XX Cracow Epiphany Conference
on the Physics at the LHC
8-10 January 2014, Cracow, Poland

Heavy-Ion results from the CMS experiment

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on behalf of the CMS Collaboration

Outline

- Introduction
- Experimental results: PbPb vs. **pPb**
  - Signals of (possible) collective behaviour
    - Two-particle correlations
    - p_T spectra of identified hadrons
  - Hard probes
    - Nuclear modification factors
    - Study of dijet events
    - Quarkonia
- Summary

26 published/submitted papers
12 Physics Analysis Summaries (PAS)
http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

Only some selected results presented today …

CMS detector

EM Calorimeter (ECAL)

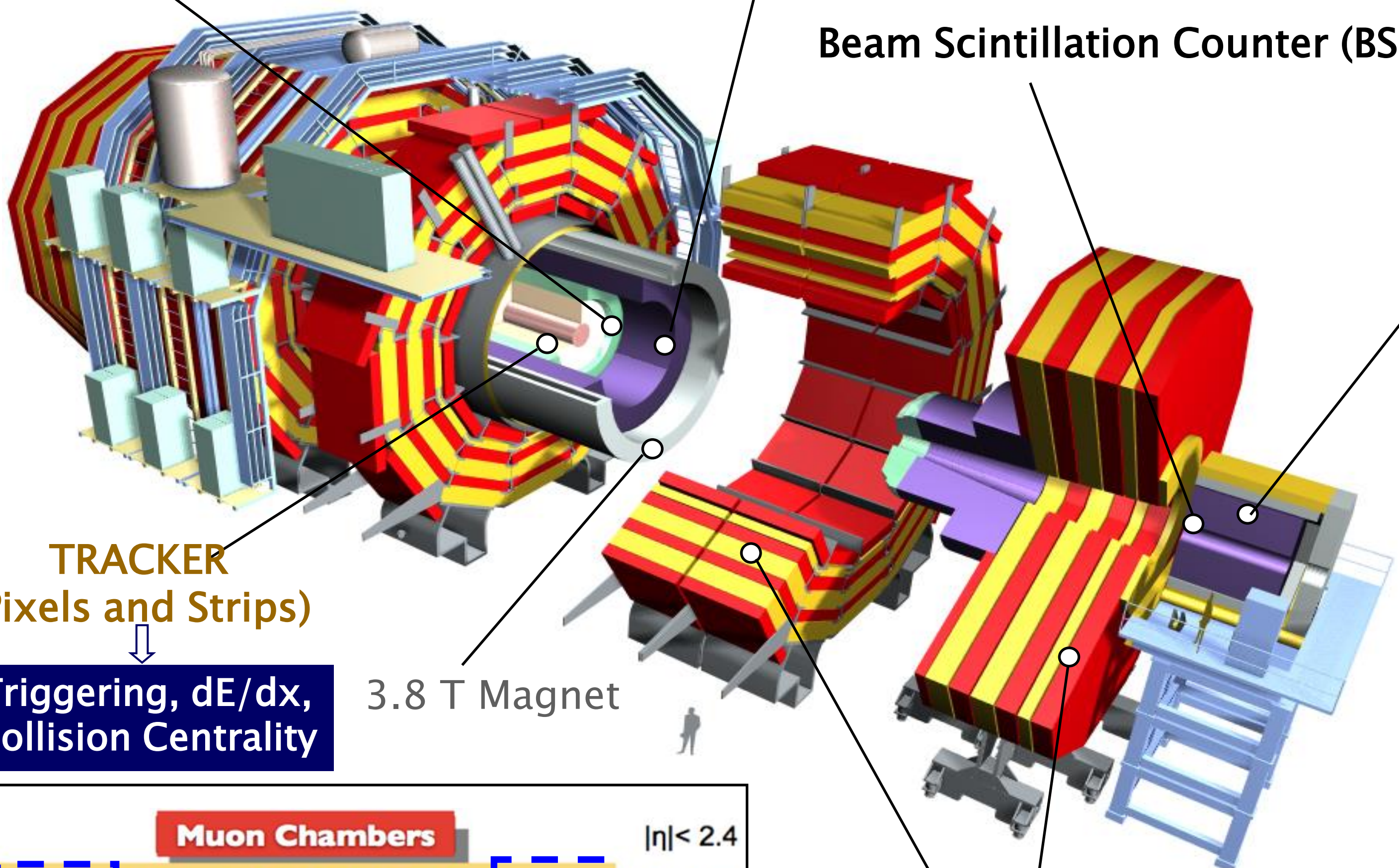
Hadron Calorimeter (HCAL)

Beam Scintillation Counter (BSC) ⇨ MinBias Trigger

Forward Hadron Calorimeter (HF)

⇩

Collision Centrality, Triggering



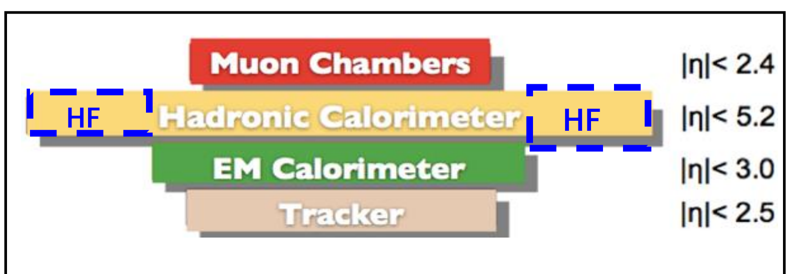
TRACKER (Pixels and Strips)

⇩

Triggering, dE/dx, Collision Centrality

3.8 T Magnet

Muon System

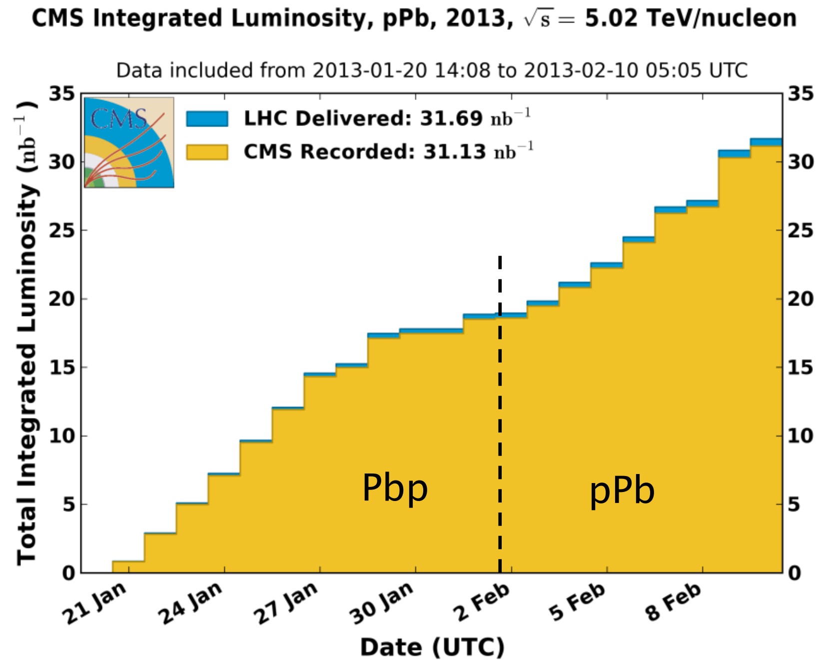


$\eta = -\ln(\mathrm{tg}\,\theta/2)$

Heavy-Ion data sets

	Year	Integrated luminosity
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV	2010 2011	8.3 μb^{-1} 150 μb^{-1}
pp $\sqrt{s}$ = 2.76 TeV	2011 2013	231 nb^{-1} 5.4 pb^{-1}
pPb $\sqrt{s_{NN}}$ = 5.02 TeV	2012 (pilot run) 2013	1 μb^{-1} 31 nb^{-1} (pPb) + (Pbp)

pPb@5.02TeV, 2013

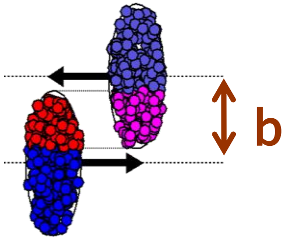


Different trigger selections used

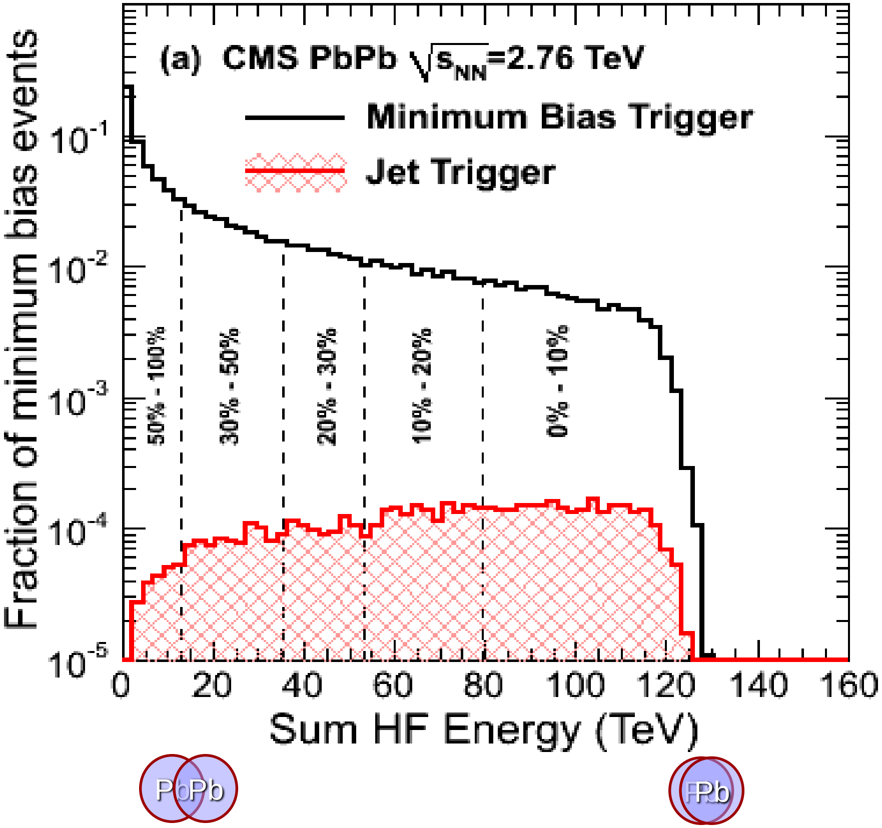
- MinBias Trigger
- Photon Trigger
- Jet Trigger
- (Di)Muon Trigger
- High-multiplicity Trigger

Centrality determination

- Collision centrality related to the energy deposit in forward calorimeters (HF) and multiplicity measured in Inner Tracker



- Example distribution of the total HF energy used to divide the PbPb sample into centrality bins



Collision centrality is related to geometrical quantities:

- N_{part} – number of participating nucleons
- N_{coll} – number of elementary NN collisions

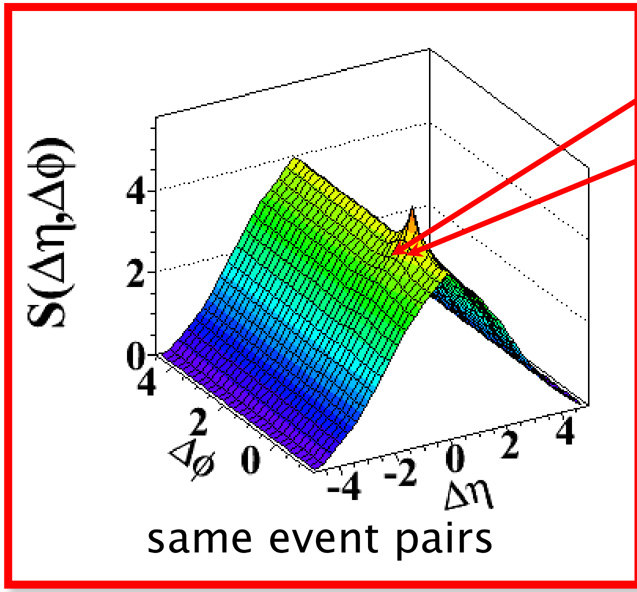
Two–particle correlations

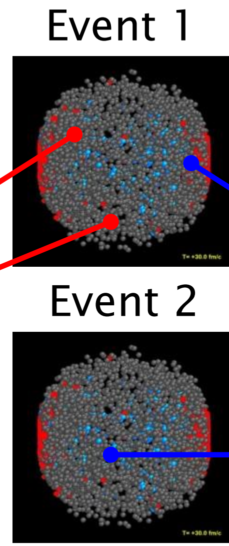
Signal pair distribution:

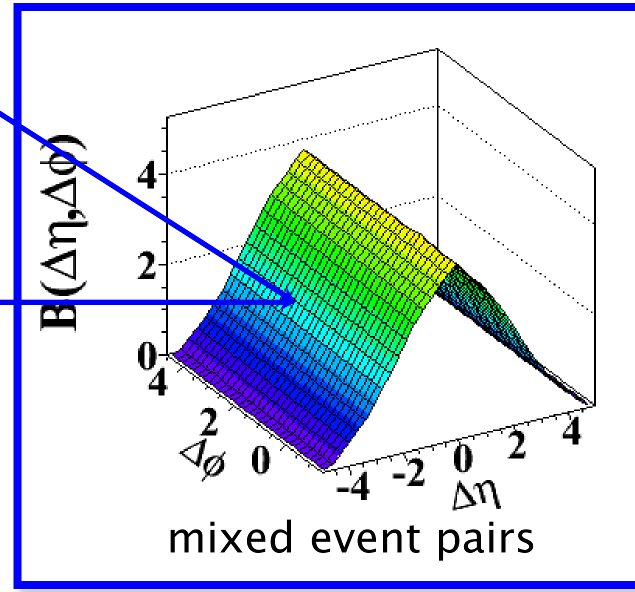
$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}}\frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}$$

