From Heavy-Ion Collisions to Quark-Gluon matter

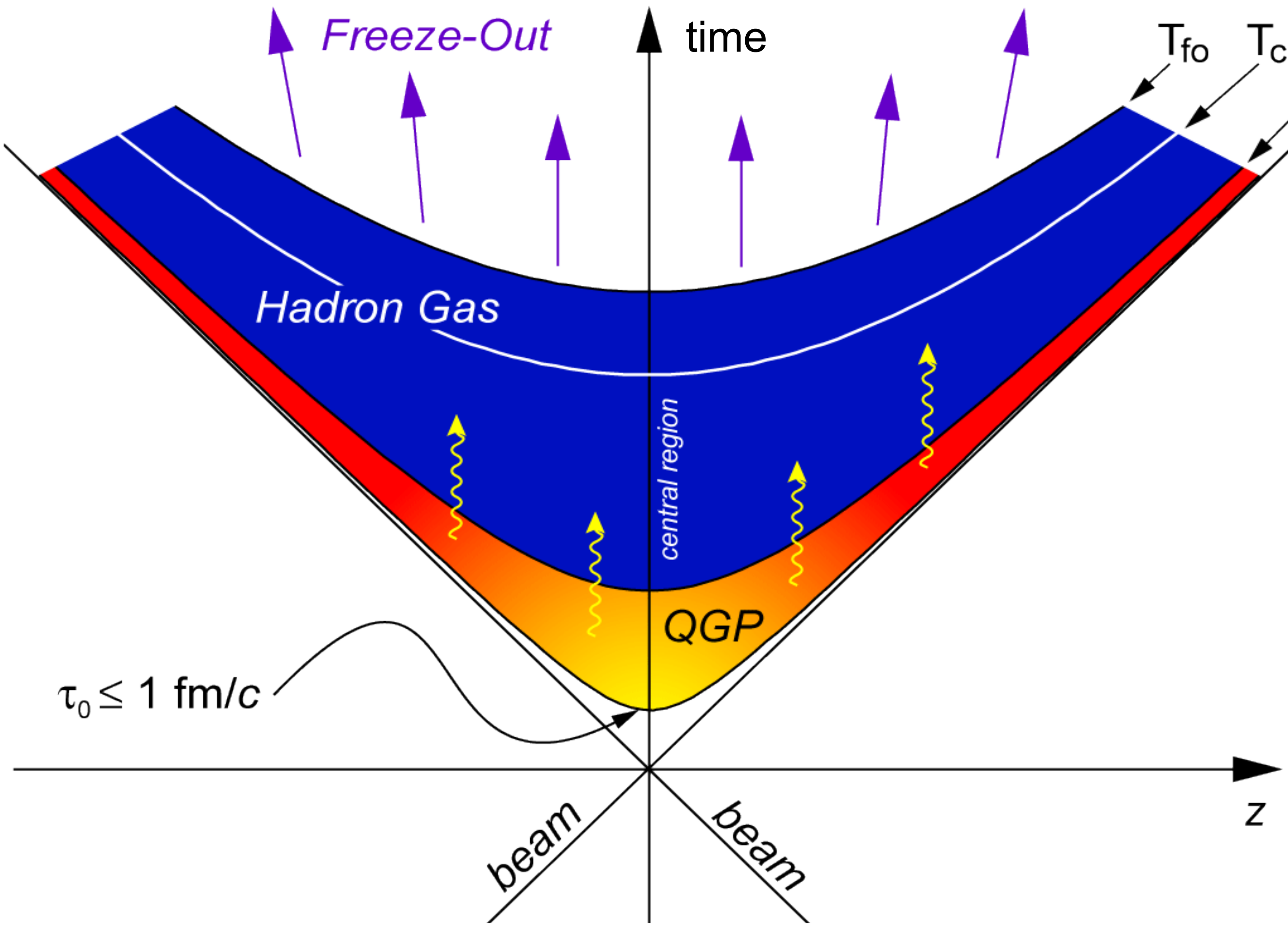
Constantin Loizides
(LBNL)

- Part I: Introduction and background
- Part II: Results mainly related to bulk properties
- Part III: Results mainly related to hard probes

CERN summer student programme 2016

What quantities to measure?

(Recap part II)



Observables

Multiplicity
HBT
Particle yields
Particle spectra

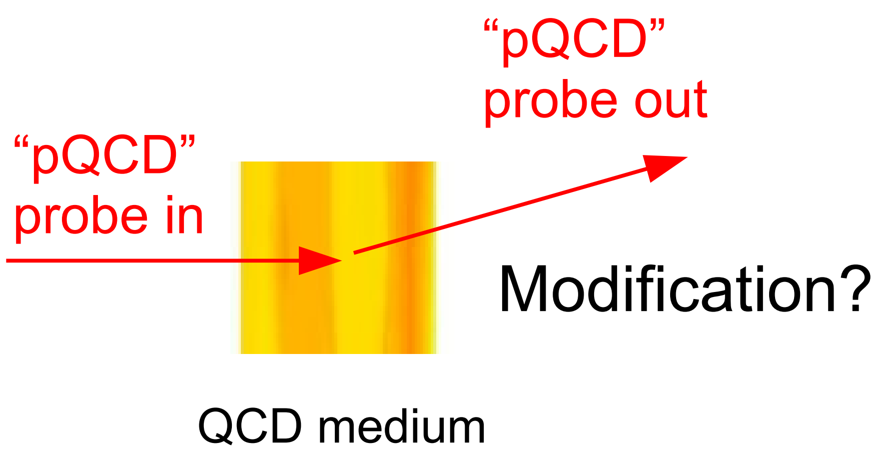
Transverse flow
Thermal photons

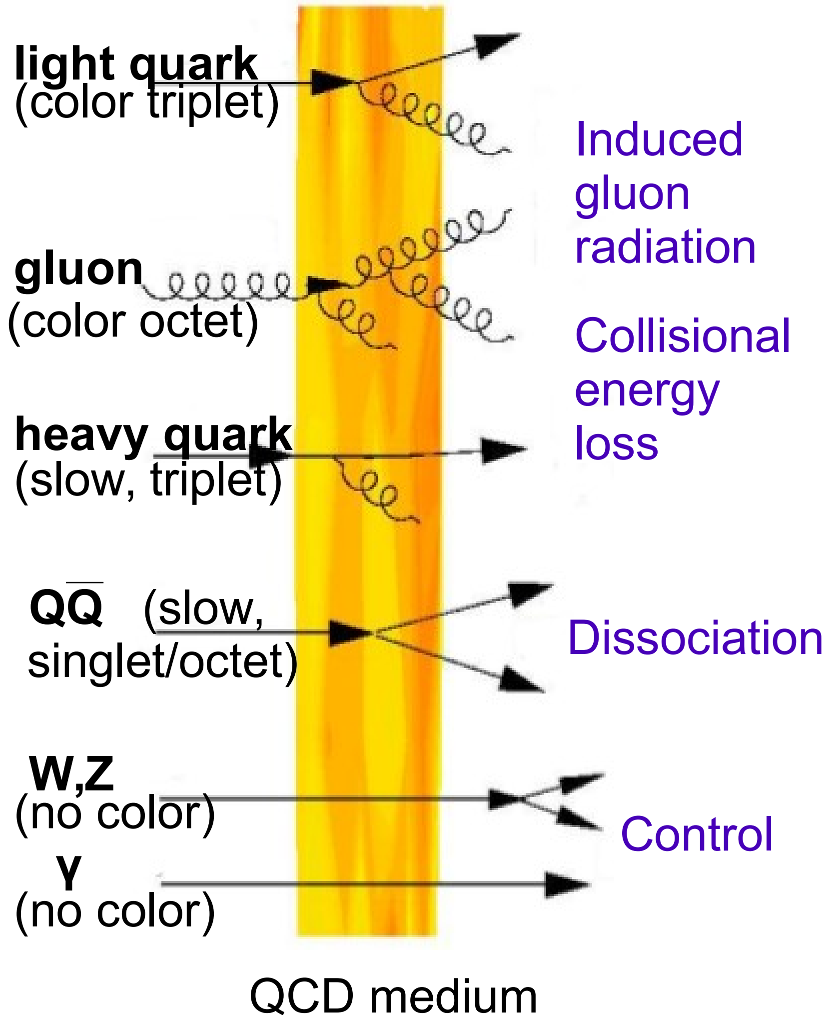
Hard probes
(jets, heavy flavor,
EW bosons)

Experimental approach is to study various observables with different sensitivity to the different stages of the collision

Tomography of QCD matter

- Hard (large Q^2) probes of QCD matter:
  jets, heavy-quark, $Q\bar{Q}$, γ, W, Z
    - Measurable in pp/pA
      and/or calculable in pQCD
- "Self-generated" in the collision
  at proper time $\tau \approx 1/Q^2 << 0.1$ fm/c
- "Tomographic" probes of hottest
  and densest phase of medium





Hard processes in pp

Hard processes in pp

In pp collisions, the following factorized approach in pQCD is used:

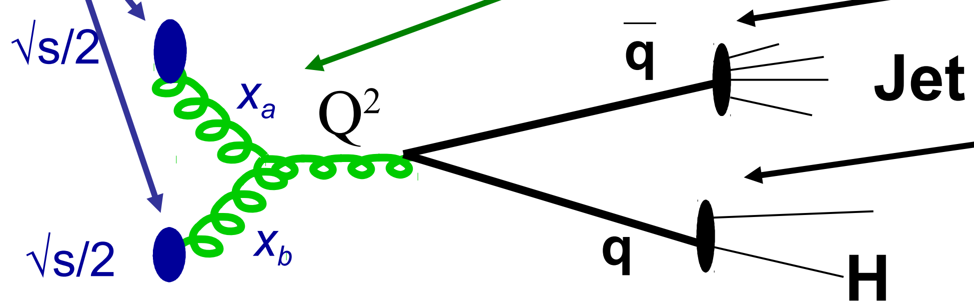
$$\sigma_{pp\to Hx} = PDF(x_a,Q^2)\,PDF(x_b,Q^2)\otimes\sigma_{ab\to q\bar{q}}\otimes D_{q\to H}(z_q,Q^2)$$

Cross section for hadronic collisions (pp)

Parton Distribution Functions
x_a, x_b are momentum fractions of partons in hadrons a,b

Partonic cross section

Fragmentation of quark q into hadron H



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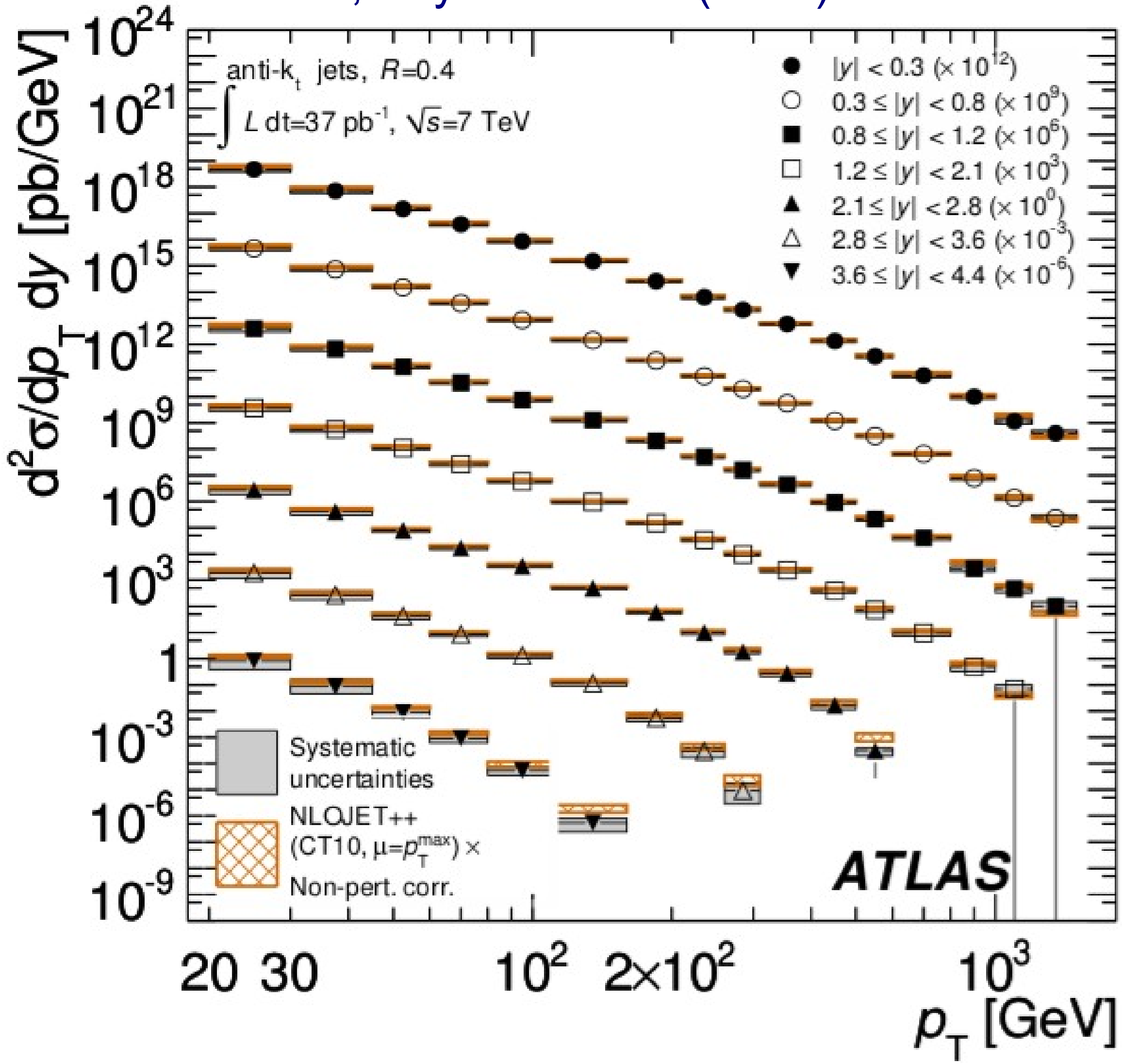
ATLAS, Phys.Rev. D86 (2012) 014022



Successfully describing data over many orders of magnitude!

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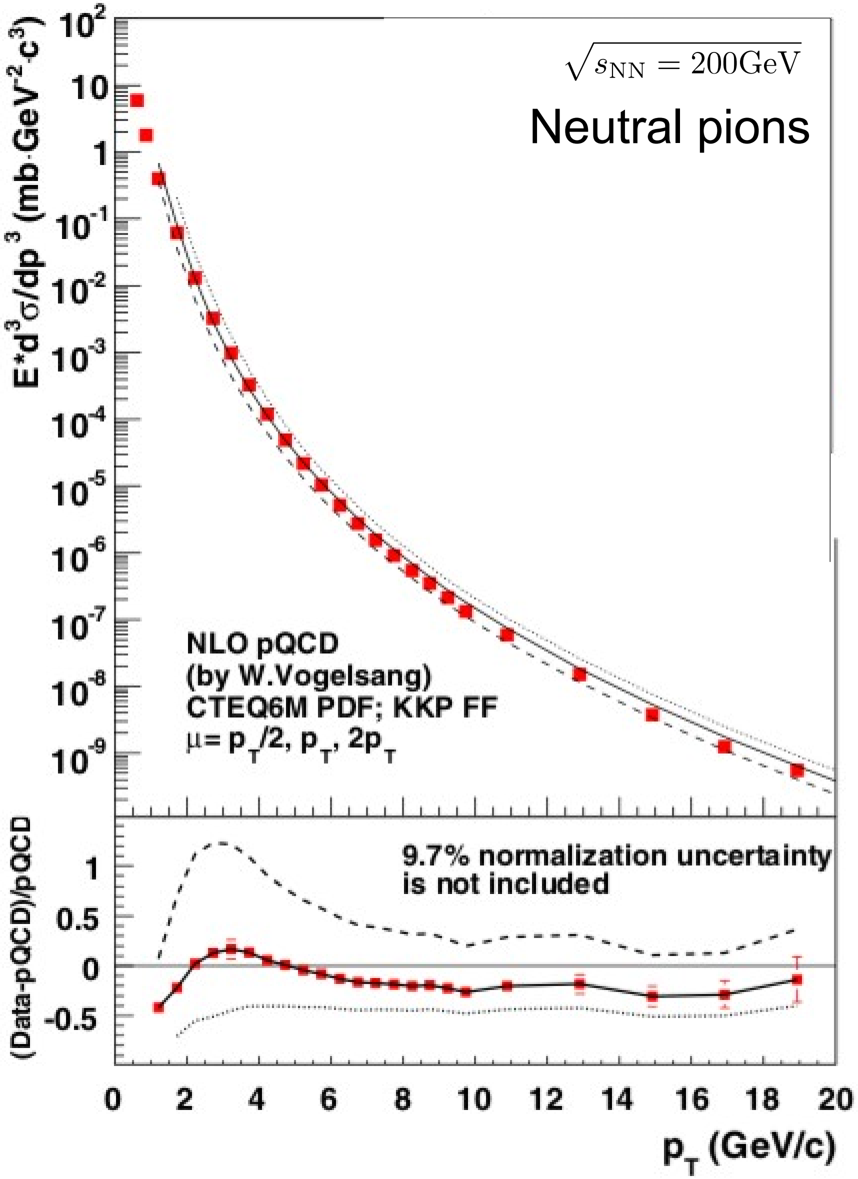
PHENIX, PRD 76 (2007) 051106(R)



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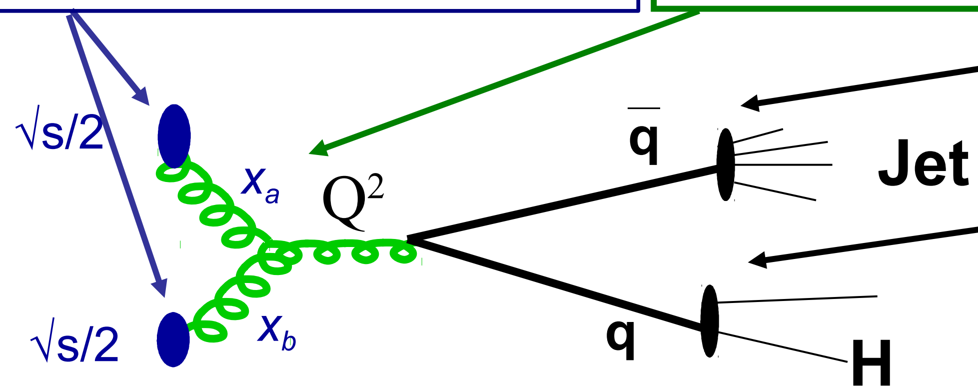


In AA collisions, in absence of nuclear and/or QGP effects expect N_{coll} scaling:

$$\frac{dN_{AA}}{dp_T} = N_{coll}\frac{dN_{pp}}{dp_T}$$

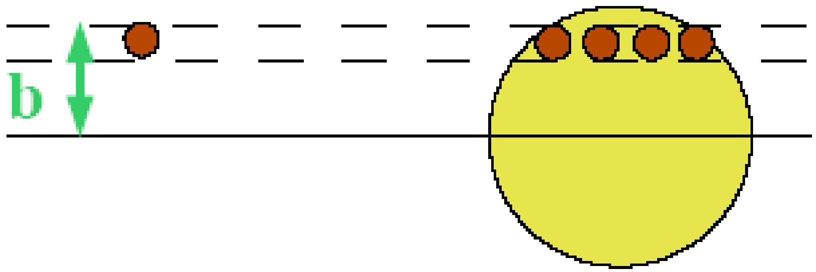
Glauber Ncoll scaling

(see e.g. arXiv:0701025)

Nuclear geometry and hard processes: Glauber theory

Glauber scaling:

- Apply to hard processes with large momentum transfer
- Short coherence length → successive NN collisions independent



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

$$\int \mathrm{d}z\, \mathrm{d}^2 b\, \rho(b,z) = 1$$

Nuclear thickness function: $T_{\mathrm{A}}(b) = \int \mathrm{d}z\, \rho(z,b)$

Inelastic cross section for p+A collisions: $\sigma_{\mathrm{pA}}^{\mathrm{inel}} = \int \mathrm{d}^2 b \left(1 - \left[1 - T_{\mathrm{A}}(b)\, \sigma_{\mathrm{NN}}^{\mathrm{inel}}\right]^A\right)$

$$\sigma_{\mathrm{pA}}^{\mathrm{hard}} \simeq A\, \sigma_{\mathrm{NN}}^{\mathrm{hard}} \int \mathrm{d}^2 b T_{\mathrm{A}} = A\, \sigma_{\mathrm{NN}}^{\mathrm{hard}}$$

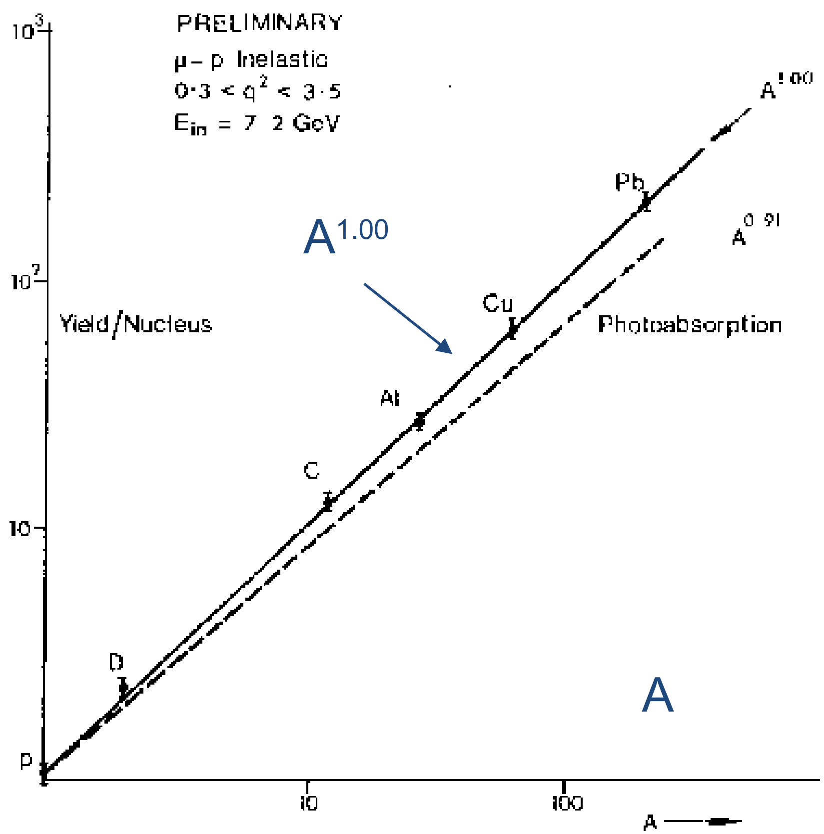
$\sigma_{\mathrm{NN}}^{\mathrm{hard}} \ll \sigma_{\mathrm{NN}}^{\mathrm{inel}}$

Experimental tests of Glauber scaling: hard cross sections in p(μ)A collisions

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

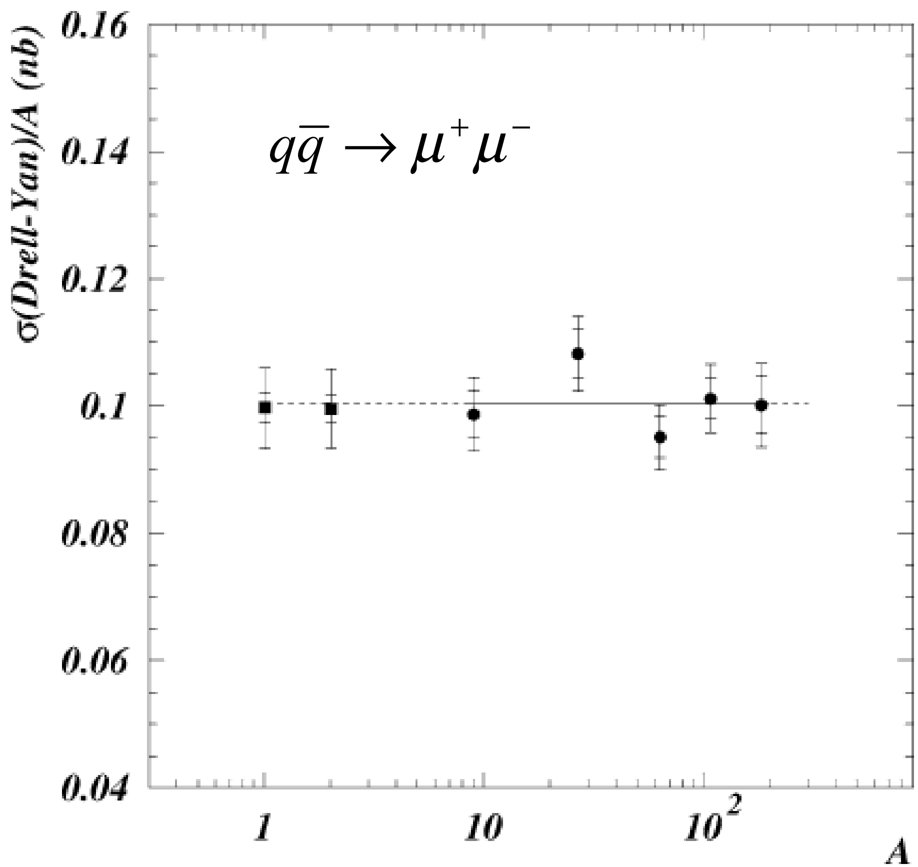
$\sigma_{\rm inel}$ for 7 GeV muons on nuclei

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



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

NA50 Phys Lett B553, 167 (2003)

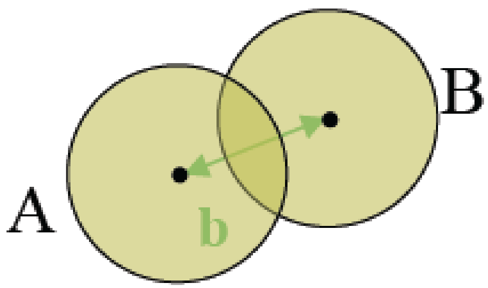


These hard cross sections in p+A found to scale as $A^{1.0}$

Glauber scaling for AB collisions

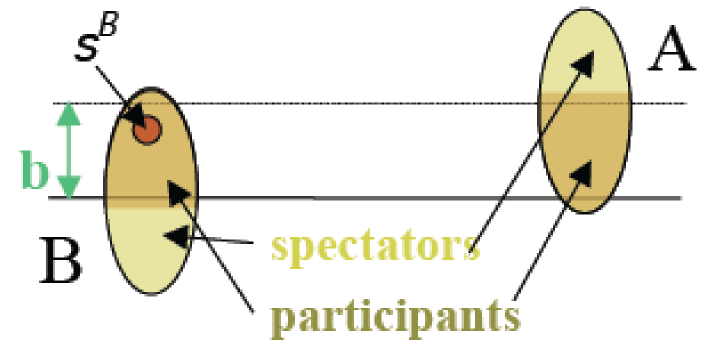
Nuclear overlap function:

$$T_{\mathrm{AB}}(b) = \int \mathrm{d}^2 s \, T_{\mathrm{A}}(s) \, T_{\mathrm{B}}(s-b)$$



Average number of binary NN collisions for nucleon from B at coordinate s_B:

$$N_{\mathrm{coll}}^{\mathrm{nA}}(b-s_{\mathrm{B}}) = A \, T_{\mathrm{A}}(b-s_{\mathrm{B}}) \, \sigma_{\mathrm{NN}}^{\mathrm{inel}}$$



