XXII Cracow Epiphany Conference
on the Physics in LHC Run2
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Heavy Ion Results of the CMS Experiment

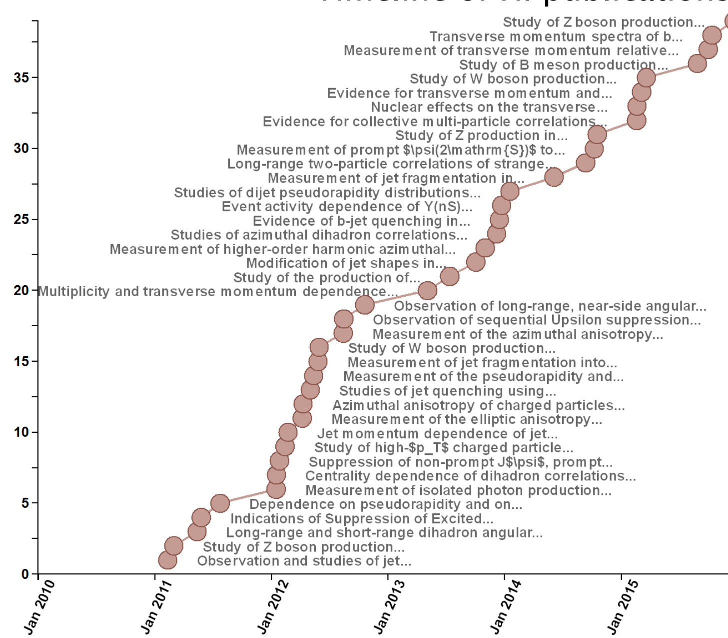
Bożena Boimska
National Centre for Nuclear Research

on behalf of the CMS Collaboration

Outline

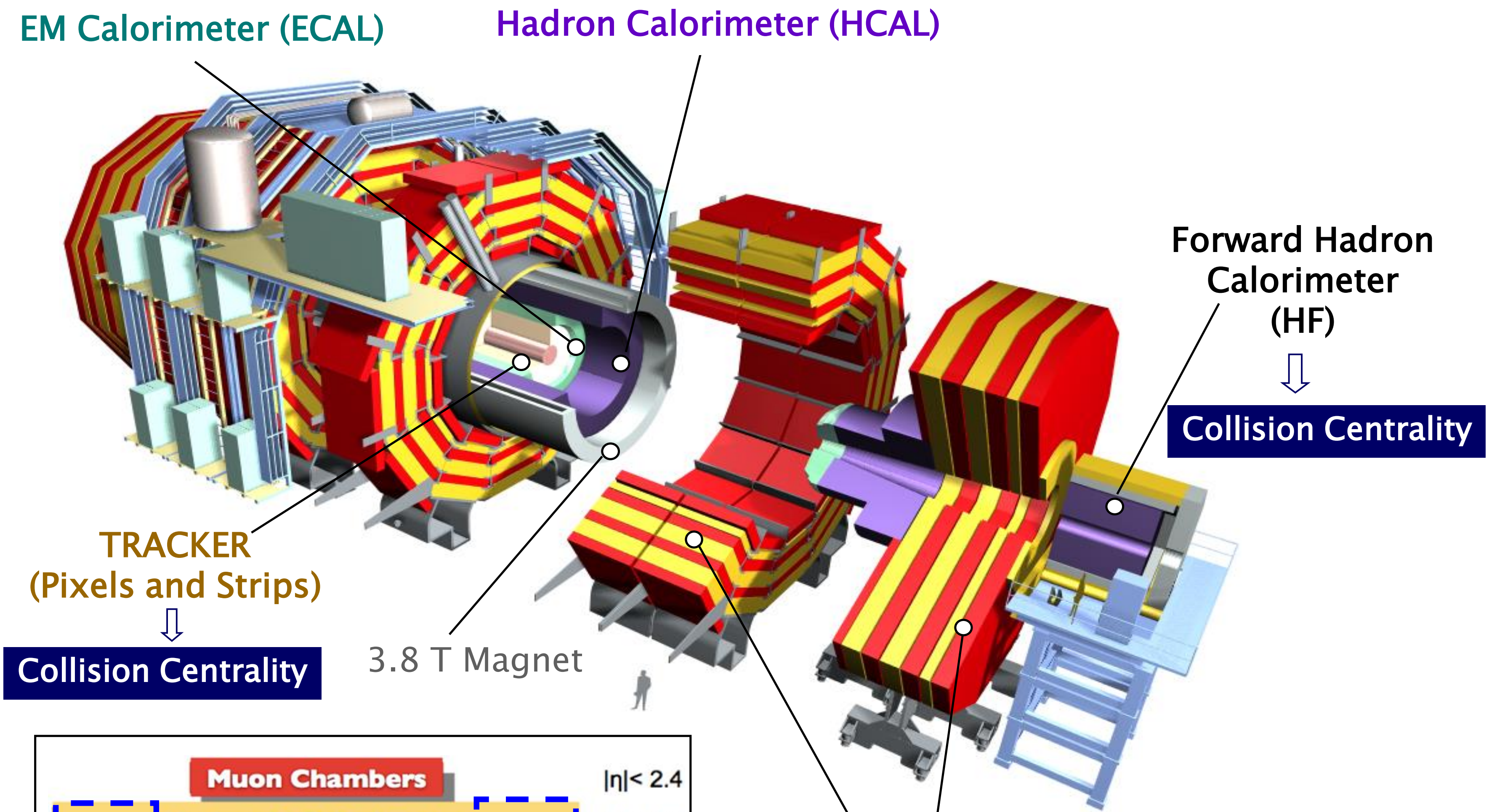
- Introduction
- Experimental results: PbPb vs. pPb
  - Jet-quenching effect
  - Quarkonia production
  - Signals of (possible) collective behavior
- Results for pp collisions at 13 TeV
- Summary

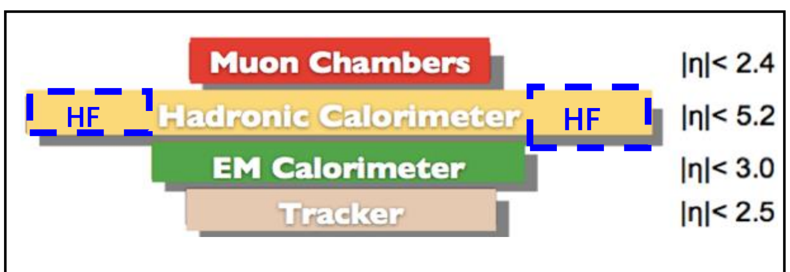
Timeline of HI publications



39 published/submitted papers
~30 Physics Analysis Summaries (PAS)
http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN
Only some selected results presented today …

CMS detector



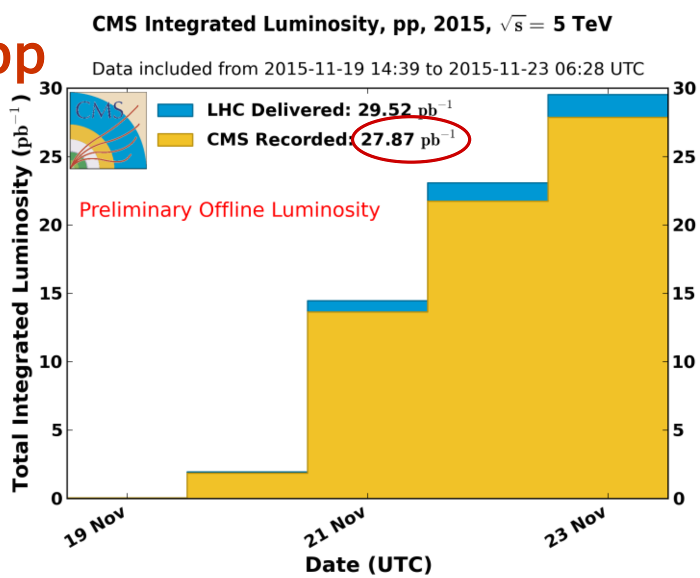


$\eta = -\ln(\mathrm{tg}\,\theta/2)$

Heavy-ion oriented data samples

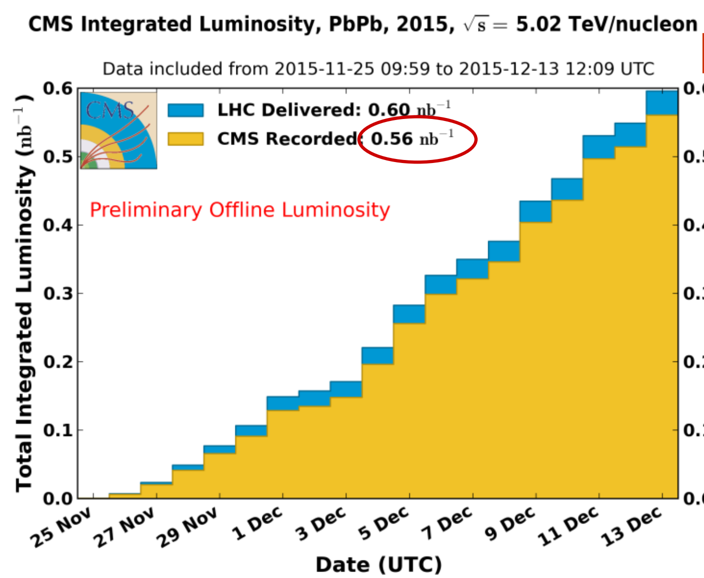
Period	System	Energy (TeV)	Rec. Lumi.	
2010	p+p	7	6.2 nb^{-1}	low pile-up
2010	Pb+Pb	2.76	7 μb^{-1}	
2011	Pb+Pb	2.76	150 μb^{-1}	
2011	p+p	2.76	230 nb^{-1}	
2013	p+Pb	5.02	35 nb^{-1}	
2013	p+p	2.76	5.4 pb^{-1}	
2015	p+p	13	270 nb^{-1}	low pile-up

pp



2015

PbPb



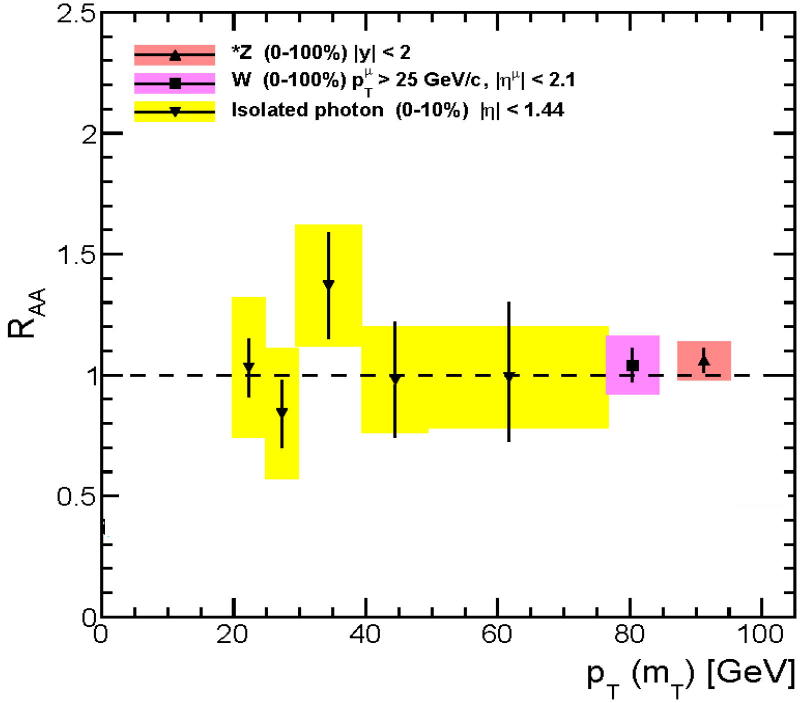
Nuclear modification factor

Study of jet quenching by looking at magnitude of particle yield suppression.

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dp_T d\eta}{d^2 N_{pp} / dp_T d\eta}$$

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

PbPb 2.76 TeV



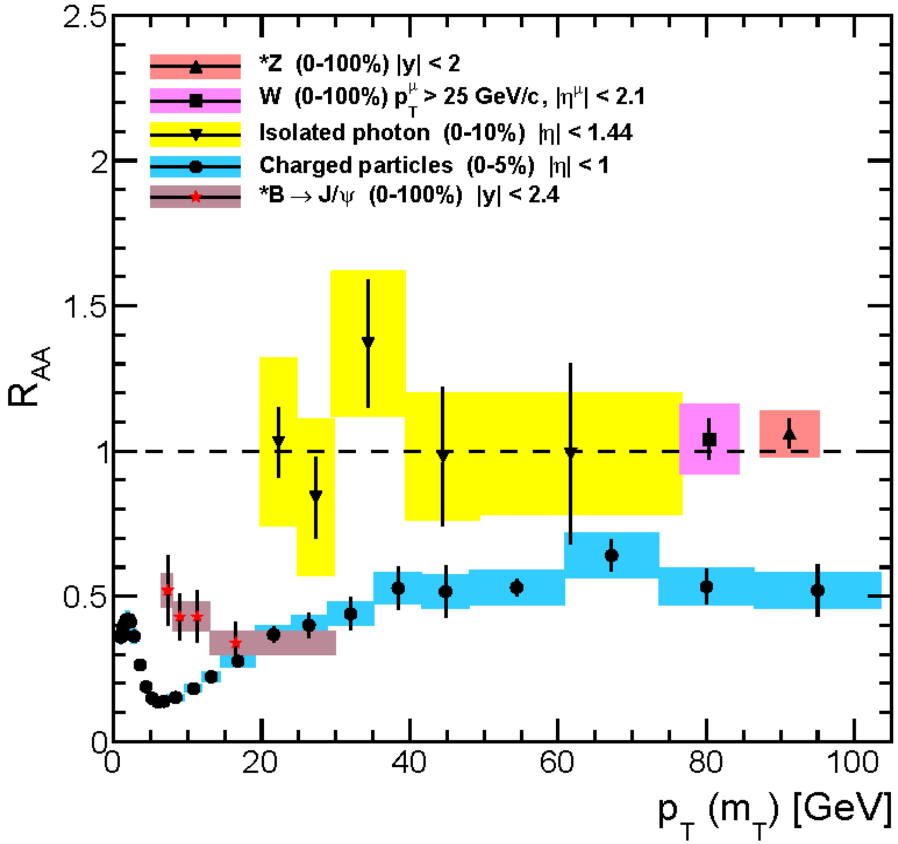
Isolated γ	PLB 710 (2012) 256
W $\rightarrow \mu\nu$	PLB 715 (2012) 66
$Z^0 \rightarrow \mu^+\mu^-$	JHEP 03 (2015) 022

