From Heavy-Ion Collisions to Quark Matter

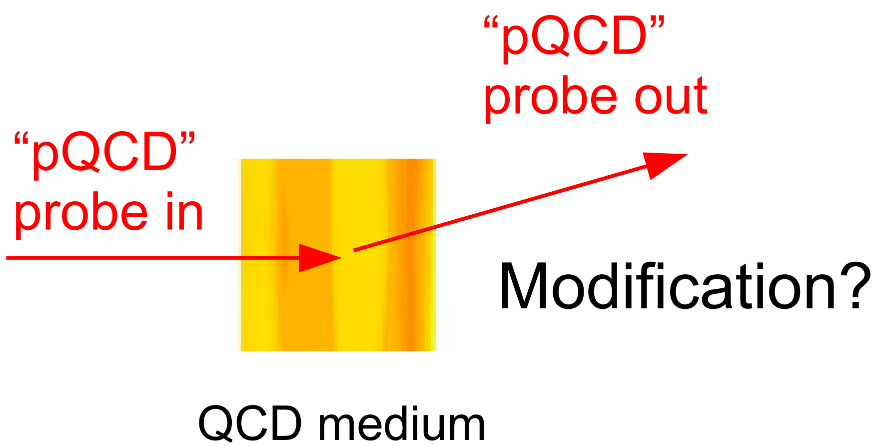
Lecture 3

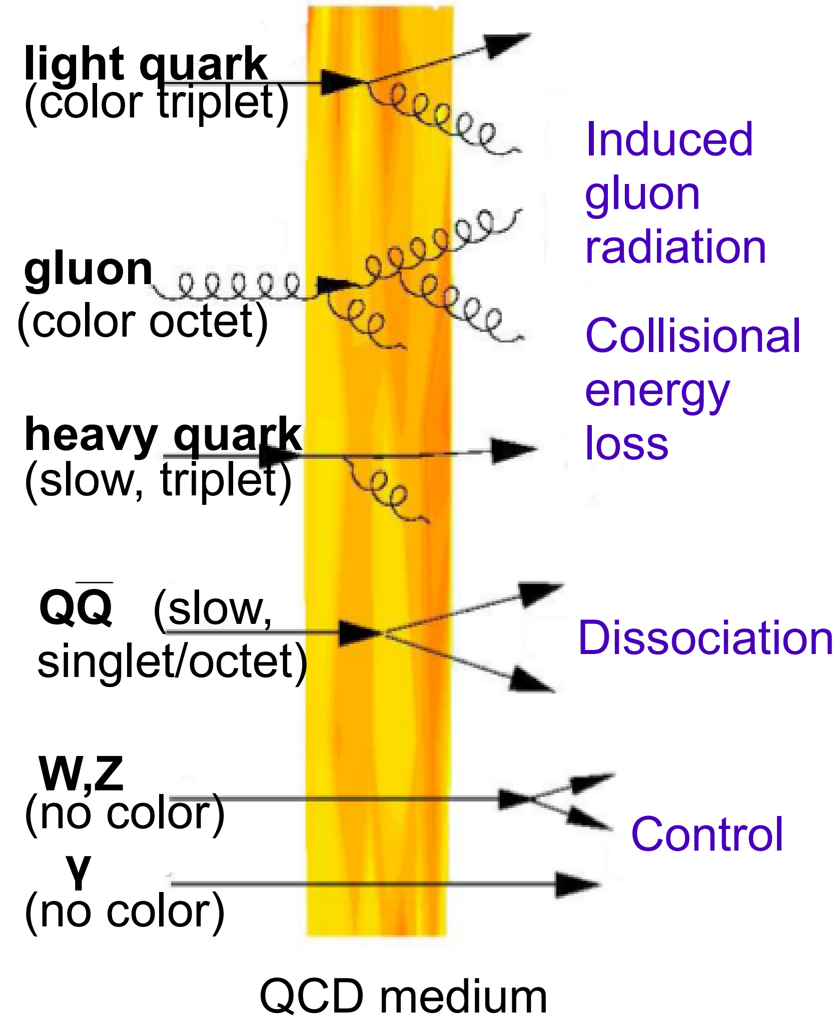
Constantin Loizides
(LBNL)

CERN summer student programme 2014

Tomography of QCD matter

- Hard (large Q^2) probes of QCD matter: jets, heavy-quark, $Q\bar{Q}$, γ, W, Z
- "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

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

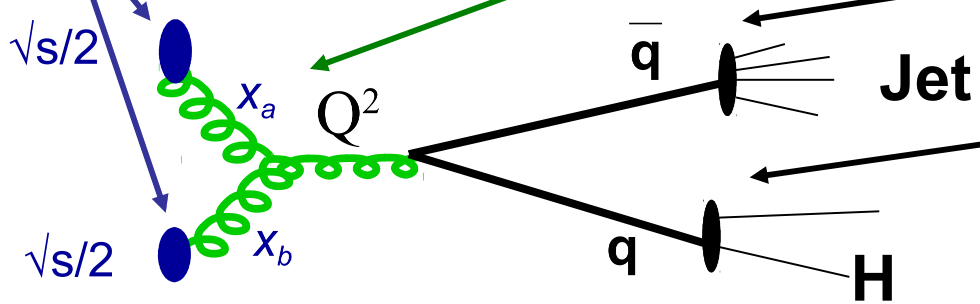
$$\sigma_{hh\to Hx} = PDF(x_a, Q^2)\, PDF(x_b, Q^2) \otimes \sigma_{ab\to q\bar{q}} \otimes D_{q\to H}(z_q, Q^2)$$

Cross section for hadronic collisions (hh)

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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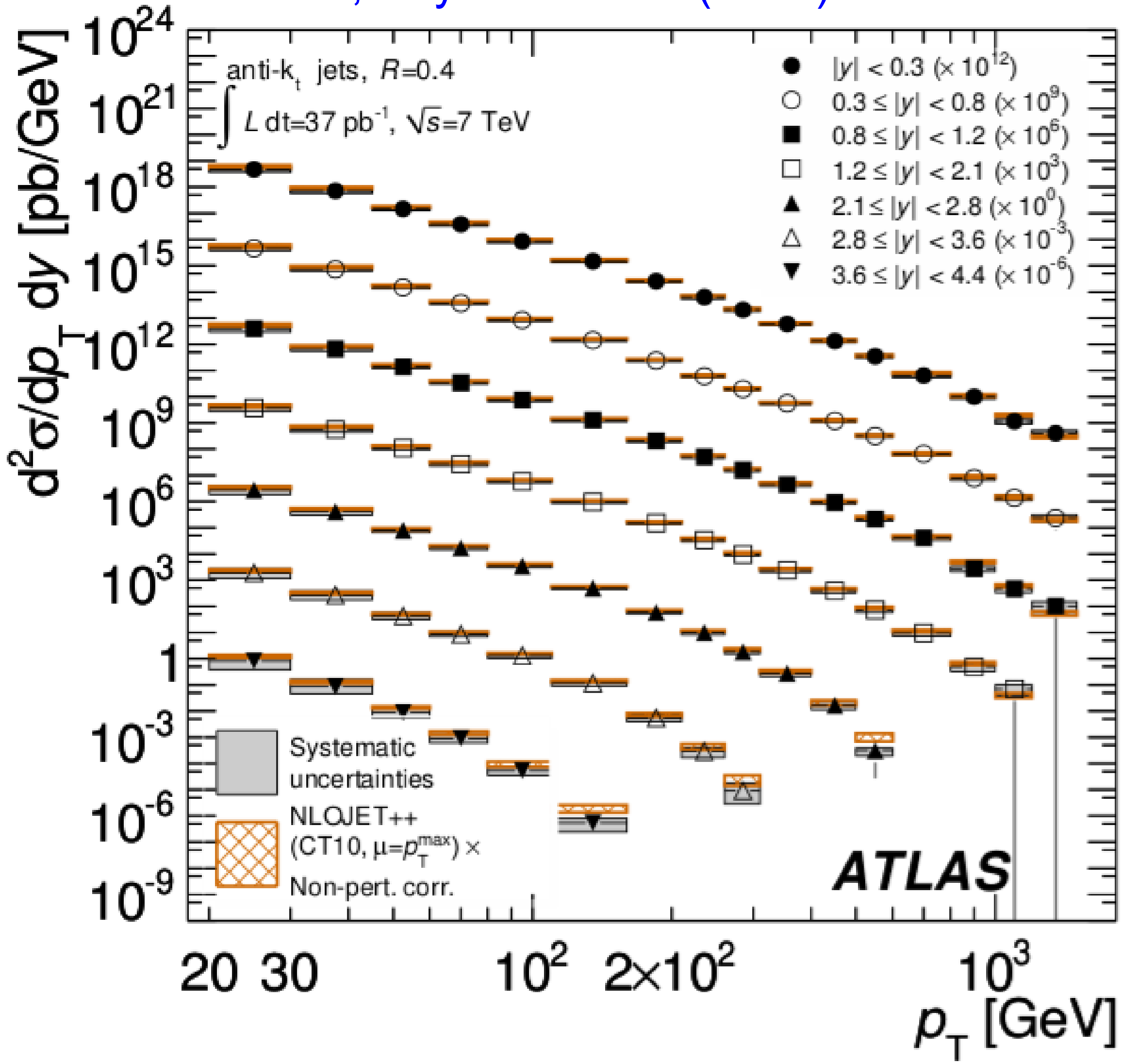
ATLAS, Phys.Rev. D86 (2012) 014022



Successfully describing data over many orders of magnitude!

Hard processes in pp

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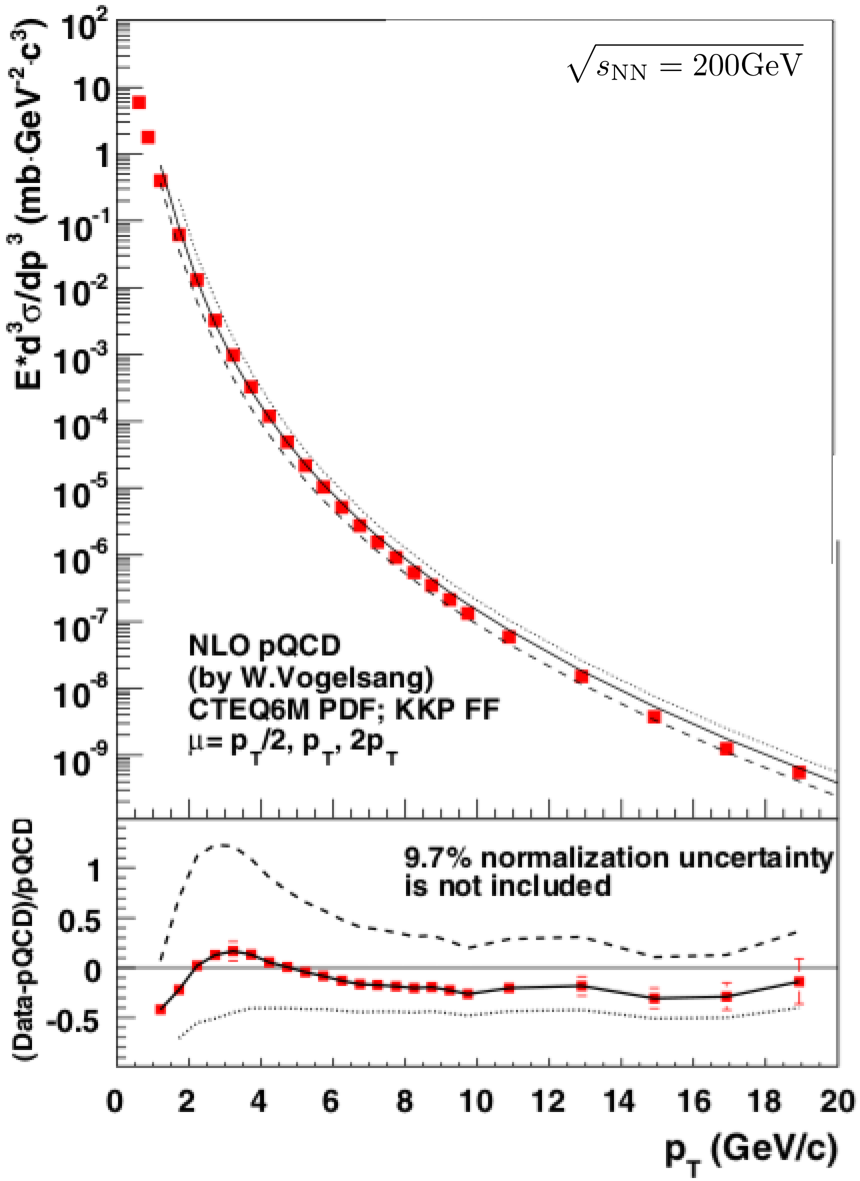
PHENIX, PRD 76 (2007) 051106(R)



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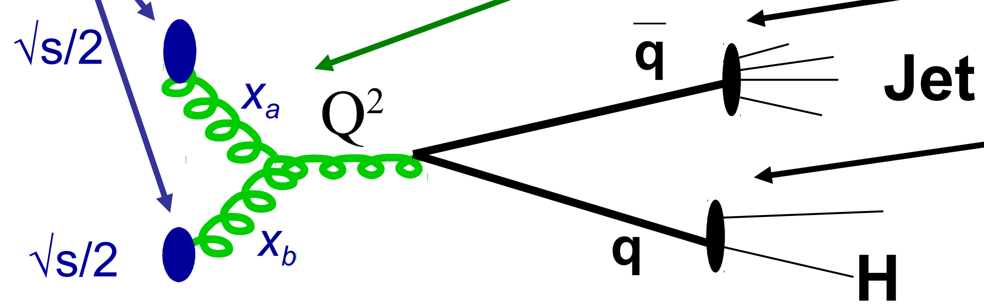


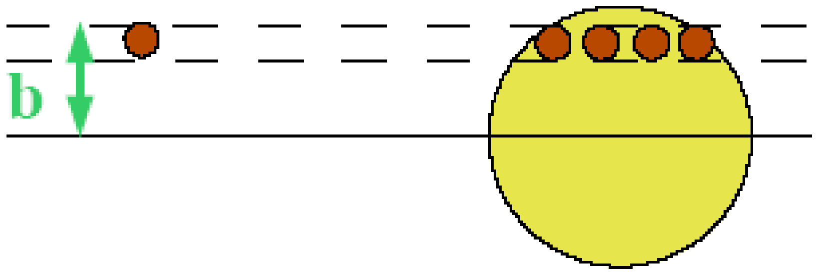
In AA collisions, in absence of nuclear and/or QGP effects expect N_{coll} scaling:

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

Nuclear geometry and hard processes: Glauber theory

Glauber scaling: hard processes with large momentum transfer

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



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

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

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

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

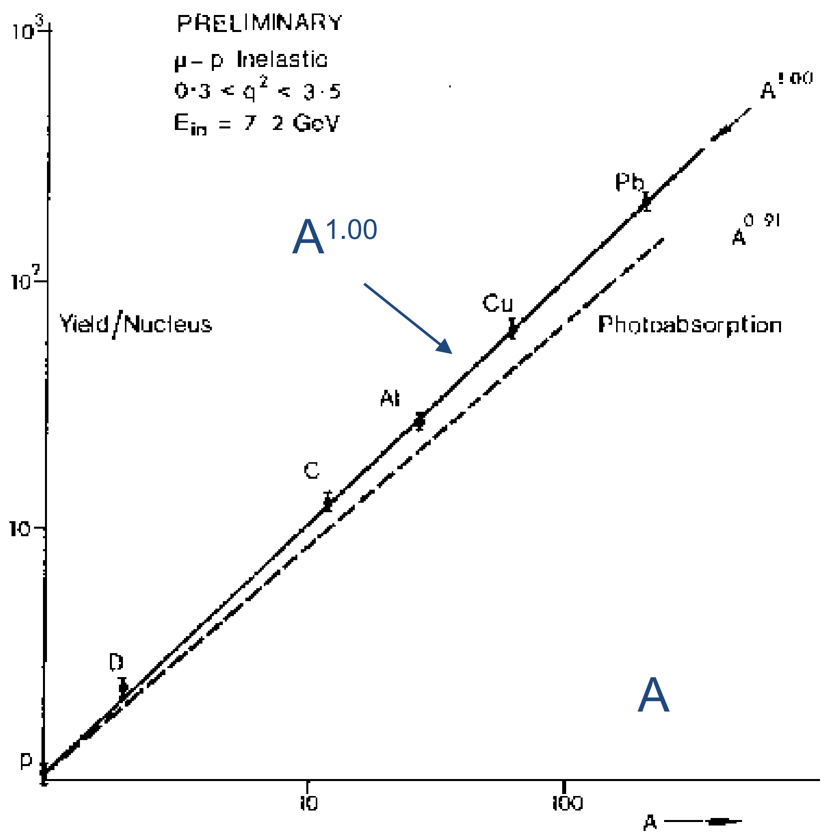
$$\sigma^\mathrm{hard}_\mathrm{pA} \simeq A\,\sigma^\mathrm{hard}_{NN} \int \mathrm{d}b T_\mathrm{A} = A\,\sigma^\mathrm{hard}_{NN}$$

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

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

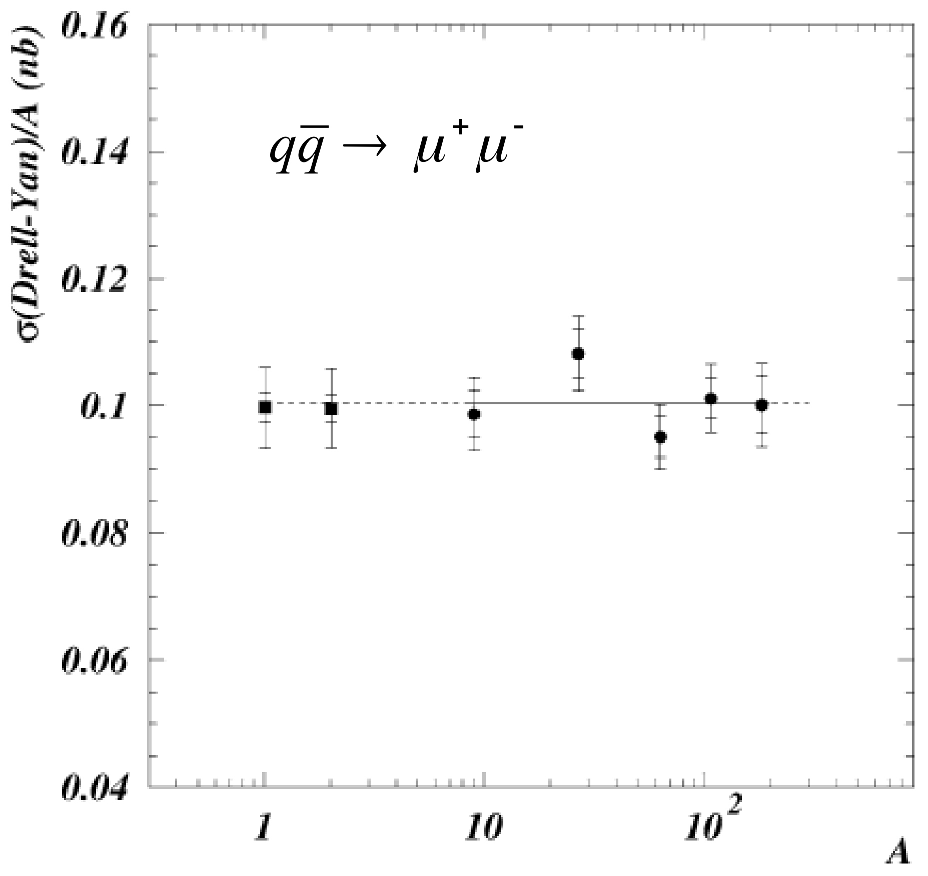
σ_{inel} for 7 GeV muons on nuclei

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



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

NA50 Phys Lett B553, 167

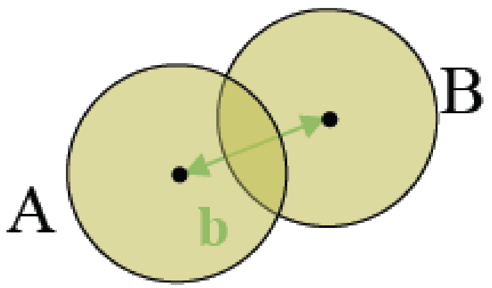


These hard cross sections in p+A found to scale as $A^{1.0}$

Glauber scaling for A+B collisions

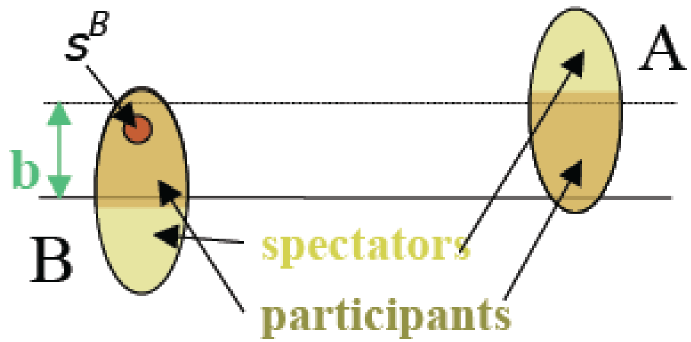
Nuclear overlap function:

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



Average number of binary NN collisions for B nucleon 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:

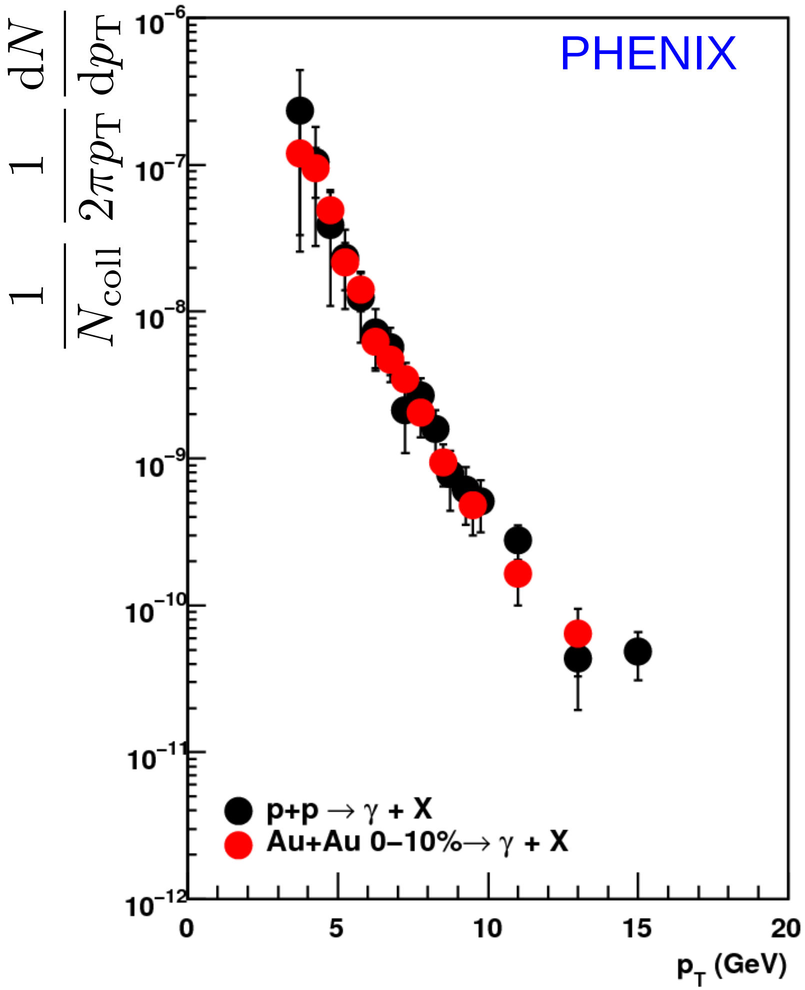
$$N_{\mathrm{coll}}^{\mathrm{AB}}(b) = B \int \mathrm{d}s_{\mathrm{B}}\, T_{\mathrm{B}}(s_{\mathrm{B}})\, N_{\mathrm{coll}}^{\mathrm{nA}}(b-s_{\mathrm{B}}) = \mathrm{AB}\, \mathrm{T}_{\mathrm{AB}}(b)\, \sigma_{\mathrm{NN}}^{\mathrm{inel}}$$

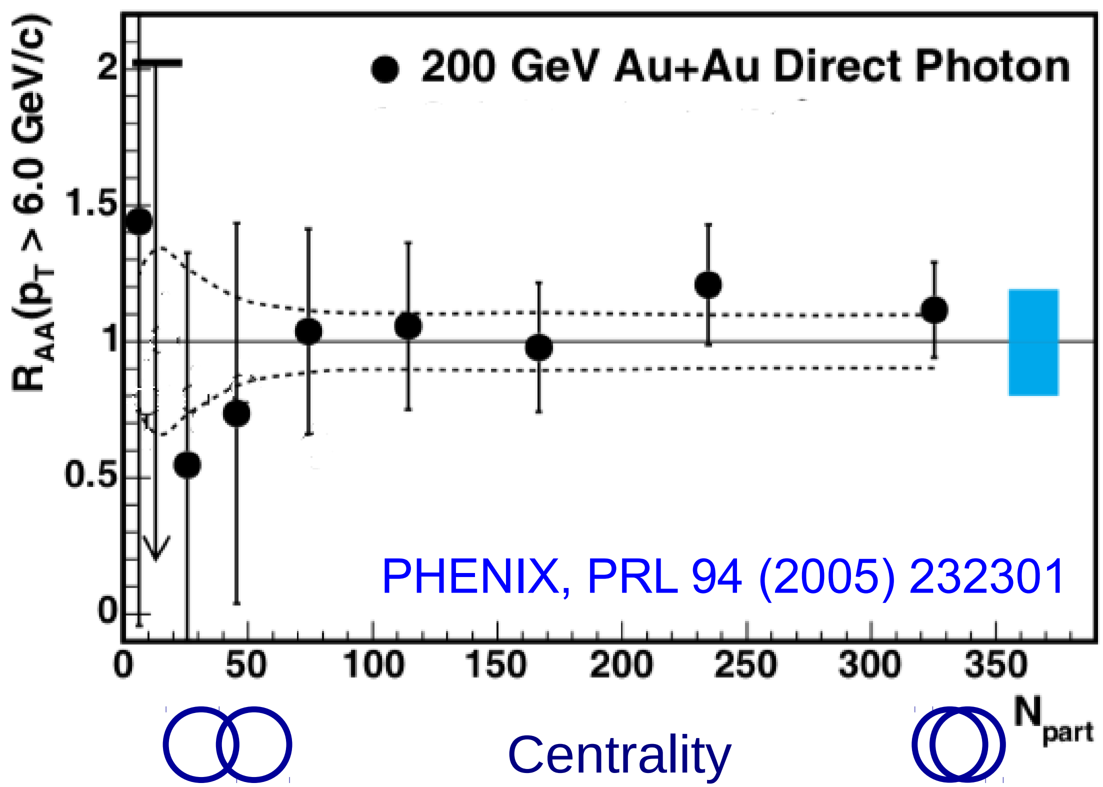
$$N_{\mathrm{hard}}^{\mathrm{AB}}(b) = \mathrm{N}_{\mathrm{coll}}^{\mathrm{AB}}(b)\, \sigma_{\mathrm{NN}}^{\mathrm{hard}} / \sigma_{\mathrm{NN}}^{\mathrm{inel}}$$

