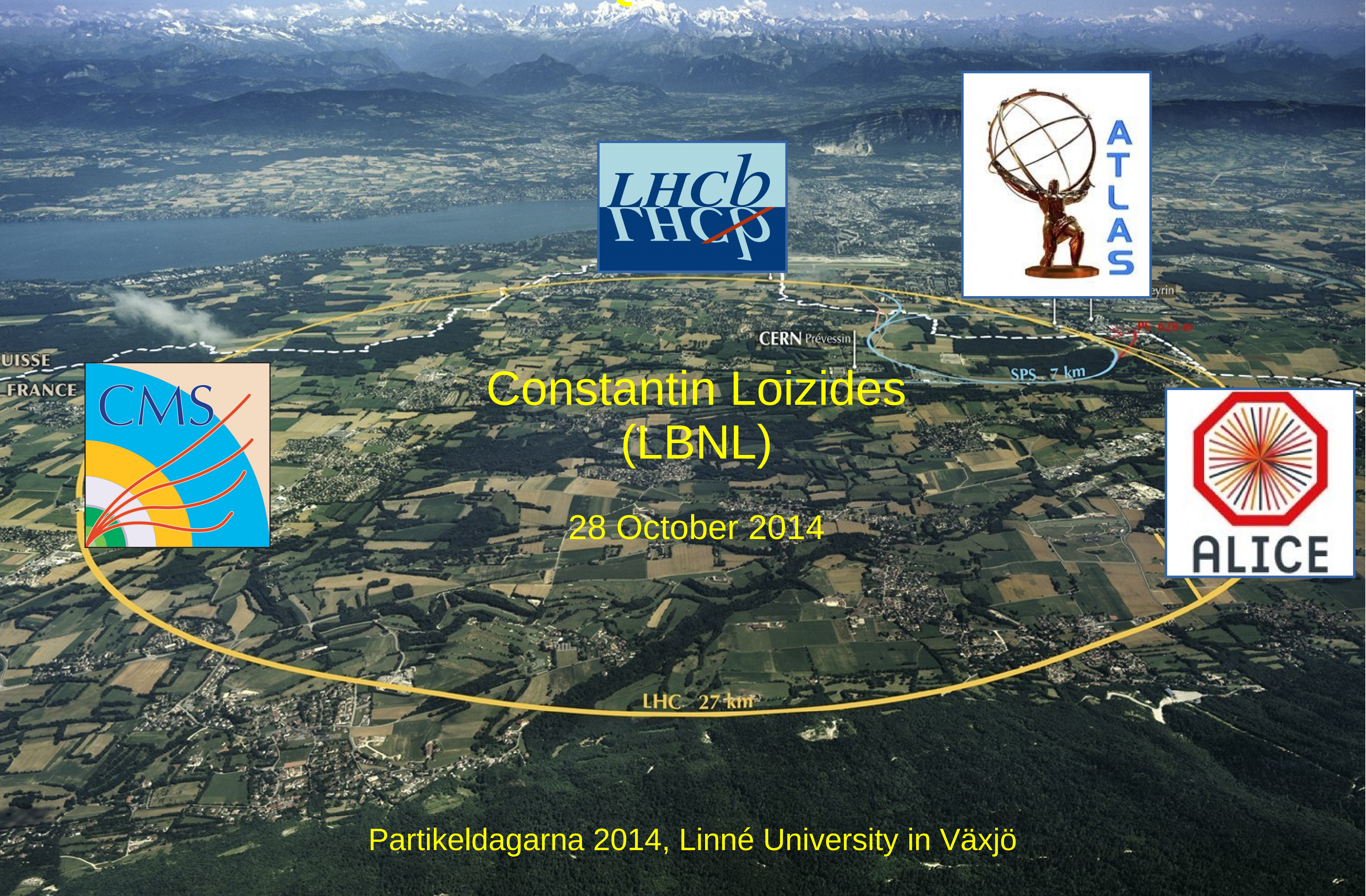
What did run 1 data from LHC and ALICE tell us about the Quark-Gluon Plasma?

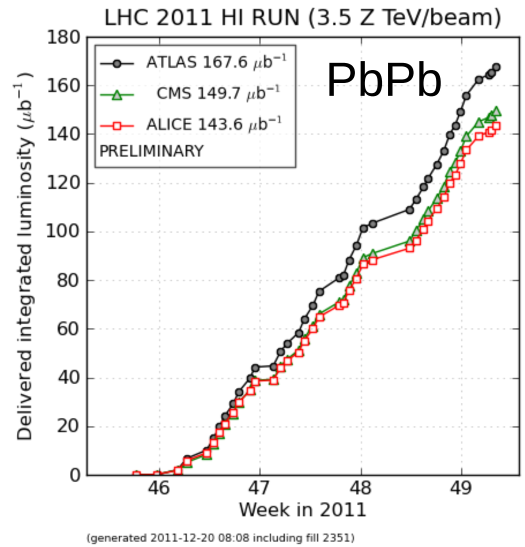


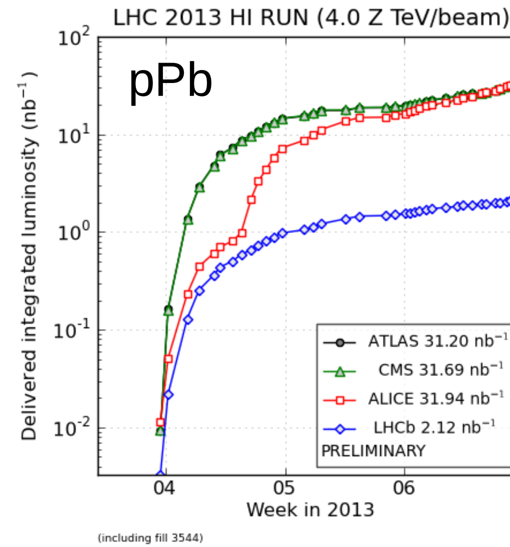
Constantin Loizides
(LBNL)

28 October 2014

Partikeldagarna 2014, Linné University in Växjö

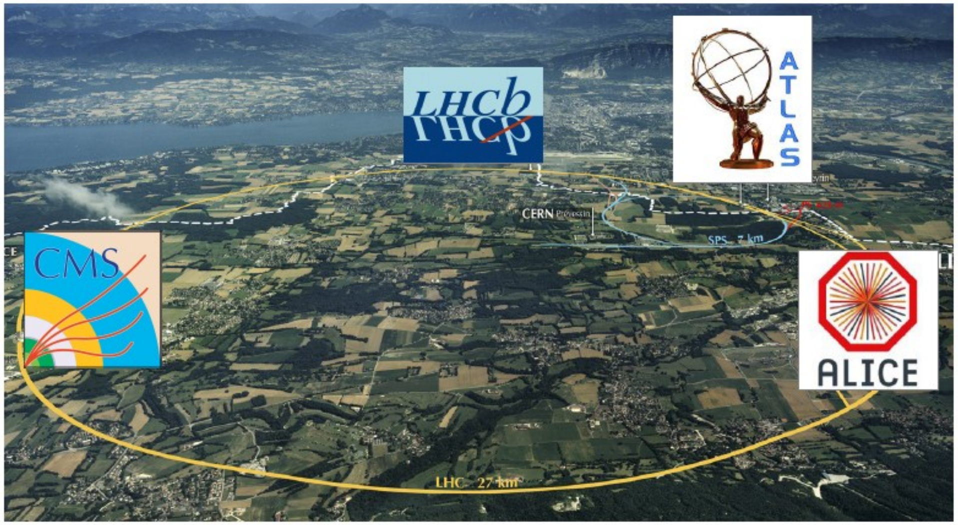
LHC run I period (2009-2013)





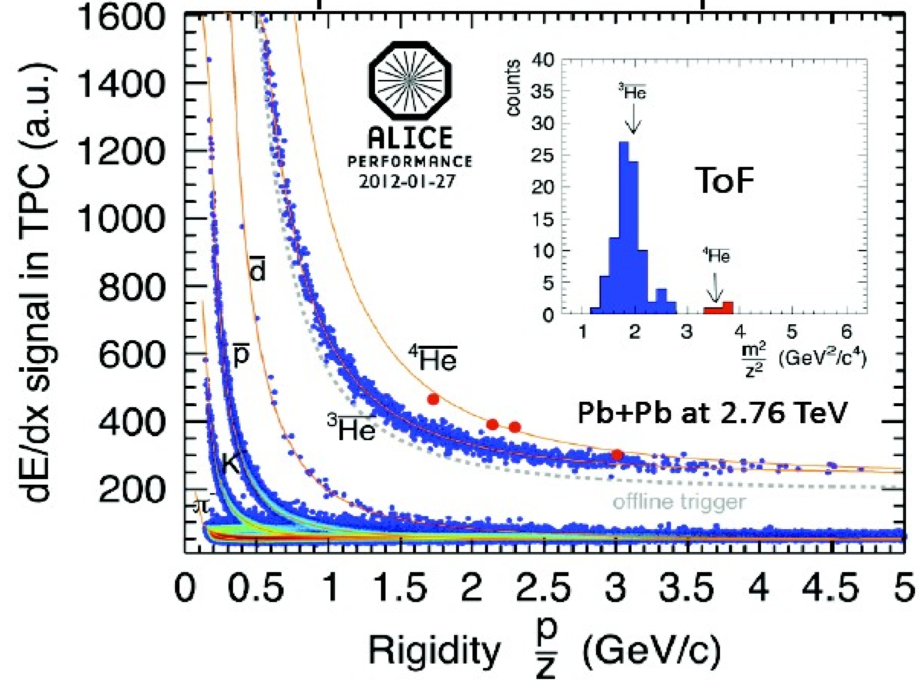
- 2009: Commissioning and first pp data (0.9 and 2.36 TeV)
- 2010: First pp run (7 TeV) and first PbPb run (2.76 TeV, ~10/μb)
- 2011: First pp (2.76 TeV) and long pp (7 TeV) run,
  and second PbPb run (2.76 TeV, ~150/μb)
- 2012: Long pp run (8 TeV) and 8 hours pPb (5.02 TeV, ~1/μb)
- 2013: Long pPb (5.02 TeV, ~30/nb) and second pp run (2.76 TeV, 5/pb)
- Mar 2013 – end of 2014: Long Shutdown 1 (LS1)
  - Consolidation + upgrade of machine and experiments

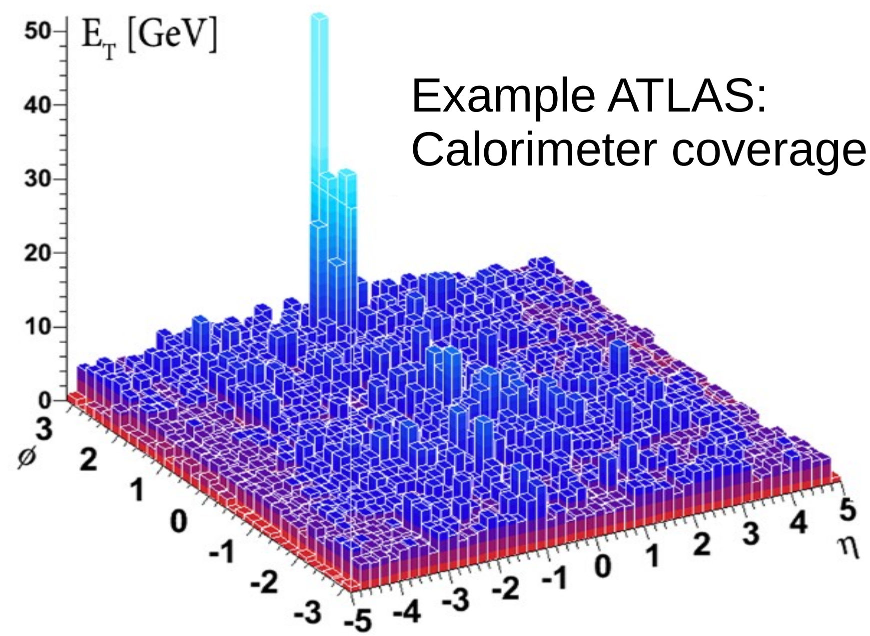
(Heavy-)Ion data-taking experiments



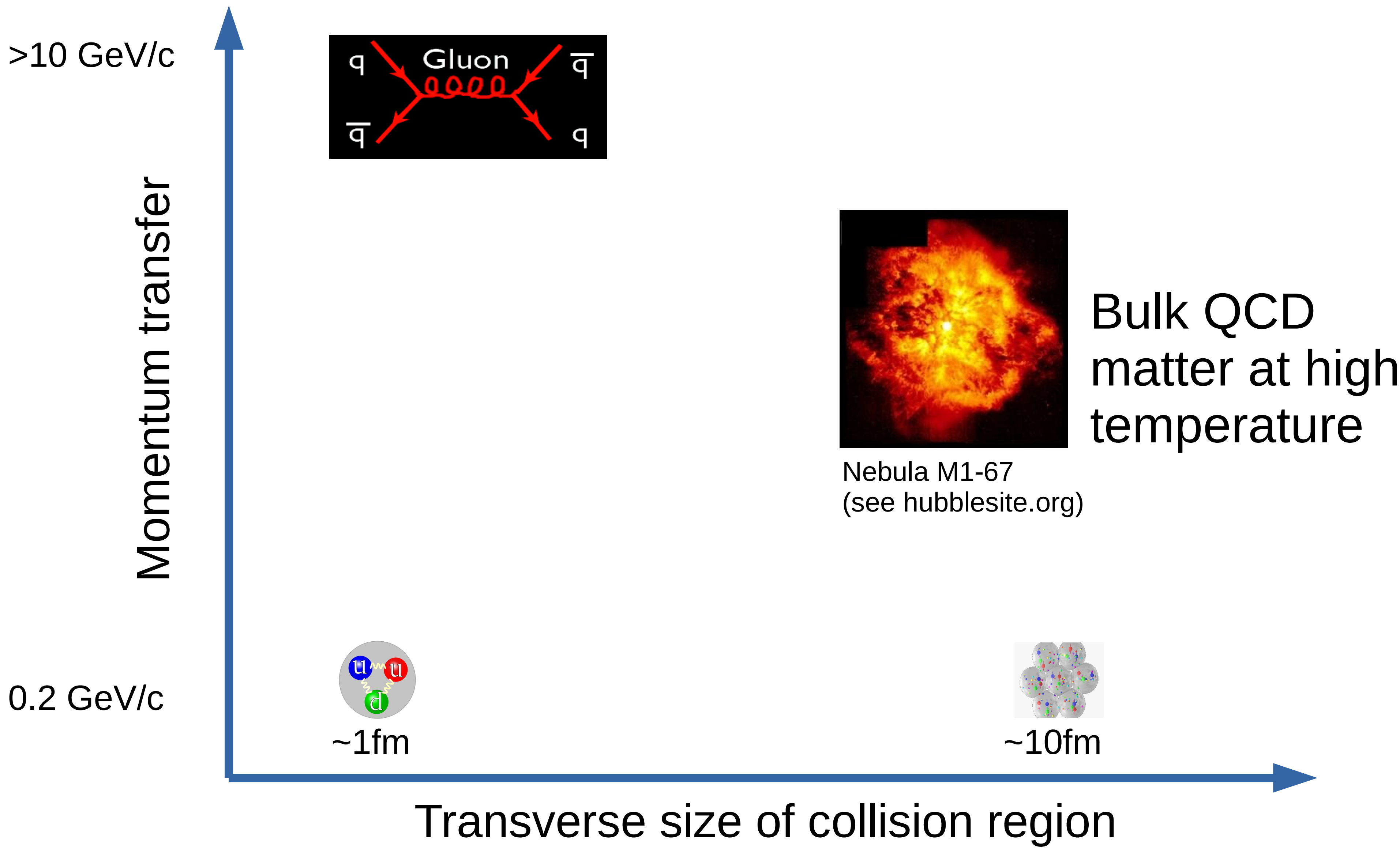
- ALICE dedicated HI experiment
  - Low-p_T tracking, PID, $|\eta|<1$
  - Forward muon spectrometer
- ATLAS/CMS large HEP experiments
  - Large acceptance, full calorimetry
- LHCb (recorded pPb data)
  - Forward tracking+calorimetry, PID

Example ALICE: PID capabilities





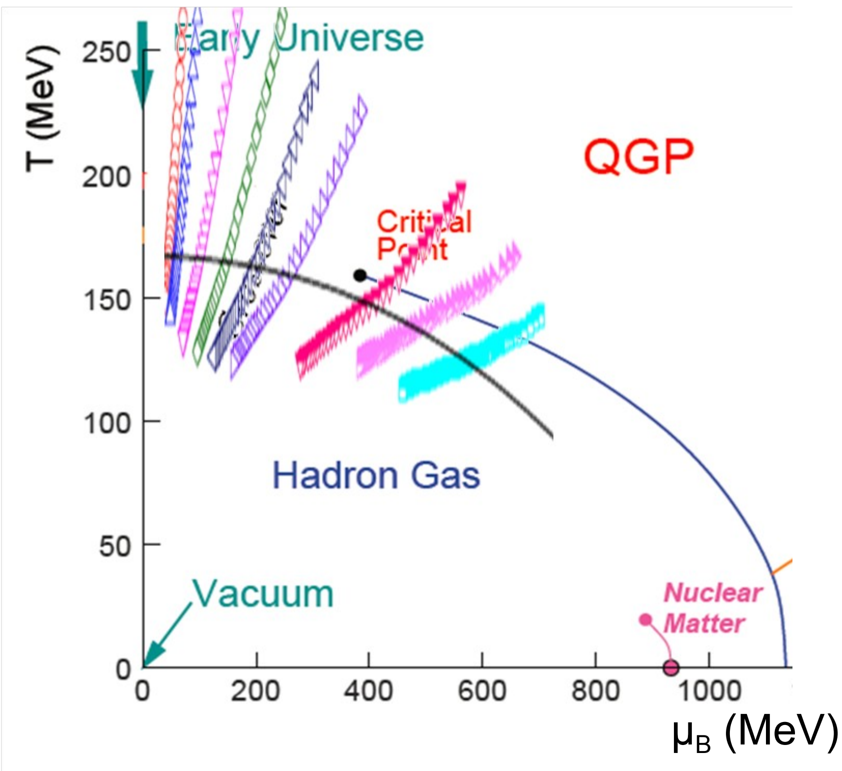
Study QCD bulk matter at high temperature



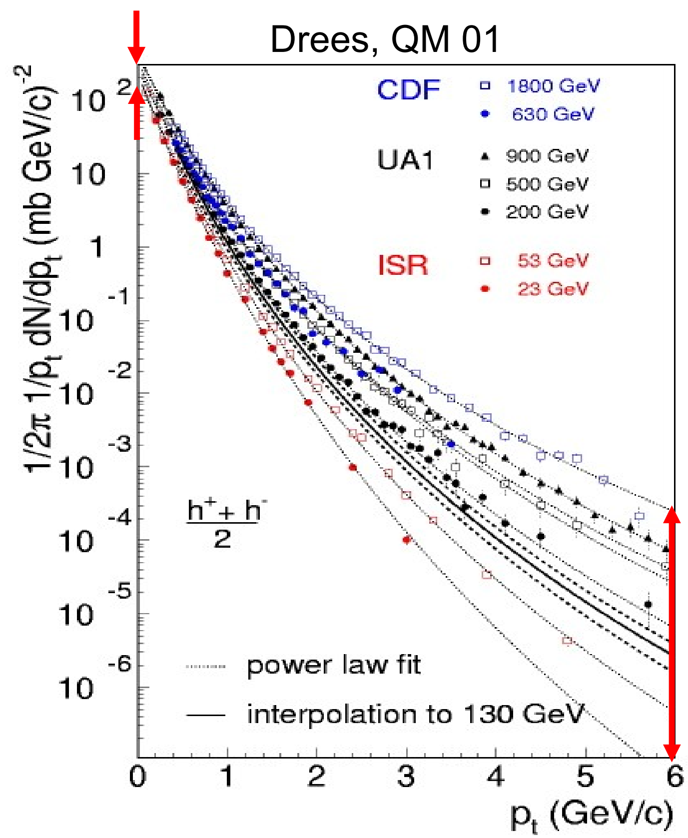
External parameters: Collision energy

Collision energy

Initial conditions
and freeze-out paths

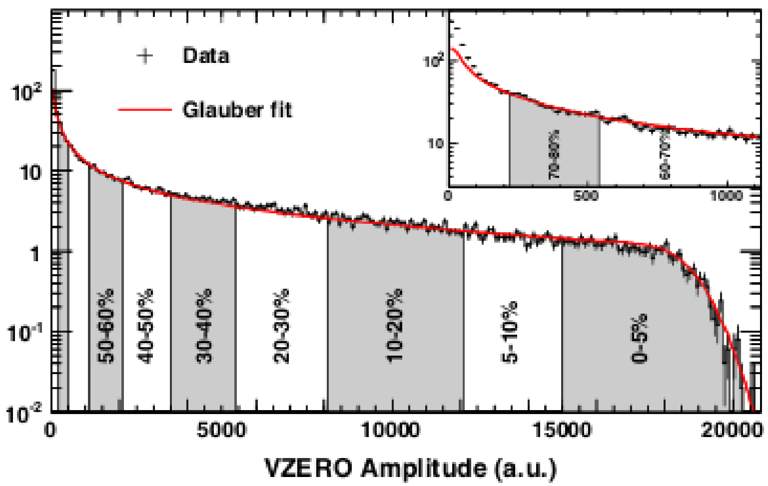


Ratio of “soft” to “hard” processes

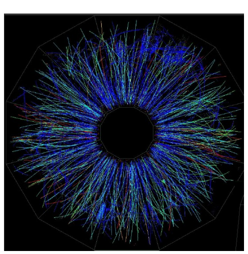


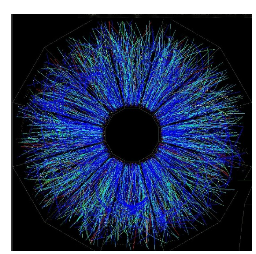
External parameters: Collision centrality

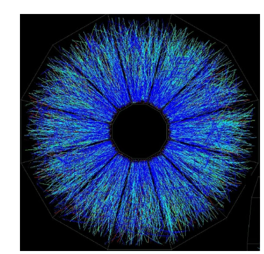
Nuclear cross-section classes
(by slicing in bins of multiplicity)



Cross-section percentile (in %)





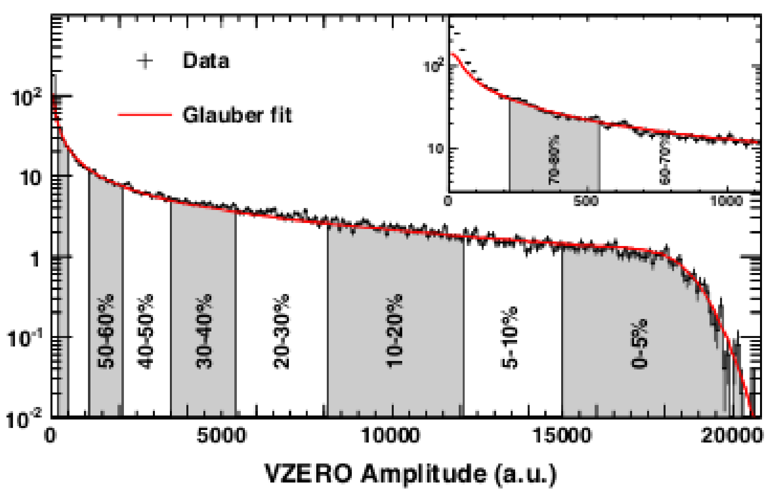


Collision energy

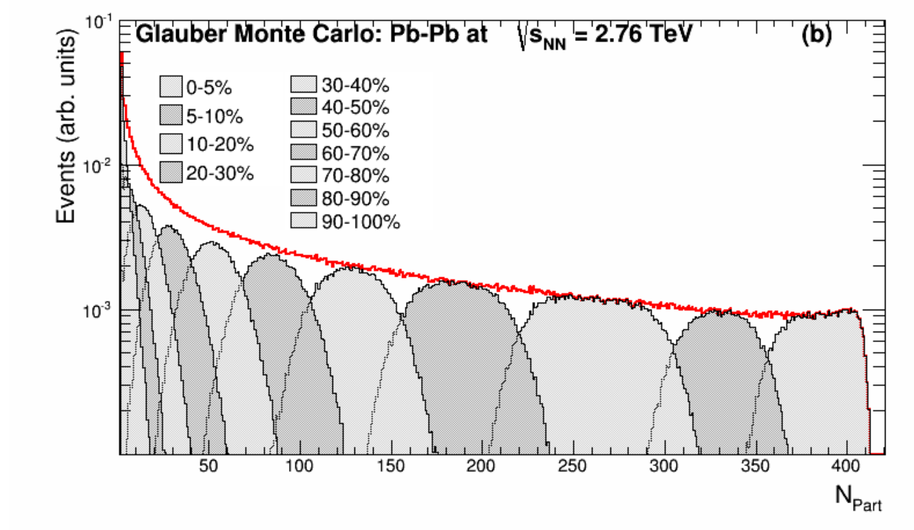
Collision centrality

External parameters: Collision centrality

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



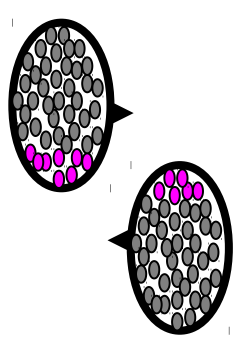
Glauber model

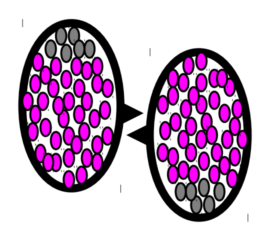


Collision energy

Cross-section percentile (in %) ⟷ Number of participants (collisions)

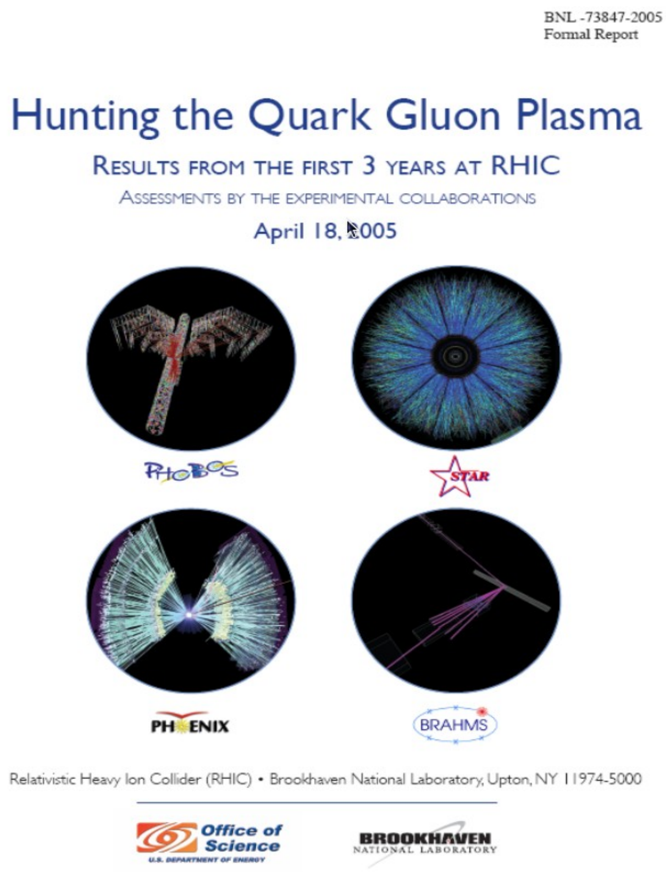
Via model





Collision centrality

The sQGP at RHIC ($\sqrt{s_{NN}}$=0.2 TeV)

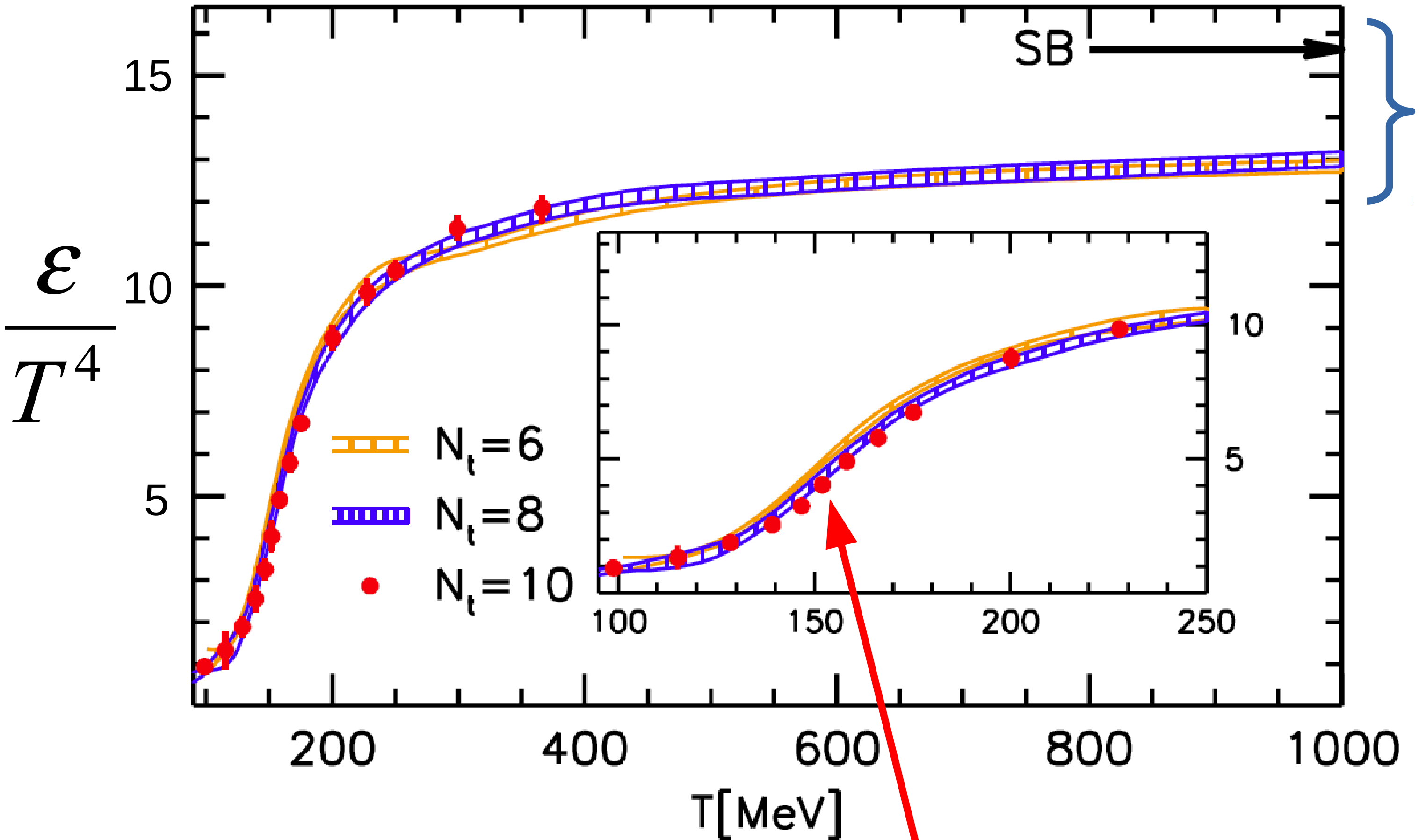


RHIC whitepapers: NPA 757 1-283 (2005)

- Strongly coupled QGP
  - Not freely roaming quarks and gluons
  - Instead, strongly coupled liquid with almost the minimum value of shear viscosity to entropy density ratio (η/s)

Lattice QCD: Energy density (μ=0)

Fodor et al., JHEP 11 (2010) 077



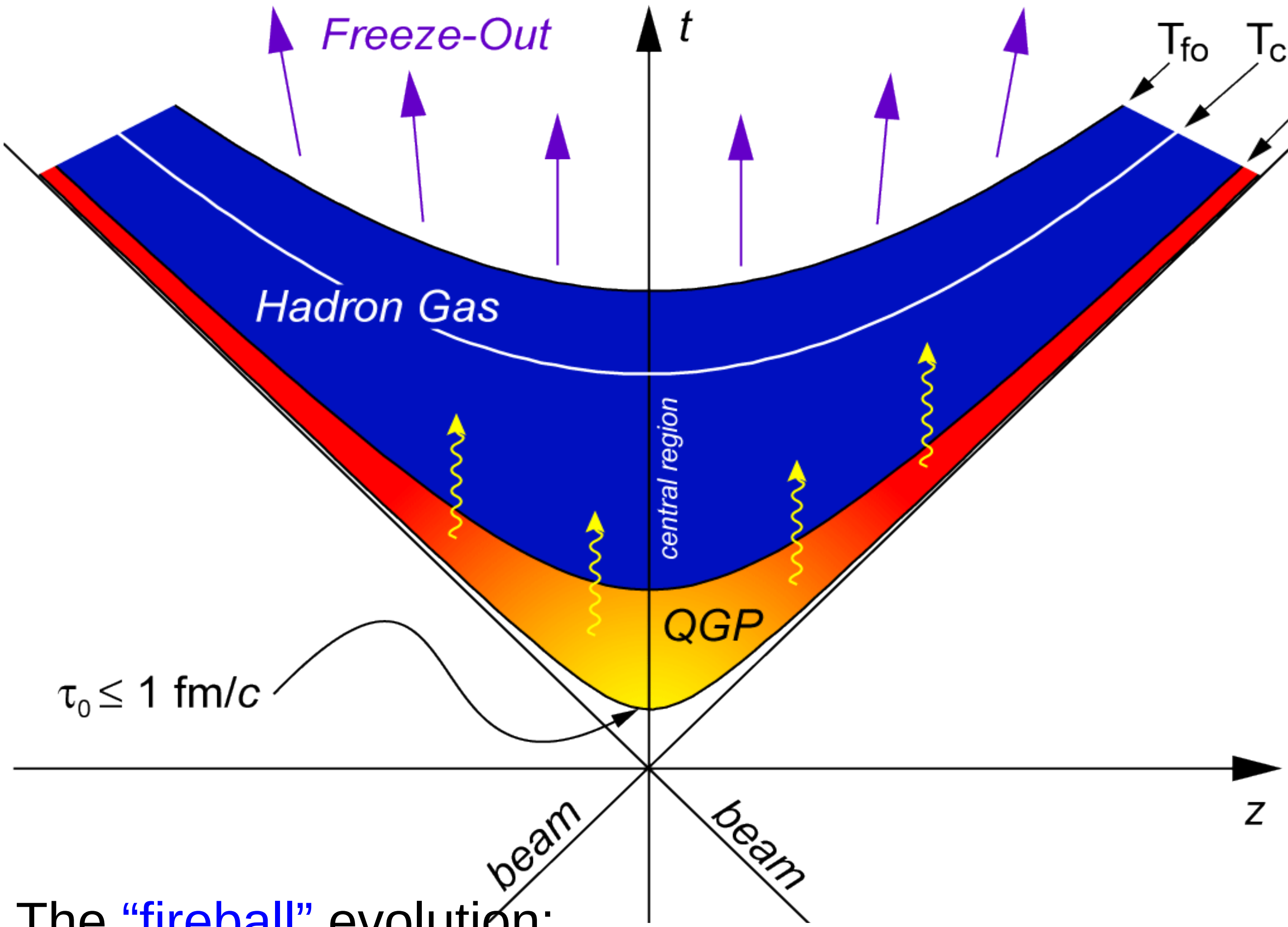
Slow convergence to ideal gas (SB) limit

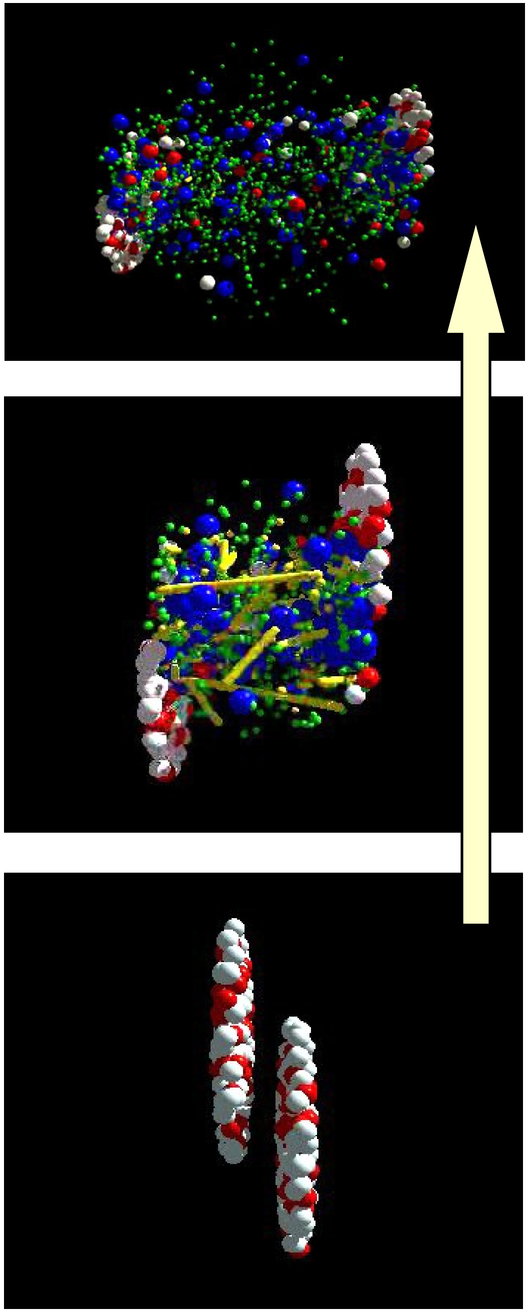
What carries the energy? Complex bound states of q and g? Strongly coupled plasma?

Cross-over, not sharp phase transition (like ionization of atomic plasma)

Transition temperature region between 140 and 200 MeV, with wide range of energy density between 0.2 and 1.8 GeV/fm^3

Time evolution in heavy-ion collisions

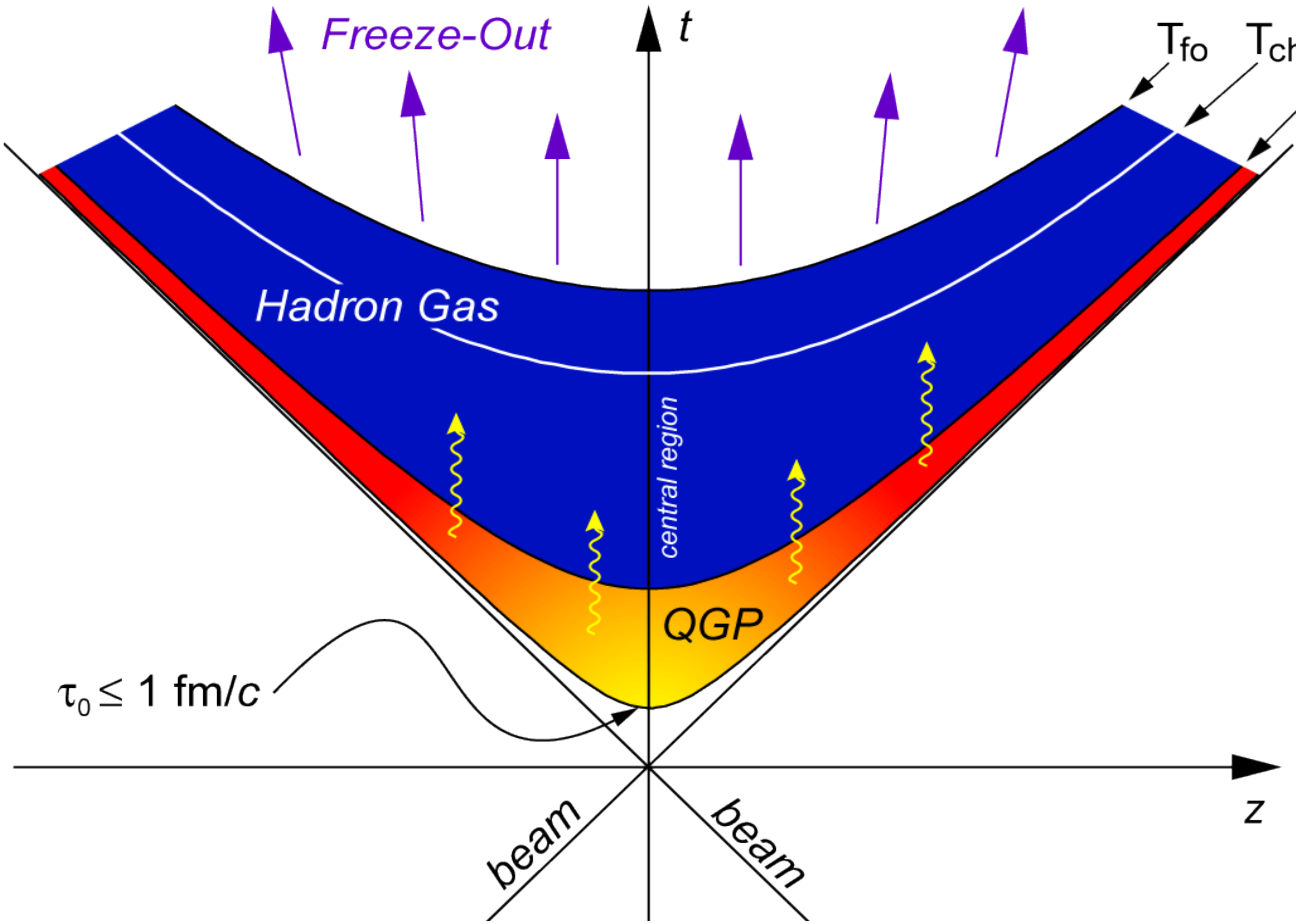




The "fireball" evolution:

- Starts with a "pre-equilibrium state"
- Forms a QGP phase (if T is larger than T_c)
- At chemical freeze-out, T_{ch}, hadrons stop being produced
- At kinetic freeze-out, T_{fo}, hadrons stop scattering

Time evolution in heavy-ion collisions



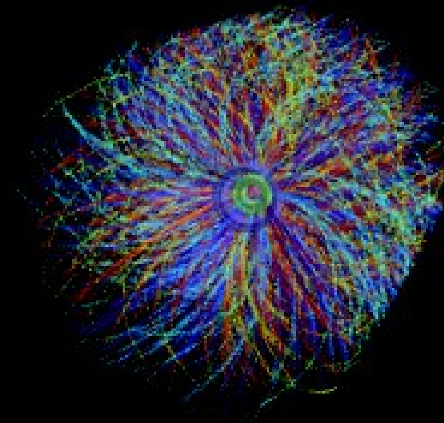
Observables

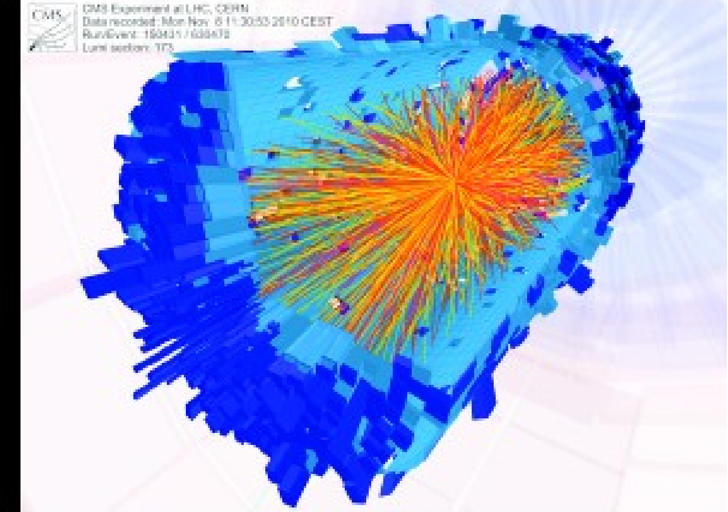
Multiplicity
Thermal photons
HBT
Particle yields
Particle spectra

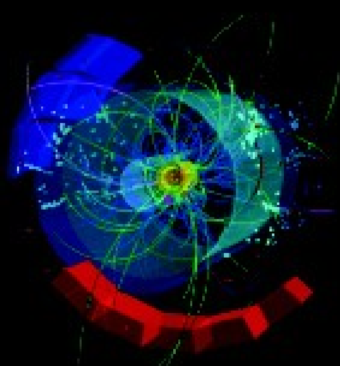
Transverse flow

Hard probes
(jets, heavy flavor)

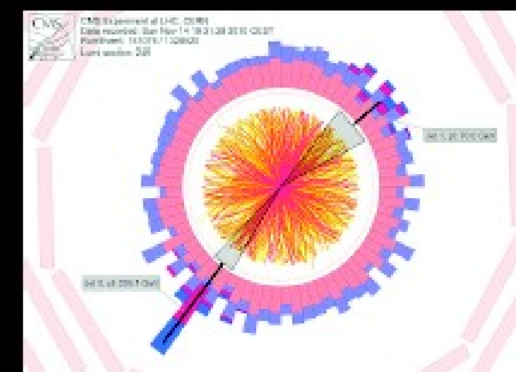
Experimental approach is to study various observables
with different sensitivity to the different stages of the collision

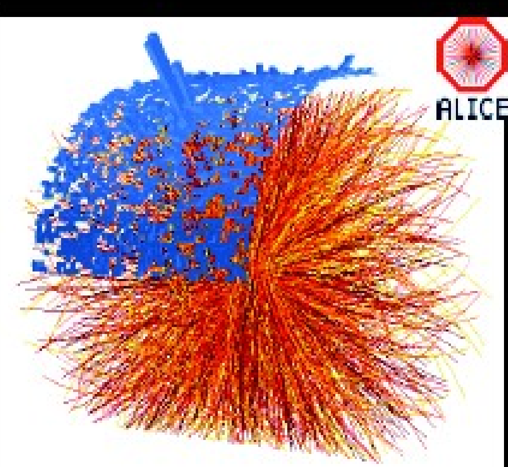


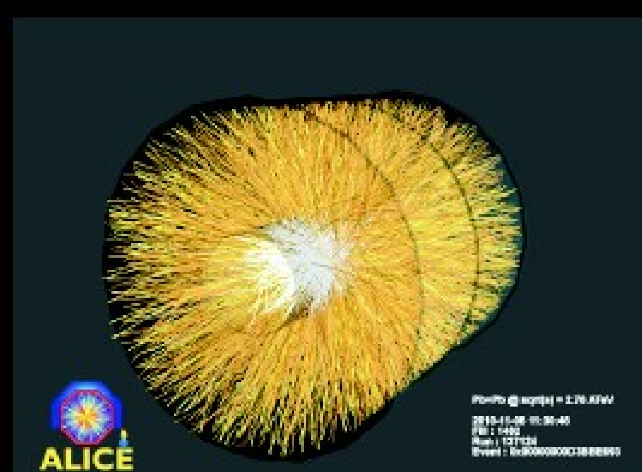




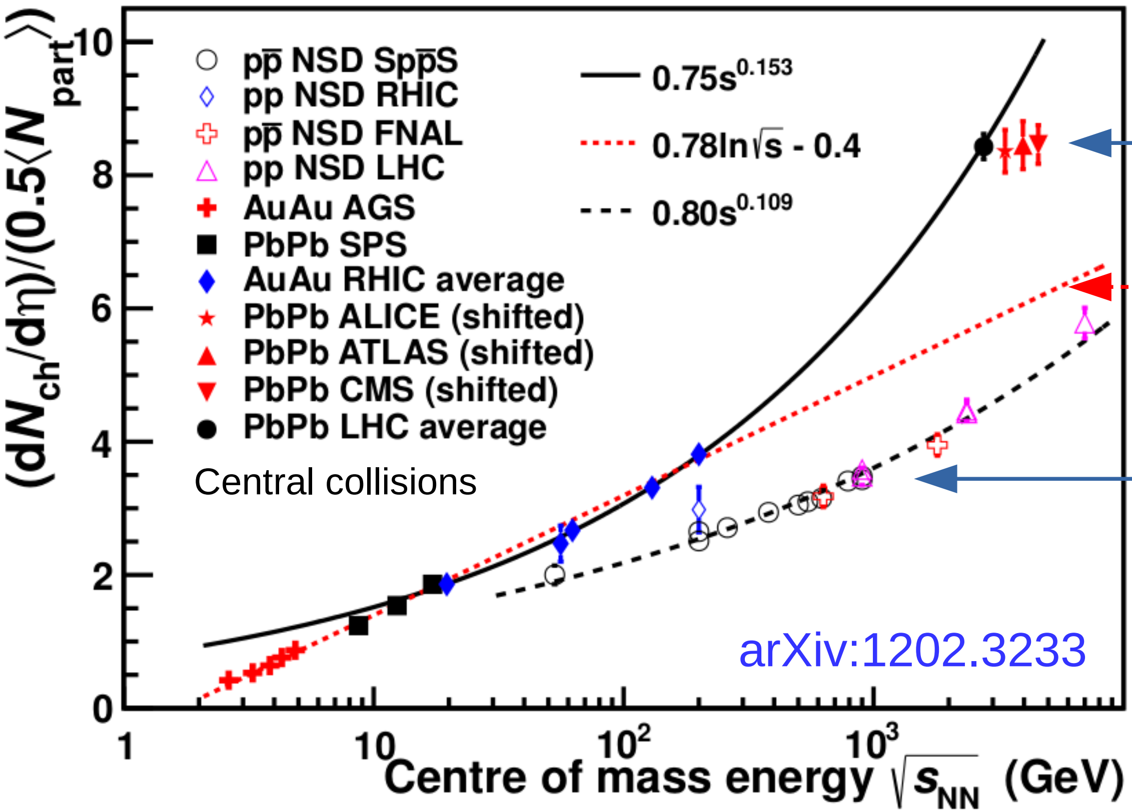
Results from PbPb collisions at the LHC







Energy dependence of dN/dη



Avg. Pb+Pb (ALICE, ATLAS, CMS)

$\sim s^{0.15}$ fit

Previous fit: ~ln s

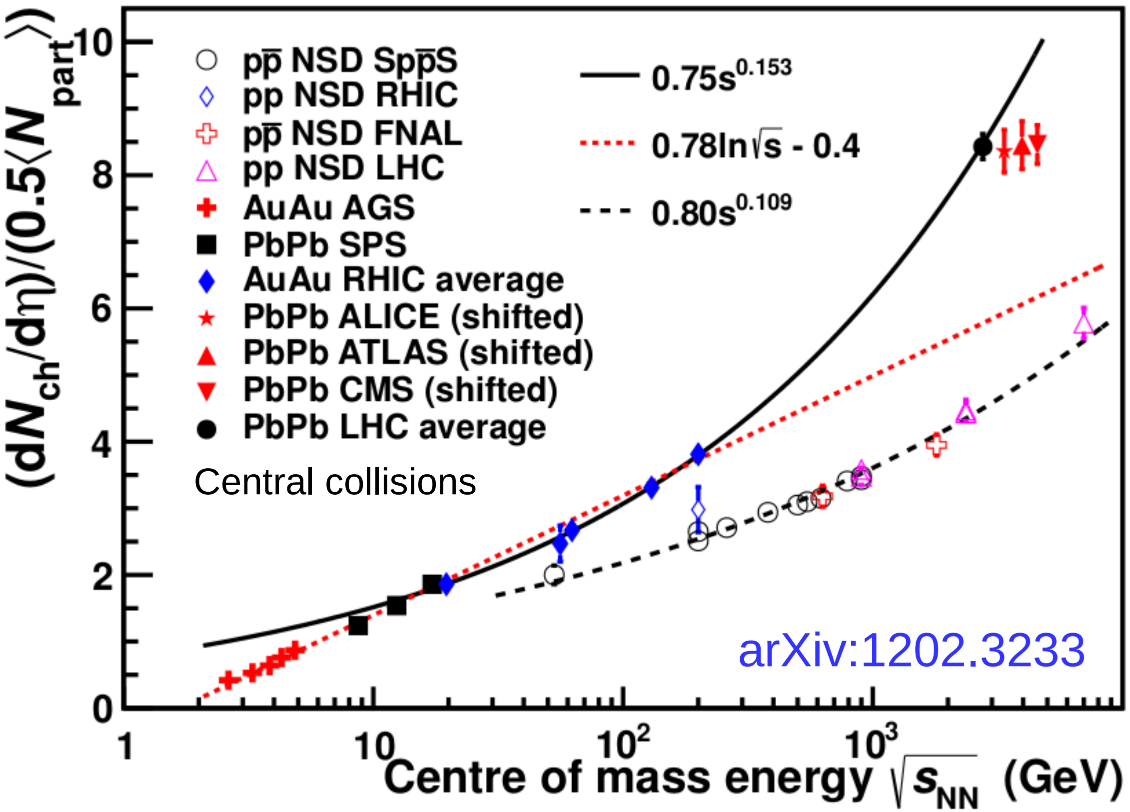
pp (LHC energies)

$\sim s^{0.11}$ fit

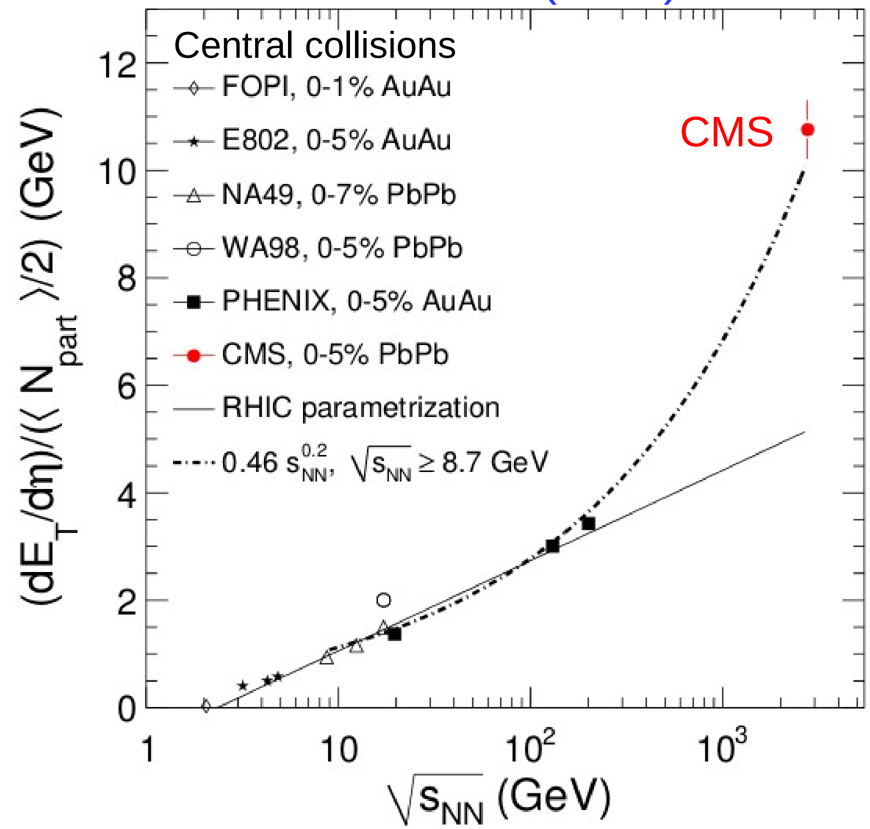
Stronger rise with center-of-mass energy in AA wrt to pp, and wrt to extrapolations from lower energies ($dNch/d\eta_{LHC} \approx 1600 \sim 2 \times dNch/d\eta_{RHIC}$)

ALICE, PRL 105 (2010) 252301
CMS, JHEP 1108 (2011) 141
ATLAS, PLB 710 (2012) 363

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



PRL 109 (2012) 152303



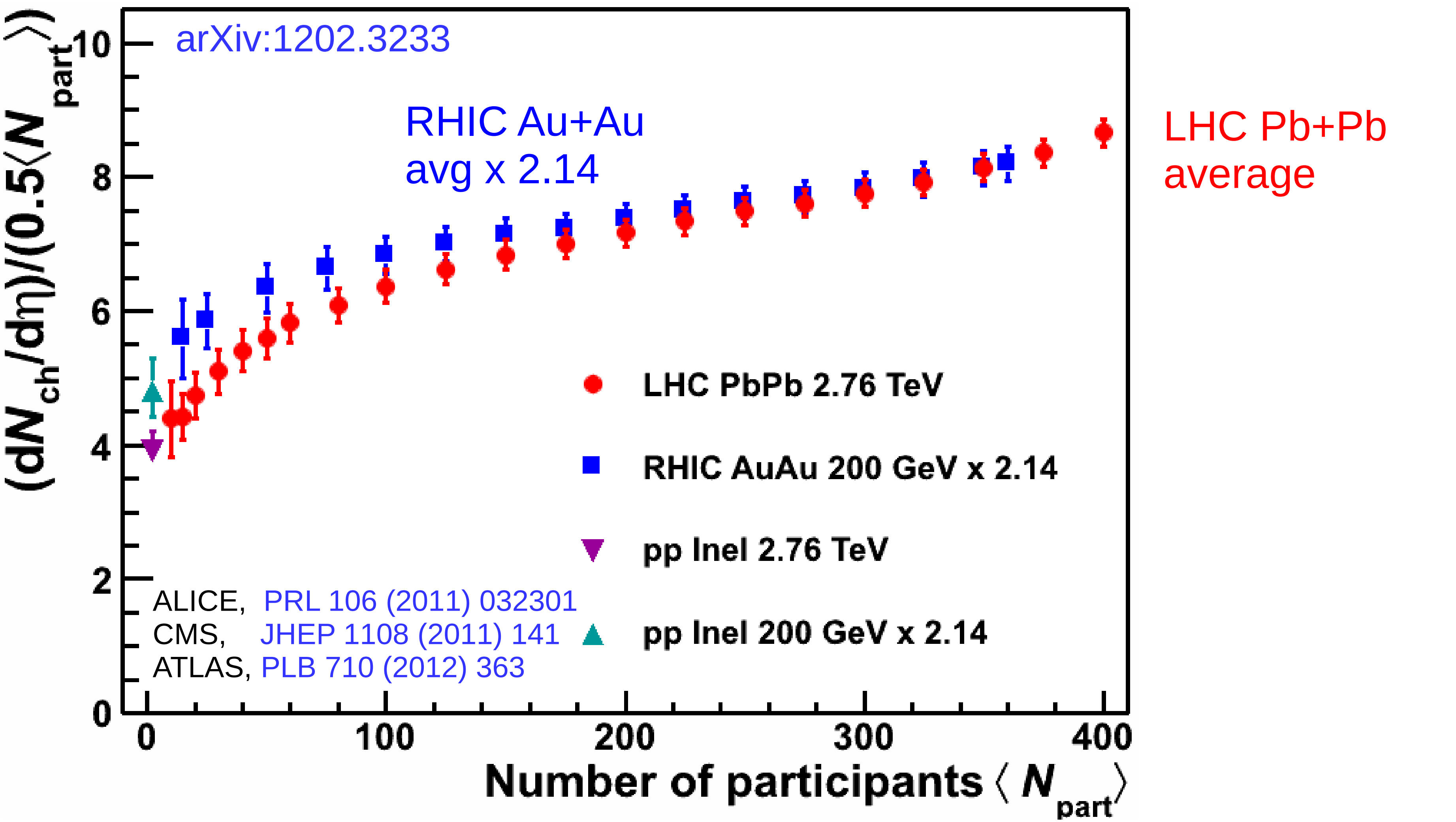
Stronger rise with center-of-mass energy in AA wrt to pp, and wrt to extrapolations from lower energies ($dNch/d\eta_{LHC}$ ≈1600 ~ 2 x $dNch/d\eta_{RHIC}$)