Colorless probes (control probes) are not modified by the medium

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

Nuclear modification factor

PbPb 2.76 TeV



EPJC 72 (2012) 1945

JHEP 05 (2012) 063

charged hadrons & b-quarks

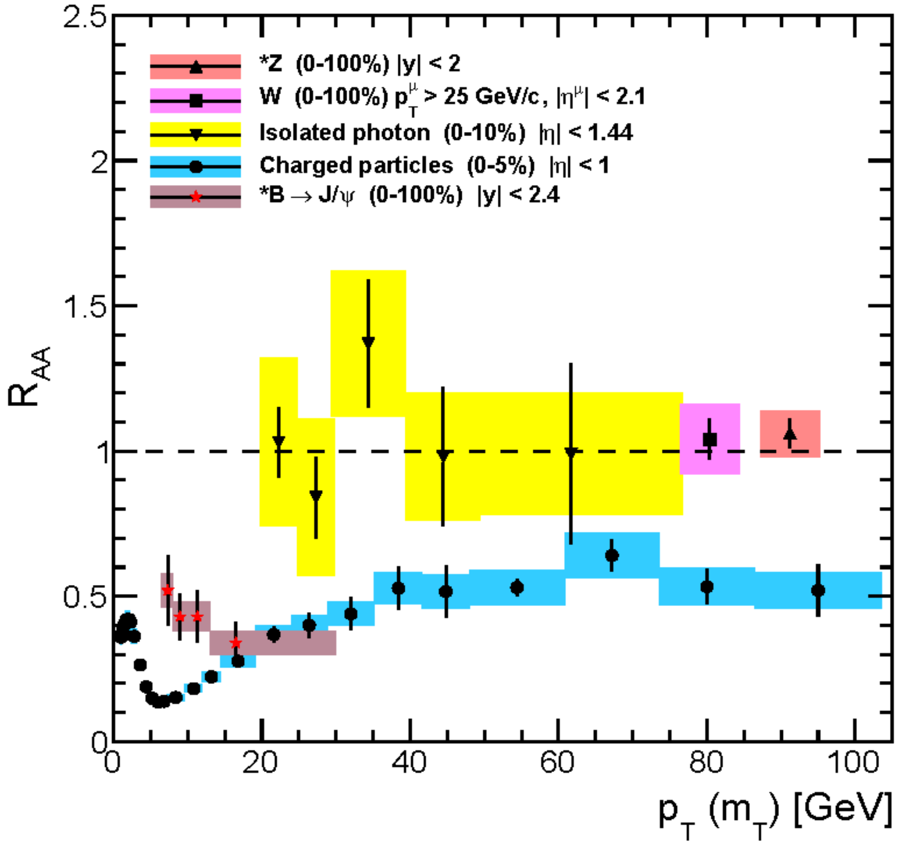
are suppressed, $R_{AA}<1$

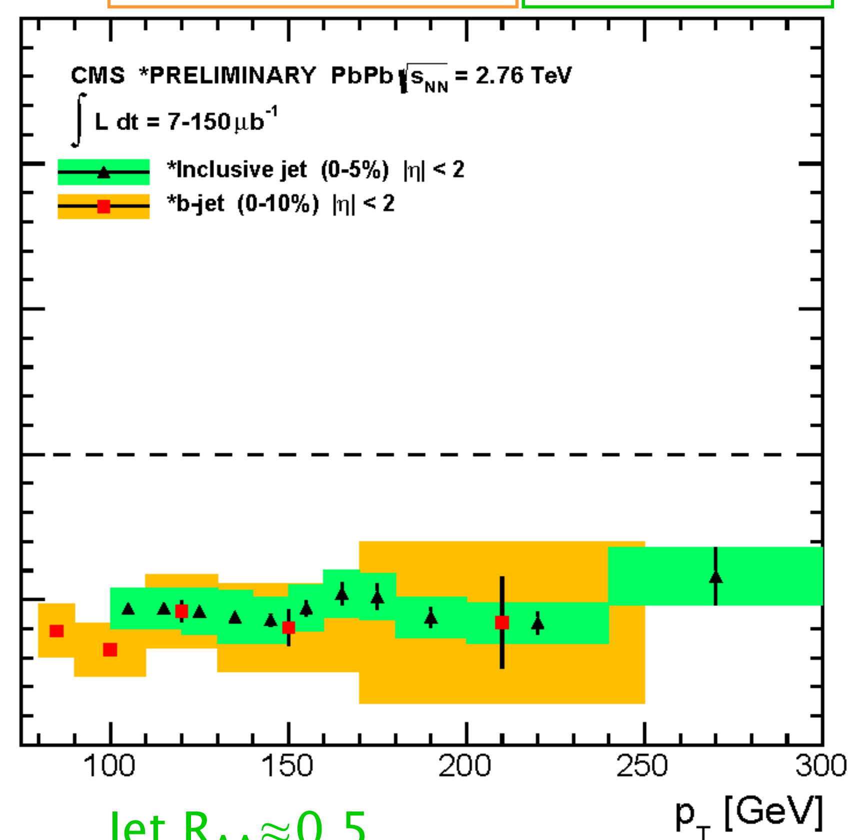
- Colorless probes are unsuppressed
- Hadrons are modified (jet quenching)
- Less b-hadron suppression at low p_T

Nuclear modification factor

PbPb 2.76 TeV

PRL 113 (2014) 132301 | PAS-HIN-12-004





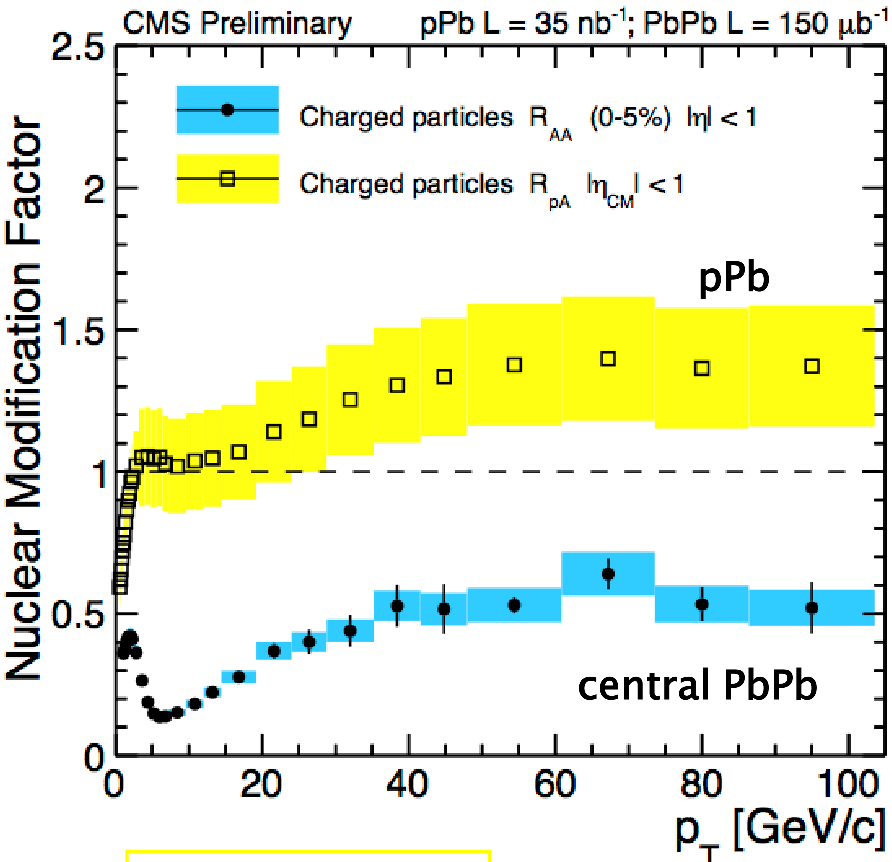
Jet $R_{AA} \approx 0.5$

First measurement of b-jet R_{AA}

- Colorless probes are unsuppressed
- Hadrons and jets are modified (jet quenching)
- Less b-hadron suppression at low p_T; b-jets are similar to q/g jets

Nuclear modification factor: PbPb vs. pPb

Charged particles



EPJC 75 (2015) 237

EPJC 72 (2012) 1945

At high p_T:

Enhancement in pPb collisions, $R_{pA}>1$

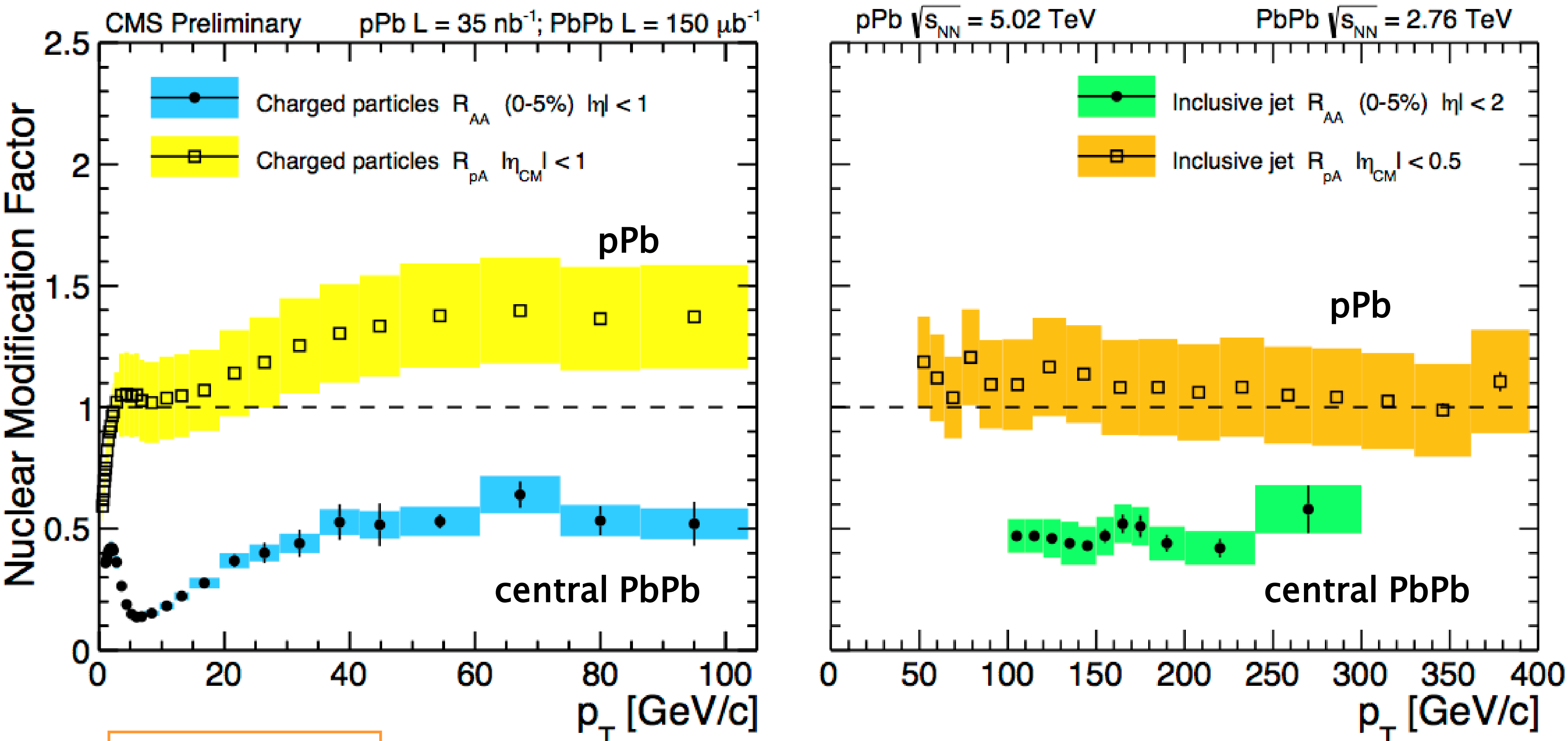
Suppression in PbPb collisions, $R_{AA}<1$

Similar trend in R_{pA} and R_{AA} as a function of p_T

Need pp reference data at 5.02 TeV to reduce systematics

Nuclear modification factor: PbPb vs. pPb

Charged particles **Jets**



PAS-HIN-14-001

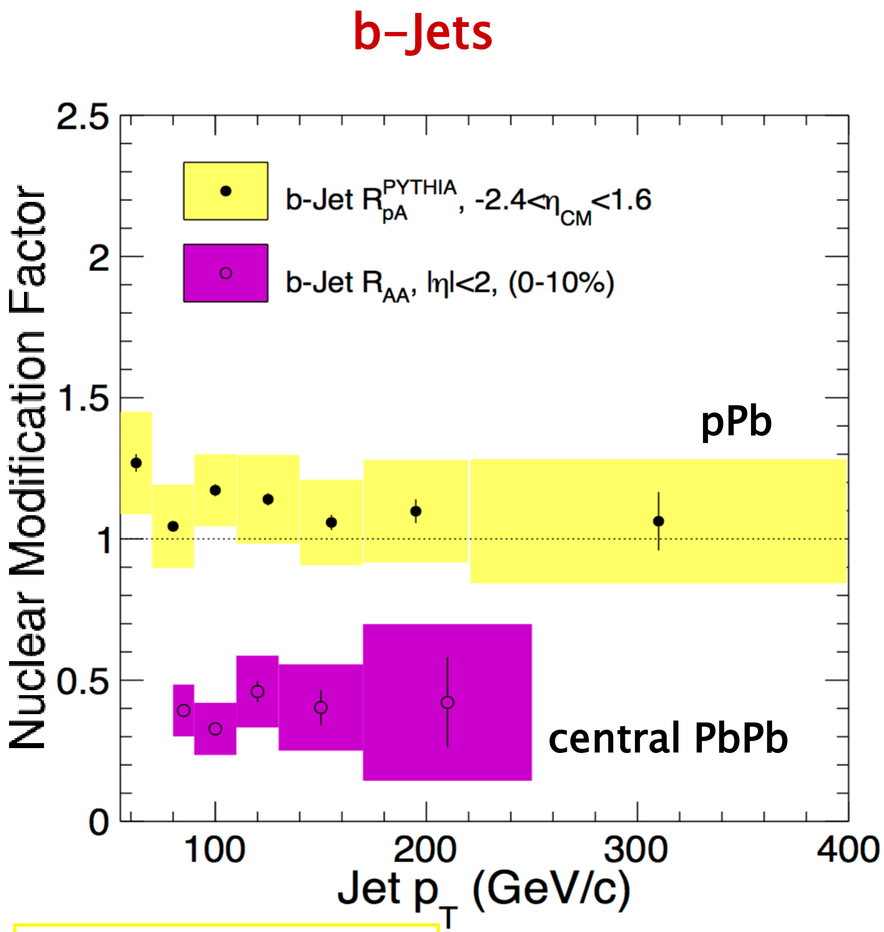
PAS-HIN-12-004

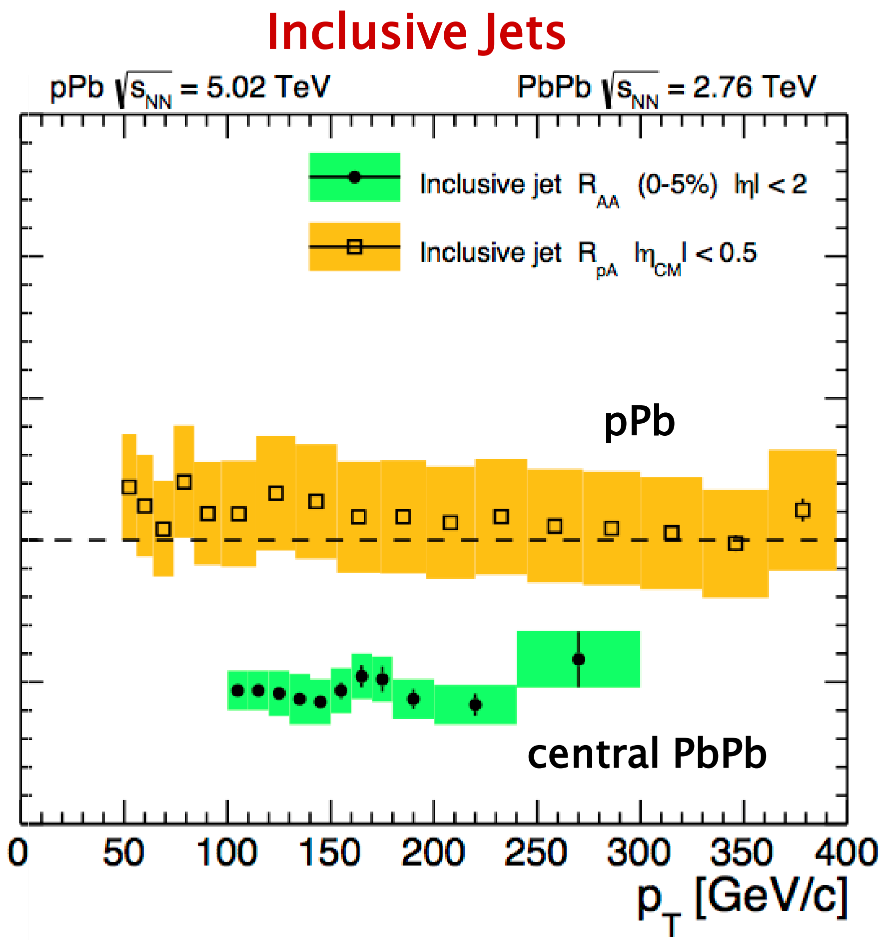
For pPb $R_{pA} \approx 1$

For PbPb $R_{AA} < 1$

Jet suppression observed in PbPb collisions is the final state effect

Nuclear modification factor: PbPb vs. pPb





arXiv: 1510.03373

PRL 113 (2014) 132301

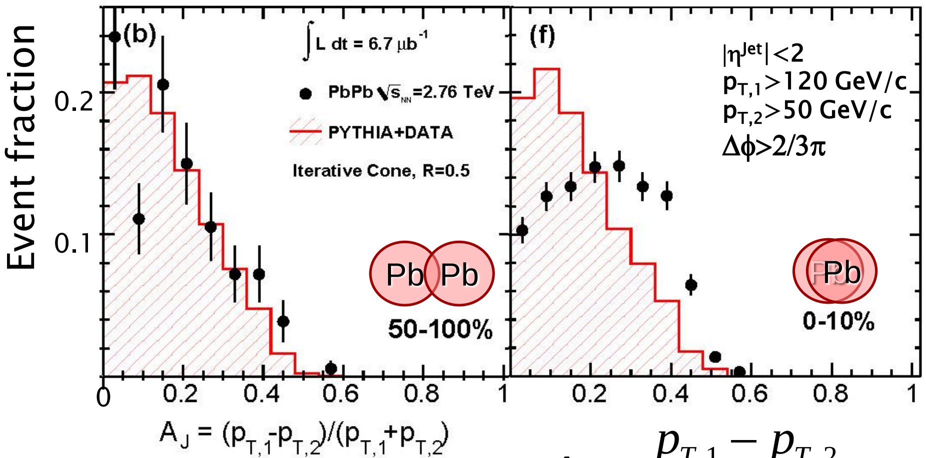
For central PbPb: b-jets show similar suppression to inclusive jets, $R_{AA}\approx 0.5$