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

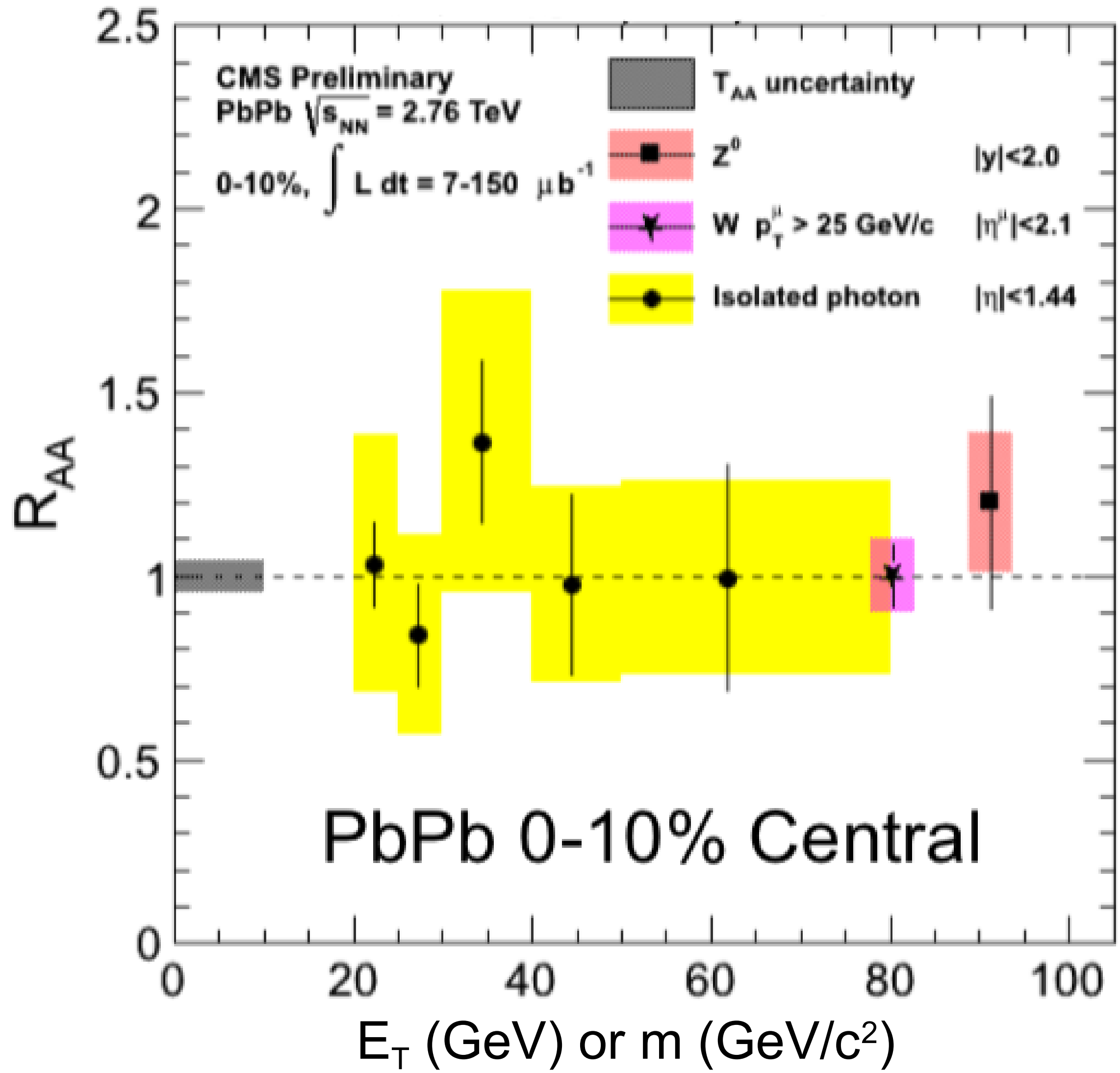
Glauber test at LHC: Scaling of control yields in pp vs PbPb

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

<ins>Isolated γ:</ins>
ATLAS, ATLAS-CONF-2012-051
CMS, PLB 710 (2012) 256

<ins>Z boson:</ins>
ATLAS, PLB 697 (2011) 294
CMS, PRL 106 (2011) 212301

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

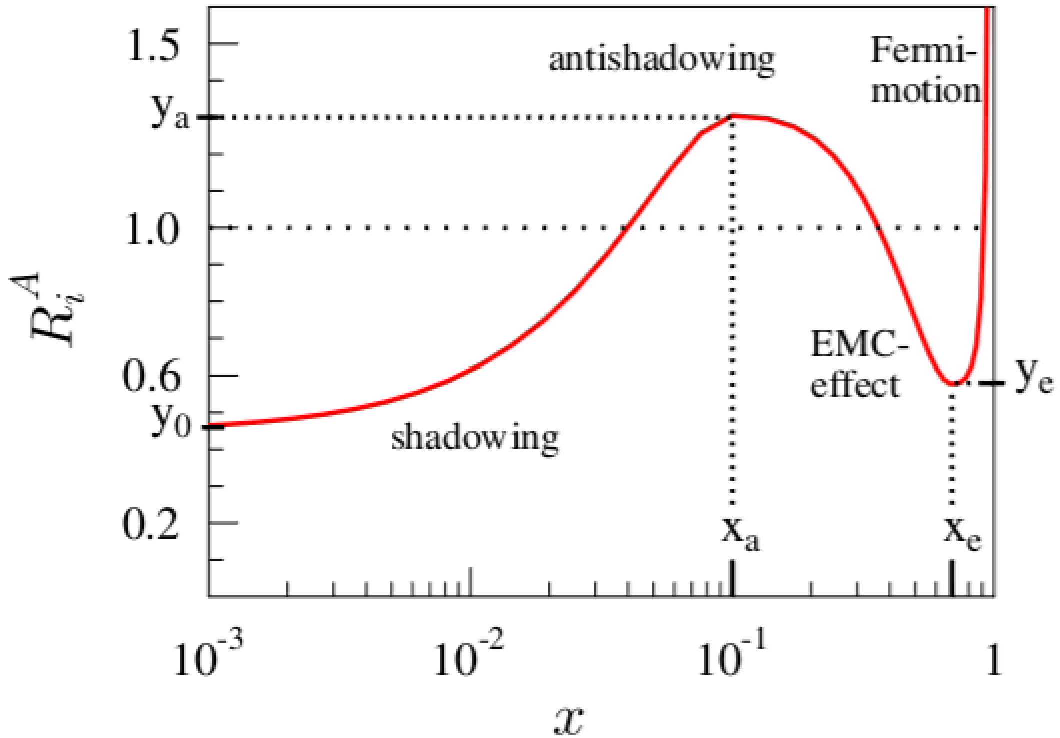


Control probes (direct +isolated γ, Z, W) scale with Ncoll

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

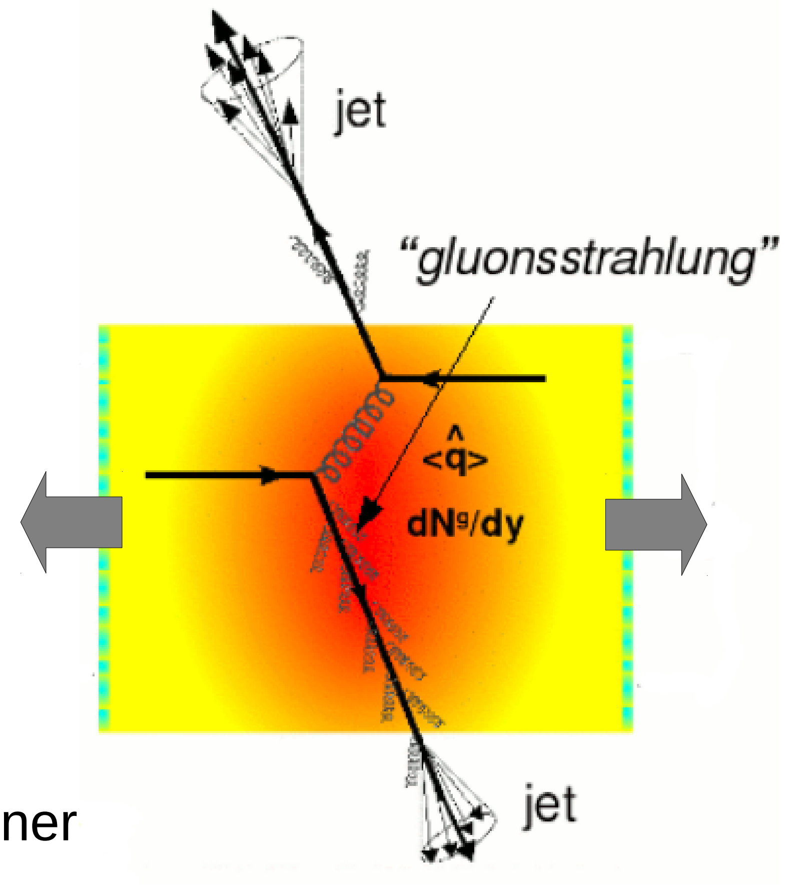


- By definition, R_{AA}=1 in absence of nuclear or QGP matter effects
- Binary scaling can be broken due to initial state effects
  - Transverse k_T broadening (called "Cronin effect")
  - PDF modifications in nuclei (shadowing)

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

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 ener



Breaking of binary scaling

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  lose energy via
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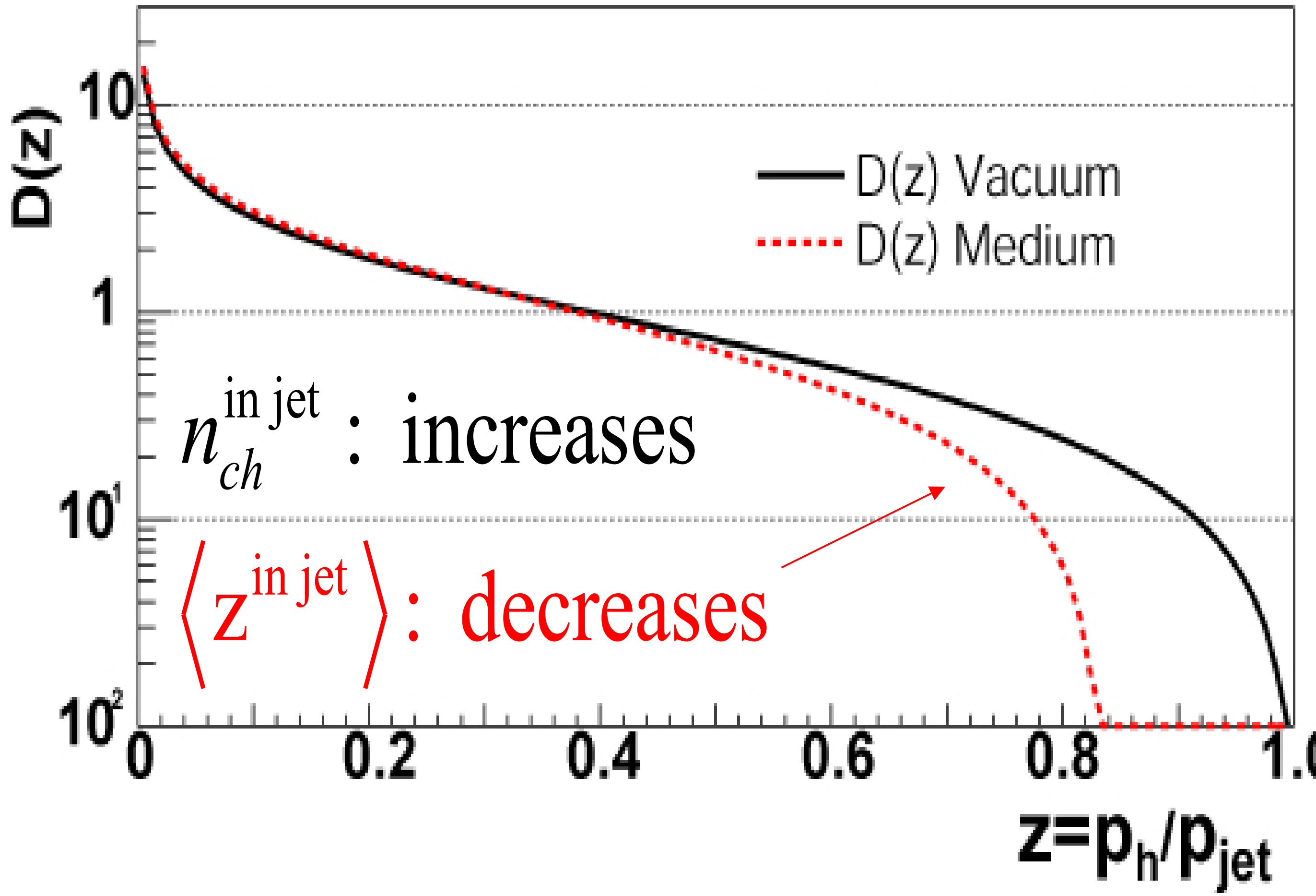
    (collisional energy
  - Gluonstrahlung (r
    - Radiative mech
  - The net-effect is a decrease of the p_T of hard partons
    - Quenching of the high p_T spectrum
    - Modification of jet properties



Fermi National Accelerator Laboratory

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

Bjorken, 1982

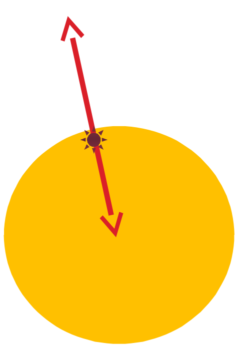
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

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

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.

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



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)

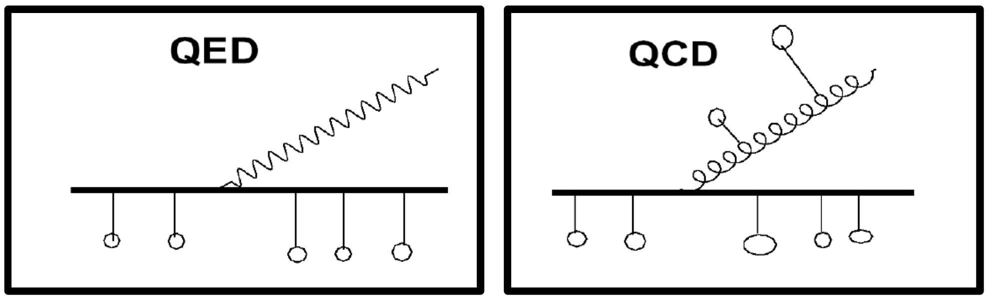
Energy loss from parton

Casimir factor

Transport coefficient

Length traversed in medium

α_S = QCD coupling constant (running)
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,
proportional to gluon density



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

Average energy loss (example)

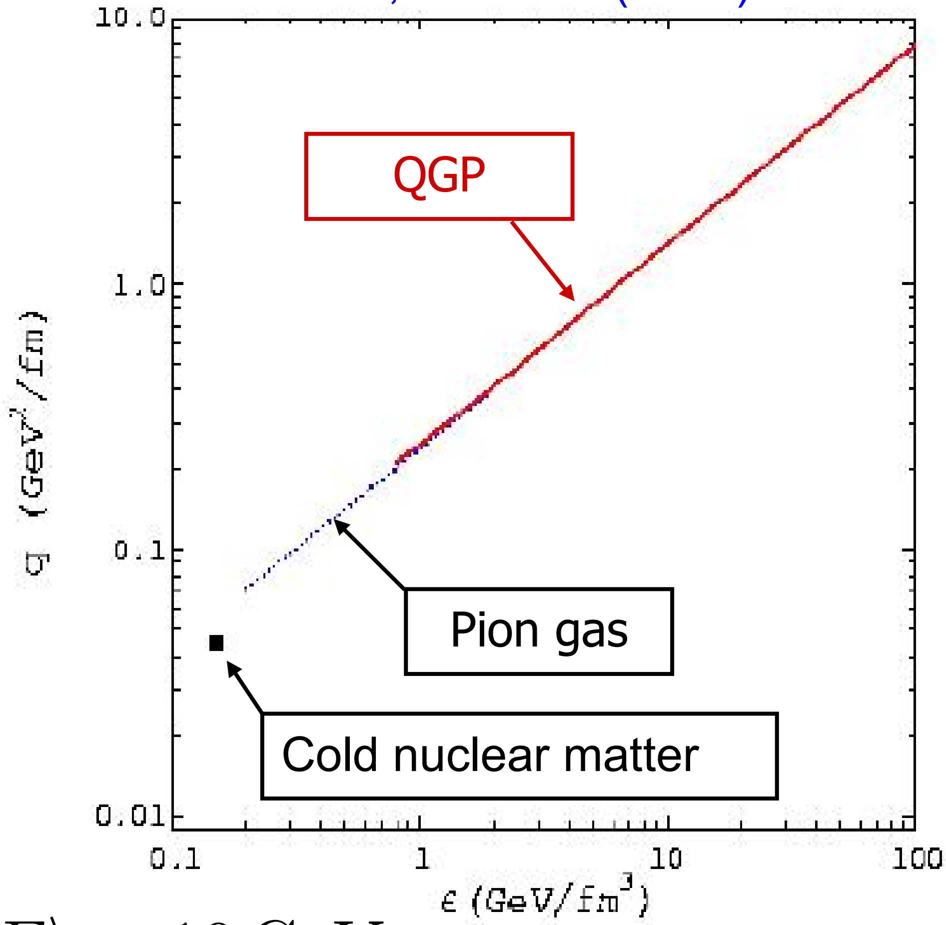
- The transport coefficient relates to the energy density via

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

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

$$\varepsilon_{\mathrm{BJ}} = 5.4\,\mathrm{GeV/fm^3}$$
$$\hat{q} = 1\mathrm{GeV^2/fm}$$
$$\alpha_{\mathrm{S}} = 0.2$$
$$C_{\mathrm{R}} = 4/3$$
$$L = 5\,\mathrm{fm}$$

Baier, NPA 715 (2003) 209

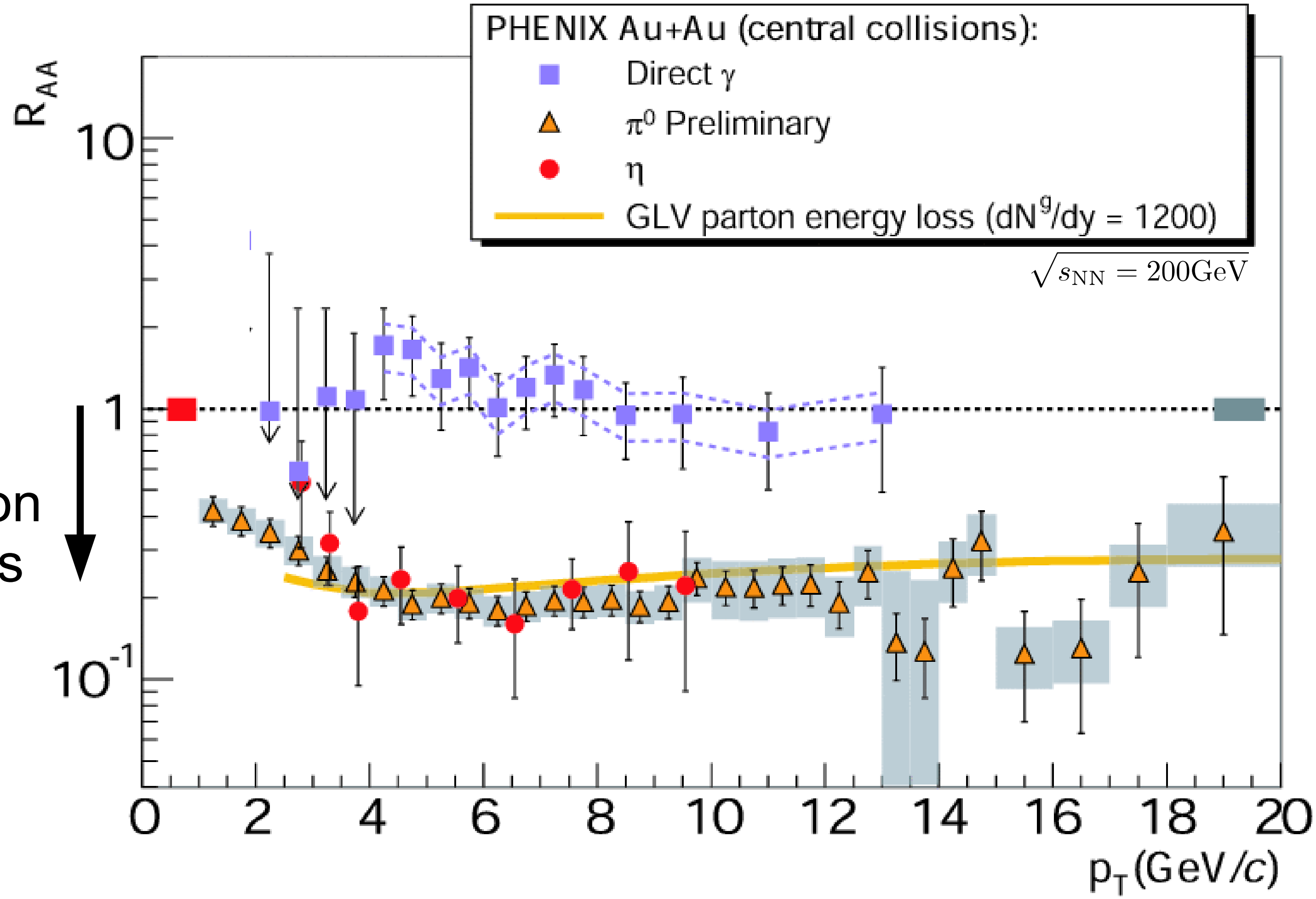


$$\langle \Delta E \rangle \simeq 10\,\mathrm{GeV}$$

(From formula on previous slide)

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

Leading hadron suppression at RHIC



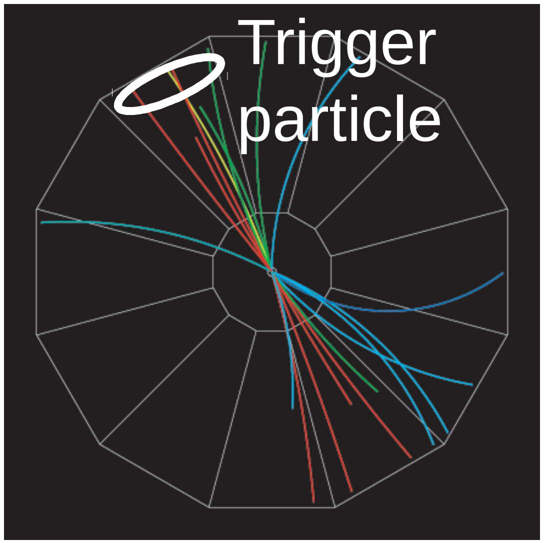
Factor 5 suppression for hadrons

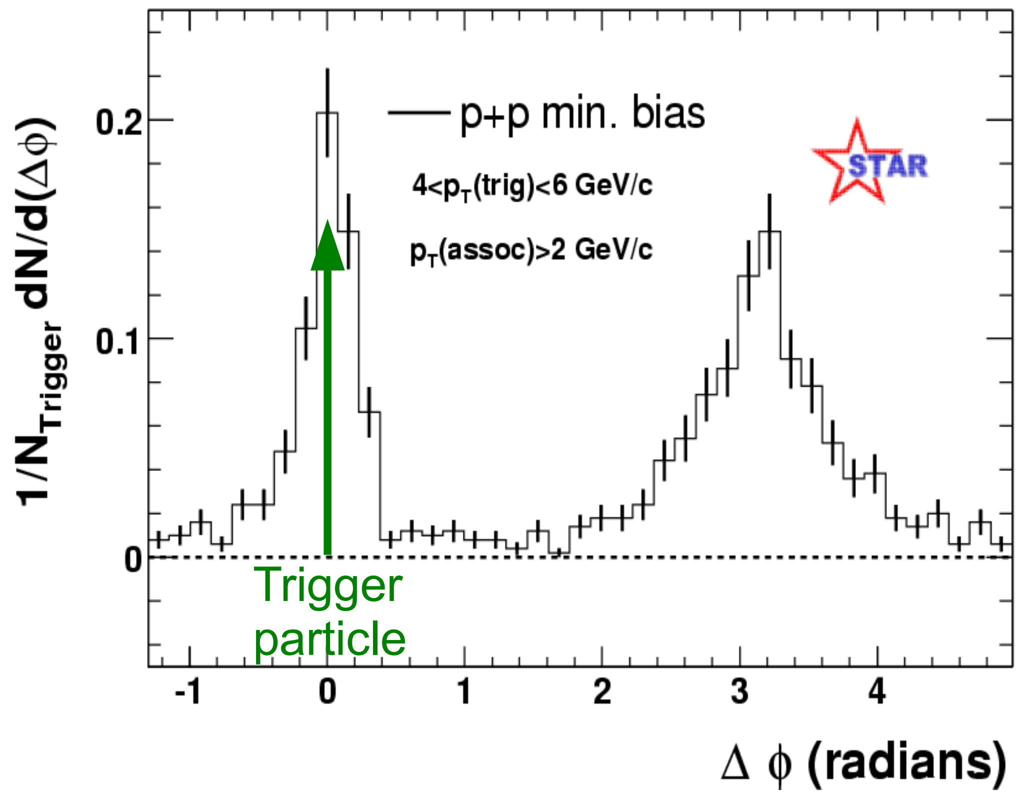
Jet quenching observed:
Strong suppression of hadrons in central Au+Au collisions

(first reported in PRL 88 (2001) 022301)

Di-hadron correlations

PRL 90 (2003) 082392

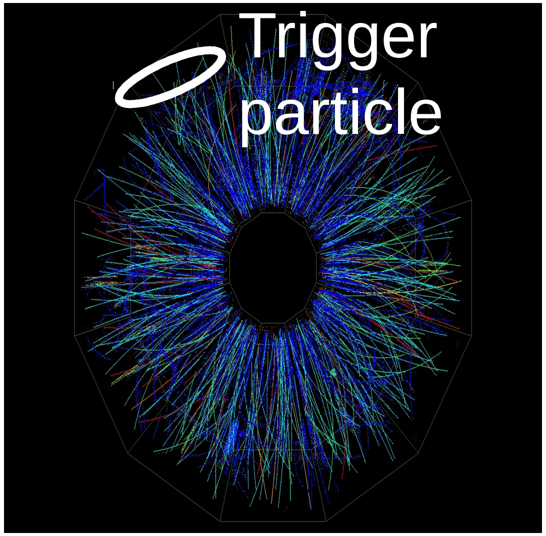


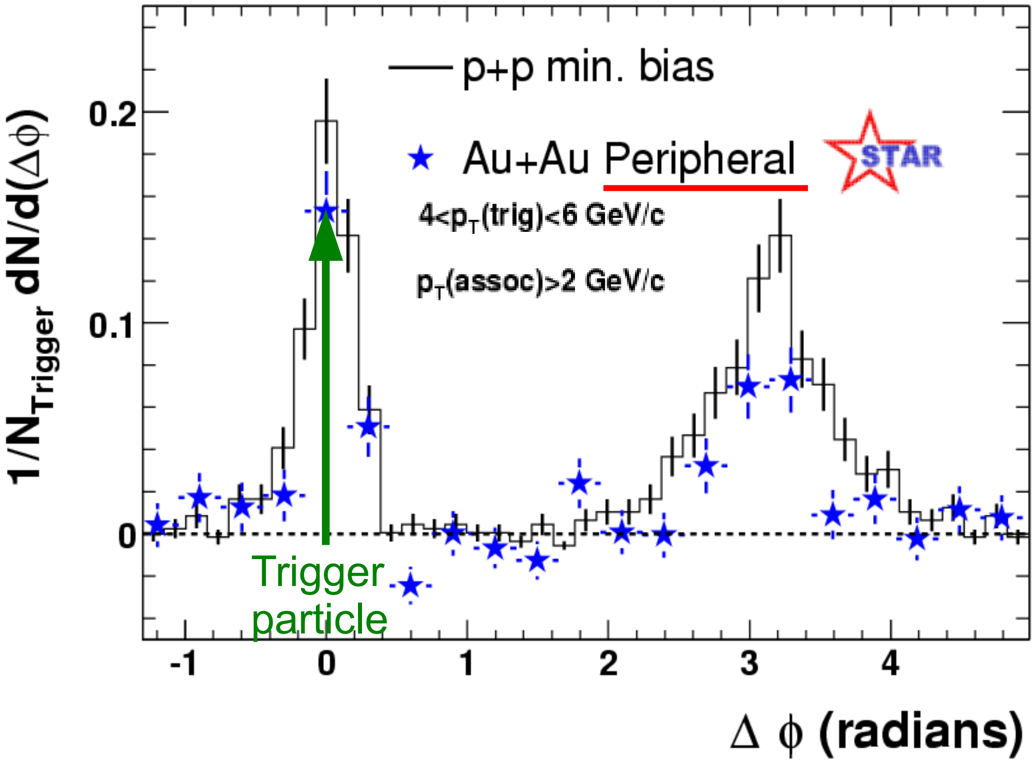


Study two particle angular correlations relative to high-p_T (trigger) particle:
Proxy for di-jet measurements

