QCD in
Heavy Ion Collisions
@ LHC

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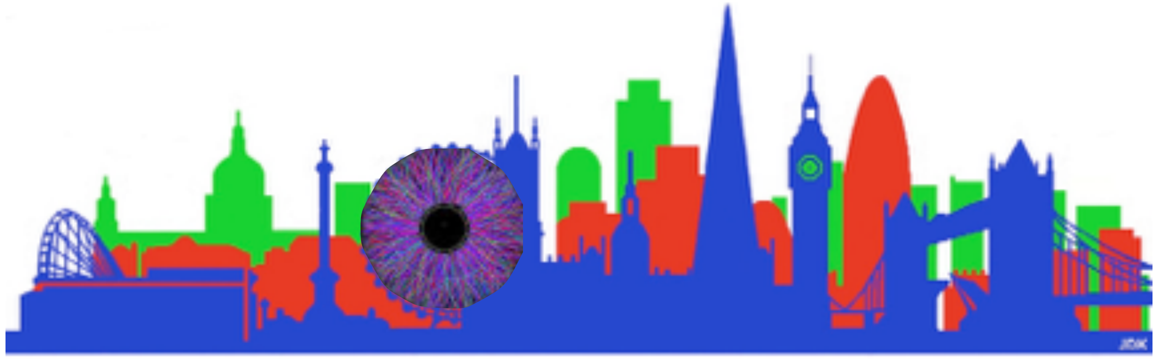
CERN

QCD@LHC 2015

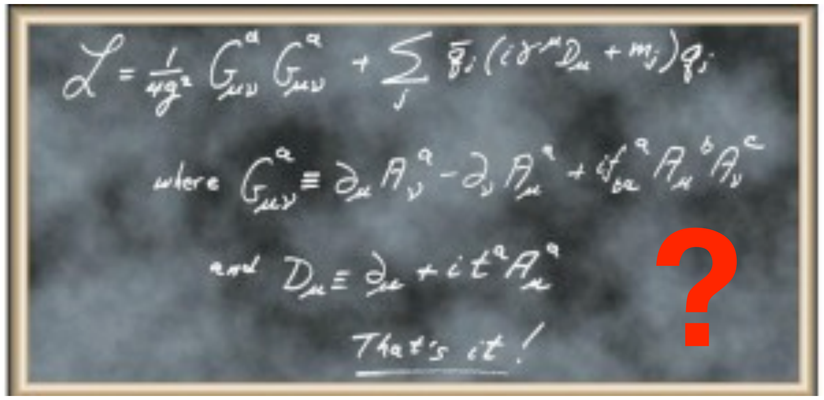
Queen Mary University of London
1st – 5th September 2015



Outline

- Introduction
- What have we learnt about bulk properties of the QGP ?
- Interesting phenomena related to dynamic properties
  - almost ideal fluid cooling into a hadron gas
  - semi-opaque to high-p_T partons
  - melts and regenerates heavy quarkonia states
- Outlook

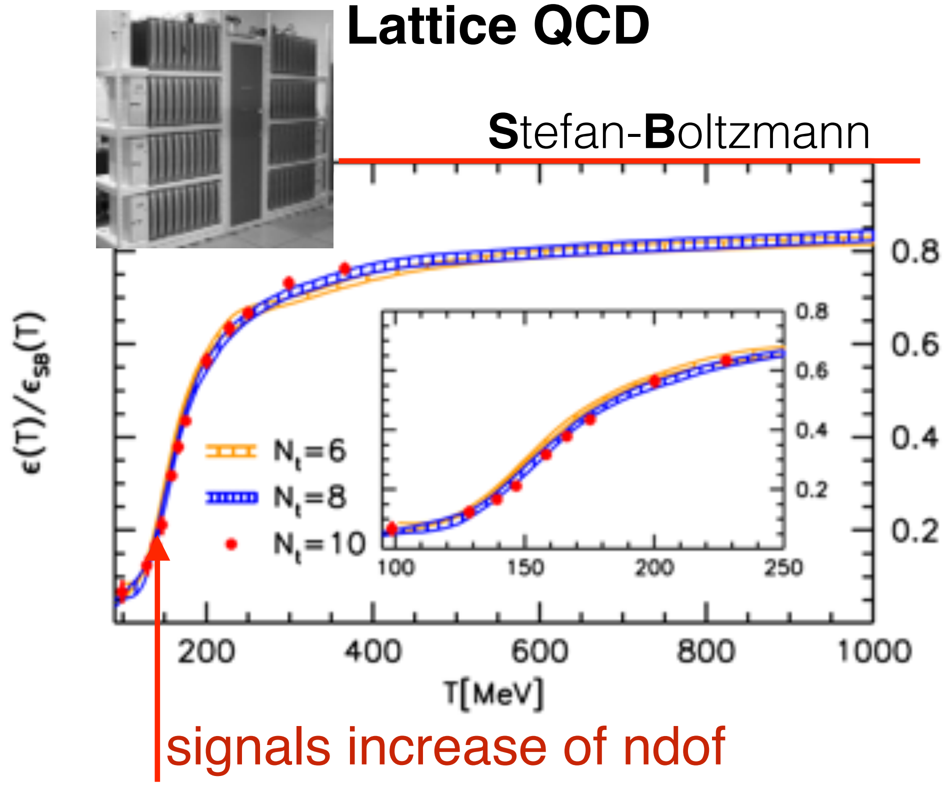
Ultra-Relativistic Heavy Ion Physics



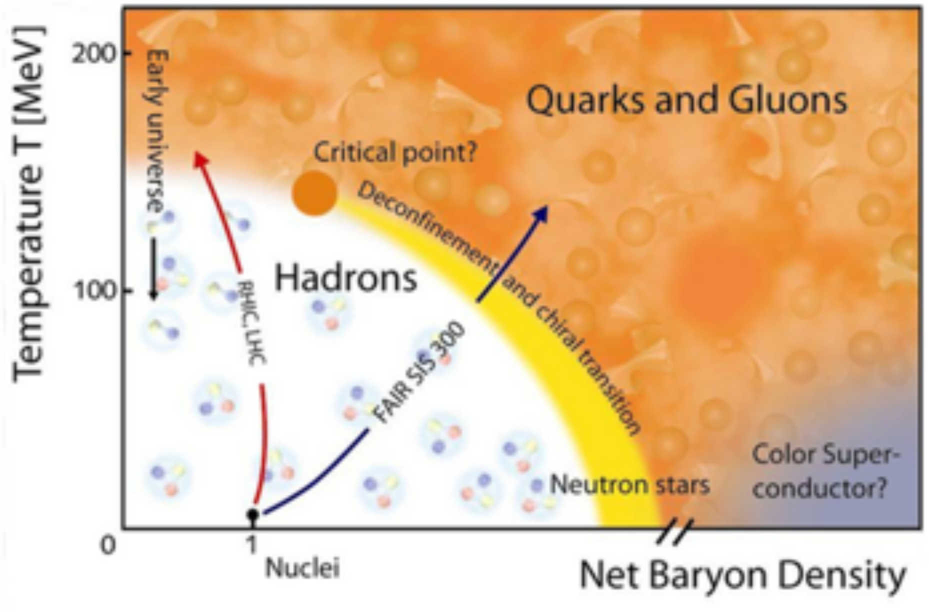
- Study strongly interacting matter under extreme conditions
  - high temperature and/or
  - high density
- QCD predicts transition from ordinary hadronic matter to de-confined partonic medium (**Q**uark **G**luon **P**lasma)
- Need large volume of hot and dense matter
  - **⇒ Ultra Relativistic Heavy Ion collisions**
  - **⇒ however: ephemeral (10^{-23} s),**

    rapidly expanding and cooling medium

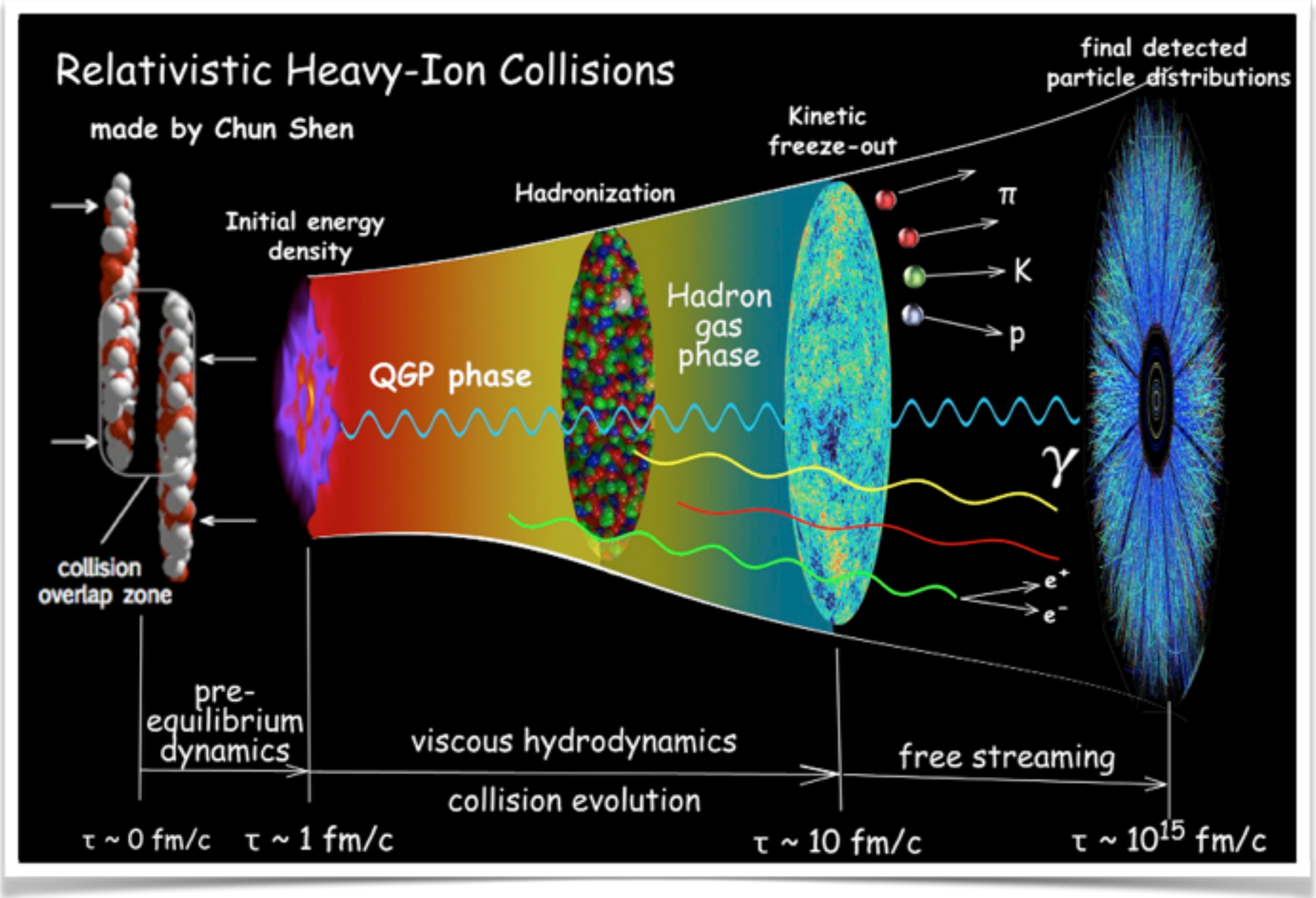
Lattice QCD



signals increase of ndof



Basic Stages of HI Collision



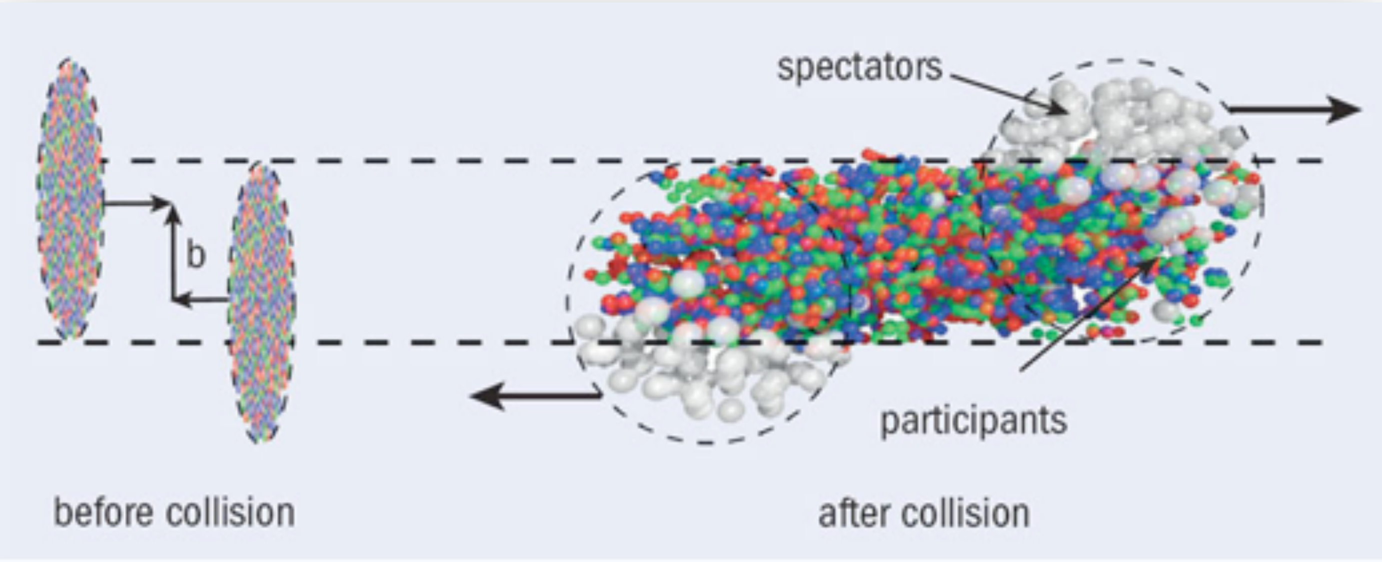
collision → QGP far from equilibrium → thermalisation → local equilibrium (hydro) →expansion cooling
→ hadron gas

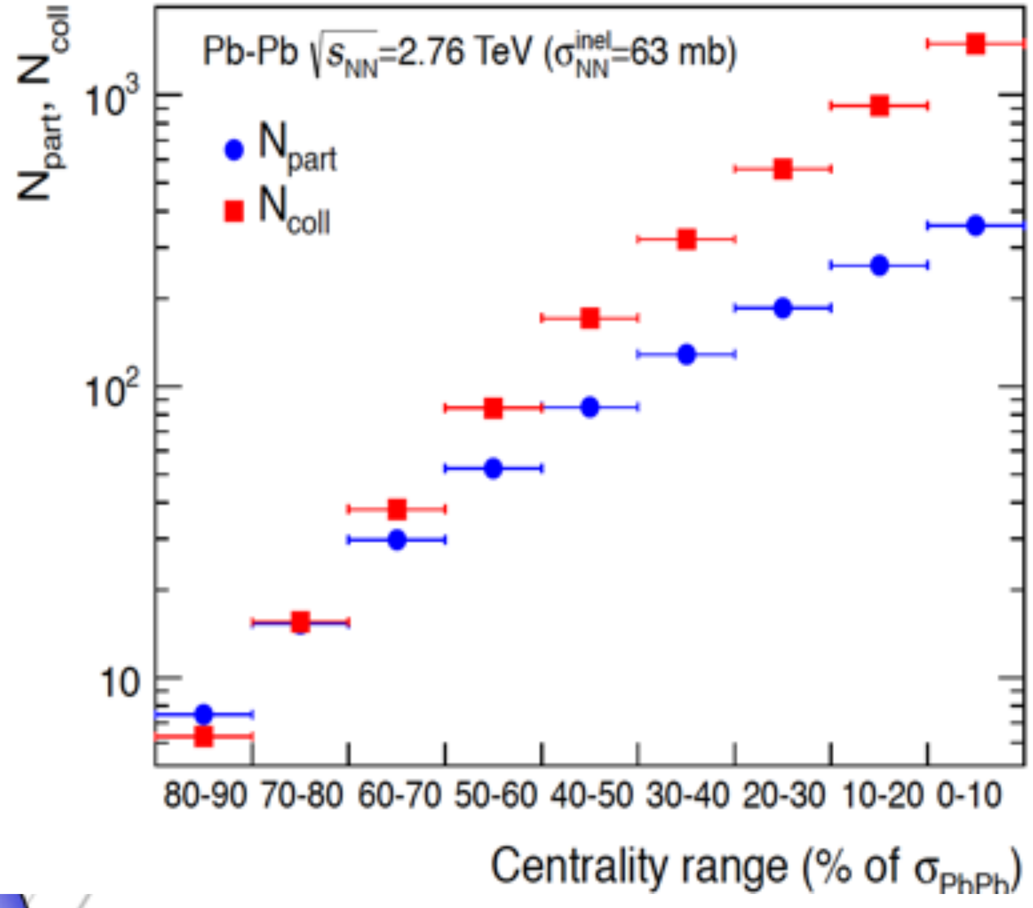
Hard Probes: High Q^2, produced at early times ~1/Q, weakly coupled, penetrating

What do we control ?

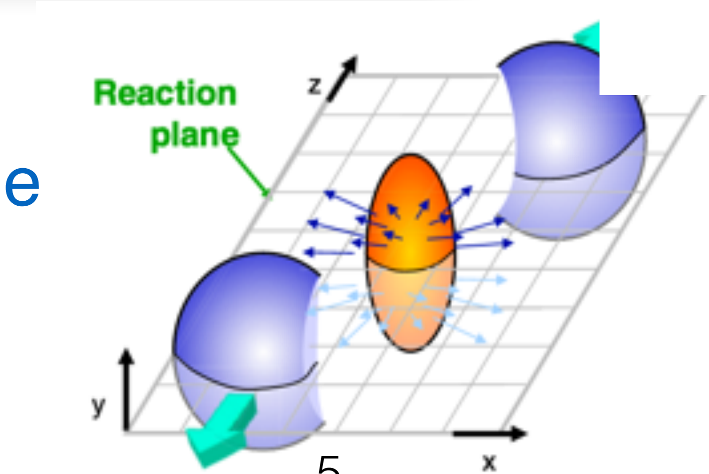
- Collision system: Pb-Pb, p-Pb, …
- $\sqrt{s_{NN}}$ per nucleon pair
  - LHC: Pb-Pb @ 2.76 TeV, p-Pb @ 5 TeV; RHIC Au-Au @200 GeV

- *b*: Impact Parameter (“Centrality”)
  N_{coll}: binary collisions, N_{part}: participants





- Reaction plane azimuthal angle



What (else) do we control ?

Initial Rate of Hard Processes

- Scale *Q* above any scale of the medium

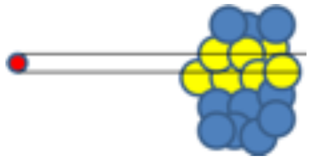
$Q \gg \Lambda_{QCD},\ Q_s,\ T$

- Factorisation:

$$\frac{d\sigma^{AA\to X}}{dp_T} \propto A^2 f_i^A\left(x_1,Q^2\right)\circ f_j^A\left(x_1,Q^2\right)\circ\sigma^{ii\to k}\left(x_1,x_2,p_T/z,Q^2\right)\circ D_{k\to X}(z,Q^2)\otimes FS\ \text{Effects}$$

- Cross-section calculable in pQCD and control measurements in pp, pA

Initial State

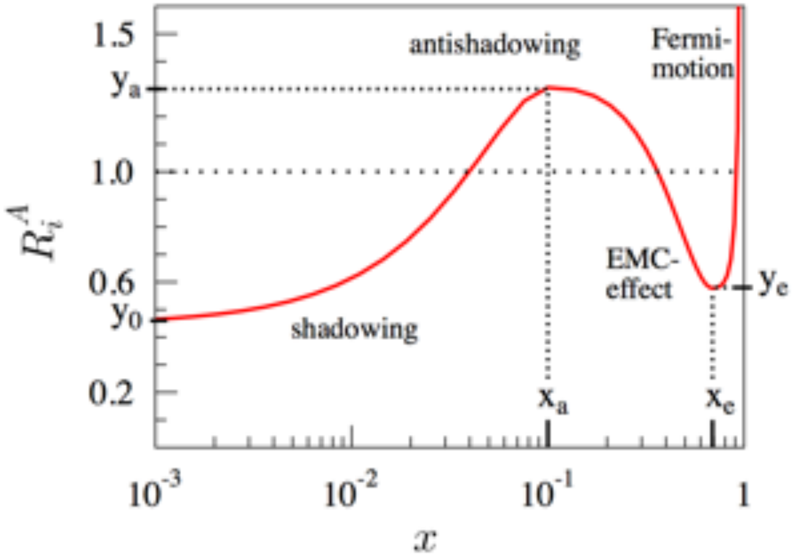


pA

Final State

nuclear mod. of *pdf*

$$f_i^A(x_i,Q^2) = R_i^A(x,Q^2)\,f_i^p(x,Q^2)$$



Nuclear Modification Factor

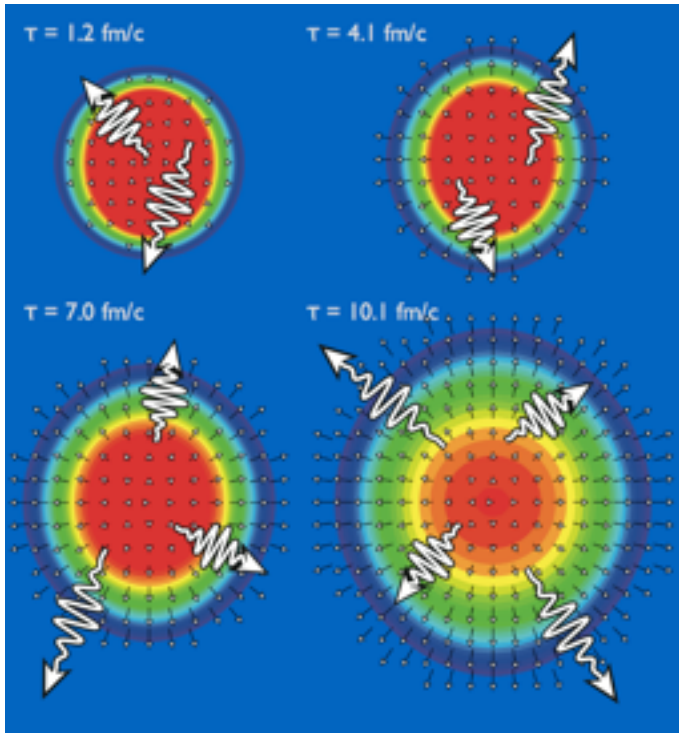
$$R_{AA} = \frac{yield(\mathrm{AA})}{yield(N_{\mathrm{coll}}\ \text{incoherent NN})} = \frac{dN/dp_{\mathrm{T}}\big|_{AA}}{N_{\mathrm{coll}}\,dN/dp_{\mathrm{T}}\big|_{pp(pA)}}$$

What have we learned about bulk properties of the medium ?

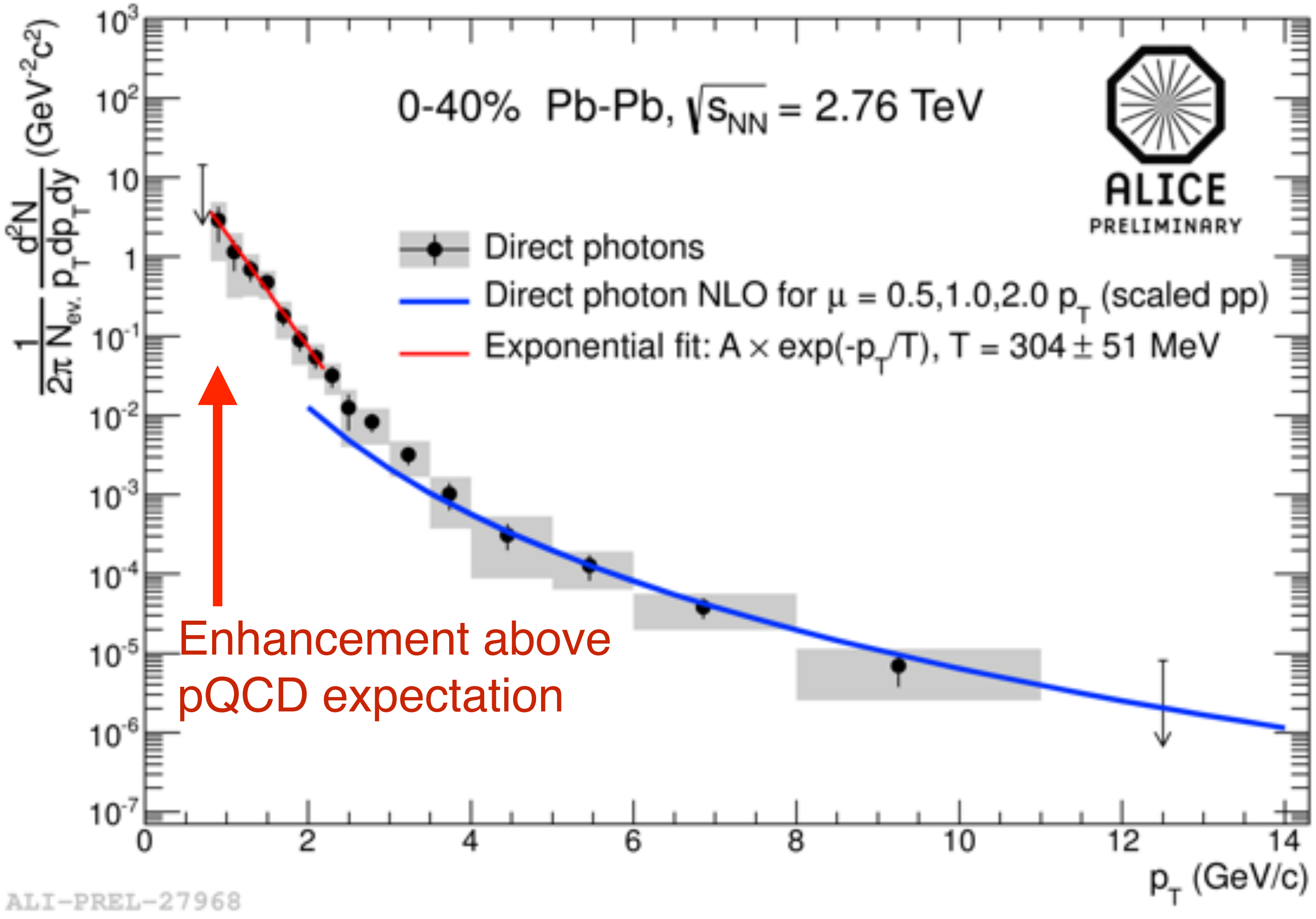
Denser, hotter, longer lived …

Temperature: Thermal Radiation

photons leave medium unscathed



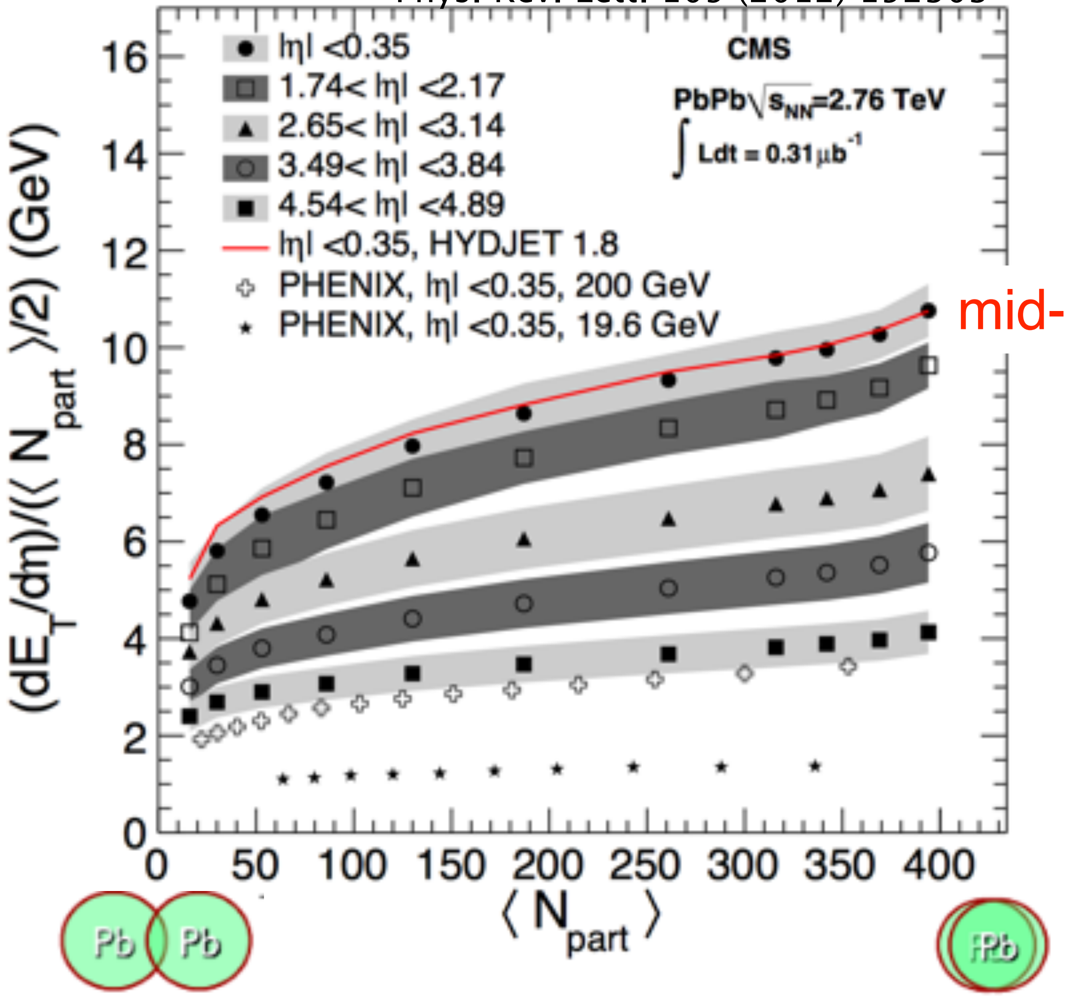
Direct photon spectrum



Enhancement above pQCD expectation

- Inverse slope: T = 304±51 MeV (~40% higher than at RHIC)
- In hydrodynamic model T corresponds to an effective temperature averaged over the time evolution of the medium
- Suggests initial temperatures well above the critical temperature for QGP formation
  - RHIC: $T_{in} \geqq 300$ MeV; LHC: $T_{in} \geqq 390$-420 MeV (ie 30-40% higher)

