Quarkonia in Heavy-Ion Collisions at the LHC: a CMS perspective

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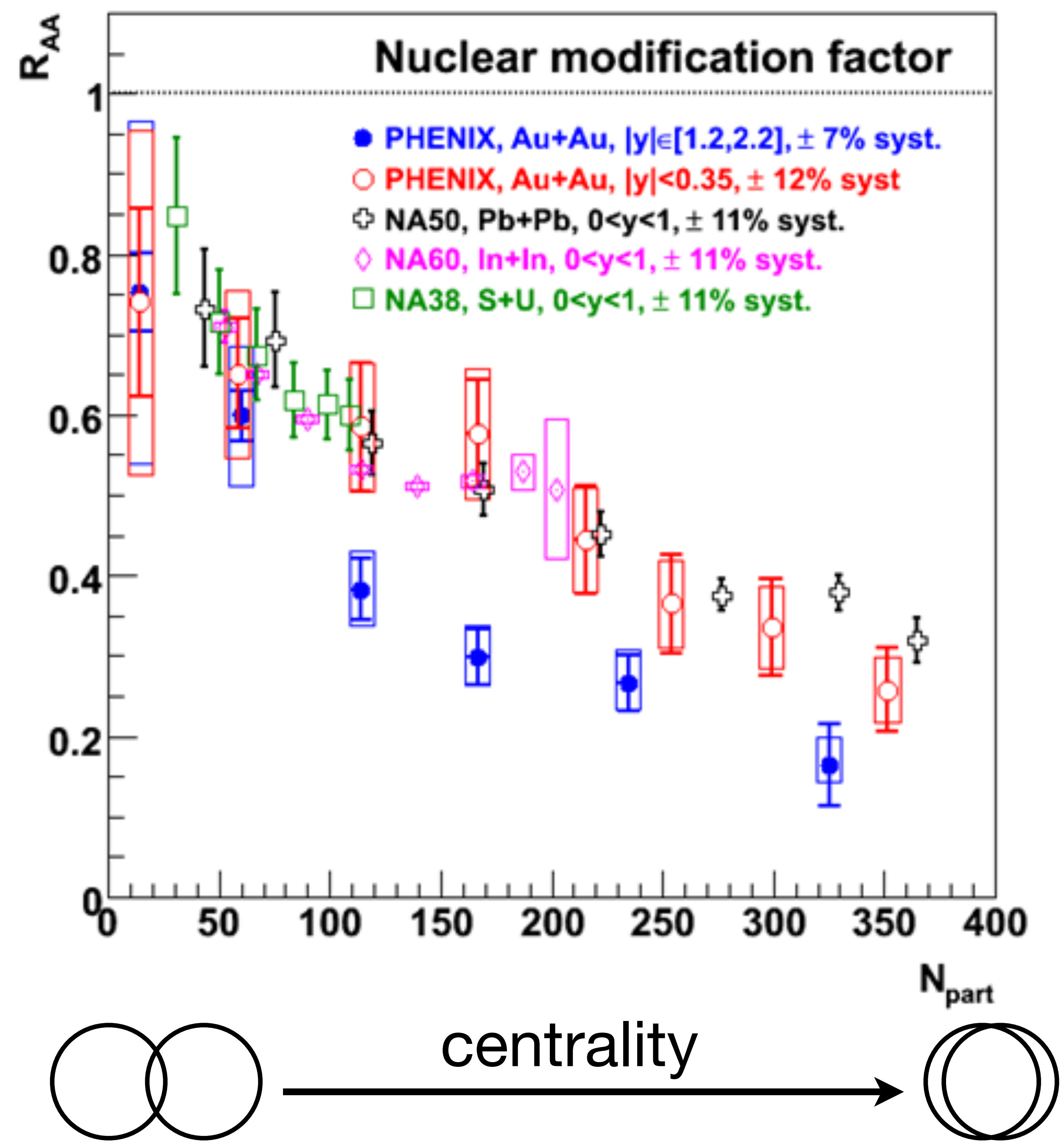
Excellence Cluster
Universe

Technische Universität München

Puzzles from SPS and RHIC

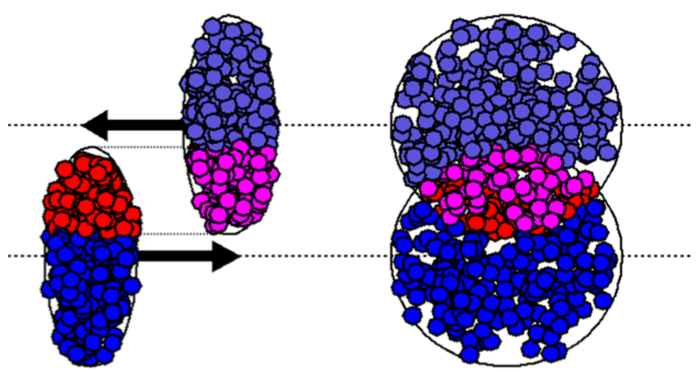
- Similar J/ψ suppression at the SPS and RHIC!
  - despite 10× higher $\sqrt{s_{NN}}$
- Suppression does not increase with local energy density
  - R_{AA}(forward) < R_{AA}(mid-rapidity)
- Possible ingredients
  - cold nuclear matter effects
  - sequential melting
  - (re)generation
- What happens at the LHC?
  - higher energy + higher luminosity
  - more charm (more regeneration?)
  - more bottom → a new probe: ϒ

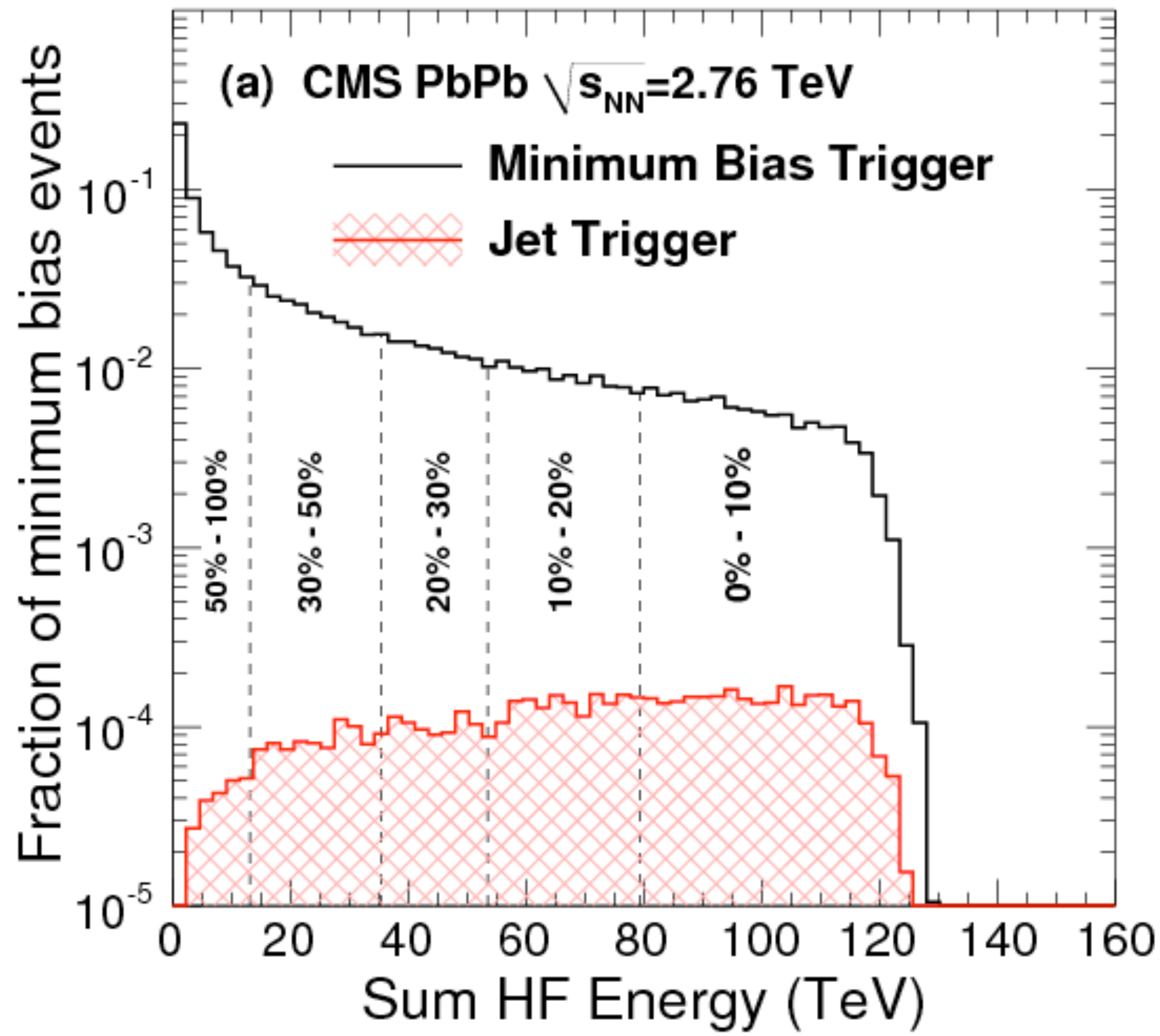
PHENIX, PRL 98 (2007) 232301
also PRC 84 (2011) 054912
SPS from Scomparin @ QM06



Heavy-Ion Collisions: Centrality

- Collision centrality (overlap of the nuclei) related to the energy deposit in forward calorimeters
- Then: relate to geometrical quantities with a Glauber MC model
  - N_{part} = number of participating nucleons





  - N_{coll} = number of binary collisions
  - Yield of hard probes is expected to scale with N_{coll} in absence of medium effect: R_{AA} = 1

$$R_{AA} = \frac{N_{\text{PbPb}}}{N_{\text{coll}} \cdot N_{pp}}$$

Defining "Suppression"

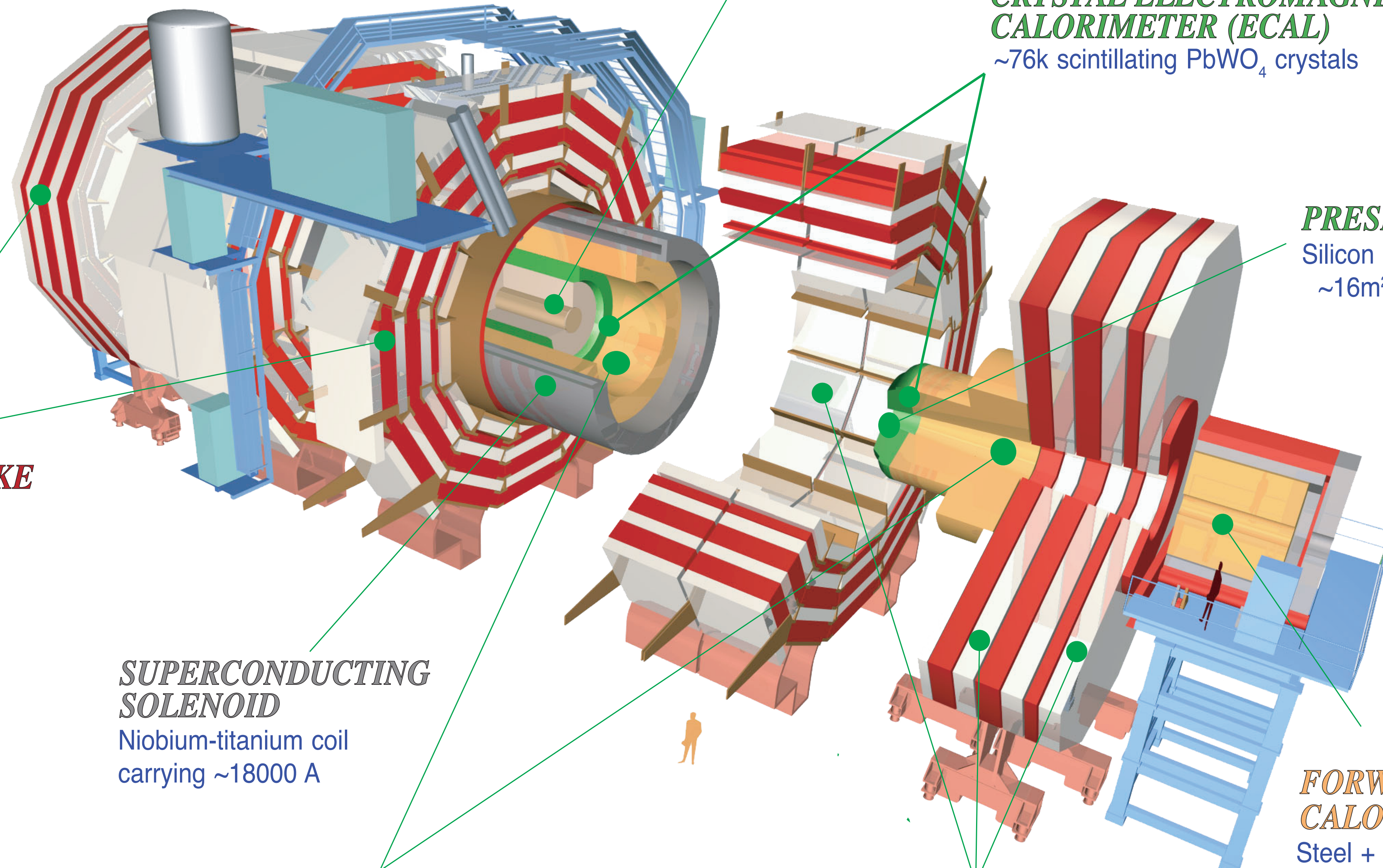
- pp (R_{AA}<1):
  - binary scaling holds for colourless probes (γ, $W^{\pm}$, Z)
  - easy to measure
  - does not distinguish between hot and cold nuclear matter (CNM) effects
- pA:
  - includes CNM effects
  - measure CNM effects by comparing pA to binary scaled pp (R_{pA})
  - but how to scale from pA to AA?
- Open heavy flavour (D and B mesons):
  - same production mechanism as quarkonia
    - shares the same initial state effects, including CNM
  - challenging to measure total cross section, i.e. at low p_T
  - how to compare vs. p_T?
- Later: interesting effects in all collision systems vs. event multiplicity
  - how to incorporate this into the reference?

The Large Hadron Collider

The Compact Muon Solenoid…

CMS Detector

Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons



SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals

PRESHOWER
Silicon strips
~16m² ~137k channels

STEEL RETURN YOKE
~13000 tonnes

SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A

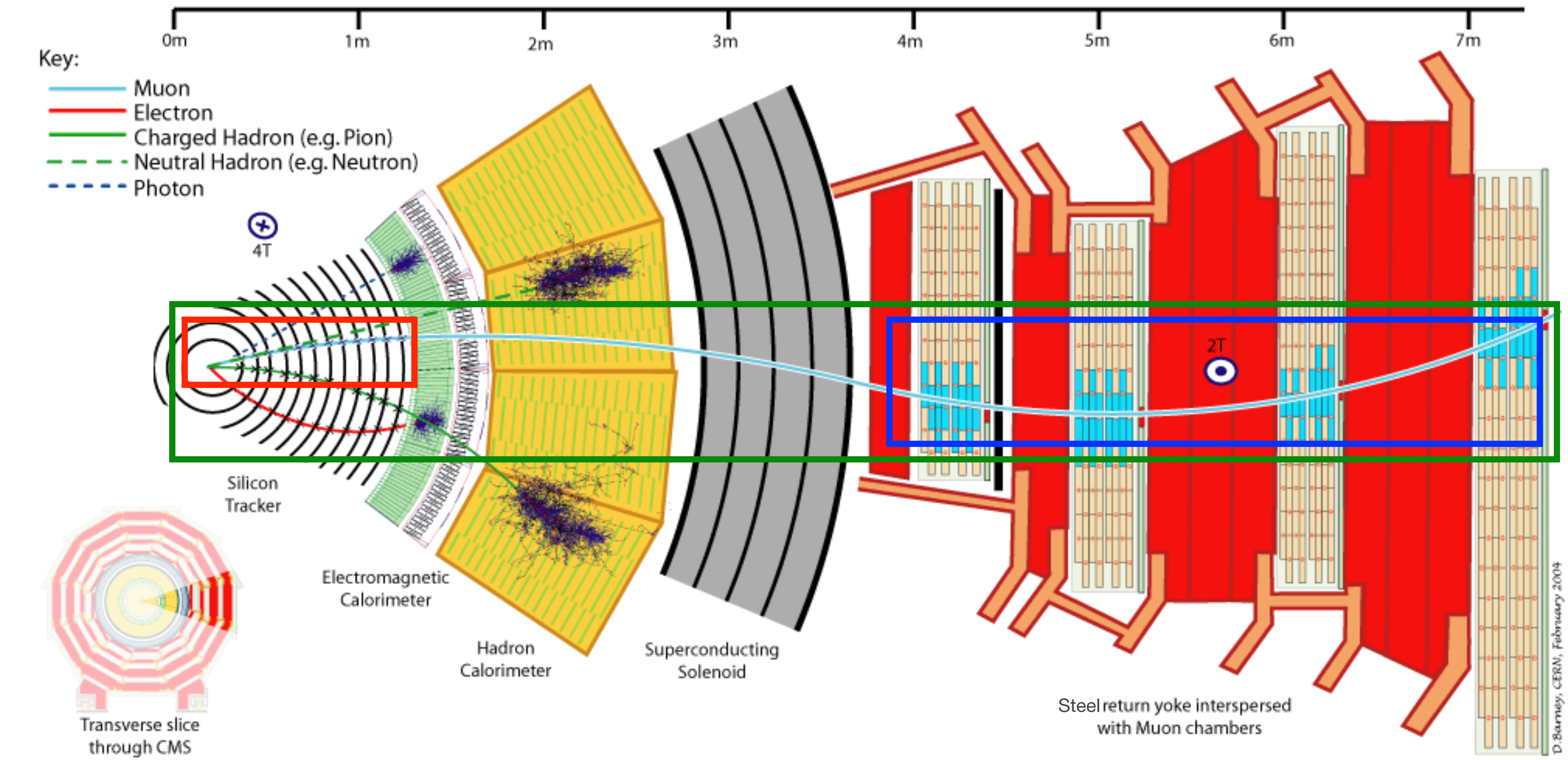
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels

FORWARD CALORIMETER
Steel + quartz fibres
~2k channels

MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers

Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

Muon reconstruction in CMS

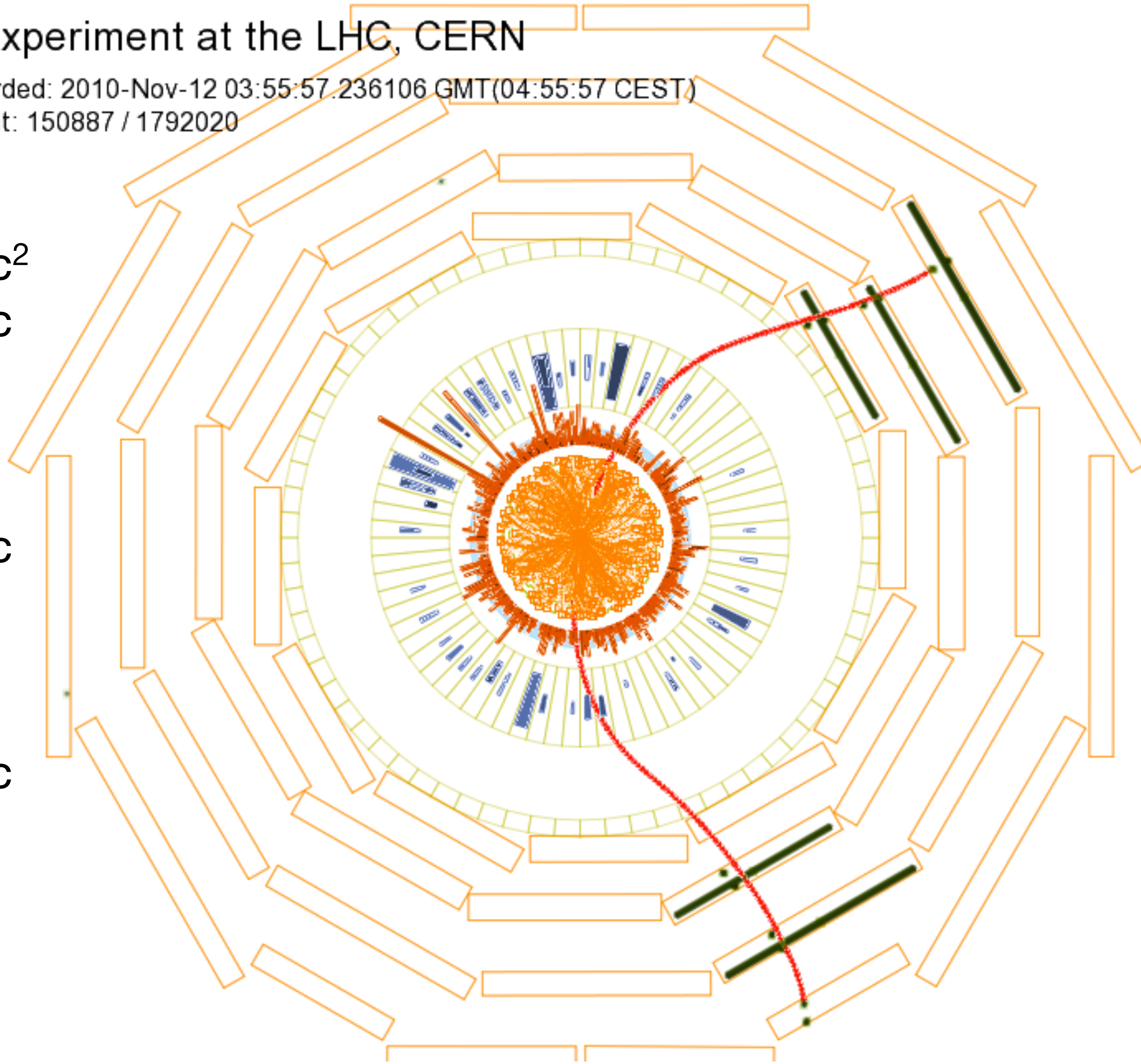


- Global muons reconstructed by combining inner tracker and muon stations
- Further muon ID based on track quality (χ^2, # hits…)

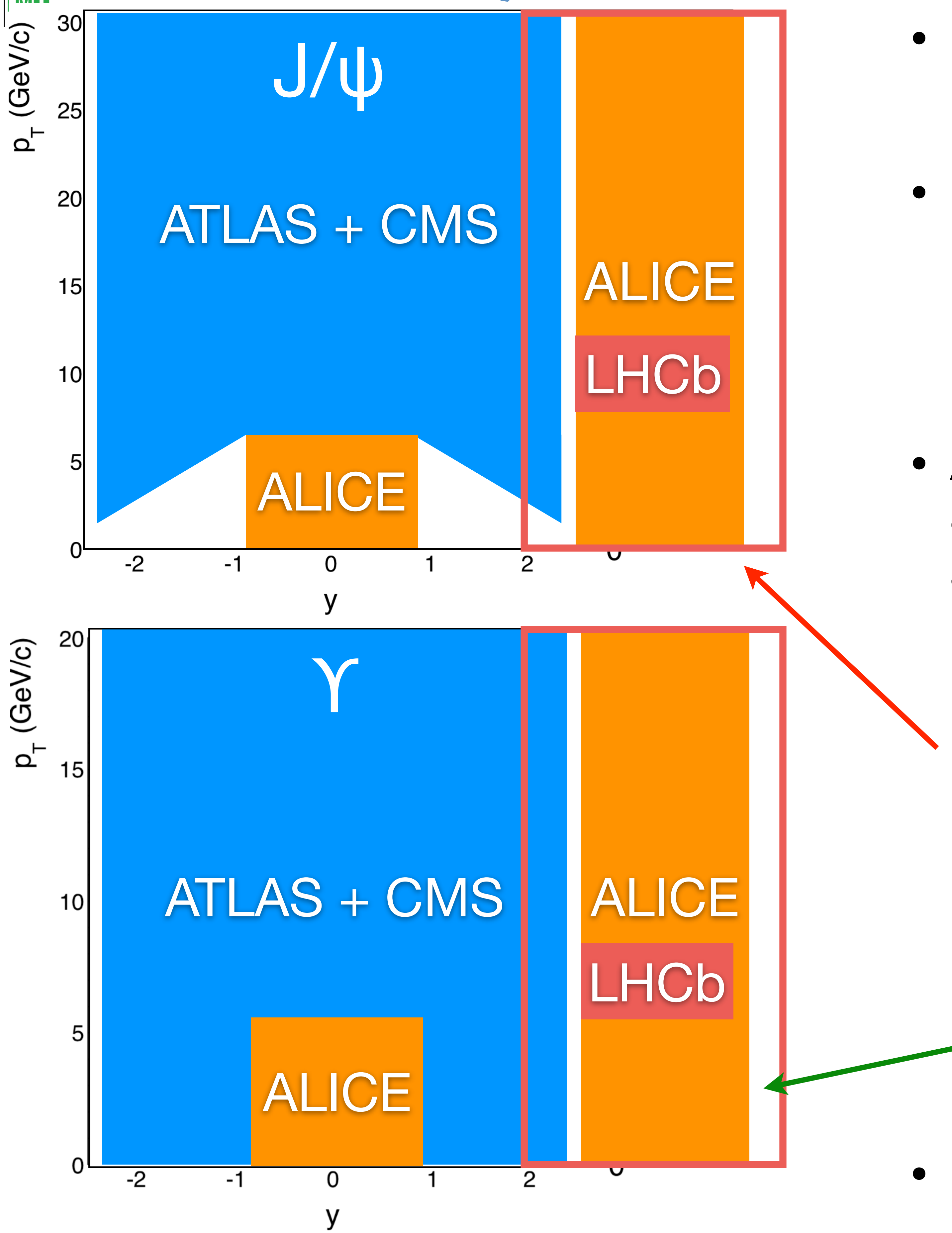
$\mu^+\mu^-$ pair:
mass: 9.46 GeV/c^2
p_T: 0.06 GeV/c
rapidity: –0.33

μ^+:
p_T = 4.74 GeV/c
η = –0.39

μ^-:
p_T = 4.70 GeV/c
η = –0.28

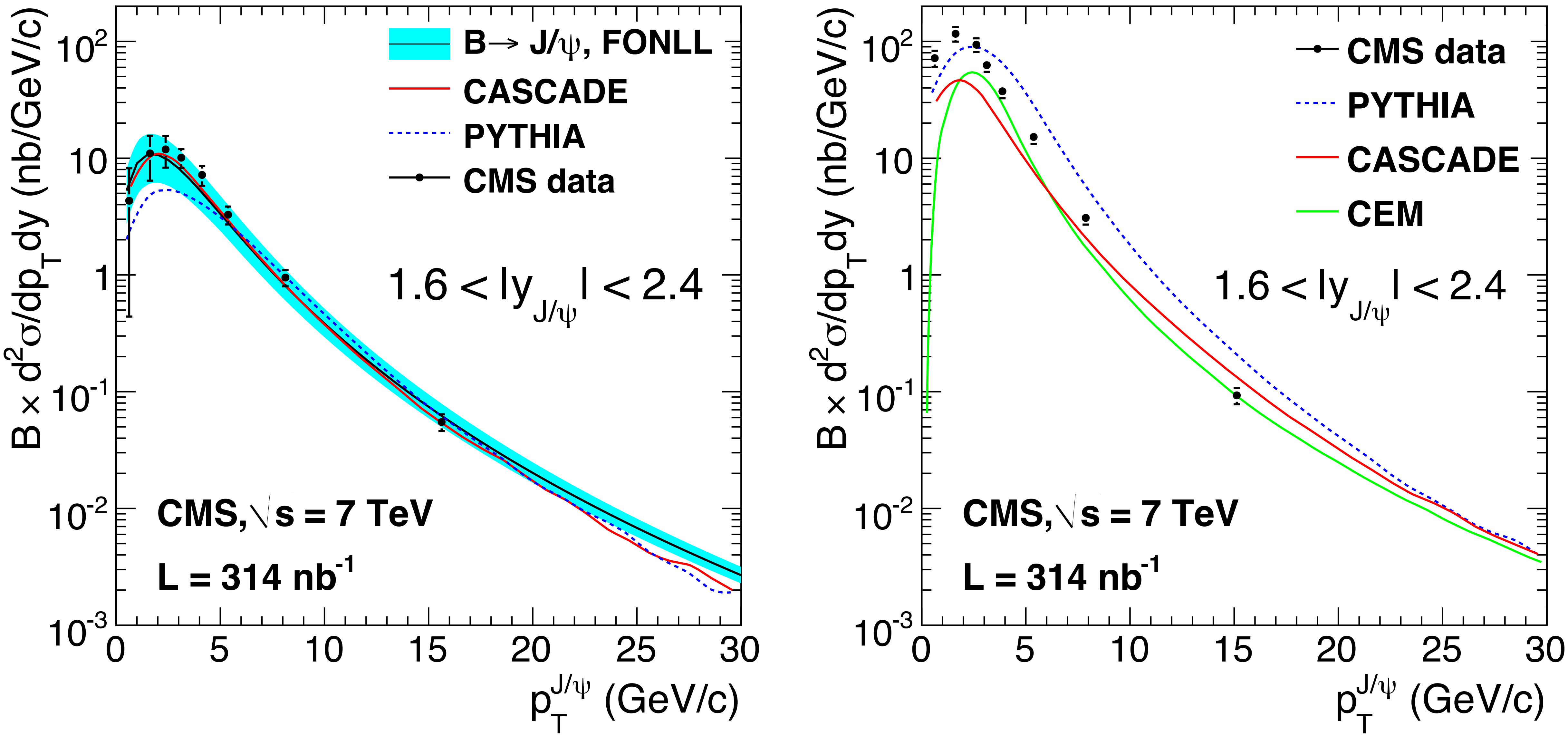


Quarkonia Acceptance



- LHCb: acceptance for $p_T > 0$
  - forward rapidity: longitudinal boost
- ALICE: acceptance for $p_T > 0$
  - mid-rapidity: no absorber and low magnetic field
  - forward rapidity: longitudinal boost
- ATLAS and CMS: Muons need to overcome strong magnetic field and energy loss in the absorber
  - minimum total momentum p~3–5 GeV/c to reach the muon stations
  - Limits J/ψ acceptance (in PbPb):
    - mid-rapidity: $p_T > 6.5$ GeV/c
    - forward rapidity: $p_T > 3$ GeV/c
    - (values for CMS, but similar for ATLAS)
  - Υ acceptance:
    - $p_T > 0$ GeV/c for all rapidity
- Complementary acceptances

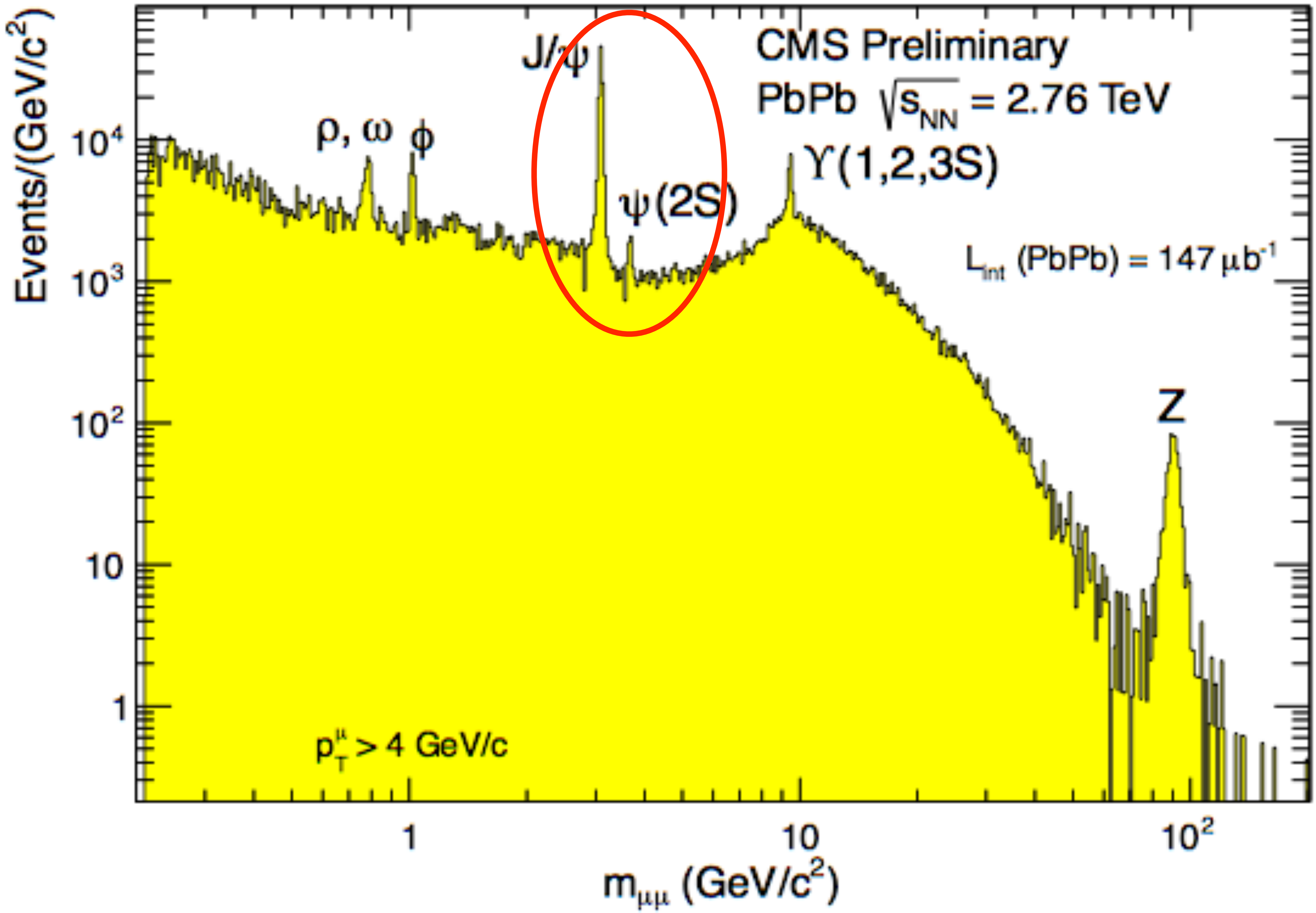
Reminder: J/ψ in pp at √s = 7 TeV



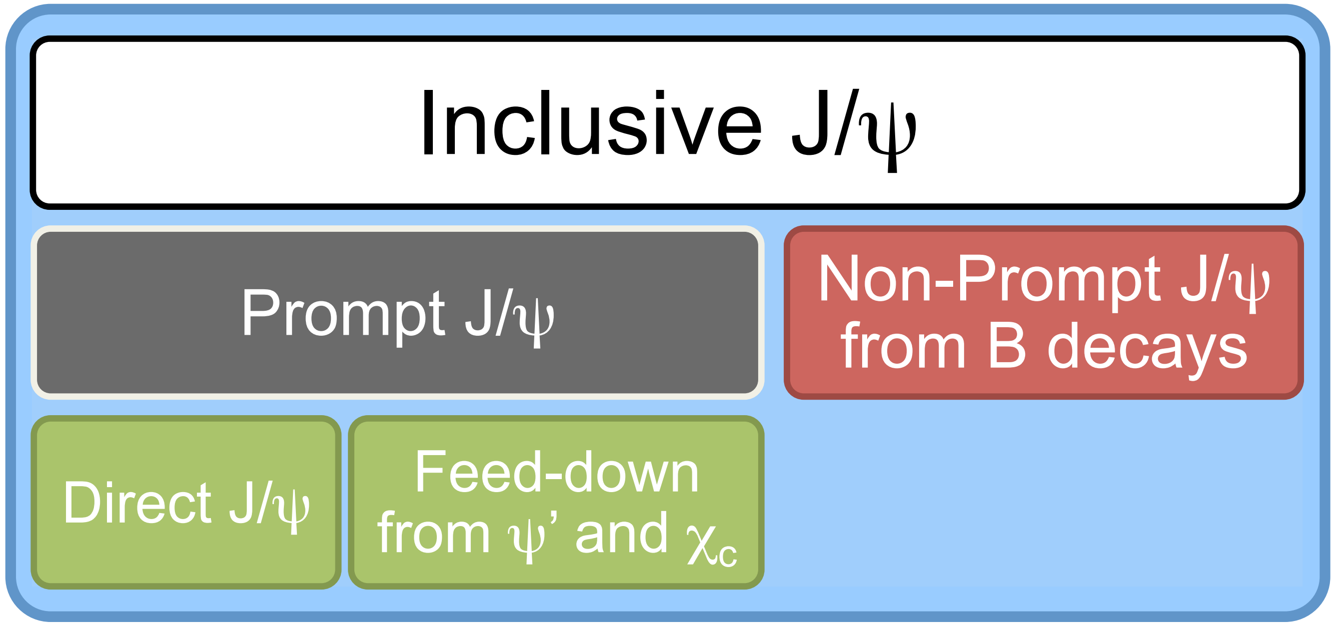
- Prompt and non-prompt J/ψ cross sections measured down to $p_T = 0$ in 1.6<|y|<2.4
- Less stringent muon ID than in PbPb thanks due to lower background rate