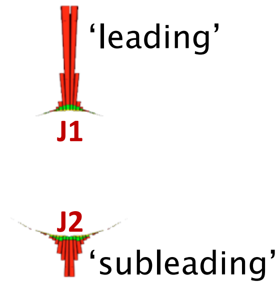
For pPb: inclusive and b-jets are not suppressed, $R_{pA}\approx 1$

No jet flavor dependence is observed

Dijet events in PbPb collisions

Dijet Imbalance





PRC 84 (2011) 024906

PLB 712 (2012) 176

• exp. DATA

– ref. DATA

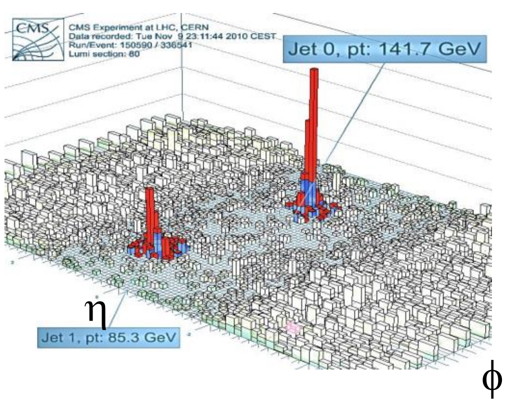
Asymmetry: $A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$

➡ Dijet p_T imbalance (A_J) increases with centrality

→ **Direct observation of jet quenching in central PbPb collisions**

Energy deposits in calorimeters:

$\eta = -\ln \mathrm{tg}\frac{\theta}{2}$



Unbalanced jets

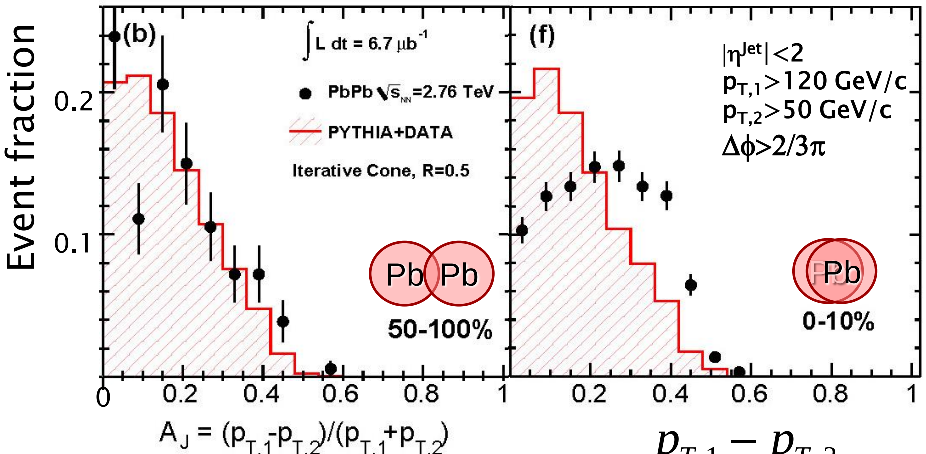
Dijet p_T imbalance quantified by asymmetry A_J

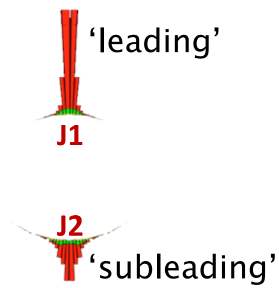
Dijet events in PbPb collisions

PRC 84 (2011) 024906

PLB 712 (2012) 176

Dijet Imbalance





• exp. DATA

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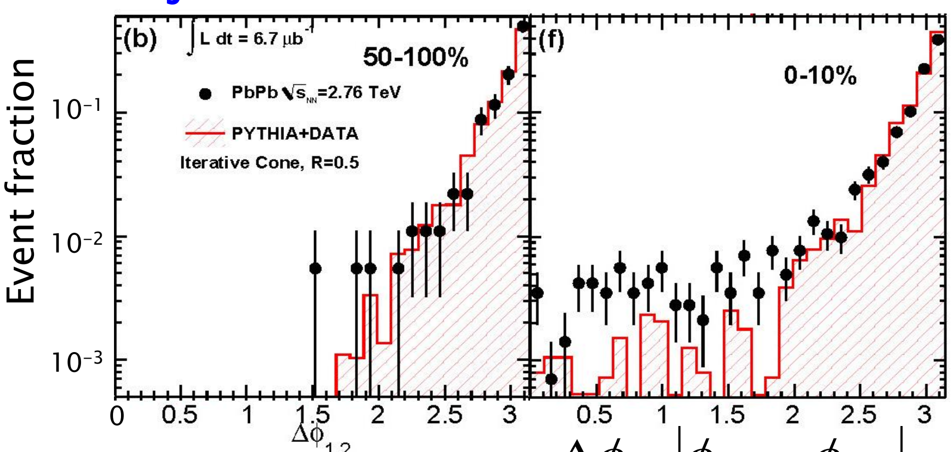
Asymmetry: $$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

➡ Dijet p_T imbalance (A_J) increases with centrality

→ **Direct observation of jet quenching in central PbPb collisions**

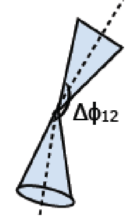
Dijet Azimuthal Correlation



$$\Delta\phi = \left|\phi_{jet1} - \phi_{jet2}\right|$$

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

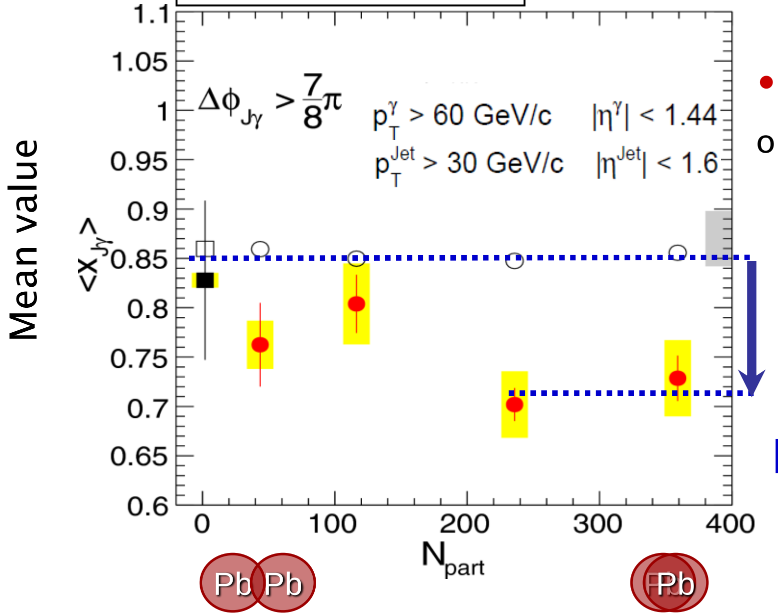
→ Propagation of high p_T partons in dense nuclear medium does not lead to a strong angular decorrelation



Photon–jet events in PbPb collisions

Direct measure of the jet energy loss is **the ratio of jet to photon p_T**:

PLB 718 (2013) 773



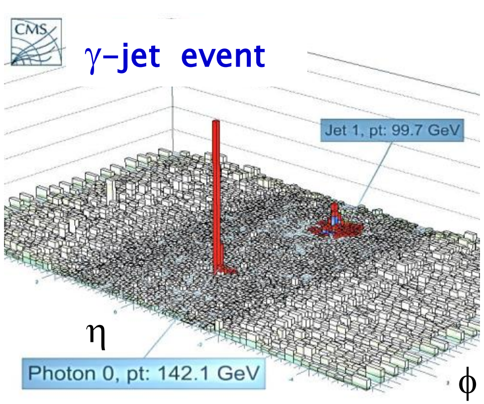
$$x_{J\gamma} = p_T^{Jet} / p_T^{\gamma}$$

• exp. DATA

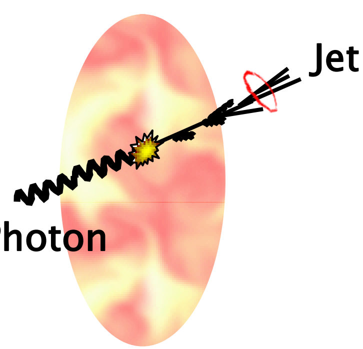
o ref. DATA (PYTHIA+HYDJET)

Jets lose about 15% of their initial energy

p_T imbalance larger for more central collisions



$$\eta = -\ln \mathrm{tg}\frac{\theta}{2}$$



Photon does not interact with the medium:

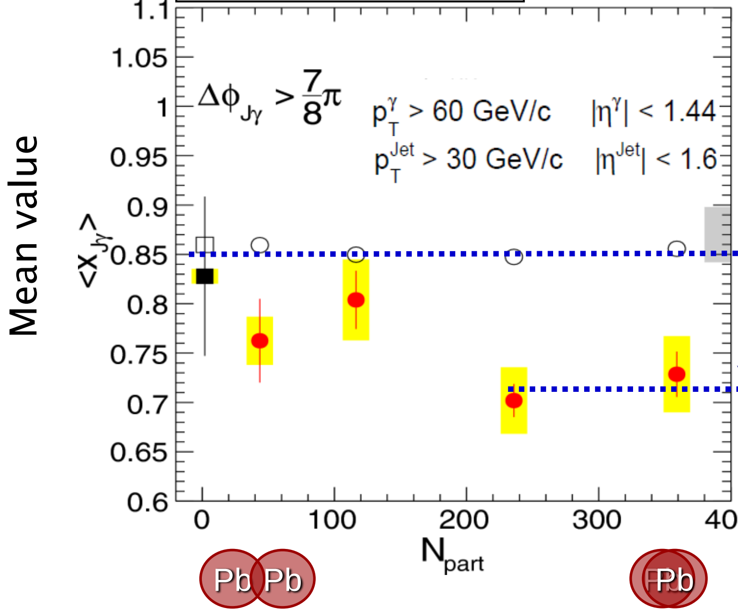
- provides initial parton p_T
- provides initial parton direction

Photon-jet events in PbPb collisions

Direct measure of the jet energy loss is **the ratio of jet to photon p_T**:

PLB 718 (2013) 773

$x_{J\gamma}=p_T^{Jet}/p_T^{\gamma}$



• exp. DATA

o ref. DATA (PYTHIA+HYDJET)

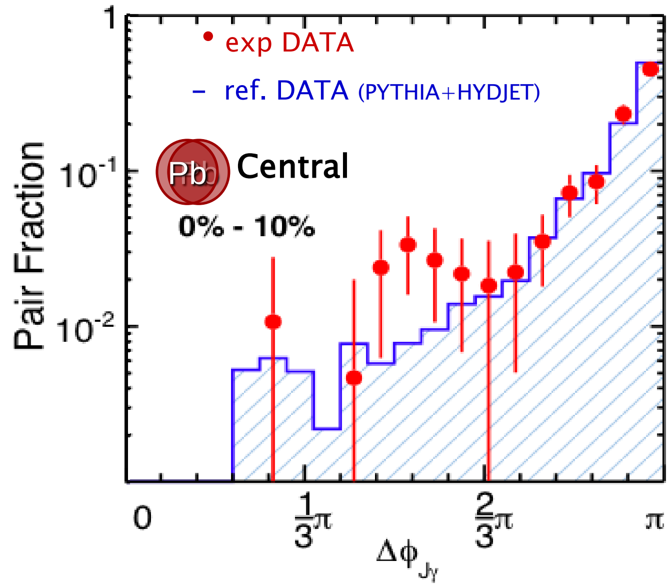
Jets lose about 15% of their initial energy

p_T imbalance larger for more central collisions

Azimuthal Correlation:

$$\Delta\phi_{J\gamma} = \left|\phi^{Jet} - \phi^{\gamma}\right|$$

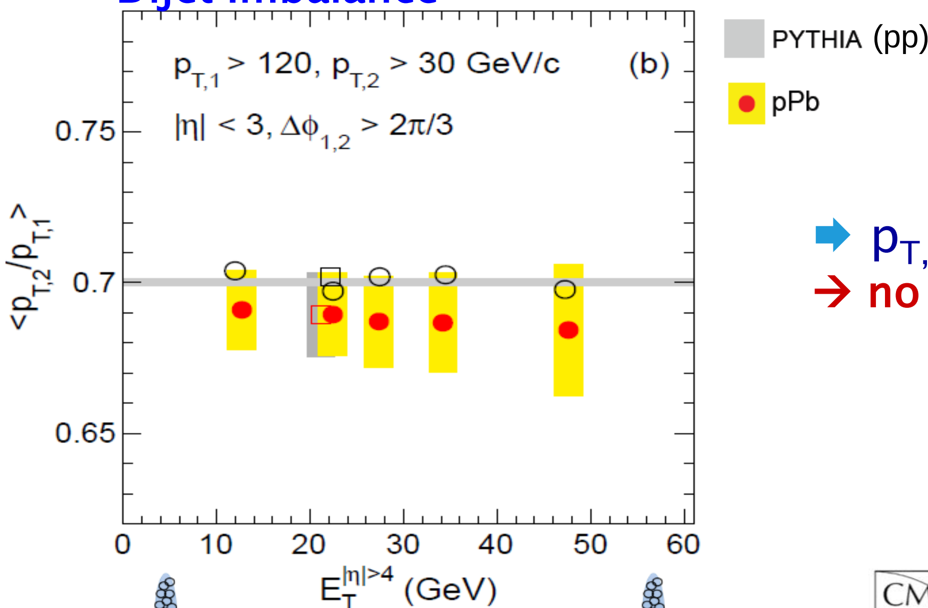
Photon and jet are 'back-to-back' ($\Delta\phi_{J\gamma} \sim \pi$), also for other centralities.

