CMS results from PbPb collisions at the LHC

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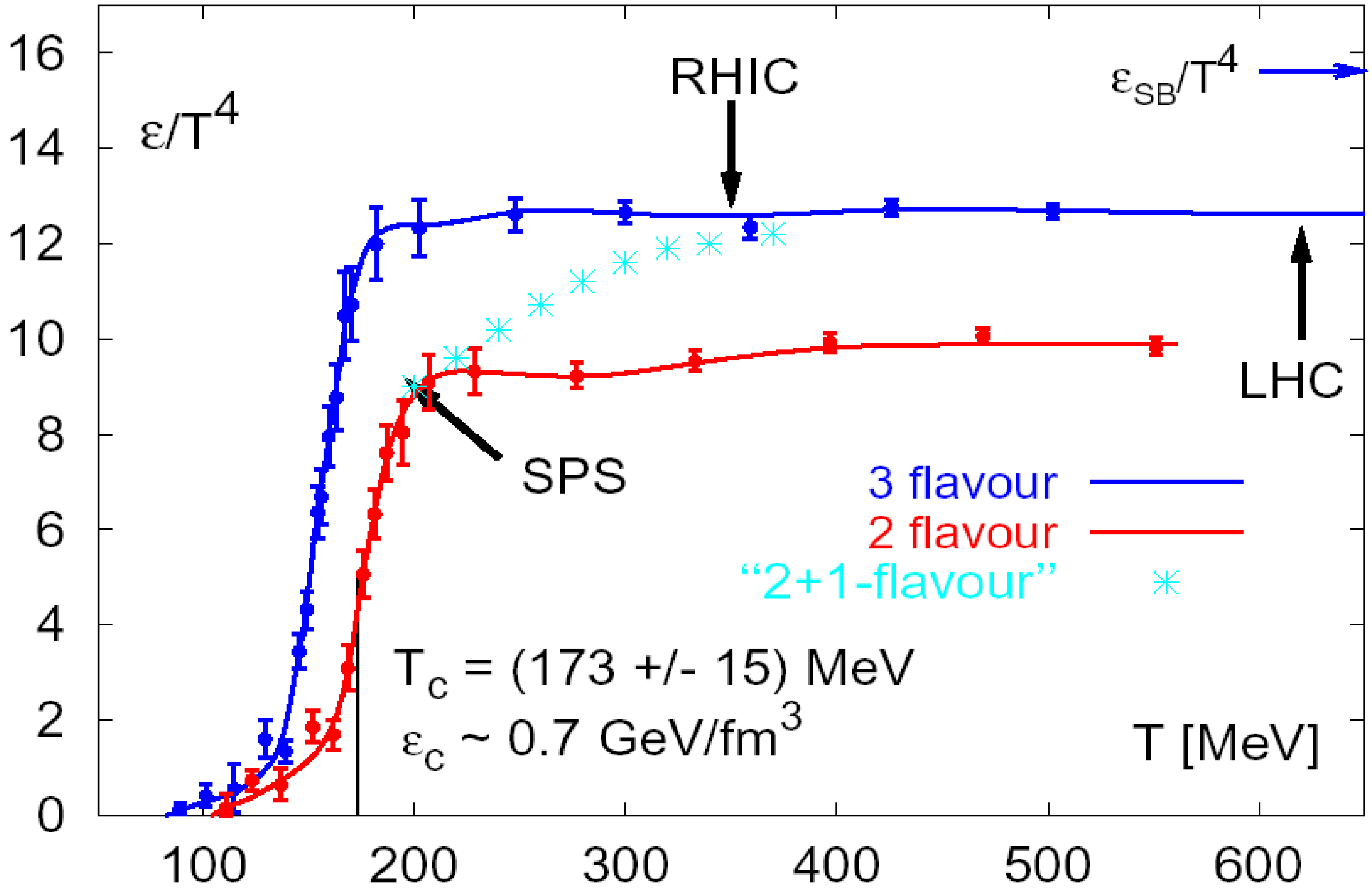
- Heavy ion physics with CMS detector
- First CMS results on PbPb collisions
  - ➔ *Jets*
  - ➔ *Photons*
  - ➔ *Z^0 -bosons*
  - ➔ *Quarkonia*
  - ➔ *Hadron multiplicity and spectra*
  - ➔ *Two-particle correlations*
  - ➔ *Elliptic flow*
- Summary and outlook

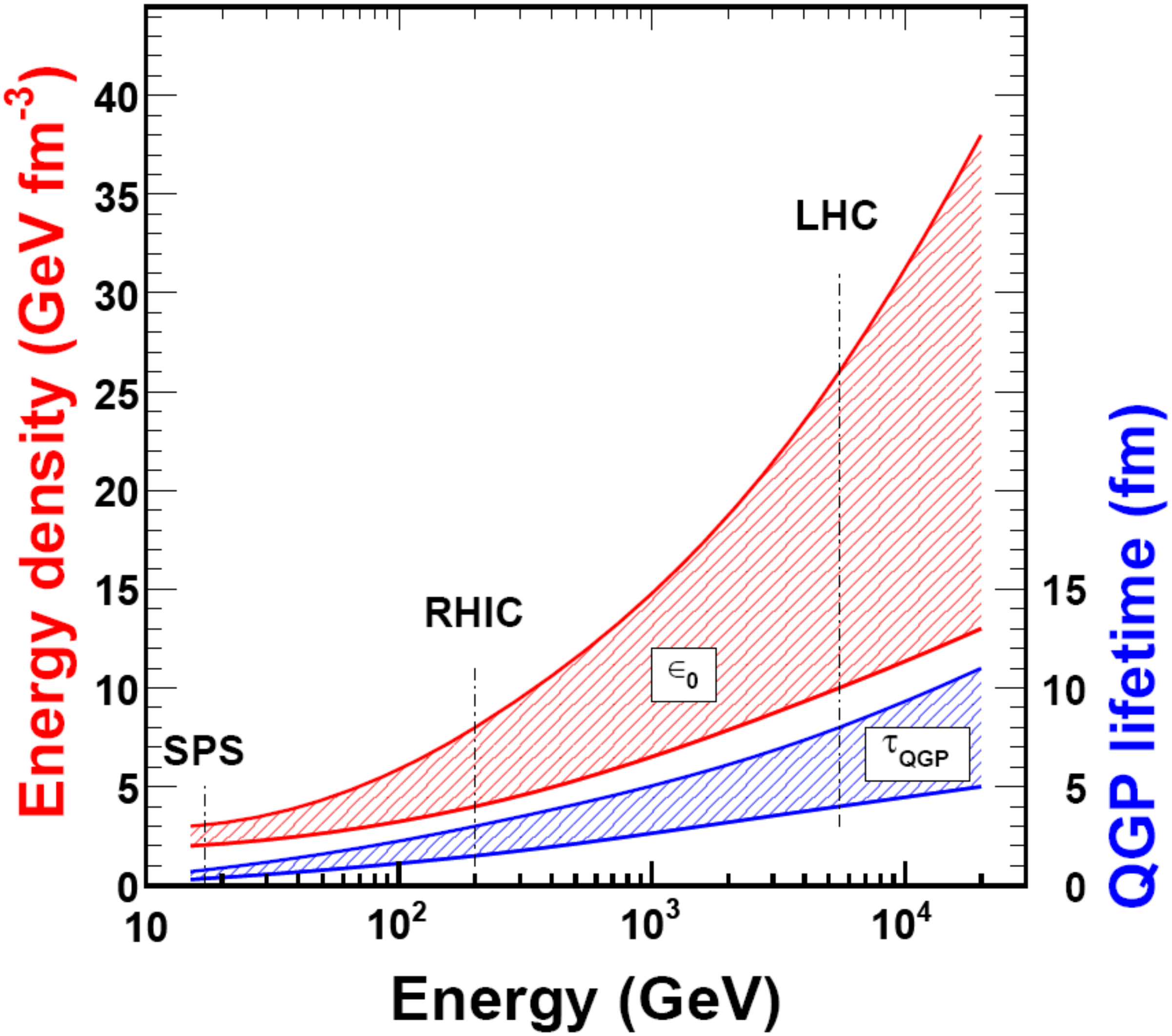
Deconfinement of nuclear matter



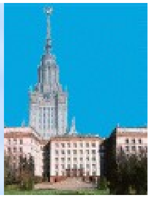
Deconfinement of nuclear matter and quark-gluon matter (QGM) formation – the prediction of Lattice Quantum Chromodynamics (QCD) for systems with high enough temperature and/or baryon density

Study of quark-gluon matter in HI collisions

SPS (CERN) → RHIC (BNL) → LHC (CERN)

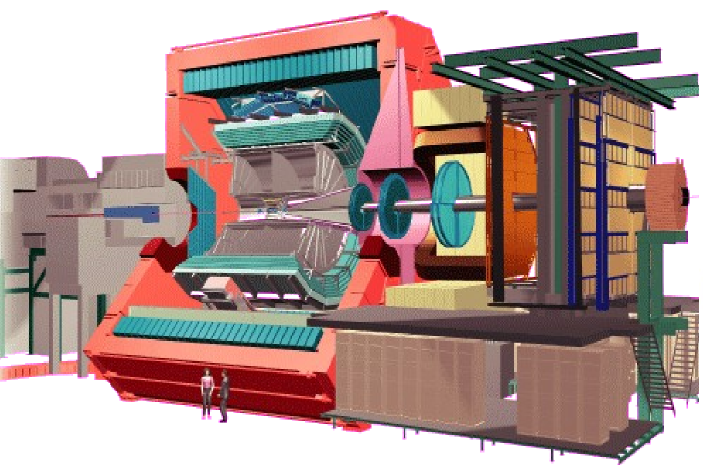


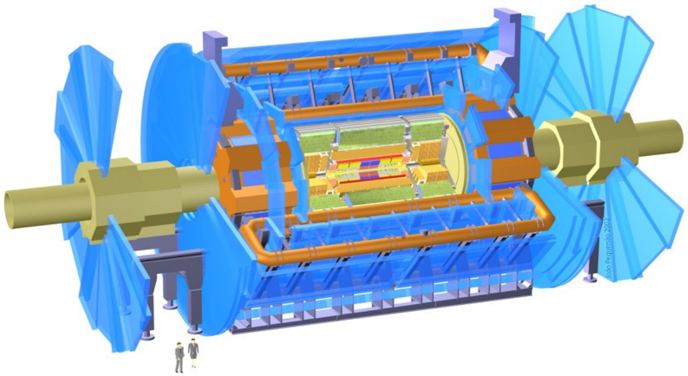
Heavy ion physics at the LHC

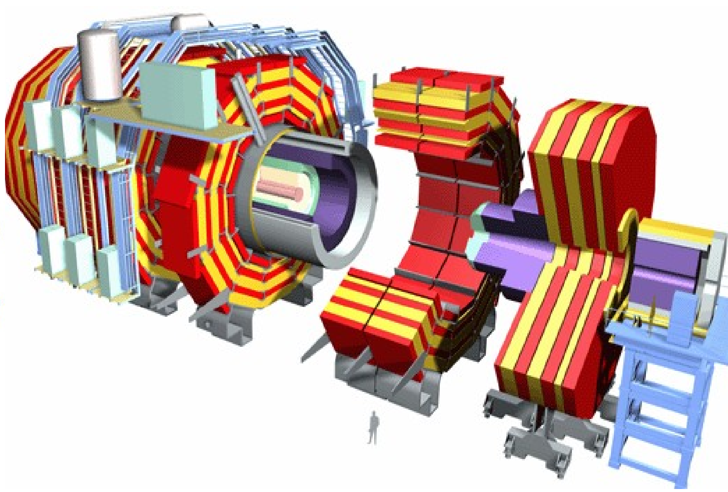


New regime of heavy ion physics with the important role of hard QCD-processes in hot and long-live quark-gluon medium
complementary measurements from ALICE & CMS/ATLAS

ALICE | **ATLAS** | **CMS**



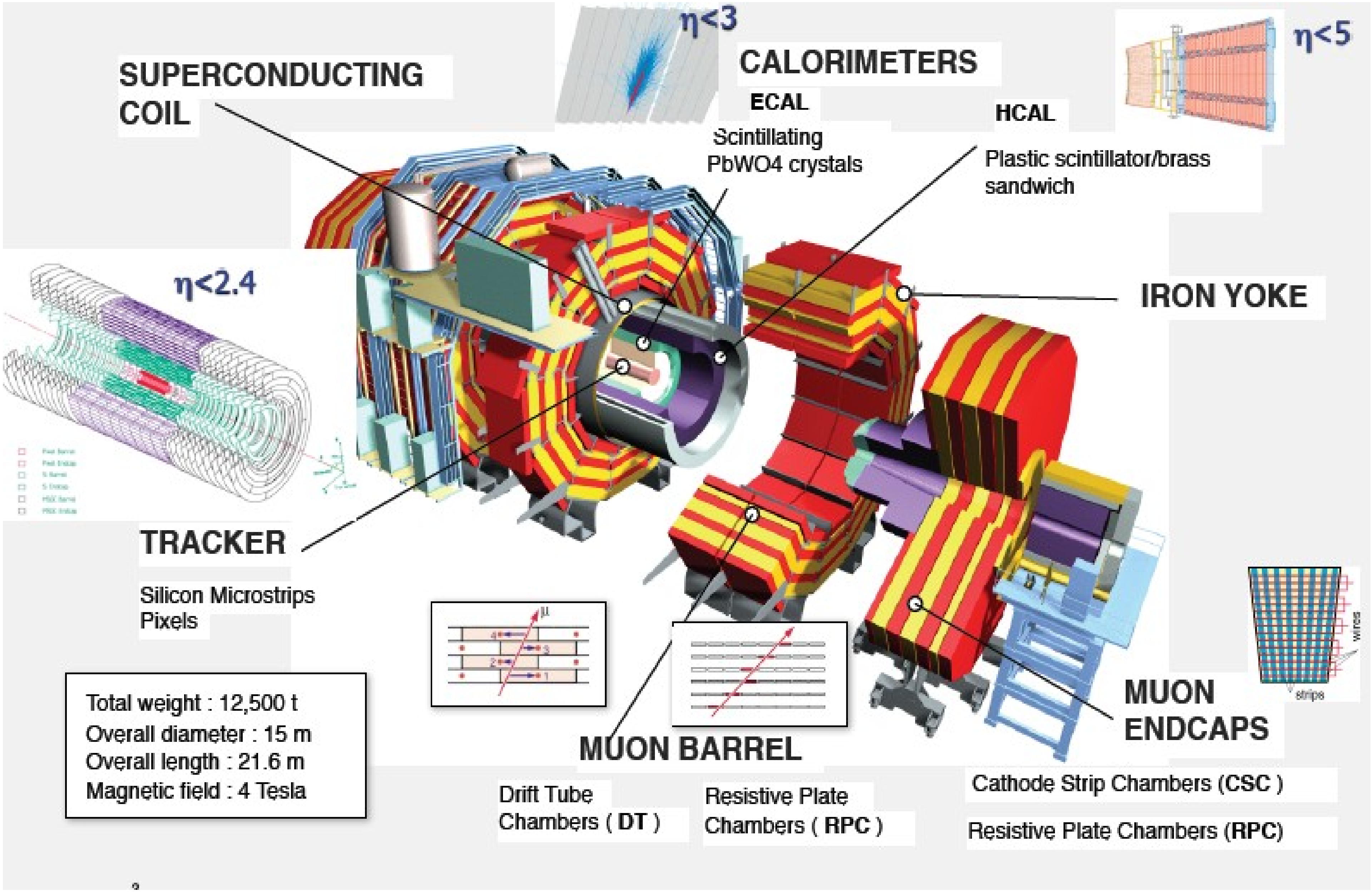




ALICE (low-p_T charged particle tracking, hadron ID, central *e*, forward μ (J/ψ, Υ), γ multiplicity,...)
soft probes + selected hard probes

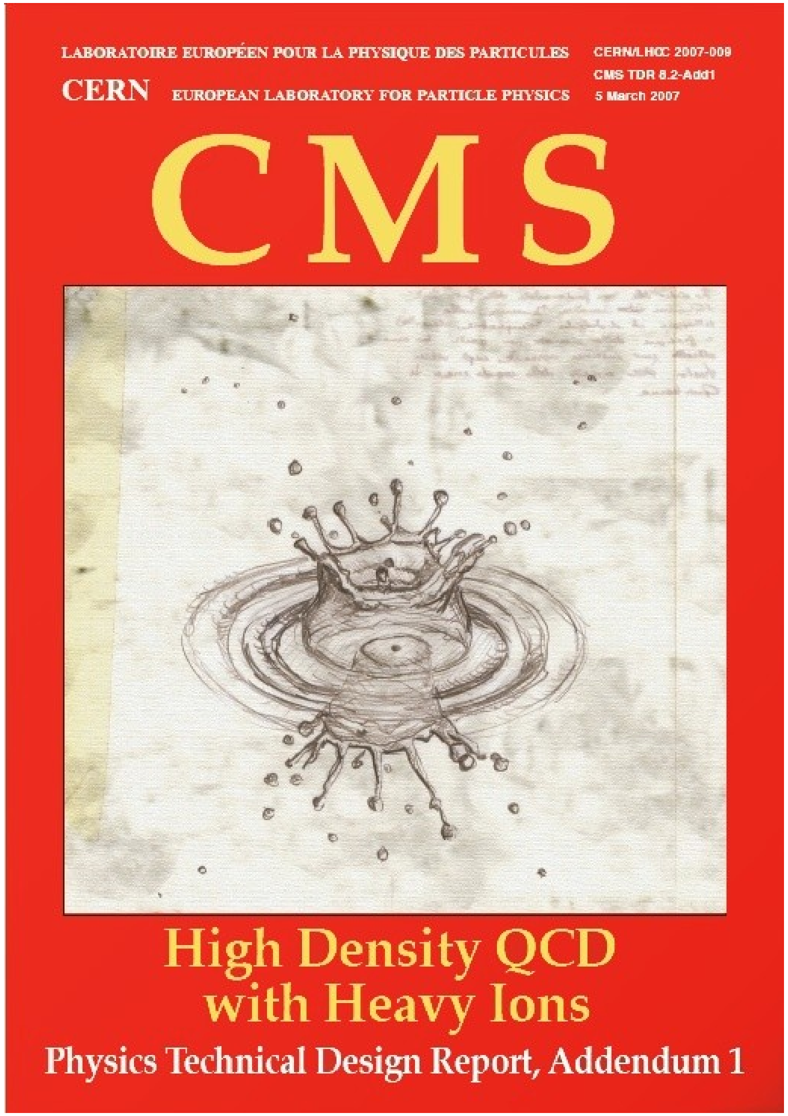
CMS/ATLAS (high-p_T charged particle tracking, central μ (J/ψ, Υ, Z), hard γ, calorimetric jets...)
hard probes + selected soft probes

CMS Detector



CMS Heavy Ion Program

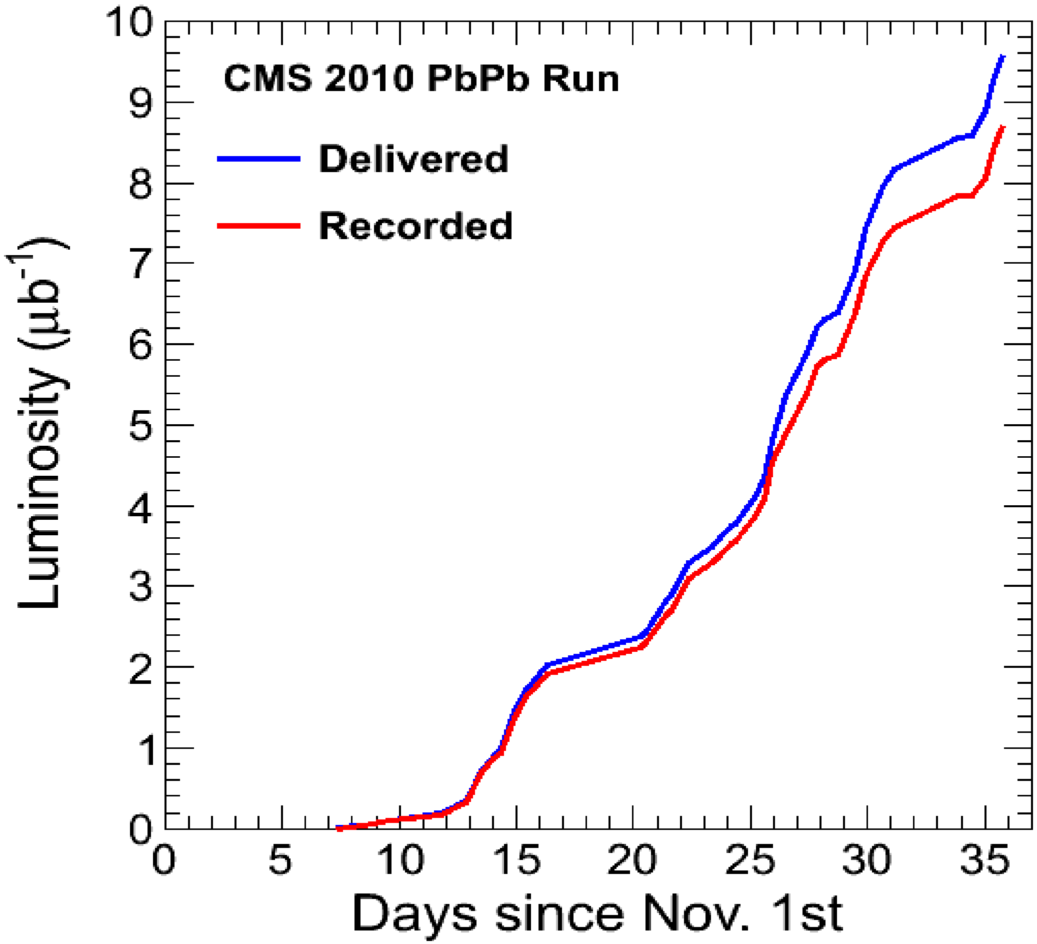
J. Phys. G: Nucl. Part. Phys. 34 (2007) 2307-2455



Broad and exciting range of observables

- Jets and photons
- Quarkonia, Z^0 and heavy quarks in high-mass dimuon decay modes
- Charged hadron spectra
- Elliptic flow
- Ultraperipheral collisions, forward physics

LHC: 2010 Heavy Ion Run



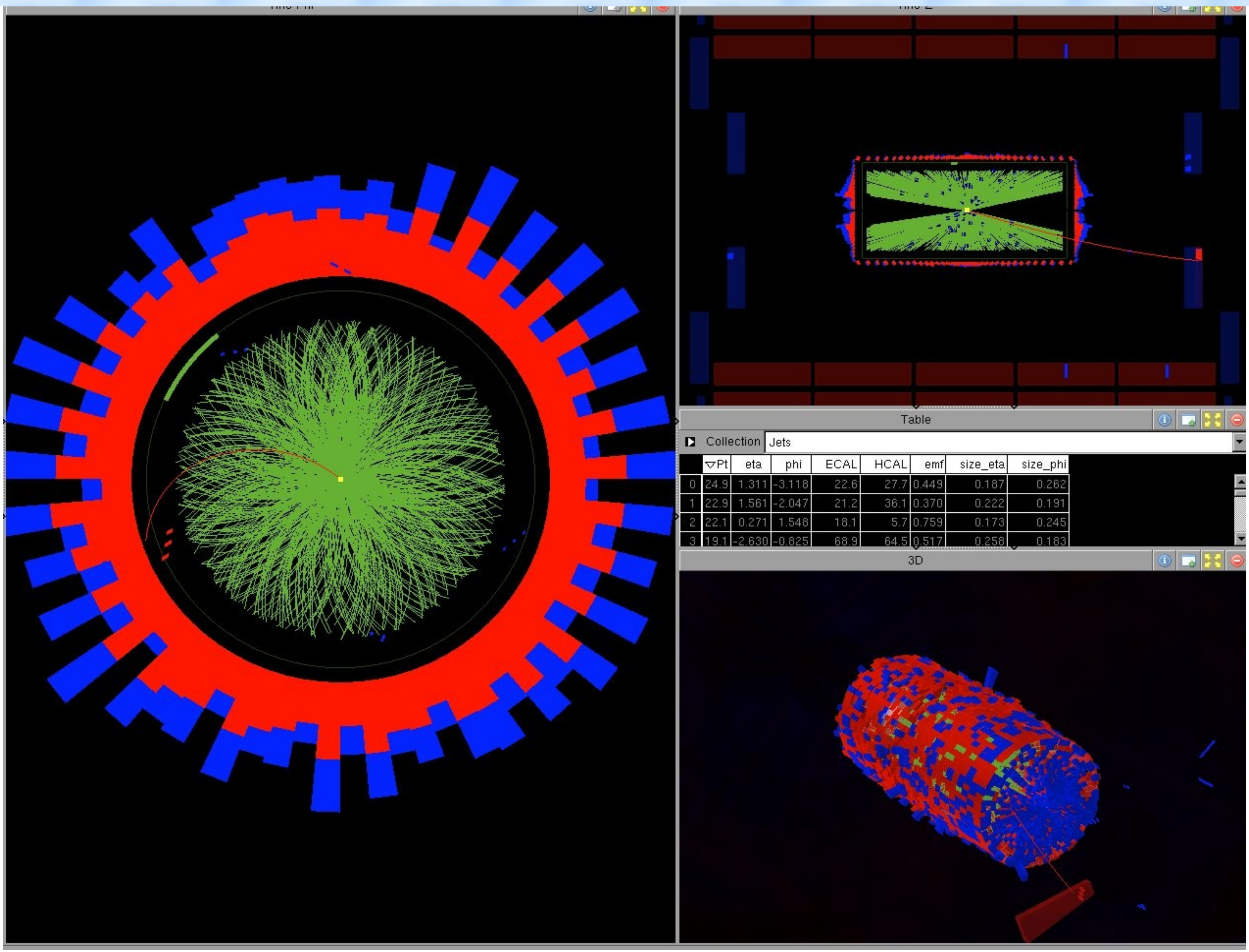
2010: LHC delivered 8.7 μb^{-1} of PbPb data at $\sqrt{s}$=2.76 A TeV

~7 μb^{-1} used in hard probes analysis (equivalent to ~300 nb^{-1} of pp hard processes)

