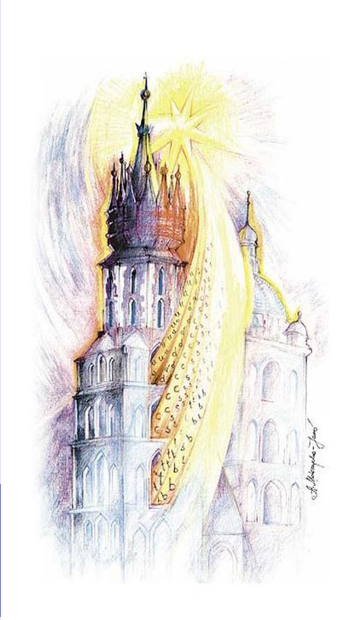


Cracow Epiphany Conference
On the physics after the first phase of the LHC
7-9 January 2013, Cracow, Poland

Results on Heavy-Ion Physics with the CMS detector at LHC

Bożena Boimska

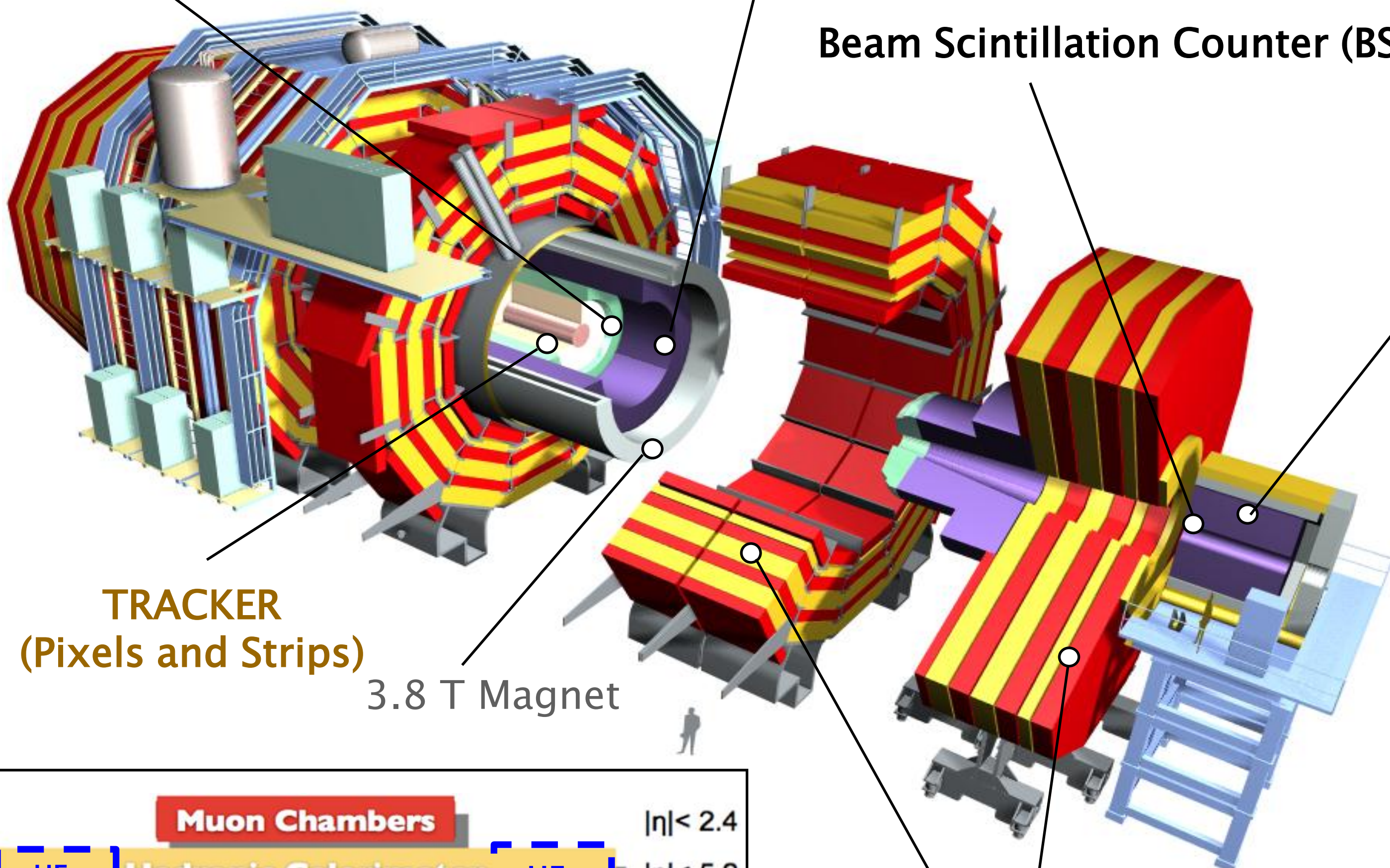
National Centre for Nuclear Research

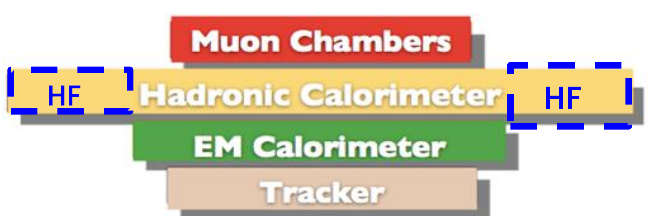
on behalf of the CMS Collaboration

Outline

- Introduction
- Experimental results
  - (Selected) PbPb results
    - Jet quenching
    - Quarkonium suppression
  - First pPb results
    - Two-particle correlations
- Summary

CMS detector

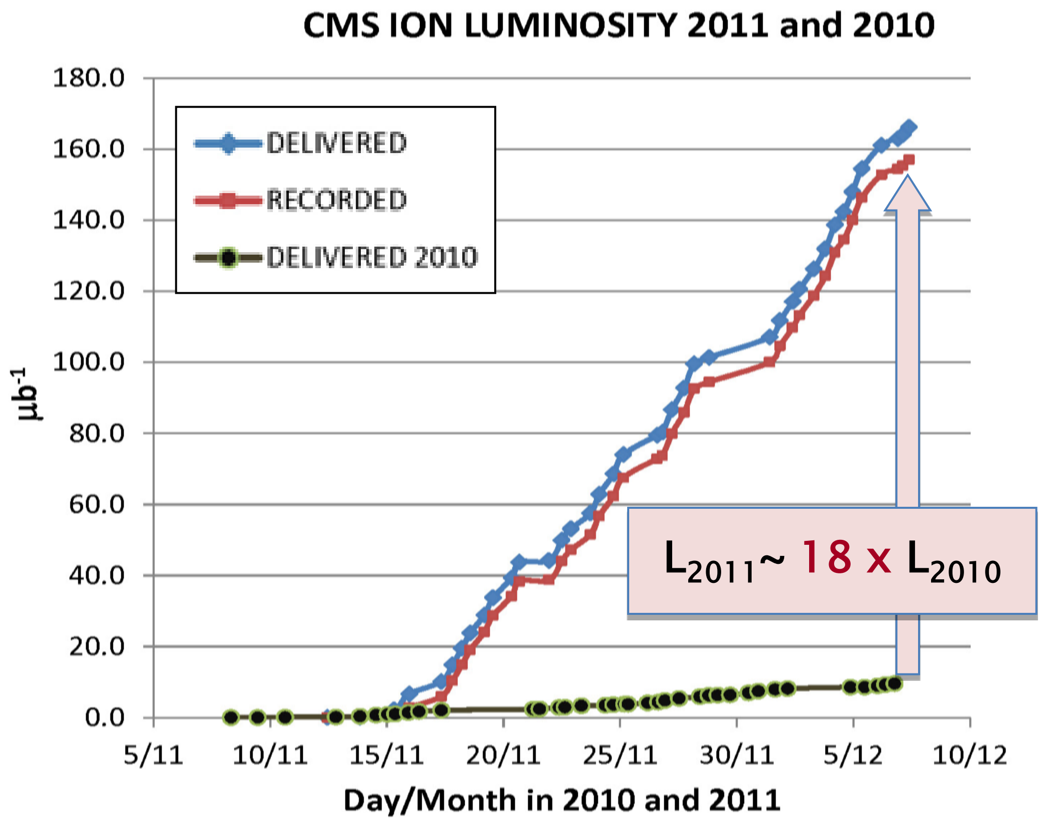




$\eta = -\ln(\mathrm{tg}\,\theta/2)$

Heavy-Ion data-takings

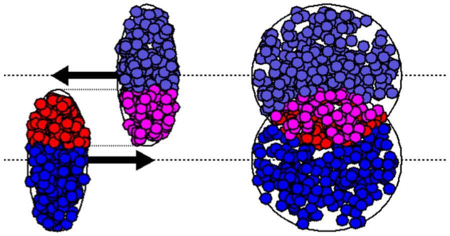
- PbPb @ 2.76 TeV
  - 2010 data: 8.7 μb^{-1}
  - 2011 data: 157.6 μb^{-1}
- Reference data
  - 2011 pp @ 2.76 TeV: 231 nb^{-1}
  - 2012 pPb @ 5.02 TeV test run: 1.05 μb^{-1}

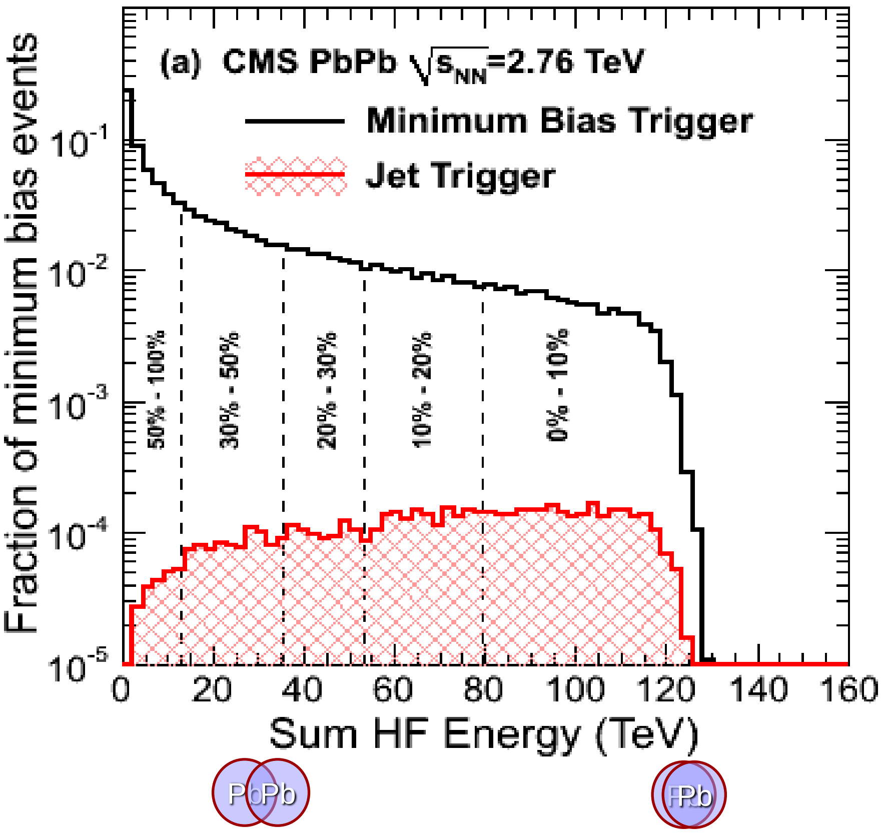


Trigger selections:
- MinBias Trigger (coincidence of BSC or HF signals)
- Photon Trigger
- Jet Trigger
- (Di)Muon Trigger

Centrality determination

- Energy deposit in forward calorimeters (HF) used for centrality determination
- Distribution of the total HF energy used to divide the sample into centrality bins





Collision centrality is related to geometrical quantities:

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

Publications

1. HIN-10-004 (dijet imbalance): PRC 84 (2011) 024906
2. HIN-11-007 (Υ2s/Υ1s ratio): PRL 107 (2011) 052302
3. HIN-10-005 (R_{AA}): EPJC 72 (2012) 1945
4. HIN-10-006 (quarkonia): JHEP 05 (2012) 063
5. HIN-10-003 (Z): PRL 106 (2011) 212301
6. HIN-11-013 (dijets): PLB 712 (2012) 176
7. HIN-11-010 (γ-jet): PLB 718 (2013) 773
8. HIN-11-012 (high p_T v_2): PRL 109 (2012) 022301
9. HIN-11-002 (photons): PLB 710 (2012) 256
10. HIN-11-004 (jet FF): JHEP 10 (2012) 087
11. HIN-11-011 (Υ): PRL 109 (2012) 222301
12. HIN-11-008 (W): PLB 715 (2012) 66
13. HIN-10-001 ($dN_{ch}/d\eta$): JHEP 08 (2011) 141
14. HIN-11-003 ($dE_T/d\eta$): PRL 109 (2012) 152303
15. HIN-11-001 (correlations): JHEP 07 (2011) 076
16. HIN-11-006 (correlations): EPJC 72 (2012) 2012
17. HIN-12-015 (pPb ridge): PLB 718 (2013) 795

18. HIN-10-002 (v_2 flow): PRC } accepted
19. HIN-11-009 (π^0 v_2) : PRL } accepted

Topics studied:

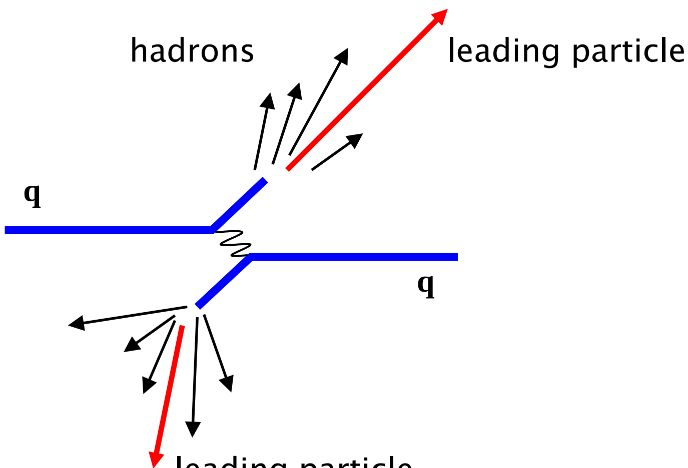
- ‘bulk’ observables
- ‘hard’ observables:
  - control probes
  - modified probes

Only some selected results presented today …

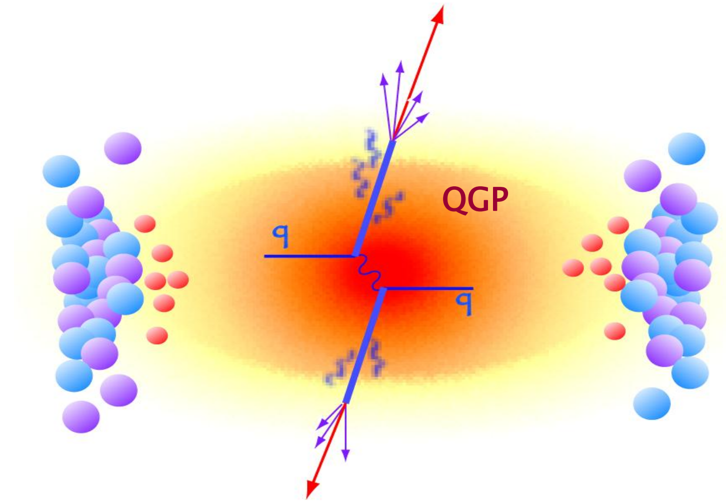
Jet quenching

signature of QGP – J.D.Bjorken (1982)

