Quarks and Gluons in Heavy-Ion Collisions: A Quick Tour of Recent Results

DIS 2012, 26-30 March 2012, Bonn

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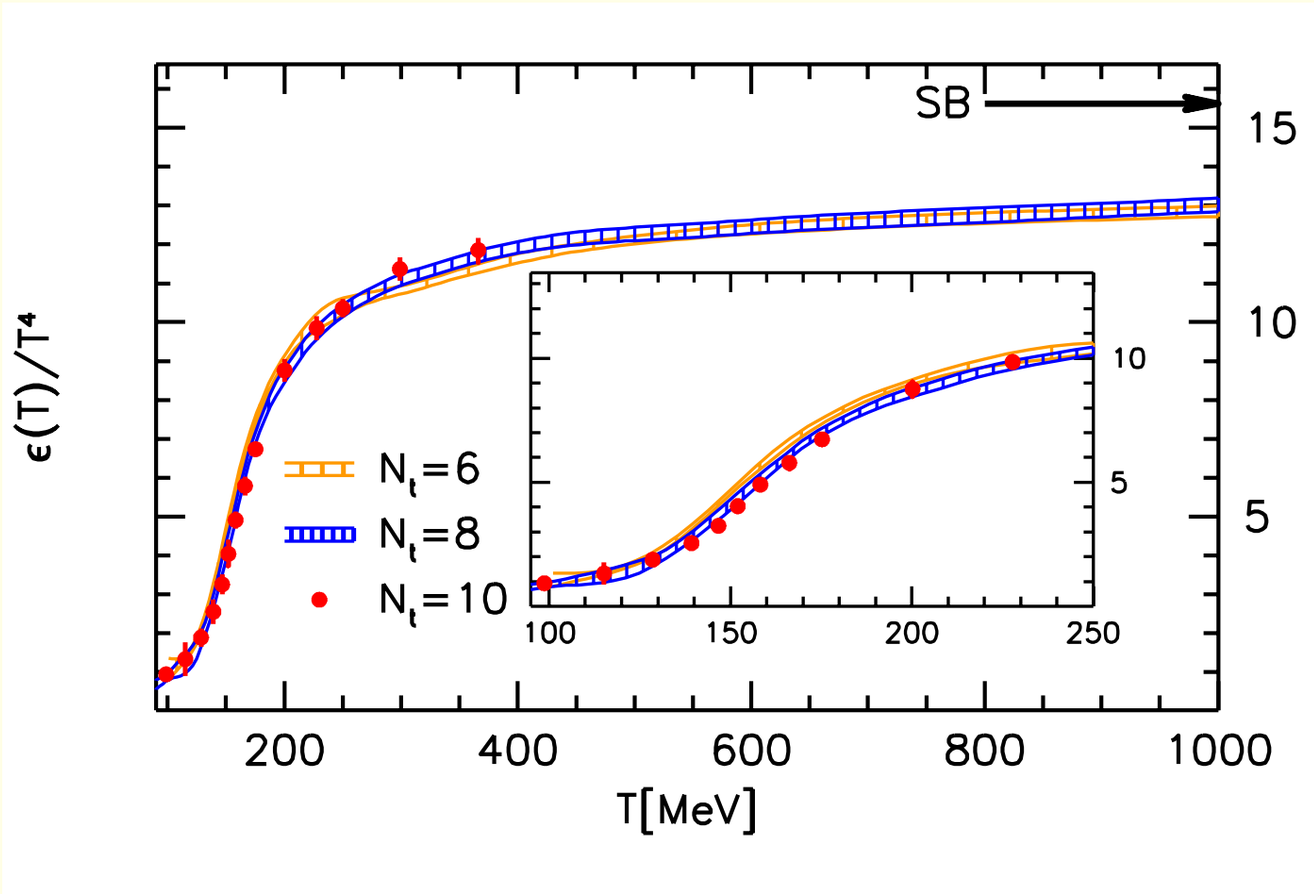
The Mission of Ultra-Relativistic Heavy-Ion Physics: Explore QCD in the High Temperature & High Density Sector



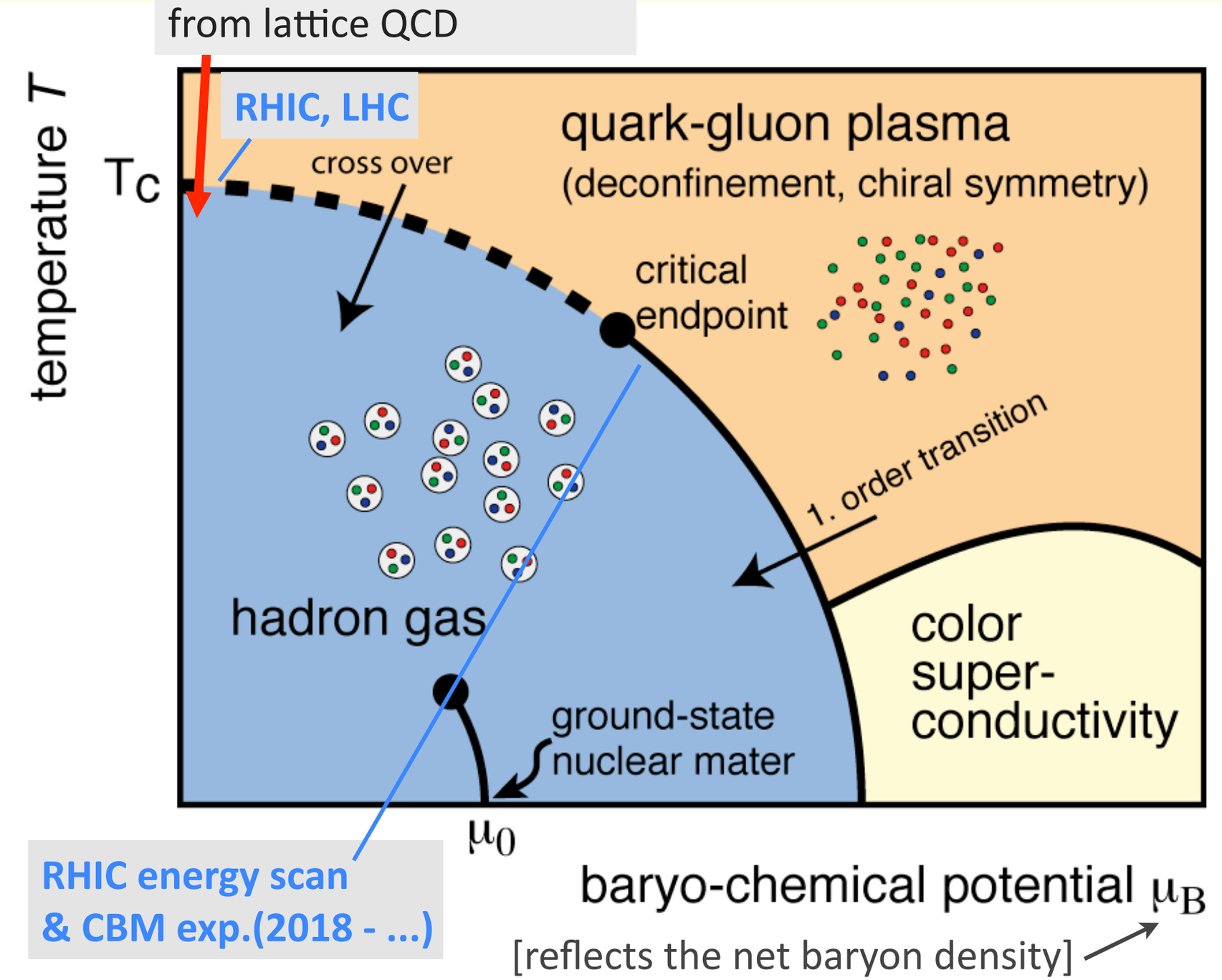
Borsanyi et al., JHEP 1011 (2010) 077

- Well-tested sectors of QCD
  - Weak coupling, low parton densities (pQCD): Hard scattering, e.g., jet spectra, ...
  - Strong coupling at $T \approx 0$: Hadron masses from lattice QCD
- Heavy-Ion Physics: Strong coupling at $T >> 0$:
- Prediction from first QCD principles (lattice QCD): Transition to deconfined quarks and gluons at $T_c = 150 - 160$ MeV, corresponding to $\varepsilon_c \approx 0.5$ GeV/fm^3

Heavy-Ion Physics = QCD thermodynamics

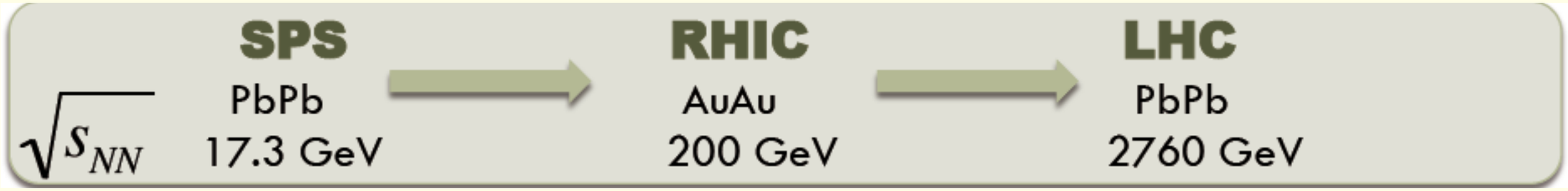
Proposed Phase Diagram of QCD Matter

Early universe ($t \approx 10^{-5}$ s),
T_c = 150 - 160 MeV
from lattice QCD



- RHIC/LHC:
  zero net baryon density
- RHIC energy scan / FAIR-CBM:
  - Lower energies
  - Study dense, baryon rich nuclear matter
- FAIR-CBM:
  High beam intensities
  → rare probes

The Role of the LHC



- SPS
  - First hints for deconfined matter
- RHIC
  - Strong evidence for deconfined matter
  - Start of characterization of this medium
  - QGP = strongly coupled fluid with small viscosity-to-entropy density ratio (η/s)
  - Medium opaque to jets
- LHC
  - Very high initial energy densities ($\varepsilon > 12$ GeV/fm^3) and temperatures
  - Large volume, long QGP lifetime
  - Abundant production of hard probes (jets, heavy-quarks, ...) as tools to probe the medium
  - Test models at 14 times larger cms energies

[B. Muller, J. Schukraft and B. Wyslouch, First Results from Pb+Pb collisions at the LHC, arXiv:1202.3233]

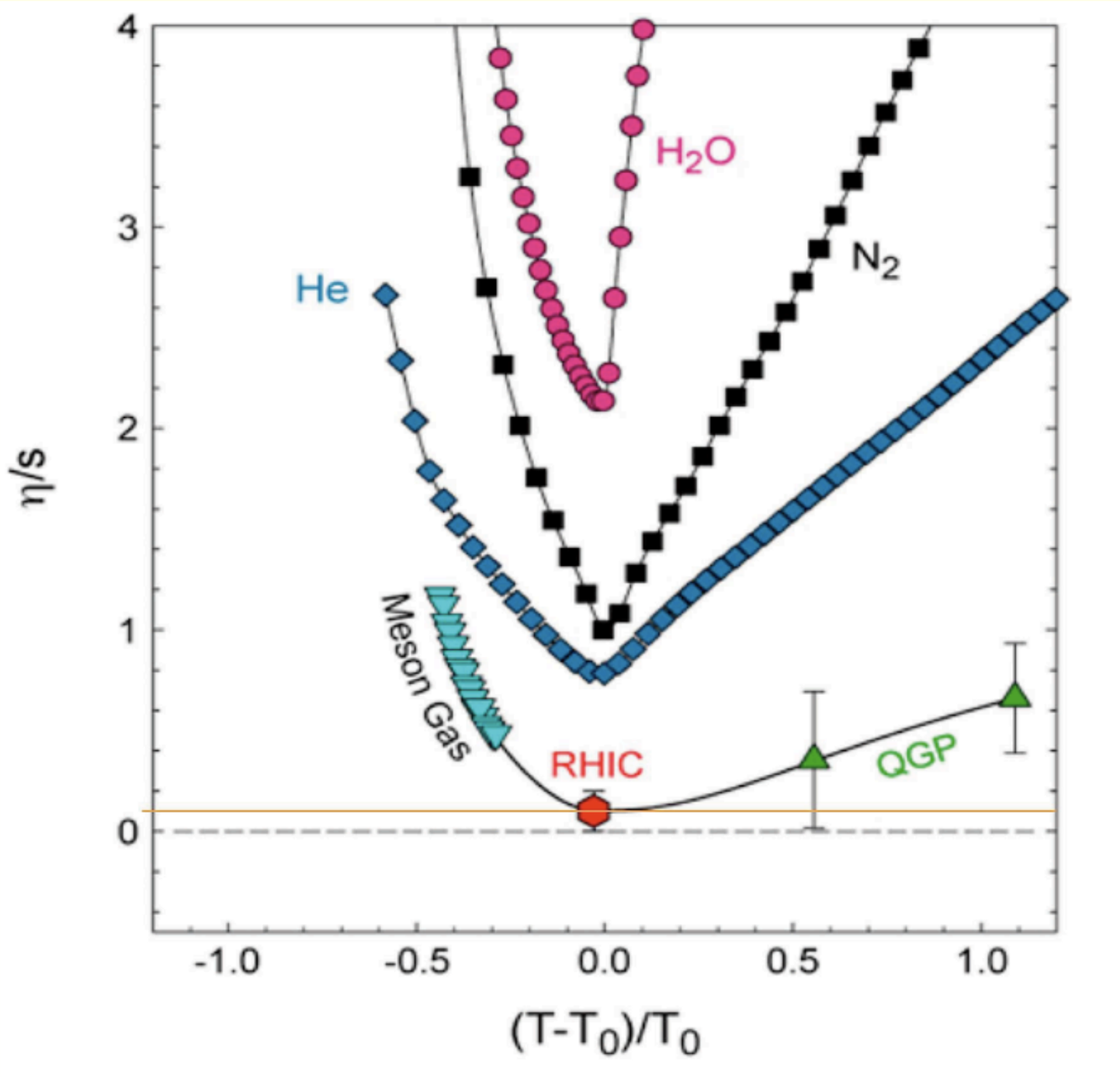
What Do We Want to Learn?

1. Understand the complex phenomenology of A+A collisions
2. Based on that, learn something about QCD thermodynamics

- Proof of deconfinement
- Equation of State
- Number of degrees of freedom
- Viscosity
- Velocity of sound
- Mechanism of parton energy loss
- ...

Example for Characterization of the Medium: Shear Viscosity to Entropy Ratio (η/*s*)

Phys.Rev.Lett. 98 (2007) 092301



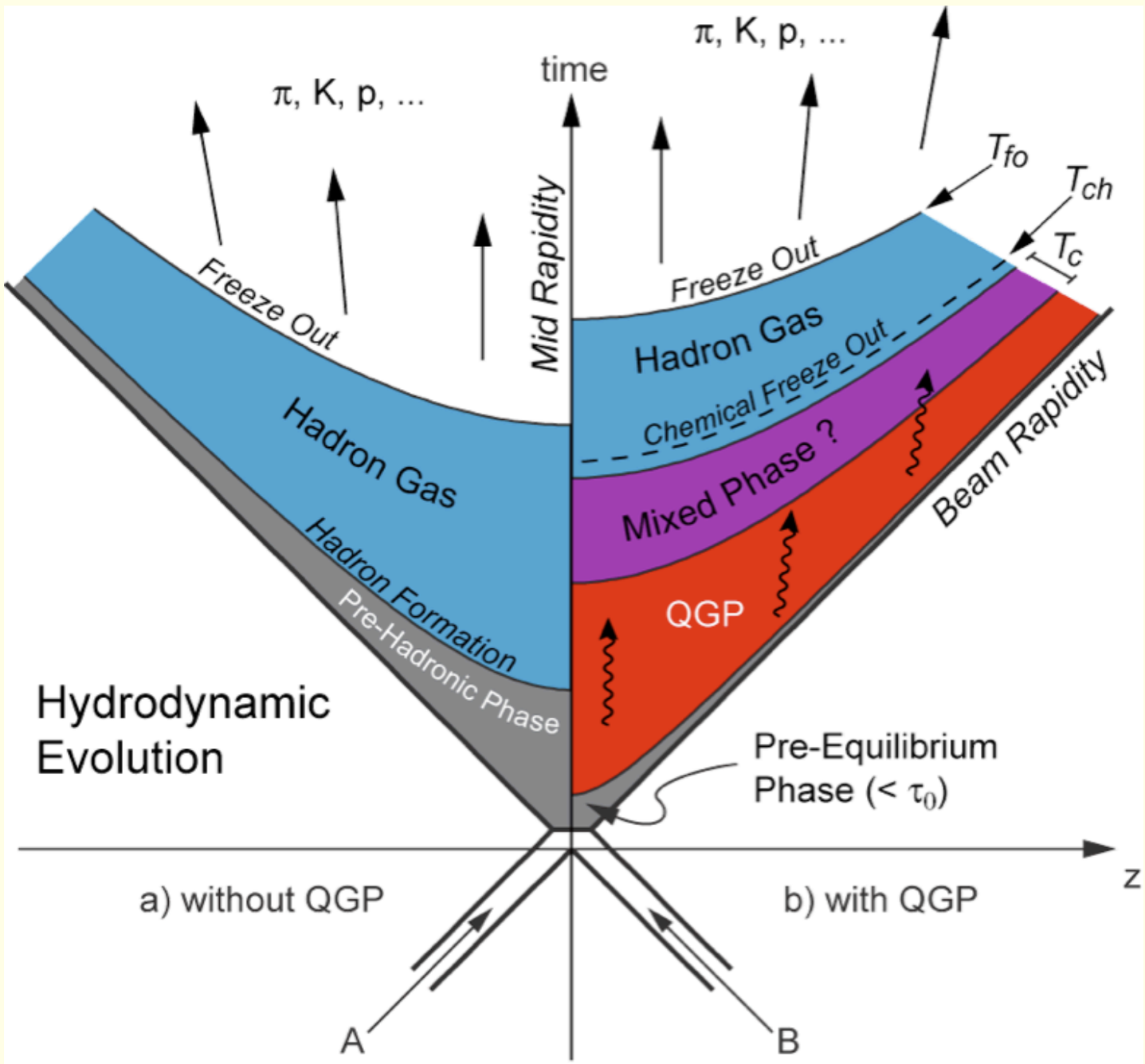
- η/*s* of the QGP smaller than for most of known fluids („perfect liquid“)
- Contact to string theory via gauge gravity duality (AdS/CFT)
- Lower bound from AdS/CFT

$$\frac{\eta}{s} \geq \frac{1}{4\pi} \quad (\hbar = k_B = 1)$$

- RHIC data + viscous hydro:

$$\frac{\eta}{s} < (4-5) \times \frac{1}{4\pi}$$

Heavy-Ion Collisions: Standard Reaction Model

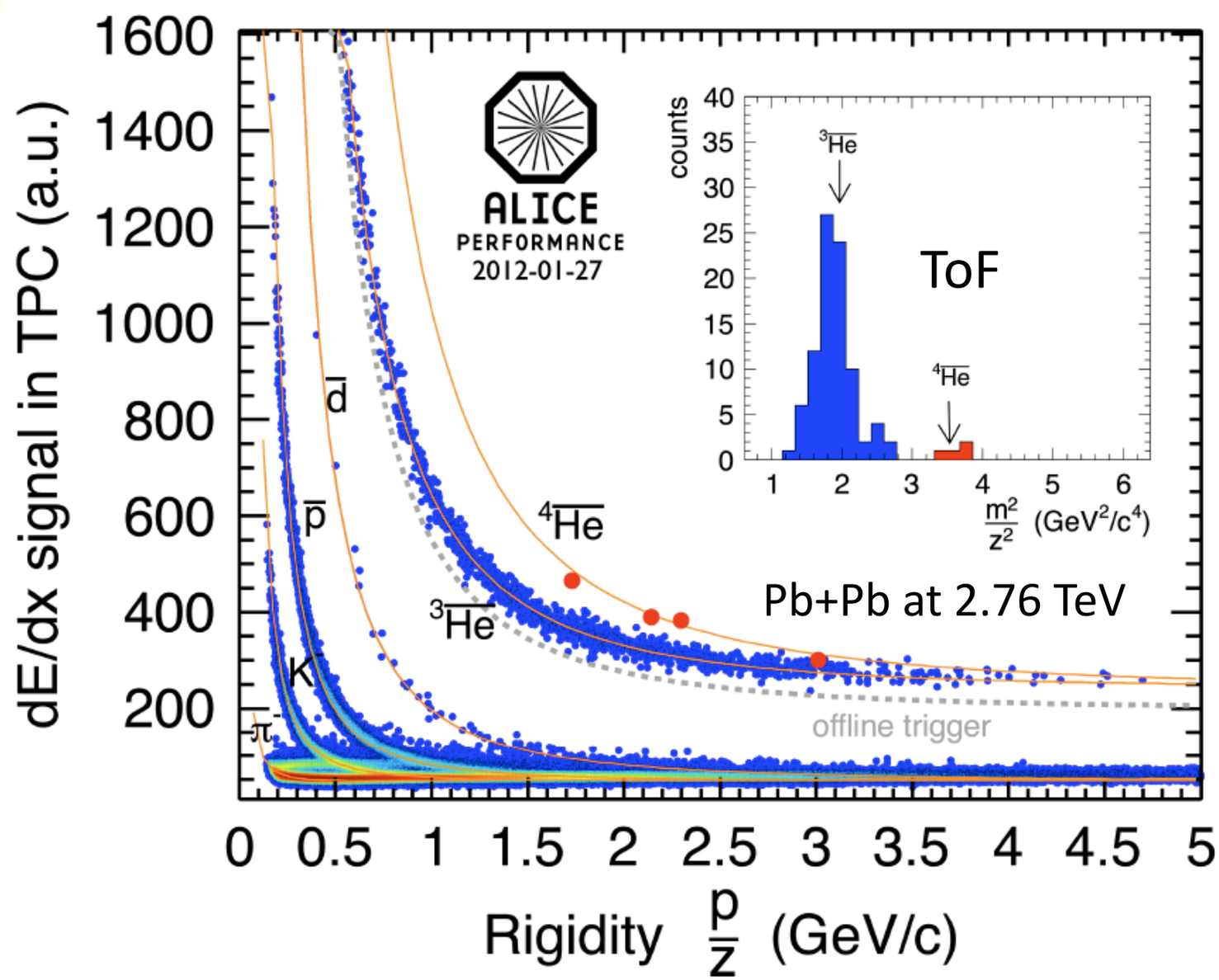


- Gluons liberated from the nuclear wave function during collision
- Rapid thermalization: QGP created at ~ 1 fm/*c*
- Longitudinal and transverse expansion describable by almost ideal hydro
- Transition QGP → hadrons
- Chemical freeze-out at $T_{ch} \approx T_c$, (T_c = 150 - 160 MeV)
- Kinetic freeze-out at $T_{fo} \sim 100$ MeV

