



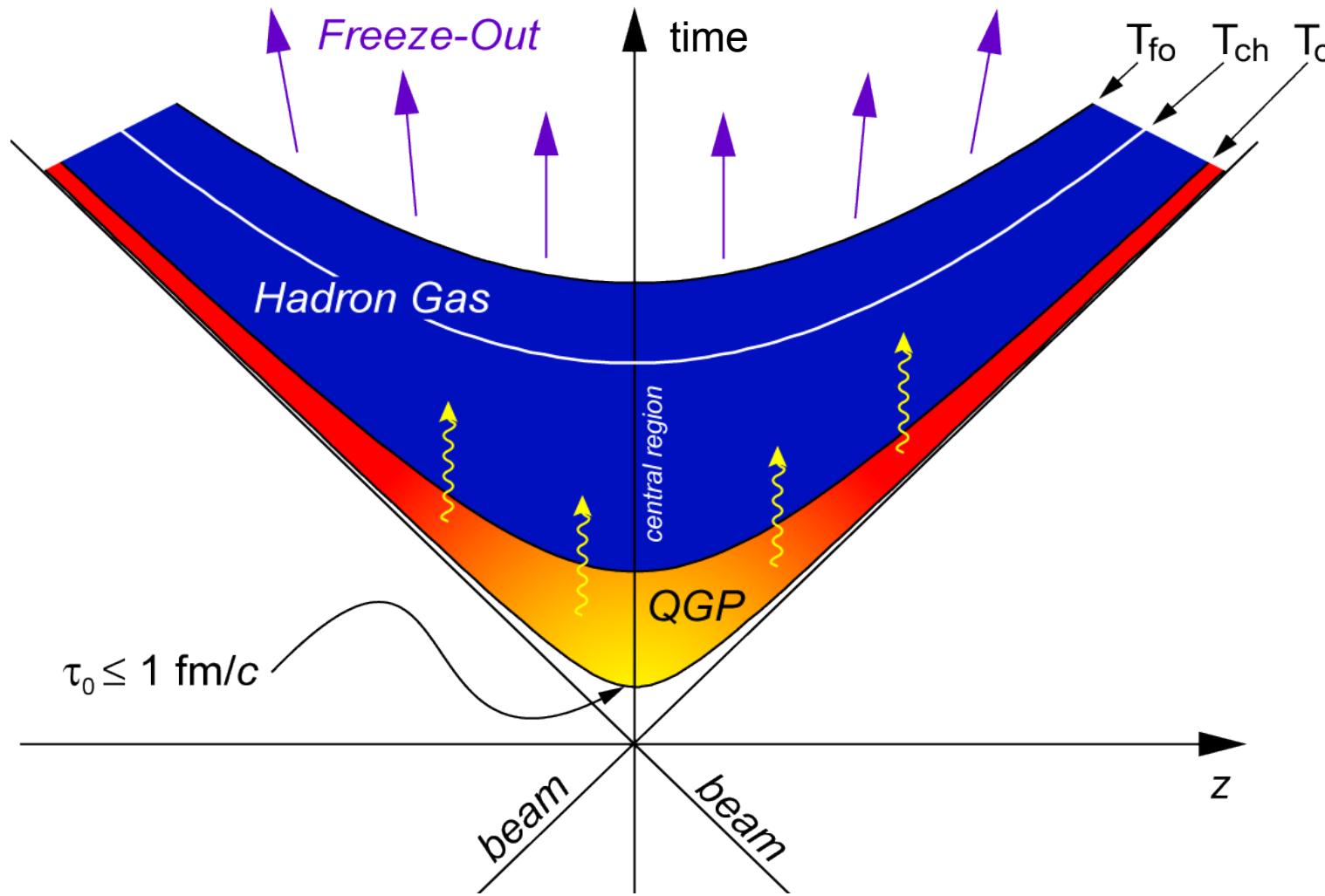
# From Heavy-Ion Collisions to Quark-Gluon matter

Constantin Loizides  
(LBNL)

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

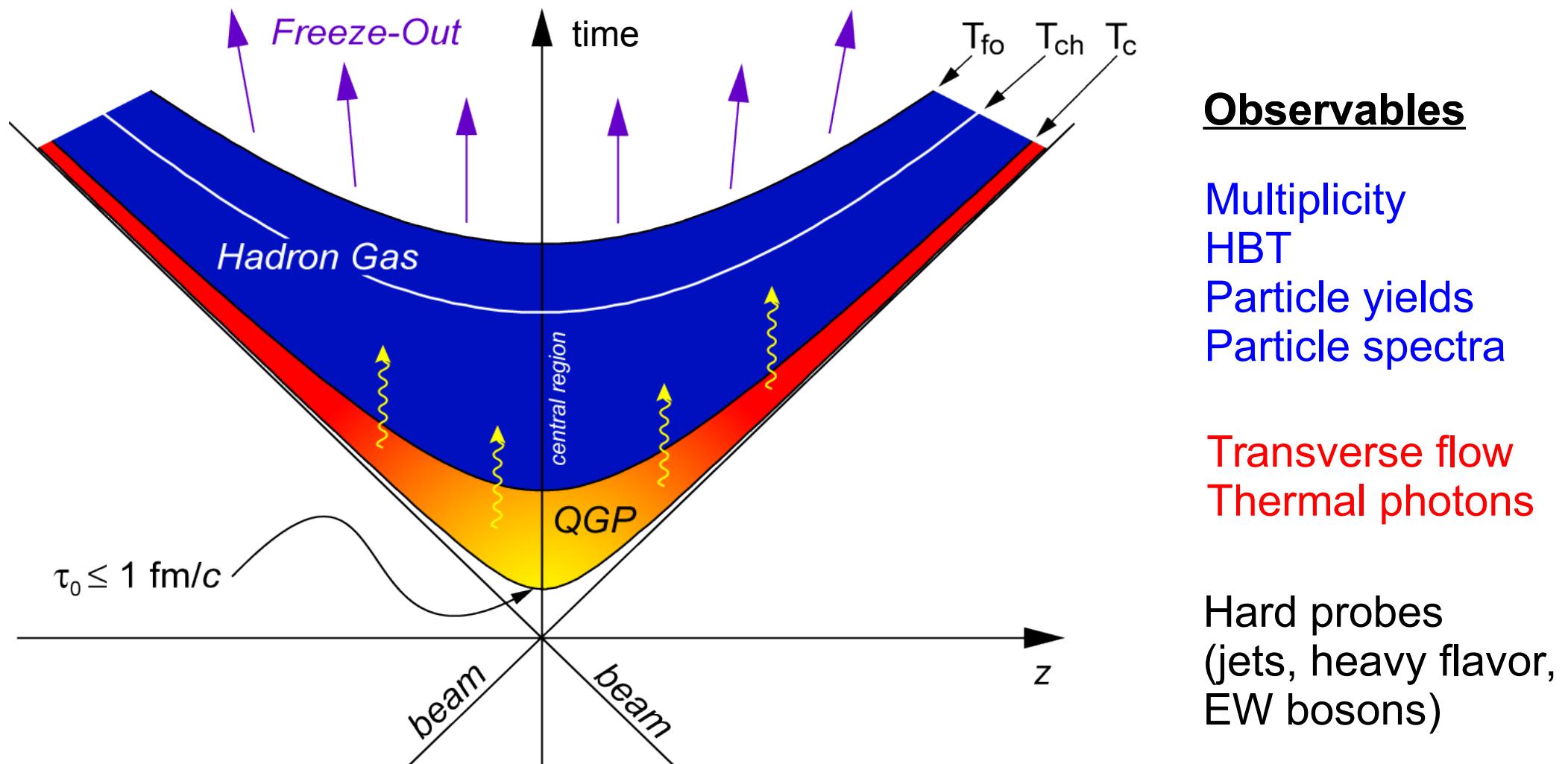
# What quantities to measure?

## (Recap part II)



# What quantities to measure?

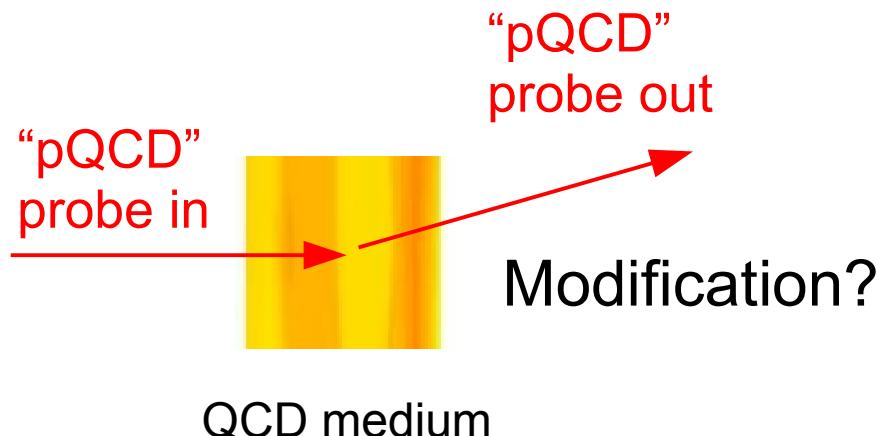
## (Recap part II)



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

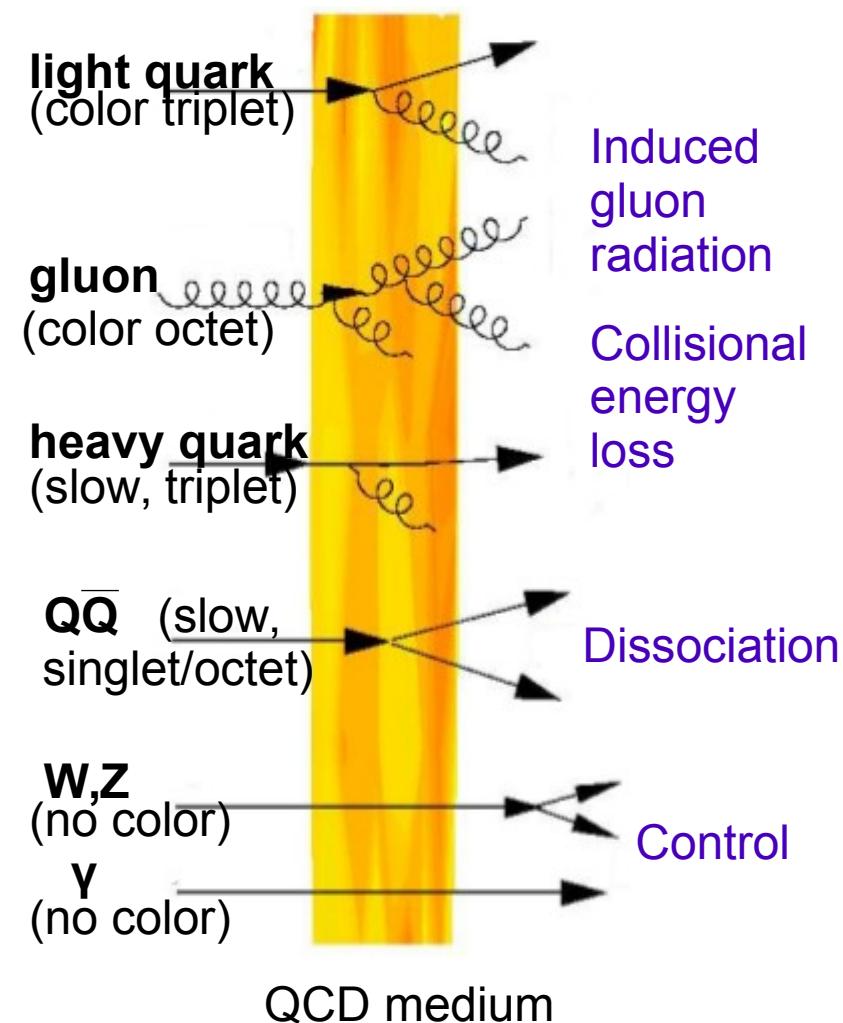
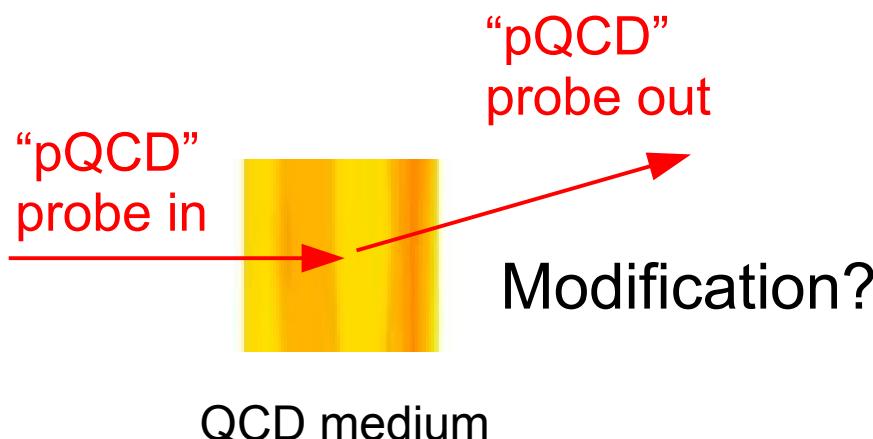
# Tomography of QCD matter

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



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# Hard processes in pp

# Hard processes in pp

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

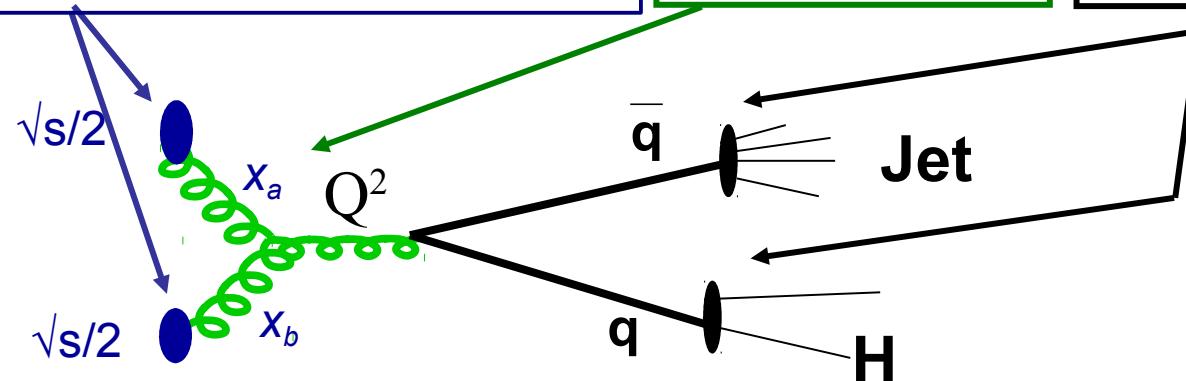
$$\sigma_{pp \rightarrow Hx} = PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \sigma_{ab \rightarrow q\bar{q}} \otimes D_{q \rightarrow H}(z_q, Q^2)$$

Cross section  
for hadronic  
collisions (pp)

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

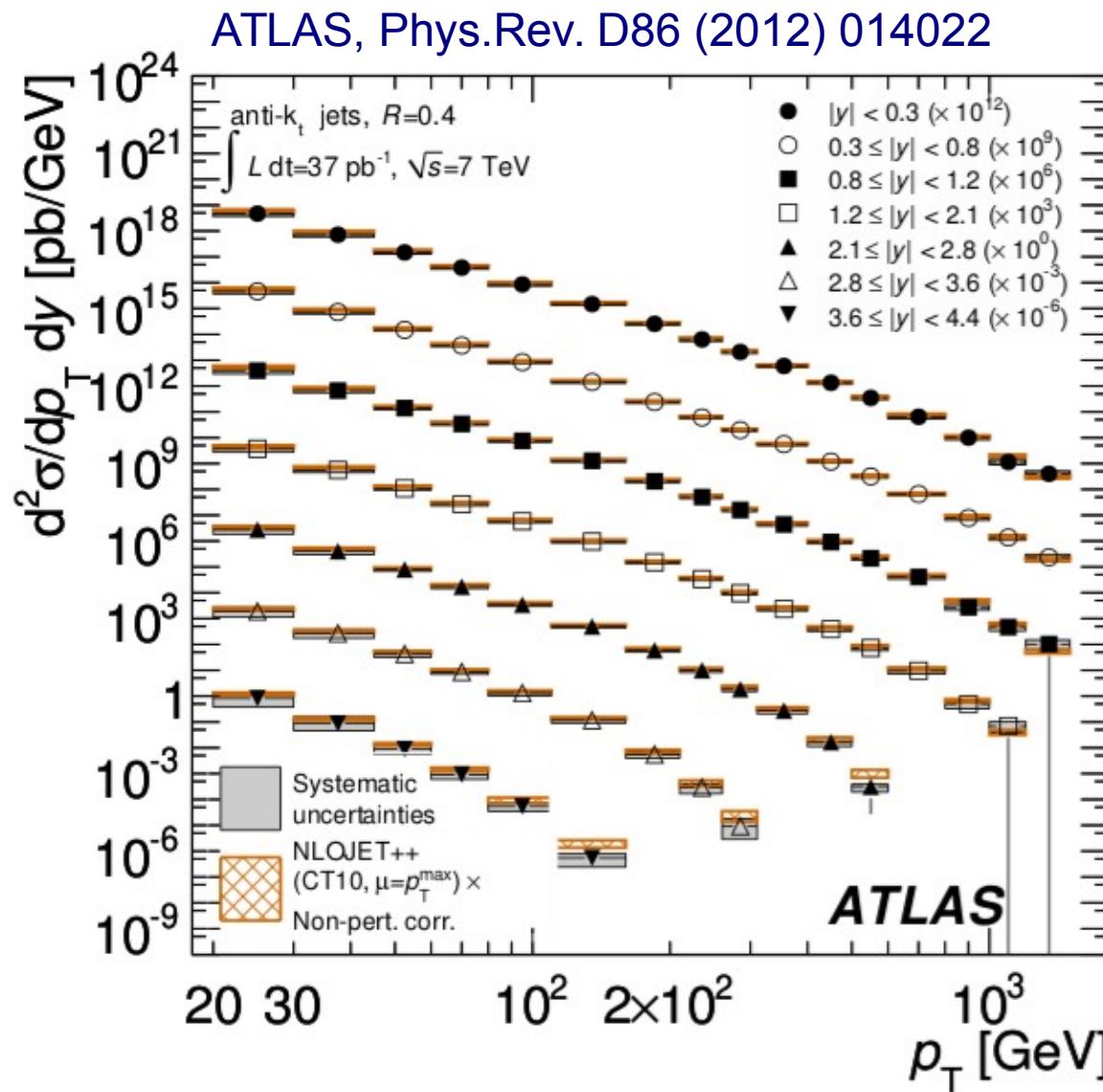
Partonic  
cross section

Fragmentation  
of quark q into  
hadron H



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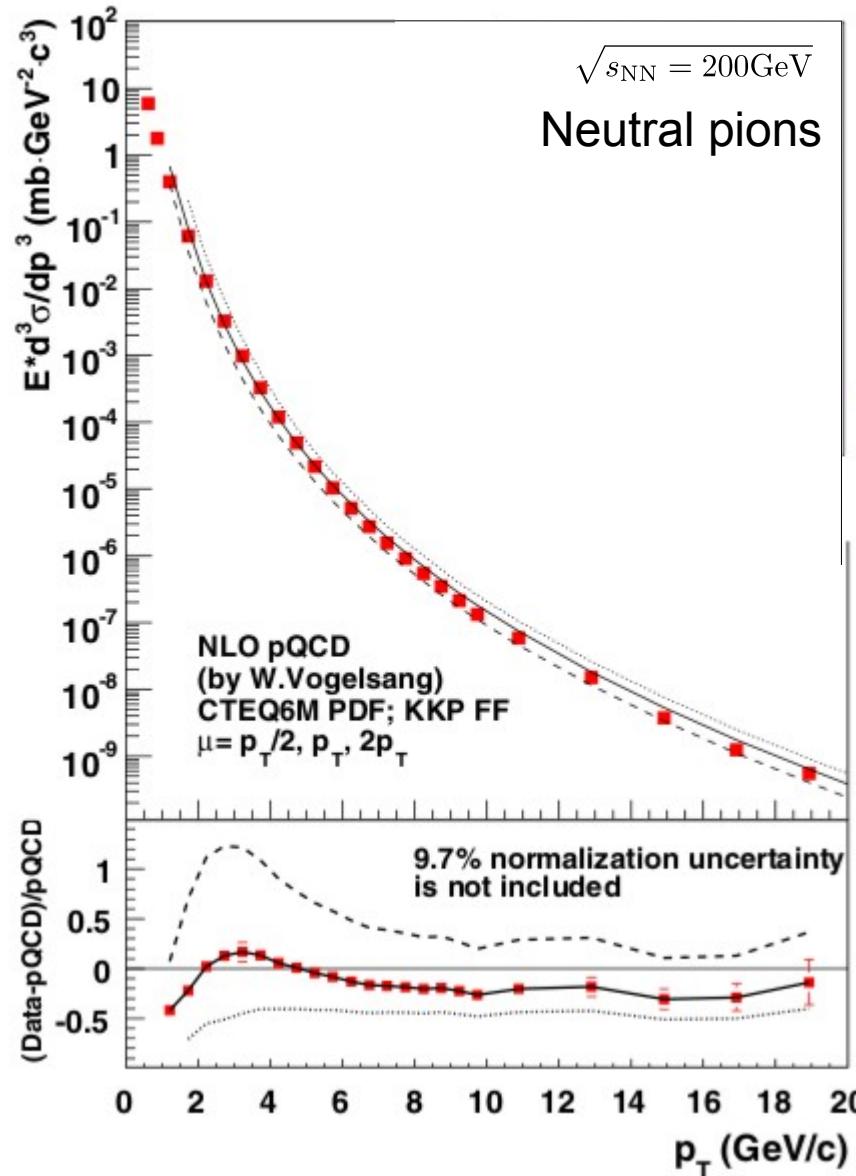


Successfully  
describing  
data over  
many orders  
of magnitude!

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PHENIX, PRD 76 (2007) 051106(R)

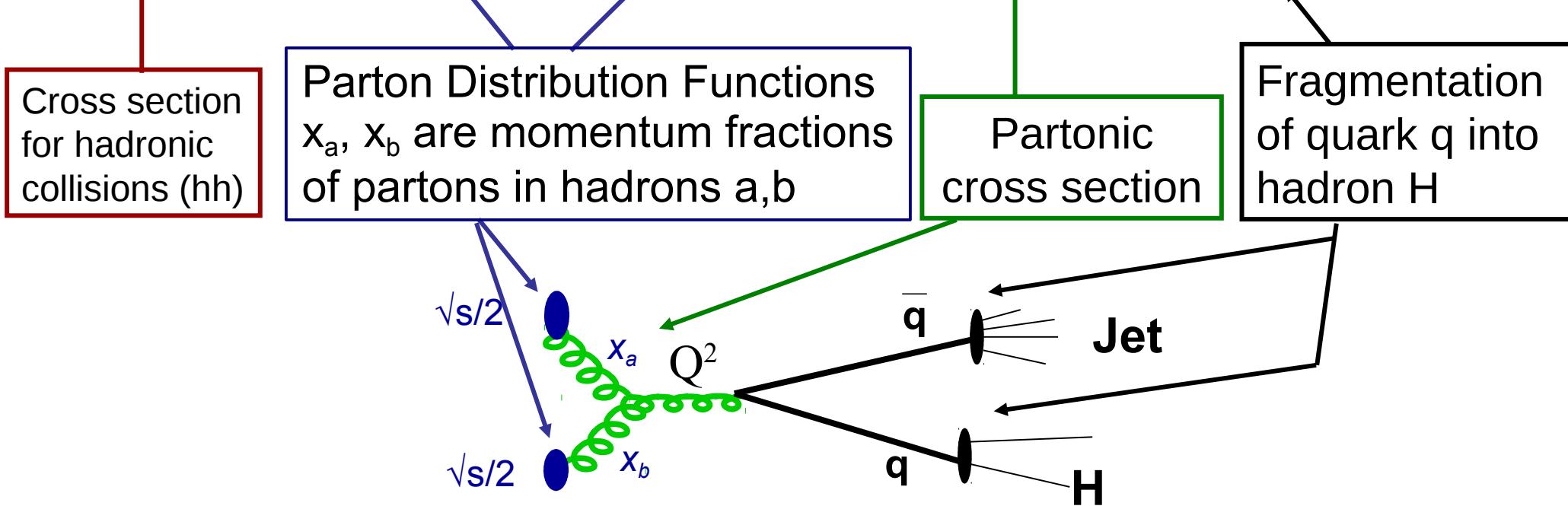


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$$\sigma_{pp \rightarrow Hx} = PDF(x_a, Q^2) PDF(x_b, Q^2) \otimes \sigma_{ab \rightarrow q\bar{q}} \otimes D_{q \rightarrow H}(z_q, Q^2)$$



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

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

# Glauber Ncoll scaling

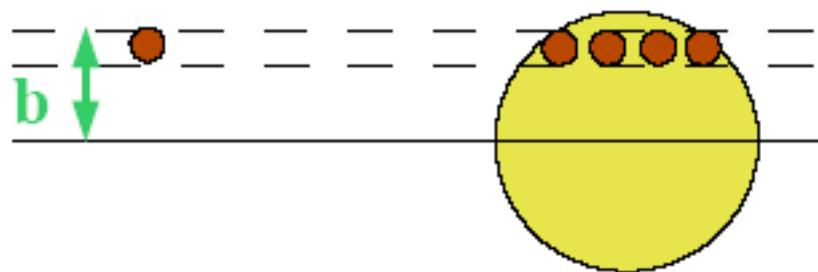
(see e.g. arXiv:0701025)

# Nuclear geometry and hard processes: Glauber theory

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Glauber scaling:

- Apply to hard processes with large momentum transfer
- Short coherence length → 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:  $\sigma_{pA}^{\text{inel}} = \int d^2b \left( 1 - [1 - T_A(b) \sigma_{NN}^{\text{inel}}]^A \right)$

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

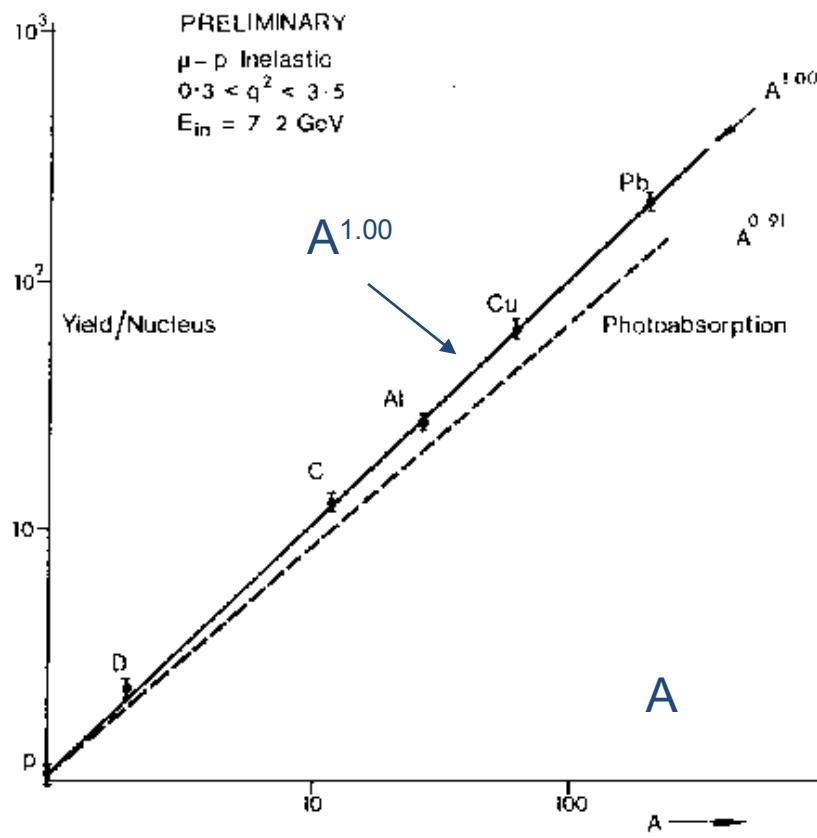
$$\sigma_{NN}^{\text{hard}} \ll \sigma_{NN}^{\text{inel}}$$

# Experimental tests of Glauber scaling: hard cross sections in $p(\mu)A$ collisions

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

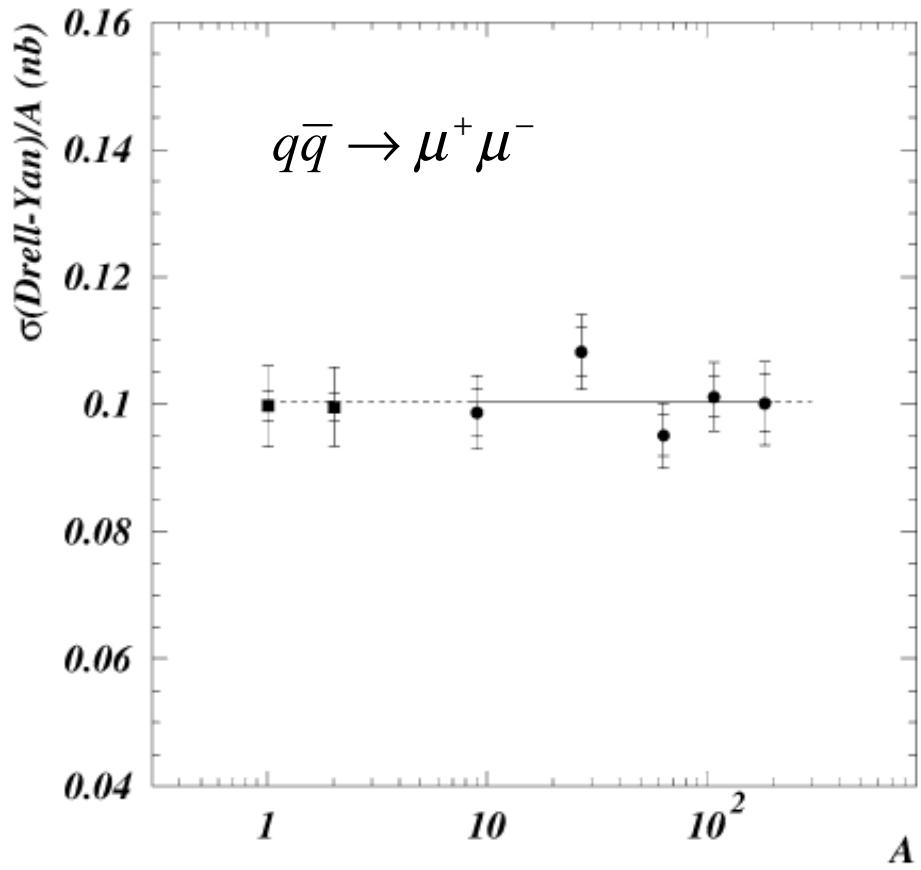
$\sigma_{\text{inel}}$  for 7 GeV muons on nuclei

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  $A^{1.0}$

# Glauber scaling for AB collisions

Nuclear overlap function:

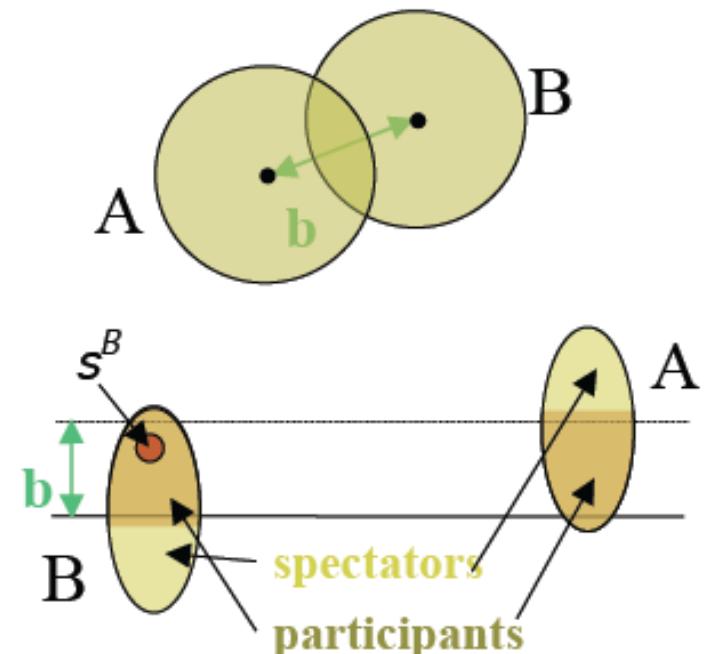
$$T_{AB}(b) = \int d^2 s T_A(s) T_B(s - b)$$

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  $b$ :

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

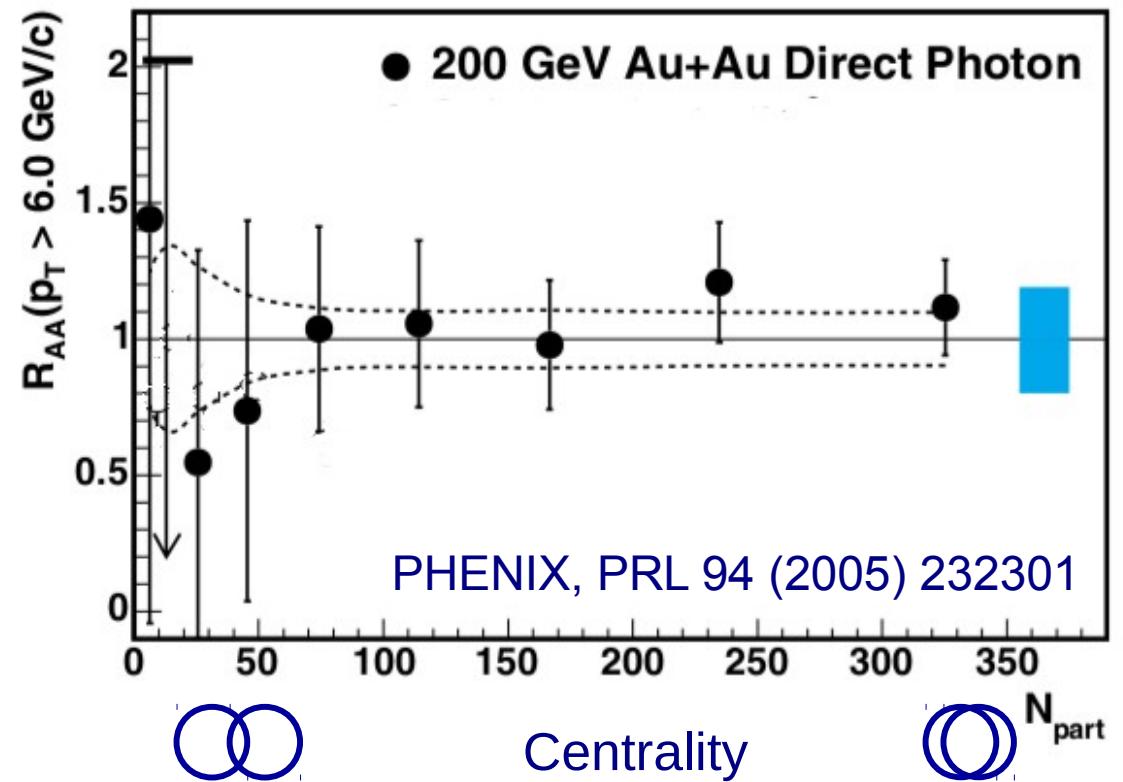
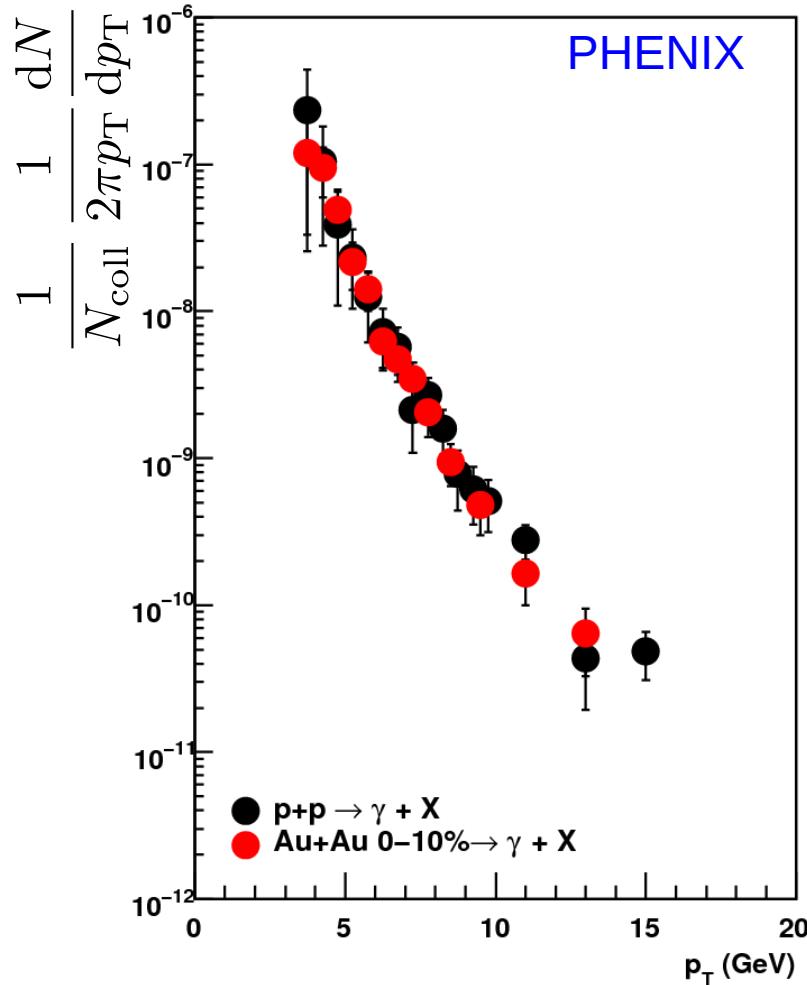


$$N_{\text{hard}}^{AB}(b) = N_{\text{coll}}^{AB}(b) \sigma_{\text{NN}}^{\text{hard}} / \sigma_{\text{NN}}^{\text{inel}} = N_{\text{coll}}^{AB}(b) N_{\text{pp}}^{\text{hard}}$$

