What Have Hard Probes Taught us about the QGP ?

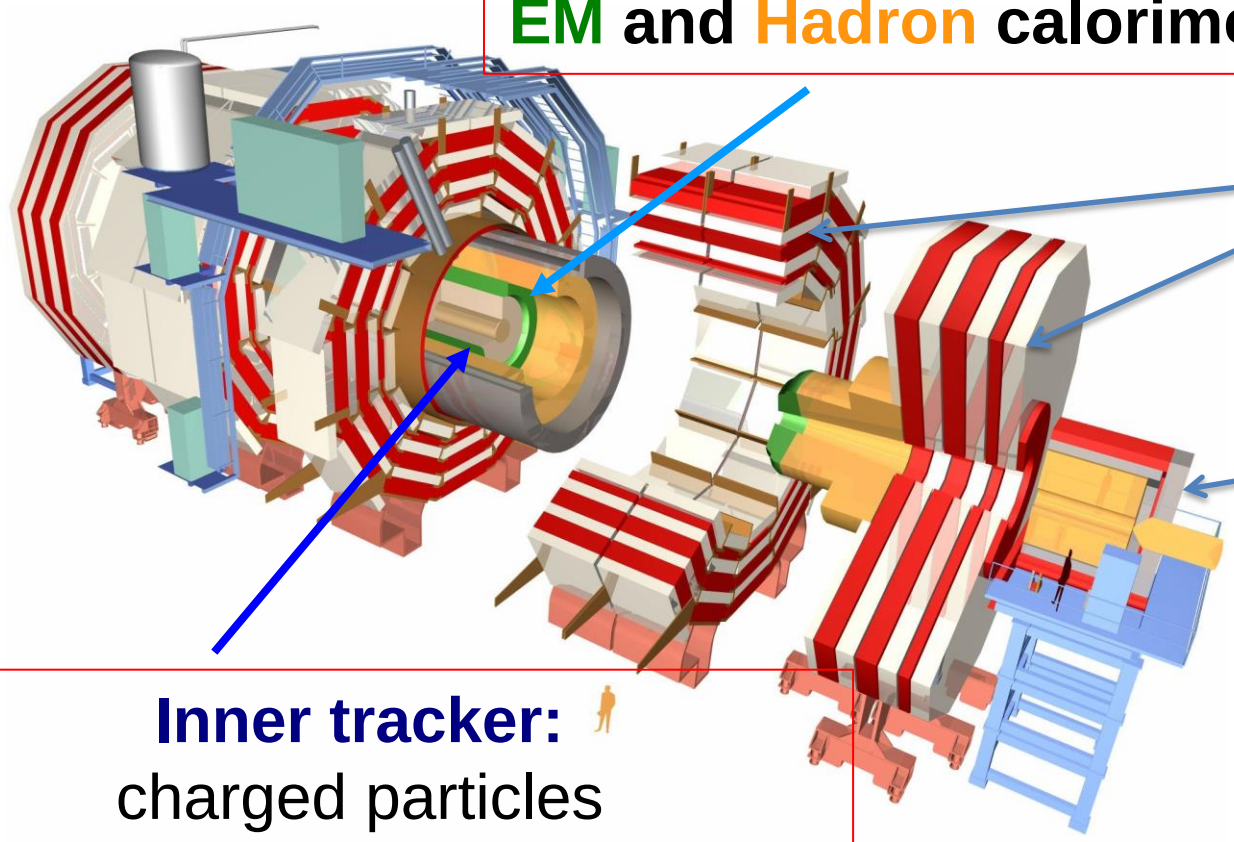
Julia Velkovska

for the CMS Collaboration

Hard Probes, Stellenbosch, South Africa

Nov 4th, 2013

Hard probes in CMS



EM and Hadron calorimeters: jets, γ, Z

Muon system
W,Z, heavy flavor
quarkonia

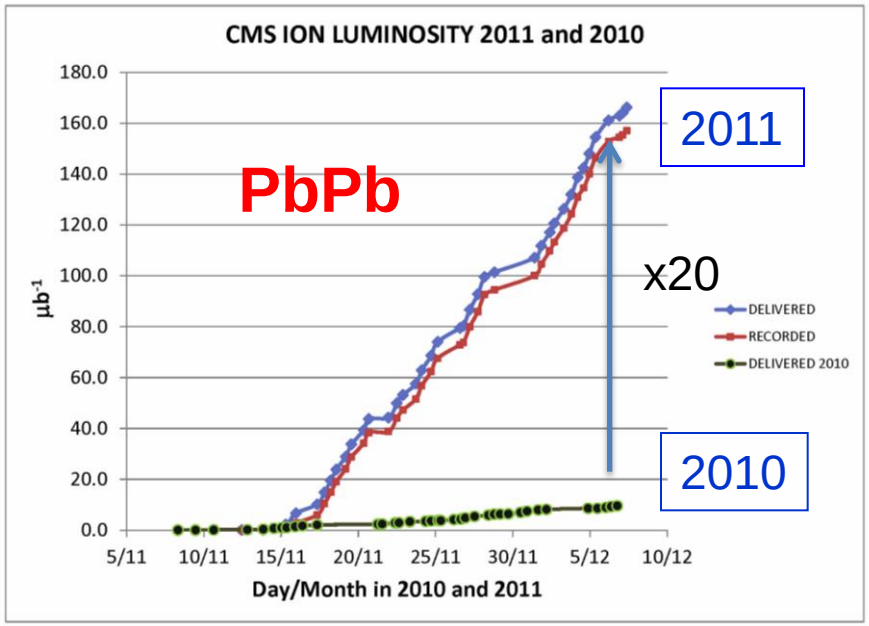
HF
event selection
centrality
event plane

Inner tracker:
charged particles
PF jets, displaced vtx, γ isolation, μ reco

- **Excellent resolution of tracking, calorimetry, muon systems**
- **Trigger selectivity**

Over a large range in rapidity and full azimuth
Full palette of **hard probes** along with access to the bulk medium

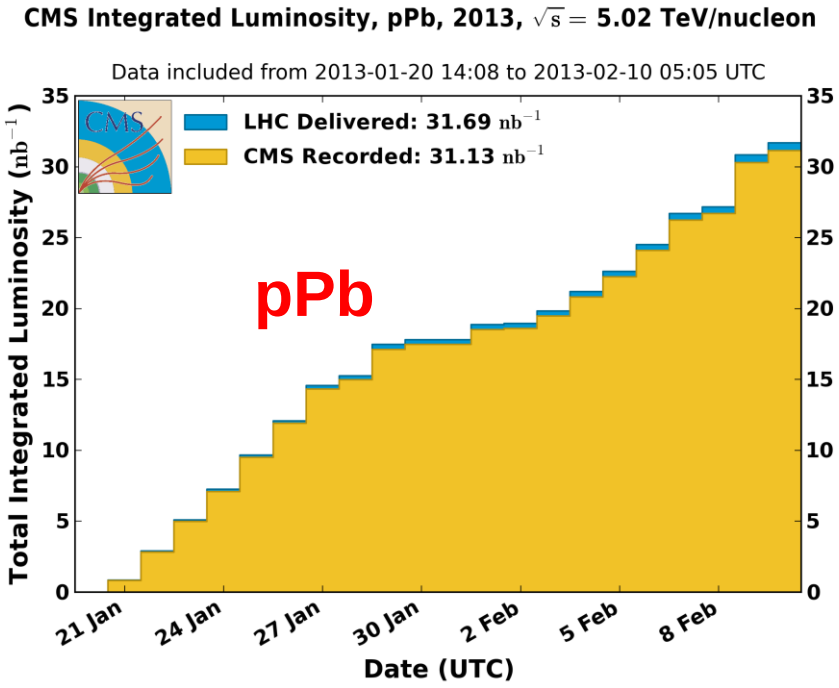
Run 1: operations



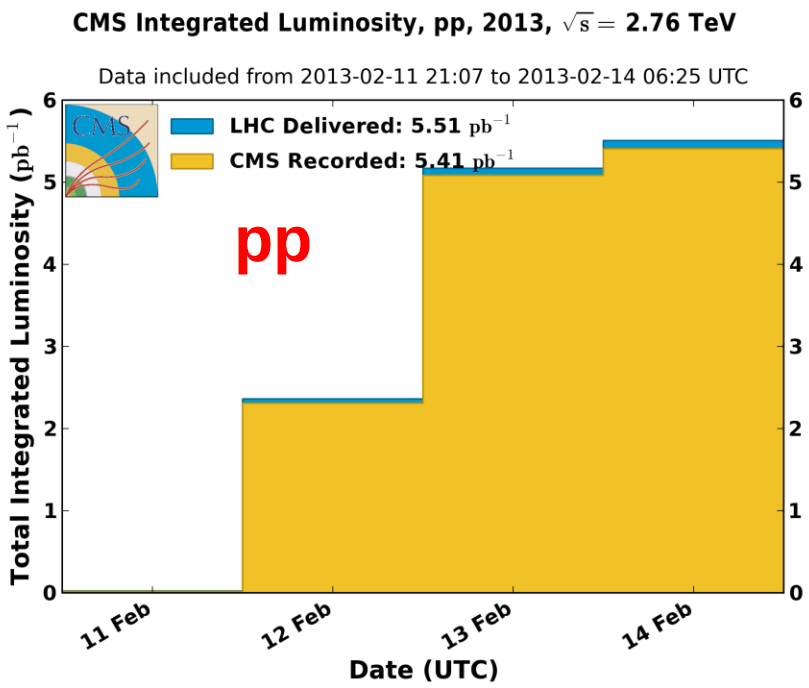
Rare “object” triggers sample full luminosity

photon	high-p_T track
jet	high-multiplicity
(di)muon	ultra-central collisions

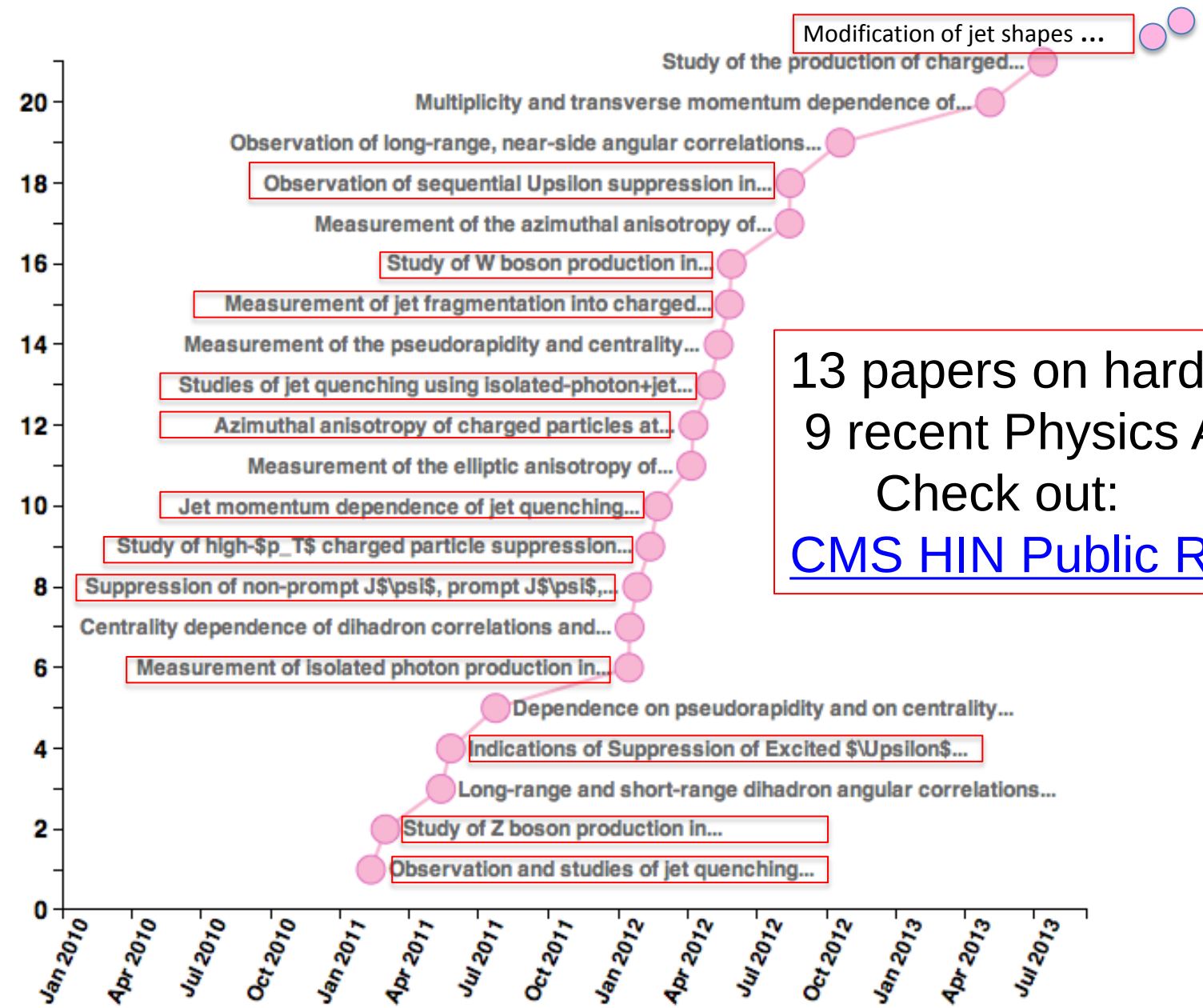
~ 5% of min bias in PbPb



2013



Run 1: HIN 23 published/submitted papers



13 papers on hard probes

9 recent Physics Analysis Summaries

Check out:

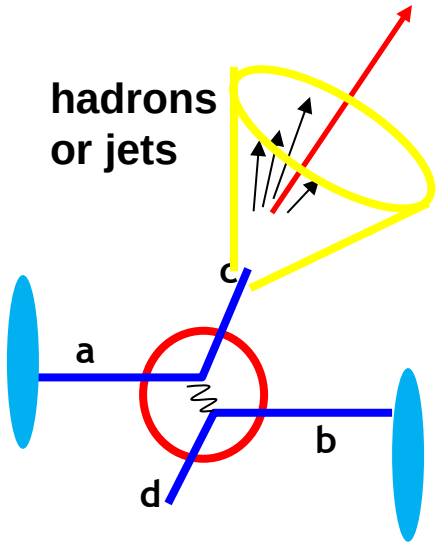
[CMS HIN Public Results page](#) !

The approach and outline:

Parton Distribution Function

Hard-scattering cross-section

Fragmentation function



- Part 1:
  - Hard probe production in PbPb
  - Compared to production in pp

} QGP+nPDF effects ?