Heavy-Ion Experiments at the LHC: ALICE, ATLAS, CMS

- ALICE
  - Robust tracking over large p_T range (~ 0.1 GeV $< p_T <$ 100 GeV)
  - Excellent Momentum Reconstruction + Particle ID a Low p_T (TPC, TRD, TOF, ...)
- ATLAS/CMS
  - Ideal for high rates / jets
  - Important contribution to heavy-ion program

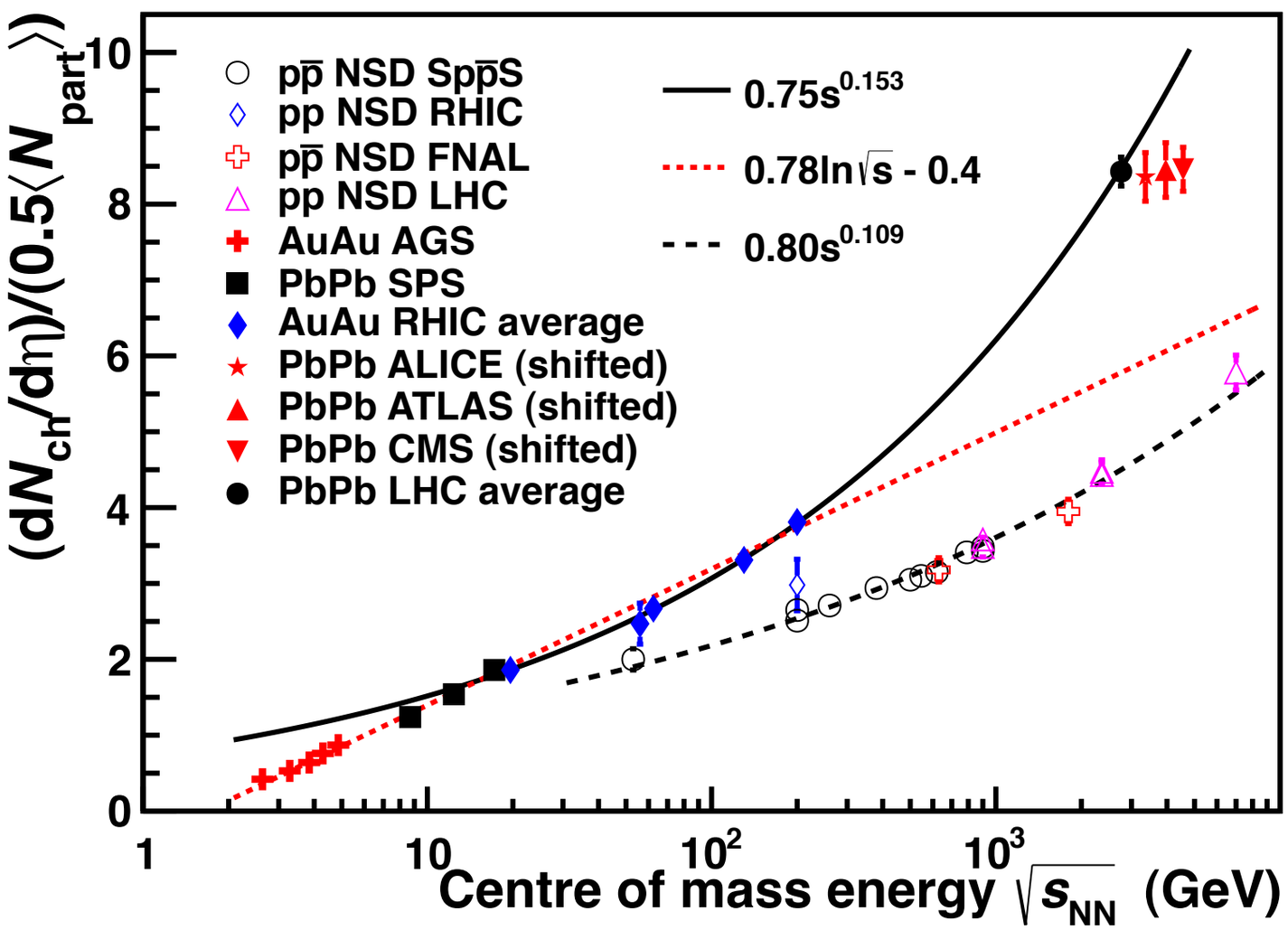
Application of ALICE's PID capabilities:
Identification of anti nuclei up to anti-^{4}He



[ALICE upgrades, Talk by Thomas Peitzmann, Tuesday]

Global Event Properties

$dN_{ch}/d\eta$: Rise with $\sqrt{s_{NN}}$ Stronger in A+A than in p+p



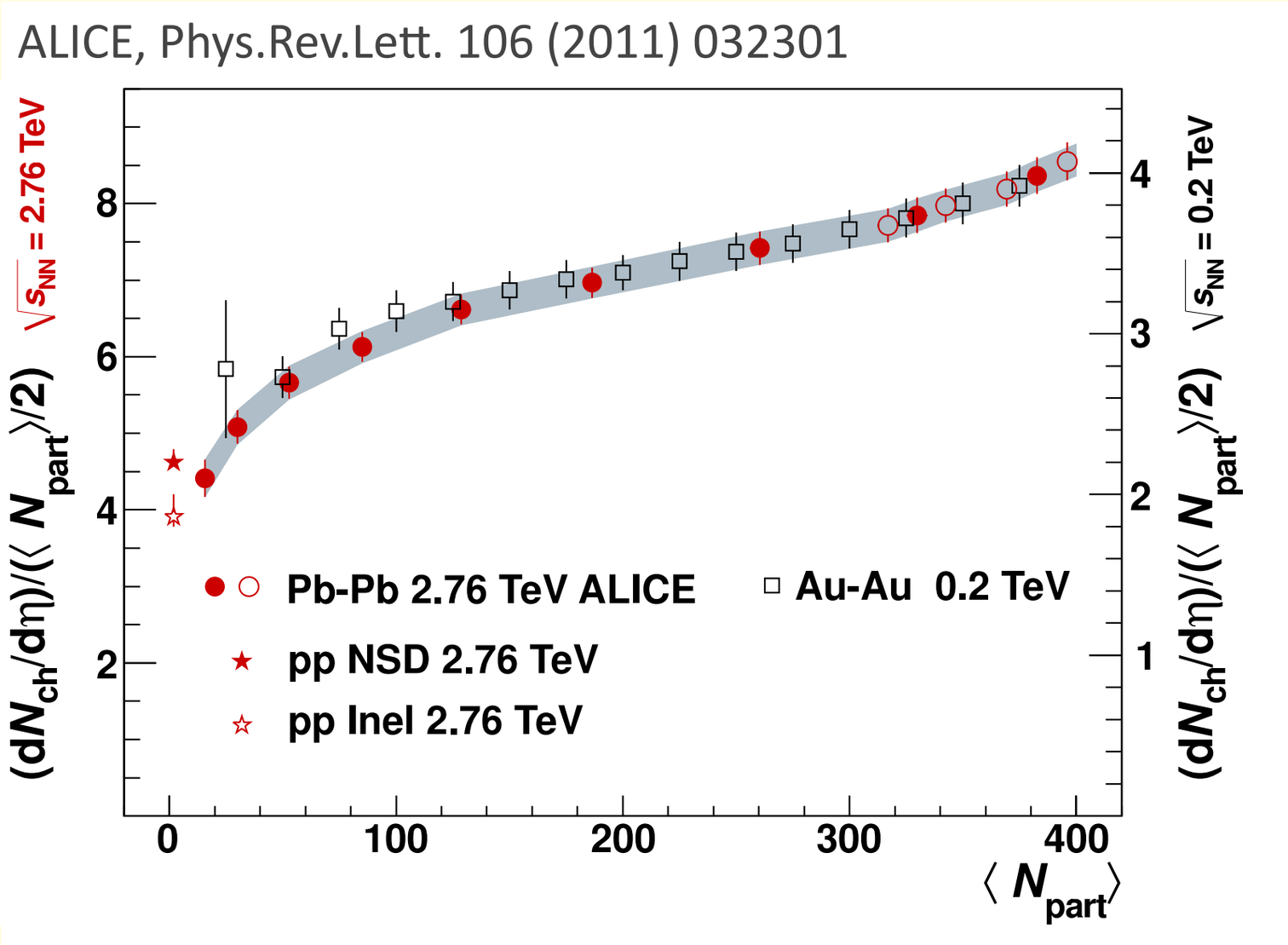
ALICE, Phys.Rev.Lett. 105 (2010) 252301

- Increase of $dN_{ch}/d\eta$ in A+A stronger than $\ln\sqrt{s}$
- Ratio $dN_{ch}/d\eta$ / ($N_{part}/2$) increases with $\sqrt{s}$
  - p+p: $\sim s^{0.11}$
  - central A+A: $\sim s^{0.15}$
- Energy density from Bjorken formula (for τ_0 = 1 fm/c): $\varepsilon_{LHC} \approx 15$ GeV/fm$^3 \approx 3 \times \varepsilon_{RHIC}$

$$\varepsilon = \frac{dE_T/dy}{\tau_0 \pi R^2} \approx \frac{3}{2}\langle m_T\rangle \frac{dN_{ch}/d\eta}{\tau_0 \pi R^2}$$

Initial energy density at LHC and RHIC well above $\varepsilon_c \approx 0.5$ GeV/fm^3

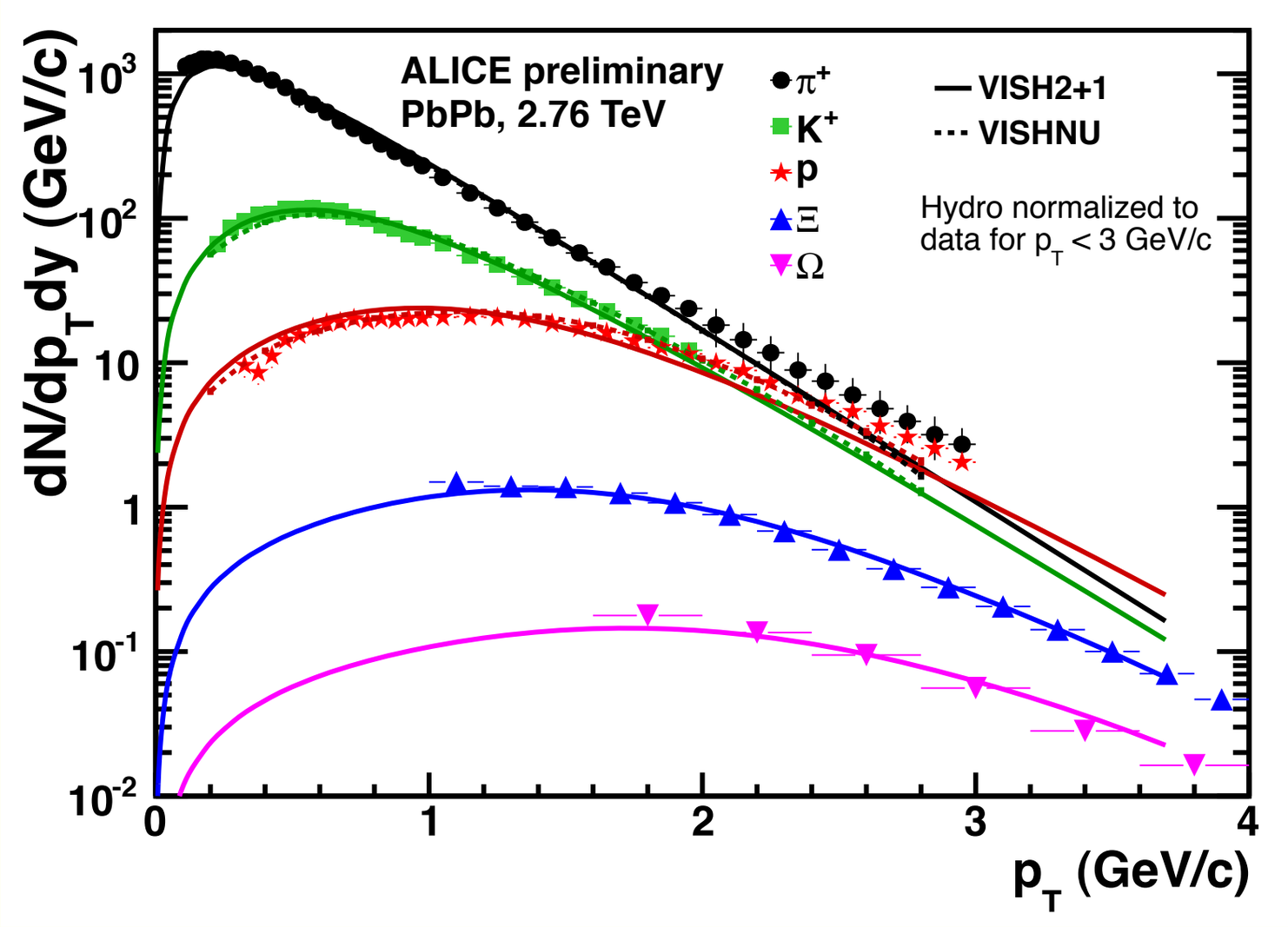
Centrality Dependence of $dN_{ch}/d\eta$: The Unreasonable Effectiveness of Geometry in A+A Collisions



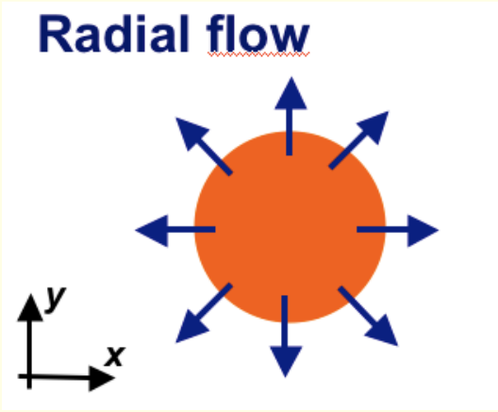
- Relative Increase from p+p to central A+A identical at RHIC and LHC
- This actually holds for $20 < \sqrt{s_{NN}} < 2760$ GeV
- A bit surprising in two-component models (soft+hard)

Lesson: Geometry Rules

Identified Particle Spectra: Compelling Evidence for Radial Flow

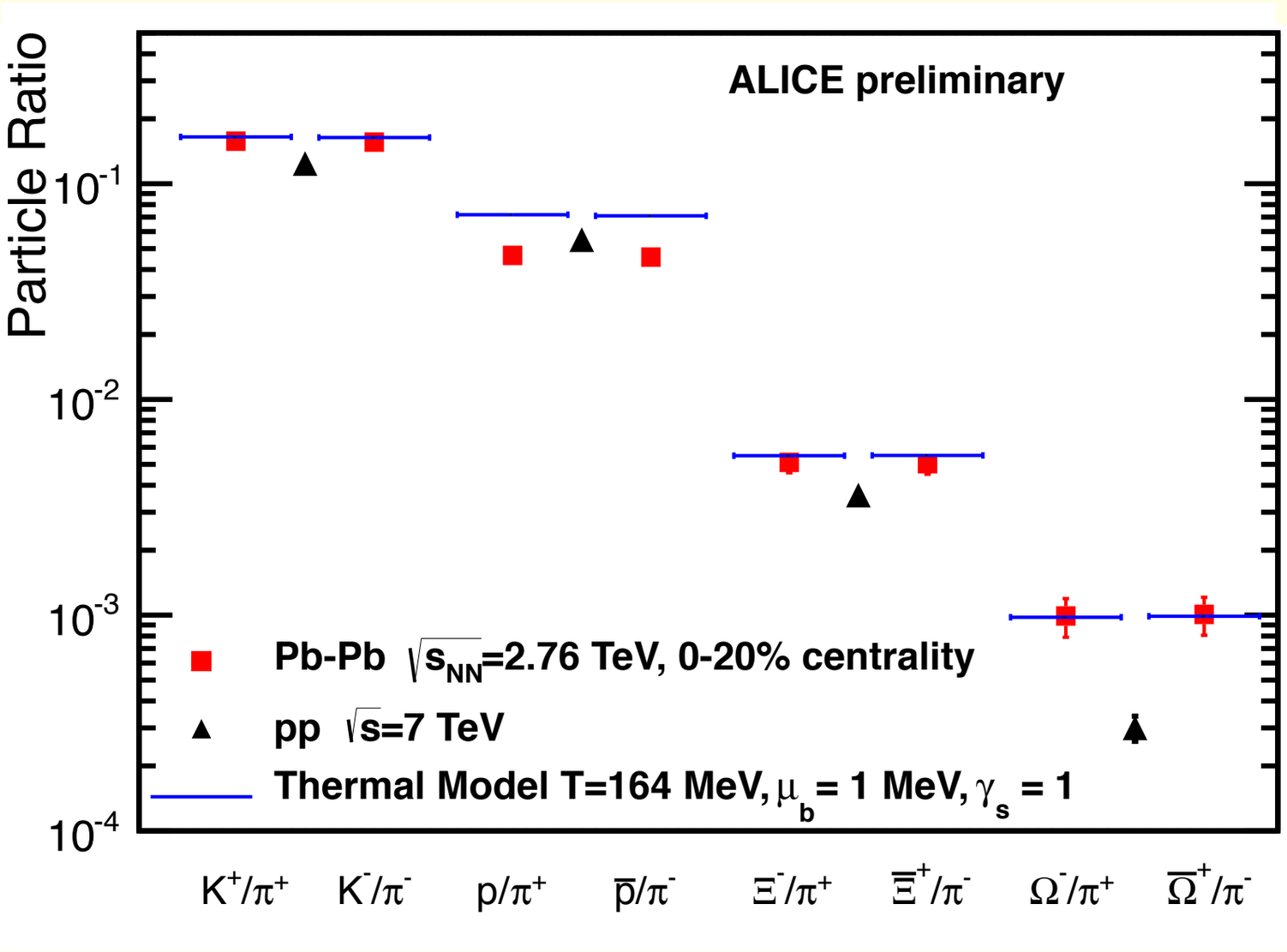


- Shapes of p_T spectra for particles with different masses indicate radial flow
- Hydro models describe data
- Hydro inspired blast wave fits for central Pb+Pb at LHC:
  - $\langle\beta_{T,\mathrm{flow}}\rangle \approx 0.65\ c$
  - $\langle\beta_{T,\mathrm{flow}}\rangle_{\mathrm{LHC}} \approx 1.1 \times \langle\beta_{T,\mathrm{flow}}\rangle_{\mathrm{RHIC}}$
  - kinetic freeze-out: $T_{\mathrm{fo}} \approx$ 80 - 100 MeV