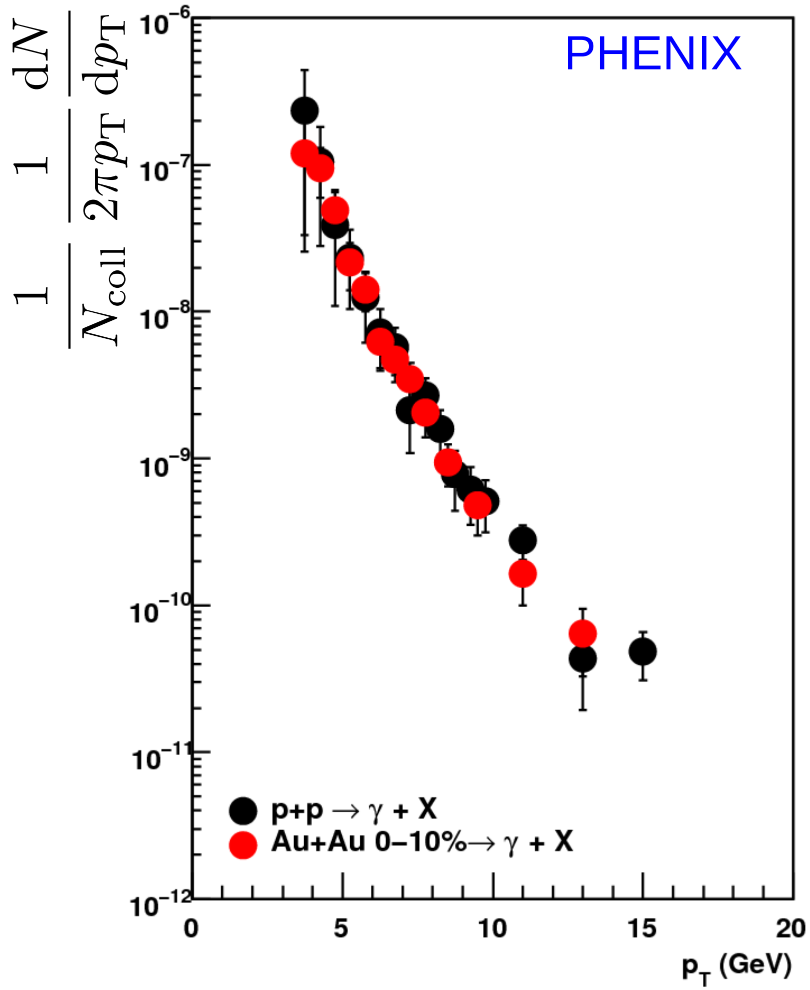
Average number of binary NN collisions for A+B collision with impact parameter b:

$$N_{\mathrm{coll}}^{\mathrm{AB}}(b) = B \int \mathrm{d}^2 s_{\mathrm{B}} \, T_{\mathrm{B}}(s_{\mathrm{B}}) \, N_{\mathrm{coll}}^{\mathrm{nA}}(b-s_{\mathrm{B}}) = \mathrm{AB} \, \mathrm{T}_{\mathrm{AB}}(b) \, \sigma_{\mathrm{NN}}^{\mathrm{inel}}$$

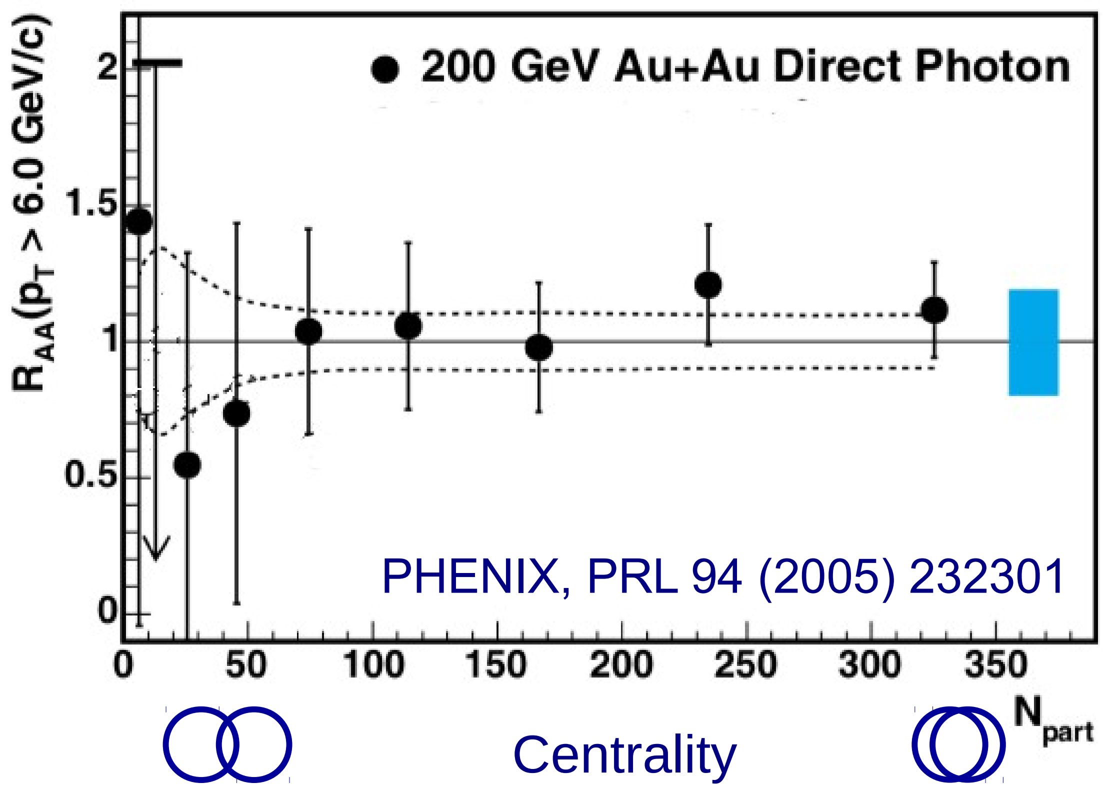
$$N_{\mathrm{hard}}^{\mathrm{AB}}(b) = \mathrm{N}_{\mathrm{coll}}^{\mathrm{AB}}(b) \, \sigma_{\mathrm{NN}}^{\mathrm{hard}} / \sigma_{\mathrm{NN}}^{\mathrm{inel}} = \mathrm{N}_{\mathrm{coll}}^{\mathrm{AB}}(b) \, N_{\mathrm{pp}}^{\mathrm{hard}}$$

Glauber test at RHIC: Scaling of direct photon yield in pp vs AuAu

Direct photon inclusive yield (normalized by N_{coll})



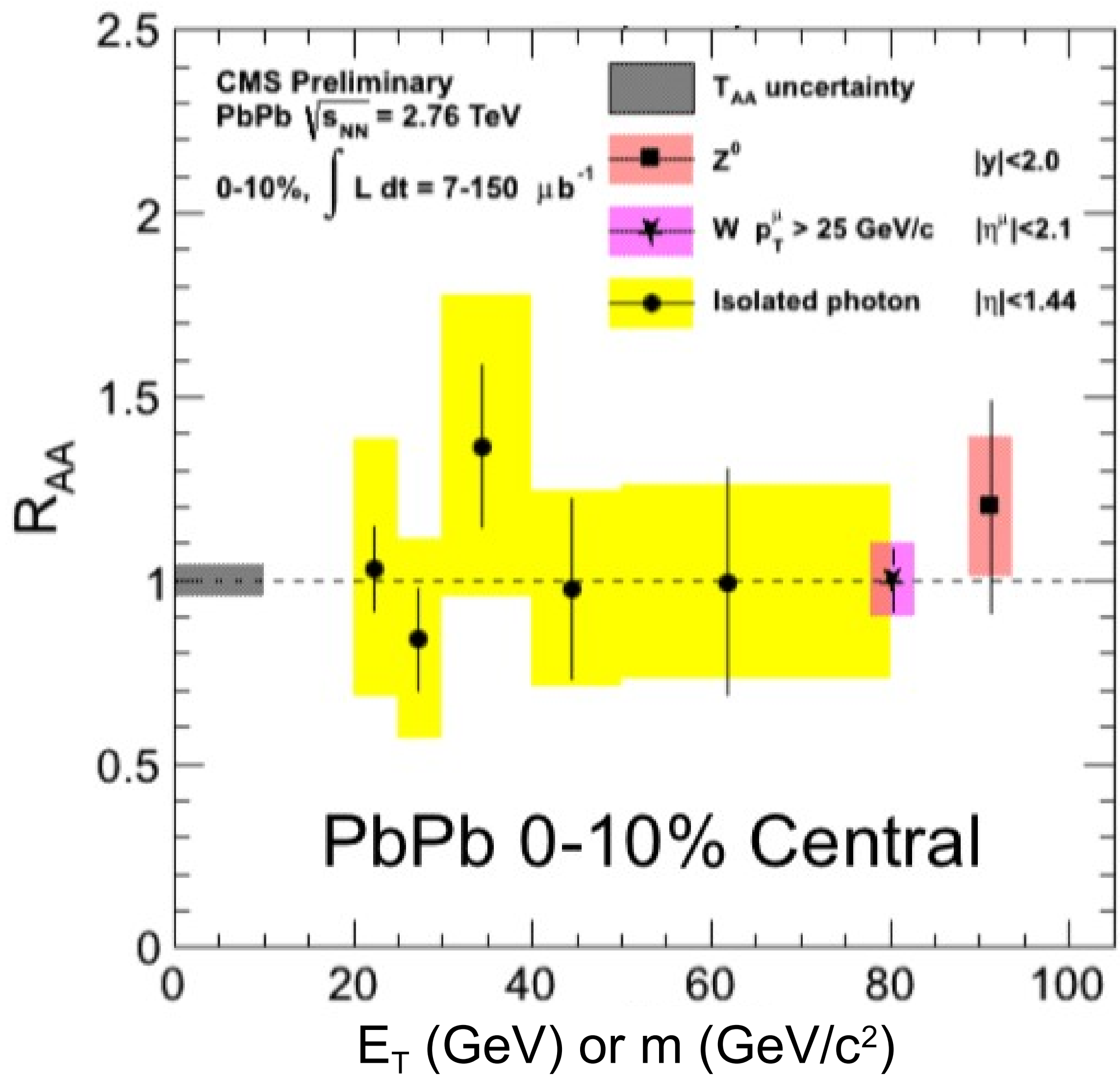
$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{coll}\, dN_{pp}/dp_T}$$



Direct photons in Au+Au scale with Ncoll

Glauber test at LHC:
Scaling of control yields in pp vs PbPb

$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{coll}\, dN_{pp}/dp_T}$$



Isolated γ:
ATLAS, ATLAS-CONF-2012-051
CMS, PLB 710 (2012) 256

Z boson:
ATLAS, PLB 697 (2011) 294
CMS, PRL 106 (2011) 212301

W boson:
ATLAS, ATLAS-CONF-2011-78
CMS, PLB 715 (2012) 66

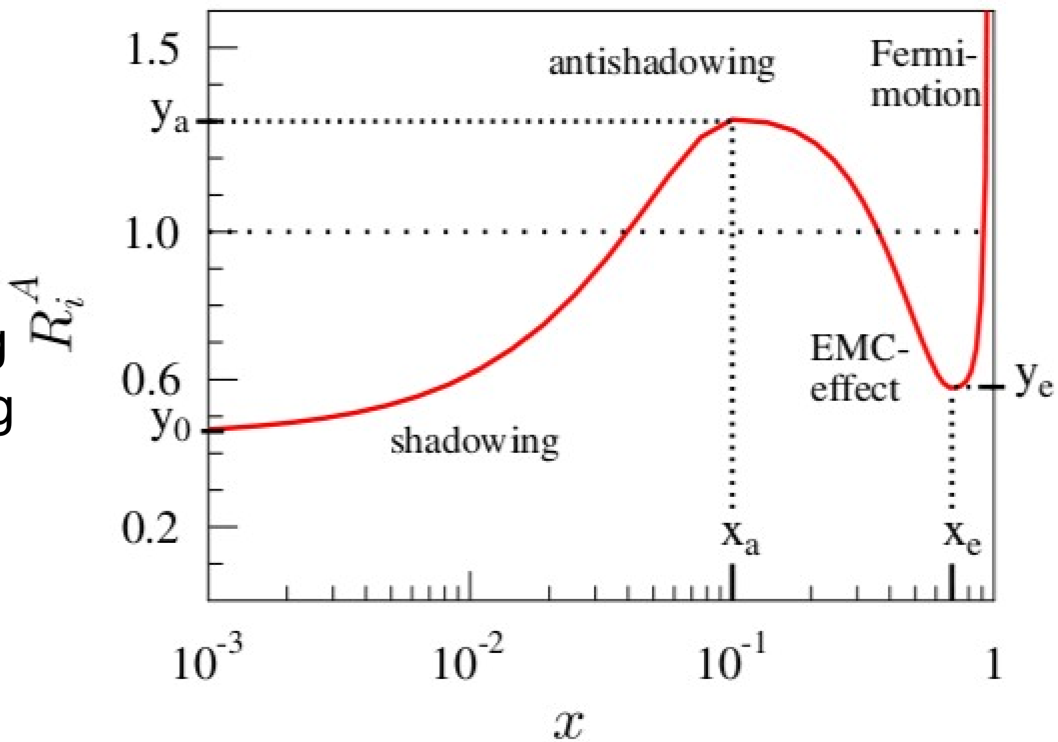
Control probes (direct +isolated γ, Z, W) scale with Ncoll

Parton energy loss

Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_{\mathrm{T}}}{N_{\mathrm{coll}}\,\mathrm{d}N_{pp}/\mathrm{d}p_{\mathrm{T}}}$$

$R_{AA} > 1 \rightarrow$ enhancement wrt binary scaling
$R_{AA} = 1 \rightarrow$ no deviation from binary scaling
$R_{AA} < 1 \rightarrow$ suppression wrt binary scaling



- By definition, R_{AA}=1 in absence of nuclear or QGP matter effects
- Binary scaling can be broken due to initial state effects
  - Transverse k_T broadening (called "Cronin effect")
  - PDF modifications in nuclei (shadowing)

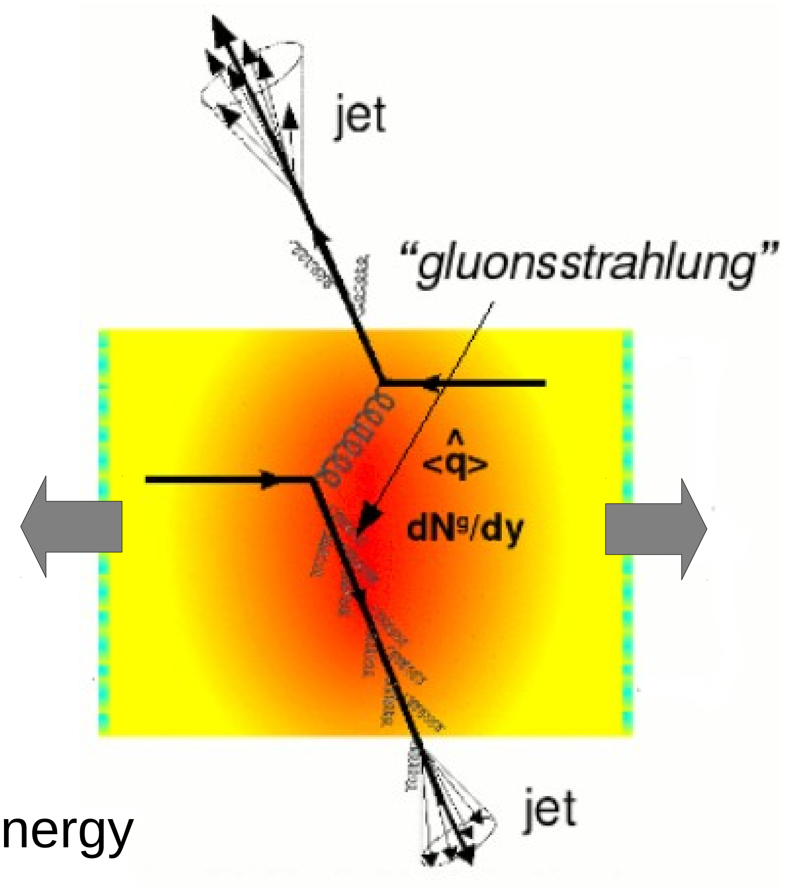
$$f_i^A(x,Q^2) \equiv R_i^A(x,Q^2)\, f_i^{\mathrm{CTEQ6.1M}}(x,Q^2)$$

(Prime reason for measurements in pA)

- Binary scaling can be broken due final state effects

Breaking of binary scaling

- Final state effects
  - Change of fragmentation
    due to the presence of the medium
    - e.g. jet quenching or jet modification
- Parton traversing the medium
  lose energy via
  - Scattering with partons in the medium
    (collisional energy loss)
  - Gluonstrahlung (radiative energy loss)
    - Radiative mechanism dominant at high energy



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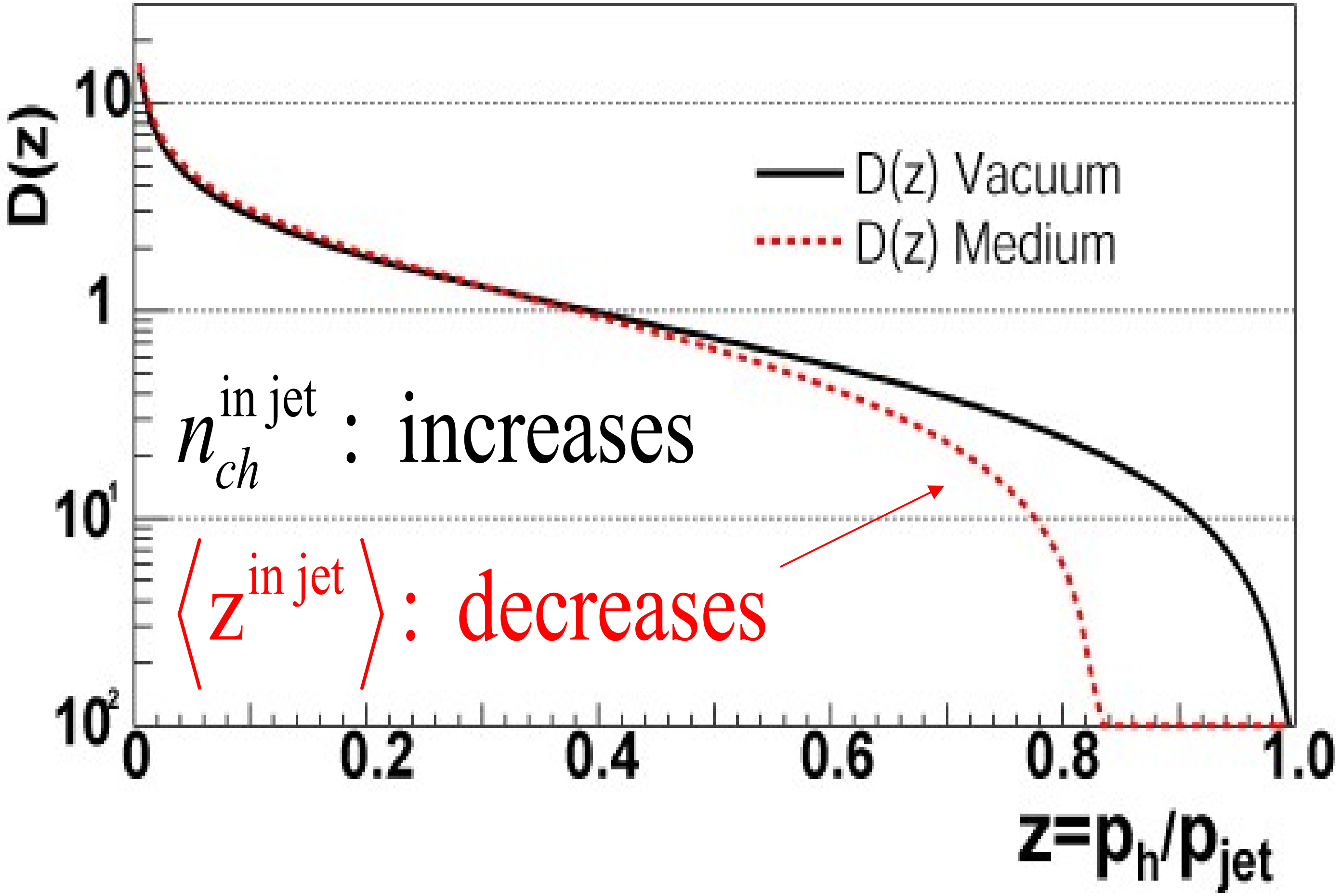
    - Radiative mech
  - The net-effect is a
    - Quenching of the high p_T spectrum
    - Modification of jet properties



FERMILAB-Pub-82/59-THY
August, 1982

Bjorken, 1982

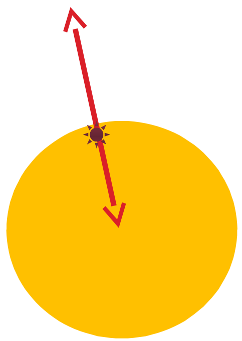
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

First idea by Bjorken on collisional energy loss in pp collisions!

Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For hadron-hadron collisions with high associated multiplicity and with transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.



Radiative energy loss (BDMPS approach)

$$\langle \Delta E \rangle \propto \alpha_S \, C_R \, \hat{q} \, L^2$$

(Crude approximation see arXiv:1002.2206 for more accurate approaches)

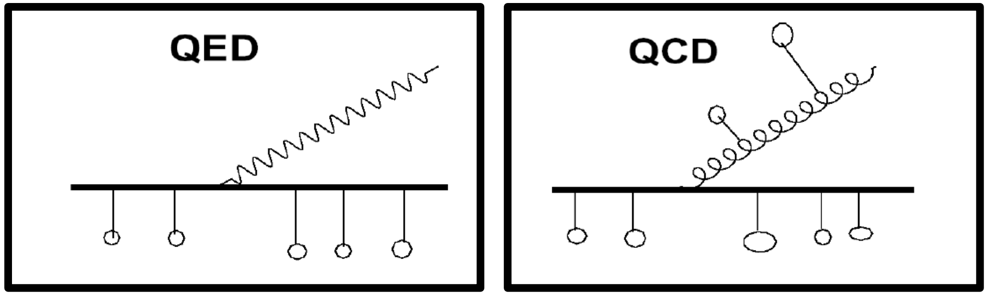
Energy loss from parton

Casimir factor

Transport coefficient

Length traversed in medium

α_S = QCD coupling constant
CR = Casimir coupling factor
Equal to 4/3 for quark-gluon and 3 for gluon-gluon coupling
q = Transport coefficient
Related to the properties (opacity) of the medium:
Defined as average transverse momentum kick per unit path length of probe (prop. to gluon density)



L^2 dependence related to the fact that radiated gluons interact with medium

Average energy loss (example)

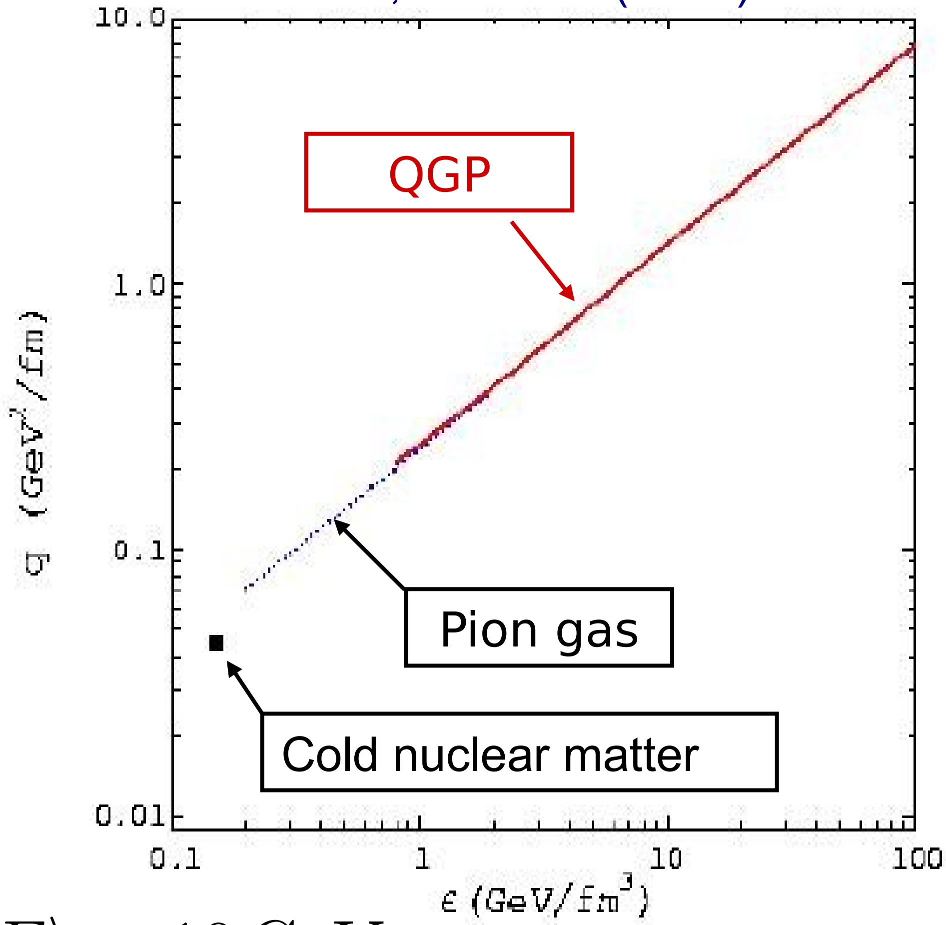
- The transport coefficient relates to the energy density via

$$\hat{q} \propto \epsilon^{\frac{3}{4}}$$

- Use energy density from multiplicity measurements to get an order of magnitude estimate
    - For central RHIC collisions

$$\varepsilon_{\mathrm{BJ}} = 5.4\,\mathrm{GeV/fm^3}$$
$$\hat{q} = 1\mathrm{GeV^2/fm}$$
$$\alpha_{\mathrm{S}} = 0.2$$
$$C_{\mathrm{R}} = 4/3$$
$$L = 3\,\mathrm{fm}$$

Baier, NPA 715 (2003) 209

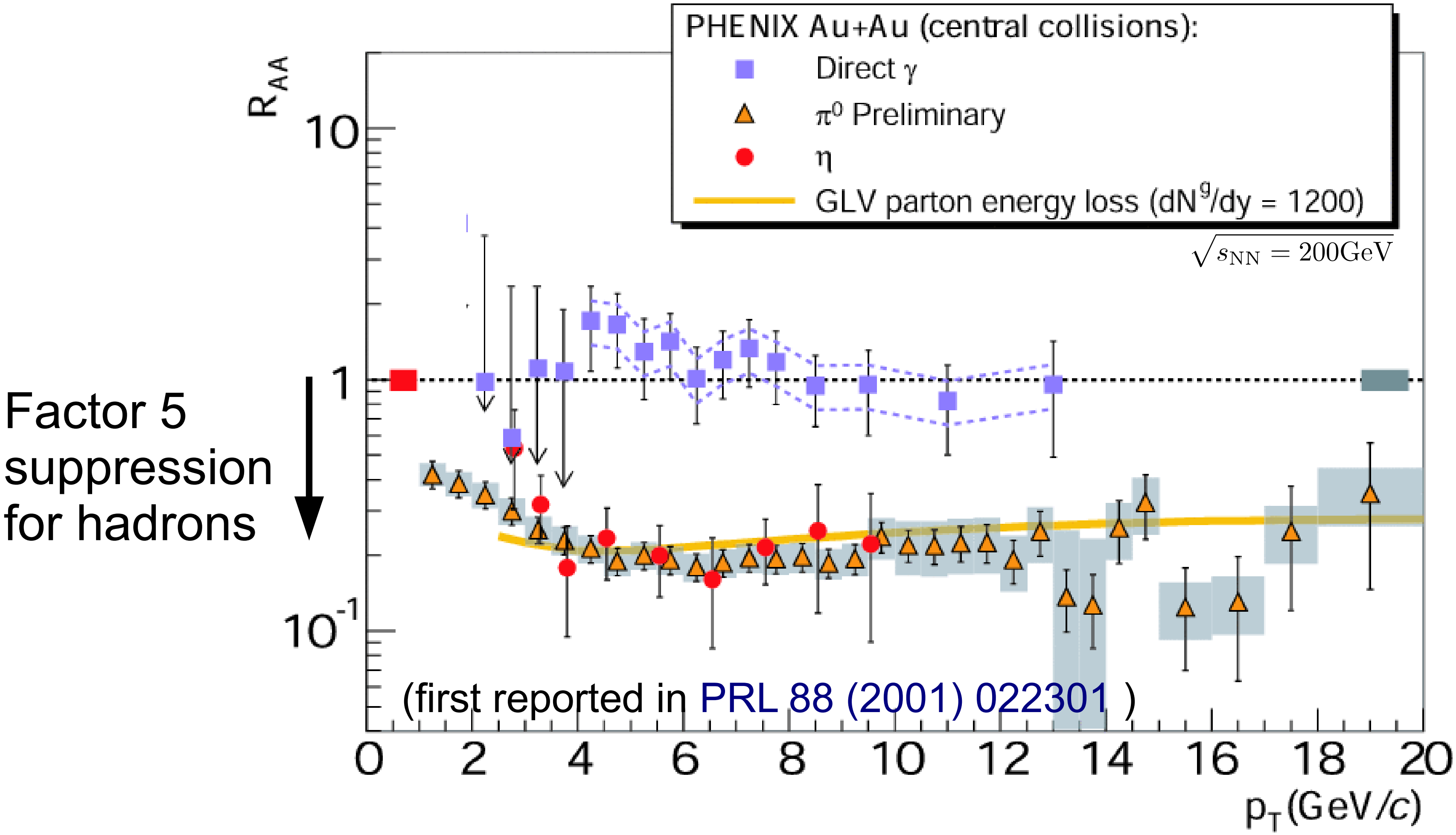


(From formula on previous slide)

$$\langle \Delta E \rangle \simeq 10\,\mathrm{GeV}$$

Enormous! Only high-p_T partons survive (or those that are produced "close to the surface" of the QGP)