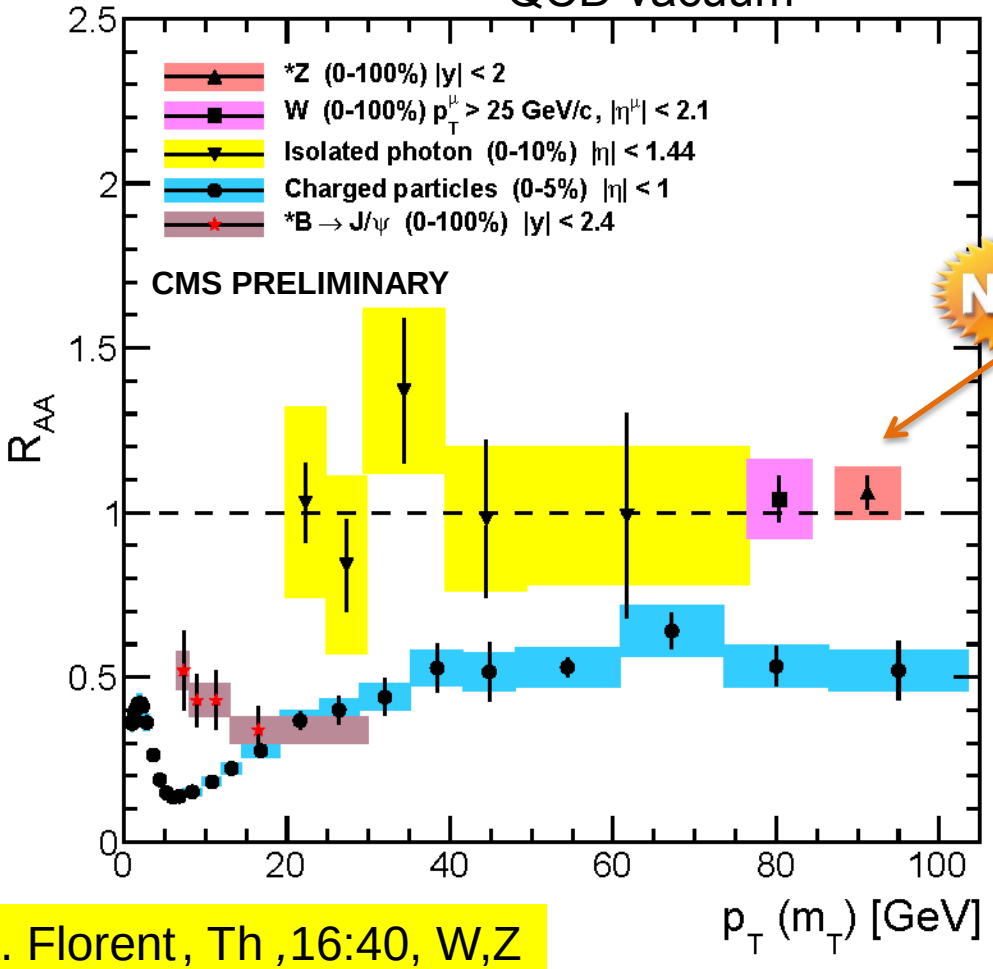
  - Updates in Z, b-jet, γ-jet, FF, jet shapes, J/ψ v_2 , and NEW high luminosity pp reference
- Part 2:
  - Hard probe production in pPb compared to pp
  - quarkonia, dijets, γ-jet, charged hadrons

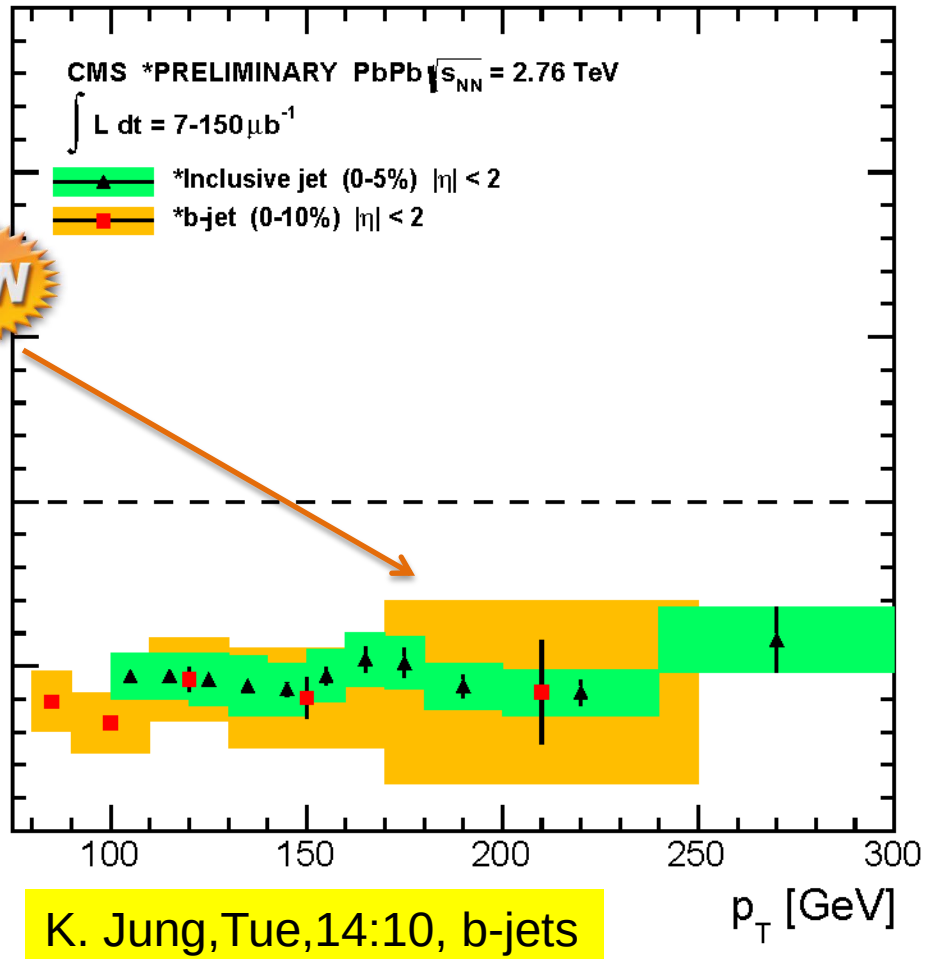
} nPDF ?

The R_{AA} collection

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2N_{pp}/dp_T d\eta} \sim \frac{\text{“QCD medium”}}{\text{“QCD vacuum”}}$$

EPJC 72 (2012) 1945 , PLB 715 (2012) 66, PLB 710 (2012) 256
HIN-12-014, HIN-13-004, HIN-12-004, HIN-12-003





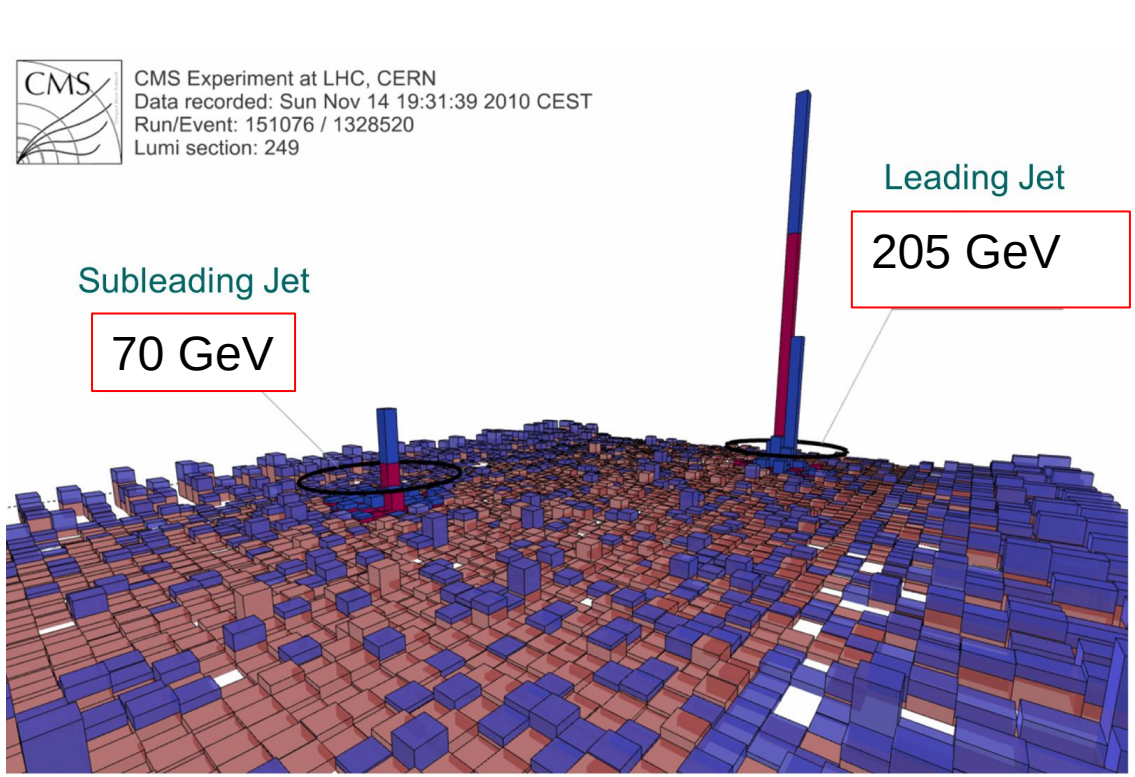
NEW

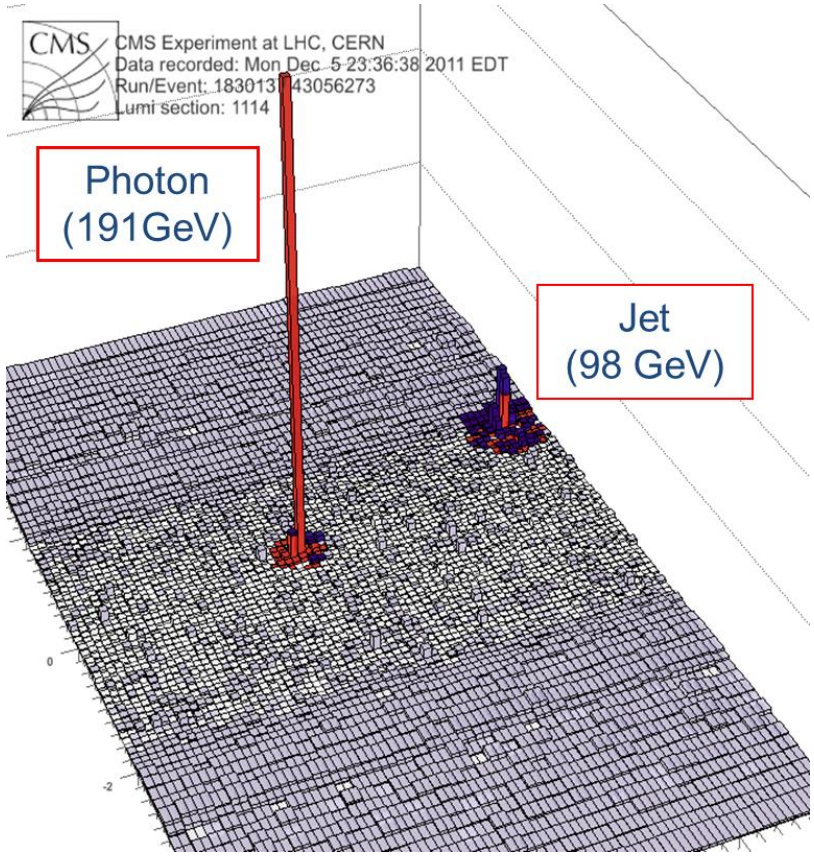
A. Florent, Th ,16:40, W,Z

K. Jung,Tue,14:10, b-jets

Colorless probes unsuppressed; hadrons and jets - modified
Less b-hadron suppression at low p_T; b-jets - similar to q/g jets

Probing the medium with dijets and γ+jet



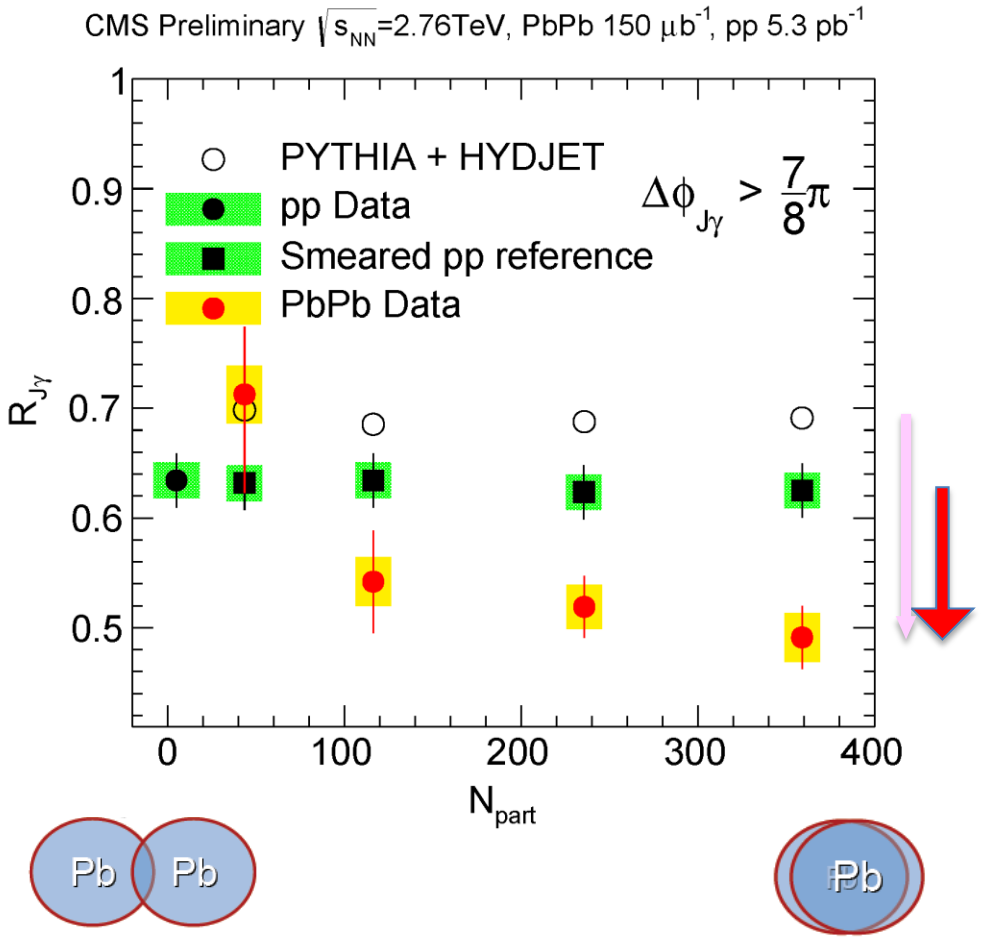


Large dijet momentum imbalance in PbPb

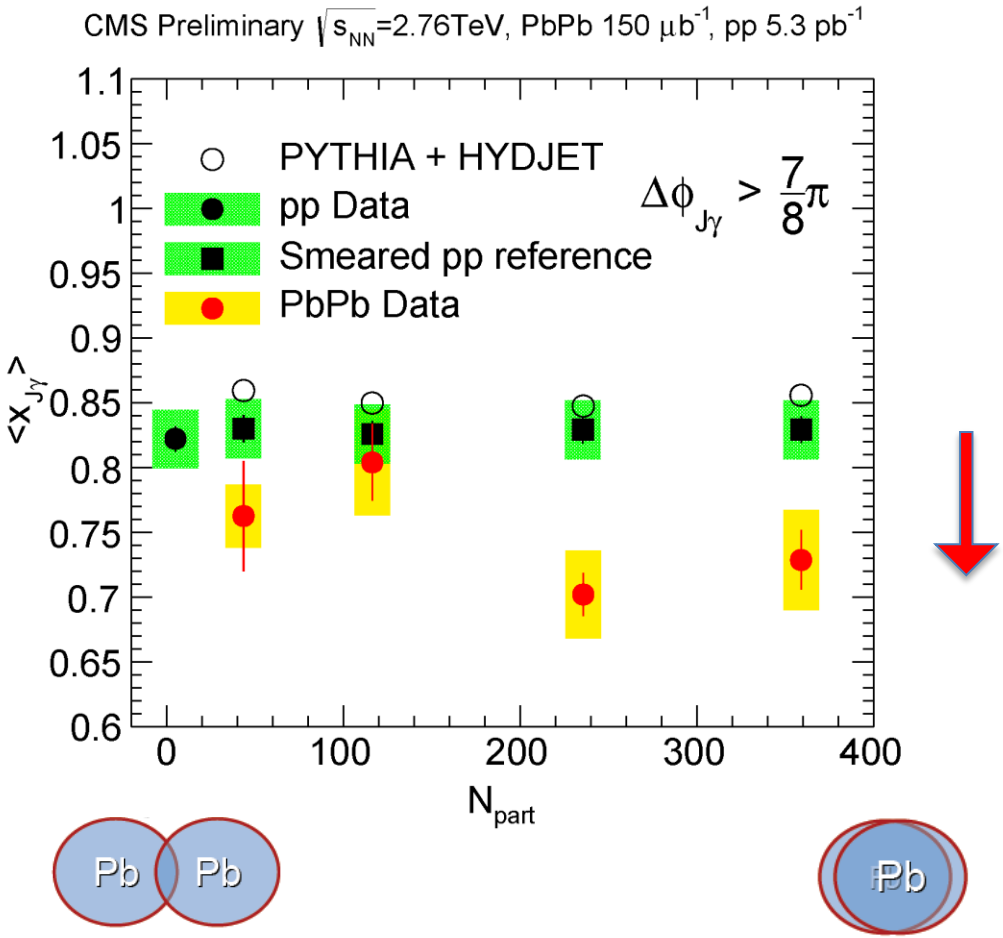
Photon tag:

- Access to enriched quark-jet sample
- Calibrated energy loss (initial parton p_T)

NEW γ+jet updated with pp reference !