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

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

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



Direct photons in Au+Au scale with  $N_{\text{coll}}$

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

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

## Isolated $\gamma$ :

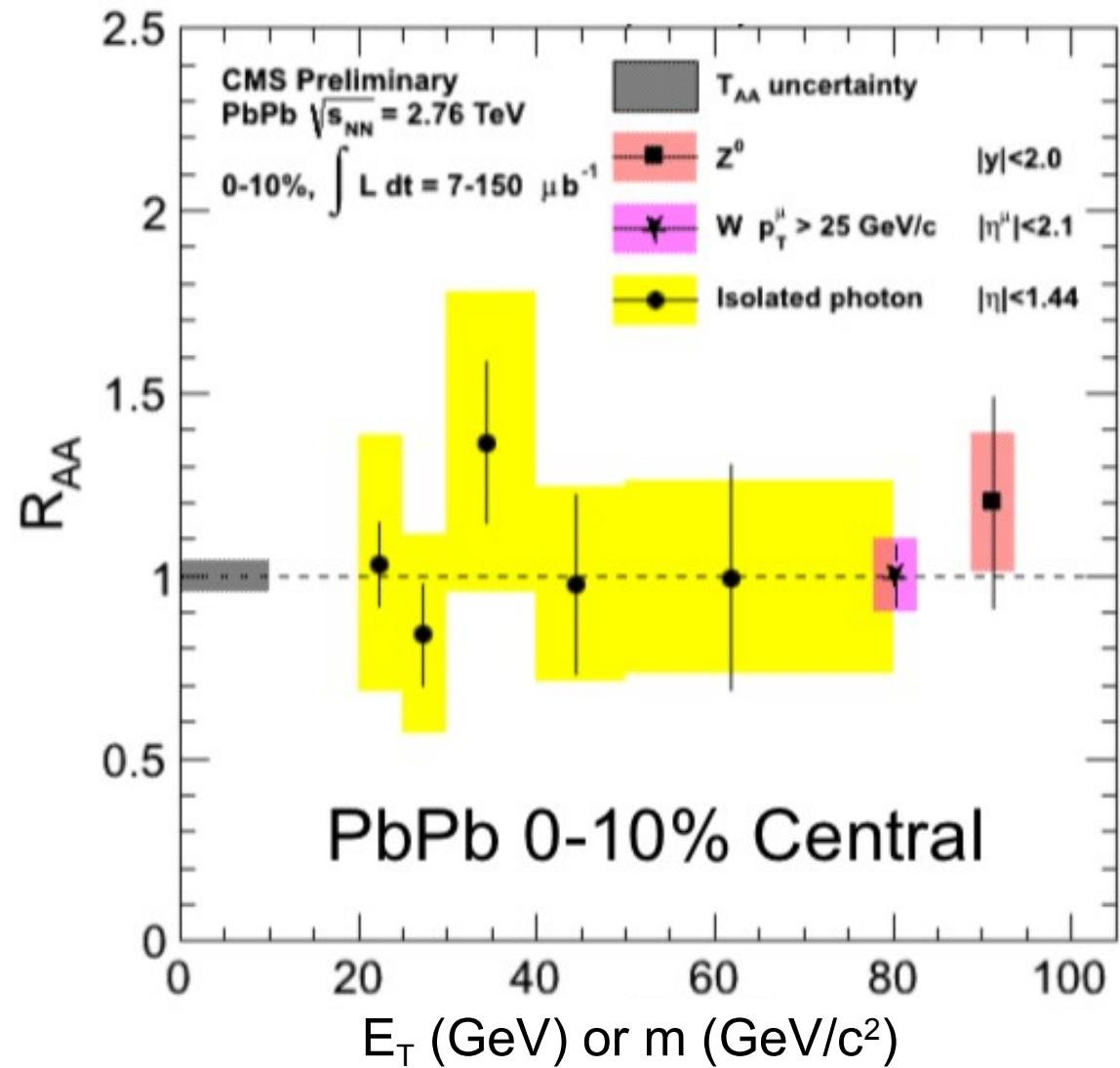
ATLAS, [ATLAS-CONF-2012-051](#)  
 CMS, [PLB 710 \(2012\) 256](#)

## 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  $\gamma$ , Z, W) scale with Ncoll

# Parton energy loss

# Nuclear modification factor

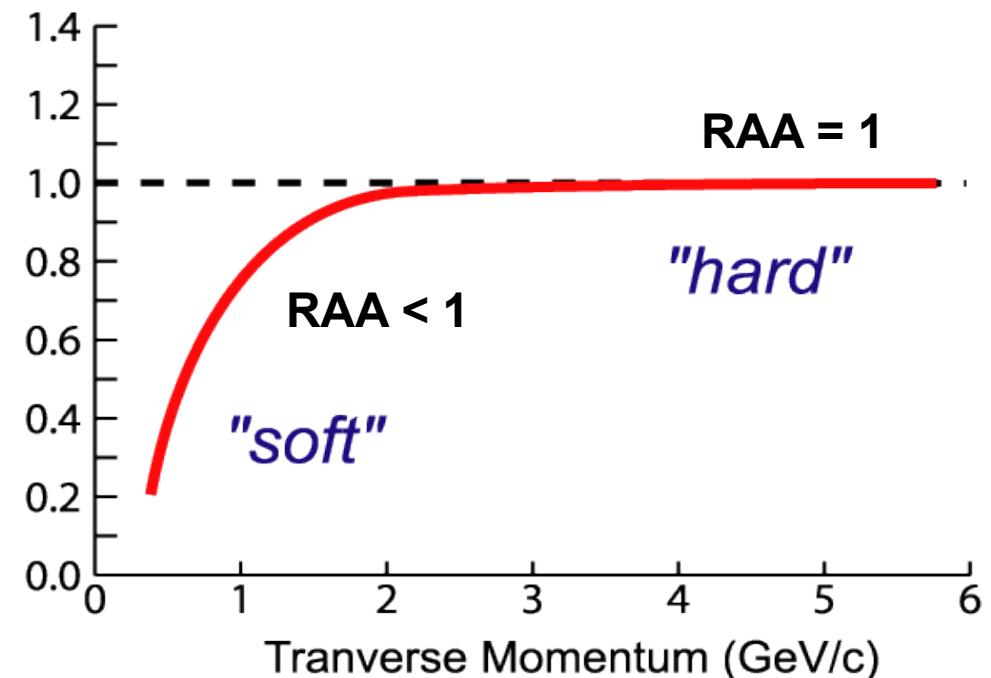
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$$R_{AA} = \frac{dN_{AA}/dp_T}{N_{\text{coll}} dN_{pp}/dp_T}$$

$R_{AA} > 1 \rightarrow$  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

# Nuclear modification factor

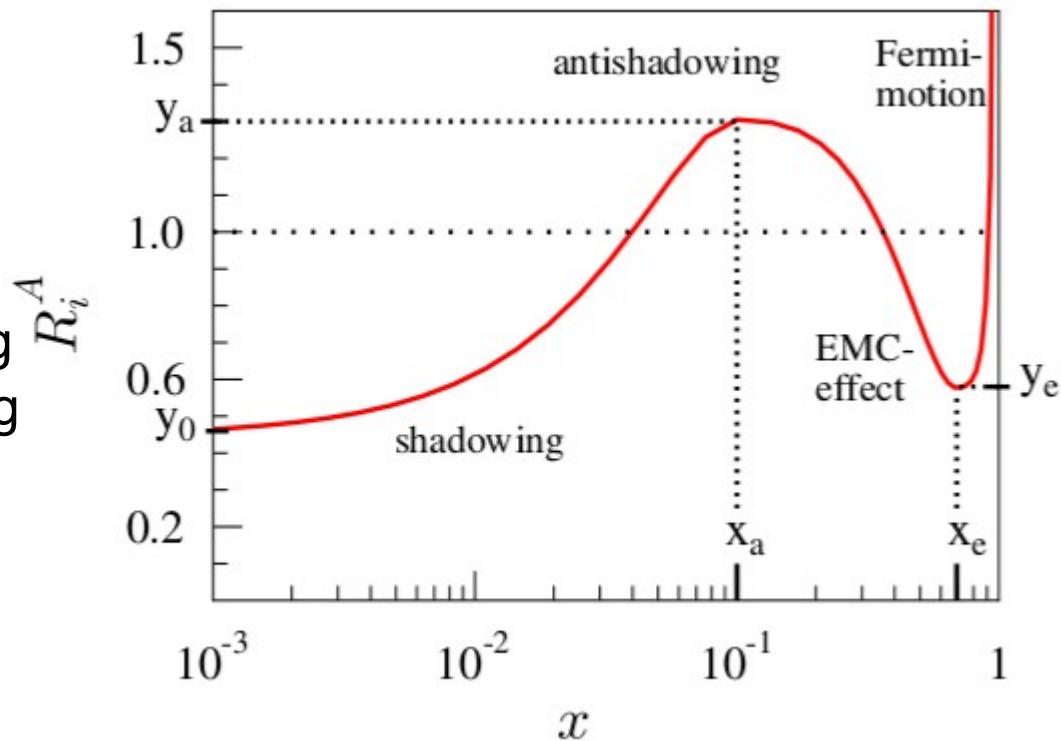
19

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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)

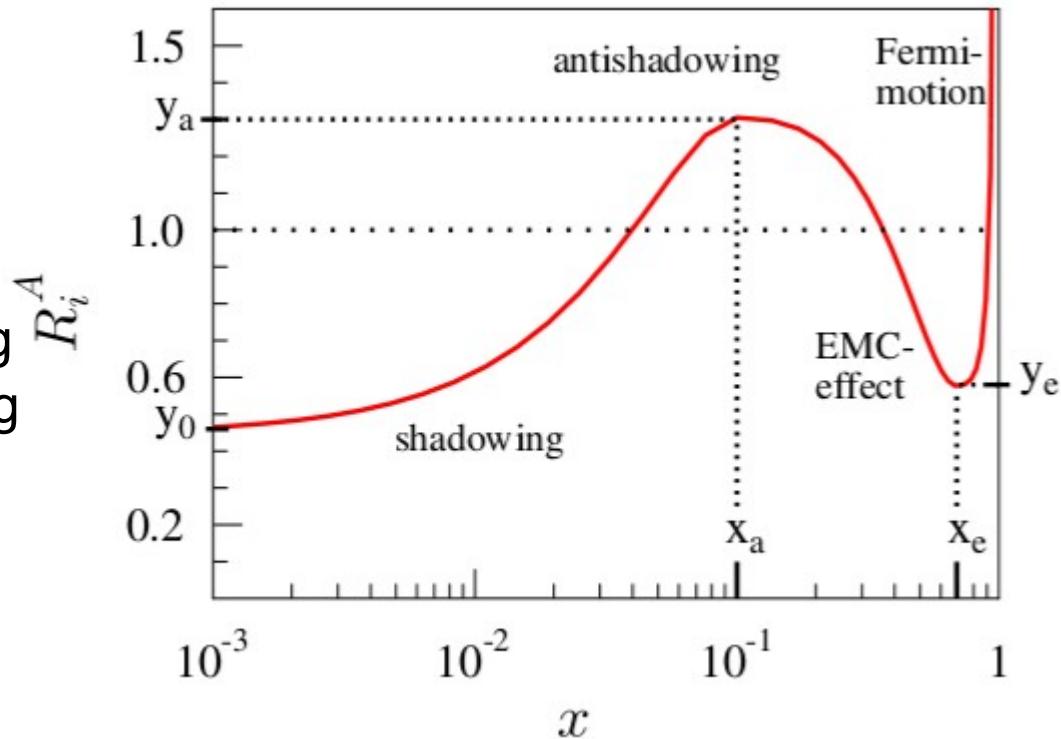
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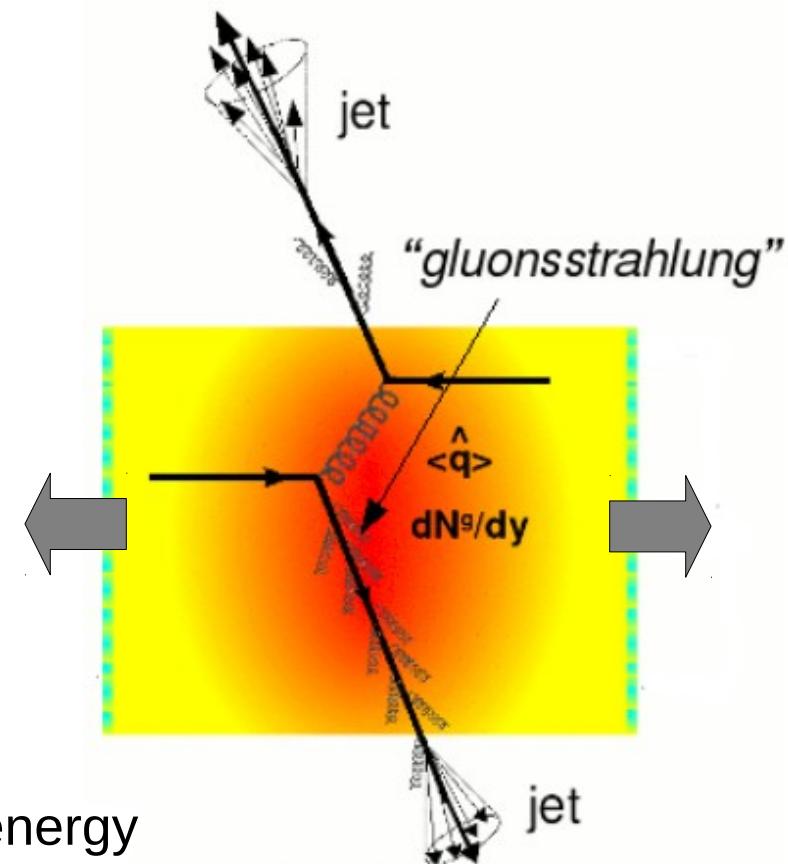


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- $f_i^A(x, Q^2) \equiv R_i^A(x, Q^2) f_i^{\text{CTEQ6.1M}}(x, Q^2)$
- Binary scaling can be broken due final state effects

(Prime reason for measurements in pA)

# Breaking of binary scaling

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



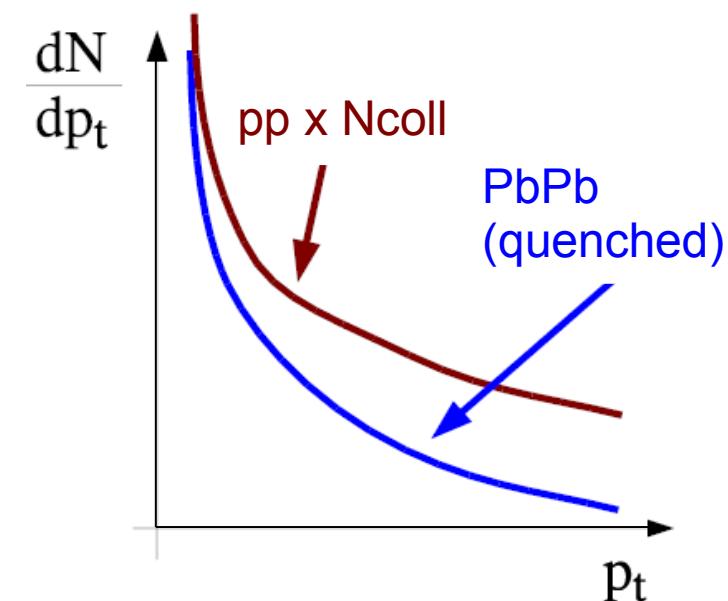
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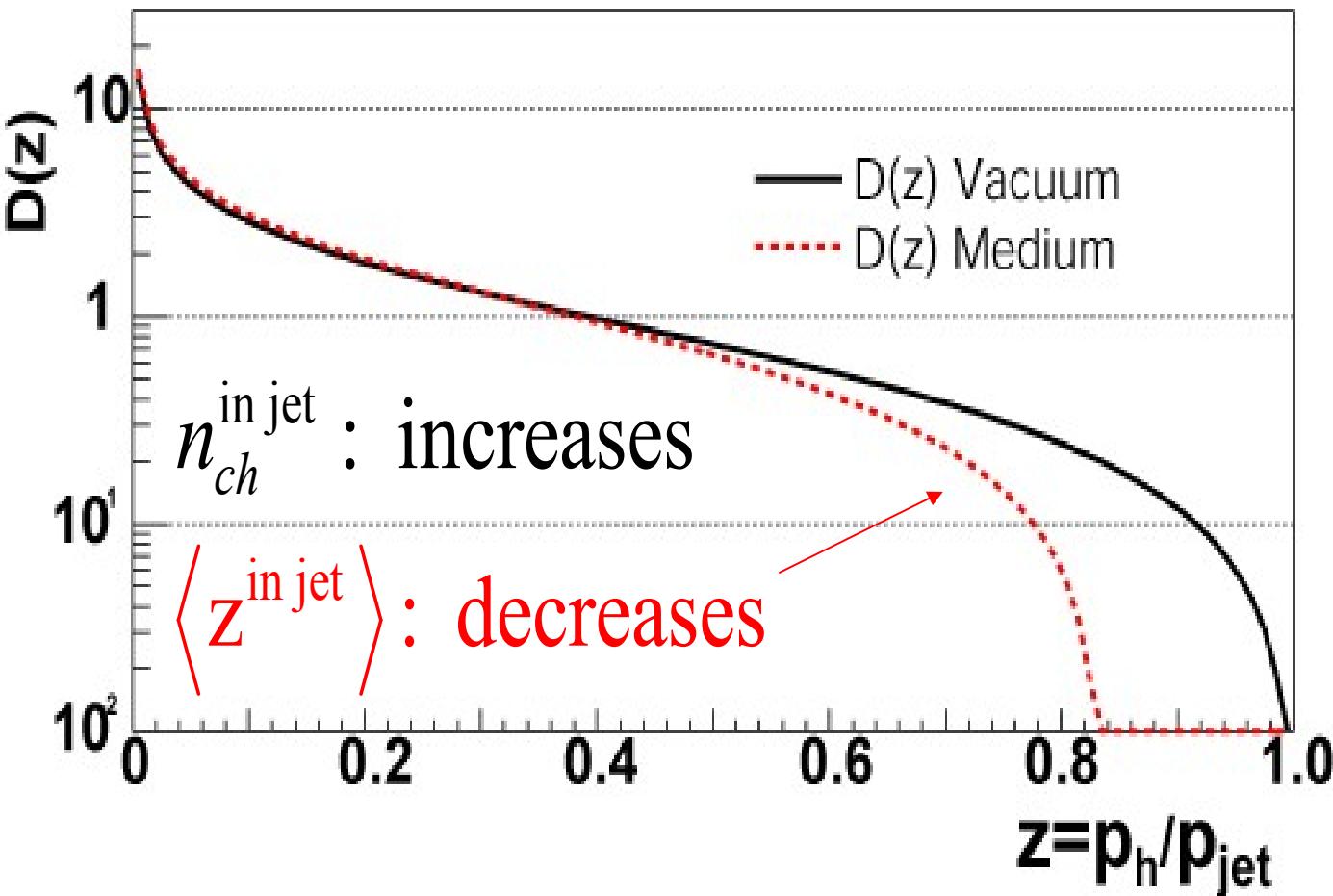
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- Gluonstrahlung (radiative energy loss)
  - Radiative mechanism dominant at high energy
- The net-effect is a decrease of the  $p_T$  of hard partons
  - Quenching of the high  $p_T$  spectrum
  - Modification of jet properties



# Breaking of binary scaling

- Final state effects
  - Change of fragmentation due to the presence of matter
    - e.g. jet quenching
- Parton traversing the medium loses energy via
  - Scattering with partons (collisional energy)
  - Gluonstrahlung (radiation)
    - Radiative mechanism
  - The net-effect is  $\varepsilon$ 
    - Quenching of the high  $p_T$  spectrum
    - Modification of jet properties





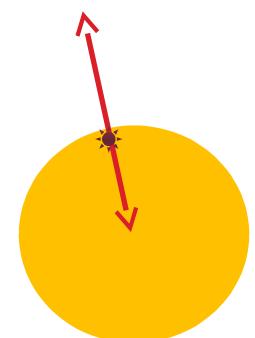
Energy Loss of Energetic Partons in Quark-Gluon Plasma:  
Possible Extinction of High  $p_T$  Jets in Hadron-Hadron Collisions.

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](https://arxiv.org/abs/1002.2206)  
for more accurate  
approaches)

Energy loss  
from parton

Casimir factor

Transport coefficient

Length traversed  
in medium

$\alpha_s$  = QCD coupling constant

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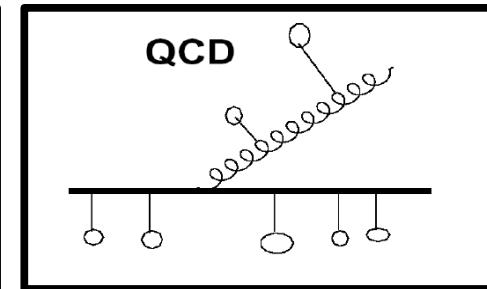
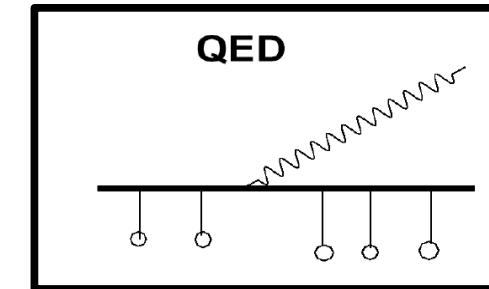
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$L^2$  dependence related to the  
fact that radiated gluons interact  
with medium

# Average energy loss (example)

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- 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

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

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

$$\alpha_S = 0.2$$

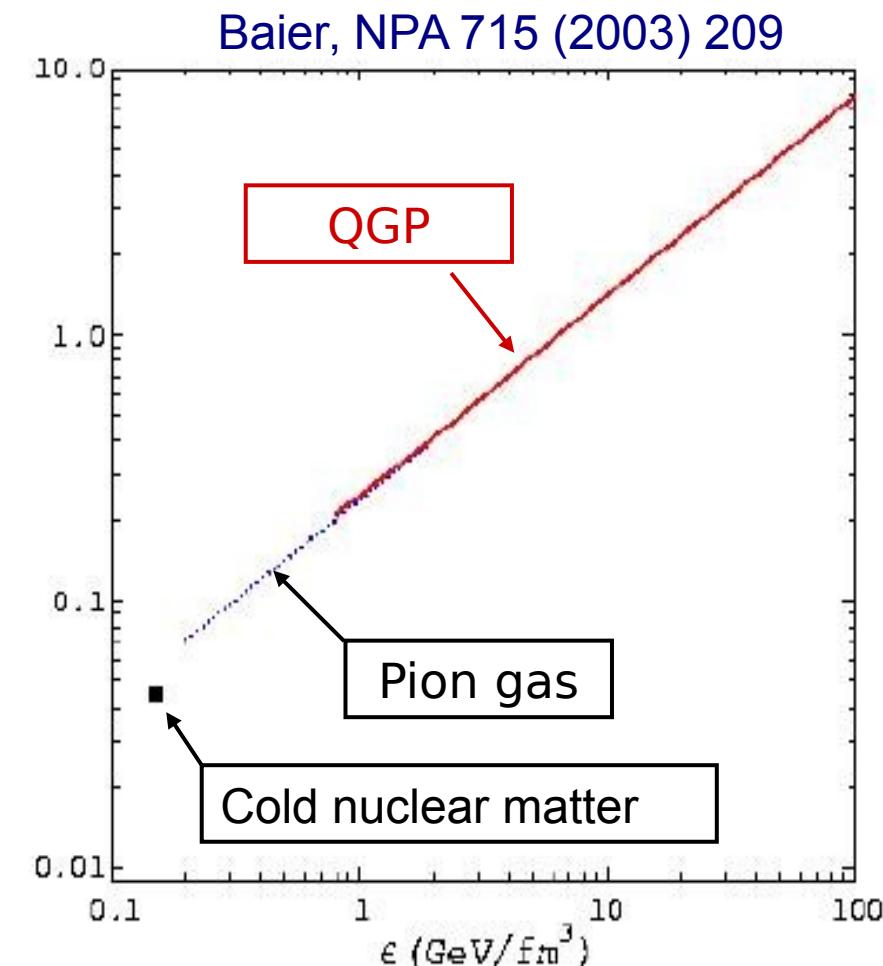
$$C_R = 4/3$$

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



(From formula  
on previous slide)

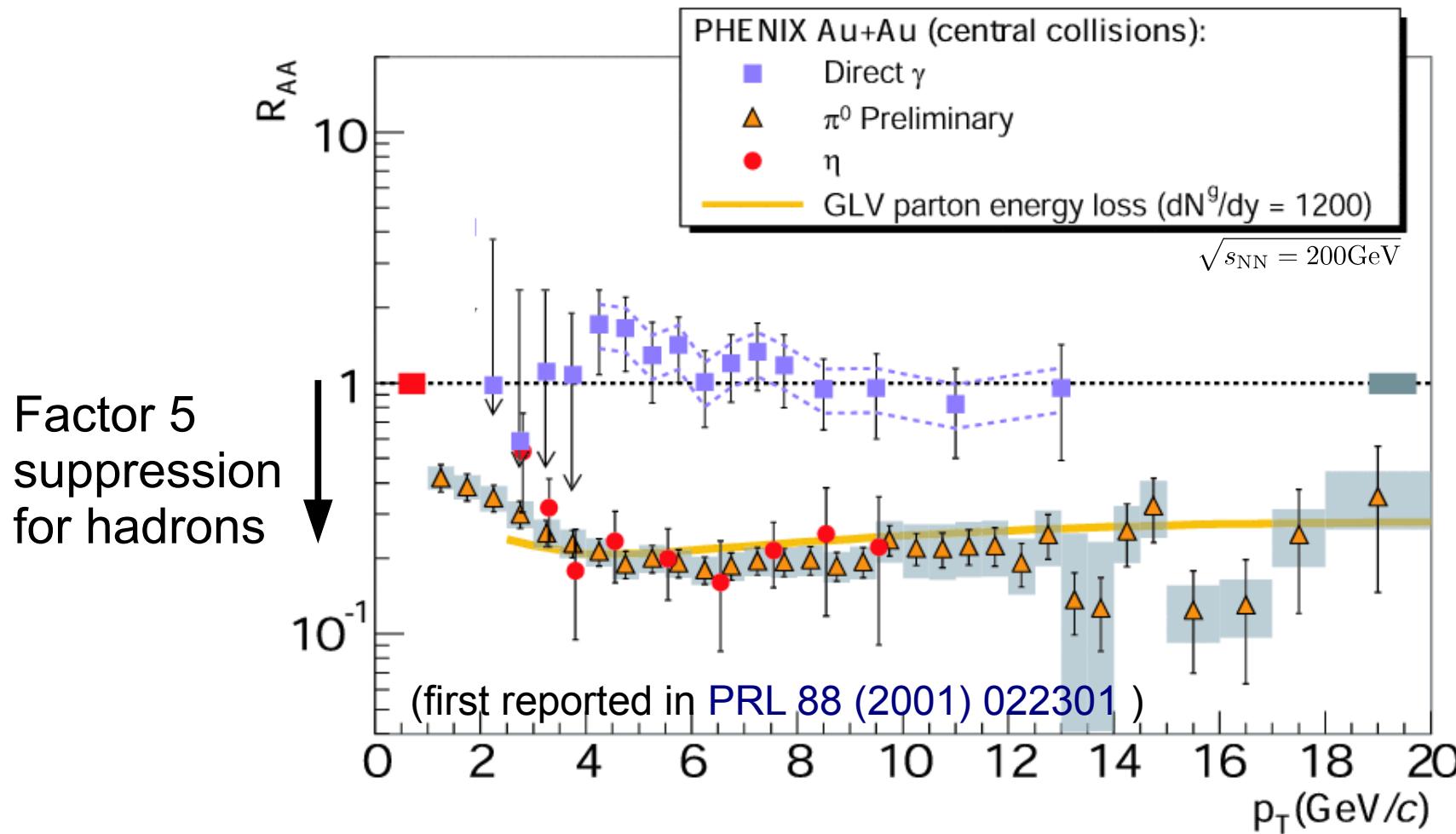
$$\langle \Delta E \rangle \simeq 10 \text{ GeV}$$



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

# Leading hadron suppression at RHIC

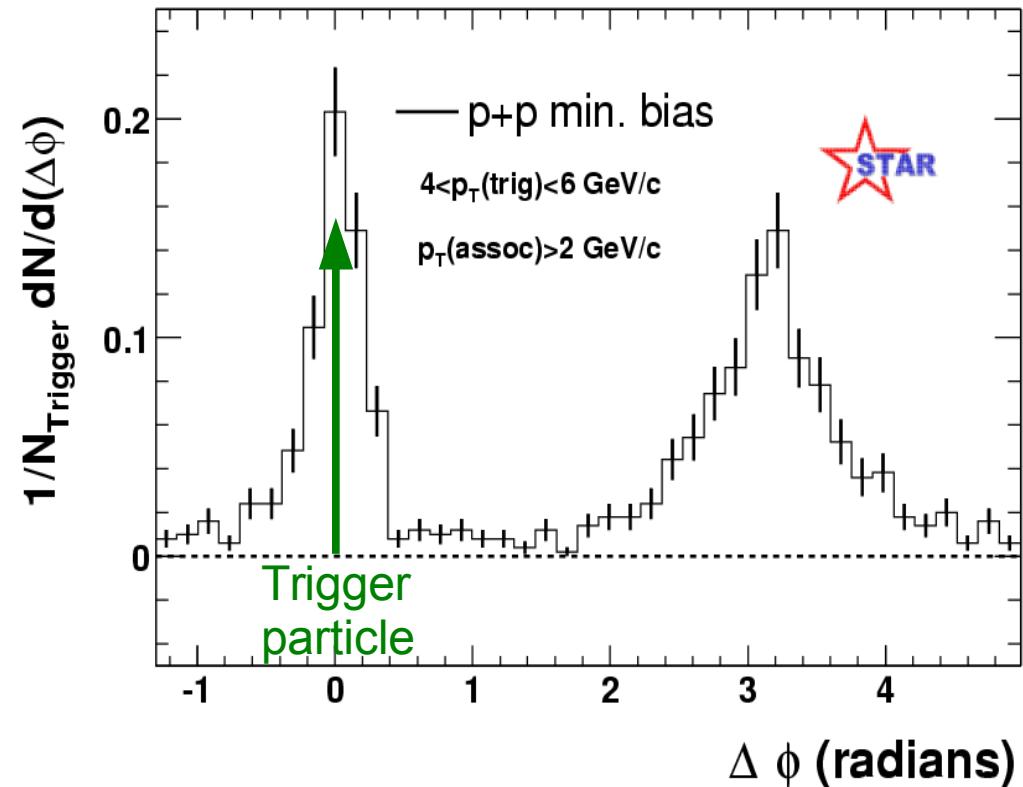
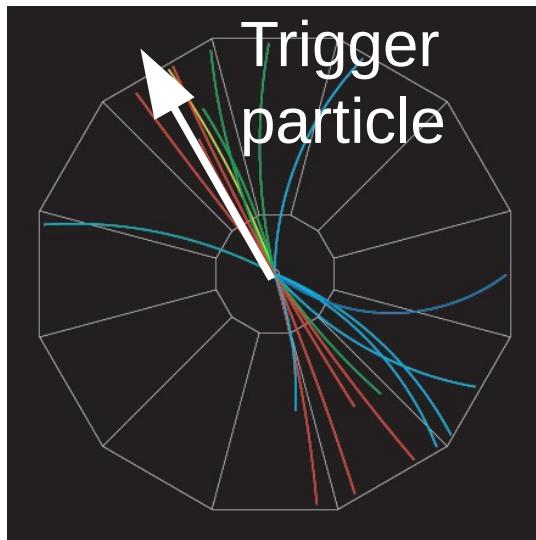
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Strong suppression of hadrons in central Au+Au collisions  
(extracted transport coefficient similar to initial expectations, see arXiv:1312.5003)