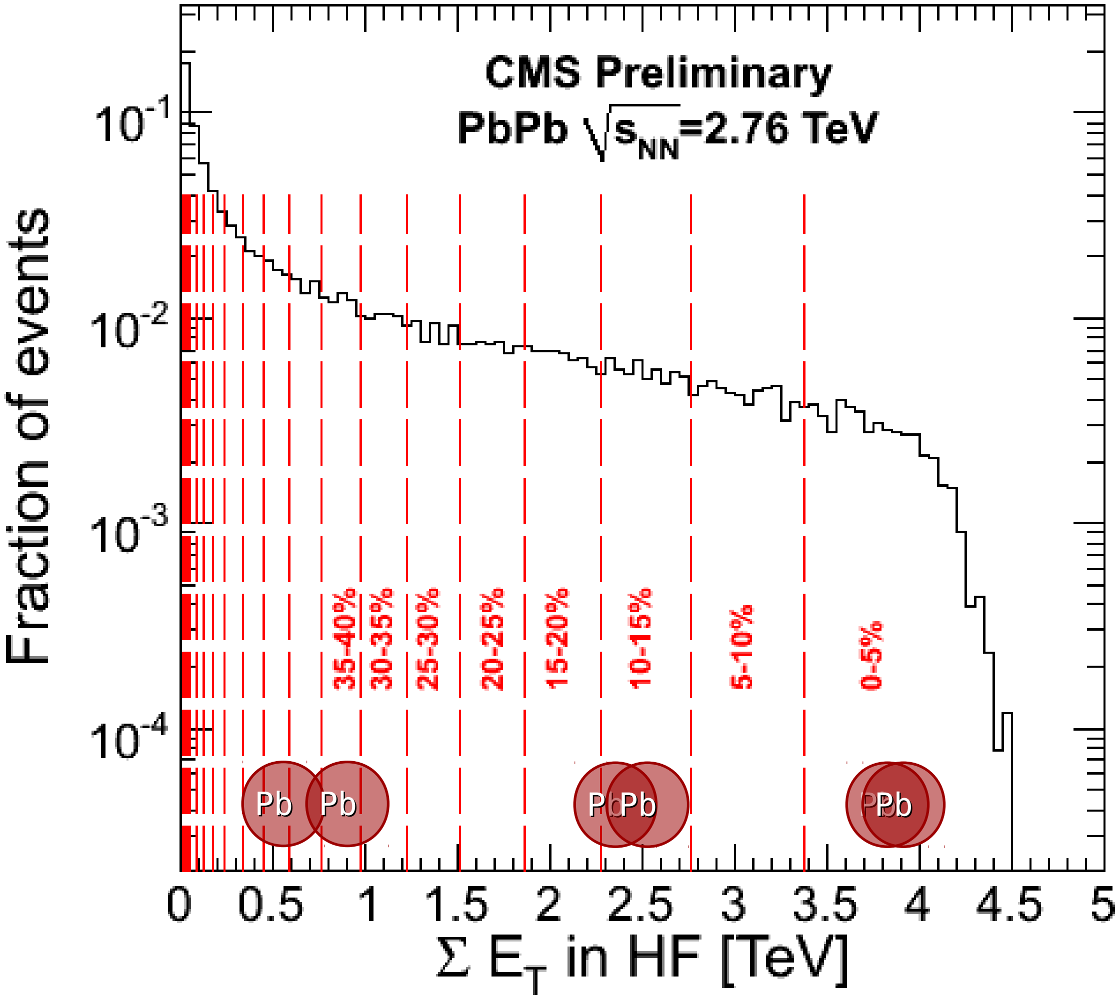
2011: LHC delivered 241 nb^{-1} of pp data at $\sqrt{s}$=2.76 TeV

baseline measurement for PbPb (statistics are comparable)

One of the first PbPb events seen by CMS

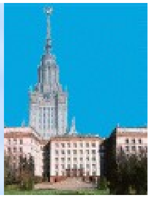


Event centrality determination



Events are classified according to the percentile of the PbPb inelastic cross section based on total deposited HF energy

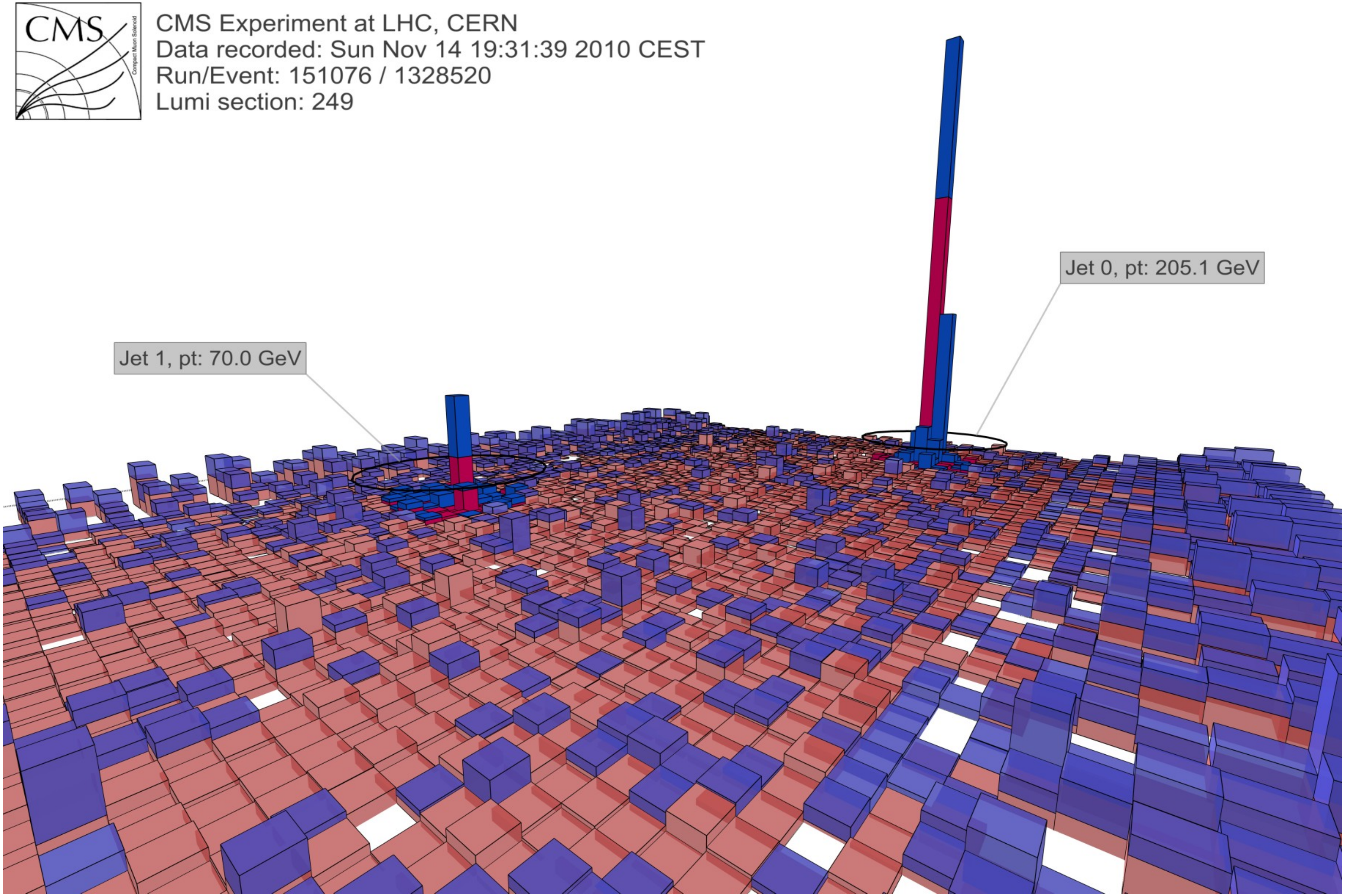
First CMS papers on PbPb collisions



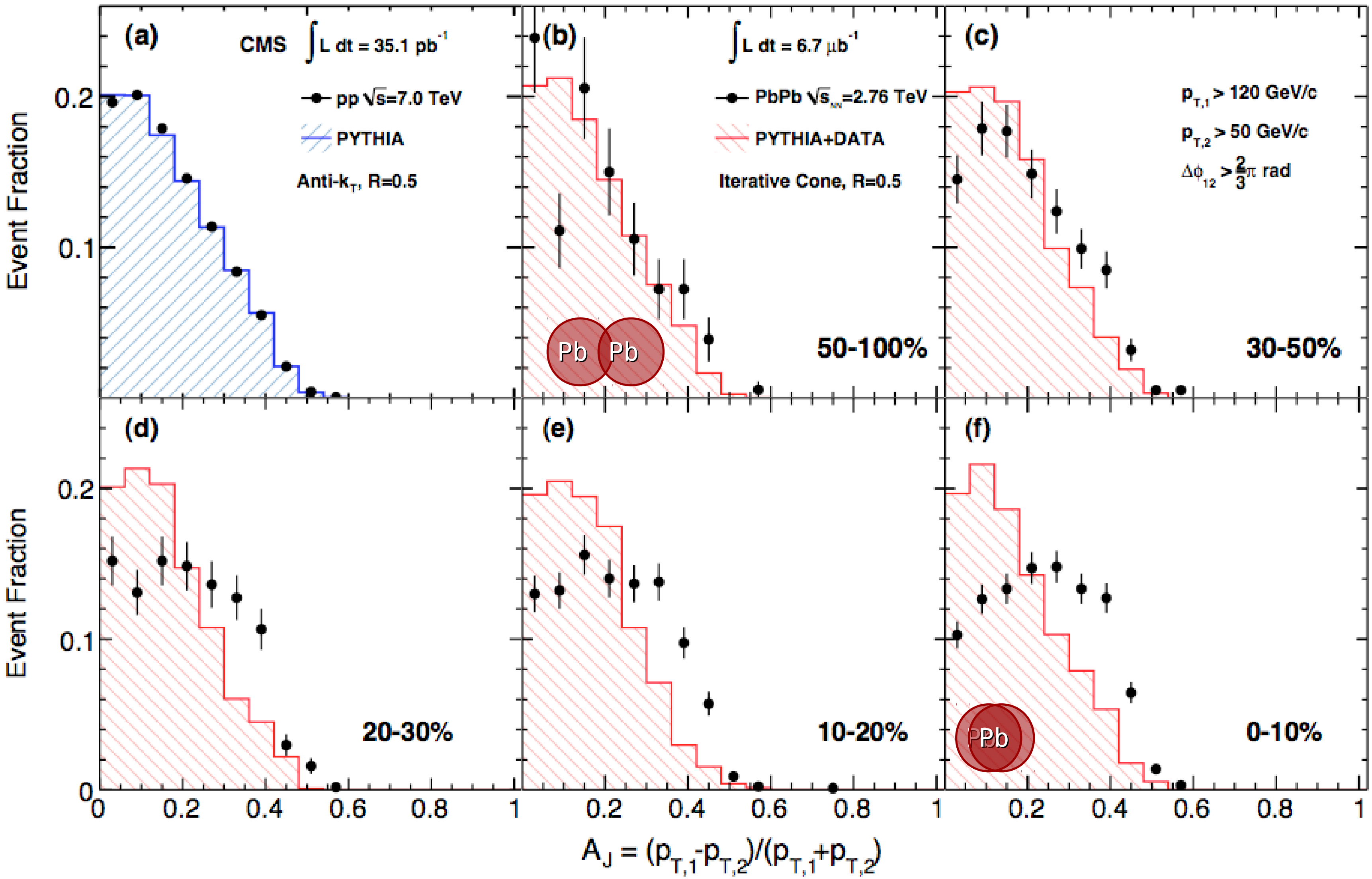
13 CMS HI papers from LHC PbPb run 2010

* HIN-10-001: Multiplicity → JHEP 1108 (2011) 141
* HIN-10-002: Elliptic flow → PAS (CDS record 1347788)
* HIN-10-003: Z bosons → PRL 106 (2011) 212301
* HIN-10-004: Dijets → PRC 84 (2011) 024906
* HIN-10-005: Charged spectra → PAS (CDS record 1352777)
* HIN-10-006: Quarkonia → PAS (CDS record 1353586)
* HIN-11-001: Correlations (“ridge”) → JHEP 1107 (2011) 076
* HIN-11-002: Photons → PAS (CDS record 1352779)
* HIN-11-003: Energy flow → PAS (CDS record 1354215)
* HIN-11-004: Fragmentation functions → PAS (CDS record 1354531)
* HIN-11-005: Flow (higher harmonics) → PAS (CDS record 1361385)
* HIN-11-006: “Ridge” vs. centrality → PAS (CDS record 1353583)
* HIN-11-007: Upsilon → PRL 107 (2011) 052302

Imbalance (asymmetry) of dijet energy

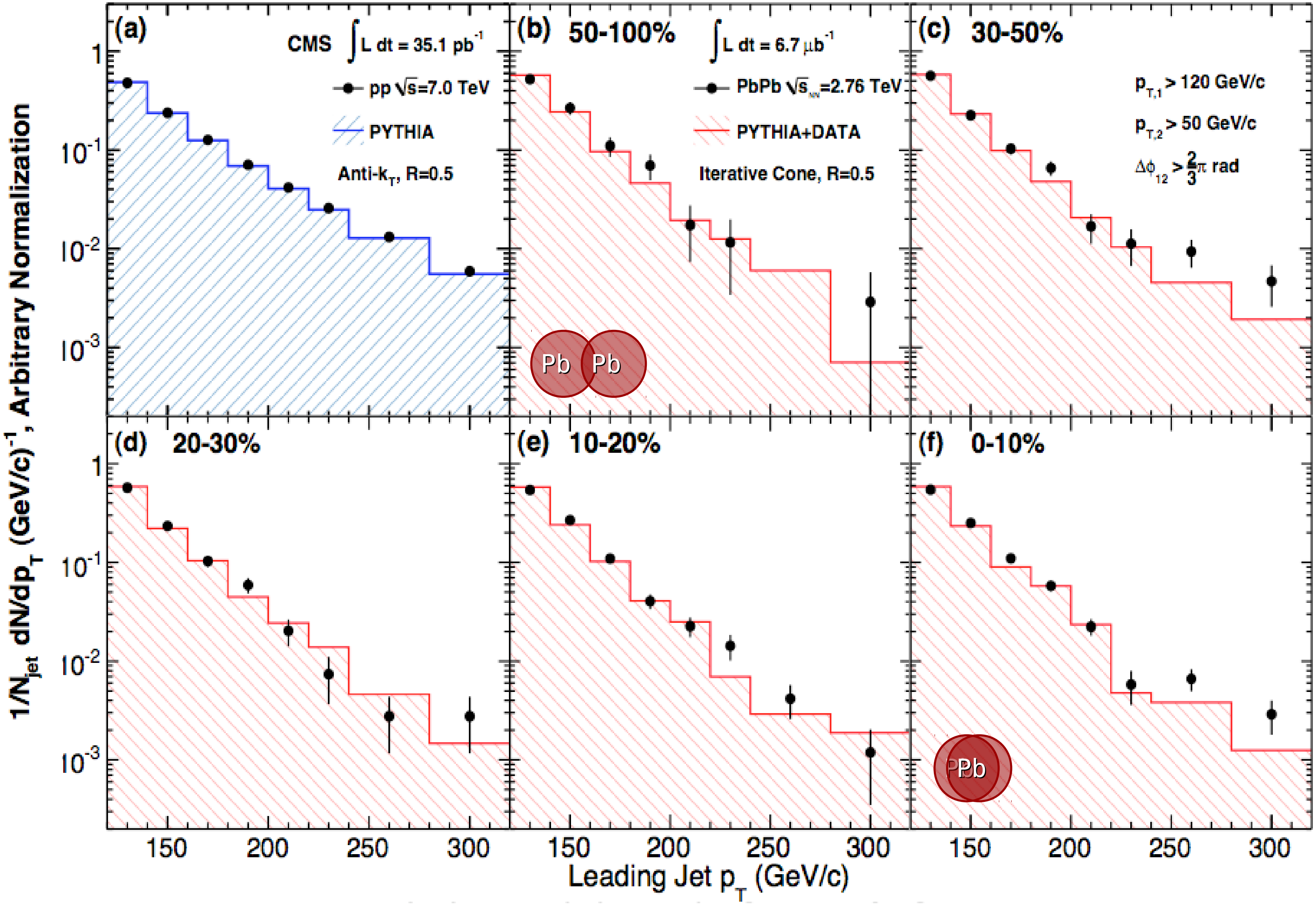


Imbalance (asymmetry) of dijet energy



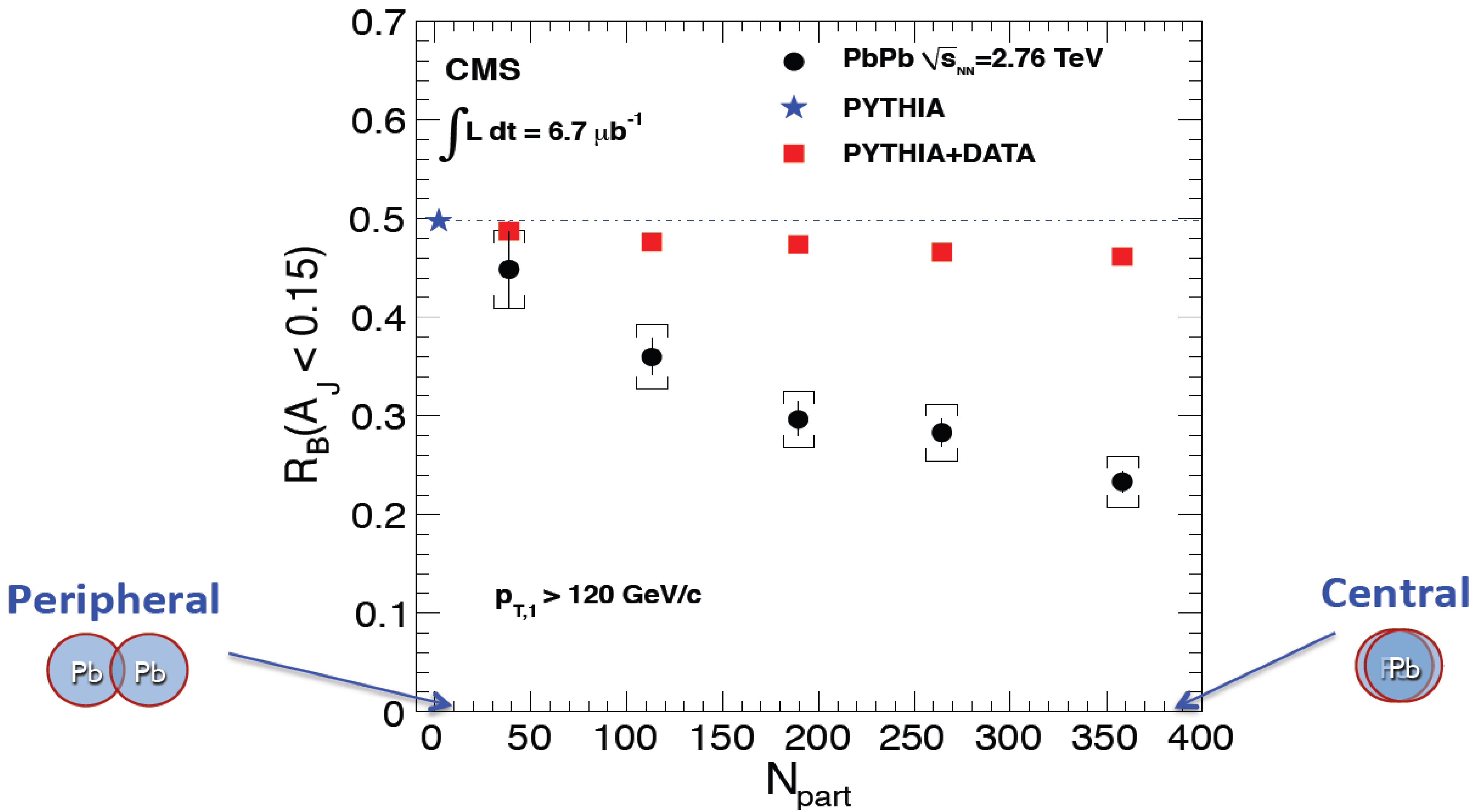
Dijet imbalance increases with centrality & is not reproduced by MC (PYTHIA+PbPb DATA)

Leading jet spectra



Leading jet spectra are not affected by medium & reproduced by MC (PYTHIA+PbPb DATA)

Imbalance (asymmetry) of dijet energy

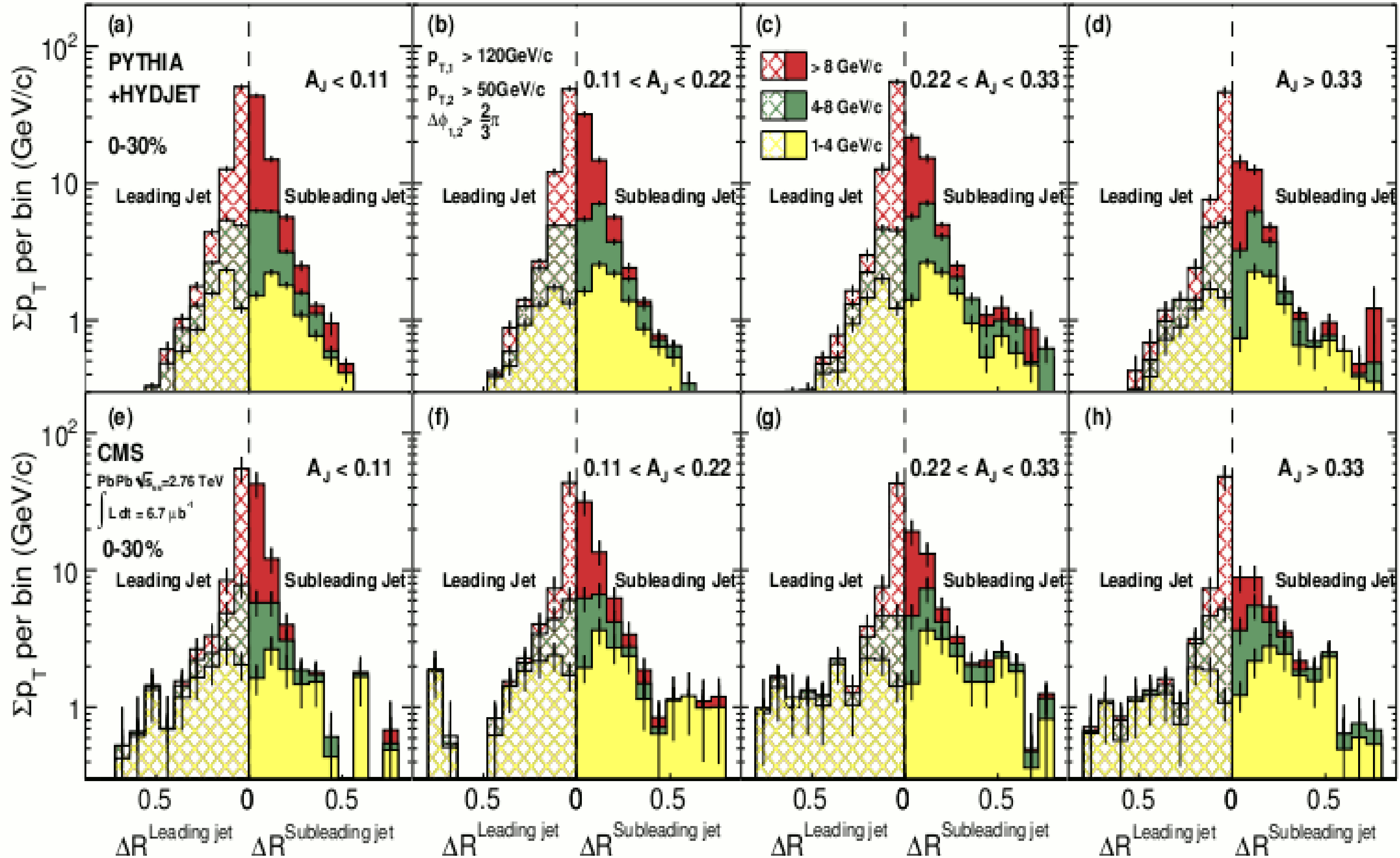


Fraction of "balanced" dijets ($A_J < 0.15$) drops with PbPb centrality & is constant for MC

Jet-track correlation

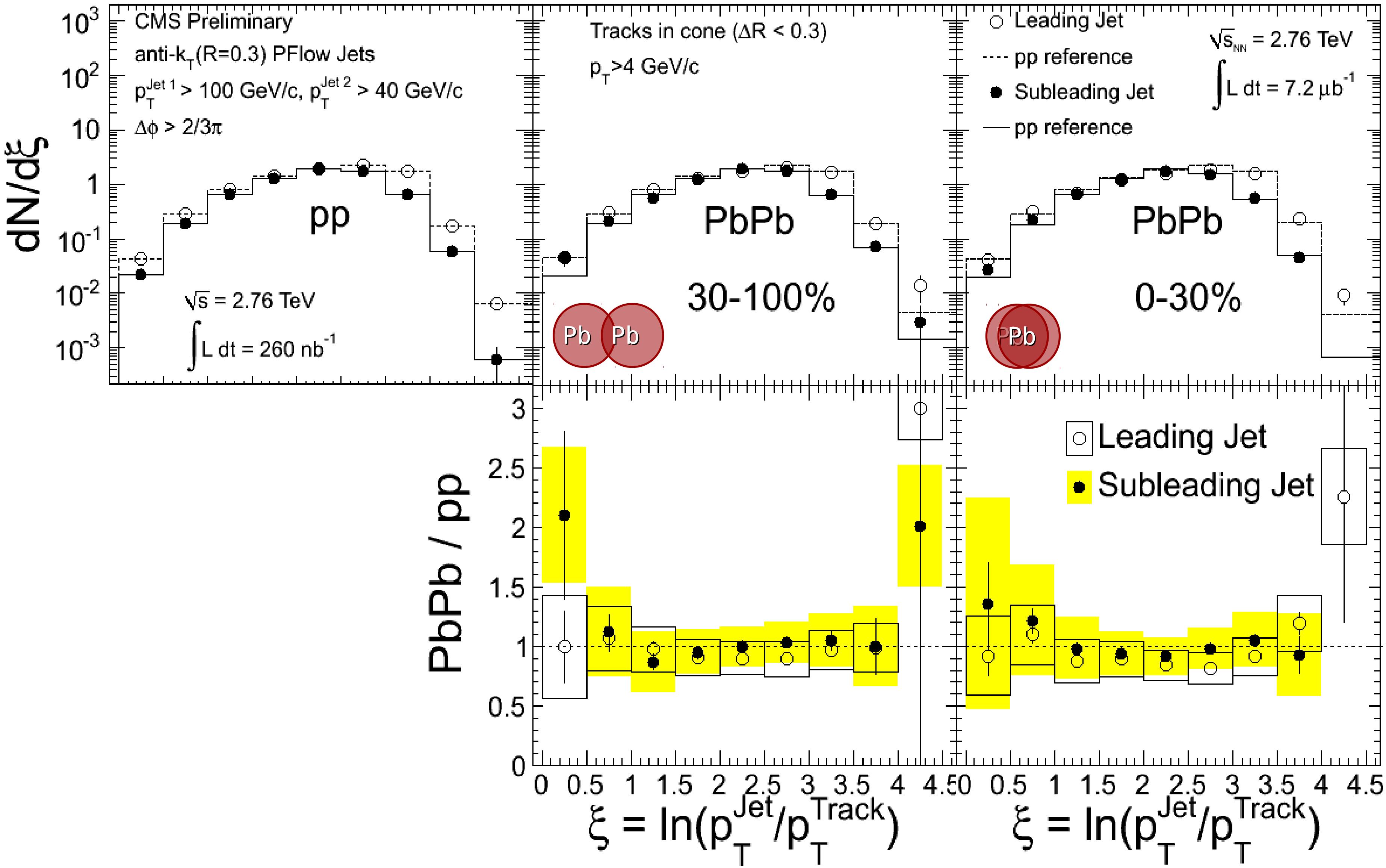
MC

Data



Relative contribution of low-p_T tracks grows with A_J & spreads at large distances to the jet axis