Initial Energy Density: Transverse Energy



Phys. Rev. Lett. 109 (2012) 152303

mid-rapidity

Bjorken Estimate:

$$\varepsilon = \frac{1}{A_\perp c\tau_0}\frac{\mathrm{d}E_\mathrm{T}}{\mathrm{d}\eta} = 14\ \frac{\mathrm{GeV}}{\mathrm{fm}^3}$$

$$A_\perp = \pi R^2$$

$$\tau_0 = 1\ \mathrm{fm}/c\ \text{(very conservative)}$$

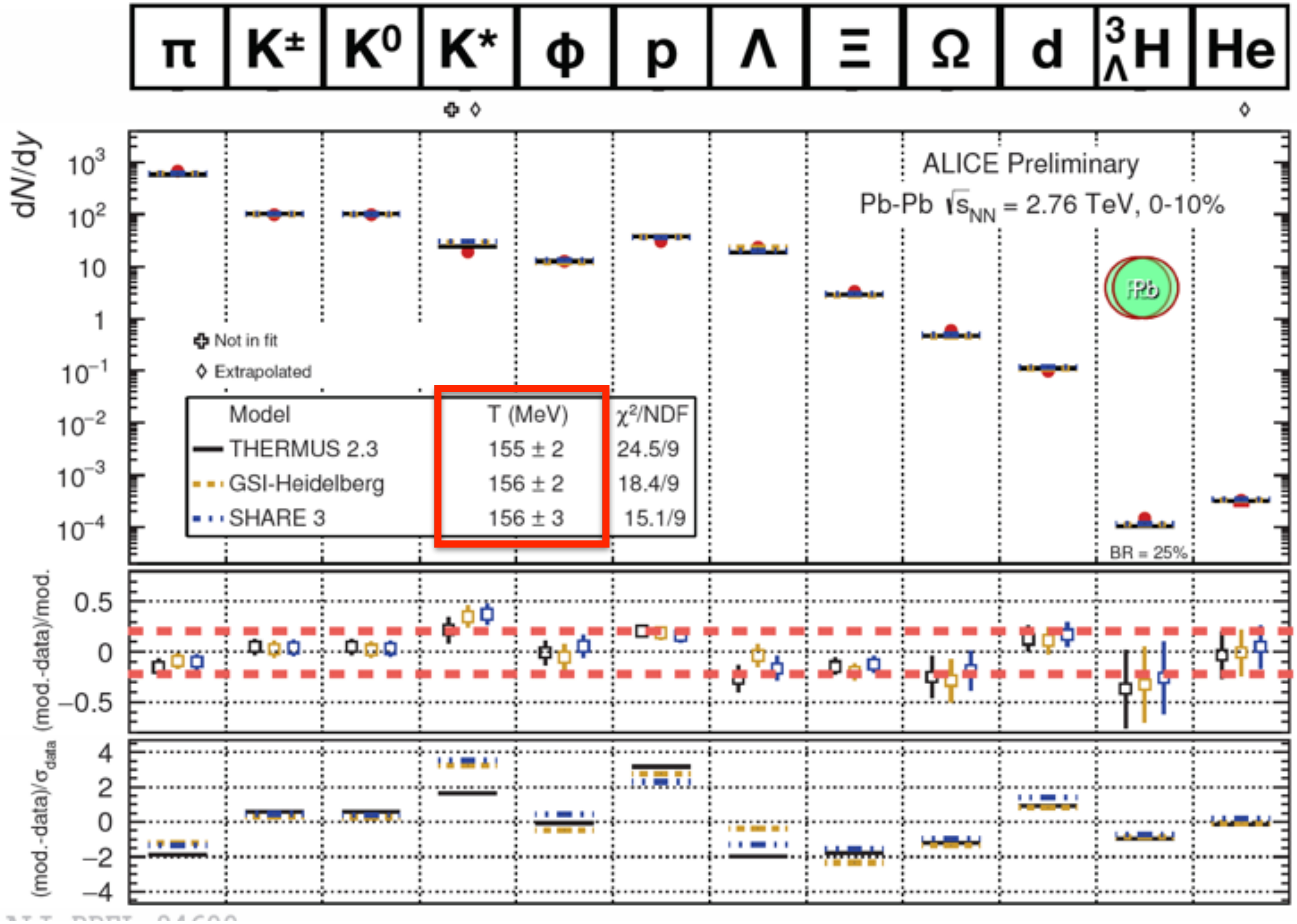
Factor 2.6 higher than at RHIC

with $\varepsilon \sim T^4$: ~ 30% higher initial temperature

Consistent with thermal radiation!

Freeze-Out Temperature: Yields

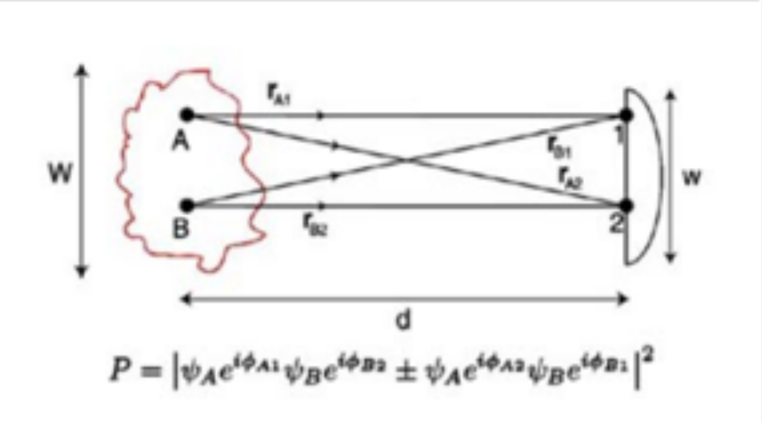
Thermal fit: Boltzmann $\mathbf{e}^{-m/T}$ + strangeness suppression γ_s



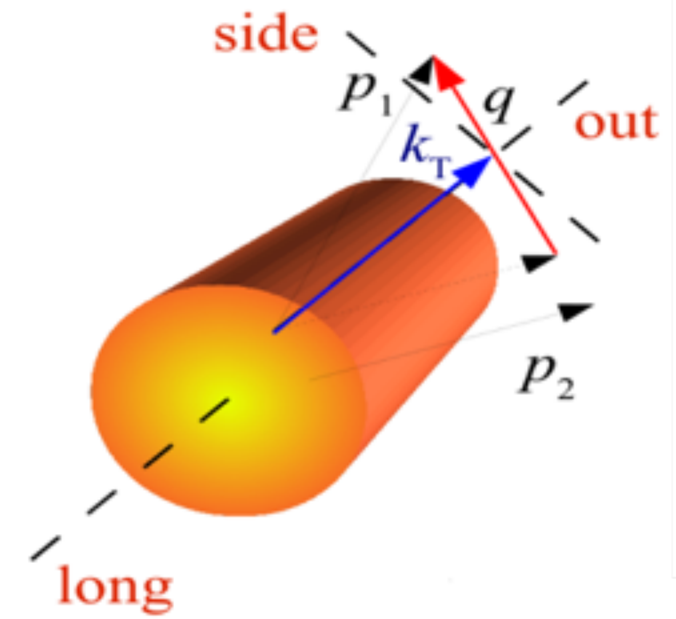
T_{fo} ≈156 MeV (close to T_c)

Size at Freeze-Out: HBT

Identical Bose Particle Interferometry
(HBT, Femtoscopy)

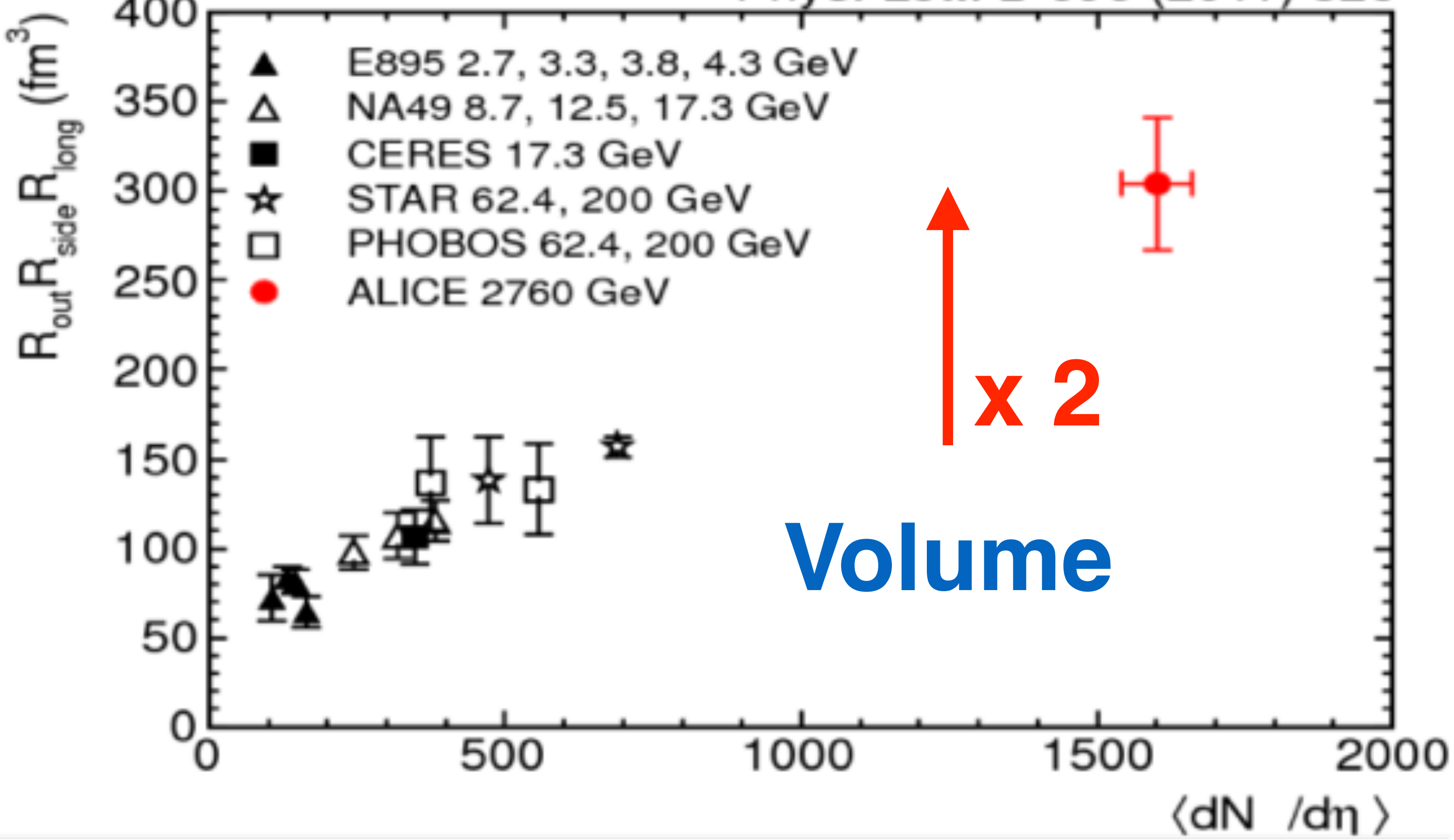


Hanbury-Brown Twiss optical interferometry



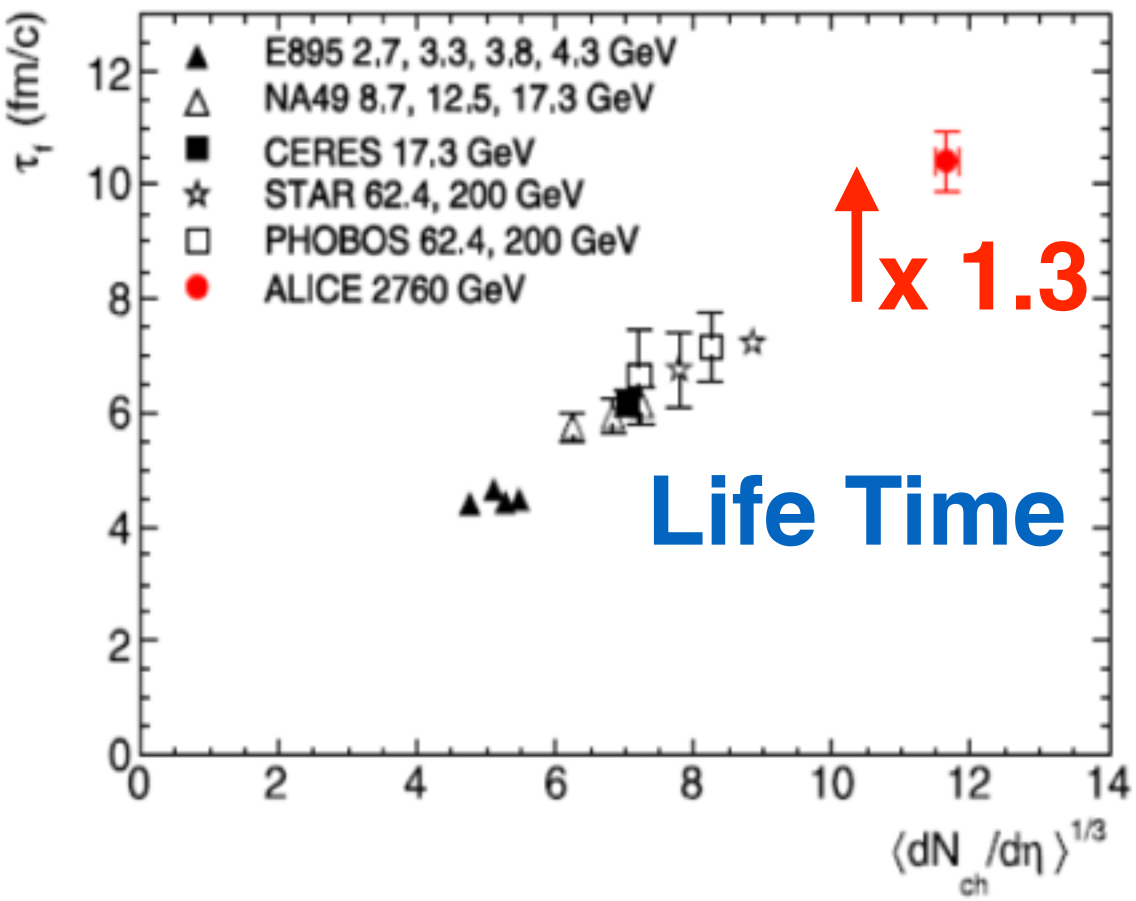
2-particle momentum correlations in three orthogonal directions

Phys. Lett. B 696 (2011) 328



x 2

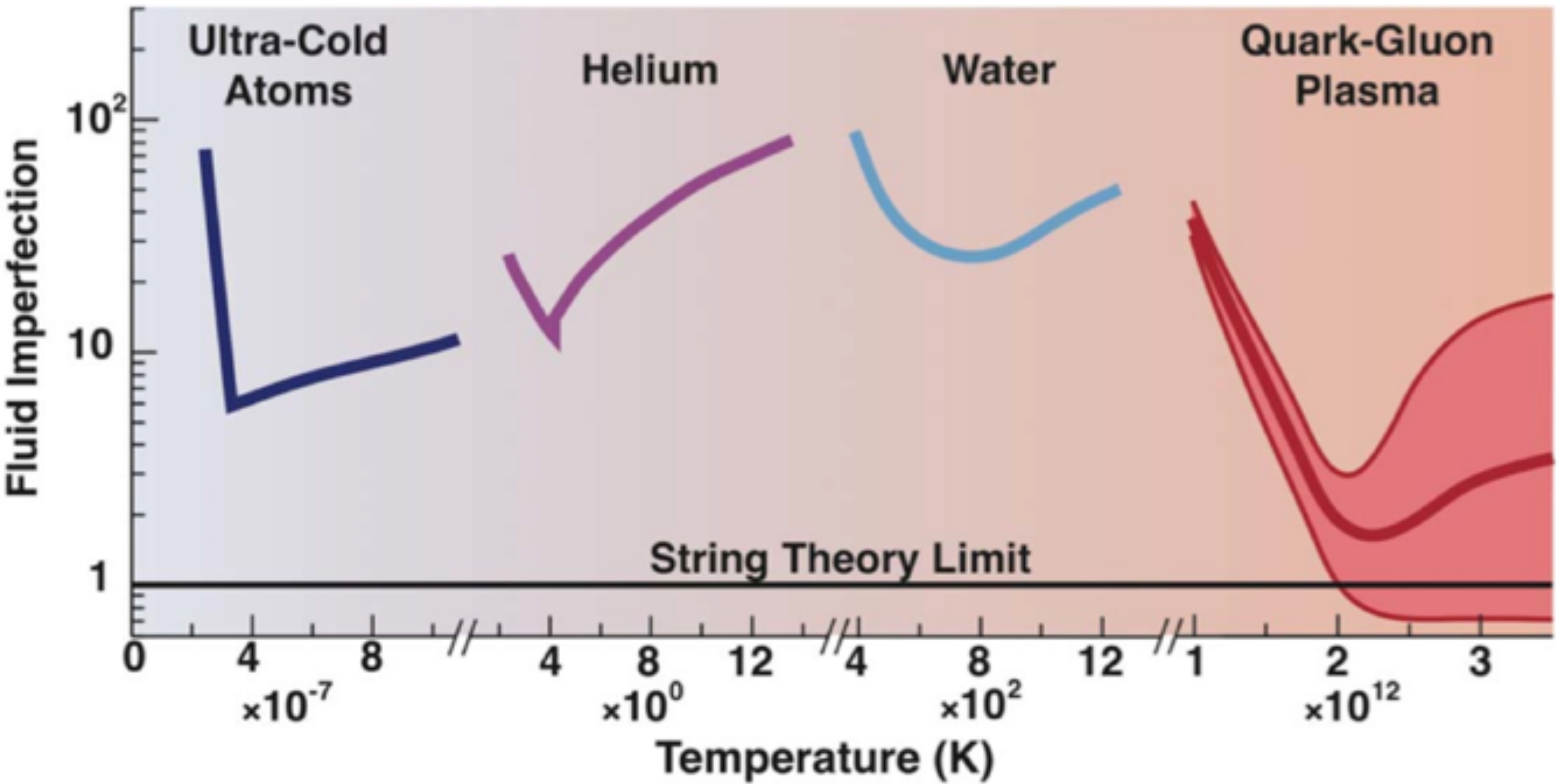
Volume



x 1.3

Life Time

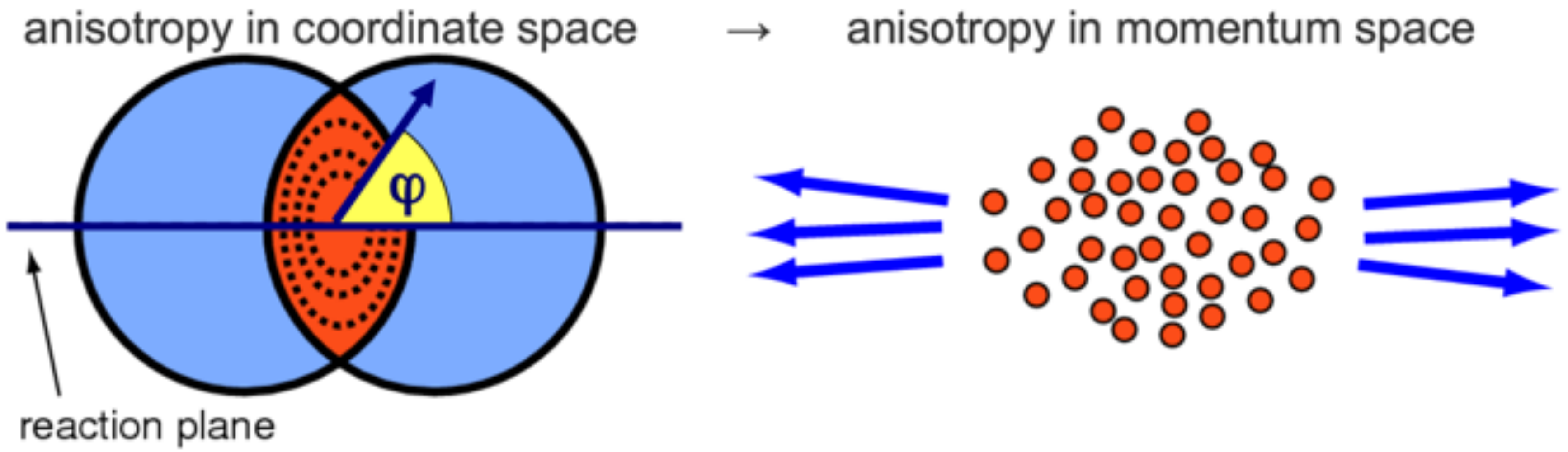
An Almost Ideal Fluid
("Flow")

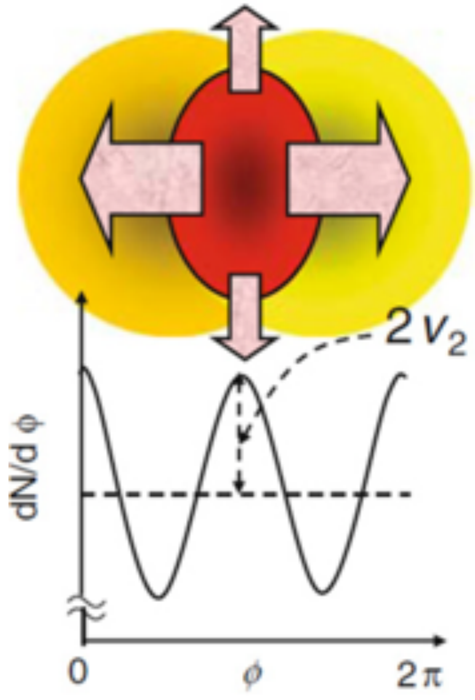


Chun Shen and Ulrich Heinz,
arXiv 1507.01558

QGP Fluid Dynamics

non central collisions: overlap region almond shaped





- Medium shows a very strong response to the initial shape
- Space anisotropy (pressure gradients) converted into momentum anisotropy
  - Measurable with final state particles (cos-modulation of azimuthal distribution)

Elliptic Flow

$$E\frac{d^3N}{d^3\vec{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1+2v_2\cos\left(2(\varphi-\Psi)\right)\right]$$

v_2 eliptic flow

Hydrodynamics Calculations

Medium response and evolution described by Hydro effective theory:
Transport of energy and momentum in matter on long distance and time scales

$$\partial_\mu T^{\mu\nu} = 0;\ \partial_\mu N^\mu = 0$$

+Equ. of motion for dissipative currents

Behaviour most directly controlled by shear viscosity (*η*) to entropy density (*s*) ratio

Kinetic Theory (weak coupling)	holographic gravity duals (AdS/CFT, strong coupling)
$\frac{\eta}{s} \approx \frac{l}{\lambda_C} > \mathcal{O}(1)$	$\frac{\eta}{s} \geq \frac{1}{4\pi} \approx 0.08$

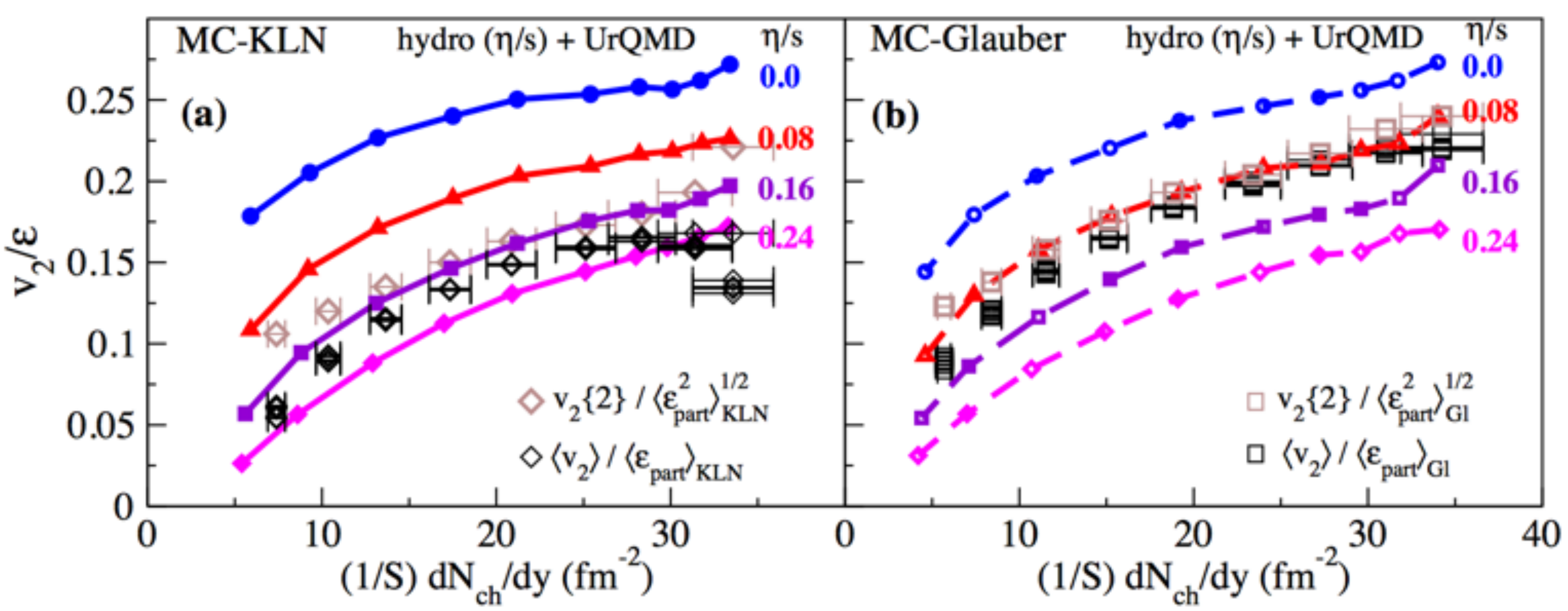
l : mean free path

λ_C : Compton length

Lower limit in both cases!