Di-hadron correlations

PRL 90 (2003) 082392

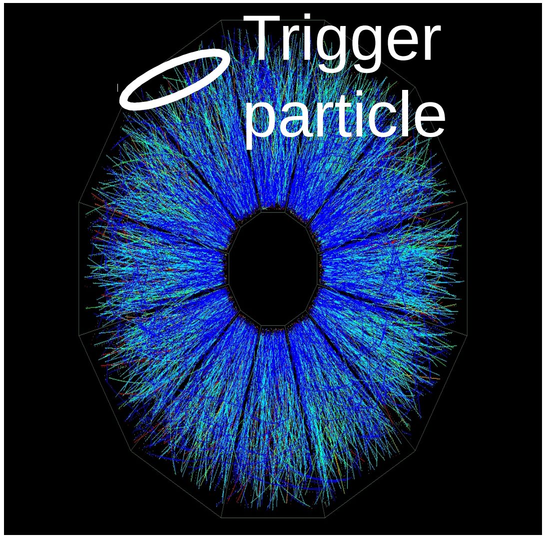


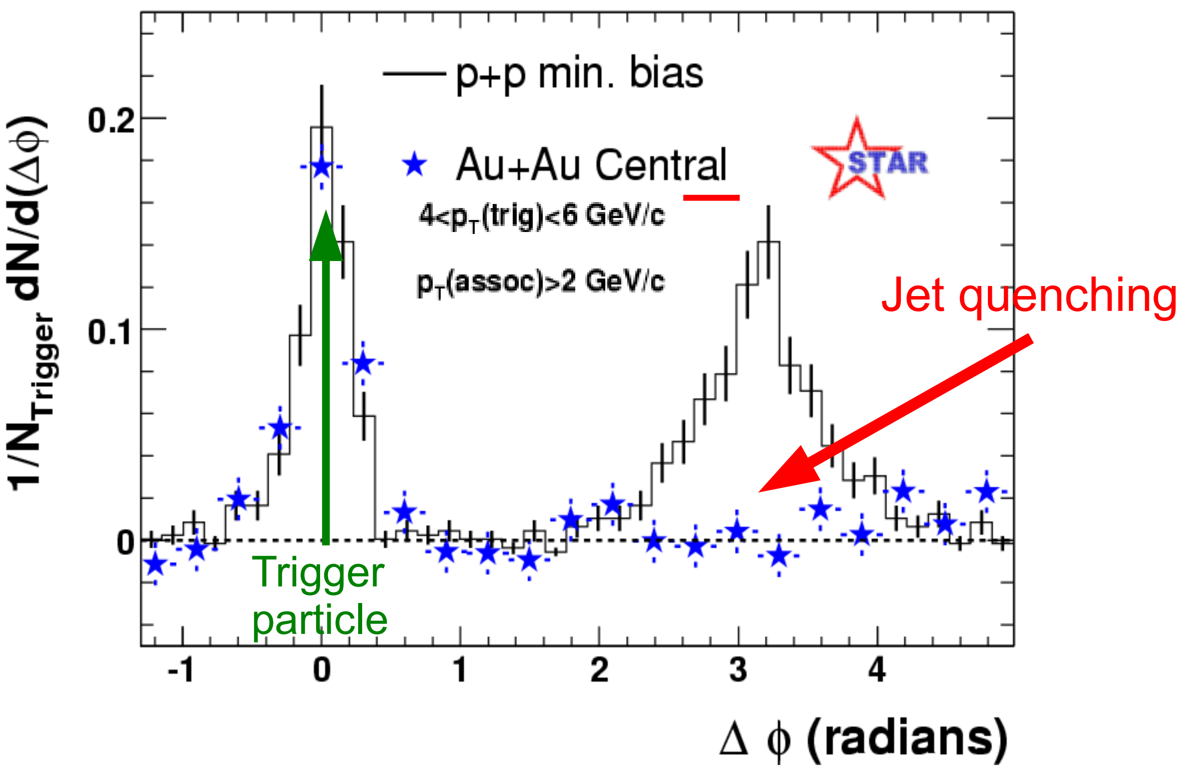


No clear change visible (relative to pp) in peripheral collisions

Di-hadron correlations

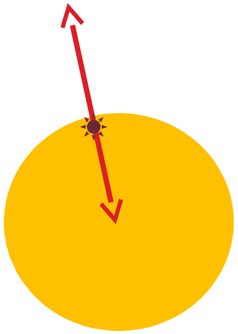
PRL 90 (2003) 082392





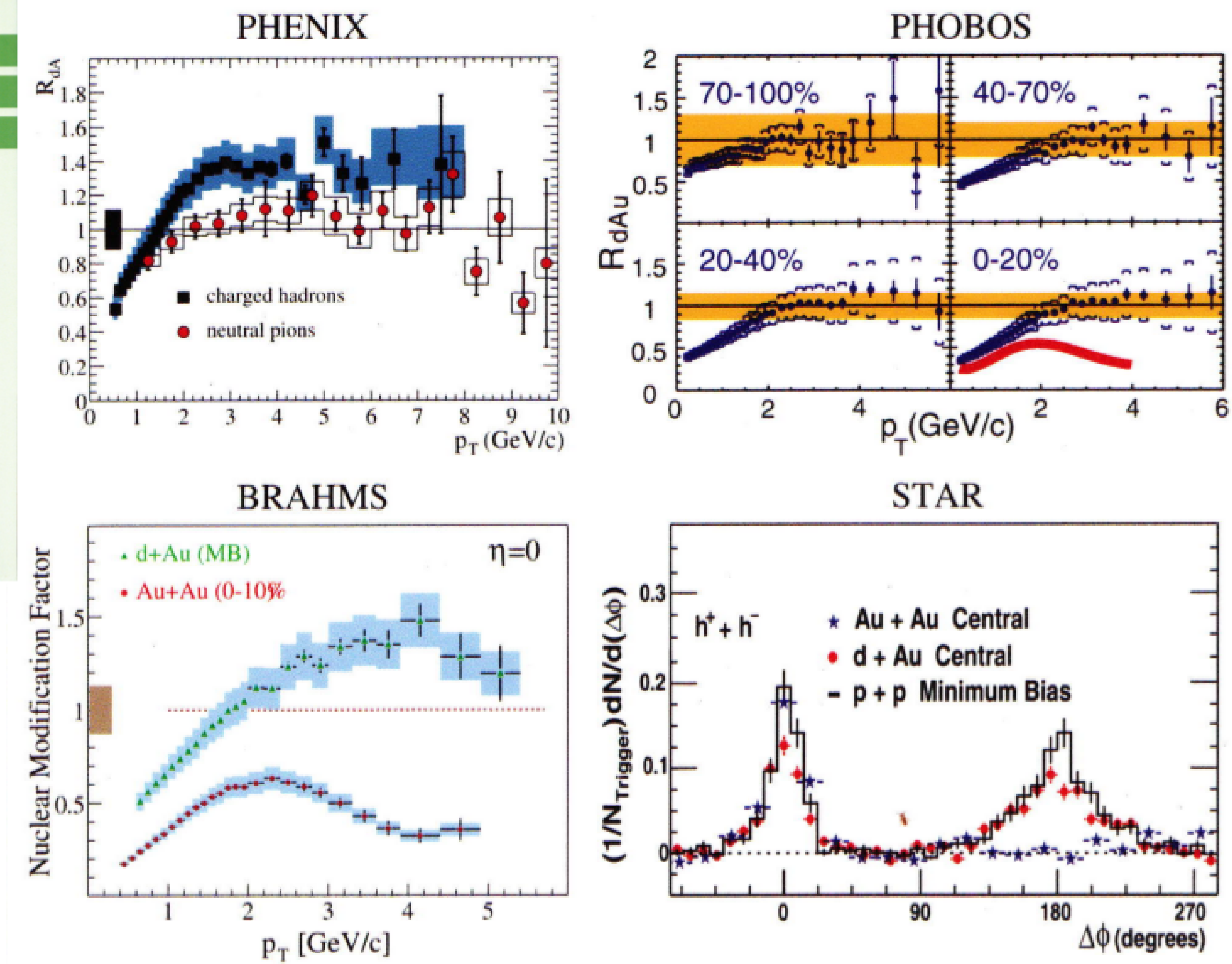
Recoiling jet is strongly altered (swallowed) by medium

Clear evidence for presence of very high density matter



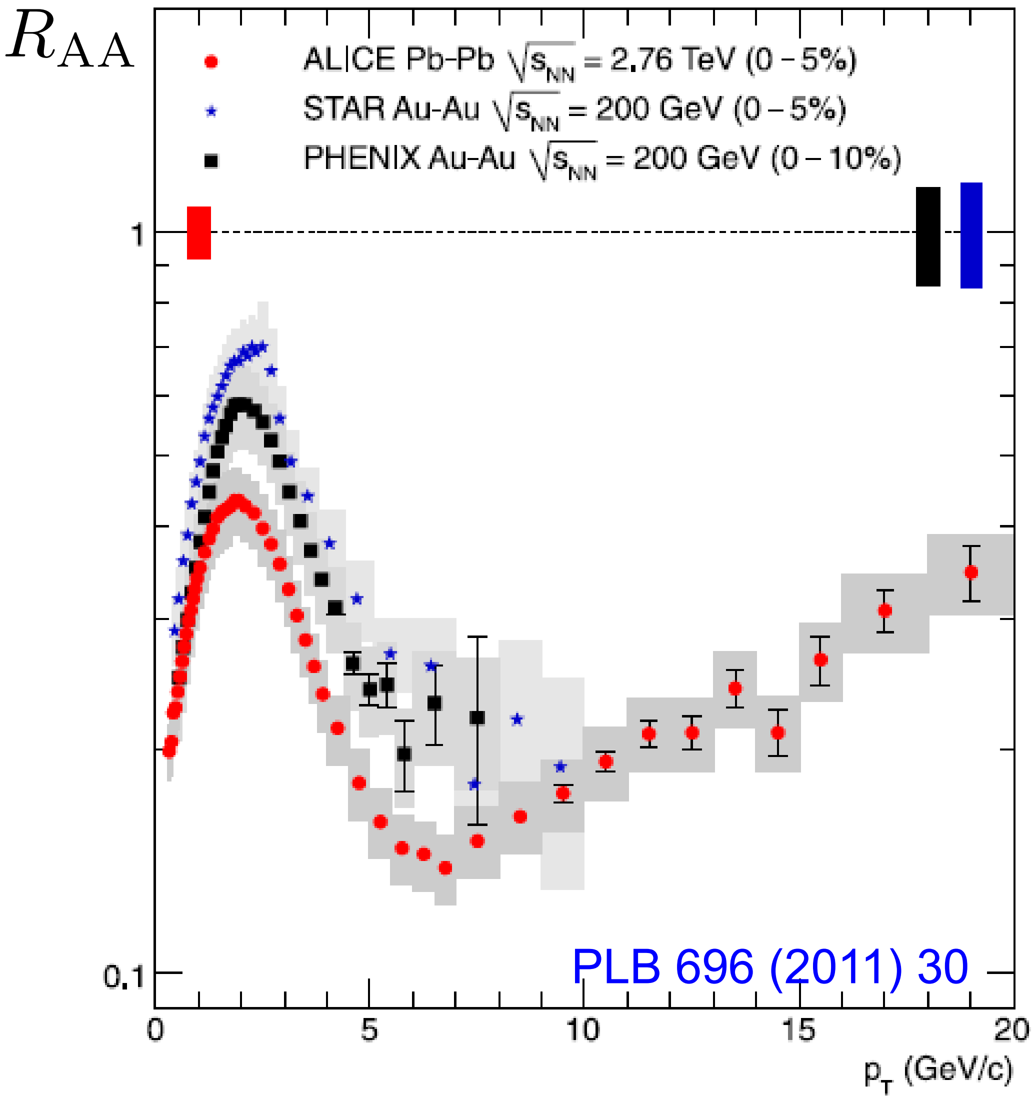
dAu control experiment at RHIC

PRL 91 (2003) vol 7



Conclusion from control experiment:
Jet quenching is a final state effect

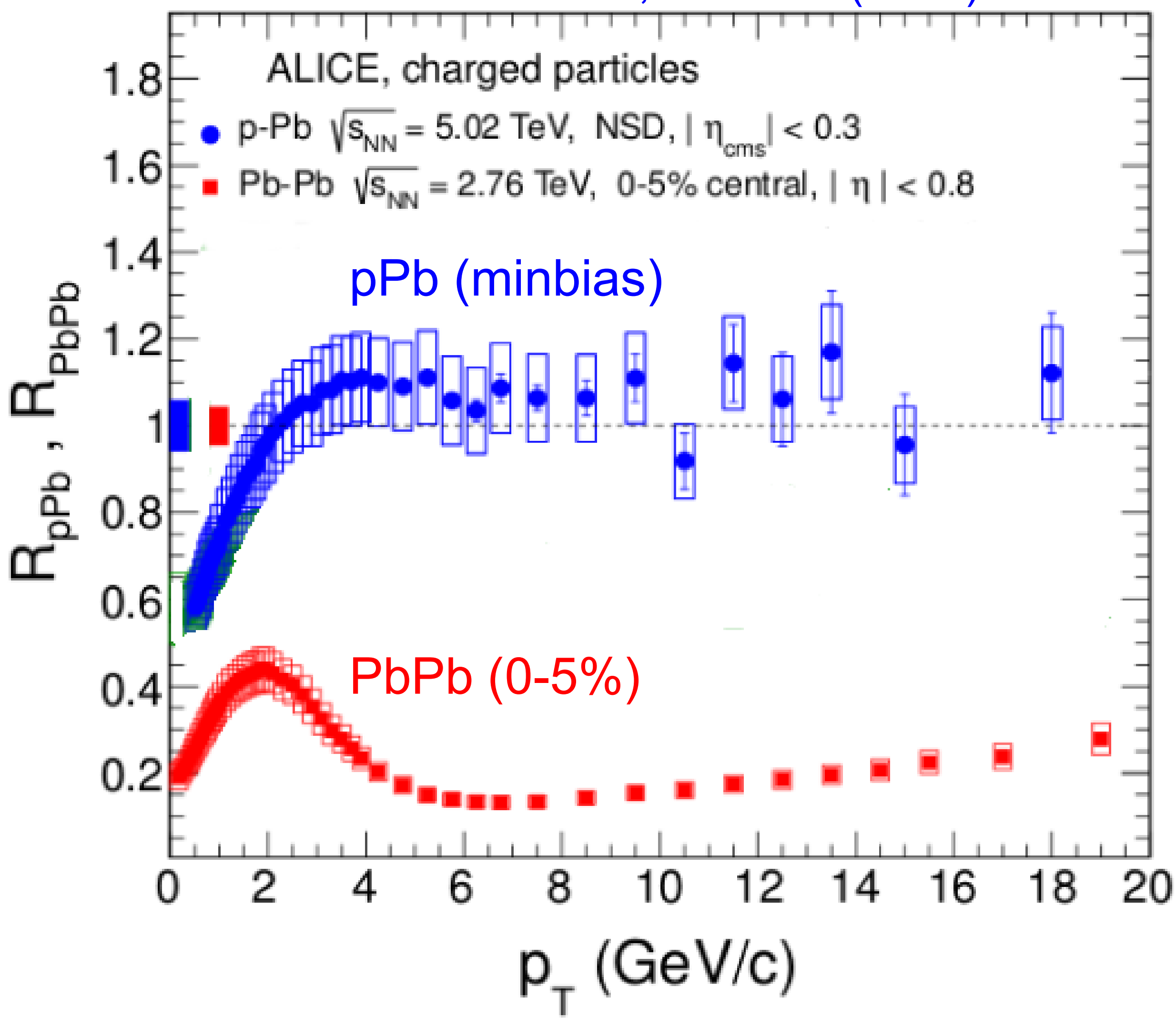
Leading particle suppression at the LHC



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

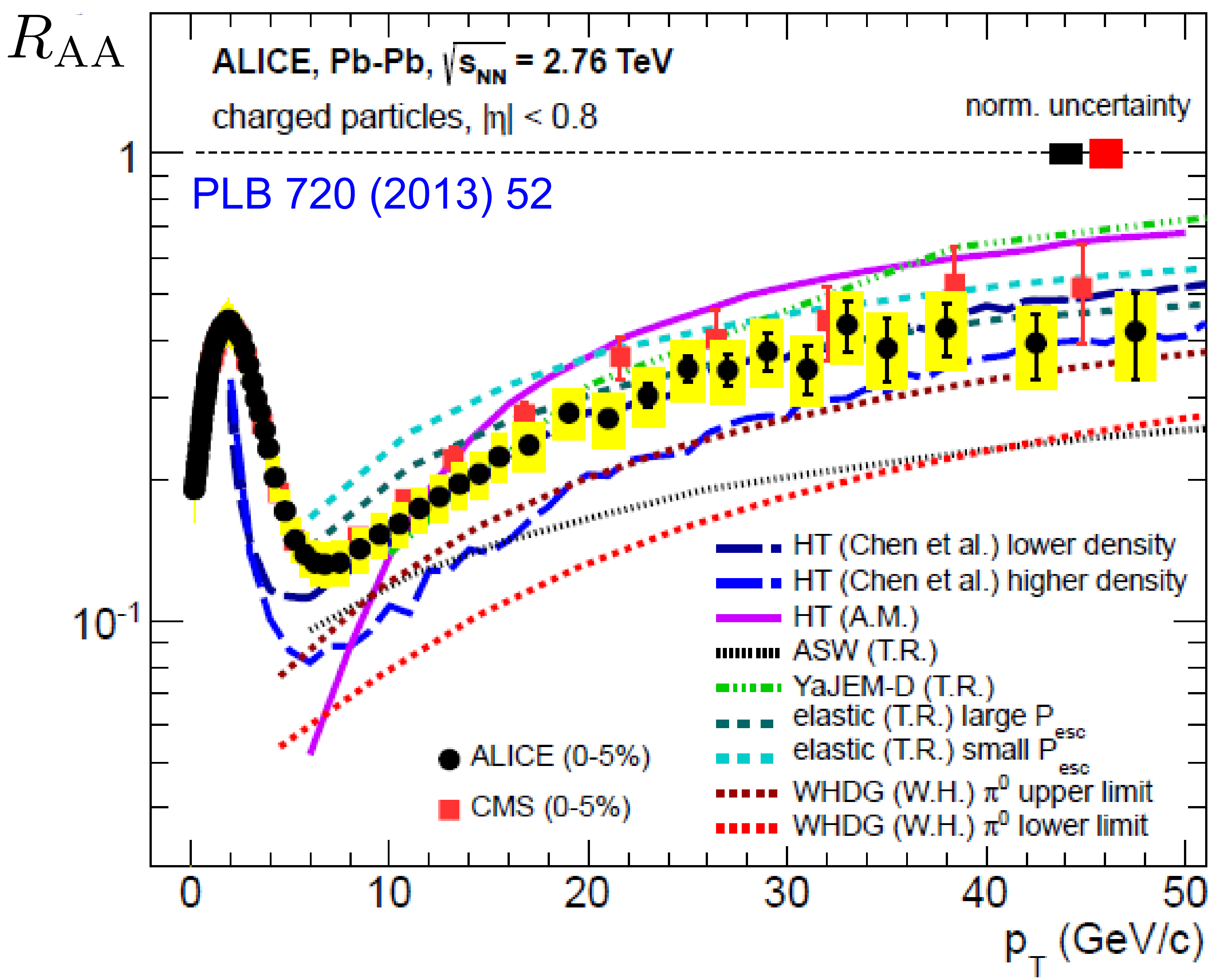
Leading particle suppression at the LHC

ALICE, PRL 110 (2013) 082302



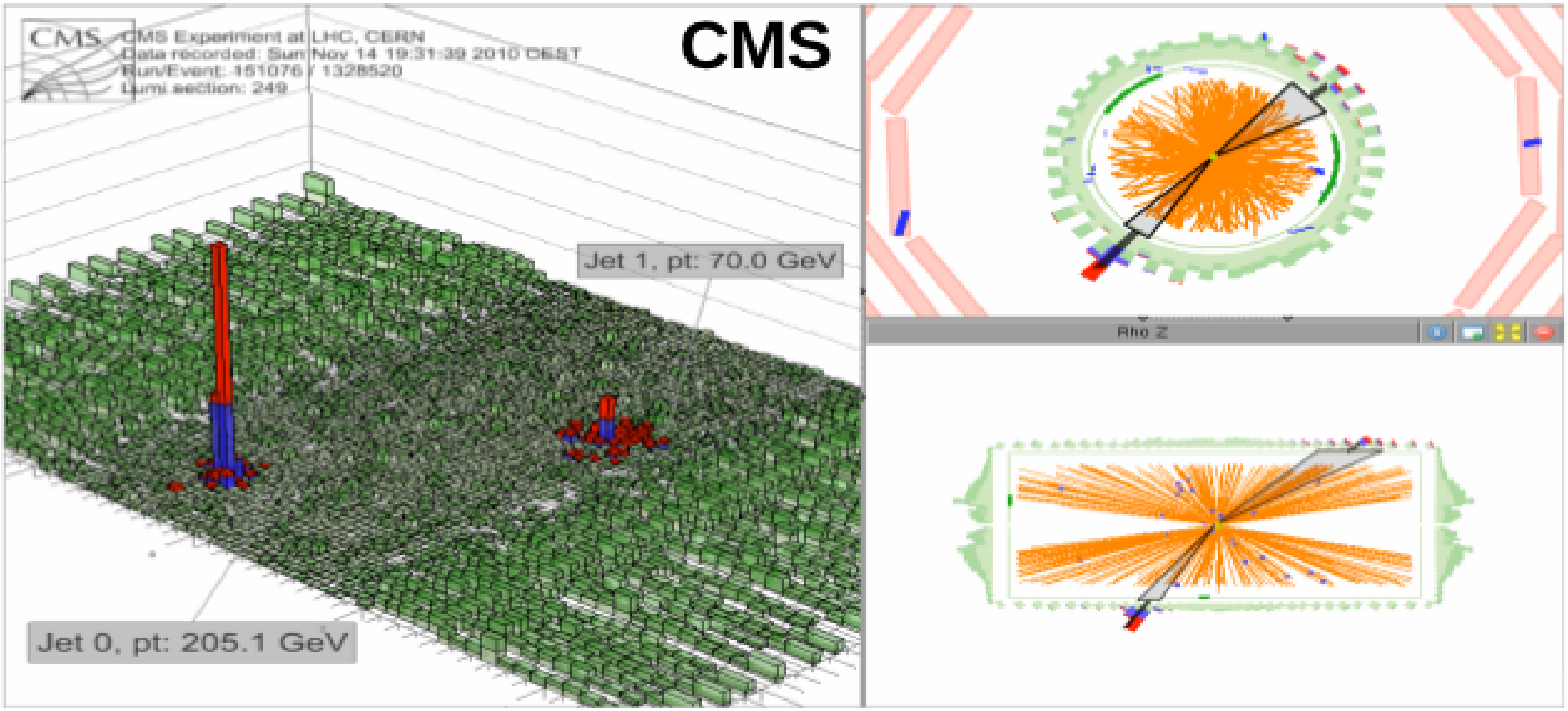
- Strong leading particle suppression also at LHC energies
- Qualitatively similar to the one at RHIC
- As at RHIC from final state (ie not observed in pPb collisions)

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!

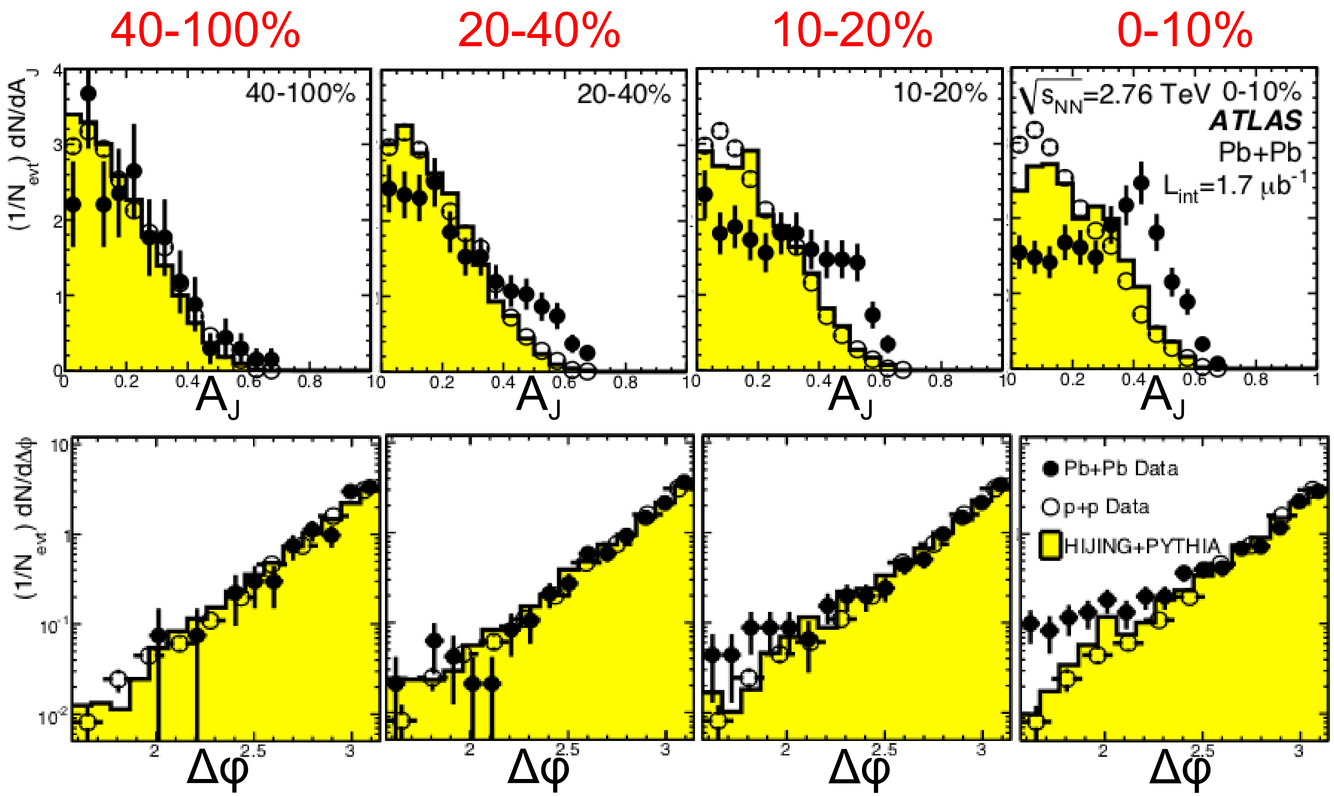
Jet quenching in dijet events



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

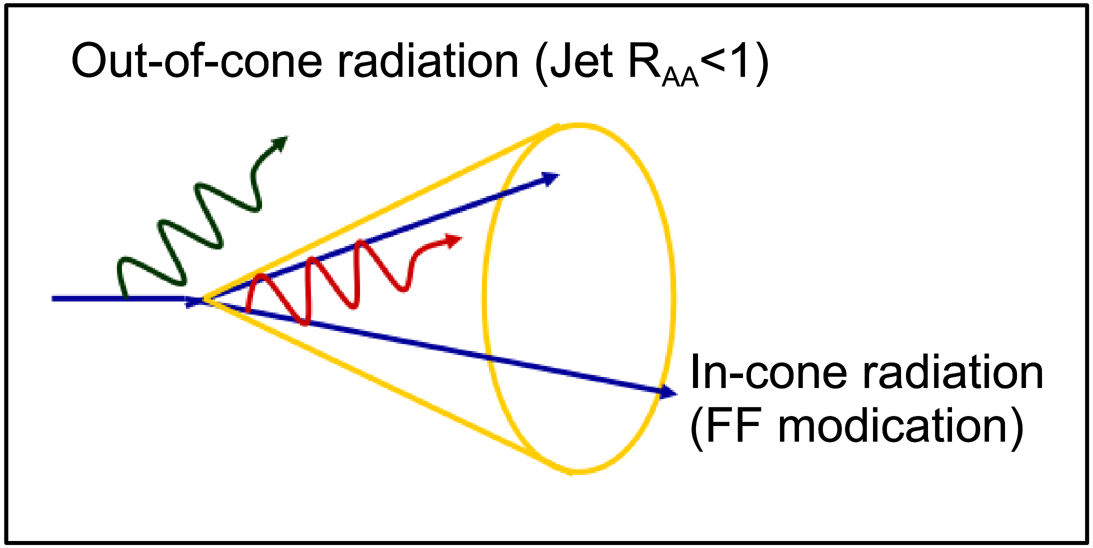


Momentum imbalance wrt to MC (pp) reference increases with increasing centrality.
No (or very little) azimuthal decorrelation.

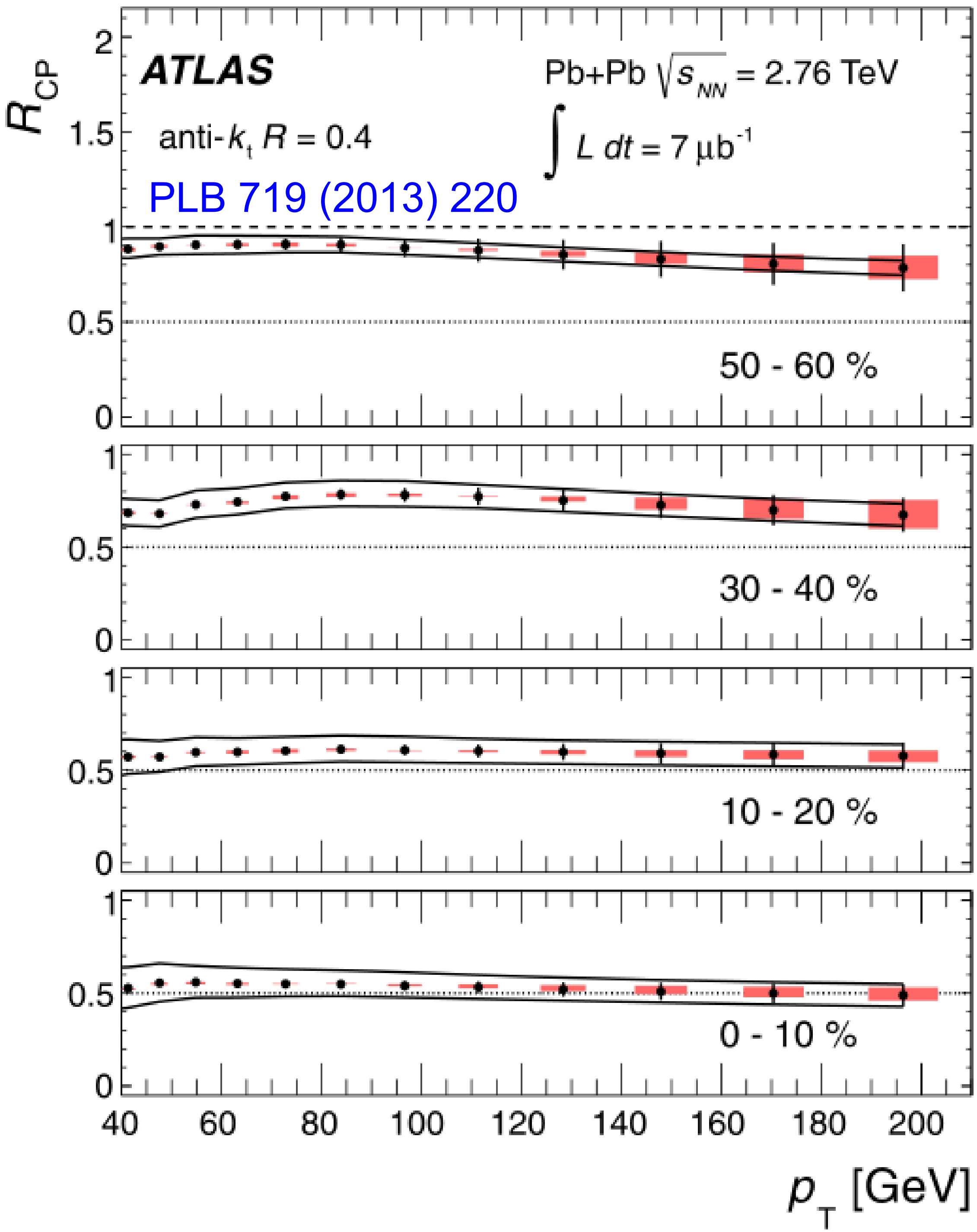
ATLAS, PRL 105 (2010) 252303
CMS, PRC 84 (2011) 024906

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

Where does the radiated energy go?



