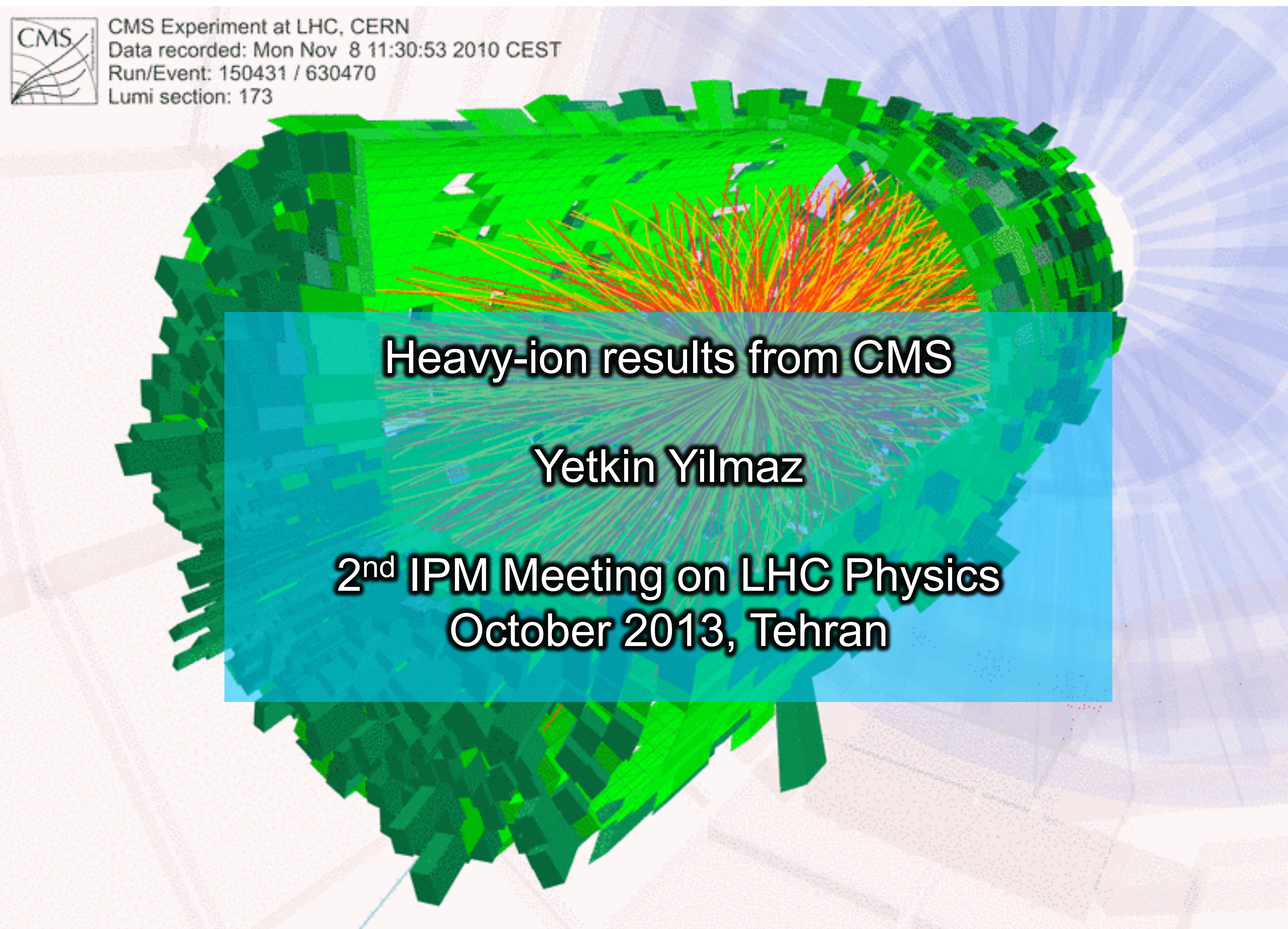
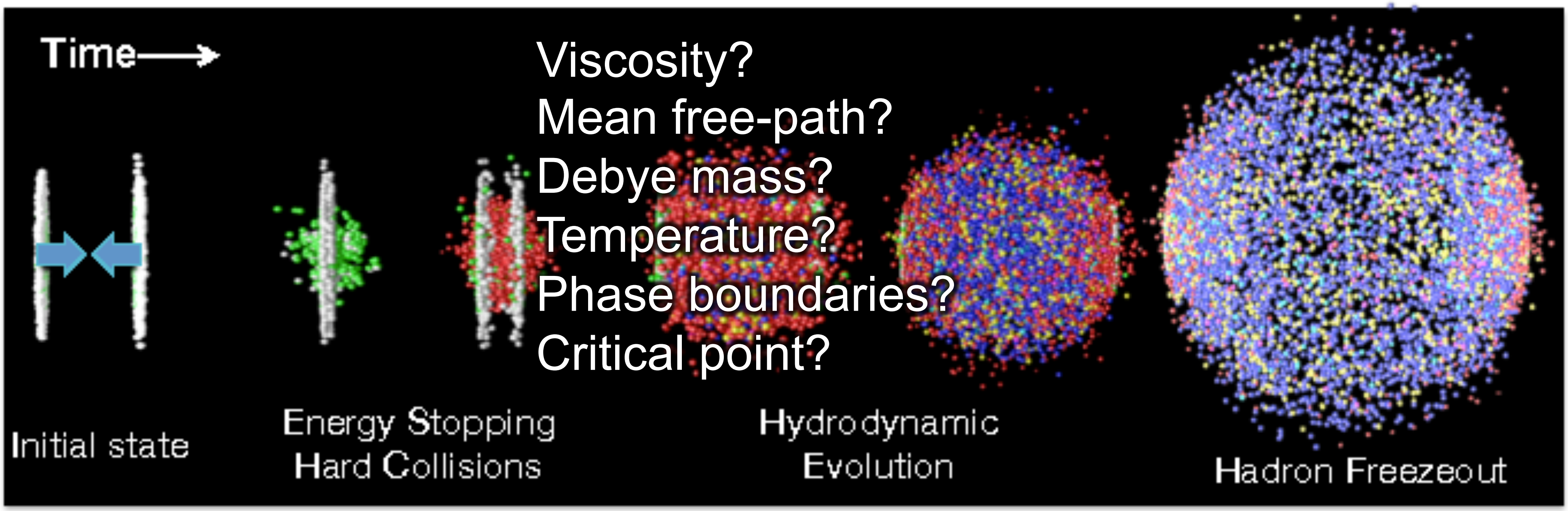


Heavy-ion results from CMS

Yetkin Yilmaz

2nd IPM Meeting on LHC Physics
October 2013, Tehran

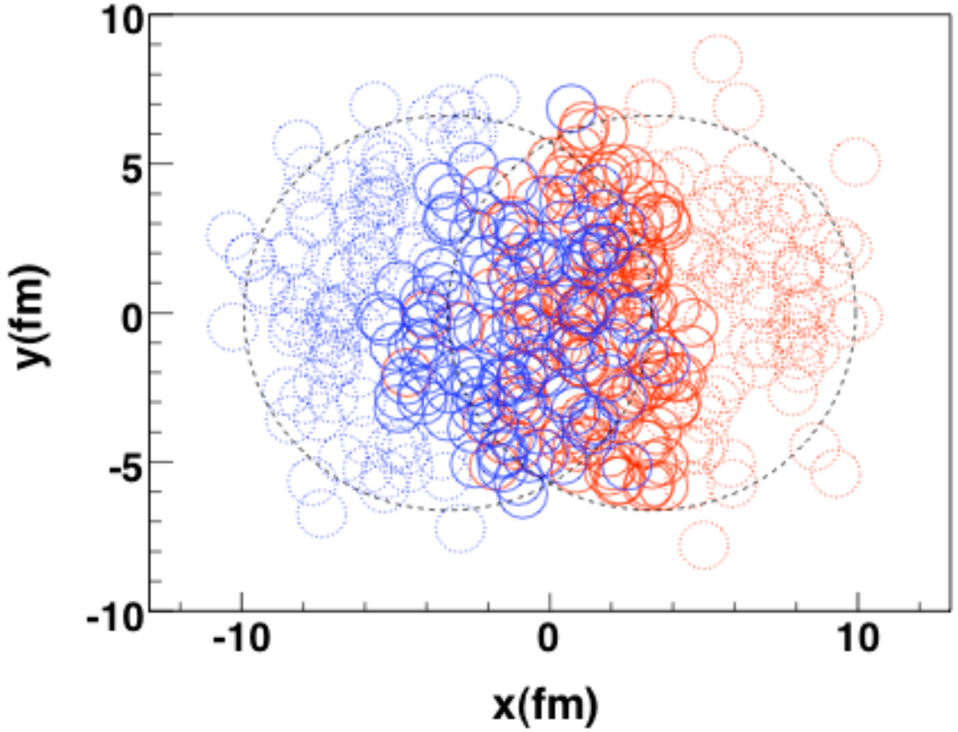
Physics of ion collisions



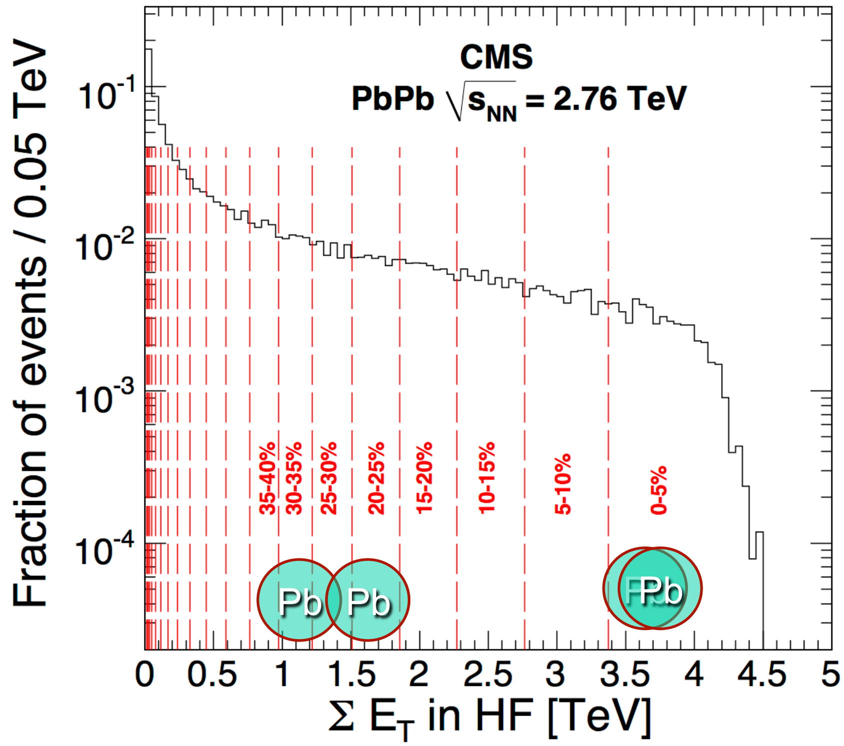
"soft" observables:
hadron multiplicity
p_T spectrum
angular correlations
azimuthal fourrier coefficients

"hard" observables:
jets, high-p_T hadrons
photons
electroweak bosons
quarkonia

Characteristics of ion collisions



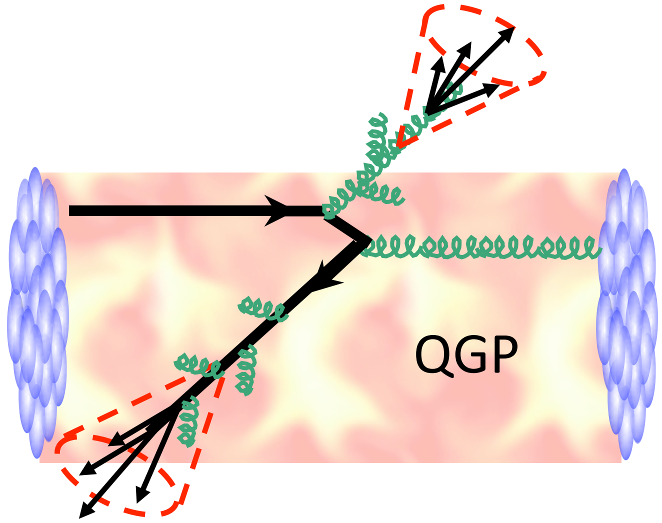
JHEP 08 (2011) 141

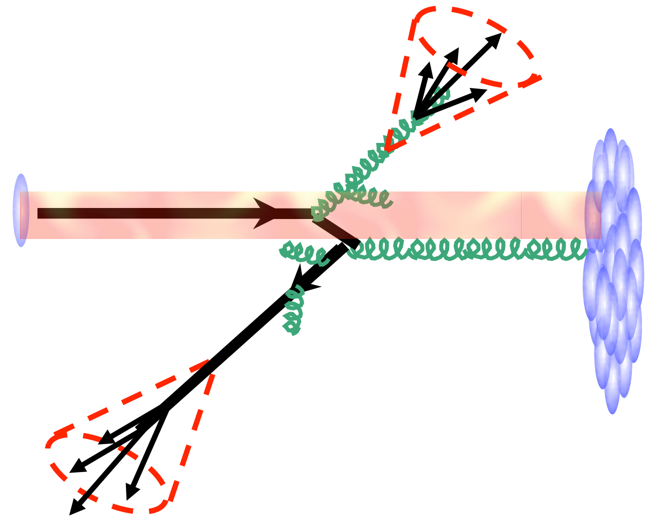


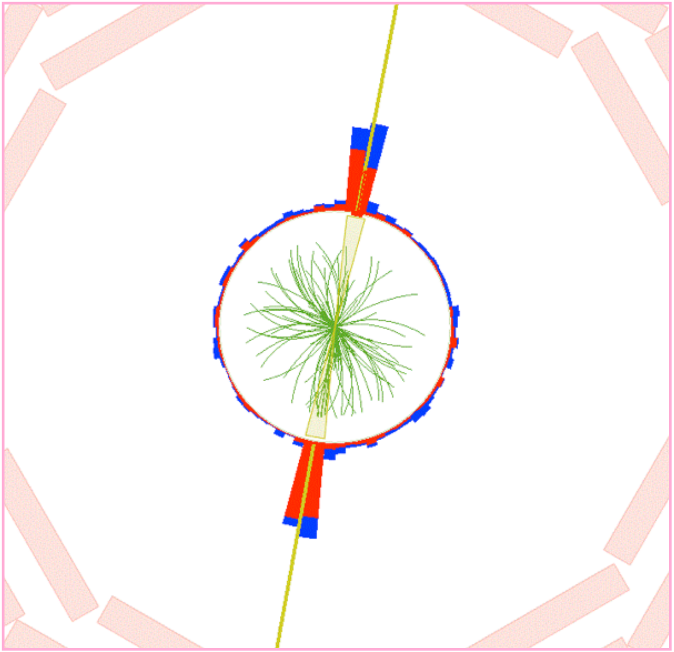
Centrality : the measure of how head-on a collision is, determined by total forward E_T (HF), expressed in fractions of cross-section (e.g. 0-10% of most central events)

N_{part} : Number of "participating" nucleons

New QCD playground: pPb colisions

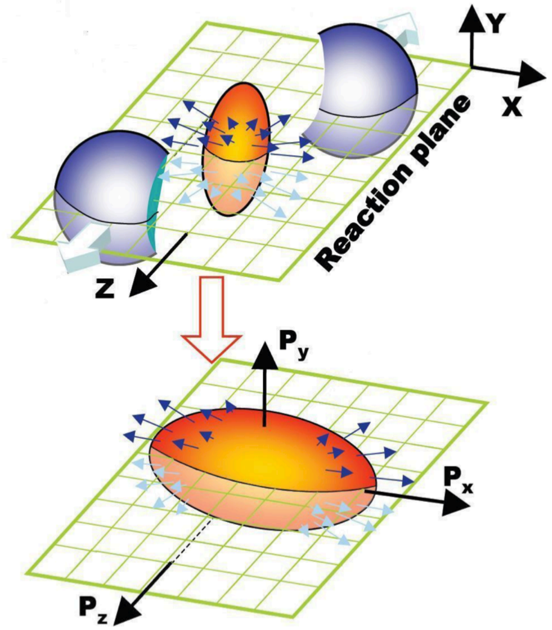






- 31 nb^{-1} data collected in 2013
- Baseline for PbPb collisions
  - Cold nuclear effects, nPDFs
  - Medium effects at lower density?

Anisotropic Flow



Initial State Spatial Anisotropy

↓

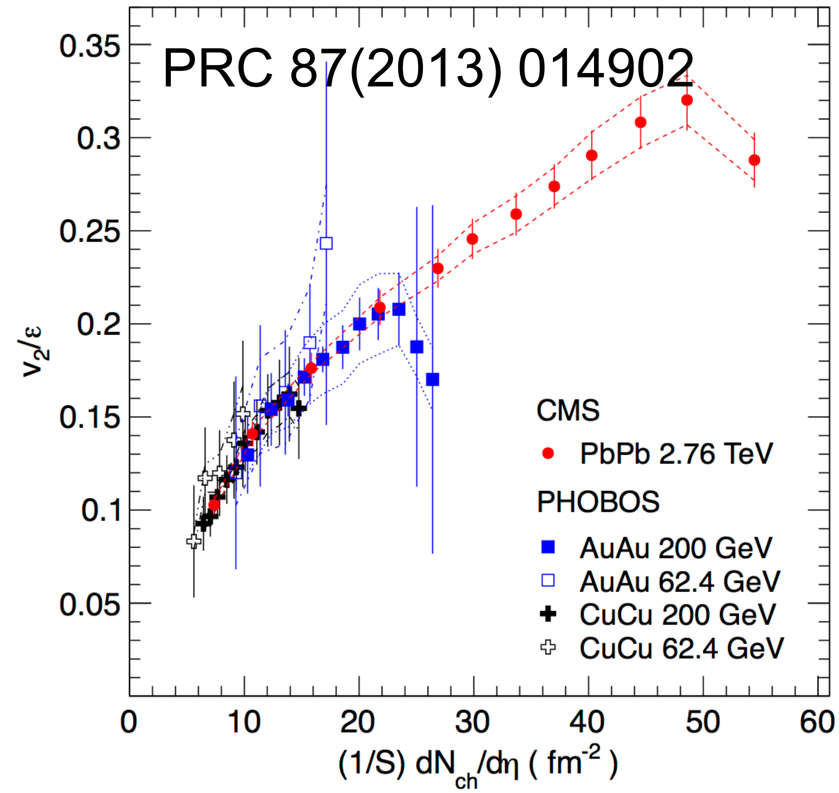
Pressure Driven Expansion

↓

Final State Momentum Anisotropy

The azimuthal dependence of the particle yield with respect to the reaction plane can be expanded in a Fourier series:

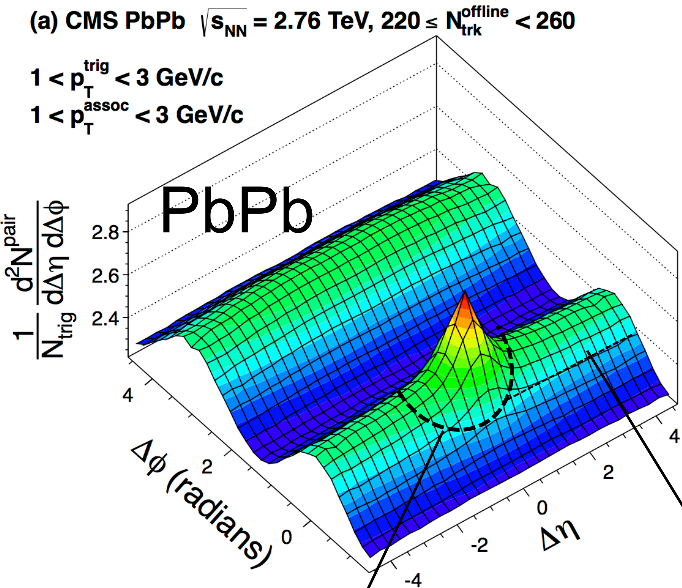
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left[n\left(\varphi - \Psi_R\right)\right]\right)$$