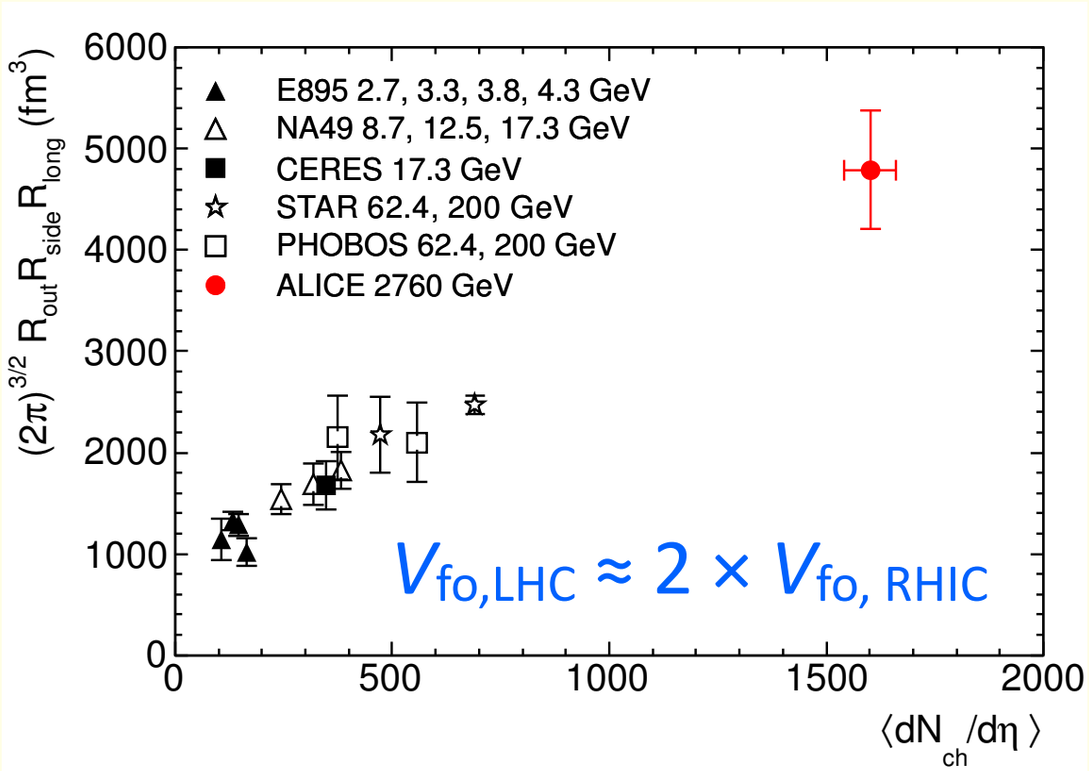
$$p_T^{\mathrm{w/\ flow}} = p_T^{\mathrm{w/o\ flow}} + \beta_{T,\mathrm{flow}}\gamma_{T,\mathrm{flow}}\, m$$

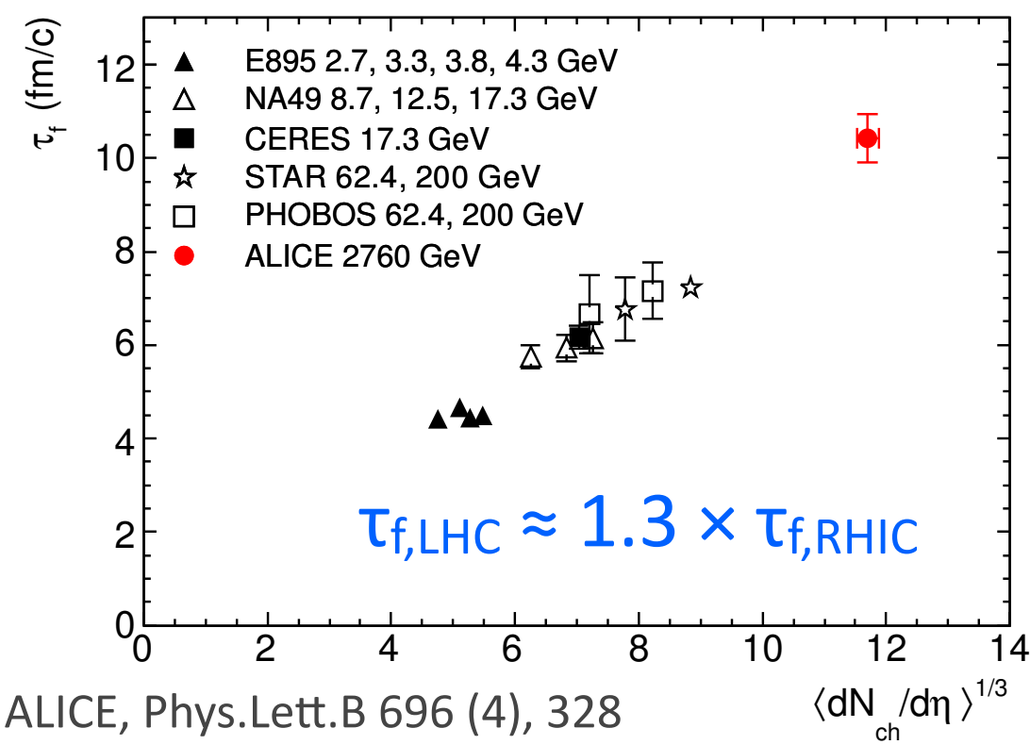
Particle Ratios in Pb+Pb at the LHC: Chemical Freeze-Out at $T_{ch} \approx T_c$



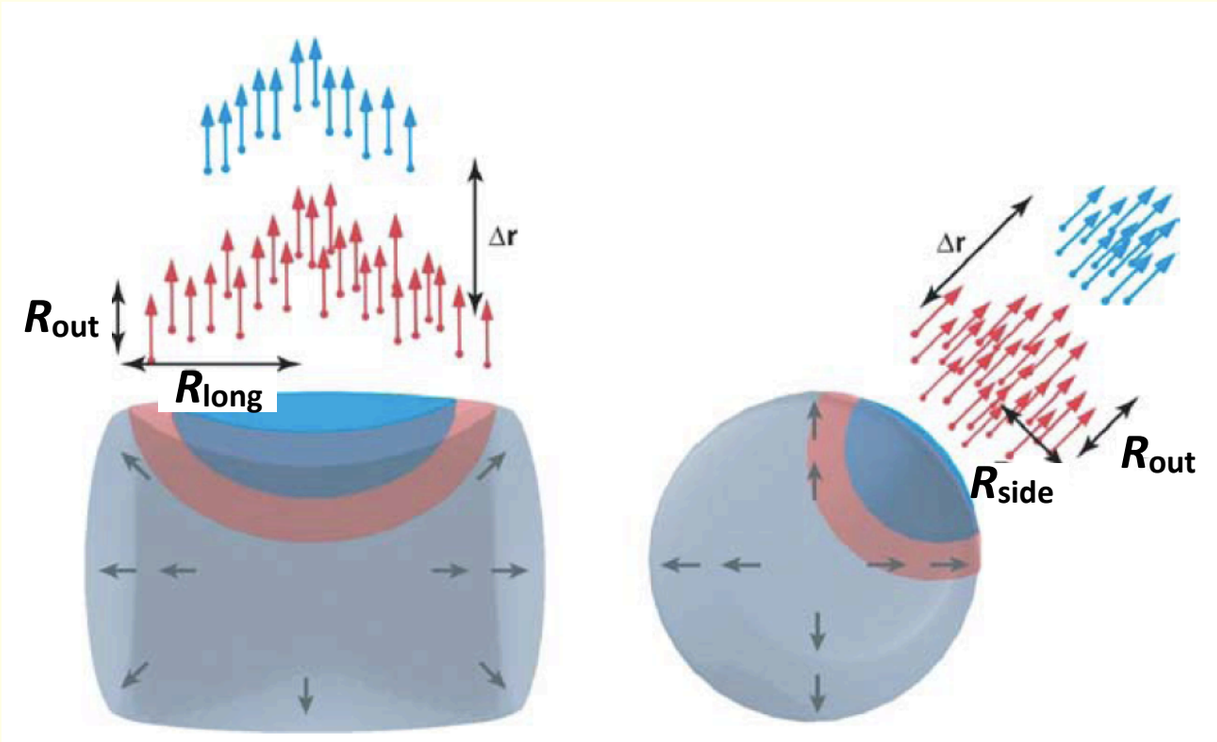
- Statistical/thermal model
  - Yield $\propto m^{3/2} \exp(-m/T)$
  - chemical potential depending on baryon number, strangeness, and isospin of the particle
  - two free parameters: T_{ch}, μ_B
- $T_{ch} \approx 164$ MeV $\approx T_c$, actually holds for $\sqrt{s_{NN}} > 10$-20 GeV
- Strangeness enhancement in A+A nicely described
- p/π ratio at the LHC to be understood

Space-time Evolution of the System from Two-Pion Bose-Einstein Correlations (HBT)





ALICE, Phys.Lett.B 696 (4), 328



Freeze-out volume:

$$V_{\rm fo} \sim (2\pi)^{3/2} R_{\rm out} R_{\rm side} R_{\rm long}$$

Emission time: $\tau_f \sim R_{\rm long}\sqrt{m_T/T}$

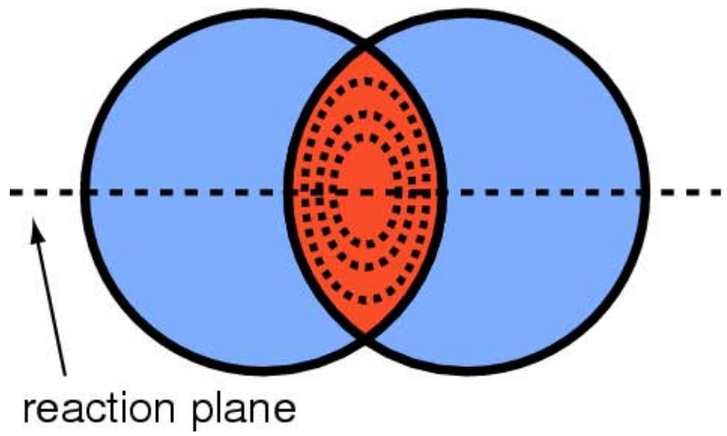
- $V_{PbPb,central}$ at LHC: ≈ 5000 fm^3
- V_{Pb} ≈ 800 fm^3

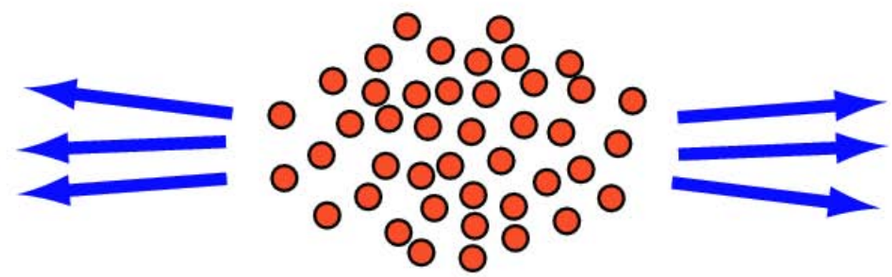
  → $V_{PbPb,central} \approx 6.25 \times V_{Pb}$

Collective Flow

Anisotropic Flow

Initial spatial anisotropy ➜ anisotropy in momentum space

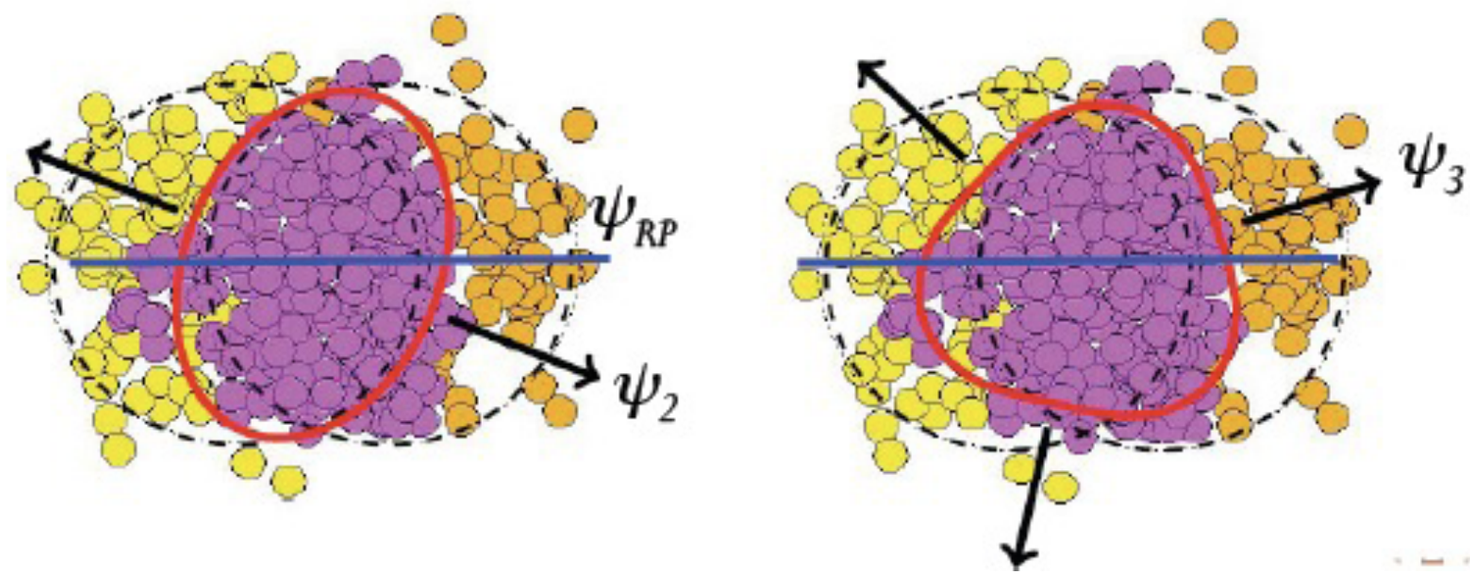




Fluctuations of the initial geometry & energy density distribution are important

$\psi_2 \approx \psi_{RP}$

ψ_3 not correlated with ψ_2

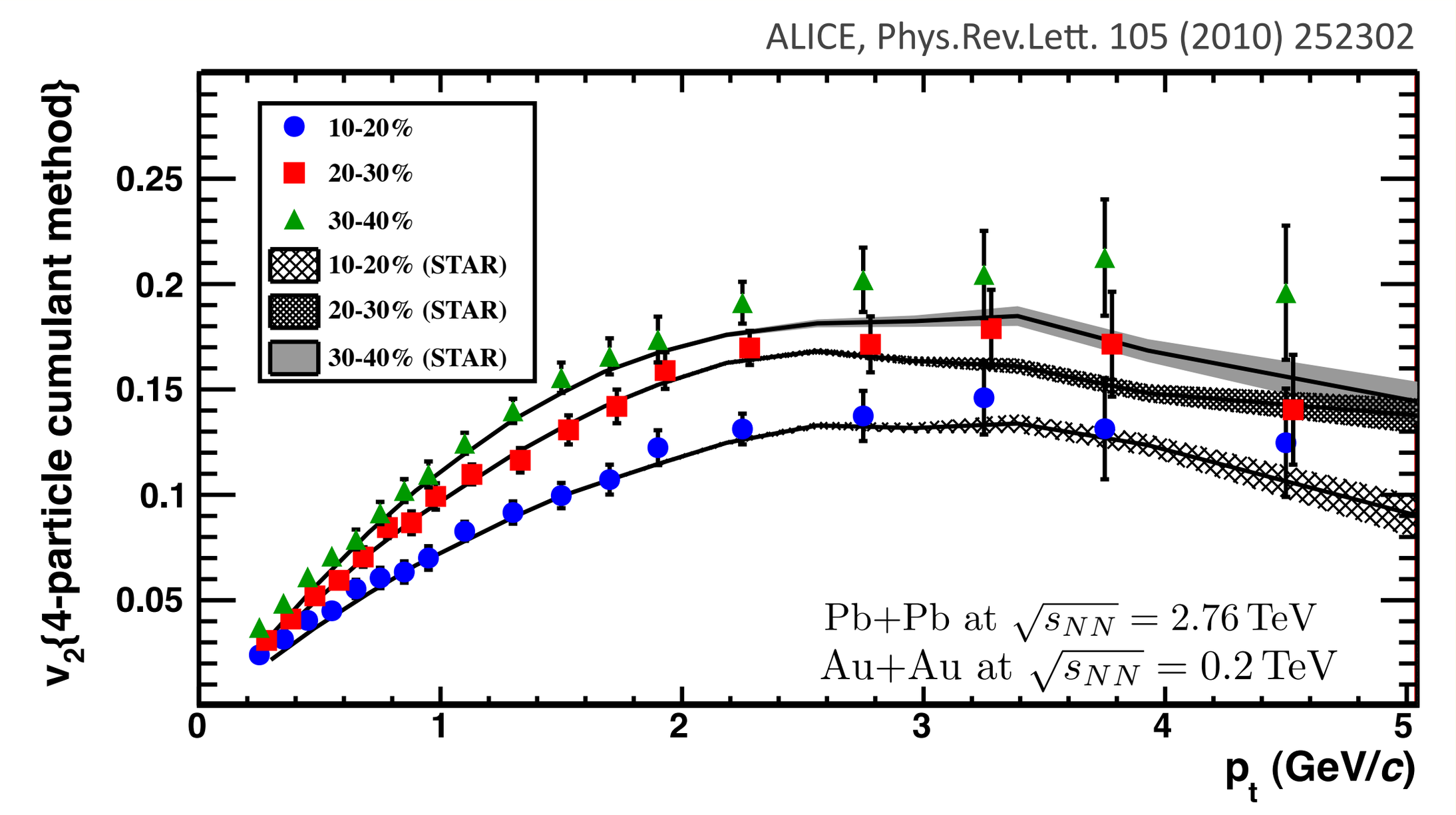


Fourier decomposition:

$$\mathrm{E}\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_T\mathrm{d}p_T\mathrm{d}y}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\varphi - \Psi_n)\right]\right)$$