Fraction of photons with jet partner



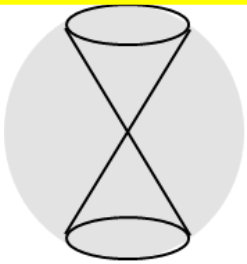
Jet-photon p_T(im)balance

Detailed studies vs photon p_T:

CMS-PAS-HIN-13-006
R. Barbieri, Th, 15:40

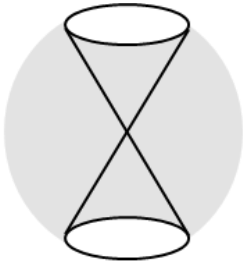
Can we find the lost energy ?

PRC 84 (2011) 024906

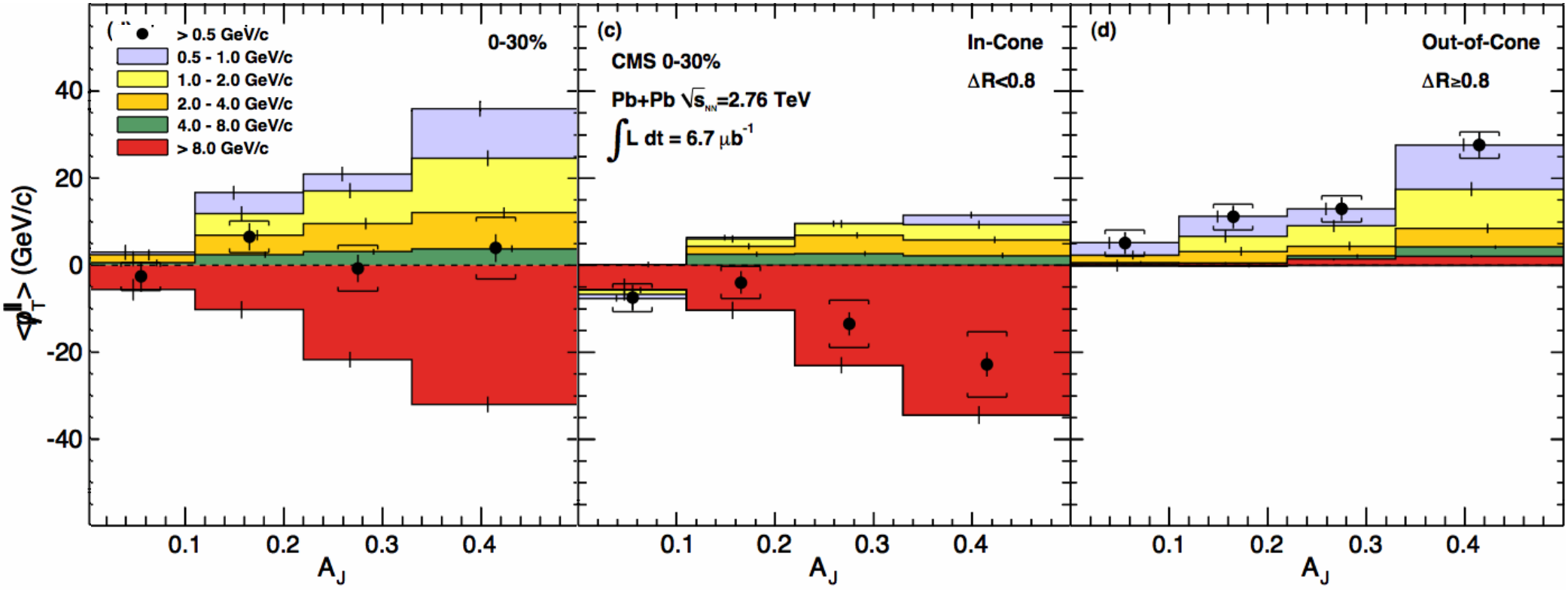


All tracks

Tracks in the jet cone $\Delta R<0.8$



Tracks out of the jet cone $\Delta R>0.8$



balanced

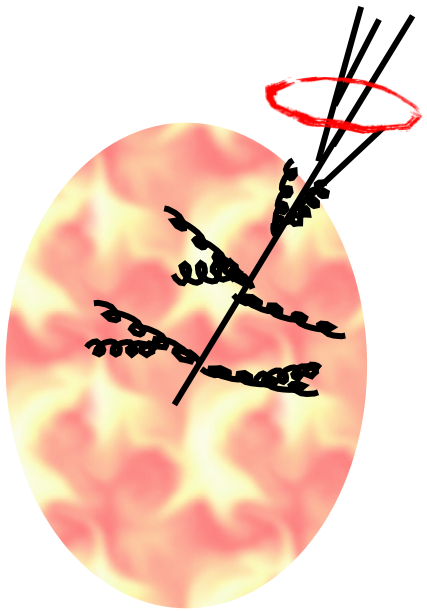
excess in leading jet direction

low p_T excess away from leading jet

Fragmentation function and jet shapes

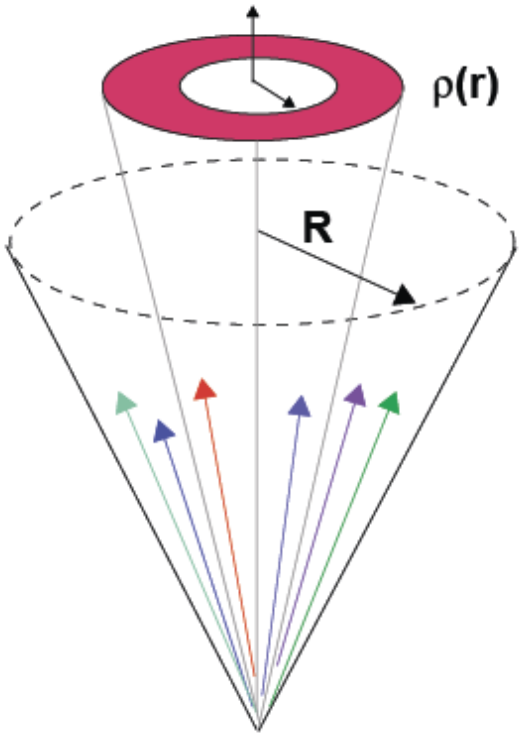
Is the jet energy in PbPb redistributed in particle p_T ?
Fragmentation functions

Is the jet energy in PbPb redistributed in radius ?
Differential jet-shapes



along jet-axis

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



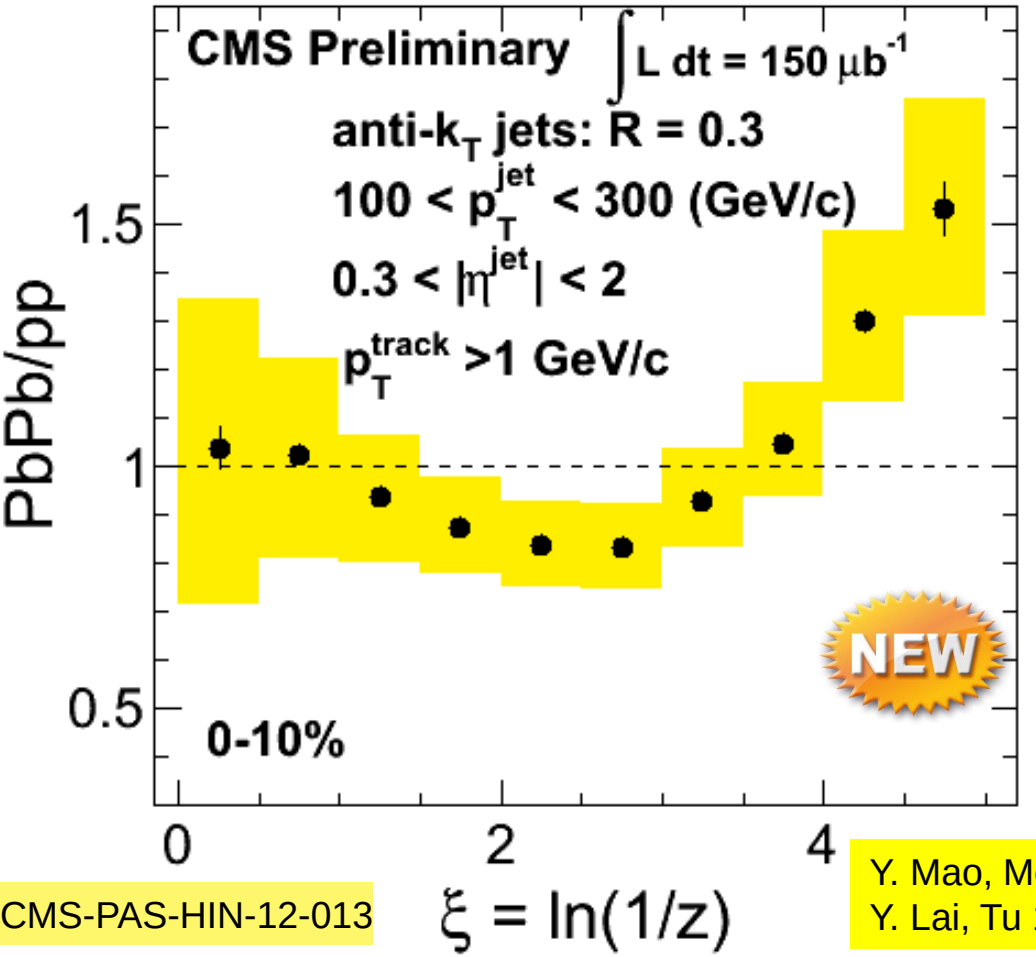
Fractional radial energy distribution

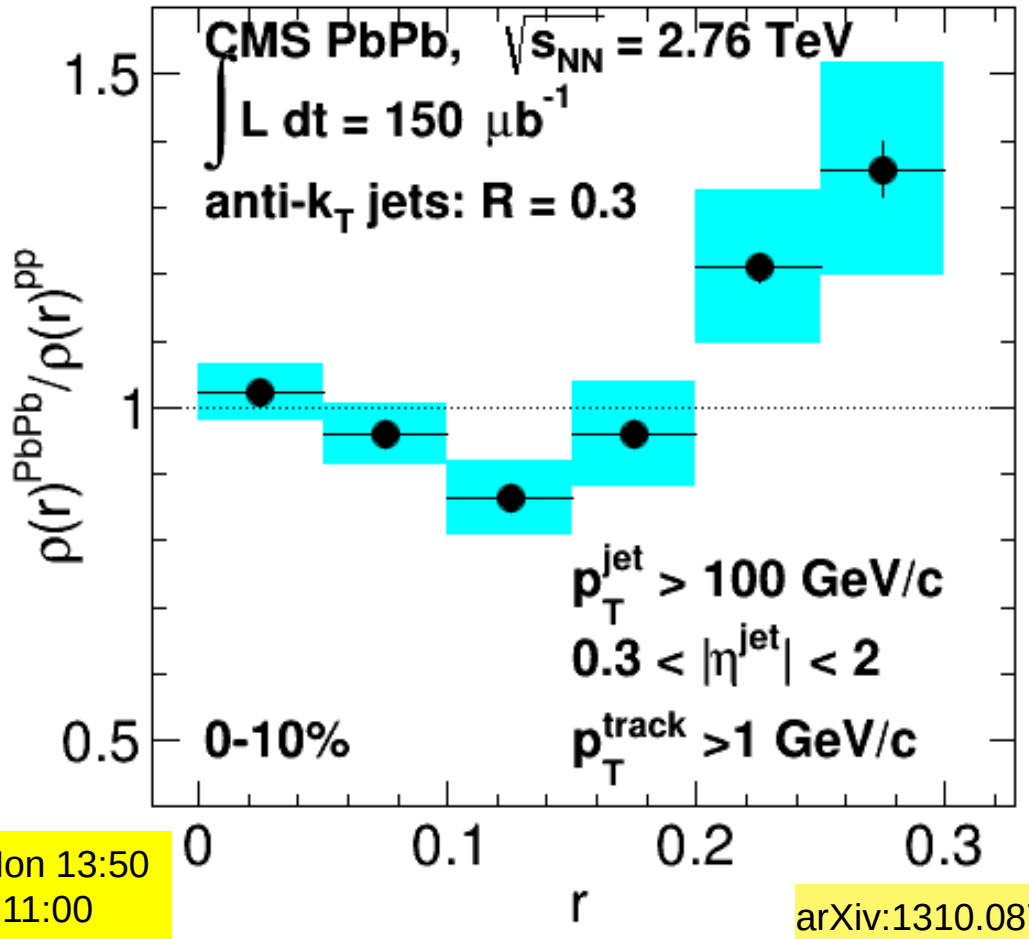
Fragmentation function and jet shapes

Is the jet energy in PbPb redistributed in particle p_T ?
Fragmentation functions

