



From Heavy-Ion Collisions to Quark-Gluon matter

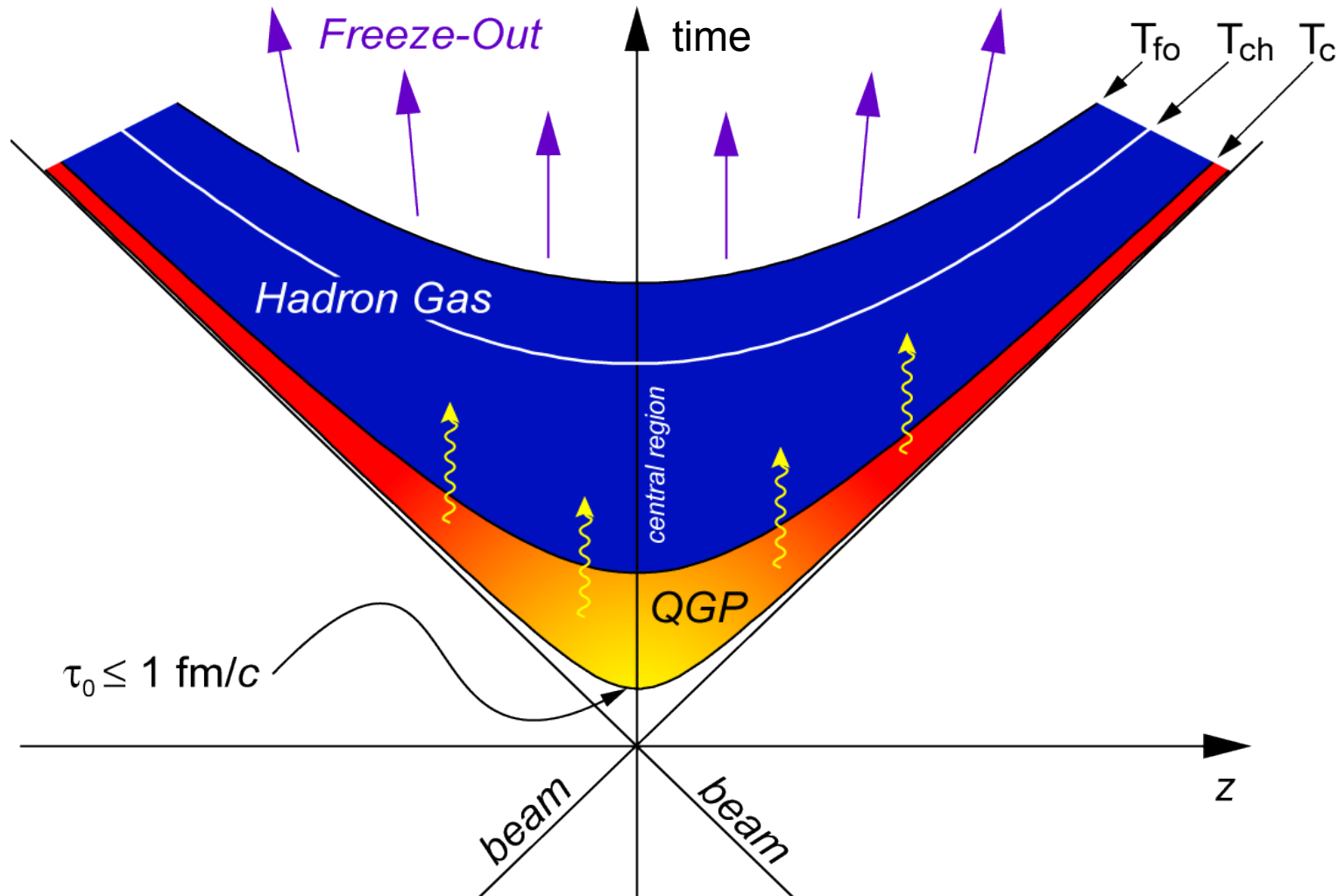
Constantin Loizides
(LBNL)

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

What quantities to measure?

2

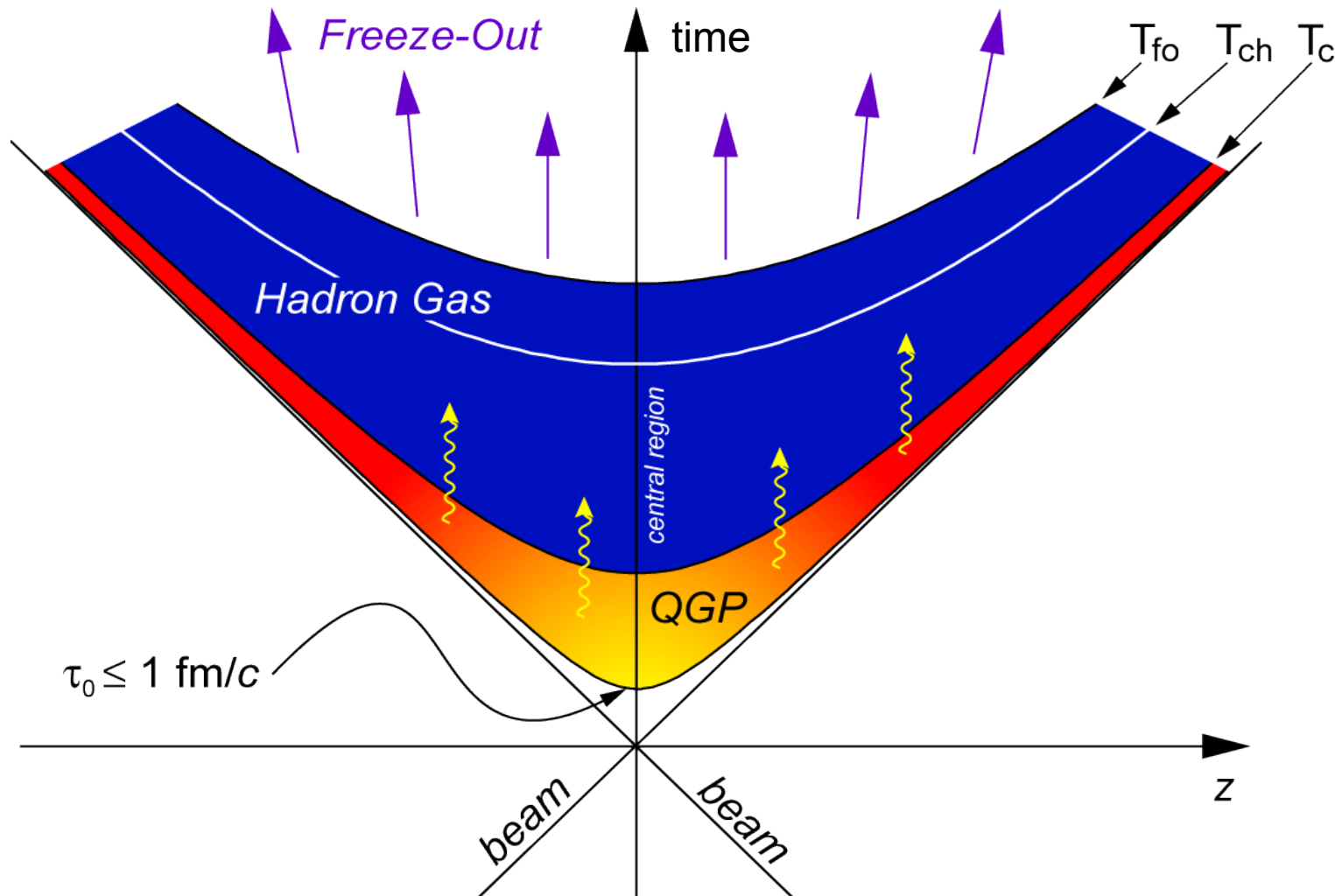
(Recap part II)



What quantities to measure?

3

(Recap part II)



Observables

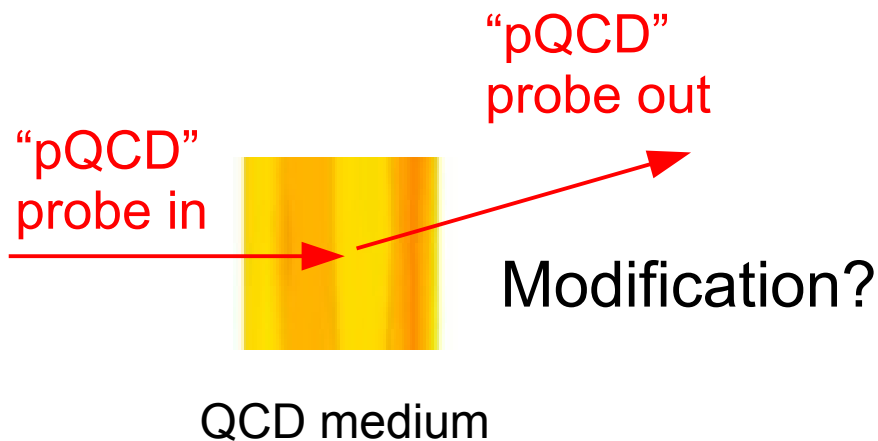
Multiplicity
HBT
Particle yields
Particle spectra

Transverse flow
Thermal photons

Hard probes
(jets, heavy flavor,
EW bosons)

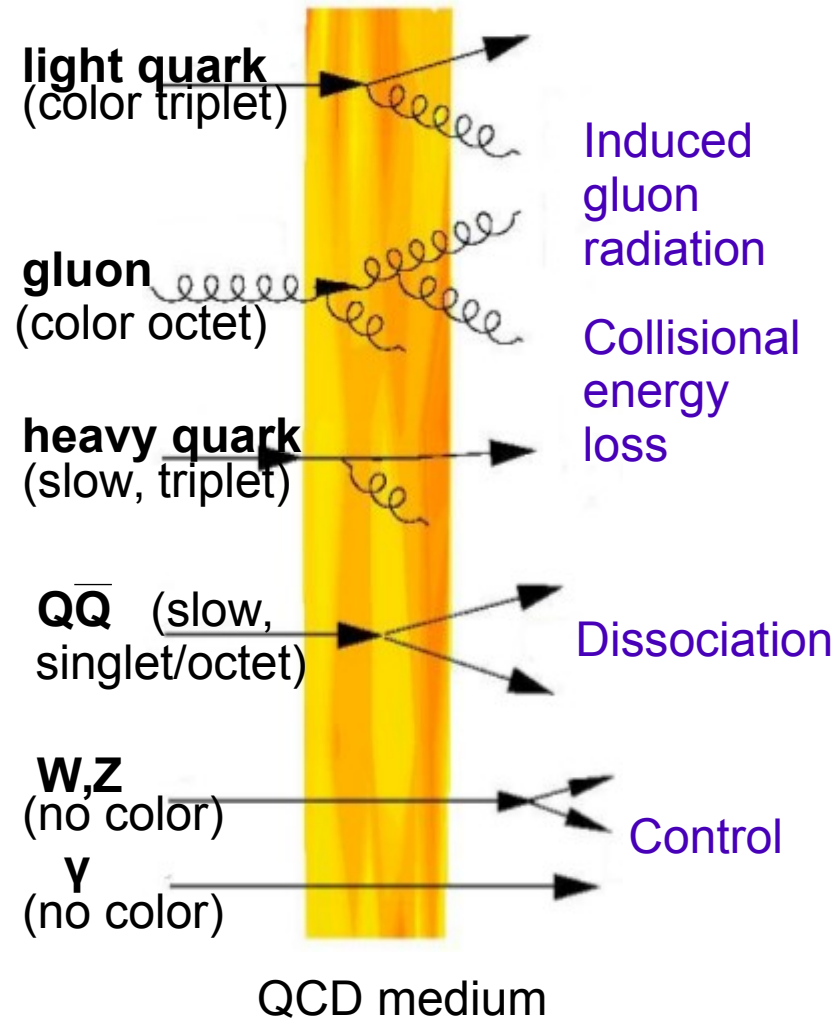
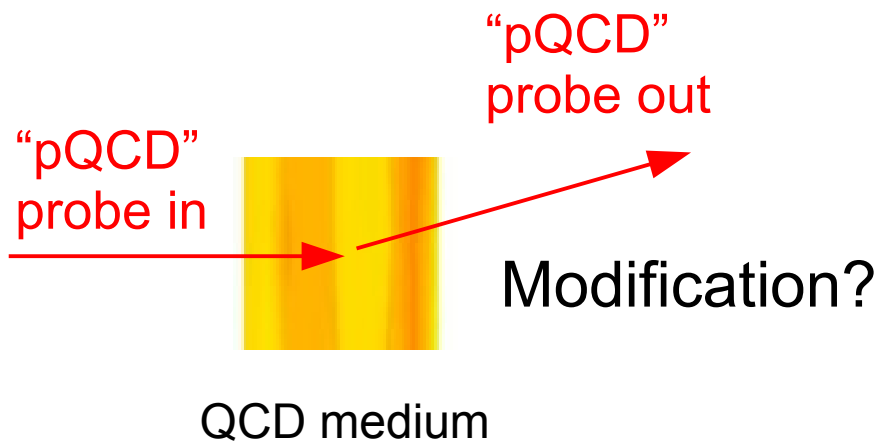
Experimental approach is to study various observables with different sensitivity to the different stages of the collision

- 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 $\tau \approx 1/Q^2 \ll 0.1$ fm/c
- “Tomographic” probes of hottest
and densest phase of medium



Tomography of QCD matter

- Hard (large Q^2) probes of QCD matter:
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Hard processes in pp

Hard processes in pp

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

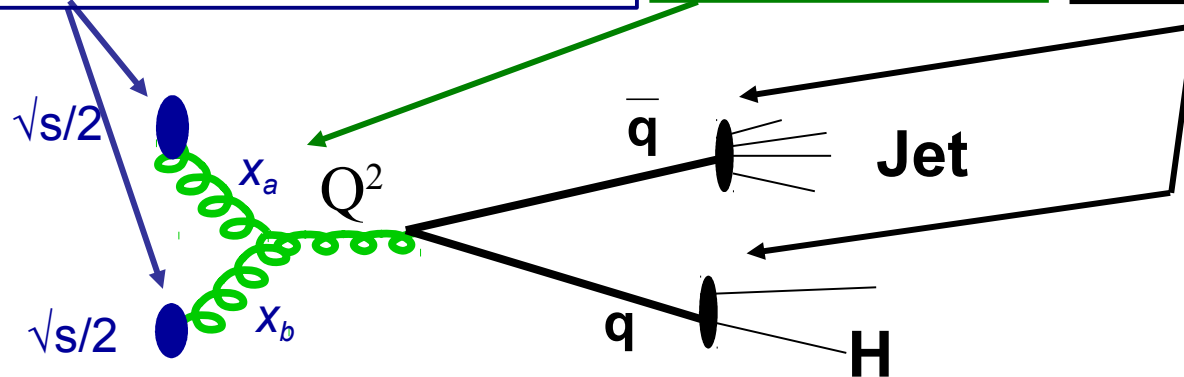
$$\sigma_{pp \rightarrow Hx} = PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \sigma_{ab \rightarrow q\bar{q}} \otimes D_{q \rightarrow H}(z_q, Q^2)$$

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

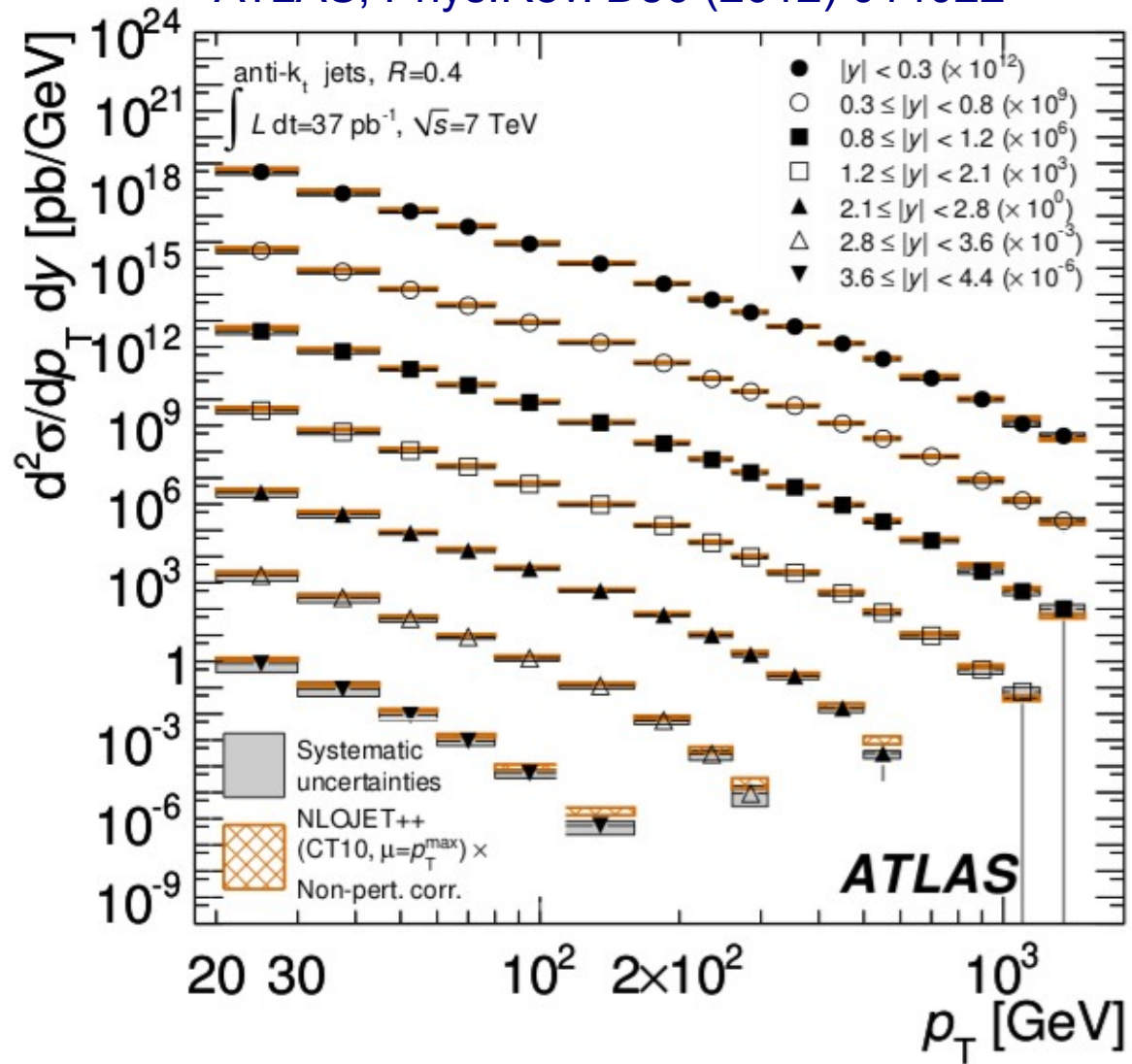
Fragmentation of quark q into hadron H



Hard processes in pp

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

ATLAS, Phys.Rev. D86 (2012) 014022

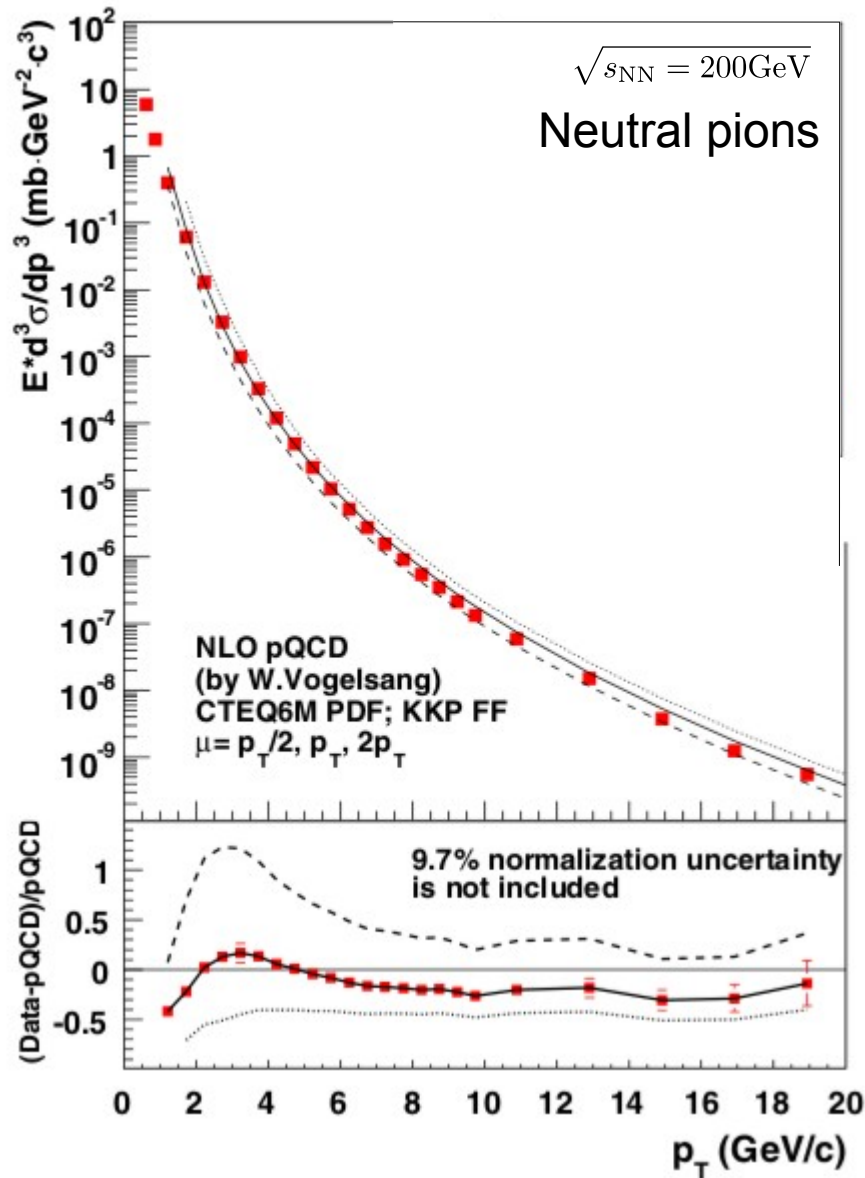


Successfully describing data over many orders of magnitude!

Hard processes in pp

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

PHENIX, PRD 76 (2007) 051106(R)



Successfully describing data over many orders of magnitude!

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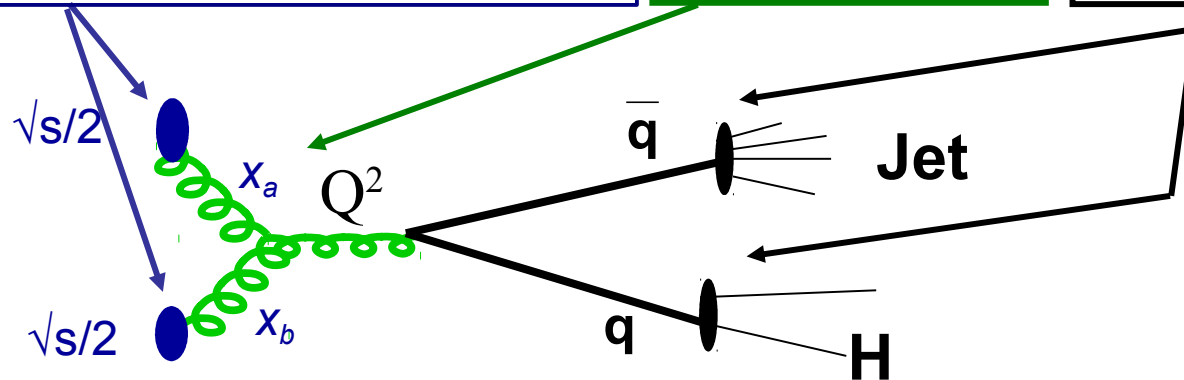
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Cross section for hadronic collisions (hh)

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



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

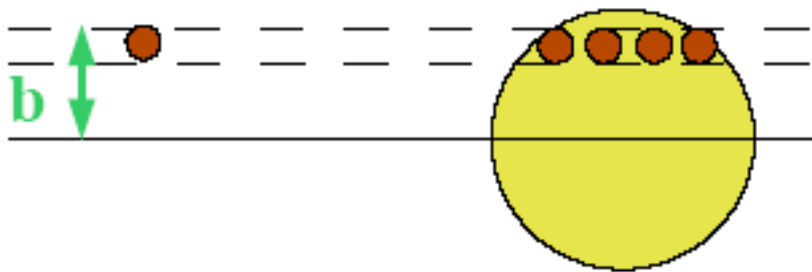
$$\frac{dN_{AA}}{dp_T} = N_{\text{coll}} \frac{dN_{pp}}{dp_T}$$

Glauber Ncoll scaling

Nuclear geometry and hard processes: Glauber theory

Glauber scaling:

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



Normalized nuclear density $\rho(b, z)$:

$$\int dz d^2b \rho(b, z) = 1$$

Nuclear thickness function: $T_A(b) = \int dz \rho(z, b)$

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

$$\sigma_{pA}^{\text{hard}} \simeq A \sigma_{NN}^{\text{hard}} \int d^2b T_A = A \sigma_{NN}^{\text{hard}}$$

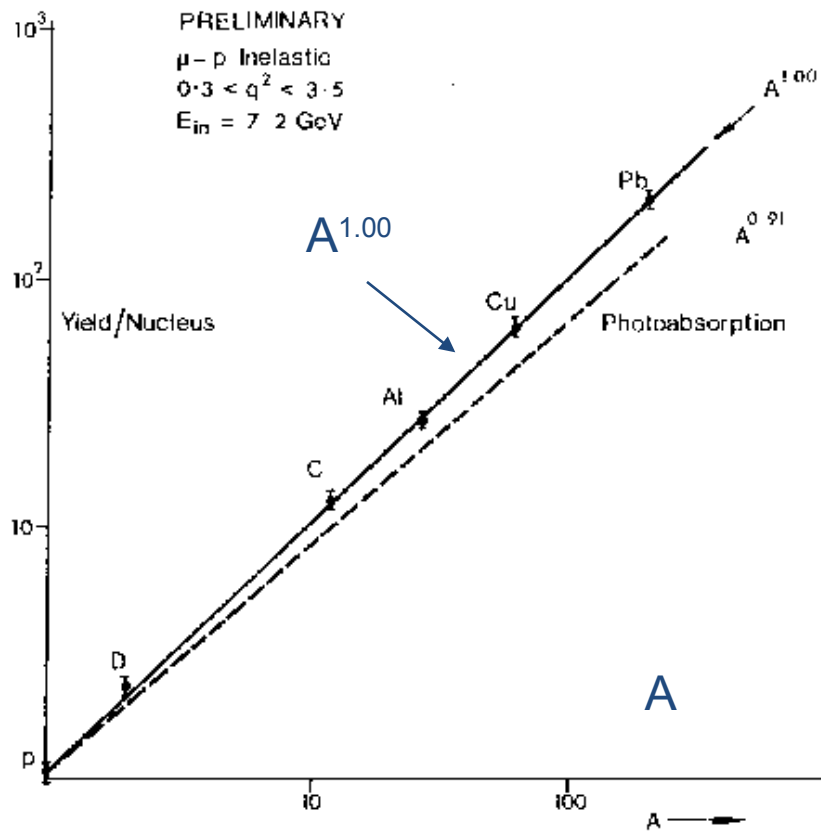
$$\sigma_{NN}^{\text{hard}} \ll \sigma_{NN}^{\text{inel}}$$

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

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

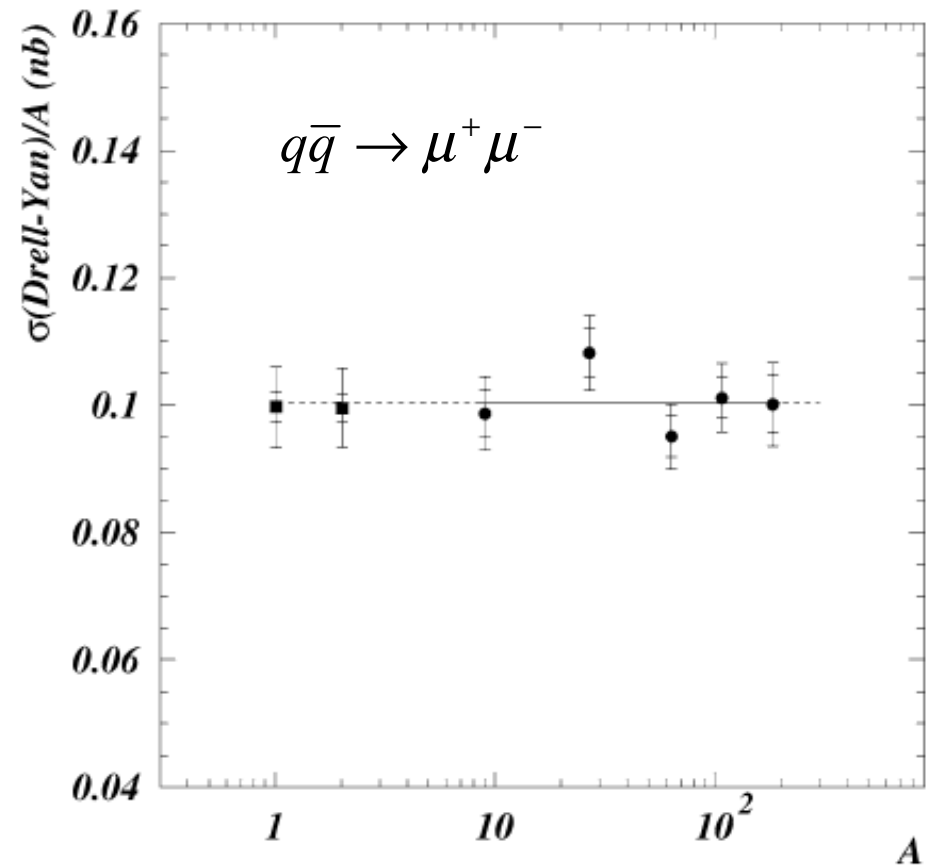
σ_{inel} for 7 GeV muons on nuclei

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



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

NA50 Phys Lett B553, 167 (2003)



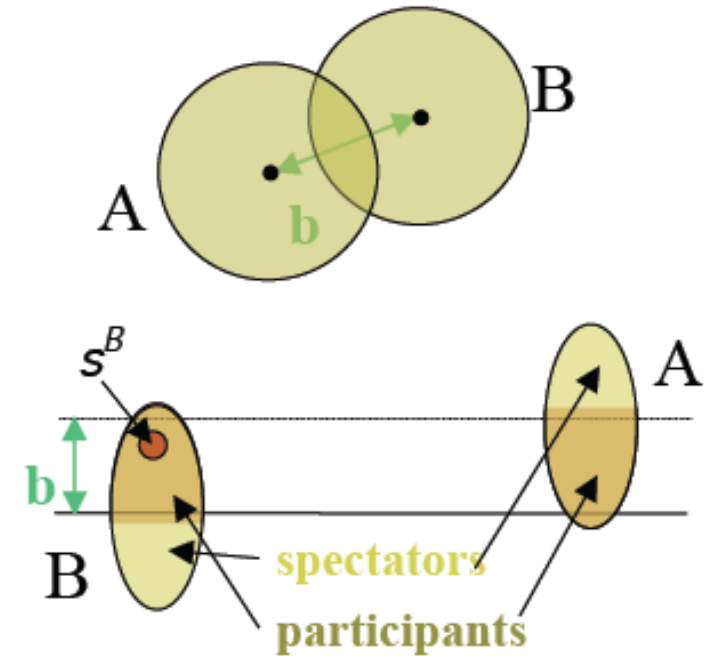
These hard cross sections in p+A found to scale as $A^{1.0}$

Nuclear overlap function:

$$T_{AB}(b) = \int d^2s T_A(s) T_B(s - b)$$

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

$$N_{\text{coll}}^{\text{nA}}(b - s_B) = A T_A(b - s_B) \sigma_{\text{NN}}^{\text{inel}}$$