Schematic view of jet production:



pp collision



AA collision

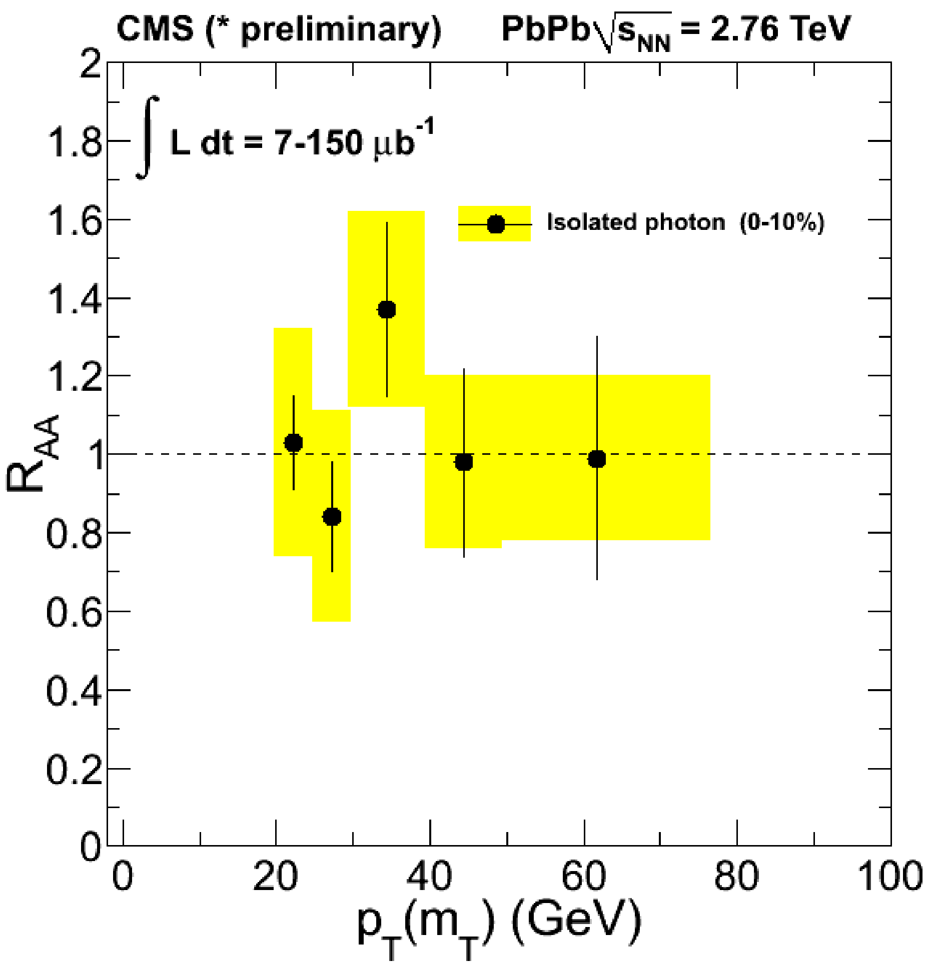
Start with a study of nuclear modification factor – R_{AA} :

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

$R_{AA} < 1$ suppression
$R_{AA} = 1$ no modification
$R_{AA} > 1$ enhancement

Nuclear modification factor

Control probes do not interact strongly



photons

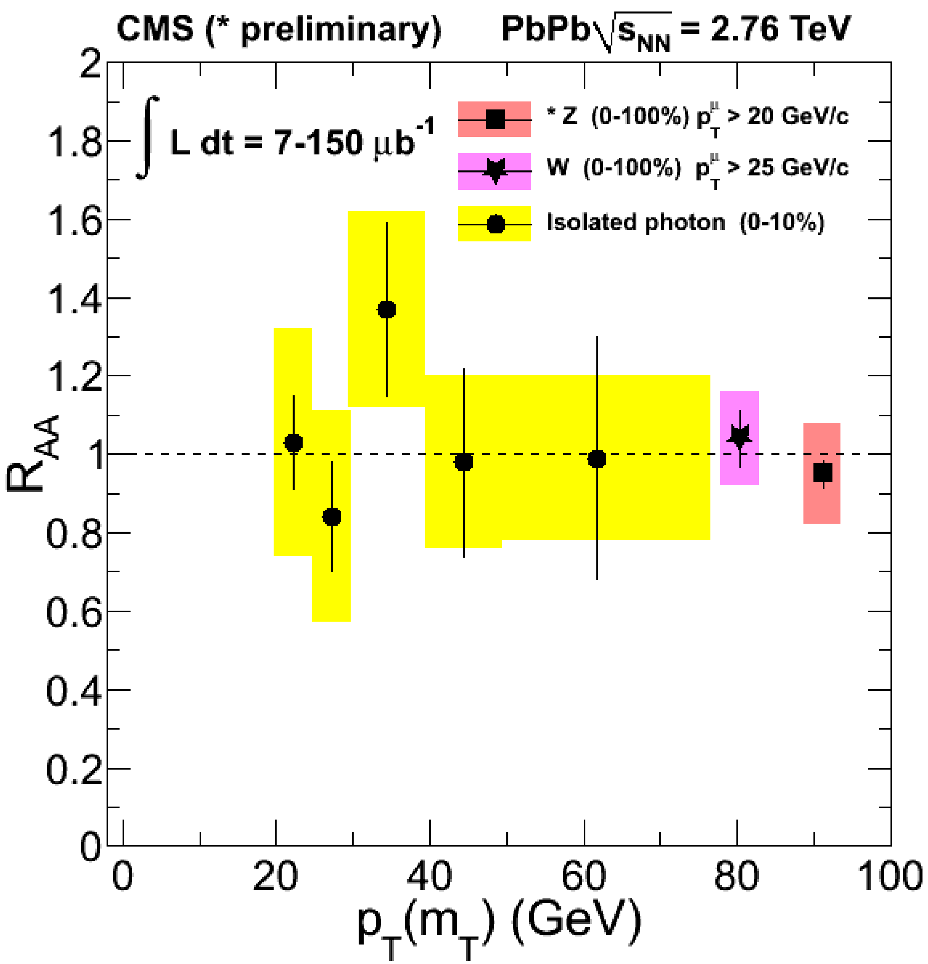
PLB 710 (2012) 256

are not modified by the medium

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

Nuclear modification factor

Control probes do not interact strongly



Z
W
photons

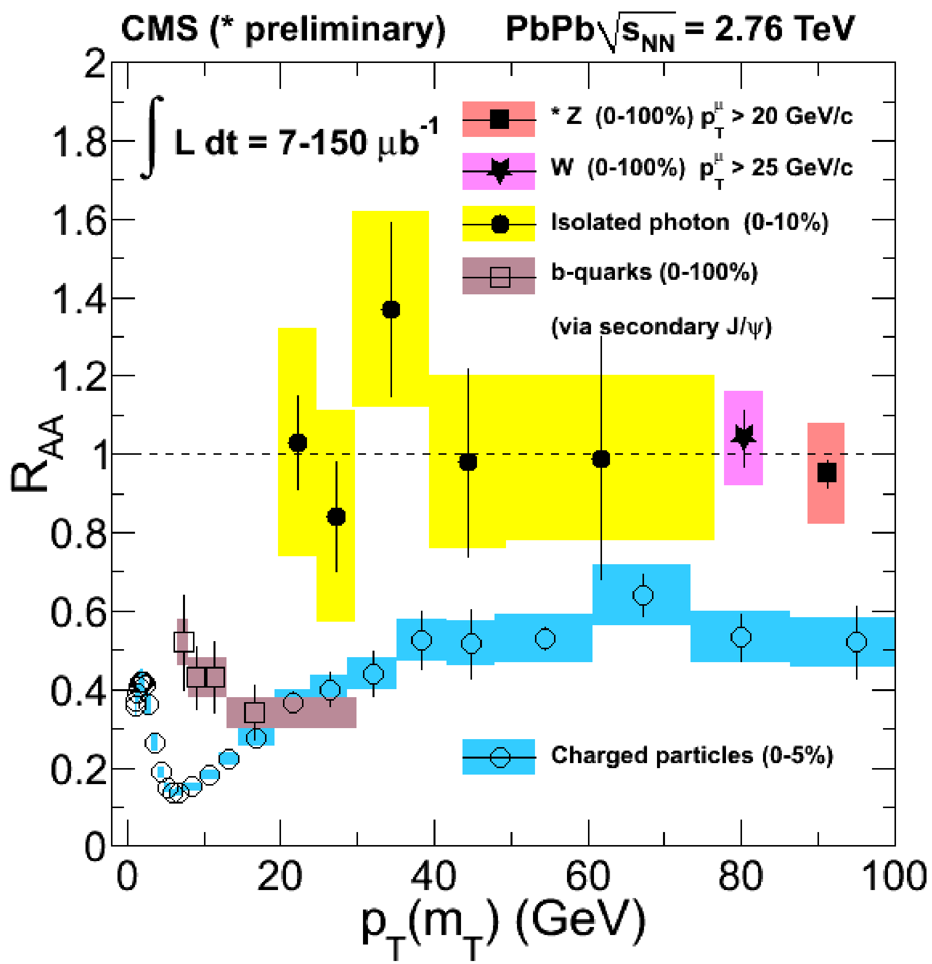
are not modified by the medium

PAS-HIN-12-008
PLB 715 (2012) 66
PLB 710 (2012) 256

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

Nuclear modification factor

Modified probes do interact strongly



EPJC 72 (2012) 1945

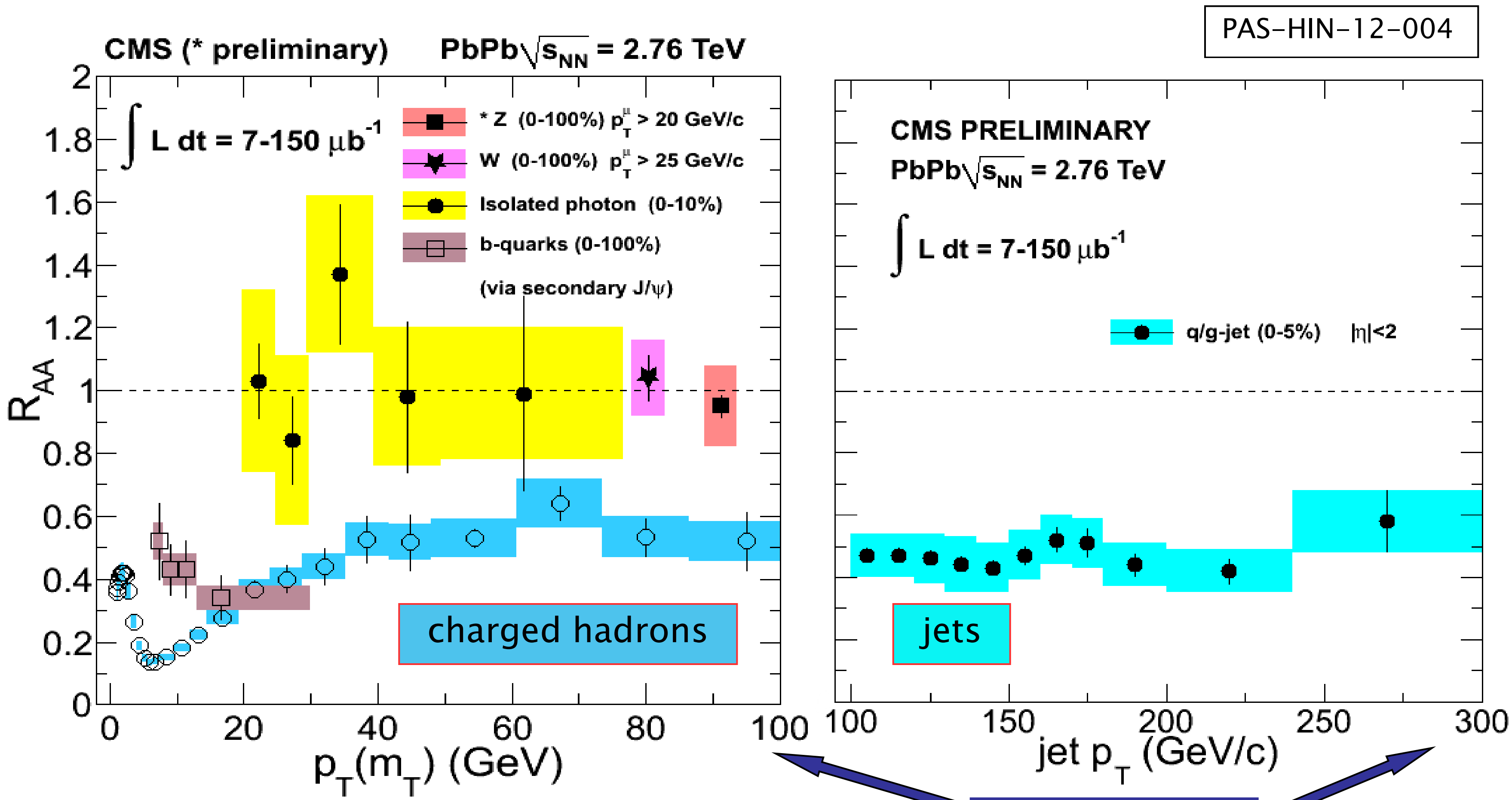
PAS-HIN-12-014

charged hadrons & **b-quarks**

are suppressed, $R_{AA}<1$

Nuclear modification factor

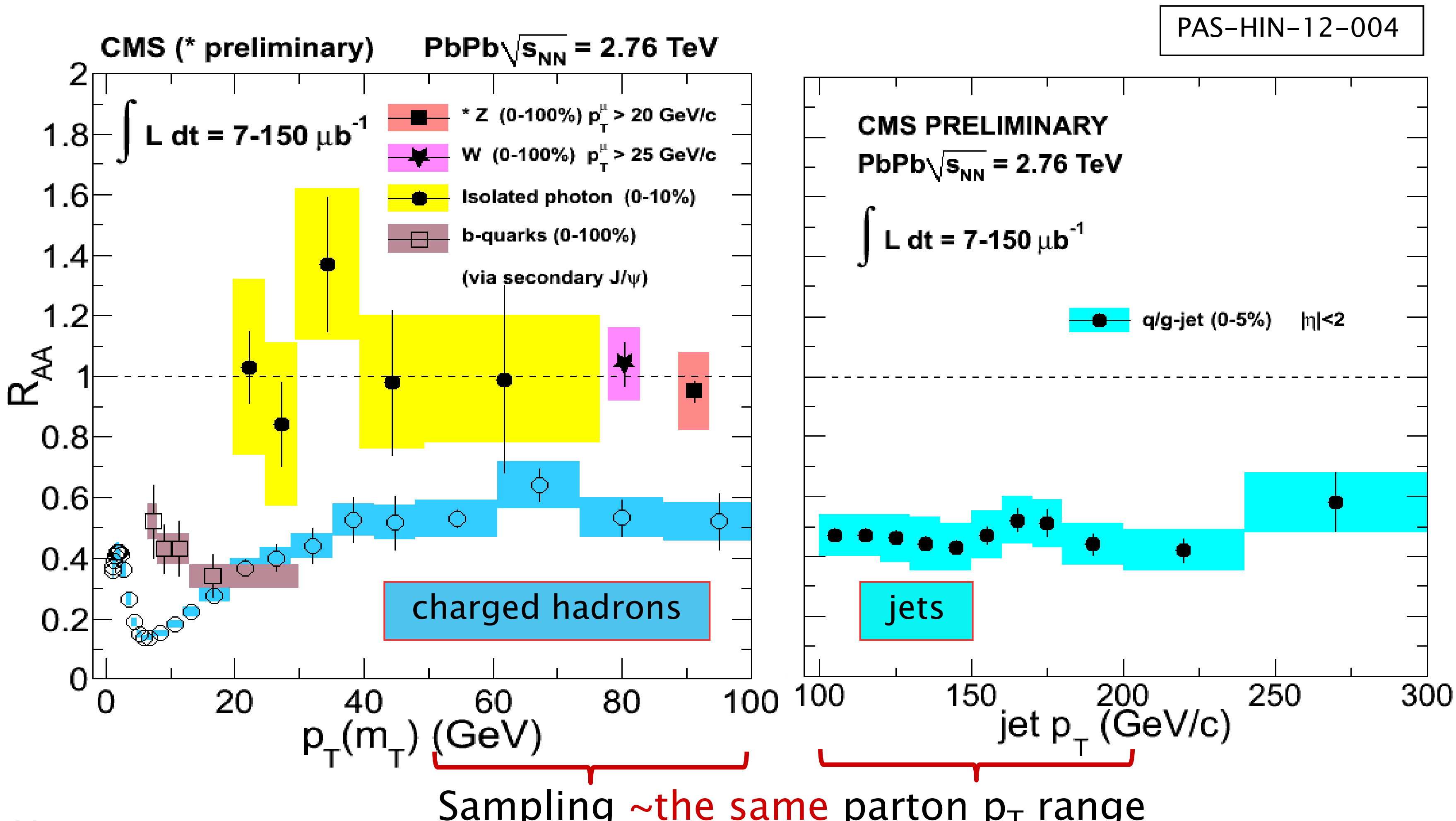
Modified probes : charged hadrons and jets