Is the jet energy in PbPb redistributed in radius ?
Differential jet-shapes

Depletion at mid p_T and radius; enhancement at low p_T and larger radius



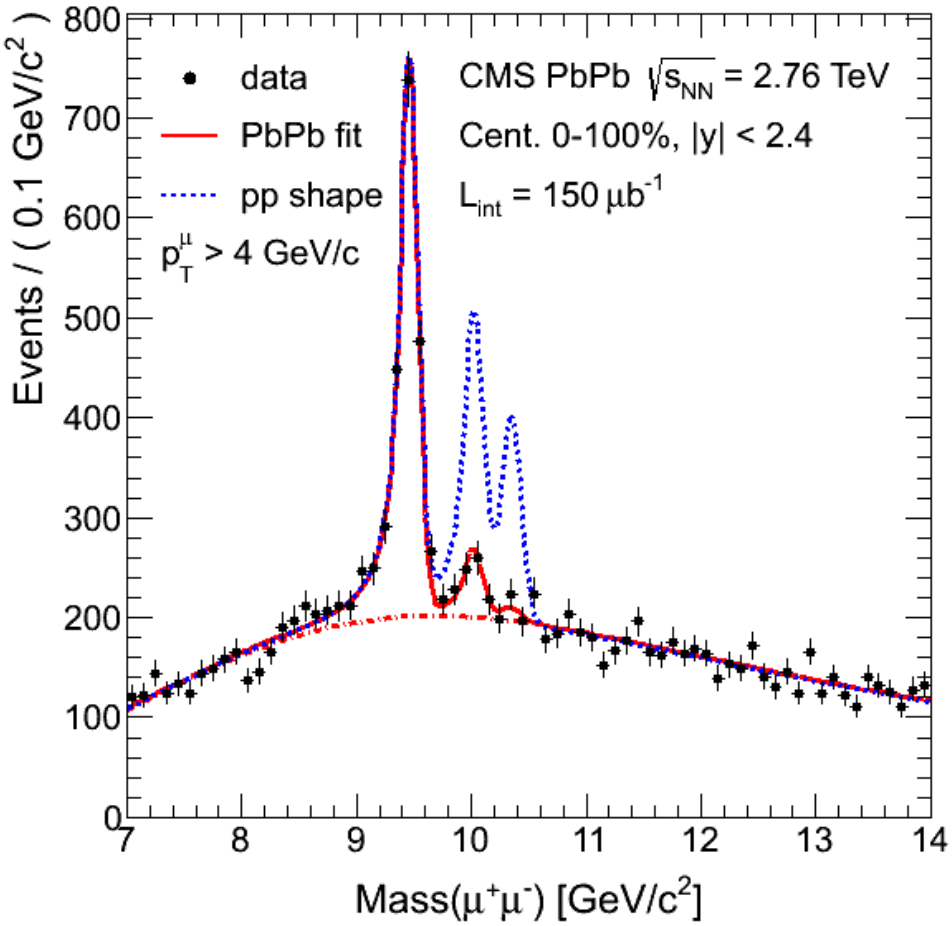


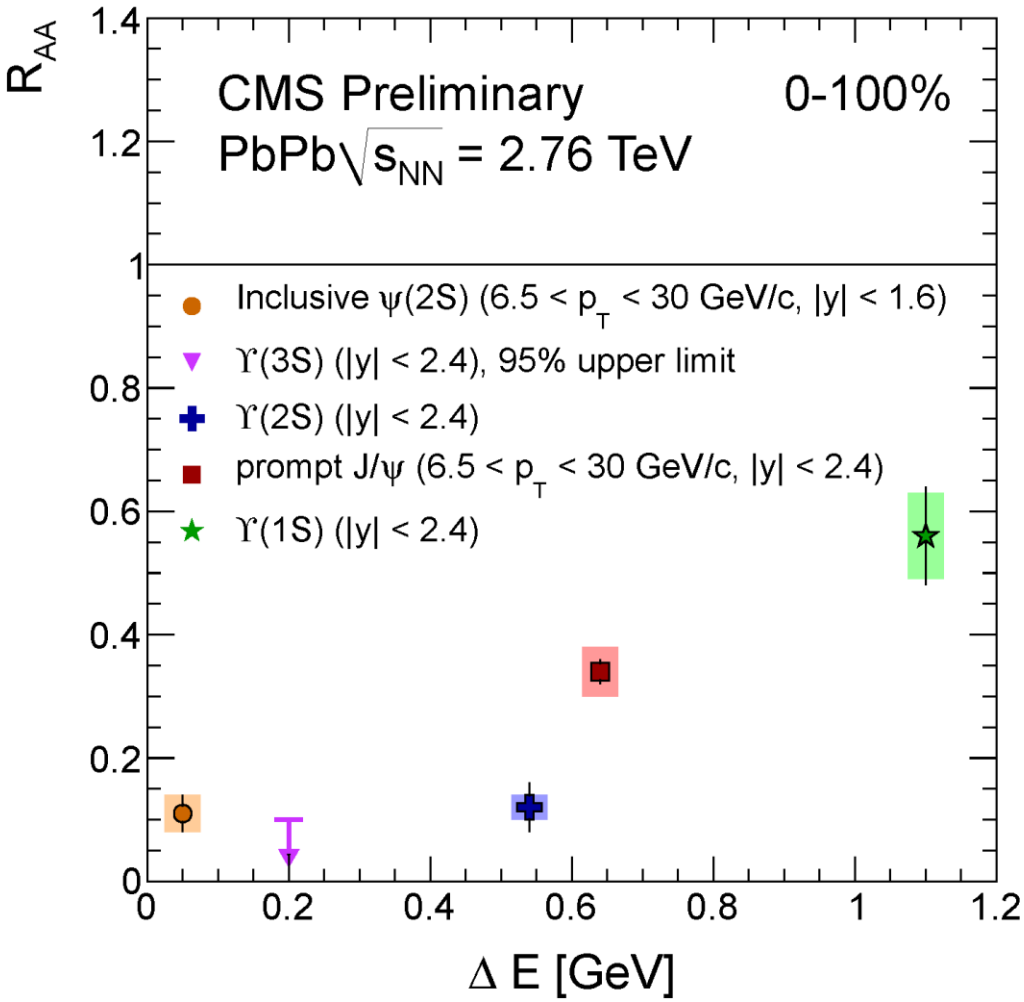
CMS-PAS-HIN-12-013

Y. Mao, Mon 13:50
Y. Lai, Tu 11:00

arXiv:1310.0878

Quarkonia probe initial temperature

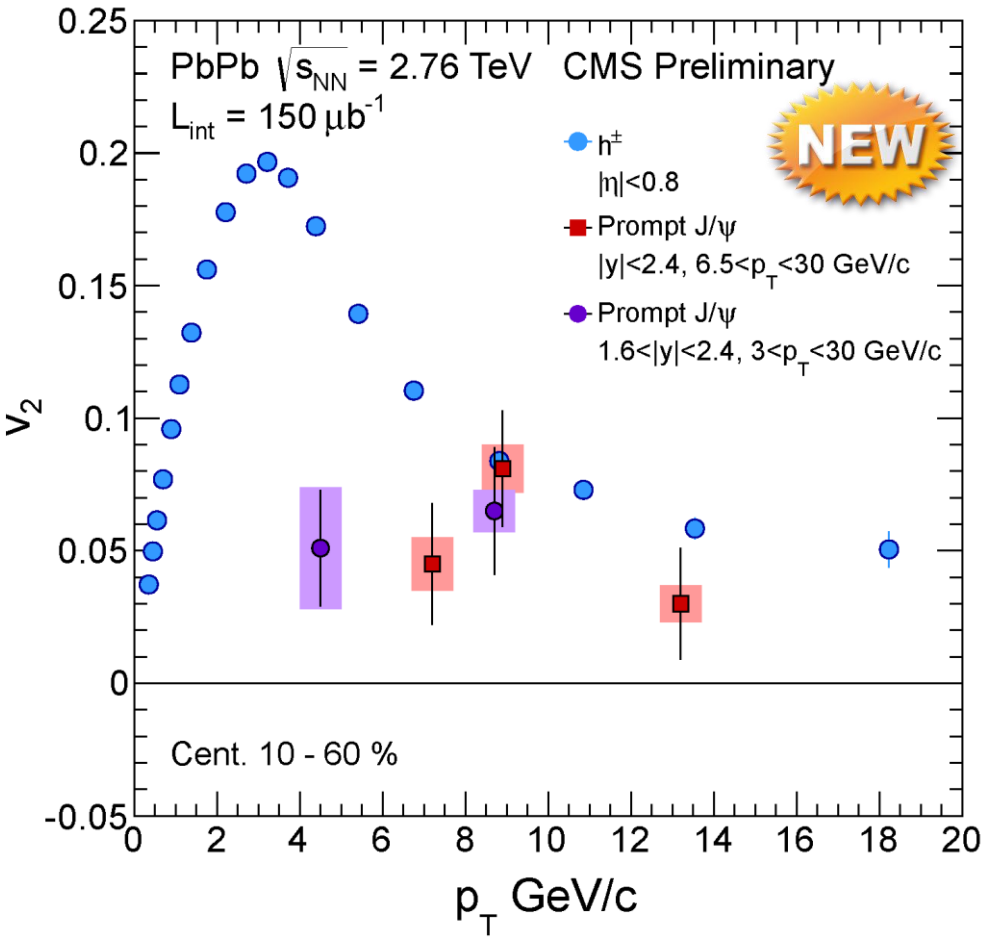


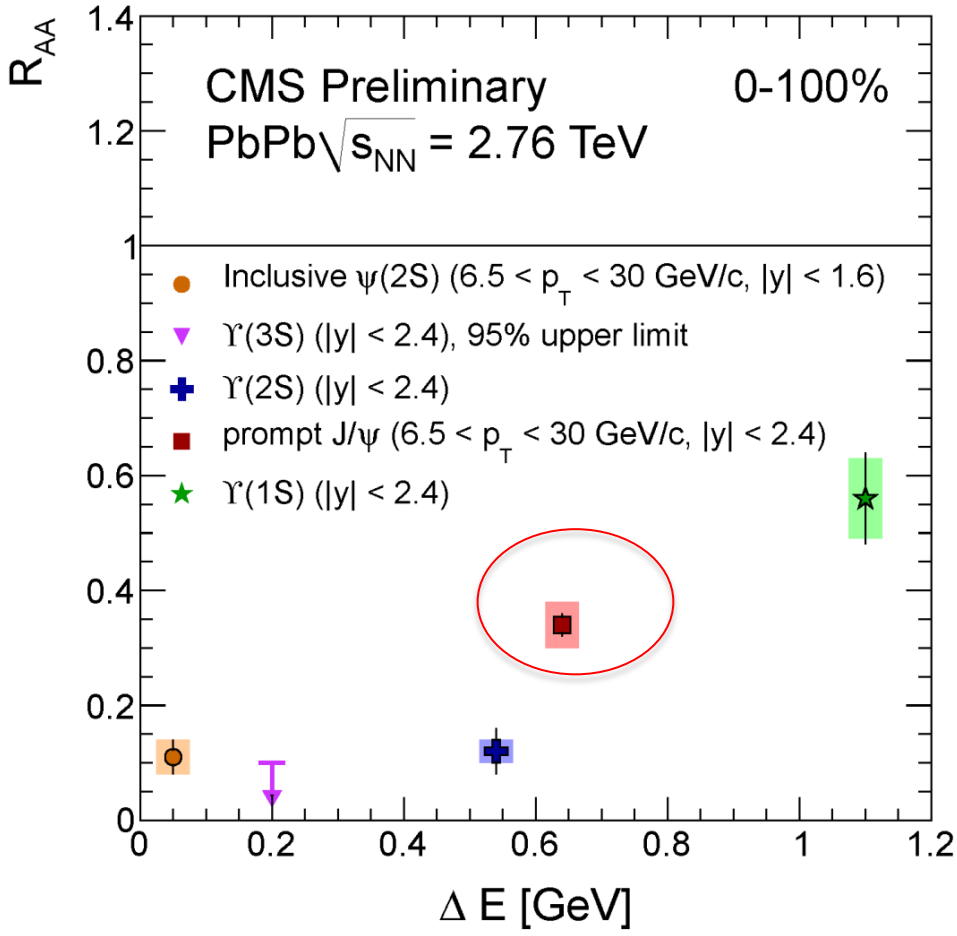


PRL107 (2011) 052302, JHEP 05 (2012) 063
PRL109 (2012) 222301, CMS-PAS-HIN-12-014
CMS-PAS-HIN-12-007, CMS-PAS-HIN-12-001

Suppression ordered by binding energy

Does suppression depend on path length ?





Low p_T:
J/ψ has smaller v_2 than hadrons
High p_T:
Similar v_2 for all: path length dependence

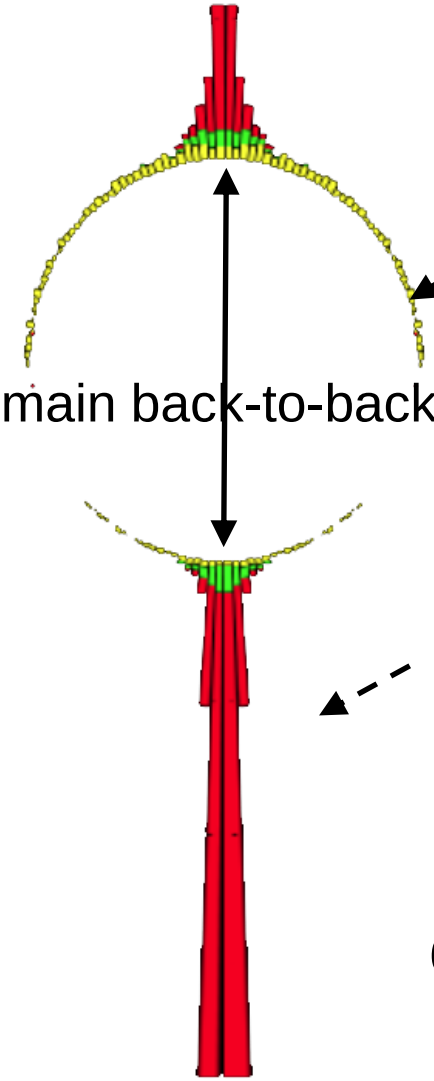
Suppression ordered by binding energy

L. Benhabib , Fri 12:00 plenary
D. Moon , Mon 16:40, Quarkonia parallel
M. Jo - poster

What have we learned from hard probes in CMS PbPb data?

1. High p_T jet suppression:
large average dijet and
photon-jet p_T imbalance
No suppression in colorless probes

Constrain amount of E loss



2. Jets remain back-to-back

3. p_T difference found at
low p_T particles far away from the jets

Constrain E loss mechanism fragmentation and shower evolution

4. Observation of modified jet
fragmentation function and jet shape

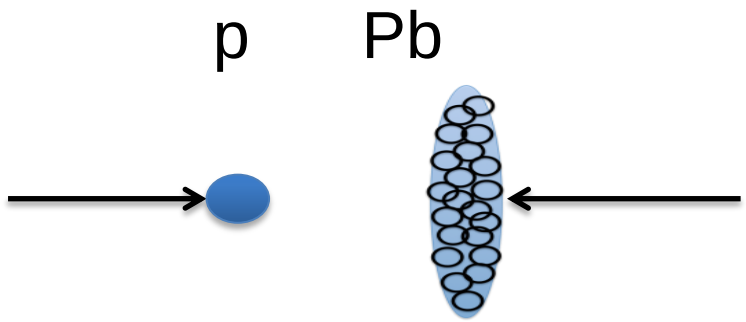
5. b-jets are also quenched
low-p_T b-hadrons: less E_{loss} than light q/g

E loss flavor dependence

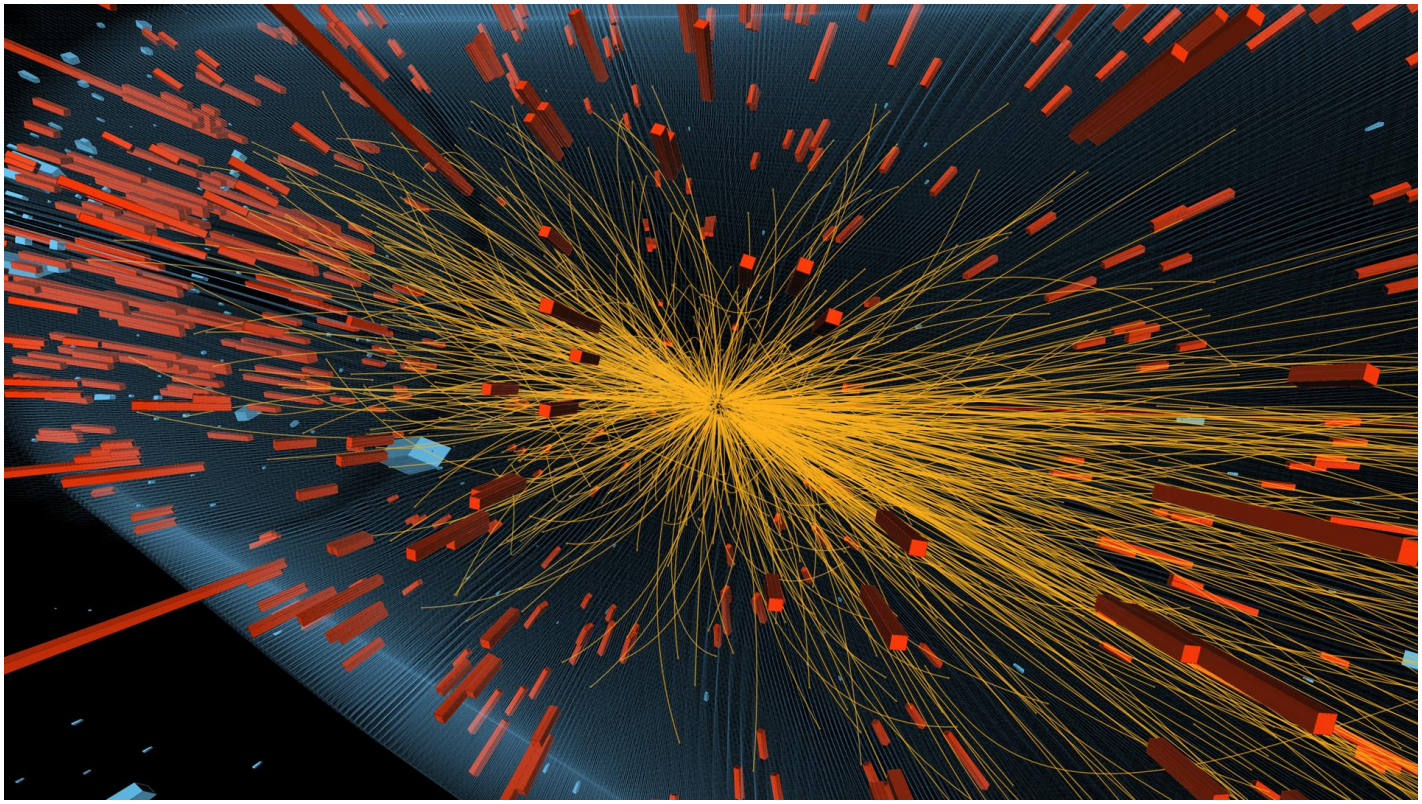
6. Quarkonia melt with the expected pattern

Access to initial T

Doesn’t quite work as “control” in all events



High-multiplicity pPb collision at $\sqrt{s_{NN}}$ = 5 TeV 418 particles detected !