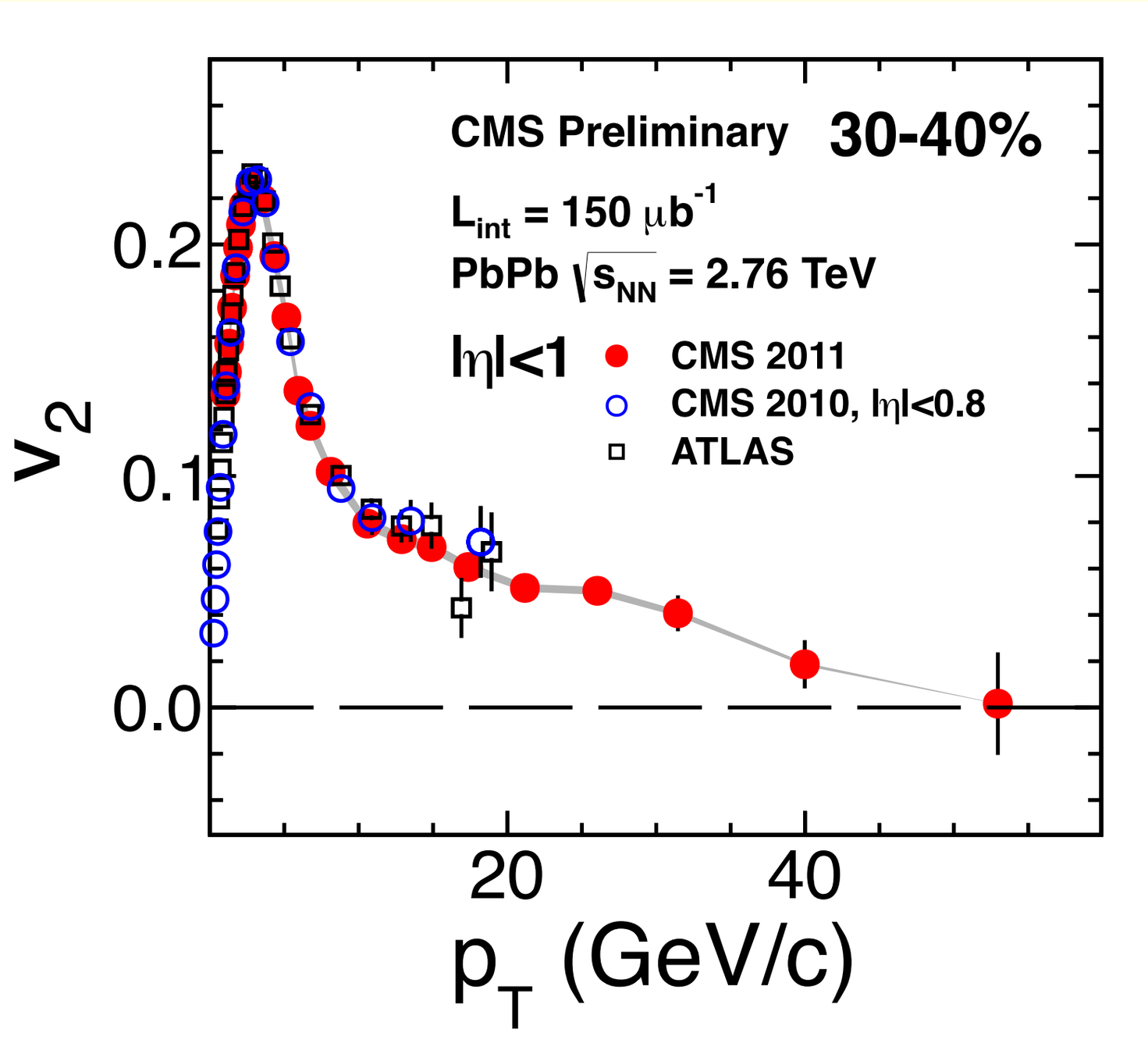
v_2 : elliptic flow, v_3 : triangular flow

Charged Particle $v_2(p_T)$ at Low p_T: RHIC vs. LHC

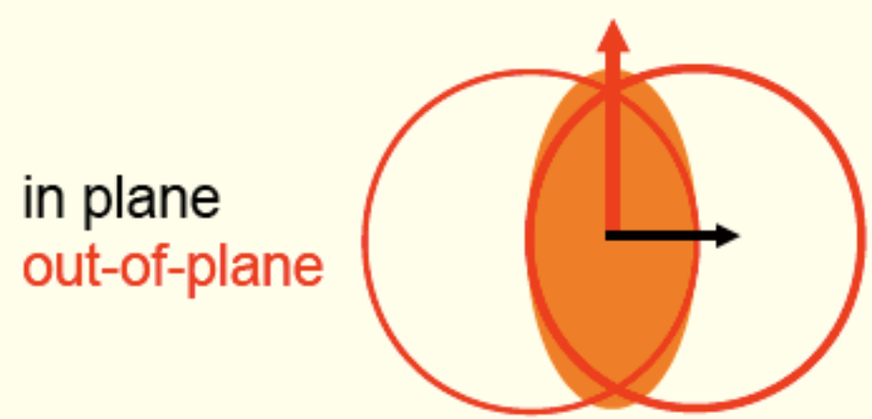


- $v_2(p_T)$[LHC] = $v_2(p_T)$[RHIC], despite factor 14 increase in $\sqrt{s_{NN}}$
- p_T-integrated v_2 at LHC 30% larger due to larger $\langle p_T \rangle$

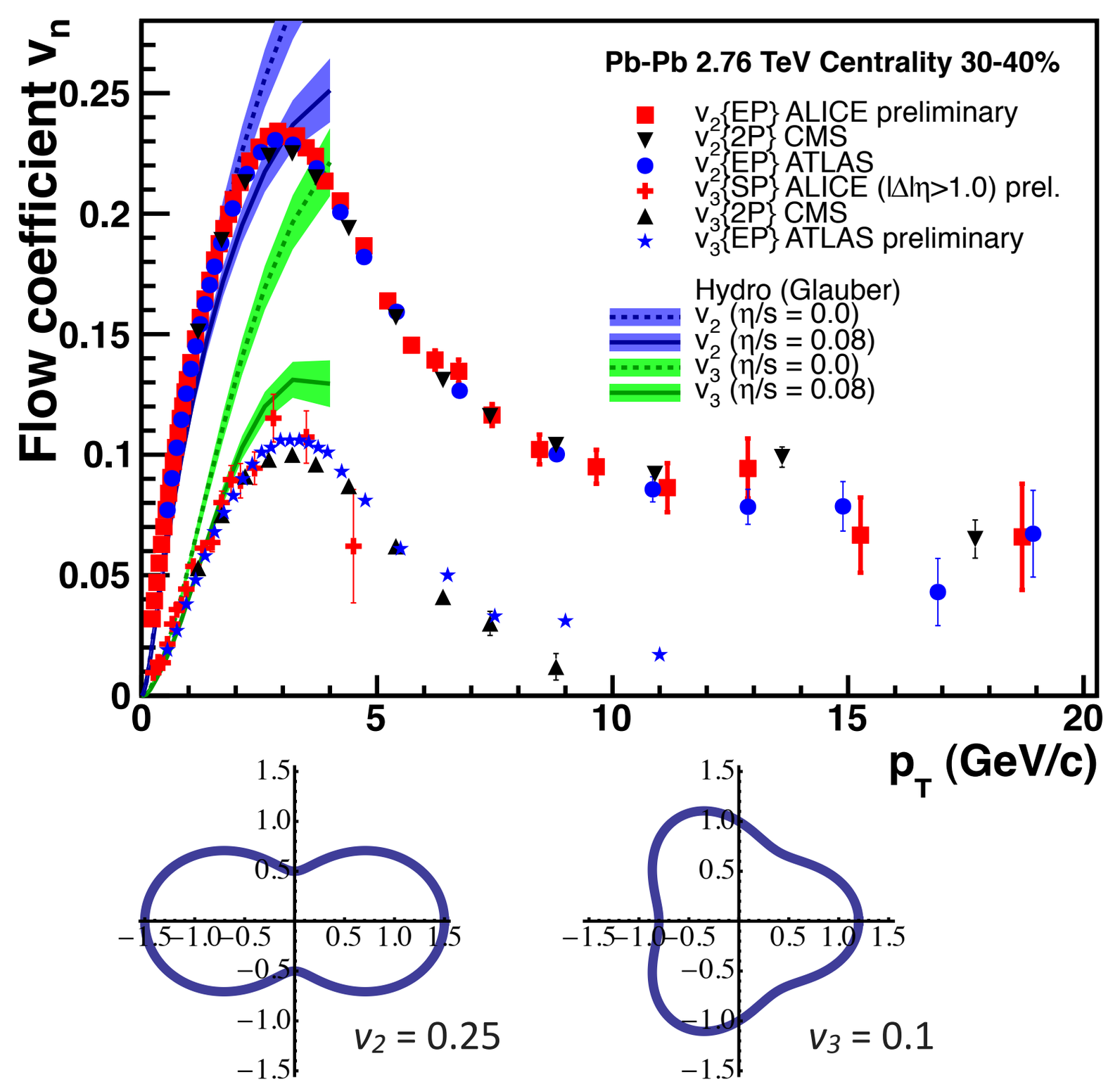
Charged Particle $v_2(p_T)$ at High p_T



- v_2 at low p_T (< 1.5 GeV/c) due to hydro expansion
- v_2 at high p_T due to path length dependence of parton energy loss



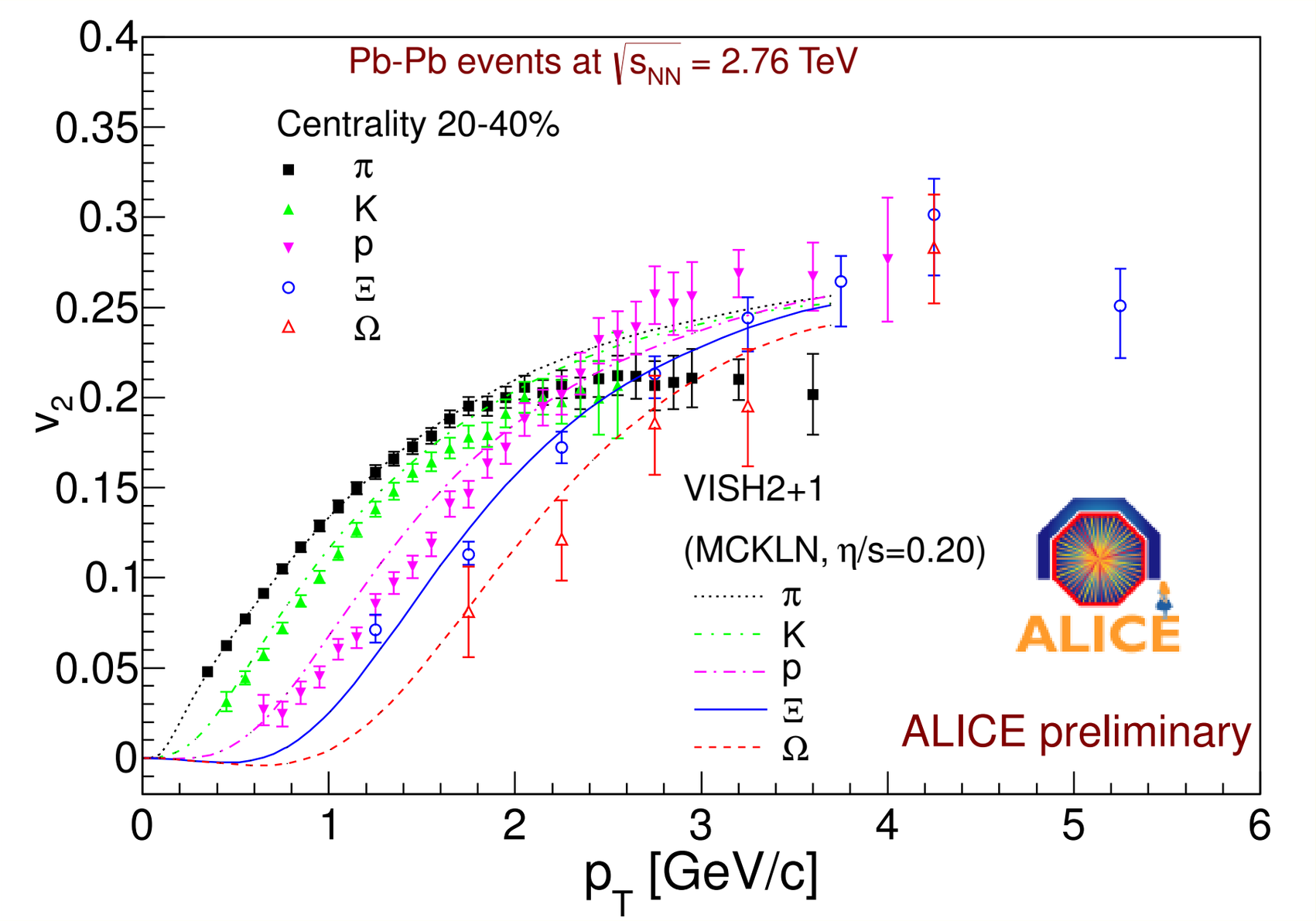
Limits on η/s from Charged Particle v_2 and v_3



- Significant v_3 component
- Viscosity dissipates initial pressure gradients and reduces collective flow
- v_3 helps constrain η/s
- Current bound from LHC: $\eta/s < 2/(4\pi) = 2\cdot(\eta/s)_{min}$

Qui, Shen, Heinz, Phys.Lett. B707 (2012) 151

Elliptic Flow of Identified Particles: Mass Ordering as Expected from Hydro Expansion



- Hydro predicts mass ordering (due to radial flow):

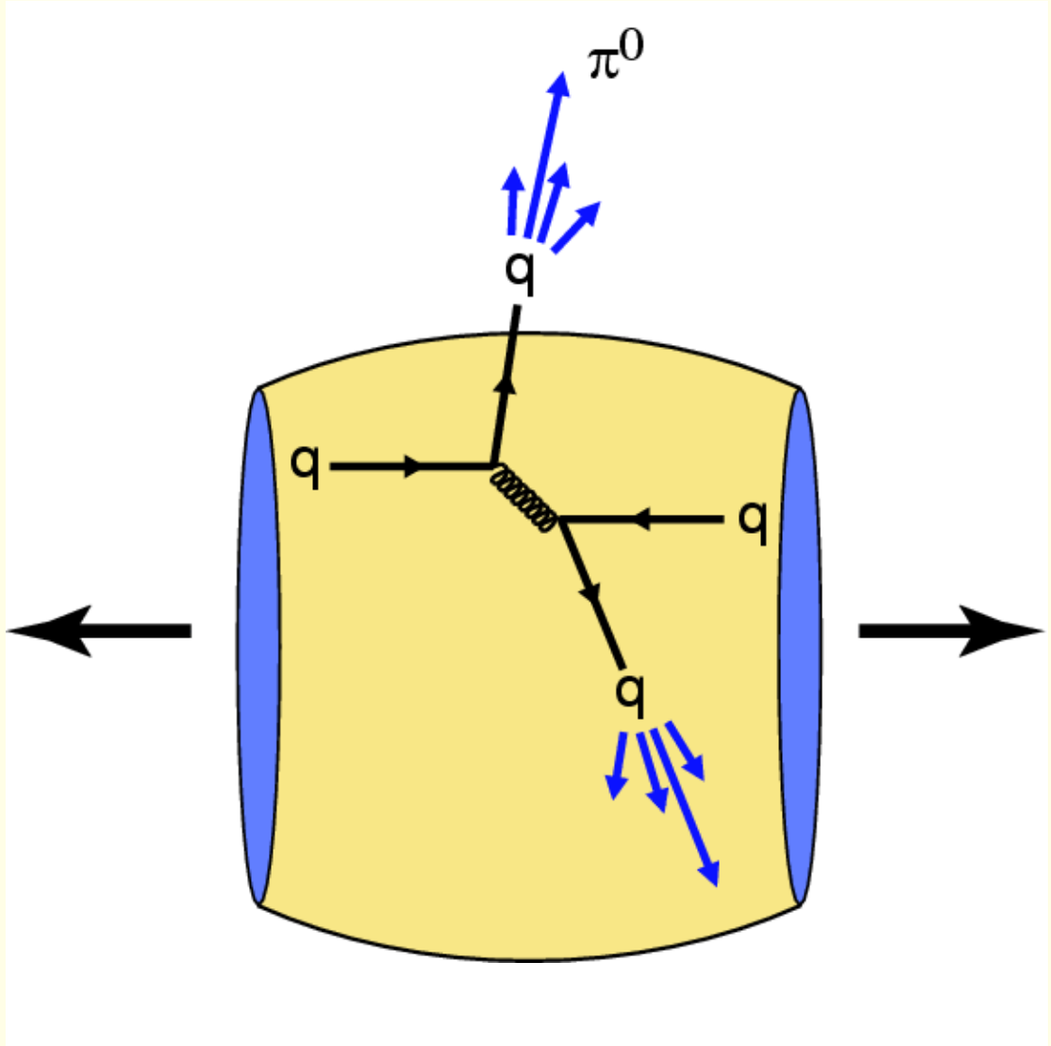
$$v_2 \sim \frac{1}{T}(p_T - v \cdot m_T) \qquad v = \text{mean transv. flow velocity}$$

- Indeed observed → Further evidence for hydro picture

Jet Quenching

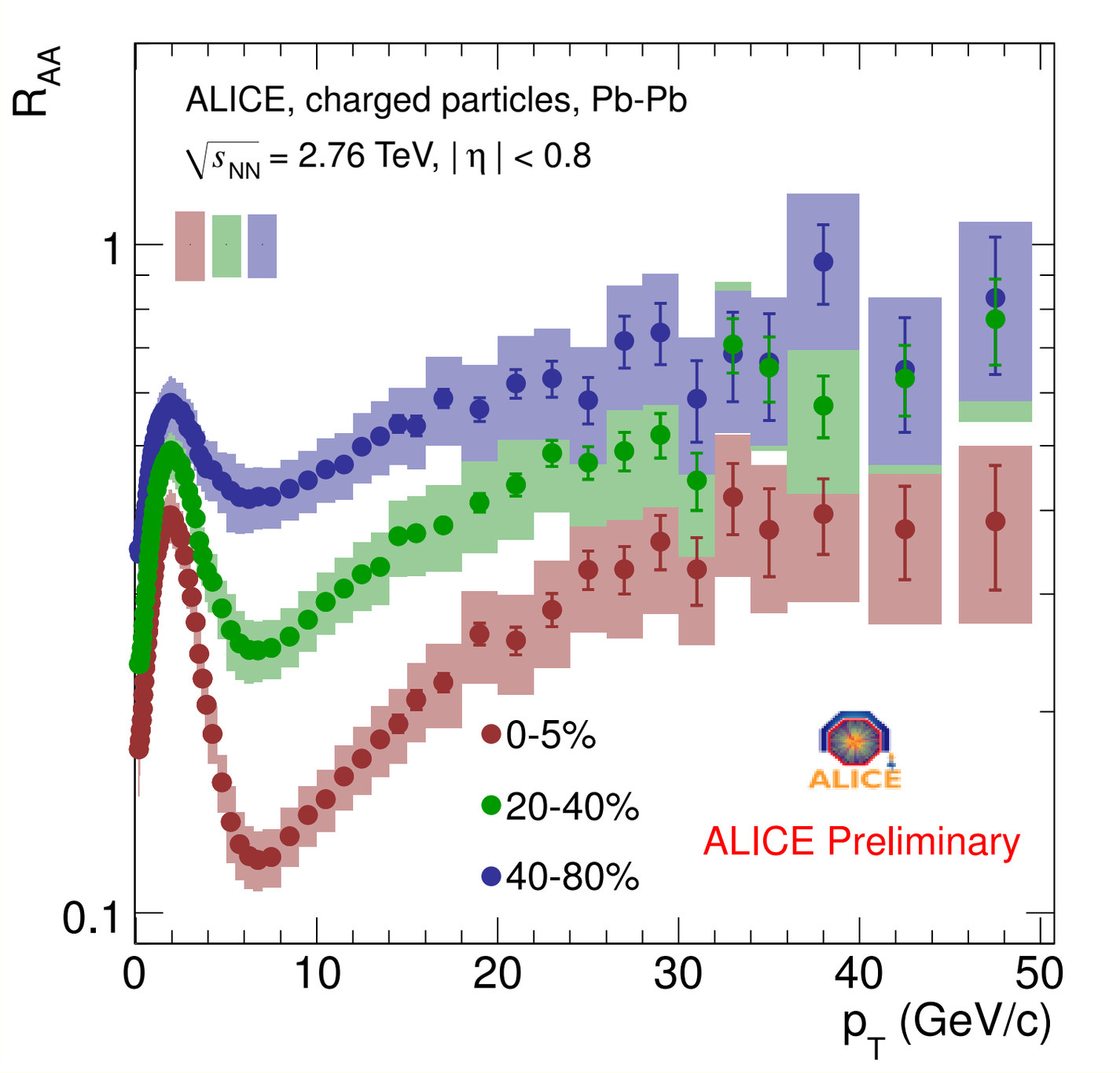
Hard Probes in Heavy-Ion Collisions

- Hard probes are a useful tool because
  - they are produced in the early stage of a heavy-ion collisions, prior to the formation of the quark-gluon plasma
  - their initial production rate can be calculated with perturbative QCD („calibrated probe“)