CMS BPH-10-002
Eur. Phys. J. C71 (2011) 1575

Muon Pairs in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

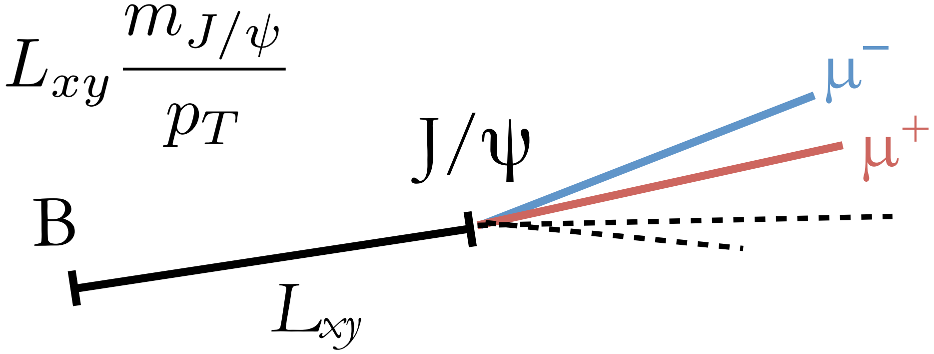


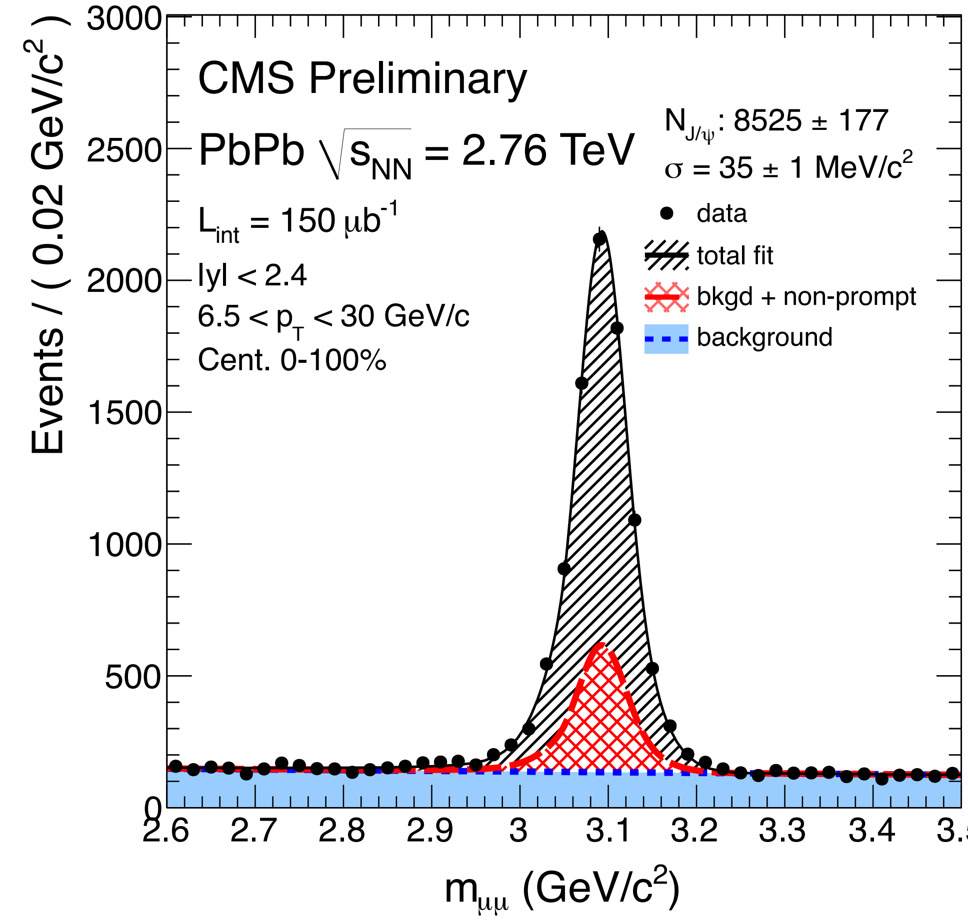
J/ψ in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

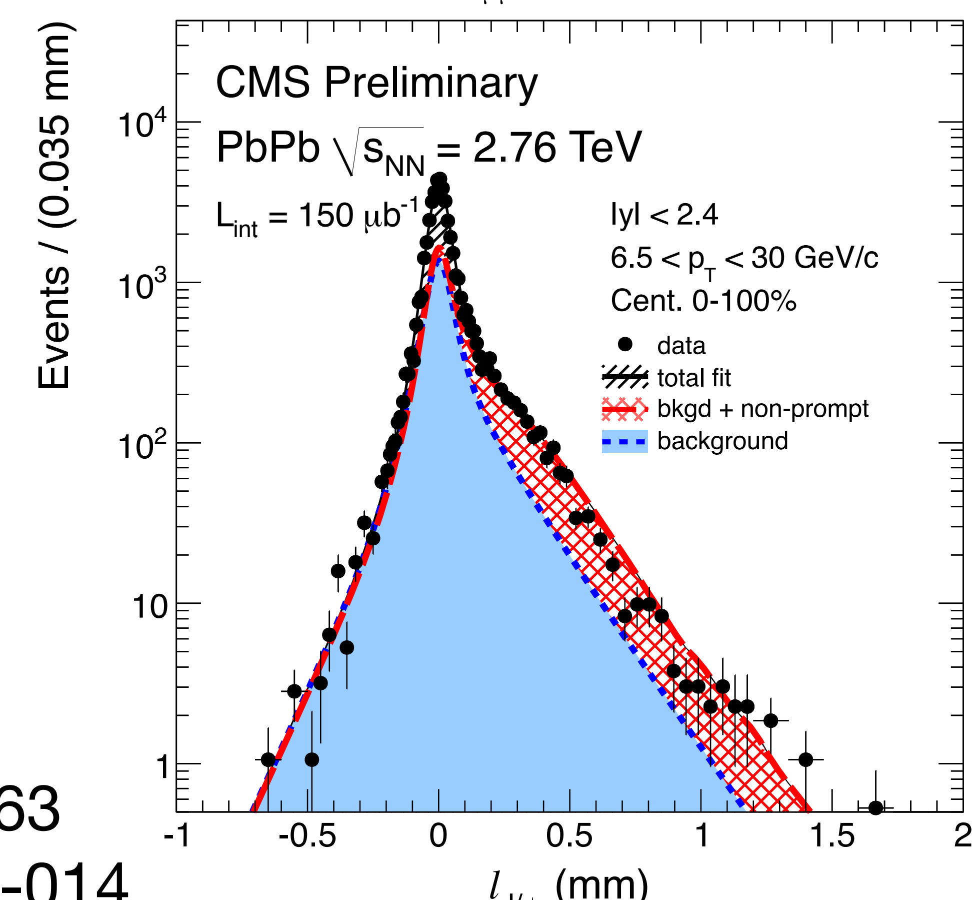


- Non-prompt J/ψ become significant towards higher p_T: 20–30%
- Reconstruct $\mu^+\mu^-$ vertex
- Simultaneous fit of $\mu^+\mu^-$ mass and pseudo-proper decay length

$$\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$

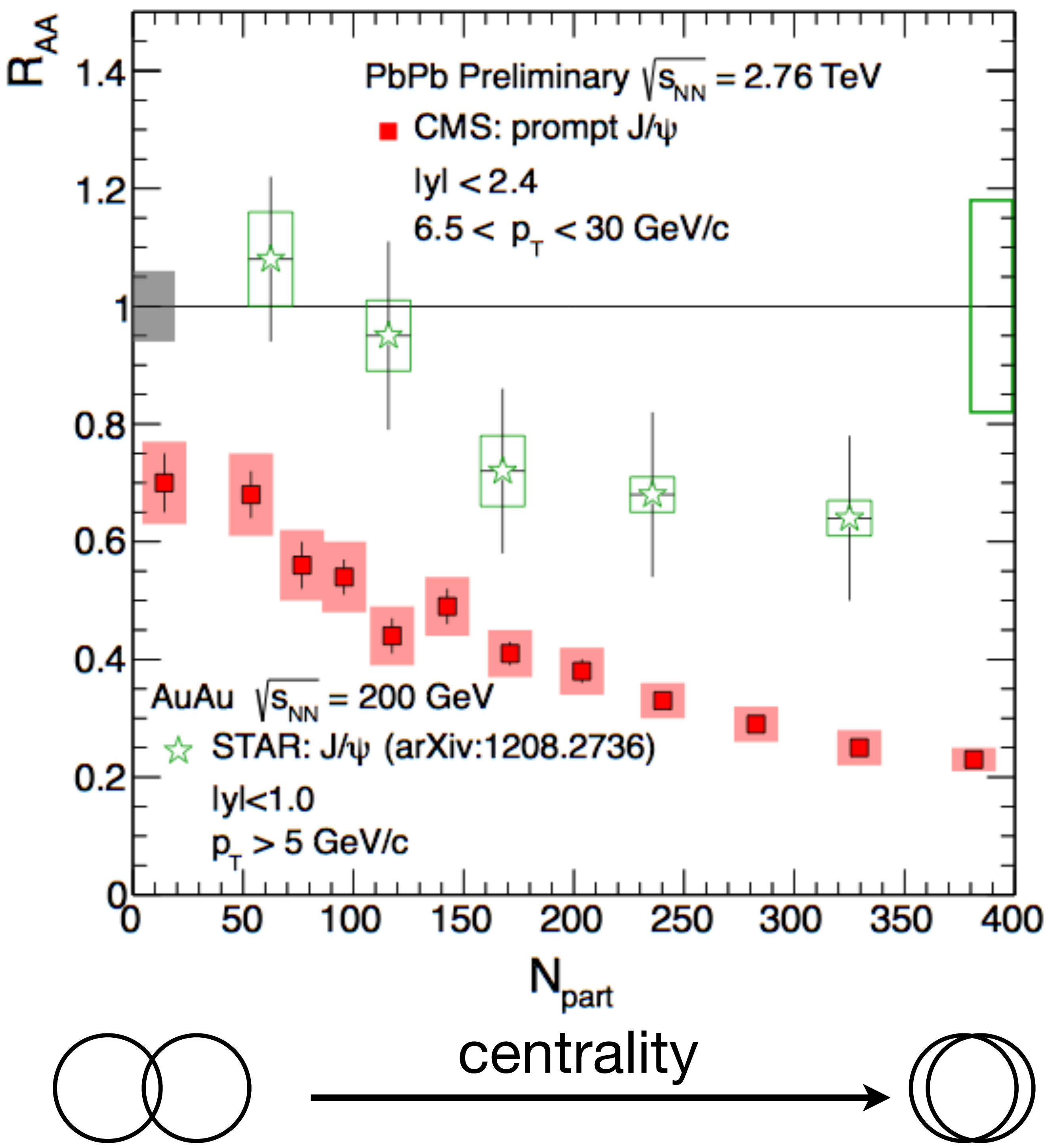






2010 data: JHEP 05 (2012) 063
2011 data: CMS PAS HIN-12-014

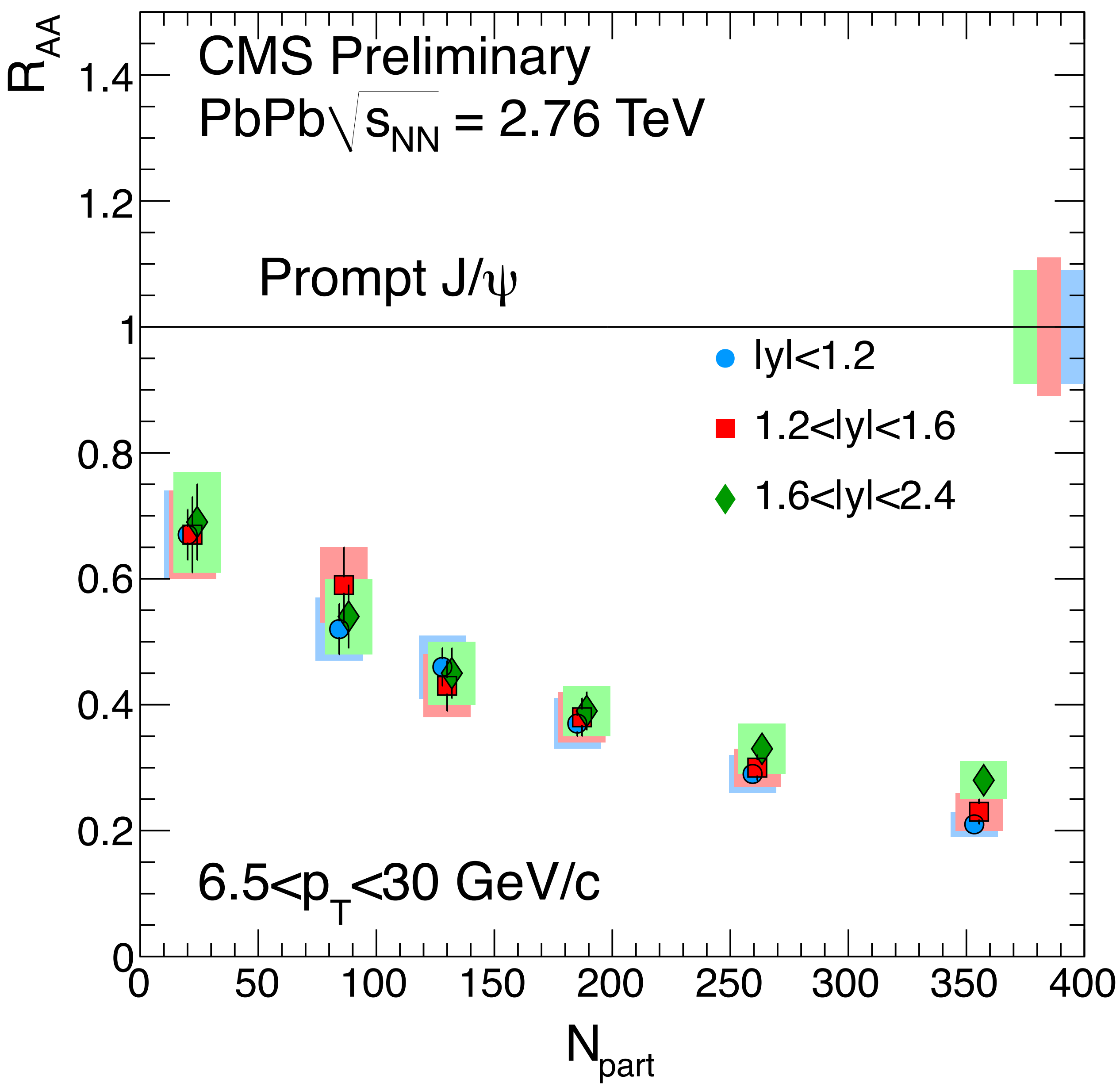
Prompt J/ψ at high p_T: RHIC - LHC

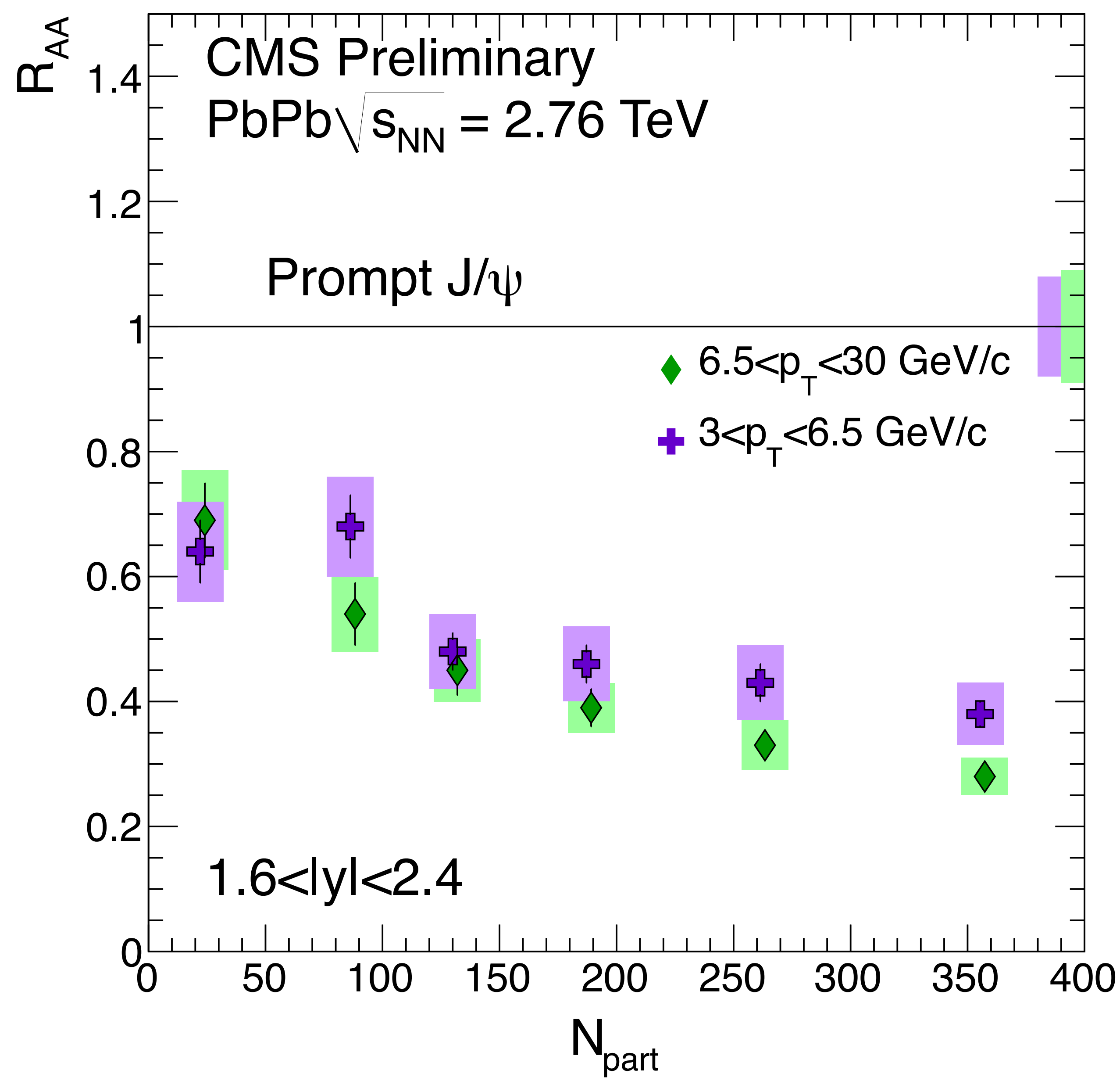


- CMS: Prompt J/ψ
  - p_T > 6.5 GeV/c & |y| < 2.4
  - in 0–5% centrality: suppressed by a factor 5
  - in 60–100% centrality: suppressed by a factor ~1.4
- STAR: inclusive J/ψ
  - p_T > 5 GeV/c & |y| < 1
  - less suppression at RHIC than at the LHC

CMS PAS HIN-12-014

Prompt J/ψ R_{AA}: double differential



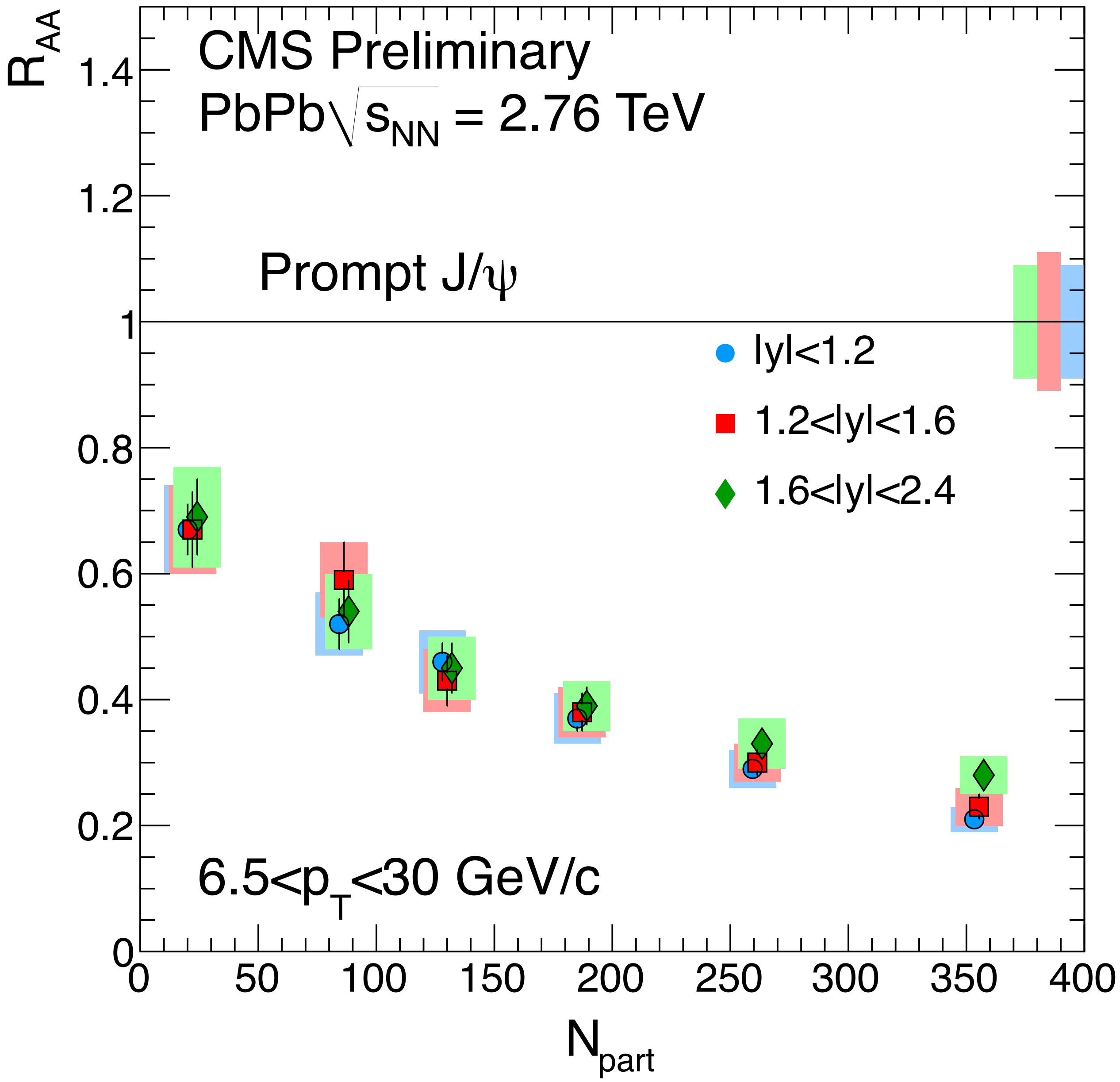


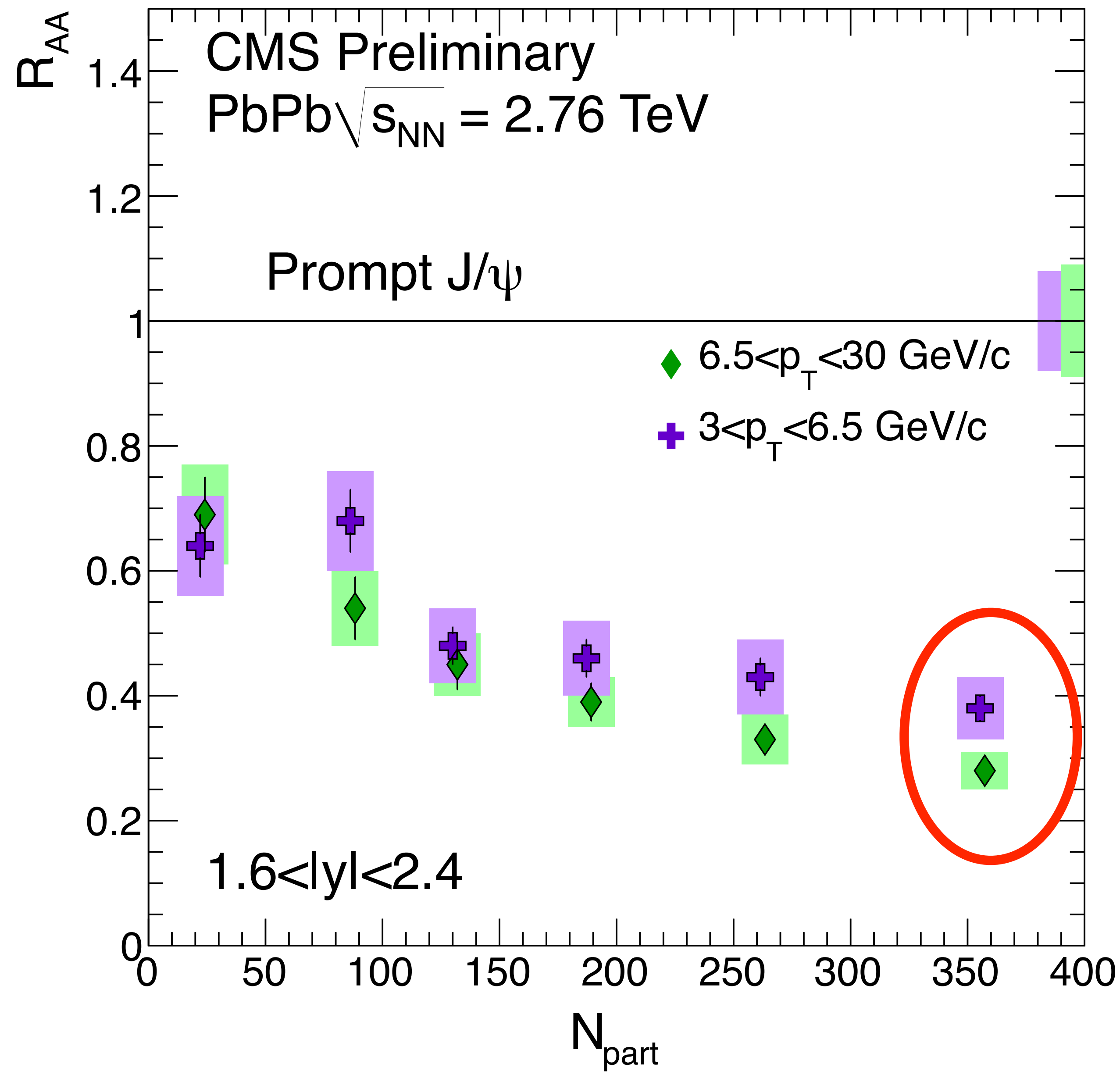
- Centrality dependence is independent of rapidity

CMS PAS HIN-12-014

- At forward rapidity: access to lower p_T ($3 < p_T < 6.5$ GeV/c)
  - slightly less suppression in most central collision at low p_T than at high p_T

Prompt J/ψ R_{AA}: double differential





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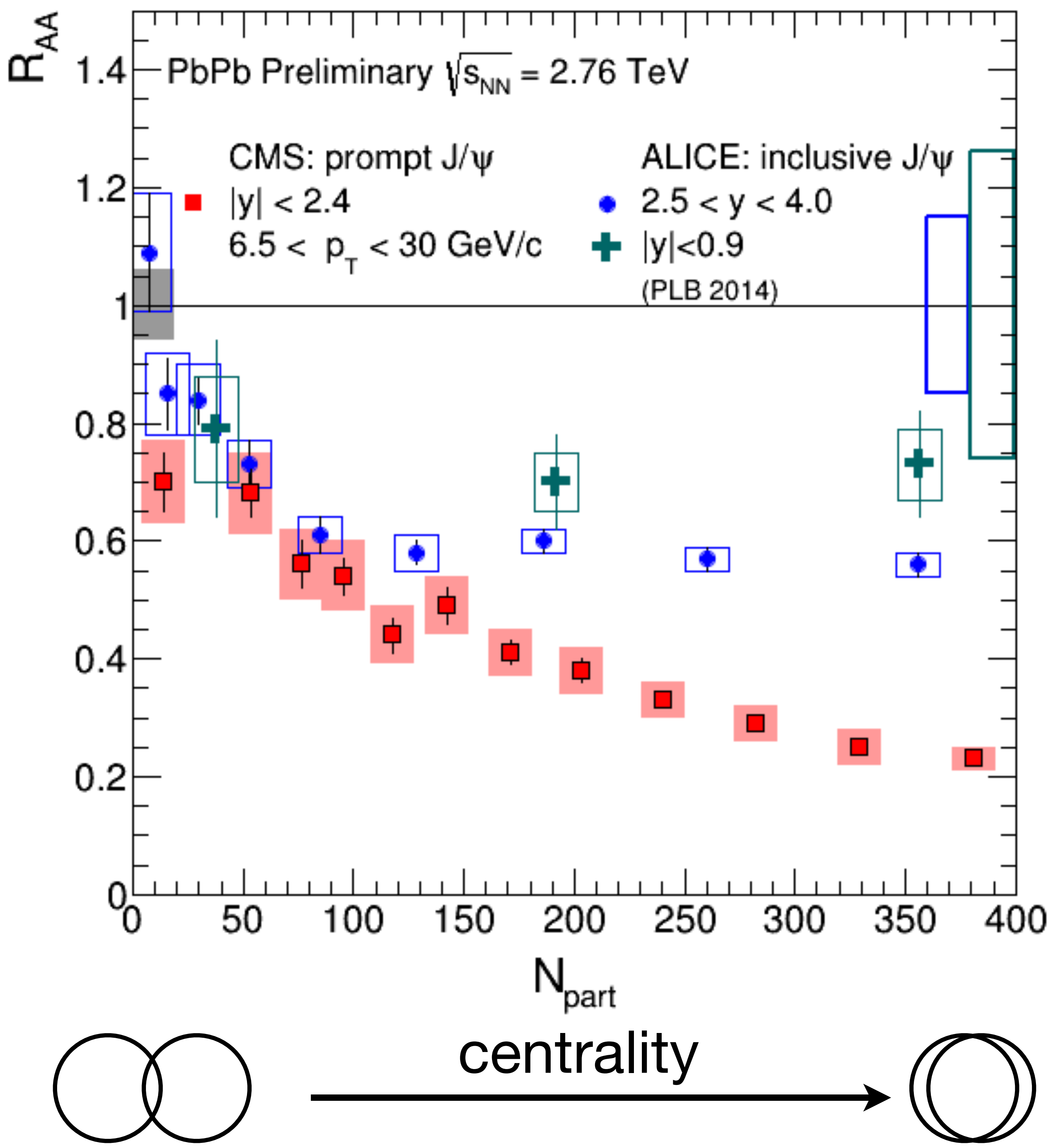
J/ψ vs. centrality: CMS - ALICE



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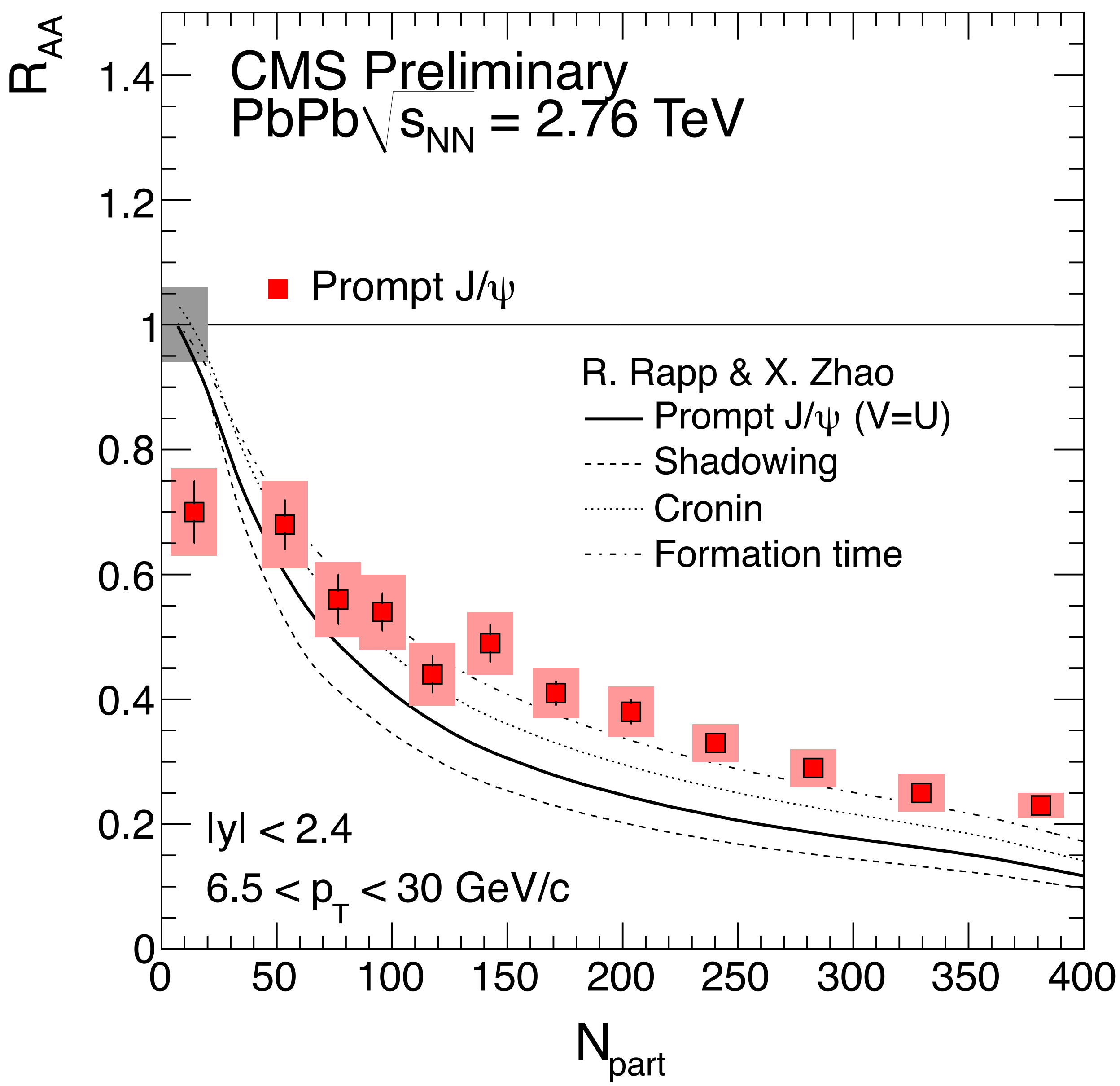
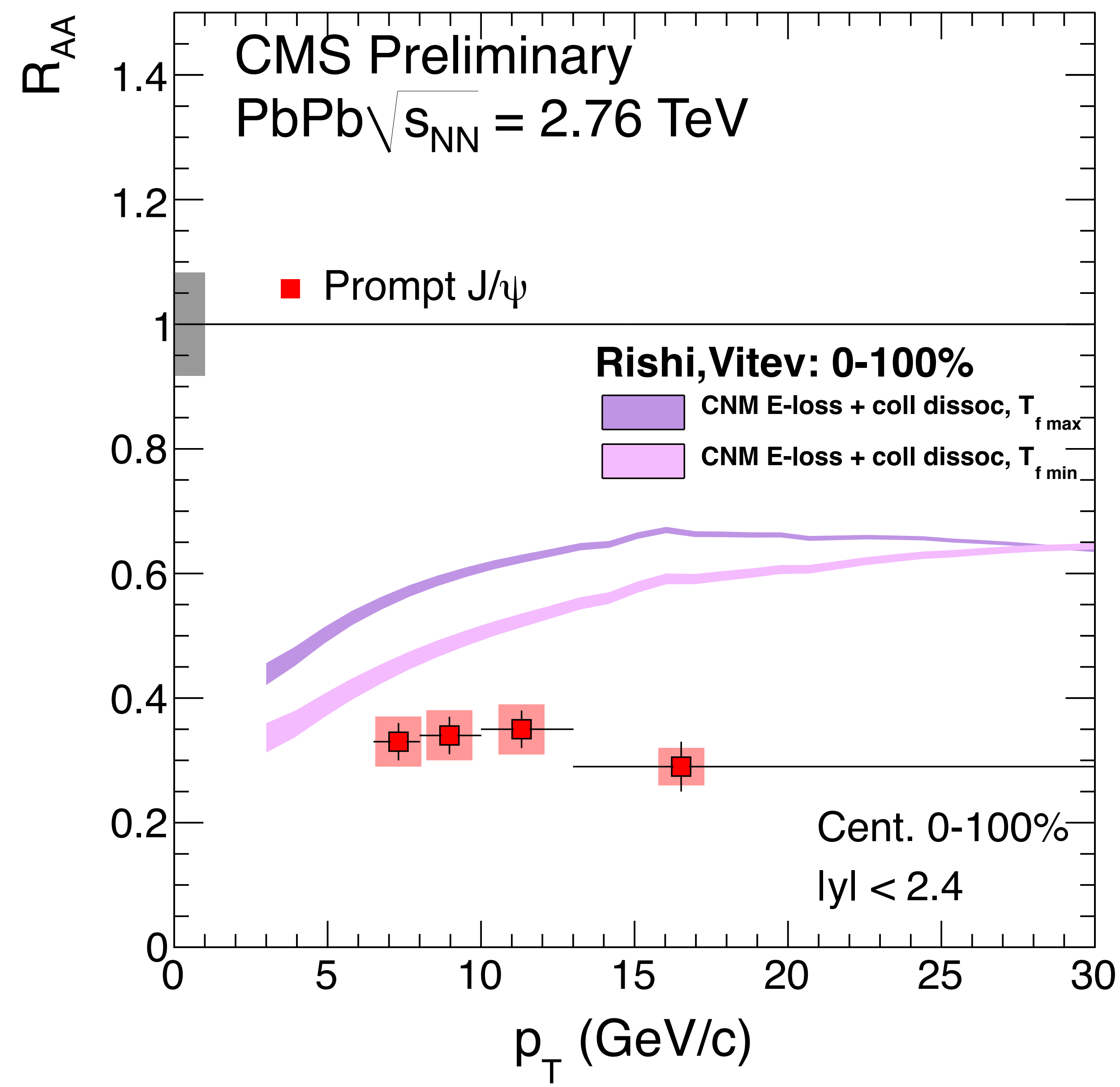
  - p_T > 6.5 GeV/c & |y| < 2.4
  - in 0–5% centrality: suppressed by a factor 5
  - in 60–100% centrality: suppressed by a factor ~1.4
- ALICE: inclusive J/ψ (p_T > 0)
  - less suppression at low p_T, both at mid- and forward rapidity
  - includes ~10% b-fraction

