


Selected results from nucleus collisions at the LHC

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(LBNL/EMMI)

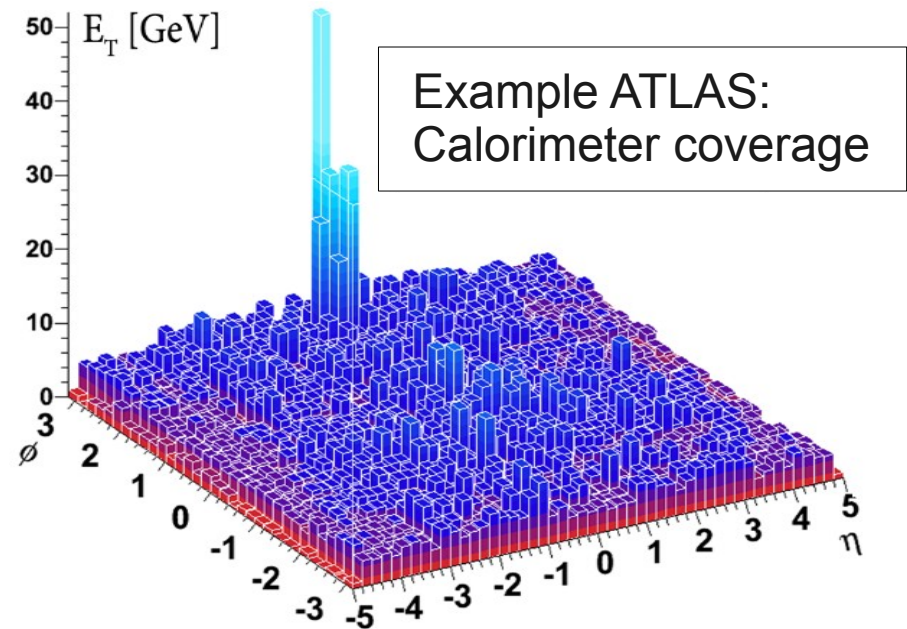
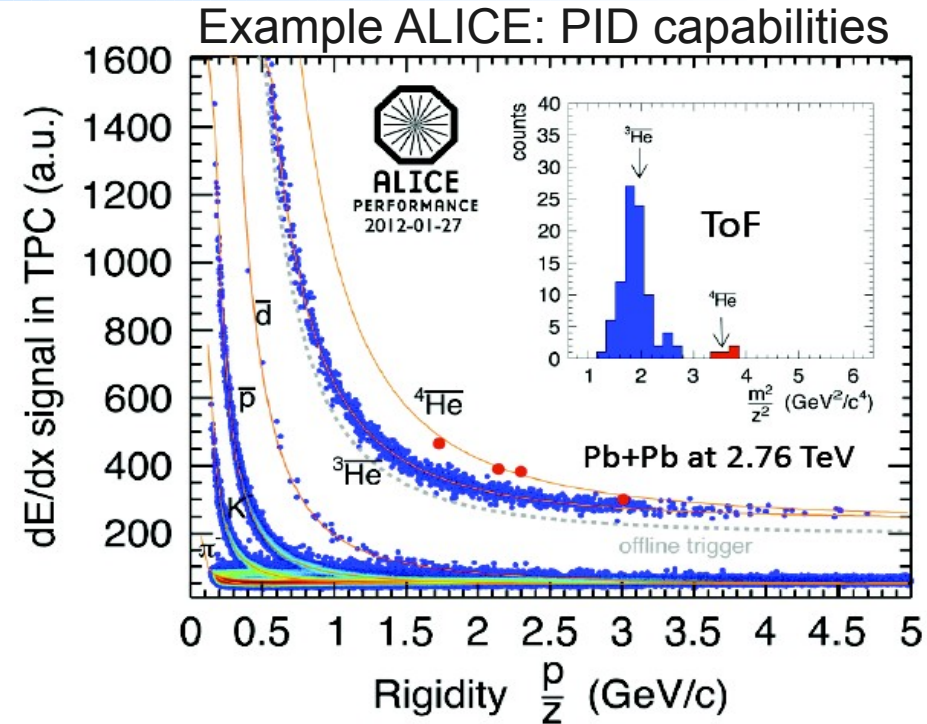


EMMI Physics Days 2012
GSI, Darmstadt, Germany
November 13-14, 2012

Heavy-ion data-taking experiments at LHC 2

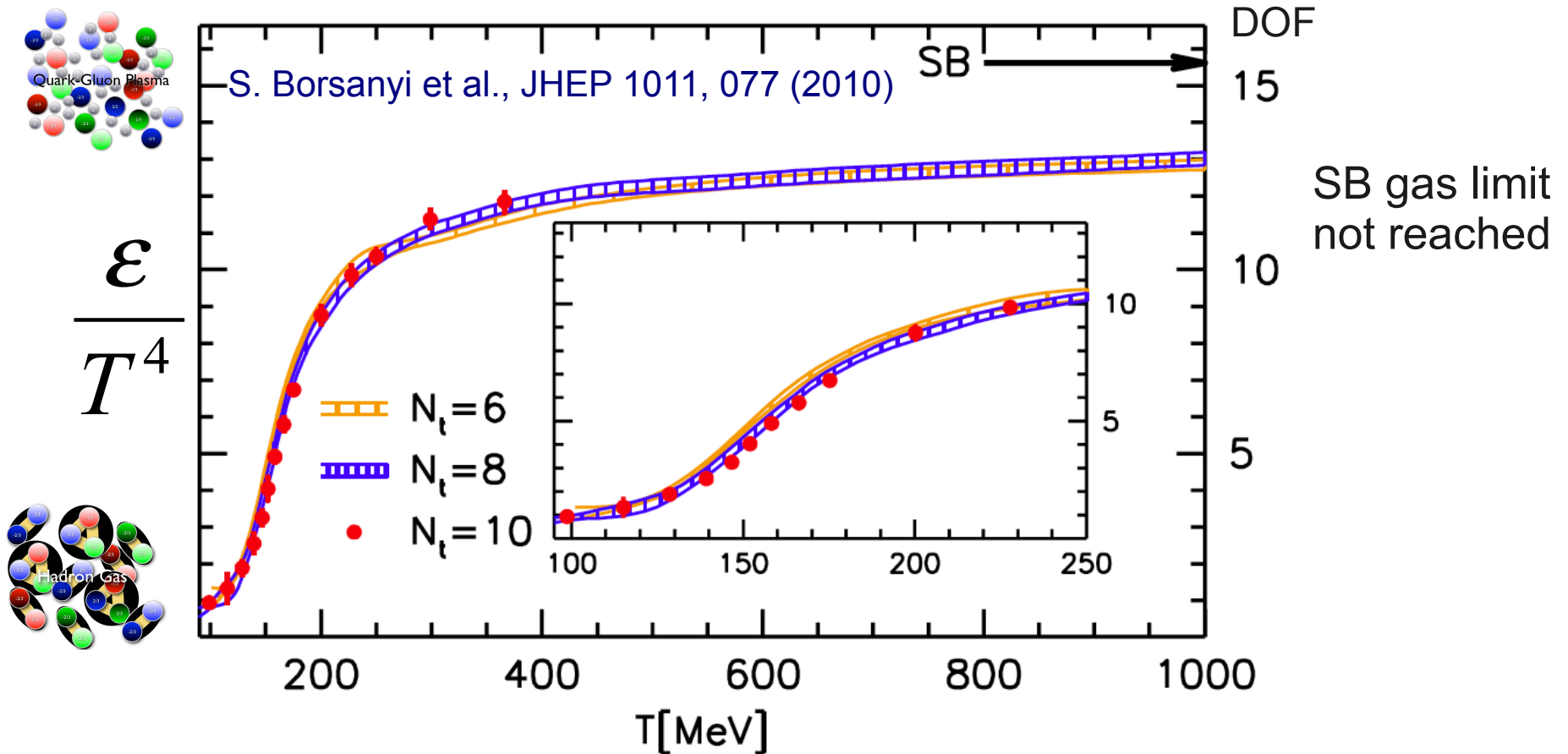


- LHC: First beams in Nov 2009
 - p+p (900, 2.36, 2.76, 7, 8 TeV)
 - Pb+Pb at 2.76 ATeV in Nov 2010/11 (~10/ μb and ~150/ μb)
 - p+Pb at 5.02 ATeV in Nov 2012
- ALICE dedicated HI experiment
 - Low- p_T tracking, PID, mid-rapidity
- ATLAS/CMS large HEP experiments
 - Large acceptance, full calorimetry



QCD cross-over transition from lattice

3

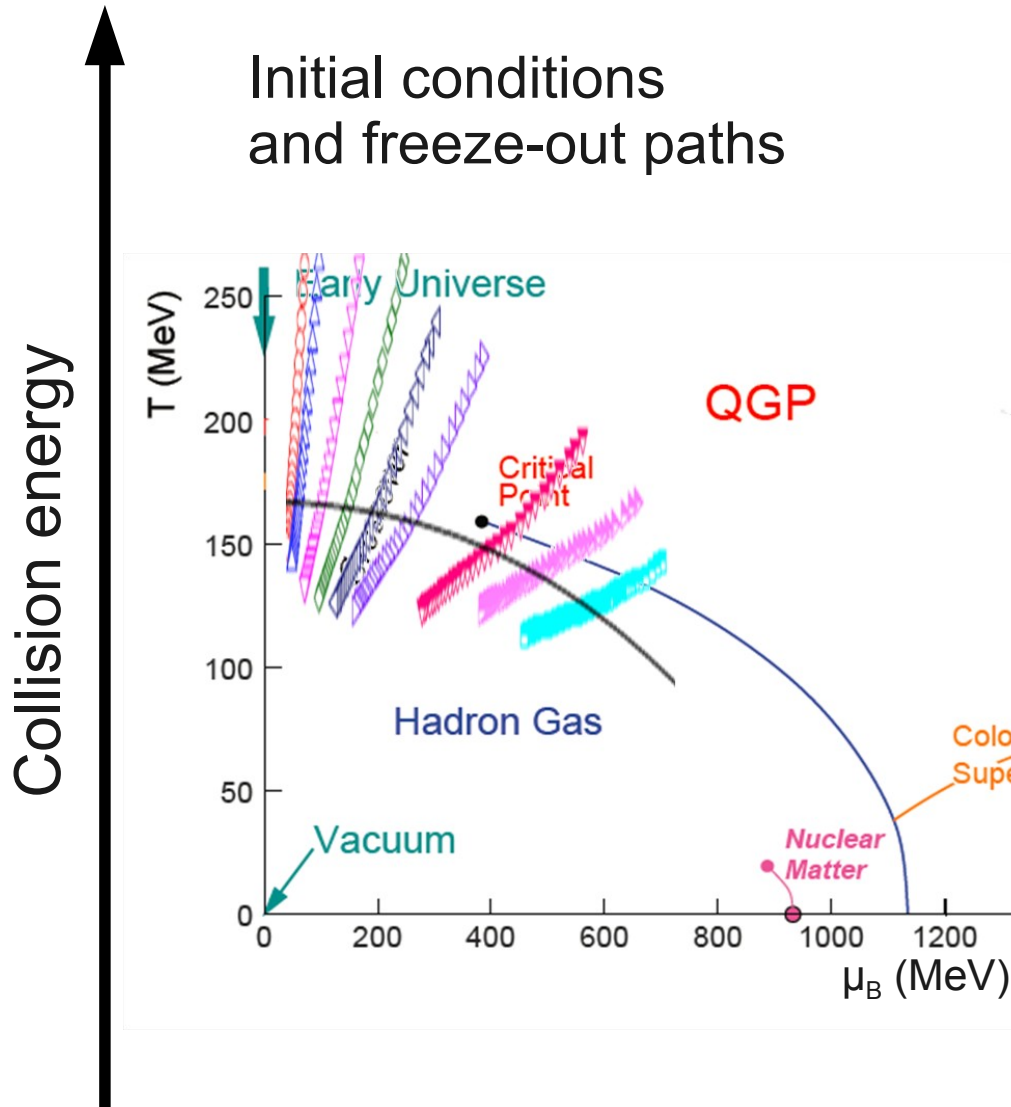


Lattice calculations predict a cross-over transition from hadronic to partonic degrees of freedom at

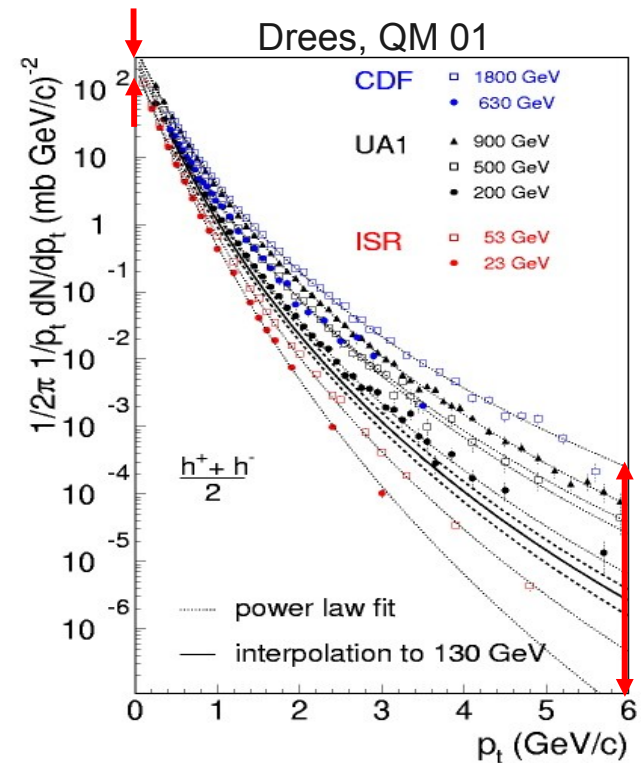
$$T_c \approx 150-160 \text{ MeV}$$
$$\epsilon_c \approx 0.5 \text{ GeV/fm}^3$$

External parameters: Collision energy

4



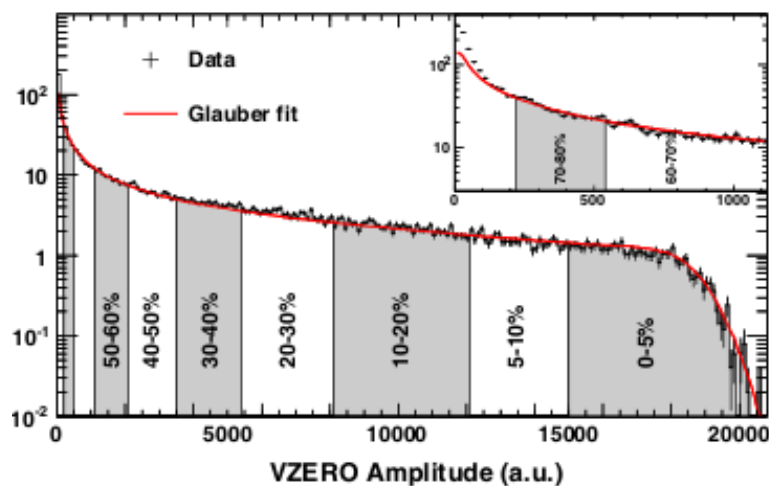
Ratio of “soft” to “hard” processes



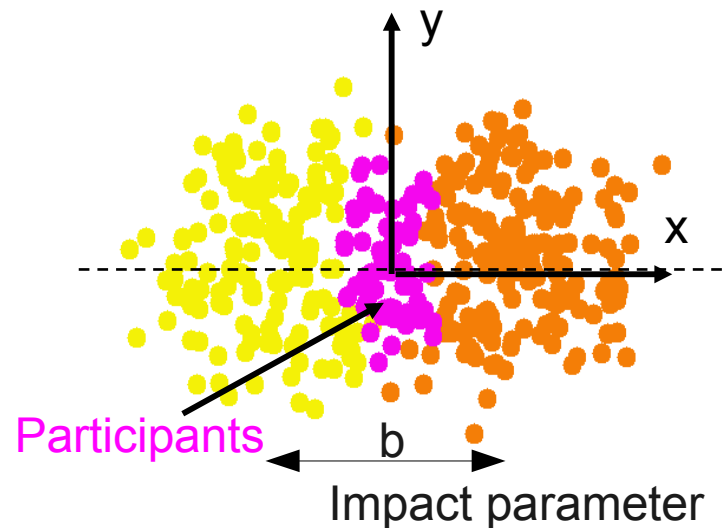
External parameters: Collision centrality

5

Nuclear cross-section classes
(by slicing in bins of multiplicity)



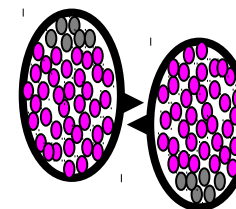
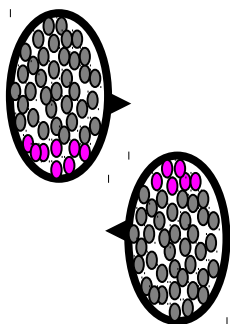
Glauber model



Cross-section percentile (in %)



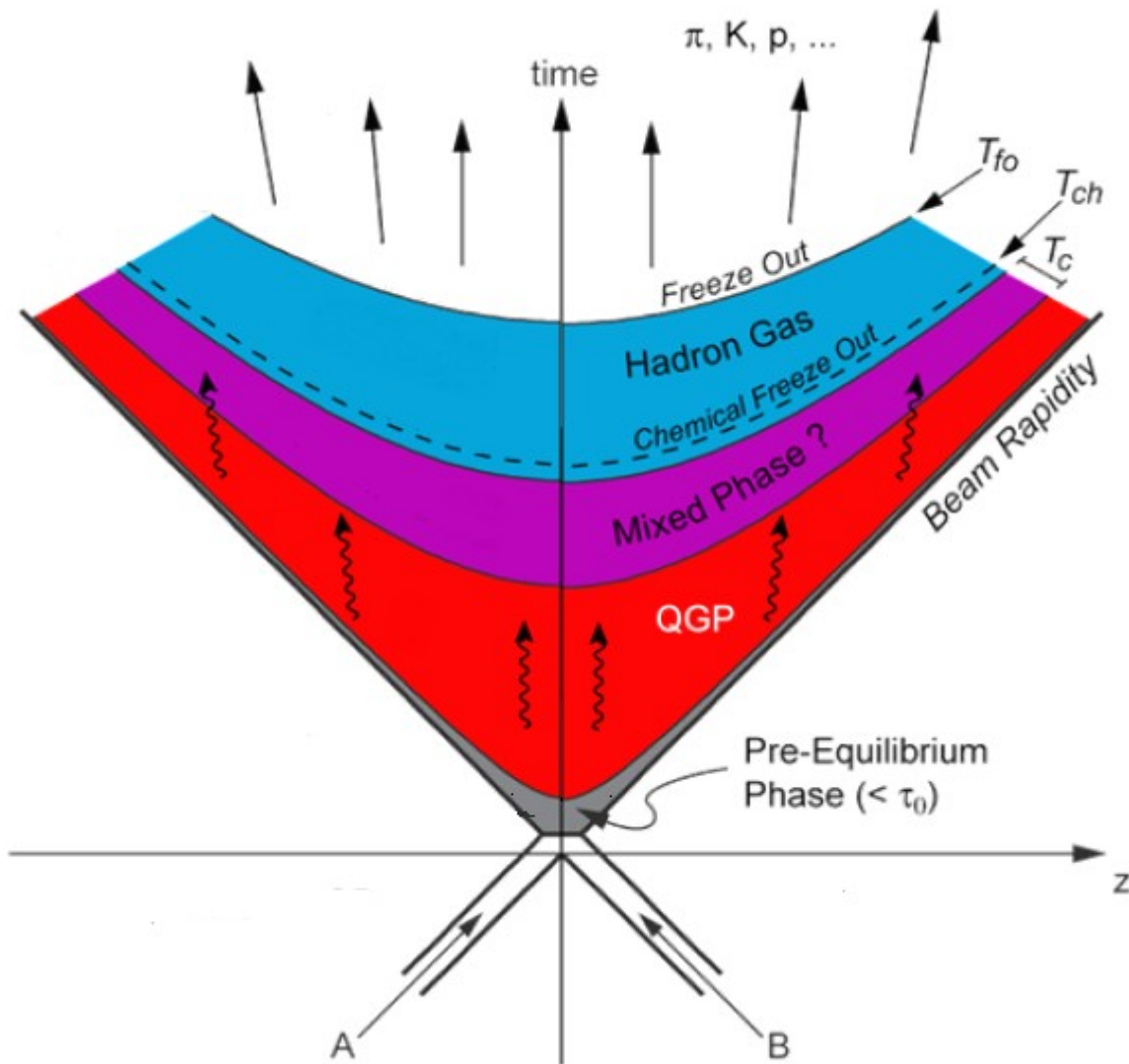
Number of participants (collisions)



Collision centrality

Heavy-ion standard reaction model

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Global properties

Kinetic freeze-out

Chemical freeze-out

Collective flow

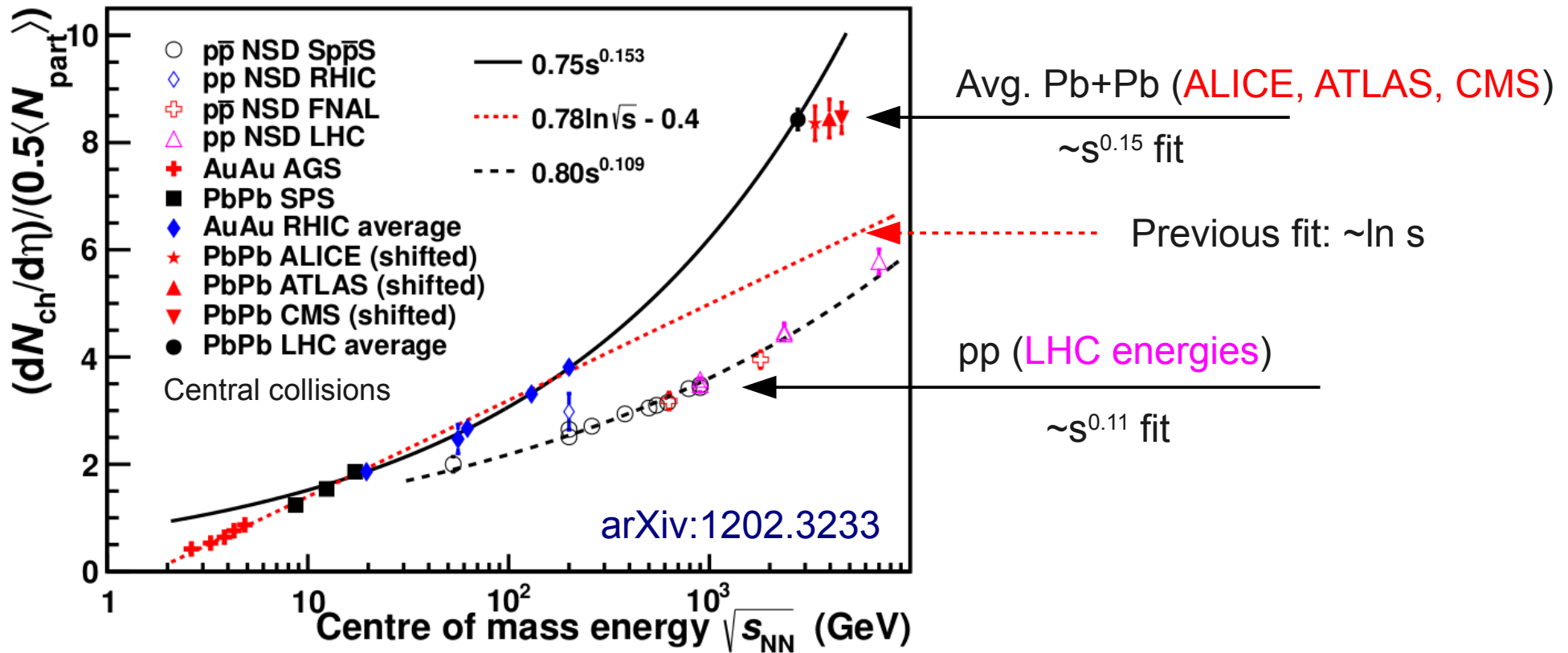
Hard probes
(jets, heavy flavor)

Order discussed in talk

“Rewind dynamical evolution” to access QGP by studying many observables with different sensitivity to the stages of the collision

Energy dependence of $dN/d\eta$

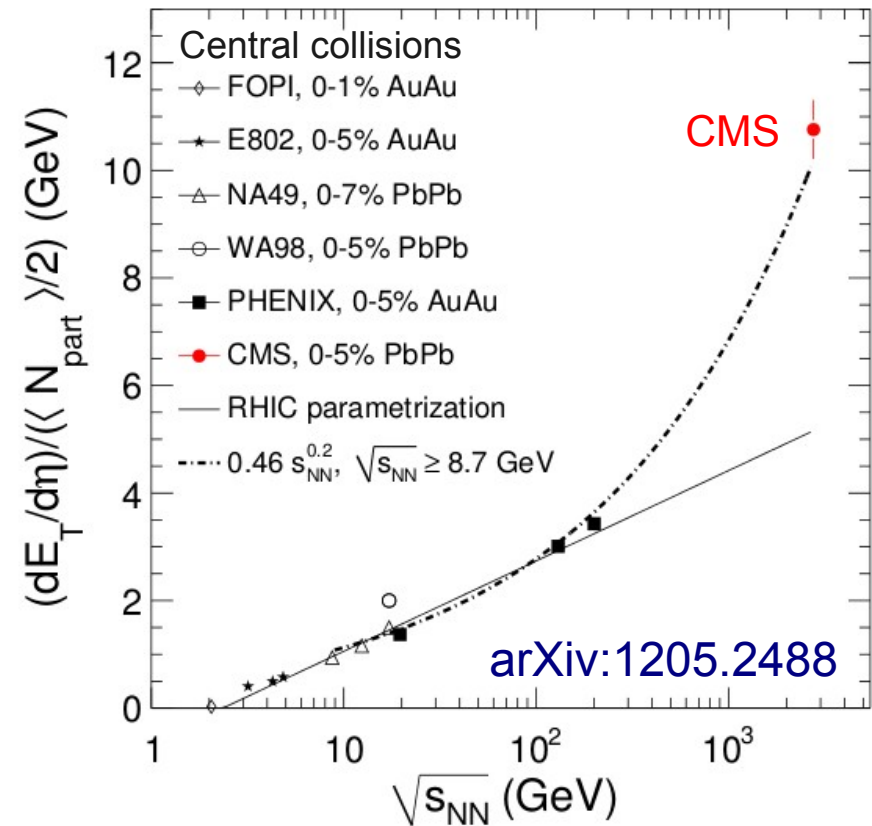
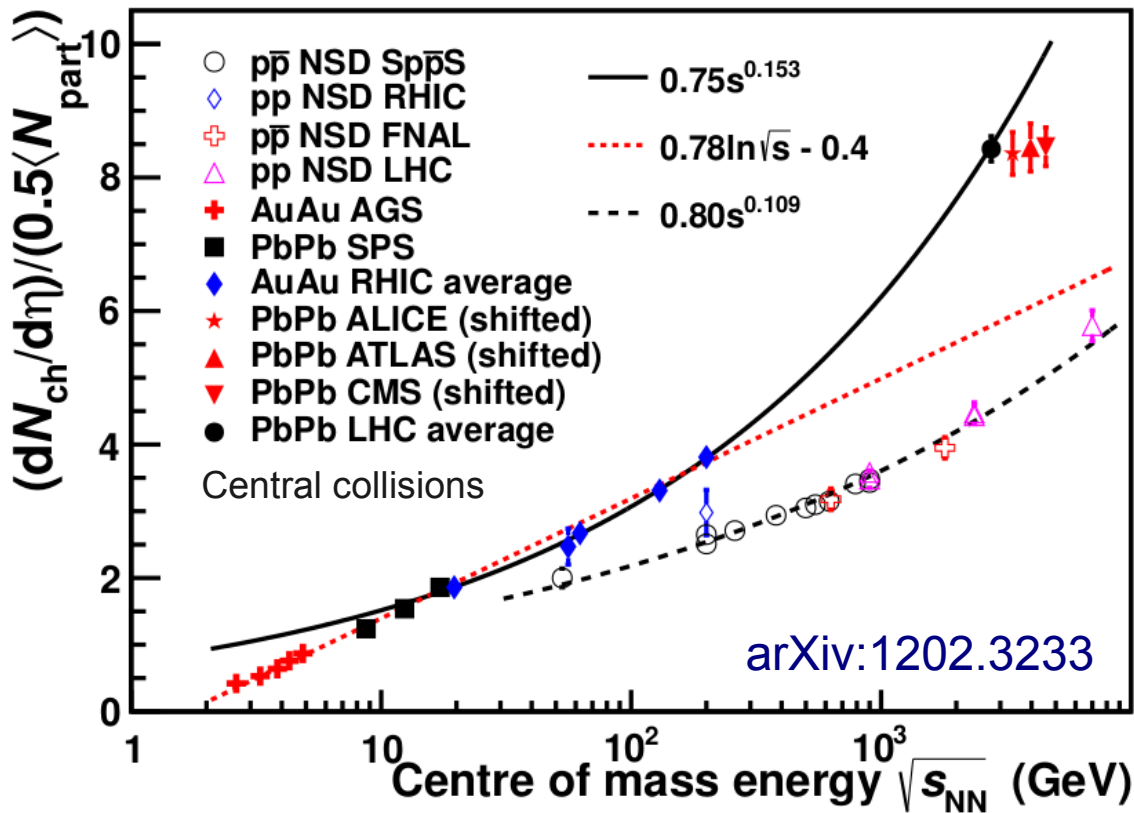
7



Stronger rise with center-of-mass energy in AA wrt to pp, and wrt to extrapolations from lower energies ($dN_{ch}/d\eta_{LHC} \approx 1600 \sim 2 \times dN_{ch}/d\eta_{RHIC}$)

ALICE, PRL 106 (2011) 032301
 CMS, JHEP 1108 (2011) 141
 ATLAS, PLB 710 (2012) 363

Energy dependence of $dN/d\eta$ and $dE_T/d\eta$ 8



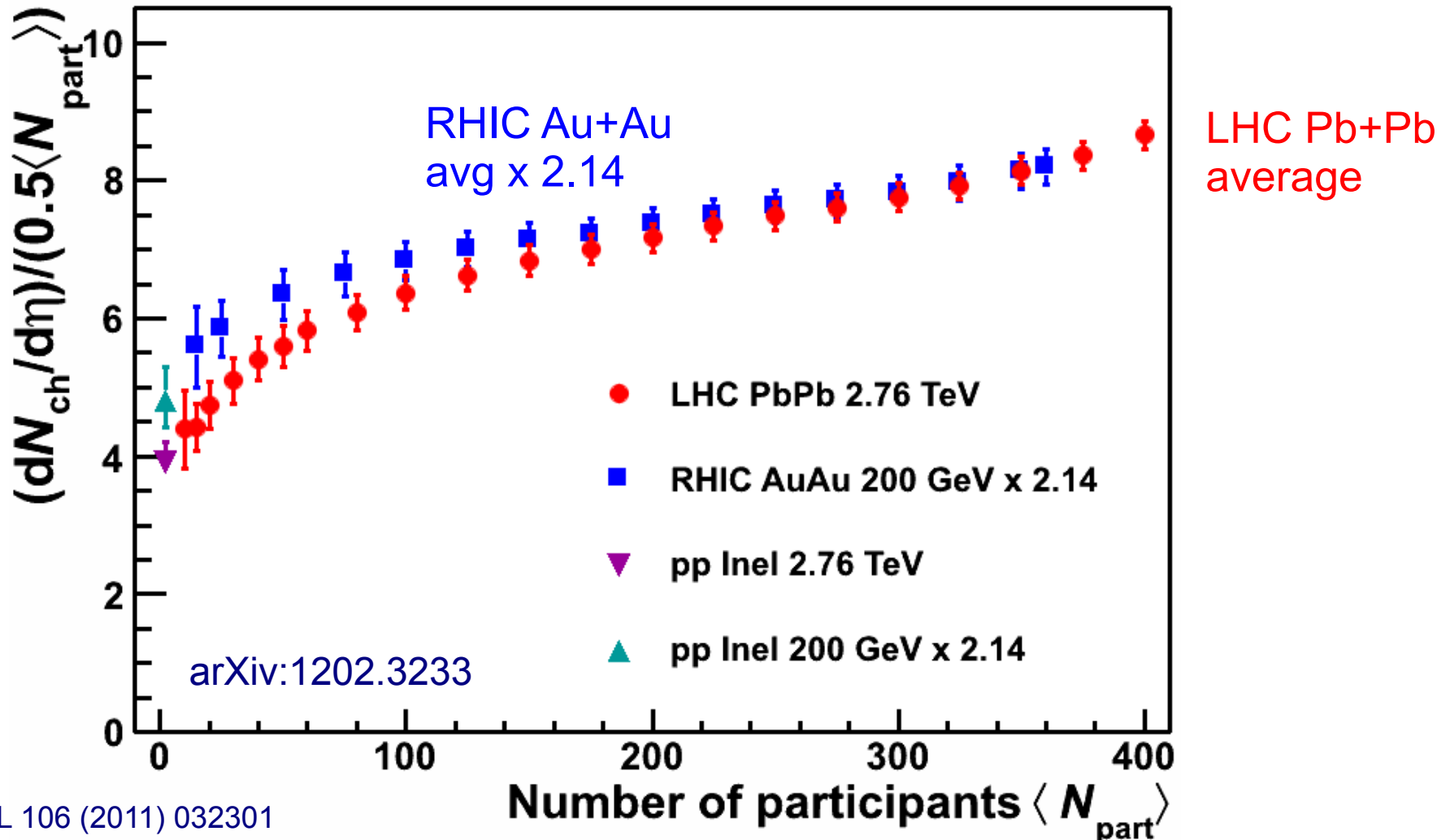
Stronger rise with center-of-mass energy in AA wrt to pp, and wrt to extrapolations from lower energies ($dN_{ch}/d\eta_{LHC} \approx 1600 \sim 2 \times dN_{ch}/d\eta_{RHIC}$)

$$\epsilon(\tau) = \frac{dE_T/d\eta}{\pi R^2 \tau} \approx 3/2 \langle m_T \rangle \frac{dN_{ch}/d\eta}{\pi R^2 \tau}$$

$$\tau \epsilon_{LHC} \approx 2.5 \times \tau \epsilon_{RHIC}$$

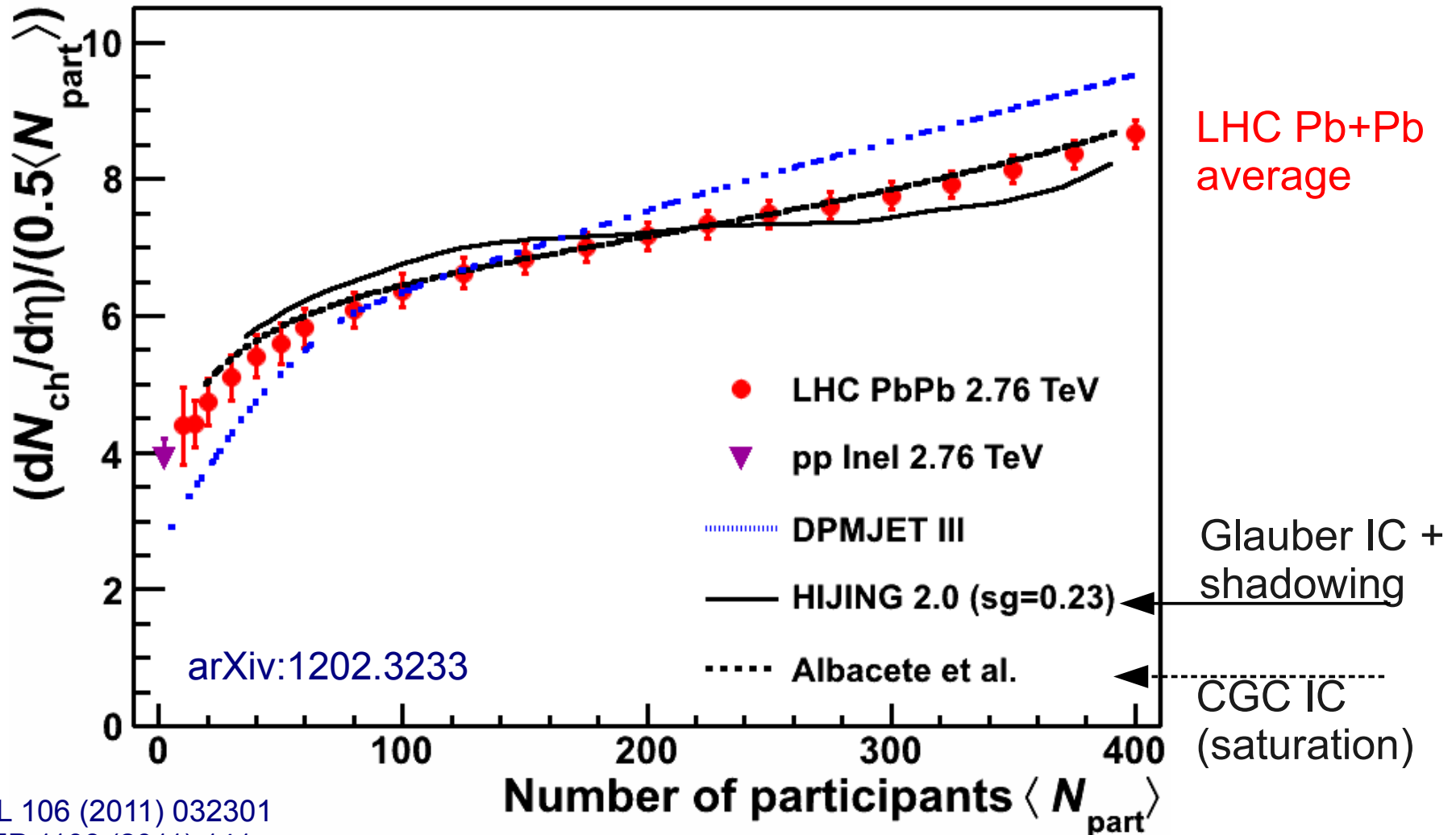
Initial energy density at LHC (as at RHIC) is well above $\epsilon_c \approx 0.5 \text{ GeV}/\text{fm}^3$

Centrality dependence of $dN/d\eta$



ALICE, PRL 106 (2011) 032301
CMS, JHEP 1108 (2011) 141
ATLAS, PLB 710 (2012) 363

Centrality dependence is strikingly similar to RHIC.
This actually holds all the way down to 19.6 GeV (not shown)



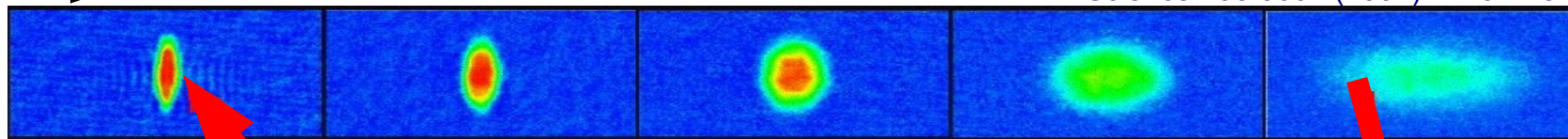
ALICE, PRL 106 (2011) 032301
 CMS, JHEP 1108 (2011) 141
 ATLAS, PLB 710 (2012) 363

Two-component models need to incorporate strong nuclear modification. Models based on Glauber and CGC initial conditions can describe the data.