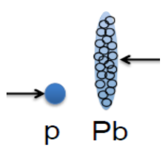


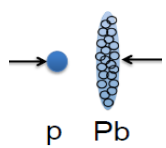
Dijet events in pPb collisions

EPJC 74 (2014) 2951

Dijet Imbalance





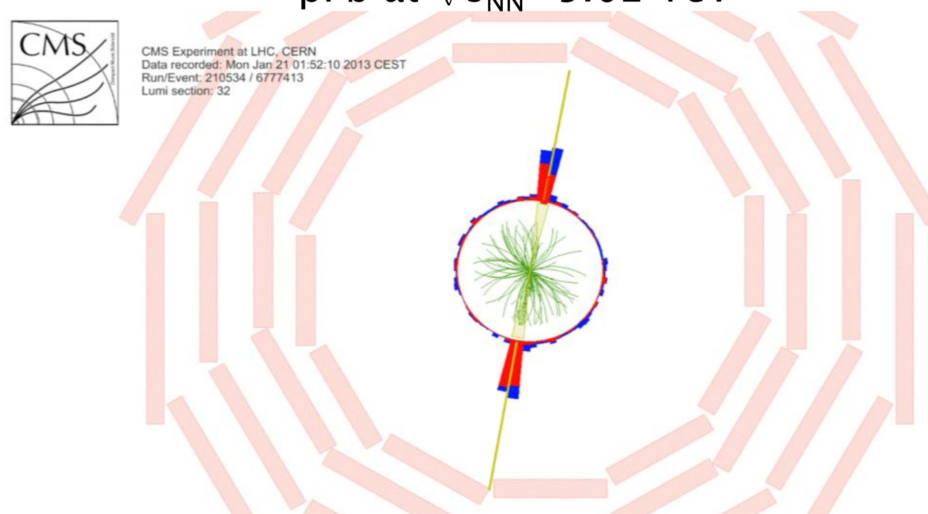


Centrality characterized by E_T at large $|\eta|$

➡ $p_{T,2}/p_{T,1}$ for pPb dijets the same as in pp

→ no jet quenching observed

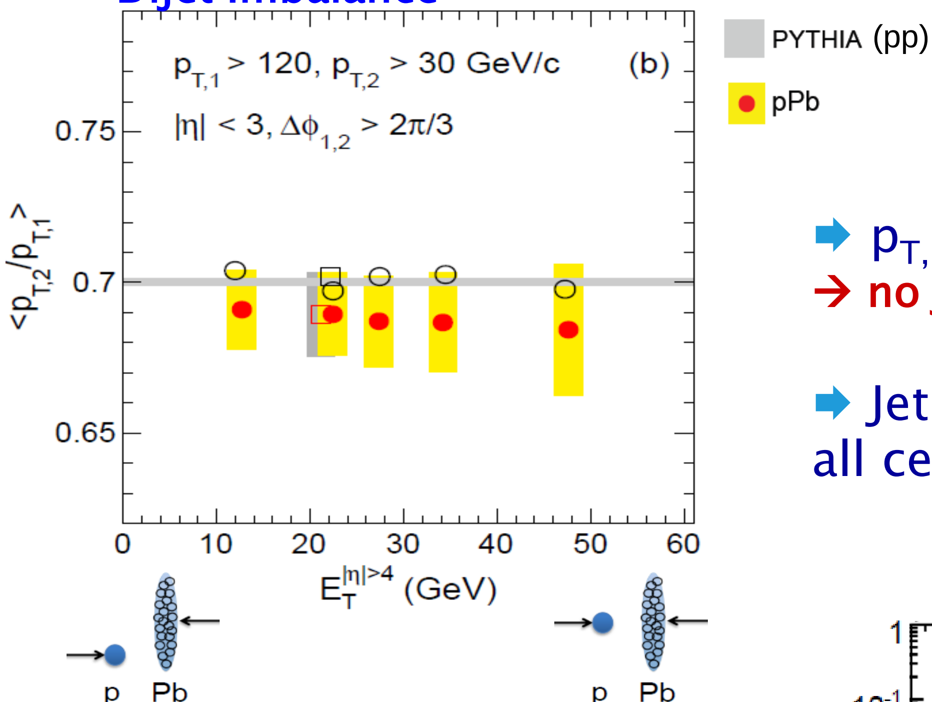
pPb at $\sqrt{s_{NN}}$=5.02 TeV



Dijet events in pPb collisions

EPJC 74 (2014) 2951

Dijet Imbalance

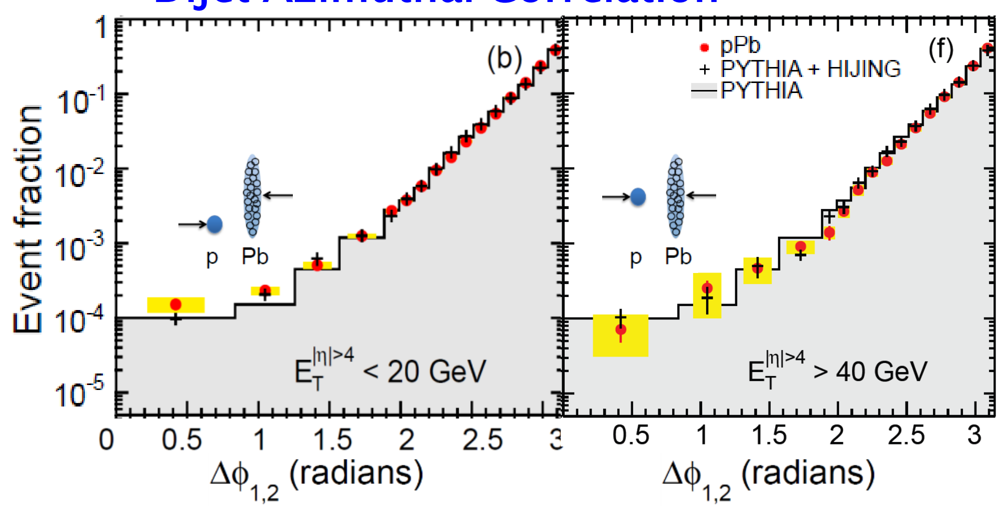


Centrality characterized by E_T at large $|\eta|$

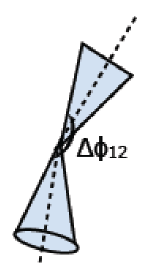
- $p_{T,2}/p_{T,1}$ for pPb dijets the same as in pp
→ no jet quenching observed

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

Dijet Azimuthal Correlation



$$\Delta\phi_{1,2} = \left|\phi_{jet1} - \phi_{jet2}\right|$$



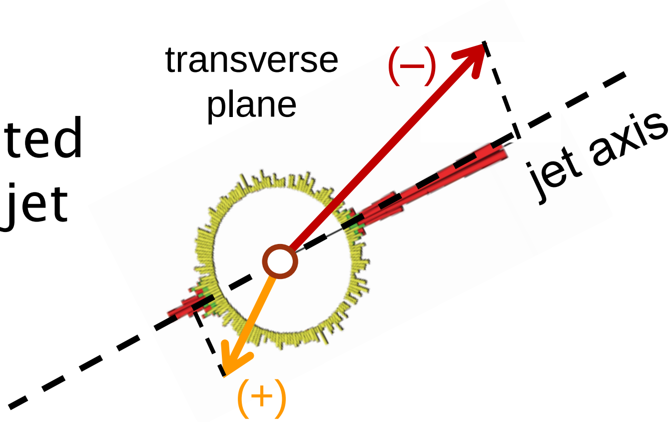
Dijet events in PbPb collisions

Where does the lost energy go?

„missing" $p_T^{||}$:

$$\not{p}_{\mathrm{T}}^{||} = \sum_{\mathrm{Tracks}} -p_{\mathrm{T}}^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

Sum the projections of p_T of all reconstructed charged tracks (in the event) onto leading jet axis



Study dependence of mean „missing" $<p_T^{||}>$ on dijet asymmetry A_J

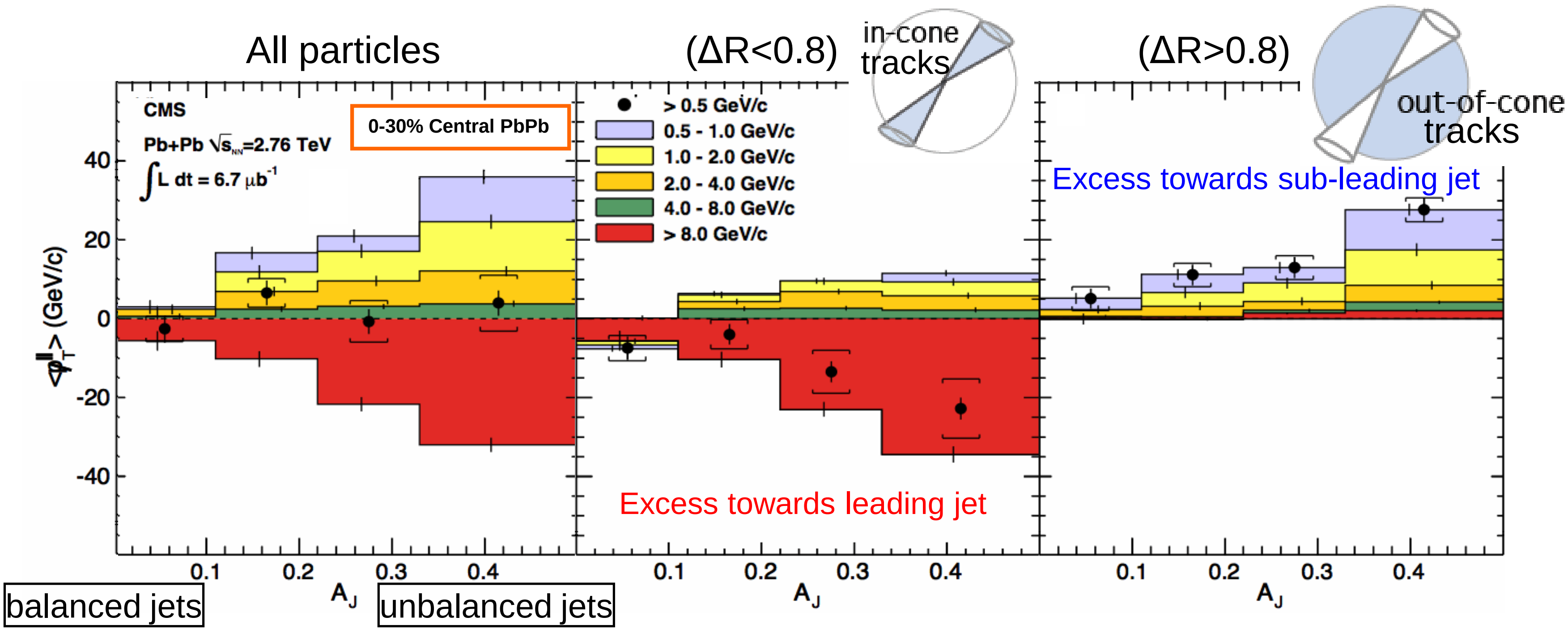
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

$p_{T,1}$ – leading jet
$p_{T,2}$ – subleading jet

"Missing" $p_T^{||}$ vs. A_J

PRC 84 (2011) 024906

Radial dependence of the momentum balance:



Momentum balance restored when summing over all particles in the event, independently of A_J

In-cone excess of high p_T tracks is balanced by out-of-cone low p_T tracks.

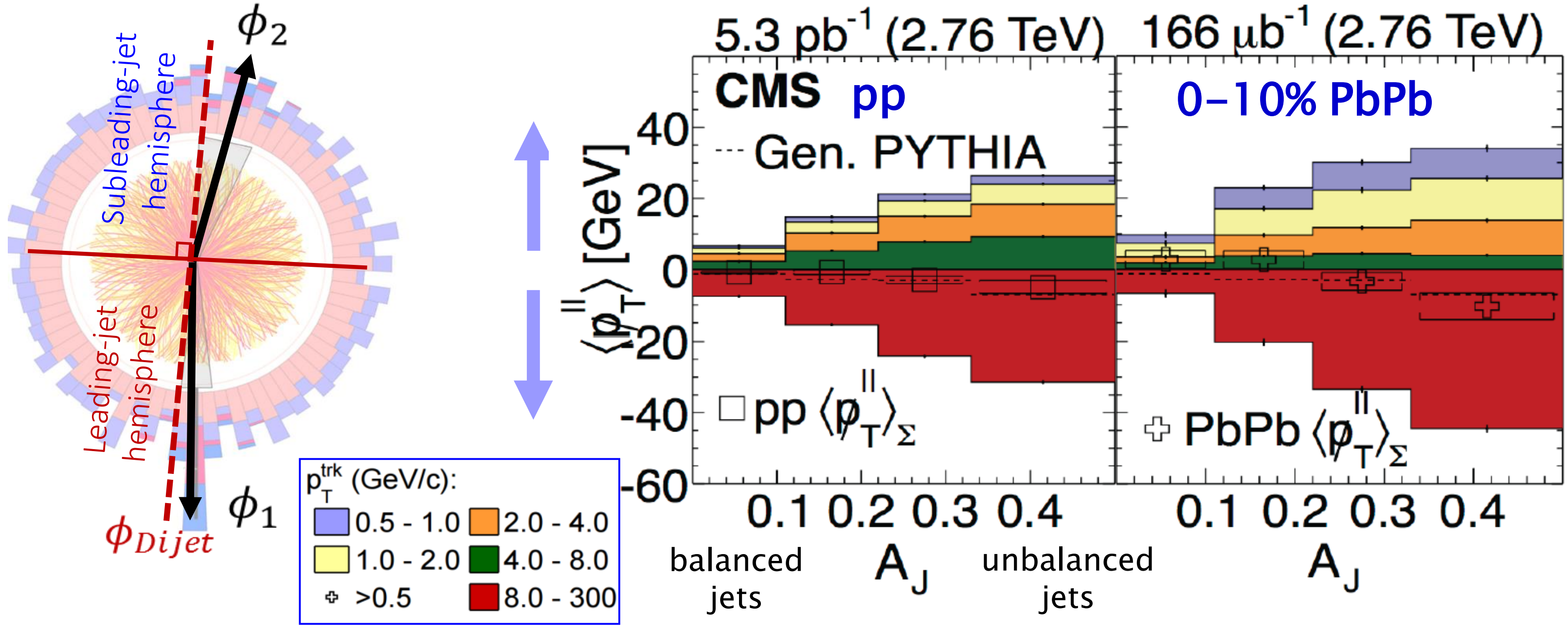
Momentum difference in the dijet is balanced by low p_T particles at large angles relative to the jet axis.

"Missing" $p_T^{||}$ vs. A_J

arXiv:1509.09029

New analysis: projection of p_T for reconstructed charged tracks onto ϕ_{Dijet}

$$\not{p}_T^{||} = \sum_i -p_T^i \cos(\phi_i - \phi_{Dijet})$$



Missing p_T from high p_T particles increases as a function of A_J in the leading-jet direction

- pp: balanced by 2-8 GeV/c particles in the subleading-jet direction
- central PbPb: balanced by softer particles with p_T < 2 GeV/c

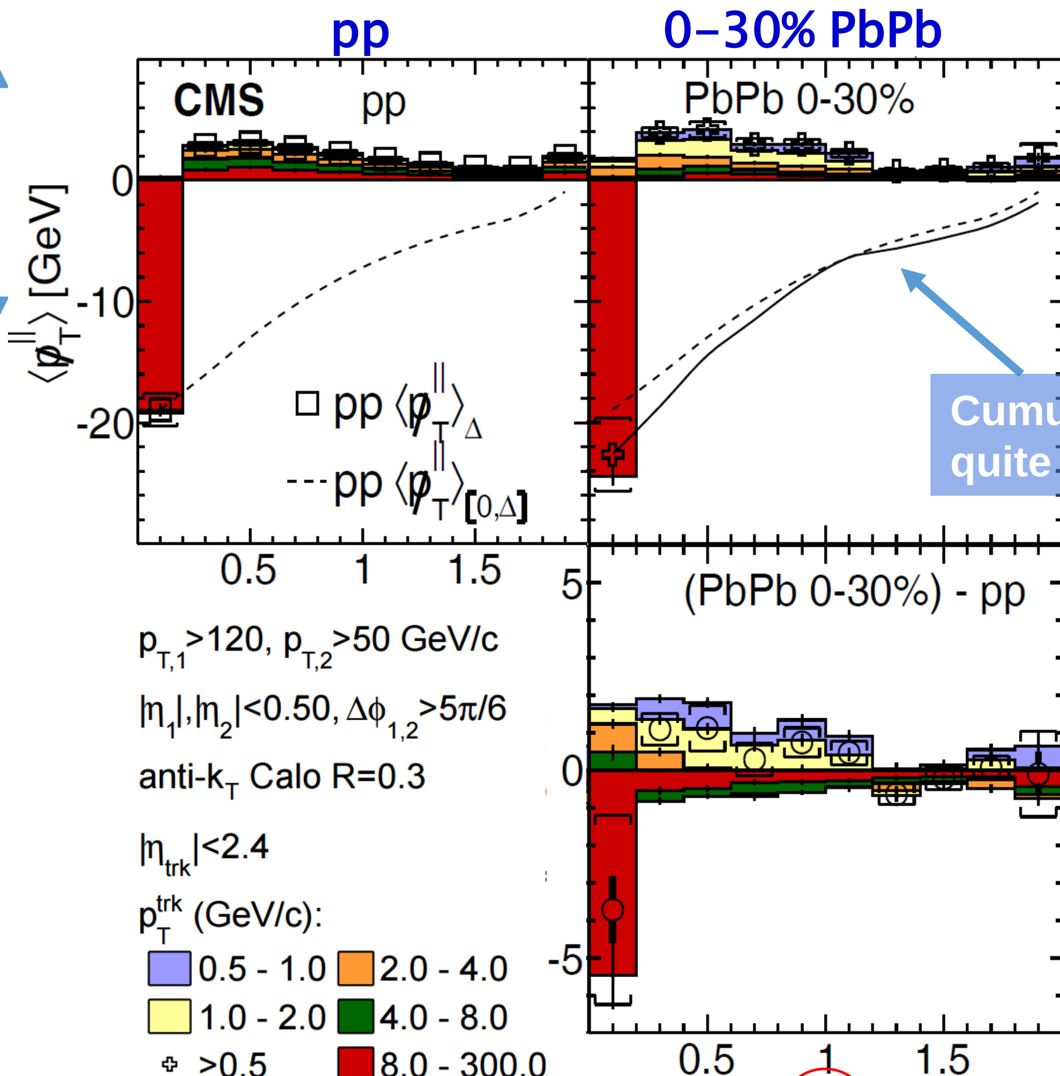
"Missing" $p_T^{||}$ vs. Δ

arXiv:1509.09029

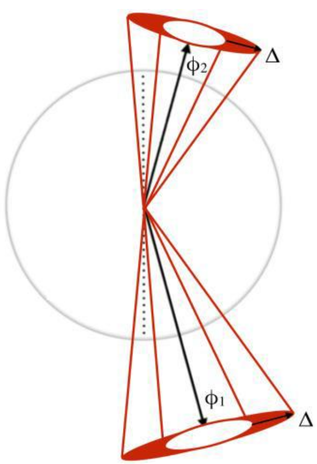
Inclusive A_J

excess towards subleading jet

excess towards leading jet



Cumulative curves quite similar



$$\Delta = \sqrt{(\eta_{\rm trk} - \eta_{\rm jet})^2 + (\phi_{\rm trk} - \phi_{\rm jet})^2}$$