CMS PAS HIN-12-014
ALICE PLB 743 (2014) 314

Prompt J/ψ: Theory meets Experiment



NPA 859 (2011) 114
+ private communication

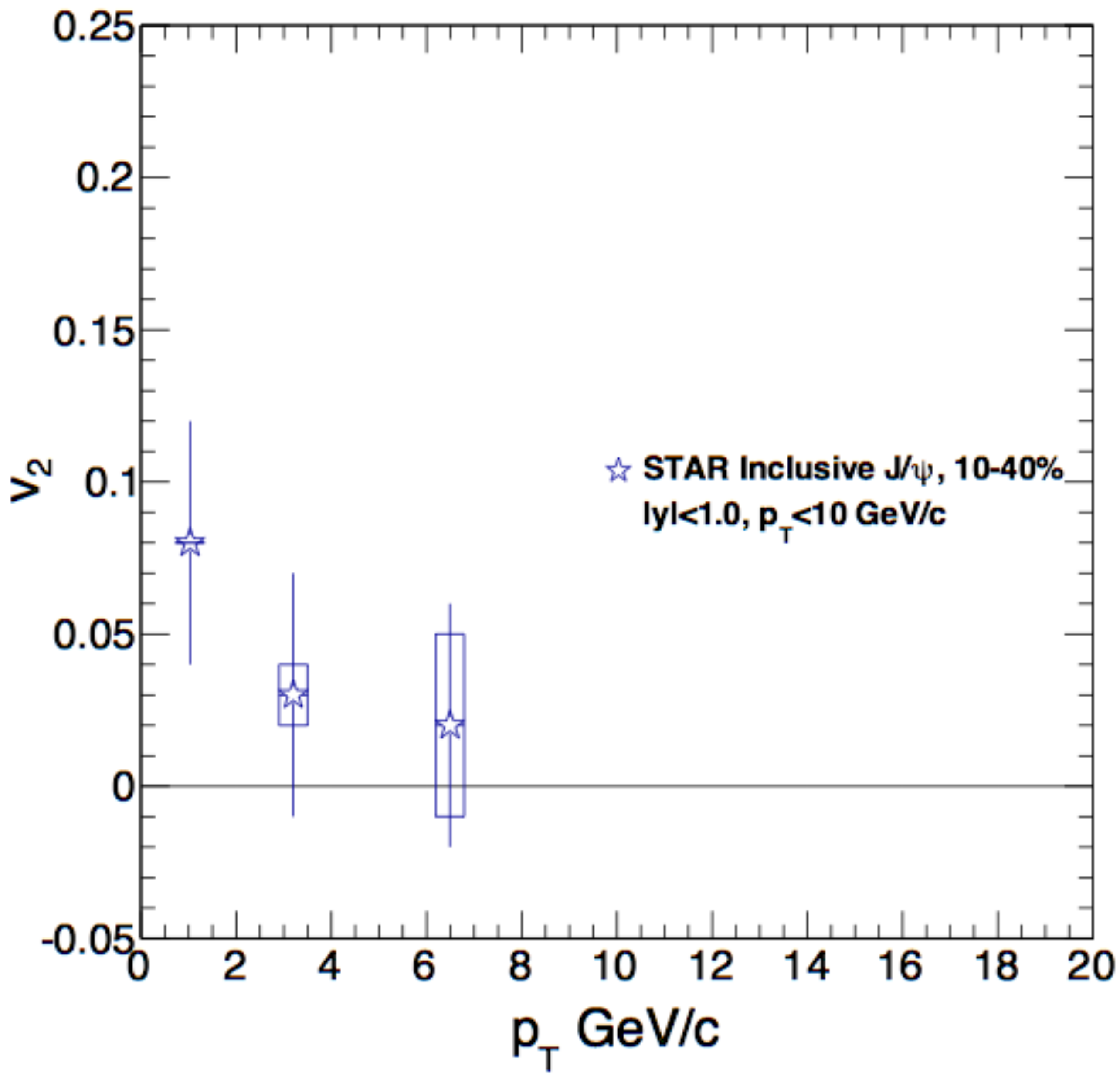


PRC 87 (2013) 044905
+ private communication

- Rapp: no need for recombination to describe data at high p_T (p_T > 6.5 GeV/c)
- Vitev: quarkonium suppression due to energy loss (similarly to open heavy-flavour) not enough to describe data

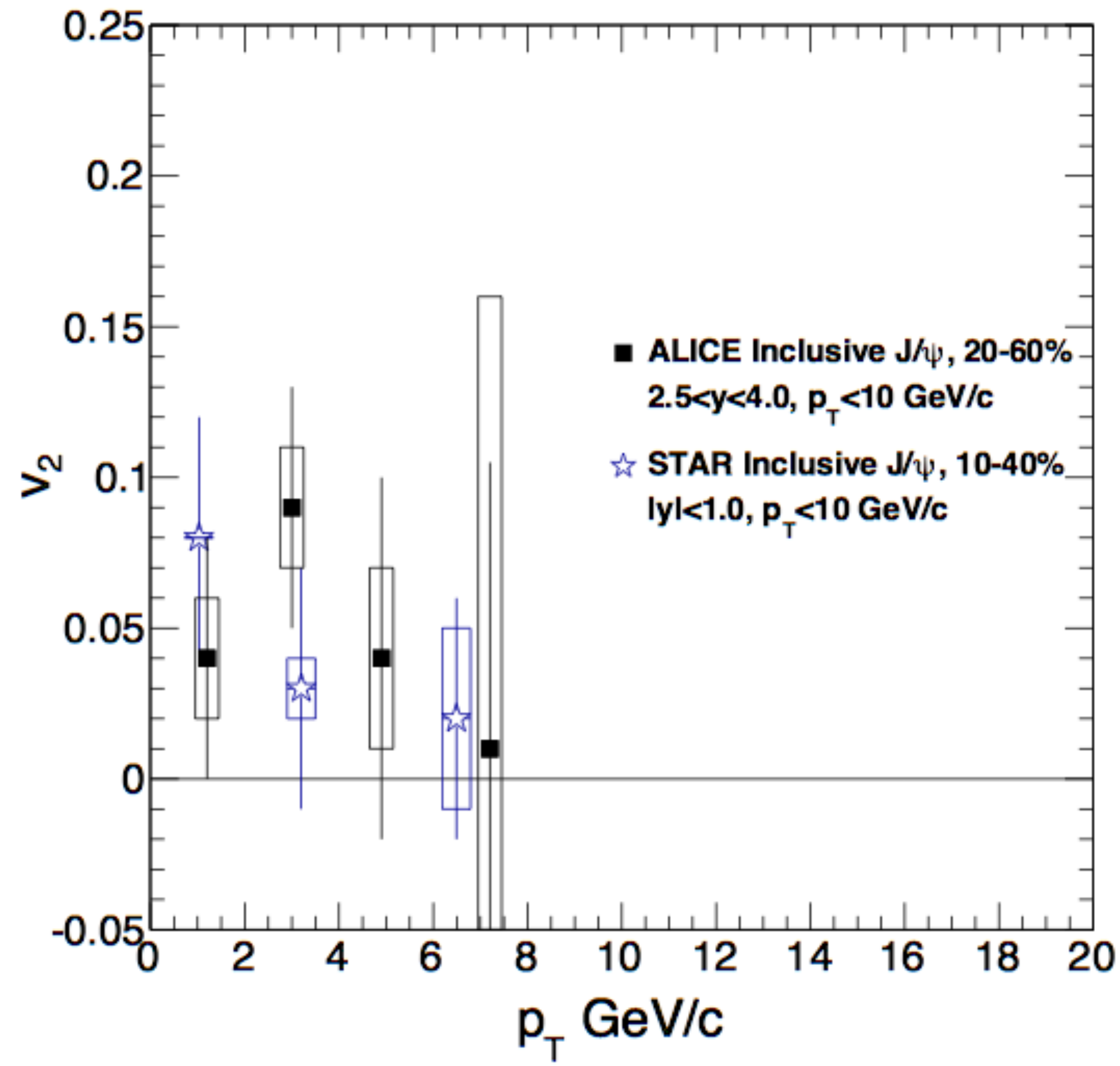
J/ψ v_2

- STAR found v_2 consistent with 0



J/ψ v_2

- STAR found v_2 consistent with 0
- ALICE found "hint of v_2"
  - as expected for recombination



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- STAR found v_2 consistent with 0
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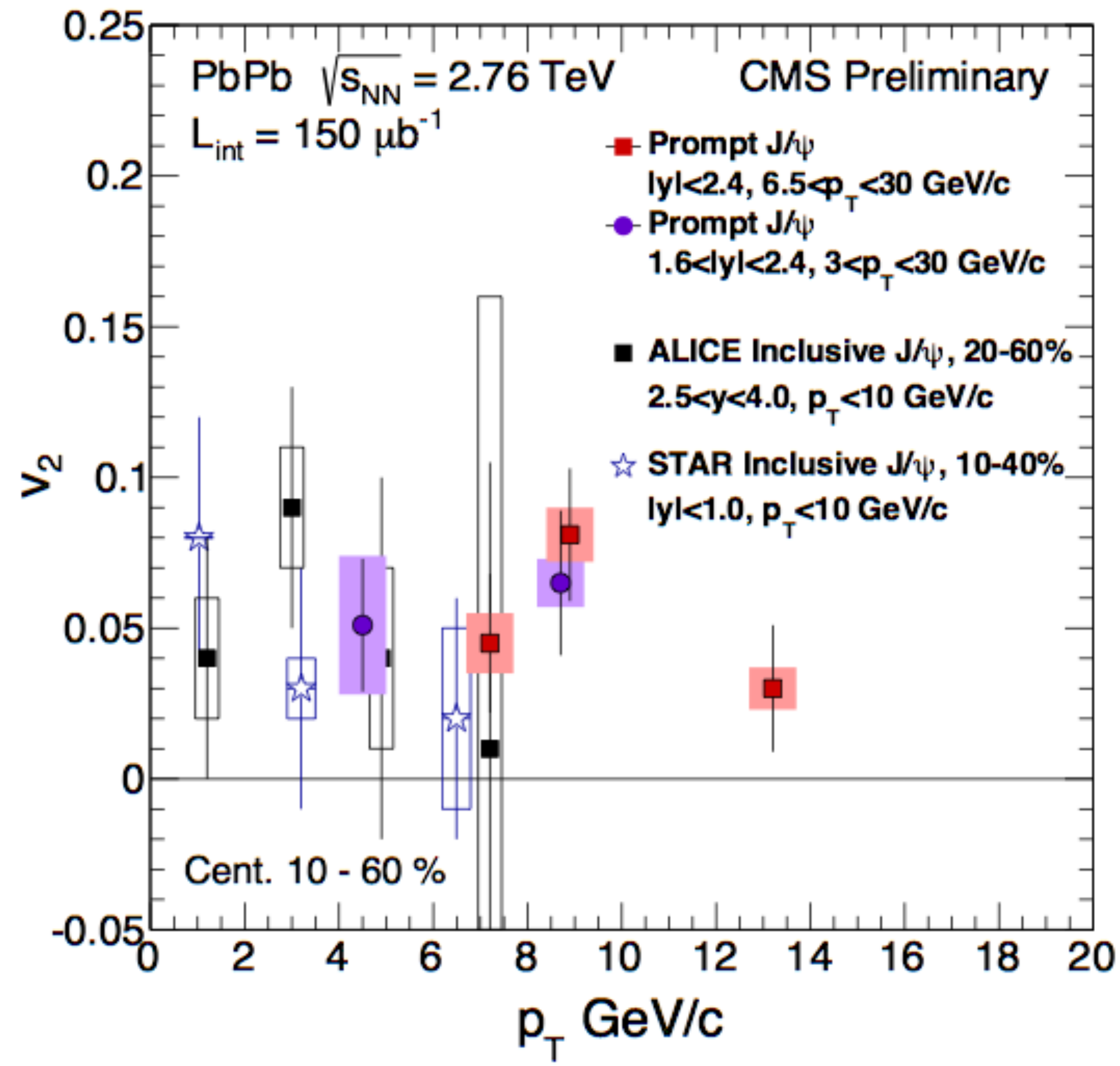
- CMS measured significant v_2
    - though only above 6.5 GeV/c
    - measurement also for $3<p_T<6.5$ GeV/c
    - high-p_T v_2 → path-length dependent suppression
- Taking all results together
    - J/ψ has non-zero v_2



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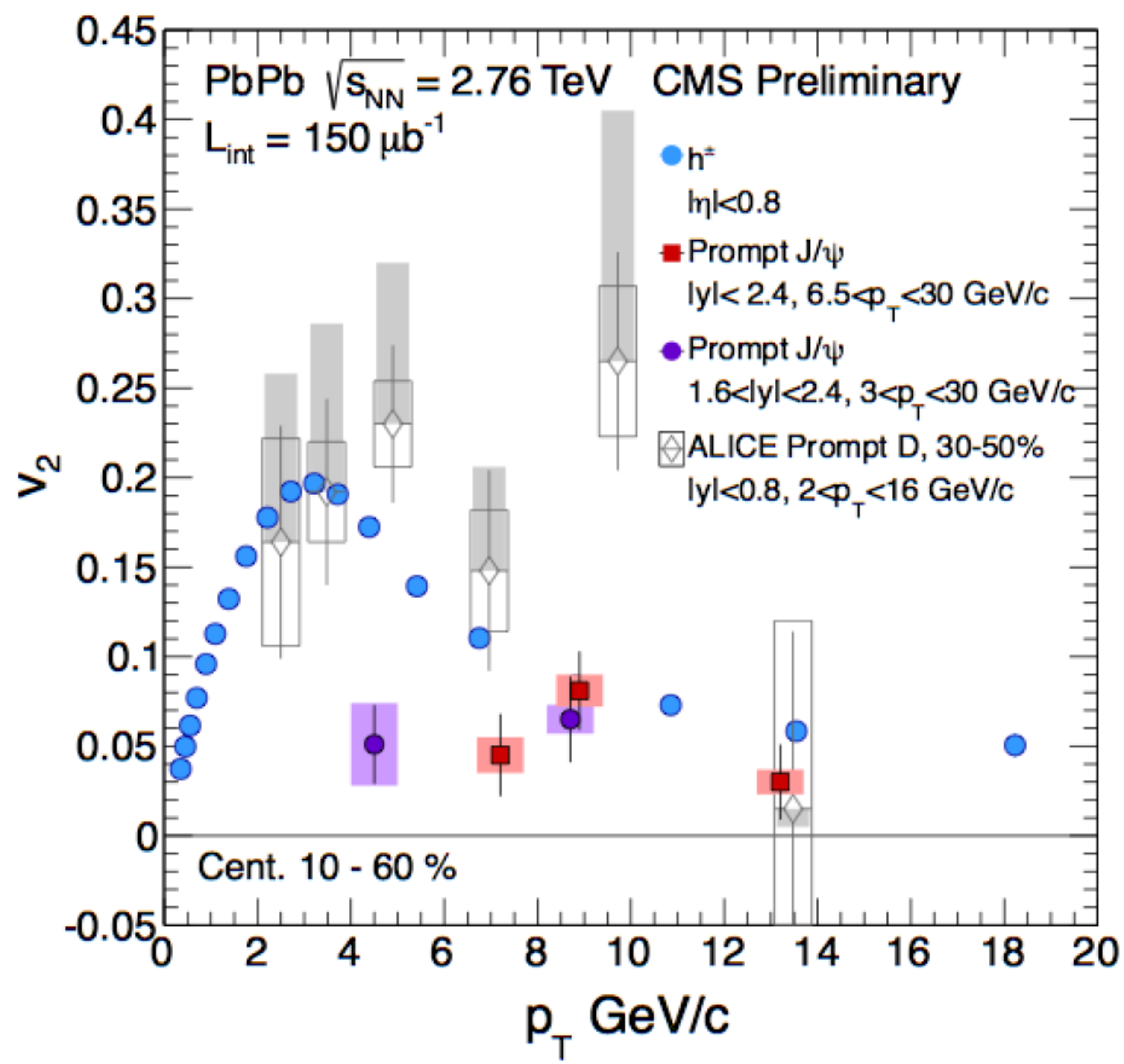
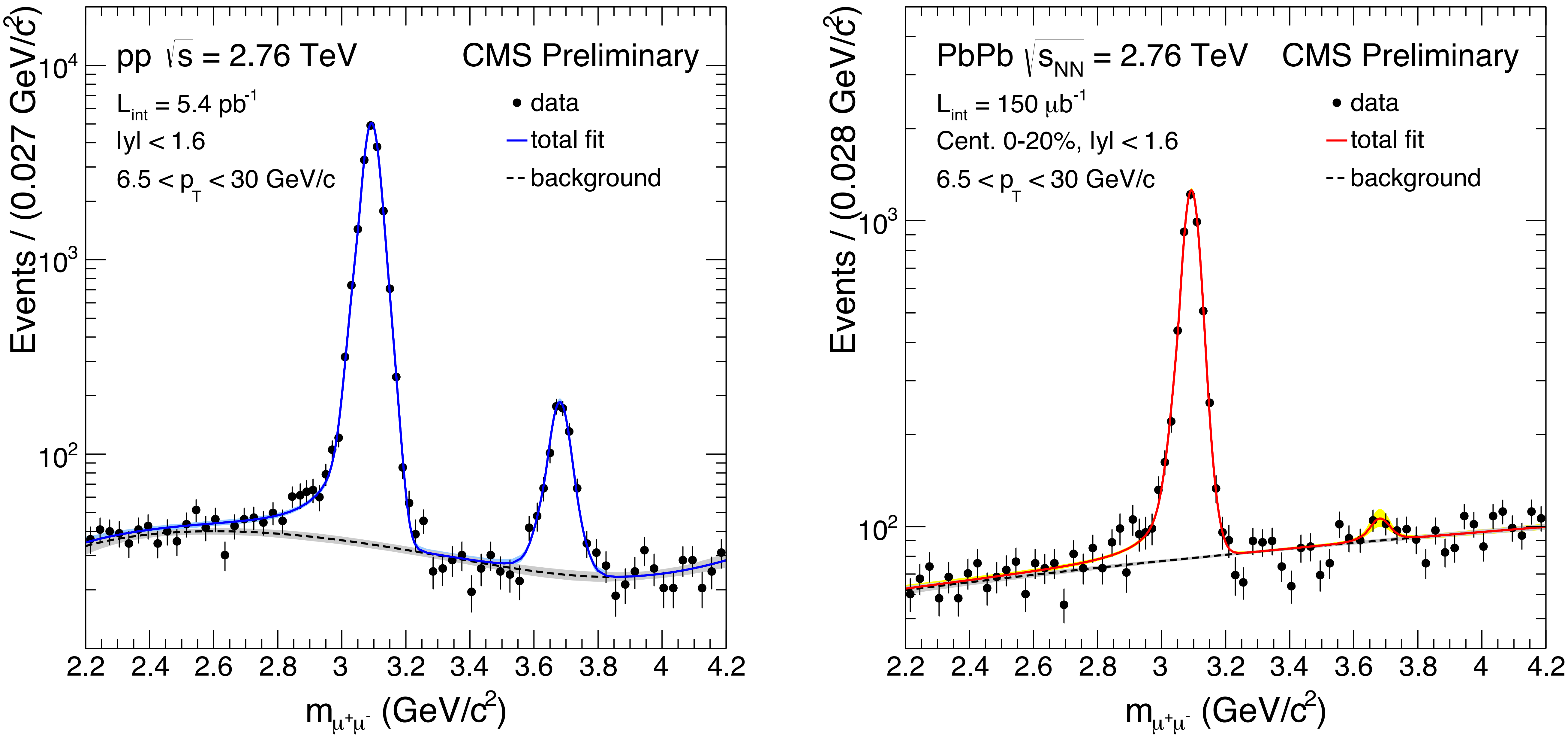
  - J/ψ has non-zero v_2
- Comparison to light hadrons and D



ψ(2S) in pp & PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV



- Raw yield ratio of ψ(2S) / J/ψ: $R_{\psi(2S)}$

CMS HIN-12-007

- Non-prompt charmonia removed via cut on pseudo-proper decay length
- For p_T > 6.5 GeV/c and |y| < 1.6:
  $R_{\psi(2S)}$ in 0–20% PbPb ~2× smaller than in pp

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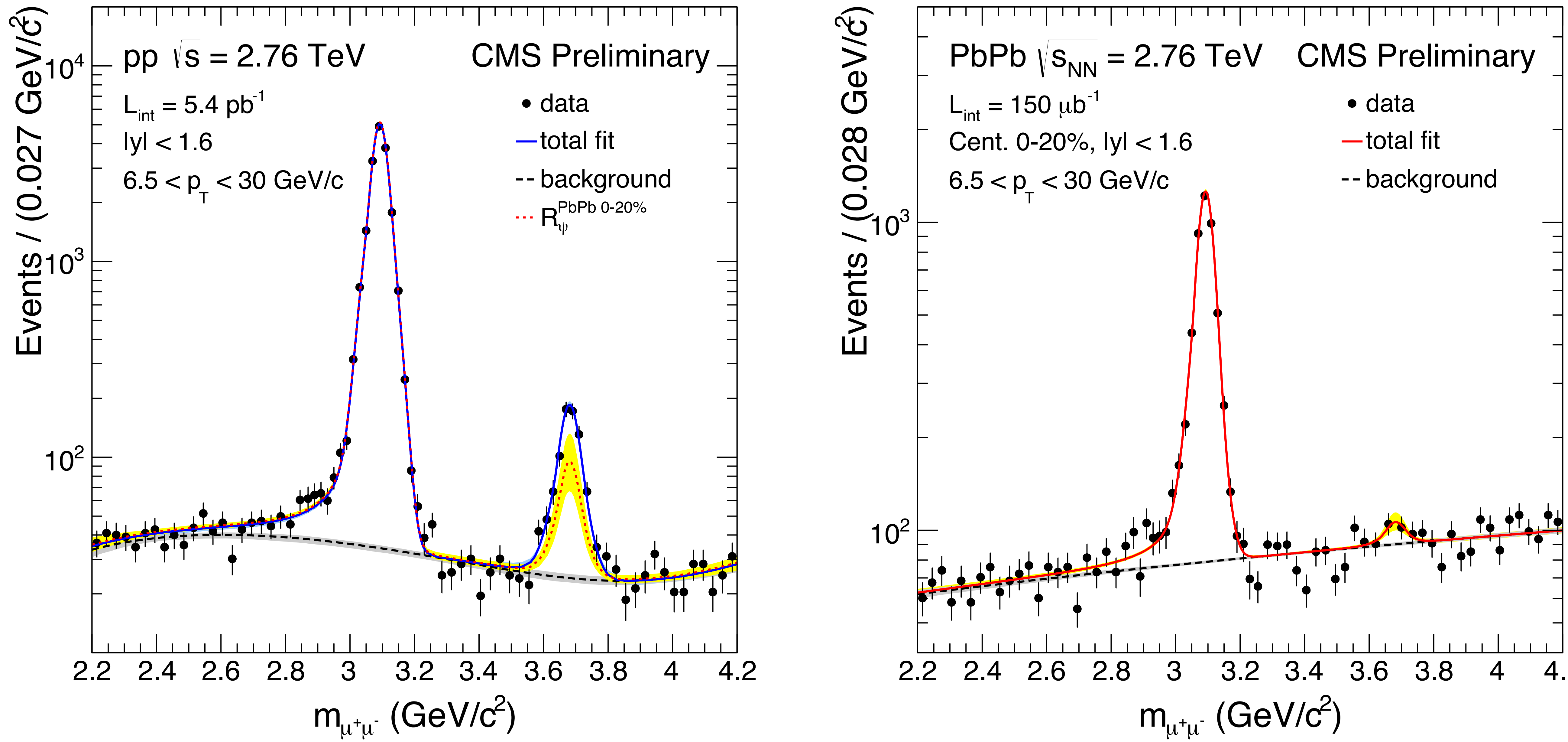

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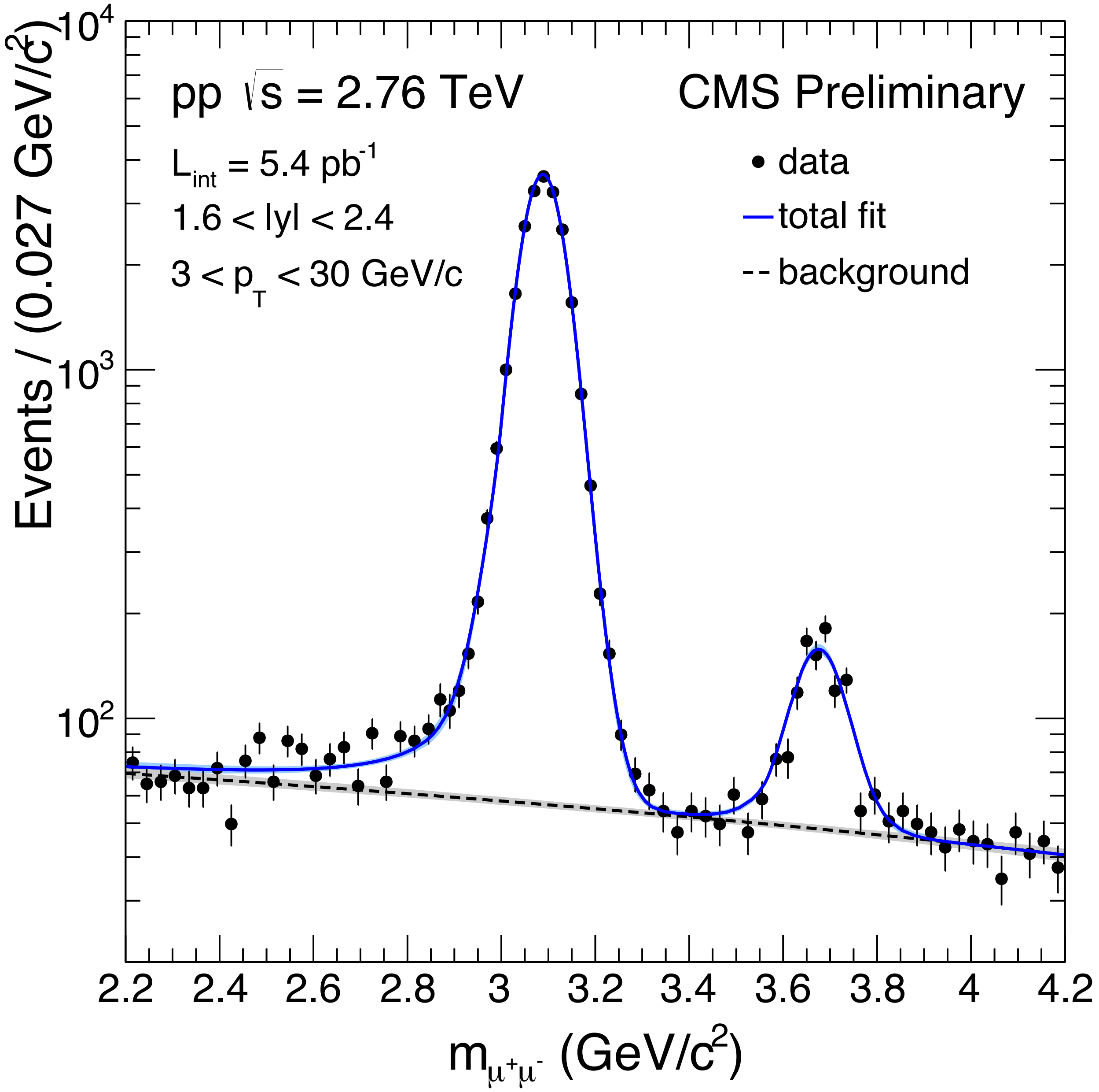
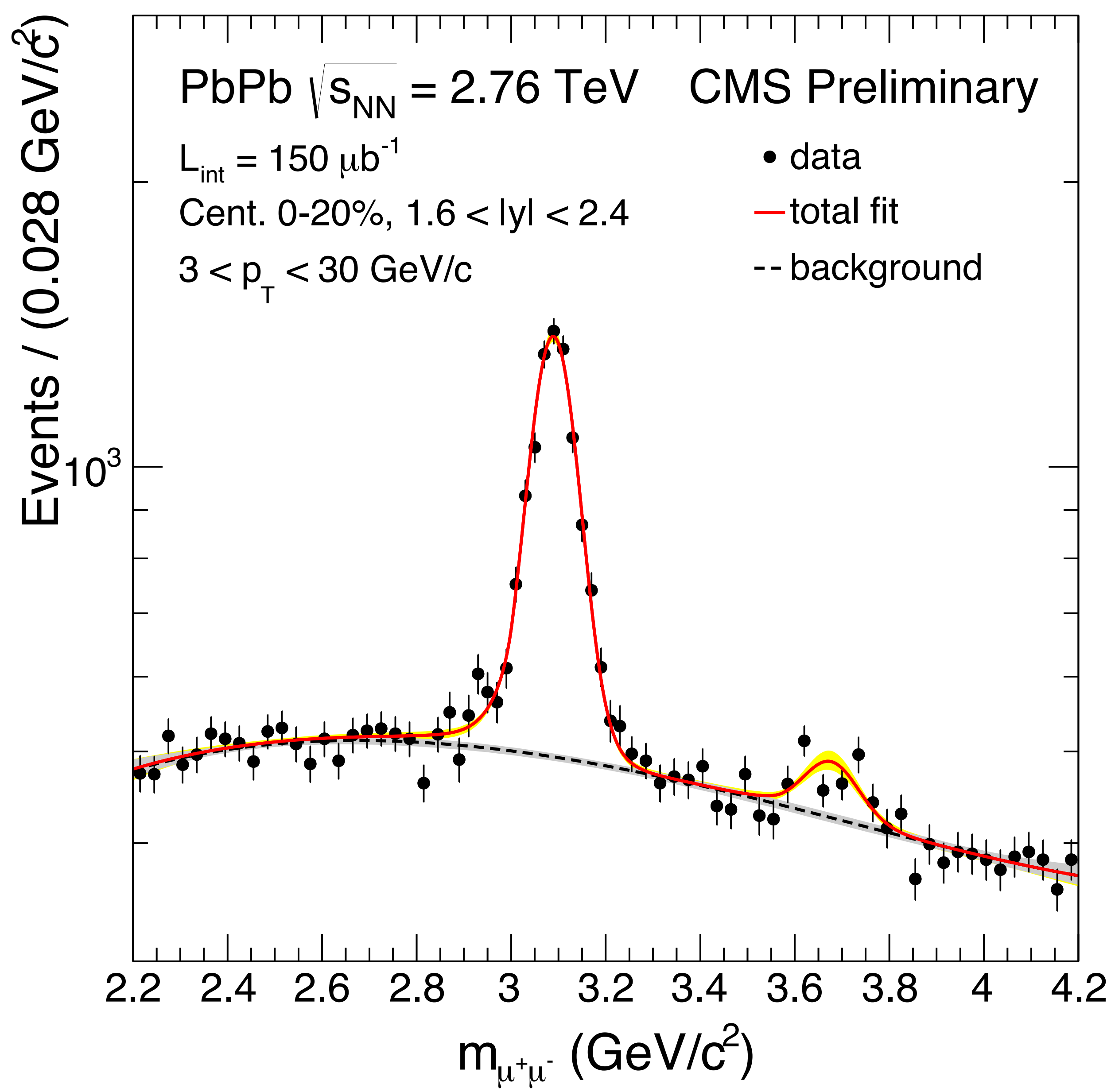
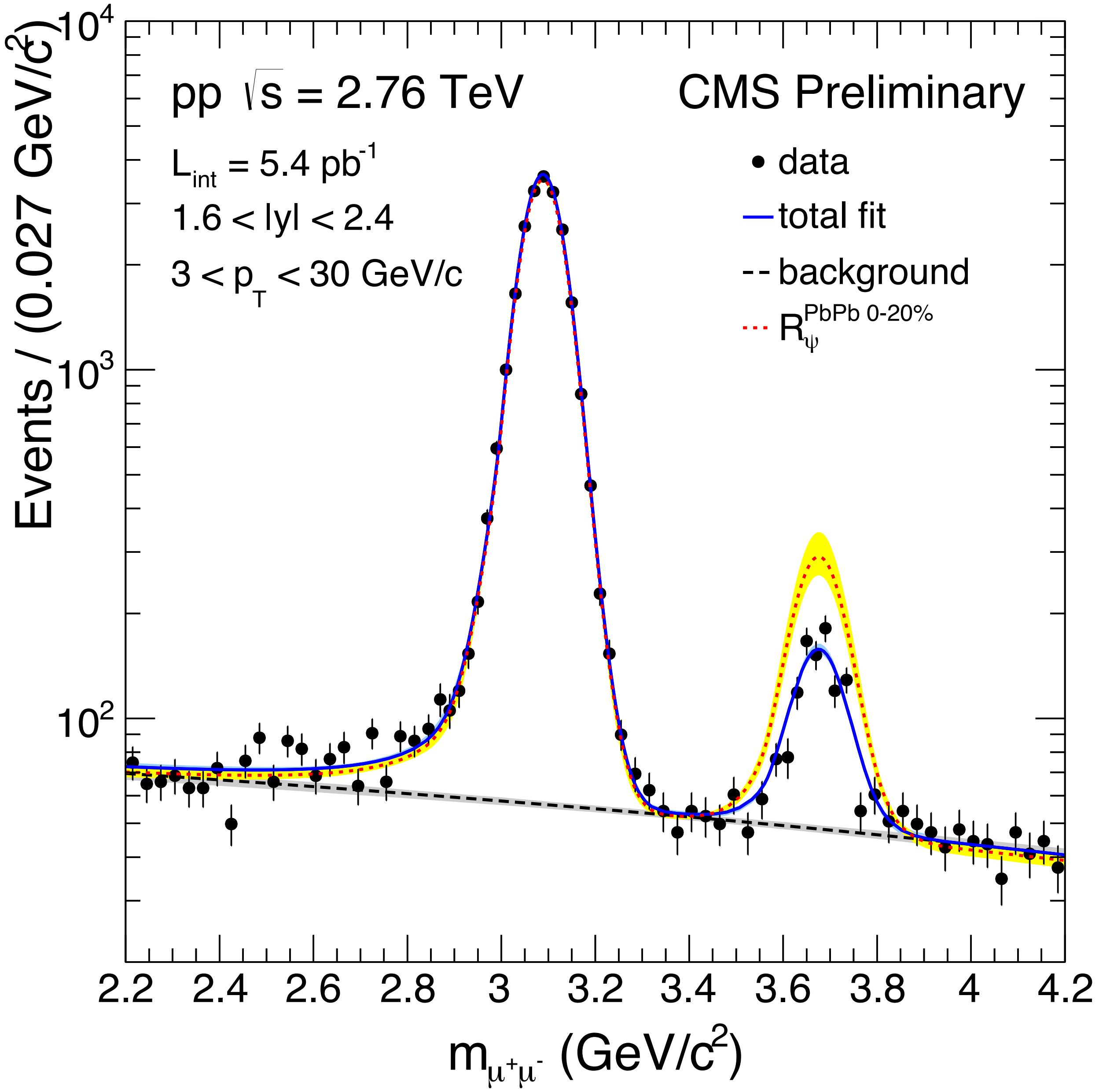


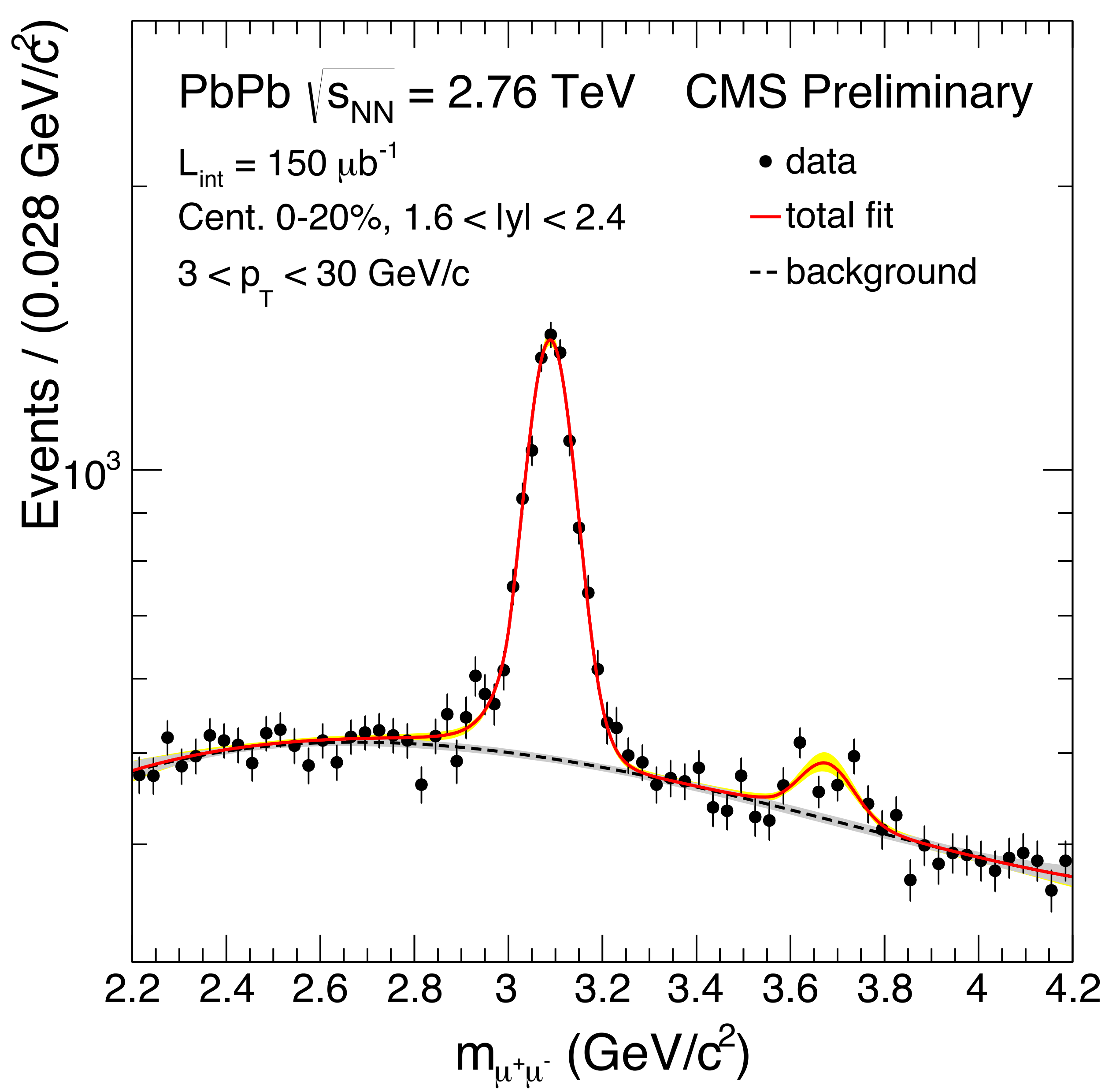


CMS HIN-12-007

- Raw yield ratio of ψ(2S) / J/ψ: $R_{\psi(2S)}$
- Non-prompt charmonia removed via cut on pseudo-proper decay length
- For p_T > 3 GeV/c and 1.6 < |y| < 2.4:
  $R_{\psi(2S)}$ in 0–20% PbPb ~2× larger than in pp