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

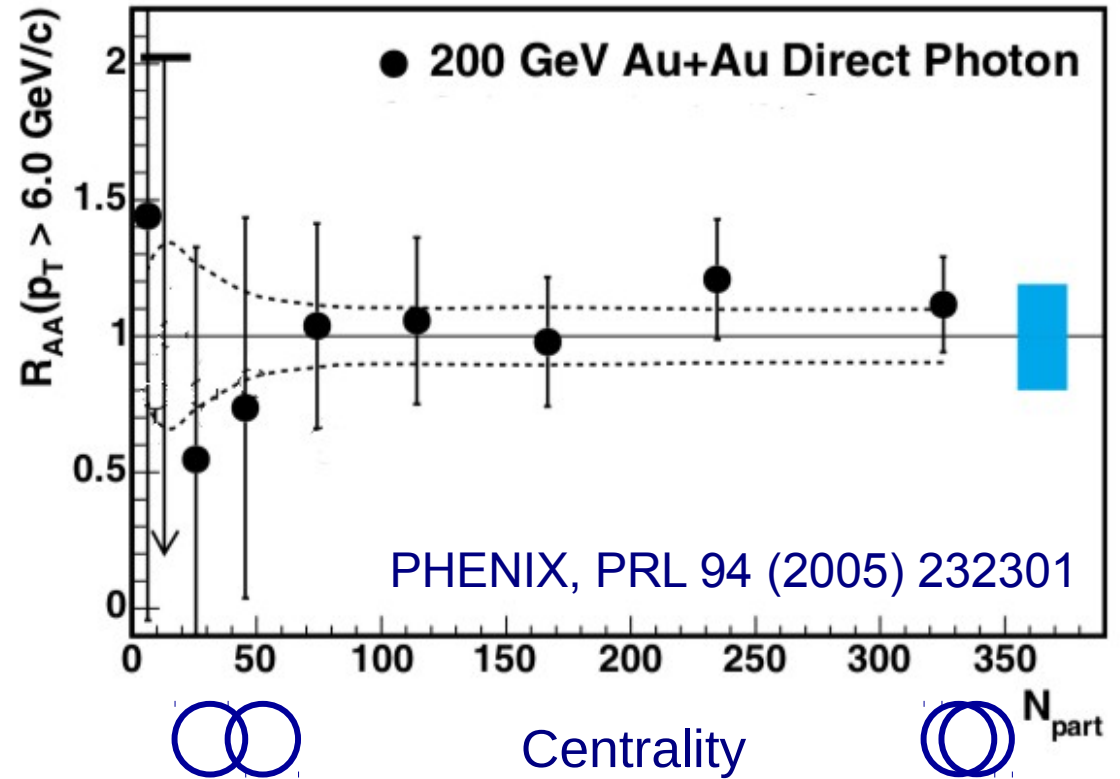
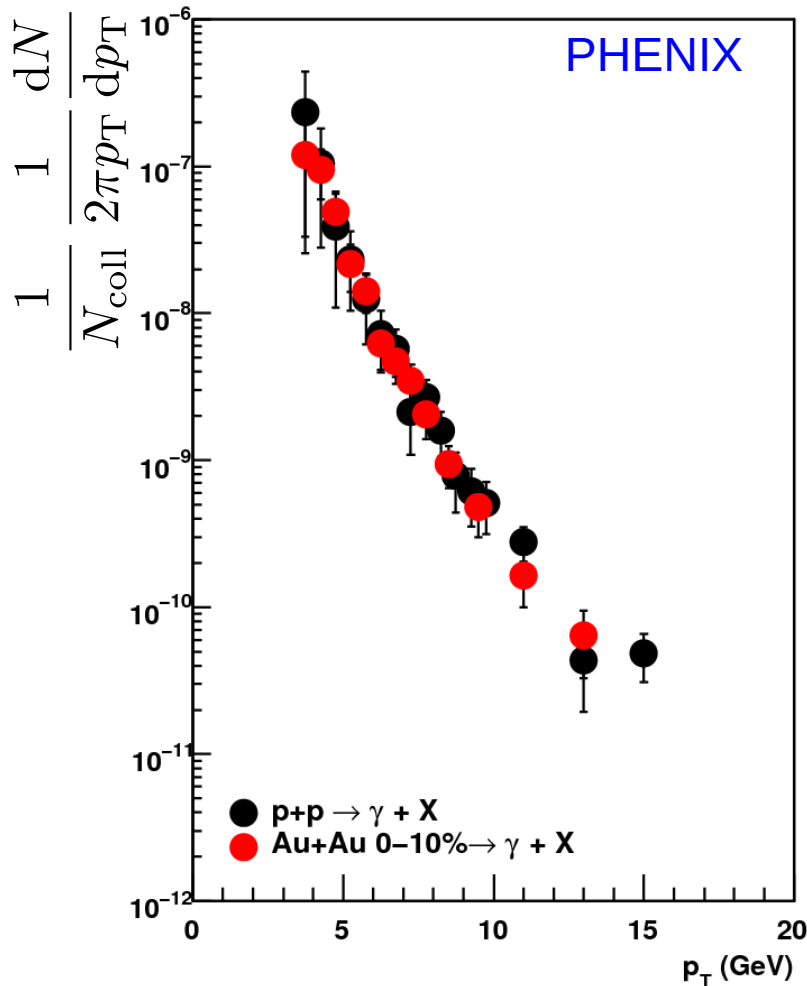
$$N_{\text{coll}}^{\text{AB}}(b) = B \int d^2s_B T_B(s_B) N_{\text{coll}}^{\text{nA}}(b - s_B) = AB T_{AB}(b) \sigma_{\text{NN}}^{\text{inel}}$$

$$N_{\text{hard}}^{\text{AB}}(b) = N_{\text{coll}}^{\text{AB}}(b) \sigma_{\text{NN}}^{\text{hard}} / \sigma_{\text{NN}}^{\text{inel}} = N_{\text{coll}}^{\text{AB}}(b) N_{\text{pp}}^{\text{hard}}$$

Scaling of direct photon yield in pp vs AuAu

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

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



Direct photons in Au+Au scale with N_{coll}

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:

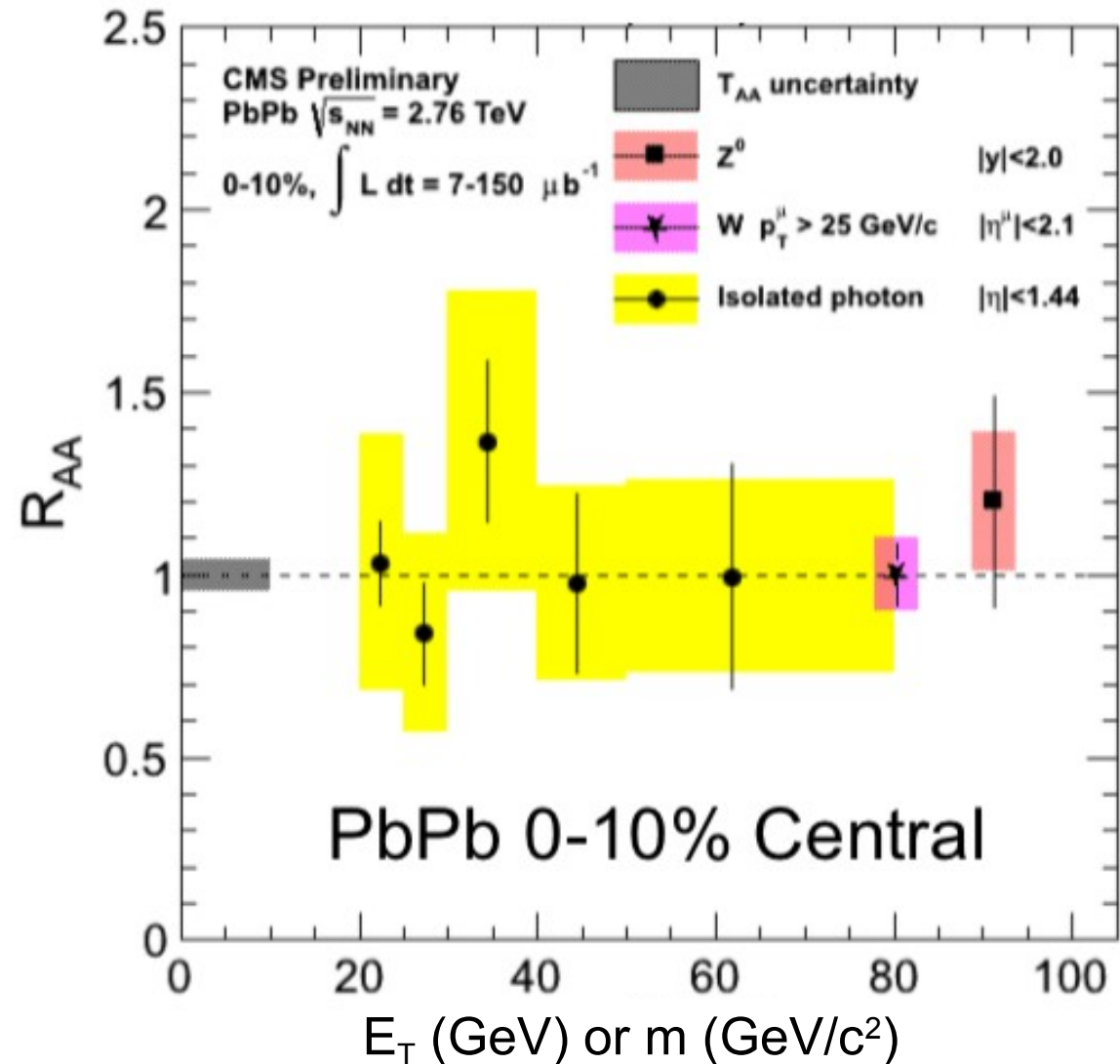
ATLAS, PLB 697 (2011) 294

CMS, PRL 106 (2011) 212301

W boson:

ATLAS, ATLAS-CONF-2011-78

CMS, PLB 715 (2012) 66

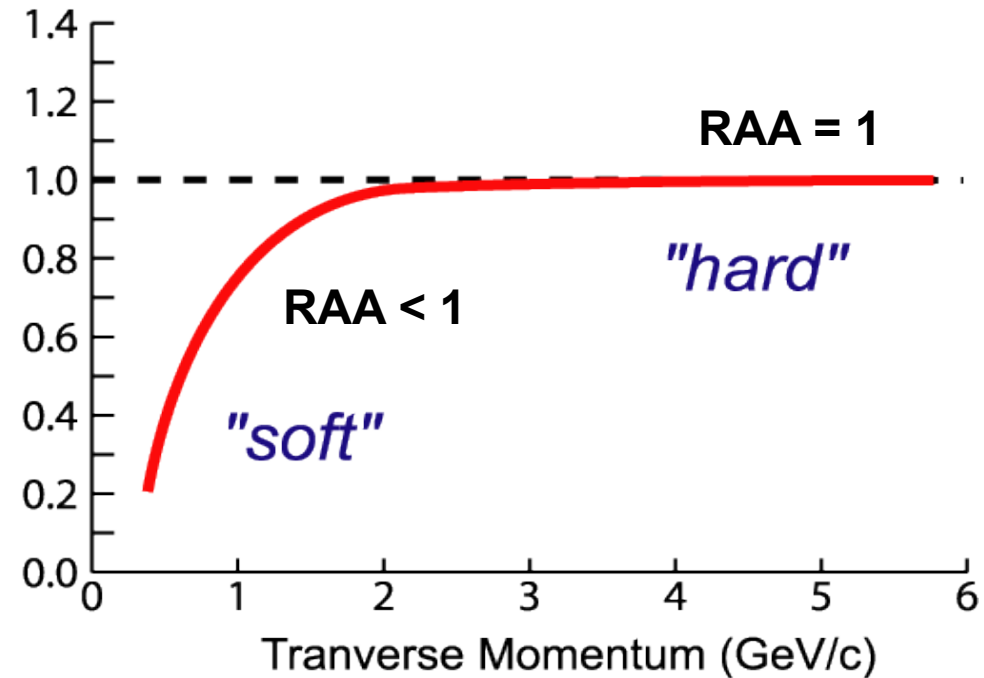


Control probes (direct +isolated γ , Z, W) scale with N_{coll}

Parton energy loss

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

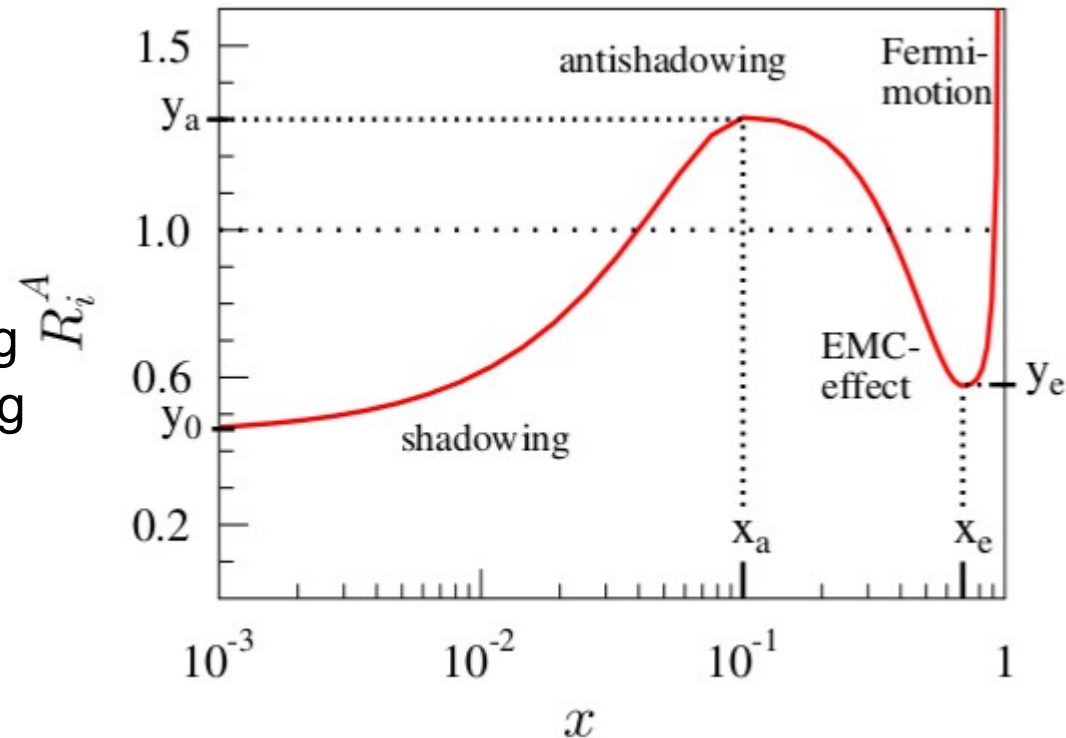
- $R_{AA} > 1 \rightarrow$ enhancement wrt binary scaling
- $R_{AA} = 1 \rightarrow$ no deviation from binary scaling
- $R_{AA} < 1 \rightarrow$ suppression wrt binary scaling



- By definition, $R_{AA}=1$ in absence of nuclear or QGP matter effects

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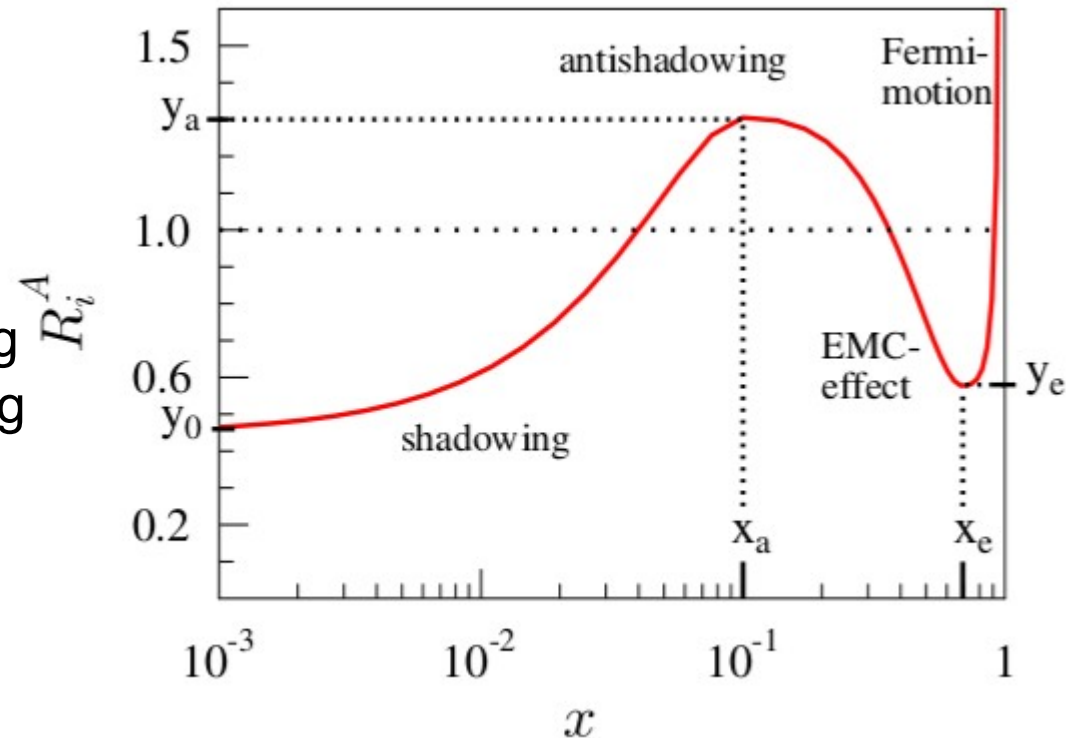
- By definition, $R_{AA}=1$ in absence of nuclear or QGP matter effects
- Binary scaling can be broken due to initial state effects
 - Transverse k_T broadening (called “Cronin effect”)
 - PDF modifications in nuclei (shadowing)

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

(Prime reason for measurements in pA)

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

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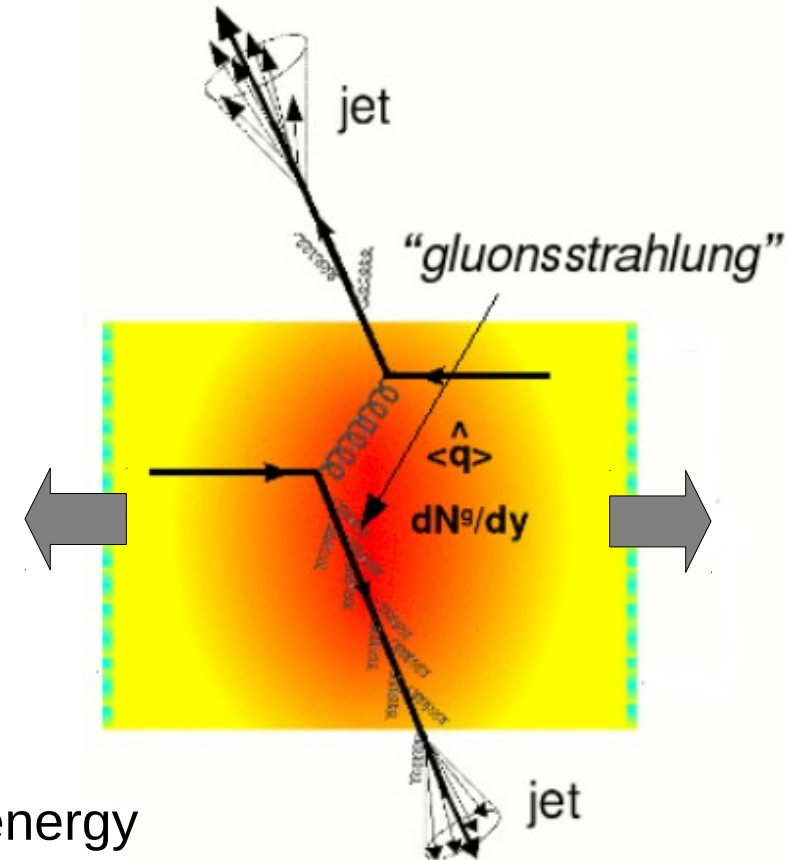
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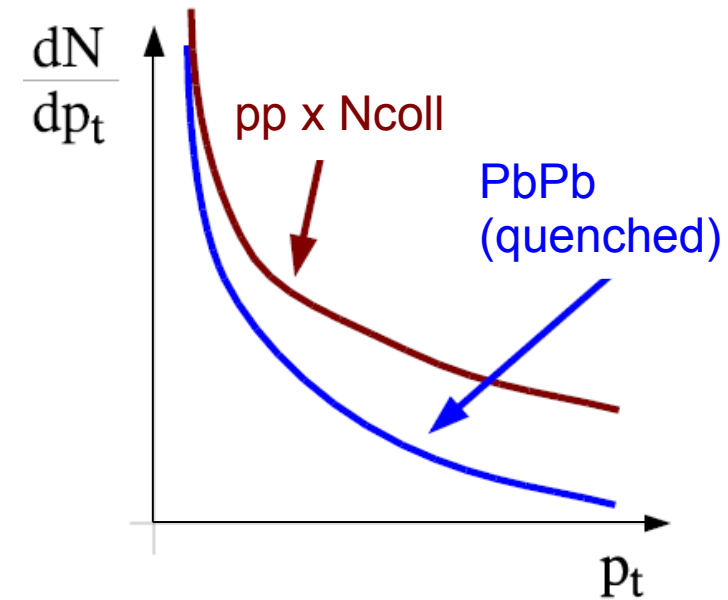
(Prime reason for measurements in pA)

- Binary scaling can be broken due final state effects

- 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 mechanism dominant at high energy
 - The net-effect is a decrease of the p_T of hard partons
 - Quenching of the high p_T spectrum
 - Modification of jet properties



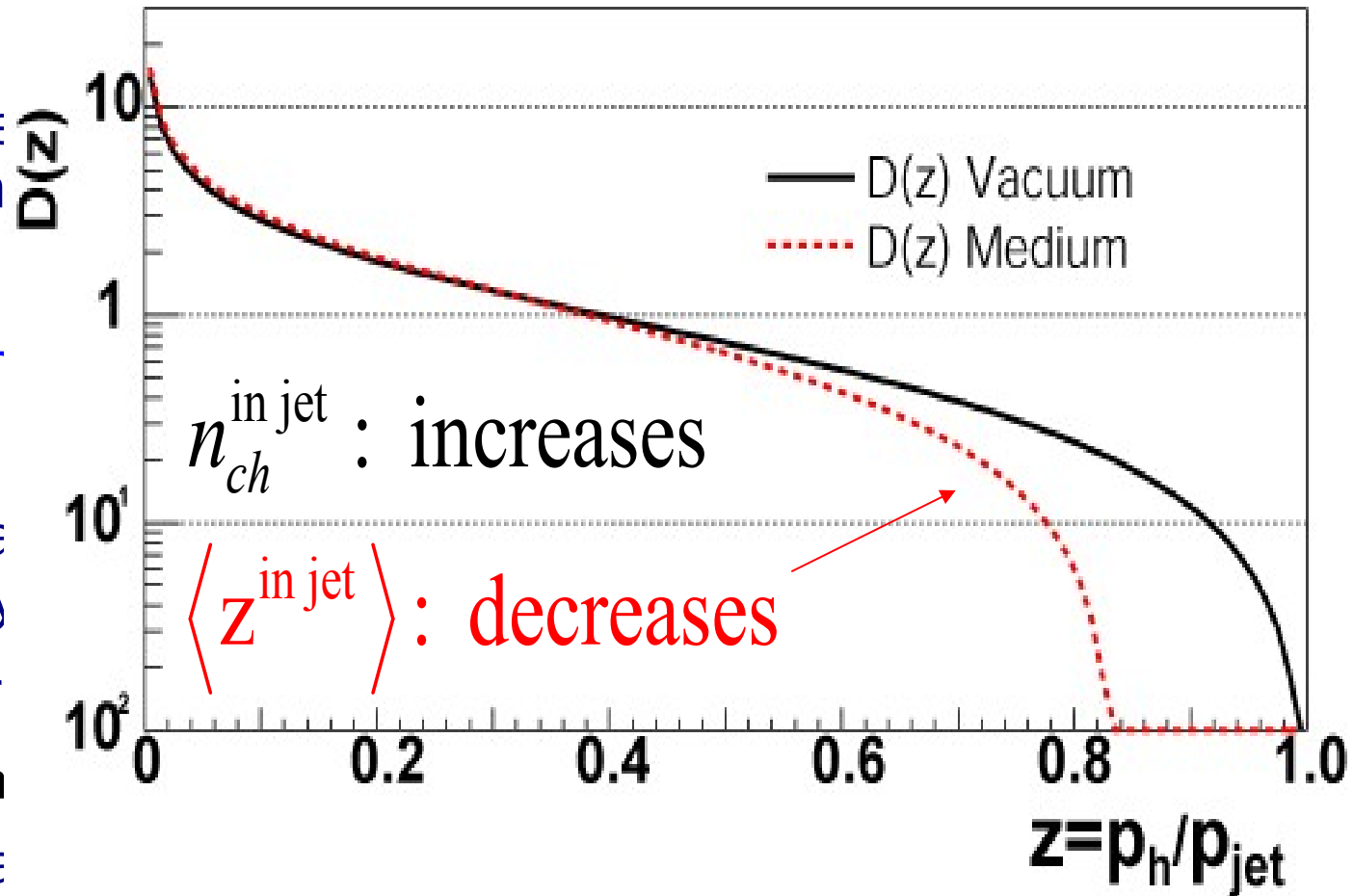
- Final state effects

- Change of fragmentation function due to the presence of the medium
 - e.g. jet quenching

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- Modification of jet properties





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

Bjorken, 1982

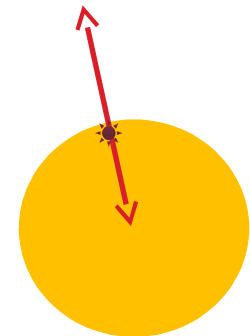
Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

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

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)

25

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

(Crude approximation
see [arXiv:1002.2206](https://arxiv.org/abs/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)

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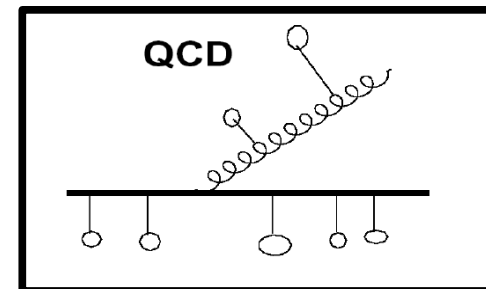
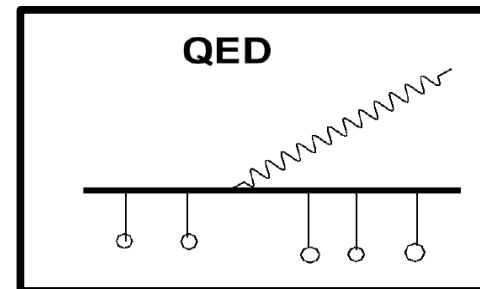
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\hat{q} = **Transport coefficient**

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

- 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

$$\epsilon_{\text{BJ}} = 5.4 \text{ GeV}/\text{fm}^3$$

$$\hat{q} = 1 \text{ GeV}^2/\text{fm}$$

$$\alpha_S = 0.2$$

$$C_R = 4/3$$

$$L = 3 \text{ fm}$$

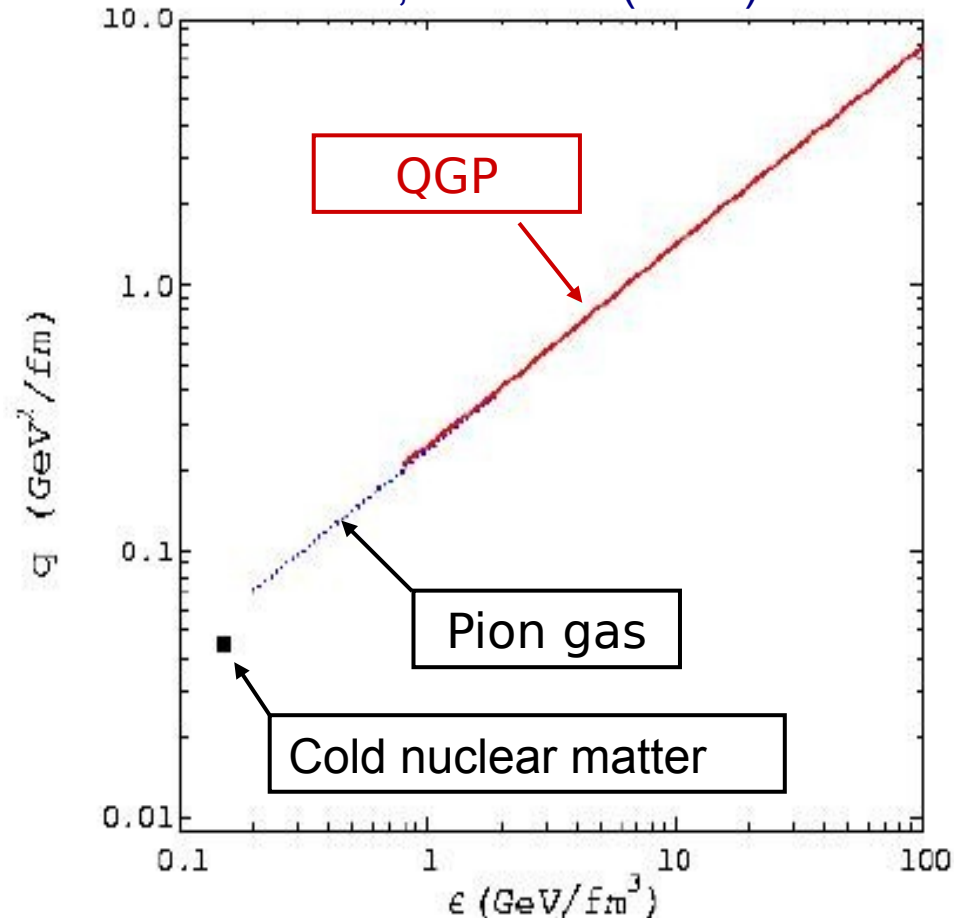


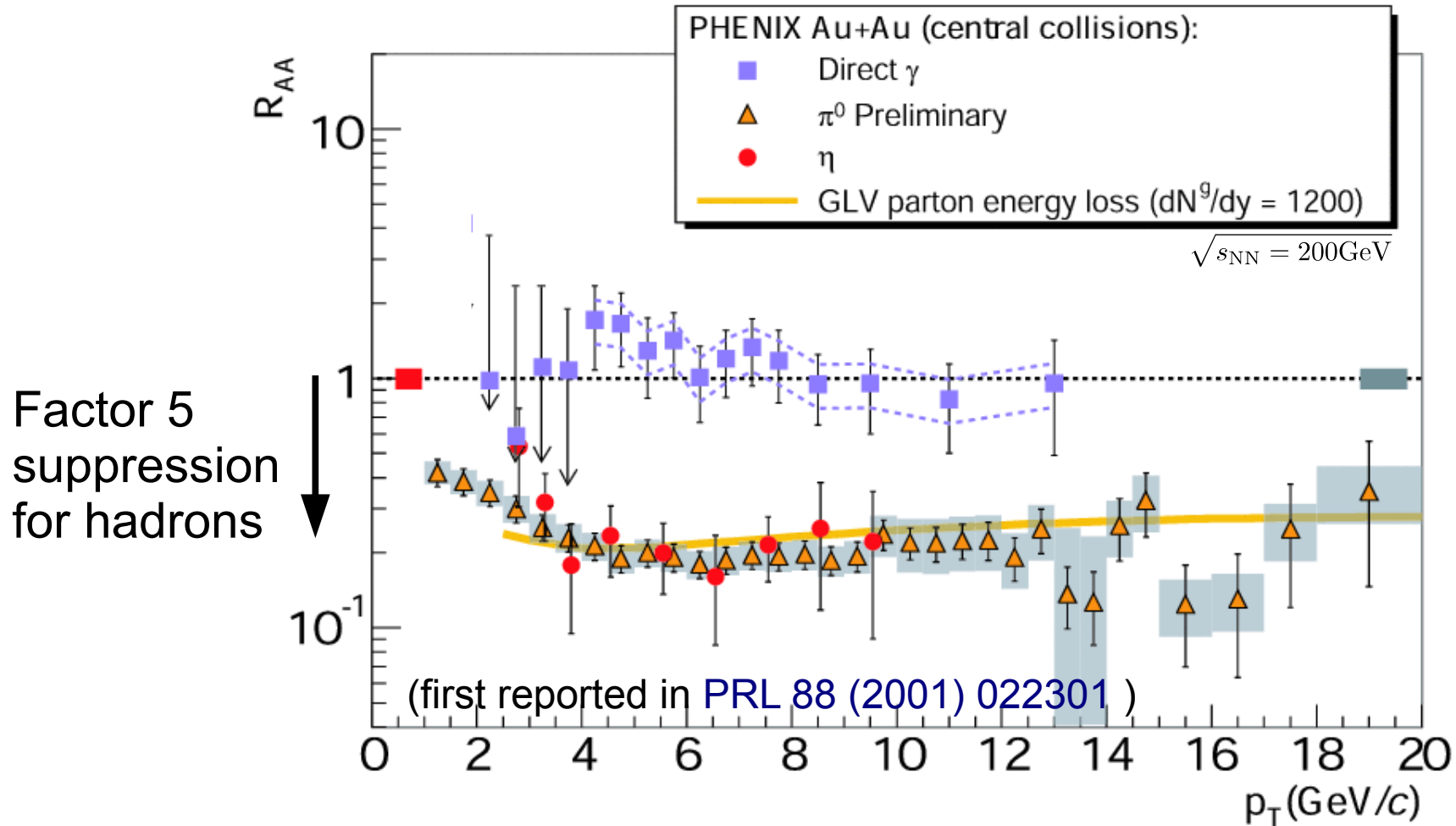
(From formula on previous slide)

$$\langle \Delta E \rangle \simeq 10 \text{ GeV}$$

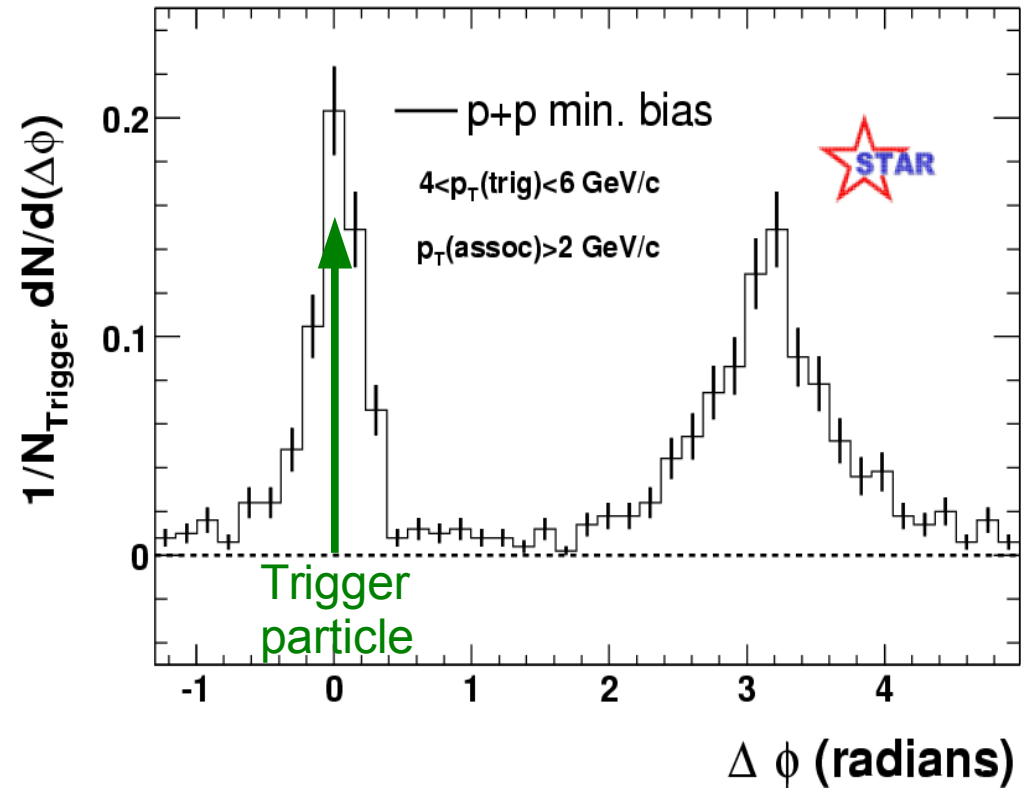
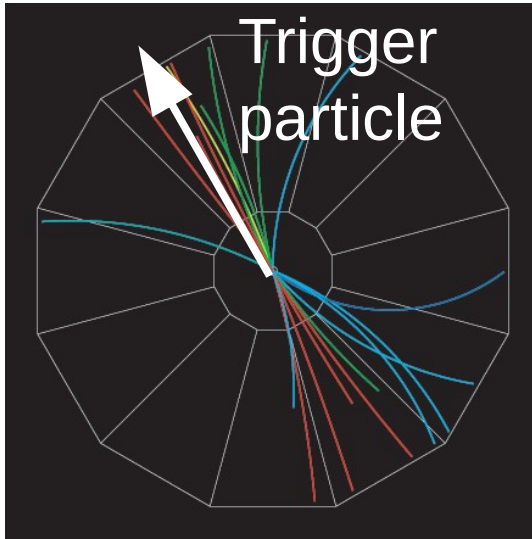
Enormous! Only high- p_T partons survive (or those that are produced “close to the surface” of the QGP)