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

$$\tau\,\epsilon_{LHC} \simeq 2.5 \times \tau\,\epsilon_{RHIC}$$

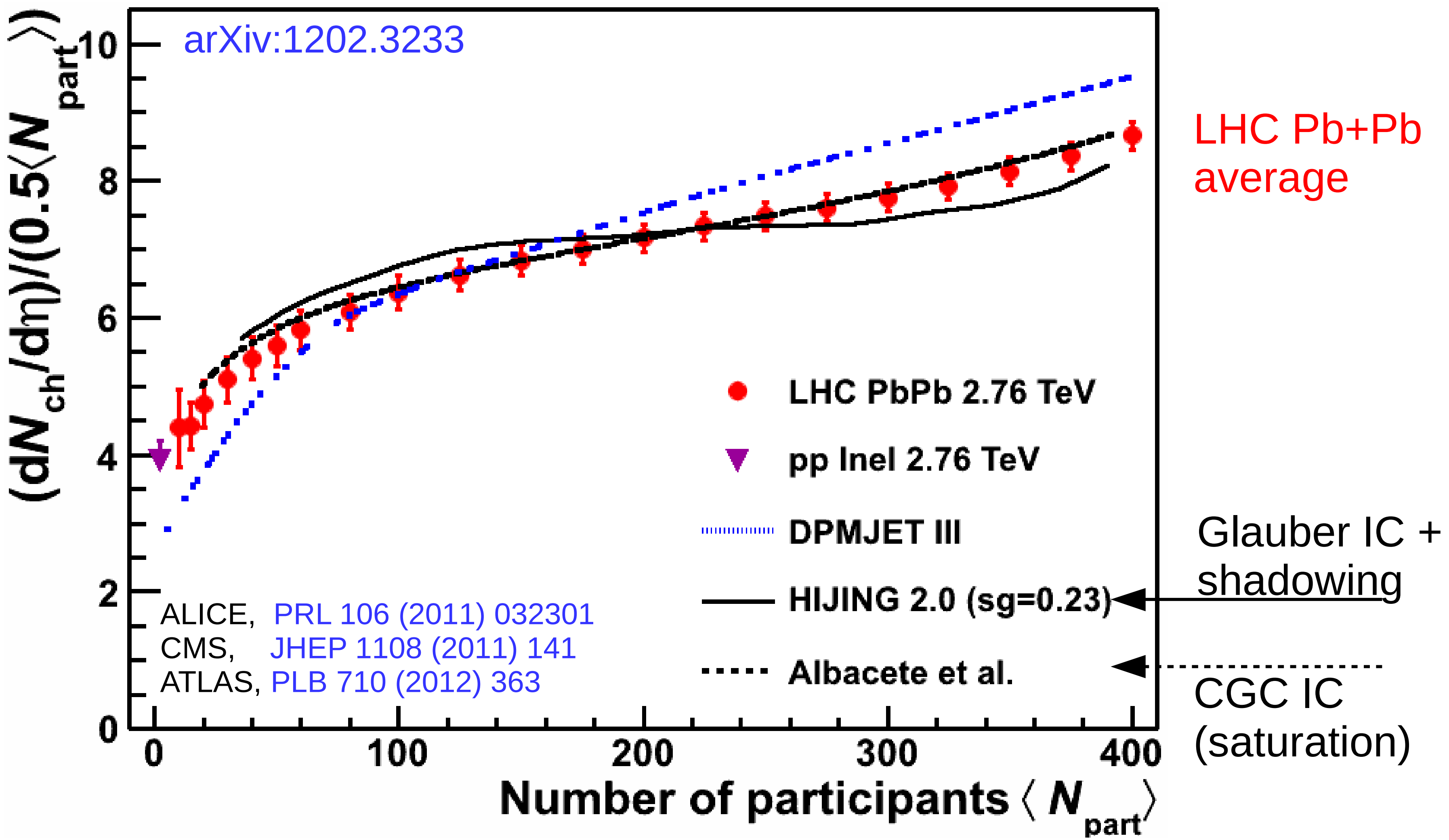
Initial energy density at LHC (as at RHIC) is well above $\varepsilon_c \approx 0.5$ GeV/fm^3

Centrality dependence of dN/dη



Factorization in energy and centrality:
Shape is strikingly similar to RHIC
(holds all the way down to 19.6 GeV, not shown)

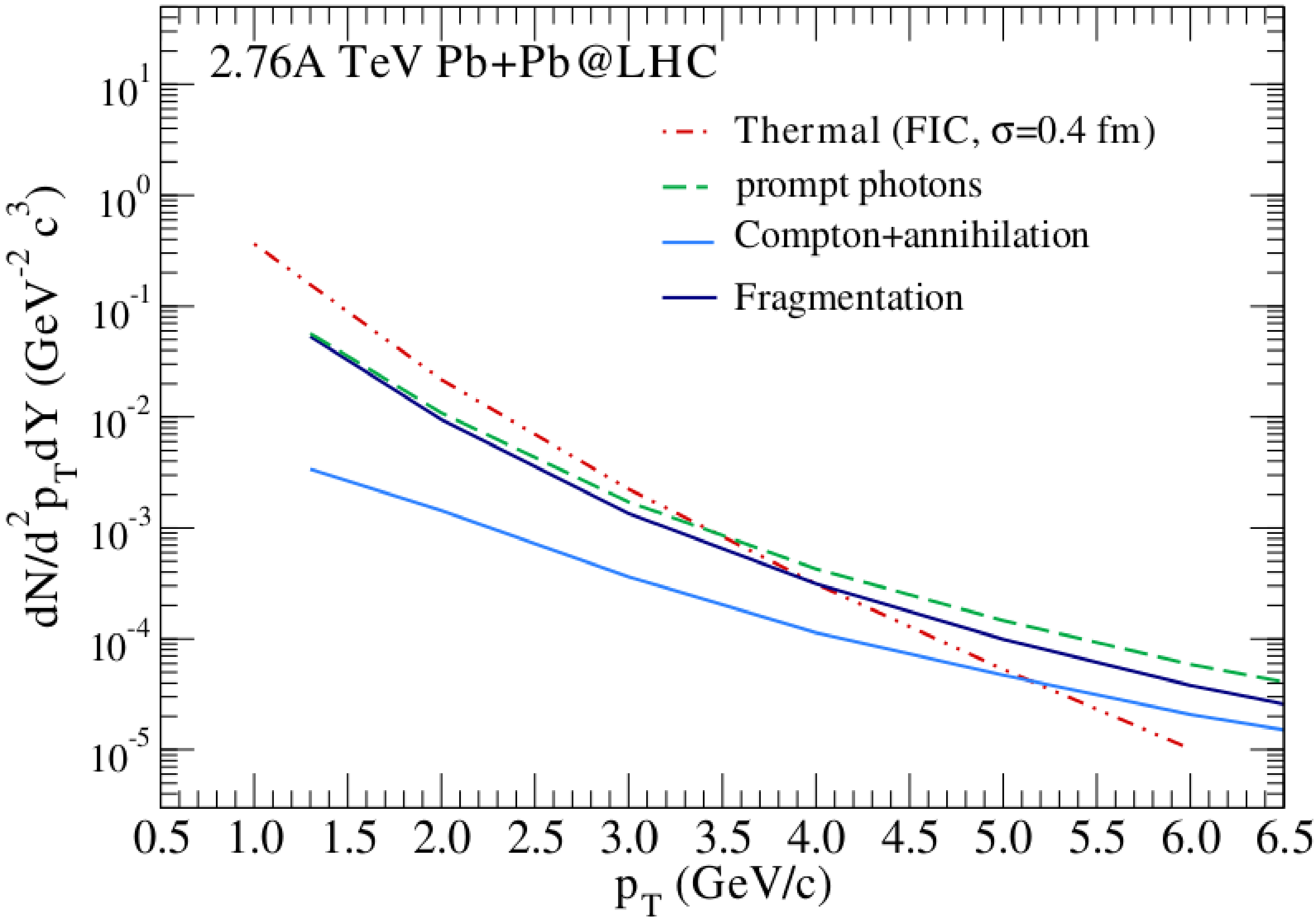
Centrality dependence of dN/dη



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

Direct photon production in PbPb

arXiv:0809.0548

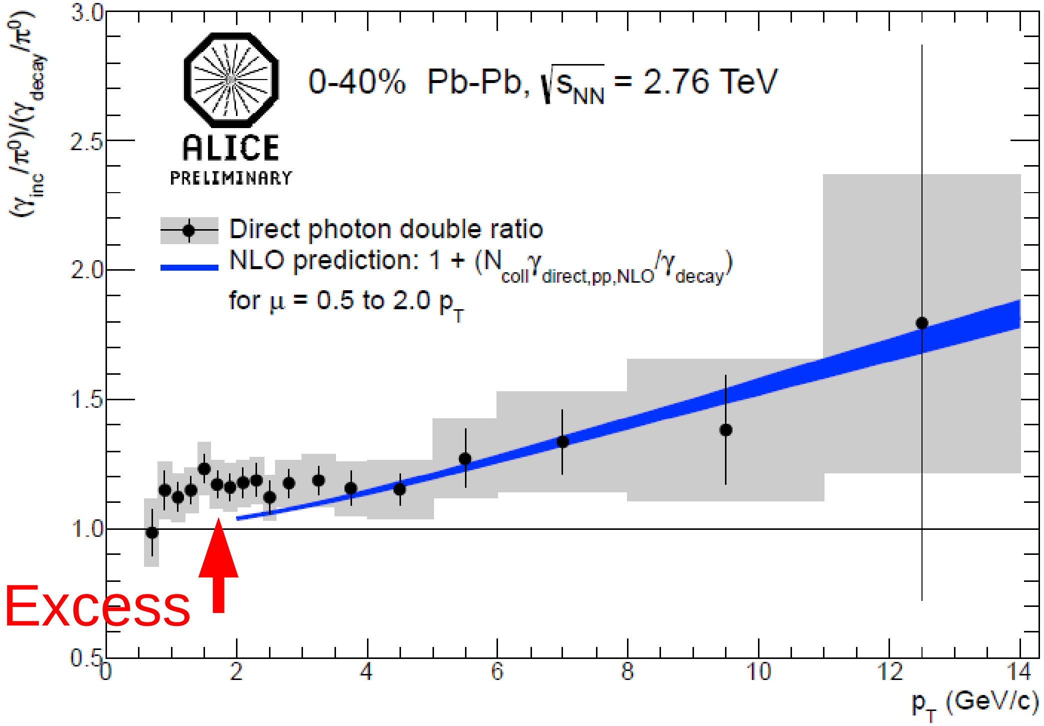


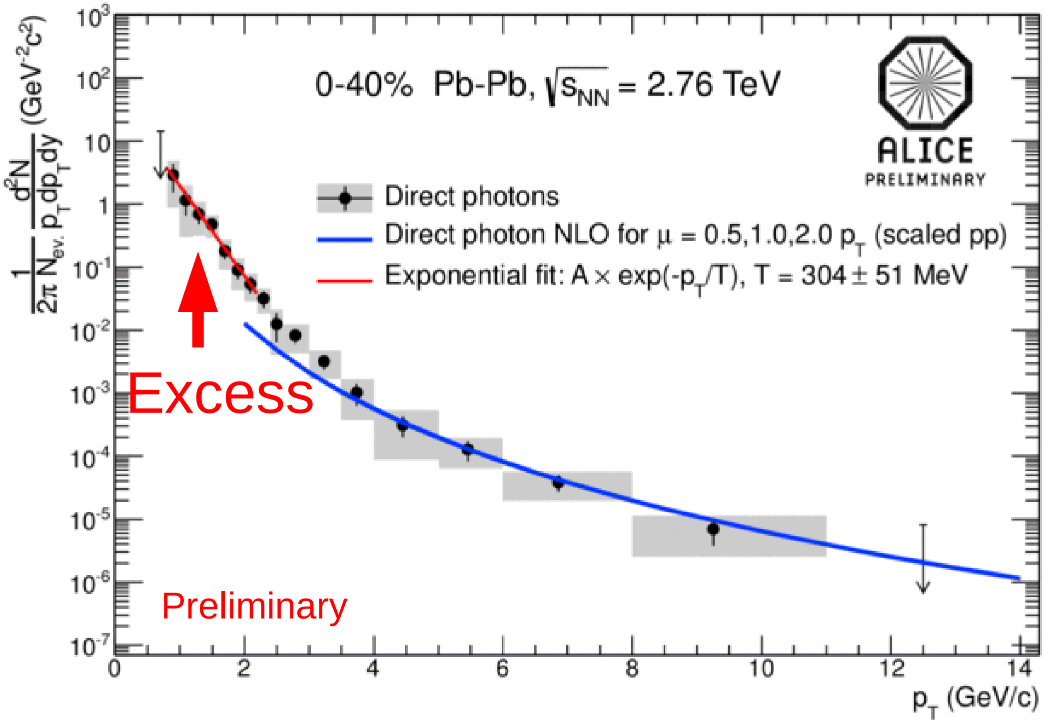
Thermal photons

Prompt photons

Initial temperature at LHC

$$R = (\gamma/\pi^0)_{\rm inc} \,/\, (\gamma/\pi^0)_{\rm mc} \qquad \gamma^{\rm dir} = (1 - 1/R)\,\gamma^{\rm inc}$$

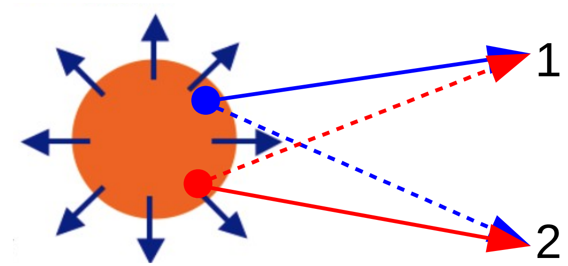




- Measure $R = (\gamma/\pi^0)_{inc} / (\gamma/\pi^0)_{mc}$
- Uncertainties (exactly or partially) cancel in the ratio
  - Normalization
  - Photon reconstruction efficiency
- Inverse slope: T=304±51 MeV
  - Larger than at RHIC
- T_{init} expected to be > T
  - But models have difficulties reproducing the yield !!!

Intensity interferometry (HBT)

- Two particles whose production or propagation are correlated in any way exhibit wave properties in their relative momentum difference
  - First used with photons by Hanbury Brown and Twiss to measure size of star Sirius
    HBT, Nature 178 (1956) 1046



$$C_f(\mathbf{q}) = \int S(r,\mathbf{q})|\Psi(\mathbf{q},r)|^2 d^4 r$$

$q = p_1 - p_2 \quad r = r_1 - r_2$

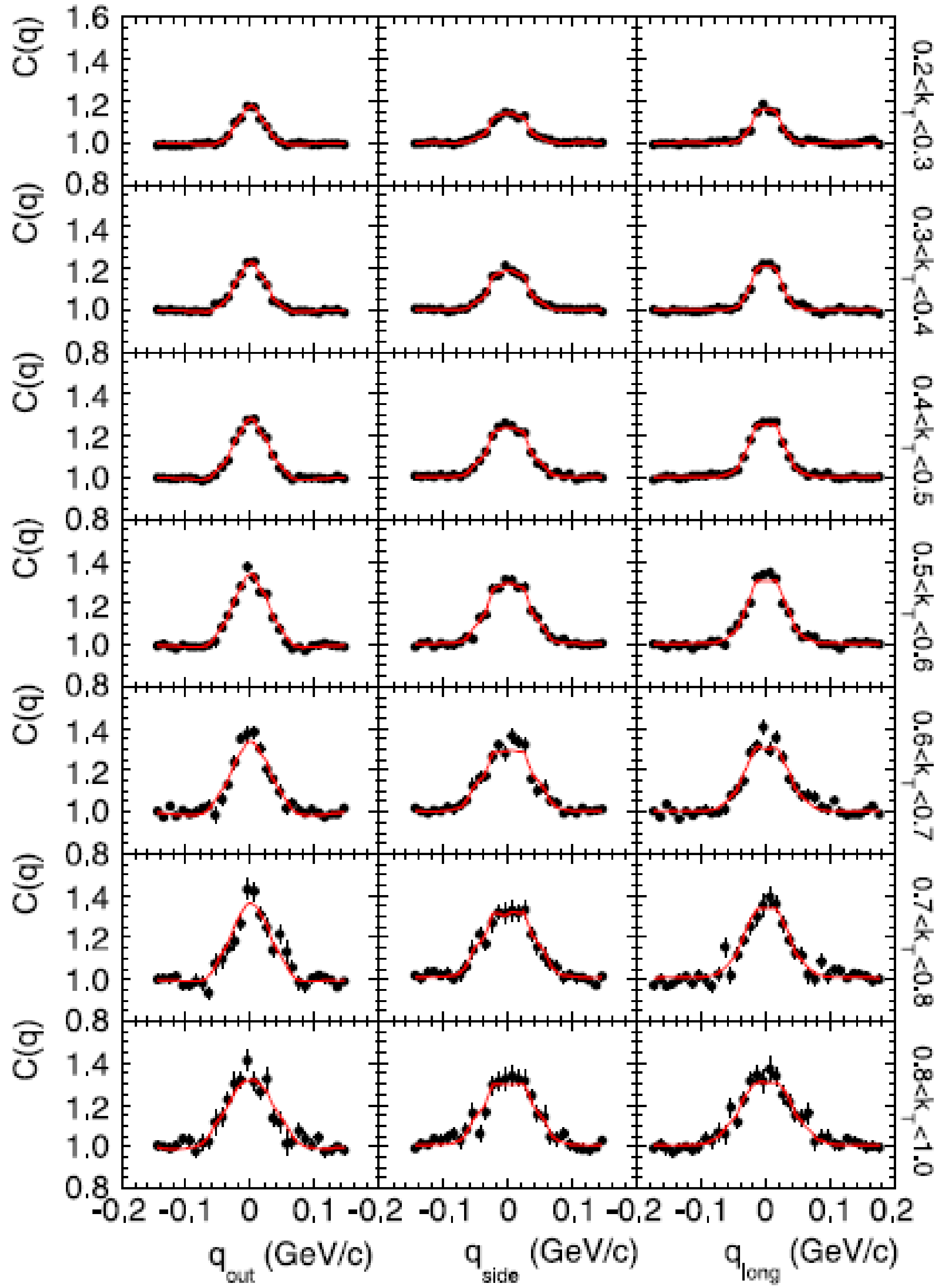
- Quantum statistics effect: Enhancement of correlation for identical bosons
- From uncertainty principle
  - $\Delta q \, \Delta x \sim 1$
  - Use to extract source size from correlation function
  - Need $\Delta q \sim 200$ MeV to be sensitive to fm scale

Intensity interferometry (HBT)

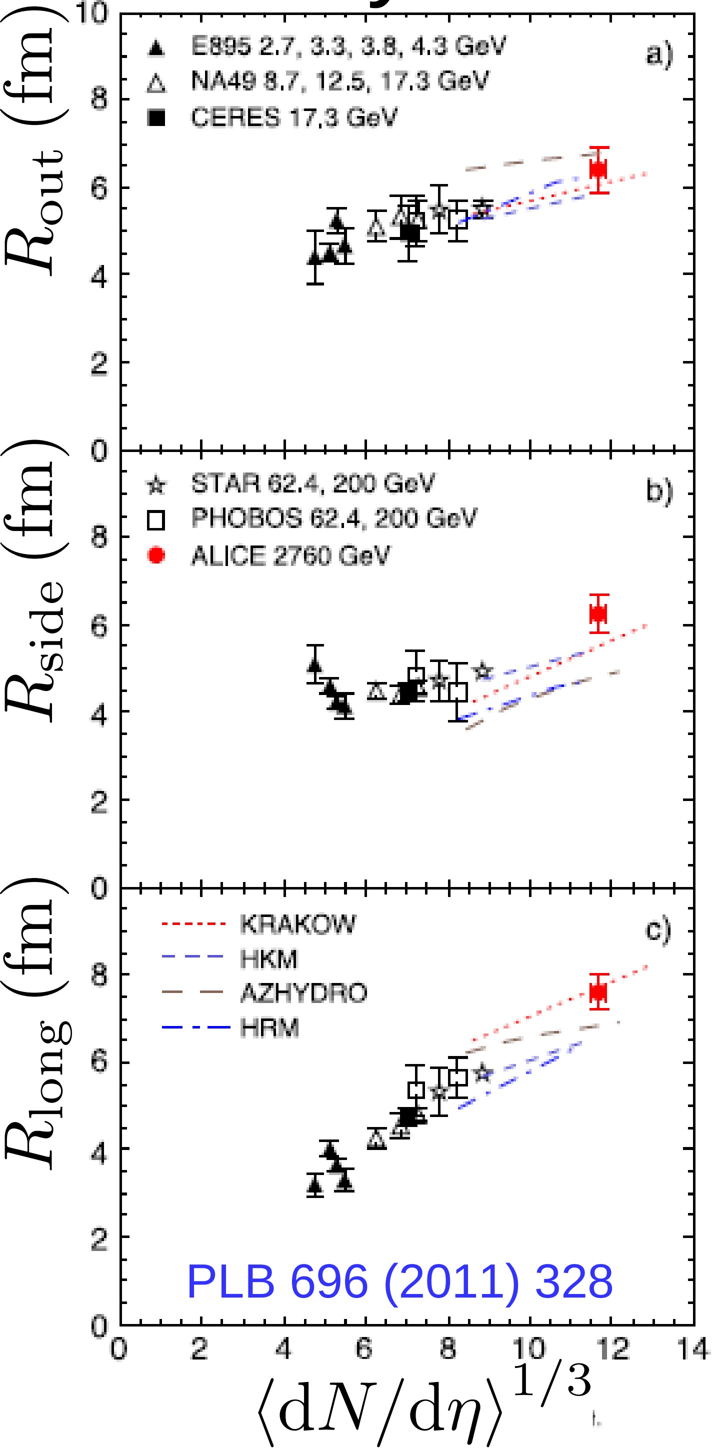
- In LCMS ($p_{L,1}+p_{L,2}=0$) of each pair decompose correlation function in three directions
  - Longitudinal direction
  - Outward (along k_T direction)
  - Sideward (orthogonal) direction
- Assuming Gaussian for correlation

$$C_2(q) \propto 1 + \exp\left(-R_{\rm out}^2 q_{\rm out}^2 - R_{\rm side}^2 q_{\rm side}^2 - R_{\rm long}^2 q_{\rm long}^2\right)$$

- Three components of C(q) for pairs of identical pions in pair transverse momentum $k_{\rm T} = 0.5\,(\vec{p}_1 + \vec{p}_2)_T$



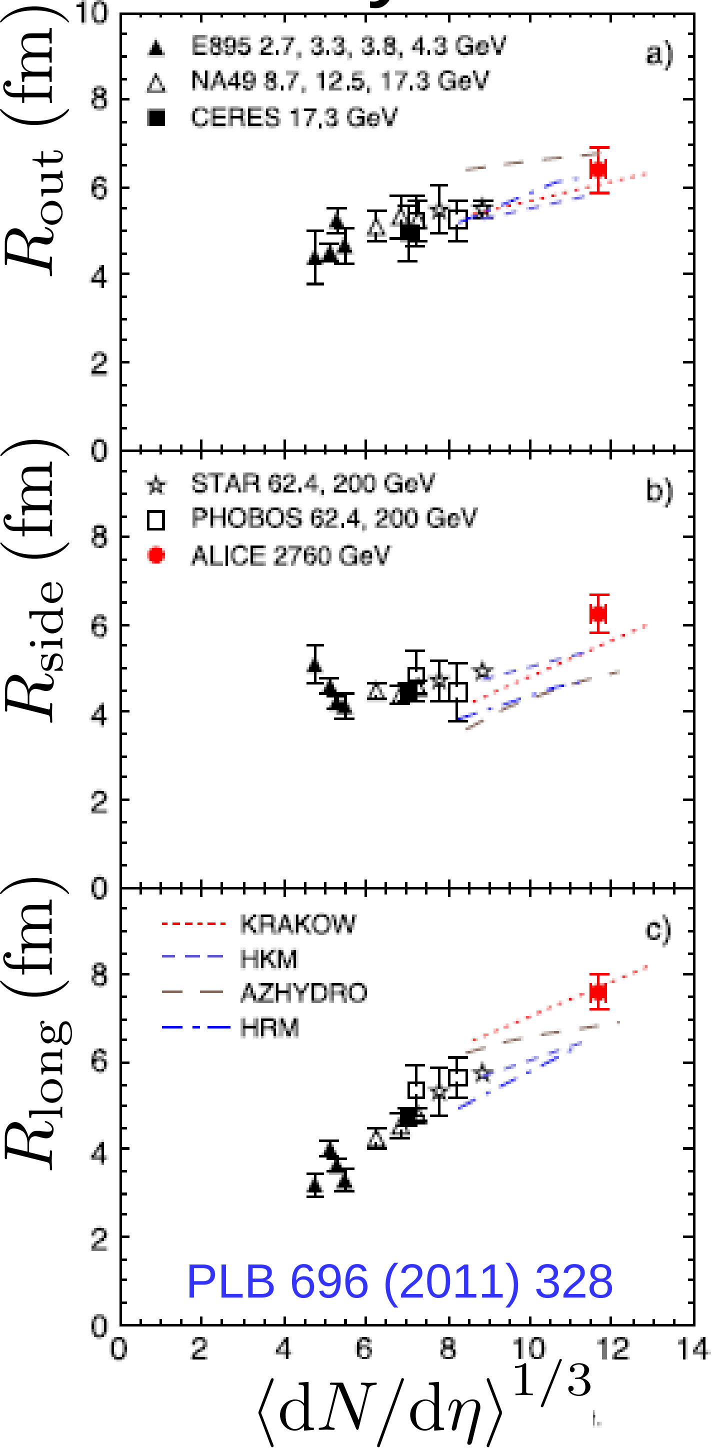
Intensity interferometry (HBT)



From RHIC to LHC

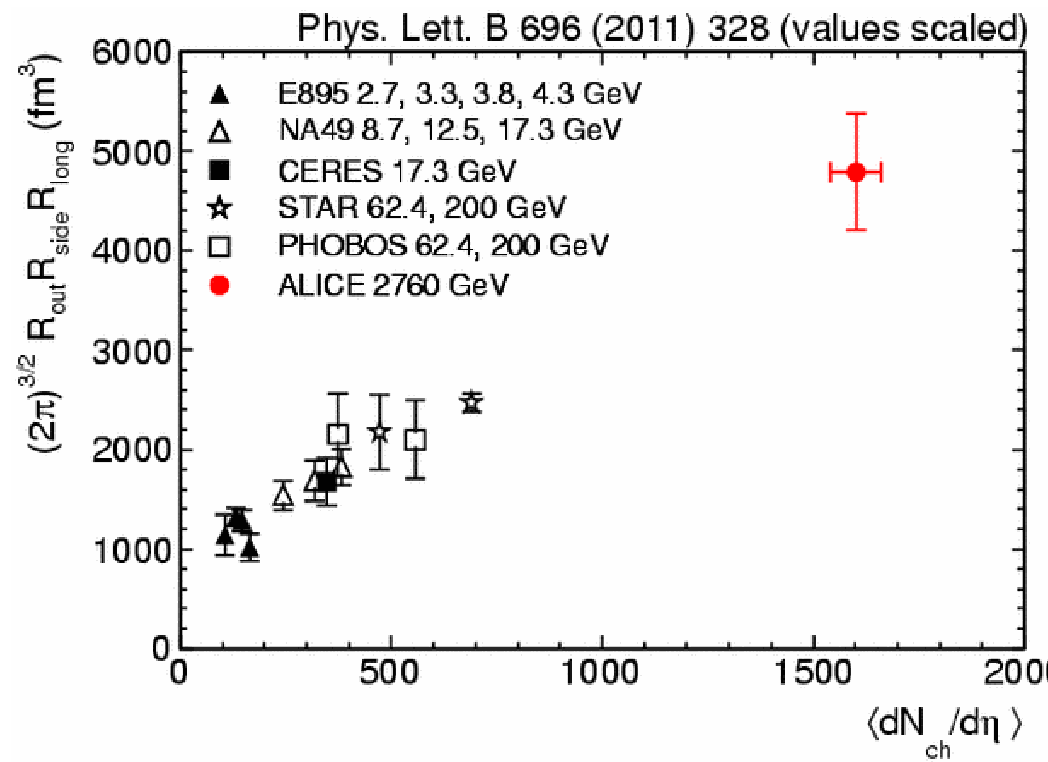
- Increase of radii in all directions
  - Out, side and long

Intensity interferometry (HBT)



From RHIC to LHC

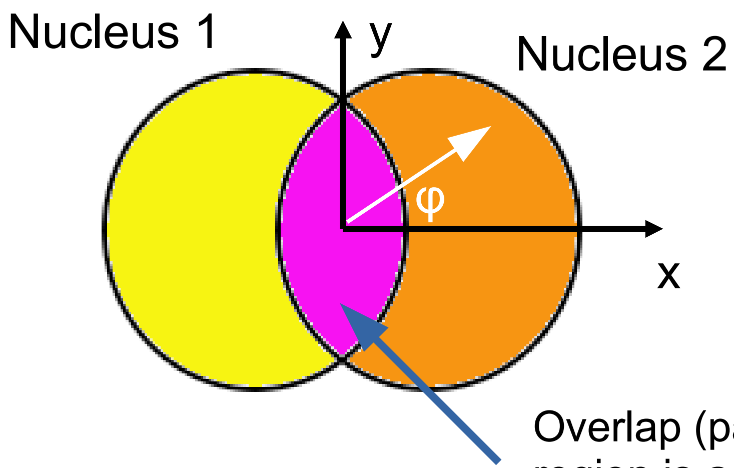
- Increase of radii in all directions
  - Out, side and long
- "Homogeneity" volume: 2x RHIC



- Substantial expansion
  - For comparison: R(Pb) ~ 7fm → V~1500fm^3
  - Lifetime (extr. from R_{long}) ~ 10fm/c

External parameters: Transverse geometry

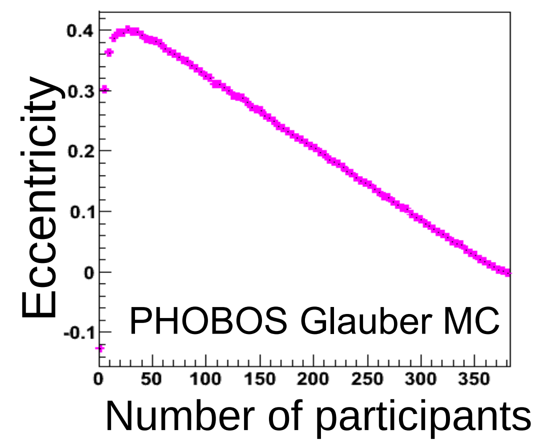
Center of mass energy



Overlap (participant) region is asymmetric in azimuthal angle

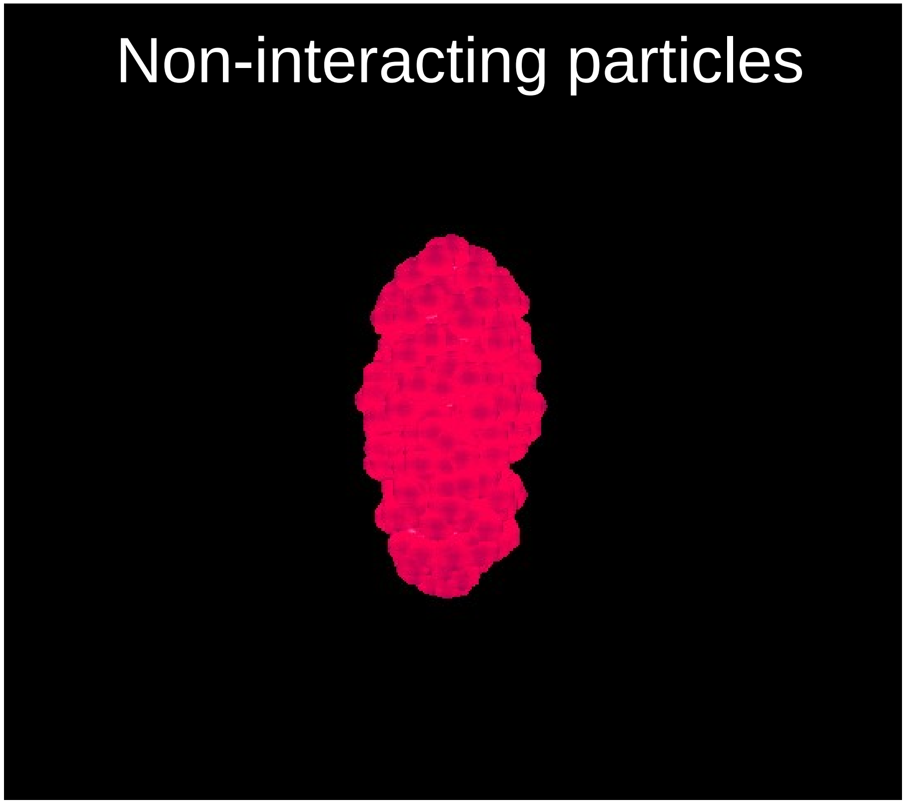
$$\epsilon_{\mathrm{std}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

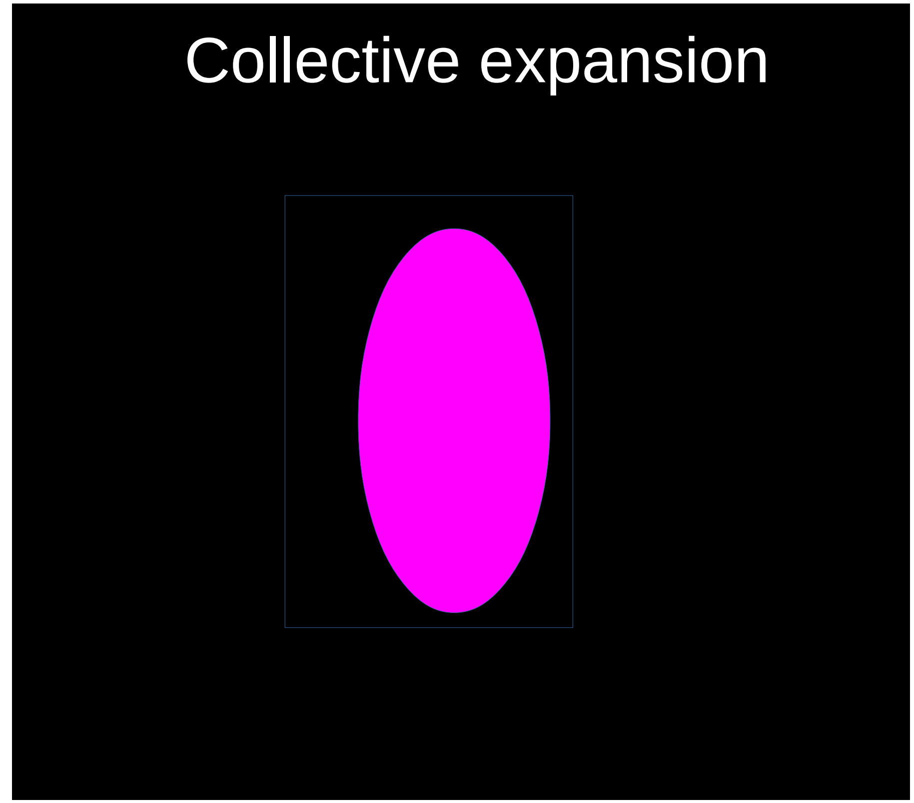
Initial state eccentricity



Collision centrality

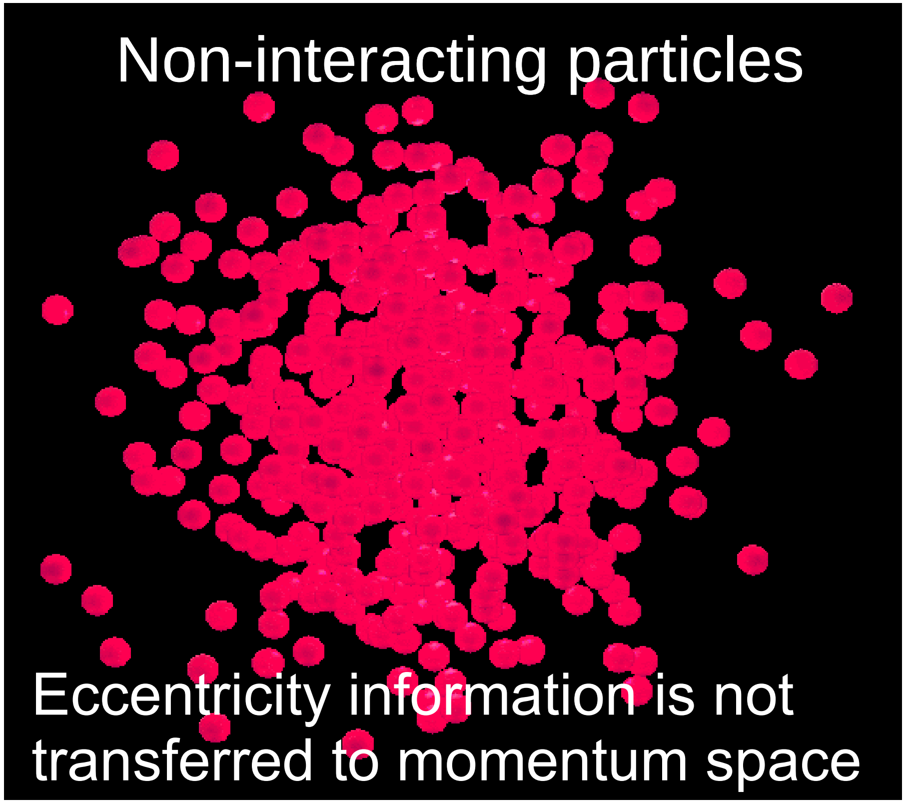
How do we prove that we make "matter"?

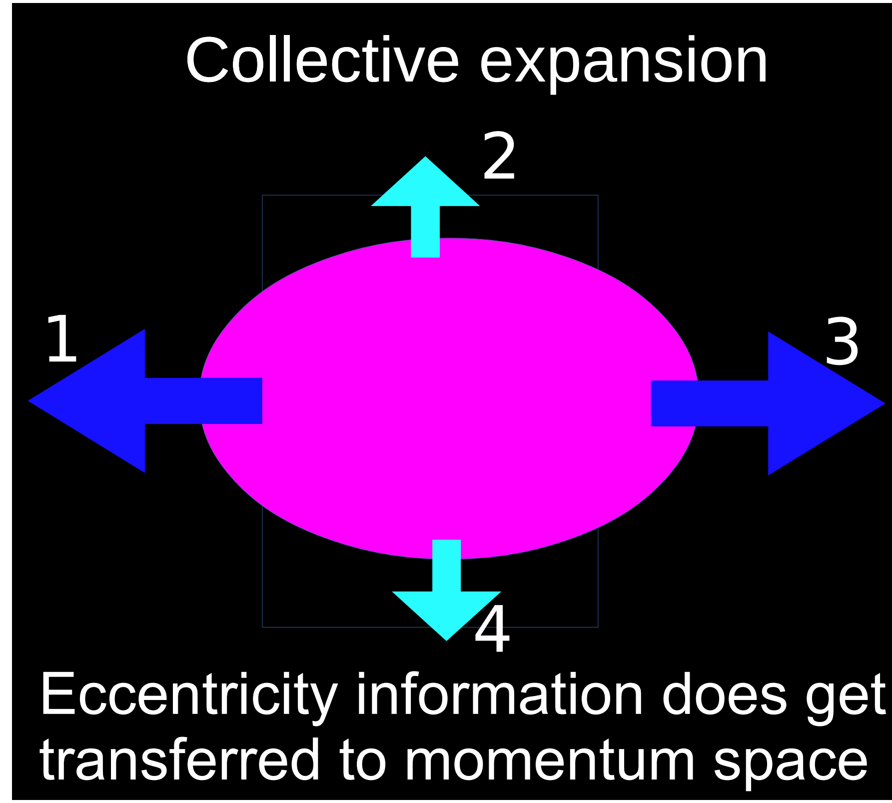


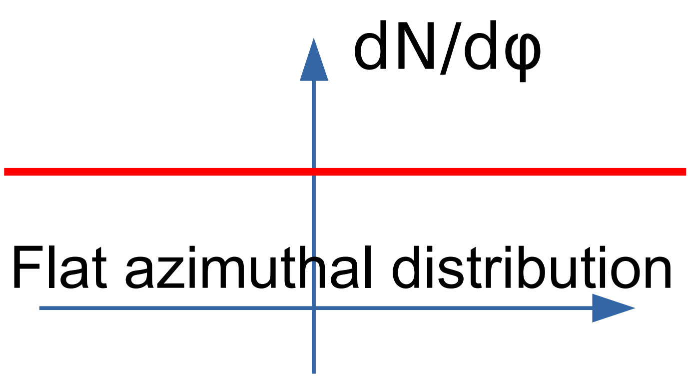


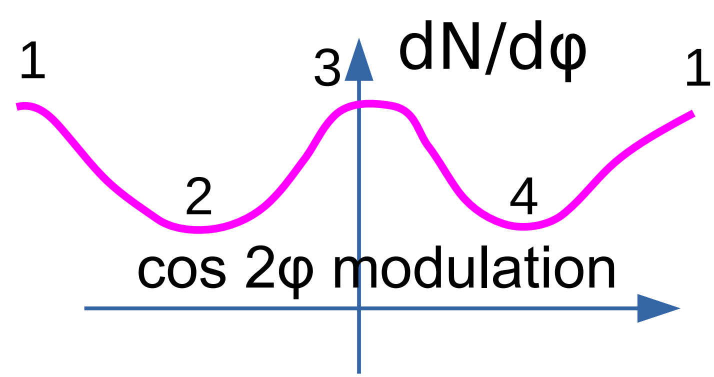
What happens to the shape (eccentricity) information during the expansion?

How do we prove that we make “matter”?

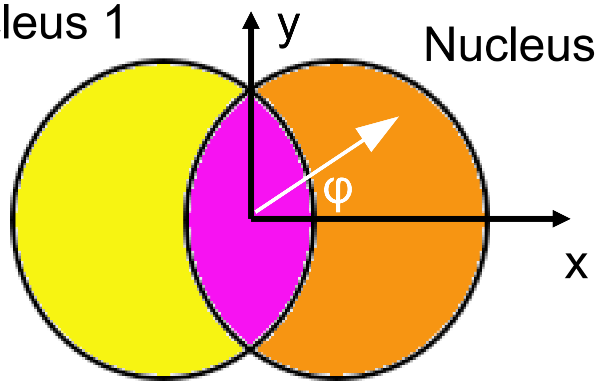


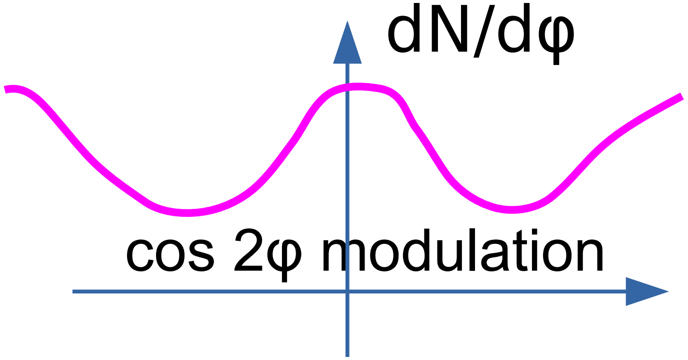






Initial and final state anisotropy





$$\frac{dN}{d\varphi} \sim 1 + 2 v_2 \cos[2(\varphi - \psi_R)] + \ldots$$

Initial spatial anisotropy:
Eccentricity

$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

Interactions present early

(self quenched)

Momentum space anisotropy:
Elliptic flow

$$v_2 = \langle \cos(2\varphi - 2\Psi_R) \rangle$$

Measuring the v_2 coefficient

$$v_2 = \langle \cos(2\varphi - 2\Psi_R) \rangle$$

Need to deal with the reaction plane angle:
Use differences between particles in azimuth
(or attempt to reconstruct it directly)

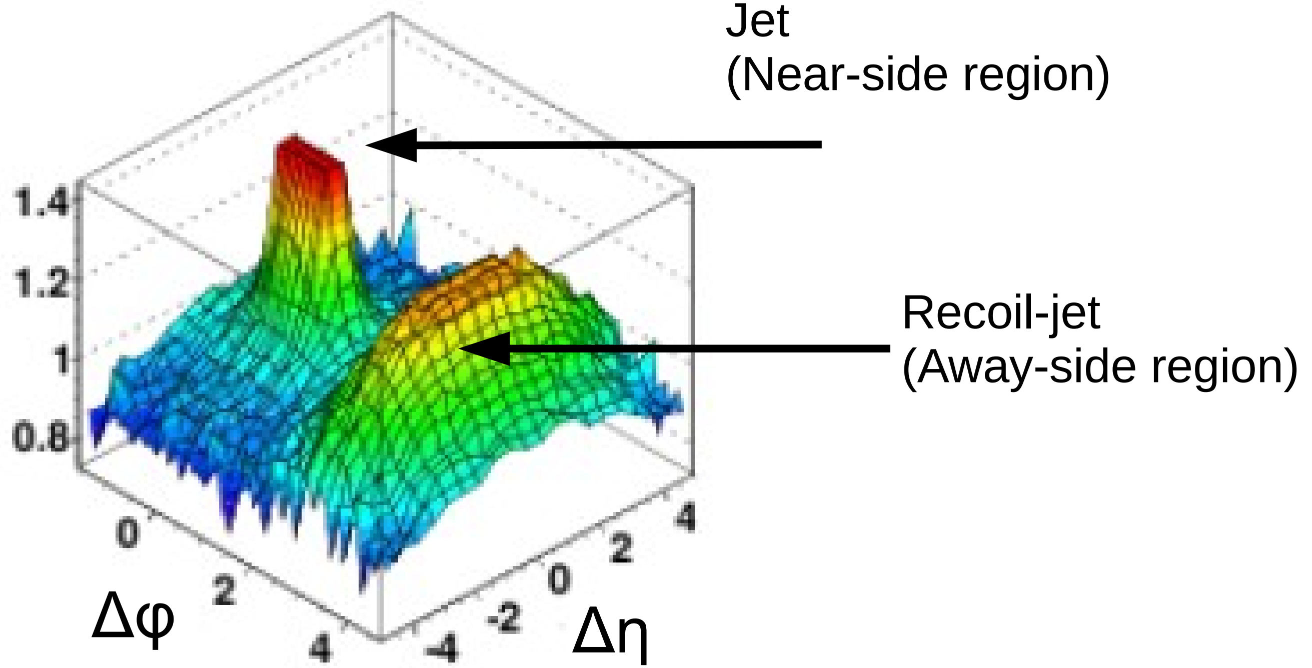
Two-particle correlations

$$v_2\{2\} = \sqrt{\langle \cos(2\varphi_1 - 2\varphi_2) \rangle}$$

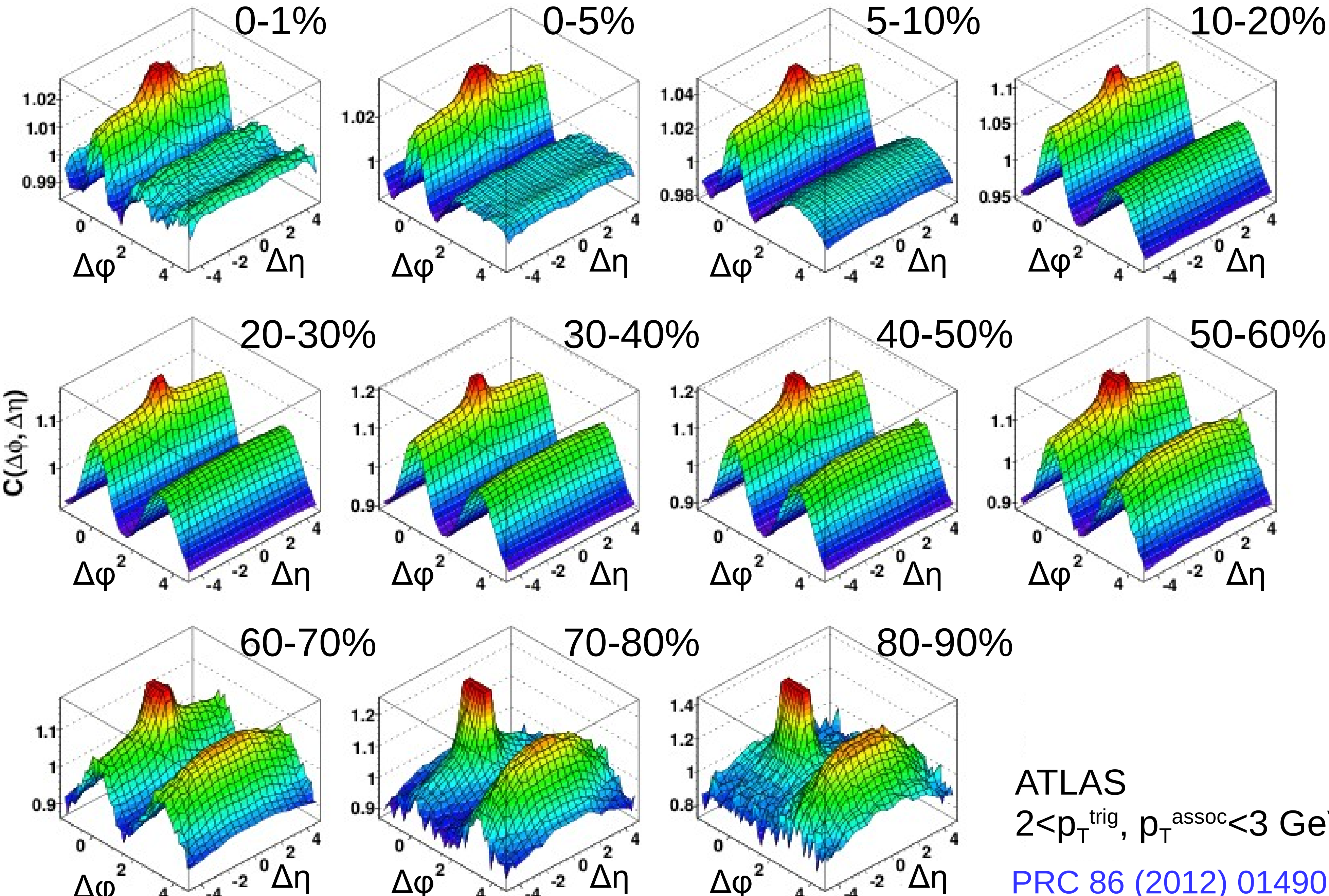
Can suppress “non-flow” by employing cuts in $|\Delta\eta|$

If p_T cuts are used:

$$v\{2\} = \sqrt{v(p_{T,1})\, v(p_{T,2})}$$



Two-particle angular correlations at LHC



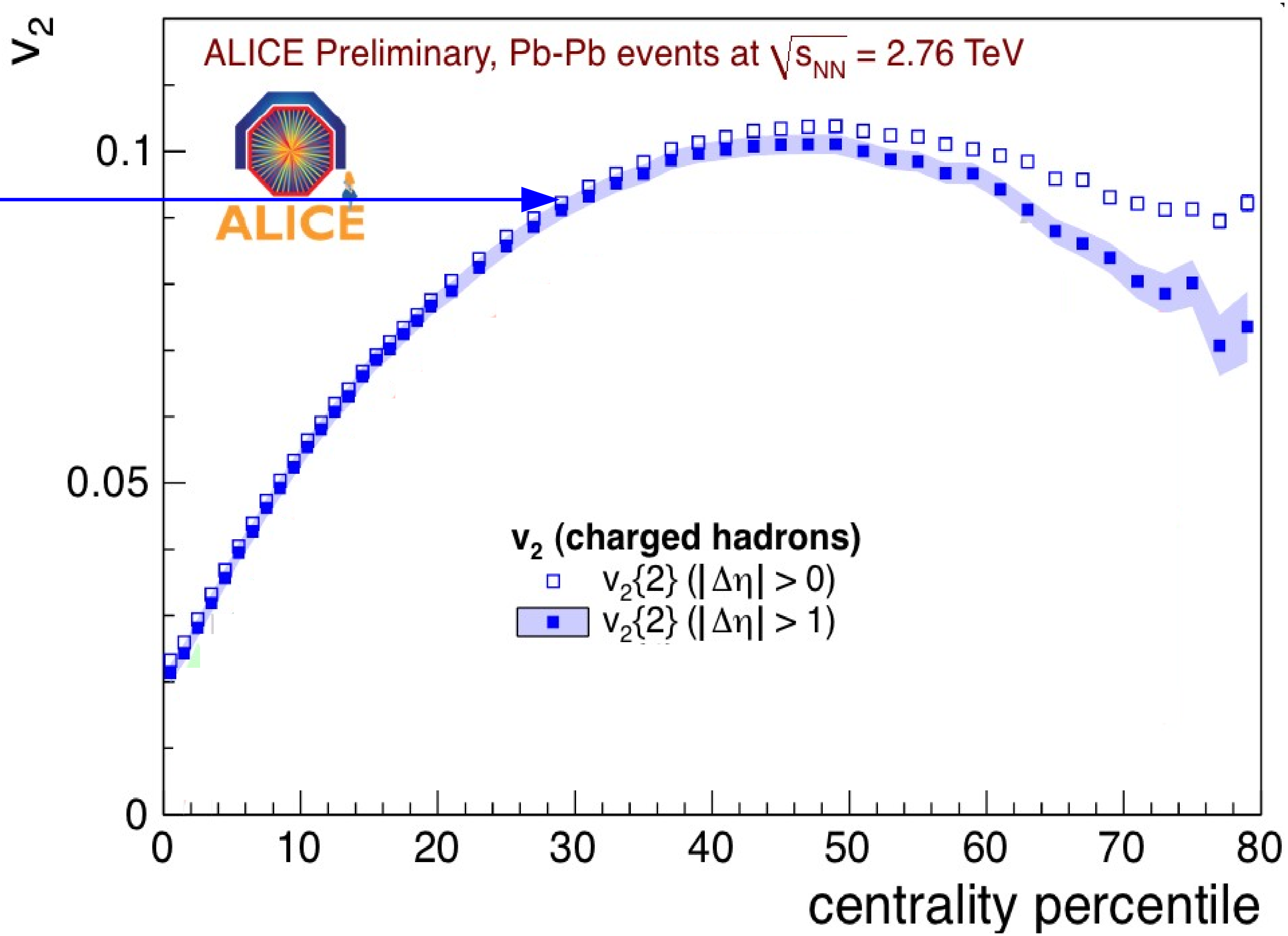
ATLAS

$2 < p_T^{trig}, p_T^{assoc} < 3$ GeV/c

PRC 86 (2012) 014907

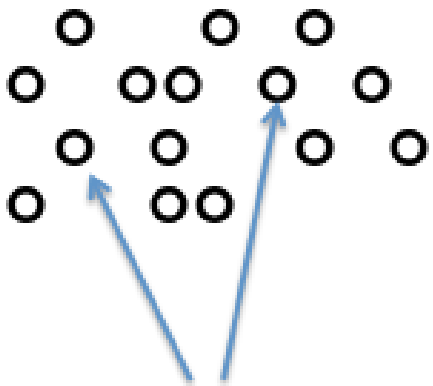
Measured v_2 vs centrality at LHC

Two-particle methods

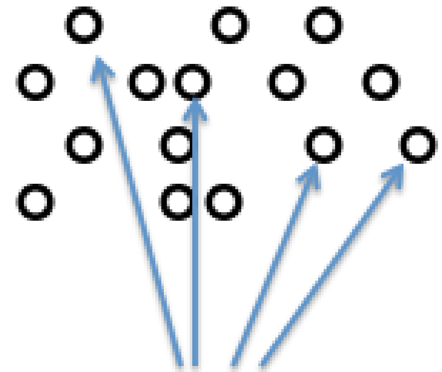


Multi-particle correlations: $v_2\{4\}$ and higher

(From S. Tuo)