Like for charged particles,
high-p_T jet R_{AA} is flat and equal ≈0.5

Nuclear modification factor

Modified probes : charged hadrons and jets

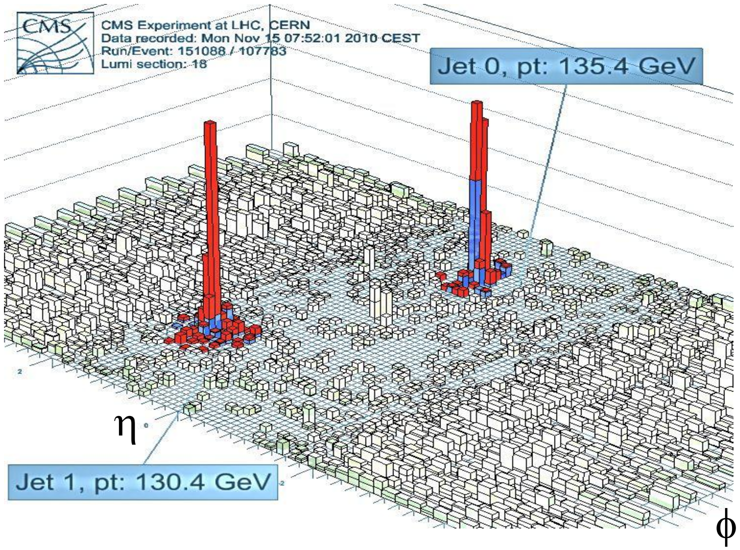


Note:

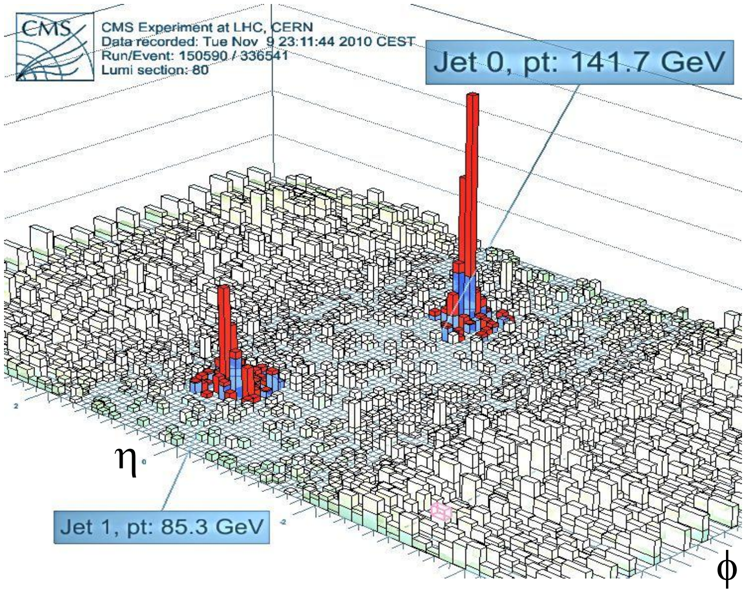
In PbPb jets fragment into high-p_T particles the same way as in pp → *shown later*

Dijet events in PbPb collisions

Balanced jets



Unbalanced jets



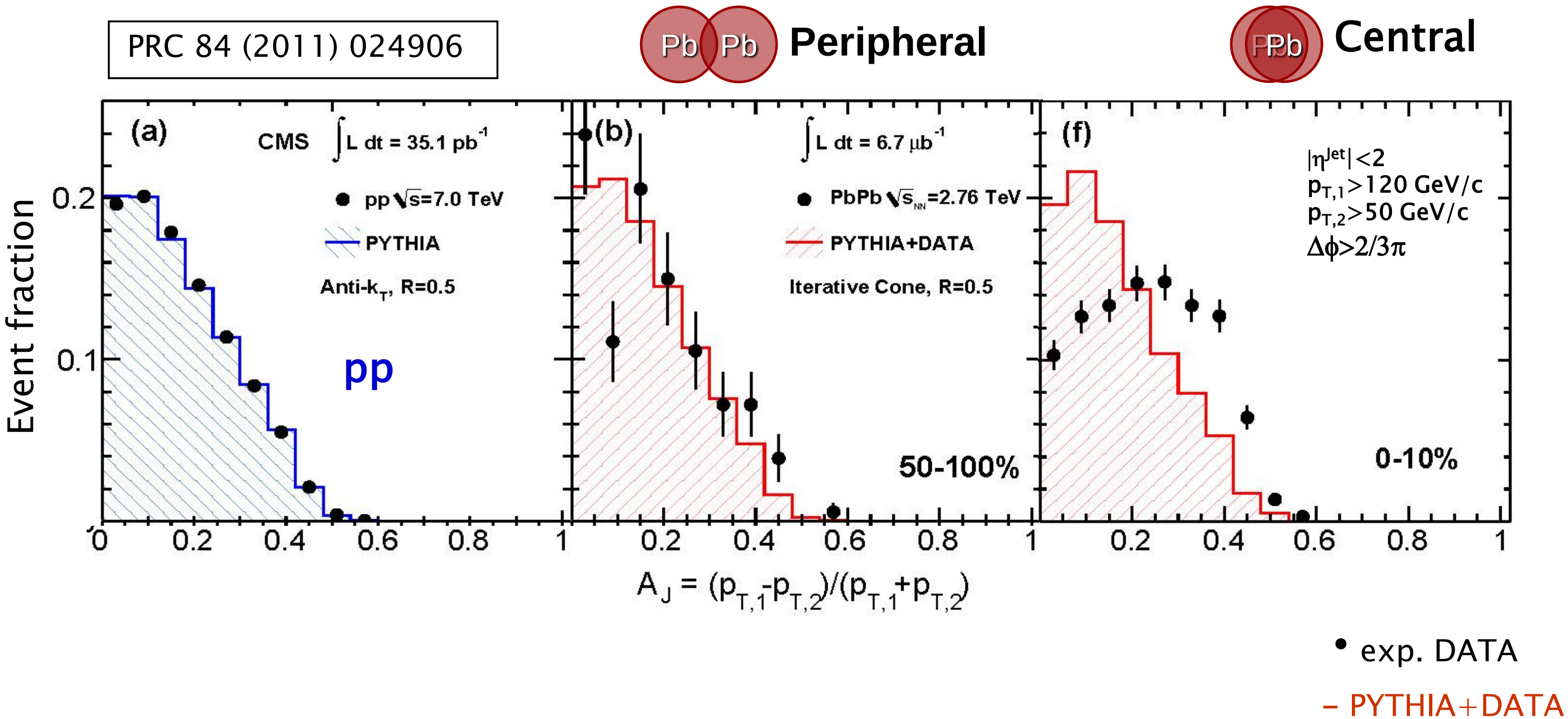
Dijet p_T imbalance quantified by asymmetry ratio:

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

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

Dijet asymmetry A_J

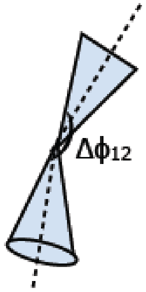
PRC 84 (2011) 024906



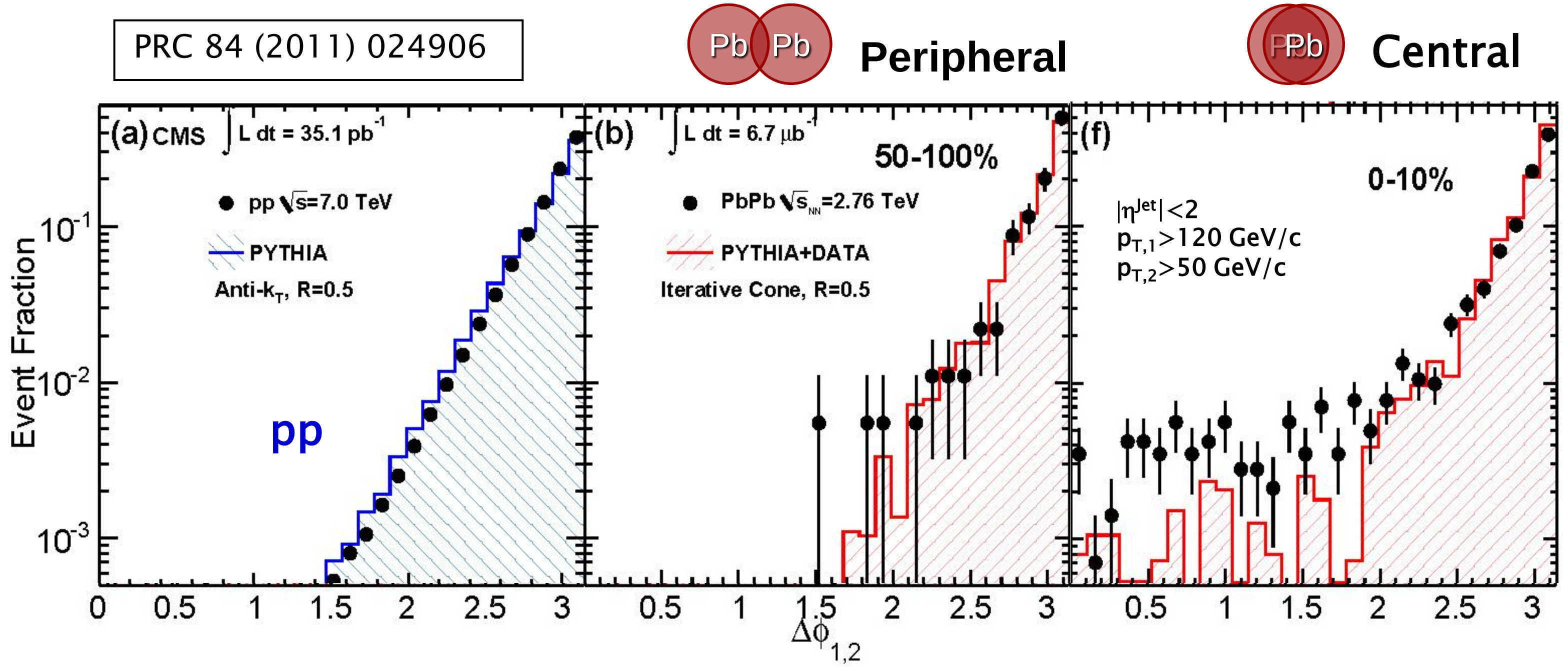
- Dijet p_T imbalance (A_J) increases with collision centrality
- Not reproduced by MC (PYTHIA+DATA)

Dijet azimuthal angle correlation

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



PRC 84 (2011) 024906



• exp. DATA

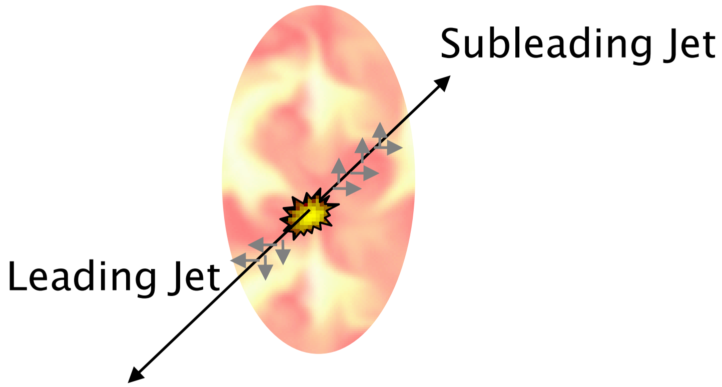
– PYTHIA+DATA

- Dijets 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

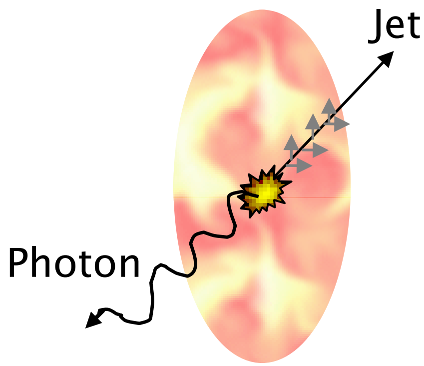
Photon–jet events in PbPb collisions

Jet–Jet



Leading jet could also lose some energy → analysis is biased

Photon–Jet

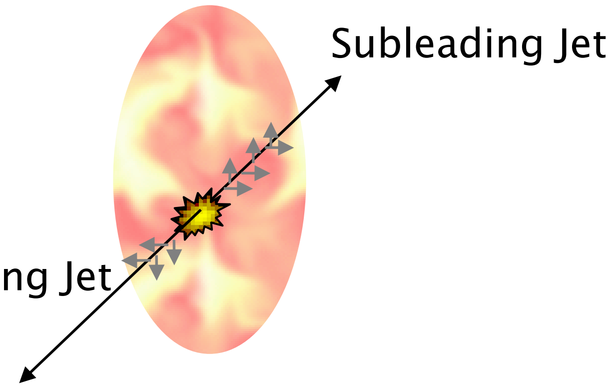


'Prompt' photon does not interact with the medium:

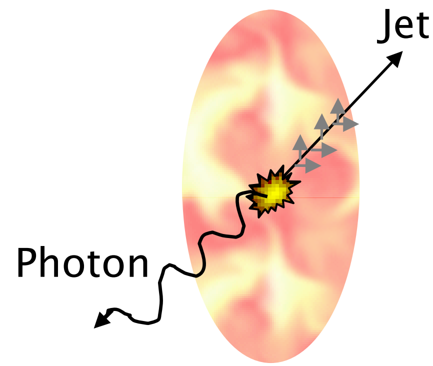
- **provides initial parton direction**
- **provides initial parton p_T**

Photon–jet events in PbPb collisions

Jet–Jet



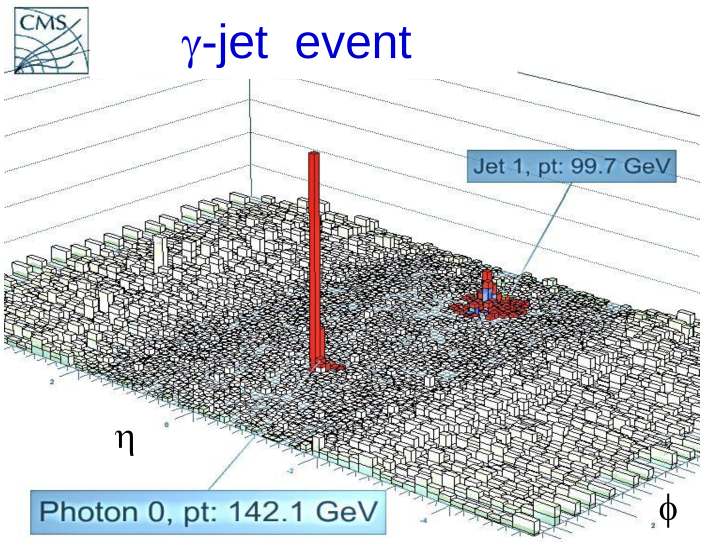
Photon–Jet



Leading jet could also lose some energy → analysis is biased

'Prompt' photon does not interact with the medium:

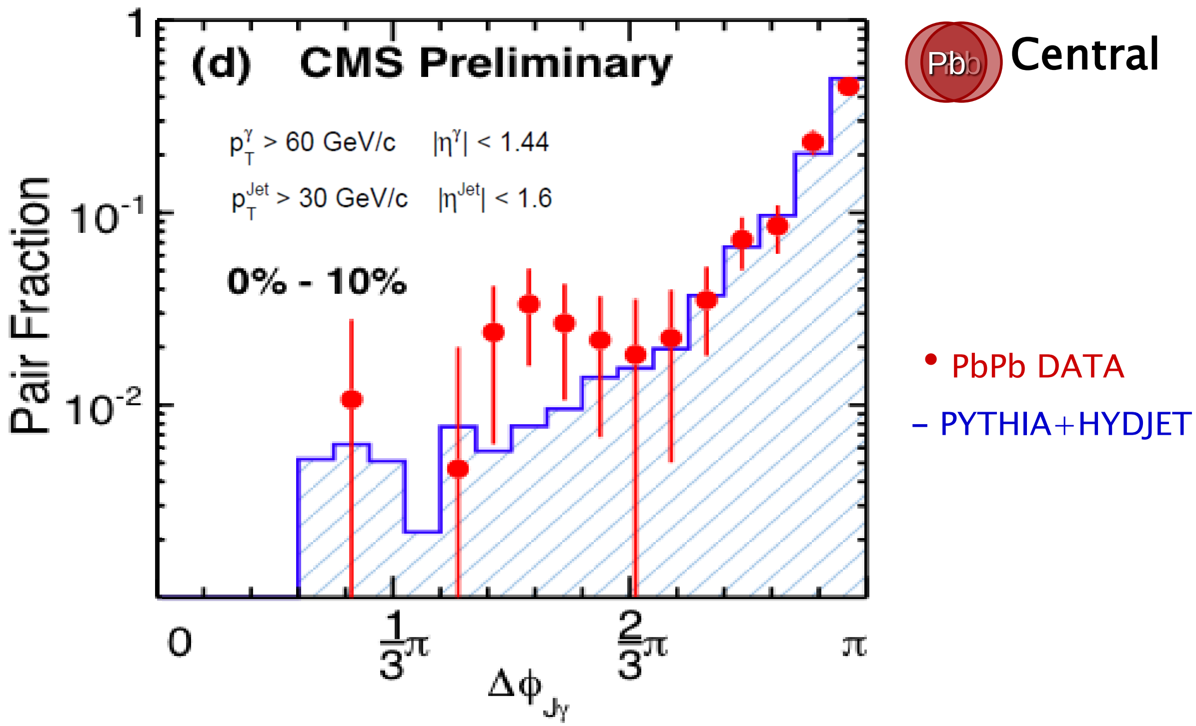
- **provides initial parton direction**
- **provides initial parton p_T**



⇨ Direct measurement of parton energy loss in the medium

Photon–jet angular correlation

PLB 718 (2013) 773

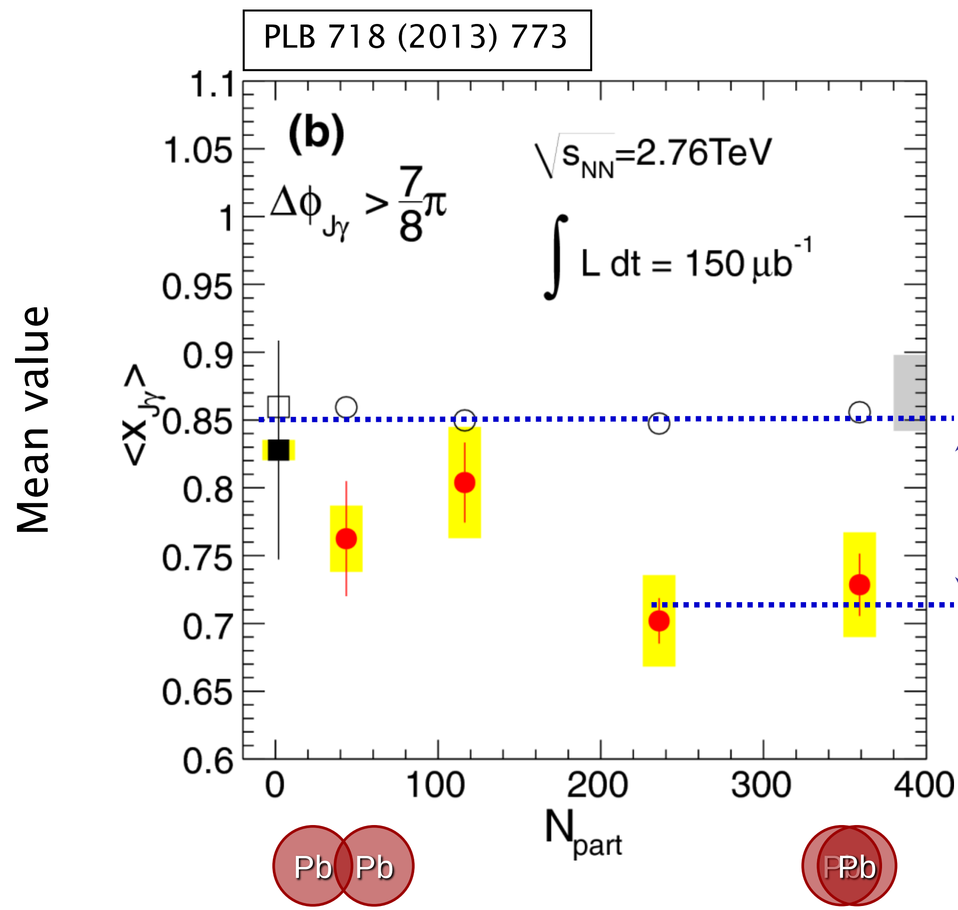


Photon and jet are 'back-to-back' ($\Delta\phi_{J\gamma}$ ~π), also for other centralities.

Photon–jet momentum balance

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

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



• PbPb DATA

o PYTHIA+HYDJET

■ pp DATA

Jets lose about 15% of their initial energy

p_T imbalance larger for more central collisions

Where does the missing p_T go?

Calculate "missing" $p_T^{||}$:

$$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

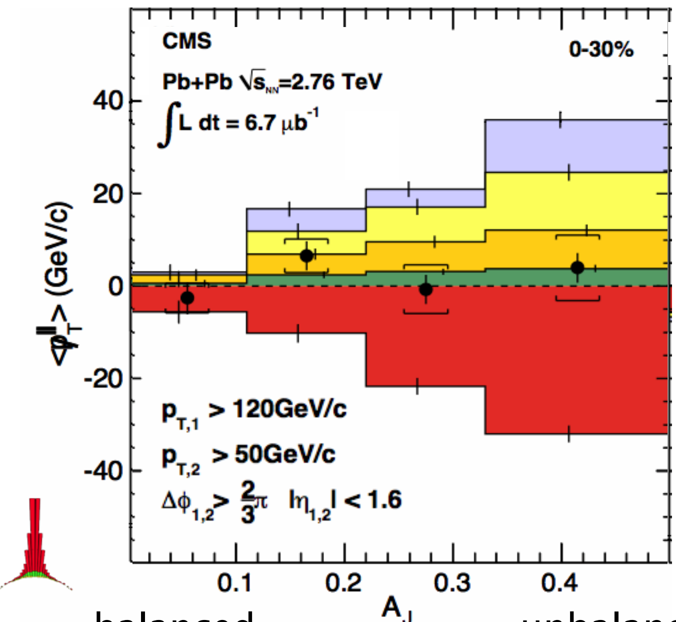
- Calculate, and then sum, projections of p_T of all reconstructed charged tracks in the event onto leading jet axis
- Average over events to obtain mean missing $\langle p_T^{||} \rangle$

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

PRC 84 (2011) 024906

Integrating over all tracks in the final state the momentum balance is restored (●), independently of the dijet asymmetry.

0–30% Central PbPb



excess away from leading jet

excess towards leading jet

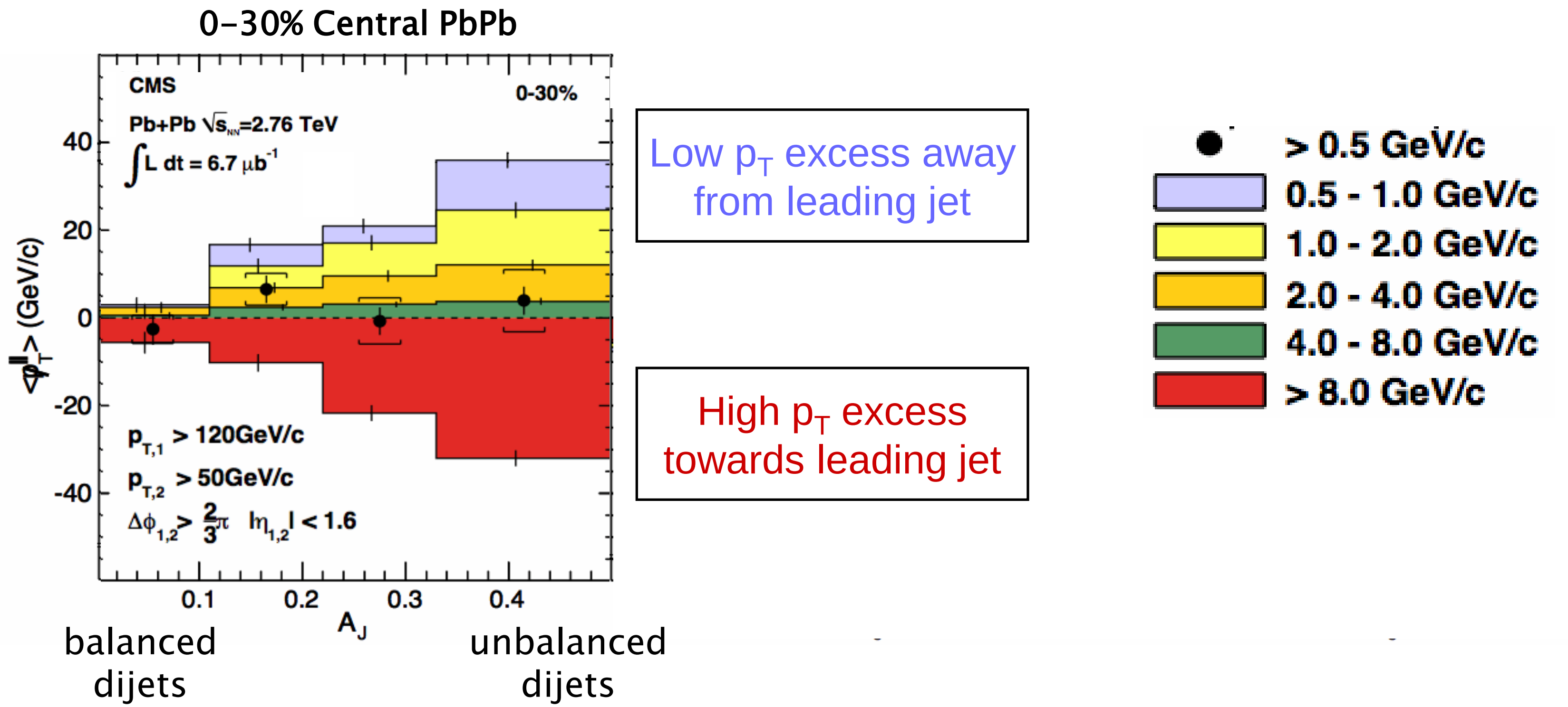
balanced dijets

unbalanced dijets

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

PRC 84 (2011) 024906

Contributions of different p_T ranges:

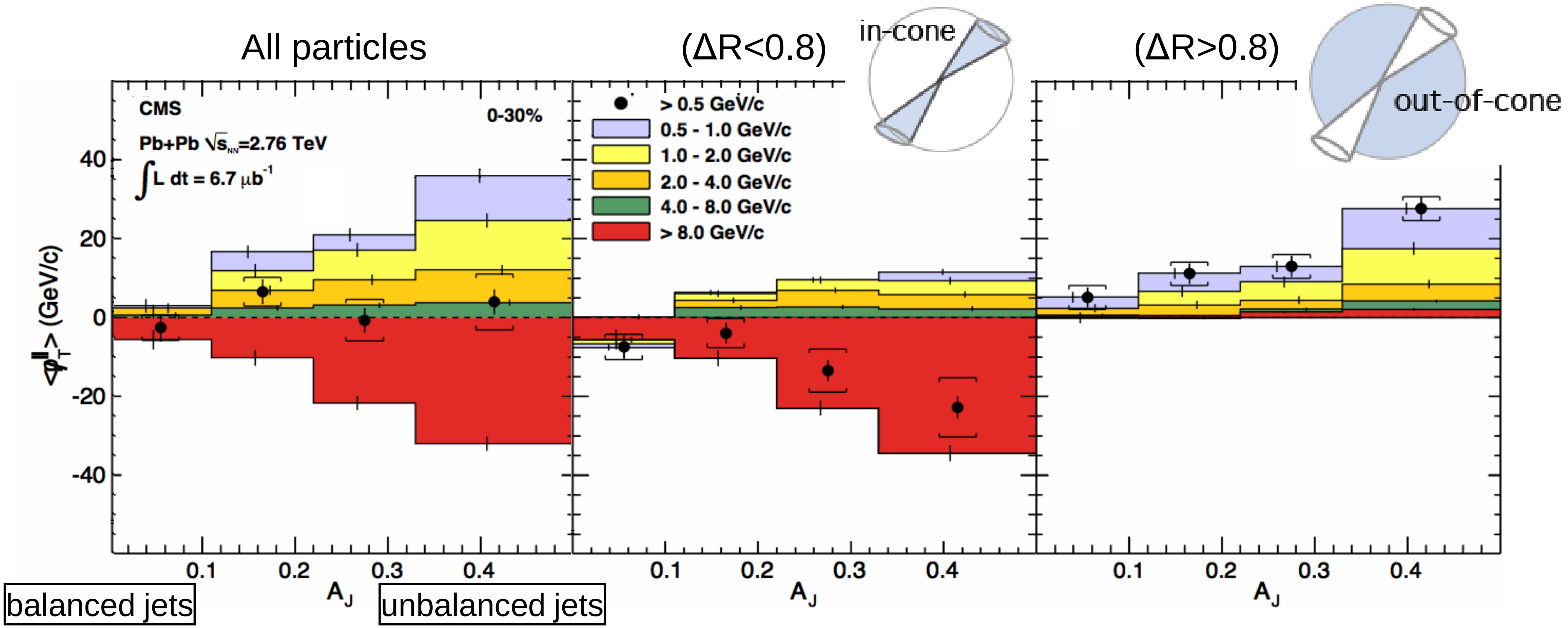


High p_T (>8GeV/c) excess towards leading jet balanced by low p_T tracks (<8GeV/c) away from leading jet.

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

PRC 84 (2011) 024906

Radial dependence of the momentum balance:

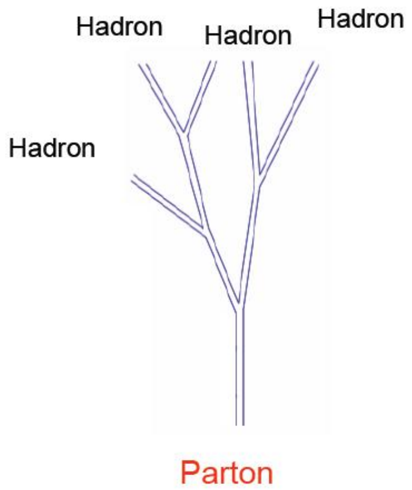


In-cone excess of high p_T tracks is balanced by out-of-cone low p_T tracks.

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

Is jet fragmentation affected?