Baier, NPA 715 (2003) 209

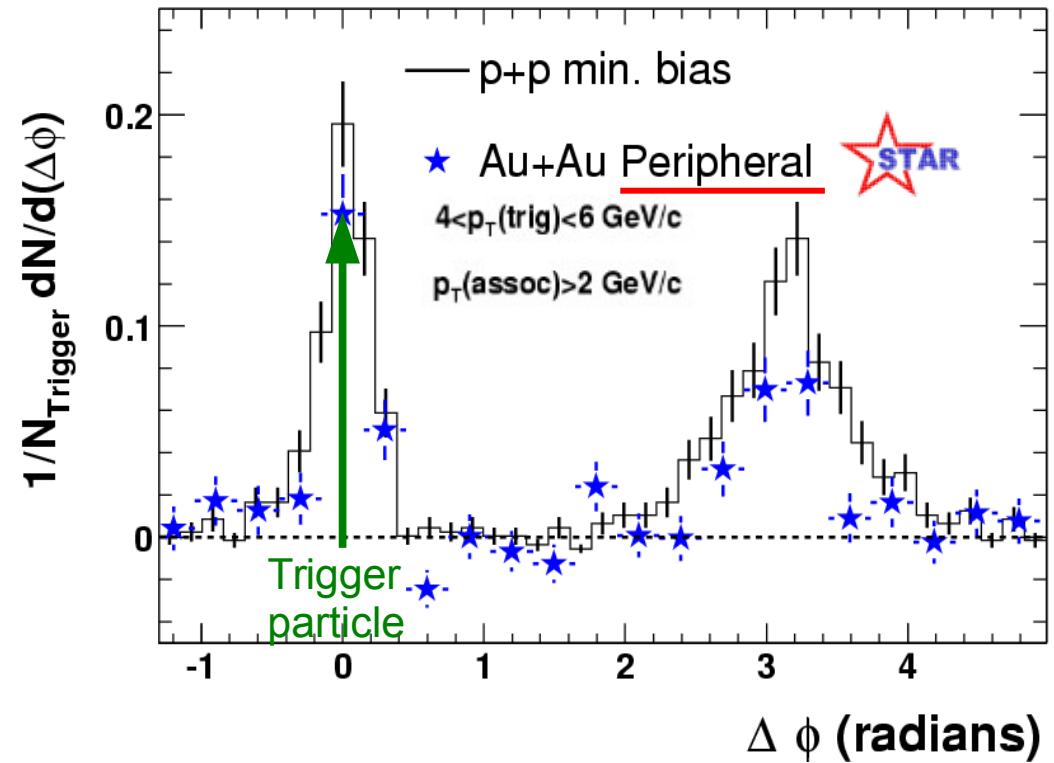
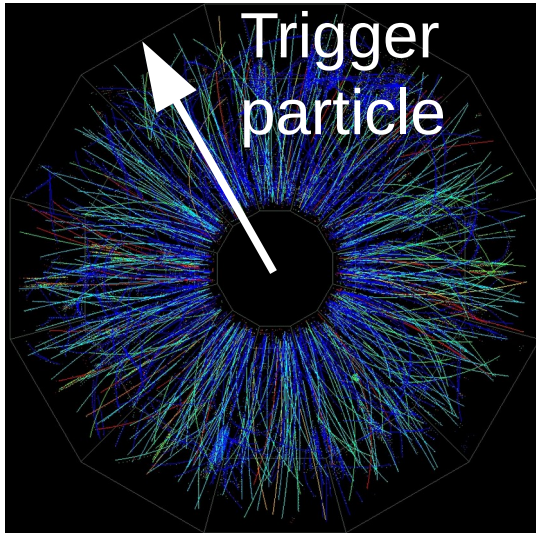




Strong suppression of hadrons in central Au+Au collisions
 (extracted transport coefficient similar to initial expectations, see [arXiv:1312.5003](#))



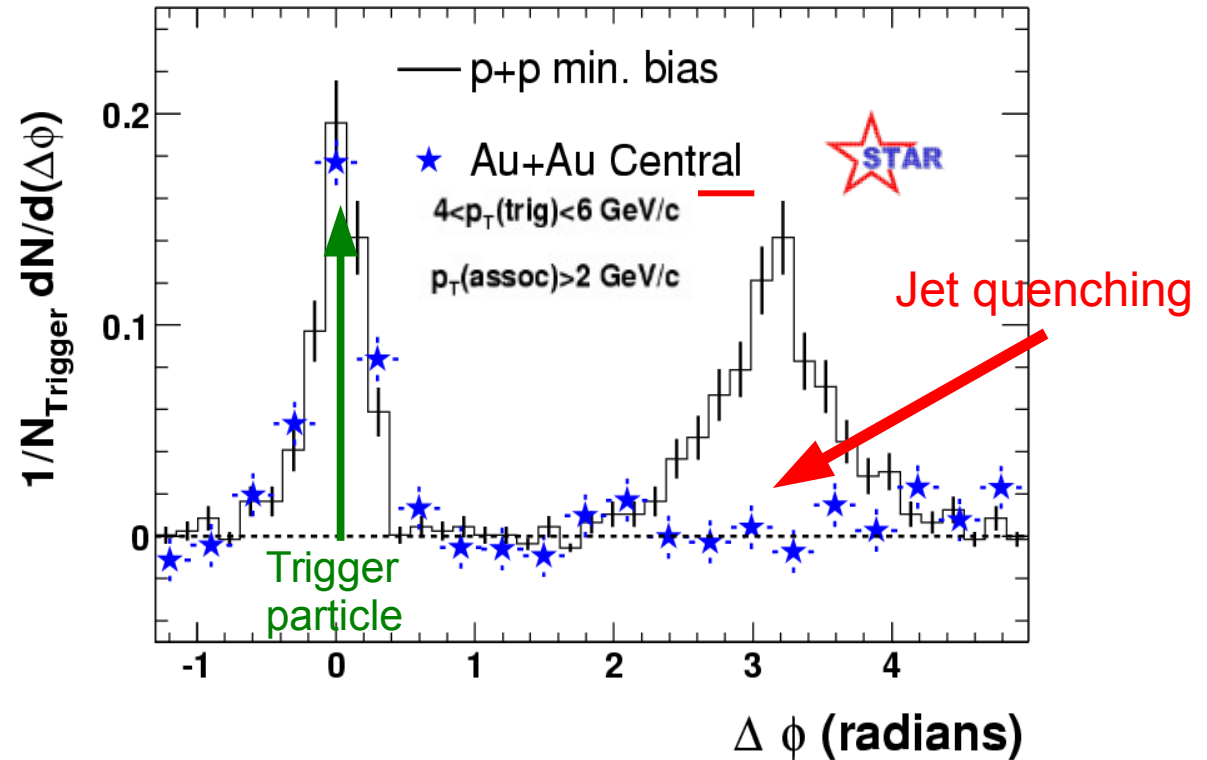
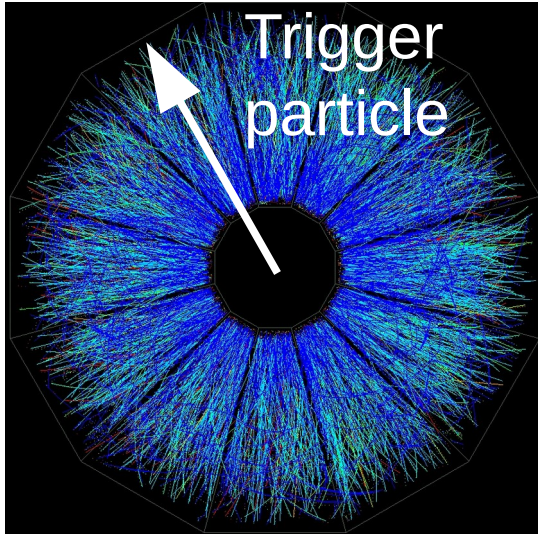
Study two particle angular correlations relative to high- p_{T} (trigger) particle:
Proxy for di-jet measurements



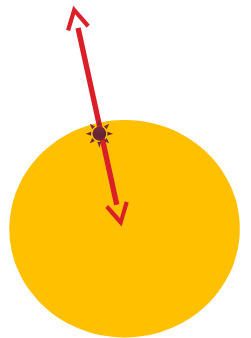
No clear change visible (relative to pp) in peripheral collisions

Di-hadron correlations

PRL 90 (2003) 082392

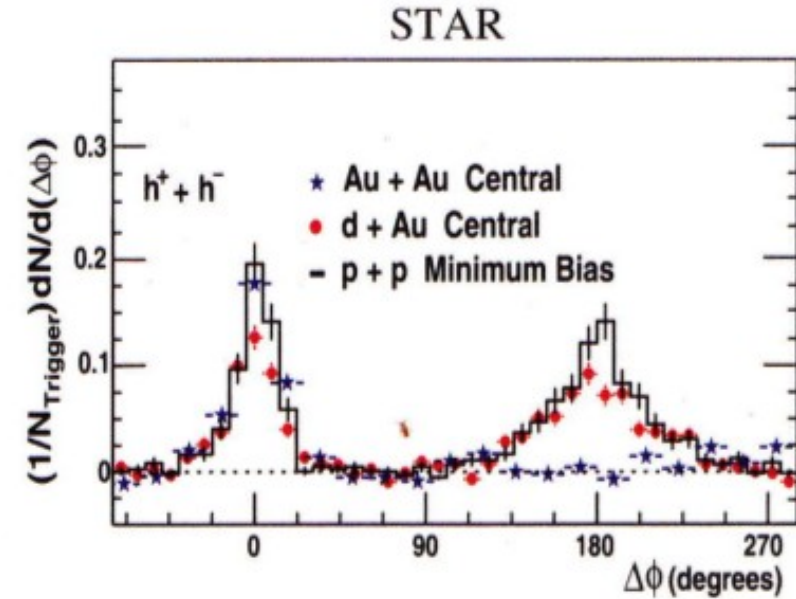
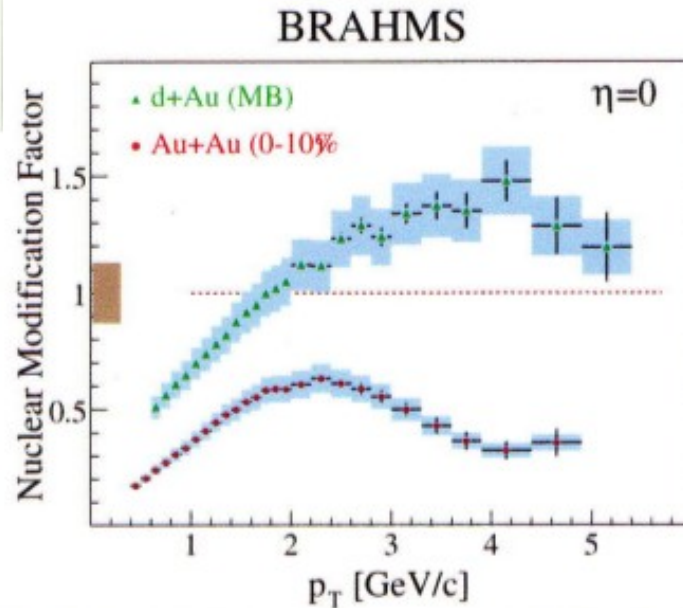
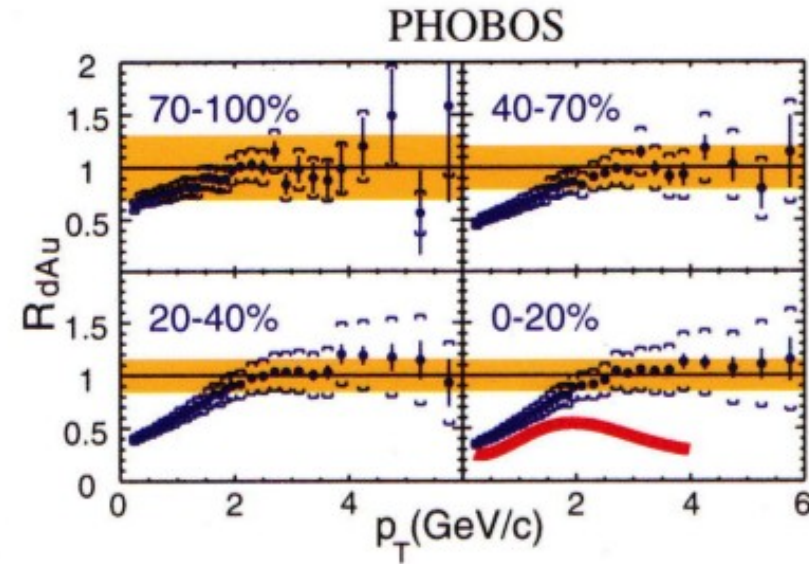
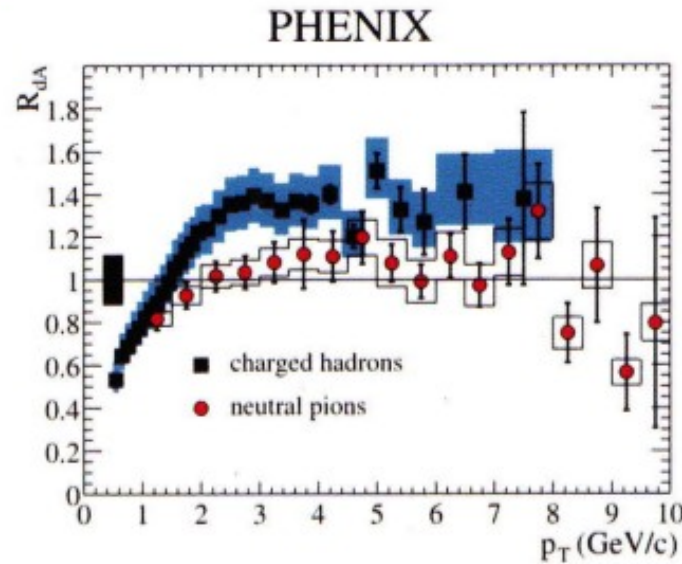


Recoiling jet is strongly altered (swallowed) by medium
Clear evidence for presence of very high density matter



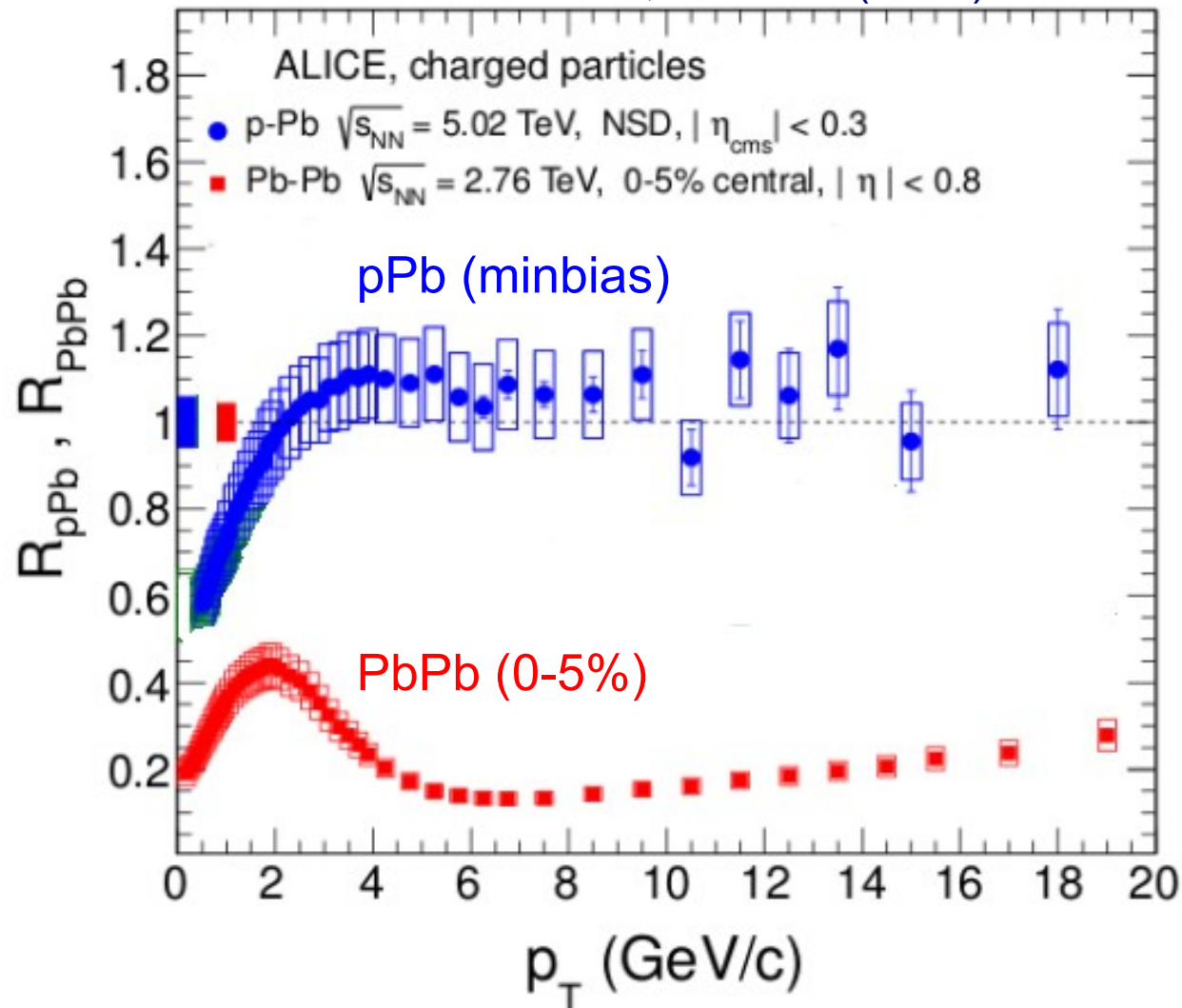


PRL 91 (2003) vol 7



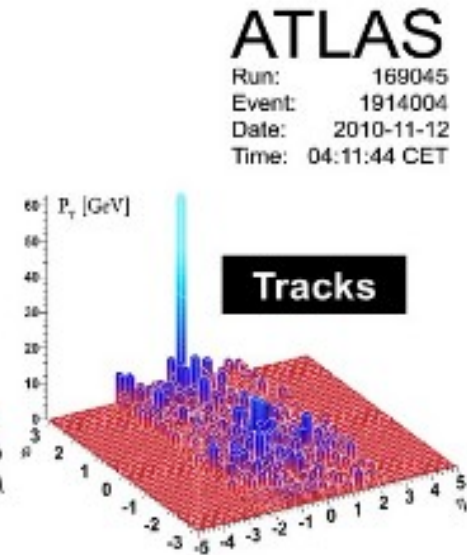
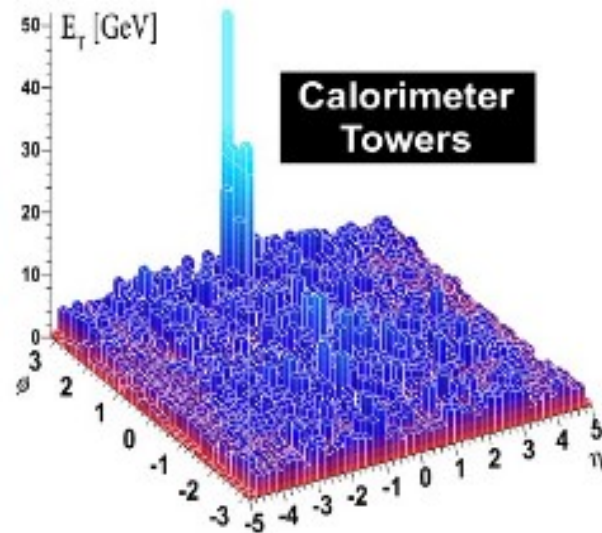
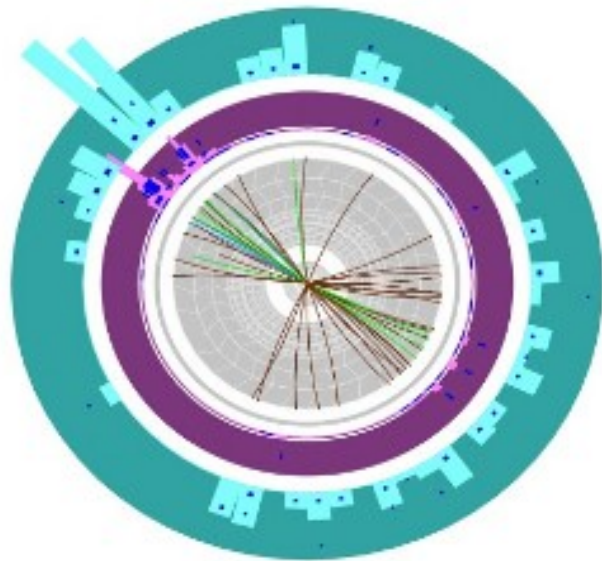
Parton energy loss is a final state effect

ALICE, PRL 110 (2013) 082302

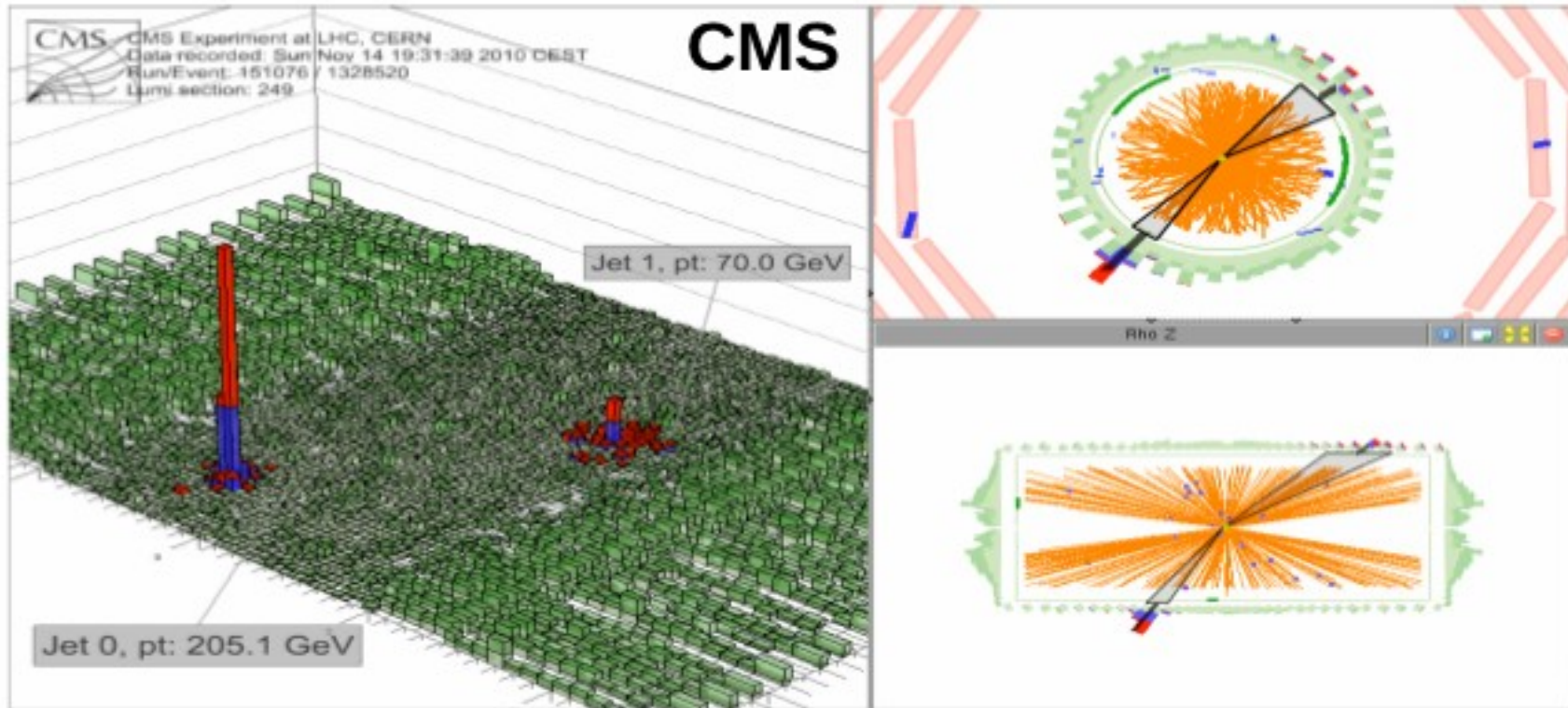


- Strong leading particle suppression also at LHC energies
- Qualitatively similar to the one at RHIC
- As at RHIC from final state (ie not observed in pPb collisions)

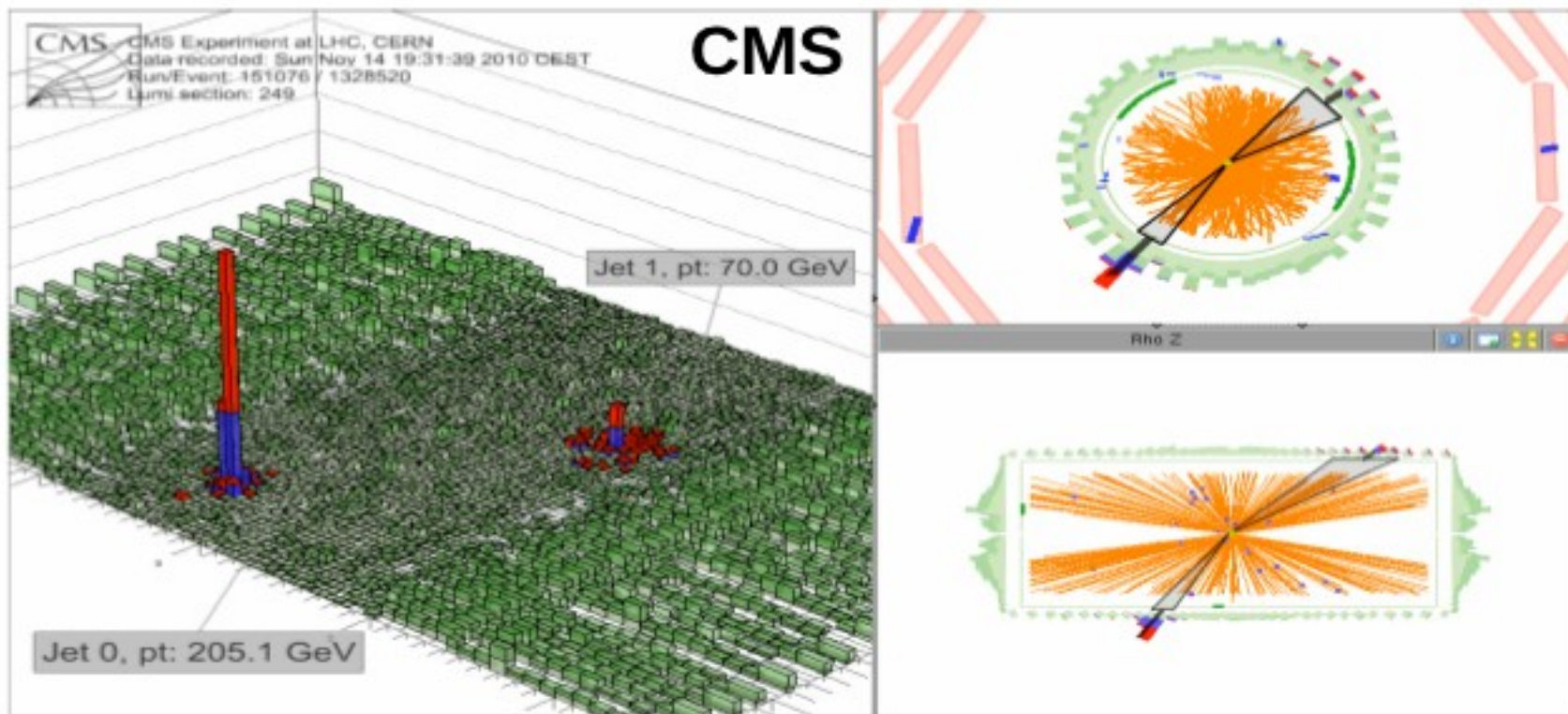
Jet quenching



Can even be seen in event displays!!!



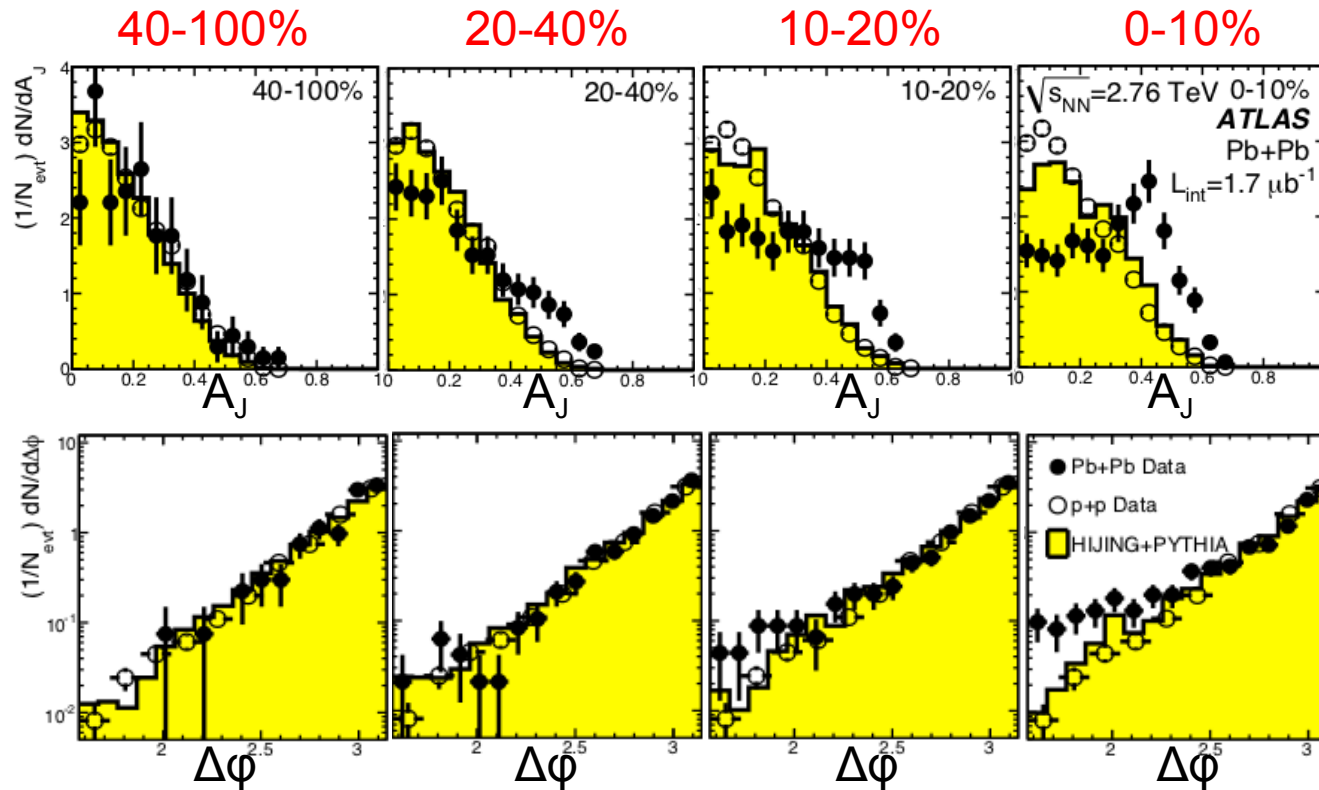
Can even be seen in event displays!!!



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 38



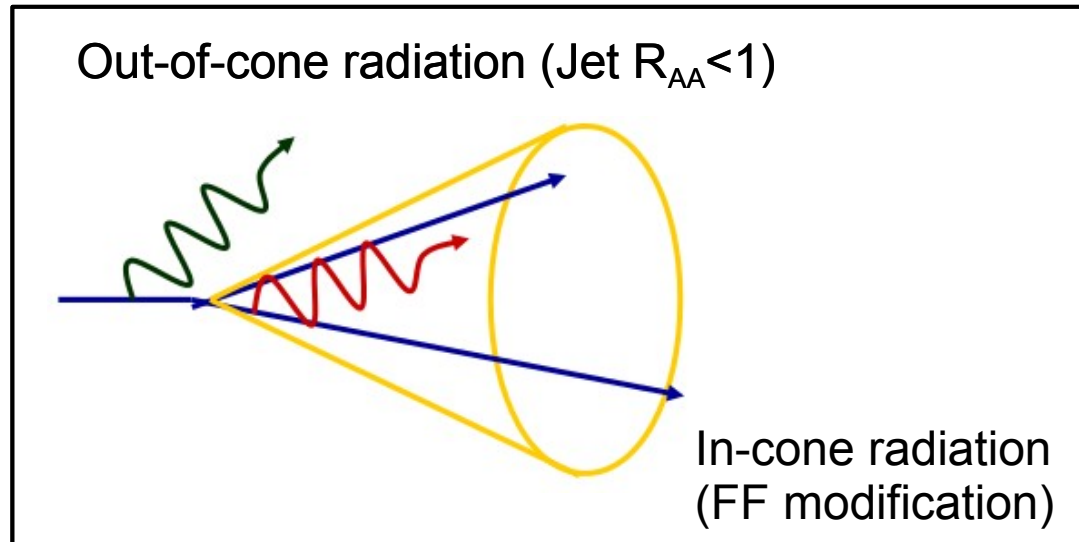
Momentum imbalance wrt to MC (pp) reference increases with increasing centrality.
 No (or very little) azimuthal decorrelation.

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?