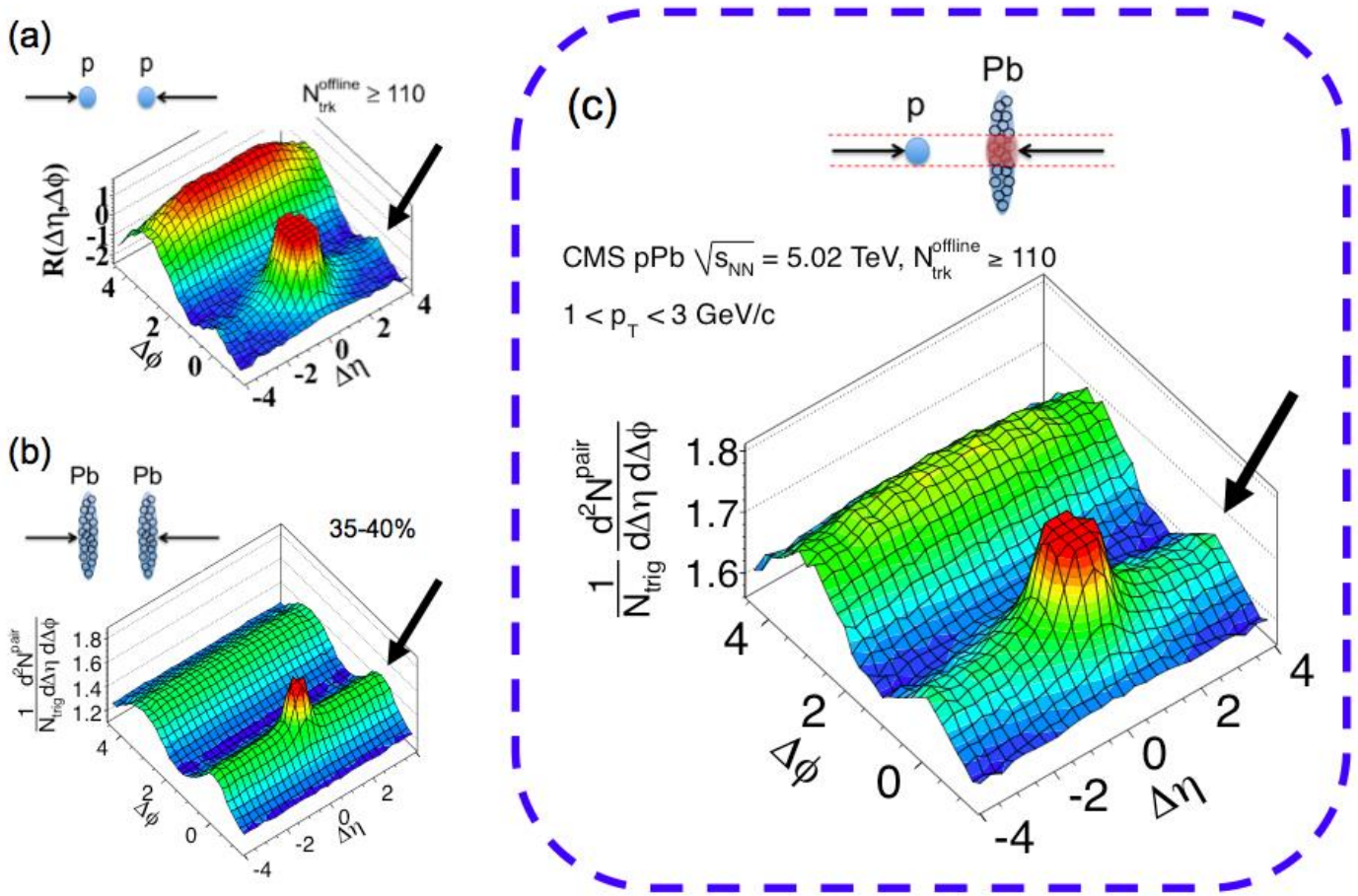


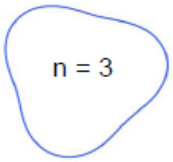
Ridges everywhere !

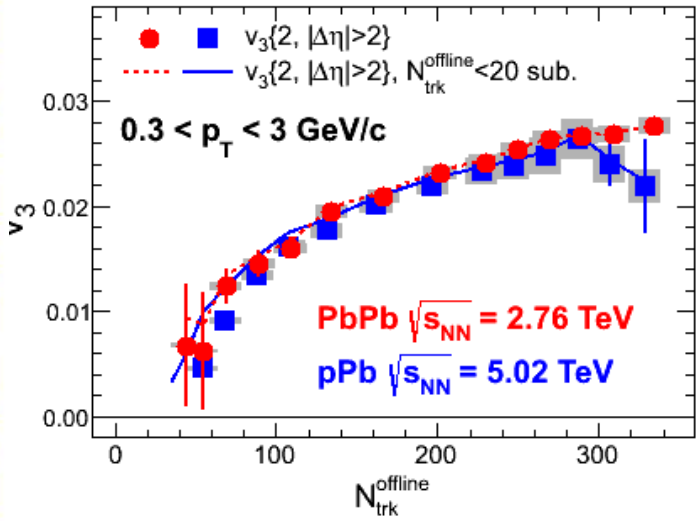
2010: Discovery ridge in pp
High multiplicity events
JHEP 1009 (2010) 091

2012 pilot run:
Discovery of ridge in pPb
High multiplicity events
PLB 718 (2013) 795

2013 pPb run:
flow harmonics studied
PLB 724 (2013) 213

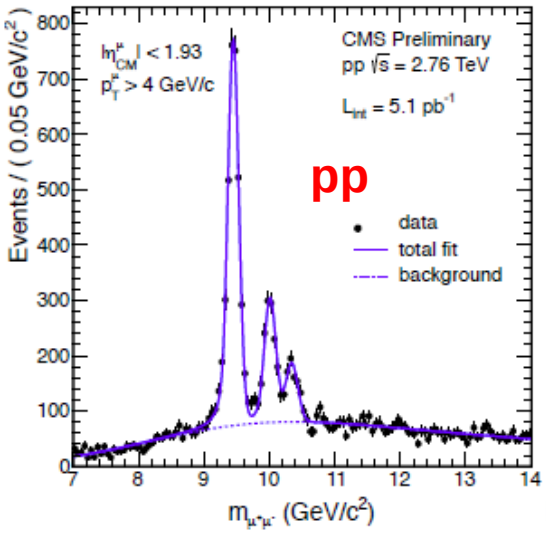


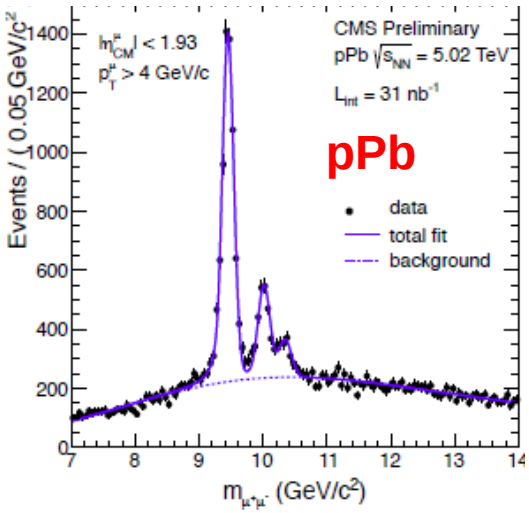




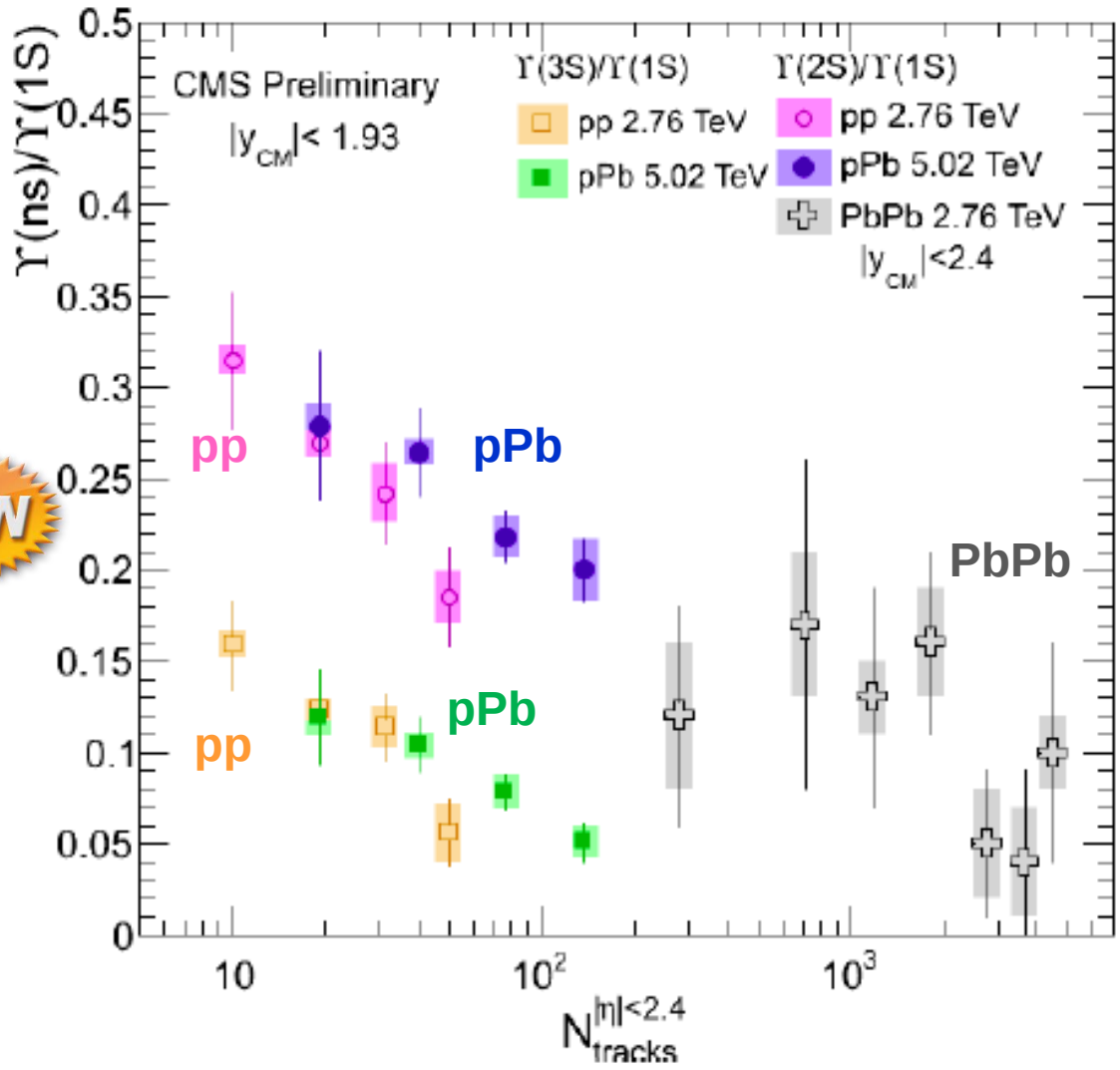
W.Li , Th 11:30, plenary

Υ (1S,2S,3S) and event activity





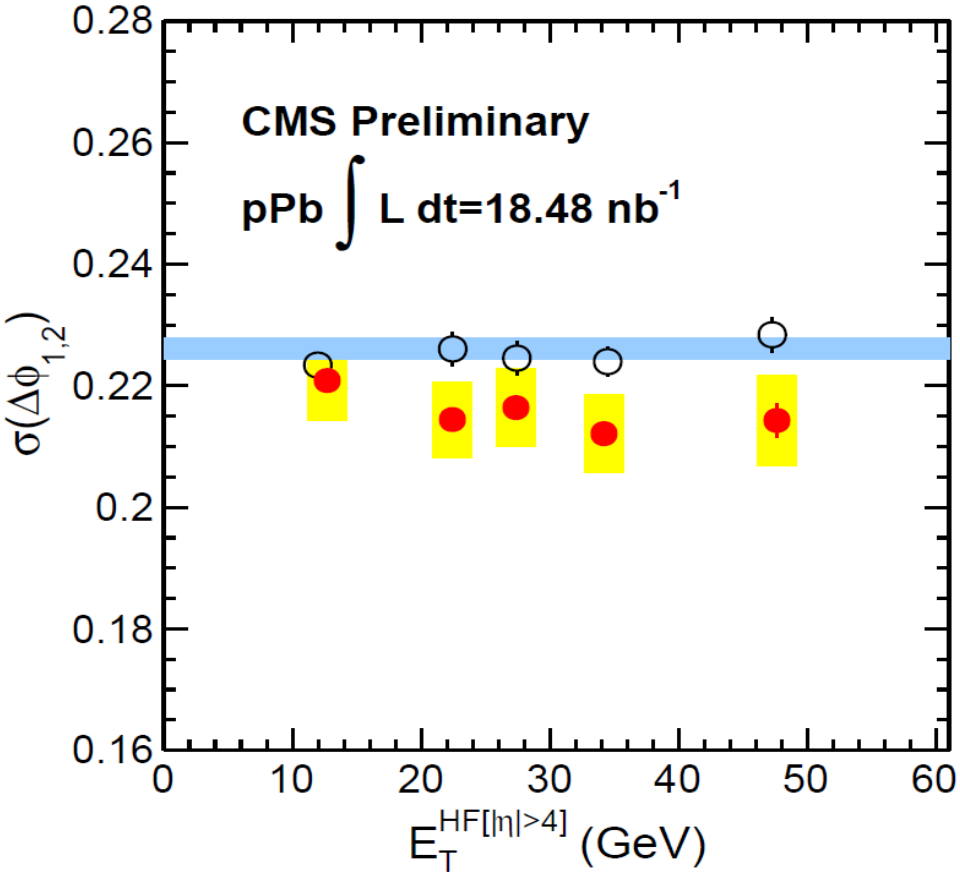
NEW



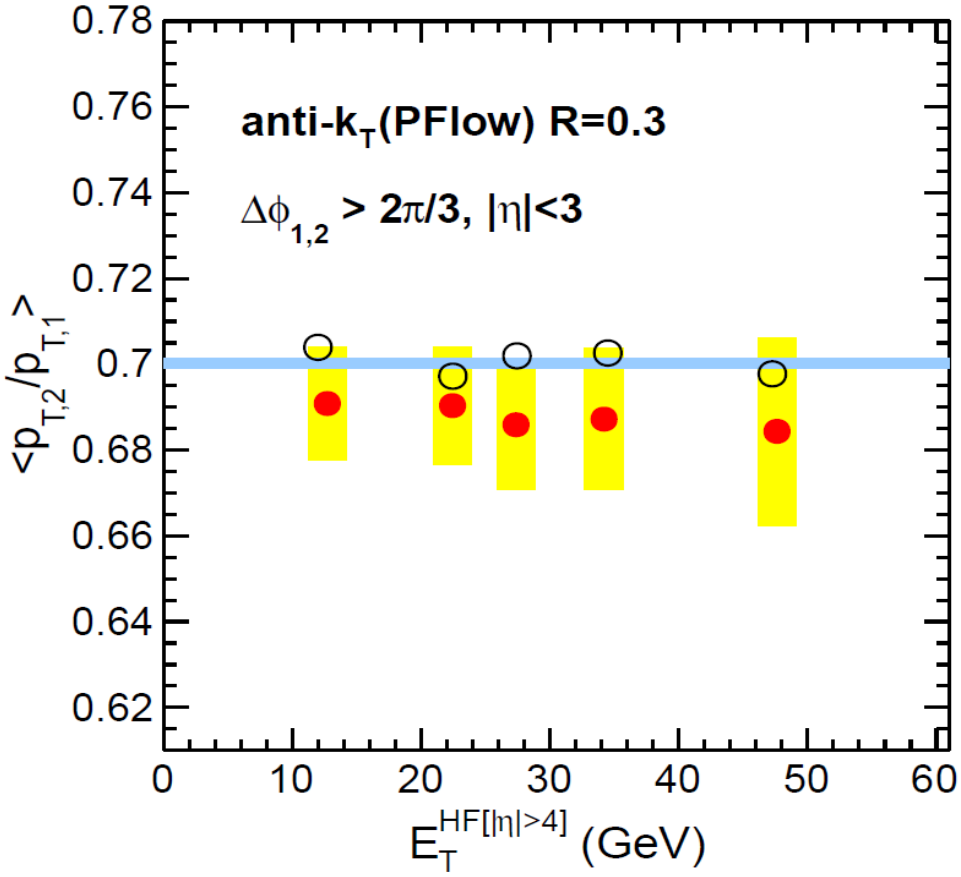
- Less suppression of excited states in pPb compared to PbPb
- Interesting behavior vs event activity in all collision systems
- What is the correct reference for PbPb collisions ?