Jet fragmentation function

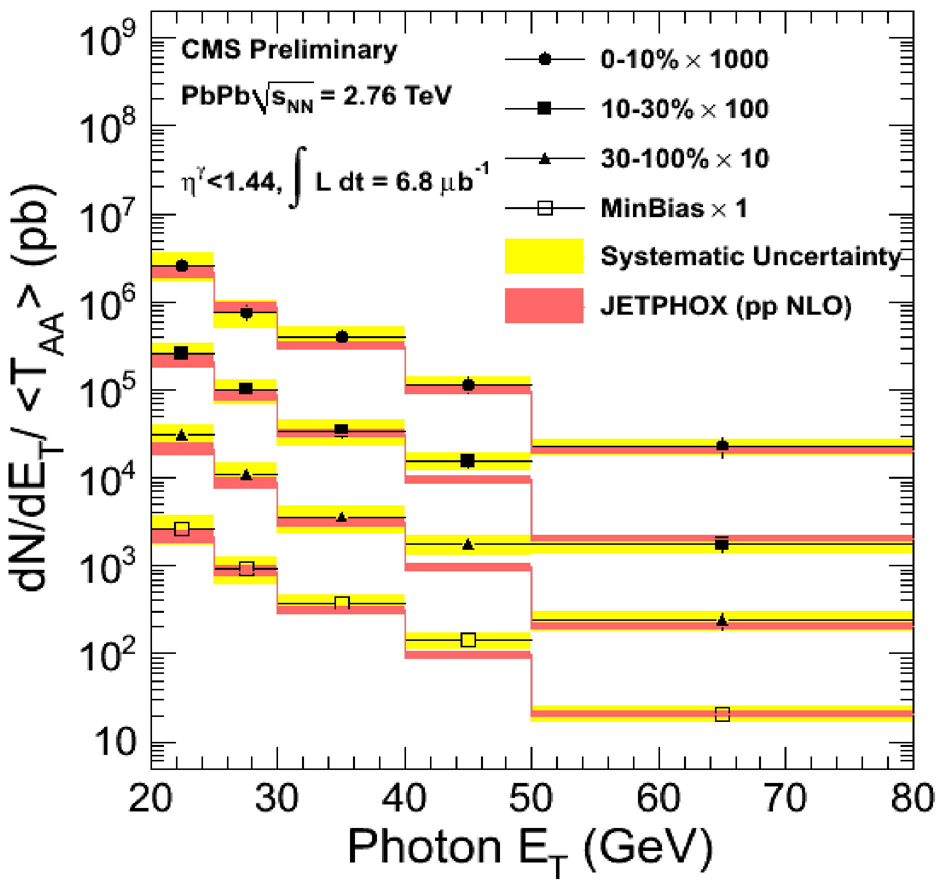


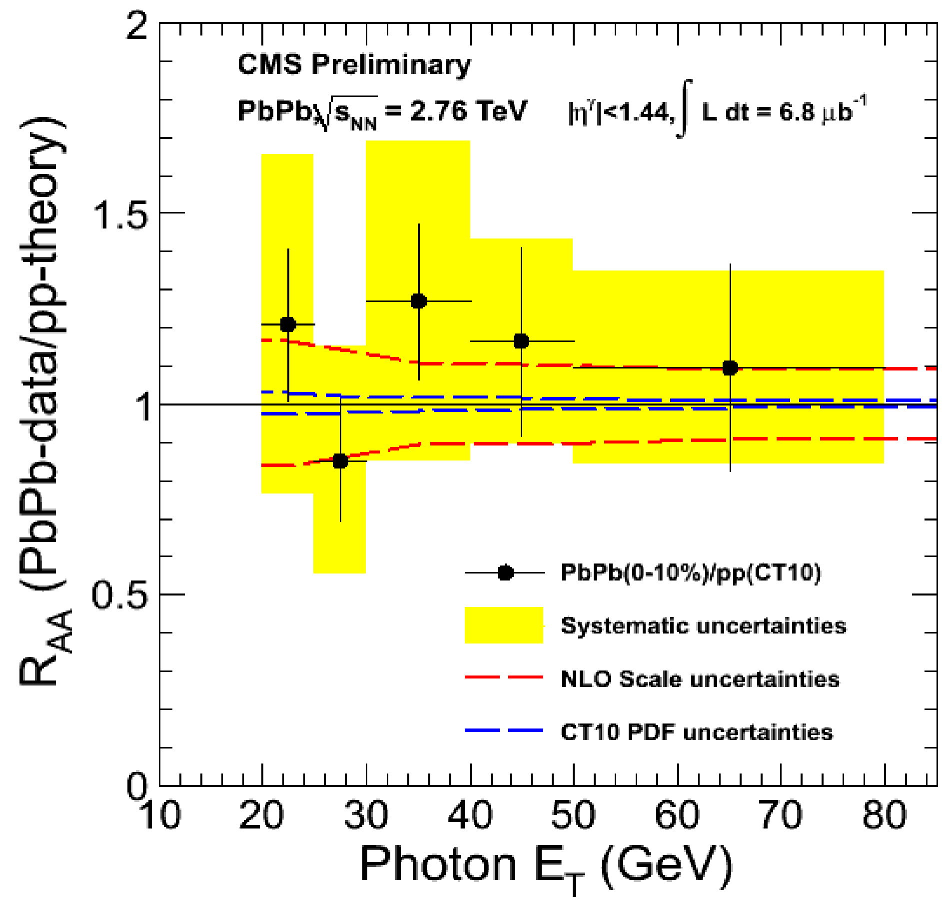
Leading and sub-leading jet fragmentation functions in PbPb and pp collisions are similar

Prompt photons E_T-spectra and R_{AA}

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{"QCD Medium"}}{\text{"QCD Vacuum"}}$$

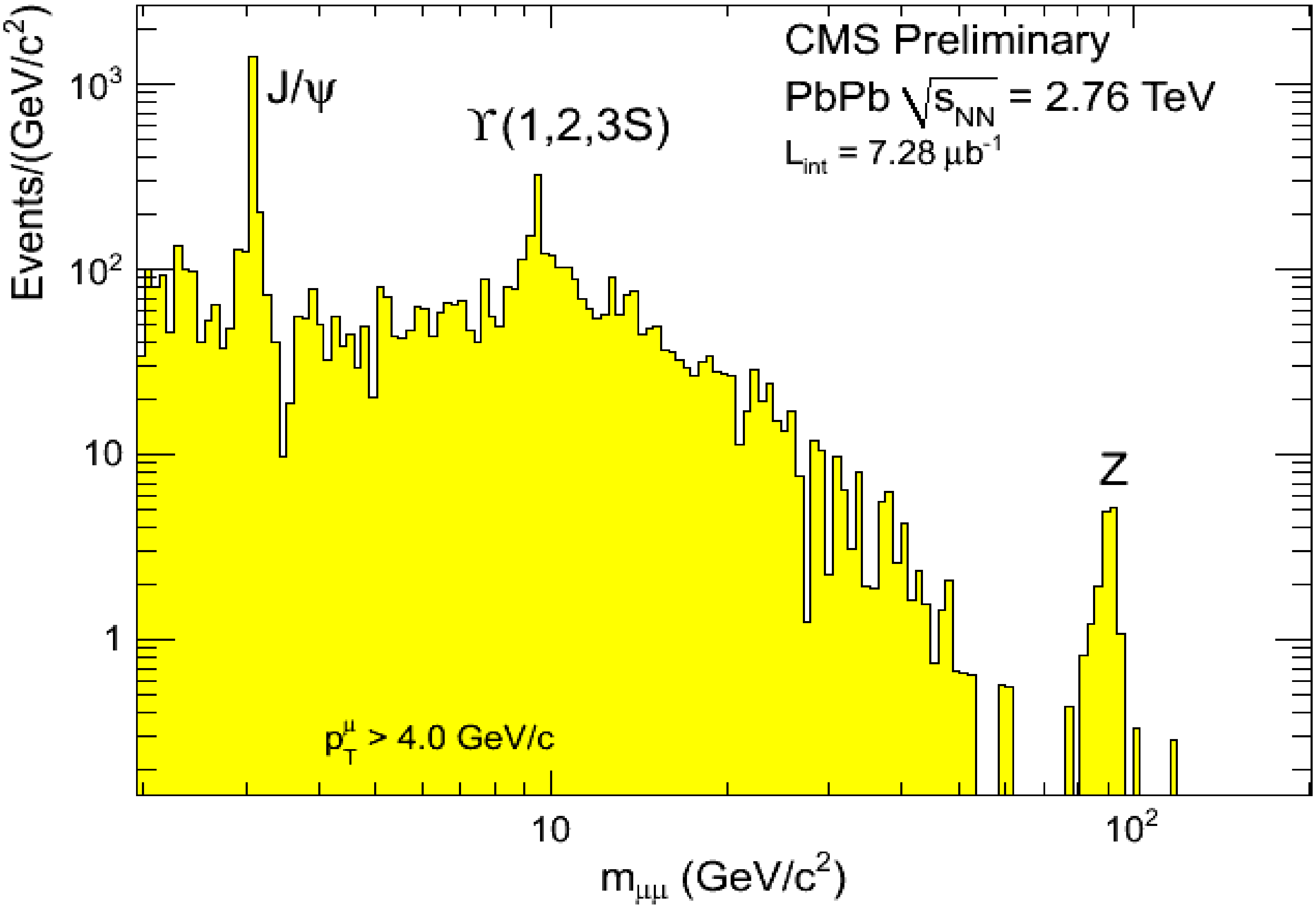
- $R_{AA}>1$: enhancement
- $R_{AA}=1$: no medium effect
- $R_{AA}<1$: suppression





- Energy spectrum is consistent with next-to-leading order pQCD calculations
- Within uncertainties, no violation of binary NN collision scaling is observed

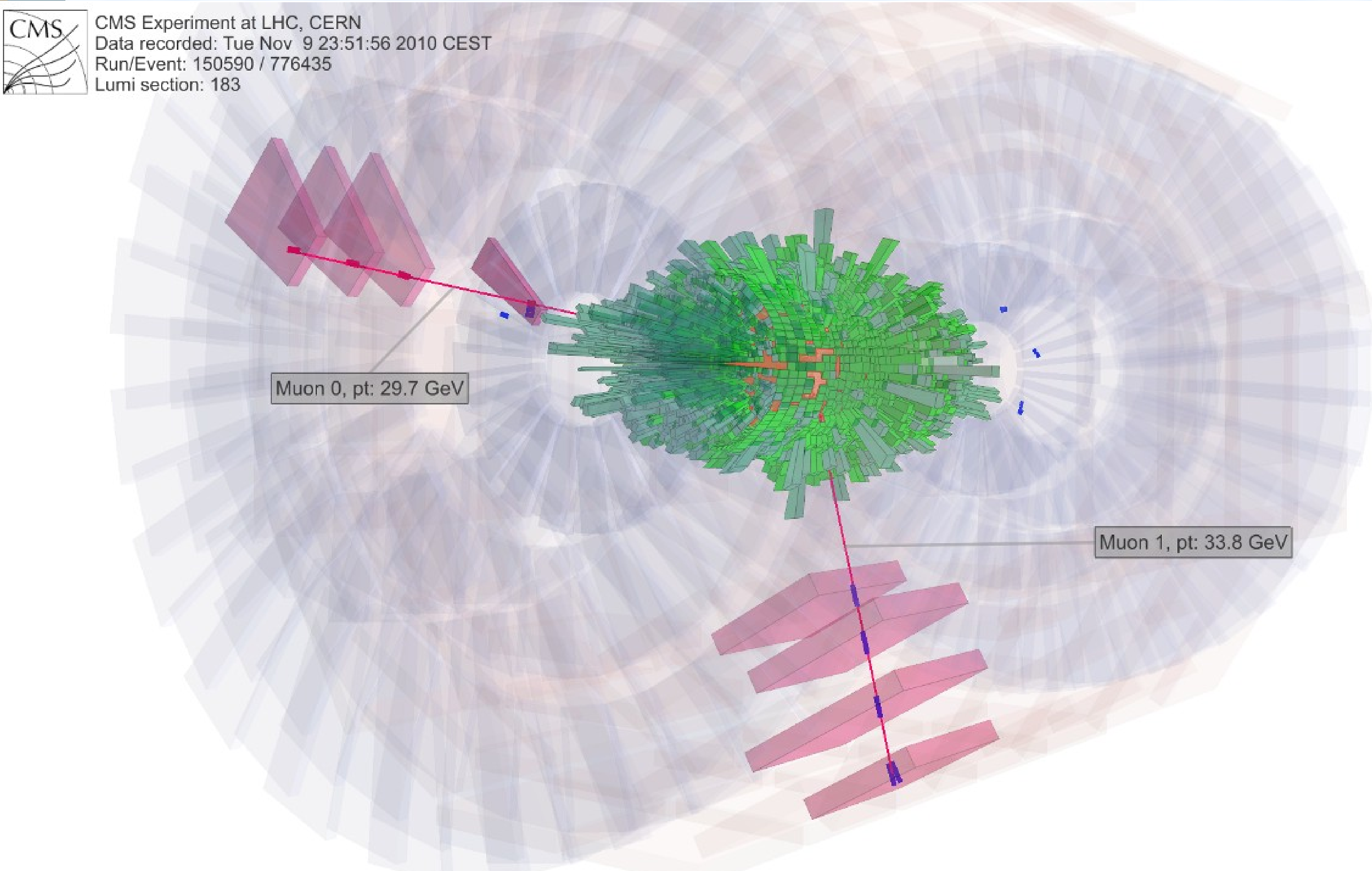
Dimuon mass spectrum



J/ψ, ϒ(1S, 2S, 3S) and Z^0 peaks are clearly visible

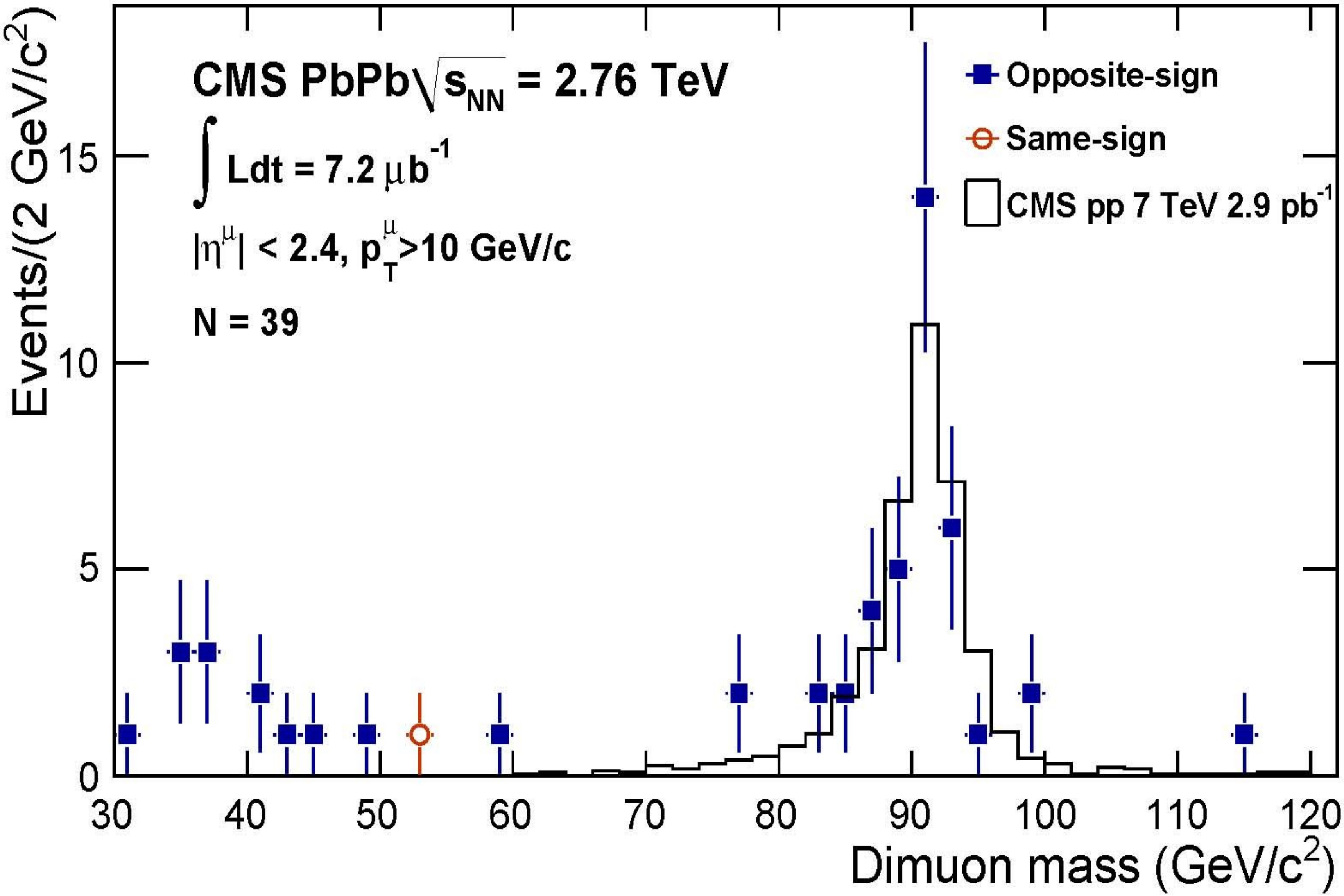
(best mass resolution of all LHC experiments in heavy ion collisions)

$Z^0 \rightarrow \mu^+\mu^-$ in PbPb collisions at CMS



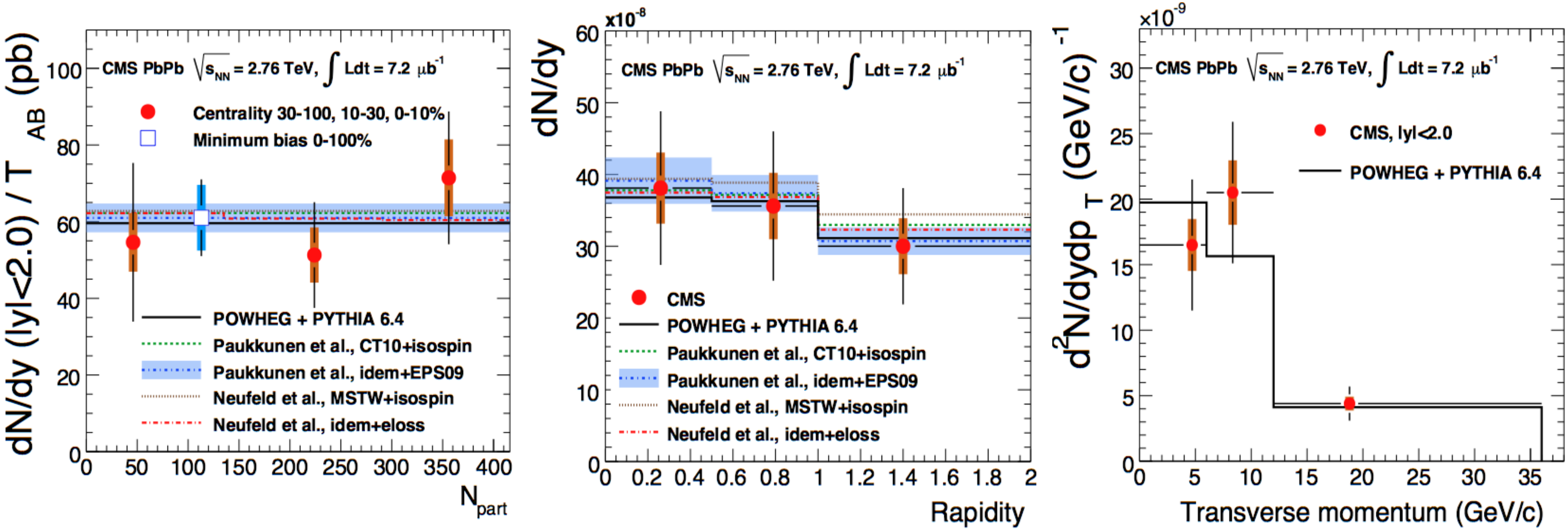
Z-boson is not affected by the medium, and so probes initial state (PDF, nuclear shadowing)

Z^0 mass distribution



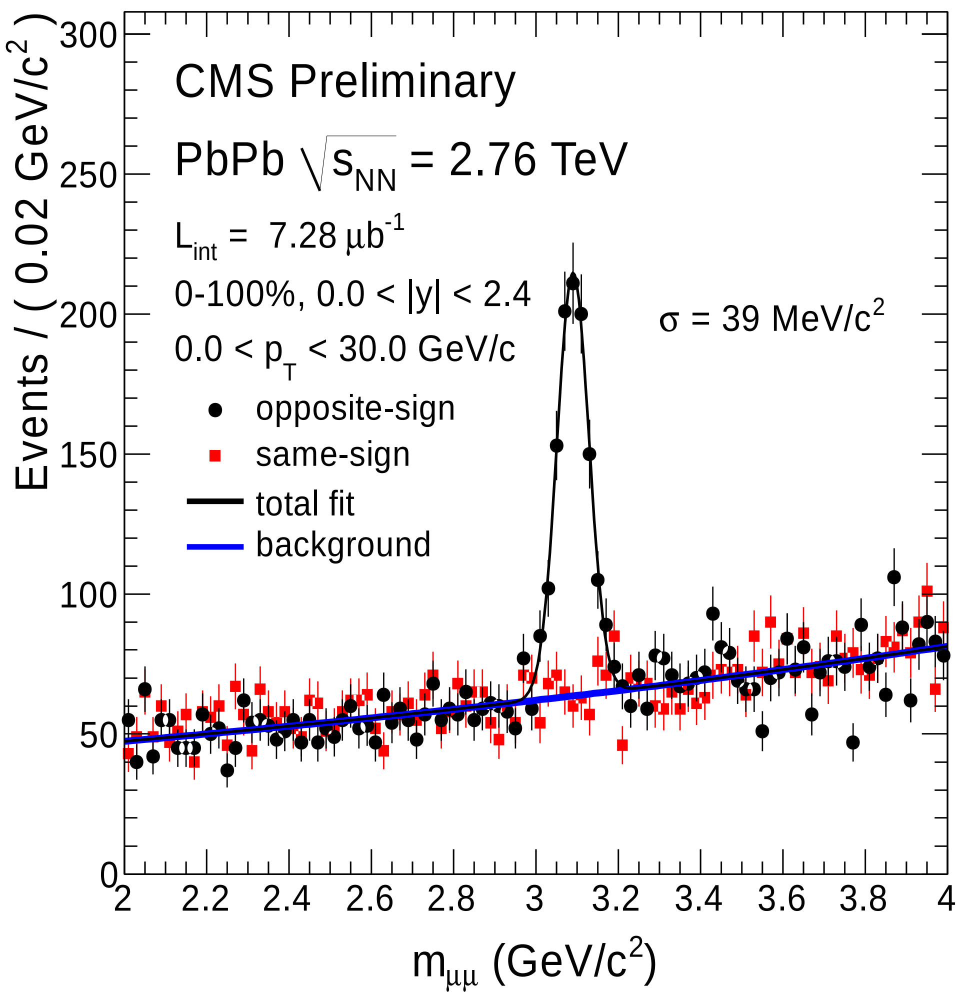
39 reconstructed Z^0's, mass resolution is close to pp one

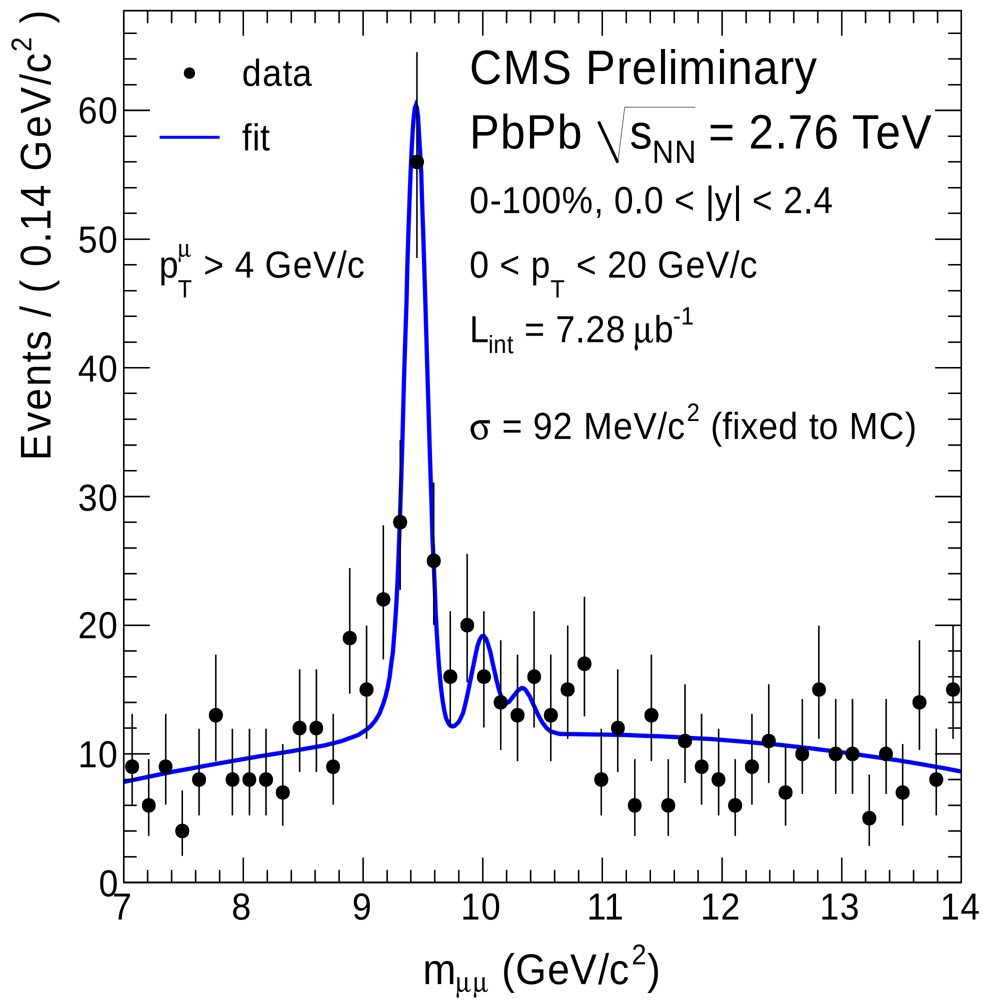
Z^0 vs. centrality, y and p_T



- Kinematic distributions are consistent with pQCD calculations
- Within uncertainties, no violation of binary NN collision scaling is observed