39

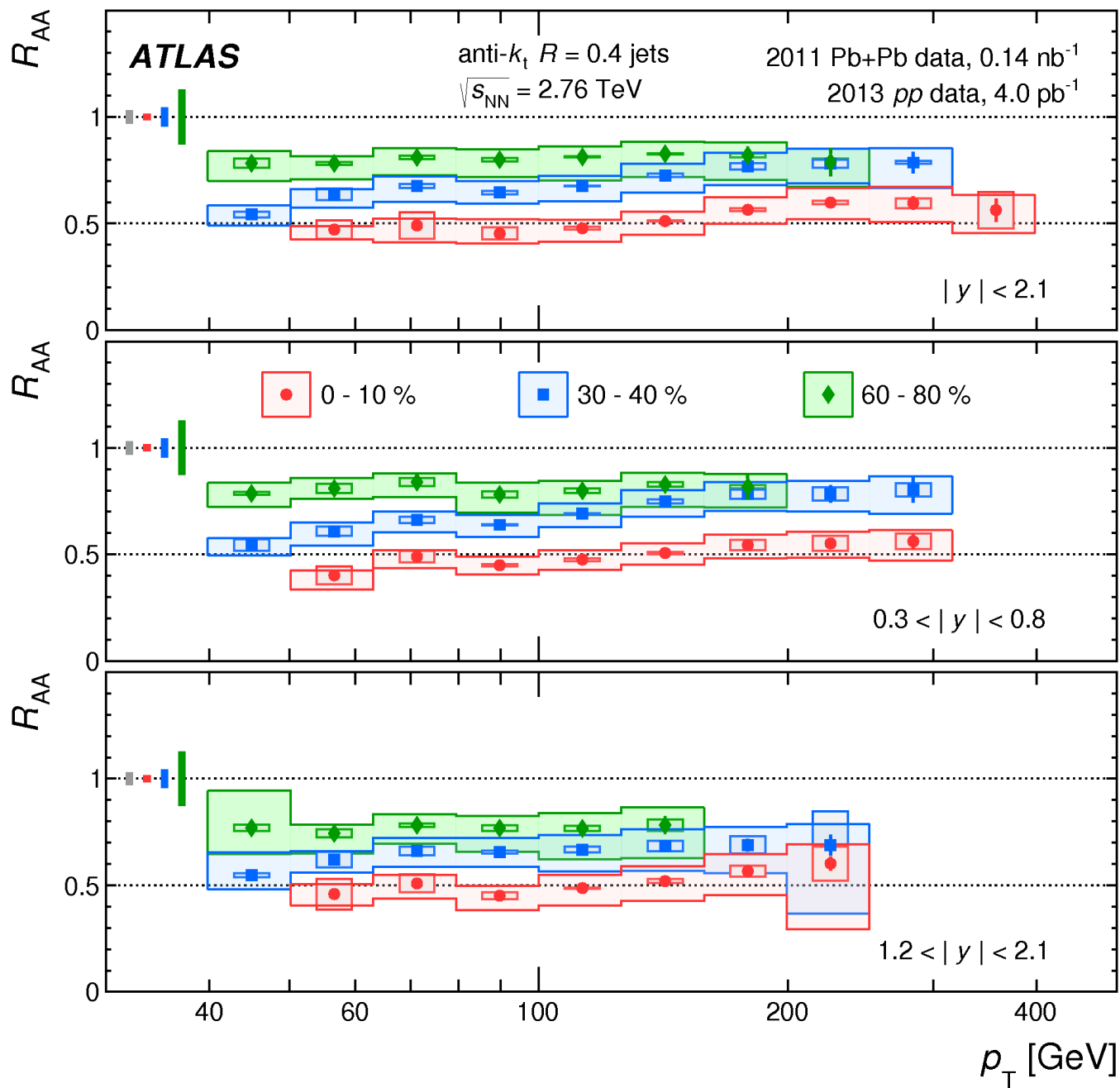


Jet R_{AA} up to very high p_T

40

arXiv:1506.08656

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

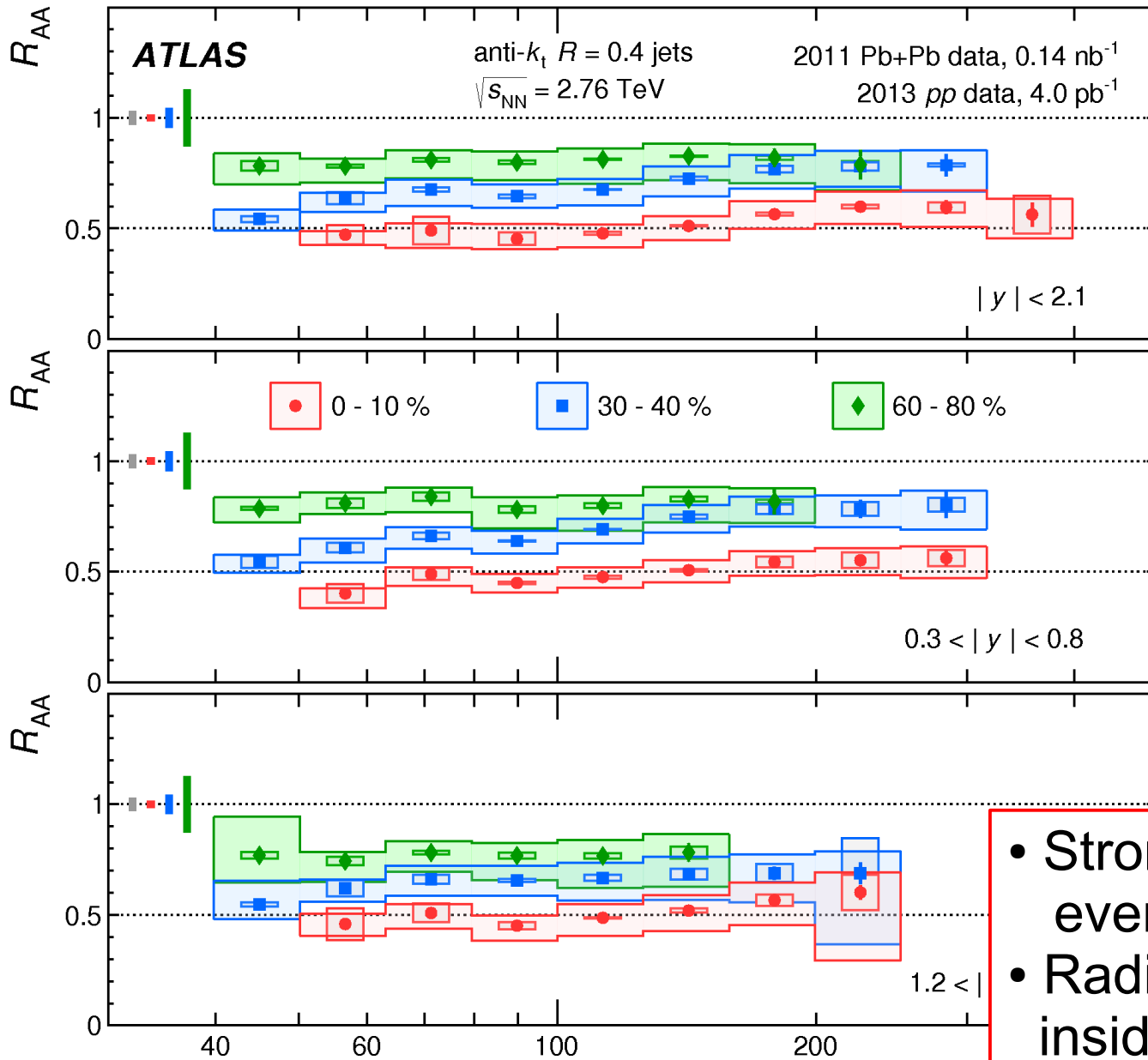


Jet R_{AA} up to very high p_T

41

arXiv:1506.08656

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

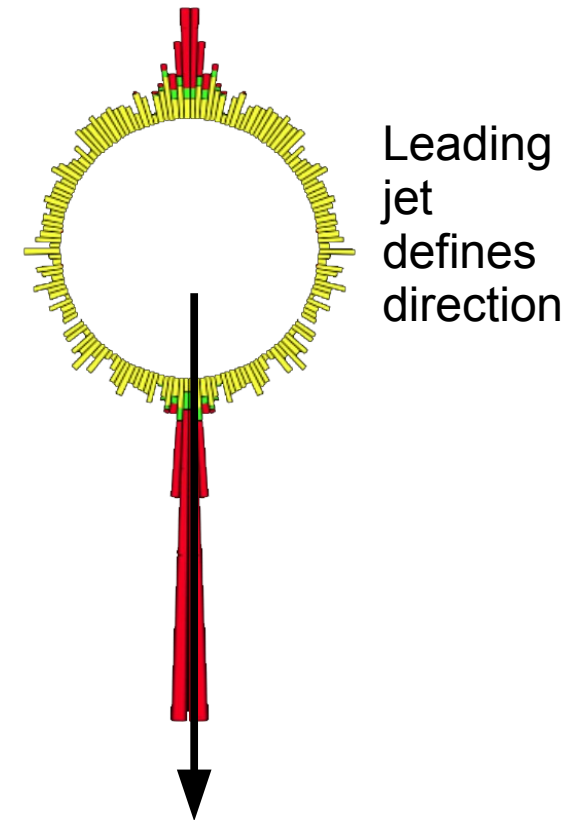


- Strong jet suppression even at up to 200-300 GeV
- Radiation not captured inside cone $R=0.4$
- Where does the energy go?

Where does the energy go?

42

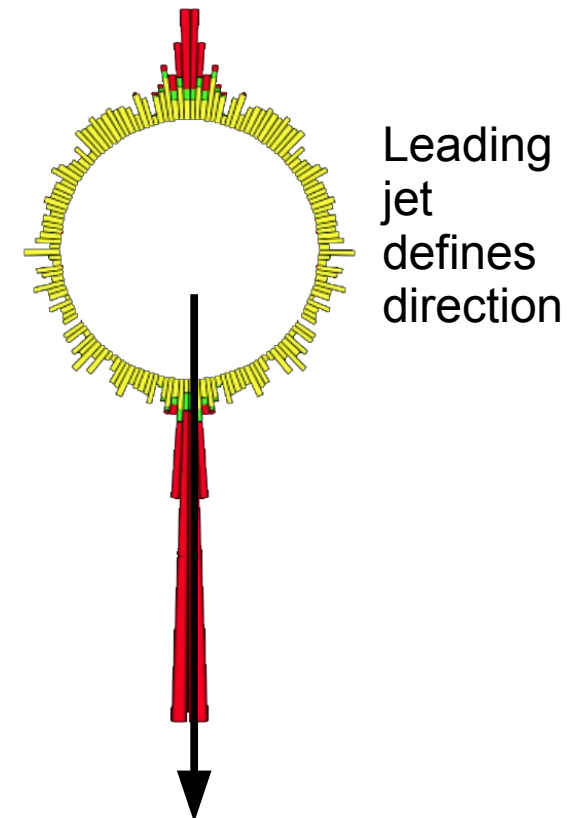
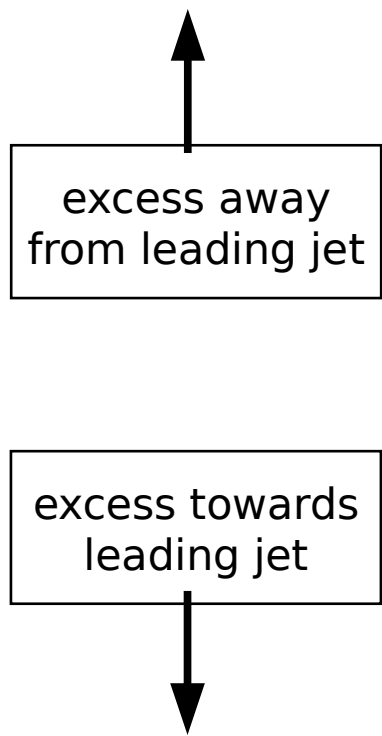
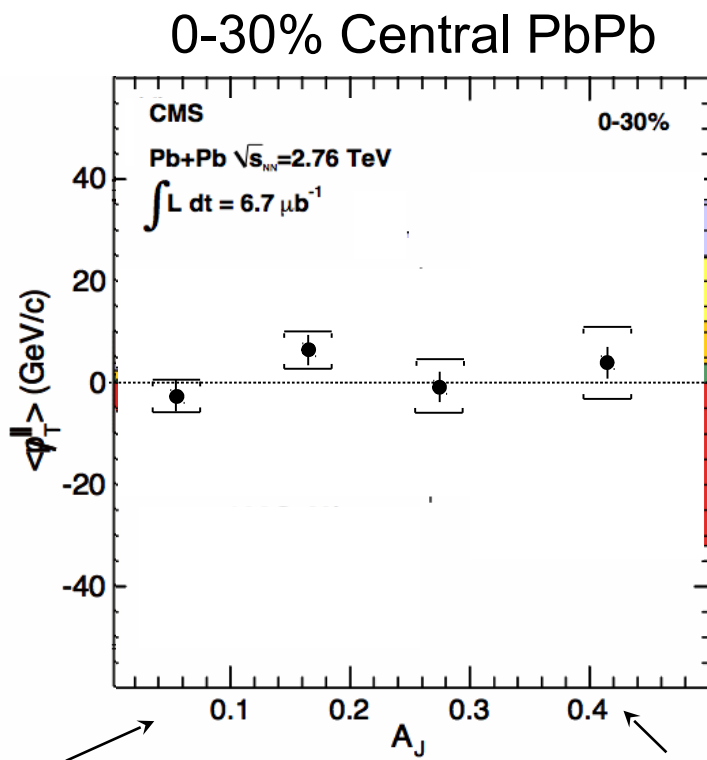
- Calculate projection of p_T on leading jet axis and average over selected tracks with $p_T > 0.5$ GeV/c and $|\eta| < 2.4$
- Define missing p_T
$$\cancel{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos(\phi_{\text{Track}} - \phi_{\text{Leading Jet}})$$
- Averaging over event sample in bins of A_j
find missing p_T consistent with zero



Where does the energy go?

43

- Calculate projection of p_T on leading jet axis and average over selected tracks with $p_T > 0.5$ GeV/c and $|\eta| < 2.4$
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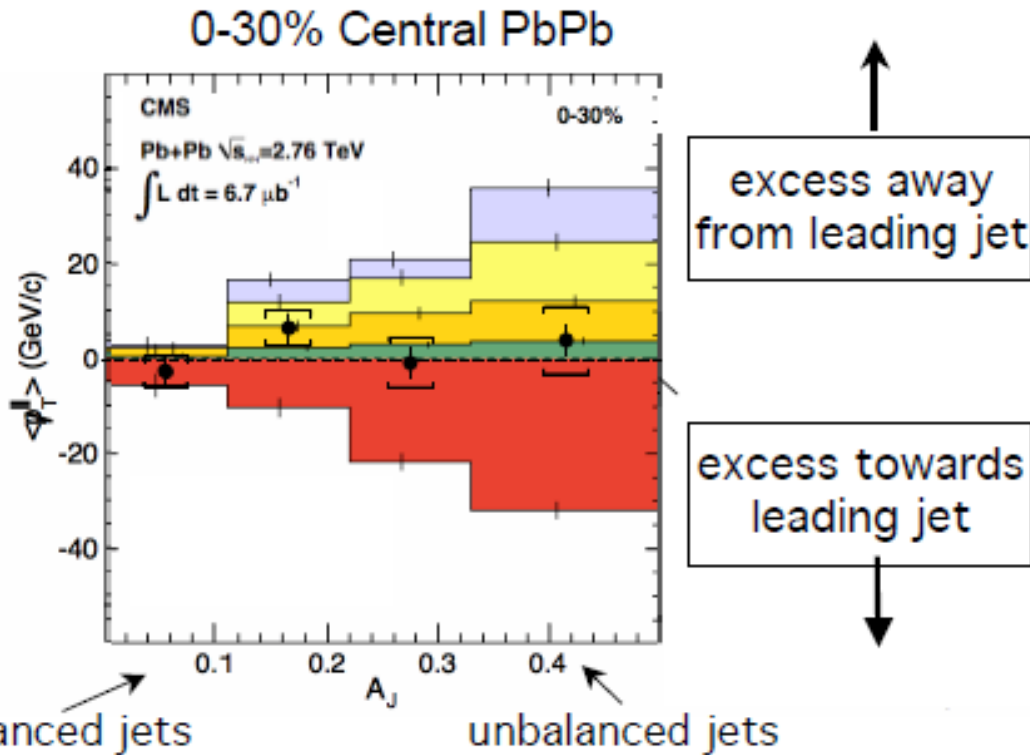


balanced jets

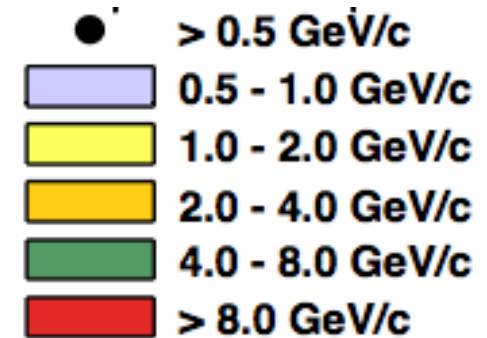
unbalanced jets

Where does the energy go?

44



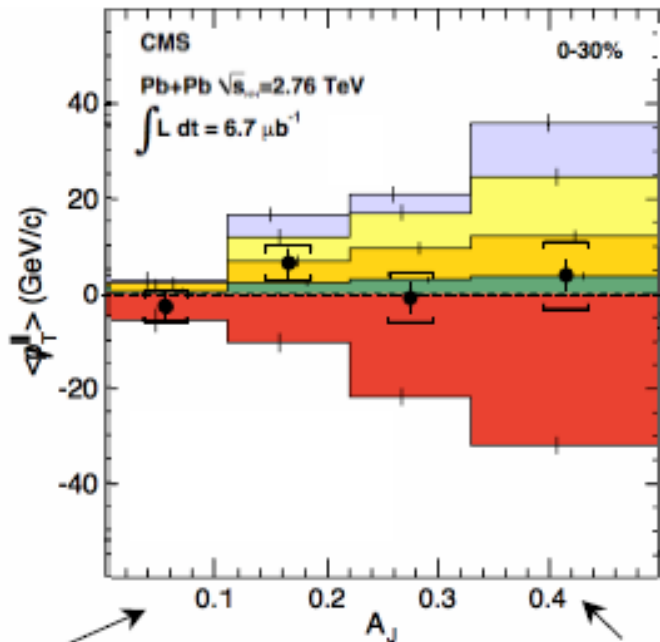
Calculate missing p_{\perp}
in bins of track p_{\perp}



The momentum difference in the leading jet is compensated by low p_{\perp} particles

Where does the energy go?

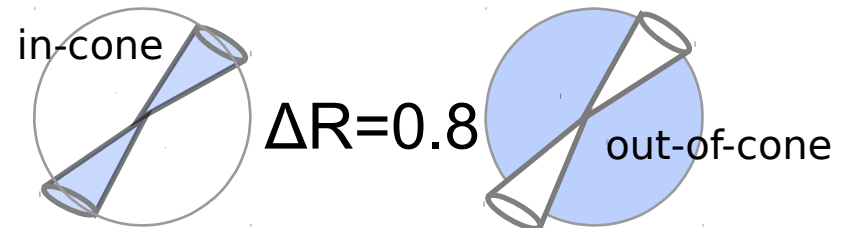
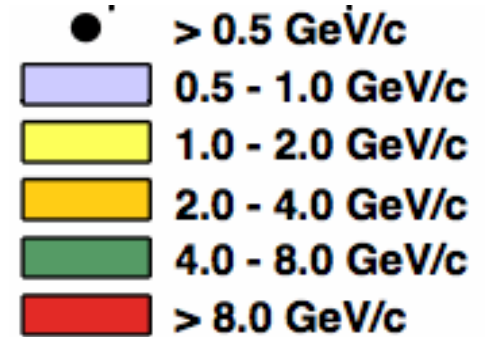
0-30% Central PbPb



↑
excess away
from leading jet

↓
excess towards
leading jet

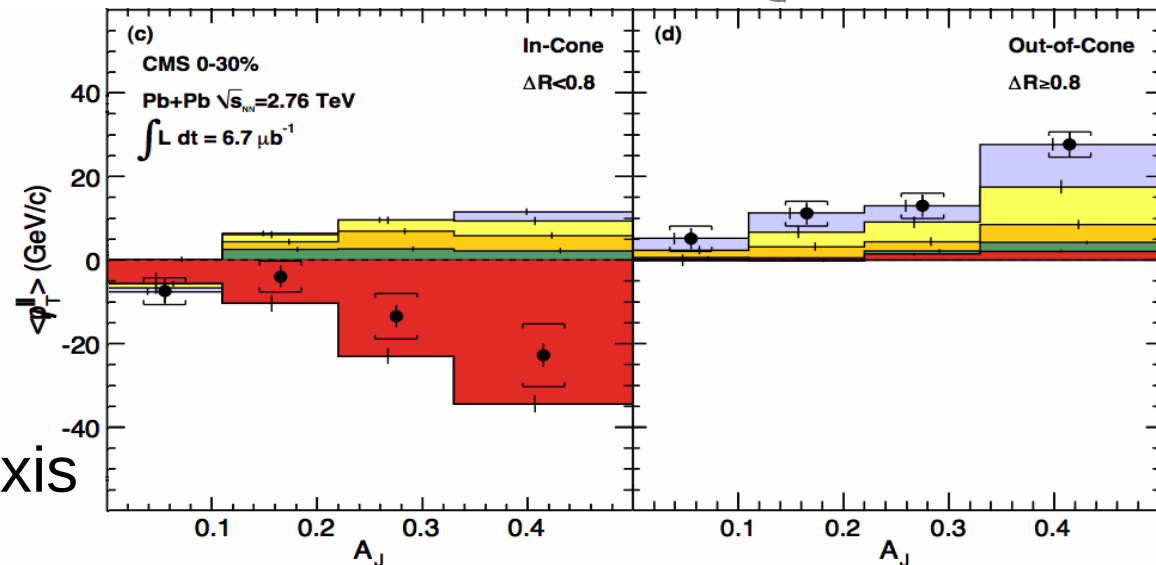
Calculate missing p_T
in bins of track p_T



balanced jets

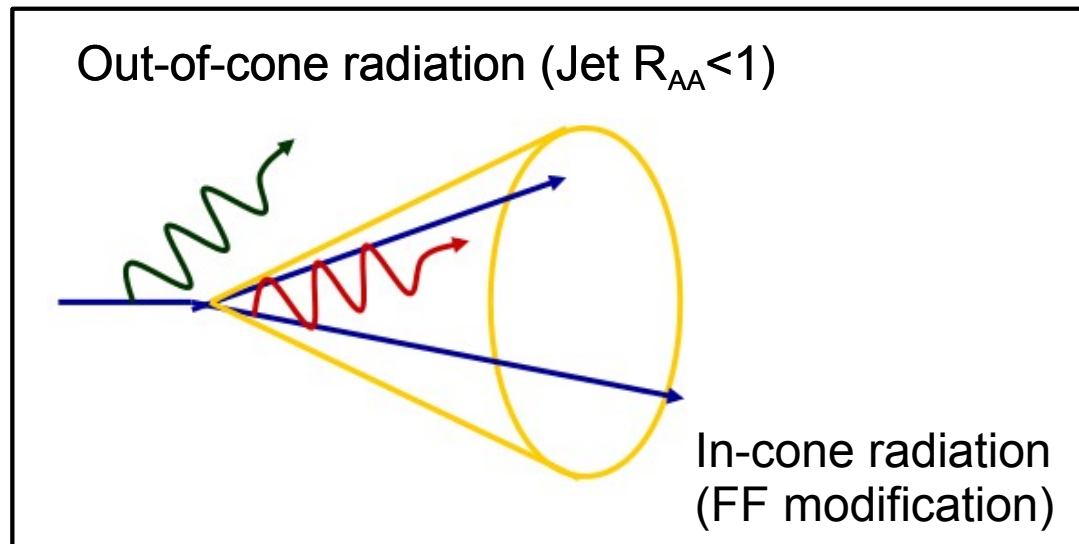
unbalanced jets

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?

46



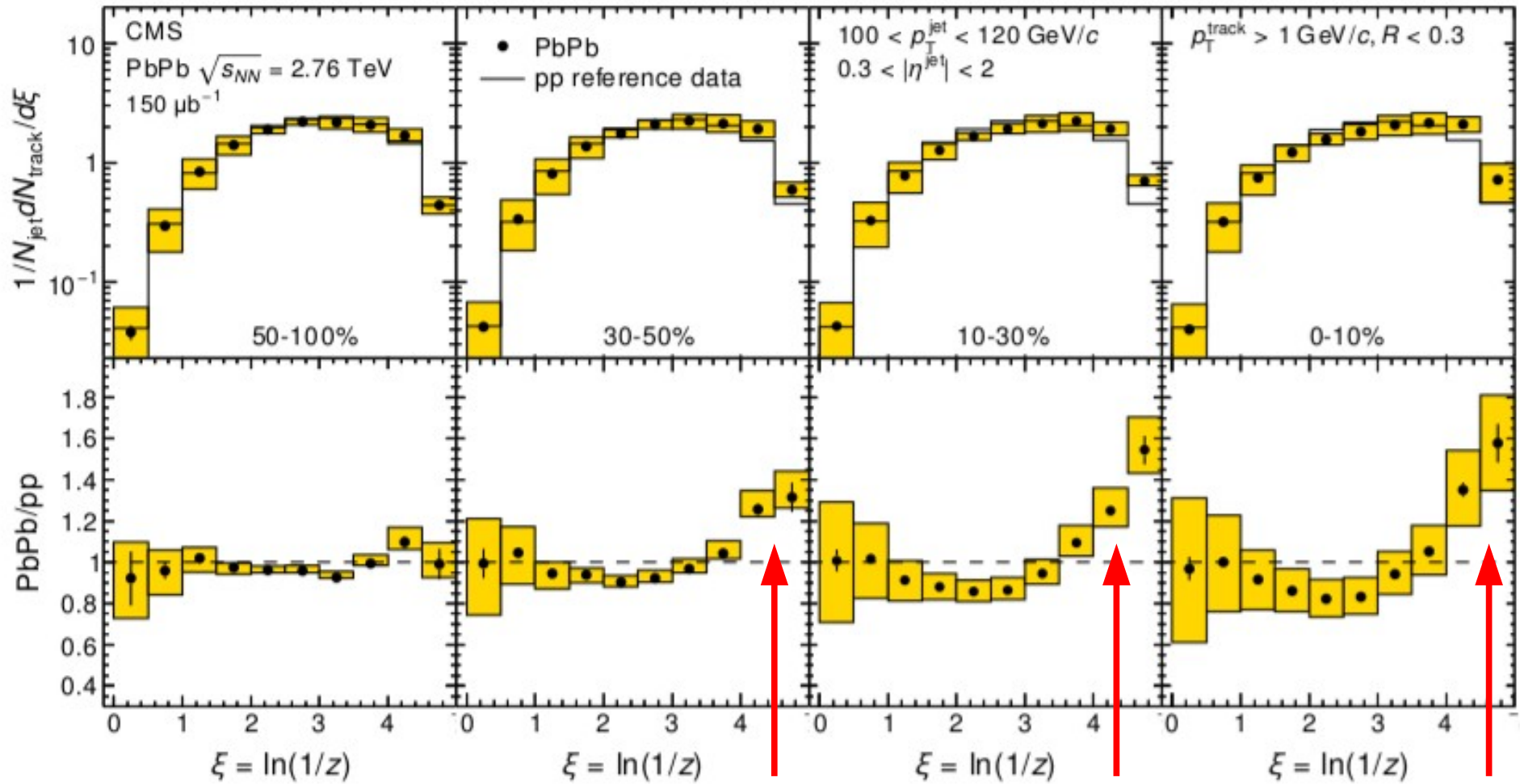
Is there an observable difference in the jet cone?

Jet fragmentation function

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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

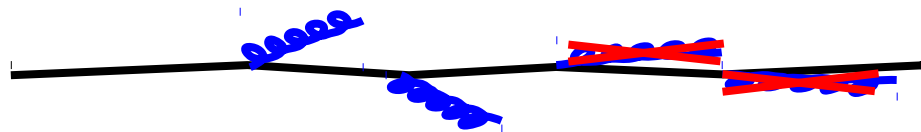
Fragmentation function is modified:

More particles at low p_T in more central collisions

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

Energy loss of massive quarks

- 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 \rightarrow smaller Casimir factor, smaller energy loss
 - Dead cone effect:
Suppression of gluon radiation at small angles dep. on quark mass



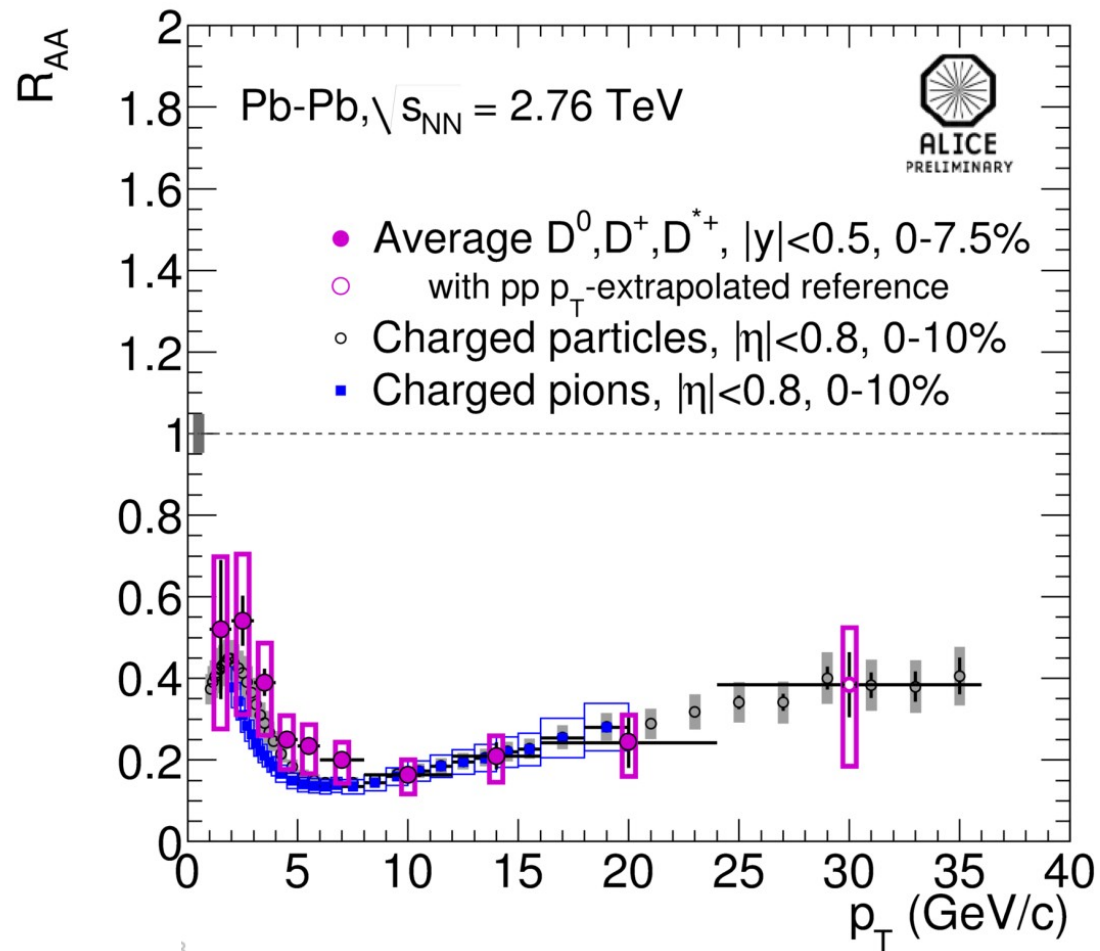
Suppression for
 $\theta < M_Q/E_Q$

- Should lead to a suppression hierarchy

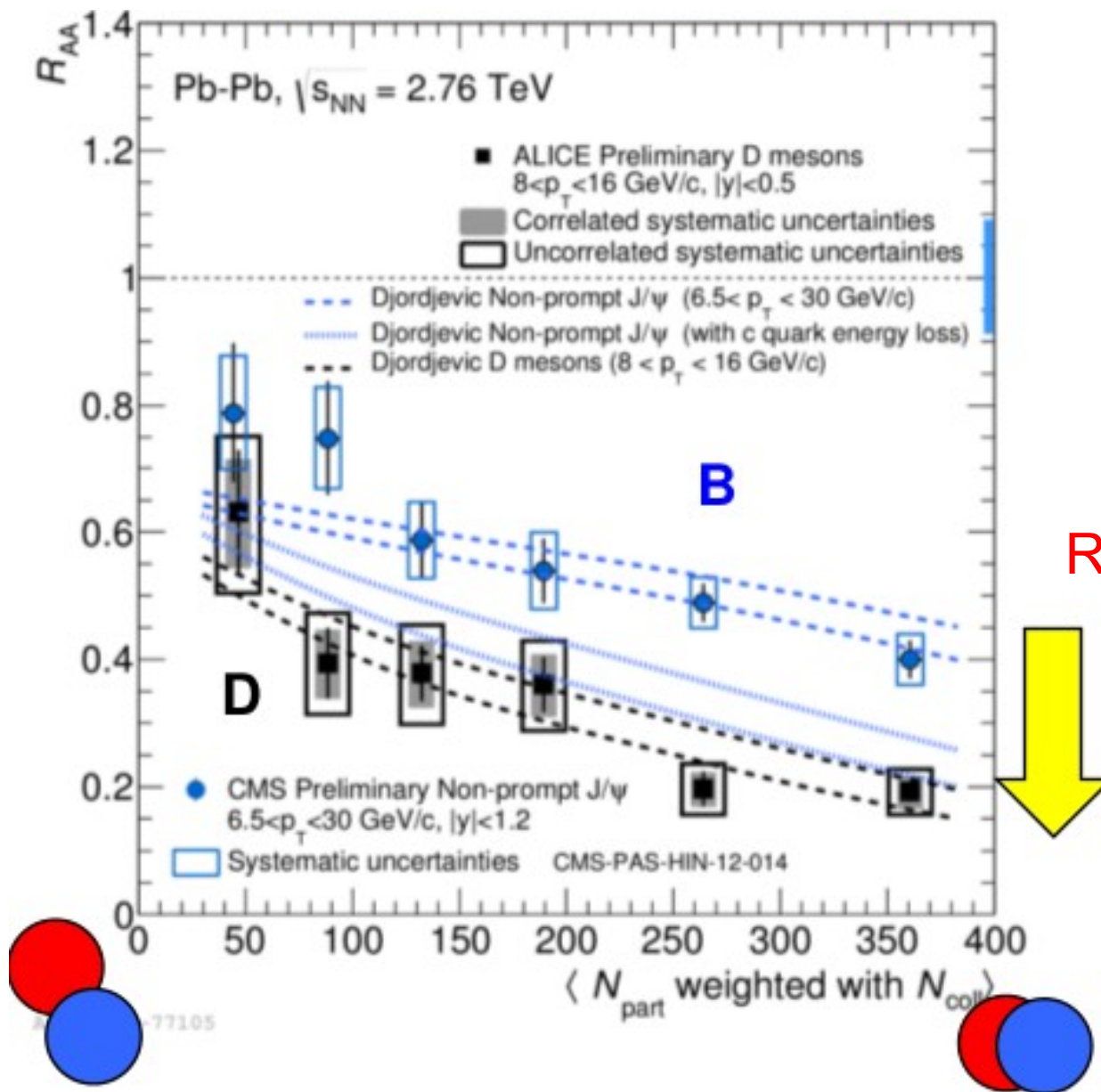
$$\Delta E_{\text{gluon}} > \Delta E_{\text{charm}} > \Delta E_{\text{beauty}}$$