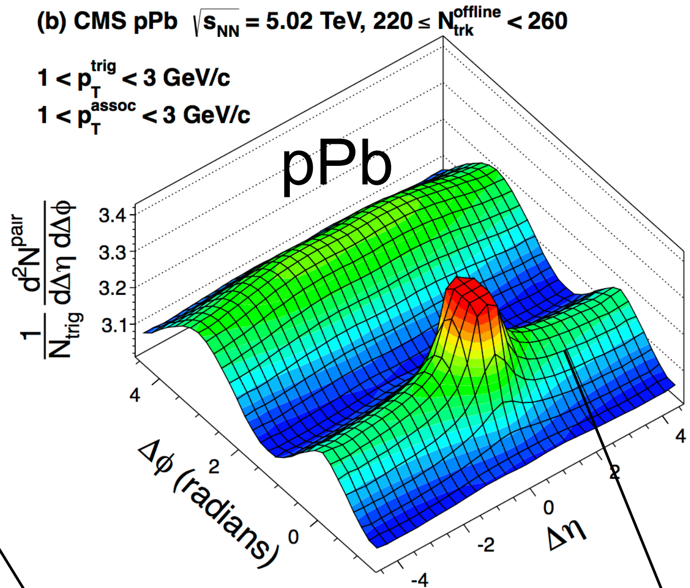


- Ψ_R is the 'event plane angle'
- v_2 is known as 'elliptic flow'
- 'higher harmonics' (v_n) also measured

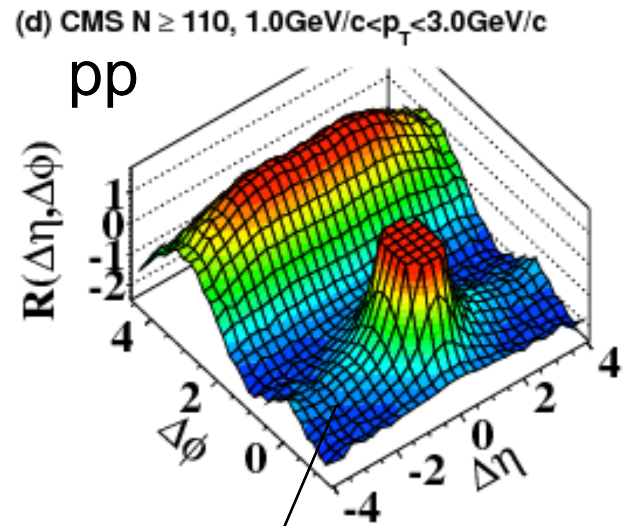
Correlations in PbPb, pPb and pp

PLB 724 (2013) 213





JHEP 1009:091,2010



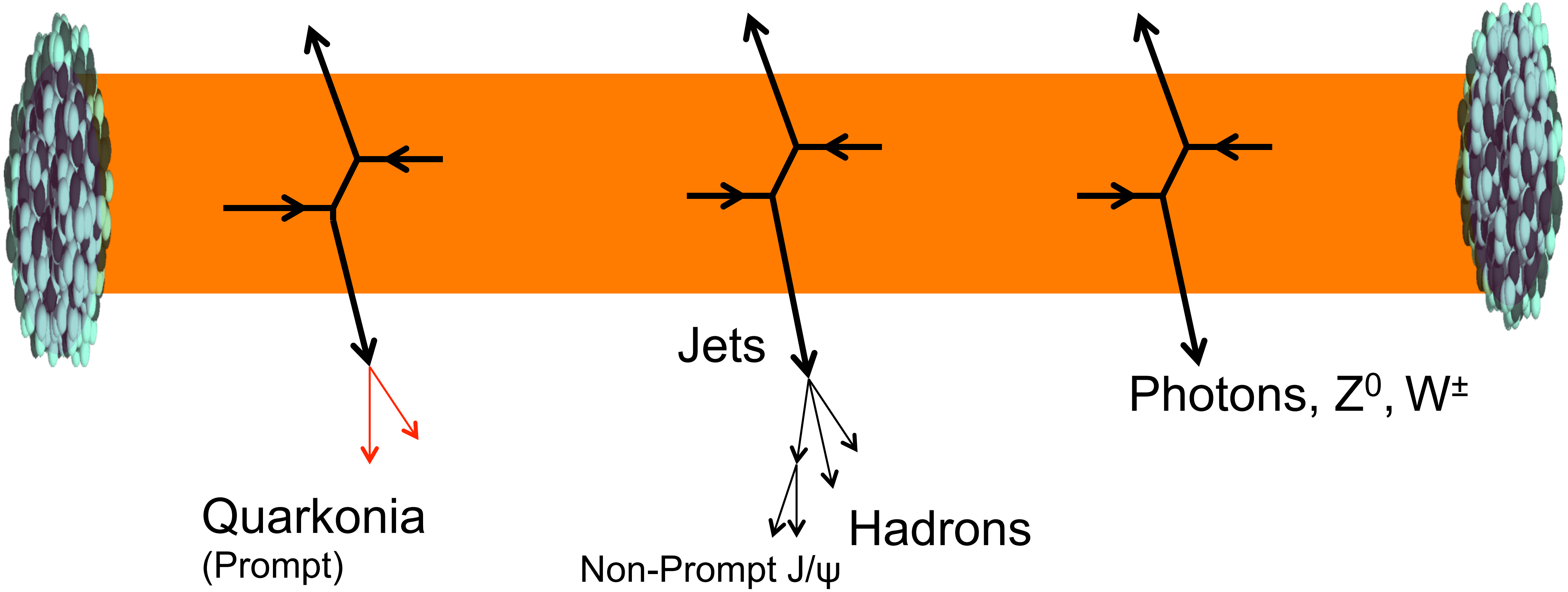
Jet-like correlations

Flow-like correlations

Also present in pPb and very high multiplicity pp

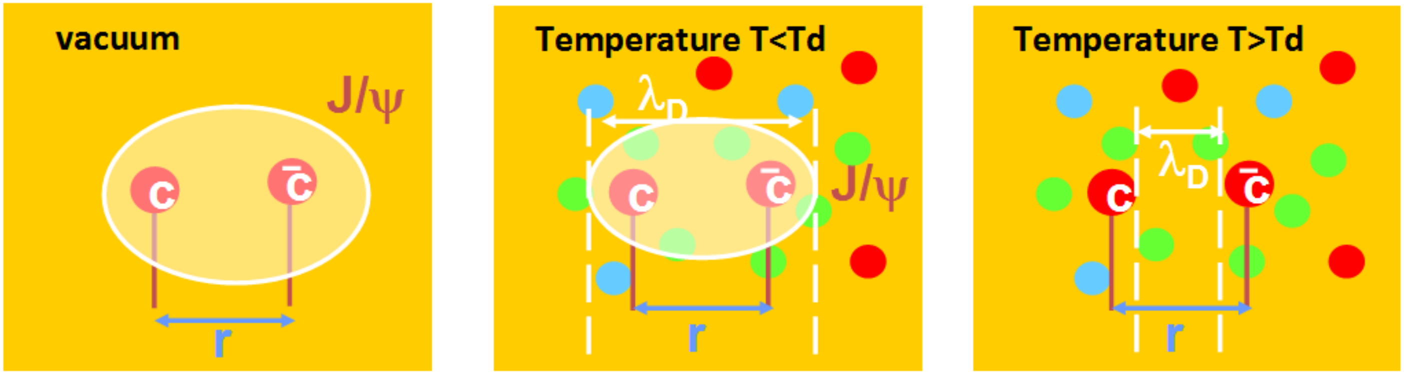
Hard Probes

Hard processes in vacuum:
Well understood in pQCD
Measured in pp collisions
What happens to final state, in hot, dense medium?

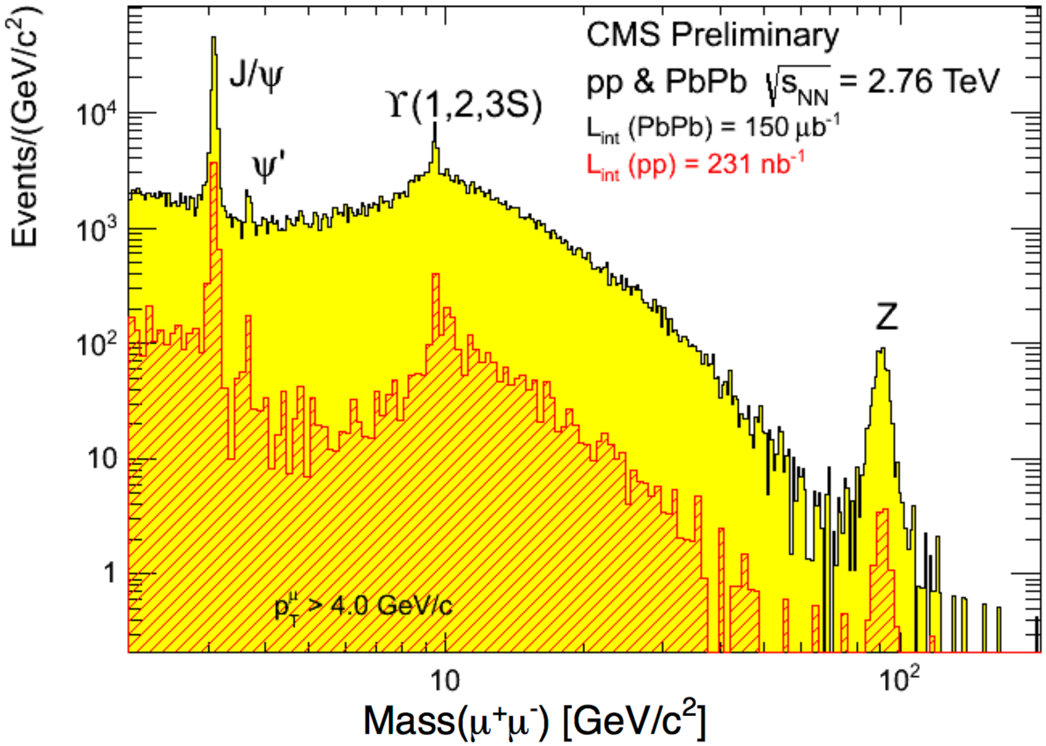


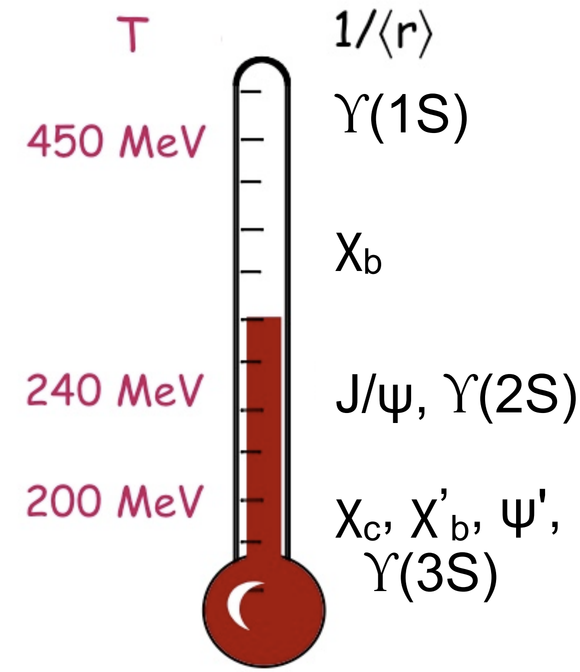
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

QGP thermometer: Quarkonia states



Matsui & Satz, PLB168 (1986) 415





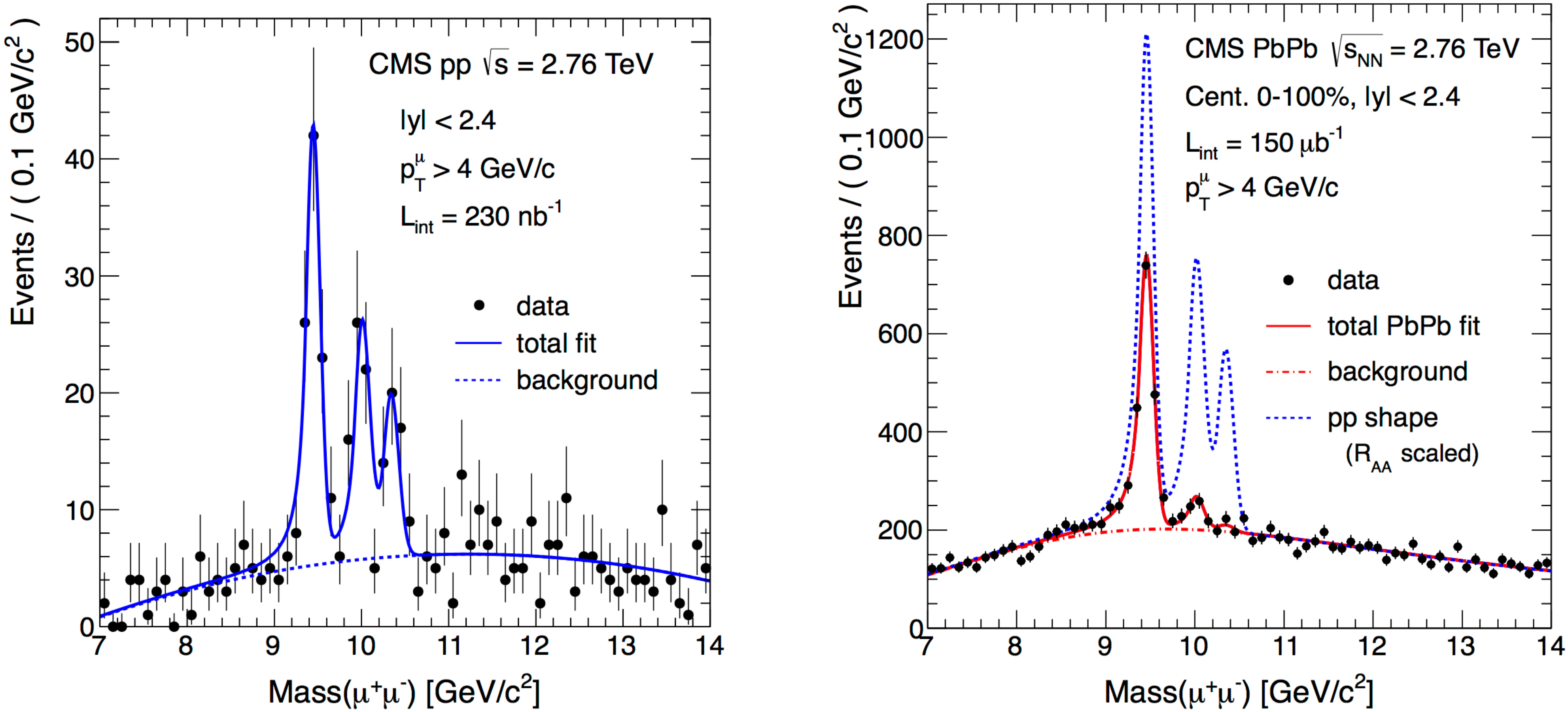
Mocsy, EPJC61 (2009) 705

Other effects (initial state, cold matter, recombination) also take role in the observed cross-sections

theory tries to incorporate all

QGP thermometer: Quarkonia states

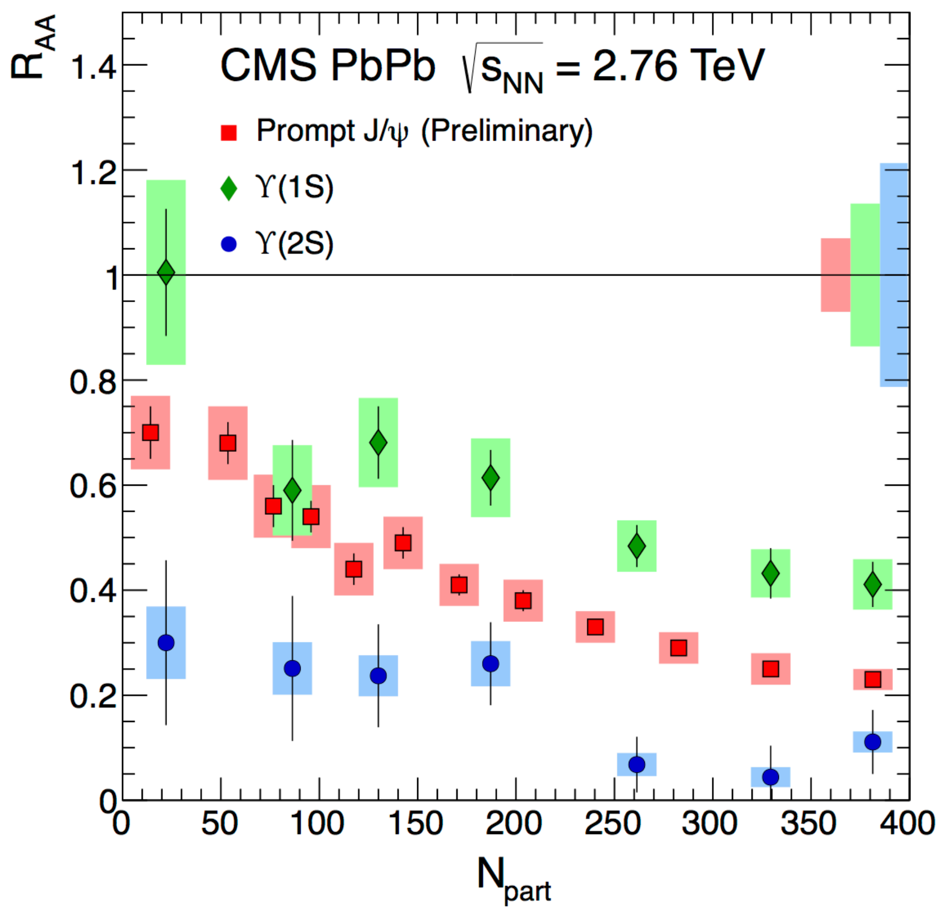
PRL 109 (2012) 222301

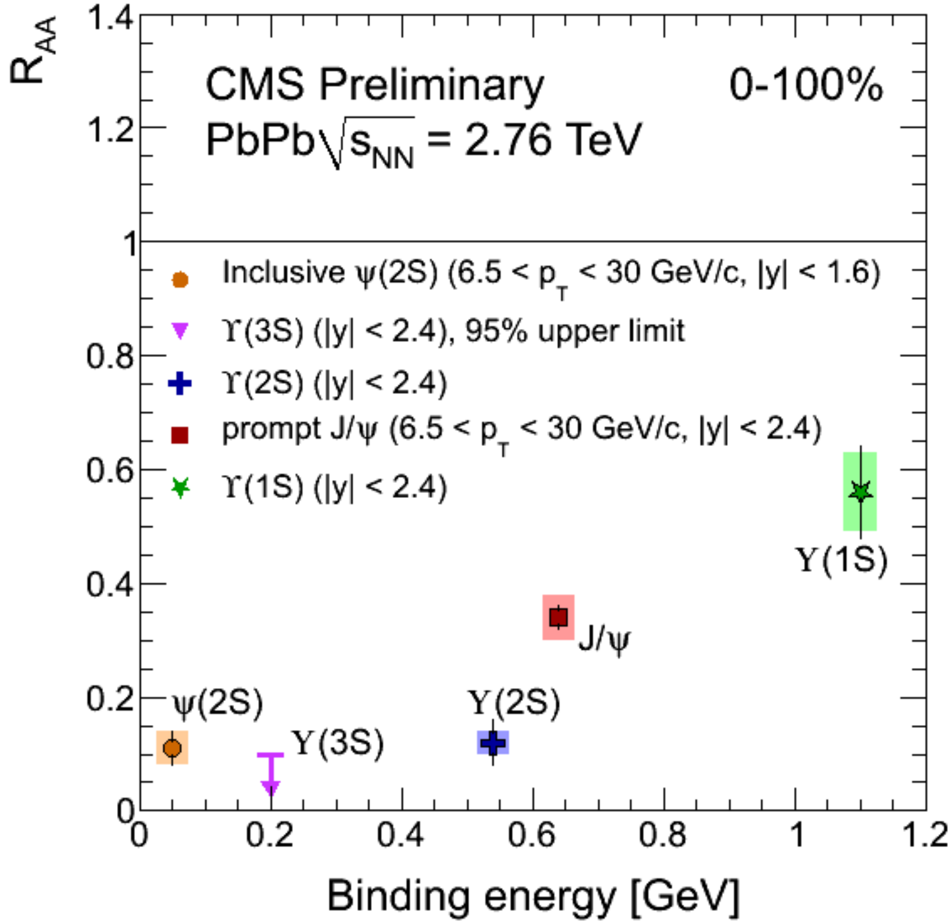


Upsilons suppressed, especially the higher states

QGP thermometer: Quarkonia states

CMS-PAS-HIN-12-014

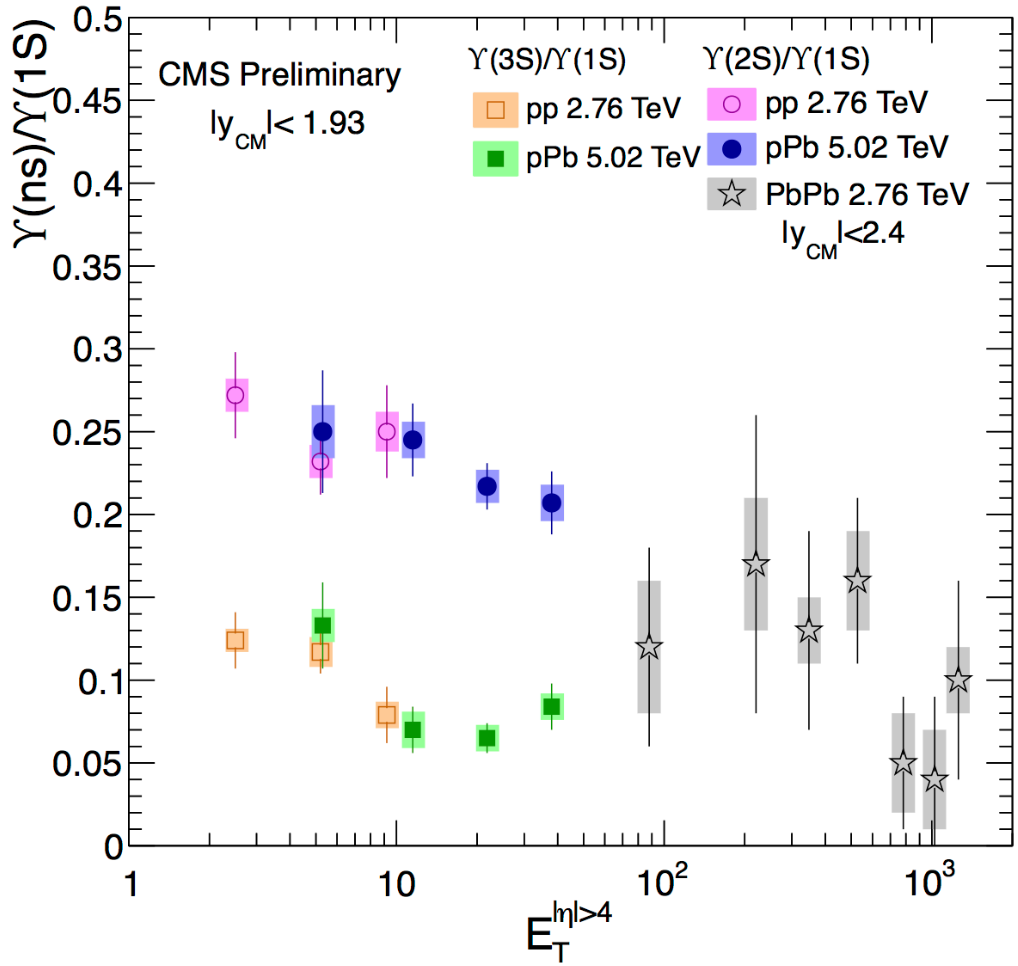




At high temperature, the excited states are dissociated first (more)