Background pair distribution:

$$B(\Delta\eta,\Delta\varphi) = \frac{1}{N_{trig}}\frac{d^2N^{mix}}{d\Delta\eta d\Delta\varphi}$$







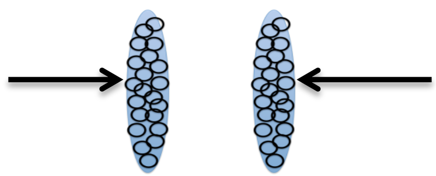
$\Delta\eta = \eta^{assoc} - \eta^{trig}$
$\Delta\phi = \phi^{assoc} - \phi^{trig}$

Associated hadron yield per trigger:

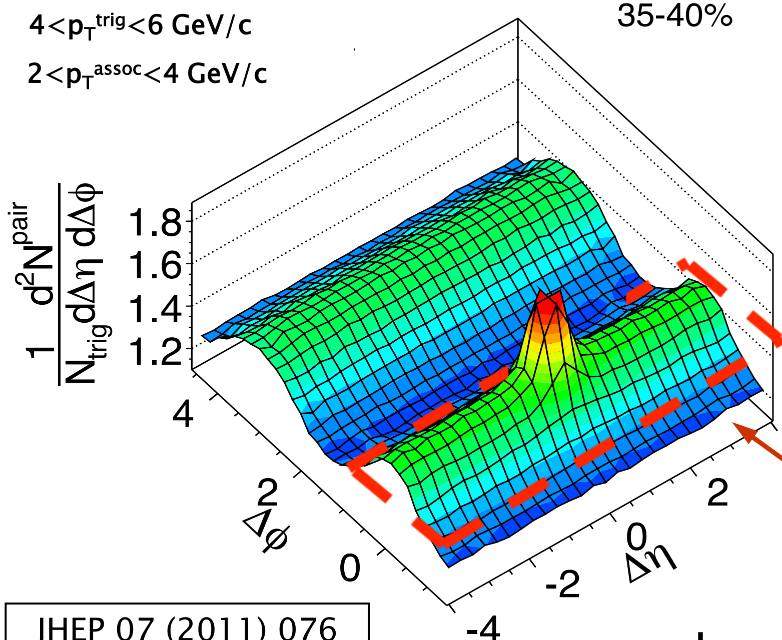
$$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi} = B(0,0)\times\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

Two-particle correlations

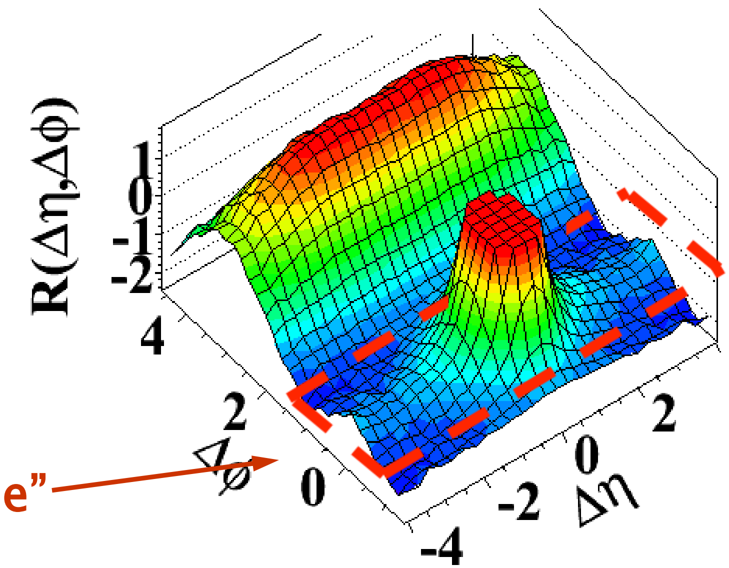
Pb Pb 2.76 TeV



p p 7 TeV



JHEP 07 (2011) 076
EPJC 72 (2012) 2012



„ridge"

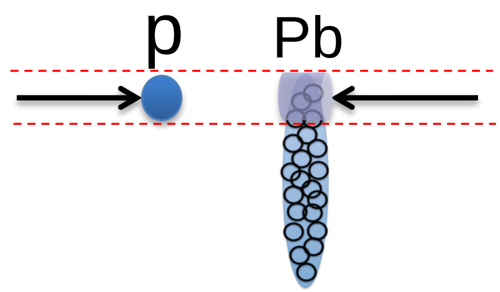
long-range (Δη), near-side (Δϕ≈0) correlations

JHEP 09 (2010) 091

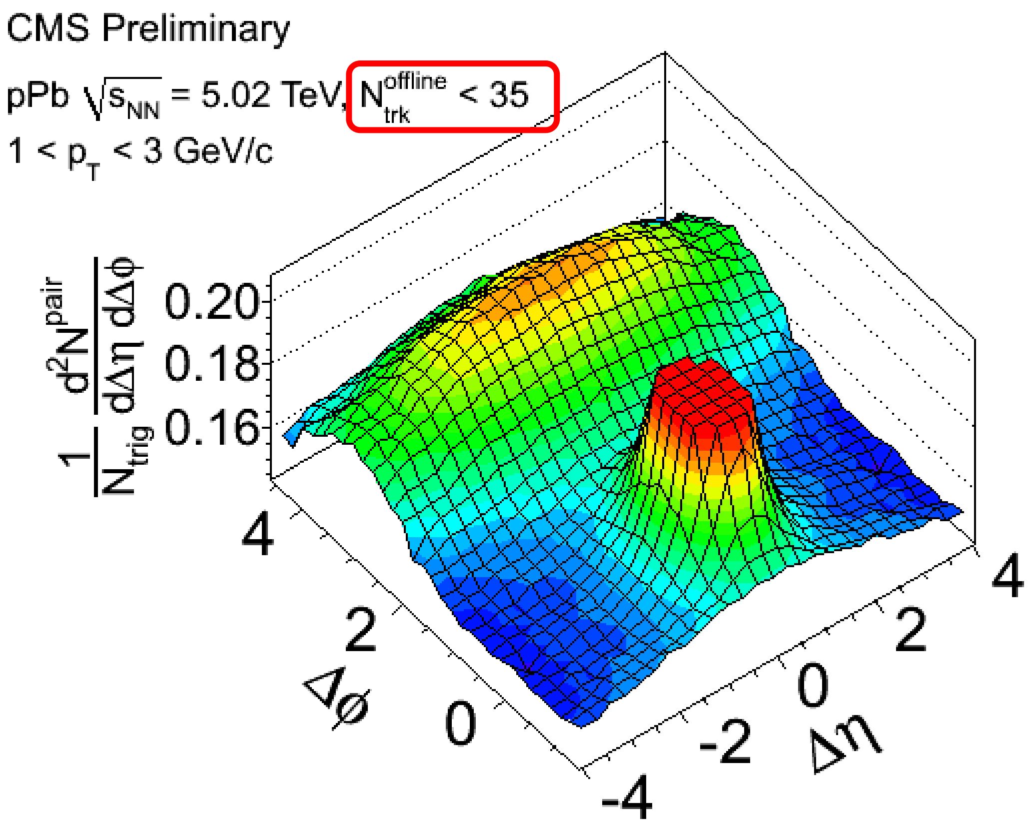
Unexpected „ridge" in high-multiplicity pp collisions

Two–particle correlations

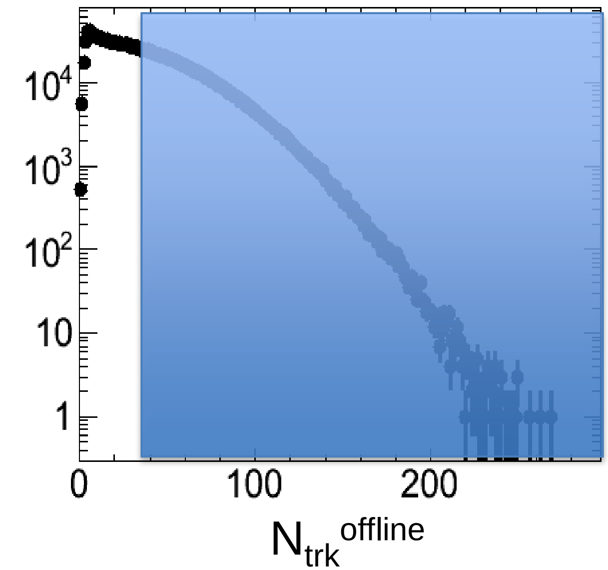
First results for pPb



PLB 718 (2013) 795



Low multiplicity

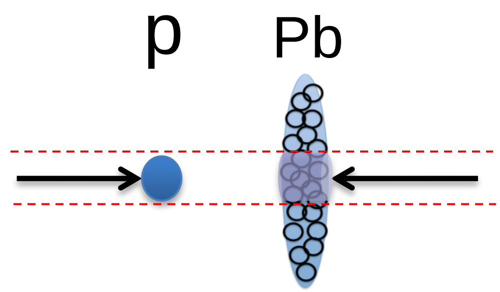


$N_{trk}^{offline}$ – number of offline tracks with p_T>0.4GeV/c

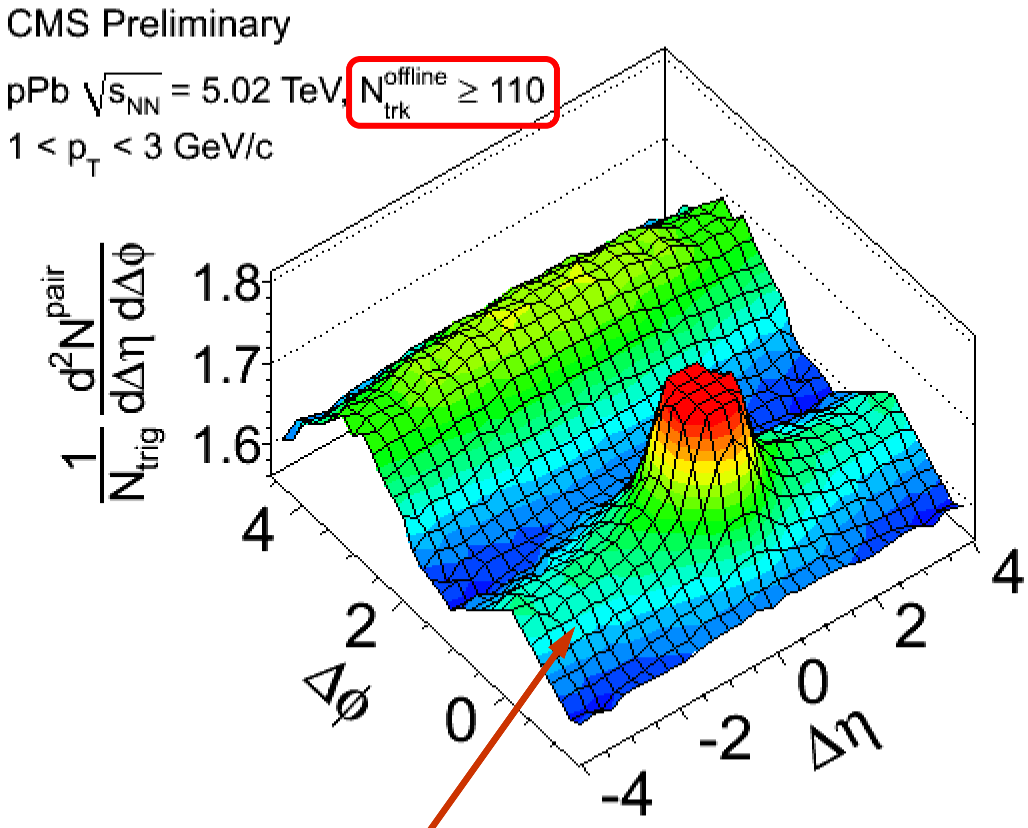
Ridge is not observed in low–multiplicity pPb collisions

Two-particle correlations

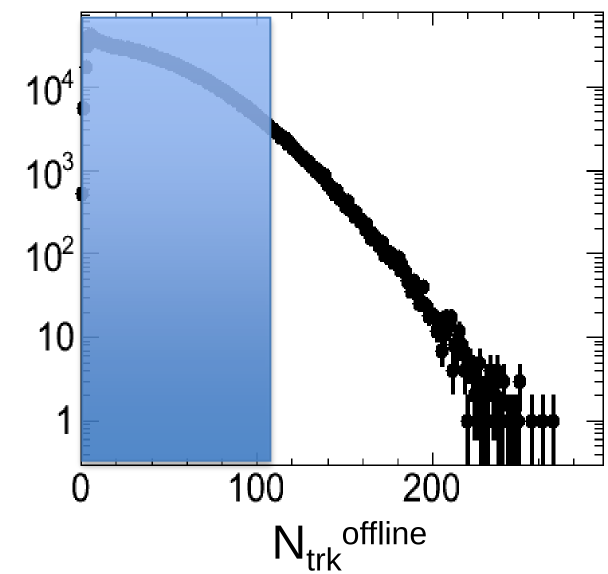
First results for pPb



PLB 718 (2013) 795



High multiplicity



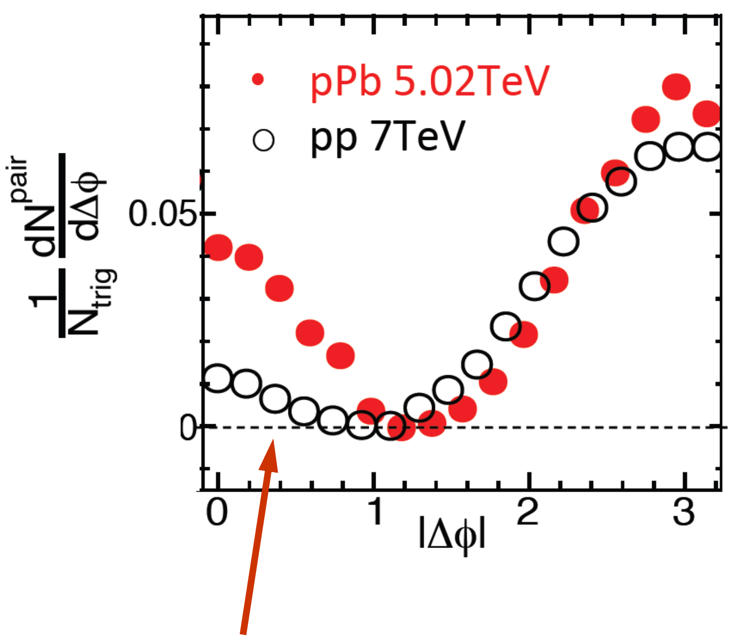
$N_{trk}^{offline}$ – number of offline tracks with p_T>0.4GeV/c