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

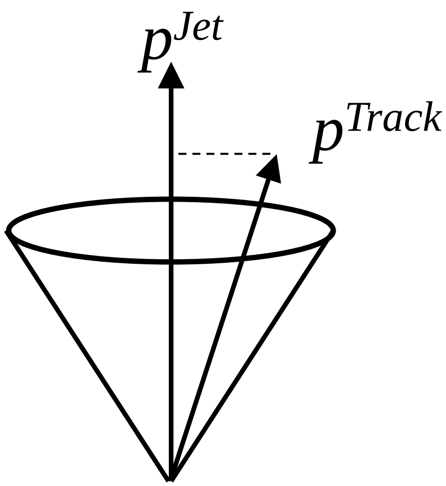


Fraction of parton's momentum carried by hadron:

$z = p_{Hadron} / p_{Parton}$

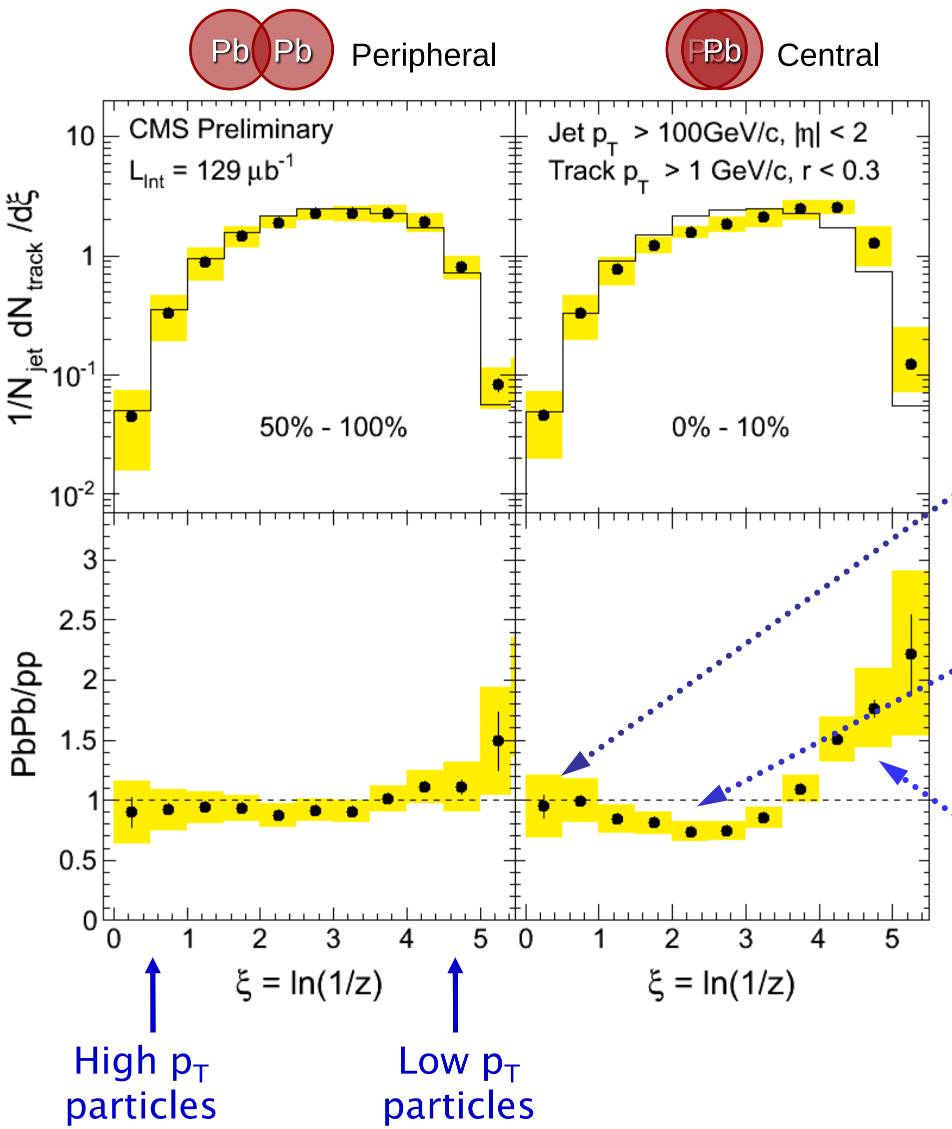
Jet Fragmentation Function: $$\frac{1}{N_{Jet}} \frac{dN_{Track}}{d\xi}$$

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



Jet fragmentation functions

PAS-HIN-12-013



Central PbPb:

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

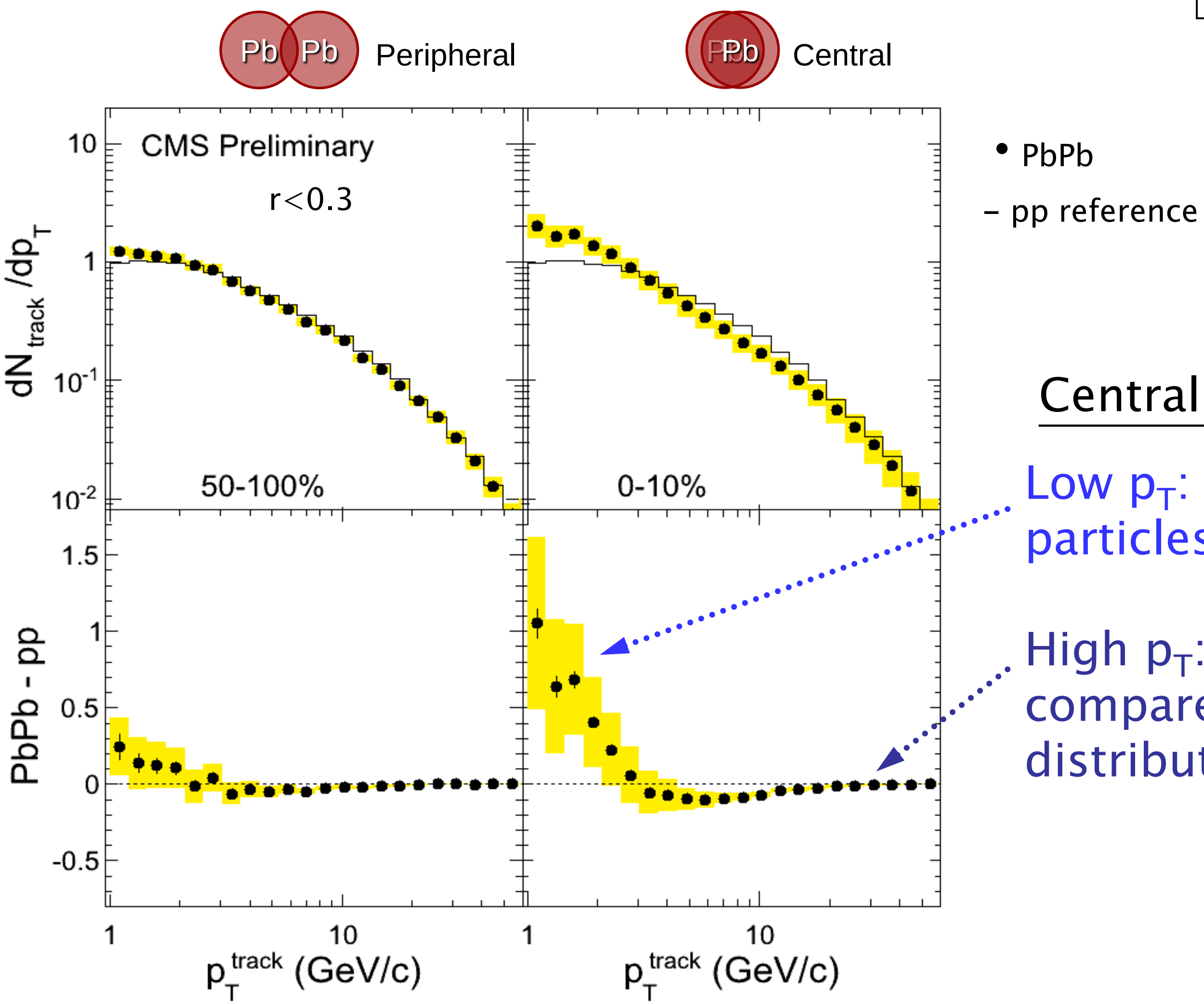
Suppression of intermediate p_T particles

Enhancement of low p_T particles

$$\xi = \ln\frac{1}{z}\ ;\ \ z = \frac{p_{\parallel}^{\mathrm{track}}}{p^{\mathrm{jet}}}$$

Track p_T distributions in jets

PAS-HIN-12-013



Central PbPb:

Low p_T: excess of charged particles (quenched jets)

High p_T: no change compared to track distribution in pp jets

Quarkonium suppression

signature of QGP – **Matsui & Satz (1986)**

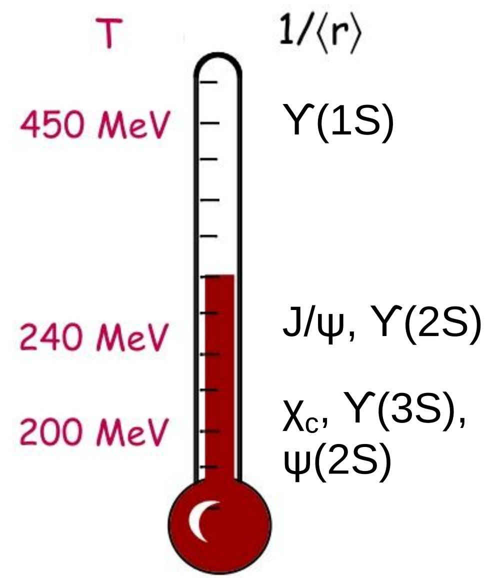
Due to colour screening, quarkonia should 'melt' above a given temperature of the medium – depending on their binding energy.

Binding energies and radii for various quarkonium states:

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

More bound state → smaller size

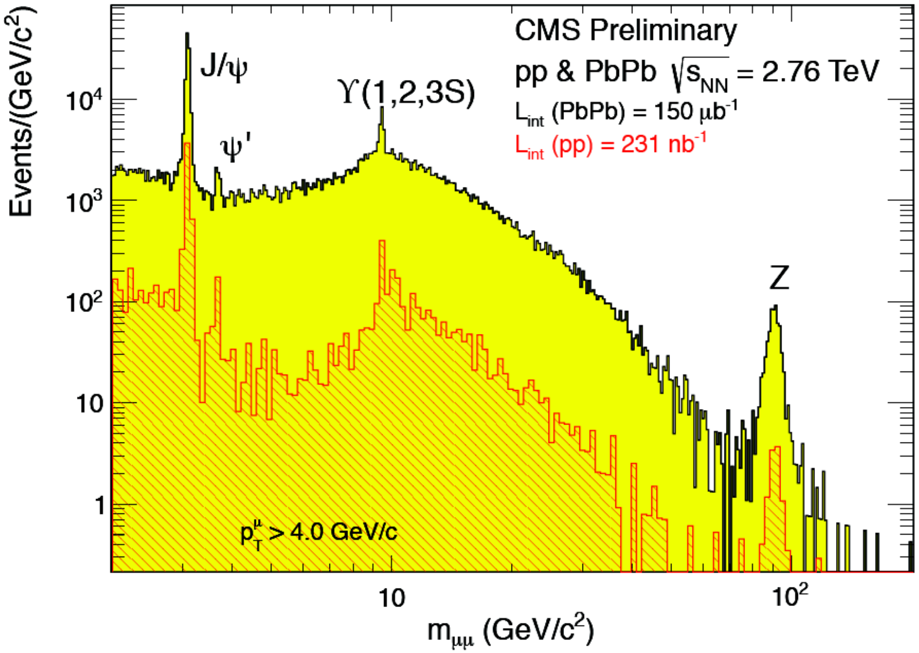
state	Υ(1S)	Υ(2S)	Υ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_o(fm)	0.28	0.56	0.78



Mocsy, EPJC61 (2009) 705

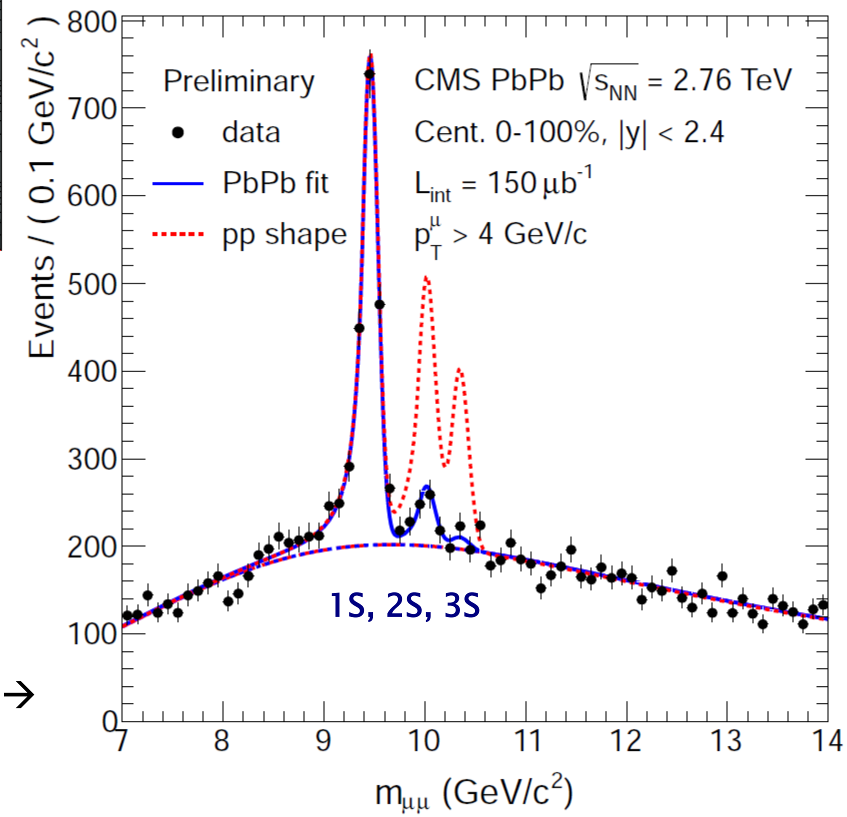
Observation of the melting (yield suppression) of quarkonium states serves as a thermometer of the medium.

Dimuon spectrum



pp & PbPb data

ϒ family in detail

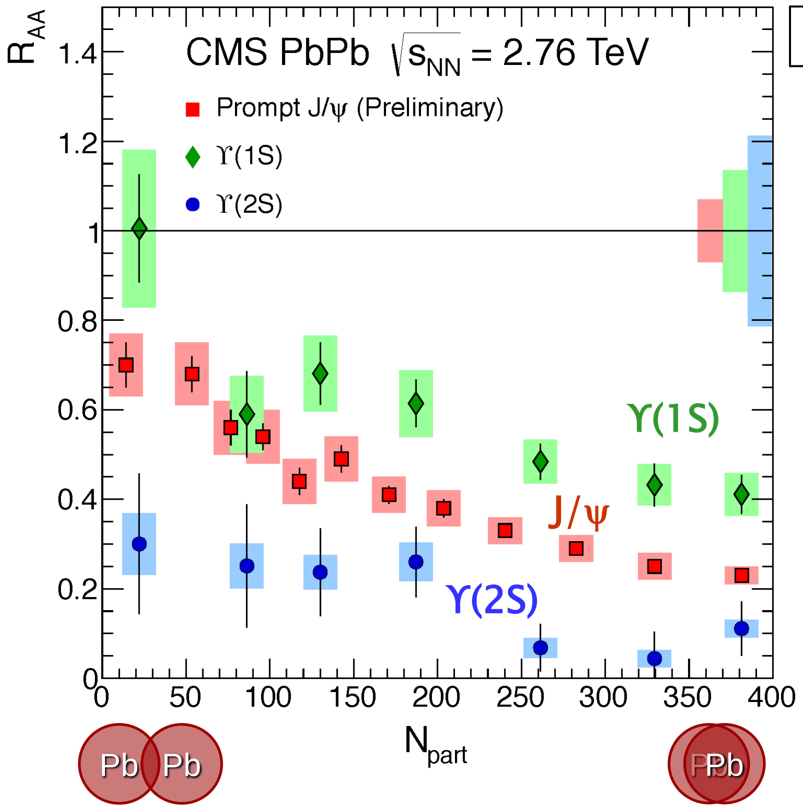


In PbPb: relative suppression of ϒ(2S) and ϒ(3S) excited states wrt to the ground state ϒ(1S).