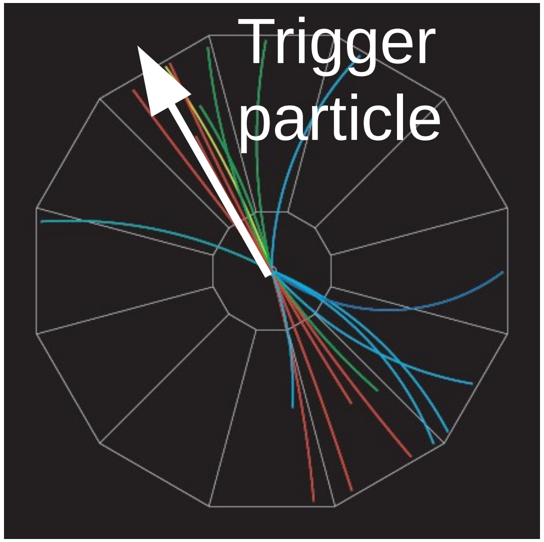
Leading hadron suppression at RHIC

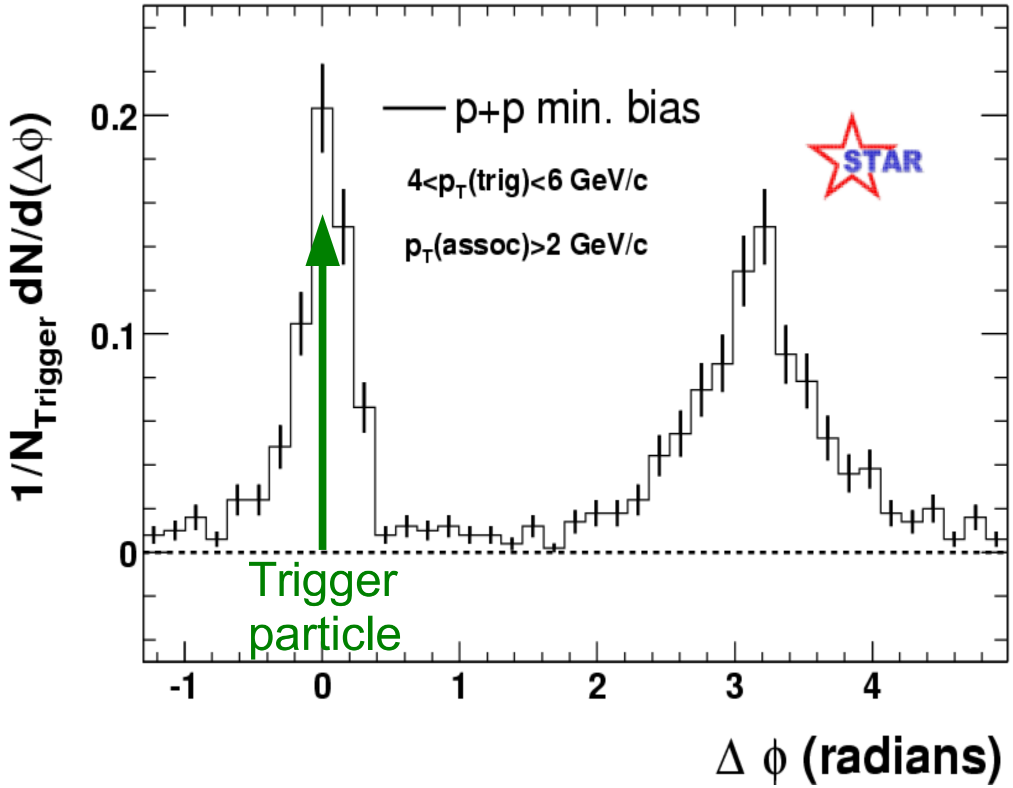


Strong suppression of hadrons in central Au+Au collisions
(extracted transport coefficient similar to initial expectations, see arXiv:1312.5003)

Di-hadron correlations

PRL 90 (2003) 082392

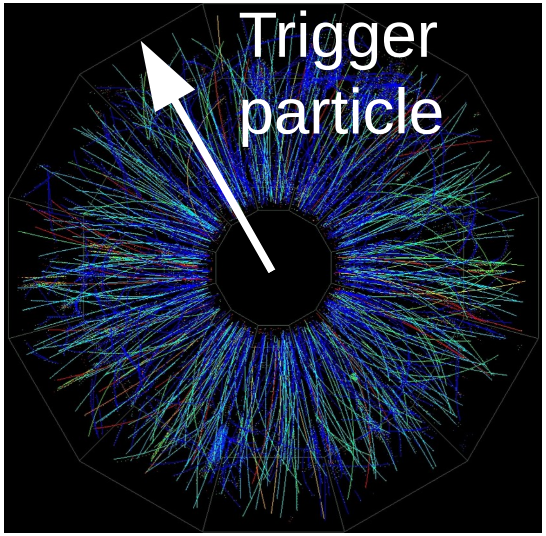


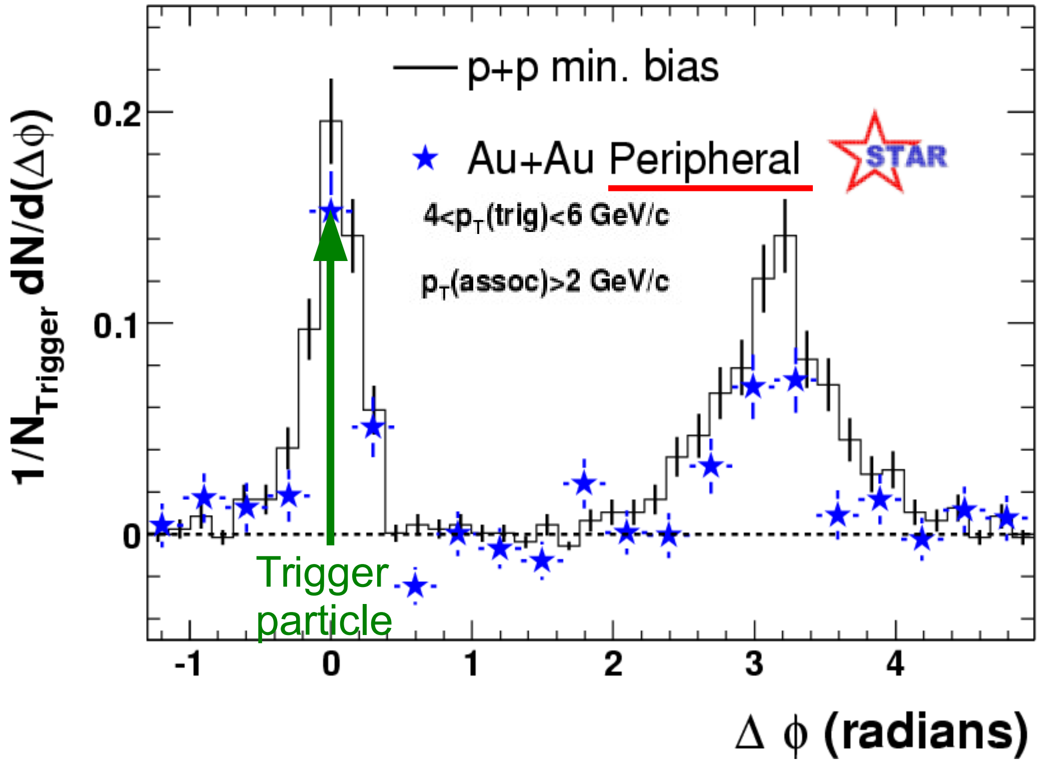


Study two particle angular correlations
relative to high-p_T (trigger) particle:
Proxy for di-jet measurements

Di-hadron correlations

PRL 90 (2003) 082392

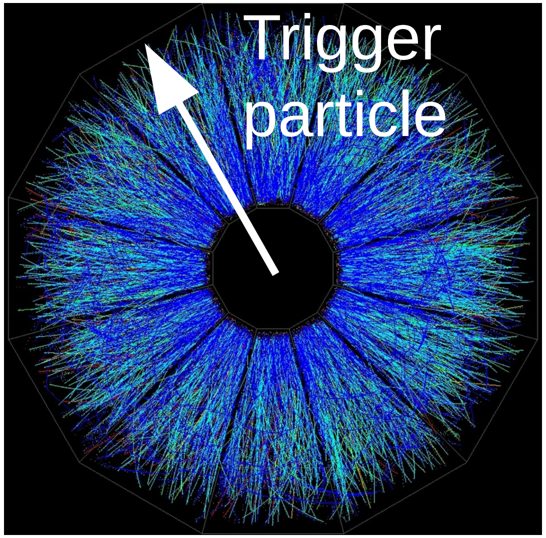


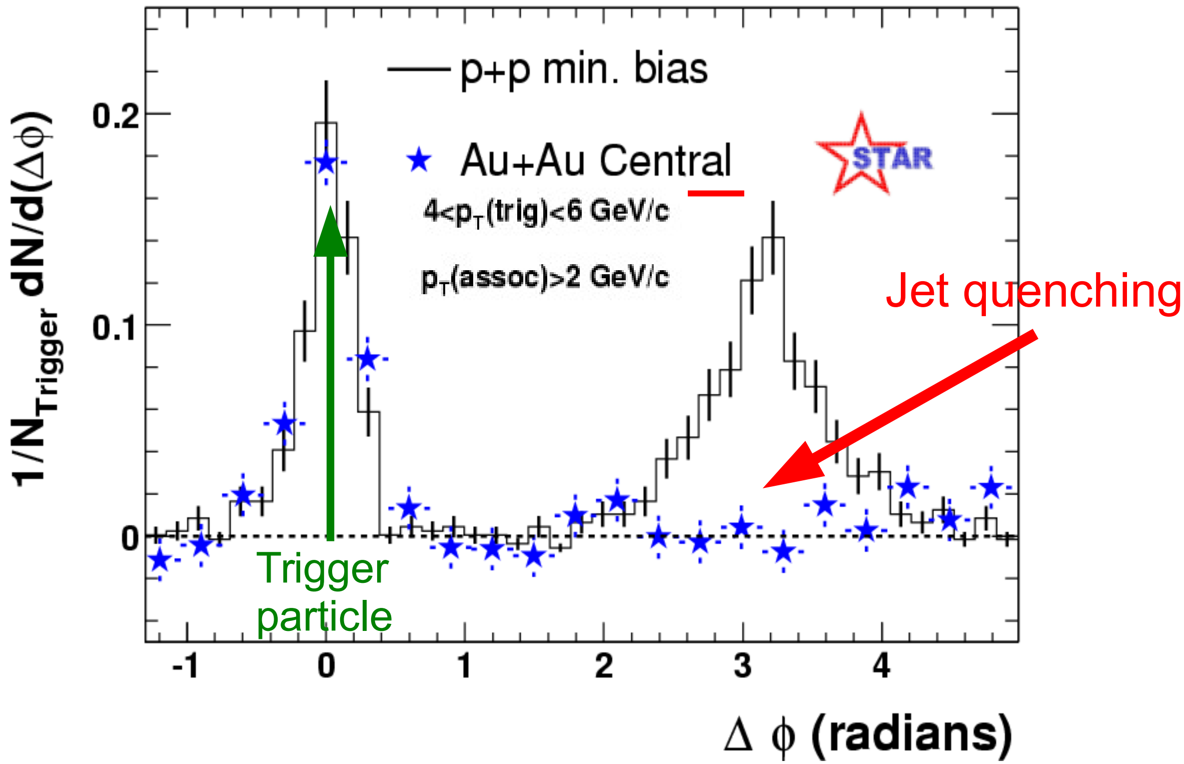


No clear change visible (relative to pp) in peripheral collisions

Di-hadron correlations

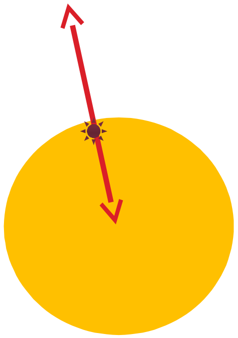
PRL 90 (2003) 082392





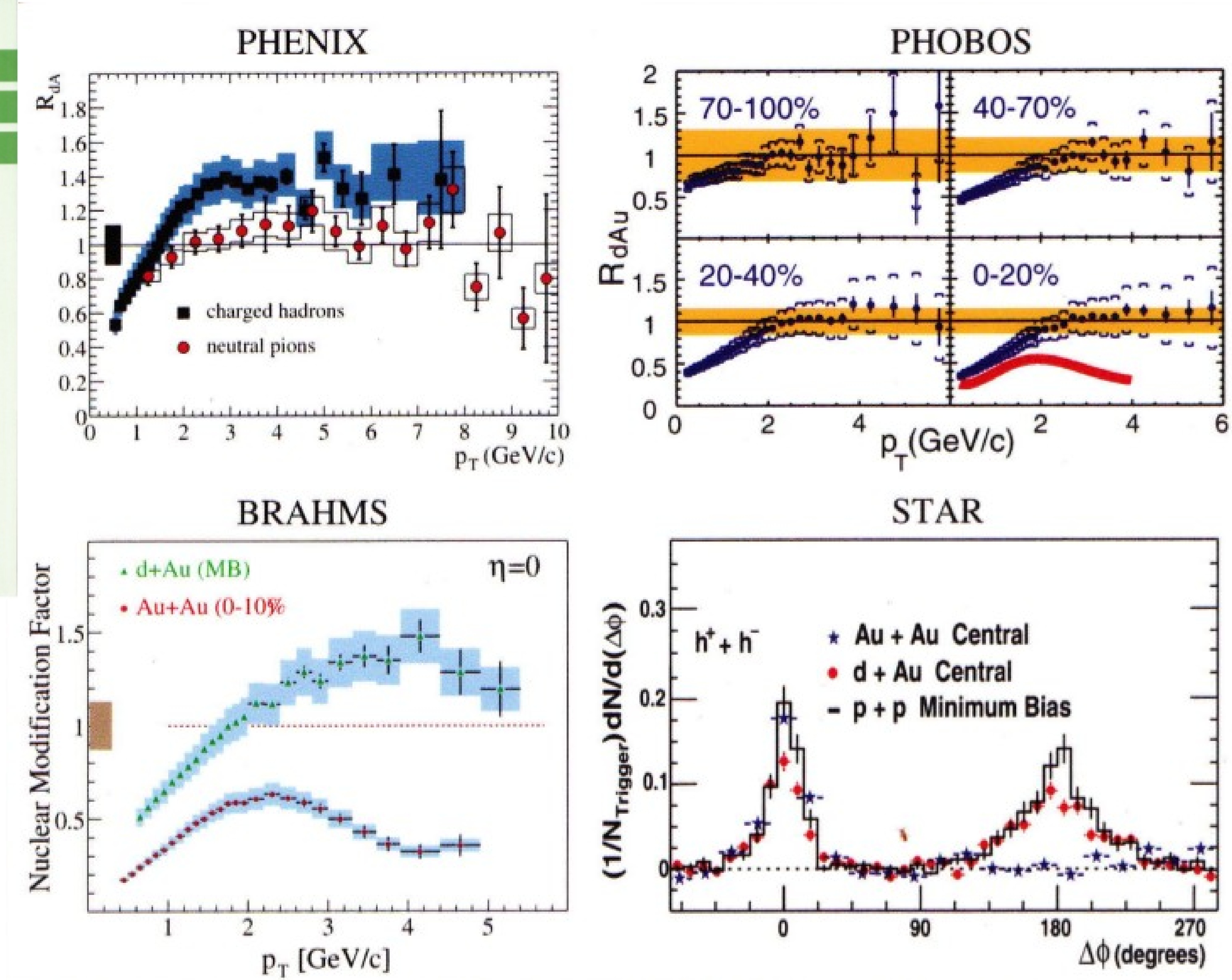
Recoiling jet is strongly altered (swallowed) by medium

Clear evidence for presence of very high density matter



dAu control experiment at RHIC

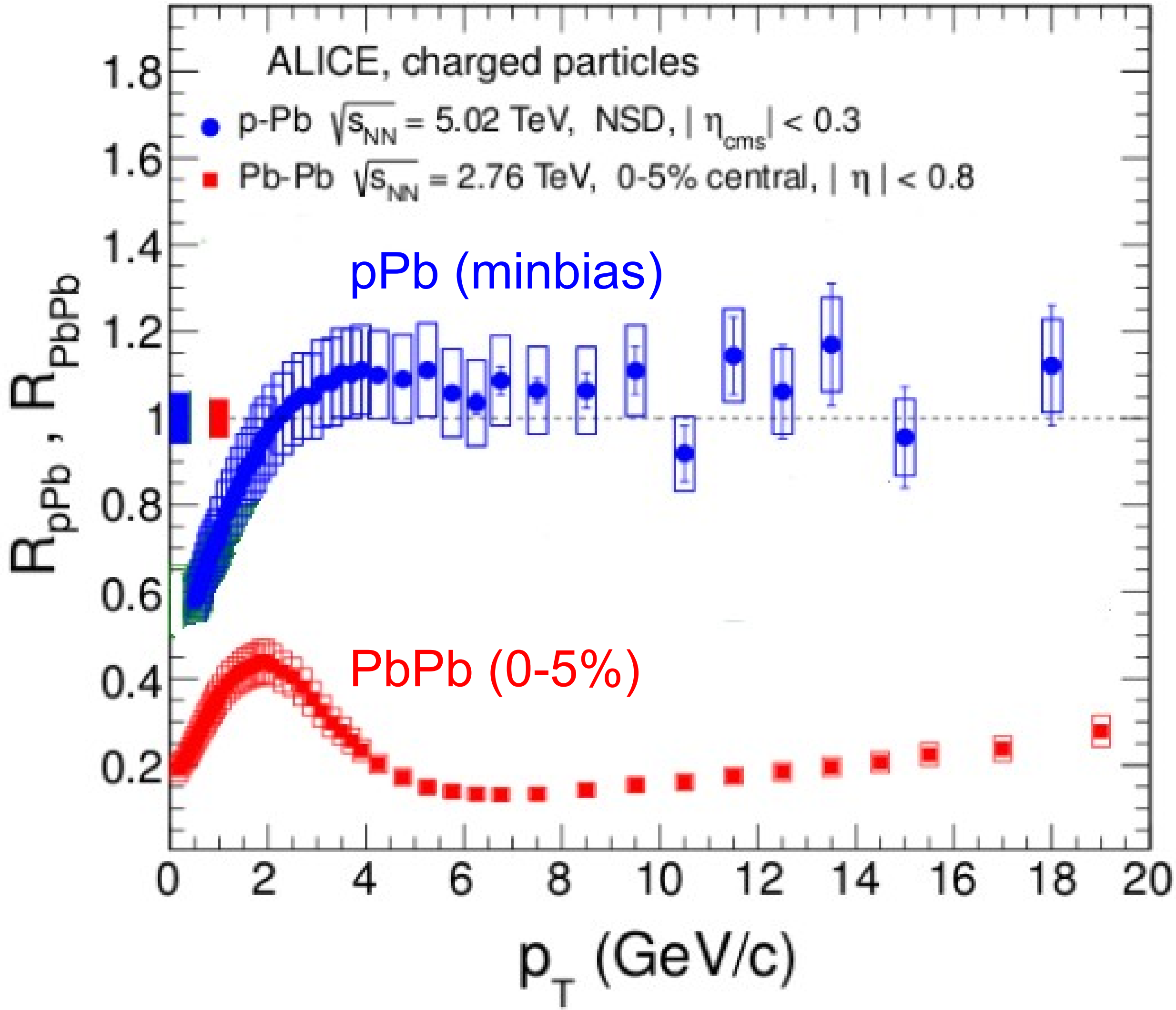
PRL 91 (2003) vol 7



Parton energy loss is a final state effect

Leading particle suppression at the LHC

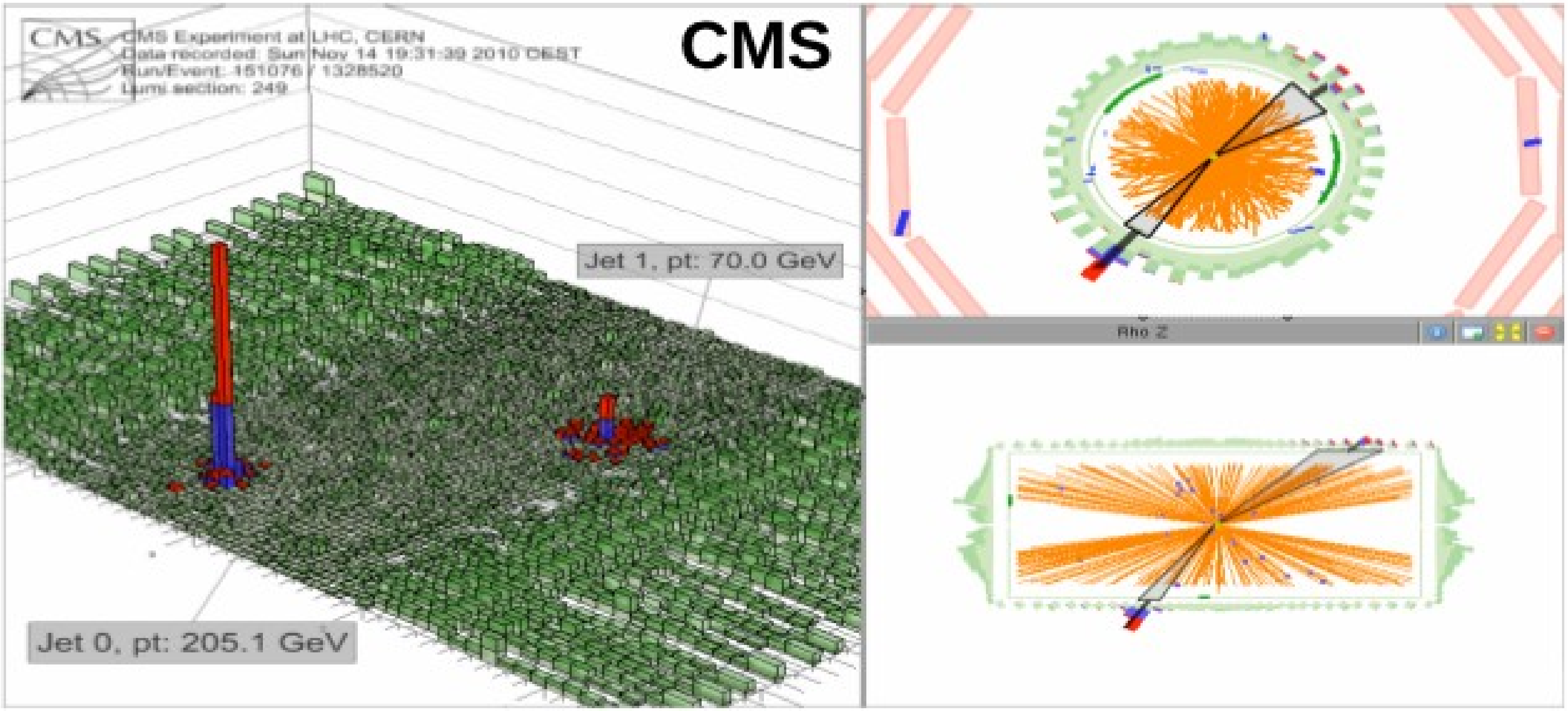
ALICE, PRL 110 (2013) 082302



- Strong leading particle suppression also at LHC energies
- Qualitatively similar to the one at RHIC
- As at RHIC from final state (ie not observed in pPb collisions)

Jet quenching

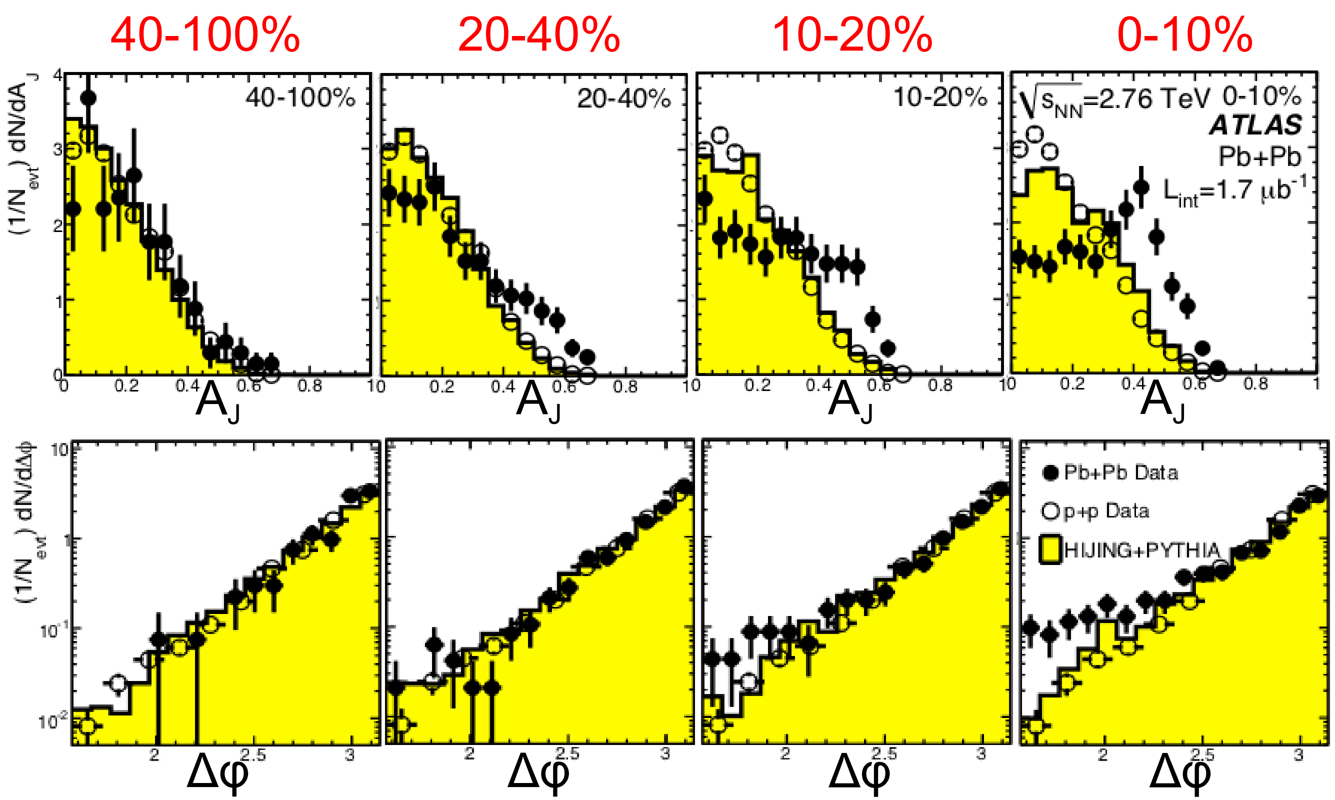
Jet quenching in dijet events



Can even be seen in event displays!!!

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad \Delta\varphi_{12} > \frac{\pi}{2}$$

Dijet imbalance: clear signal in PbPb at LHC

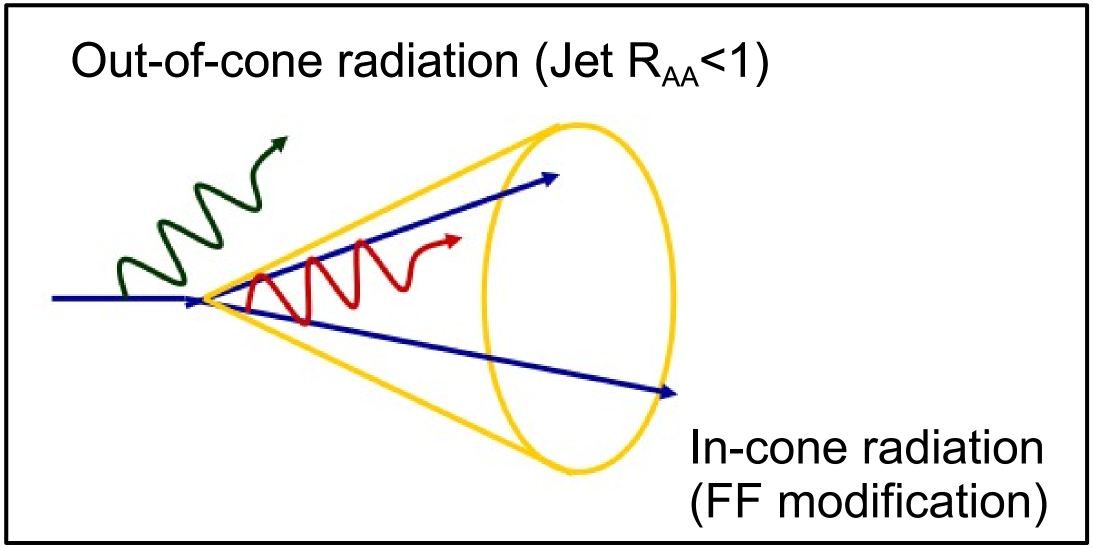


Momentum imbalance wrt to MC (pp) reference increases with increasing centrality.
No (or very little) azimuthal decorrelation.