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



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

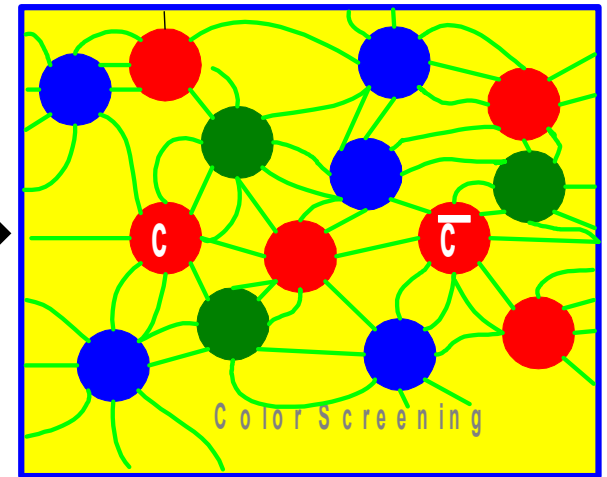
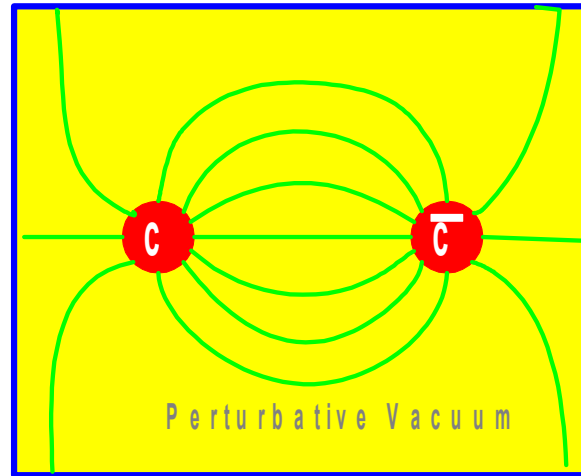


Suppression pattern compatible with expected energy loss hierarchy

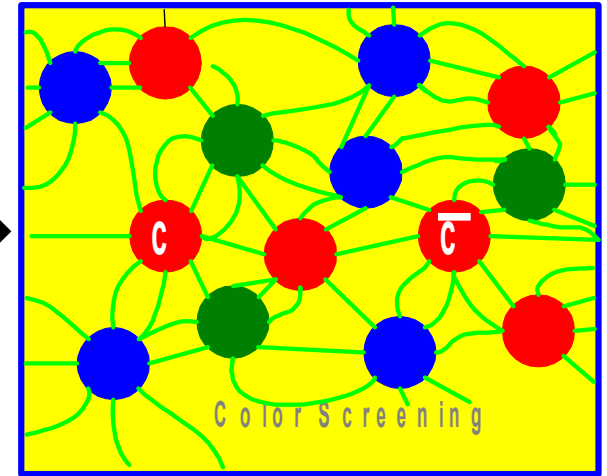
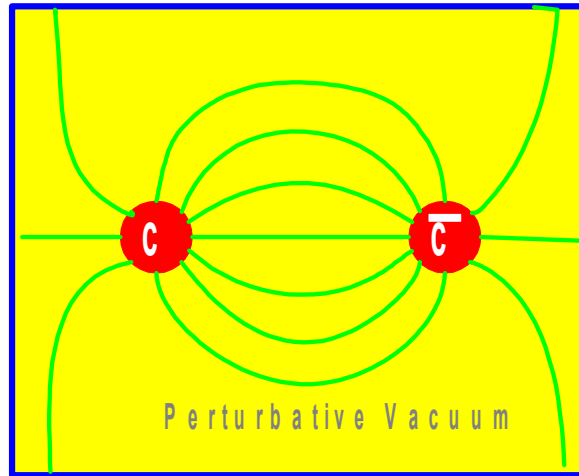
Quarkonia

Quarkonia melting at high temperature

Screening of strong interactions in QGP

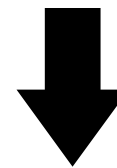


Screening of strong interactions in QGP

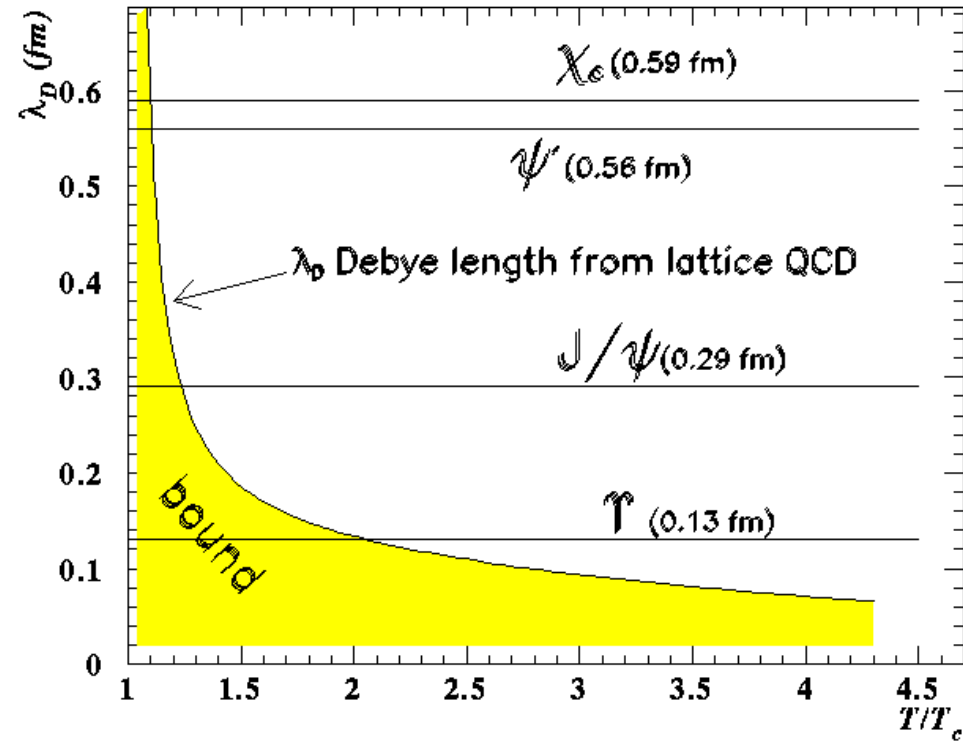
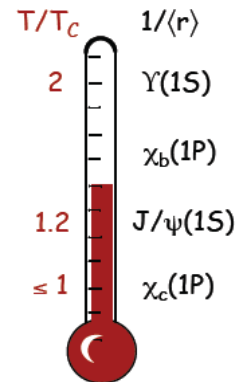


- Screening stronger at high T
- $\lambda_D \sim$ maximum size of a bound state, decreases when T increases
- Different states with different sizes

Resonance melting



QGP thermometer

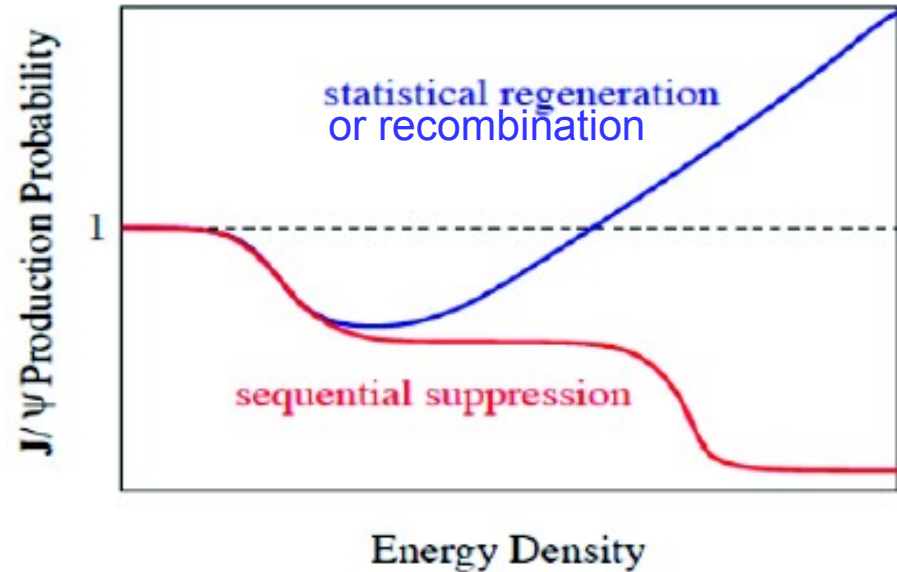


(original idea Matsui and Satz, 1986)

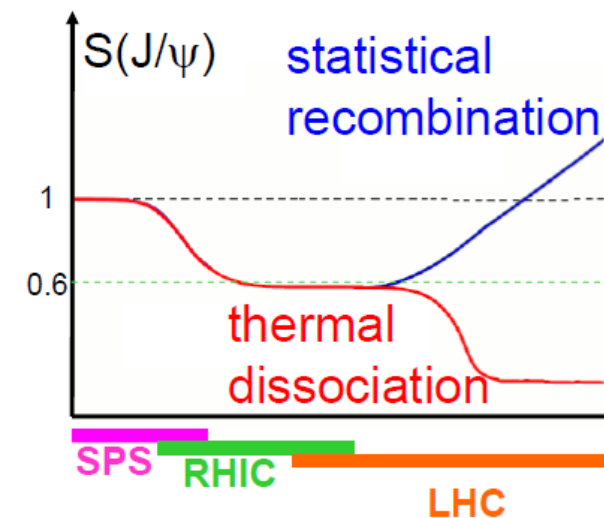
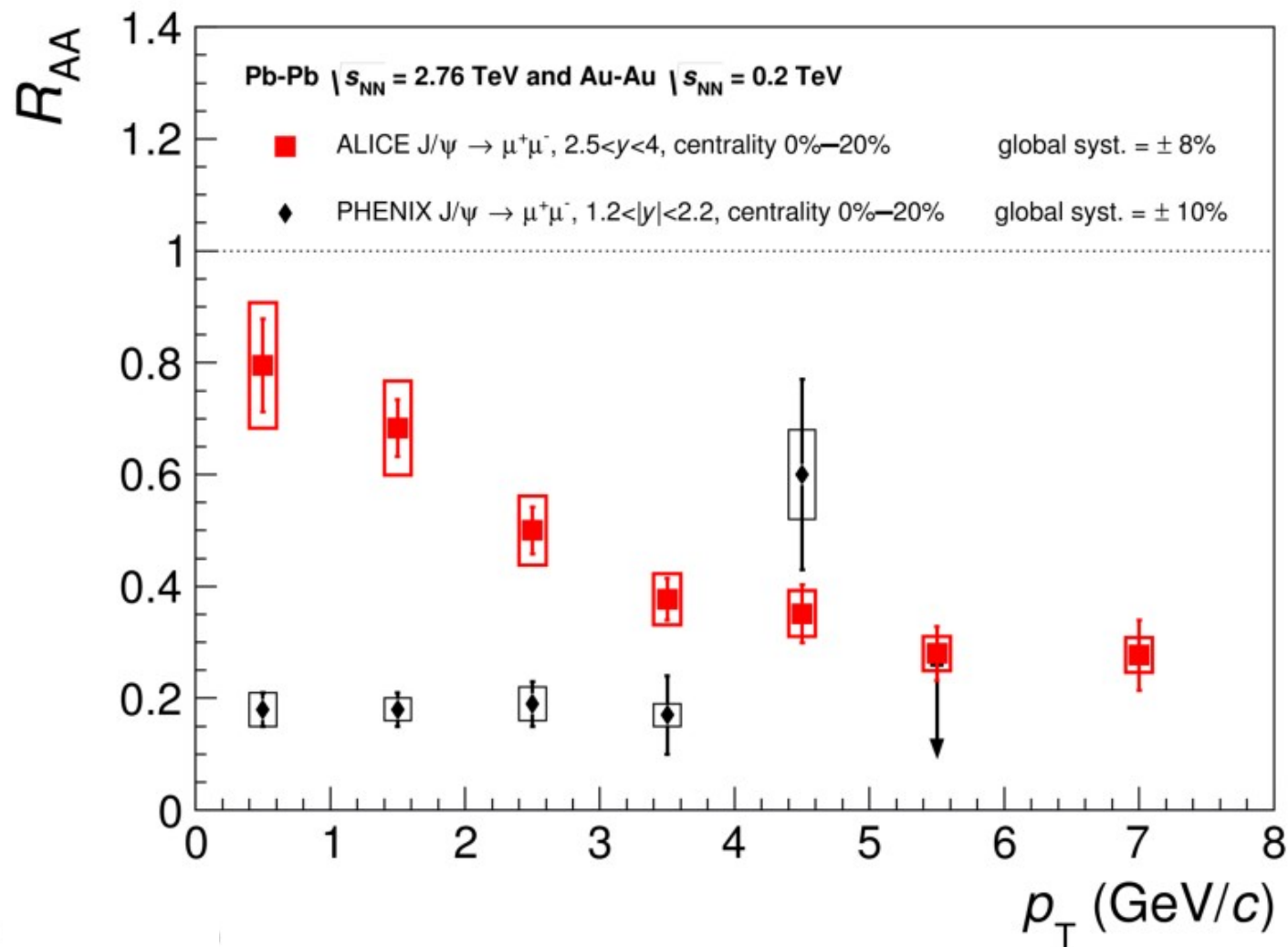
At sufficiently high energy, the cc pair multiplicity becomes large

In most central A-A collisions	SPS 20 GeV	RHIC 200 Gev	LHC 2.76 TeV
$N_{c\bar{c}}$ /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



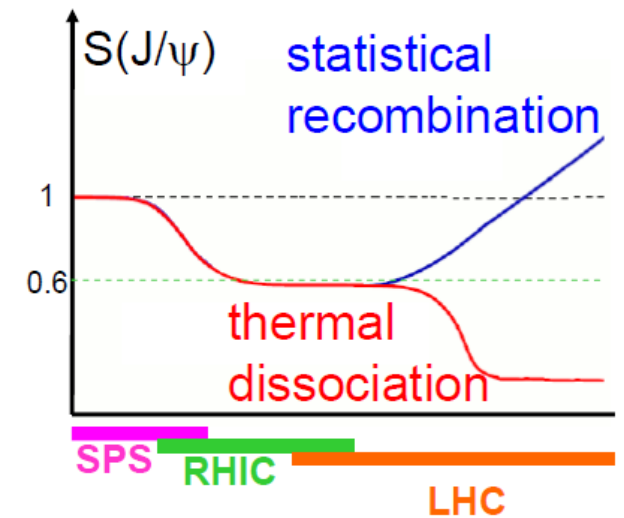
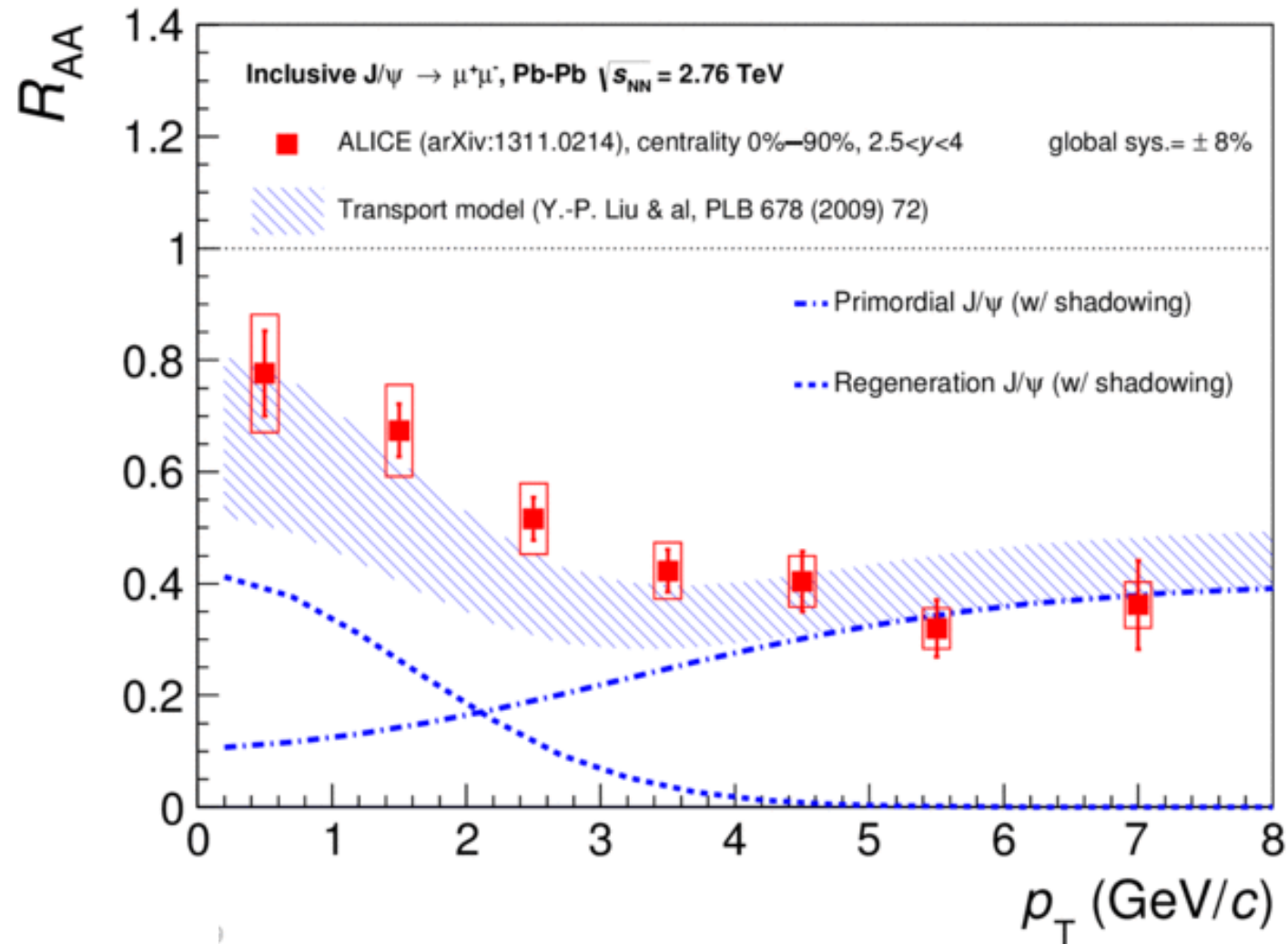
Contrary to the suppression / melting scenario, these approaches may lead to J/ψ enhancement



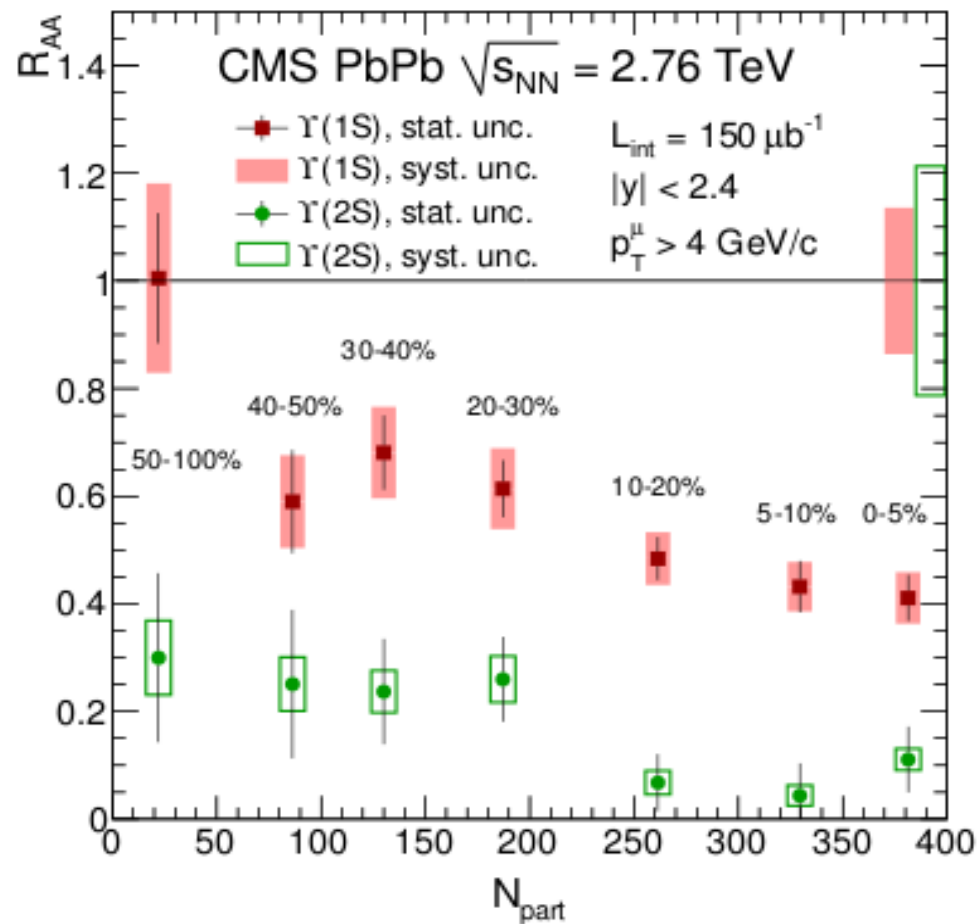
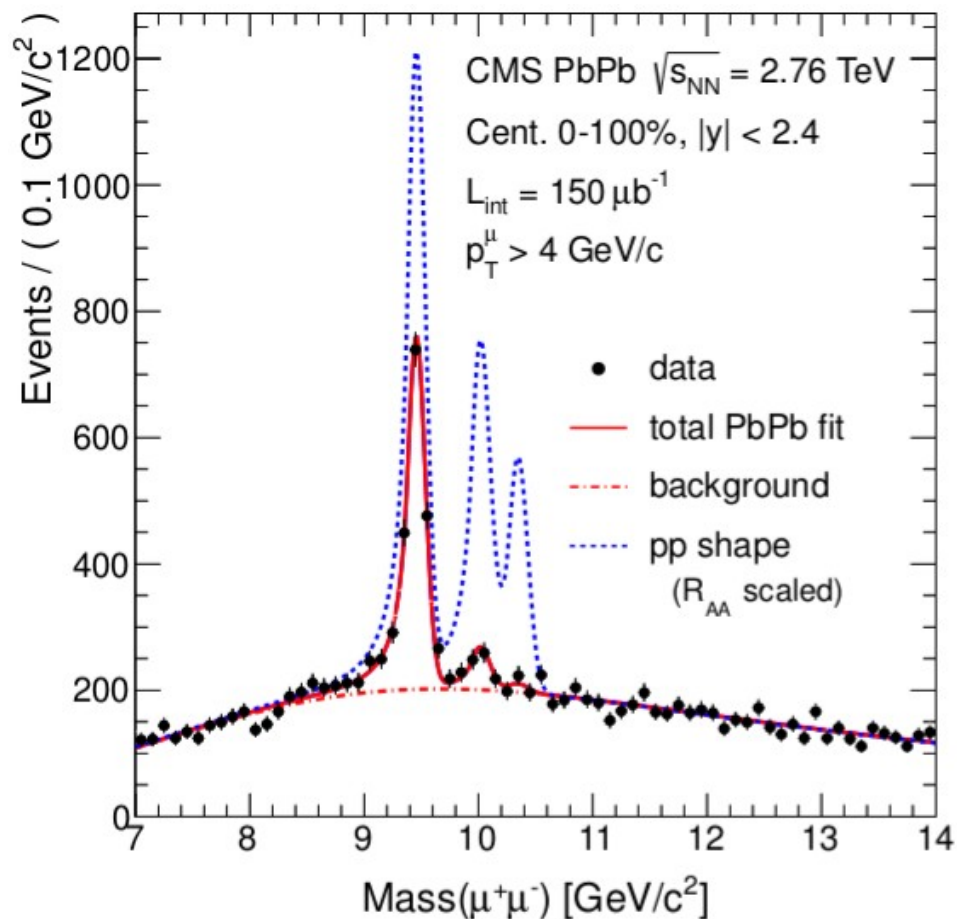
Different p_T (and centrality) dependence of J/ψ R_{AA} at LHC and RHIC

J/ψ production in Pb-Pb

arXiv:1311.0214

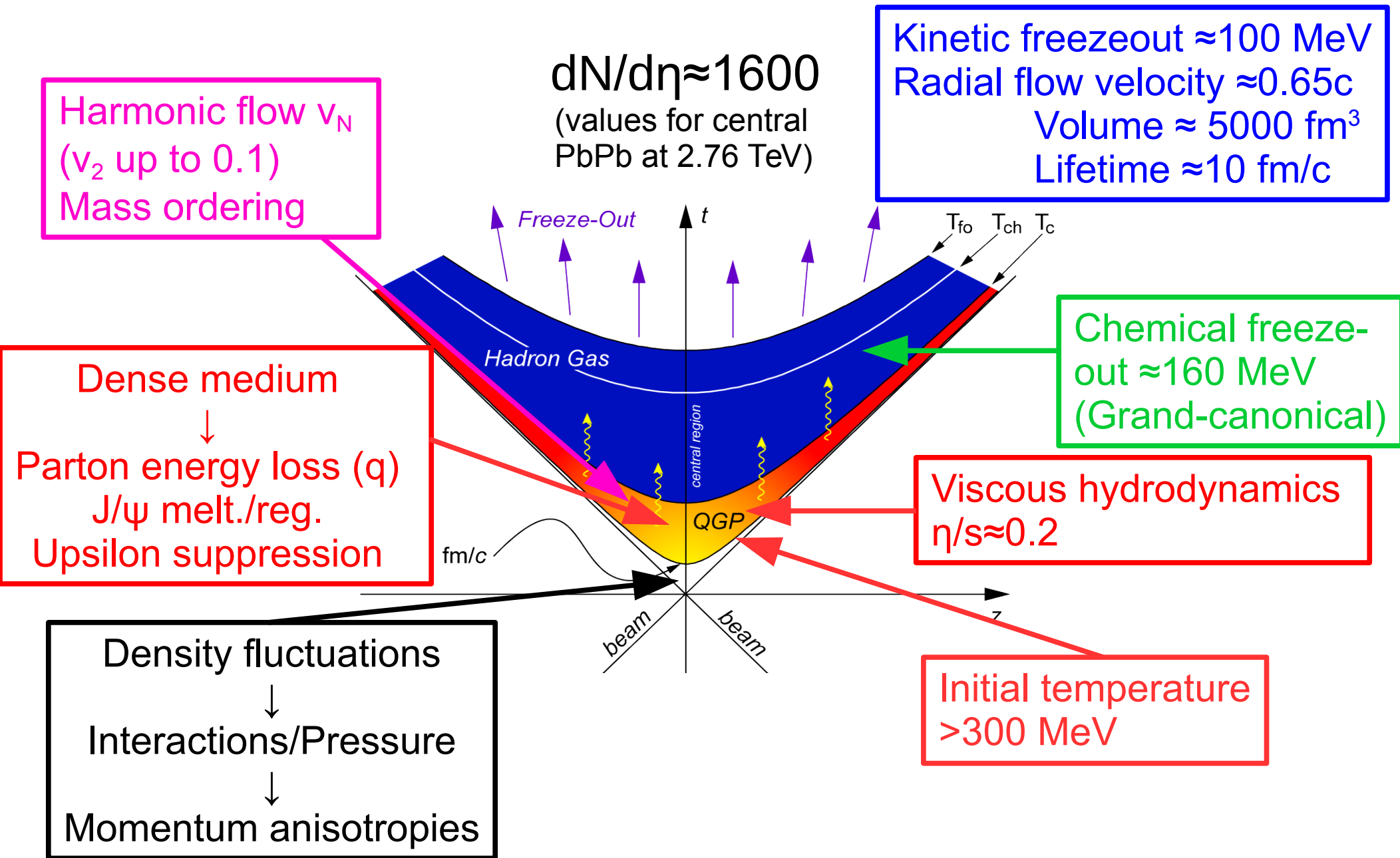


As expected in a scenario with $c\bar{c}$ recombination, especially at low p_T



Suppression of $\Upsilon(1S)$ ground, and excited $\Upsilon(2S)$ and $\Upsilon(3S)$ 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)



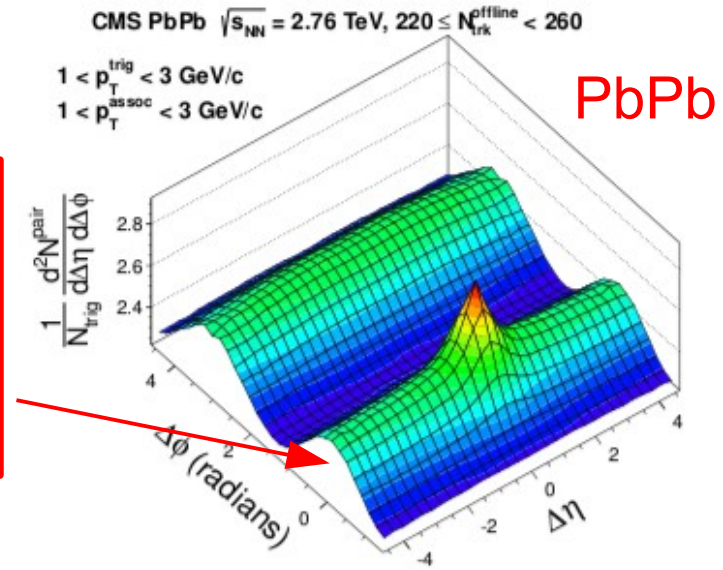
All observations (+ absence in control systems) point to the formation of hot deconfined matter!

