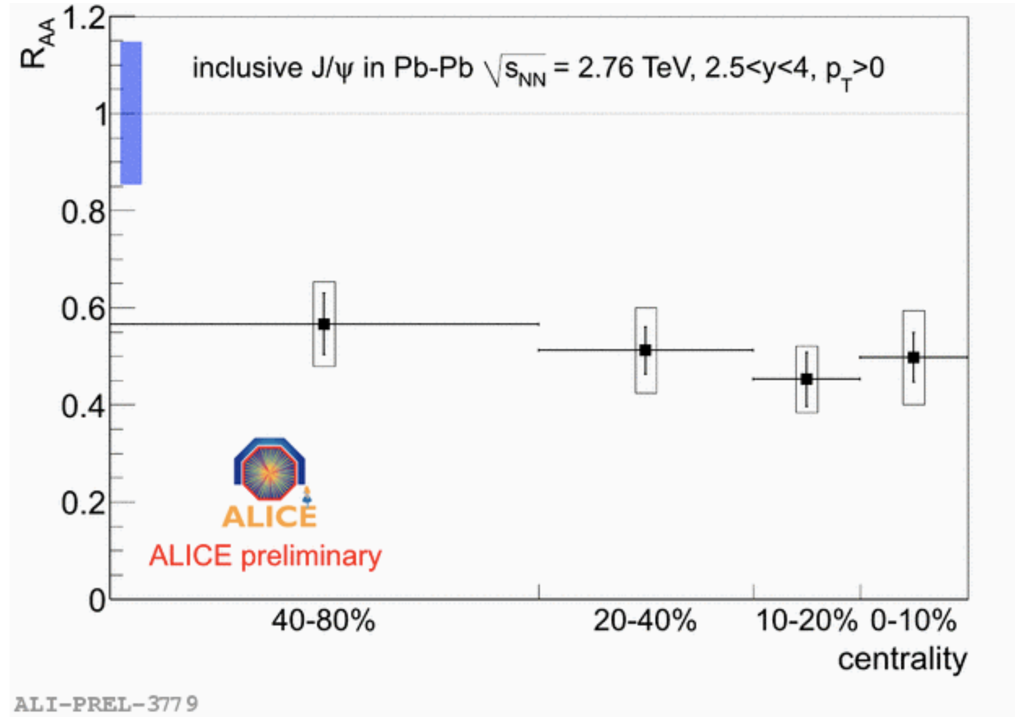
- Many recent theoretical studies: coherence between emitters (Salgado et al., Casalderrey-Iancu), energy corrections (Grigoryan-Vitev, d'Eramo et al.), color reconnections (Beraudo et al., Aurenche et al.),...



Quarkonia:



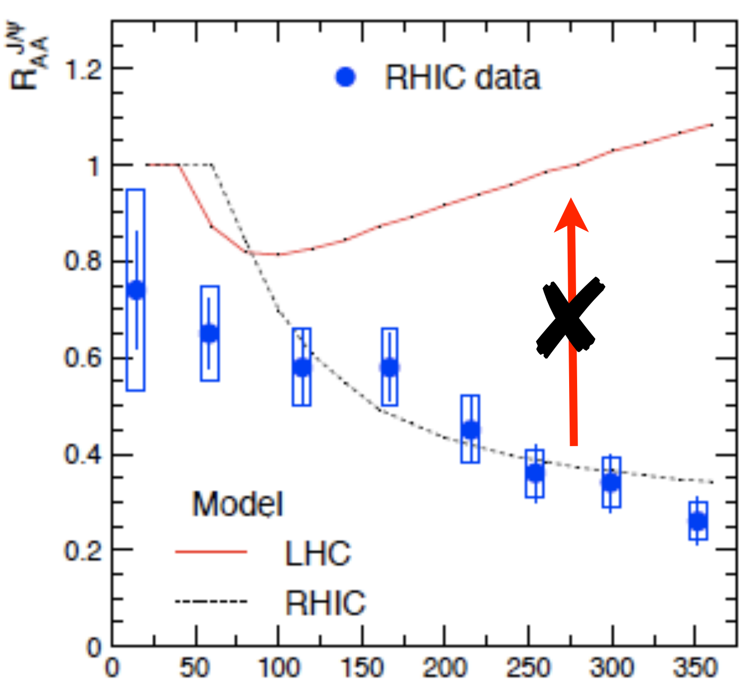




$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

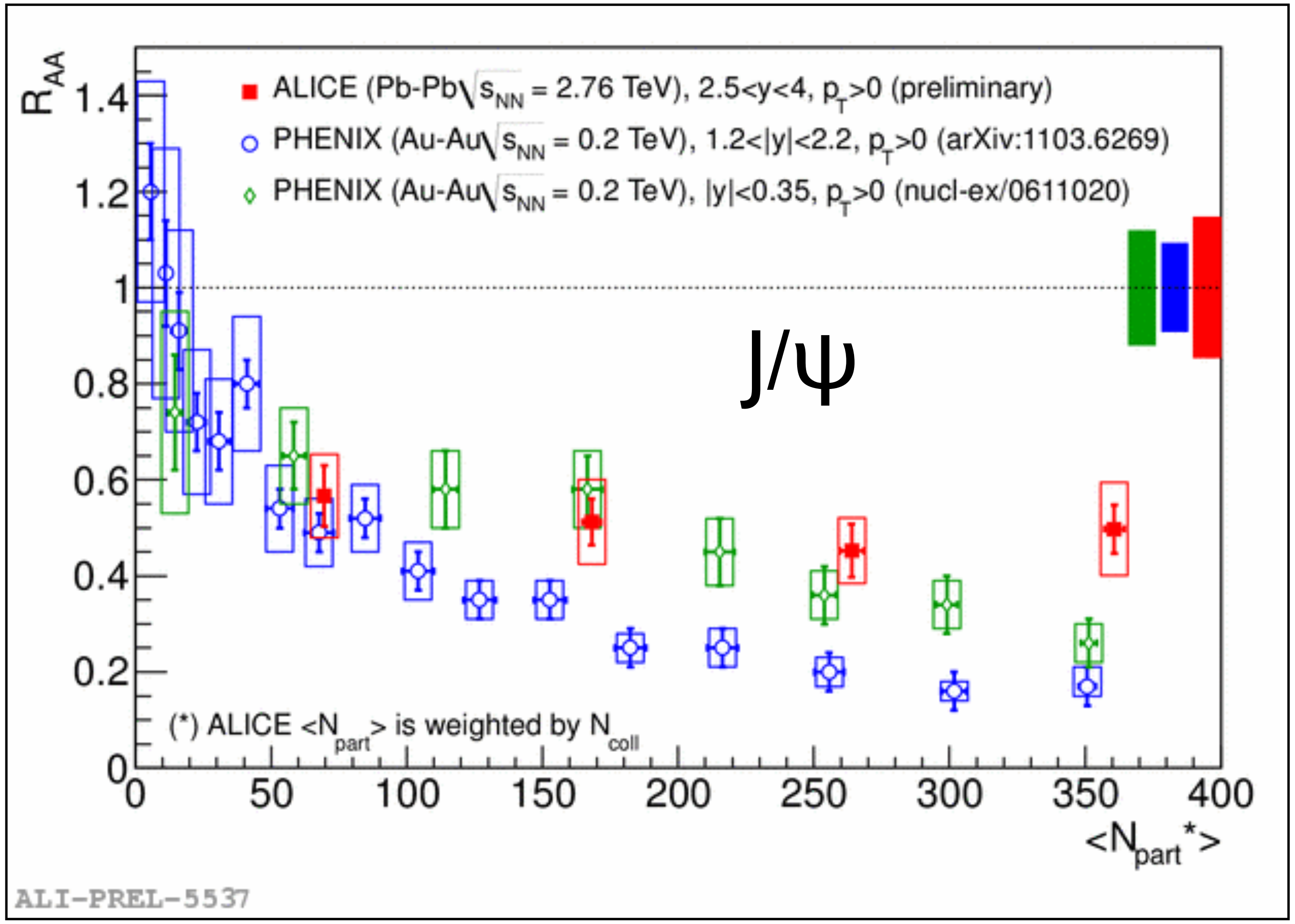
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

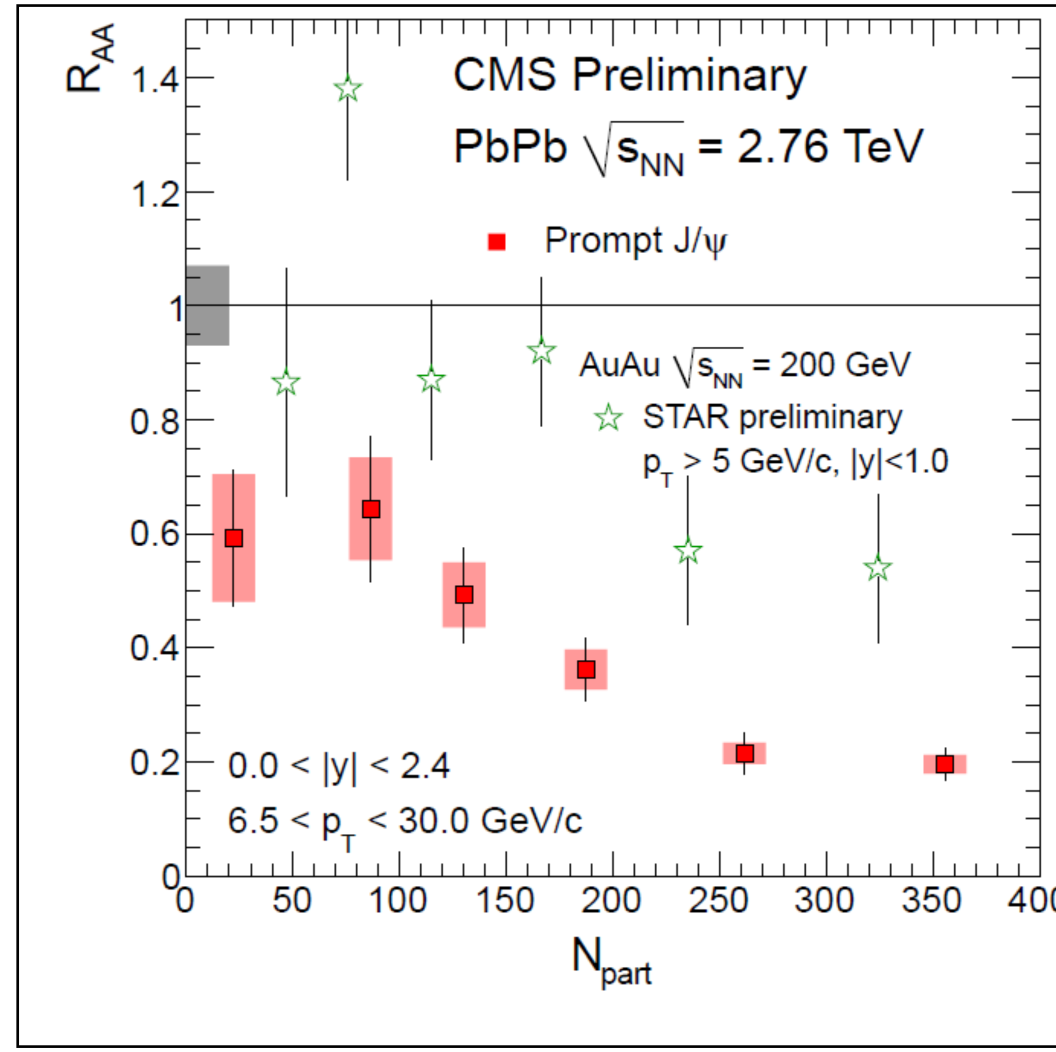
- J/ψ results do not show enhancement.
- Higher BBbar states show larger suppression (CMS): thermometer?