Jet R_{CP}: Pushing to high p_T



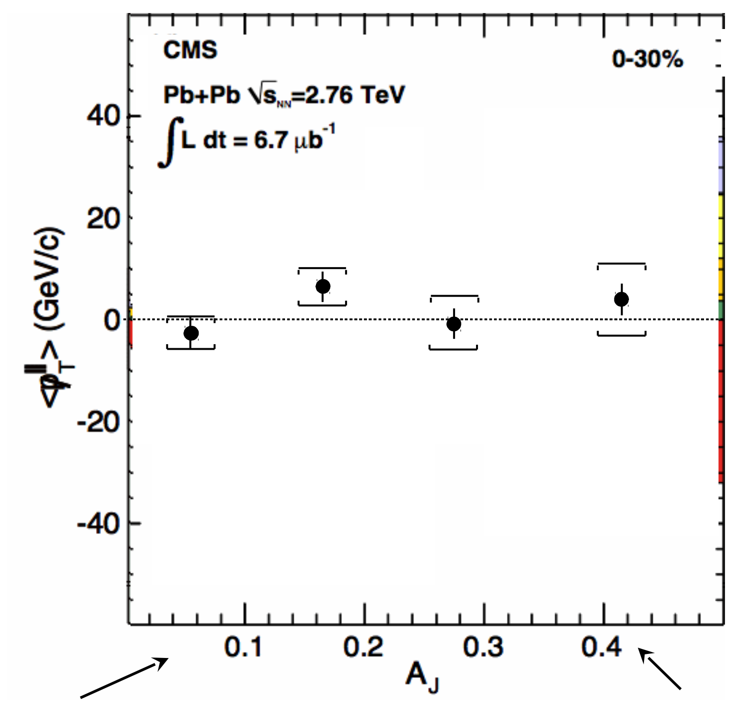
$$R_{\mathrm{CP}} = \frac{\left.\frac{1}{N_{\mathrm{coll}}}\frac{\mathrm{d}N}{p_{\mathrm{T}}}\right|_{\mathrm{cent}}}{\left.\frac{1}{N_{\mathrm{coll}}}\frac{\mathrm{d}N}{p_{\mathrm{T}}}\right|_{60-80\%}}$$

- Strong jet suppression up to 200 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 $|\eta| < 2.4$
- Define missing p_T $$\not{p}_T^{\parallel} = \sum_{\mathrm{Tracks}} -p_T^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$
- Averaging over event sample in bins of A_J find missing p_T consistent with zero

0-30% Central PbPb

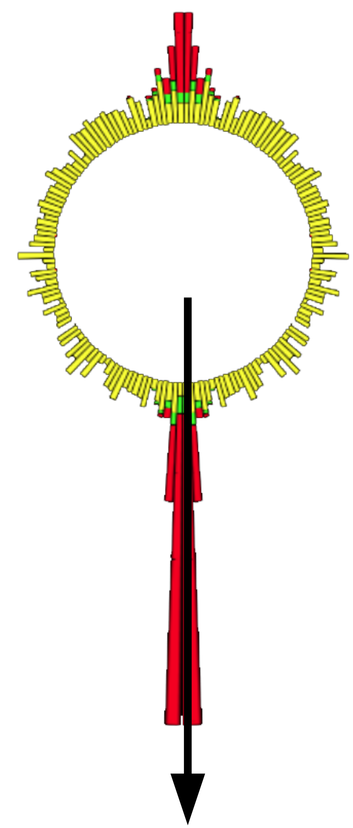


balanced jets

unbalanced jets

excess away from leading jet

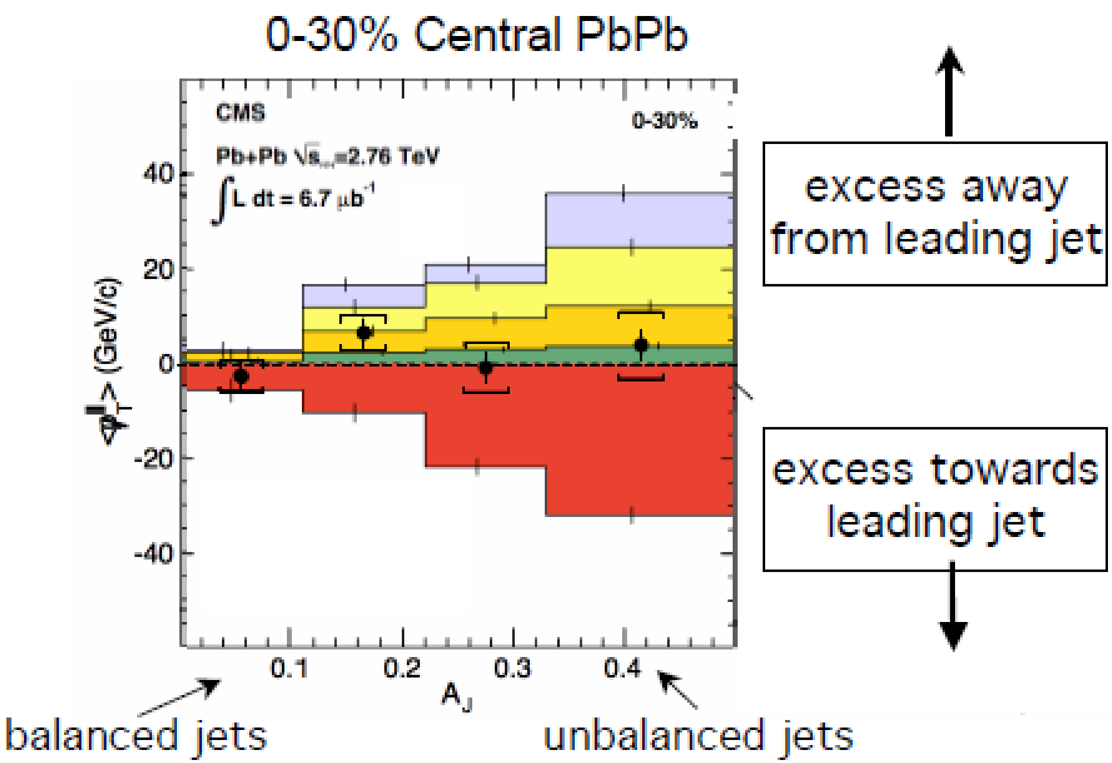
excess towards leading jet



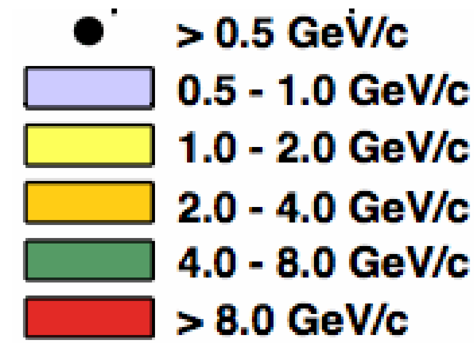
Leading jet defines direction

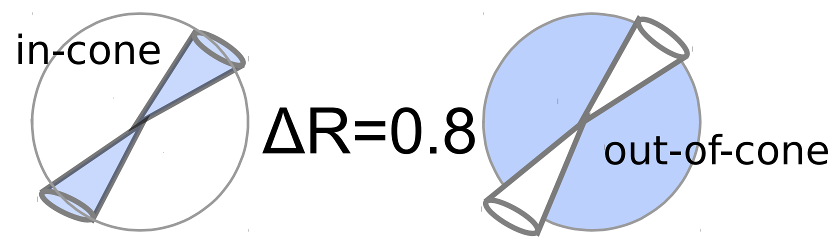
PRC 84 (2011) 024906

Where does the energy go?

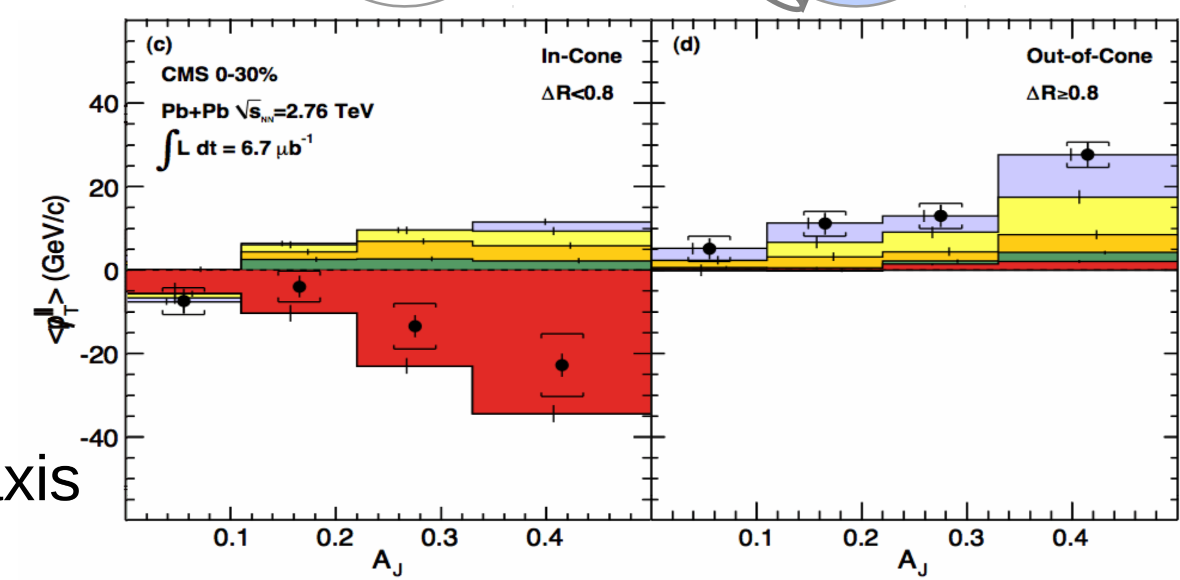


Calculate missing p_T in bins of track p_T

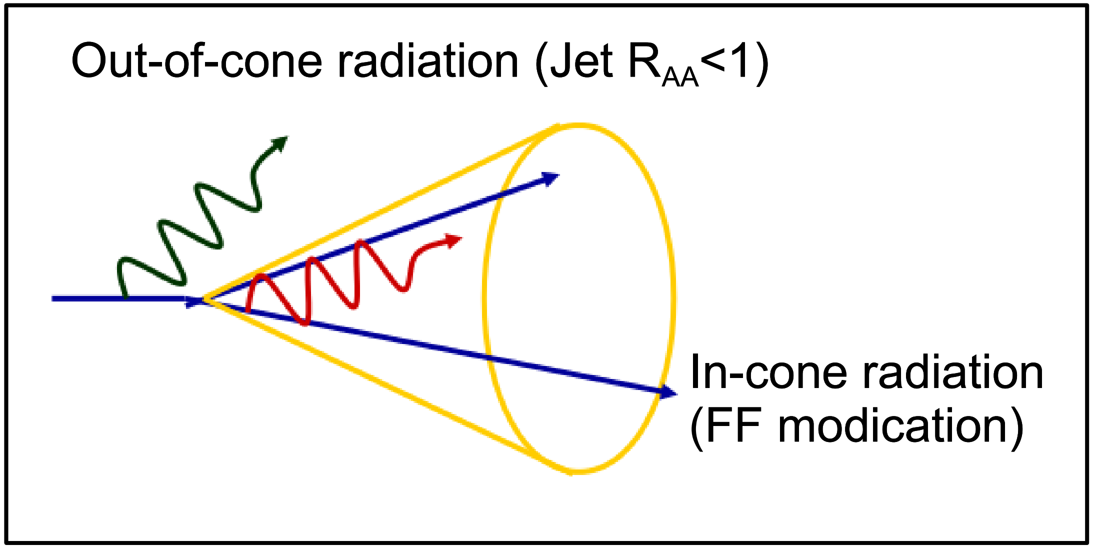




The momentum difference in the leading jet is compensated by low p_T particles at large angles with respect to the jet axis



Where does the radiated energy go?

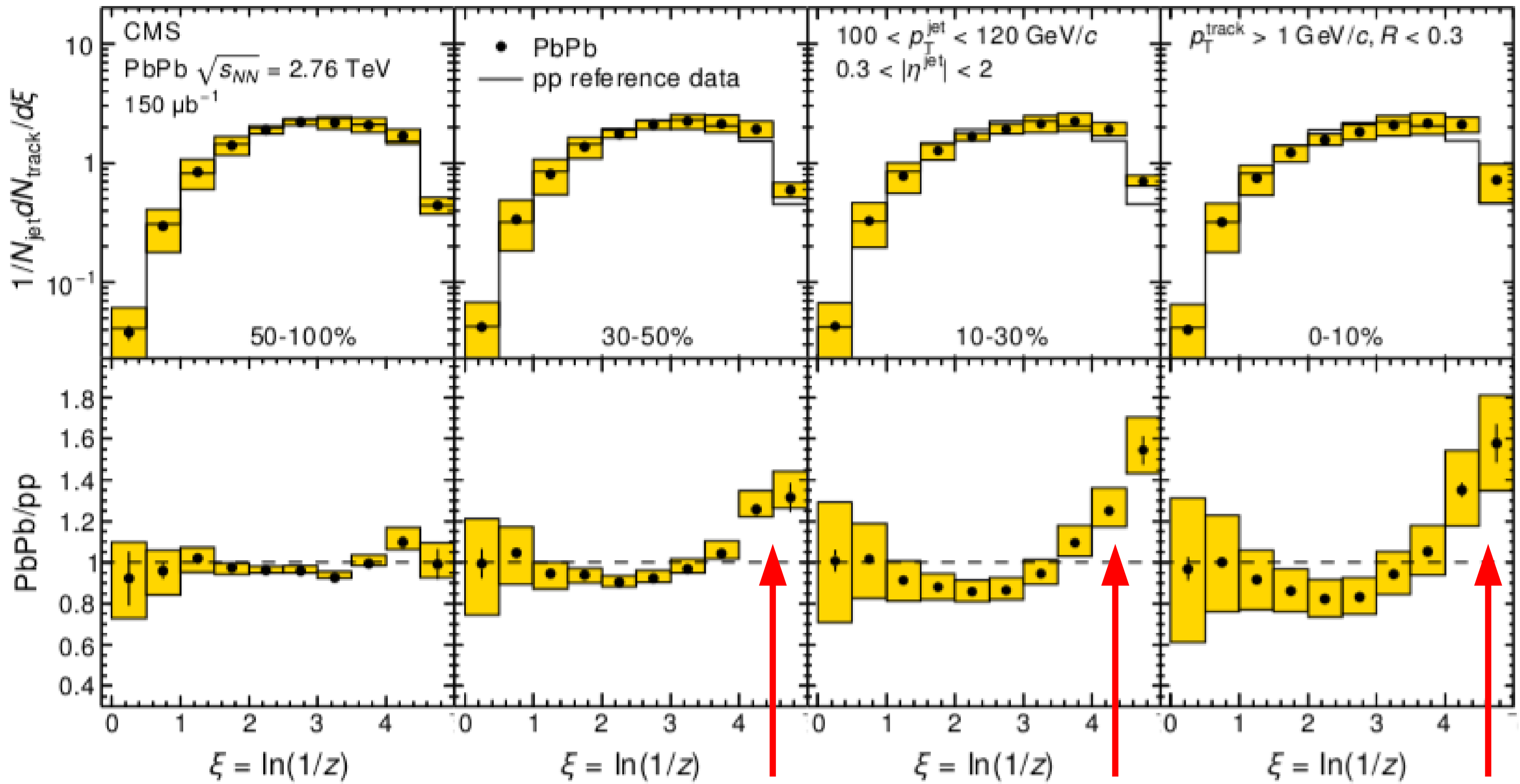


Is there an observable difference in the jet cone?

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

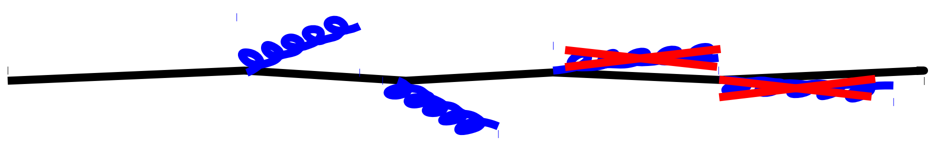
100<p_T<120 GeV/c

Track p_T>1 GeV/c

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

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
- 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

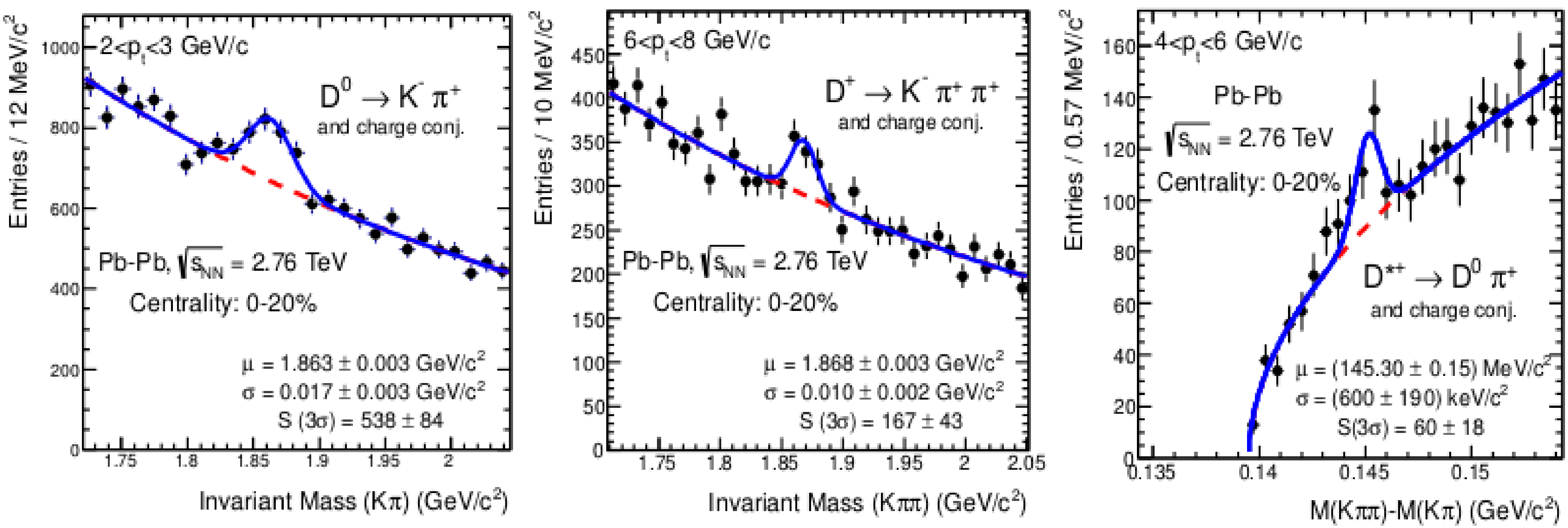
$$\Delta E_g > \Delta E_{charm} > \Delta E_{beauty}$$

↓

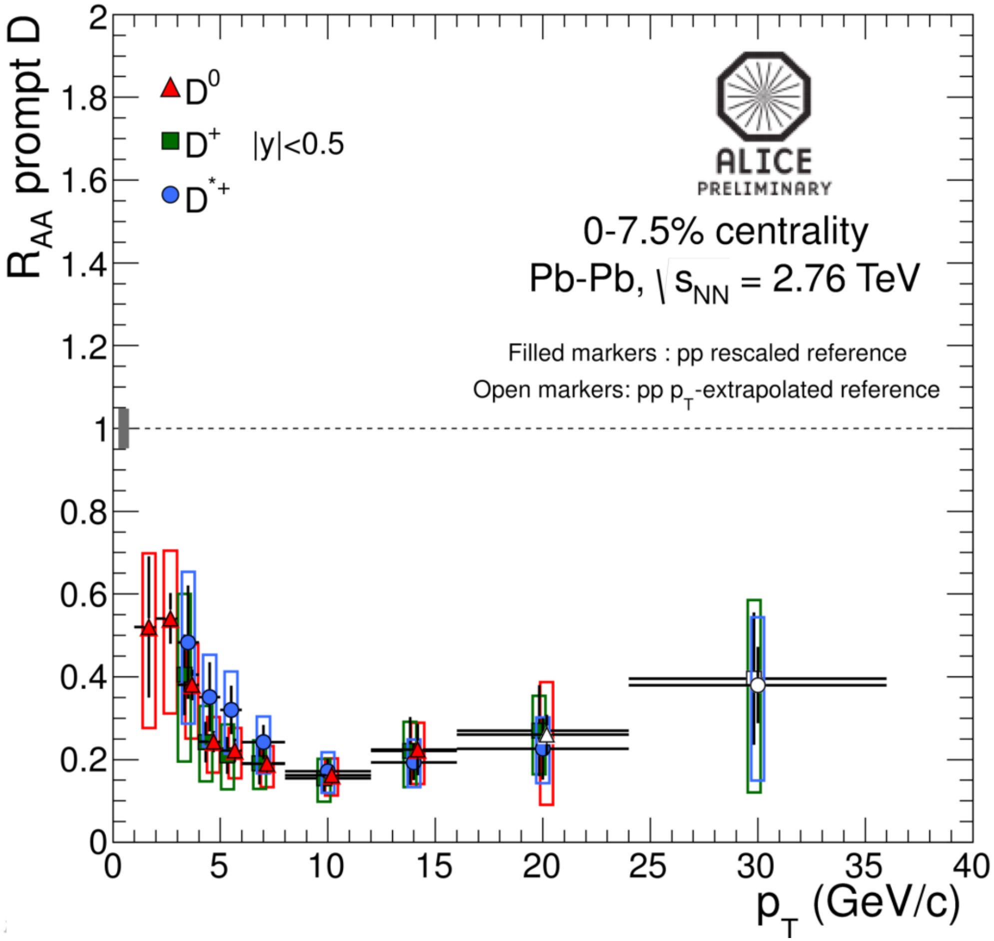
$$R_{AA}(\text{light hadrons}) < R_{AA}(D) < R_{AA}(B)$$

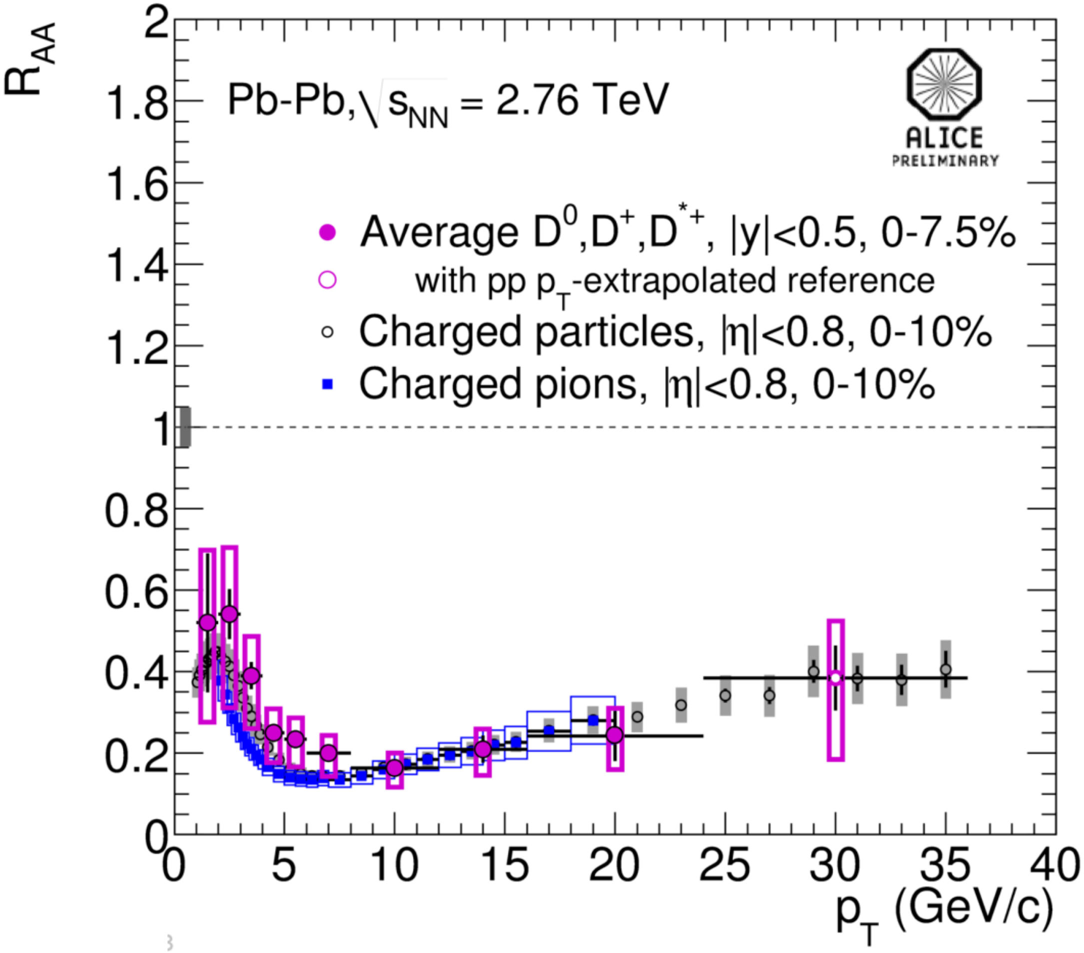
Various techniques
for heavy flavor measurements

- 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)



LHC results: D-mesons

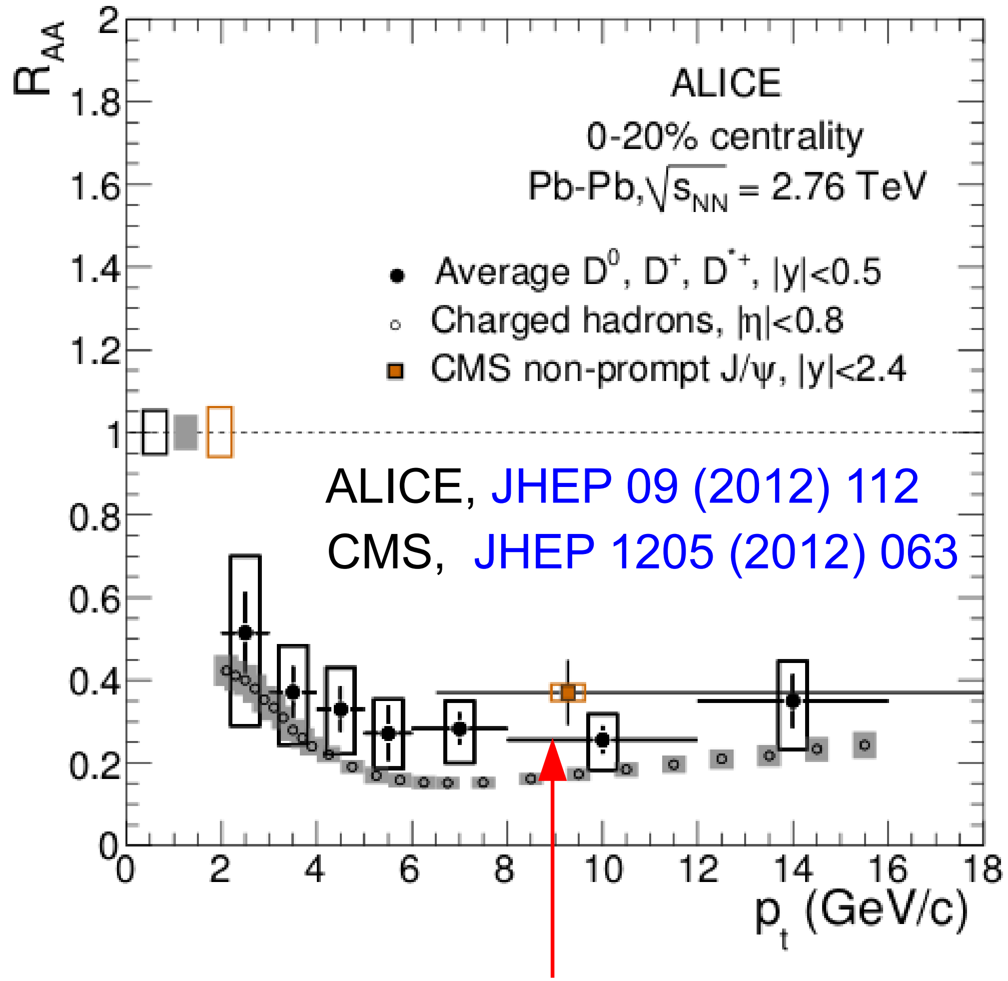




- Good agreement between D-meson types
- Still, large suppression (factor ~5)

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

LHC: Beauty via non-prompt J/ψ



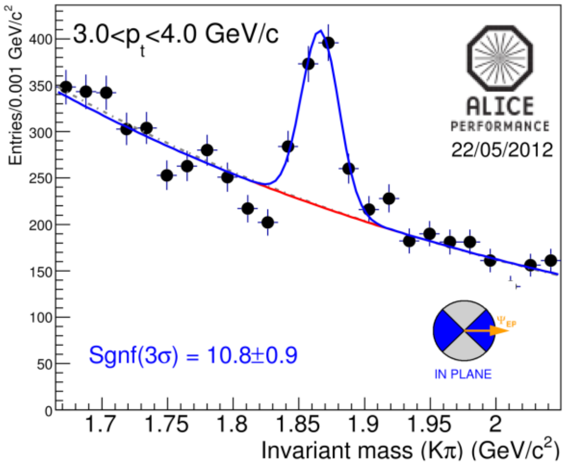
$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B)$?