ATLAS, PRL 105 (2010) 252303
CMS, PRC 84 (2011) 024906

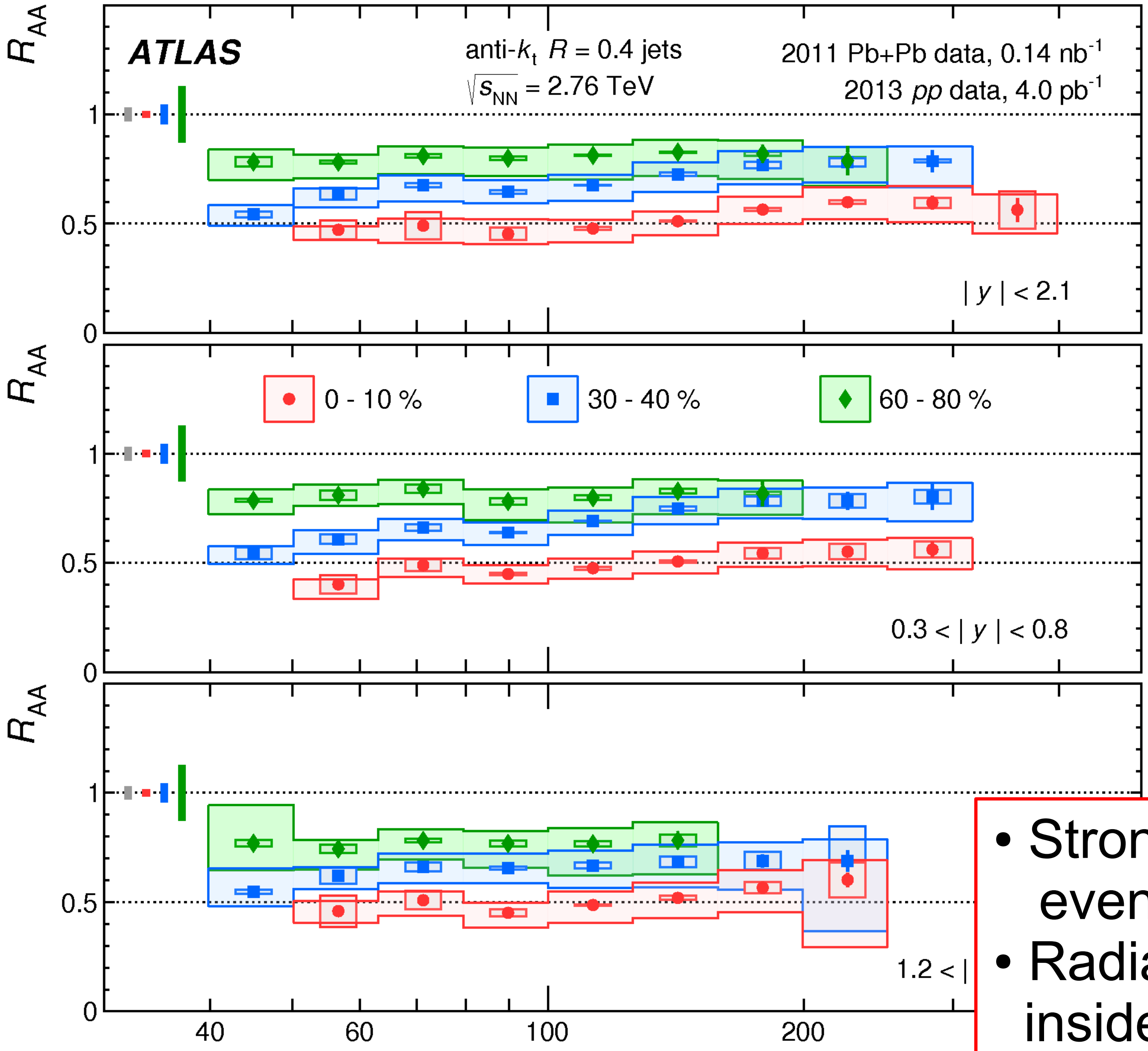
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \quad \Delta\varphi_{12} > \frac{\pi}{2}$$

Where does the radiated energy go?



Jet R_{AA} up to very high p_T

arXiv:1506.08656



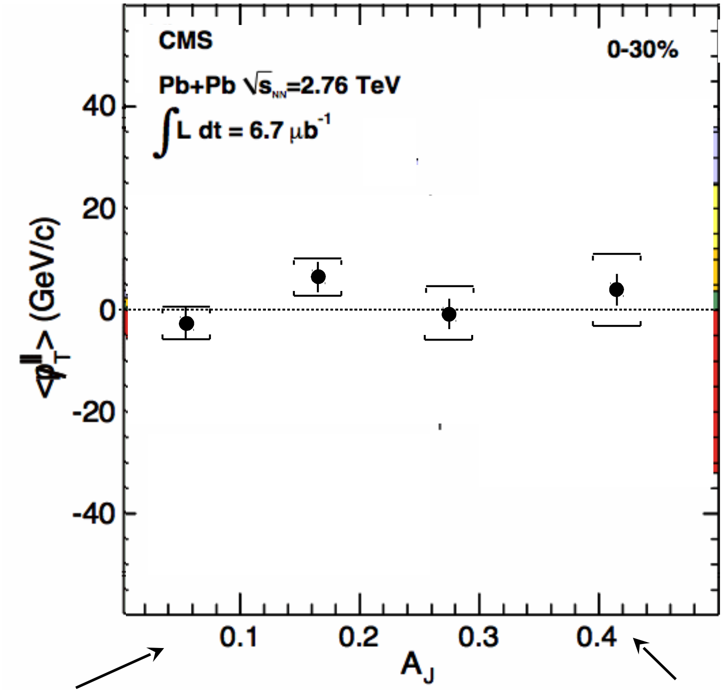
$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{coll}\, dN_{pp}/dp_T}$$

- Strong jet suppression even at up to 200-300 GeV
- Radiation not captured inside cone R=0.4
- Where does the energy go?

Where does the energy go?

- Calculate projection of p_T on leading jet axis and average over selected tracks with p_T>0.5 GeV/c and |η| < 2.4
- Define missing p_T $$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$
- Averaging over event sample in bins of A_J find missing p_T consistent with zero

0-30% Central PbPb

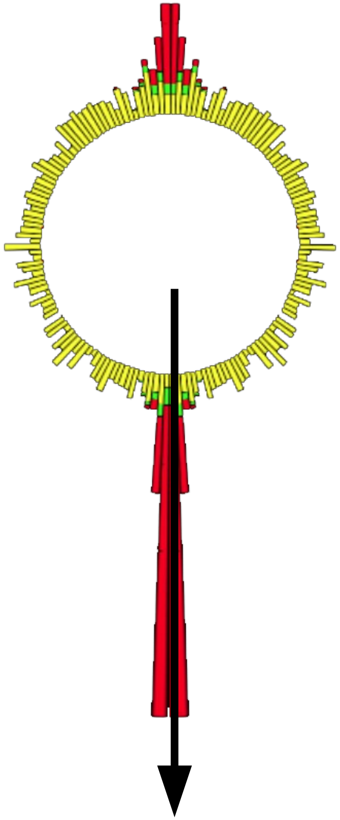


excess away from leading jet

excess towards leading jet

balanced jets

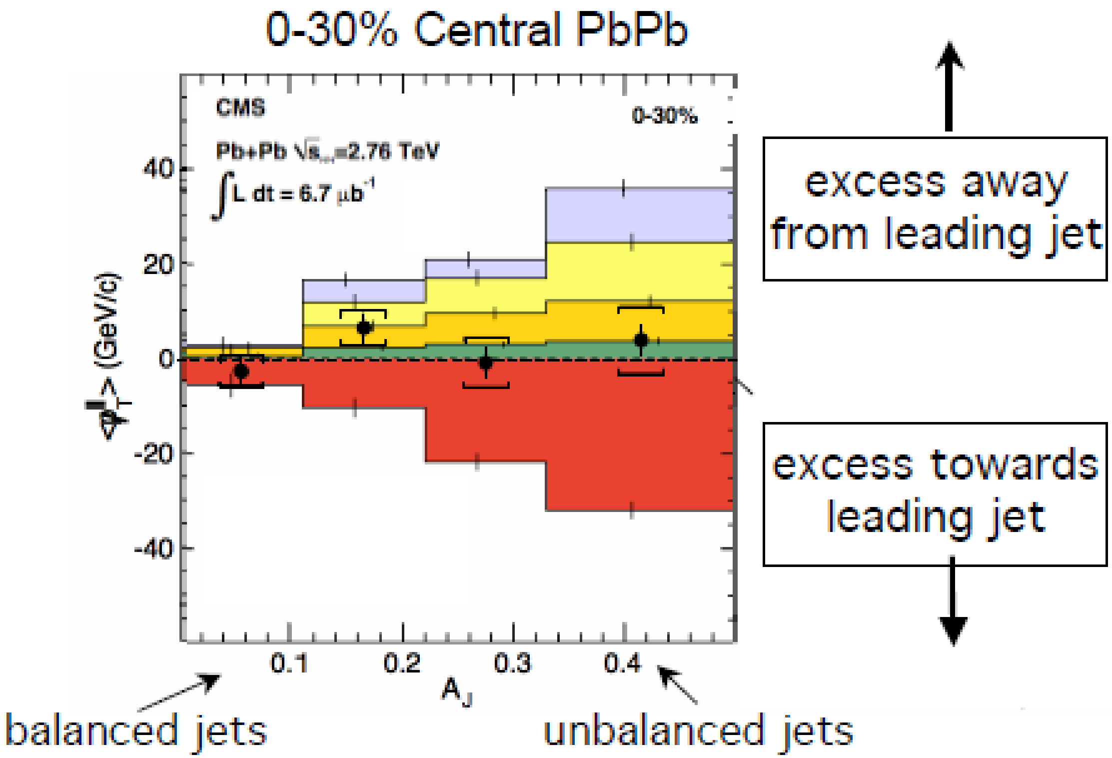
unbalanced jets



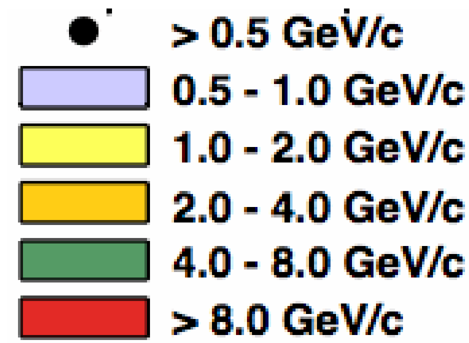
Leading jet defines direction

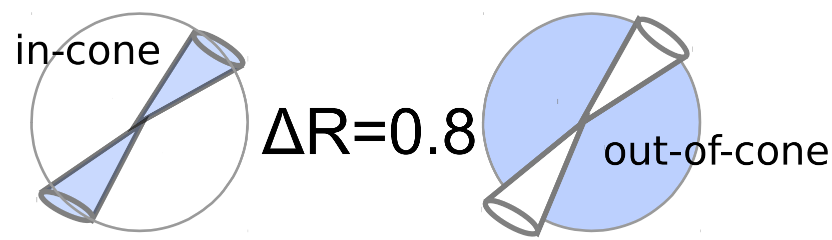
PRC 84 (2011) 024906

Where does the energy go?

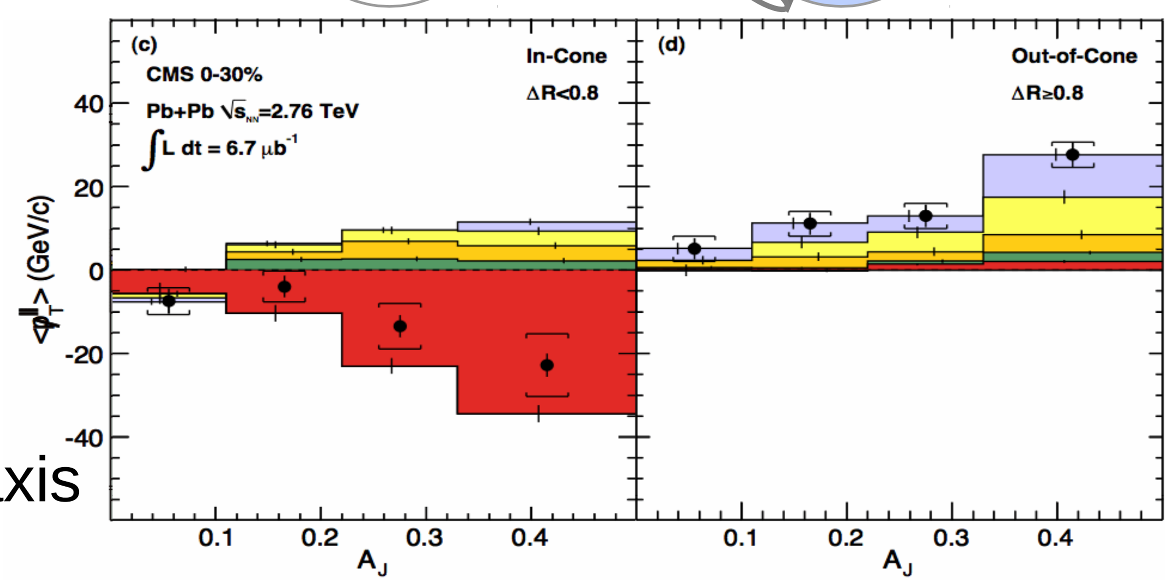


Calculate missing p_T in bins of track p_T

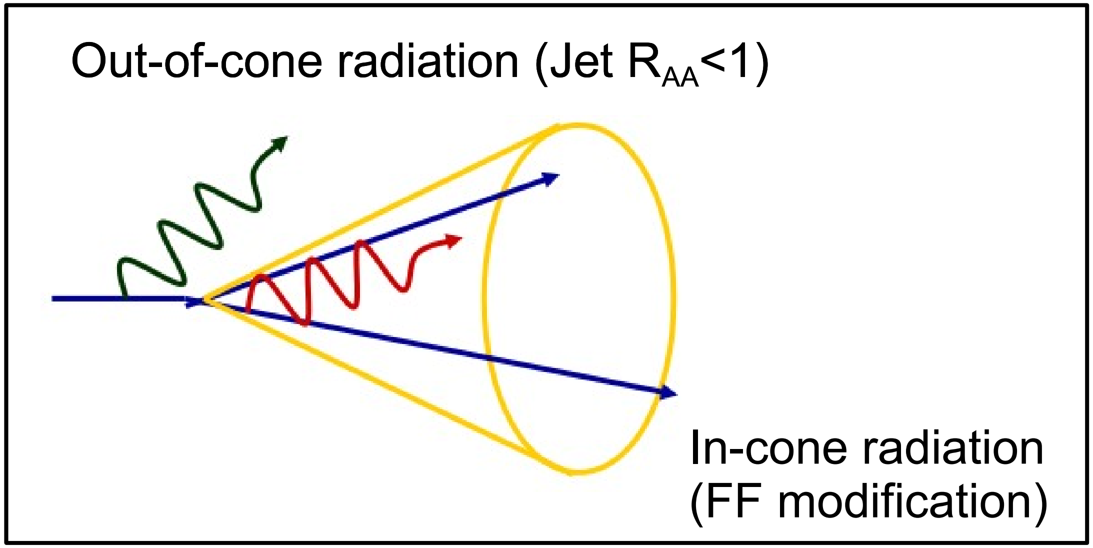




The momentum difference in the leading jet is compensated by low p_T particles at large angles with respect to the jet axis



Where does the radiated energy go?

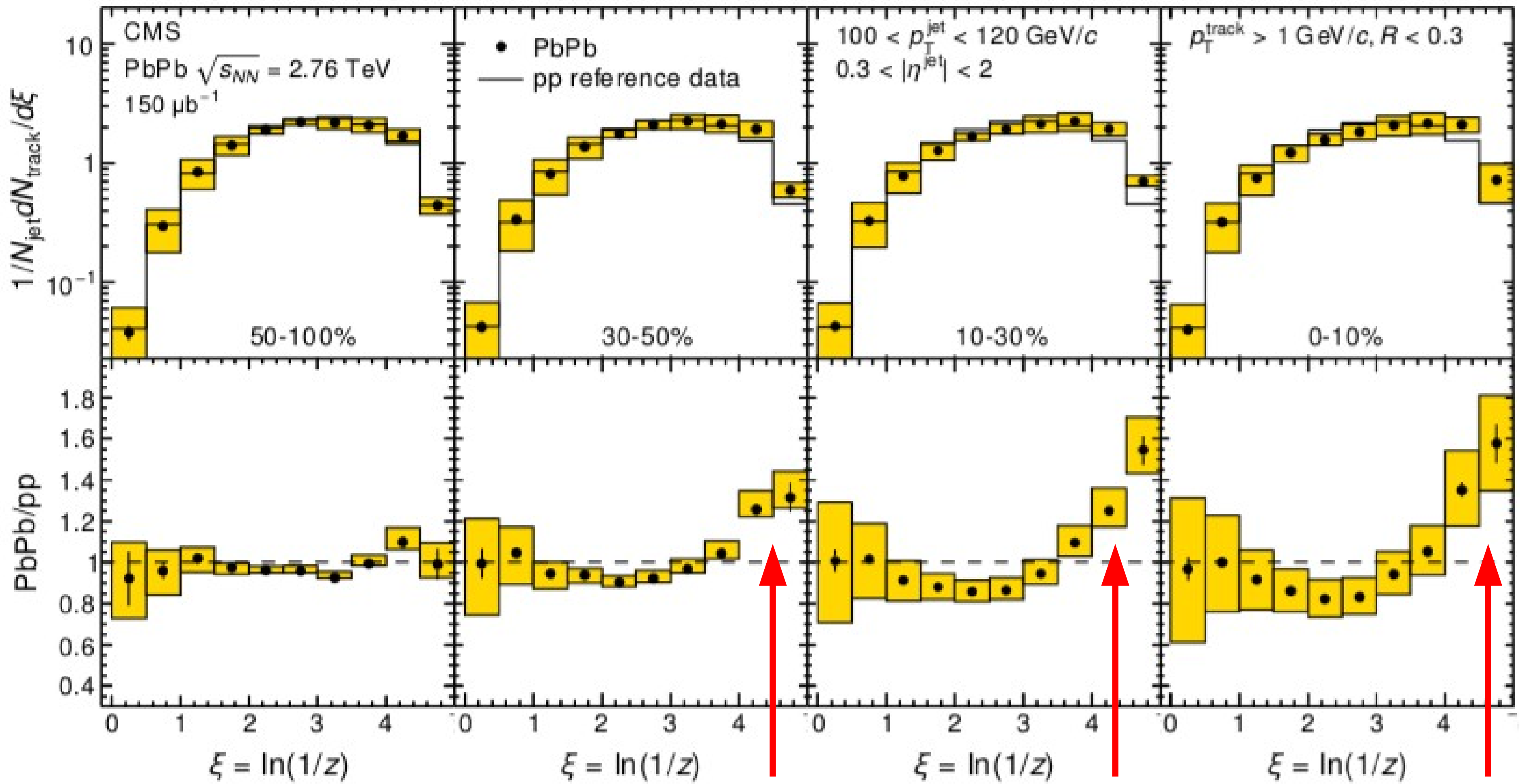


Is there an observable difference in the jet cone?

Jet fragmentation function

arXiv:1406.0932

Fragmentation functions constructed using tracks with p_T>1 GeV/c in R<0.3 and the reconstructed (quenched) jet energy



R=0.3

100<p_T<120 GeV/c

Track p_T>1 GeV/c

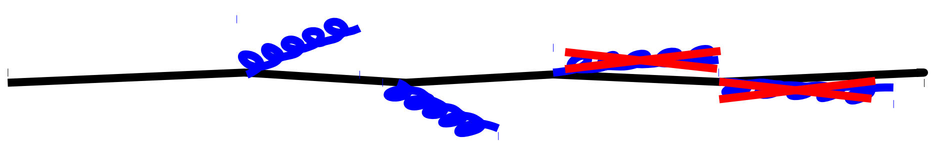
$$z = p_T^{track}/p_T^{jet}$$

Fragmentation function is modified:
More particles at low p_T in more central collisions

Energy loss of massive quarks

Energy loss of (open) heavy flavor

- The study of open heavy flavor in AA collisions is a crucial test for the understanding of parton energy loss
- A smaller energy loss is expected for D or B mesons relative to that of light flavored hadrons
- In particular at LHC energy
  - Heavy flavor mainly come from quark fragmentation, while light flavor from gluons → smaller Casimir factor, smaller energy loss
  - Dead cone effect:
    Suppression of gluon radiation at small angles dep. on quark mass



Suppression for
$\theta < M_Q/E_Q$

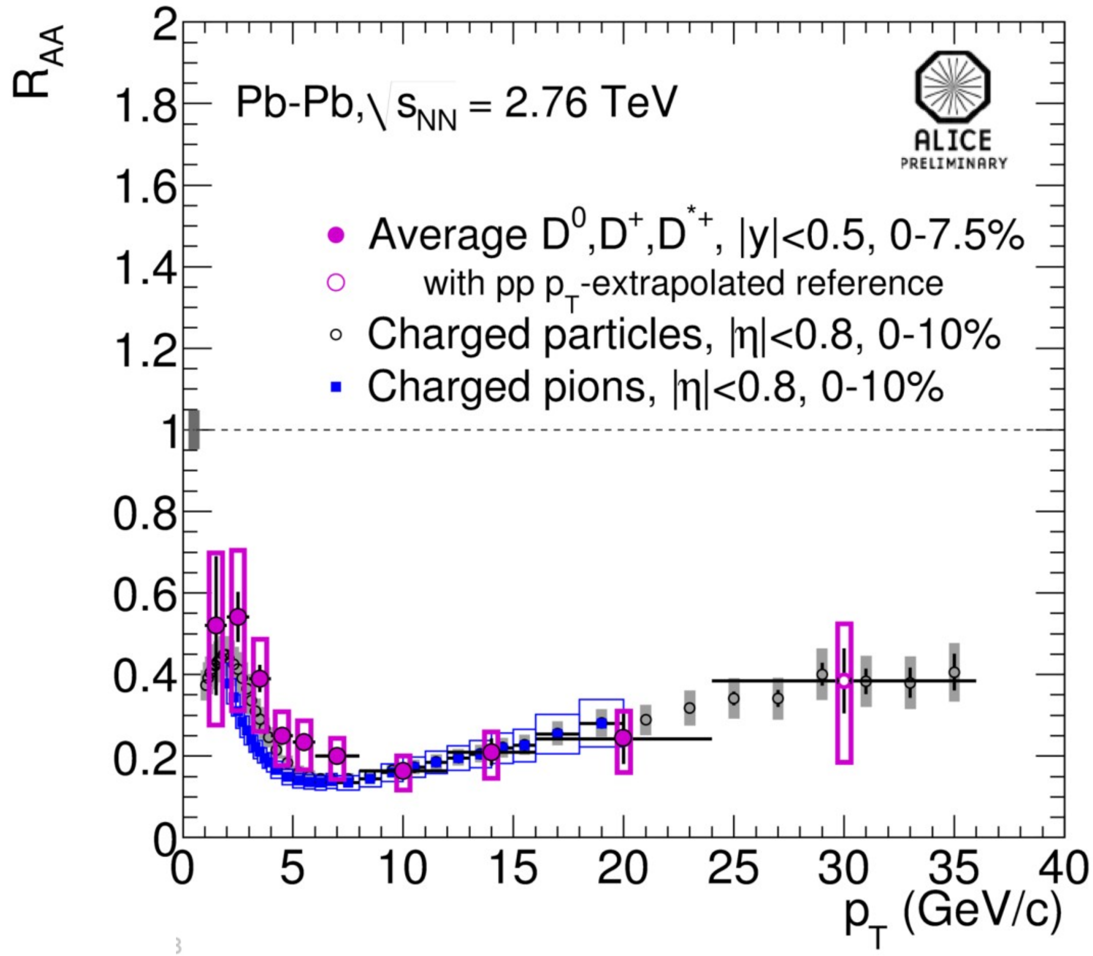
  - Should lead to a suppression hierarchy

$$\Delta E_{gluon} > \Delta E_{charm} > \Delta E_{beauty}$$

↓

$$R_{AA}(\text{light hadrons}) < R_{AA}(D) < R_{AA}(B)$$

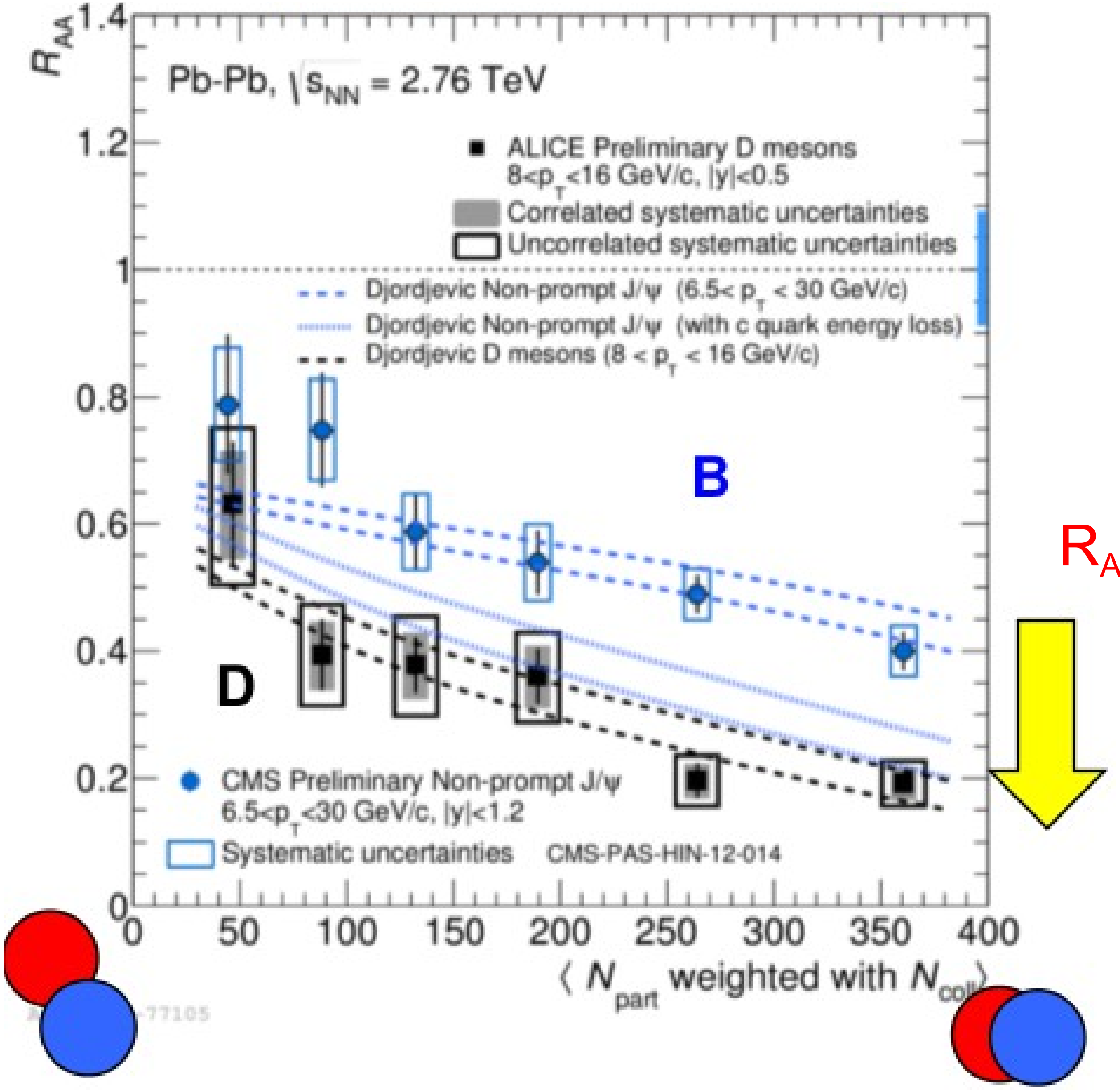
D-mesons



- Similar trend vs p_T for D, charged particles and charged pions
- Hint of $R_{AA}(D) > R_{AA}(\pi)$?

