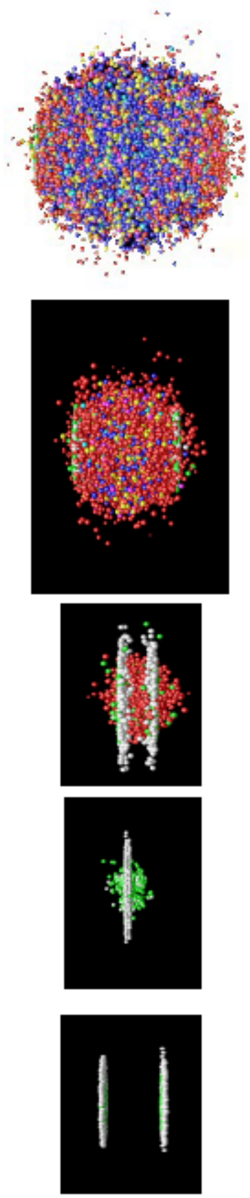
Heavy Ion Physics with CMS at LHC (hard probes)

6th Workshop of the APS/GHP

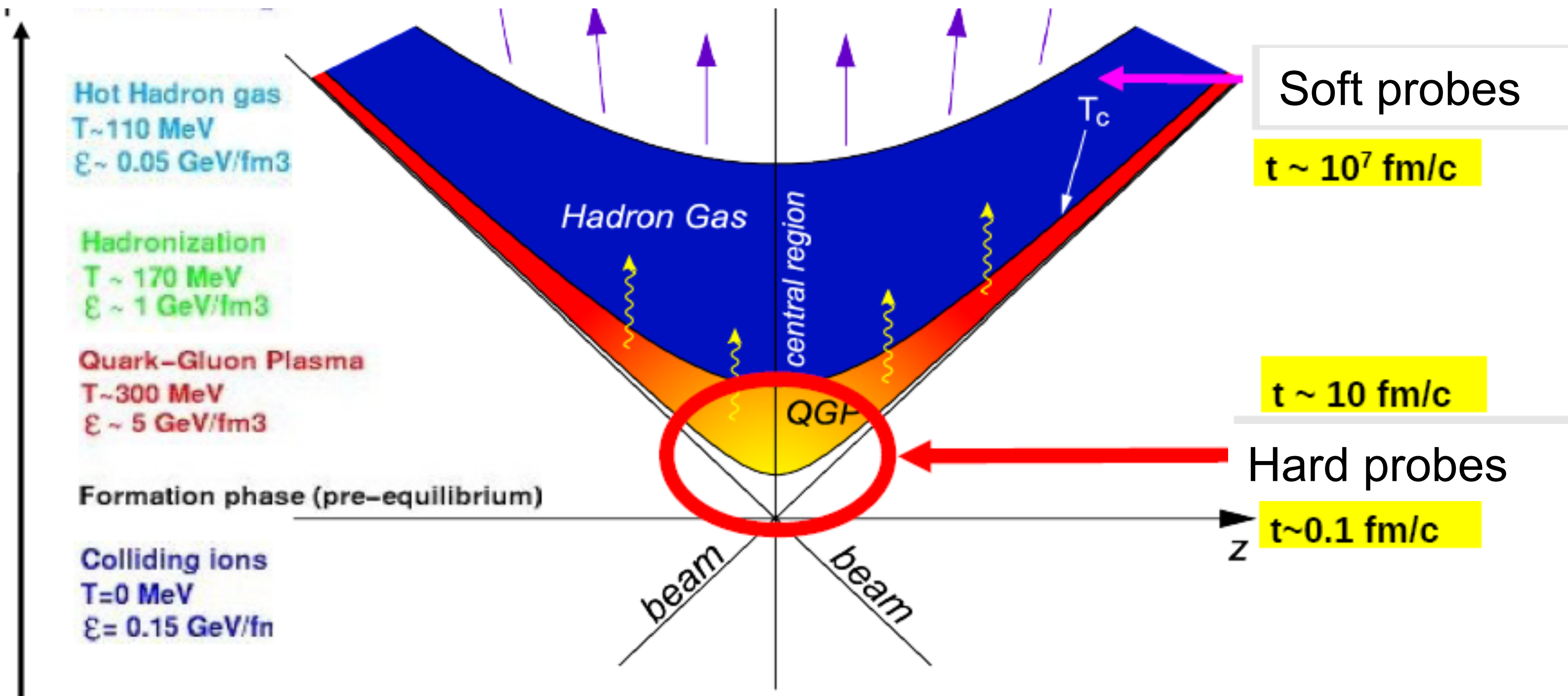
Baltimore, April 8, 2015

Bolek Wyslouch

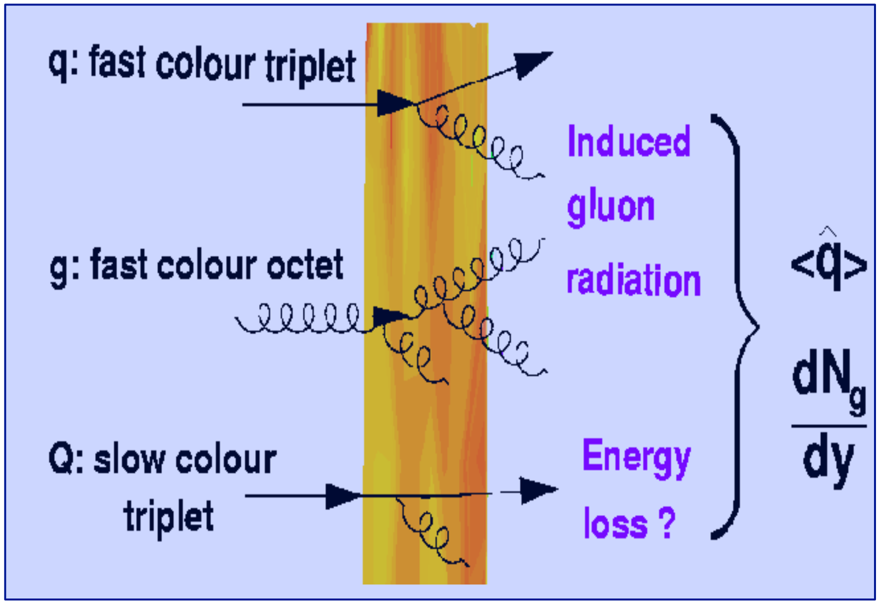
Creating hot and dense matter in the laboratory

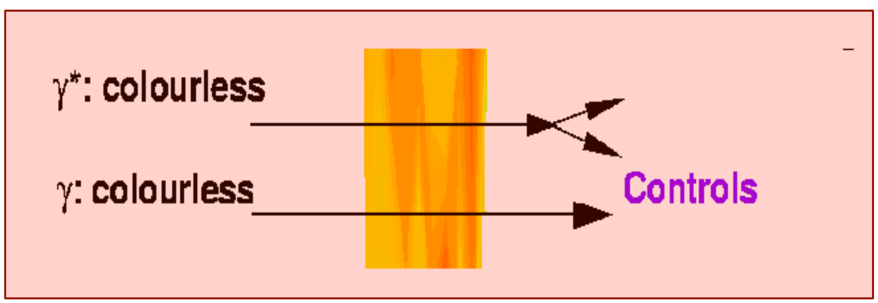


- High energy nucleus-nucleus collisions at highest energies RHIC@Brookhaven: $\sqrt{s_{NN}}$= 200 GeV, LHC,@CERN $\sqrt{s_{NN}}$= 2760 GeV
- Expanding plasma of quarks and gluons with volume of ~1000 fm^3 temperature of few * 10^{12} K (200-800 MeV) and energy density 10-20 GeV/ fm^3
- Particle “probes” sensitive to the matter at different stages of the expansion

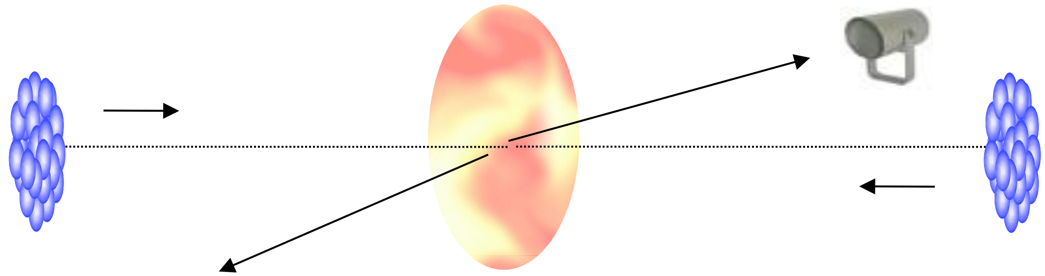


Focus on hard probes in nuclear collisions





Hot and dense medium



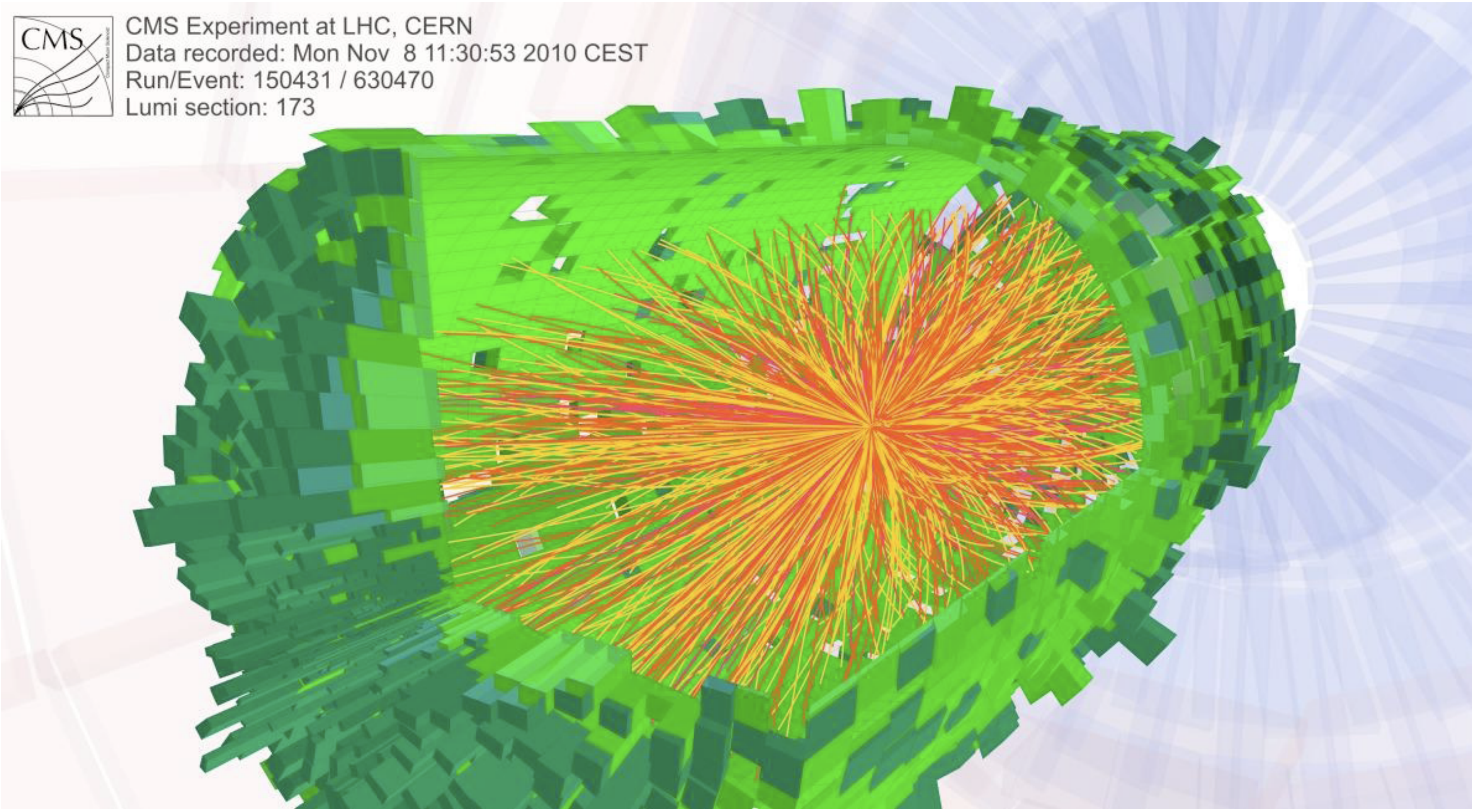
Jets, Quarkonia : originated from the hard scattered partons which carry color charges and interact with the medium. Probe the medium

Photons, W, Z : Colorless, provide initial state information. Nuclear parton distribution function (nPDF).

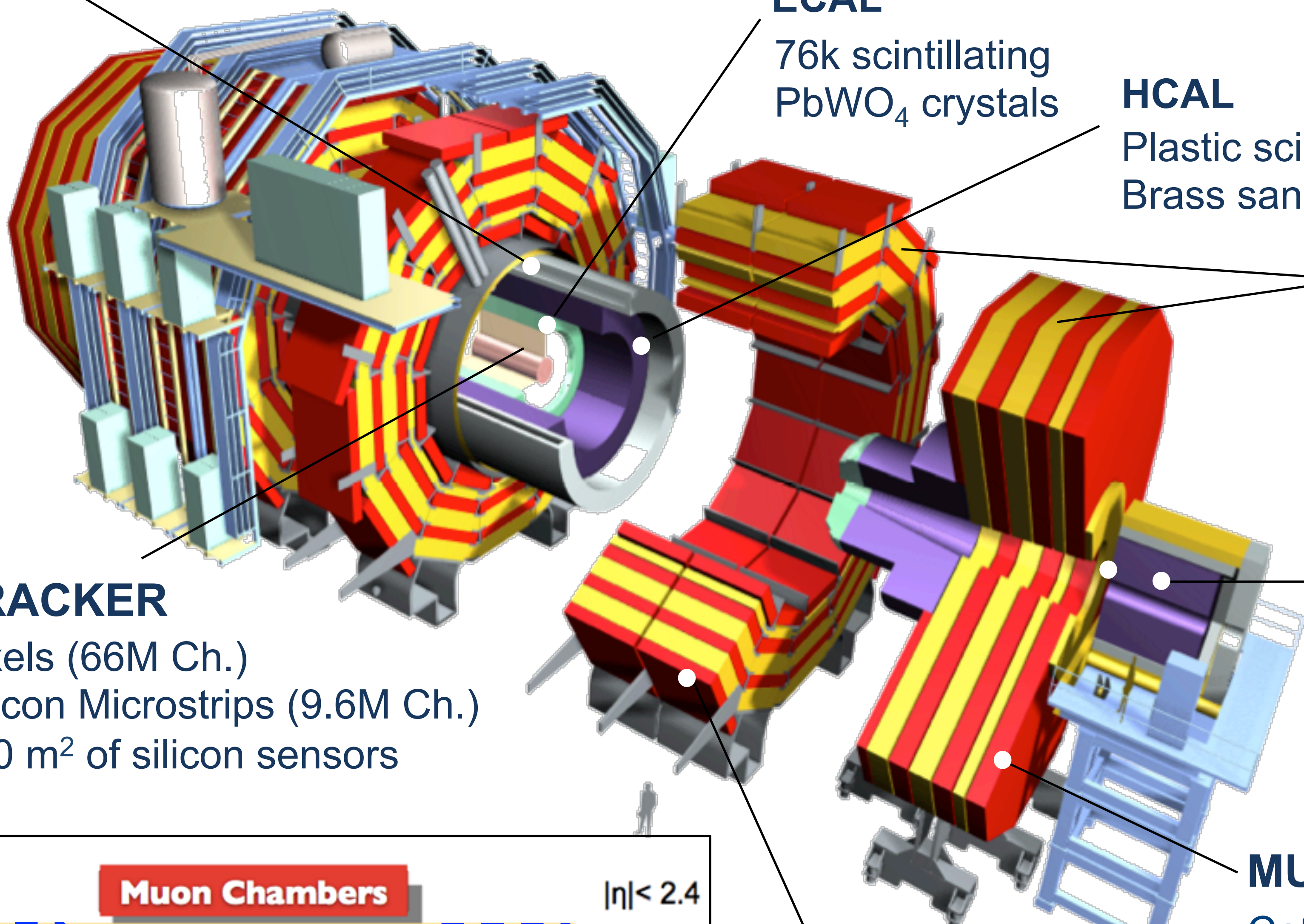
pA collisions: information about nPDF, helps disentangle different physics effects

PbPb collision at LHC

- Central collision (b≈0 fm) at $\sqrt{s_{NN}}$ = 2.76 TeV
- >10000 charged particles produced



CMS detector



Superconducting Coil (3.8 T)

CALORIMETERS

ECAL

76k scintillating
$PbWO_4$ crystals

HCAL

Plastic scintillator/
Brass sandwich

Weight: 12,500 tons
Diameter: 15 m
Length: 22 m

Steel YOKE

HF

MB trigger
Centrality in HI

TRACKER

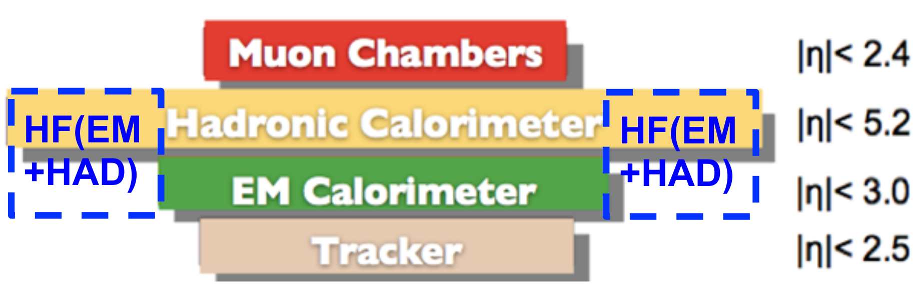
Pixels (66M Ch.)
Silicon Microstrips (9.6M Ch.)
220 m^2 of silicon sensors