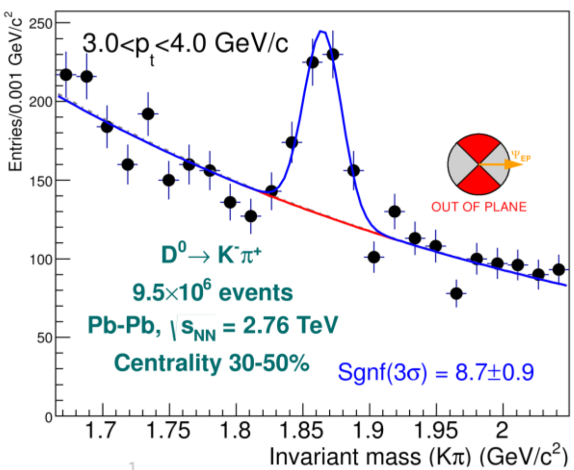
Suppression pattern may be compatible with expected energy loss hierachy

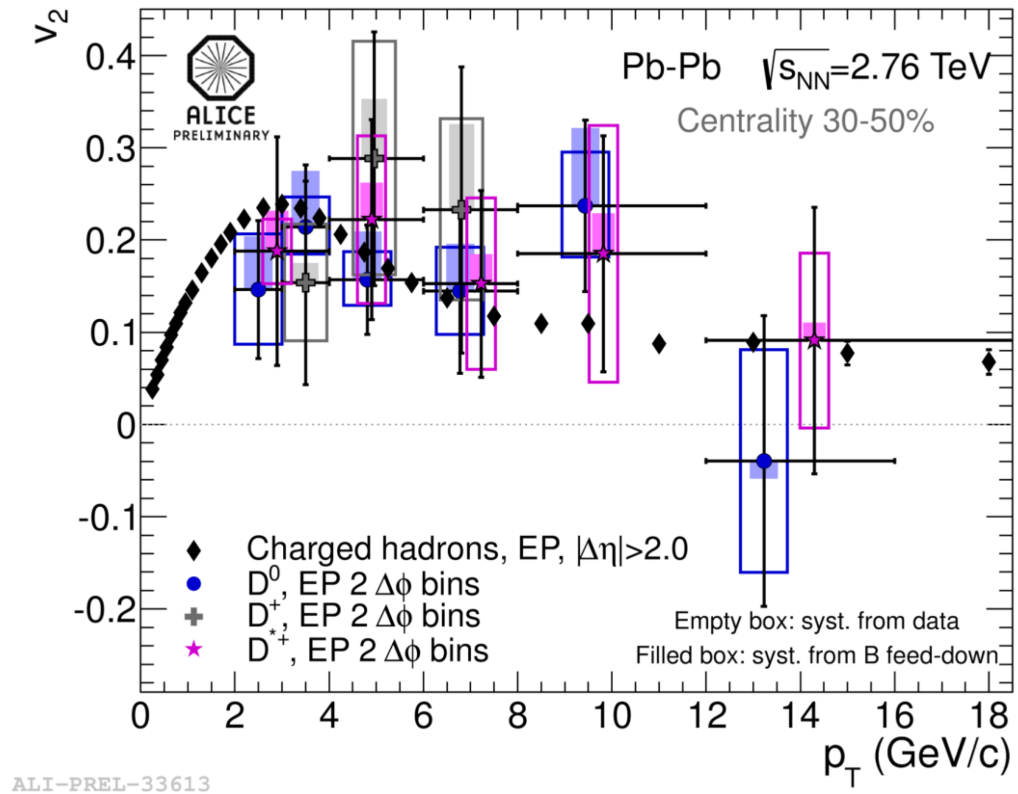
Heavy-quark v_2 at the LHC

arXiv:1405.2001

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





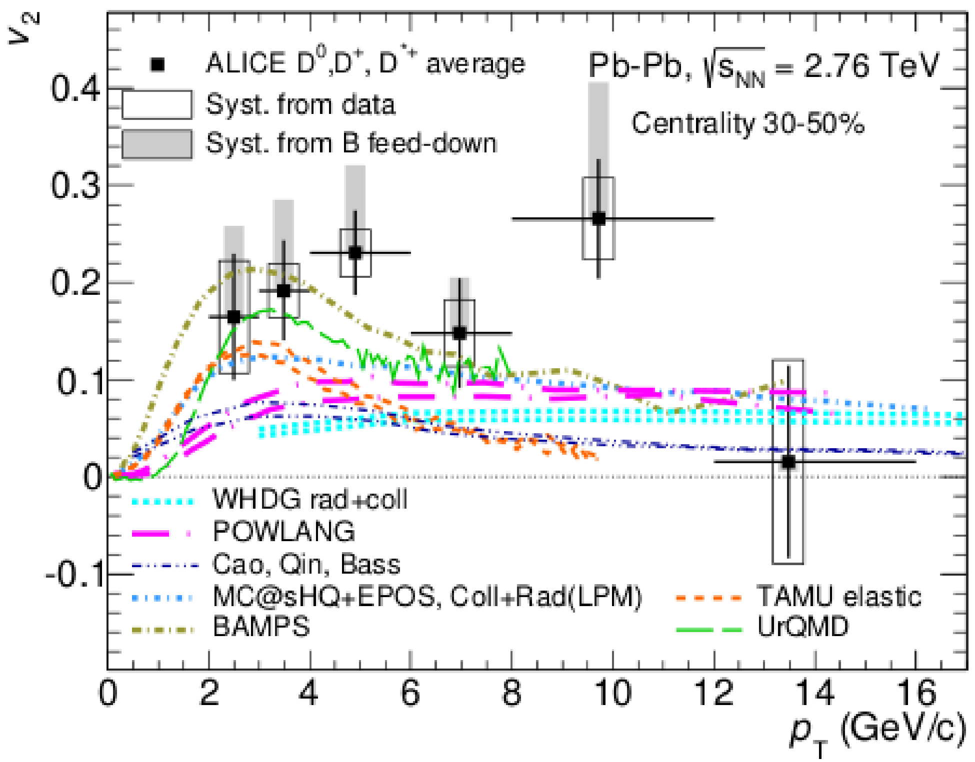


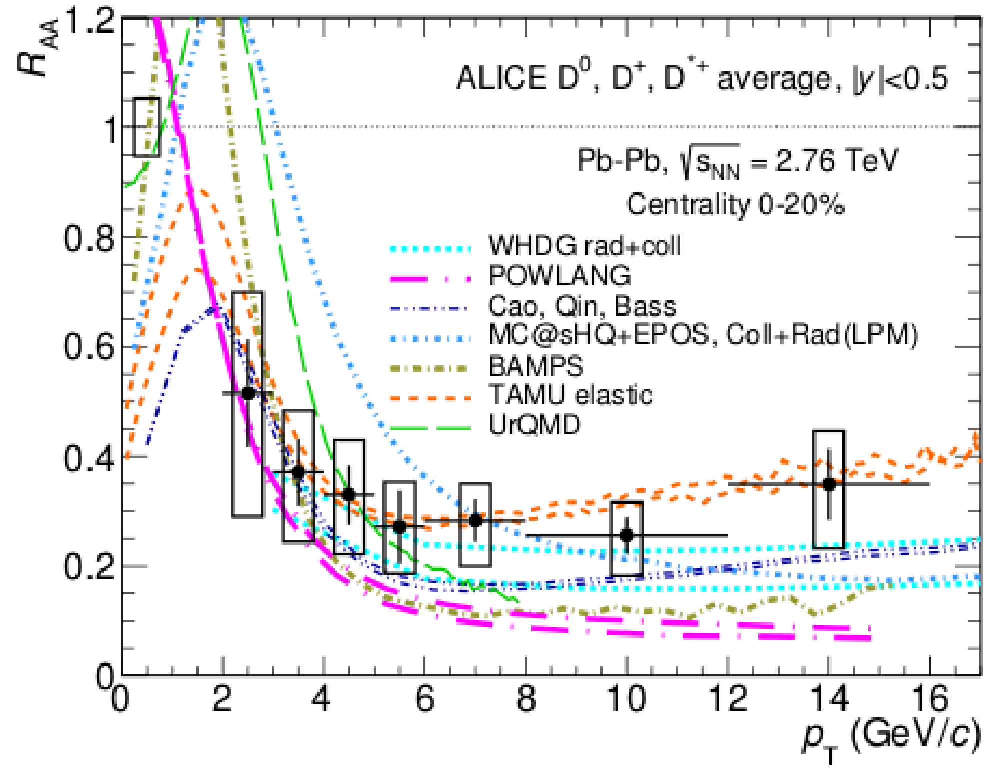
Indication of non-zero D meson v_2: It implies that heavy quarks also thermalize and participate in the collective expansion.

→ Need more data and to measure at lower p_T

LHC D-mesons: Data vs models

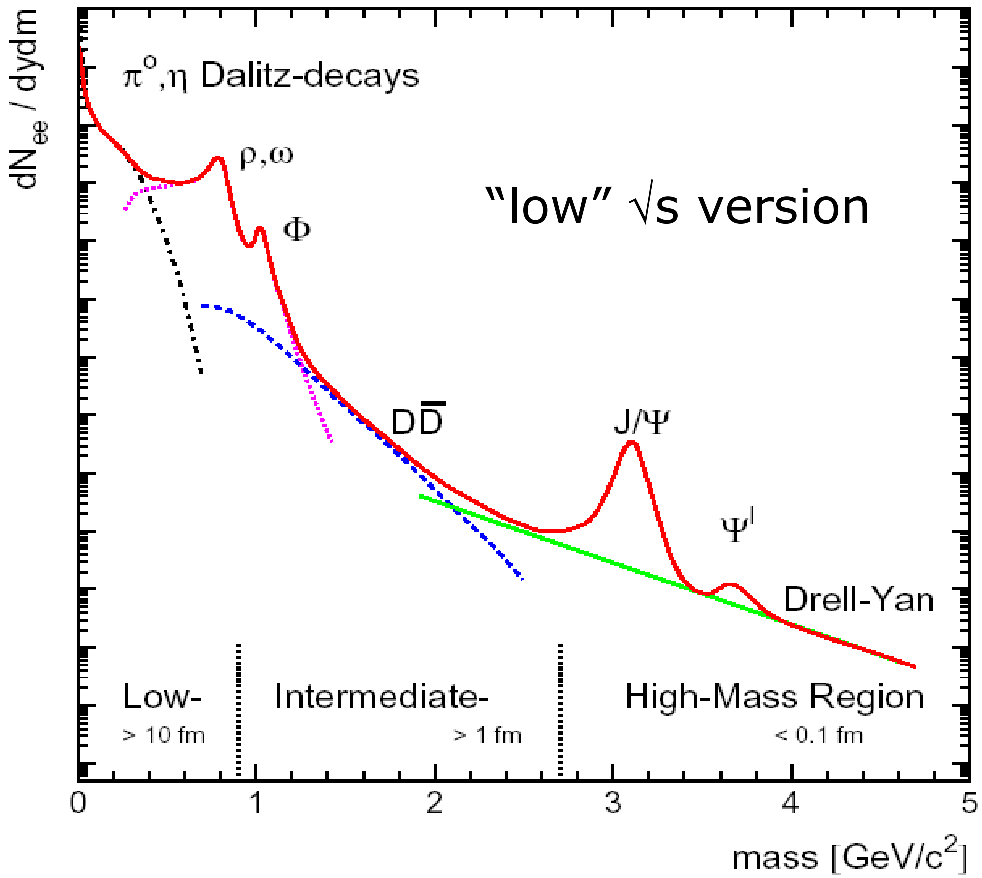
arXiv:1405.2001

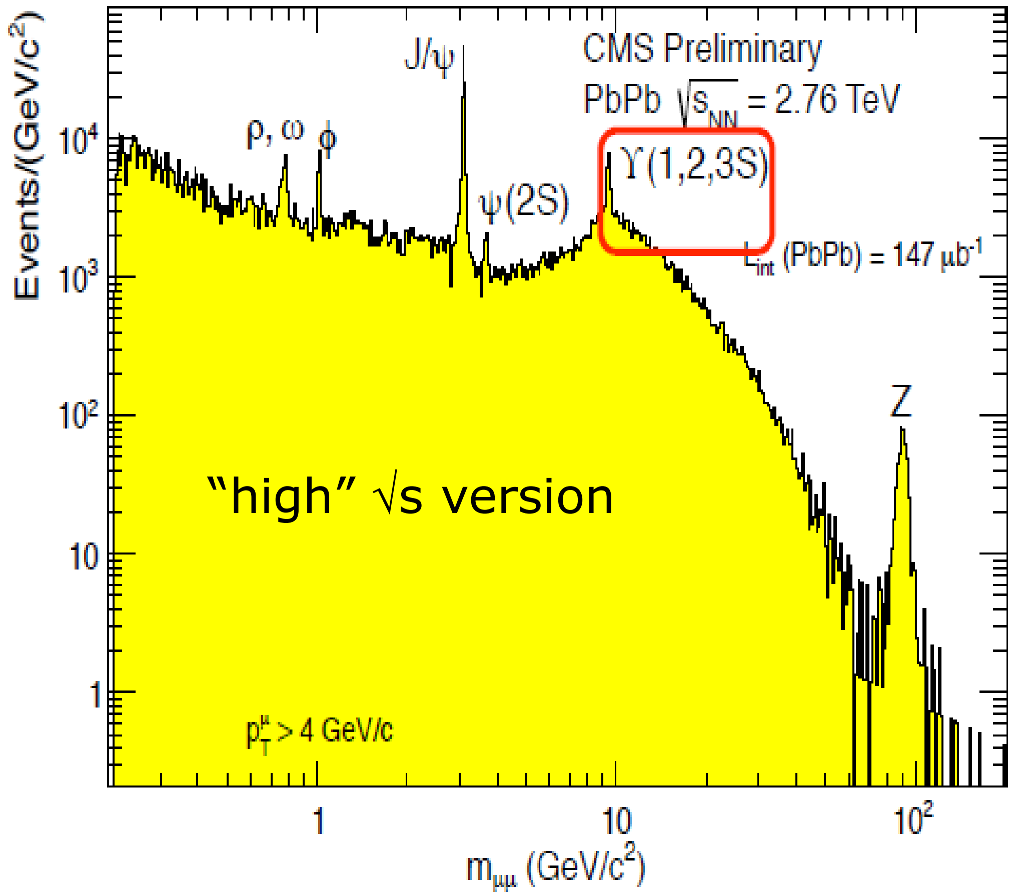




Consistent description of charm RAA and v2 challenging for models.
Can bring insight into medium transport properties, and
with more data from future LHC runs.

The dilepton invariant mass spectrum

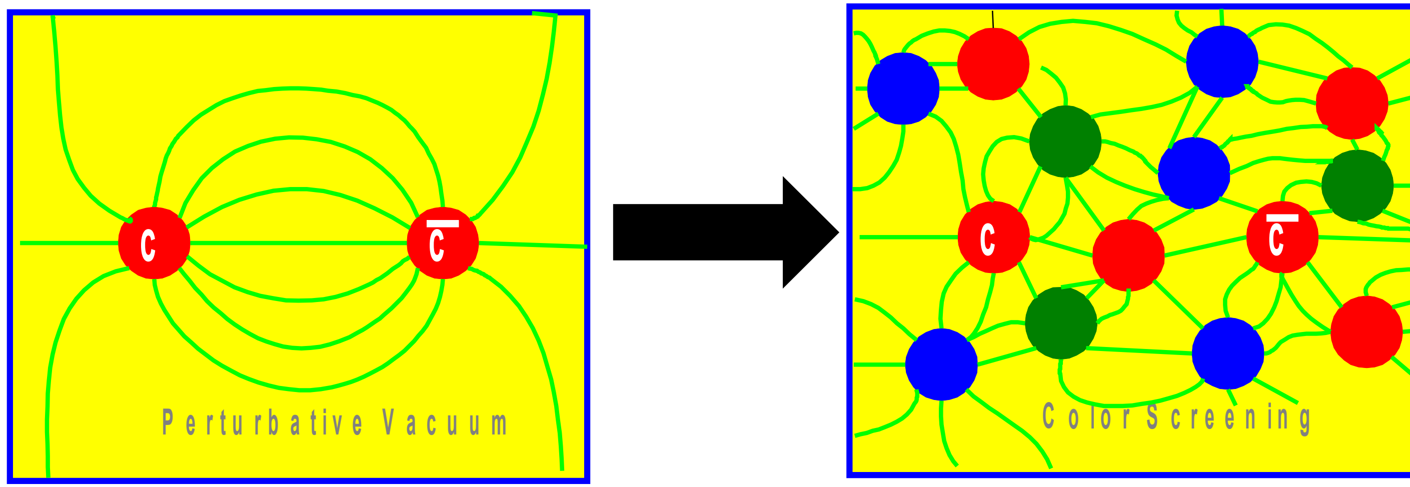


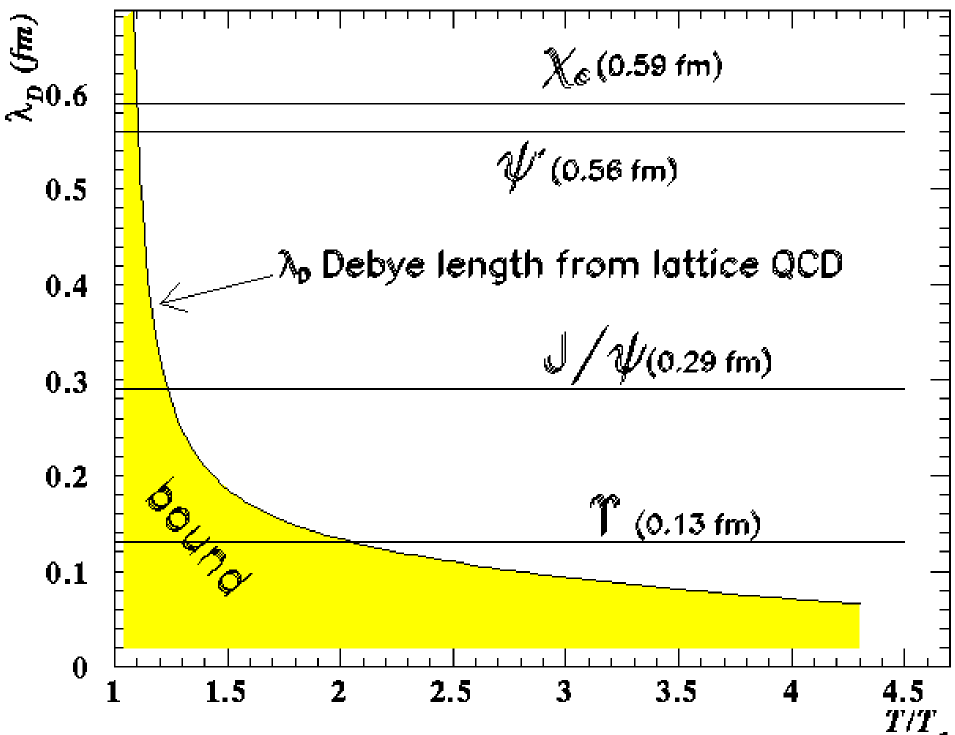


- The study of lepton pairs also allows to extract information about the early stages of the collision
- Dileptons (like photons) do not interact strongly and once produced can without significant re-interactions (not altered by later stages) escape the collision

Melting at high temperature

Screening of strong interactions in QGP





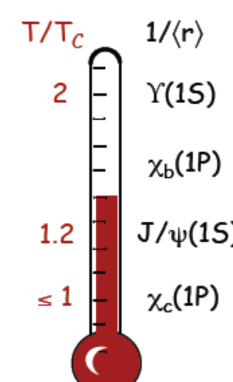
Screening stronger at high T

λ_D ~ maximum size of a bound state, decreases when T increases

Different states, different sizes

Resonance melting

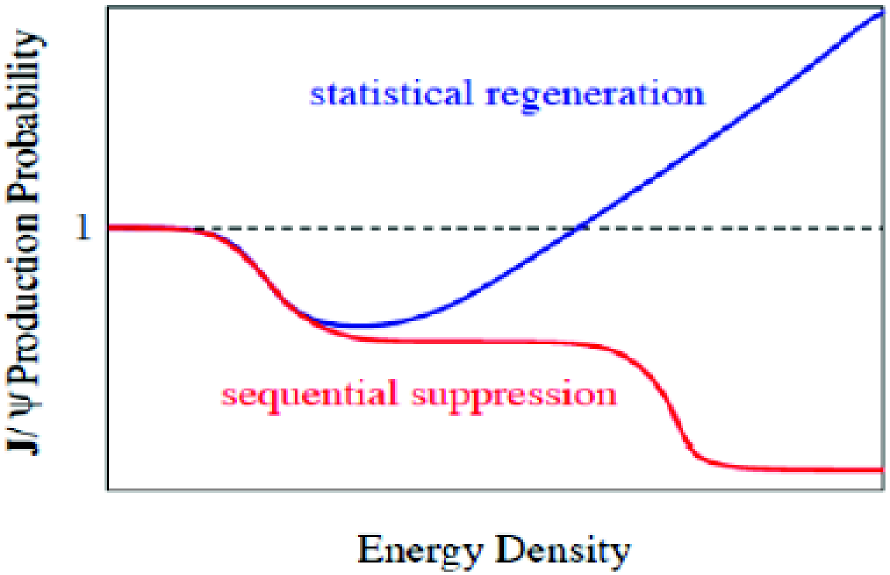
QGP thermometer



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

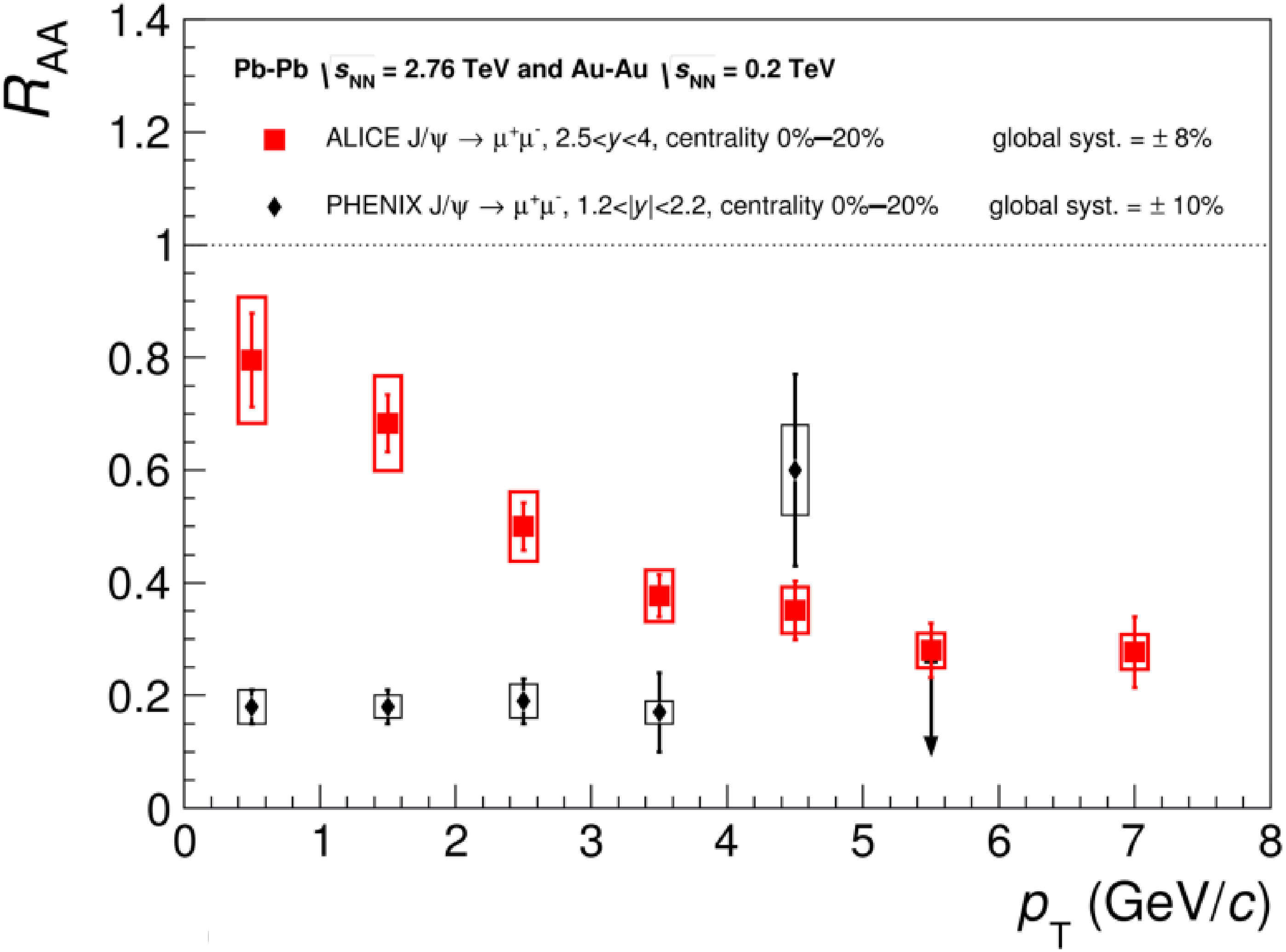


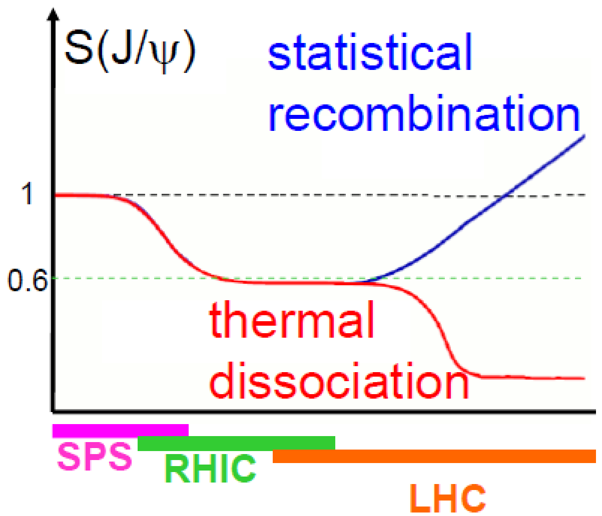
- Statistical approach
  - Charmonium fully melted in QGP
  - Charmonium produced together with all other hadrons at chemical freeze-out according to statistical weights
- Kinetic recombination
  - Continuous dissociation and regeneration over QGP lifetime