Initial State Uncertainties

Fits with two different initial conditions models



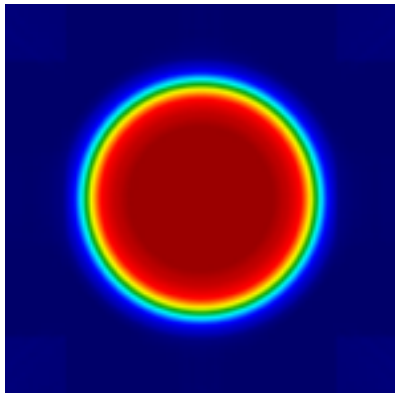
C. Shen et al. J. Phys. G 38, 124045 (2011)

$$\frac{1}{4\pi} \leq \left[\frac{\eta}{s}\right]_{\mathrm{QGP}} \leq 2.5 \times \frac{1}{4\pi}$$

- Initial conditions can be further constrained by higher harmonics v_n in azimuthal distribution
  - v_n/v_2 ratios
  - event-by-event fluctuations $v_2/\langle v_2\rangle \approx \varepsilon_2/\langle\varepsilon_2\rangle$
- Precise measurements possible at LHC due to high particle density

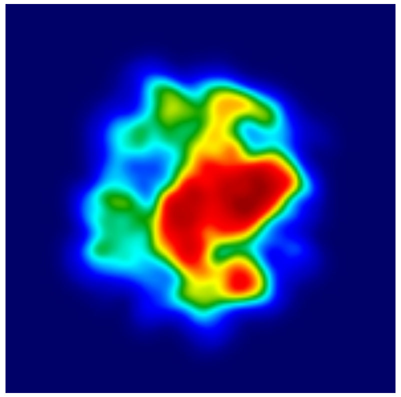
Higher Harmonics & Flow Fluctuations

smooth initial conditions ($\mathcal{O}$(5 fm))



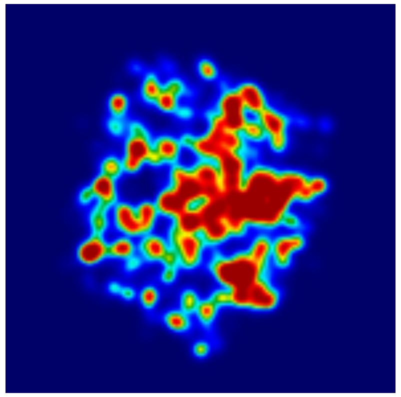
no higher harmonics

fluctuation of nucleon positions ($\mathcal{O}$(1 fm))

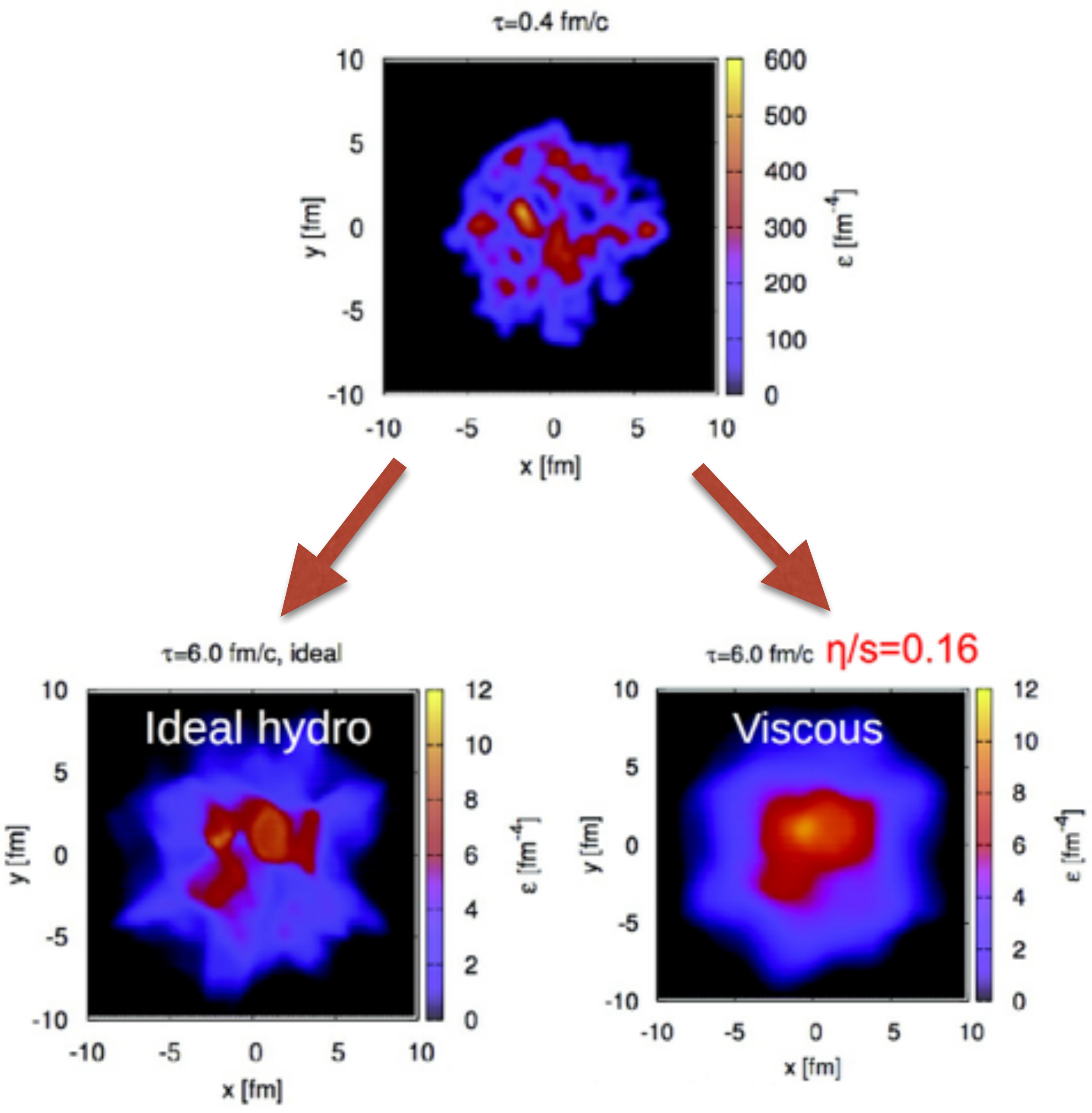


generate higher harmonics

sub fermionic fluctuations



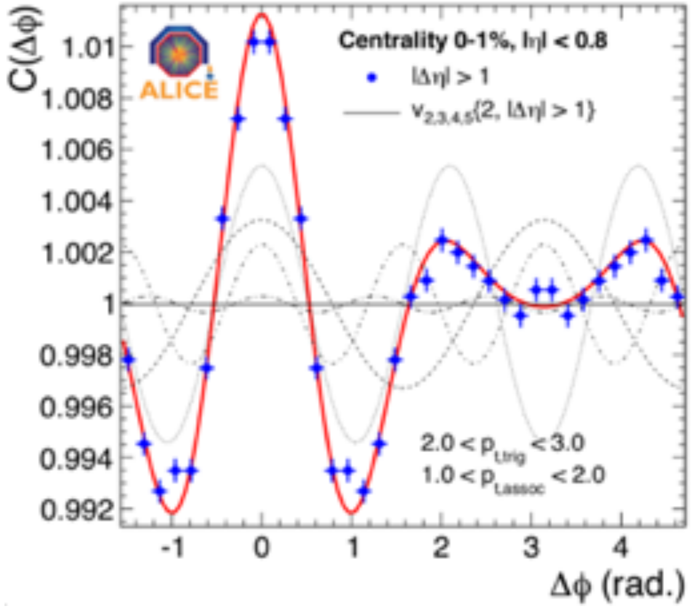
event-by-event
flow fluctuations



small scale fluctuations blurred by viscosity
➜ additional sensitivity to *η/s*

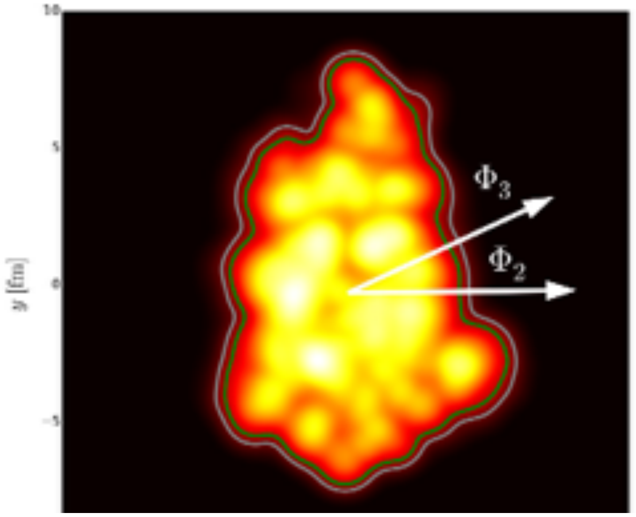
Including Higher Harmonics

@LHC naked eye observable!



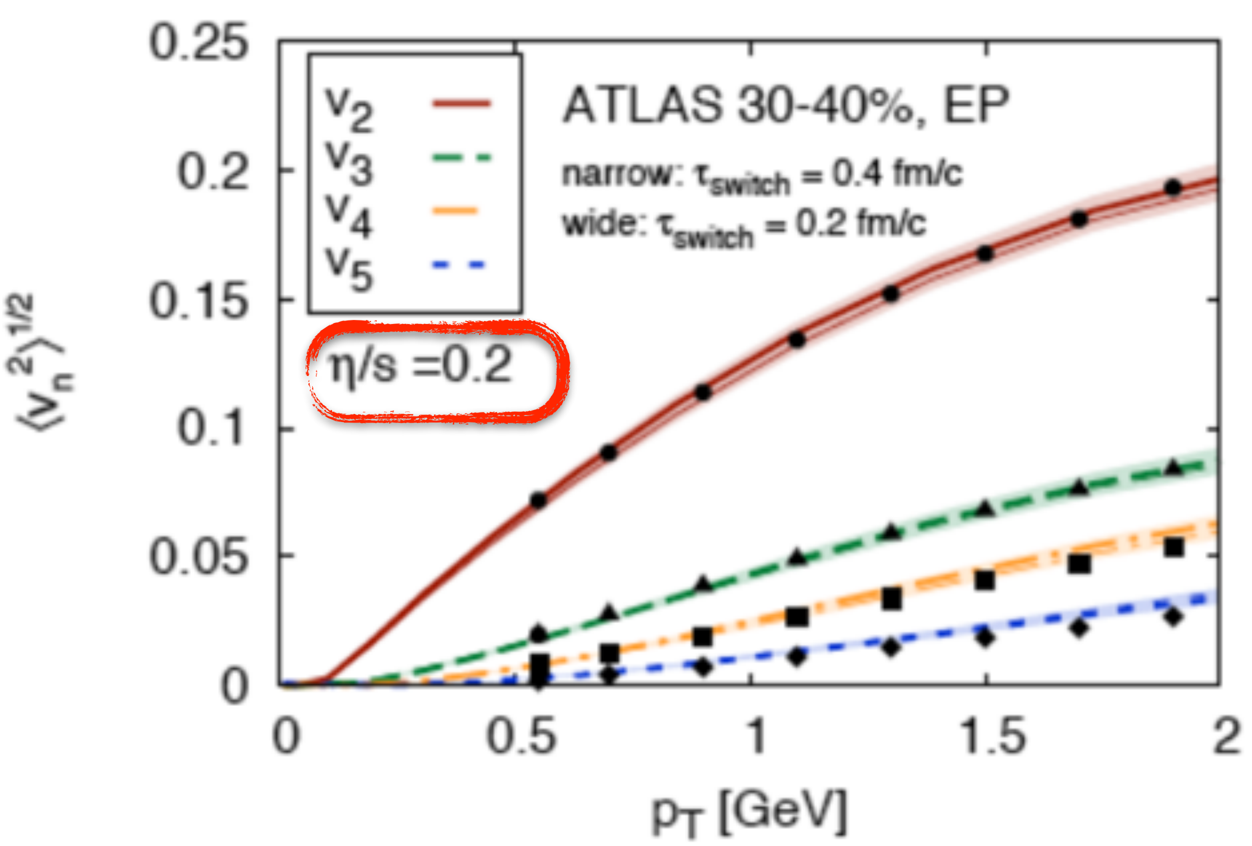
Fourier expansion:

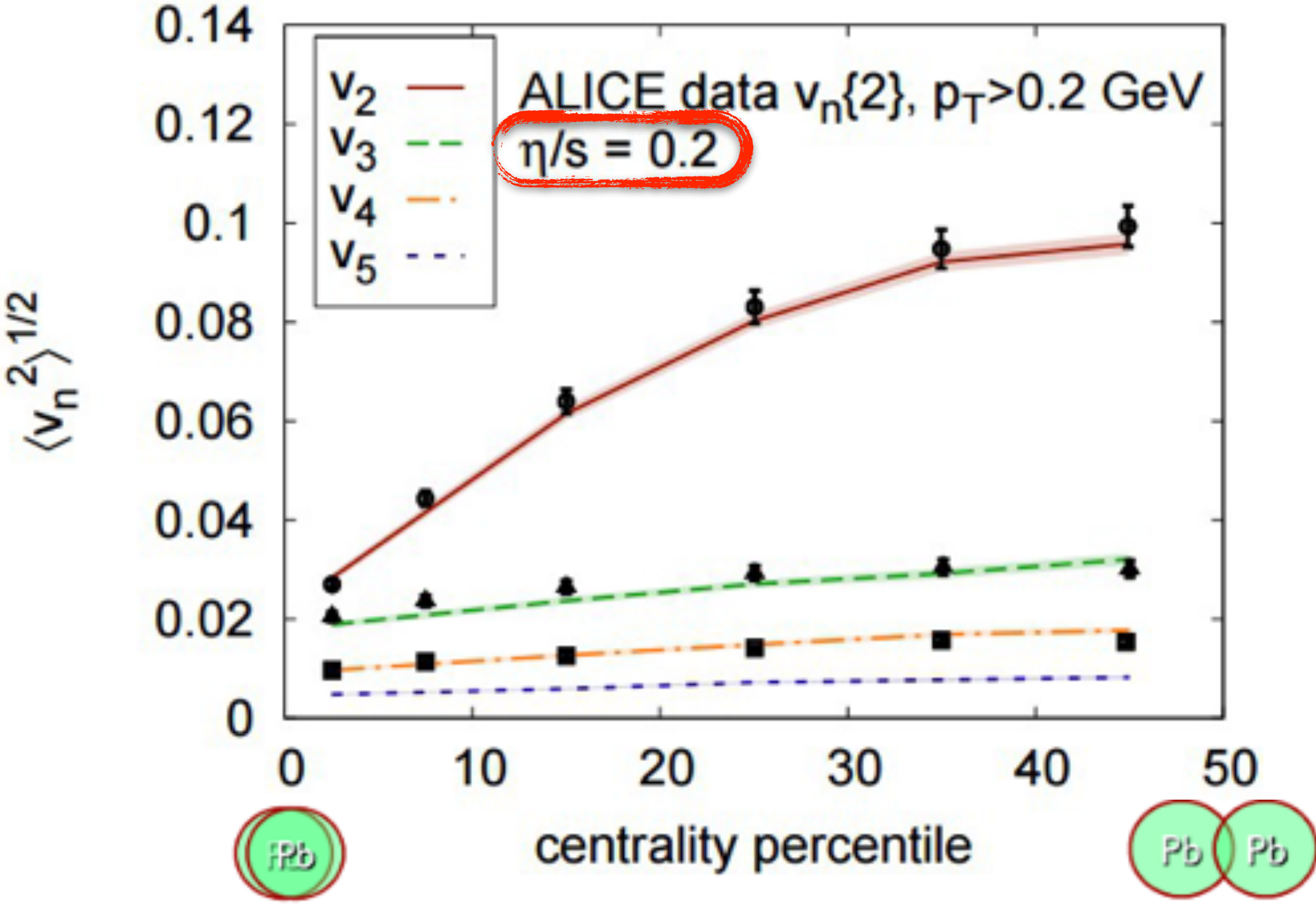
$$E\frac{d^3N}{d^3\vec{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1+2\sum_1^{\infty} v_n \cos\left[n\left(\varphi-\Psi_n\right)\right]\right]$$



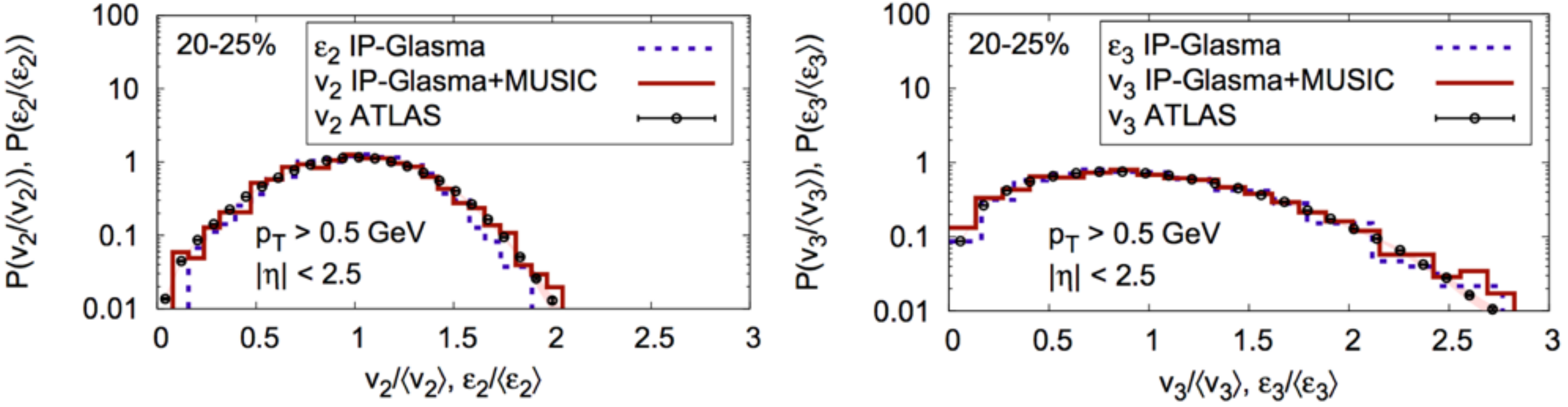
$$\varepsilon_n, \Phi_n \xrightarrow[\frac{\eta}{s}]{} v_n, \Psi_n$$

Gale, Jeon, Schenke, Tribedy and Venugopalan, PRL 110, 012302 (2013)





Event-by-Event Flow Fluctuations



$v_2 / \langle v_2 \rangle$

Gale, Jeon, Schenke, Tribedy, Venugopalan,
Phys. Rev. Lett. 110, 012302 (2013)

$v_3 / \langle v_3 \rangle$

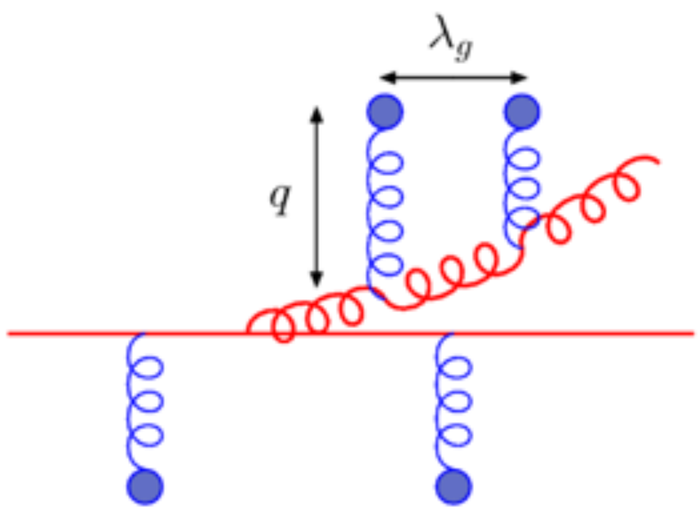
- Current η/s uncertainty ≈ 50%
- Consistent picture for RHIC ($\eta/s = 0.12$) and LHC (0.2)

Response to High p_T Partons (“Jet Quenching”)

Parton Energy Loss

A self generated probe of the medium …

- High p_T partons produced at early stage (« 1 fm) of the collision
- Loose energy through
  - elastic scatterings
  - induced gluon radiation (dominant at high p_T)

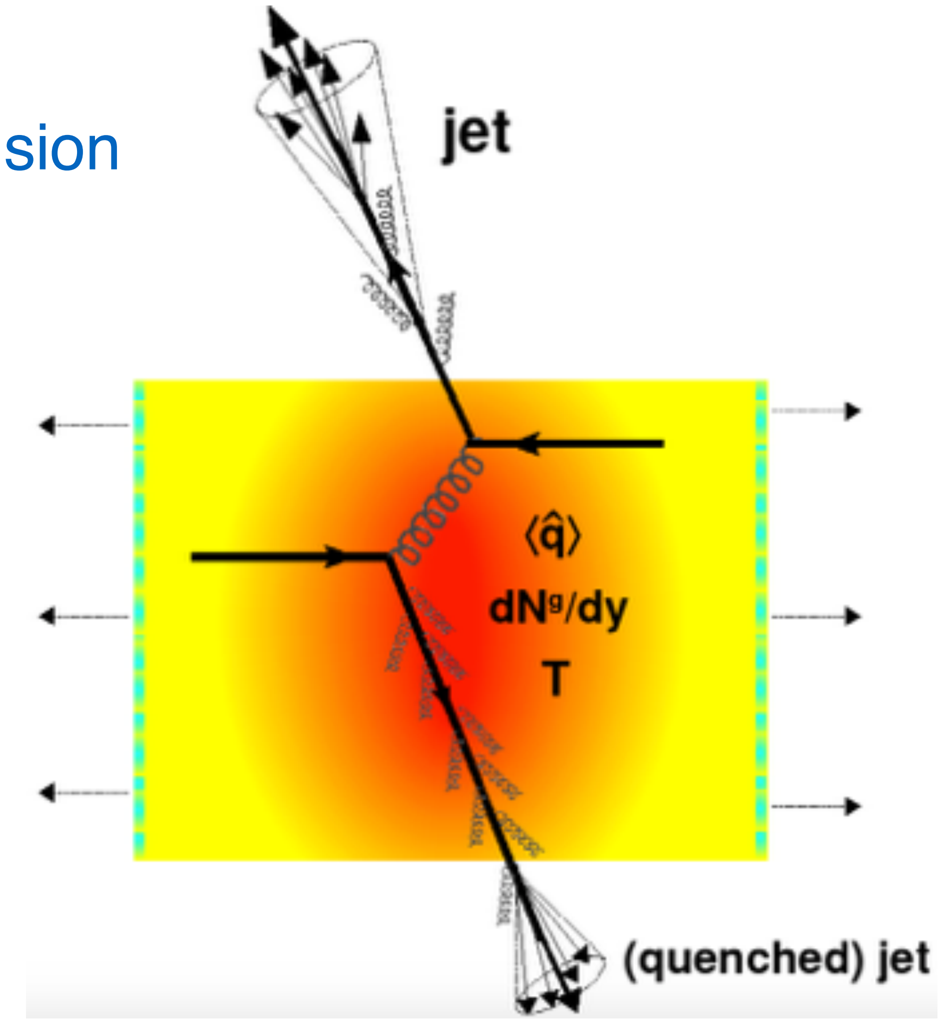


Example BDMPS

$$\Delta E_{rad} \sim \alpha_S C_R \hat{q} L^2$$

$$\hat{q} = \frac{\langle p_T^2 \rangle}{\lambda} \quad \text{(transport parameter)}$$

$$C_R = \begin{cases} 4/3 & quarks \\ 3 & gluons \end{cases}$$

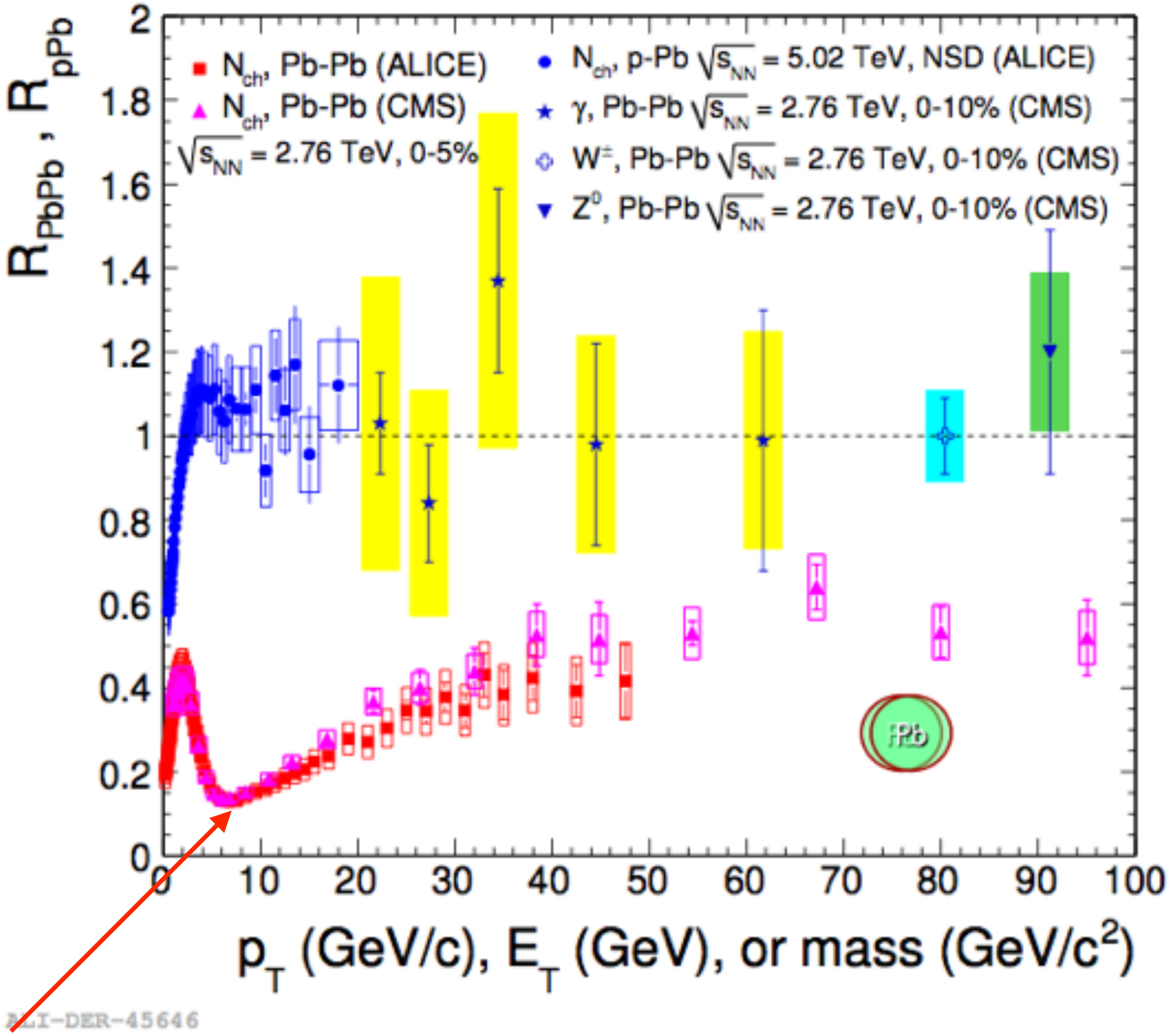


Expect: $\Delta E_{\text{gluon}} > \Delta E_{\text{light quark}} > \Delta E_{\text{heavy quark}}$ (dead cone effect)

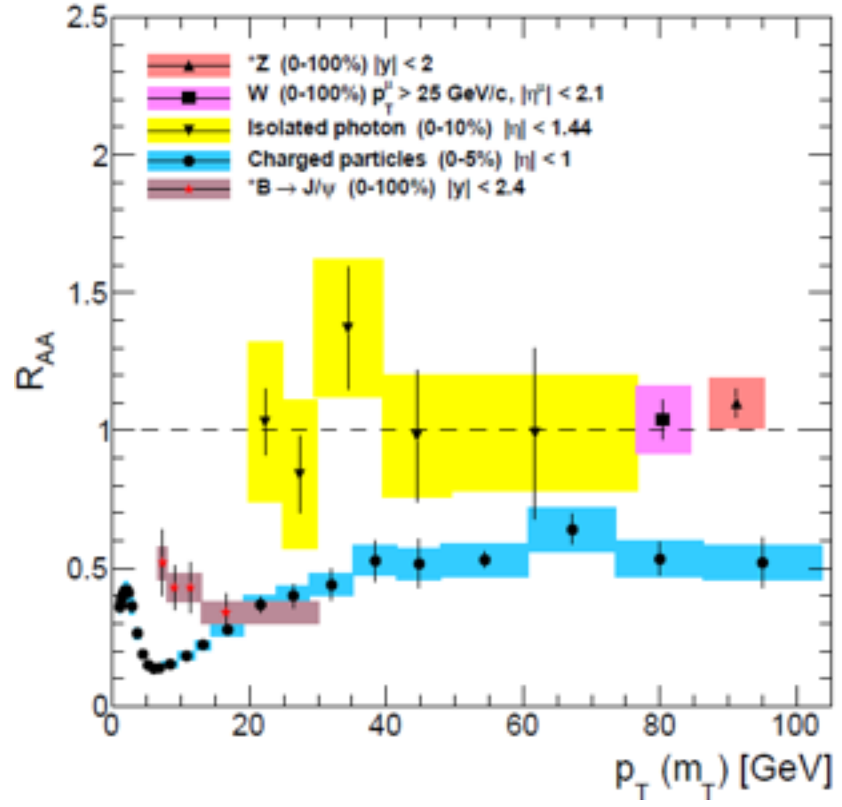
The energy loss of the leading particle or central, hard part of the jet depends has the highest sensitivity to the transport parameter.