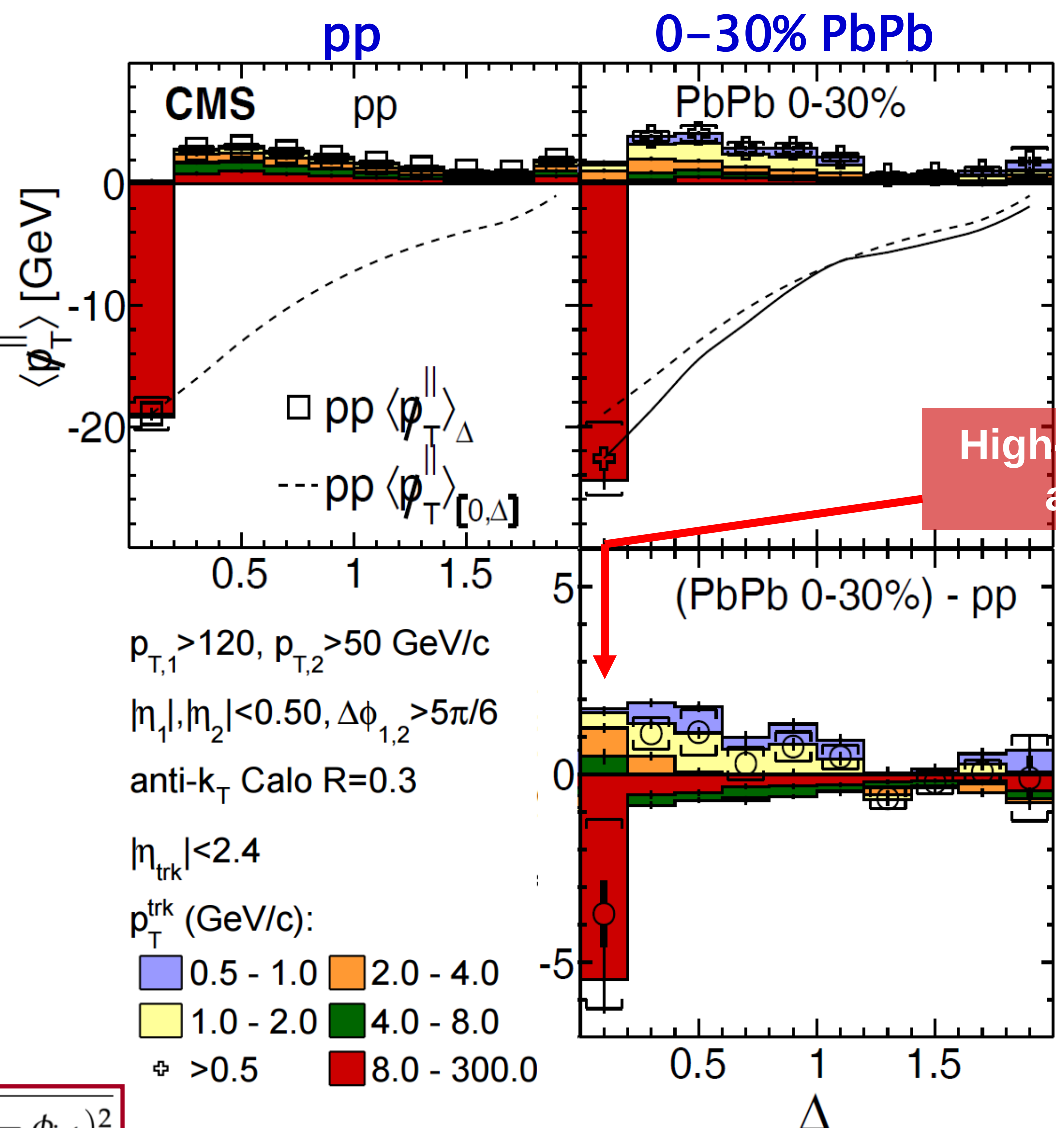
"Missing" $p_T^{||}$ vs. Δ

arXiv:1509.09029

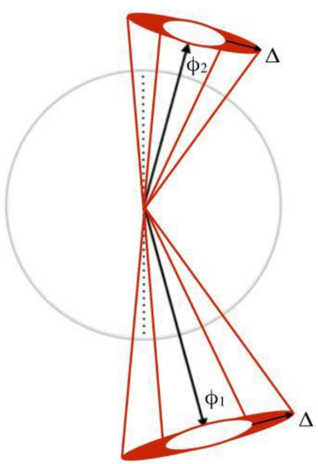
Inclusive A_J

excess towards subleading jet

excess towards leading jet



High-p_T imbalance at small Δ



$$\Delta = \sqrt{(\eta_{trk} - \eta_{jet})^2 + (\phi_{trk} - \phi_{jet})^2}$$

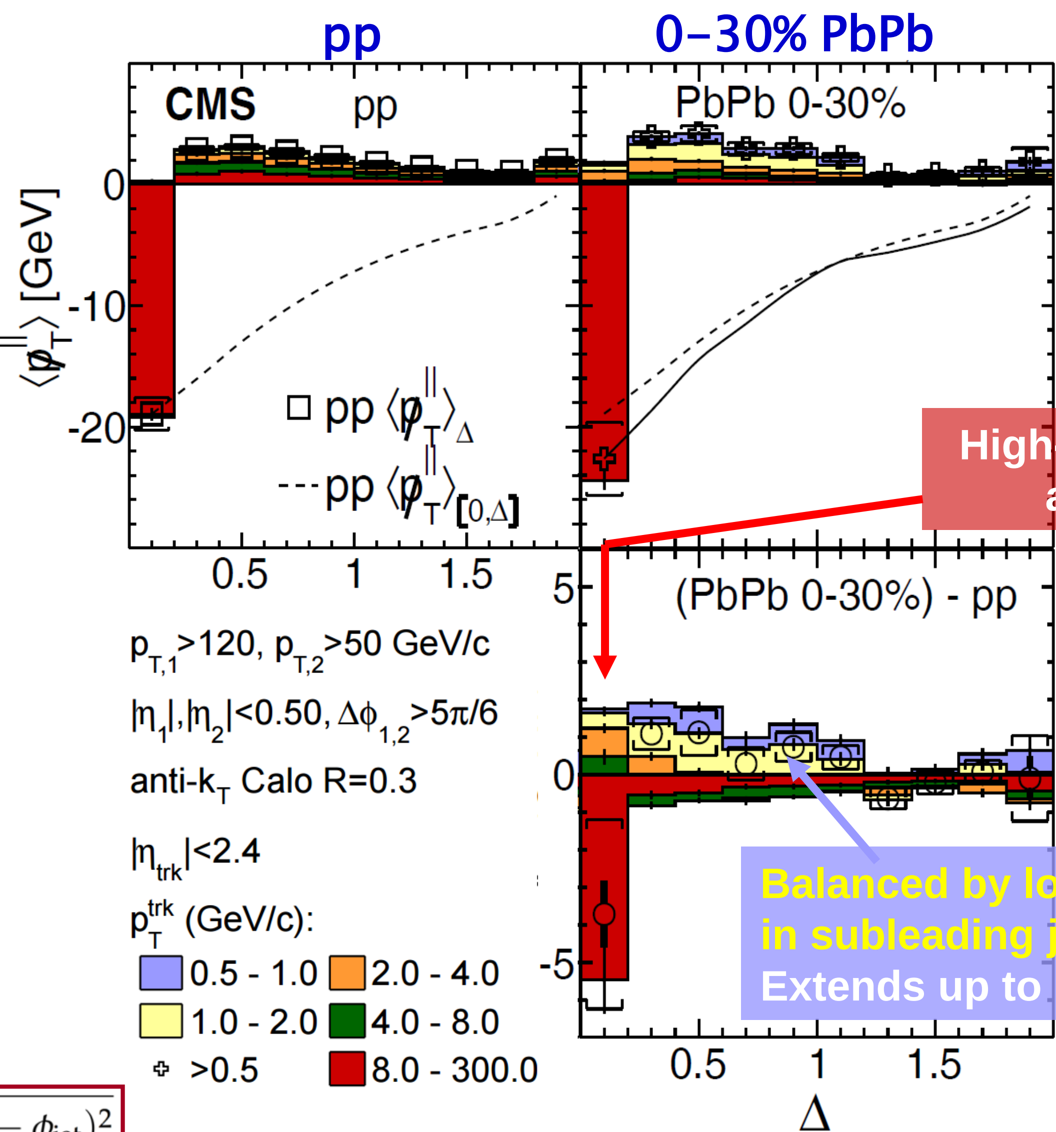
"Missing" $p_T^{||}$ vs. Δ

arXiv:1509.09029

Inclusive A_J

excess towards subleading jet

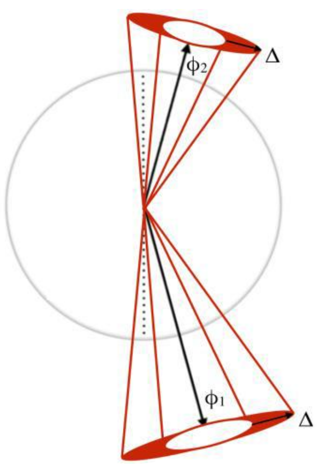
excess towards leading jet



High-p_T imbalance at small Δ

Balanced by low-p_T particles in subleading jet direction

Extends up to large Δ



$$\Delta = \sqrt{(\eta_{\rm trk} - \eta_{\rm jet})^2 + (\phi_{\rm trk} - \phi_{\rm jet})^2}$$

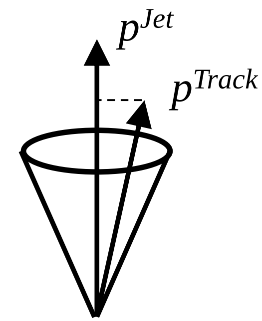
Is jet fragmentation affected?

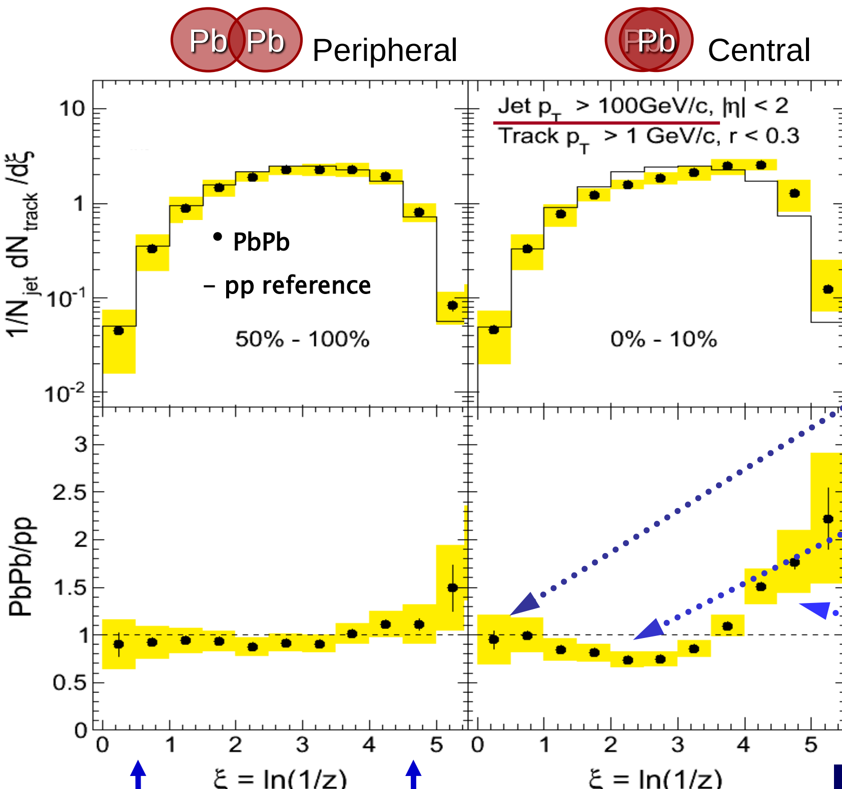
Measure Fragmentation Functions to check if energy loss mechanisms modify fragmentation of partons.

Jet Fragmentation Function: $\frac{1}{N_{Jet}} \frac{dN_{Track}}{d\xi}$

$$\xi = \ln(1/z) = \ln\left(\frac{p^{Jet}}{p_{\parallel}^{Track}}\right)$$

z– fraction of parton's momentum carried by hadron





High p_T particles

Low p_T particles

PRC 90 (2014) 024908

Central PbPb:

For high p_T particles (in jet cone) fragmentation as in pp

Suppression of intermediate p_T particles

Enhancement of low p_T particles

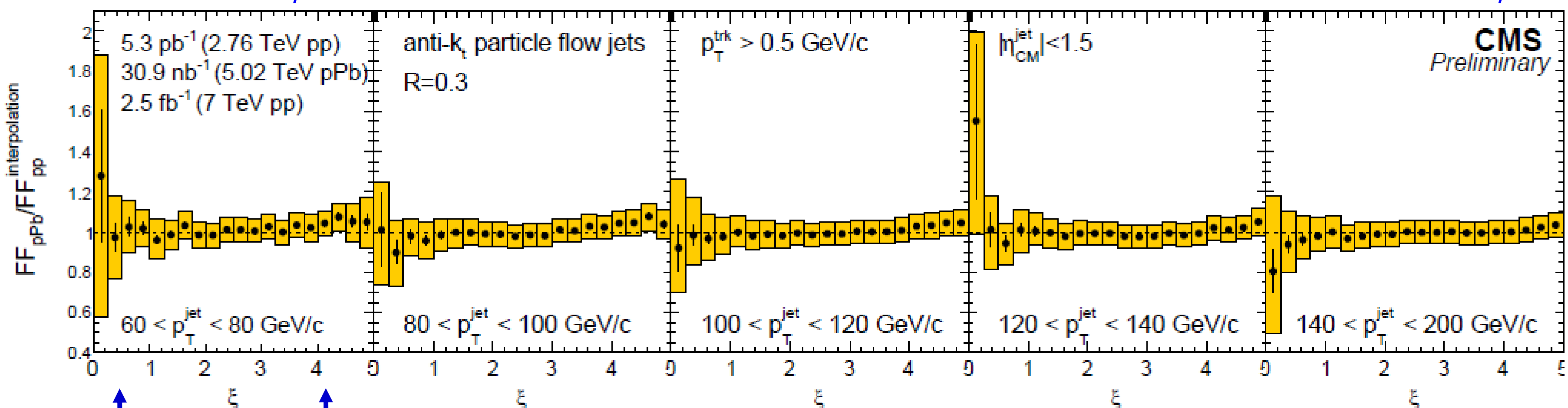
Centrality dependent modification of jet fragmentation functions in PbPb collisions

Is jet fragmentation affected?

pPb collisions

Ratio of Jet Fragmentation Functions:

Low p_T jet 60–80 GeV/c → High p_T jet 140–200 GeV/c



High p_T particles ↑ ↑ Low p_T particles

$$\xi = \ln(1/z) = \ln\left(\frac{p^{Jet}}{p_{\parallel}^{Track}}\right)$$

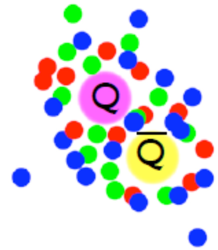
PAS-HIN-15-004

➡ No modification of jet fragmentation function in pPb with respect to the interpolated pp reference

➡ Without modification in jet R_{pPb} and FF_{pPb}, the observed PbPb modification can be attributed to the final-state hot nuclear matter effect

Sequential melting of quarkonia

- In QGP, color 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

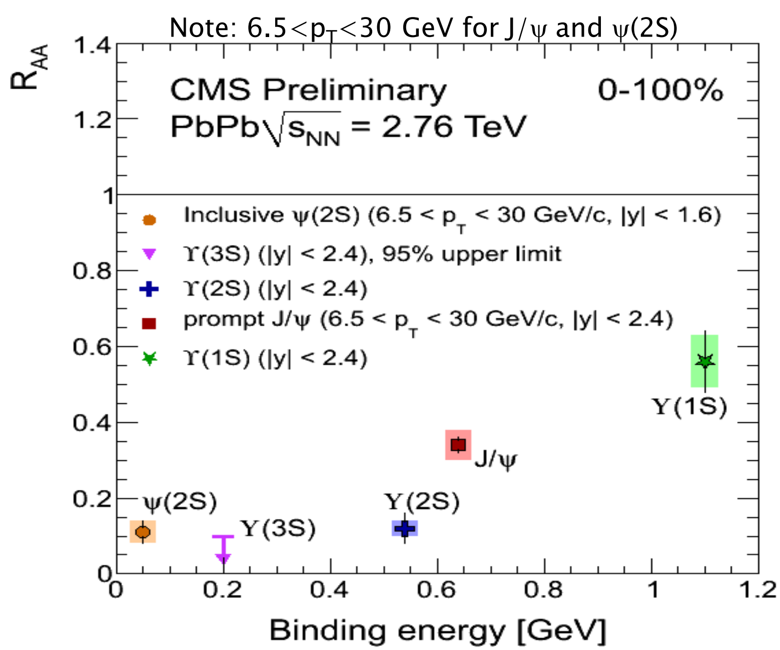
state	Υ(1S)	Υ(2S)	Υ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o(fm)	0.28	0.56	0.78