Centrality integrated →

Quarkonium suppression

ϒ states and J/ψ dependence on centrality:



PRL 109 (2012) 222301

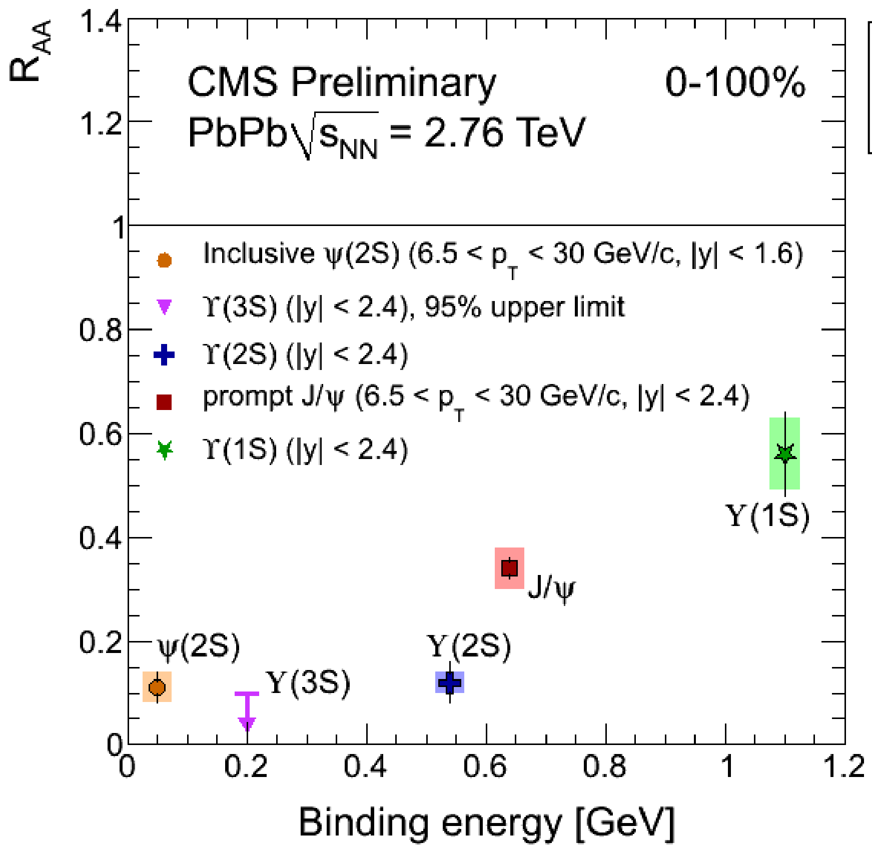
$$R_{AA} = \frac{\text{(yield in AA)}}{N_{COLL}(AA) \times \text{(yield in pp)}}$$

- Suppression with centrality observed
- In most central collisions, suppression pattern as expected from sequential melting

Quarkonia melting map

Centrality-integrated R_{AA} vs. binding energy:

Note: $6.5<p_T<30$ GeV for J/ψ and ψ(2S)



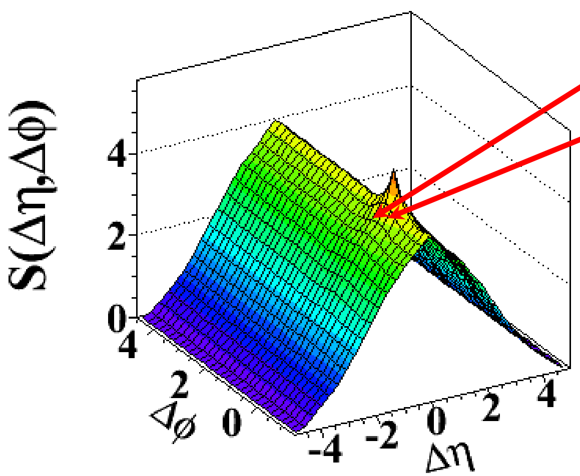
PRL 109 (2012) 222301
PAS-HIN-12-007
PAS-HIN-12-014

Looser bound states are more suppressed than the tighter bound ones.

Two–particle correlations

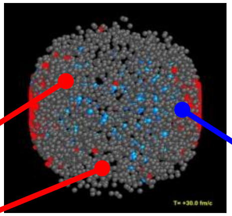
Signal pair distribution:

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

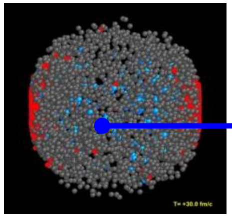


same event pairs

Event 1

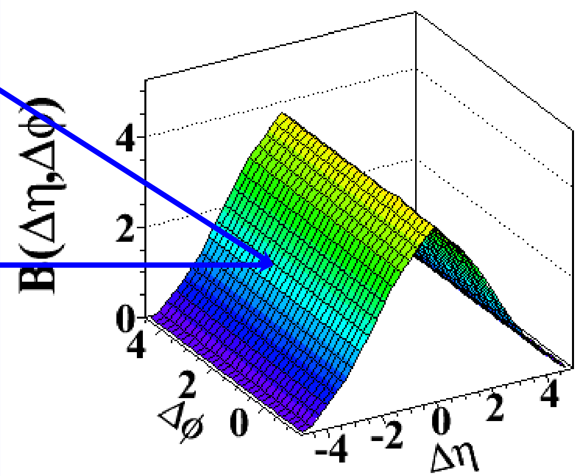


Event 2



Background pair distribution:

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



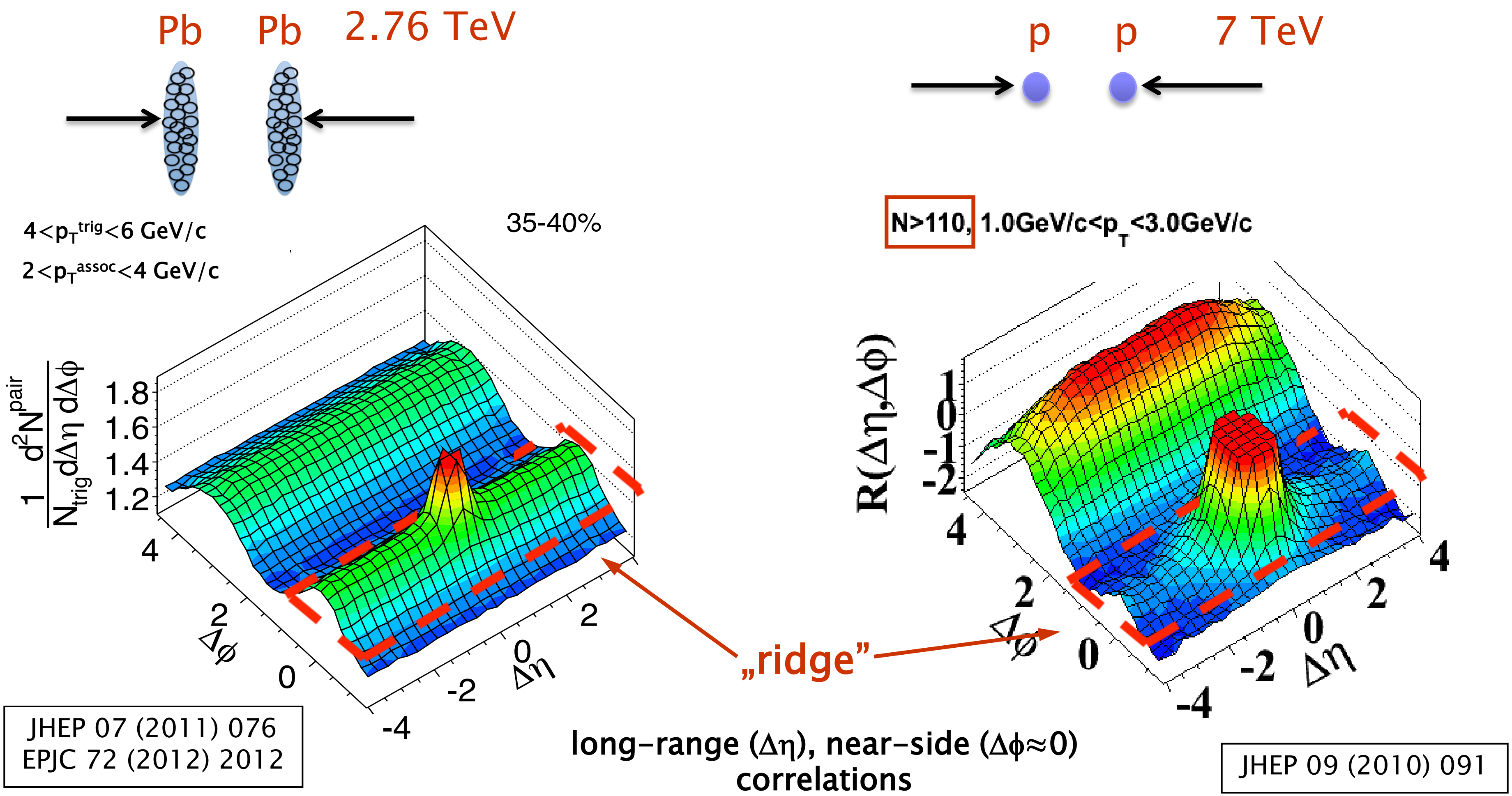
mixed event pairs

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

Associated hadron yield per trigger:

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

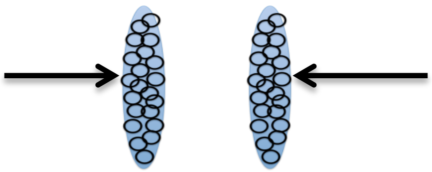
Two-particle correlations



Unexpected „ridge” in high-multiplicity pp collisions

Two-particle correlations

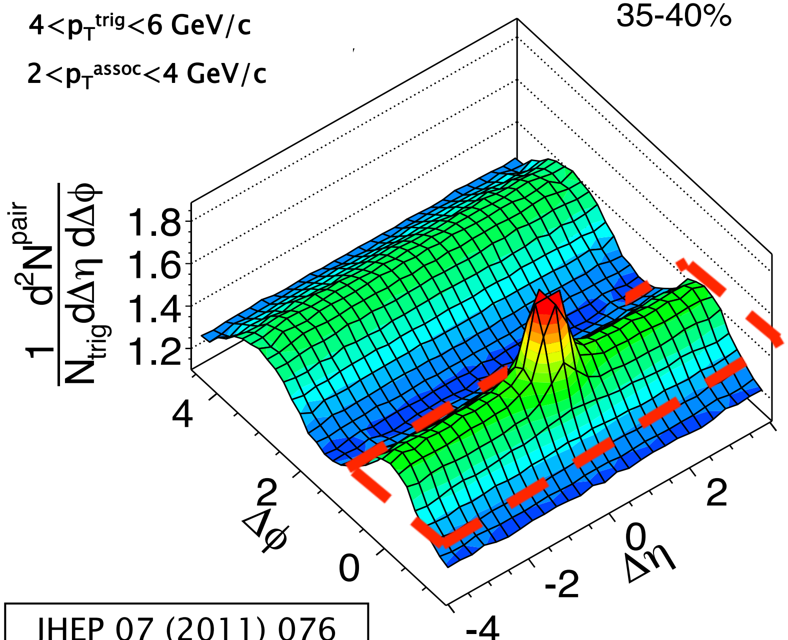
Pb Pb 2.76 TeV



p p 7 TeV

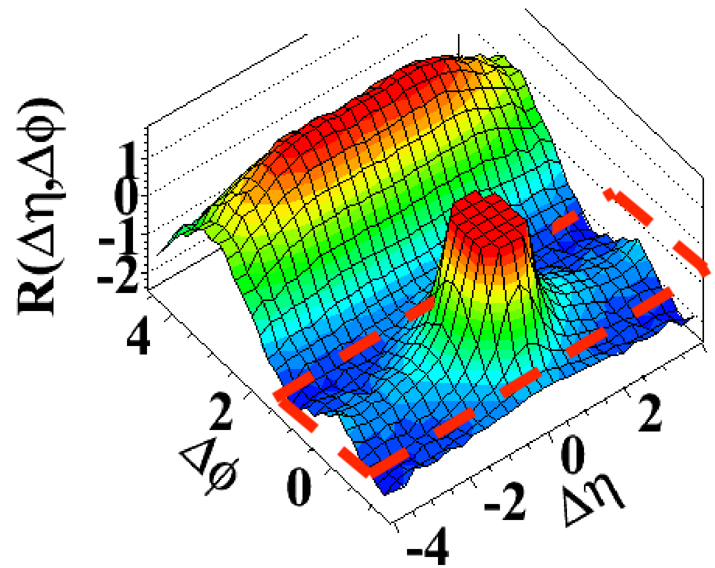
$4<p_T^{trig}<6$ GeV/c

$2<p_T^{assoc}<4$ GeV/c



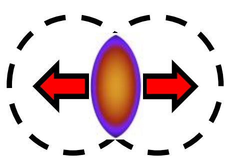
JHEP 07 (2011) 076
EPJC 72 (2012) 2012

N>110, 1.0GeV/c<p_T<3.0GeV/c



JHEP 09 (2010) 091

Initial-state geometry
+
collective expansion



Physical origin unclear:
- Collective effect in pp ?
- Initial-state gluon saturation (CGC) ?
- ...

pPb@5TeV: Multiplicity Evolution

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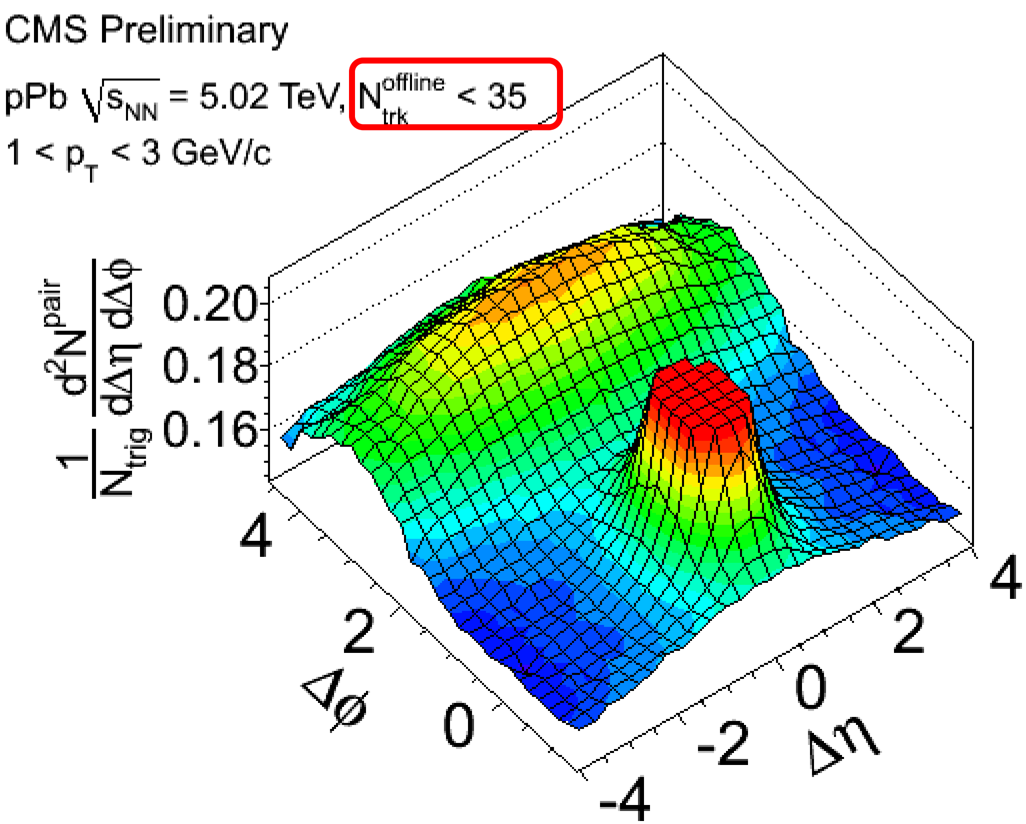
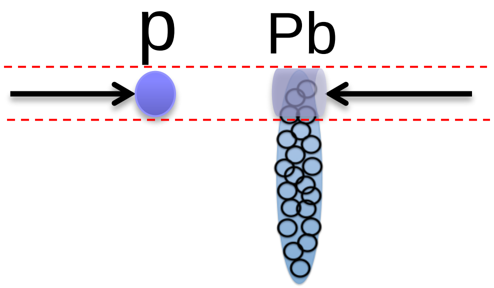
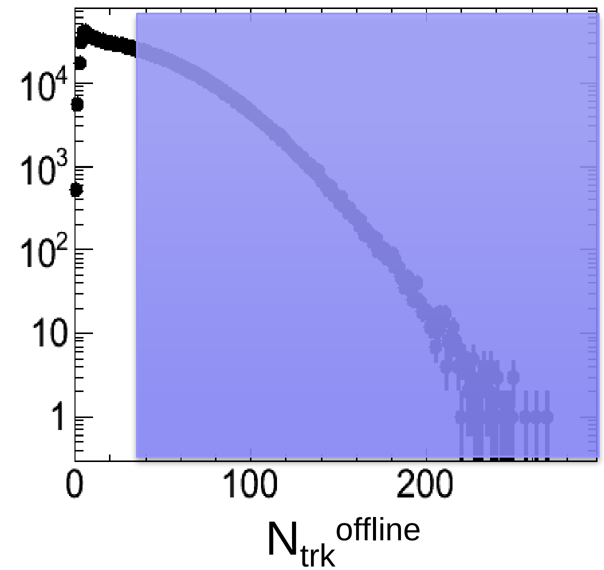
Low multiplicity