- Observables related to jet quenching may help to
  - understand the mechanism of parton energy loss
  - characterize the new state of matter above T_c

Charged-Particle Nuclear Modification Factor



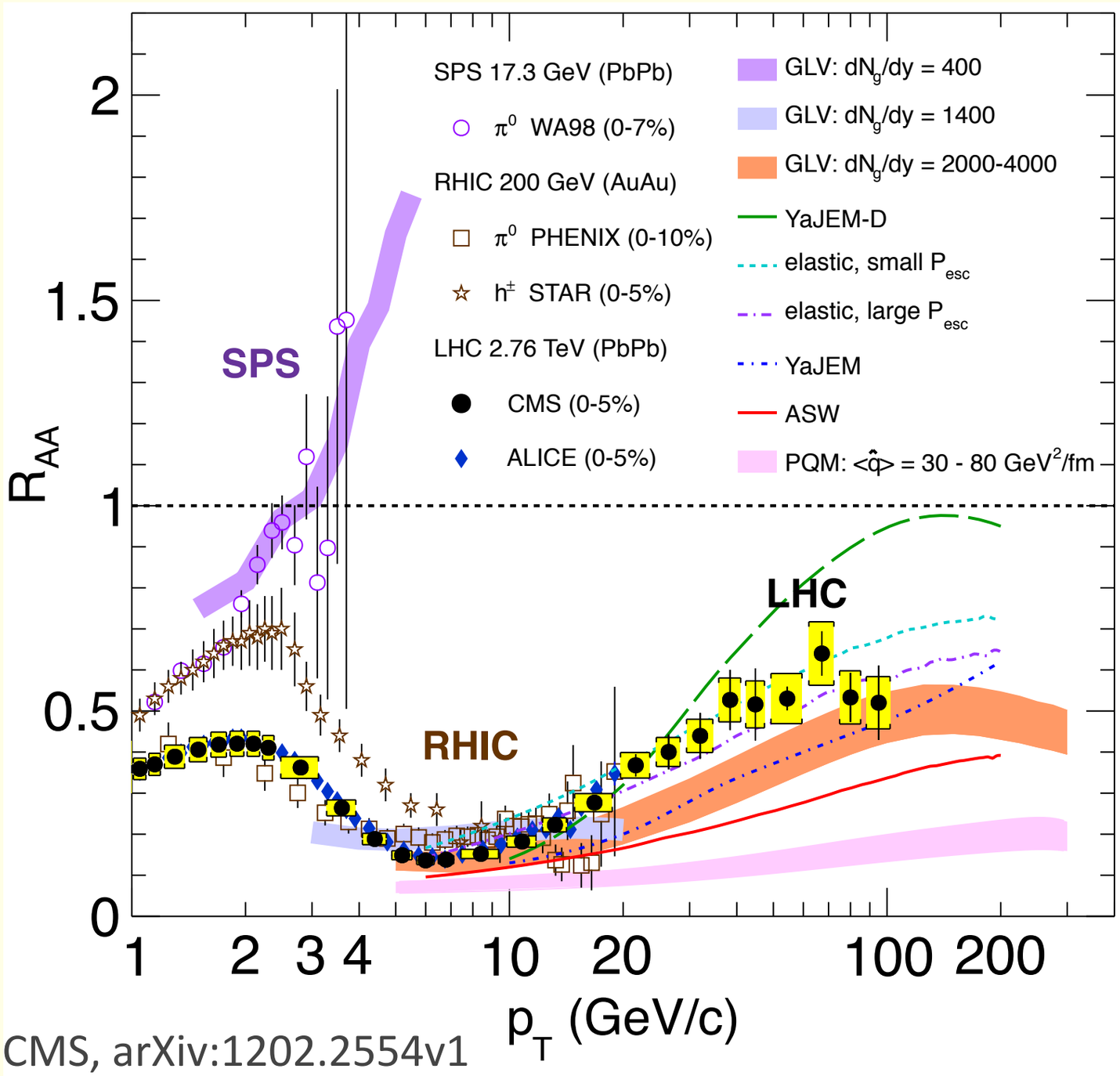
$$R_{AA} = \frac{\mathrm{d}N/\mathrm{d}p_T(A+A)}{\langle T_{AA}\rangle \times \mathrm{d}\sigma/\mathrm{d}p_T(p+p)}$$

$$\langle T_{AA}\rangle = \langle N_{\mathrm{coll}}\rangle/\sigma^{pp}_{\mathrm{inel}}$$

from Glauber calculation

- R_{AA} = 1 in the hard scattering regime without nuclear effects
- Suppression by a factor of more than 5 observed
- R_{AA} affected by
  - nuclear shadowing (p_T < 10 GeV/c)
  - parton energy loss
  - steepness of initial parton spectrum

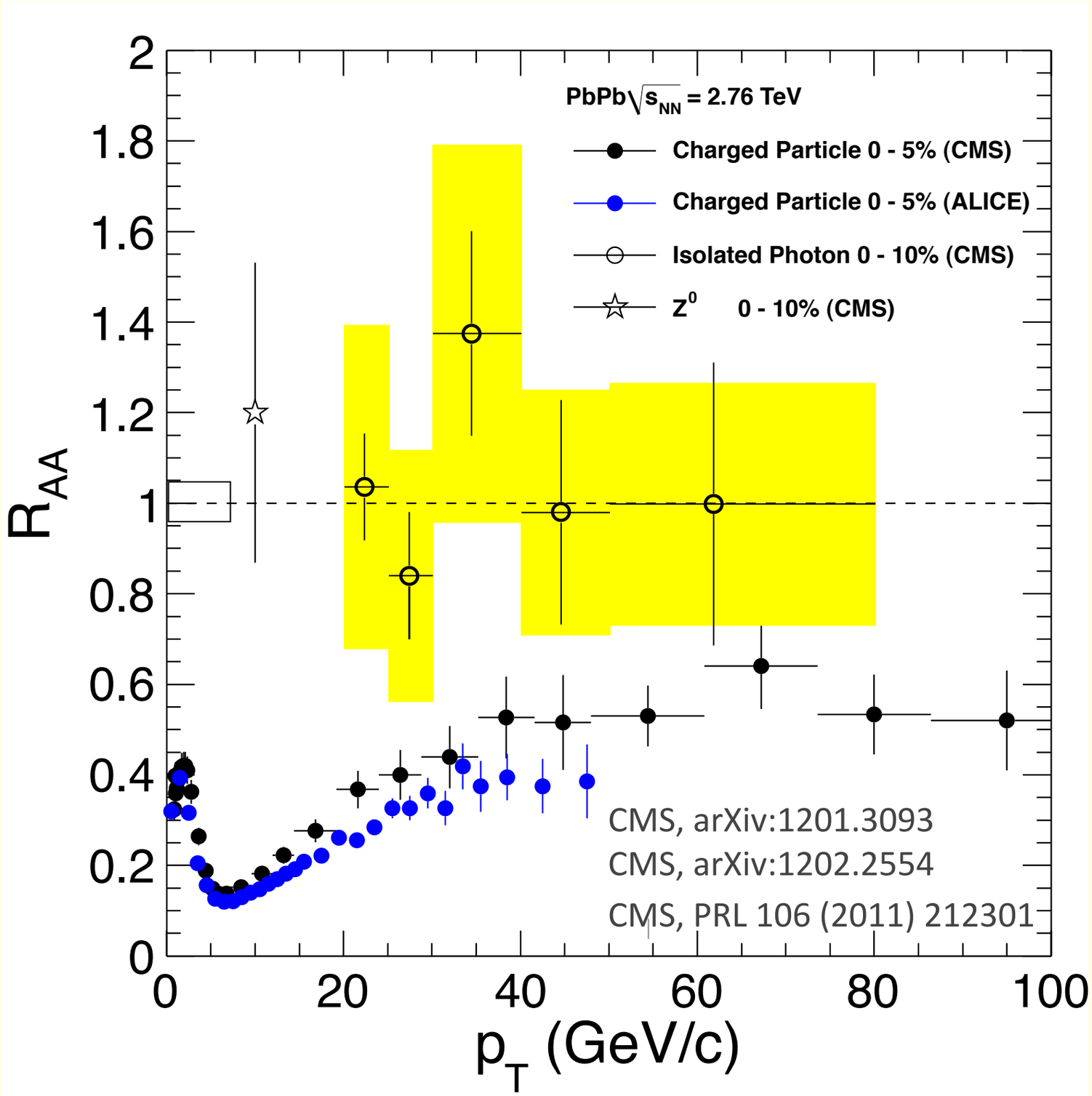
Charged Particle R_{AA} at the LHC: Large p_T Reach Helps Constrain Models



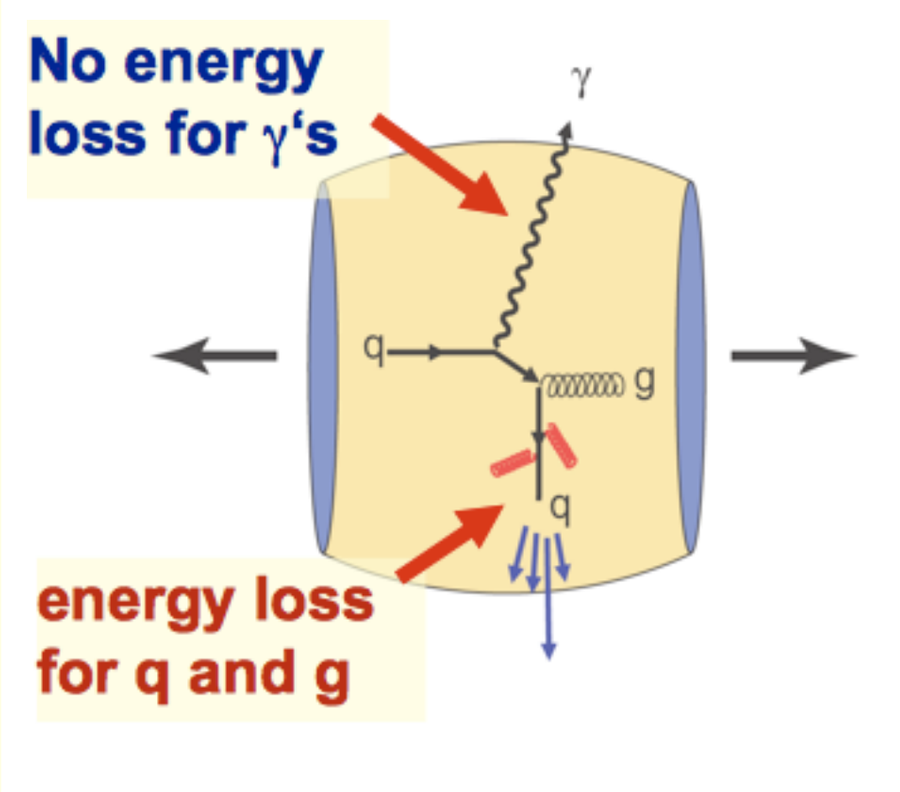
CMS, arXiv:1202.2554v1

- Rise of R_{AA} with p_T for the first time established at the LHC
- Large p_T reach helps unveil how energy loss depends on initial parton energy
- Data consistent with decrease of fractional energy loss $\Delta E/E$ with increasing parton energy E (as in expected in pQCD energy loss models)

Test of T_{AA} Scaling With Prompt Photons (and Z Bosons)

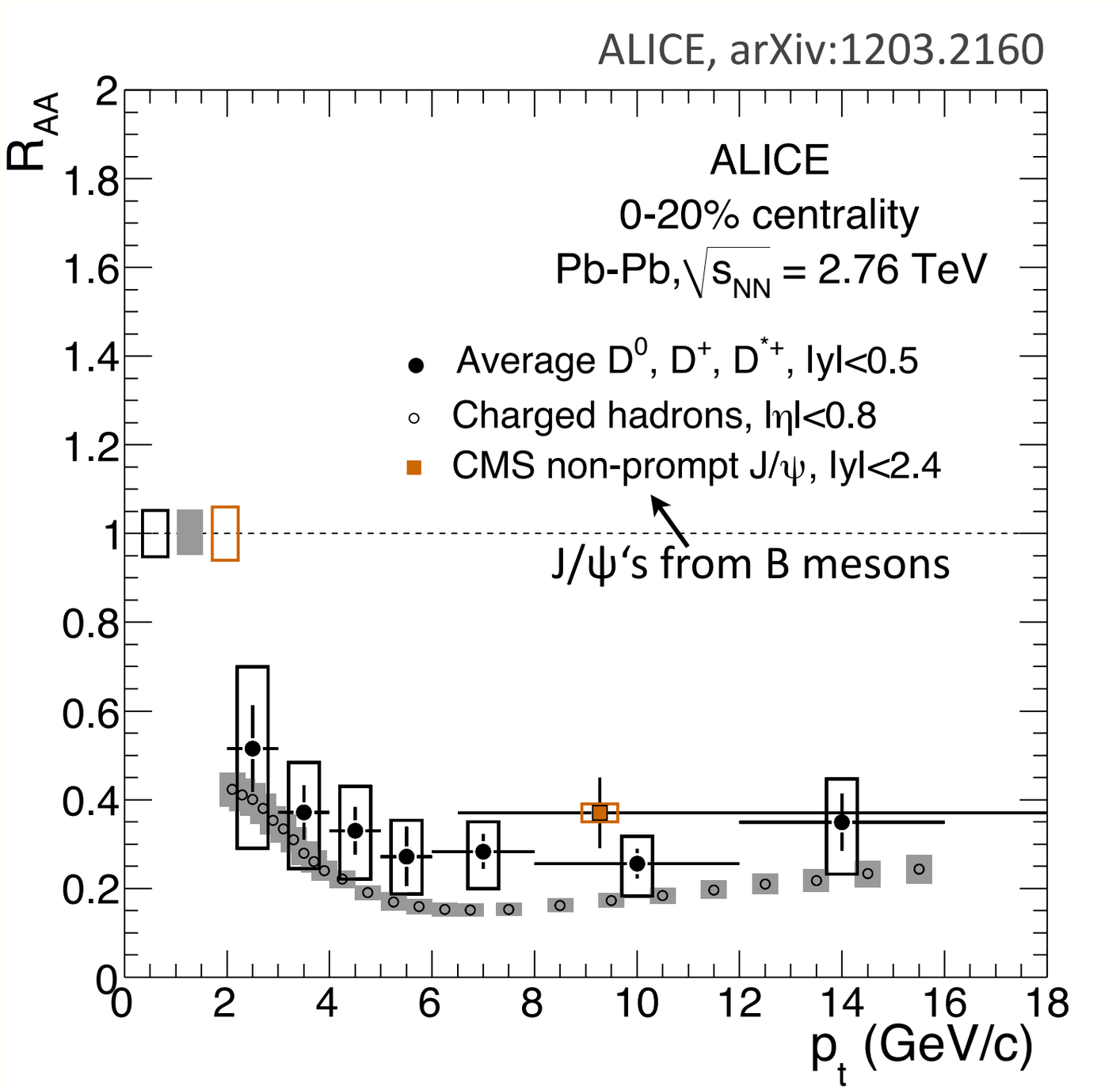


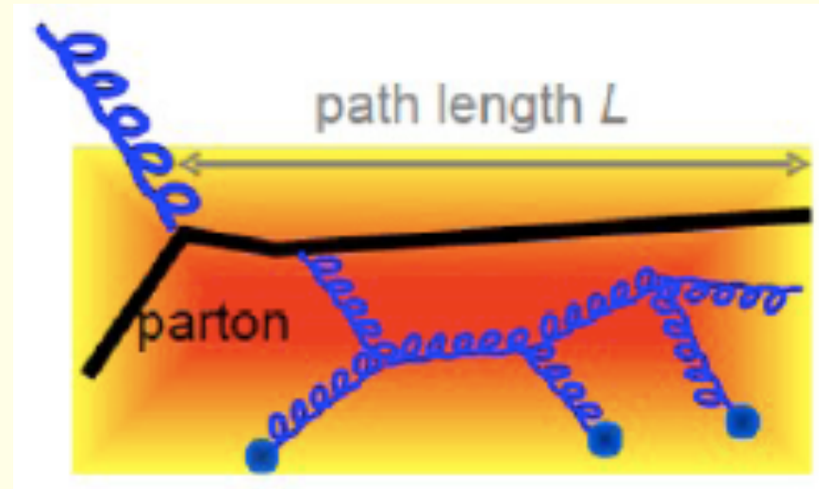
$$R_{AA} = \frac{\mathrm{d}N/\mathrm{d}p_T(A+A)}{\langle T_{AA}\rangle \times \mathrm{d}\sigma/\mathrm{d}p_T(p+p)}$$



Prompt Photons (and Z^0's) are not suppressed: Strong Evidence for Parton Energy Loss Picture

Parton Energy for Heavy Quarks: D Meson R_{AA}





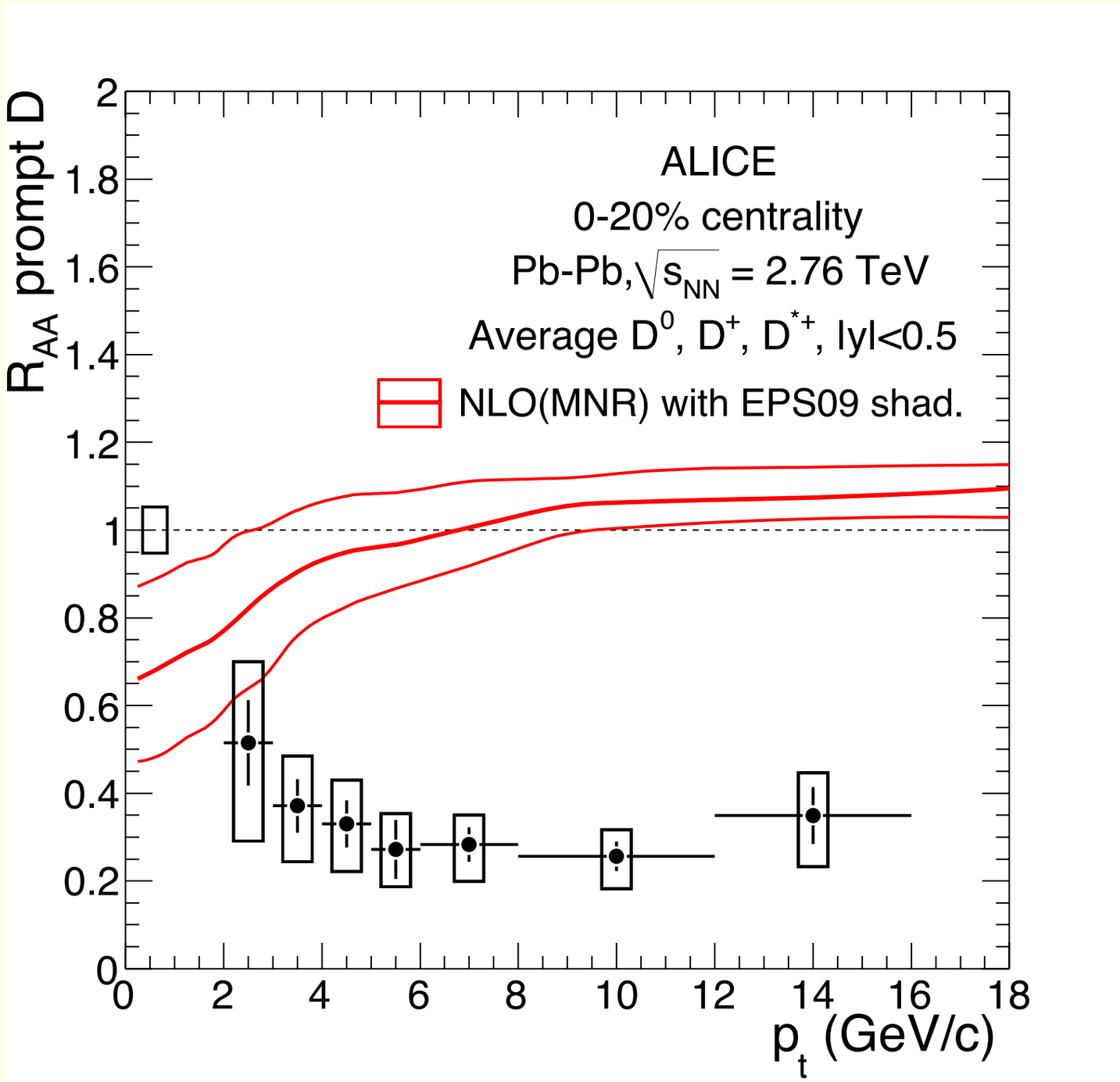
$$\Delta E_g > \Delta E_{u,d,s} > \Delta E_c > \Delta E_b$$

color factor — dead cone effect

- Surprisingly similar R_{AA} for D mesons and pions
  - pions mainly from gluons
  - dead cone effect
- Maybe some indication for expected hierarchy