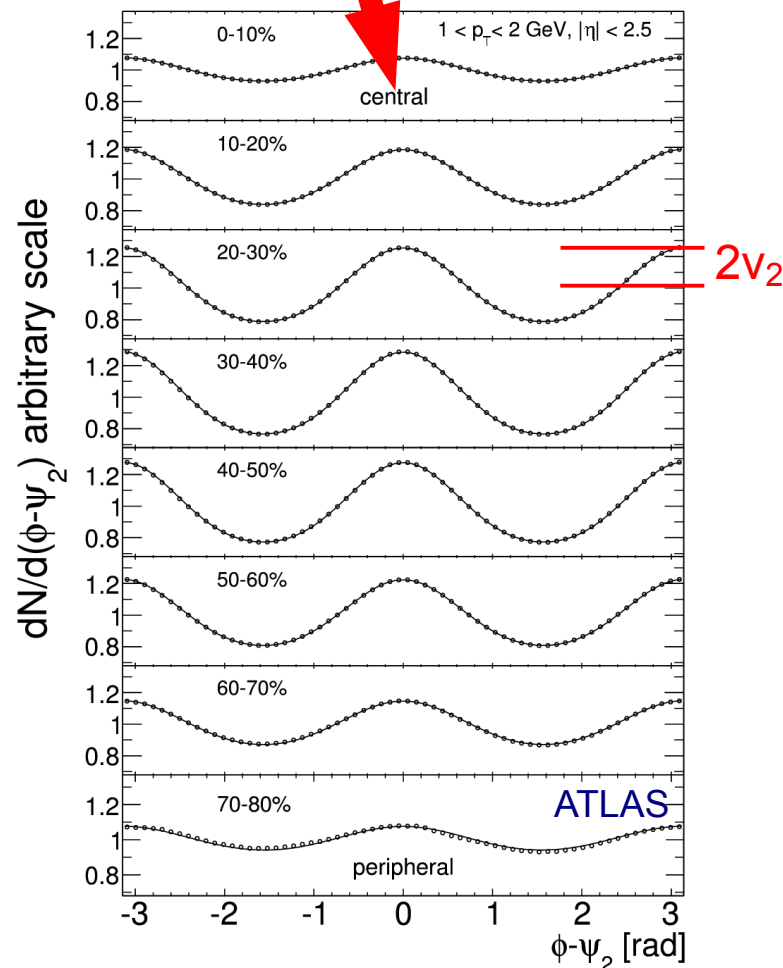
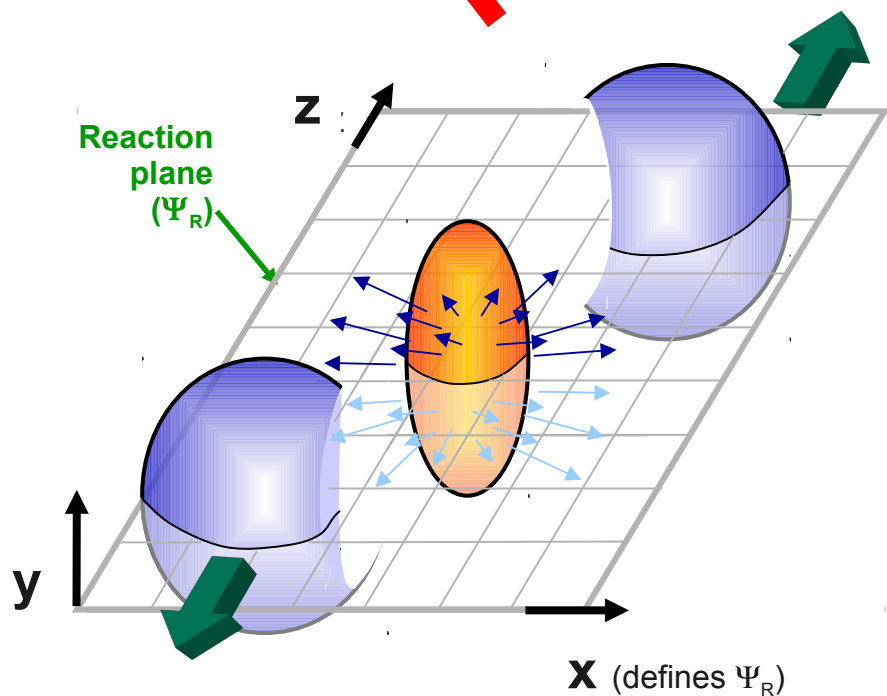
Initial and final state anisotropy

Time →

Science 298 5601 (2002) 2179-2182



(self quenching)



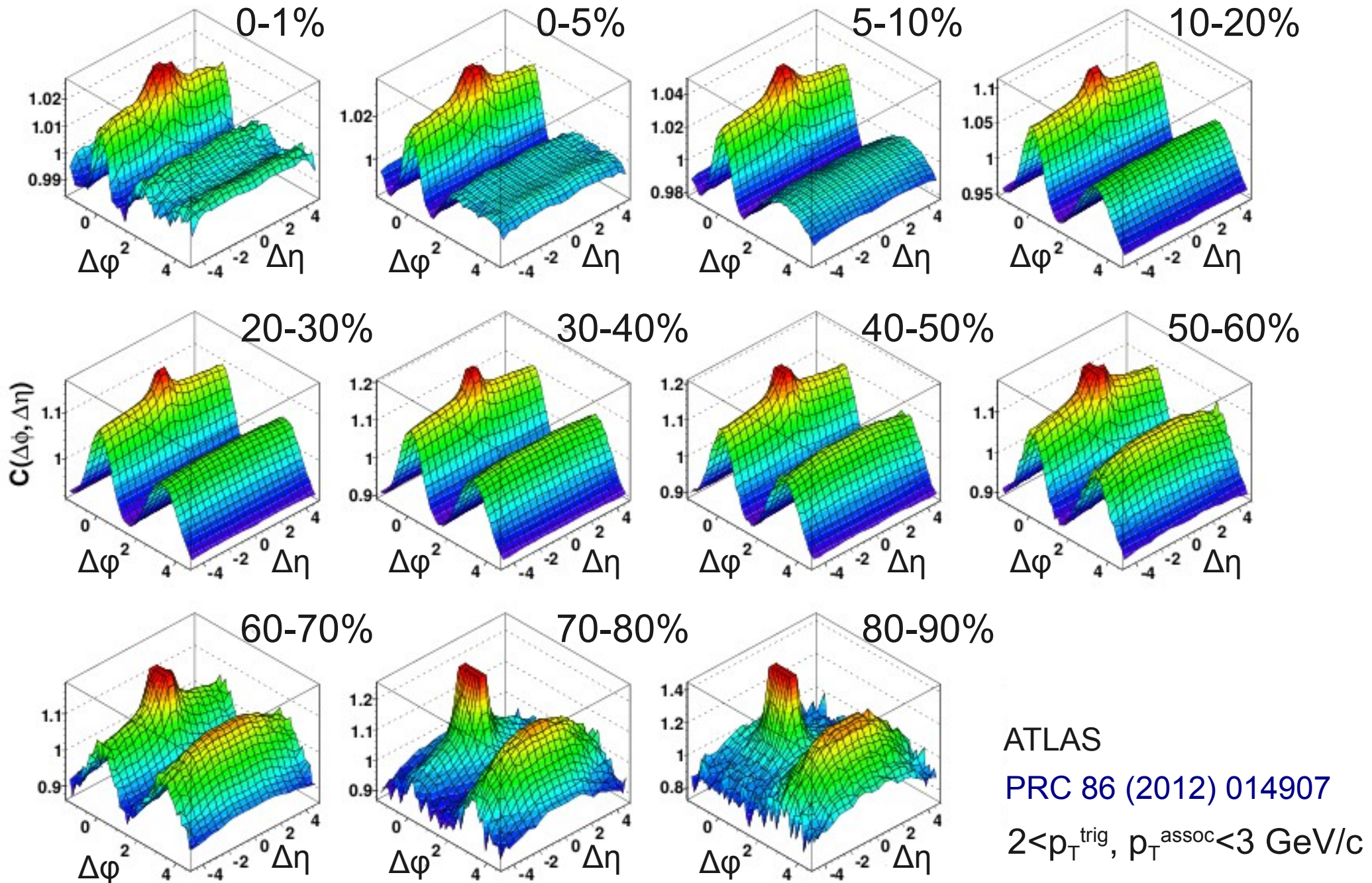
Initial spatial anisotropy:
eccentricity ϵ

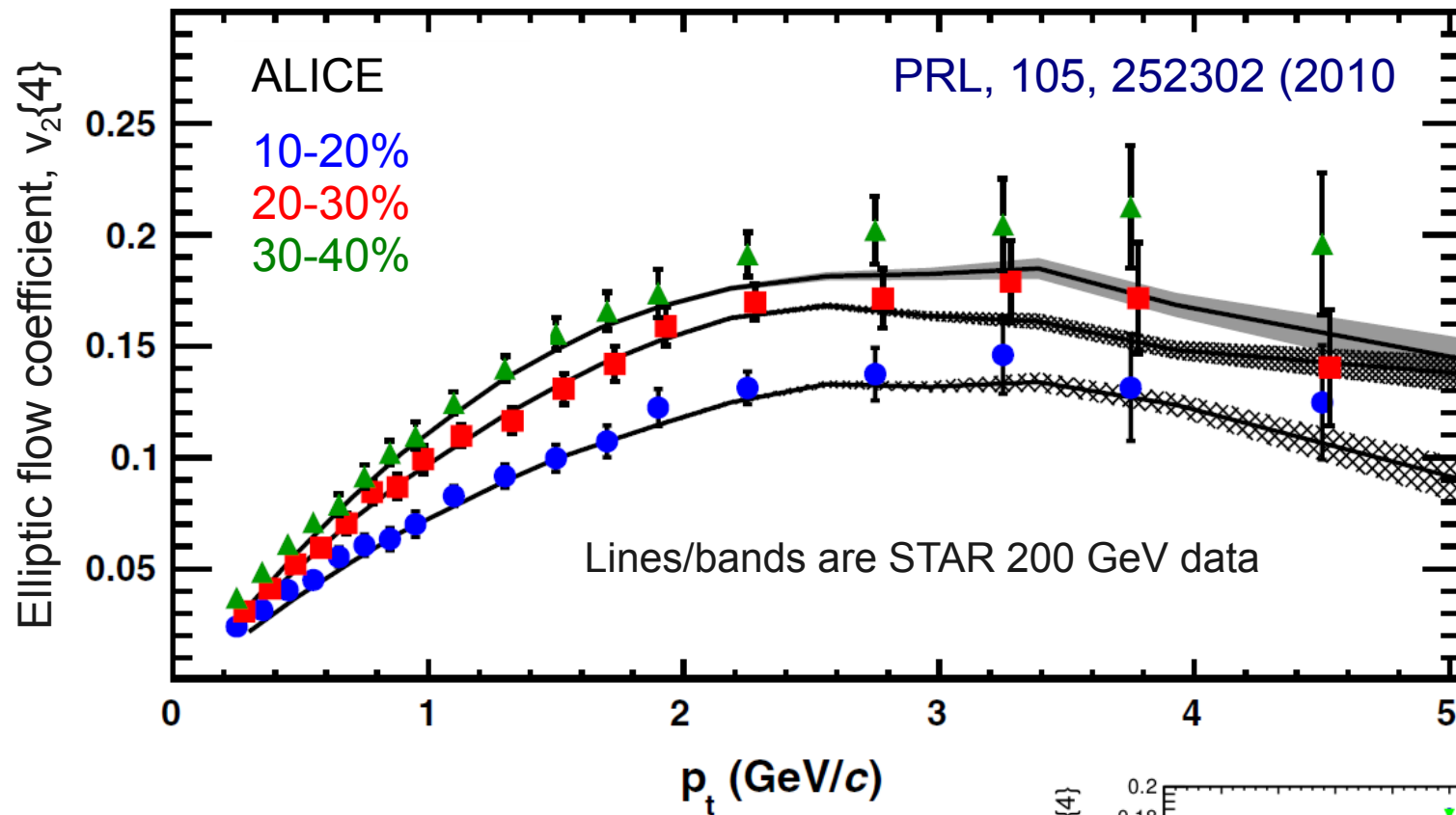
→
Interactions
present early

Momentum space anisotropy:
elliptic flow $v_2 = \langle \cos(2\phi - 2\Psi_R) \rangle$

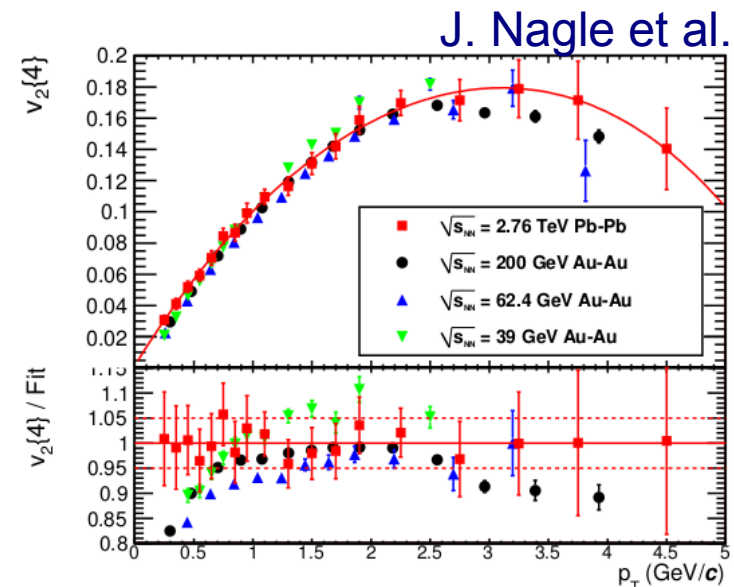
Two-particle correlations

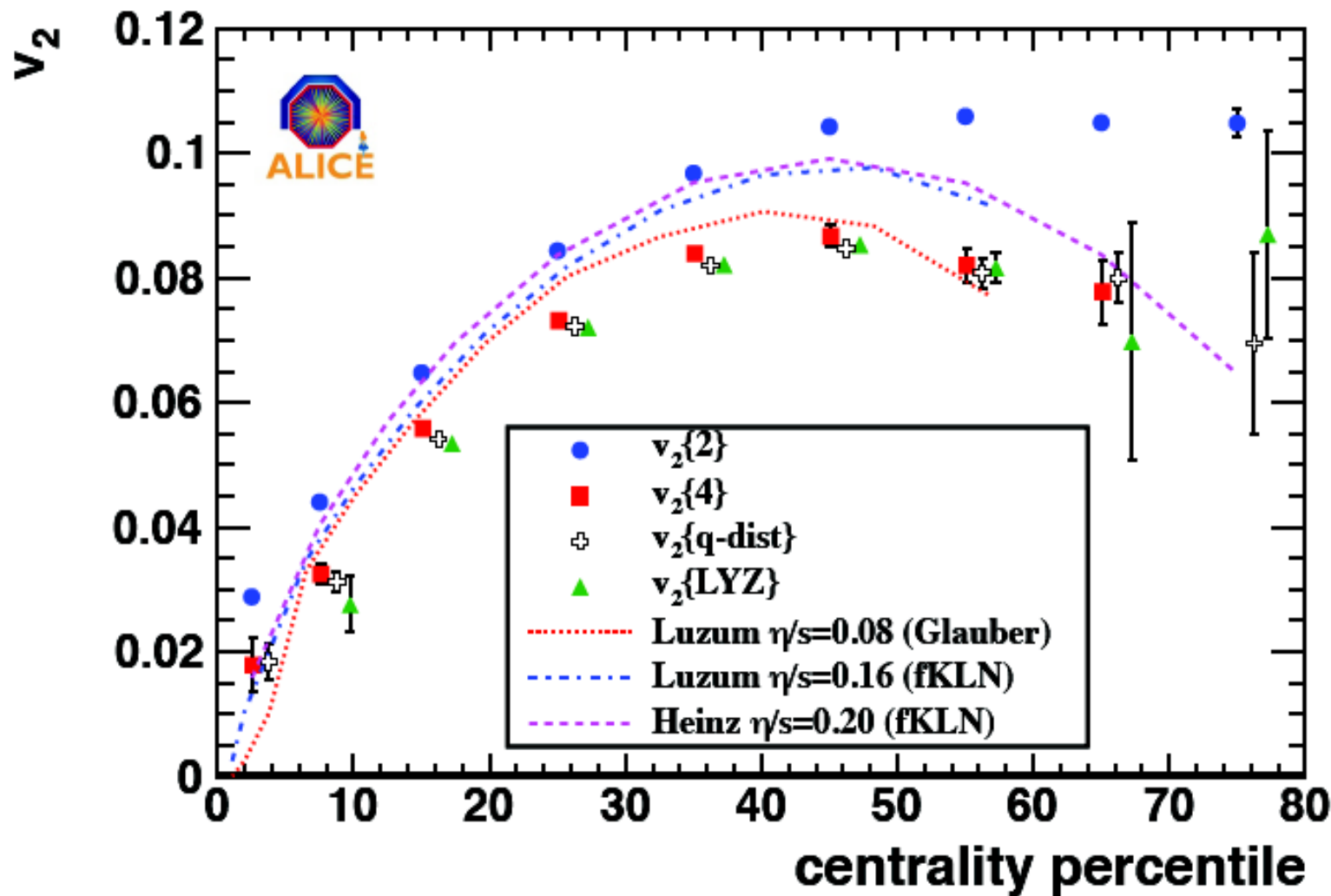
12





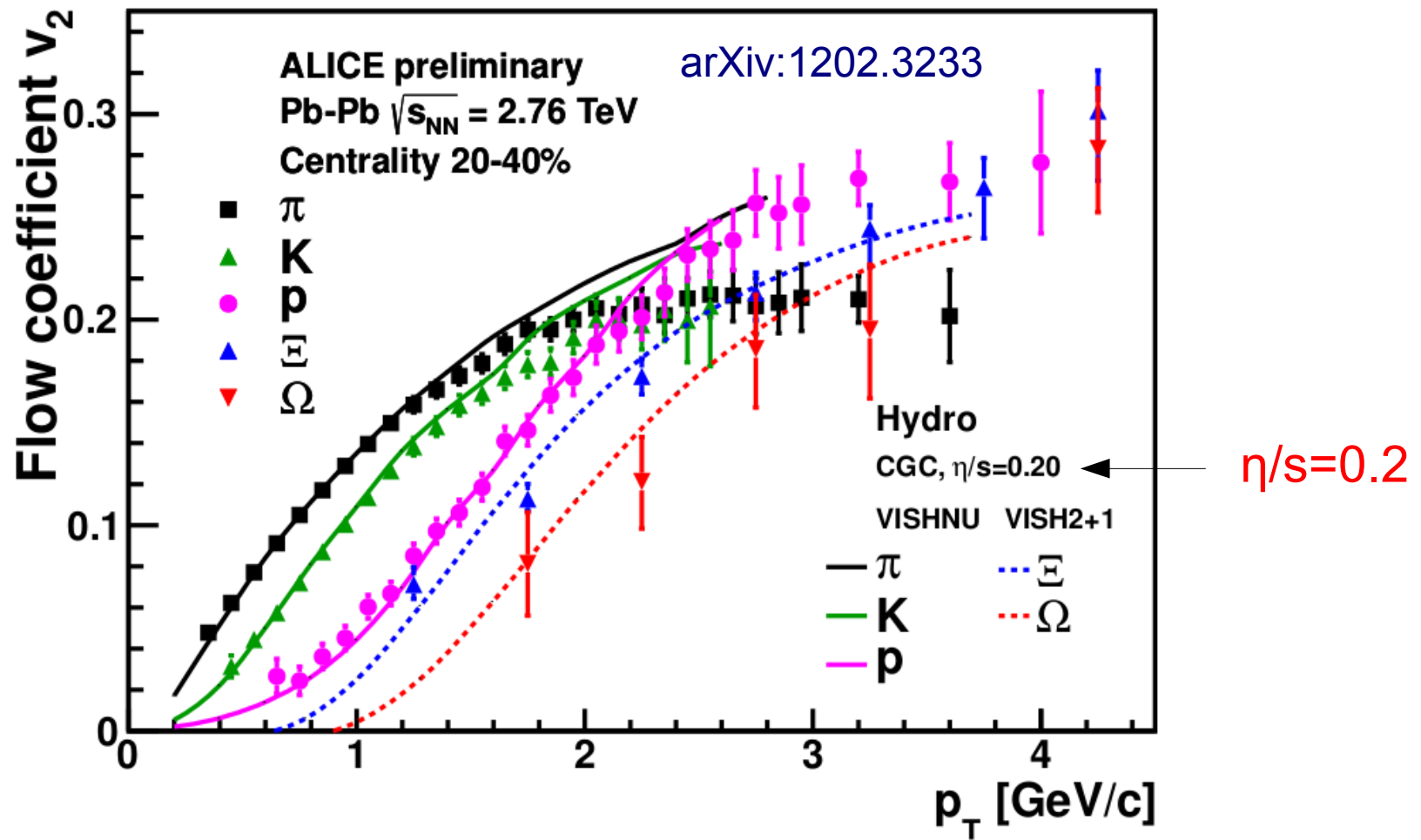
Observe $v_2(p_T)_{LHC} \approx v_2(p_T)_{RHIC}$,
 despite factor 14 increase in cms energy!
 (Integrated v_2 30% larger due to radial flow)



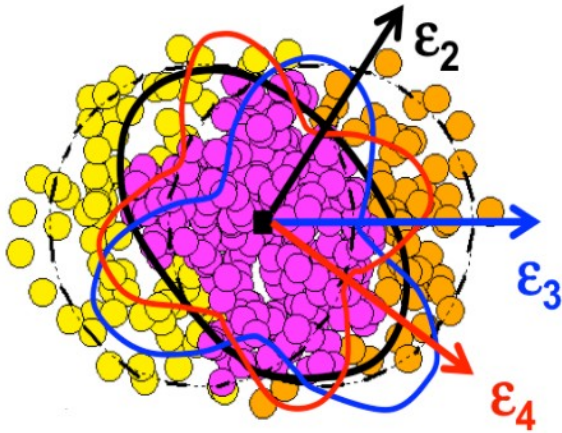


Calculation:
M.Luzum,
arXiv:1011.5173

Increase well within the range of viscous hydro predictions



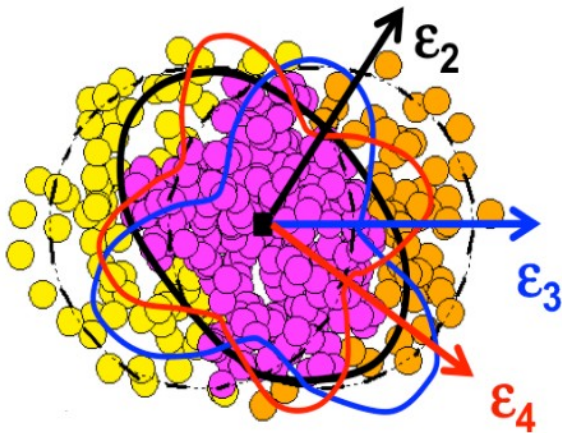
Observed mass ordering due to radial flow as predicted by hydrodynamical calculations



Alver, Roland

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

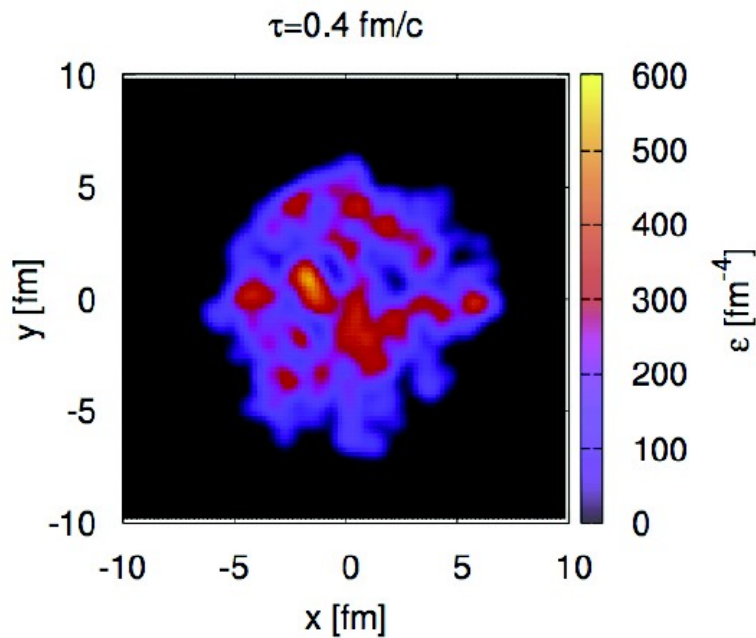
$$\frac{dN}{d\phi} \sim 1 + \underbrace{2v_2}_{\text{black}} \cos[2(\phi - \psi_2)] + \underbrace{2v_3}_{\text{blue}} \cos[3(\phi - \psi_3)] \\ + \underbrace{2v_4}_{\text{red}} \cos[4(\phi - \psi_4)] + \underbrace{2v_5}_{\text{magenta}} \cos[5(\phi - \psi_5)] + \dots$$



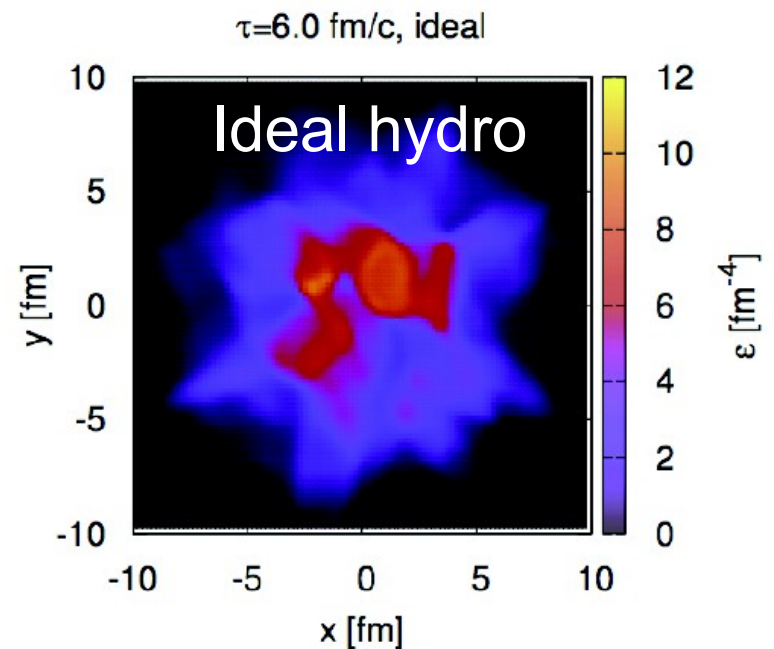
Alver, Roland

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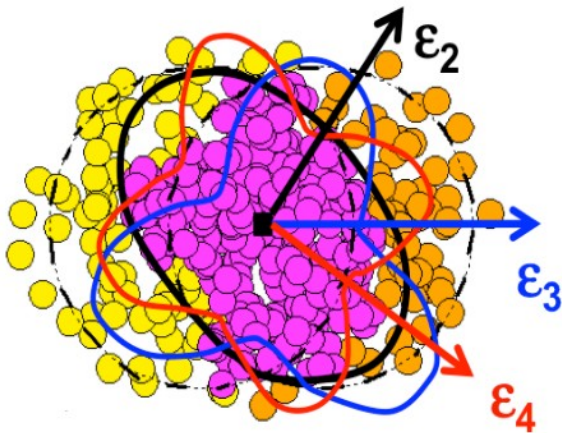
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e-by-e hydro
 →
 B. Schenke et al.



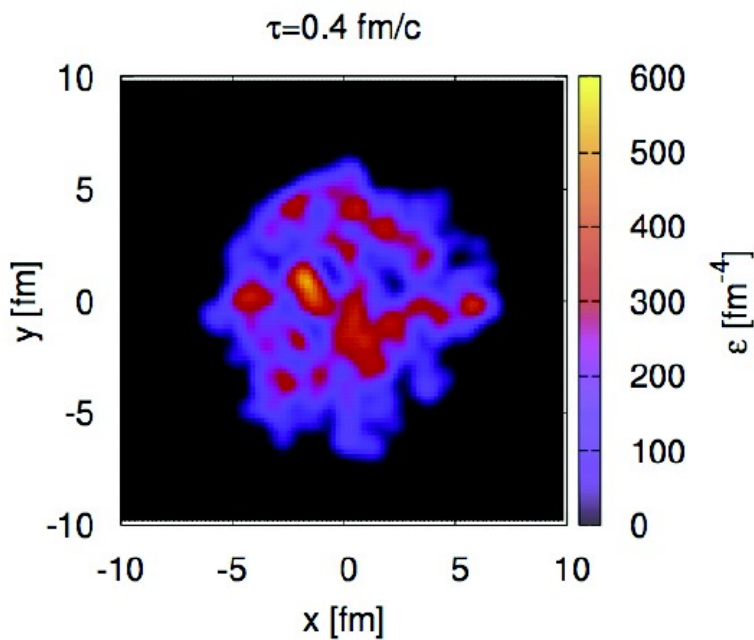
Ideal hydrodynamical models preserves these “clumpy” initial conditions



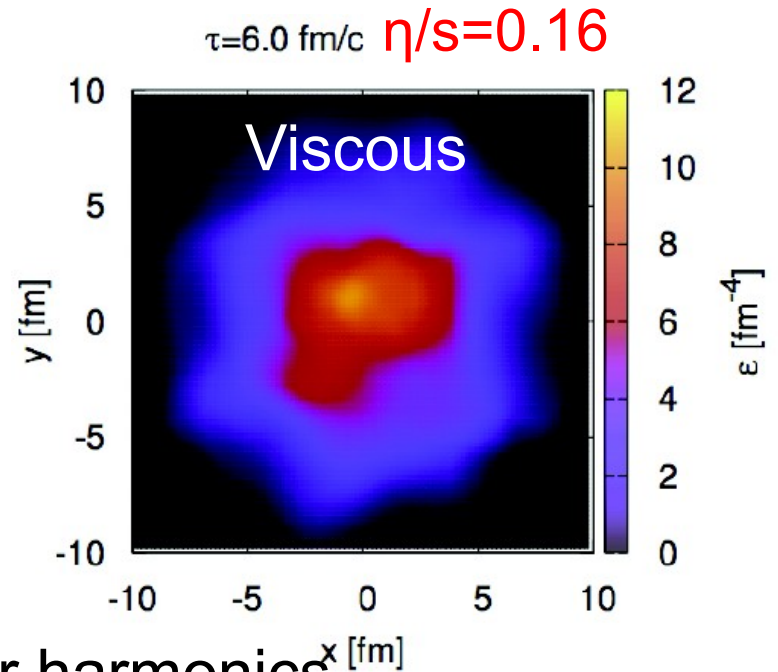
Alver, Roland

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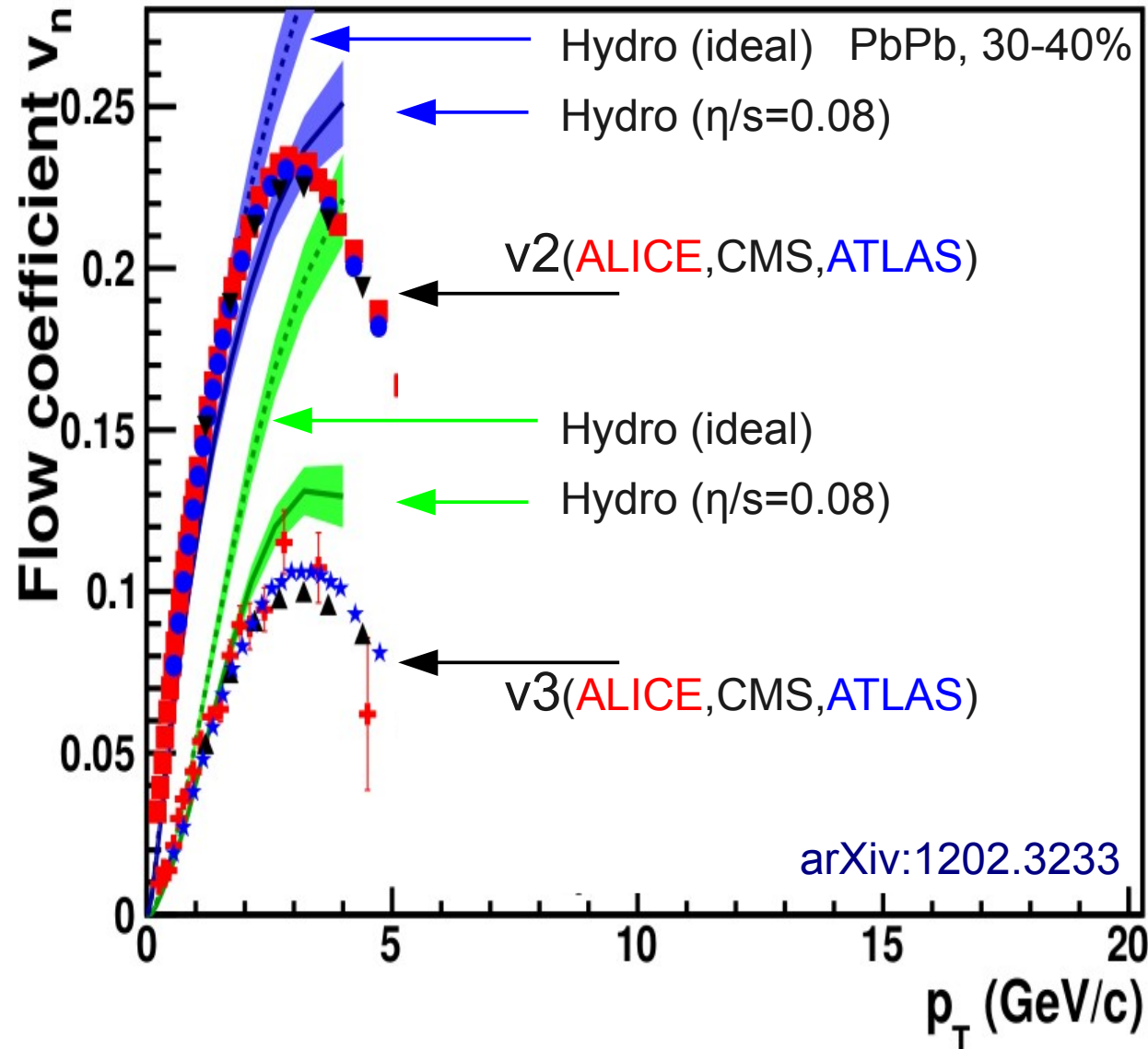
$$\frac{dN}{d\phi} \sim 1 + \underbrace{2v_2}_{\text{black}} \cos[2(\phi - \psi_2)] + \underbrace{2v_3}_{\text{blue}} \cos[3(\phi - \psi_3)] + \underbrace{2v_4}_{\text{red}} \cos[4(\phi - \psi_4)] + \underbrace{2v_5}_{\text{magenta}} \cos[5(\phi - \psi_5)] + \dots$$



e-by-e hydro
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 B. Schenke et al.