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

LHC: J/ψ production in Pb-Pb

arXiv:1311.0214

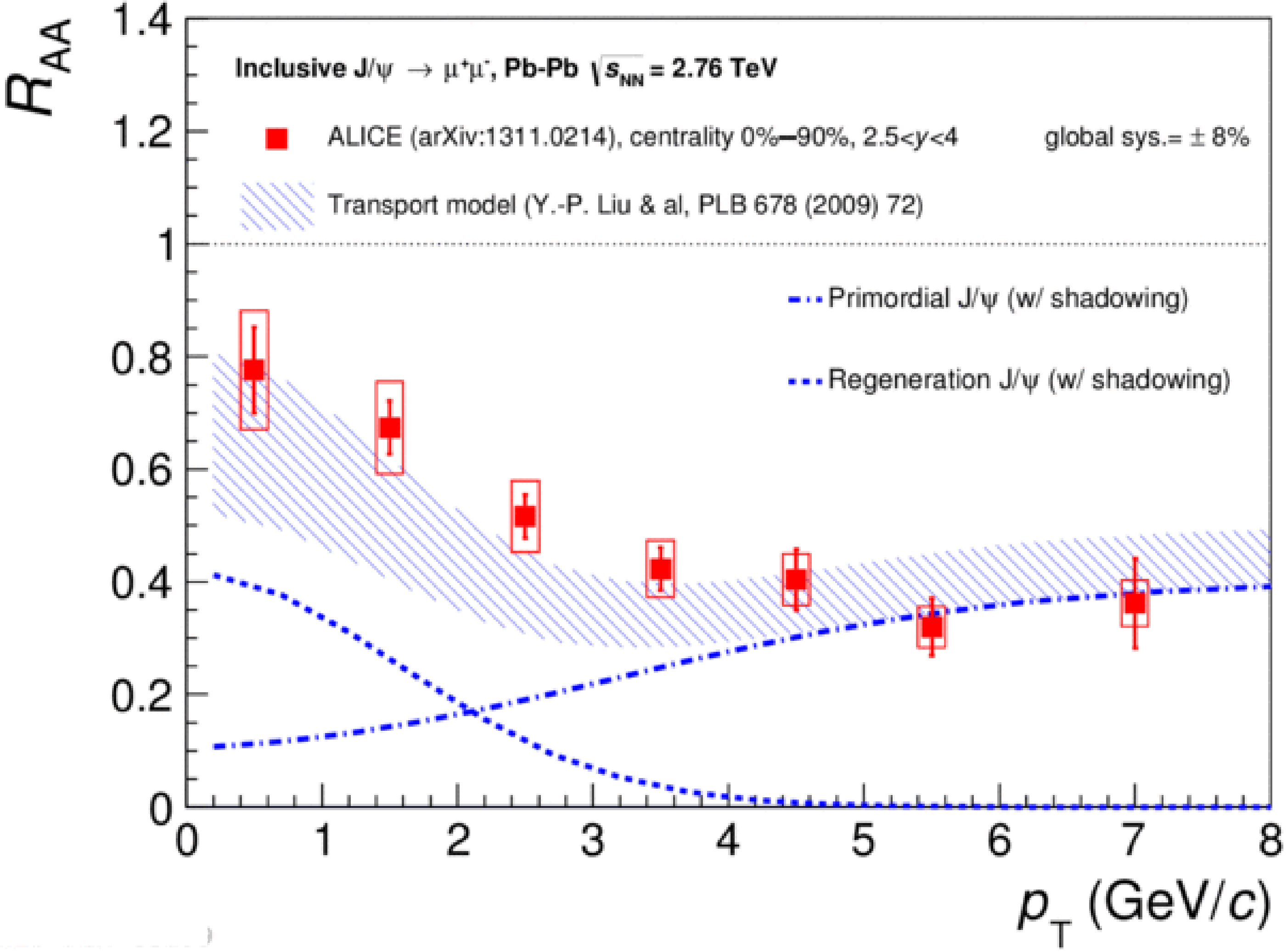


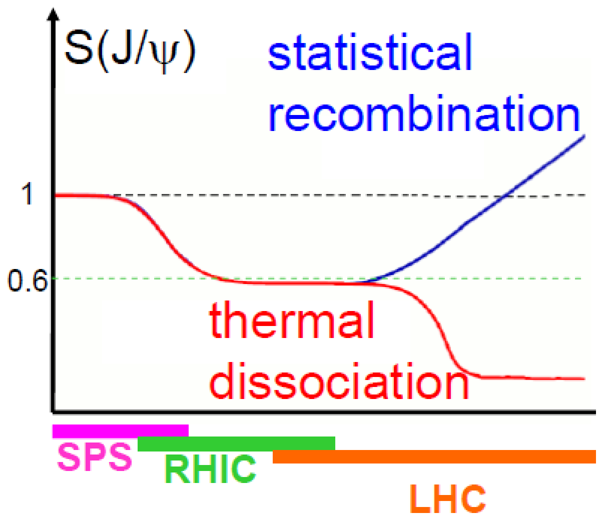


Different p_T (and centrality) dependence of J/ψ R_{AA} at LHC and RHIC

J/ψ production in Pb-Pb

arXiv:1311.0214

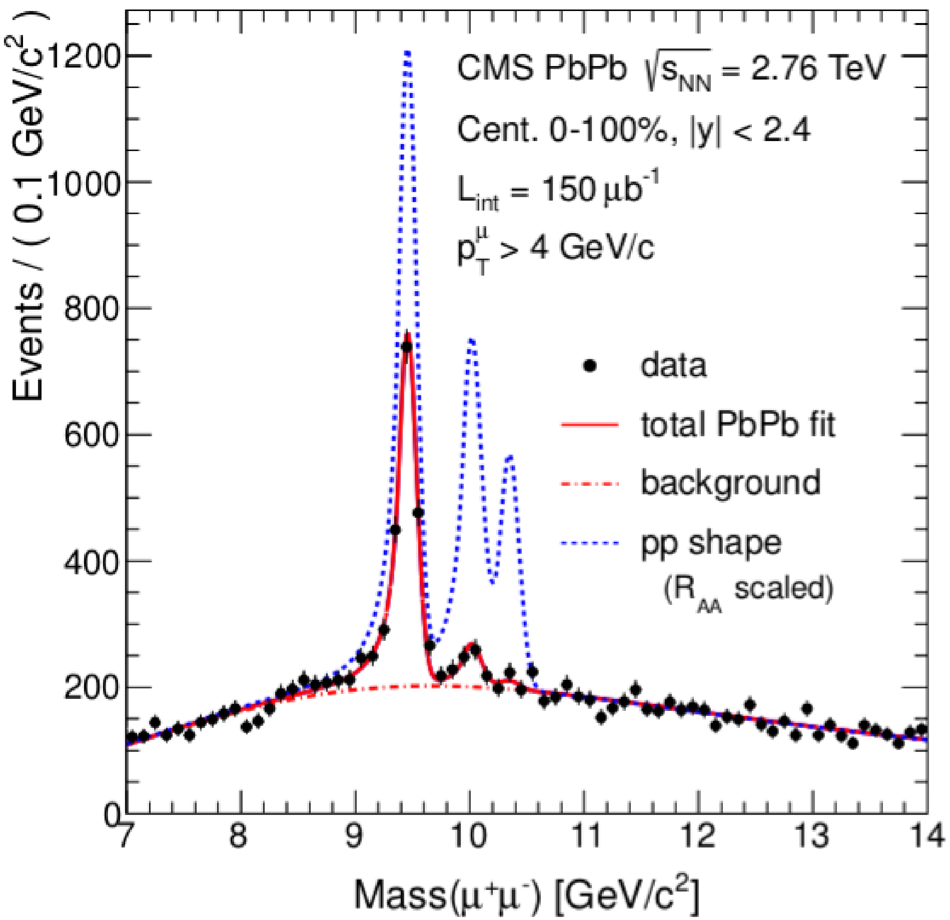


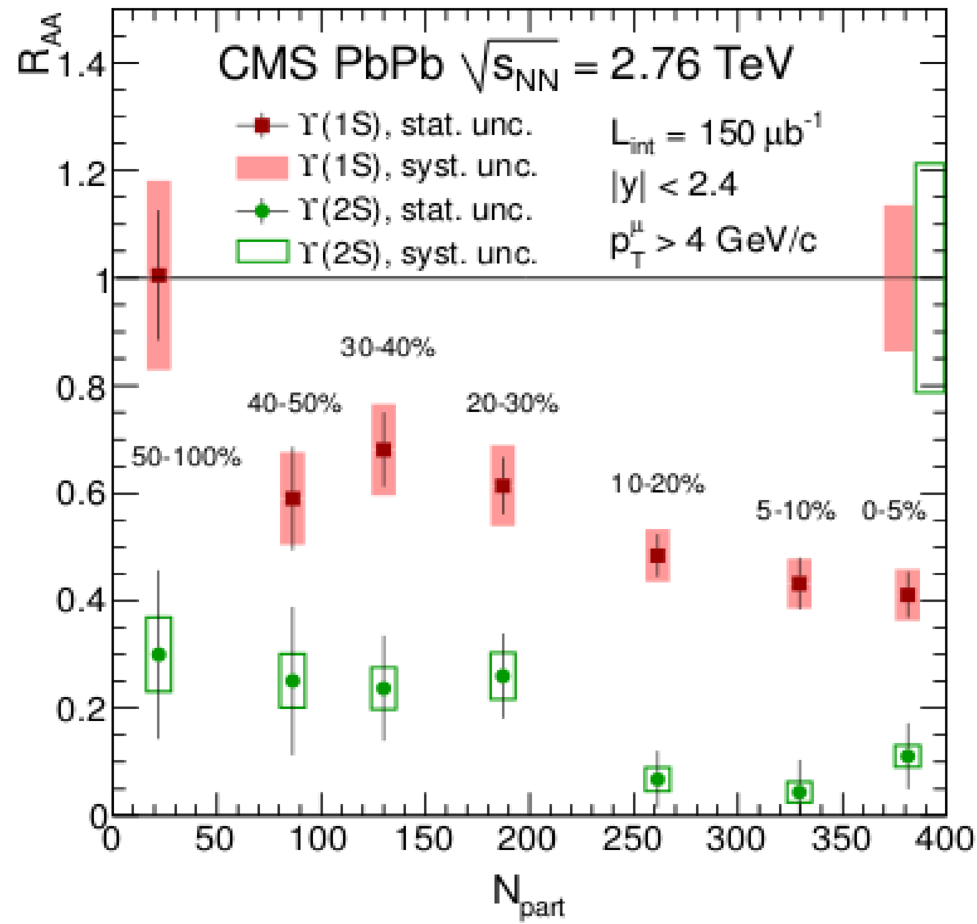


As expected in a scenario with $c\bar{c}$ recombination, especially at low p_T

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.

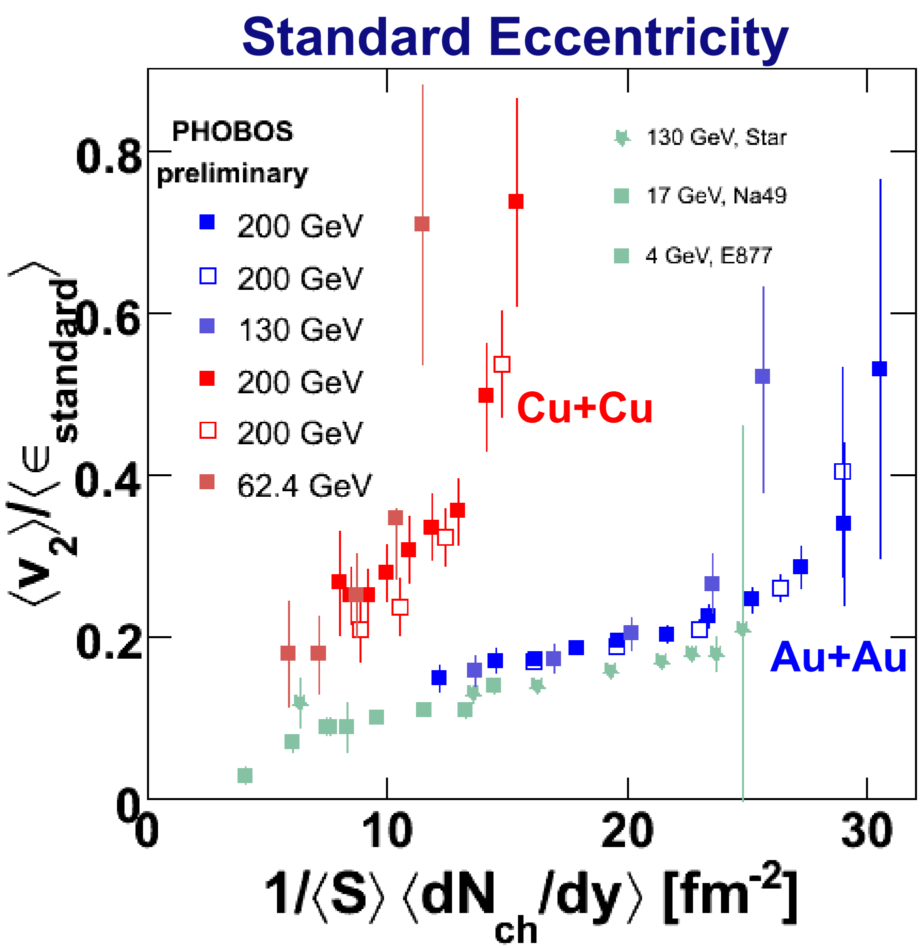
Summary

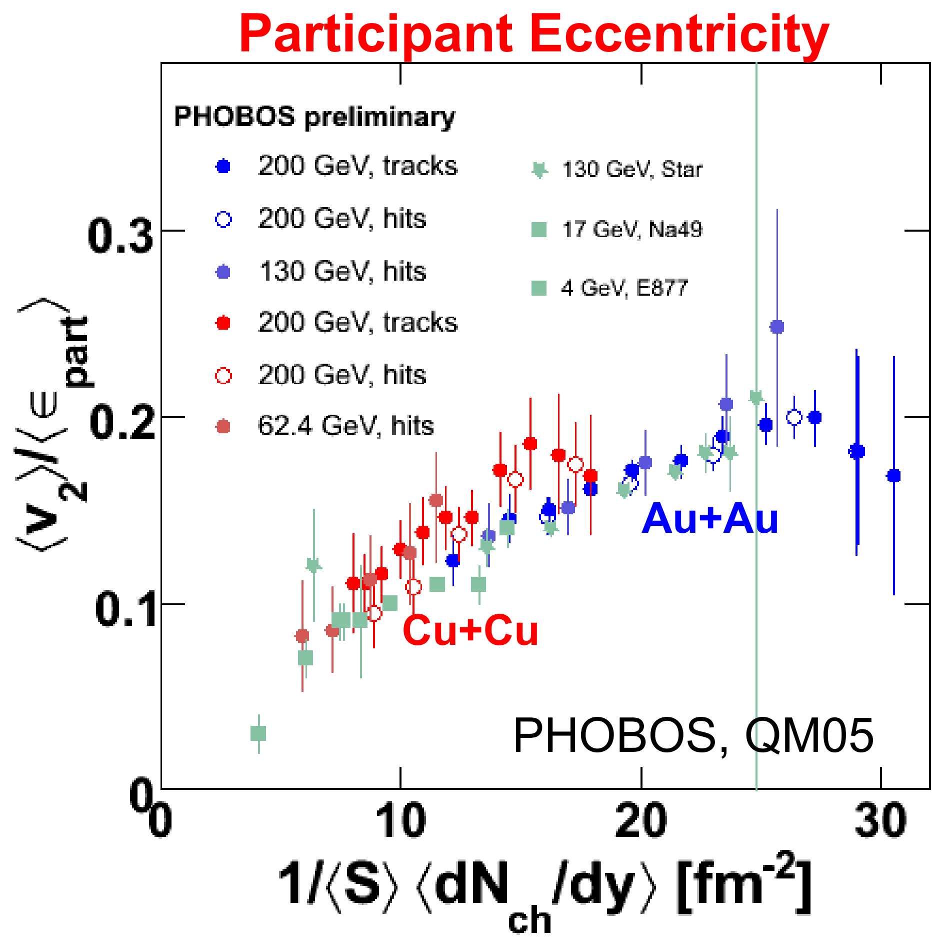
- The study of heavy-ion collisions allow to investigate properties of the strong interaction at very high energy density
- Experiments at various facilities provided lots of results with a strong sensitivity to the properties of the medium
- The medium behaves almost like a perfect fluid with the characteristics predicted for a QGP, and has spectacularly strong effects on hard probes (quarkonia, jet,…)
- With the advent of the LHC we are answering some of the long-standing questions, but we also face new challenges.
  So, there might be QGP physics waiting for you...

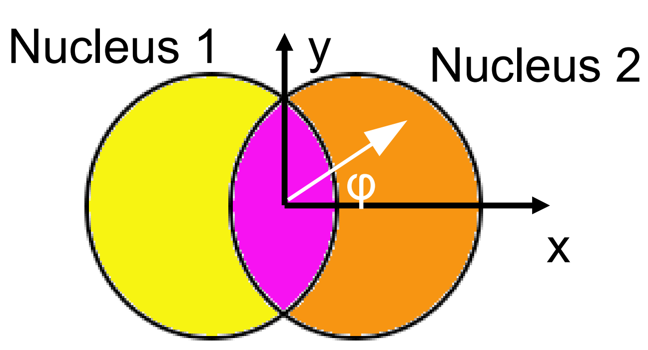
If you have questions about today's lecture please send them to “cloizides at lbl dot gov”

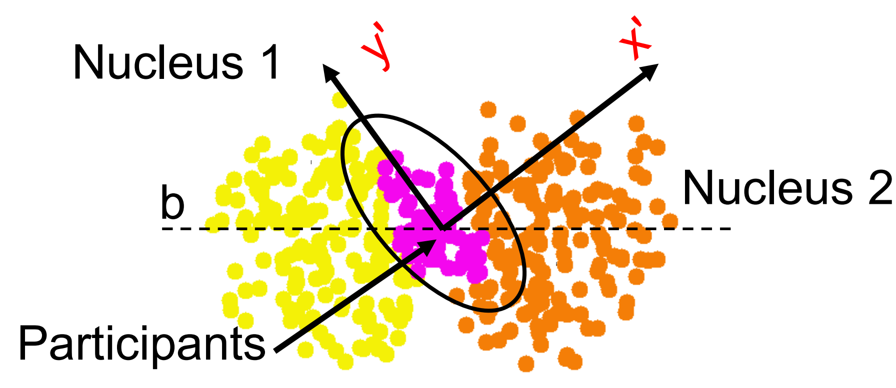
Some more advanced topics ...

Importance of initial state fluctuations

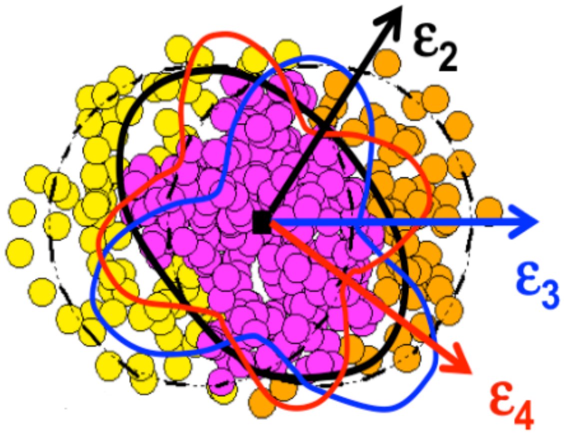








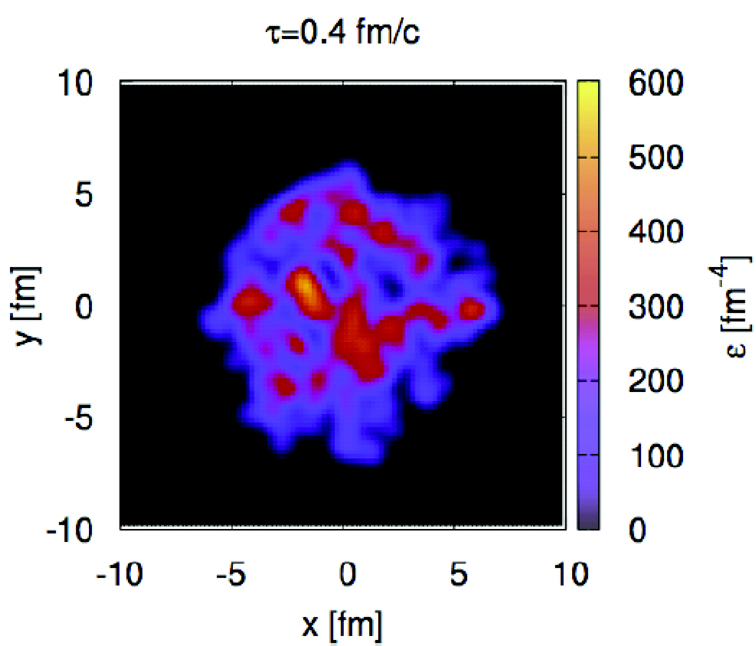
Higher harmonics and viscosity



Alver, Roland

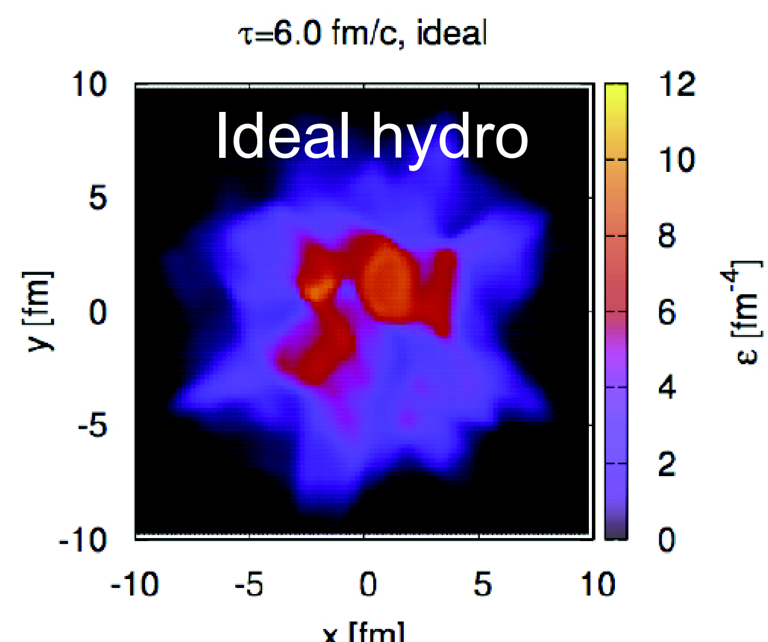
Initial spatial anisotropy not smooth, leads to higher harmonics / symmetry planes.

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



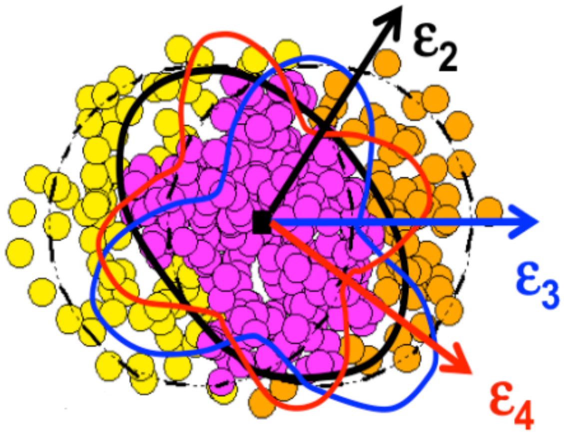
e-by-e hydro →

B. Schenke et al.



Ideal hydrodynamical models preserves these “clumpy” initial conditions

Higher harmonics and viscosity



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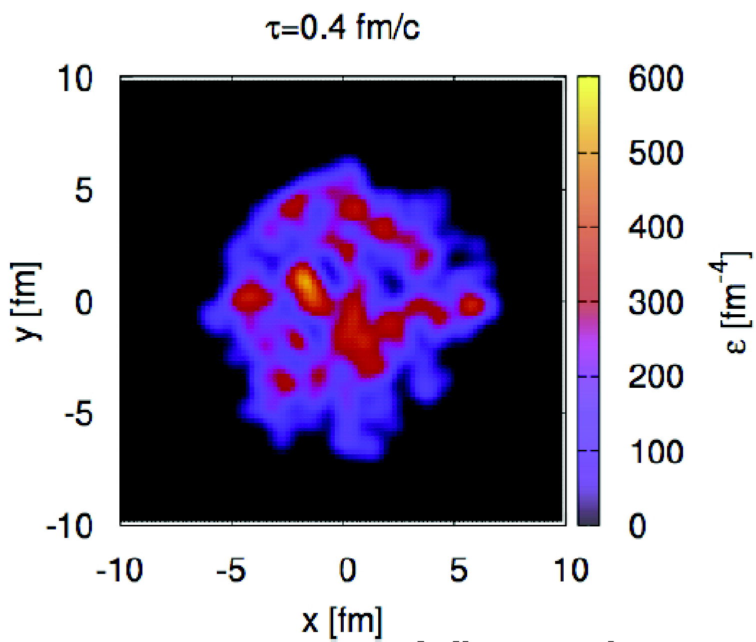
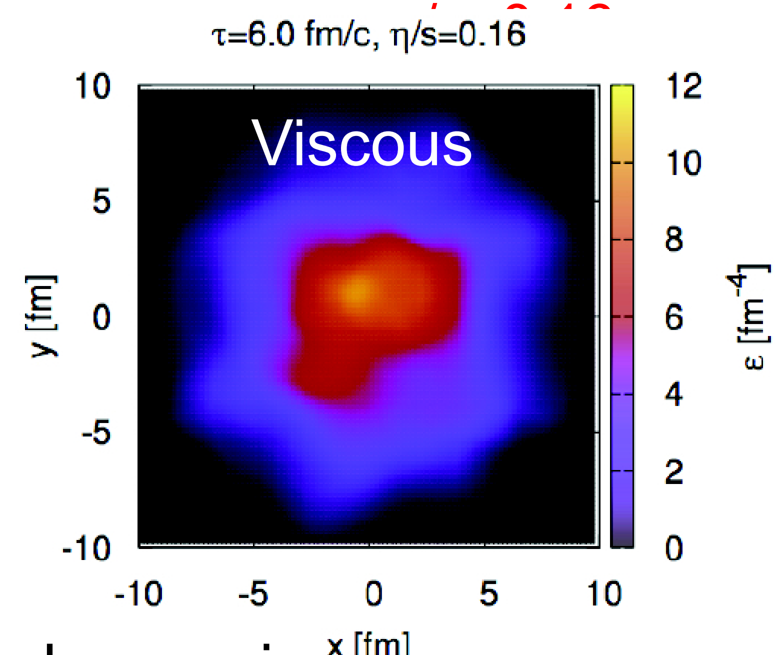


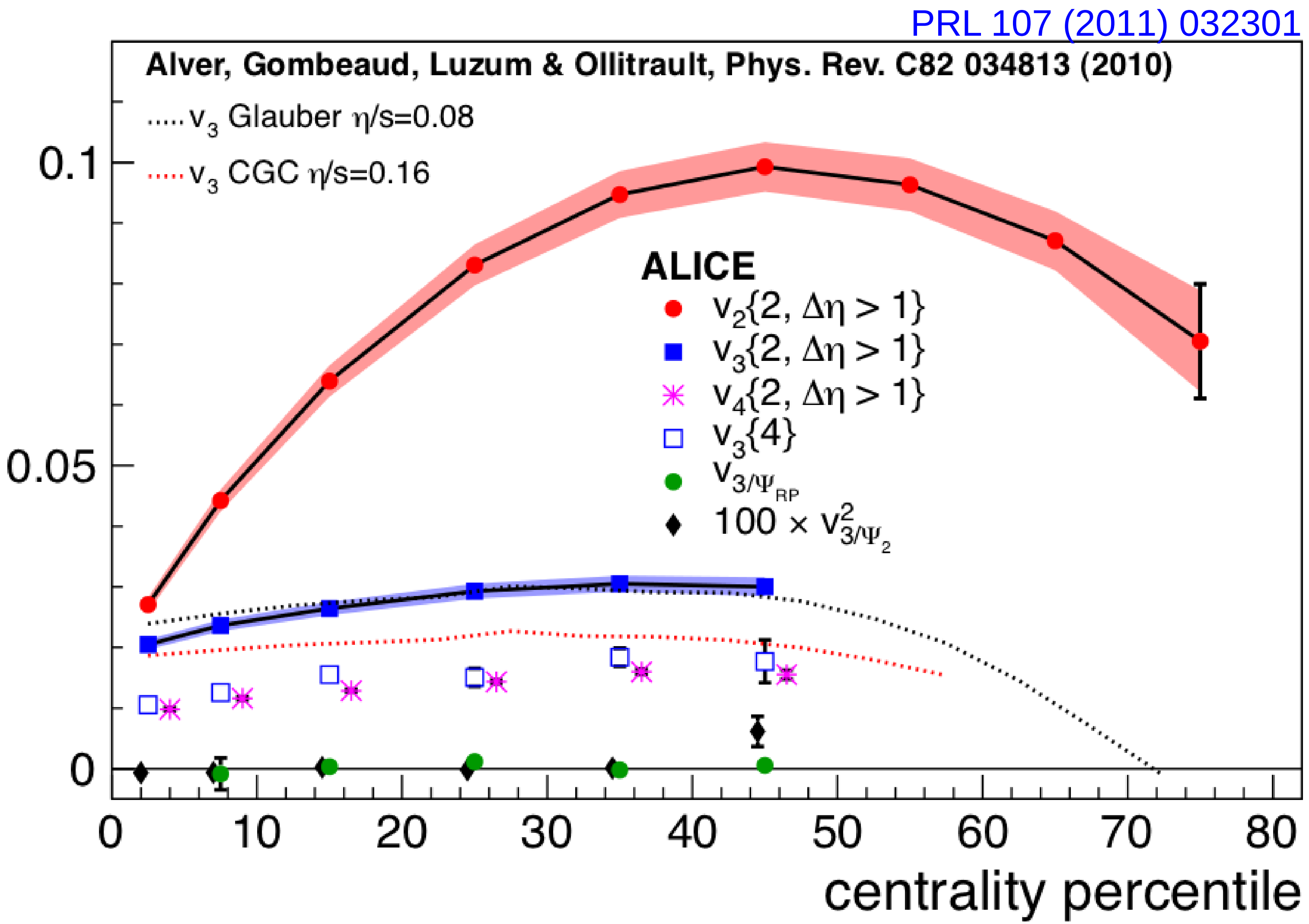
e-by-e hydro →

B. Schenke et al.



Viscosity suppresses higher harmonics,
→ v_n provide additional sensitivity to η/s