# Di-hadron correlations

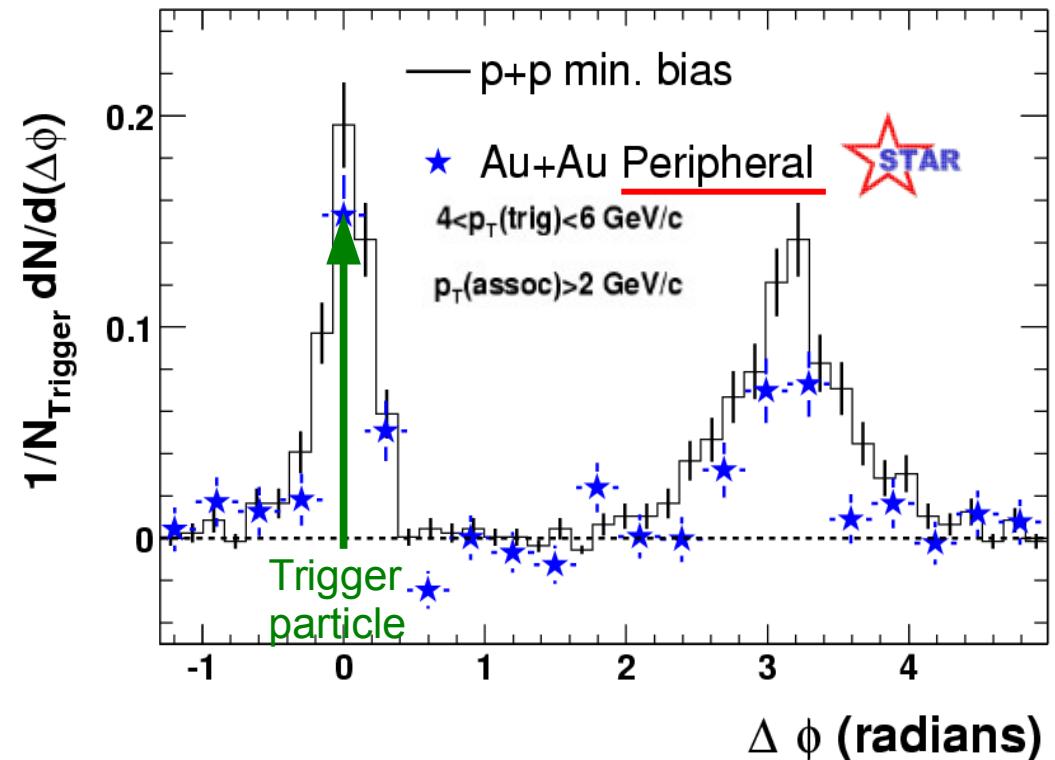
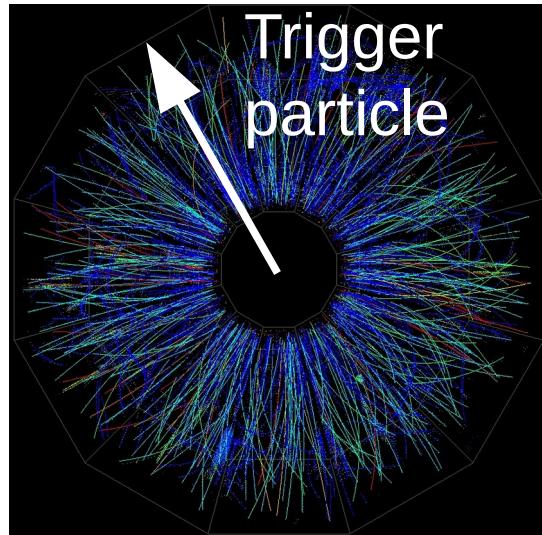
PRL 90 (2003) 082392



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

# Di-hadron correlations

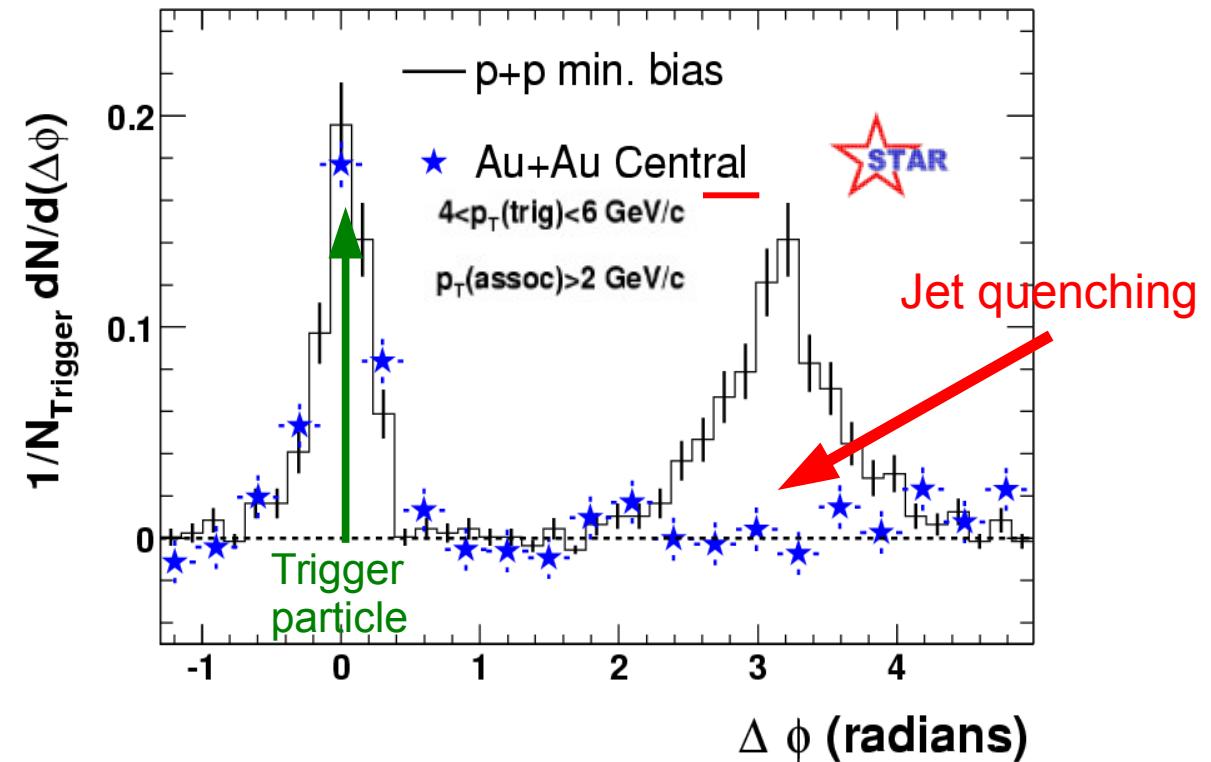
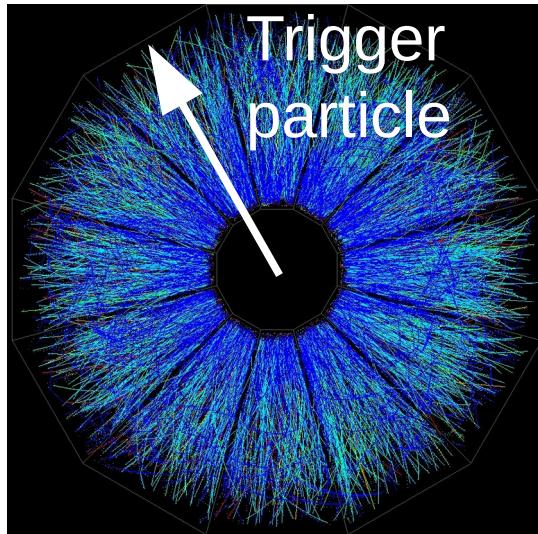
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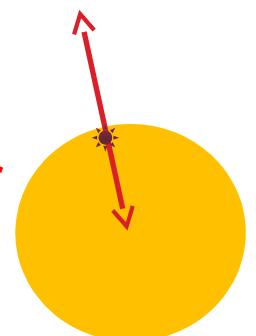
No clear change visible (relative to pp) in peripheral collisions

# Di-hadron correlations

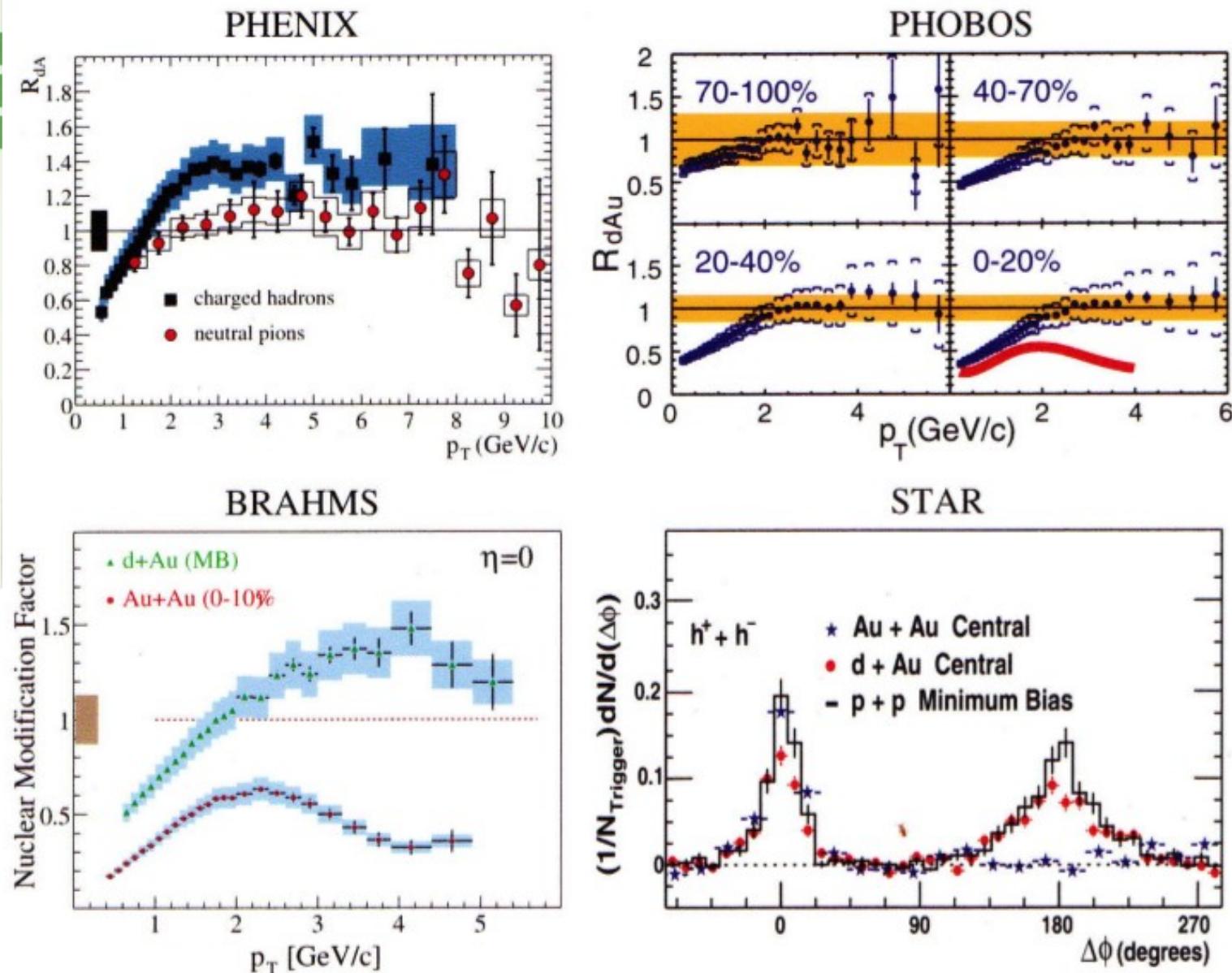
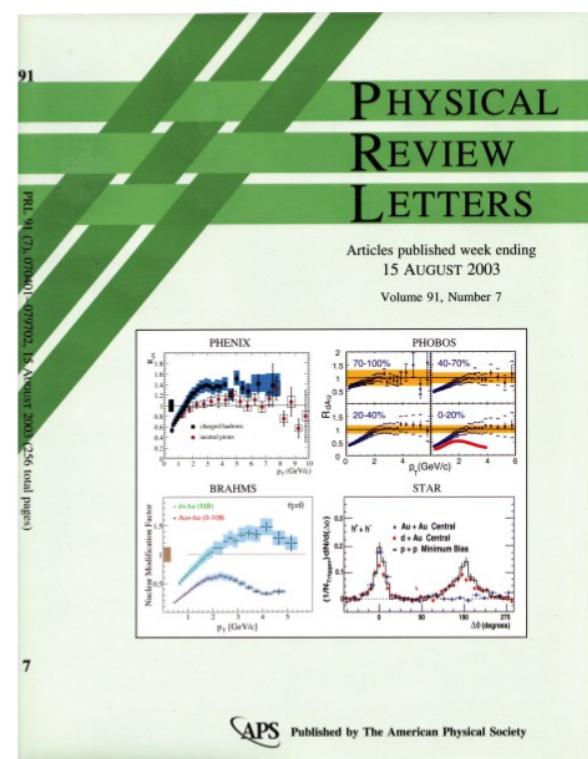
PRL 90 (2003) 082392



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



# dAu control experiment at RHIC

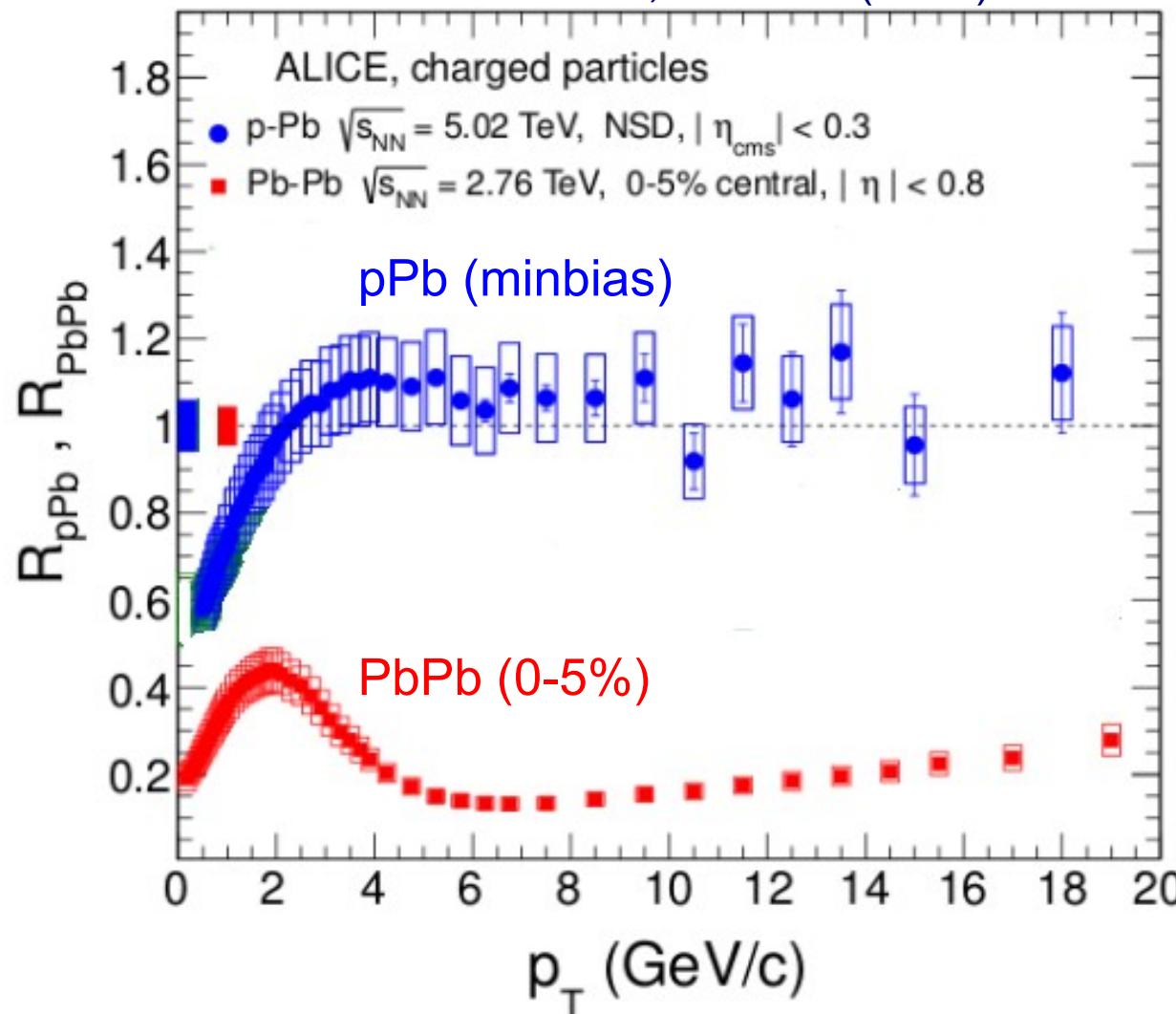


Parton energy loss is a final state effect

# Leading particle suppression at the LHC

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ALICE, PRL 110 (2013) 082302

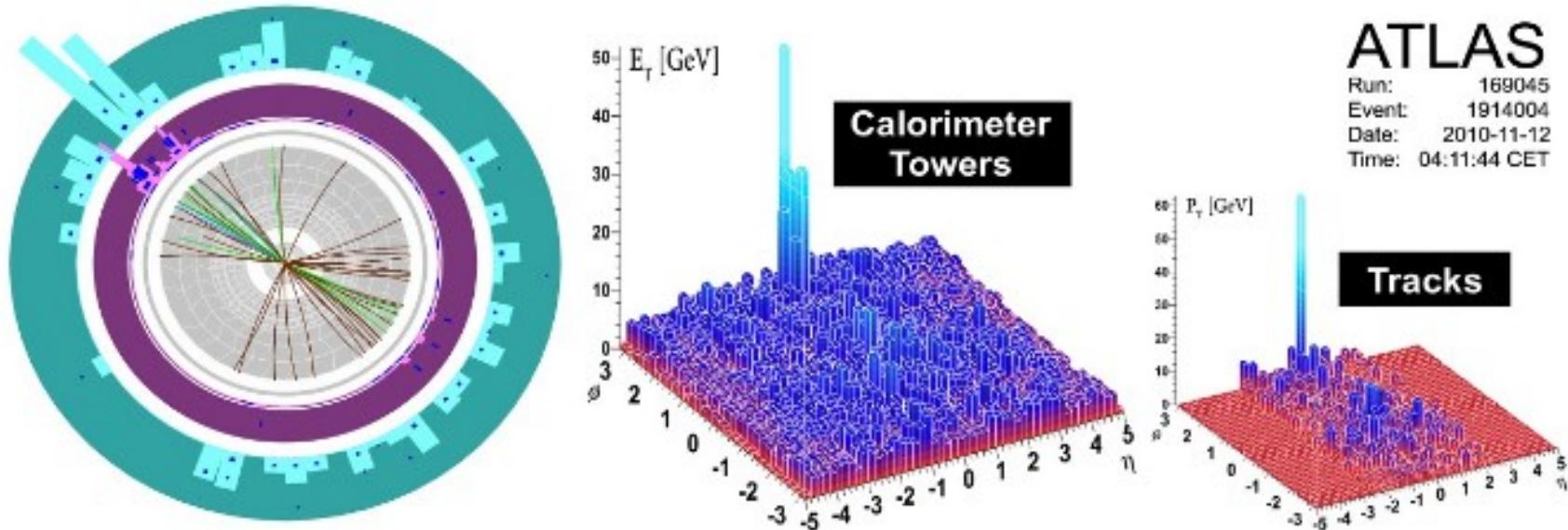


- Strong leading particle suppression also at LHC energies
- Qualitatively similar to the one at RHIC
- As at RHIC from final state (ie not observed in pPb collisions)

# Jet quenching

# Jet quenching in dijet events

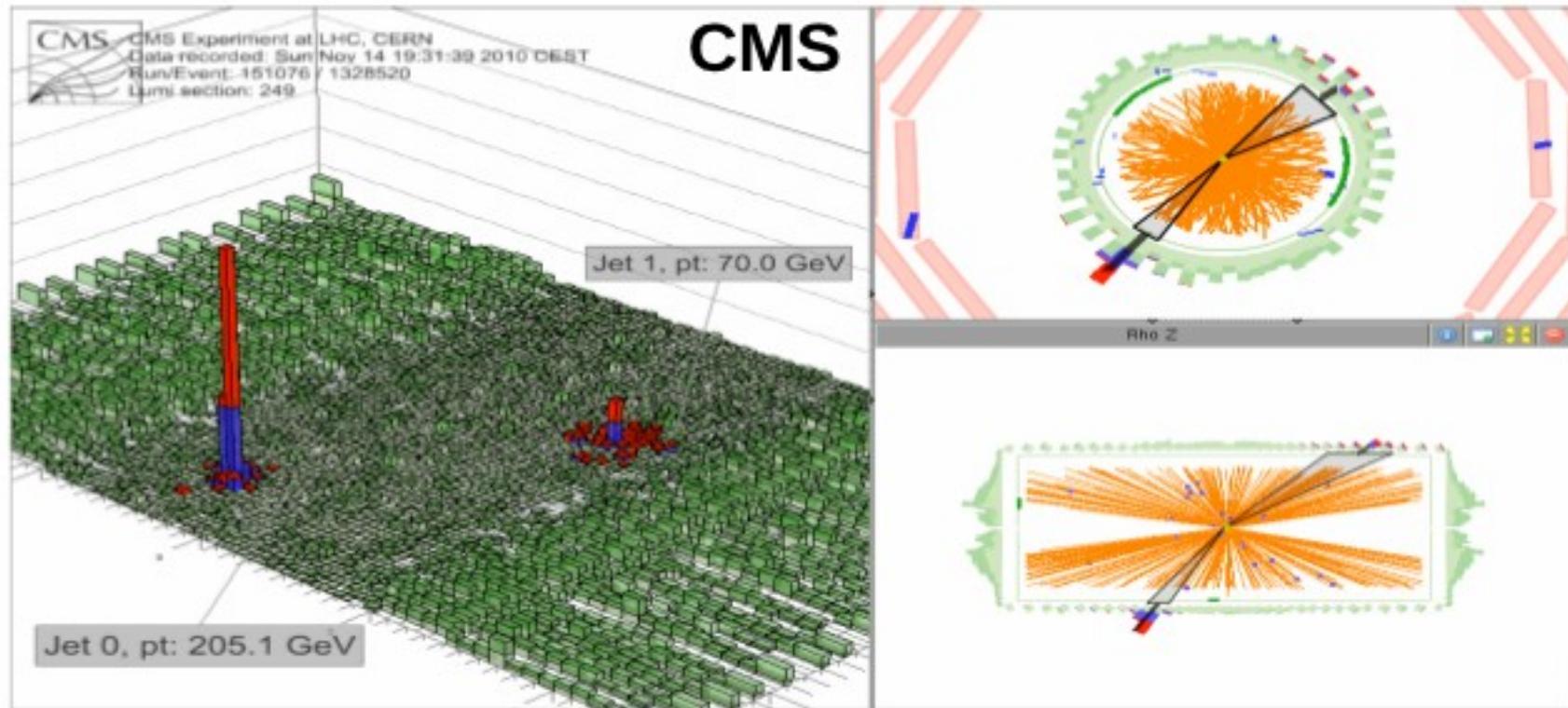
35



Can even be seen in event displays!!!

# Jet quenching in dijet events

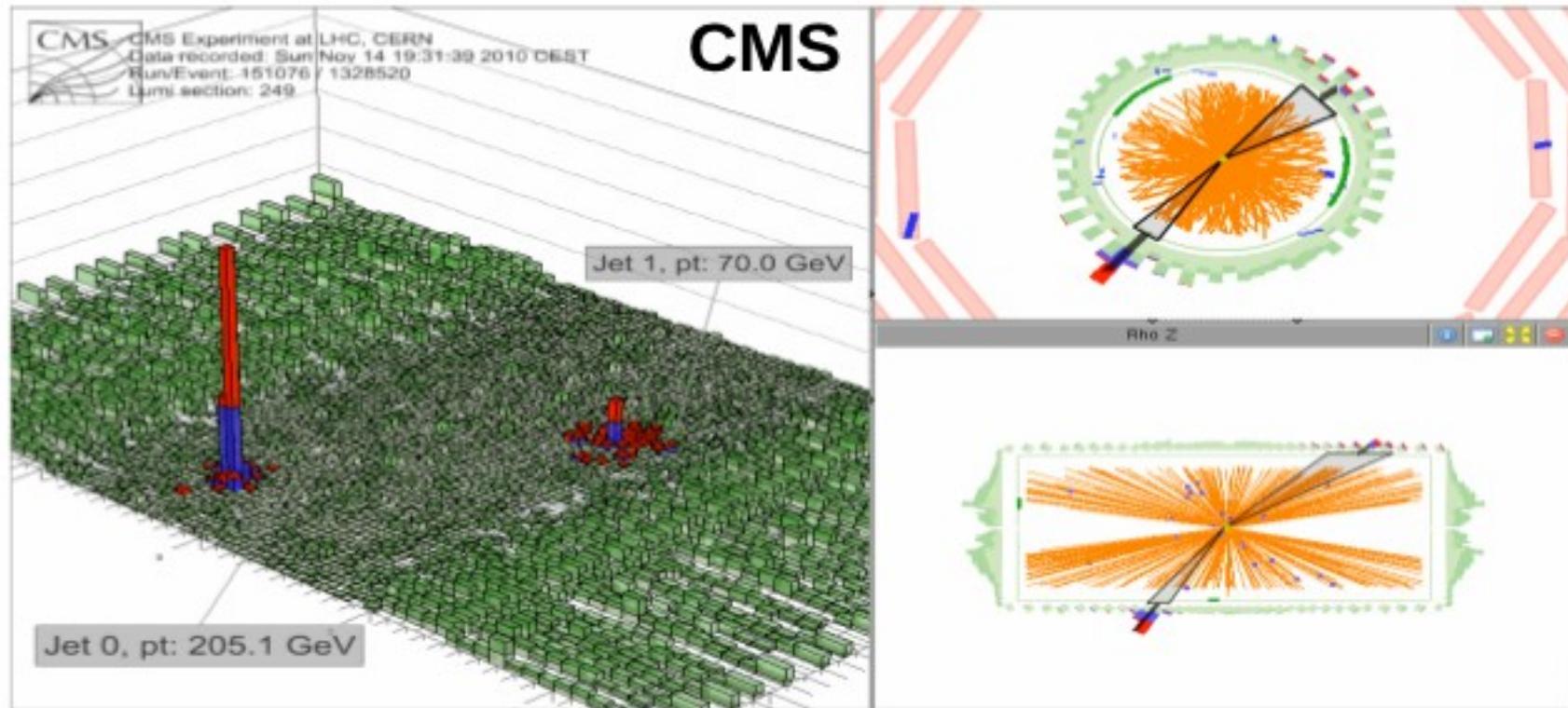
36



Can even be seen in event displays!!!

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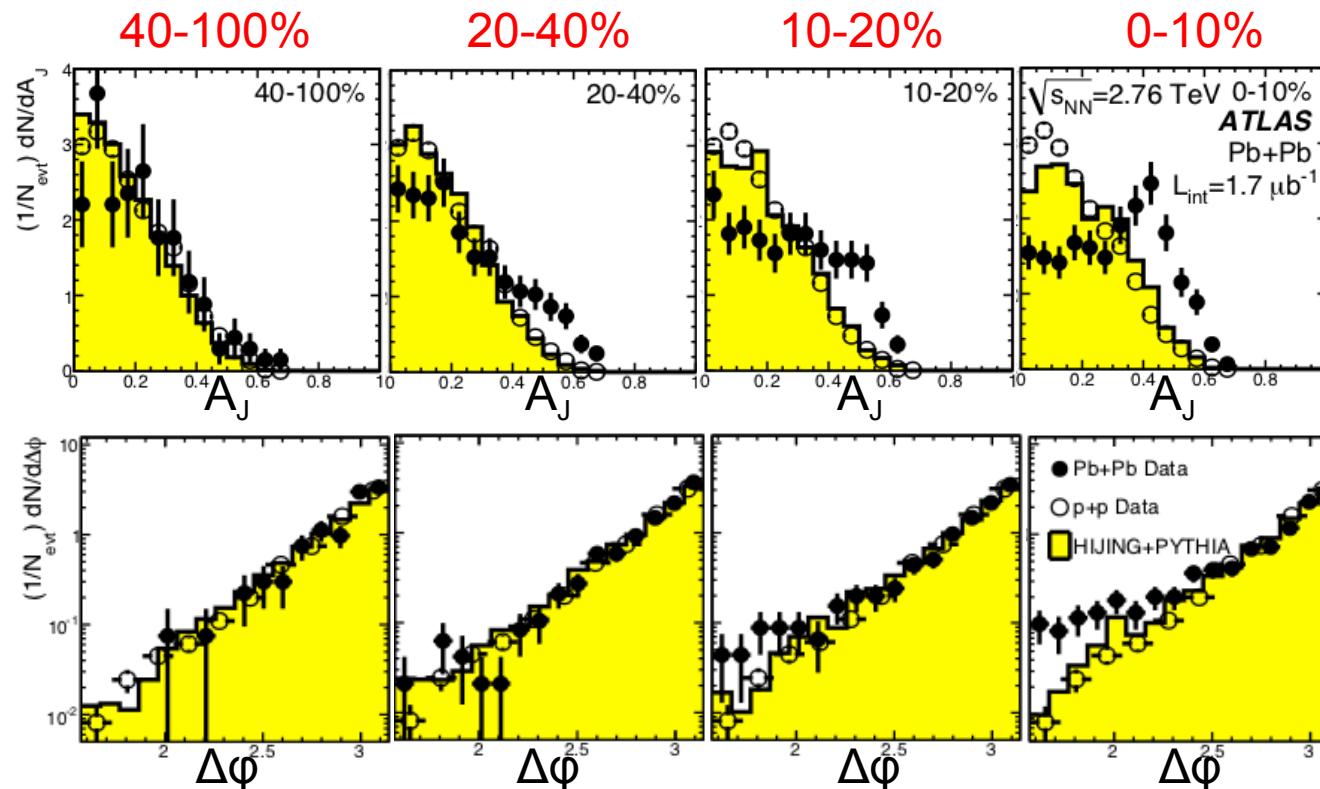
37



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

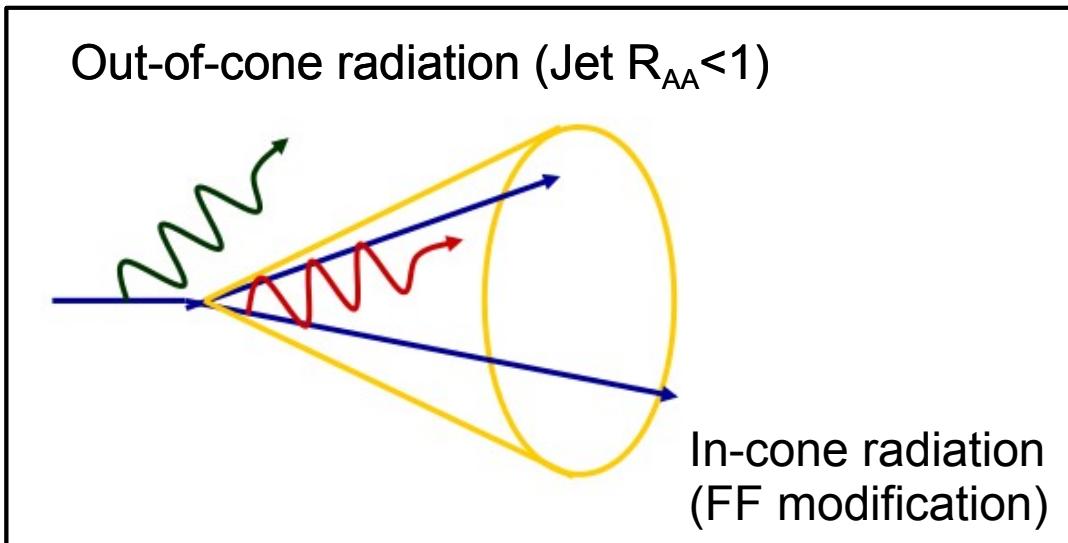


Momentum imbalance wrt to MC (pp) reference increases with increasing centrality.  
No (or very little) azimuthal decorrelation.