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

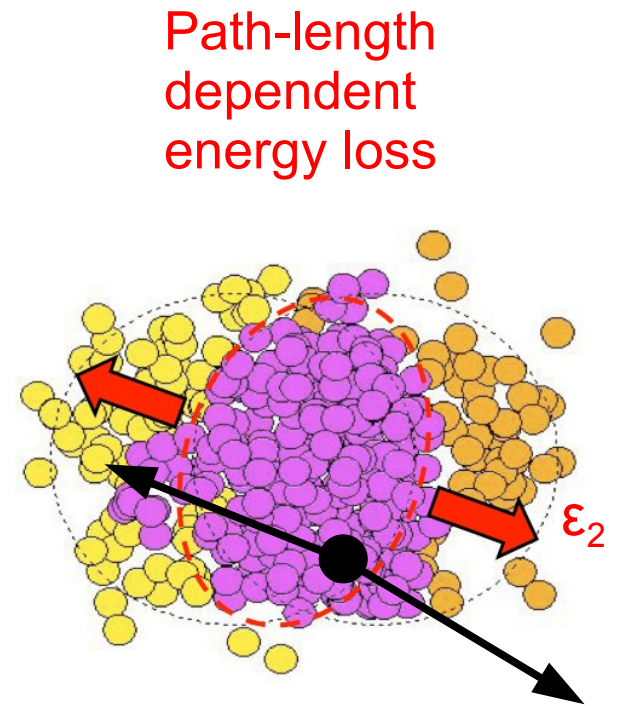
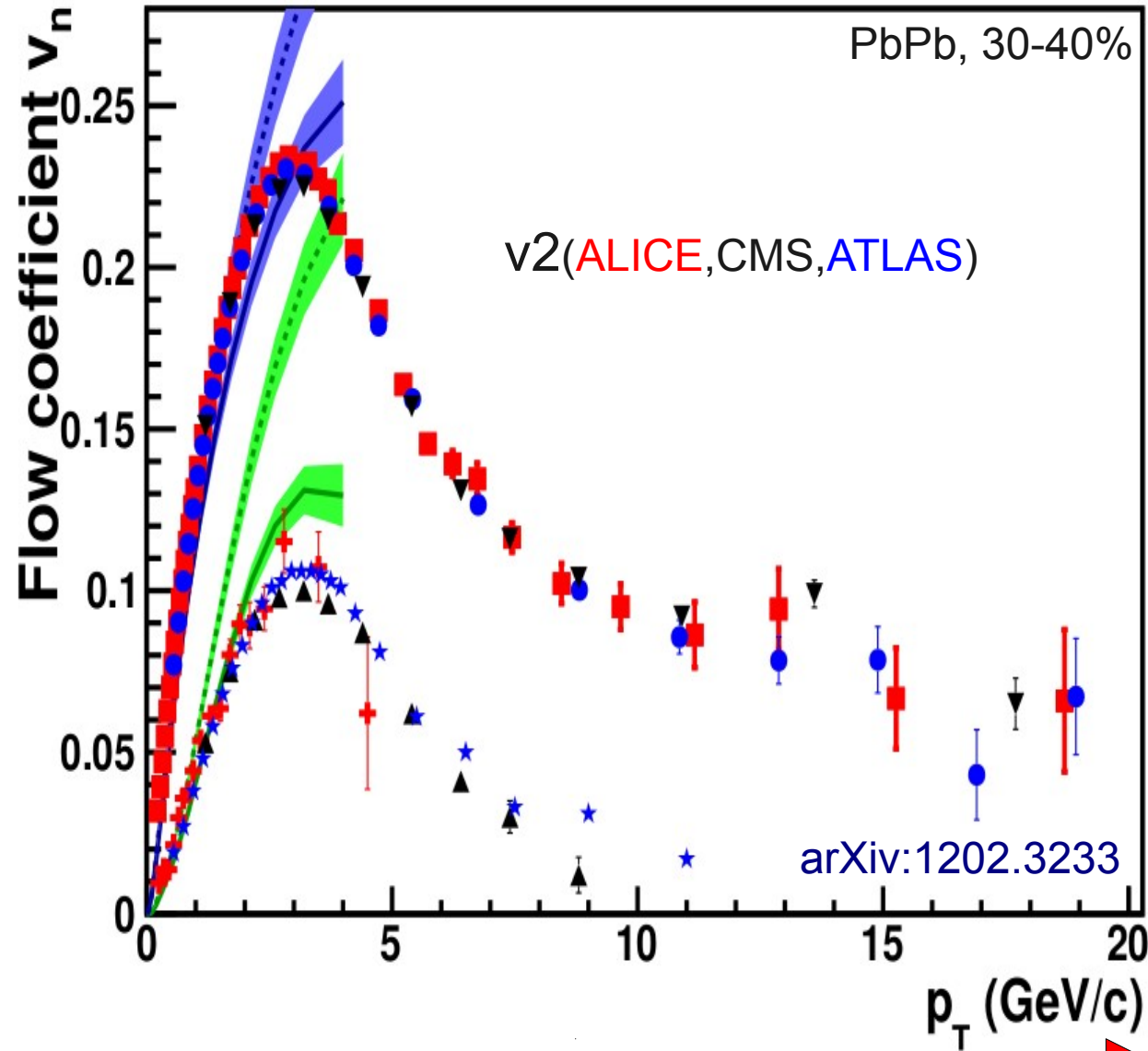


- Significant v_3 component
- Viscosity dissipates initial pressure gradients and reduces the collective flow
- v_3 provides additional constraints on η/s
- Current bound at LHC
 - $\eta/s < 2/(4\pi) = 2(\eta/s)_{\min}^{\text{ADS/CFT}}$

Qui, Shen, Heinz, PLB 707 (2012) 151

ALICE, PRL 107 (2011) 032301
 ATLAS, PLB 707 (2012) 330
 ATLAS, PRC 86 (2012) 014907
 CMS, arXiv:1204.1409

The quark-gluon plasma at the LHC is still a nearly perfect liquid

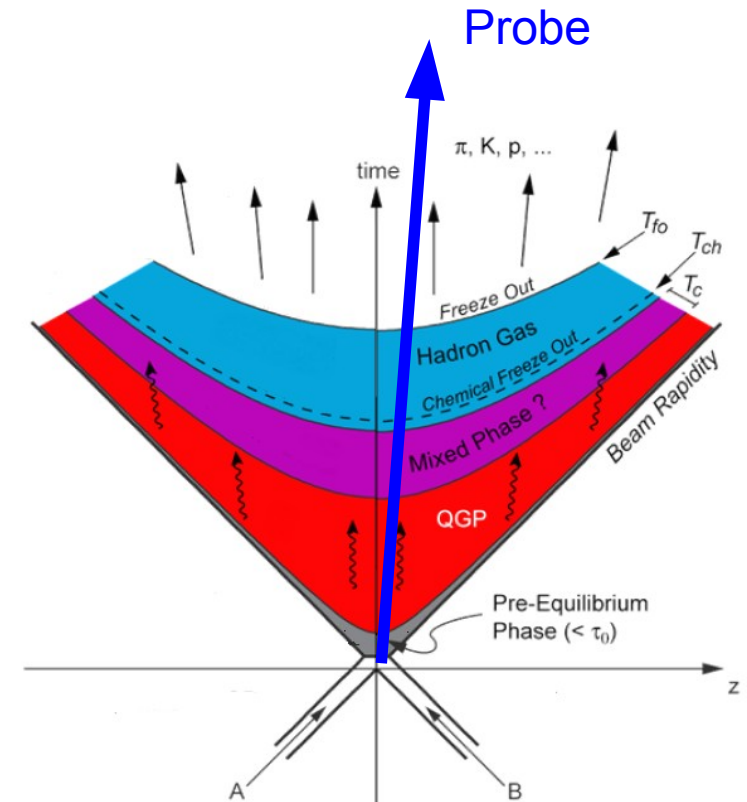
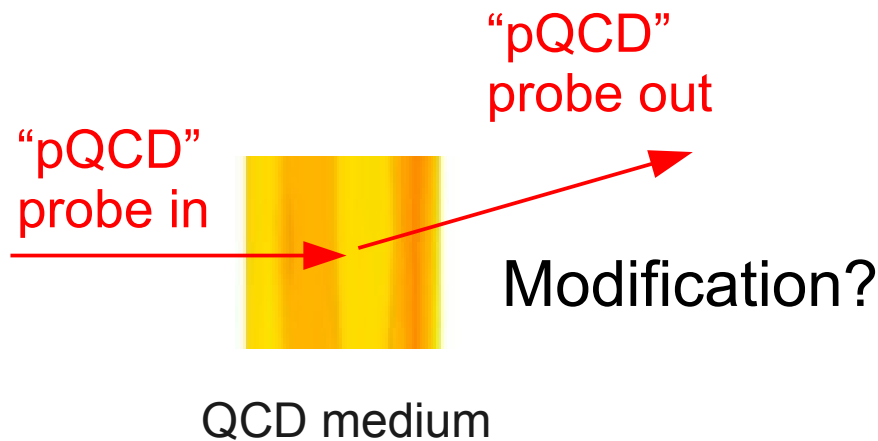


Soft p_T

High p_T

Parton energy loss

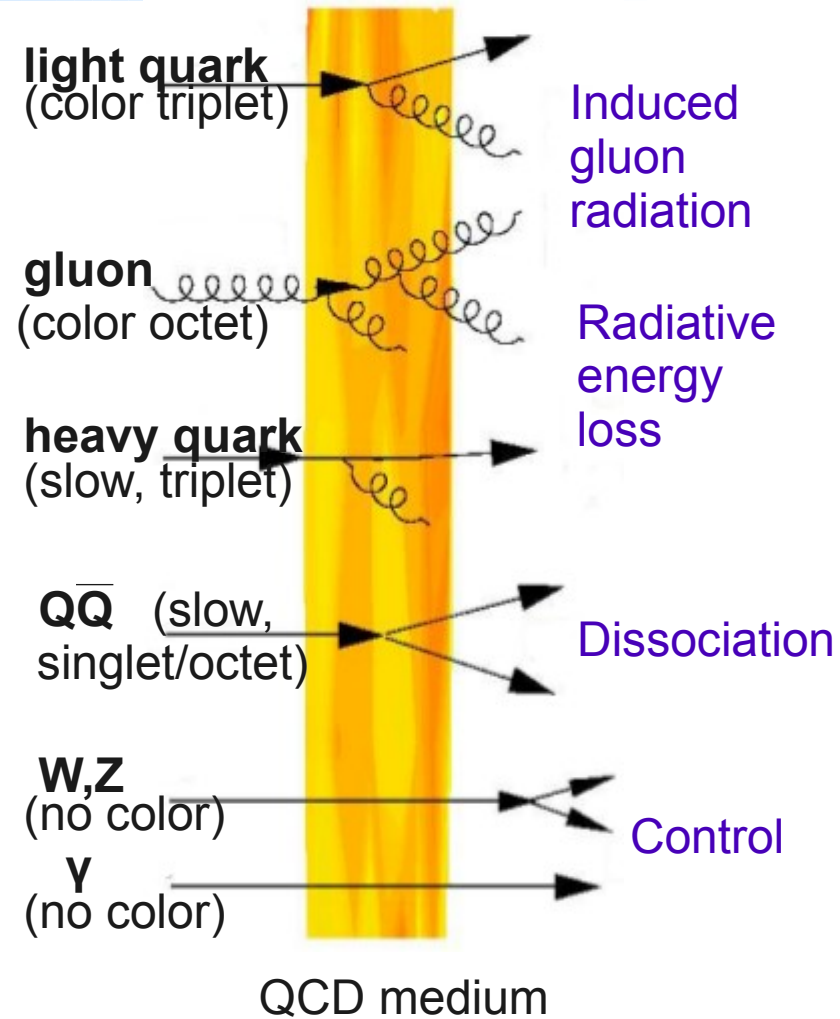
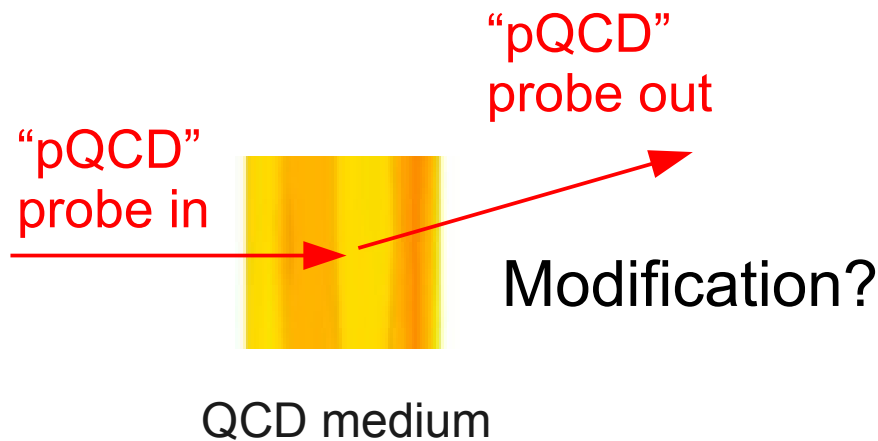
- Hard (large Q^2) probes of QCD matter:
jets, heavy-quark, $Q\bar{Q}$, γ , W , Z
 - “Self-generated” in the collision at $\tau < 1/Q$ (or $\tau < 1/m$) < 0.1 fm/c
 - “Tomographic” probes of hottest and densest phase of medium



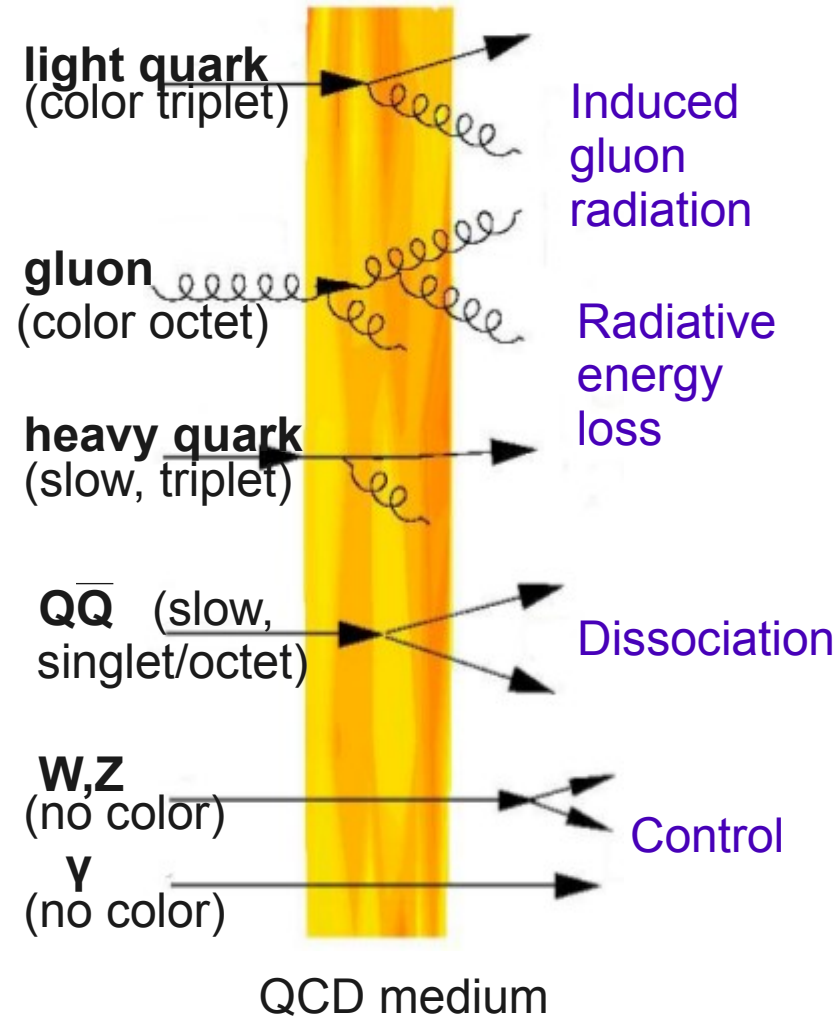
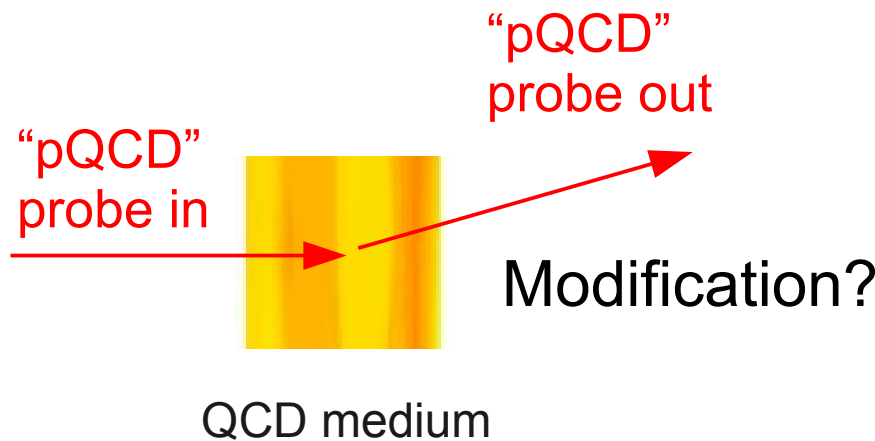
Tomography of QCD matter

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

$$R_{AA}(p_T) = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T} = \frac{dN_{AA}/dp_T}{T_{AA} d\sigma_{pp}}$$

$R_{AA} = 1 \rightarrow$ no deviation from scaling

$R_{AA} < 1 \rightarrow$ suppression

- Quantify change of production rates from expected binary scaling

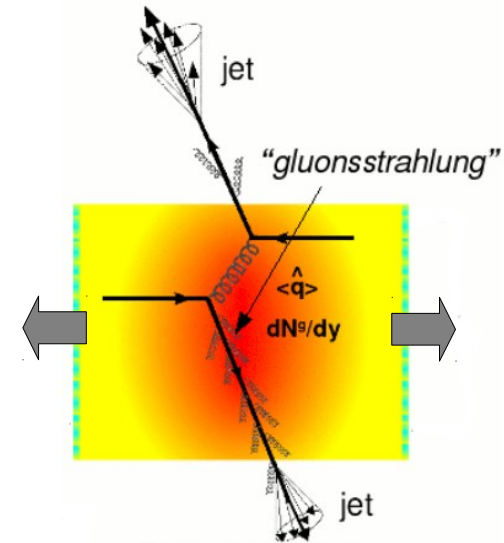
Elastic energy loss:

$$\frac{dE}{dx} = -C_2 \hat{e}$$

Radiative energy loss:

$$\frac{dE}{dx} = -C_2 \hat{q} L$$

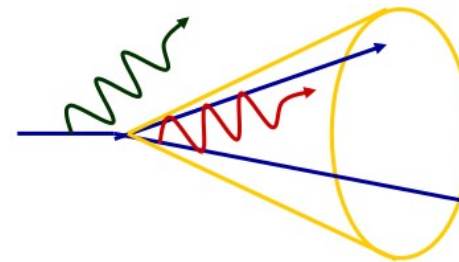
Energy/momentum diffusion tensor:
encodes properties of the medium.



- **Induced radiation**
 - Increased splitting probability (broadens radiation)
 - Finite quark mass vetos small angle radiation (dead-cone effect)
 - Modified angular pattern due to enhanced incoherence between successive splittings
- **Color exchange with medium**
 - Modifies color flow in the jet (affects hadronization)
- **Modelling dependence**
 - Piecewise description
 - Approximations

Search for effects in data:

Out-of-cone radiation (Jet $R_{AA} < 1$)

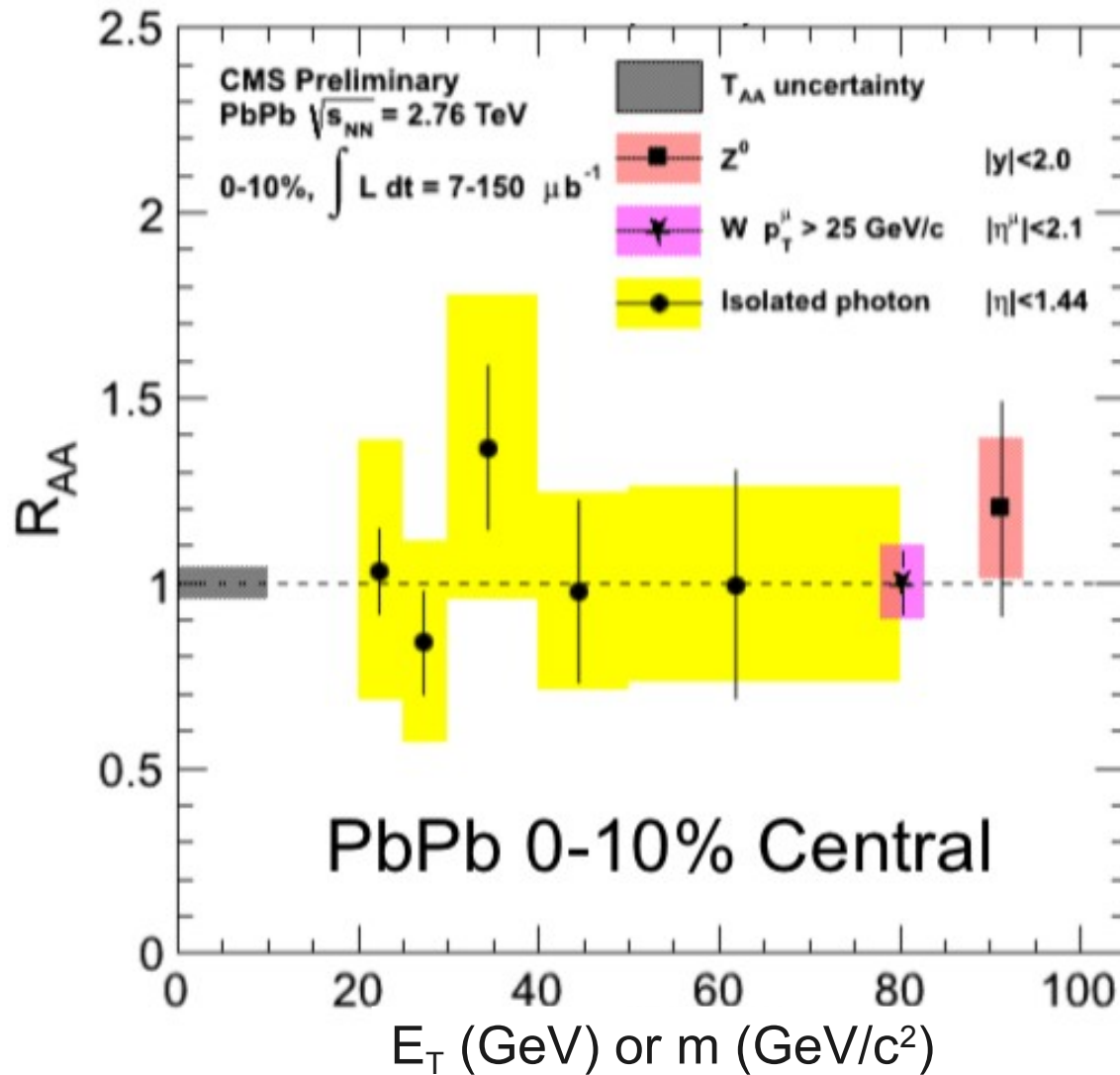


In-cone radiation
(FF modification)

$$\Delta E_{\text{loss}}(g) > \Delta E_{\text{loss}}(q) > \Delta E_{\text{loss}}(Q)$$

(color factor) (dead-cone effect)

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



Isolated γ :

ATLAS, [ATLAS-CONF-2012-051](#)

CMS, [PLB 710 \(2012\) 256](#)

Z boson:

ATLAS, [arXiv:1210.6486](#)

ATLAS, [PLB 697 \(2011\) 294](#)]

CMS, [PRL 106 \(2011\) 212301](#)

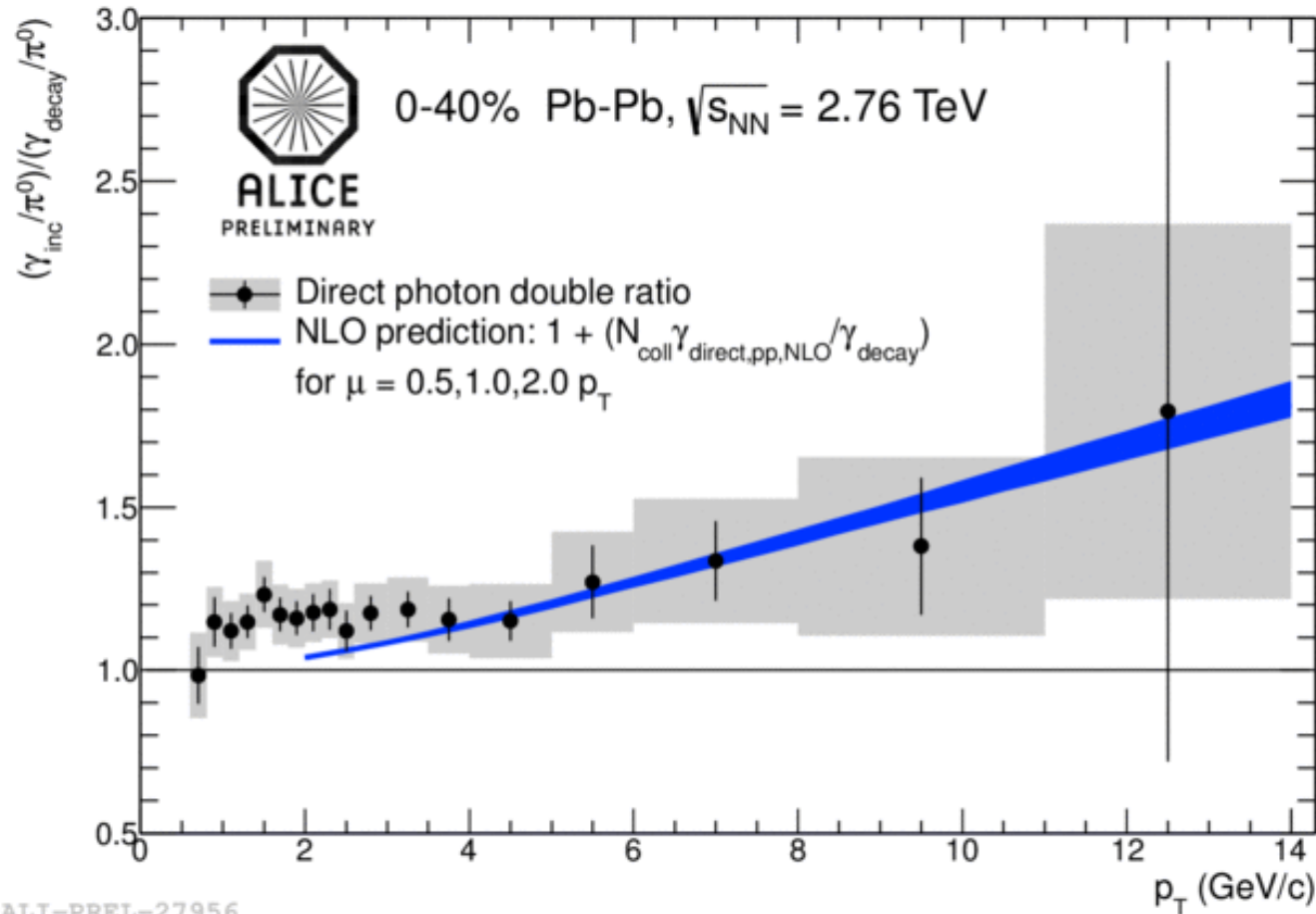
W boson:

ATLAS, [ATLAS-CONF-2011-78](#)

CMS, [PLB 715 \(2012\) 66](#)

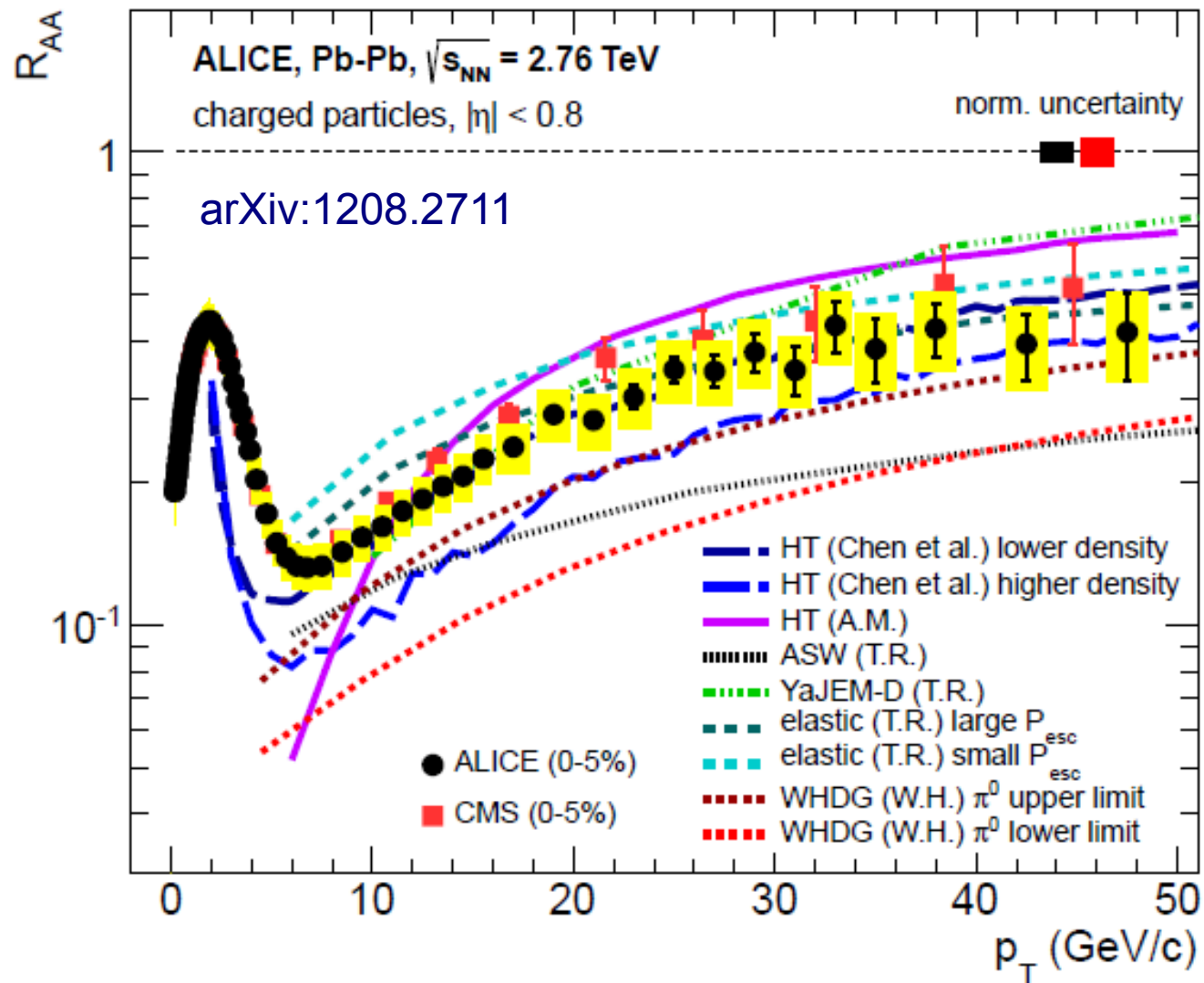
Control probes (isolated γ , Z, W) follow expected scaling ie. $R_{AA} \sim 1$

Double Ratio (Inclusive γ/π^0 divided by decay γ/π^0)



- Reconstruction of converted photons in ITS+TPC
- Double ratio strategy ala PHENIX
 - Measure inclusive photons and π^0
 - Model decay contribution with cocktail of all decay photon sources
- Ratio > 1 for direct γ

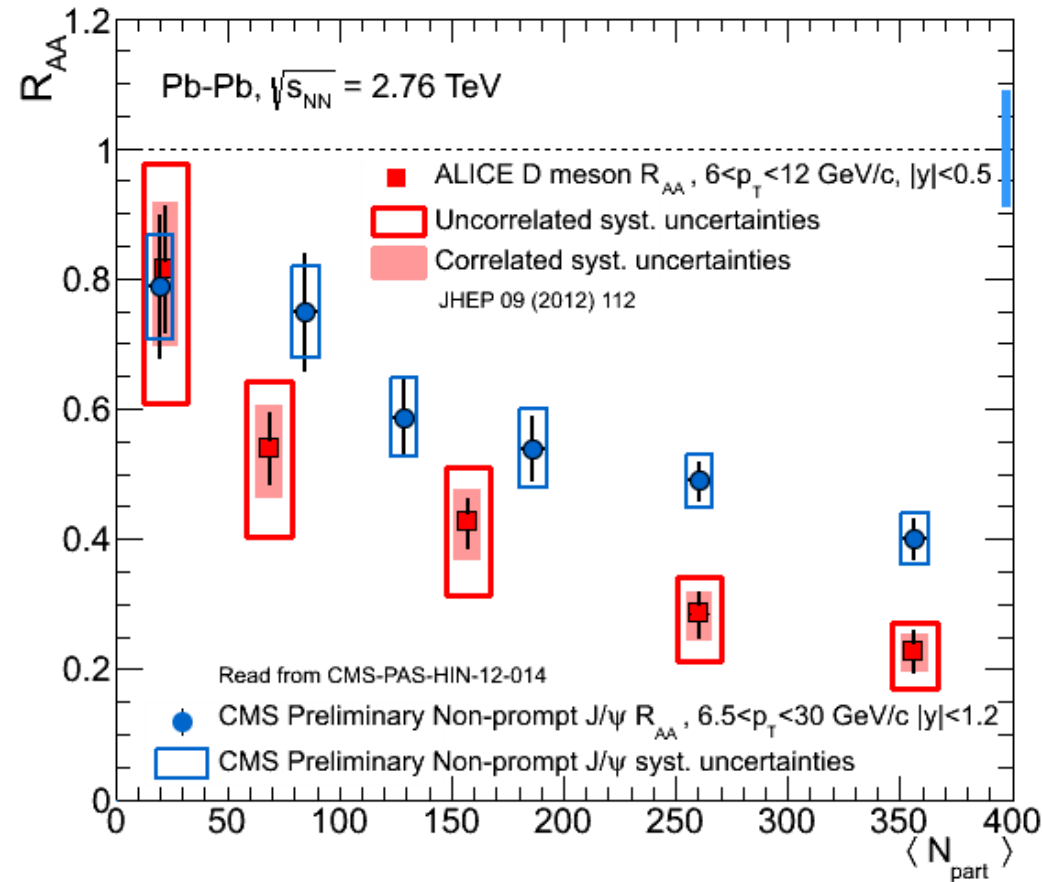
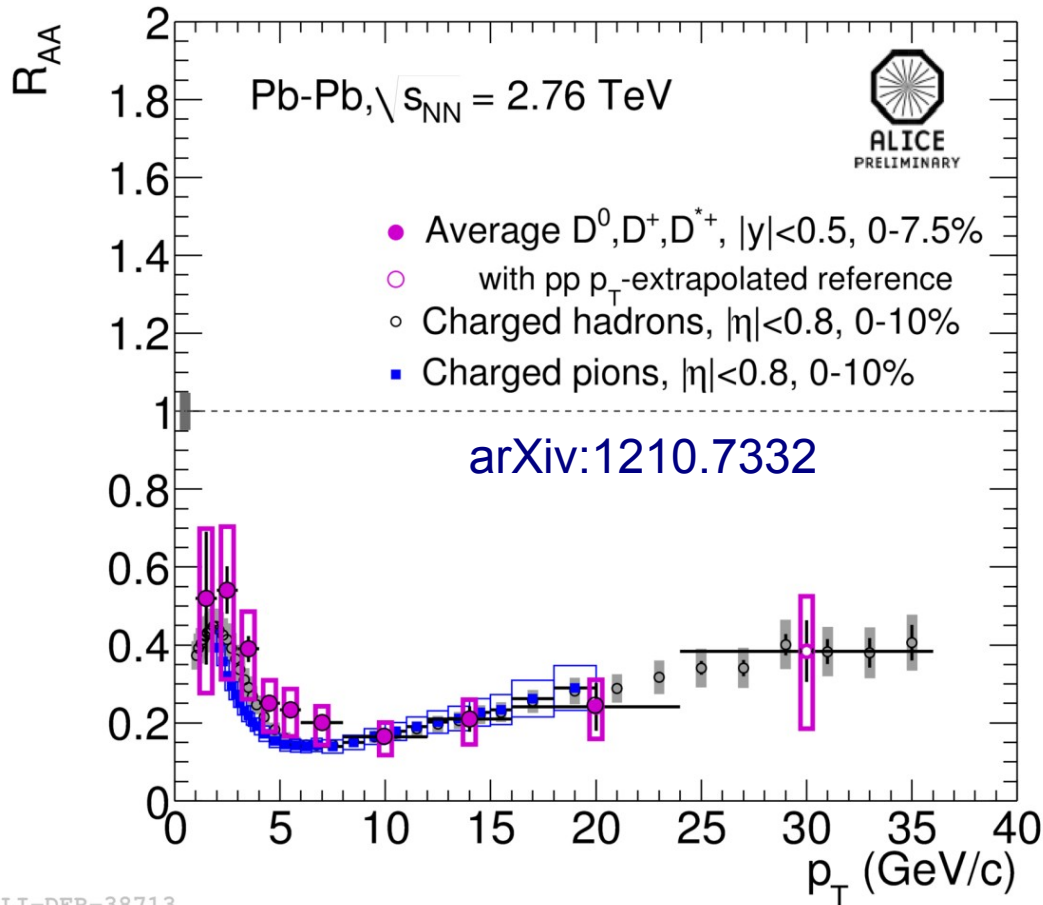
Double ratio consistent with Ncoll scaling of NLO direct γ prediction
 Excess at low p_T indicates source of non-decay photons at low p_T



Strong suppression observed; max at 6-7 GeV/c, followed by slow rise. Sensitivity to energy dependence of quenching, or effect of initial state?