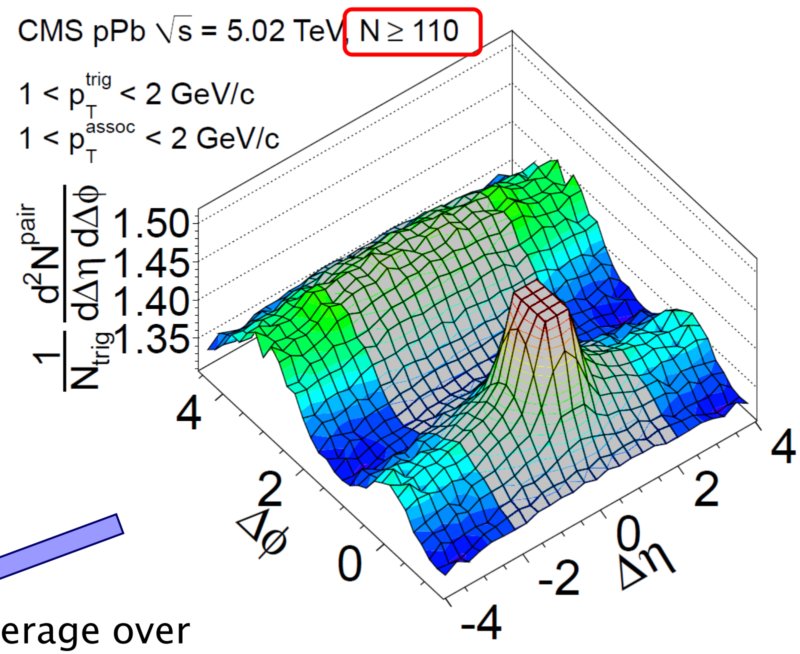
Ridge-like structure observed in high-multiplicity (central) pPb collisions

Δϕ−projected correlation function

PLB 718 (2013) 795

Comparison of pPb and pp:



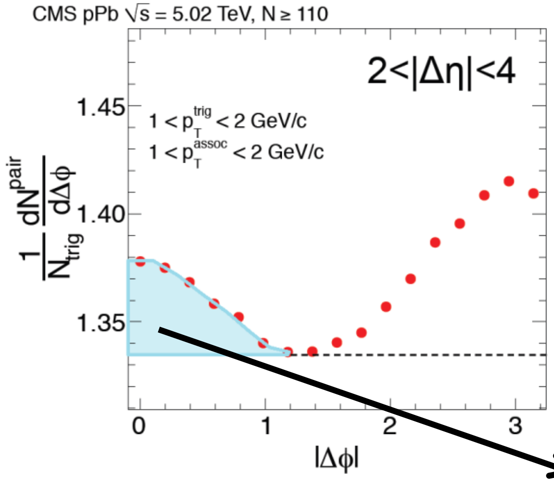


Average over ridge region ($2<|\Delta\eta|<4$)

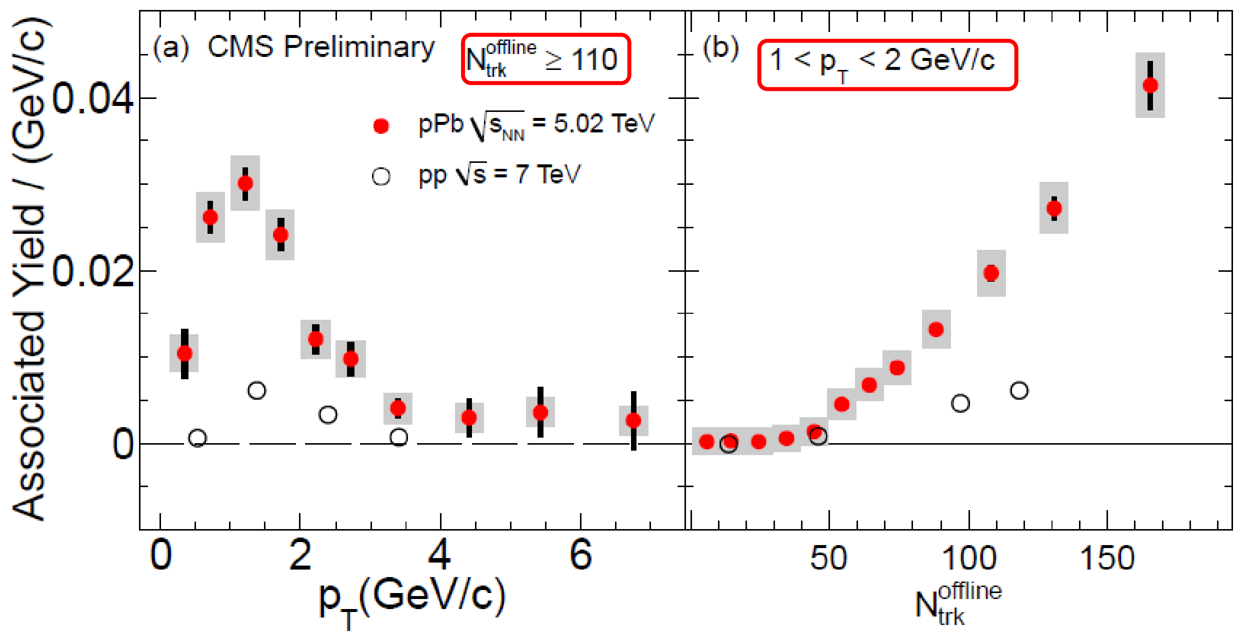
Magnitude of the ridge in pPb much larger than in pp

Integrated associated yield

PLB 718 (2013) 795



p_T and multiplicity dependence:



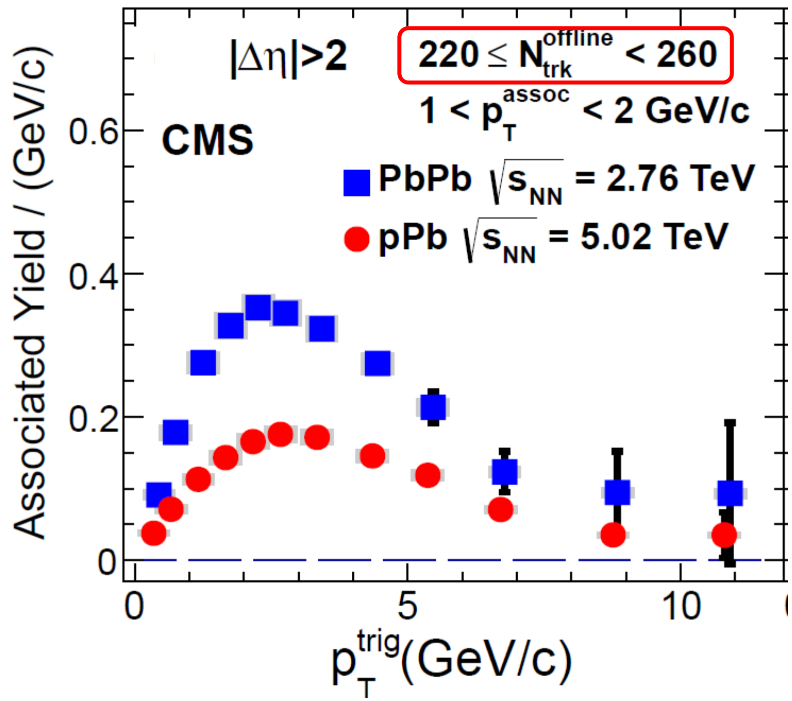
- Similar behaviour for pPb and pp collisions
- But, trends for pPb much stronger than for pp

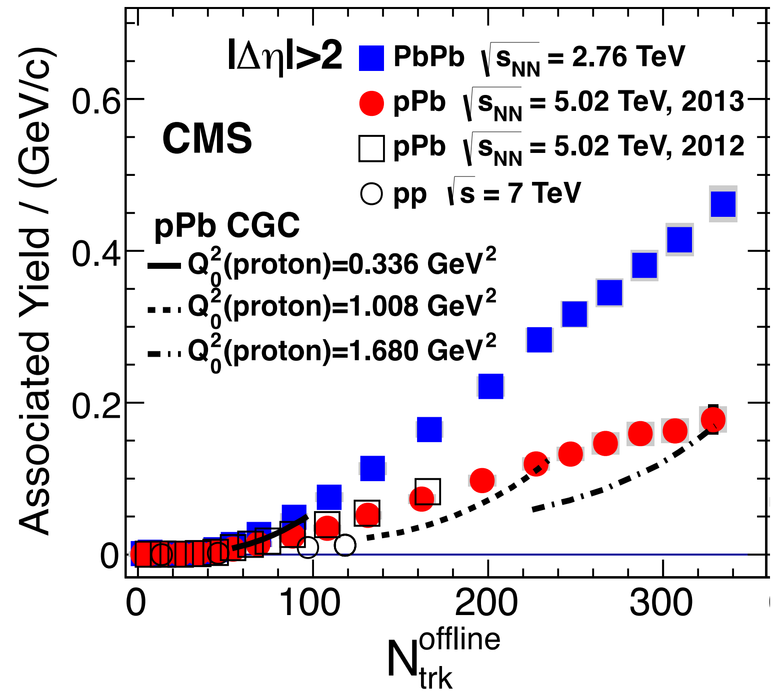
Integrated associated yield

For high statistics pPb 2013 data set, study for events with even higher multiplicity possible → direct comparison with PbPb collisions

PLB 724 (2013) 213

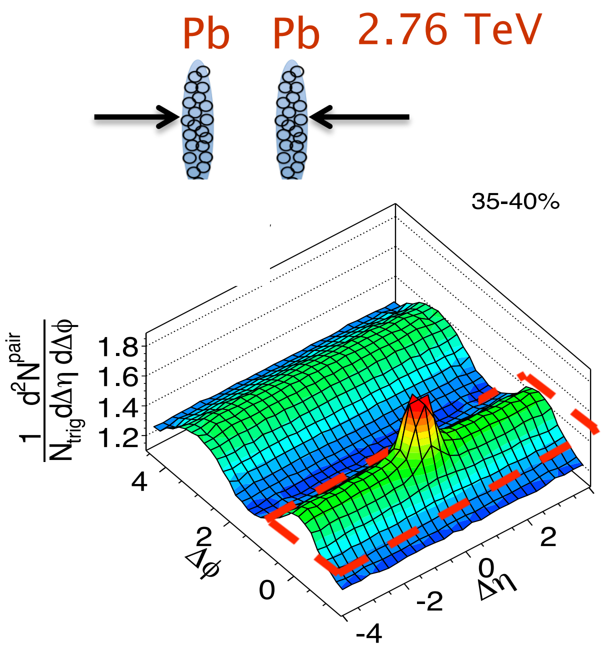
p_T and multiplicity dependence:



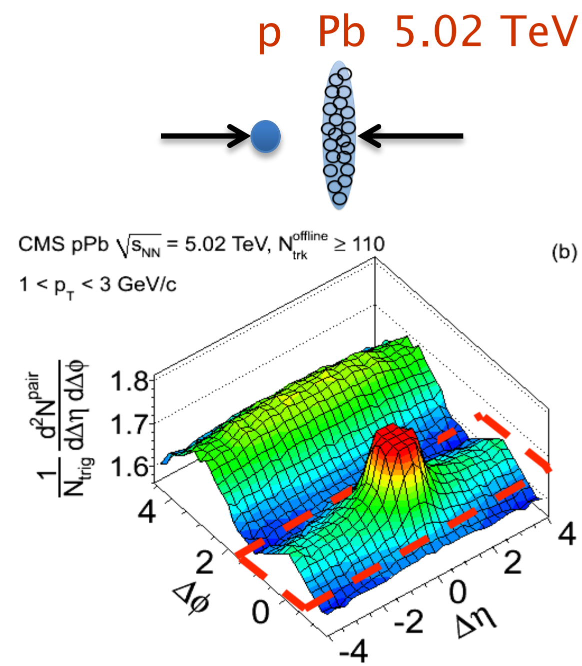


- Similar behaviour for pPb and PbPb collisions
- But, trends for pPb not as strong as for PbPb