Andronic et al '10

Quarkonia:





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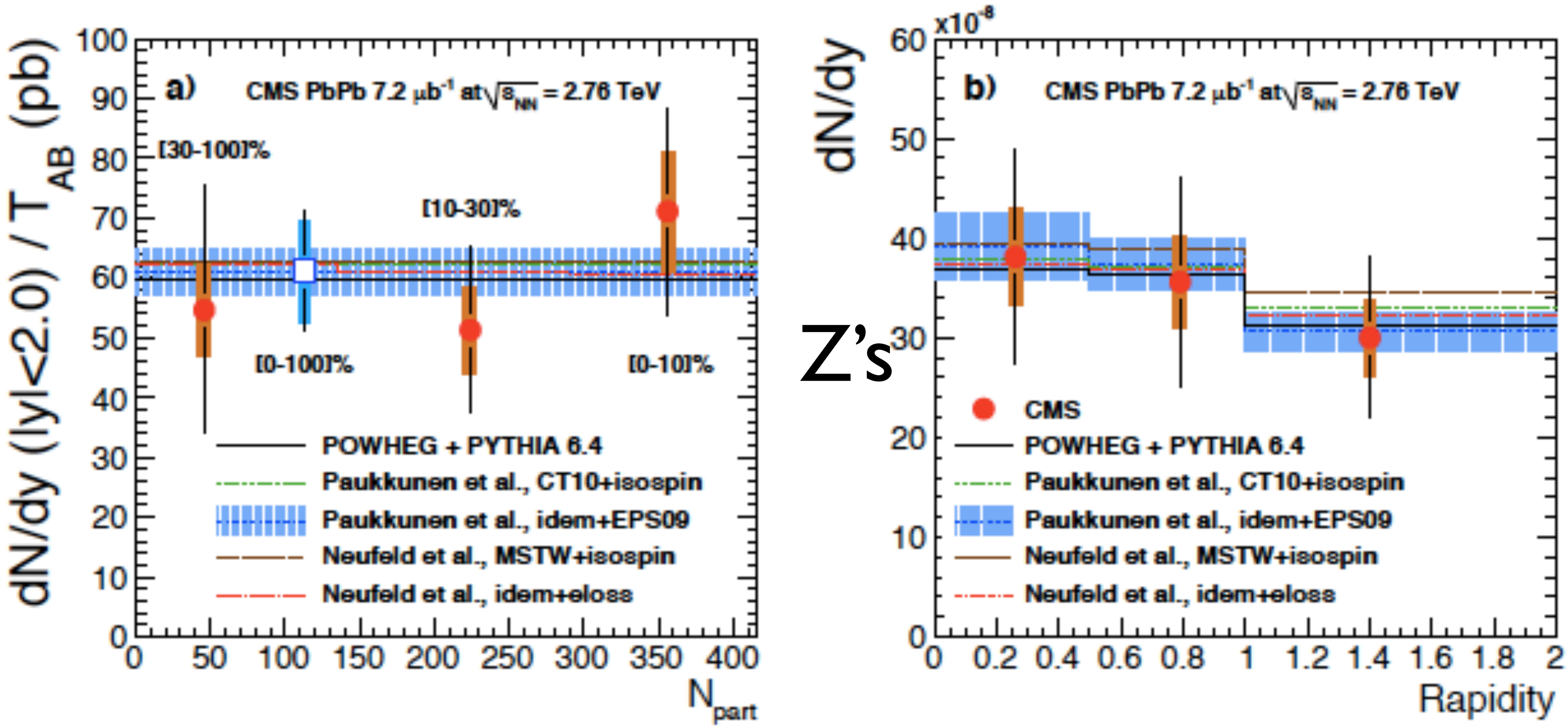
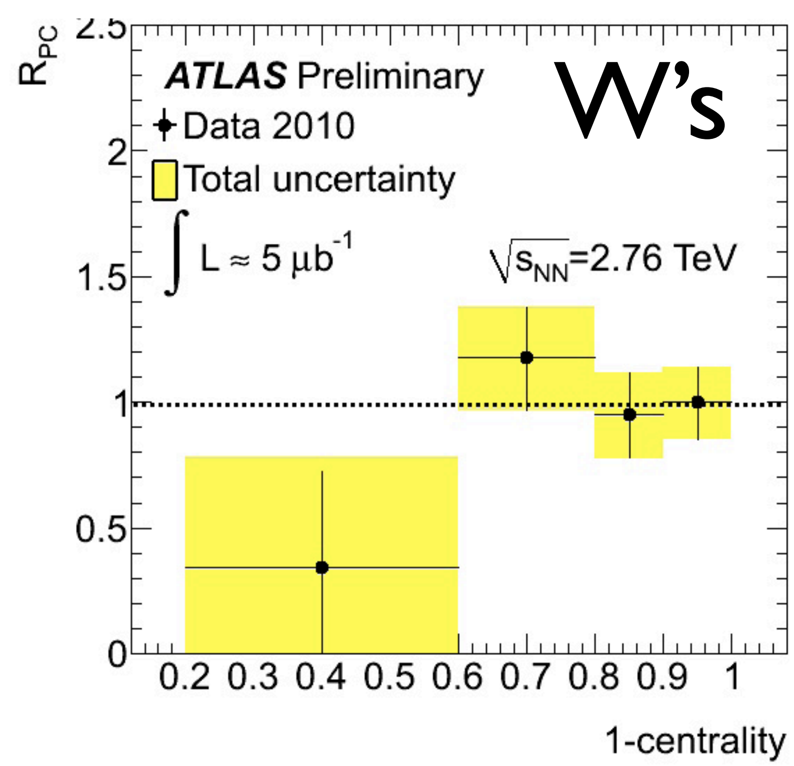
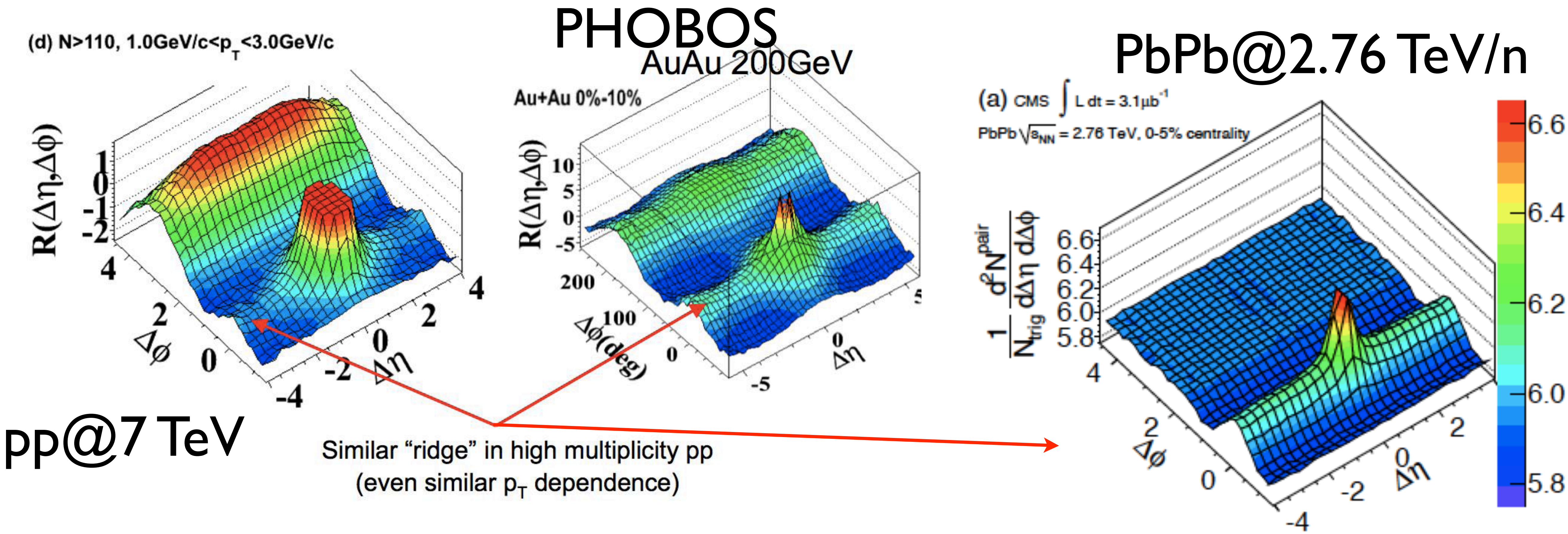
W/Z (LHC-specific):