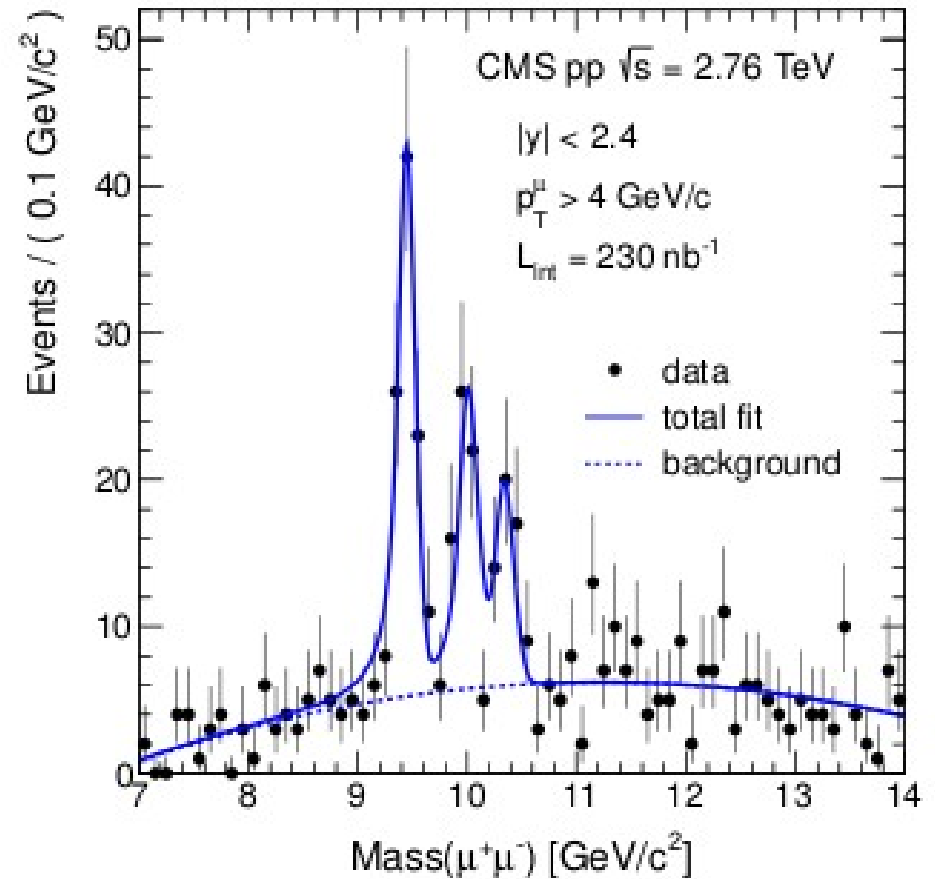
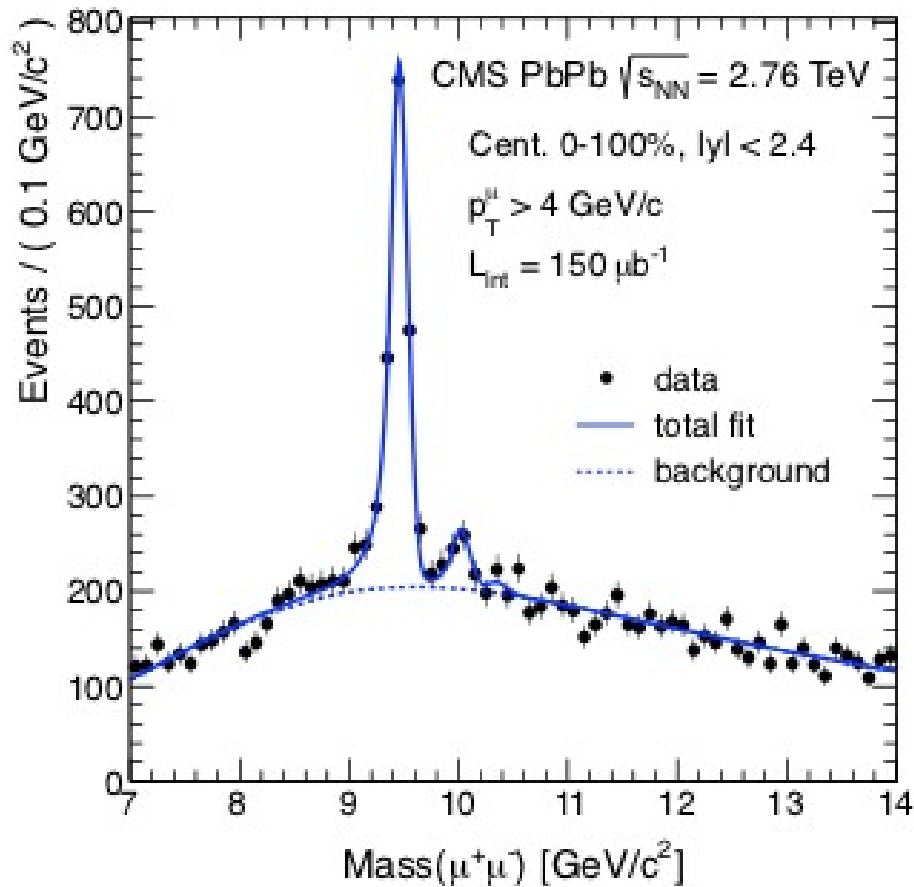
Heavy-quark suppression

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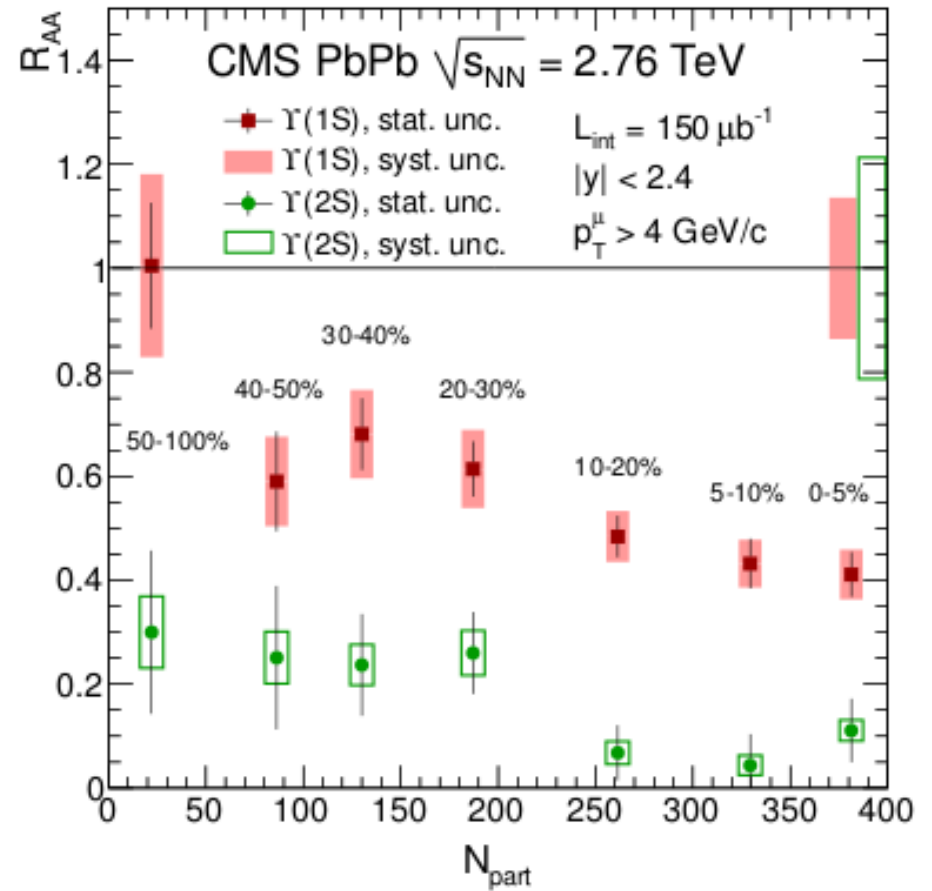
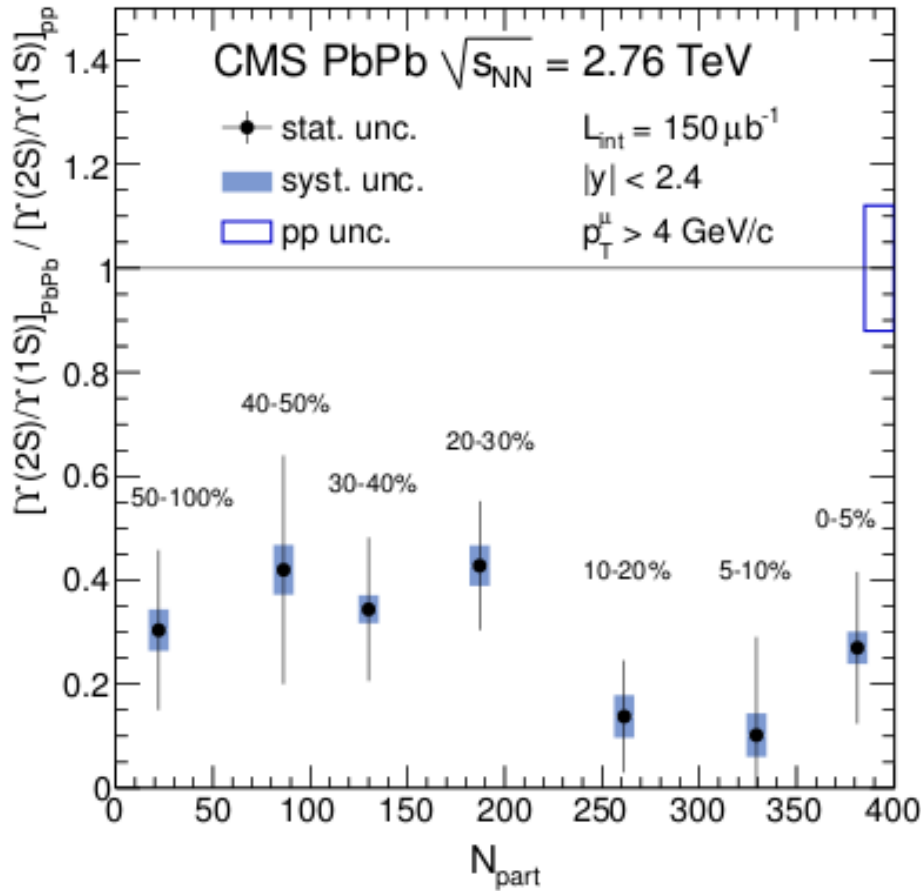


$$R_{AA}(\pi) < R_{AA}(D) < R_{AA}(B) ?$$

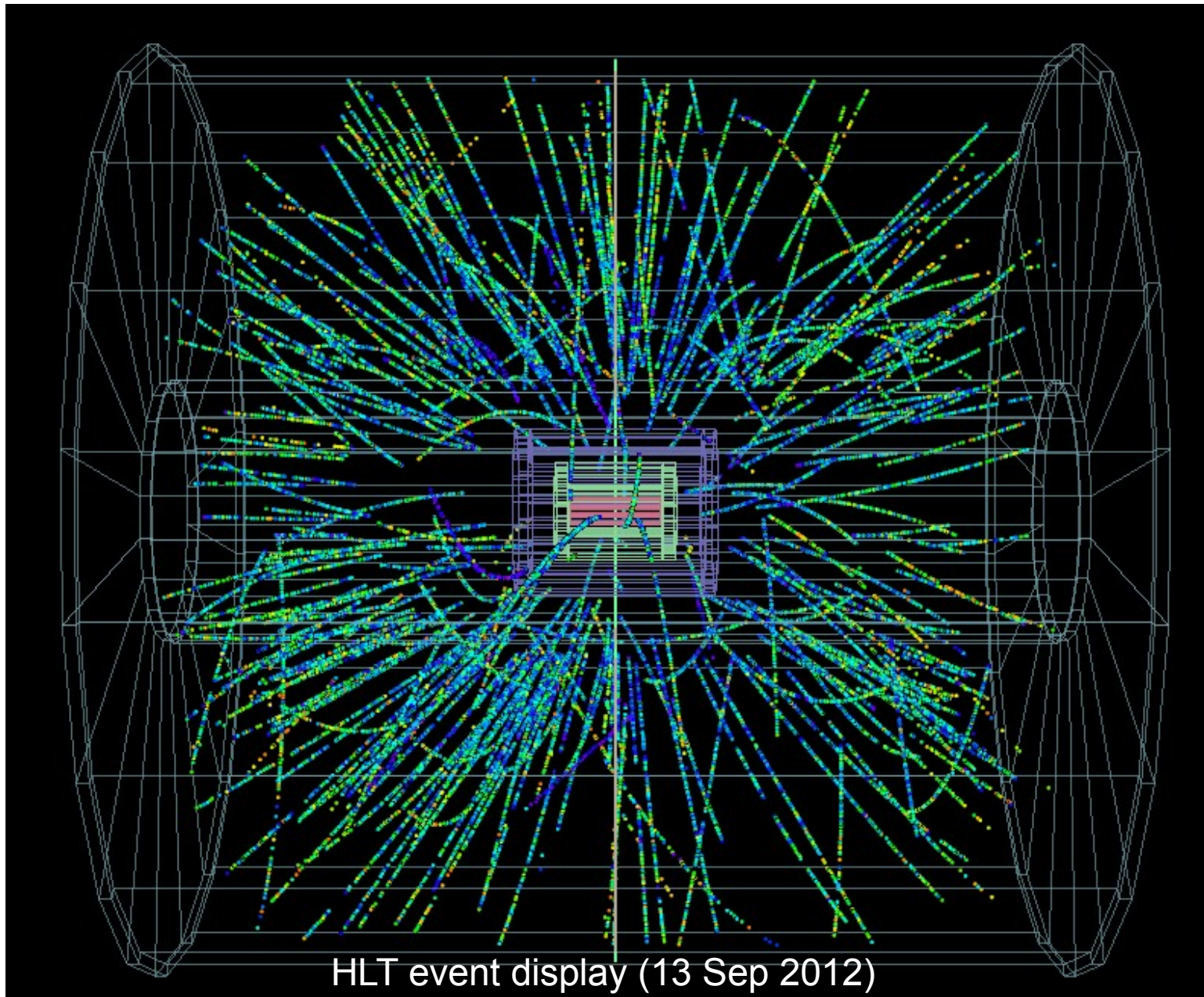
Above 8 GeV/c, suppression same for D and π , below smaller.
At $>6-7$ GeV/c indication that beauty is less suppressed!

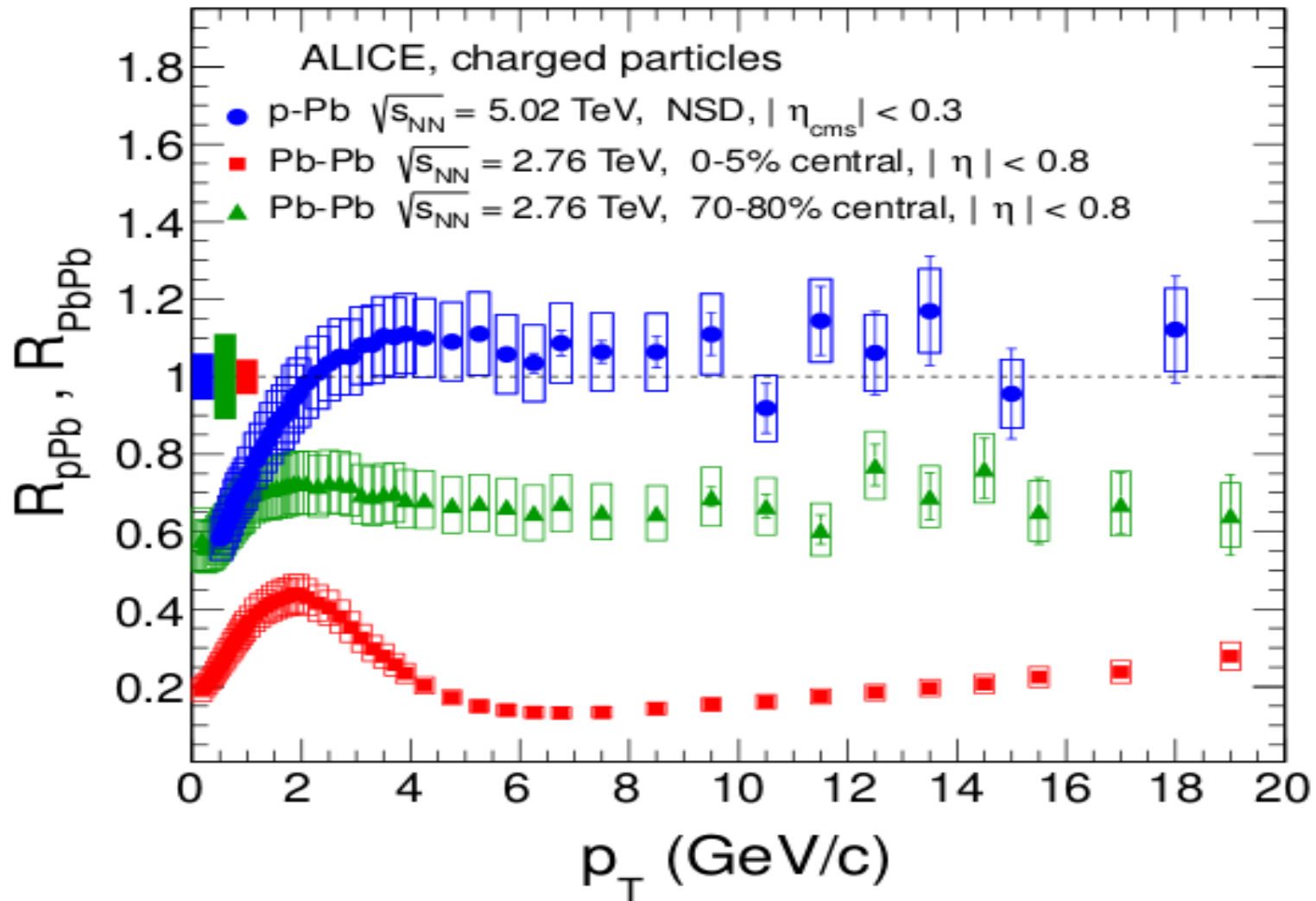


Combined line-shape fit for Y(1S), Y(2S) and Y(3S) state to extract yields. Note already by eye the 3S state is not visible.



Even Ypsilons are dissociated by the medium.
 As expected, suppression much larger for 2S than 1S.



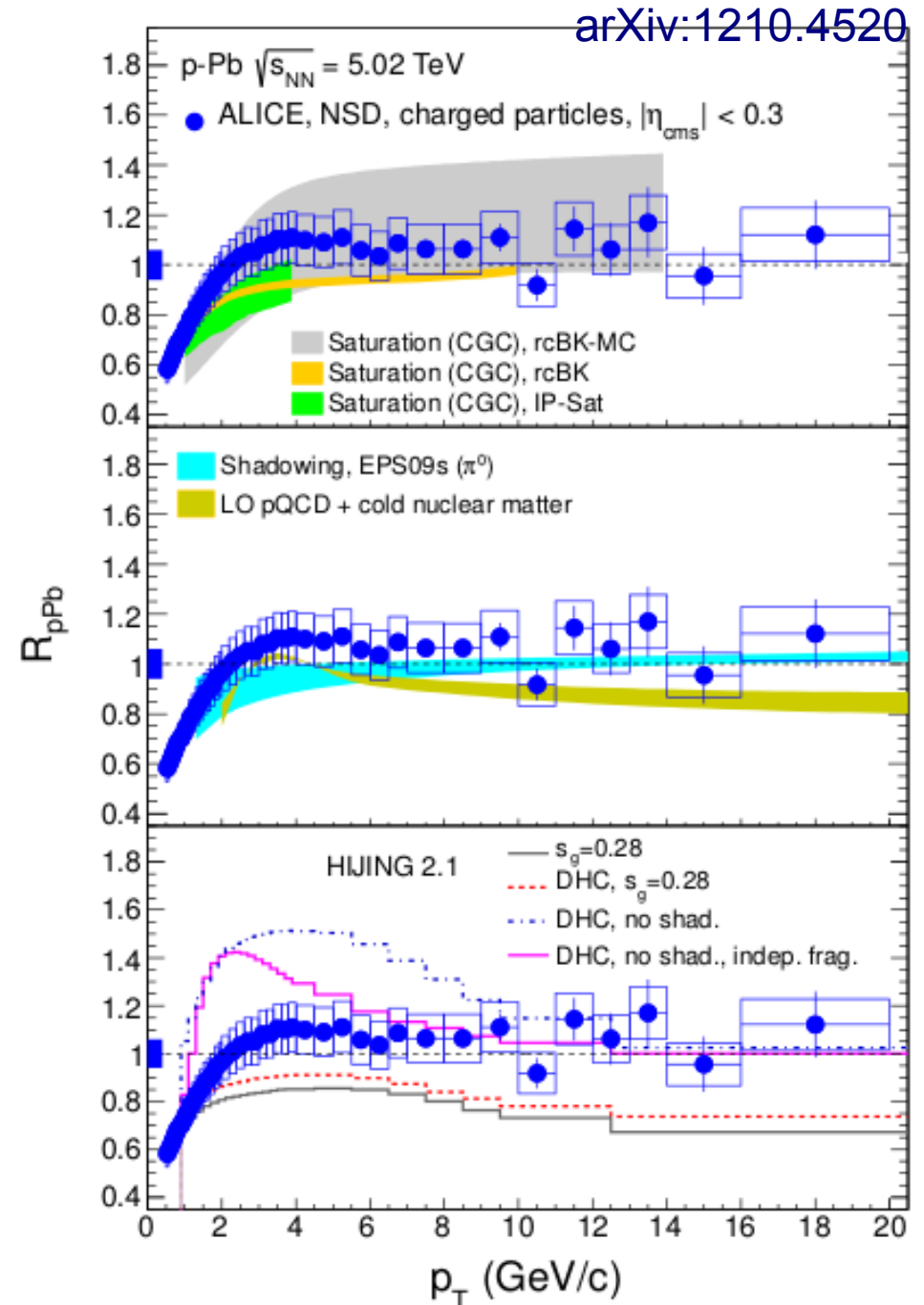


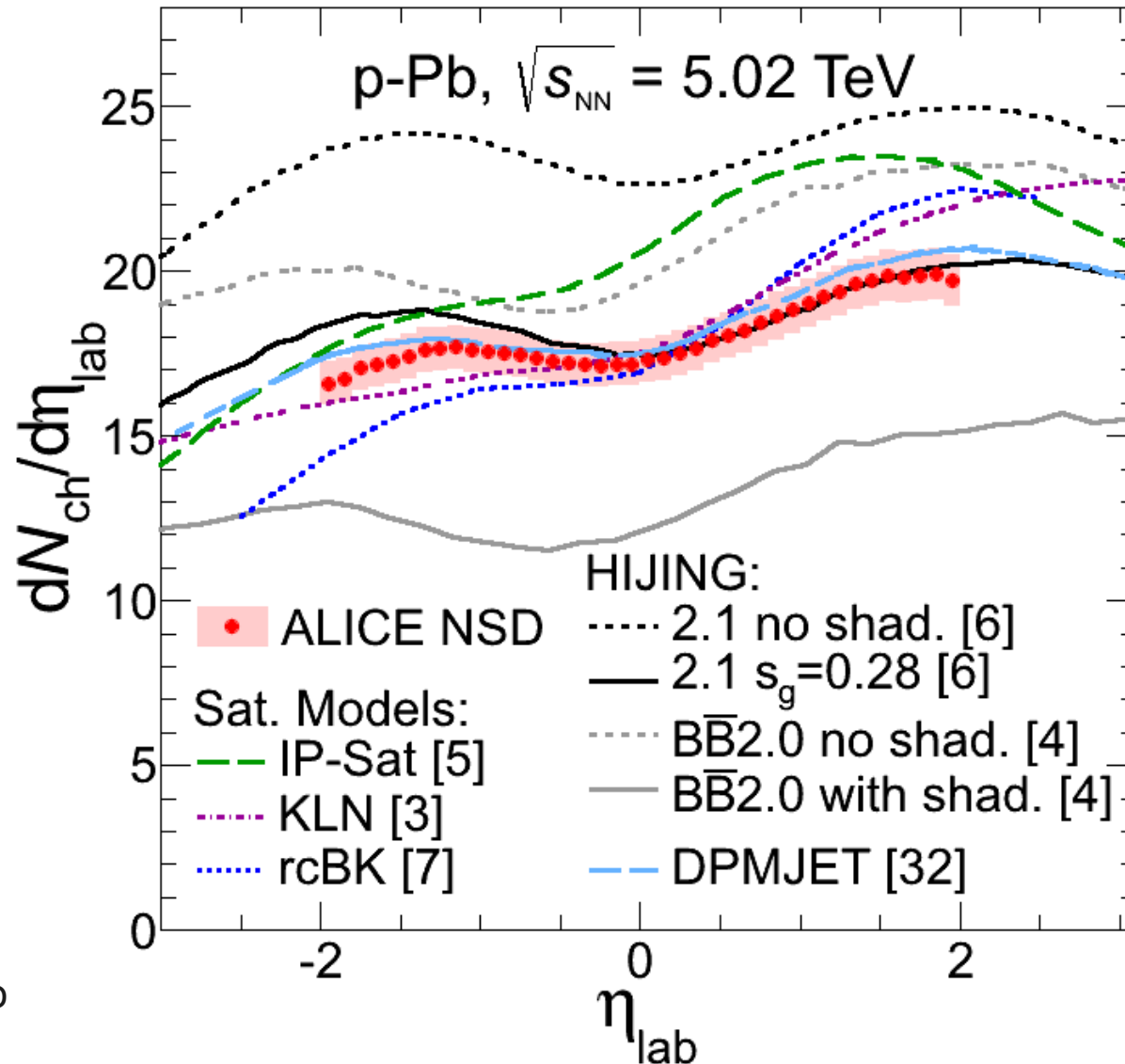
High- p_T charged particles exhibit binary scaling. Initial state effects are small.
 (Note: pp reference interpolated between 2.76 and 7 TeV)

p+Pb: Comparison to model predictions 33

- Most models describe R_{pPb} quite well at high p_T
- Differences mainly at low p_T
- HIJING 2.1 with $s_g=0.28$ parameter overshadows
- Neither HIJING 2.1 nor DPMJET describe the p_T spectra itself

NB:
HIJING calculations
for NSD expected to
increase by ~4%

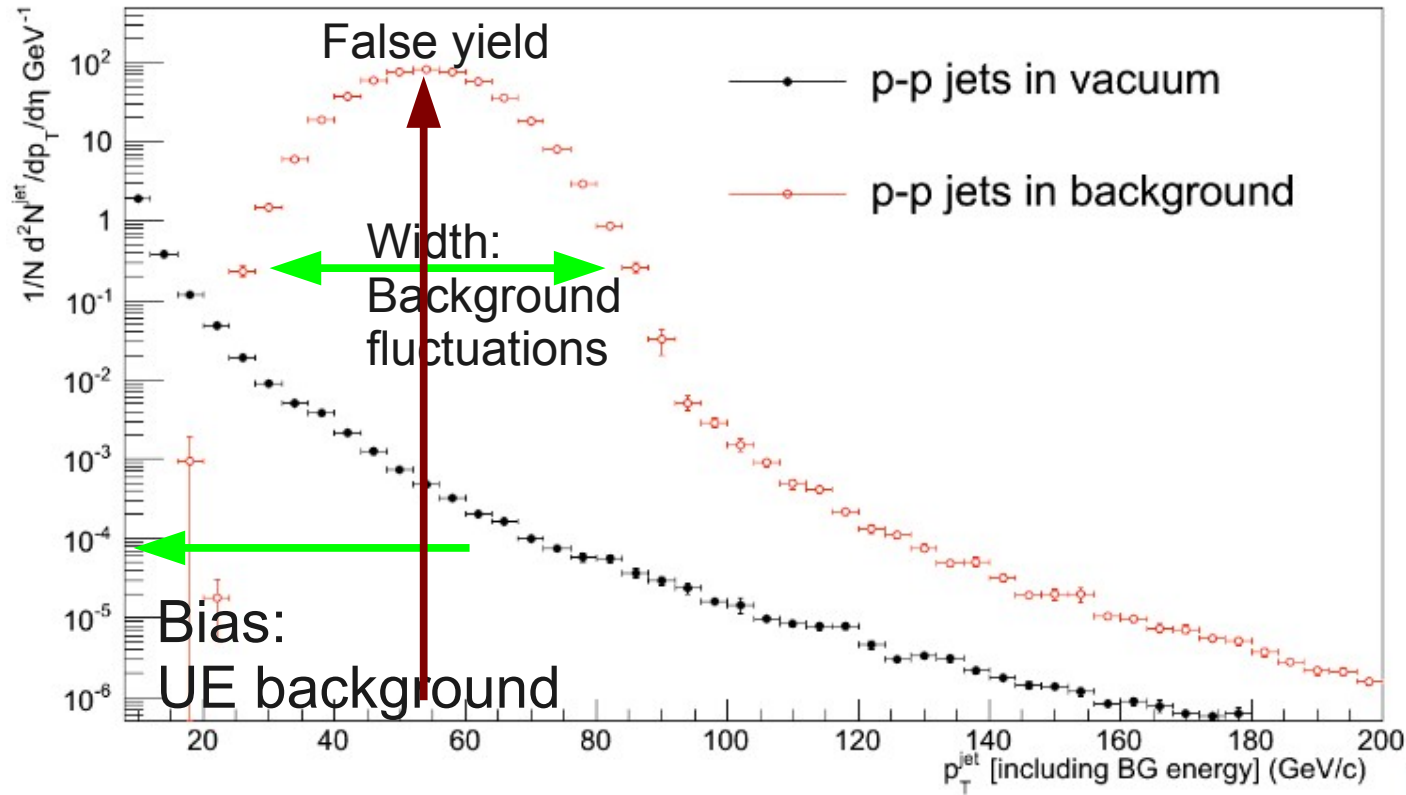
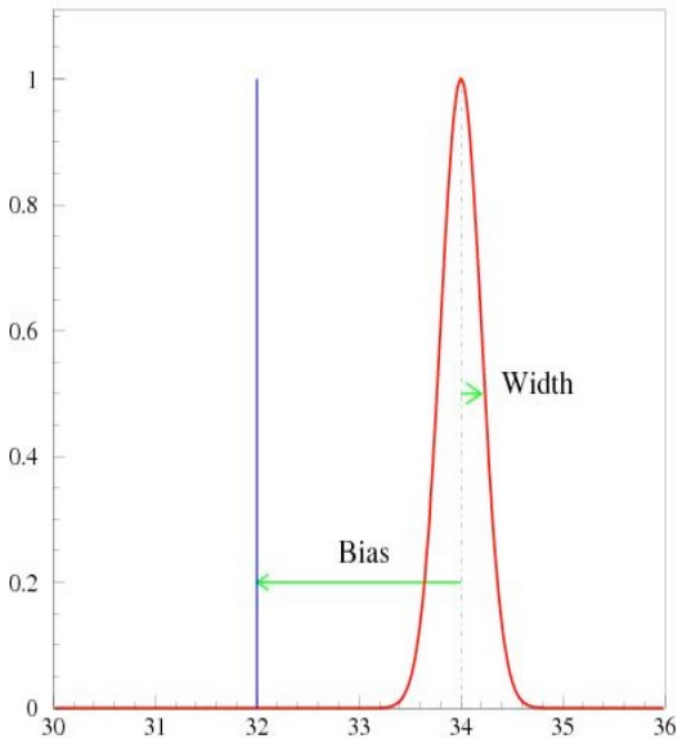




NB:
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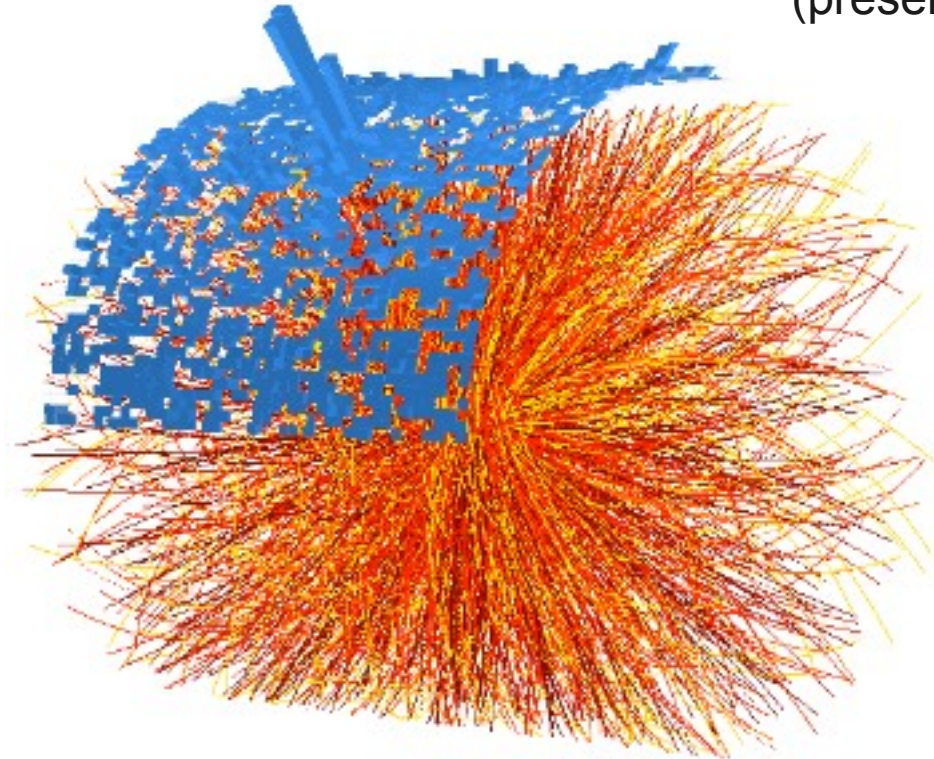
Most models predicted values within 20%. Saturation models have too steep rise between p and Pb region.

Pythia + Thermal BG Simulation

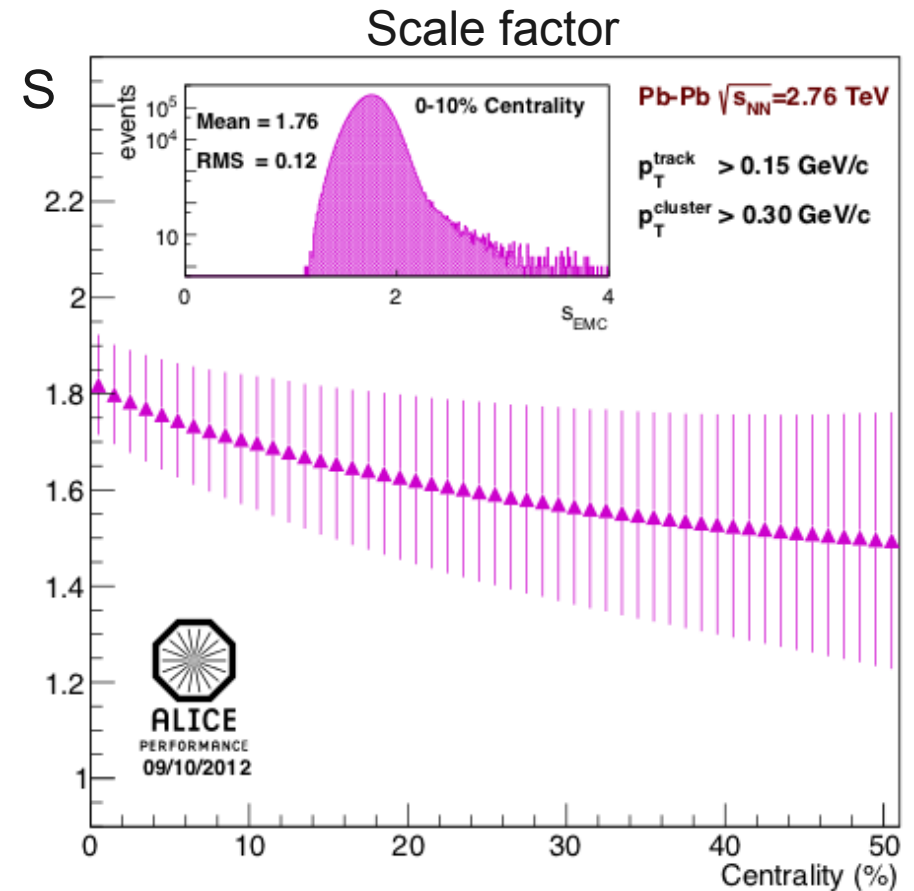
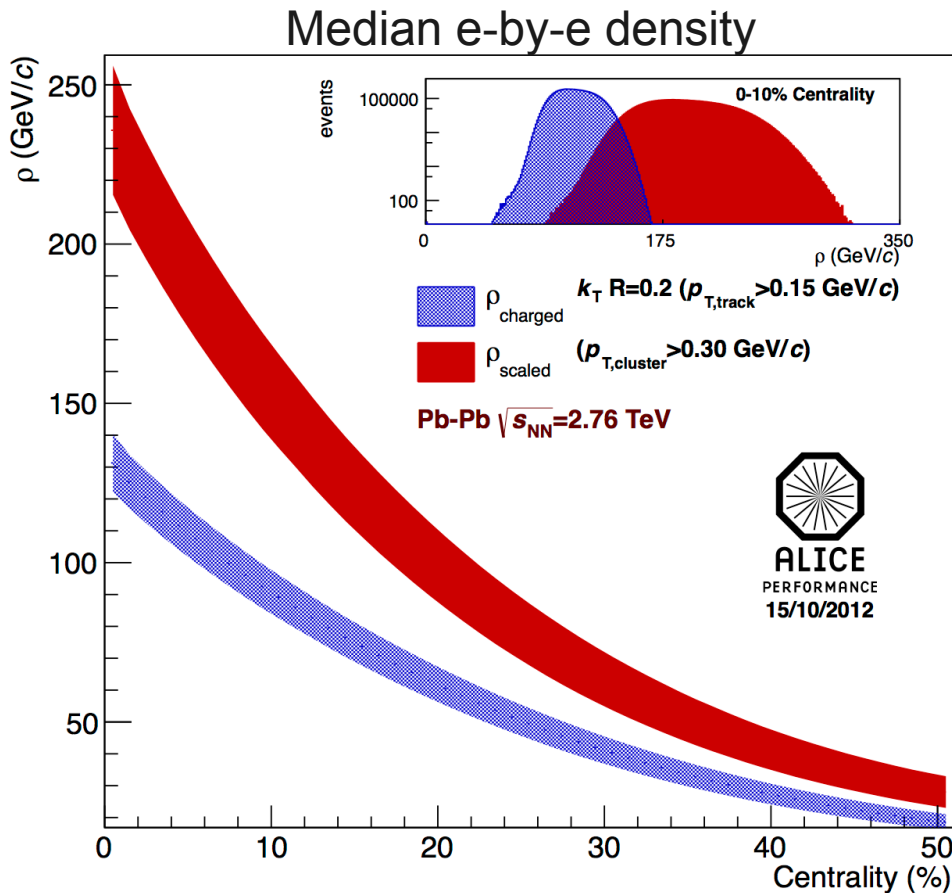


- Procedure
 - Subtract background
 - Correct for background fluctuations

First ALICE full jet result for Pb+Pb
(presented at HQ'12)



- Challenge: Underlying event (UE)
 - Average background
 - Background fluctuations
 - Combinatorial (fake) jets



- Calculate density on event-by-event basis
 - The median of the density of k_T charged jets: $\rho_{ch} = \text{median} \{p_{Ti}/A_i\}$
 - Use scale factor to obtain $\rho = s \times \rho_{ch}$
 - Similar to arXiv:1201.2423

- Region-to-region background fluctuations limit the jet energy resolution

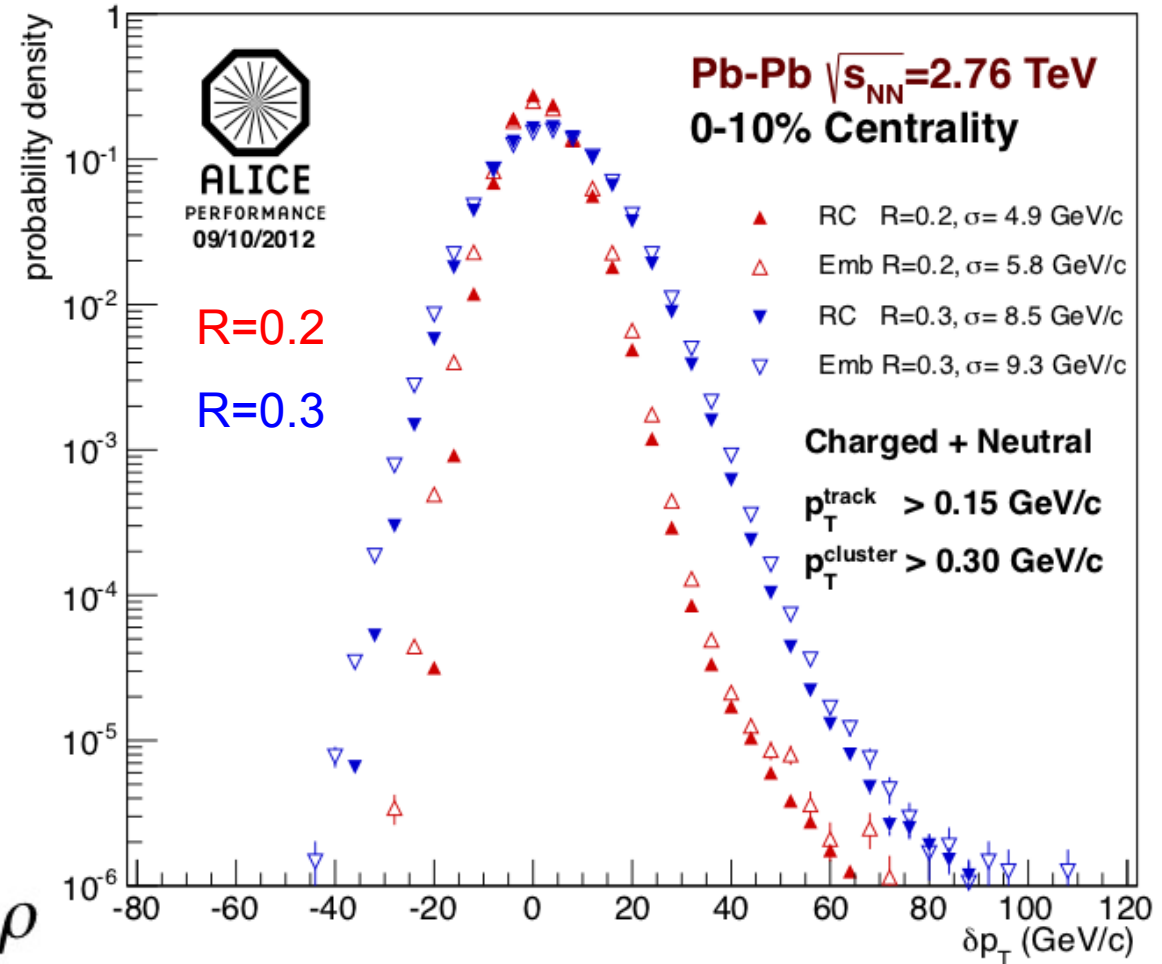
- Size of fluctuations are estimated using