MUON BARREL

Drift Tube Chambers
Resistive Plate Chambers

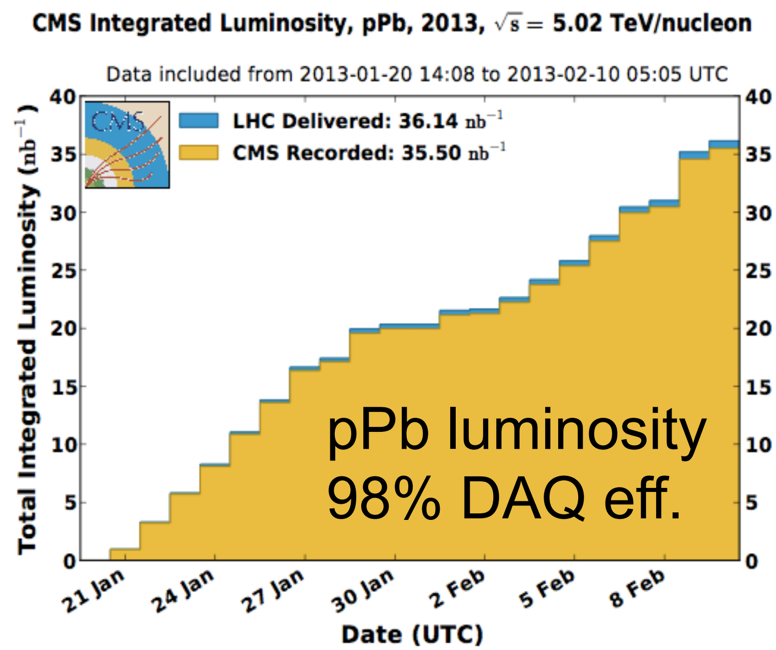
MUON ENDCAPS

Cathode Strip Chambers
Resistive Plate Chambers



HI-oriented runs: past and future

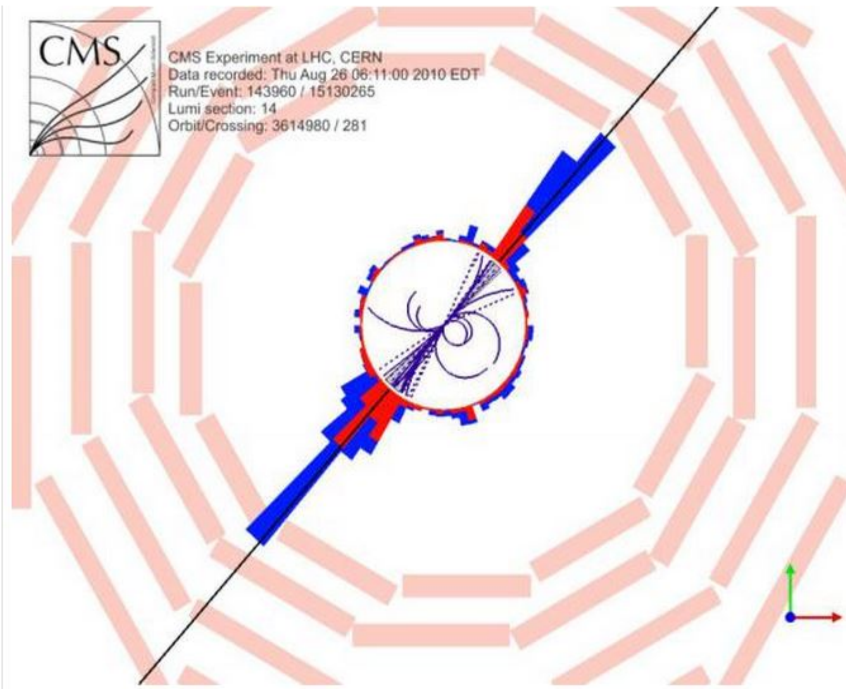
Period	Species	Energy	Lumi
Dec. 2010	Pb+Pb	2.76 TeV	7 μb^{-1}
Dec. 2011	Pb+Pb	2.76 TeV	150 μb^{-1}
Mar. 2011	p+p	2.76 TeV	230 nb^{-1}
Jan. 2013	p+Pb	5.02 TeV	35 nb^{-1}
Feb. 2013	p+p	2.76 TeV	5.4 pb^{-1}
Nov 2015	*Pb+Pb*	*~5 TeV*	*~0.8 nb^{-1}*
?	*p+p*	*~5 TeV*	*?*
Nov 2016	*p+Pb*	*?*	*?*



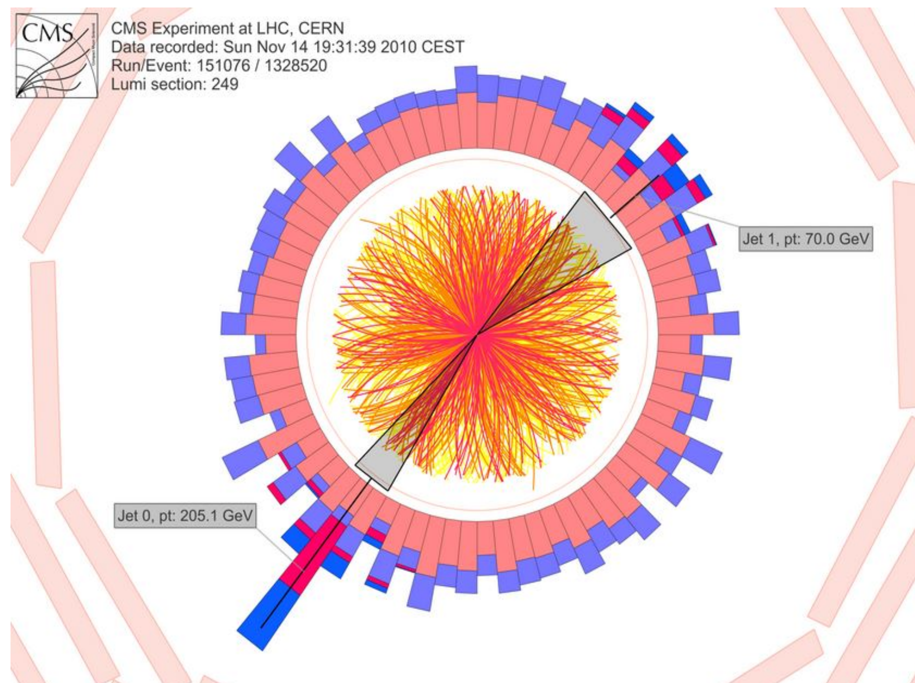
- Same N_{coll} scaled luminosities for pp, pPb, PbPb
  - (as many Z's and W's, modulo the $\sqrt{s}$ dependence)

Probe plasma with energetic quarks and gluons

Quark-gluon plasma is incredibly strongly interacting – It can slow down and even stop very high energy quarks and gluons passing through it



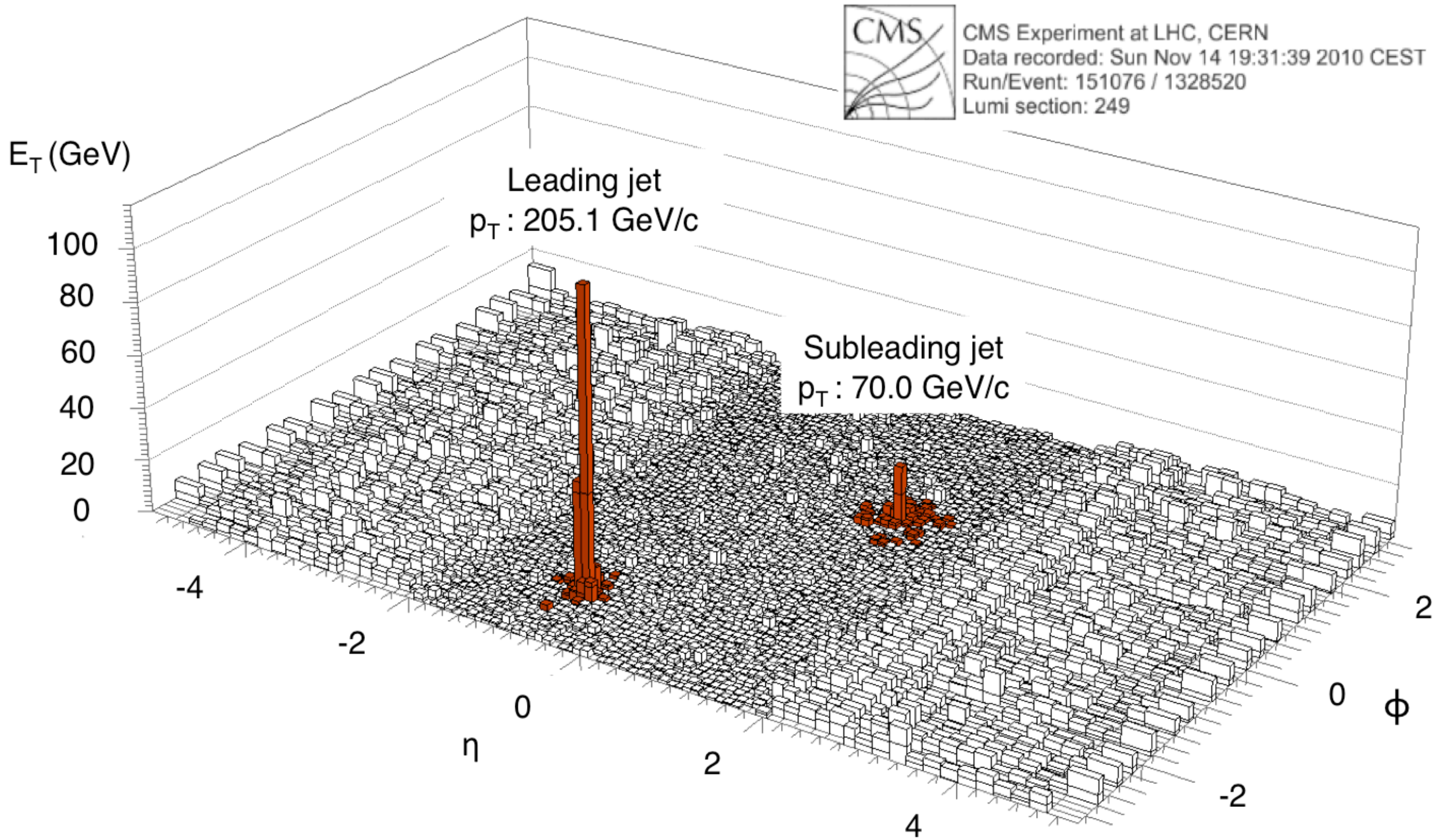
P + P



Pb + Pb

PRC 84 (2011) 024906

Jet quenching in PbPb

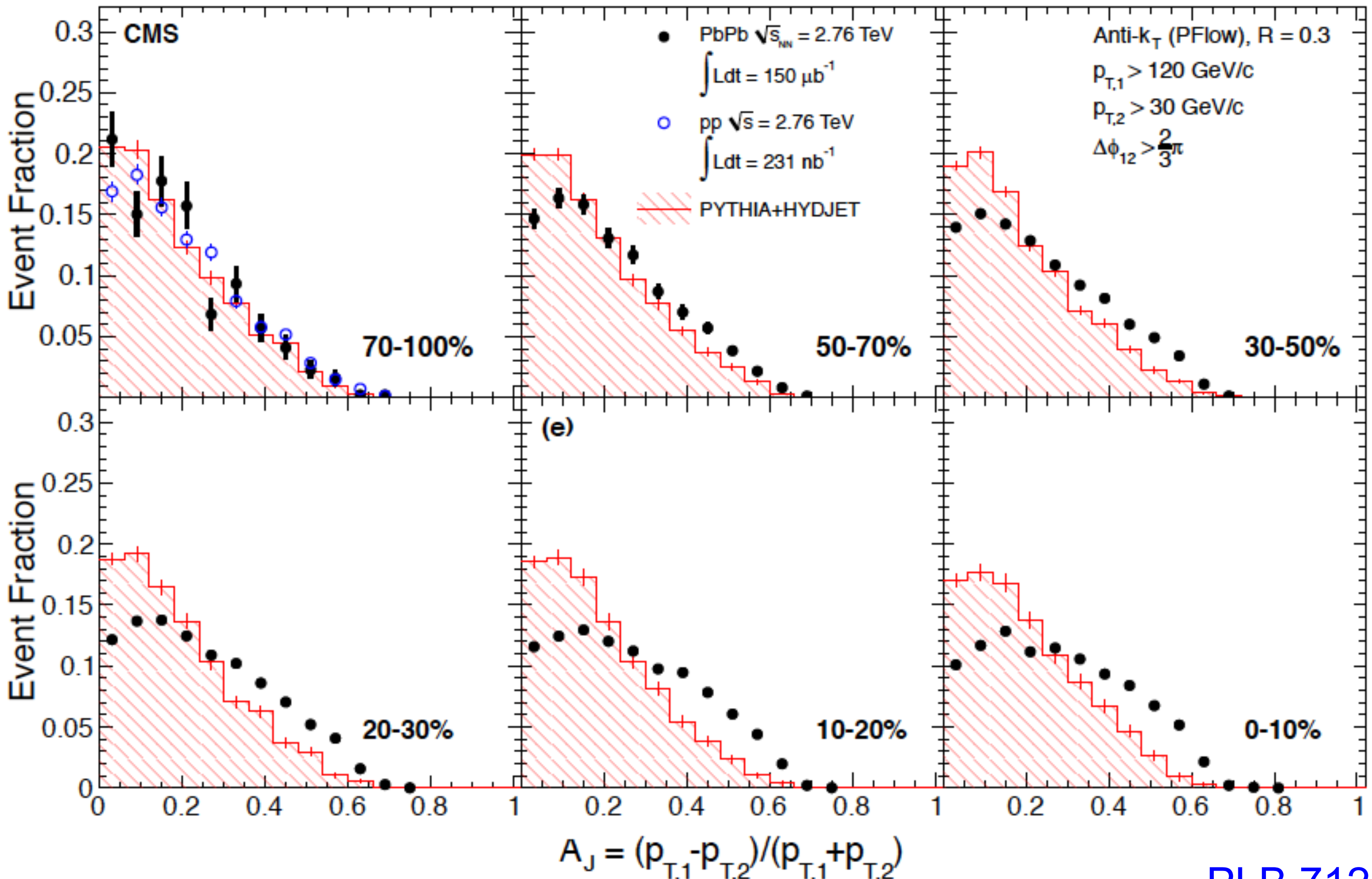


Large jet quenching at the LHC gives rise to asymmetric dijets in central collisions

See the talk by Raghav Kunnawalkam Elayavalli on Friday

Dijet asymmetry in PbPb

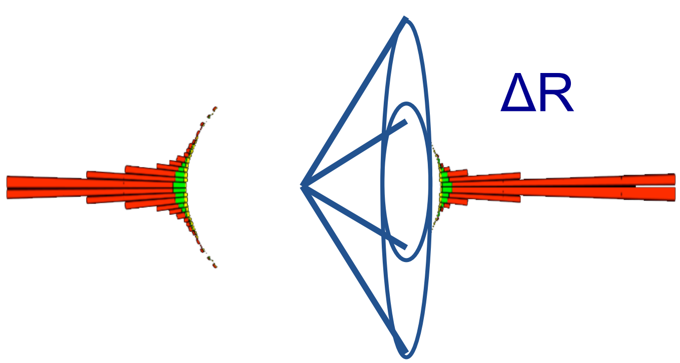
- Compare two back-to-back jets: huge asymmetry for most central events

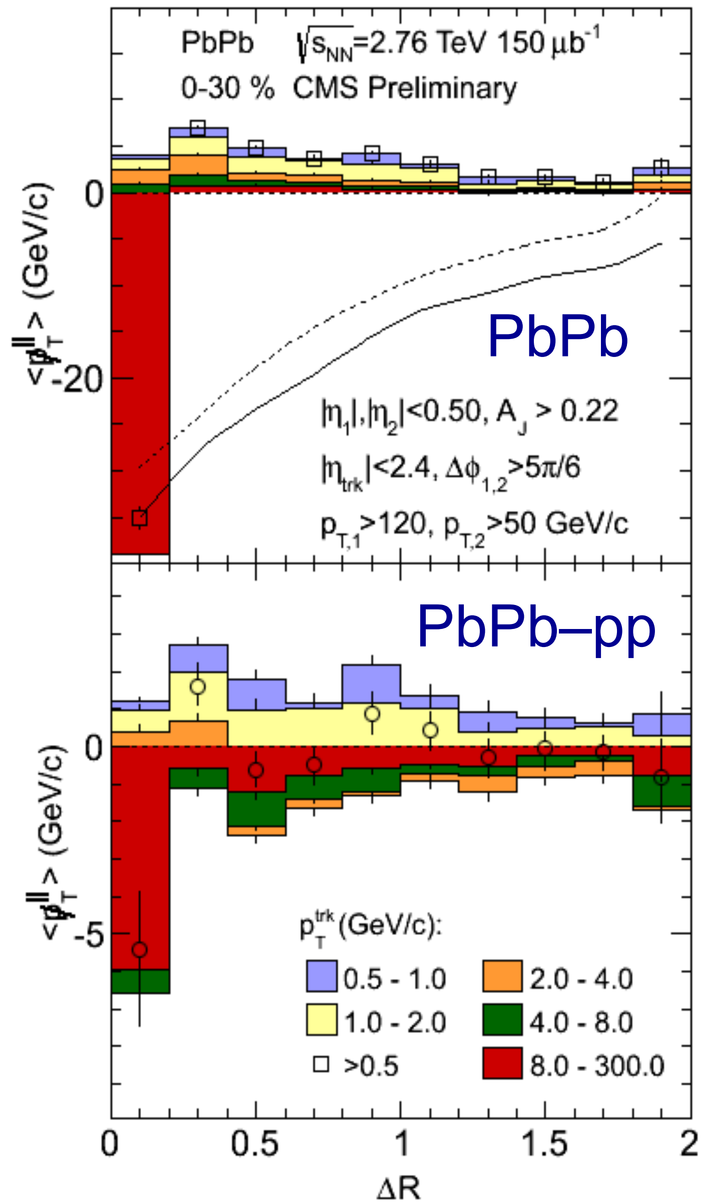


[PLB 712 (2012) 176]