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

# Where does the radiated energy go?

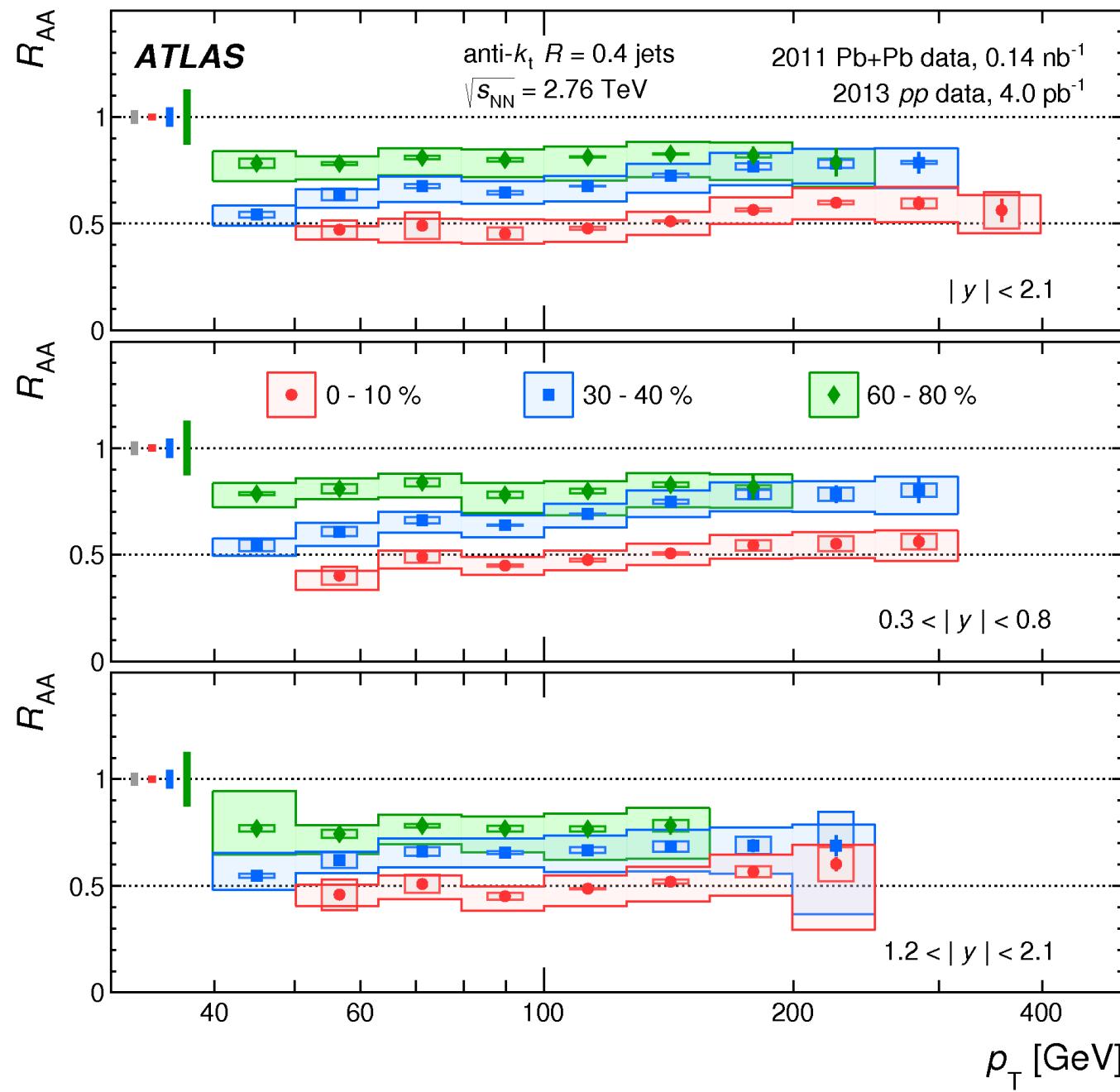
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# Jet $R_{AA}$ up to very high $p_T$

arXiv:1506.08656

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

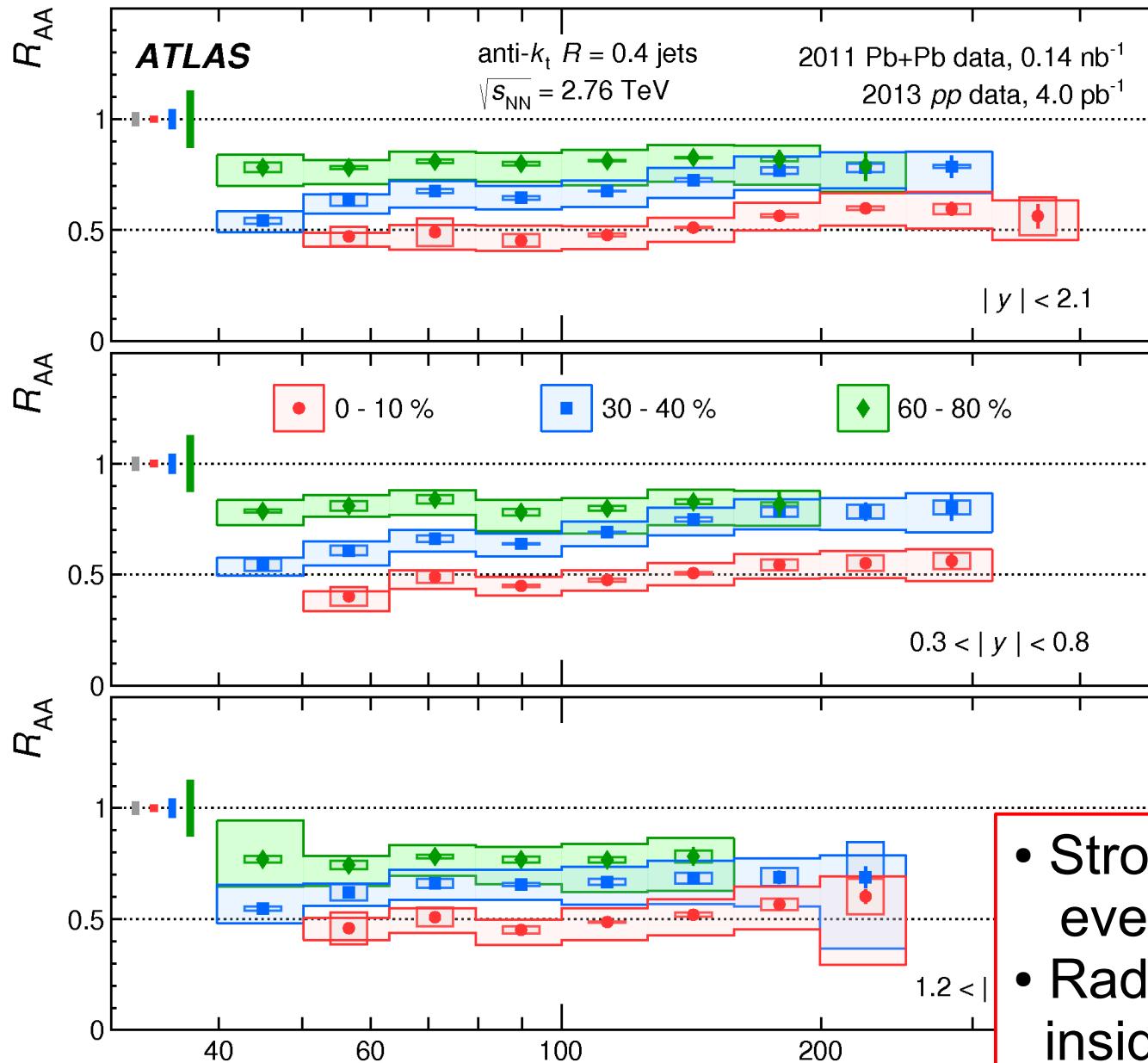


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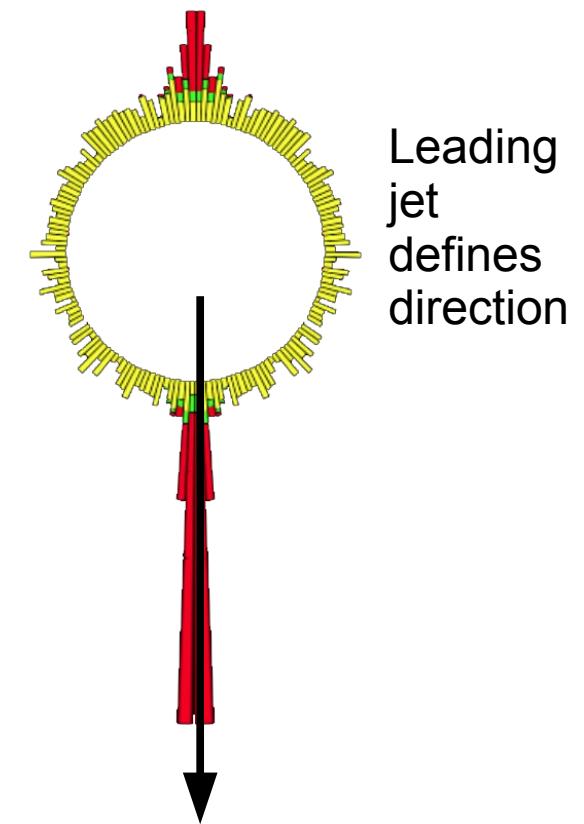


- Strong jet suppression even at up to 200-300 GeV
- Radiation not captured inside cone  $R=0.4$
- Where does the energy go?

# Where does the energy go?

42

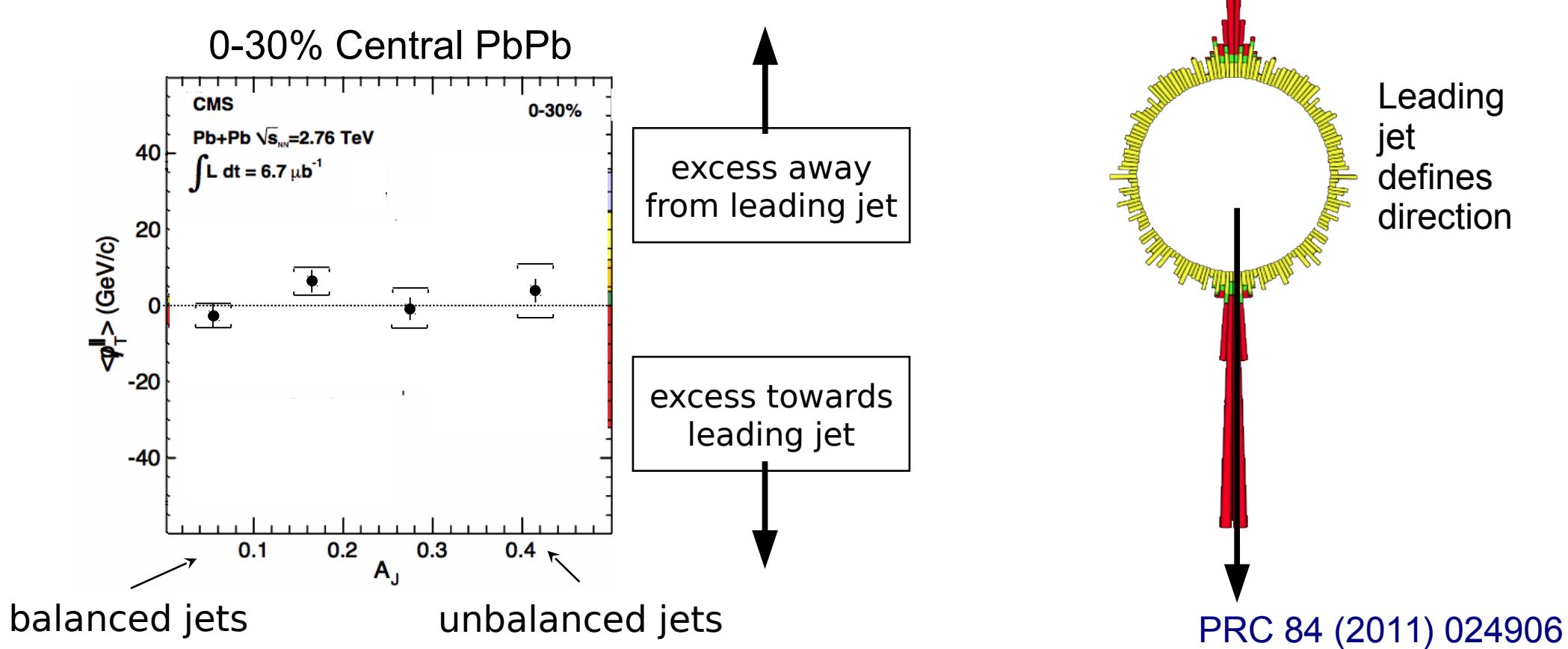
- Calculate projection of  $p_T$  on leading jet axis and average over selected tracks with  $p_T > 0.5 \text{ GeV}/c$  and  $|\eta| < 2.4$
- Define missing  $p_T$   $\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos(\phi_{\text{Track}} - \phi_{\text{Leading Jet}})$
- Averaging over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



# Where does the energy go?

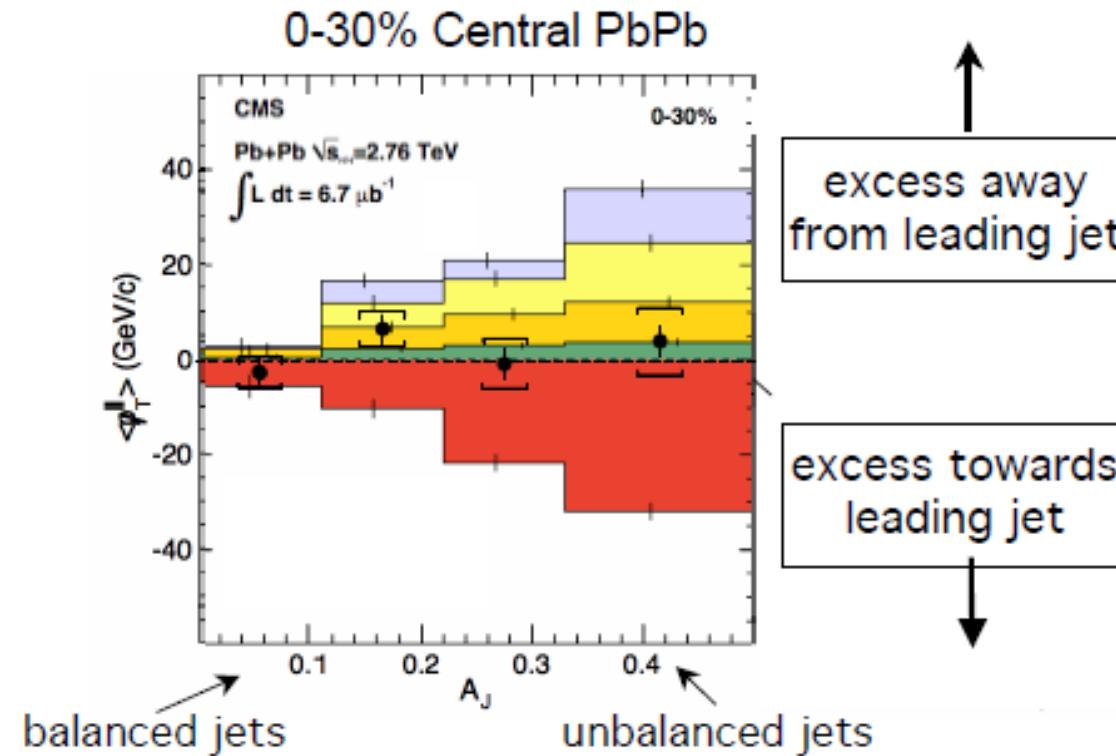
43

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

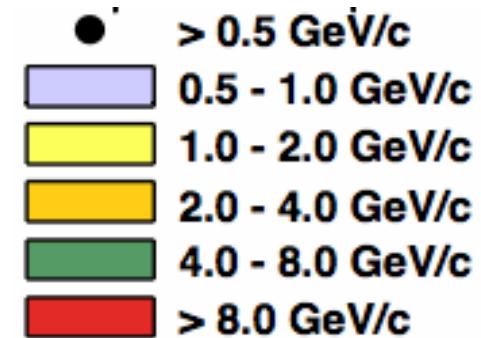


# Where does the energy go?

44



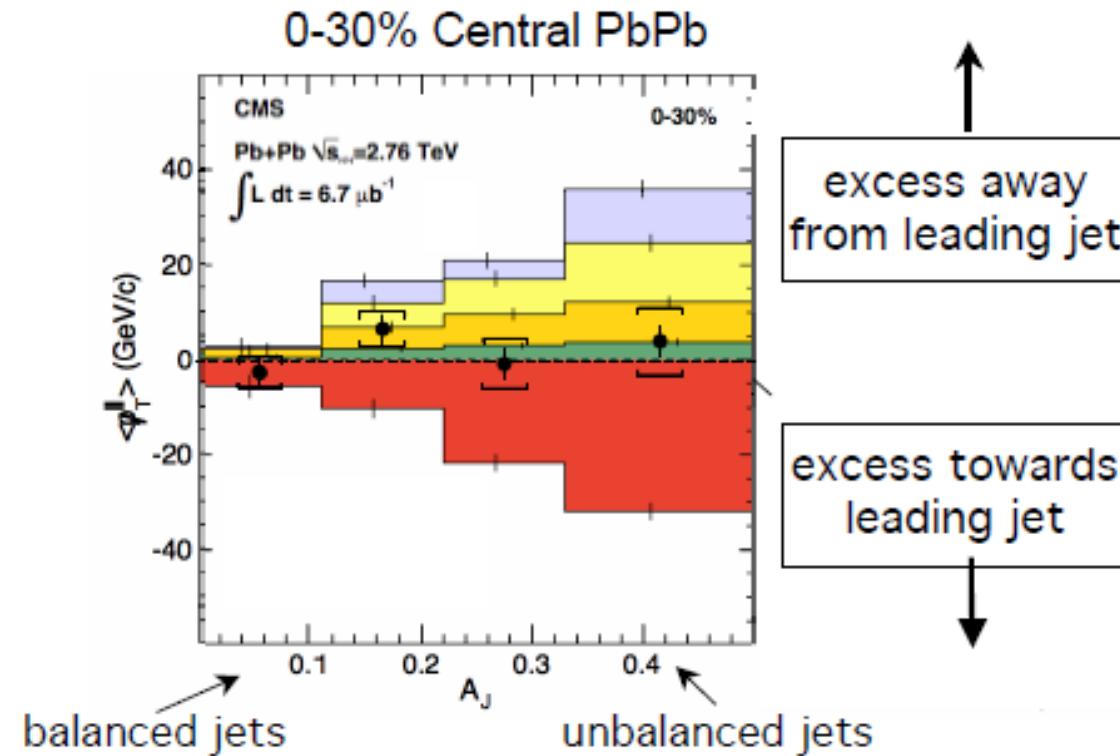
Calculate missing  $p_T$   
in bins of track  $p_T$



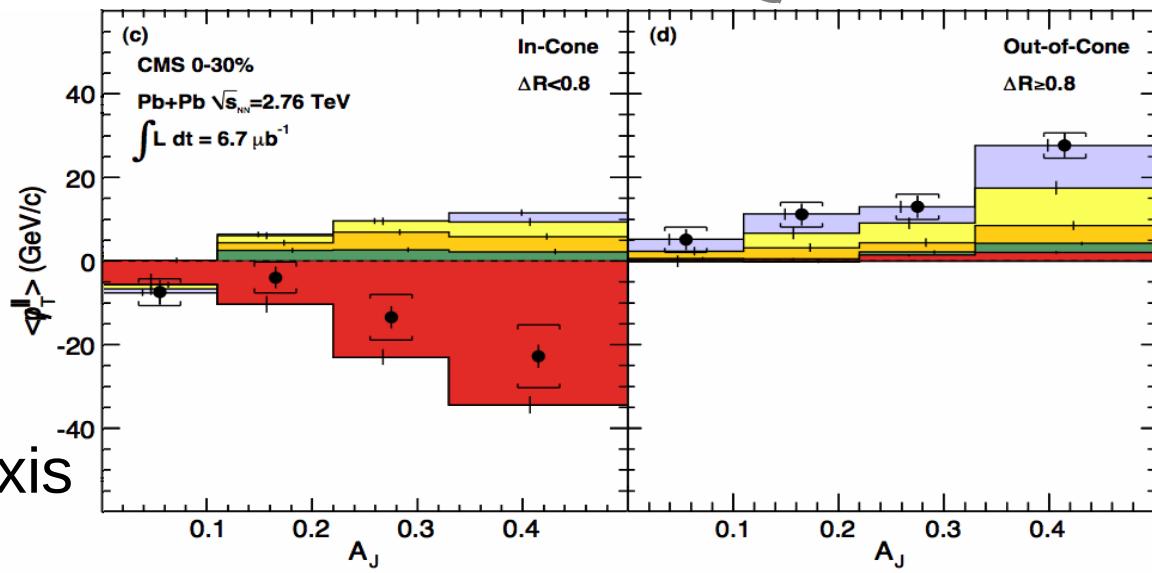
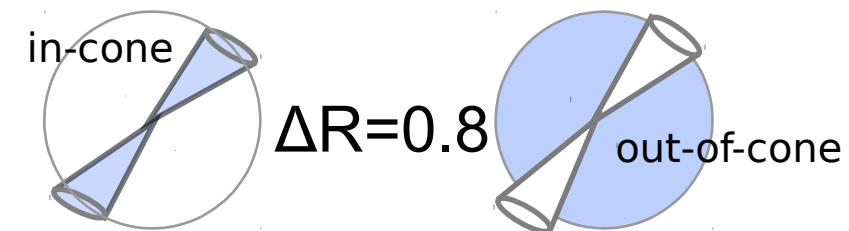
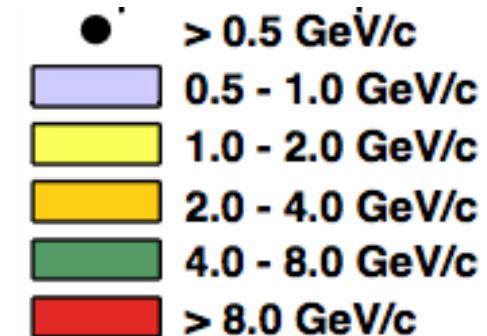
The momentum difference in  
the leading jet is compensated  
by low  $p_T$  particles

# Where does the energy go?

45



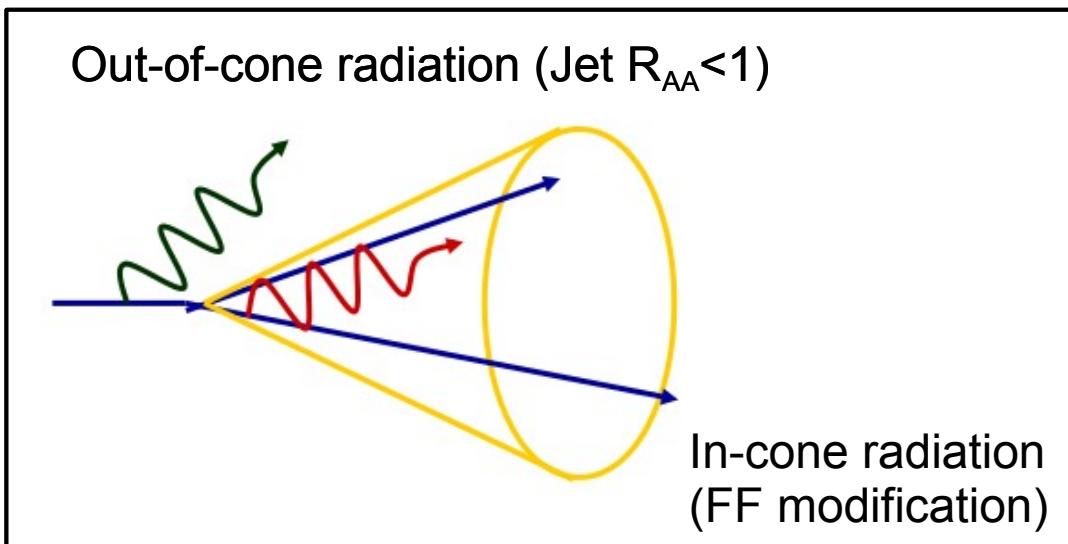
Calculate missing  $p_T$  in bins of track  $p_T$



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?

46



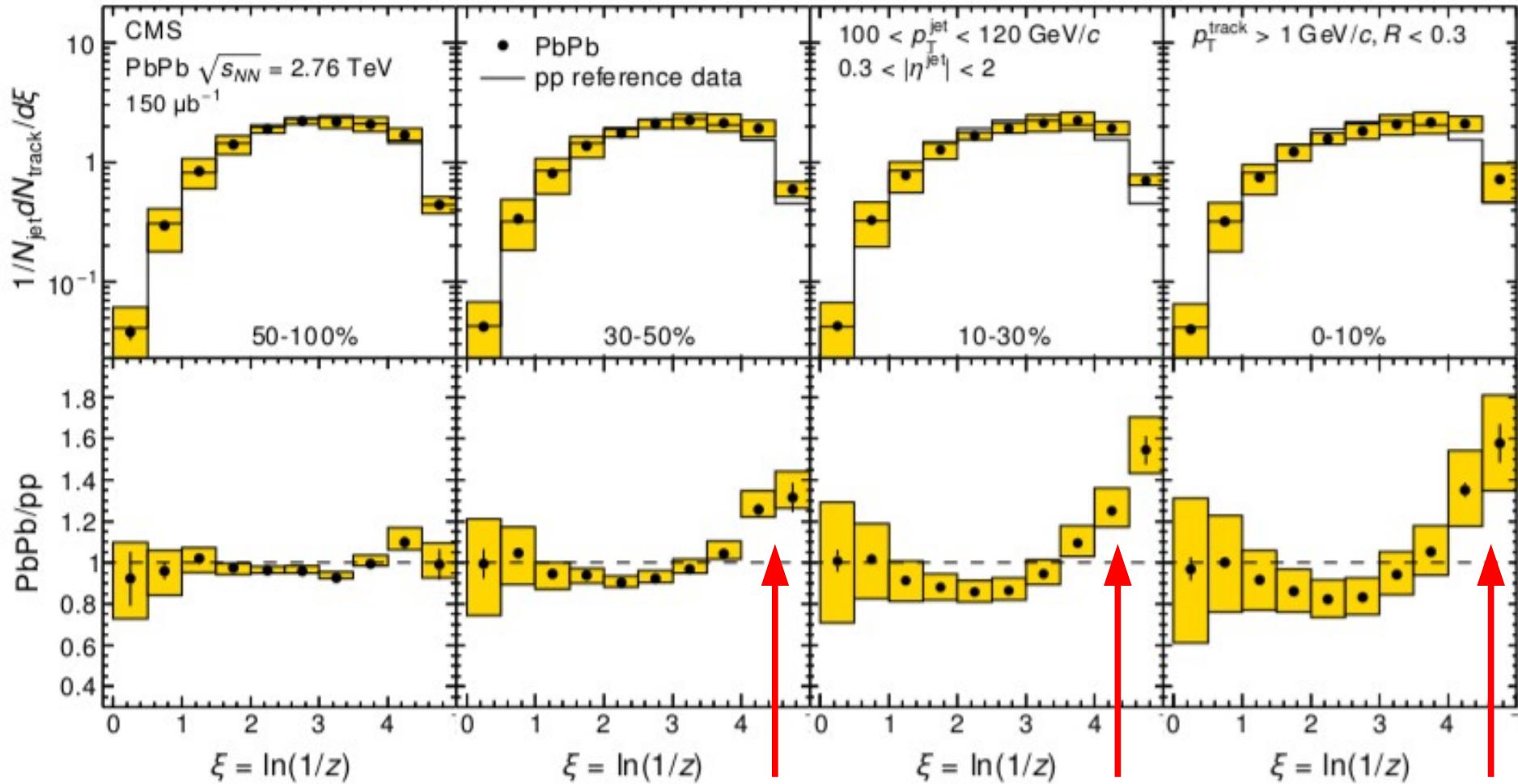
Is there an observable difference in the jet cone?

# Jet fragmentation function

47

arXiv:1406.0932

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



$R=0.3$

$100 < p_T < 120 \text{ GeV}/c$

Track  $p_T > 1 \text{ GeV}/c$

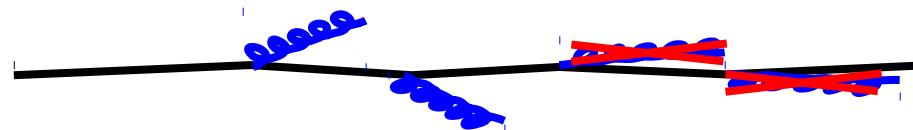
Fragmentation function is modified:

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



Suppression for  
 $\theta < M_Q/E_Q$

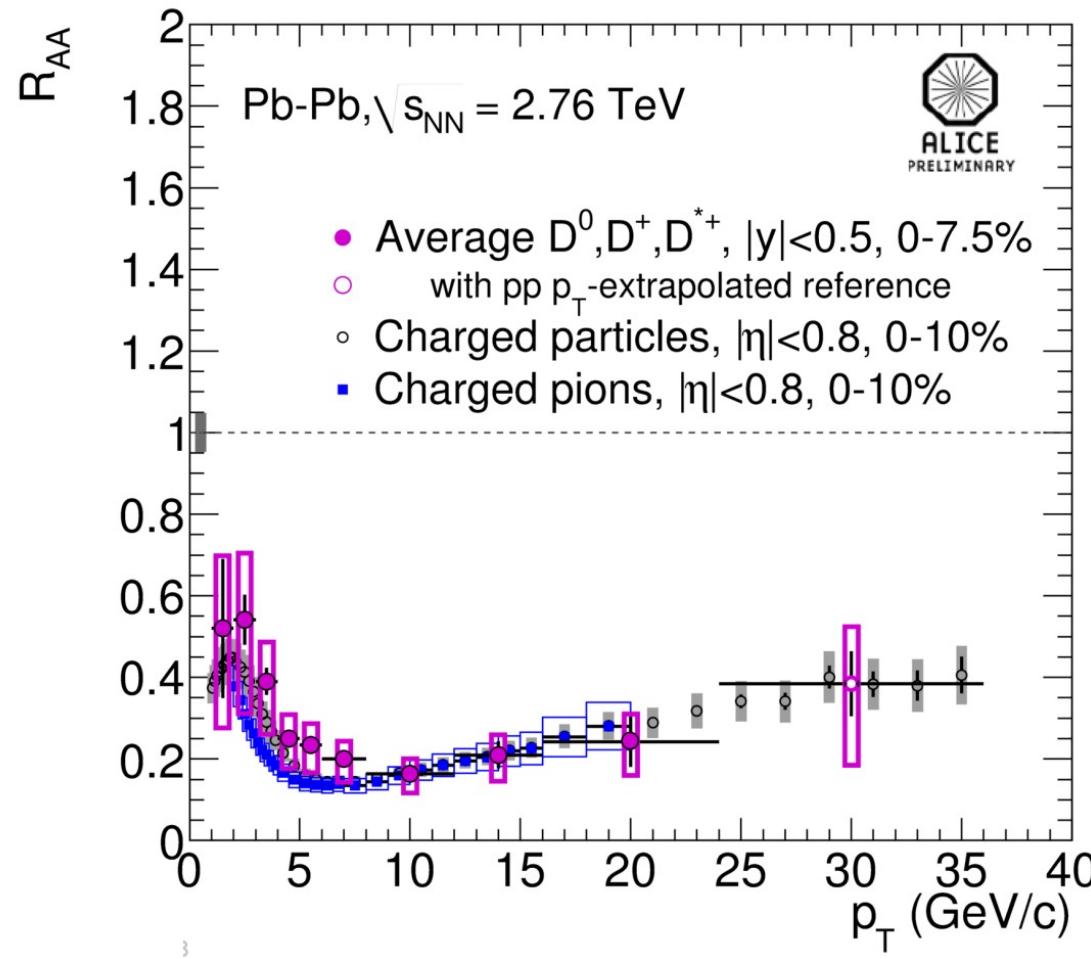
- Should lead to a suppression hierarchy

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



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

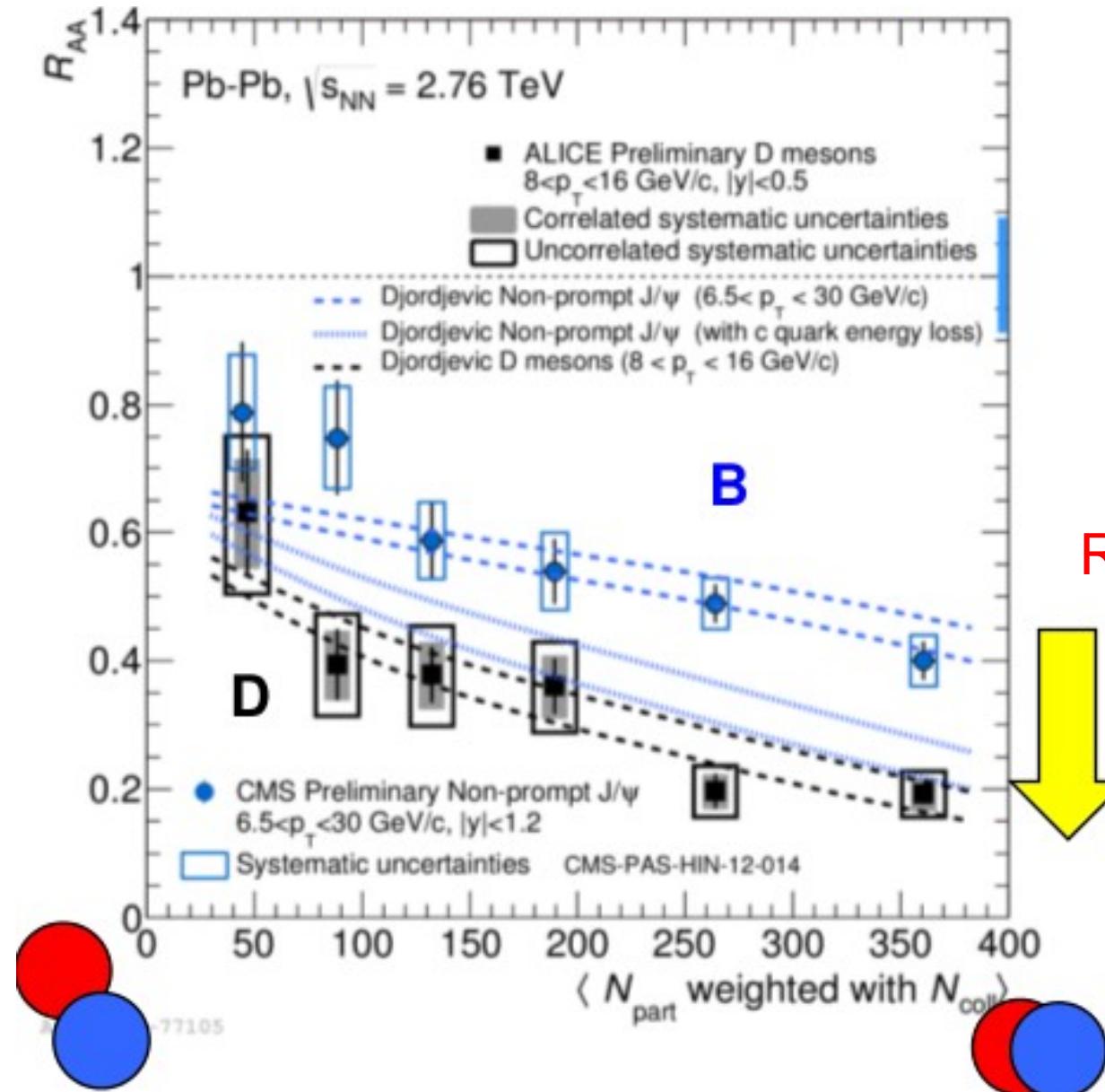
# D-mesons



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

# Beauty via non-prompt J/ $\psi$

51



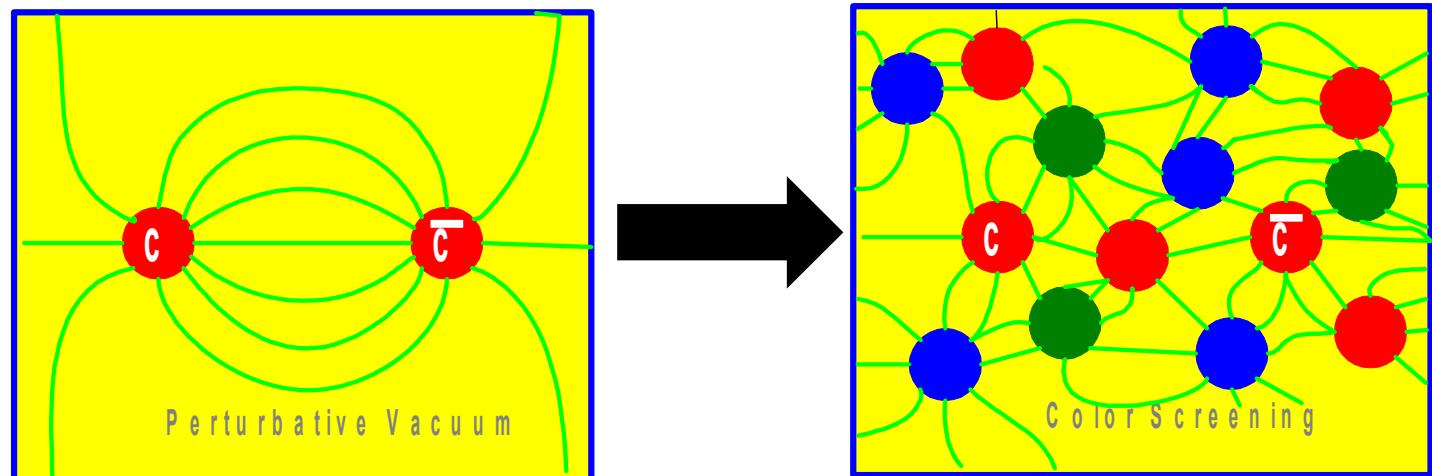
Suppression pattern compatible  
with expected energy loss hierarchy