Is there jet quenching in pPb for dijets?

CMS-PAS-HIN-13-001



no significant
angular decorrelation



no significant
momentum imbalance

No final state effects→ Can we access the initial state ?

Probing nPDF with dijets and hadrons

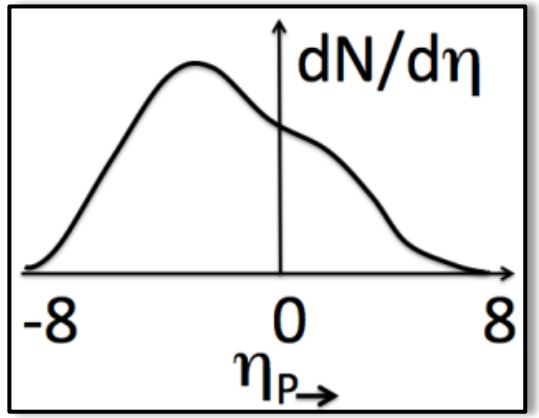
- Terminology: what is where and what are we after ?

x - fractional momentum from a colliding nucleon carried by the parton

large x from nucleus

"backward"

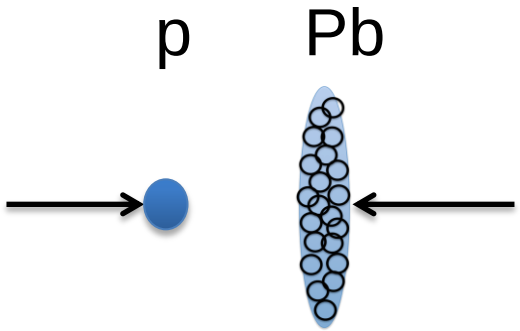
Antishadowing and EMC effect ?



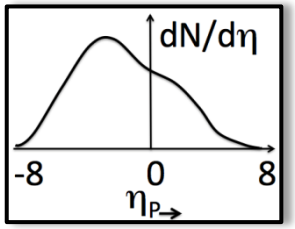
small x from nucleus

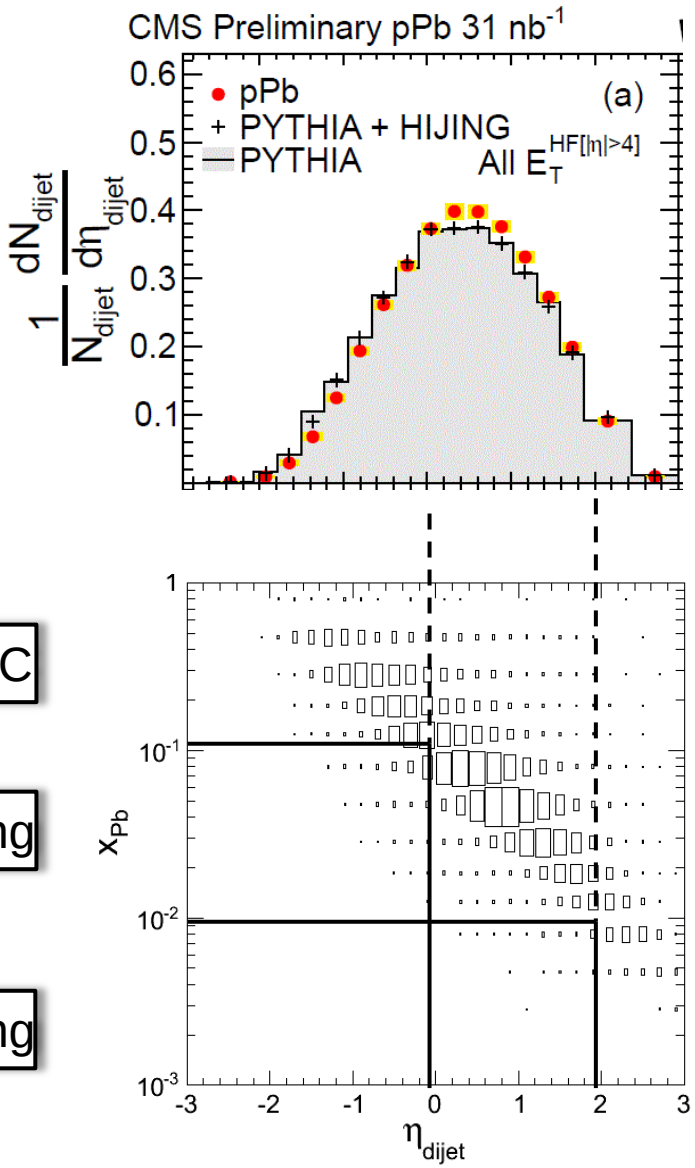
"forward"

Shadowing ?



How to get to different x values ?





Min. bias

EMC

Anti-shadowing

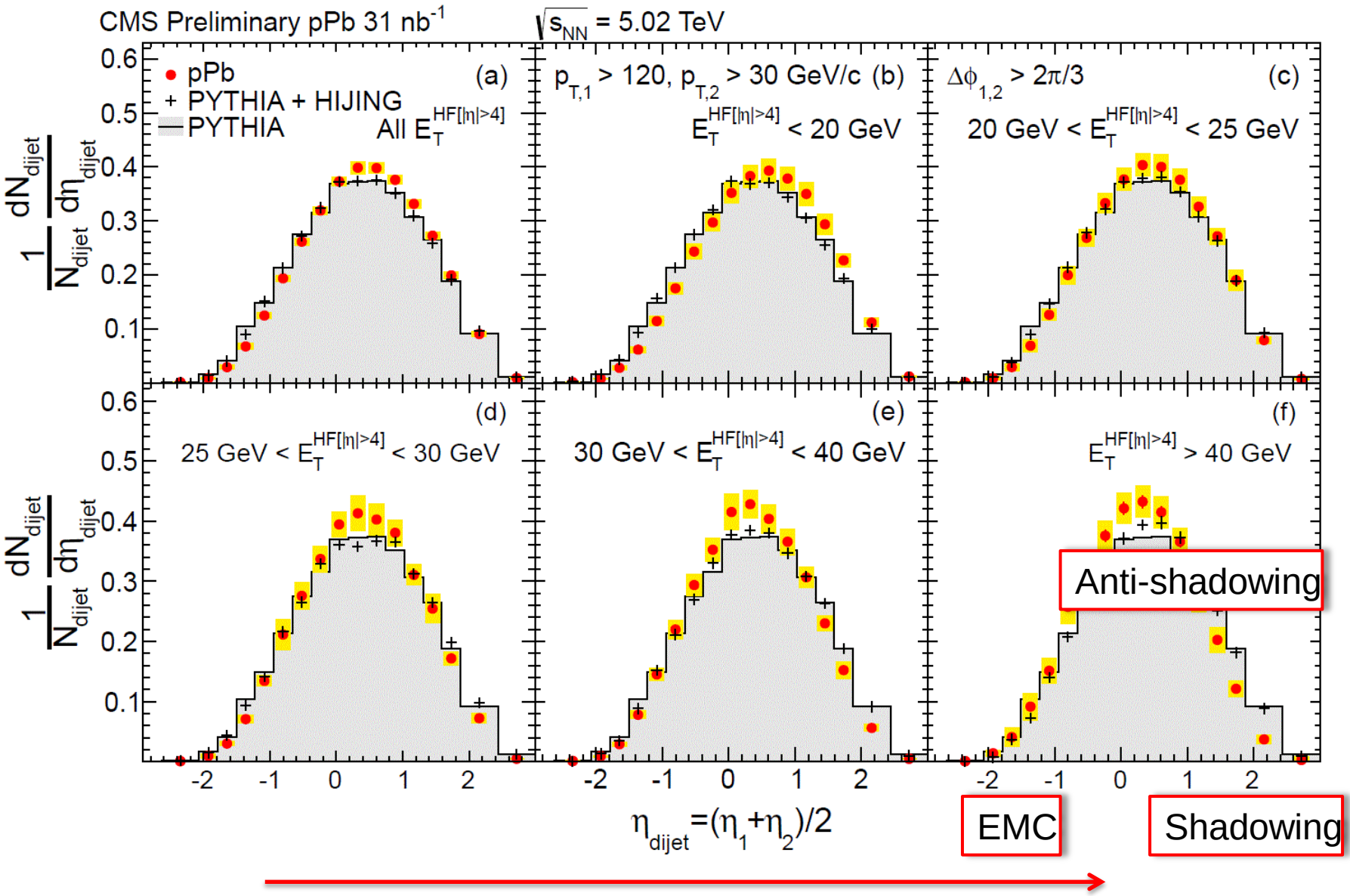
Shadowing

CMS-PAS-HIN-13-001

D. Gulhan, Moday 14:30

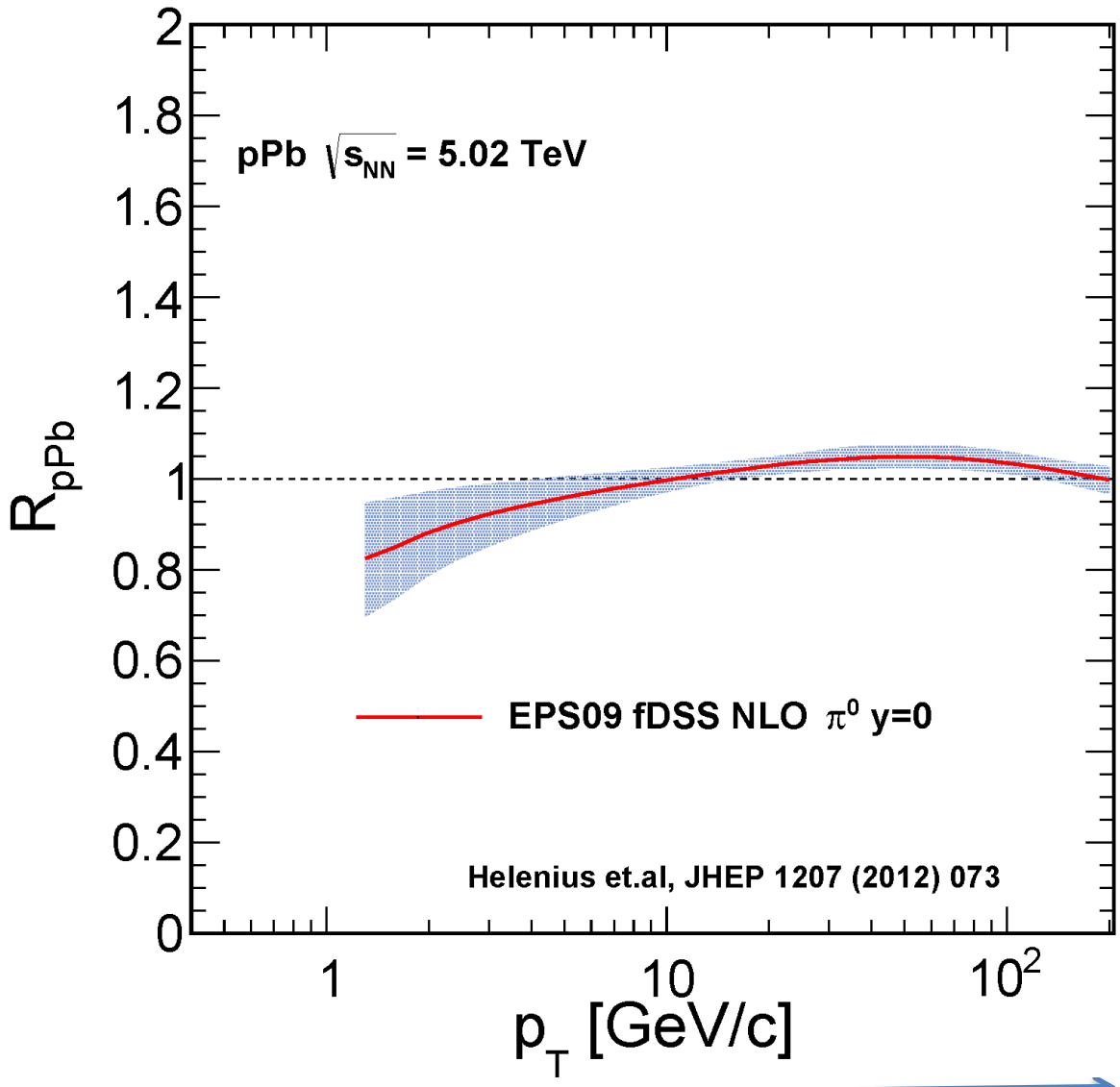
- Dijet η distribution correlated with parton x from Pb

How to get to different x values ?



The shape of the distribution evolves with event activity

What to expect for hadron R_{pPb} ?