Tracing back the lost energy…

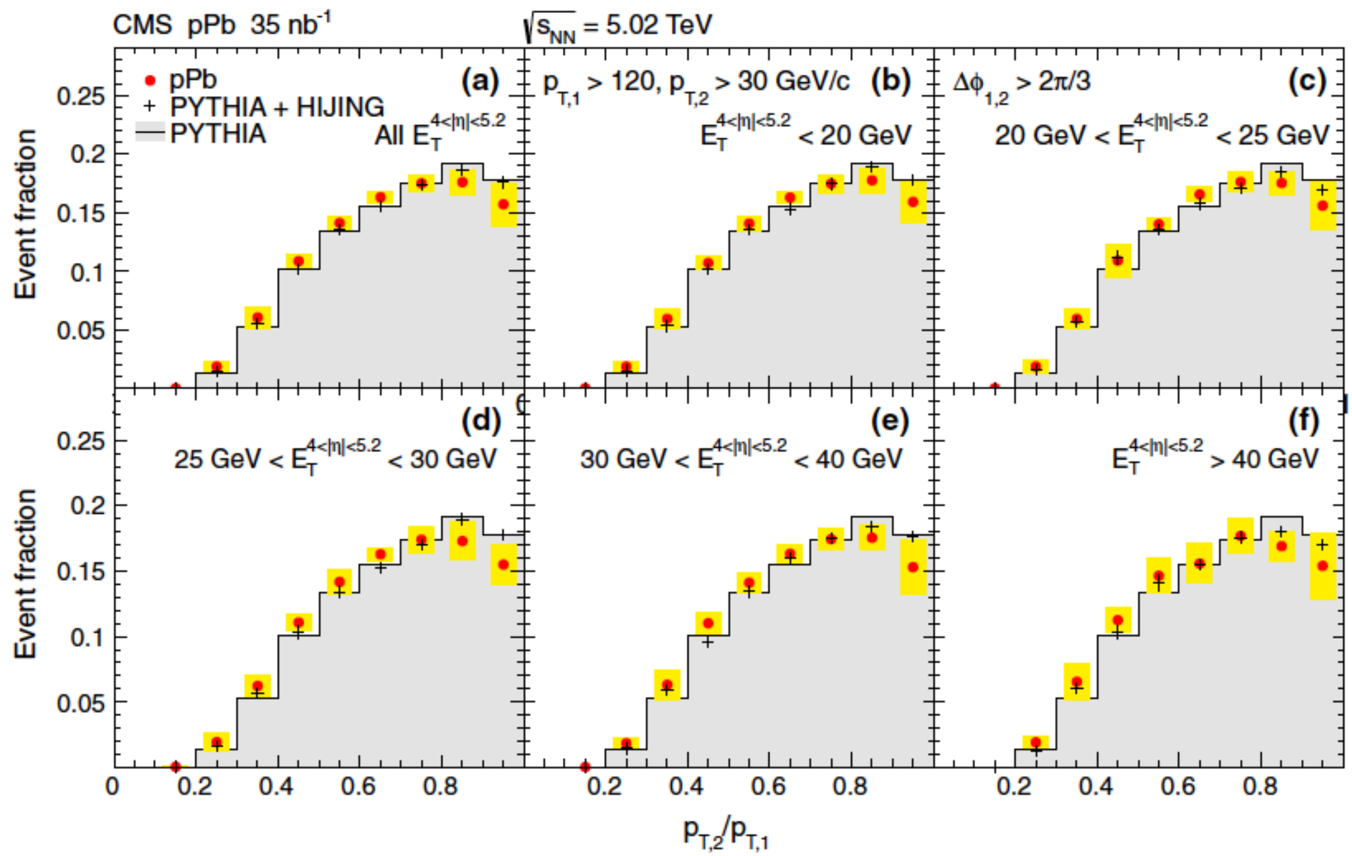
- Detailed $(\Delta R, p_T)$ distributions
  - Summing charged particles for unbalanced ($A_J>0.22$) dijets in central (0–30%) collisions…
  - 35 GeV missing at $\Delta R<0.2$, large p_T particles
  - Balanced by low p_T particle up to very large ΔR
  - Subtracting the same distribution from pp shows that there is different p_T mix between two systems





Jet quenching in pPb

Compare two jets in dijet events as a function transverse energy activity (pPb) EPJC 74 (2014) 2951



p_{T1} / p_{T2}

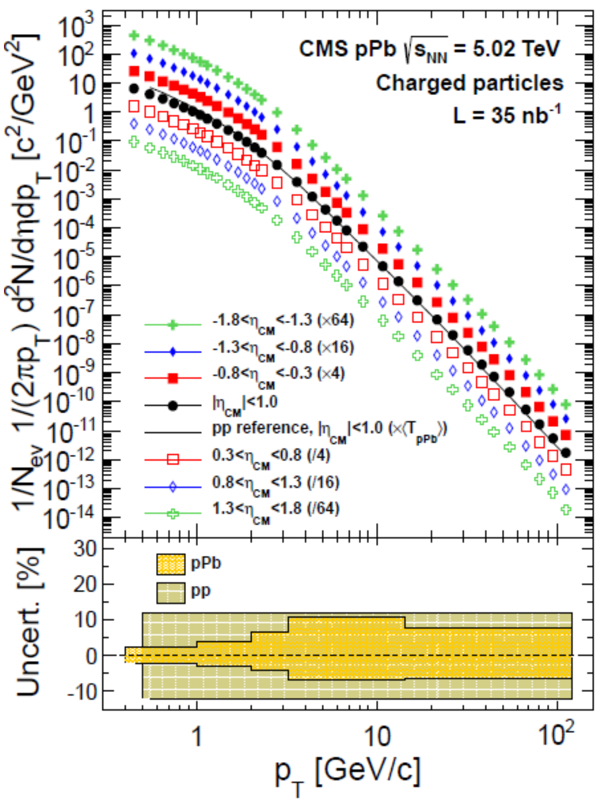
No quenching observed in pPb, but …

- Quenching already modest in 50-100% PbPb
- It is difficult to pick out central pPb collisions

Detailed information about hadrons, jets & b-jets in pPb

Charged hadrons

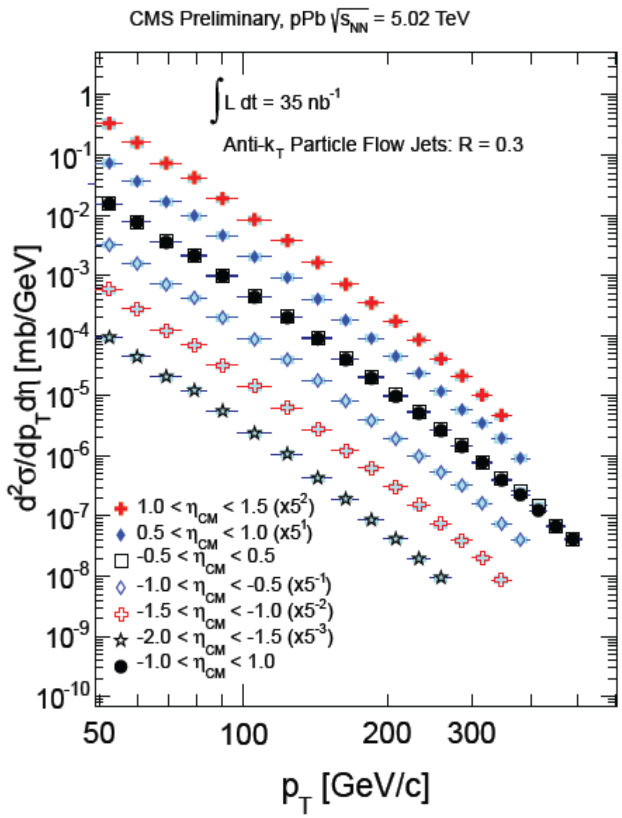
PAS-HIN-12-017
arXiv:1502.05387



pp: interpolation using CDF and CMS data

Jets

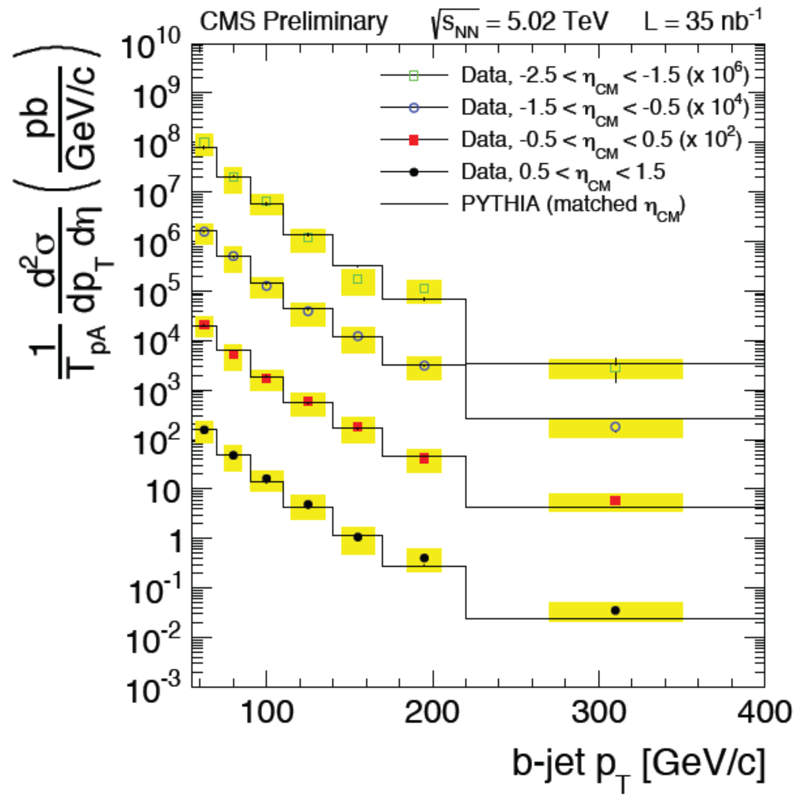
PAS-HIN-14-001



pp: extrapolation using CMS data at 7 TeV and PYTHIA Z2

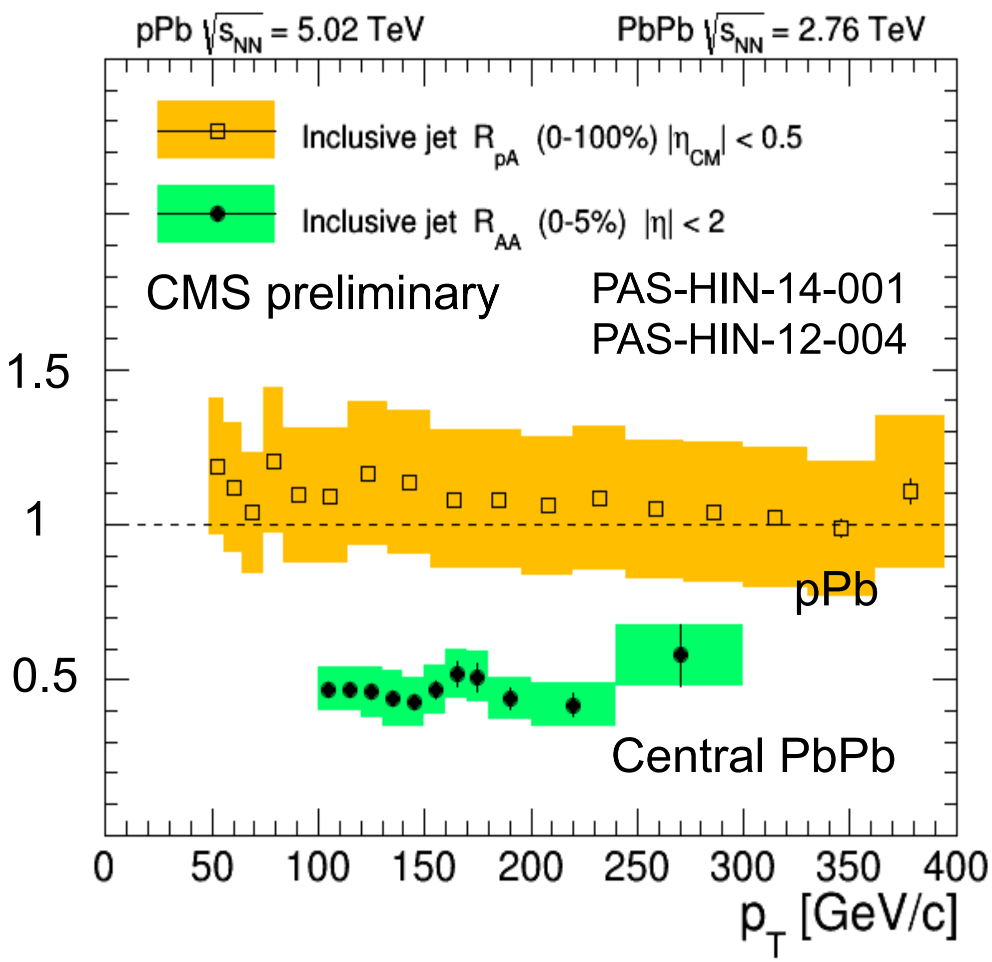
b-Jets

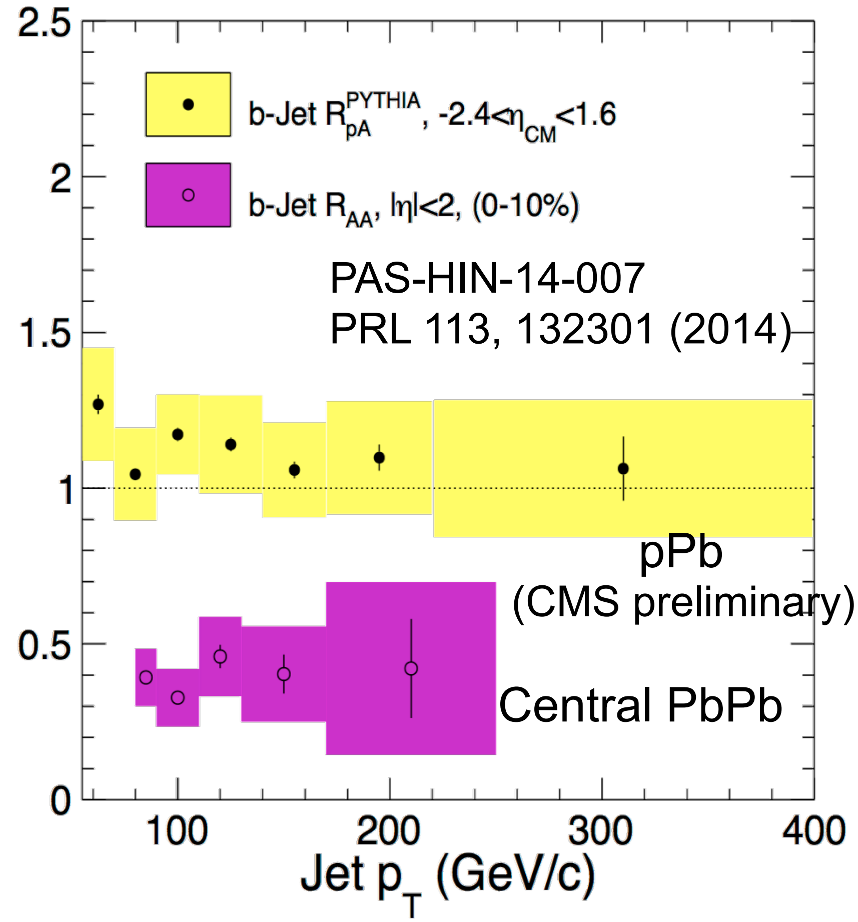
PAS-HIN-14-007



pp: PYTHIA
Use displaced vertex technique to identify b-jets

Jets & b-jets in PbPb & pPb

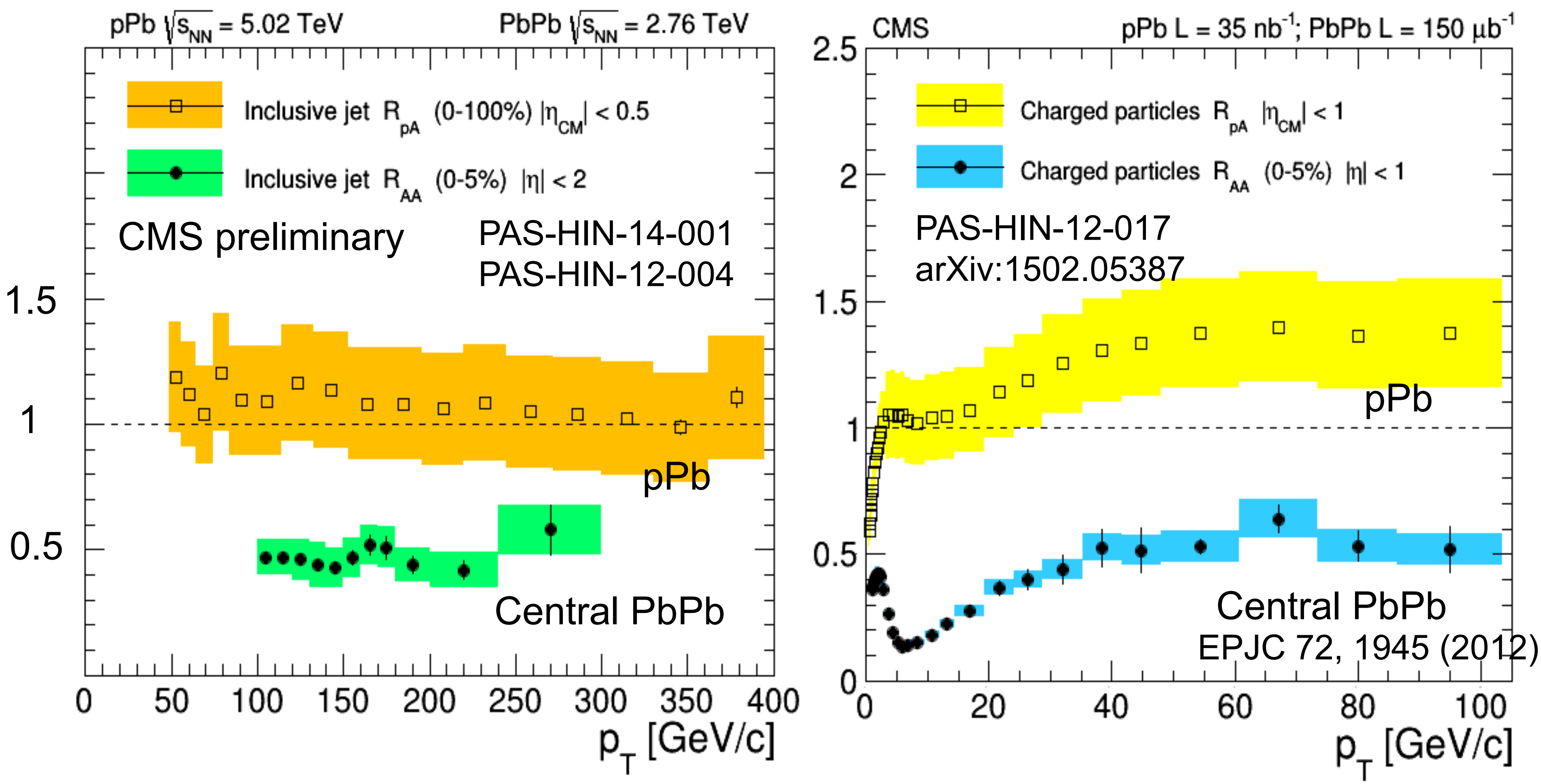




- Little or no modification in pPb
- Strong suppression in PbPb
- No strong flavor dependence

$$R_{AA} = \frac{ions}{protons}$$

Jets & hadrons in PbPb & pPb



- Significant enhancement observed for hadrons at high p_T!