More surprises: Suppression in pPb

CMS-PAS-HIN-13-003



Multiplicity dependence of relative suppression

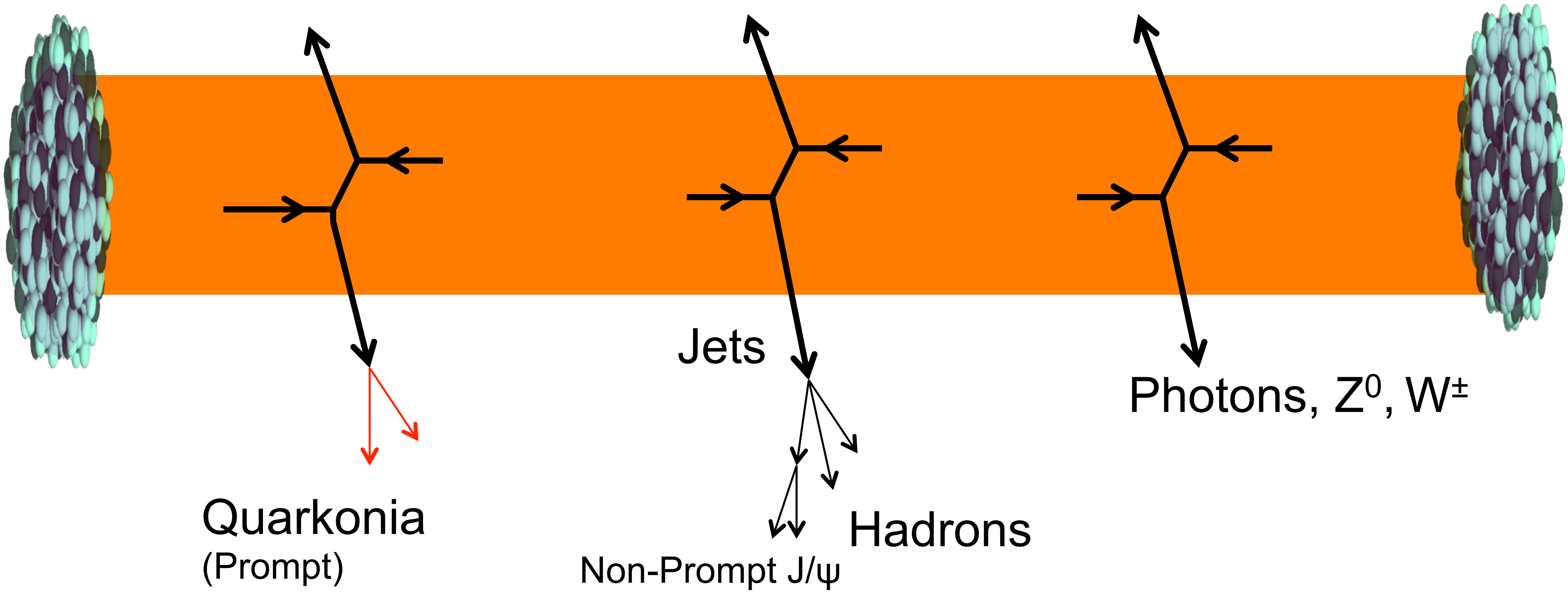
Hints of similar trend in pp

Initial-state effect?

Melting?

Medium tomography with jets and electroweak bosons

Partons, having color charge, lose energy while traversing the medium
Colorless electroweak bosons leave medium unaffected

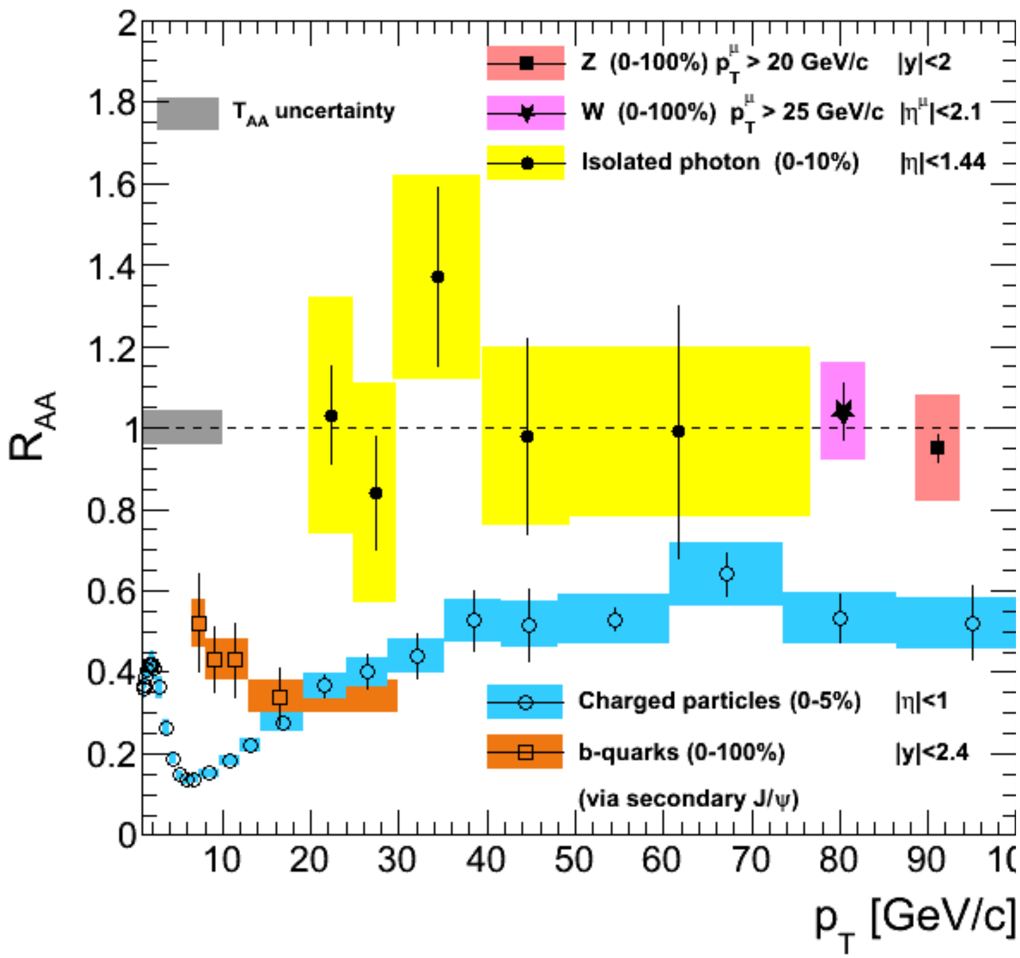


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

Nuclear Modification Factor (R_{AA})

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T\, d\eta}{d^2 \sigma_{pp}/dp_T\, d\eta} = \frac{\text{Rate in PbPb}}{\text{Rate expected from pp}}$$

PLB 710 (2012) 256 | JHEP 05 (2012) 063 | EPJC 72 (2012) 1945 | PLB 715 (2012) 66 | PRL 106 (2011) 212301



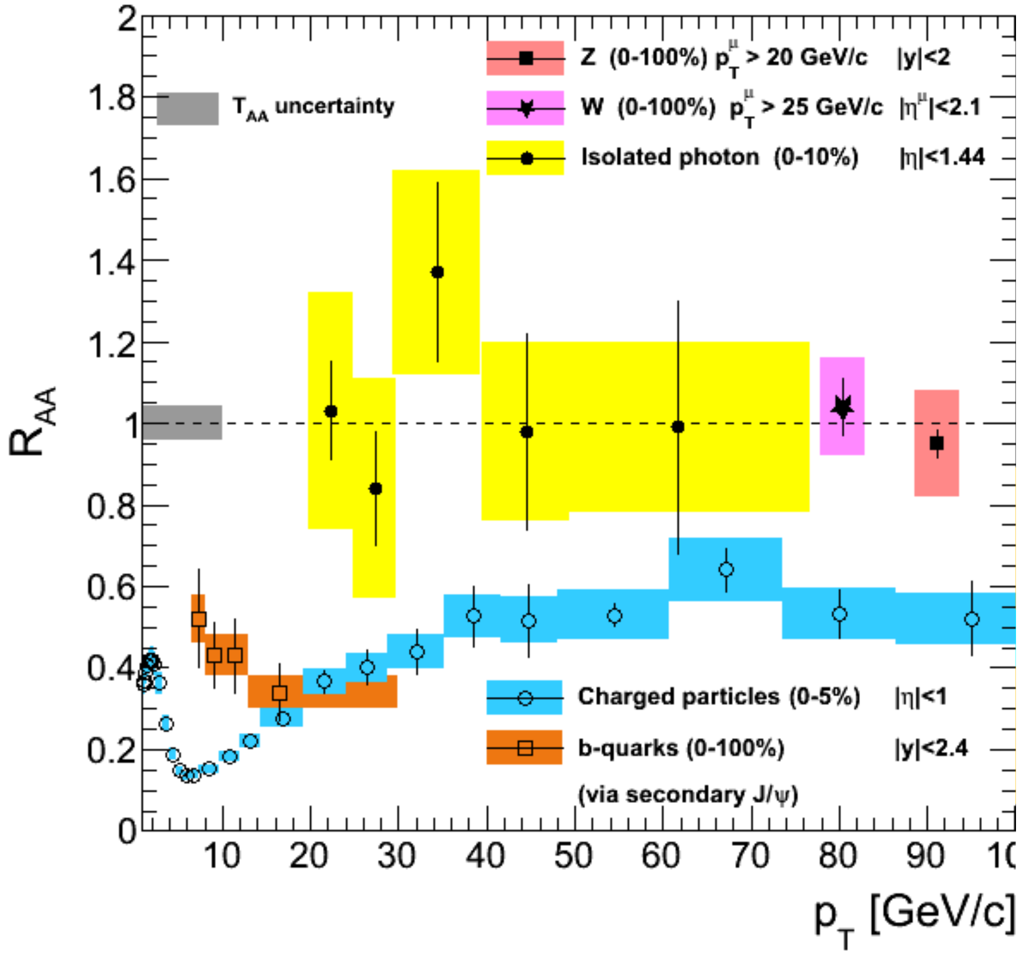
Colorless probes unmodified

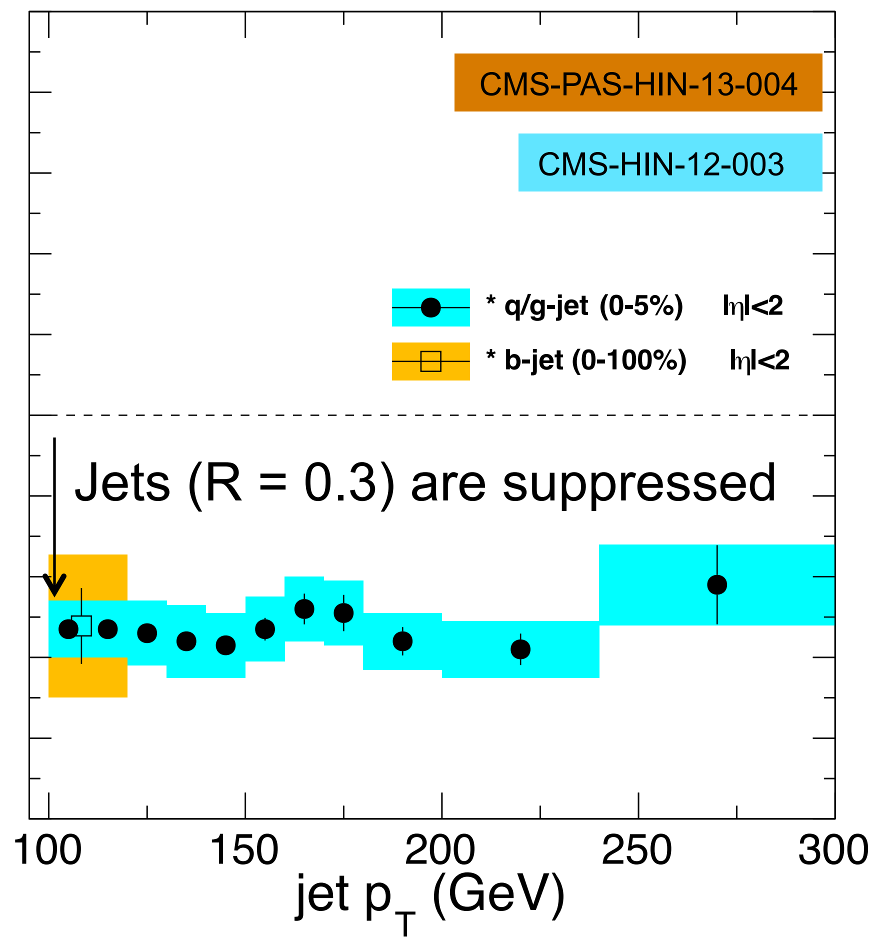
Hadrons suppressed
Is the energy still in the jet cone?

Nuclear Modification Factor (R_{AA})

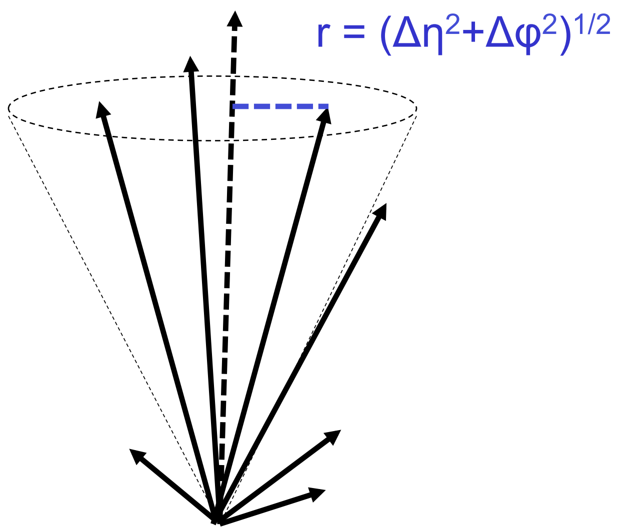
$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta} = \frac{\text{Rate in PbPb}}{\text{Rate expected from pp}}$$