- Random cones

$$\delta p_T^{RC} = p_T^{RC} - \pi R^2 \rho$$

- Single particle embedding

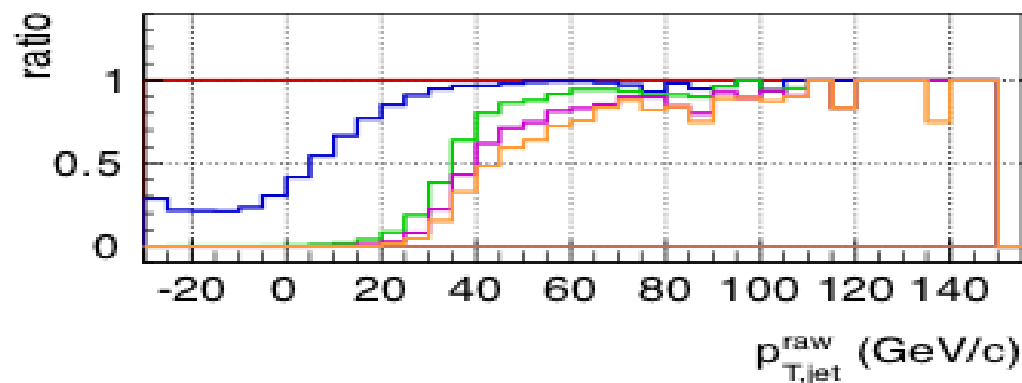
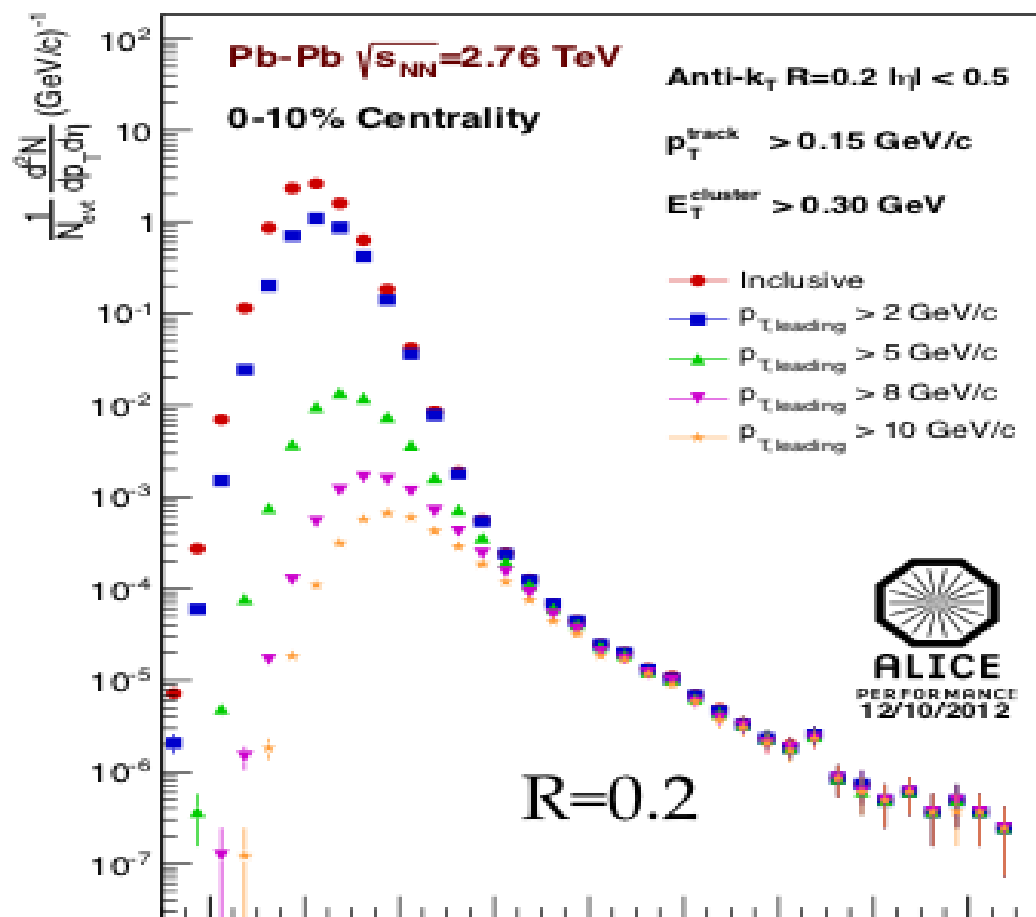
$$\delta p_T^{emb} = p_T^{jet} - p_T^{probe} - A^{jet} \rho$$



$\sigma \approx 5.5$ GeV/c for R=0.2

$\sigma \approx 9.0$ GeV/c for R=0.3

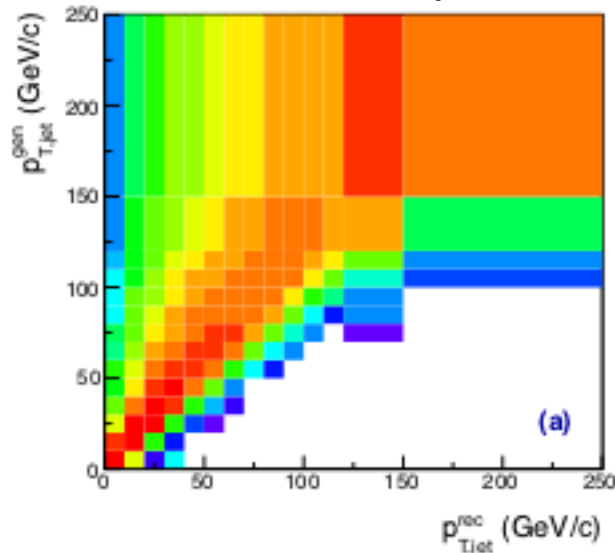
- Combinatorial jets are obtained from jet finder by clustering soft, mostly uncorrelated particles from UE
- Leading hadron bias
 - Combinatorial jets can be effectively suppressed by requiring a high p_T track
 - Bigger effect when changing from 0 to 5 GeV, than from 5 to 10 GeV
 - Bias present up to 60-100 GeV
 - Use 5 GeV/c for $R=0.2$



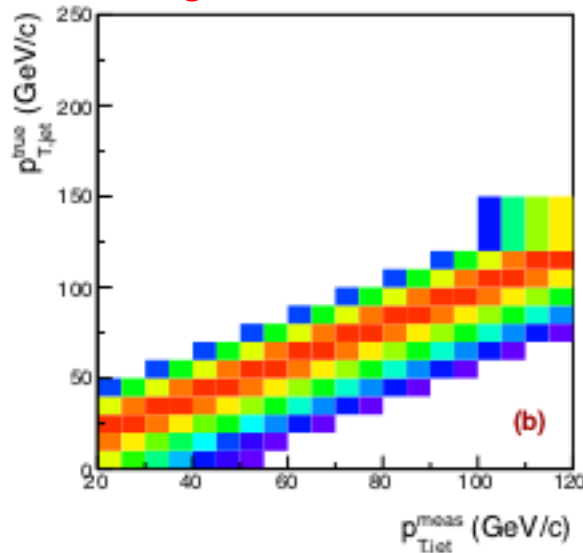
Response matrix

40

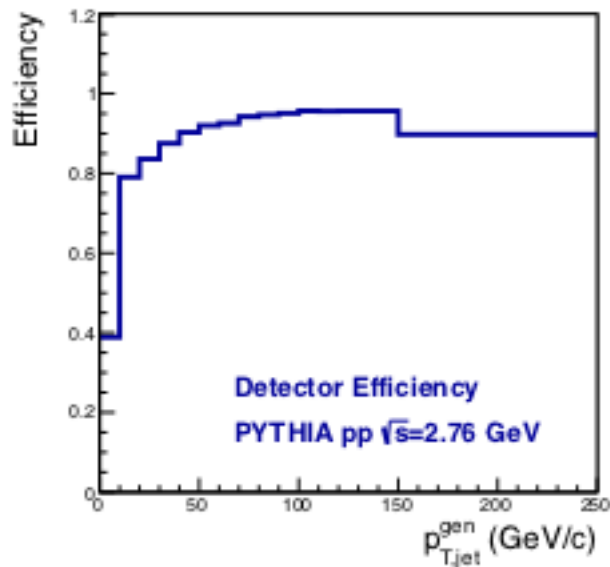
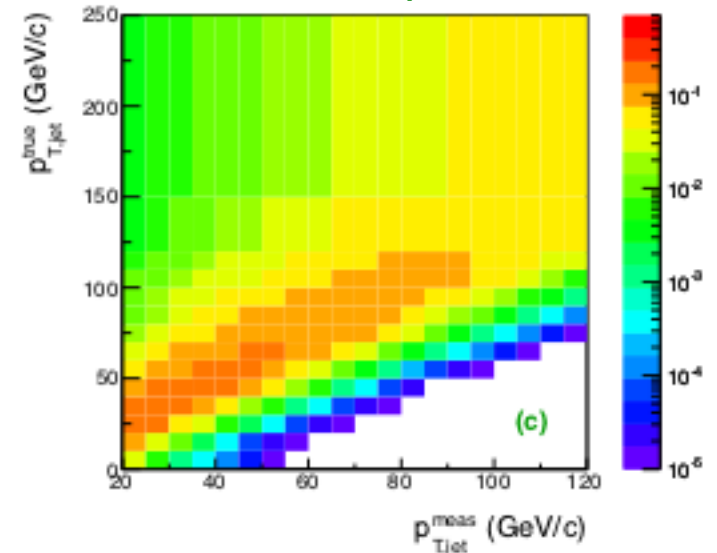
Detector response



Background fluctuations



Final response



Anti- K_T jet finder:

$$R = 0.2$$

$$p_{T, \text{track}} > 0.150 \text{ GeV}/c$$

$$E_{T, \text{clus}} > 0.3 \text{ GeV}/c$$

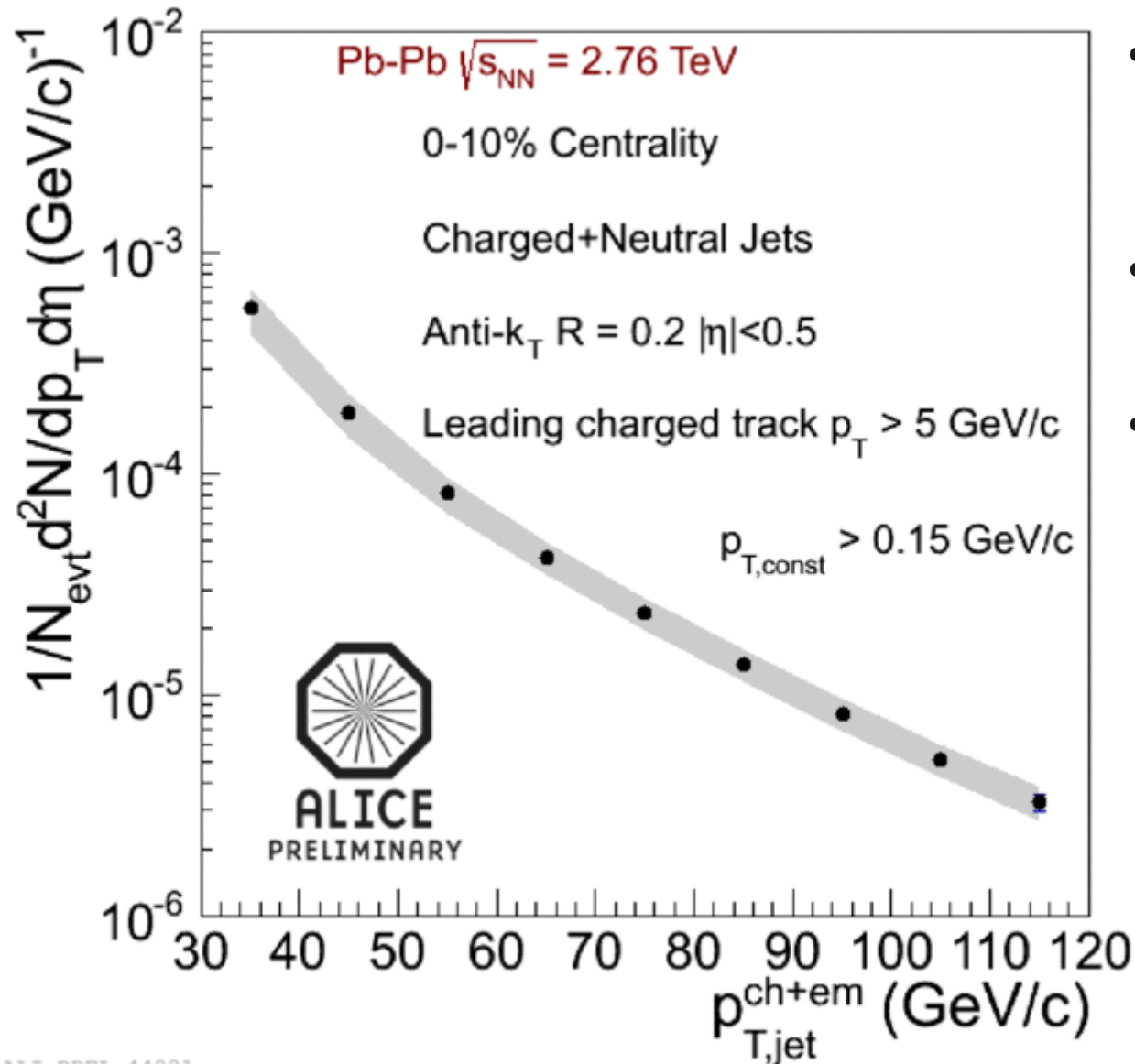
$$p_{T, \text{leading track}} > 5 \text{ GeV}/c$$

Pb-Pb $\sqrt{s_{NN}}=2.76$ TeV

0-10% Centrality



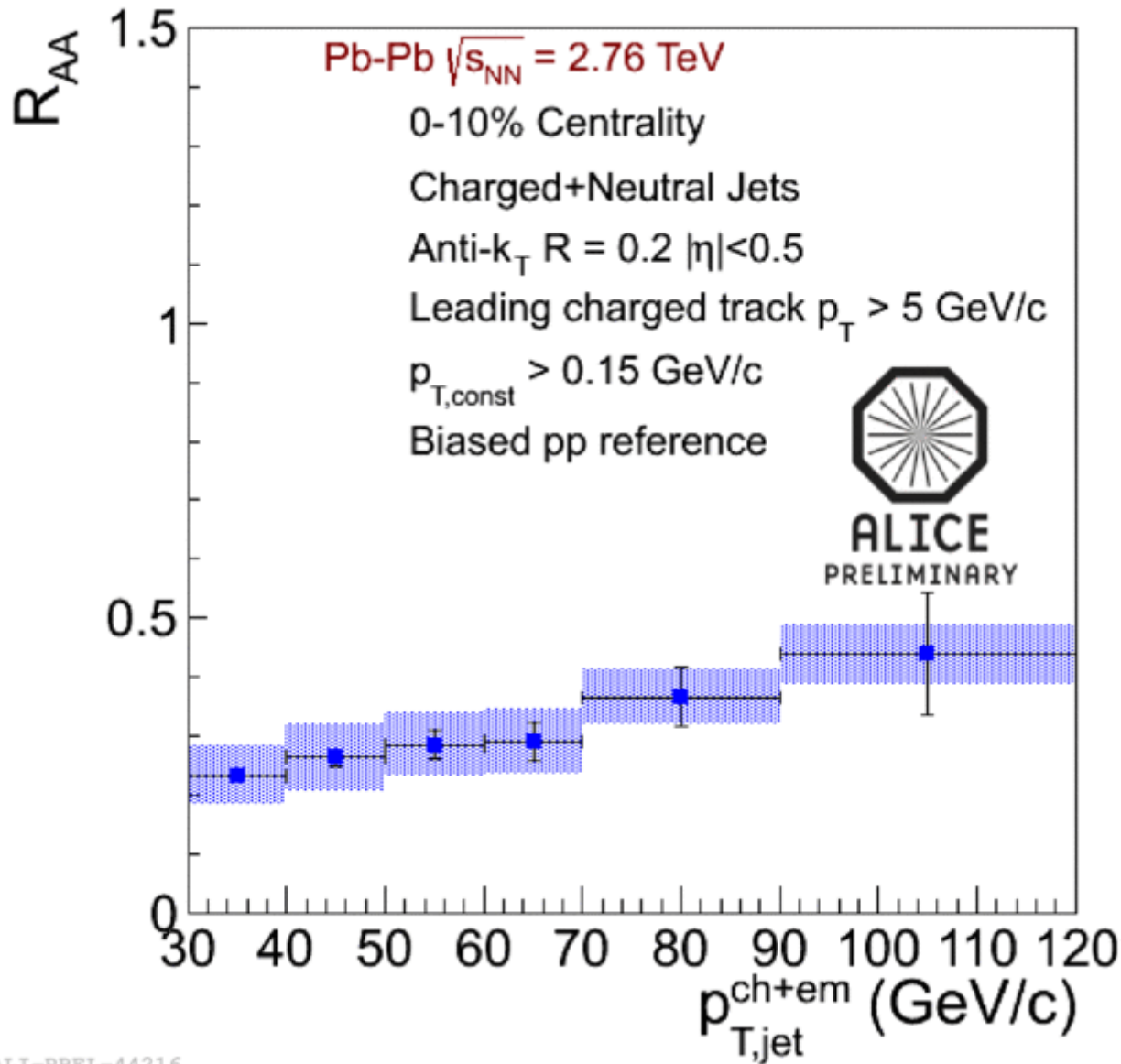
ALICE
PERFORMANCE
10/10/2012



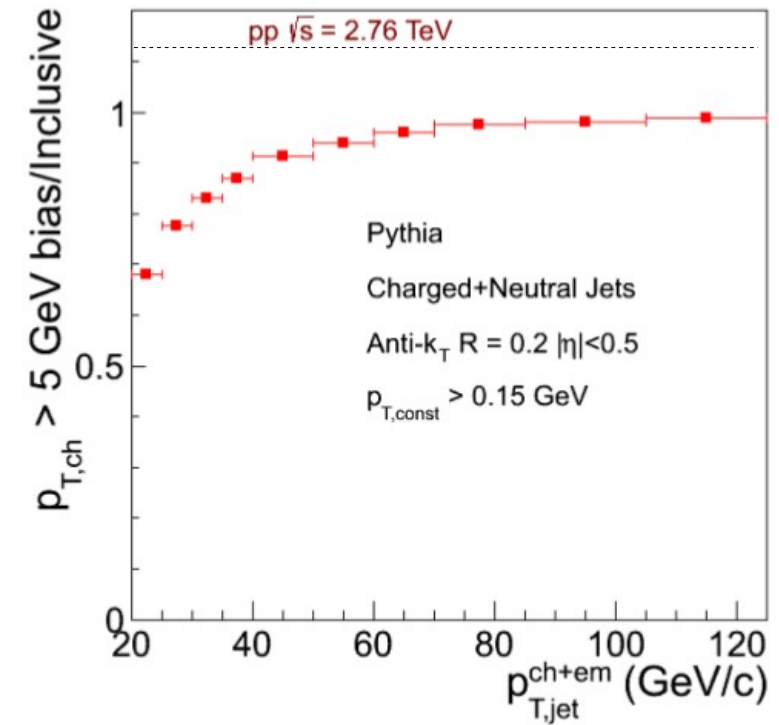
- Jet spectrum after background correction and unfolding
- Statistical uncertainty from cov. matrix
- Systematic uncertainties
 - ~20% (p_T dependent)
 - Unfolding
 - Hadronic correction
 - Tracking efficiency
 - EMCal related effects (energy resolution + scale, clusterizer, non-linearity)
 - Background fluctuations

Jet R_{AA} in central collisions

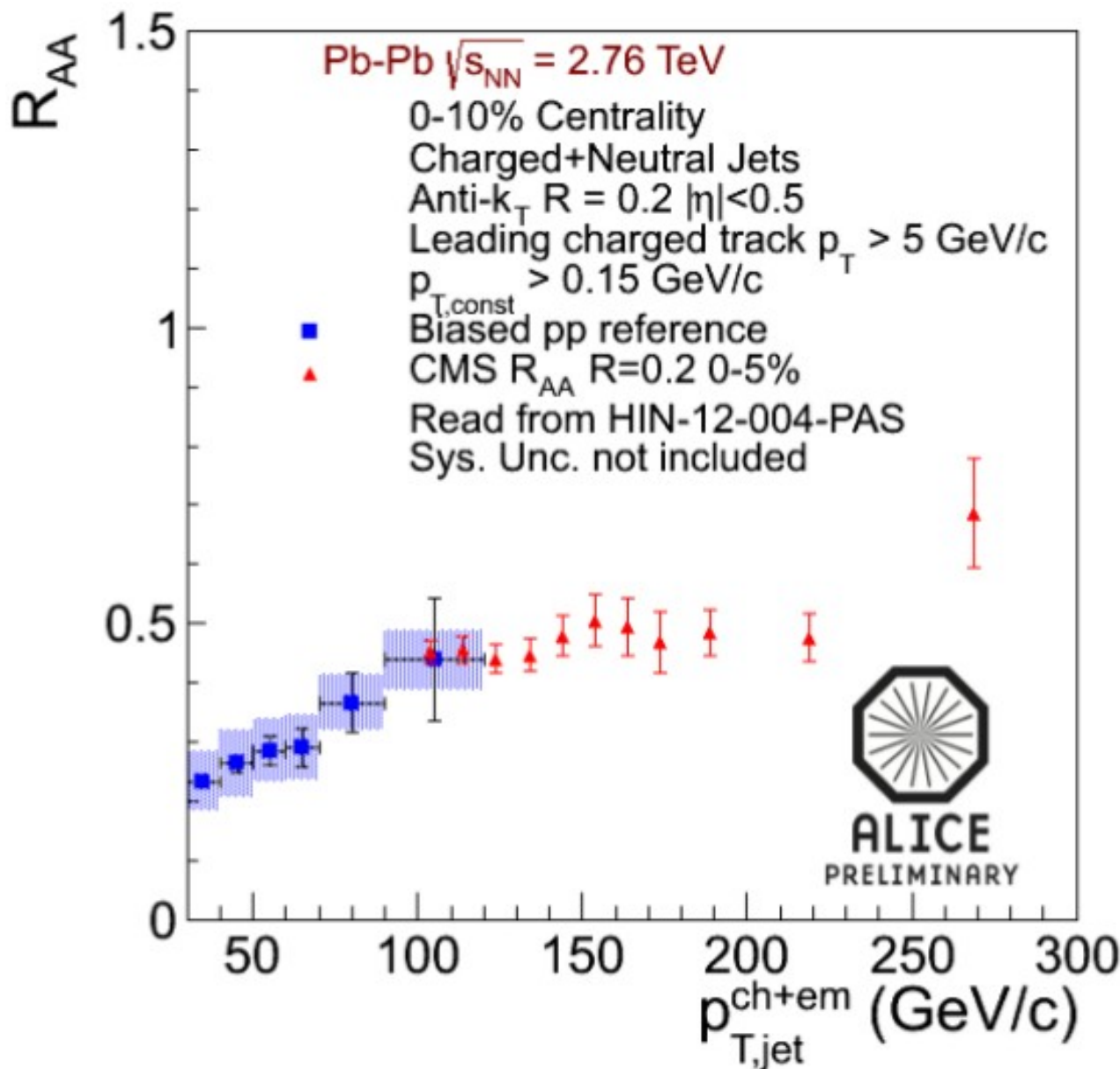
42



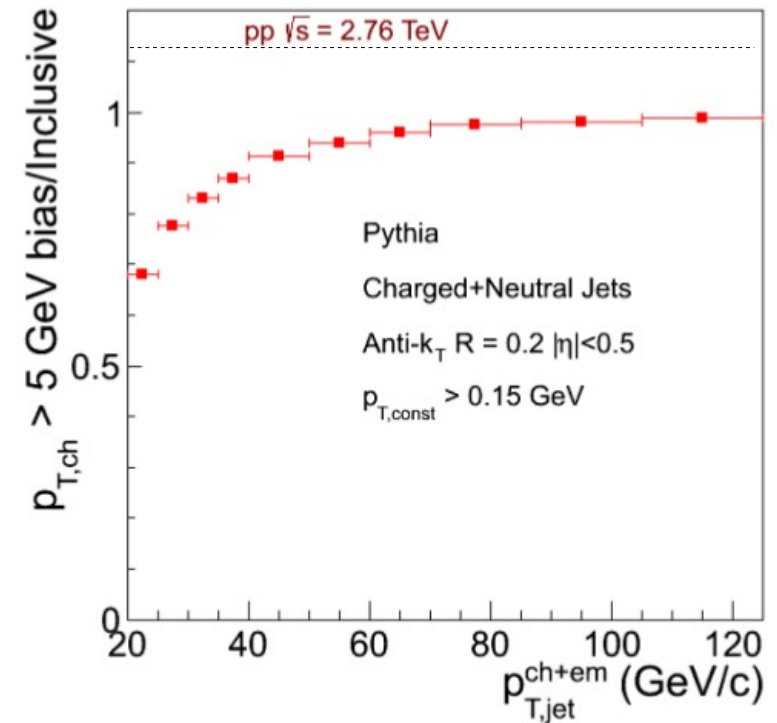
Bias/Inclusive PYTHIA
(~0.85 at 30-40 GeV/c)



Jet suppression is jet p_T dependent



Bias/Inclusive PYTHIA
 (~0.85 at 30-40 GeV/c)

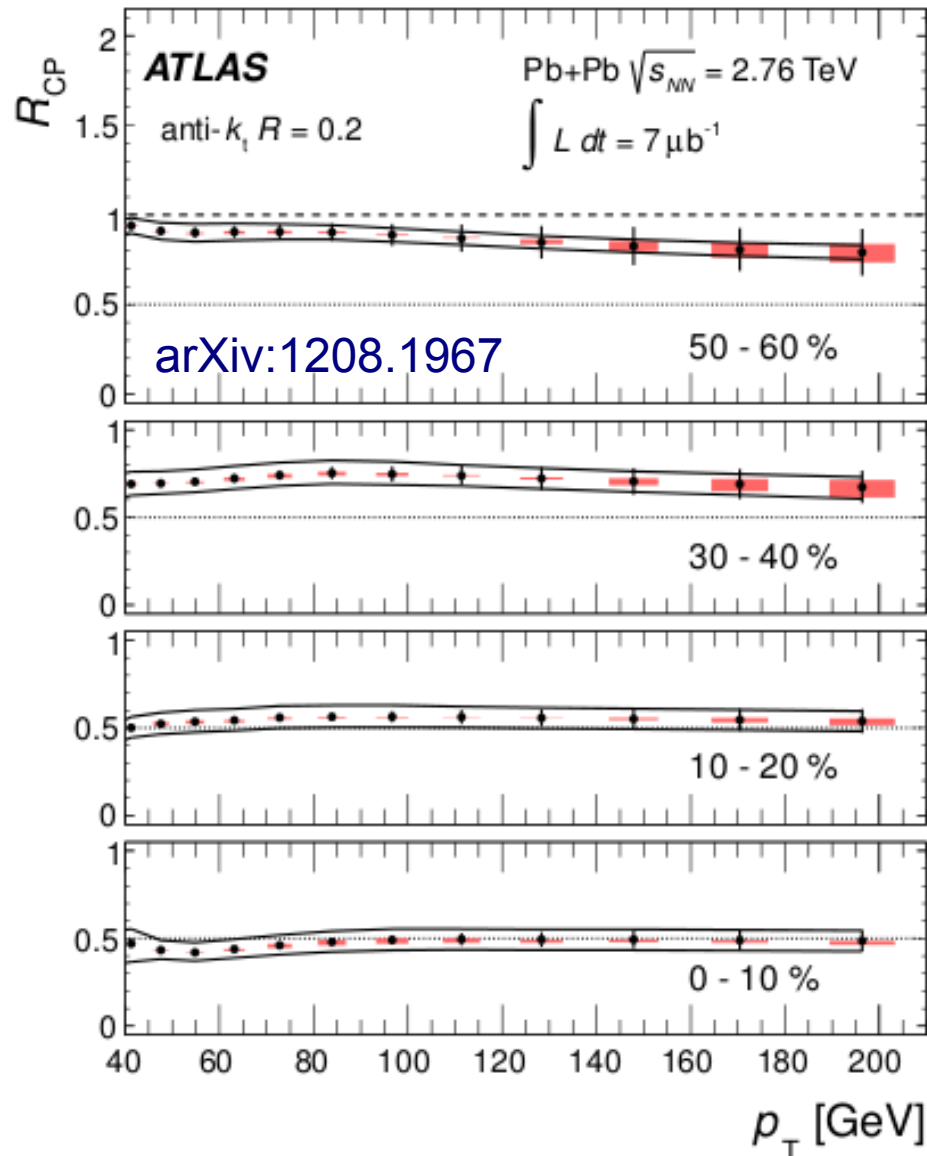


Consistent with CMS prel. results at 100 GeV/c

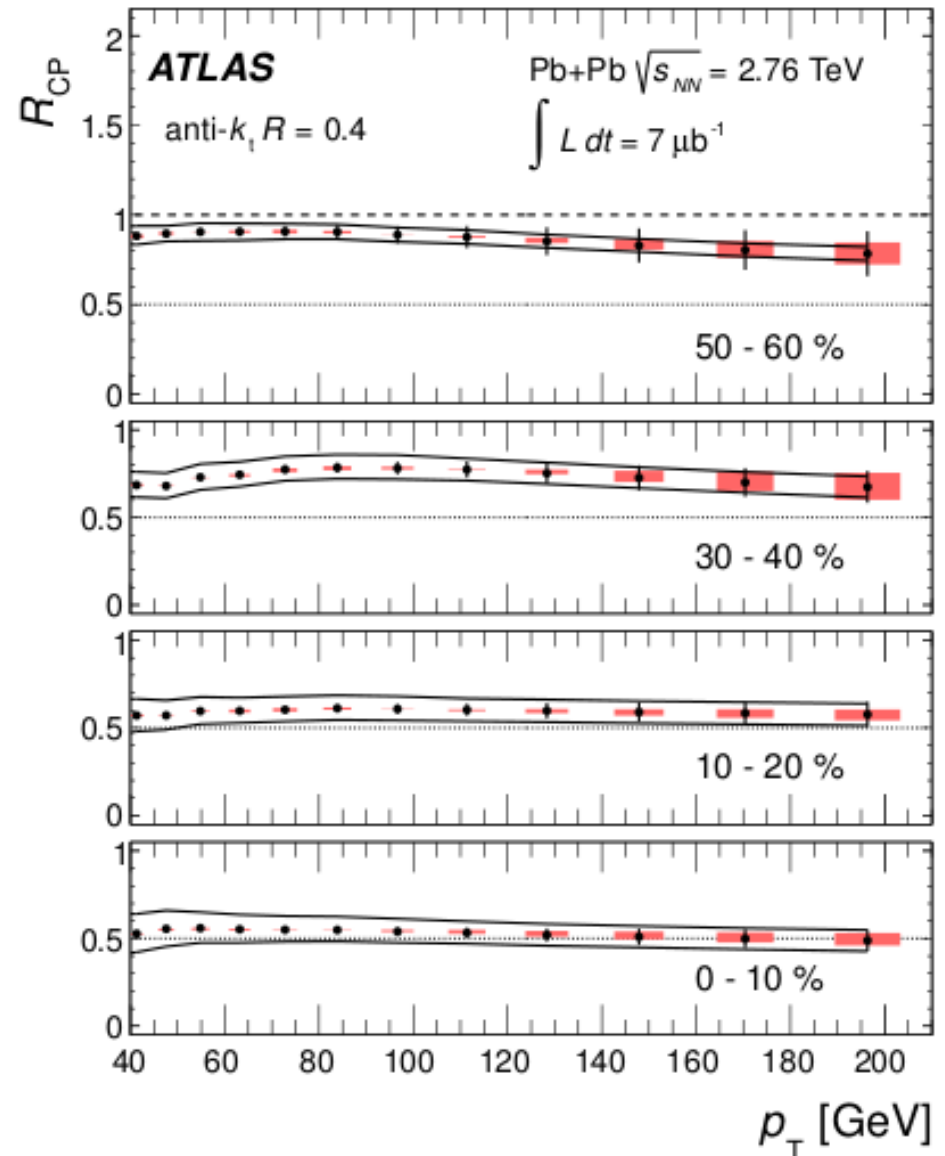
Jet suppression (R_{CP})