Single Particle Nuclear Modification Factor

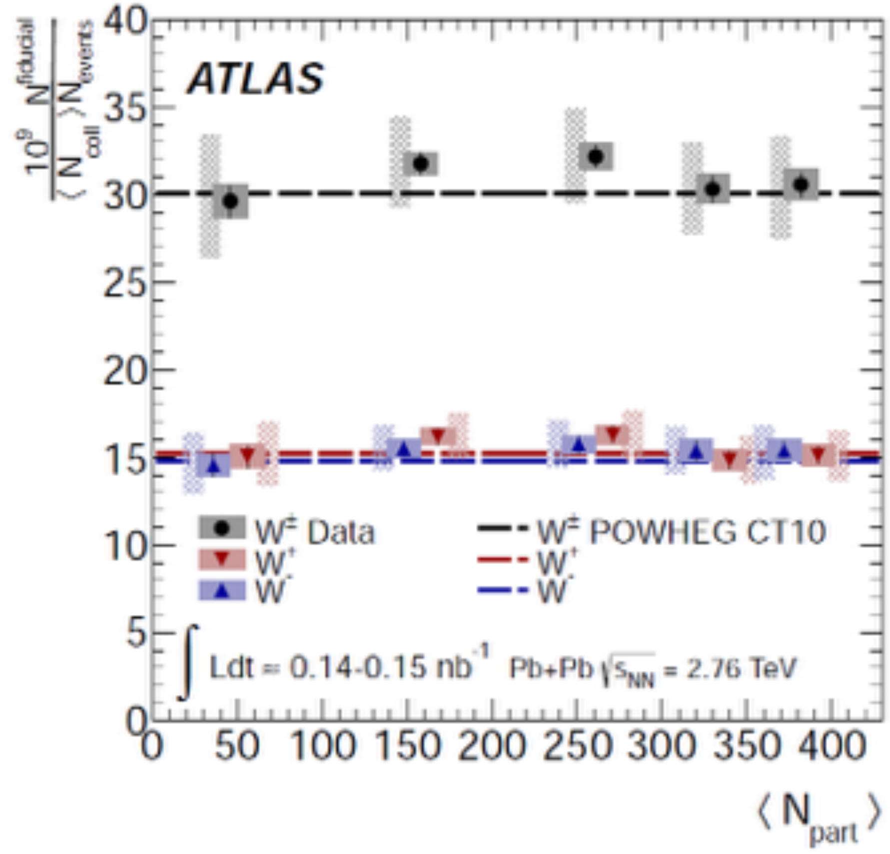
Inclusive hadron suppression compared to references: electroweak and p-Pb



≈1/7 at 7 GeV



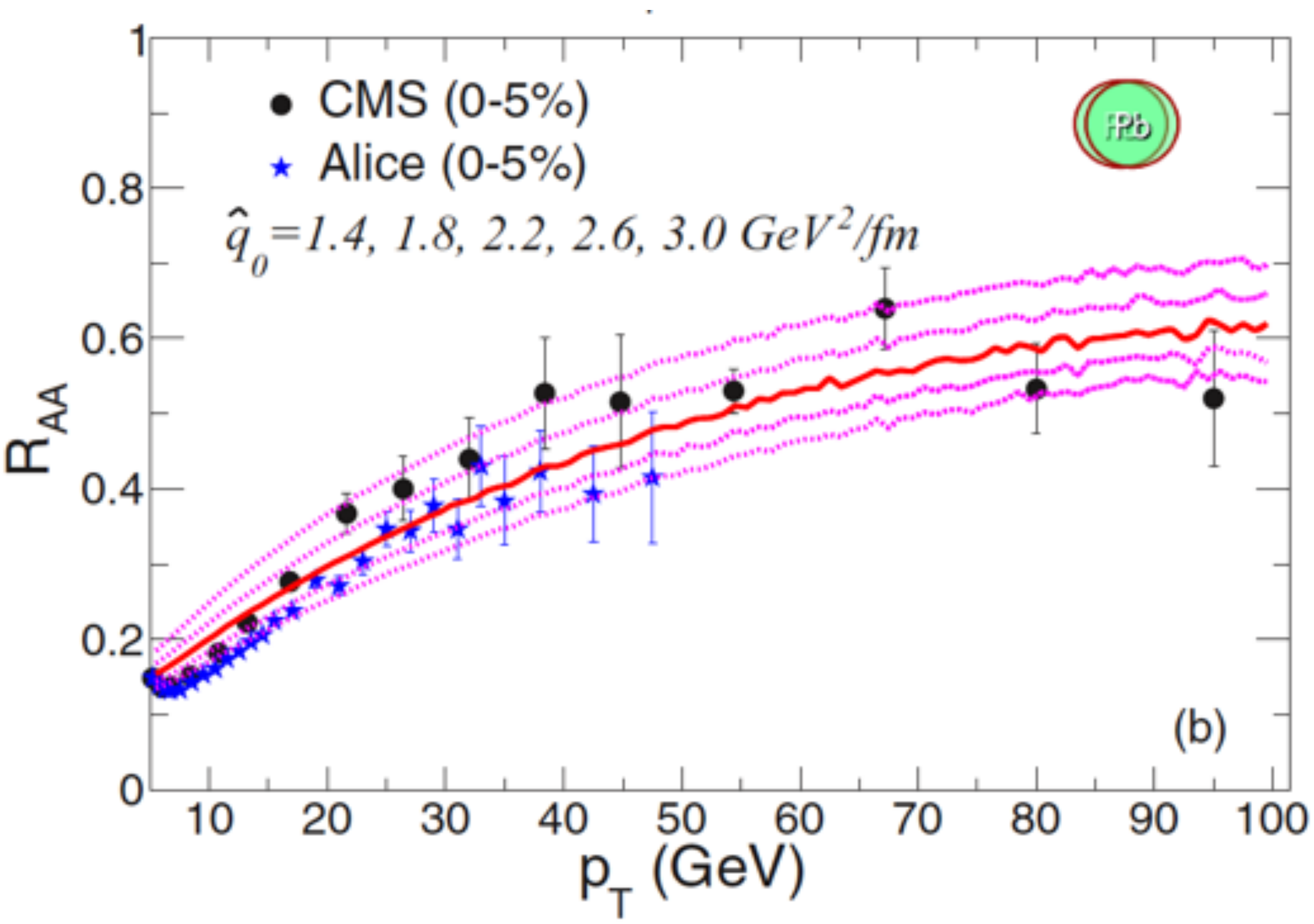
PLB 710 (2012) 256,
JHEP 03 (2015) 022,
PLB 715 (2012) 66, PLB 715 (2012) 66

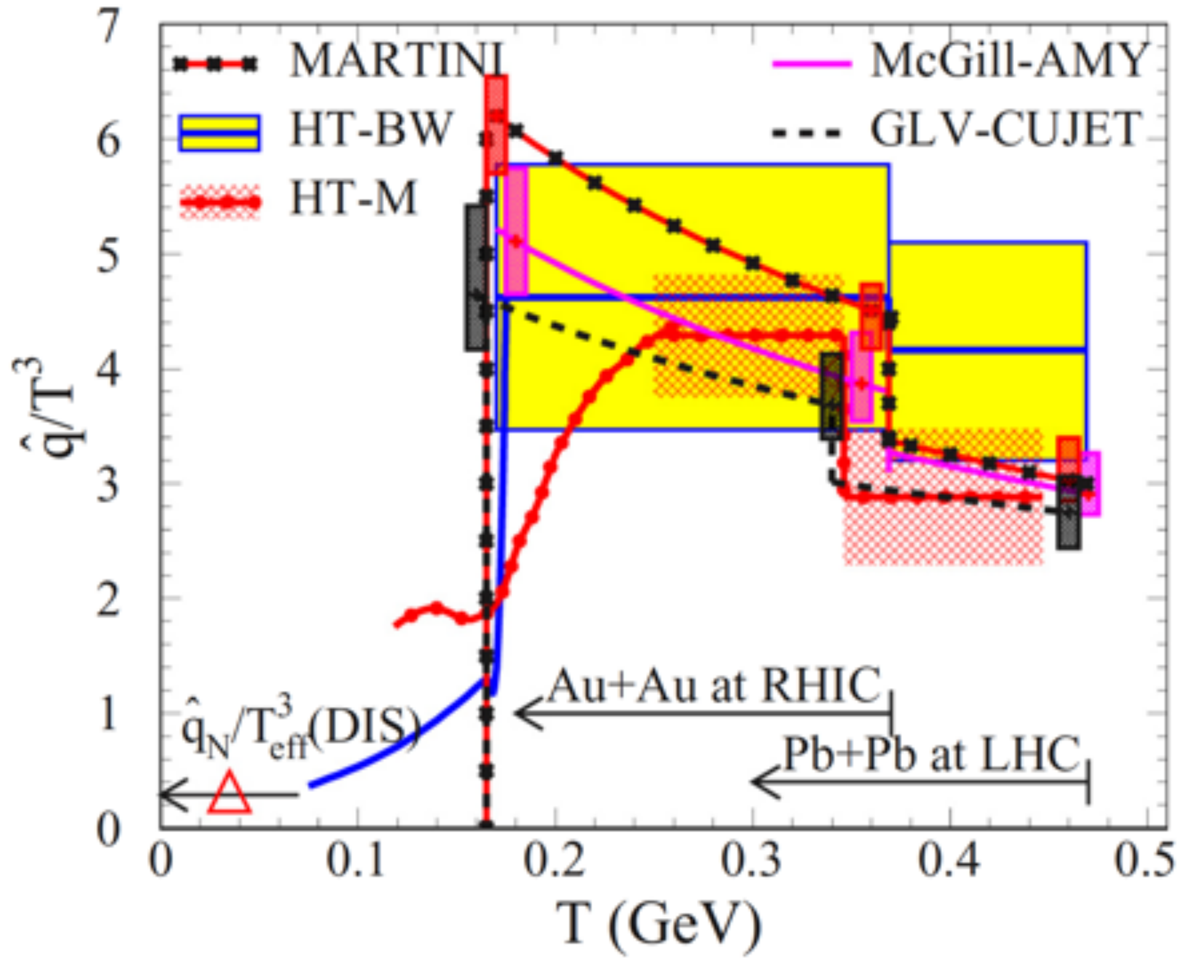


EPJC (2015) 75:23

Transport Parameter from R_{AA} at High p_T

JET Collaboration, PHYSICAL REVIEW C 90, 014909 (2014)



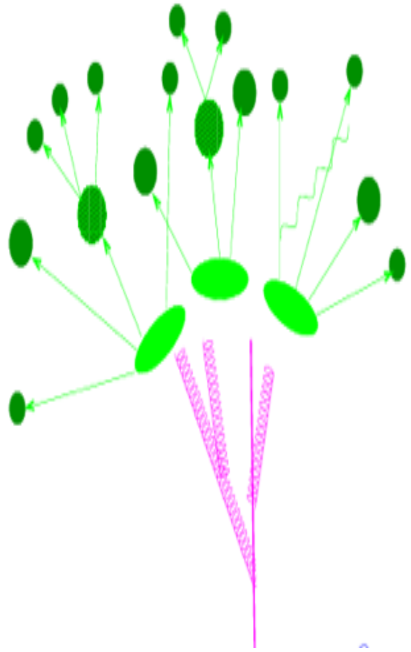


$$\frac{\hat{q}}{T^3} \approx \begin{cases} 4.6 \pm 1.2 & \text{at RHIC} \\ 3.7 \pm 1.4 & \text{at LHC} \end{cases}$$

$$\hat{q} \approx \begin{cases} 1.2 \pm 0.3 \\ 1.9 \pm 0.7 \end{cases} \text{GeV}^2/\text{fm at} \quad \begin{matrix} T = \text{ 370 MeV} \\ T = \text{ 470 MeV} \end{matrix}$$

Jet Yield and Structure Modifications

- Evolution of jets inside medium wrt vacuum more difficult to model:
- Affected by different (evolving) scales:



m_{had}
$<$
Q_2
$<$
Q_1
$<$
Q_0

Initial virtuality Q^2

- As Q^2 evolves partons probe medium at different length and time scales

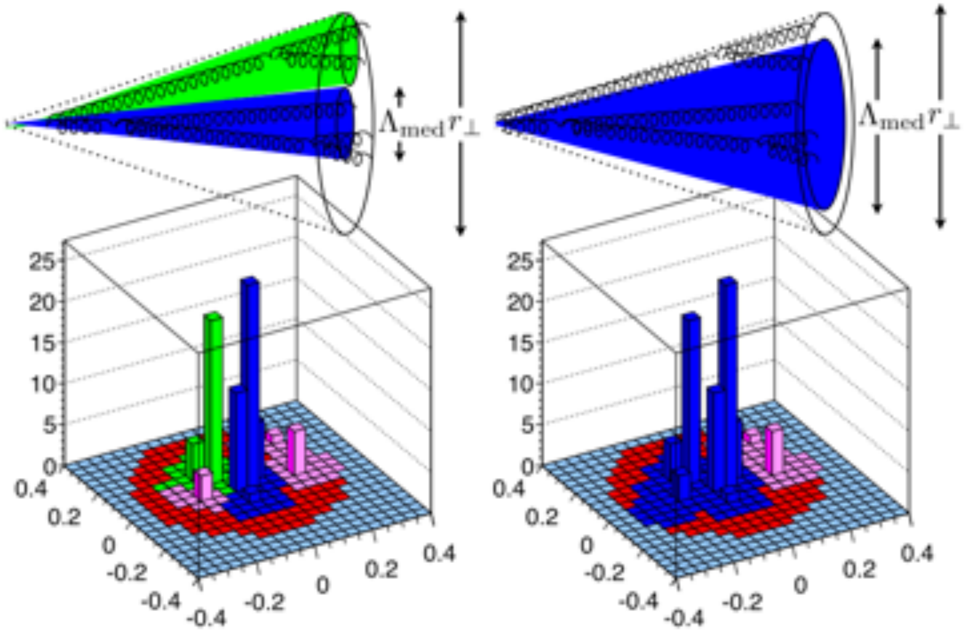
  - evolution governed by $Q/(\hat{q}\ \tau)$

Resolution scale of the medium $\Lambda_{\mathrm{med}} = 1/\sqrt{\hat{q}L}$

- coherent energy loss for $\Lambda_{\mathrm{med}} > \mathrm{r}_{\perp}$

Hadronization time scale

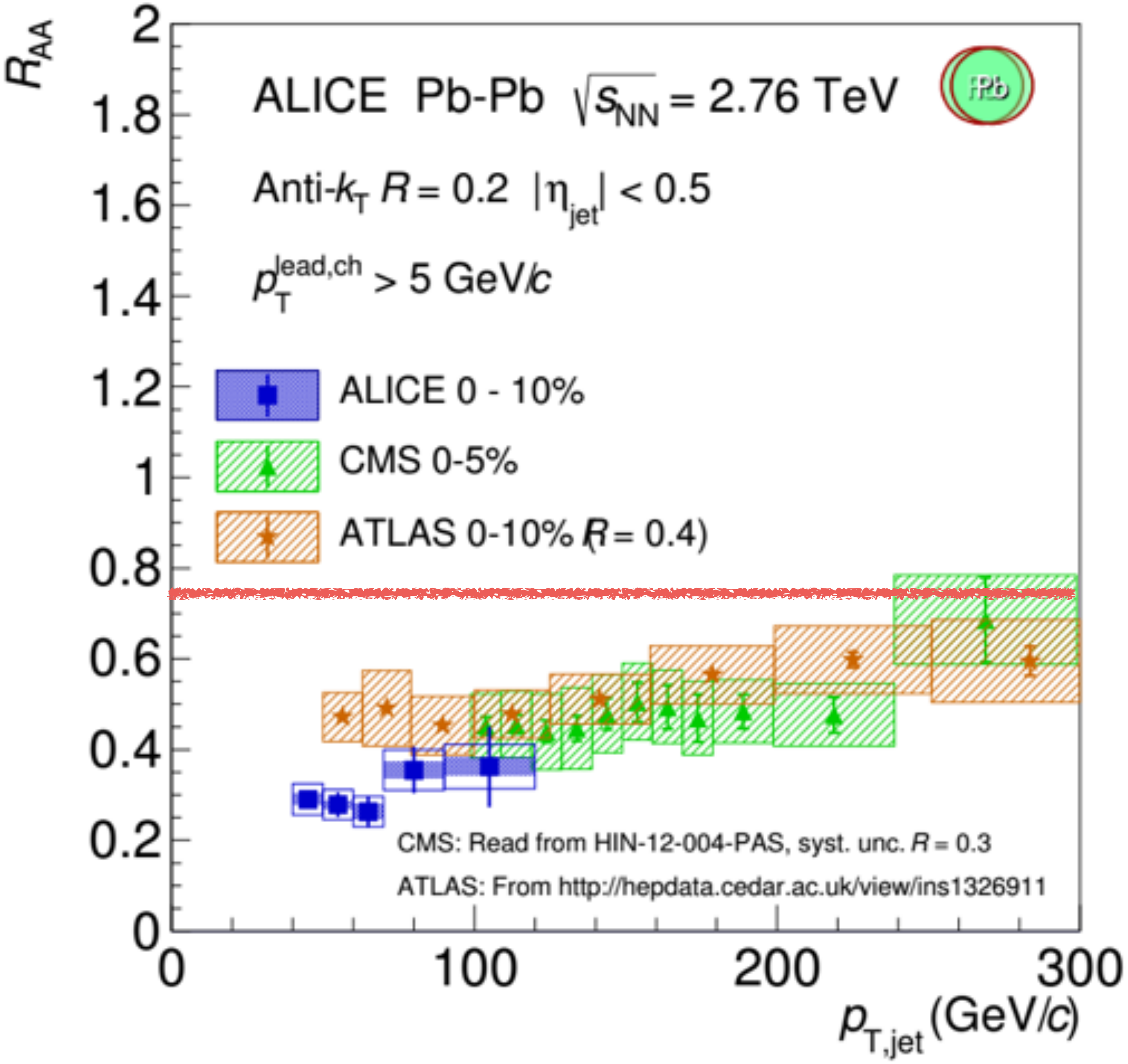
- $t_{\mathrm{had}} \approx E/m_{\mathrm{hadron}}^2$

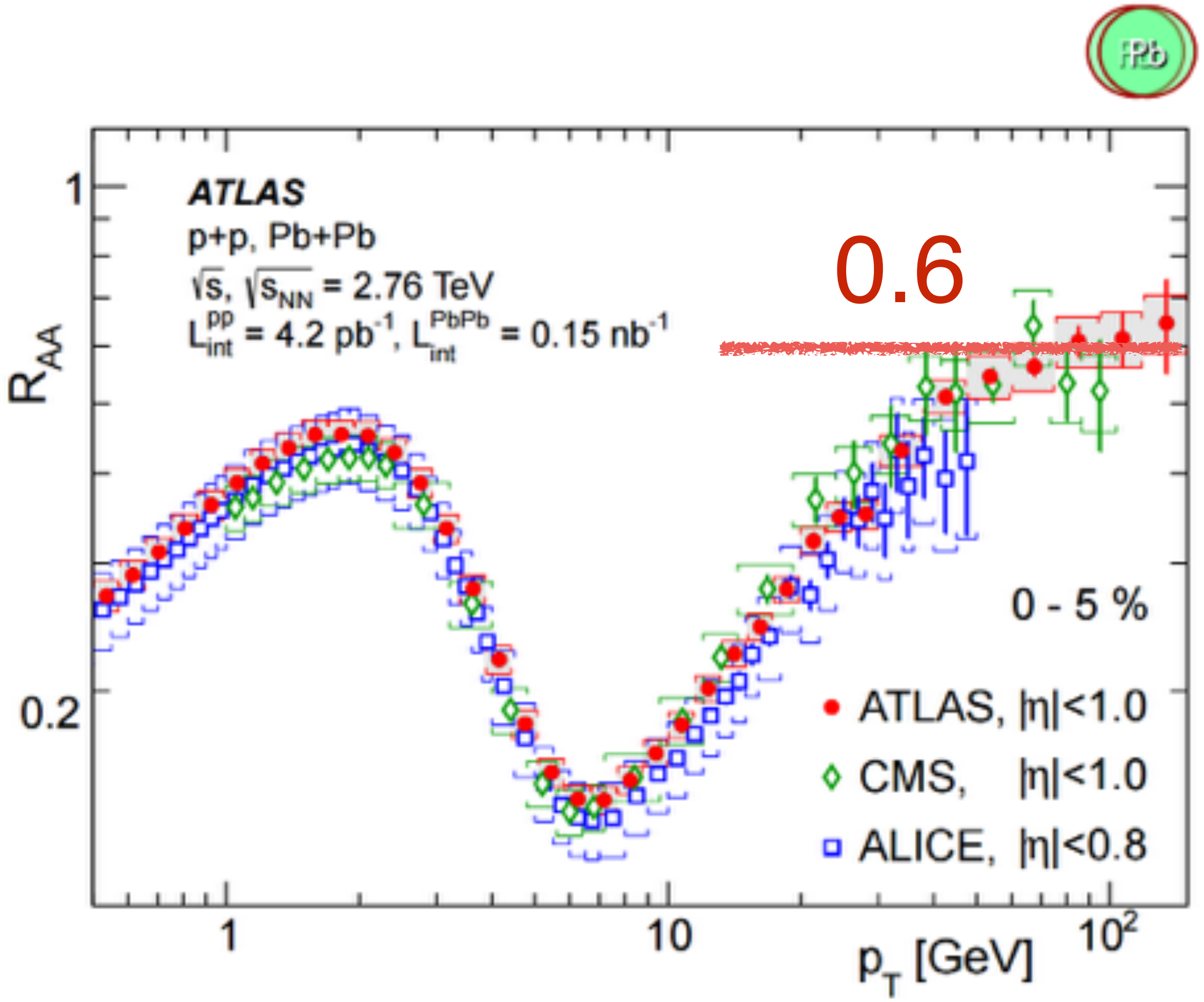


J. Casalderrey-Solana et al, arXiv:1210.7765

Jet R_{AA}

Jet Suppression = Out of Cone Radiation



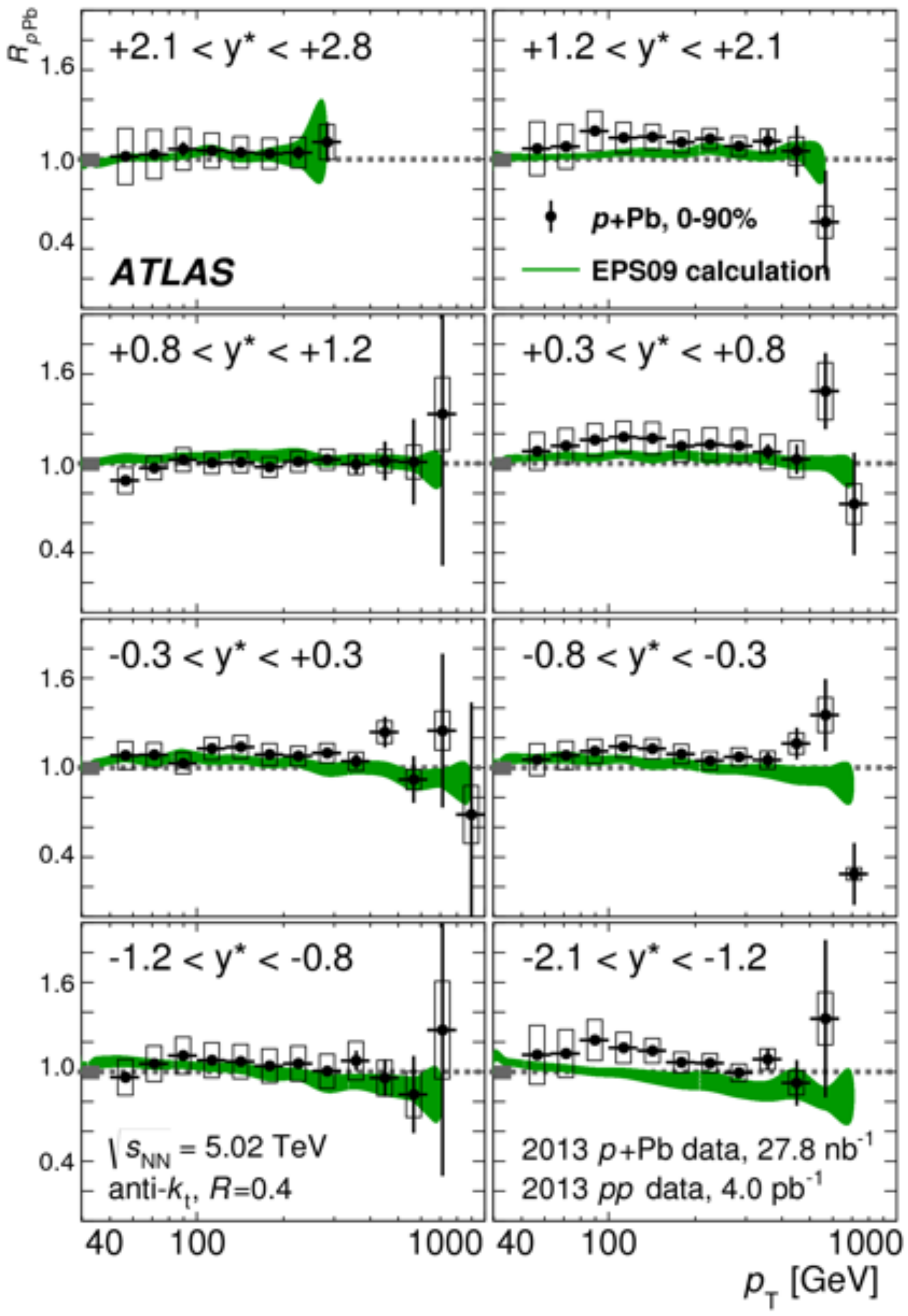


At high p_T: Similar suppression of inclusive hadrons and jets

Indicative of coherent energy loss of the jet core.

p-Pb Reference Measurement

Phys. Lett. B 748 (2015) 392-413

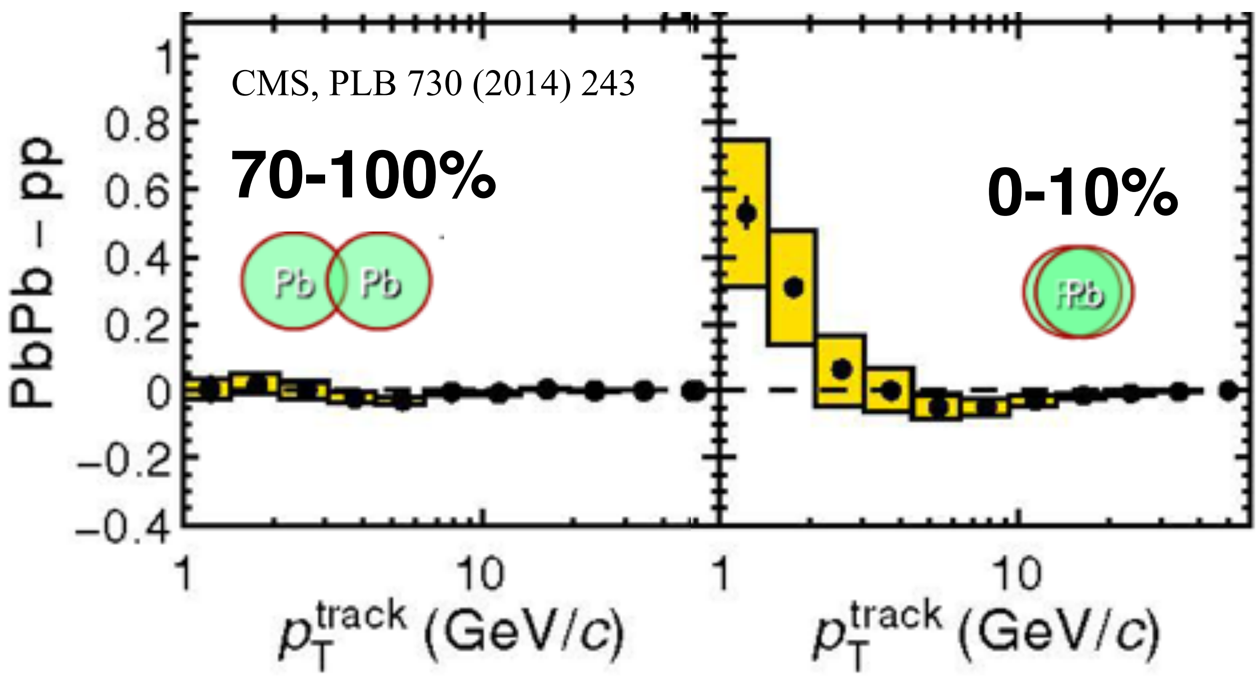


Jet rates unmodified in p-Pb control measurement!