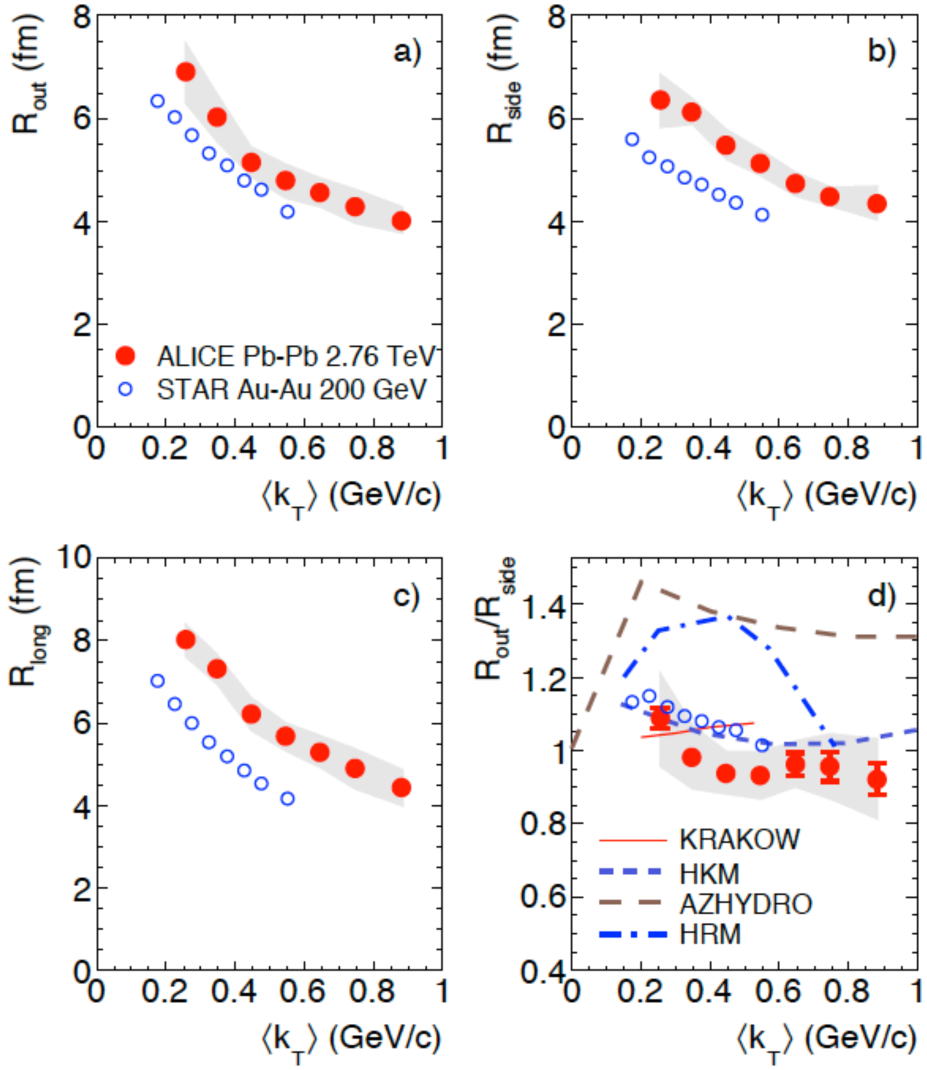
- First Z/W measurement in heavy-ion collisions!!! Benchmark (nuclear pdf's, N_{coll}-scaling) for future.

Rapidity correlations:

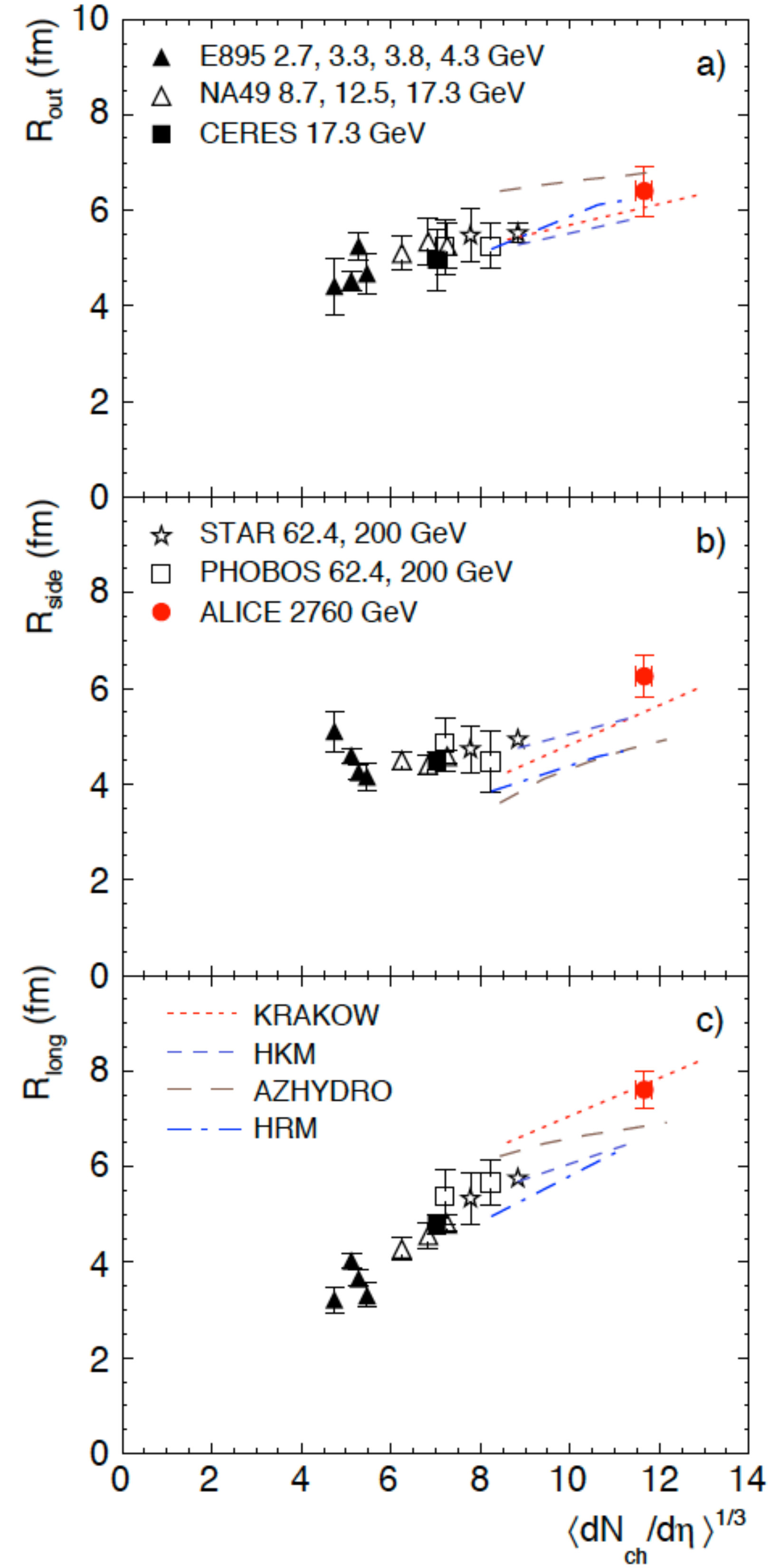


- η-elongated structure in the two-particle correlation in the near (ridge) and away side regions in central pp and AuAu/PbPb.
- Long range y-correlations natural in string models, CGC,...
- Origin of the elongation in η for the ridge unsettled yet: coupling fragmentation ↔ flowing medium, ISR, flow itself (v_3; thus no longer a signature of jet-medium response),...

Femtoscopy:



- Information about the dimensions of the region of particle production through pion interferometry.



- Source enlarges with collision energy as expected.

- Transverse momentum dependence problematic for hydro: viscosity, i.c., fluctuations?

Summary:

Observable at RHIC	Standard interpretation	Prediction for the LHC
Low multiplicity	Strong coherence in particle production	$dN_{ch}/d\eta\|_{\eta=0}<1700$ for central collisions ✓
v_2 in agreement with ideal hydro	Almost ideal fluid	Similar or smaller $v_2(p_T)$ ✓
Strong jet quenching	Opaque medium	R_{AA}(20 GeV)~0.1-0.2 for π^0 ✓

- The very first data seem, at first sight, not to be in dispute with the claims at RHIC - the problems remain, too.

- Already new things: jets, Υ family, ridge in pp, higher harmonics.

- LHC offers new opportunities, both enlarging the lever arm (in energy, in p_T,...) for existing observables and offering new ones (identified HQ, jets, Z,γ+jet, correlations,...). We have just begun!!!

Summary:

Plans:

➜ PbPb @ 2.76 ATeV: four weeks at the end of 2011 starting 14.11; at least 3 times the luminosity in 2010. End of 2012?

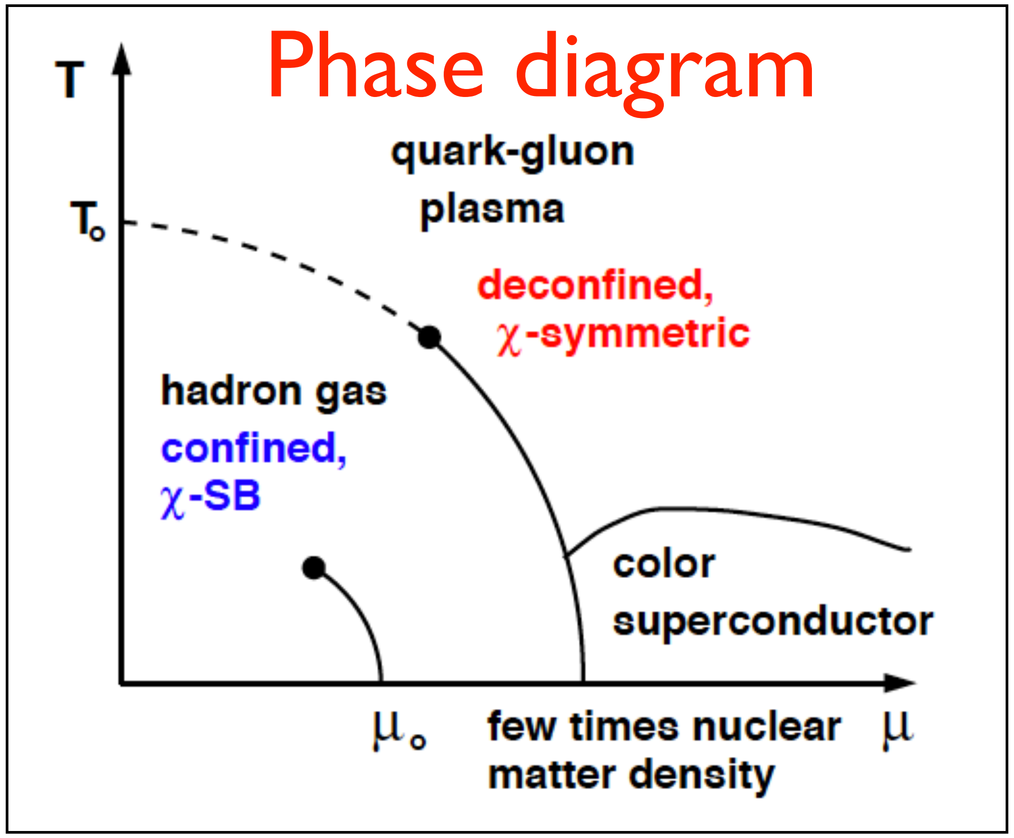
➜ pPb @ 4.4 ATeV: studies during the 2011 PbPb run, run at the end of 2012 to get 0.1 pb^{-1}?: benchmarking (nuclear pdf's and cold nuclear matter effects on jets, HQ and QQbar), small-x dynamics and UPCs (see Salgado et al., 1105.3919 [hep-ph]).