PLB 710 (2012) 256 | JHEP 05 (2012) 063 | EPJC 72 (2012) 1945 | PLB 715 (2012) 66 | PRL 106 (2011) 212301

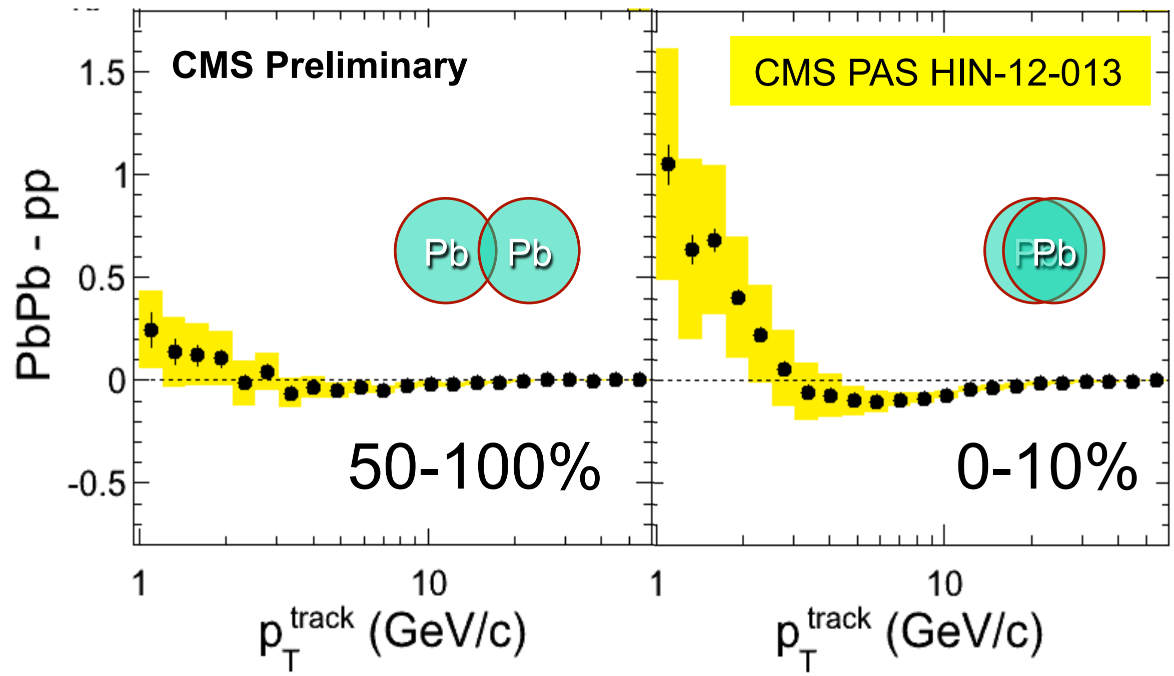




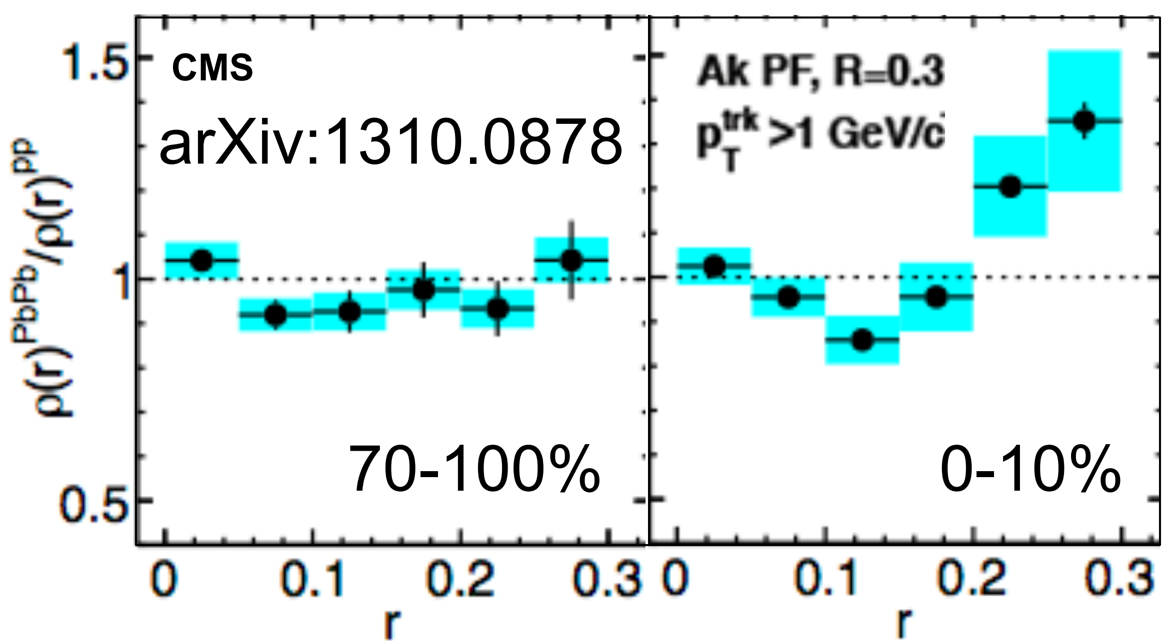
Jet shape and fragmentation



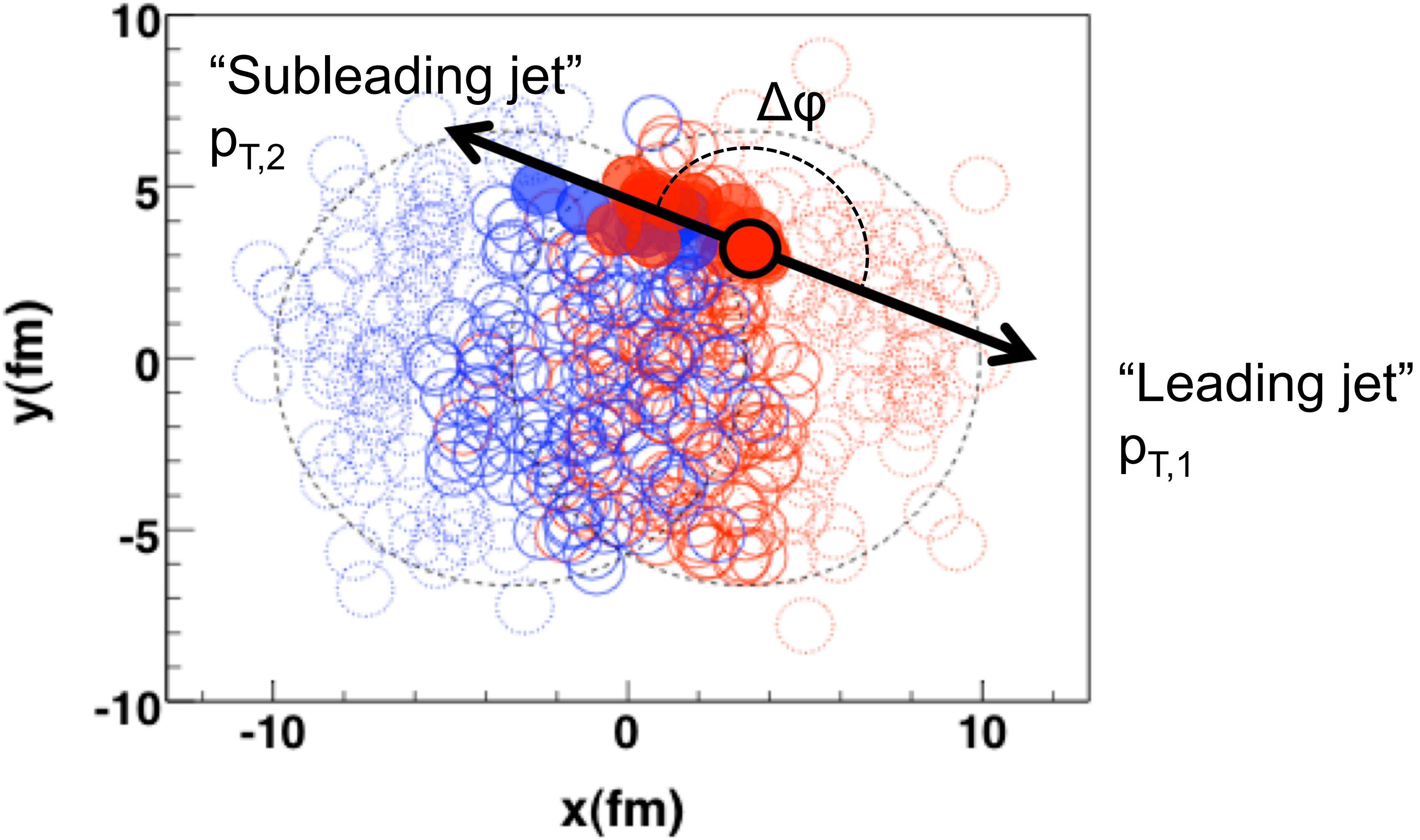
PbPb / pp
Fragmentation
Function Ratio



PbPb / pp
Jet shape
Ratio



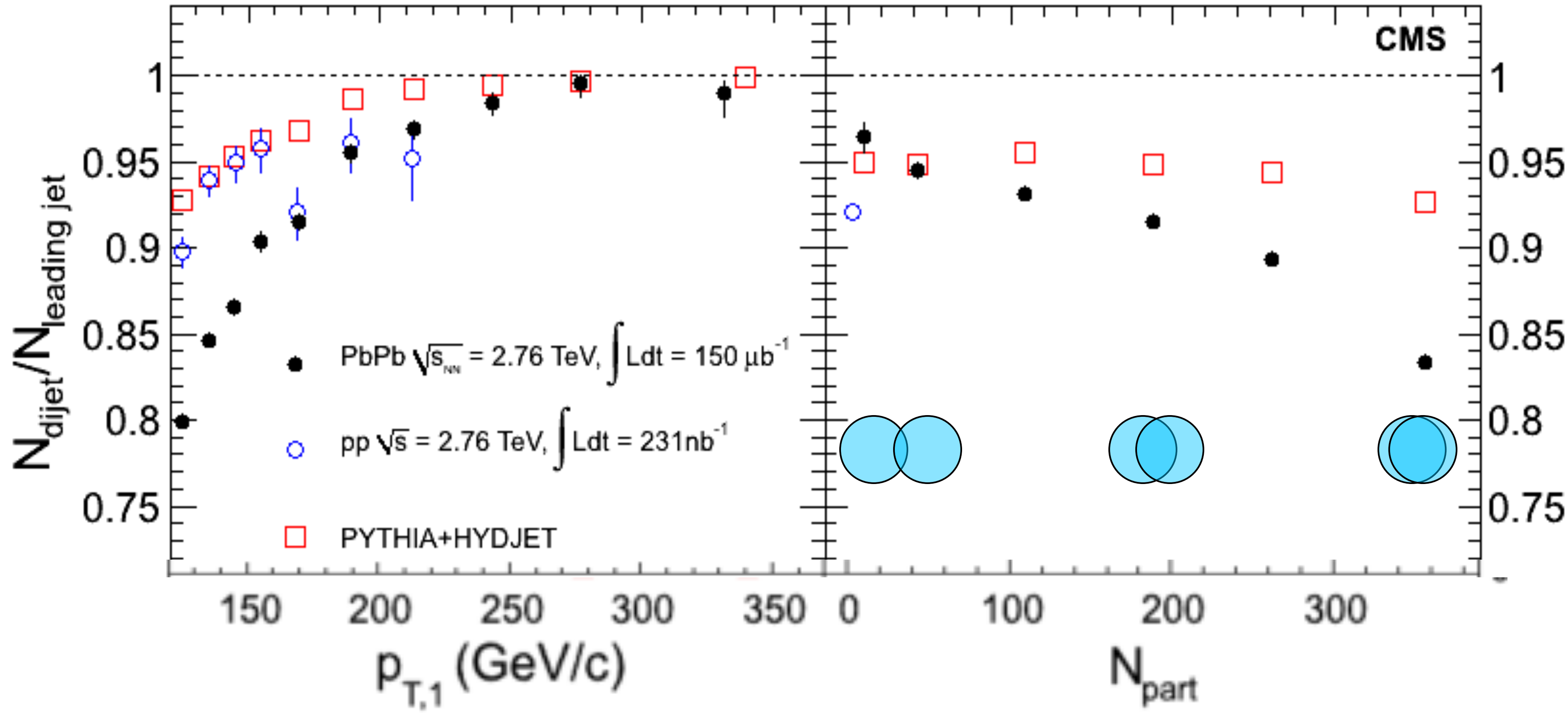
Dijet correlations



- Inclusive study samples all path-length configurations
- Dijet study reveals de-correlations due to different path-length between jets:
  The less path observed by one jet, the more observed by the other

Dijet correlations

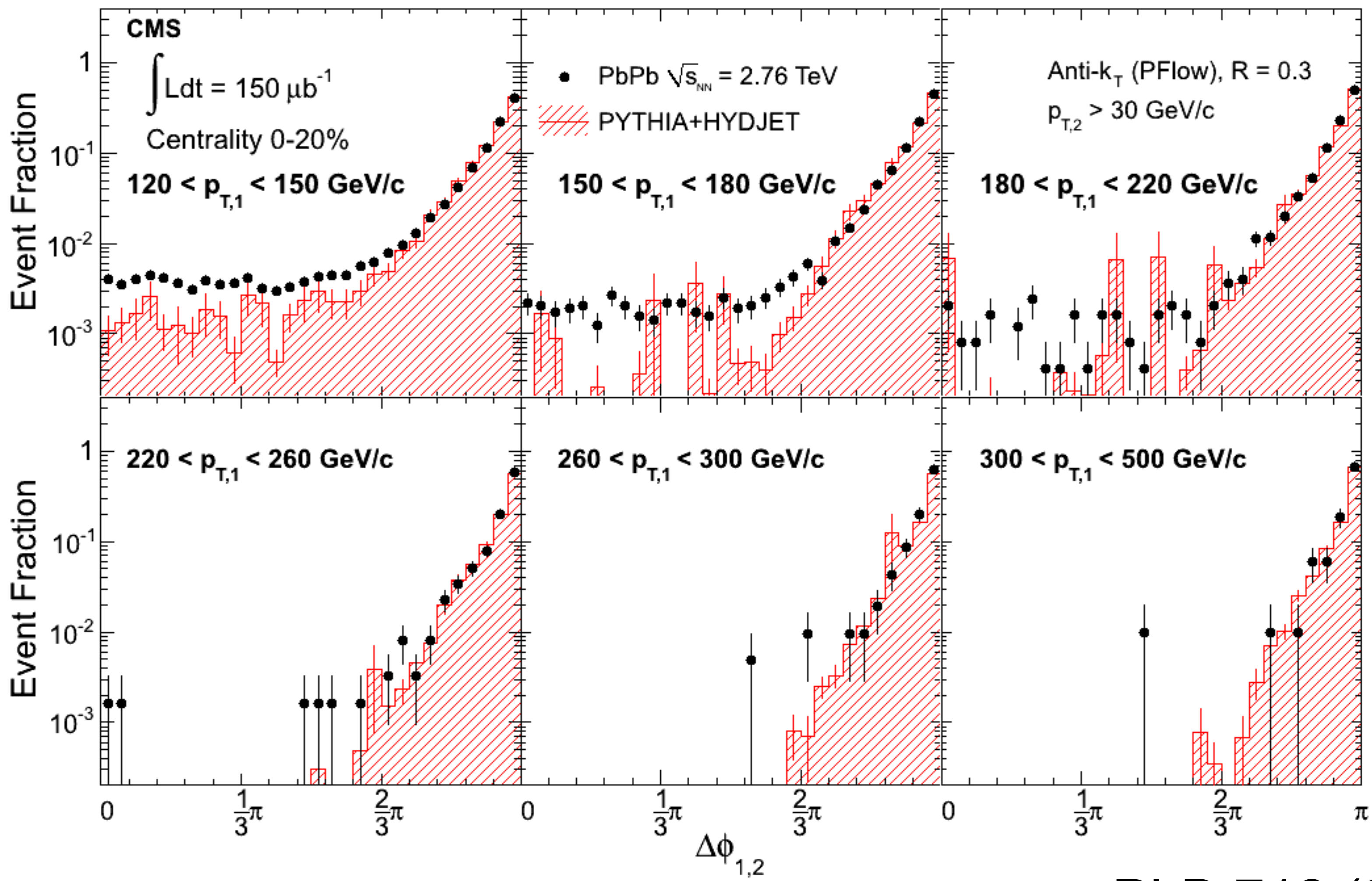
PLB 712 (2012) 176



At very high-p_T, all away-side jets remain above threshold despite the quenching

More jets are quenched below the threshold in more central events

Azimuthal correlations of dijets



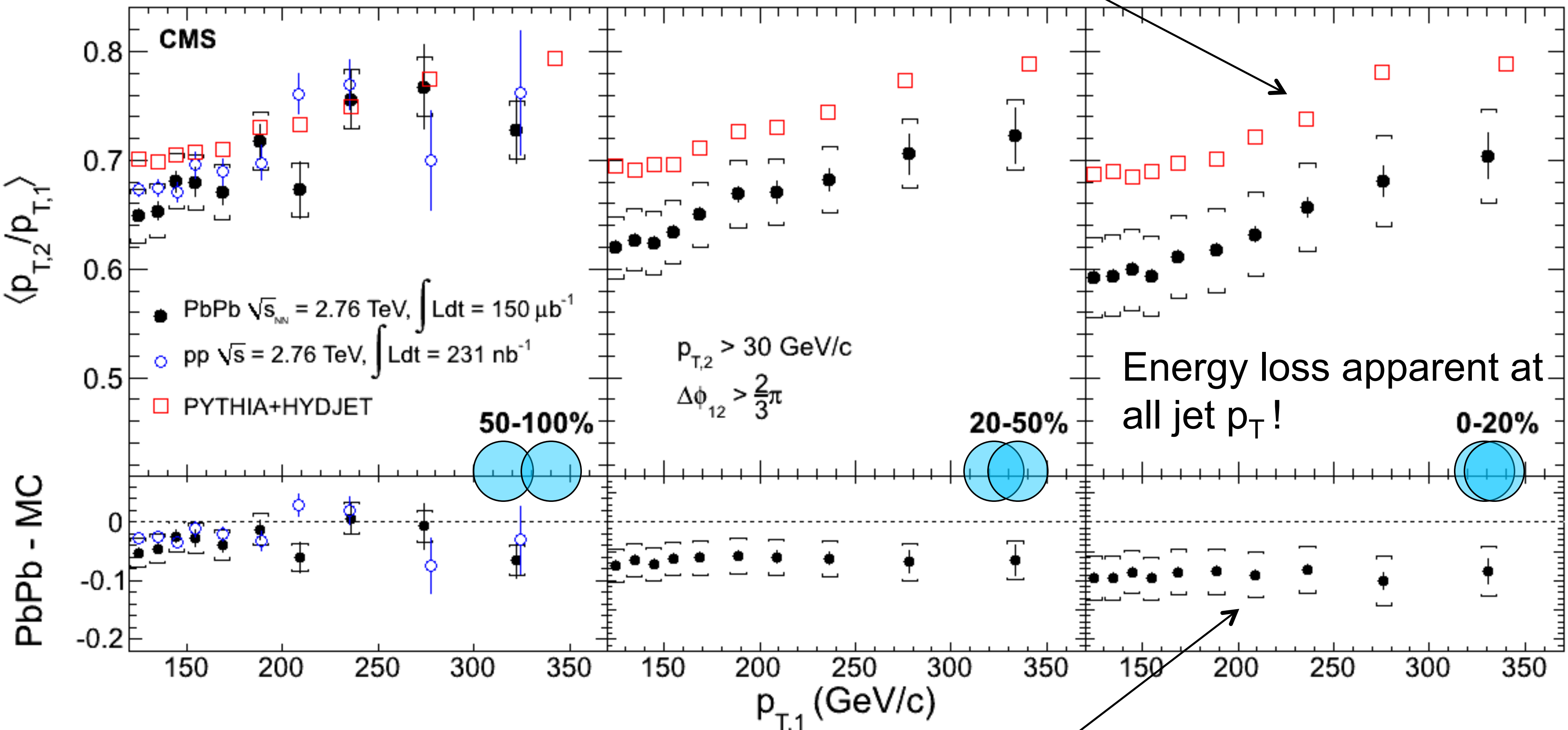
PLB 712 (2012) 176

Dijets are most of the time back-to-back,
with similar pattern to expectation,
background amounts slightly different than reference

p_T-dependence of the dijet imbalance

Reference itself has an increasing trend

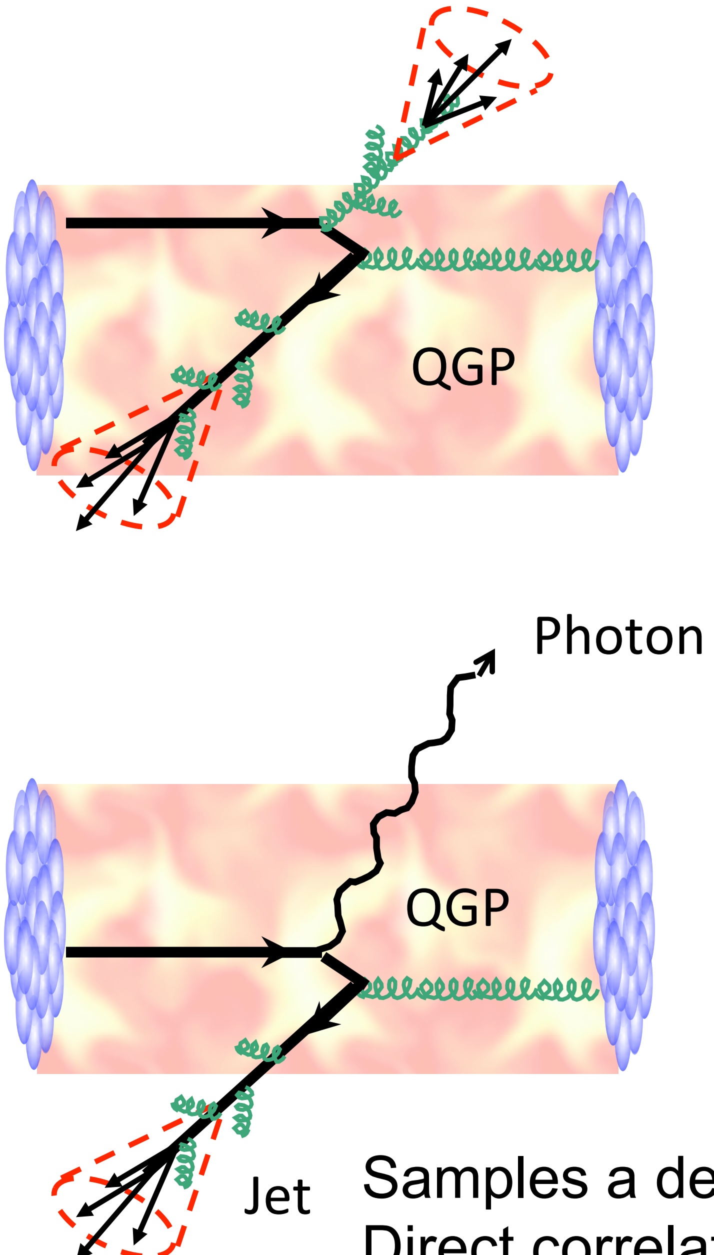
PLB 712 (2012) 176



Energy loss apparent at all jet p_T !