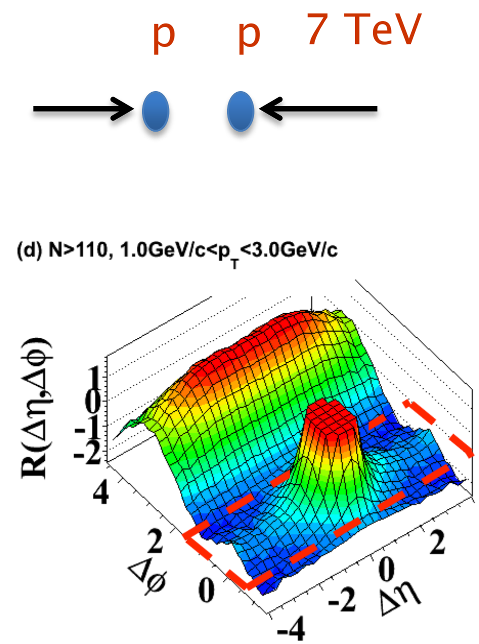
Long-range correlations: Pb+Pb, p+Pb, p+p



JHEP 07 (2011) 076
EPJC 72 (2012) 2012



PLB 718 (2013) 795
PLB 724 (2013) 213



JHEP 09 (2010) 091

Explanation of the effect:

Fluctuations of the initial geometry and hydrodynamical evolution

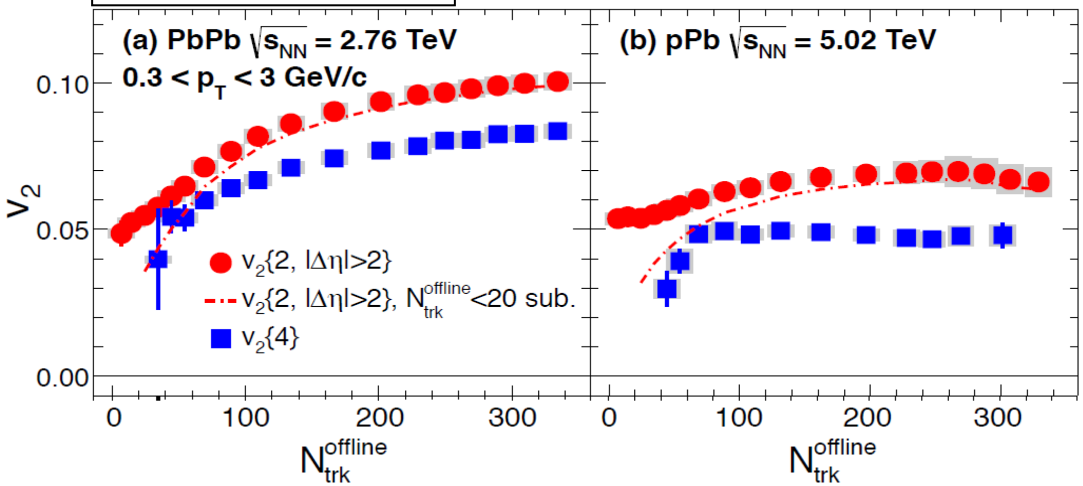
Origin unclear for the small systems:
- hydrodynamical behaviour
  (but not really expected)
- initial-state gluon saturation (CGC)

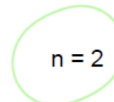
Elliptic (v_2) and triangular (v_3) flow harmonics

Azimuthal anisotropy harmonics determined from a Fourier decomposition of long-range two-particle $\Delta\phi$ correlation functions:

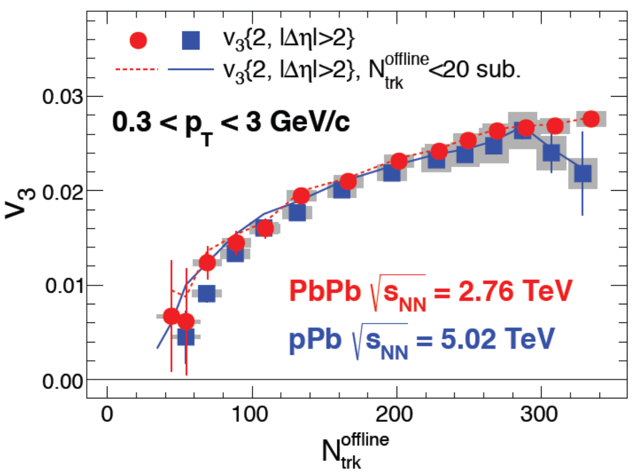
$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2\sum (v_n)^2 \cos(n\Delta\phi)$$

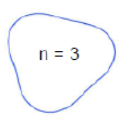
PLB 724 (2013) 213





Elliptic flow (v_2) reflects the medium response to the initial collision geometry





Triangular flow (v_3) reflects fluctuations of the initial geometry

PbPb and pPb collisions are similar:

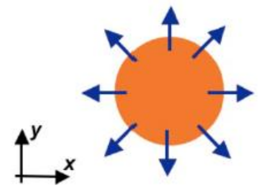
- **v_2 and v_3 increase with multiplicity for both systems**
- **However, the magnitude of v_2 smaller in pPb than in PbPb**

- **v_3 in PbPb and pPb coincide for all multiplicities**

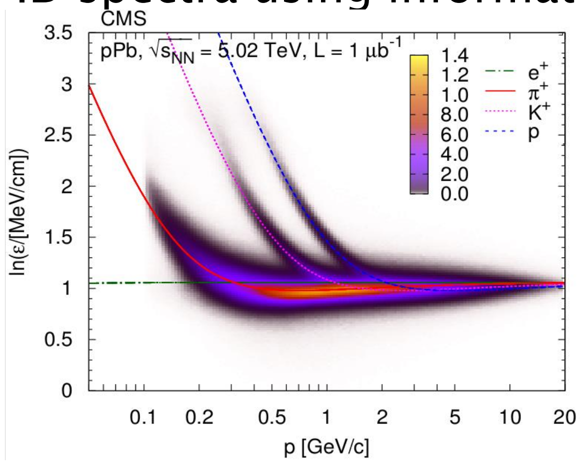
(but very different collision geometry for PbPb and pPb)
→ challenge to theoretical models

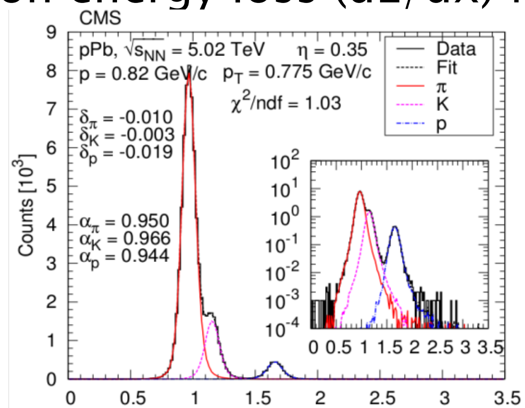
Other evidence of hydro flow in pPb?

- If azimuthal correlations are due to hydro flow, there must be also a mass splitting of p_T spectra – "radial flow"

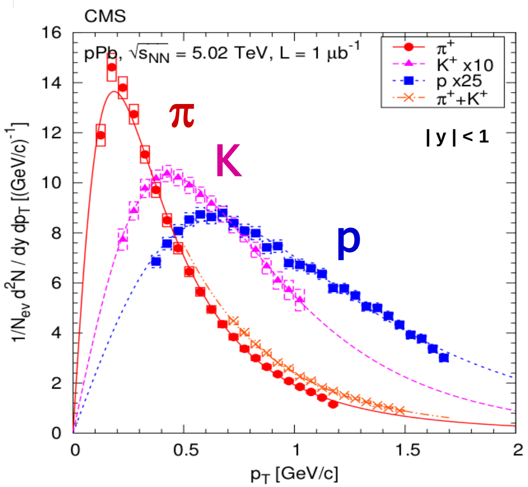


- Study PID spectra using information on energy loss (dE/dx) in silicon tracker





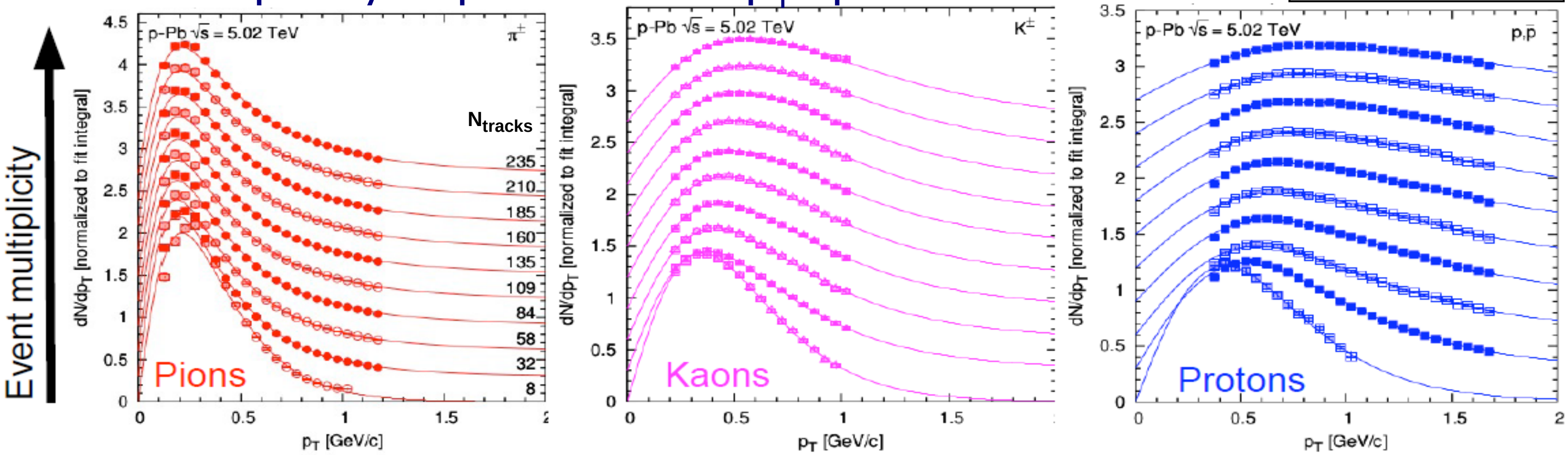
- Identified hadron p_T spectra:



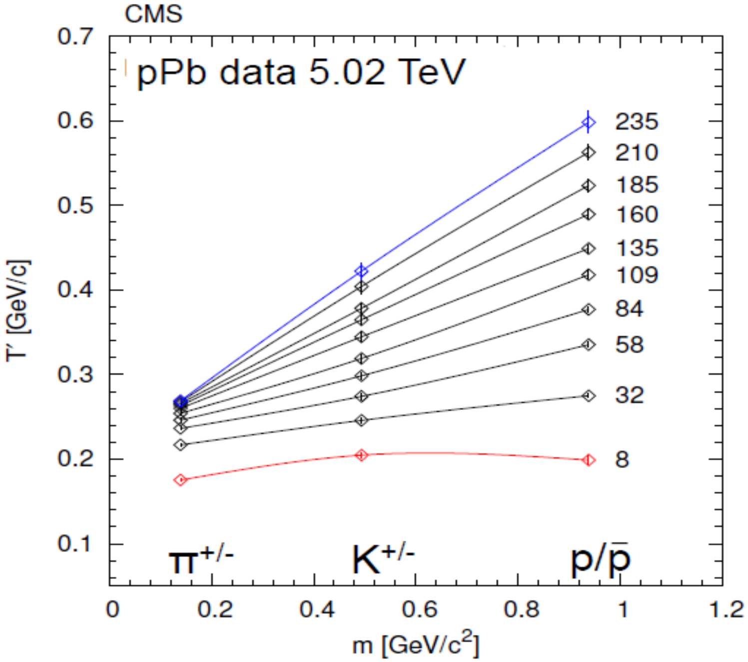
Other evidence of hydro flow in pPb?

arXiv:1307.3442

Multiplicity dependence of p_T spectra:



N_{tracks} – corrected number of hadrons in $|\eta|<2.4$



Inverse slope parameter T' taken from $p_T \exp(-m_T/T')$ fits

- **T' larger for heavier particles**
- **T' increases with particle multiplicity in the event**

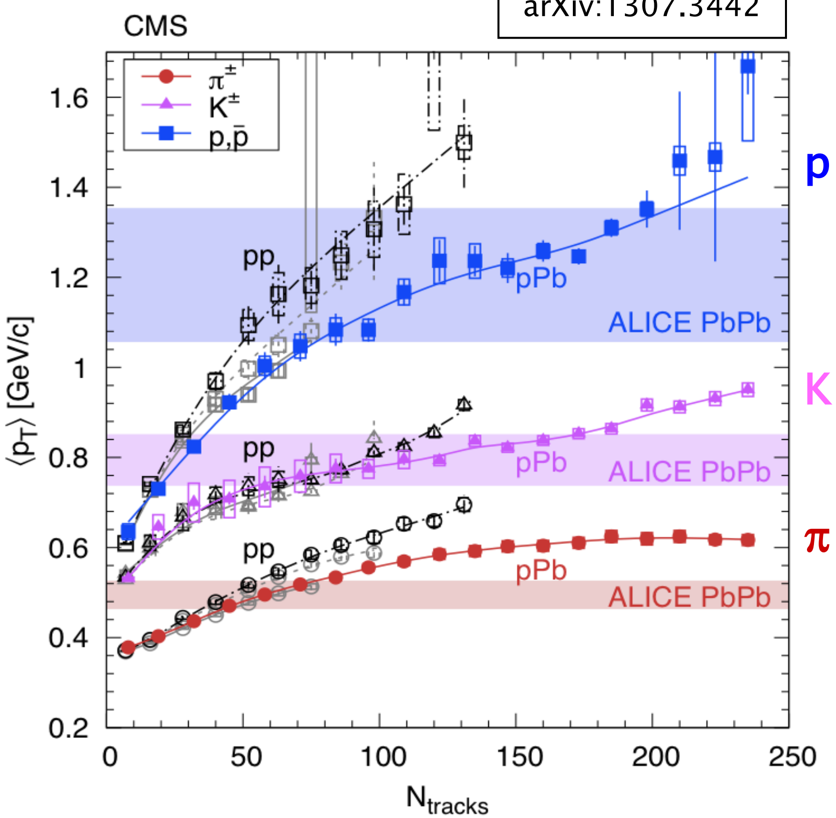
Observations reminiscent of radial flow:

$T_{slope} \sim T_{freeze-out} + m\langle u\rangle^2$

radial flow velocity

Identified hadrons: $<p_T>$ vs. multiplicity

arXiv:1307.3442



pp (0.9, 2.76, 7 TeV), pPb (5.02 TeV)

PbPb (2.76 TeV, periph to central bands)

ALICE (PRC88(2013)044910)

pPb collisions:

- $<p_T>$: pions < kaons < protons
- strong dependence of $<p_T>$ values on multiplicity

Comparison to pp and PbPb:

- pPb behaves similarly to pp for $N_{tracks}<40$ but it is flatter for larger N_{tracks}
- $<p_T>$ grows higher for pPb than for PbPb

For large N_{tracks}:

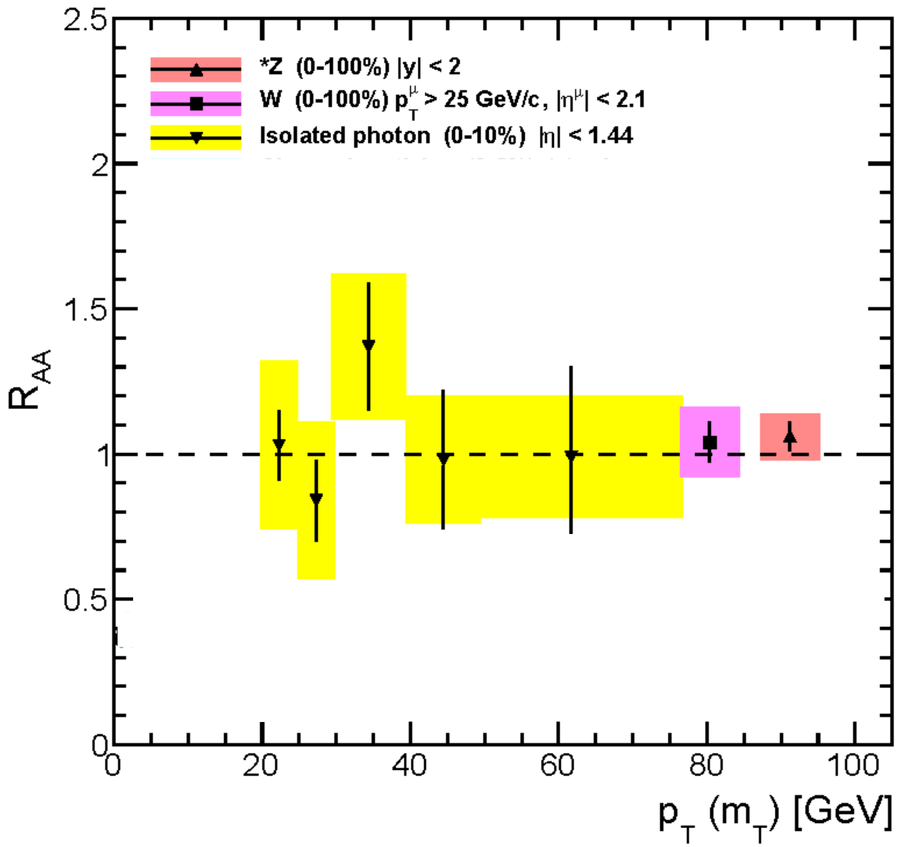
- PbPb is a mix of soft and hard collisions
- for pPb most violent collisions are selected

Nuclear modification factor

R_{AA} – the first tool for jet quenching studies

$$R_{AA} = \frac{\text{(Yield in AA)}}{N_{COLL}(AA) \times \text{(Yield in pp)}}$$

- $R_{AA}>1$ enhancement
- $R_{AA}=1$ no medium effect
- $R_{AA}<1$ suppression



PbPb 2.76 TeV

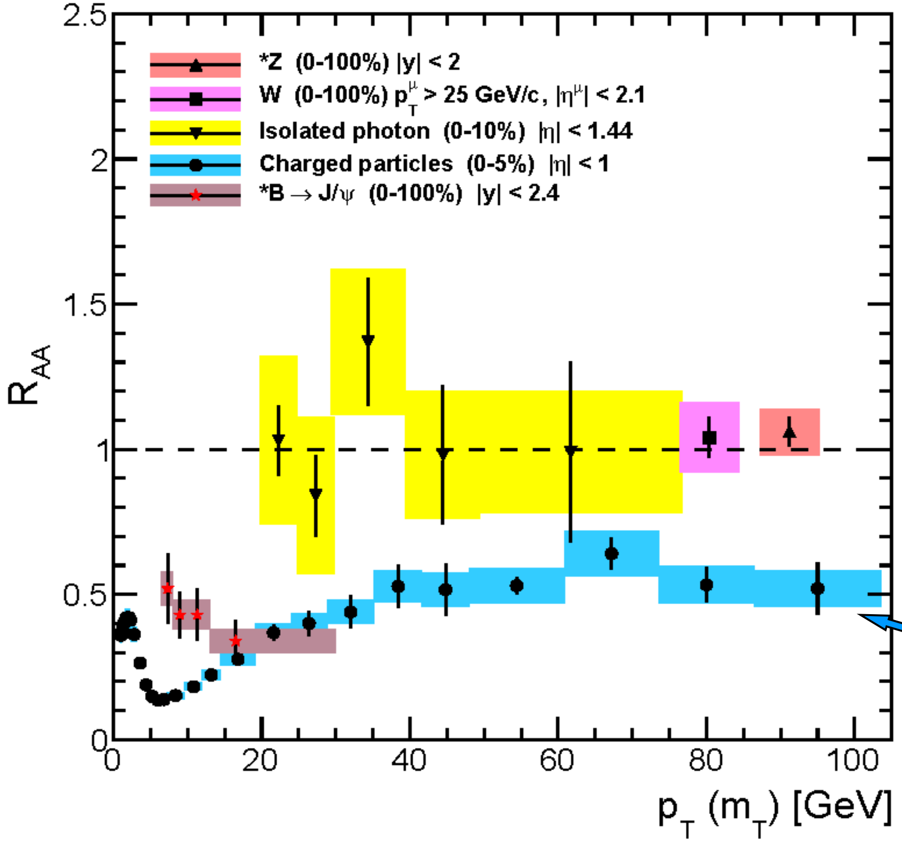
Prompt γ	PLB 710 (2012) 256
W	PLB 715 (2012) 66
Z	PAS-HIN-13-004

Non-strongly interacting probes (control probes) are not modified by the medium

Production scales with N_{coll}, $R_{AA}=1$

Nuclear modification factor

PbPb 2.76 TeV



EPJC 72 (2012) 1945

JHEP 05 (2012) 063

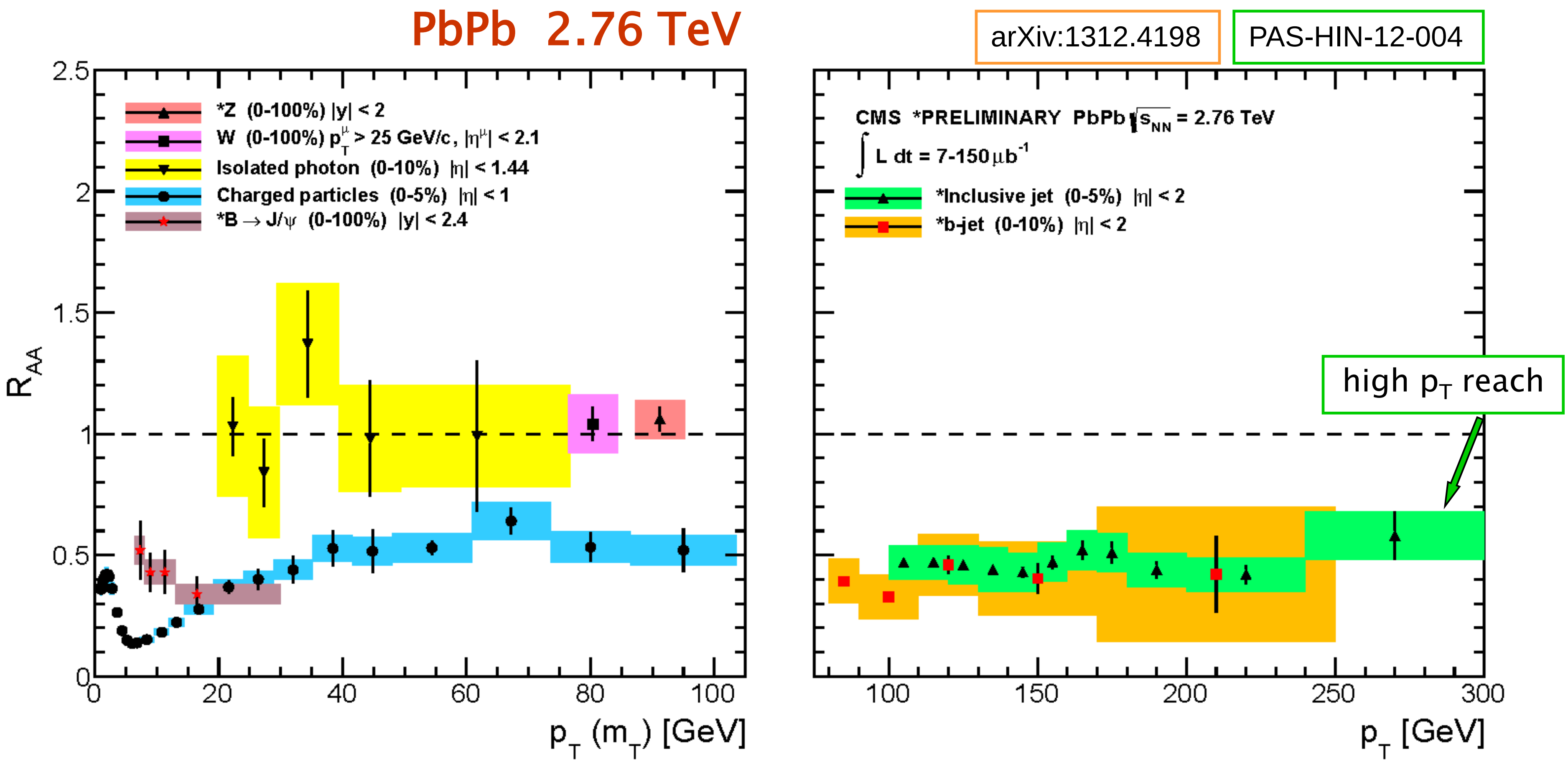
charged hadrons & b-quarks

are suppressed, $R_{AA}<1$

high p_T reach

- Control probes are unsuppressed
- Hadrons are modified (jet quenching)

Nuclear modification factor



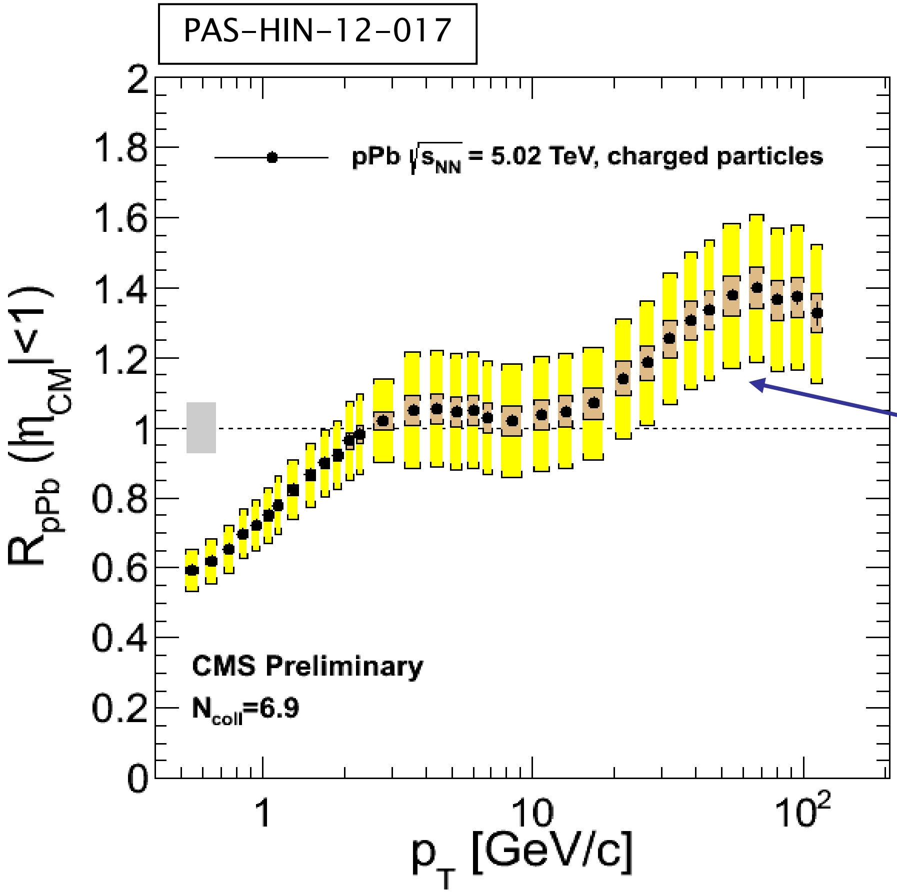
- Control probes are unsuppressed
- Hadrons and jets are modified (jet quenching)
- b-jets are similar to inclusive jets

Jet $R_{AA} \approx 0.5$

First measurement of b-jet R_{AA} !!