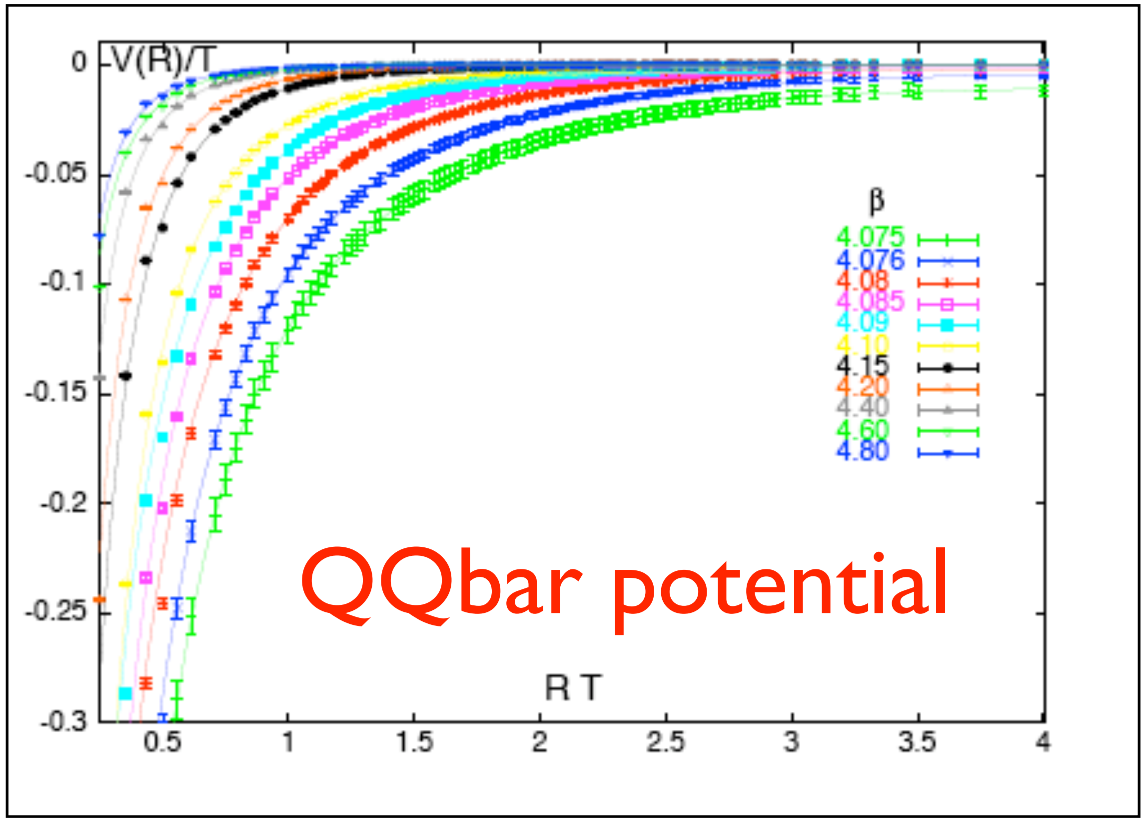
☛ Decission in Chamonix 02.2012, depending on luminosity in 2011 and prospects in 2012.

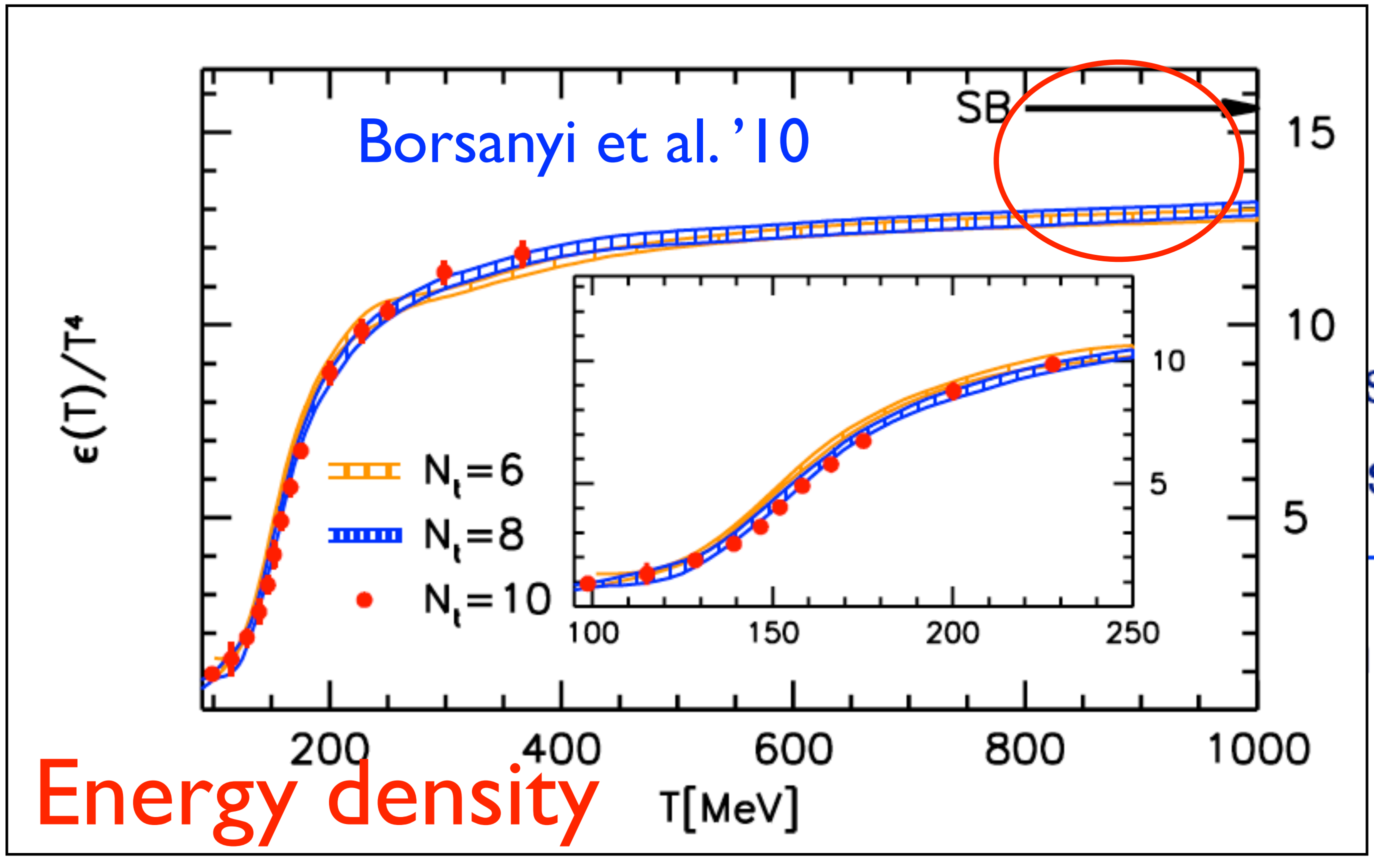
Backup:

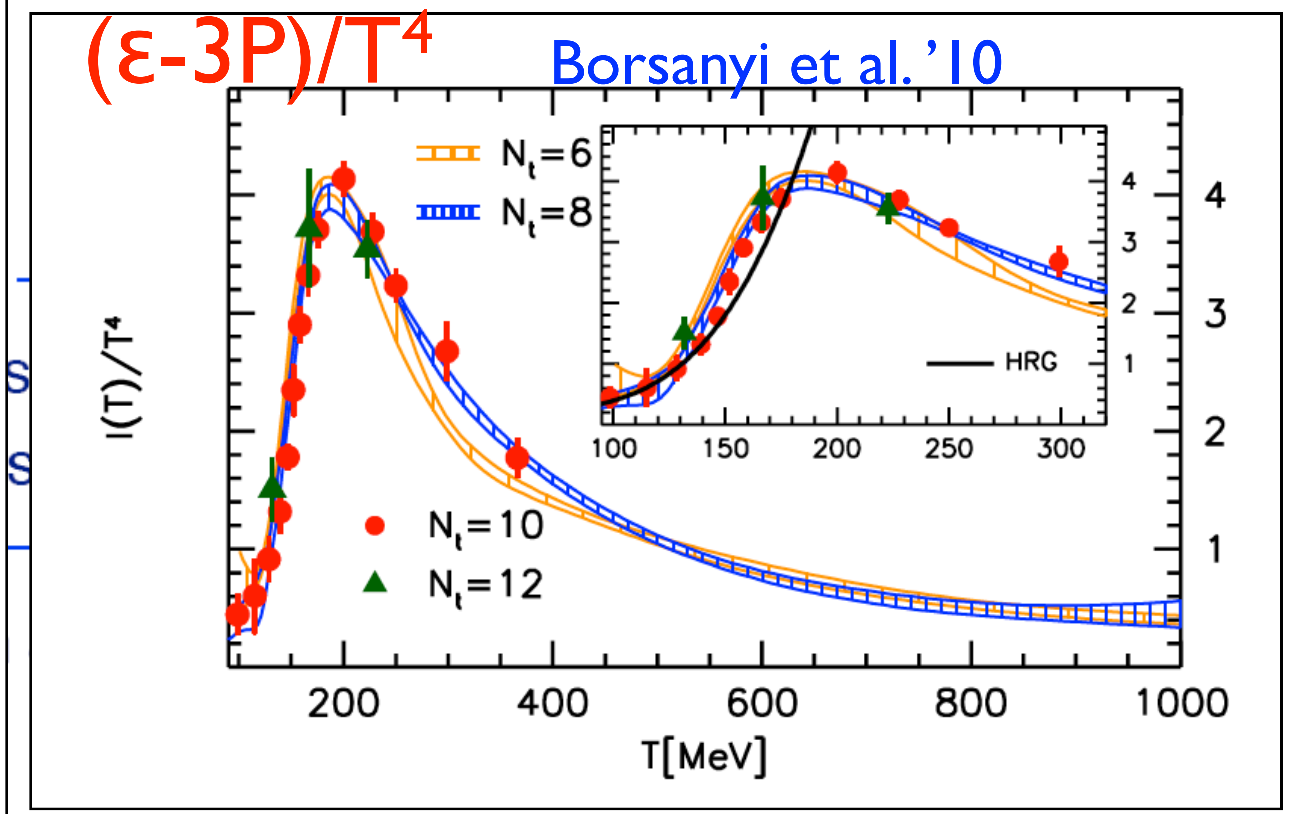
Lattice QCD:

- Lattice has achieved great accuracy.