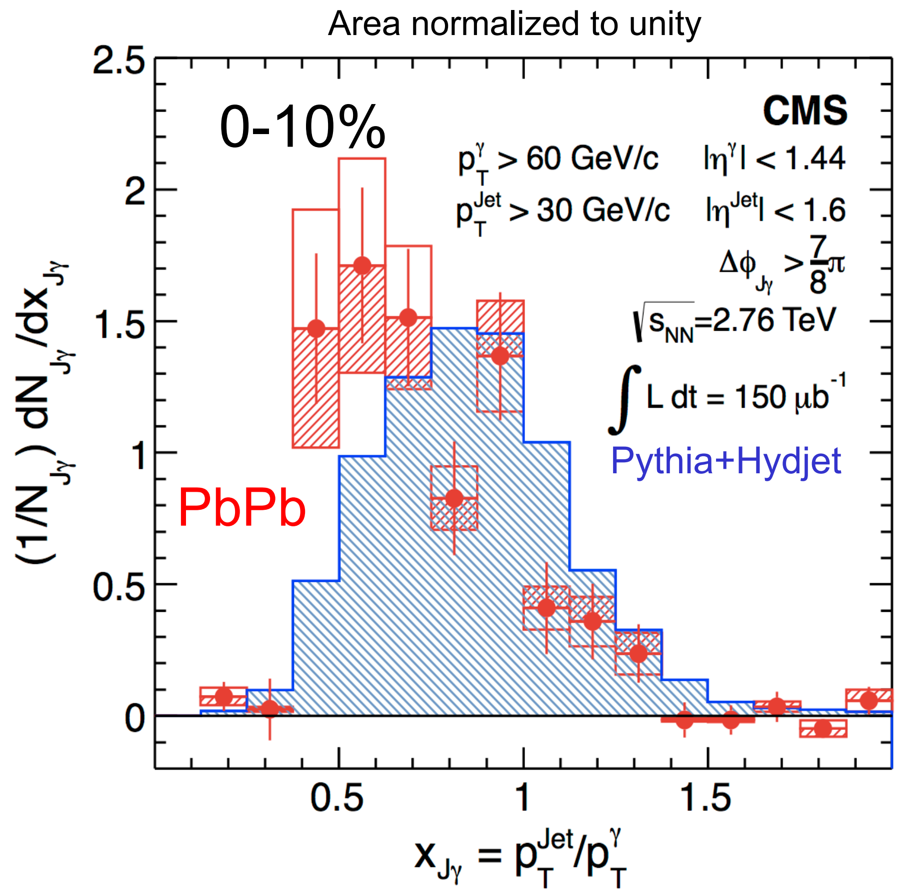
Quenching exists through all jet p_T

Tagging parton energy with photons



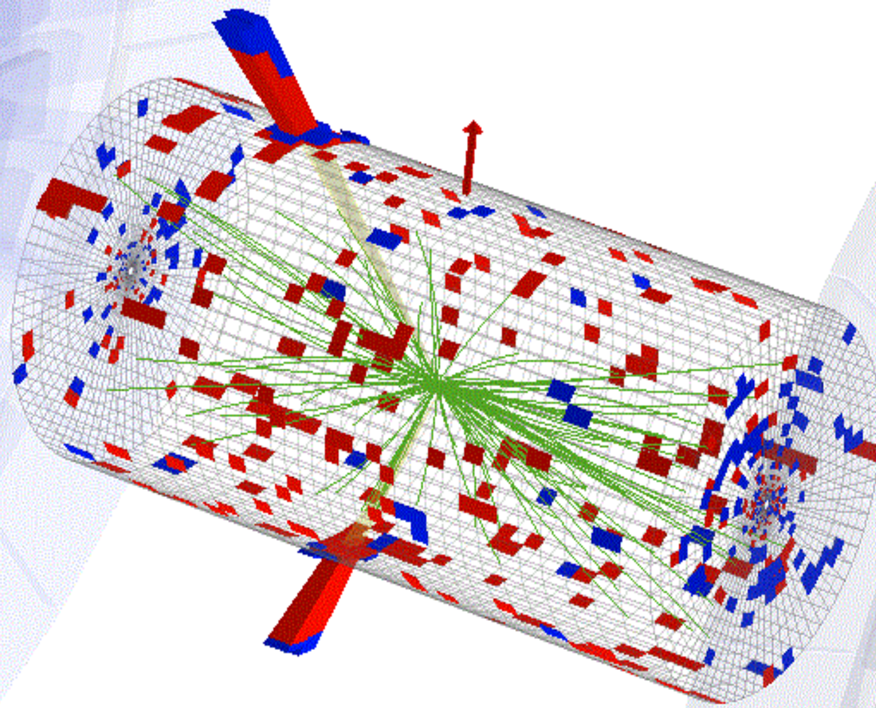
Samples a deeper medium
Direct correlation to initial parton

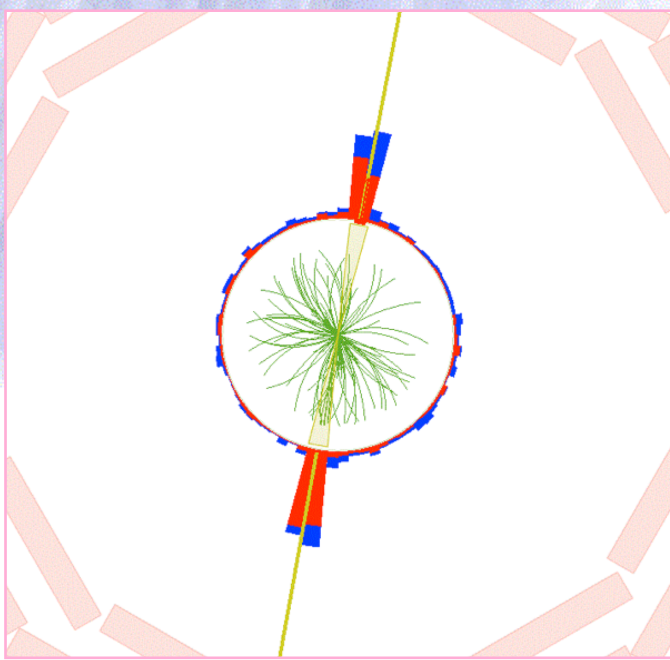
PLB 718 (2013) 773



Photon-jet momentum balance
Jet p_T / Photon p_T

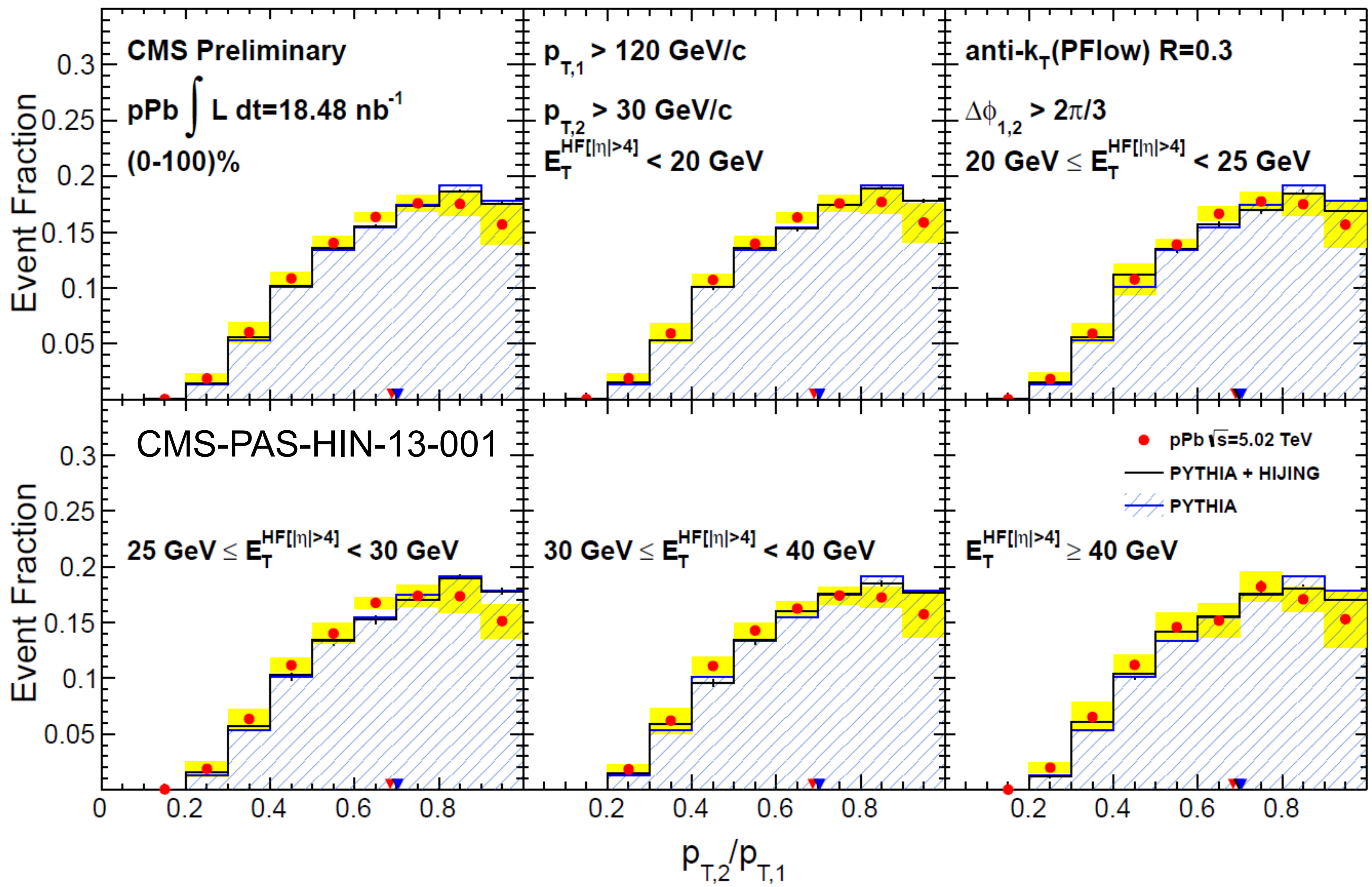
Dijets in pPb





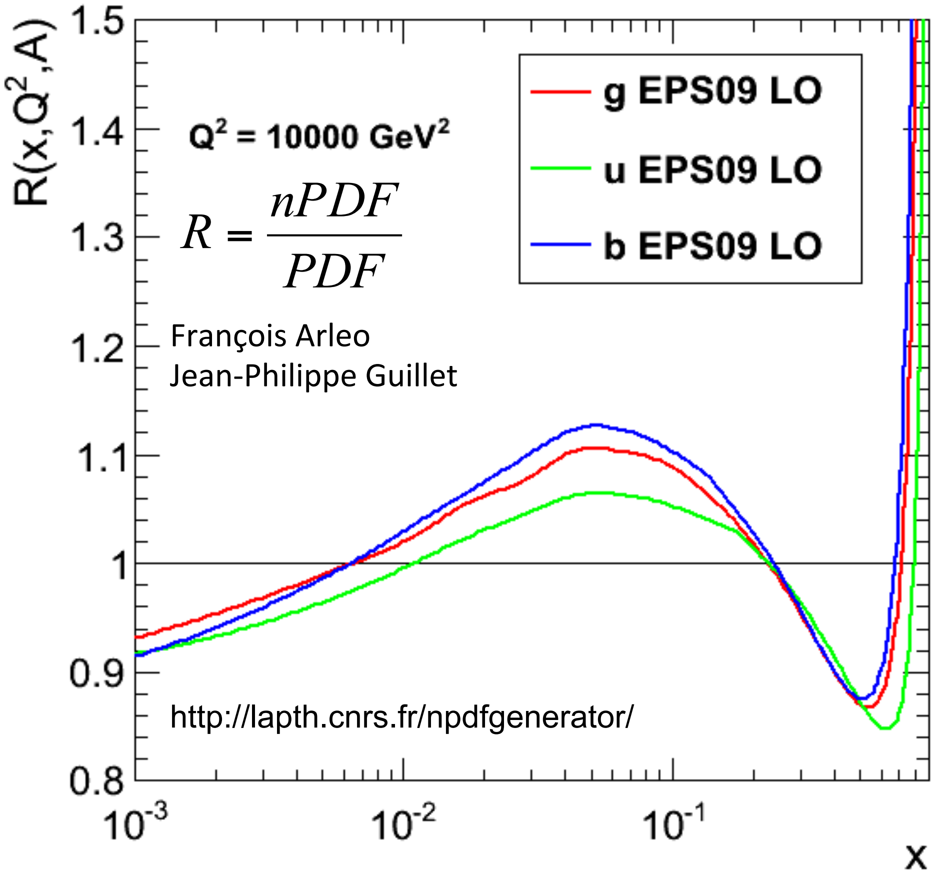
2012 pPb 1 μb^{-1}
2013 pPb 31 nb^{-1}

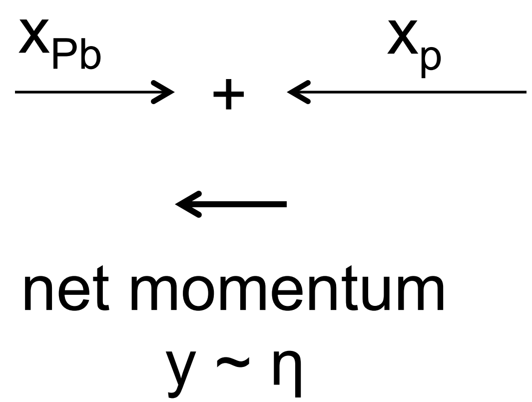
Dijets in pPb



Balance of jets not modified
No indication of energy loss

Dijet pseudorapidity and nuclear PDF





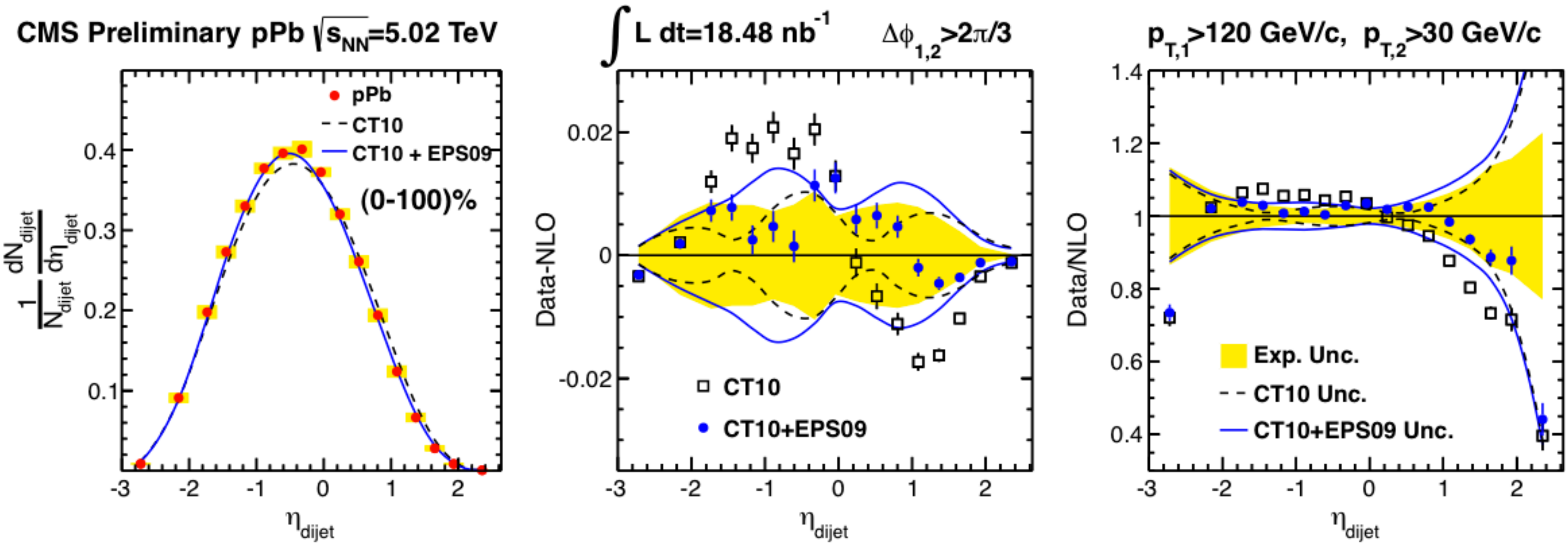
Dijet pseudorapidity $\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$ is a variable that is sensitive to the x of the parton from the Pb

Dijet pseudorapidity and nuclear PDF

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

The pseudorapidity distribution of dijets display similar pattern to expected nuclear effects

CMS-PAS-HIN-13-001



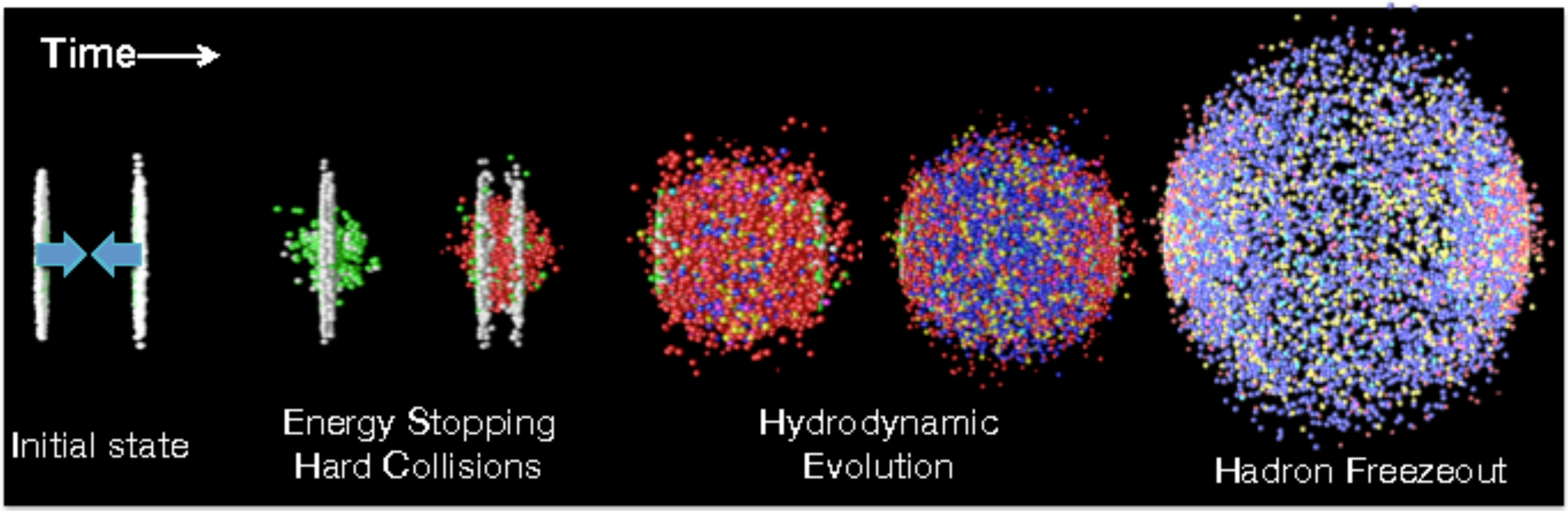
More...

CMS has performed many other measurements

- Higher-order harmonics of hydrodynamic flow
- Identified particle spectra, in PbPb, pPb, pp
- Forward energy measurements, up to $\eta = 6$
- Ultra-peripheral collisions

...