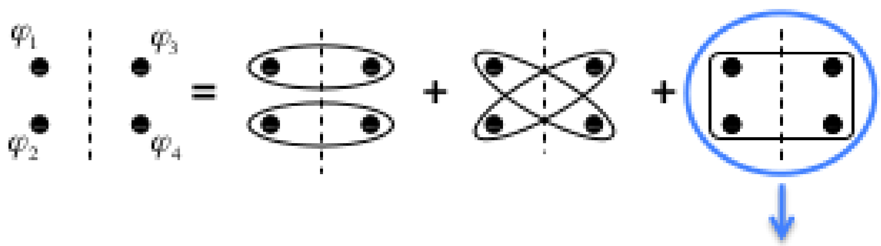


$$\left\langle e^{in(\varphi_1-\varphi_2)}\right\rangle$$



$$\left\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\right\rangle$$

Four particle correlations (Q-cumulant method):



$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\cdot\langle\langle 2\rangle\rangle^2$$

$$v_2\{4\}=\sqrt[4]{-c_n\{4\}}$$

$$\left\langle e^{in(\varphi_1+\varphi_2-\varphi_3-\varphi_4)}\right\rangle-\left\langle e^{in(\varphi_1-\varphi_3)}\right\rangle\left\langle e^{in(\varphi_2-\varphi_4)}\right\rangle-\left\langle e^{in(\varphi_1-\varphi_4)}\right\rangle\left\langle e^{in(\varphi_2-\varphi_3)}\right\rangle$$

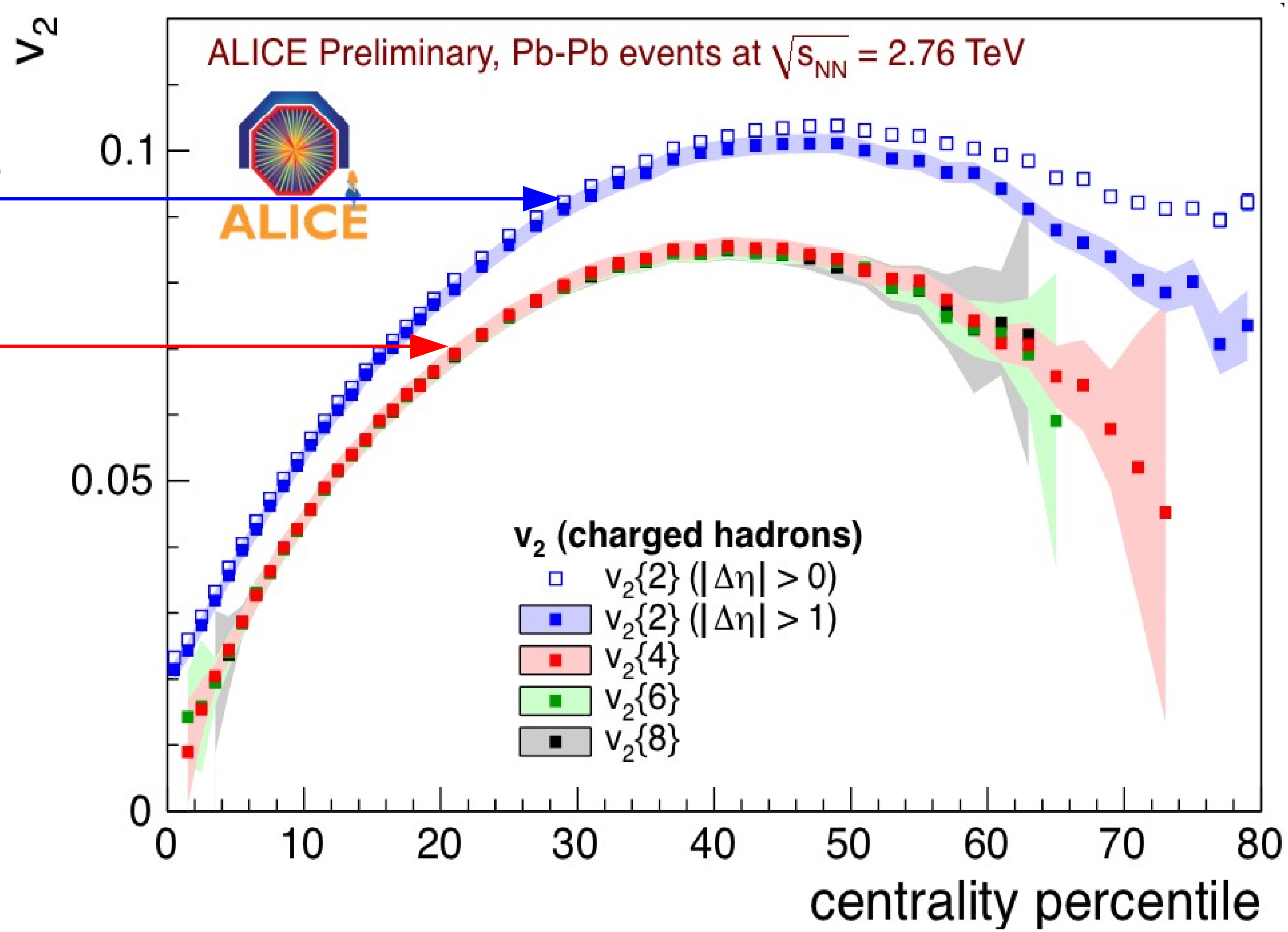
Multi-particle correlations (cumulant) studies extract the genuine multi-particle correlation

Multi-particle correlations: $v_2\{4\}$ and higher

Two-particle methods

Multi-particle methods

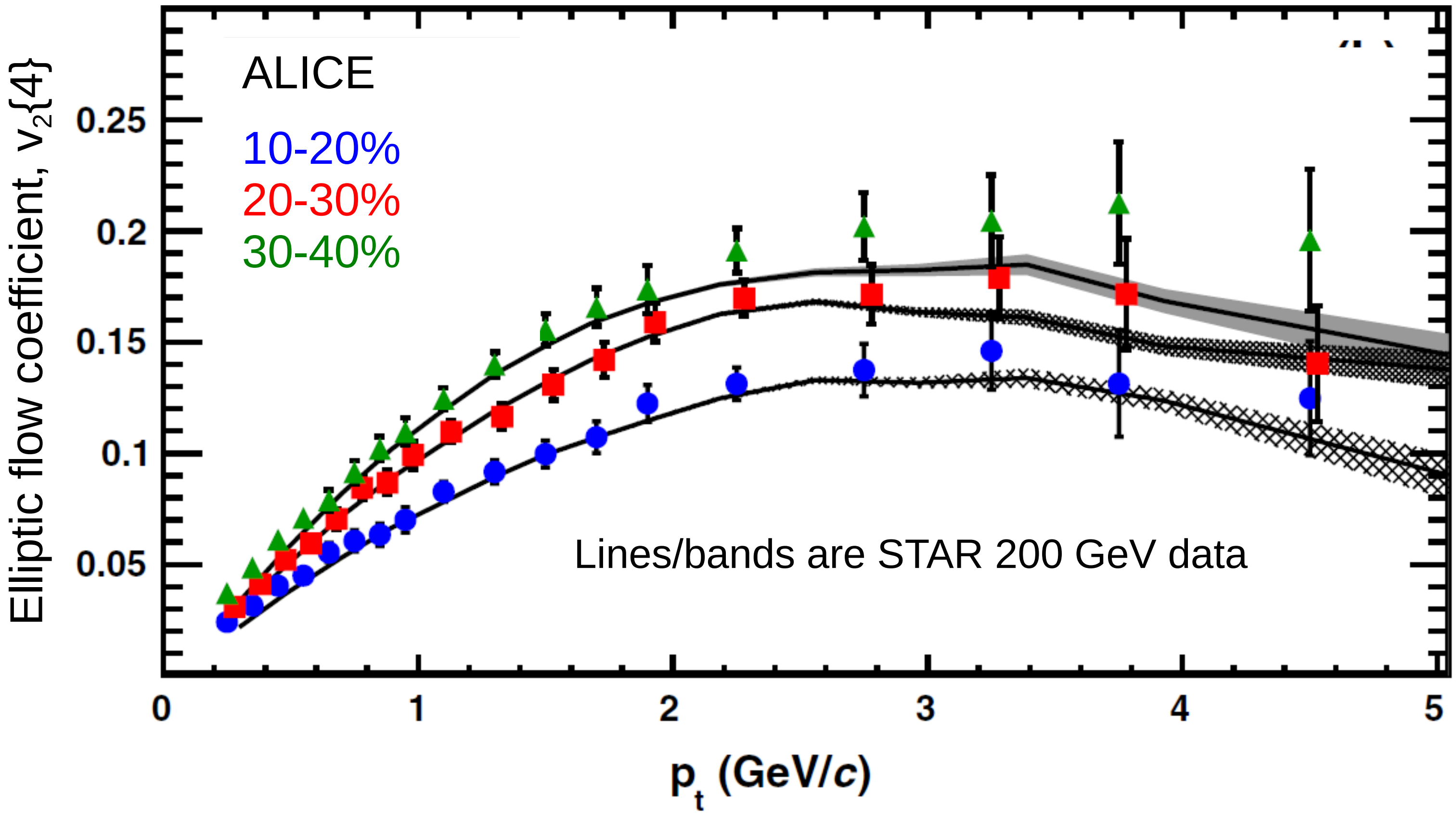
(difference between multi- and two particle correlations originates from non-flow and flow fluctuations)



Multi-particle correlation v2{n} results converge for n≥4, indicating that non-flow contribution is negligible for n≥4

Elliptic flow vs p_T (LHC vs RHIC)

PRL 105 (2010) 252302



Observe $v_2(p_T)_{LHC} \approx v_2(p_T)_{RHIC}$ above 1 GeV to about 5% despite factor 14 increase in energy, but consistent with hydro predictions! (Int.v_2 30% larger due to radial flow)

Hydrodynamical model calculations

Heinz, arXiv:0901.4355

Hydrodynamics: conservation

$$\partial_\mu T^{\mu\nu} = 0$$

Generally:

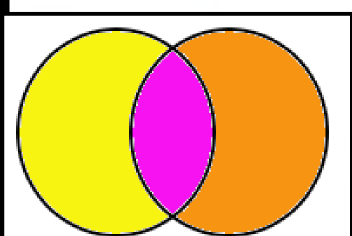
$$T^{\mu\nu} = (\epsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \pi^{\mu\nu}.$$

First order Navier Stokes theory:

$$\pi^{\mu\nu} = \pi^{\mu\nu}_{(1)} = \eta(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \tfrac{2}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha).$$

$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$

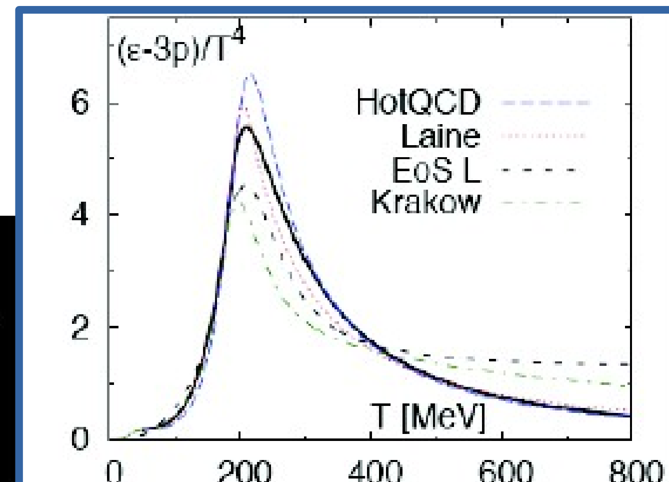
η: Shear viscosity
Large shear viscosity → transport of momentum across fluid layers



+ initial conditions

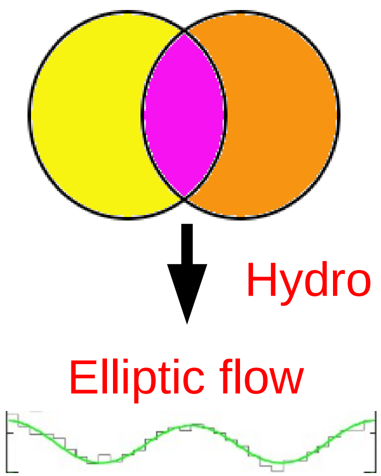
+ freeze-out conditions

+ Equation of State



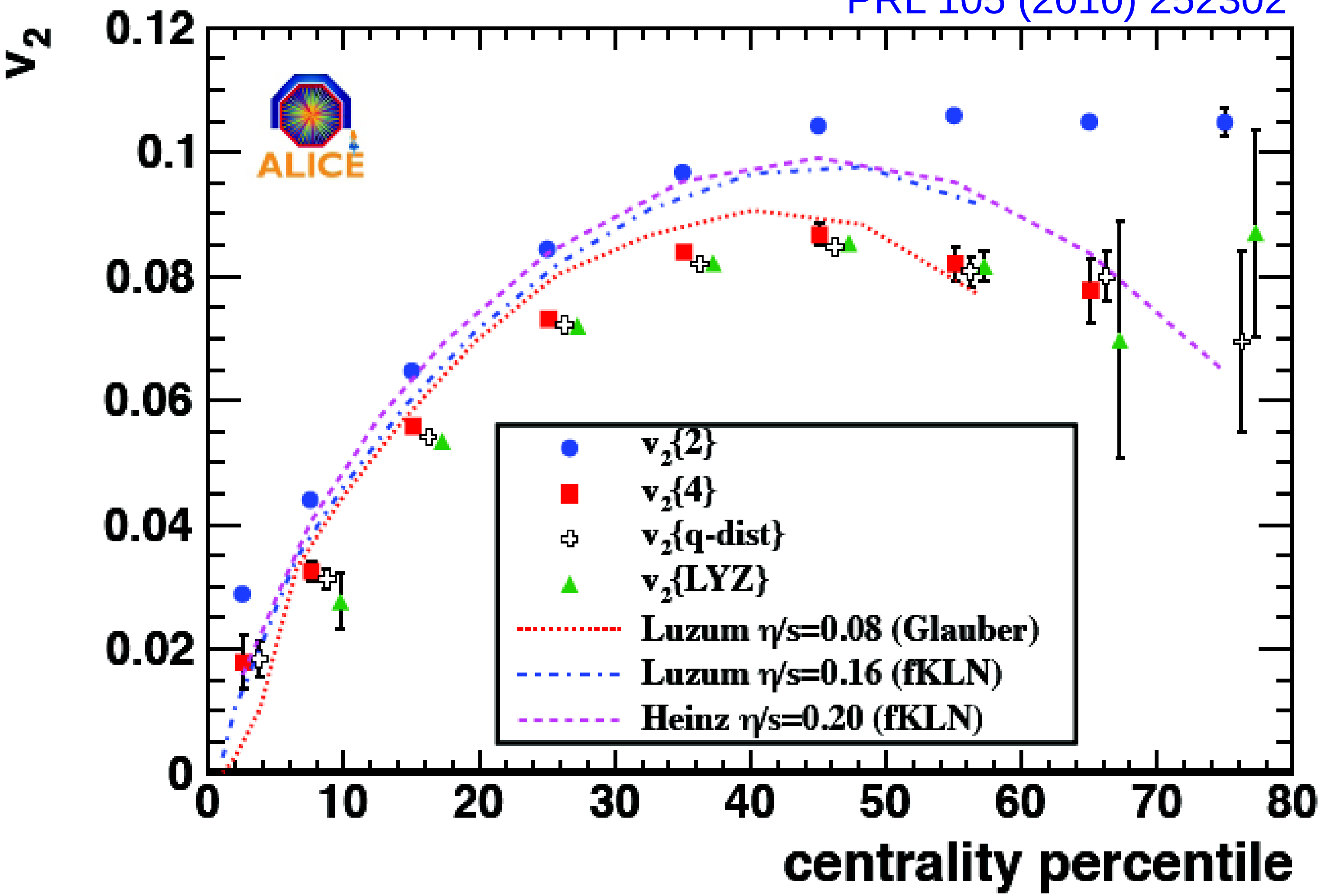
Today even second order calculations (full Israel-Stewart) calculations done.

Integrated elliptic flow and hydro



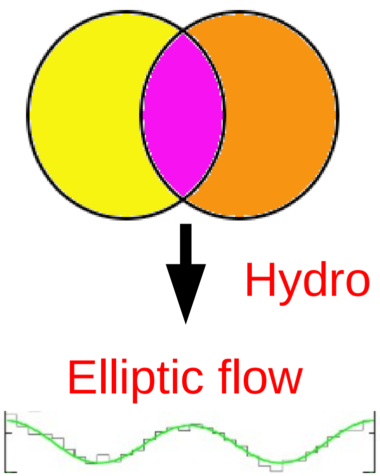
Calculation:
M.Luzum,
arXiv:1011.5173

PRL 105 (2010) 252302



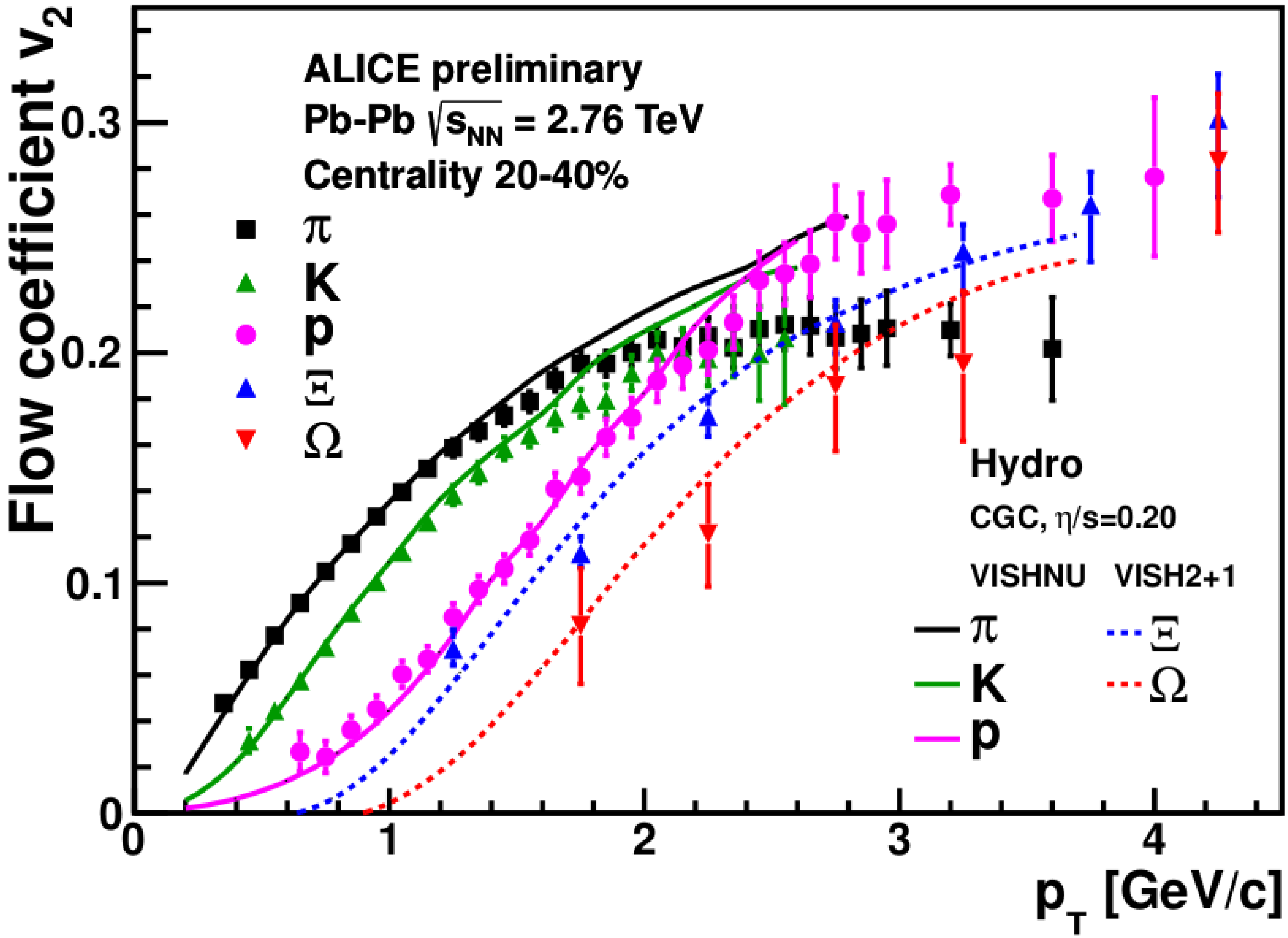
Measured v_2 well within the range of viscous hydro predictions

Identified particle elliptic flow versus p_T



Calculation:
M.Luzum,
arXiv:1011.5173

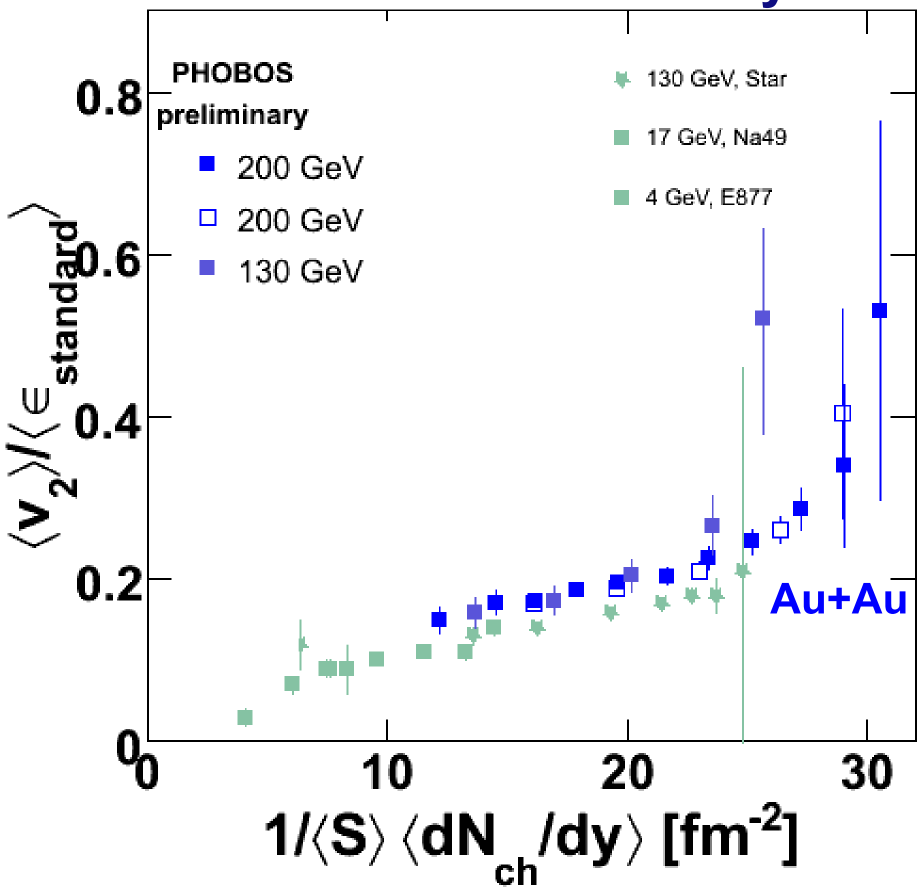
arXiv:1202.3233



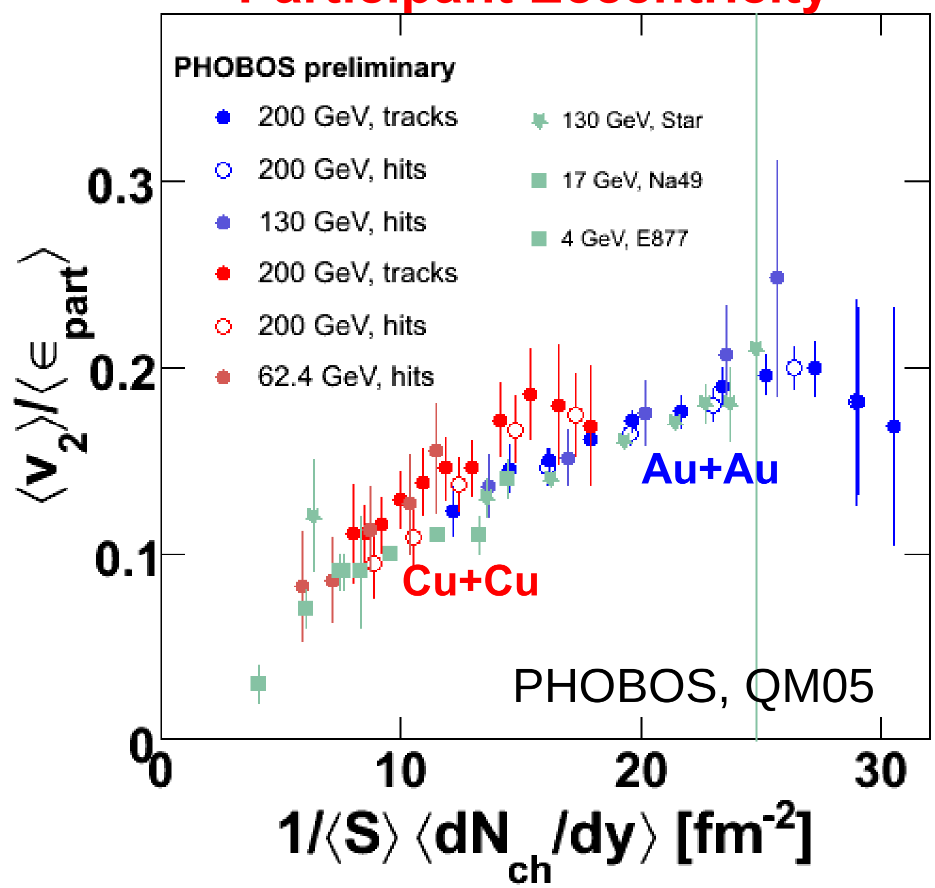
Observed mass ordering in v_2 due to radial flow can be described by hydrodynamical models

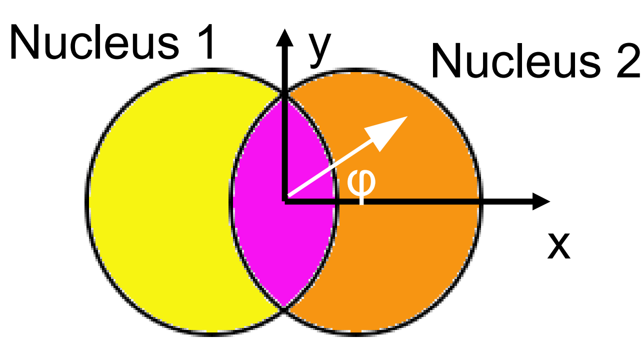
Importance of initial state fluctuations

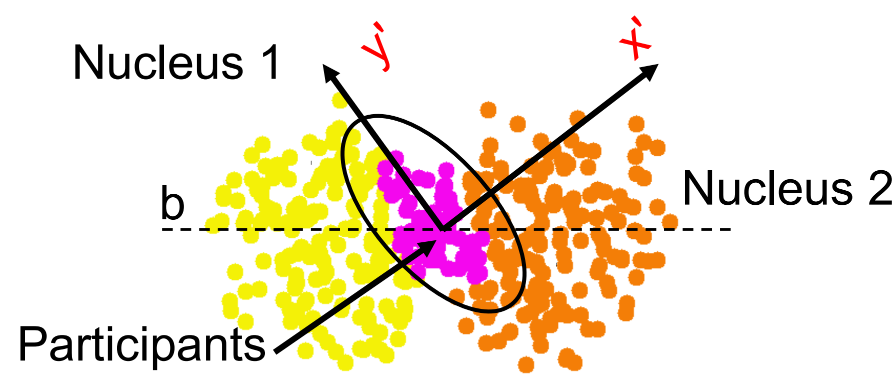
Standard Eccentricity



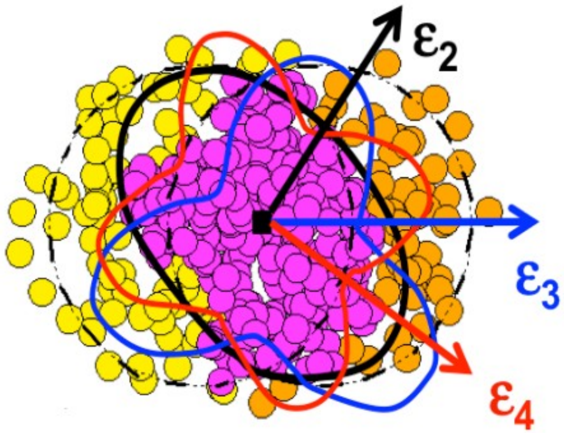
Participant Eccentricity







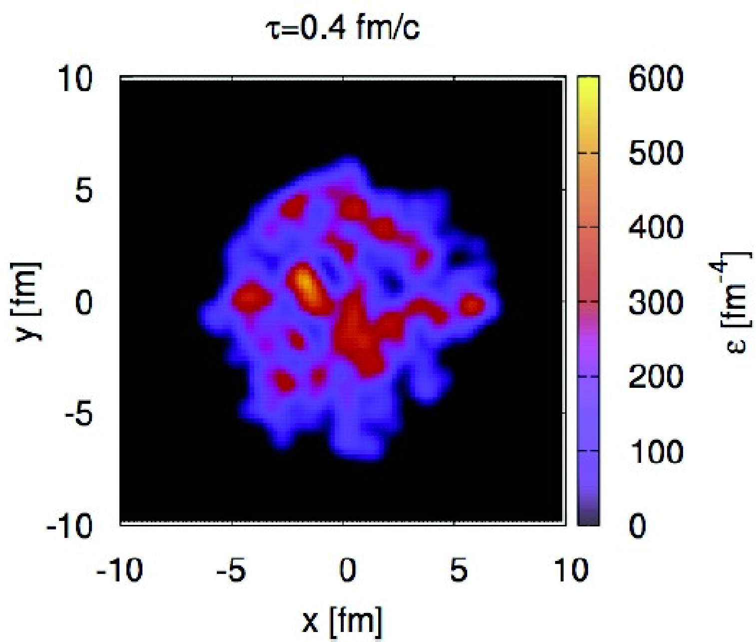
Higher harmonics and viscosity



Alver, Roland

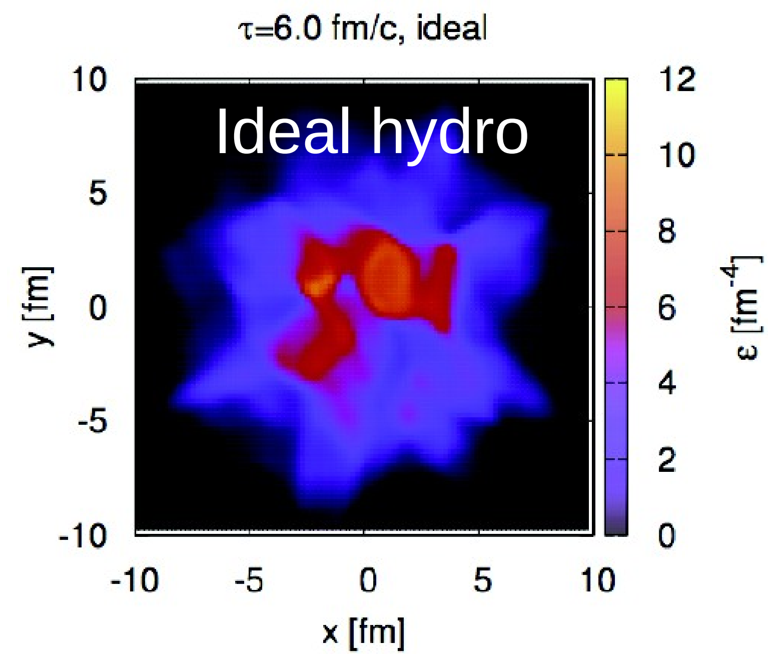
Initial spatial anisotropy not smooth, leads to higher harmonics / symmetry planes.

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



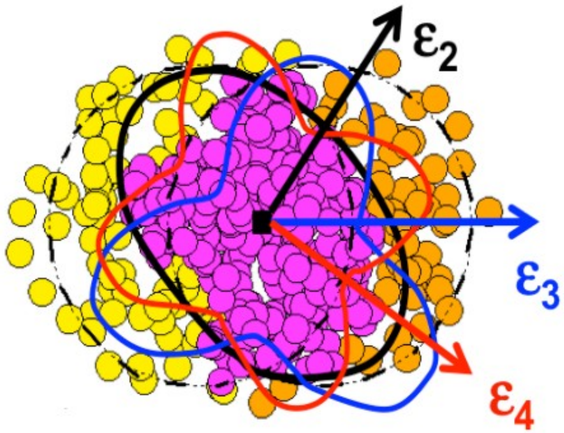
e-by-e hydro

B. Schenke et al.



Ideal hydrodynamical models preserves these “clumpy” initial conditions

Higher harmonics and viscosity



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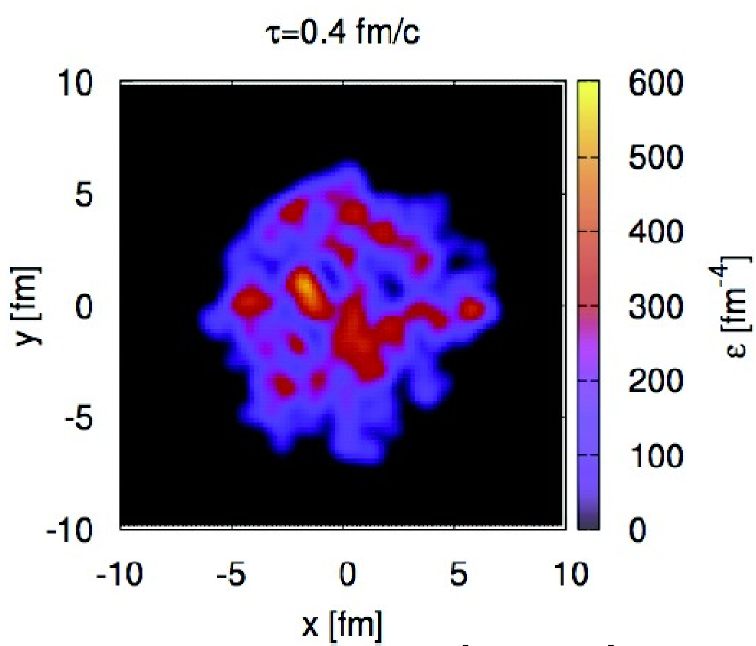
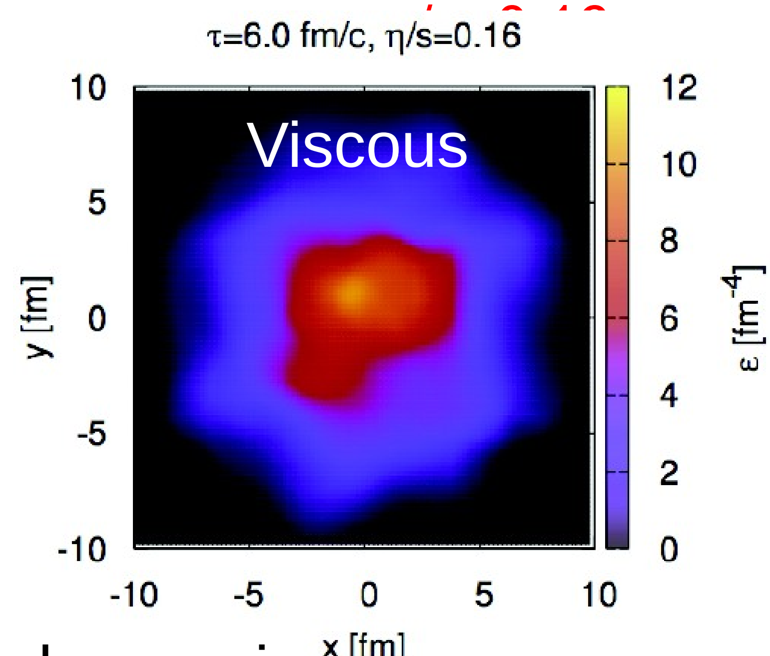


e-by-e hydro

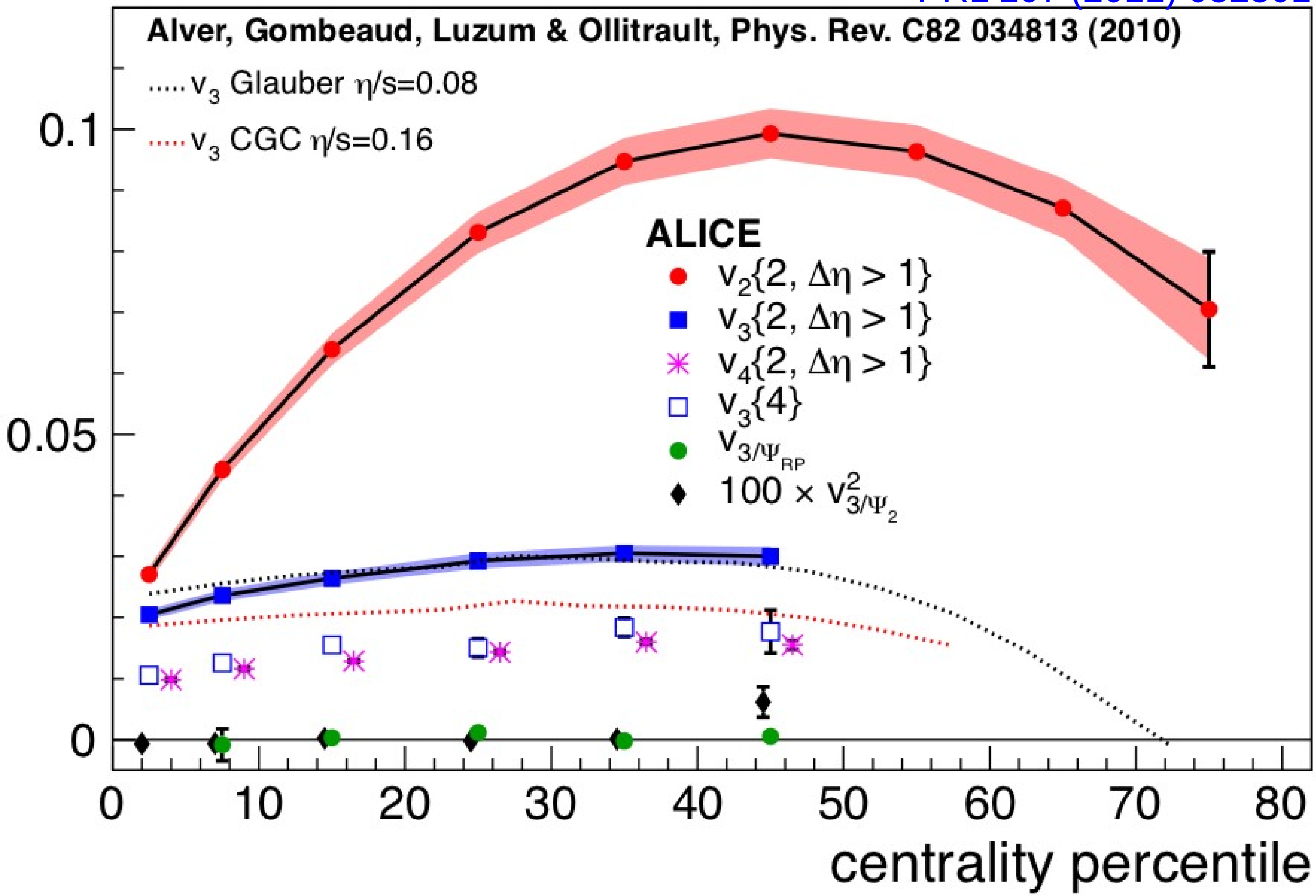
B. Schenke et al.



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

Triangular flow

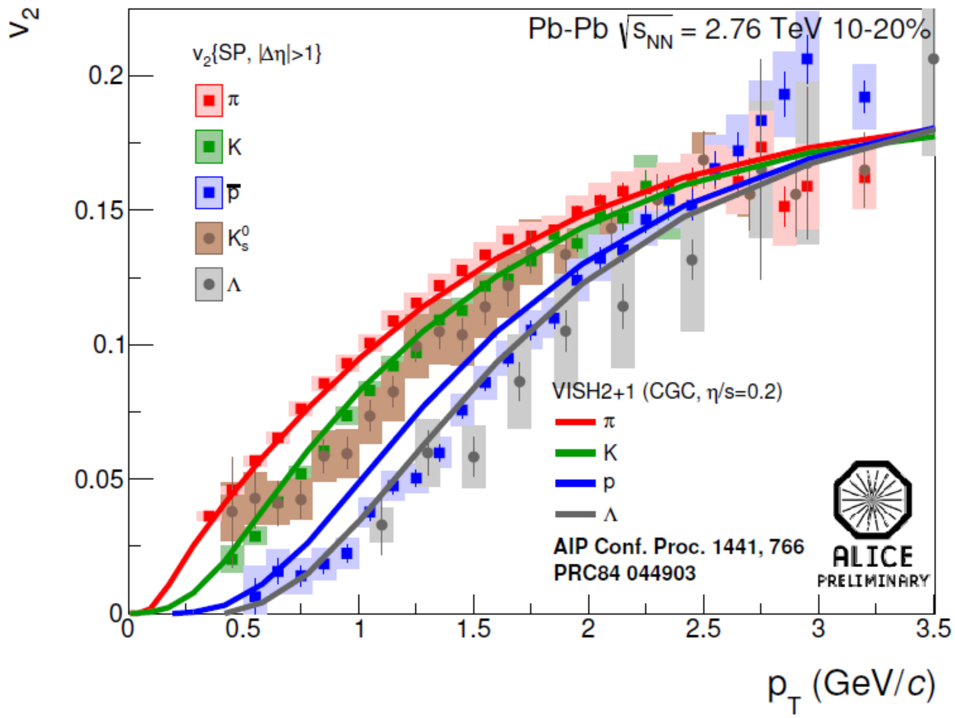
PRL 107 (2011) 032301



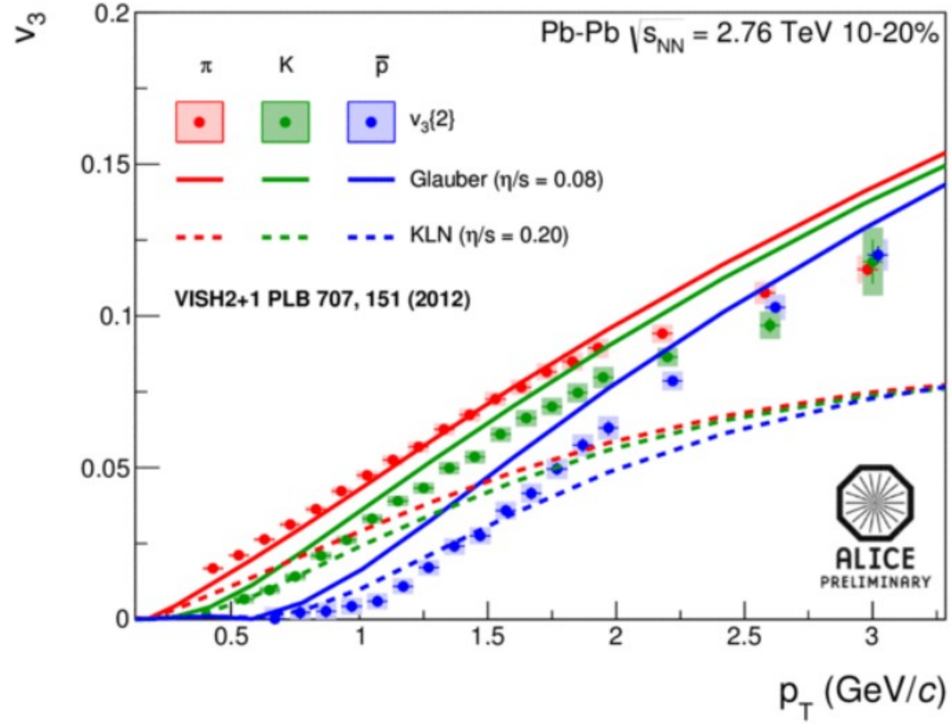
Significant triangular flow observed. Centrality dependence is different to that of elliptic flow. Measurements vs reaction plane yield zero as expected if it arises from fluctuations.

Mass-dependent splitting of v_2 and v_3

Elliptic flow



Triangular flow



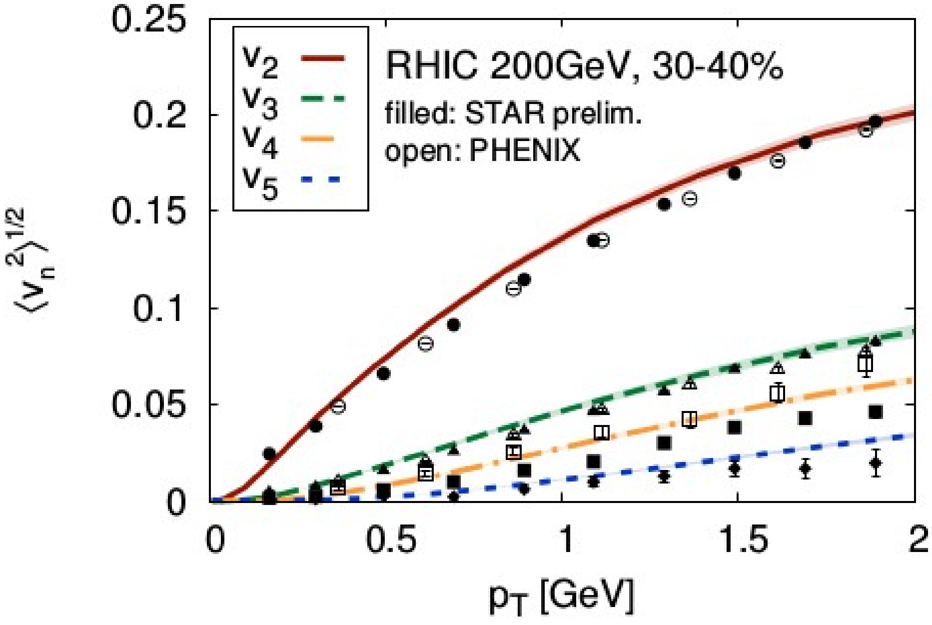
- Particle mass dependent splitting from radial flow characteristic for v_2
- Can be described by hydrodynamical models (+ hadronic afterburners)

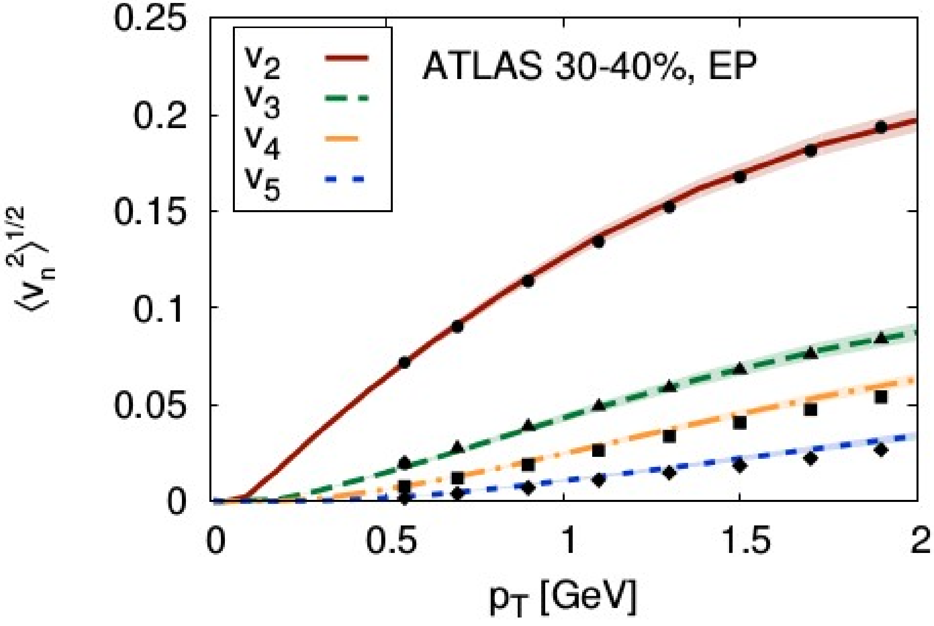
- Similar mass splitting for v_3
- Qualitatively described by hydrodynamical models (+ hadronic afterburners)
- Provides additional constraints on η/s

Constraints on η/s from model calculations

RHIC

LHC





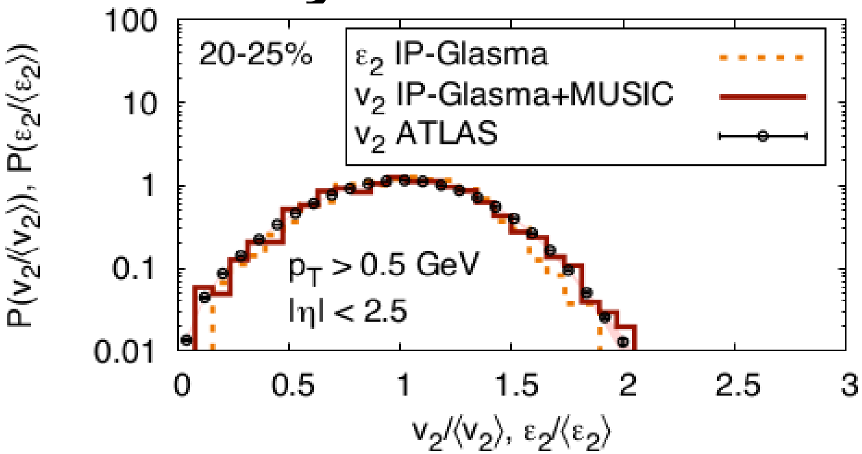
$\eta/s \approx 0.12$ at $\sqrt{s} = 0.2$ TeV

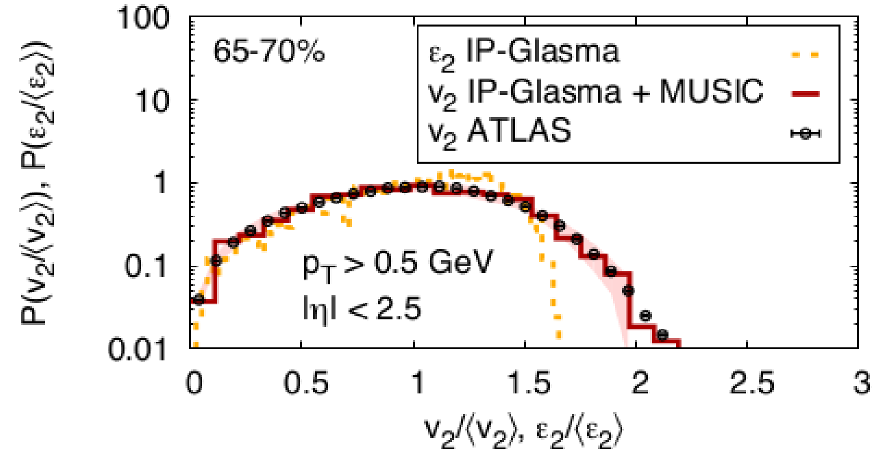
$\eta/s \approx 0.2$ at $\sqrt{s} = 2.76$ TeV

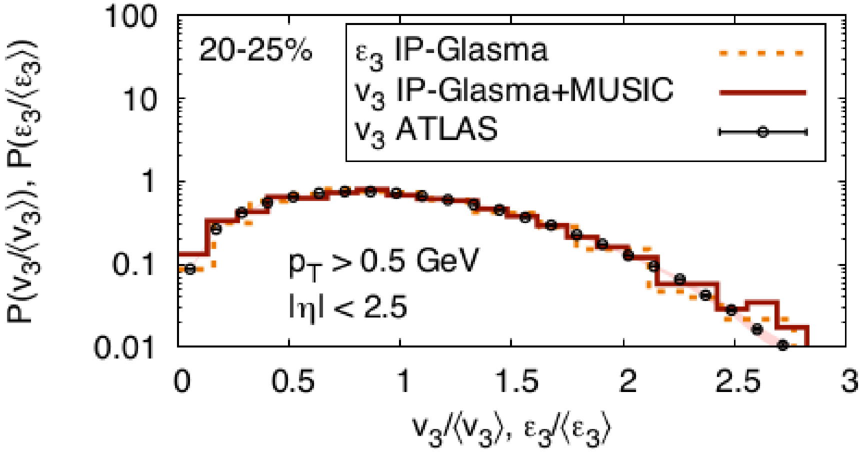
Model (IP-Glasma) consistently describes all flow harmonics for a given η/s (but uncertainty on η/s very large)

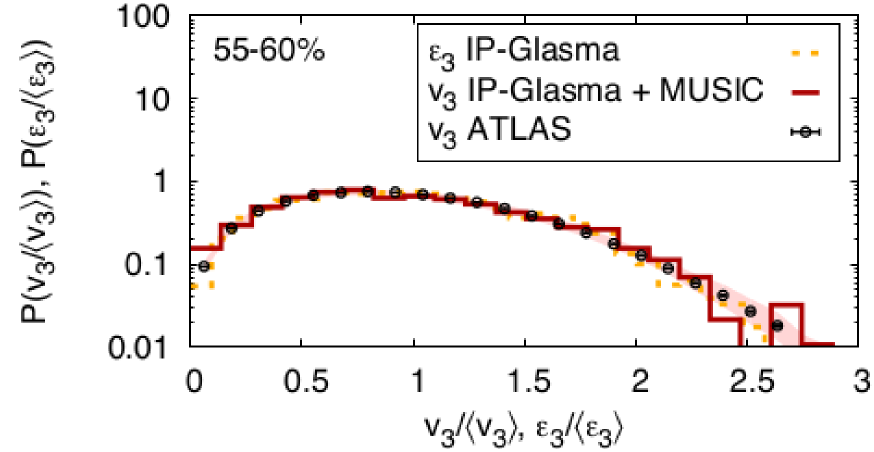
Schenke et al., PRL 110 (2013) 012302

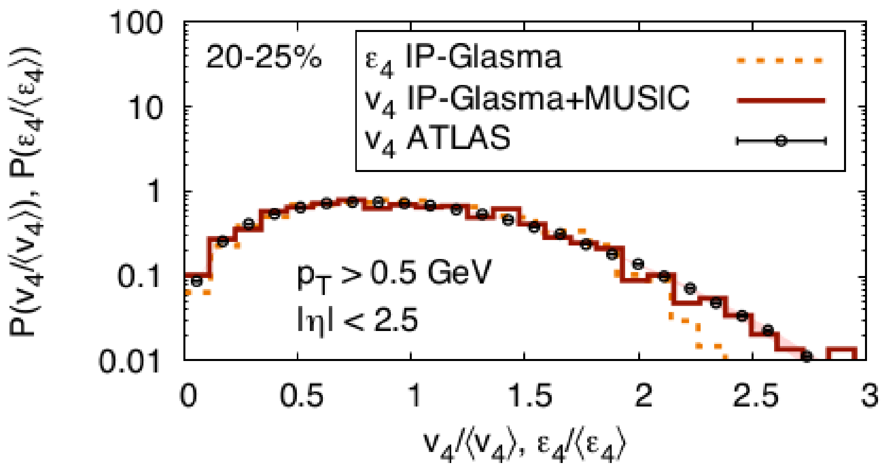
Event-by-event fluctuations









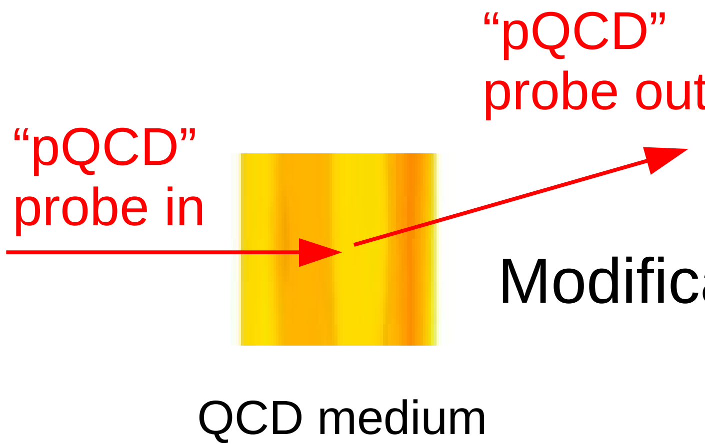


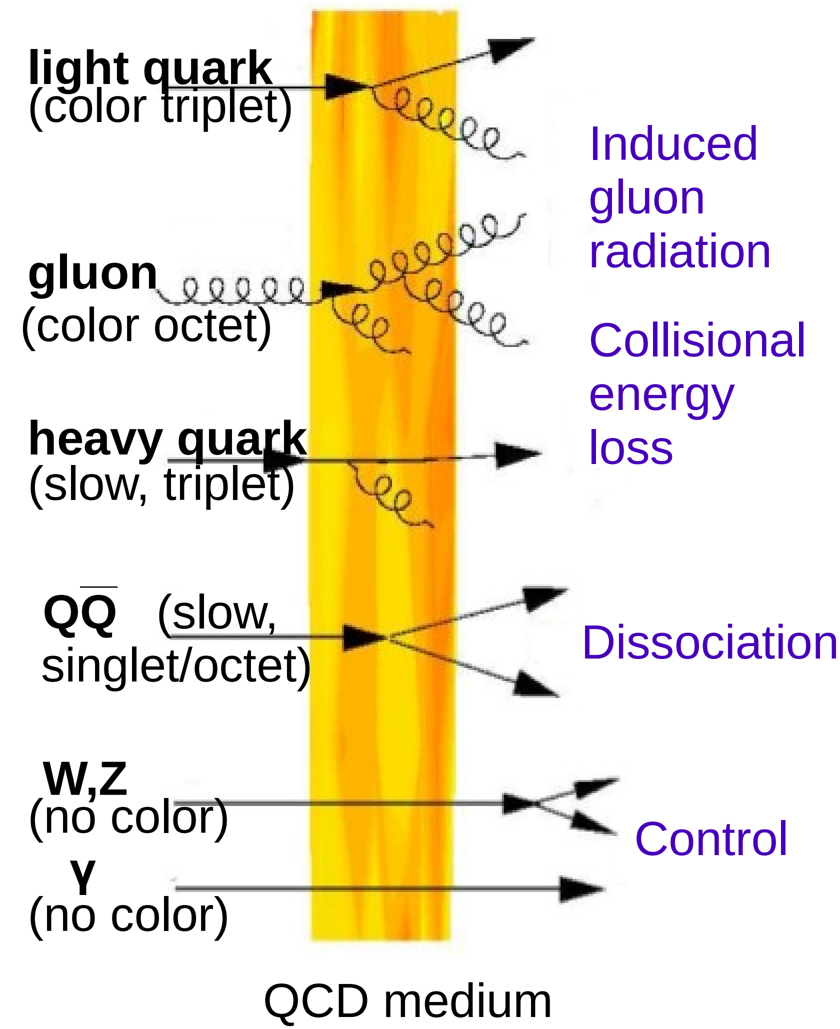
Flow fluctuations reflect initial state fluctuations

ATLAS, JHEP 11 (2013) 183
Schenke et al., PRL 110 (2013) 012302

Tomography of QCD matter

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





Fermi National Accelerator Laboratory

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

Bjorken, 1982

Energy loss of energetic partons in QGP:
Possible extinction of high p_T jets in hh collisions

First idea by Bjorken on collisional energy loss in pp 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.