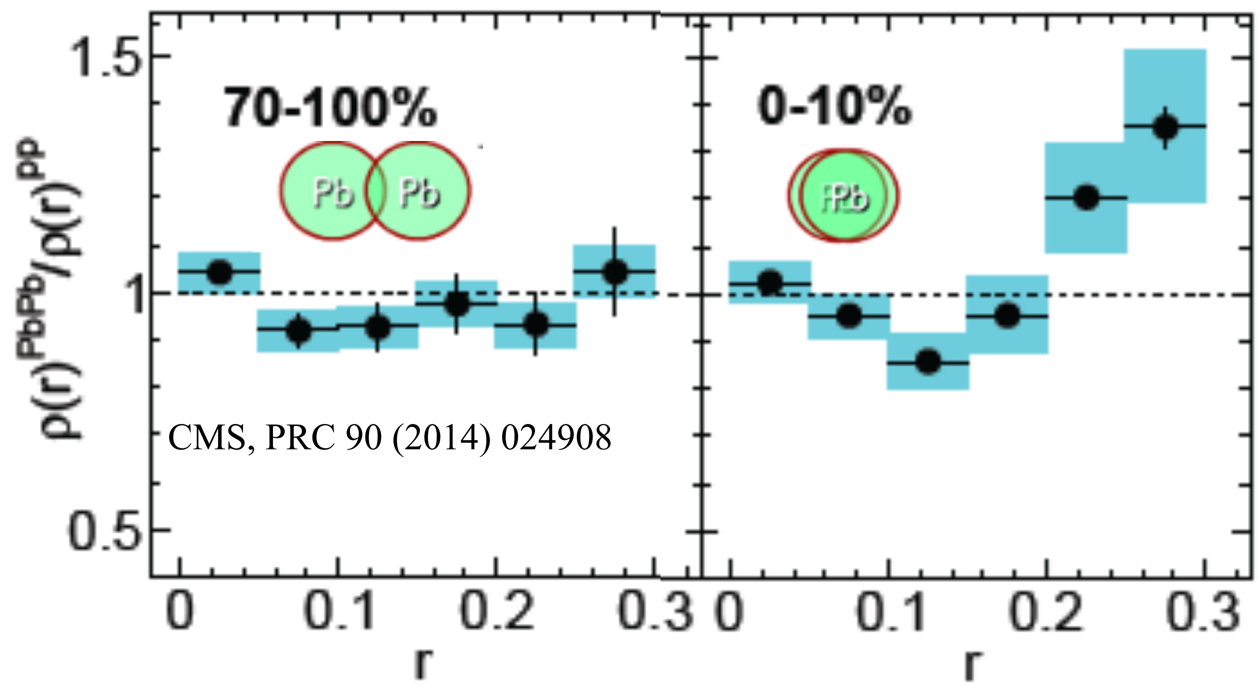
Suppression in Pb-Pb is final state effect.

Jet Shape Modifications

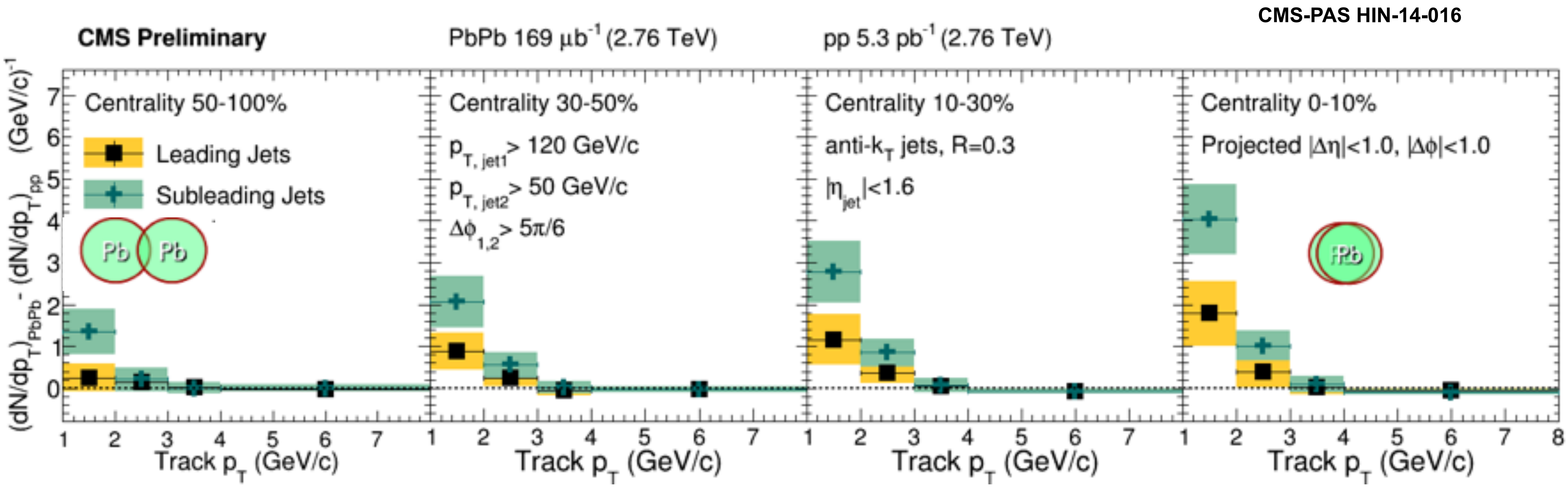
Pb-Pb vs pp fragmentation functions


CMS, PLB 730 (2014) 243

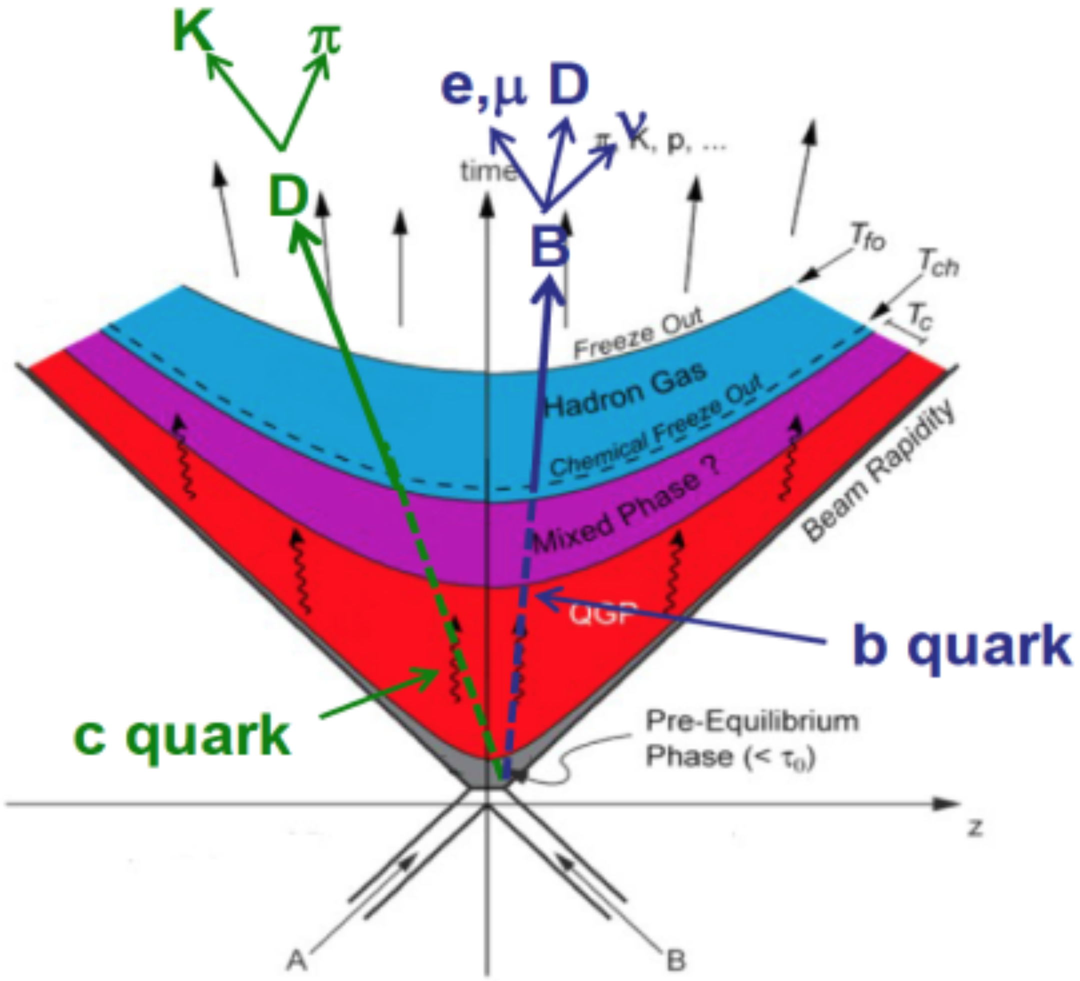
Ratio of Pb-Pb to pp differential jet shapes


CMS, PRC 90 (2014) 024908

Modest increase of low-p_T particle yield within jet cone, stronger inclusive increase


CMS-PAS HIN-14-016

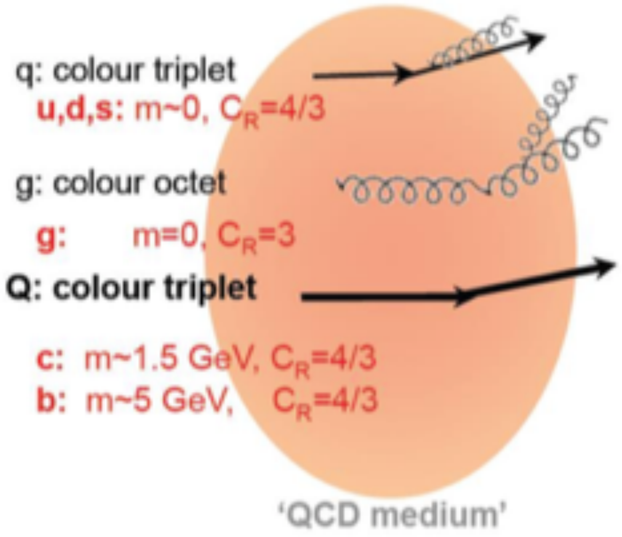
Heavy Quarks



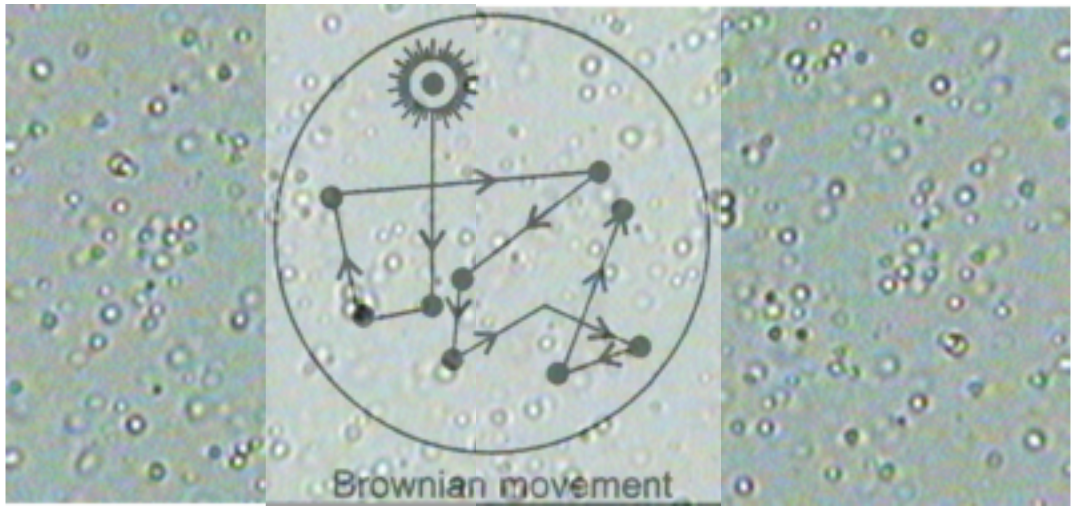
See arXiv:1506.03981 and D. Stocco, EPS 2015, for a recent review

Why Study Heavy Quarks

- Large masses ($m_c \approx 1.5$ GeV, $m_b \approx 5$ GeV): $Q > 2\ m_Q$
  - Even at low p_{T}, produced at early stage of collision.
  - Represent tag for quark energy loss
  - Study possible mass effects (“dead cone”) for $p_T = \mathcal{O}(m_Q)$
- Heavy Flavour not generated/destructed in medium
  - Study scattering and diffusion in QGP for $m_q \gg T$
  - Do heavy quarks participate in collective motion ?

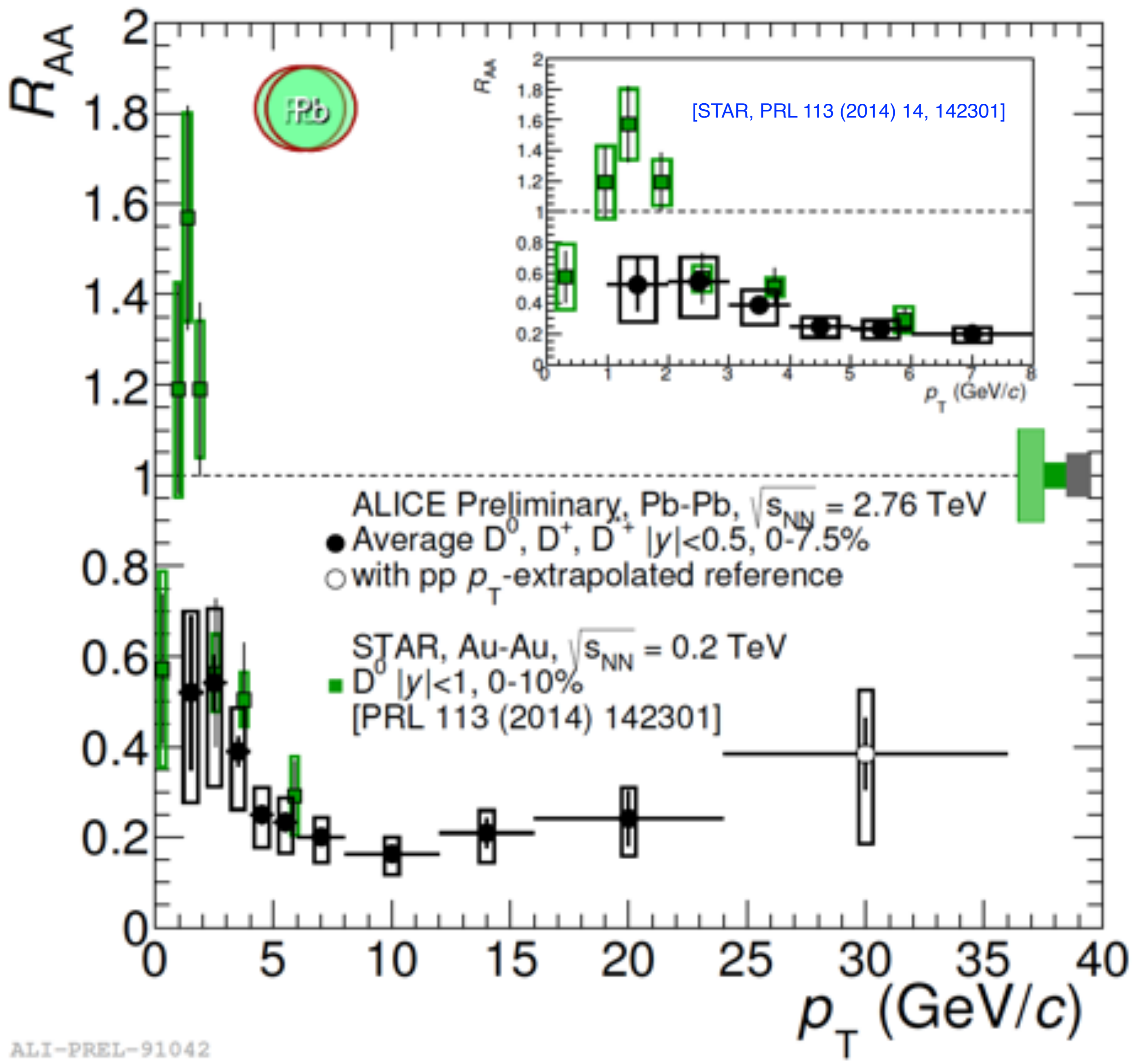


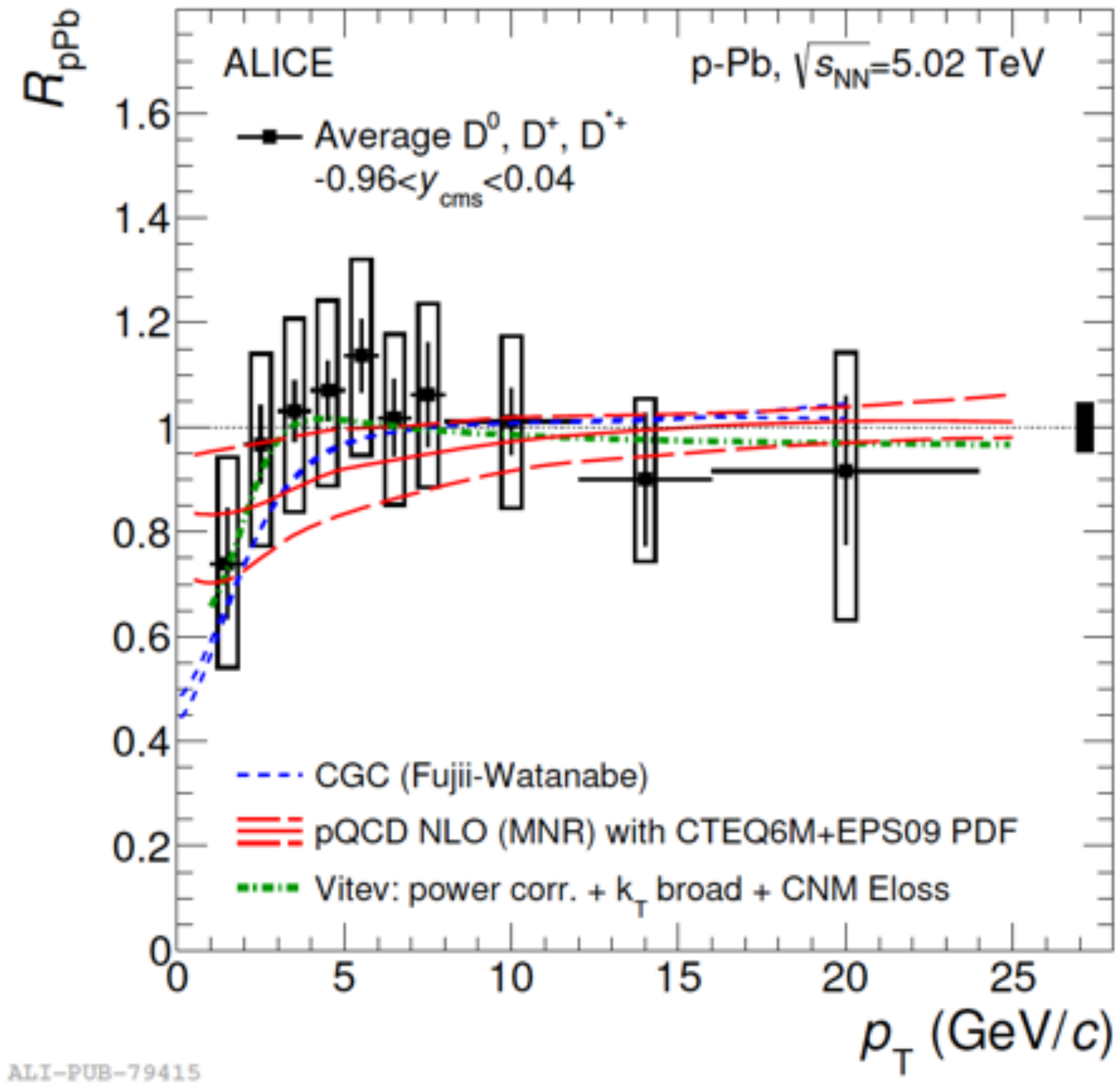
Embedded Brownian Motion Probe



D-Meson Suppression

see M. Kim
Fri parallel session

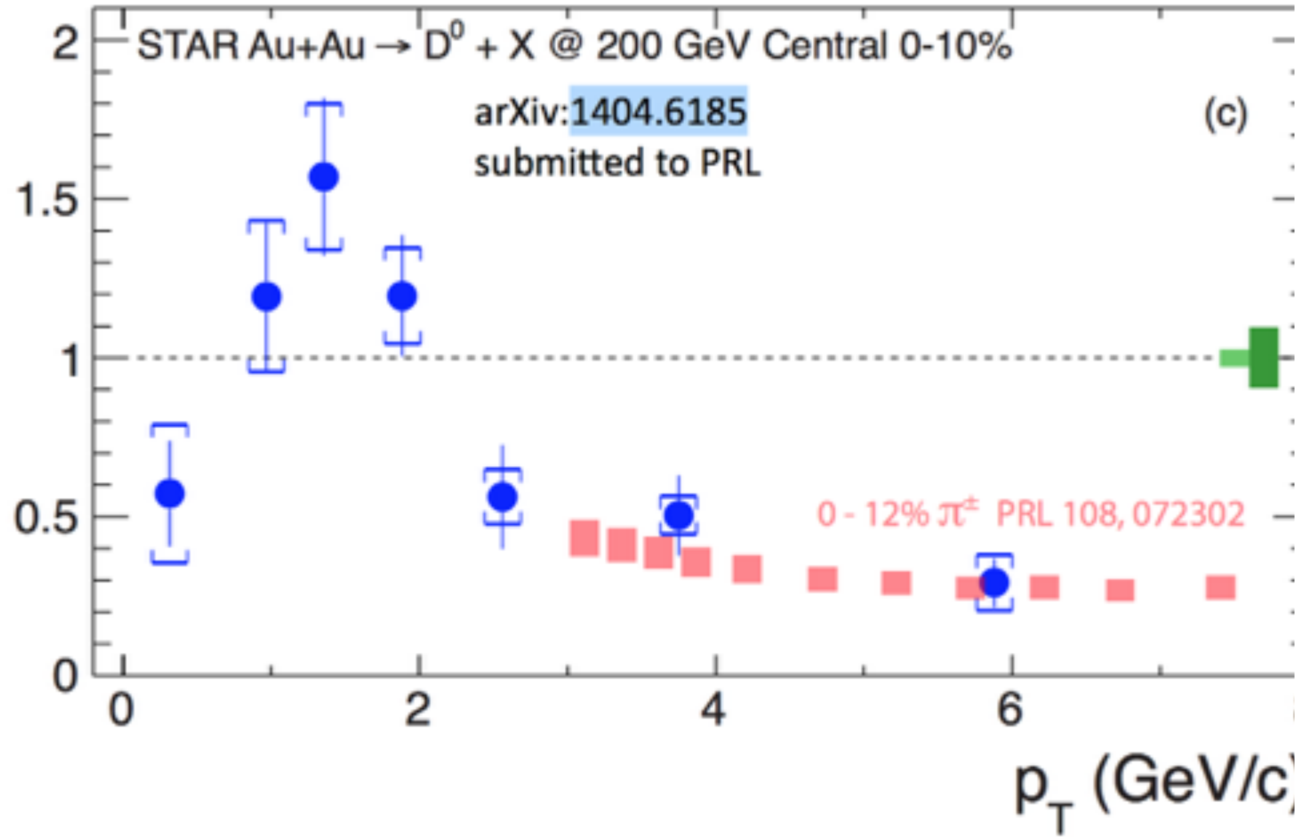




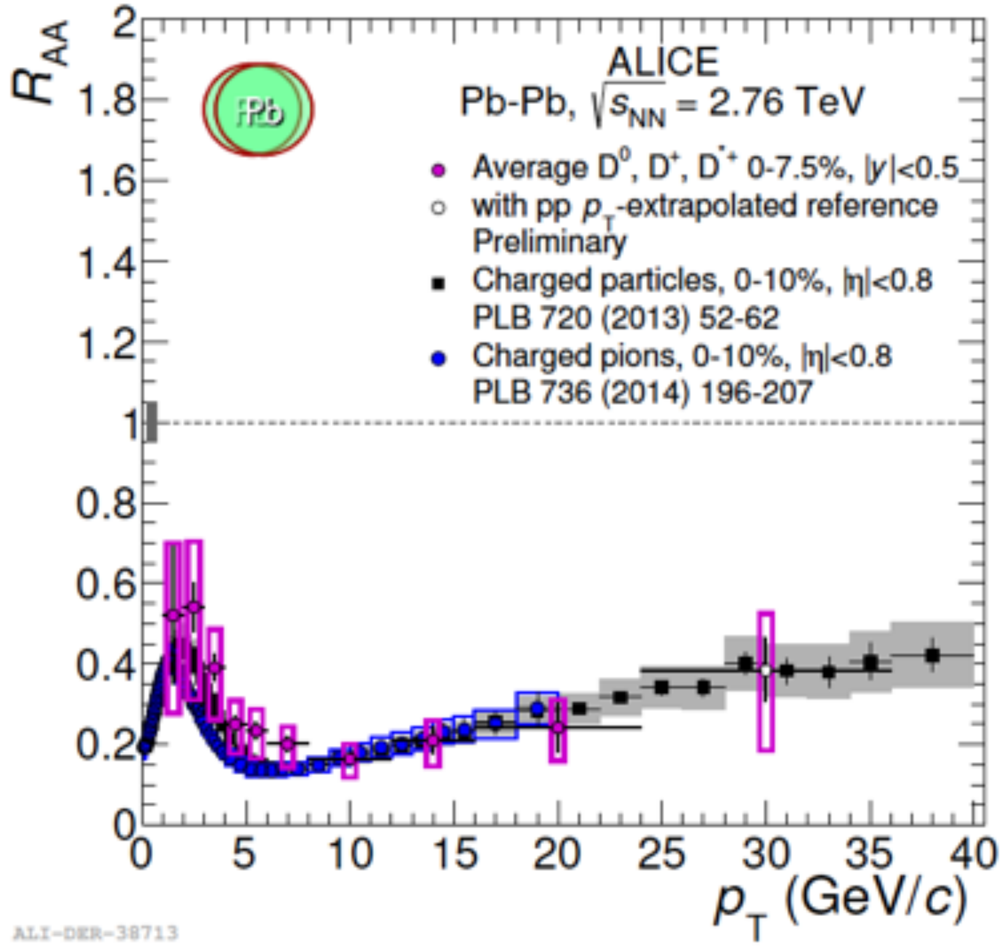
Suppression by factor ~ 5 at $p_T > 10$ GeV/c

No suppression in p-Pb
⇒ Suppression in Pb-Pb final state effect

D-Meson vs Inclusive Hadron Suppression



[STAR, PRL. 113 (2014) 14, 142301]