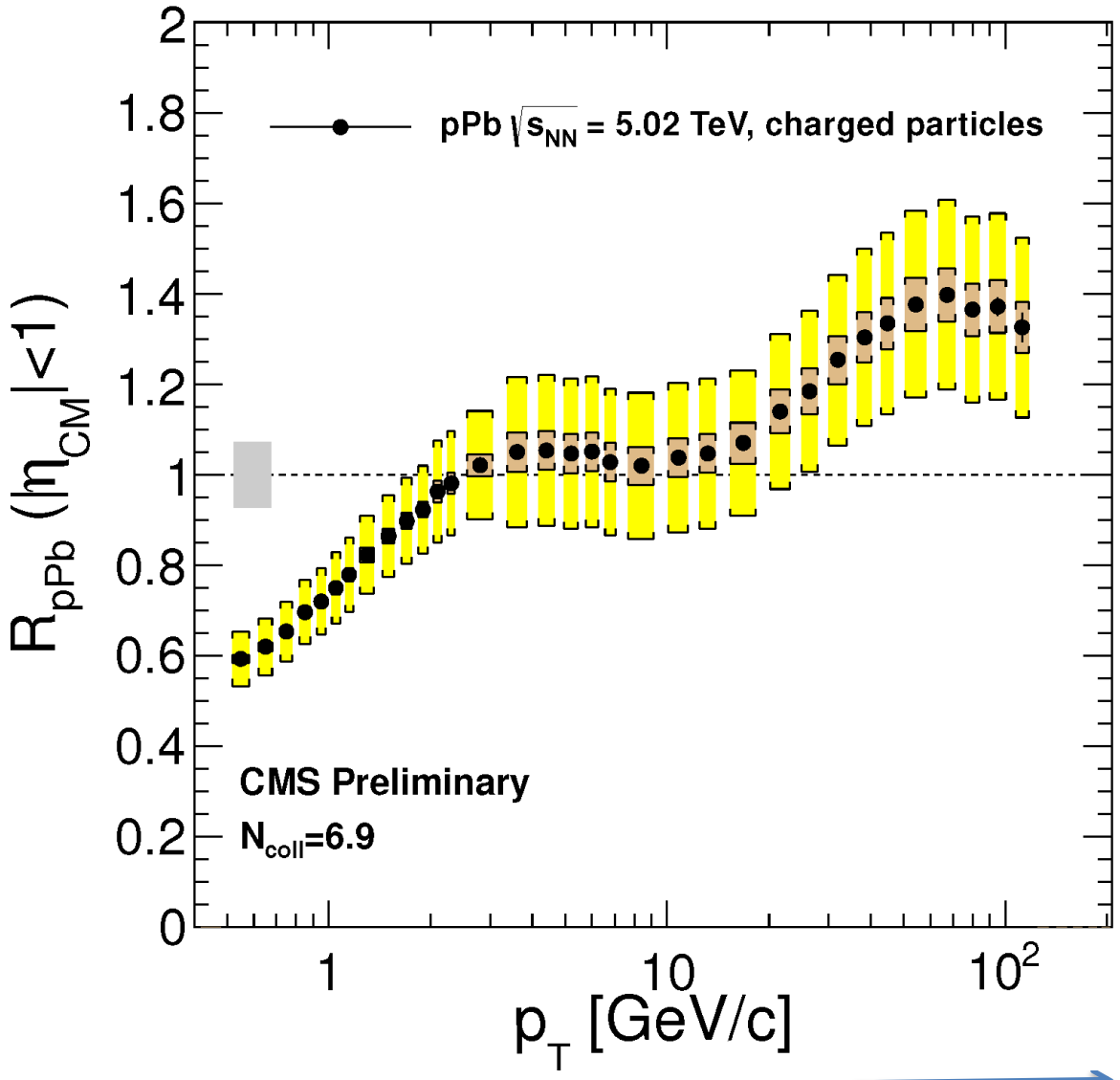


Smaller Q^2 and x

Large Q^2 and x

The R_{pPb} data !

pp reference interpolated from lower and higher energy data



Smaller Q^2 and x

Large Q^2 and x

CMS-PAS-HIN-12-017

K. Krajczar, Monday 16:20

Anti-shadowing:
larger than predicted although, with large systematic uncertainty

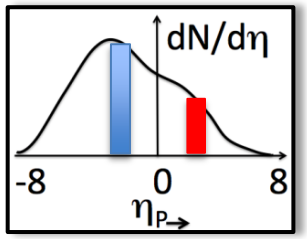
N_{coll}

Correlated

Partially correlated
10% from pp reference

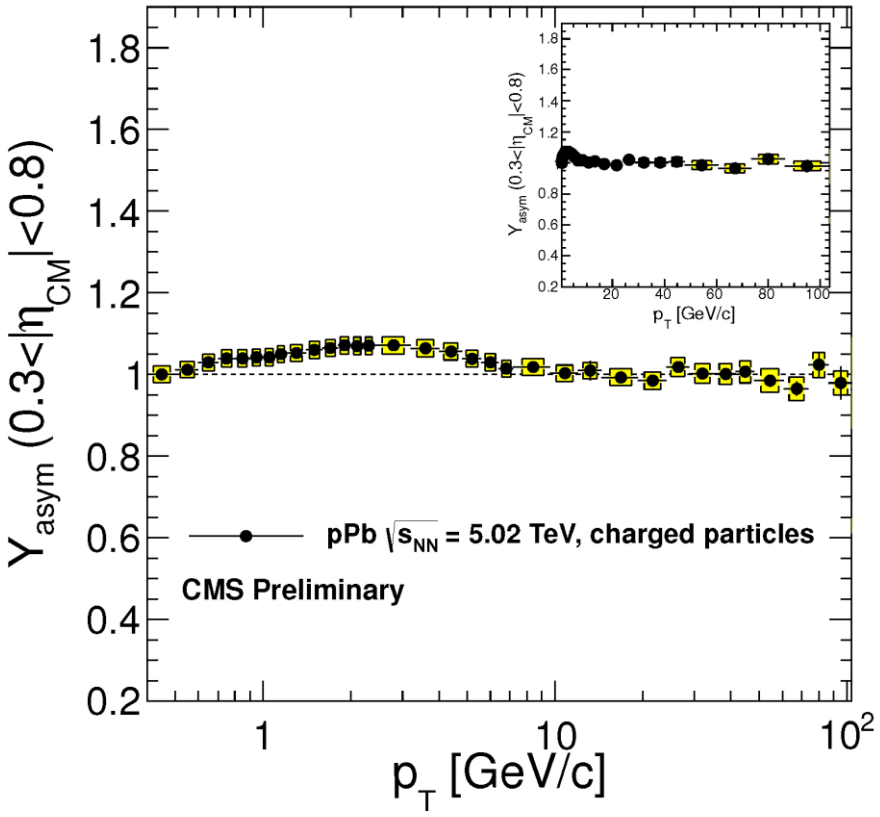
Look for asymmetry in hadron yield vs η_{cm}

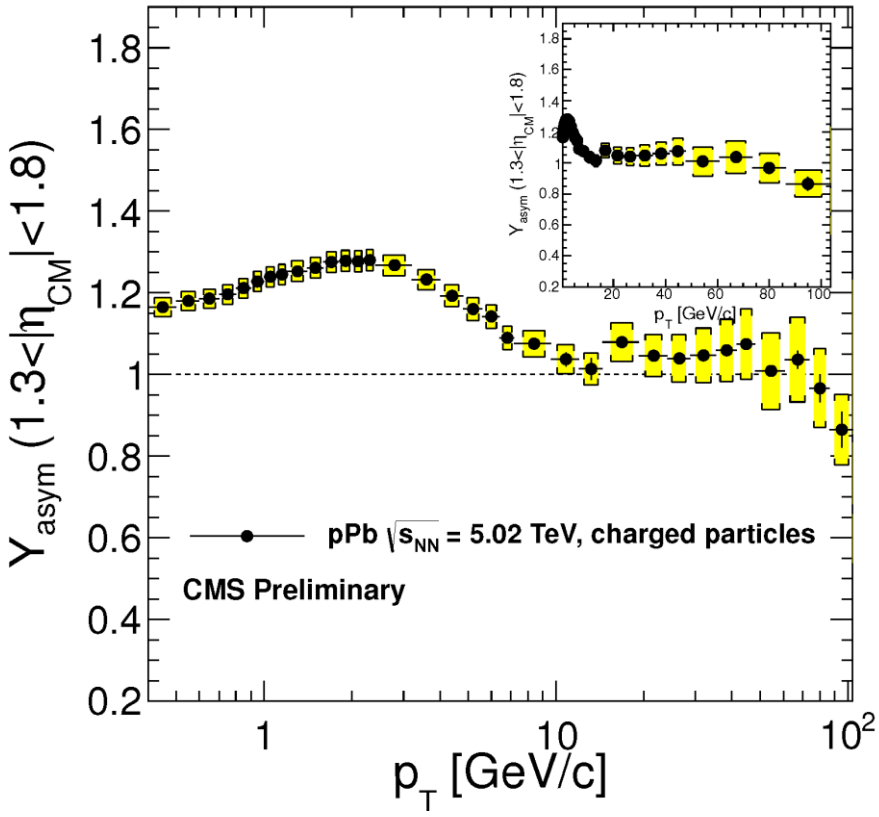
$$Y_{asym} = \frac{\text{Yield Pb-going}}{\text{Yield p-going}}$$



NEW

CMS-PAS-HIN-12-017





Small x from Pb in denominator

Large Q^2 and x

Increase in shadowing region

Small change in antishadowing

What can we learn about nPDF ?

CMS Preliminary

pPb 35 nb^{-1}

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

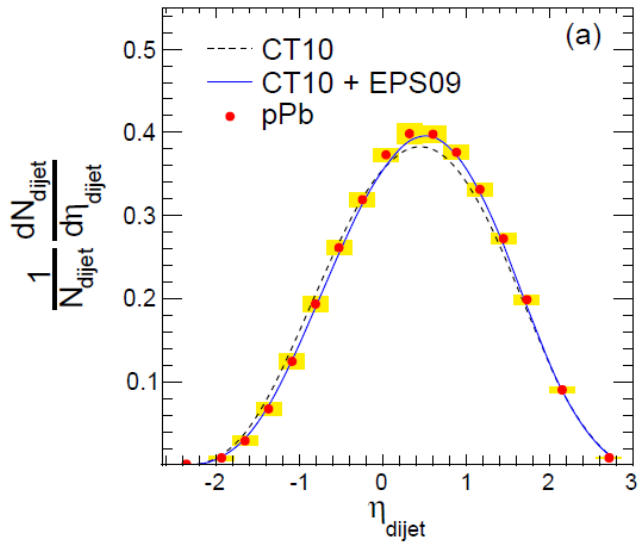
$p_{T,1}$ > 120 GeV/c

$p_{T,2}$ > 30 GeV/c

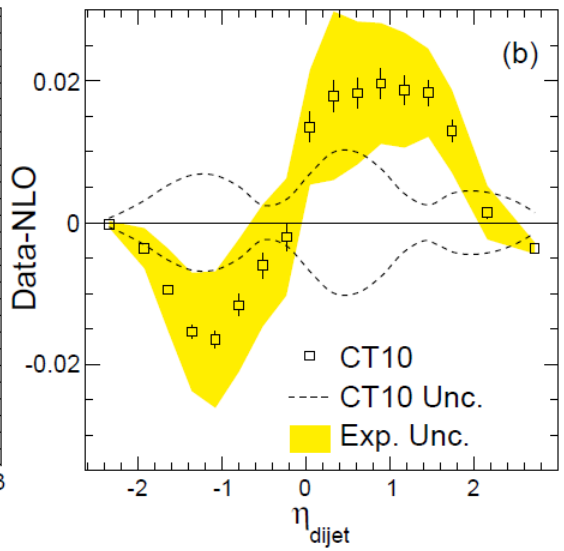
$\Delta\phi_{1,2} > 2\pi/3$

All $E_T^{HF[|\eta|>4]}$

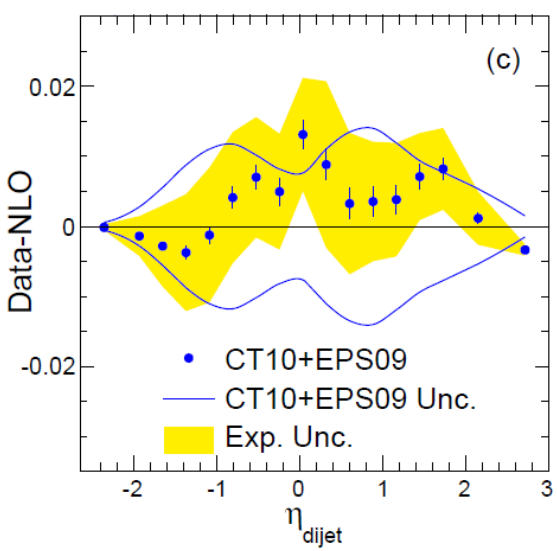
Normalized to unit area



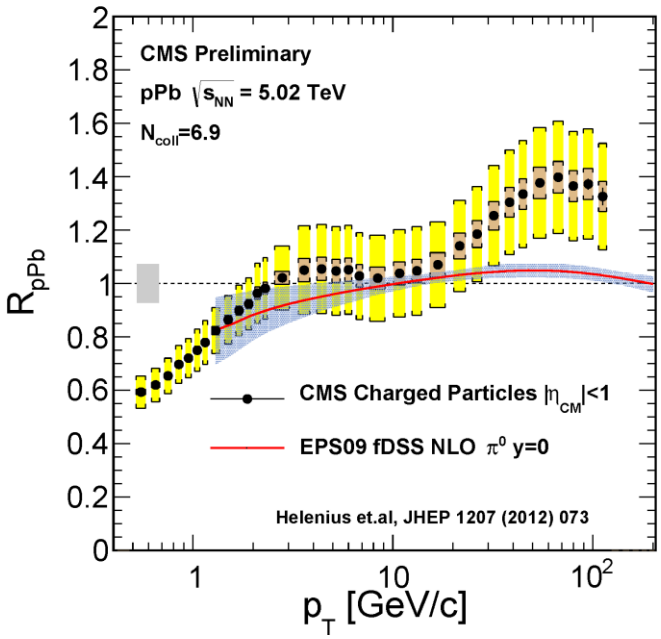
pp PDF



nPDF



- pp PDF ruled out by shape of dijet η distribution
- Good agreement with EPS09 nPDF predictions
- On absolute scale, nuclear effects could be bigger, as seen in charged hadron R_{pPb}
- Qualitative agreement between the dijet and charged hadron results



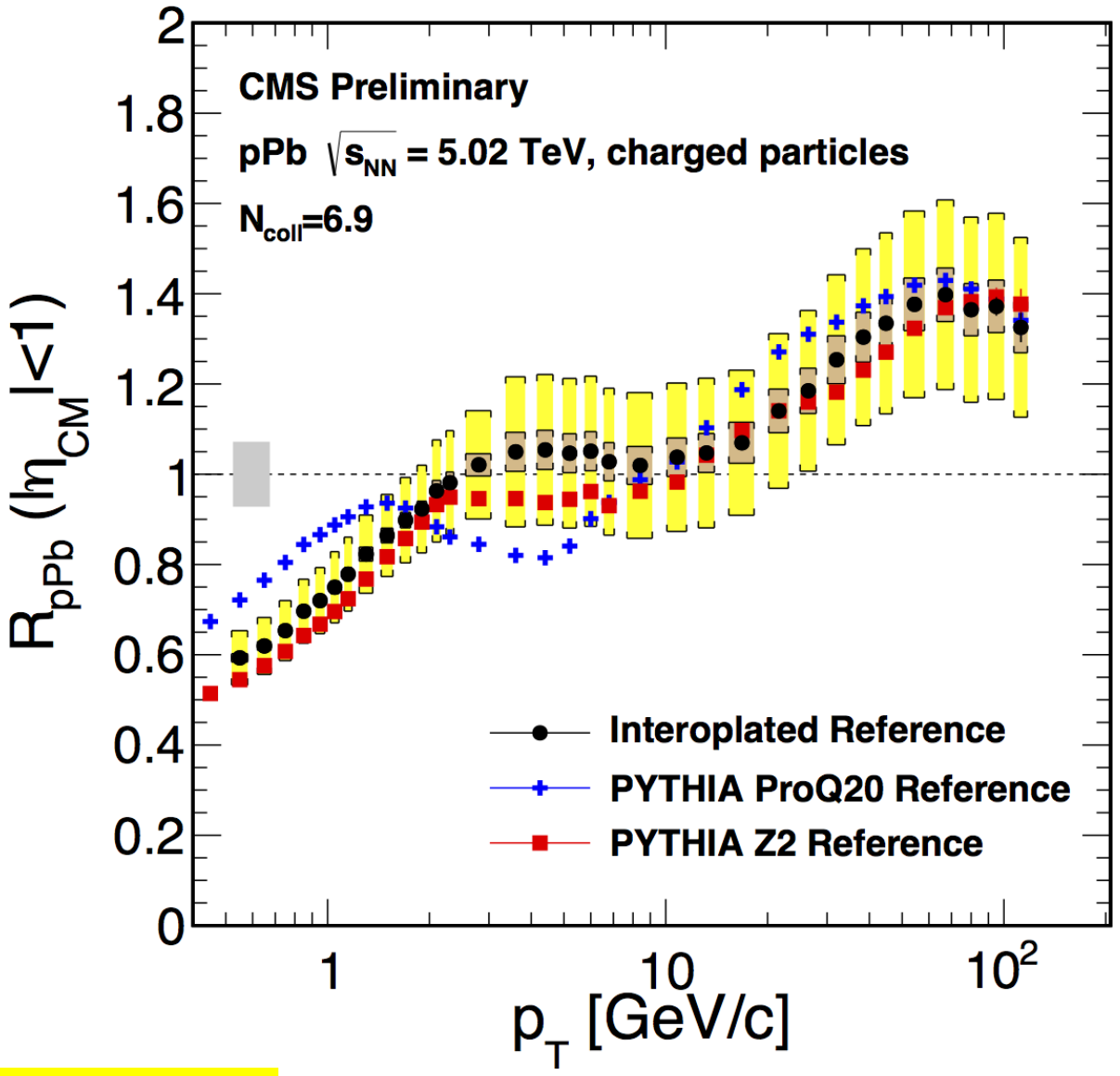
Summary

- In 2013 CMS has collected and analyzed:
  - 31 nb^{-1} of pPb collisions, 5.4 pb^{-1} of pp collisions
- Updated results with high-statistics pp reference
  - Consistent picture of dense and hot matter in PbPb
- Highlights from pPb collisions:
  - high event activity produces long-range correlations, but no jet-quenching
  - quarkonia production is correlated with event activity in all collisions systems
  - The initial state nPDF are modified!
  - Constraining these modifications will further the understanding of the final state effects