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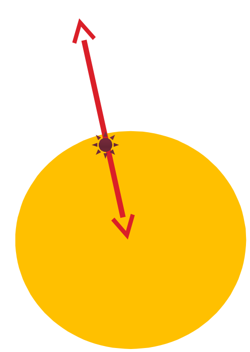
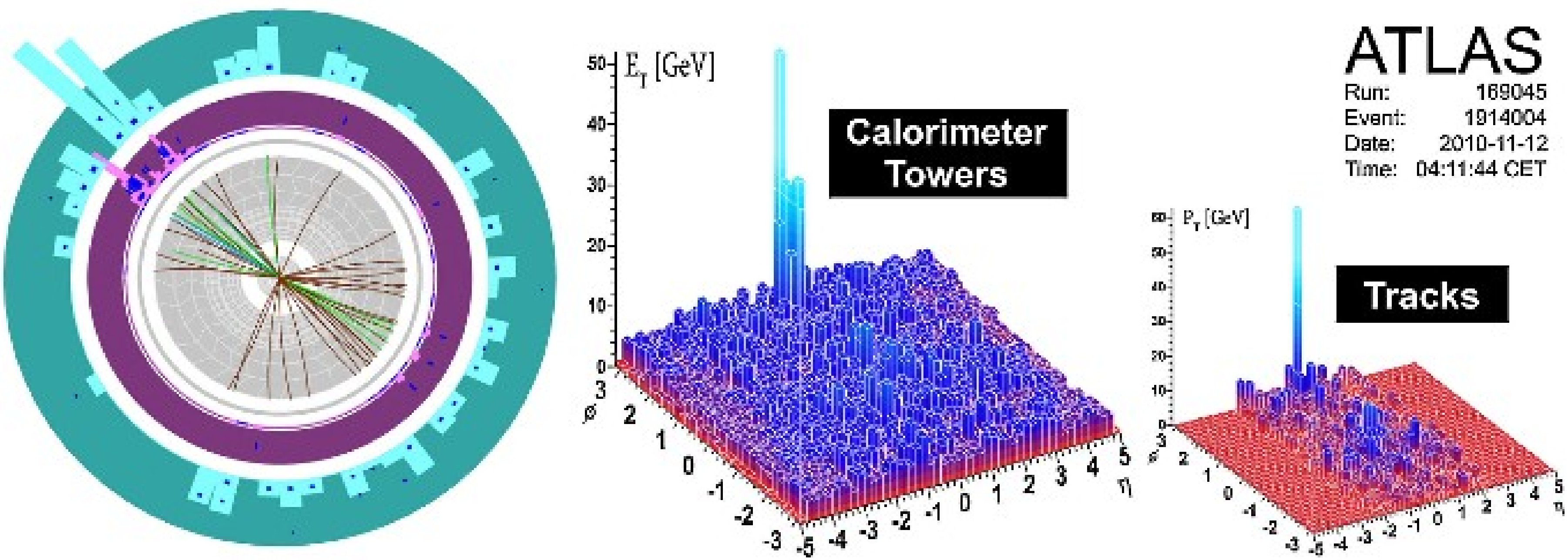


Jet quenching in dijet events (PbPb)

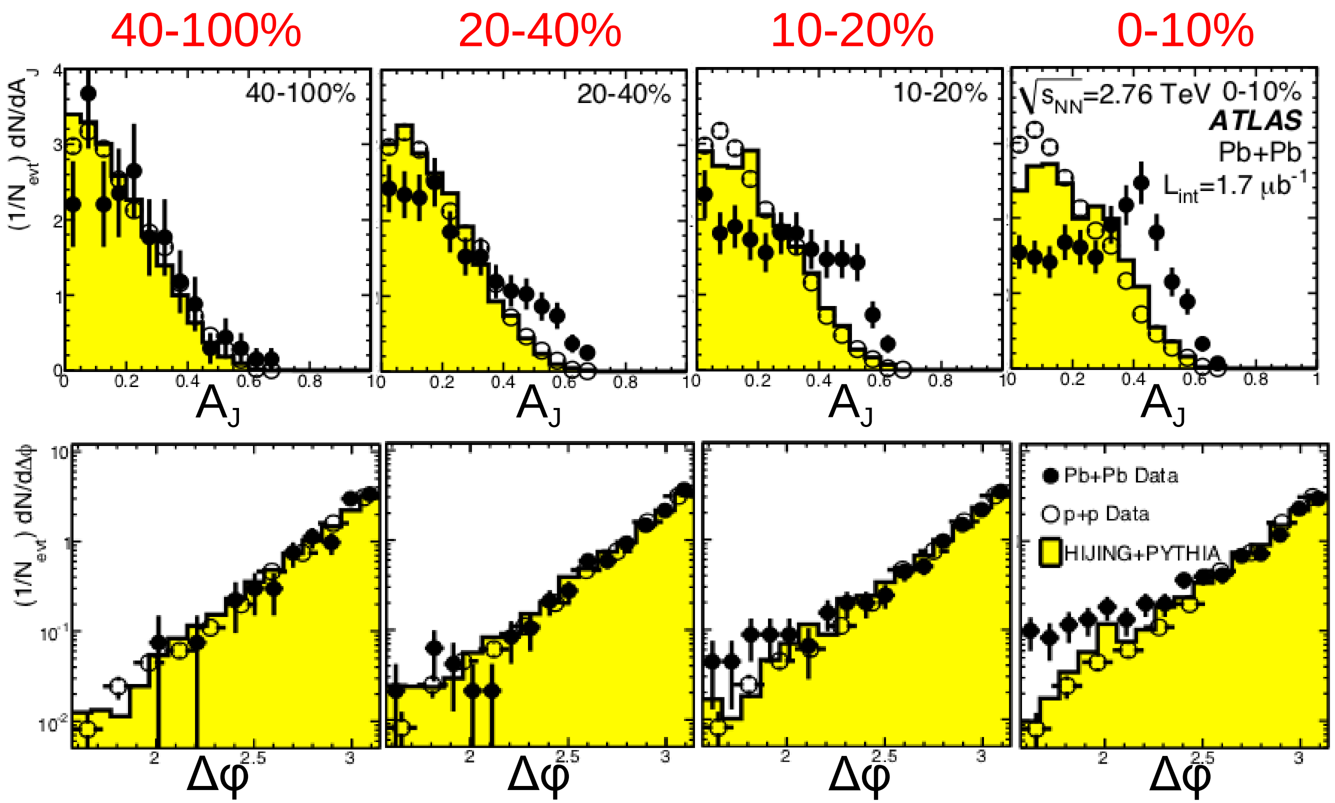


At LHC, jet quenching visible in dijet events

For measurement, need quantification

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

Jet quenching: Dijet imbalance



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

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

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

Jet quenching

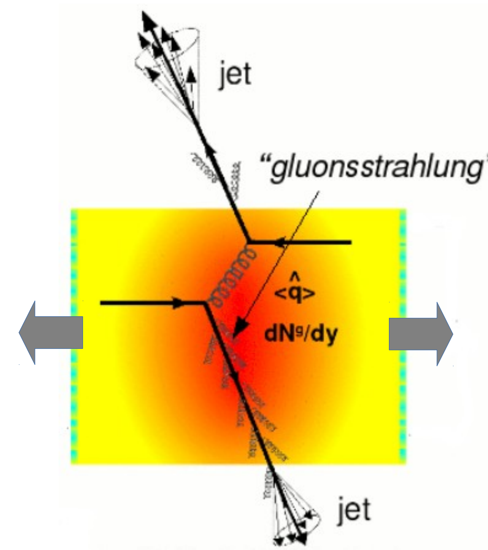
Elastic energy loss:

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

Radiative energy loss:

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

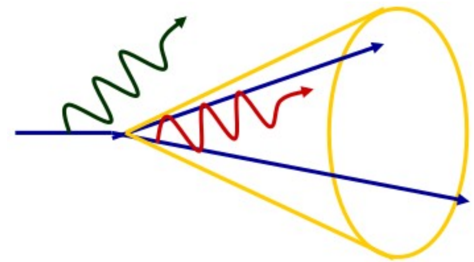
Energy/momentum diffusion tensor:
encodes properties of the medium.



- 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 modication)

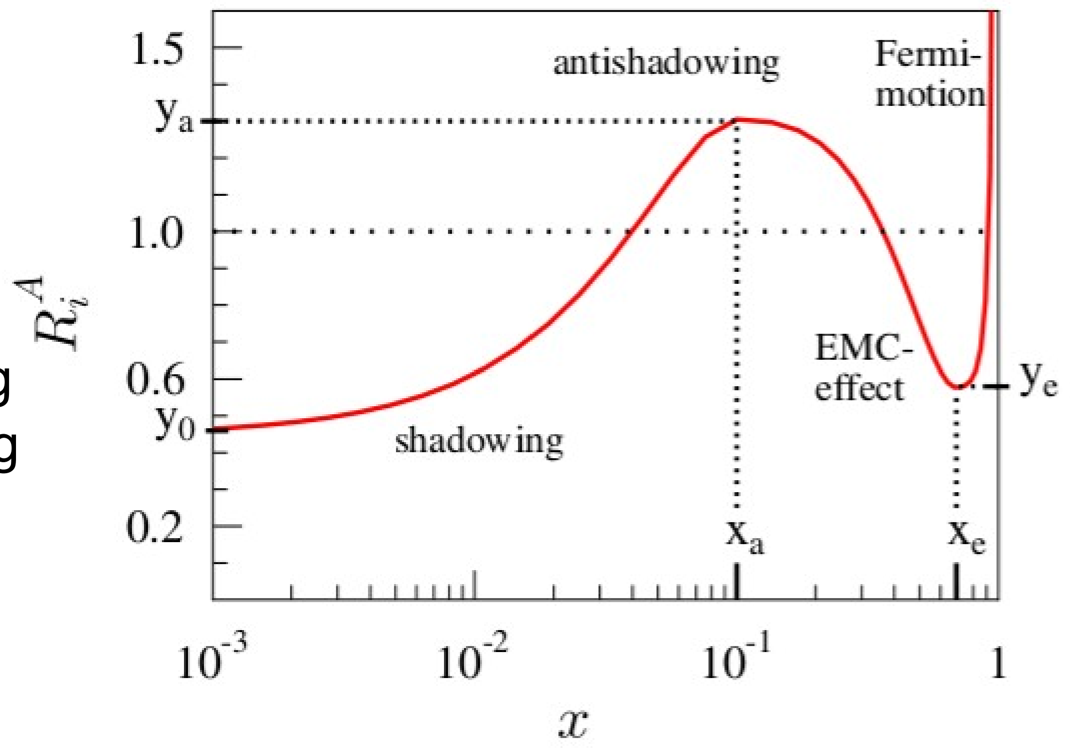
$\Delta E_{loss}(g) > \Delta E_{loss}(q) > \Delta E_{loss}(Q)$

(color factor) (dead-cone effect)

Nuclear modification factor

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

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

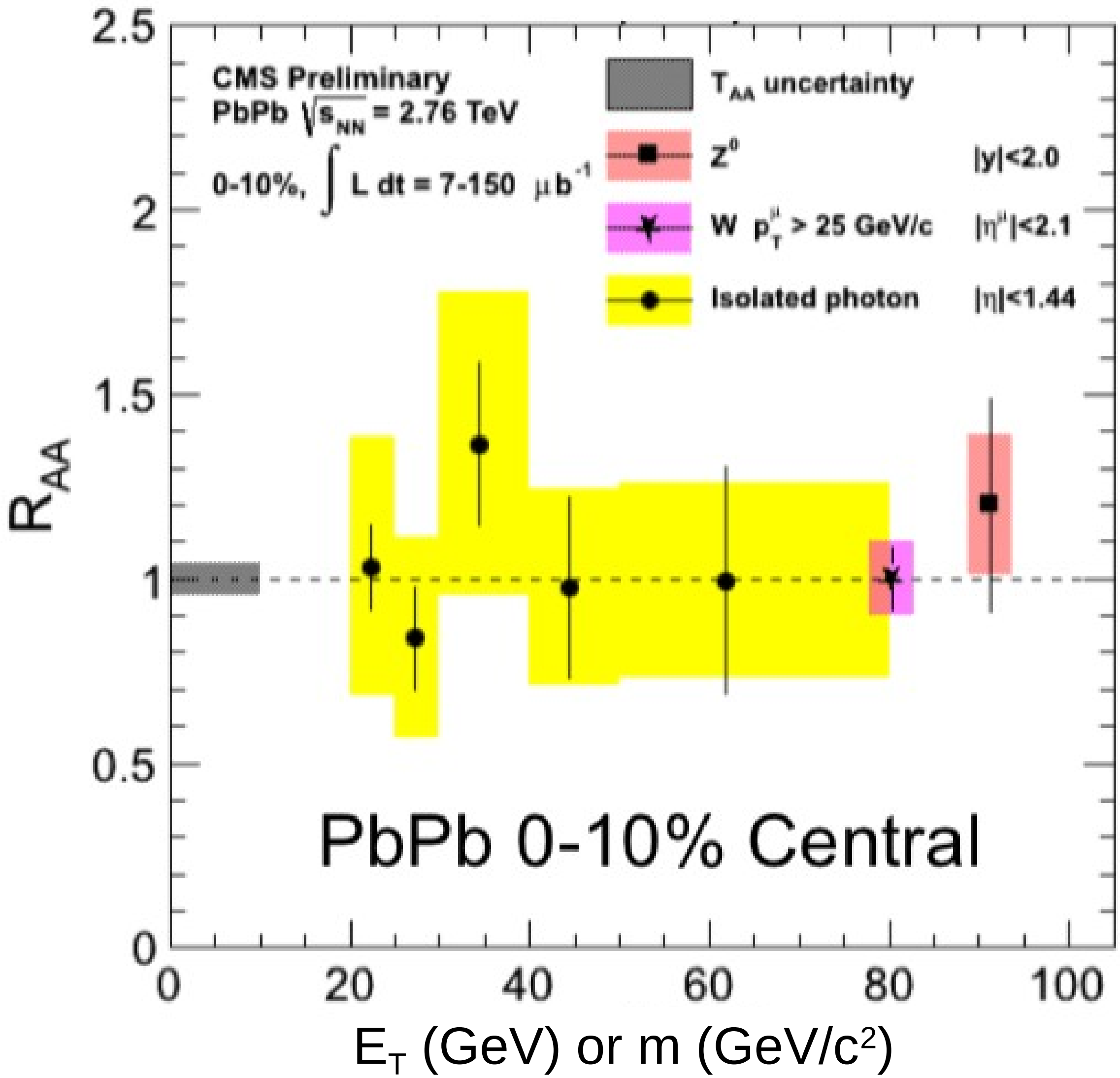


- By definition, R_{AA}=1 in absence of nuclear or QGP effects
- Binary scaling can also be broken due to initial state effects
  - Transverse k_T broadening (called “Cronin effect”)
  - PDF modifications in nuclei (shadowing)

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

Scaling of control yields in pp vs PbPb

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



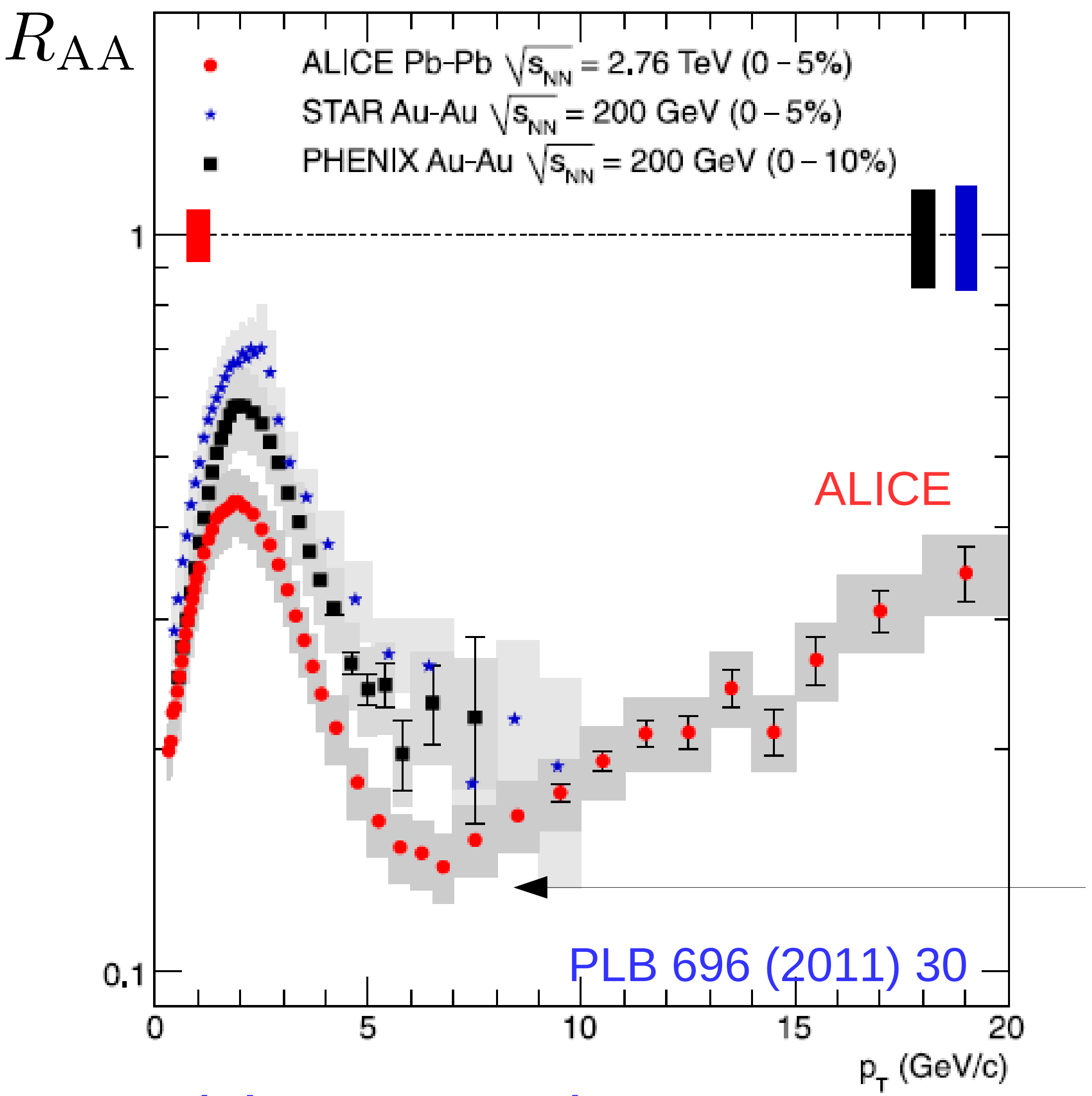
Isolated γ:
ATLAS, ATLAS-CONF-2012-051
CMS, PLB 710 (2012) 256

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

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

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

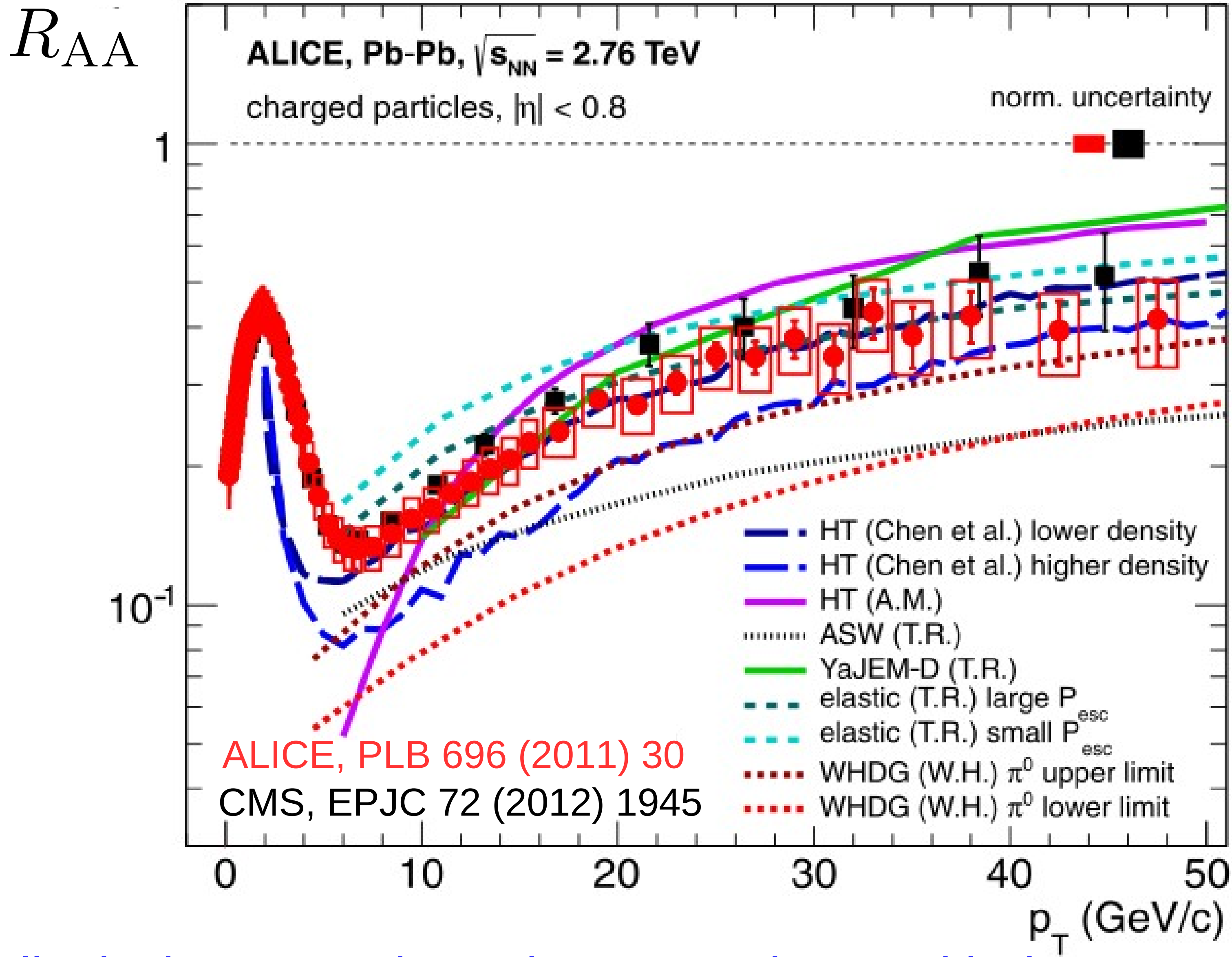
Nuclear modification factor: LHC vs RHIC



6-7 times smaller than expected from incoherent superposition of pp scatters

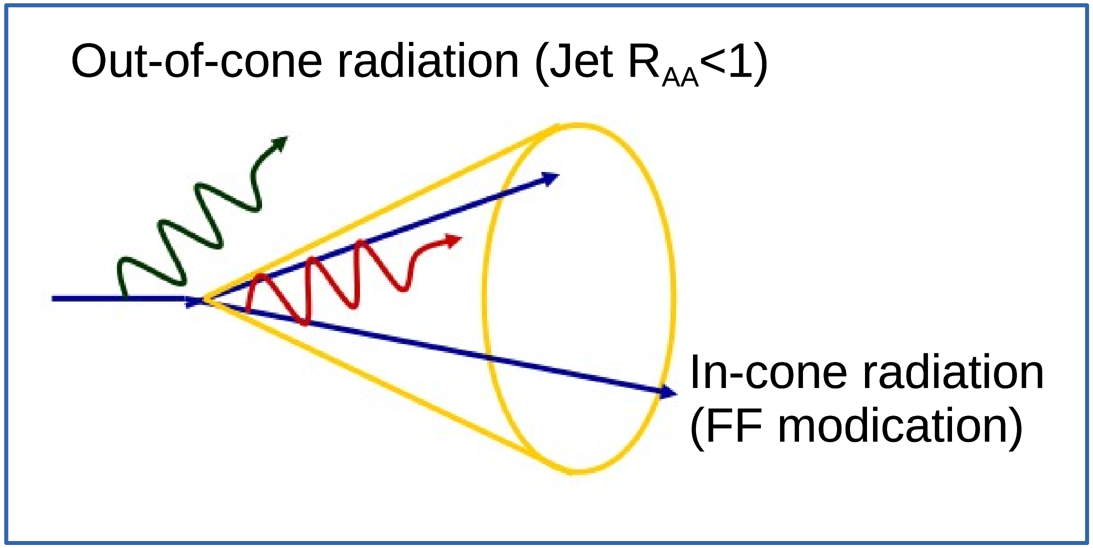
- Strong leading particle suppression
- Qualitatively similar to the one at RHIC

Nuclear modification factor: Data vs models



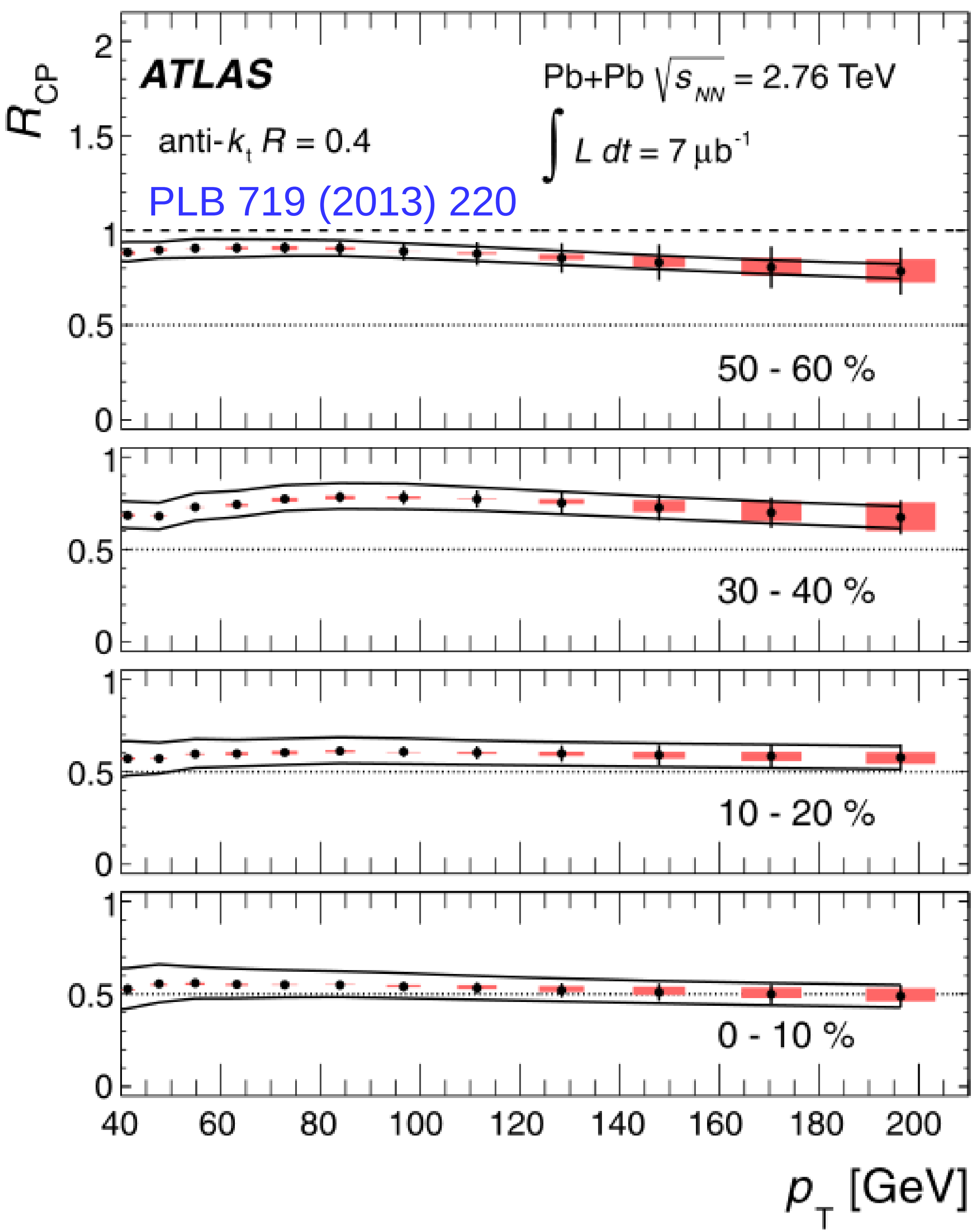
- Qualitatively: energy loss picture consistent with data
  - Models calibrated at RHIC and scaled to LHC via multiplicity growth
  - Key prediction of p_T-dependence of R_{AA}: ΔE~log(E)

Back to jets...



Can we capture where the energy goes?

Jet nuclear modification factor (R_{CP})



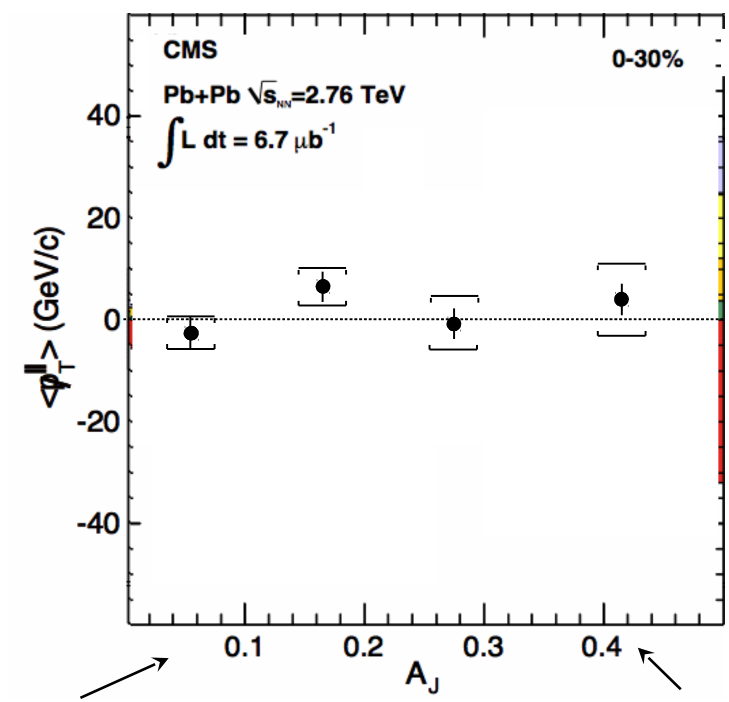
$$R_{\mathrm{CP}} = \frac{\left.\frac{1}{N_{\mathrm{coll}}}\frac{\mathrm{d}N}{p_{\mathrm{T}}}\right|_{\mathrm{cent}}}{\left.\frac{1}{N_{\mathrm{coll}}}\frac{\mathrm{d}N}{p_{\mathrm{T}}}\right|_{60-80\%}}$$

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

“Missing p_T” analysis (inclusive)

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

0-30% Central PbPb

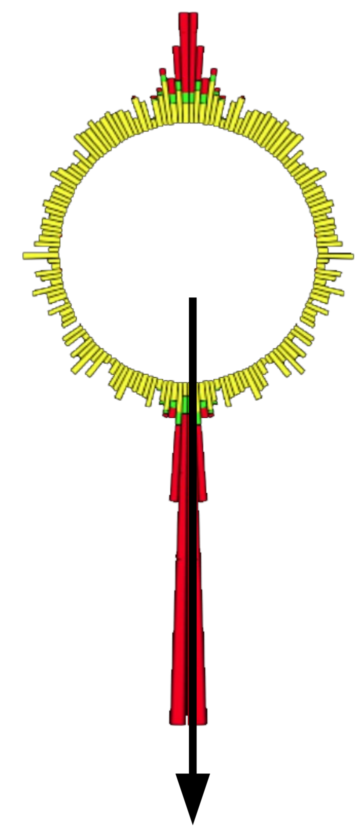


excess away from leading jet

excess towards leading jet

balanced jets

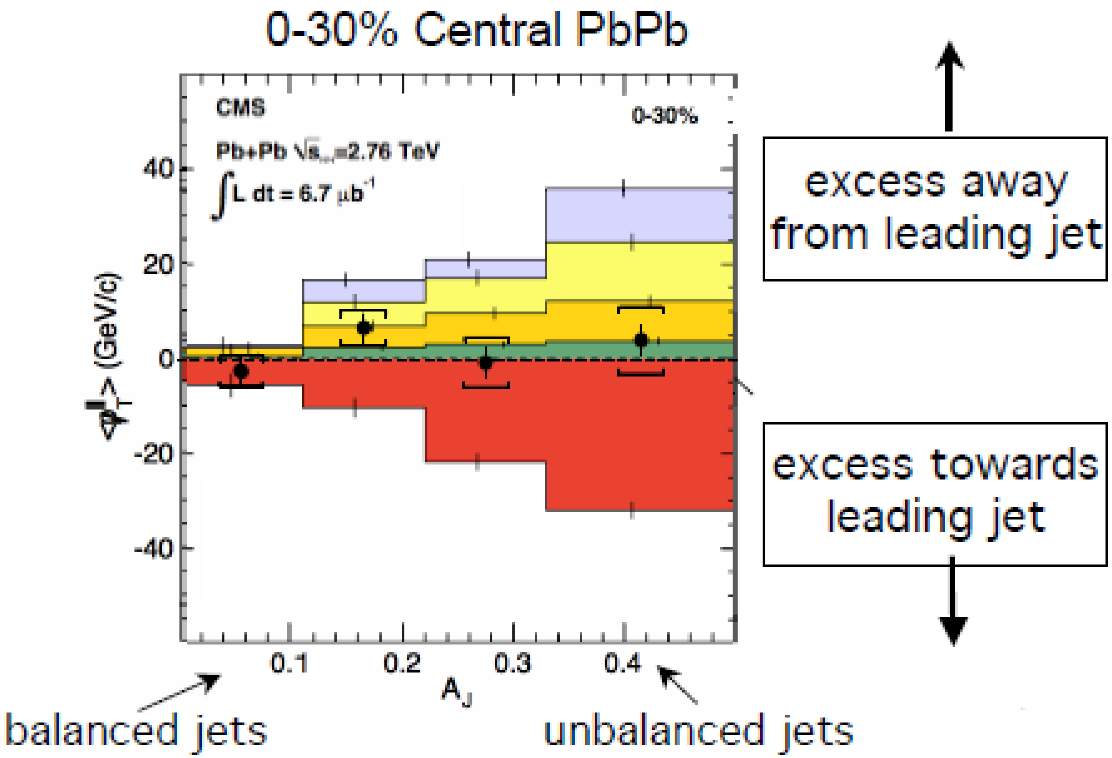
unbalanced jets



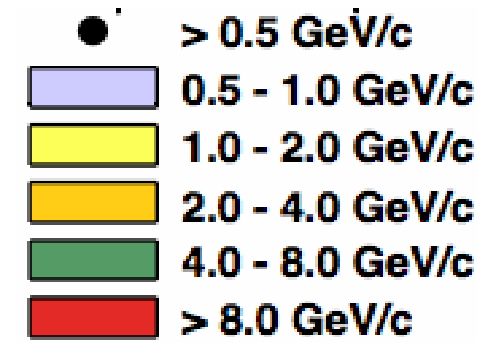
Leading jet defines direction

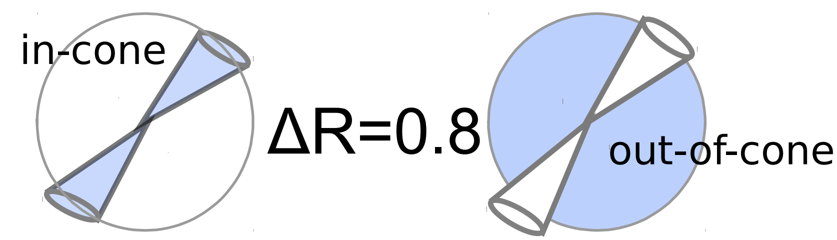
PRC 84 (2011) 024906

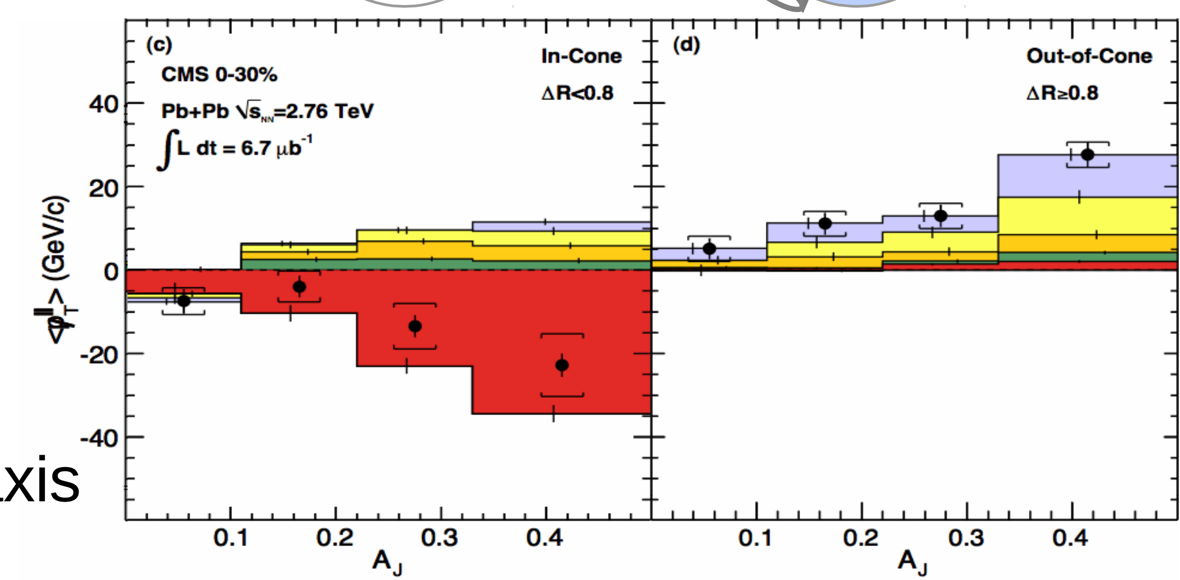
“Missing p_T” analysis (differential)



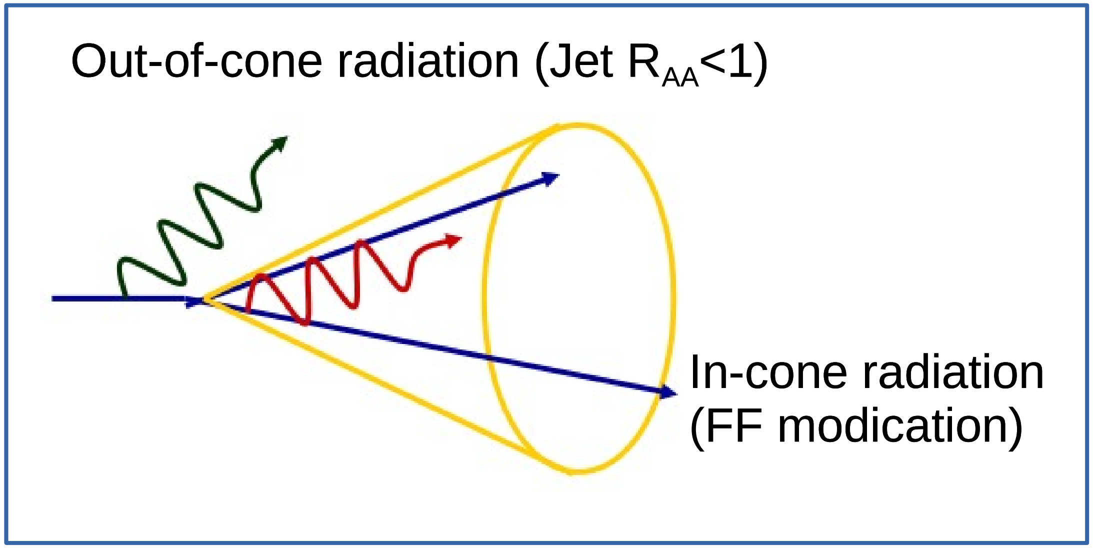
Calculate missing p_T in bins of track p_T







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

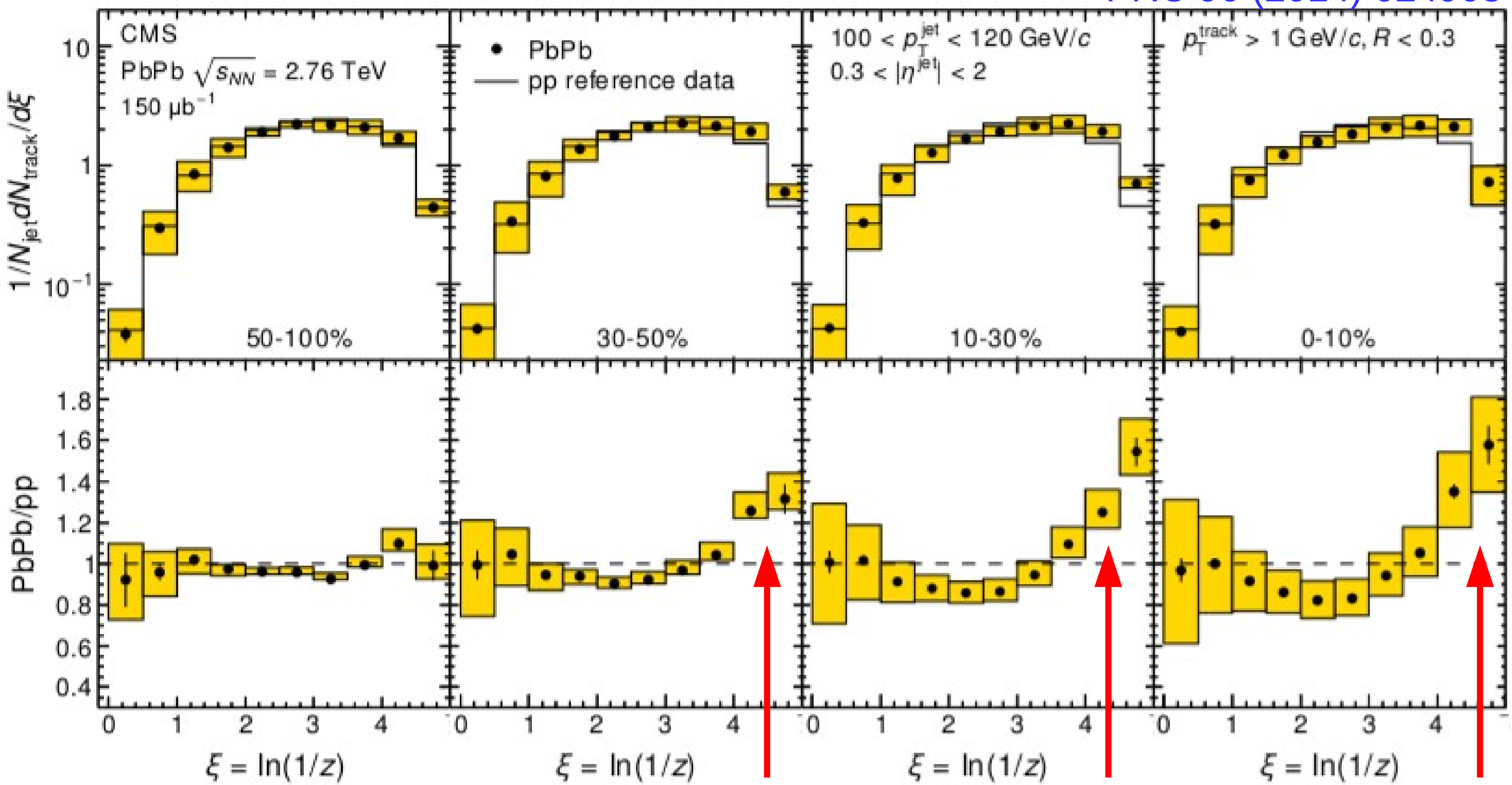


Is there an observable difference in the jet cone?

Jet fragmentation function

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

PRC 90 (2014) 024908



R=0.3

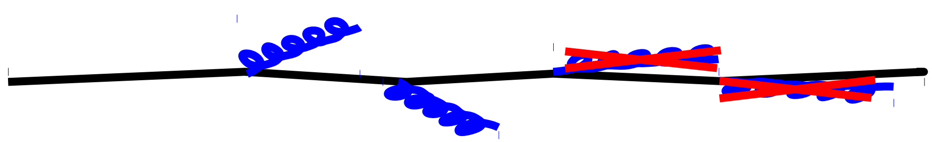
100<p_T<120 GeV/c

Track p_T>1 GeV/c

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

Energy loss of (open) heavy flavor

- The study of open heavy flavor in AA collisions provides a crucial test for the understanding of parton energy loss
- Heavy flavor mainly come from quark fragmentation, while light flavor from gluons (in particular at LHC energies)
  - Smaller Casimir factor, smaller energy loss
- Dead cone effect: Suppression of gluon radiation at small angles depends on quark mass



Suppression for
$\theta < M_Q/E_Q$

- Should lead to a suppression hierarchy

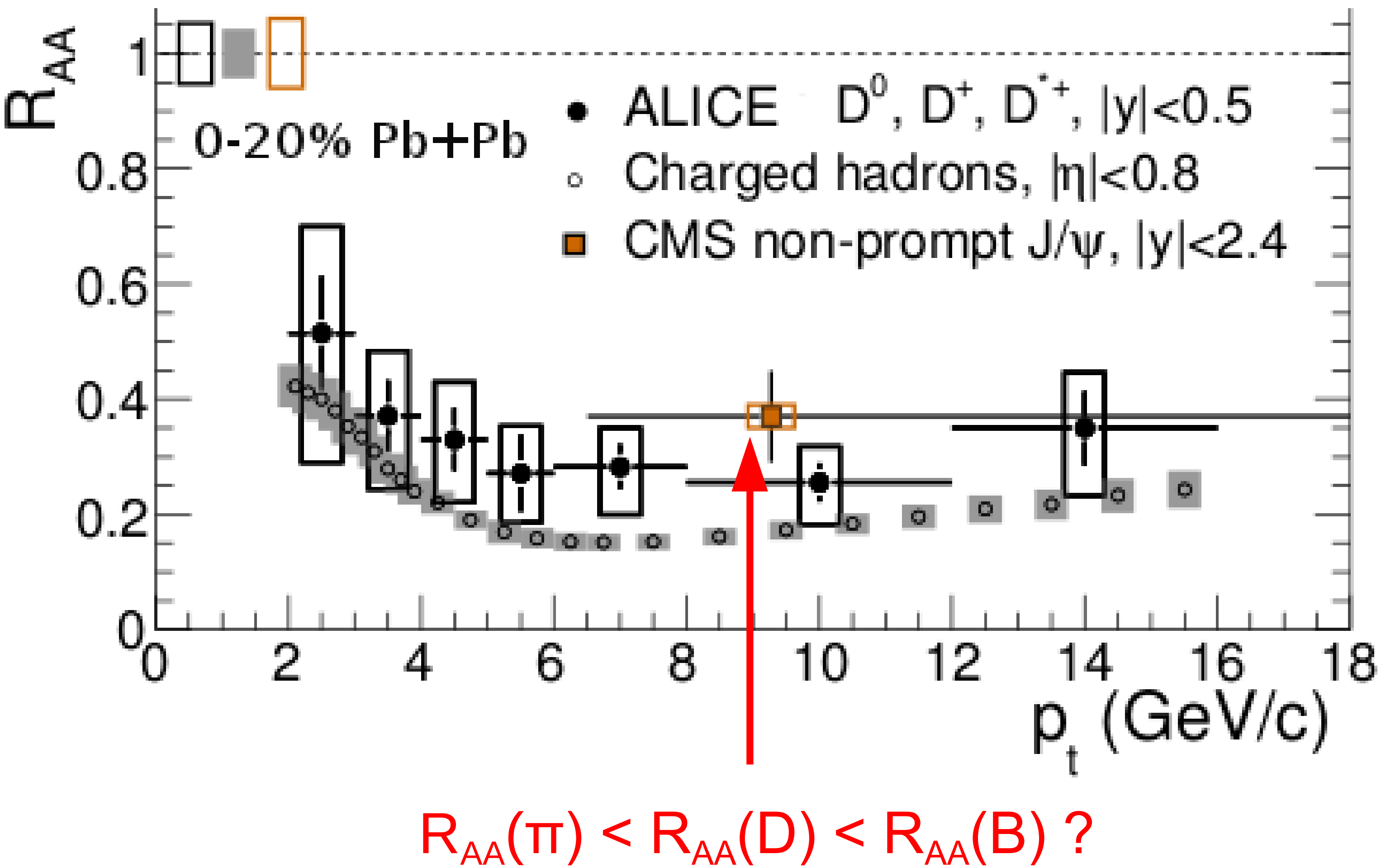
$\Delta E_g > \Delta E_{charm} > \Delta E_{beauty}$

↓

R_{AA}(light hadrons) < R_{AA}(D) < R_{AA}(B)

Prompt D-mesons and non-prompt J/ψ R_{AA}

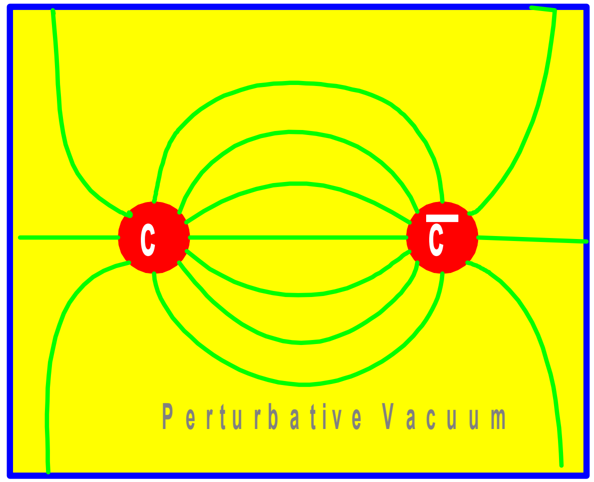
ALICE, JHEP 09 (2012) 112
CMS, JHEP 1205 (2012) 063

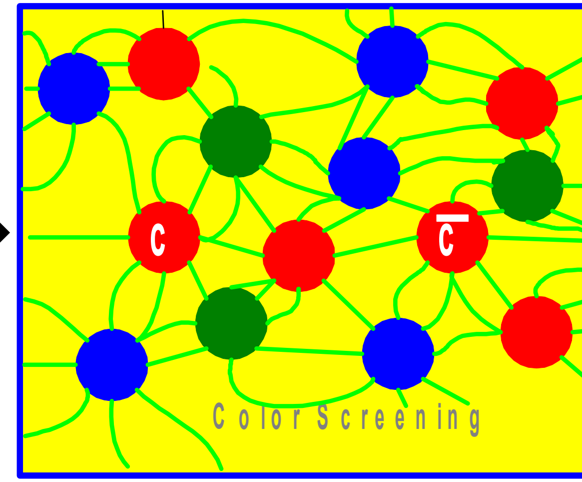


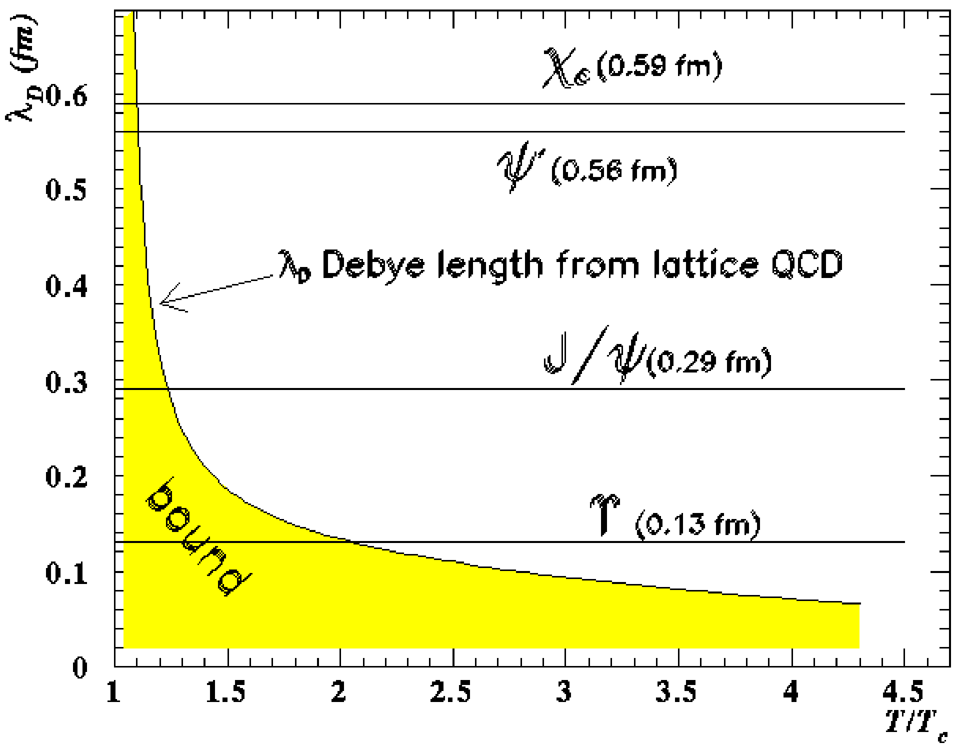
Suppression pattern may be compatible with expected energy loss hierachy

Charmonia and Bottomonia at high T

Screening of strong interactions in QGP





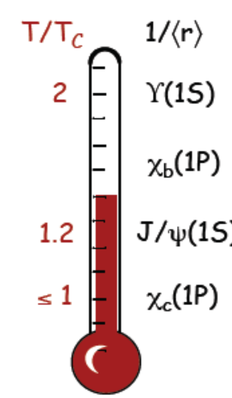


Screening stronger at high T

λ_D ~ maximum size of bound state decreases when T increases

Resonance melting

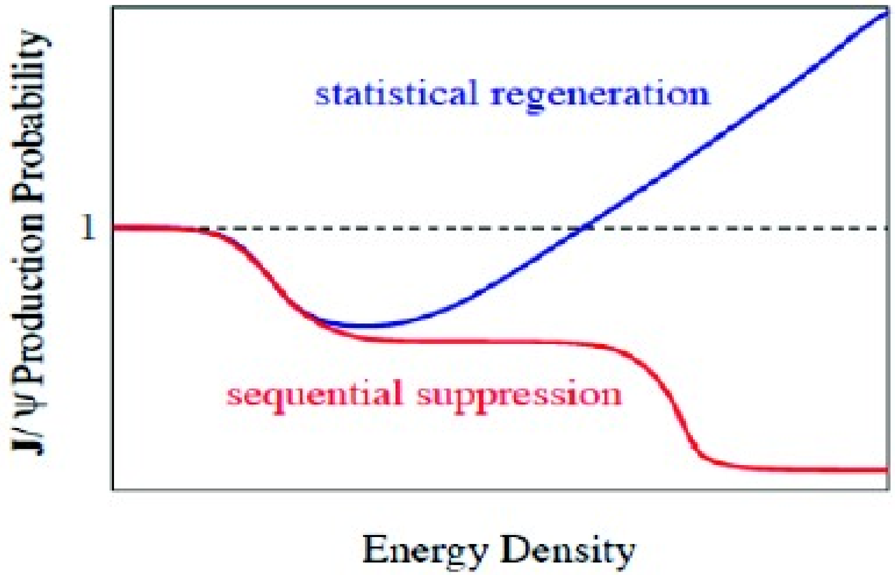
QGP thermometer



Regeneration at high temperature

At sufficiently high energy, the cc pair multiplicity becomes large

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

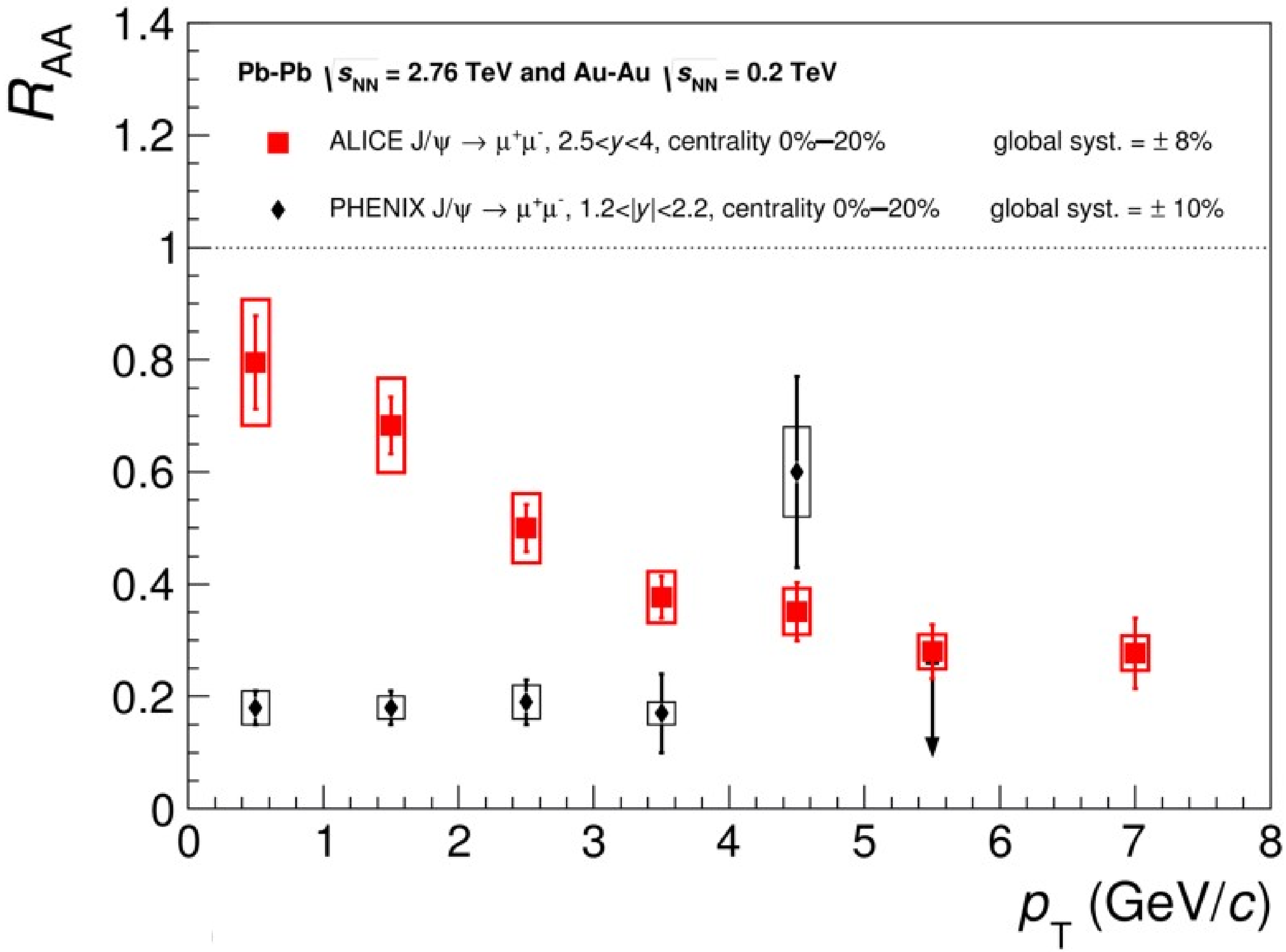


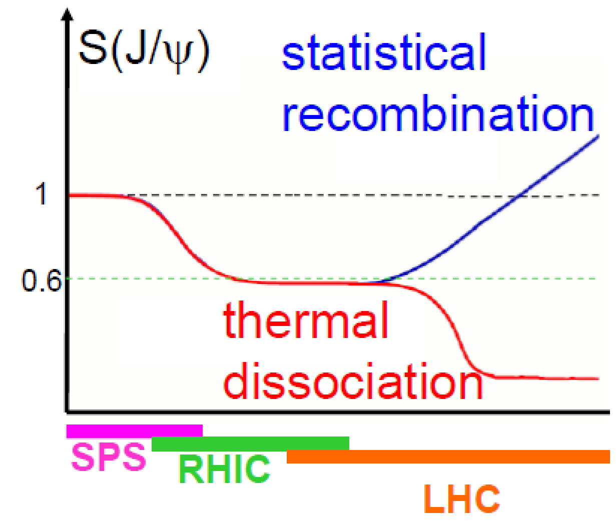
- Statistical approach
  - Charmonium fully melted in QGP
  - Charmonium produced together with all other hadrons at chemical freeze-out according to statistical weights
- Kinetic recombination
  - Continuous dissociation and regeneration over QGP lifetime