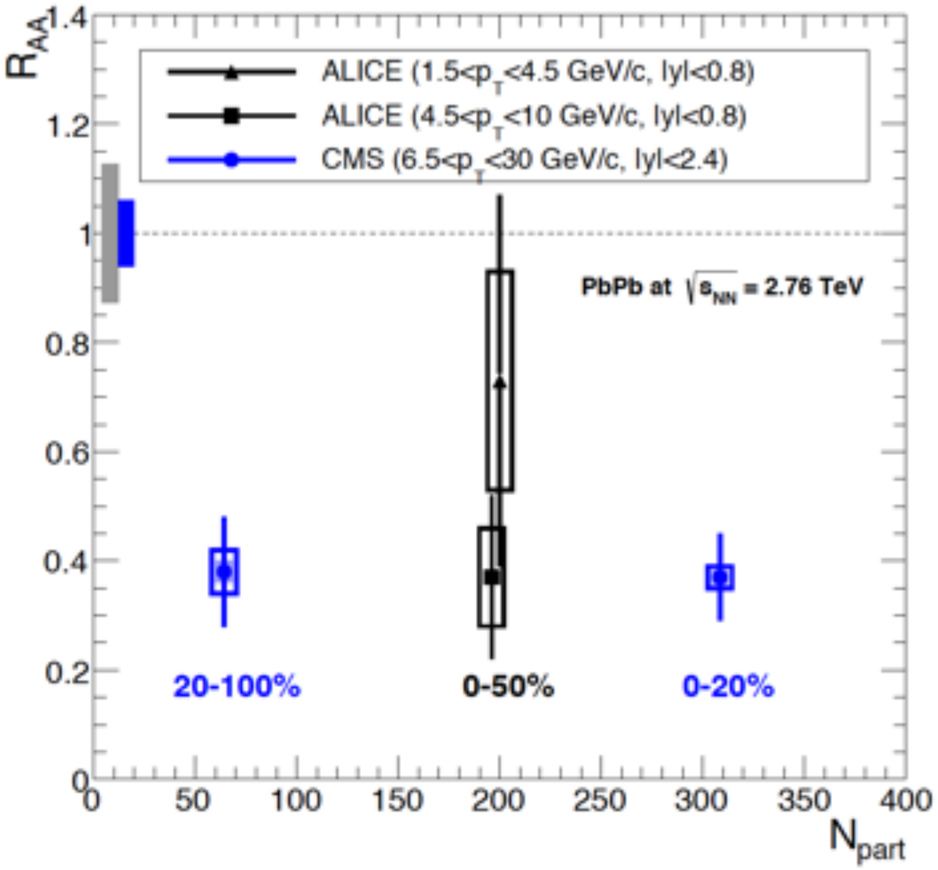


Inclusive hadron and charm suppression intriguingly similar
However, R_{AA} is sensitive to energy loss but also

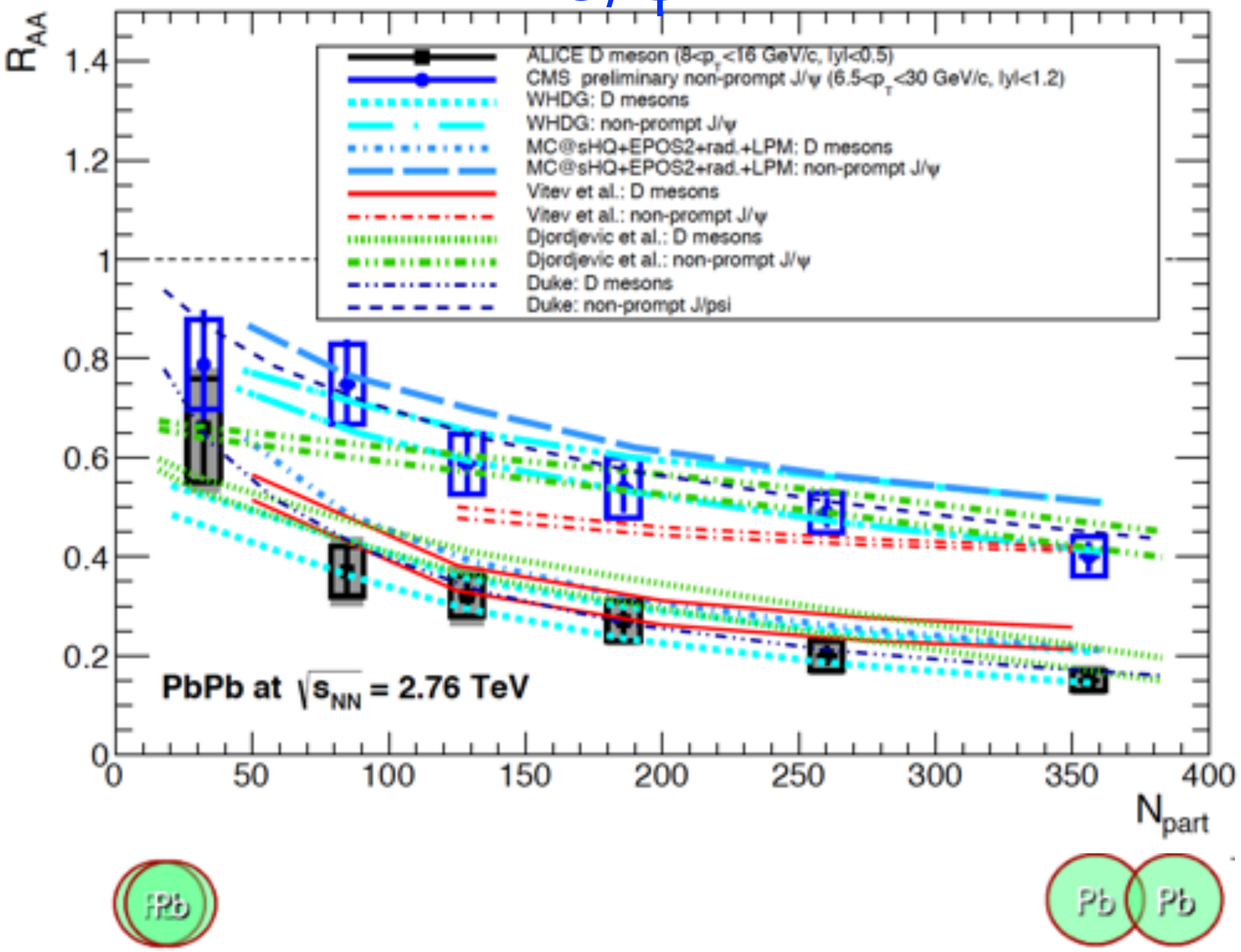
- steepness of spectrum
- fragmentation function

Beauty Meson Suppression

B→J/ψ X



B→J/ψ X



[CMS, PRL 113 (2014) 13, 132301. ALICE, arXiv:1504.07151]

Dokshitzer and Kharzeev (PLB519(01)199)

Dead Cone Effect (suppressed radiation at small angle)

$$\omega\frac{dI^{m>0}_{\text{medium}}}{d\omega} = \omega\frac{dI^{m=0}_{\text{medium}}}{d\omega}\left[\frac{k_\perp^2}{k_\perp^2+\left(\frac{m\omega}{E}\right)^2}\right]$$

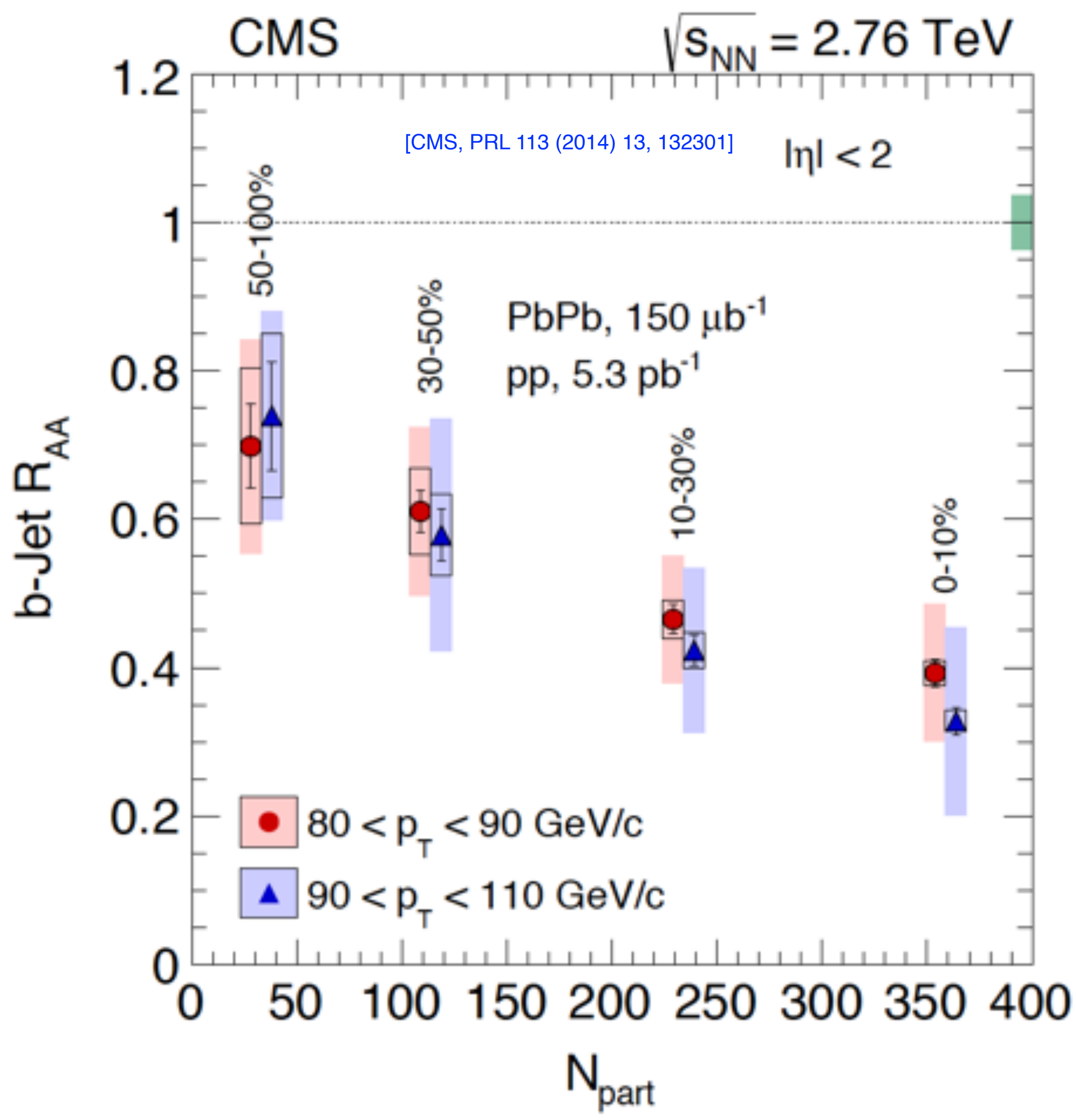
radiated gluon: ω, $k_\perp$

quark : E

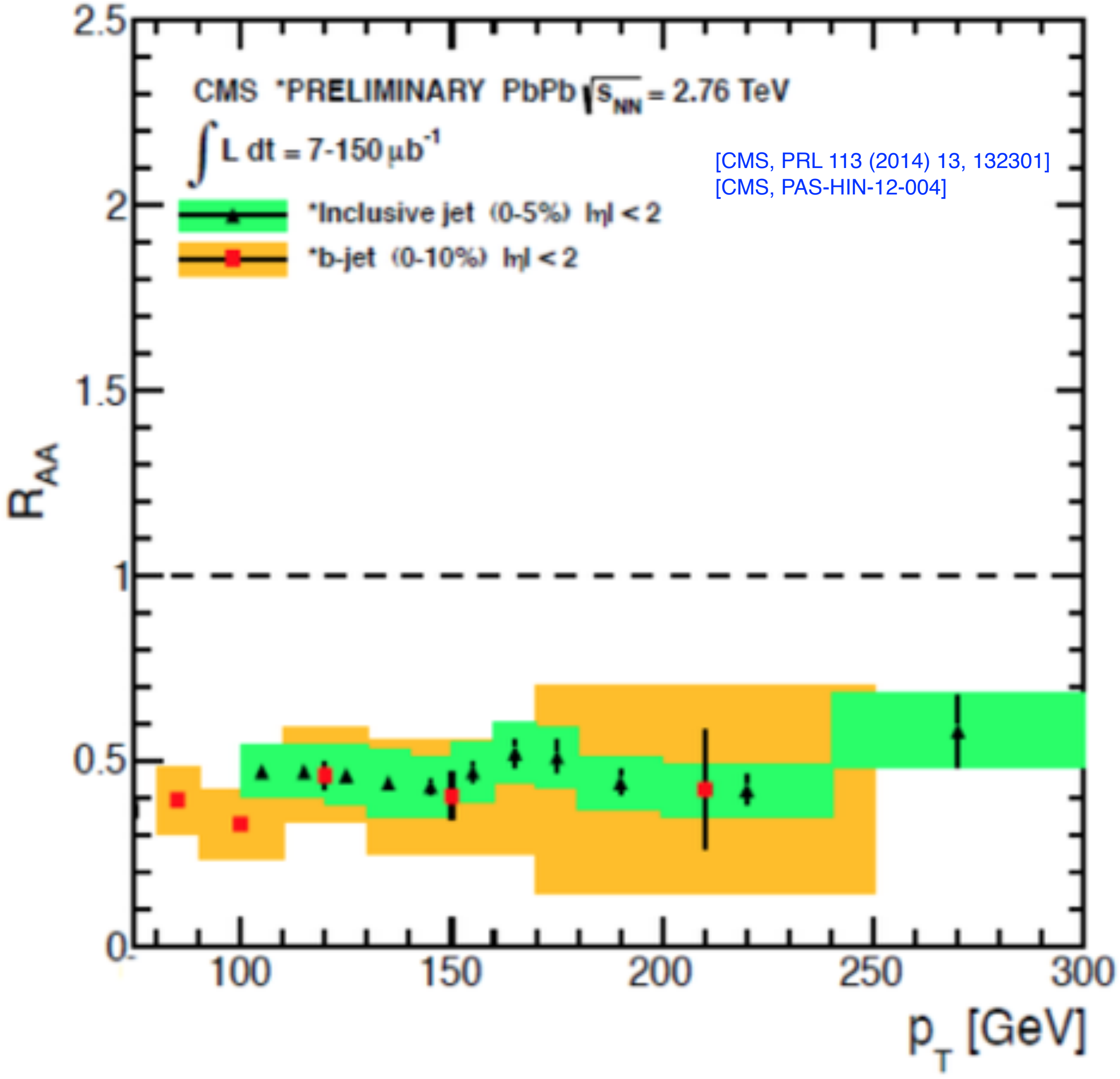
Comparison of charm and beauty suppression at similar $\langle p_T \rangle \approx 10$ GeV/c

R_{AA}(beauty) > R_{AA}(charm)
well described by models including
mass dependent energy loss.

B-Jet Suppression



[CMS, PRL 113 (2014) 13, 132301]

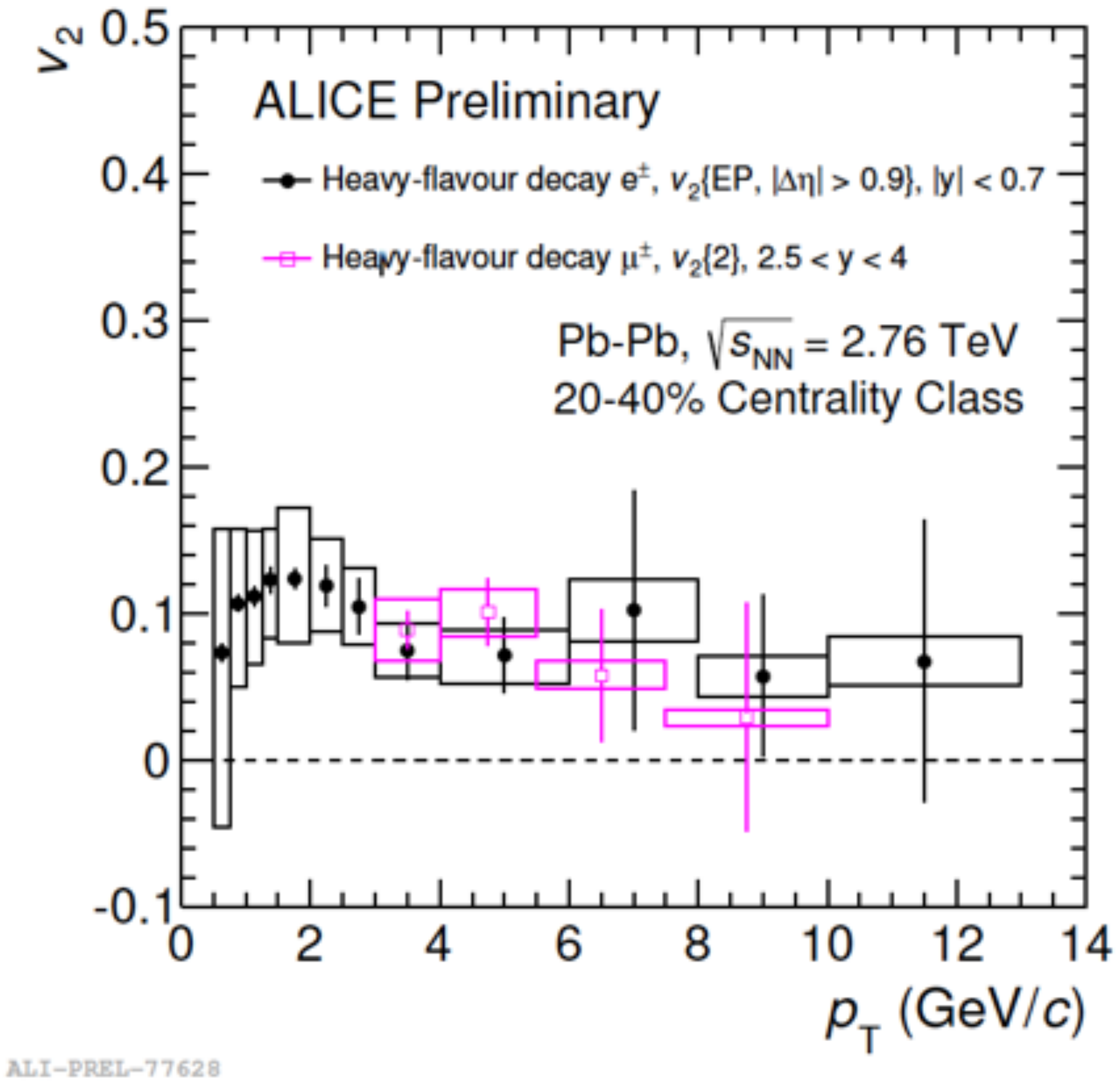


[CMS, PRL 113 (2014) 13, 132301]
[CMS, PAS-HIN-12-004]

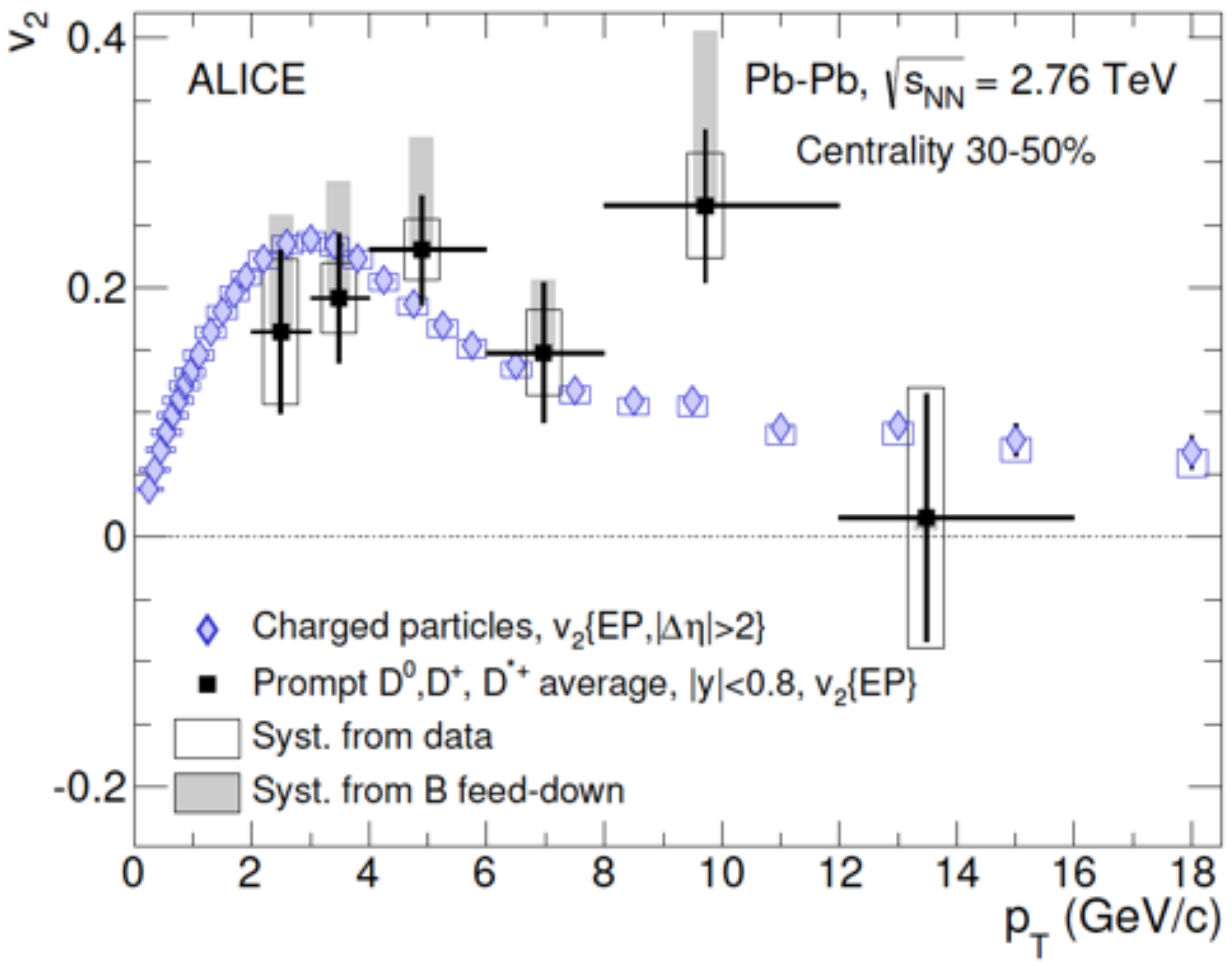
- Significant centrality dependent suppression at high p_T
- R_{AA}(b-jet) ≈ R_{AA}(incl. jet)
- mass effect vanishes for $p_T \gg m_b$

Heavy Flavour Elliptic Flow

Leptons from semi-leptonic
c(b) - hadron decays



D-mesons

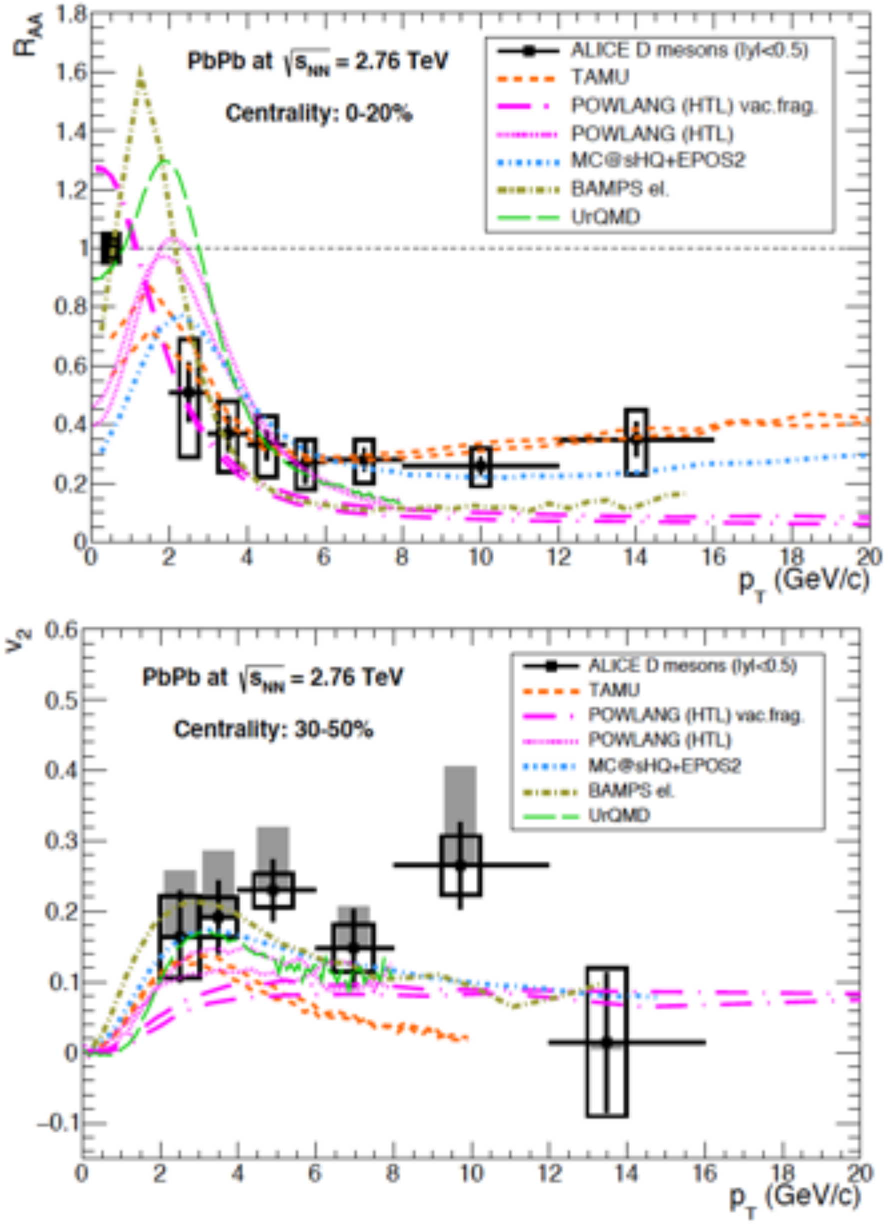


Positive v_2 compatible with charged hadrons at mid and forward-rapidities

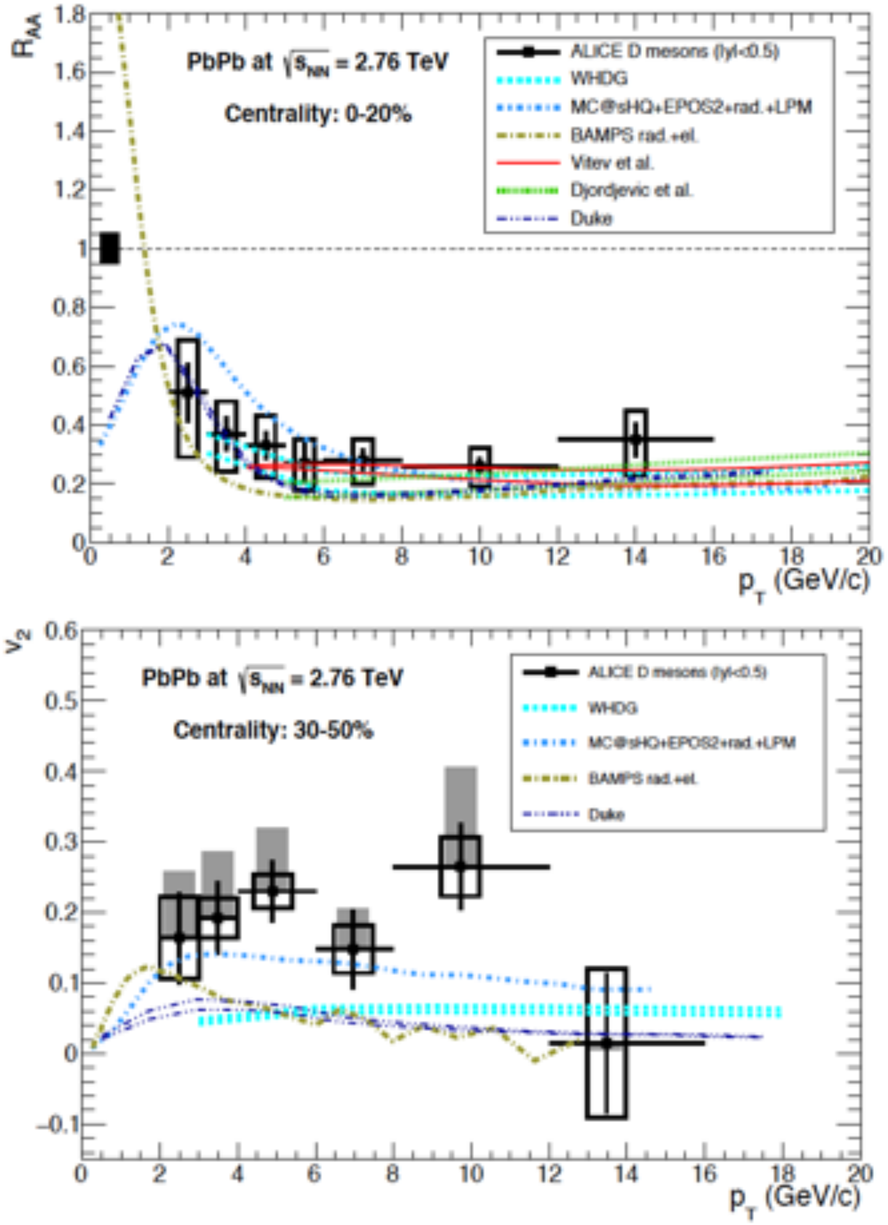
- heavy quarks participate in collective motion ?
- coalescence with flowing light quarks ?