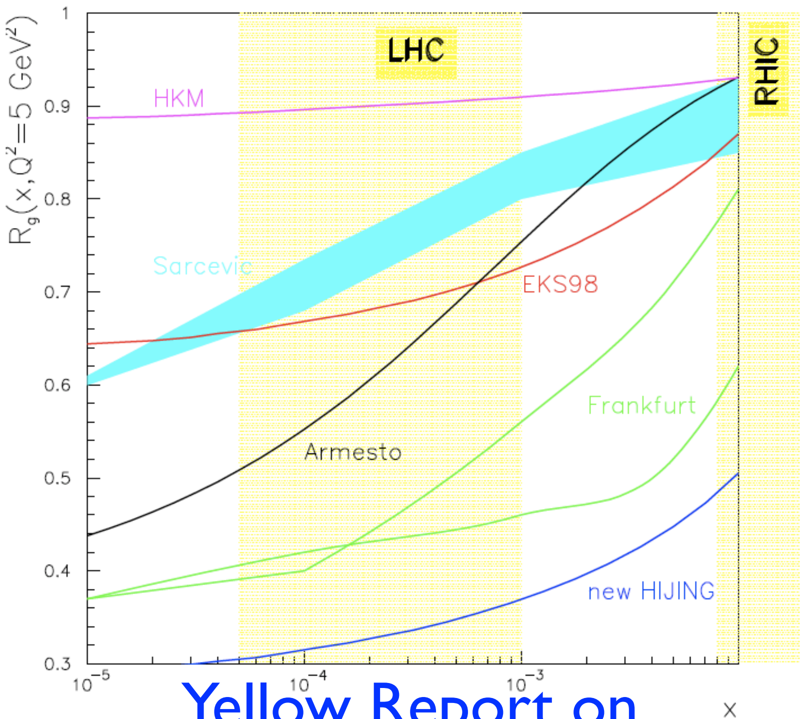






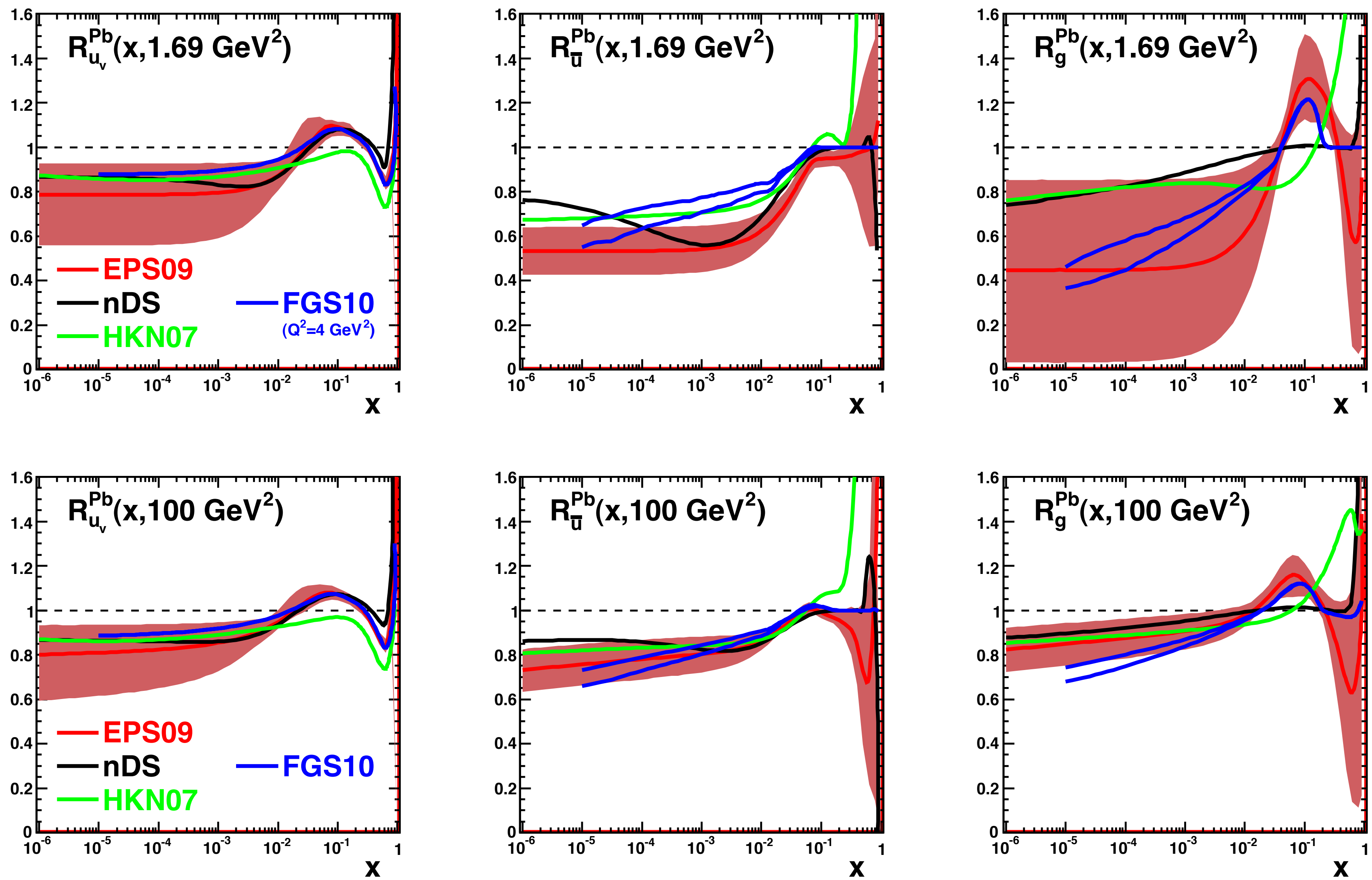


The benchmark: nPDFs



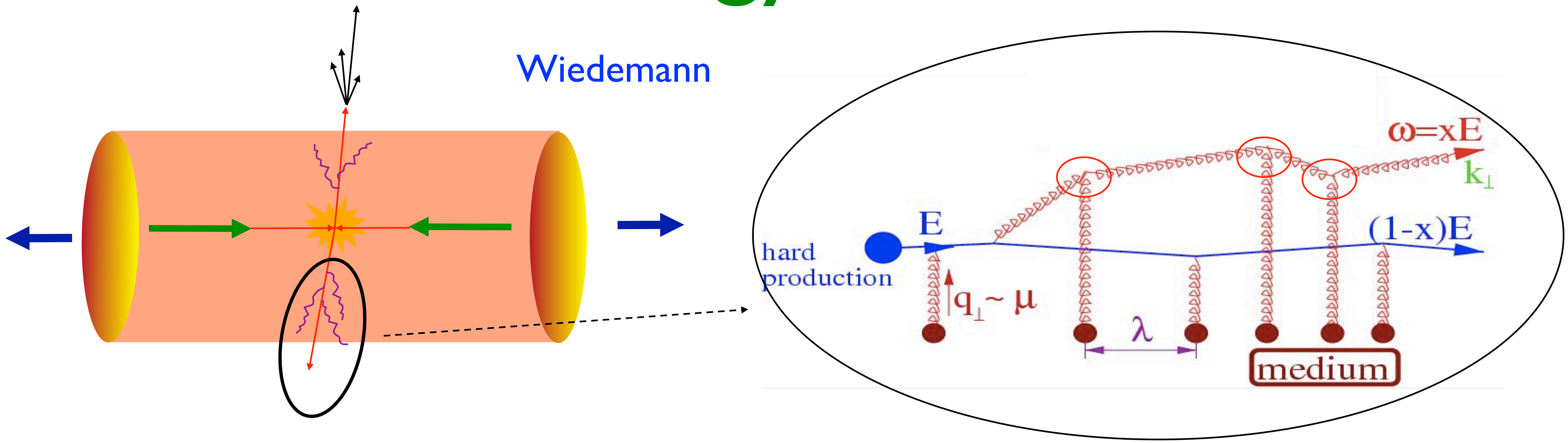
Yellow Report on Hard Probes, 2004

- Models give vastly different results for small scales and x.



- Available DGLAP analysis at NLO show large uncertainties at small scales and x.
- pPb may help (studies this year, it may happen in 2012).

Energy loss:



- RHIC has measured $R_{AA}<1$ (e.g. 0.2 for π^0 at midrapidity in central AuAu), and disappearance of back-to-back correlations.
- It is standardly interpreted as the result of partonic energy loss: interplay with the slope of the partonic spectrum.

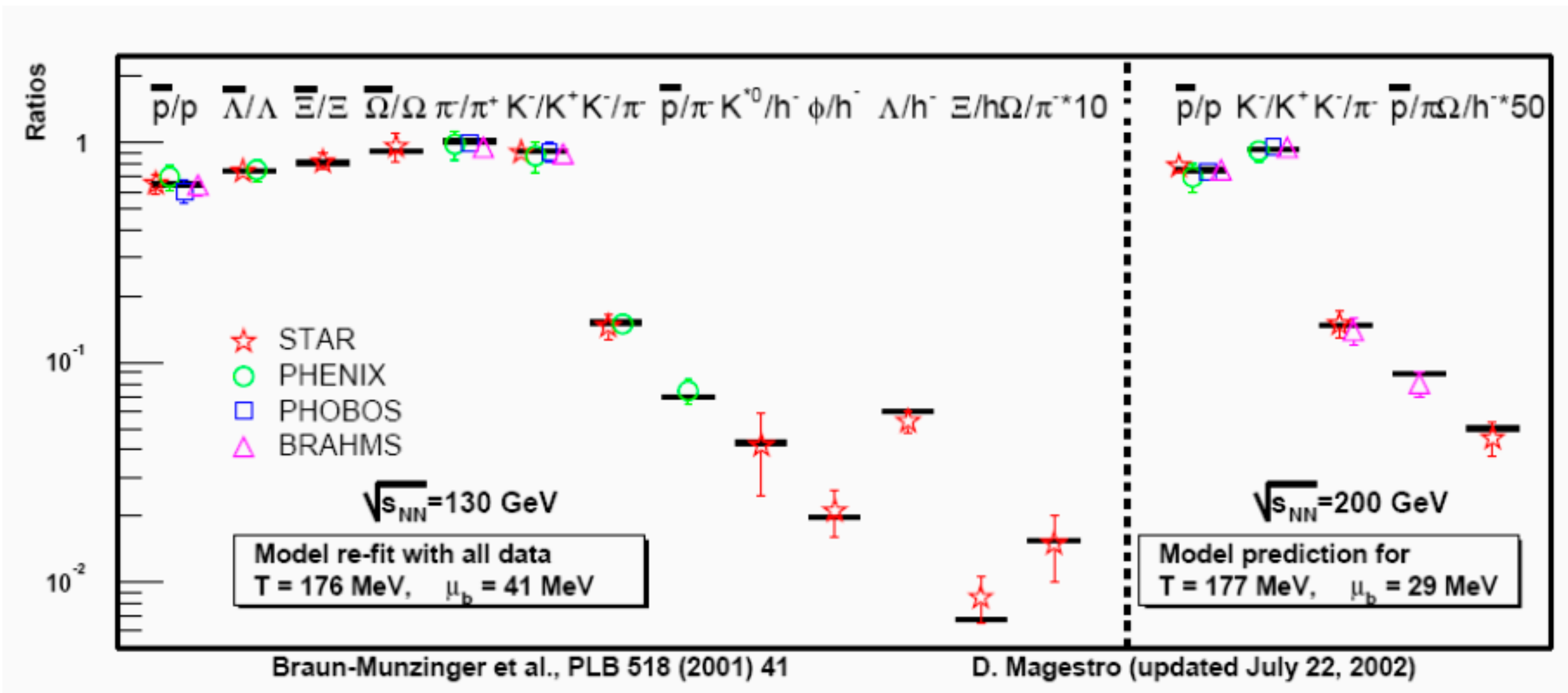
$$\frac{d\sigma^{AA}}{dE}(E) \sim \int d\left(\frac{\Delta E}{E}\right)\ P\left(\frac{\Delta E}{E}\right)\ \frac{d\sigma^{pp}}{dE}(E+\Delta E)$$