ψ(2S) in pp & PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV





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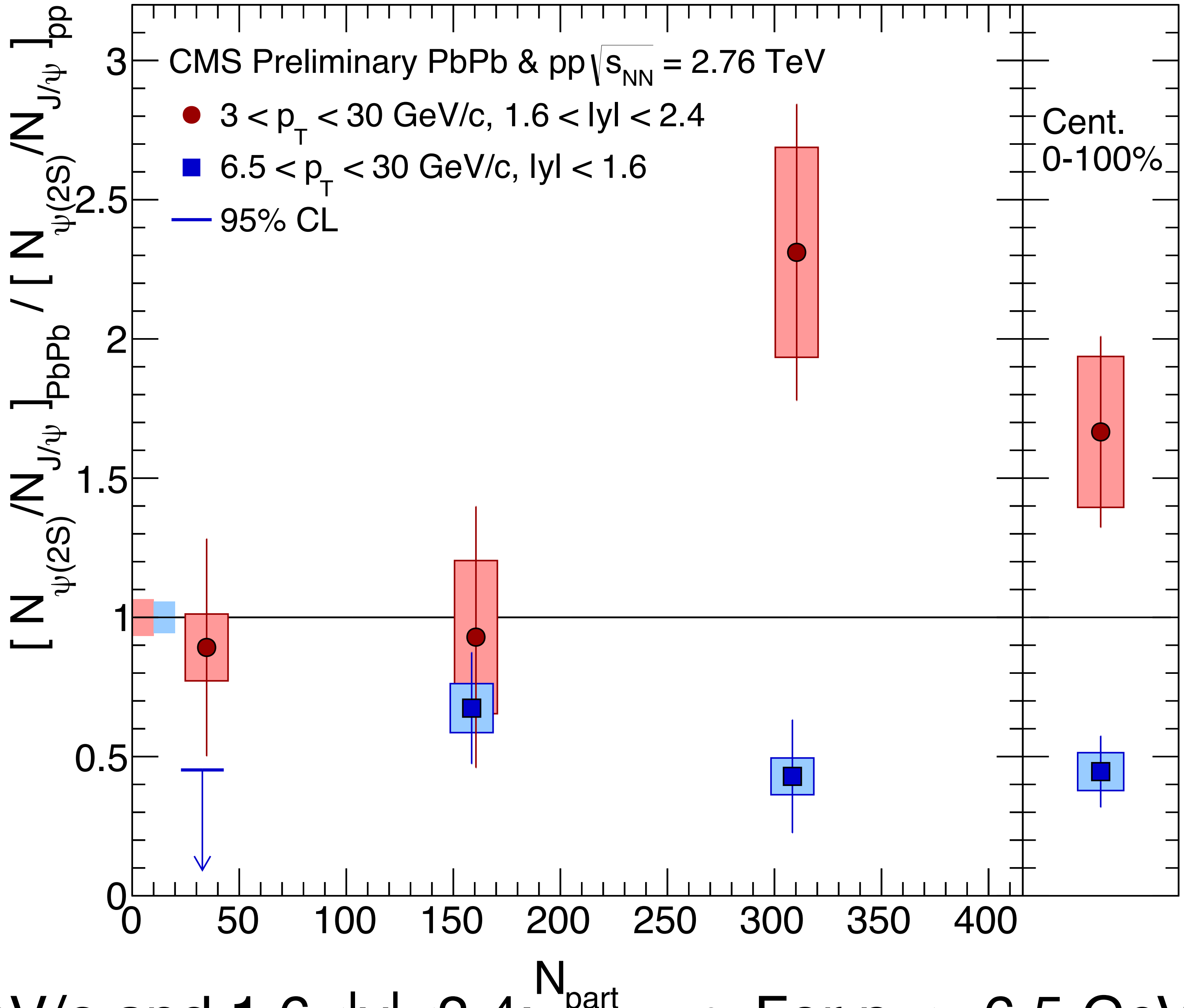
ψ(2S) / J/ψ Double Ratio

- Double ratio of $[\psi(2S) / J/\psi]_{PbPb} / [\psi(2S) / J/\psi]_{pp}$

CMS HIN-12-007

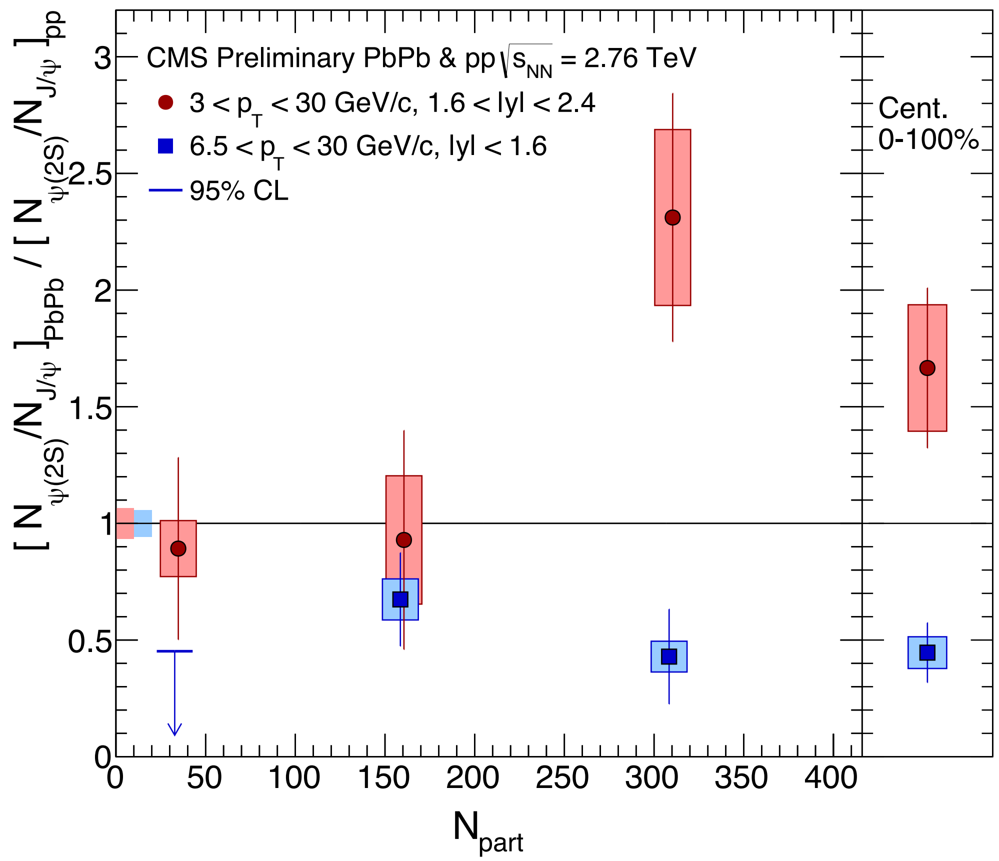


- For $p_T > 3$ GeV/c and $1.6<|y|<2.4$:
  - ψ(2S) less suppressed than J/ψ (p-value of 0.015 in 0-20%)
- For $p_T > 6.5$ GeV/c and $|y| < 1.6$:
  - ψ(2S) more suppressed than J/ψ
  - stronger suppression than at forward rapidity and lower p_T

Double Ratio

- Double ratio of $[2S / 1S]_{PbPb} / [2S / 1S]_{pp}$

< 1	> 1
sequential melting	
statistical hadronization	
	more quarks at larger distances
	...?
dissociation rate (<1 for charm, >1 for bottom)	
differences in p_T & y dependent effects	



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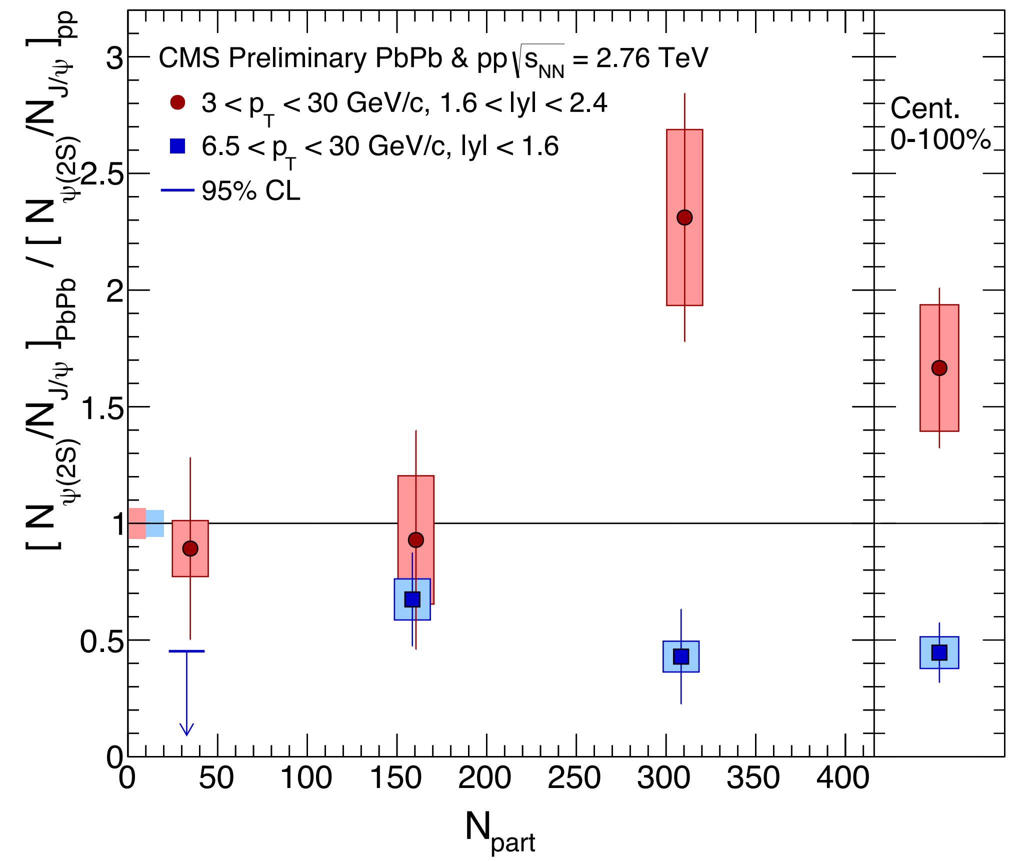

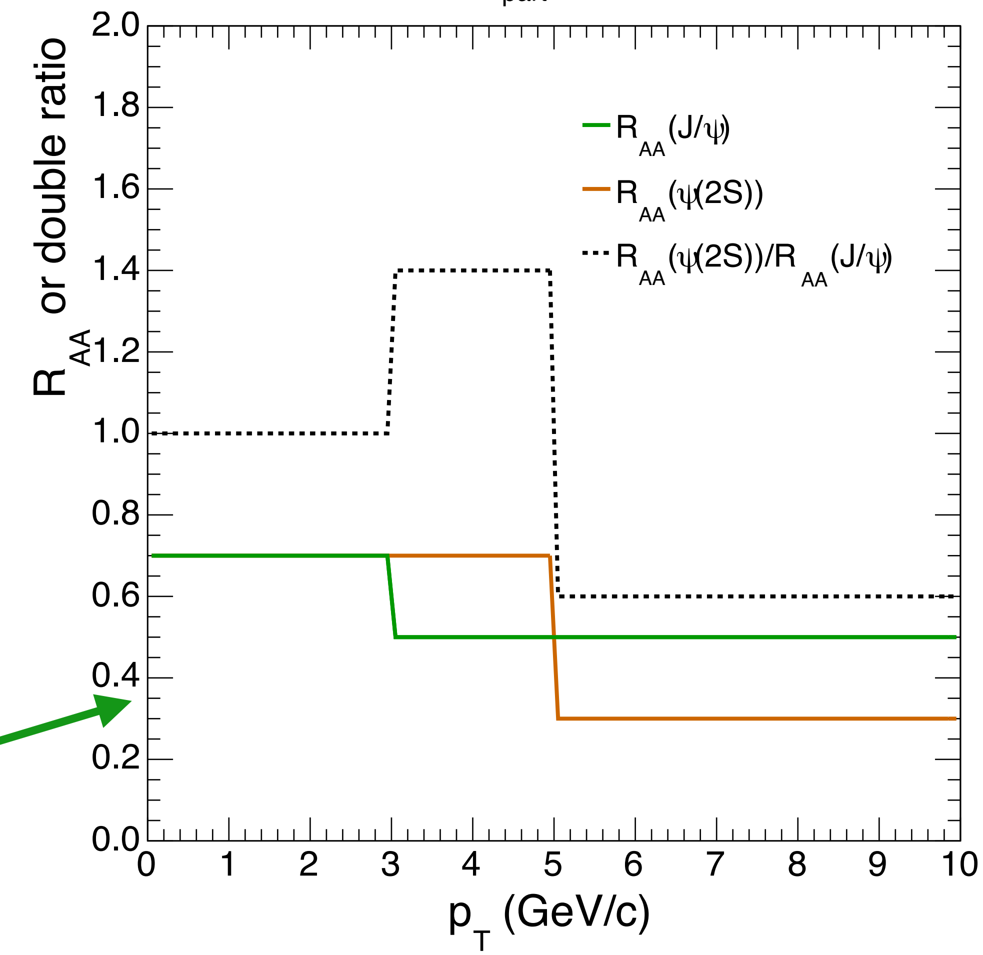

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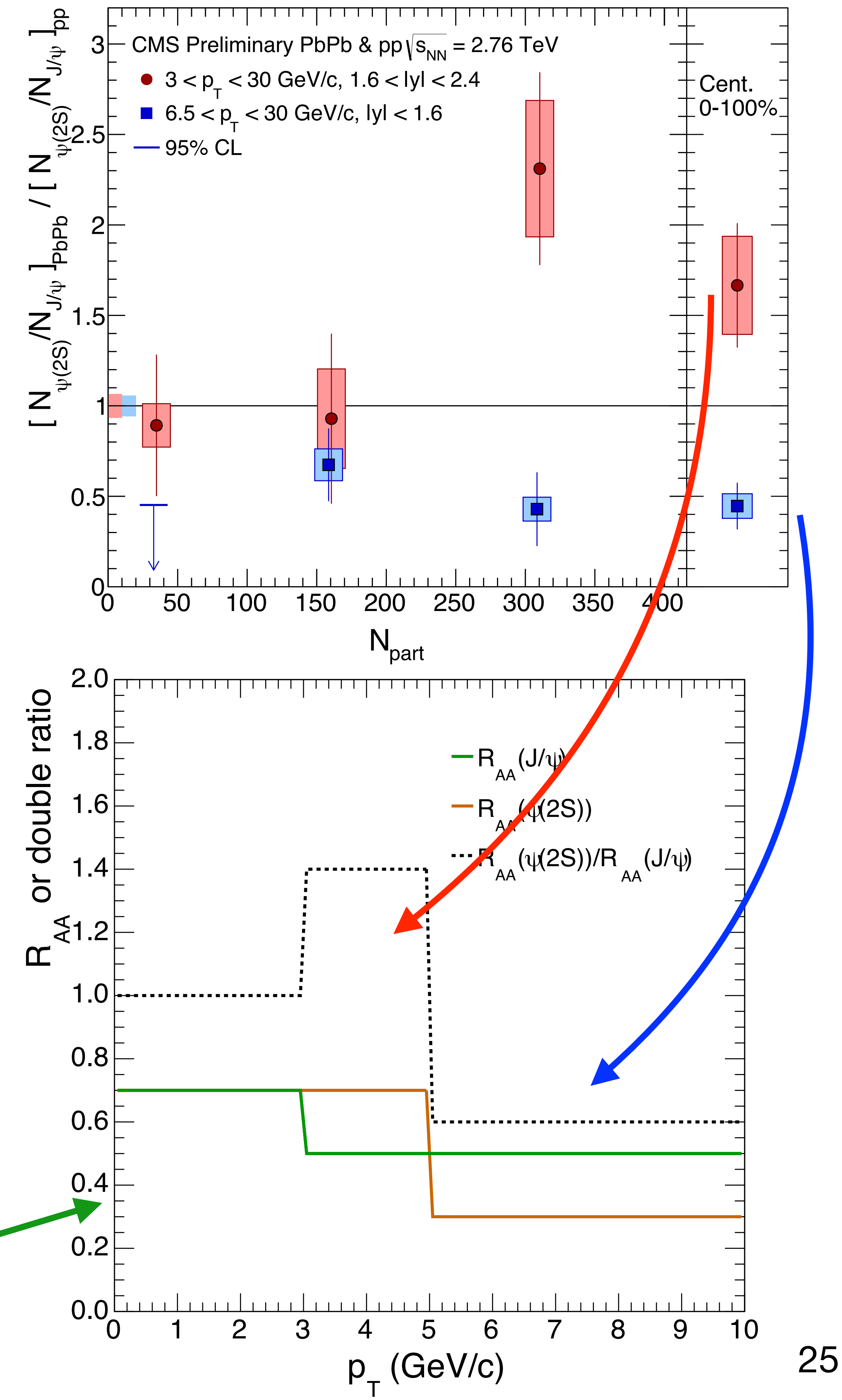
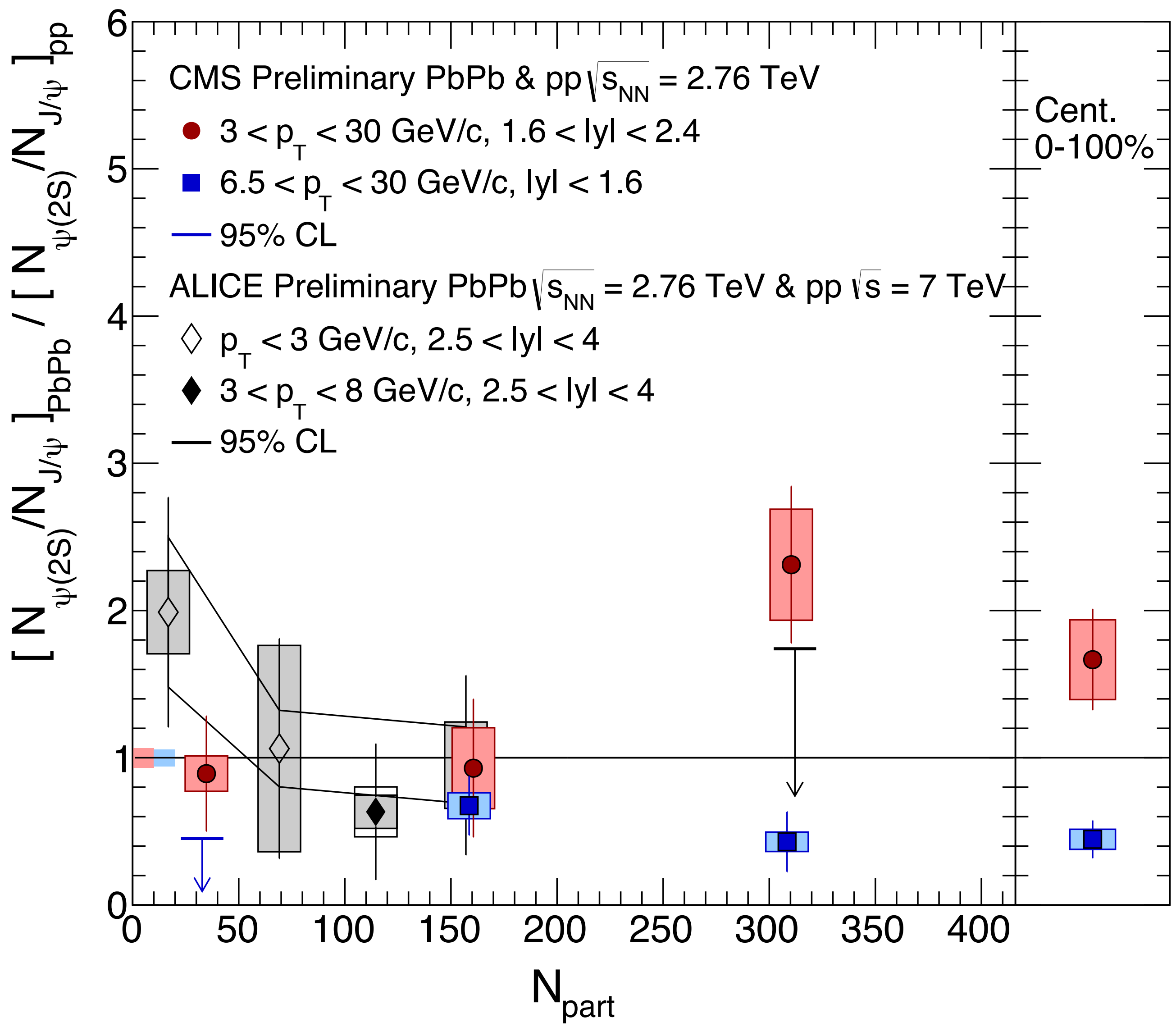
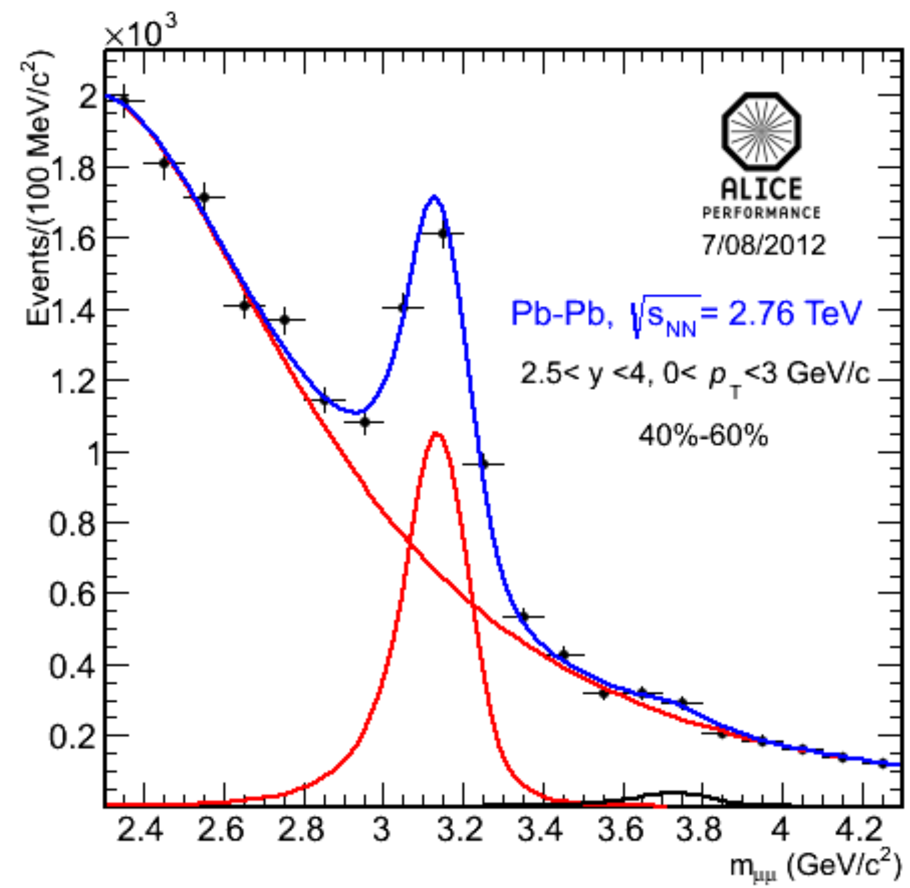


ψ(2S) Double Ratio: CMS vs. ALICE

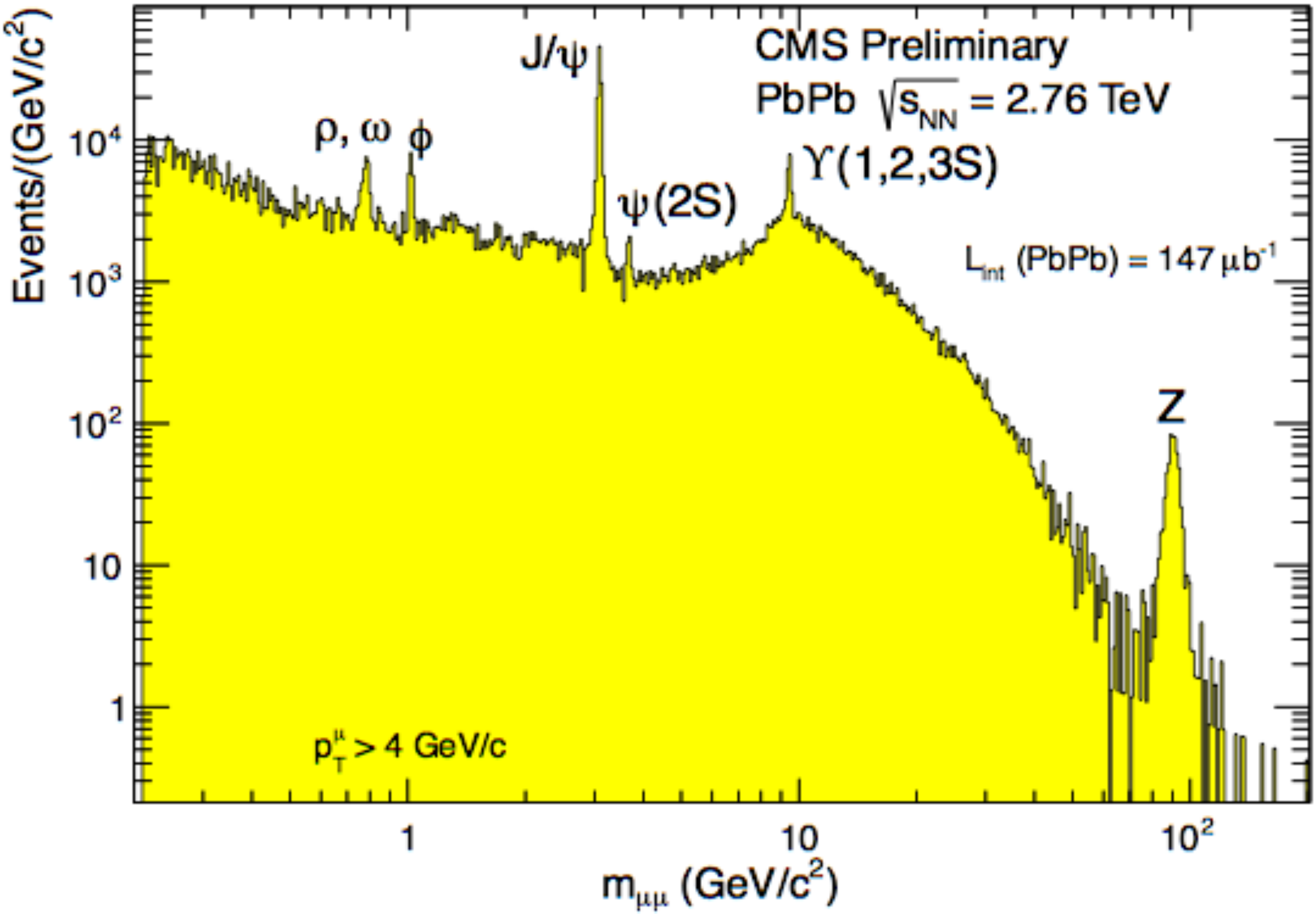


- CMS has a hint of less suppression of the ψ(2S) w.r.t. the J/ψ at lower p_T
  - used pp at $\sqrt{s}$ = 2.76 TeV
- ALICE looked and did not see it…
  - used pp at $\sqrt{s}$ = 7 TeV
- However, given the large uncertainties:
  - No discrepancy!



CMS: HIN-12-007
ALICE: Scomparin, Arnaldi (QM 2012)

Muon Pairs in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV



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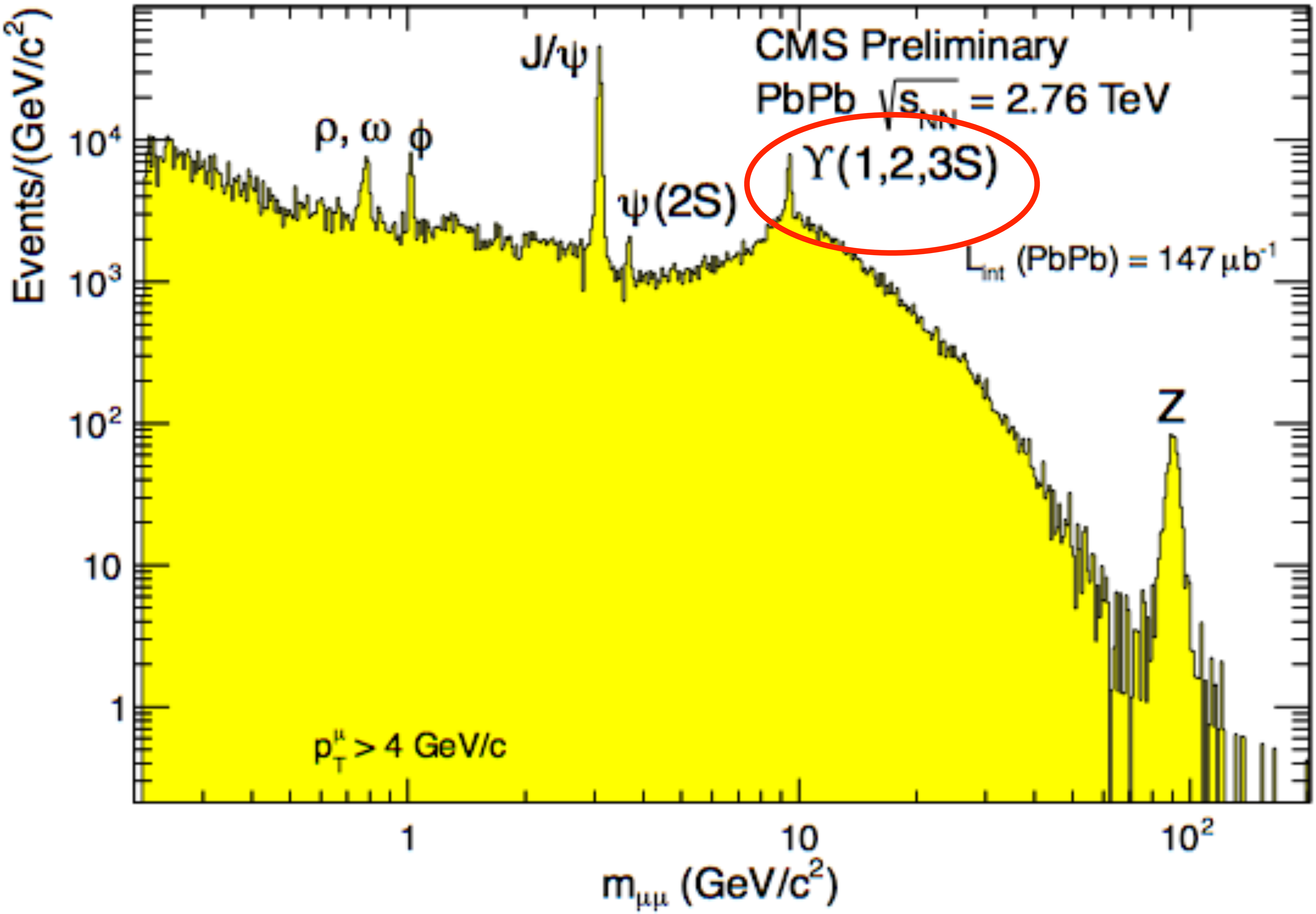
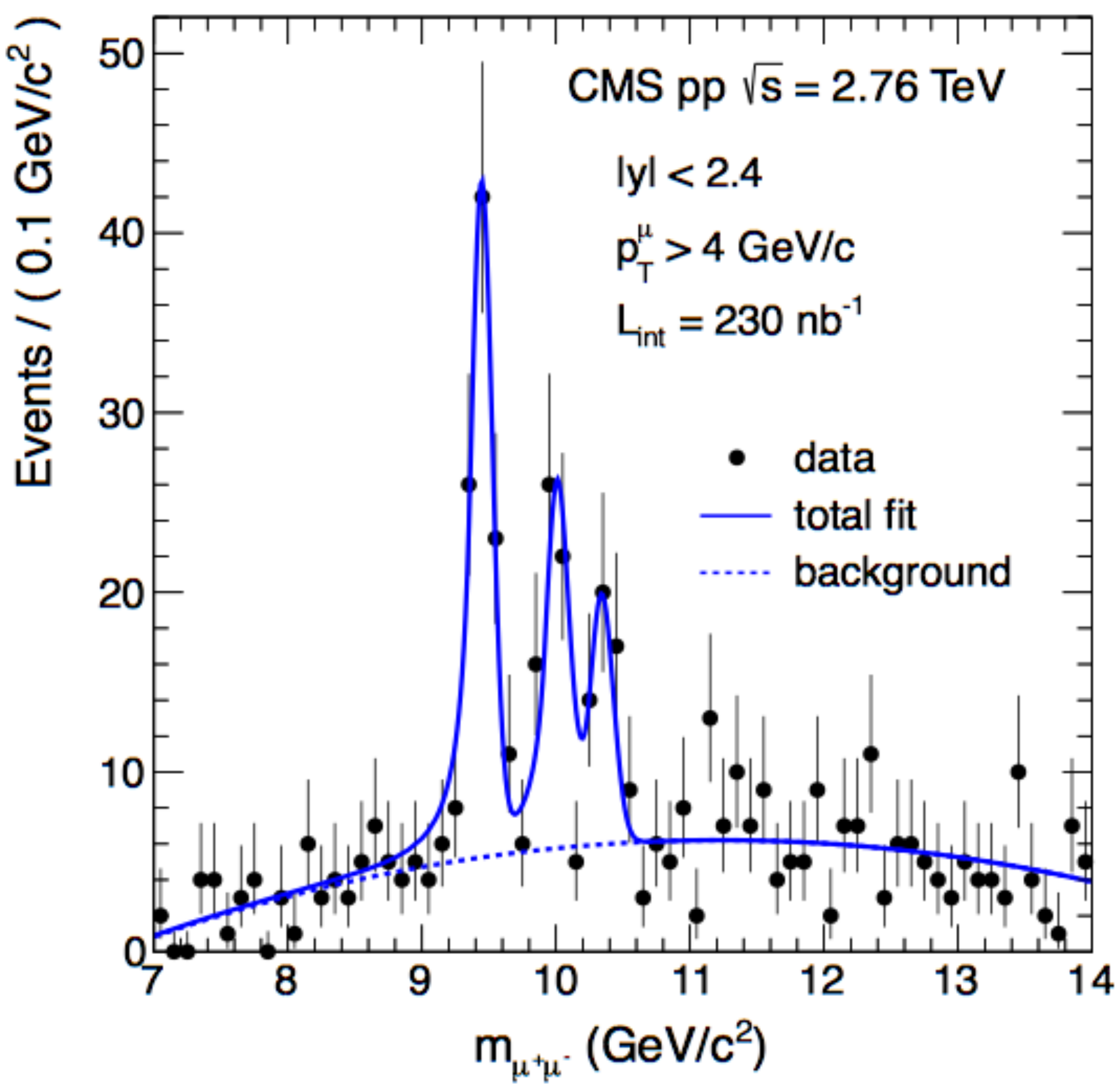
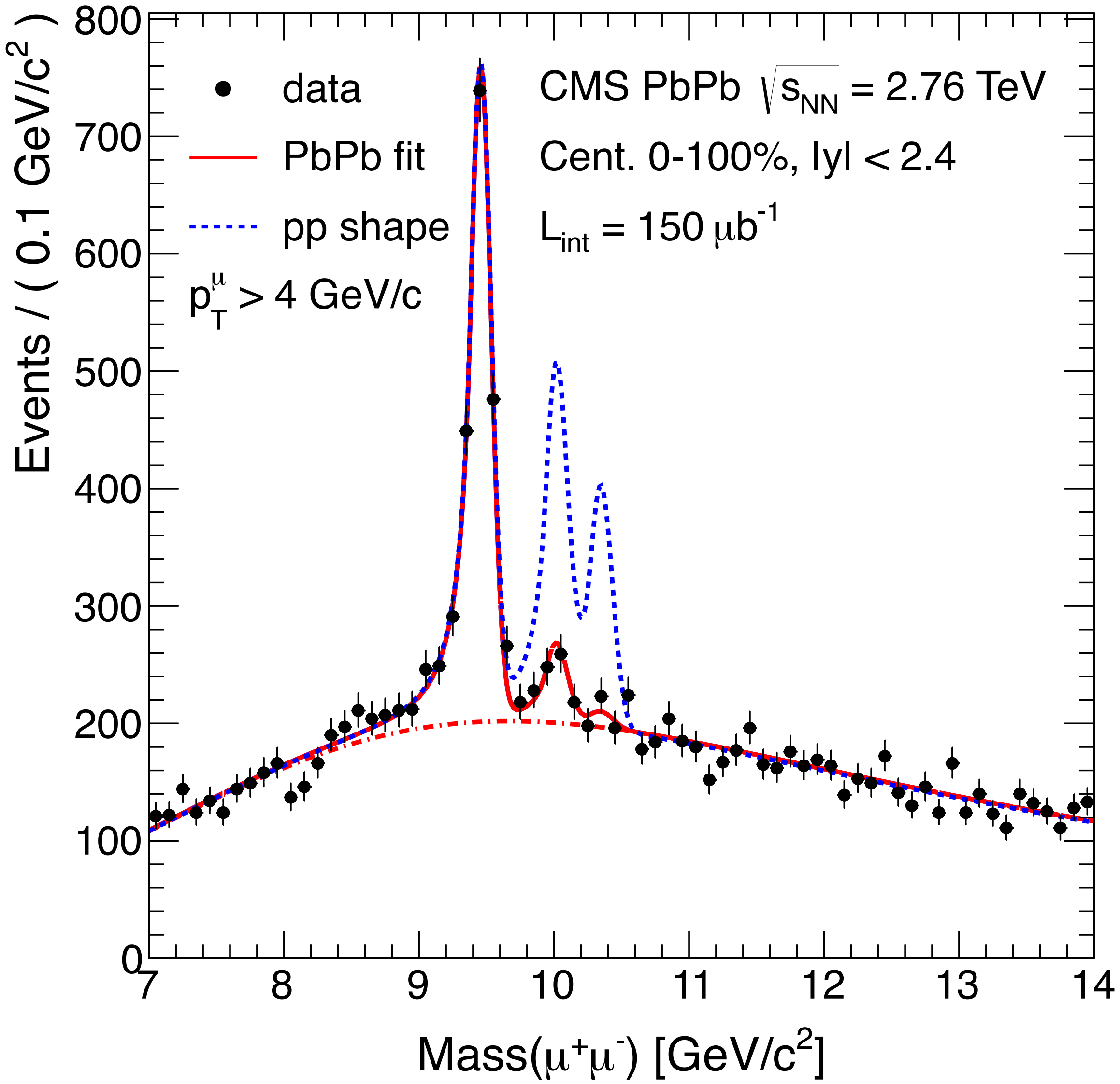