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

LHC: J/ψ production in Pb-Pb

PLB 734 (2014) 314

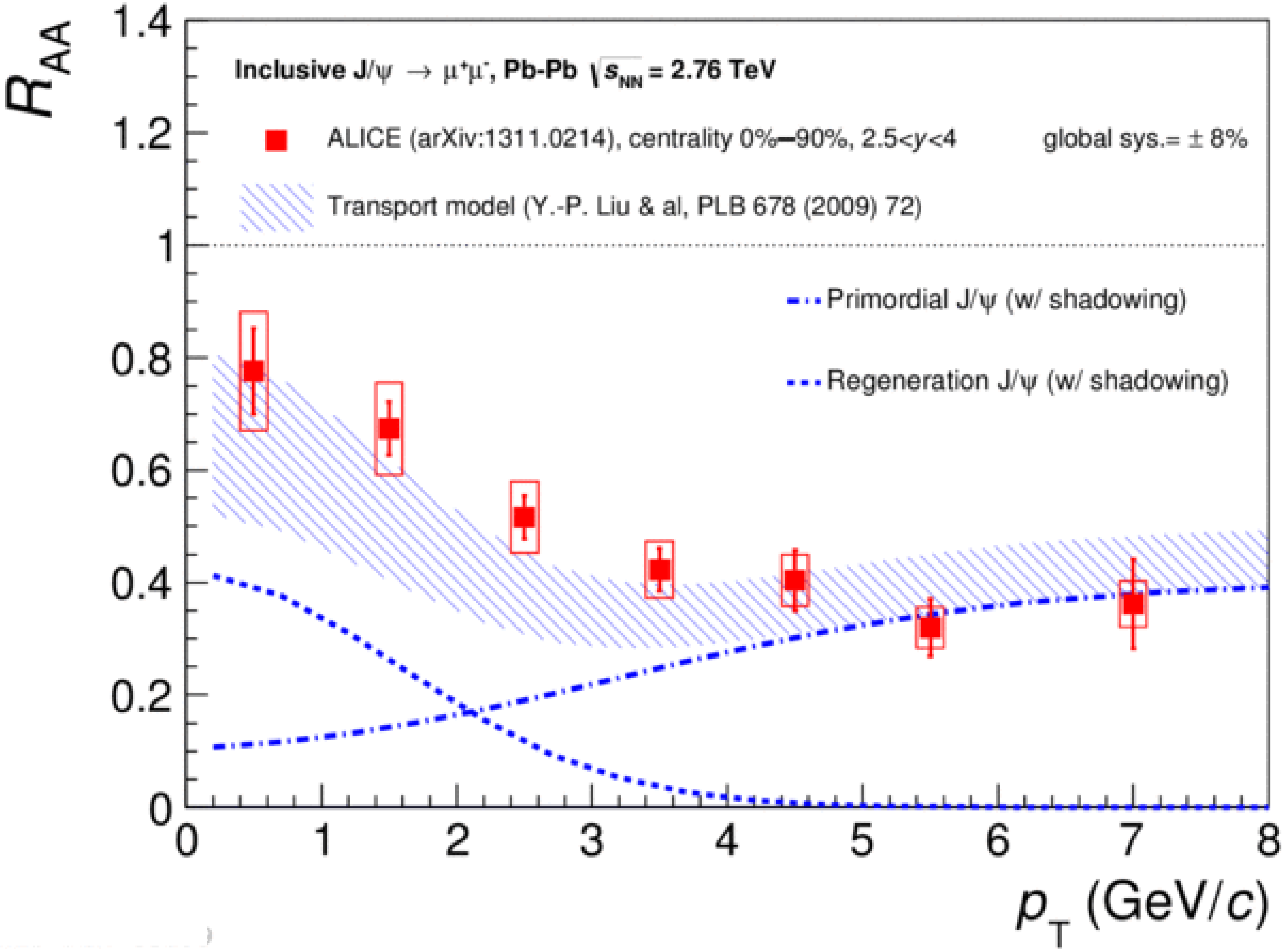


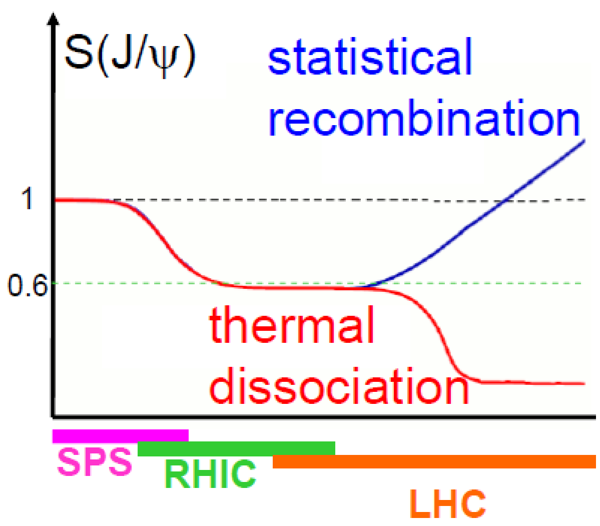


Different p_T (and centrality) dependence of J/ψ R_{AA} at LHC and RHIC

J/ψ production in Pb-Pb

PLB 734 (2014) 314

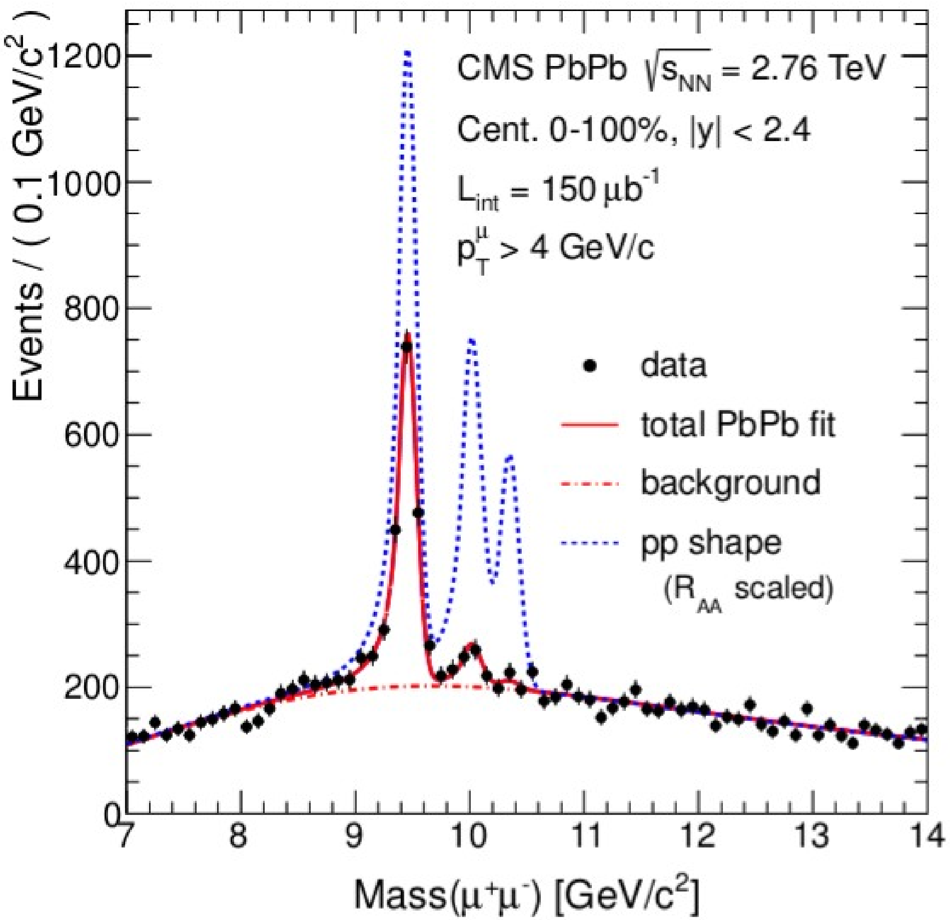


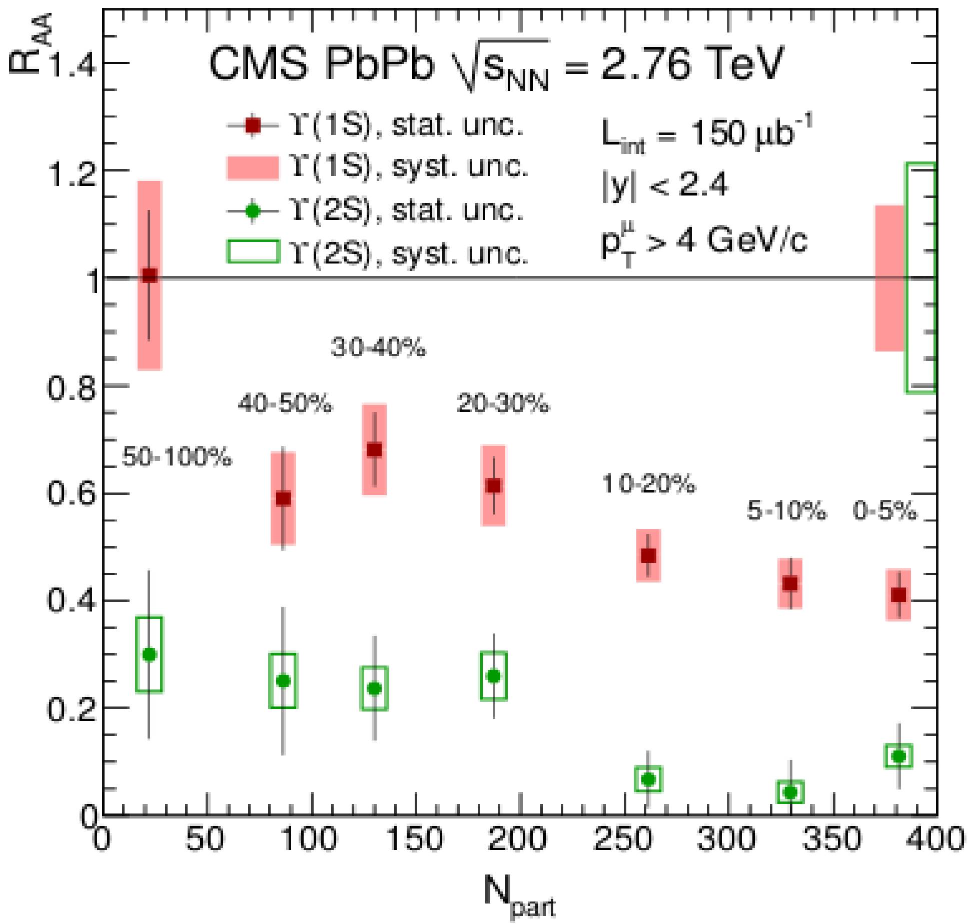


As expected in a scenario with $c\bar{c}$ recombination, especially at low p_T

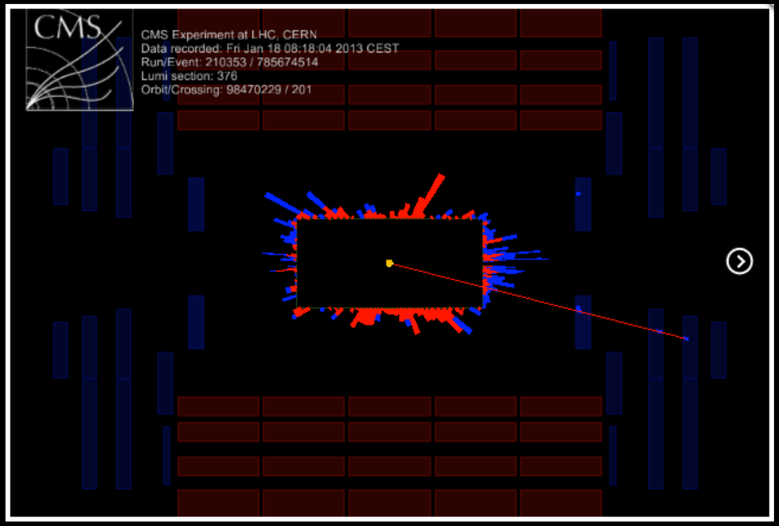
Suppression of Upsilon states

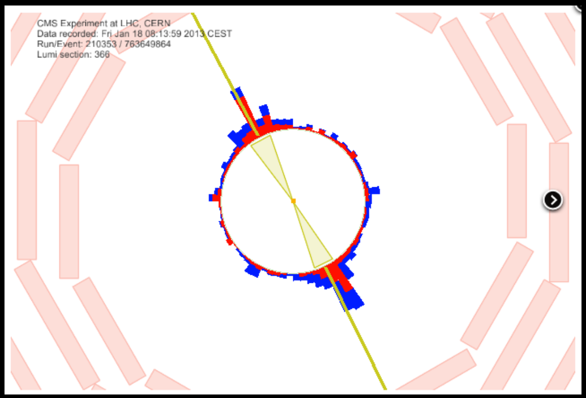
PRL 109 (2012) 222301

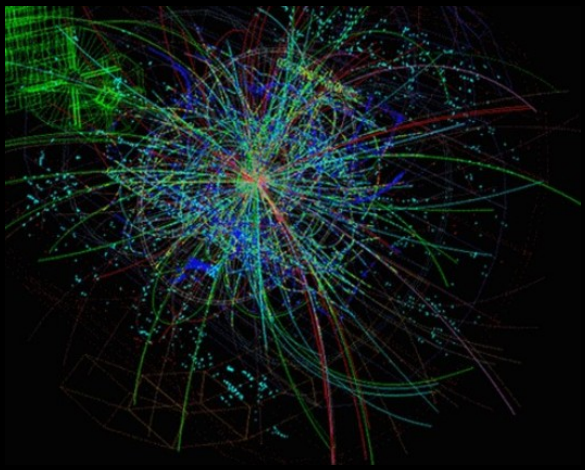


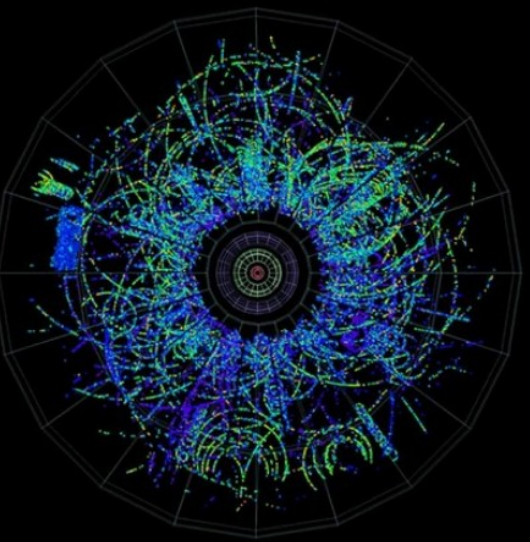


Suppression of Y(1S) ground, and excited Y(2S) and Y(3S) states.
Ordering of R(3S)<R(2S)<R(1S) consistent with sequential melting
(however it is not clear if concept applies as Y likely not thermalized)

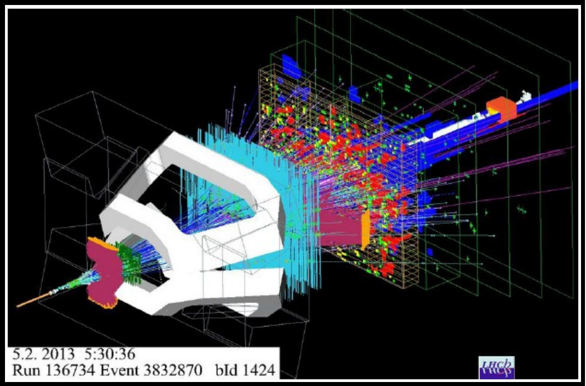


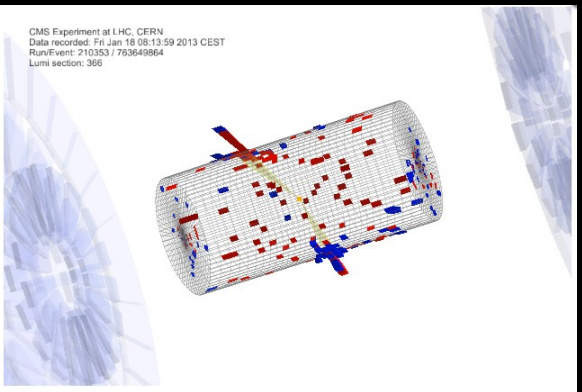


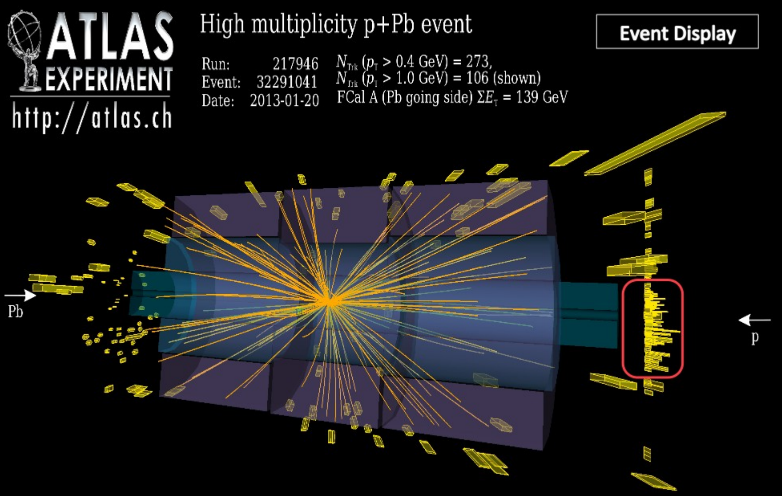


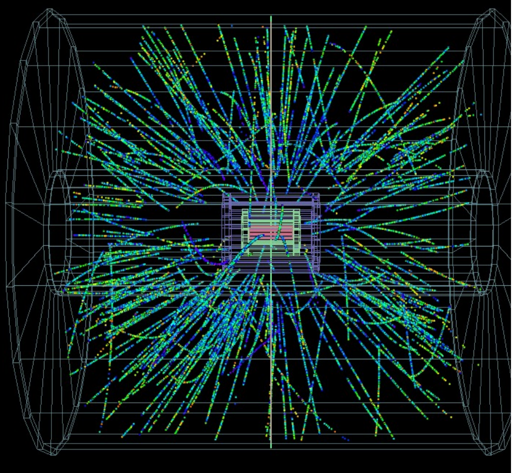


Results from pPb collisions at the LHC



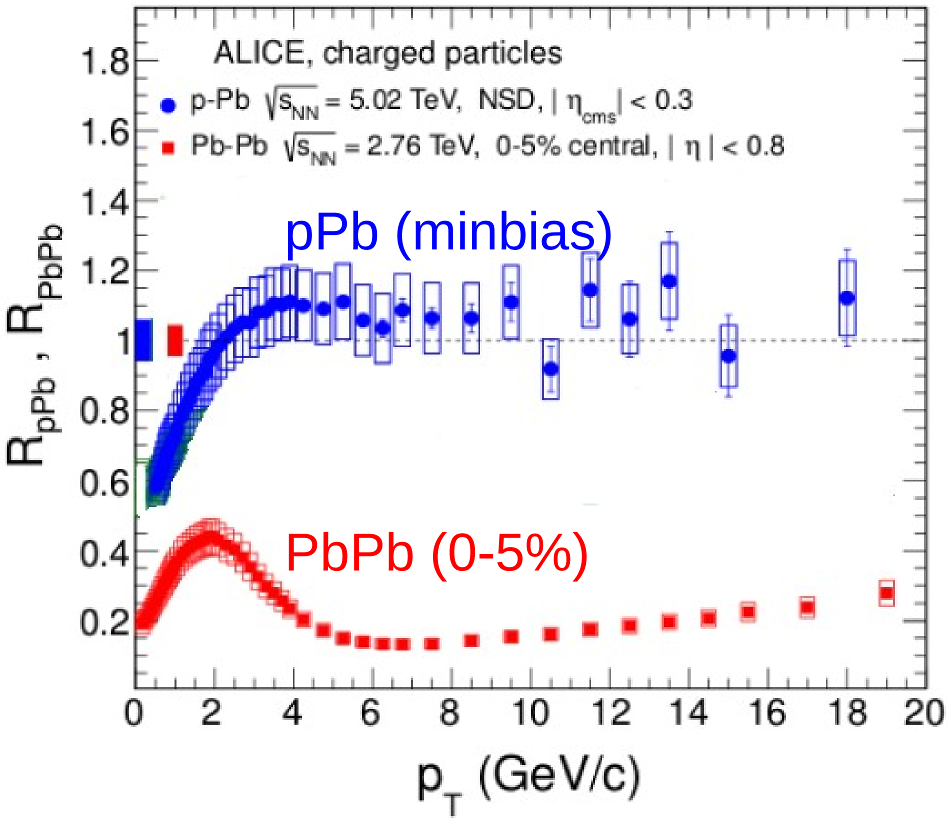




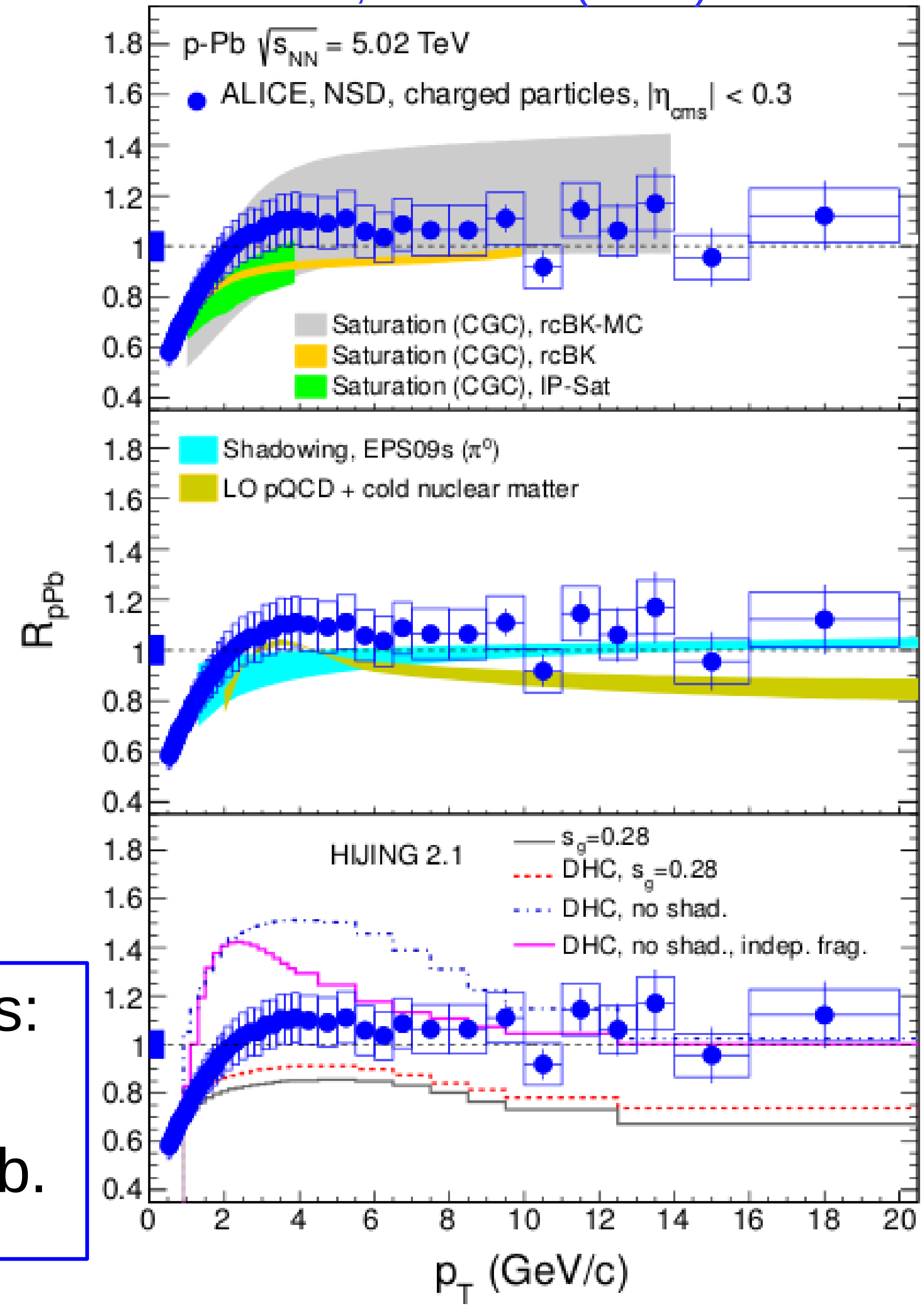


Charged particle R_{pPb}

$$R_{AB} = \frac{\mathrm{d}N_{AB}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$



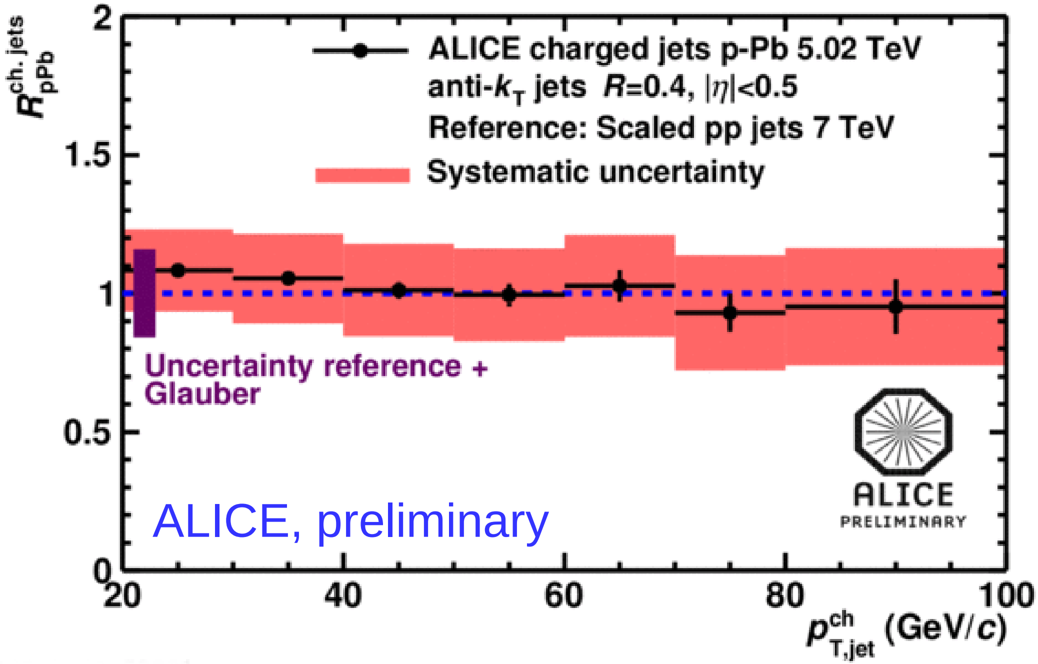
ALICE, PRL 110 (2013) 082302



No surprises at high p_T in first results:

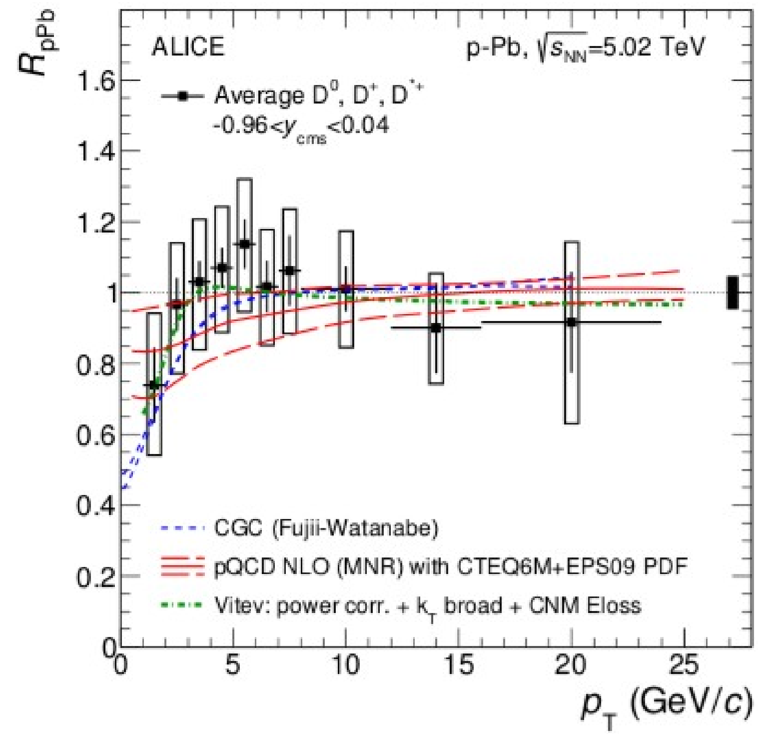
Supports existence of strong final state effects (at mid-rapidity) in PbPb.

More searches for effects at high-p_T

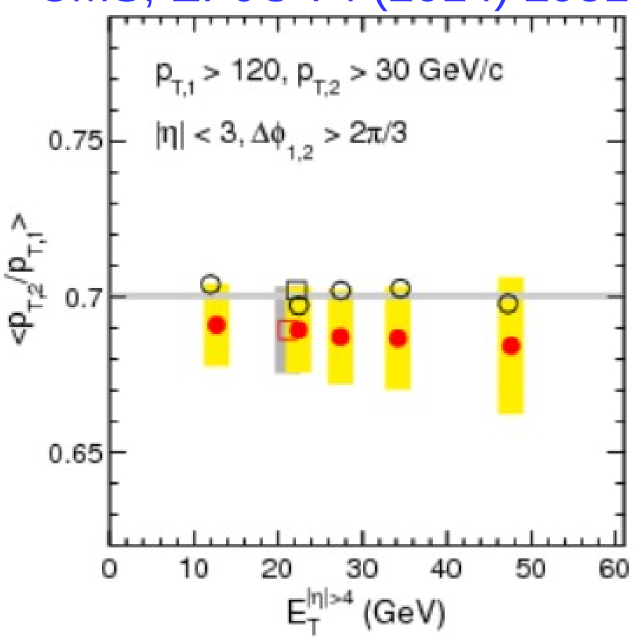


ALICE, preliminary

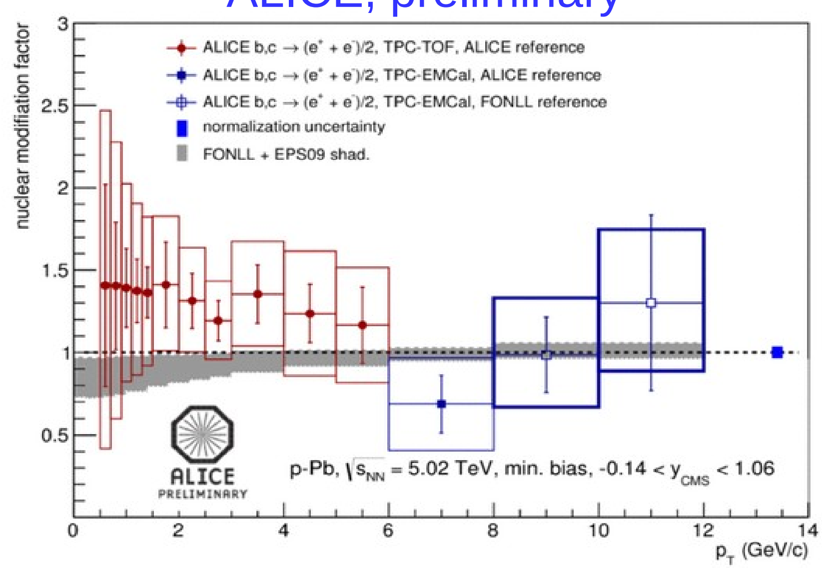
arXiv:1405.3452v1



CMS, EPJC 74 (2014) 2951

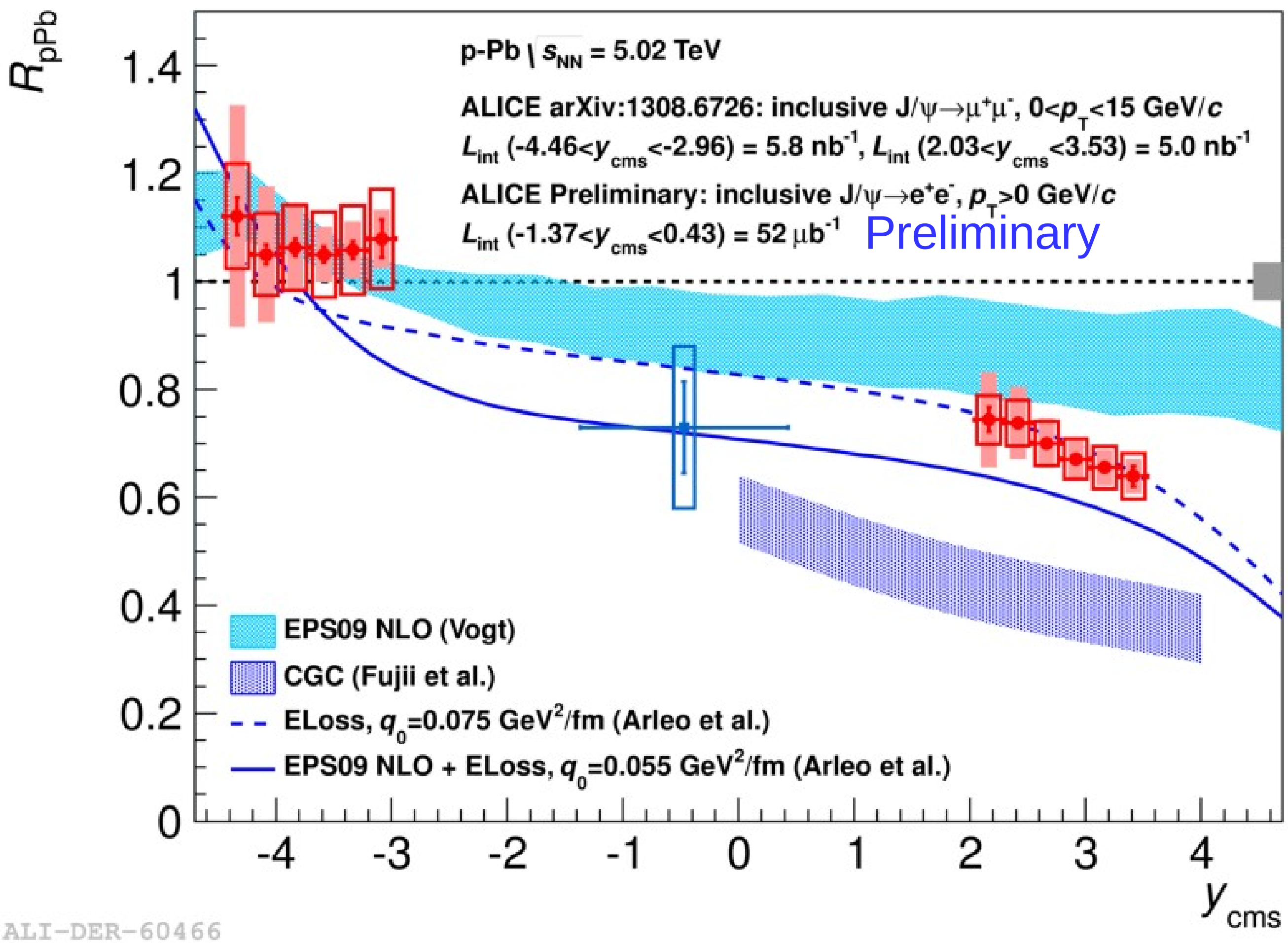


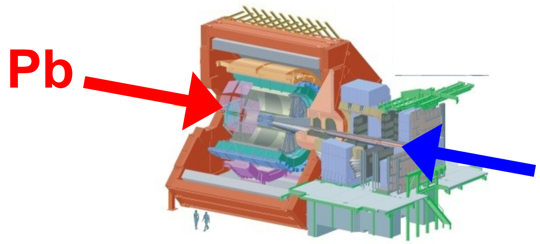
ALICE, preliminary

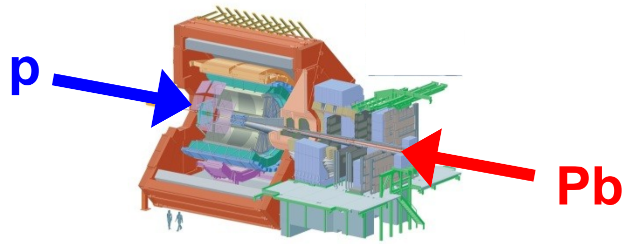


No (significant) modification for single and dijets, nor for Dmeson or HF electrons

J/ψ production versus rapidity in p-Pb



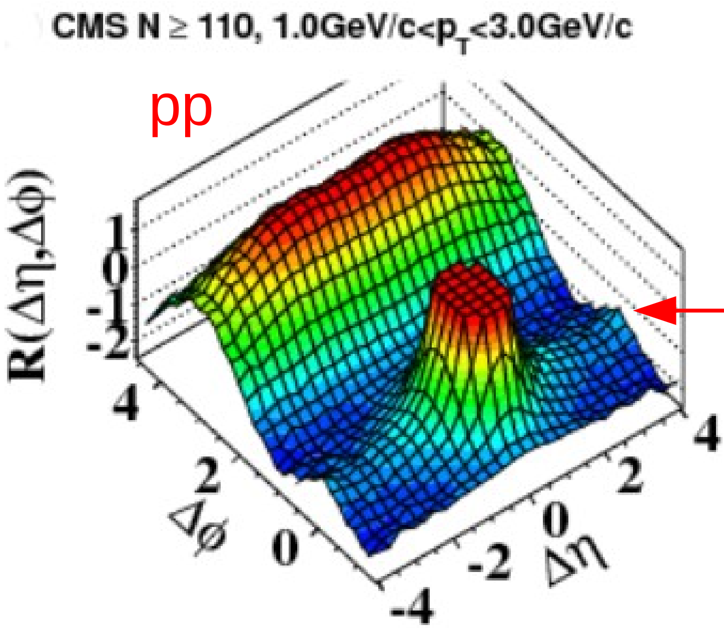




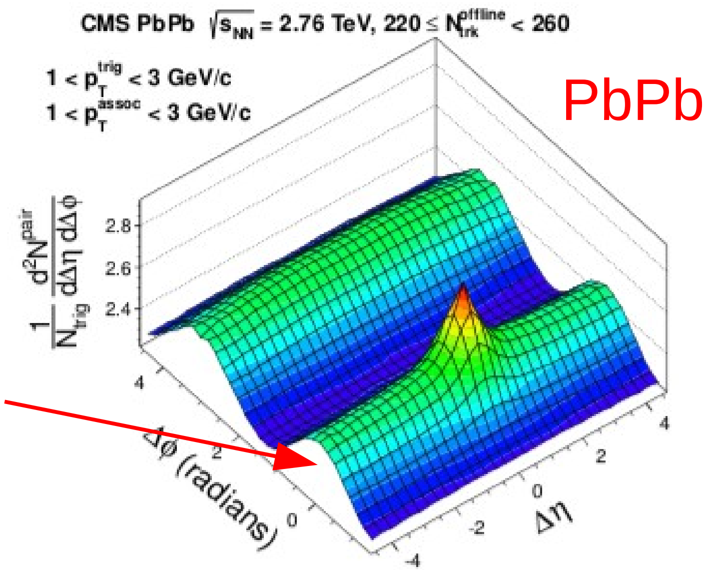
- Suppression at mid- and forward rapidity
  - Consequences for R_{AA}: Suggests even stronger recombination
- Consistent with shadowing models (EPS09 NLO) and/or coherent parton energy loss
- Specific CGC calculation disfavored

Two-particle angular correlations

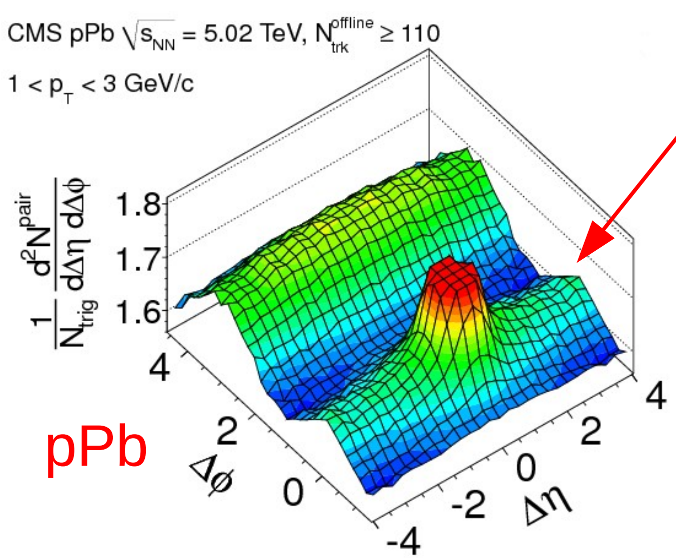
Near-side ridges apparent in high multiplicity events at LHC energies



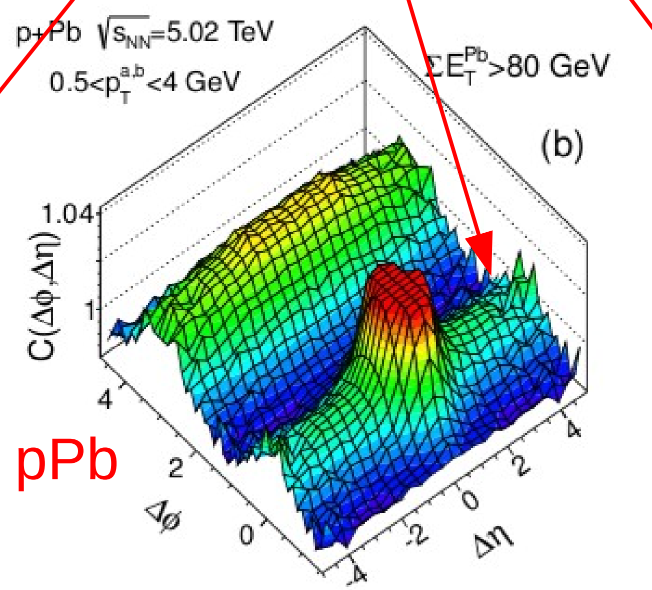
CMS, JHEP 1009 (2010) 91



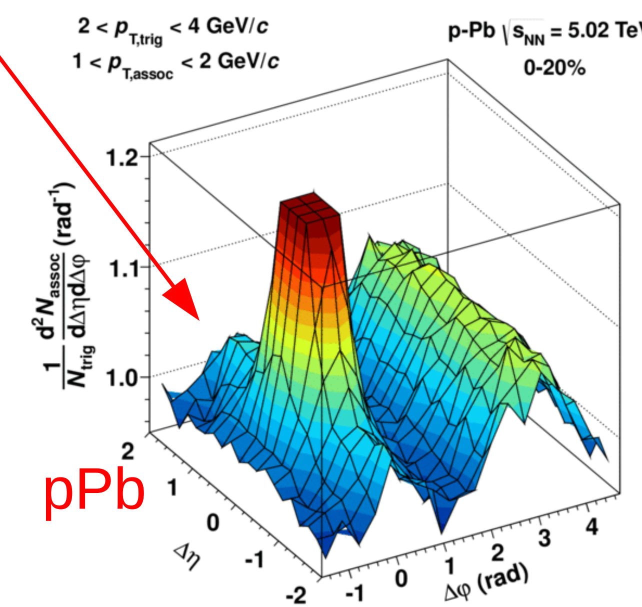
CMS, PLB 724 (2013) 213



CMS, PLB 718 (2012) 795

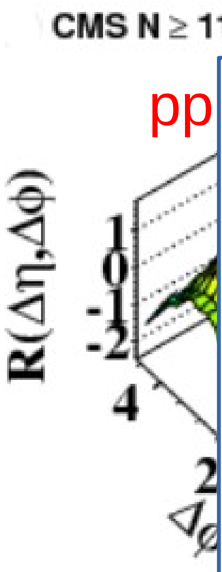


ATLAS, PRL 110 (2013) 182302



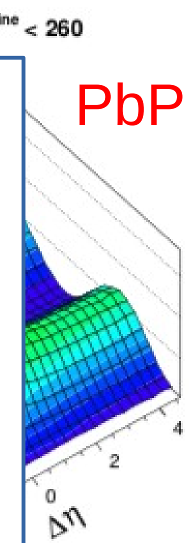
ALICE, PLB 719 (2013) 29

Two-particle angular correlations



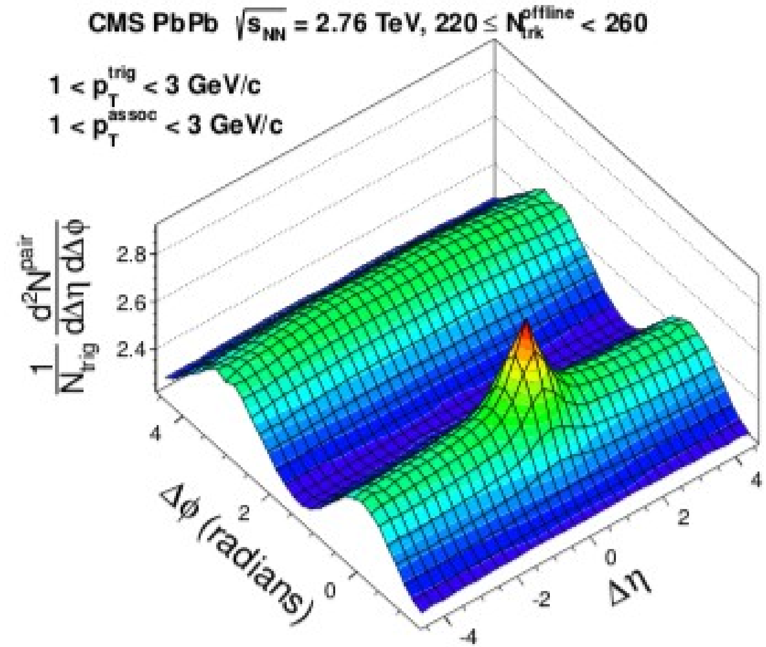
pp

CMS, J

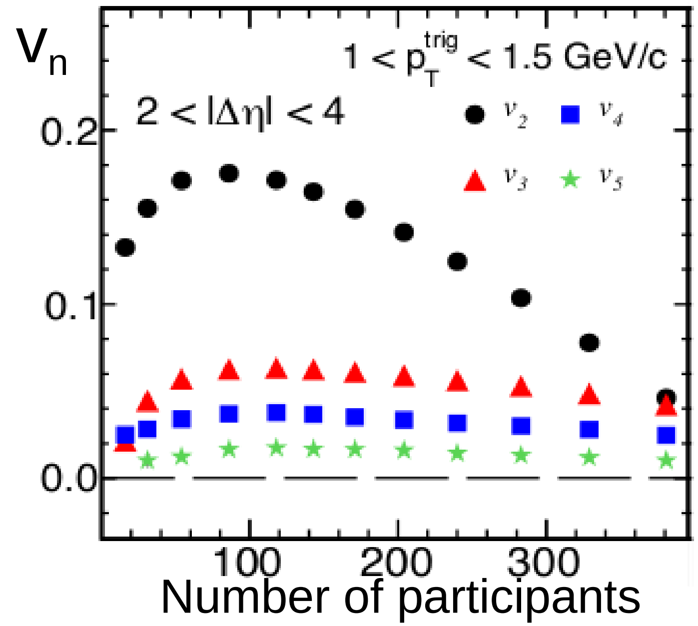


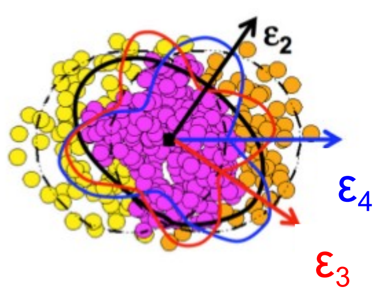
PbPb

013) 213



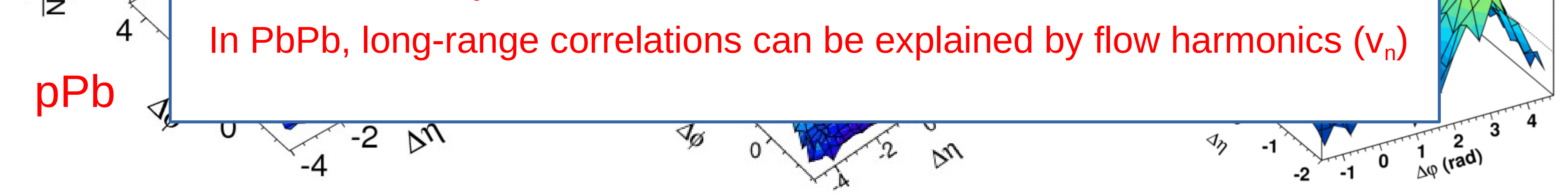
CMS, EPJC 72 (2012) 10052





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

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



pPb

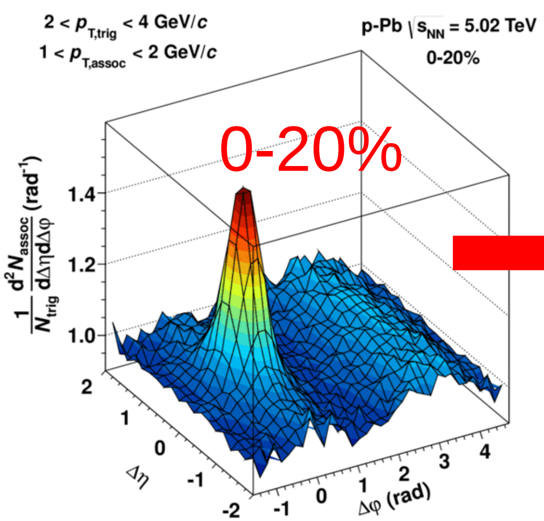
CMS, PLB 718 (2012) 795

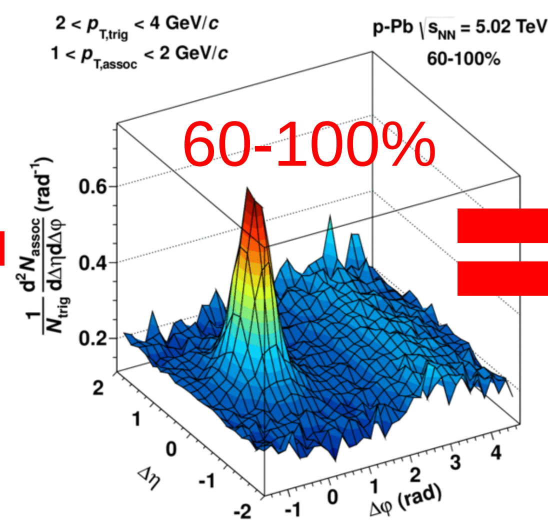
ATLAS, PRL 110 (2013) 182302

ALICE, PLB 719 (2013) 29

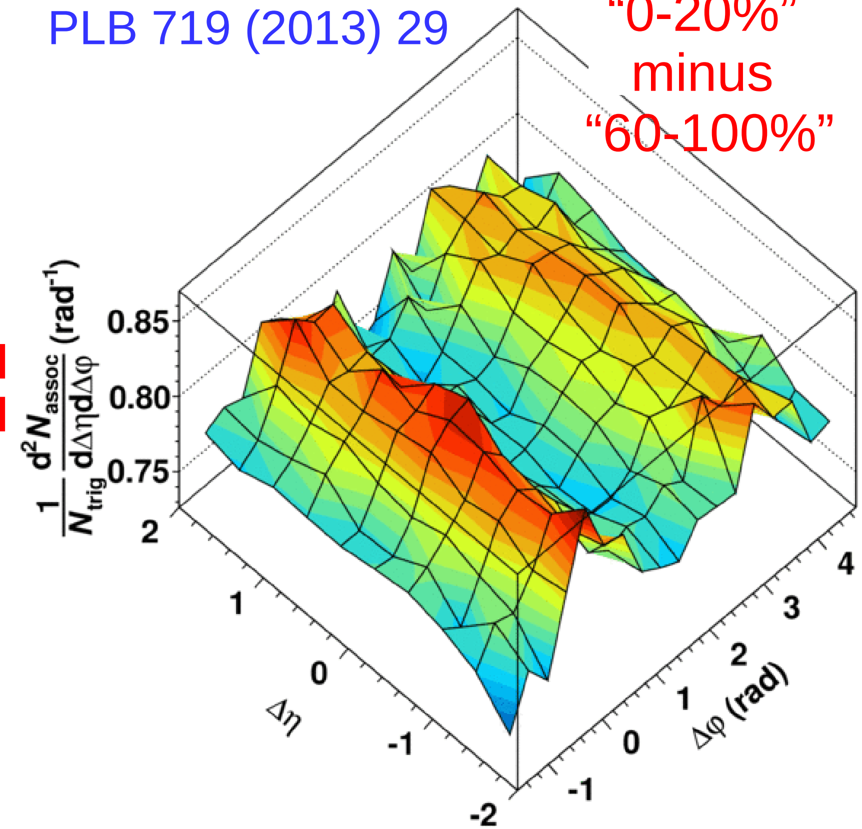
Extraction of double ridge structure

ALICE, PLB 719 (2013) 29





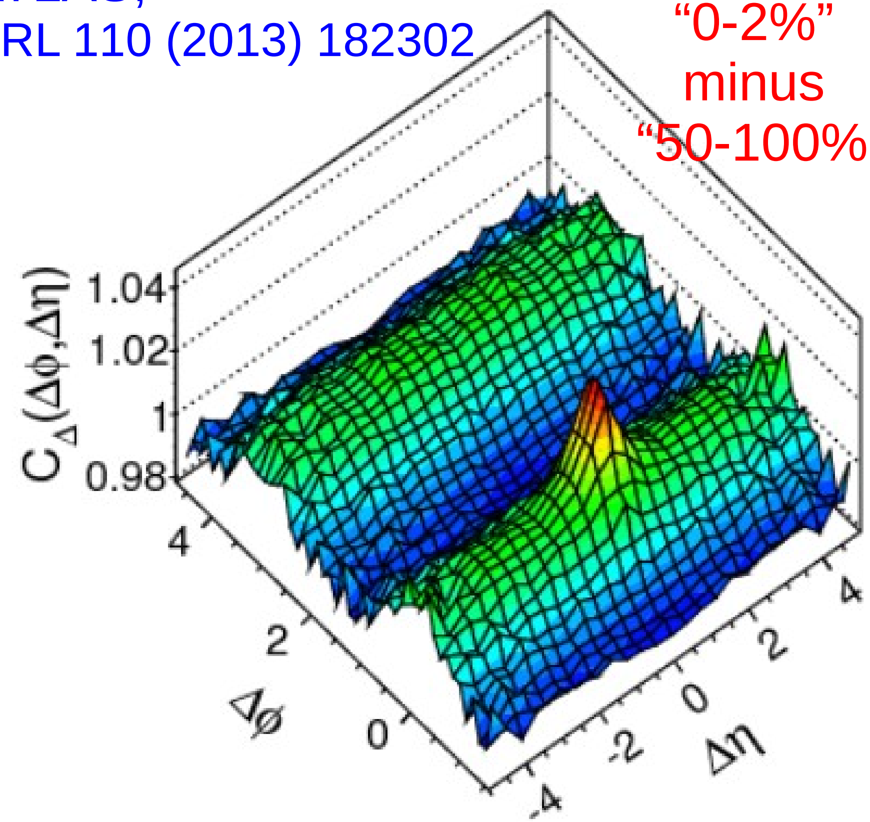
ALICE,
PLB 719 (2013) 29



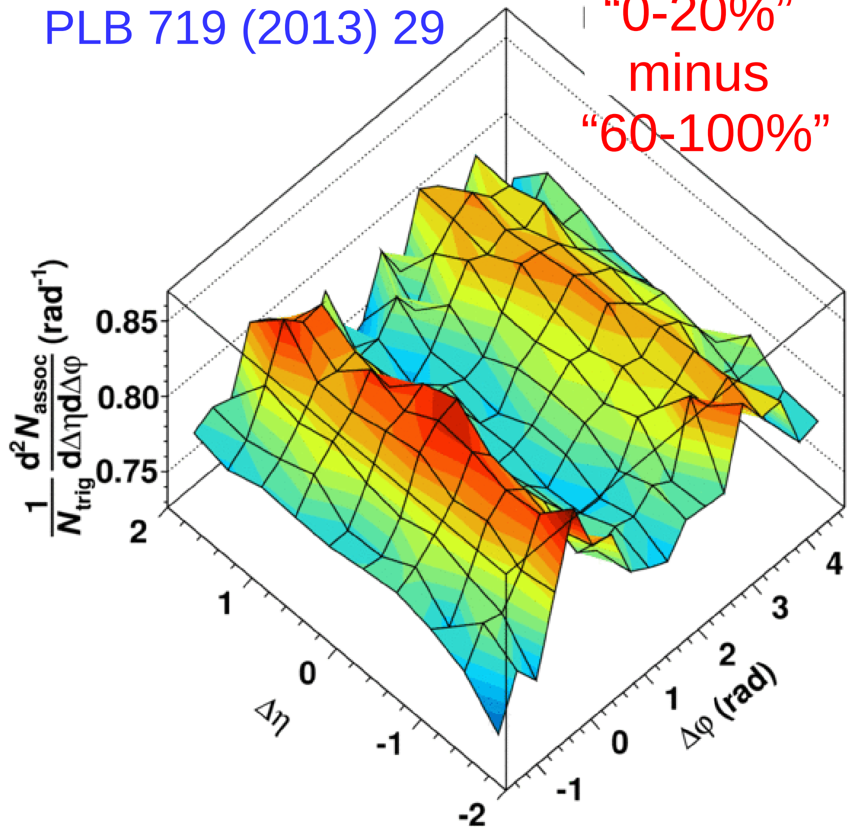
- Extract double ridge structure using a standard technique in AA collisions, namely by subtracting the jet-like correlations
  - Assumed that 60-100% class is free from non-jet like correlations