Model Comparisons

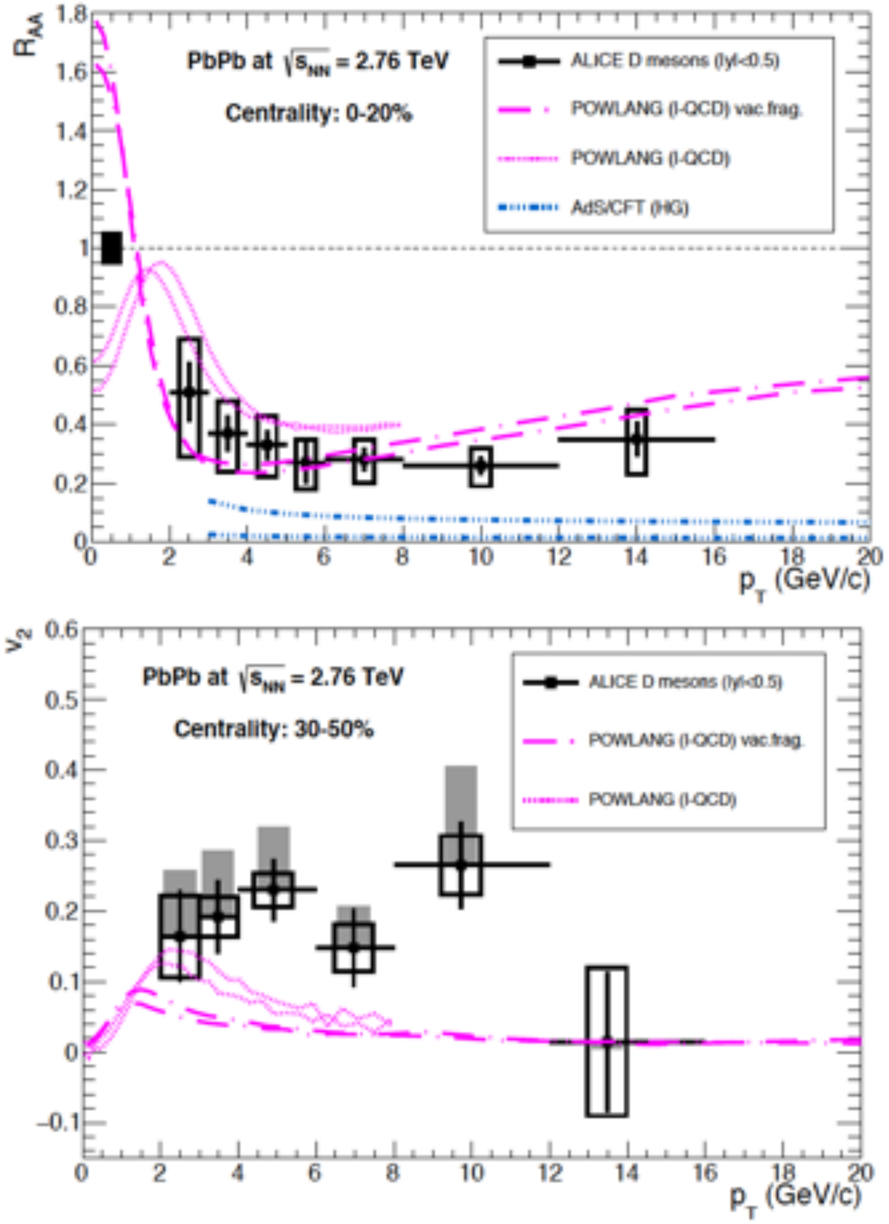
Coll.



Rad.+Coll.

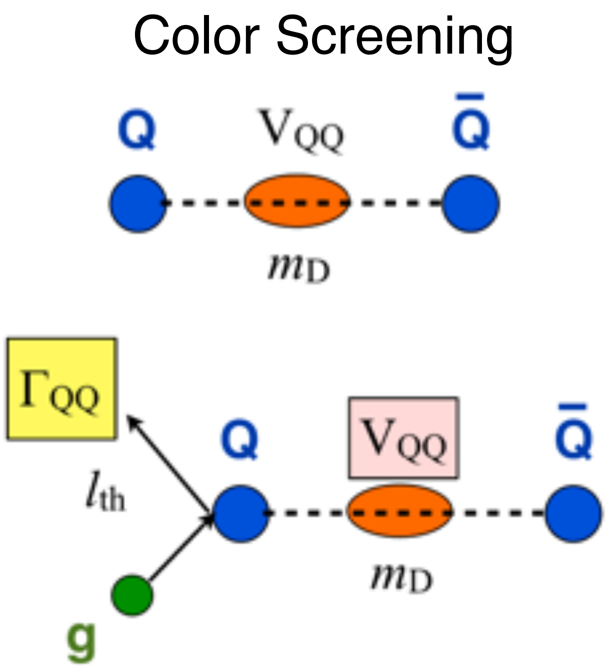


Other



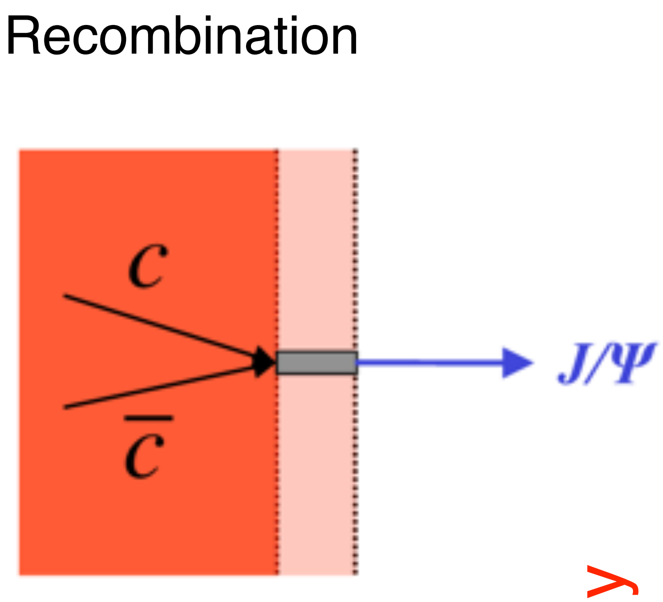
In general, models that give a good description of R_{AA} fail for v_2 and vice versa.

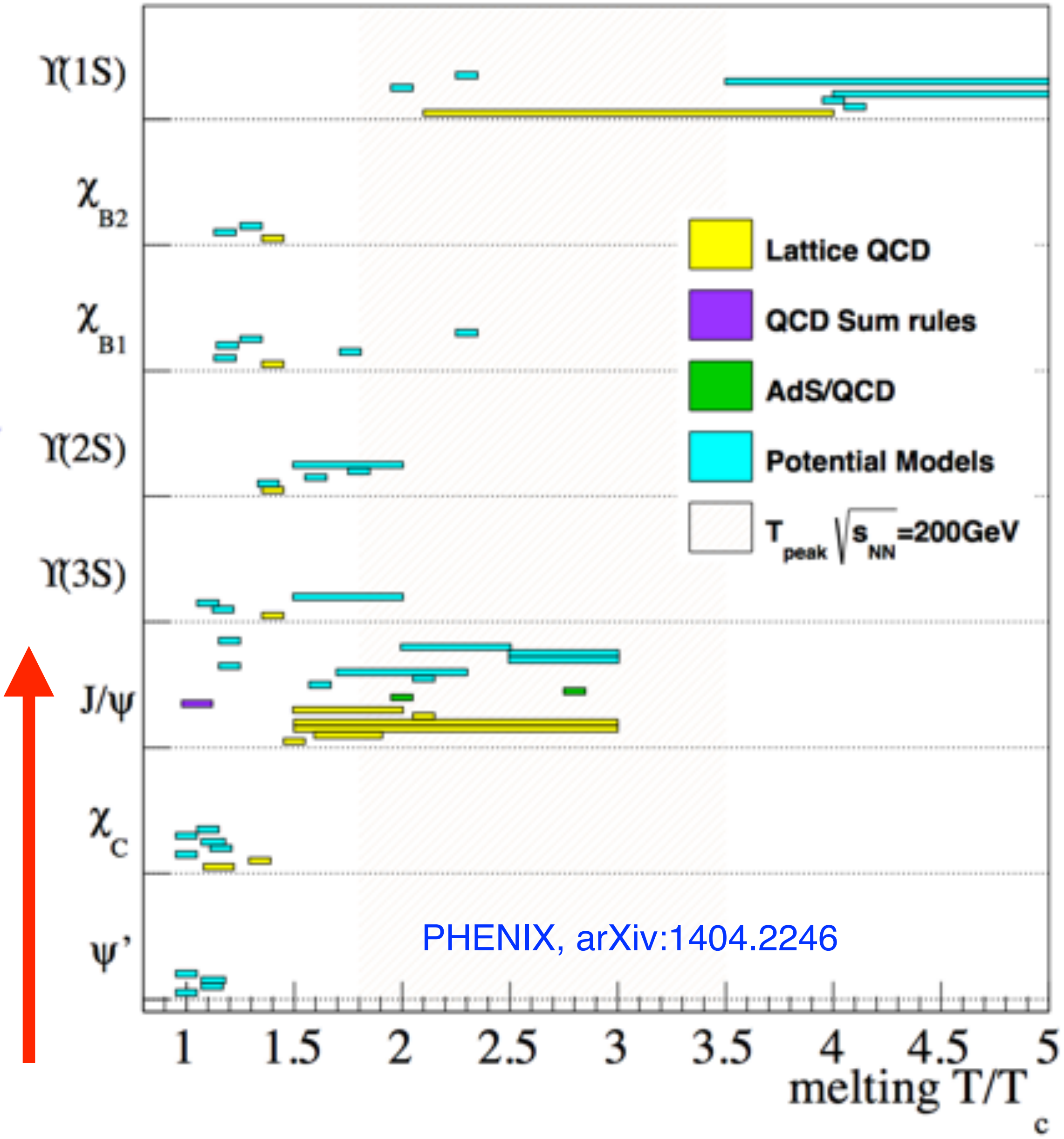
Heavy Quarkonia



Ionisation by thermal gluons

Illustration B. Müller, Phys. Scr. T158 (2013) 014004





PHENIX, arXiv:1404.2246

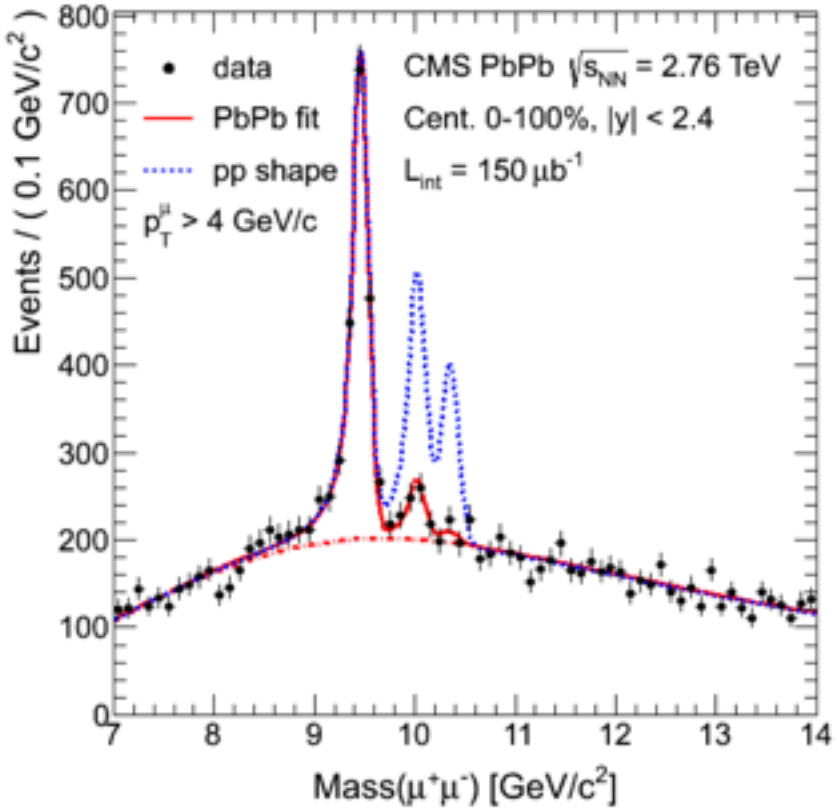
Binding Energy

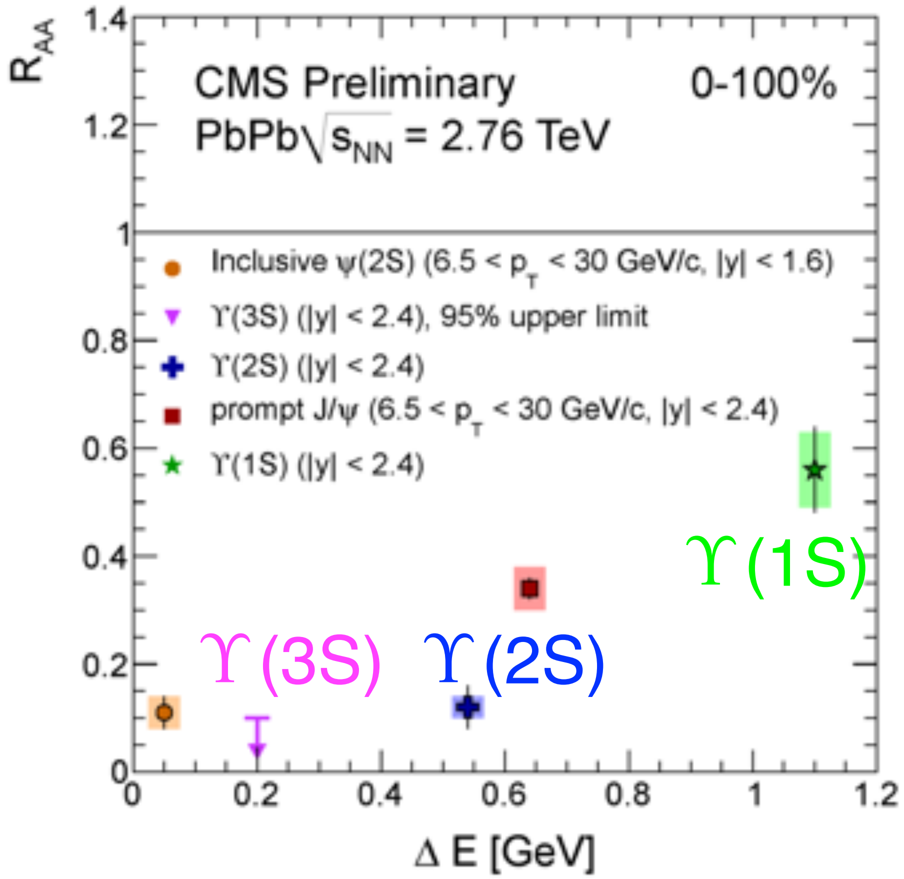
- Quarkonia are sensitive to distance at which colour charge screened ($1/m_D$)

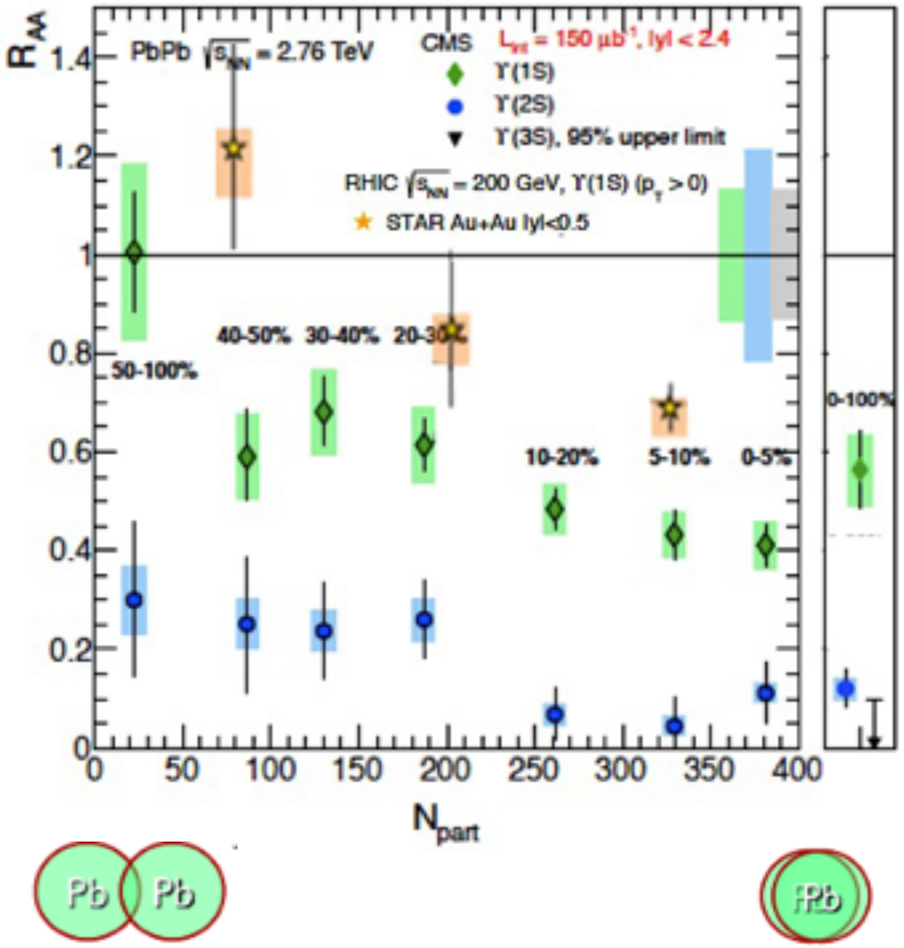
- “melting” if quarkonia radius larger than screening length
  - radii of quarkonia states vary from 0.1 -1 fm
  - ⇒ sequential melting

  - determination of temperature dependent screening length
- Caveat other “dynamic” mechanisms
  - ionisation by thermal gluons, recombination, coherent energy loss, …

Bottomonia Suppression







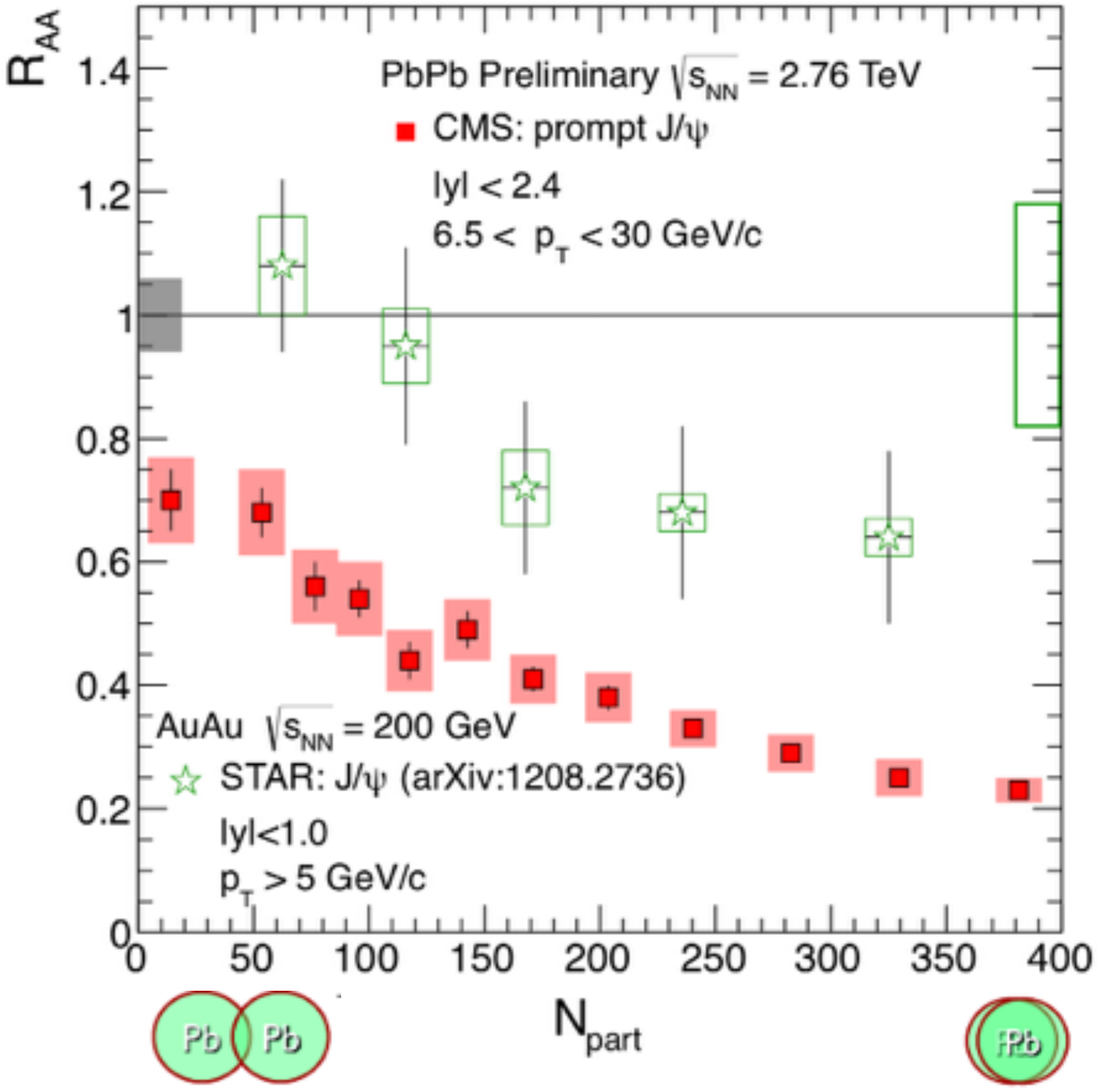
Sequential suppression with binding energy and Temperature

$R_{AA}(\Upsilon(3S))_{LHC} < R_{AA}(\Upsilon(2S))_{LHC} < R_{AA}(\Upsilon(1S))_{LHC} < R_{AA}(\Upsilon(1S))_{RHIC}$ ✔