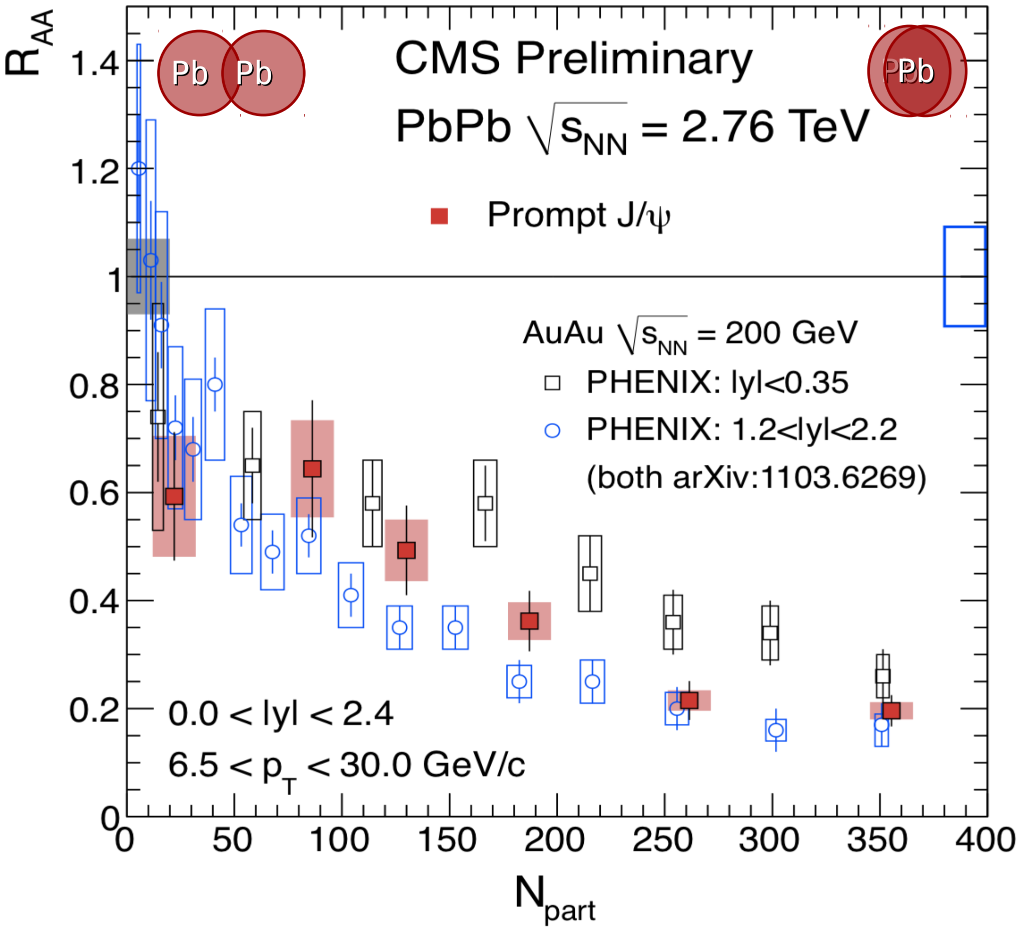
J/ψ and Υ mass distributions

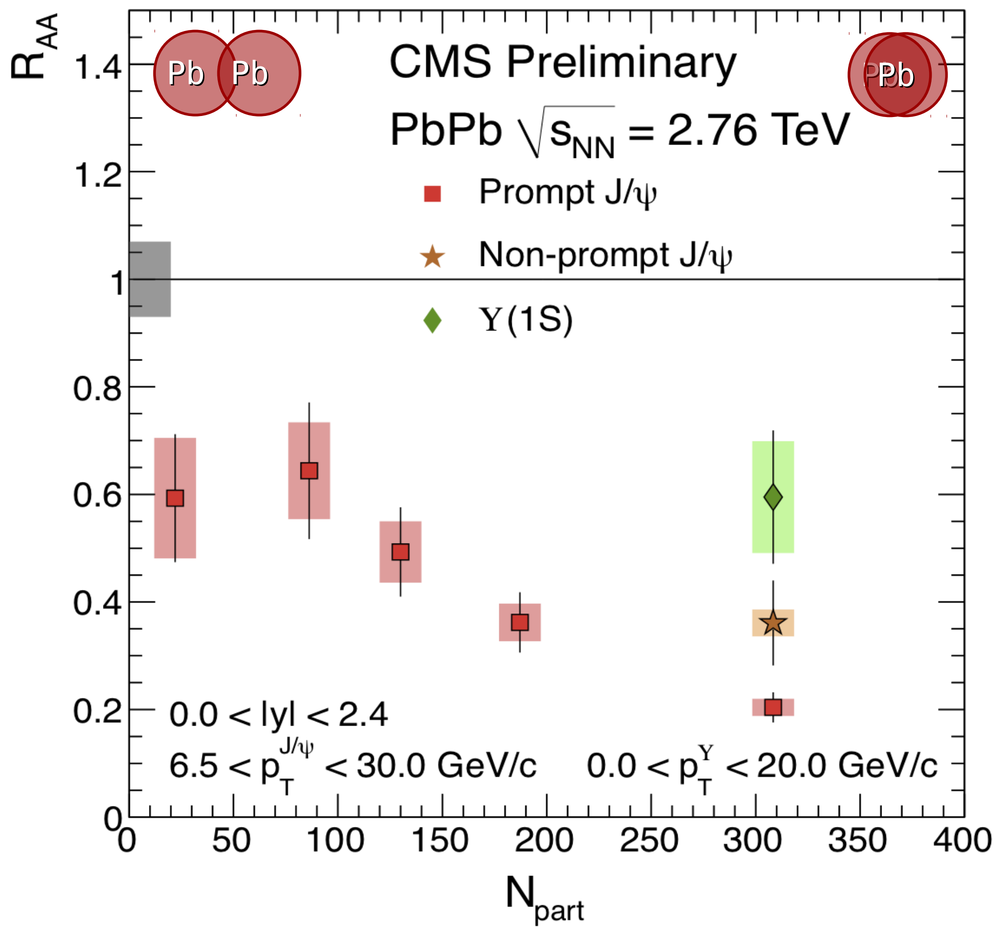




- 734 ±54 J/ψ's and 86±12 Υ's (1S), mass resolutions are close to pp ones
- CMS pp data at √s=2.76 TeV are used as reference for PbPb

J/ψ and Υ suppression vs. centrality

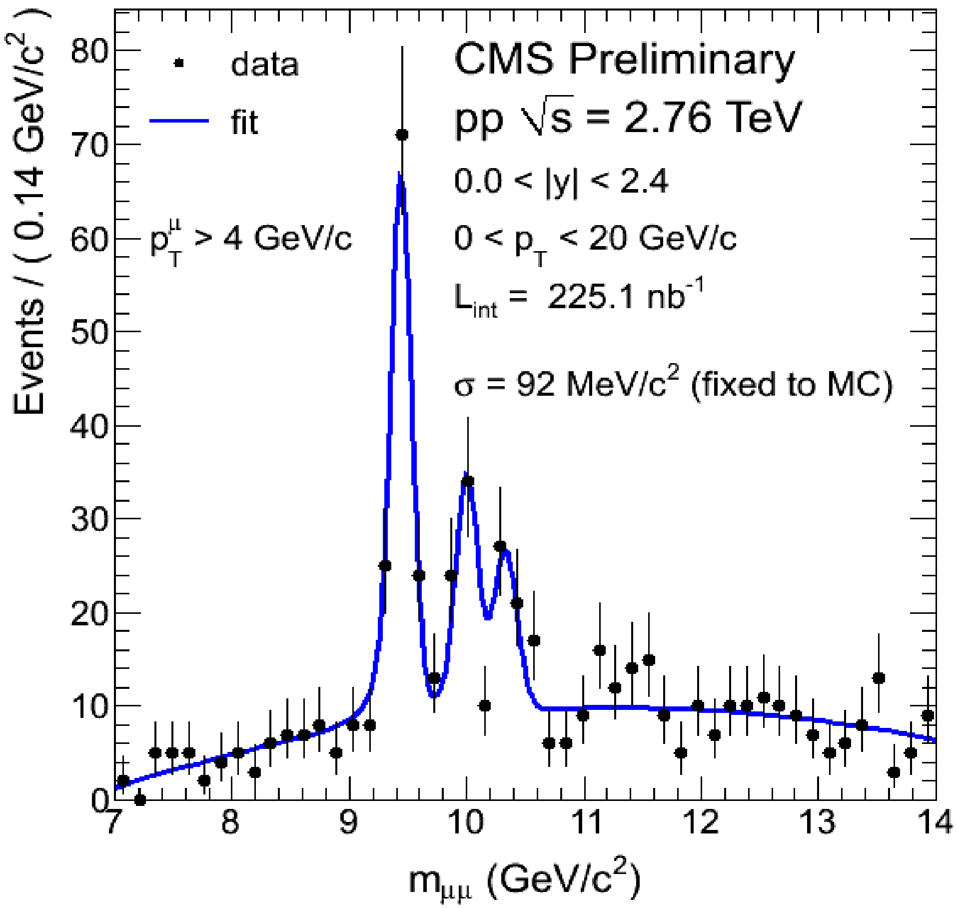




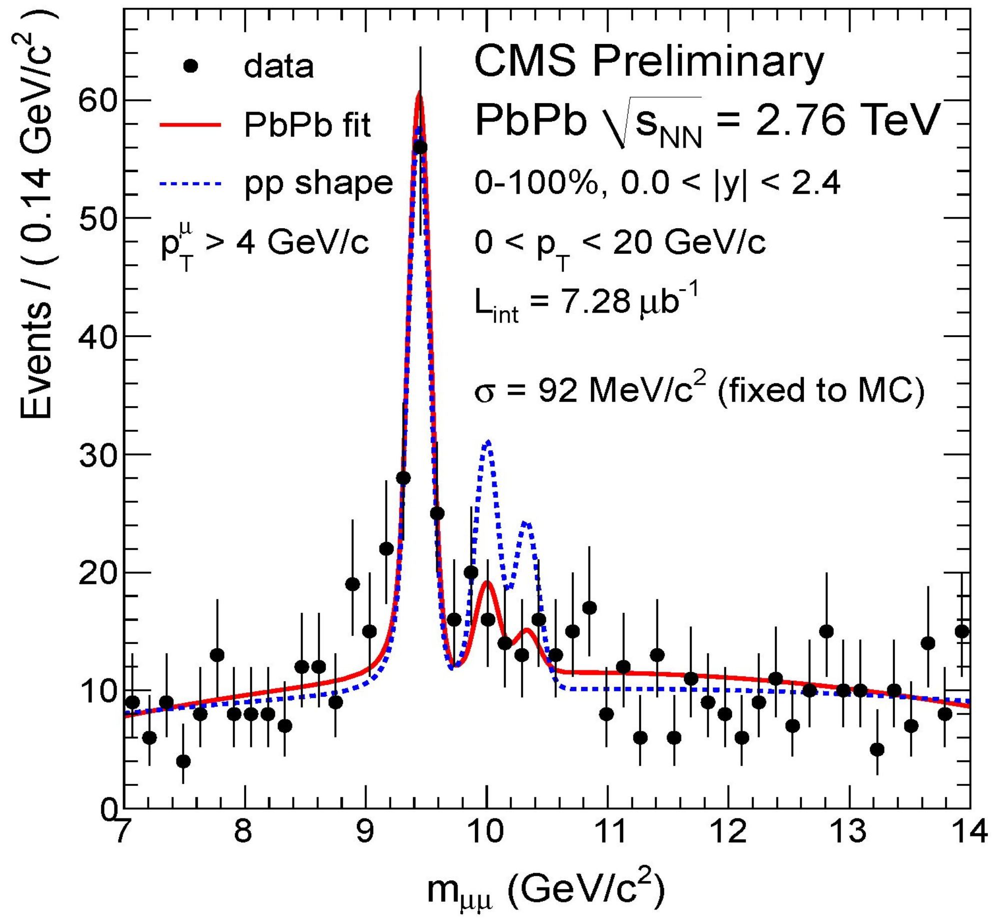
- Prompt J/ψ's are suppressed in central (peripheral) PbPb by a factor 5 (1.6) with respect to pp
(centrality dependence is similar to the one measured at RHIC, but in a different kinematic range)
- Secondary J/ψ's are suppressed in minimum bias PbPb by a factor of 2.8 with respect to pp
(first indication on medium-induced energy loss of b-quarks?)
- Υ's (1S) are suppressed in central PbPb by a factor 1.5 with respect to pp *(sequential melting?)*

$\Upsilon(2S+3S)/\Upsilon(1S)$ suppression

$\Upsilon(2S+3S)/\Upsilon(1S)_{pp}=0.78\pm0.15\pm0.02$

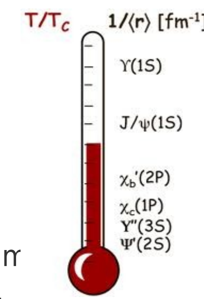


$\Upsilon(2S+3S)/\Upsilon(1S)_{PbPb}=0.24\pm0.12\pm0.02$

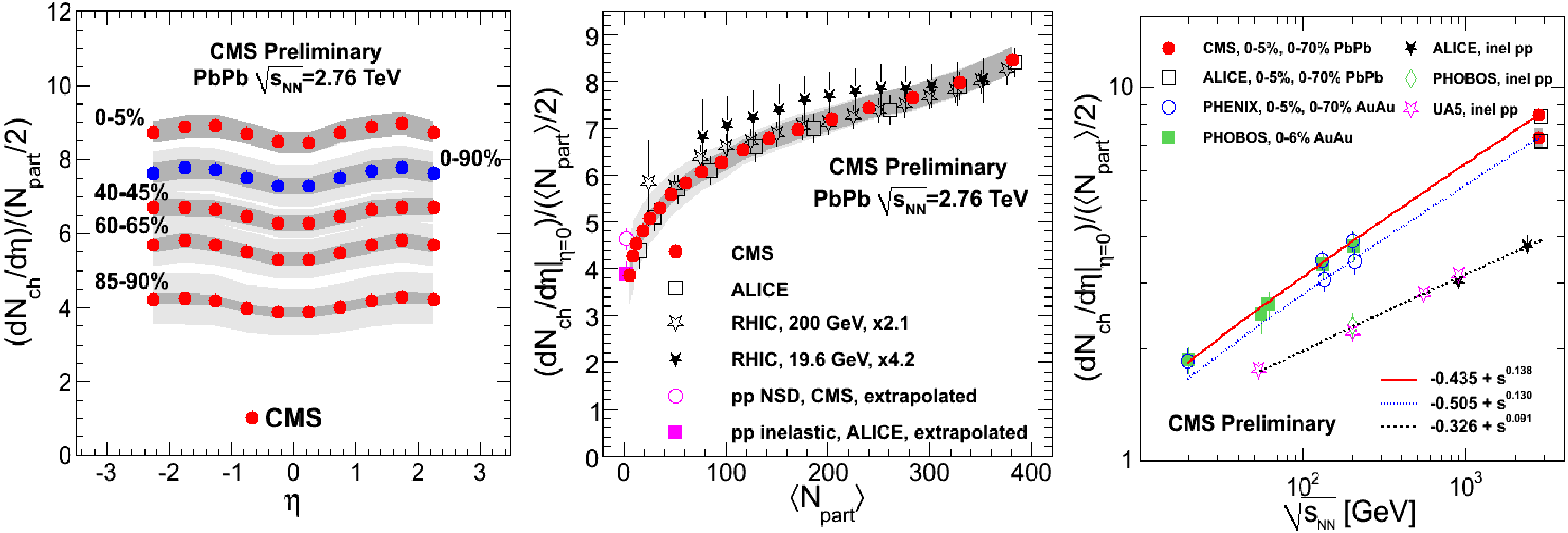


Suppression of $\Upsilon(2S+3S)$ relatively to $\Upsilon(1S)$ by a factor ~3 is seen

$[\Upsilon(2S+3S)/\Upsilon(1S)]_{PbPb}$ / $[\Upsilon(2S+3S)/\Upsilon(1S)]_{pp}$ = $0.31\pm0.17\pm0.03$



Hadron multiplicty vs. η, centrality and $\sqrt{s}_{NN}$

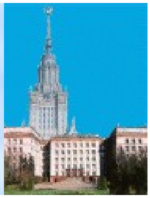


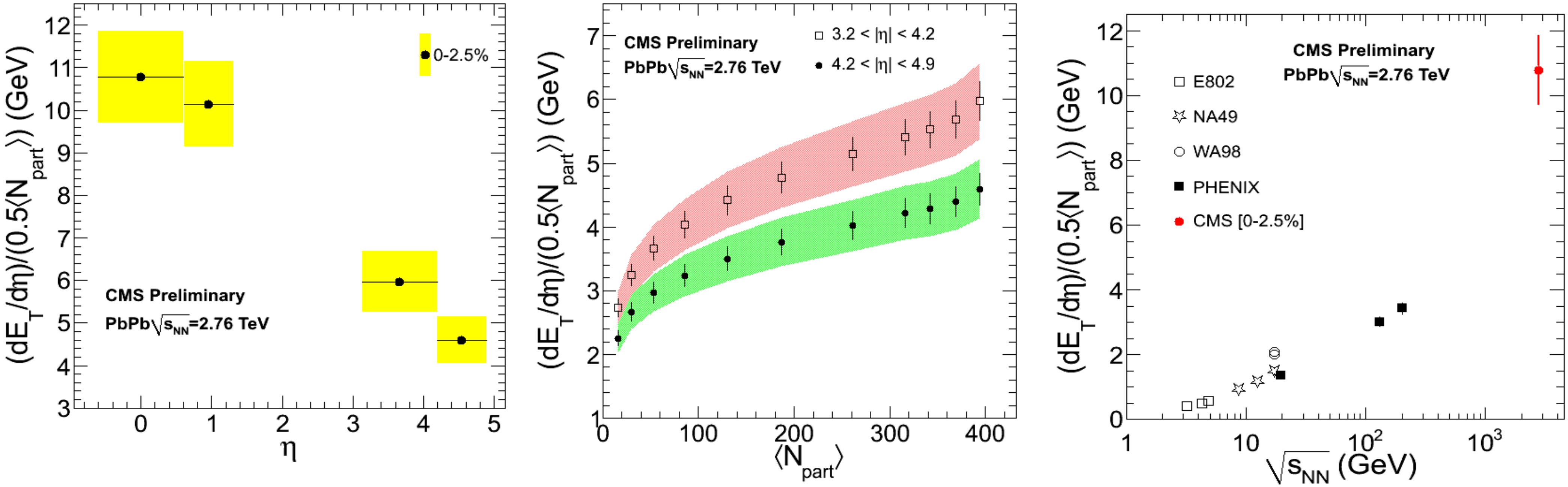
- No strong rapidity dependence of hadron multiplicity is seen (<10% variation)

central PbPb (0-5%): $dN_{ch}/d\eta\,(\eta=0) = 1610\pm55$ (by a factor of 2.2 ± 0.1 higher than at RHIC)

- Hadron multiplicity increases with centrality, CMS and ALICE are in the agreement
- Hadron multiplicity rises with $\sqrt{s}_{NN}$ in accordance with a power low (stronger than in pp)

Energy flow vs. η, centrality and $\sqrt{s}_{NN}$





- $dE_T/d\eta$ is maximal at η = 0, shape is consistent with a Gaussian with σ = 3.5±0.3

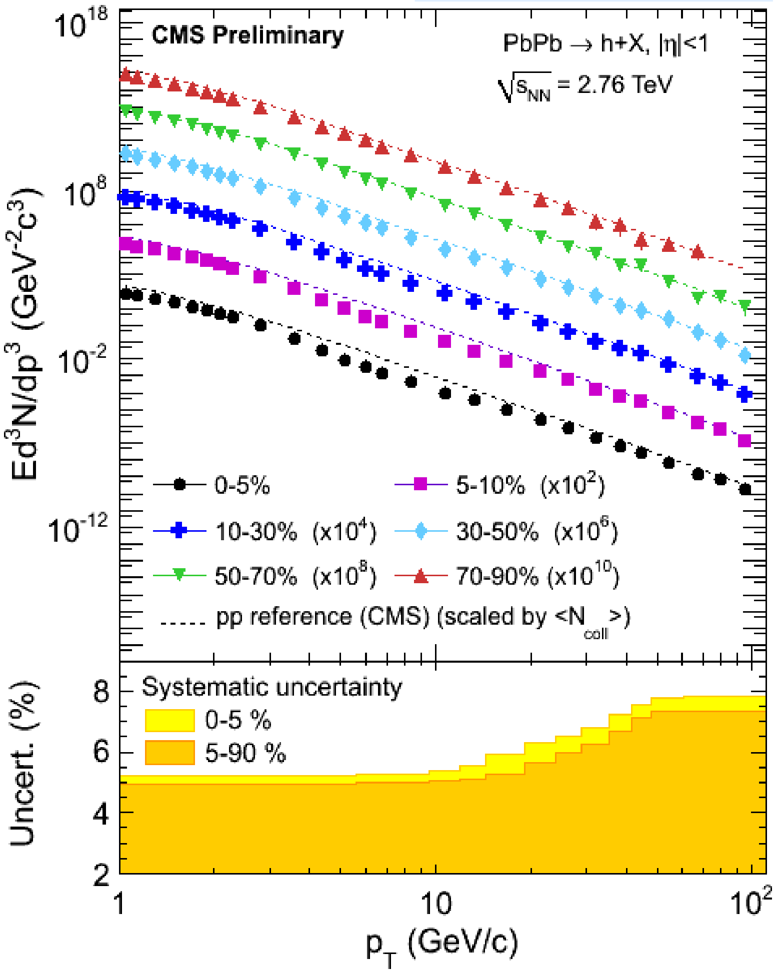
central PbPb (0-2.5%): $dE_T/d\eta$ (η=0) ≈ 2 TeV - by a factor of 3.4±0.4 higher than at RHIC

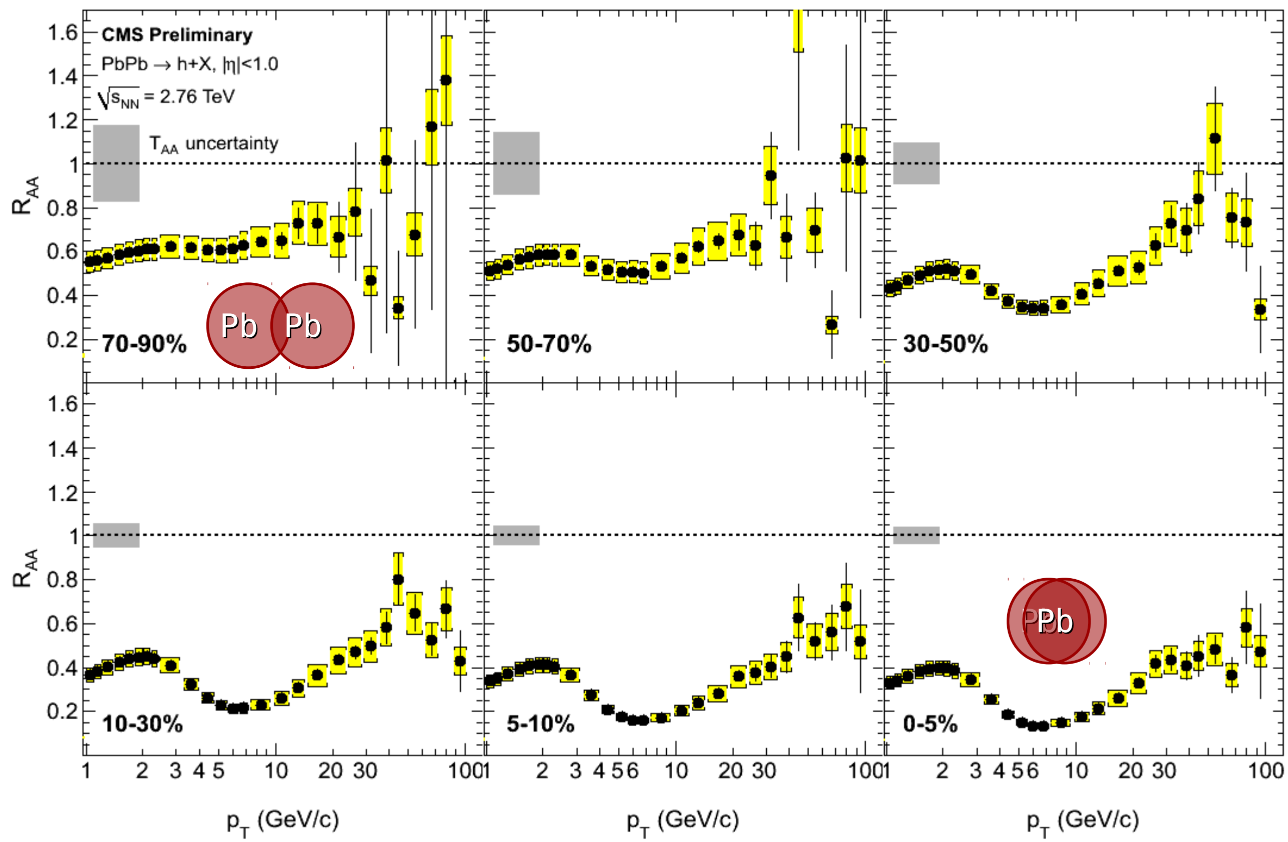
- $dE_T/d\eta/(0.5<N_{part}>)$ increases monotonically with centrality, $<N_{part}>$
- $dE_T/d\eta$ rises with $\sqrt{s}_{NN}$ more quickly than logarithmically

Charged hadron p_T-spectra and R_{AA}

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta} \sim \frac{\text{“QCD Medium”}}{\text{“QCD Vacuum“}}$$

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



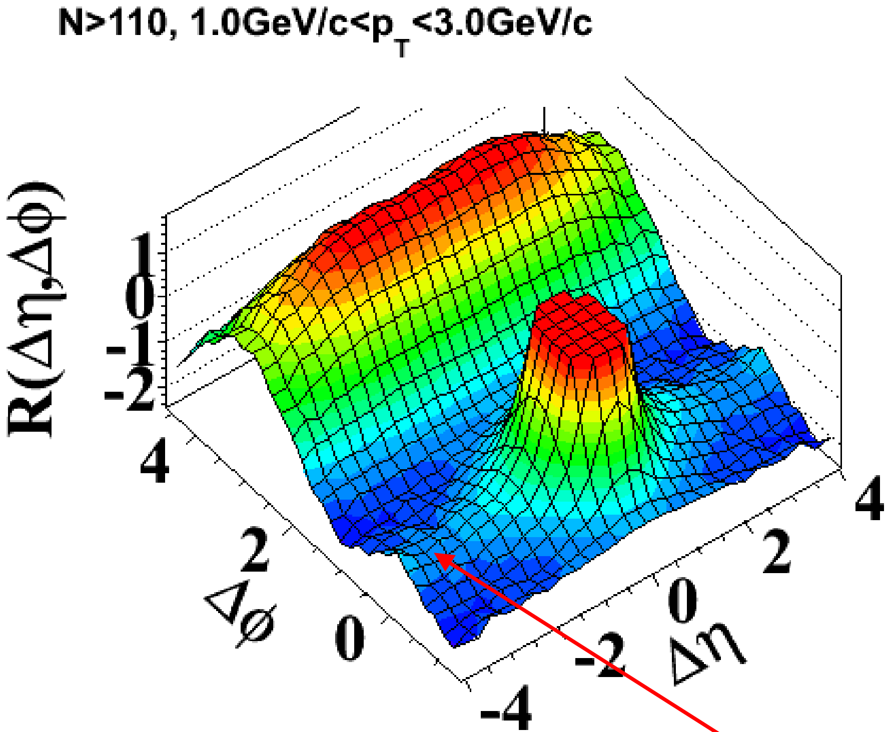


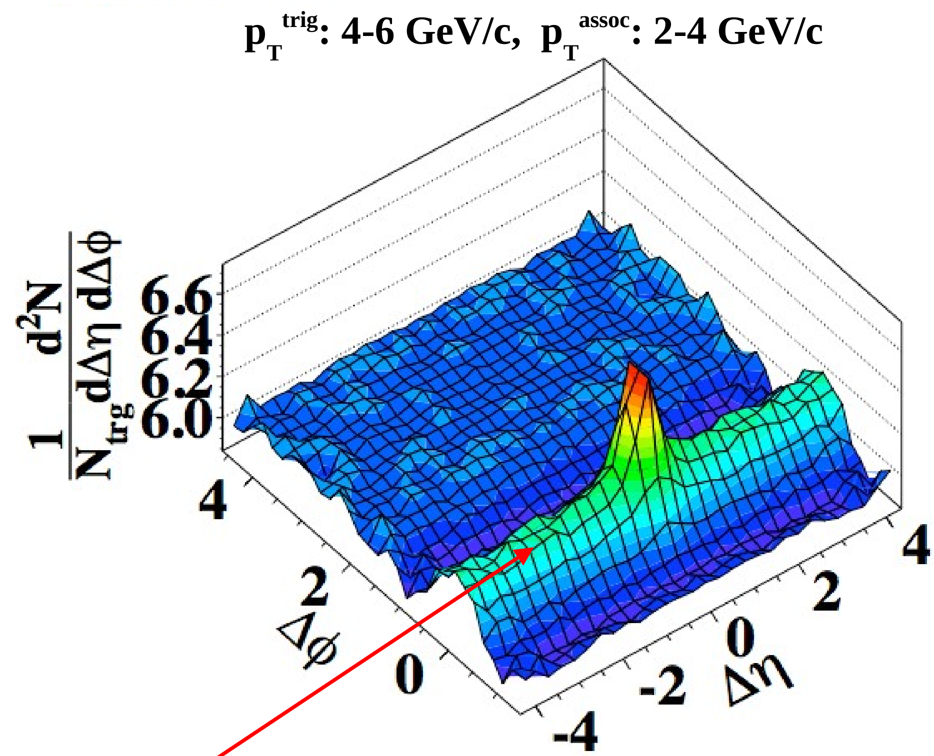
Strong momentum dependence of suppression factor is observed