Bottomonia

pp

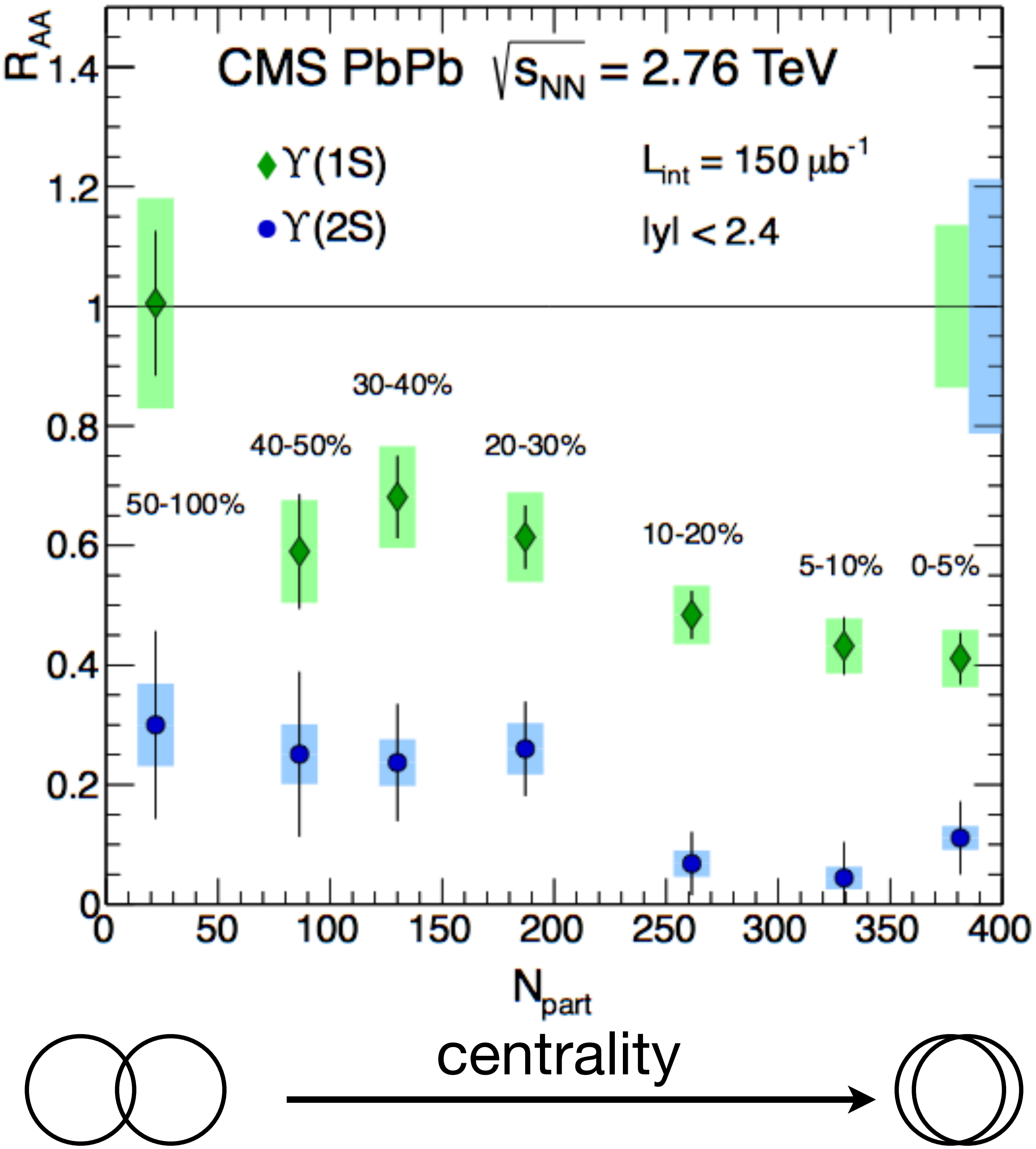


PbPb



CMS HIN-11-011
PRL 109 (2012) 222301

Υ(nS) R_{AA}: CMS



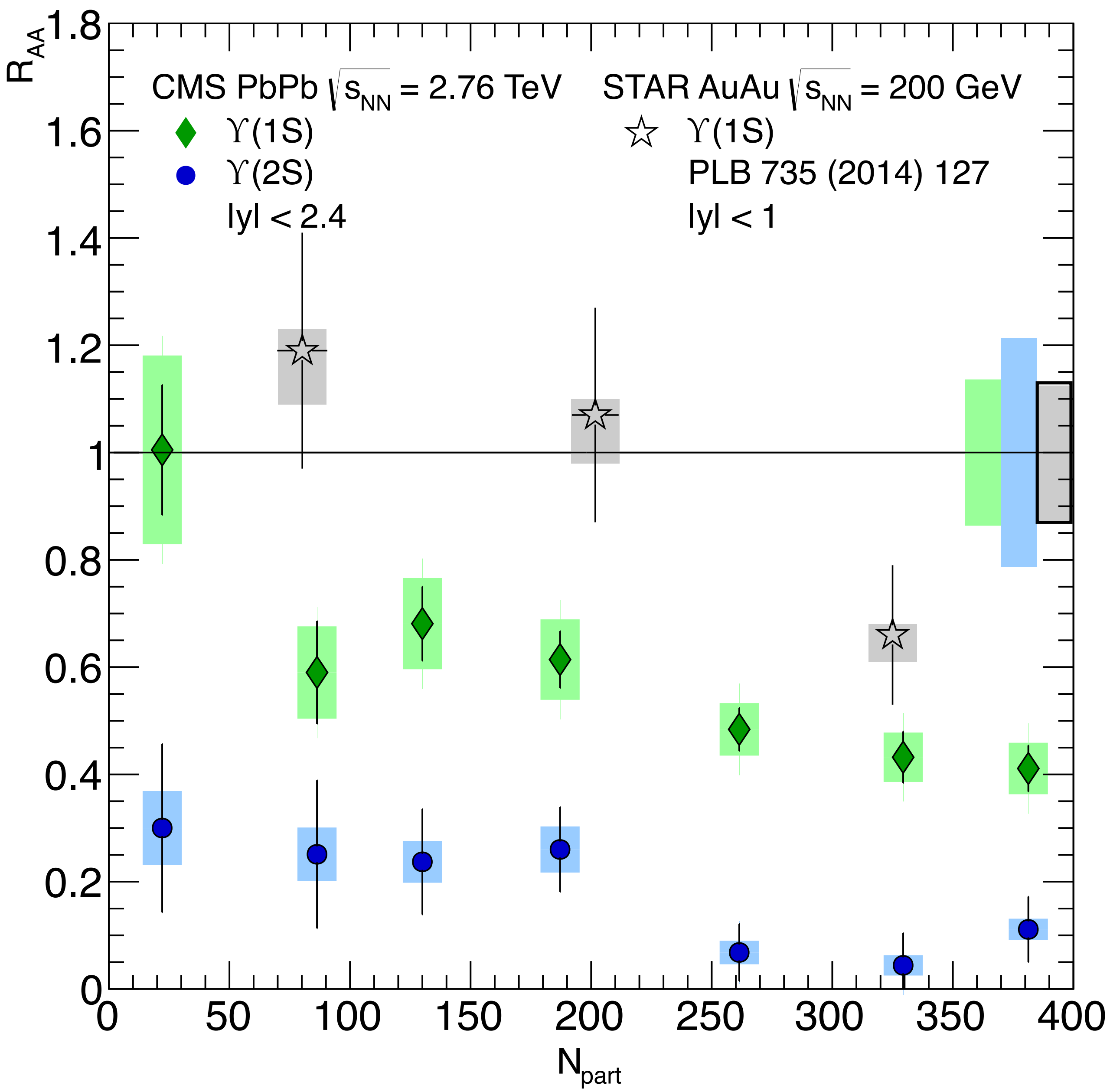
- Υ(1S) R_{AA} in 7 centrality bins
- Clear suppression of Υ(2S)
- Υ(1S) suppression consistent with excited state suppression (~50% feed down)
- Centrality integrated:

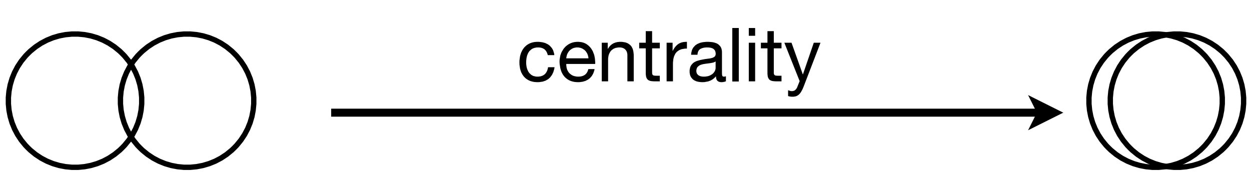
$$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08\,(\text{stat.}) \pm 0.07\,(\text{syst.})$$
$$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04\,(\text{stat.}) \pm 0.02\,(\text{syst.})$$
$$R_{AA}(\Upsilon(3S)) < 0.1\ (\text{at } 95\%\ \text{C.L.})$$

- Sequential suppression of the three states in order of their binding energy

CMS HIN-11-011
PRL 109 (2012) 222301

ϒ(nS) R_{AA}: CMS vs. STAR





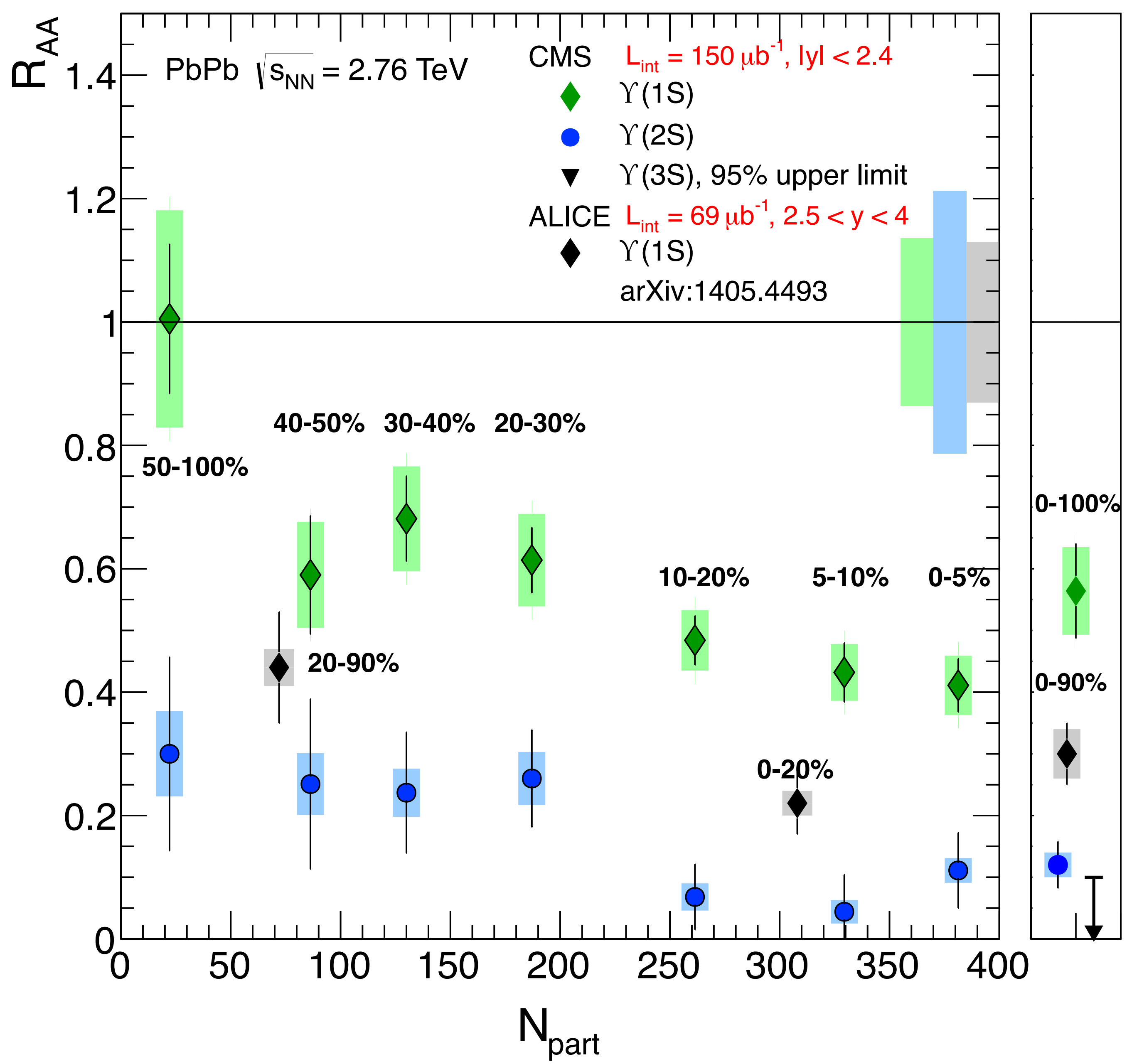
- ϒ(1S) R_{AA} in 7 centrality bins
- Clear suppression of ϒ(2S)
- ϒ(1S) suppression consistent with excited state suppression (~50% feed down)
- Centrality integrated:

$$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08\,(\text{stat.}) \pm 0.07\,(\text{syst.})$$
$$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04\,(\text{stat.}) \pm 0.02\,(\text{syst.})$$
$$R_{AA}(\Upsilon(3S)) < 0.1\ (\text{at } 95\%\ \text{C.L.})$$

- Sequential suppression of the three states in order of their binding energy
- Stronger suppression than at RHIC

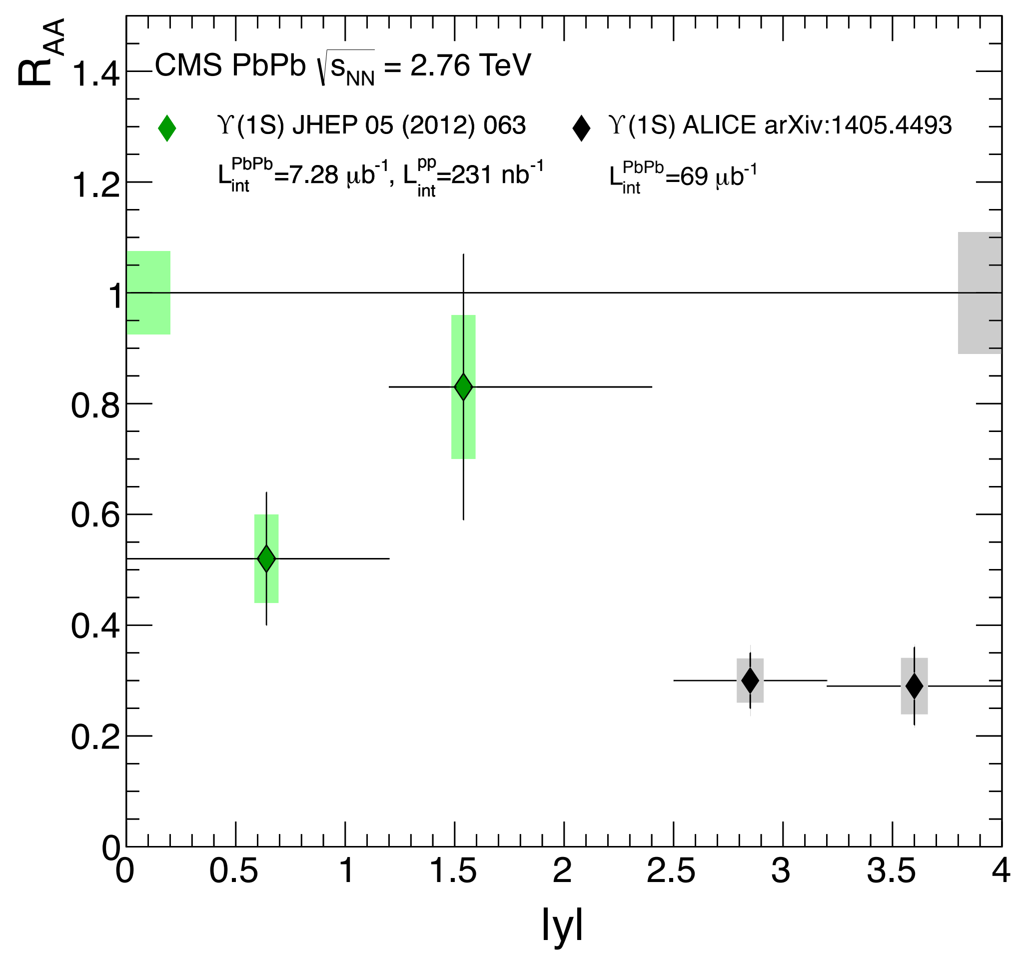
CMS HIN-11-011
PRL 109 (2012) 222301

Υ(nS) R_{AA}: CMS + ALICE



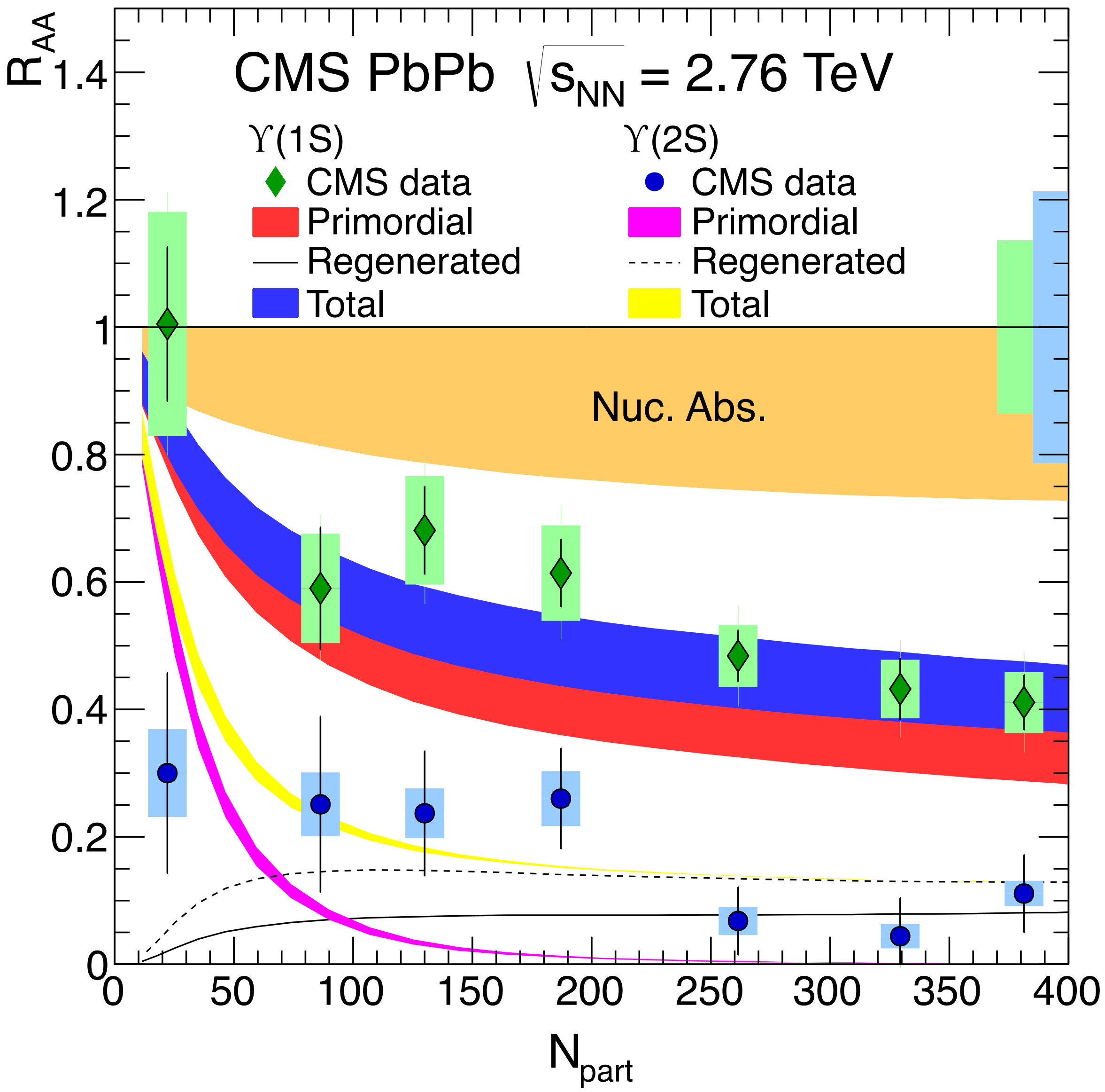
CMS HIN-11-011
PRL 109 (2012) 222301

- ALICE Υ(1S) R_{AA}:
  - Υ(1S) also suppressed at forward rapidity



CMS: JHEP 05 (2012) 063 (2010 data)
ALICE: arXiv:1405.4493 (2011 data)

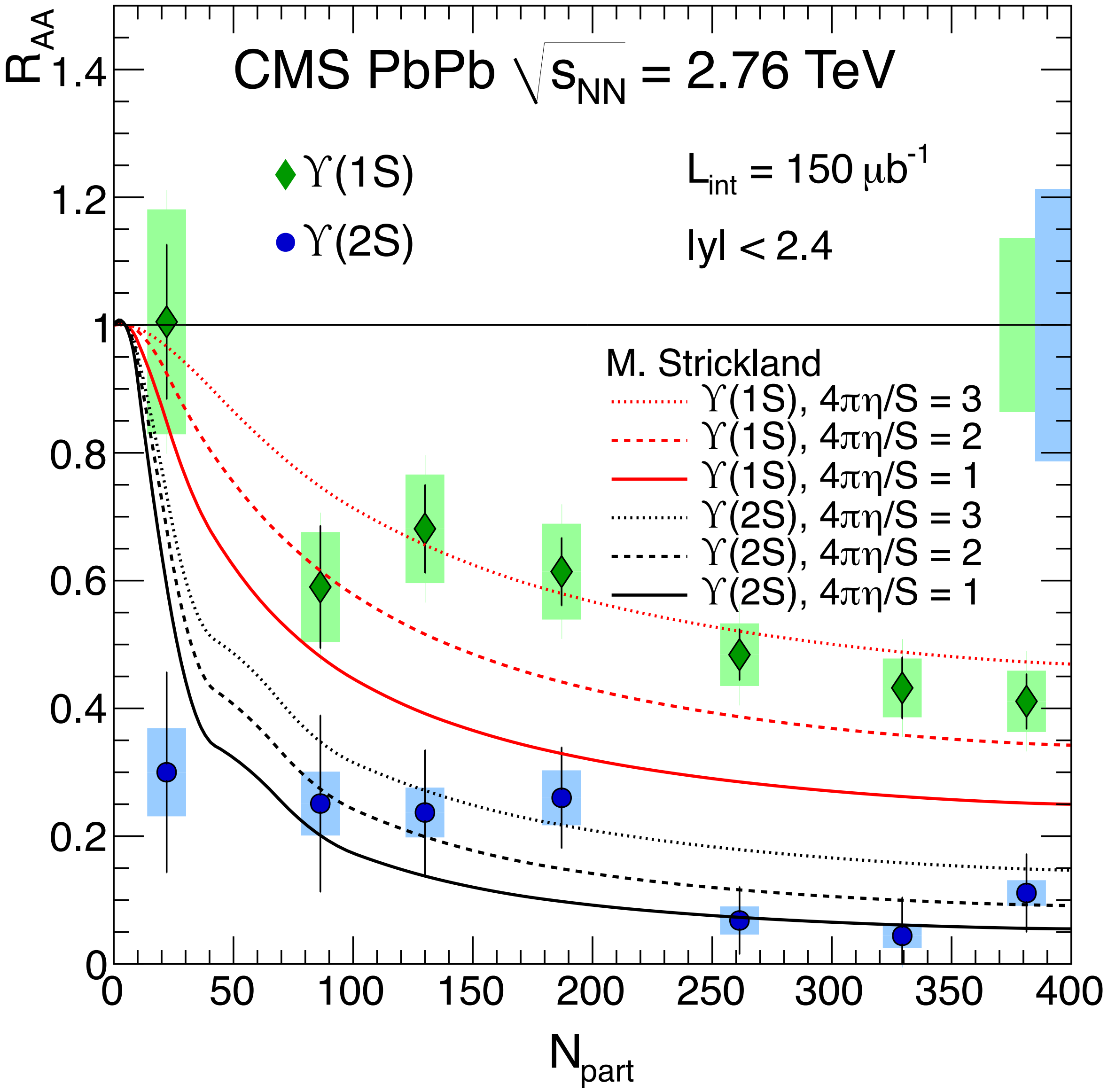
Bottomonia: Theory meets Experiment

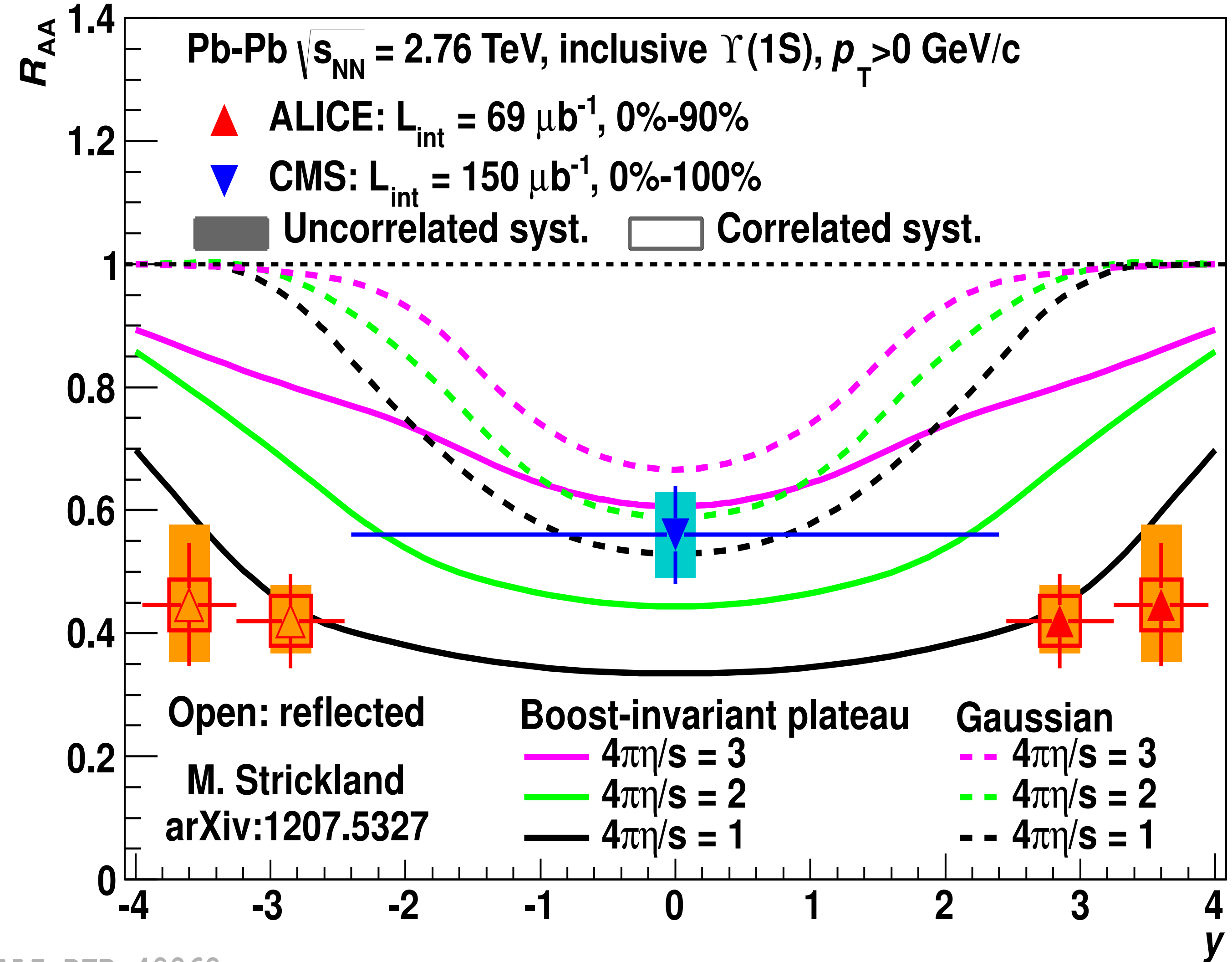


Rapp et al. EPJ A48 (2012) 72

- Multicomponent model
  - Proxy for nuclear effects: 0 to 2 mb absorption cross section
  - Rate equation in the fireball with suppression and regeneration
- Reproduces ϒ(1S) and ϒ(2S)
  - Most of ϒ(2S) from recombination

Bottomonia: Theory meets Experiment

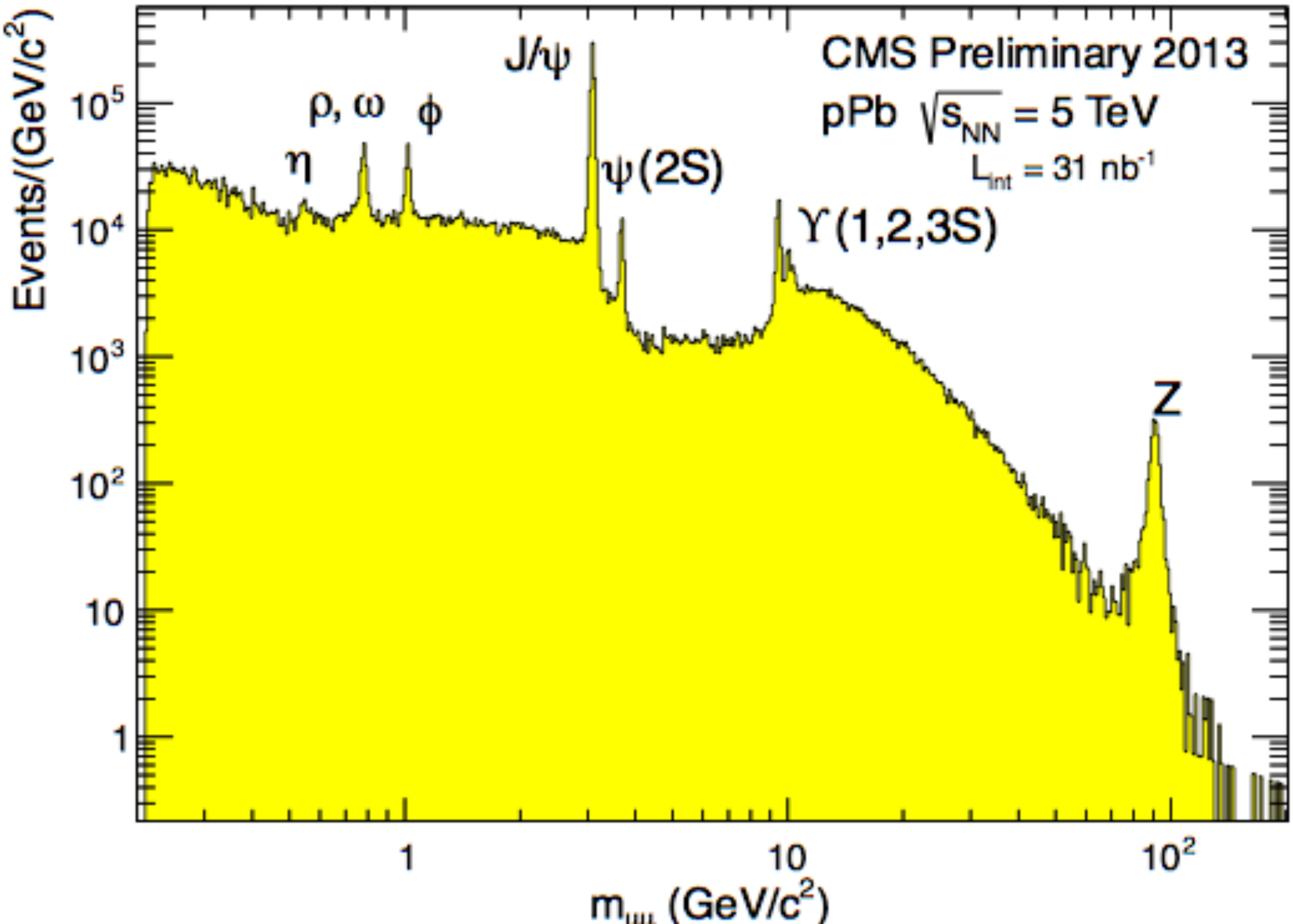




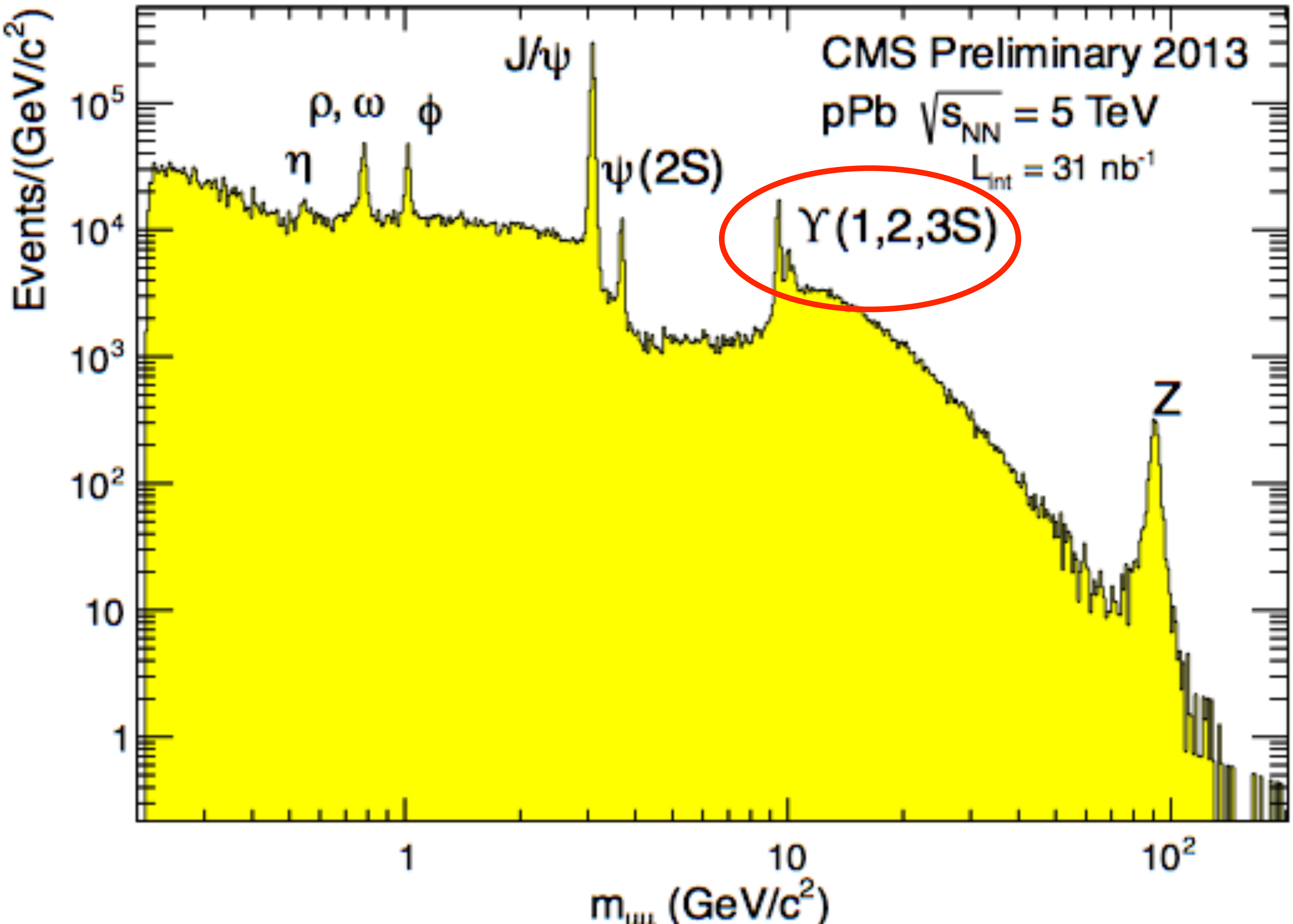
Strickland arXiv:1207.5327

- Model of thermal suppression in anisotropic hydro
  - Good description of CMS and ALICE data separately
  - Fails to describe mid- and forward rapidity ϒ(1S) data simultaneously

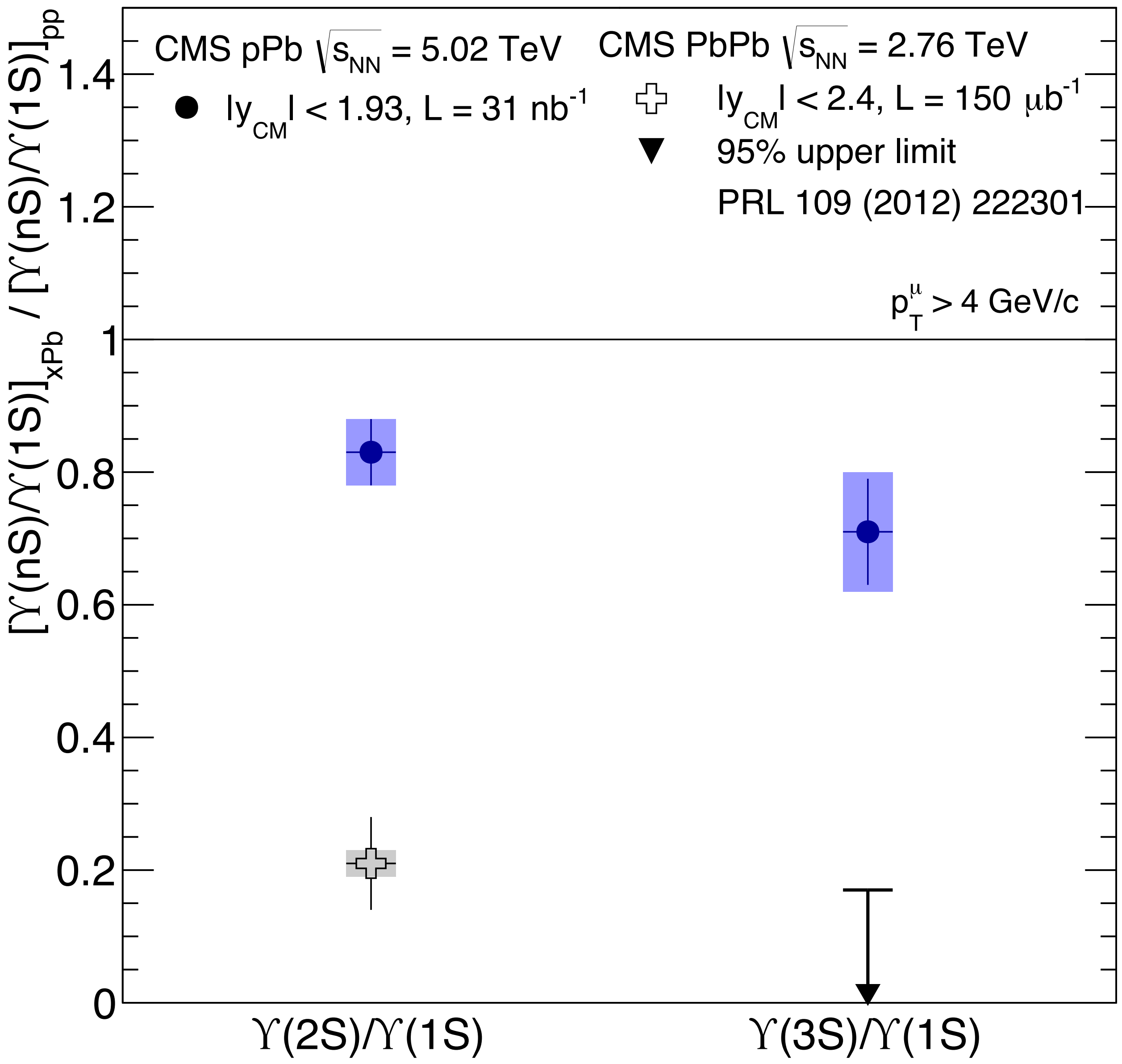
Muon Pairs in pPb at $\sqrt{s_{NN}}$ = 5.02 TeV