Enjoy the exciting CMS results coming in: 3 plenary, 7 parallel presentations and 2 posters

- D. Gulhan, Monday 14:30, Dijets in pPb
- Y.Mao Monday 13:50, Jet shapes and FF
- D. Moon Monday 16:40, Quarkonia
- K.Kraijczar Monday 16:20, RpPb
- Y. Lai Tue plenary 11:00, Jet measurements
- K. Jung Tue 14:10, b-jets
- W. LI Th 11:30, Flow plenary
- V. Knuenz Th 15:40, Quarkonia polarization, pp 7 TeV
- R. Barbieri Th 15:40, Photon-jet in pp, pPb, PbPb
- A. Florent Th 16:40, W,Z
- L. Benhabib Fri 12:00, Quarkonia plenary
- Y Yilmaz poster: Jet reconstruction
- M. Jo poster: Charmonium

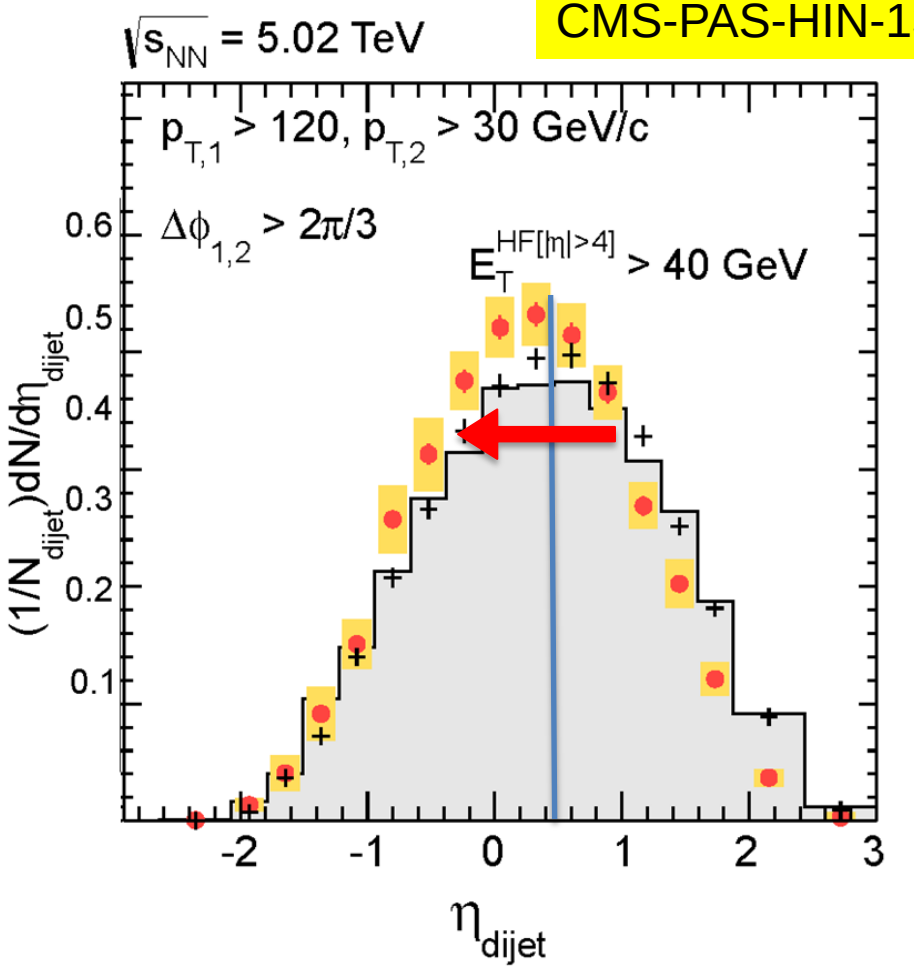
RpPb with PYTHIA reference



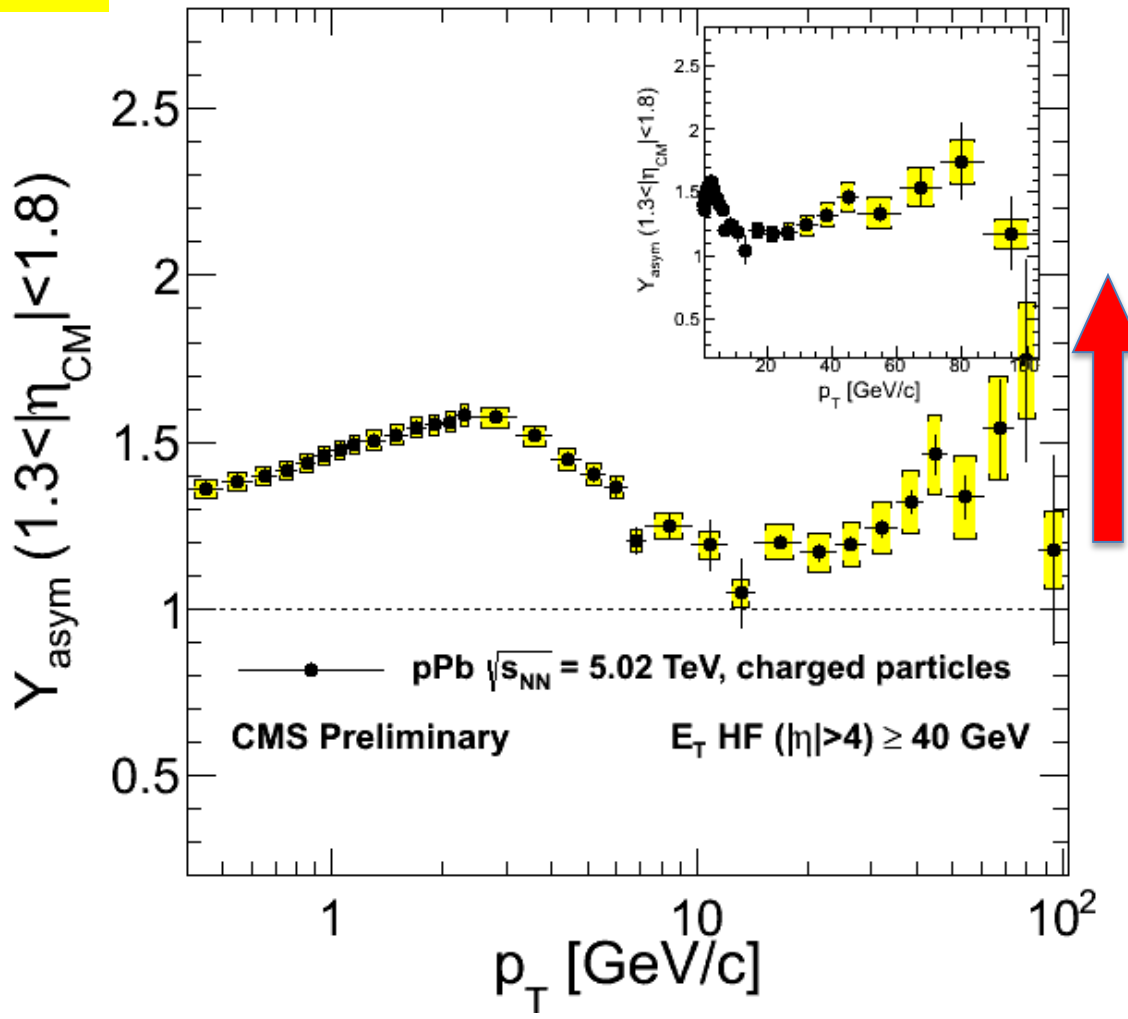
CMS-PAS-HIN-12-017

Large event activity

CMS-PAS-HIN-13-001



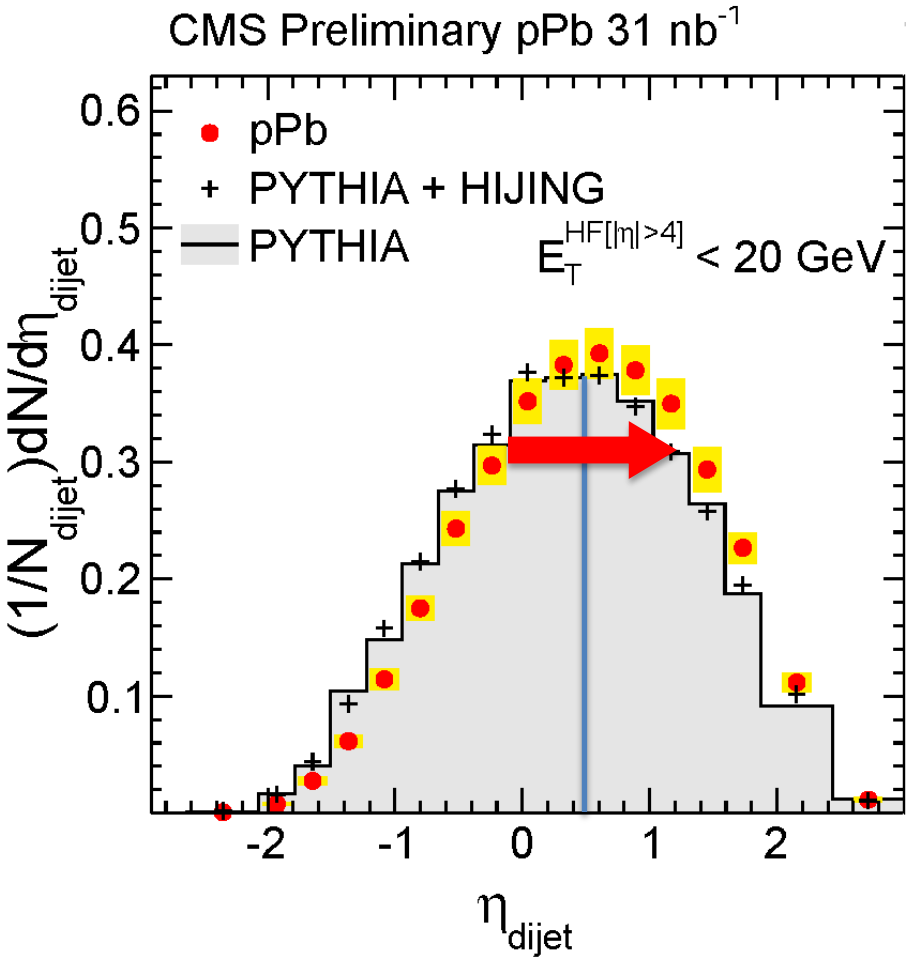
CMS-PAS-HIN-12-017



- Consistent picture from charged hadrons and dijets

Small event activity

CMS-PAS-HIN-13-001



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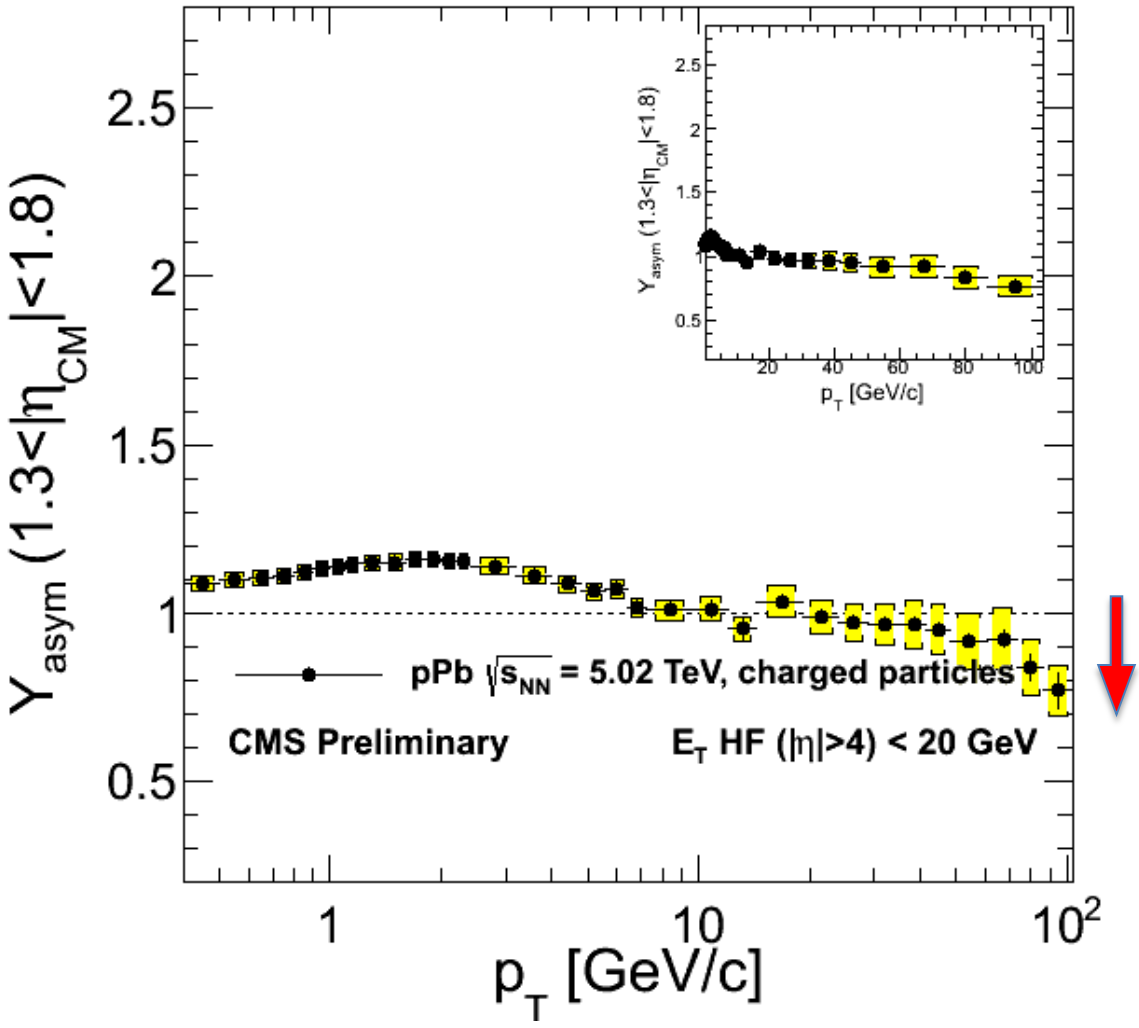

- Consistent picture from charged hadrons and dijets

Mean x vs p_T for charged hadrons: PYTHIA Z2

CMS-PAS-HIN-12-017