Two-particle correlations

pp, 7 TeV

PbPb (0-5%), 2.76 A TeV

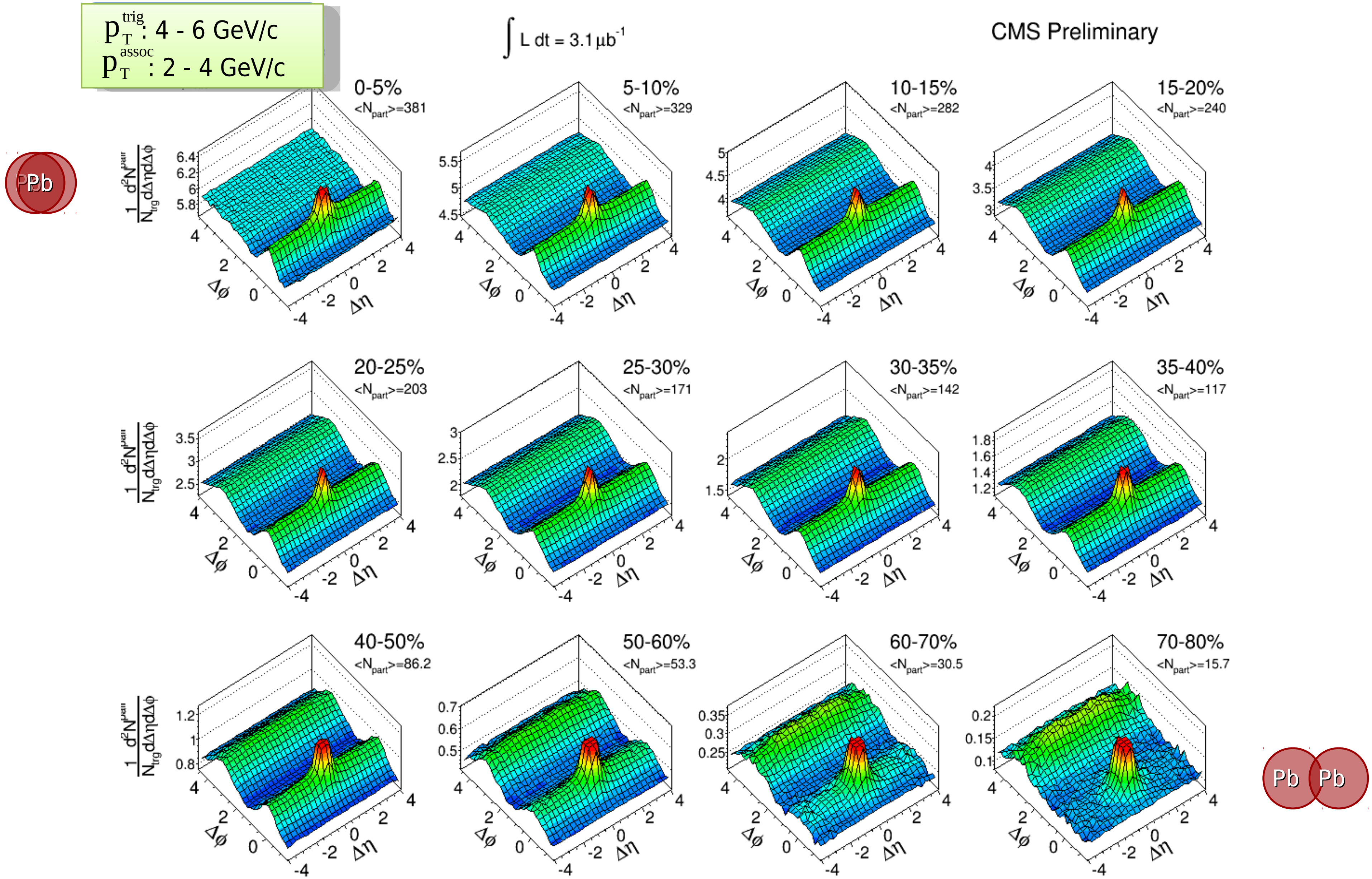




”Ridge” (long-range azimuthal correlations) is observed by CMS in high multiplicity pp as well as in central PbPb collisions

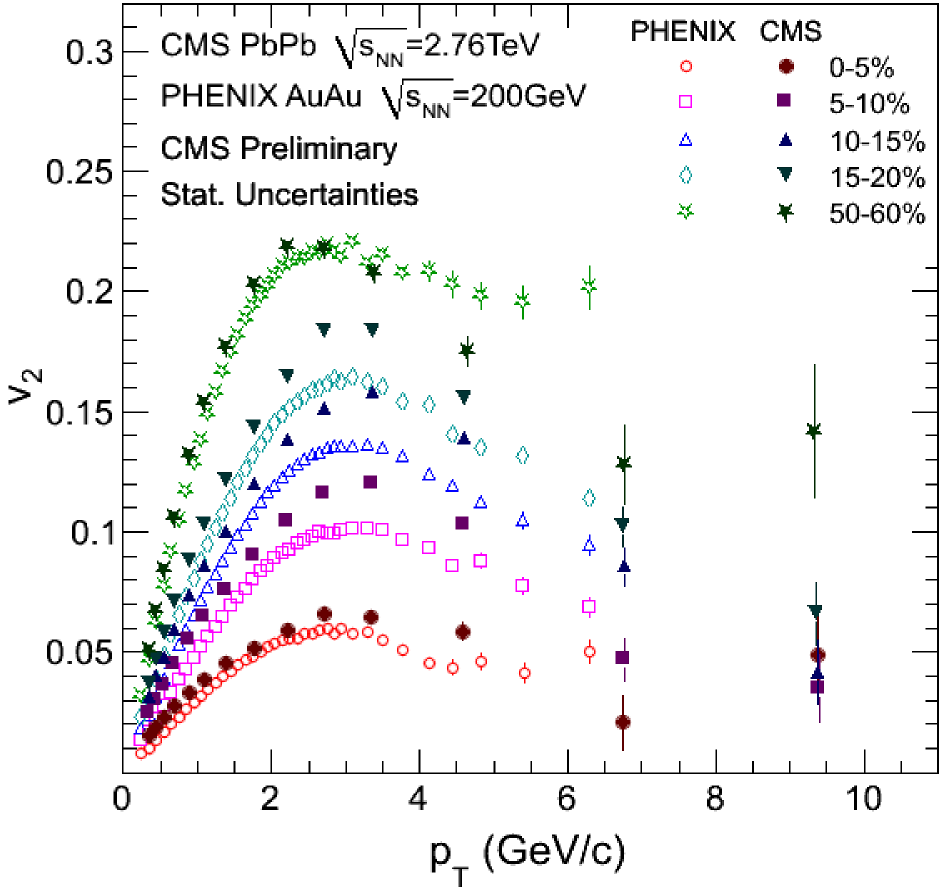
Two-particle correlations vs. centrality

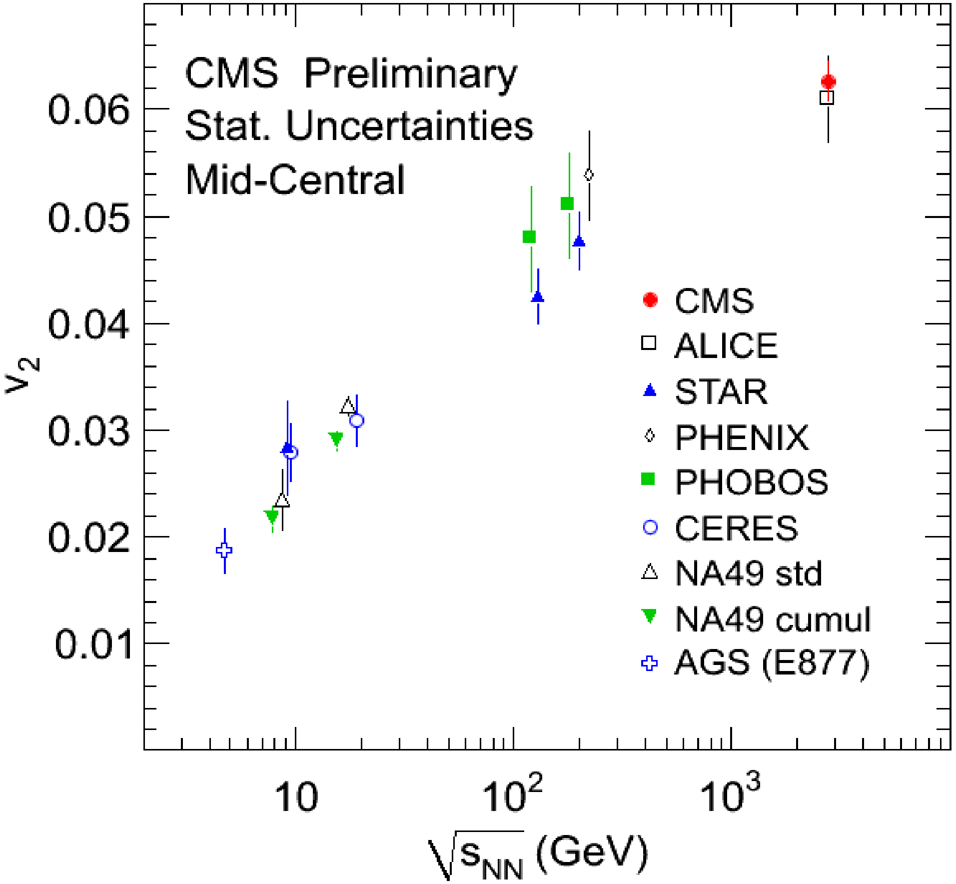
p_T^{trig}: 4 - 6 GeV/c
p_T^{assoc}: 2 - 4 GeV/c



Elliptic flow v_2 vs. p_T and $\sqrt{s}_{NN}$

$$\frac{dN}{d^2 p_t dy} = \frac{dN}{2\pi p_t dp_t dy}(1 + v_2 \cos 2\varphi + 2v_4 \cos 4\varphi + ...)$$





- $v_2(p_T)$ peaks at ~ 3 GeV/c, finite at ~10 GeV/c, strongest for 40-50% centrality
- P_T-dependence of v_2 at LHC is similar to RHIC
- Integral v_2 at the LHC is higher than at RHIC by ~15-30% (due to the rise of $<p_T>$)

Summary

First CMS results on PbPb collisions show a number of exiting collective features

- Dijet asymmetry and jet fragmentation function *(jet quenching)*
  jet energy loss spreads over low pT and large angles, unmodified fragmentation
  (the novel observables, were not studied at RHIC)
- Suppresion of high momentum hadrons *(quenching of leading partons)*
  strong momentum dependence of suppression factor
  (much higher transverse momenta than at RHIC, up to ~100 GeV/c, are available)
- J/ψ, ϒ and ϒ(2S+3S)/ ϒ(1S) suppression *(quarkonium melting)*
  the only experiment that separates ϒ family peaks in heavy ion collisions
  (ϒ and B→J/ψ suppression – the novel observables, were not studied at RHIC)
- Ridge *(long range two-particle azimuthal correlations)*
  similar to high multiplicity pp collisions at 7 TeV and AuAu collisions at RHIC
- Strong elliptic flow *(hydrodynamical behavior)*
  momentum dependence of v2 is similar to RHIC, integral v2 is larger
- Z^0 and prompt photons *(electroweak hard probes)*
  no medium effects are seen – confirmation of NN binary scaling
  (first measurements of Z and isolated photons in heavy ion collisions)

Outlook

Future studies with higher statistics (expected from LHC PbPb run 2011)

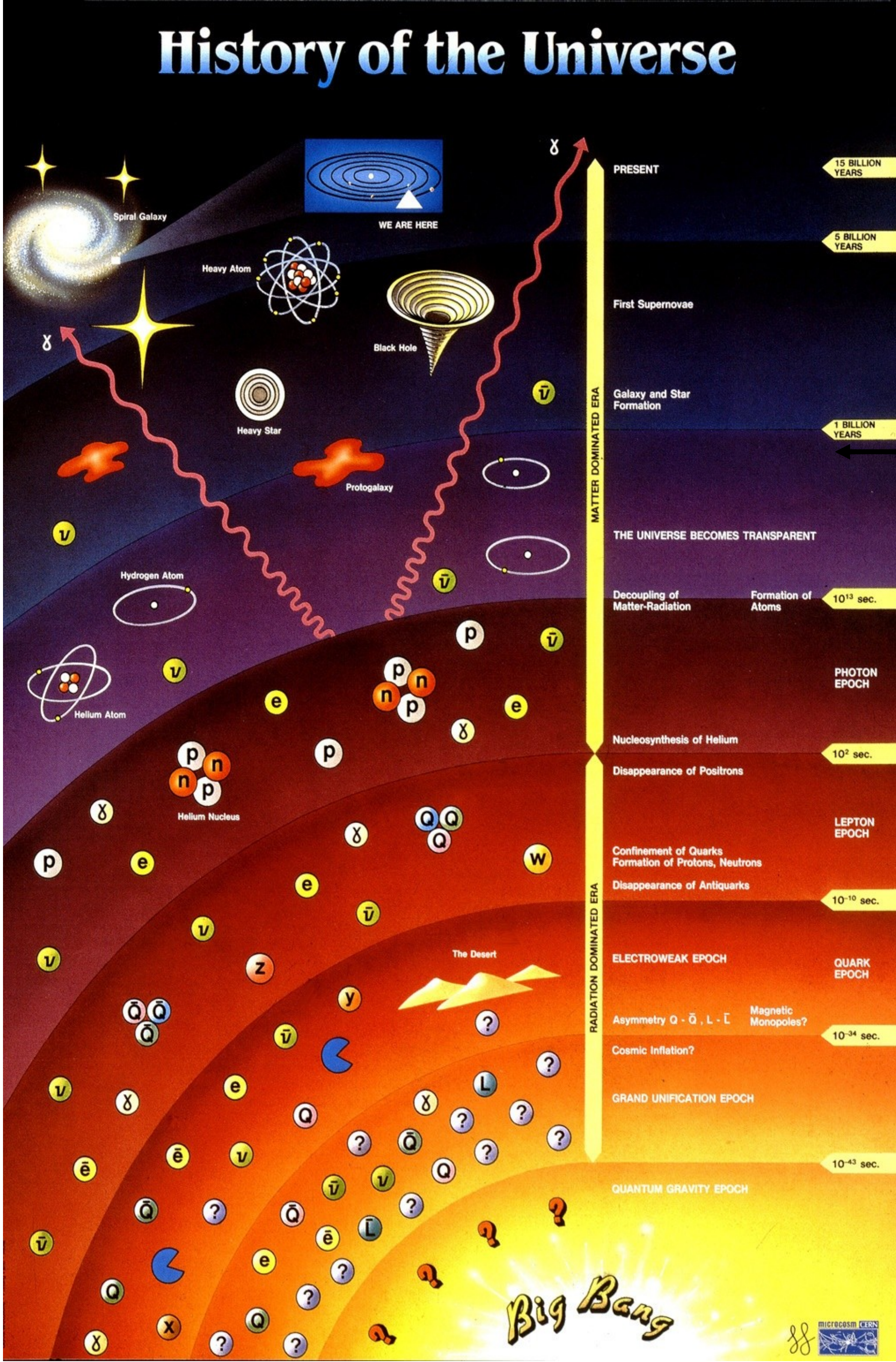
- more differential study of jets

  (fragmentation functions, jet shapes, multi-jets, ...)
- Z/γ-jet correlations
- more differential study of high-mass dimuon resonances

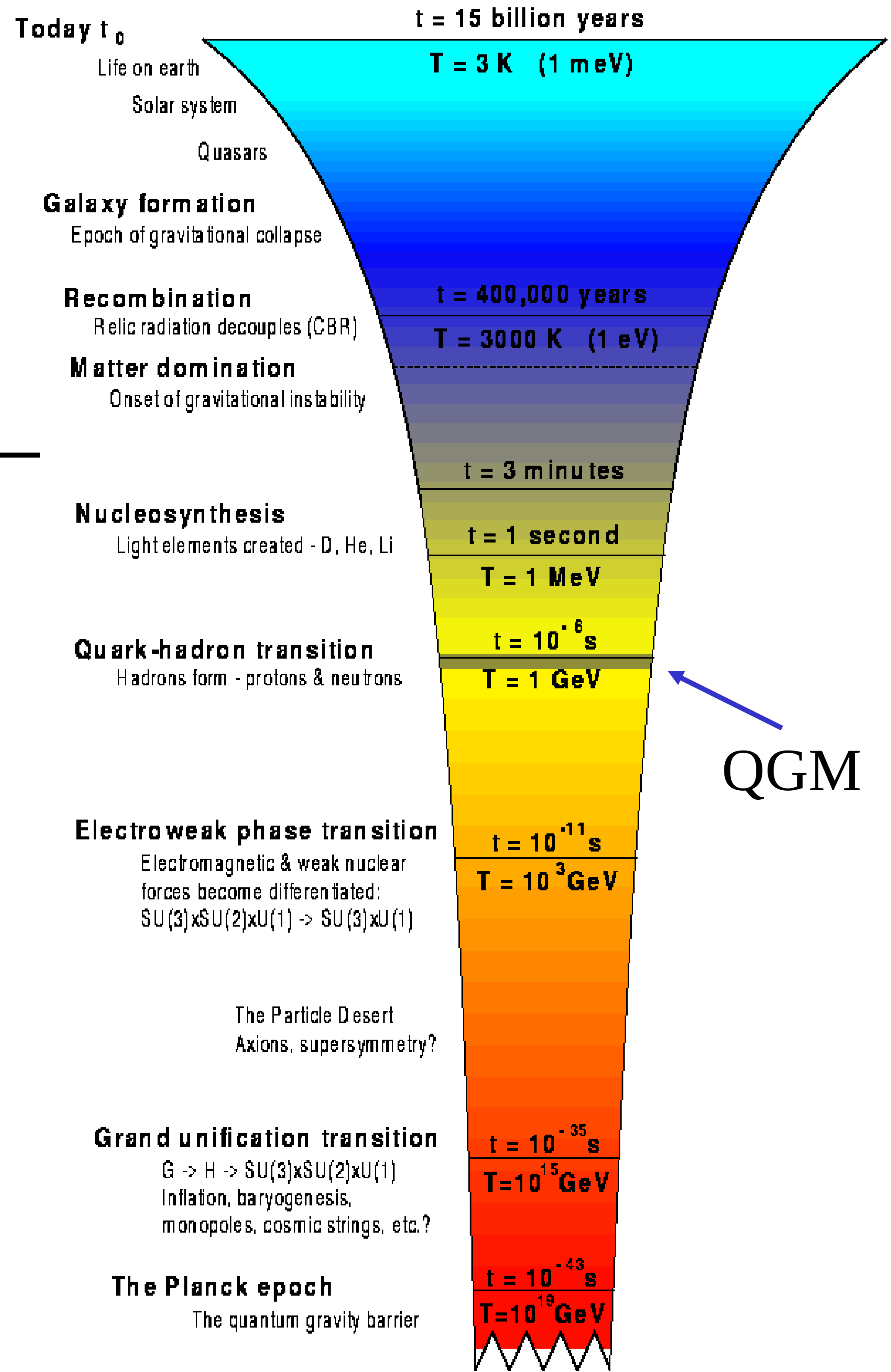
  (J/ψ, Υ, Υ', Υ'' yields vs. centrality, p_T, y, φ, ...)
- B-physics

  (B→J/ψ, high mass dimuon continuum, tagged B-jets)
- forward physics and ultraperipheral collisions
- ...

BACKUP SLIDES

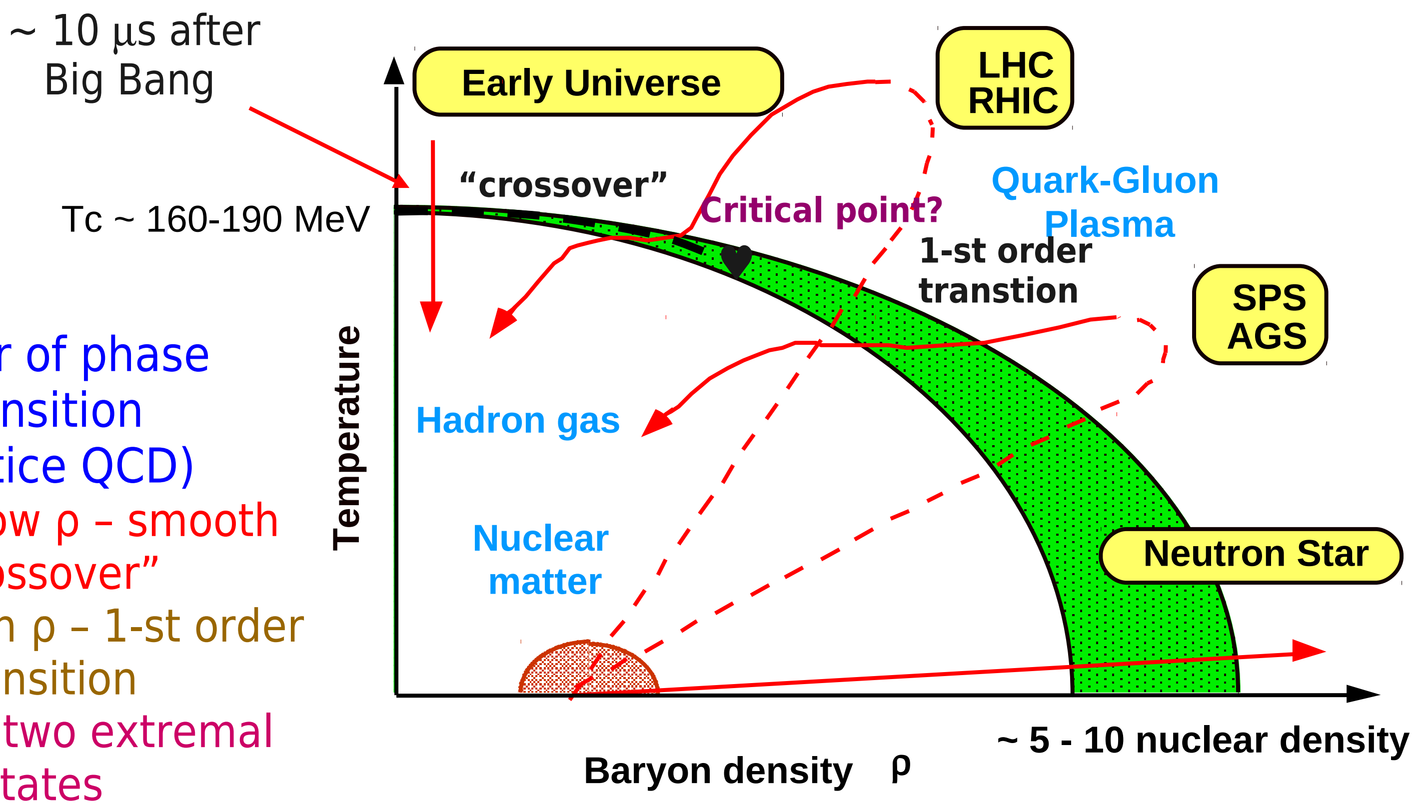


History of the Universe
PRESENT
15 BILLION YEARS
WE ARE HERE
Spiral Galaxy
Heavy Atom
5 BILLION YEARS
First Supernovae
Black Hole
Heavy Star
Galaxy and Star Formation
1 BILLION YEARS
Protogalaxy
MATTER DOMINATED ERA
THE UNIVERSE BECOMES TRANSPARENT
Hydrogen Atom
Decoupling of Matter-Radiation
Formation of Atoms
10¹³ sec.
PHOTON EPOCH
Helium Atom
Nucleosynthesis of Helium
10² sec.
Helium Nucleus
Disappearance of Positrons
LEPTON EPOCH
Confinement of Quarks Formation of Protons, Neutrons
Disappearance of Antiquarks
10⁻¹⁰ sec.
RADIATION DOMINATED ERA
The Desert
ELECTROWEAK EPOCH
QUARK EPOCH
Magnetic Monopoles?
10⁻³⁴ sec.
Cosmic Inflation?
GRAND UNIFICATION EPOCH
10⁻⁴³ sec.
QUANTUM GRAVITY EPOCH
Big Bang



Today t_0
t = 15 billion years
T = 3 K (1 meV)
Life on earth
Solar system
Quasars
Galaxy formation
Epoch of gravitational collapse
Recombination
Relic radiation decouples (CBR)
t = 400,000 years
T = 3000 K (1 eV)
Matter domination
Onset of gravitational instability
t = 3 minutes
Nucleosynthesis
Light elements created - D, He, Li
t = 1 second
T = 1 MeV
Quark-hadron transition
Hadrons form - protons & neutrons
$t = 10^{-6}$ s
T = 1 GeV
QGM
Electroweak phase transition
Electromagnetic & weak nuclear forces become differentiated:
SU(3)xSU(2)xU(1) -> SU(3)xU(1)
$t = 10^{-11}$ s
$T = 10^{3}$ GeV
The Particle Desert
Axions, supersymmetry?
Grand unification transition
G -> H -> SU(3)xSU(2)xU(1)
Inflation, baryogenesis, monopoles, cosmic strings, etc.?
$t = 10^{-35}$ s
$T = 10^{15}$ GeV
The Planck epoch
The quantum gravity barrier
$t = 10^{-43}$ s
$T = 10^{19}$ GeV

QCD phase diagram



$\varepsilon_c \sim 1$ GeV/fm^3

Order of phase transition (Lattice QCD)

high T, low ρ – smooth "crossover"

low T, high ρ – 1-st order transition

Between two extremal states

(T(cp)~140-160 MэB, μ_B(cp)~350-650 MэB)

critical point?