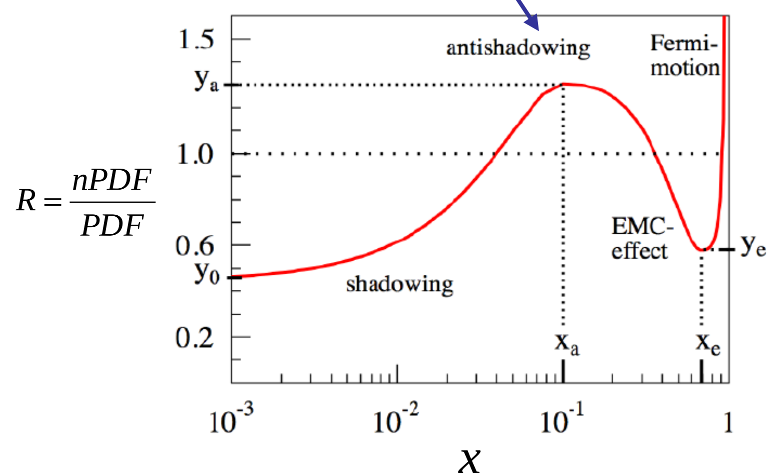
Nuclear modification factor

Reference data: **pPb 5.02 TeV**



Charged hadrons
$0.5 < p_T < 100$ GeV/c

- $R_{pPb} \approx 1$ for $2 < p_T < 30$ GeV/c; no jet quenching
- $R_{pPb} > 1$ for $p_T > 30$ GeV/c (antishadowing?)

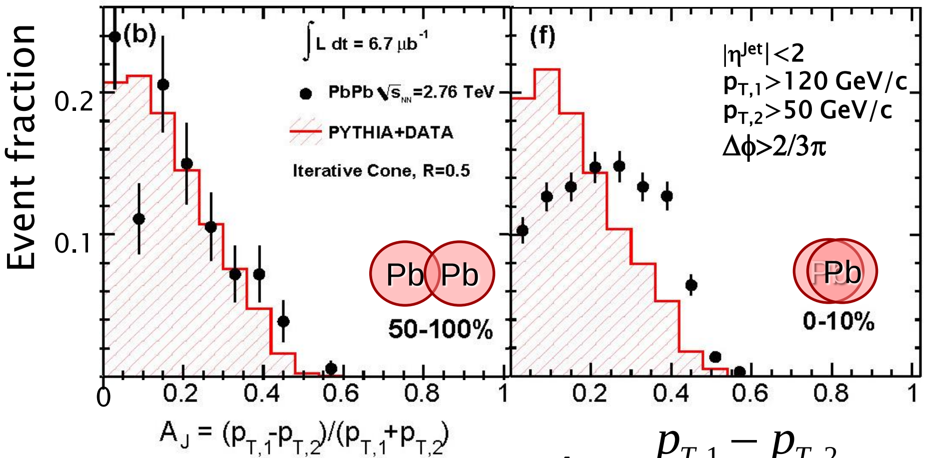


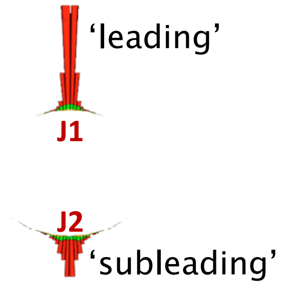
Dijet events in PbPb collisions

PRC 84 (2011) 024906

PLB 712 (2012) 176

Dijet Imbalance





• exp. DATA

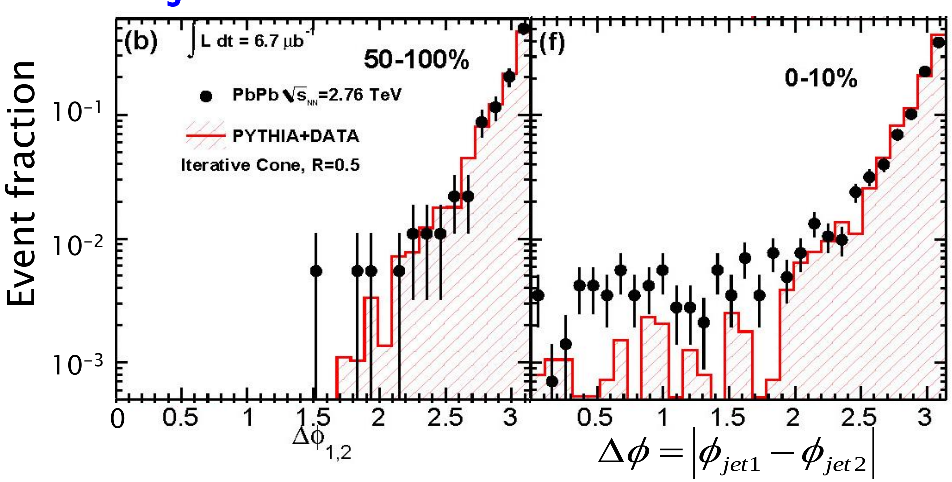
– ref. DATA

Asymmetry: $A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$

➡ Dijet p_T imbalance (A_J) increases with centrality

→ Direct observation of jet quenching in central PbPb collisions

Dijet Azimuthal Correlation



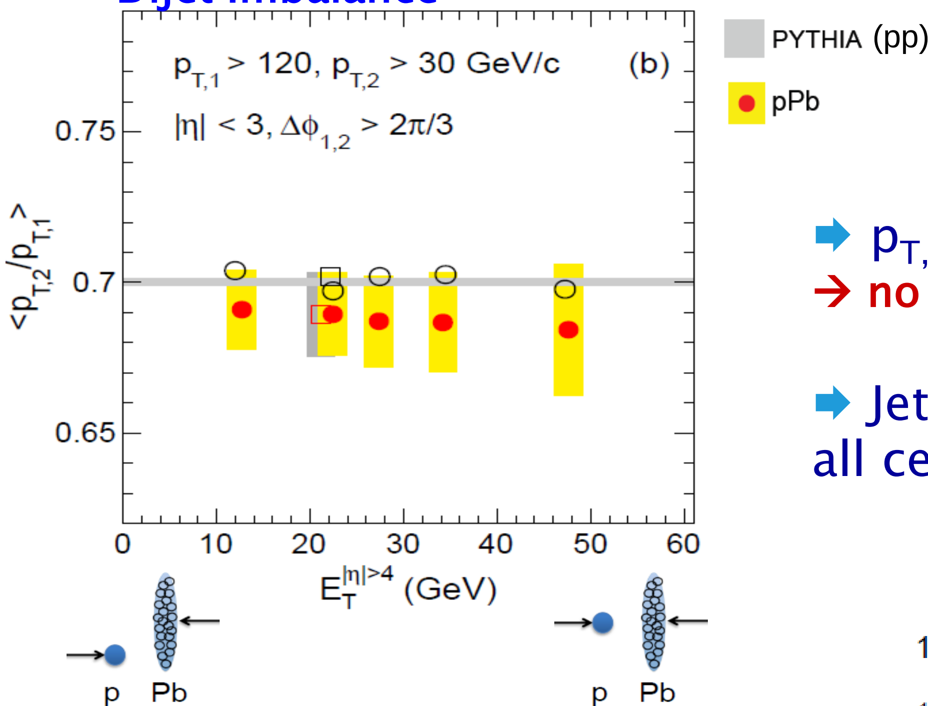
➡ Jets remain essentially back-to-back ($\Delta\phi \sim \pi$) for all centralities

→ Propagation of high p_T partons in dense nuclear medium does not lead to a strong angular decorrelation

Is there jet quenching in pPb for dijets?

PAS-HIN-13-001

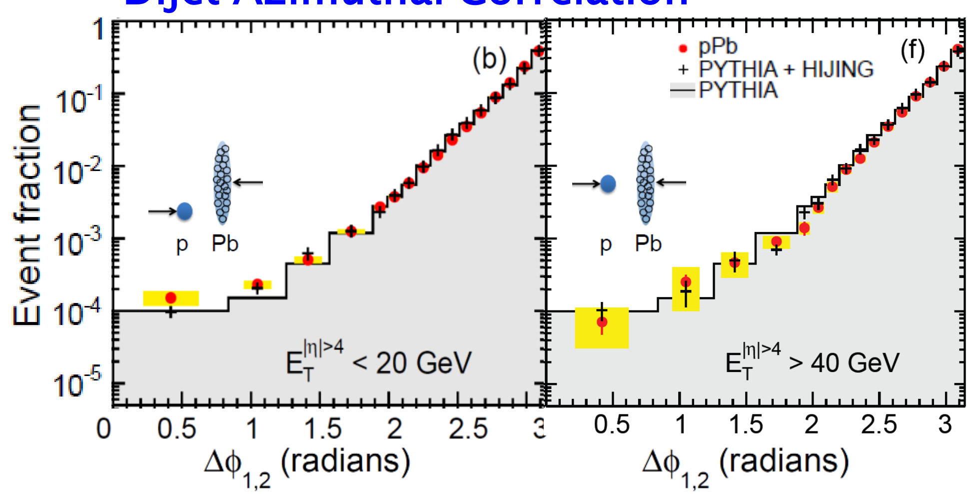
Dijet Imbalance



Centrality characterized by E_T at large $|\eta|$

- $p_{T,2}/p_{T,1}$ for pPb dijets the same as in pp
  → no jet quenching observed
- Jets remain back-to-back ($\Delta\phi \sim \pi$) for all centralities

Dijet Azimuthal Correlation



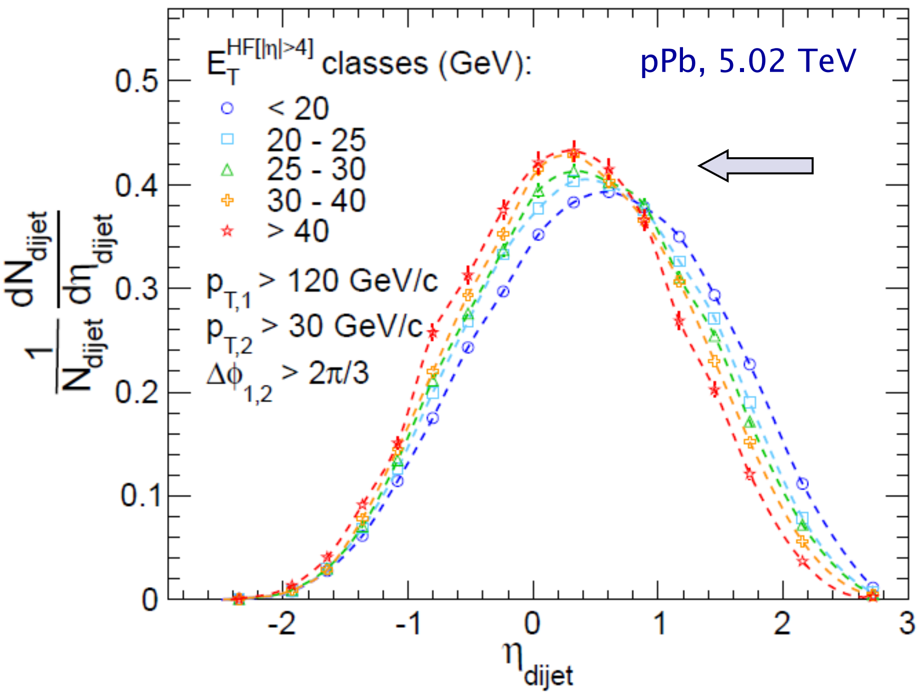
No final state effects observed for dijets in pPb → Can we access the initial state effects?