ALICE, arXiv:1203.2160

Beauty via non-prompt J/ψ

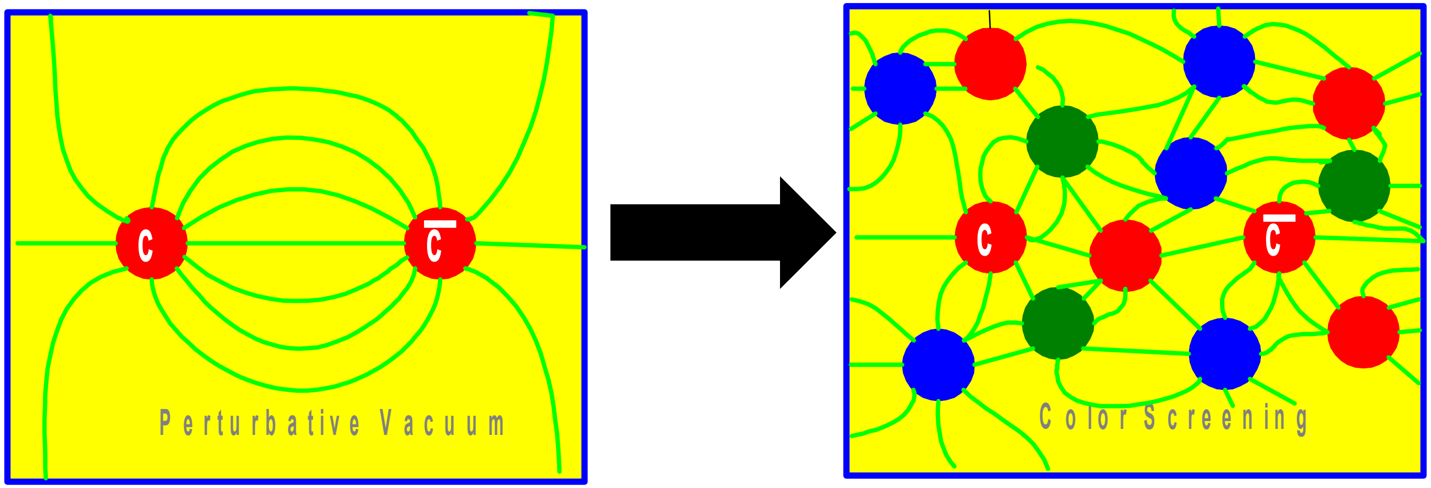


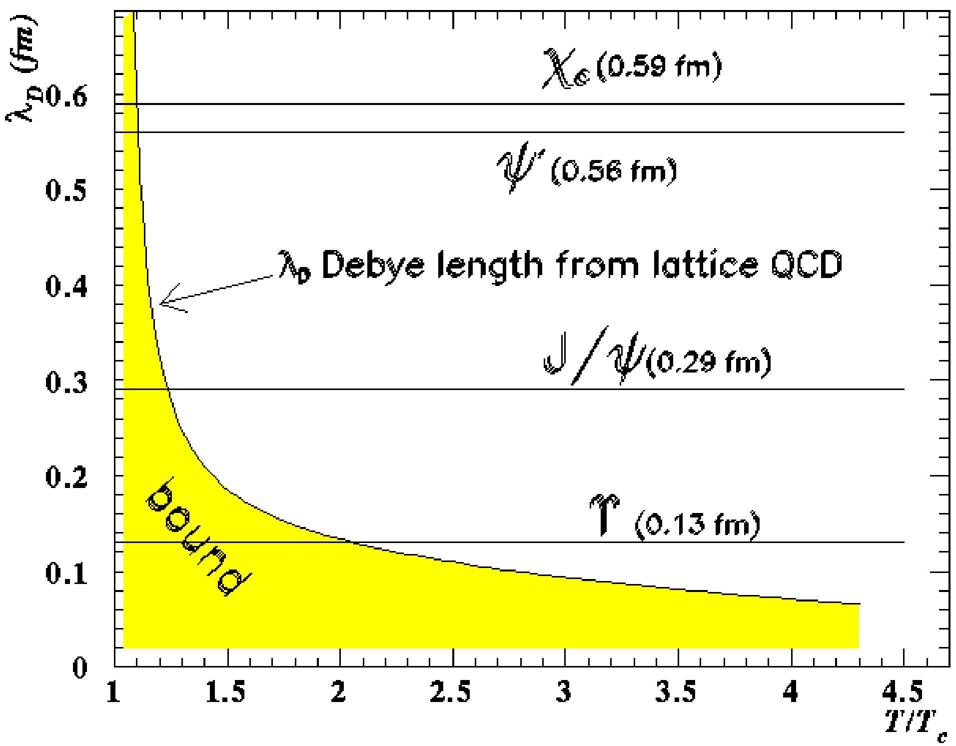
Suppression pattern compatible with expected energy loss hierachy

Quarkonia

Quarkonia melting at high temperature

Screening of strong interactions in QGP





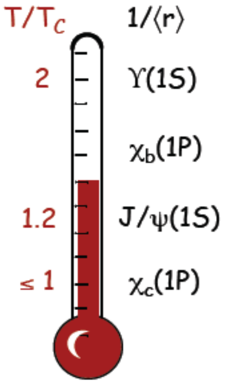
(original idea Matsui and Satz, 1986)

- Screening stronger at high T
- λ_D ~ maximum size of a bound state, decreases when T increases
- Different states with different sizes

Resonance melting

↓

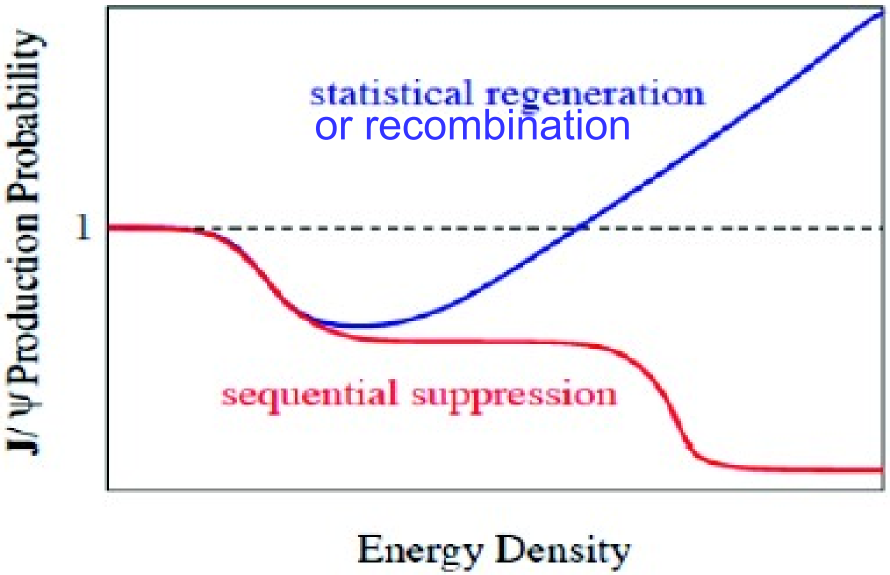
QGP thermometer



Regeneration at high temperature

At sufficiently high energy, the cc pair multiplicity becomes large

In most central A-A collisions	SPS 20 GeV	RHIC 200 Gev	LHC 2.76 TeV
N_{ccbar}/event	~0.2	~10	~60

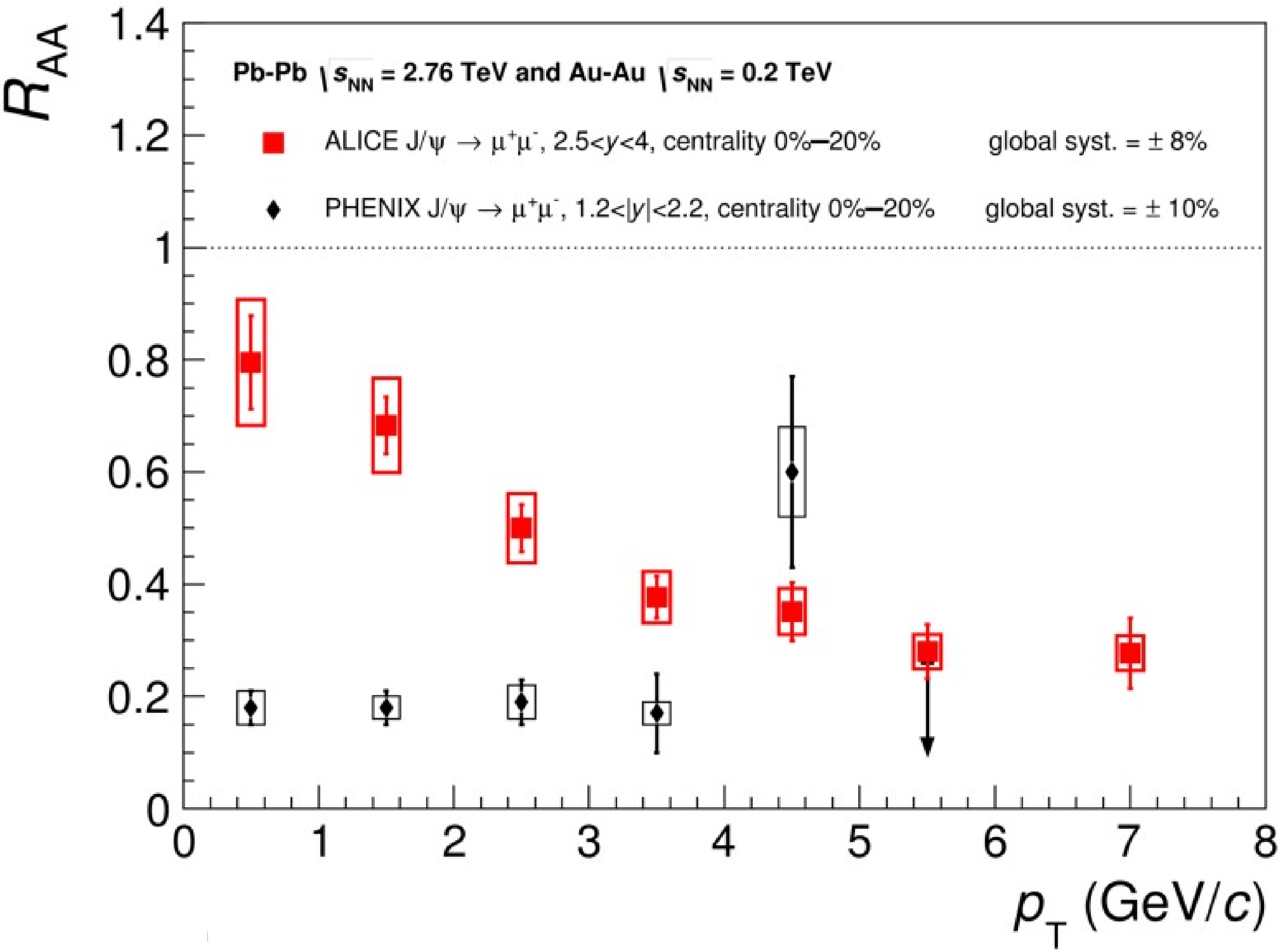


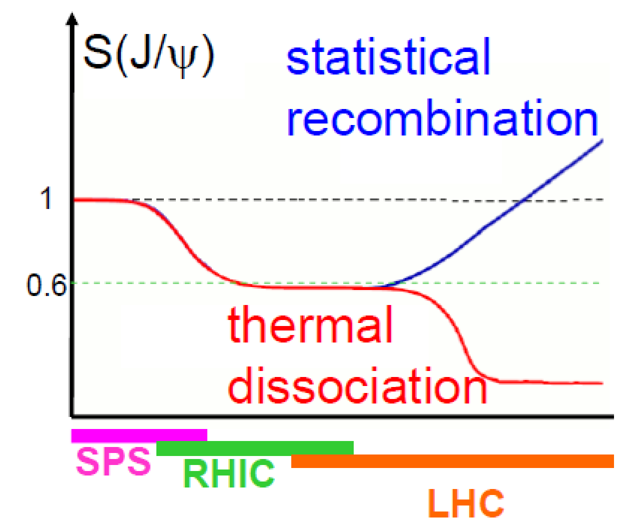
- Statistical approach
  - Charmonium fully melted in QGP
  - Charmonium produced together with all other hadrons at chemical freeze-out according to statistical weights
- Kinetic recombination
  - Continuous dissociation and regeneration over QGP lifetime

Contrary to the suppression / melting scenario, these approaches may lead to J/ψ enhancement

LHC: J/ψ production in Pb-Pb

arXiv:1311.0214

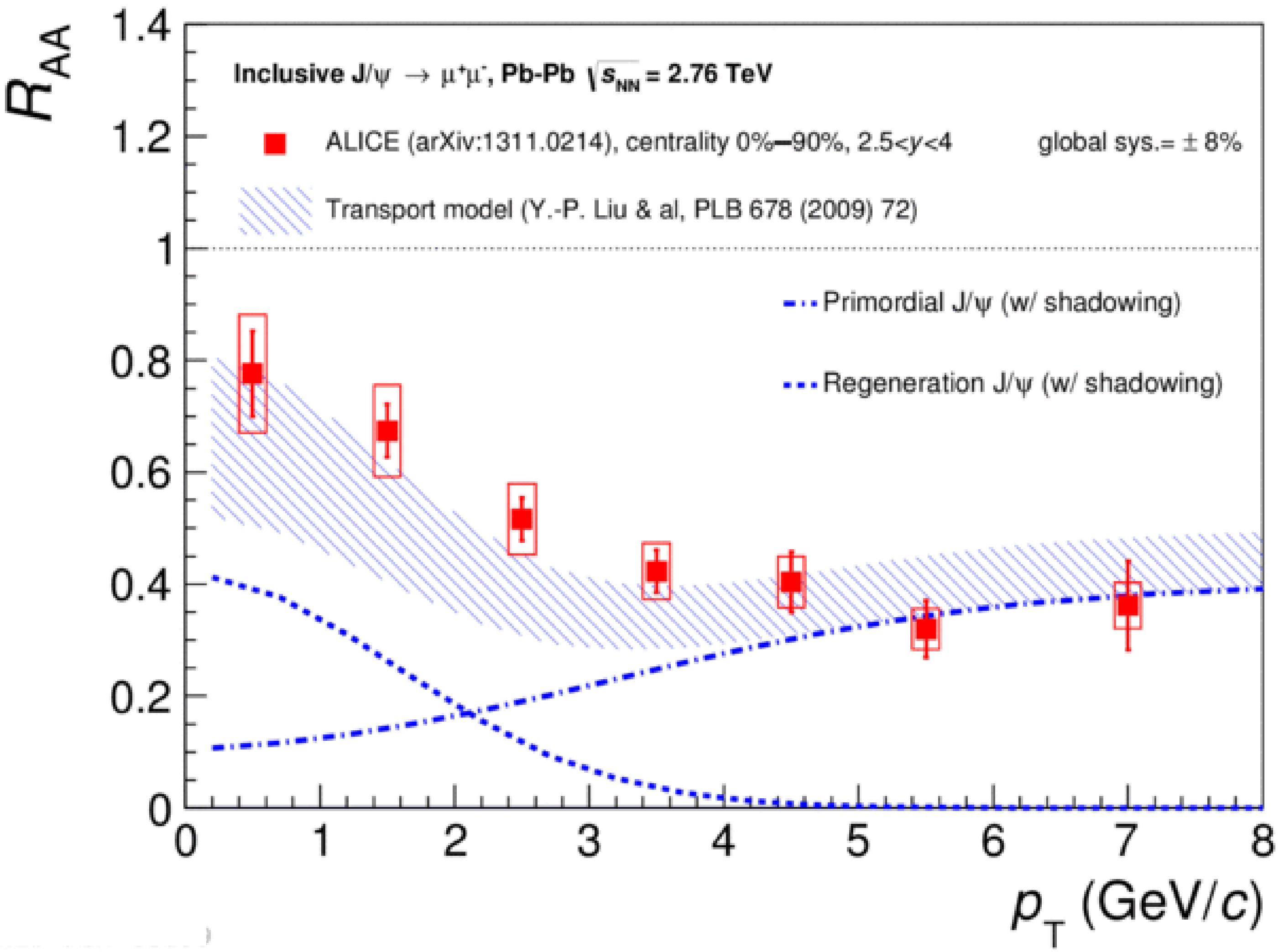


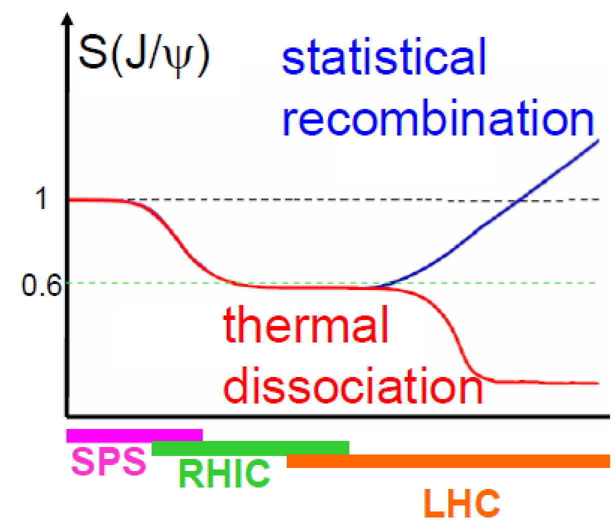


Different p_T (and centrality) dependence of J/ψ R_{AA} at LHC and RHIC

J/ψ production in Pb-Pb

arXiv:1311.0214

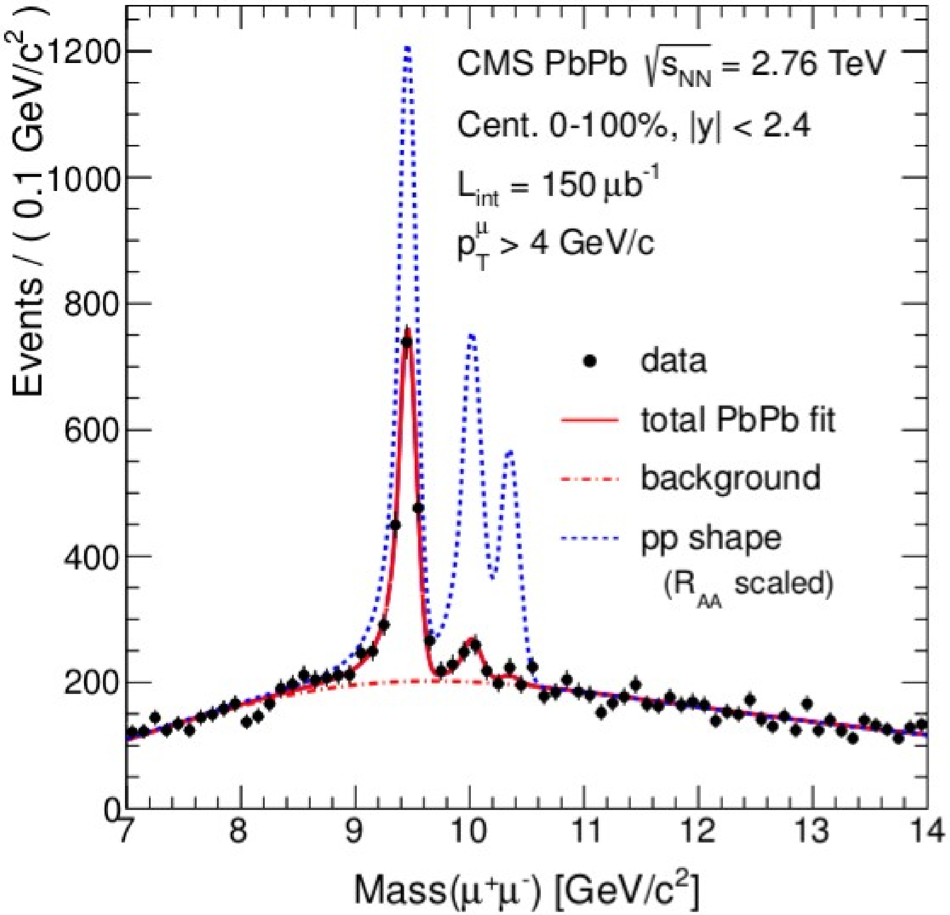


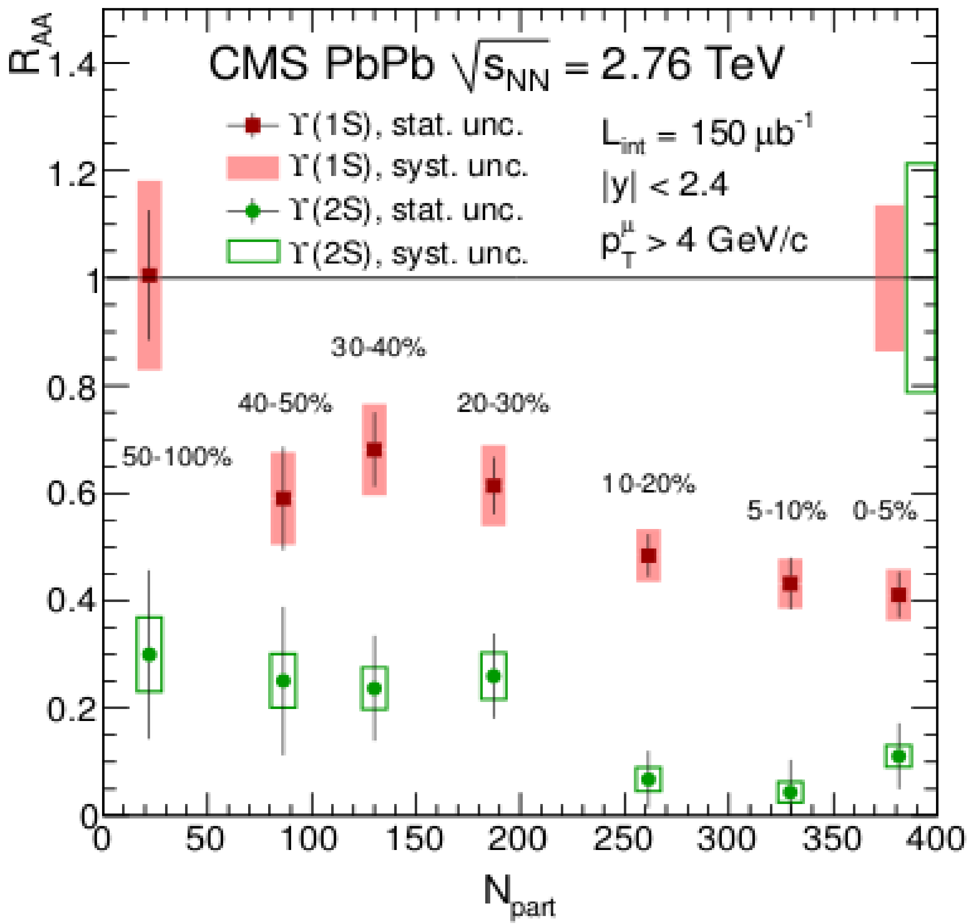


As expected in a scenario with $c\bar{c}$ recombination, especially at low p_T

Suppression of Upsilon states

PRL 109 (2012) 222301





Suppression of Y(1S) ground, and excited Y(2S) and Y(3S) states.
Ordering of R(3S)<R(2S)<R(1S) consistent with sequential melting.

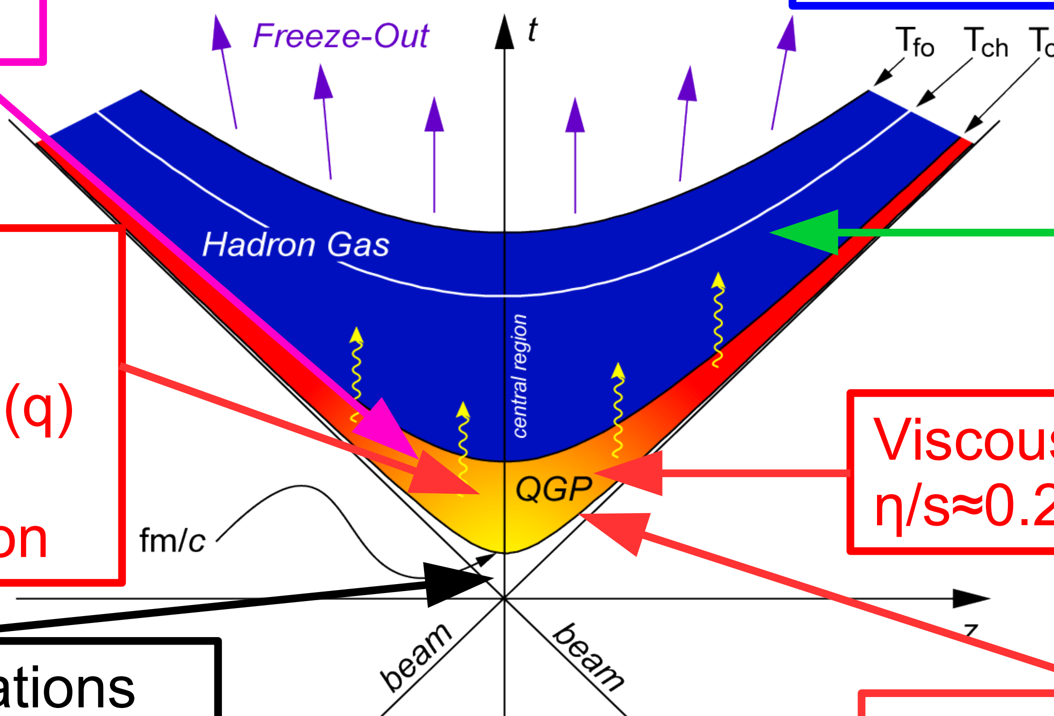
(For R(3S) only upper limit for 100% centrality could be measured)

Summary on measurements

Harmonic flow v_N
(v_2 up to 0.1)
Mass ordering

$dN/d\eta \approx 1600$
(values for central PbPb at 2.76 TeV)

Kinetic freezeout ≈100 MeV
Radial flow velocity ≈0.65c
Volume ≈ 5000 fm^3
Lifetime ≈10 fm/c



Dense medium
↓
Parton energy loss (q)
J/ψ melt./reg.
Upsilon suppression

Chemical freeze-out ≈160 MeV
(Grand-canonical)

Viscous hydrodynamics
η/s≈0.2

Density fluctuations
↓
Interactions/Pressure
↓
Momentum anisotropies

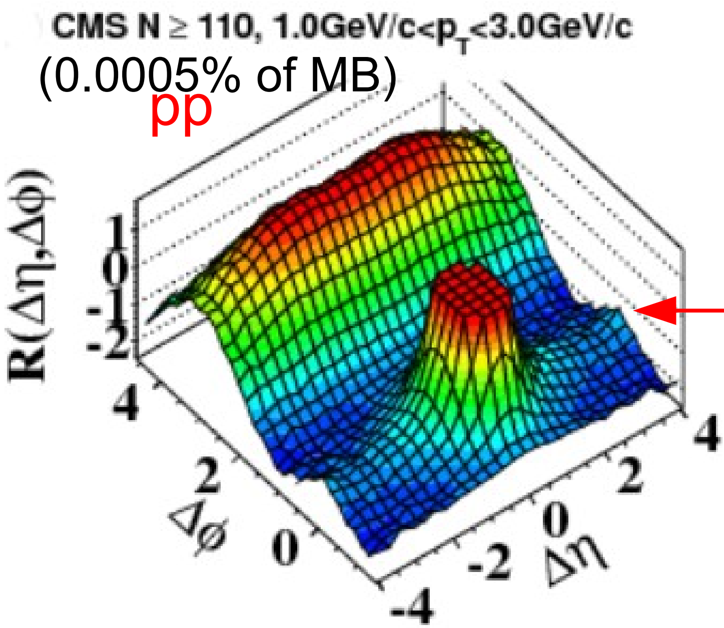
Initial temperature
>300 MeV

All observations (+ absence in control systems) point to the formation of hot deconfined matter!