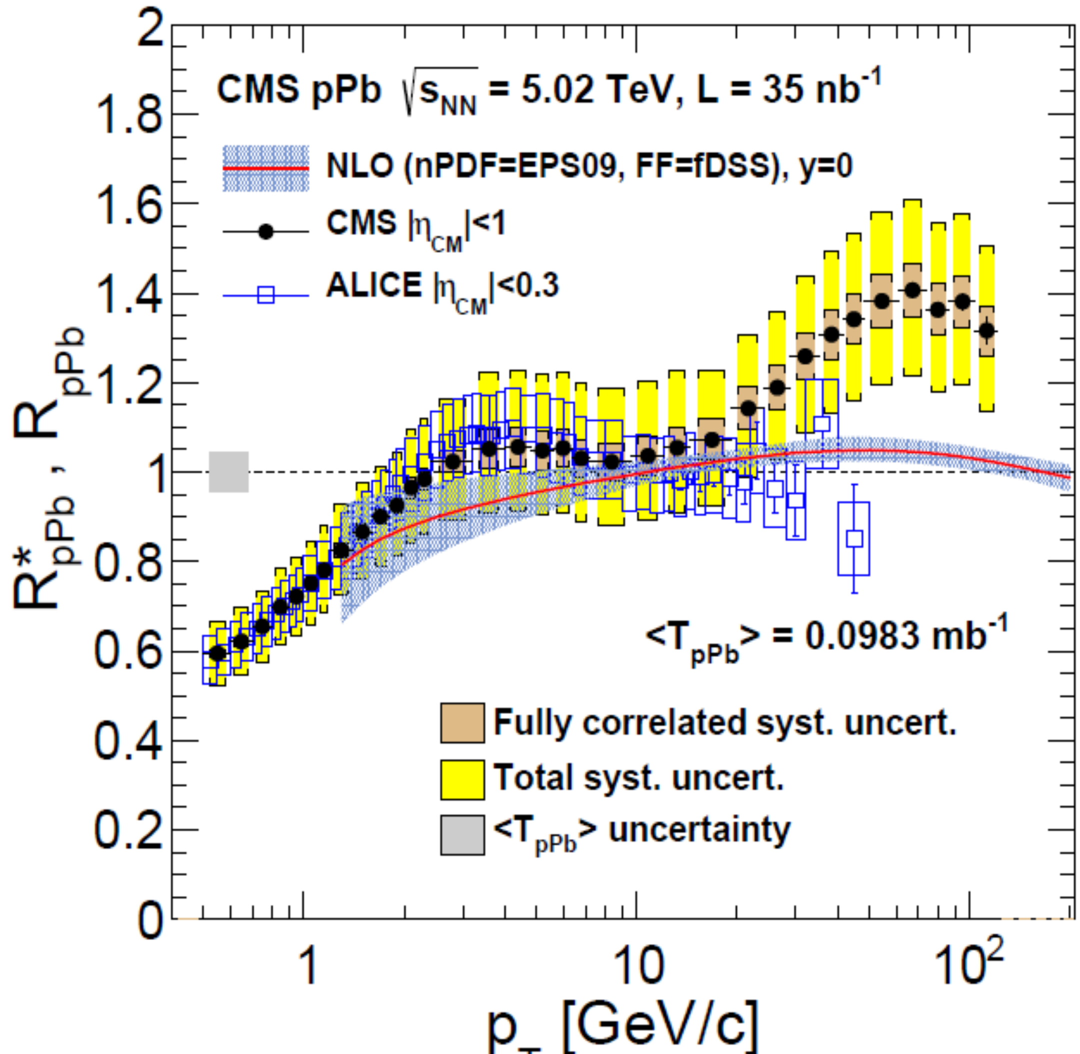
R_{pPb} for hadrons in pPb

$$R_{pPb}\left(50 < p_T < 100\, GeV/c\right) \sim 1.38 \pm 0.22$$

- CMS generally agrees with ALICE and preliminary ATLAS data
- NLO with EPS09 for π^0 is smaller than for charged hadrons [Helenius et al., JHEP 1207, 073 (2012)]

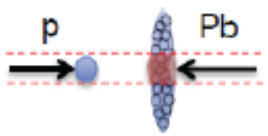
Too large to be due to antishadowing?
Other nuclear effects?

PAS-HIN-12-017, arXiv:1502.05387

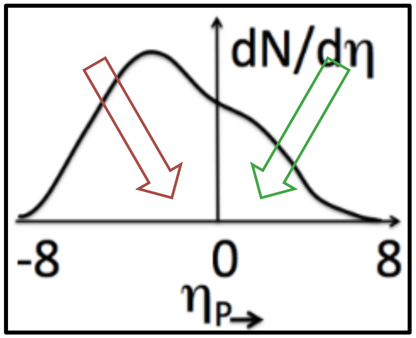


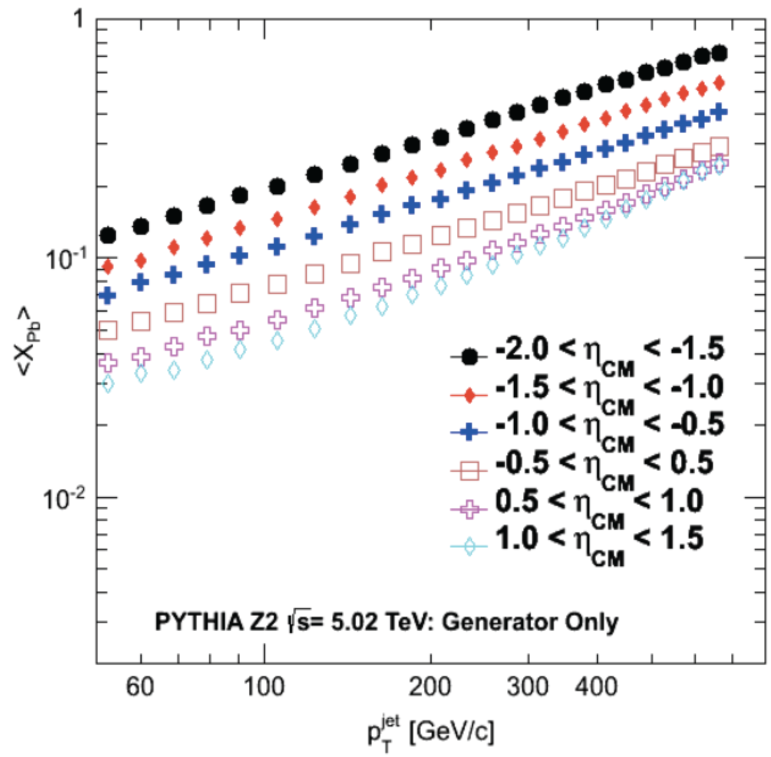
nPDF & jets in pPb: Kinematics

Backward
Large x in Pb

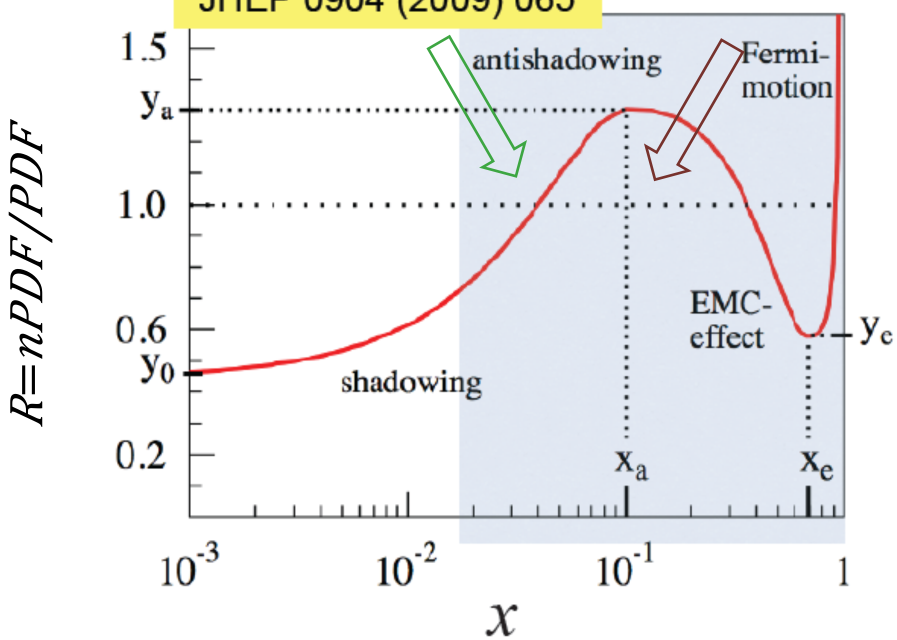


Forward
Small x in Pb





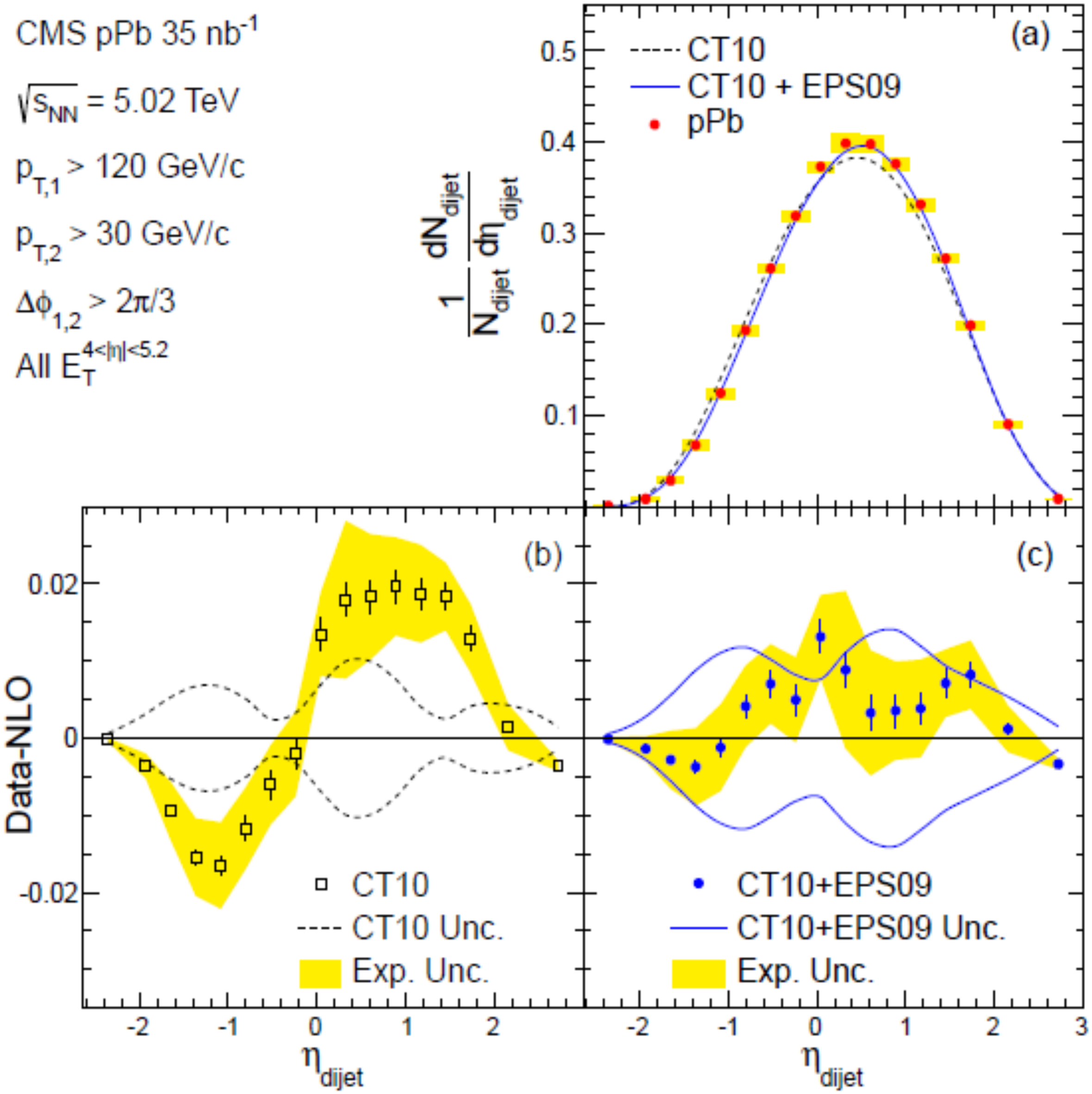
JHEP 0904 (2009) 065



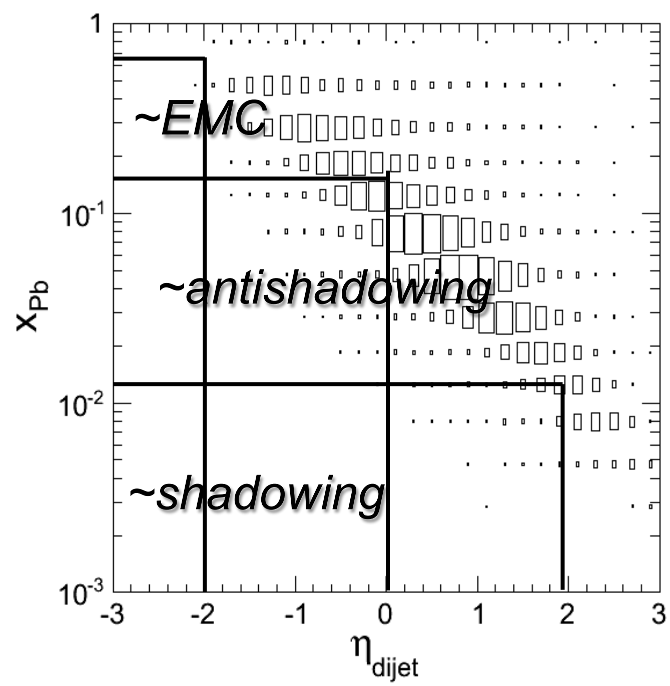
Backward region (η_{CM}<0) for antishadowing (or EMC)
Forward region (η_{CM}>0) more for shadowing (or antishadowing)

nPDF & jets in pPb: Data

EPJC 74, 2951 (2014)



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



- nPDF(+EPS09) works better than proton PDF(CT10) (Escola et al., arXiv:1308.6733)

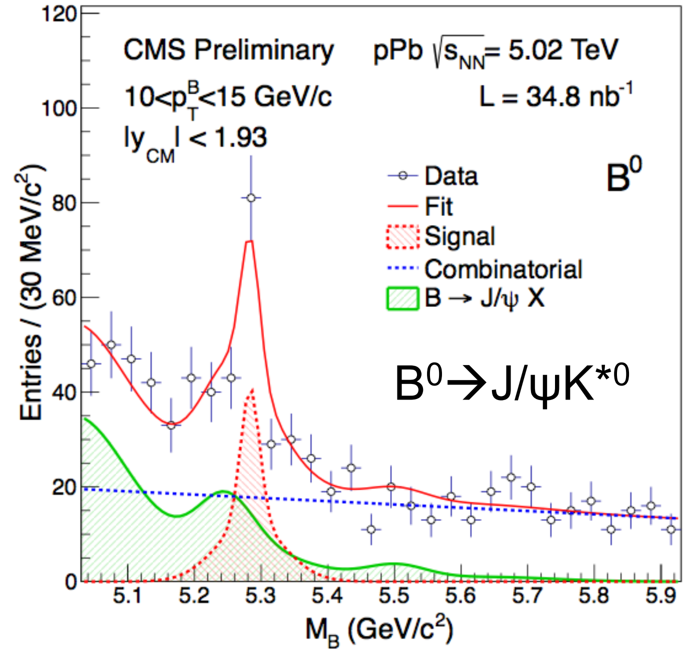
B meson production in pPb

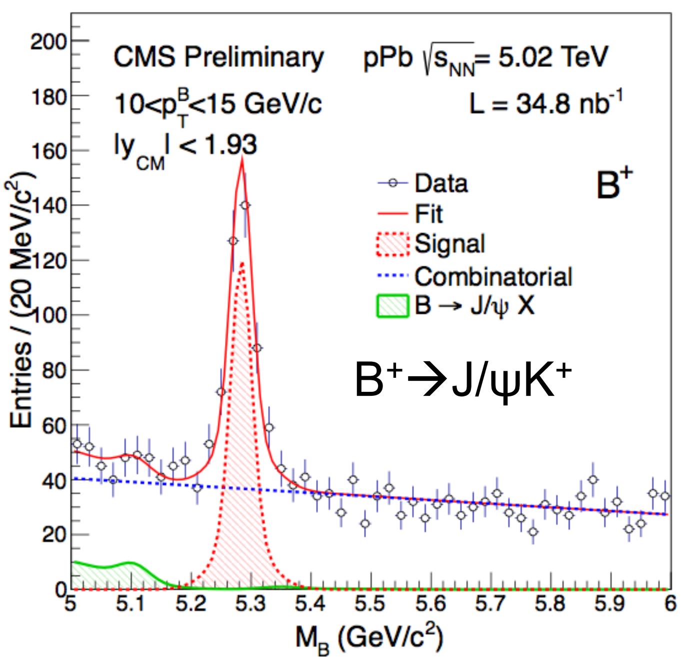
CMS PAS HIN-14-004

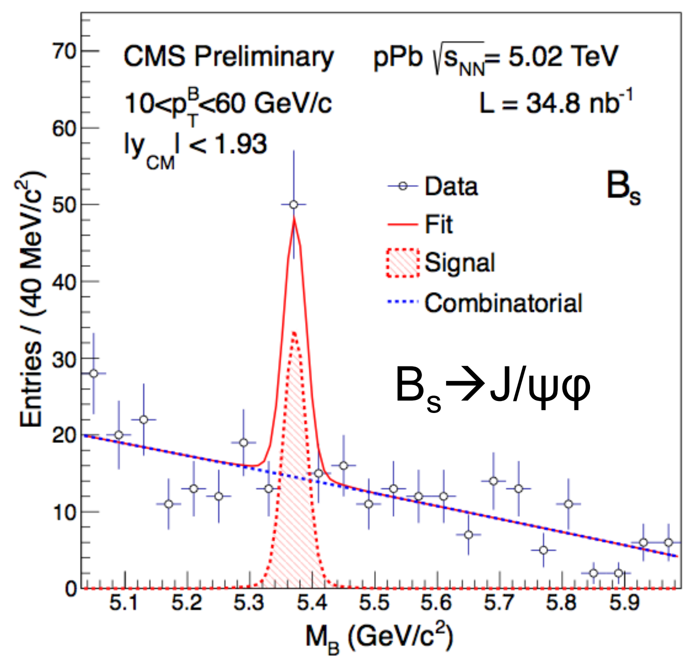
Three component fit for signal extraction:

- Signal
- Combinatorial background from J/ψ-track(s)
- Non-prompt component from other B-meson decays that form peaking structures (e.g. in B^+ analysis, bkg from $B^0 \rightarrow J/\psi\, K^{0*}$)

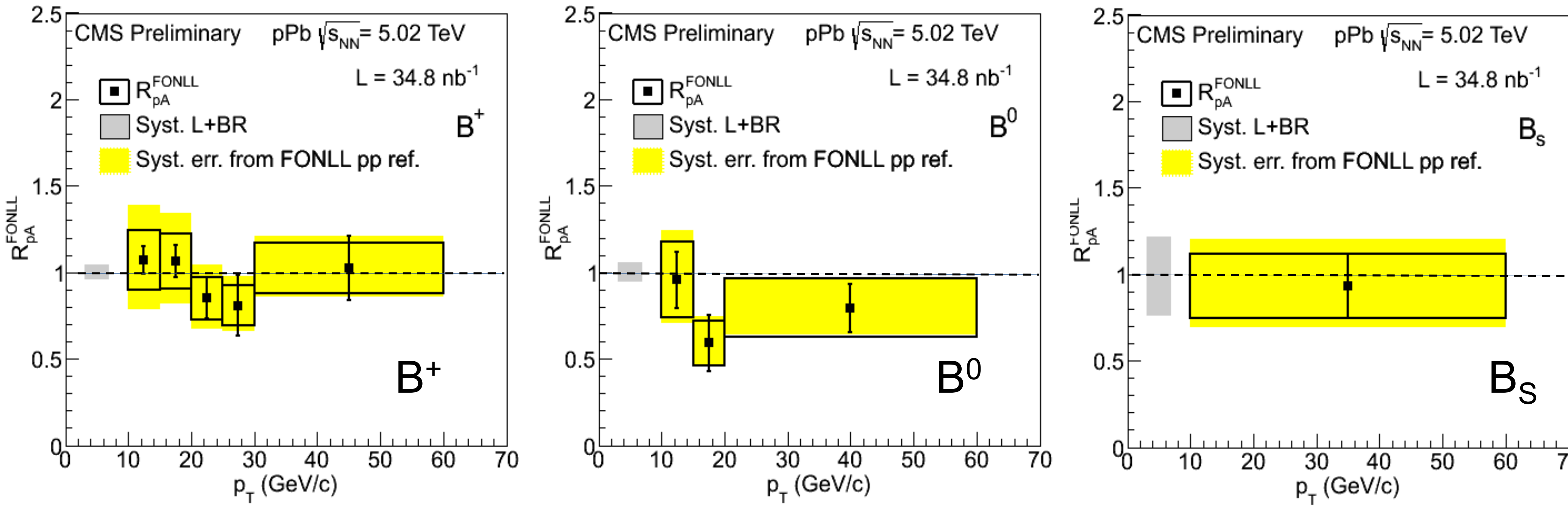
Fully reconstructed B meson signal in nuclear collisions!





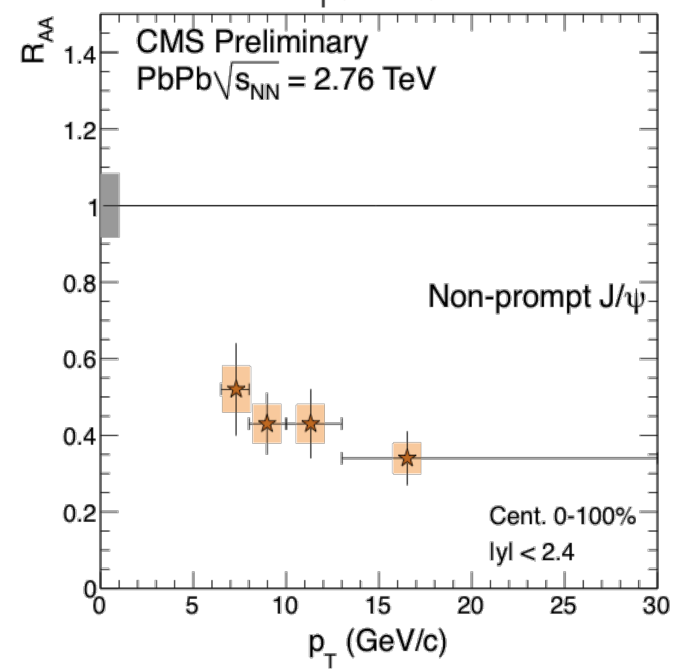


R_{pA} & R_{AA} for B mesons: pA and AA



pPb exclusive B decays (p_T(B) > 10 GeV)
($B^+ \rightarrow J/\psi K^+$, $B^0 \rightarrow J/\psi K^*$, $B_S \rightarrow J/\psi\, \varphi$)
Showing no modification
(large uncertainty, incl. the FONLL ref)

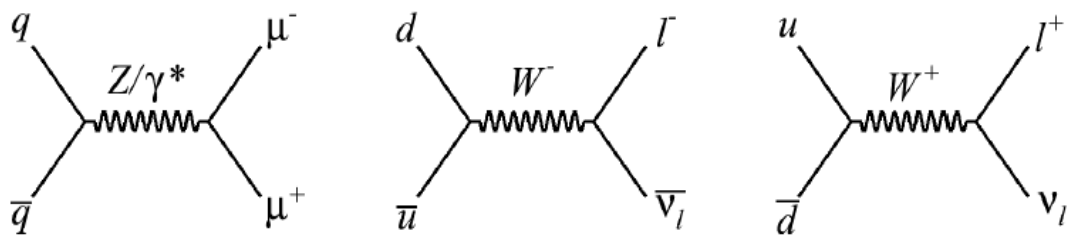
PbPb, inclusive $B \rightarrow J/\psi X$ ($p_T(\psi)$ > 6.5 GeV)
Showing strong suppression



Fixed Order + Next-to-Leading Log, Cacciari et al

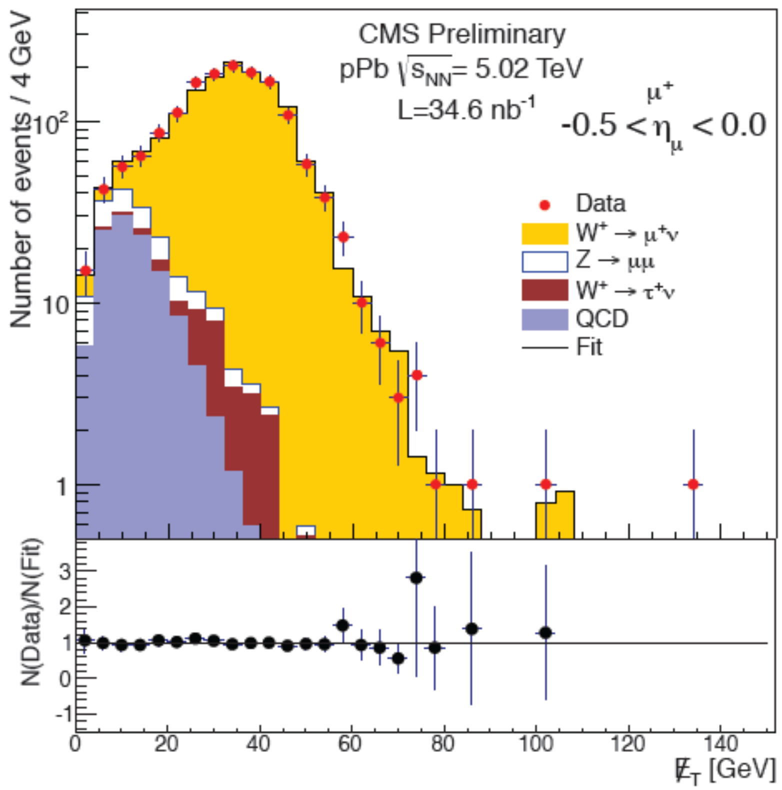
Electroweak bosons in PbPb & pPb

- Standard candles: Z^0 and $W^{\pm}$ unmodified in PbPb
- pPb providing an opportunity to probe (valence) q and (sea) $\bar{q}$ nPDF

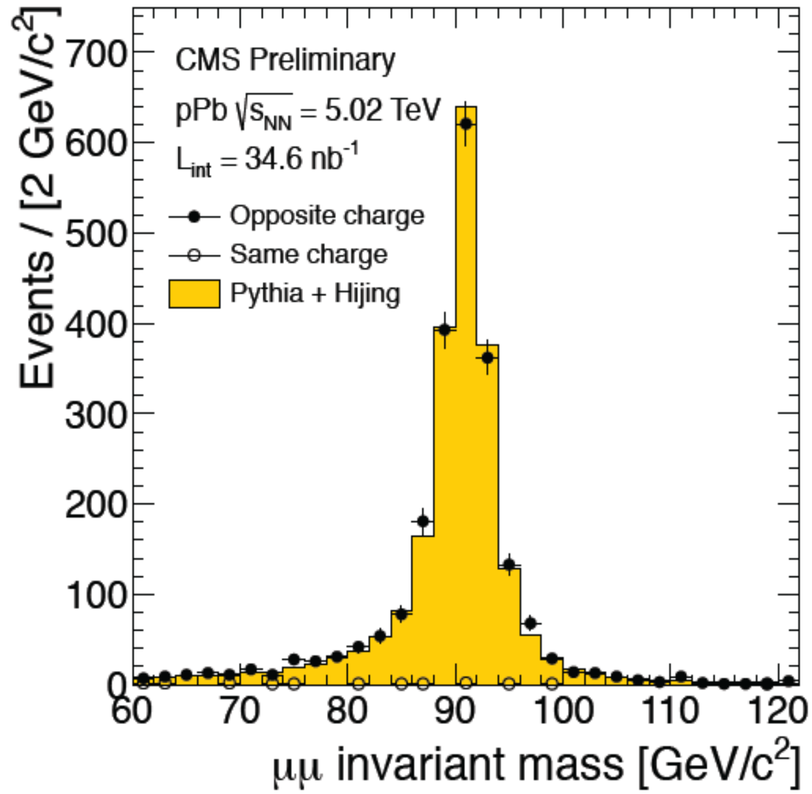


W

PAS-HIN-13-007

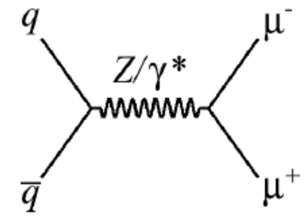


PAS-HIN-14-003

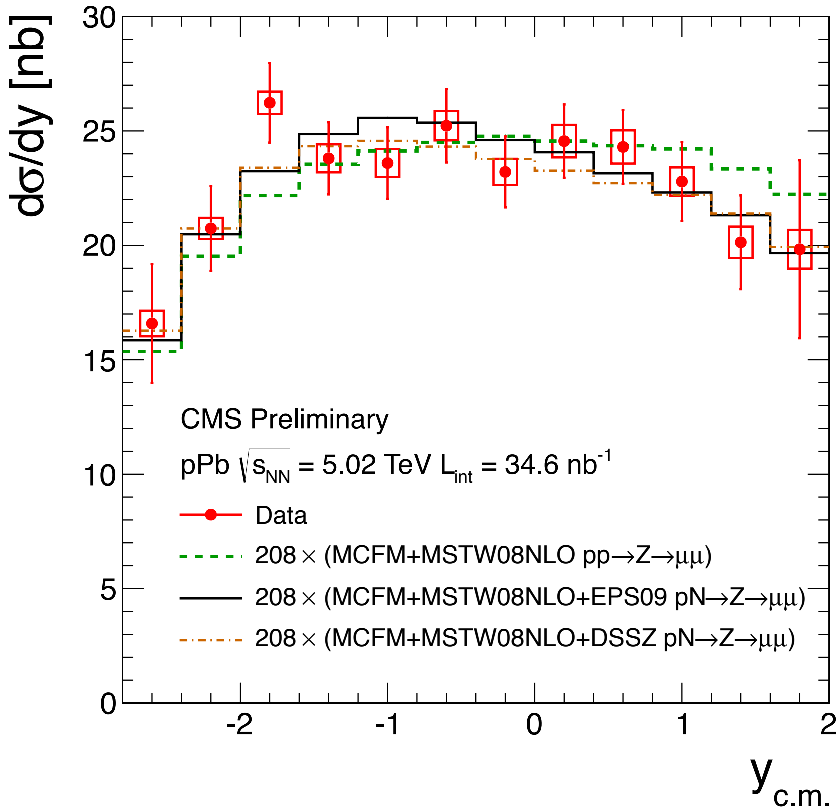


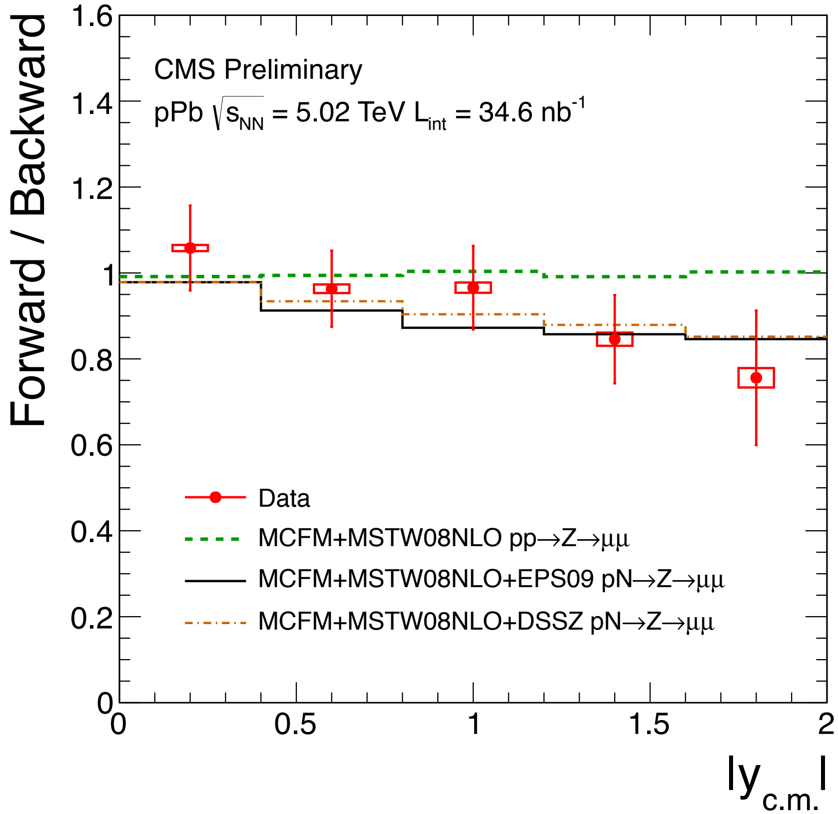
Z

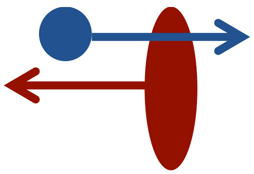
Z^0 in pPb



- ≈ 2200 Z → μμ showing little nuclear effect
  - maybe a hint of forward/backward asymmetry