# Quarkonia

# Quarkonia melting at high temperature

53

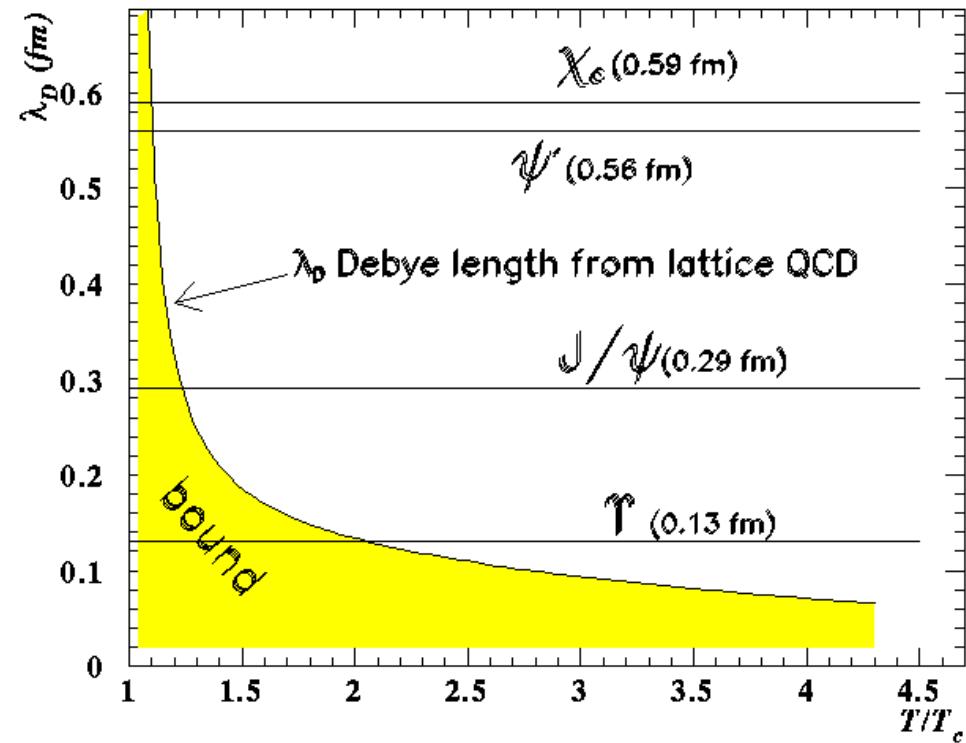
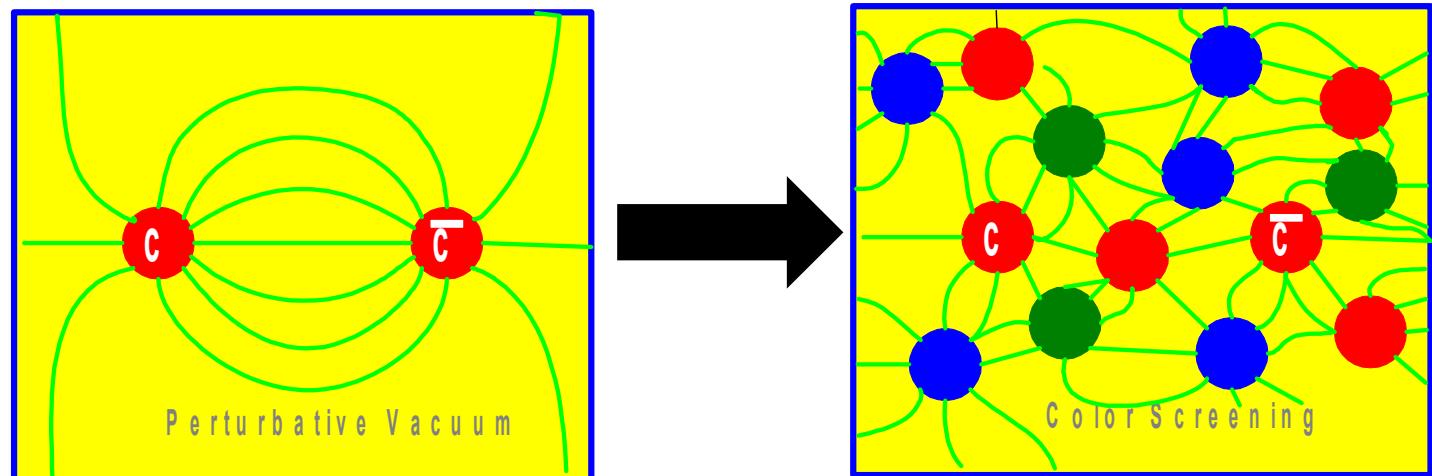
Screening of strong interactions in QGP



# Quarkonia melting at high temperature

54

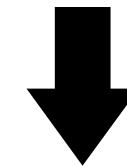
Screening of strong interactions in QGP



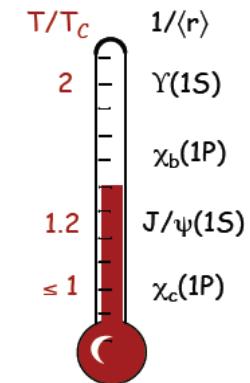
(original idea Matsui and Satz, 1986)

- 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



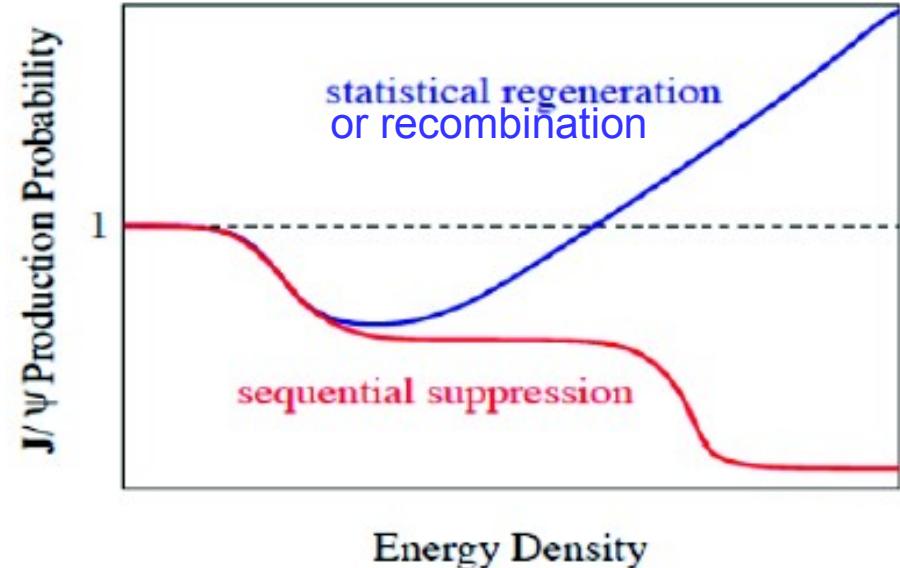
# Regeneration at high temperature

55

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
$N_{cc\bar{c}\bar{c}}/\text{event}$	~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

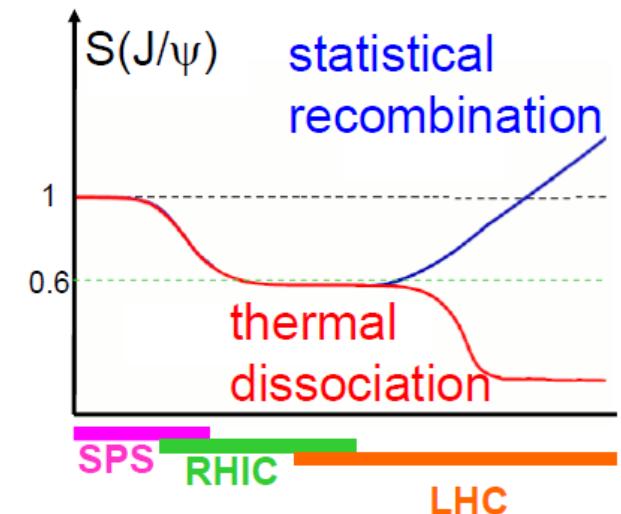
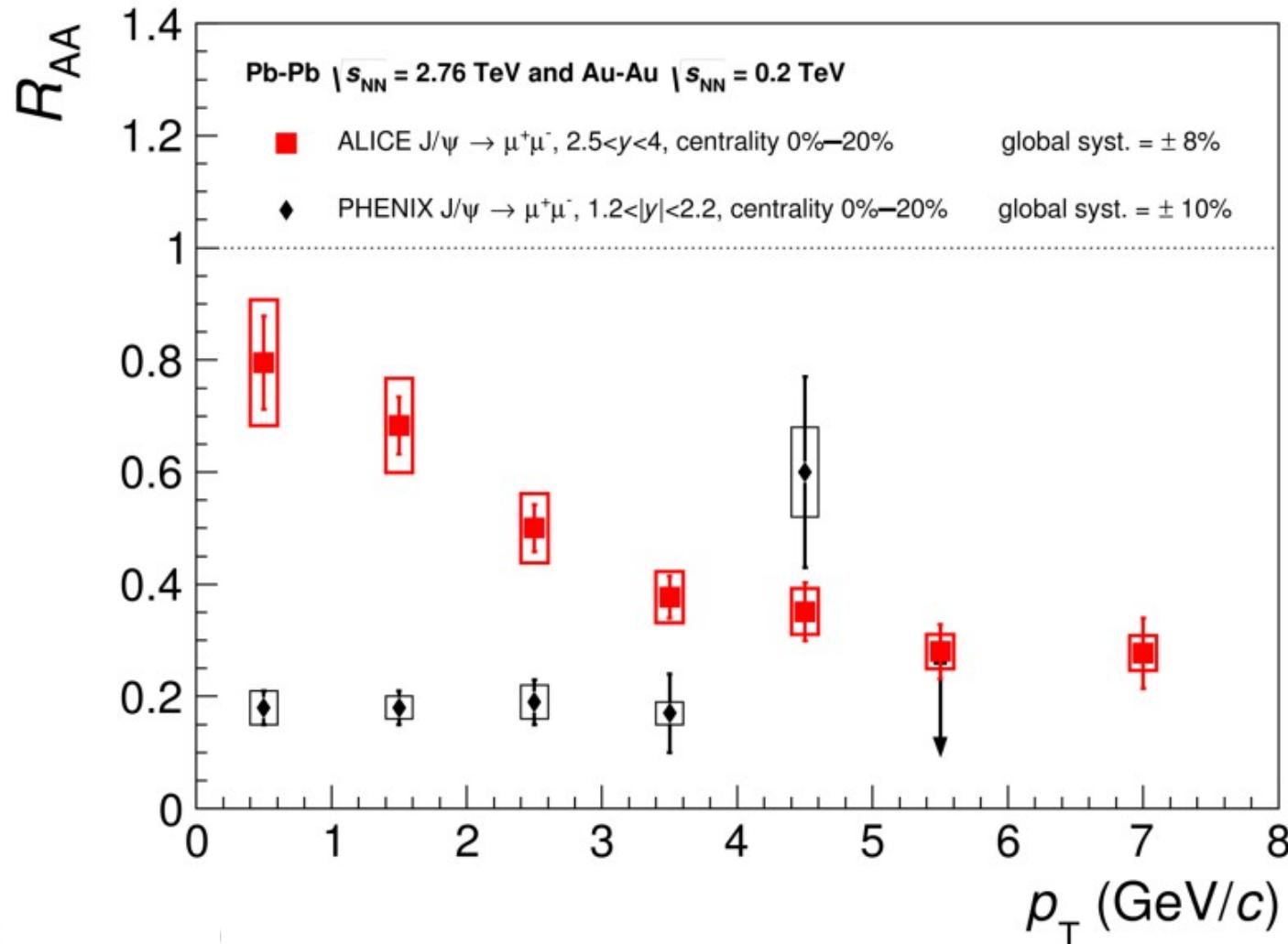


Contrary to the suppression / melting scenario, these approaches may lead to  $J/\psi$  enhancement

# LHC: J/ $\psi$ production in Pb-Pb

56

arXiv:1311.0214

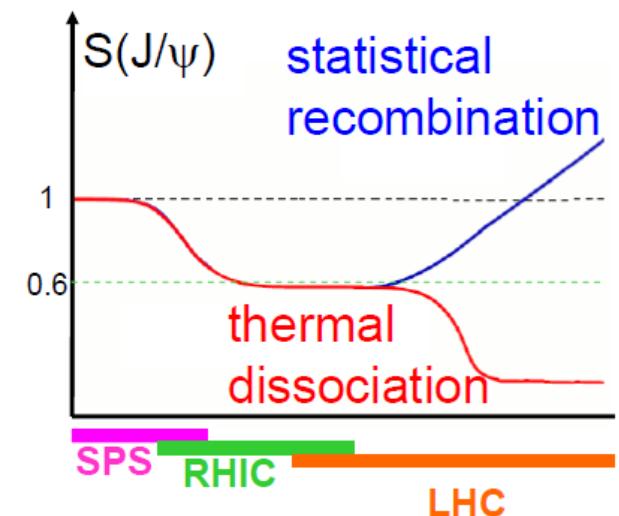
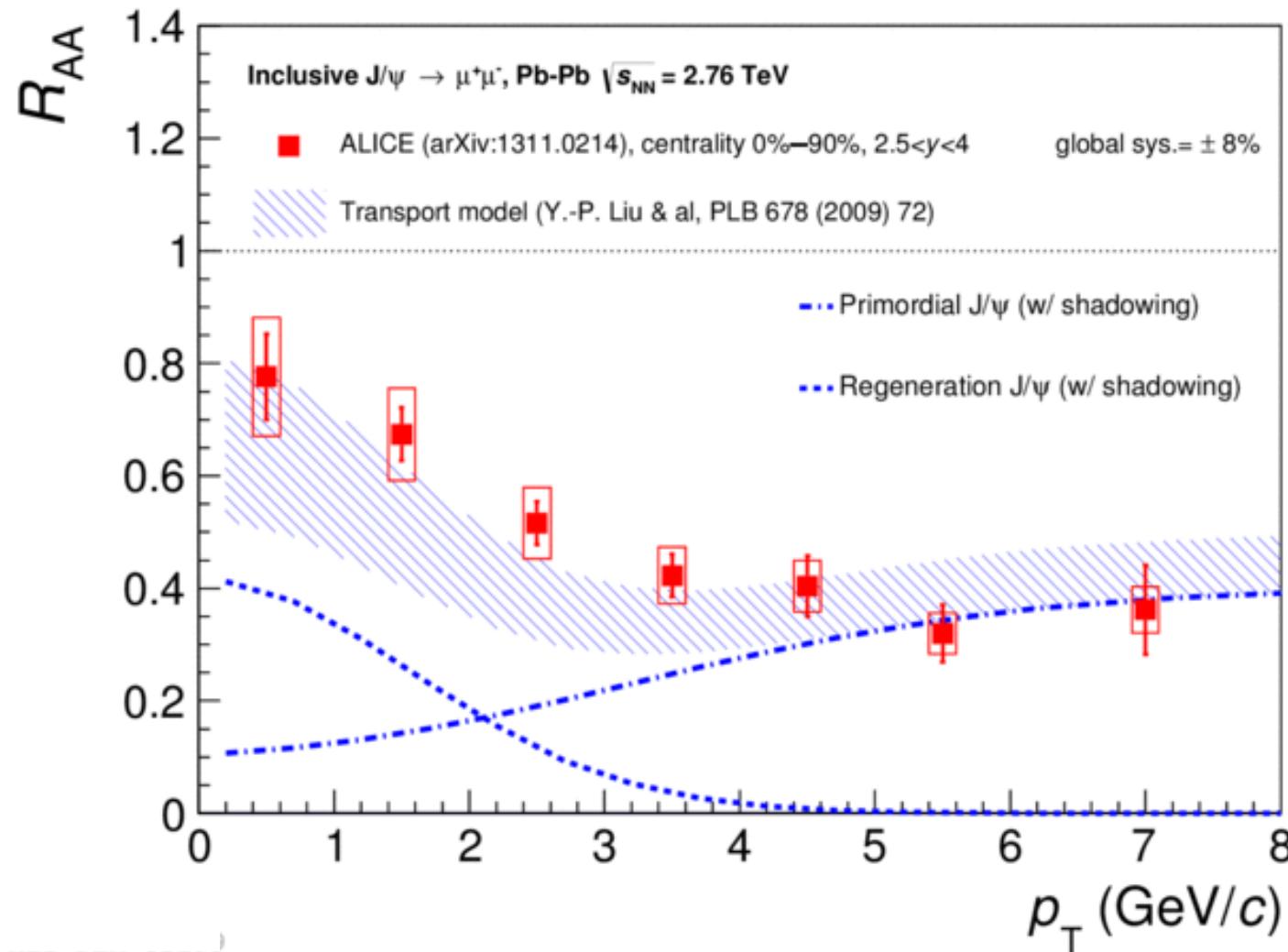


Different  $p_T$  (and centrality) dependence of  $J/\psi$   $R_{AA}$  at LHC and RHIC

# J/ $\psi$ production in Pb-Pb

57

arXiv:1311.0214

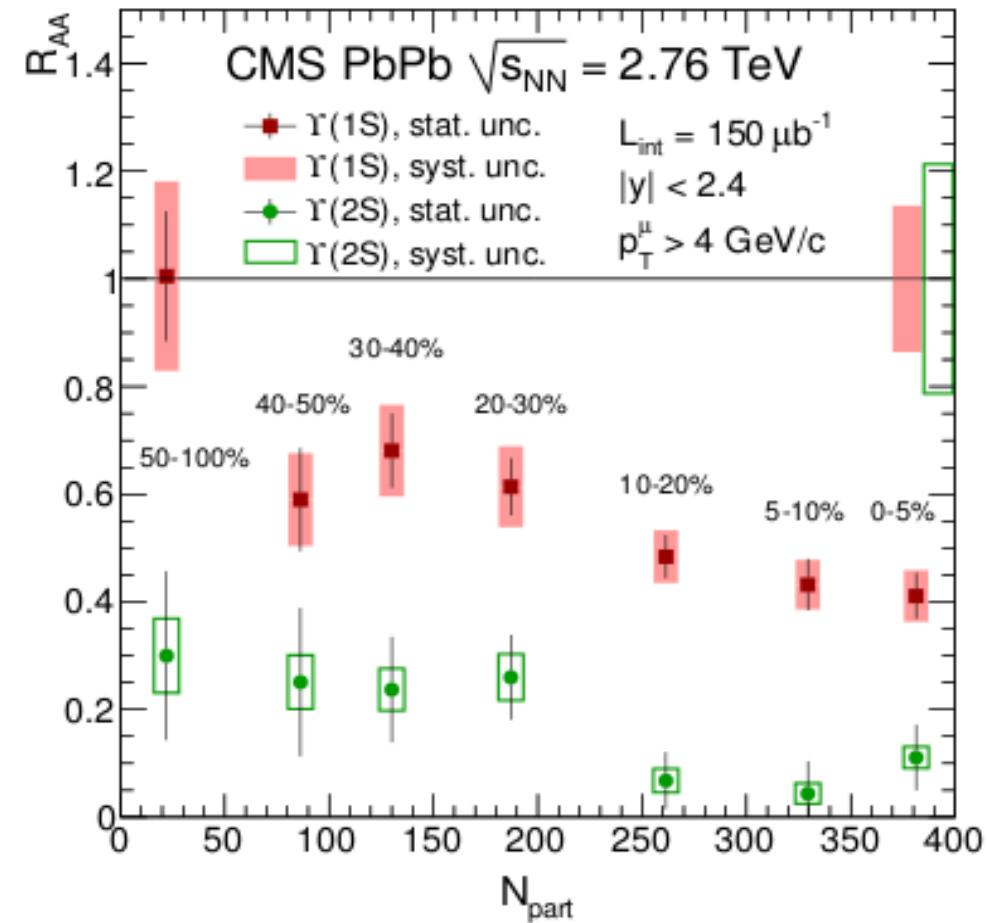
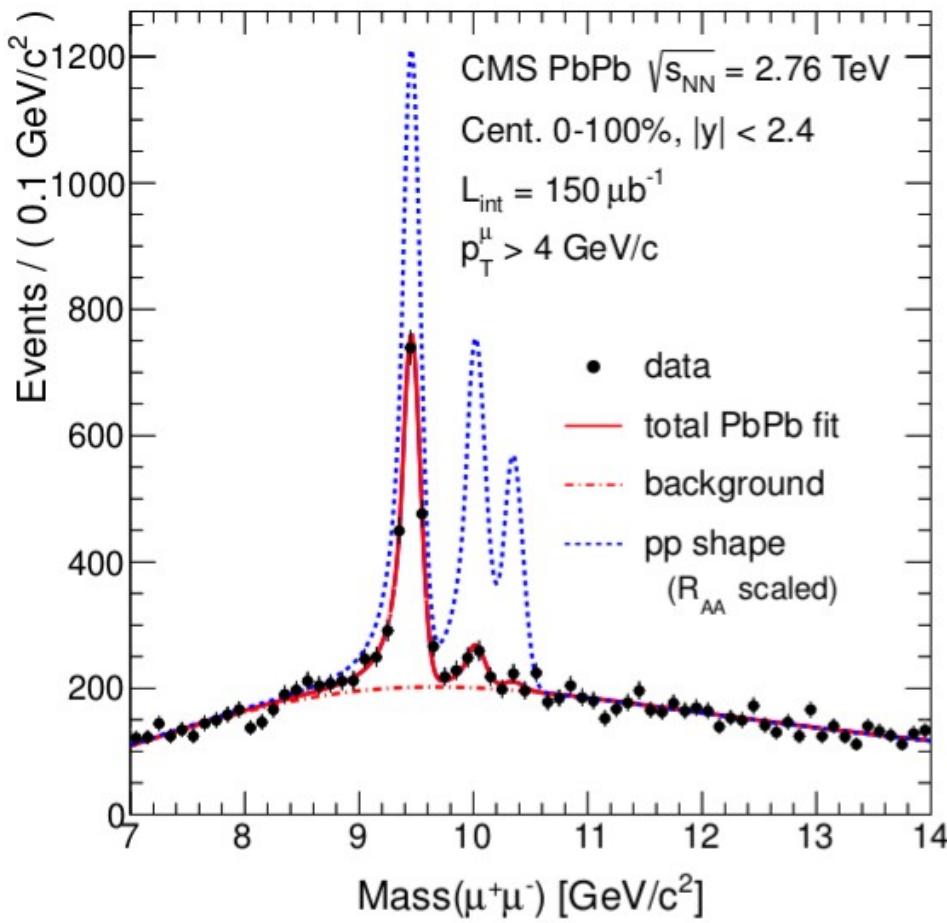


As expected in a scenario with  $c\bar{c}$  recombination, especially at low  $p_T$

# Suppression of Upsilon states

58

PRL 109 (2012) 222301

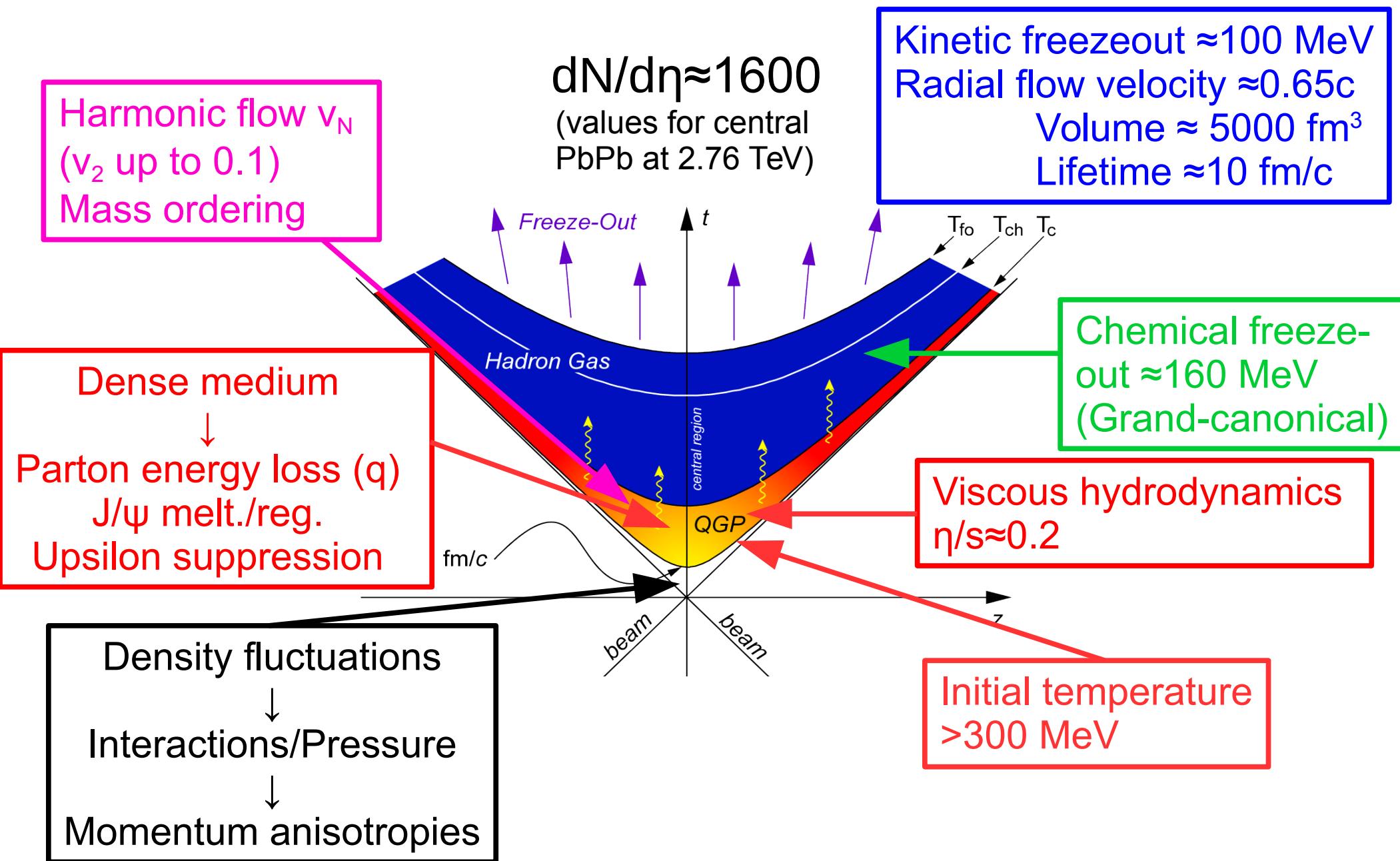


Suppression of  $\Upsilon(1S)$  ground, and excited  $\Upsilon(2S)$  and  $\Upsilon(3S)$  states.  
Ordering of  $R(3S) < R(2S) < R(1S)$  consistent with sequential melting.

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

# Summary on measurements

59

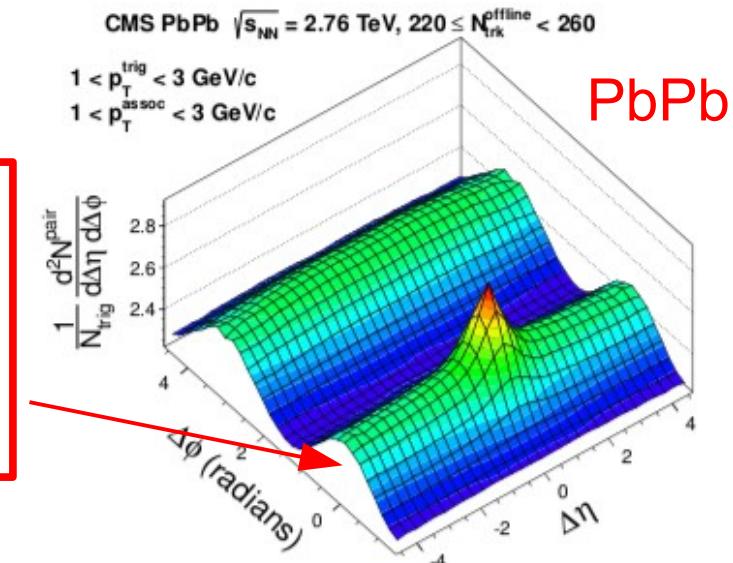


All observations (+ absence in control systems) point to the formation of hot deconfined matter!

# Collectivity in small systems

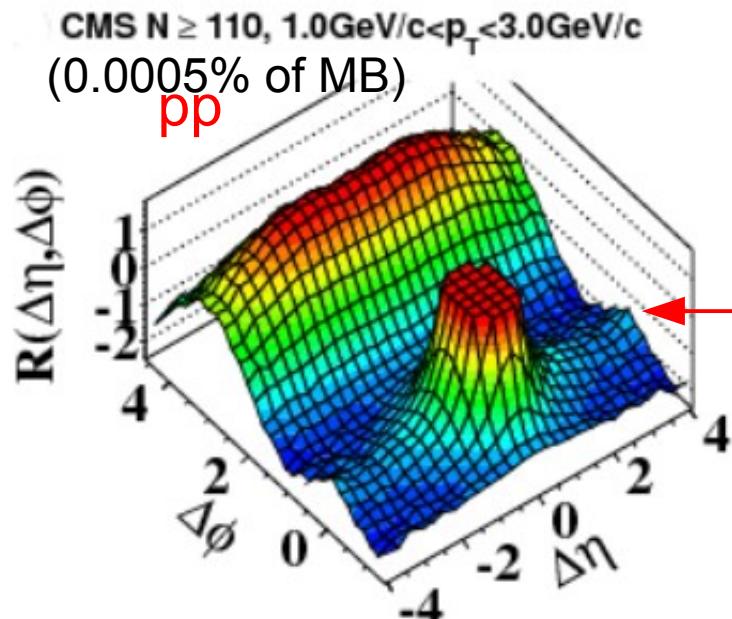
# Two-particle angular correlations

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



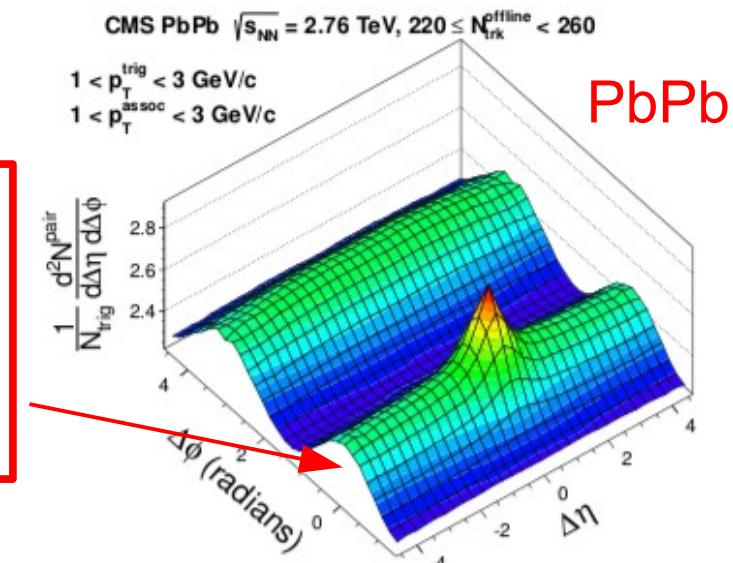
CMS, PLB 724 (2013) 213

# Two-particle angular correlations



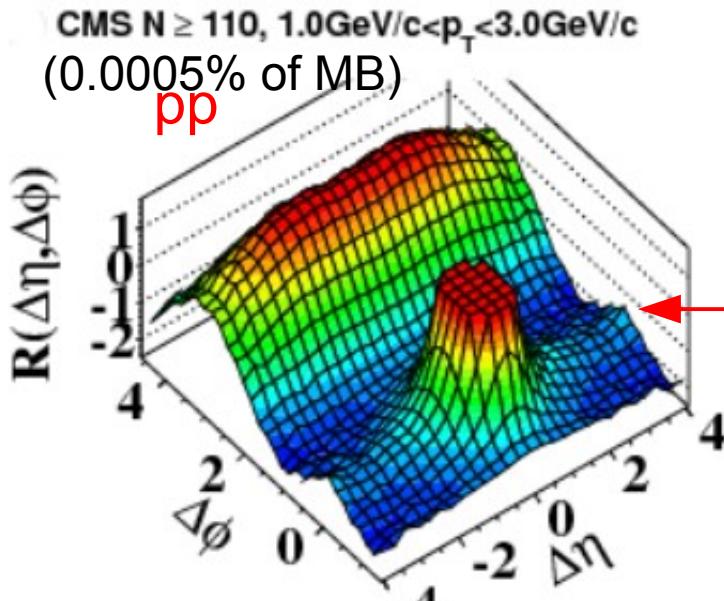
Near-side ridges  
apparent in high  
multiplicity events  
at LHC energies

CMS, JHEP 1009 (2010) 91

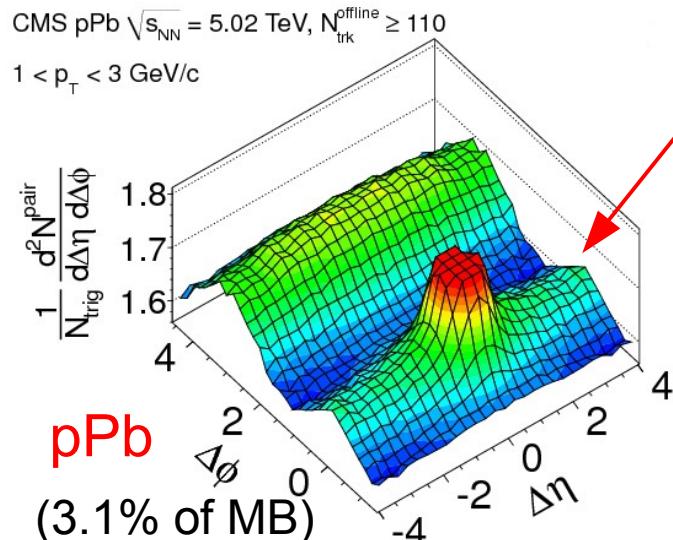


CMS, PLB 724 (2013) 213

# Two-particle angular correlations

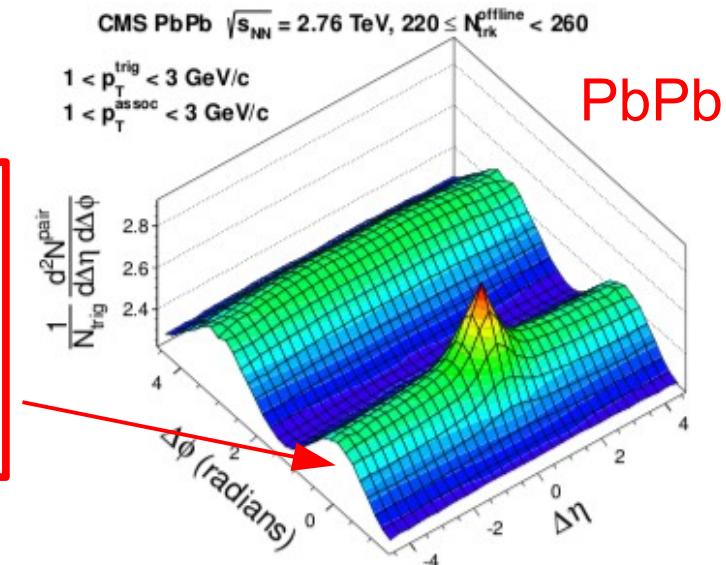


CMS, JHEP 1009 (2010) 91

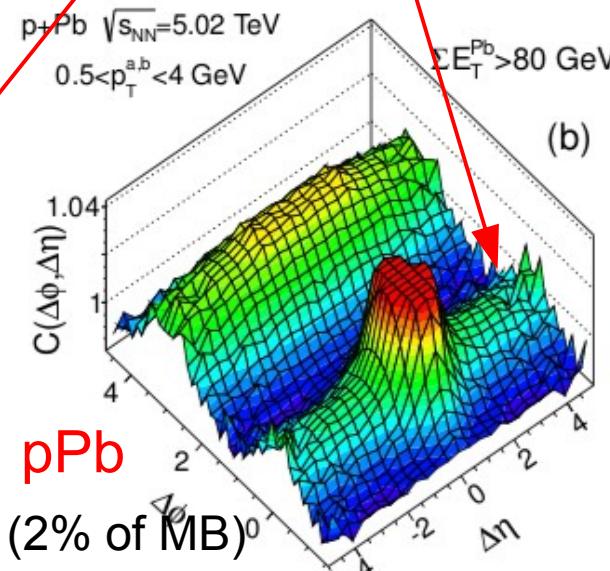


CMS, PLB 718 (2012) 795

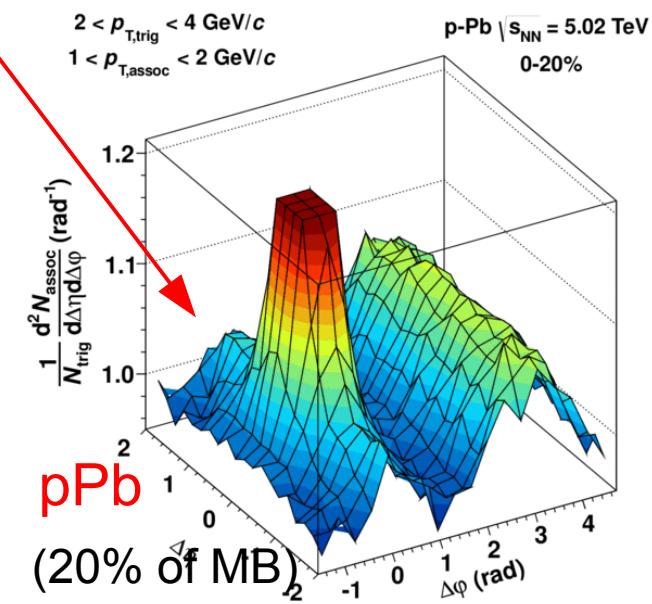
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CMS, PLB 724 (2013) 213