Collectivity in small systems

Two-particle angular correlations

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

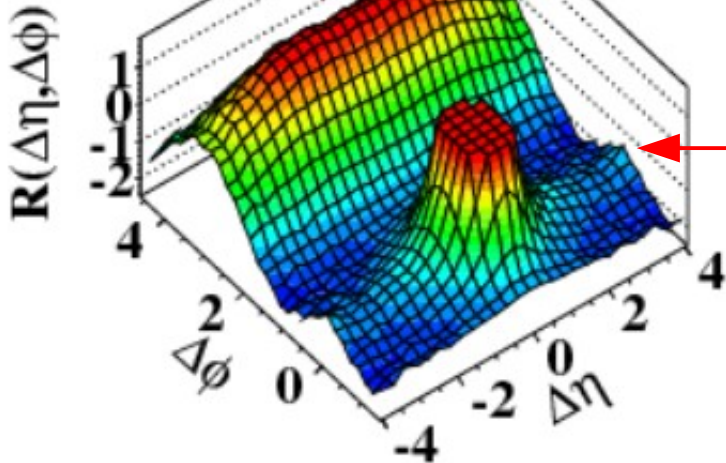


CMS, PLB 724 (2013) 213

Two-particle angular correlations

CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$
(0.0005% of MB)

pp



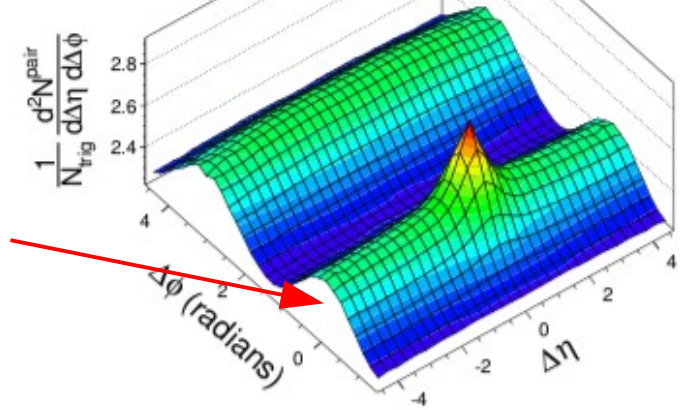
CMS, JHEP 1009 (2010) 91

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

CMS PbPb $\sqrt{s_{NN}} = 2.76 \text{ TeV}$, $220 \leq N_{trk}^{offline} < 260$

$1 < p_T^{trig} < 3 \text{ GeV}/c$
 $1 < p_T^{assoc} < 3 \text{ GeV}/c$

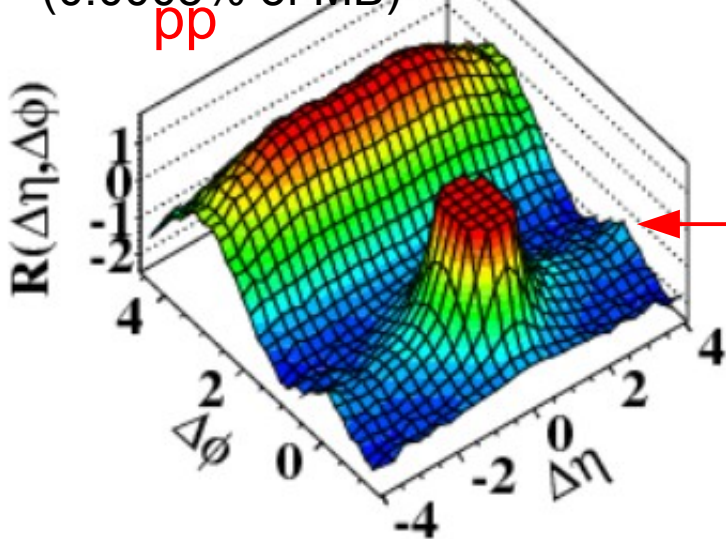
PbPb



CMS, PLB 724 (2013) 213

Two-particle angular correlations

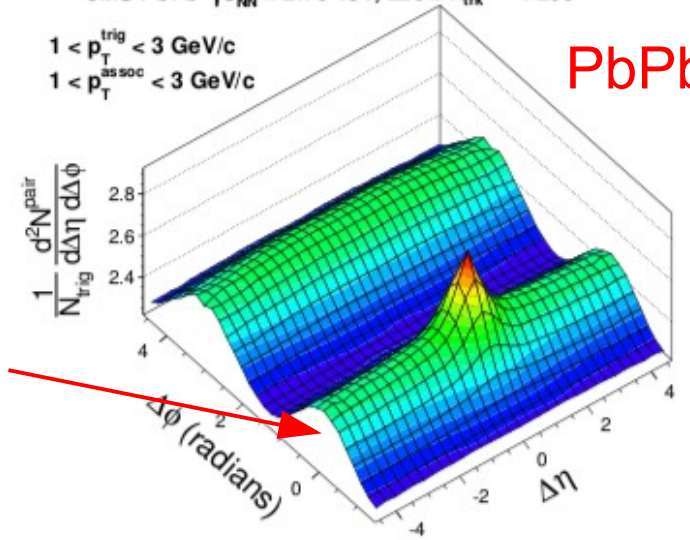
CMS N ≥ 110, 1.0 GeV/c < p_T < 3.0 GeV/c
(0.0005% of MB)



CMS, JHEP 1009 (2010) 91

CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 \leq N_{trk}^{offline} < 260$

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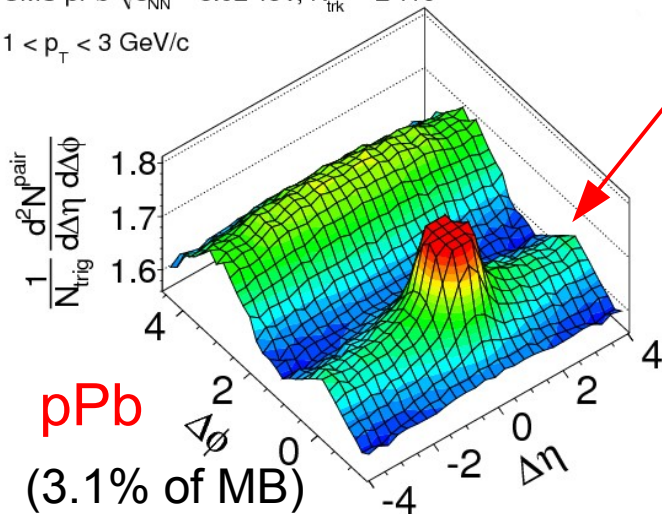


PbPb

CMS, PLB 724 (2013) 213

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

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{trk}^{offline} \geq 110$
 $1 < p_T < 3$ GeV/c

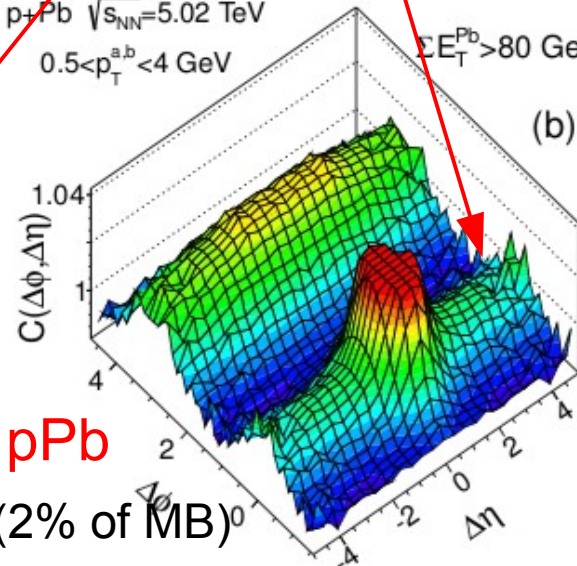


pPb

(3.1% of MB)

CMS, PLB 718 (2012) 795

p+Pb $\sqrt{s_{NN}} = 5.02$ TeV
 $0.5 < p_T^{a,b} < 4$ GeV
 $\Sigma E_T^{Pb} > 80$ GeV



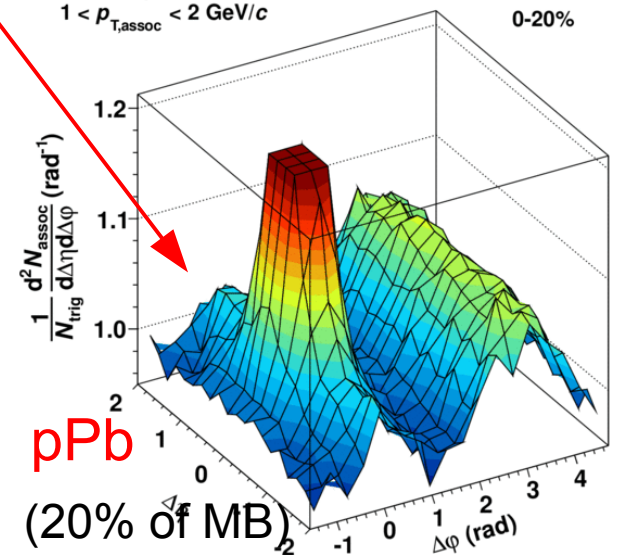
pPb

(2% of MB)

ATLAS, PRL 110 (2013) 182302

$2 < p_{T,trig} < 4$ GeV/c
 $1 < p_{T,assoc} < 2$ GeV/c

p-Pb $\sqrt{s_{NN}} = 5.02$ TeV
0-20%



pPb

(20% of MB)

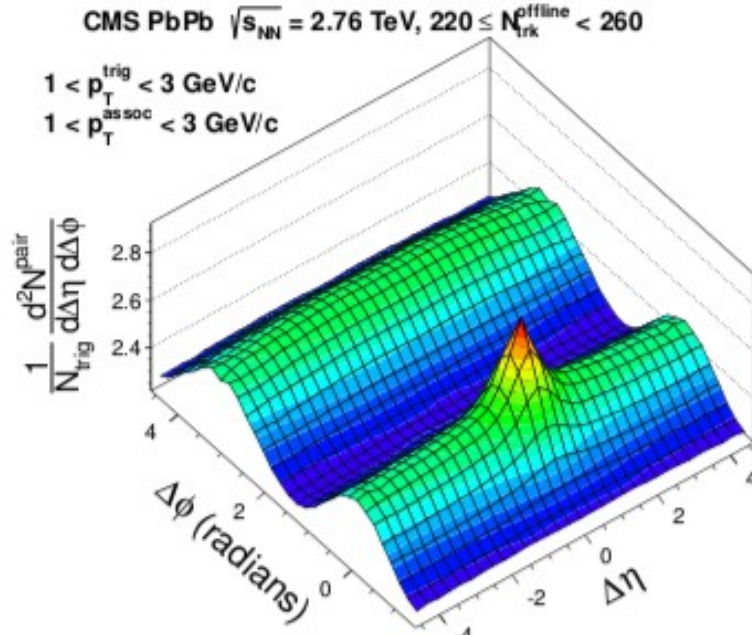
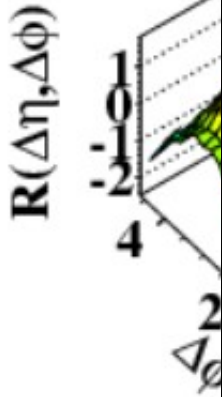
ALICE, PLB 719 (2013) 29

Two-particle angular correlations

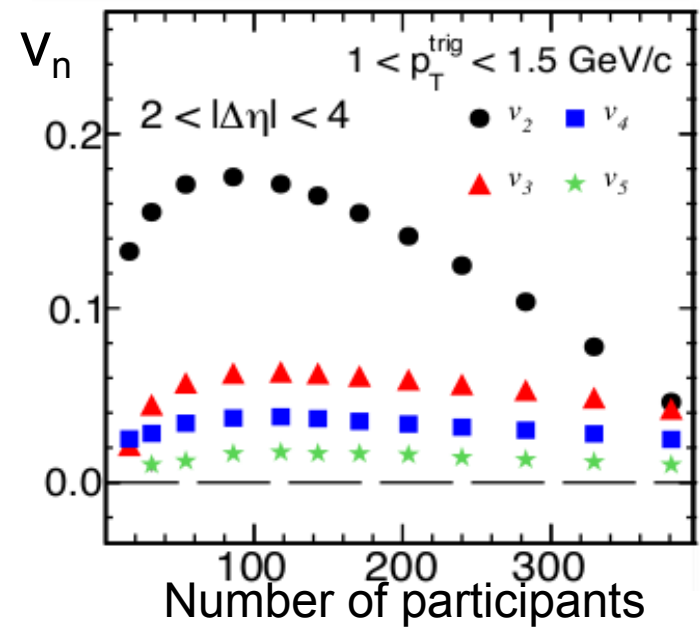
CMS $N \geq 110, 1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

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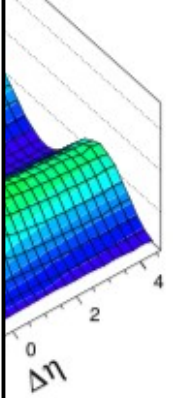
pp



CMS, EPJC 72 (2012) 10052



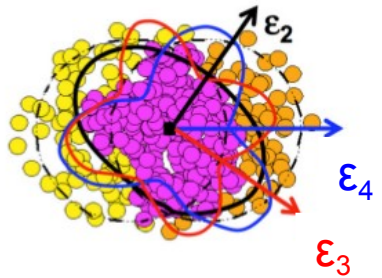
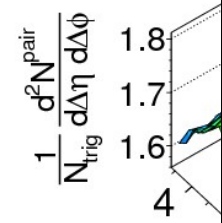
PbPb



CMS,

CMS pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

$1 < p_T < 3 \text{ GeV}/c$

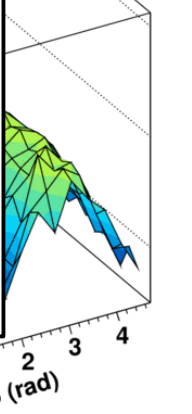


$$\frac{dN}{d\varphi} \sim 1 + 2v_2 \cos[2(\varphi - \psi_2)] + 2v_3 \cos[3(\varphi - \psi_3)] + 2v_4 \cos[4(\varphi - \psi_4)] + 2v_5 \cos[5(\varphi - \psi_5)] + \dots$$

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

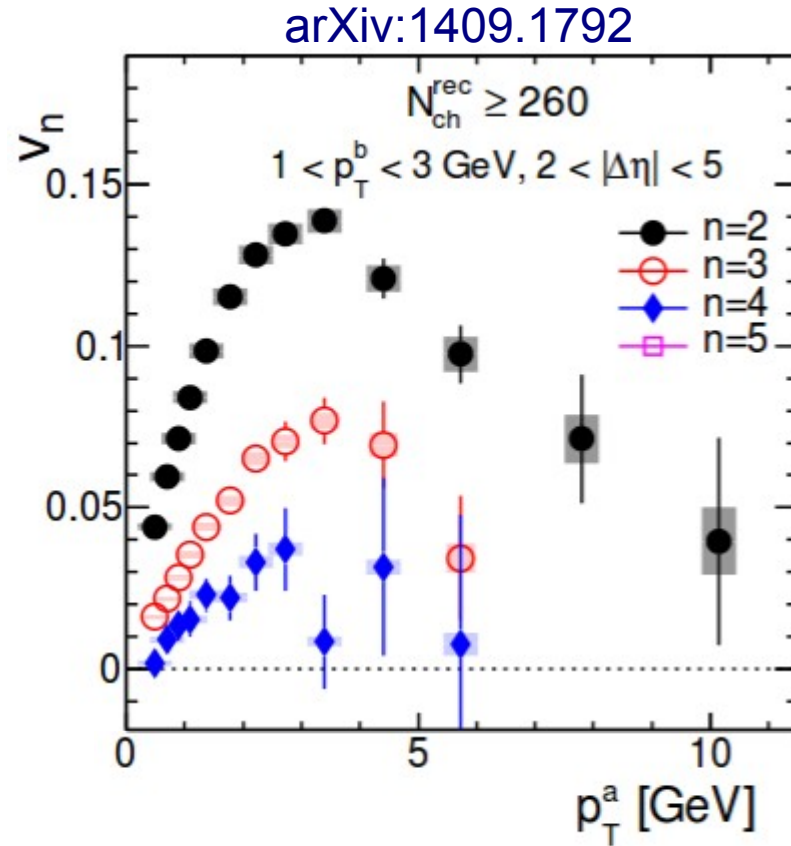
013) 213

Pb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$
0-20%

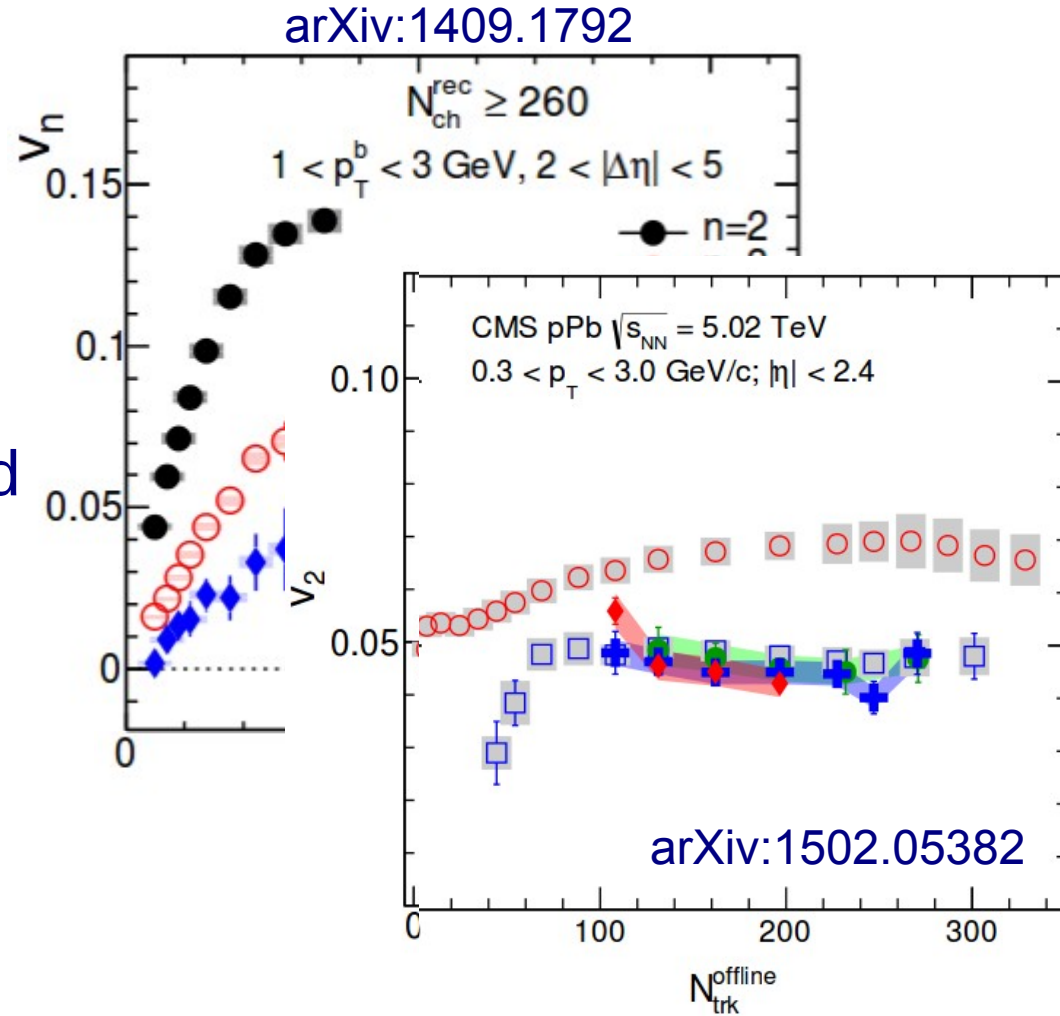


Ridge properties in pPb

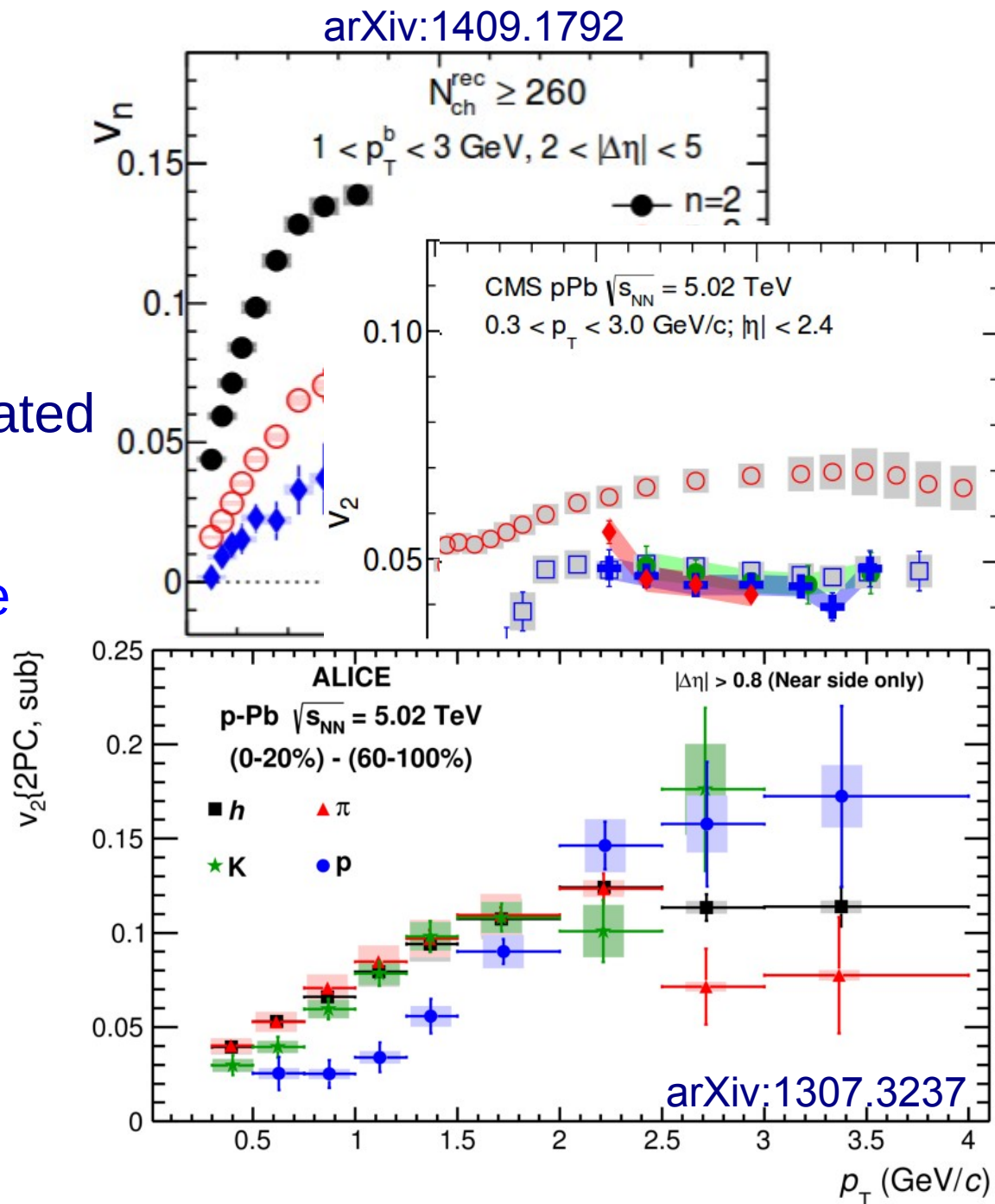
- v_n coefficients
 - Significant for $n=2$ to 5
 - Substantial to even high p_T



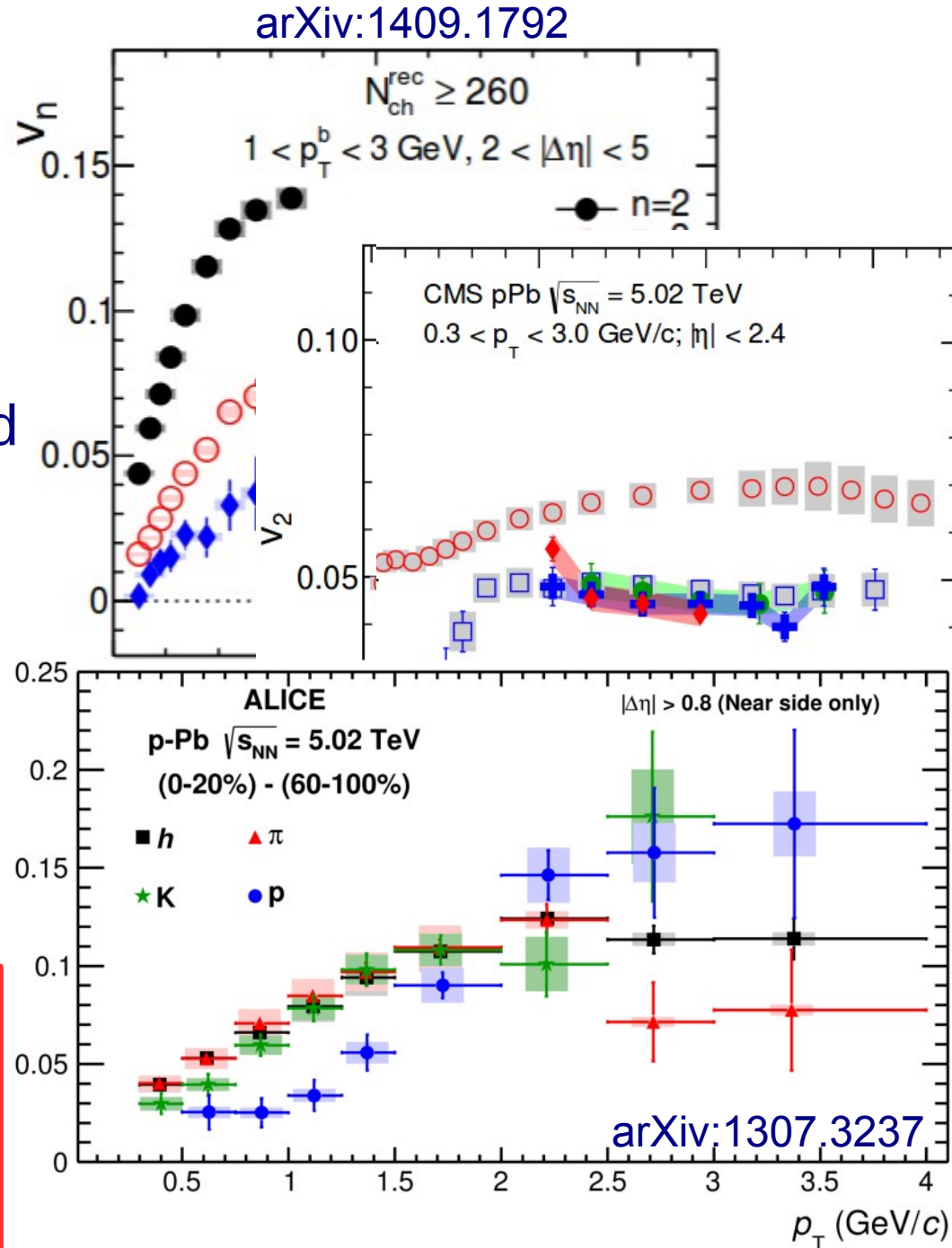
- v_n coefficients
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- Multiparticle correlations
 - At least 8 particles correlated
 - $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$



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- Particle species dependence
 - Cross of v_2 (proton) with v_2 (pion) at about 2 GeV/c for $p_T < 2$ GeV/c



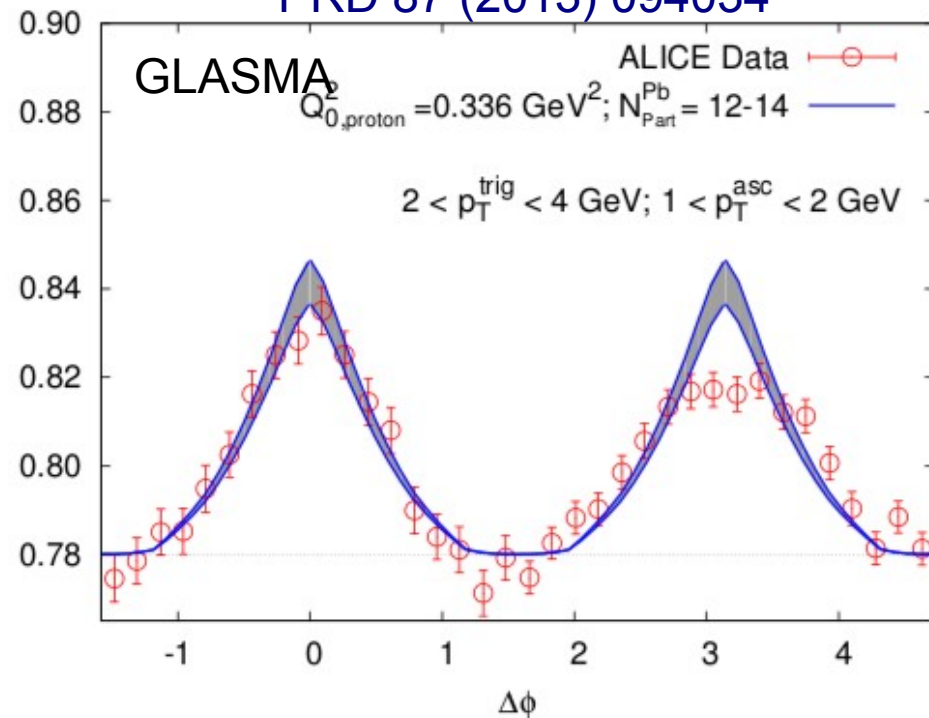
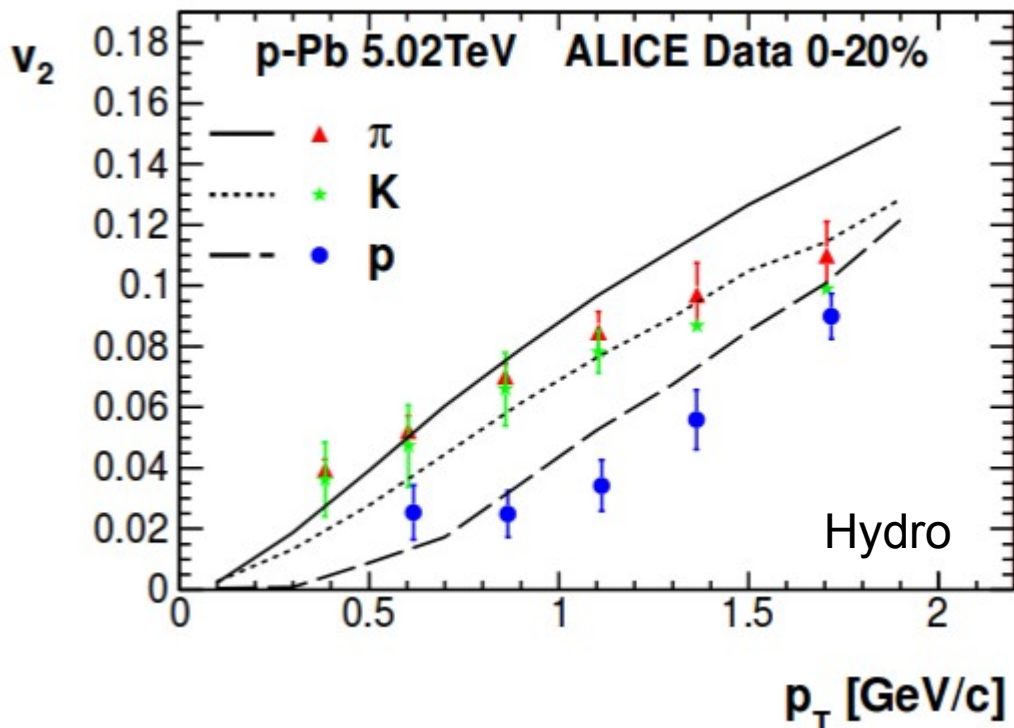
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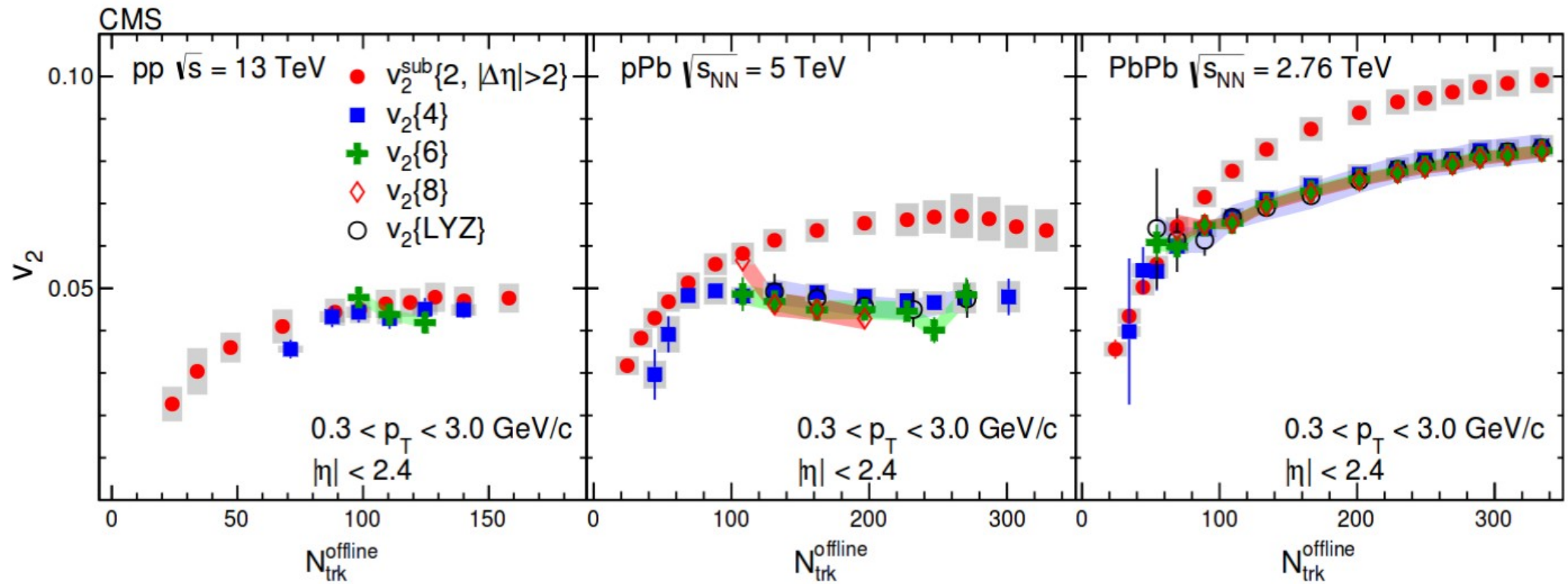
Features qualitatively similar to those seen in PbPb collisions. Suggests same physics at place?
 arXiv:1602.09138

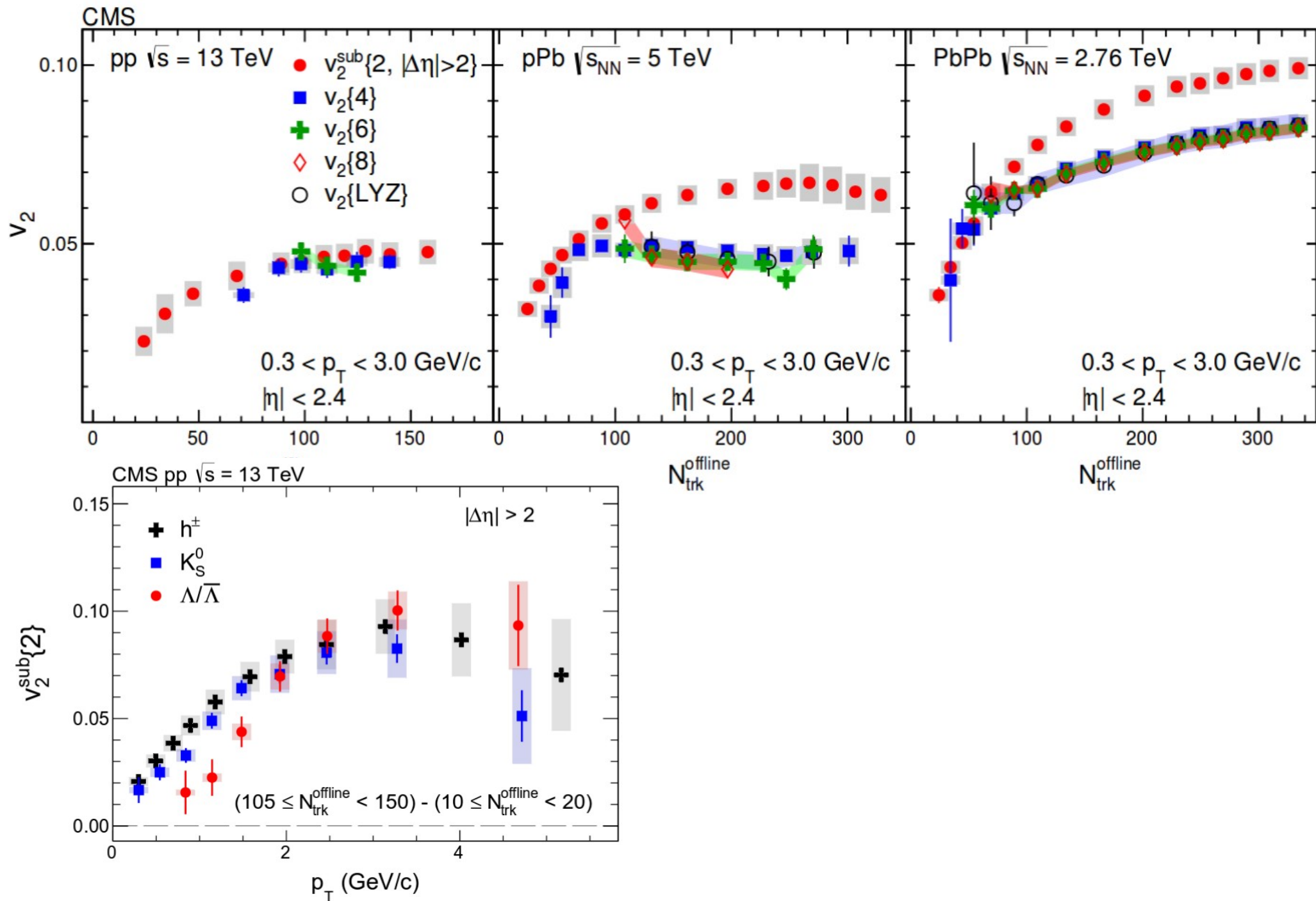
arXiv:1307.5060

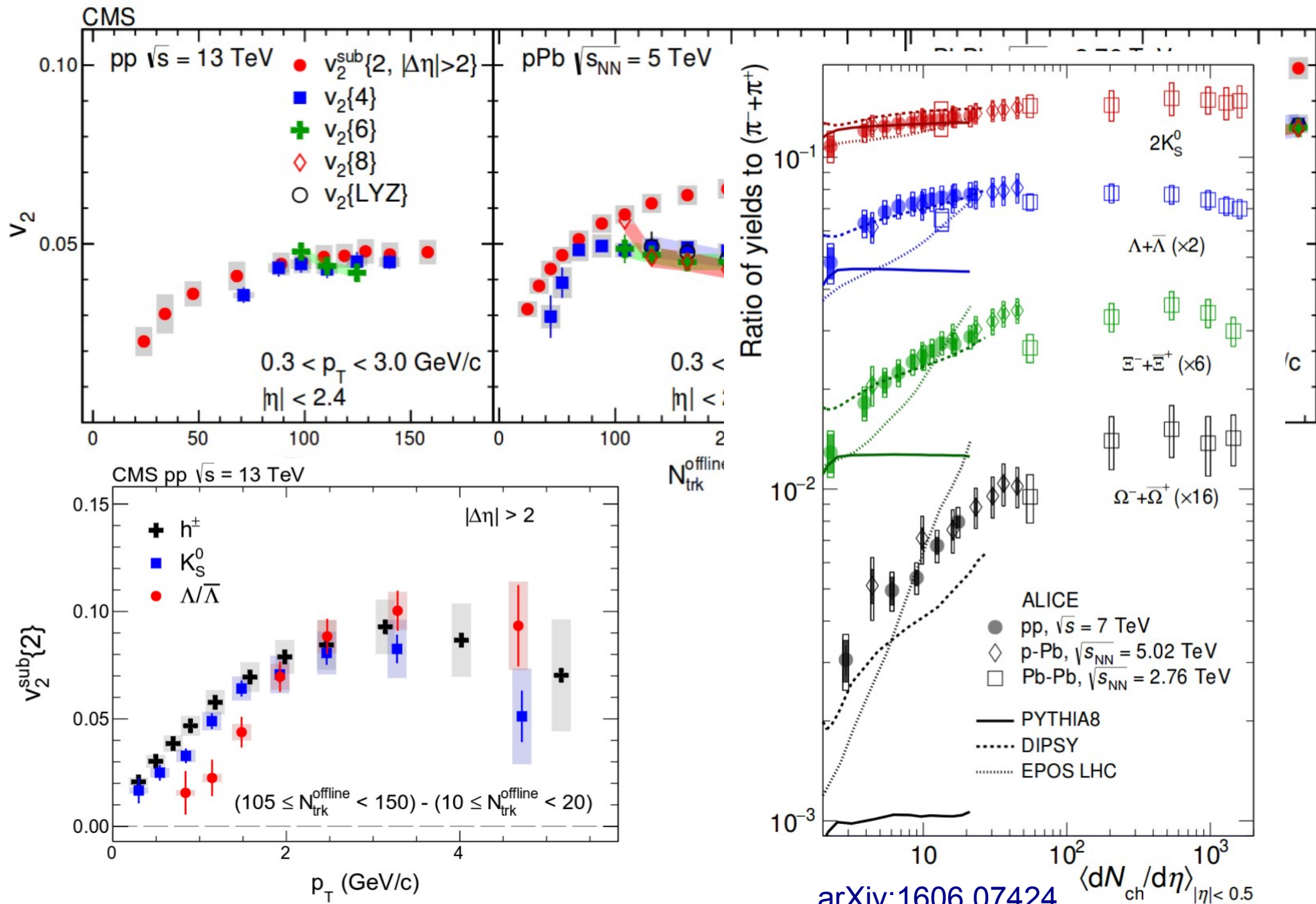
PRD 87 (2013) 094034



- 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)