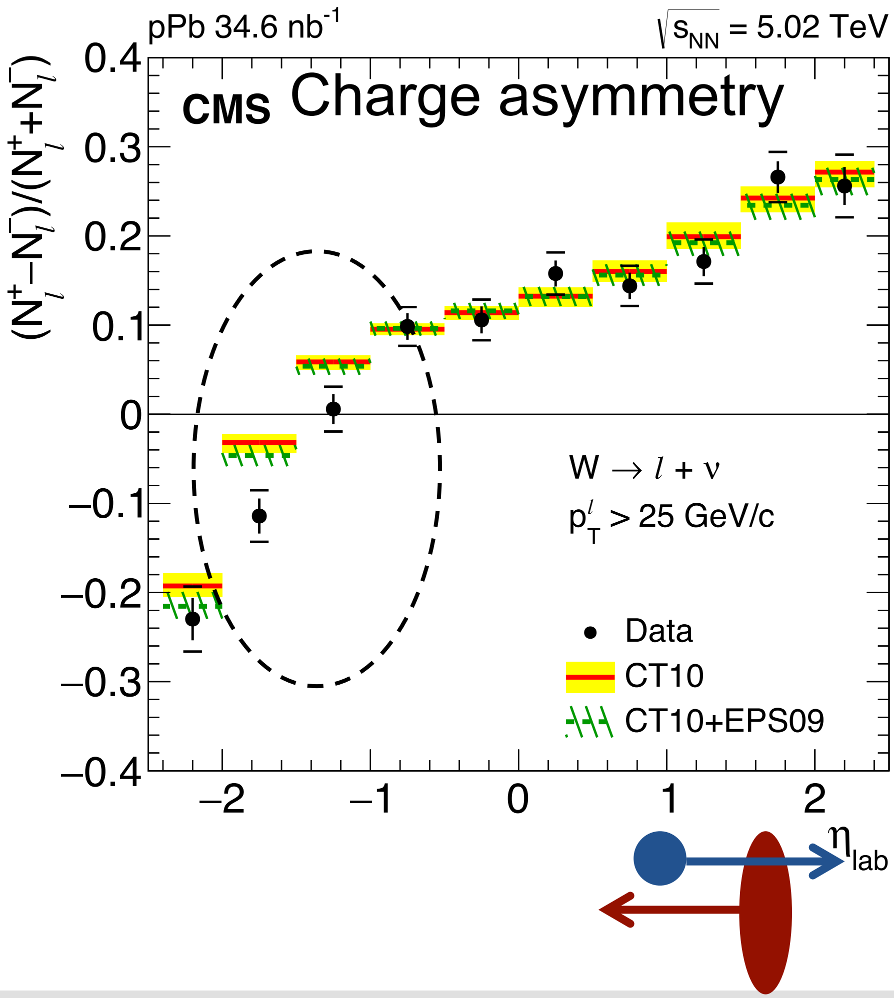


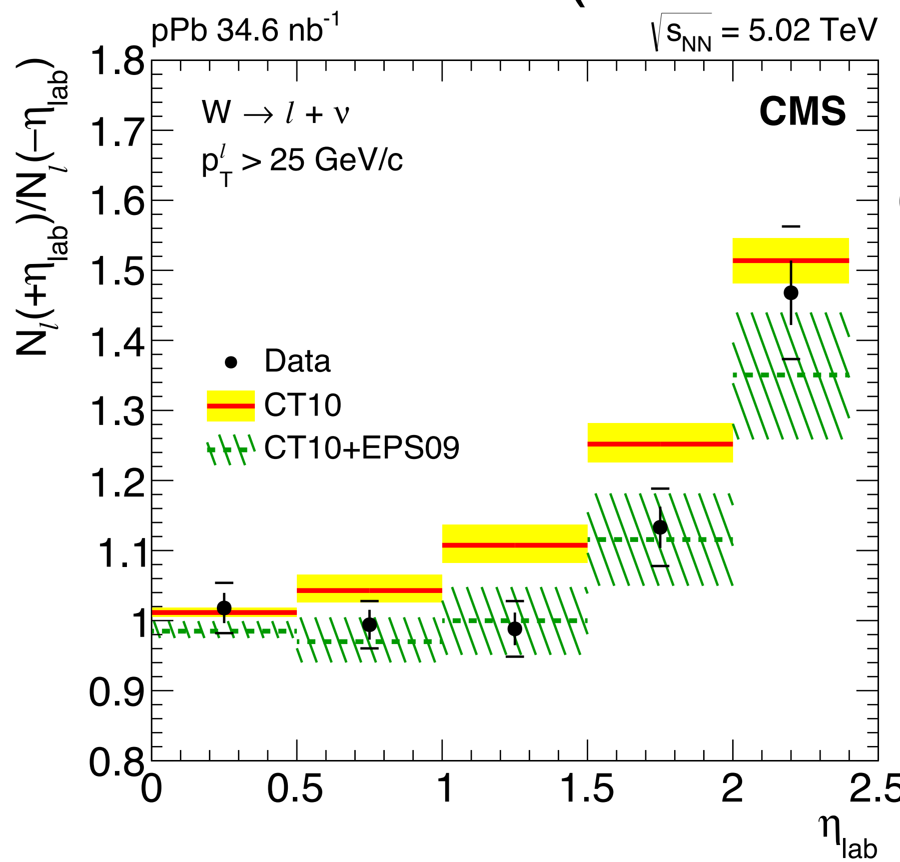




W⁺ and W⁻ in pPb

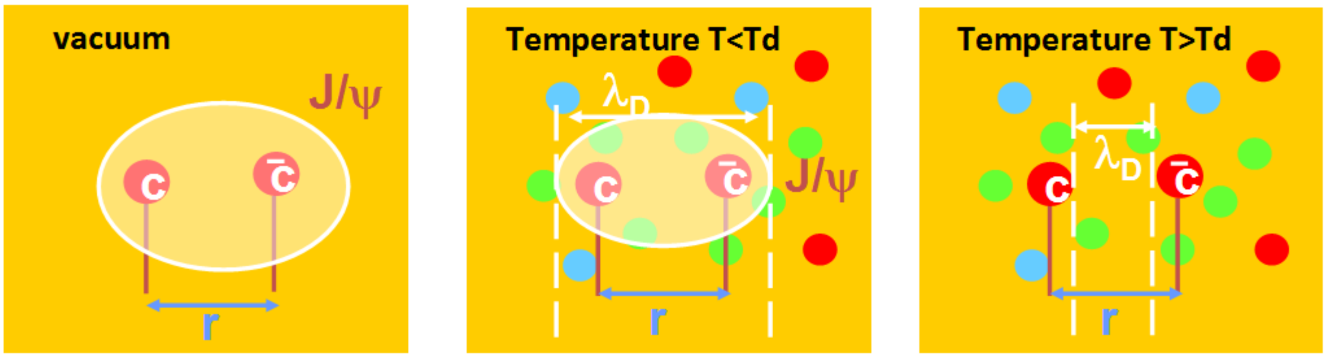
- ≈ 21000 W → μ & 16000 W → e
  - Showing small deviations from unmodified PDFs
  - A hint of a different u/d modification? (not in EPS09)



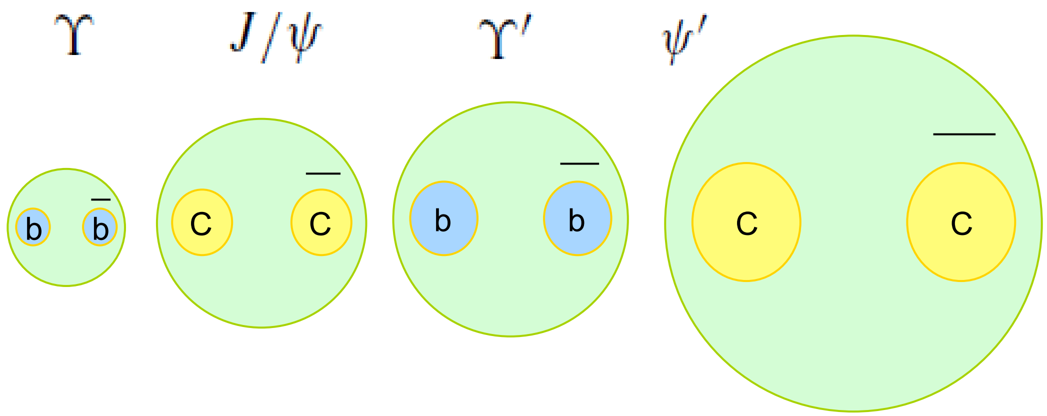


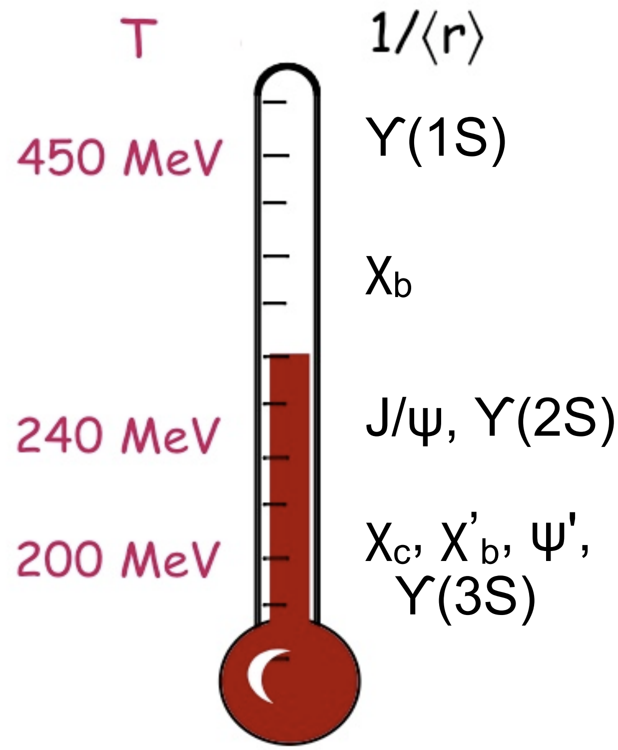
Forward/ Backward (in lab)

Quarkonia as a tool to probe the QGP



Matsui & Satz, PLB168 (1986) 415



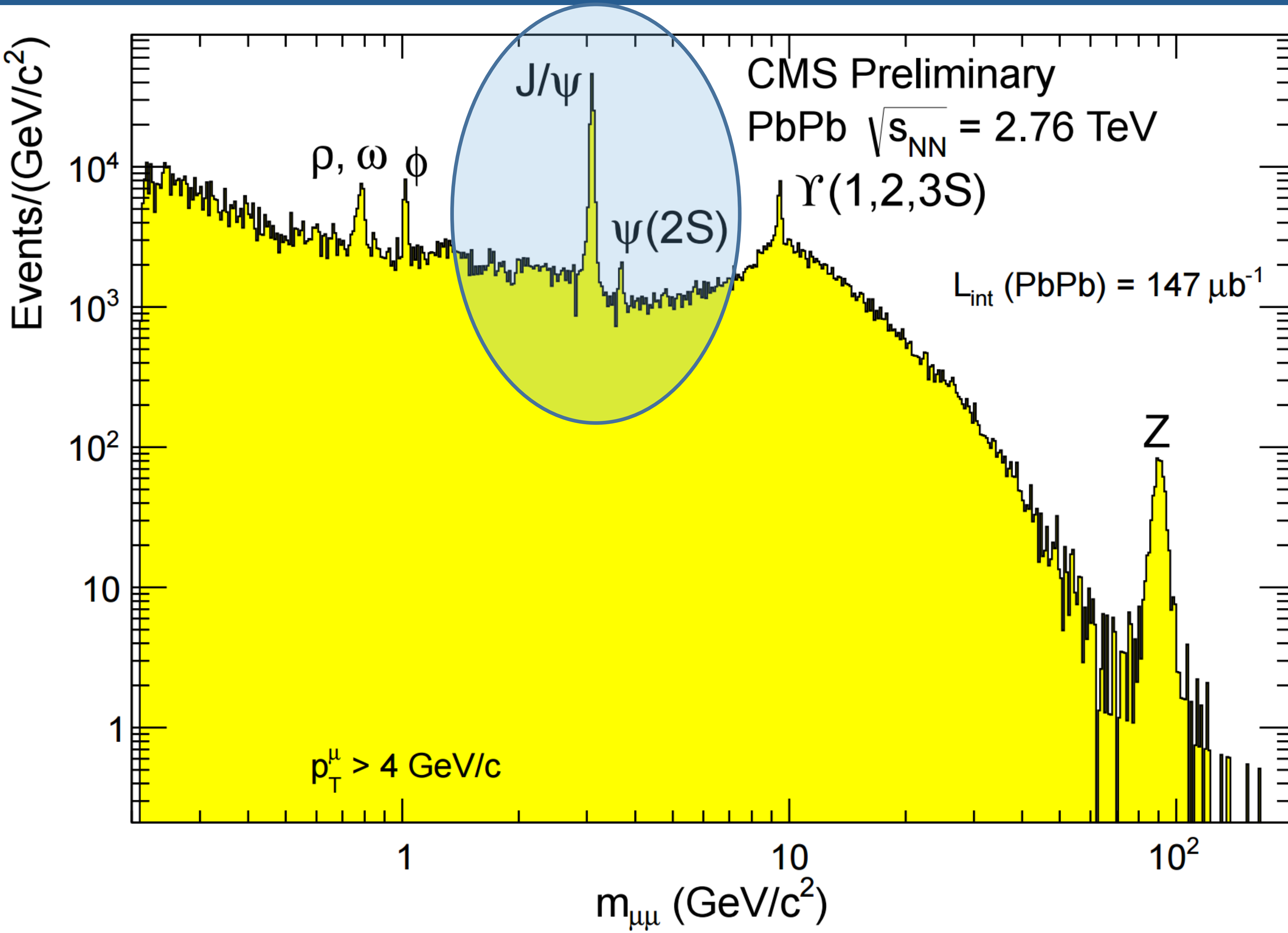


Mocsy, EPJC61 (2009) 705

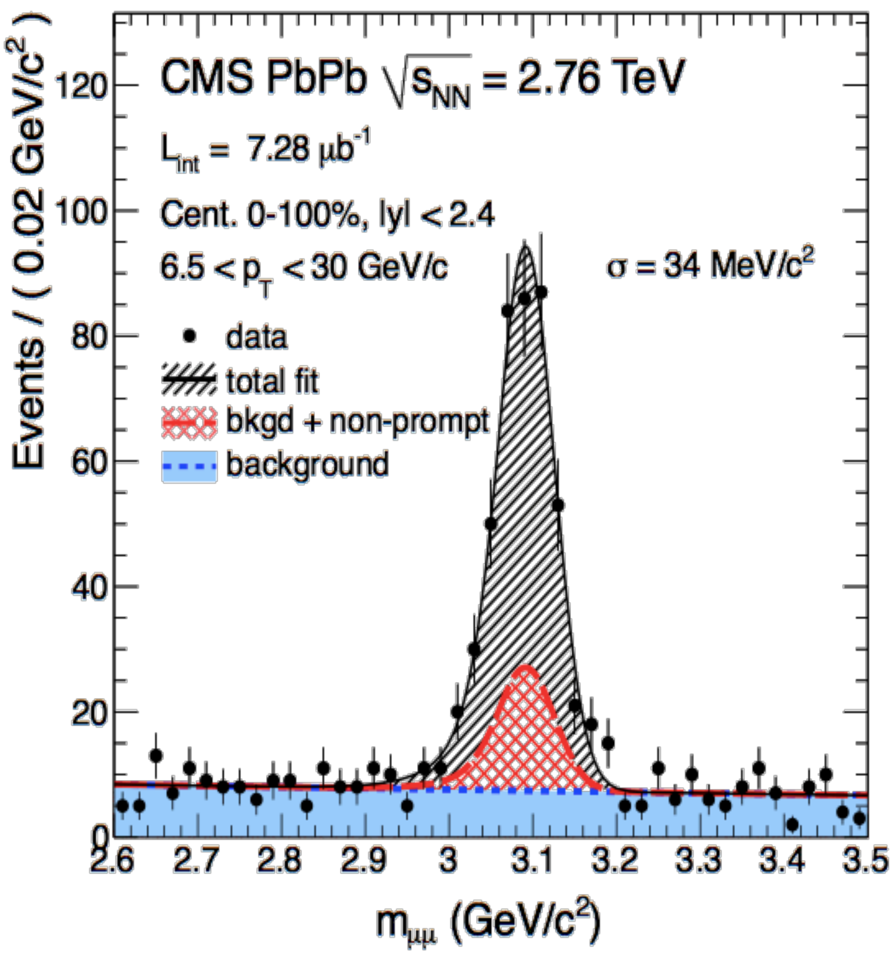
Different states have different binding energies
Loosely bound states "melt" first!

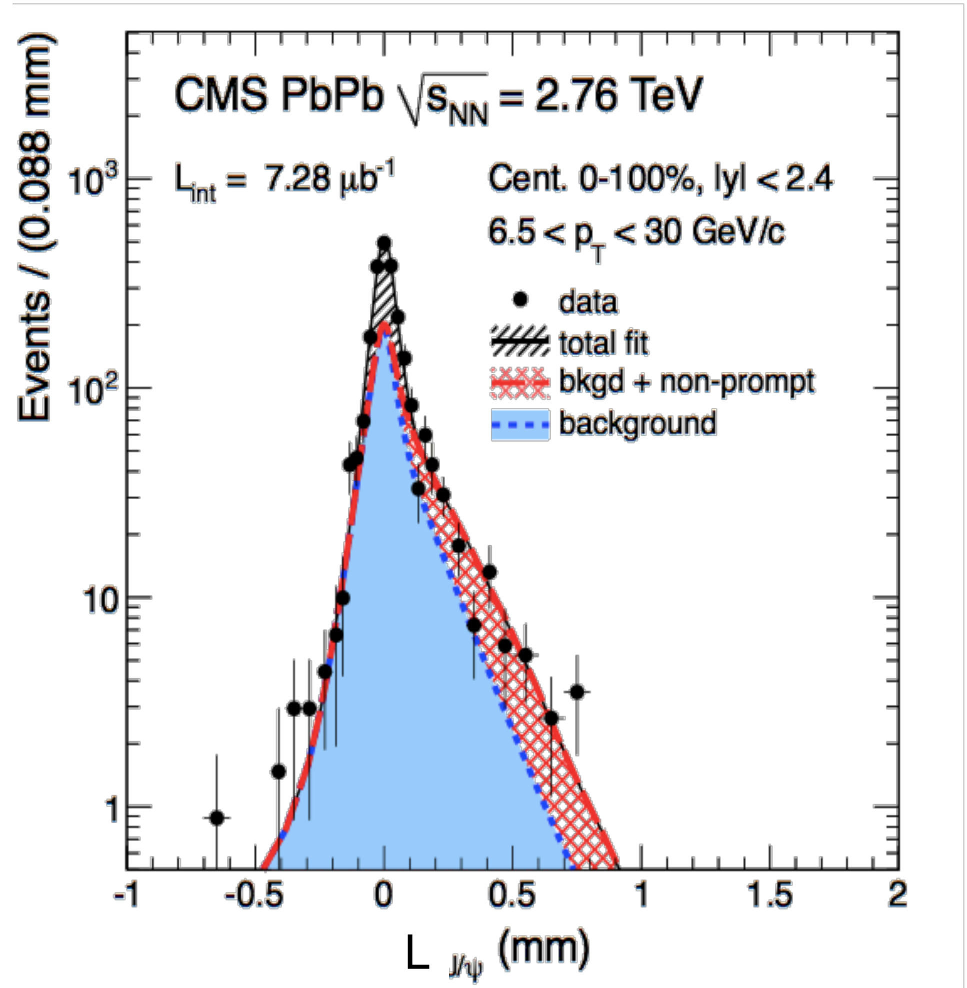
Successive suppression of individual states provides a "thermometer" of the QGP