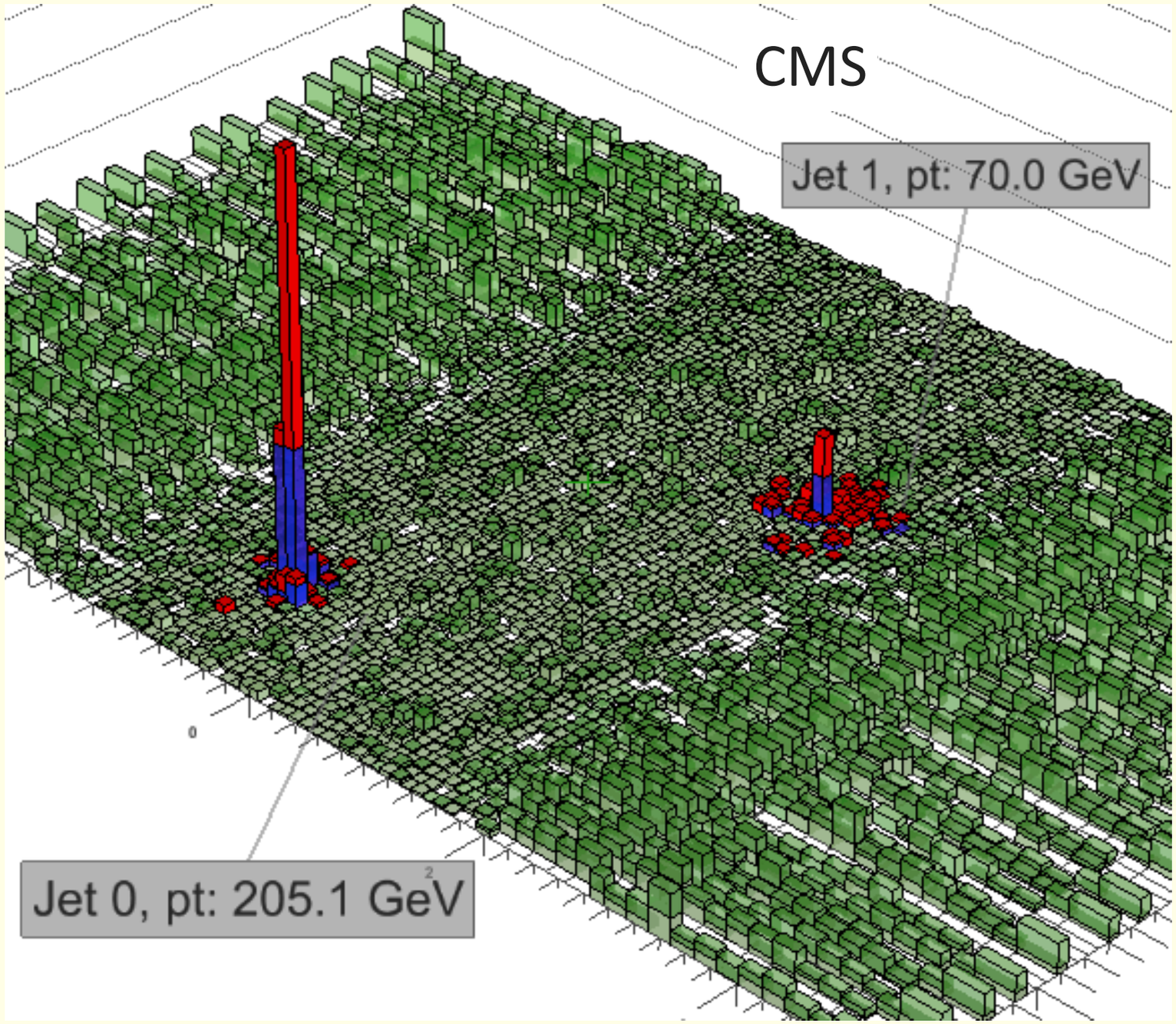
[Talk by Rosa Romita, Tuesday, Heavy Flavour Session]

D Meson R_{AA}: Expectation from Initial State Effects (Nuclear Shadowing)



- NLO pQCD calculation with EPS09 nuclear PDF
- Shadowing only relevant for p_T < ~ 5 - 10 GeV/c

Studying Jet Quenching with Jets

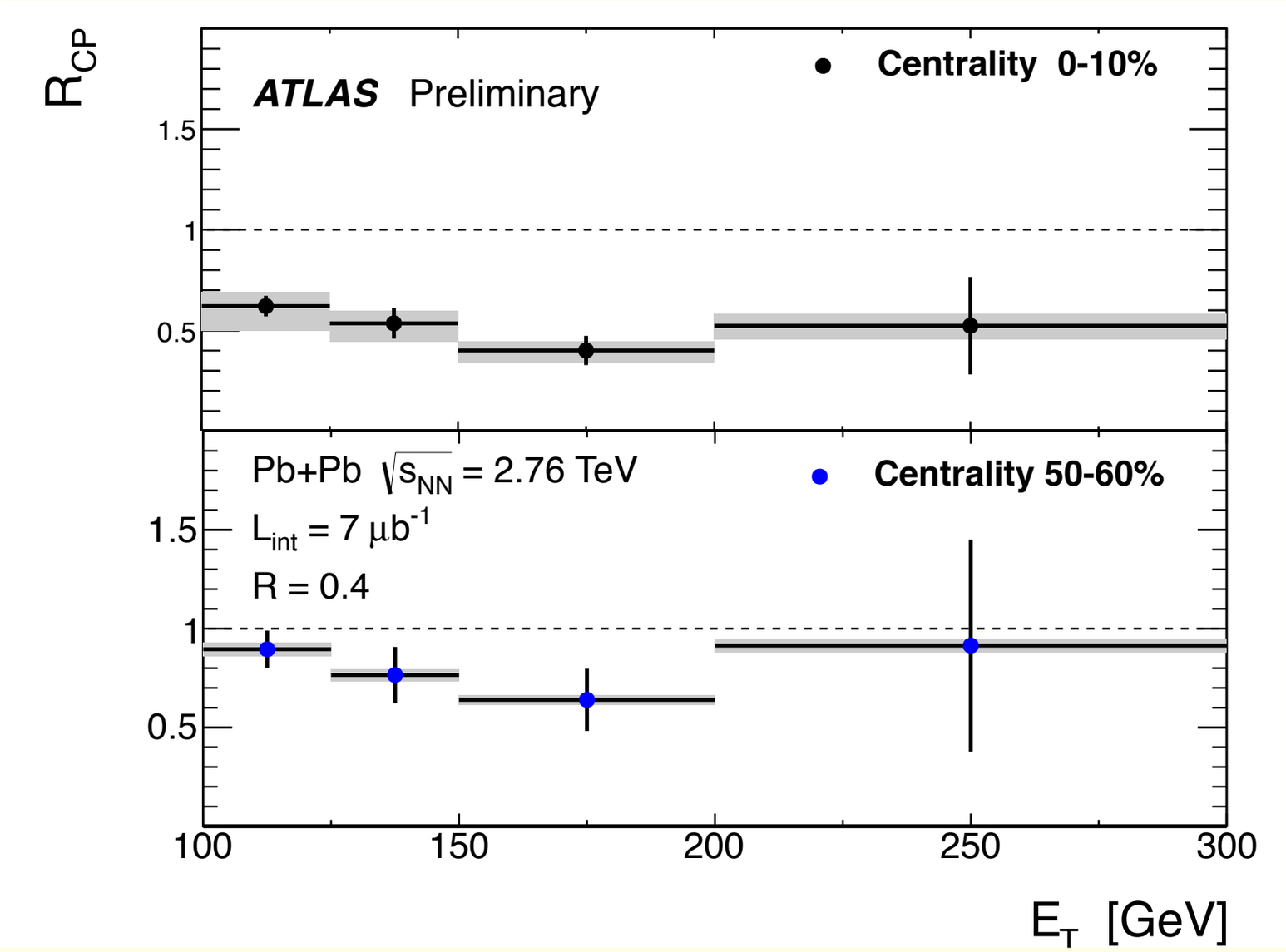


CMS, Phys Rev C84 (2011) 024906
ATLAS, Phys.Rev.Lett. 105 (2010) 252303

- ATLAS and CMS find large asymmetry in energy of dijets in Pb+Pb
- Observations
  - Jets in Pb+Pb still back-to-back (no angular decorrelation)
  - Particle distribution transverse to jet axis (j_T distr.) like in p+p
- Question: Where is the missing energy?

Nuclear Modifications Factor for Jets

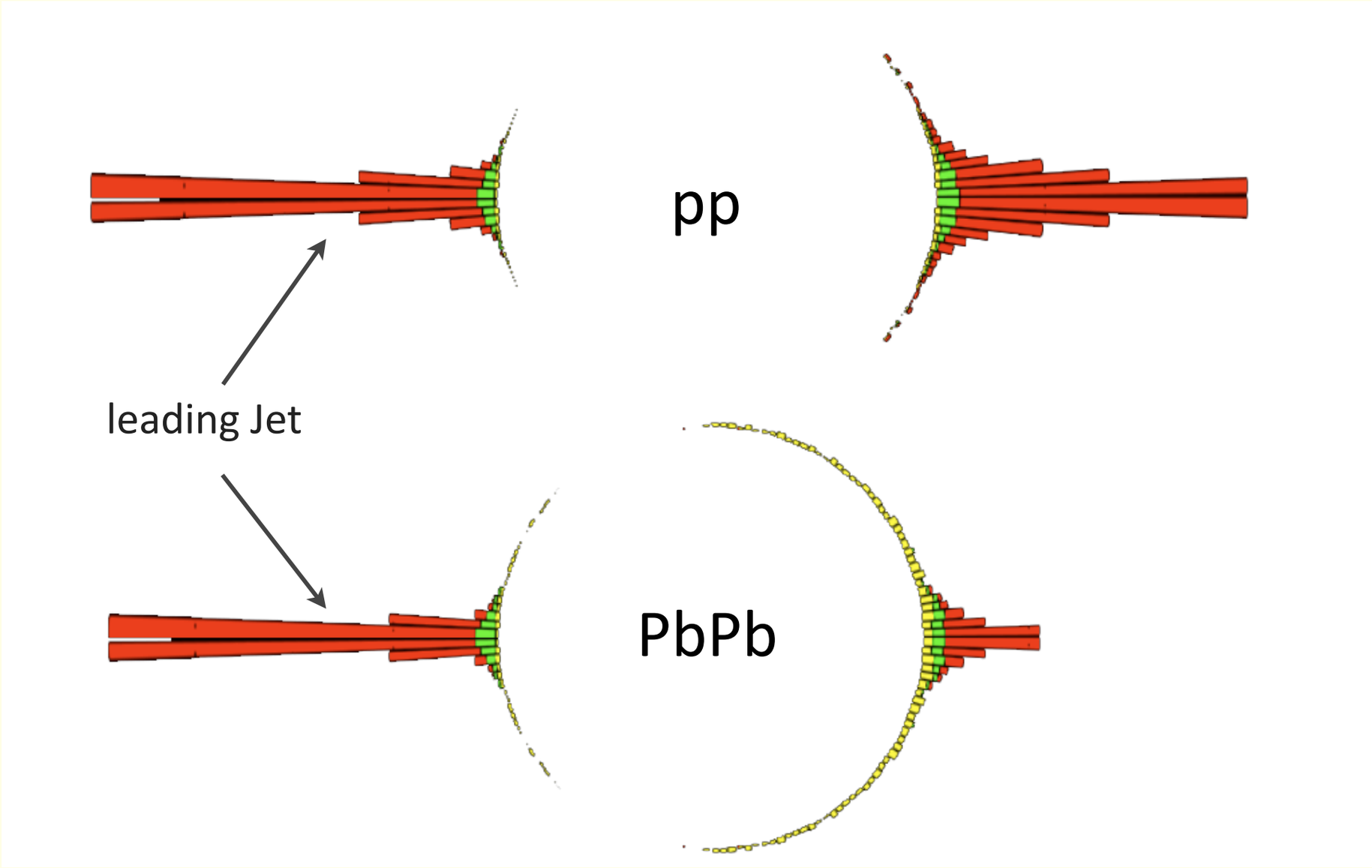
$$R_{\mathrm{CP}} = \frac{1/\langle N_{\mathrm{coll}}^{\mathrm{central}}\rangle \times \mathrm{d}N/\mathrm{d}p_T(\mathrm{central})}{1/\langle N_{\mathrm{peri}}^{\mathrm{central}}\rangle \times \mathrm{d}N/\mathrm{d}p_T(\mathrm{peri})}$$



- Anti-k_T algorithm (R = 0.4)
- $R_{\mathrm{CP}} \approx 0.5$ in central Pb+Pb

With a radius parameter of R = 0.4 the full jet energy is not recovered

Where is the Missing Energy?



Detailed study shows (correlate tracks with axis of leading jet [CMS]):

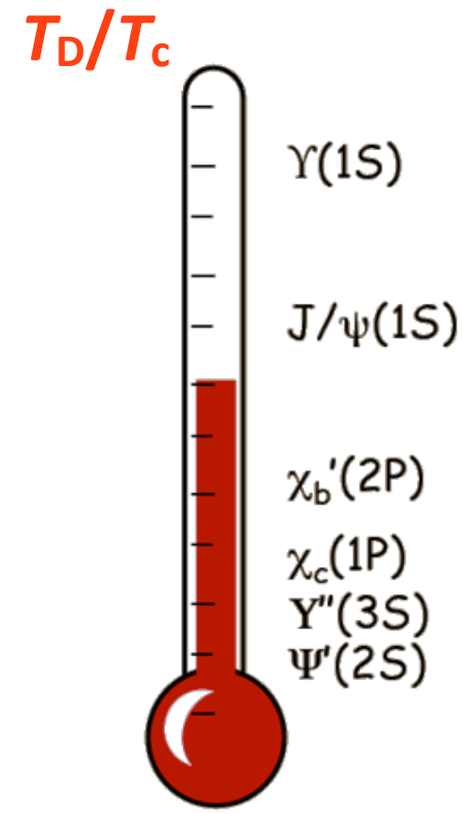
Momentum difference in dijets is balanced by low p_T particles ($0.5 < p_T < 2$ GeV/c) at large angles relative to the away-side jet axis

Quarkonia

Quarkonia as QGP Signature: Suppression at Low $\sqrt{s_{NN}}$ and J/ψ Enhancement at High $\sqrt{s_{NN}}$?

- Color screening expected to prevent *c* anti-*c* (and *b* anti-*b*) binding in deconfined matter
- Dissociation temperature depends on binding energy → „QGP thermometer“
- Recombination picture for J/ψ‘s
  - J/ψ‘s from quark recombination at phase transition (?)
  - Expect J/ψ suppression at low beam energies (SPS, RHIC) and J/ψ enhancement at high energies (LHC)

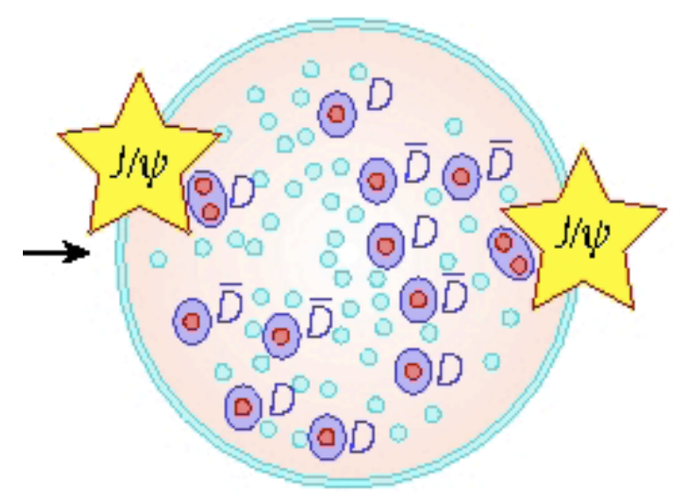
	r (fm)	T_D/T_c
J/ψ (1s)	0.42	1.2
ψ‘ (2s)	0.86	1.0
χc (1p)	0.67	1.0
ϒ (1s)	0.21	2.0
ϒ‘ (2s)	0.50	1.2
ϒ“ (3s)	0.76	1.0



Exact values model dependent, trend stable

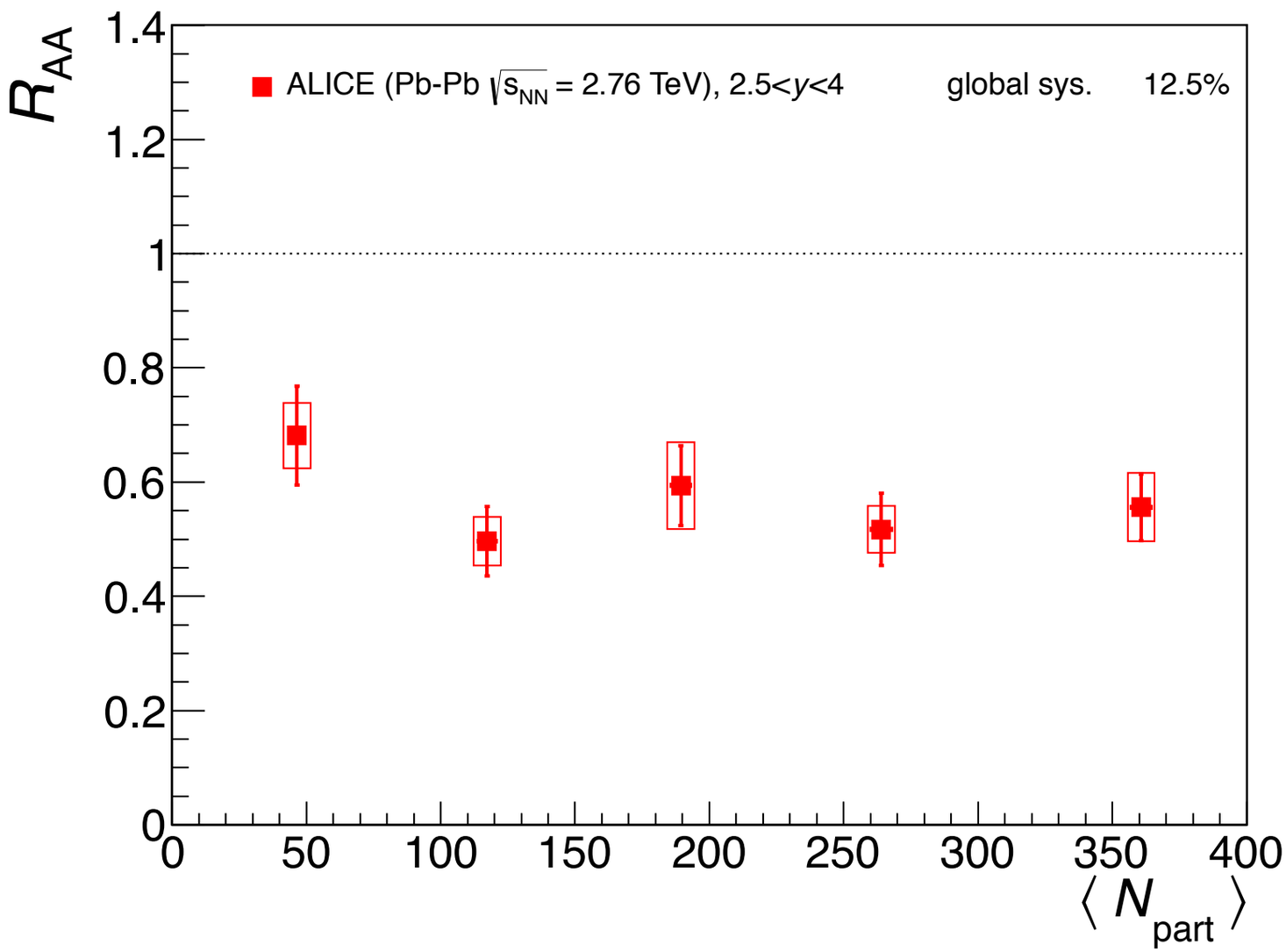
~ 100 $c\bar{c}$ pairs in central Pb+Pb at the LHC

→ J/ψ through recombination?