Divide into 4 multiplicity bins:



pPb@5TeV: Multiplicity Evolution

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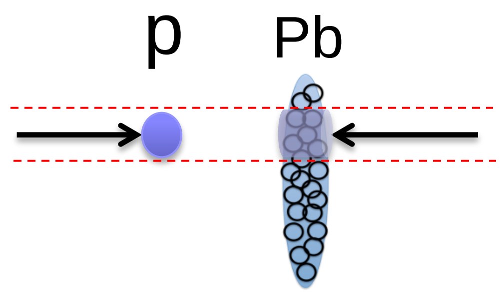
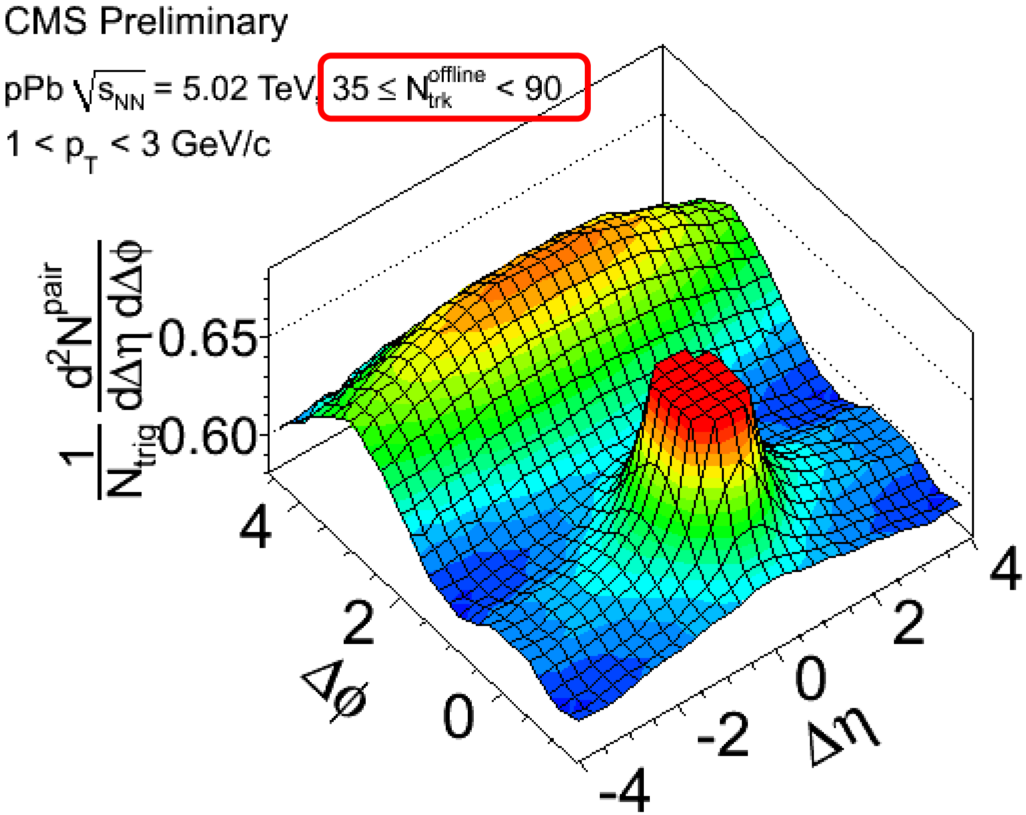
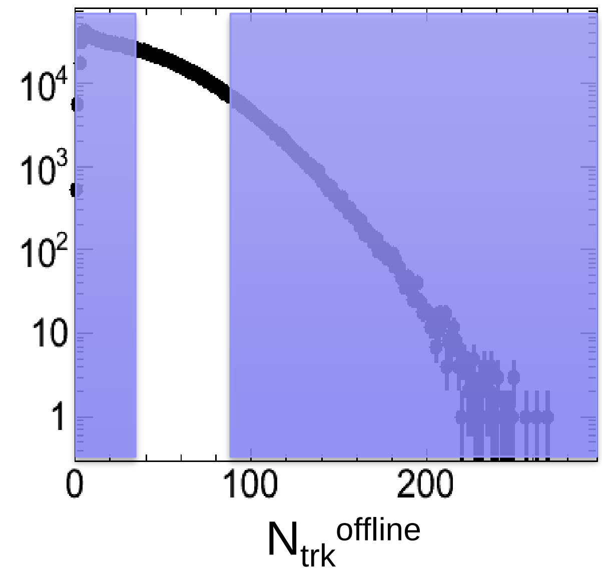
Increasing multiplicity





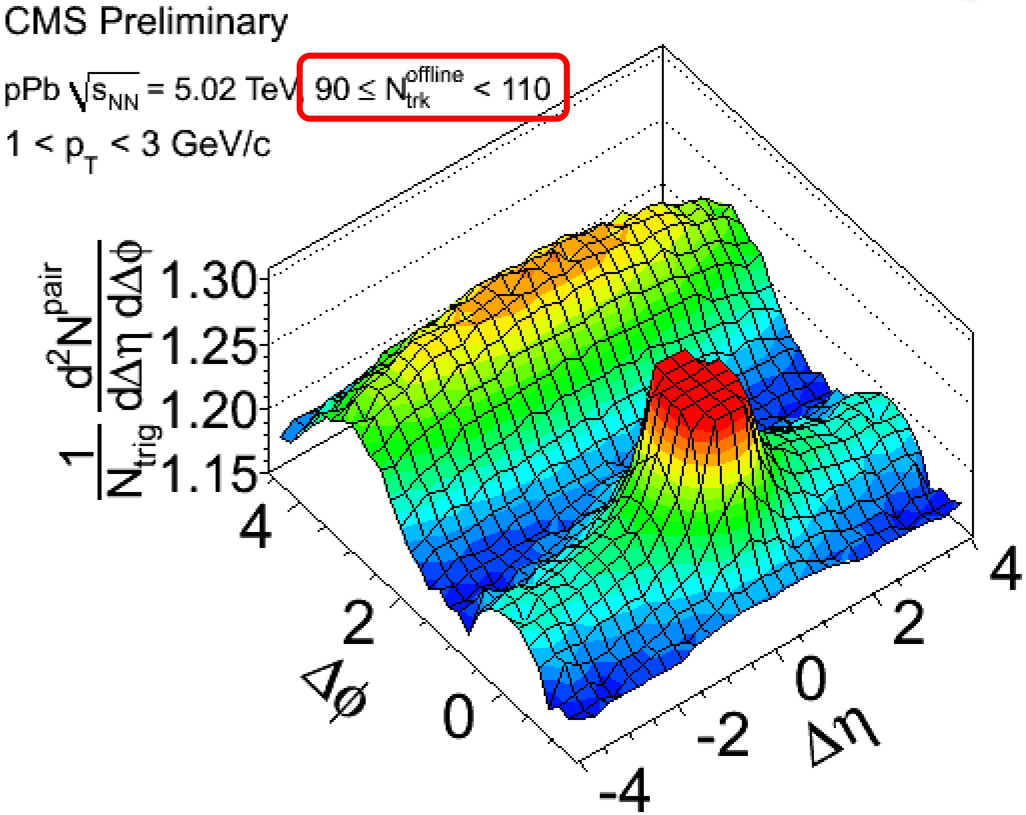
Divide into 4 multiplicity bins:

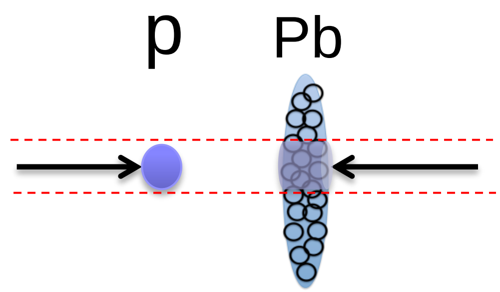


pPb@5TeV: Multiplicity Evolution

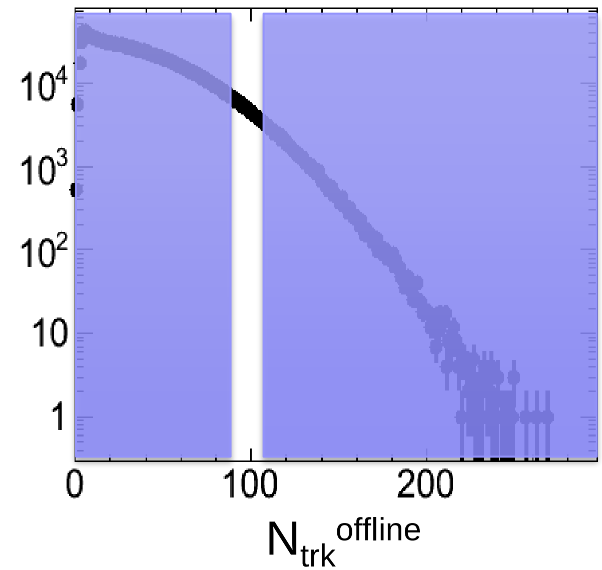
PLB 718 (2013) 795

Increasing multiplicity



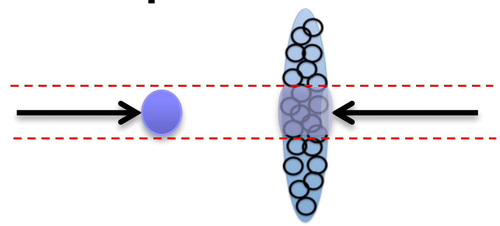


Divide into 4 multiplicity bins:

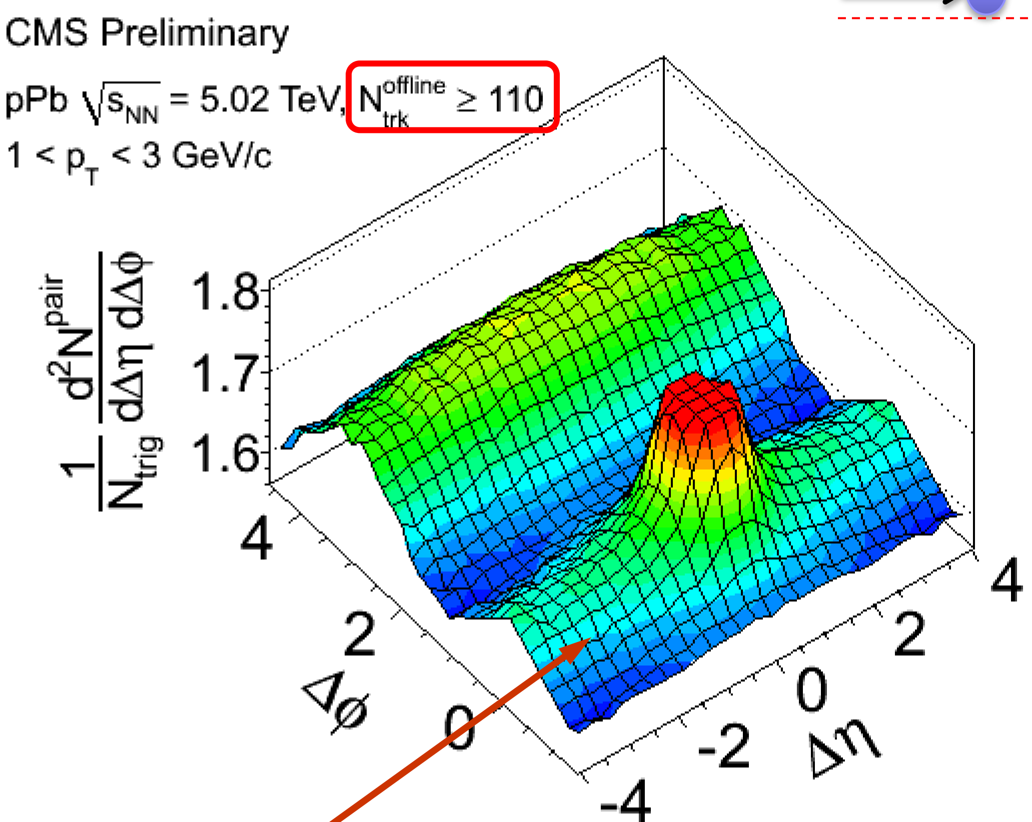


pPb@5TeV: Multiplicity Evolution

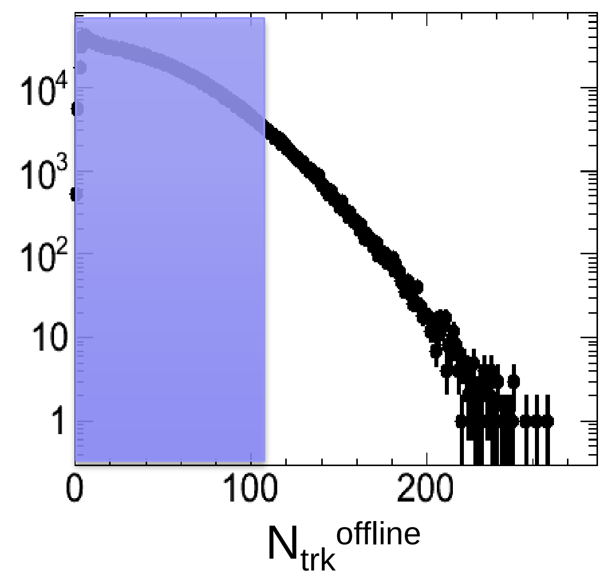
PLB 718 (2013) 795



Increasing multiplicity



Divide into 4 multiplicity bins:



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

Δϕ−projected correlation function

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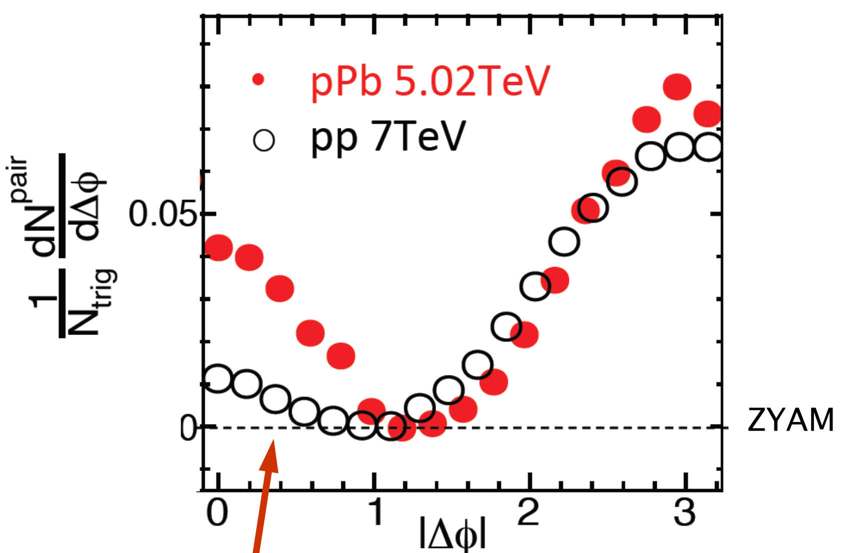
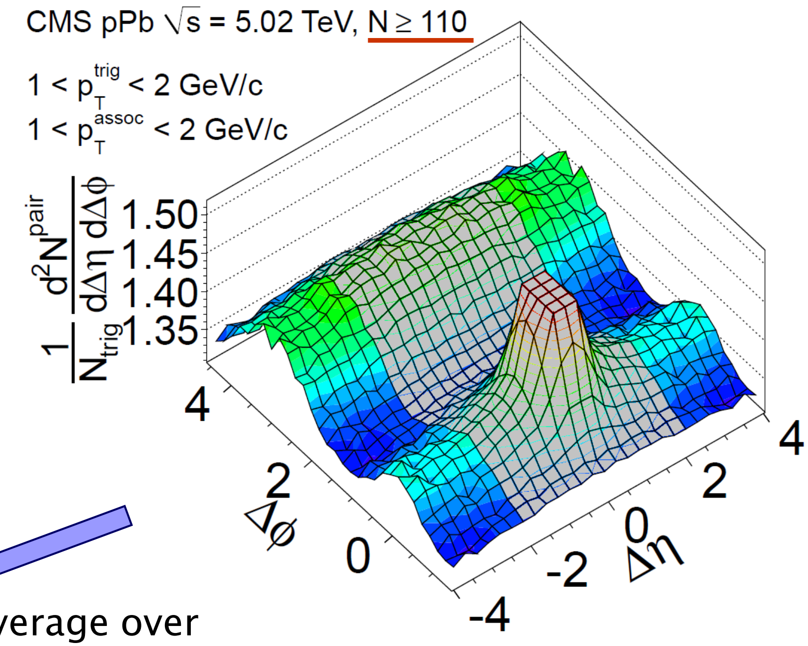
Comparison of pPb and pp:





Average over ridge region (2<|Δη|<4)