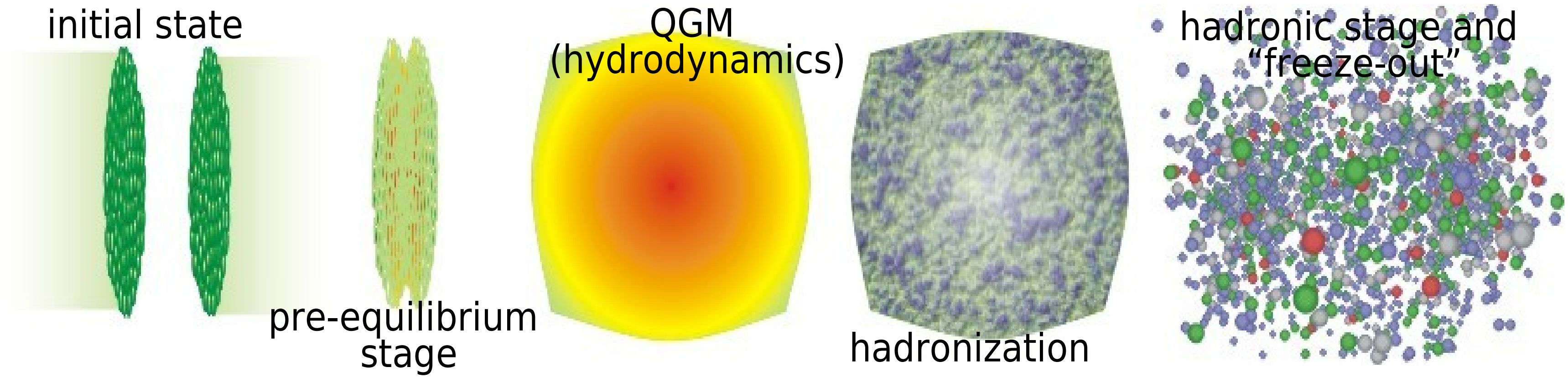
Non-statistical fluctuations!

→ energy scan at RHIC ($\sqrt{s}$ = 5-50 GeV) & NA61@SPS (E_{lab} = 10-158 GeV);

→ new projects CBM@FAIR (GSI) and NICA (JINR)

Study of quark-gluon matter in HI collisions

The formation of super-dense and hot state of QCD-matter in relativistic heavy ion collisions is possible on large space-time scales (quasi-macroscopic as compared with characteristic hadronic scales).



Soft probes ($p_T \sim \Lambda_{QCD}$=200 MeV)

- ✓ spectra of particles with low transverse momenta, femtoscopic momentum correlations;
- ✓ flow effects;
- ✓ thermal photons and dileptons;
- ✓ strange particle yield.

Hard probes ($p_T, M \gg \Lambda_{QCD}$=200 MeV)

- ✓ spectra of particles with high transverse momenta, their angular correlations;
- ✓ hadronic jets;
- ✓ quarkonia (dileptons);
- ✓ heavy quarks (leptons, tagged b-jets).

CMS PbPb trigger selection

Dimuon Trigger
- Level-1: 2 hits in the muon chambers
- HLT (only for Z): 2 reconstructed tracks in the muon chambers with $p_T > 3$ GeV/c
- ~ 94% efficient for $Z \to \mu\mu$

Jet Trigger
- Level-1: single jet with $E_T > 30$ GeV(uncorrected energy)
- HLT: single jet with $E_T > 50$ GeV (background subtracted, uncorrected energy)
- Fully efficient for corrected transverse energy above 100 GeV

Photon Trigger
- Level-1: e/m cluster $E_T > 5$ GeV (uncorrected energy)
- HLT: e/m cluster $E_T > 15$ GeV(uncorrected energy)
- > 98% efficient for corrected transverse energy above 20 GeV

Minimum Bias Trigger
- Coincidence between signals from +z and -z sides of HF or BSC
- 97±3% efficient

Imbalance (asymmetry) of dijet energy

- Leading jet with E_T > 120 GeV

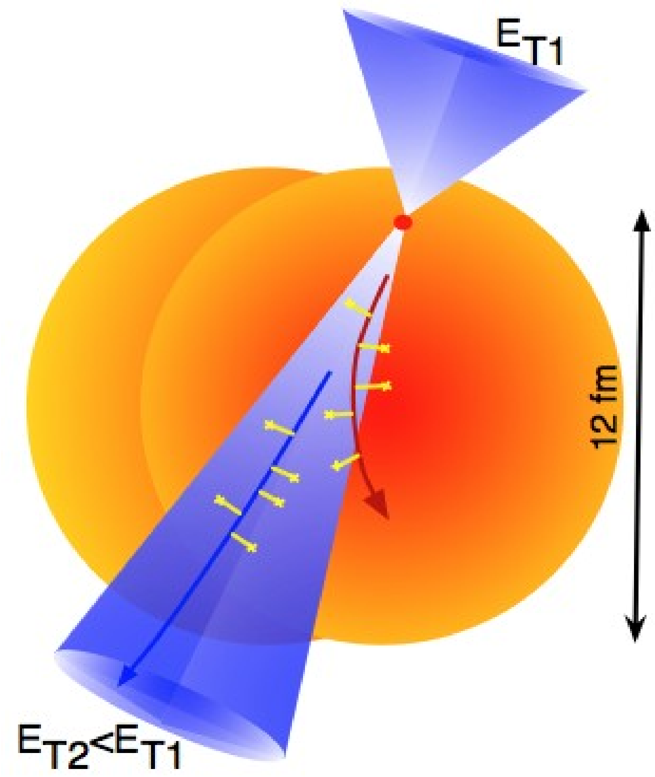
Trigger efficiency ~1

- Sub-leading jet with E_T > 50 GeV

Above background fluctuations

- Both jets within rapidity, $|\eta| < 2$

- Jets are opposite in azimuthal direction, $\Delta\varphi > 2\pi/3$



- Asymmetry of dijet energy:

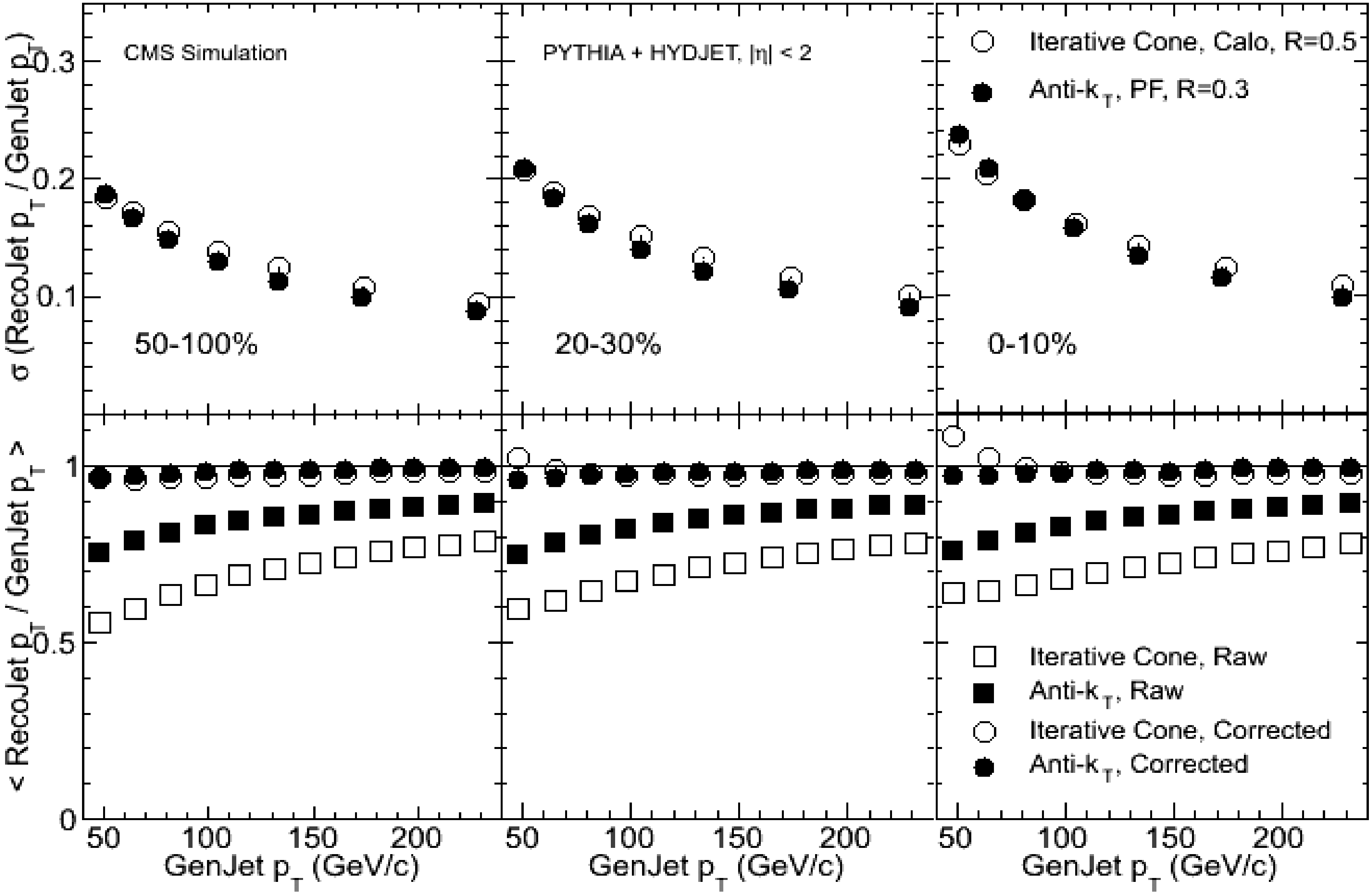
$$A_J = \frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}}$$

Jet reconstruction in HIC at CMS

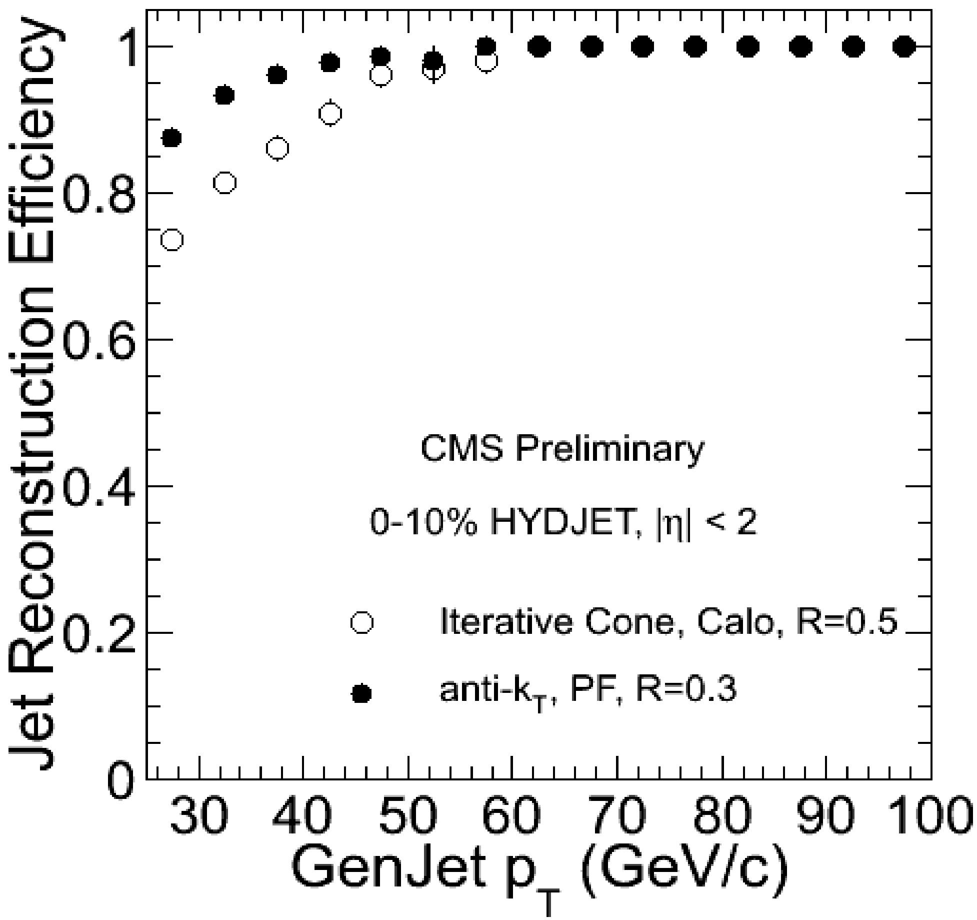
- Jets are accompanied by the large "thermal background" or "underlying event" that depends on the overall event multiplicity
  - → Use background subtraction procedures
- CMS uses several jet finding algorithms
  - → IC5 CaloJets with iterative background subtraction

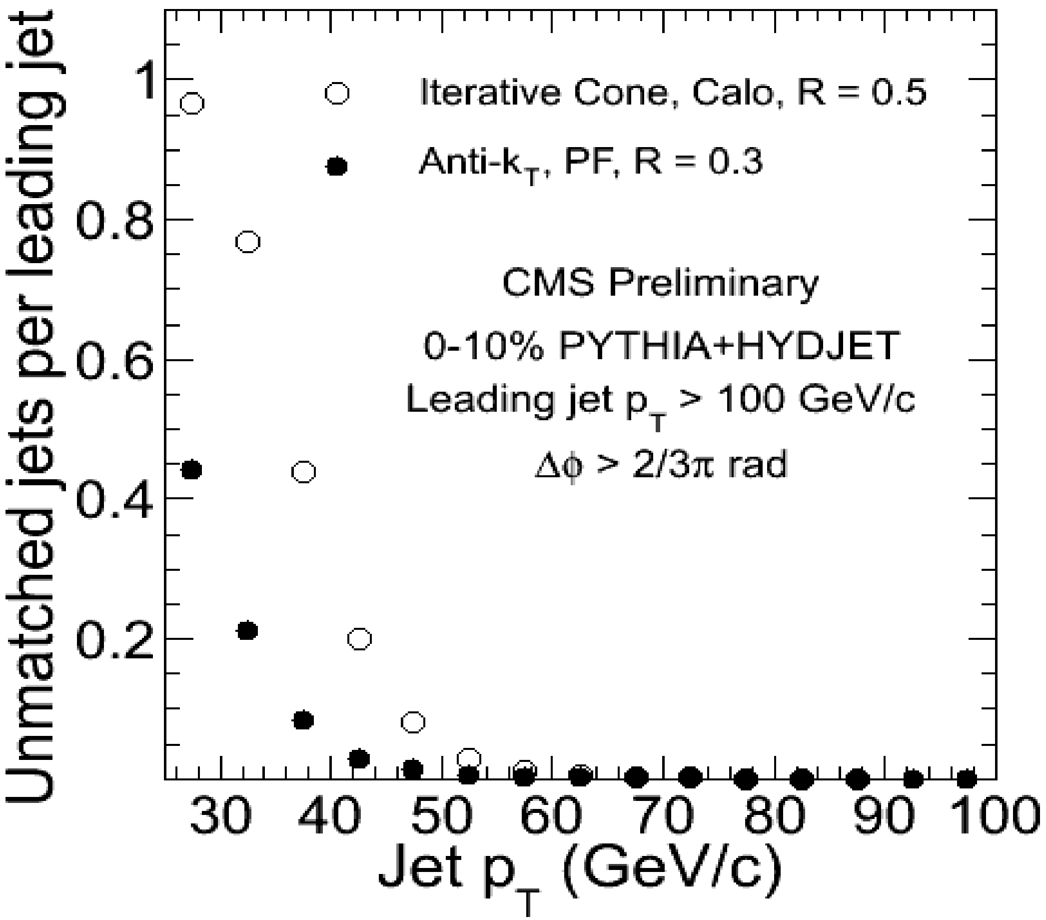
    (O. Kodolova, I.Vardanian, A.Nikitenko, A.Oulianov, EPJ C 50 (2007) 117)
  - → Anti-kT *(M. Cacciari, G. P. Salam, G. Soyez, JHEP 0804 (2008) 063)*
- Jets are found using different sets of detectors
  - → Calorimetric Jets: use ECAL and HCAL
  - → Particle Flow Jets: use Tracker and Calorimeters
- Jet cone size can vary
  - → Use R=0.5

Jet energy scale and resolution

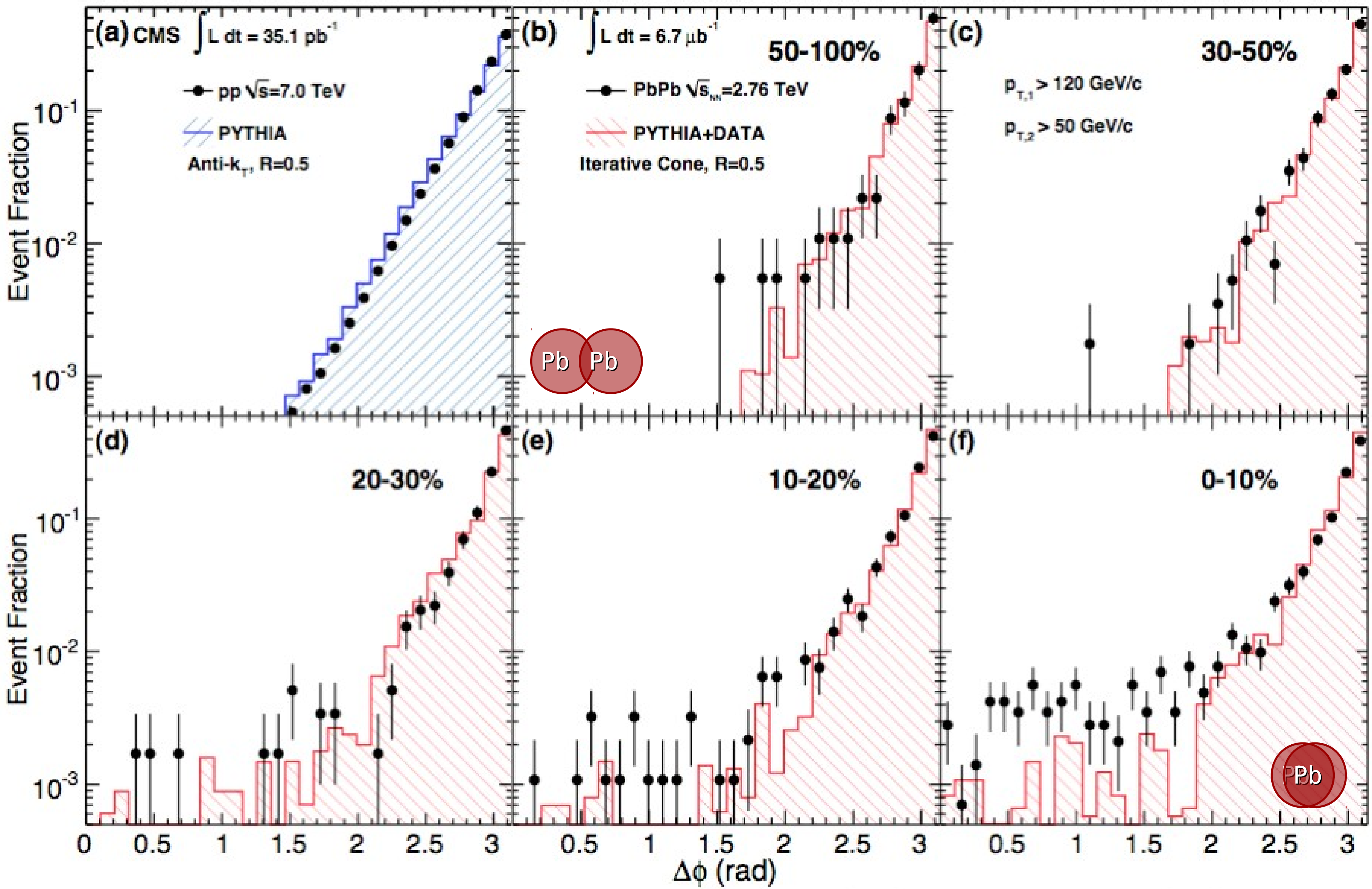


Jet finding efficiency and fake rates





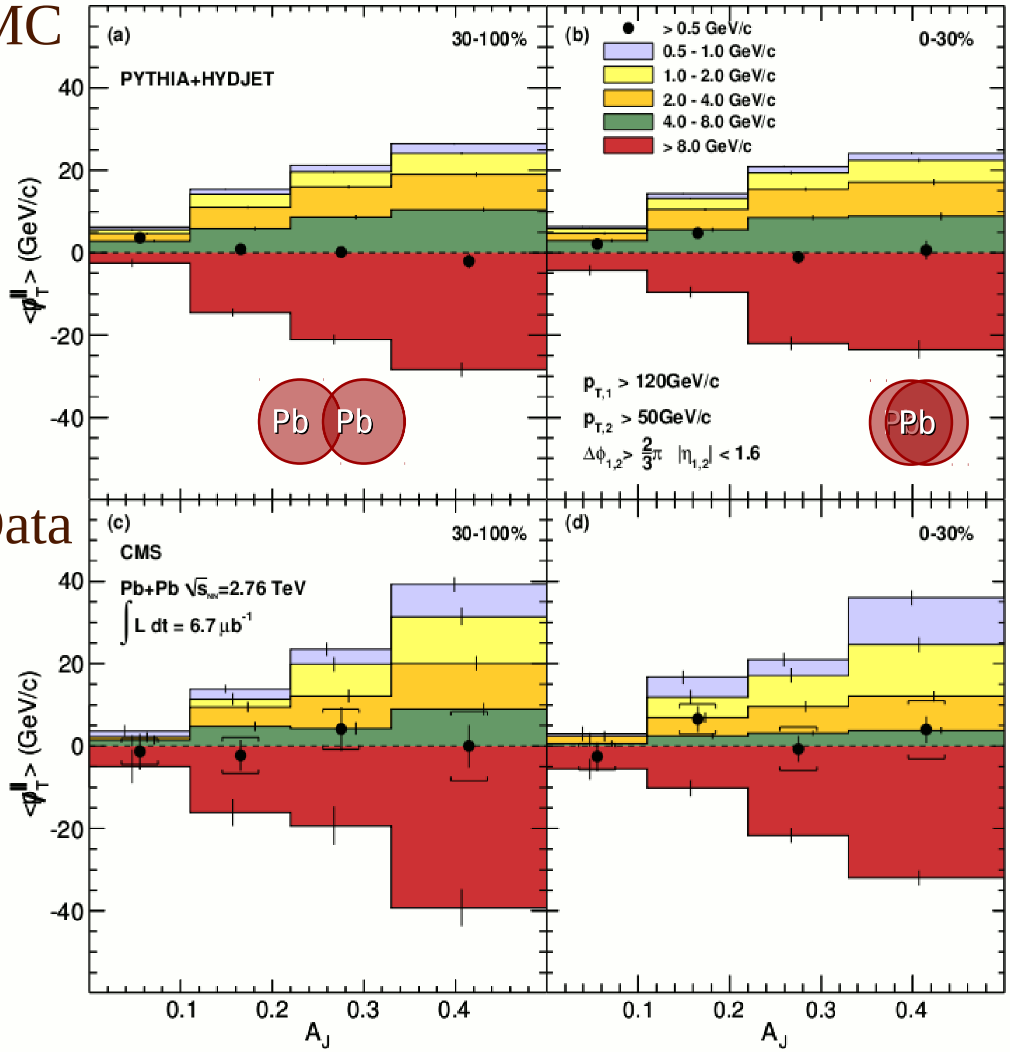
Dijet azimuthal decorrelation

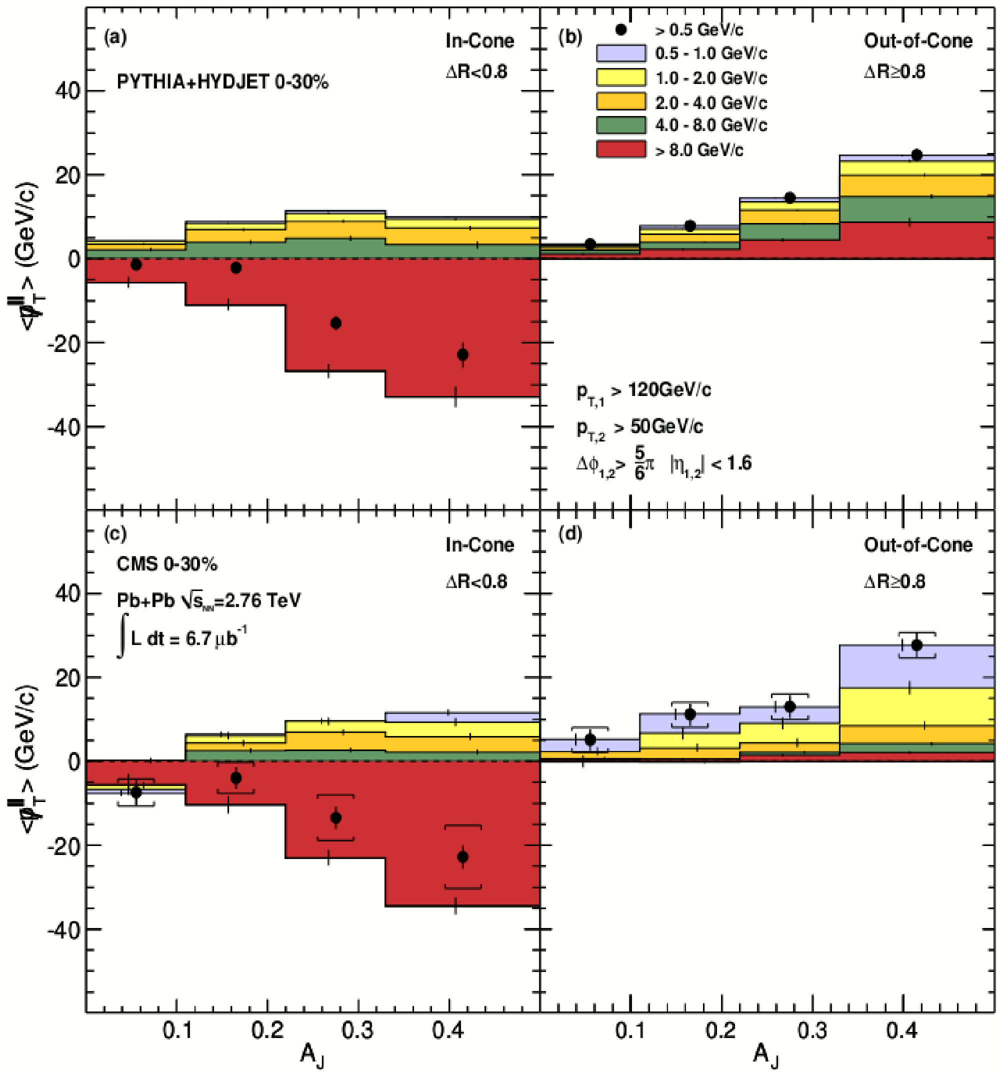


Jet-track correlation (missing p_T)