Collectivity in small systems

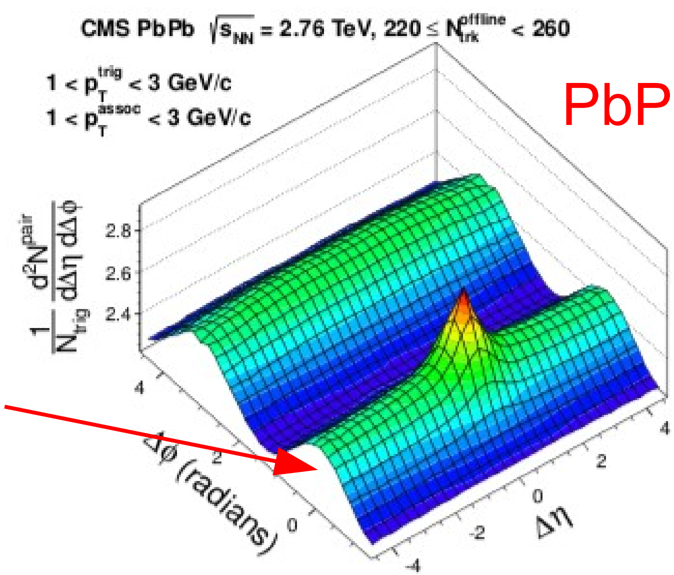
Two-particle angular correlations

Near-side ridges apparent in high multiplicity events at LHC energies



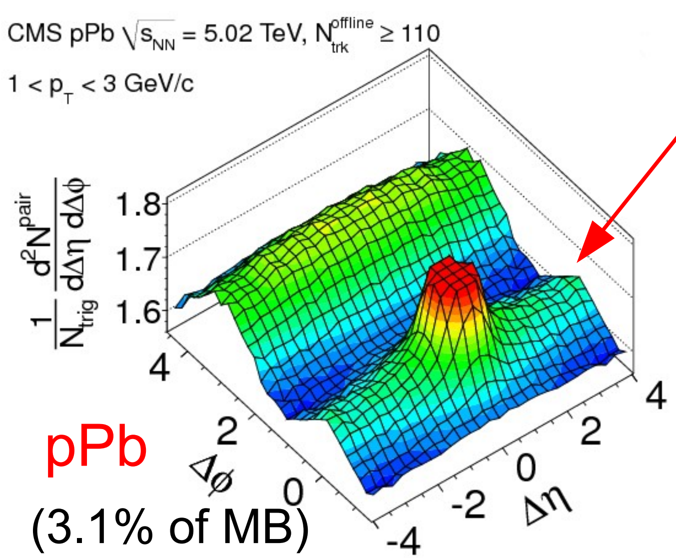
(0.0005% of MB)
pp

CMS, JHEP 1009 (2010) 91



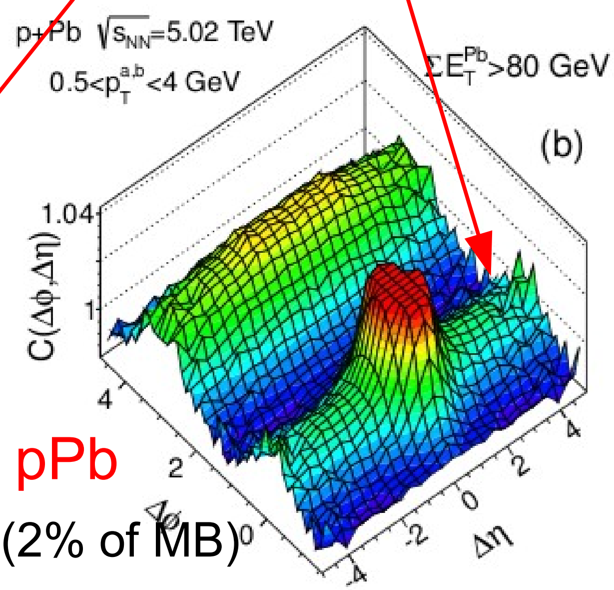
PbPb

CMS, PLB 724 (2013) 213



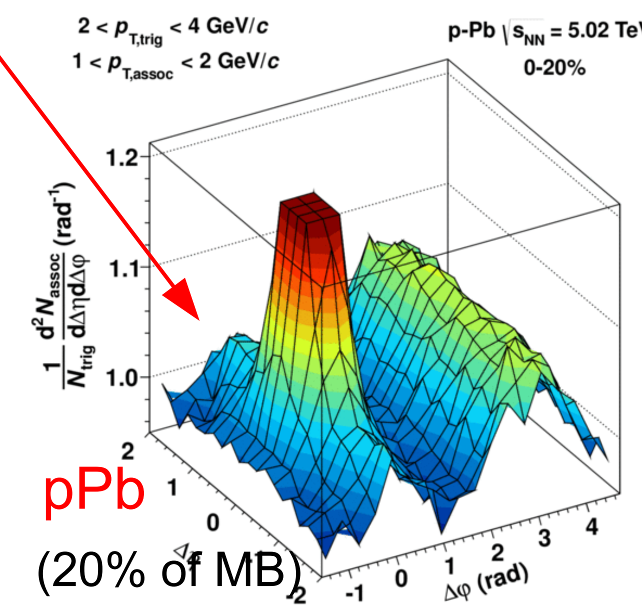
pPb
(3.1% of MB)

CMS, PLB 718 (2012) 795



pPb
(2% of MB)

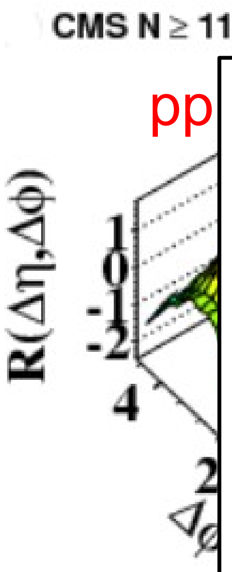
ATLAS, PRL 110 (2013) 182302

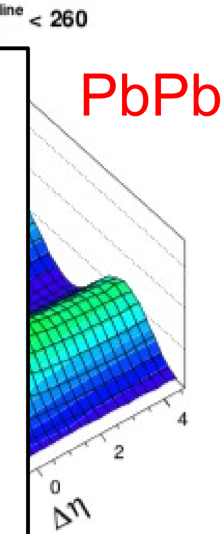


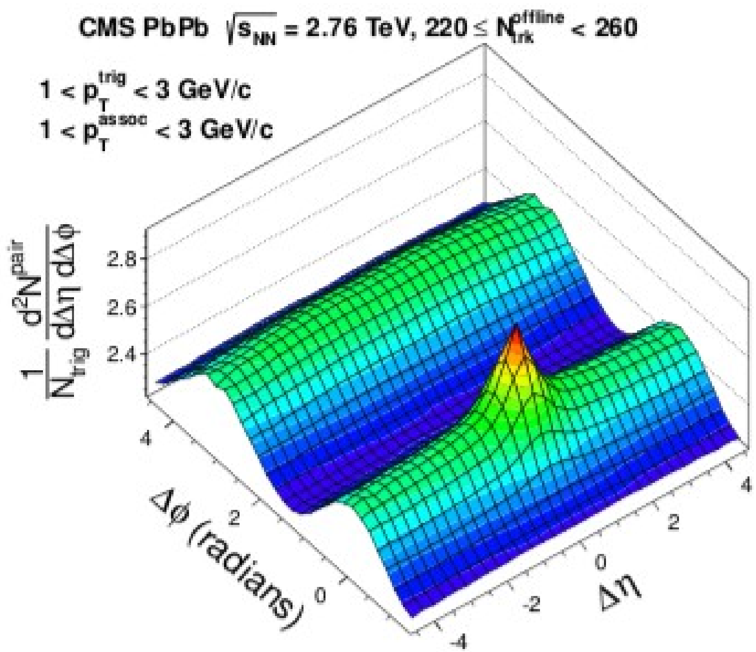
pPb
(20% of MB)

ALICE, PLB 719 (2013) 29

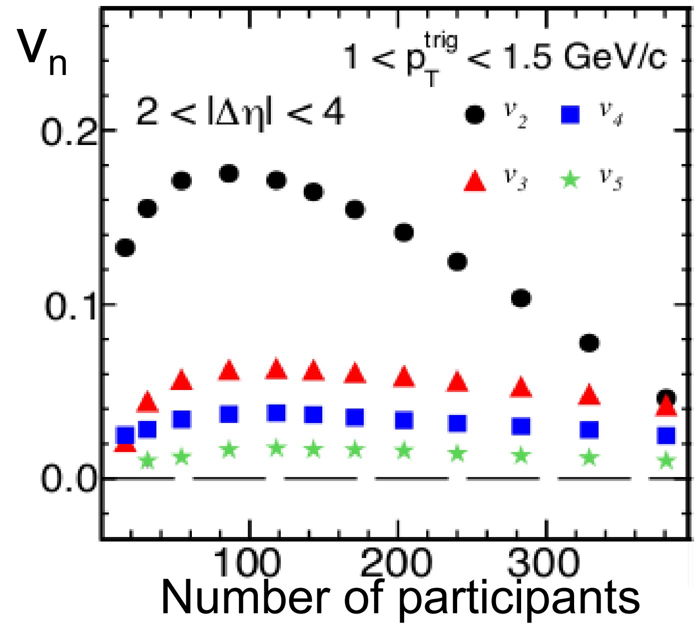
Two-particle angular correlations



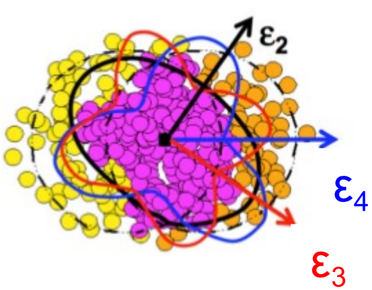




CMS, EPJC 72 (2012) 10052

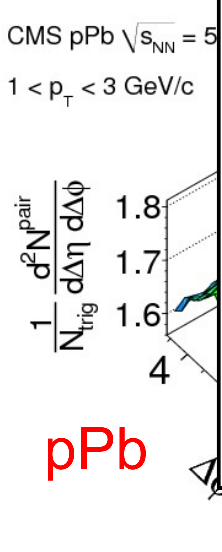


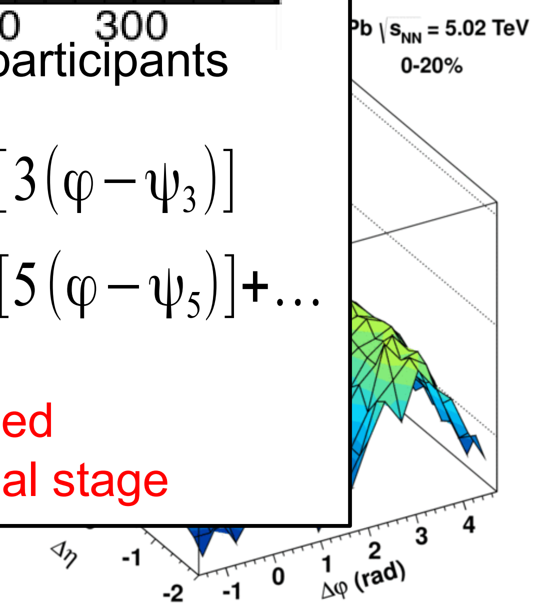
CMS, ... (2013) 213



$$\frac{dN}{d\varphi} \sim 1 + 2v_2\cos[2(\varphi-\psi_2)] + 2v_3\cos[3(\varphi-\psi_3)] + 2v_4\cos[4(\varphi-\psi_4)] + 2v_5\cos[5(\varphi-\psi_5)] + \ldots$$

In PbPb, long-range harmonics (v_n) are explained as a result of pressure gradients created in initial stage



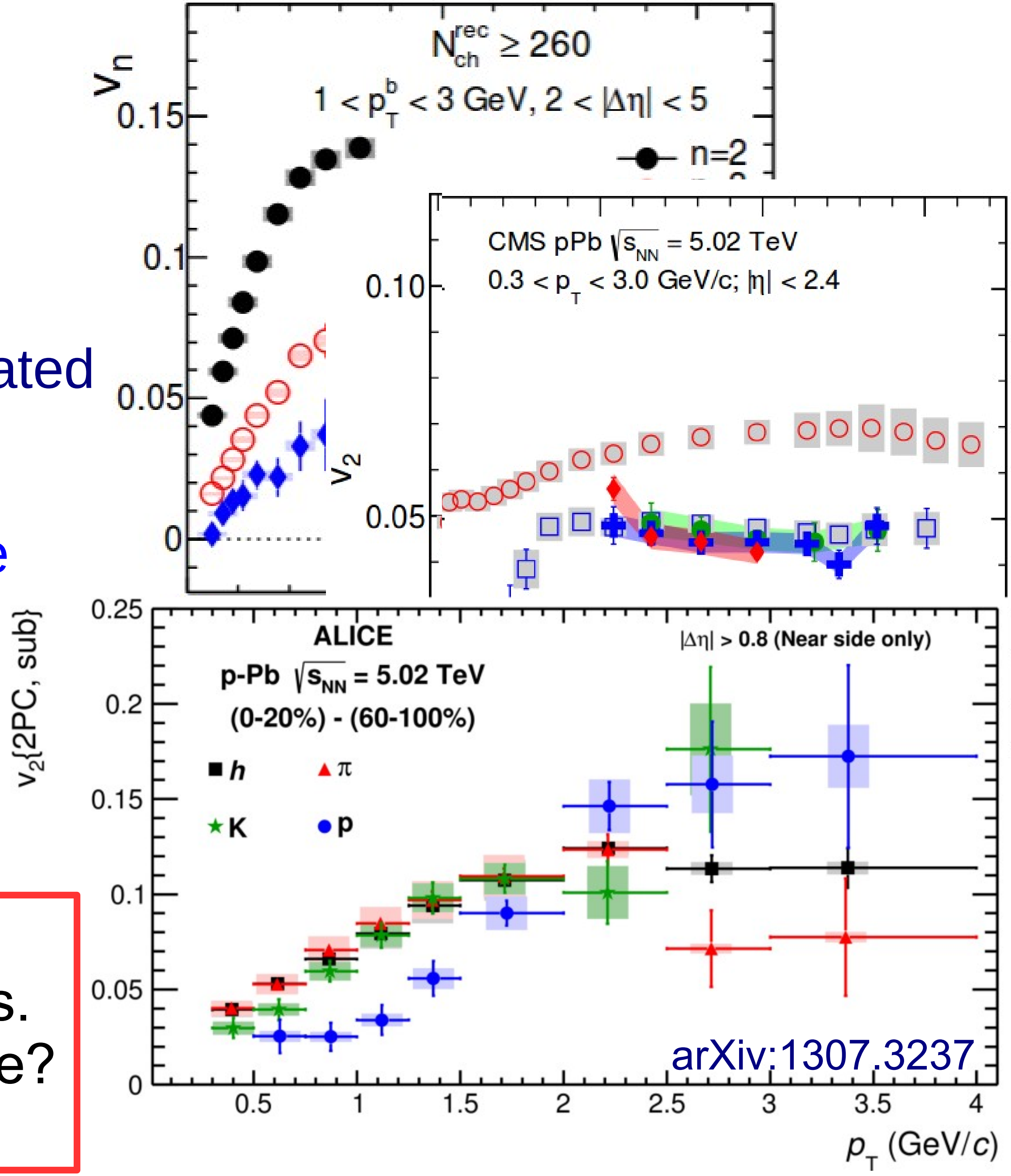


CMS, PLB 718 (2012) 795 ATLAS, PRL 110 (2013) 182302 ALICE, PLB 719 (2013) 29

Ridge properties in pPb

- v_n coefficients
  - Significant for n=2 to 5
  - Substantial to even high p_T
- Multiparticle correlations
  - At least 8 particles correlated
  - $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Particle species dependence
  - Cross of v_2(proton) with v_2(pion) at about 2 GeV/c for p_T<2 GeV/c

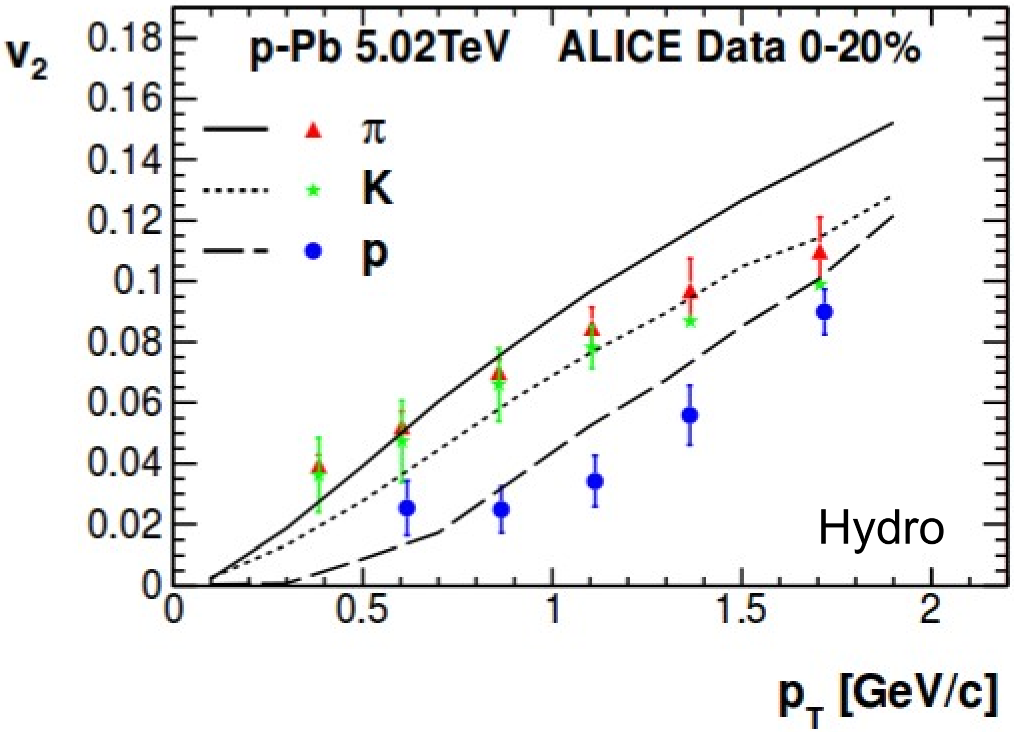
arXiv:1409.1792



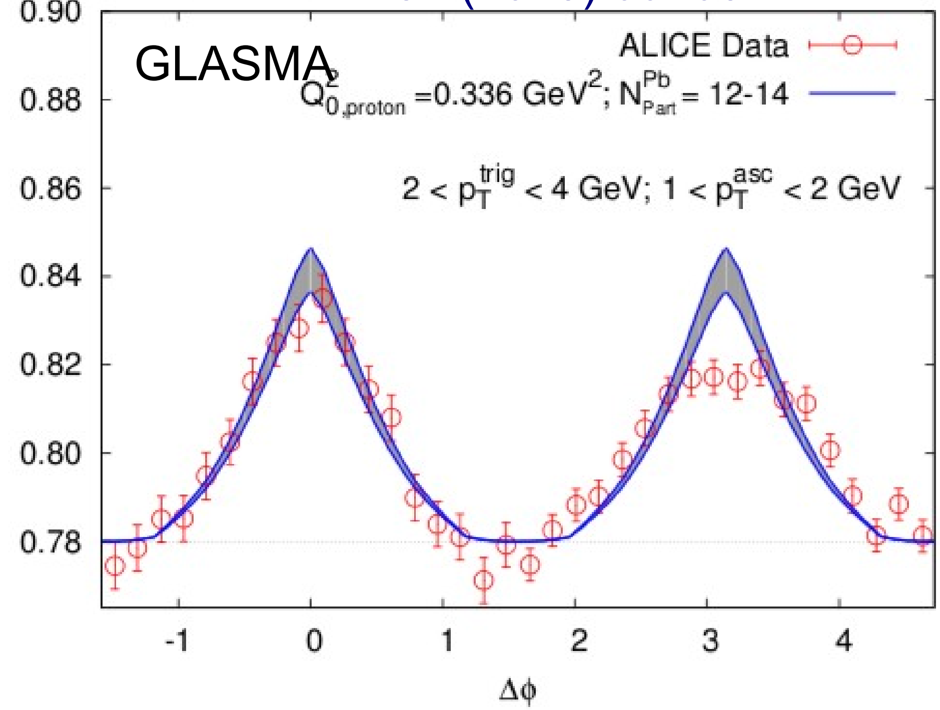
Features qualitatively similar to those seen in PbPb collisions. Suggests same physics at place?
arXiv:1602.09138

Interpretation: active debate

arXiv:1307.5060



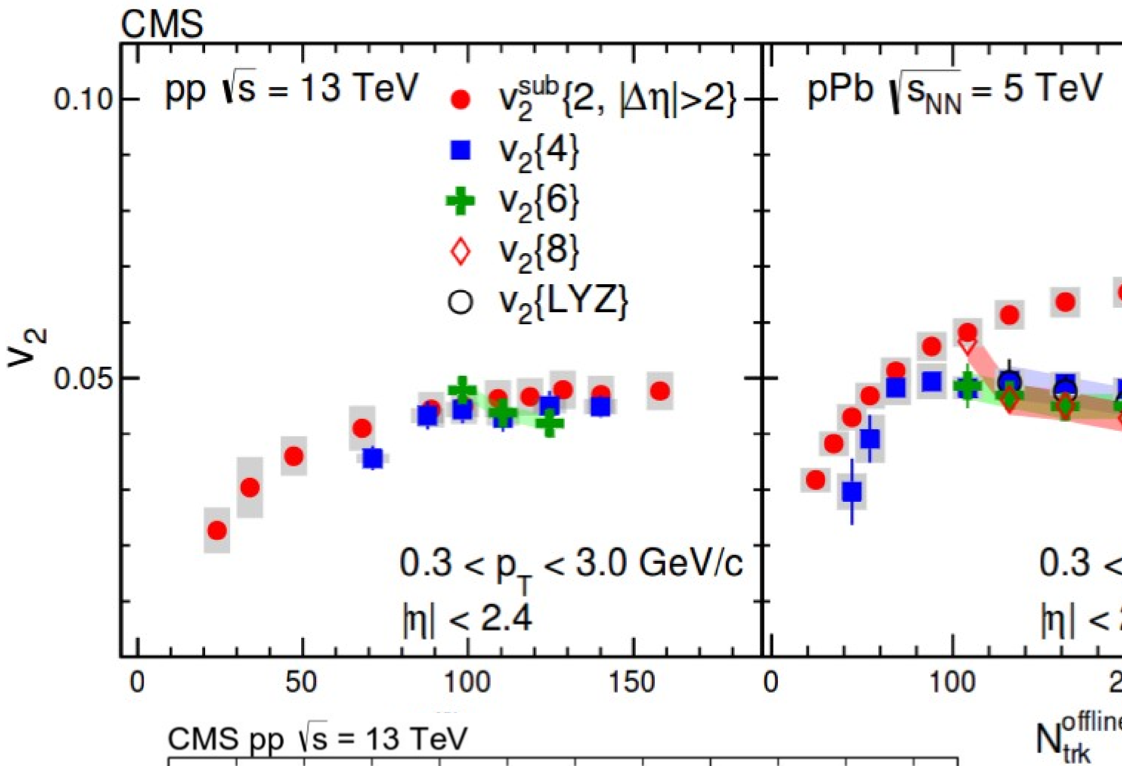
PRD 87 (2013) 094034

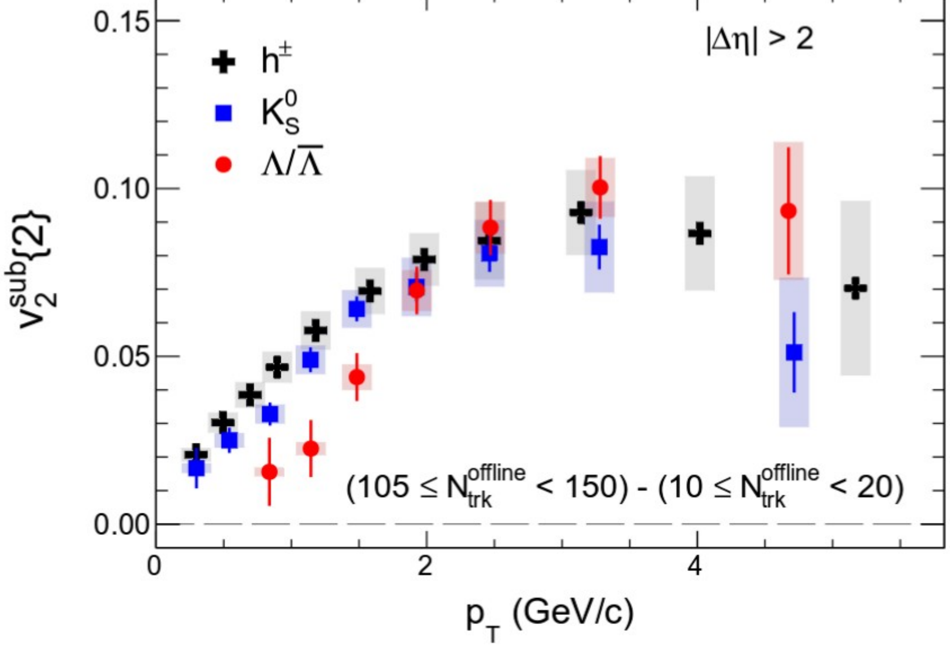


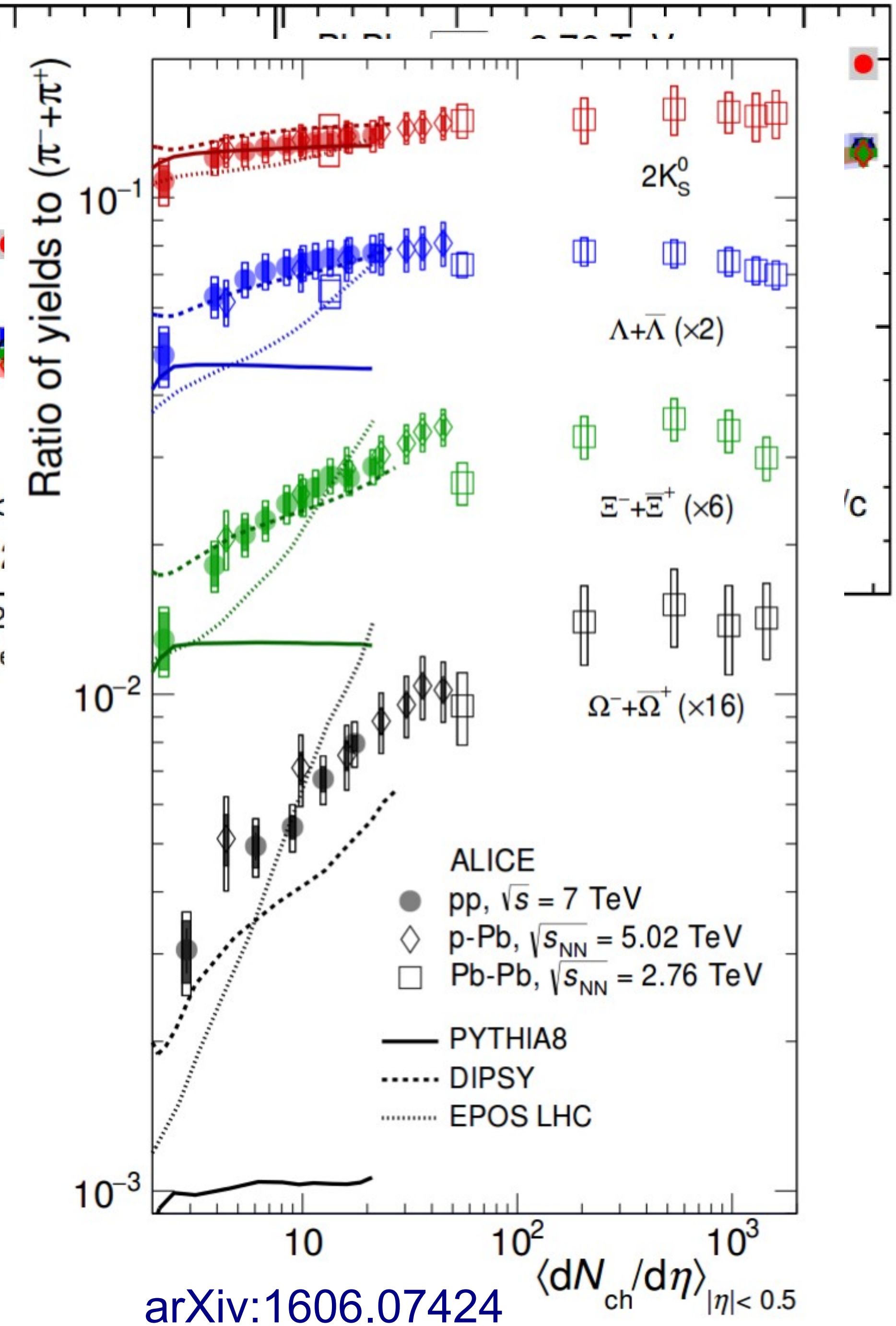
- Two orthogonal approaches with (semi-) quantitative predictions:
  - Formation of mini-QGP with hydrodynamical evolution
  - Entanglement of gluons in the initial state (GLASMA graphs)
- Many alternative ideas but often only at qualitative level
- Change of paradigm wrt role of “control” systems (under debate)

arXiv:1606.06198

And even in pp collisions







arXiv:1606.07424

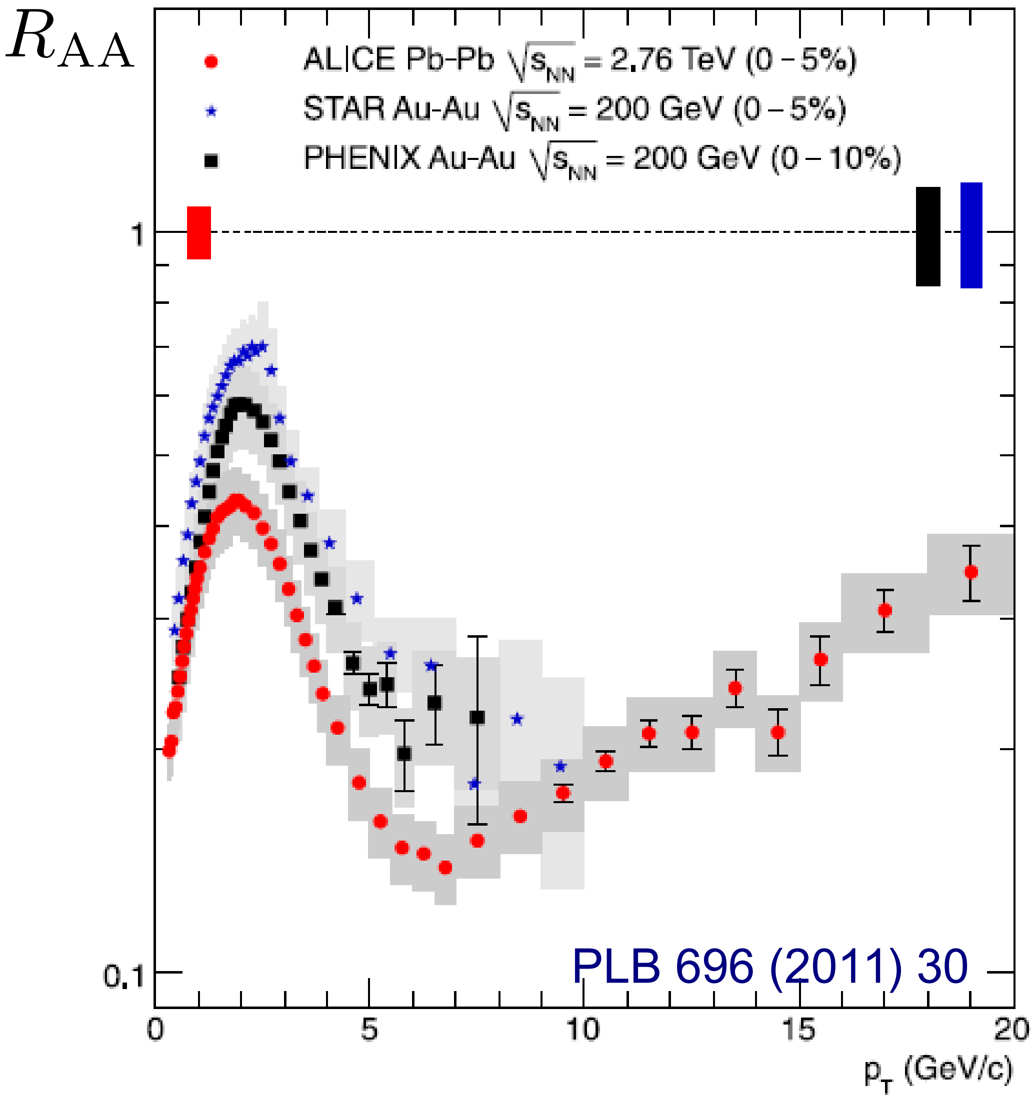
Summary

- QCD is a quantum field theory with rich dynamical content, complex phase structure, and important open questions
- Heavy-ion collision experiments attempt to create and probe QCD matter at high temperature and energy density
- The medium (at RHIC/LHC) behaves almost like a perfect fluid with the characteristics predicted for a QGP, in particular with spectacularly strong effects on hard probes (jets, quarkonia, …)
- With the advent of the LHC we answered some of the long-standing questions, but we also face new interesting questions, which may be tackled with the help of you!