J/ψ R_{AA} at RHIC and LHC: Smaller Suppression at LHC for Low p_T (> ~ 0 GeV/c)

ALICE, arXiv:1202.1383



Note: Contribution from B feed-down small: ~ 10% (from pp-measurement)

- Pb+Pb at LHC:
  - J/ψ $R_{AA} \approx 0.6$ (for $p_T > 0$)
  - independent of centrality
  - Indication for moderate final state suppression (expect $R_{AA} \approx 0.8$ from initial state effects, i.e.nuclear shadowing)
- Suppression in central A+A weaker than at RHIC

[Talk by Ionut Arsene, Wednesday, Heavy Flavour Session]

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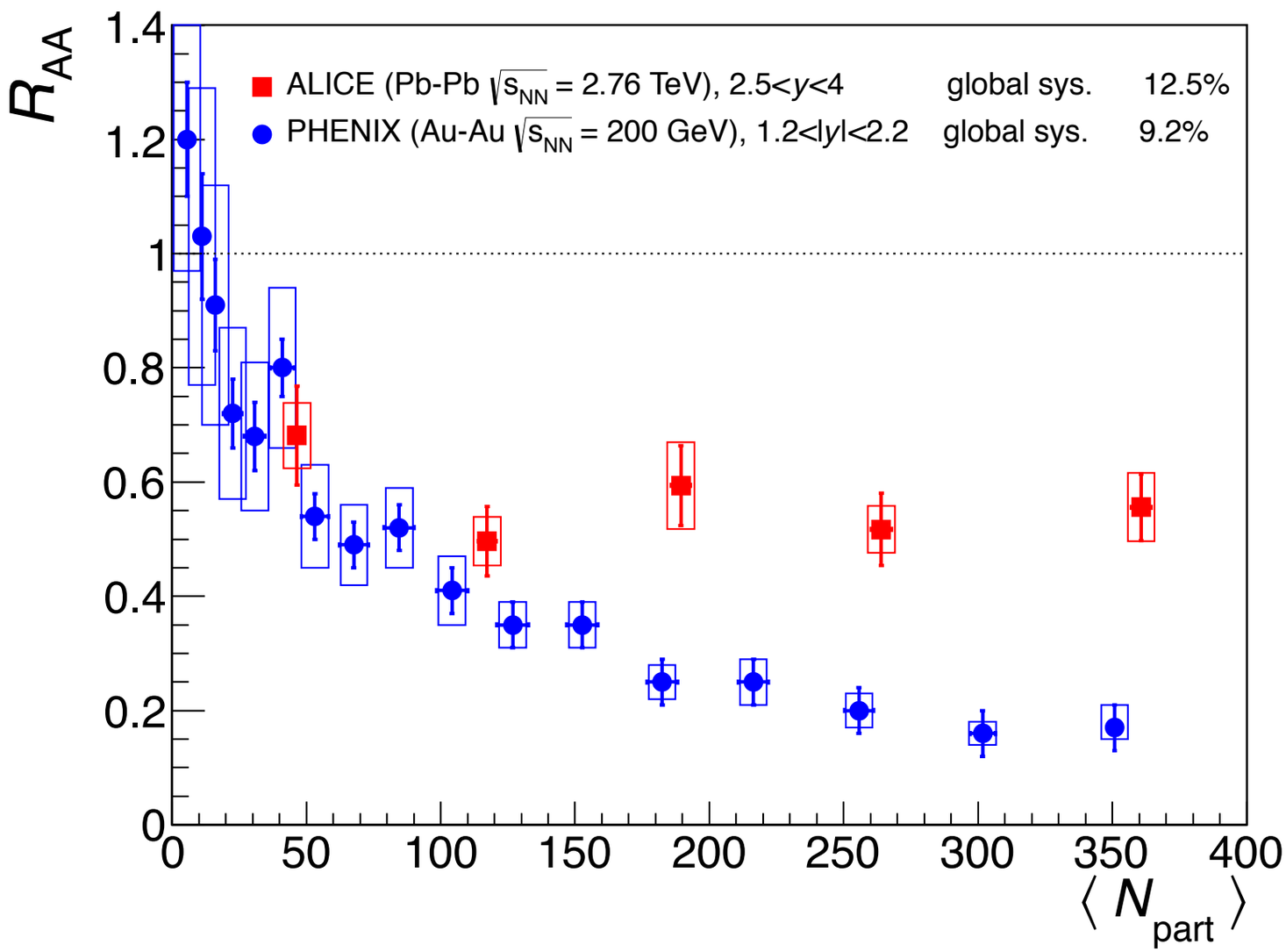

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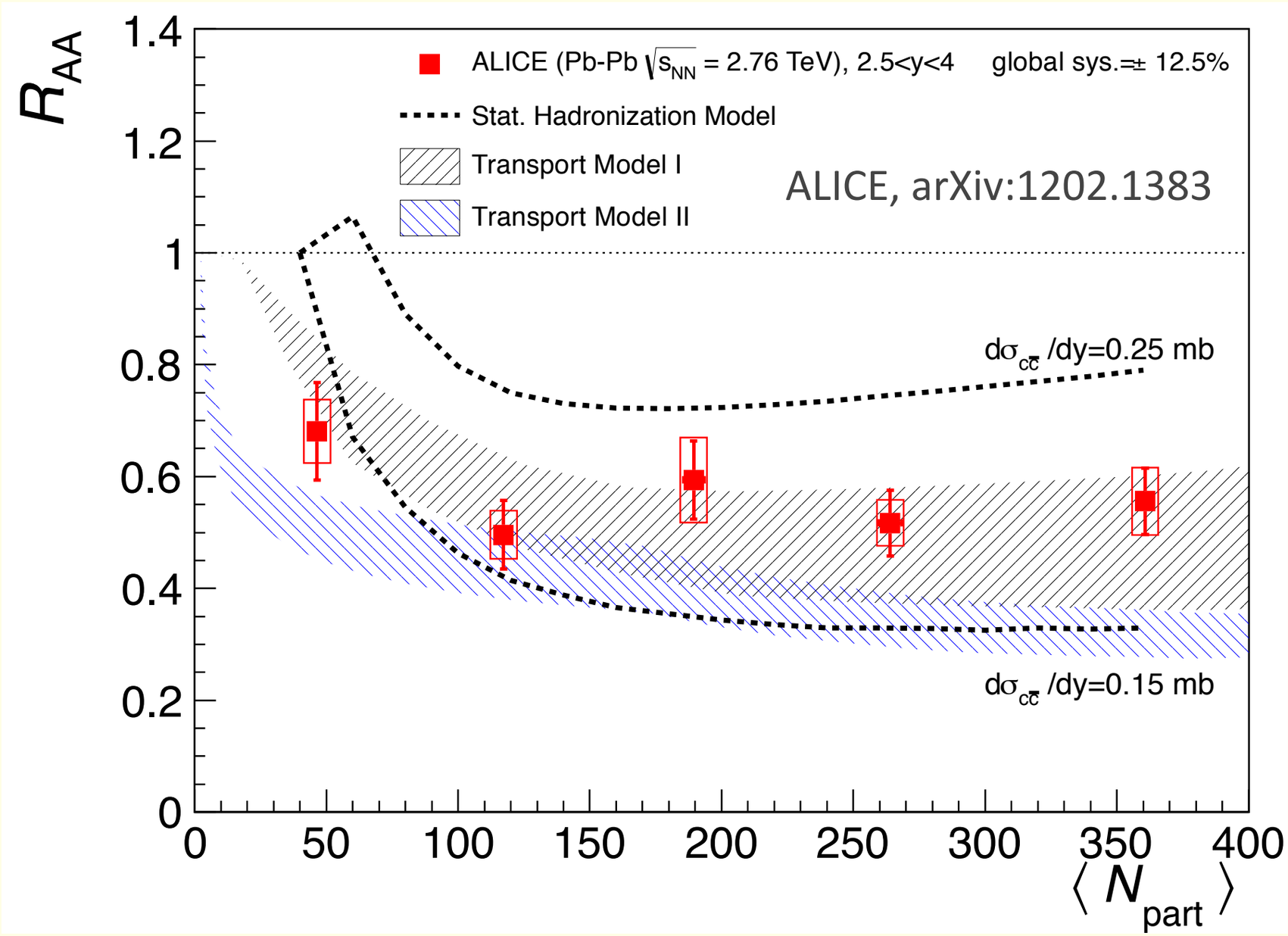
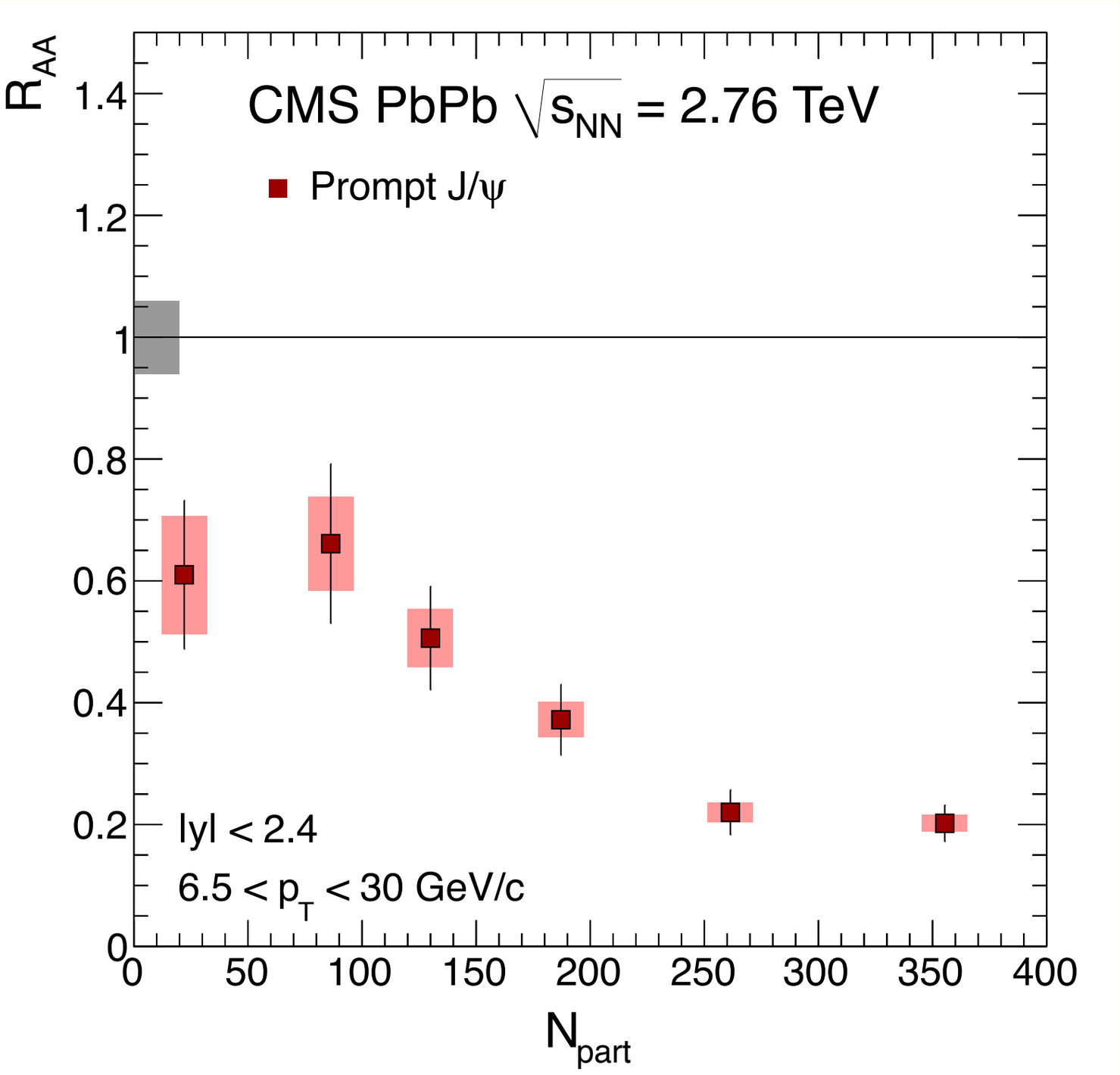
J/ψ R_{AA} at LHC vs. Statistical Hadronization Model



- Qualitatively consistent with recombination picture
- Need precise charm production cross section for firm conclusions

Recombination model requires thermalized charm quarks $\rightarrow$ QGP signature

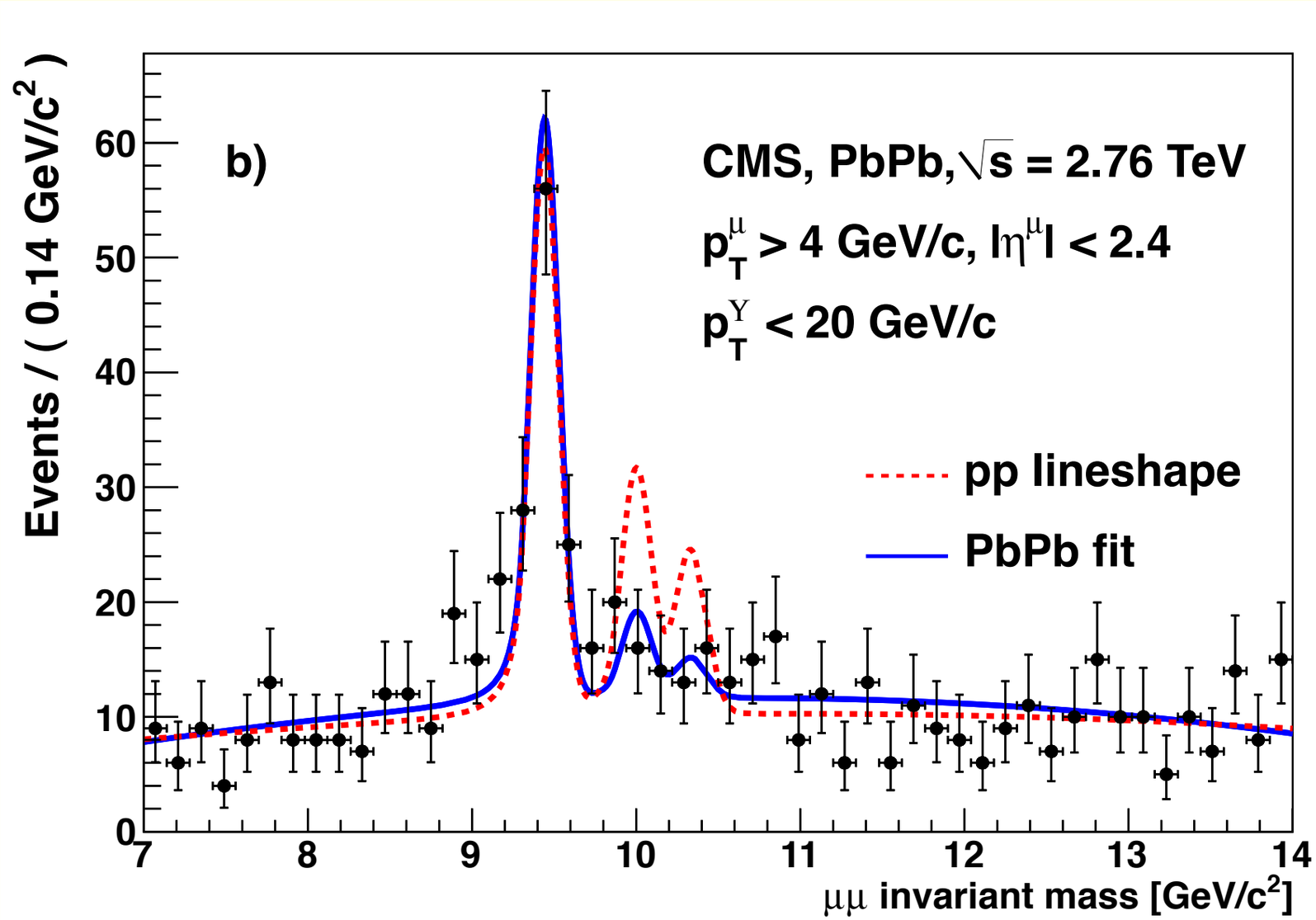
J/ψ Suppression at Higher p_T (> 6.5 GeV/c): Stronger Suppression than at Low p_T



Stronger suppression at higher p_T in qualitative agreement with recombination picture

CMS, arXiv:1201.5069

Upsilon States in Pb+Pb at the LHC: Suppression of $\Upsilon(2S)$, $\Upsilon(3S)$ Relative to $\Upsilon(1S)$



Consistent with expectation that more loosely bound 2S and 3S states are more strongly suppressed

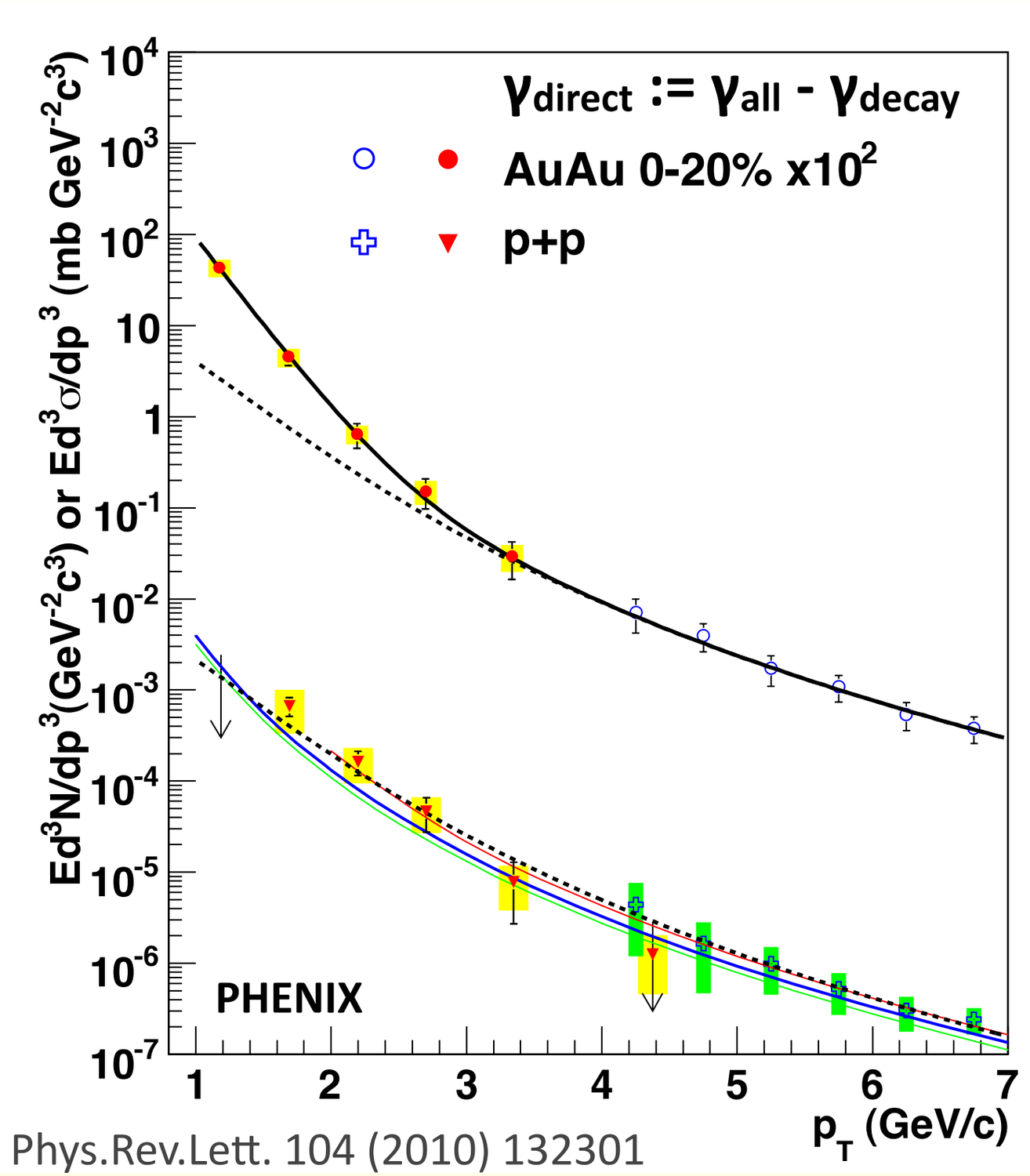
CMS, PRL 107 (2011) 052302

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

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

Thermal Photons

Low p_T Direct Photon Excess at RHIC: A Handle to Measure the Temperature of the QGP