Extraction of double ridge structure

ATLAS,
PRL 110 (2013) 182302



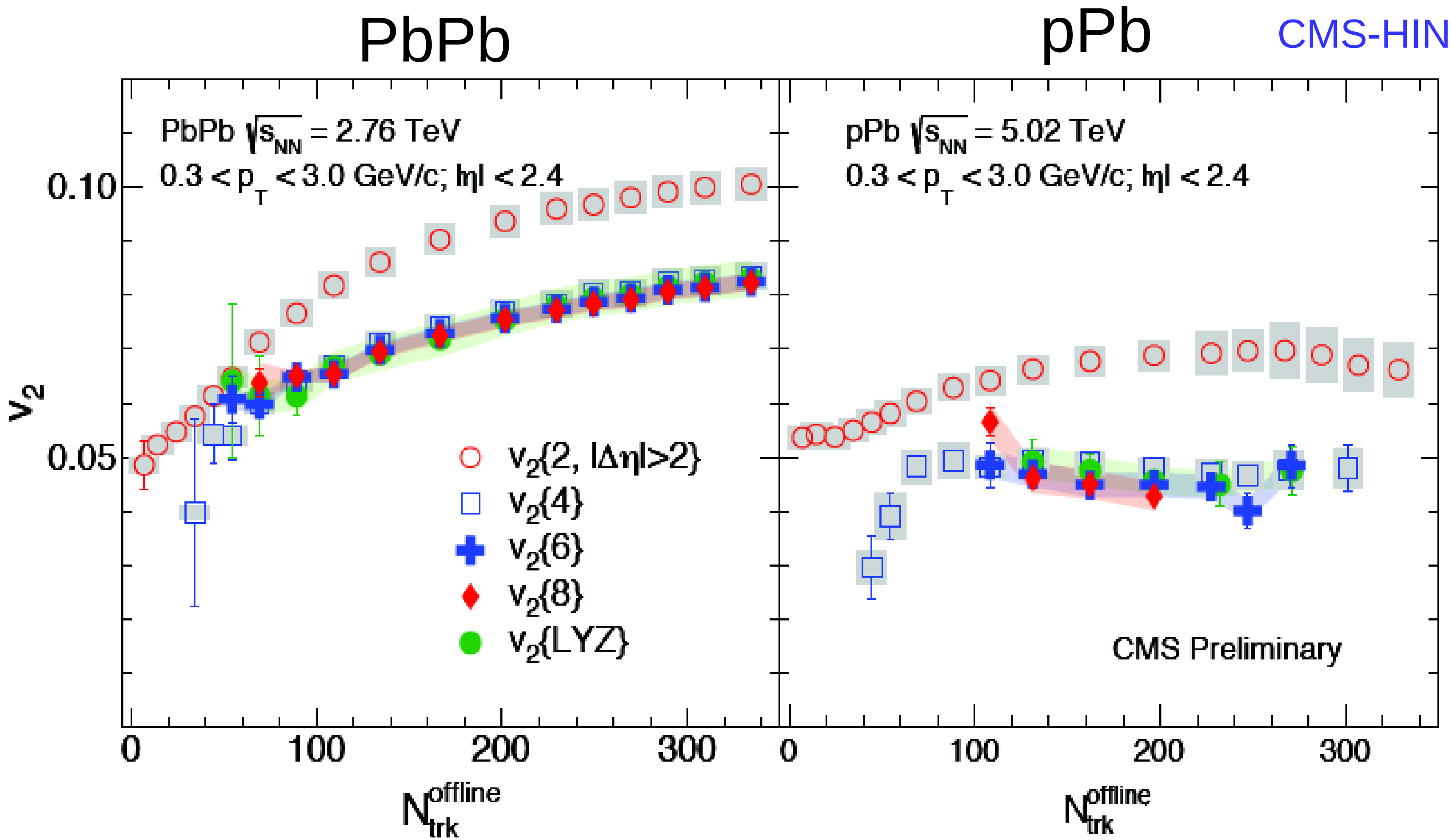
ALICE,
PLB 719 (2013) 29



- Extract double ridge structure using a standard technique in AA collisions, namely by subtracting the jet-like correlations
  - Assumed that 60-100% class is free from non-jet like correlations
  - Similar analysis strategy by ATLAS

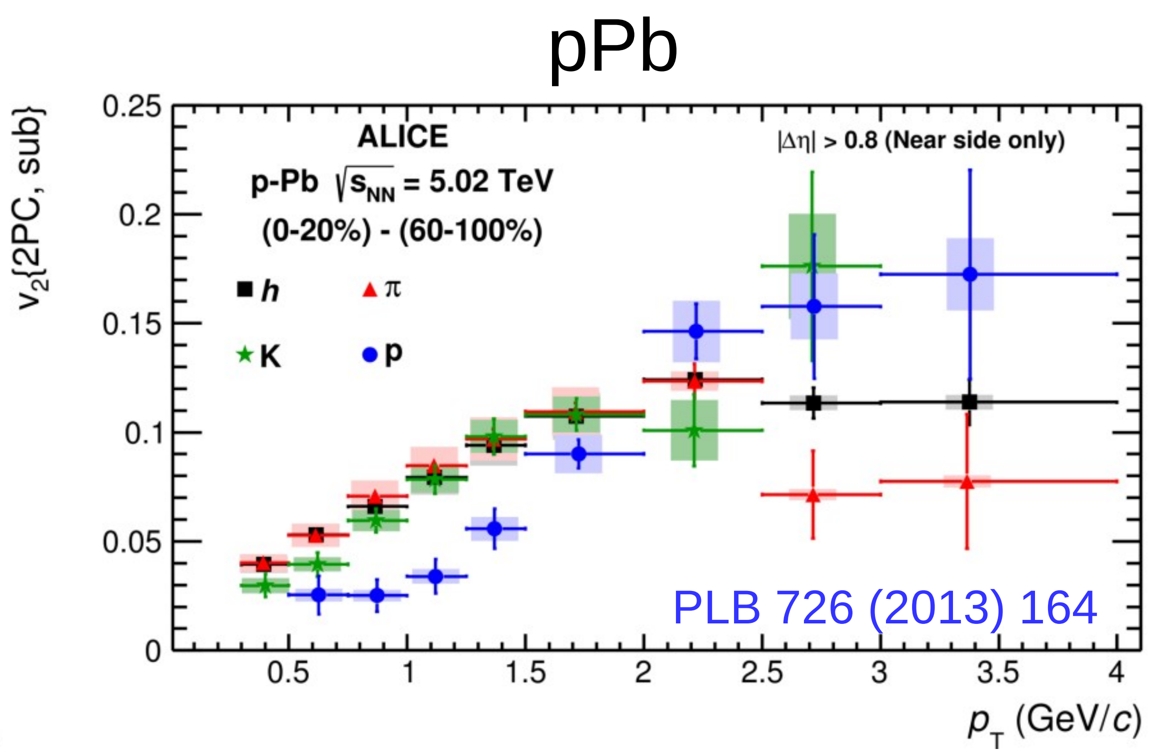
Multi-particle correlations: CMS

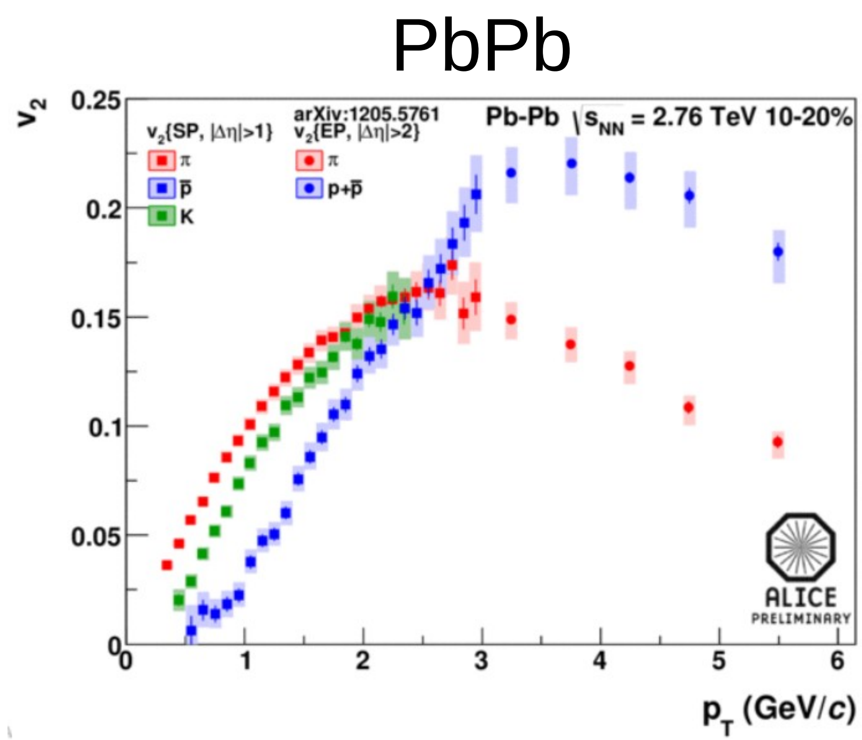
CMS-HIN-14-006



Multi-particle correlation results are the same within 10% in pPb
True collective effects in pPb?

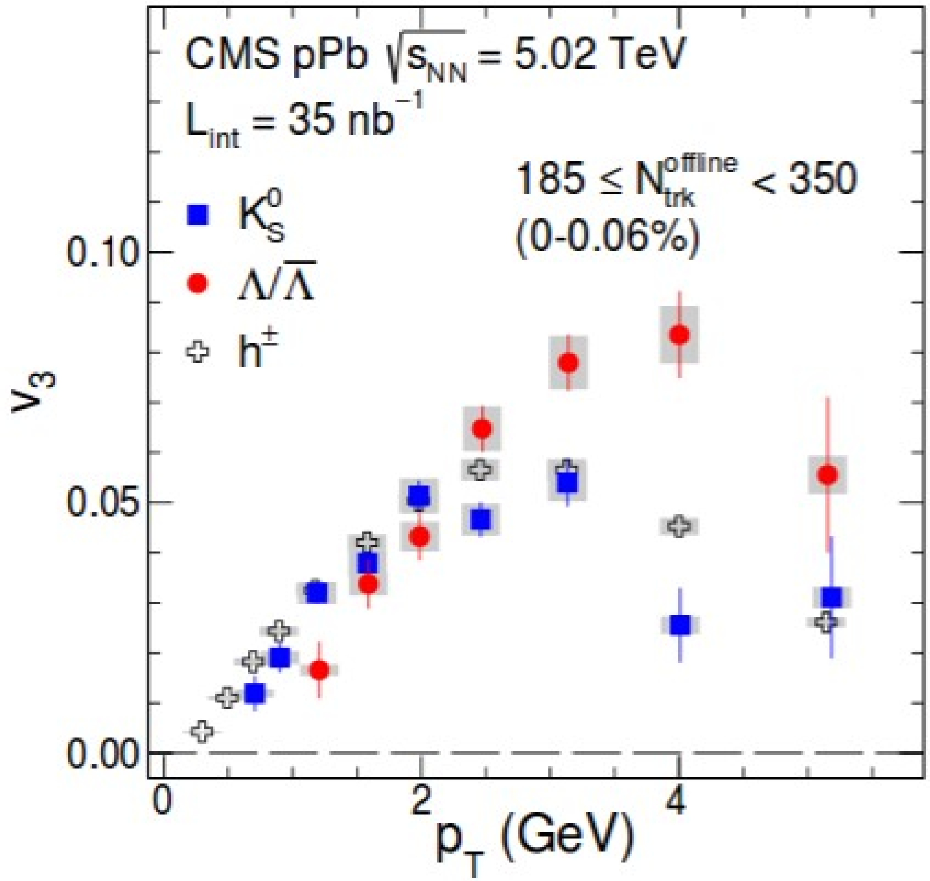
Identified particle v_2

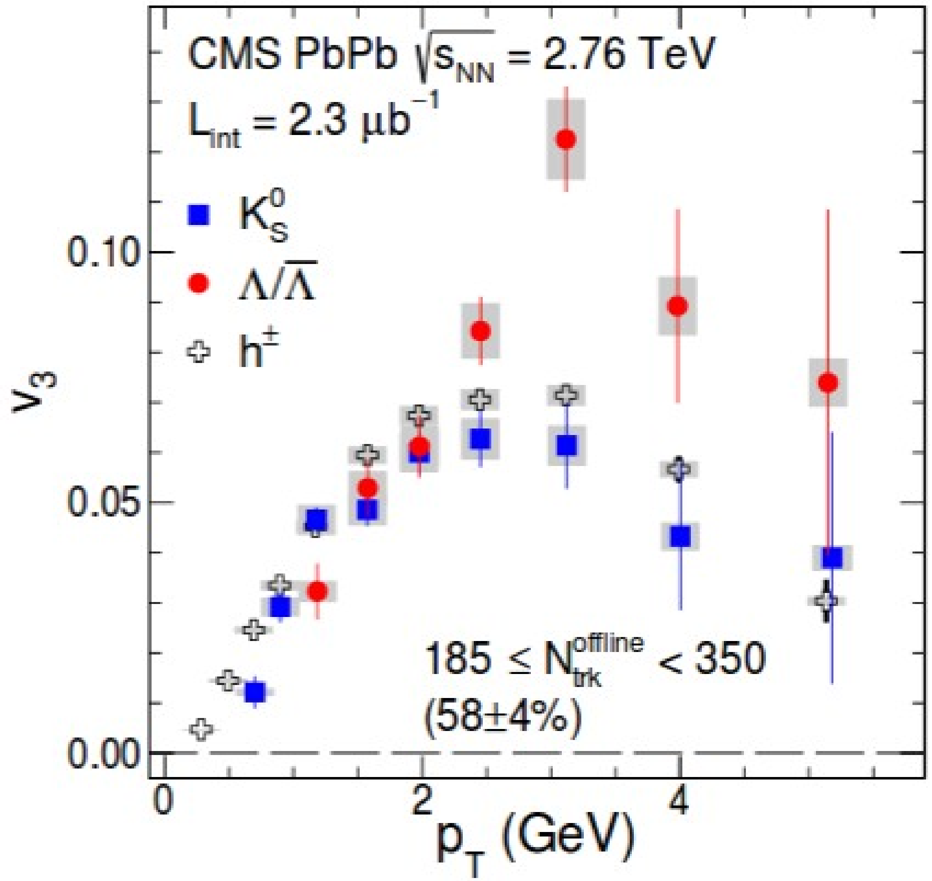




- Characteristic mass splitting observed as known from PbPb
- Crossing of proton and pion at similar p_T (2-3 GeV/c) with protons pushed further out in the pPb case
  - If interpreted in hydro picture, suggestive of strong radial flow

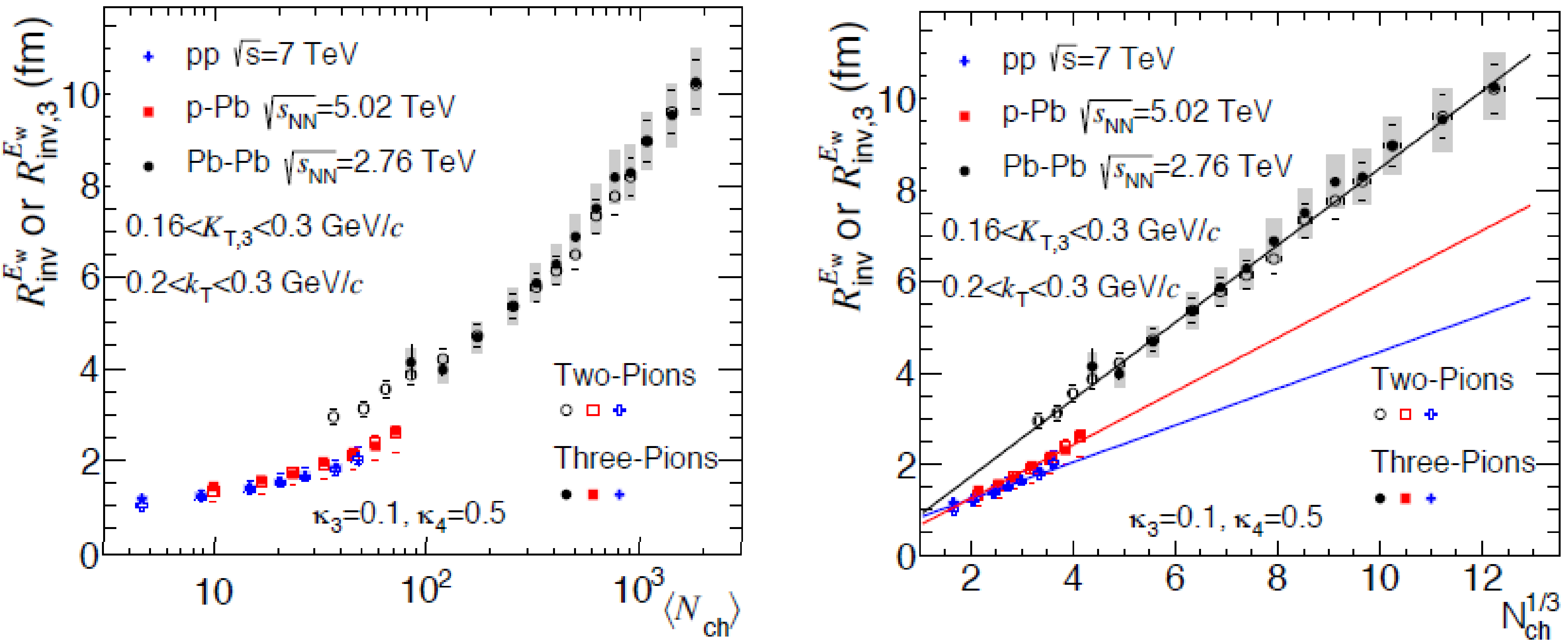
Identified particle v_3





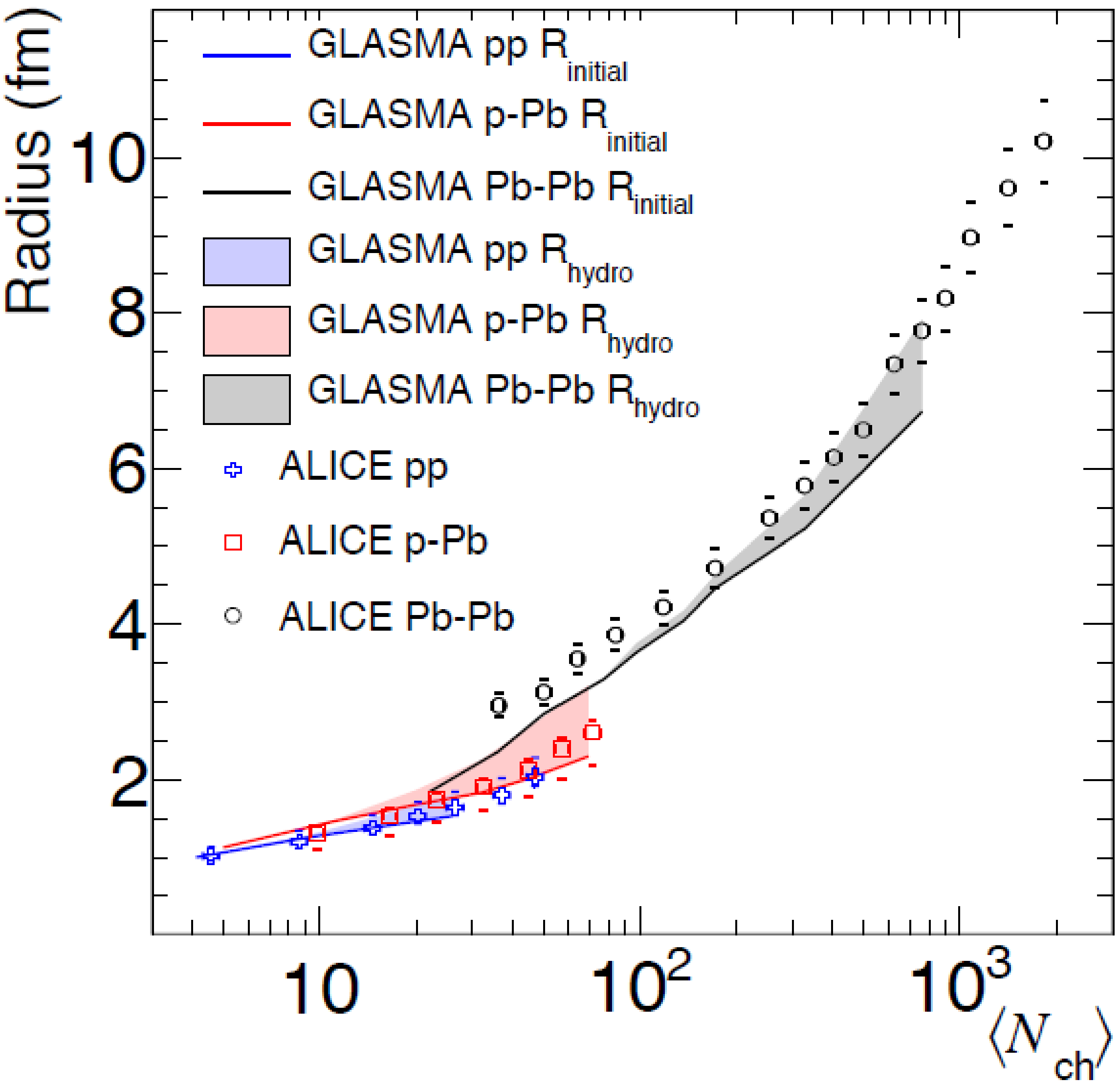
Also for v_3, crossing at around 2 GeV/c,
same physics origin for v_3 in pPb as in PbPb?

Freeze-out radii (R_{inv}) vs N_{ch}



- Exhibit different trend (with linear fit over measured region)
- Radii in pp and pPb at similar measured Nch are with 5-15% while larger difference (up to 30-50%) between pPb and PbPb
- Not much room for a hydro-dynamical expansion in pPb beyond what might already be there in pp

Radii comparison with IP-Glasma model



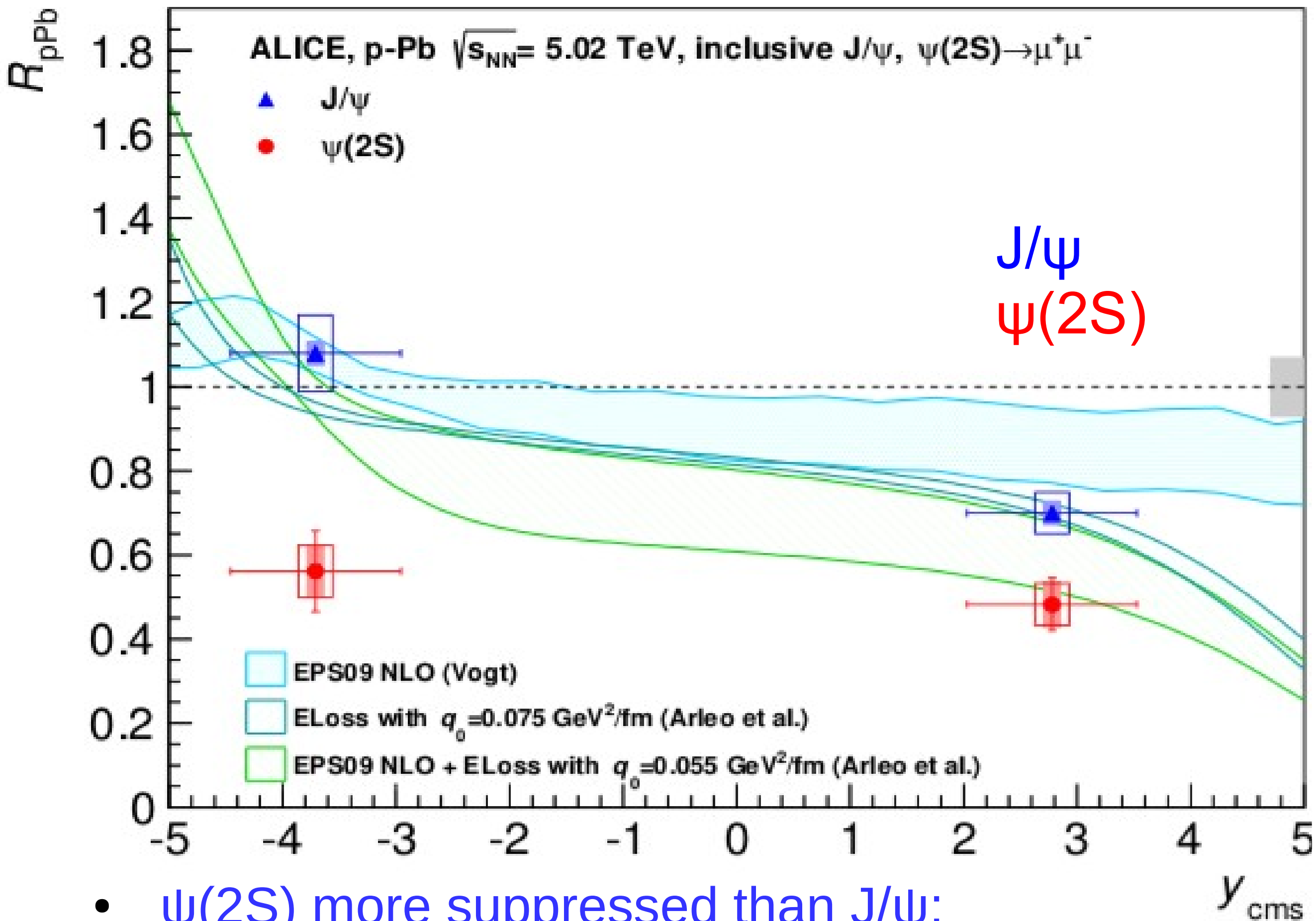
- Similarity between radii in pPb and pp can be described by Yang-Mills evolution alone
- They also can be reproduced by adding a hydrodynamic phase

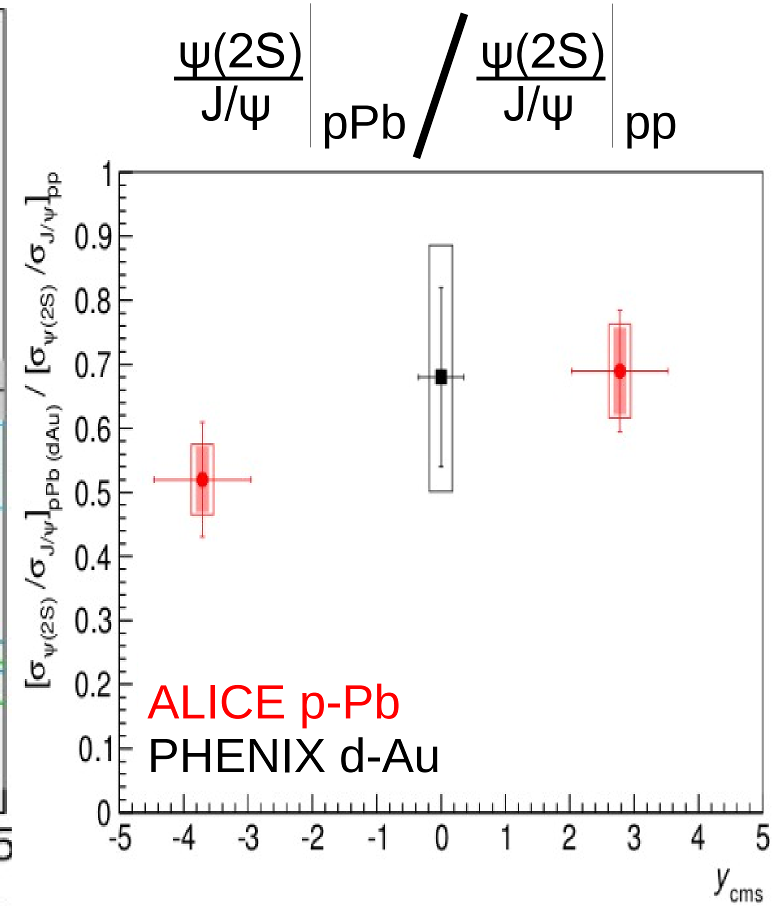
GLASMA points are first scaled such that the calculations in pp match the ALICE pp data. Scale = 1.15. GLASMA calculations have uncertainty due to infrared cutoff (m=0.1 GeV).

Schenke, Venugopalan, arXiv:1405.3605

ψ(2S) production in p-Pb

arXiv:1405.3796





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

Summary/Outlook

- As at RHIC, the QGP formed at the LHC behaves like a strongly interacting liquid, almost opaque for colored high p_T processes
  - Indication that η/s larger than at RHIC
  - Indication of partonic energy loss flavor and mass hierarchy
  - Indication of J/ψ recombination
- But prominent signatures of collectivity also present in pPb question our understanding of the baseline
  - Opportunity at LHC to consistently study high mult. pp, pPb and (peripheral) PbPb collisions at high energy
- Run 2 and run 3 will provide orders of magnitude more data
  - Will enable more differential and qualitatively new results
- Only a selection of all available results shown, you find them here

ALICE results: http://aliceinfo.cern.ch/ArtSubmission/publications

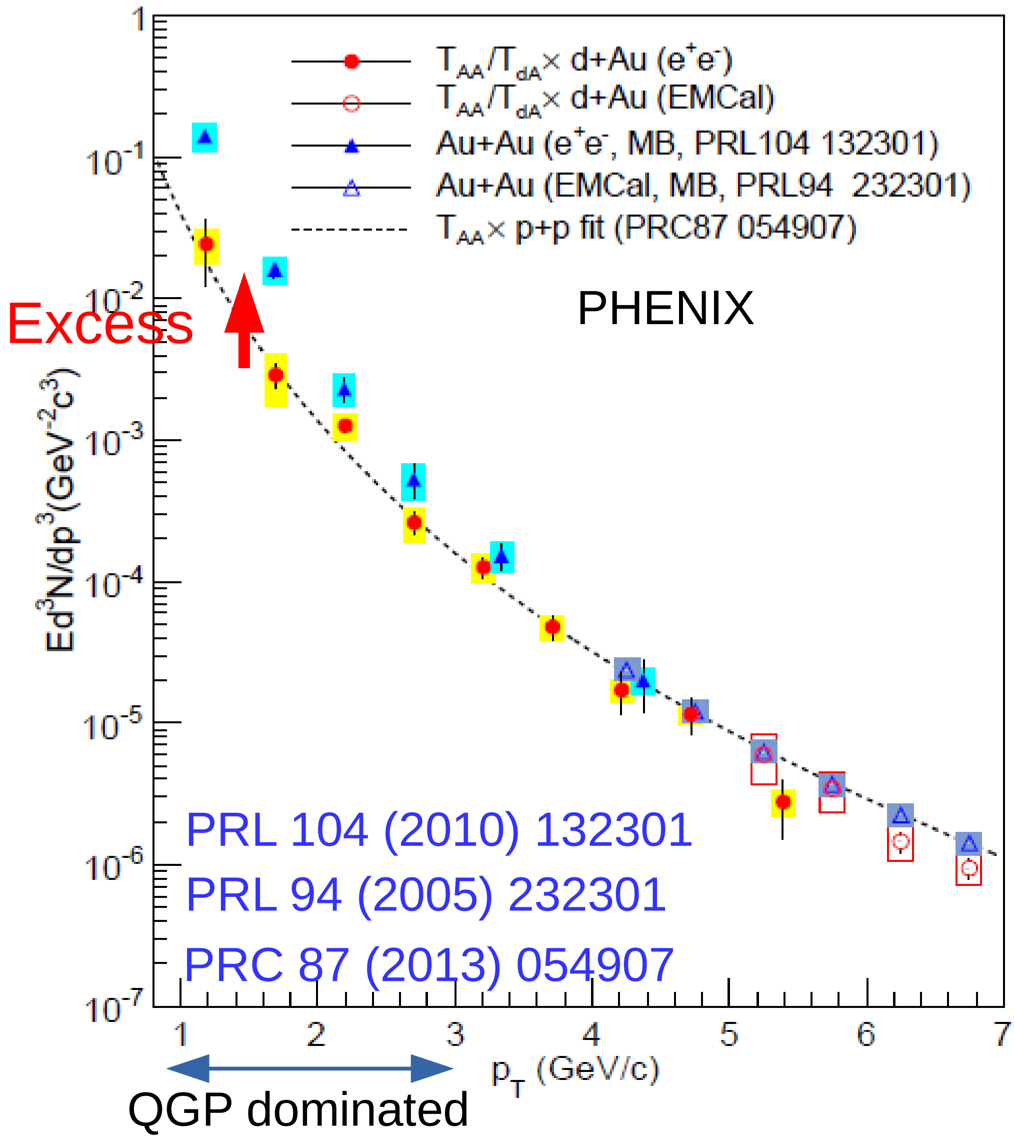
ATLAS results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

CMS results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

Extra

Initial temperature at RHIC

Direct photons: No charge, no color, ie. they do not interact after
Use (at low p_T) to extract temperature of the system.



- Different measurements performed using real and virtual photons
- Exponential (thermal) shape with inverse slope of T~200 MeV in excess region
- No excess seen in d+Au (or pp)

Initial temperature at RHIC

Direct photons: No charge, no color, ie. they do not interact after
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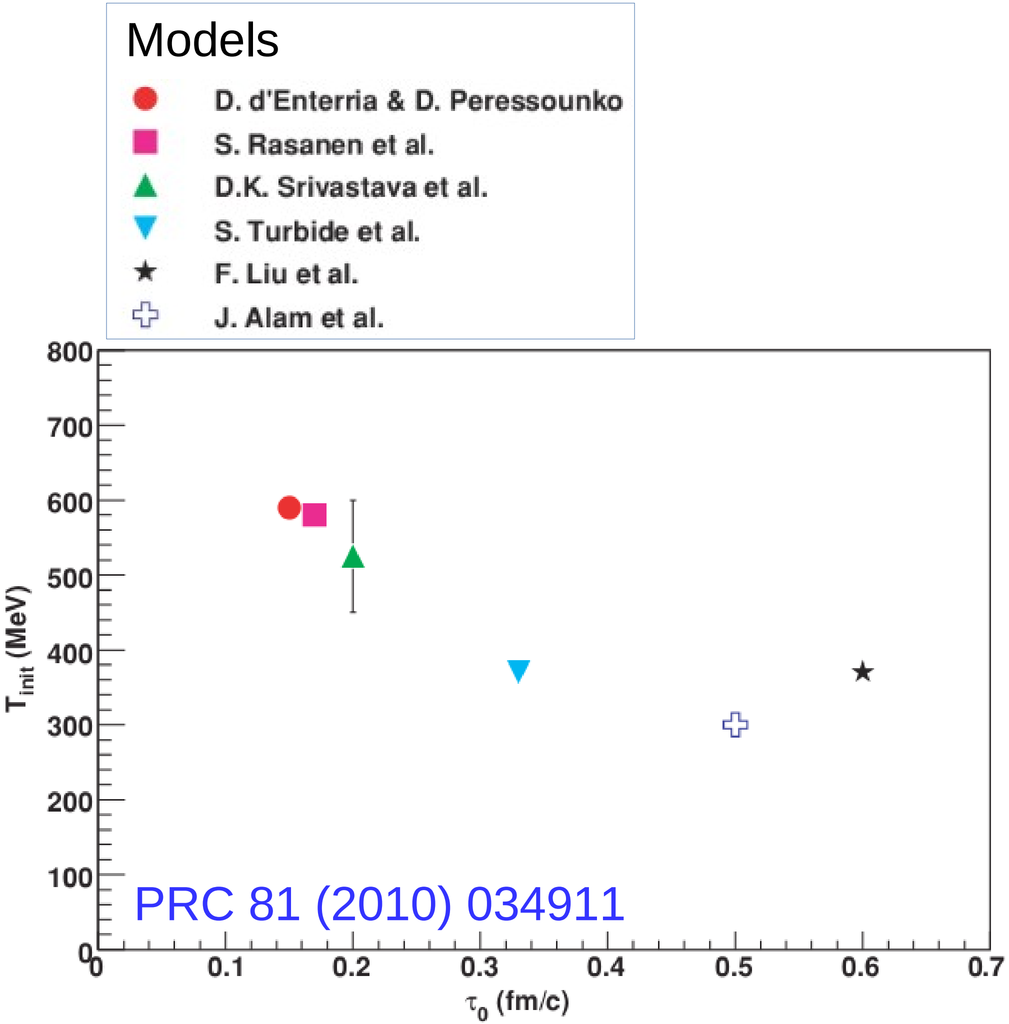


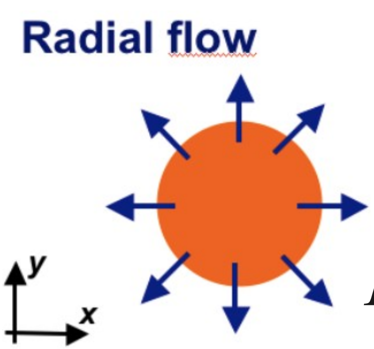
- Different measurements performed using real and virtual photons
- Exponential (thermal) shape with inverse slope of T~220 MeV in excess region
- No excess seen in d+Au (or pp)
- Emission rate and shape consistent with that from equilibrated matter
- From models:
  T_{init} = 300 - 600 MeV (> 2 Tc)

First experimental observation of $T>T_c$

Radial flow and kinetic freeze-out

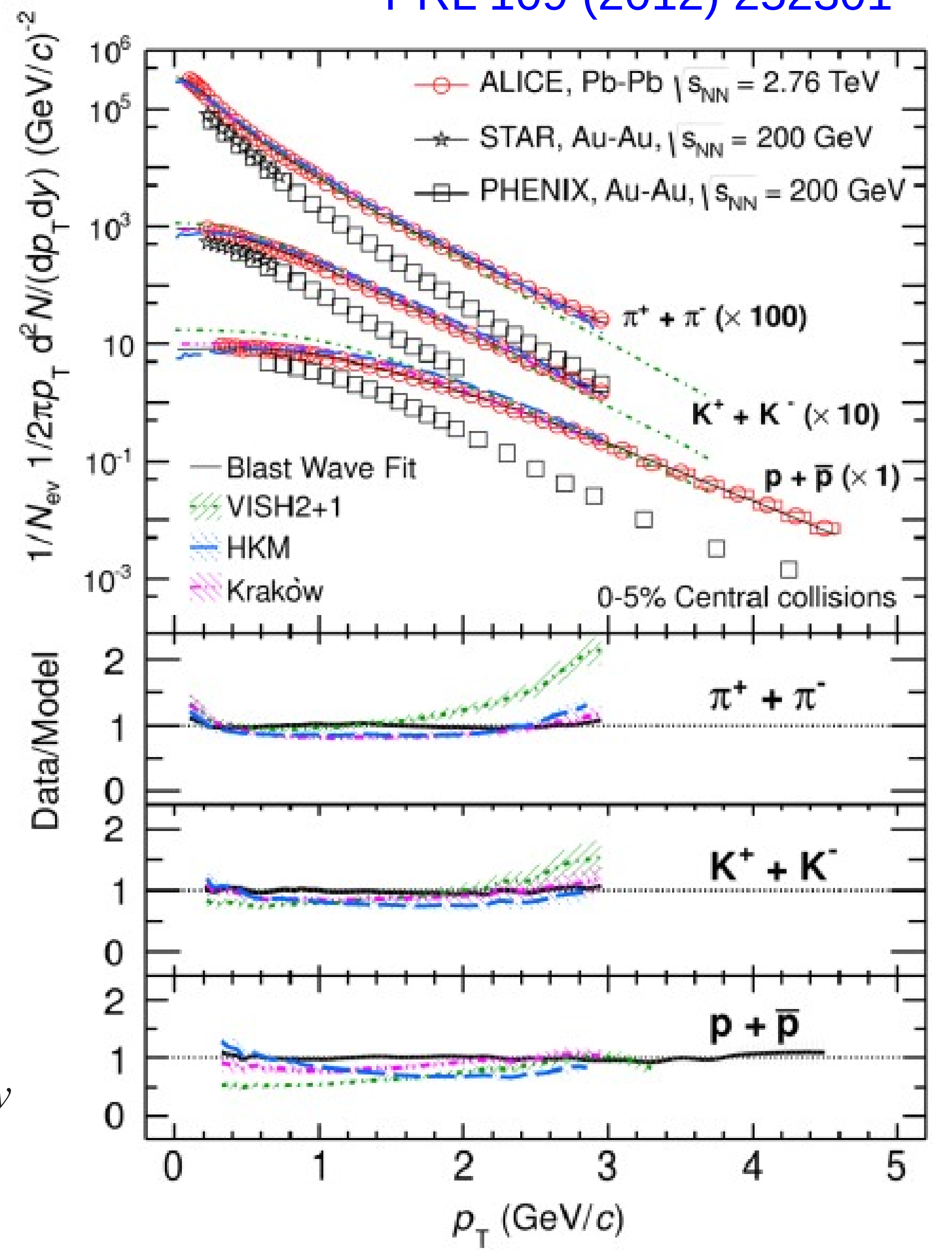
- Different shape for particles with different masses indicate radial flow
- Hydro calculations can describe the data
- Blast-wave fits assuming a boosted thermal source with a common temperature and radial velocity

BW model: PRC 48, 2462 (1993)



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

PRL 109 (2012) 252301



$$E\frac{d^3N}{dp^3} \sim f(p_t) = \int_0^R m_T K_1(m_T \cosh\rho / T_{fo}) I_0(p_T \sinh\rho / T_{fo}) r dr \quad \text{where } m_T = \sqrt{m^2 + p_T^2};\ \beta_r(r) = \beta_s(\tfrac{r}{R})^n;\ \rho = \tanh^{-1}\beta_r.$$

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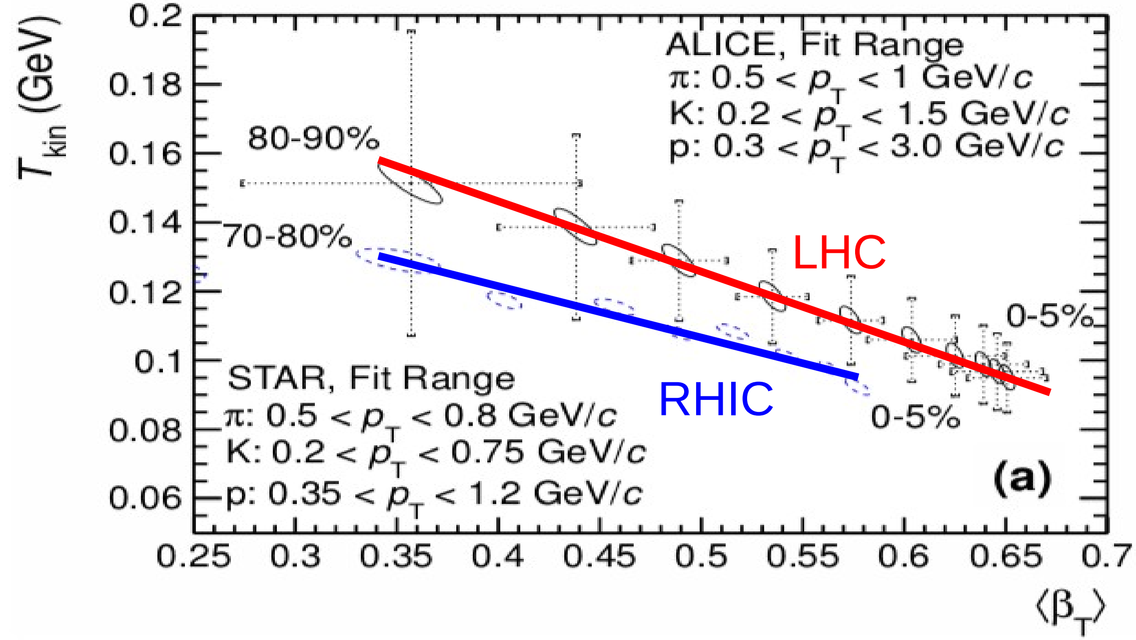
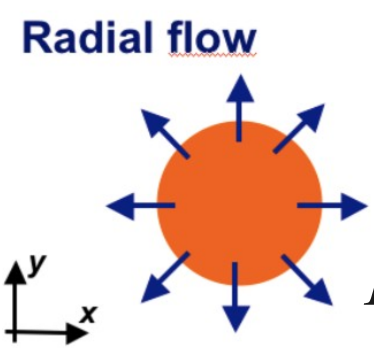
PRL 109 (2012) 252301



- Strong radial flow up to $\beta_{LHC,central} = 0.65c$
  - $\beta_{LHC,central} = 1.1\ \beta_{RHIC,central}$
- Similar kinetic freeze-out T_{kin}



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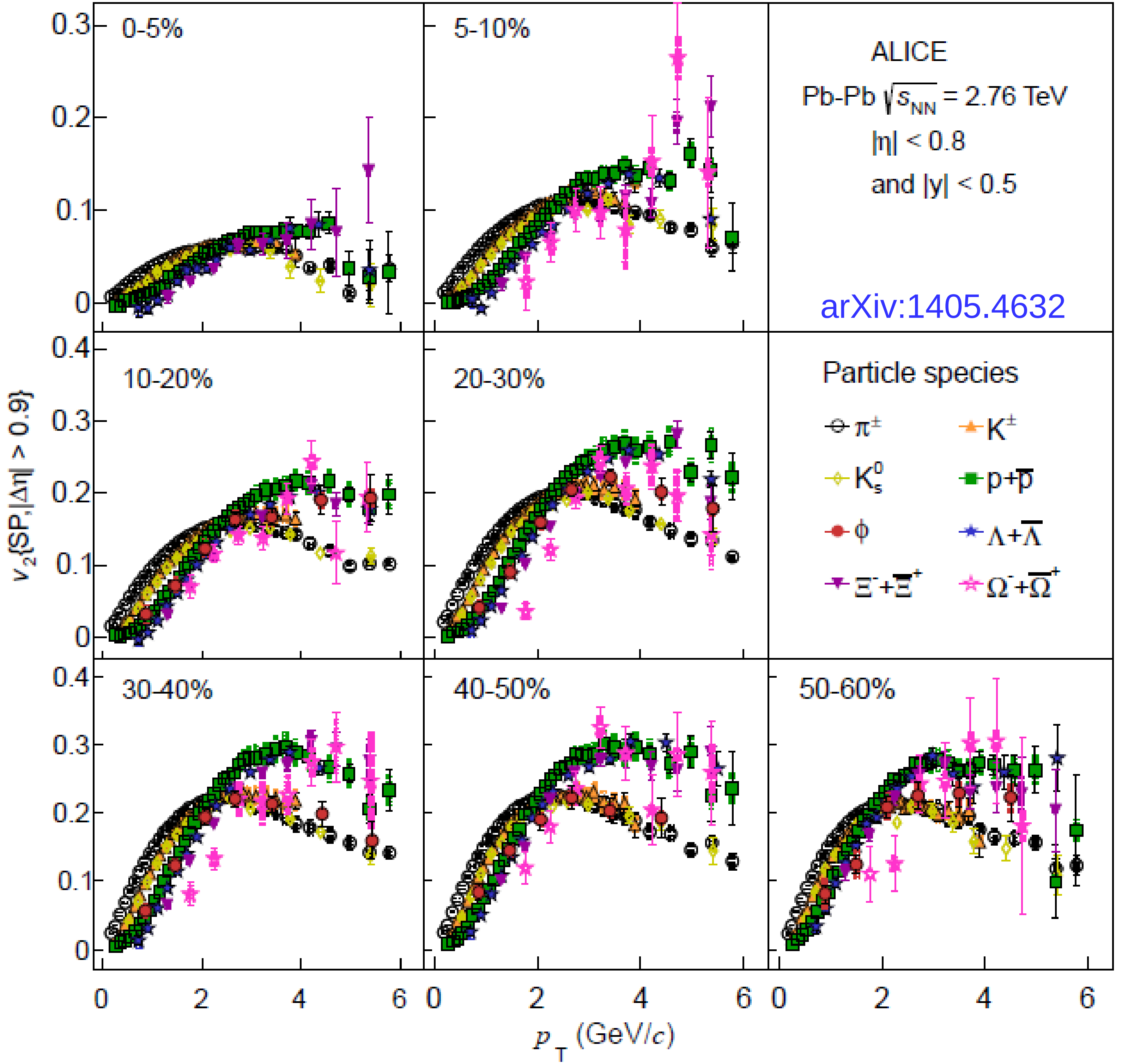
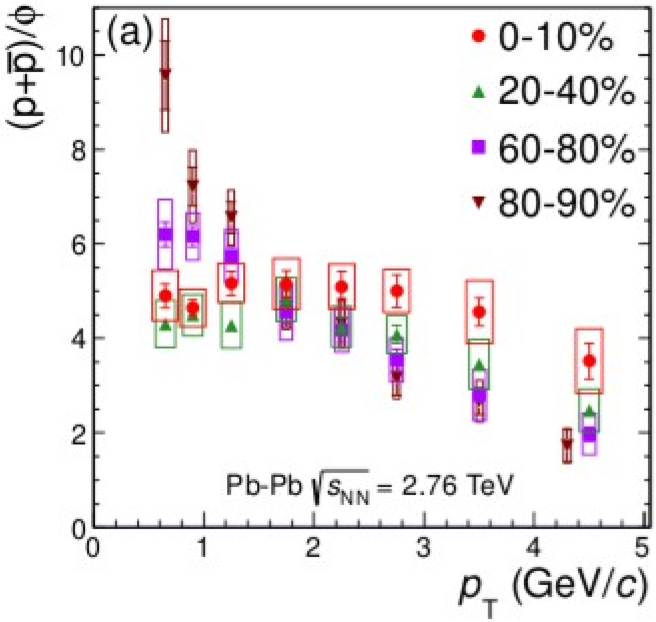
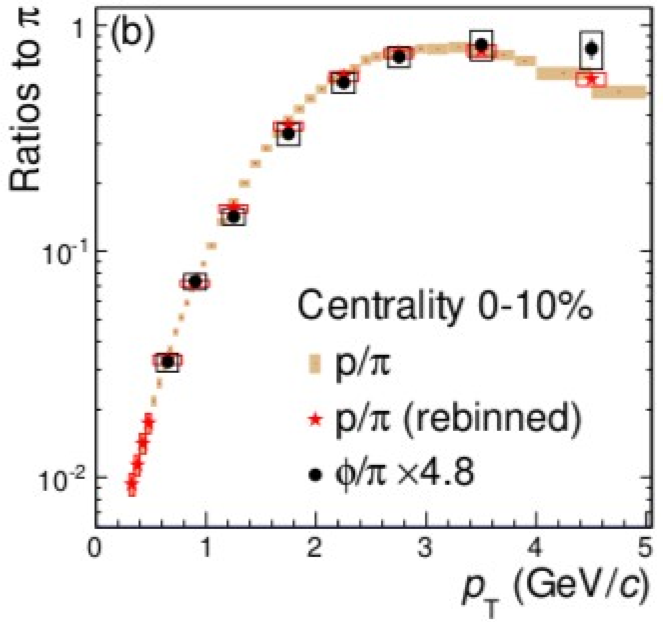

0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
50-60%
ALICE
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
|η| < 0.8
and |y| < 0.5
arXiv:1405.4632
Particle species
π±
K±
K^0_s
p+p̄
φ
Λ+Λ̄
Ξ⁻+Ξ̄⁺
Ω⁻+Ω̄⁺
v_2{SP,|Δη| > 0.9}
p_T (GeV/c)