44

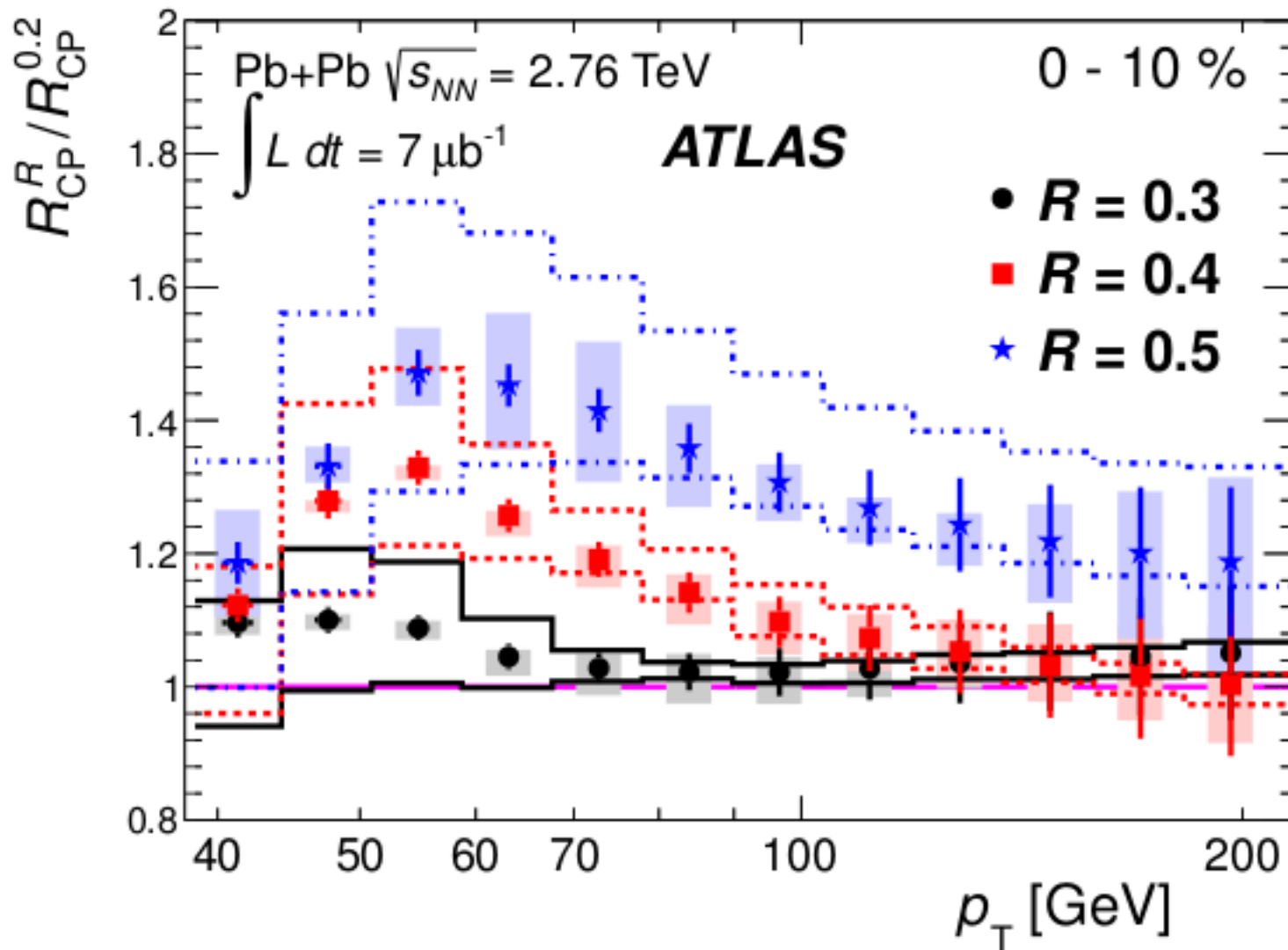
$R=0.2$



$R=0.4$



Substantial suppression, out to very high jet energy



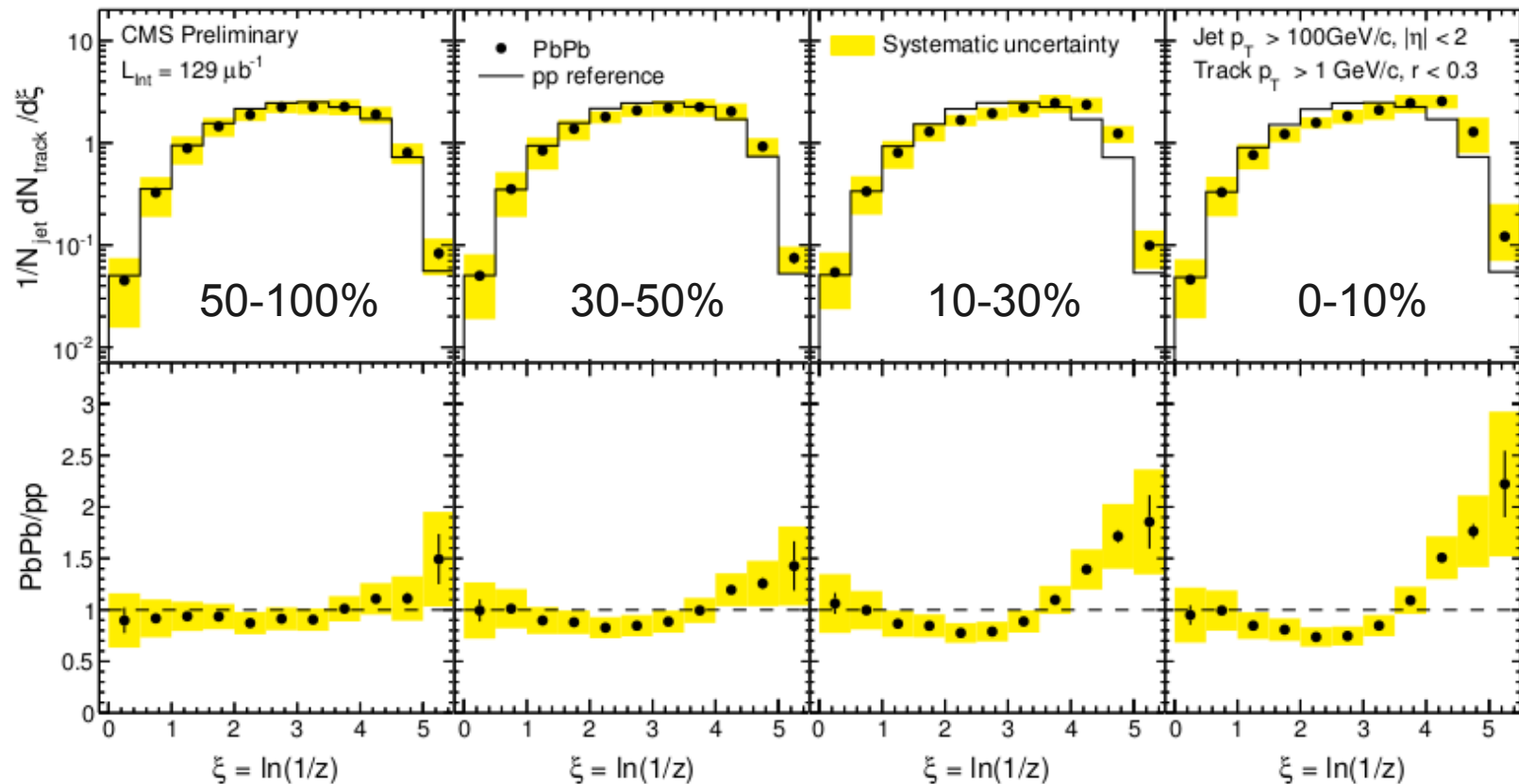
Interesting modulation at 60 GeV/c

Jet fragmentation function

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

CMS-HIN-12-013



$R=0.3$

$P_T > 100 \text{ GeV}/c$

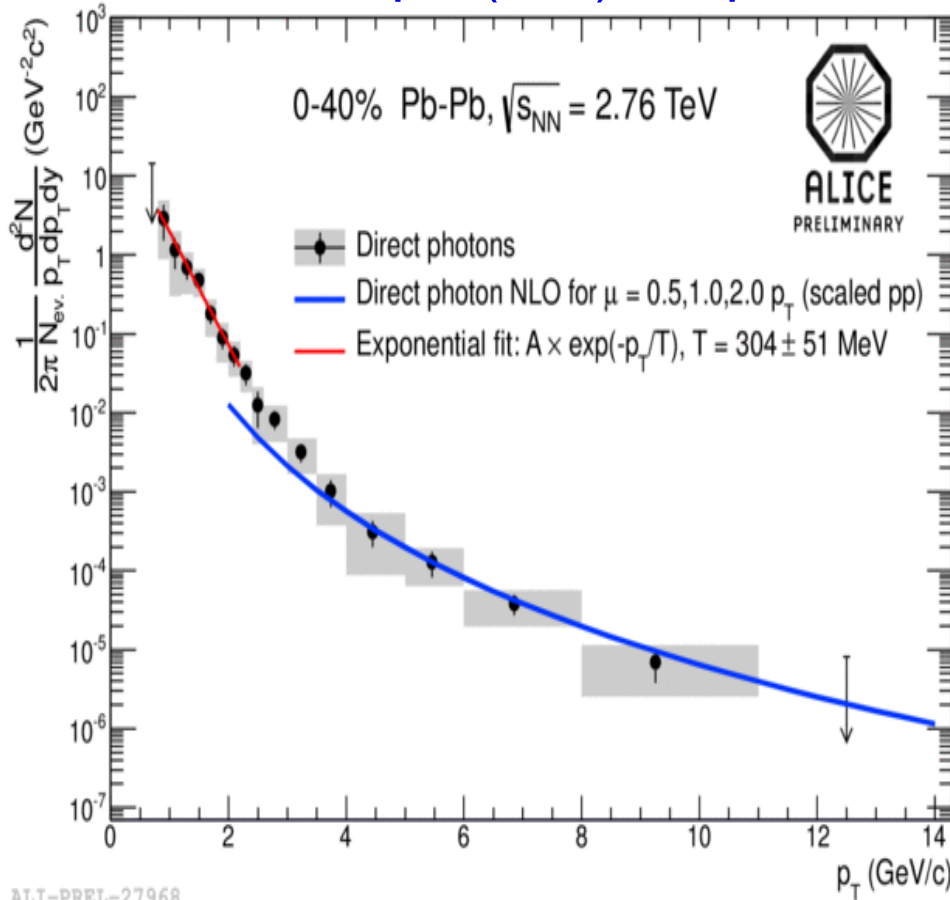
Track $p_T > 1 \text{ GeV}/c$

Fragmentation function is modified: More particles at low p_T ($< 3 \text{ GeV}/c$) in more central collisions rel. pp

Direct photon spectrum and their v_2

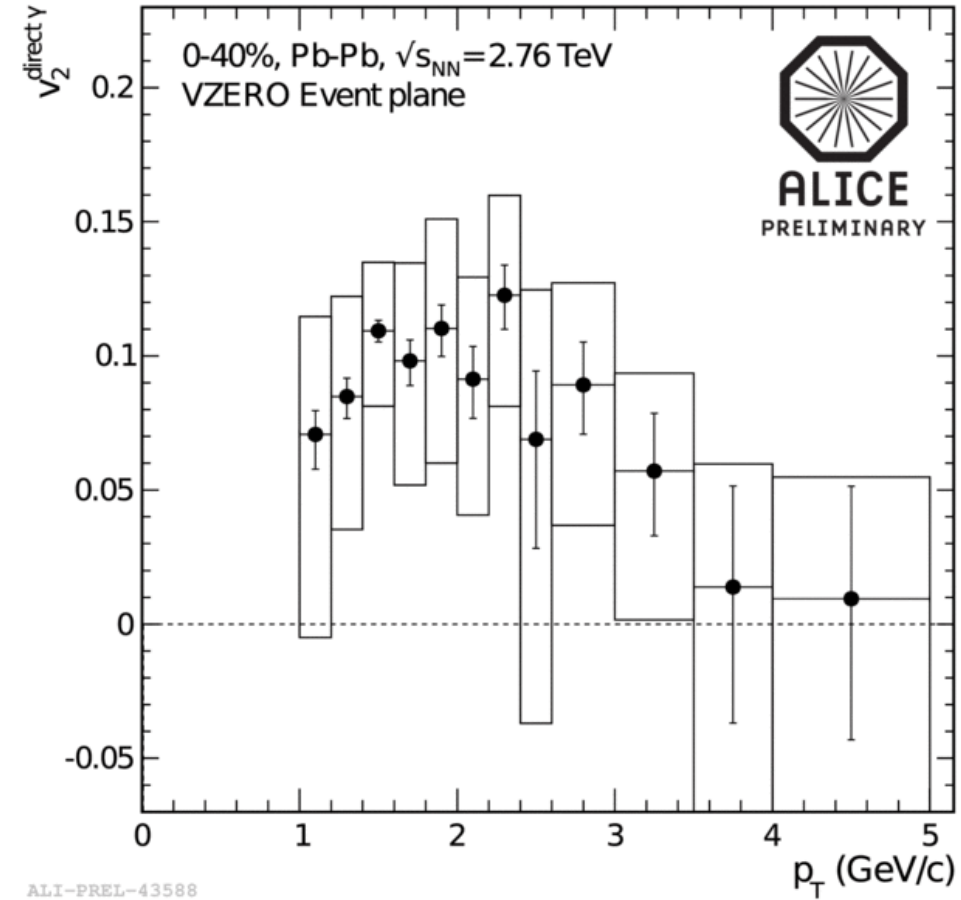
47

$$dir\gamma = (1-R) \cdot incl\gamma$$



- Inverse slope: $T=304 \pm 51$ MeV
 - If interpreted naively close to initial temperature
 - Consistent with Y(2) and Y(3S) melting

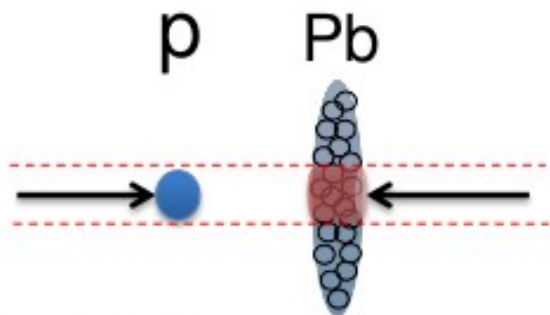
$$v_2^{dir\gamma} = (R \cdot v_2^{incl\gamma} - v_2^{dec\gamma}) / (R - 1)$$



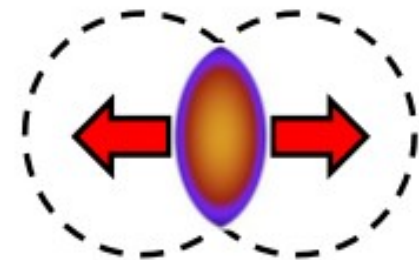
- Significant $v_2^{dir\gamma}$ below 3 GeV/c
 - Compatible to charged hadrons or no direct γ
 - Difficult to reconcile with T

Near-side ridge structure in p+Pb

48



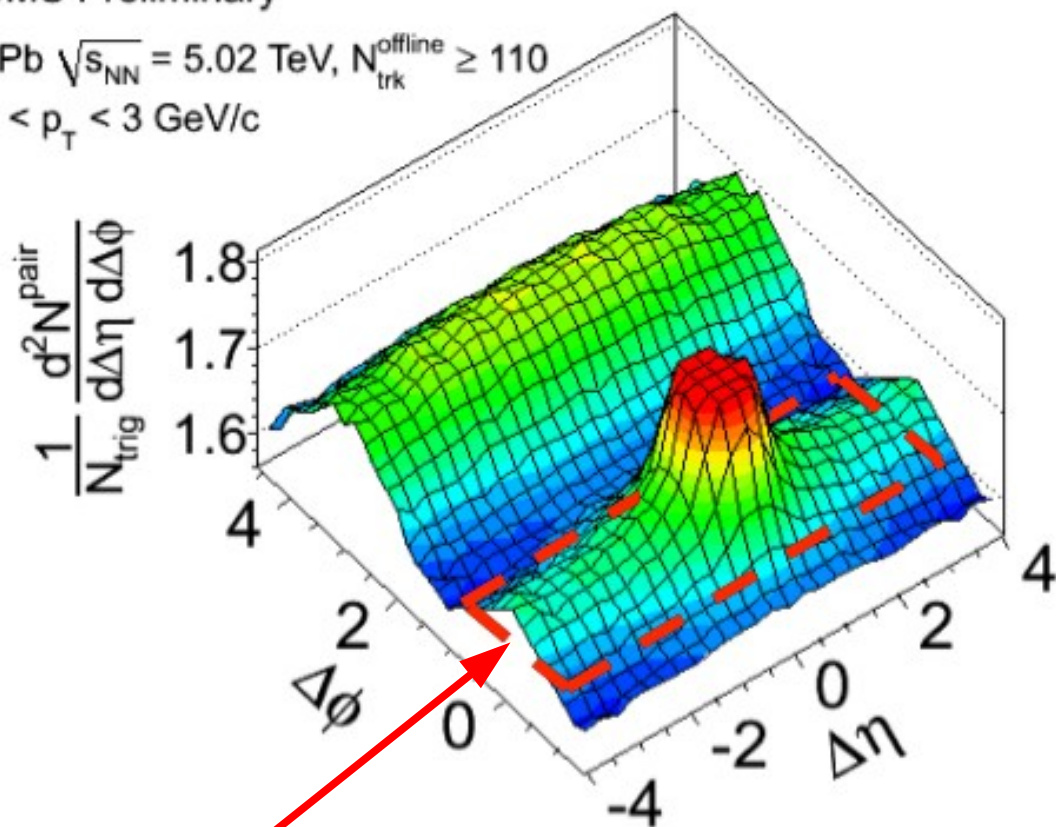
Initial-state geometry
+
collective expansion



35-40%

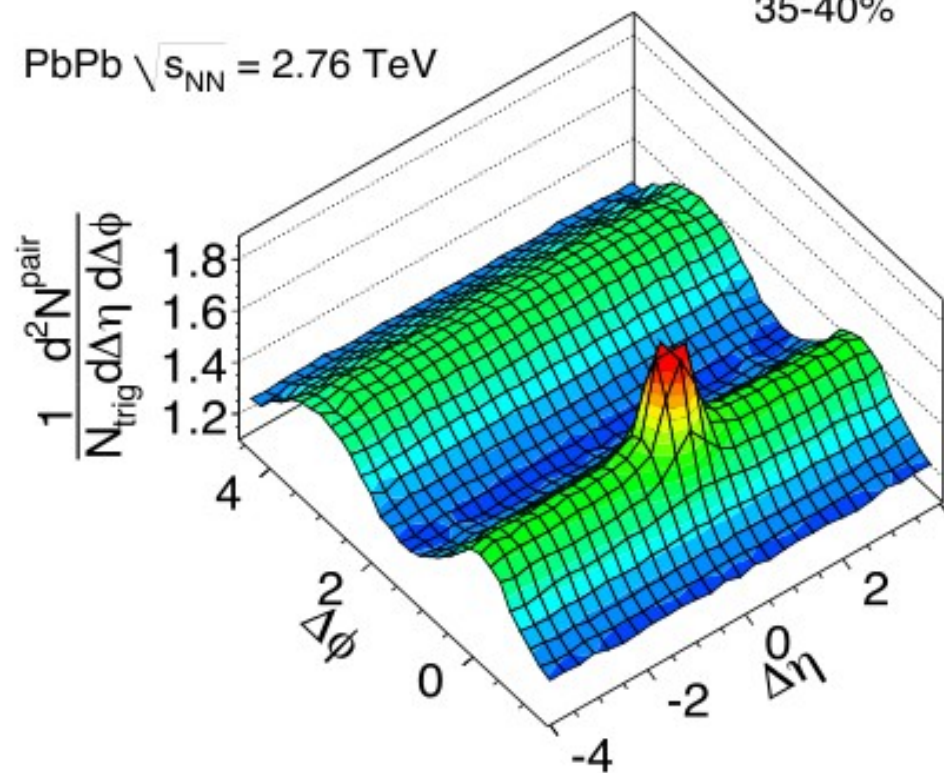
CMS Preliminary

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



Near-side
ridge

PbPb $\sqrt{s_{NN}} = 2.76$ TeV



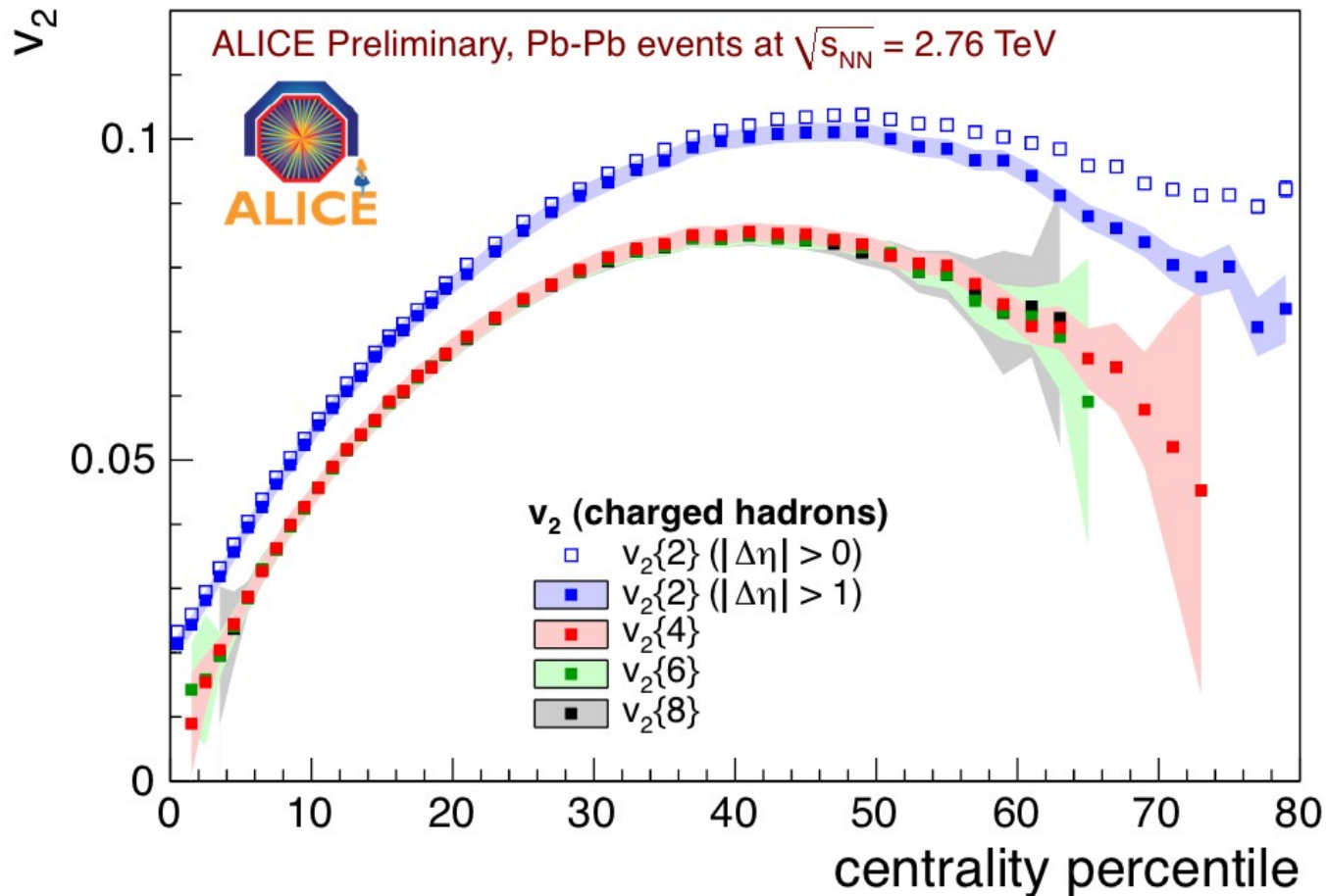
Courtesy of D. Velicanu (CMS)

- The LHC is ideal for studying the QGP
 - $\epsilon_{\text{init}} > \epsilon_c$, large volume, long life-time, plenty of hard probes
 - QGP has similar “perfect liquid” properties as at RHIC
- Hard probe results constrain the physics of parton energy loss
 - There has been a burst of new data. And more to come!
 - We are in exploratory phase with some of the observables
 - Should attempt to describe all aspects in common model.
 - Upcoming p+Pb run in Jan 2013 will further clarify role of initial state effects
- Watch out for (further) surprises at the LHC

CMS HI results
ALICE HI papers
ATLAS HI results

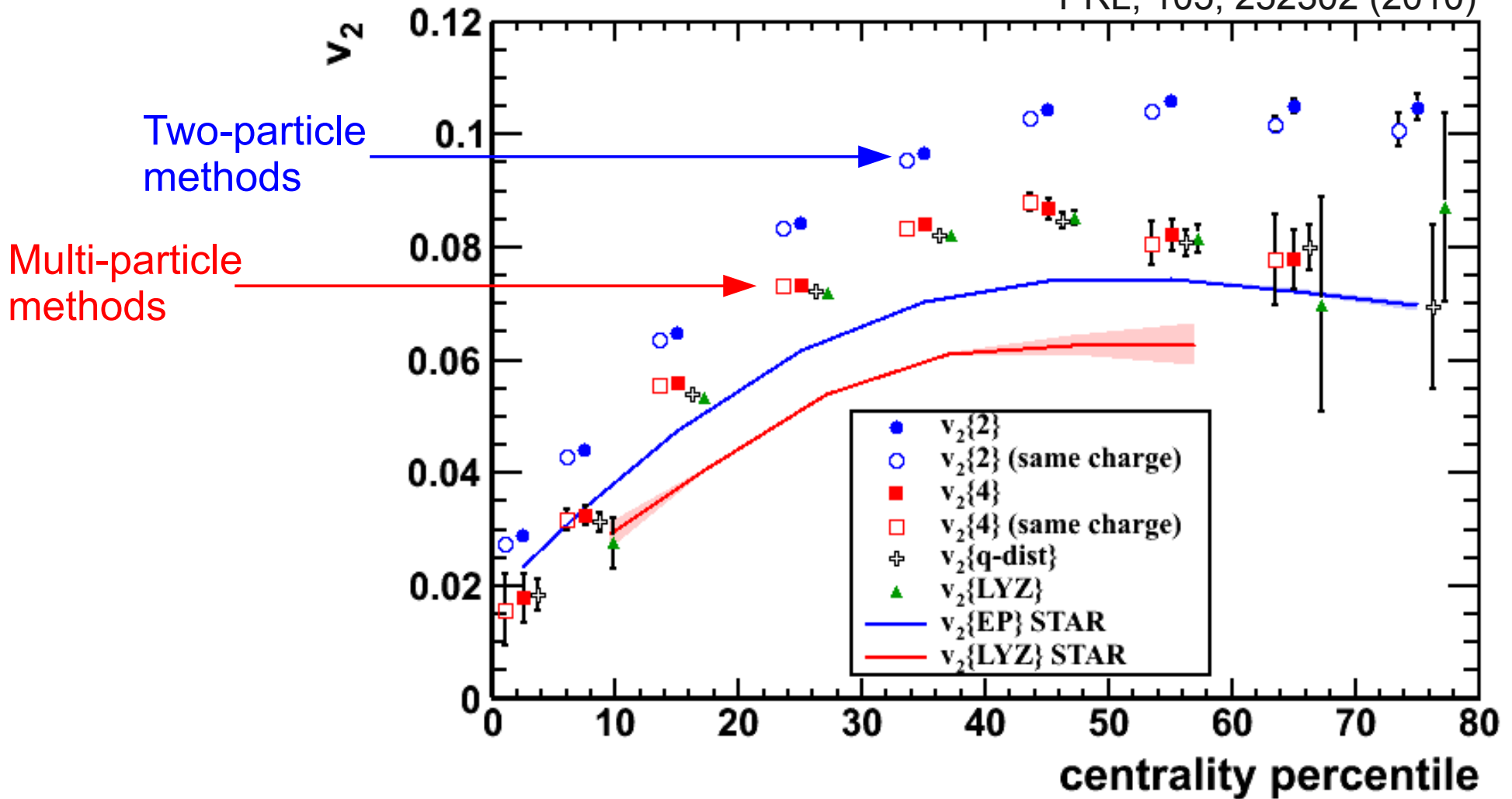
Special thank you to my ALICE, ATLAS and CMS colleagues for their great material, and to the LHC for fantastic operations in the past years!

A. Bilandzic for ALICE, QM'11



Multi-particle correlations (cumulant) studies extract the genuine multi-particle correlation

PRL, 105, 252302 (2010)



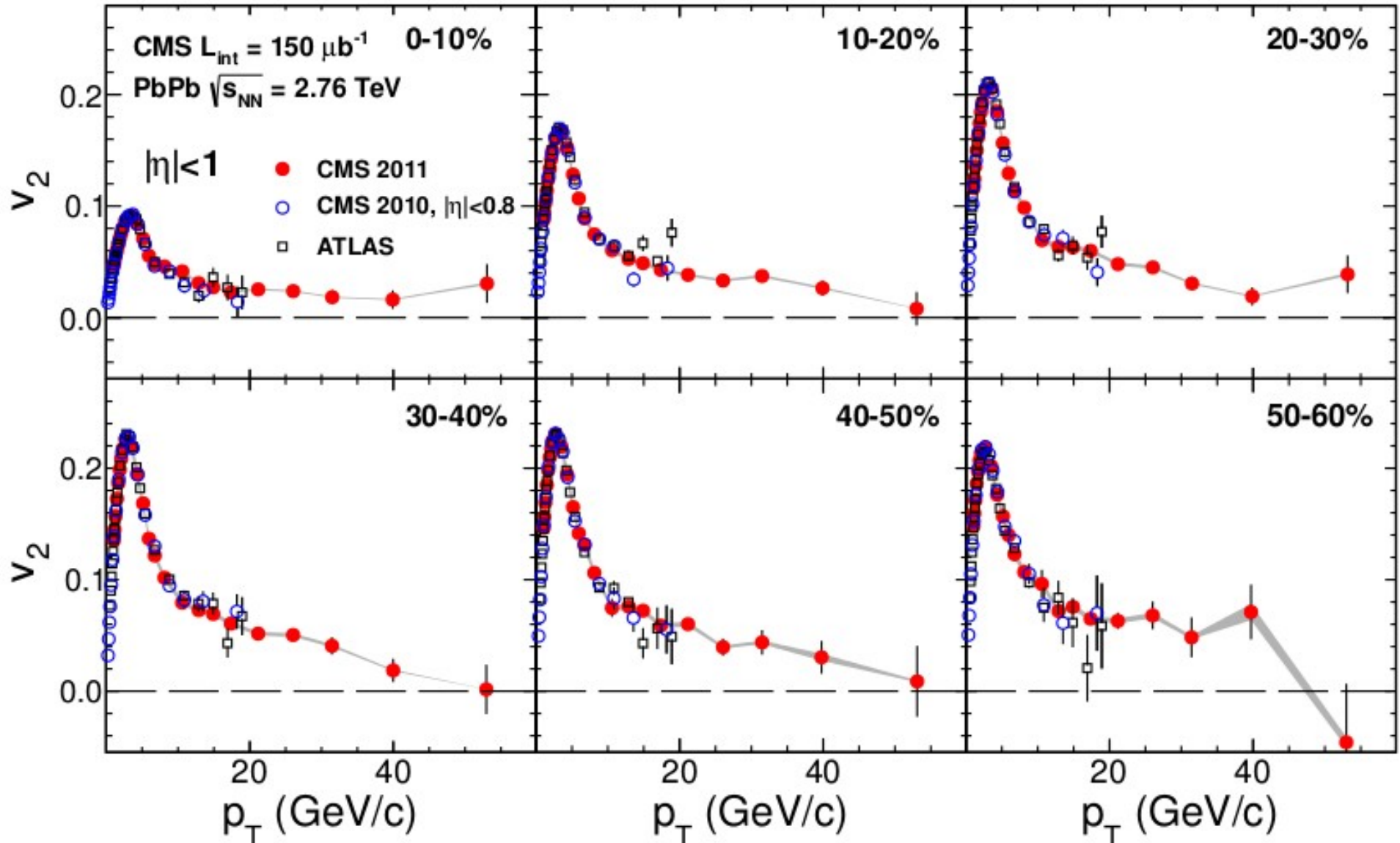
Integrated v_2 : **~30% larger** than at RHIC
 (due to the increase of $\langle p_T \rangle$)

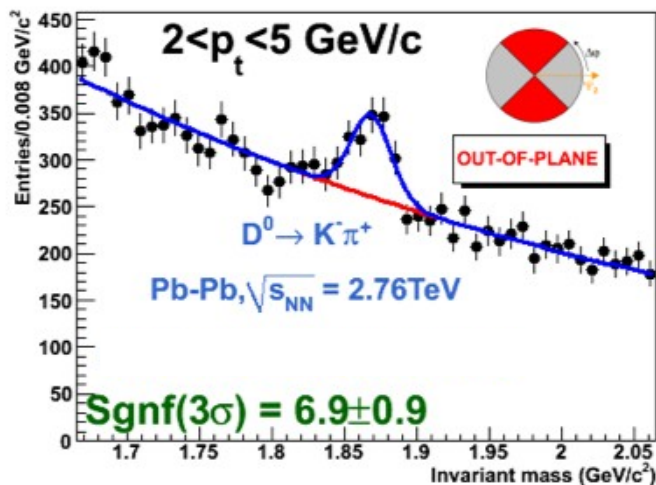
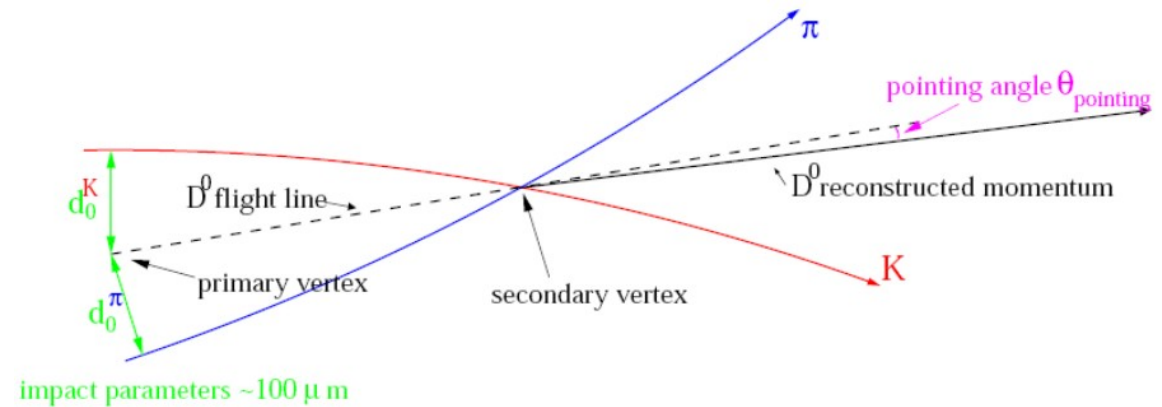
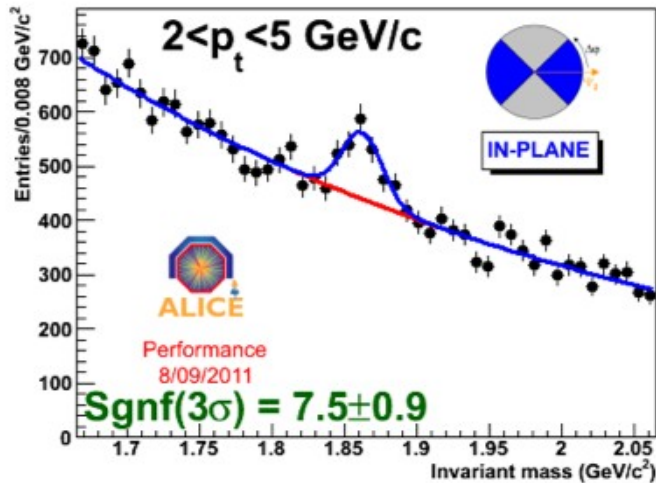
$$v_2 = \langle \cos [2(\phi - \Psi_{RP})] \rangle$$

Elliptic flow at high p_T

53

arXiv:1204.1850

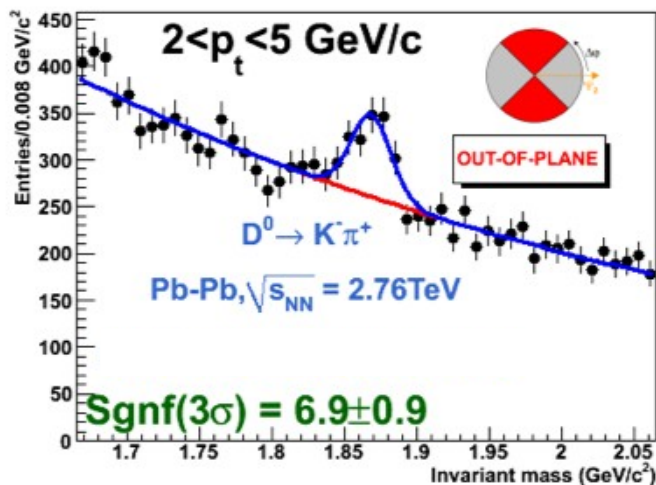
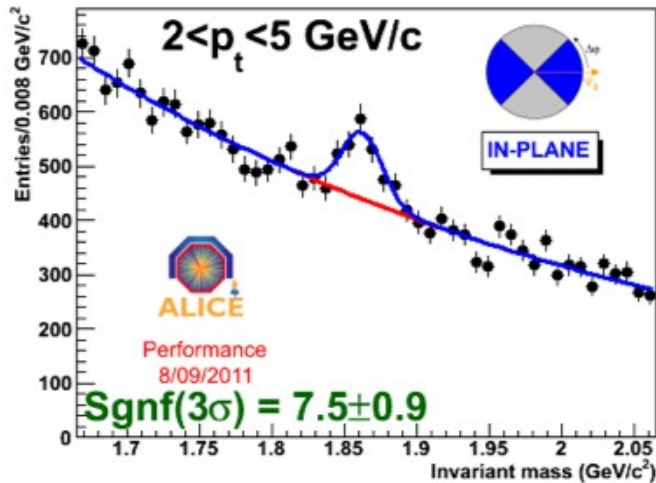




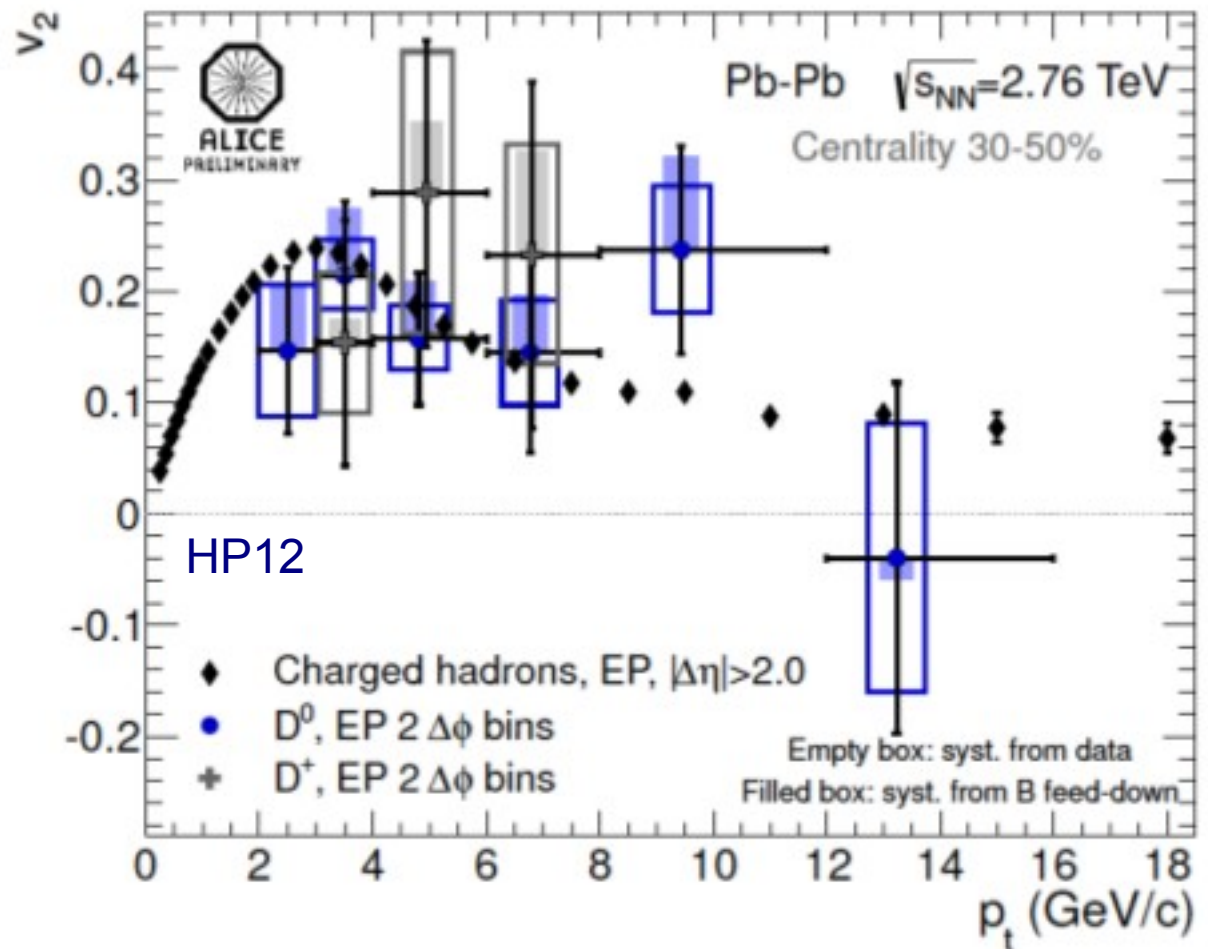
- Invariant mass analysis of fully reconstructed decay topologies (inc. PID)
- Displacement from primary vertex
- Feed-down from B (10-15%) after cuts subtracted using FONLL
 - Conservative hypothesis on Raa of D from B