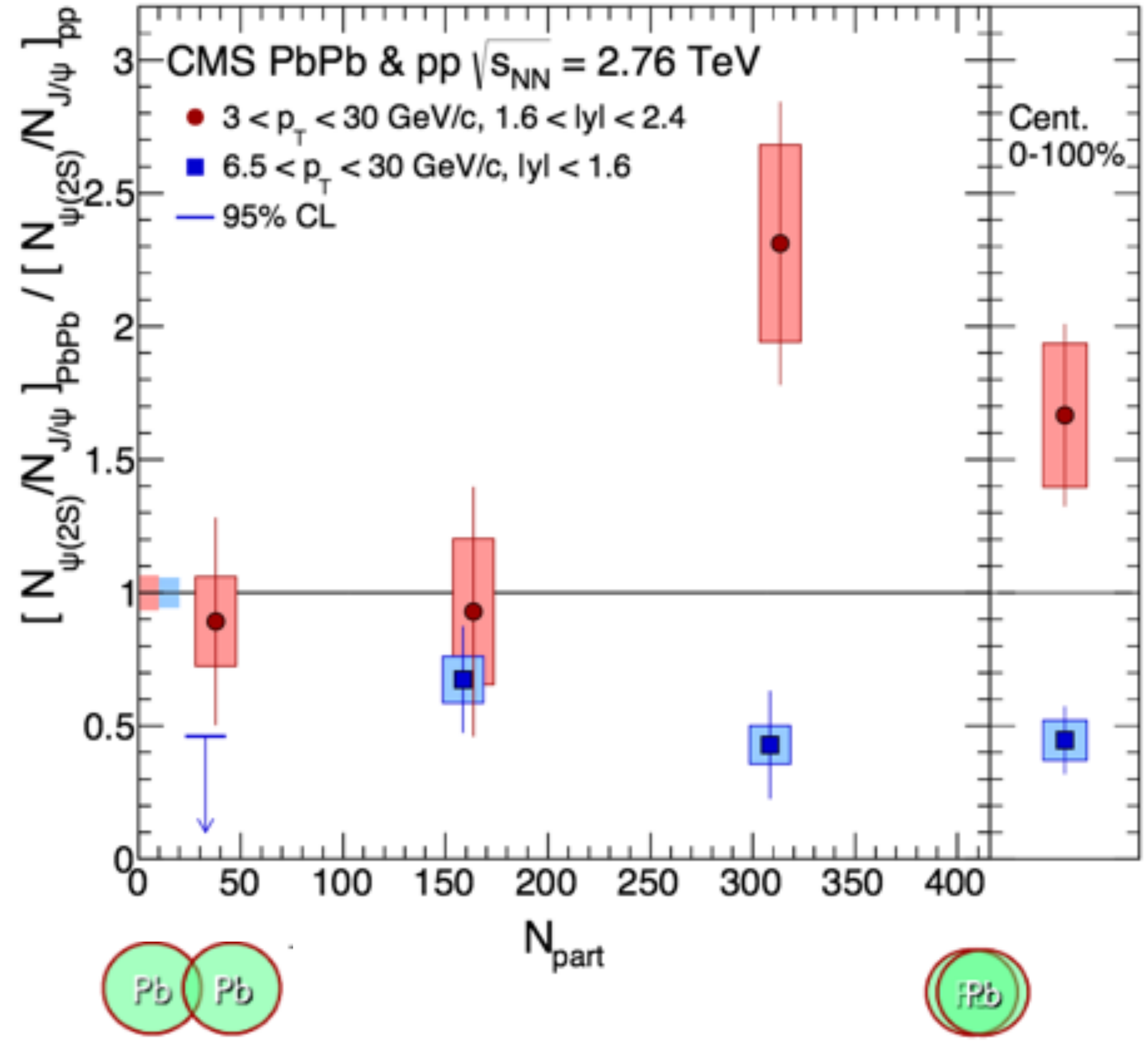
High-p_T Charmonium Suppression

see J. Kamin
Tue parallel session

$p_T > 6.5$ GeV



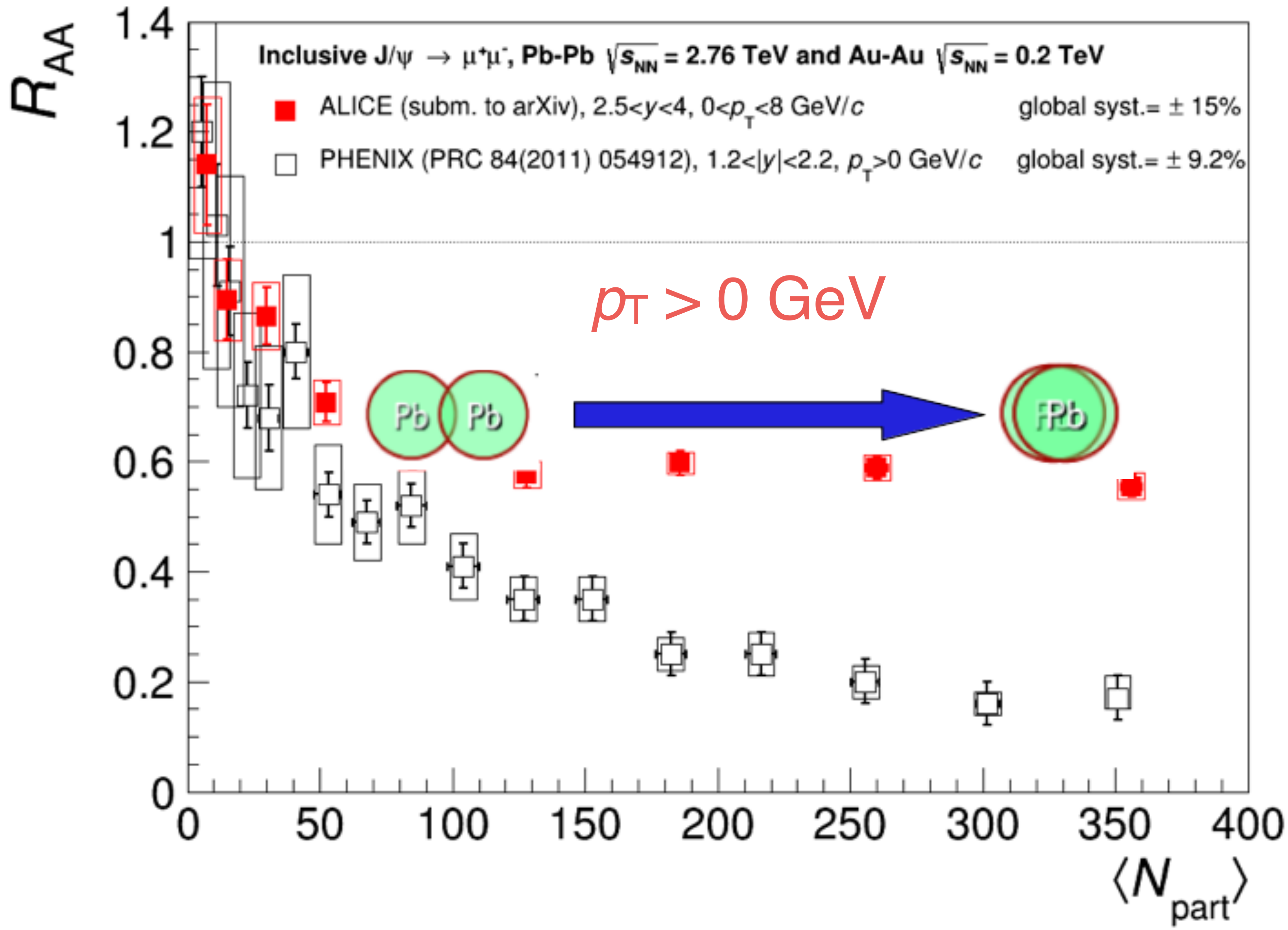
$p_T > 6.5$ GeV



Sequential suppression

$R_{AA}(\psi(2S))_{LHC} < R_{AA}(J/\psi)_{LHC} < R_{AA}(J/\psi)_{RHIC}$ ✔

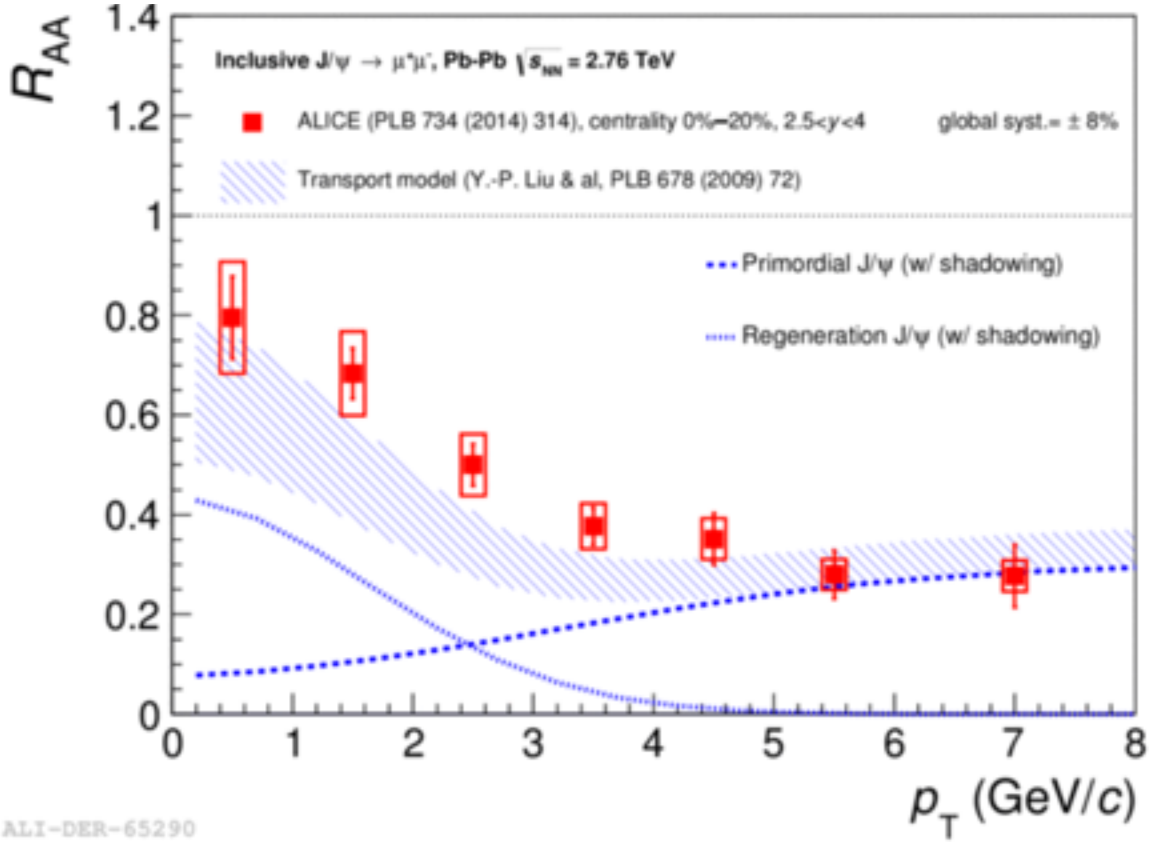
Inclusive J/ψ Suppression (low-p_T)

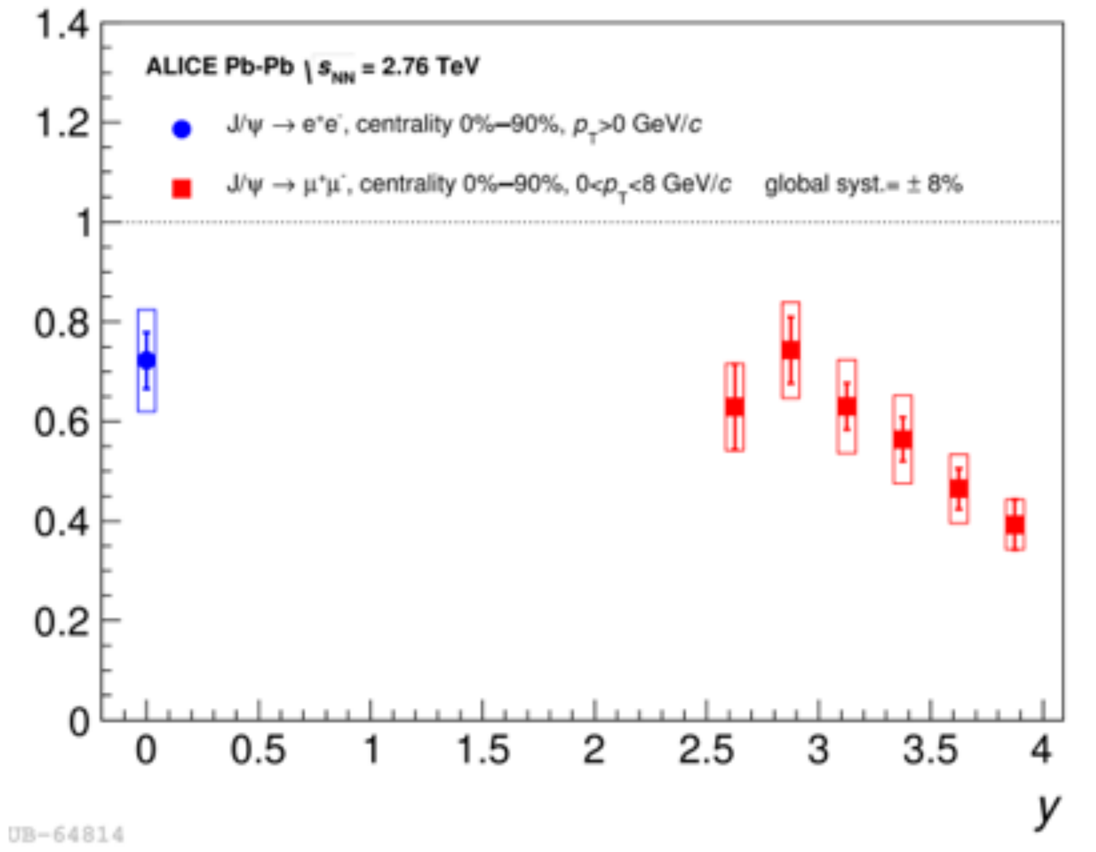


$p_T > 0$ GeV

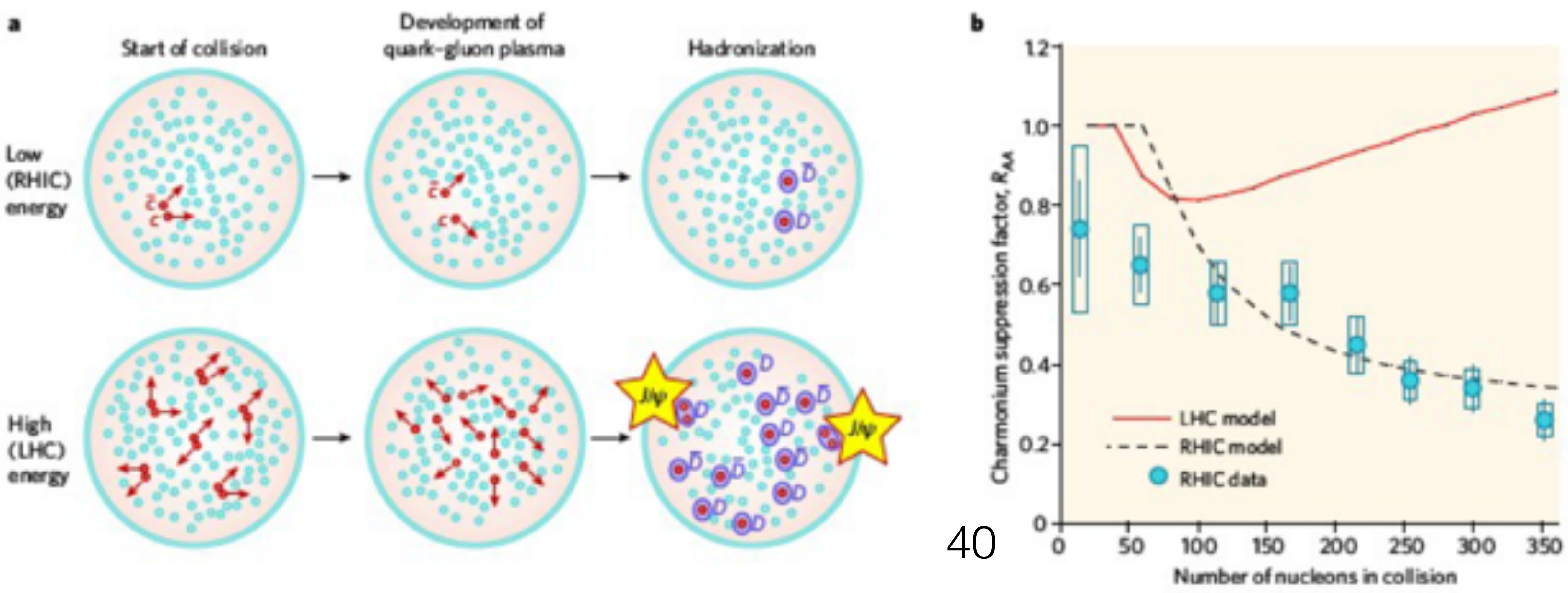
R_{AA}(J/ψ) larger (= less suppression) at LHC than at RHIC in comparable kinematic region.

Charmonium Suppression



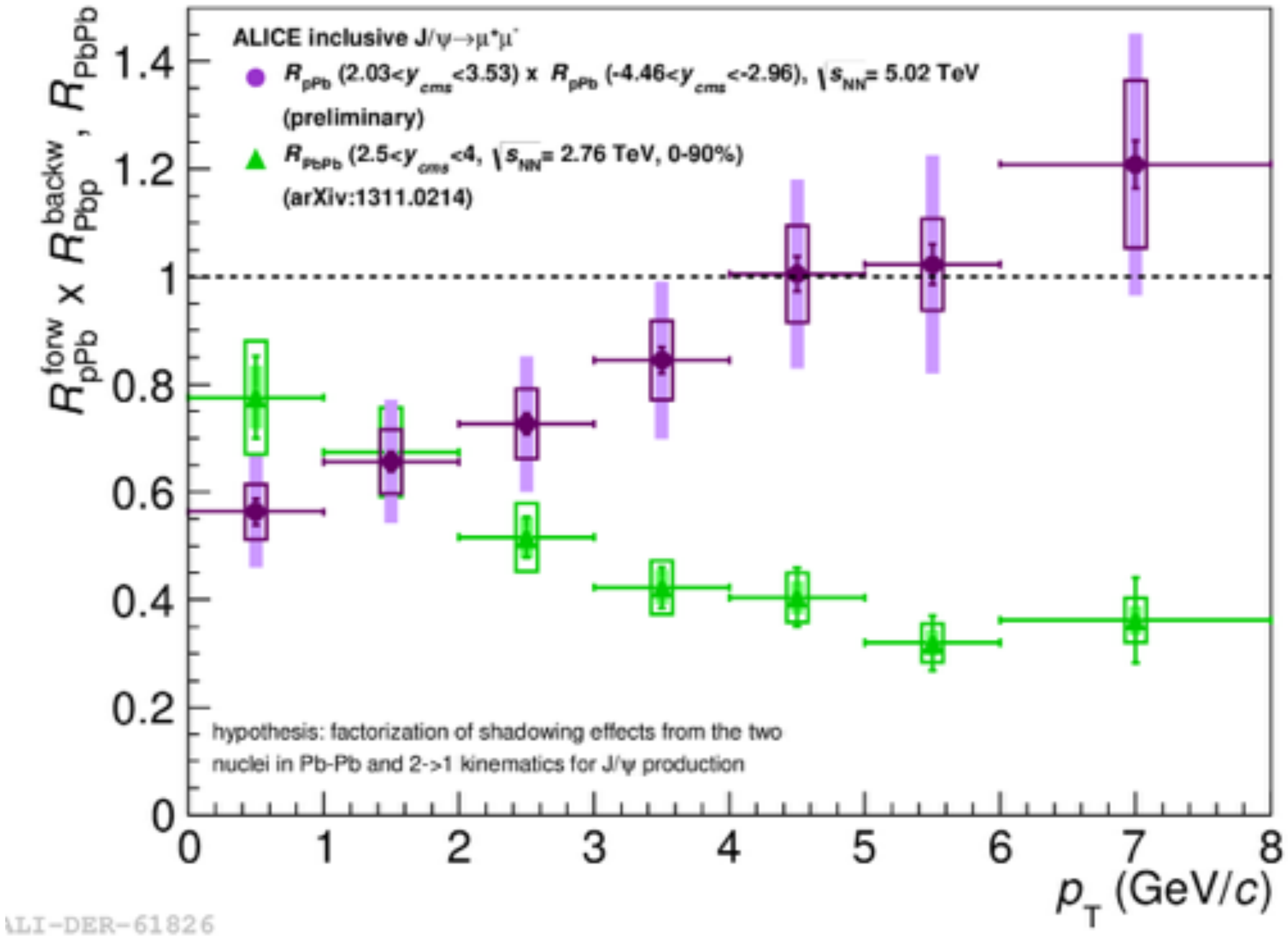


Suppression reduced where charm density is high:
low-p_T, mid-rapidity, central collisions

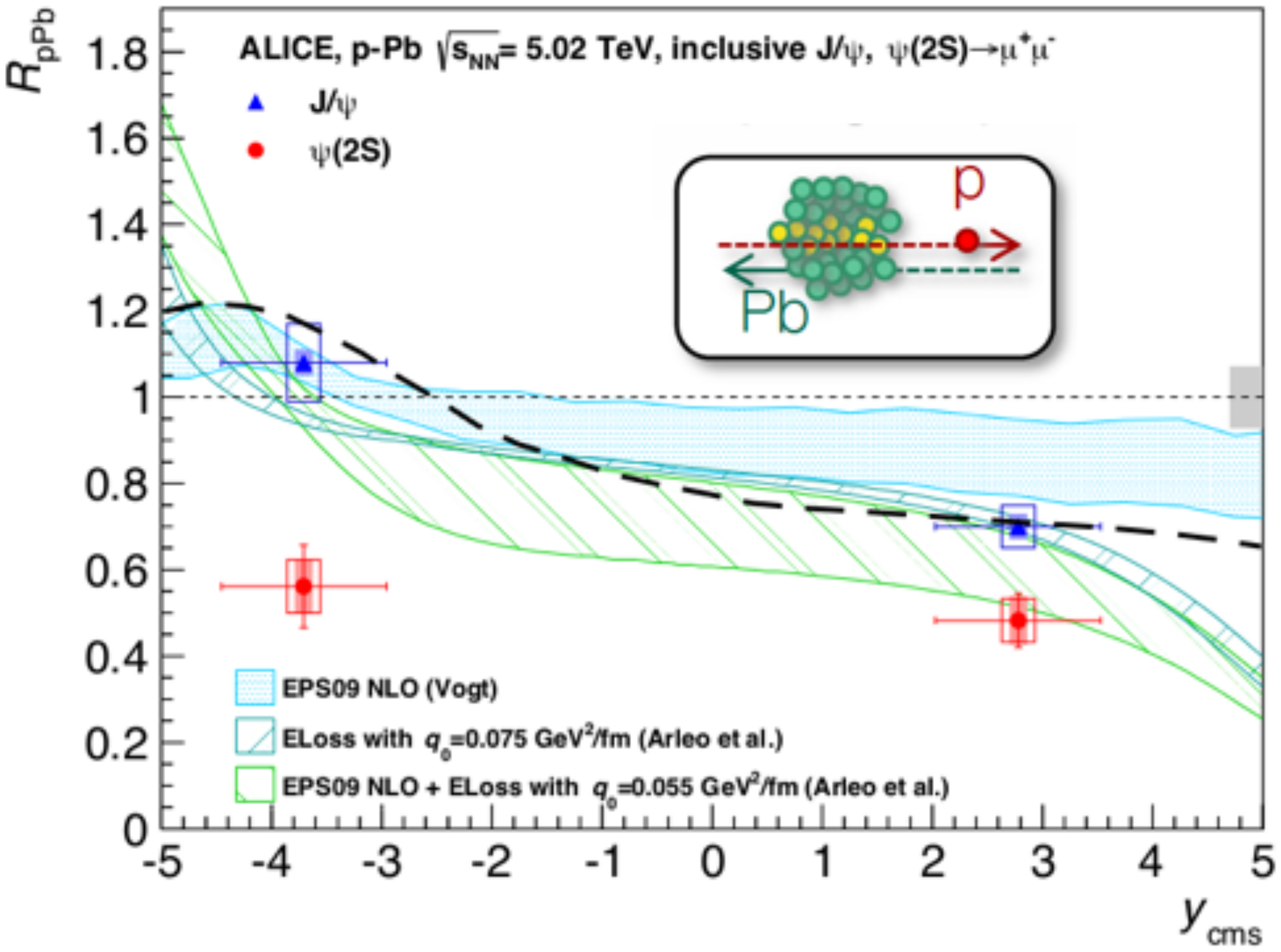


Regeneration ?

p-Pb Reference



Suppression at high-p_T observed in Pb-Pb
final state effect



For cold nuclear effects:

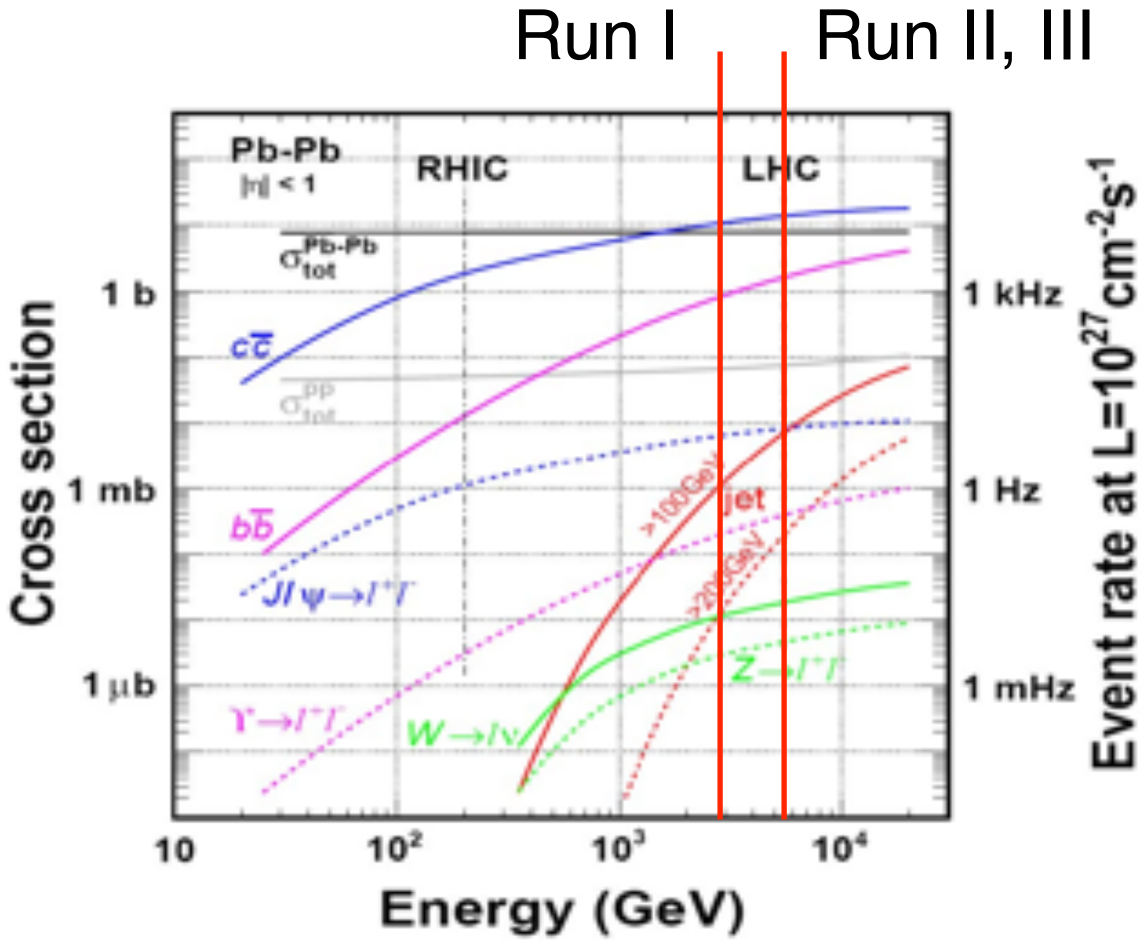
$R_{pA}(\psi(2S)) \approx R_{pA}(J/\psi(2S))$

Observed:

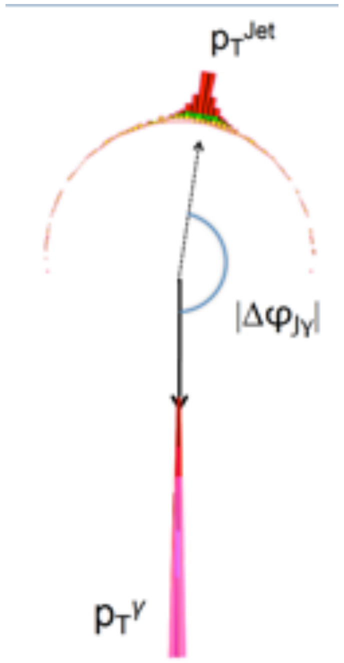
$R_{pA}(\psi(2S)) < R_{pA}(J/\psi(2S))$

Run II Outlook

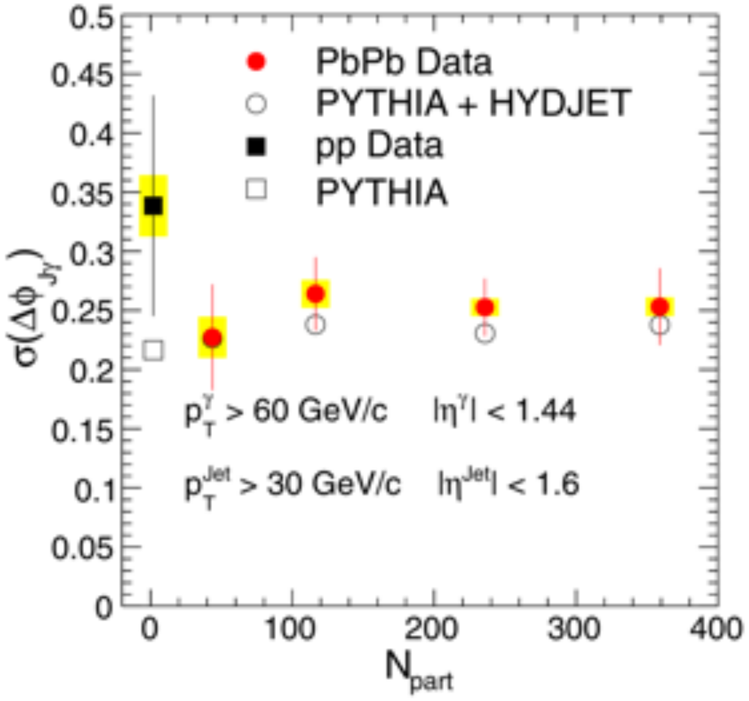
- $\sqrt{s_{NN}}$ = 5.1 TeV
- hard cross-sections
  - Jets x 5
  - bbbar, electroweak x 2
- Integrated Luminosity x 5
- Physics Prospects
  - first Z-jet Correlations
  - Multi-Jet Correlations
  - γ-Jet Imbalance
  - Improved h-Jet Correlations
  - Improves Jet Shape Modifications
  - Improved measurements of Quarkonia suppression patterns



$$\langle \Delta q_T^2 \rangle = \int dy\, \hat{q}(y,E)$$

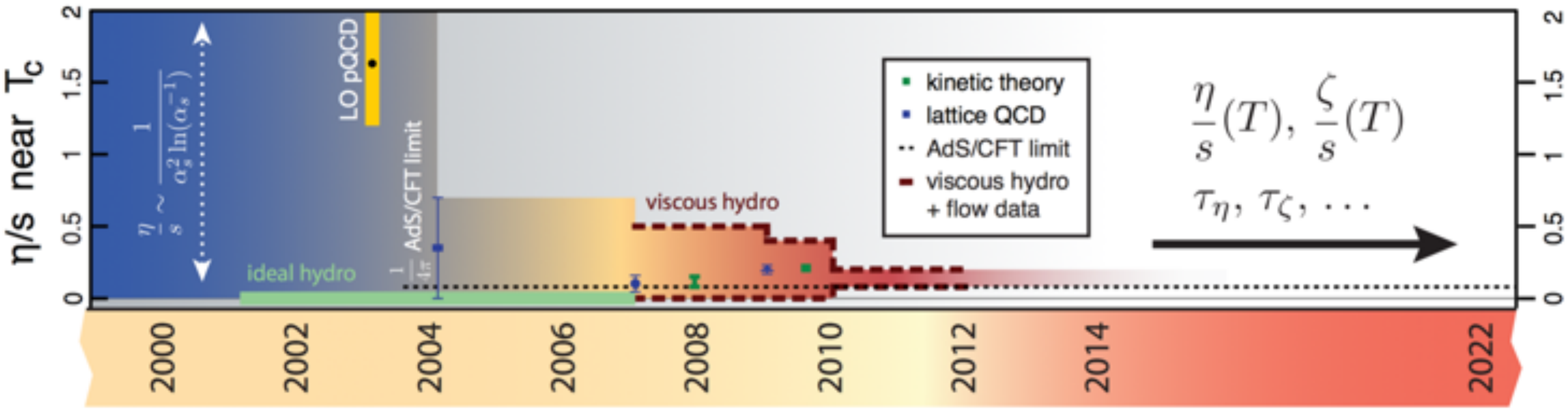


γ-Jet Decorrelation



Outlook II

- Improved Measurements of flow
  - D mesons
  - Quarkonia
  - Photons
- Probe earlier QGP dynamics
- Larger sensitivity to temperature dependence of *η/s*



Hot & Dense QCD White Paper", solicited by the NSAC subcommittee on Nuclear Physics funding in the US. Available at http://www.bnl.gov/npp/docs/Bass_RHI_WP_final.pdf

pp and p-Pb reference runs at the Pb-Pb energy are essential for the interpretation of heavy ion data !