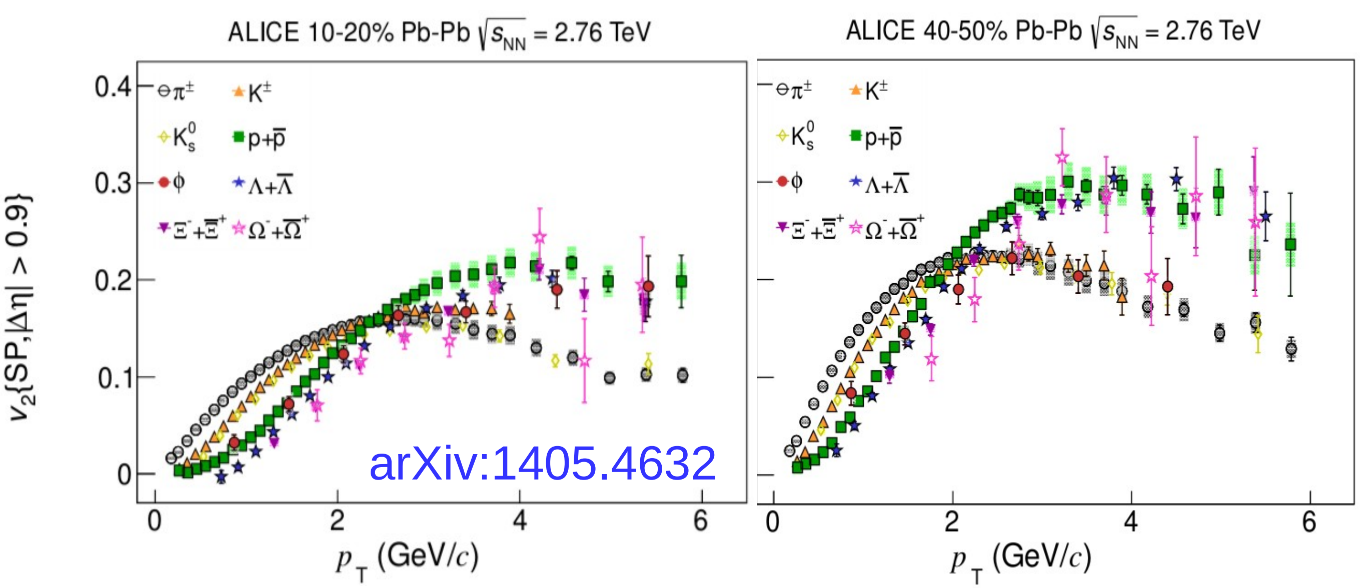
The Φ meson

- At low p_T follows mass ordering
- At high p_T close to p in central and close to π in mid-central
- In central collisions p and Φ have similar shape up to ~4 GeV/c.
  - As expected from radial flow
- Mass (and not number of constituent quarks) scaling drives the v_2 and spectra in central collisions

arXiv:1404.0495



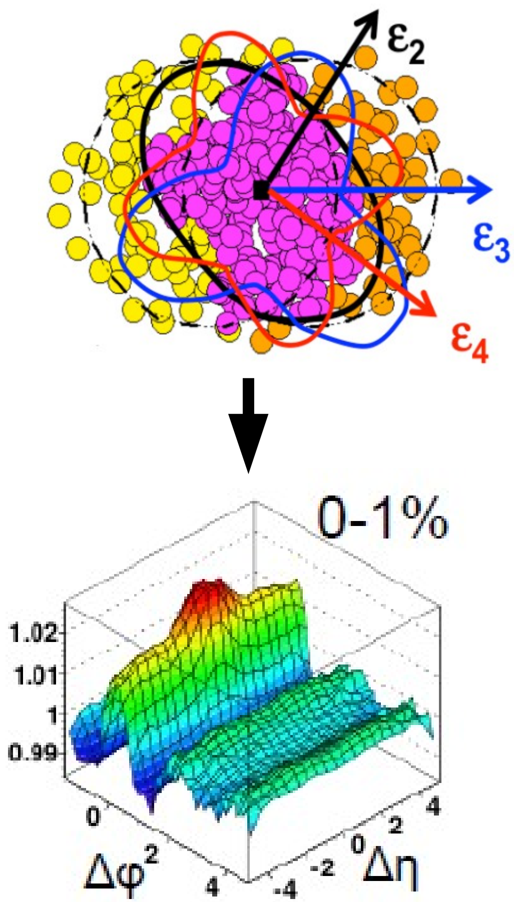




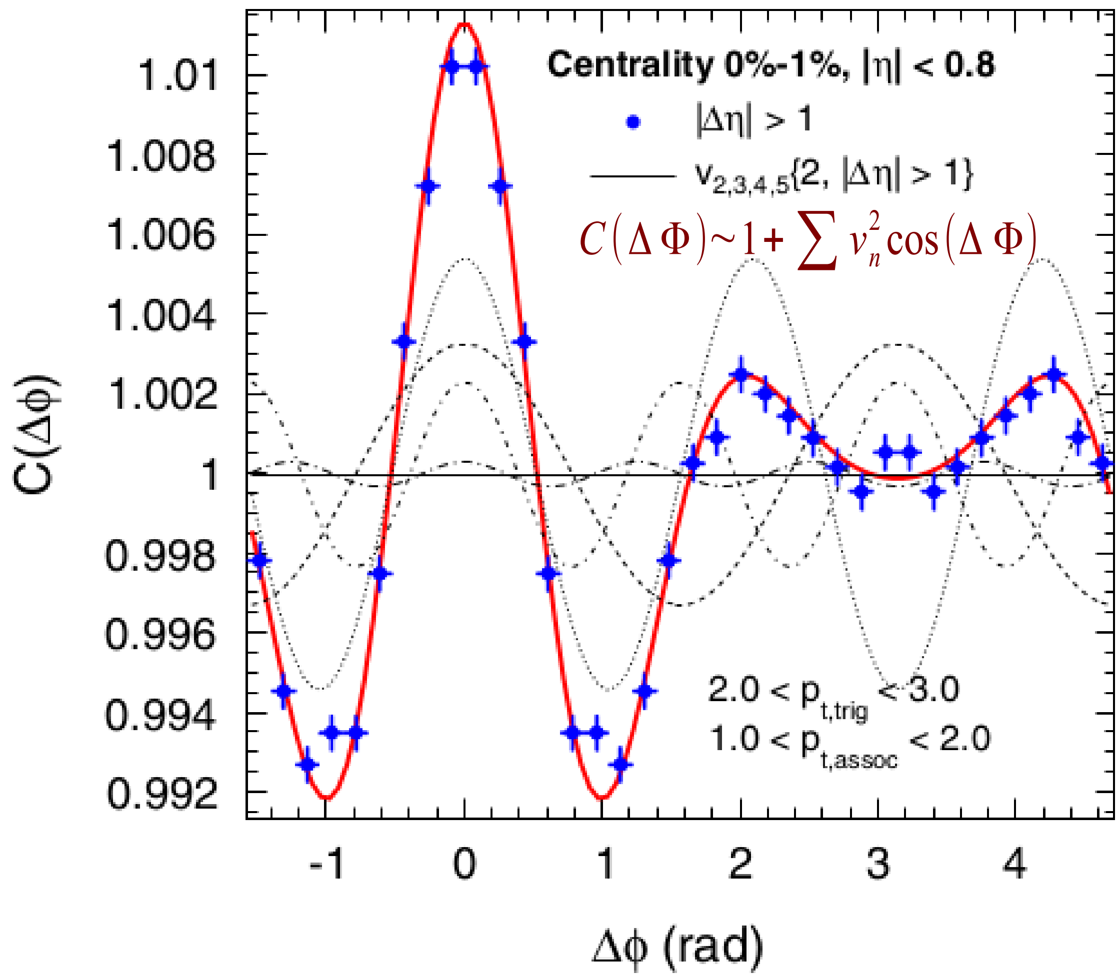
arXiv:1405.4632

Initial state fluctuations and flow ridges

Alver+Roland, 2010



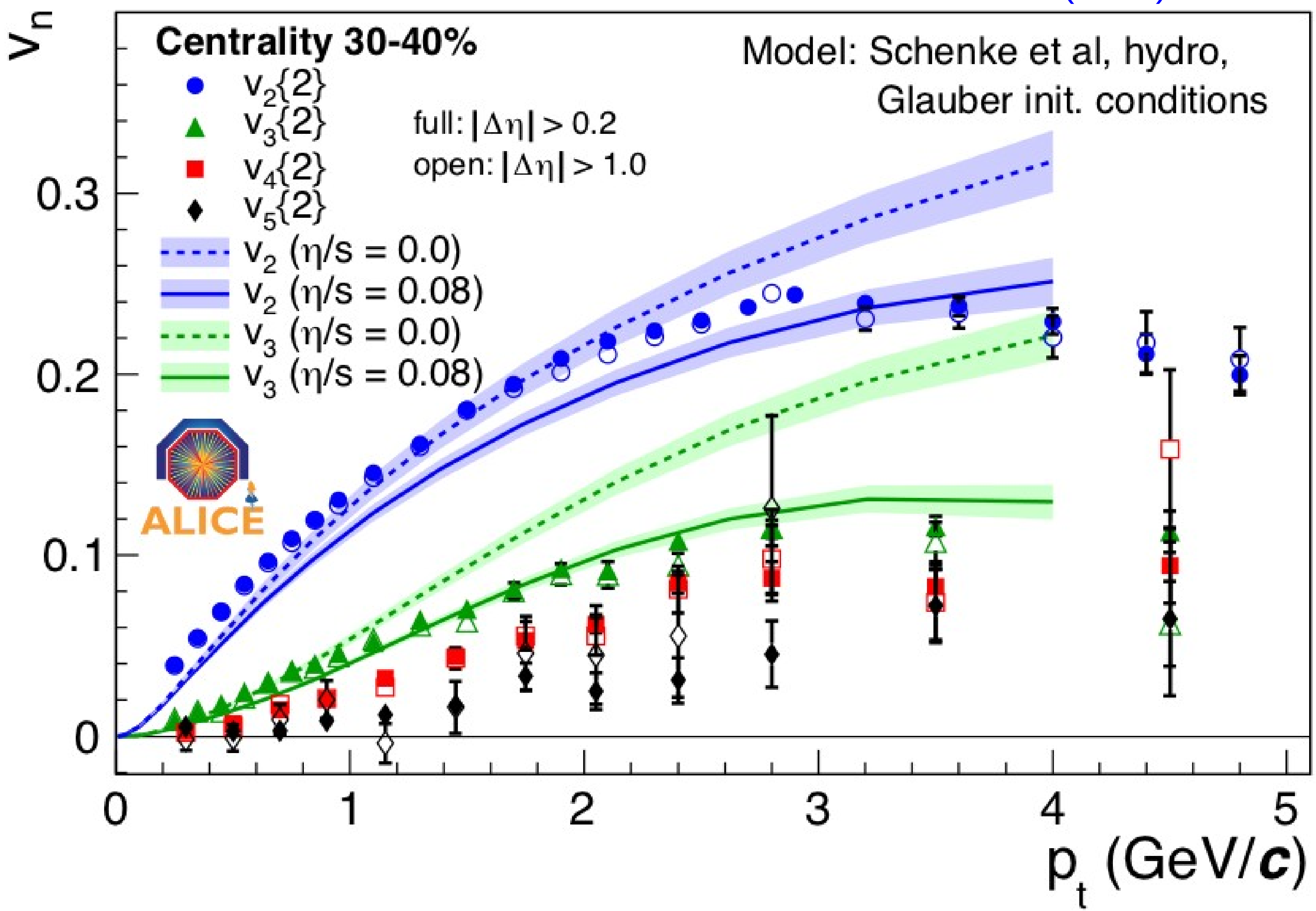
ALICE, PRL 107 (2011) 032301



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

Measurement of higher harmonics

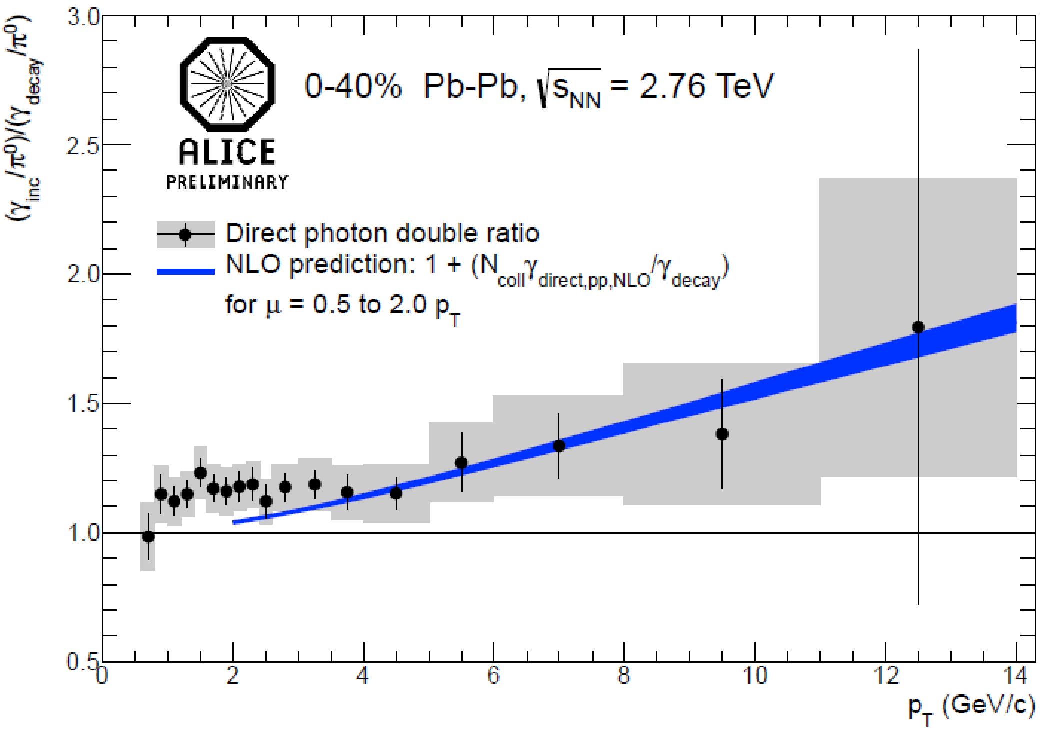
PRL 107 (2011) 032301



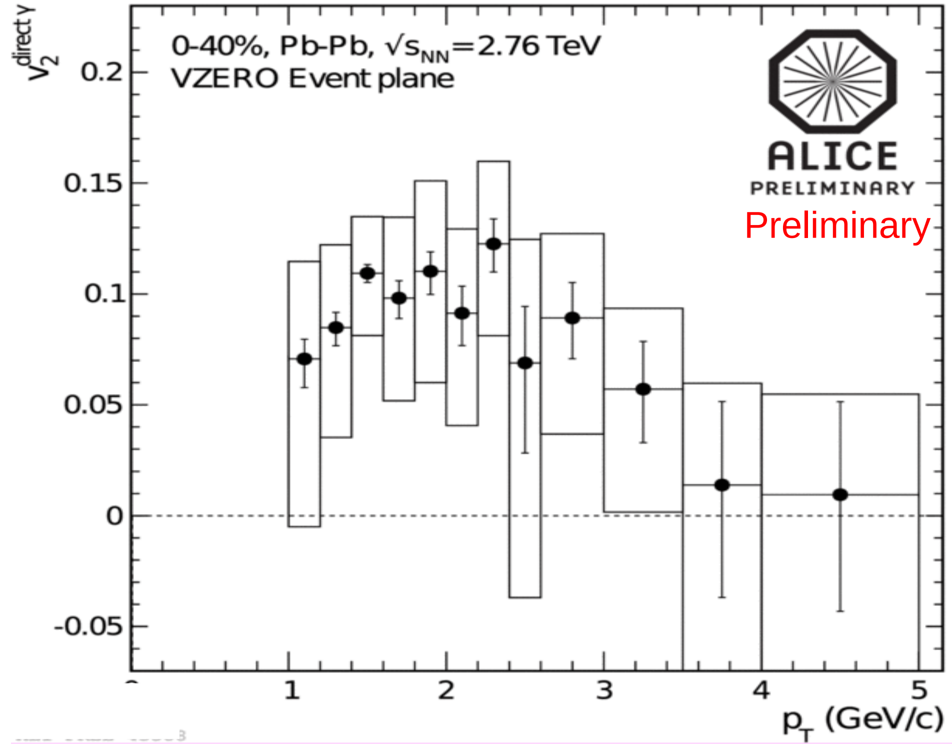
Strong constraints on hydro calculations.

Double ratio and direct photon spectrum

$R = (\gamma/\pi^0)_{inc} / (\gamma/\pi^0)_{mc}$



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



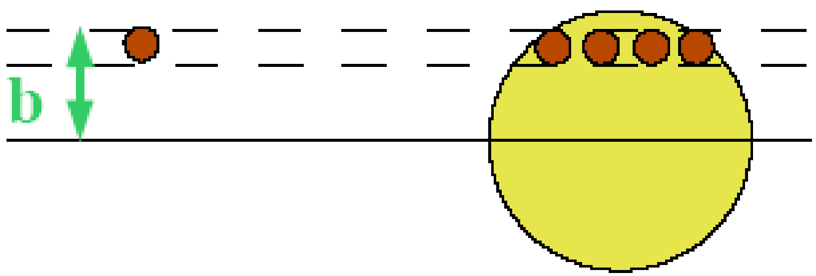
- Analysis strategy ala PHENIX
- Uncertainties (exactly or partially) cancel in the ratio
  - Normalization
  - π^0 - measurement
  - Reconstruction efficiency

- Inverse slope: T=304±51 MeV
  - Should be related to initial temperature, but ...
- Significant $v_2^{dir\gamma}$ between 1-3 GeV/c
  - Same as charged hadrons (or not from direct γ)
  - Difficult to reconcile with T

Nuclear geometry and hard processes: Glauber theory

Glauber scaling: hard processes with large momentum transfer

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



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

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

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

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

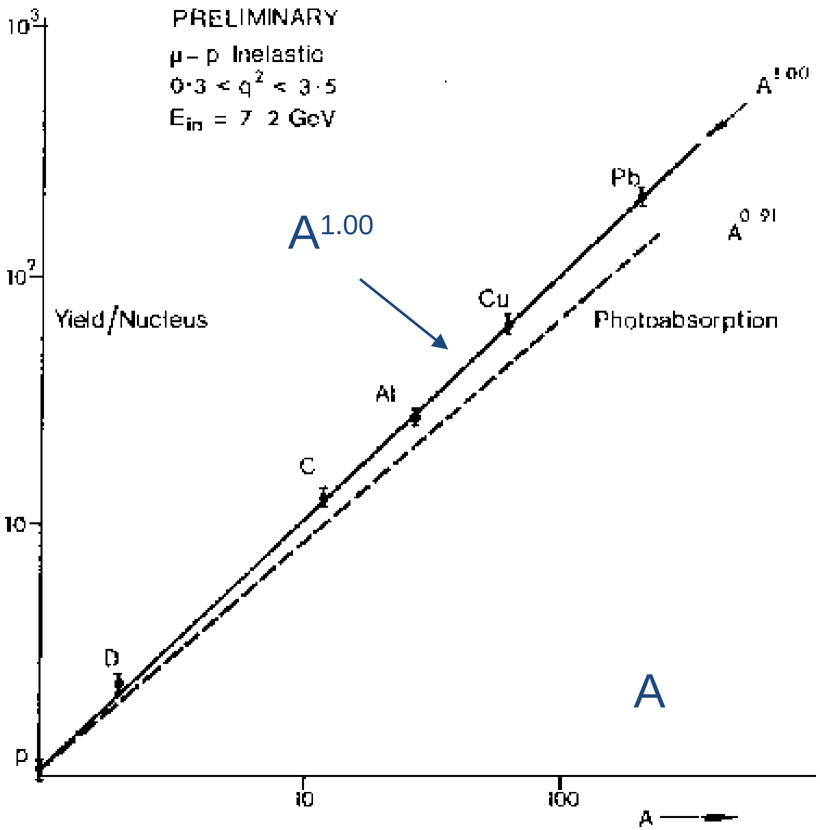
$$\sigma_{\mathrm{pA}}^{\mathrm{hard}} \simeq A\,\sigma_{NN}^{\mathrm{hard}} \int \mathrm{d}b T_{\mathrm{A}} = A\,\sigma_{NN}^{\mathrm{hard}}$$

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

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

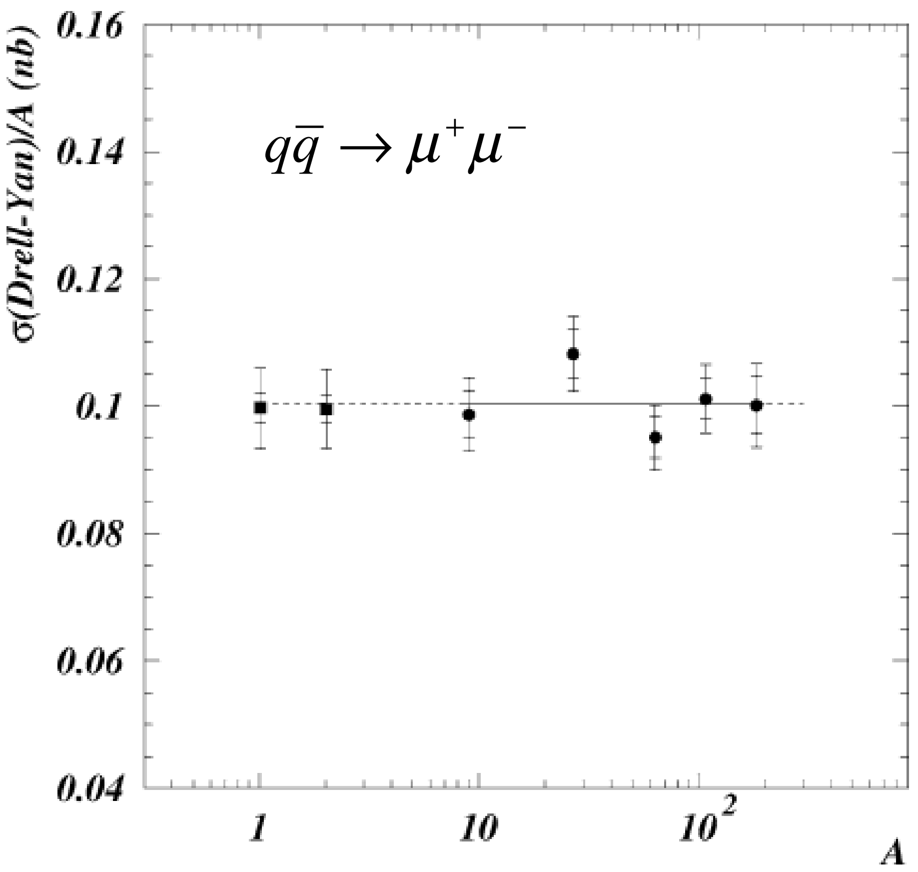
σ_{inel} for 7 GeV muons on nuclei

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



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

NA50 Phys Lett B553, 167

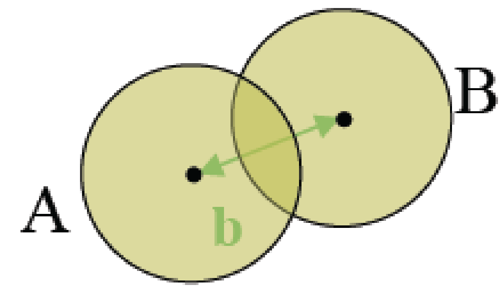


These hard cross sections in p+A found to scale as $A^{1.0}$

Glauber scaling for A+B collisions

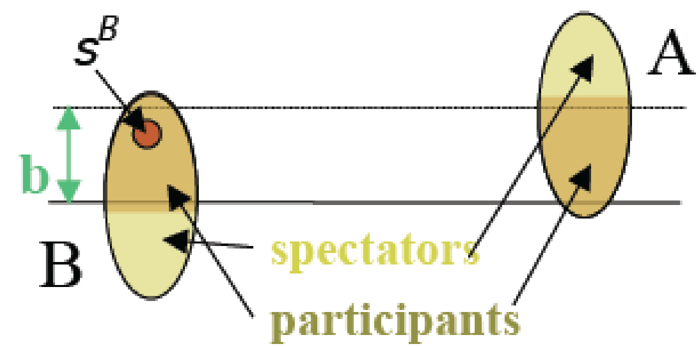
Nuclear overlap function:

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



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

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

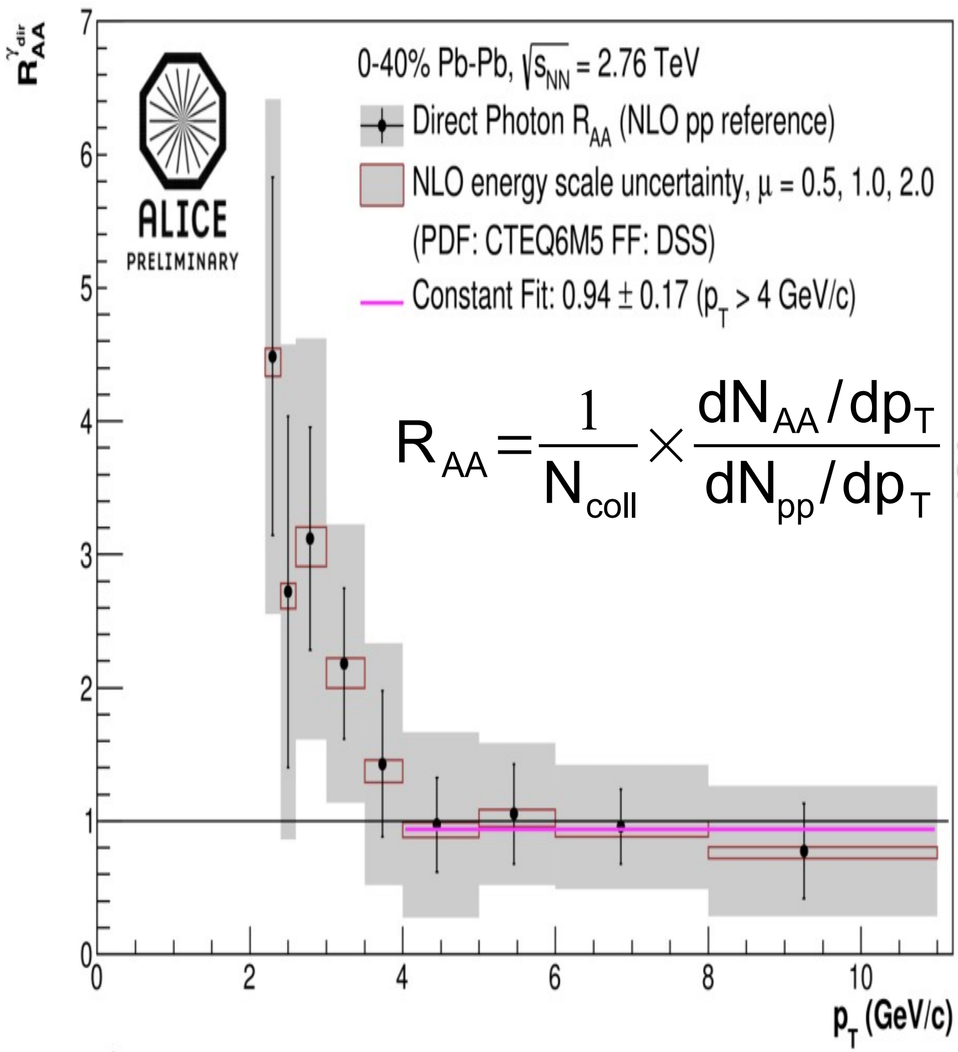


Average number of binary NN collisions for A+B collision with impact parameter b:

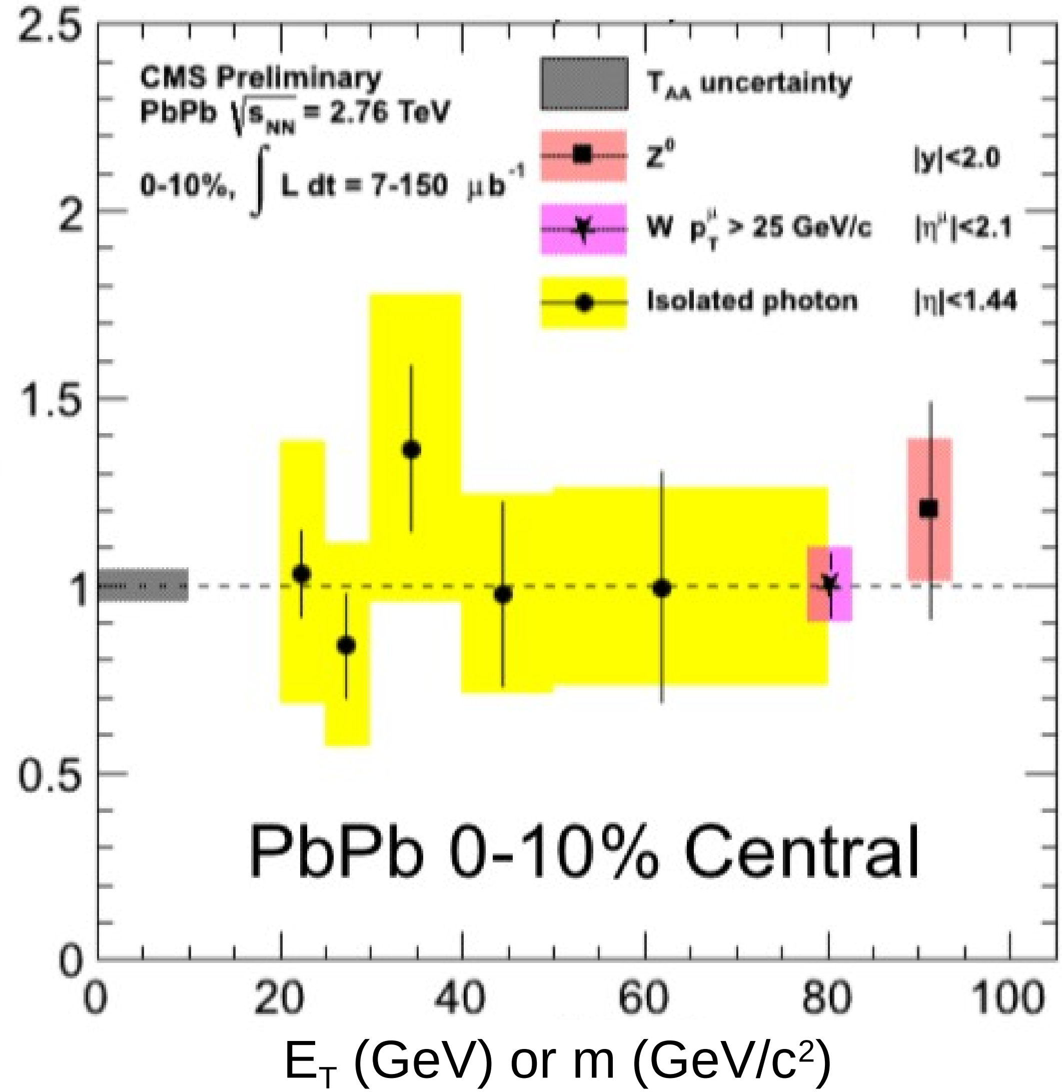
$$N_{\mathrm{coll}}^{\mathrm{AB}}(b) = B \int \mathrm{d}s_{\mathrm{B}}\, T_{\mathrm{B}}(s_{\mathrm{B}})\, N_{\mathrm{coll}}^{\mathrm{nA}}(b - s_{\mathrm{B}}) = \mathrm{AB}\, \mathrm{T}_{\mathrm{AB}}(b)\, \sigma_{\mathrm{NN}}^{\mathrm{inel}}$$

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

Nuclear modification factor: Control probes



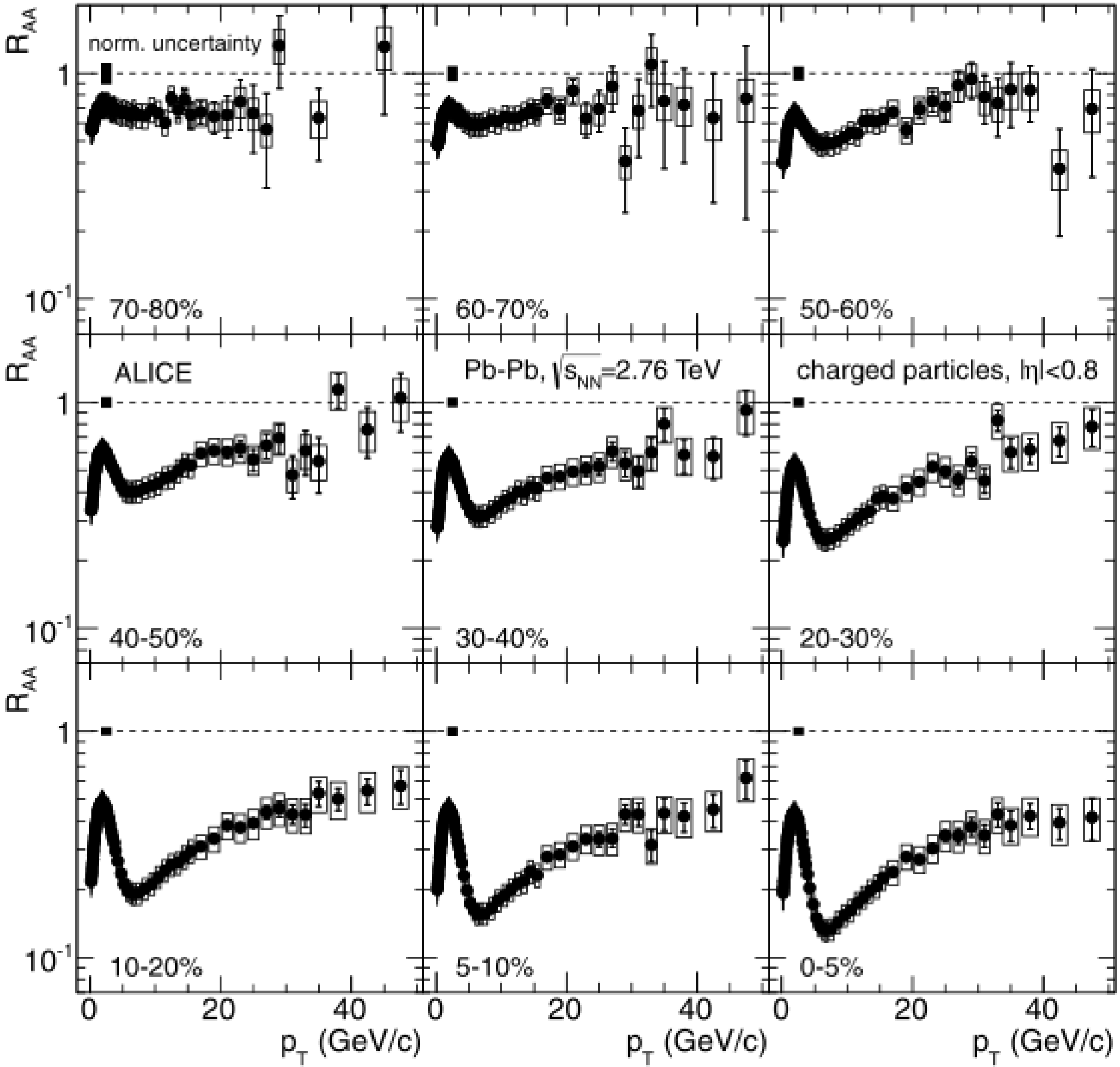
$$R_{AA} = \frac{1}{N_{coll}} \times \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



Control probes > 4 GeV/c (direct +isolated γ, Z, W) scale ie. R_{AA} ~ 1

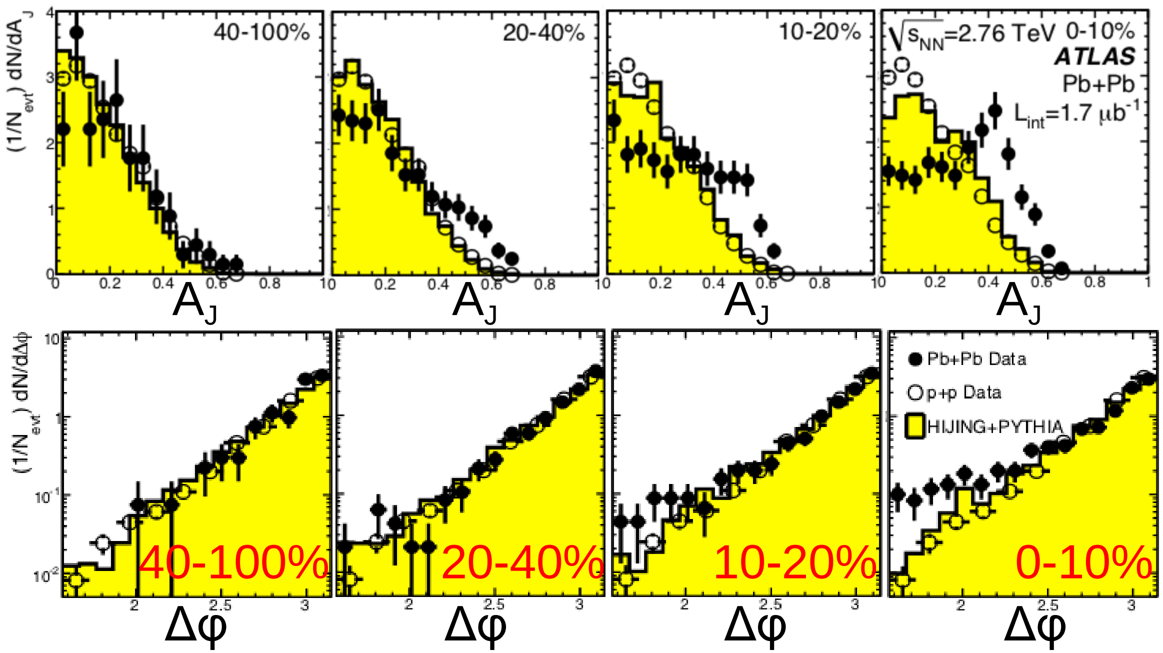
Nuclear modification factor

PLB 696 (2011) 30



Dijet momentum imbalance

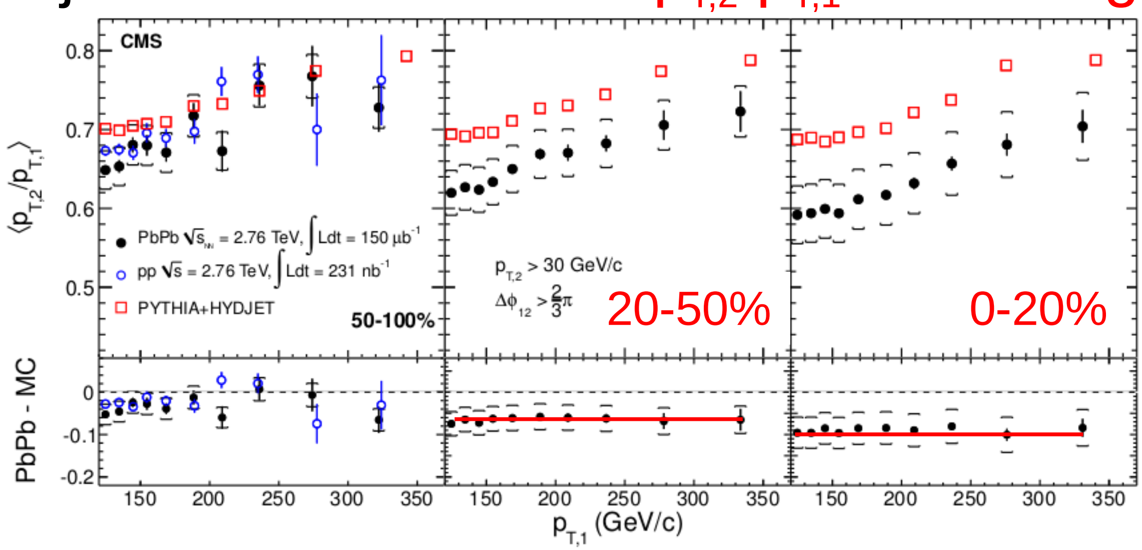
Dijet momentum imbalance: $A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$



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, PRC 84 (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.

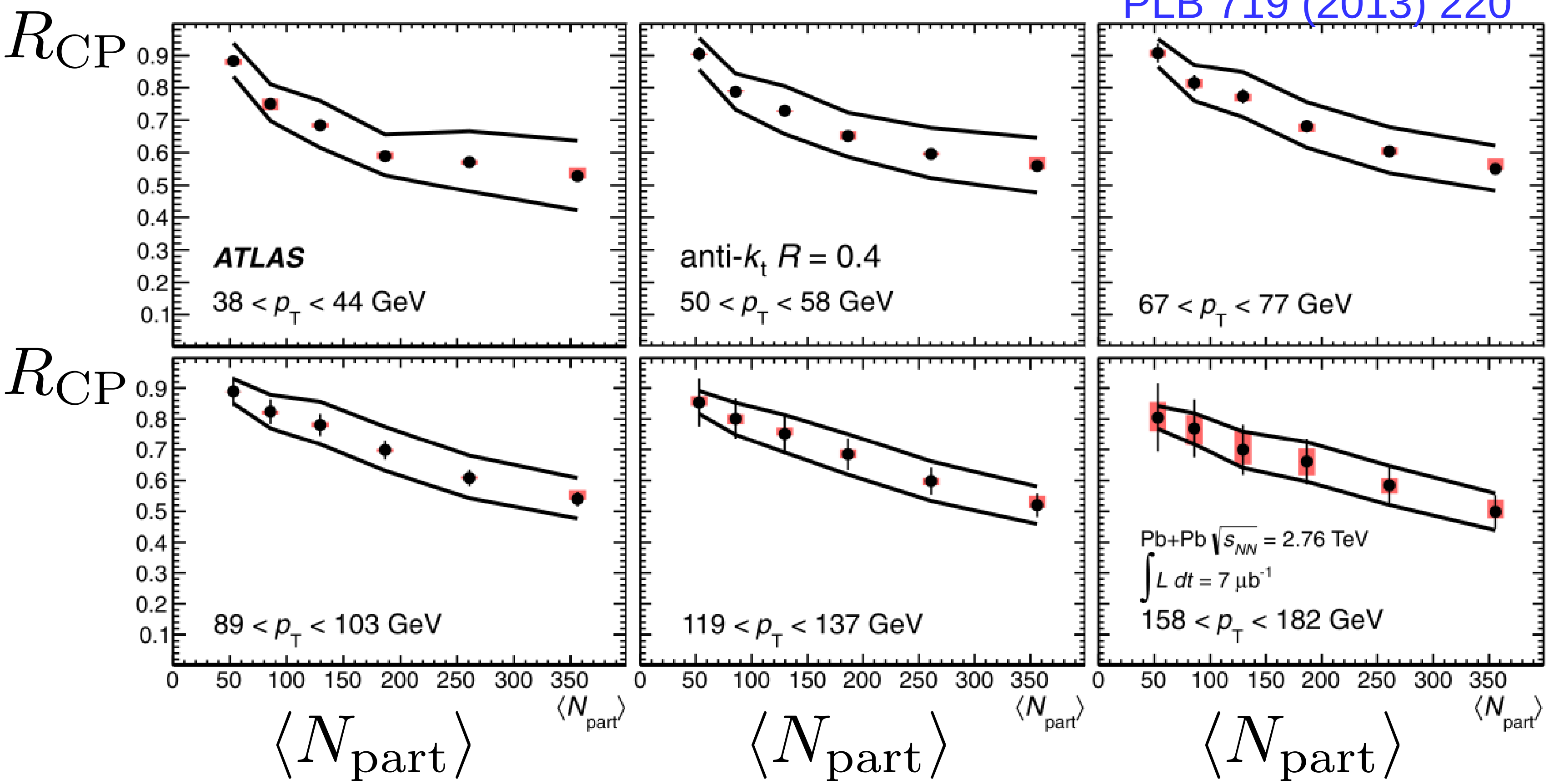
CMS, PLB 712 (2012) 176

Jet R_{CP} vs centrality

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

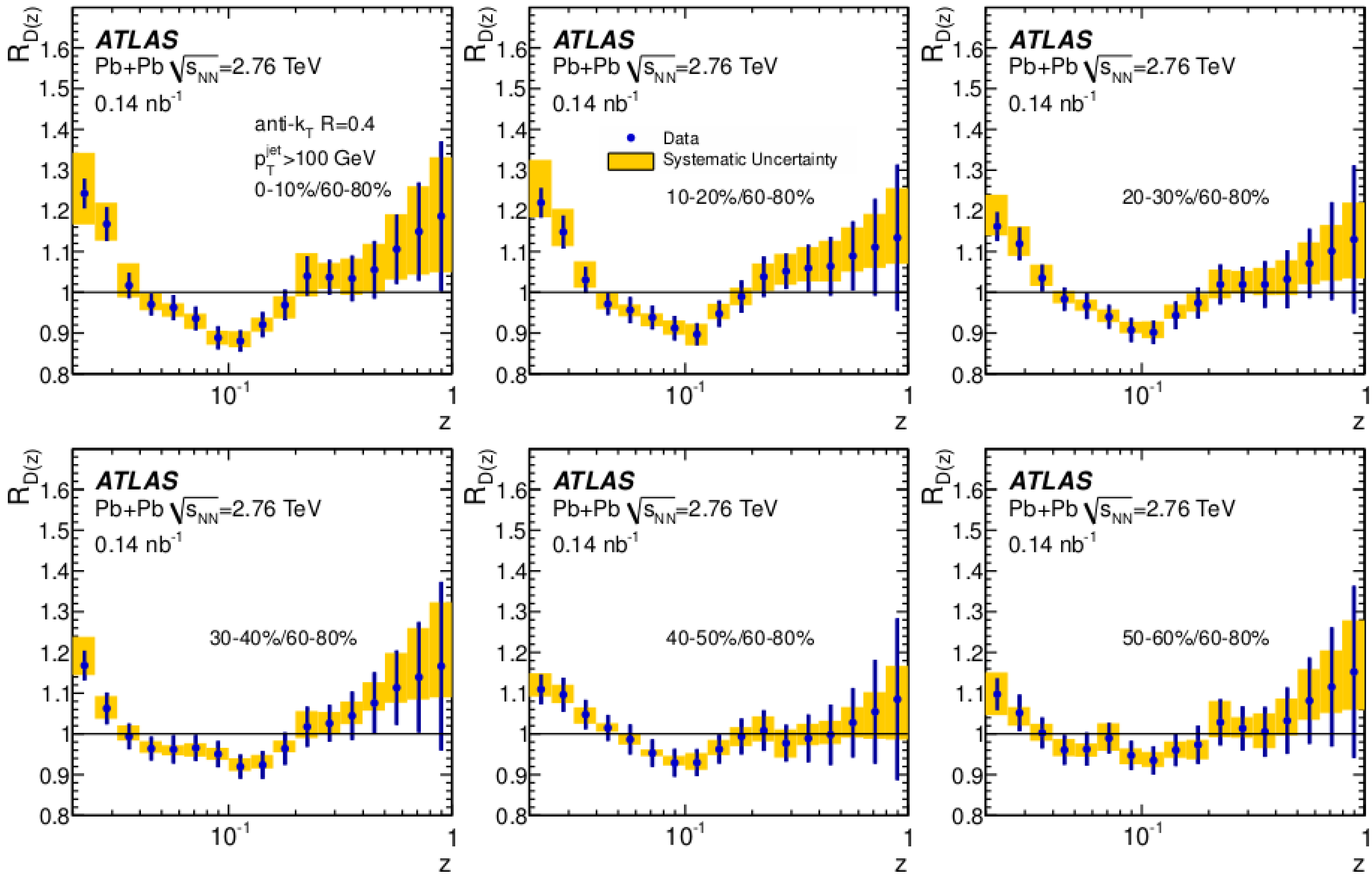
$$R_{\mathrm{CP}} = \frac{\left.\frac{1}{N_{\mathrm{coll}}}\frac{\mathrm{d}N}{p_{\mathrm{T}}}\right|_{\mathrm{cent}}}{\left.\frac{1}{N_{\mathrm{coll}}}\frac{\mathrm{d}N}{p_{\mathrm{T}}}\right|_{60-80\%}}$$

PLB 719 (2013) 220



Jet fragmentation function

arXiv:1406.2979



R=0.4

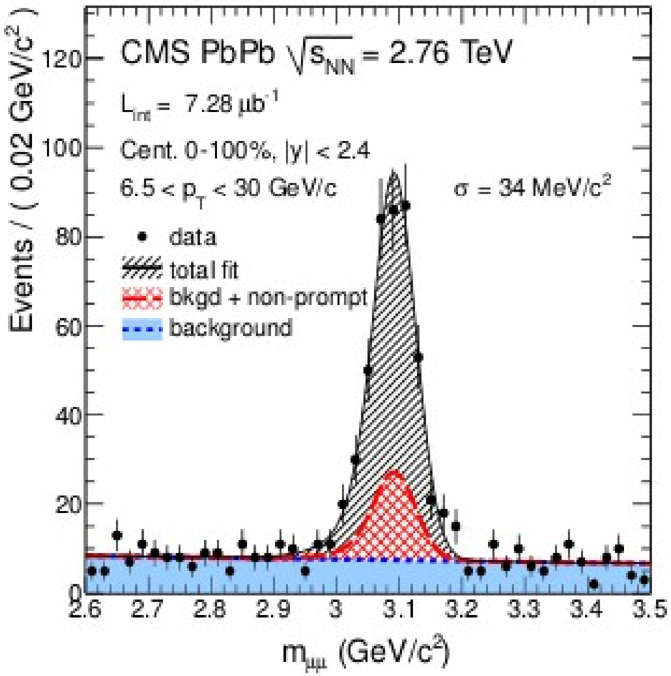
P_T > 100 GeV/c

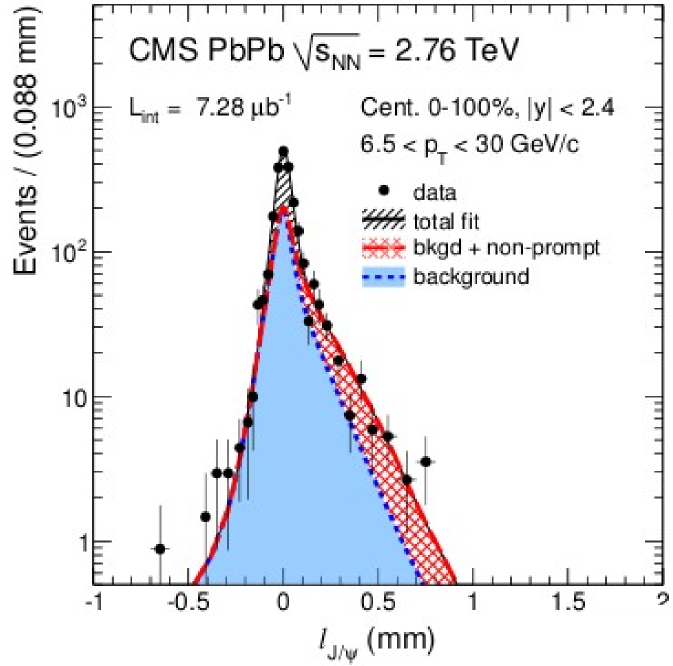
Track p_T>2 GeV/c

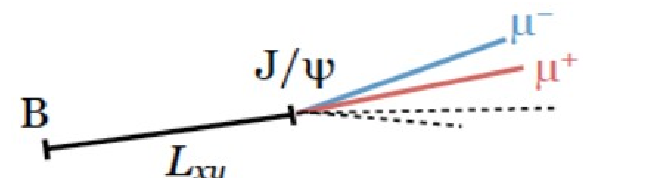
Beauty via displaced J/ψ

B mesons via secondary J/ψ:

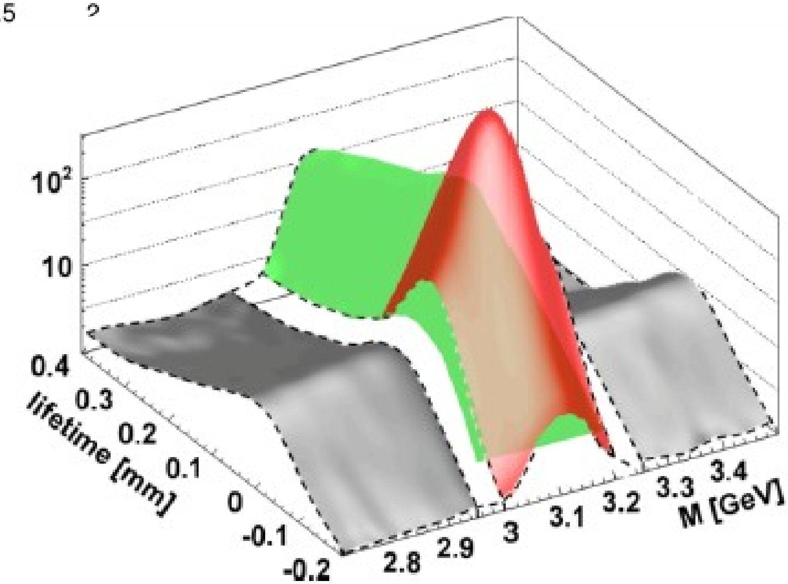
CMS, JHEP 1205 (2012) 063







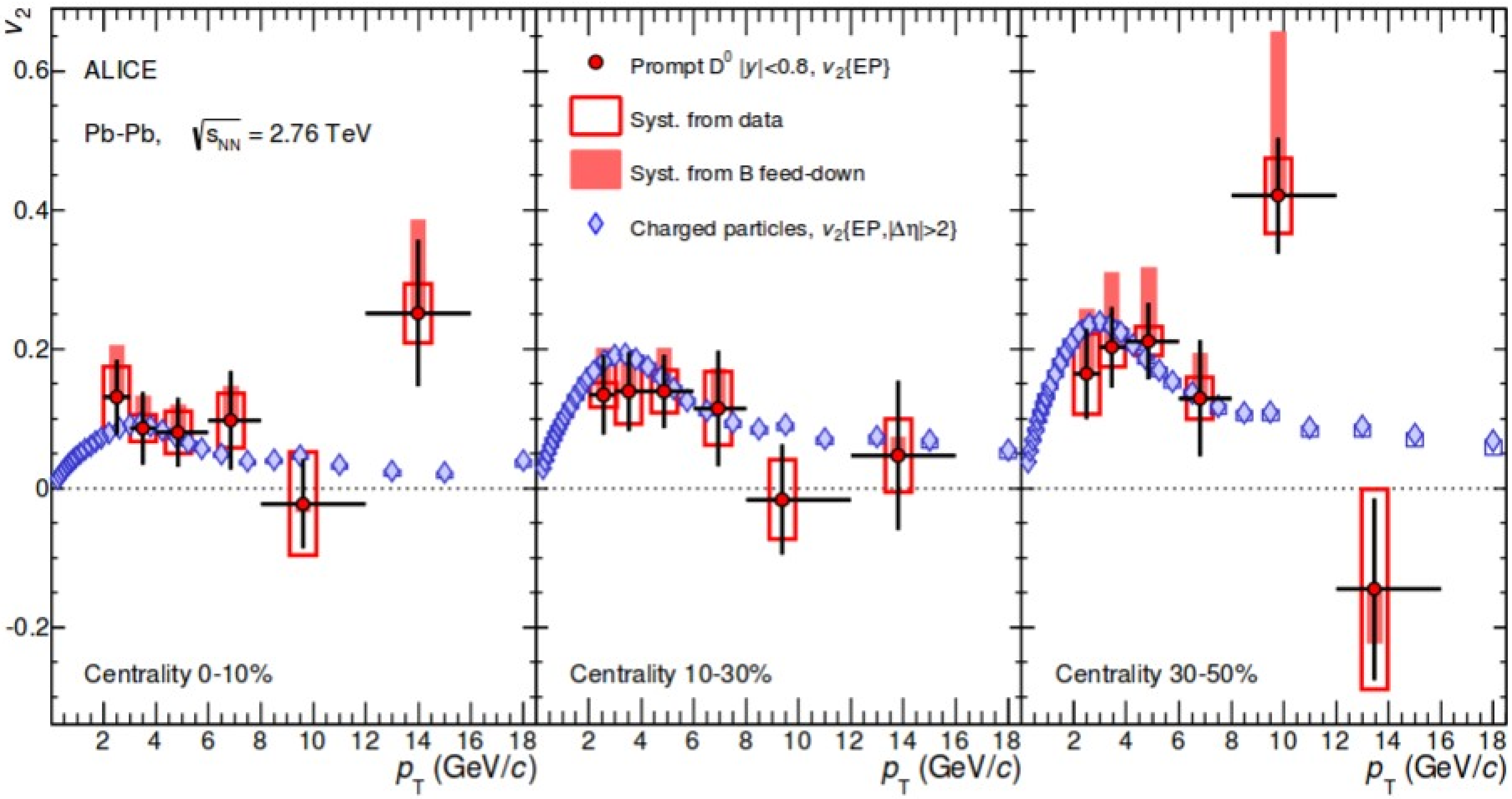
Clean separation of 2nd vertex for J/ψ with p_T>6.5 GeV/c



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

D-meson v_2 at the LHC

PRC 90 (2014) 034904

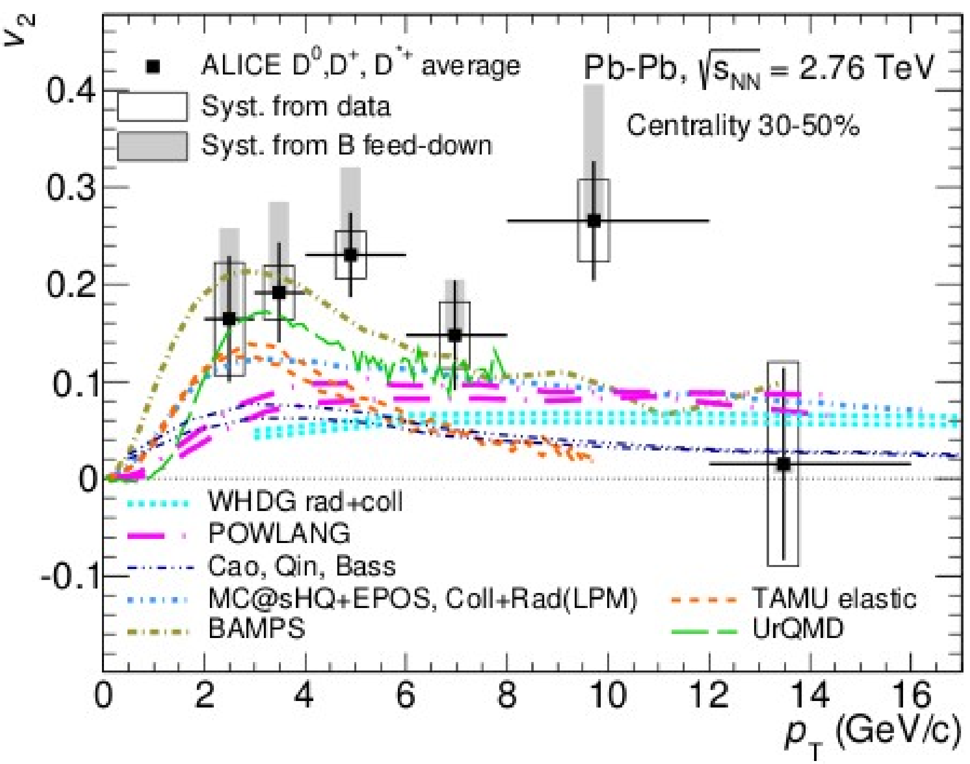


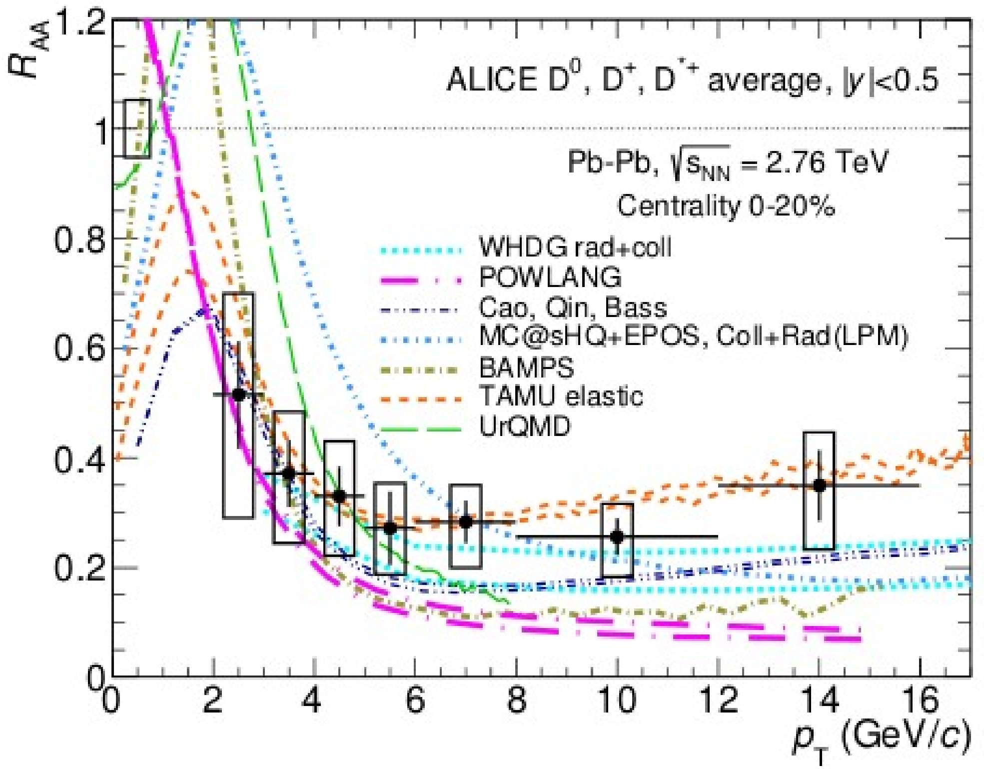
Indication of non-zero D meson v_2: It implies that heavy quarks participate in the collective expansion.