- Radiative eloss characterized by a density parameter and by medium length / geometry.

Statistical model:

- Within the grand-canonical ensemble, equilibrium hadron/parton densities can be computed: T, μ, V (γ_s to include chemical non-equilibrium effects).
- Good description of particle ratios in AB, with $T \sim T_c$ (and $\gamma_s \sim 1$ at RHIC): partonic equilibrium?

$$n_{q(\bar{q})}(T,\mu_q) = \frac{N_c N_s}{(2\pi)^3}\int_0^\infty \frac{4\pi p^2 dp}{e^{\left(\sqrt{p^2+m_q^2}\mp\mu_q\right)/T}+1}$$



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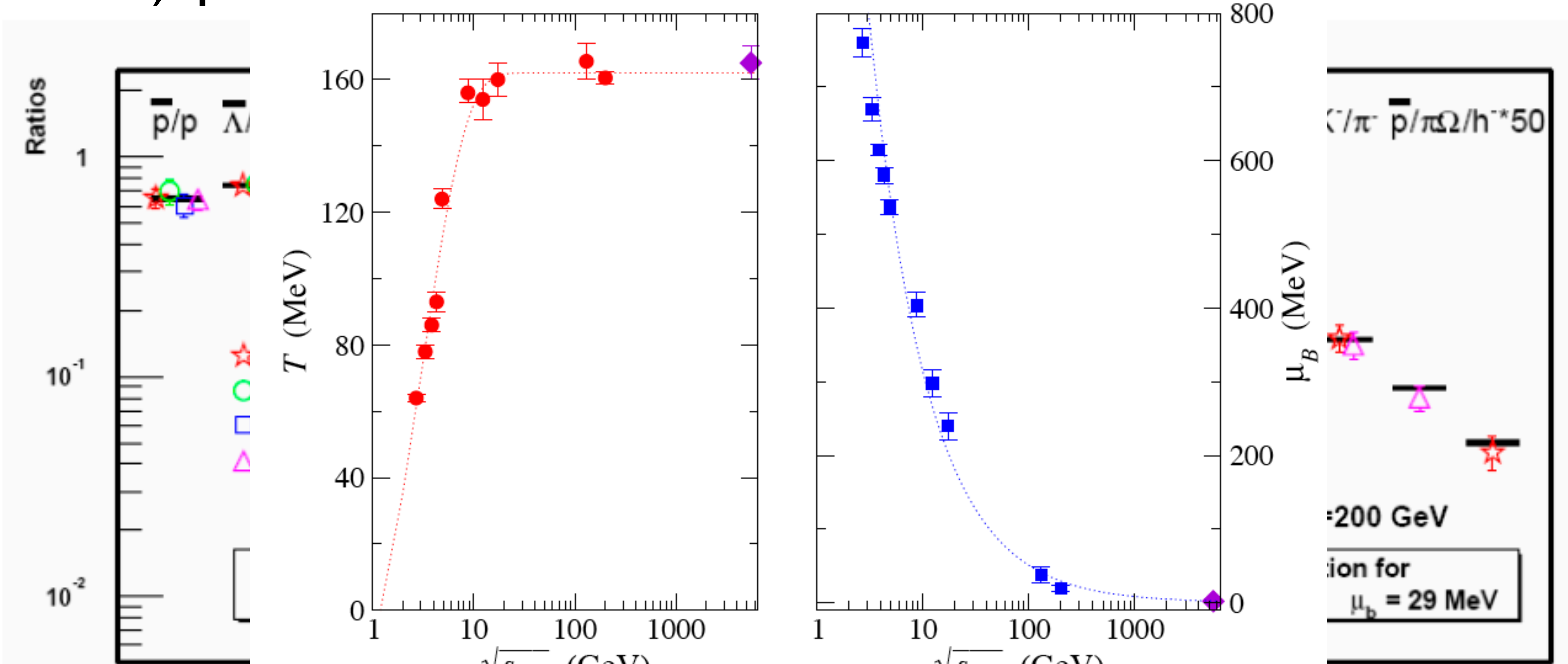
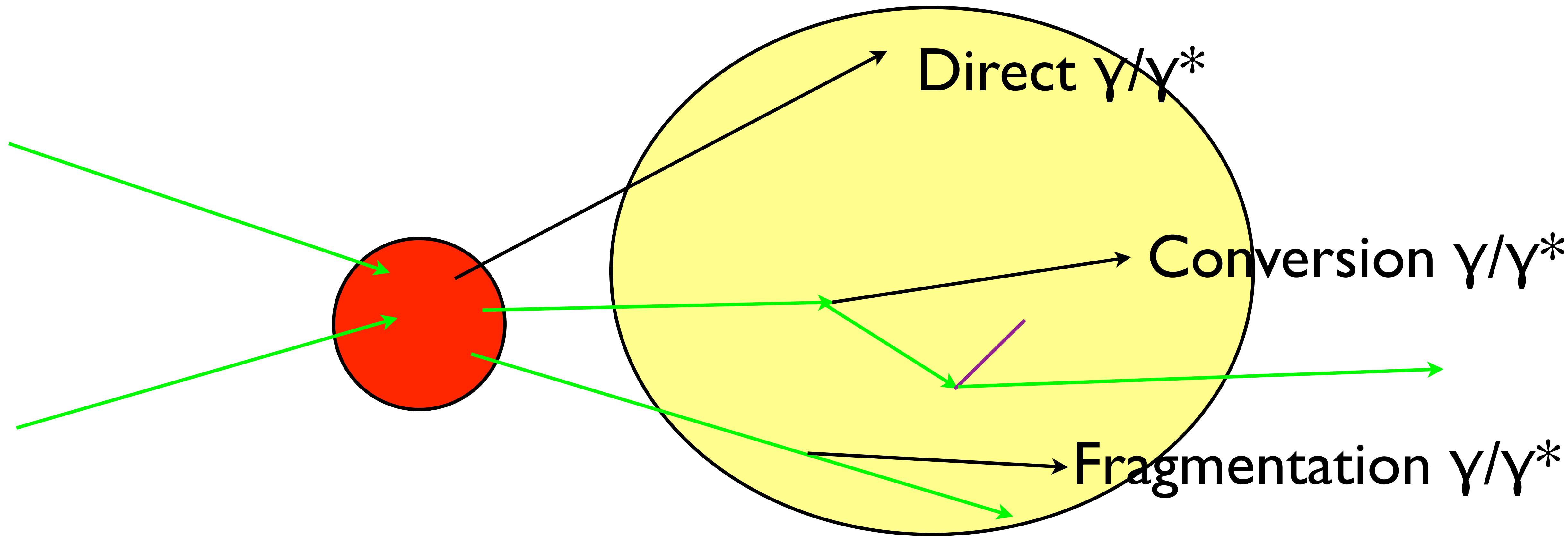


Borghini, Wiedemann, '07

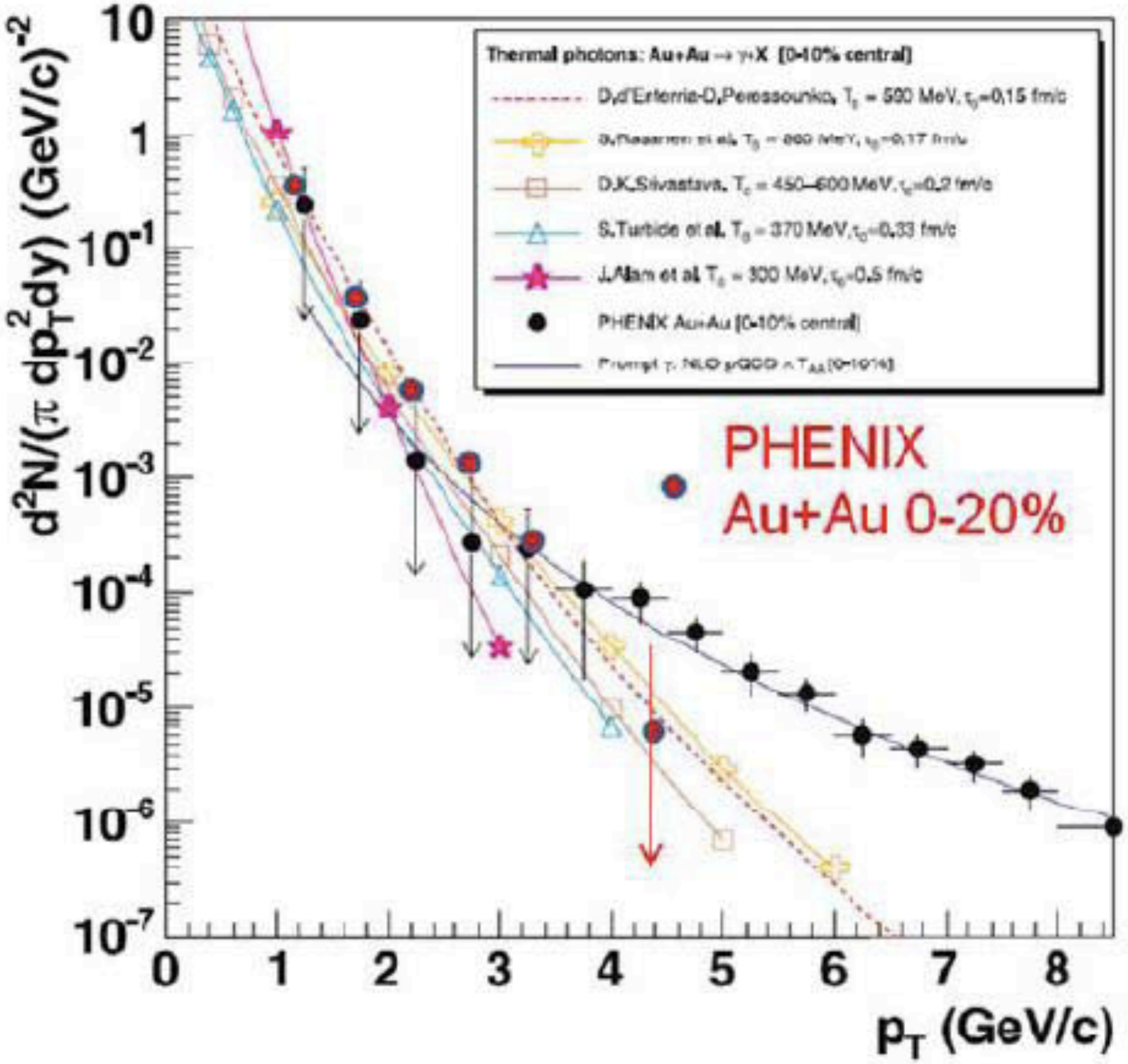
Photons and dileptons:

- Photons and dileptons (EM probes) may be produced by decays and by direct sources:
  - * Thermal (black-body) radiation, direct proof of T.
  - * From the hard parton scattering: benchmark.
  - * From fragmentation of partons: affected by medium.
  - * From jet conversions: determined by the medium.



- All these mechanisms have to be implemented within a realistic medium model: density and evolution.

Photons:



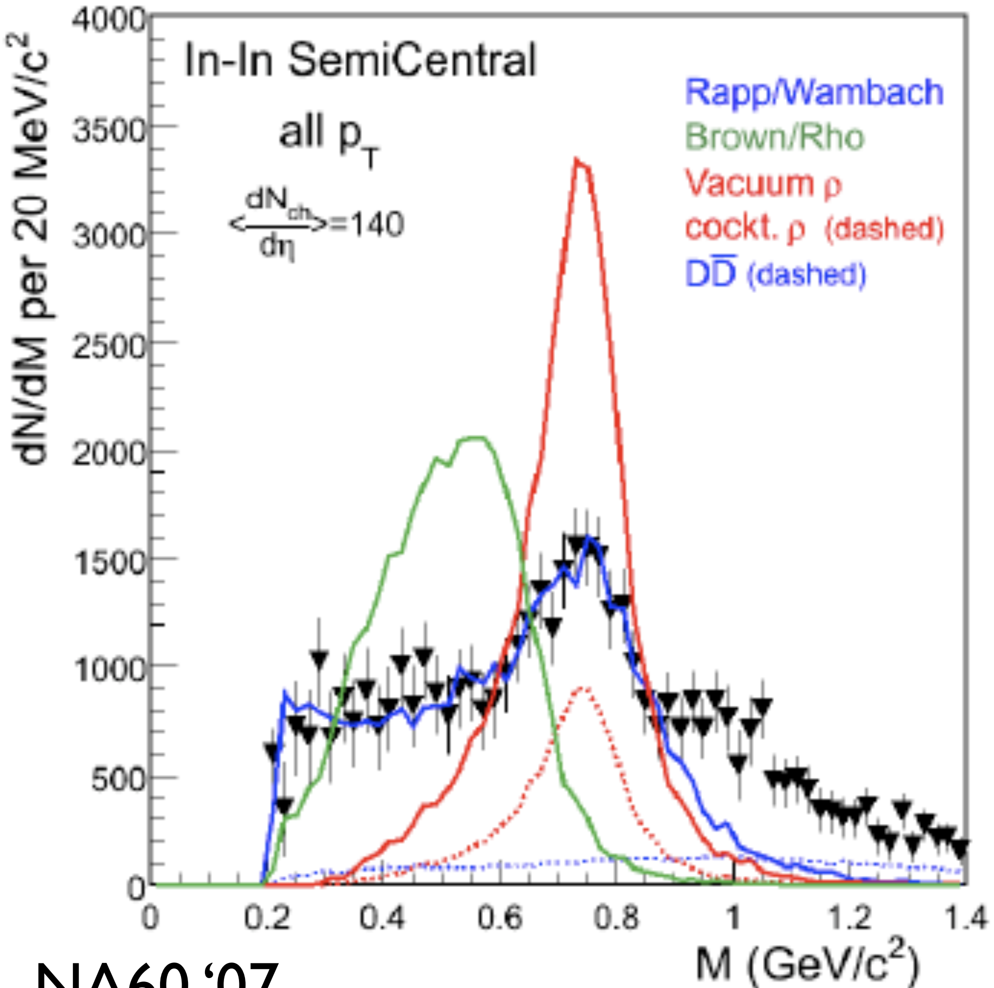
- Small-p_T excess compatible with thermal production:

  * T_{in}=300-600 MeV.

  * τ_0=0.15-0.5 fm/c.

  Early thermalization and high temperature, well about deconfinement.

Dileptons:

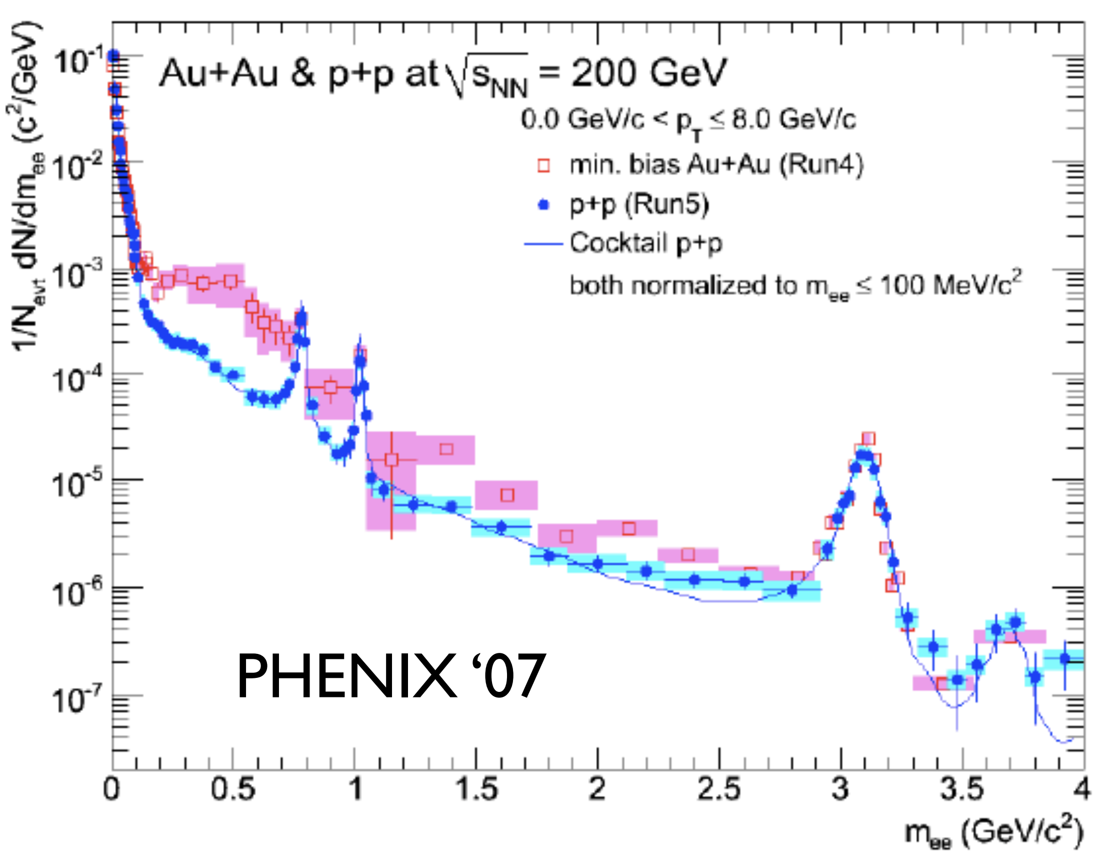


NA60 '07

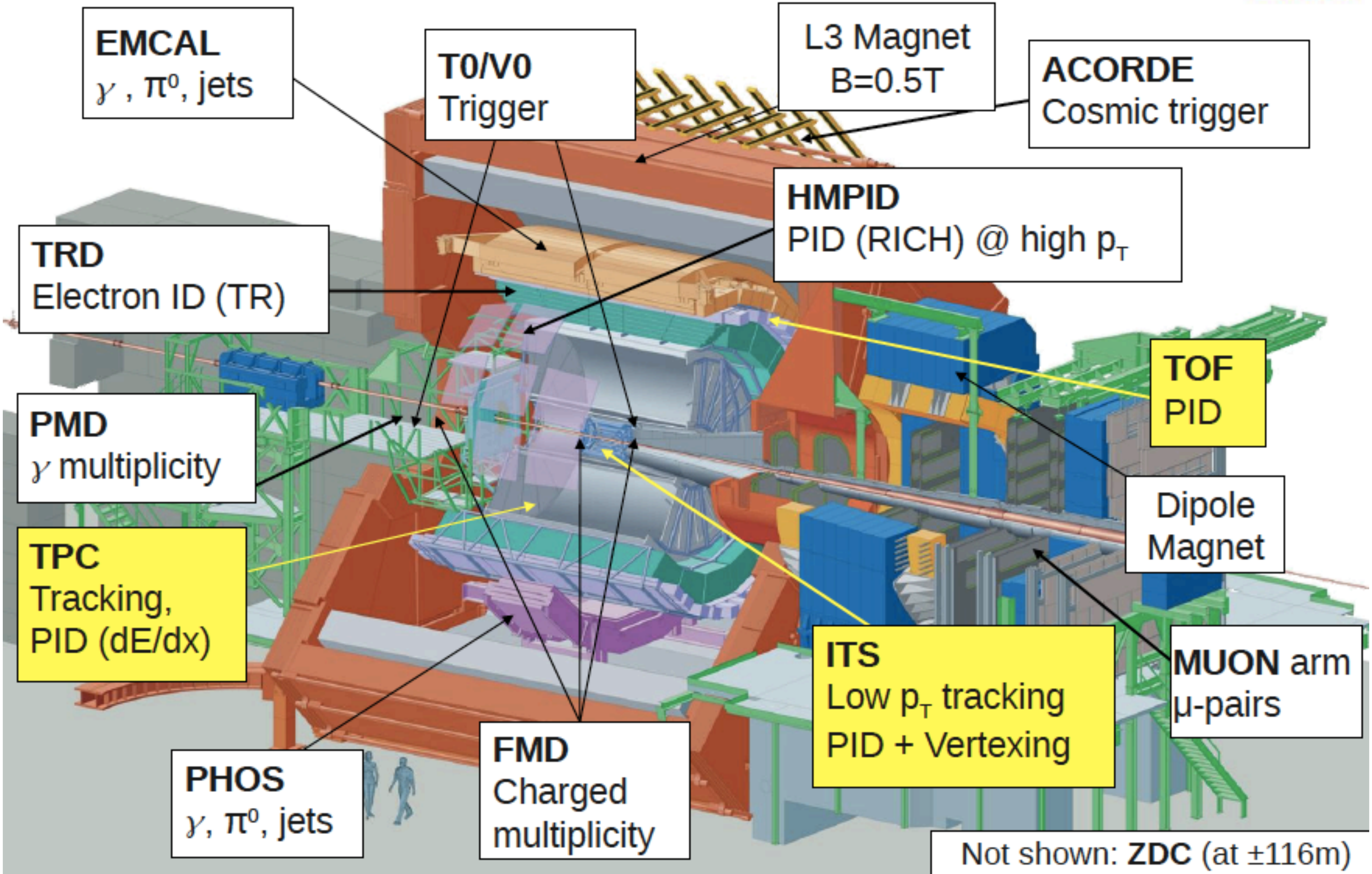
- NA60 sees an excess in the region M<1 GeV/c^2, compatible with ρ-broadening (but no mass shift).

- NA60 sees an excess in the region 1<M<1.5 GeV/c^2 which is not charm: thermal?

- PHENIX sees an excess in the region M<1 GeV/c^2.



A Large Ion Collider Experiment



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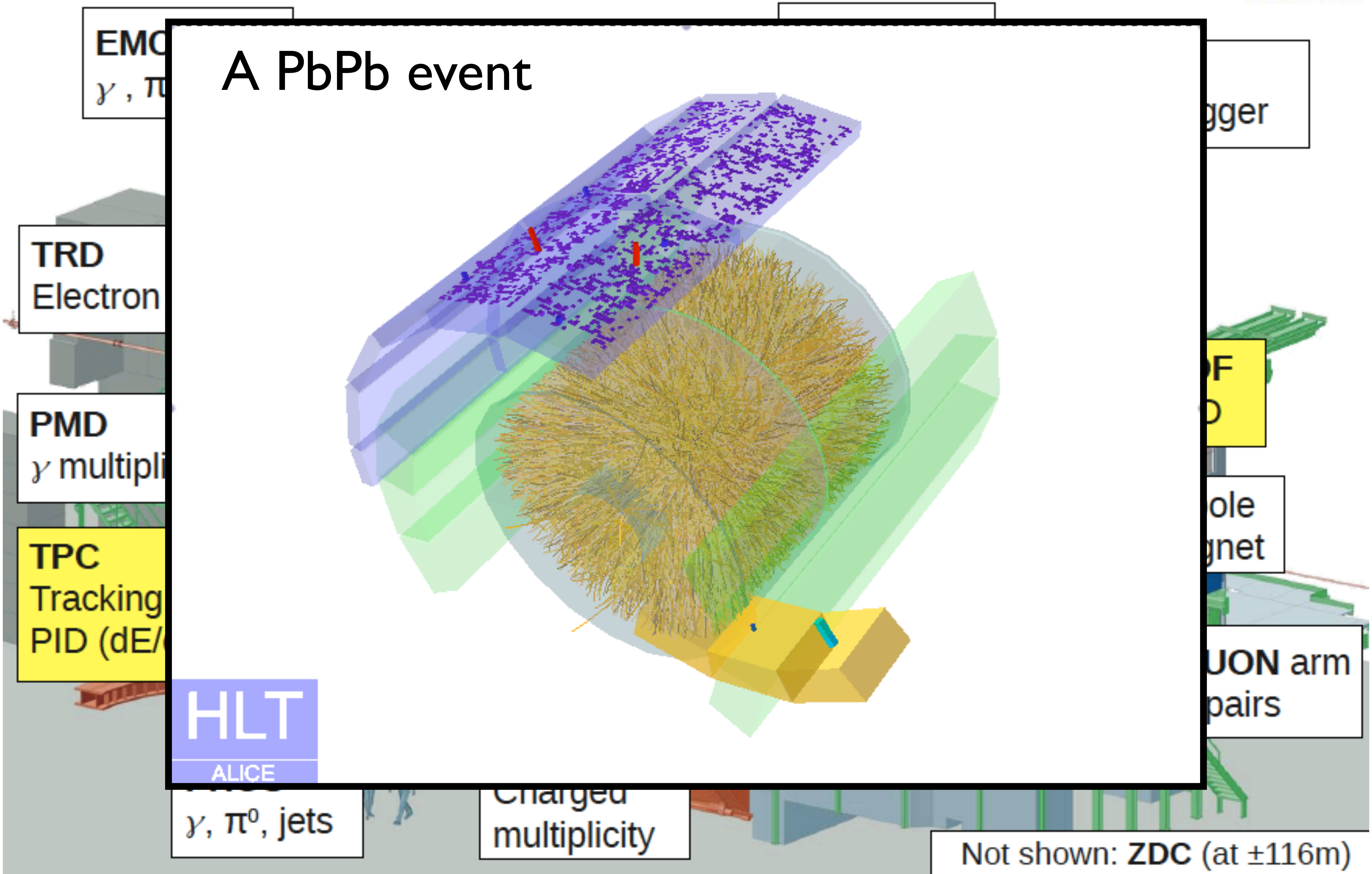


Rapidity correlations:

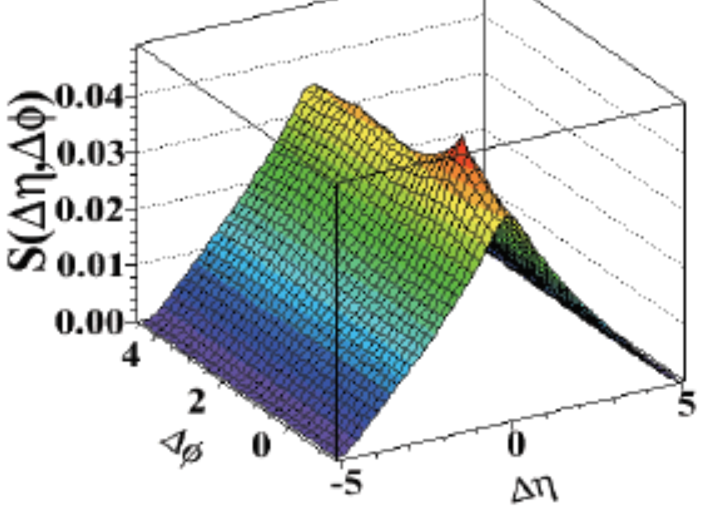
Correlation Function Definition

Signal distribution:

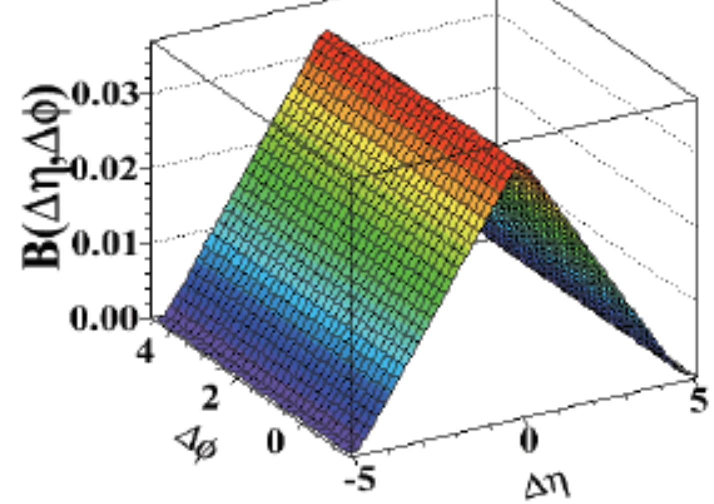
$$S_N(\Delta\eta,\Delta\varphi) = \frac{1}{N(N-1)}\frac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi}$$

Background distribution:

$$B_N(\Delta\eta,\Delta\varphi) = \frac{1}{N^2}\frac{d^2N^{bkg}}{d\Delta\eta d\Delta\varphi}$$

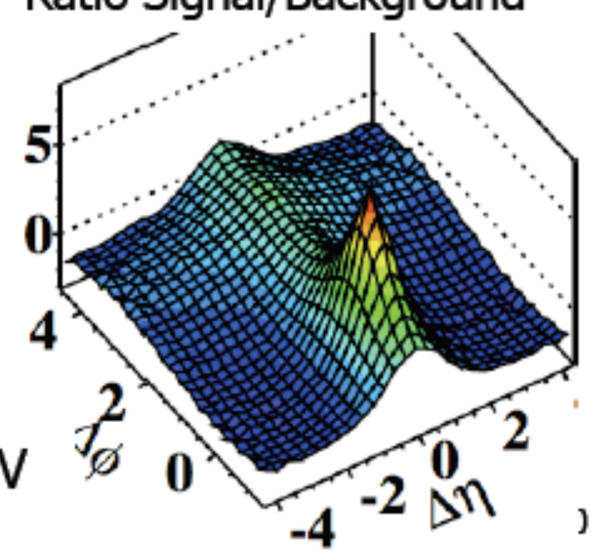


Same event pairs



Mixed event pairs

Ratio Signal/Background



$$R(\Delta\eta,\Delta\varphi) = \left\langle (N-1)\left(\frac{S_N(\Delta\eta,\Delta\varphi)}{B_N(\Delta\eta,\Delta\varphi)} - 1\right)\right\rangle_N$$

$$\Delta\eta = \eta_1 - \eta_2$$
$$\Delta\varphi = \varphi_1 - \varphi_2$$

CMS pp 7TeV

p_T-inclusive two-particle angular correlations in min bias collisions

3