If you have questions about today's lecture please send them to “cloizides at lbl dot gov”

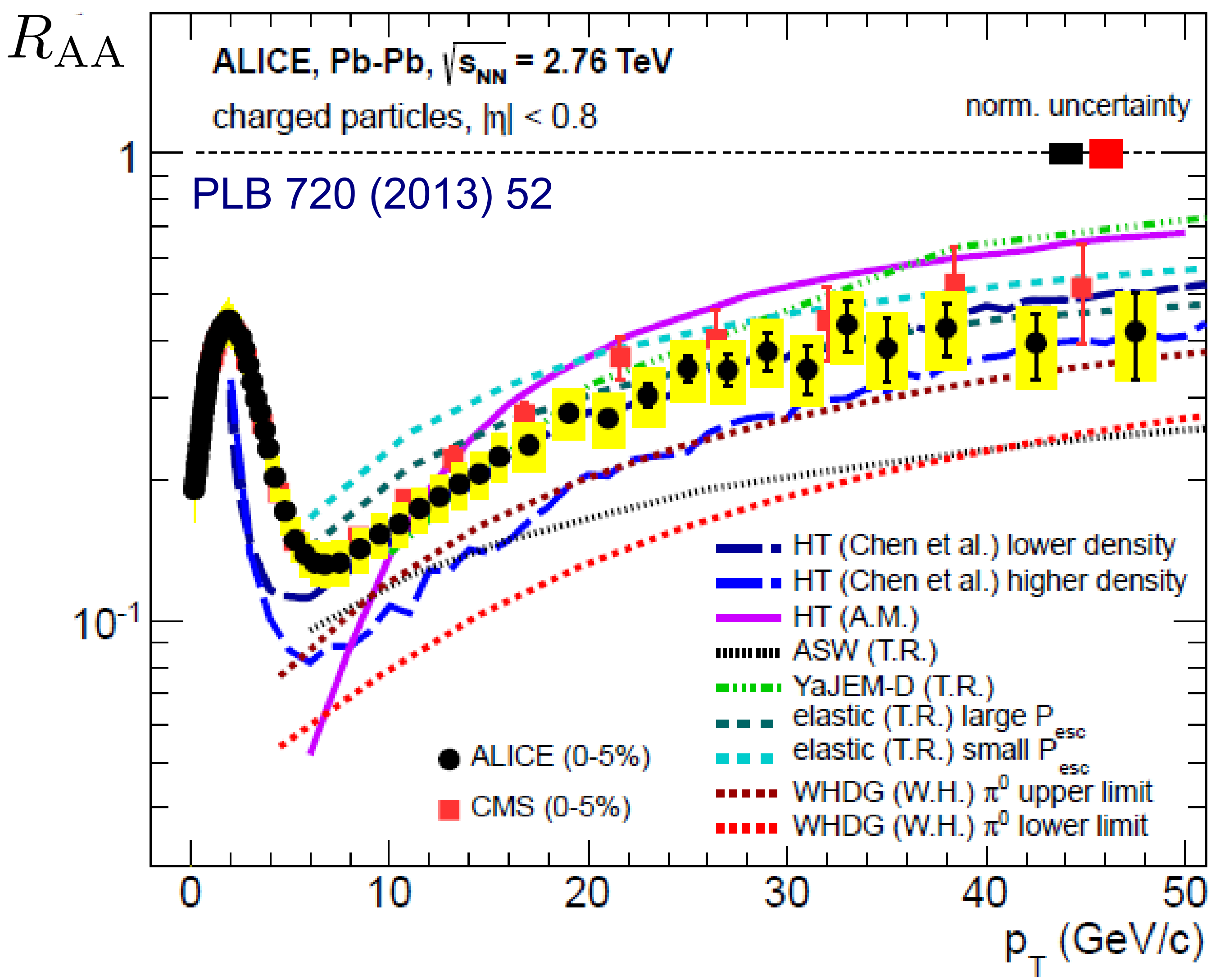
Extra

Leading particle suppression at the LHC



- Strong leading particle suppression also at LHC energies
- Qualitatively similar to the one at RHIC

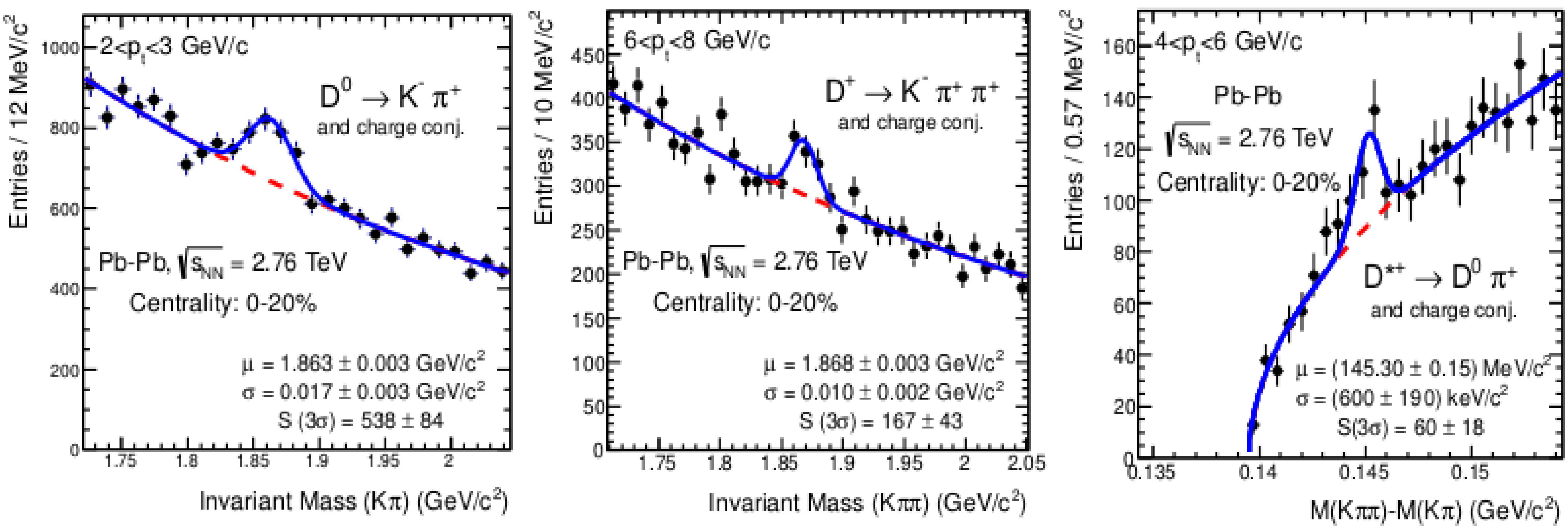
LHC jet quenching: Comparison to pQCD-based models



- Qualitatively: energy loss picture consistent with data
  - Models calibrated at RHIC and scaled to LHC via multiplicity growth
  - Key prediction of p_T-dependence of R_{AA}: ΔE~log(E) ok!

Various techniques for heavy flavor measurements

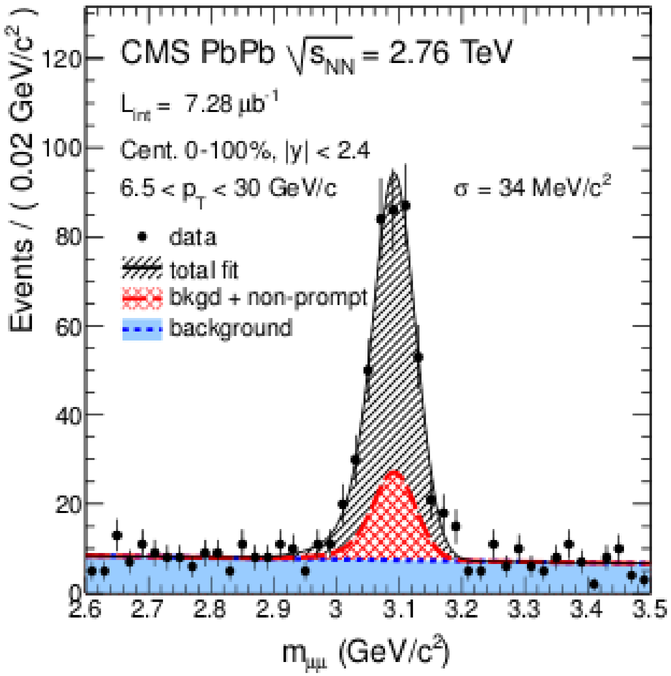
- Indirect measurement via non-photonic electrons
    - Exploit semi-leptonic decay channels of heavy quark mesons
- Direct reconstruction of hadronic decay channels
    - Fully combinatorial analysis (build all pairs/triplets etc) unfeasible
    - Instead use invariant mass analysis of decay topologies separated from the interaction vertex (need ~100µm resolution)
    - Kaon identification (TOF, dE/dx)

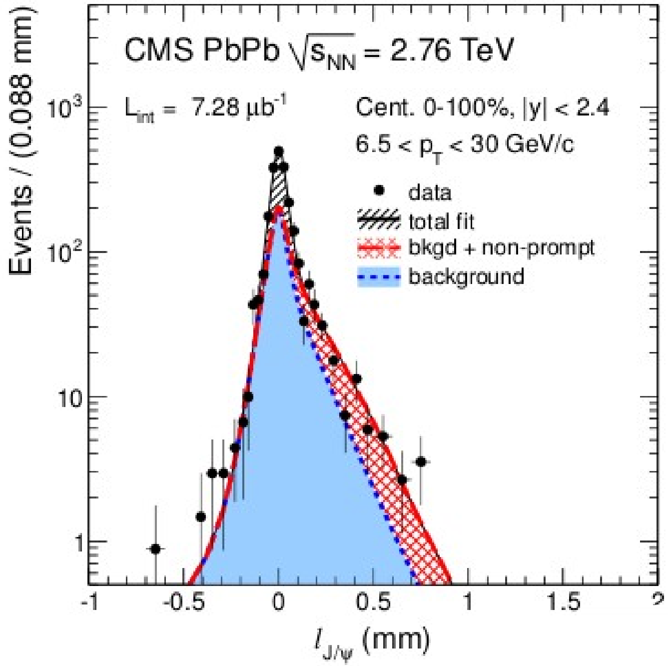


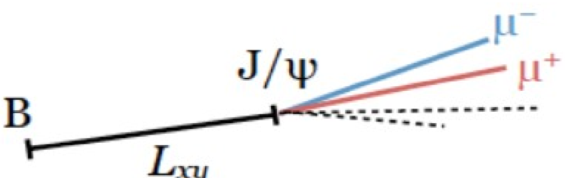
Beauty via displaced J/ψ

B mesons via secondary J/ψ:

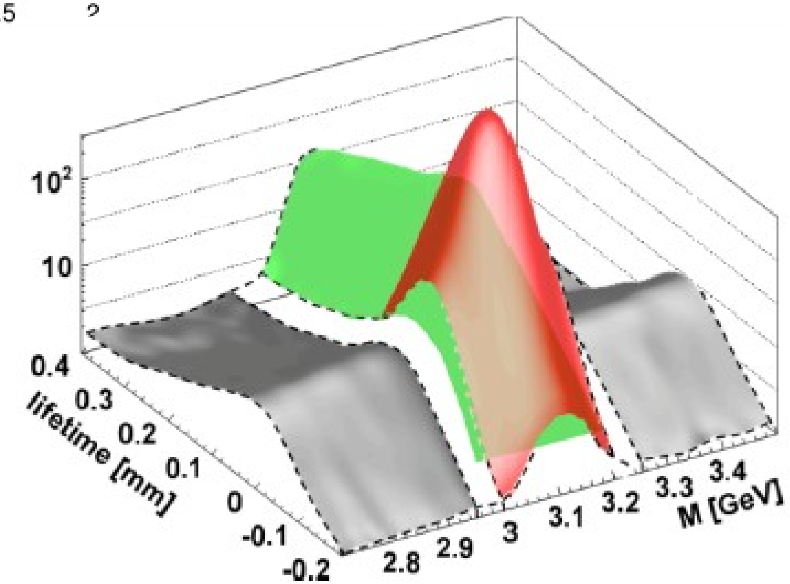
CMS, JHEP 1205 (2012) 063







Clean separation of 2nd vertex for J/ψ with p_T>6.5 GeV/c

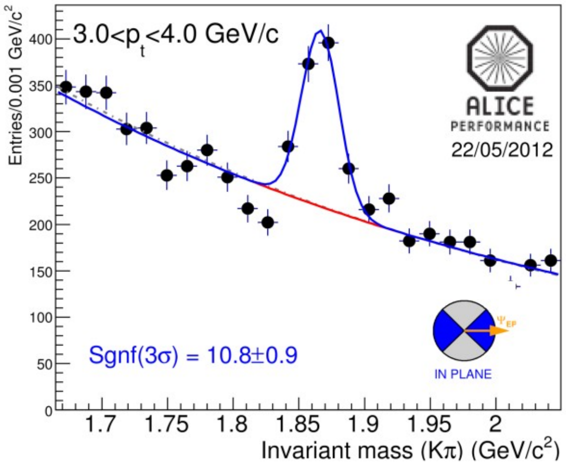


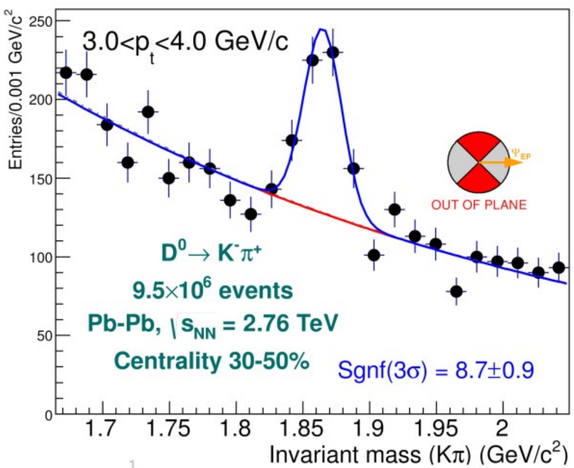
Fraction of non-prompt J/y from simultaneous fit to m+m- invariant mass spectrum and pseudo-proper decay length distributions (pioneered by CDF)

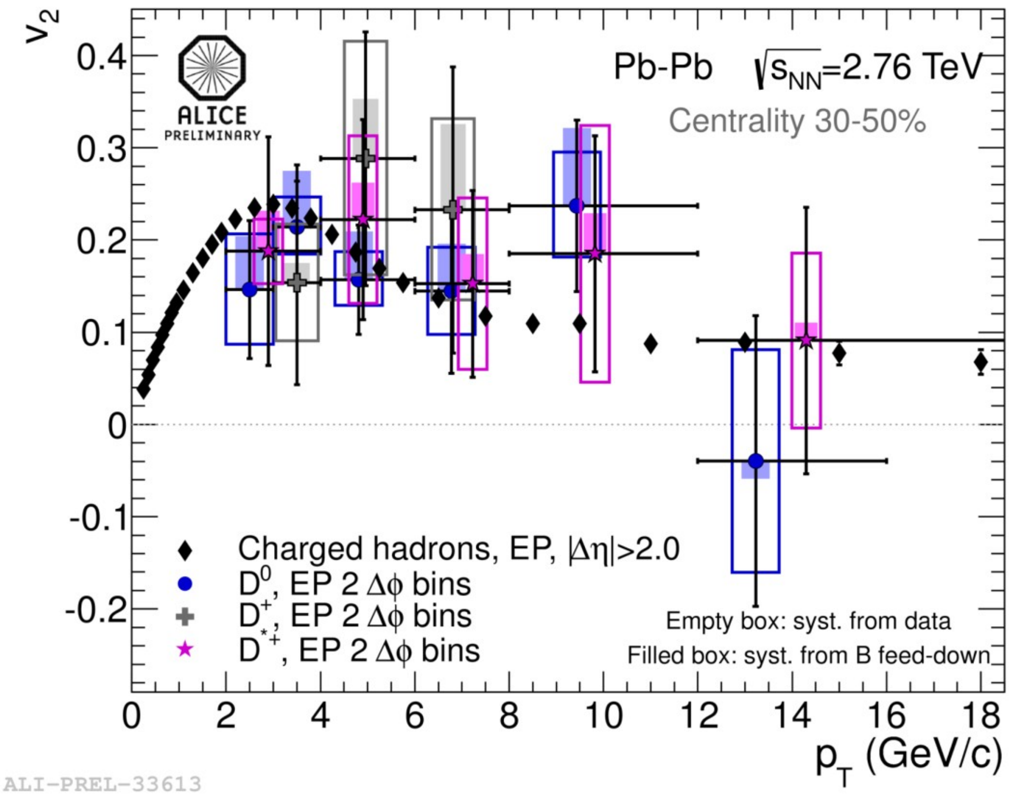
Heavy-quark v_2 at the LHC

arXiv:1405.2001

$$v_2 = \frac{1}{R}\frac{\pi}{4}\frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$





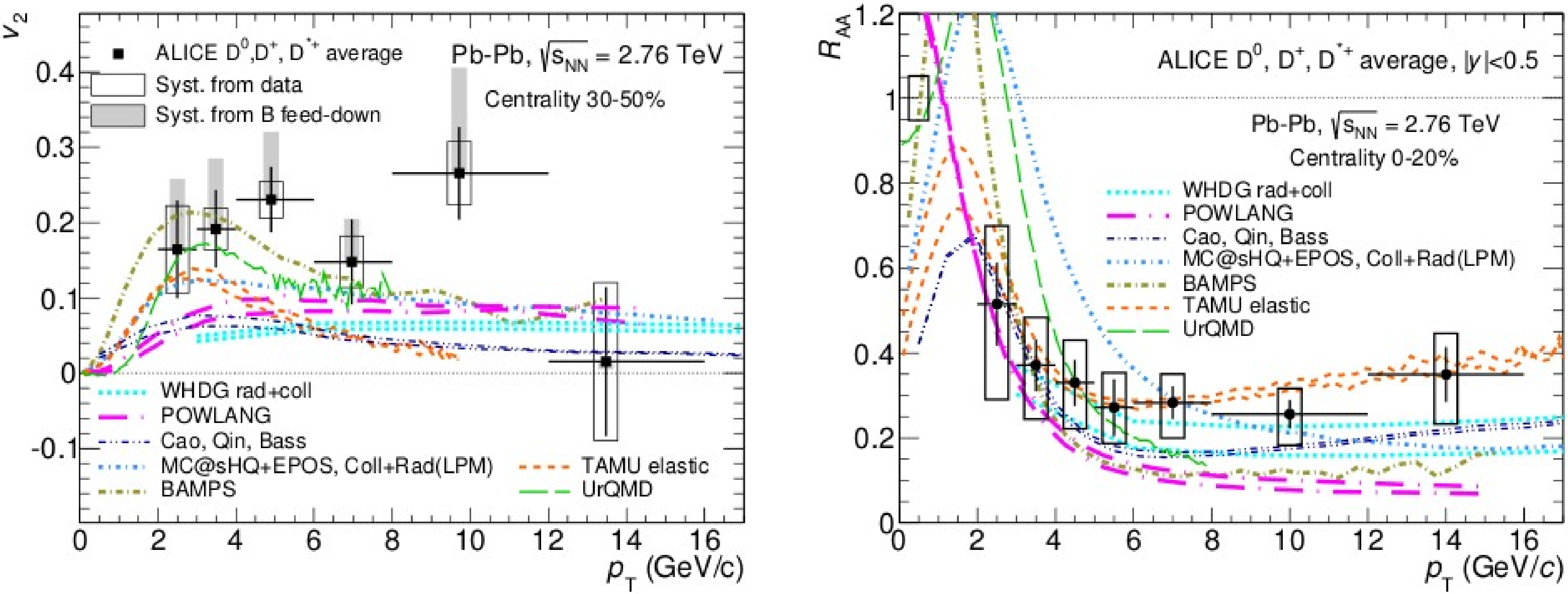


Indication of non-zero D meson v_2: It implies that heavy quarks also thermalize and participate in the collective expansion.

→ Need more data and to measure at lower p_T

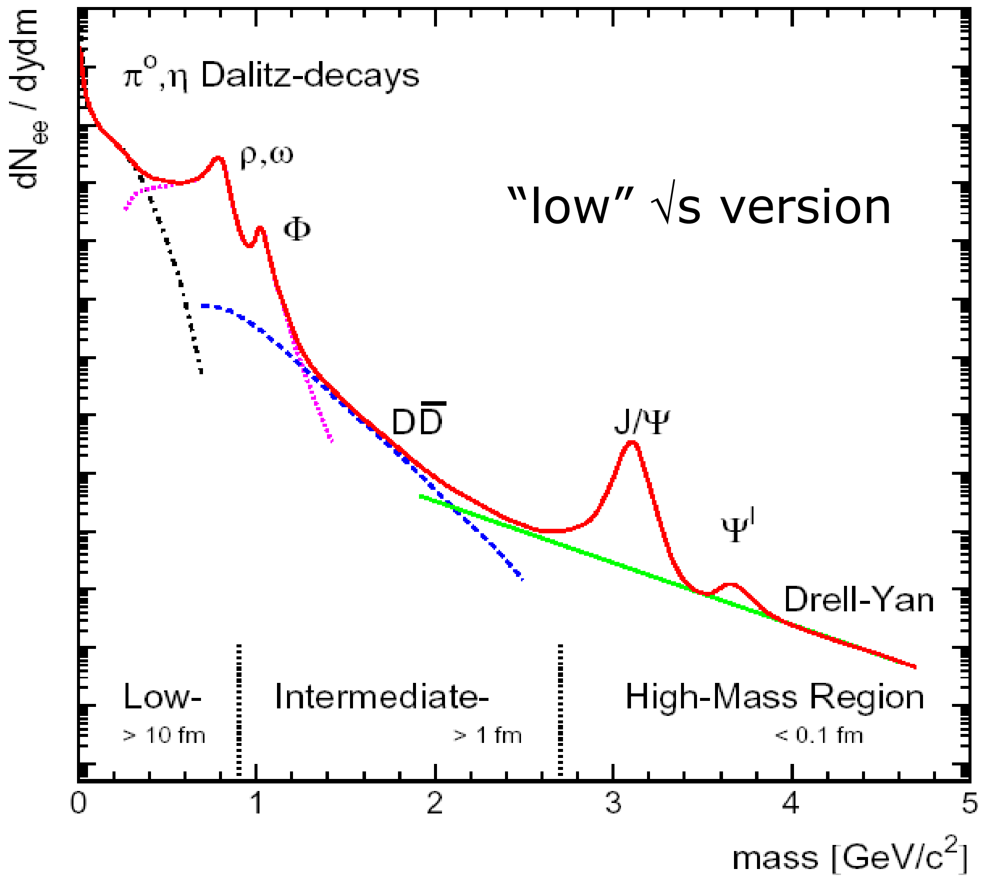
LHC D-mesons: Data vs models

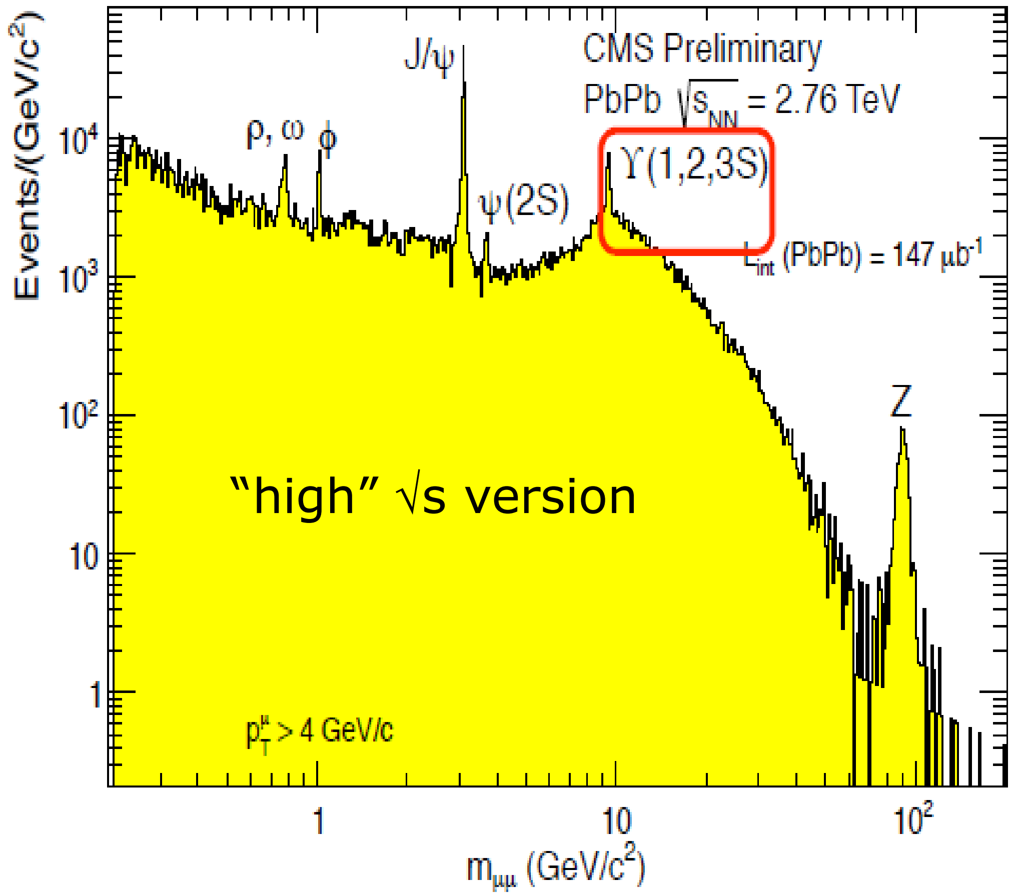
arXiv:1405.2001



Consistent description of charm RAA and v2 challenging for models.
Can bring insight into medium transport properties, and
with more data from future LHC runs.