→ Need more data and to measure at lower p_T

D-mesons: Data vs models

PRC 90 (2014) 034904



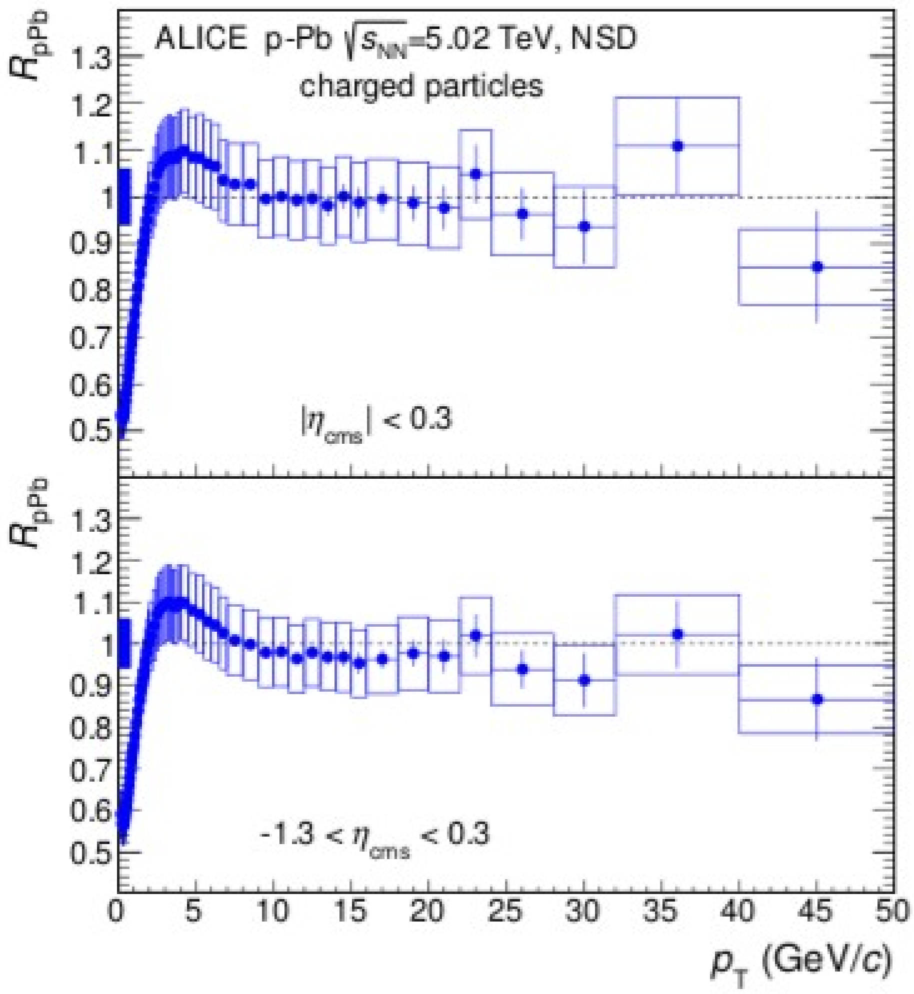


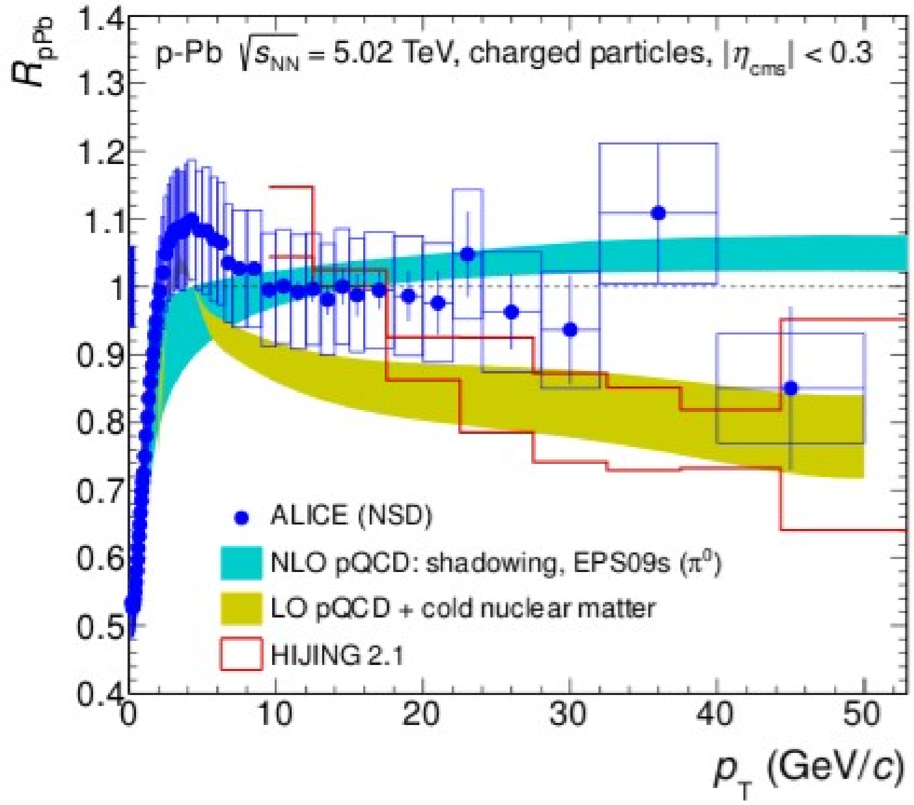
Consistent description of charm v_2 and R_{AA} challenging for models.
Needs more data from future LHC runs.

Charged particle R_{pPb}

arXiv:1405.2737

$$R_{AB} = \frac{\mathrm{d}N_{AB}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle \mathrm{d}N_{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

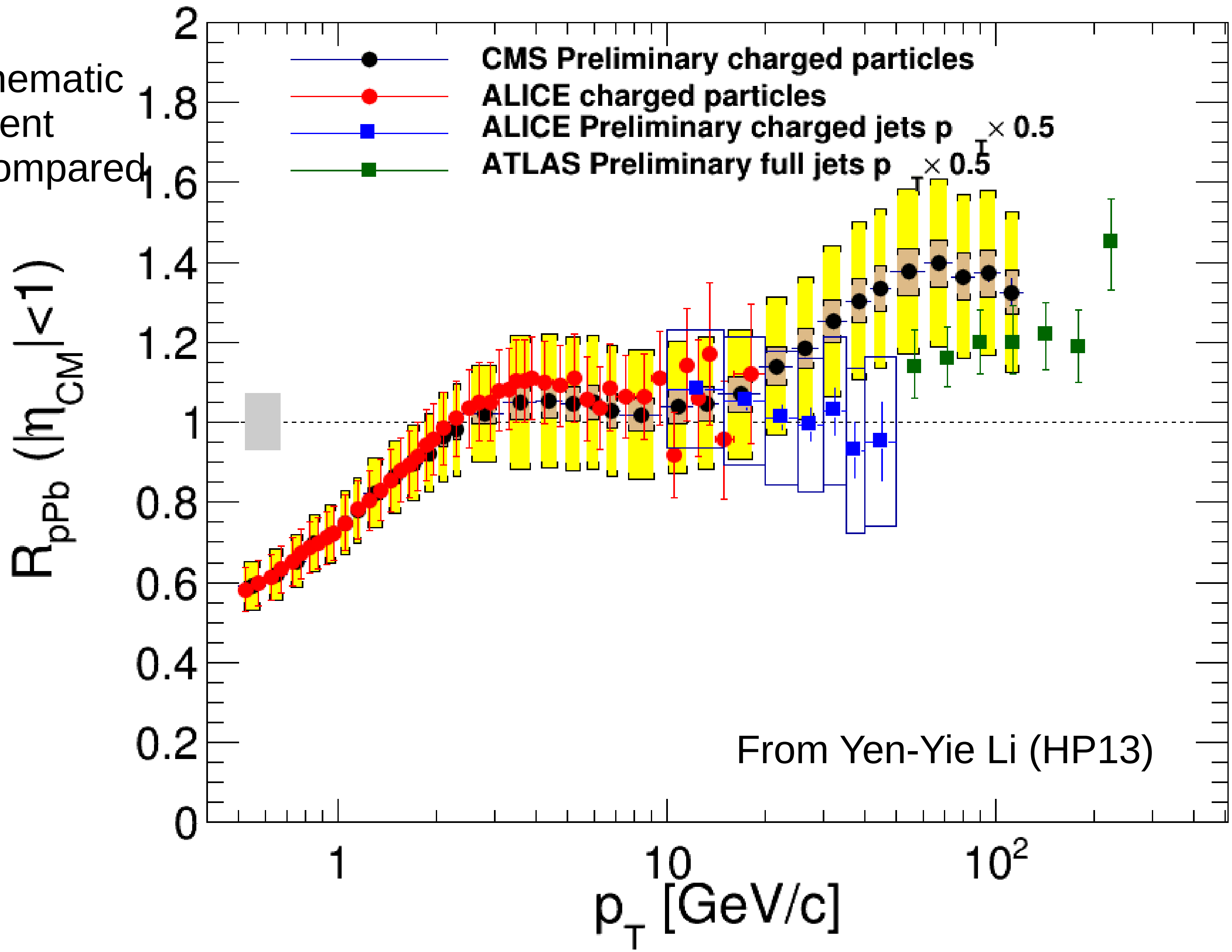




Extended measurements up to 50 GeV/c: No change of message

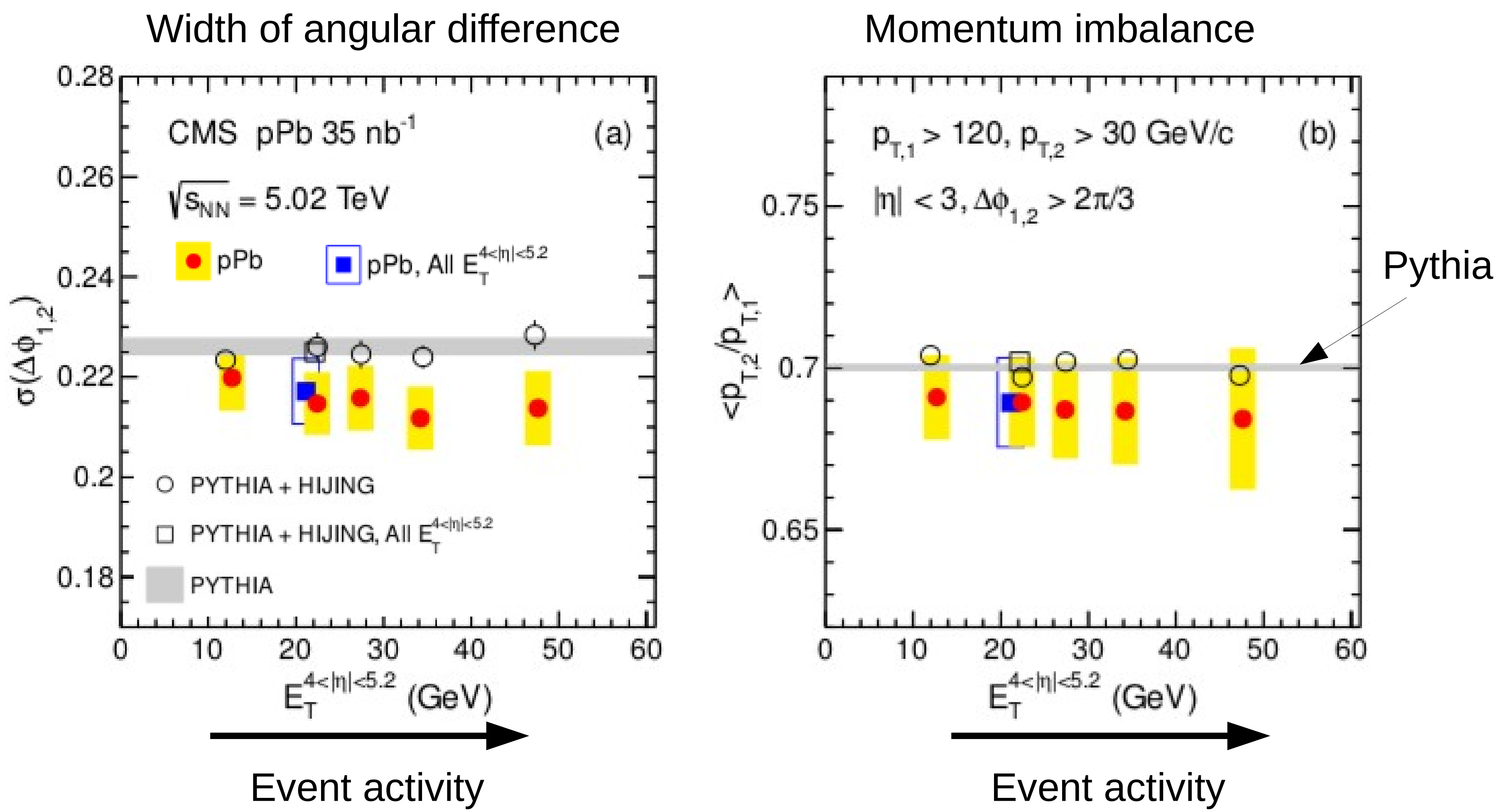
Comparison of minbias measurements

Note:
Different kinematic cuts and event Selection compared



Stronger than expected anti-shadowing?
Confirmed by ATLAS measurement.
Need pp reference data

Dijet imbalance: Not present in pPb

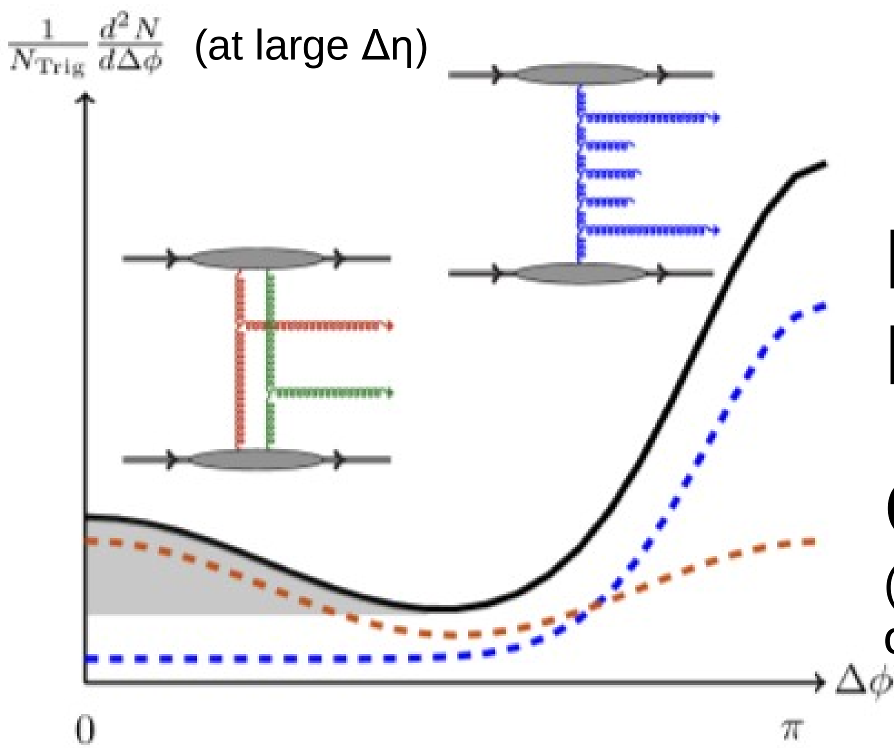


Dijet imbalance not observed in pPb collisions, hence final state effect in PbPb

EPJC 74 (2014) 2951

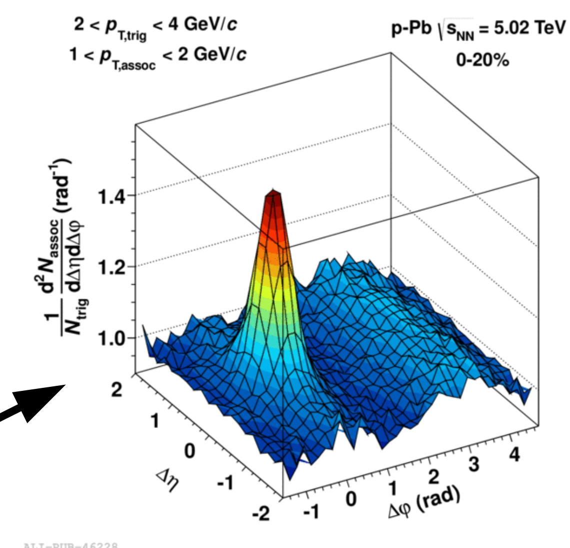
Ridge modulation v_2 and v_3 and CGC

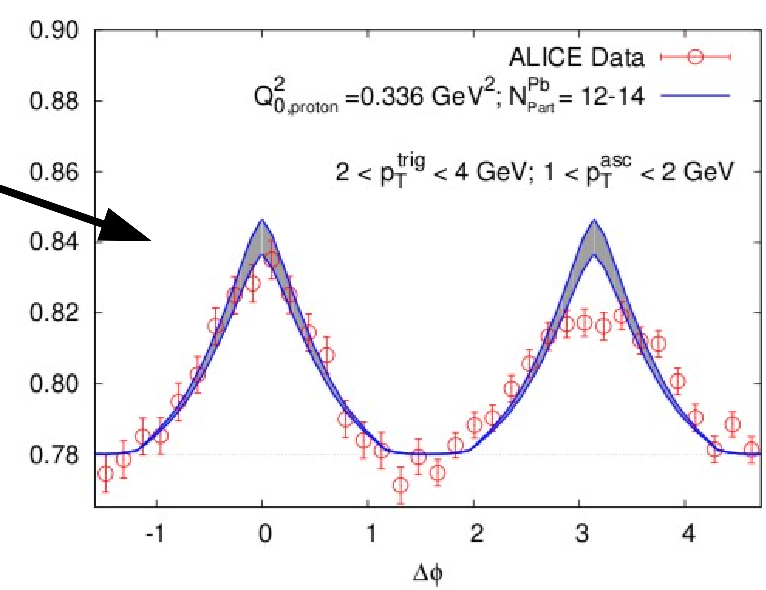
- Two symmetric ridges predicted by CGC glasma graphs found to describe the ridge yields and shape
- However, a large v_3 component would be a challenge for the model



BFKL-Minijets

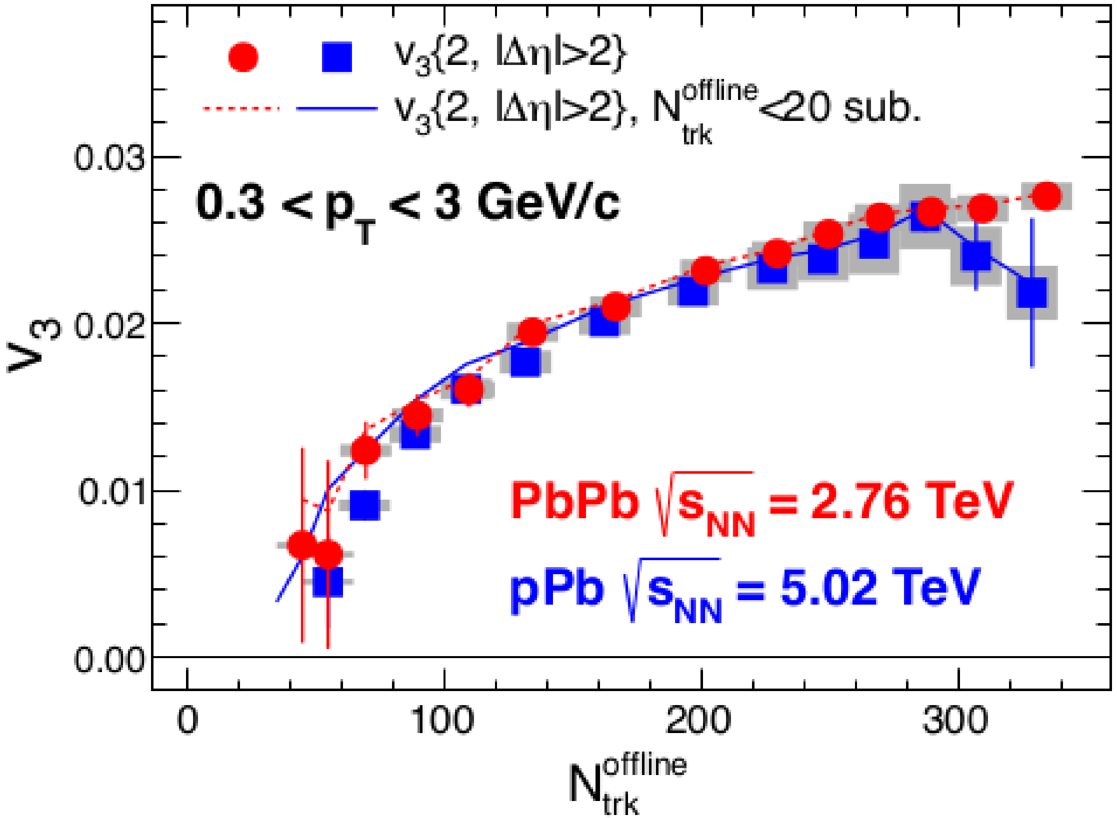
Glasma
(enhanced by α_s^{-8} for $k_T < Q_s$)



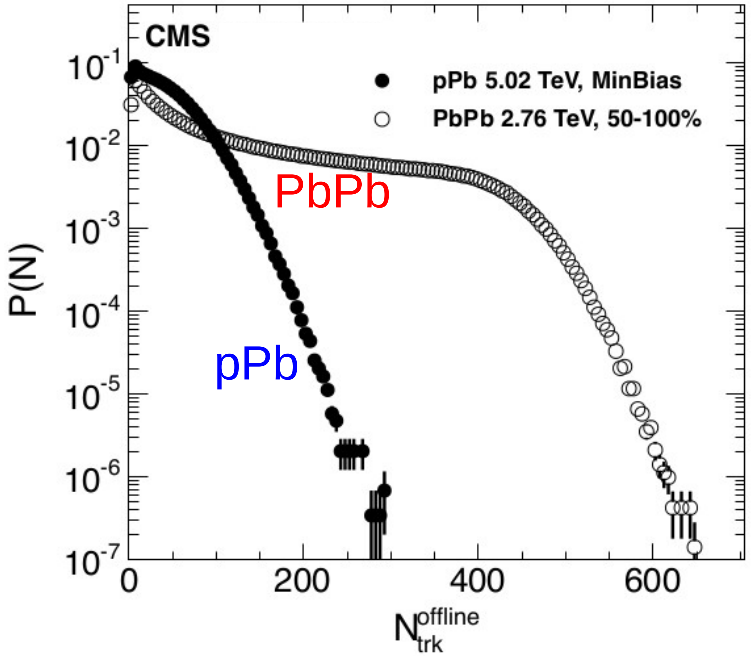


Dusling and Venugopalan, PRD 87 (2013) 094034

Integrated v_3 in PbPb and pPb



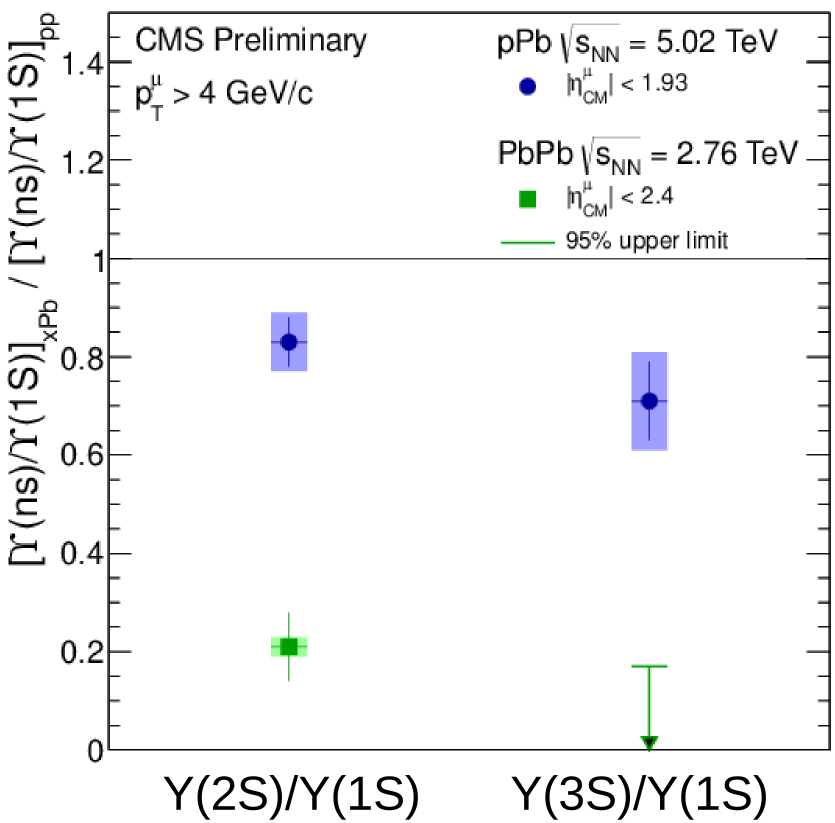
CMS, PLB 724 (2013) 213



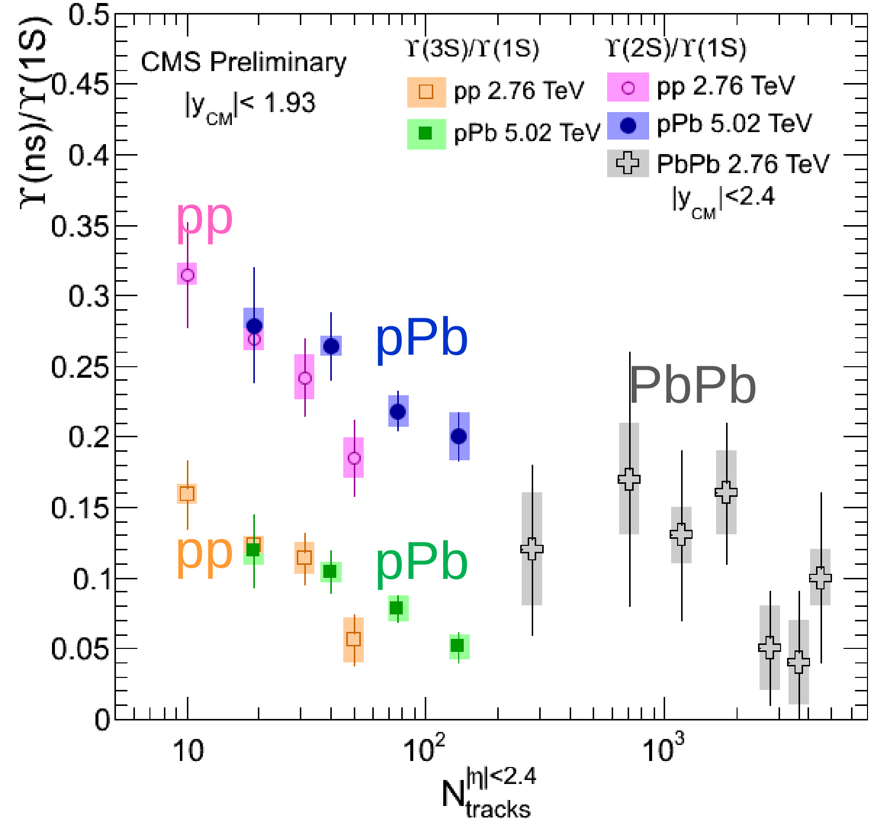
- Same v_3 in pPb as in PbPb
- Turn on at around M=50 tracks (~minbias pPb)
- Established picture in PbPb
  - Transformation of IS fluctuations into FS via interactions

- Same physics mechanism despite different underlying dynamics (+ system size)?
- Maybe we select on events in which the proton wave function fluctuated to large values (fat proton, Mueller, arXiv:1307.5911v2)

Y(2S)/Y(1S) and Y(3S)/Y(1S)

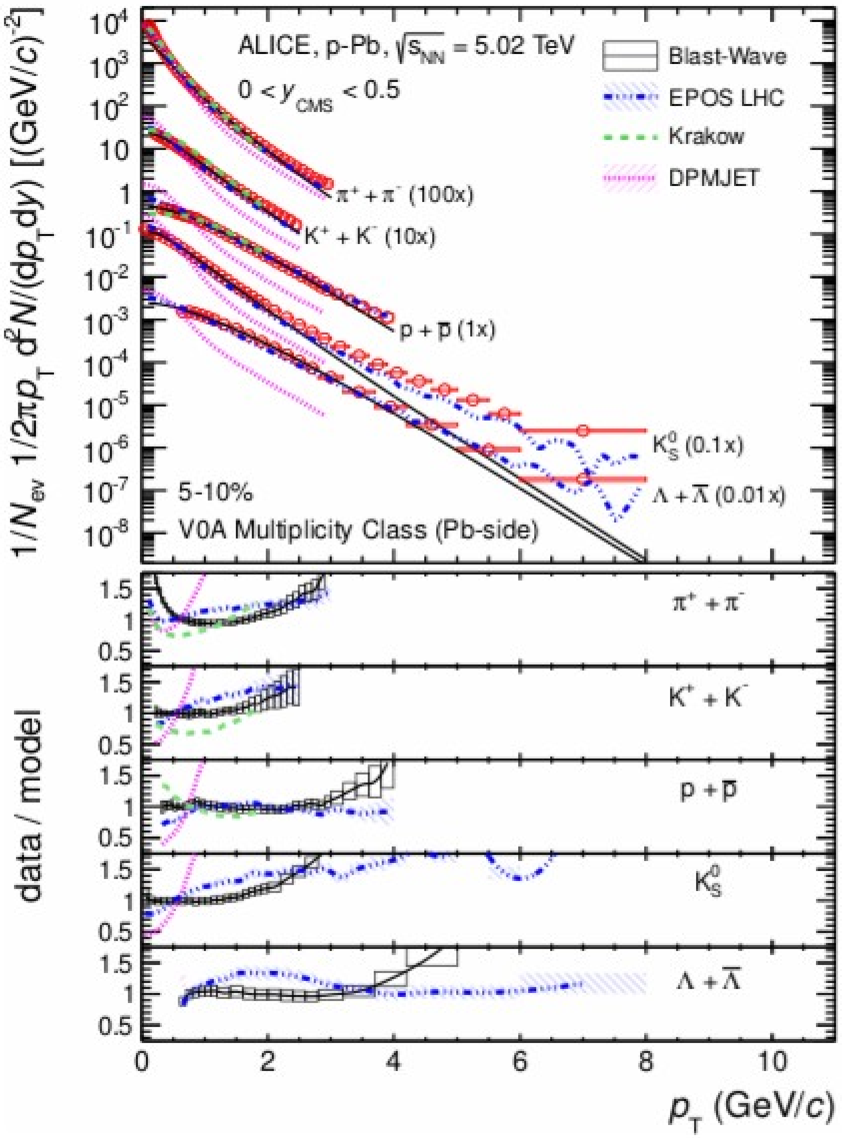


CMS, arXiv:1312.6300



- Strong suppression (even in pPb)
  - Despite similar Q^2
- Final state effect?
  - Suppression in PbPb much stronger!
- Multiplicity scaling of suppression?
- Higher Y states affect multiplicity?
- Same mechanism as in PbPb?

Identified particle spectra



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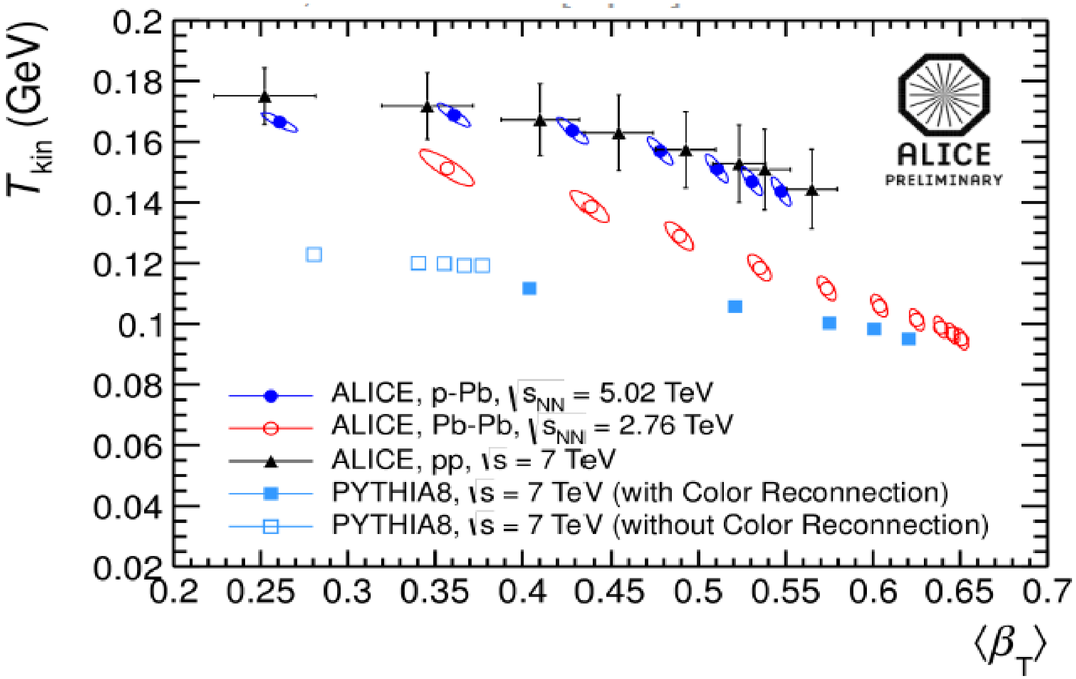
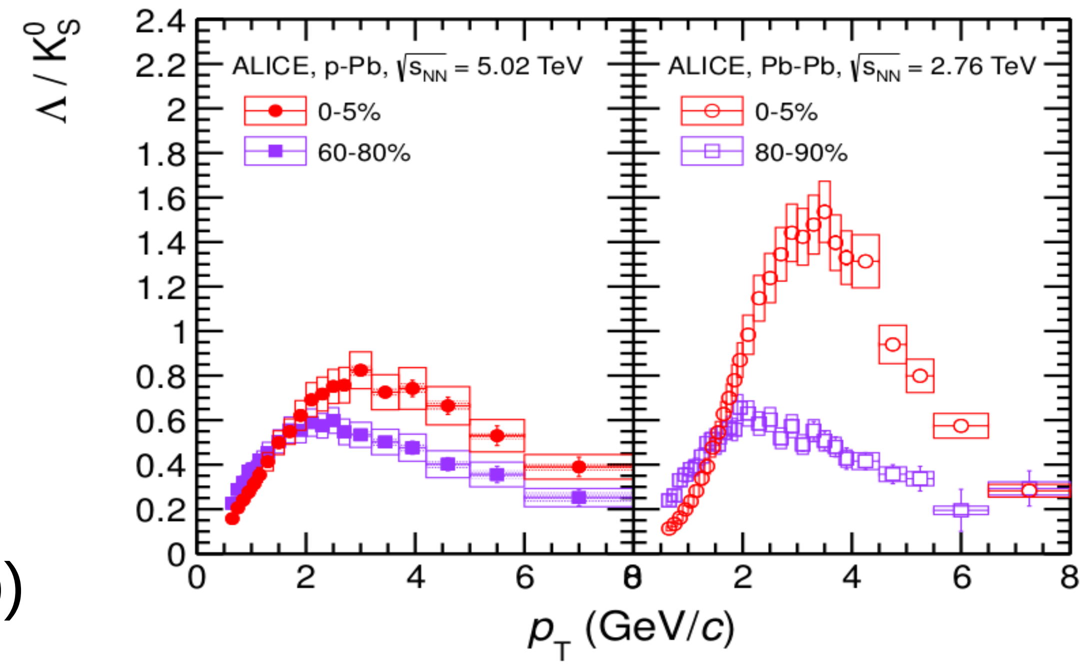
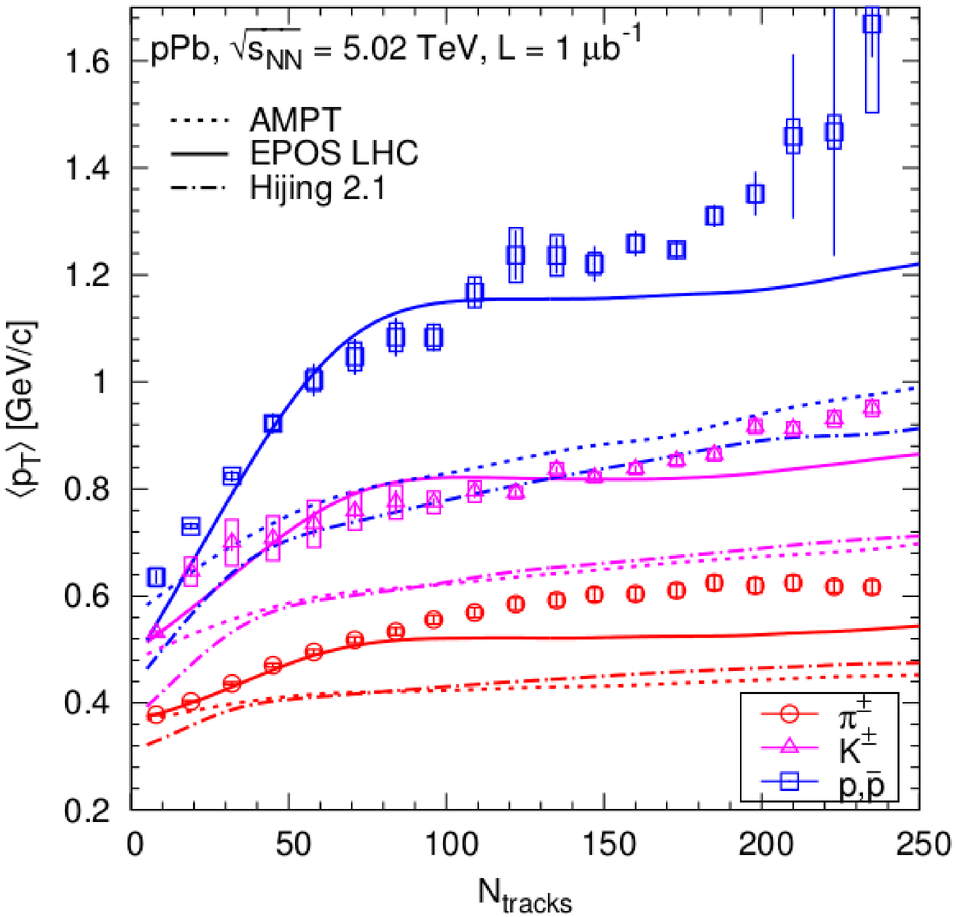




Spectra consistent with radial flow picture (also in pp)

Identified particle spectra

CMS, arXiv:1307.3442



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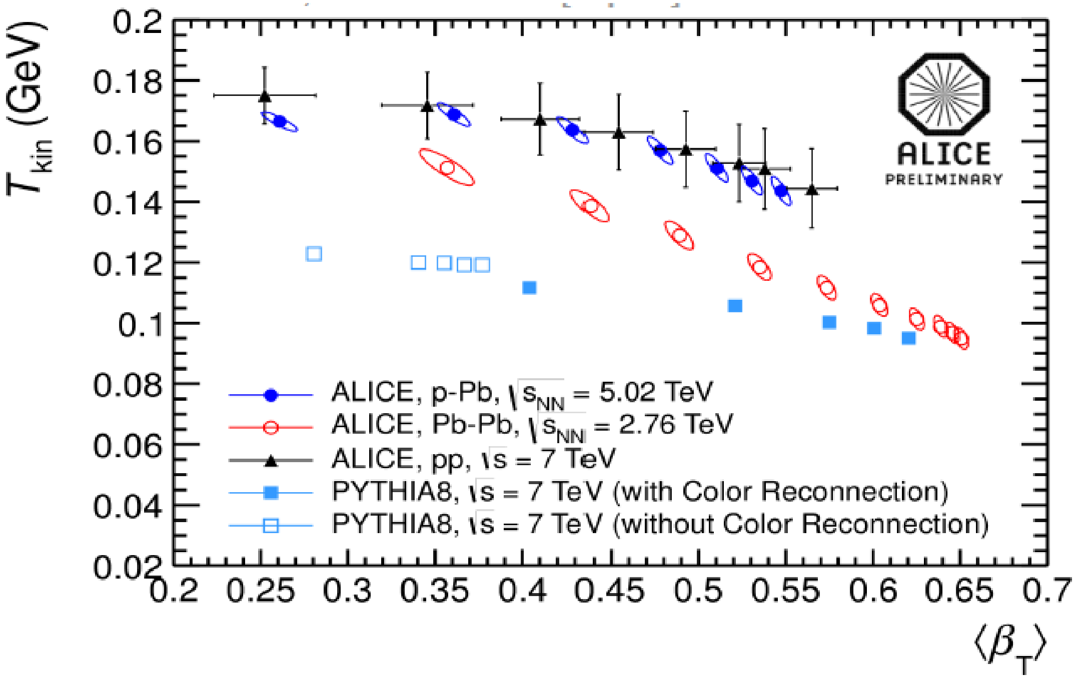

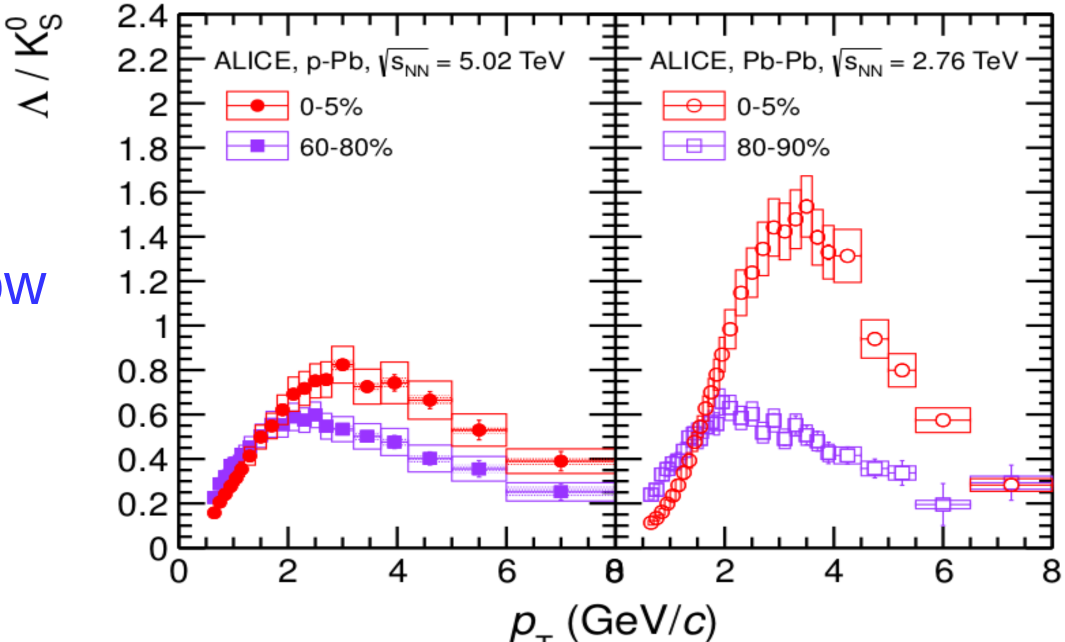

- Spectra feature effects of radial flow
- In Pythia, these can be mimicked by Color Reconnections of strings
- Data in pp and pPb can be related by geometrical scaling

Coherent MPI effects

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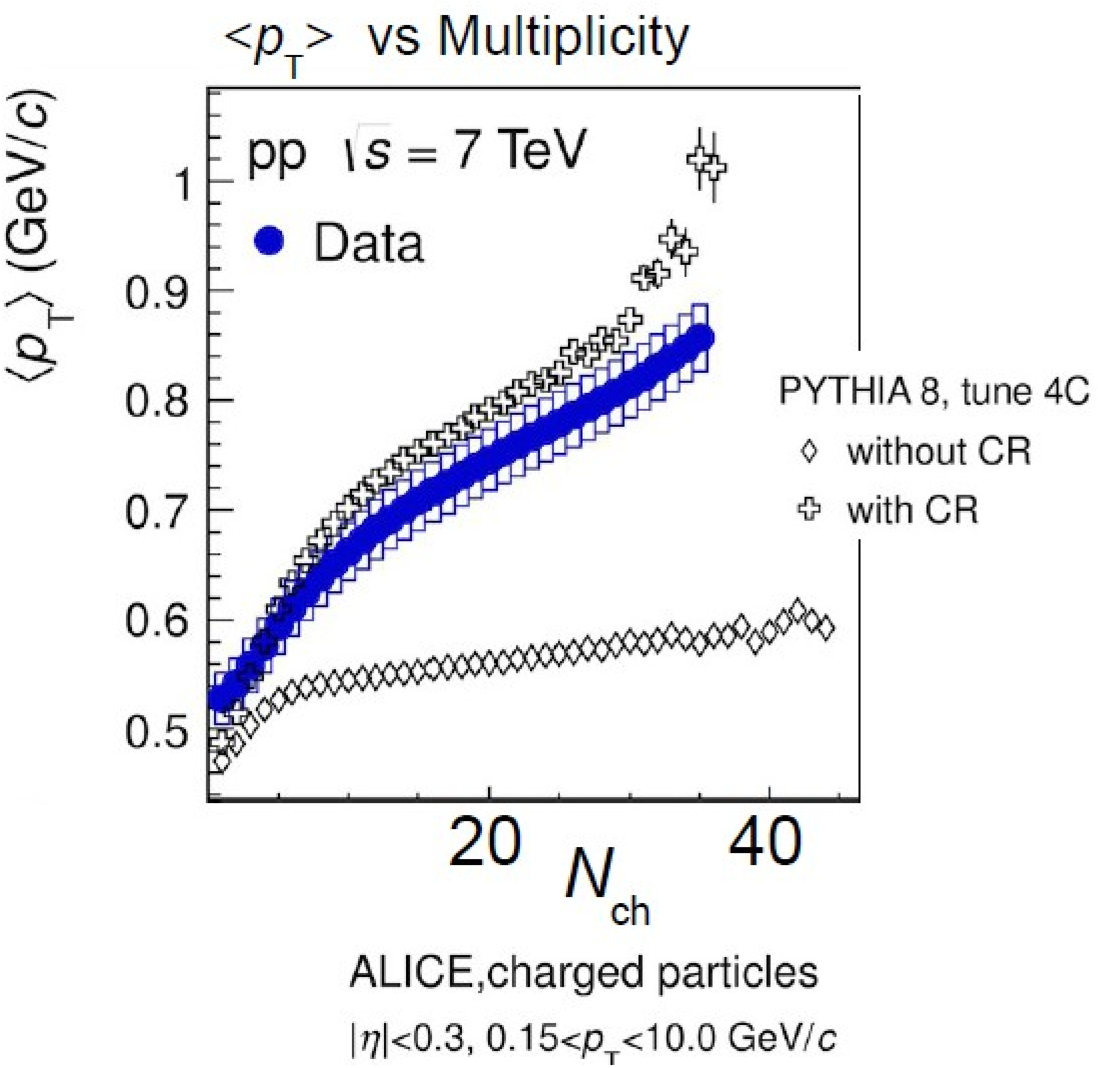

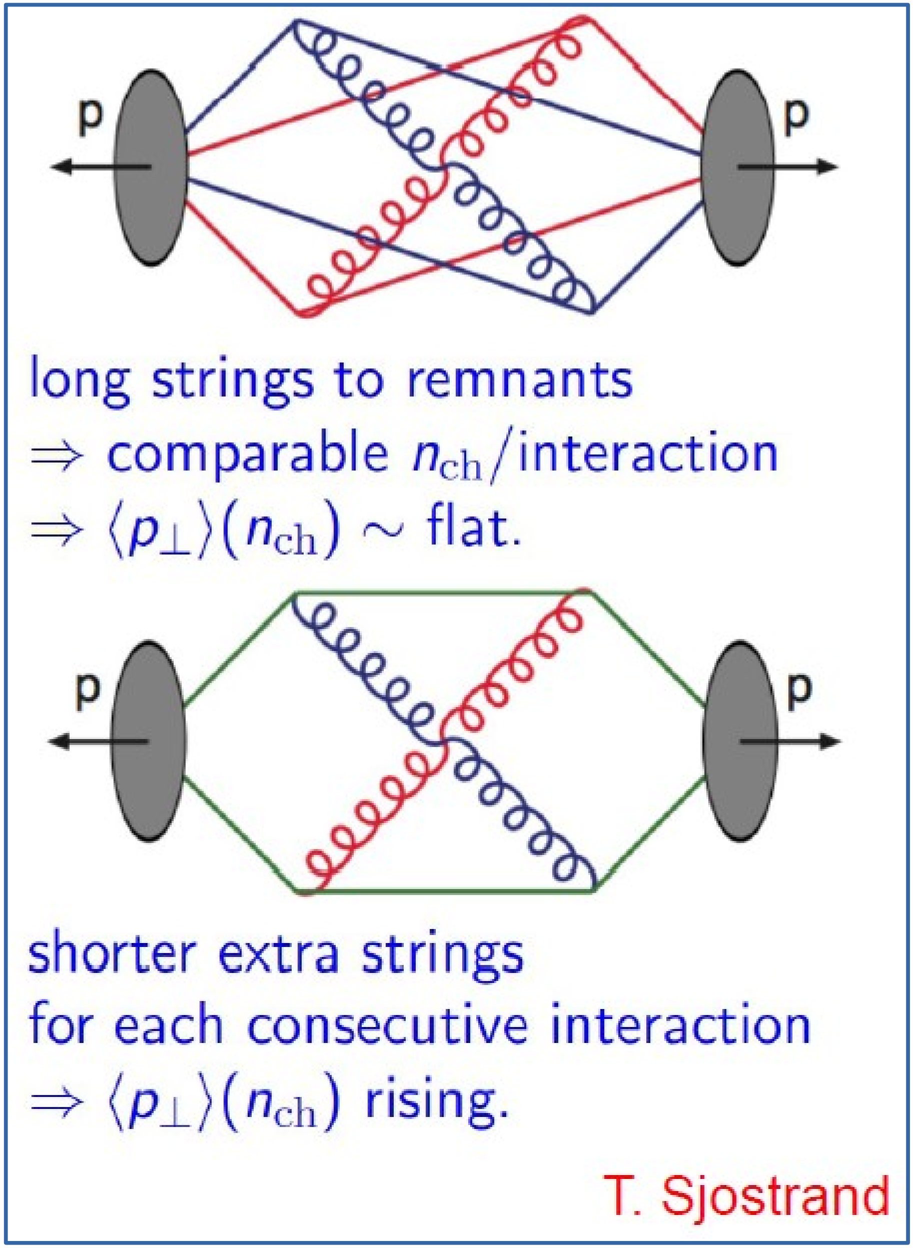

Rise of $\langle p_T \rangle$ can not be reproduced by incoherent superposition of MPI

Average p_T versus N_{ch}

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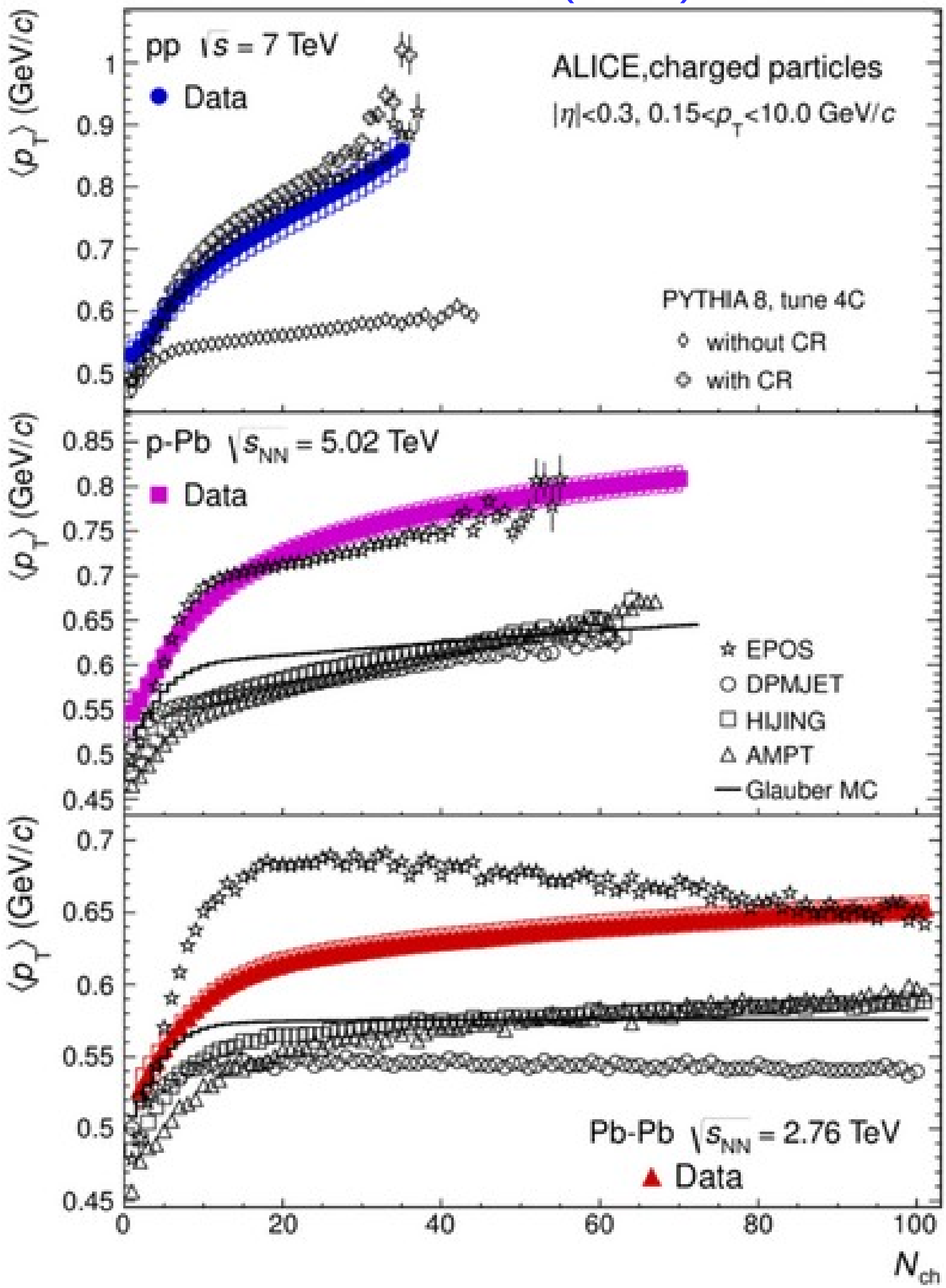
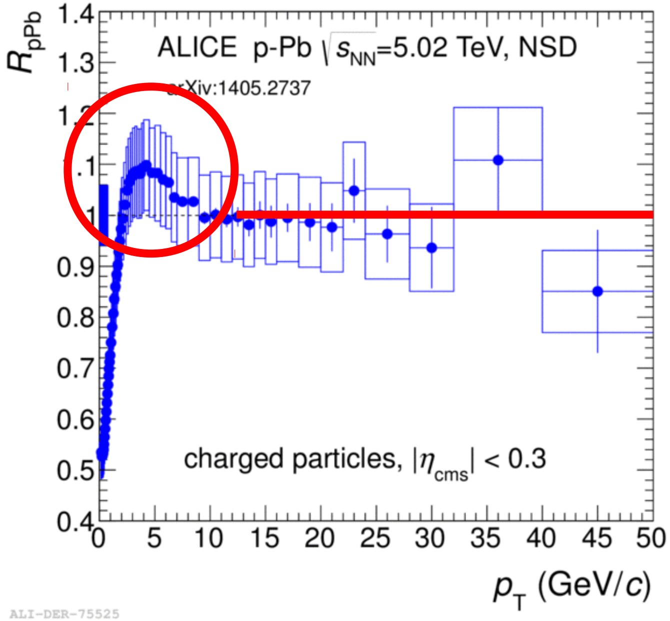


- pp
  - Within PYTHIA model increase in mean p_T can be modeled with Color Reconnections between strings
  - Can be interpreted as collective effect (e.g. Velasquez et al., arXiv:1303.6326v1)
- pPb
  - Increase follows pp up to N_{ch}~14 (90% of pp cross section, pp already biased)
  - Glauber MC (as other models based on incoherent superposition) fails
  - Like in pp: Do we need a (microscopic) concept of interacting strings?
  - EPOS LHC which includes a hydro evolution describes the data (also pp)
- PbPb
  - As expected, incoherent superposition can not describe data



The Cronin peak region

- "Cronin peak" from 2-6 GeV/c
  - Dependence on particle type
  - Enhancement dominated by protons
- Nowadays would attribute effect to be due to radial flow?
  - However, weak for the Φ