D meson elliptic flow

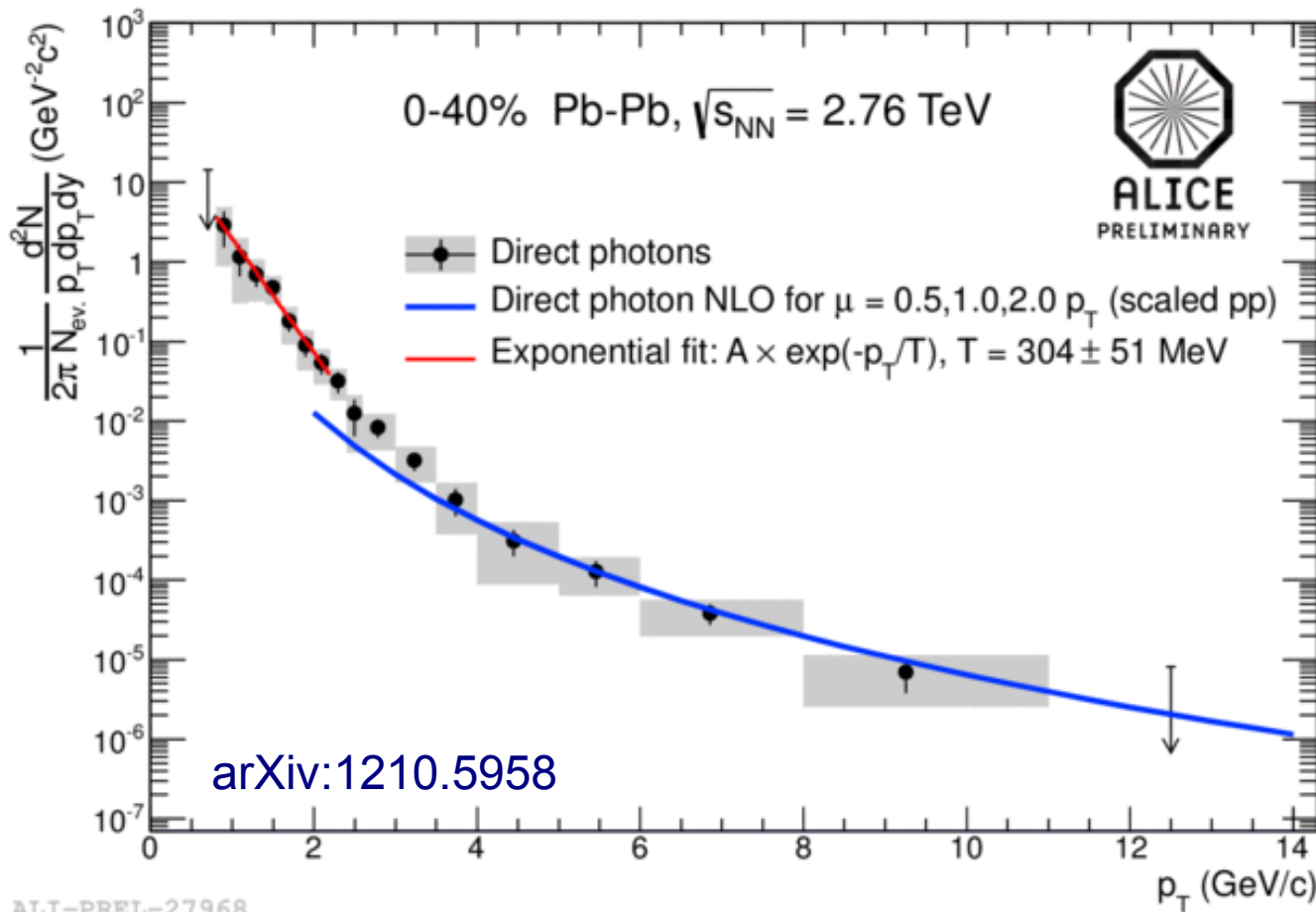
55



$$V_2 = \frac{\pi}{4} \frac{N_{IN} - N_{OUT}}{N_{IN} + N_{OUT}}$$



Even charm mesons exhibit elliptic flow



- Reconstruction of converted photons in ITS+TPC
- Double ratio strategy ala PHENIX
 - Measure inclusive photons and π^0
 - Model decay contribution with cocktail of all decay photon sources
- Spectrum derived as direct $\gamma = (1-R) \gamma^{inc}$

Spectrum above 3-4 GeV/c consistent with NLO prediction scaled by N_{coll} . Below it can be fit with exponential with inverse slope: $T=304\pm 51$ MeV (combined Hagedorn+Exponential fit gives similar value)

Heavy-quark probes: D and B mesons

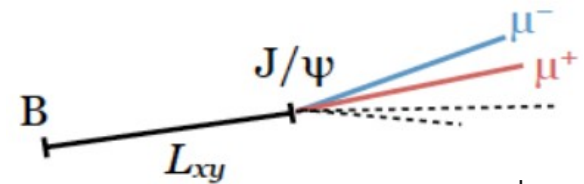
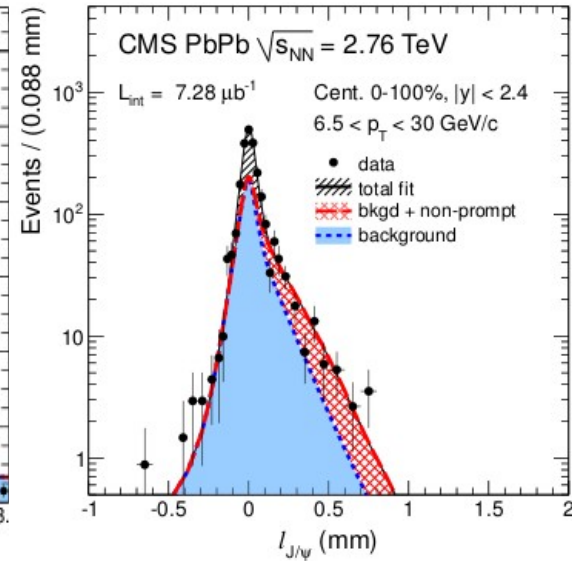
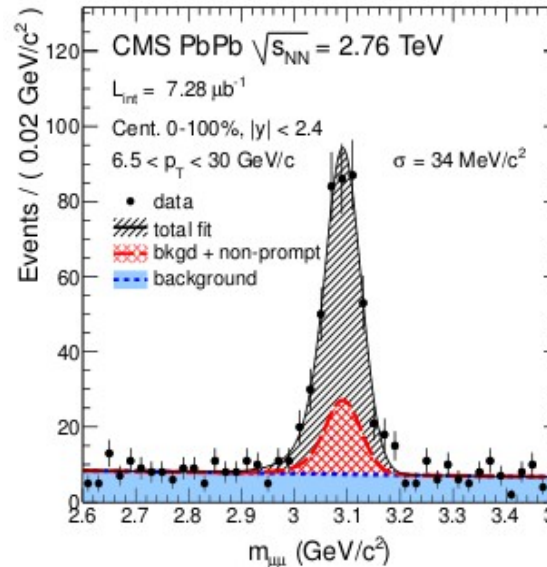
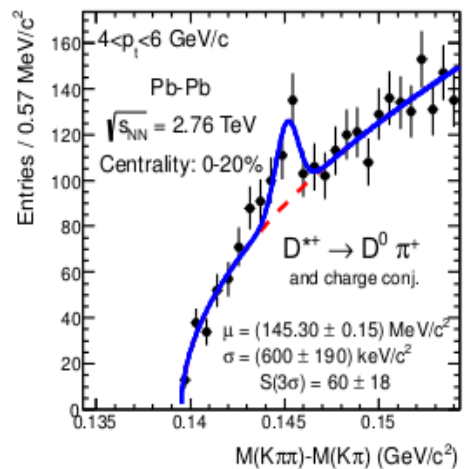
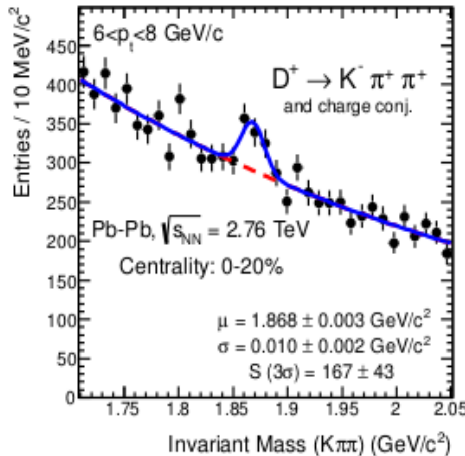
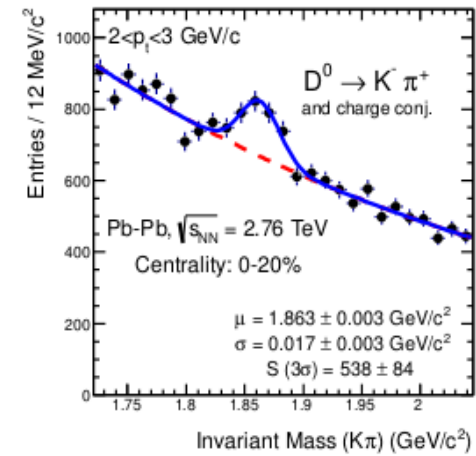
57

D mesons reconstructed from displaced vertices in 3 invariant mass channels. Contribution from B subtracted with FONLL.

ALICE, [arXiv:1203.2160](https://arxiv.org/abs/1203.2160)

B mesons via secondary J/ψ :

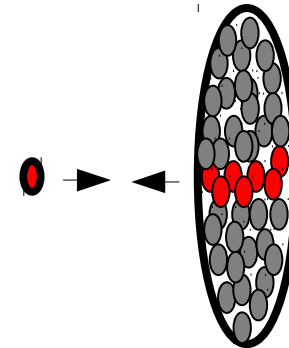
CMS, [JHEP 1205 \(2012\) 063](https://arxiv.org/abs/1205.063)



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

Also recently presented (not discussed here):
 ATLAS HF muon, mid-rapidity ([ATLAS-CONF-2012-050](https://arxiv.org/abs/1205.050))
 ALICE HF muon, forward ([arxiv:1205.6443](https://arxiv.org/abs/1205.6443))

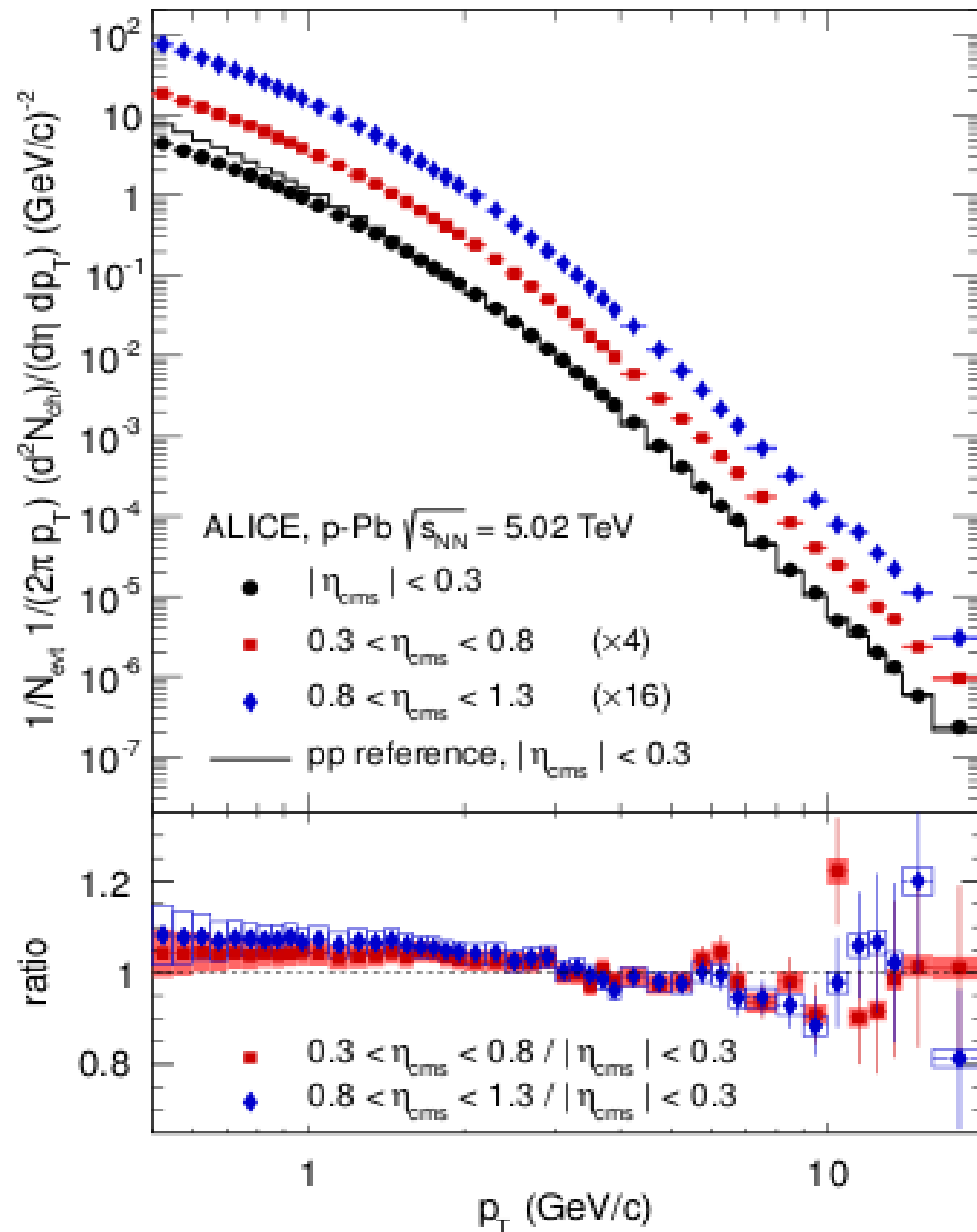
- Event selection
 - VZERO-A and VZERO-C
 - Cross check with ZDC on nucleus side
- Resulting event sample
 - **Non single-diffractive** with negligible contamination from SD and EM processes
- Validated from cocktail
 - DPMJET for NSD (2b)
 - PHOJET + Glauber for incoherent SD part (0.1b)
 - SD/INEL = 0.2 (arXiv:1208.4968)
 - EM with STARLIGHT (0.1-0.2b)
- **Normalization uncertainty: 3.1%**



A p-Pb collision is defined to be NSD if at least one binary collision is NSD.

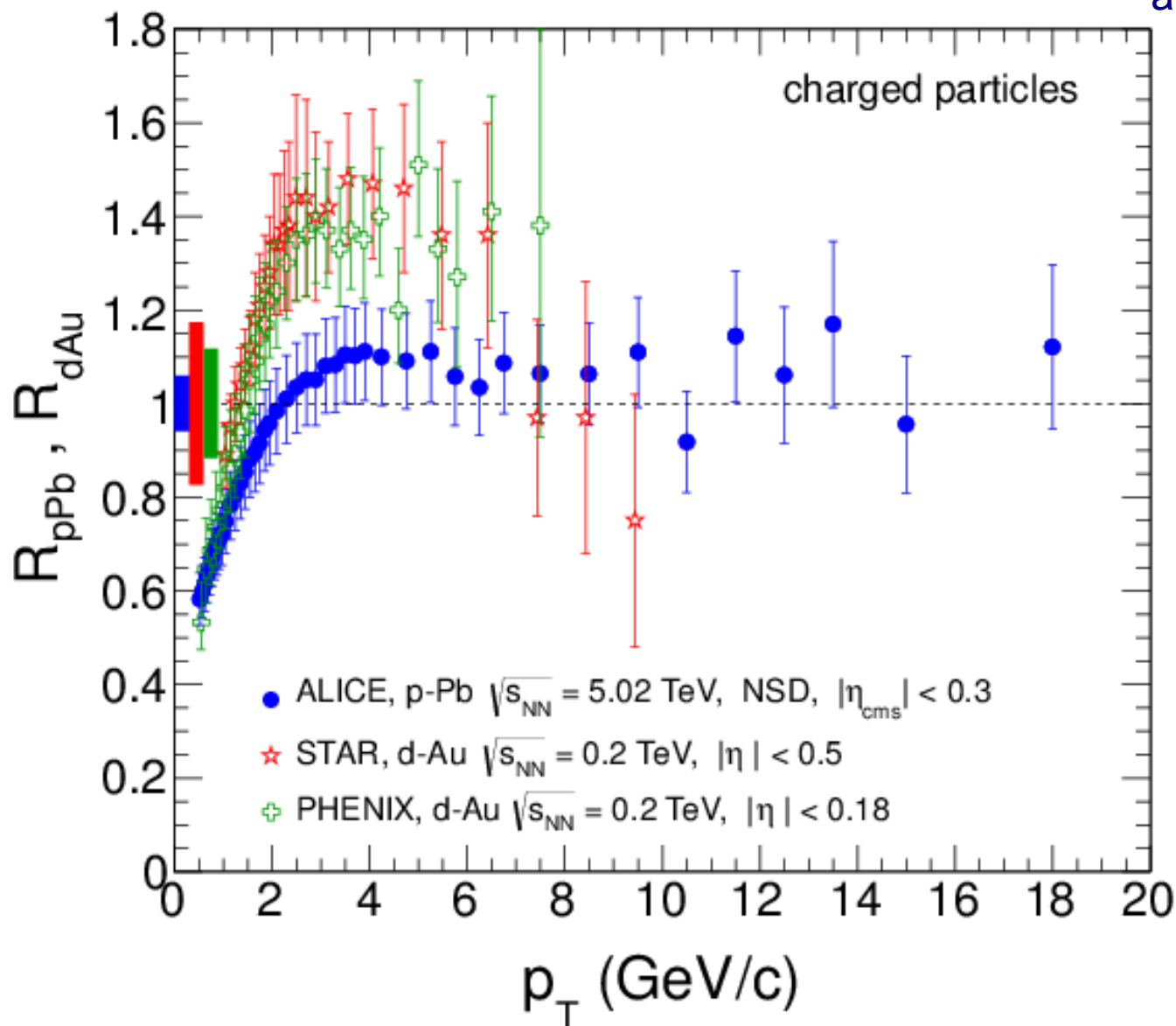
(Fraction of SD p-Pb collisions is dominated by $N_{part} = 2$ events.)

- Measurement (track based) in p-Pb in 3 η -intervals
 - Corrections based on DPMJET and HIJING
 - Systematic uncertainty: $\sim 5.3\%$
 - NSD normalization: 3.1 %
- No strong η dependence within our acceptance
- Reference constructed from pp (INEL) data at 2.76 and 7 TeV
 - Scaled by factor obtained from NLO calculation
 - Interpolation below 5 GeV/c
 - $\langle T_{pPb} \rangle = 0.0983 \pm 0.0035 \text{ mb}^{-1}$ from Glauber model



p+Pb: Comparison to d+Au at 0.2 TeV 60

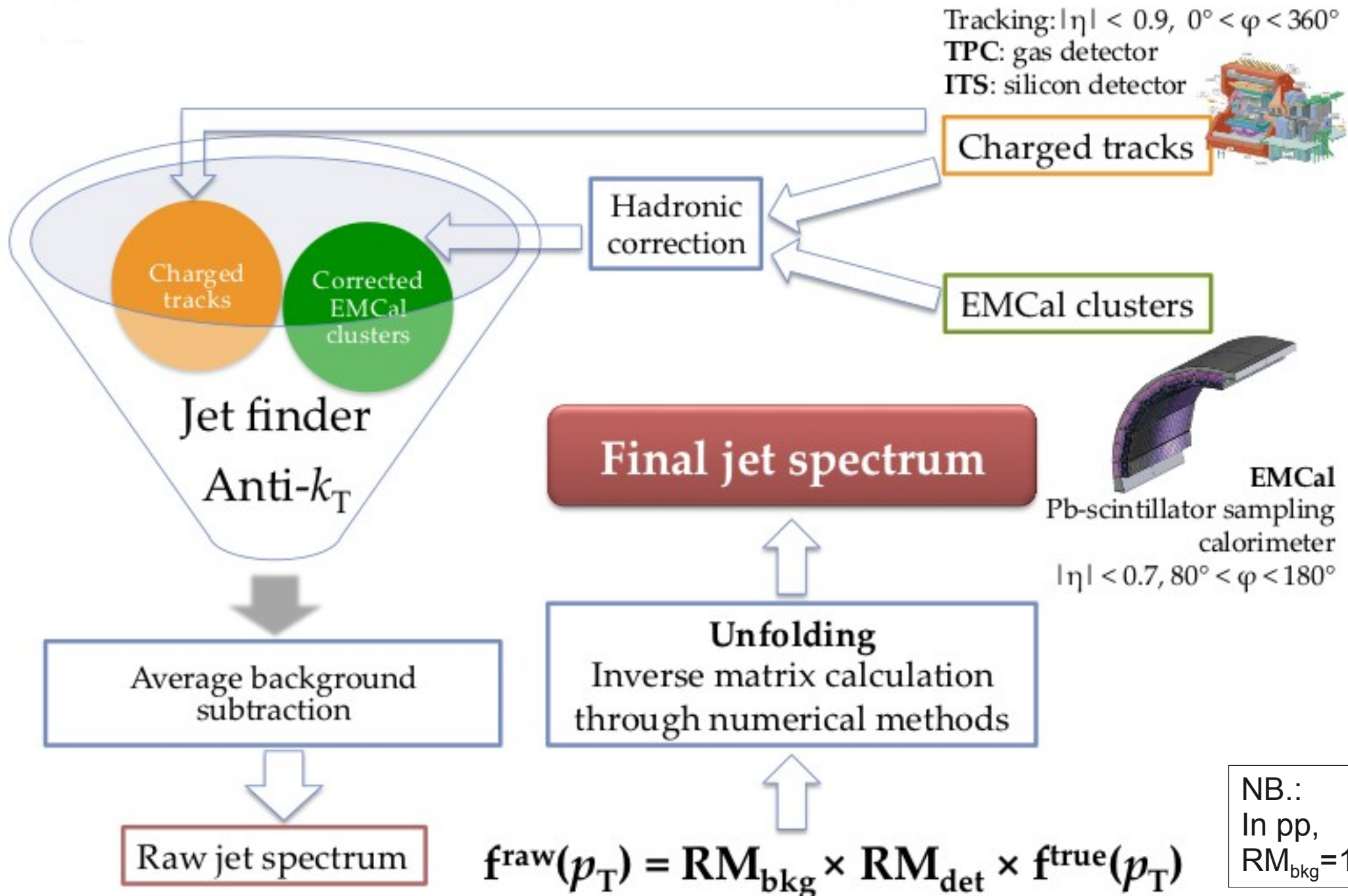
arXiv:1210.4520



Cronin effect much smaller (if at all present) at the LHC energies.

Jet reconstruction overview

61



Jet reco in pp and Pb+Pb at 2.76 TeV 62

- Constituents (input to jet finder)
 - Assumed to be massless
 - Charged tracks with $p_T > 150$ MeV/c
 - EMCAL clusters with $E_T > 300$ MeV/c after hadronic correction
 - Correction for track-matched clusters to prevent double counting

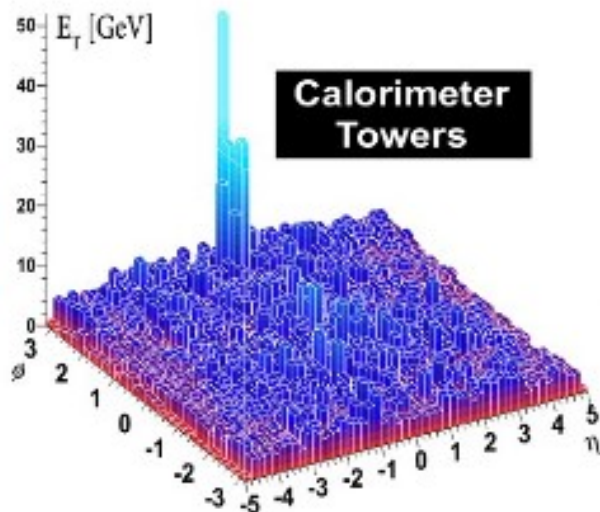
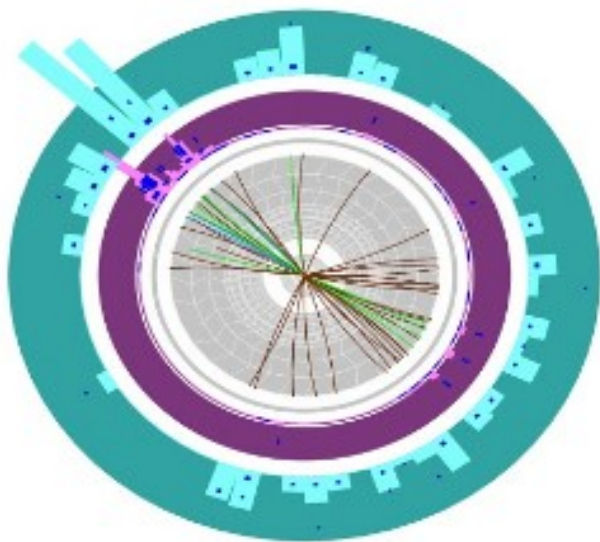
$$E_{clus}^{cor} = E_{clus}^{orig} - f \sum p_{track}^{matched}, \quad E_{clus}^{cor} \geq 0$$

- As default, $f=100\%$ used

- Jet reconstruction using FASTJET
 - $R=0.2$ (also $R=0.4$ for pp)
 - Anti- k_T for signal jets
 - Area cut $> 0.6 \pi R^2$
 - Fiducial cuts to select jets fully contained within the EMCAL
 - K_T for background estimate (Pb-Pb)

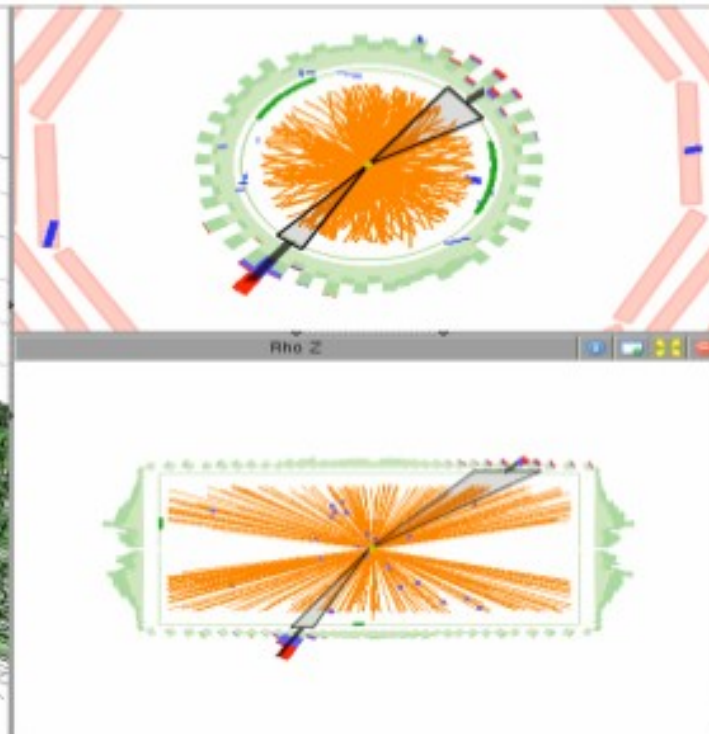
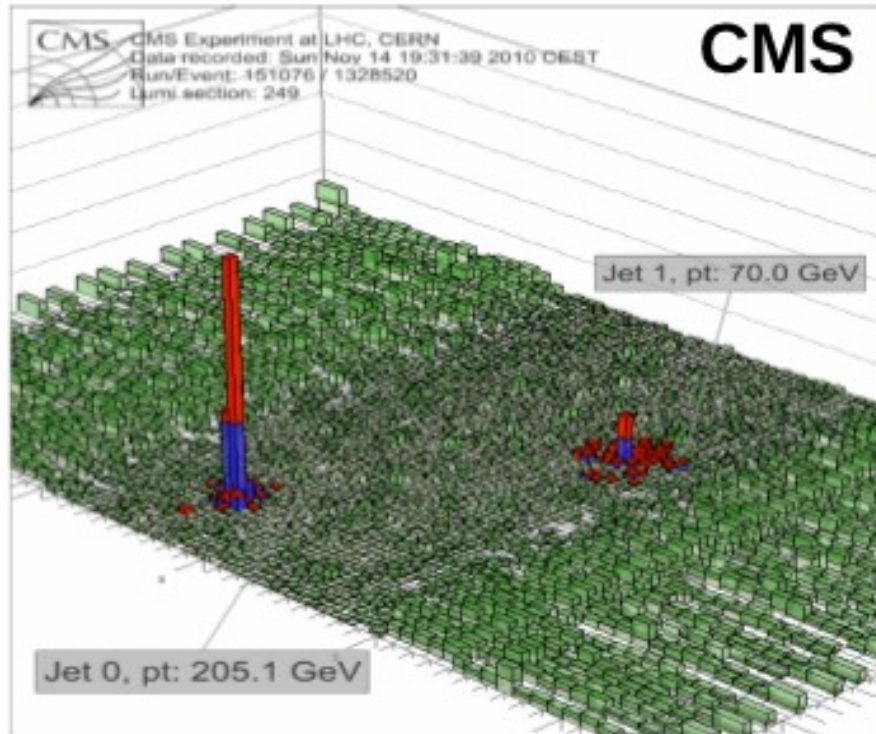
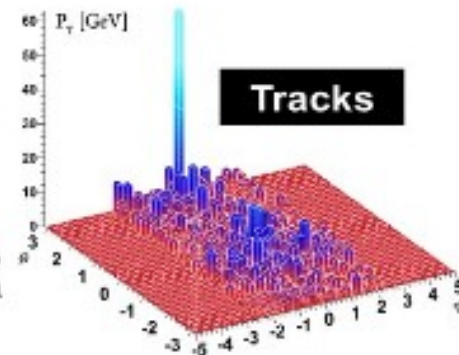
Jet quenching in dijet events

63



ATLAS

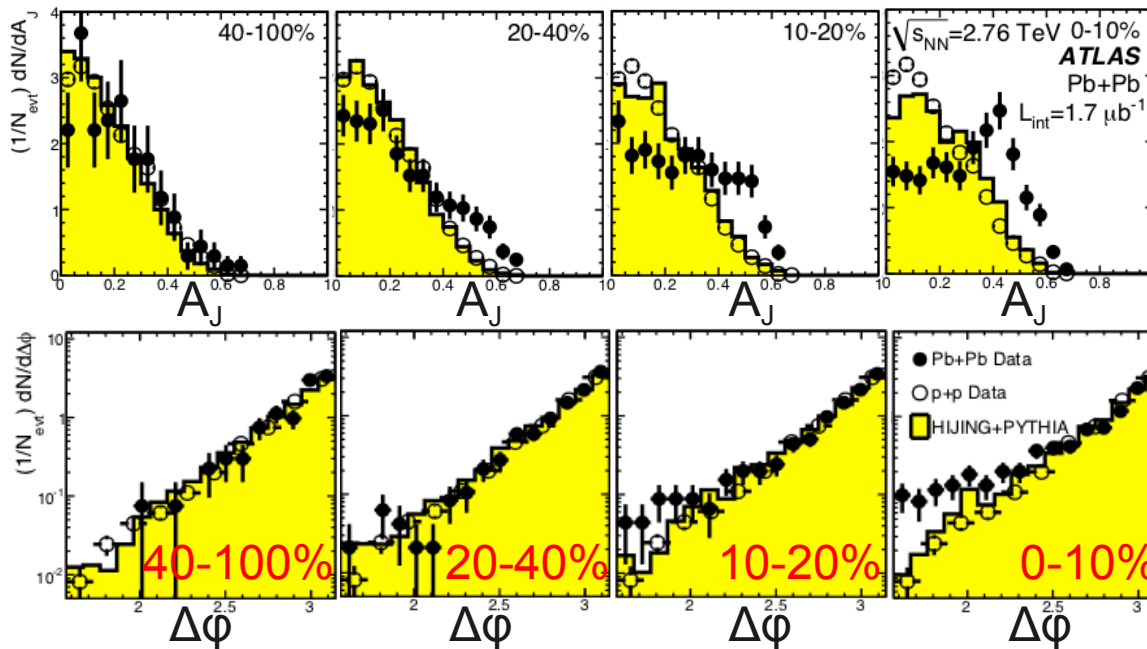
Run: 169045
Event: 1914004
Date: 2010-11-12
Time: 04:11:44 CET



Dijet momentum imbalance

64

Dijet momentum asymmetry: $A_J = (p_{T,1} - p_{T,2}) / (p_{T,1} + p_{T,2})$



Larger momentum imbalance wrt to MC reference.

Difference increases with increasing centrality.

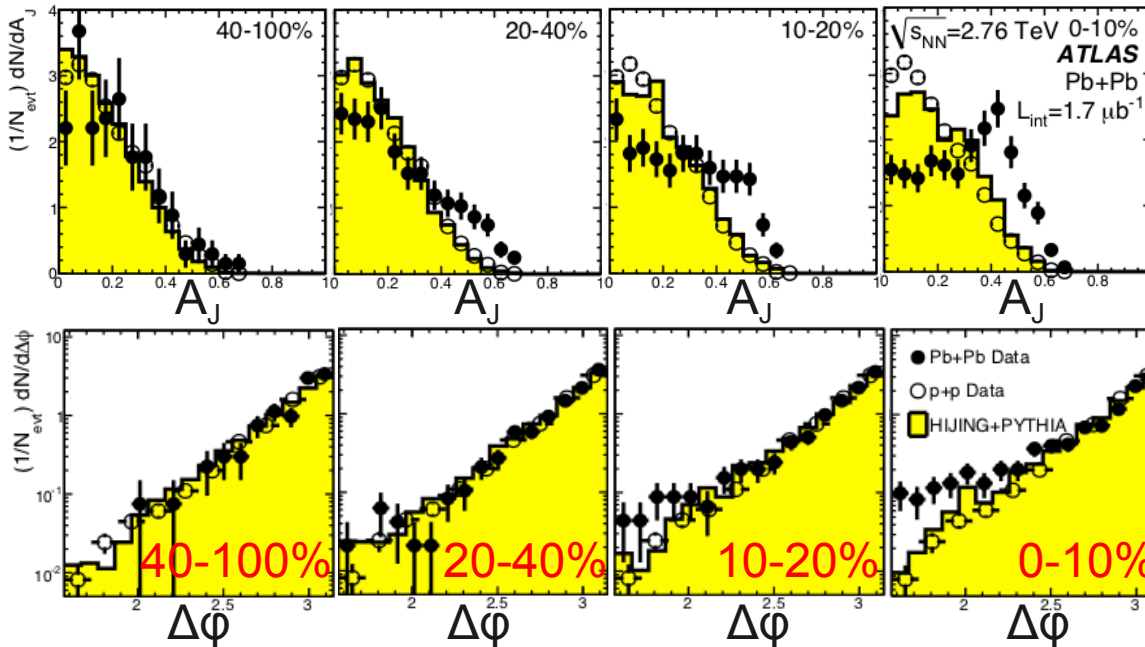
But **no** (very little) increasing azimuthal decorrelation.

ATLAS, PRL 105 (2010) 252303
CMS, PRC84 (2011) 024906

Dijet momentum imbalance

65

Dijet momentum asymmetry: $A_J = (p_{T,1} - p_{T,2}) / (p_{T,1} + p_{T,2})$



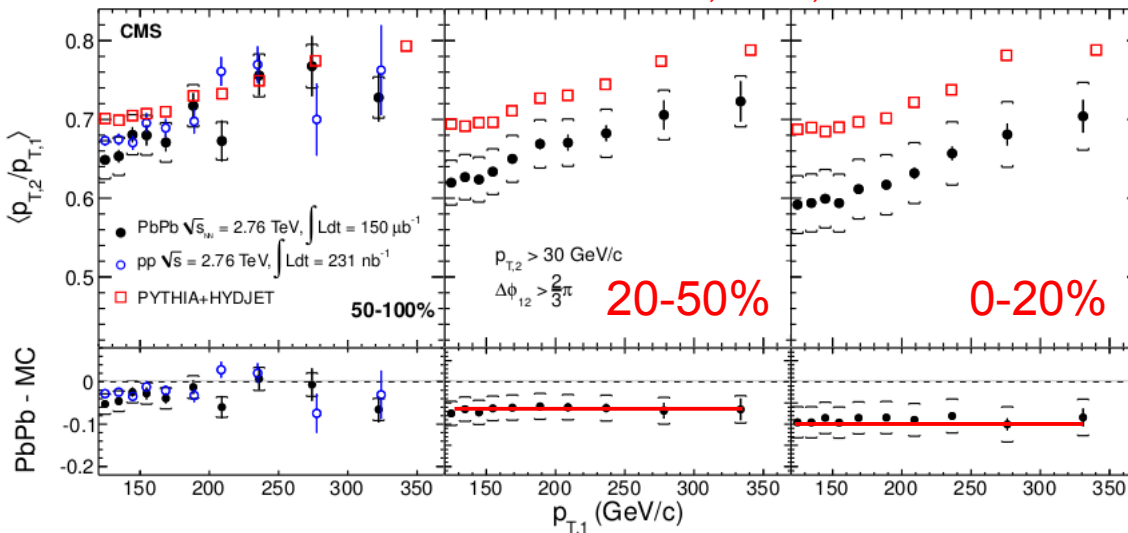
Larger momentum imbalance wrt to MC reference.

Difference increases with increasing centrality.

But **no** (very little) increasing azimuthal decorrelation.

ATLAS, PRL 105 (2010) 252303
CMS, PRC84 (2011) 024906

Dijet momentum ratio: $p_{T,2}/p_{T,1}$ vs leading jet $p_{T,1}$



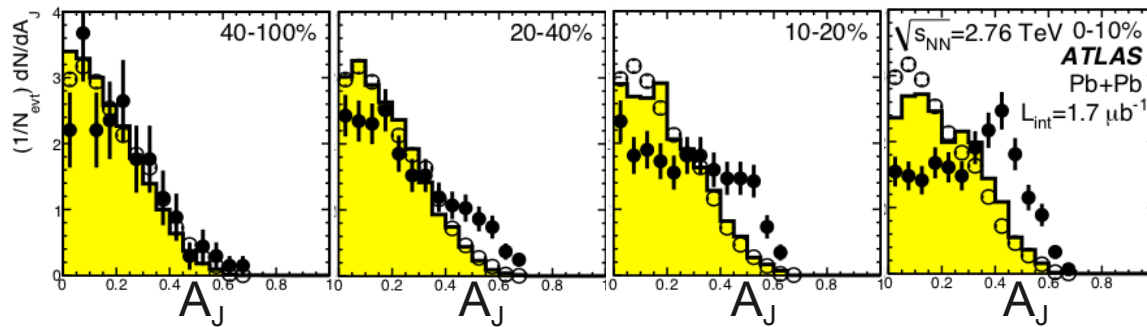
Even ~ 350 GeV/c jets are quenched!
Fraction of energy lost constant up to ~ 350 GeV/c.