Magnitude of the ridge in pPb much larger than in pp

Integrated associated yield

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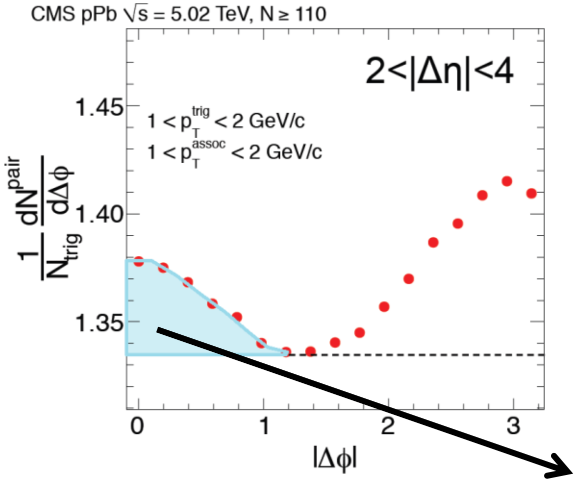
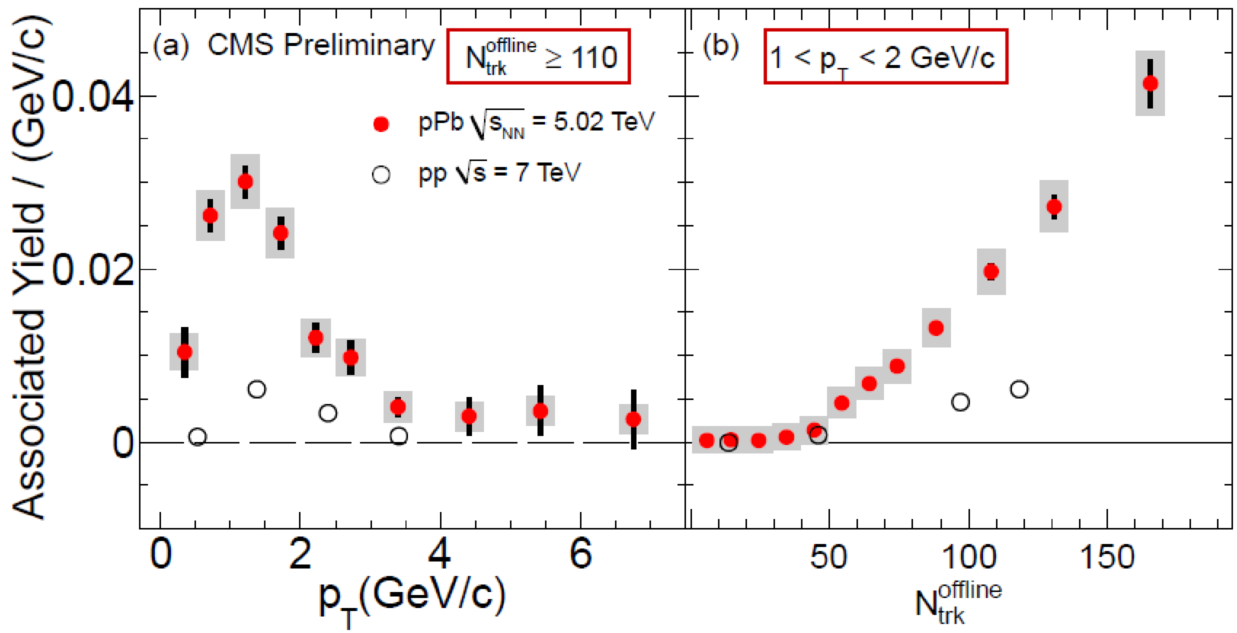


p_T and multiplicity dependence:



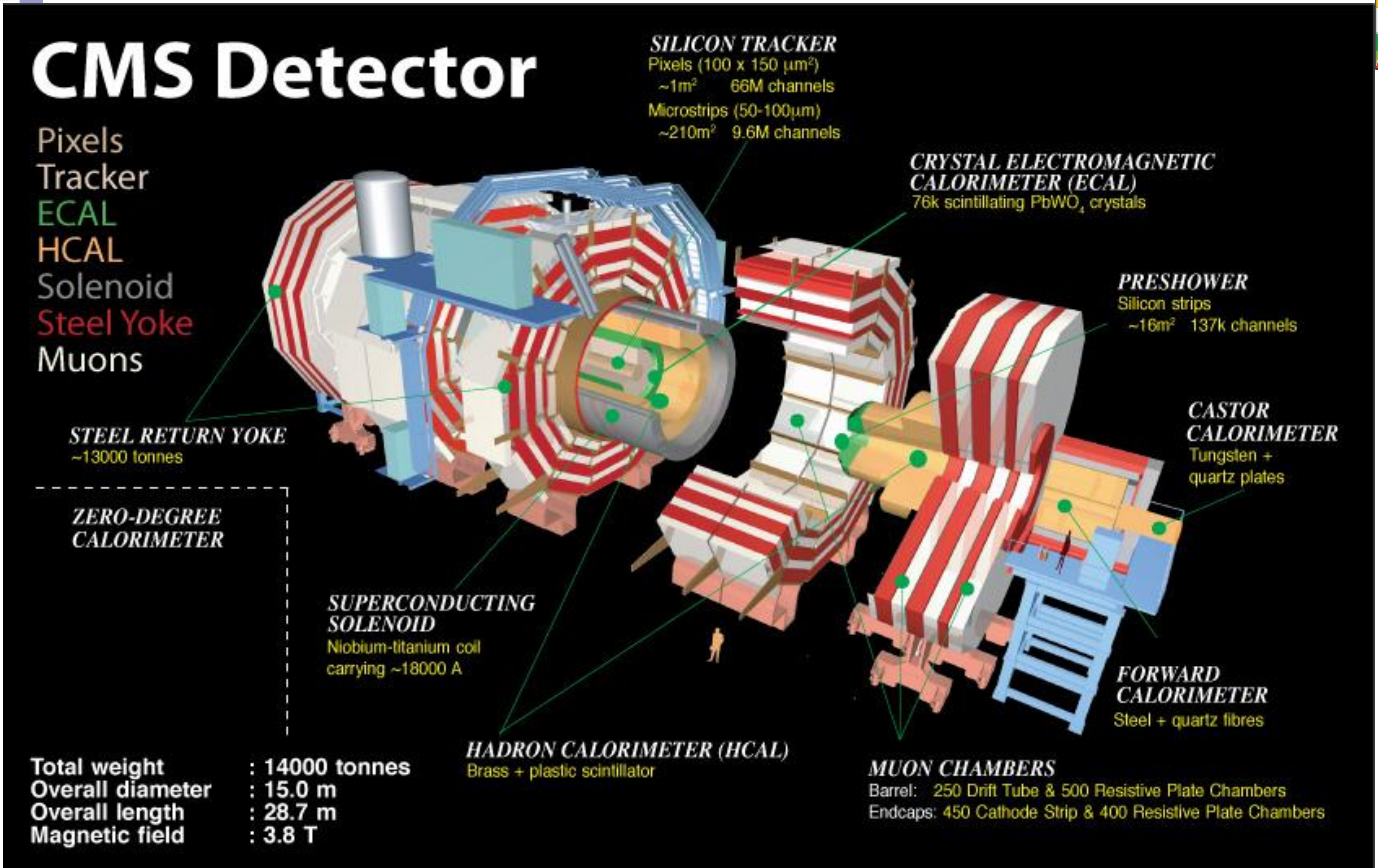
Similar behaviour as observed in pp – **but trends much stronger for pPb**

Summary

- CMS has a broad heavy-ion program
- In 2010 and 2011 a significant amount of PbPb data collected
- Our measurements indicate that the medium created:
  - Does not quench control probes (γ, W, Z)
  - Strongly quenches partons, including b-quarks
  - Causes dijet and photon-jet p_T imbalance, but does not modify their angular correlation
  - Modifies fragmentation functions of jets (enhancement at low p_T)
  - Suppresses quarkonia, including excited states of the Υ
- pPb collisions
  - First result on ridge – strong effect observed
  - Looking forward to 2013 data …

More results:
http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

Backup slides



Silicon Tracker:
Pixels (100x150 μm^2)
Microstrips (50-100 μm)
Mom. resol. ~1% at p_T=100GeV/c

ECAL: Scintillating $PbWO_4$ crystals
Granularity:
$\Delta\eta \times \Delta\phi$ =0.0174x0.0174 and 0.05x0.05
Energy resol. ~3%/√E(GeV)

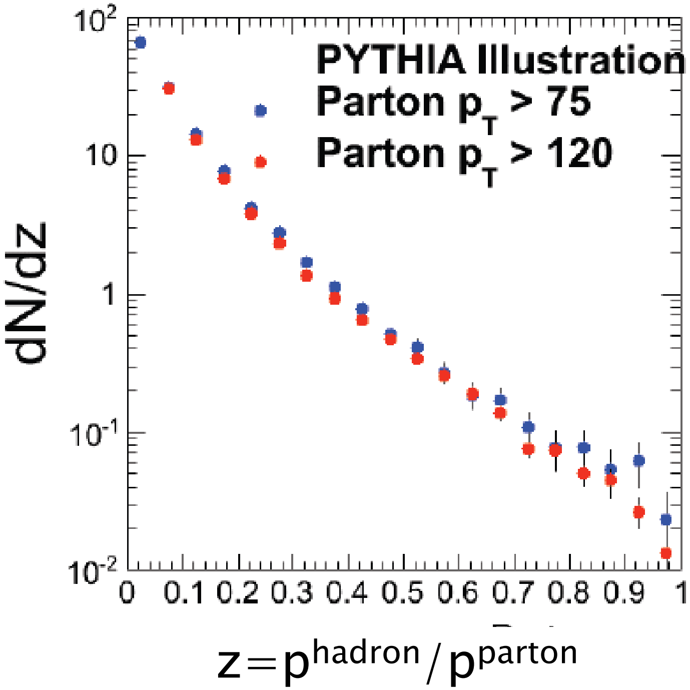
HCAL: Plastic scintillator/brass sandwich
Granularity:
$\Delta\eta \times \Delta\phi$ =0.087x0.087
Energy resol. ~100%/√E(GeV)

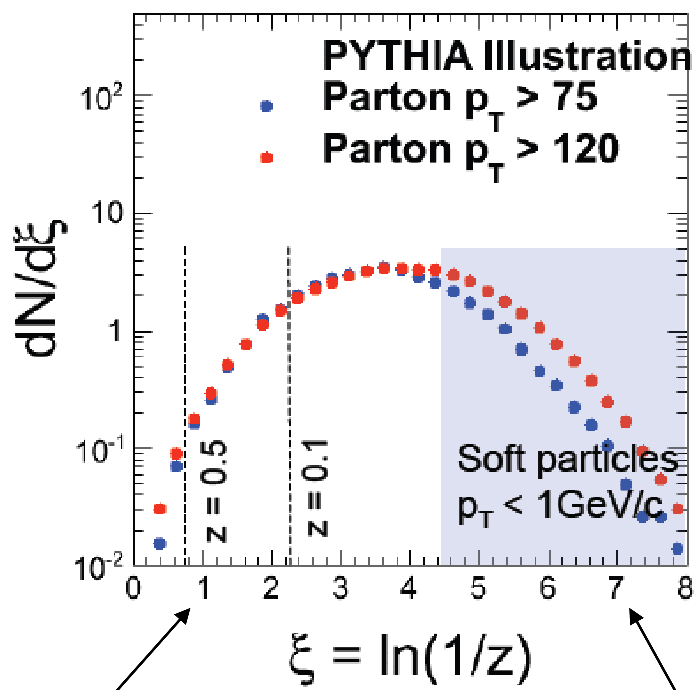
Parton Fragmentation

Momentum Fraction

$z = p^{hadron} / p^{parton}$

$\xi = \ln(1/z)$ Representation:



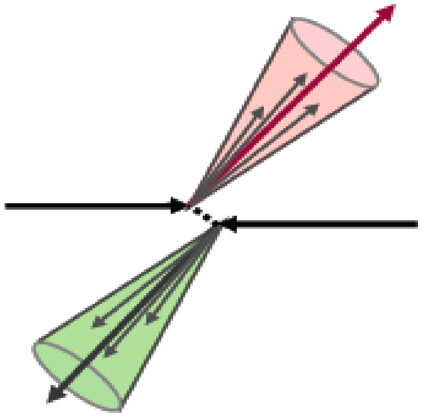


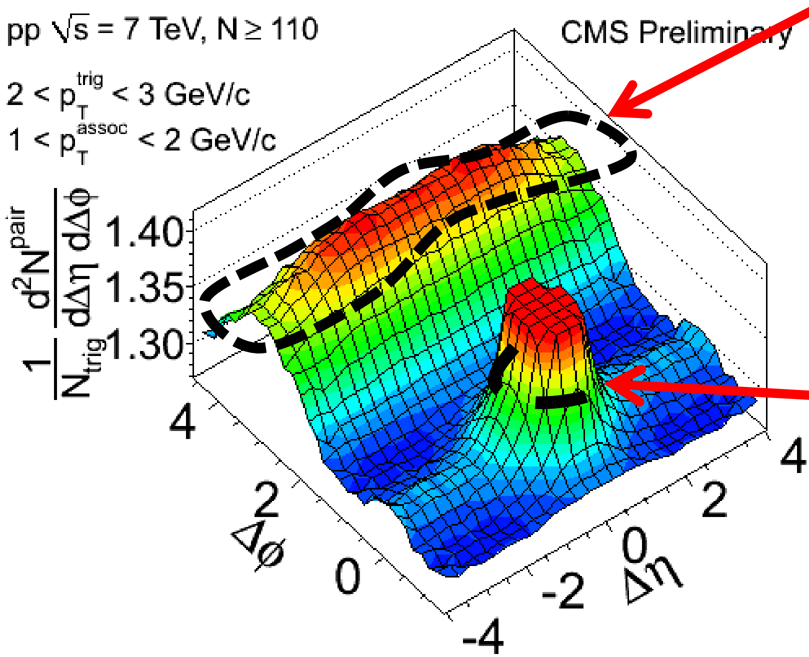
particles carrying large fraction of parton momentum

particles carrying small fraction of parton momentum

Understanding the correlation function

“Away-side” ($\Delta\phi \sim \pi$)
back-to-back jet correlations



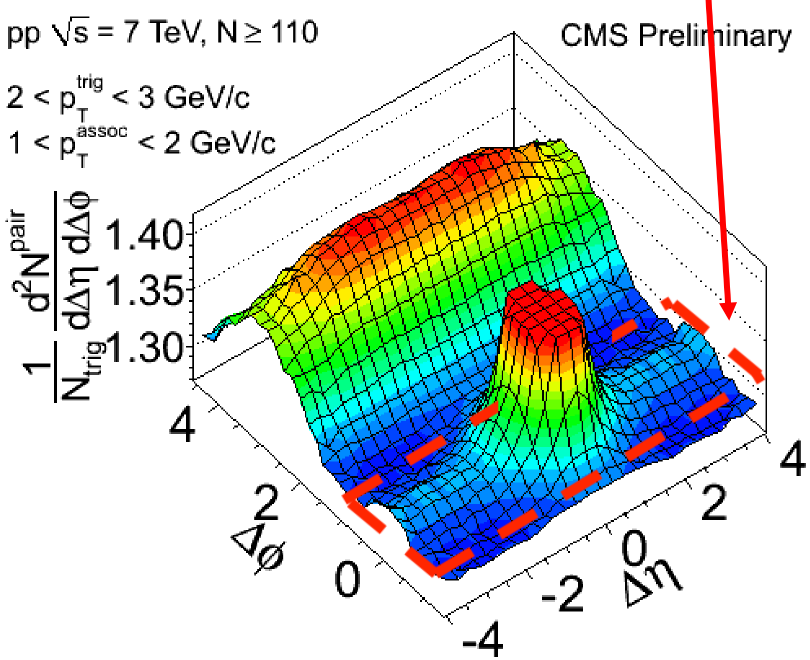


“Near-side” ($\Delta\phi$, $\Delta\eta \sim 0$)
correlations from single jets

Understanding the correlation function

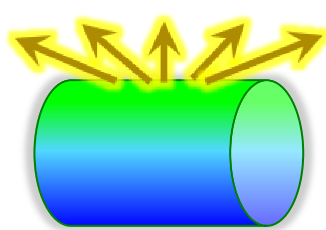
Striking **“ridge-like”** structure extending over $\Delta\eta$

at $\Delta\phi \approx 0$



In high-multiplicity , $N \geq 110$ where:

$N \equiv$ number of offline tracks with $p_T > 0.4$ GeV/c



Understanding the correlation function