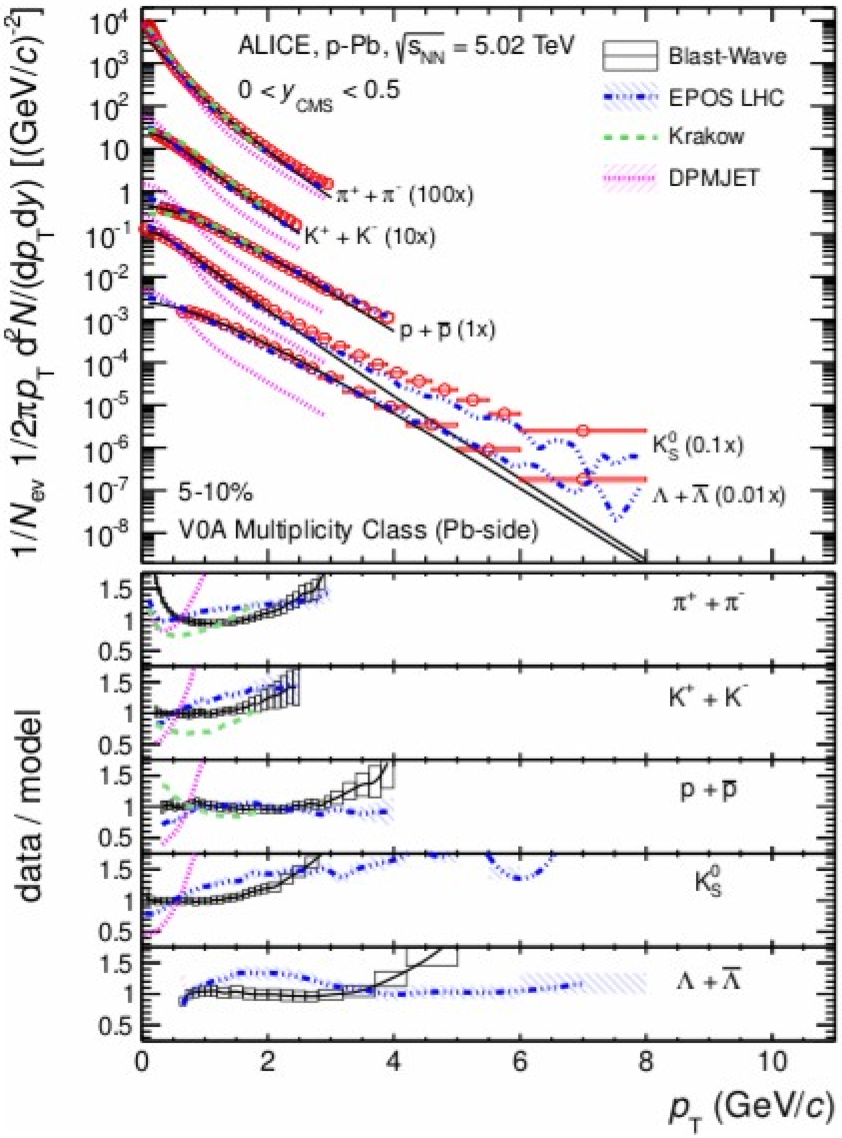
The dilepton invariant mass spectrum



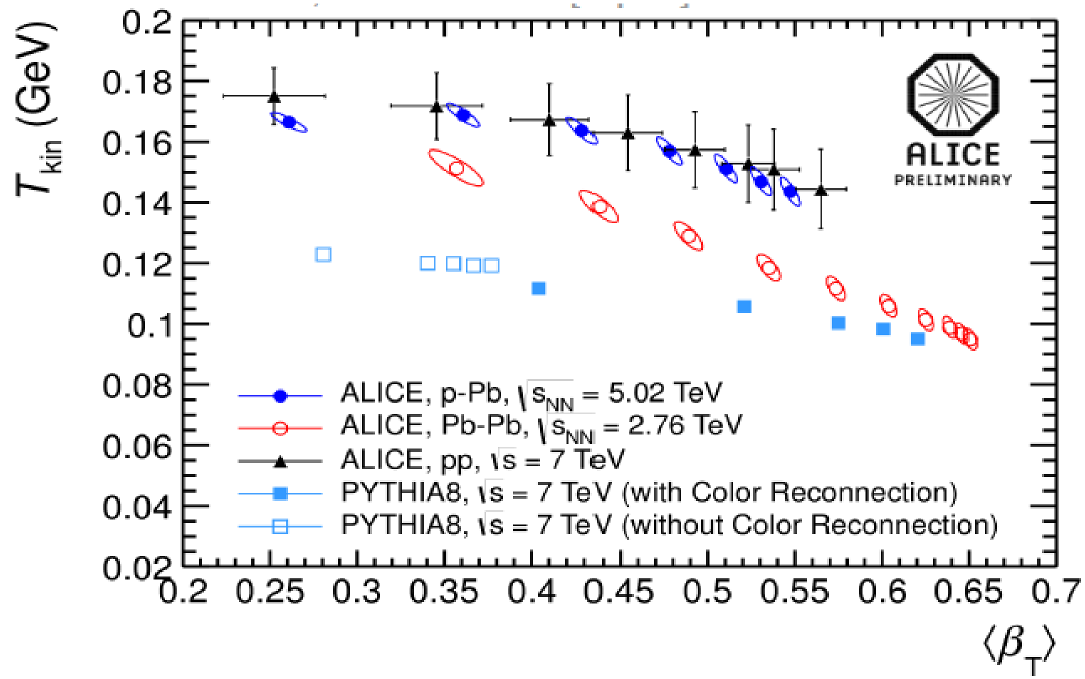


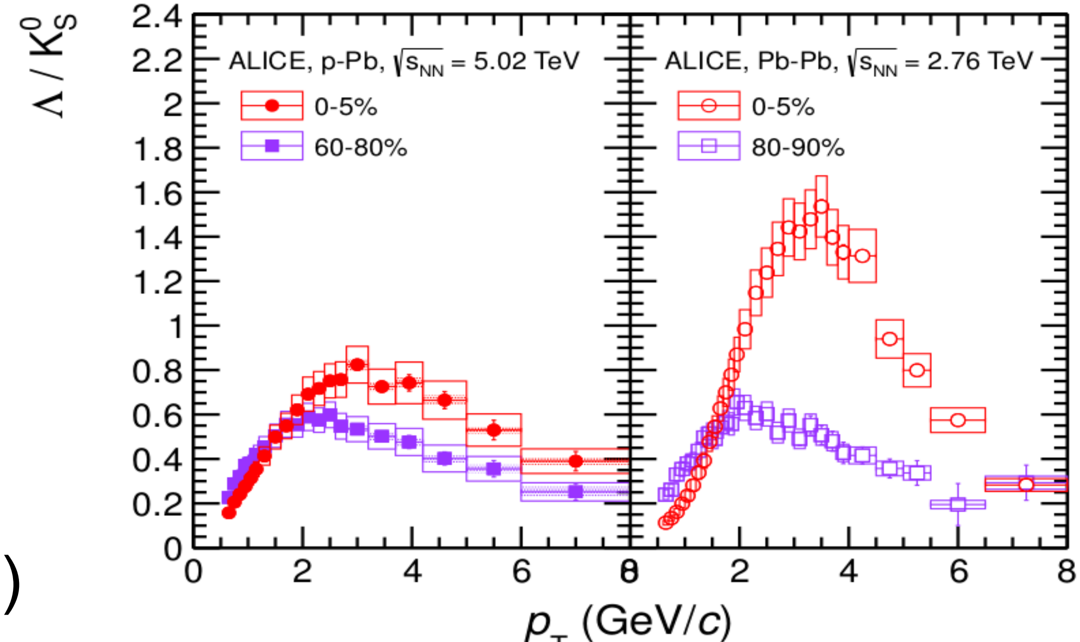
- The study of lepton pairs also allows to extract information about the early stages of the collision
- Dileptons (like photons) do not interact strongly and once produced can without significant re-interactions (not altered by later stages) escape the collision

Identified particle spectra



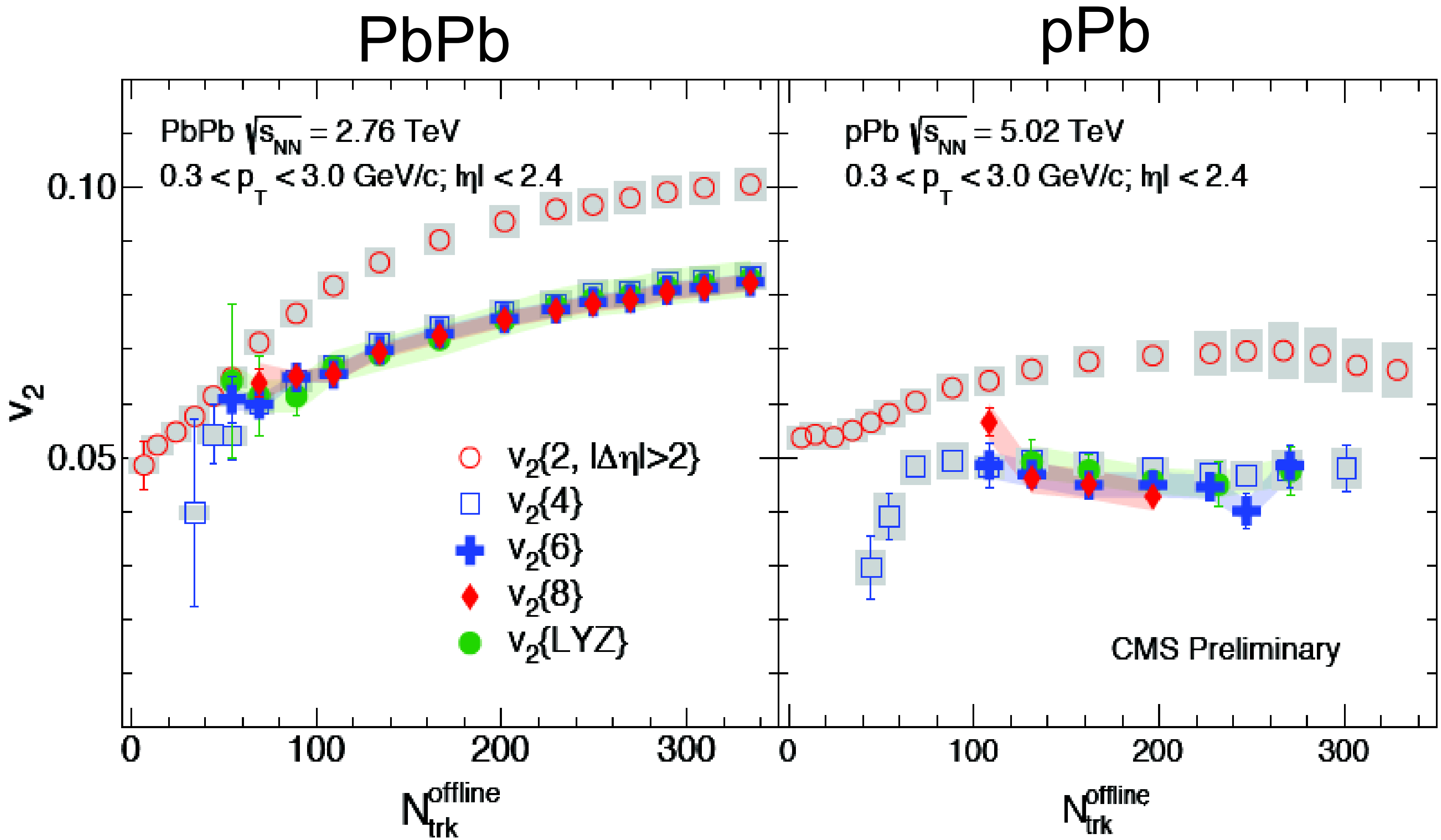
ALICE, PLB 278 (2014) 25





Spectra consistent with radial flow picture (also in pp)

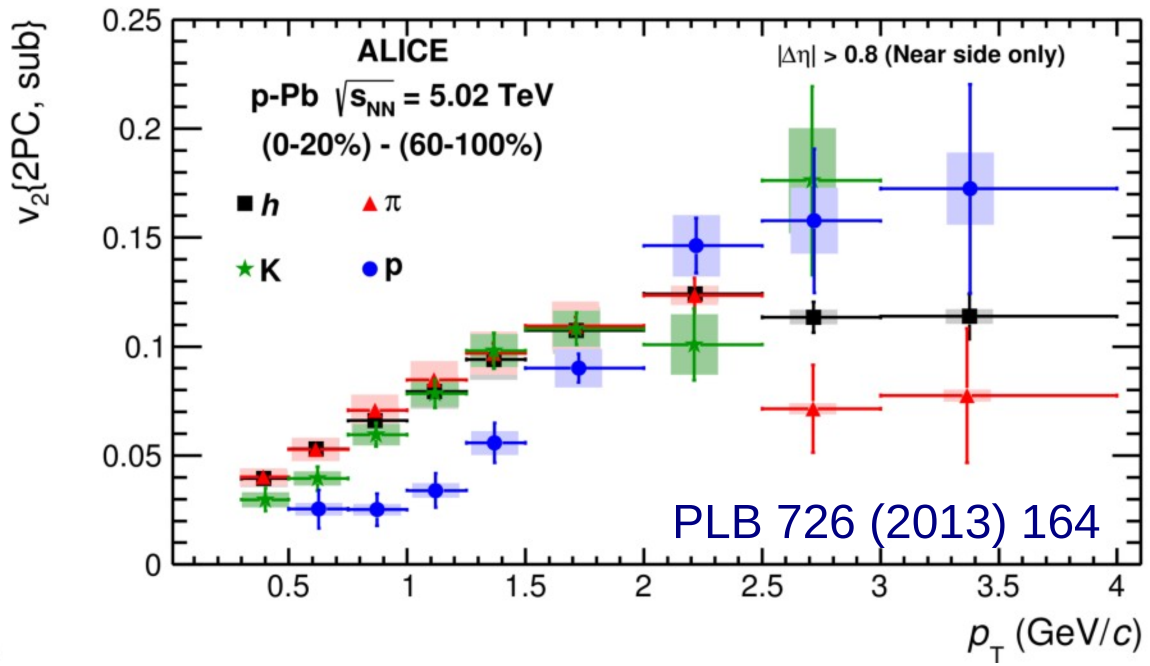
Multi-particle correlations: CMS



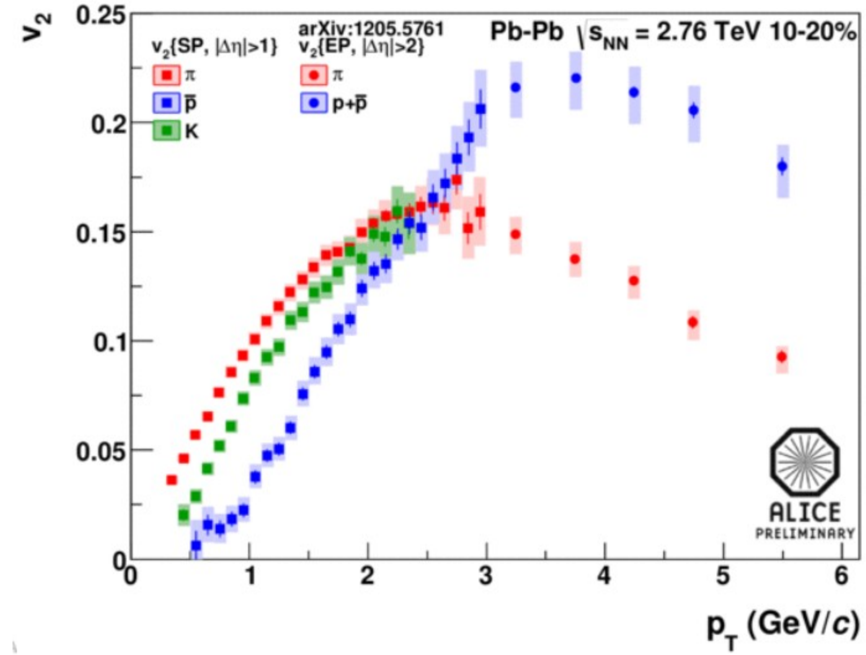
Multi-particle correlation results are the same within 10% in pPb

Identified particle v_2

pPb



PbPb

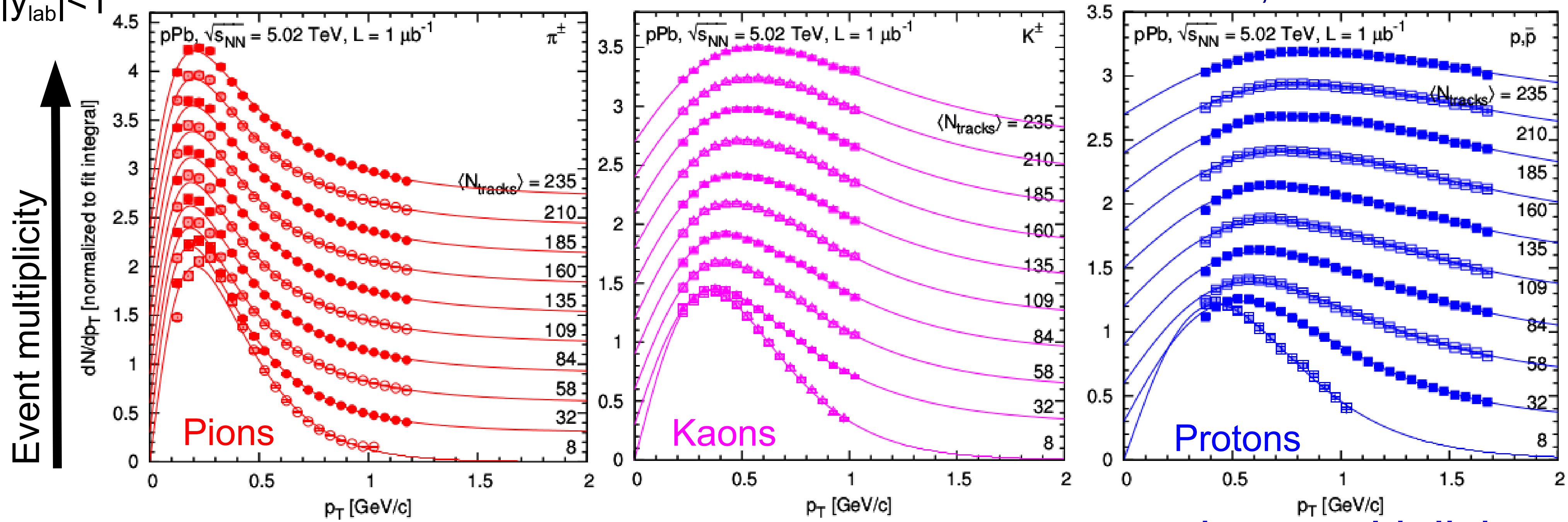


- Characteristic mass splitting observed as known from PbPb
- Crossing of proton and pion at similar p_T (2-3 GeV/c) with protons pushed further out in the pPb case
  - If interpreted in hydro picture, suggestive of strong radial flow

Radial flow

CMS, arXiv:1307.3442

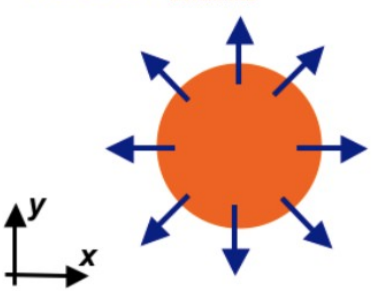
$|y_{lab}|<1$



$\pi^{\pm}$	0.1 – 1.2 GeV/*c*
$K^{\pm}$	0.2 – 1.05 GeV/*c*
$p(\bar{p})$	0.4 – 1.7 GeV/*c*

- Spectra measured vs. multiplicity
  - For kaons and more for protons shape changes with increasing multiplicity
  - As expected from radial flow

Radial flow



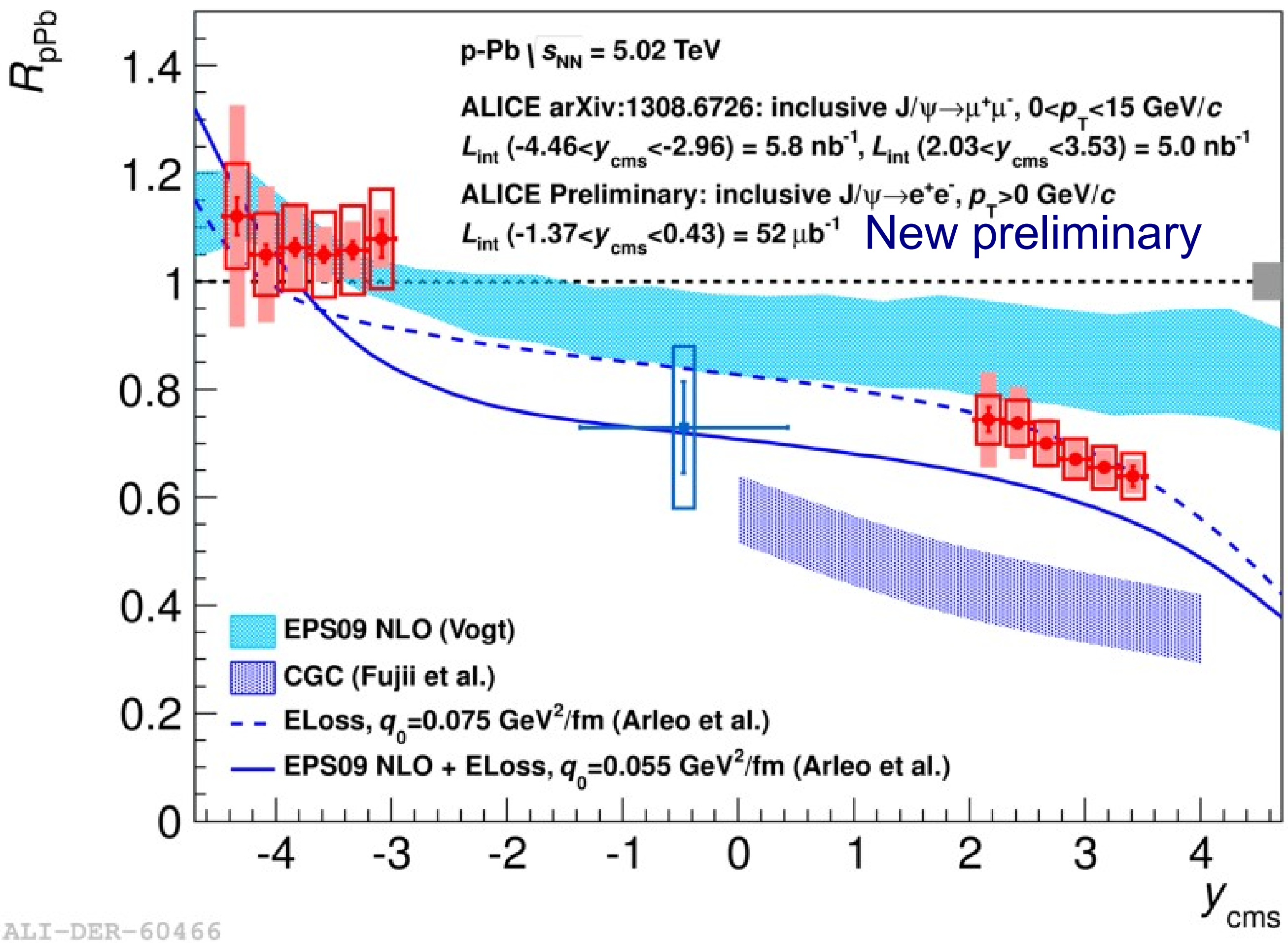
$$p_T^{flow} = p_T + m\beta_T^{flow}\gamma_T^{flow}$$

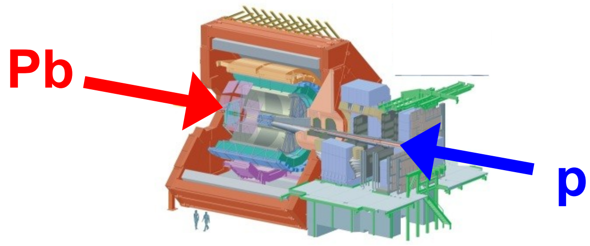
Radial flow expected to reflect in spectra, in particular in p/π ratio

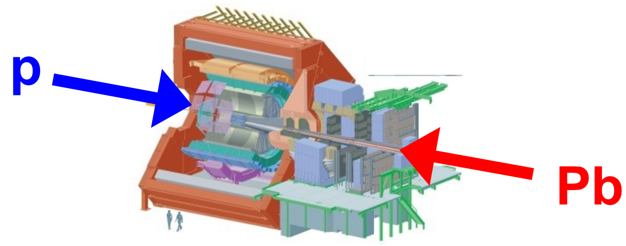
Shuryak and Zahed, PRC 88 (2013) 044915

(Note also present in high mult pp)

J/ψ production versus rapidity in p-Pb



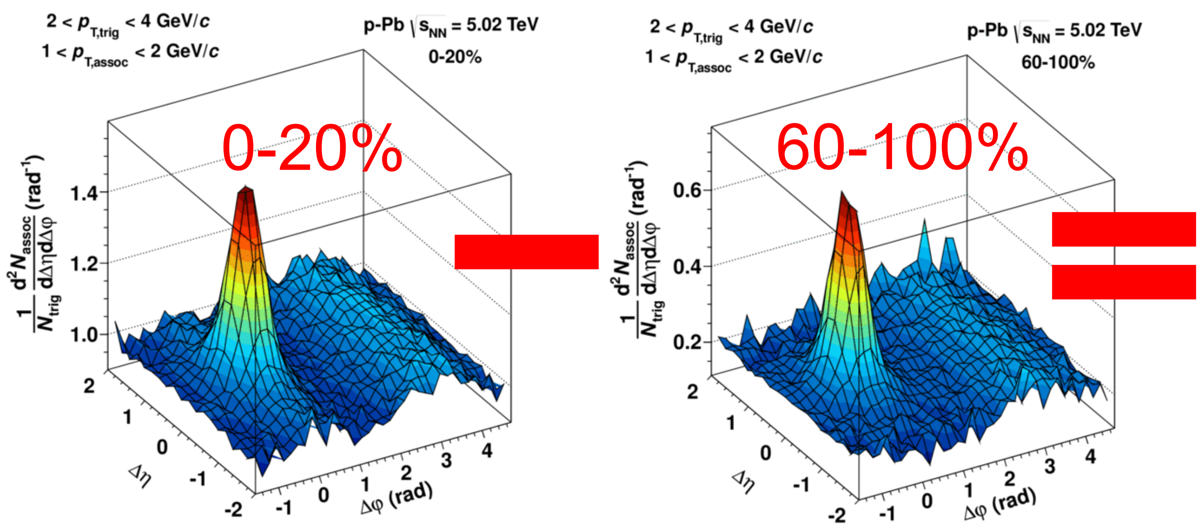


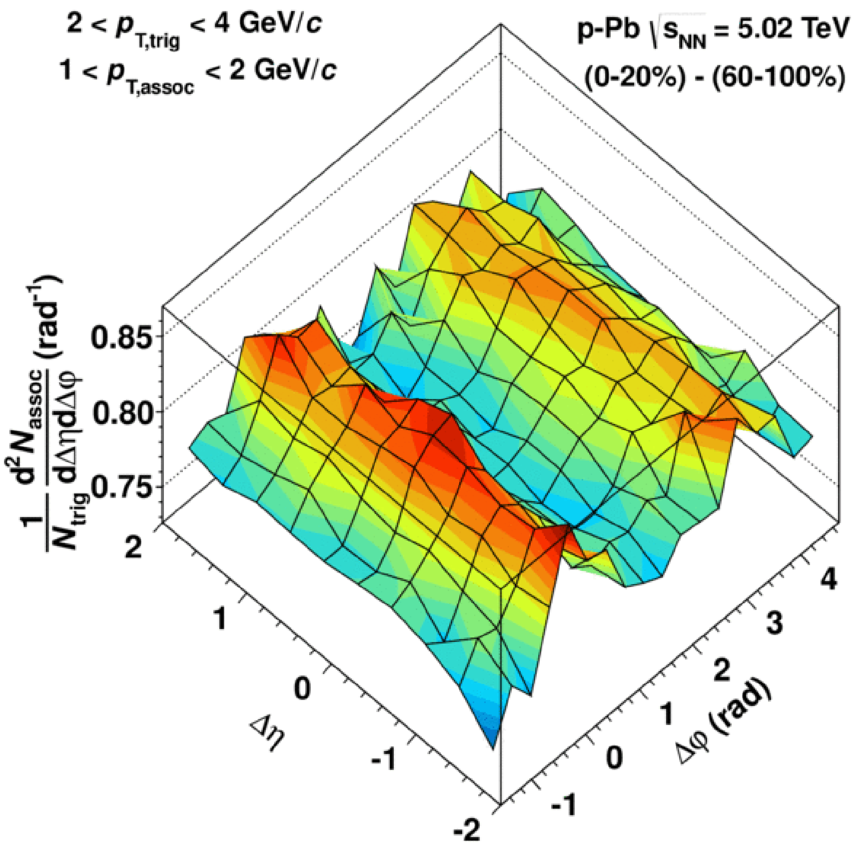


- Suppression at mid- and forward rapidity
  - Consequences for R_{AA}: Suggests even stronger recombination
- Consistent with shadowing models (EPS09 NLO) and/or coherent parton energy loss
- Specific CGC calculation disfavored

Observation of double ridge

ALICE, PLB 719 (2013) 29





- Extract double ridge structure by subtracting the jet-like correlations from 60-100% low multiplicity class
  - Standard technique in AA collisions
  - Checked that correlations in 60-100% look similar to pp