MC

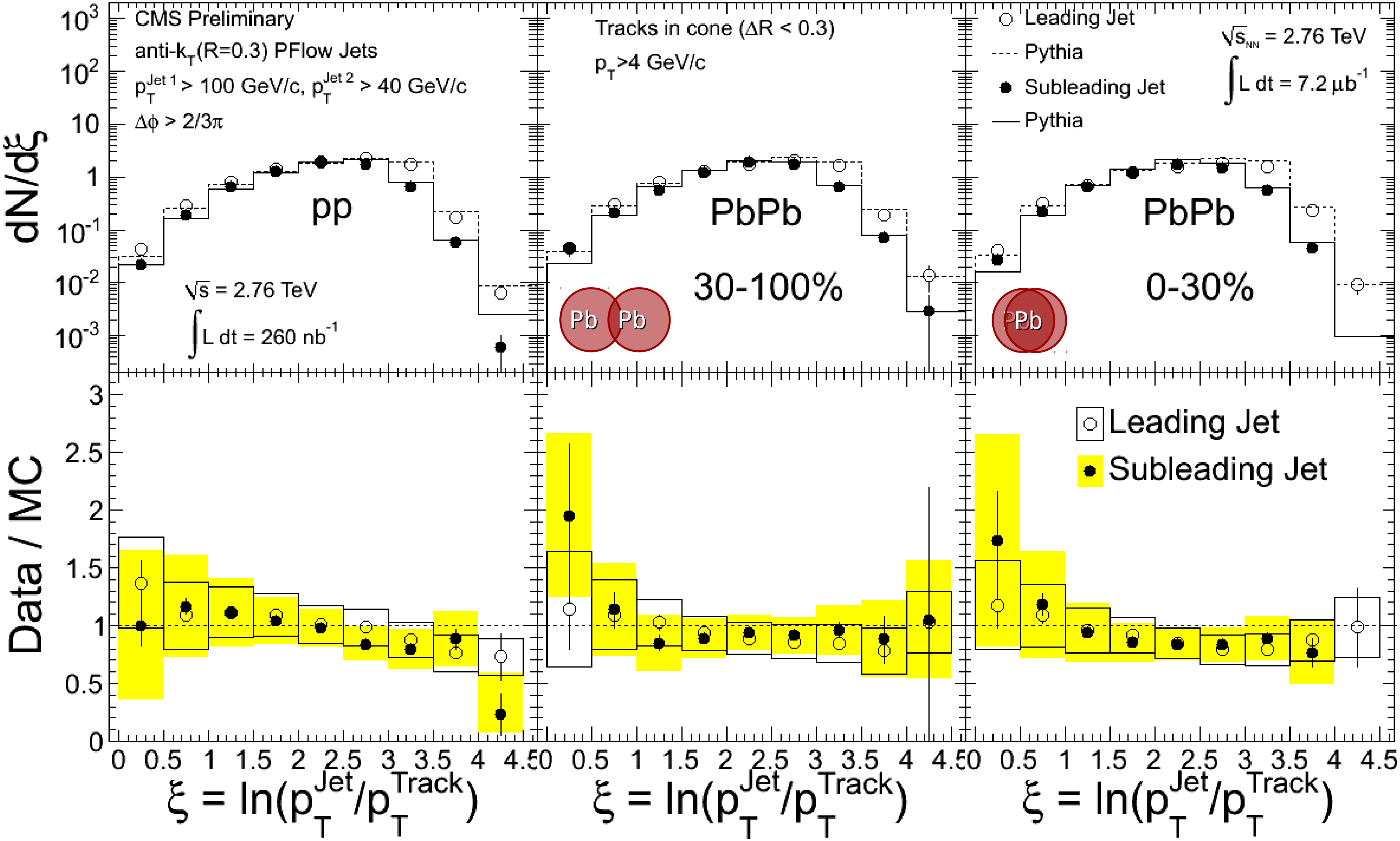
Data





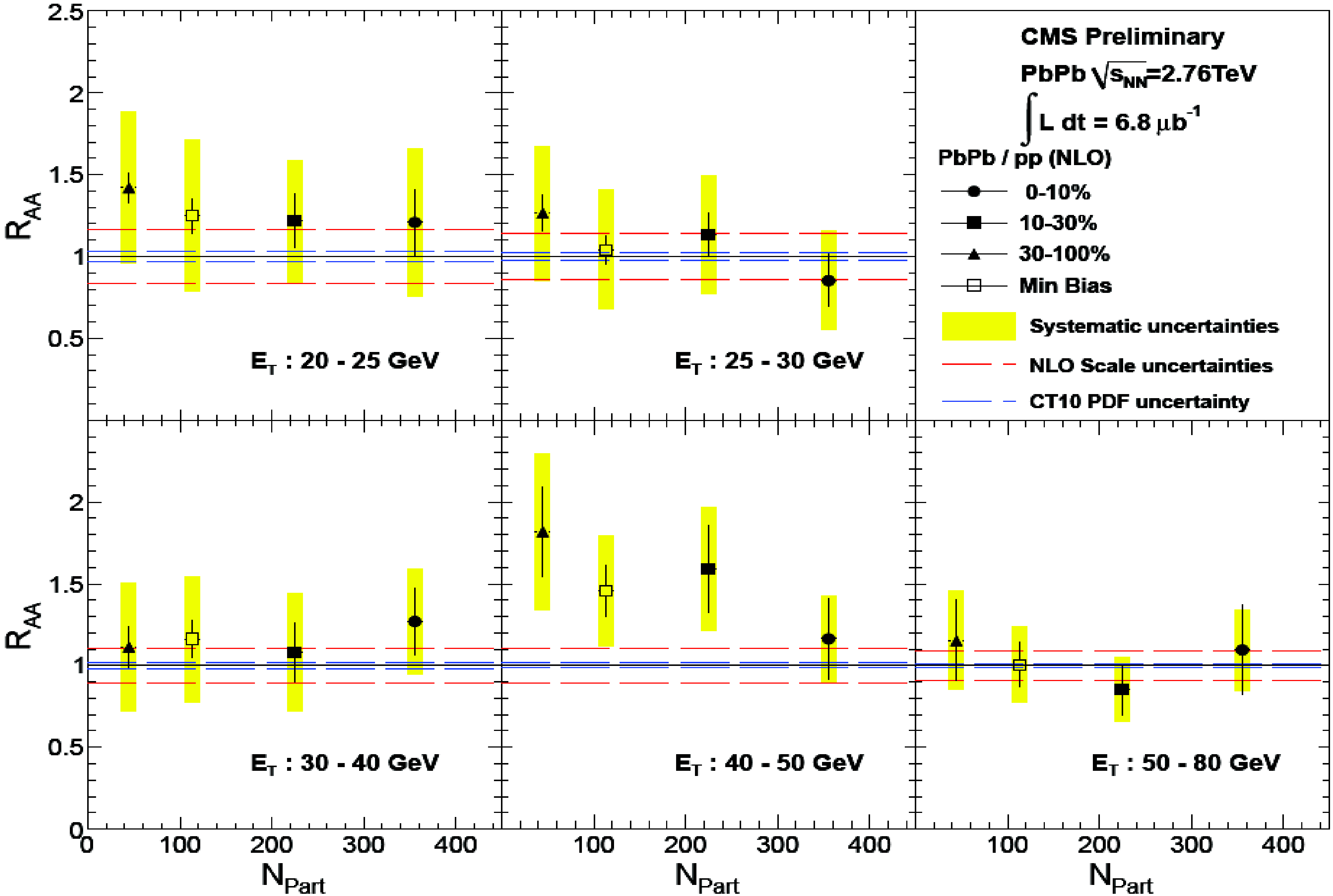
Dijet momentum balance for PbPb data is covered by out-of-cone low p_T tracks

Jet fragmentation function

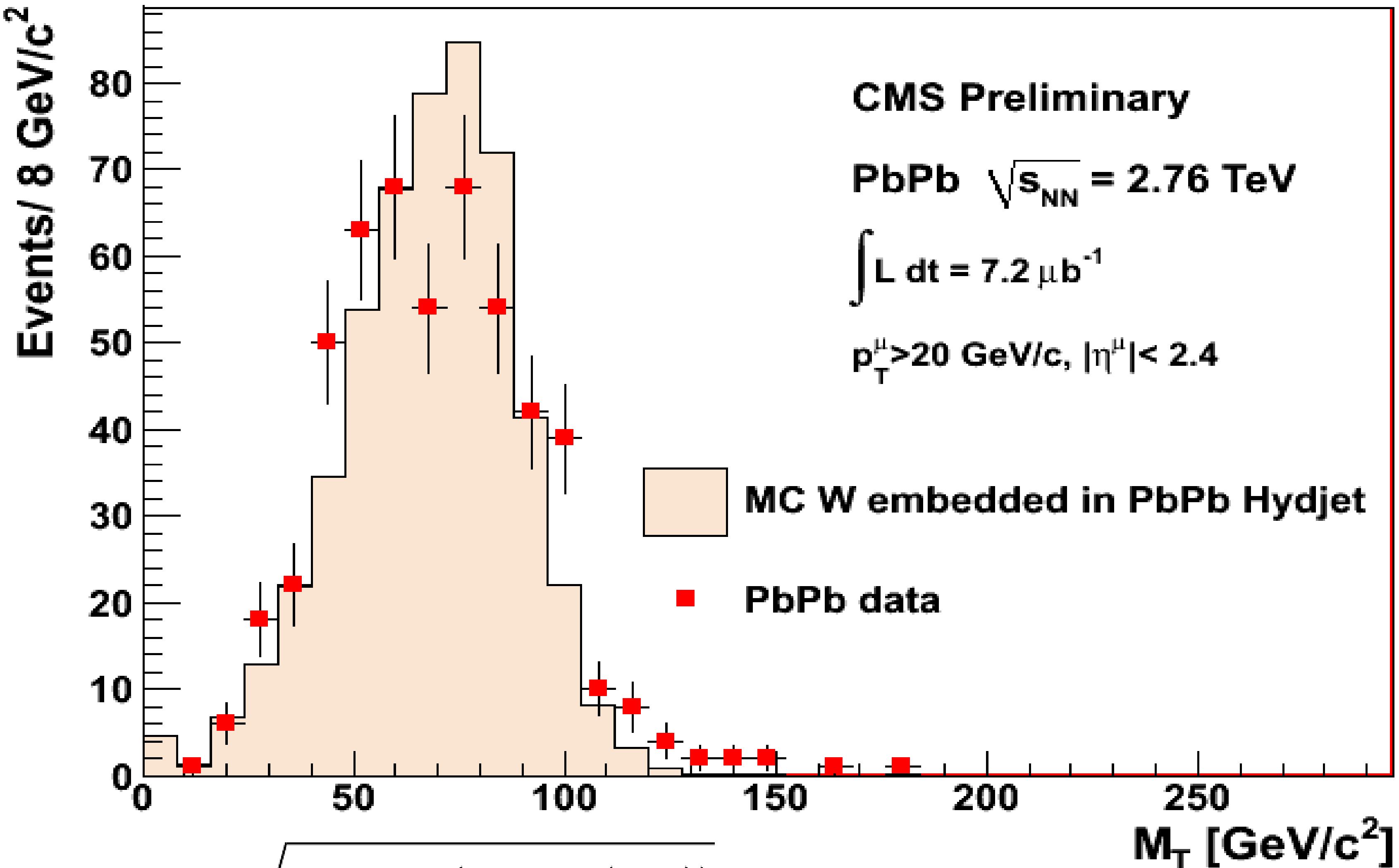


Leading and sub-leading jet fragmentation functions in PbPb and pp collisions are similar

Prompt photons R_{AA} vs. centrality

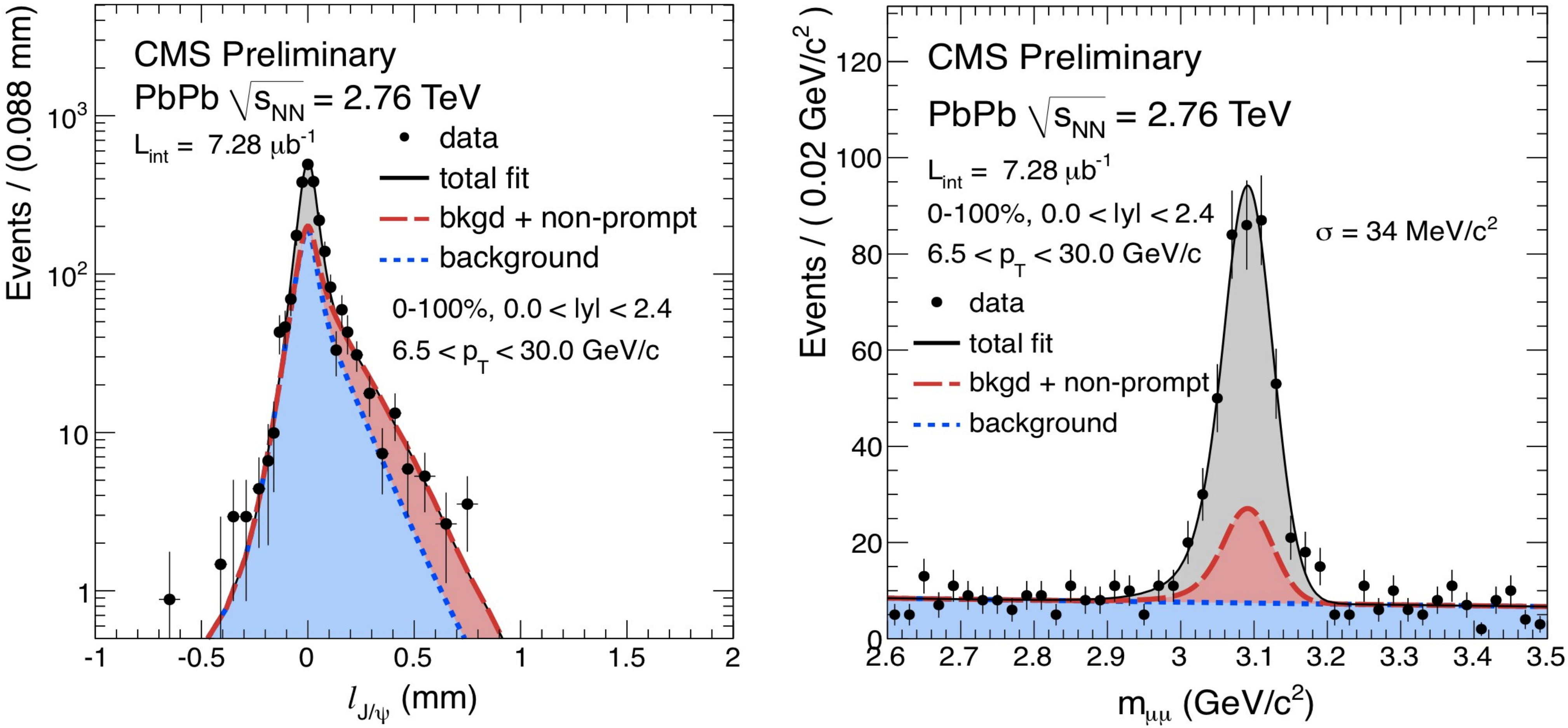


$W^{\pm} \rightarrow \mu^{\pm} \nu$



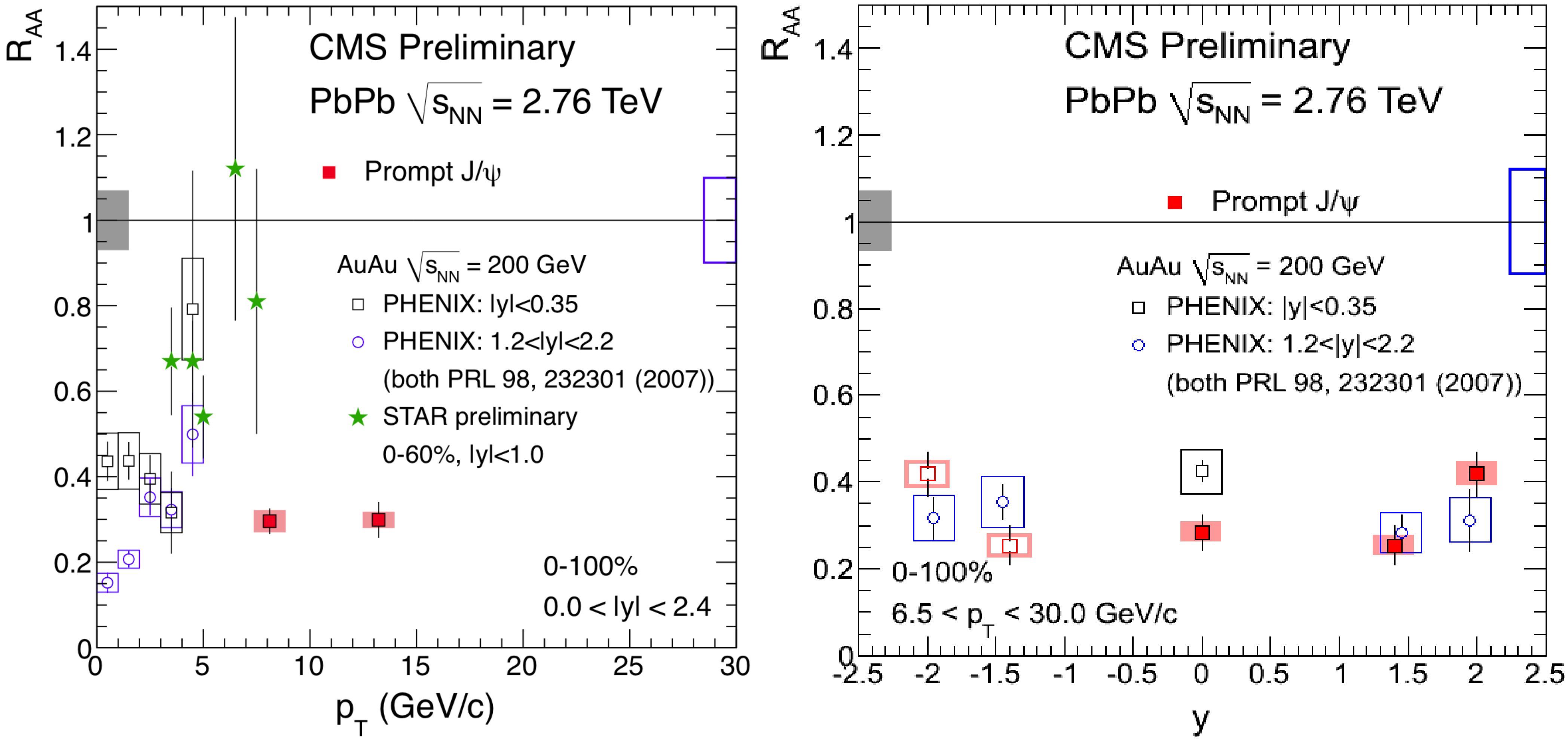
$$M_T = \sqrt{2 p_{T\mu} p_{T\nu} (1 - cos(\phi_{\mu\nu}))}$$

Prompt and secondary J/ψ separation



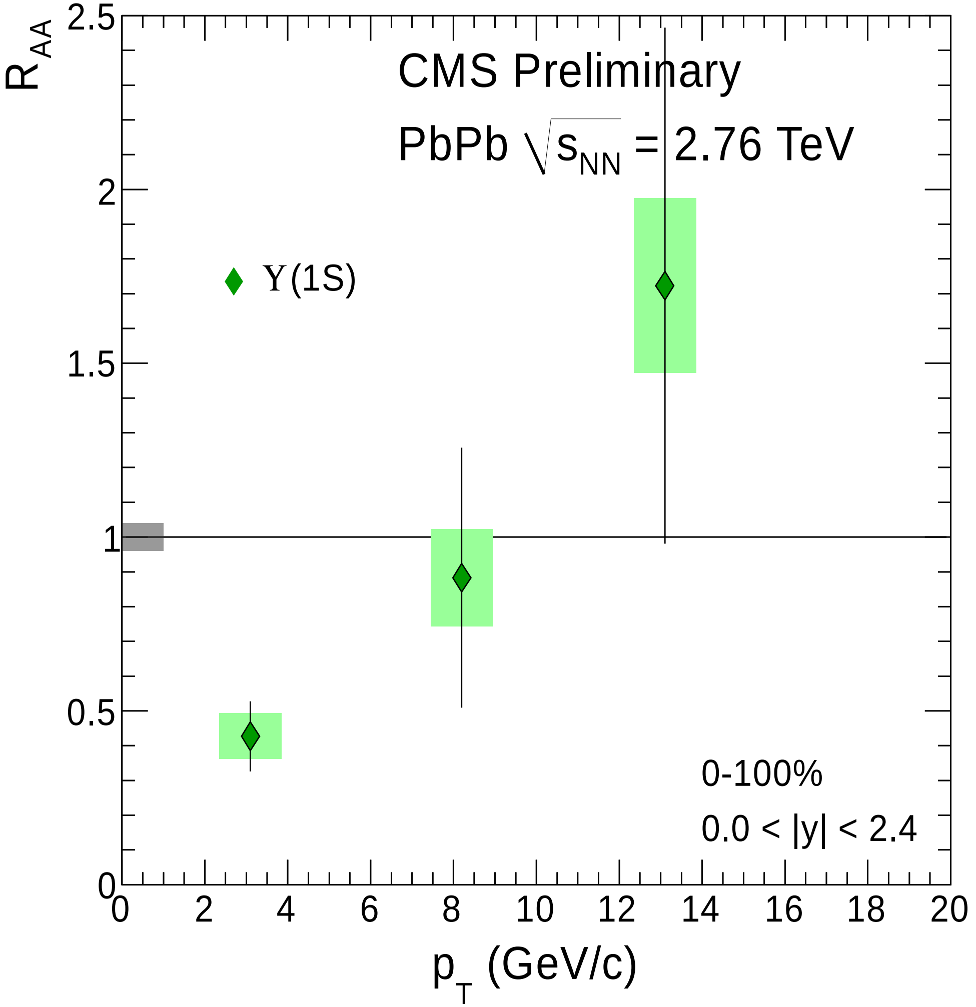
Prompt and secondary (from B decays) J/ψ's are separated using secondary vertex information

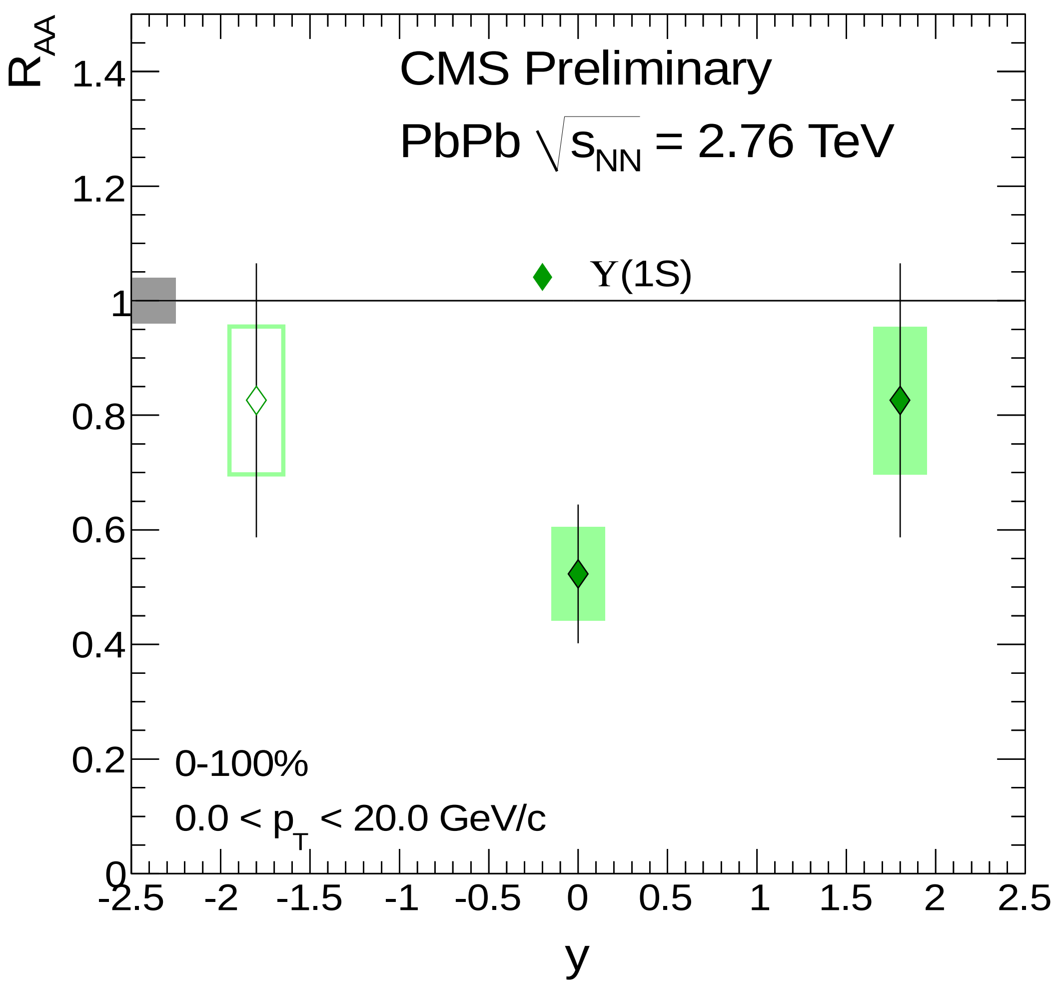
J/ψ suppression vs. p_T and y



- No dependence of suppression factor (~ 1/3) on p_T is seen
- Less suppression at forward rapidity?

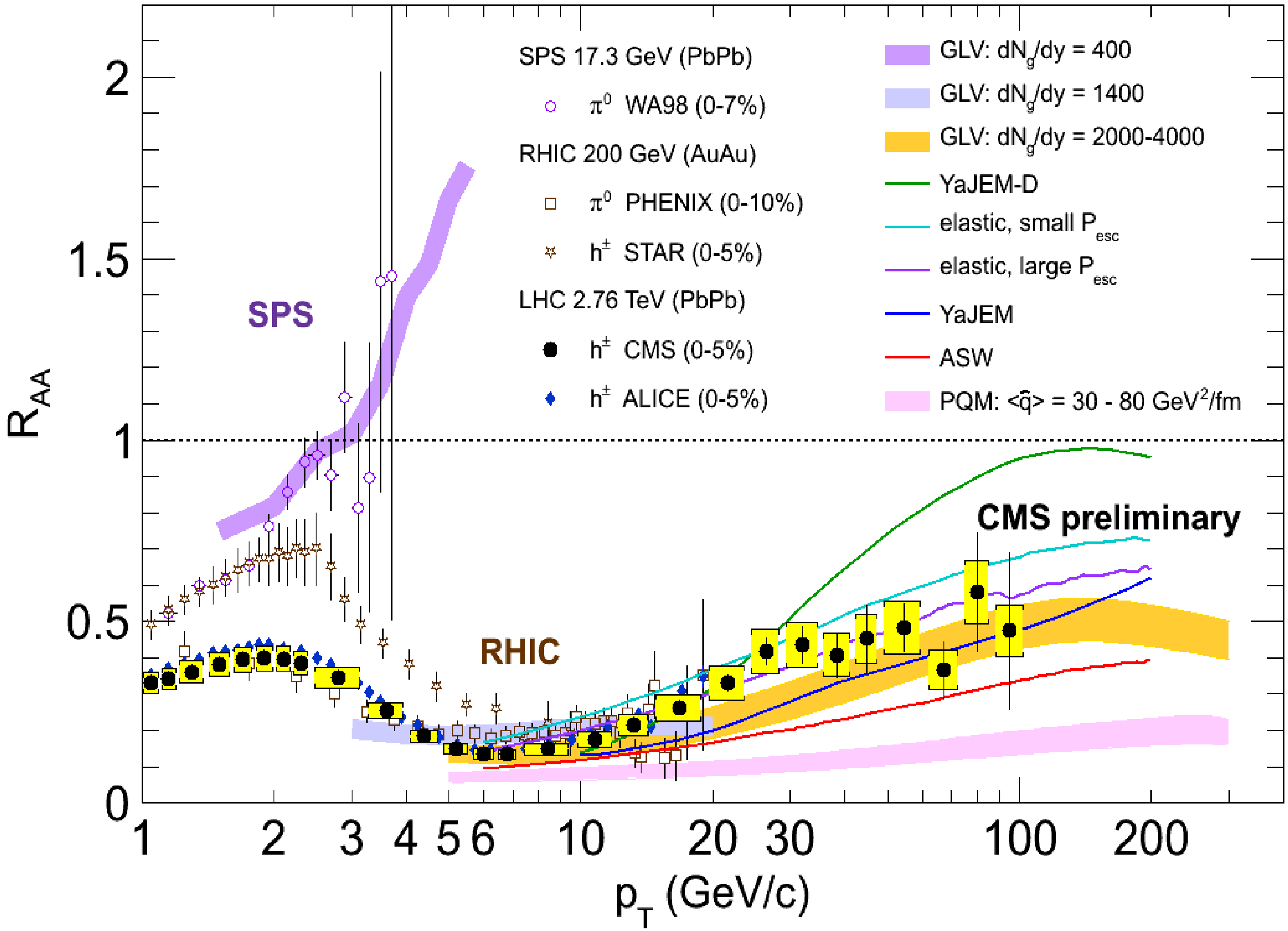
Υ(1S) suppression vs. p_T and y





- No suppression at high p_T?
- Less suppression at forward rapidity?