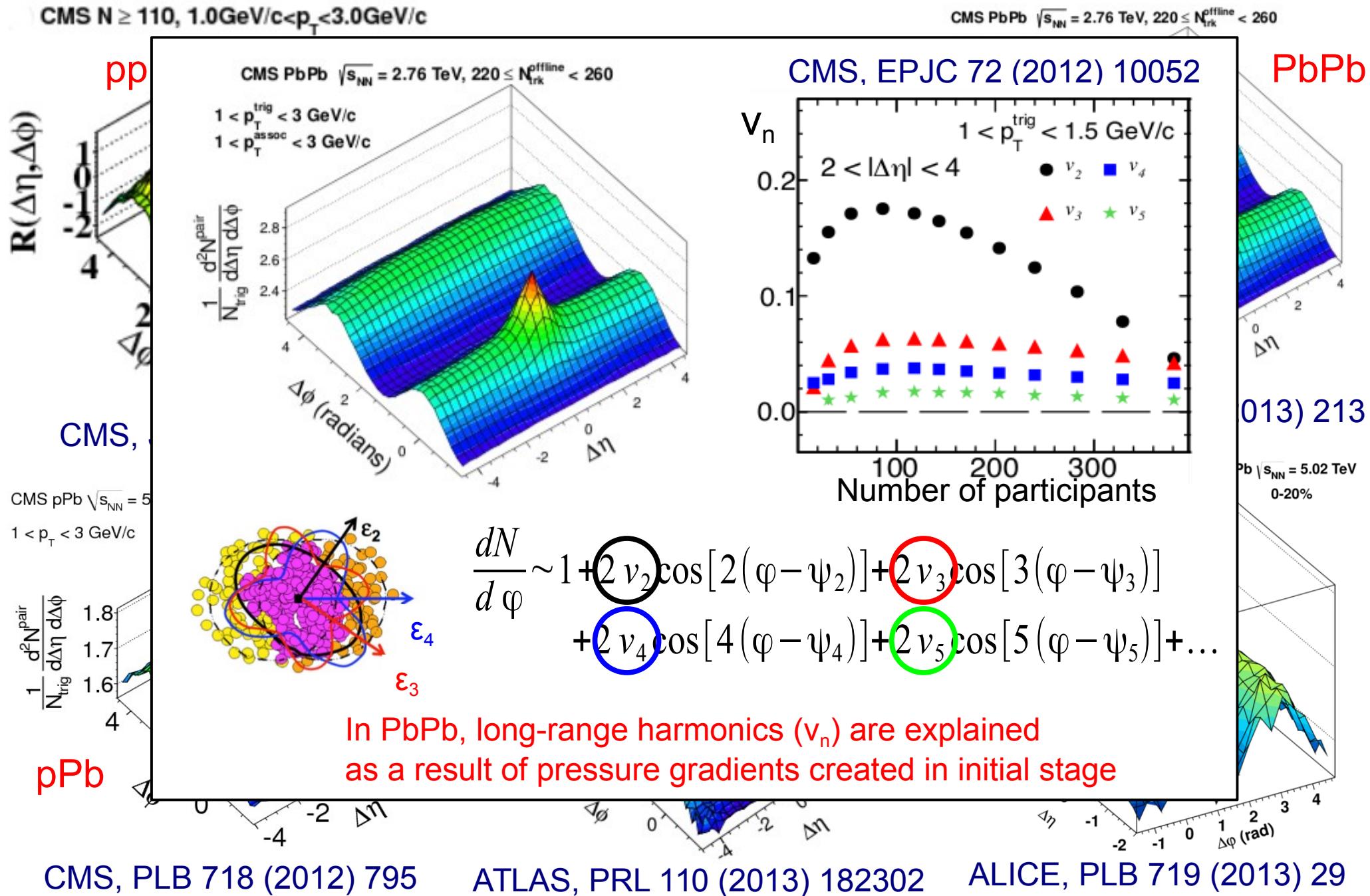


ATLAS, PRL 110 (2013) 182302



ALICE, PLB 719 (2013) 29

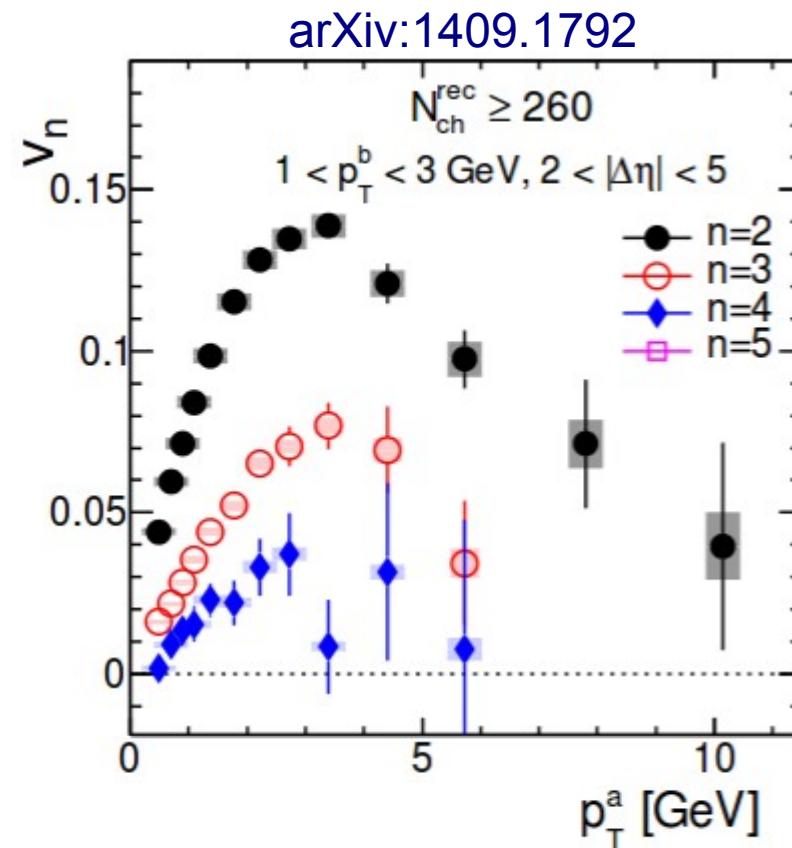
# Two-particle angular correlations



# Ridge properties in pPb

- $v_n$  coefficients

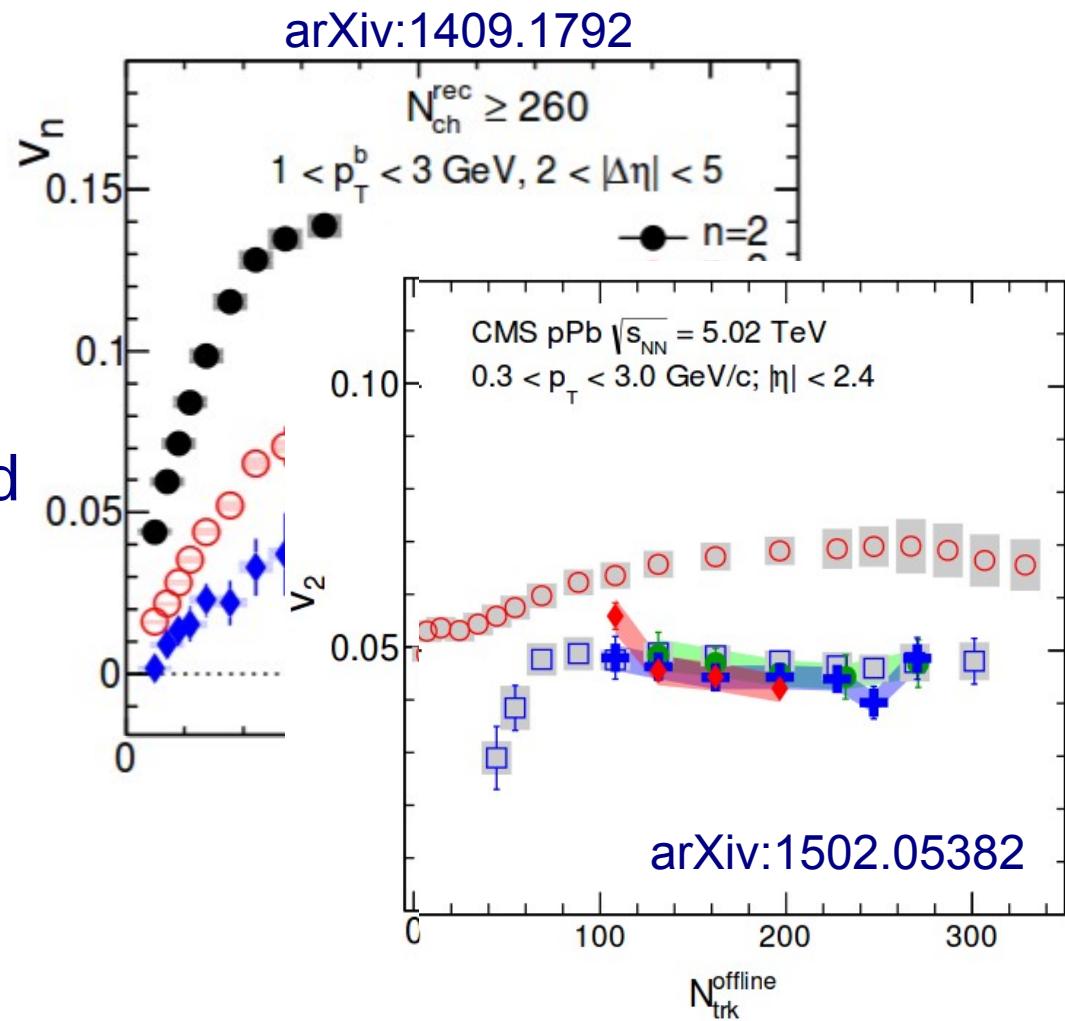
- Significant for  $n=2$  to 5
- Substantial to even high  $p_T$



# Ridge properties in pPb

66

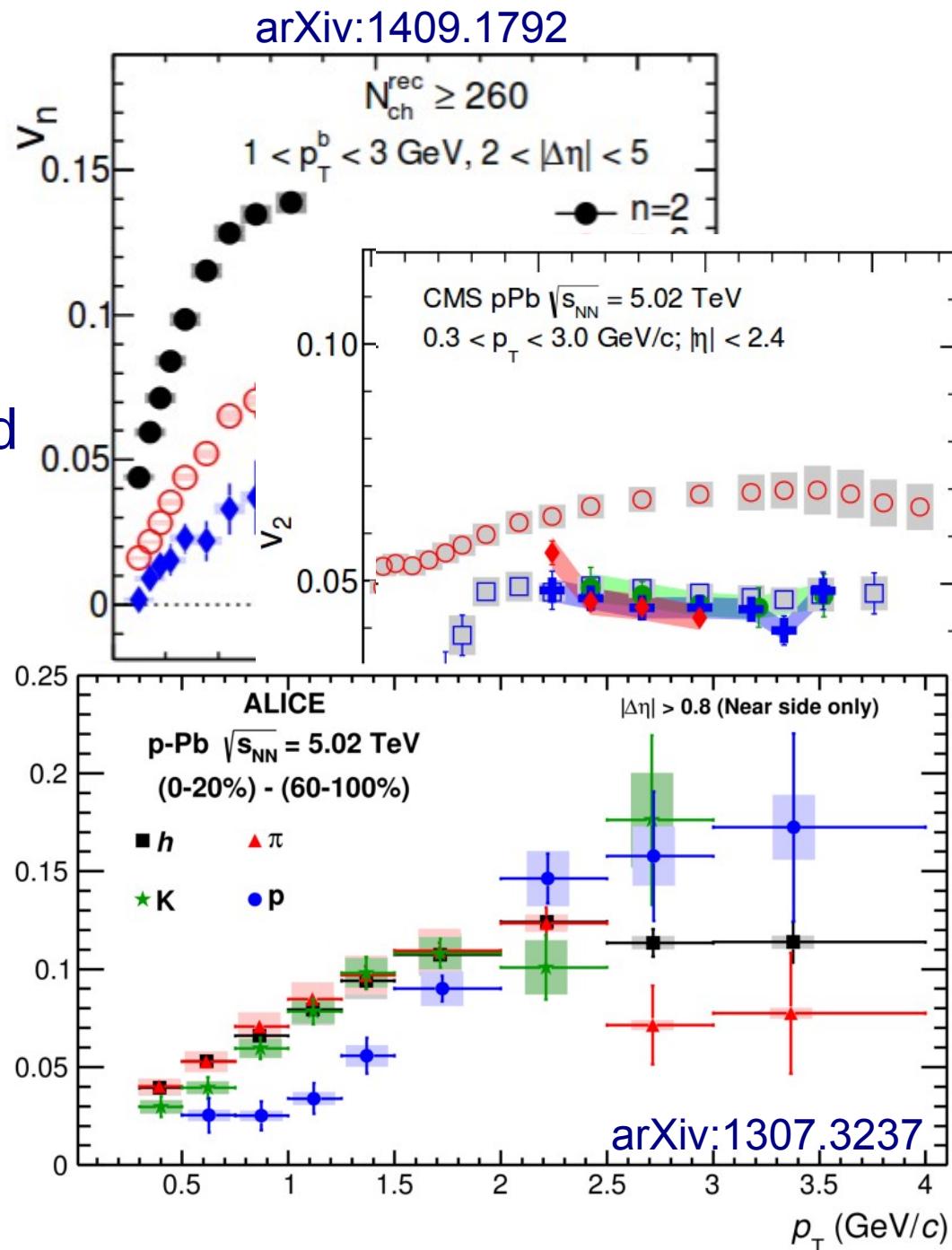
- $v_n$  coefficients
  - Significant for  $n=2$  to 5
  - Substantial to even high  $p_T$
- Multiparticle correlations
  - At least 8 particles correlated
  - $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$



# Ridge properties in pPb

67

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

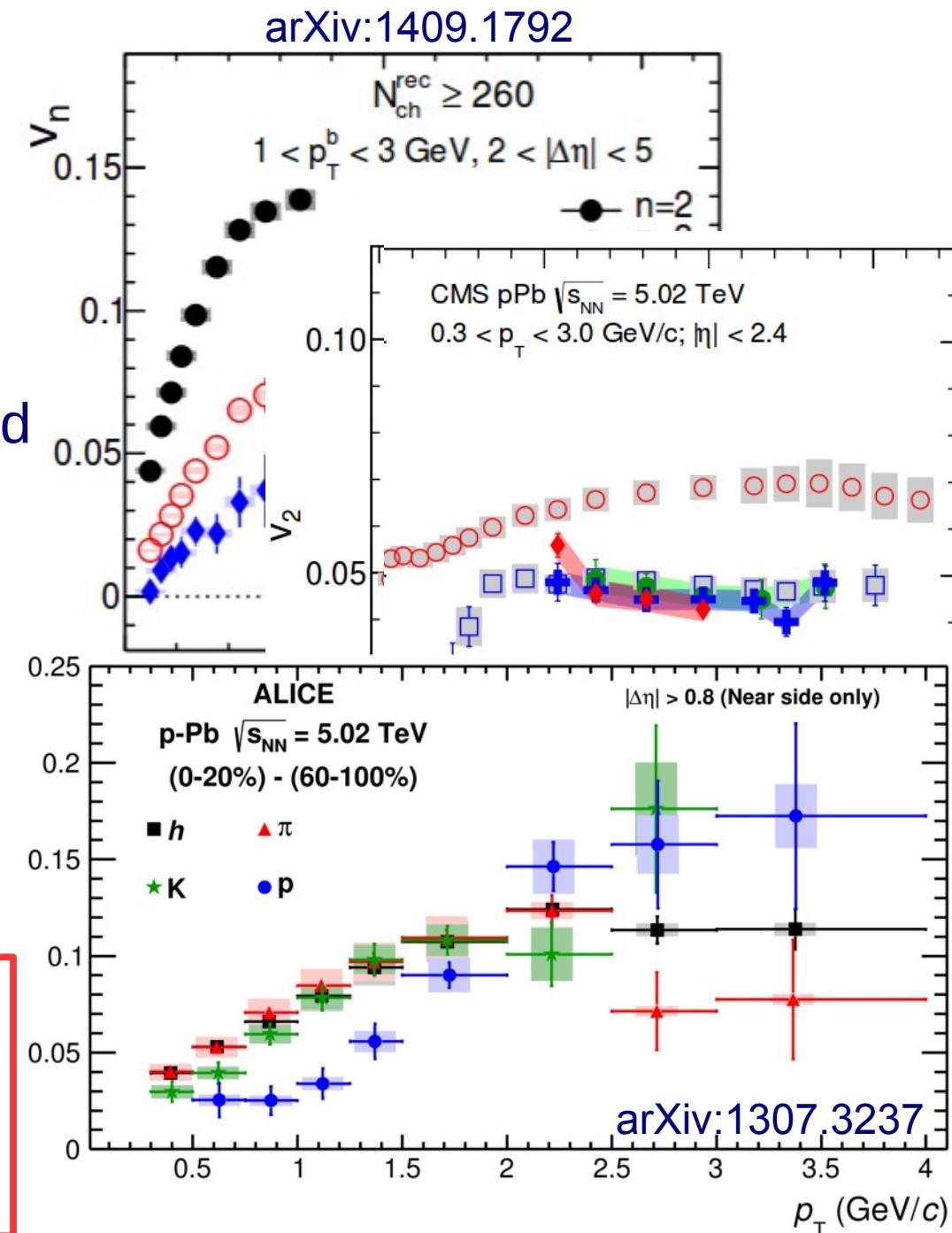


# Ridge properties in pPb

68

- $v_n$  coefficients
  - Significant for  $n=2$  to 5
  - Substantial to even high  $p_T$
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  - At least 8 particles correlated
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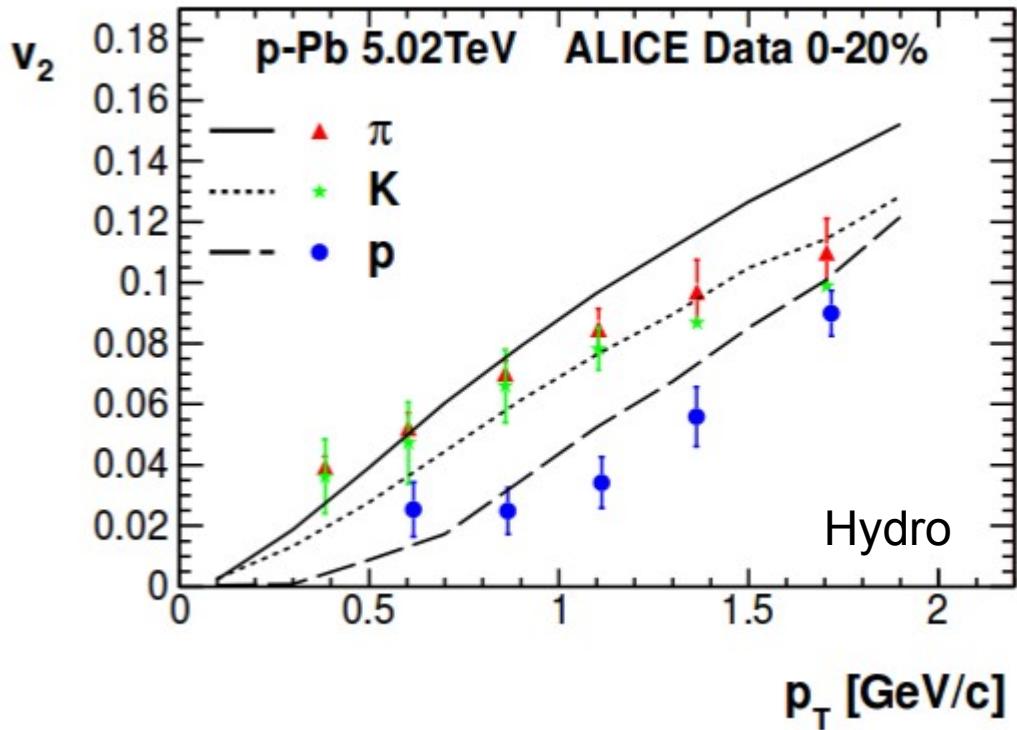
Features qualitatively similar  
to those seen in PbPb collisions.  
Suggests same physics at place?  
arXiv:1602.09138



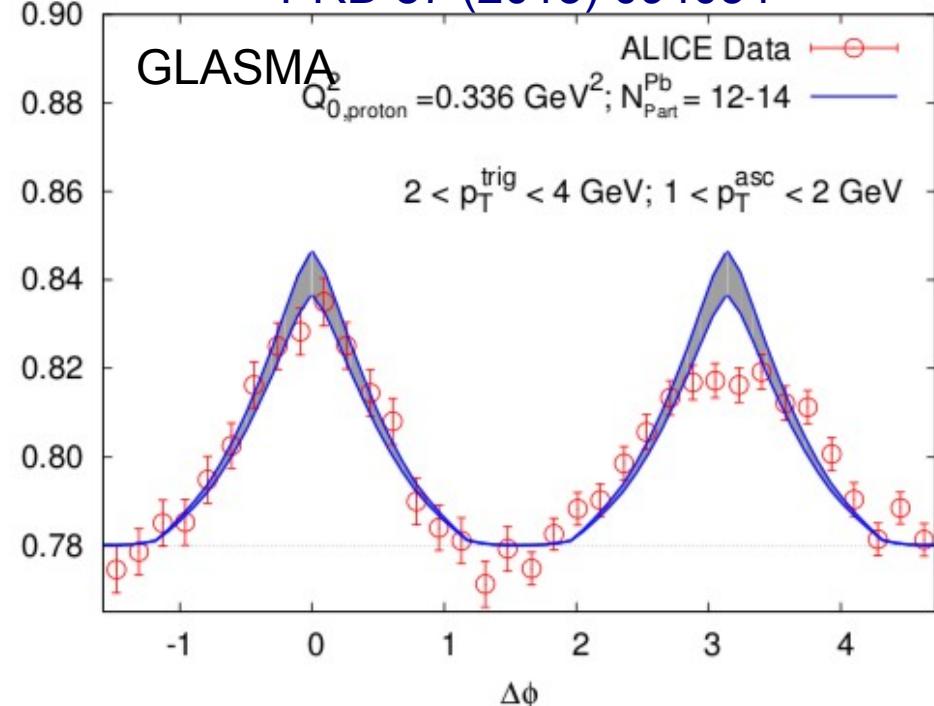
# Interpretation: active debate

69

arXiv:1307.5060

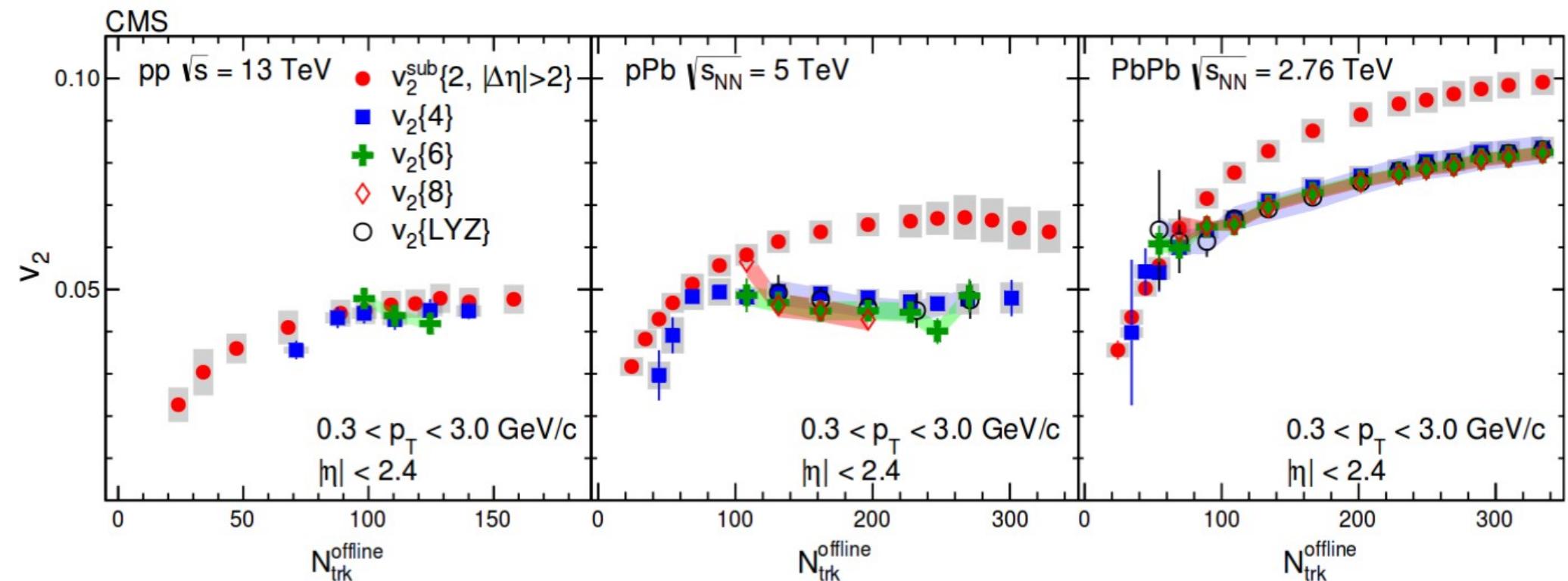


PRD 87 (2013) 094034

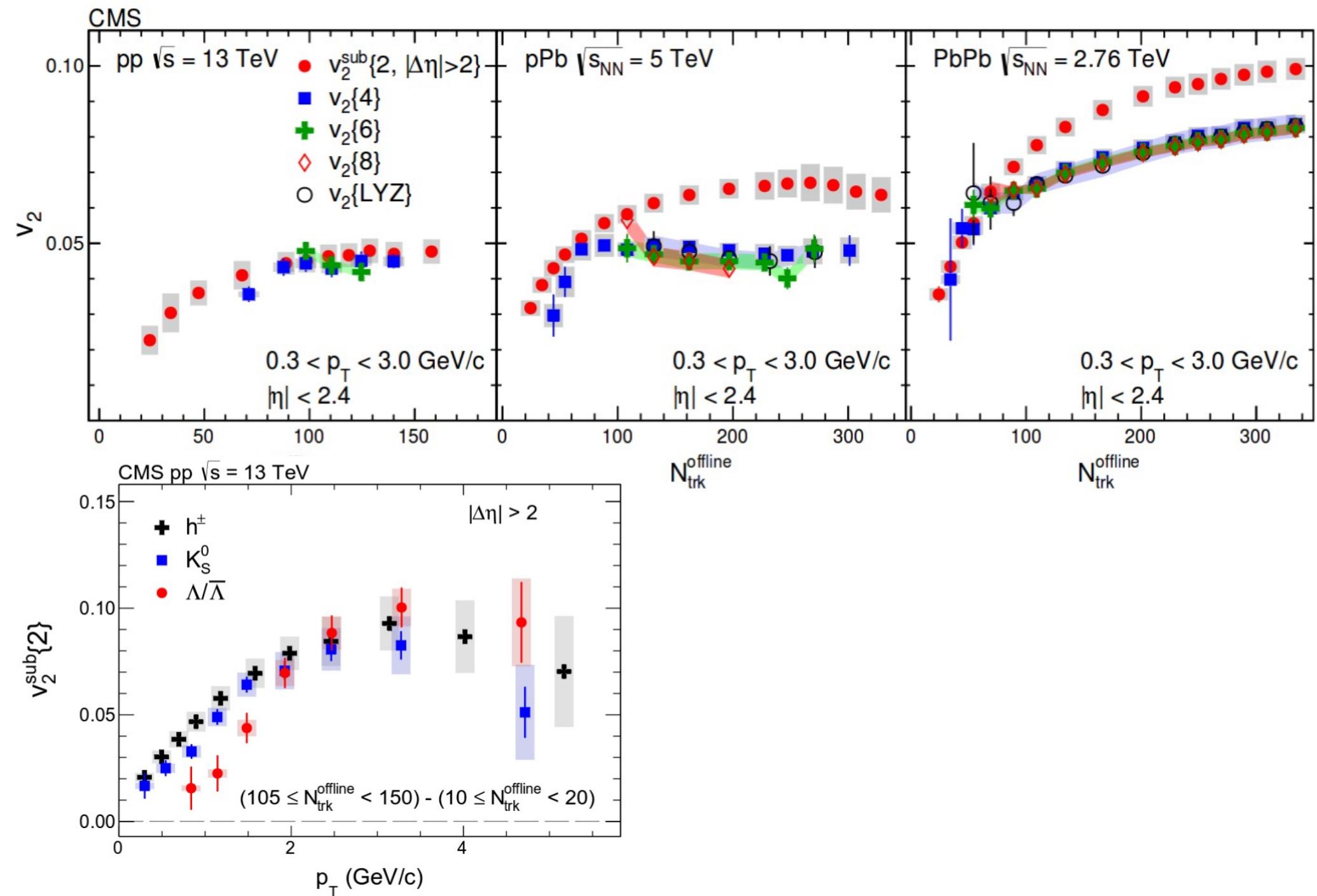


- Two orthogonal approaches with (semi-) quantitative predictions:
  - Formation of mini-QGP with hydrodynamical evolution
  - Entanglement of gluons in the initial state (GLASMA graphs)
- Many alternative ideas but often only at qualitative level
- Change of paradigm wrt role of “control” systems (under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

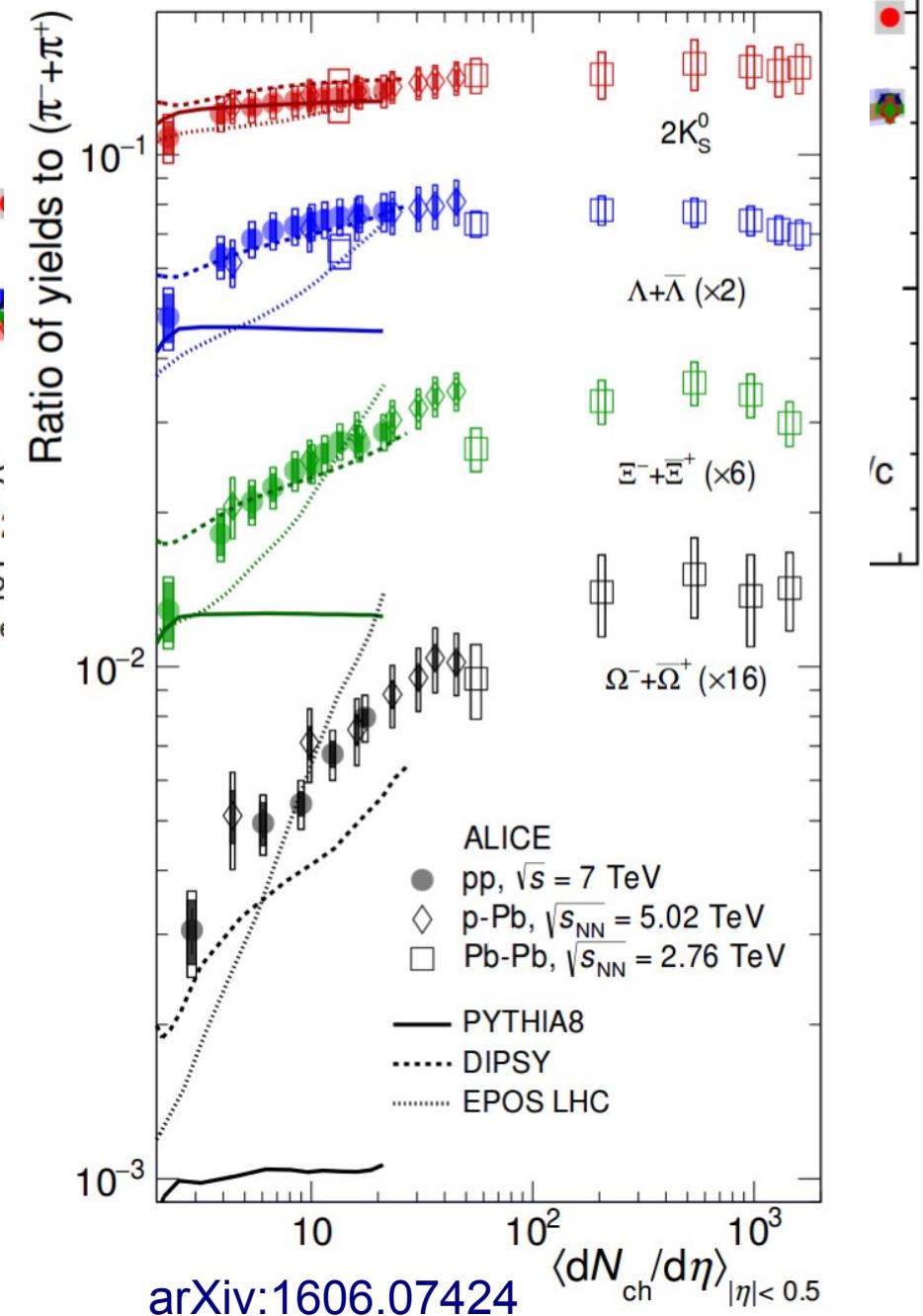
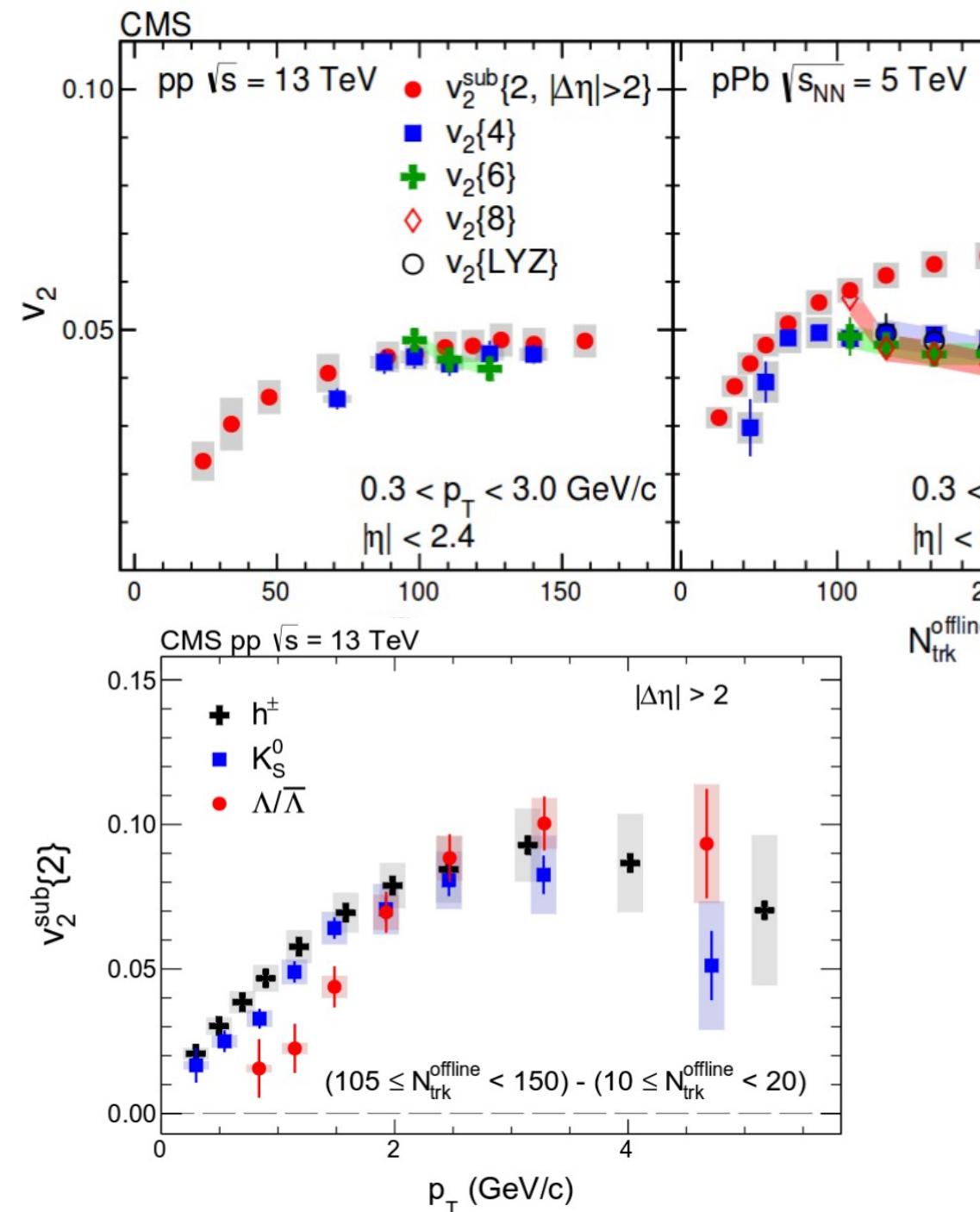
## And even in pp collisions



## And even in pp collisions



## And even in pp collisions



- 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!