Dijet η distribution

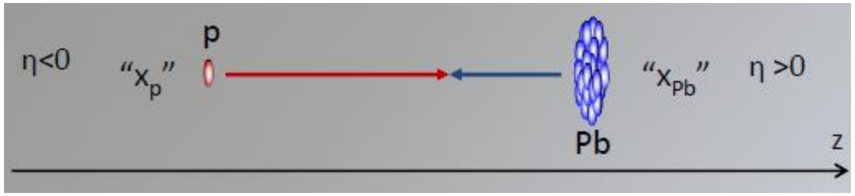
For different centrality classes:

$$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$$

Centrality characterized by E_T at large $|\eta|$



PAS-HIN-13-001



Backward direction

Forward direction

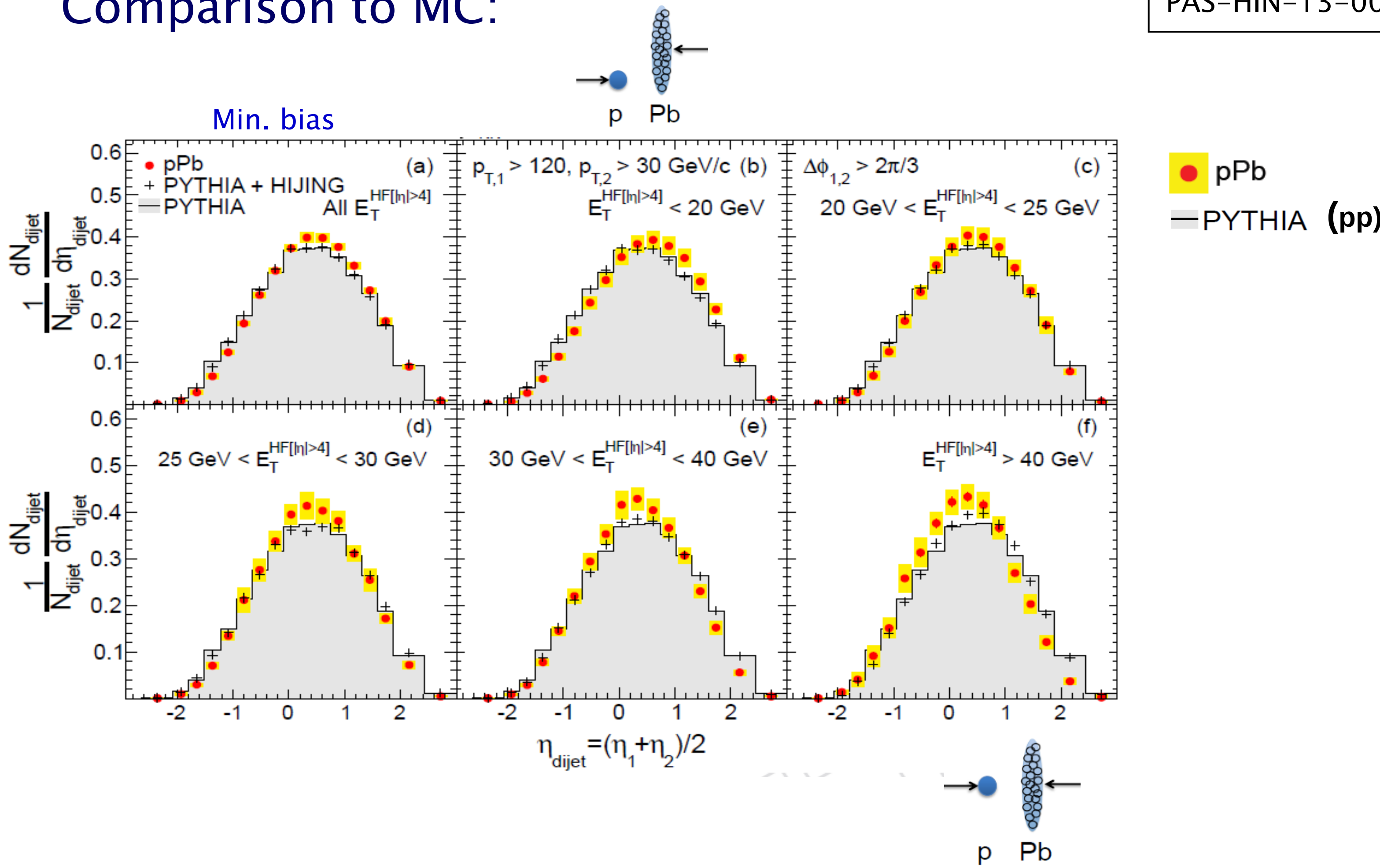
For more central collisions:

- η_{dijet} distribution shifts towards Pb-going side (negative values)
- shape of η_{dijet} distribution also changes – it gets narrower

Dijet η distribution

PAS-HIN-13-001

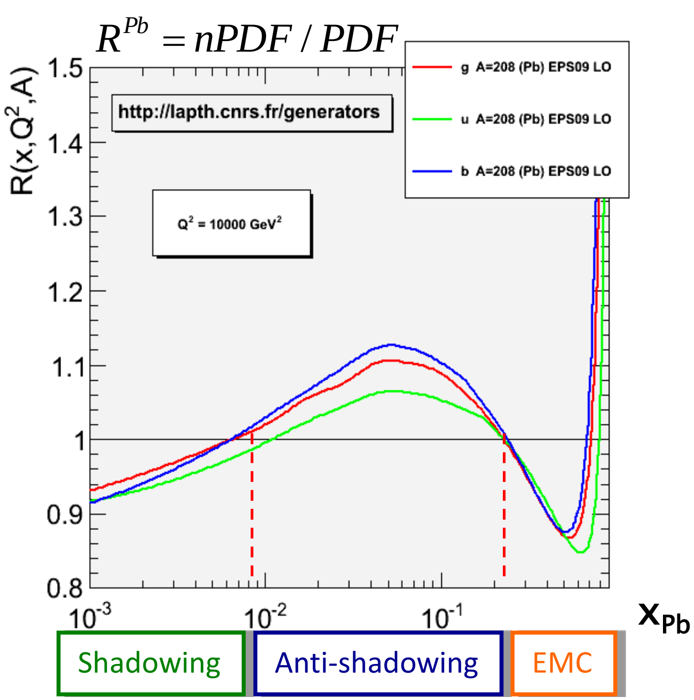
Comparison to MC:

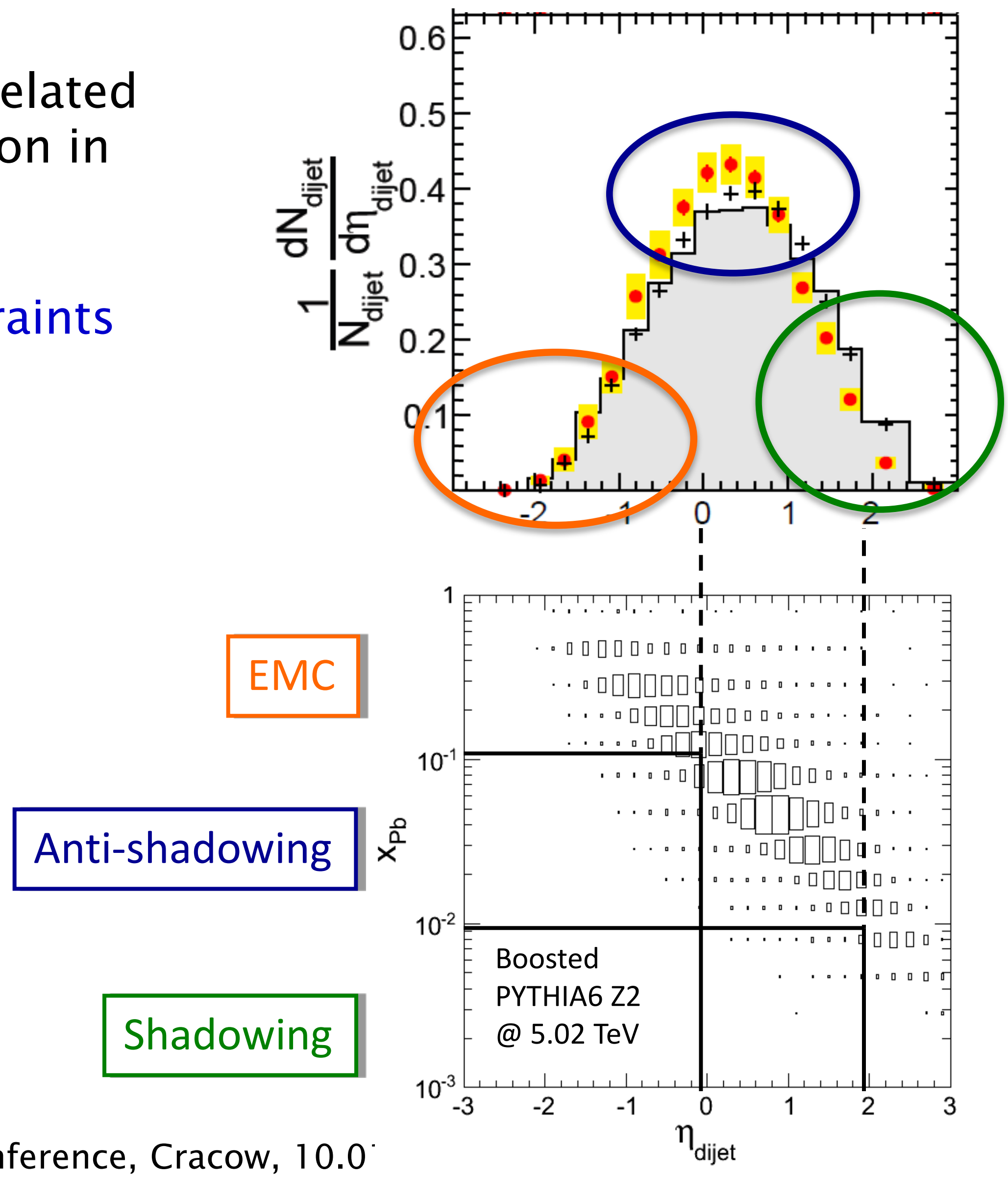


Dijet pseudorapidity distribution for pPb collisions is modified with respect to PYTHIA MC (pp)

Dijet η and nuclear PDFs

- Dijet η_{dijet} distribution correlated with parton momentum fraction in Pb-ion (x_{Pb})
- Results for η_{dijet} give constraints on nPDFs





Quarkonia and the Quark-Gluon Plasma

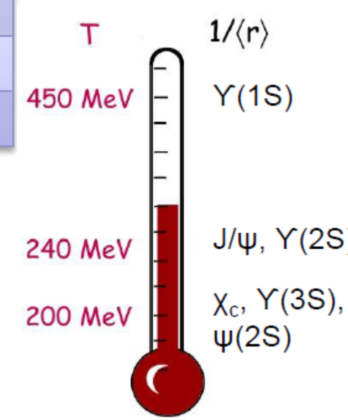
- Bound states of heavy quark and antiquark
- Produced at early stage of collision ($\tau \approx 1/m_Q \approx 0.05\text{–}0.15$ fm/c)
- Produced in hard collisions → pQCD applicable

- In QGP, colour screening (Debye screening) leads to melting of quarkonia → **suppression of quarkonium yields.**
- Quarkonium states have different binding energies (radii) → they melt at different temperatures of the created medium.

Quarkonia: mass, binding energy and radius

state	J/ψ	χ_c	ψ(2S)
Mass(GeV)	3.10	3.53	3.69
ΔE (GeV)	0.64	0.20	0.05
r_o(fm)	0.25	0.36	0.45

state	Υ(1S)	Υ(2S)	Υ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o(fm)	0.28	0.56	0.78



- **Sequential melting of quarkonia** → thermometer of QGP

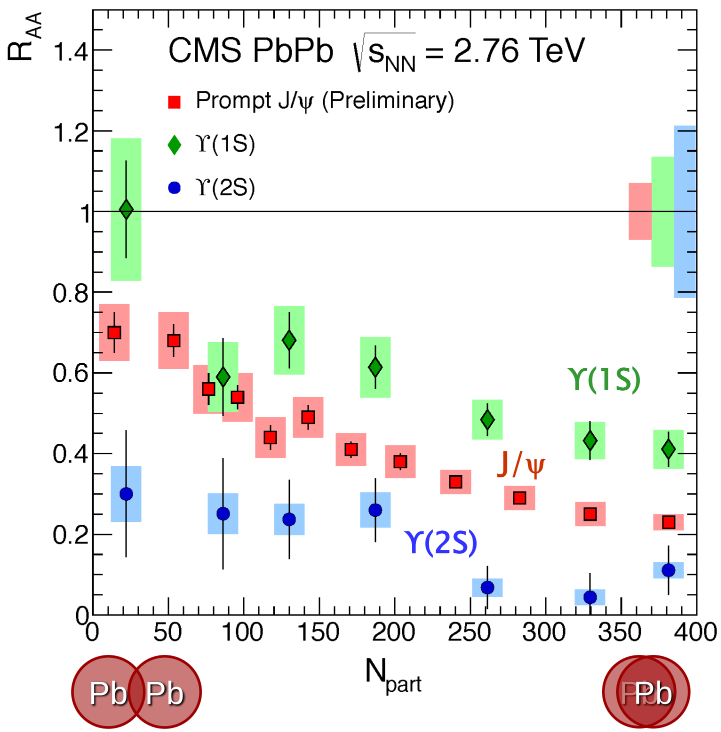
Mocsy, EPJC61 (2009) 705

Quarkonium suppression in PbPb

$$R_{AA} = \frac{\text{(Yield in AA)}}{N_{COLL}\text{(AA)} \times \text{(Yield in pp)}}$$

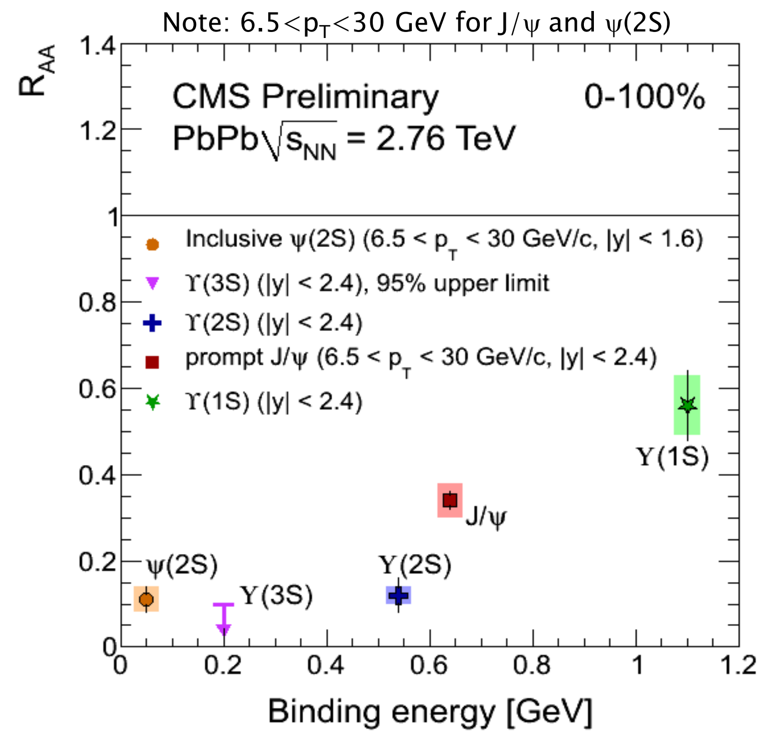
PRL 109 (2012) 222301
PAS-HIN-12-007
PAS-HIN-12-014