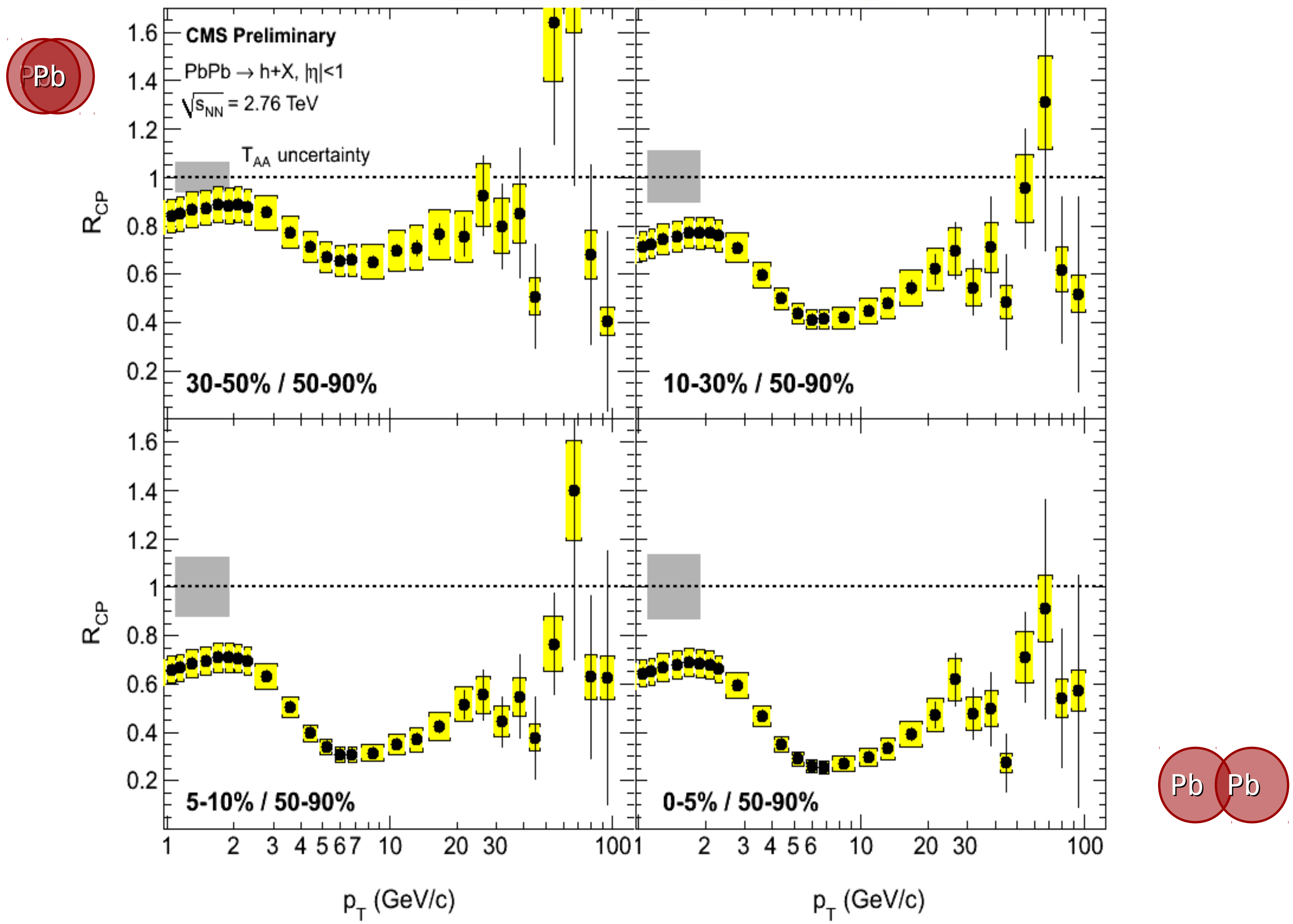
R_{AA}: CMS vs. ALICE, RHIC and models



- CMS and ALICE are in agreement, but CMS reaches higher p_T (due to using the jet trigger)
- Much higher p_T than at RHIC, up to ~ 100 GeV/c, are available
- $R_{AA}(p_T)$ – strong constraints on partonic energy loss model (access to medium properties)

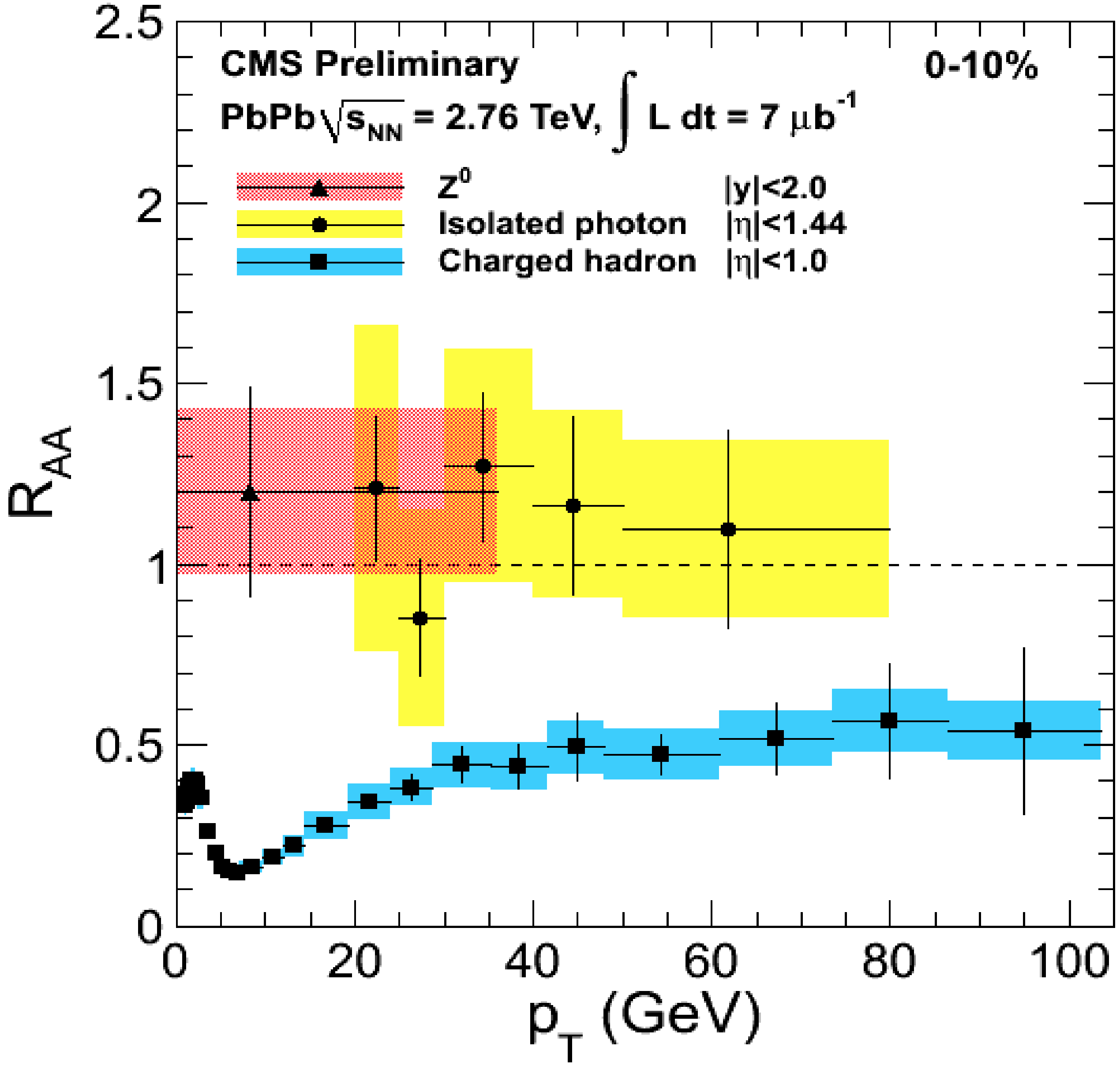
Charged hadron R_{CP}

$$R_{CP}(p_T) = \frac{(d^2N^{AA}_{ch}/dp_T d\eta)/N_{coll}\ [\text{central}]}{(d^2N^{AA}_{ch}/dp_T d\eta)/N_{coll}\ [\text{peripheral}]}$$



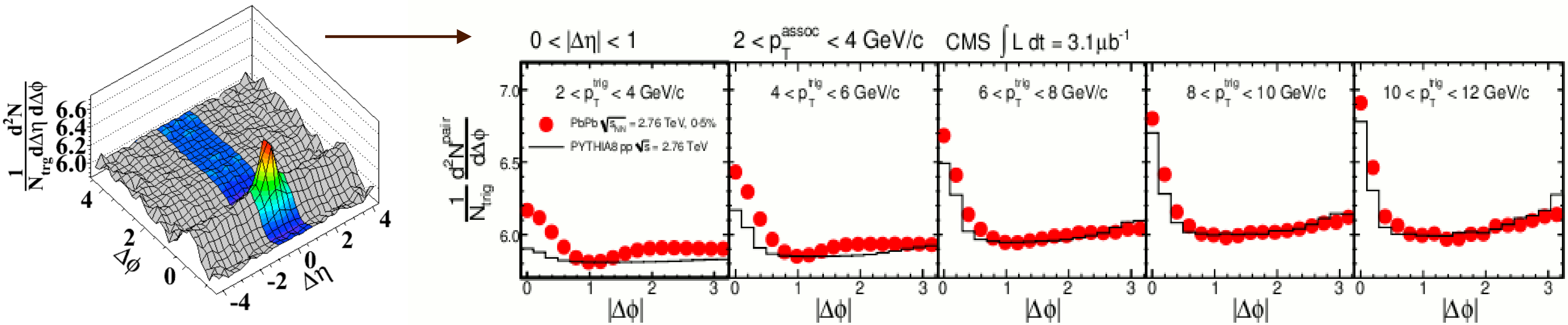
Strong momentum dependence of suppression factor is observed

Summary of R_{AA}

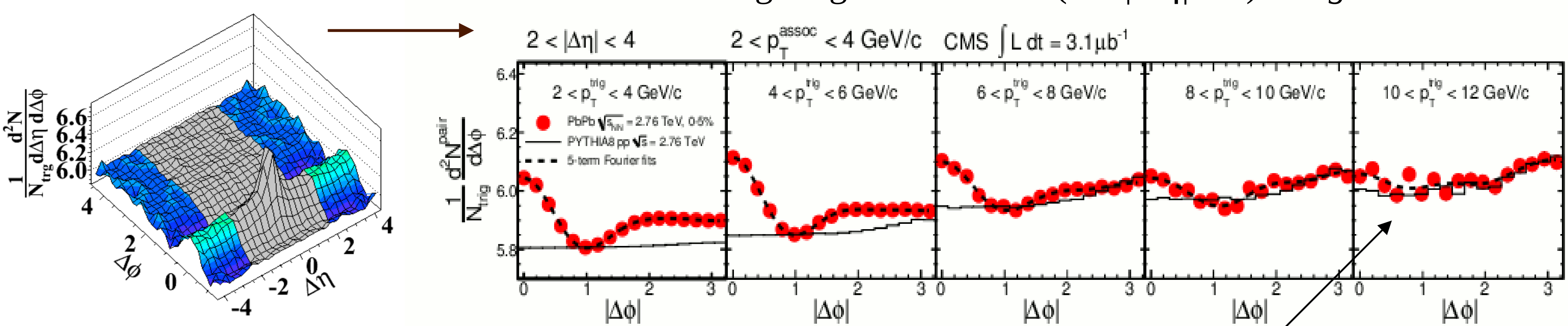


Two-particle correlations

Short range correlations ($0 < |\Delta\eta| < 1$): *Jet + Ridge*



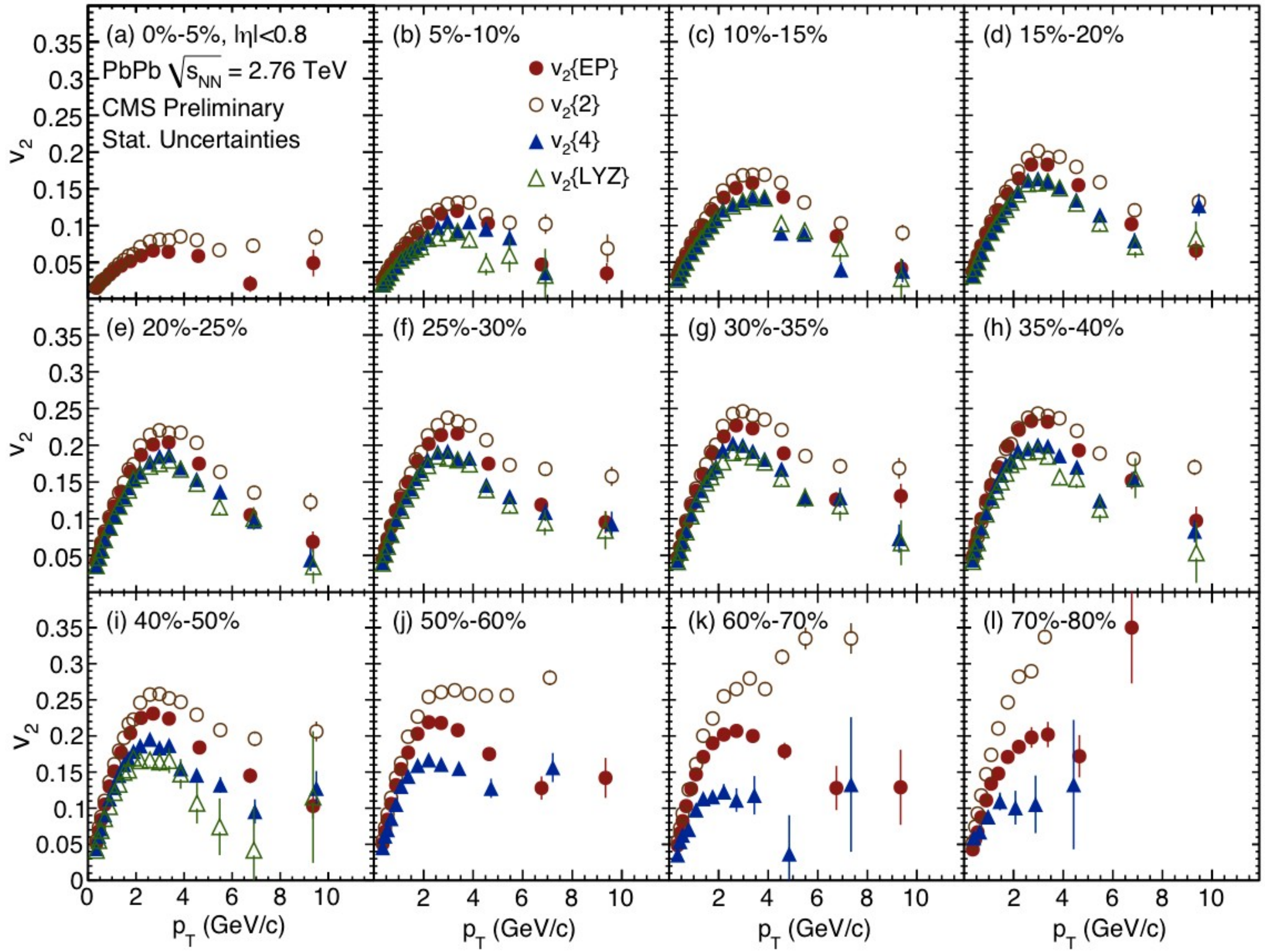
Long range correlations ($2 < |\Delta\eta| < 4$): *Ridge*



Ridge disappears at high p_T

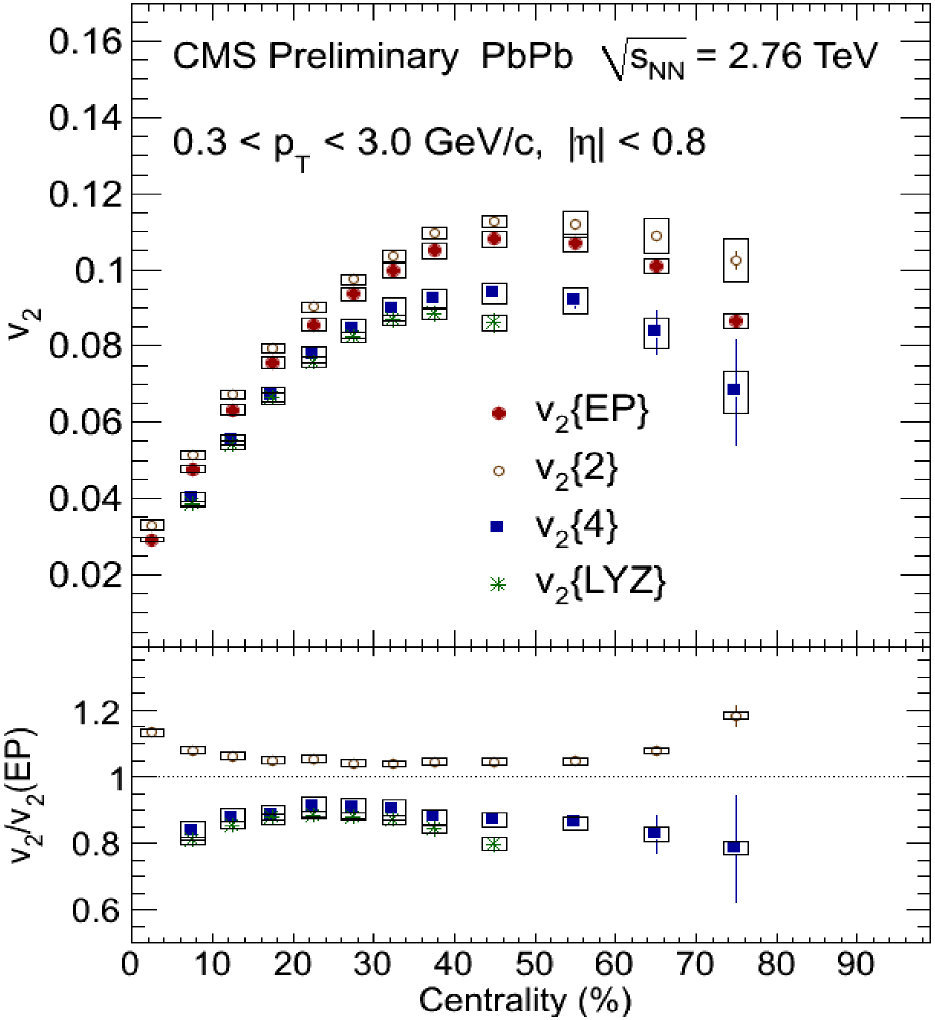
Elliptic flow v_2 vs. p_T and centrality

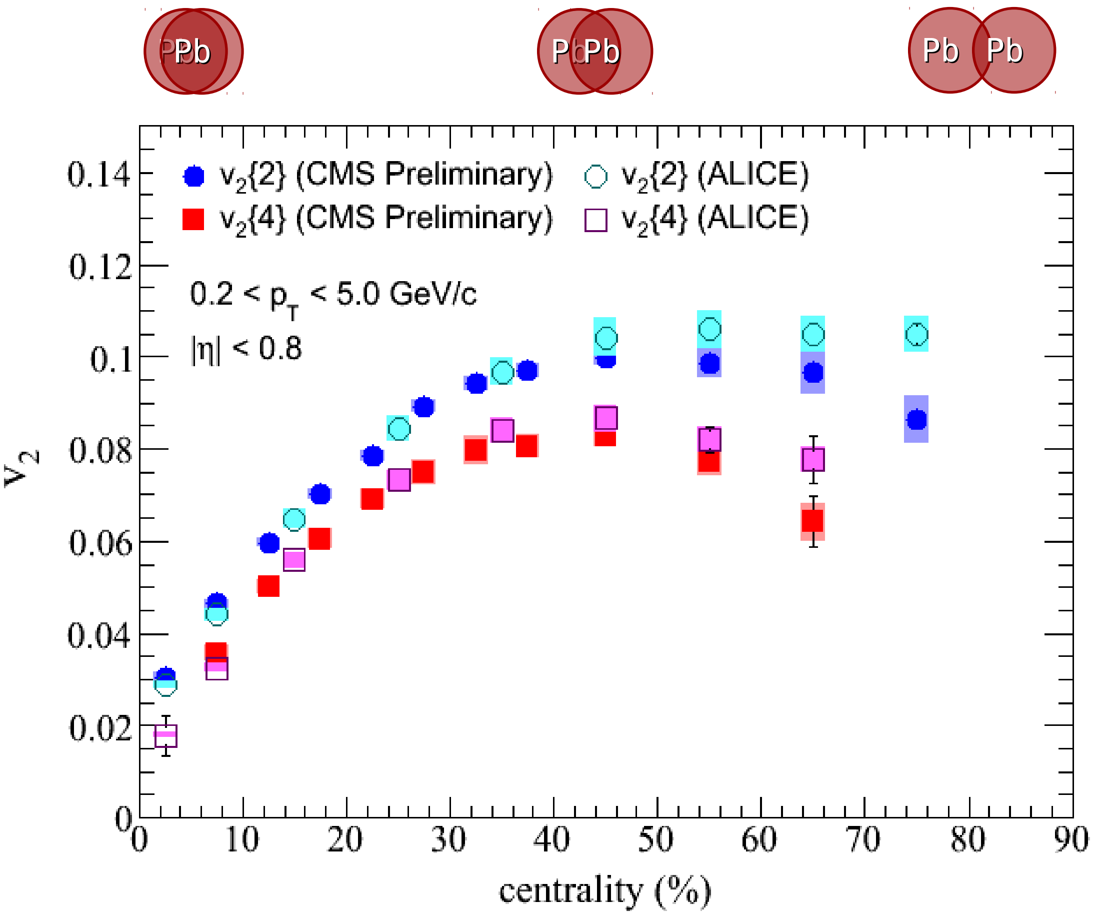
$$\frac{dN}{d^2 p_t dy} = \frac{dN}{2\pi p_t dp_t dy}(1 + v_2 \cos 2\varphi + 2v_4 \cos 4\varphi + ...)$$



- $v_2(p_T)$ peaks at ~ 3 GeV/c, finite at ~10 GeV/c, strongest for 40-50% centrality
- The different methods show differences consistent with the expected sensitivity to non-flow

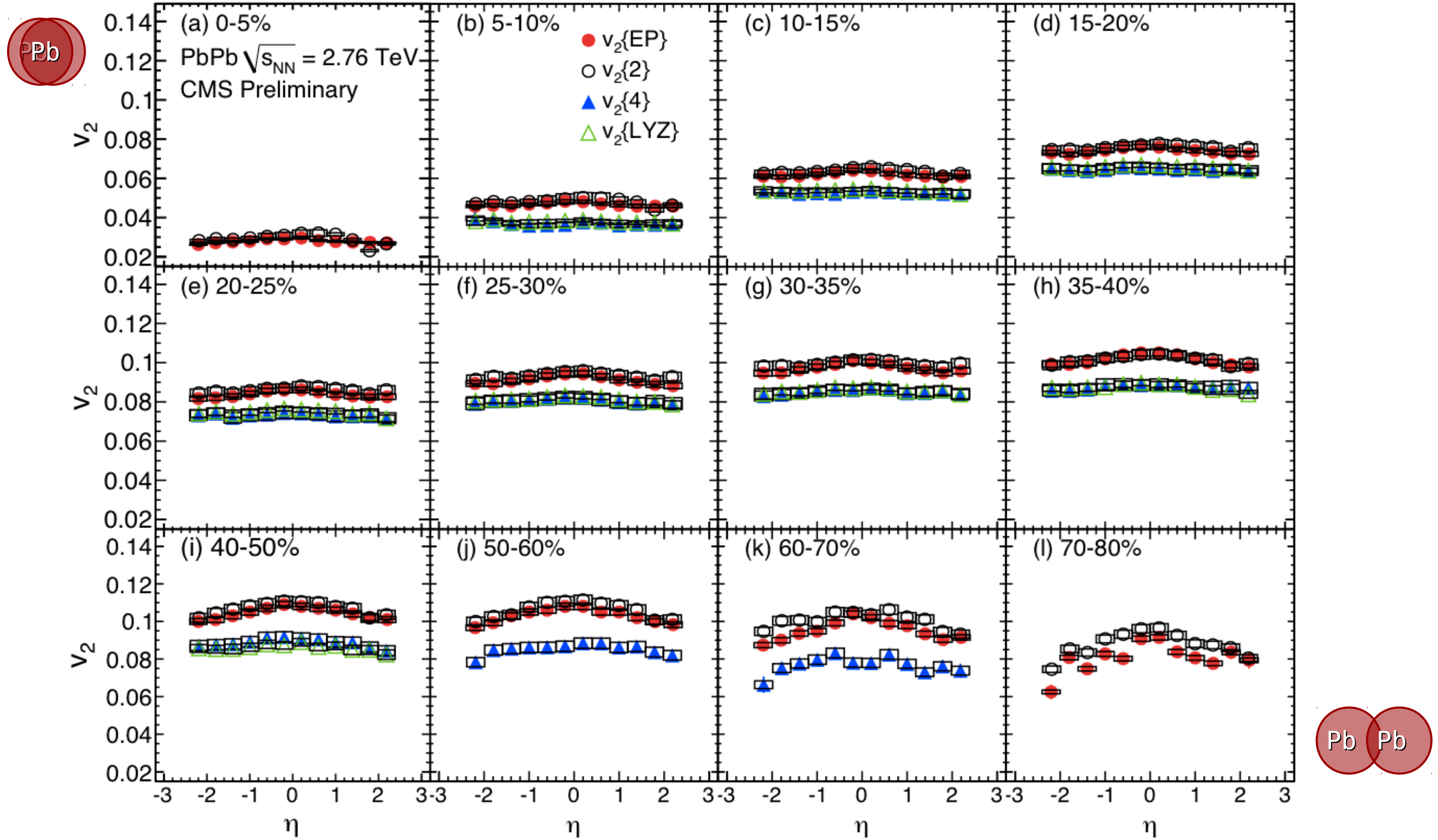
Integral v_2 vs. centrality





- Integral v_2 increases with centrality reaching a maximum at the 40-50% centrality
- CMS and ALICE data are in the agreement (except in most peripheral events)

v_2 vs. η and centrality



- v_2 slowly decreases from mid-rapidity to forward rapidity
- Stronger rapidity dependence is observed for the most peripheral collisions