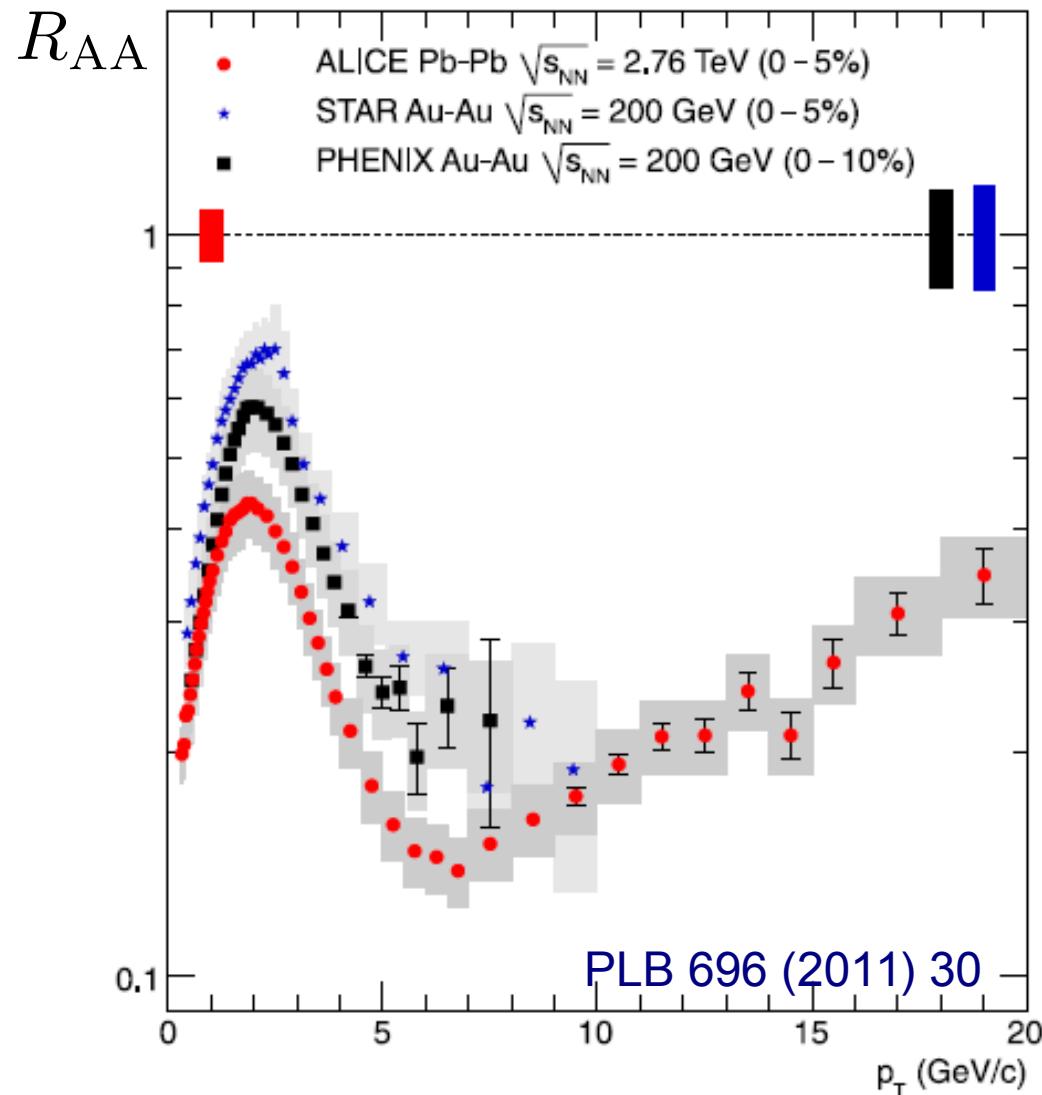
If you have questions about today's lecture please send them to "cloizides atlbl dot gov"

Extra

74

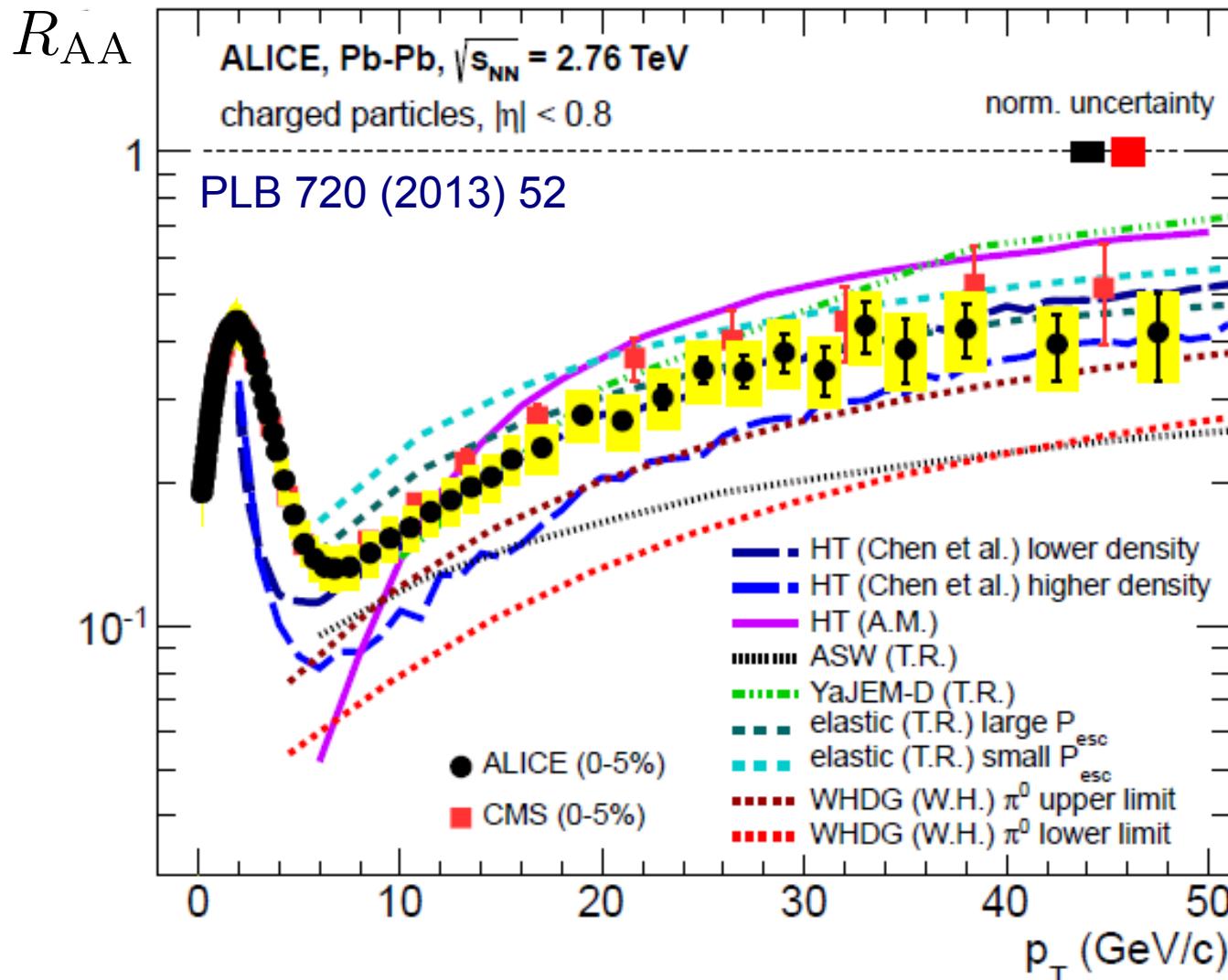
# Leading particle suppression at the LHC

75



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

# LHC jet quenching: Comparison to pQCD-based models



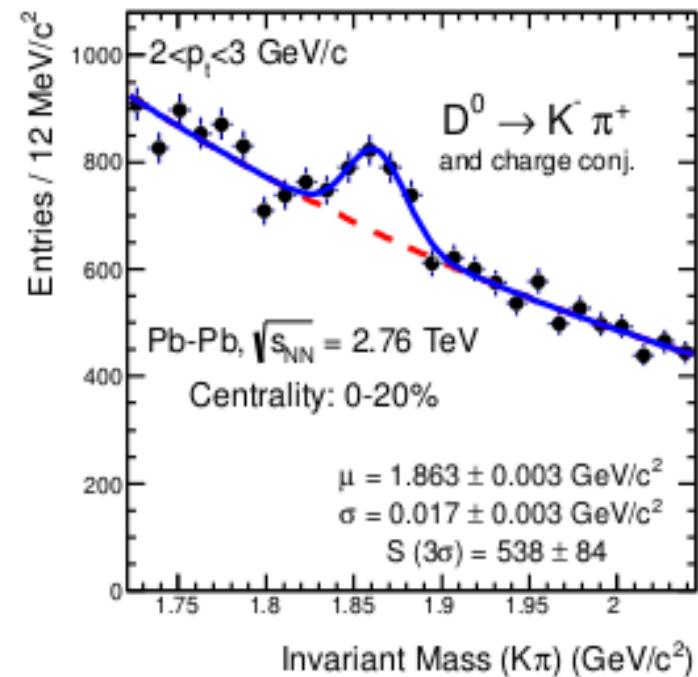
- Qualitatively: energy loss picture consistent with data
  - Models calibrated at RHIC and scaled to LHC via multiplicity growth
  - Key prediction of  $p_T$ -dependence of  $R_{AA}$ :  $\Delta E \sim \log(E)$  ok!

# 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,  $dE/dx$ )

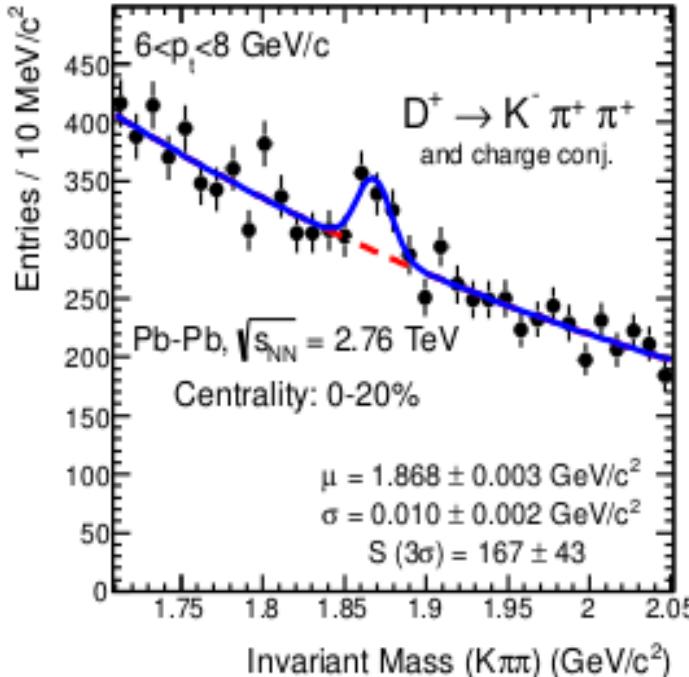
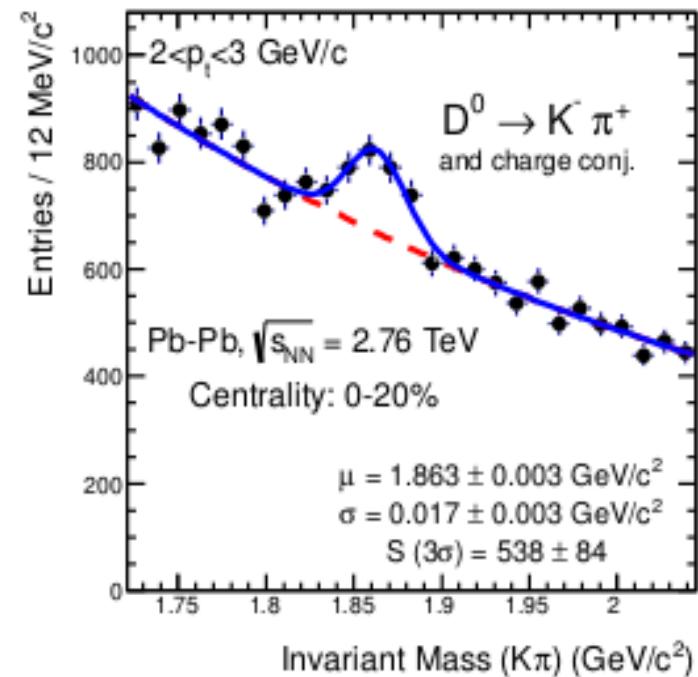
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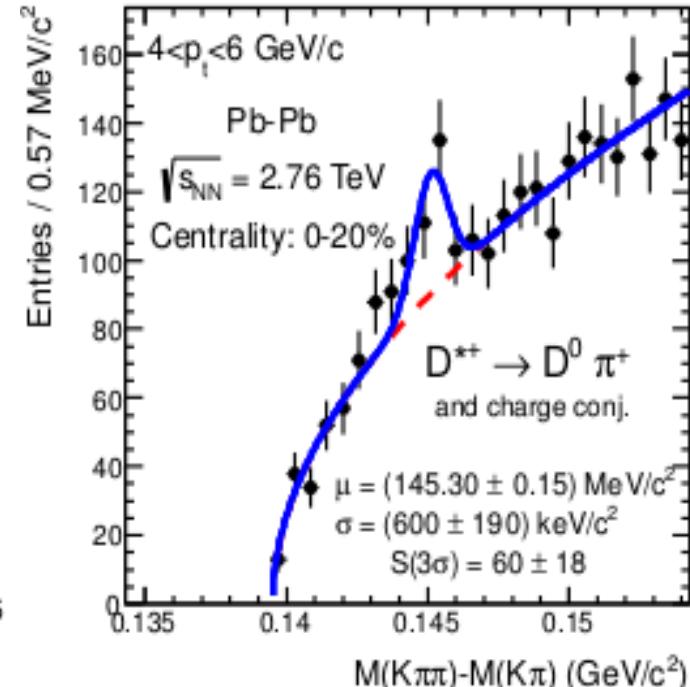
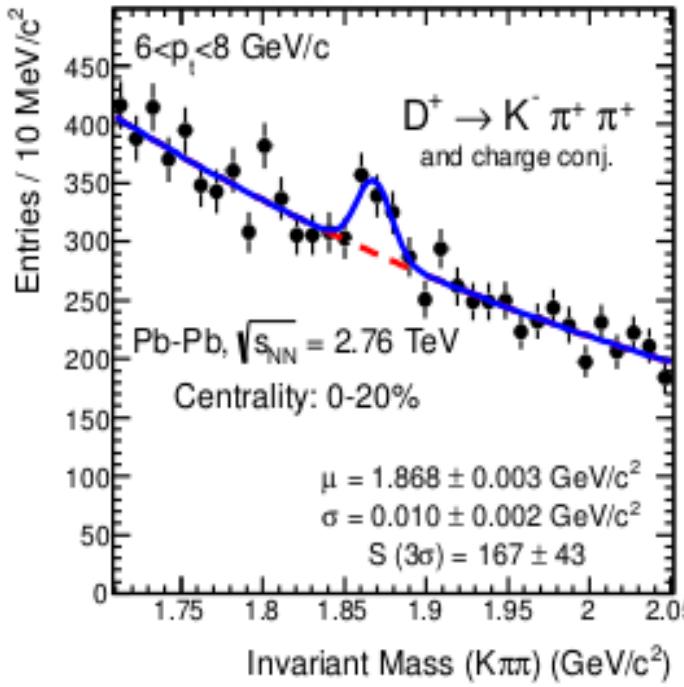
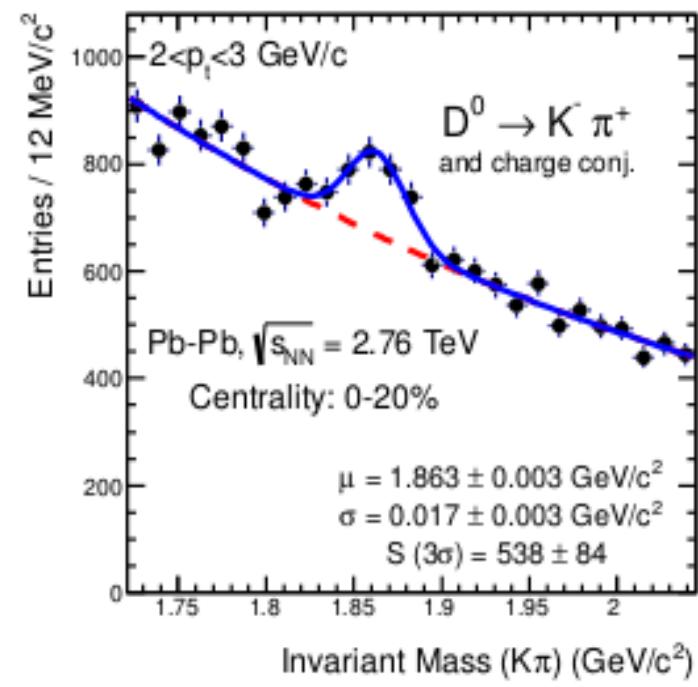
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# Various techniques for heavy flavor measurements

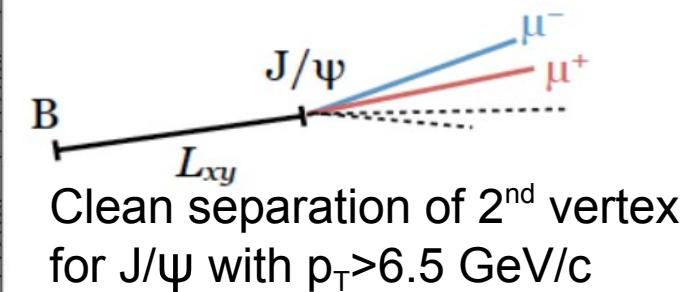
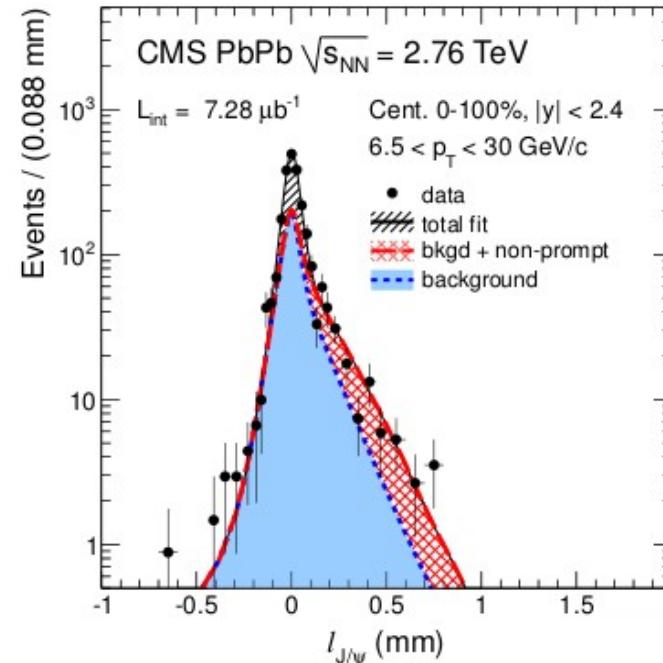
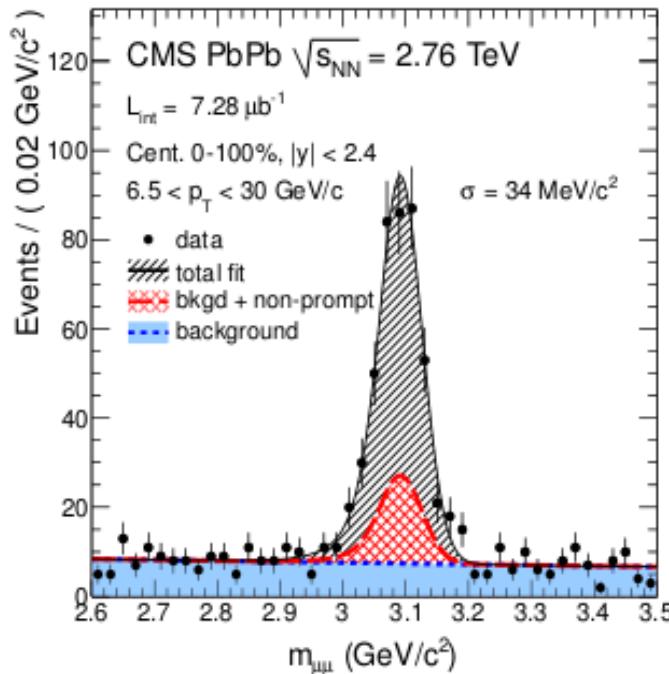
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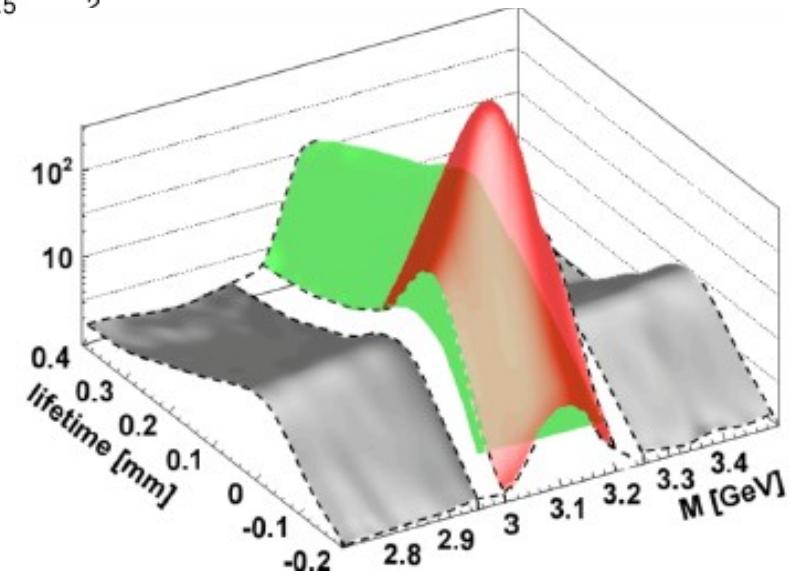
# Beauty via displaced J/ $\psi$

B mesons via secondary J/ $\psi$ :

CMS, JHEP 1205 (2012) 063



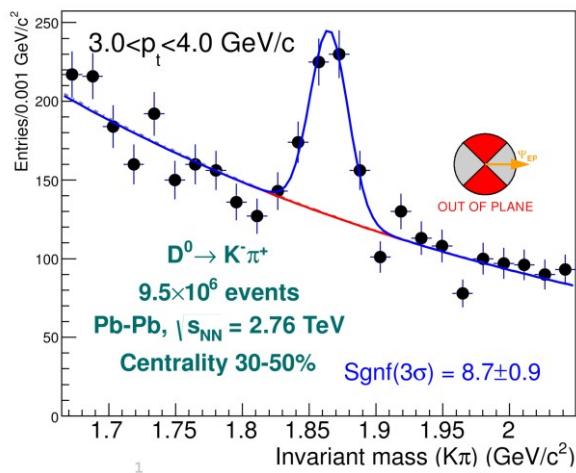
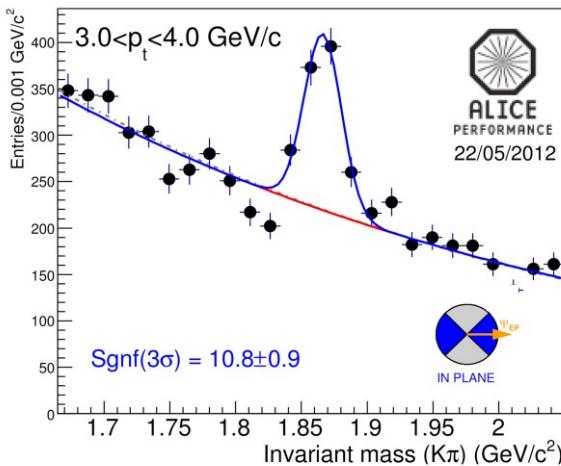
Fraction of non-prompt J/ $\psi$  from simultaneous fit to m+m- invariant mass spectrum and pseudo-proper decay length distributions (pioneered by CDF)



# Heavy-quark $v_2$ at the LHC

82

arXiv:1405.2001

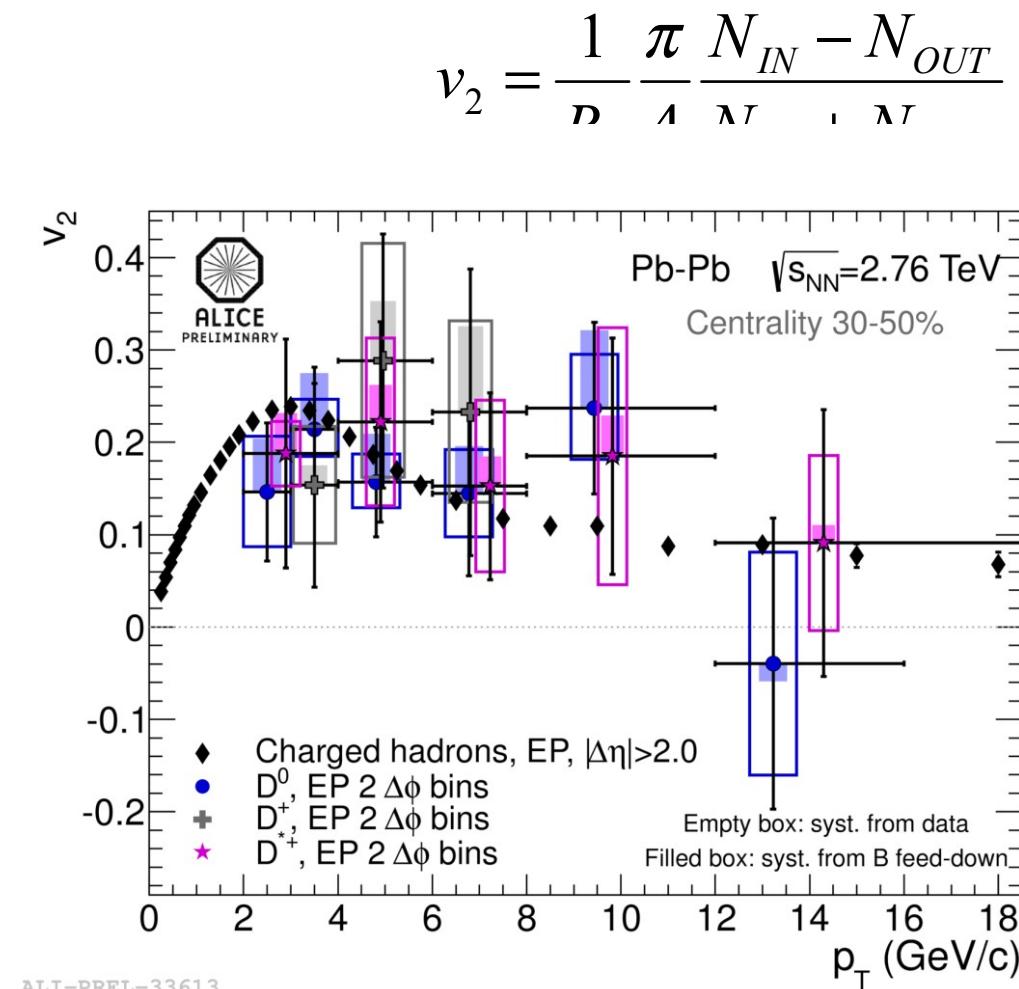
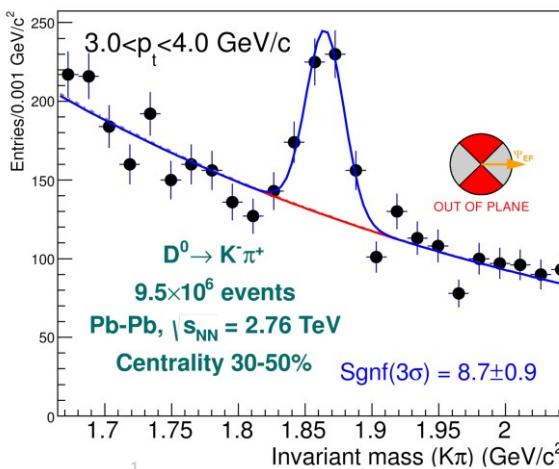
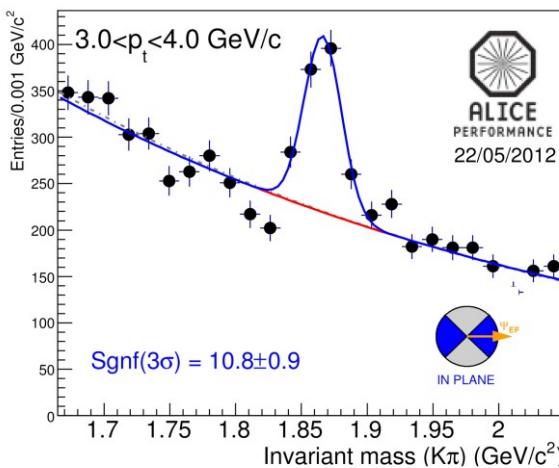


$$v_2 = \frac{1}{R_2} \frac{\pi}{4} \frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$

# Heavy-quark $v_2$ at the LHC

83

arXiv:1405.2001

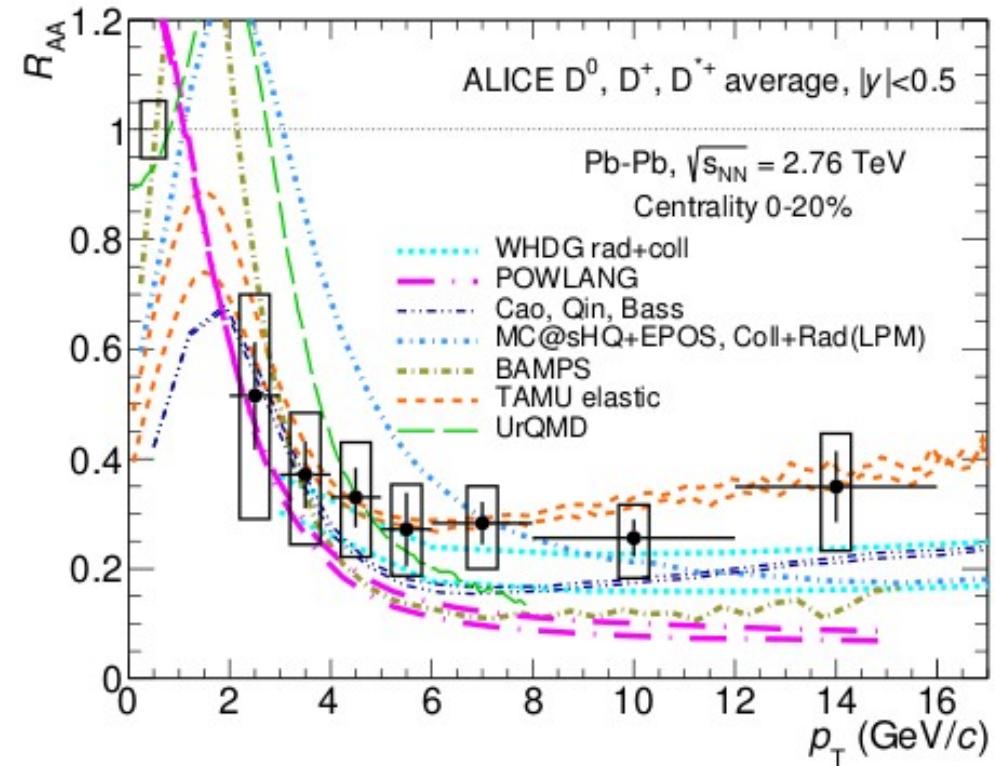
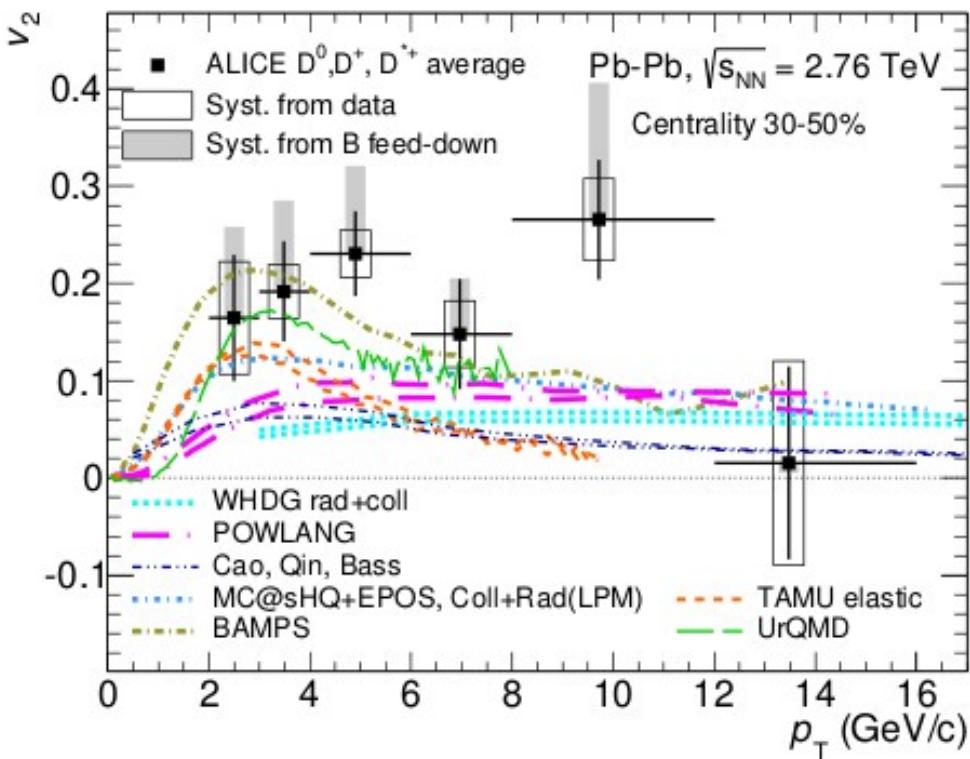