Muon Pairs in pPb at $\sqrt{s_{NN}}$ = 5.02 TeV



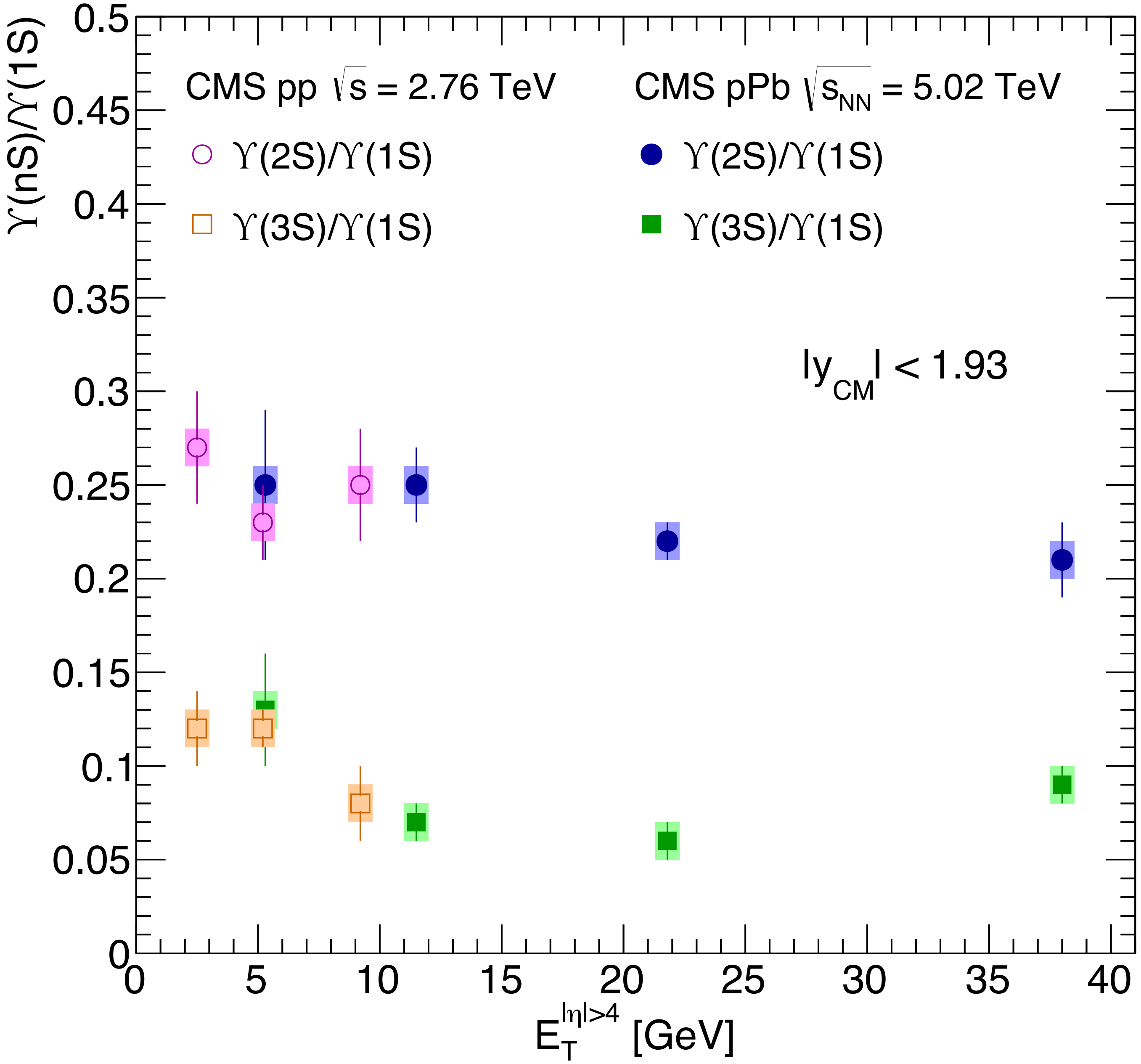
Υ(nS)/Υ(1S) Double Ratio in pPb



- PbPb: PRL 109 (2012)
  - slightly different rapidity ($|y_{CM}|<2.4$)
  - 2011 pp dataset
- Double ratios in pPb larger than in PbPb
  - suggests additional final effects in PbPb
  - but: model dependent extrapolation from pPb to PbPb:
- pPb vs pp:
  - double ratio less than unity (significance <3σ)

CMS HIN-13-003
JHEP 04 (2014) 103

Υ(nS)/Υ(1S) vs. "event activity"



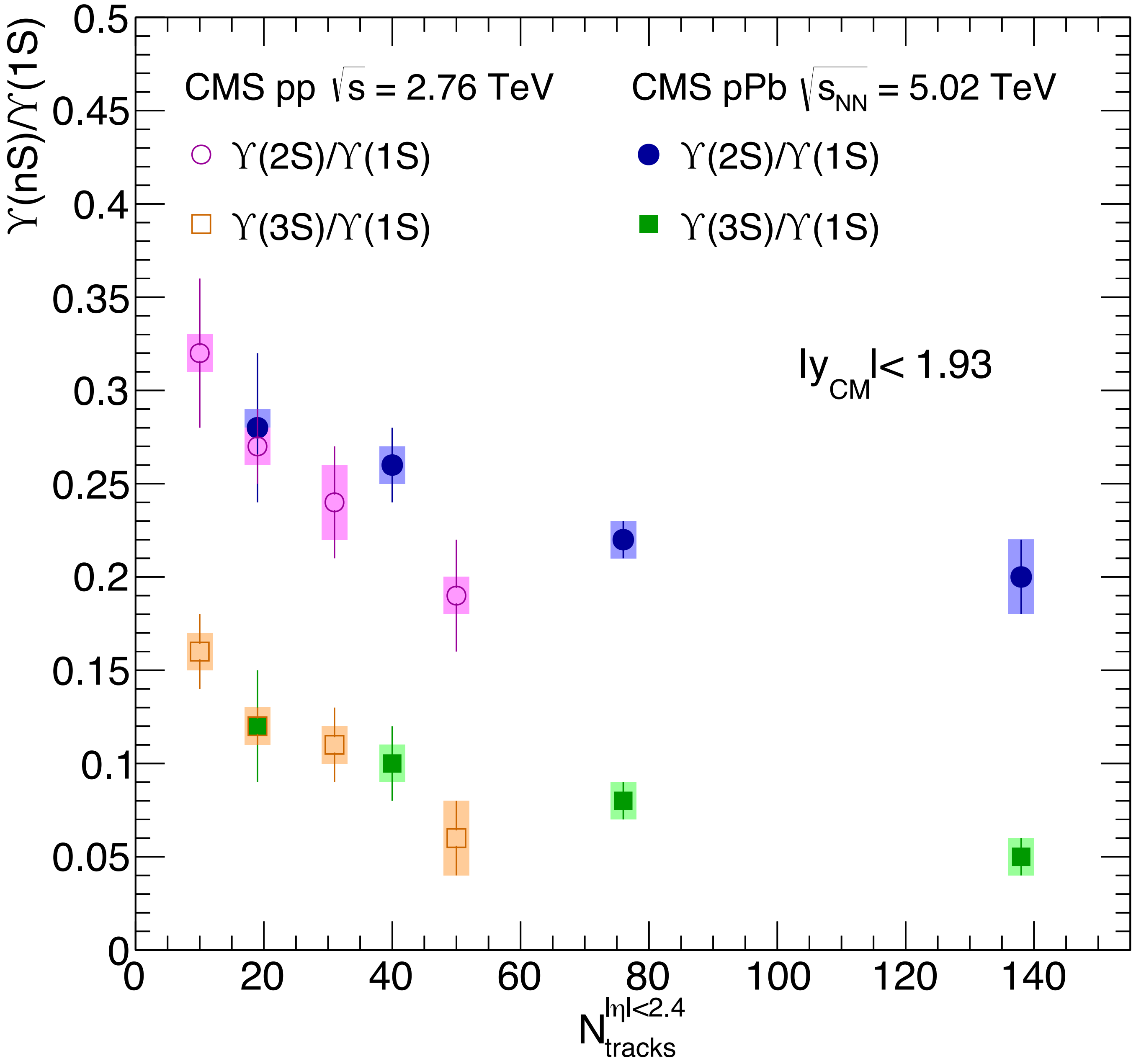
Single Ratios corrected for acceptance and efficiency

Measure event activity at

- Forward rapidity ($4<|\eta_{lab}|<5.2$)
  - $\sum E_T$ in Hadronic Forward Calorimeter
  - weak dependence
  - independent sets consistent with flat

CMS HIN-13-003
JHEP 04 (2014) 103

Υ(nS)/Υ(1S) vs. "event activity"



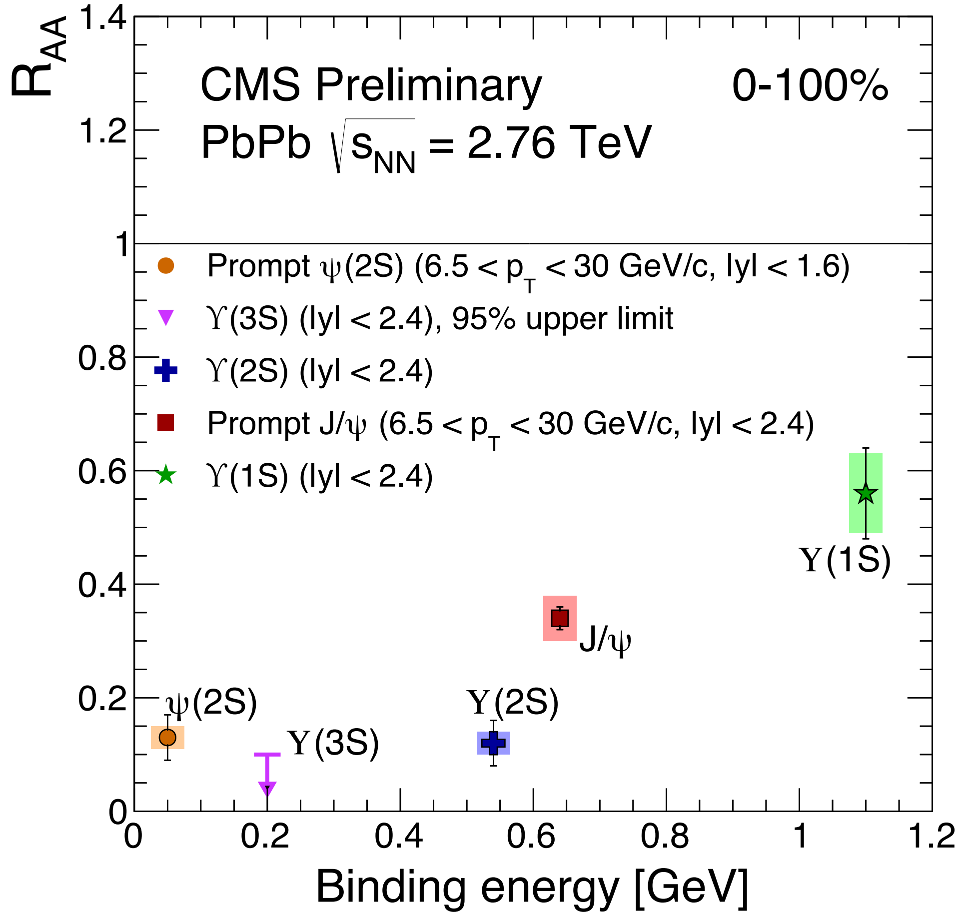
Single Ratios corrected for acceptance and efficiency

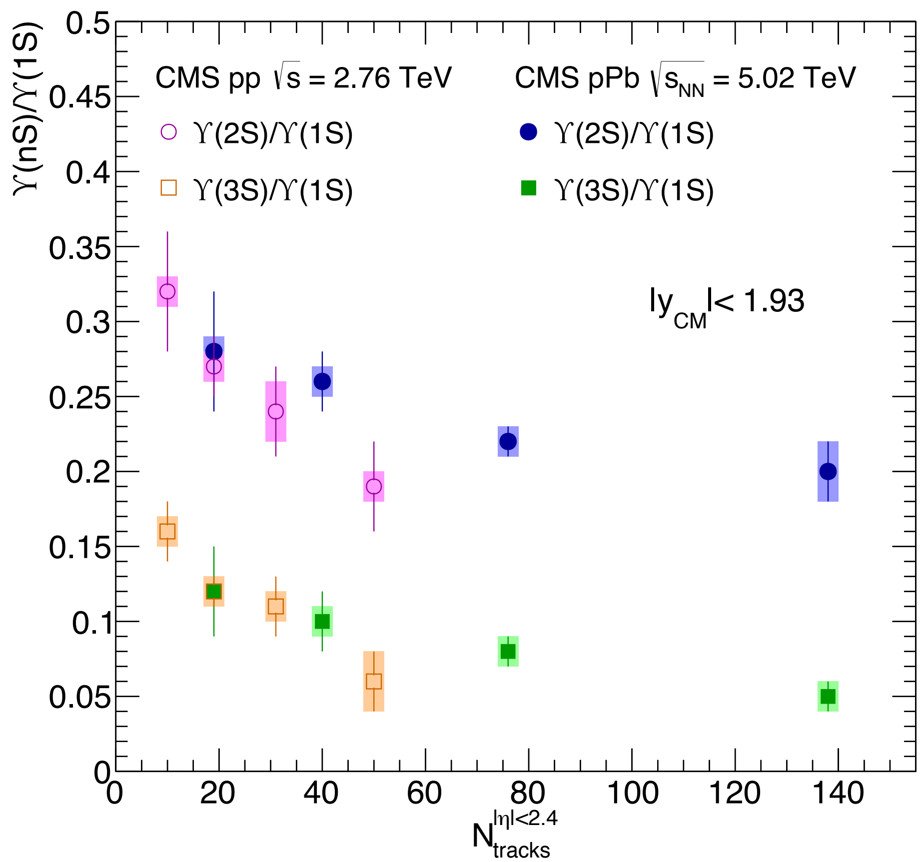
Measure event activity at

- Forward rapidity ($4<|\eta_{lab}|<5.2$)
  - $\sum E_T$ in Hadronic Forward Calorimeter
  - weak dependence
  - independent sets consistent with flat
- Midrapidity ($|\eta_{lab}|<2.4$))
  - N_{tracks}: multiplicity in silicon tracker
  - significant decrease with multiplicity
- Two options to explain results at midrapidity:
  - Υ affects multiplicity
    - ground states comes with 2 tracks more than excited state
  - multiplicity affects Υ
    - activity around the Υ breaks the state

CMS HIN-13-003
JHEP 04 (2014) 103

Summary



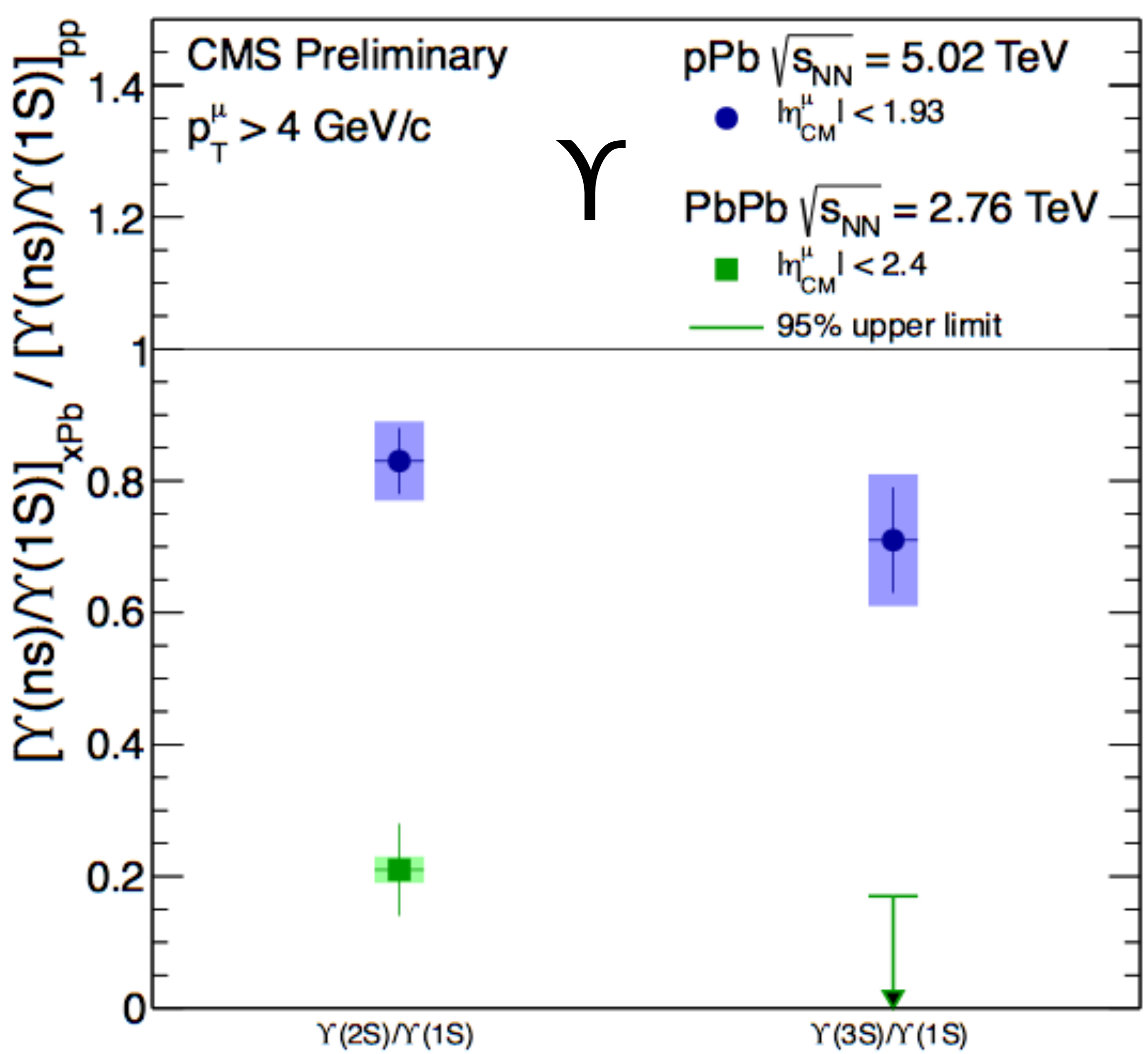


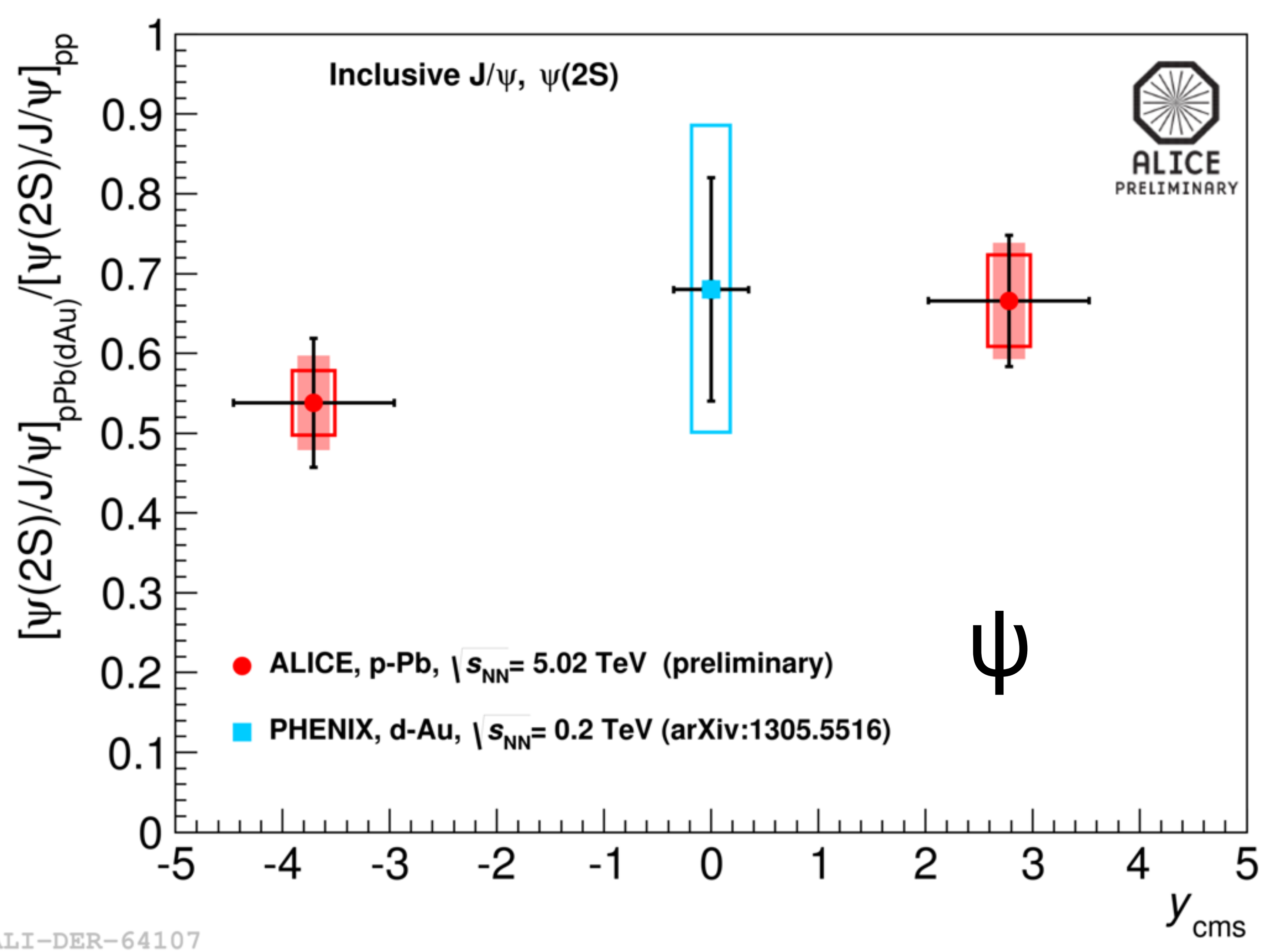
- Charmonia at low p_T
  - unexpected results on the suppression of ψ(2S): less suppression than at high p_T & midrapidity
- Charmonia at high p_T
  - J/ψ are more suppressed than at RHIC
  - ψ(2S) are more suppressed than J/ψ
  - as expected from sequential melting
- Bottomonia
  - Clear ordering of the suppression of the three ϒ states with their binding energy
  - as expected from sequential melting
- pPb data:
  - multiplicity dependence!
  - has to be considered when interpreting PbPb

Backup

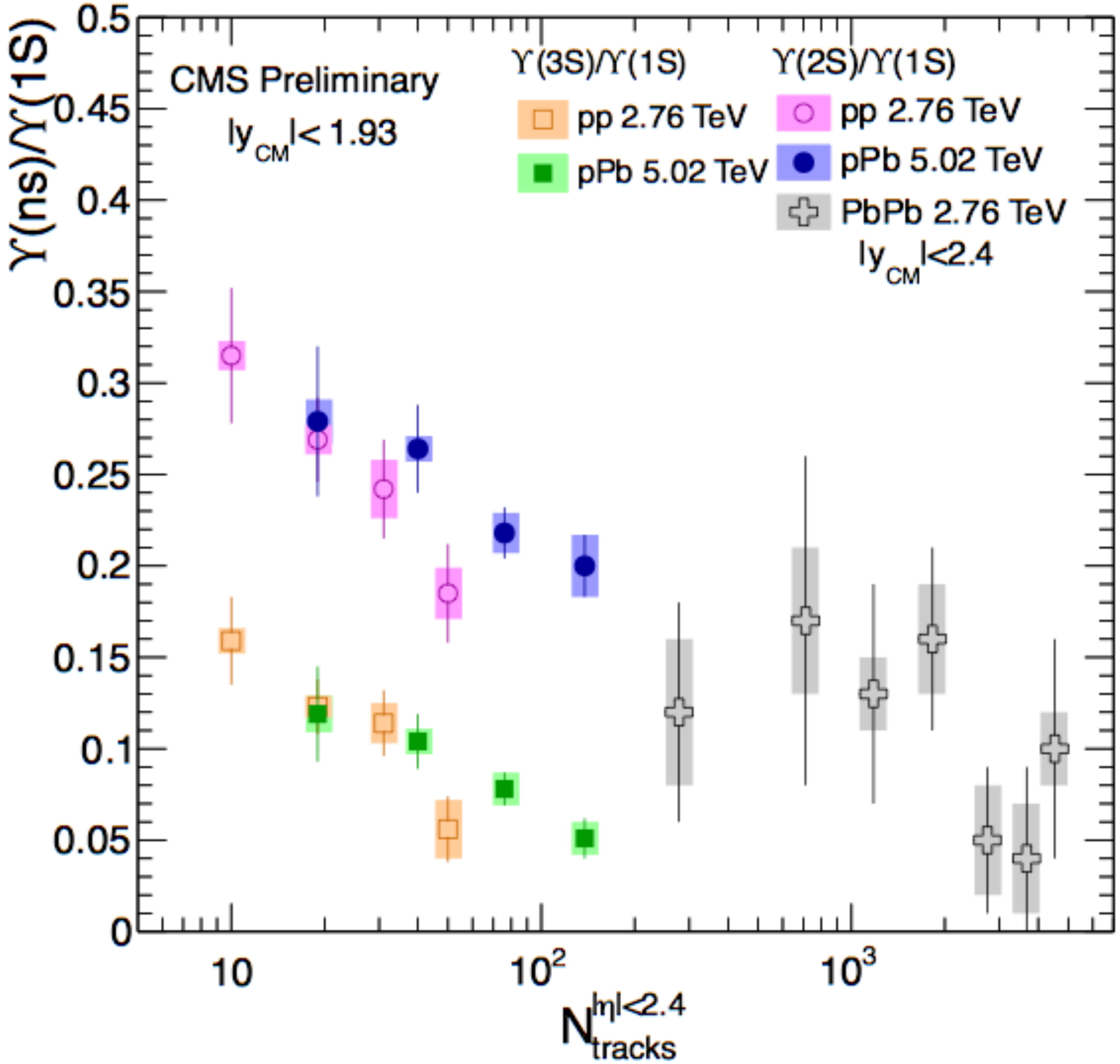
Excited quarkonia states in pA

- In pA excited states suppressed relative to ground state
  - cold effects differ for excited and ground states
- Consequences for AA results?
  - needs modelling, naive squaring for Υ would still leave room for extra hot effects
  - but then there is the multiplicity dependence…





ϒ(nS)/ϒ(1S) vs. "event activity"



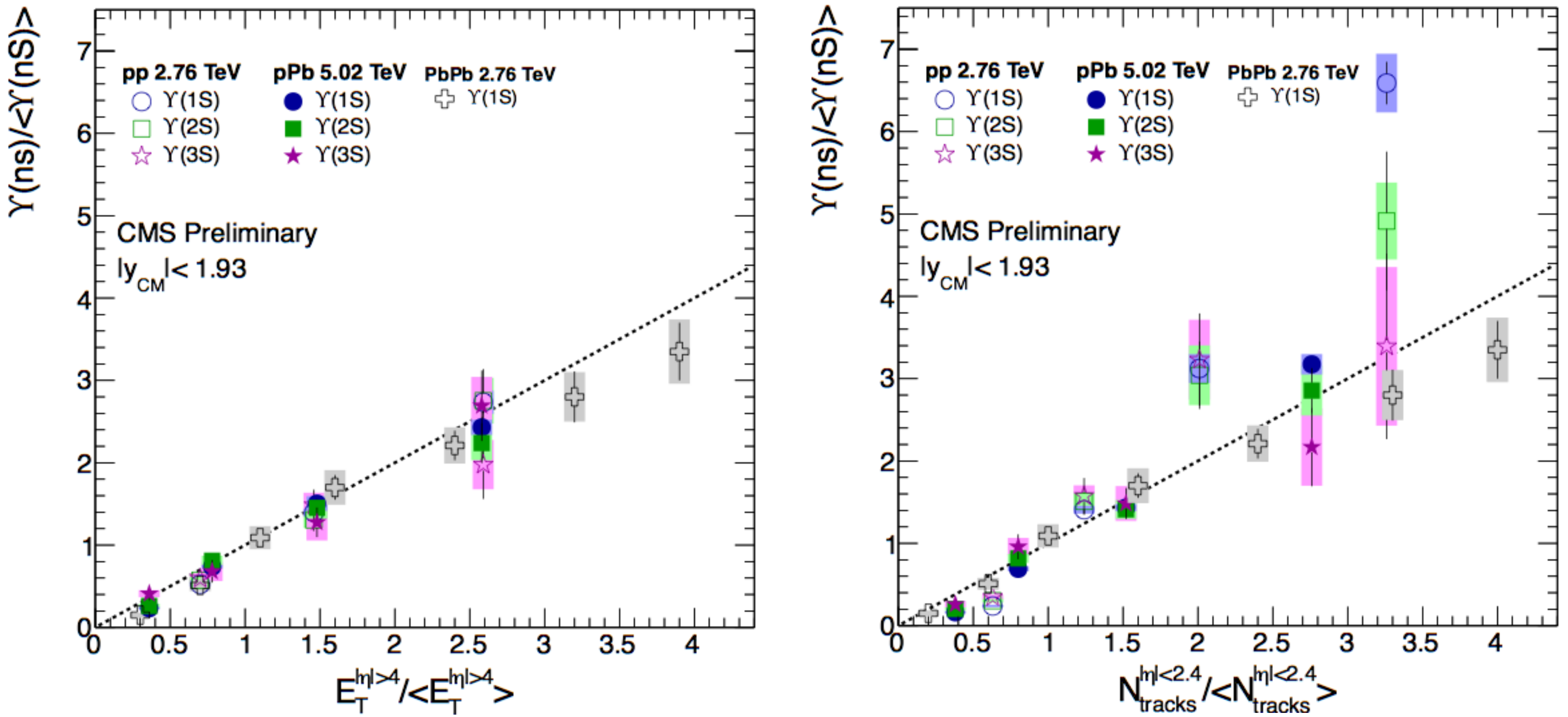
Single Ratios corrected for acceptance and efficiency

Measure event activity at

- forward rapidity ($4<|\eta_{lab}|<5.2$)
  - $\sum E_T$ in Hadronic Forward Calorimeter
  - weak dependence
  - independent sets consistent with flat
- midrapidity ($|\eta_{lab}|<2.4$))
  - N_{tracks}: multiplicity in silicon tracker
  - significant decrease with multiplicity
- PbPb data:
  - no dependence with multiplicity
  - very little overlap with pPb multiplicity
  - more PbPb data needed to check if central pPb is comparable to

CMS-HIN-13-003
Submitted to JHEP
(arXiv:1312.6300)

Self-normalized Υ(nS) yields

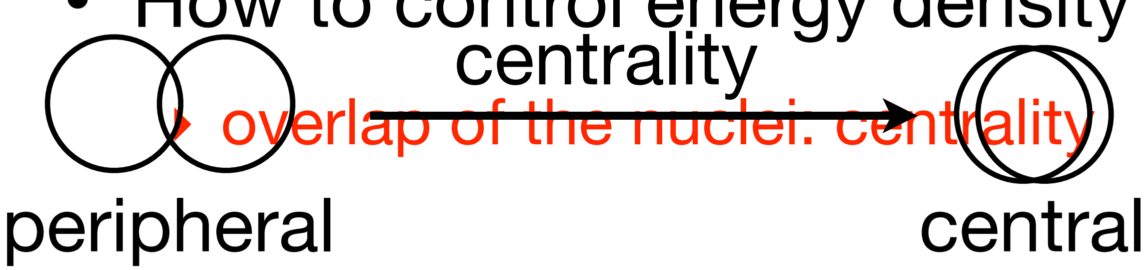


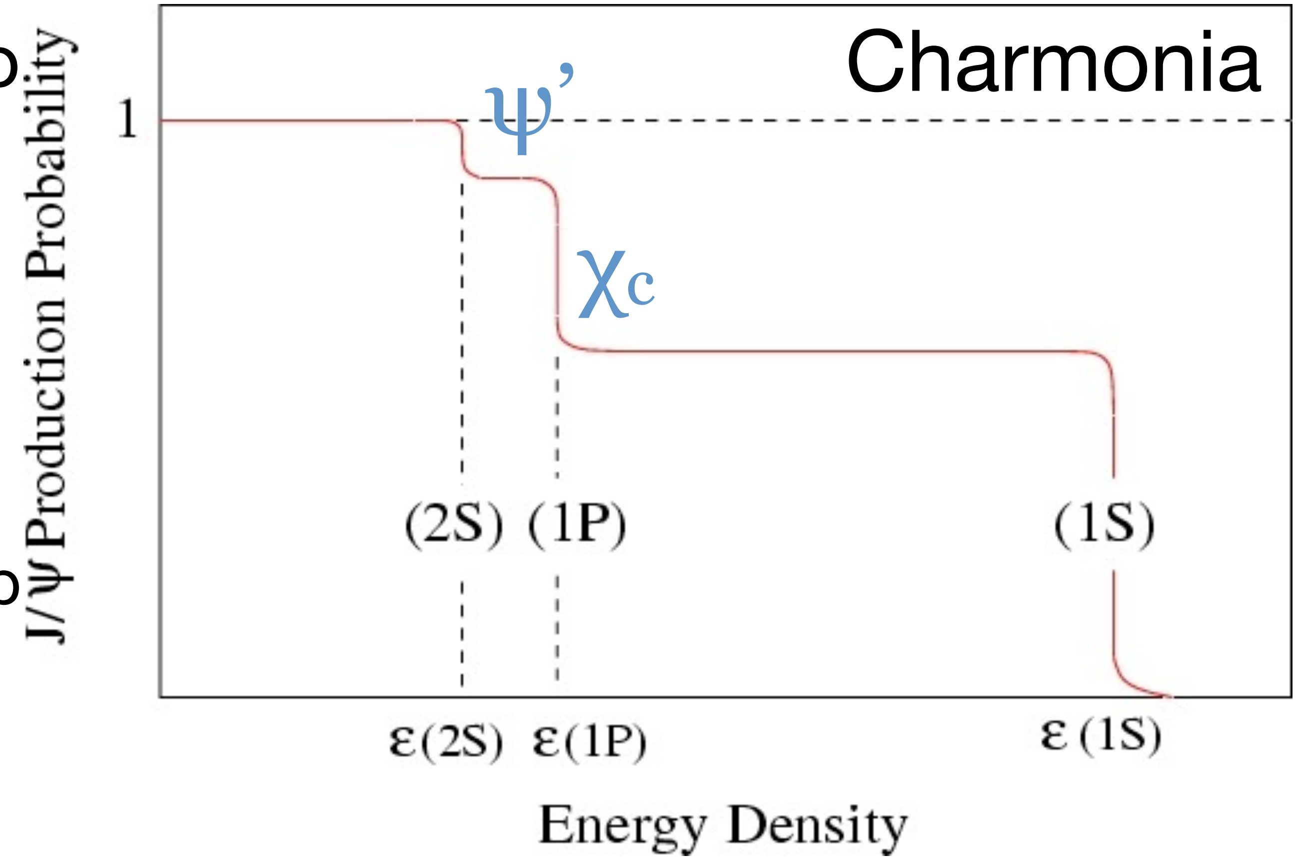
- More Υ in events with high event activity
- As a function of $\sum E_T$: all slopes consistent with 1
- As a function of N_{tracks}:
  - pPb and PbPb: approximate N_{coll} scaling

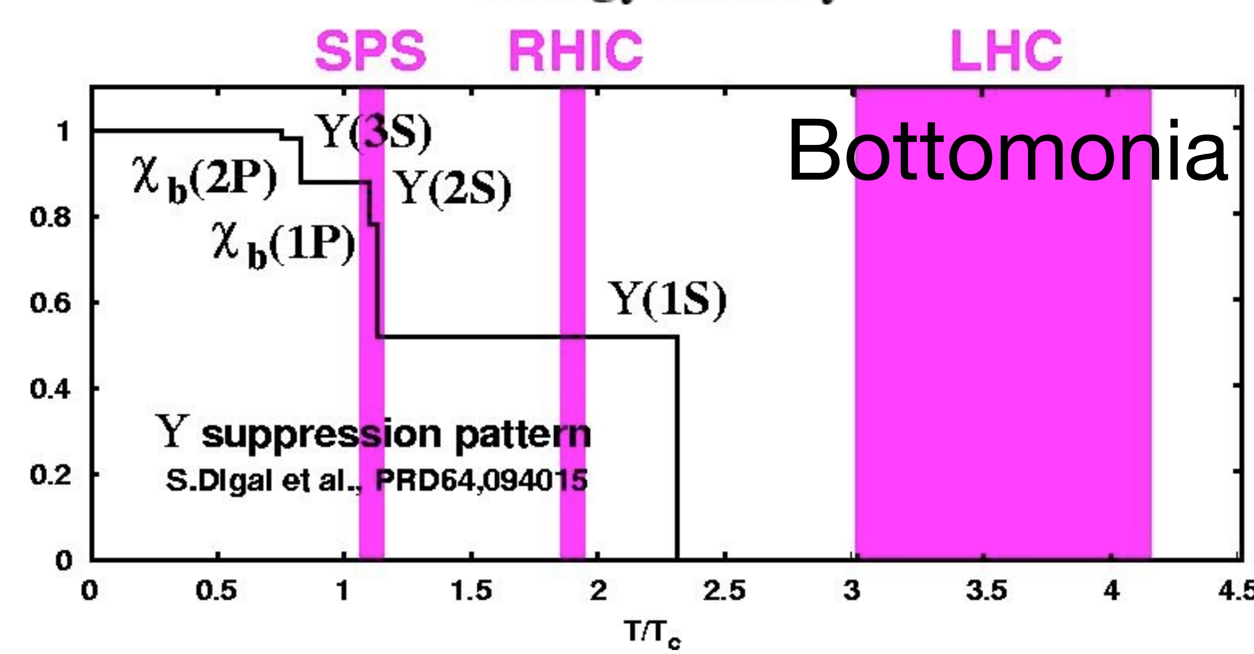
CMS HIN-13-003
Submitted to JHEP
(arXiv:1312.6300)