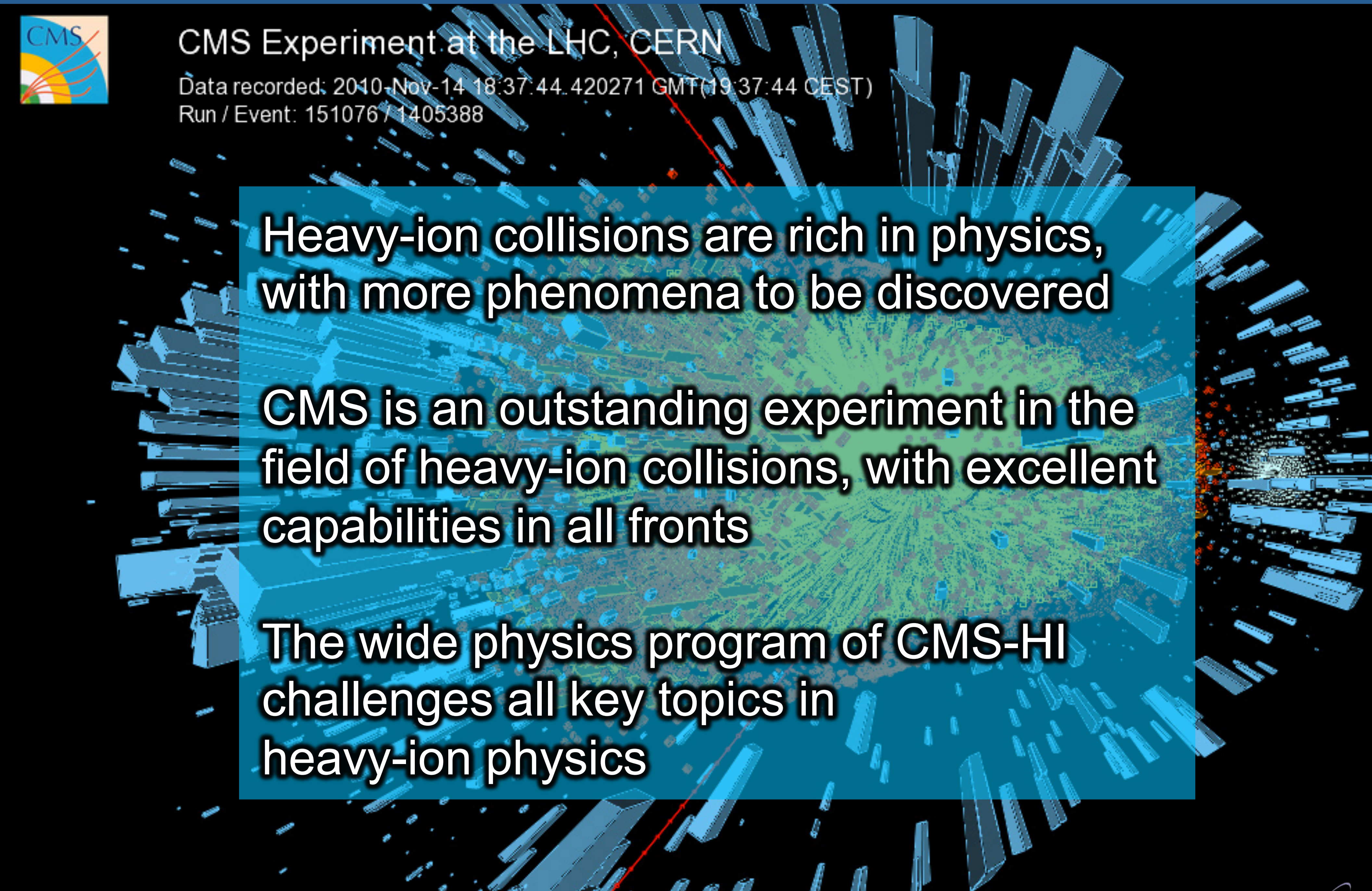
Lessons from the QGP



Many lessons learned

- Hydrodynamic flow
- p_T and centrality dependence of quenching
- Sequential suppression of quarkonia states
- Nuclear PDFs
- Collective effects in pp & pPb collisions

Final words



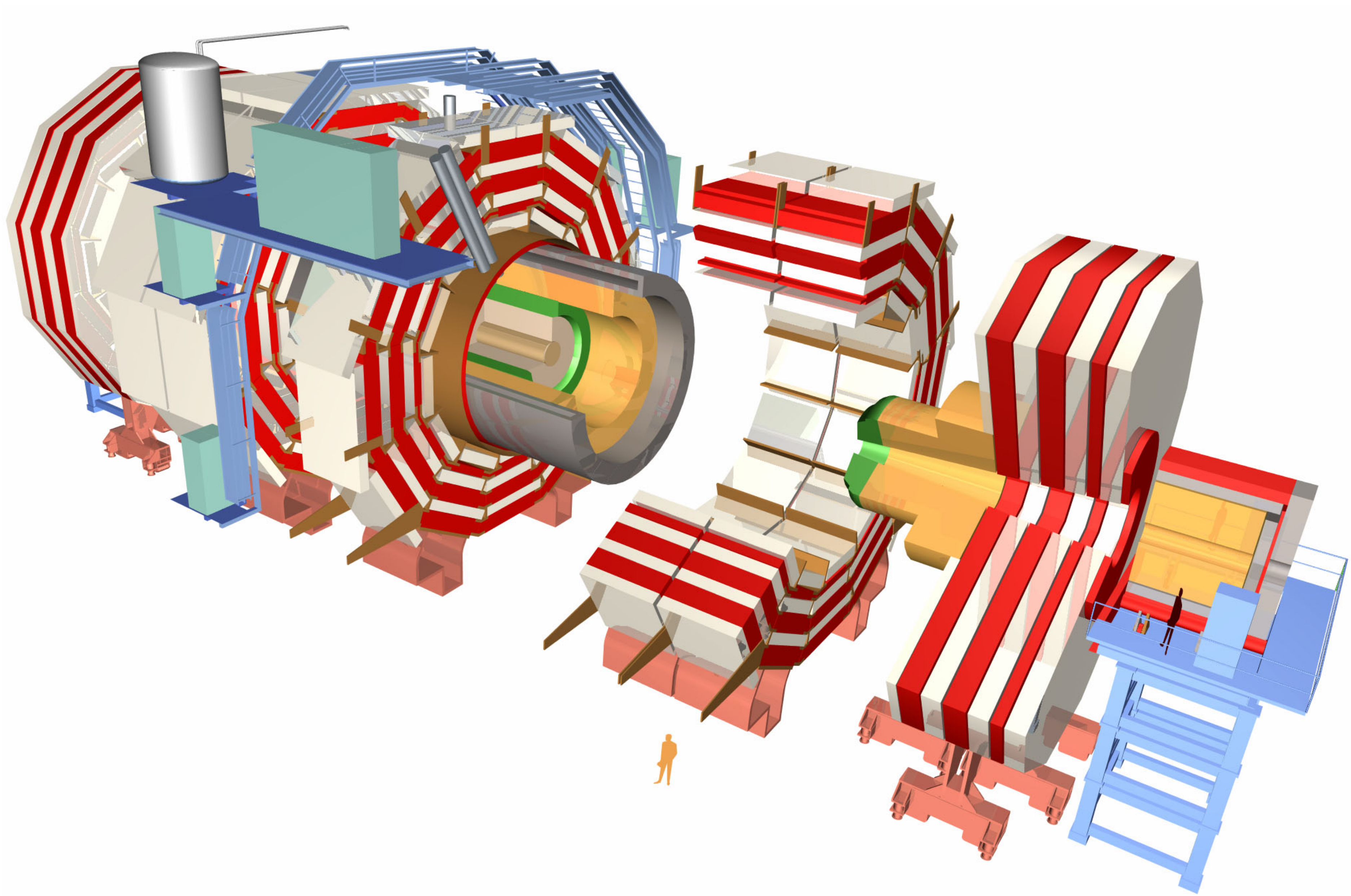
Heavy-ion collisions are rich in physics, with more phenomena to be discovered

CMS is an outstanding experiment in the field of heavy-ion collisions, with excellent capabilities in all fronts

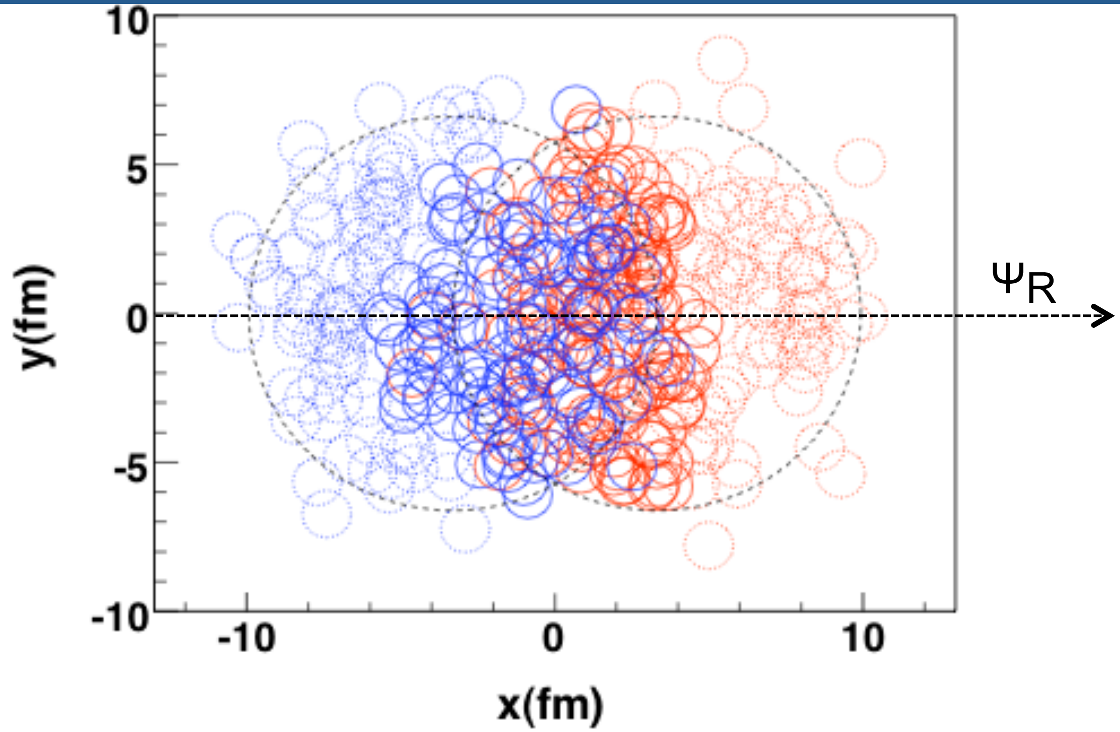
The wide physics program of CMS-HI challenges all key topics in heavy-ion physics

Back up

The CMS Detector



Characterization of events



Centrality : the measure of how head-on a collision is, determined by total forward E_T (HF), expressed in fractions of cross-section (e.g. 0-10% of most central events)

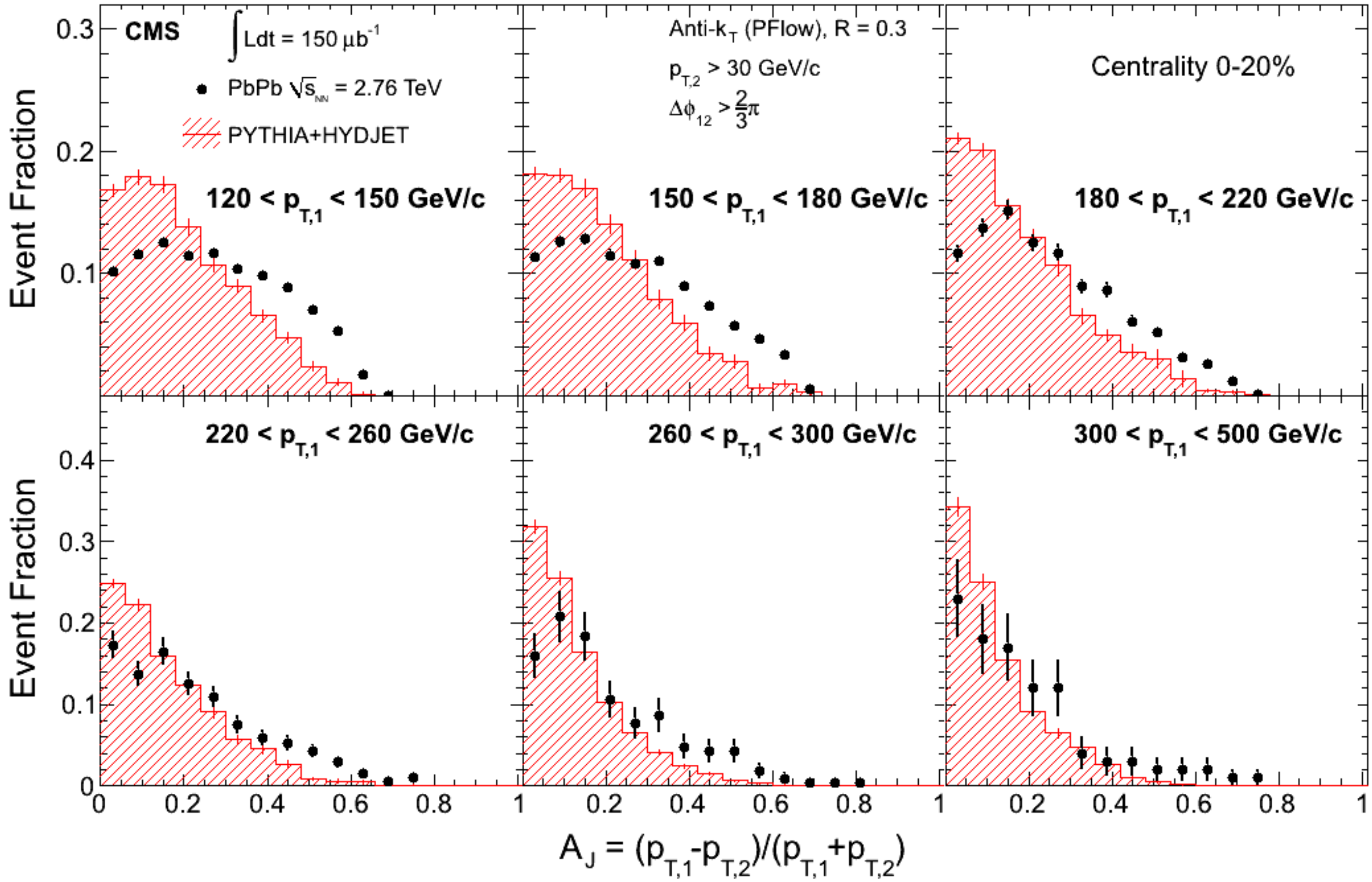
N_{part} : Number of “participating” nucleons

Event plane : the plane that particles “flow” towards

Eccentricity : The ellipticity of the colliding overlap area is

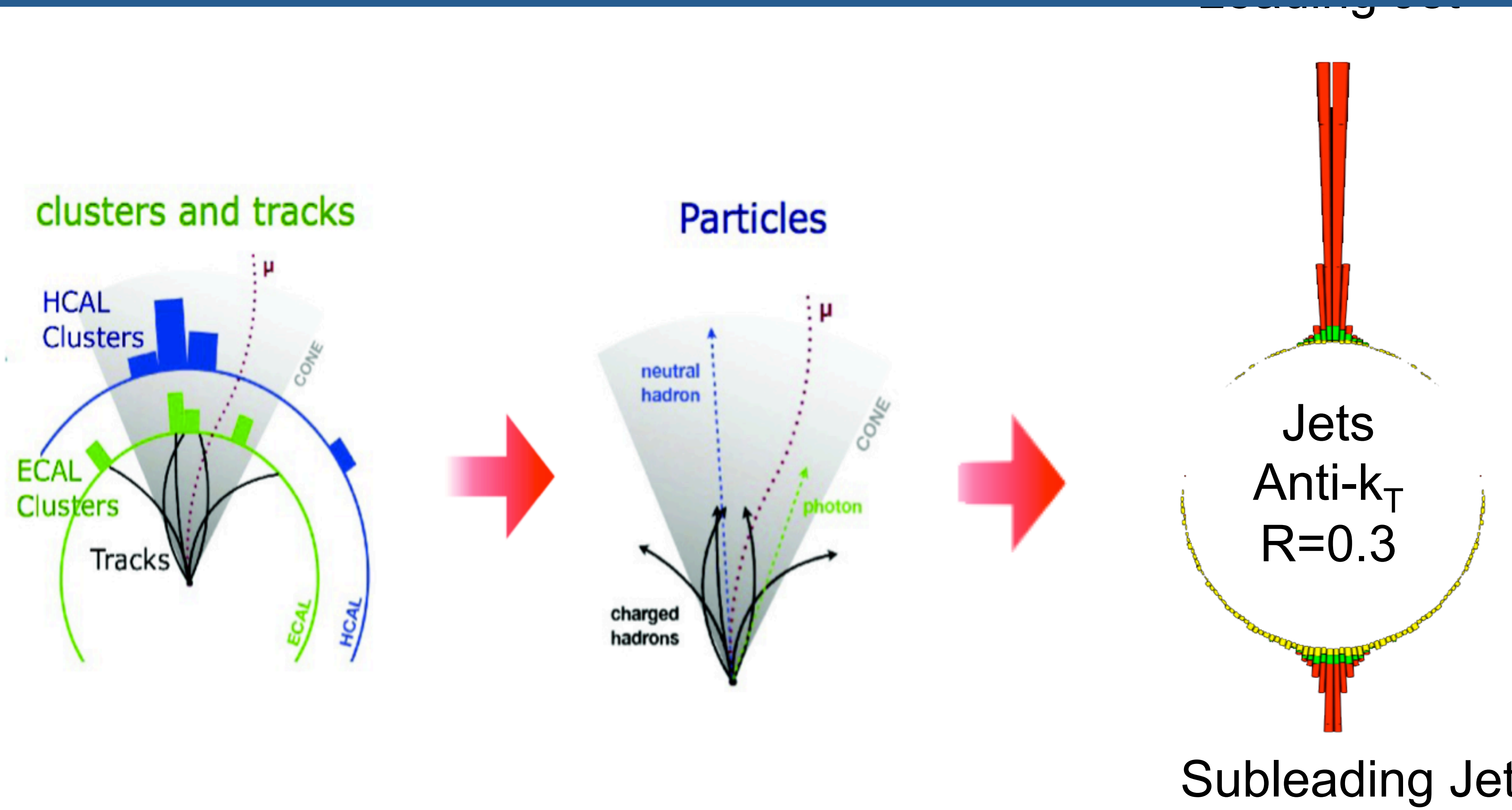
v_2 : The ellipticity of the final state particles

Leading jet momentum dependence



Dijets in PbPb are more imbalanced than Pythia at all bins of leading jet p_T

Jet measurements



Calorimeter clusters and tracks are matched and combined to obtain most detailed information of particles in the event

(Details: CMS-PAS-HIN-11-004)

Estimated background is subtracted from each calorimeter segmentation

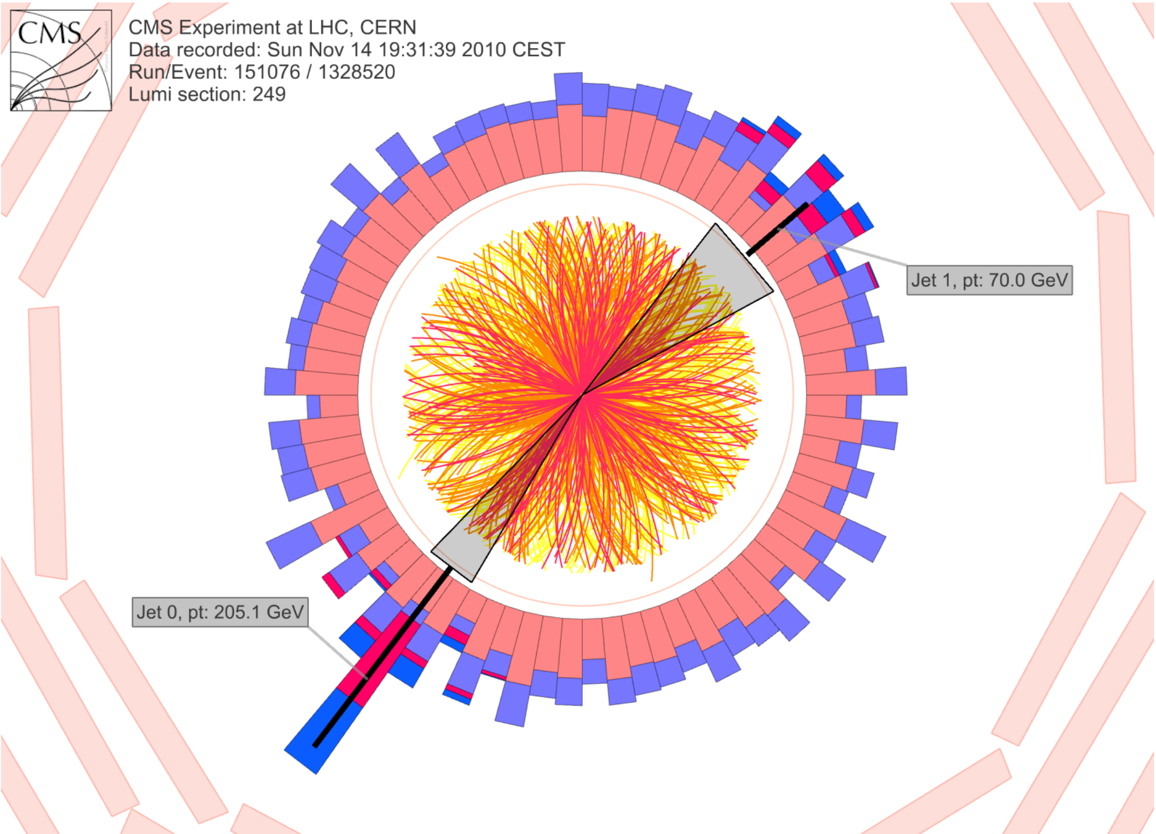
Jet Measurements

Lots of underlying event activity:

dN/dη(η=0) ~ 2000

Local fluctuations from semi-hard interactions

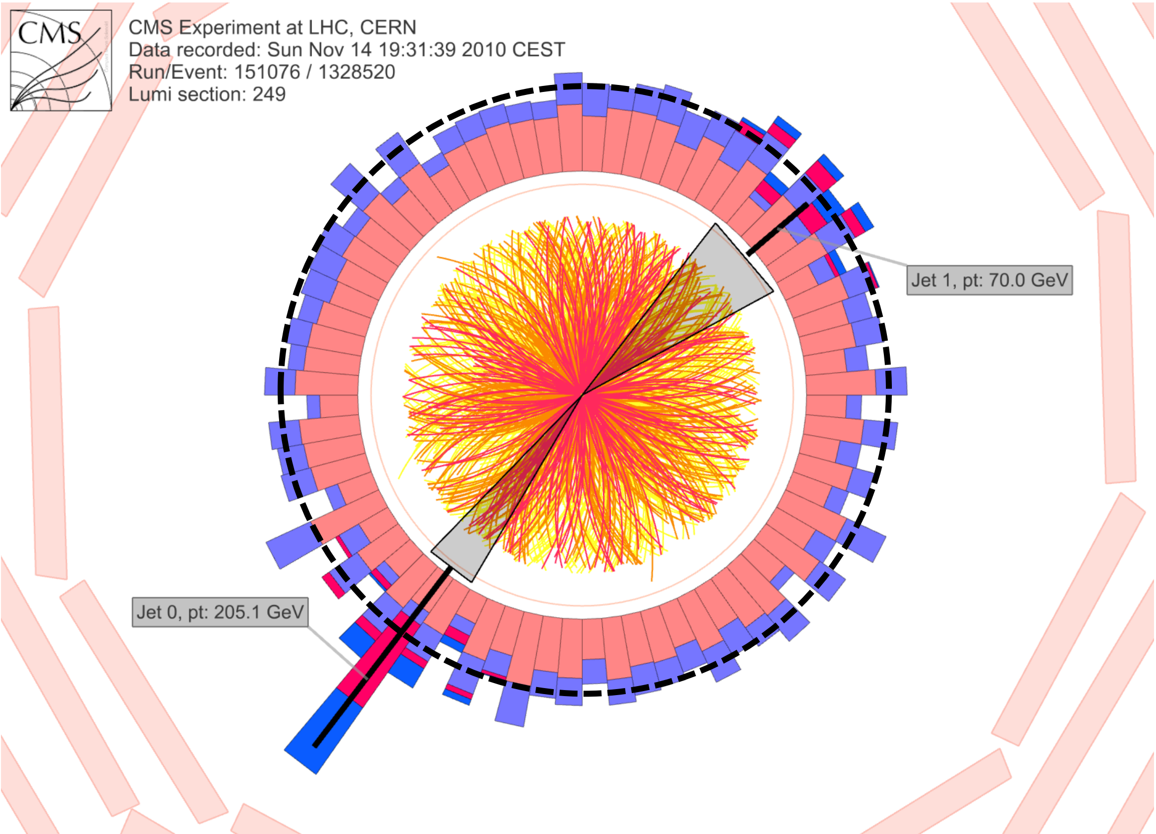
Depends on collision centrality



Jet Measurements

Background estimated for each calorimeter ring of constant η

The background estimation is re-iterated after excluding the jets found in the first iteration

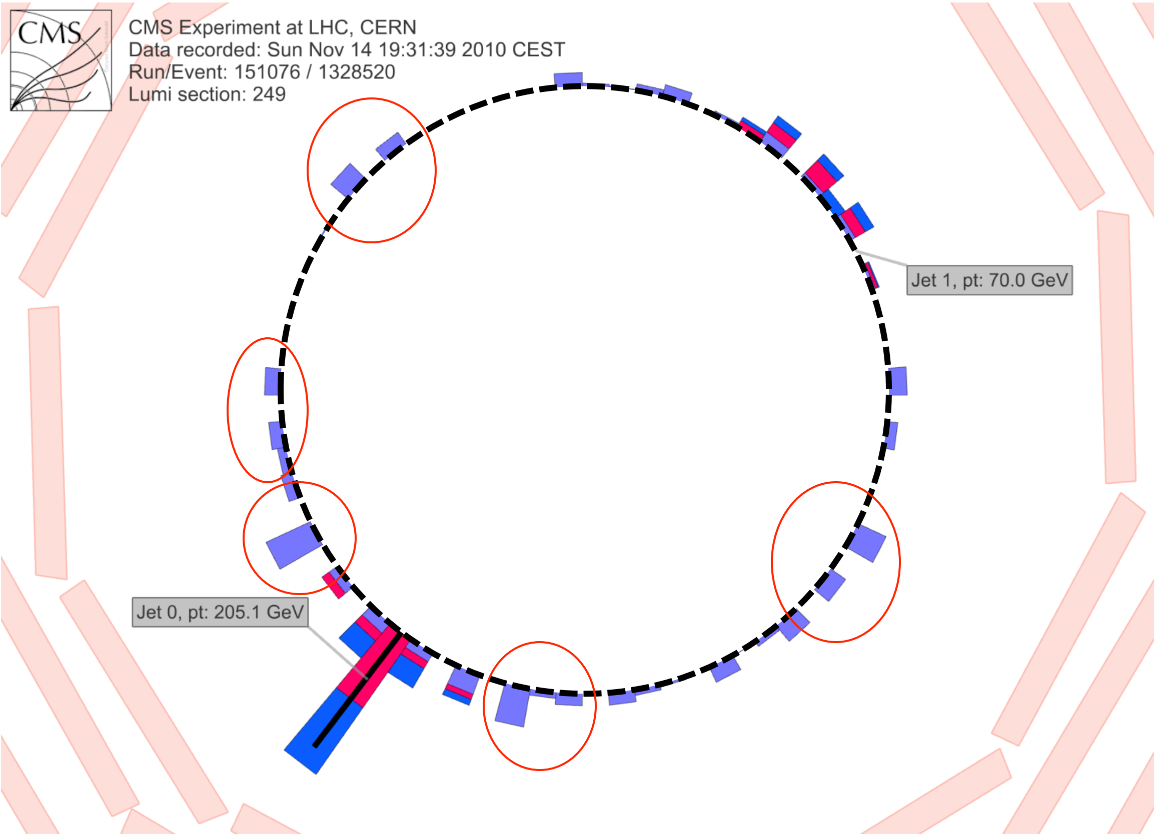


Jet Measurements

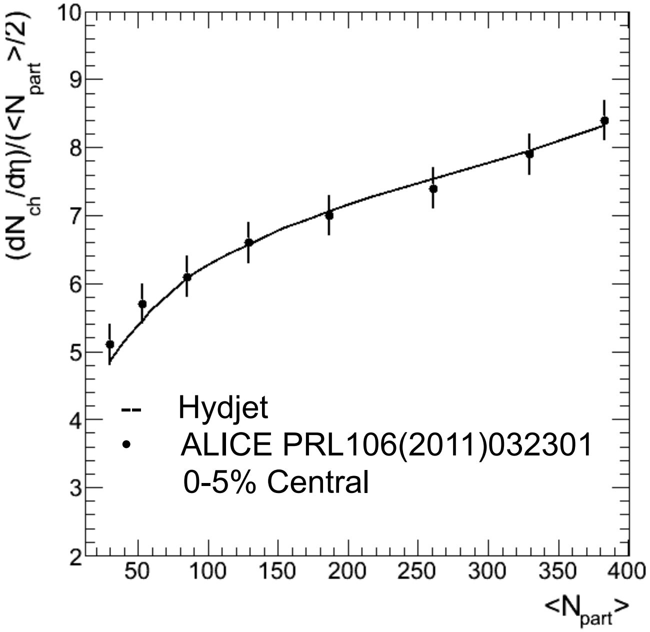
After the background subtraction, some higher local fluctuations remain (fake jets)

The fluctuations also deteriorate the jet resolution in central events

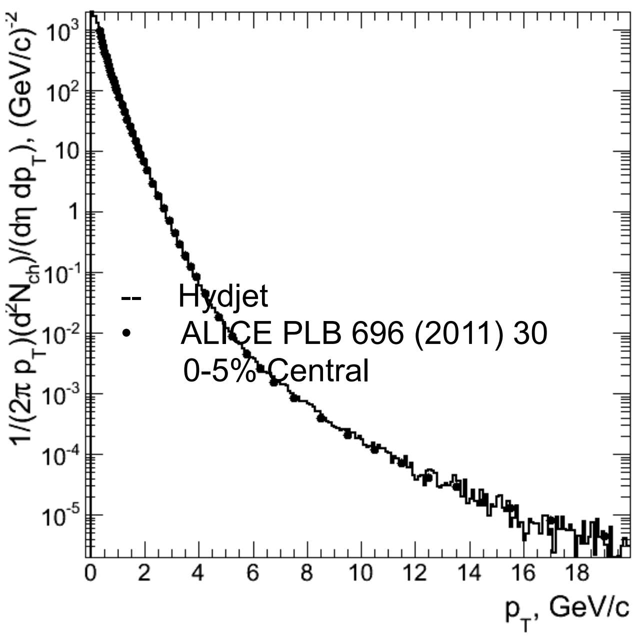
→ Important to represent these fluctuations well in simulated reference

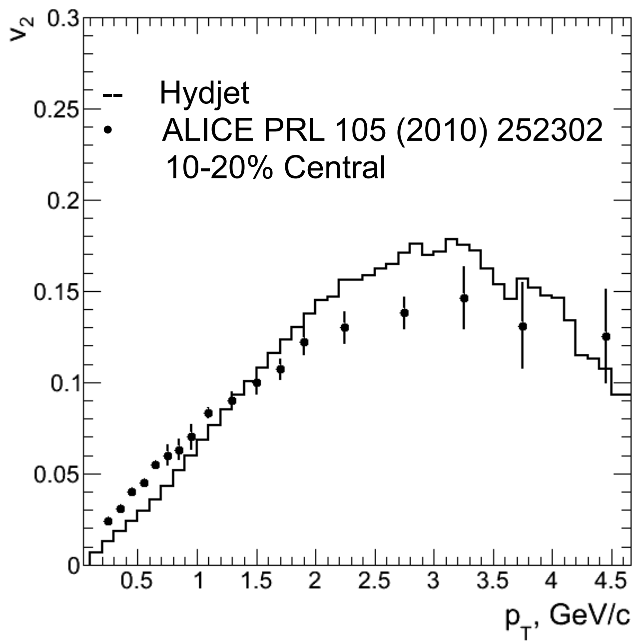


PbPb event simulations with Hydjet 1.8



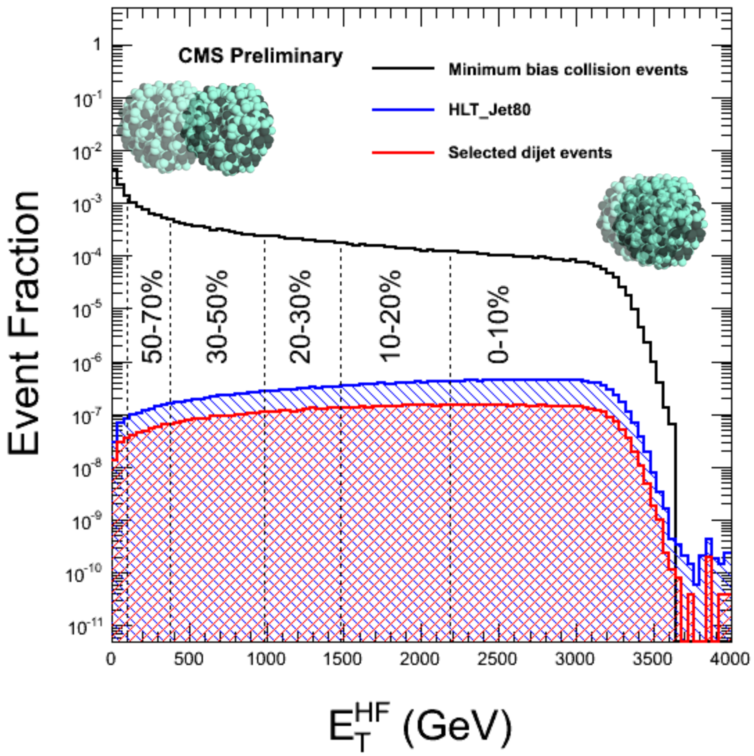
- Hydjet 1.8 default tune successfully reproduces:
  - Charged hadron multiplicity
  - Charged hadron p_T spectrum
  - Azimuthal asymmetry of low-p_T particles (Elliptic Flow)
- Pythia dijet events are mixed with the Hydjet sample at the same vertex

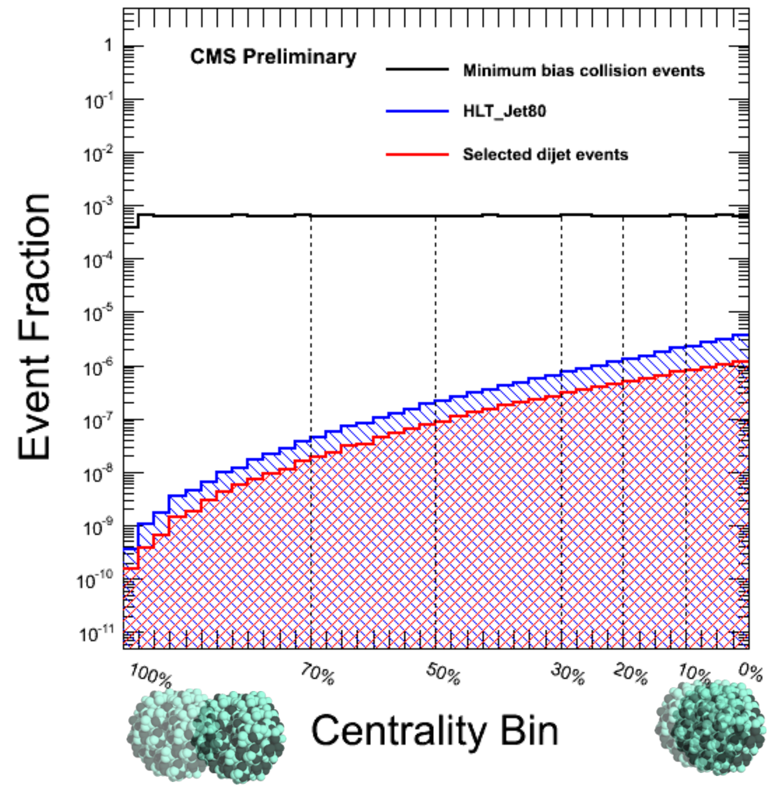




http://lokhtin.web.cern.ch/lokhtin/hydro/plots

Centrality





More peripheral ← 70-100%, 50-70%, 30-50%, 20-30%, 10-20%, 0-10% → More central

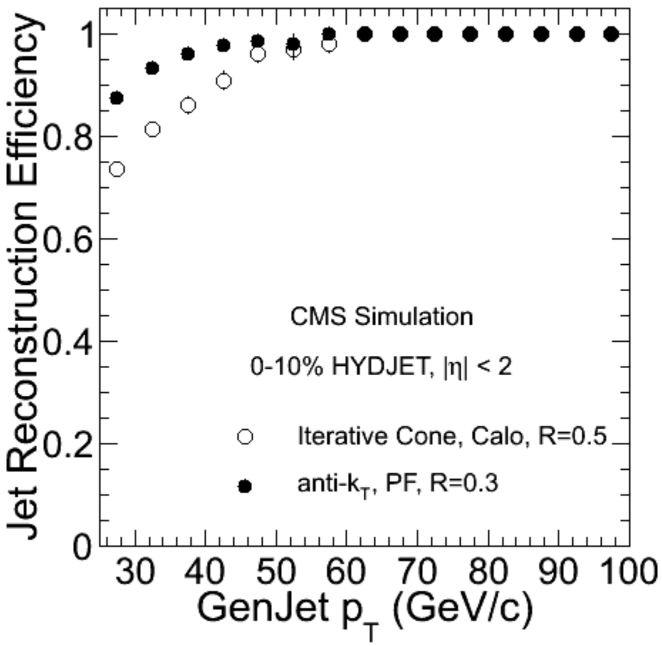
N_{part} : Number of participating (overlapping) nucleons in event

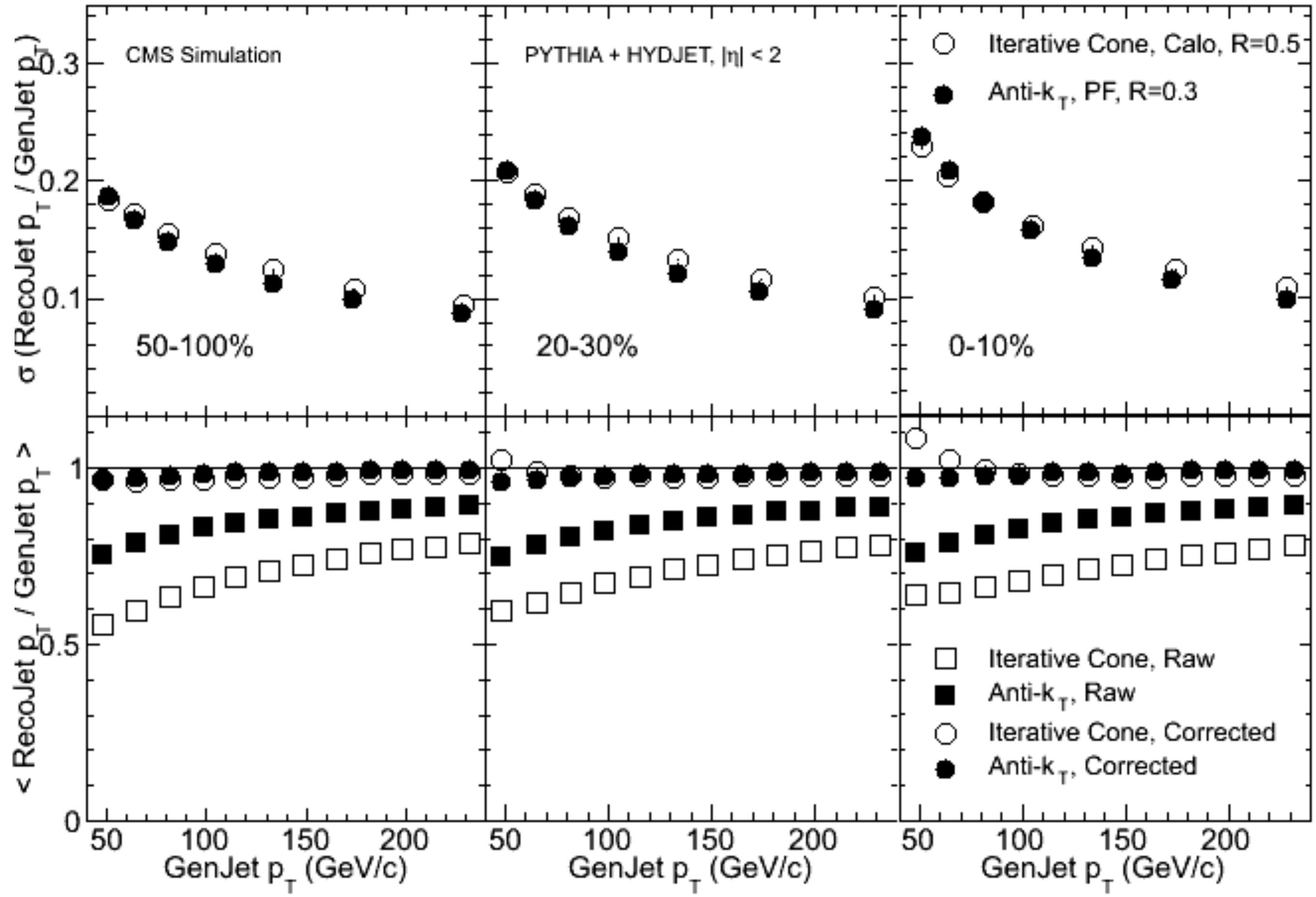
N_{coll} : Number of binary interactions in event