Indication of non-zero D meson  $v_2$ : It implies that heavy quarks also thermalize and participate in the collective expansion.  
 → Need more data and to measure at lower  $p_T$

# LHC D-mesons: Data vs models

84

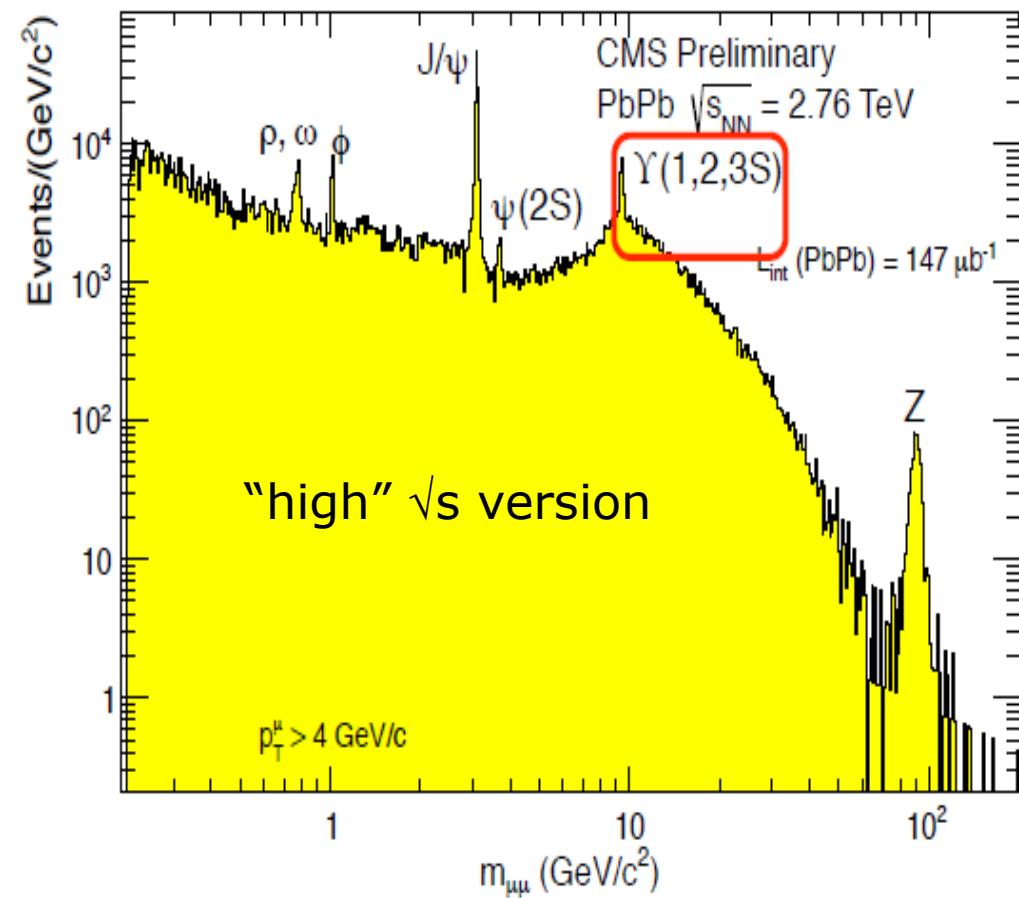
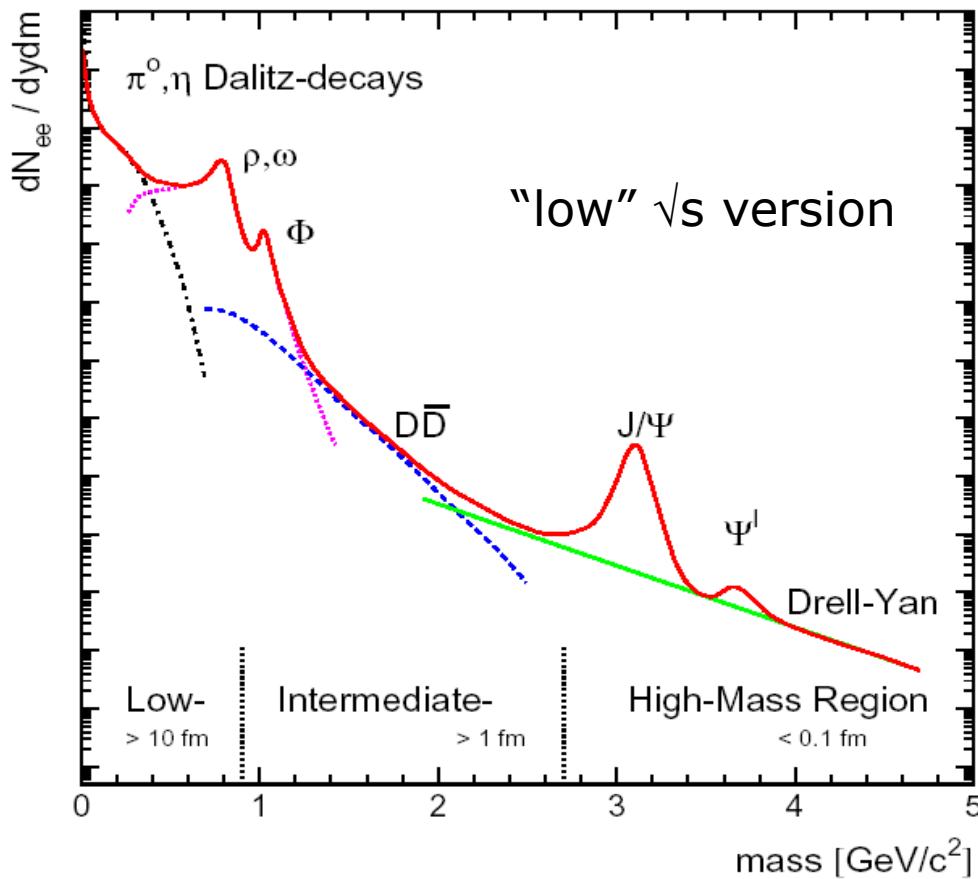
arXiv:1405.2001



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.

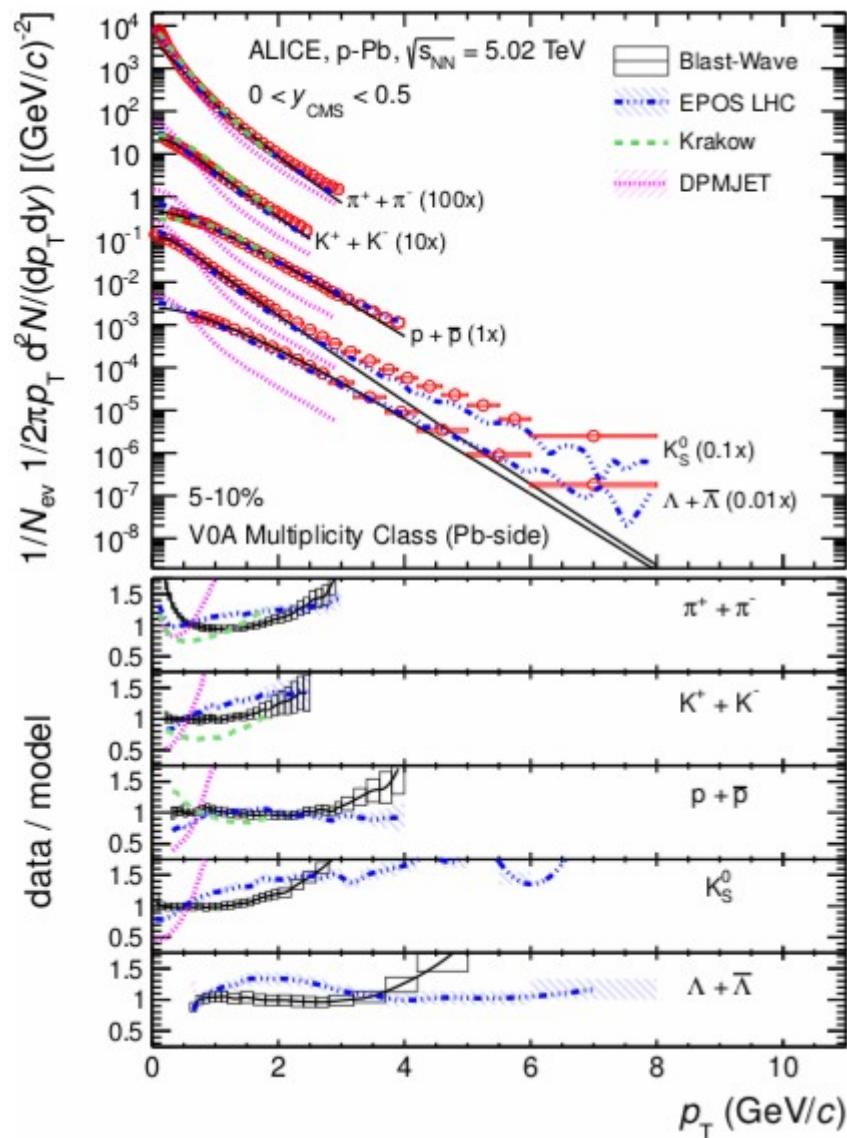
# The dilepton invariant mass spectrum

85



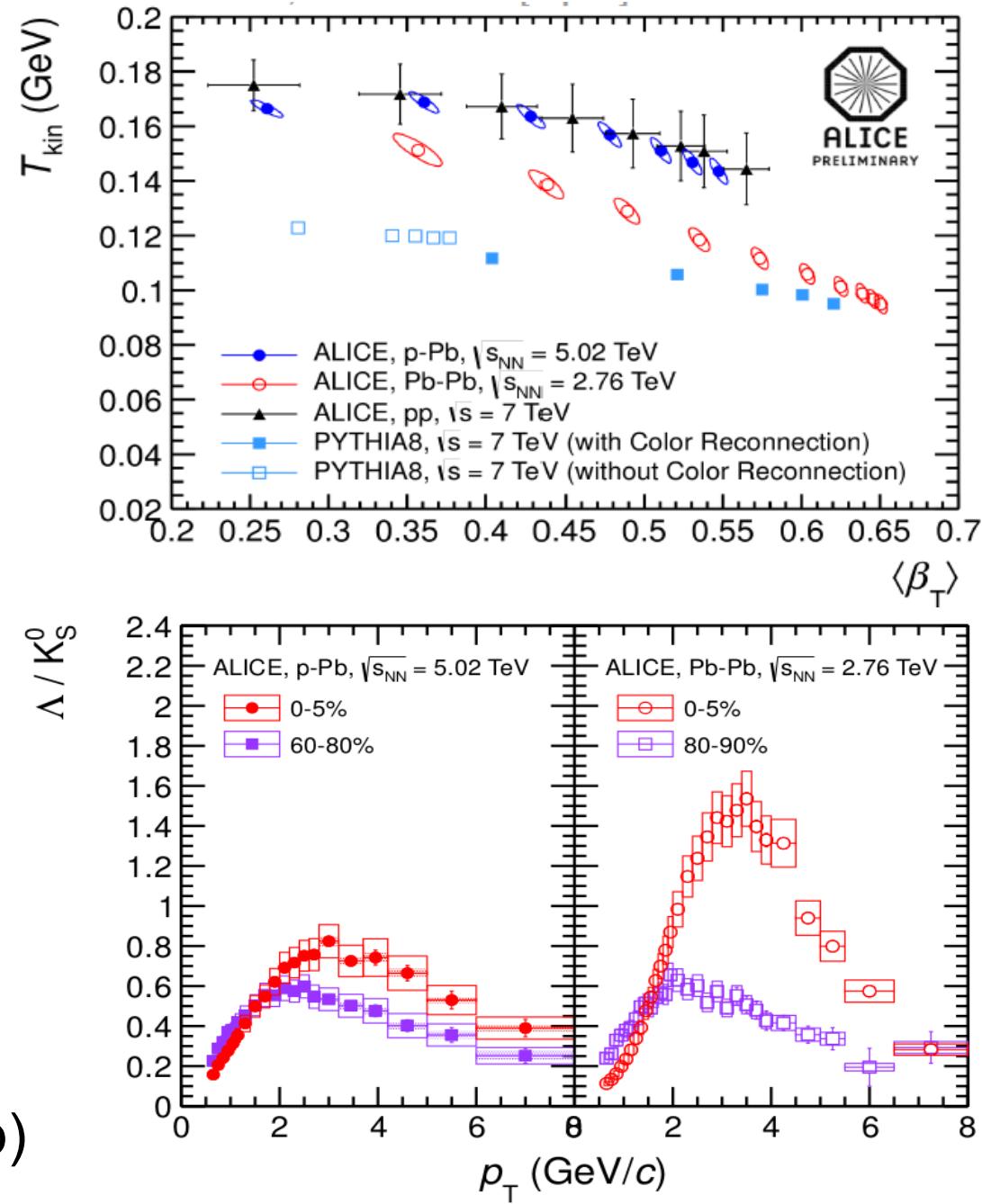
- The study of lepton pairs also allows to extract information about the early stages of the collision
- Dileptons (like photons) do not interact strongly and once produced can without significant re-interactions (not altered by later stages) escape the collision

# Identified particle spectra



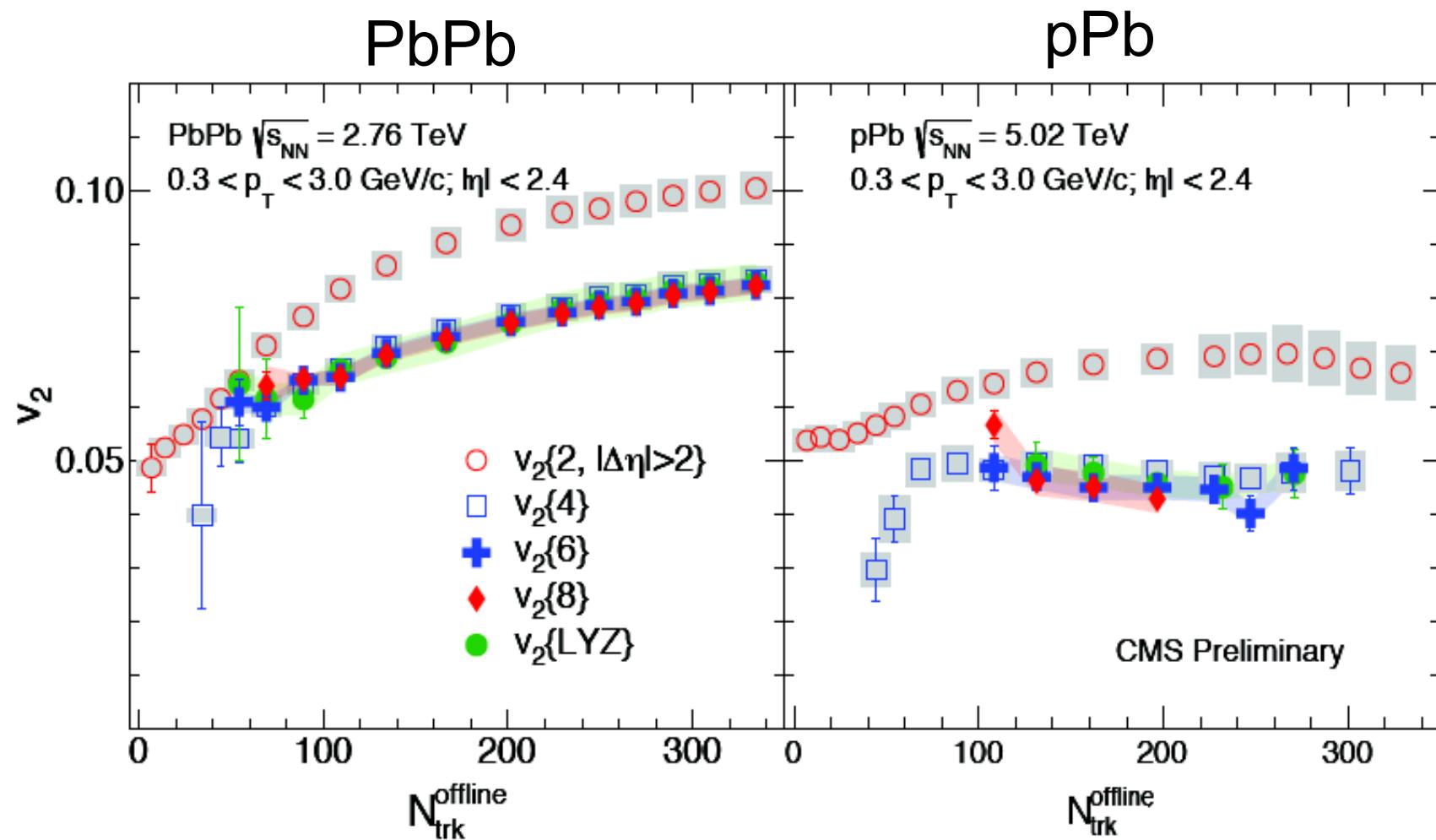
Spectra consistent with radial flow picture (also in pp)

ALICE, PLB 278 (2014) 25



# Multi-particle correlations: CMS

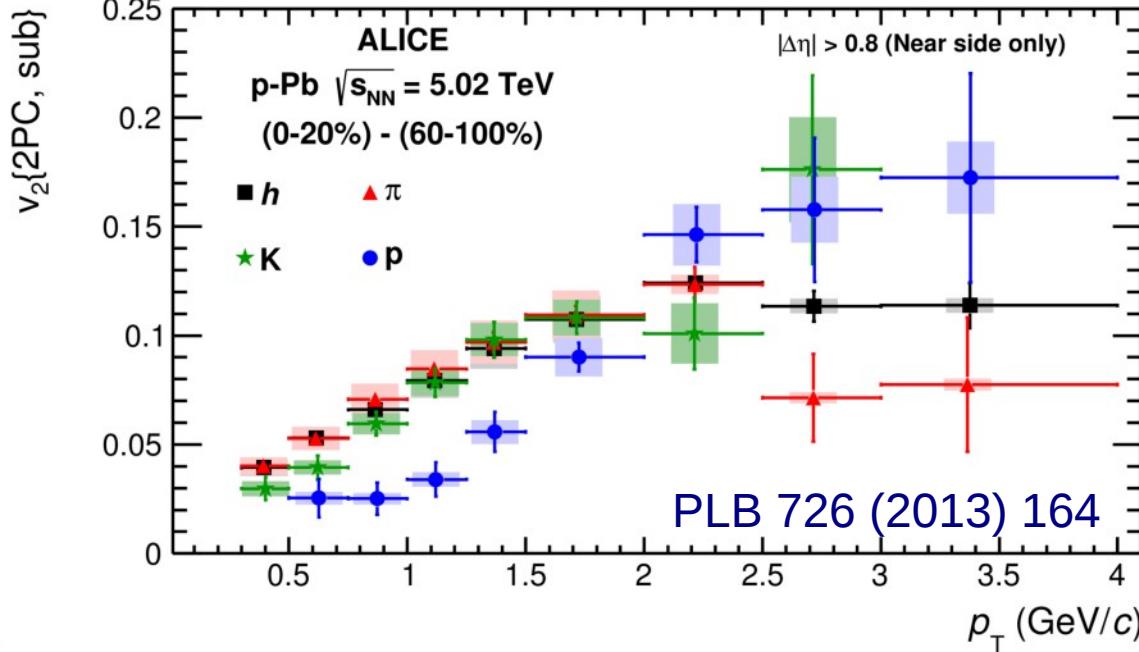
87



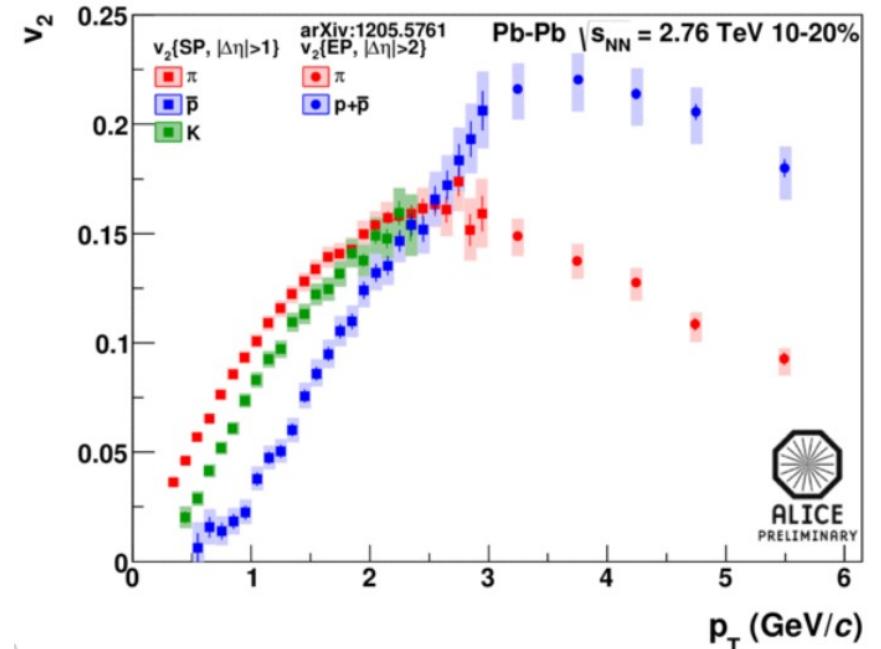
Multi-particle correlation results are the same within 10% in pPb

# Identified particle $v_2$

pPb

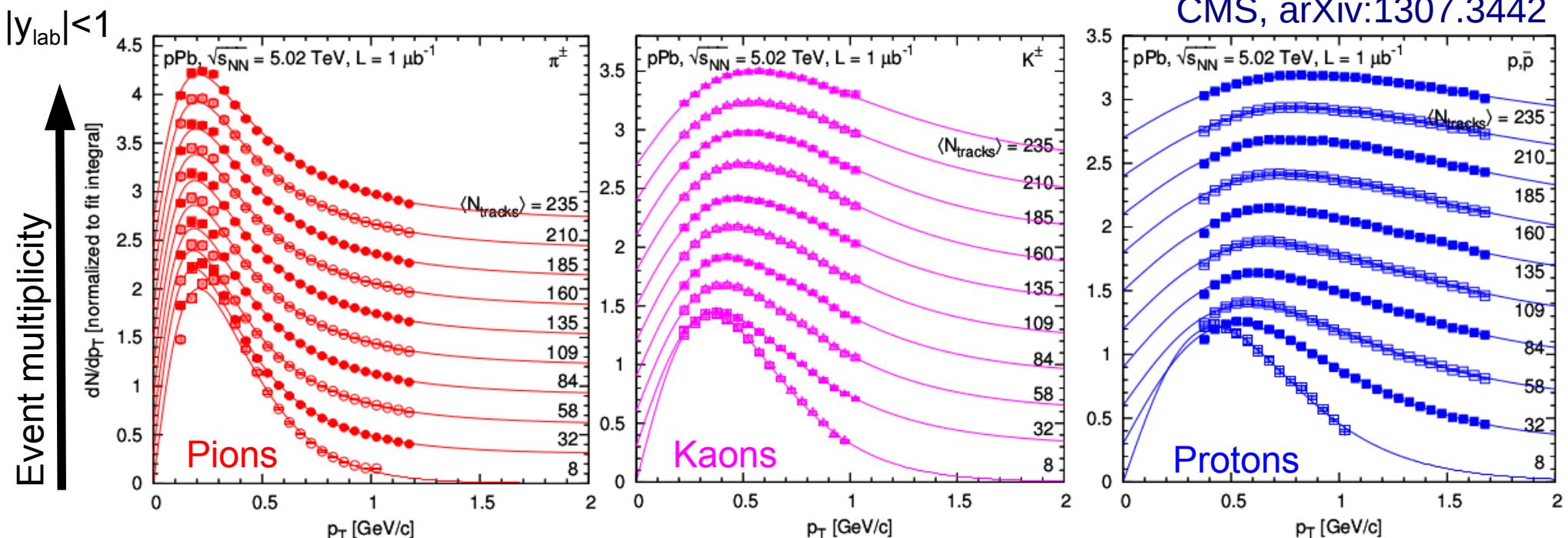


PbPb



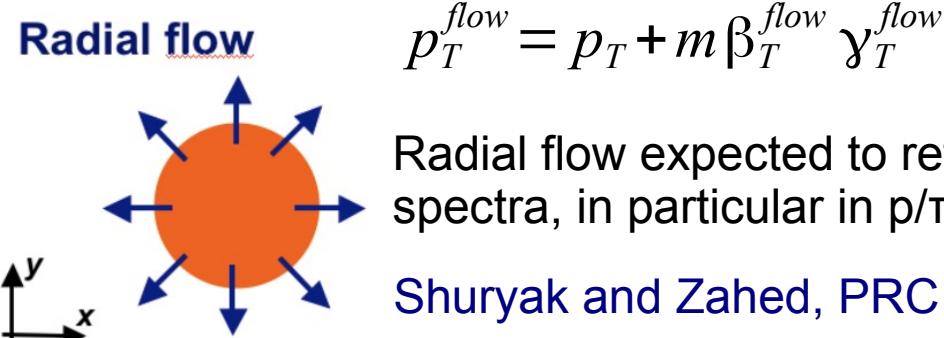
- Characteristic mass splitting observed as known from PbPb
- Crossing of proton and pion at similar  $p_T$  (2-3 GeV/c) with protons pushed further out in the pPb case
  - If interpreted in hydro picture, suggestive of strong radial flow

# Radial flow



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

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

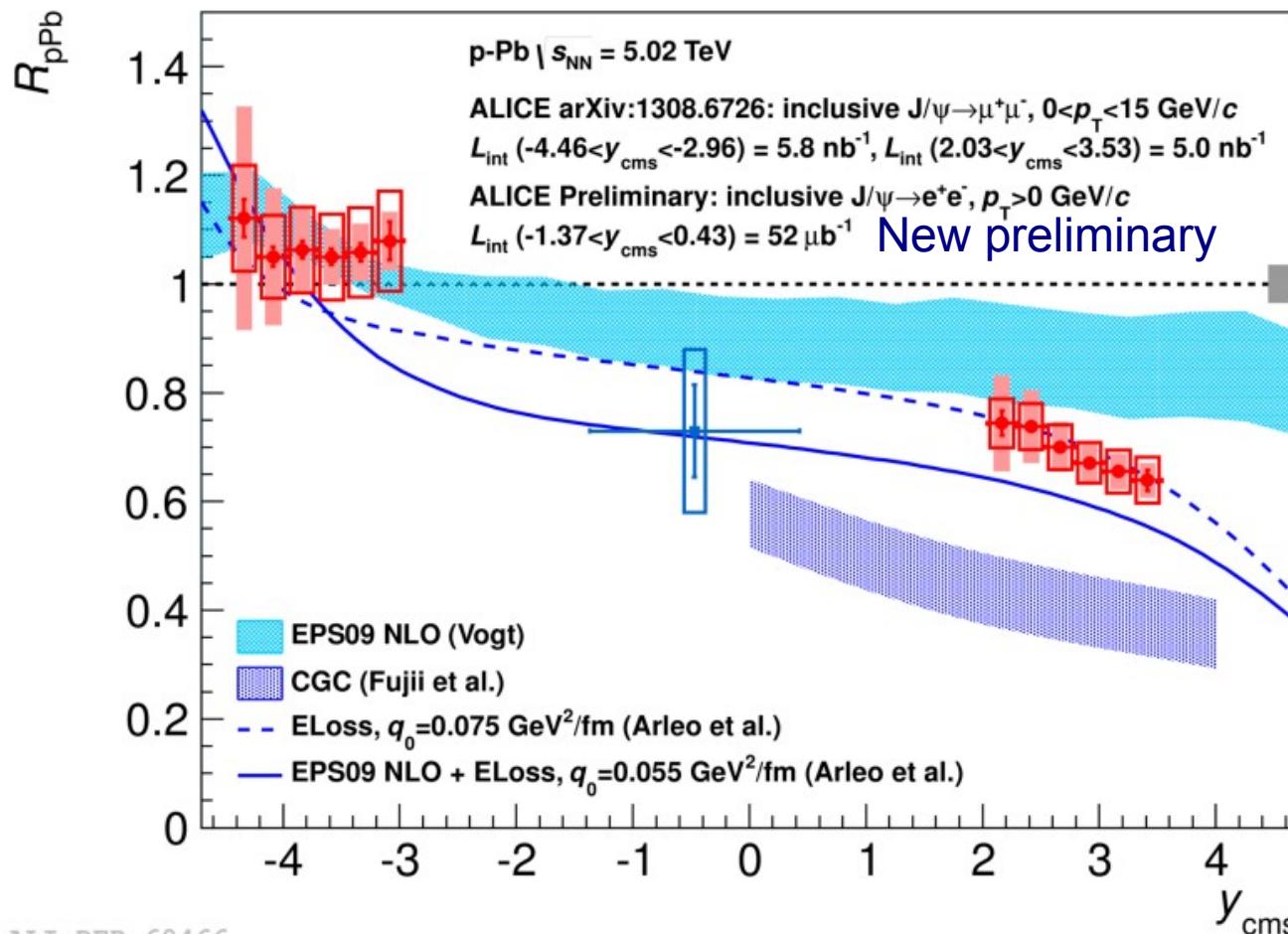


Radial flow expected to reflect in spectra, in particular in  $p/\pi$  ratio

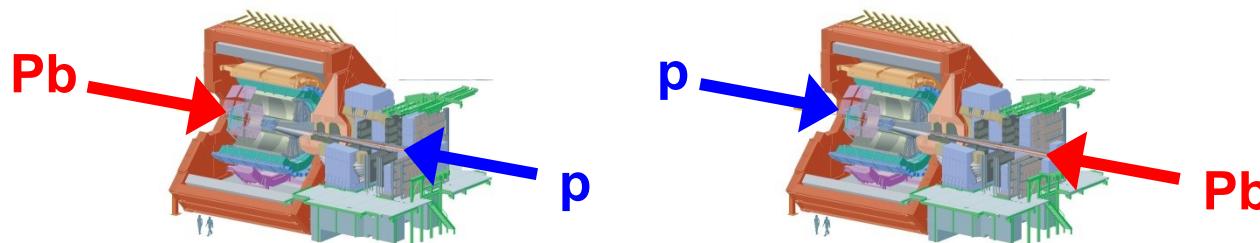
Shuryak and Zahed, PRC 88 (2013) 044915

(Note also present in high mult pp)

# J/ $\psi$ production versus rapidity in p-Pb



ALI-DER-60466

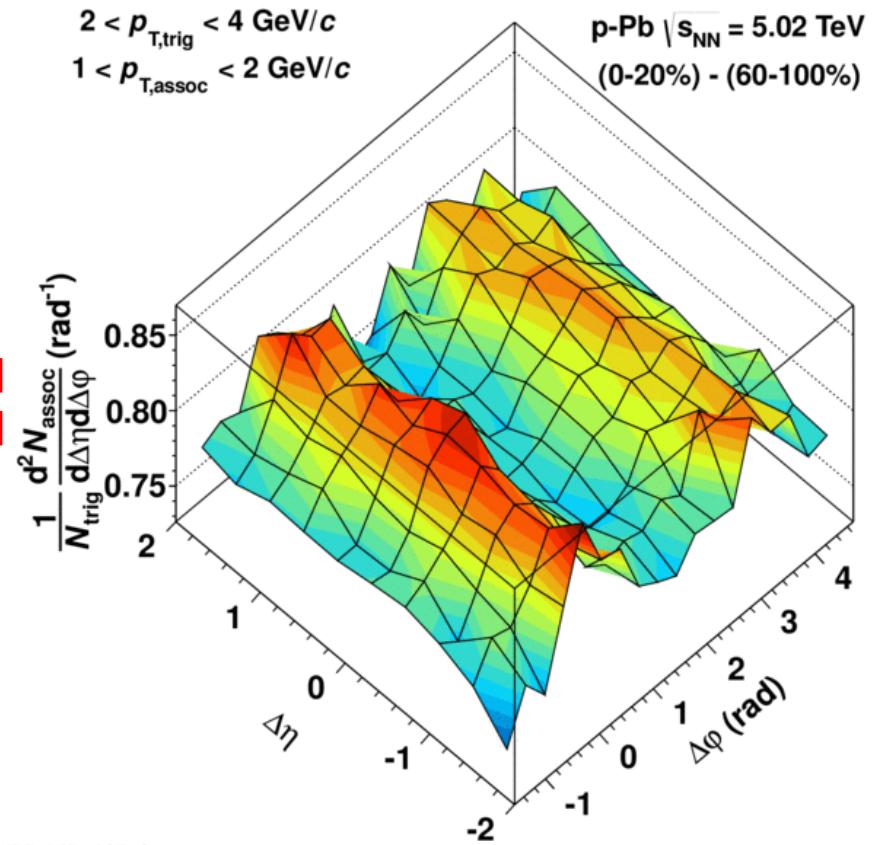
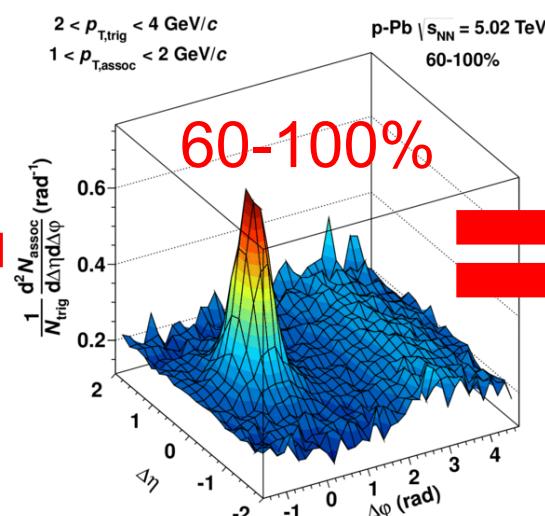
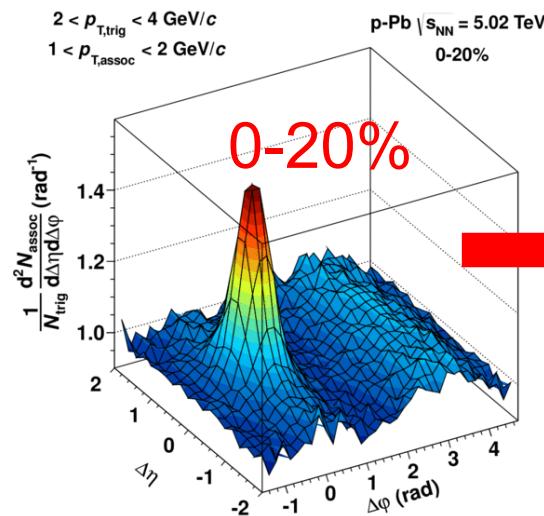


- Suppression at mid- and forward rapidity
  - Consequences for  $R_{AA}$ : Suggests even stronger recombination
- Consistent with shadowing models (EPS09 NLO) and/or coherent parton energy loss
- Specific CGC calculation disfavored

# Observation of double ridge

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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