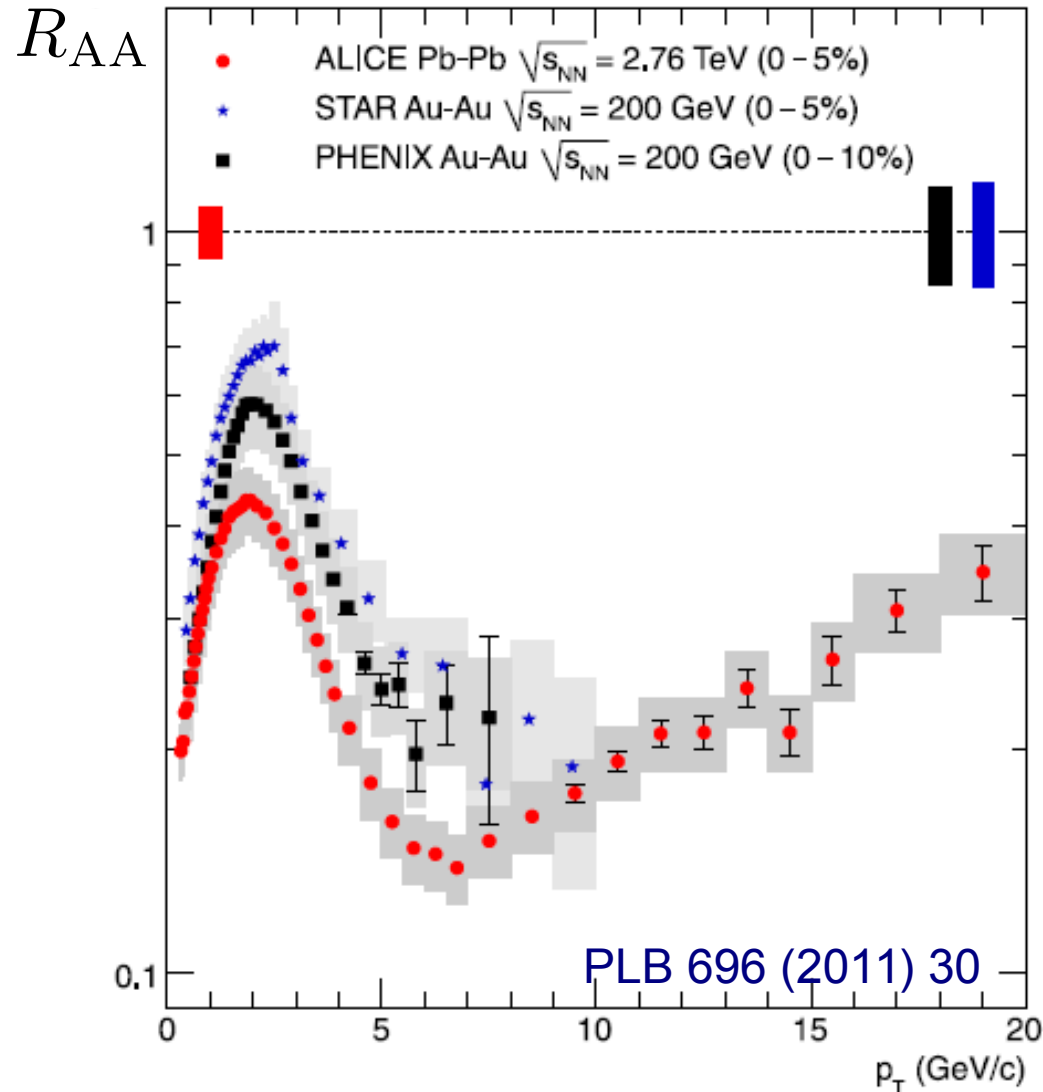






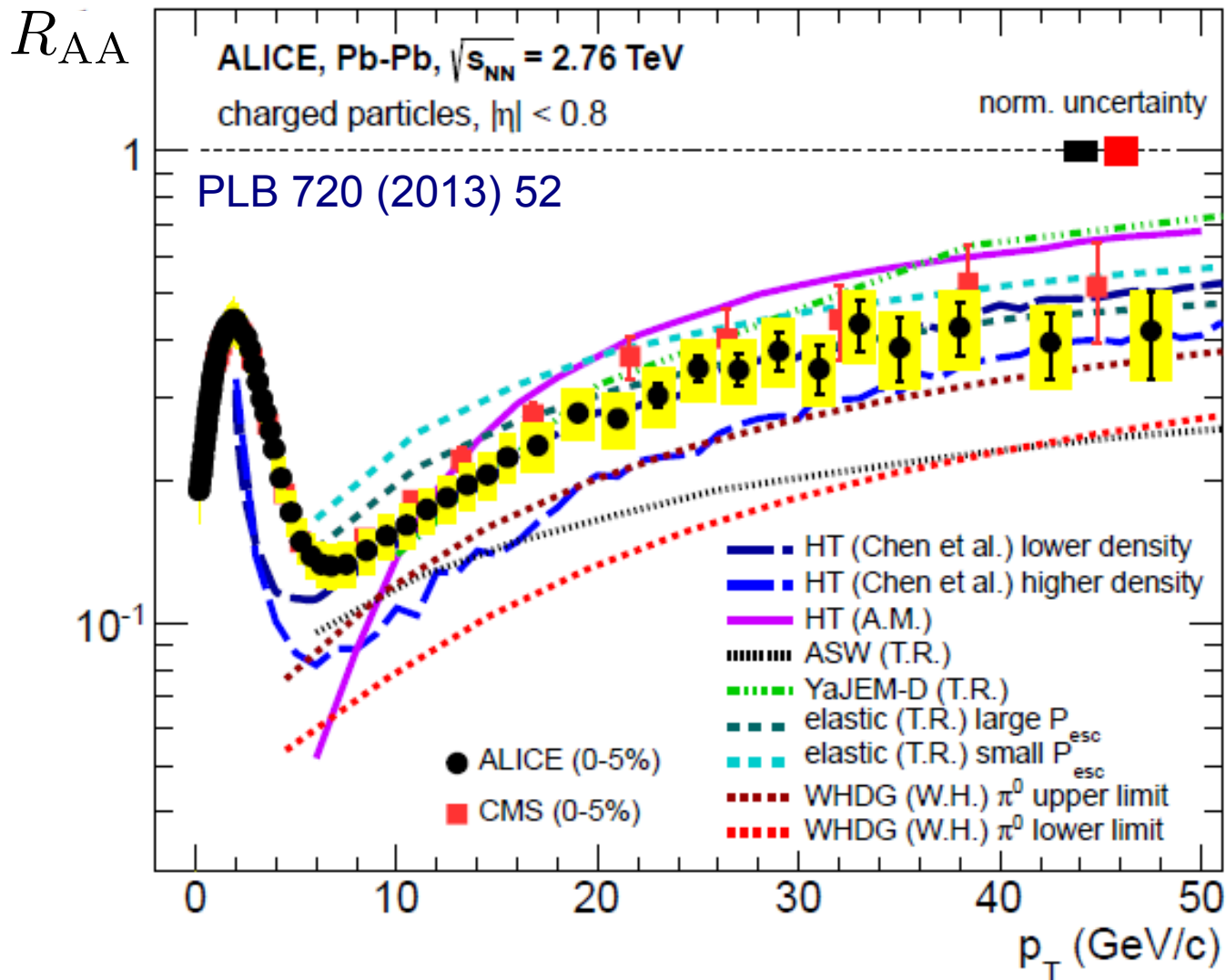
- QCD is a quantum field theory with rich dynamical content, complex phase structure, and important open questions
- Heavy-ion collision experiments attempt to create and probe QCD matter at high temperature and energy density
- The medium (at RHIC/LHC) behaves almost like a perfect fluid with the characteristics 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”



- 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} : $\Delta E \sim \log(E)$ ok!

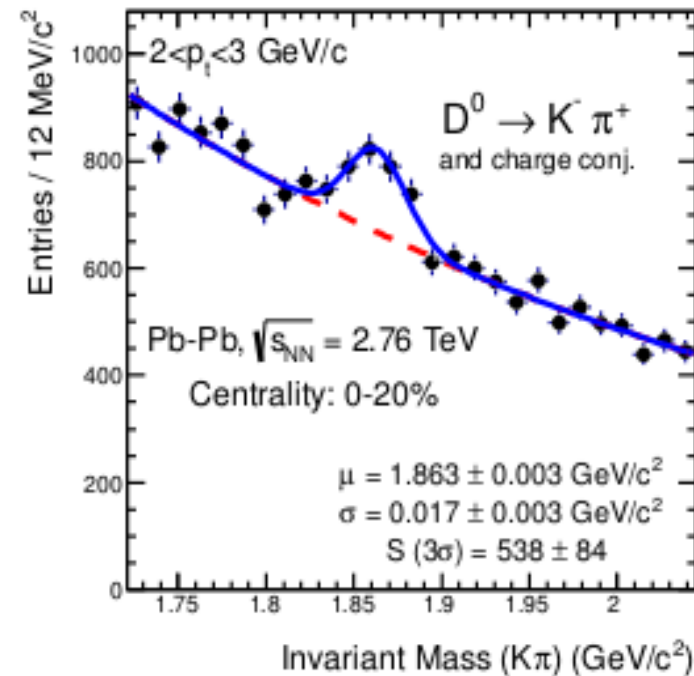
Various techniques for heavy flavor measurements

- 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 $\sim 100\mu\text{m}$ resolution)
 - Kaon identification (TOF, dE/dx)

Various techniques for heavy flavor measurements

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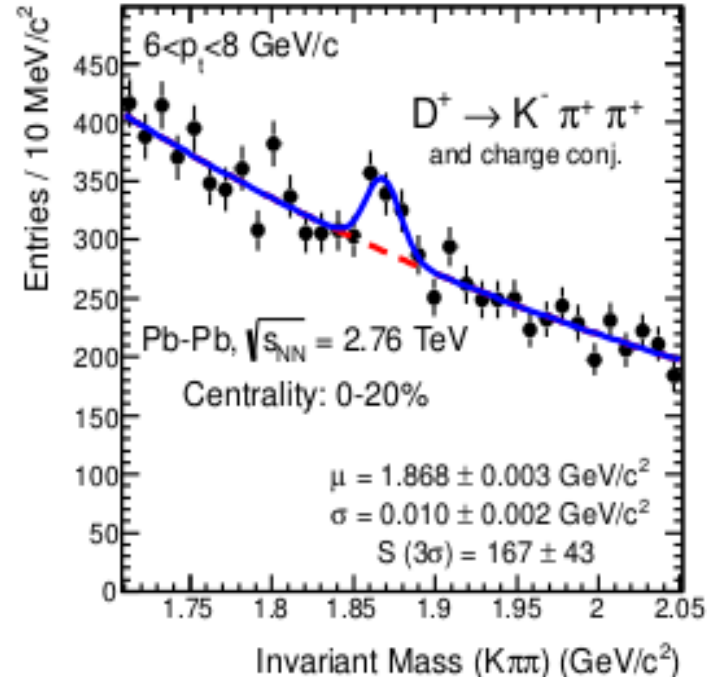
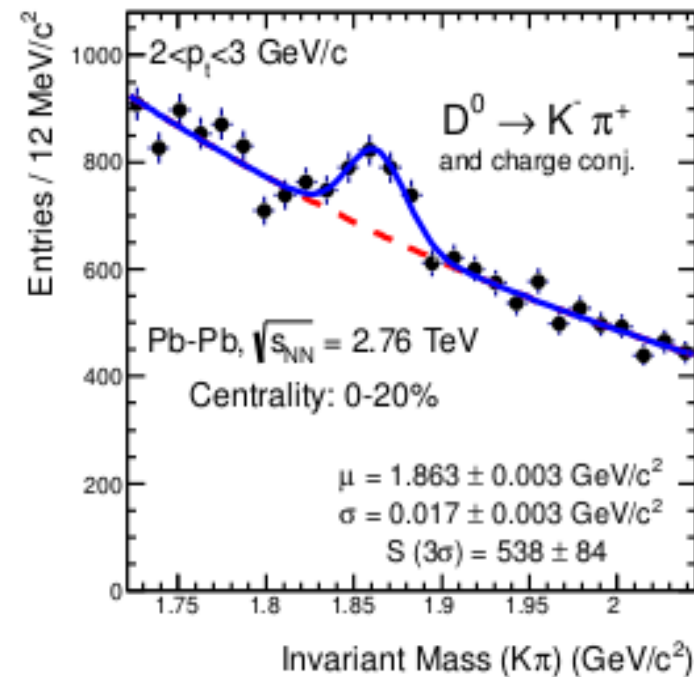
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Various techniques for heavy flavor measurements

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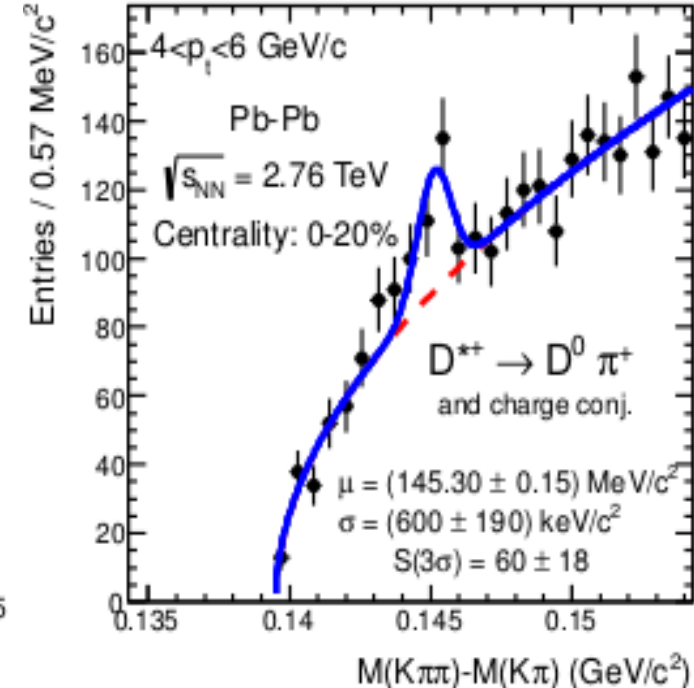
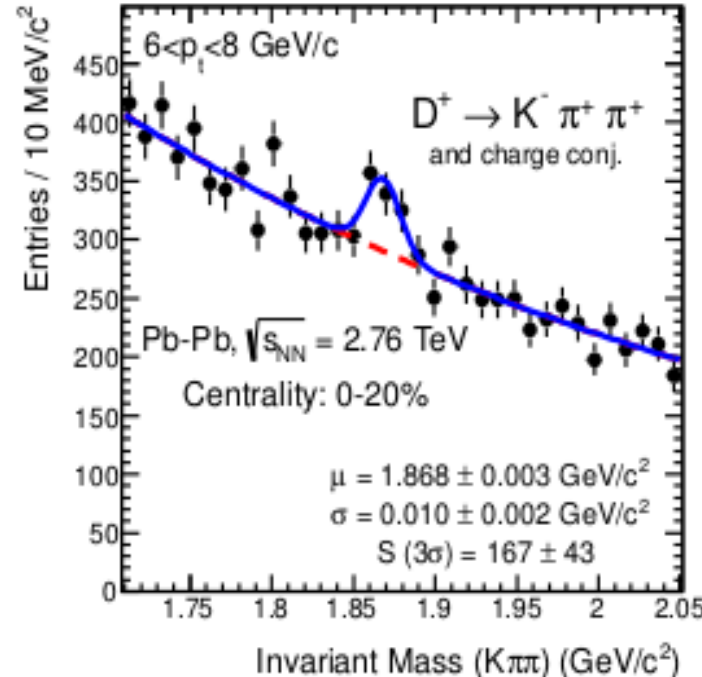
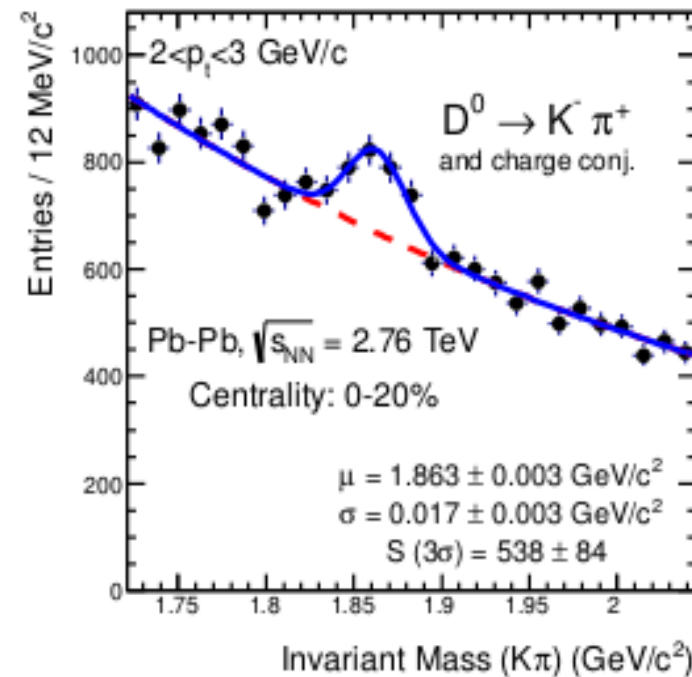
- Indirect measurement via non-photonic electrons
 - Exploit semi-leptonic decay channels of heavy quark mesons
- Direct reconstruction of hadronic decay channels
 - Fully combinatorial analysis (build all pairs/triplets etc) unfeasible
 - Instead use invariant mass analysis of decay topologies separated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



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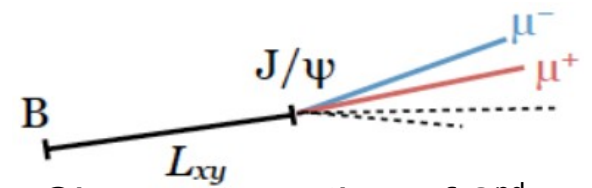
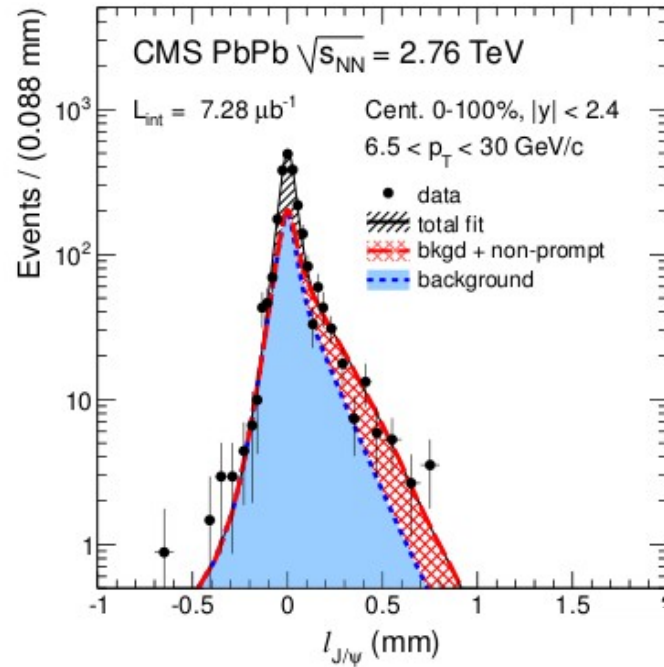
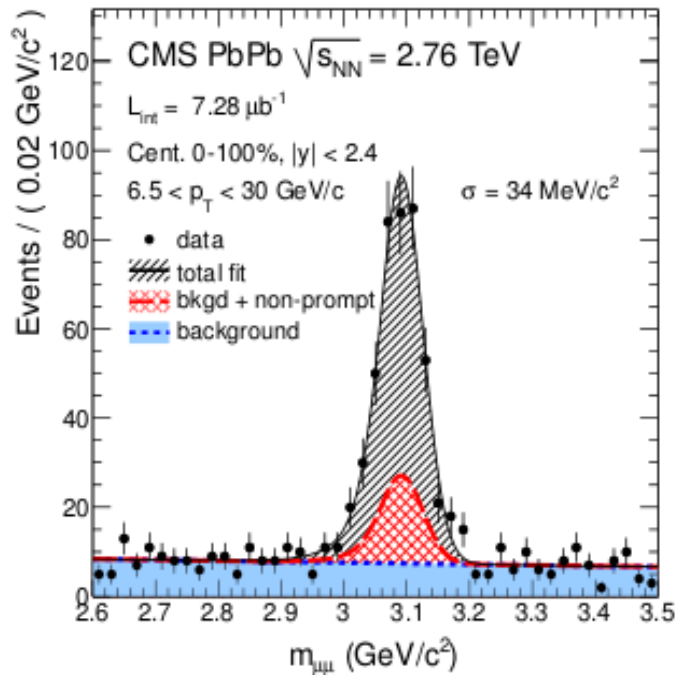


Beauty via displaced J/ψ

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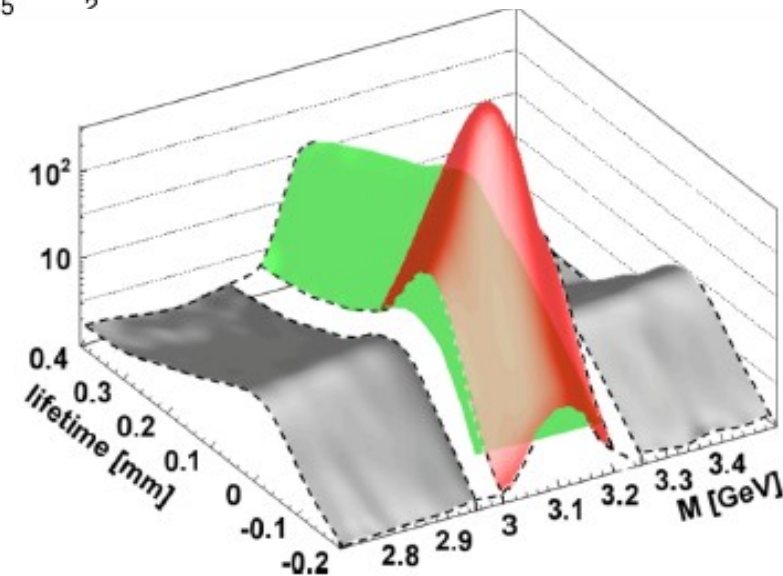
B mesons via secondary J/ψ:

CMS, JHEP 1205 (2012) 063



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

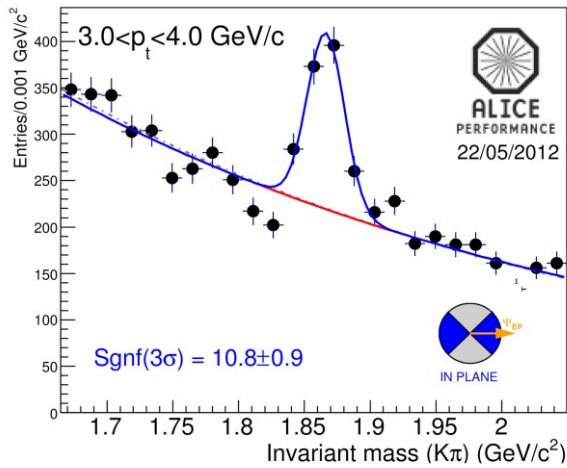
Fraction of non-prompt J/ψ from simultaneous fit to m^+m^- invariant mass spectrum and pseudo-proper decay length distributions (pioneered by CDF)



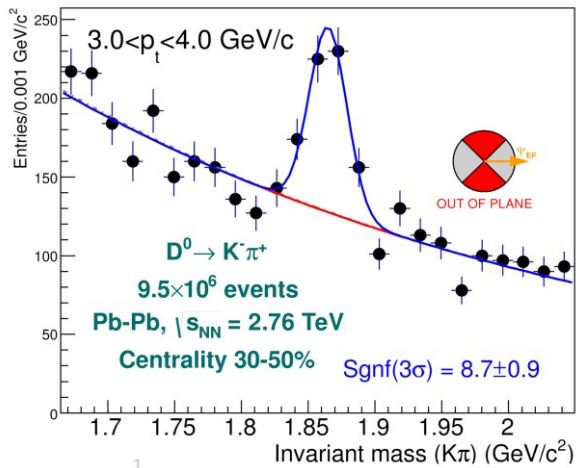
Heavy-quark v_2 at the LHC

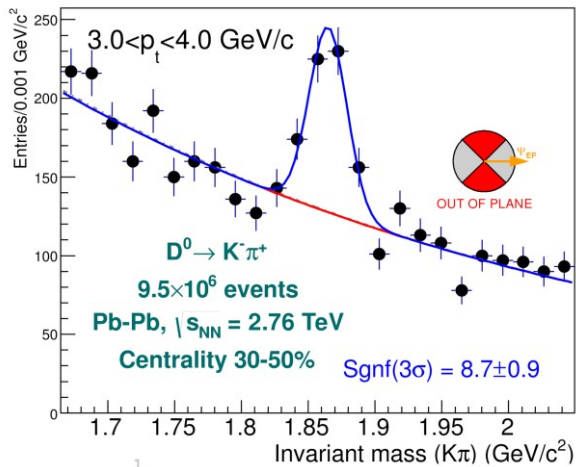
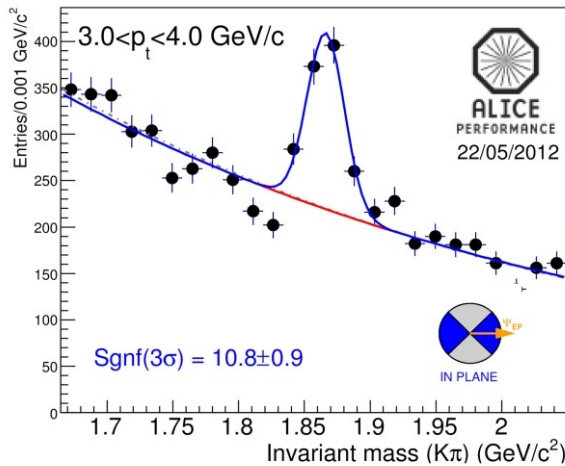
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arXiv:1405.2001

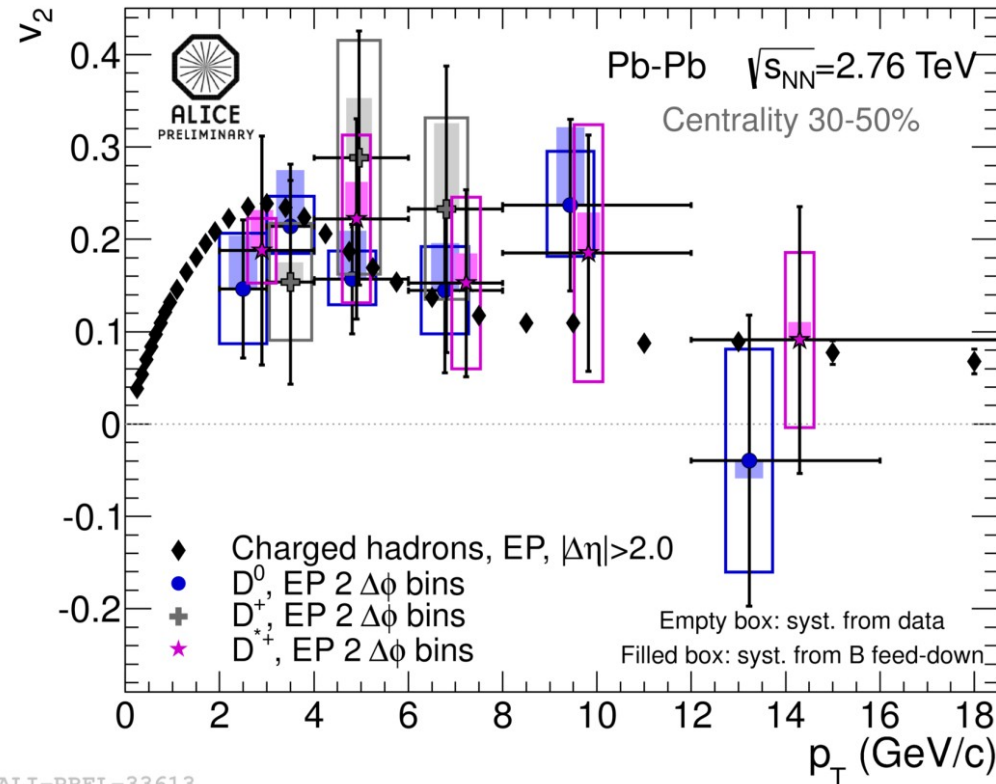


$$v_2 = \frac{1}{R_2} \frac{\pi}{4} \frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$