CMS, PLB 712 (2012) 176

Dijet momentum imbalance

66

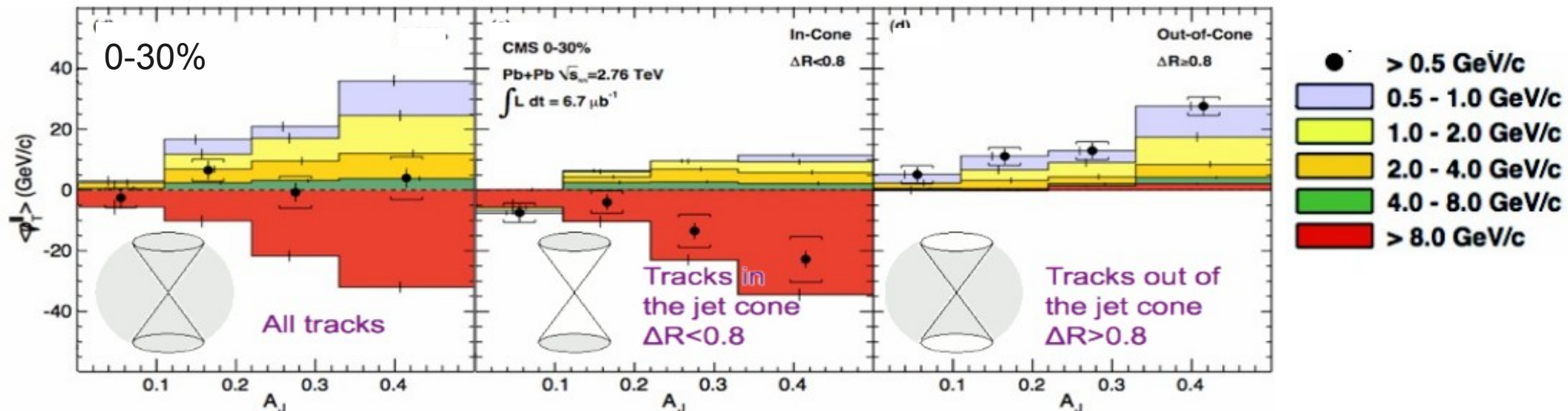
Dijet momentum asymmetry: $A_J = (p_{T,1} - p_{T,2}) / (p_{T,1} + p_{T,2})$



ATLAS, PRL 105 (2010) 252303
CMS, PRC84 (2011) 024906

Lost energy emitted at **low p_T (<4 GeV/c)** **outside jet cone (R>0.8)**

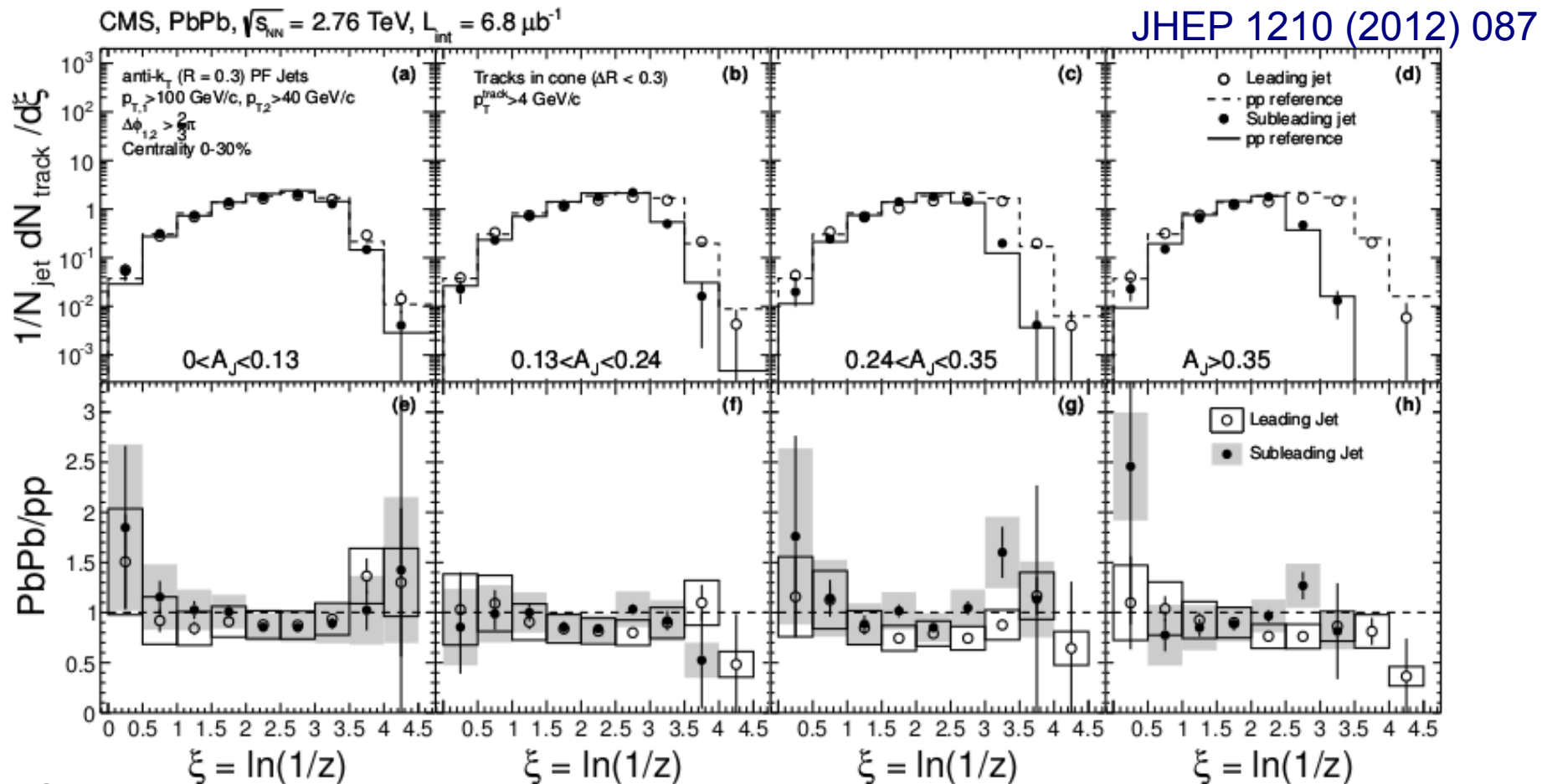
$$p_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos(\phi_{\text{Track}} - \phi_{\text{Leading Jet}})$$



Jet fragmentation function

67

Fragmentation functions constructed using tracks with $p_T > 4$ GeV/c in $R < 0.3$ and the reconstructed (quenched) jet energy



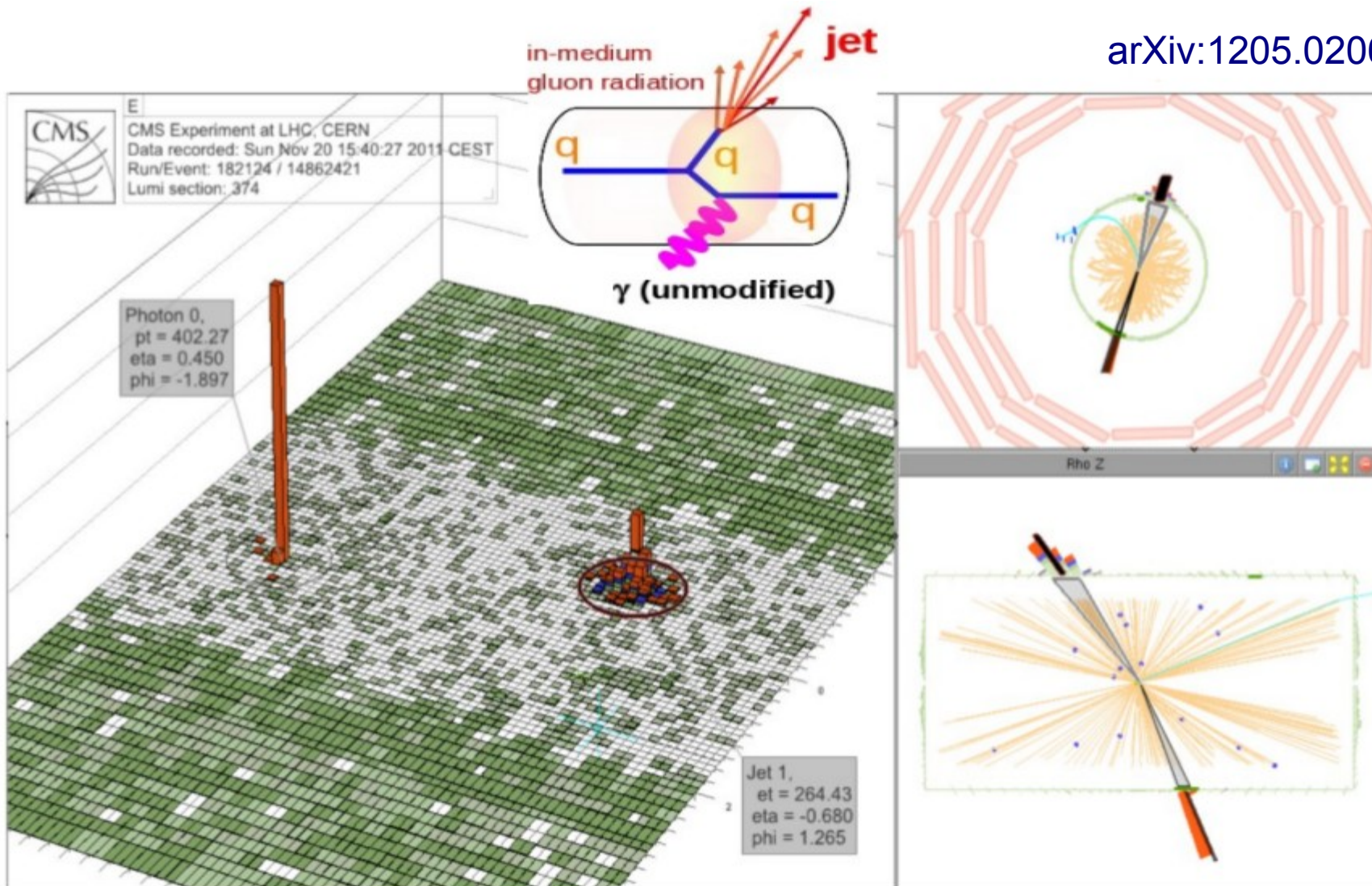
$R=0.3$
 $P_{T1} > 100$ GeV/c
 $P_{T2} > 40$ GeV/c
 $\Delta\Phi_{12} > 2/3\pi$
 Track $p_T > 4$ GeV/c

Leading and sub-leading jet in Pb+Pb fragment like jets of corresponding energy in pp

Jet quenching in γ -jet events

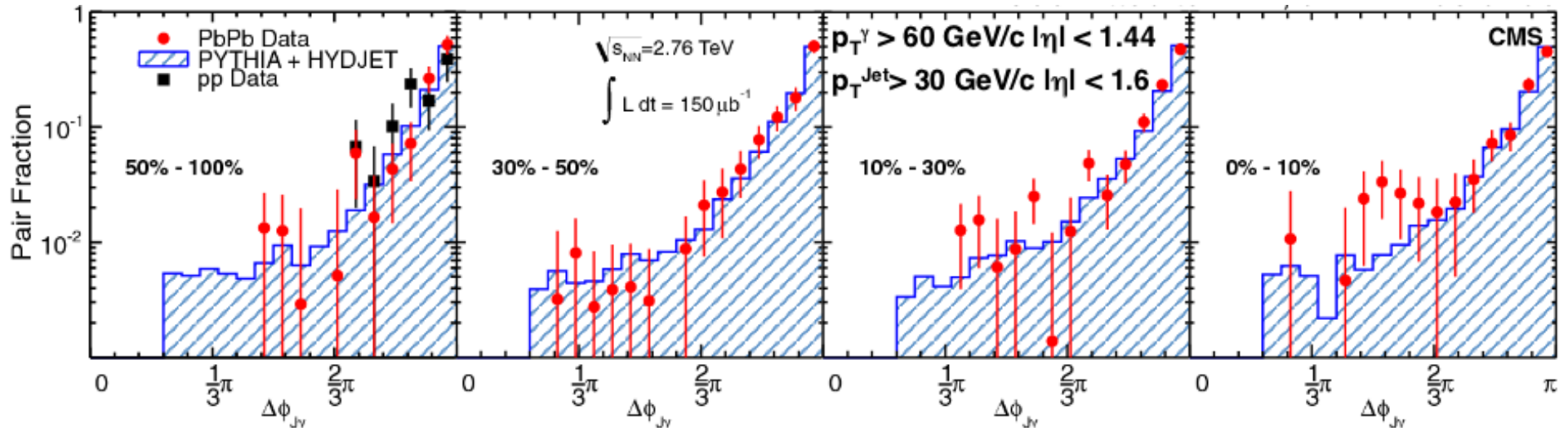
68

arXiv:1205.0206

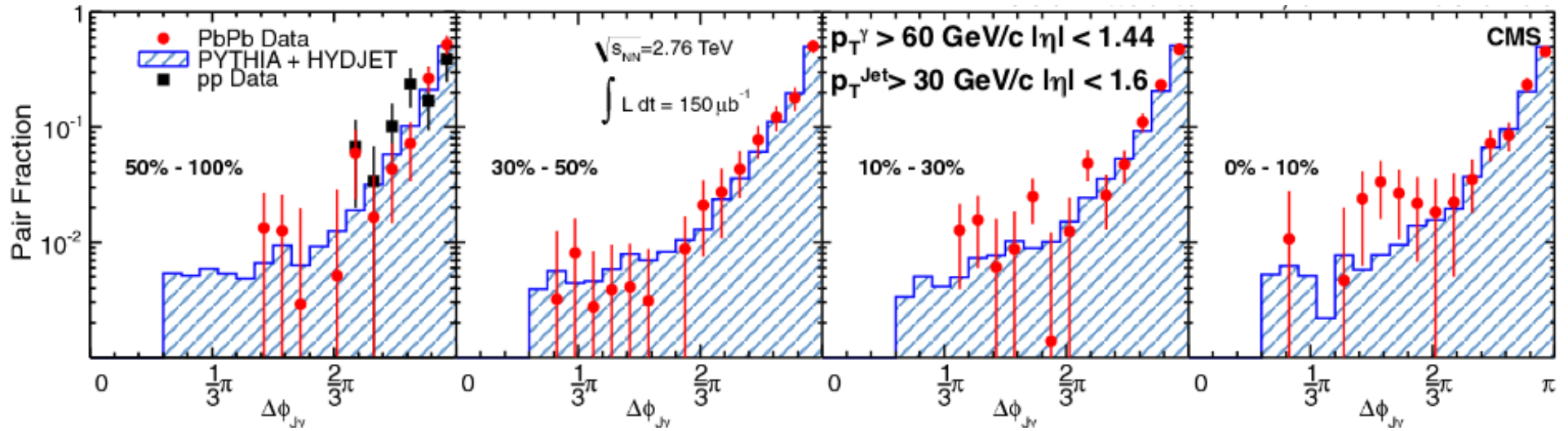


Photon $p_T > 60$ GeV/c

Jet $p_T > 30$ GeV/c



- Azimuthal decorrelation consistent with pp and MC (PYTHIA+HYDJET)



- Azimuthal decorrelation consistent with pp and MC (PYTHIA+HYDJET)

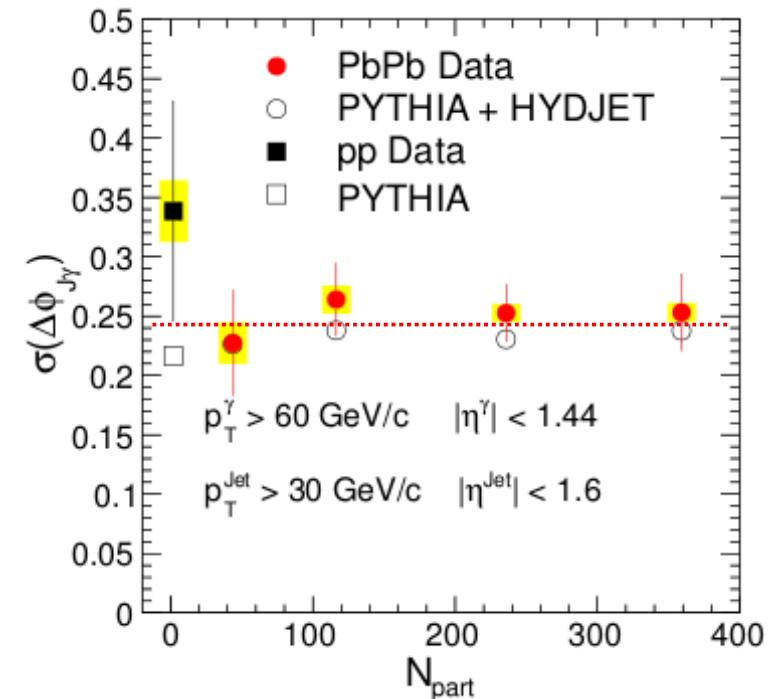
- Angular width parametrized with

$$\frac{1}{N_{J\gamma}} \frac{dN_{J\gamma}}{d\Delta\phi_{J\gamma}} = \frac{e^{(\Delta\phi - \pi)/\sigma}}{(1 - e^{-\pi/\sigma}) \sigma}$$

found to be constant vs centrality

- Quenched jet is back-to-back to γ :

Energy transfer not via one single hard gluon radiation

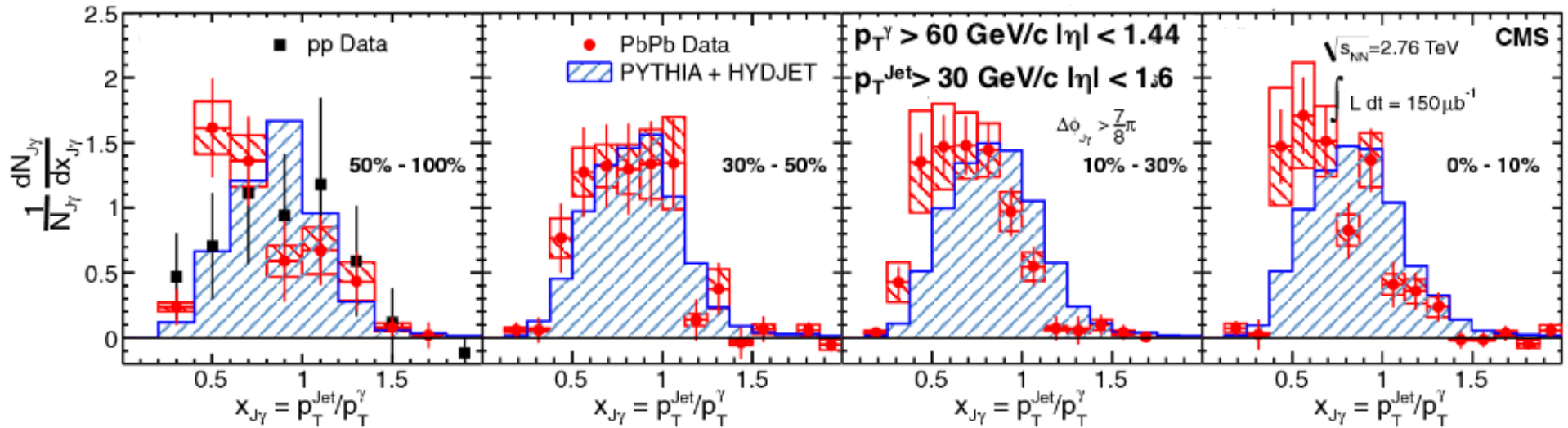


γ -jet momentum imbalance

71

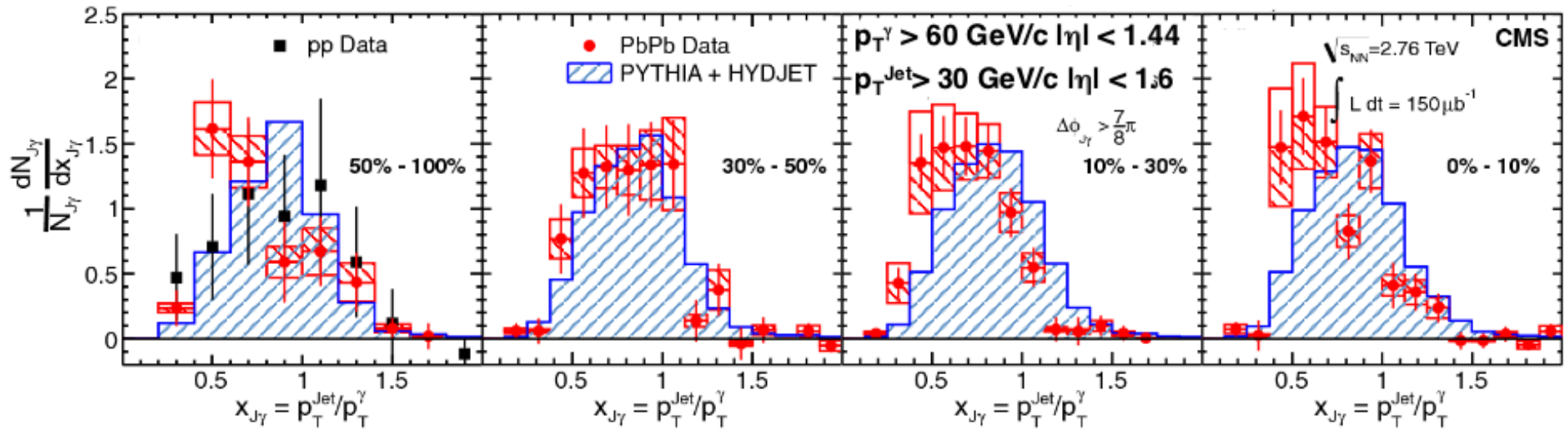
Momentum ratio distribution

arXiv:1205.0206

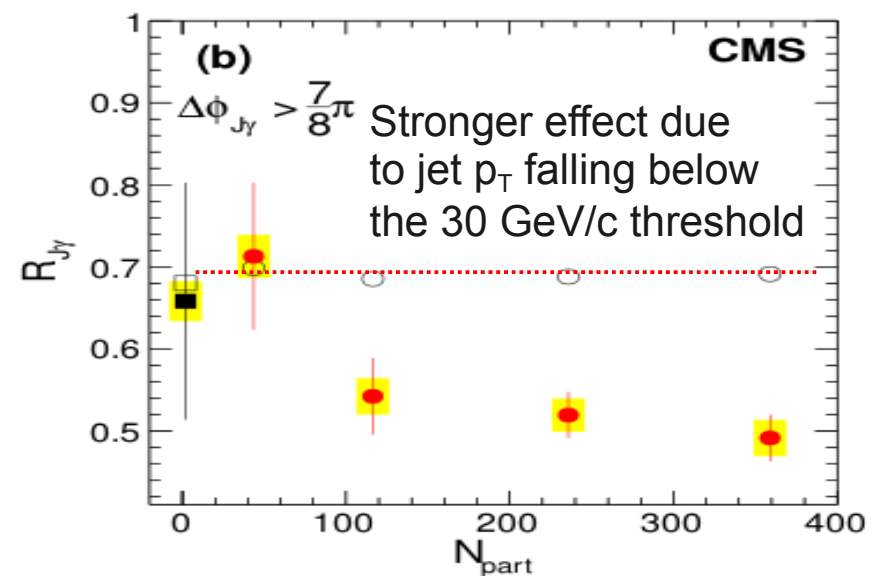
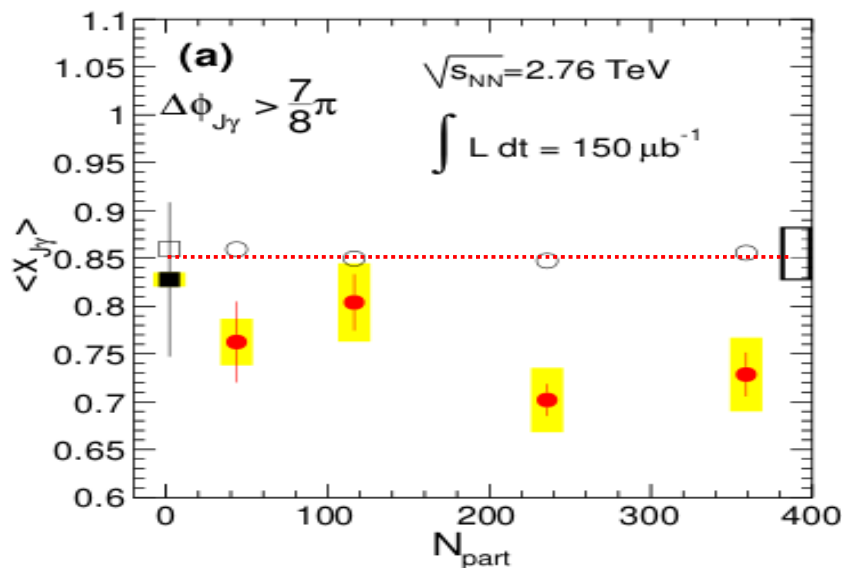


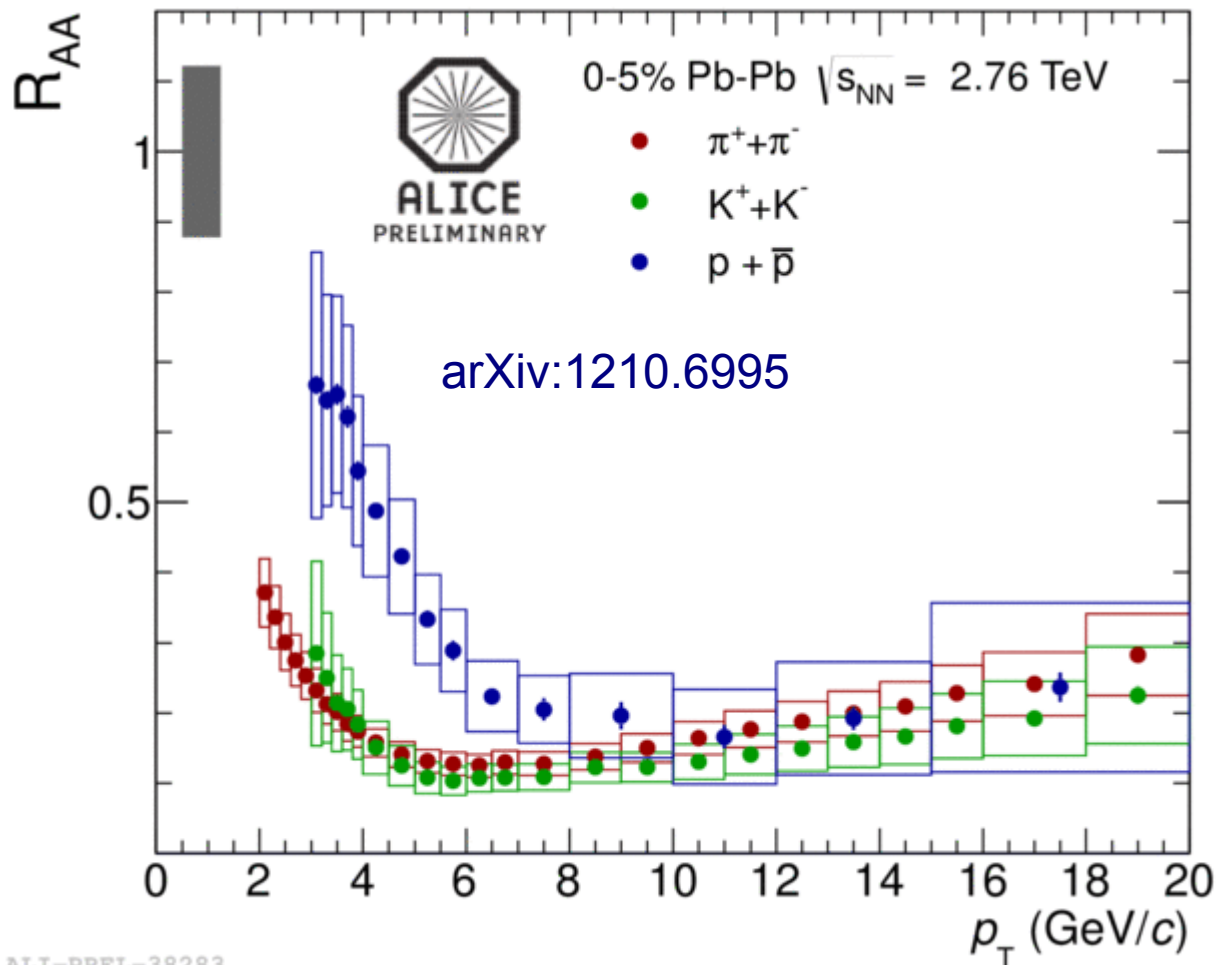
Momentum ratio distribution

arXiv:1205.0206



Momentum ratio ($x_{J\gamma}$) and fraction of γ -jet associations ($R_{J\gamma}$) decrease significantly with centrality compared to pp or MC

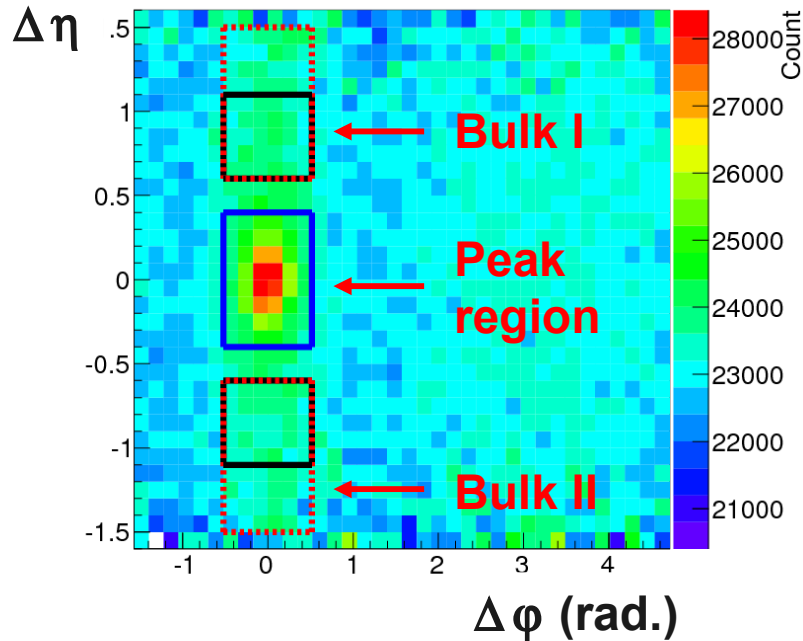




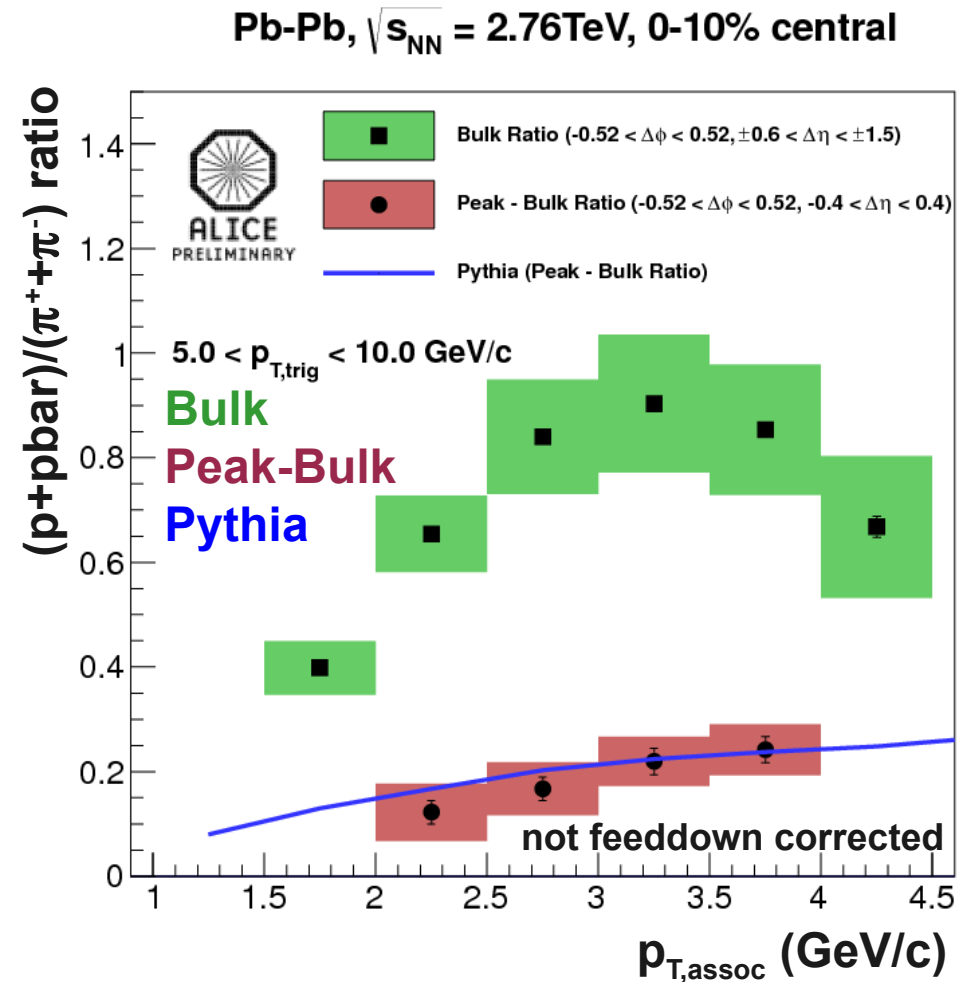
ALI-PREL-38283

- Differences only at low p_T
 - Sensitivity to in-medium hadronization
- In particular, no visible difference for p_T above 10 GeV/c
- Little room for in-medium modification at high p_T
- However, will have to measure inside reconstructed jets

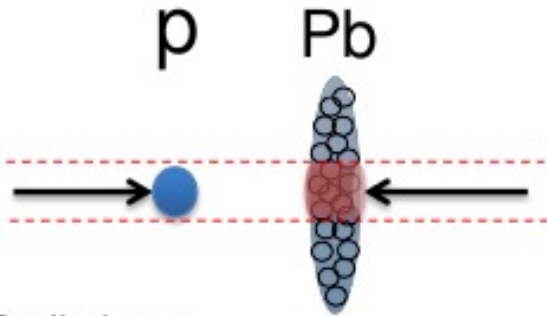
Near-side dihadron correlations: p/ π ratio 74



- p/π ratio in the bulk is consistent with inclusive p/π ratio
 - NB. Inclusive ratio in 0-5% and feed-down corrected
- p/π ratio in peak - bulk is consistent with ratio from Pythia (6.4 default tune)
- No evidence for medium-induced modification of jet fragmentation ($R \sim 0.4-0.5$) in this p_T regime



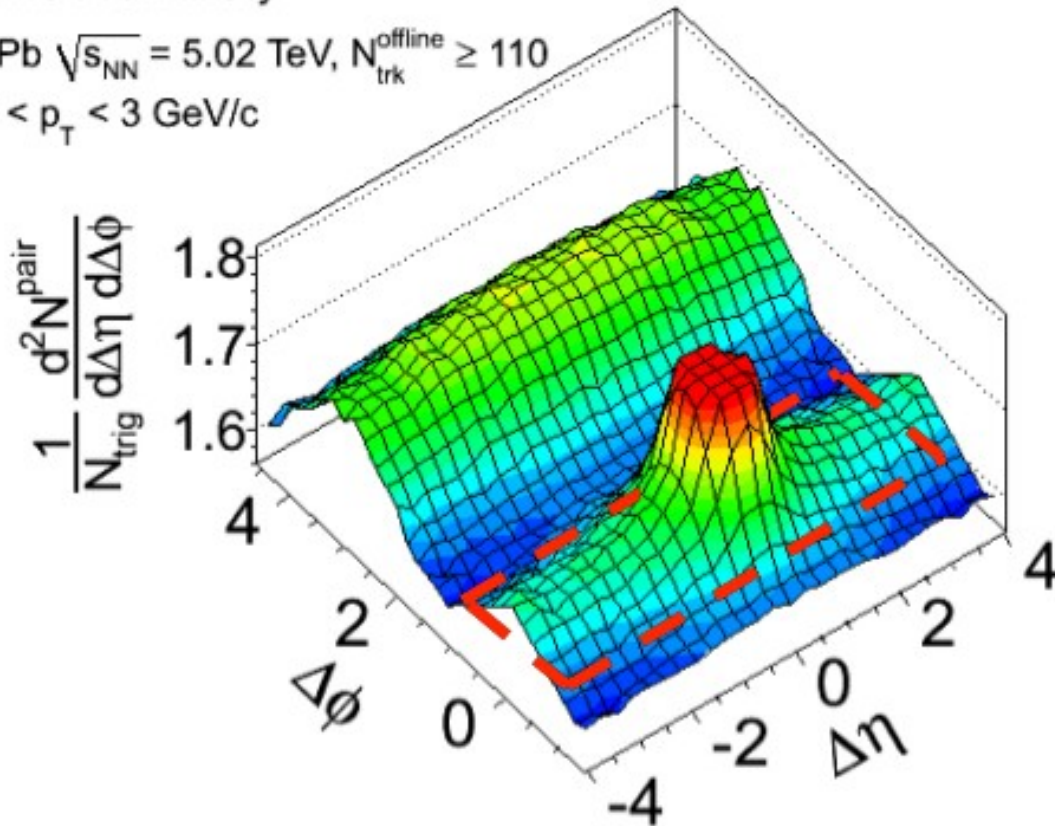
Ridges in p+Pb and pp



Physical origin still unclear

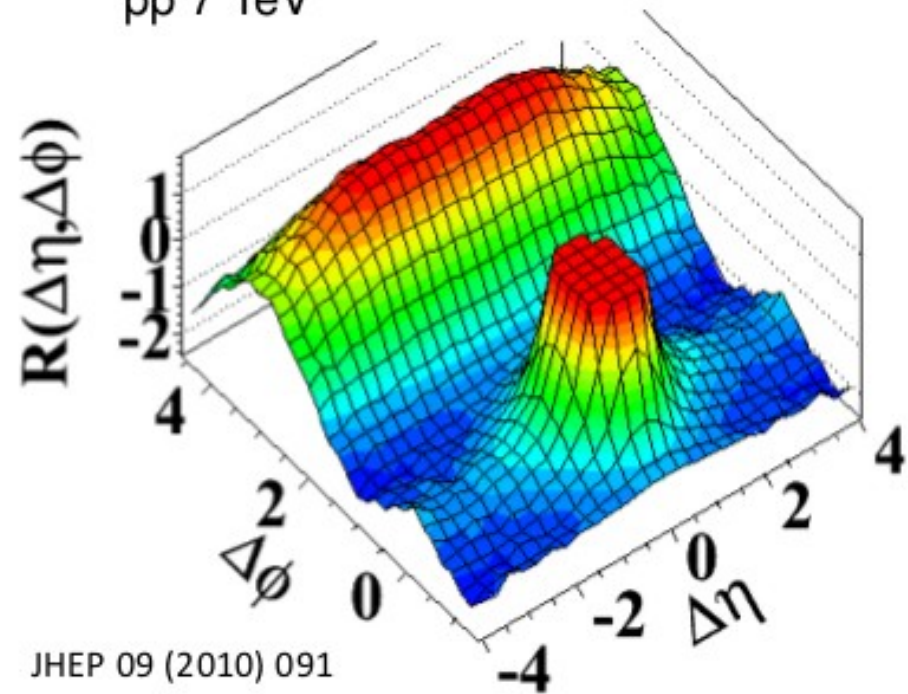
CMS Preliminary

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



Much bigger than pp

(d) $N > 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$
 pp 7 TeV



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