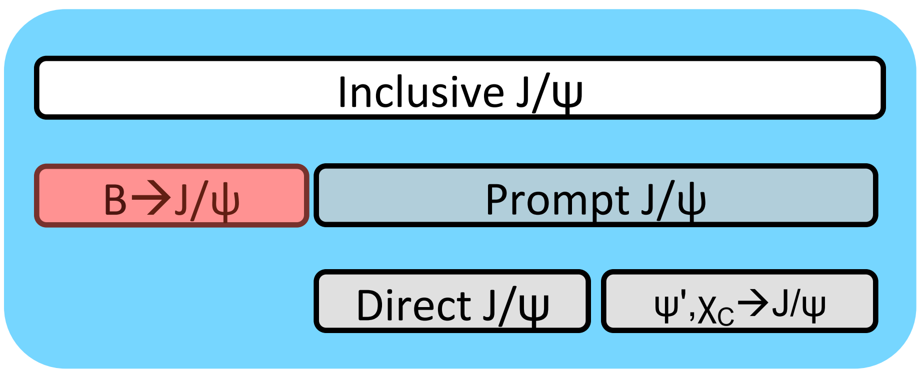
Quarkonia production: Dimuons

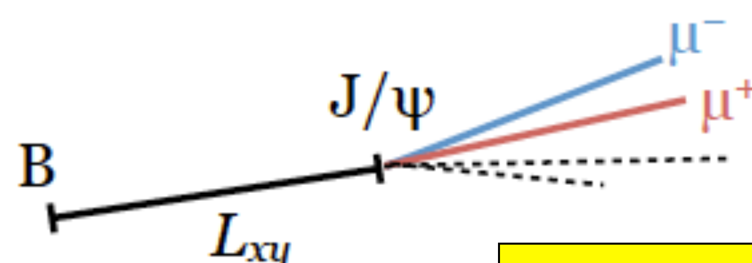


Prompt and non-prompt J/ ψ





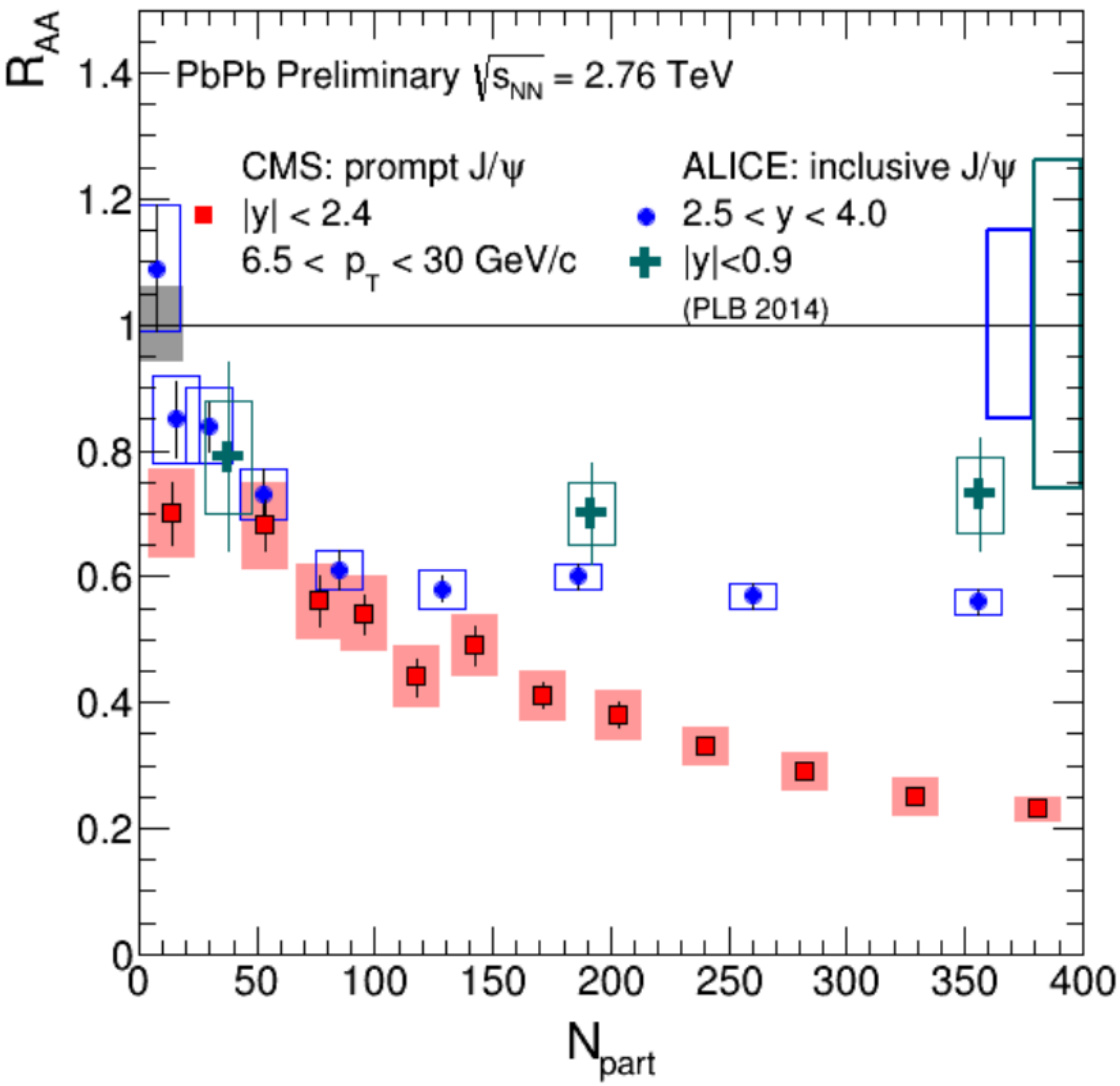




CMS PAS HIN-12-014

J/ψ R_{AA} vs. centrality in PbPb collisions

CMS PAS HIN-12-014

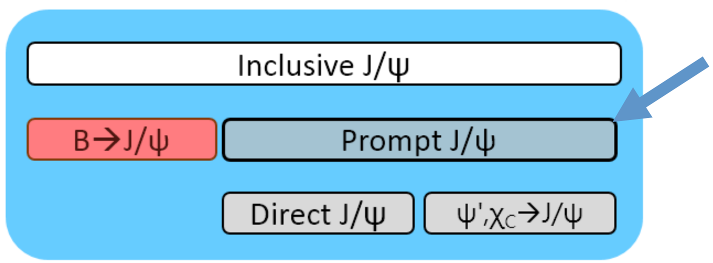


CMS: Prompt J/ψ

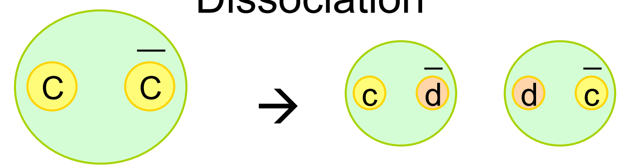
- |y|<2.4 and p_T > 6.5 GeV/c

ALICE: inclusive J/ψ

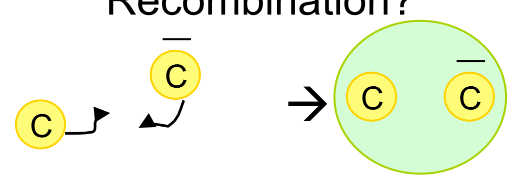
- |y|<0.9 and p_T> 0
- 2.5<|y|<4.0 and p_T> 0
- Includes ~10% non-prompt J/ψ from b decays



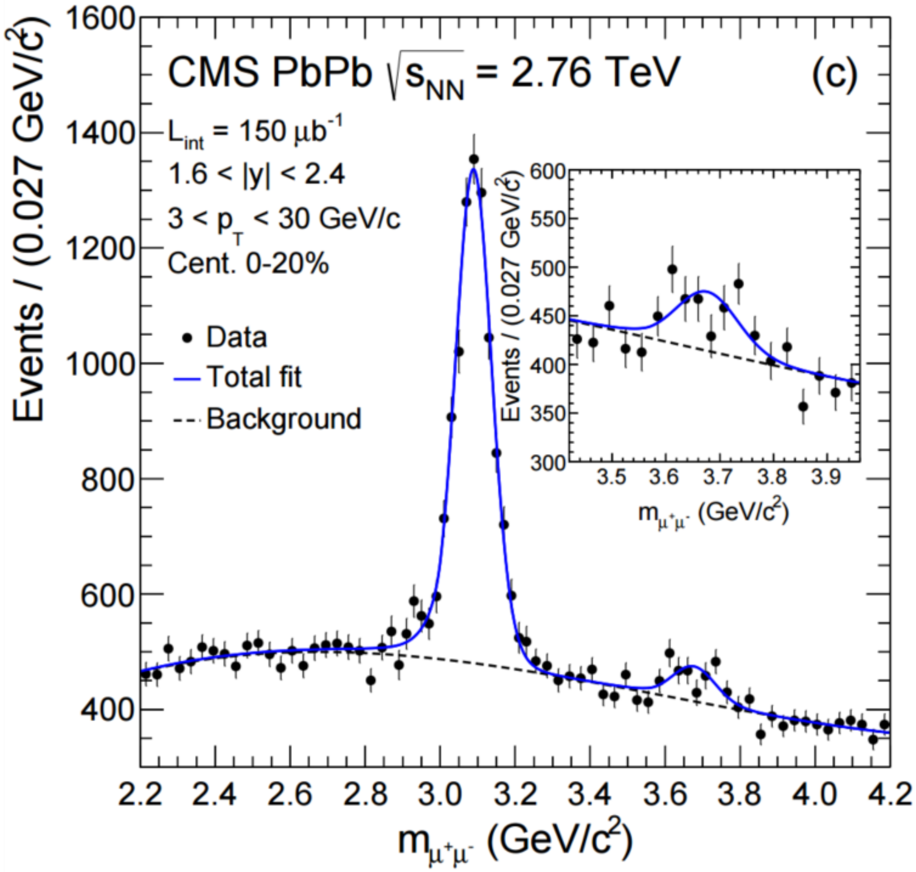
Dissociation

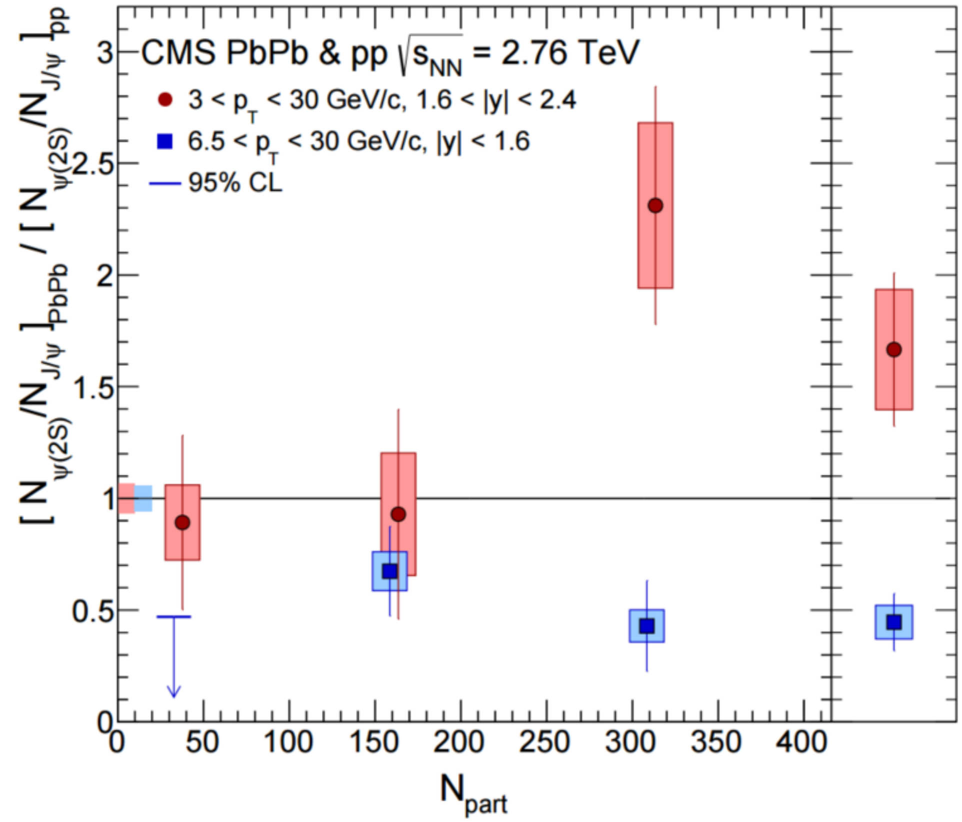


Recombination?



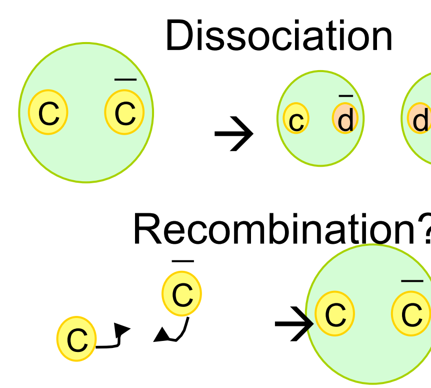
Ψ(2S) / J/Ψ Double Ratio





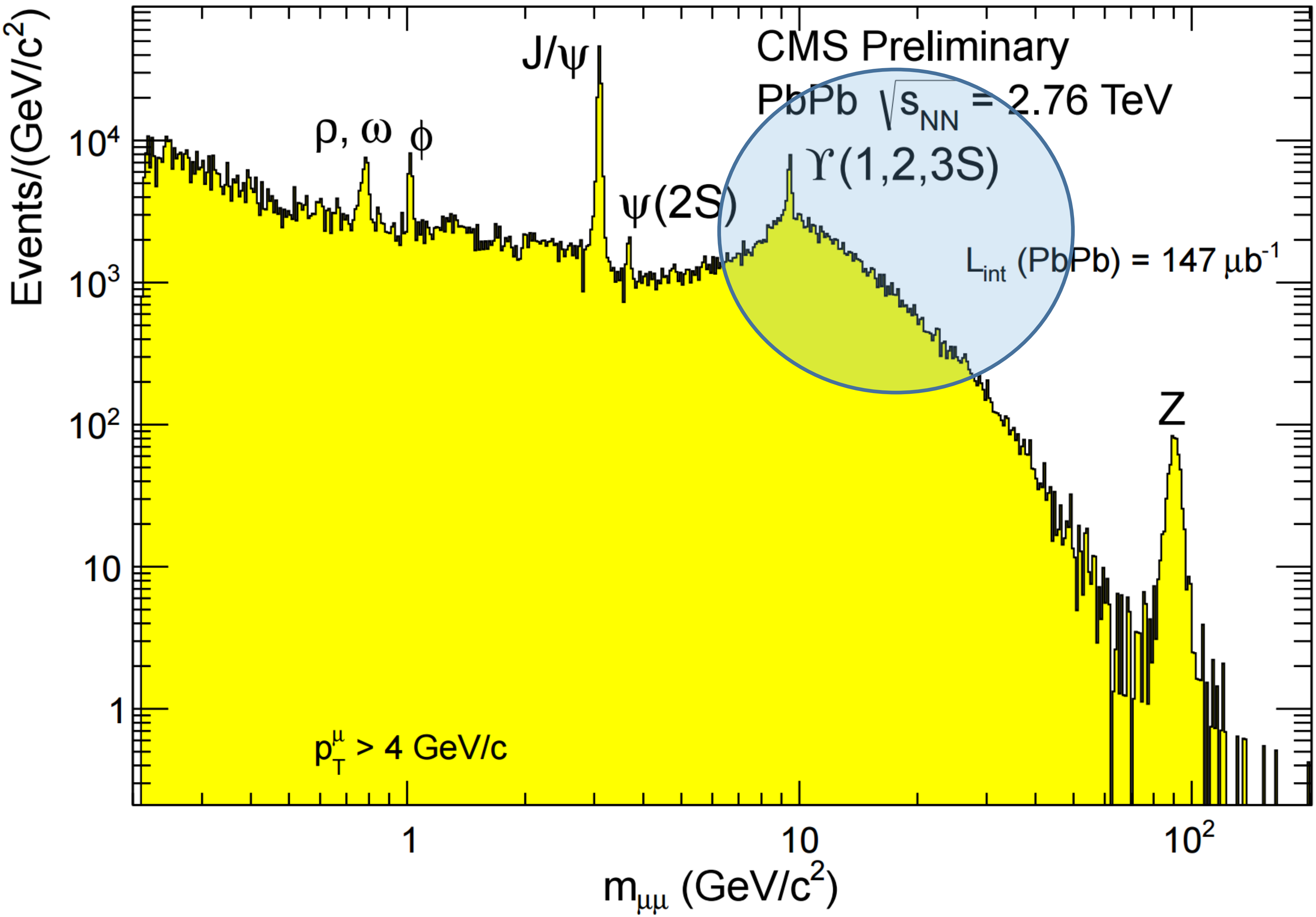
Double ratio $$\frac{\left(\frac{\psi(2S)}{J/\psi}\right)_{PbPb}}{\left(\frac{\psi(2S)}{J/\psi}\right)_{pp}}$$ >1