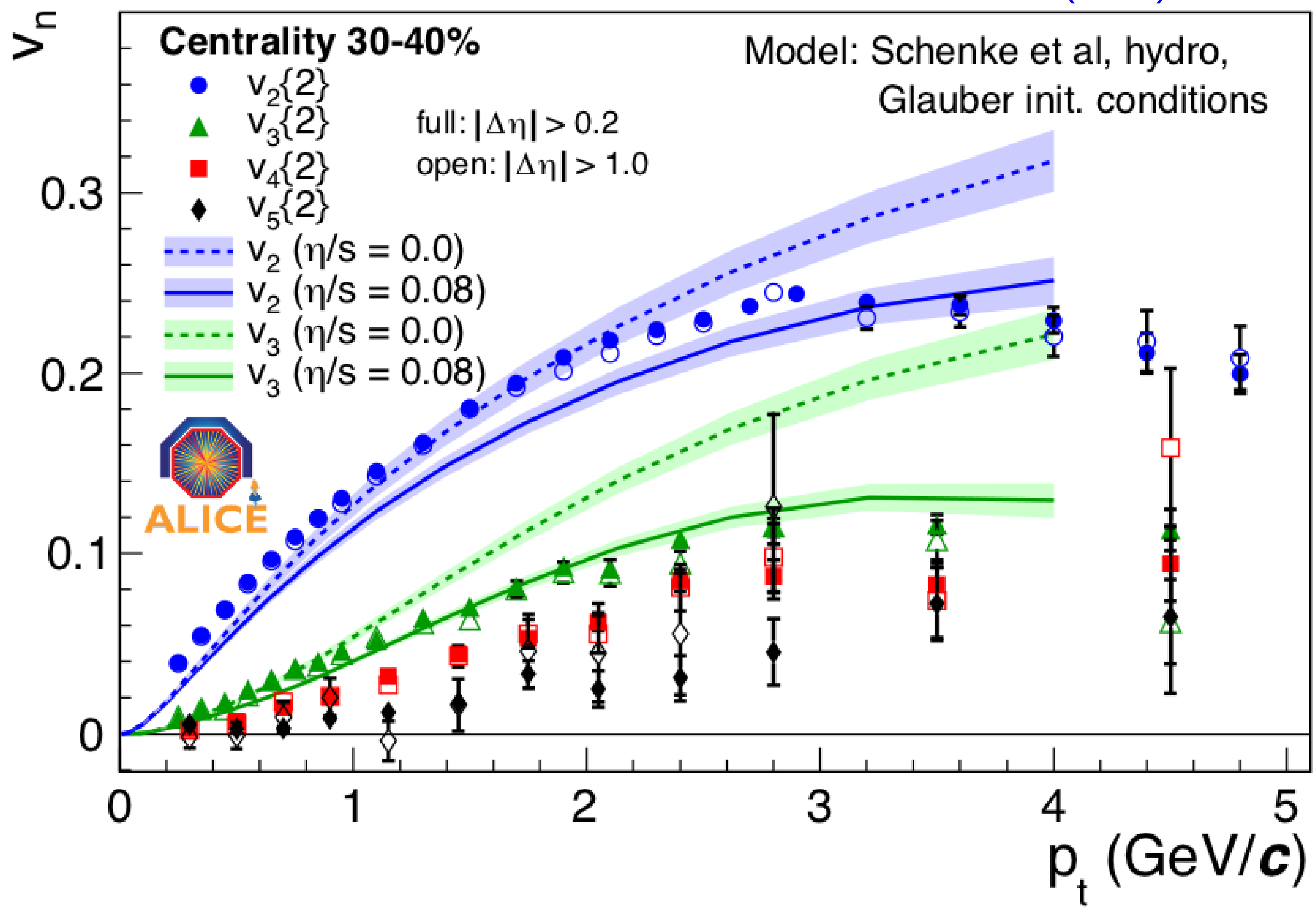
Triangular flow



Significant triangular flow observed. Centrality dependence is different to that of elliptic flow. Measurements vs reaction plane yield zero as expected if it arises from fluctuations.

Measurement of higher harmonics

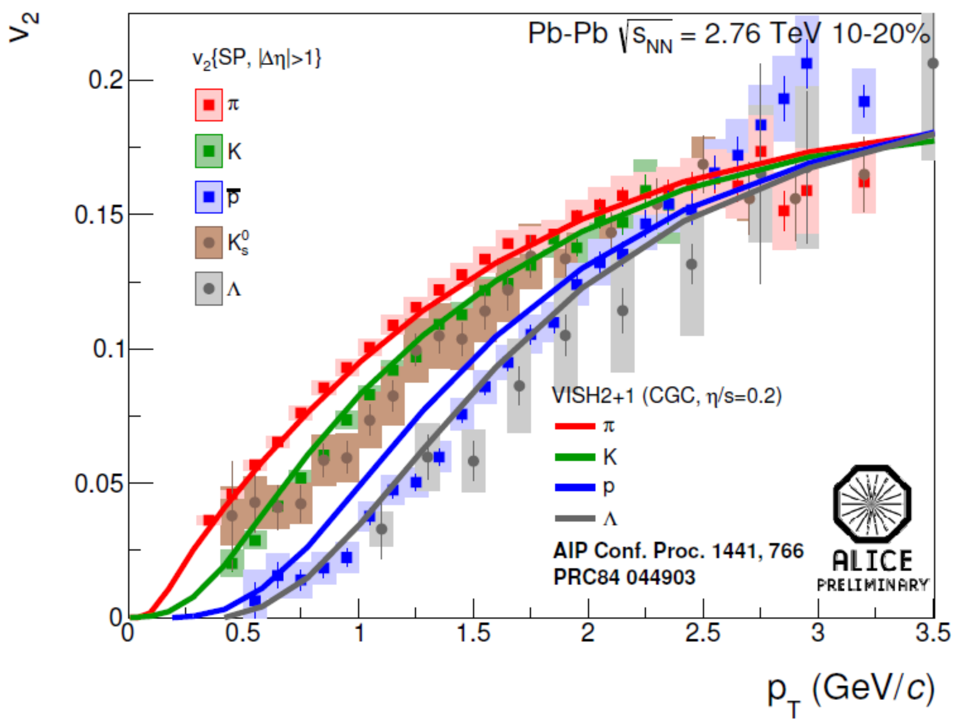
PRL 107 (2011) 032301



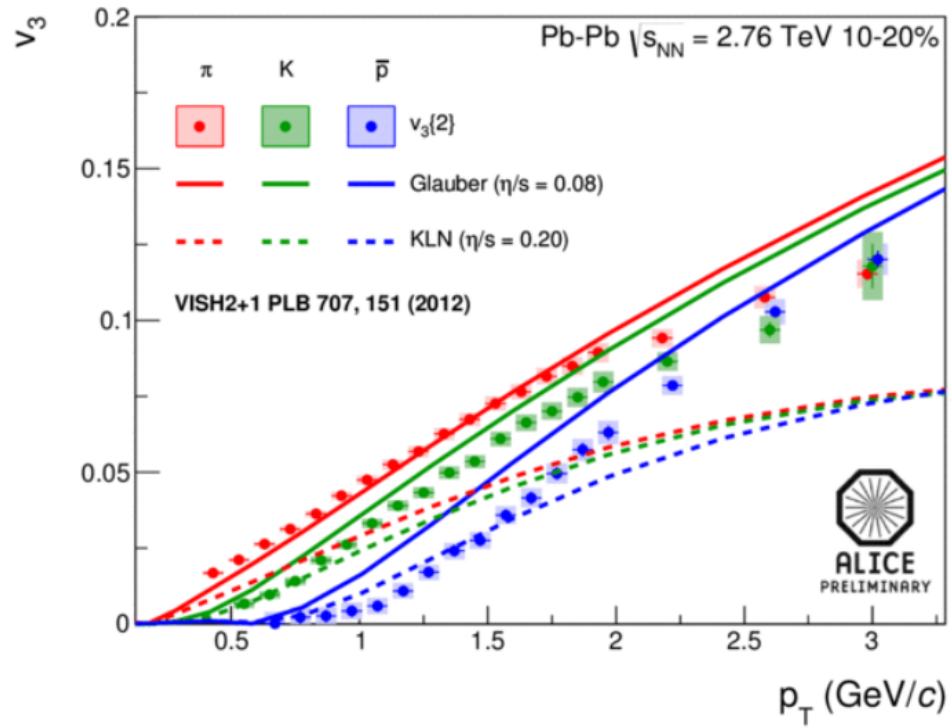
Strong constraints on hydro calculations.

Mass-dependent splitting of v_2 and v_3

Elliptic flow



Triangular flow

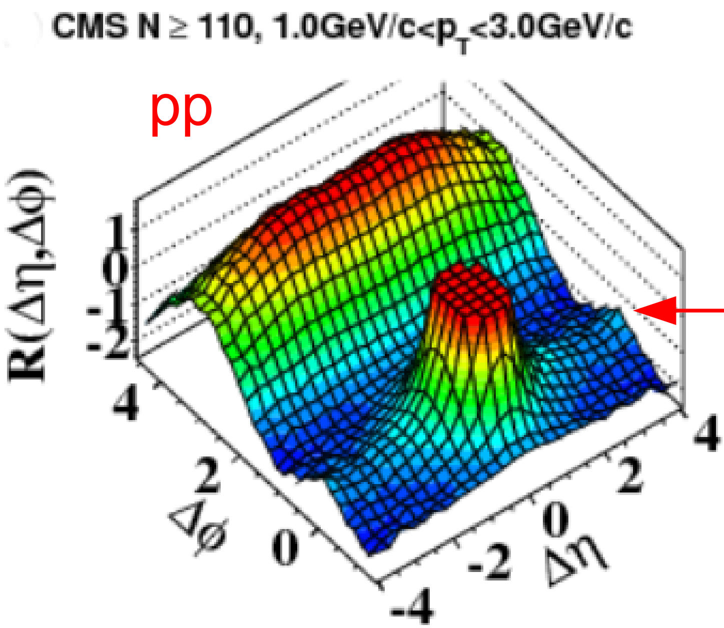


- Particle mass dependent splitting from radial flow characteristic for v_2
- Can be described by hydrodynamical models (+ hadronic afterburners)

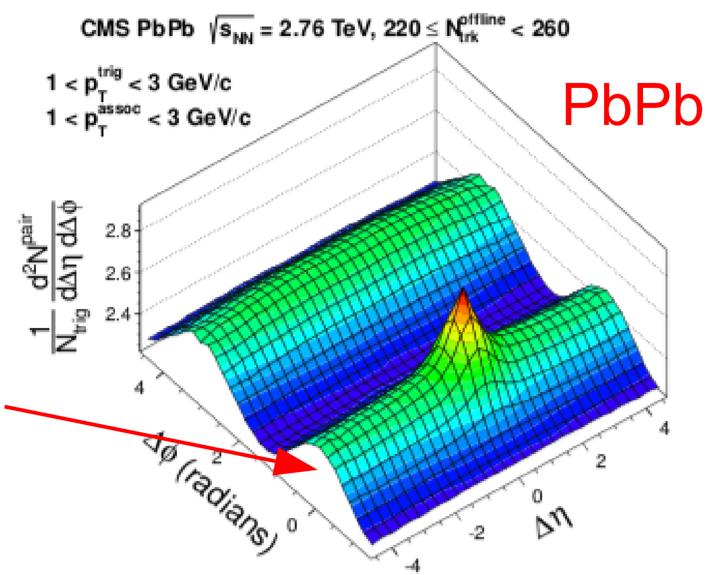
- Similar mass splitting for v_3
- Qualitatively described by hydrodynamical models (+ hadronic afterburners)
- Provides additional constraints on η/s

Two-particle angular correlations

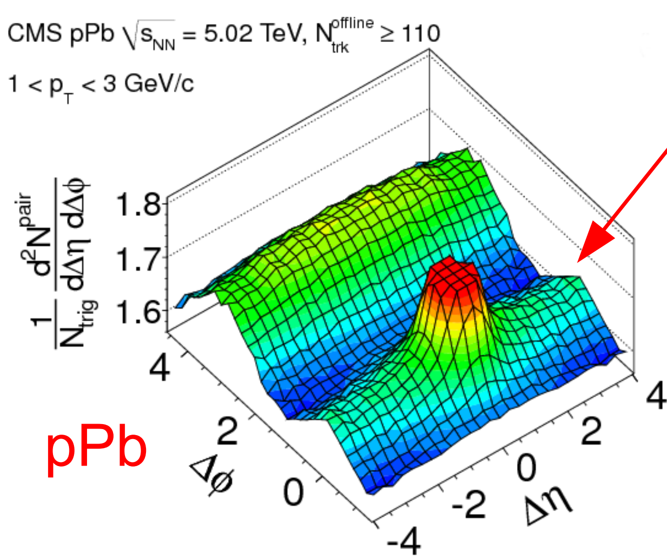
Near-side ridges apparent in high multiplicity events at LHC energies



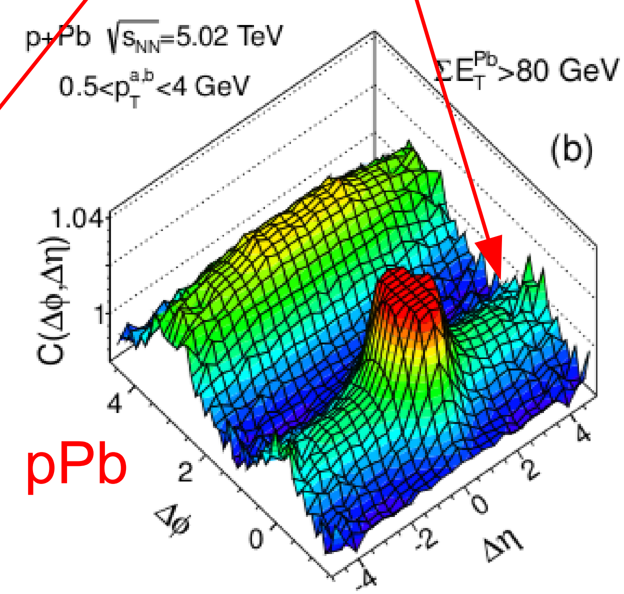
CMS, JHEP 1009 (2010) 91



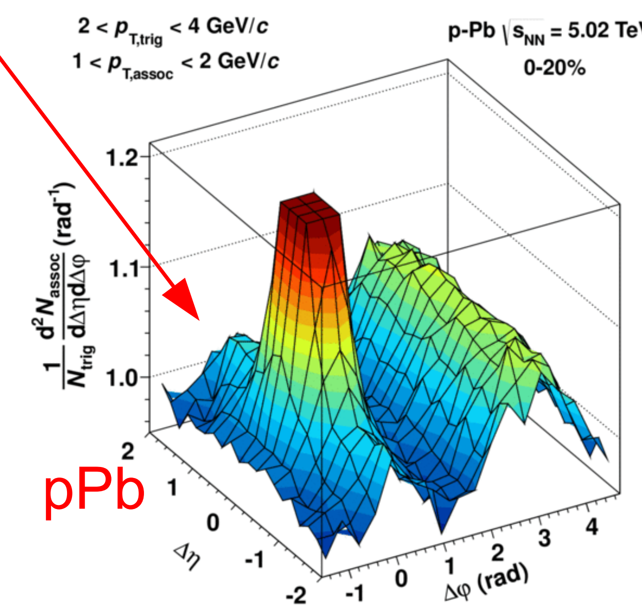
CMS, PLB 724 (2013) 213



CMS, PLB 718 (2012) 795

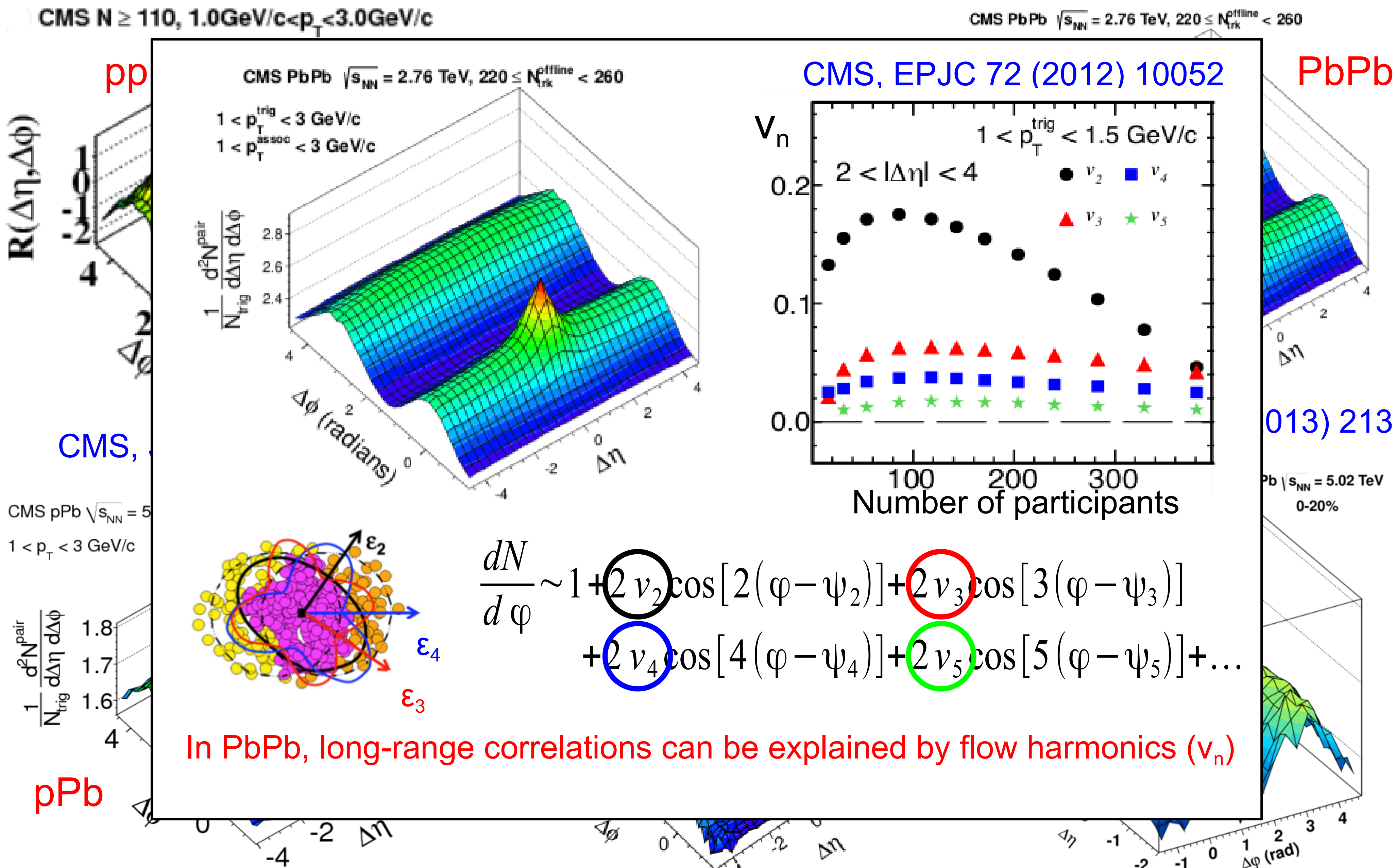


ATLAS, PRL 110 (2013) 182302



ALICE, PLB 719 (2013) 29

Two-particle angular correlations

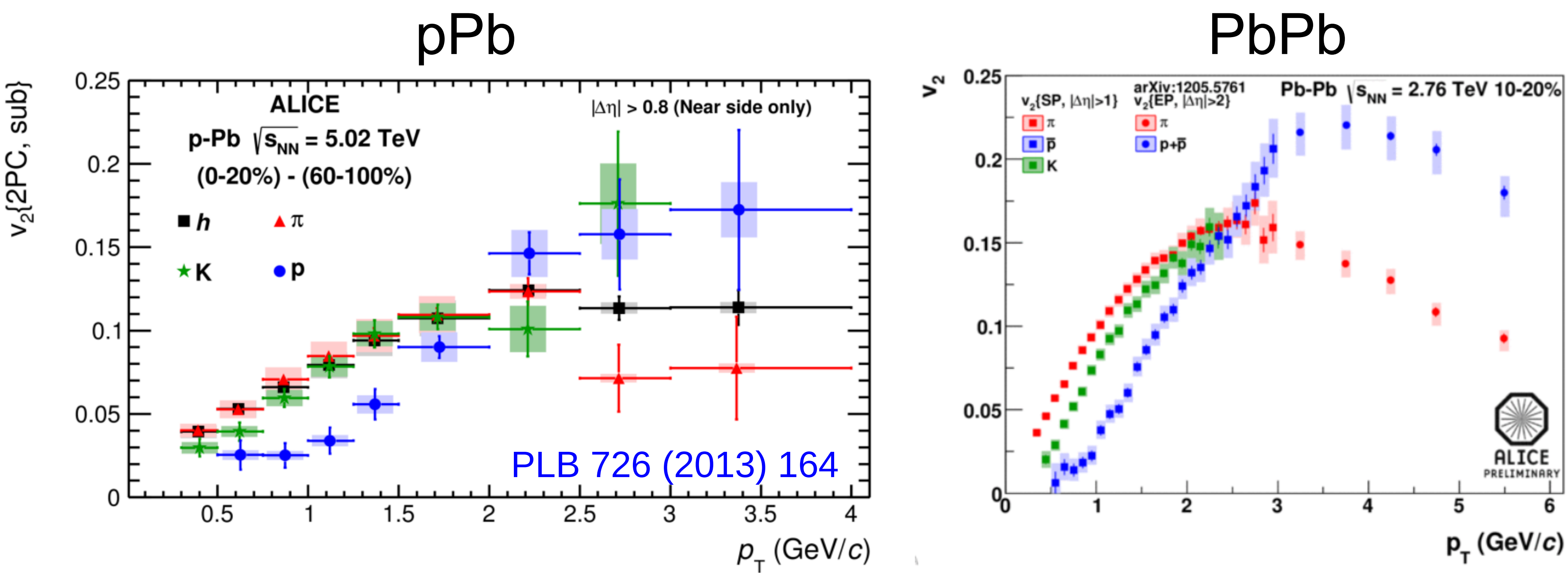


$$\frac{dN}{d\varphi} \sim 1 + 2v_2\cos[2(\varphi-\psi_2)] + 2v_3\cos[3(\varphi-\psi_3)] + 2v_4\cos[4(\varphi-\psi_4)] + 2v_5\cos[5(\varphi-\psi_5)] + \ldots$$

In PbPb, long-range correlations can be explained by flow harmonics (v_n)

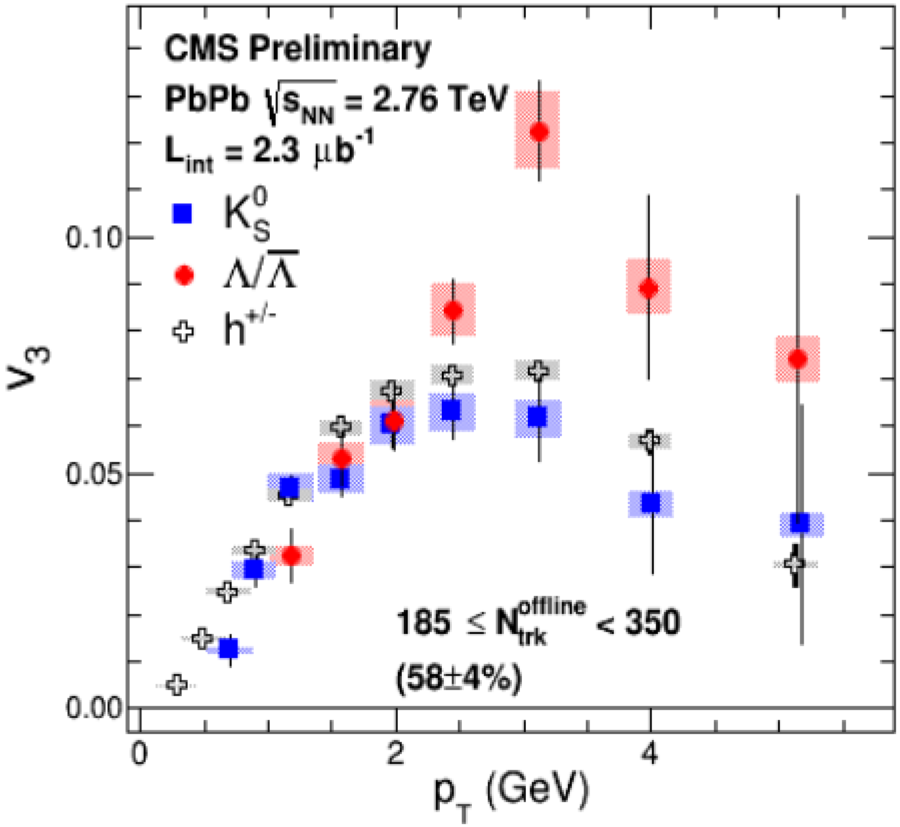
CMS, PLB 718 (2012) 795 ATLAS, PRL 110 (2013) 182302 ALICE, PLB 719 (2013) 29