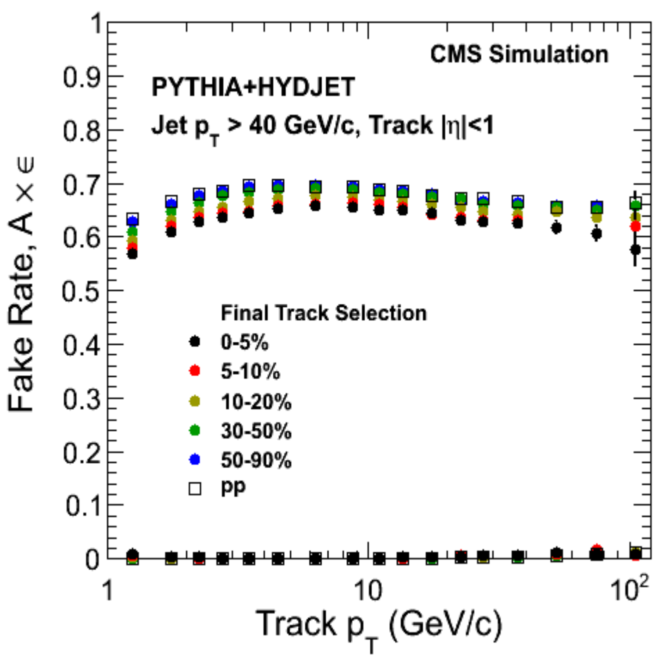
Transverse energy in the forward calorimeter is correlated to N_{part}

Rare probes exhibit a bias towards central events (N_{coll} scaling)

Jet Measurements





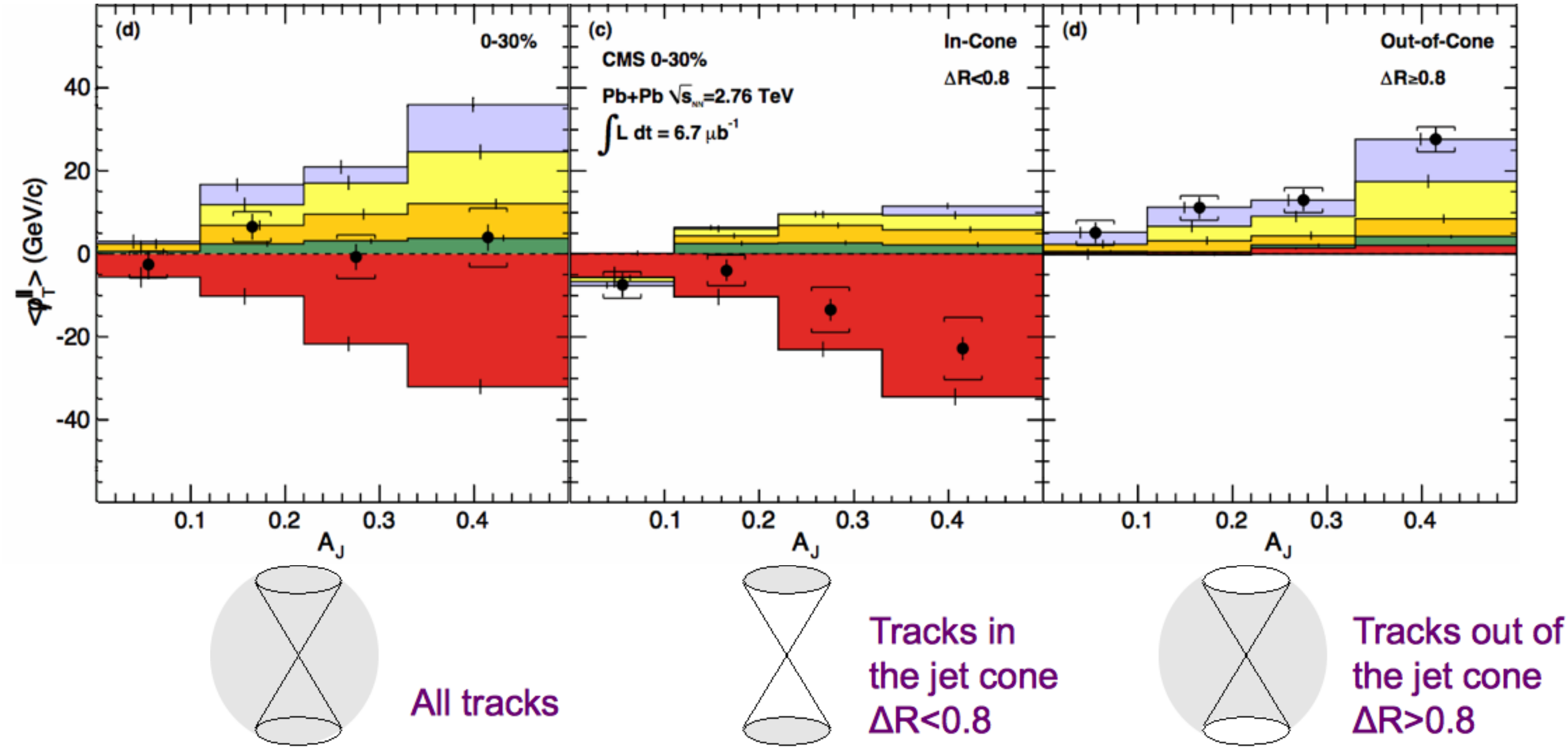


Combining various subdetectors provides strong tools for analysis of jets

Low p_T efficiency is important for unbiased measurement

Missing $p_T^{\parallel}$:

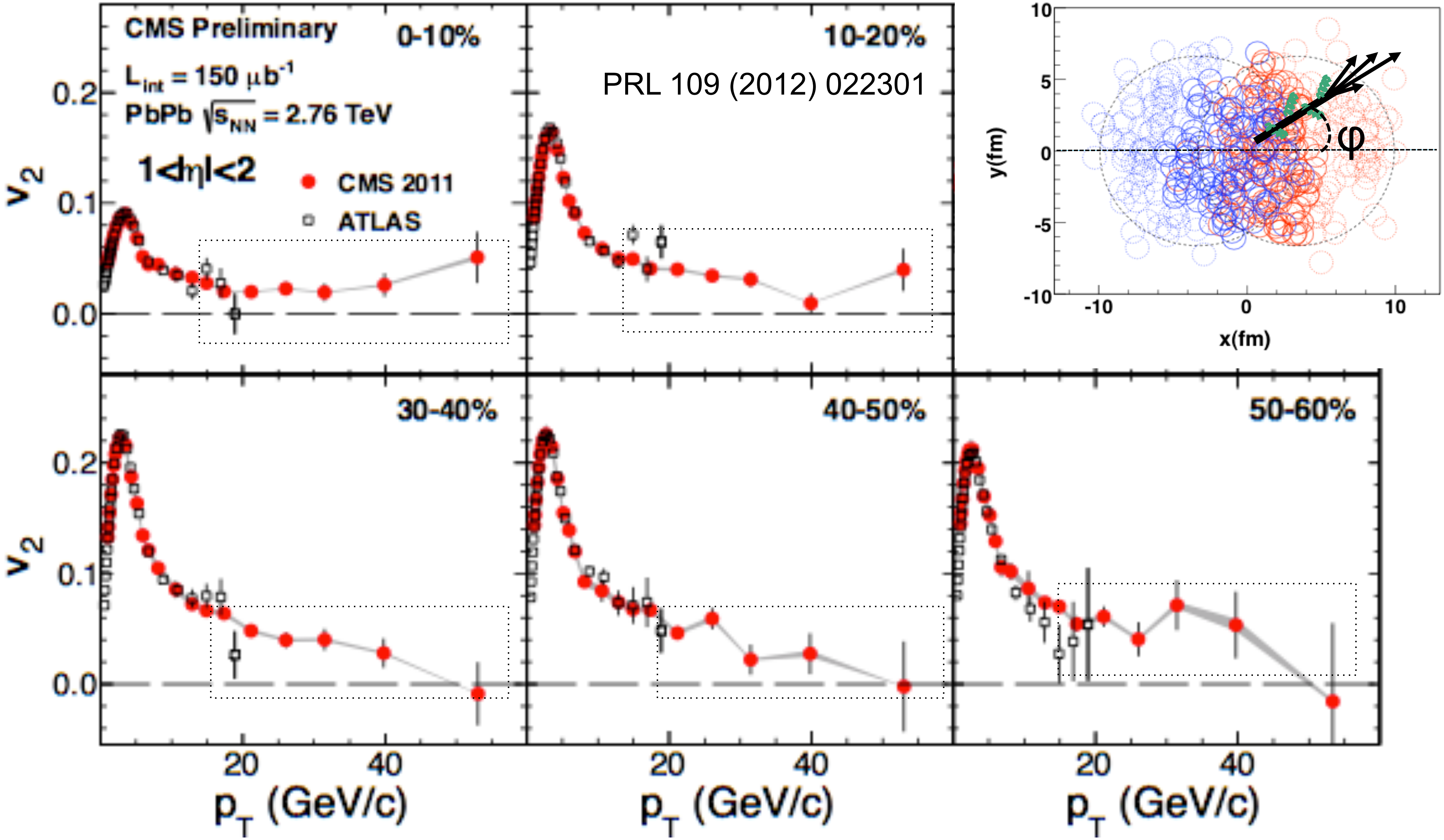
$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$



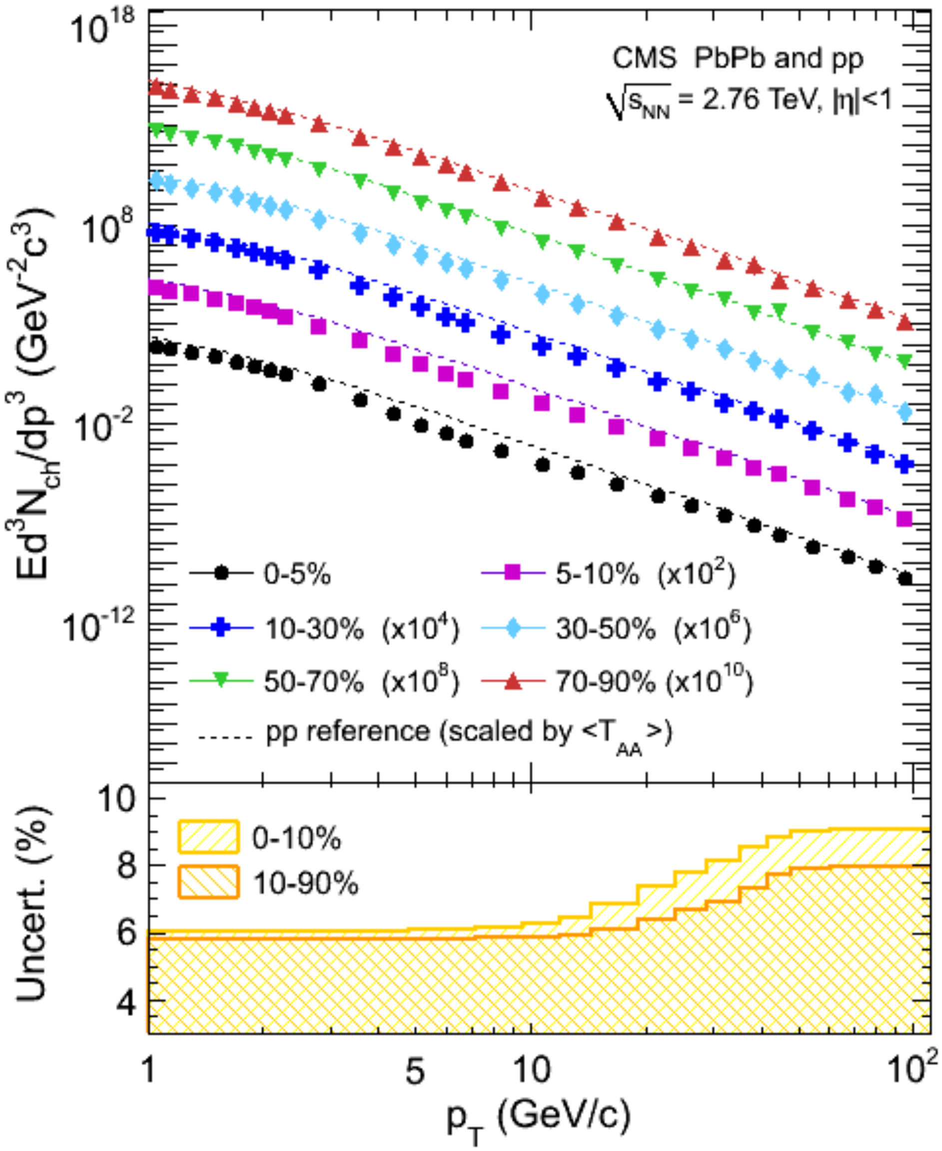
The global event properties are modified with the existence of quenching

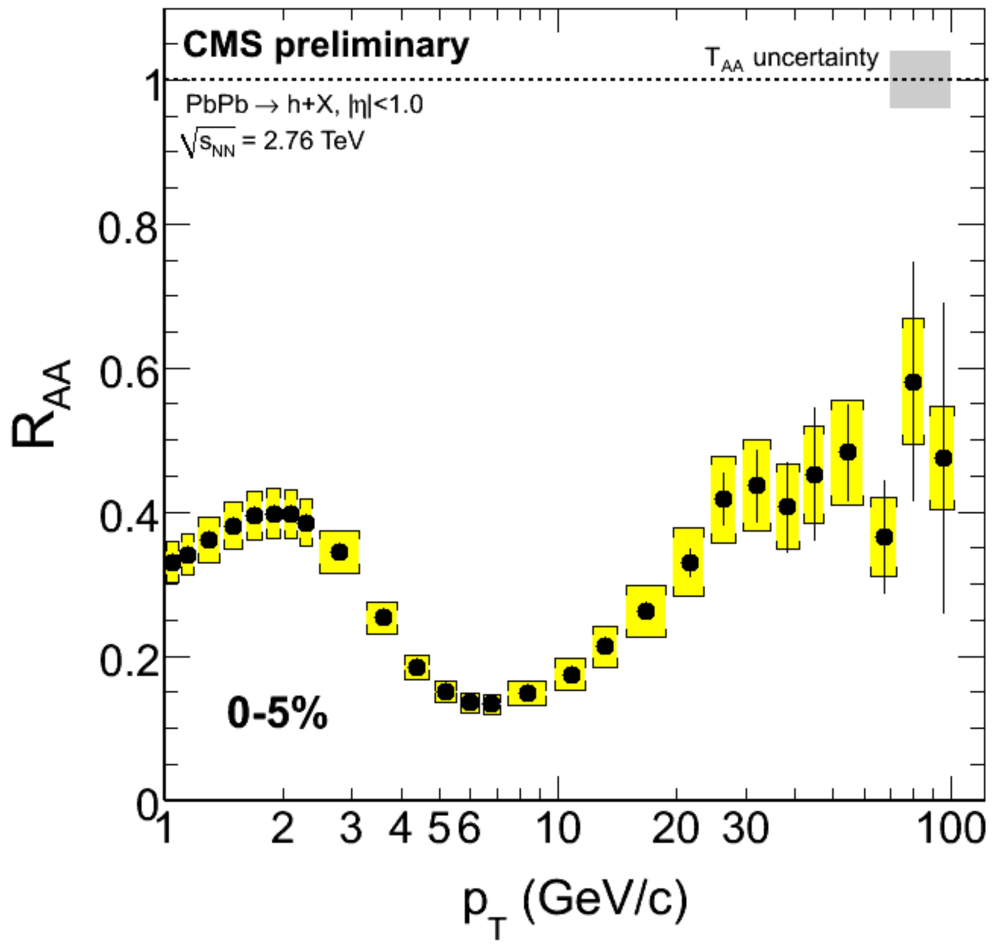
The missing energy is found at large angles from the jet axis

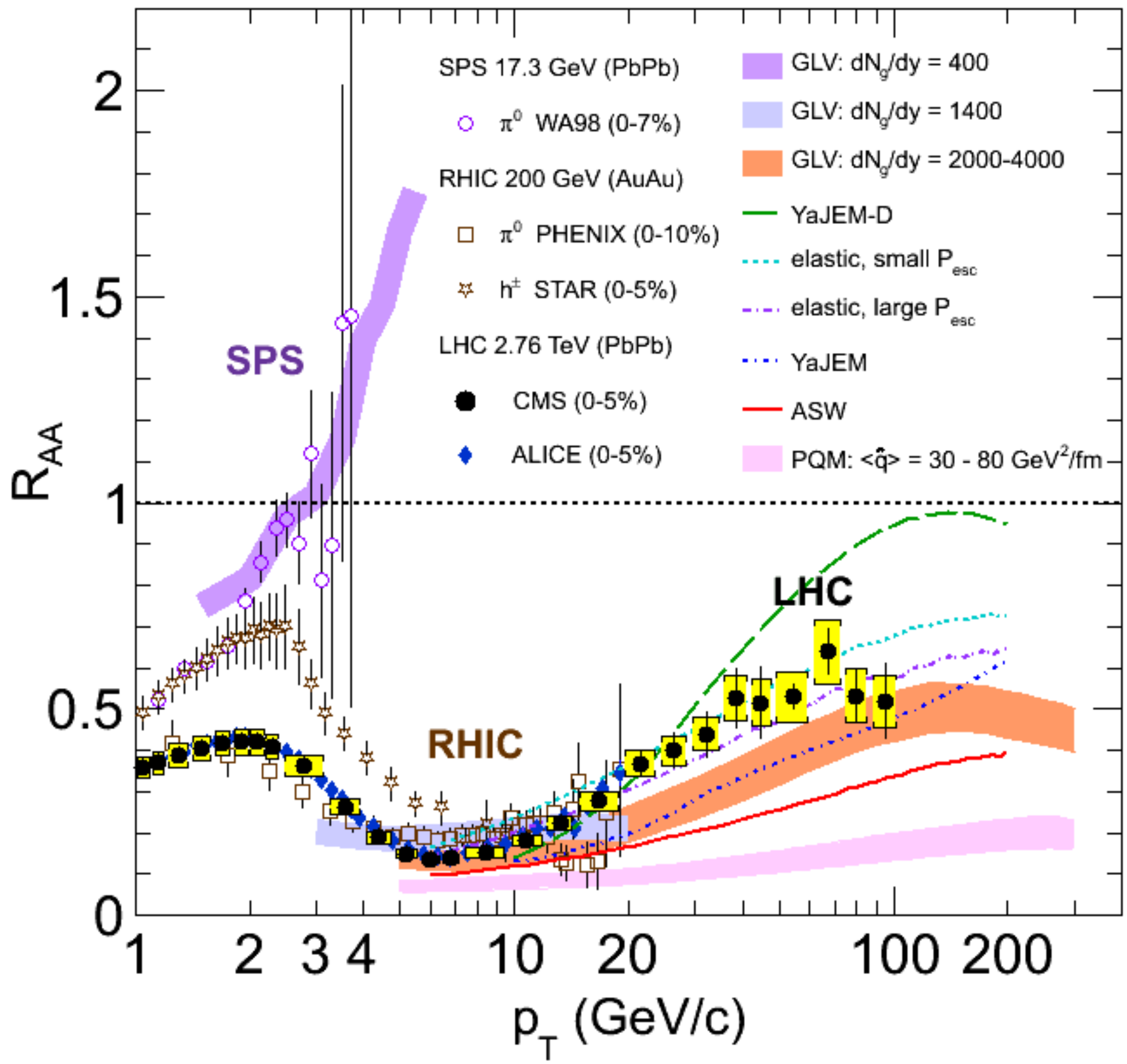
More on path-length dependence



Correlation with the event-plane is strong for high-p_T hadrons, which originate from fragmenting hard partons


CMS PbPb and pp
$\sqrt{s_{NN}}$ = 2.76 TeV, |η|<1
Ed^3N_{ch}/dp^3 ($GeV^{-2}c^3$)
0-5%
5-10% (x10²)
10-30% (x10⁴)
30-50% (x10⁶)
50-70% (x10⁸)
70-90% (x10¹⁰)
pp reference (scaled by <T_{AA}>)
Uncert. (%)
0-10%
10-90%
p_T (GeV/c)


CMS preliminary
T_{AA} uncertainty
PbPb → h+X, |η|<1.0
$\sqrt{s_{NN}}$ = 2.76 TeV
R_{AA}
0-5%
p_T (GeV/c)



SPS 17.3 GeV (PbPb)
π⁰ WA98 (0-7%)
RHIC 200 GeV (AuAu)
π⁰ PHENIX (0-10%)
h± STAR (0-5%)
LHC 2.76 TeV (PbPb)
CMS (0-5%)
ALICE (0-5%)
GLV: dNg/dy = 400
GLV: dNg/dy = 1400
GLV: dNg/dy = 2000-4000
YaJEM-D
elastic, small Pesc
elastic, large Pesc
YaJEM
ASW
PQM: <q̂> = 30 - 80 GeV²/fm
SPS
RHIC
LHC
RAA
pT (GeV/c)