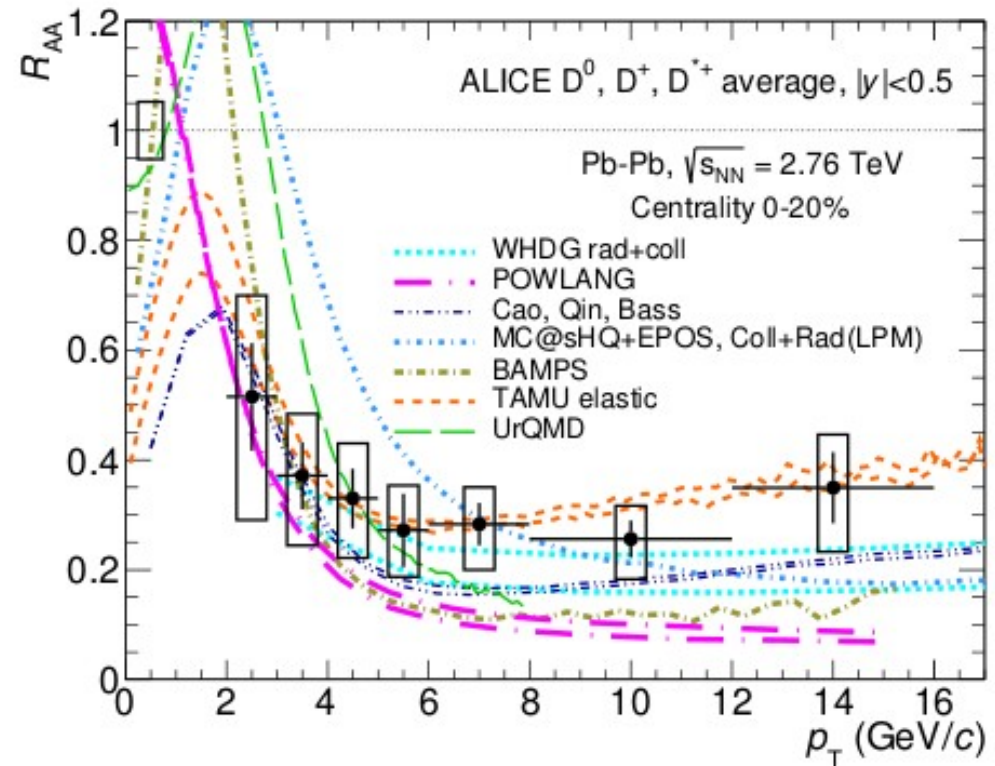
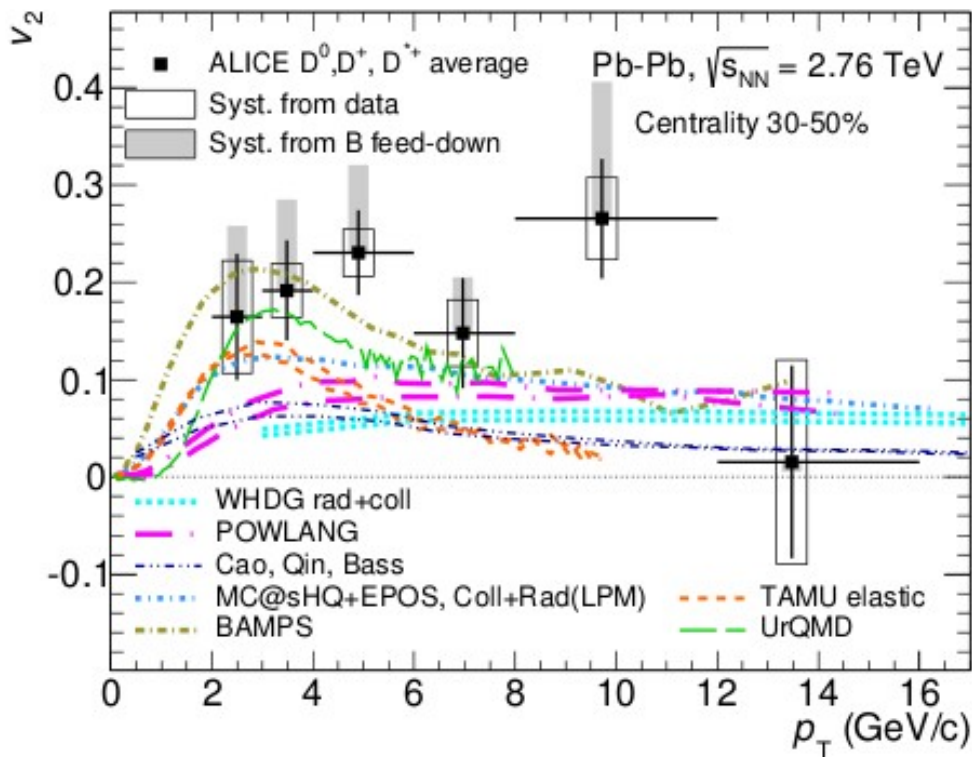


$$v_2 = \frac{1}{D} \frac{\pi}{A} \frac{N_{IN} - N_{OUT}}{\lambda_T}$$

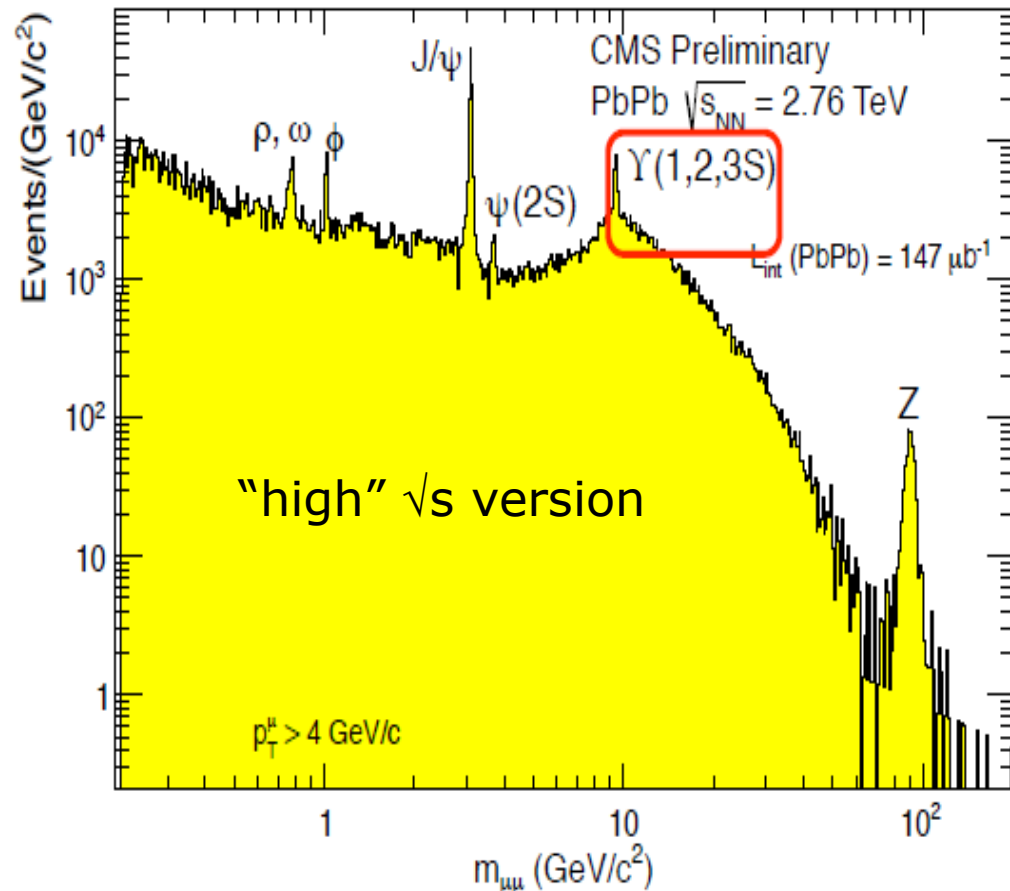
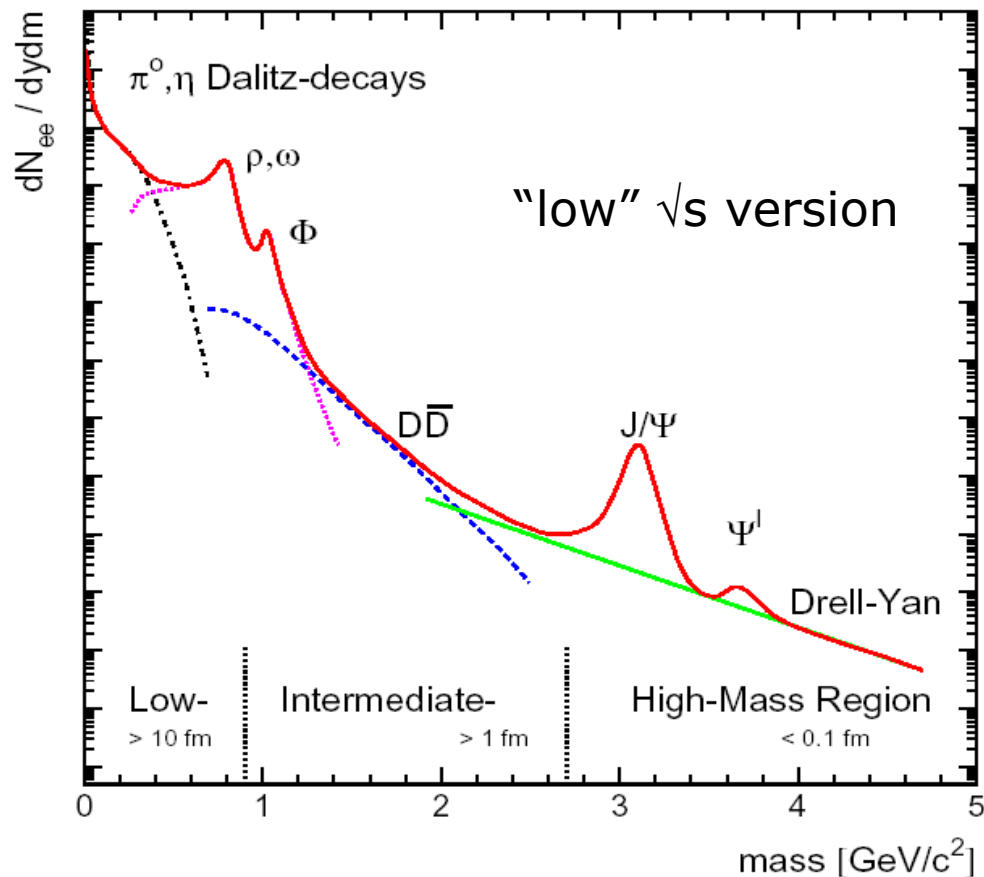


ALI-PREL-33613

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

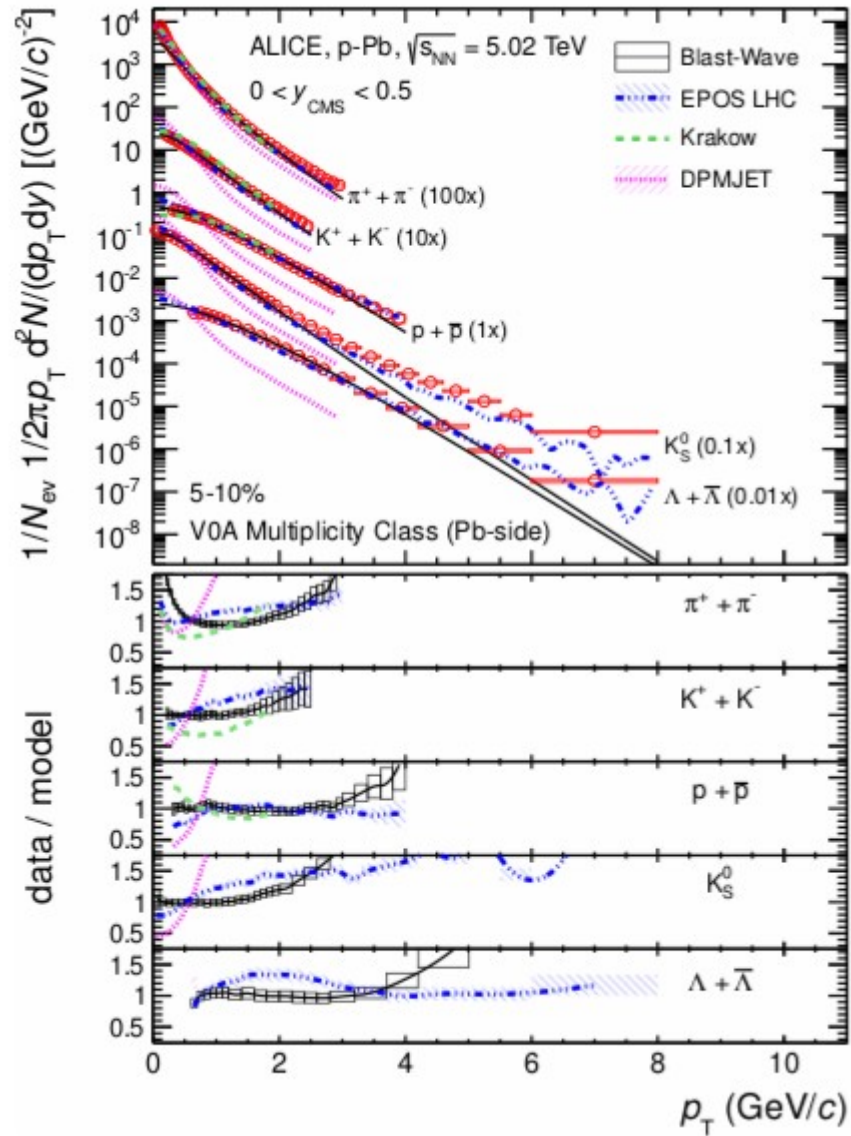


Consistent description of charm RAA and v_2 challenging for models. Can bring insight into medium transport properties, and with more data from future LHC runs.



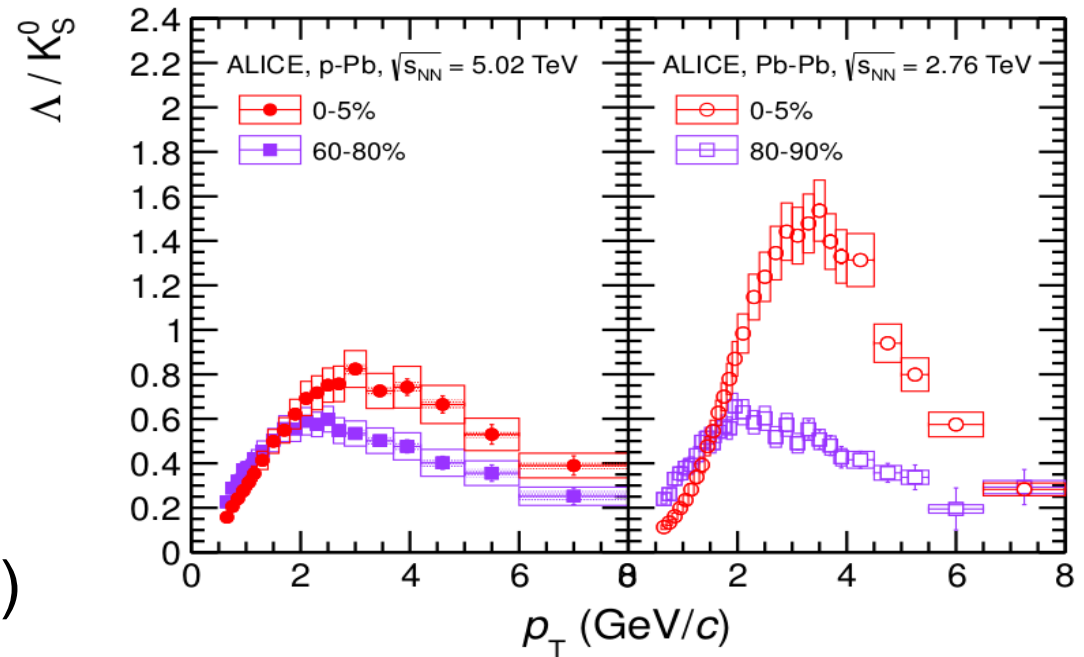
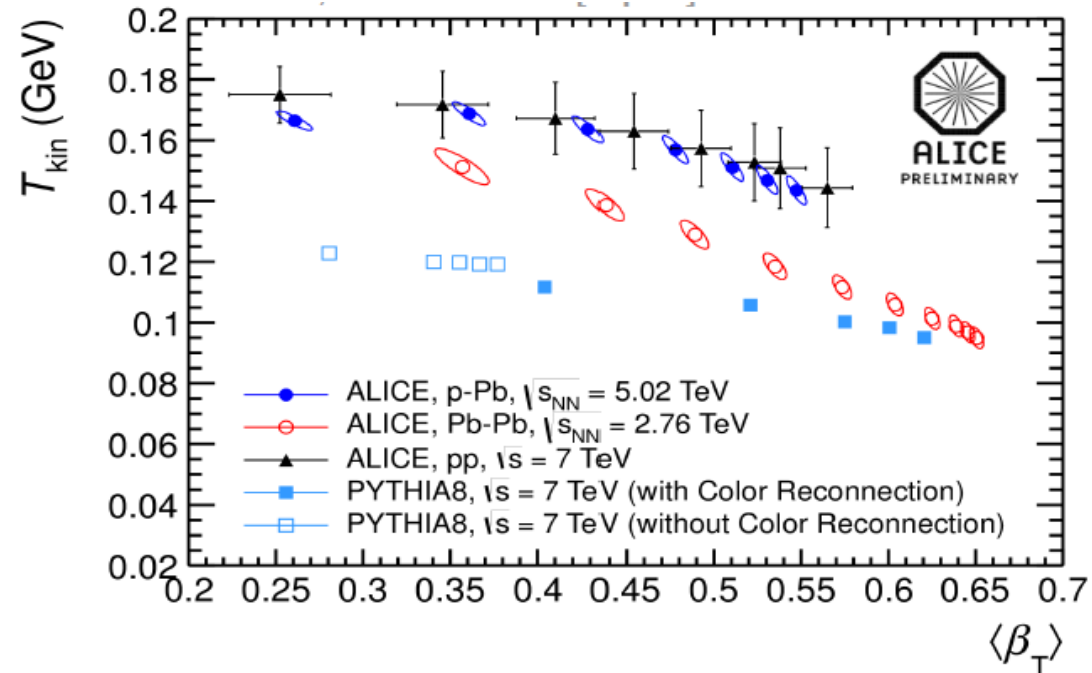
- The study of lepton pairs also allows to extract information about the early stages of the collision
- Dileptons (like photons) do not interact strongly and once produced can without significant re-interactions (not altered by later stages) escape the collision

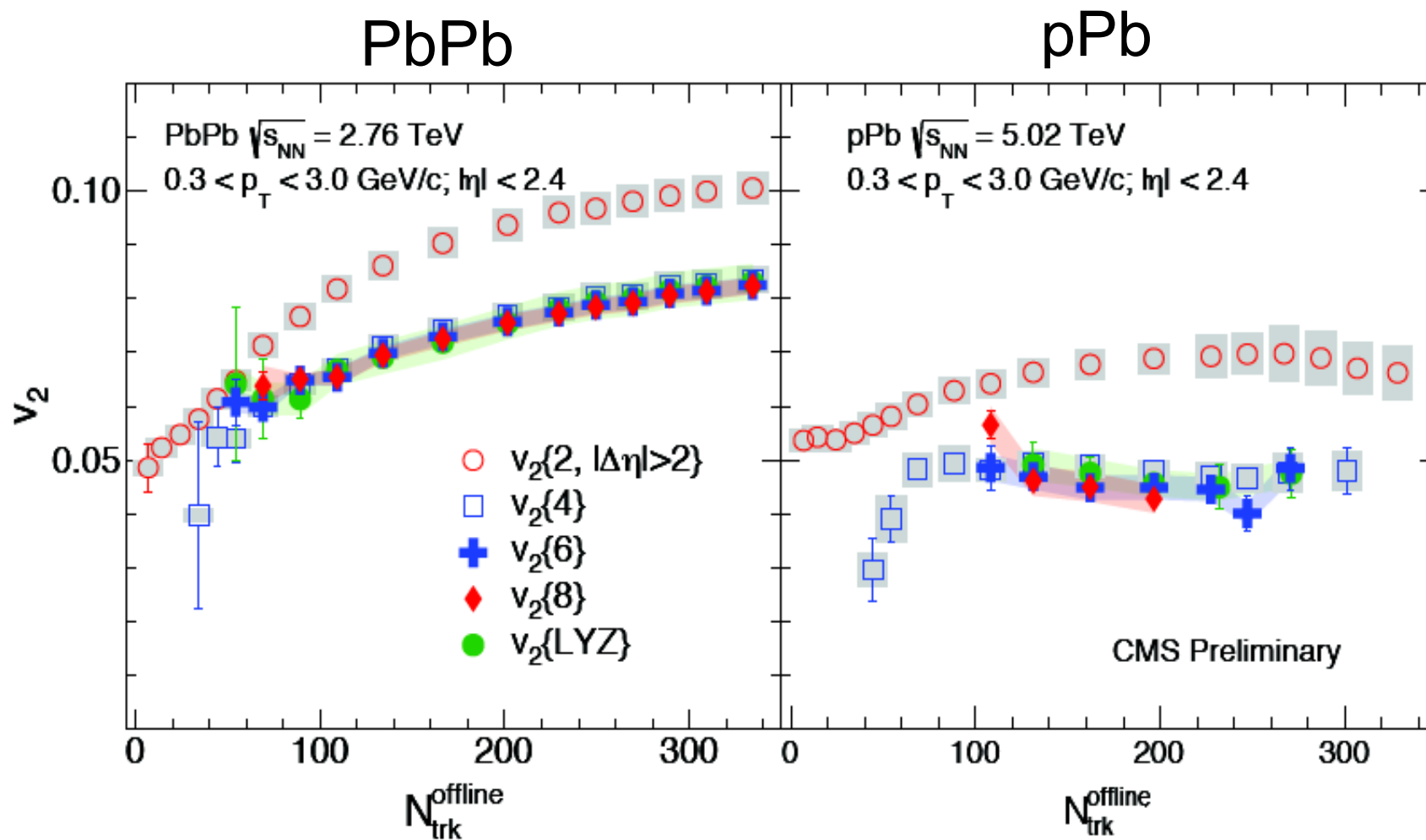
Identified particle spectra



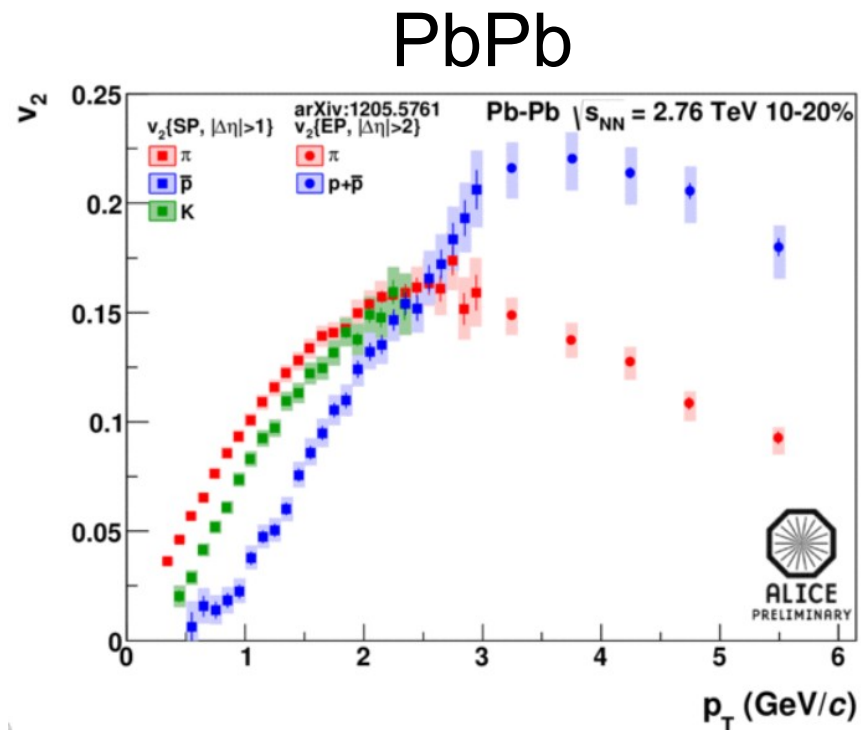
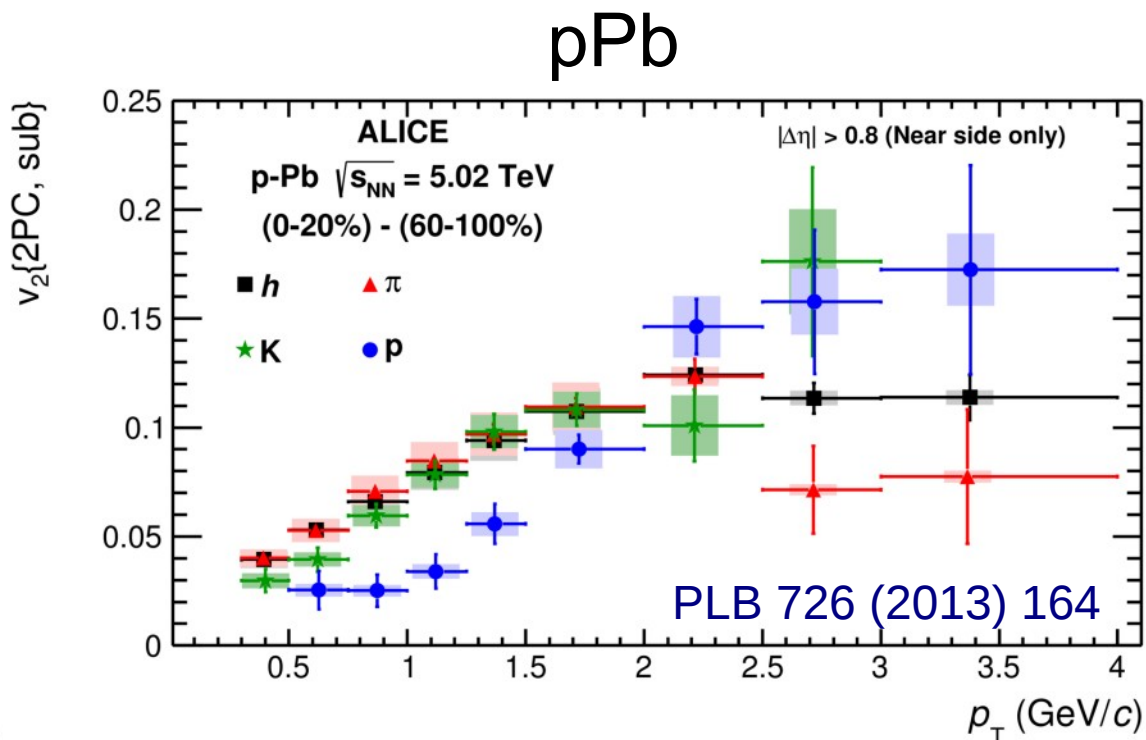
Spectra consistent with radial flow picture (also in pp)

ALICE, PLB 278 (2014) 25

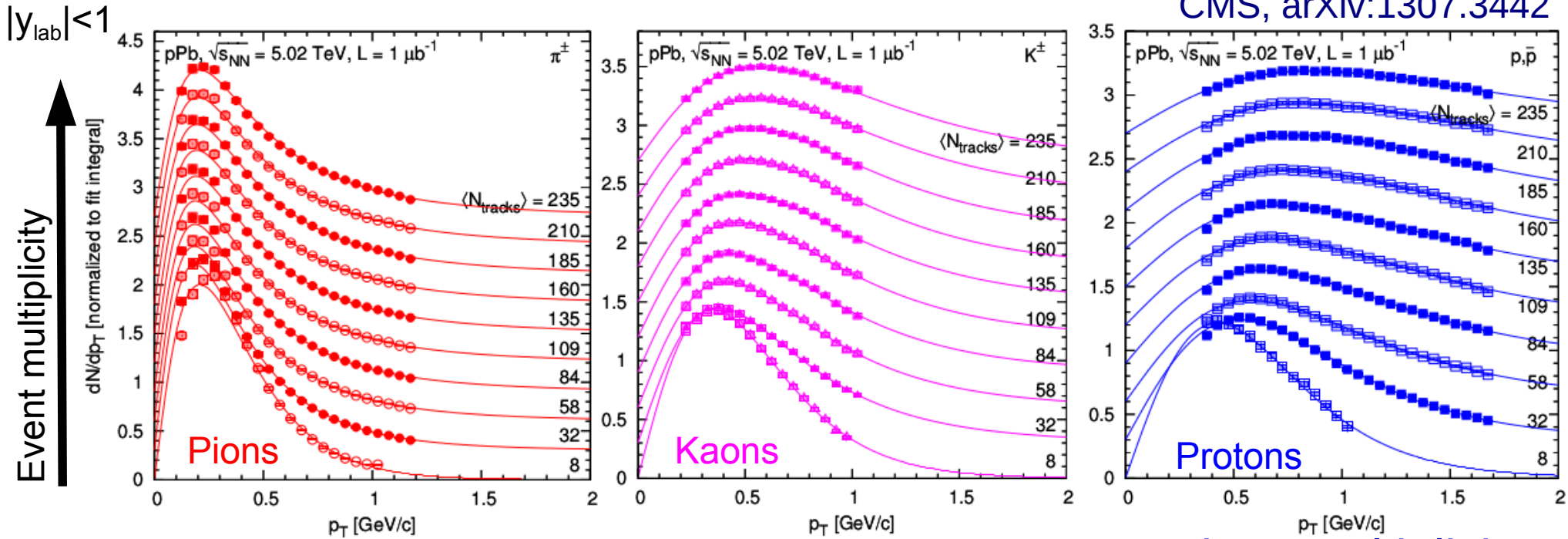




Multi-particle correlation results are the same within 10% in pPb



- 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



CMS, arXiv:1307.3442

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

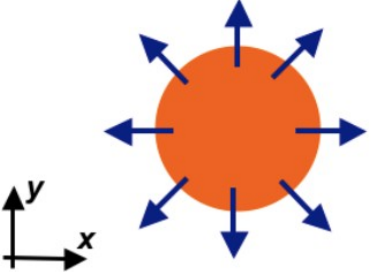
- Spectra measured vs. multiplicity
 - For kaons and more for protons shape changes with increasing multiplicity
 - As expected from radial flow

Radial flow

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

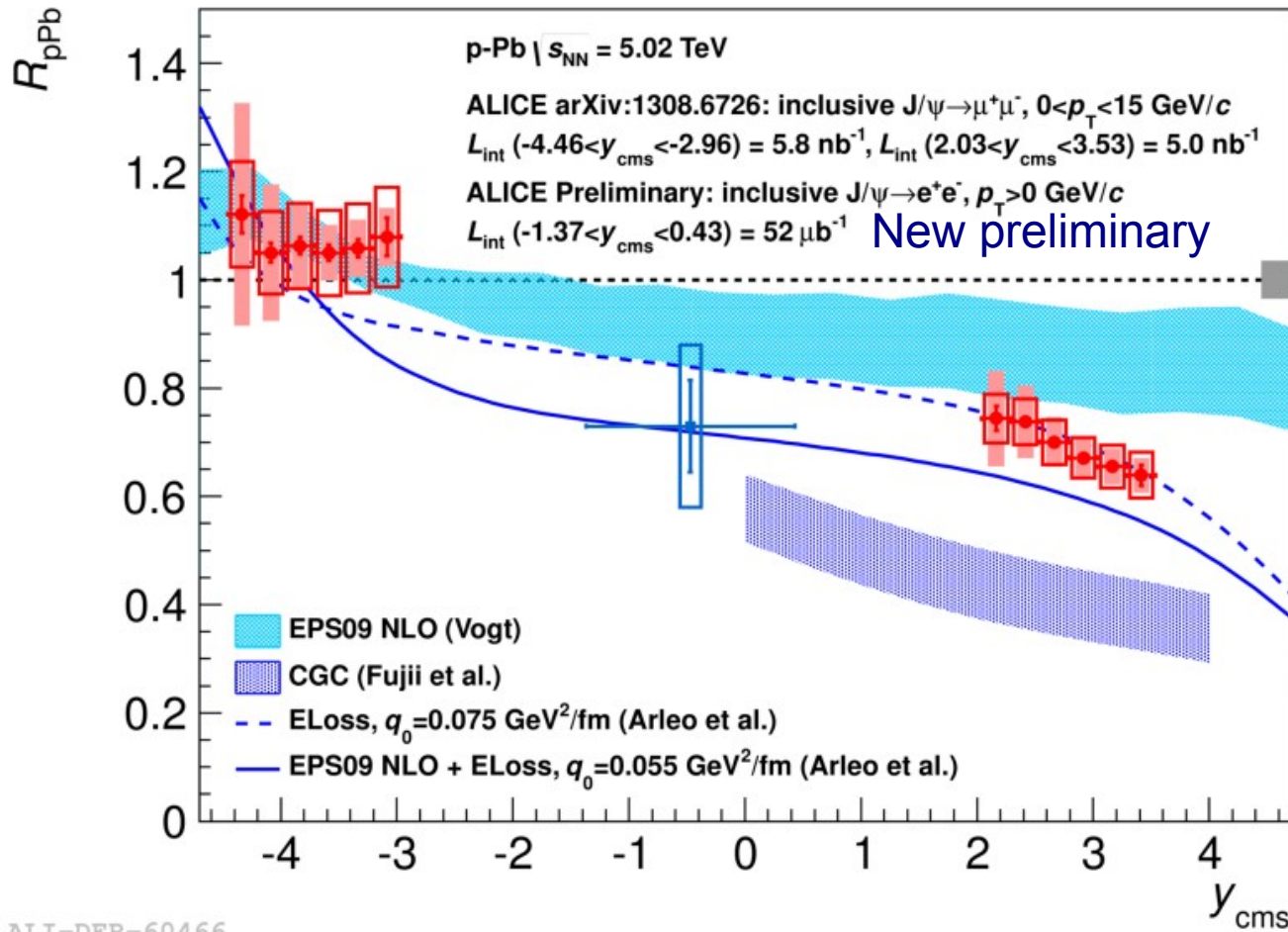
Radial flow expected to reflect in spectra, in particular in p/ π ratio

Shuryak and Zahed, PRC 88 (2013) 044915

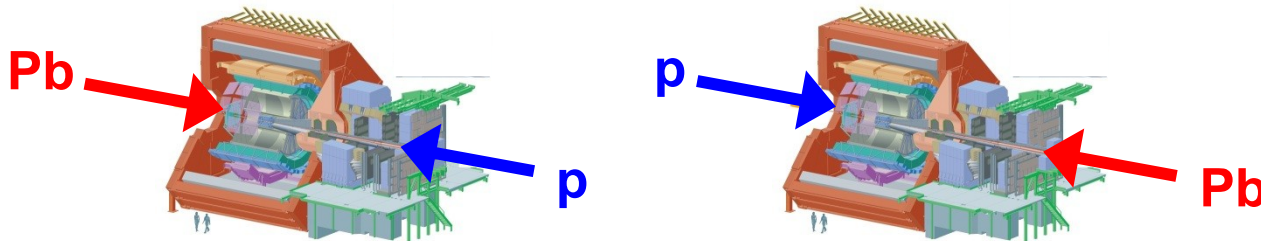


(Note also present in high mult pp)

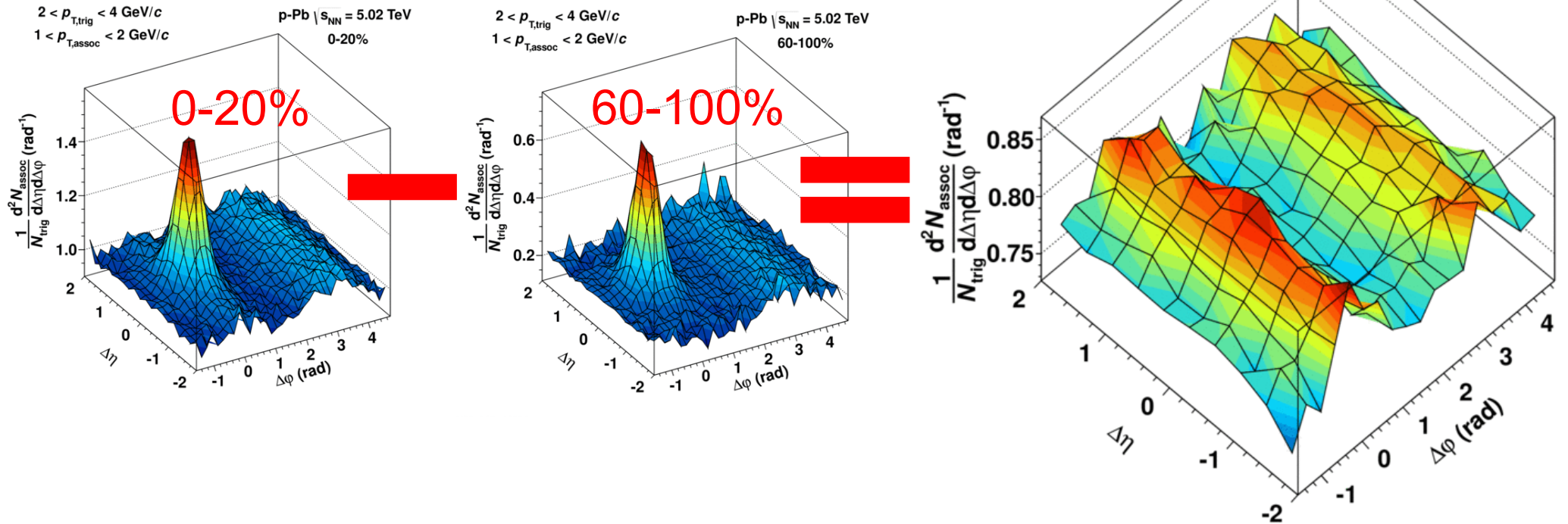
J/ψ production versus rapidity in p-Pb



- 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



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