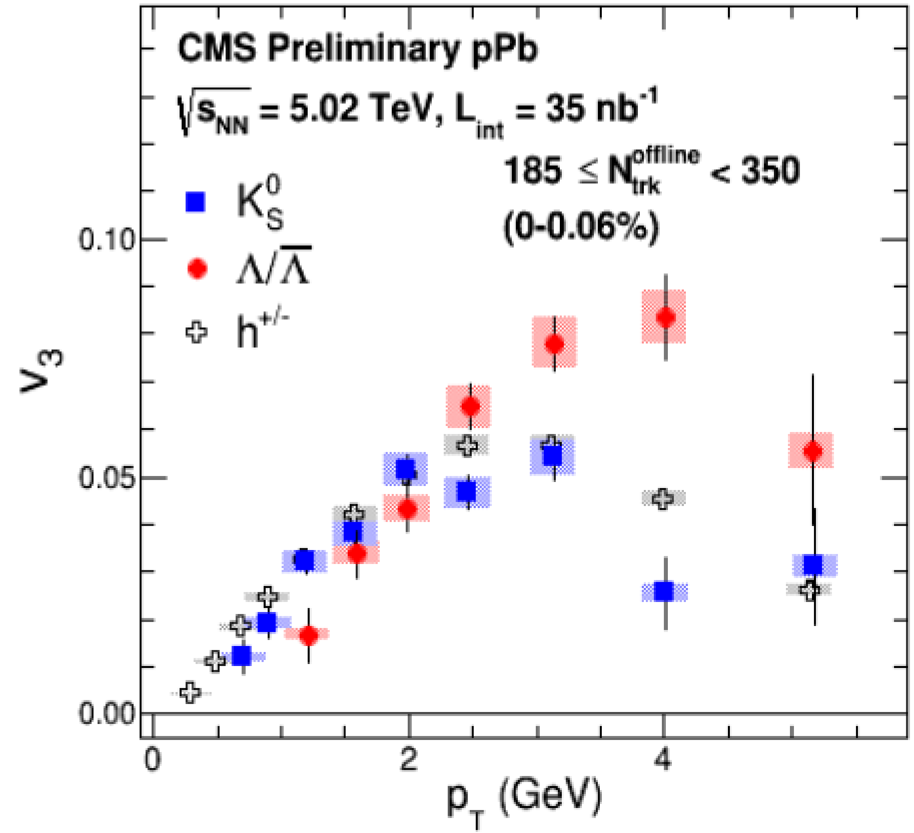
Identified particle v_2



- 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

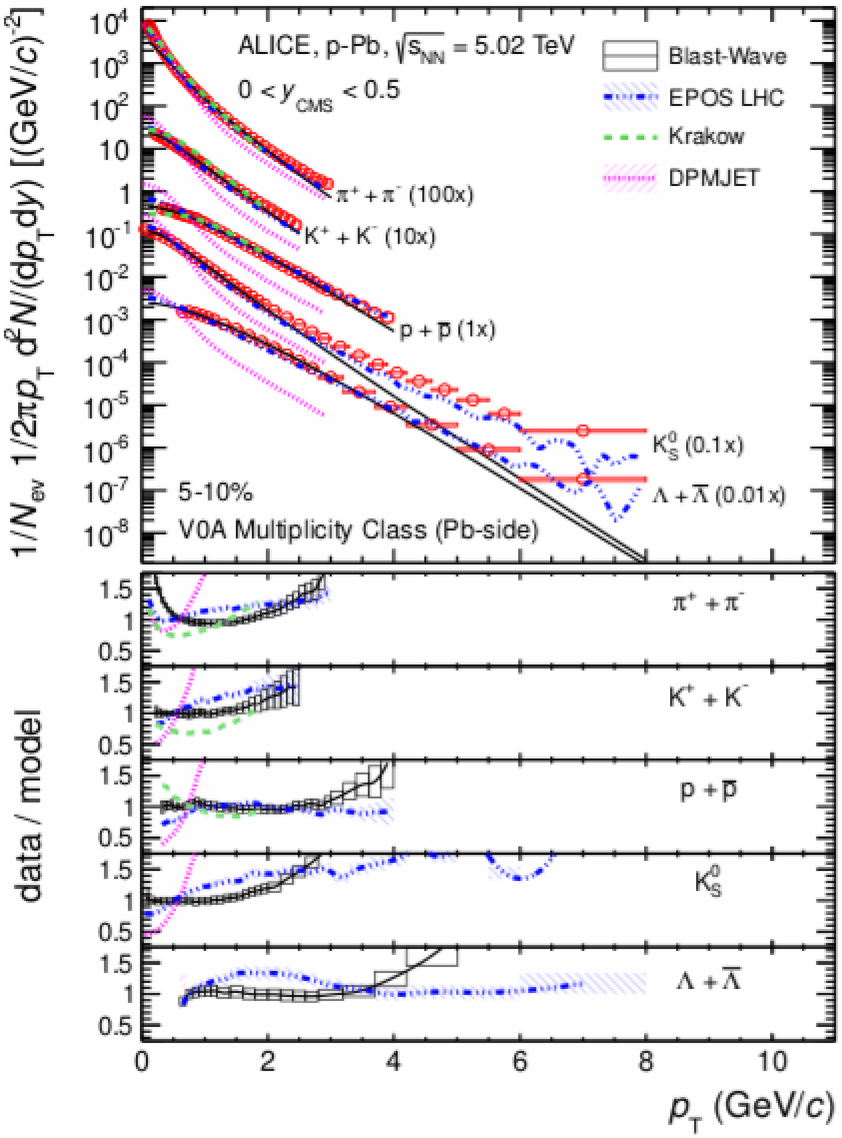
Identified particle v_3 (CMS)



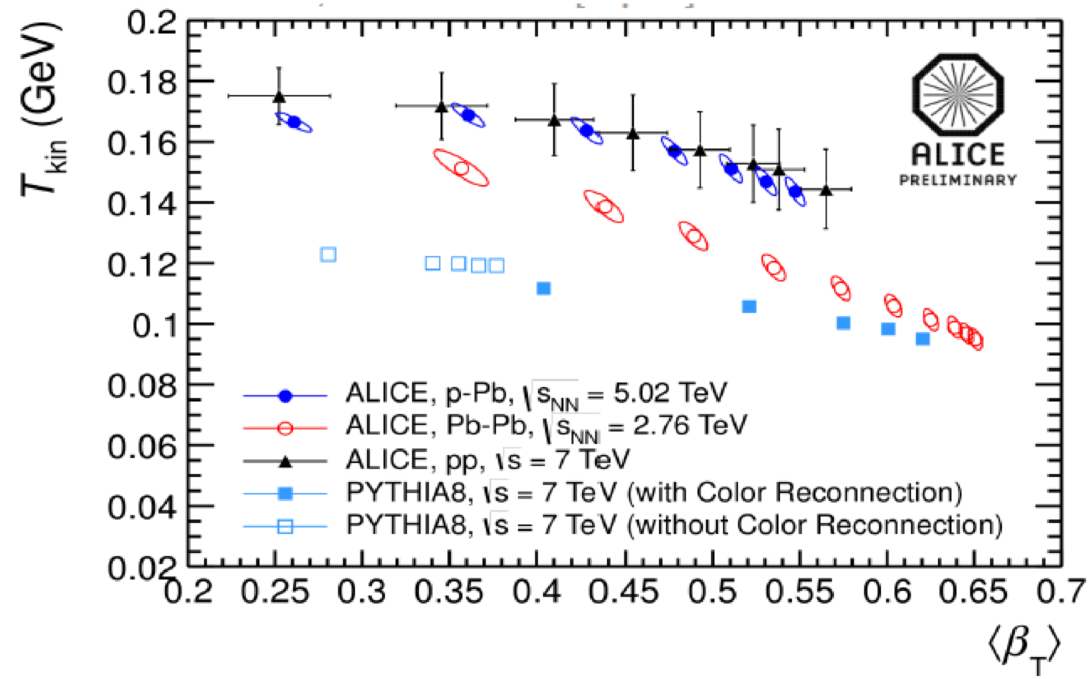


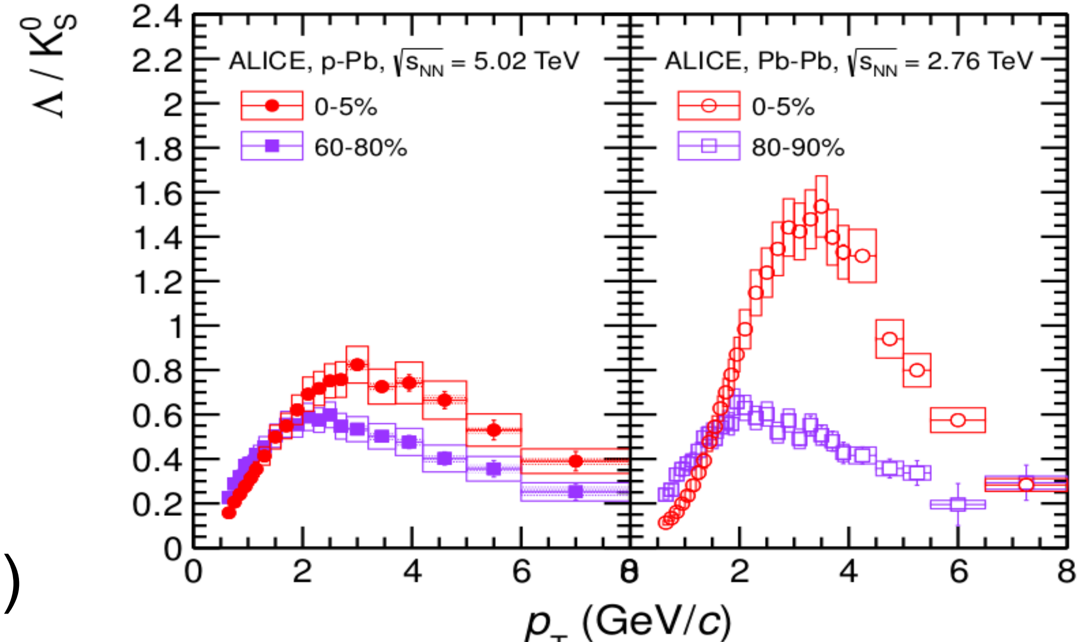
Crossing at around 2 GeV/c,
same physics origin for v_3 and v_2 in pPb as well.

Identified particle spectra



ALICE, PLB 278 (2014) 25

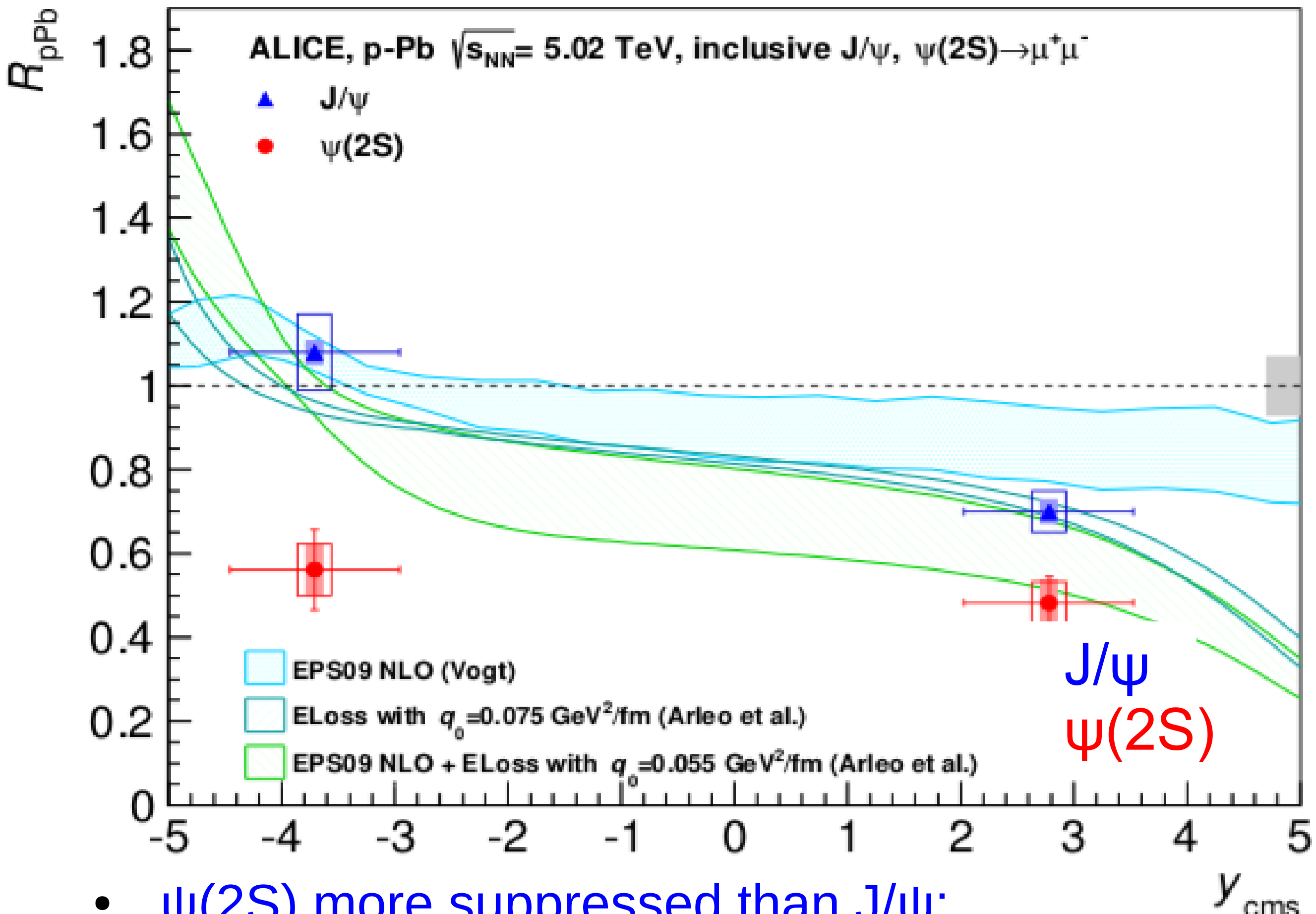


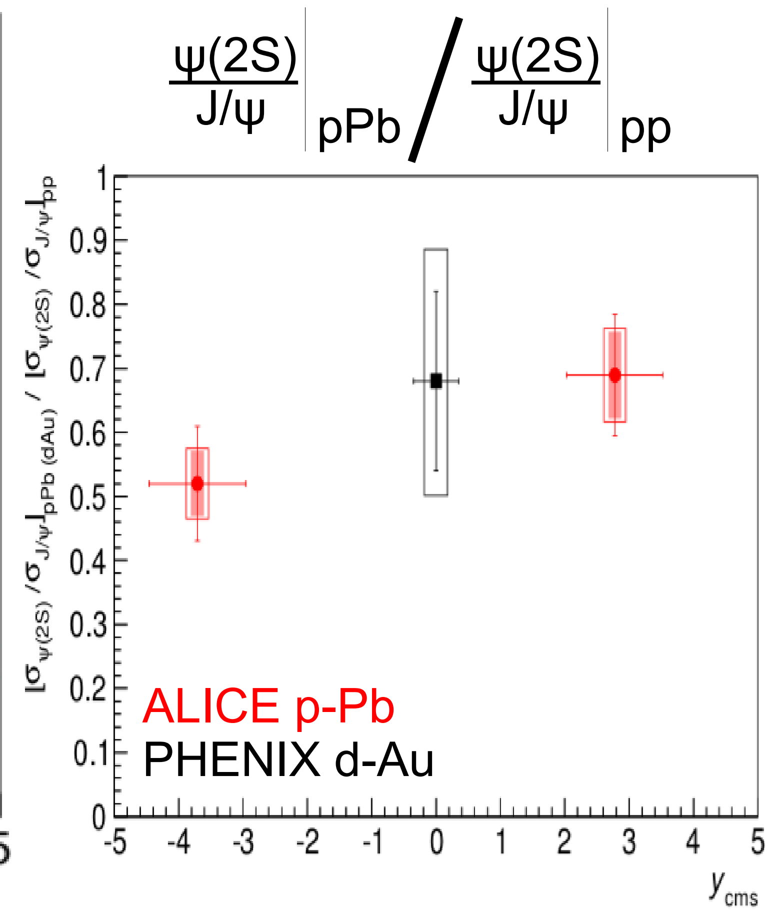


Spectra consistent with radial flow picture (also in pp)

ψ(2S) production in p-Pb

arXiv:1405.3796





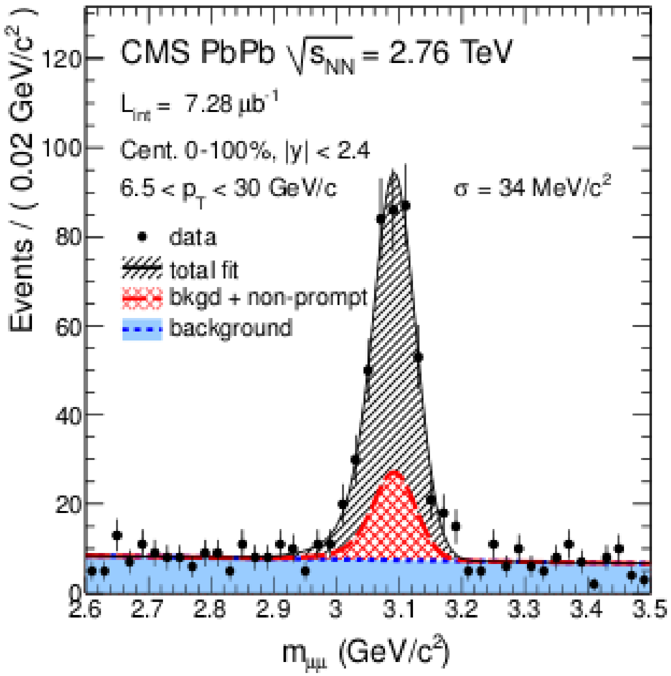
- ψ(2S) more suppressed than J/ψ:
  Not expected by initial state + CNM effects and coherent energy loss
- Stronger relative suppression in backward direction:
  Qualitatively expected from break-up due to comoving system
- But also strong suppression in forward direction
  - Final state effects?

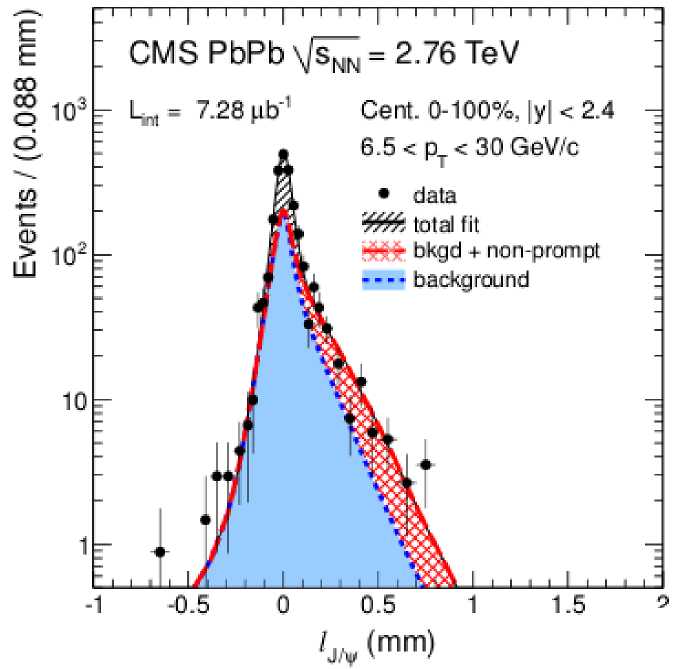
Extra

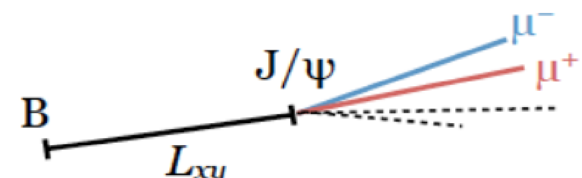
Beauty via displaced J/ψ

B mesons via secondary J/ψ:

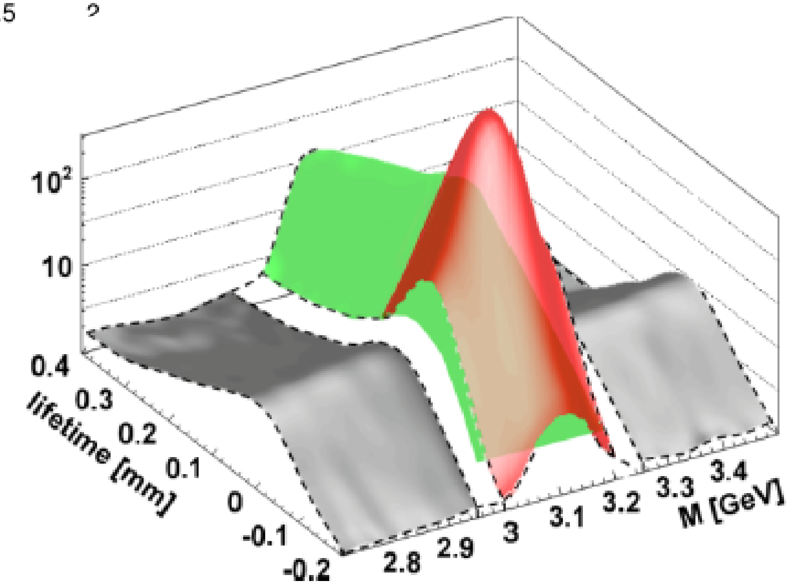
CMS, JHEP 1205 (2012) 063







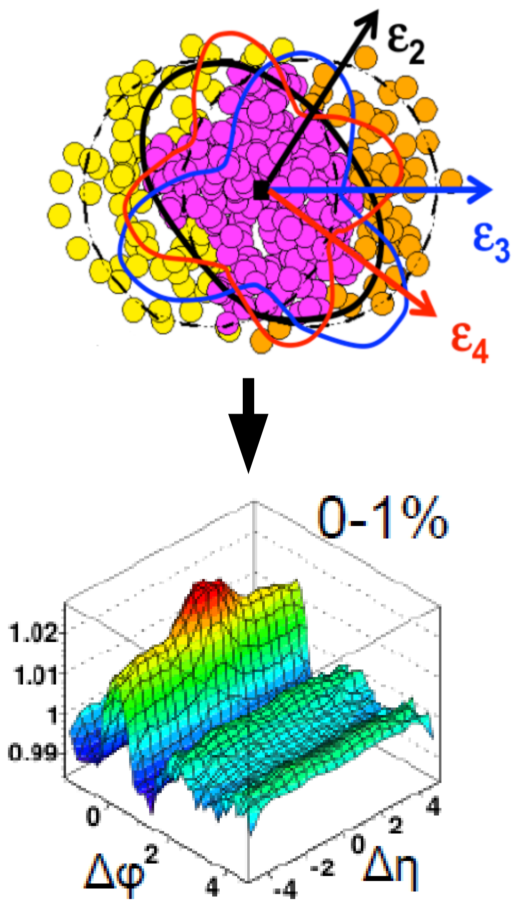
Clean separation of 2nd vertex for J/ψ with p_T>6.5 GeV/c



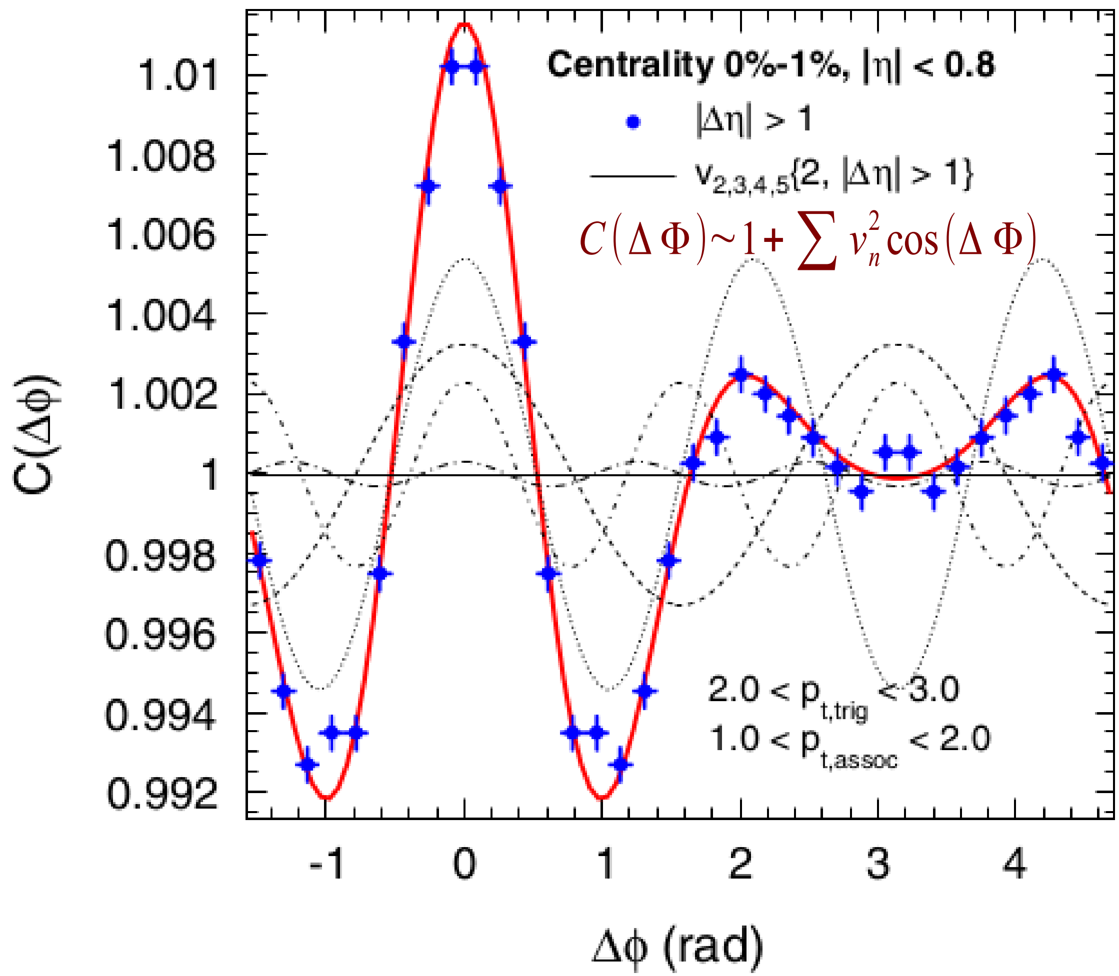
Fraction of non-prompt J/y from simultaneous fit to m+m- invariant mass spectrum and pseudo-proper decay length distributions (pioneered by CDF)

Initial state fluctuations and flow ridges

Alver+Roland, 2010

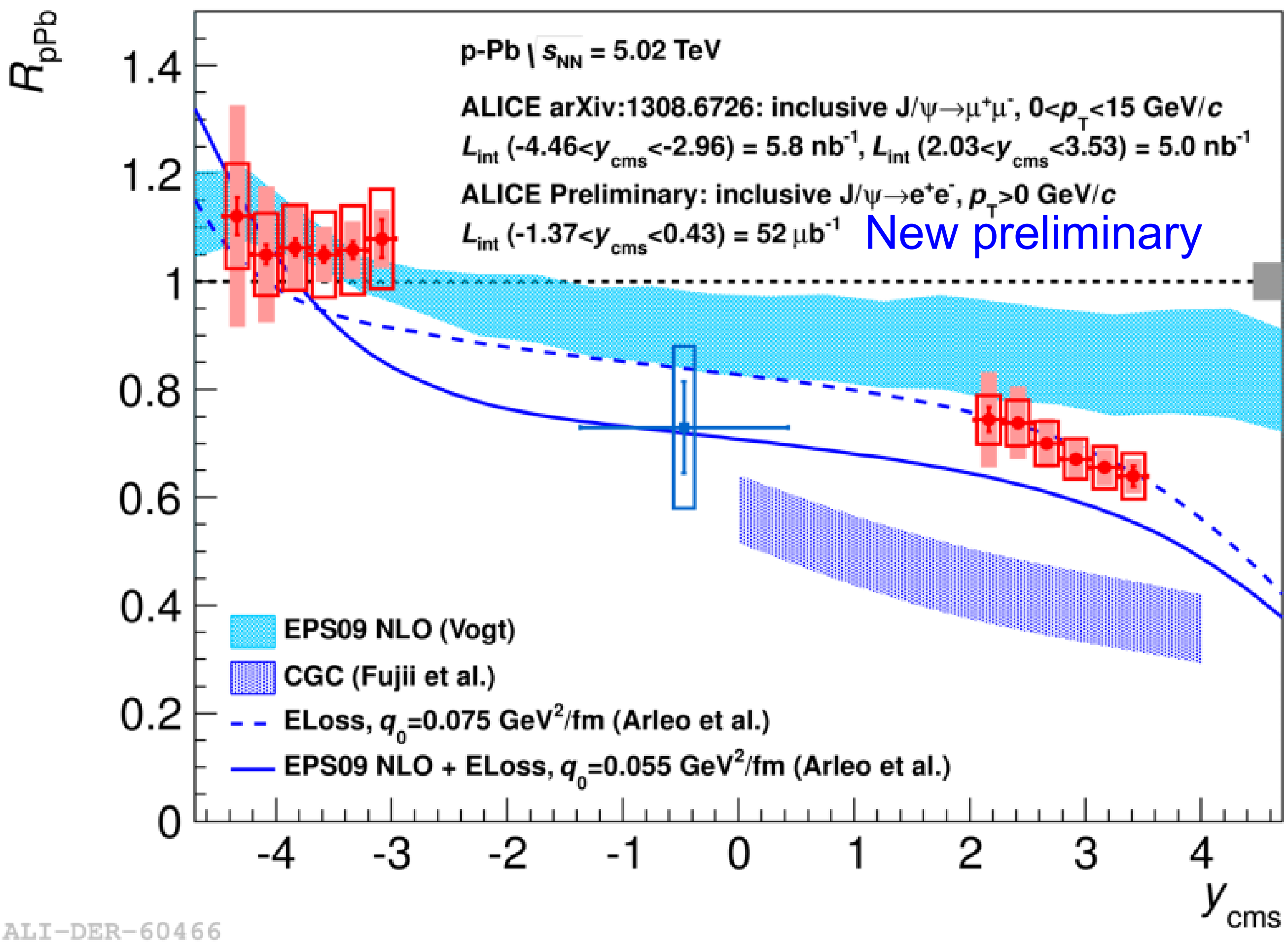


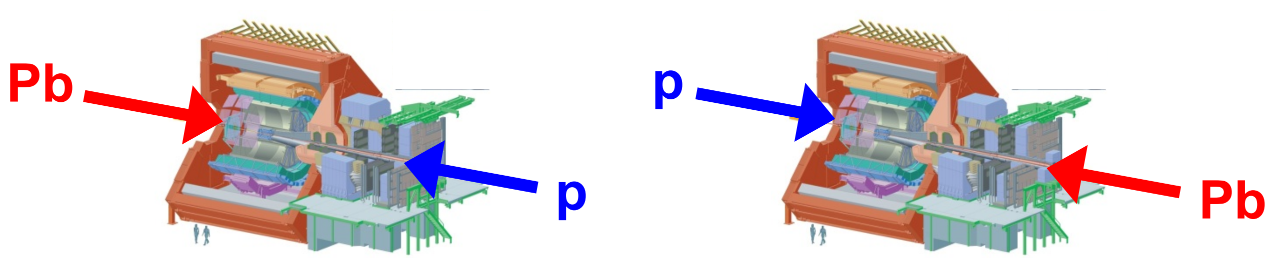
ALICE, PRL 107 (2011) 032301



Structures seen in two particle correlations are naturally explained by measured flow harmonics assuming fluctuating initial conditions.

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