Phys.Rev.Lett. 104 (2010) 132301

- Low p_T direct photons measured via internal conversion (e^+e^- pairs from virtual photons)
- Exponential excess in Pb+Pb above shape measured in p+p
- Slope: T = 221 ± 23 ± 18 MeV
- Hydro modeling leads to
  - $T_{initial}$ = 300 - 600 MeV
  - $\tau_{initial}$= 0.15 - 0.6 fm/c
- Puzzle (arXiv:1105.4126):
  - Expect lower v_2 for thermal photons
  - Observed: similar v_2 as for pions

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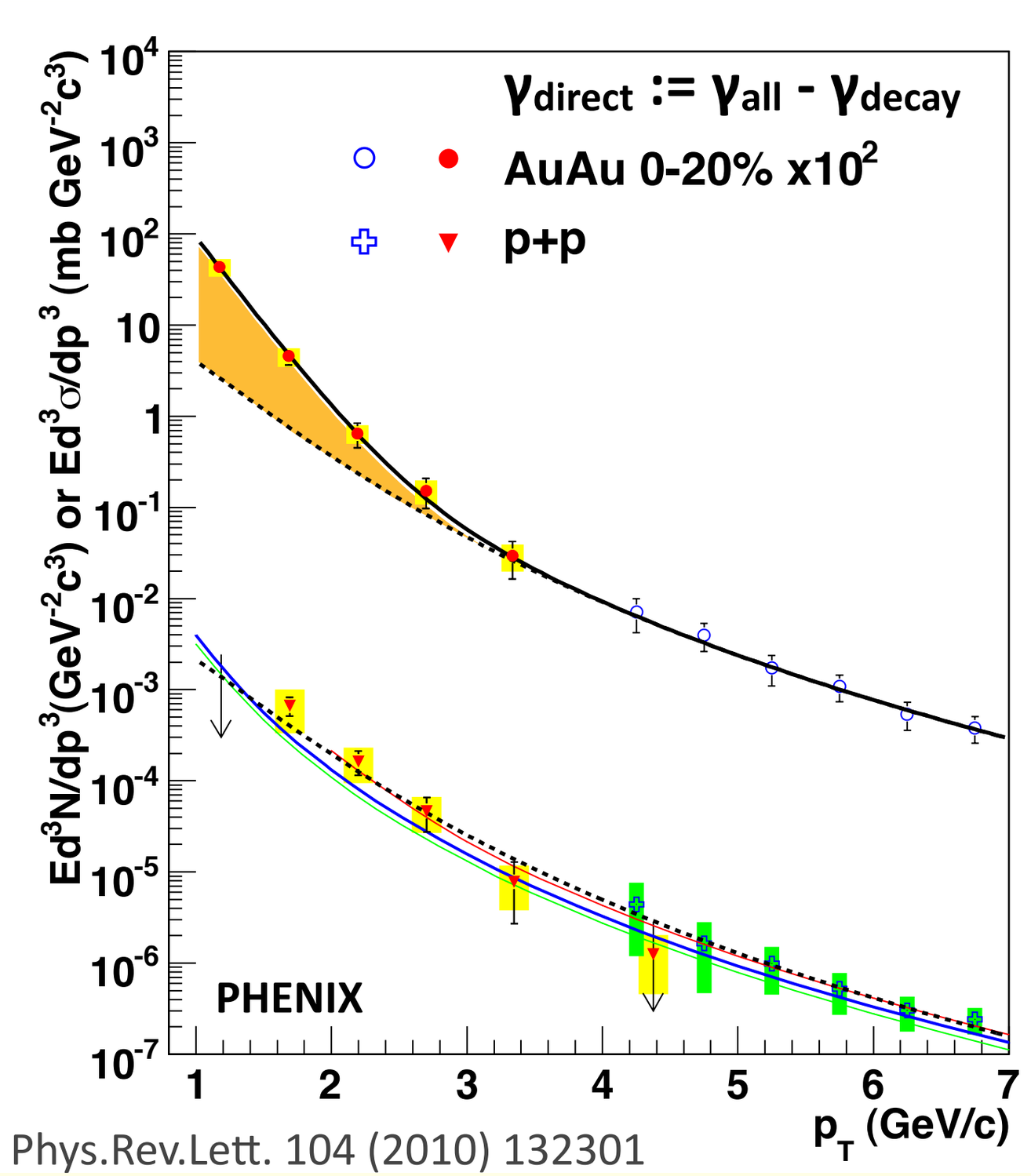

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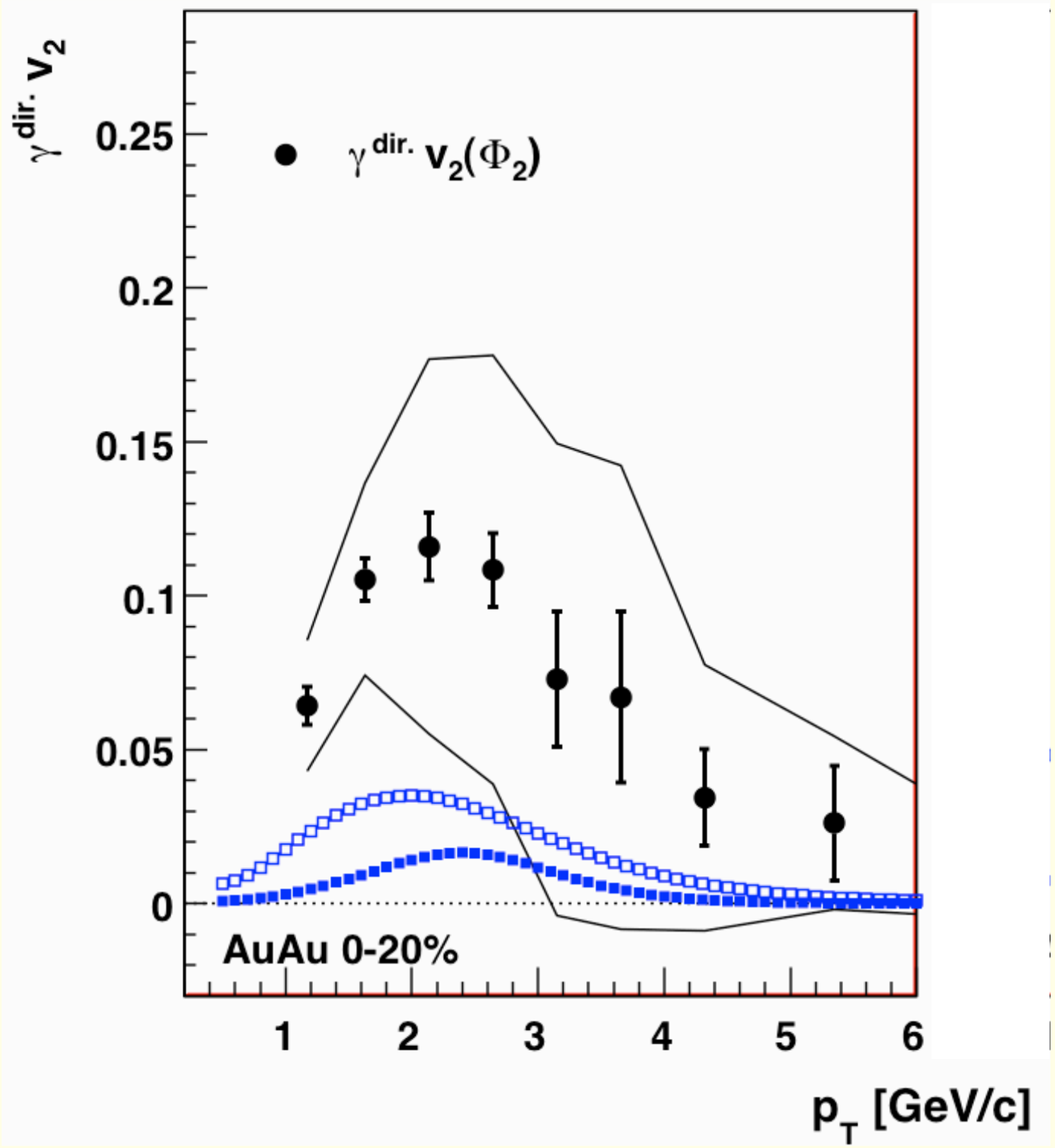
Conclusions

- LHC ideal for studying the QGP:
  $\varepsilon_{initial} >> \varepsilon_c$, large volume and QGP lifetime, hard probes
- Anisotropic flow
  - Standard reaction scenario confirmed
  - Medium at the LHC has same „perfect liquid“ properties as found at RHIC
- Medium opaque to jets
  - Large p_T reach of charged particle R_{AA} constrains models
  - Dijet energy asymmetry: energy recovered at very low p_T ($0.5 < p_T < 2$ GeV/c)
- Quarkonium saga:
  - Recombination picture for creation of low p_T J/ψ's consistent with data
  - Loosely bound ϒ(2s) and ϒ(3s) stronger suppressed than ϒ(1s)
- Outlook
  - p+Pb run in 2012 will reduce uncertainties due to initial state effects

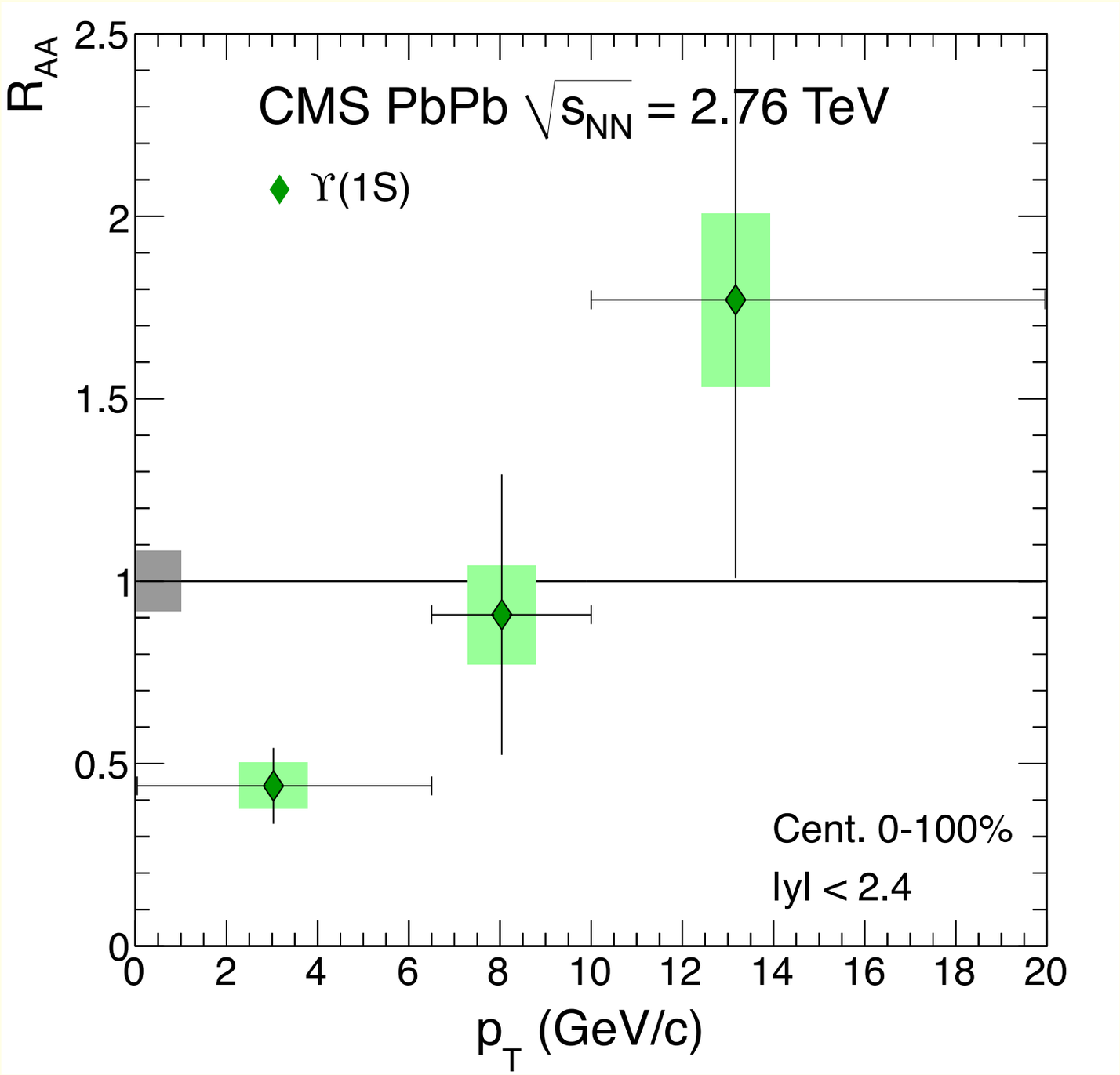
Extra Slides

Direct Photon v_2 at RHIC

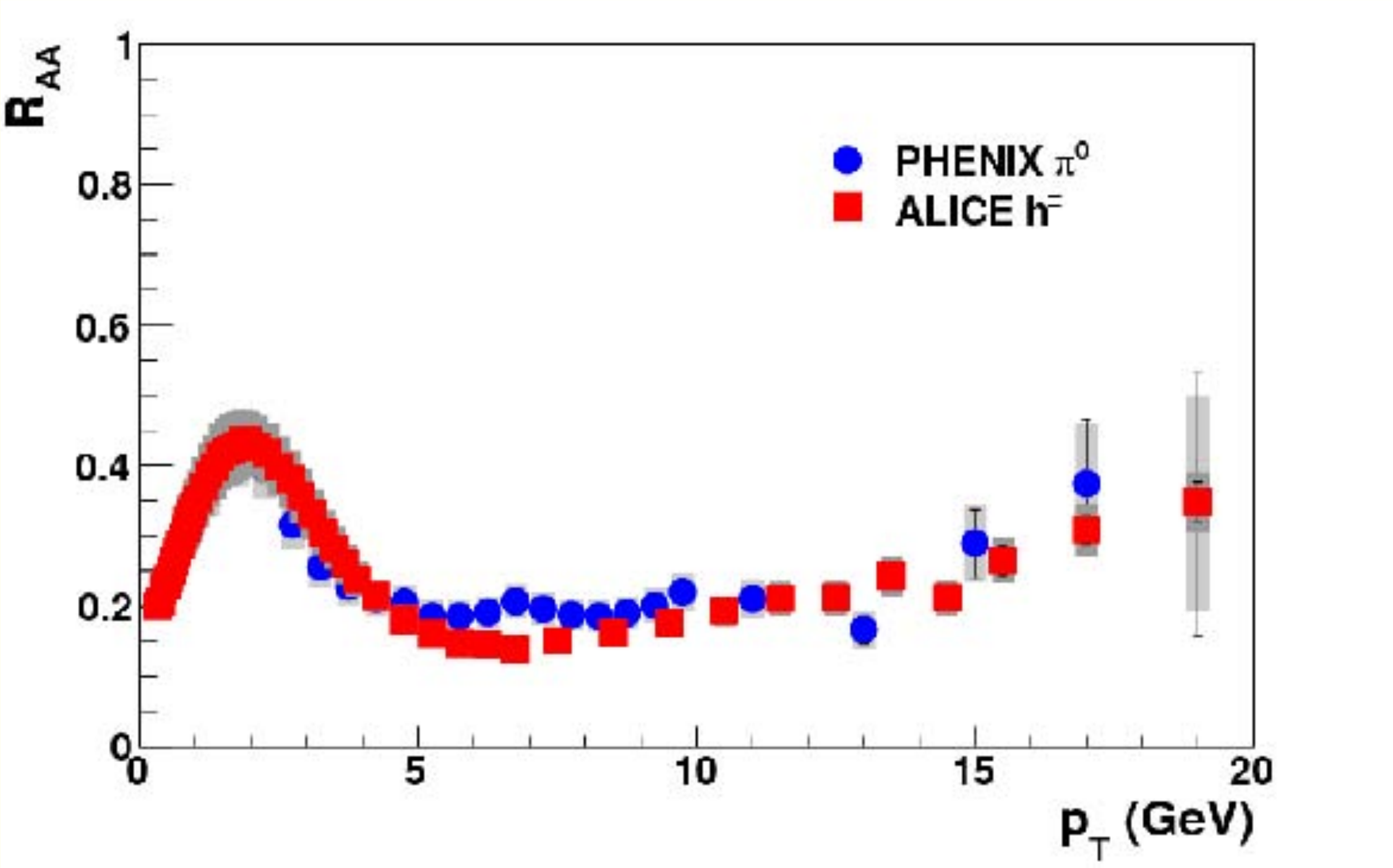


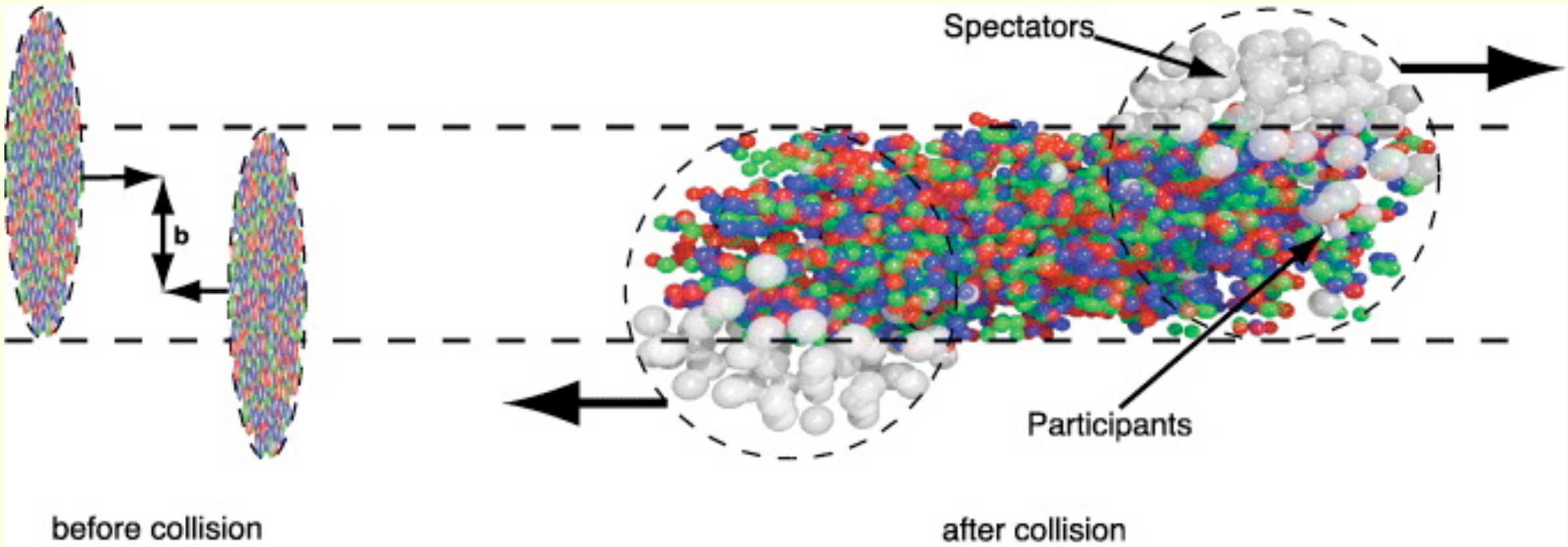
Theory calculation:
Holopainen, Räsänen, Eskola
arXiv:1104.5371v1

R_{AA} for ϒ(1S) in Min. Bias Pb+Pb



R_{AA}: LHC vs. RHIC




Spectators
b
Participants
before collision
after collision