ϒ states and J/ψ dependence on centrality



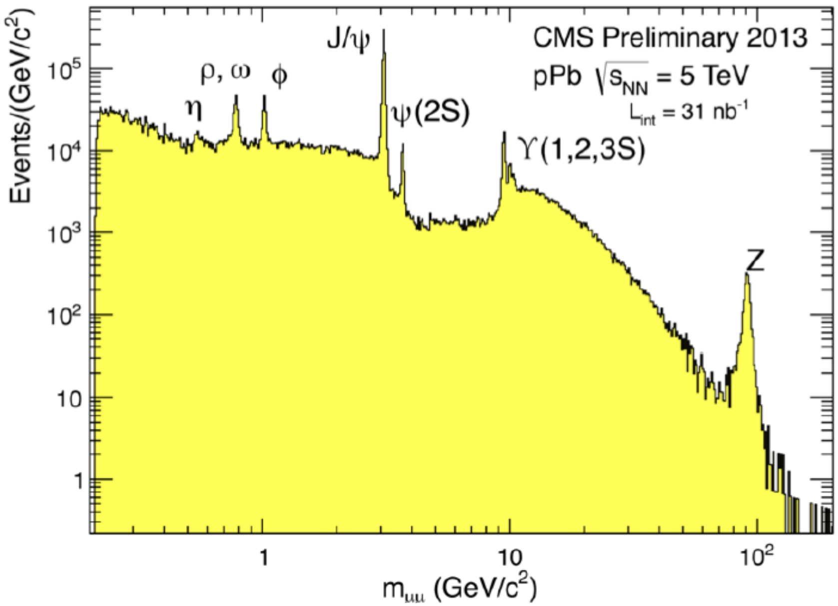
Suppression increases with collision centrality

Centrality-integrated R_{AA} vs. binding energy



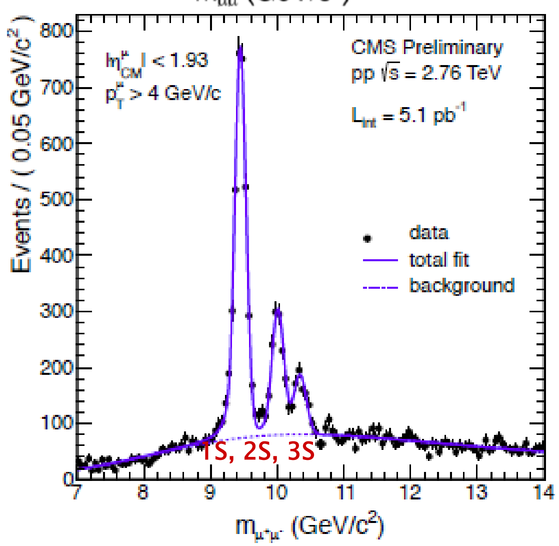
Less bound states are more suppressed than tighter bound ones → sequential suppression of quarkonia

Dimuon spectrum for 2013 data

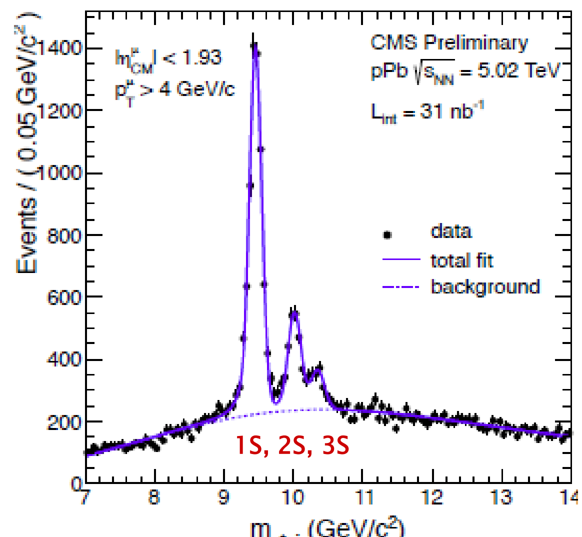


pPb data

High statistics data collected in 2013
→ study of ϒ(1S,2S,3S) states possible



pp



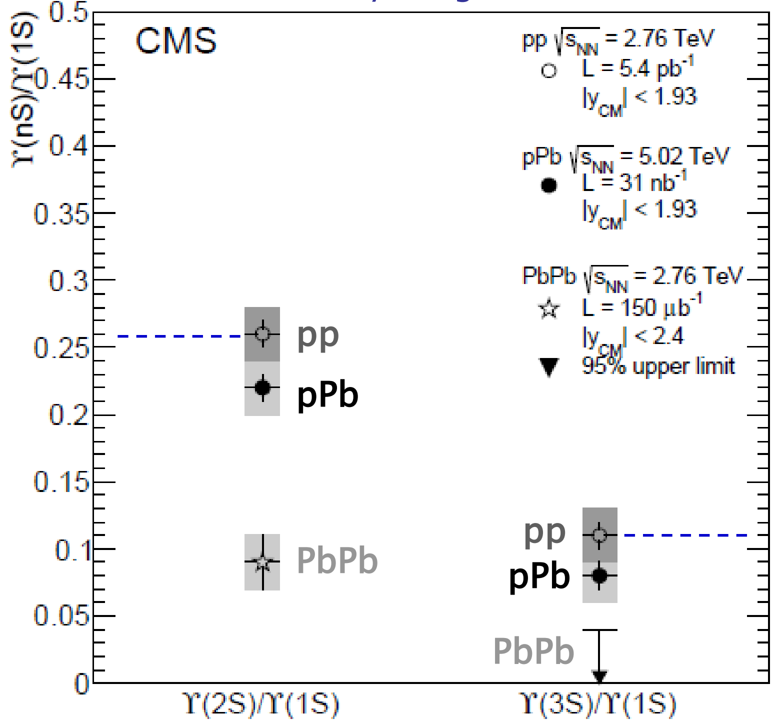
pPb

Υ(nS)/Υ(1S) Ratio

First results for pPb

arXiv:1312.6300

Centrality integrated



PbPb < pPb < pp

pPb vs **pp**:

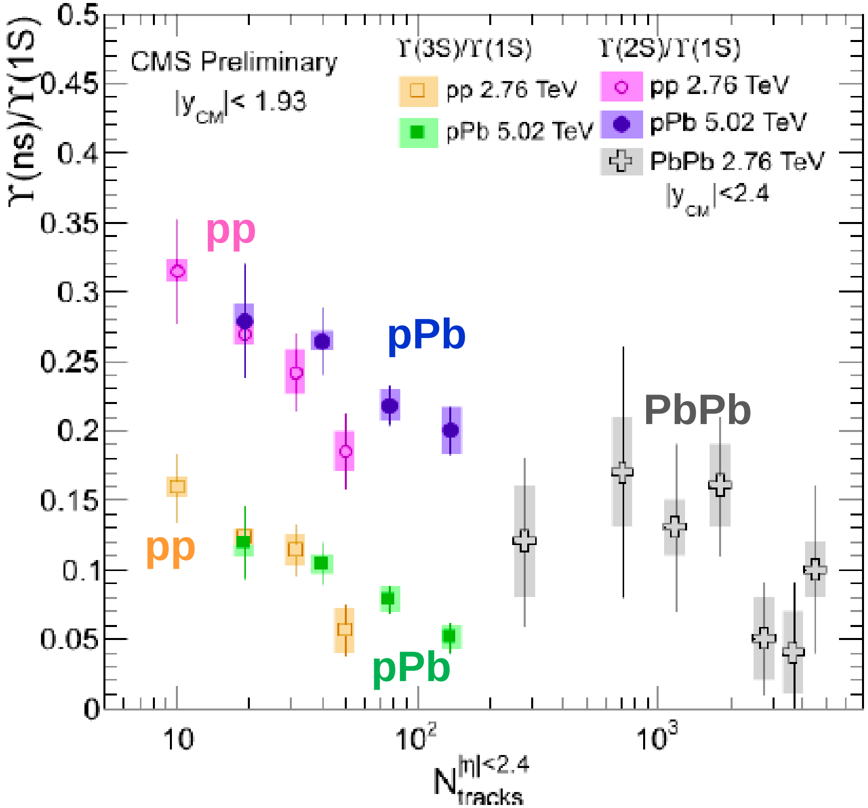
Relative production of excited state Υ(2S) or Υ(3S) to ground state Υ(1S) more suppressed in pPb

PbPb vs **pPb**:

In PbPb, presence of additional effects leading to stronger suppression of excited states compared to ground state

Υ(nS)/Υ(1S) vs. multiplicity

arXiv:1312.6300



N_{tracks} – number of tracks with p_T>400MeV/c and |η|<2.4

Υ(nS)/Υ(1S) decreases with event multiplicity for all systems: pp, pPb, PbPb*

* Large uncertainties for PbPb (need more data!)

What is the proper reference for PbPb collisions?

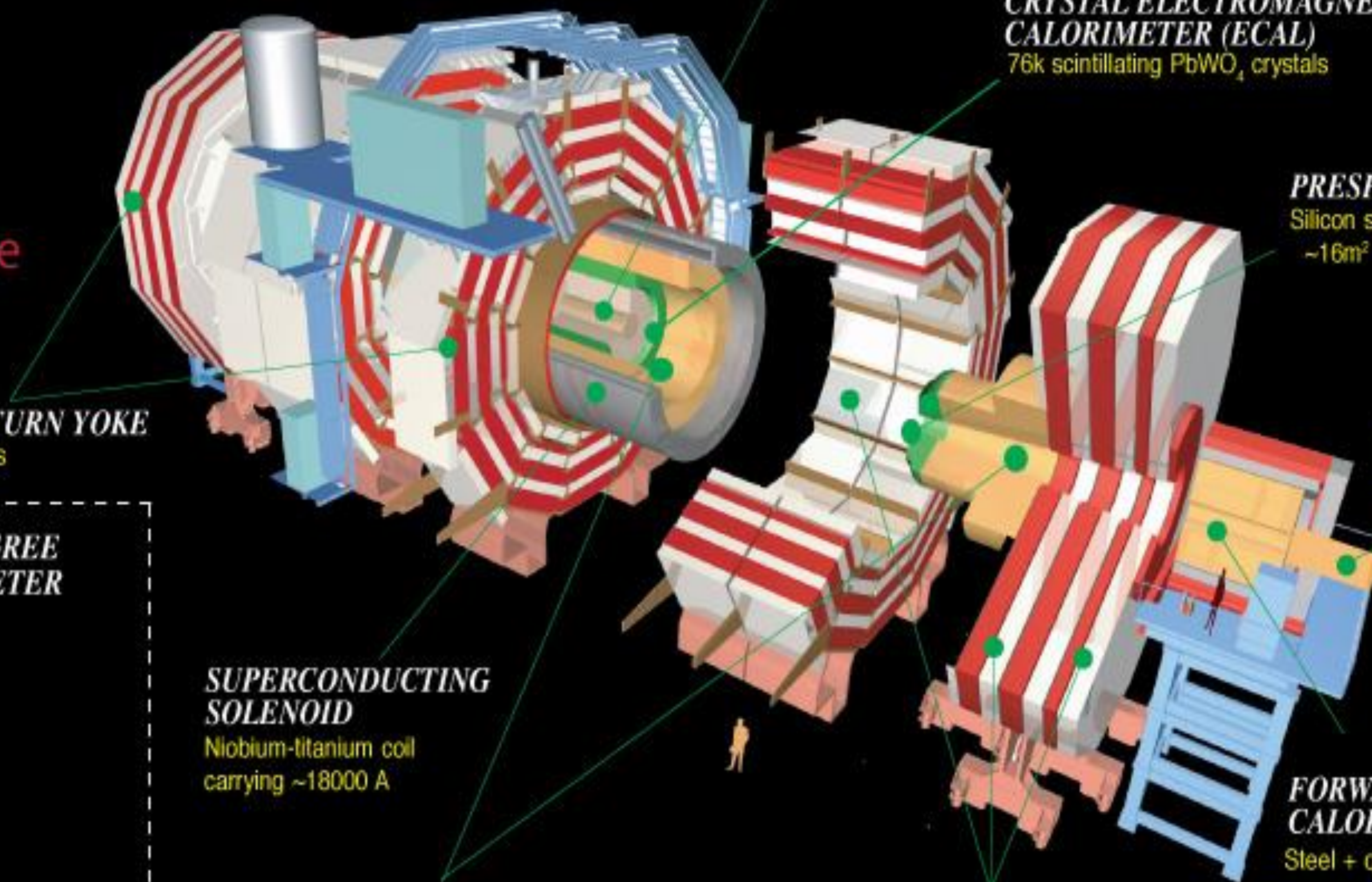
Summary

- CMS has broad heavy-ion program based on comparative studies of PbPb, pPb and pp collisions
- Presented results indicate that the medium created in PbPb:
  - Behaves collectively (ridge, v_2, v_3)
  - Does not quench control probes (γ, W, Z)
  - Strongly quenches partons, including b-quarks (R_{AA})
  - Causes dijet imbalance, but does not modify their angular correlation
  - Suppresses quarkonia, including excited states of the Υ
- For pPb also:
  - Hints of possible collective behaviour (ridge, v_2, v_3, p_T spectra)
  - Suppression of quarkonia ($\Upsilon(nS)/\Upsilon(1S)$ ratio)

  but
  - No jet quenching (R_{pPb}, dijets)
- Results for pPb collisions give constraints on nPDFs (R_{pPb}, η_{dijets})

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



Total weight	: 14000 tonnes
Overall diameter	: 15.0 m
Overall length	: 28.7 m
Magnetic field	: 3.8 T