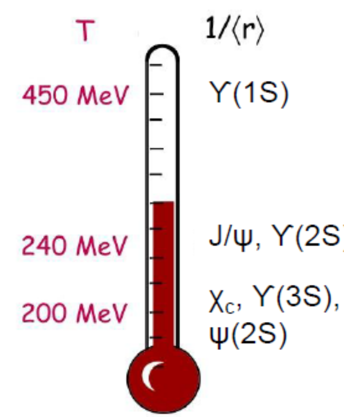
$$R_{AA} = \frac{\text{(Yield in AA)}}{N_{COLL}(AA) \times \text{(Yield in pp)}}$$

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

PRL 109 (2012) 222301
PRL 113 (2014) 262301
PAS-HIN-12-014

Centrality-integrated R_{AA} vs. binding energy





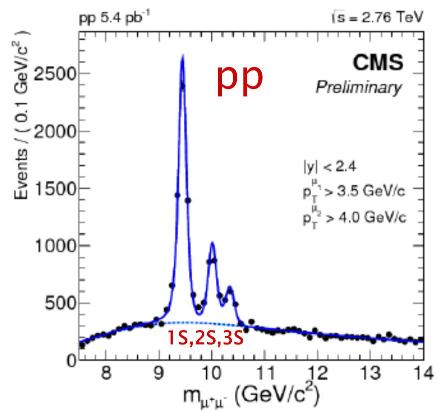
Mocsy, EPJC61 (2009) 705

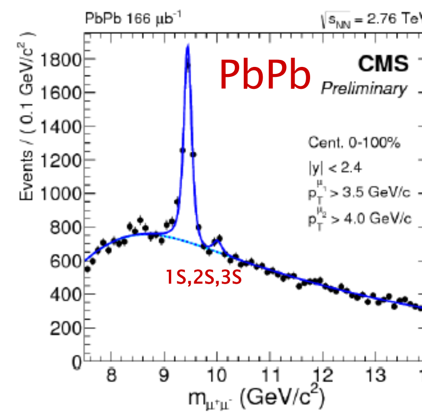
Υ production in pp and PbPb

Updated results: statistics for pp data x20; improved reconstruction for PbPb

PAS-HIN-15-001

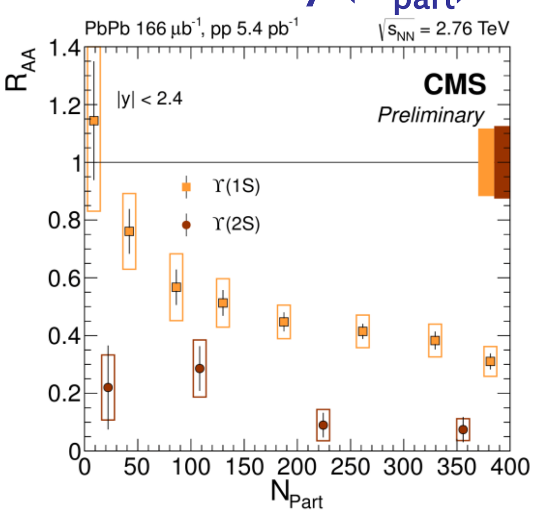
Dimuon spectra →

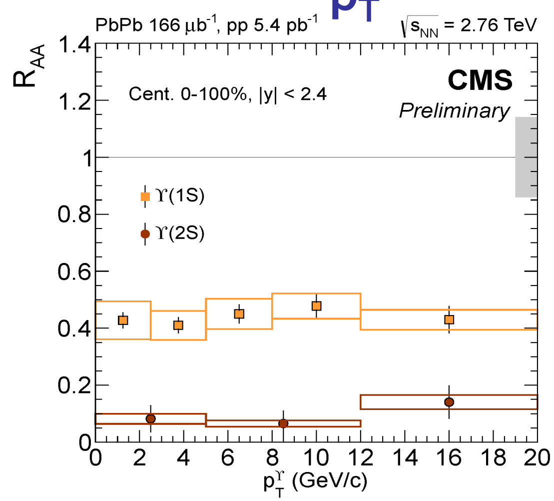


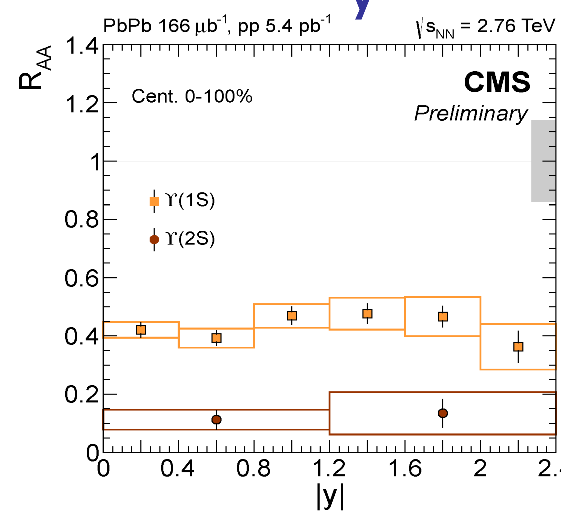


Υ(1S), Υ(2S) dependence on:

centrality (N_{part}) p_T y







- Υ suppression dependence on centrality observed and suppression is stronger for excited state
- Υ suppression does not depend on kinematics (p_T and y)

Υ production in pp, pPb and PbPb

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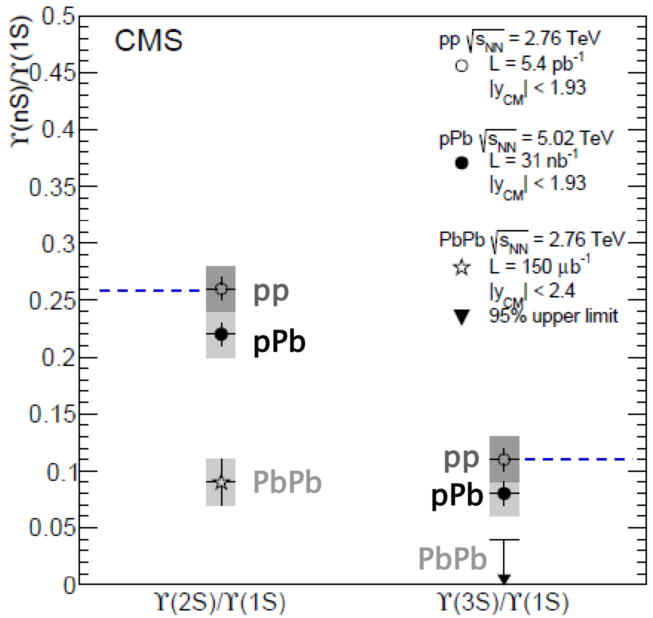
Υ(nS)/Υ(1S) ratio, centrality integrated

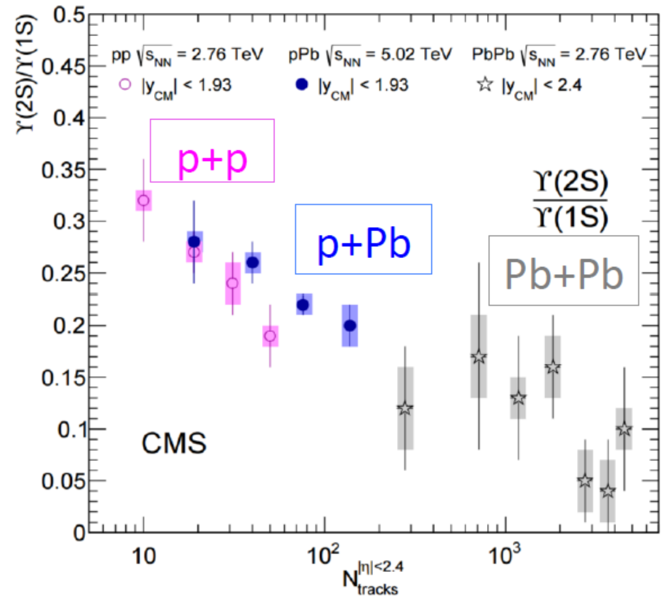


Relative production of excited state (Υ(2S) or Υ(3S)) to ground state Υ(1S) more suppressed in **pPb** than in **pp**

In **PbPb** stronger suppression than in pPb collisions

PbPb < pPb < pp

Υ(2S)/Υ(1S) ratio vs. multiplicity



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

Υ(2S)/Υ(1S) decreases with event multiplicity for all systems

Same physical mechanisms present in pp, pPb and PbPb collisions ??

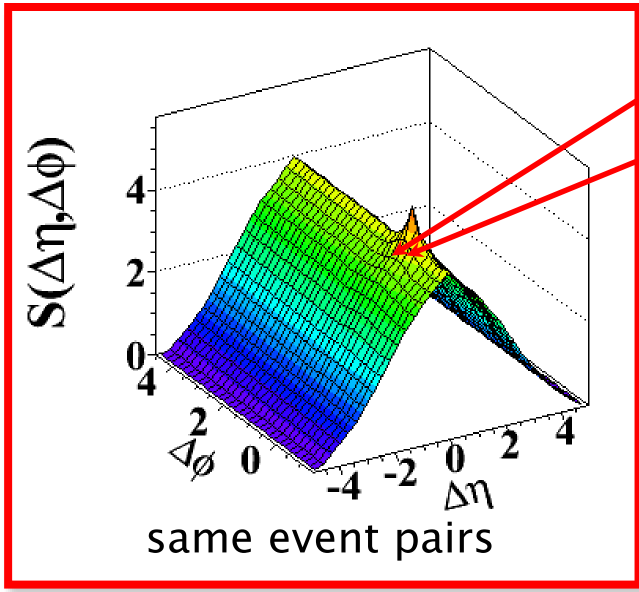
Two-particle correlations

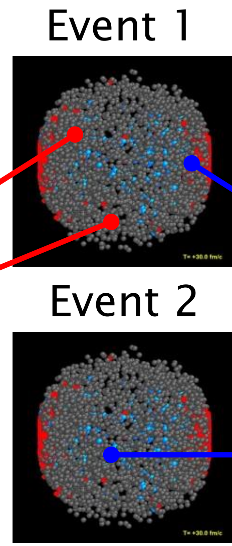
Signal pair distribution:

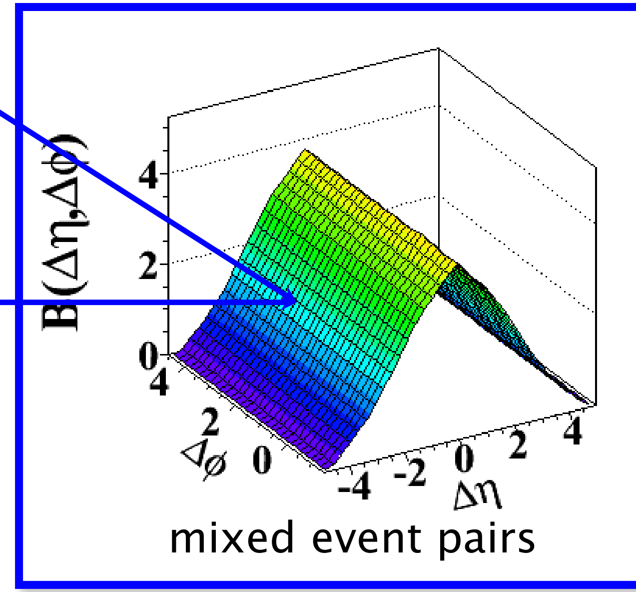
$$S(\Delta\eta,\Delta\varphi)=\frac{1}{N_{trig}}\frac{d^2N^{same}}{d\Delta\eta d\Delta\varphi}$$

Background pair distribution:

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







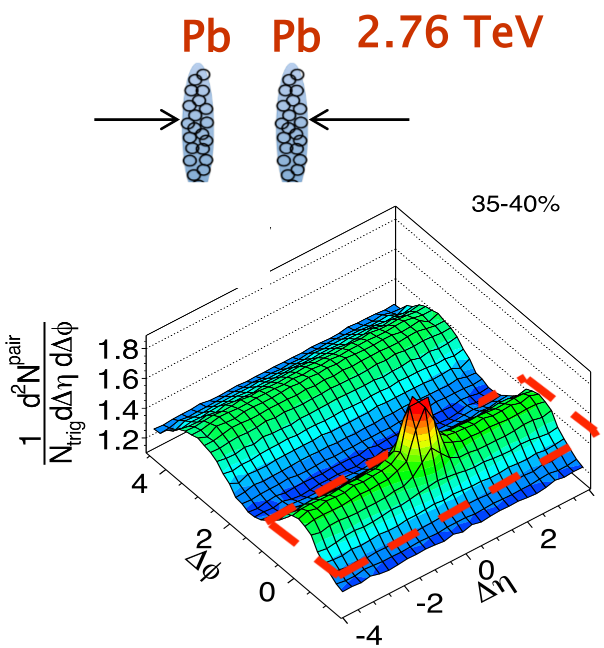
$\Delta\eta = \eta^{assoc} - \eta^{trig}$
$\Delta\phi = \phi^{assoc} - \phi^{trig}$

Associated hadron yield per trigger:

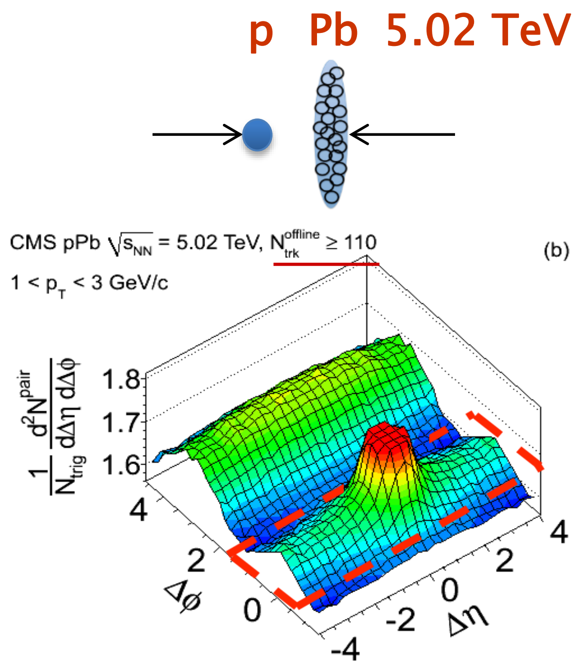
$$\frac{1}{N_{trig}}\frac{d^2N^{pair}}{d\Delta\eta d\Delta\phi}=B(0,0)\times\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

Two-particle correlations: Pb+Pb, p+Pb, p+p

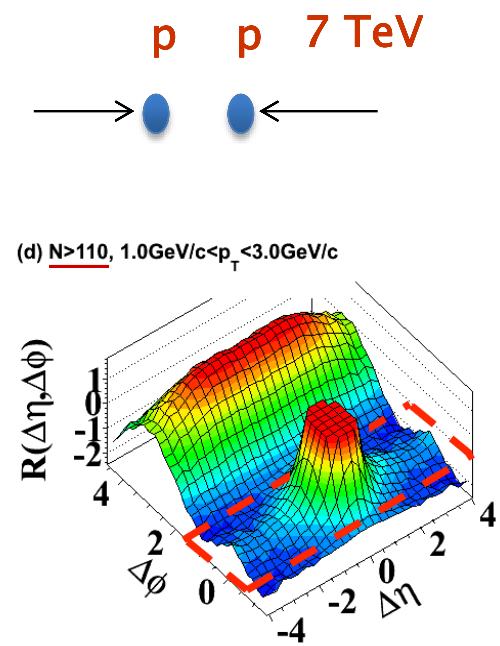
"Ridge" observed for all systems:



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



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



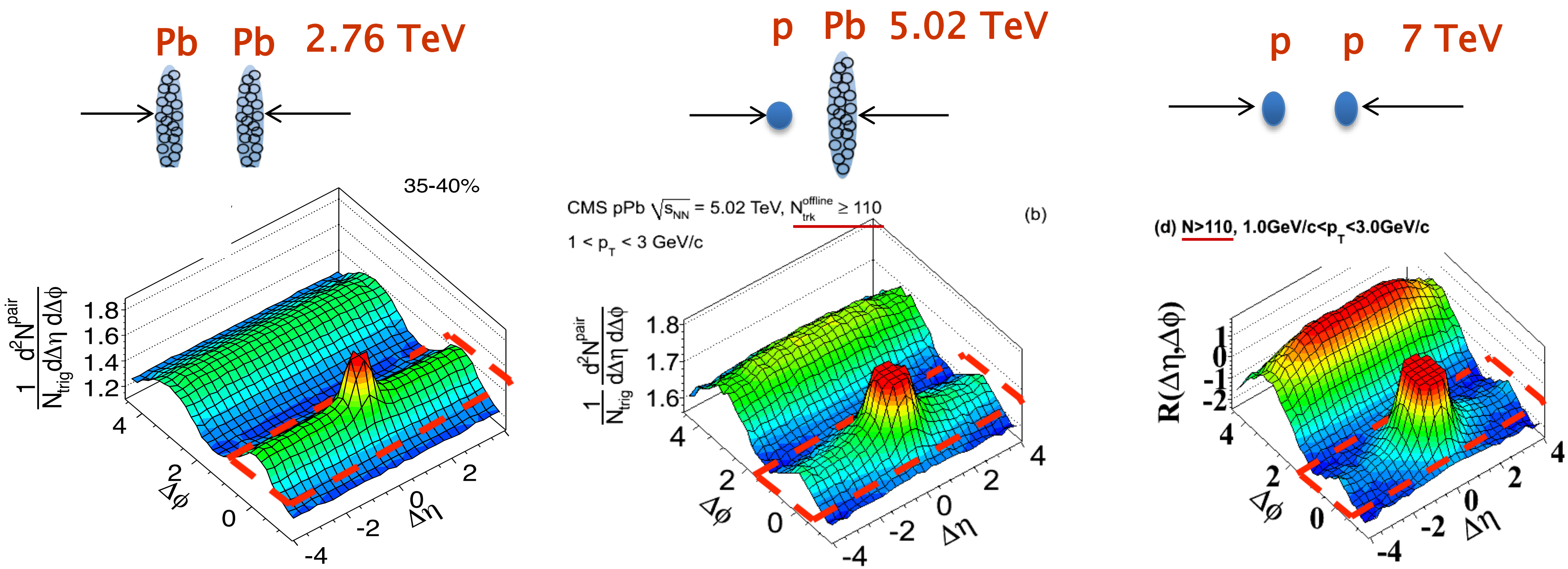
JHEP 09 (2010) 091

long-range ($\Delta\eta$), near-side ($\Delta\phi\approx 0$) correlations

Unexpected "ridge" in high-multiplicity pp collisions

Two-particle correlations: Pb+Pb, p+Pb, p+p

"Ridge" observed for all systems:



Explanation of the effect:

Fluctuations of the initial geometry and hydrodynamic evolution

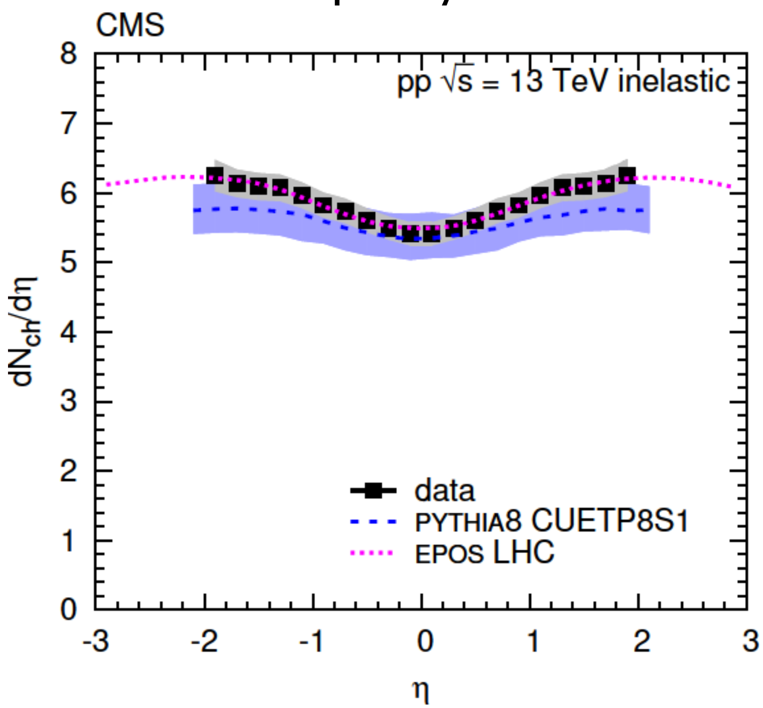
Origin unknown for the small systems:
- hydrodynamic behavior ??
- initial-state gluon saturation (CGC) ??
- …

Energy dependence study for pp collisions: 7 TeV (Run1) and 13 TeV (Run2)

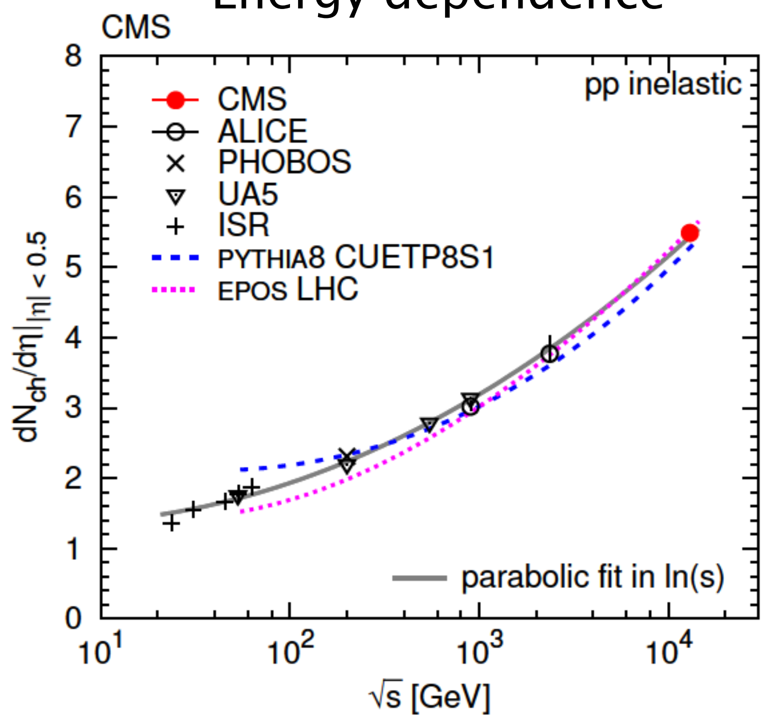
Charged hadron multiplicity in pp@13TeV

First LHC Run2 publication PLB 751 (2015) 143

Pseudo-rapidity distribution



Energy dependence



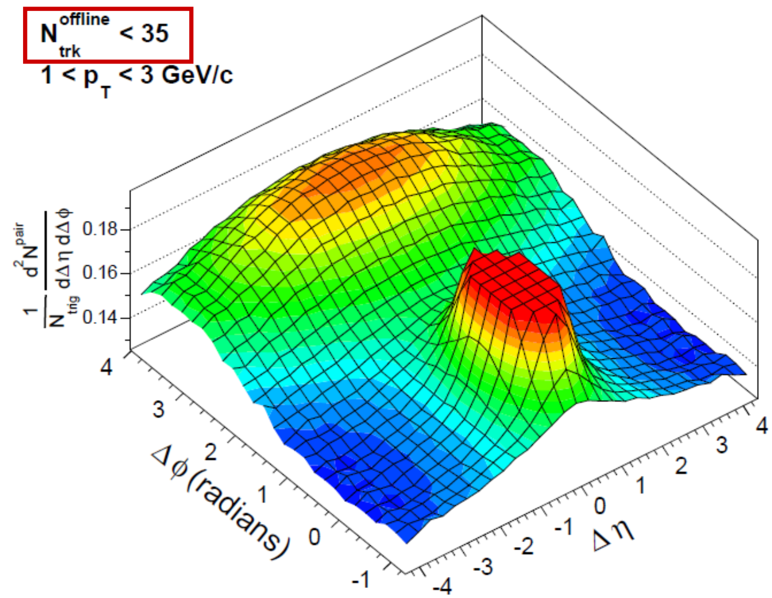
$$\left[\frac{dN_{ch}}{d\eta}\right]_{|\eta|<0.5} = 5.49 \pm 0.01(\text{stat}) + 0.17(\text{syst}) \text{ for inelastic events}$$

Energy dependence as expected

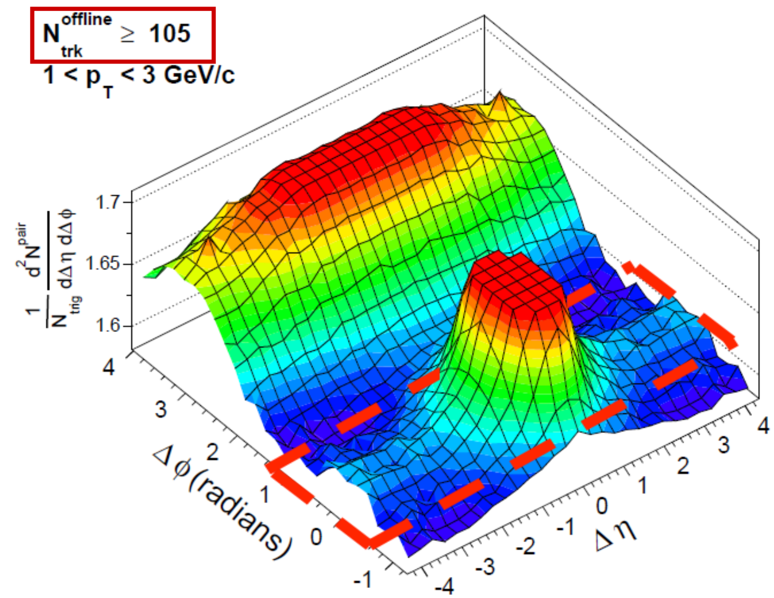
Two-particle correlations in pp at 13 TeV

p p 13 TeV

Low multiplicity



High multiplicity



arXiv:1510.03068

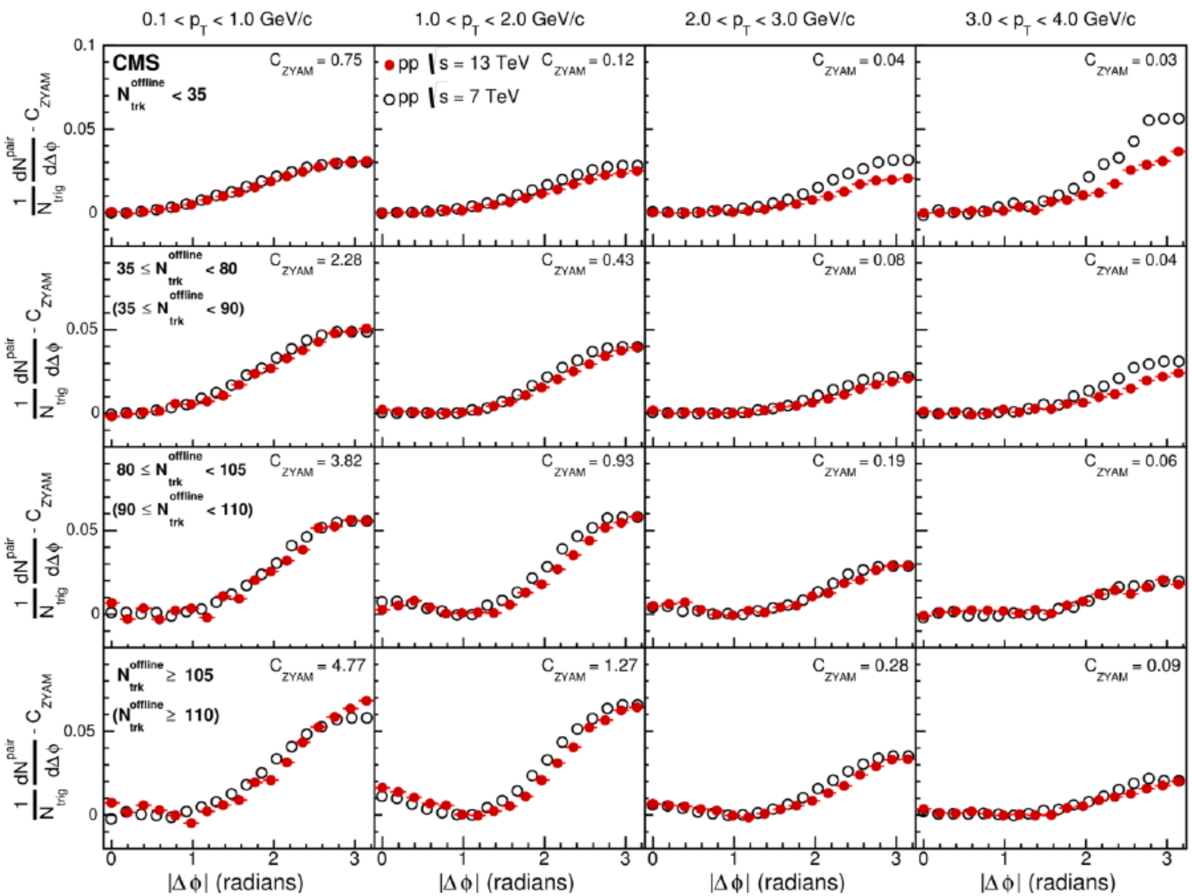
"Ridge" in high-multiplicity pp collisions at 13 TeV

Δϕ−projected correlation function

Comparison for pp collisions: ○ 7 TeV and ● 13 TeV

Increasing p_T

For $(2<|\Delta\eta|<4)$

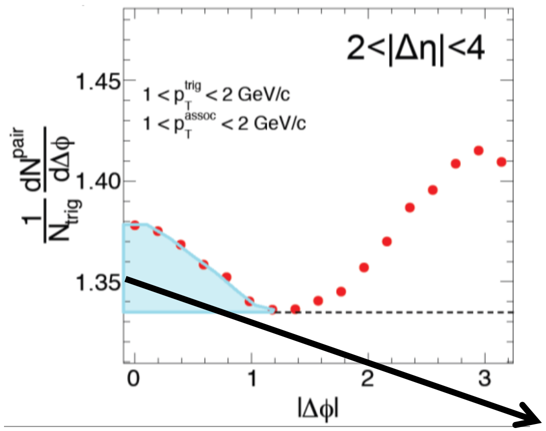


Increasing multiplicity

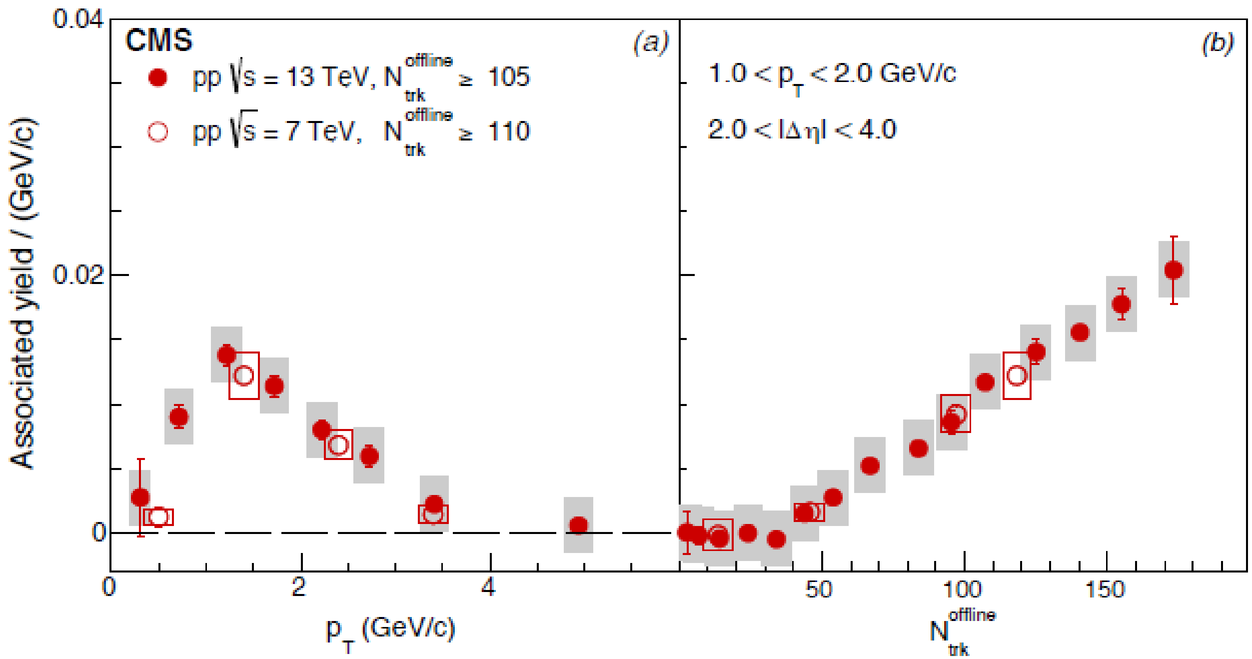
arXiv:1510.03068

Integrated associated yield

arXiv:1510.03068



p_T and multiplicity dependence:



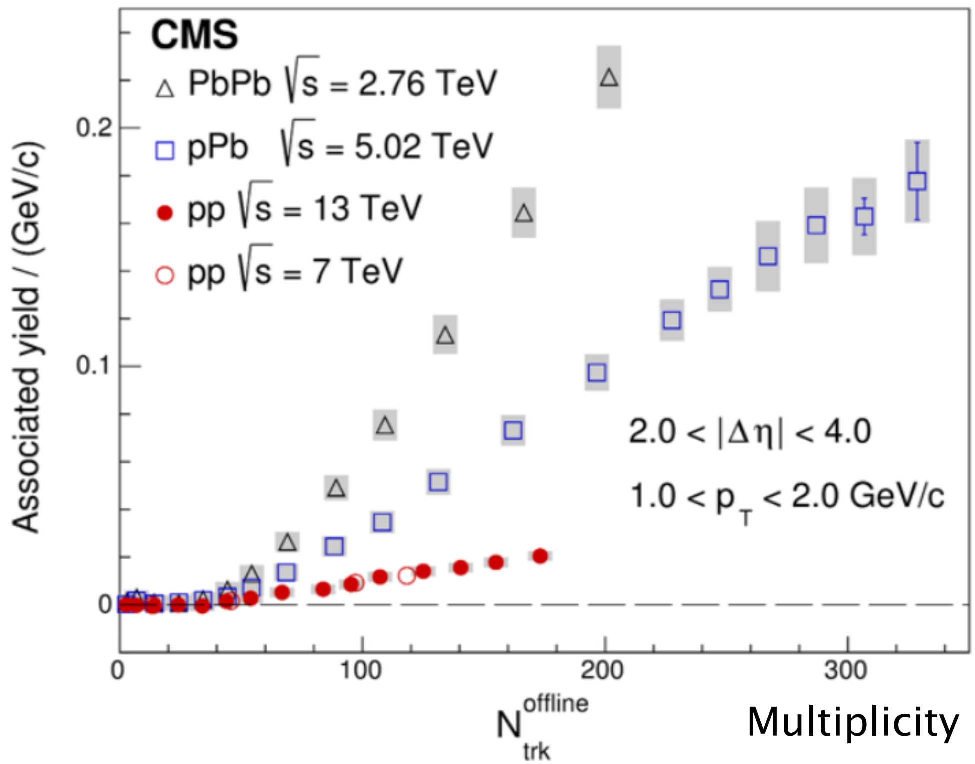
➡ No collision energy dependence observed

➡ Effect is most evident in the intermediate transverse momentum region ($1<p_T<2$ GeV/c)

➡ Approximately linear increase with multiplicity for $N_{trk}^{offline}>40$

Integrated associated yield

Comparison **pp** vs. **pPb** vs. **PbPb**



Multiplicity

arXiv:1510.03068

Strong collision system size dependence of the associated yields

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

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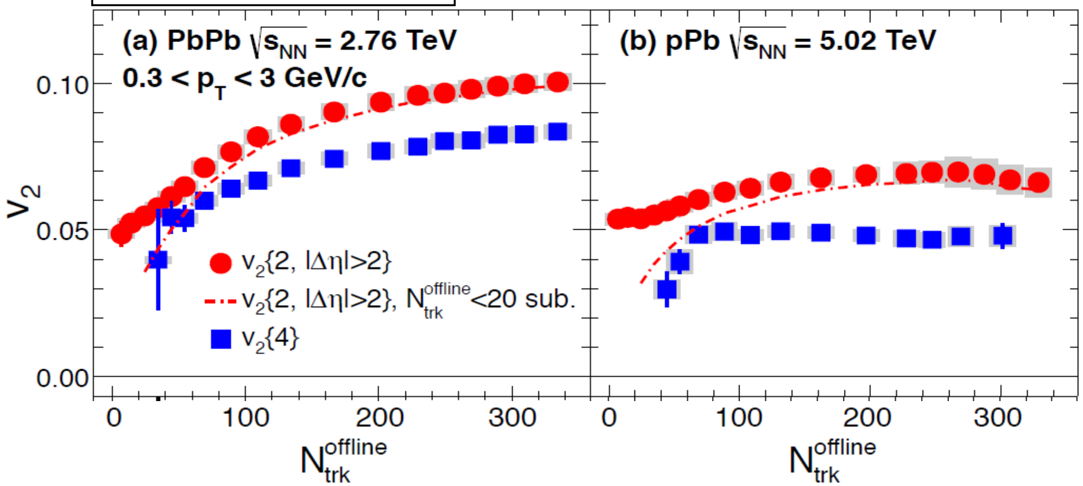
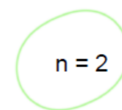
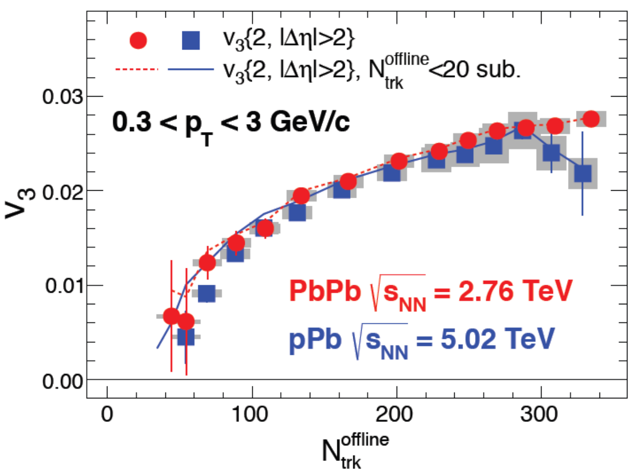
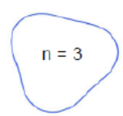




Elliptic flow (v_2) reflects the medium response to the initial collision geometry





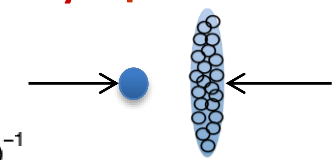
Triangular flow (v_3) reflects fluctuations of the initial geometry

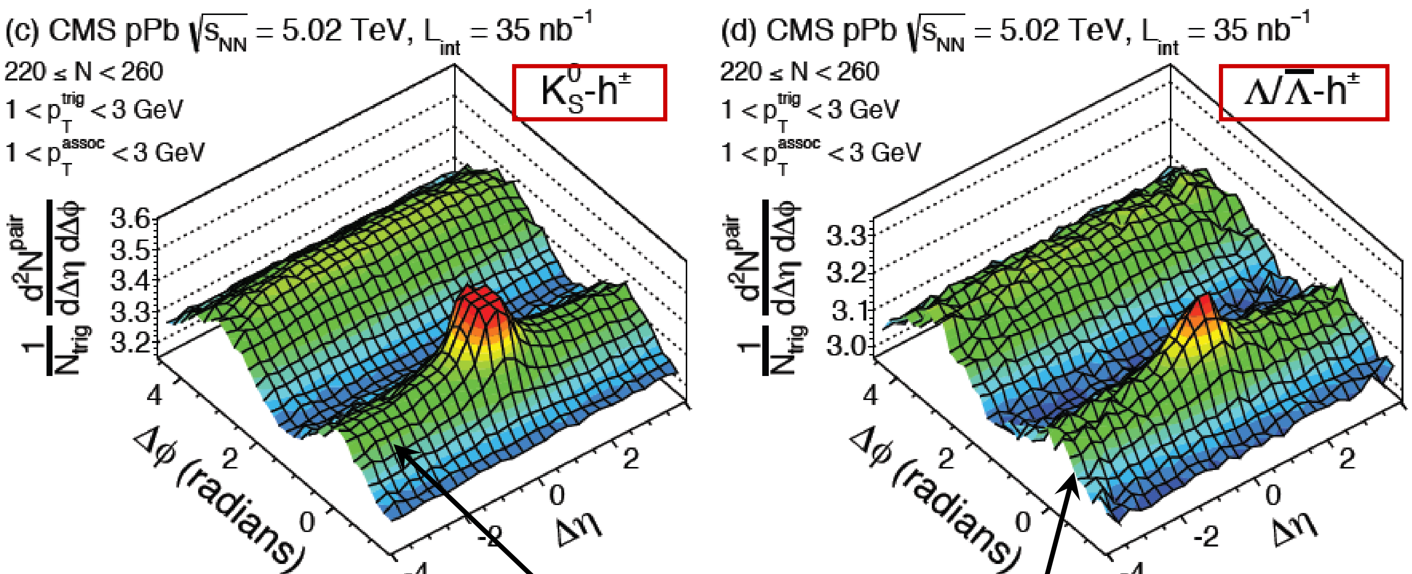
PbPb and pPb collisions are similar:

- 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)

Correlations of strange and charged hadrons

high-multiplicity p Pb 5.02 TeV





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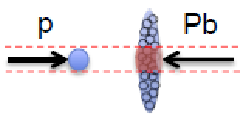
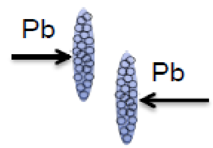
"Ridge" observed for K_S^0–h and Λ–h correlations in high-multiplicity pPb collisions

v_2 and v_2/n_q of strange hadrons

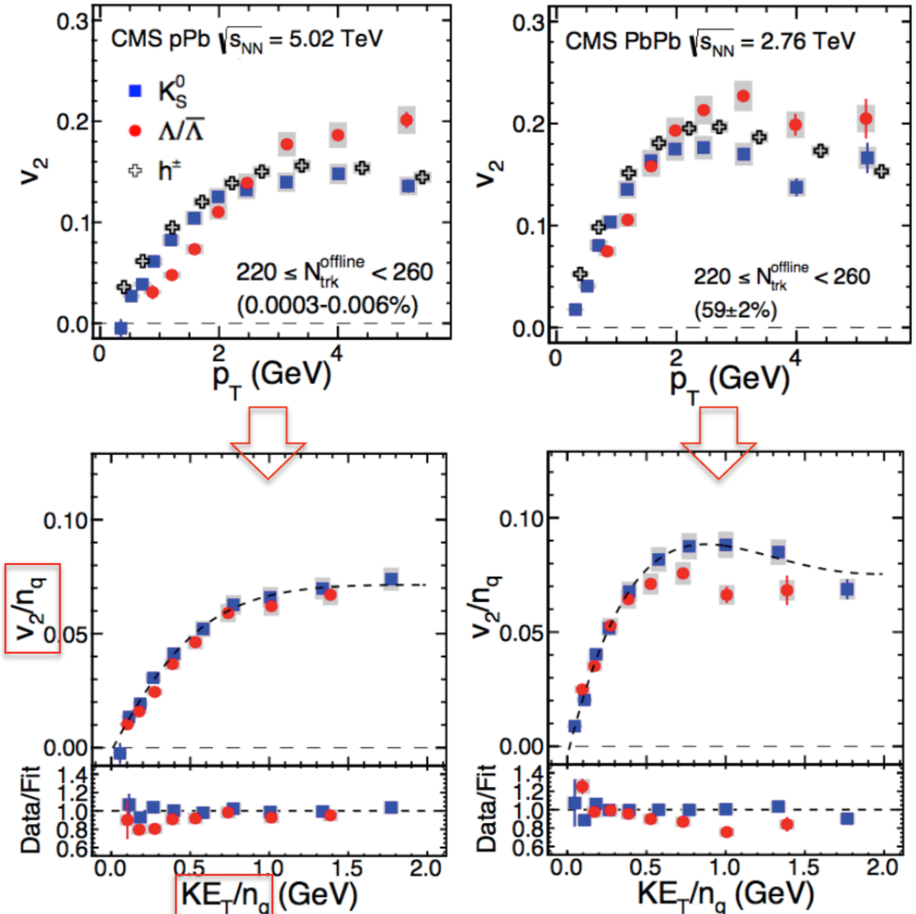
PLB 742 (2015) 200





p-Pb high-multiplicity events

Pb-Pb peripheral events



$$KE_T = \sqrt{m^2 + p_T^2} - m$$

Same multiplicity bin for pPb and PbPb

v_2 shows mass ordering in pPb and PbPb: at low p_T, smaller v_2 values for heavier particles

Mass ordering more clear in pPb than in PbPb → stronger radial flow in pPb ??

v_2 scaled by the number of constituent quarks: NCQ scaling observed **→ indication of partonic degrees of freedom in the initial stage of the collision**

Scaling better in pPb than in PbPb

v_3 and v_3/n_q of strange hadrons

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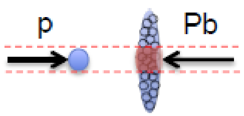
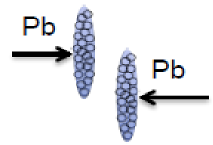
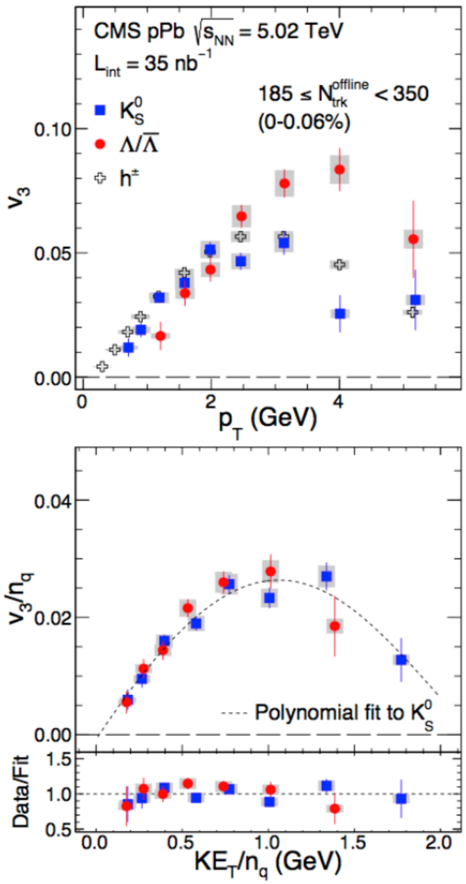
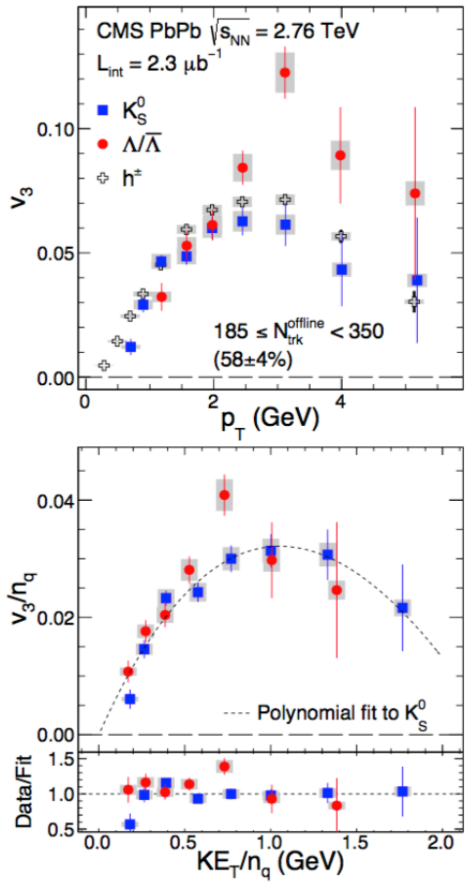




p-Pb high-multiplicity events



Pb-Pb peripheral events



Same multiplicity bin for pPb and PbPb

Similar species dependence of v_3 to that of v_2 found

Mass ordering observed for v_2 and v_3 results supports presence of collective behavior in both systems (pPb and PbPb)

Summary

Results from Run1 presented for PbPb, pPb and pp collisions. First results from pp collisions at 13 TeV (Run2) also shown.

PbPb and pPb collisions:

Jet quenching

- Suppression observed for central PbPb is a final state effect
  - No flavor dependence measured at high p_T
- High-p_T excess of jet tracks on leading jet side compensated by low-p_T excess of jet tracks on subleading jet side, which extends to large angles
- Jet fragmentation function modified in PbPb and not in pPb

Quarkonia production

- Sequential melting of quarkonium states observed in PbPb
- Υ suppression depends on collision centrality and does not depend on kinematics
- $\Upsilon(2S)/\Upsilon(1S)$ ratio decreases with event multiplicity

Collective behavior

- Results for "ridge" and elliptic (v_2) and triangular (v_3) flow similar in PbPb and high-multiplicity pPb collisions

pp collisions:

"Ridge" observed also in high-multiplicity pp collisions at 7 TeV and 13 TeV