→ ψ(2S) is less suppressed compared to J/ψ in central PbPb collisions



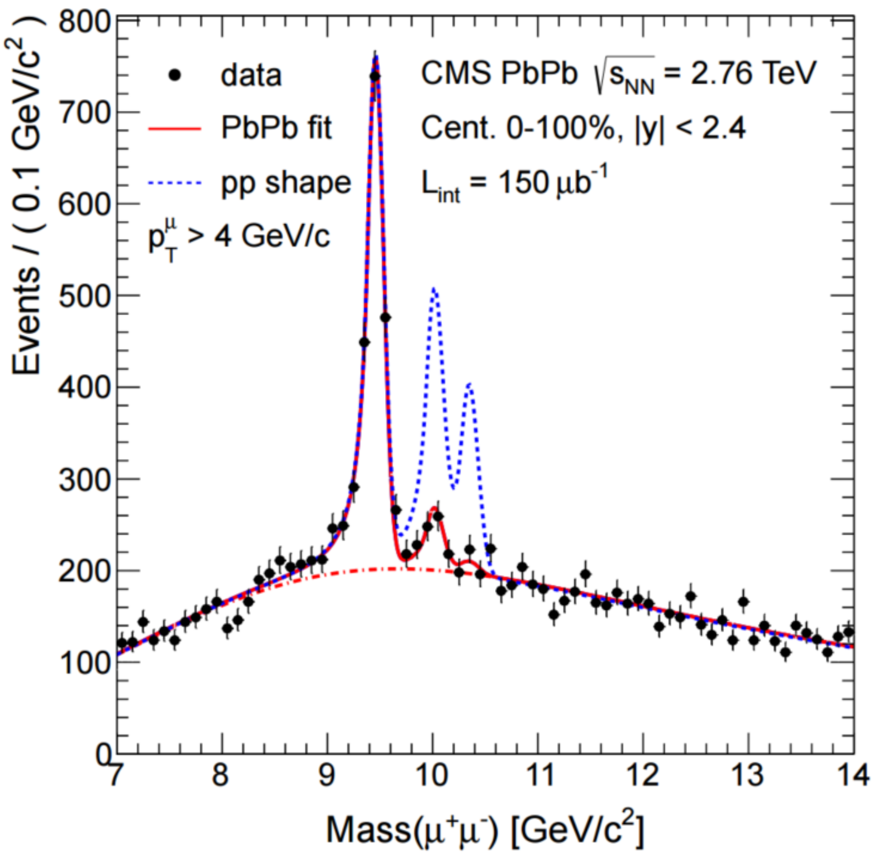
PRL 113 (2014) 262301

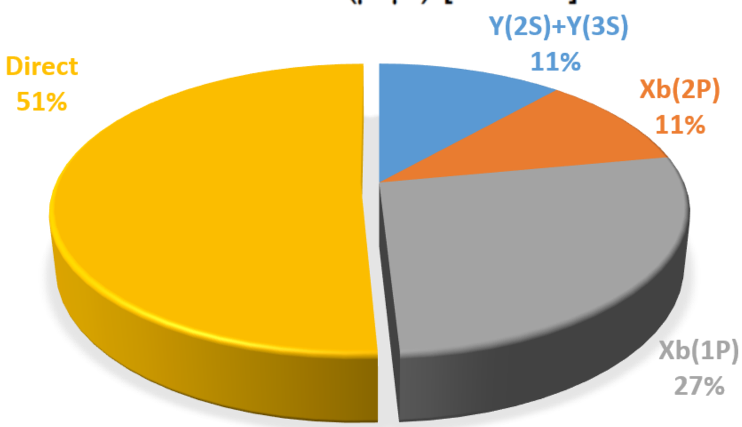
Quarkonia production: Dimuons

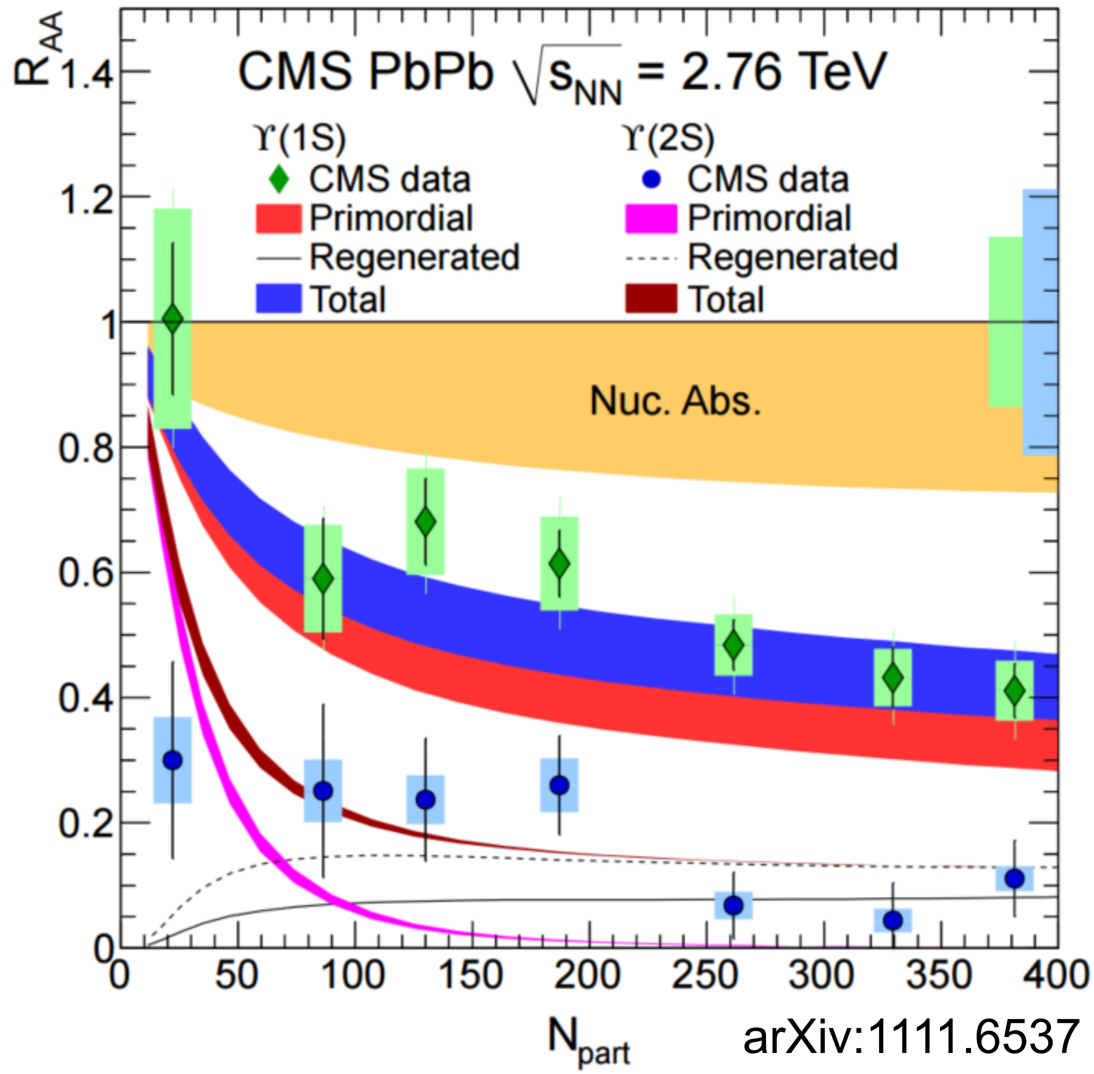


Upsilons in PbPb collisions

PRL 109 (2012) 222301

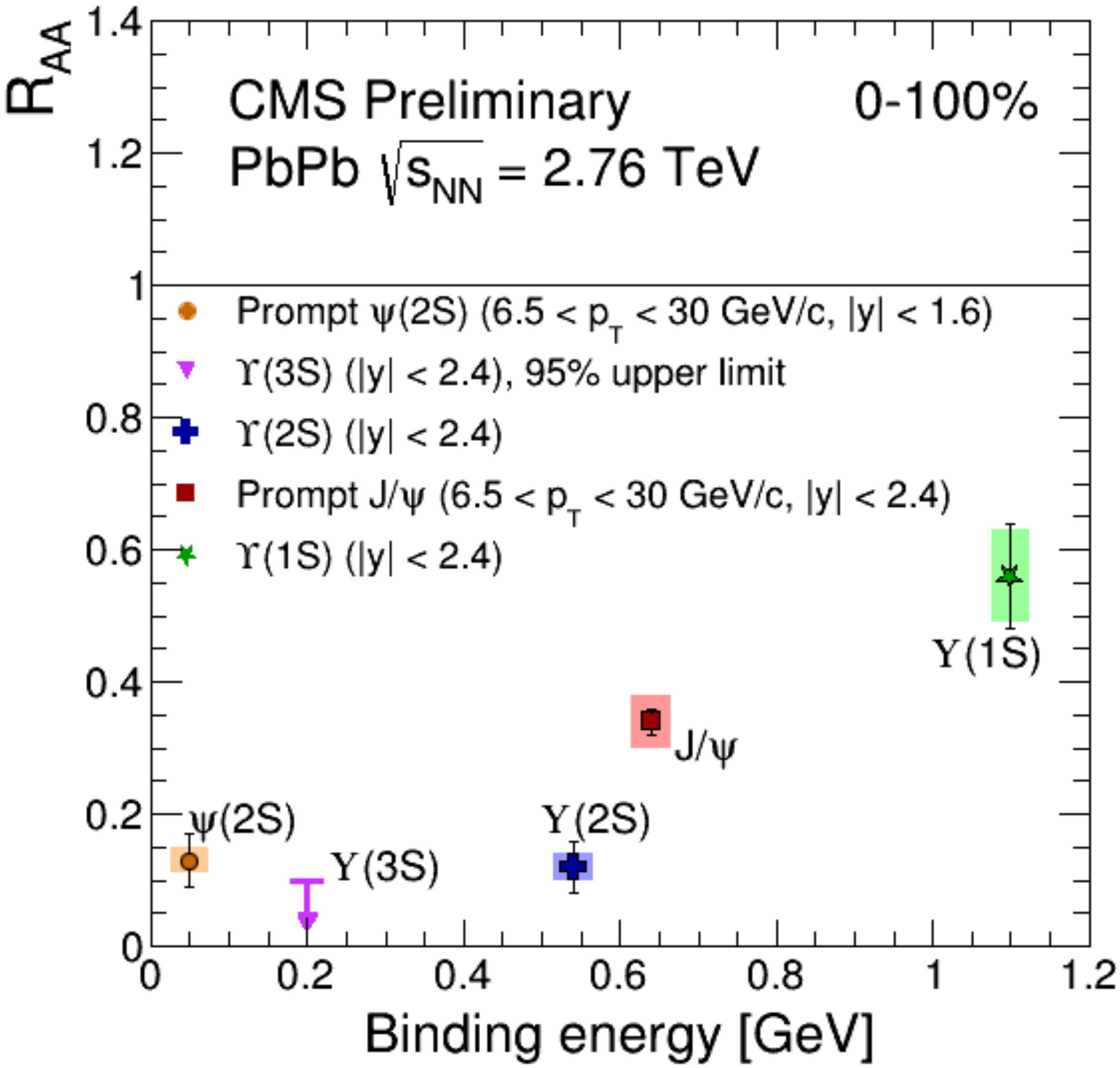




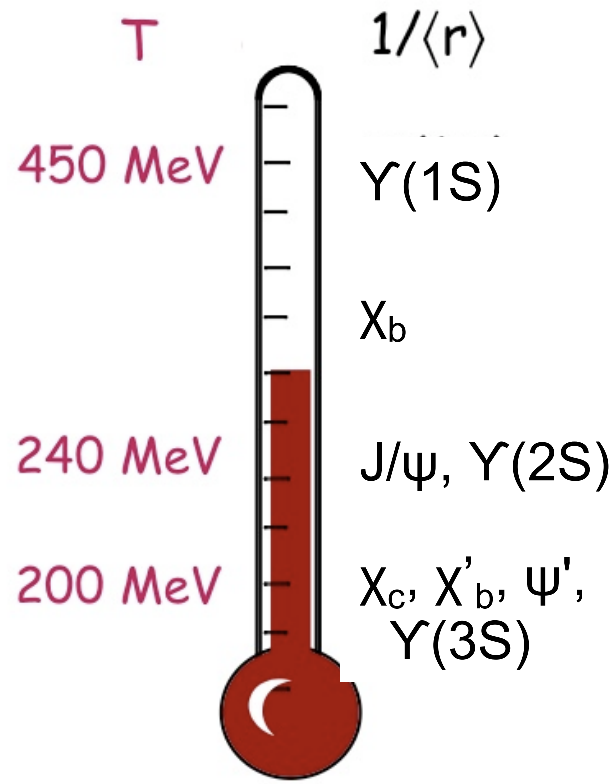


0-100% R_{AA} (Y(3S)) <0.1 (at 95% C.L)
Sequential suppression of the three states in order of their binding energy

Suppression of the five quarkonia in PbPb collisions

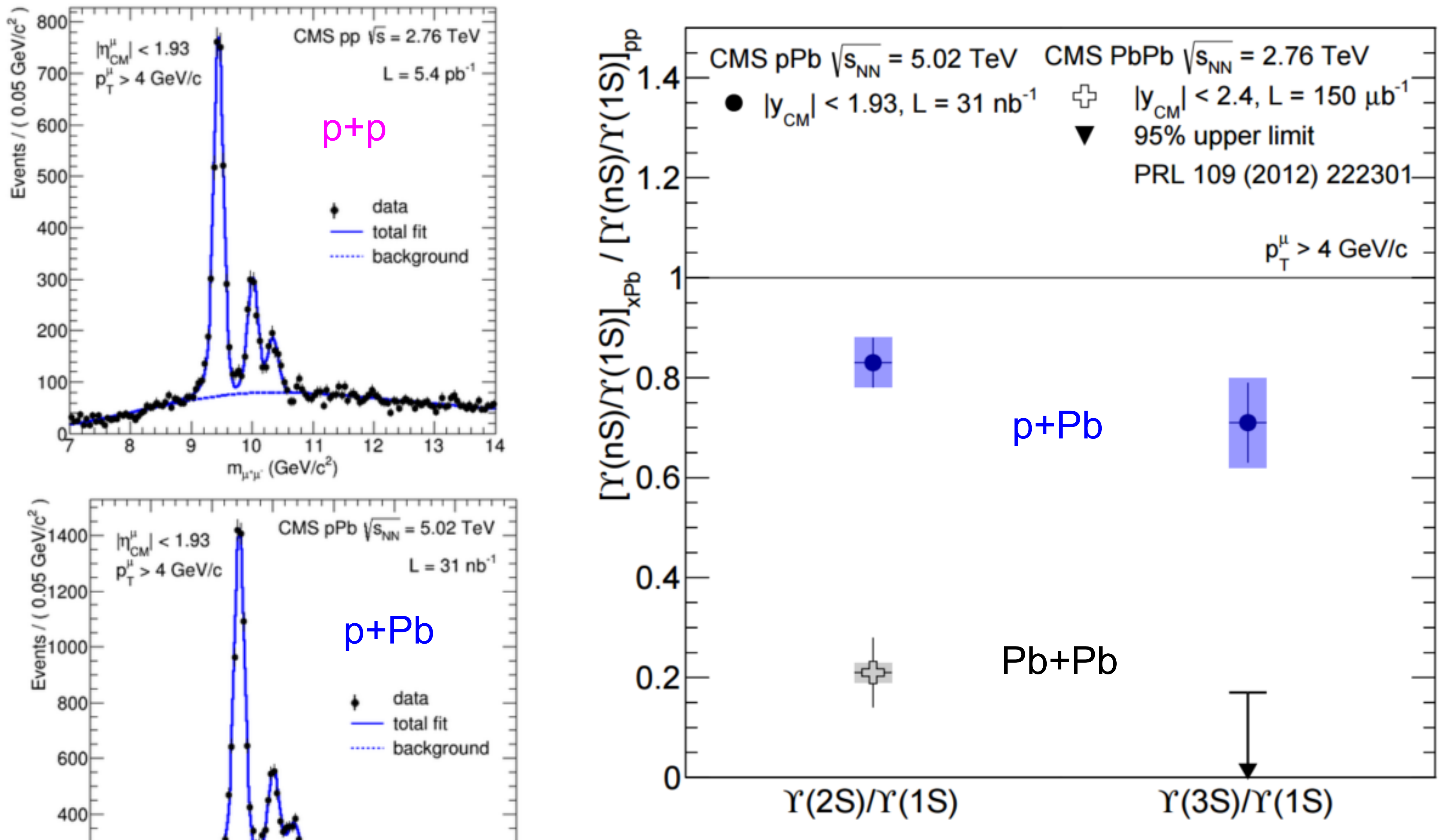


Matsui & Satz, PLB168 (1986) 415



Mocsy, EPJC61 (2009) 705

Upsilons in pp, pPb, and PbPb



Double ratios in pPb larger than in PbPb

→ Final state effects in PbPb

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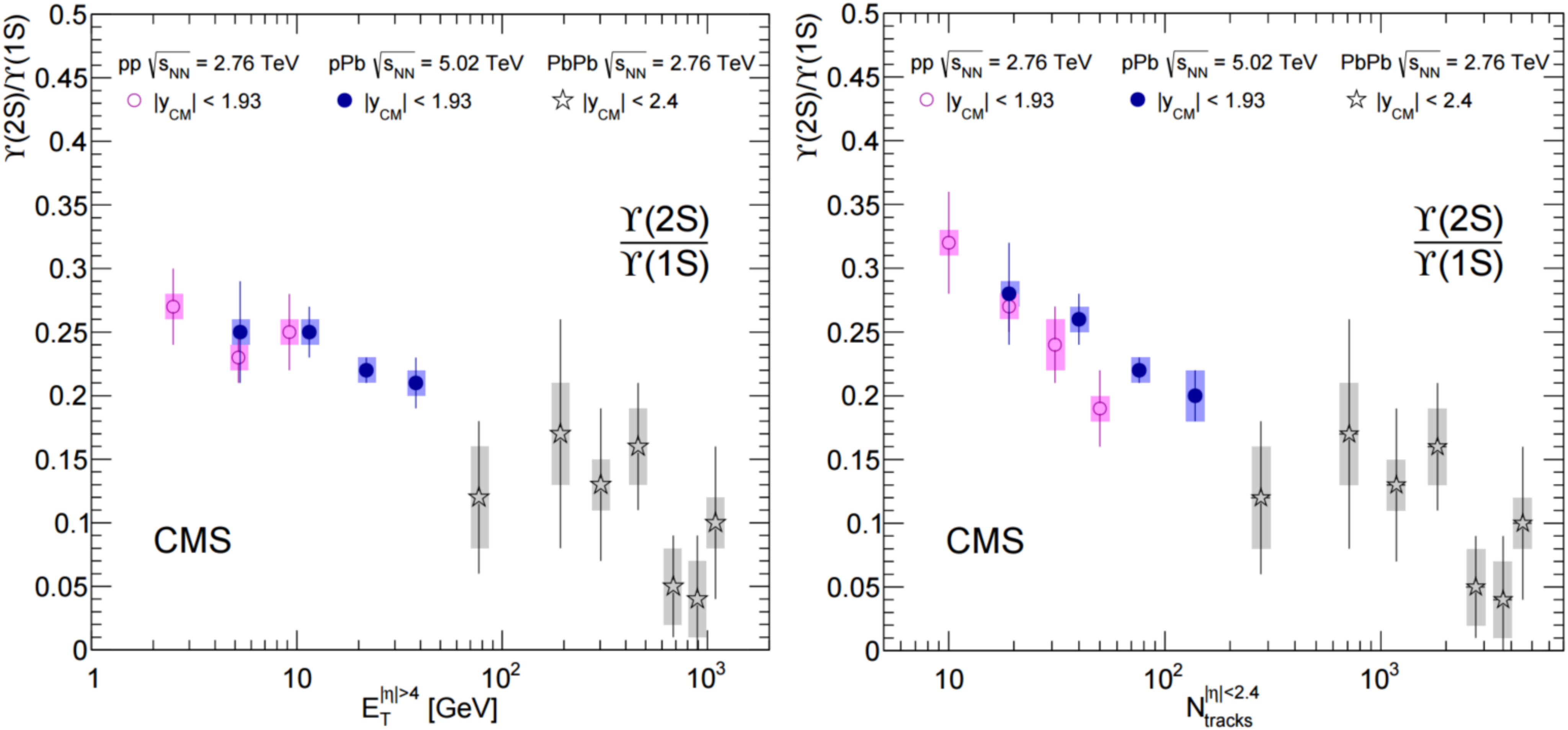
Υ(2S)/Υ(1S) ratios as a function of event activity

p+p p+Pb Pb+Pb

Vs. forward calorimeter transverse energy Vs. mid-rapidity track multiplicity



Υ(2S)/Υ(1S) ratio decreases as a function of event activity!

(1) More associated yield with Υ(1S)?

(2) Large event size (multiplicity) affects Υ states?

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Summary

- CMS experiment has collected extensive data in nuclear collisions: PbPb, pPb
- There is more to come soon at double energy and much larger luminosity at LHC
- I have shown examples of measurements that help us understand the behavior of the hot nuclear matter: jet quenching, melting of quarkonia.
- We are also gaining understanding of the structure of the nuclei by exploiting asymmetric pPb collisions