Quarkonia as Thermometer of the QGP

- Excited quarkonium states decay into ground states
- ~50% contribution to the total production of the ground state: feed down
  - fraction not well known → measure in pp
- If excited states are suppressed
  - no feed down → less production of the ground state
- Measure the rate of the ground state as function "energy density"
  - reduction of yield
    → melting of the excited state
    → T > binding energy
- How to control energy density?
  - overlap of the nuclei: centrality



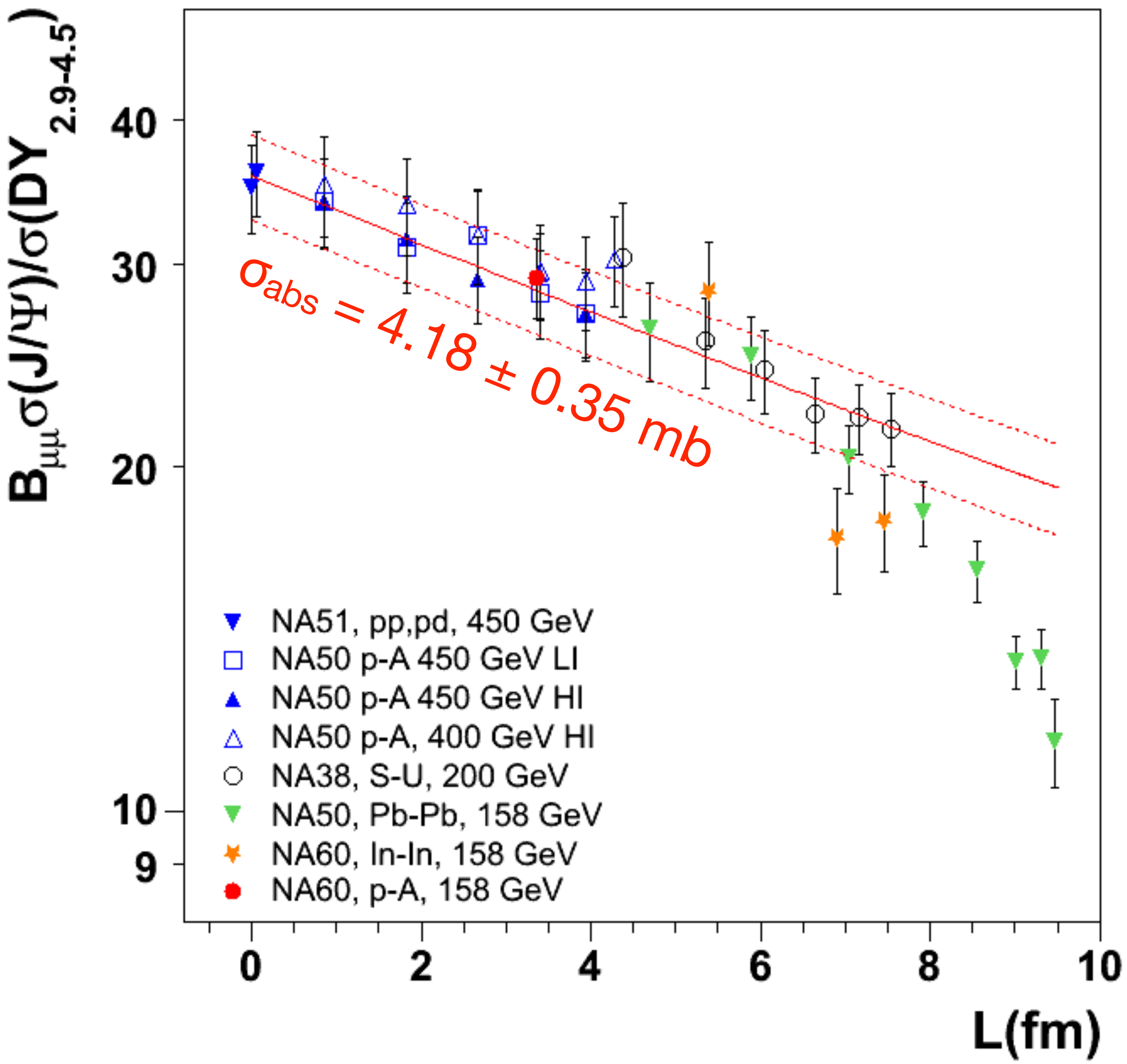


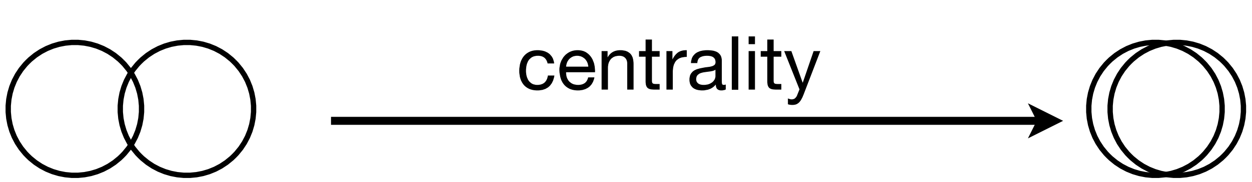


Υ (1S)	χ_b (1P)	Υ' (2S)	χ'_b (2P)	Υ'' (3S)
9.46	9.99	10.02	10.26	10.36
0.28	0.44	0.56	0.68	0.78

J/ψ suppression at the SPS

NA50, Eur. Phys. J. C39, 335 (2005)
NA60, PRL 99, 132302 (2007)

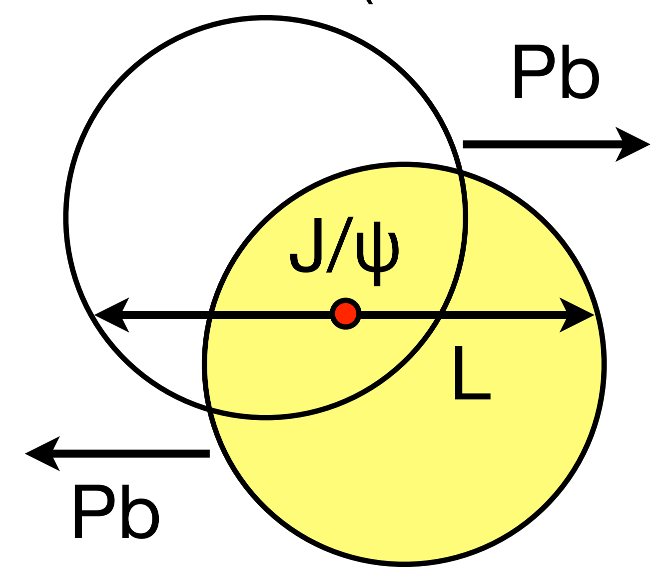




- J/ψ in pp and light ion collisions can be explained by normal nuclear absorption

$$\sigma(J/\psi) \propto \exp(-\rho_N \sigma_{\mathrm{abs}} L)$$

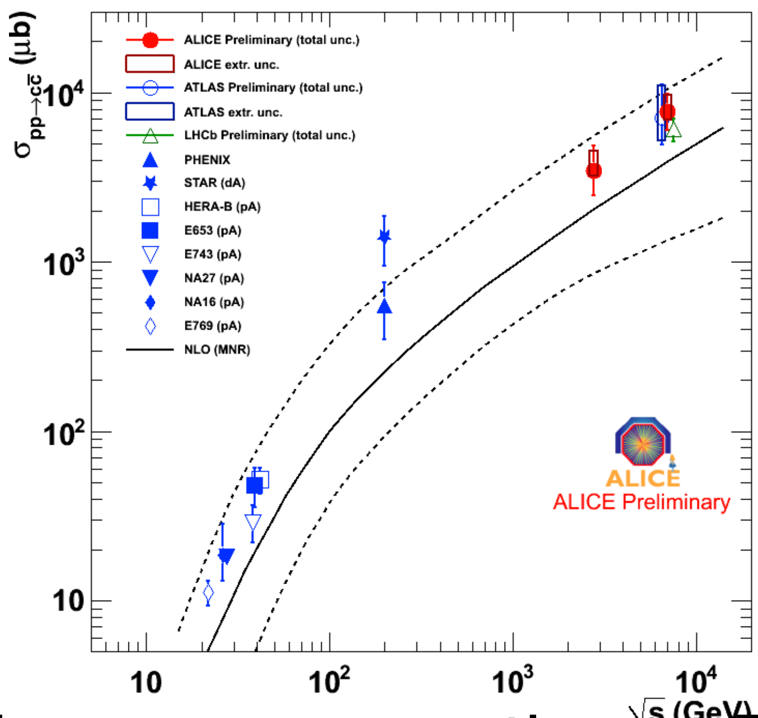
  - σ_{abs} = 4.18 ± 0.35 mb
  - ρ_N = 0.17/fm^3 (nuclear density)



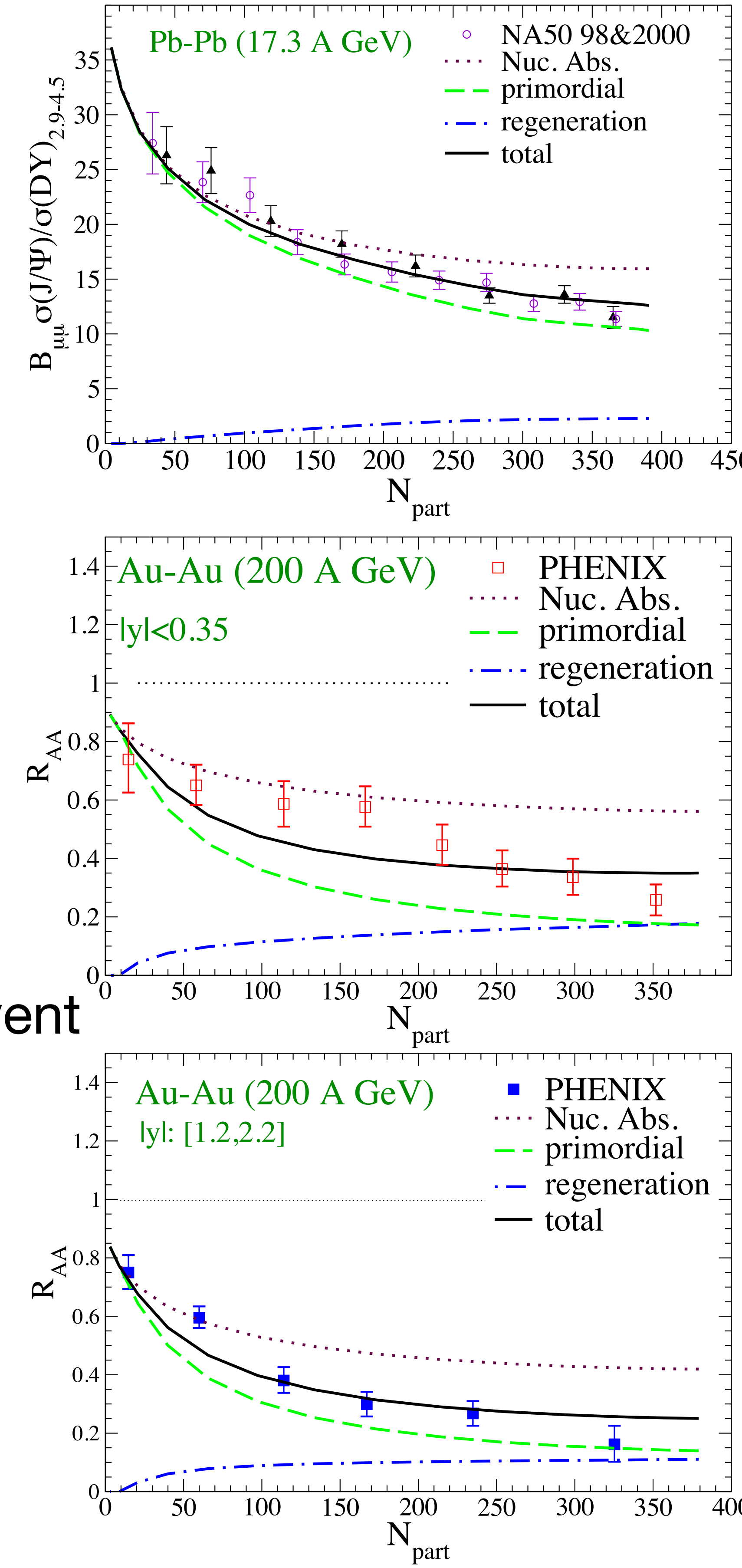
- Central InIn and PbPb collision show "anomalous suppression" beyond nuclear absorption
- Looks like the expected golden probe?!

(Re)combination?

- Charm quarks are only produced in the initial collision
- Charm quarks could thermalize in the QGP
- During the hadronization charm quarks could then combine to form J/ψ



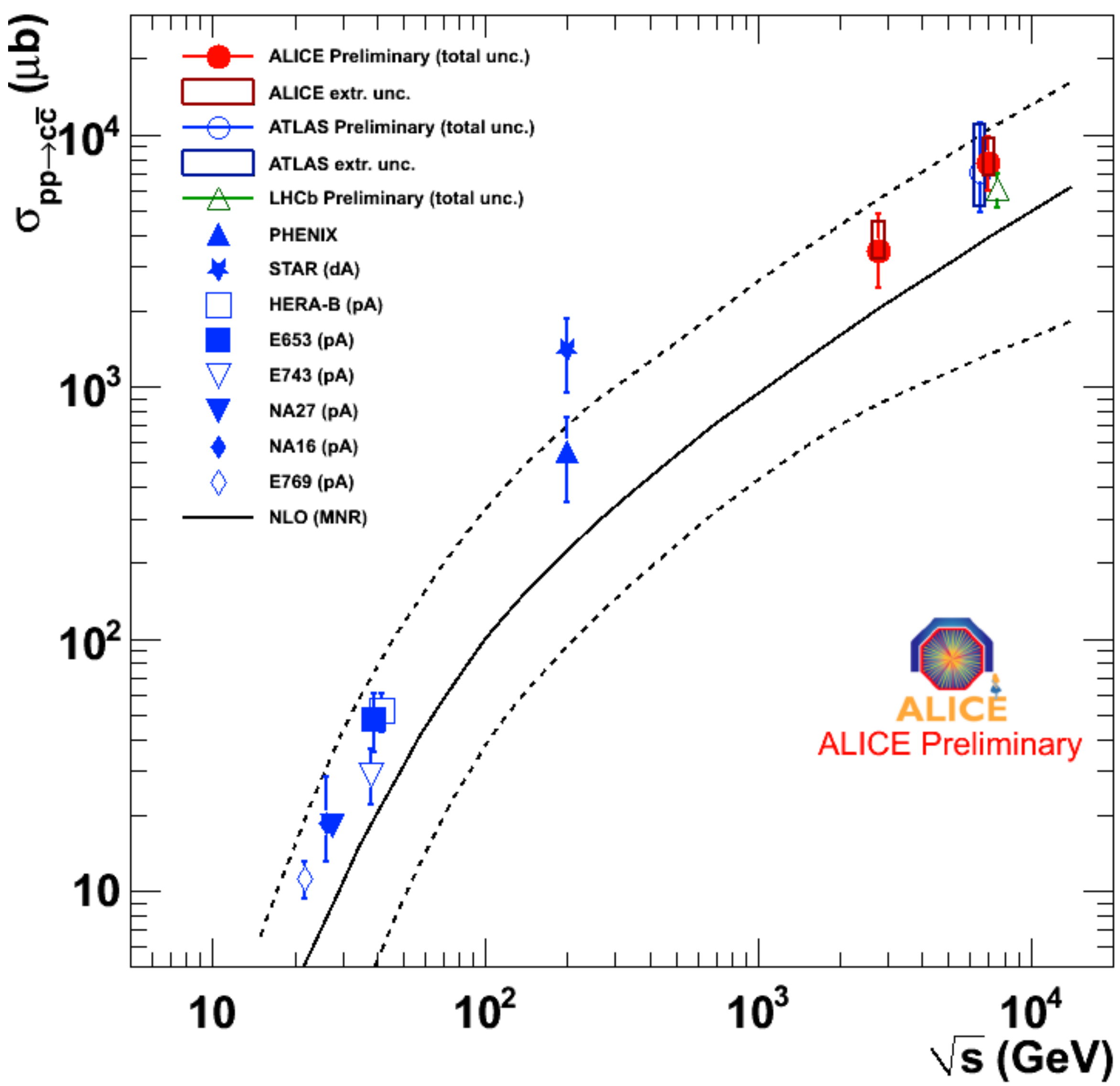
SPS: 1 cc pair/event
RHIC: 10 cc pairs/event

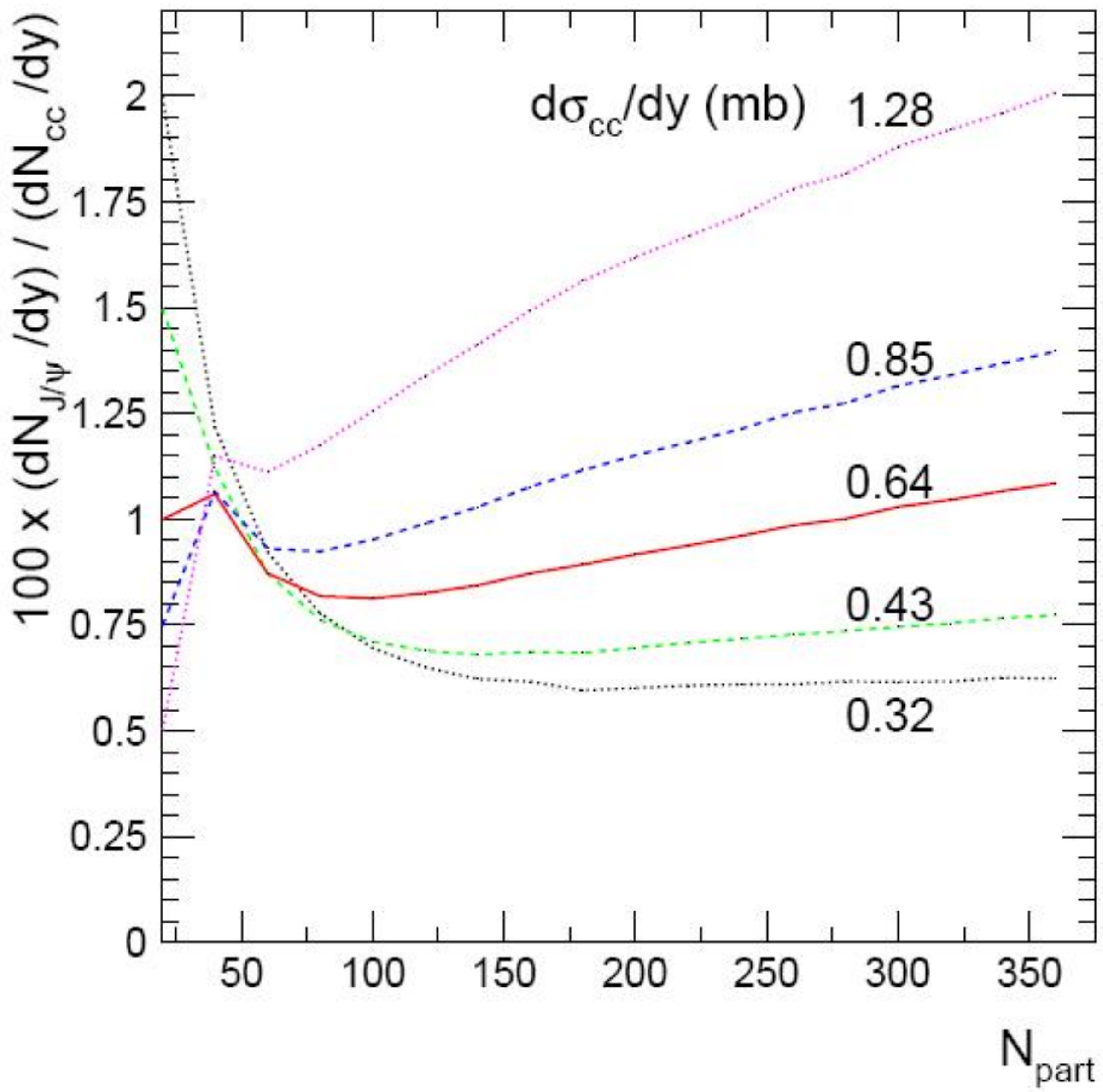


Zhao, Rapp, Phys. Rev. C82, 064905 (2010)

- Charm cross section at RHIC larger than at the SPS
  - increased recombination at RHIC counterbalances the suppression
  - less recombination at forward rapidity due to lower charm quark density

What to expect at the LHC?

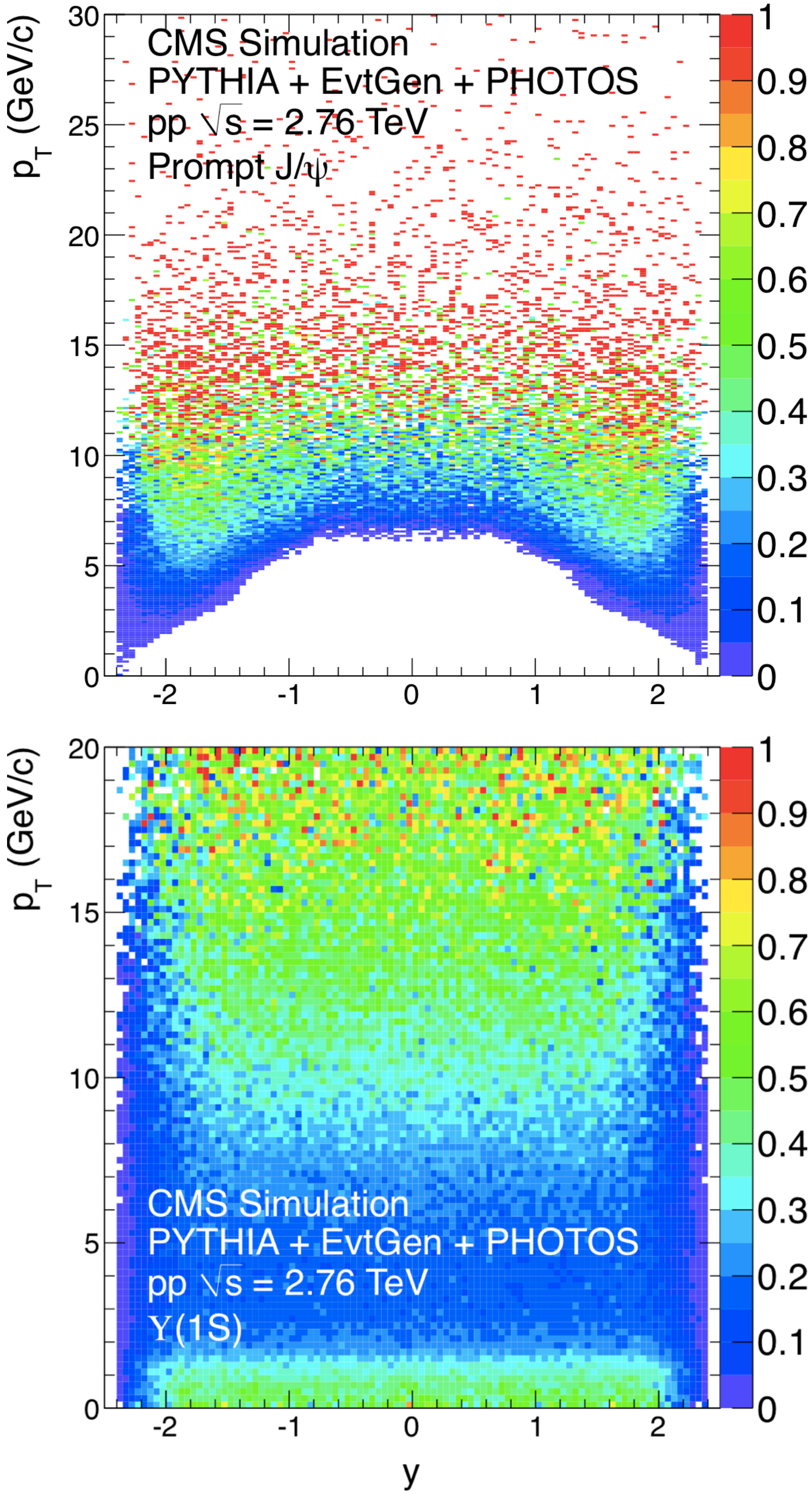




- SPS: 1 cc pair/event
- RHIC: 10 cc pairs/event
- LHC: 100 cc pairs/event (2 bb pairs/

If recombination of charm quarks occurs, expect even less suppression at the LHC

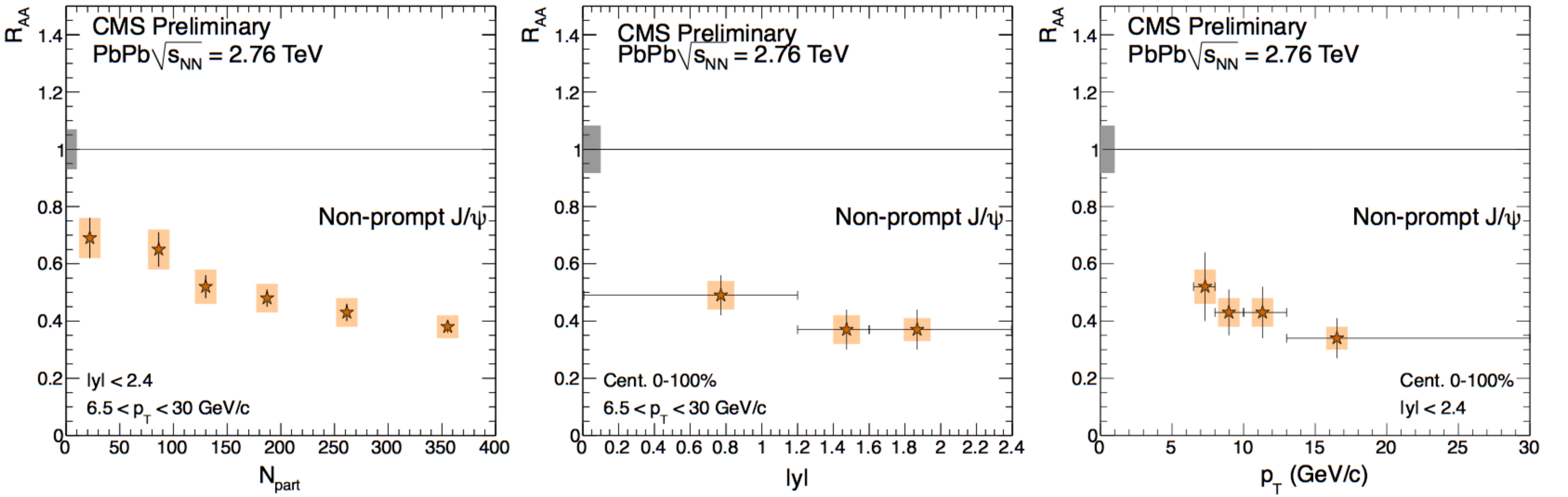
Muon Pair Acceptance



- Muons need to overcome the magnetic field and energy loss in the absorber
  - minimum total momentum p~3–5 GeV/c to reach the muon stations
- Limits J/ψ acceptance:
  - mid-rapidity: $p_T > 6.5$ GeV/c
  - forward rapidity: $p_T > 3$ GeV/c
- Υ acceptance:
  - $p_T > 0$ GeV/c for all rapidity

CMS HIN-10-006
JHEP 05 (2012) 063

Open Bottom: Non-prompt J/ψ R_{AA}

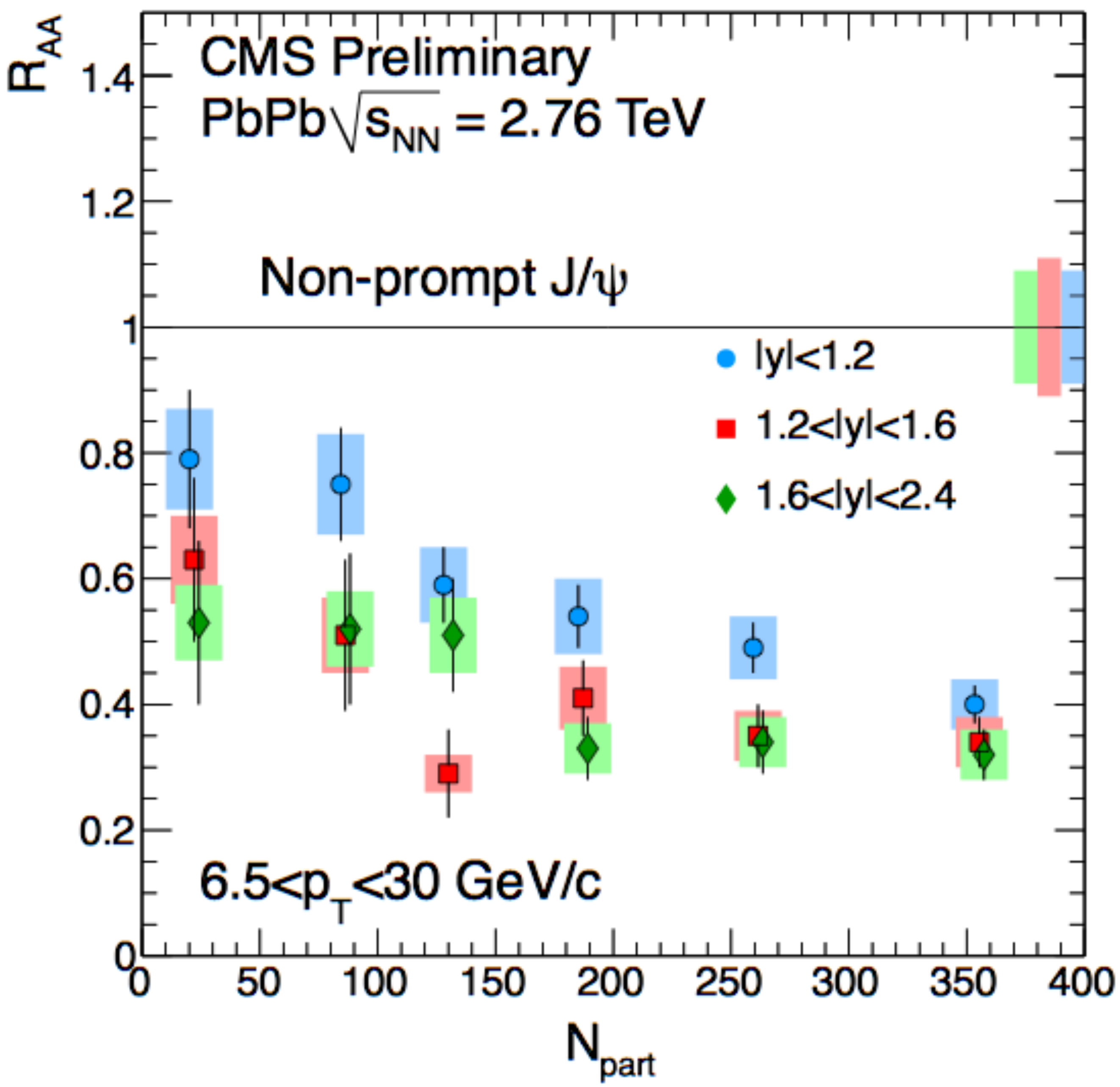


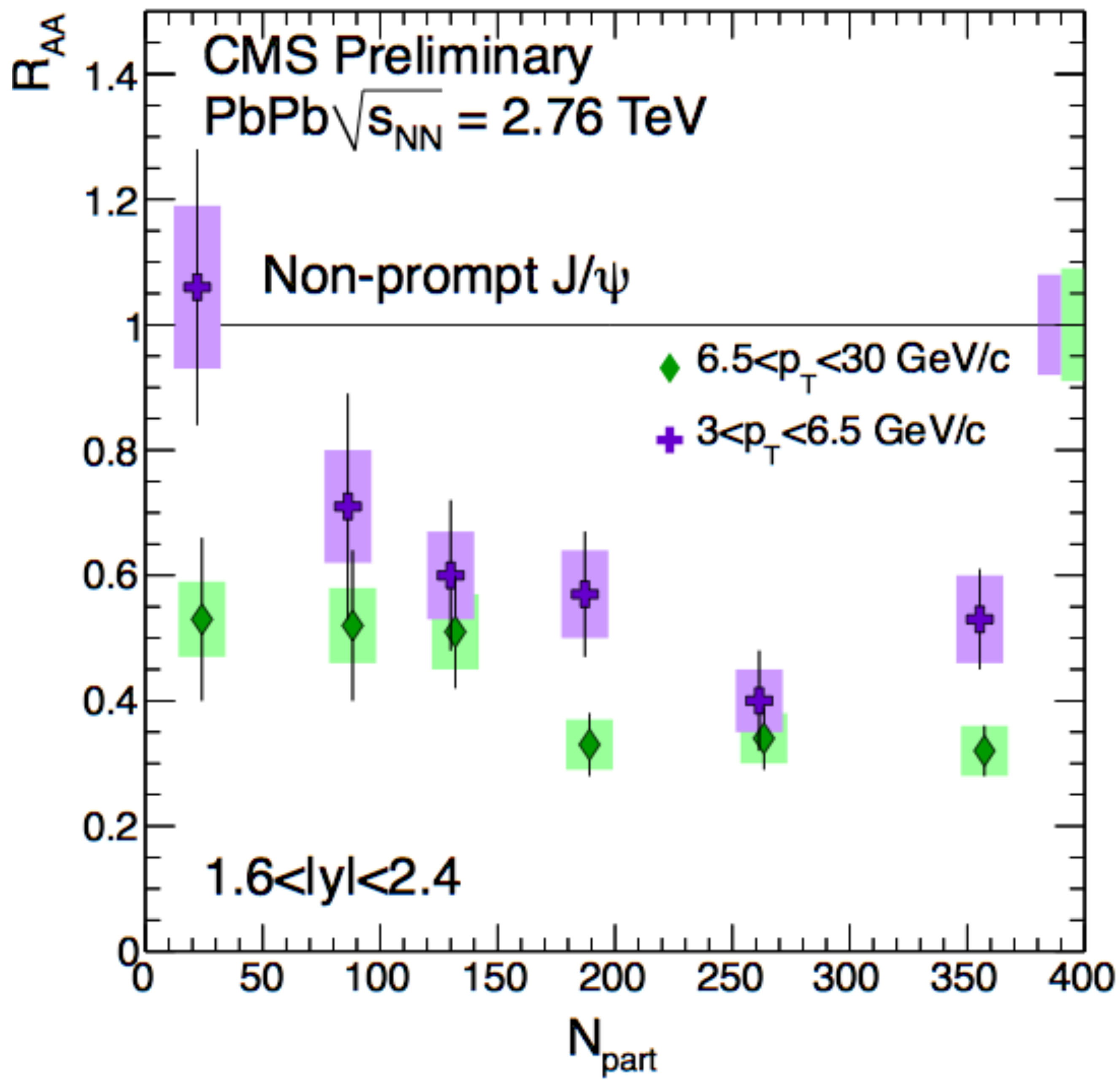
$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\mathrm{MB}}} \frac{N_{\mathrm{PbPb}}}{N_{pp}} \frac{\varepsilon_{pp}}{\varepsilon_{\mathrm{PbPb}}}$$

- Non-prompt J/ψ from b-hadron decays: direct access to energy loss of b quarks
- Integrated over p_T > 6.5 GeV/c and |y| < 2.4
  - in 0–10% centrality: suppressed by a factor 2.5
  - in 50–100% centrality: suppressed by a factor ~1.4
- Integrated over centrality:

CMS PAS HIN-12-014

Non-prompt J/ψ R_{AA}: double differential



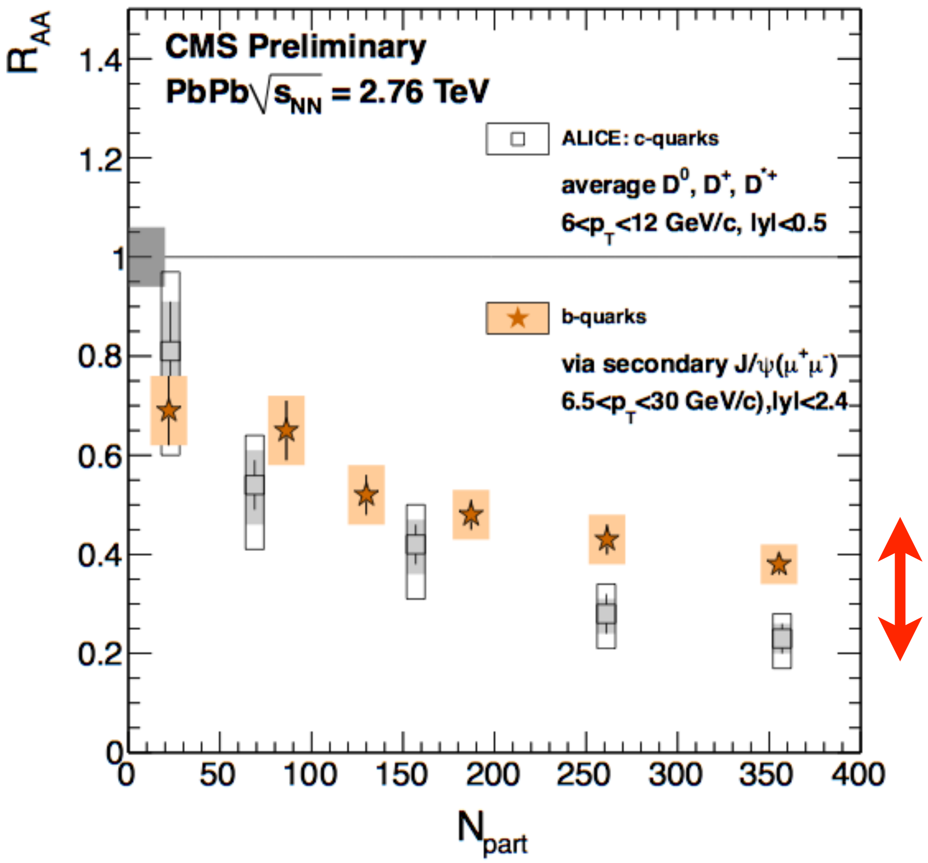


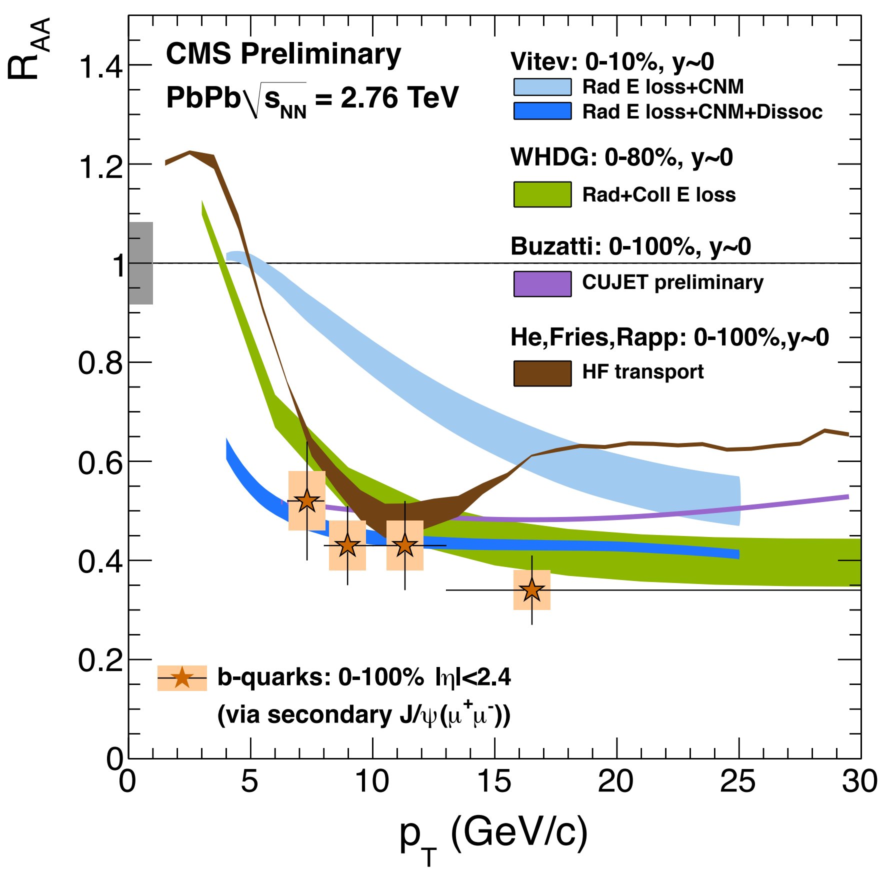
- Centrality dependence is independent of rapidity

CMS PAS HIN-12-014

- At forward rapidity: access to lower p_T ($3 < p_T < 6.5$ GeV/c)
  - slightly less suppression in most central collision at low p_T than at high p_T

Open heavy-flavour

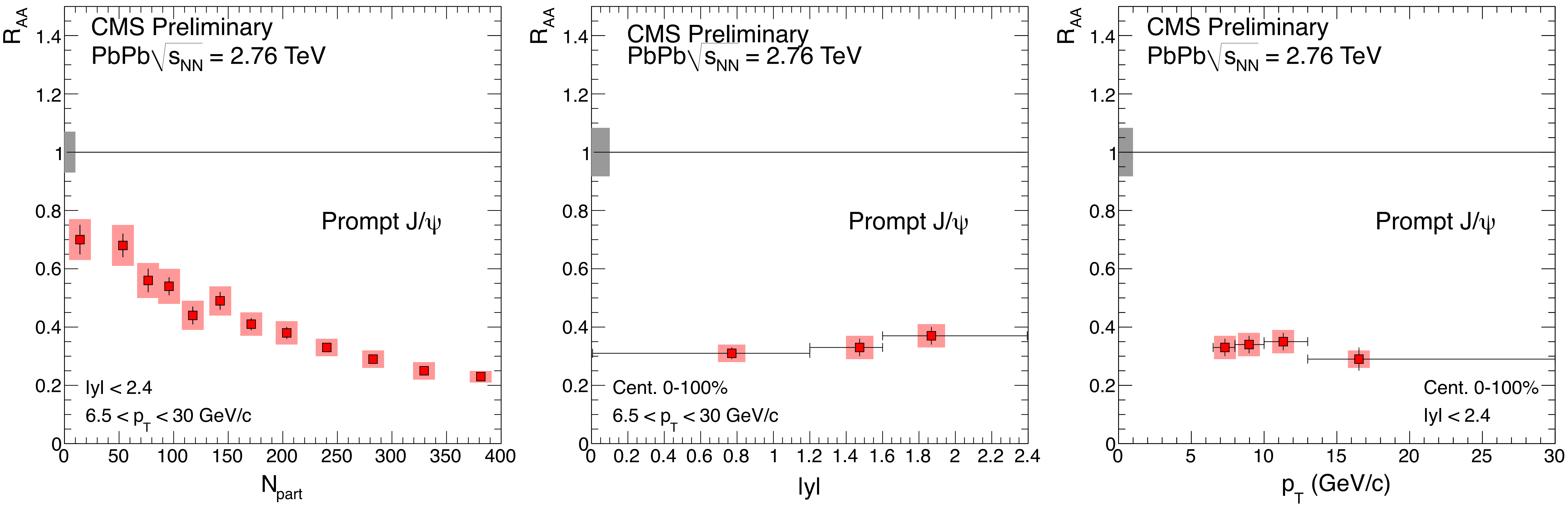




- ALICE measures R_{AA} of various D mesons
- CMS measures non-prompt J/ψ from b-hadron decays
- Expect ordering of suppression with quark mass
  - a.k.a. “dead-cone effect”
- There is order!
- Radiative energy loss alone is not enough to describe b-quark energy loss
- Models do not decay B, so are for B p_T
  - B p_T > J/ψ p_T (at high p_T)

CMS: PAS HIN-12-014
ALICE: JHEP 09 (2012) 112
Vitev: J. Phys.G35 (2008) 104011 + priv. comm.
Horowitz: arXiv:1108.5876 + priv. comm.
Buzzatti, Gyulassy: arXiv: 1207.6020 + priv. comm.
He, Fries, Rapp: PRC86(2012)014903 + priv. comm.

Prompt J/ψ R_{AA} at high p_T

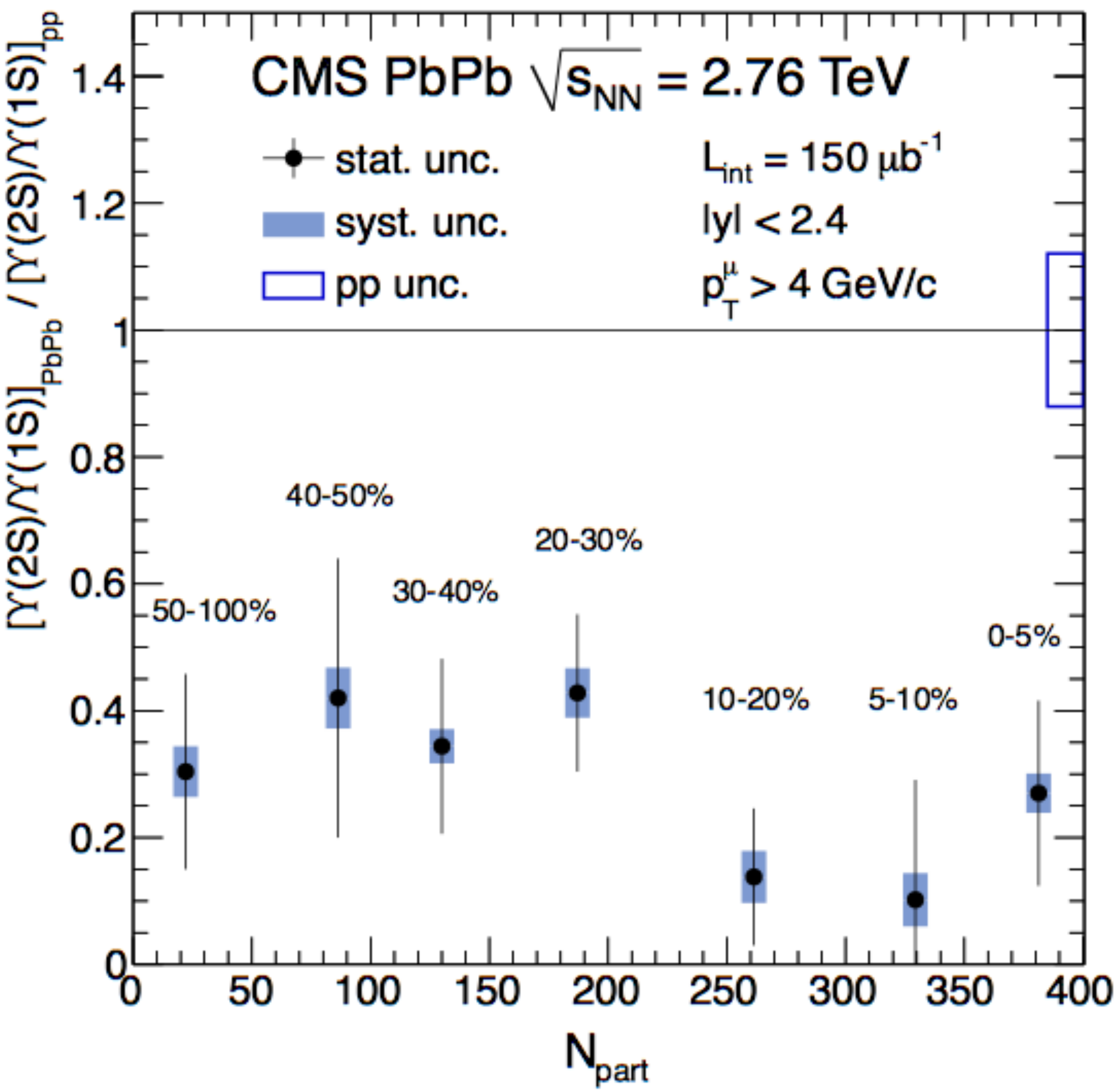


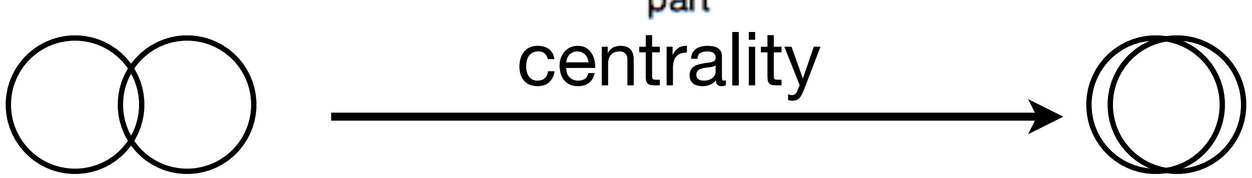
$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\rm MB}} \frac{N_{\rm PbPb}}{N_{pp}} \frac{\varepsilon_{pp}}{\varepsilon_{\rm PbPb}}$$

- Prompt J/ψ R_{AA} based on pp reference at $\sqrt{s}$ = 2.76 TeV ($\mathcal{L}_{pp}$ = 231 nb^{-1})
- Integrated over p_T > 6.5 GeV/c and |y| < 2.4
  - egrated over centrality:
  - no significant dependence on rapidity or p_T

CMS PAS HIN-12-014

Υ(nS)/Υ(1S) Double Ratio





- Separated Υ(2S) and Υ(3S)
- Measured Υ(2S)/Υ(1S) double ratio vs. centrality
  - centrality integrated

$$\frac{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\text{PbPb}}}{N_{\Upsilon(2S)}/N_{\Upsilon(1S)}|_{\text{pp}}} = 0.21 \pm 0.07 \pm 0.02$$

  - no strong centrality dependence
- Upper limit on Υ(3S)
  - centrality integrated:

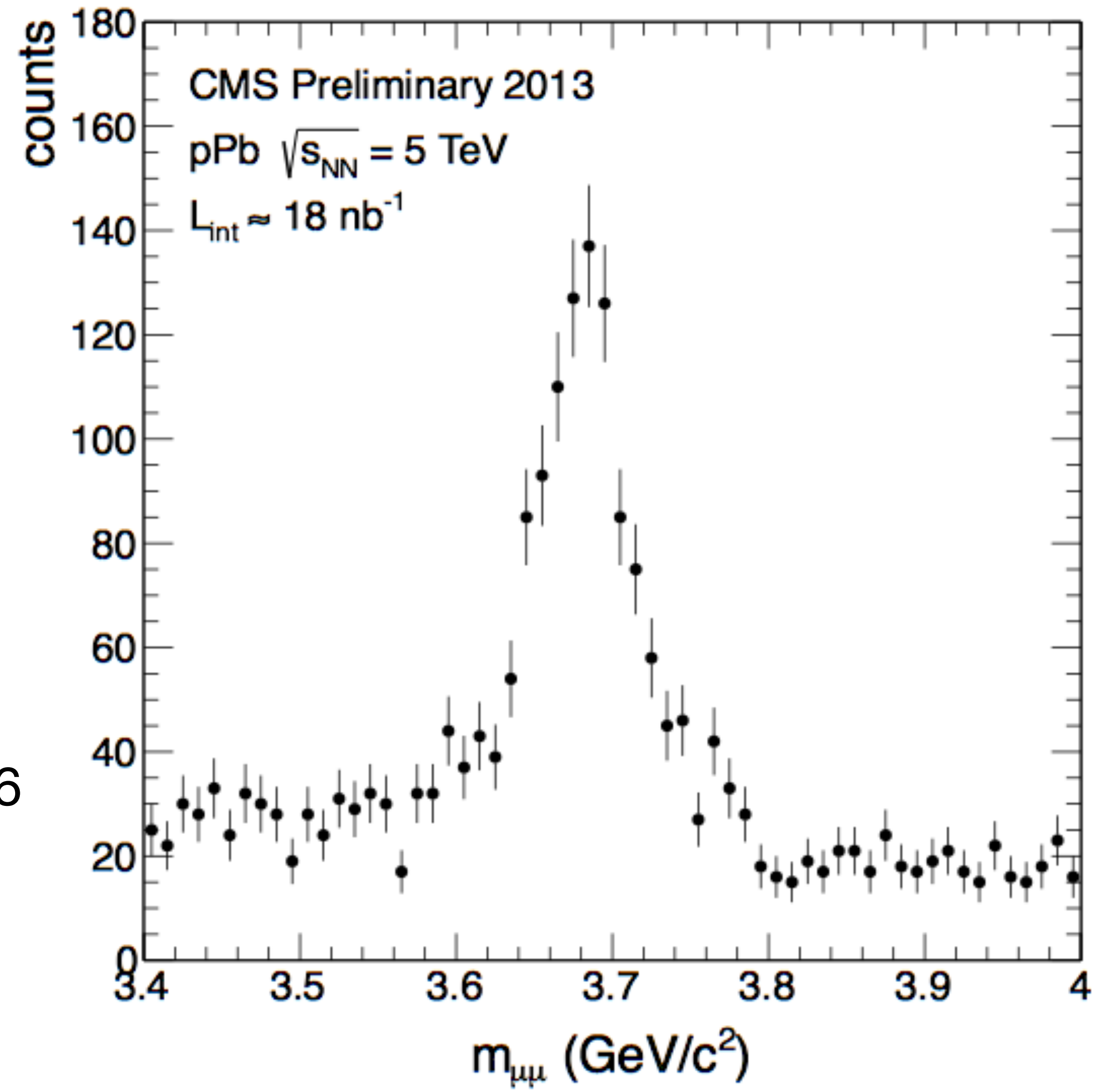
$$\frac{N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{\text{PbPb}}}{N_{\Upsilon(3S)}/N_{\Upsilon(1S)}|_{\text{pp}}} < 0.17\ (95\%\ \text{C.L.})$$

CMS HIN-11-011
PRL 109 (2012) 222301

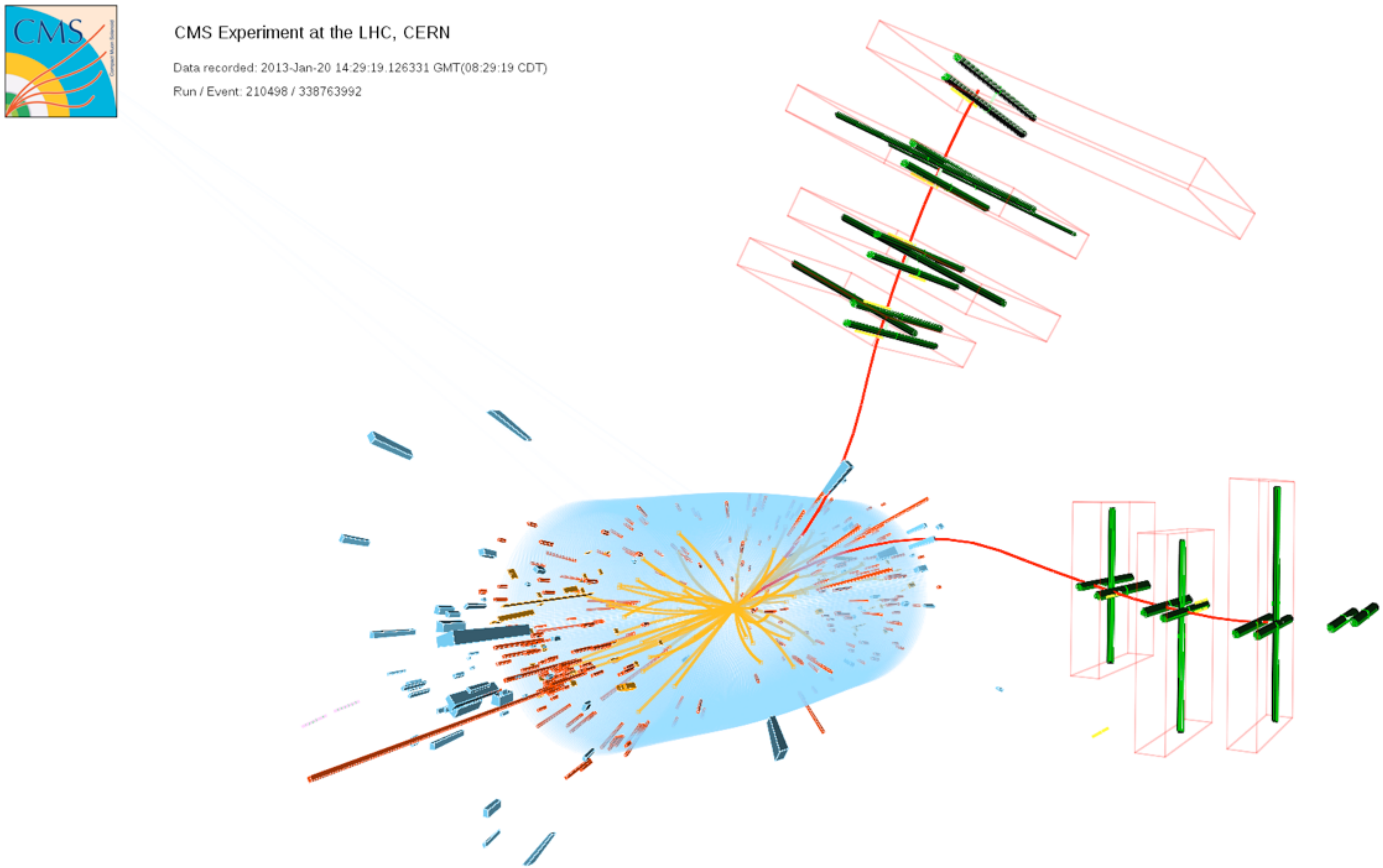
Outlook: ψ(2S)→$\mu^+\mu^-$ in pPb

CMS DP-2013-002

- Measured in pPb data at $\sqrt{s_{NN}}$ = 5 TeV
  - Integrated luminosity: 18 nb^{-1}
    - half of the total recorded luminosity
- Events selected with a double-muon trigger
- A good primary vertex is required
- A soft-muon identification is applied
- Invariant-mass spectrum of opposite-sign muon pairs in the ψ(2S) mass region is shown
- One example for quarkonium states measured by CMS
- And we just increased the pp sample at 2.76 TeV by a factor 20
  - Quarkonia RAA vs. p_T and y
  - Improve ψ(2S) double ratio



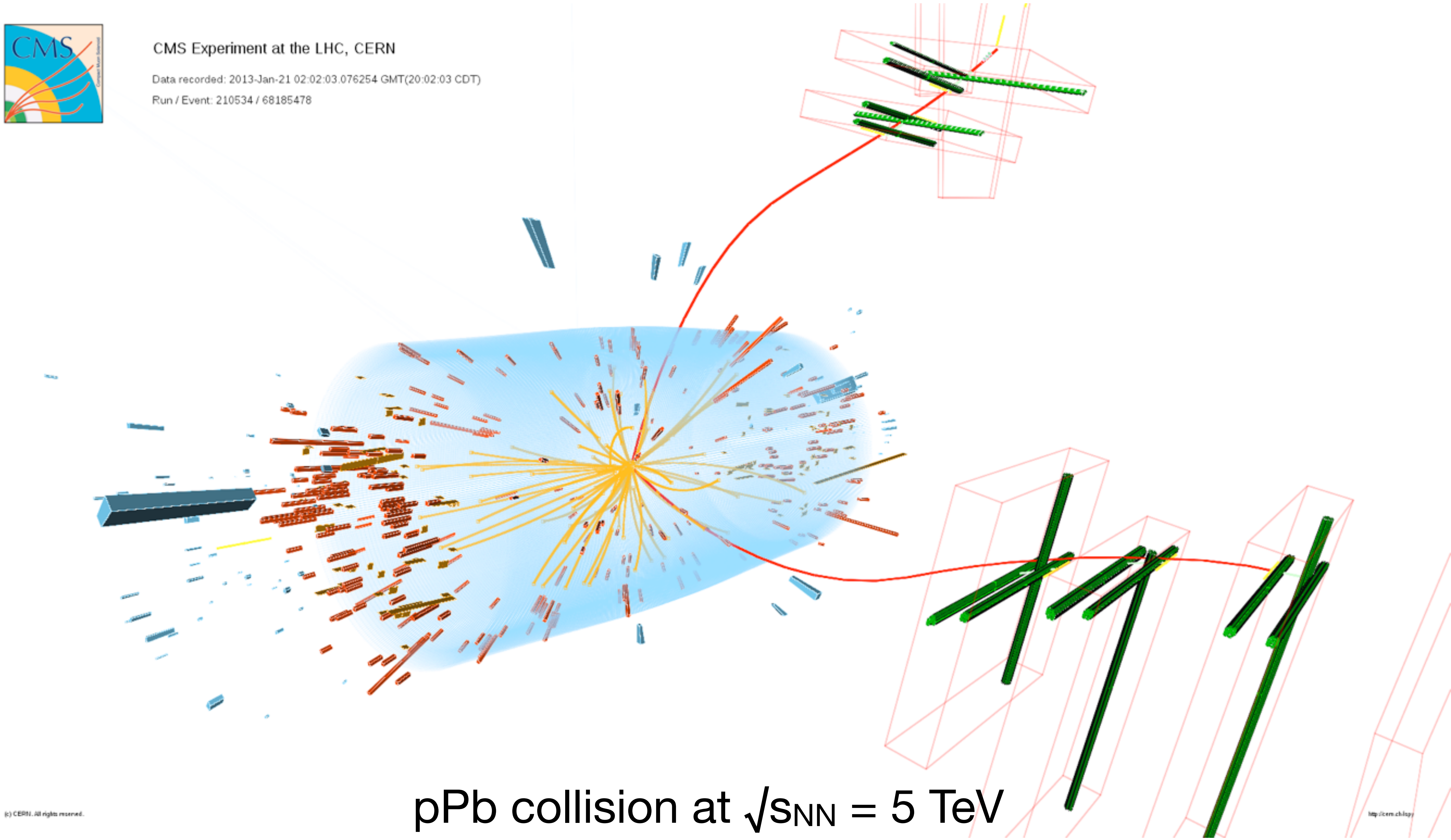
J/ψ candidate in pPb at $\sqrt{s_{NN}}$ = 5 TeV



pPb collision at $\sqrt{s_{NN}}$ = 5 TeV

CMS DP-2013-001

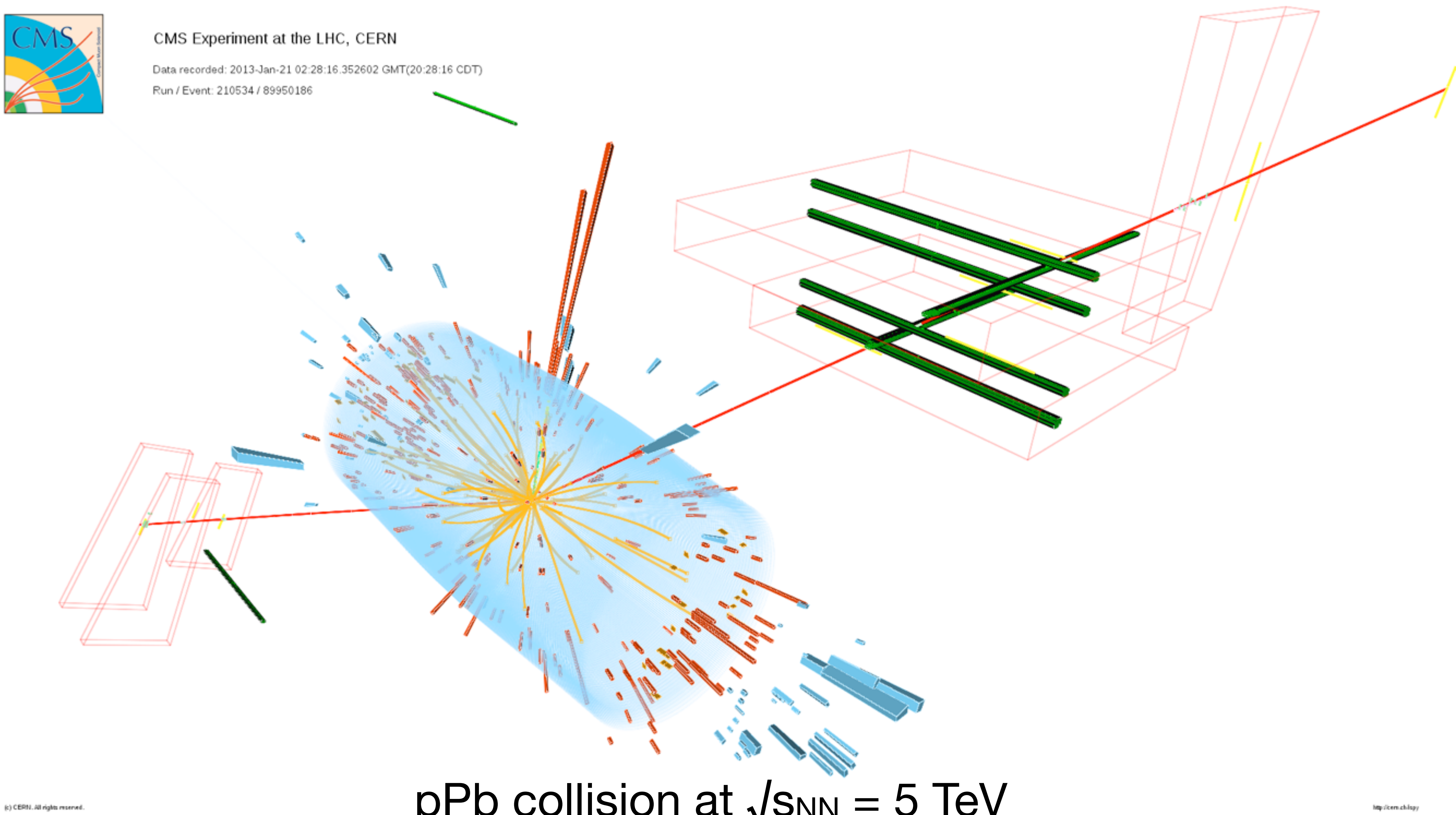
Υ(1S) candidate in pPb at $\sqrt{s_{NN}}$ = 5 TeV



pPb collision at $\sqrt{s_{NN}}$ = 5 TeV

CMS DP-2013-001

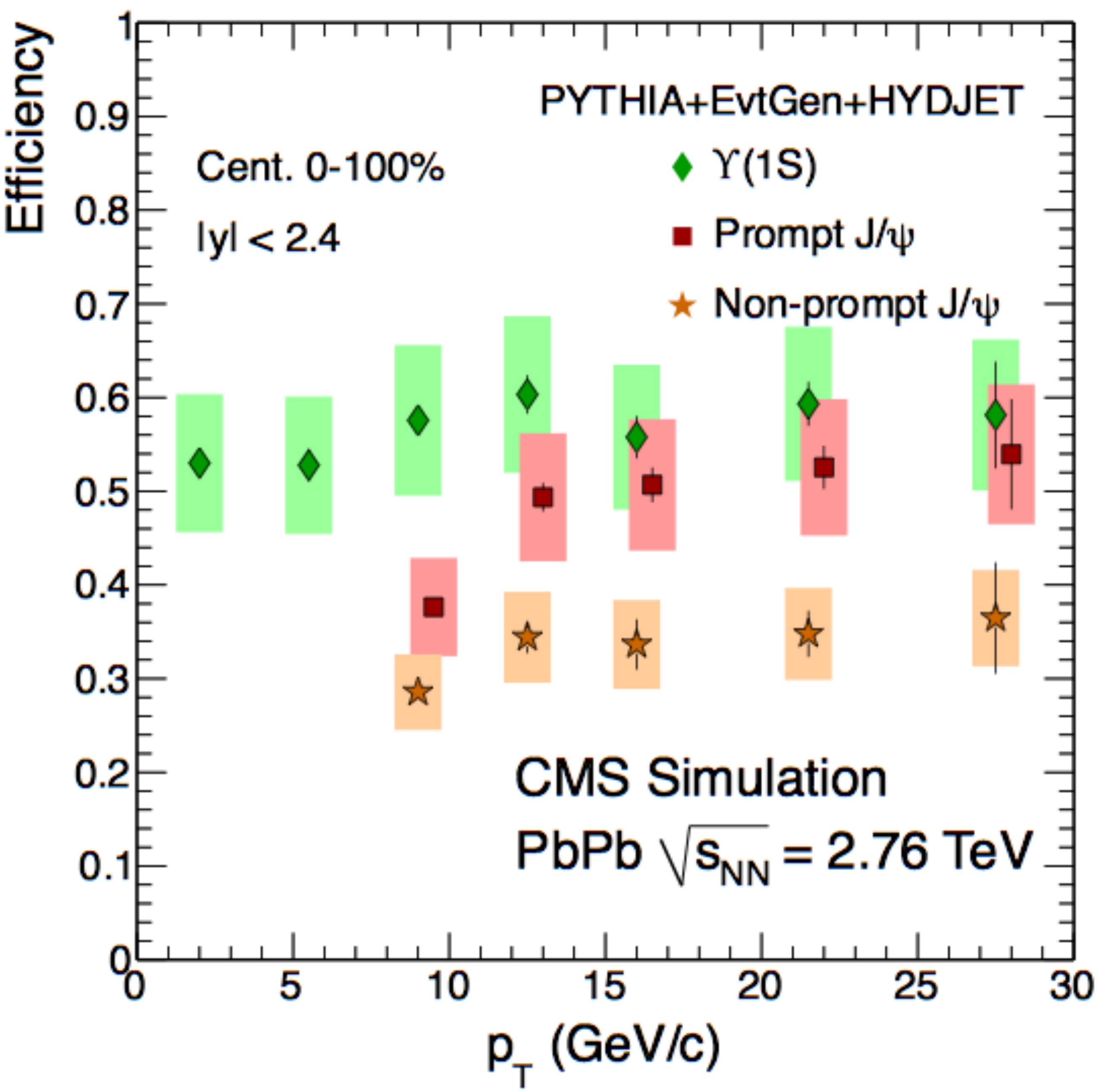
Z candidate in pPb at $\sqrt{s_{NN}} = 5$ TeV



pPb collision at $\sqrt{s_{NN}} = 5$ TeV

CMS DP-2013-001

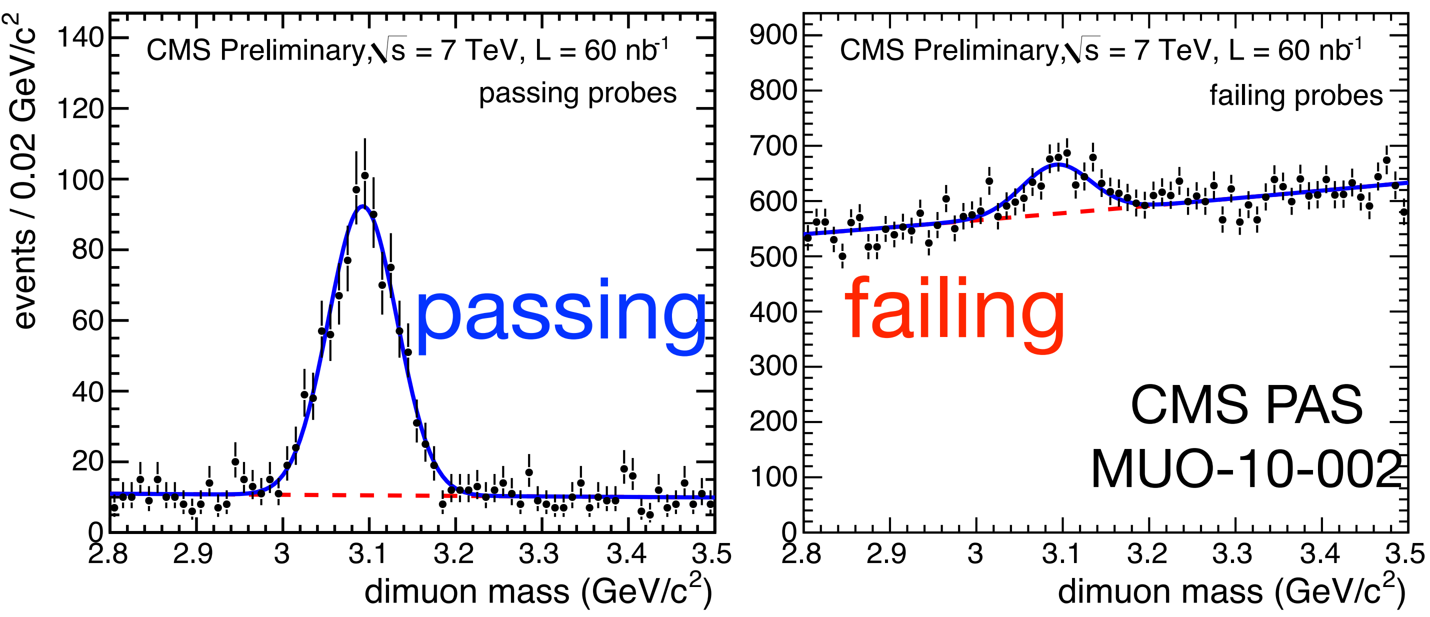
Muon Pair Reconstruction Efficiency

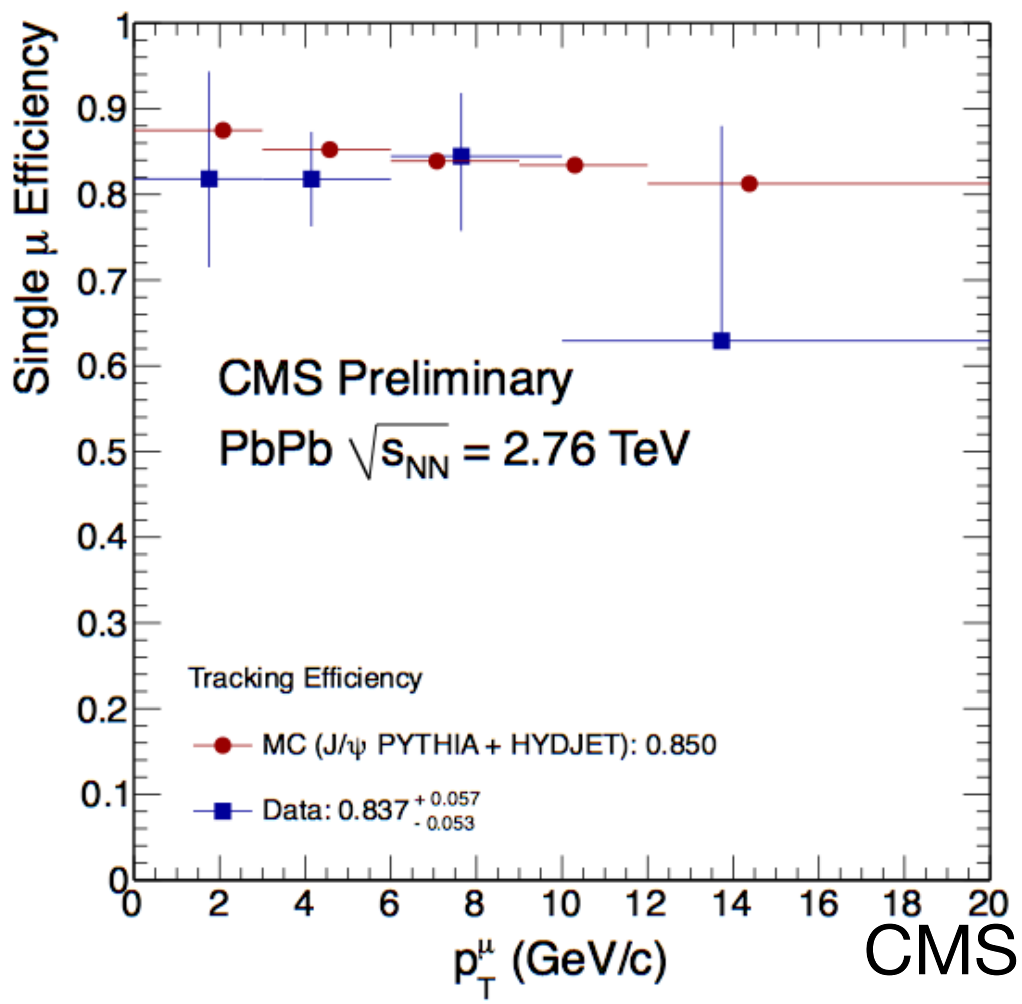


- Separate prompt & non-prompt J/ψ
- HI tracking algorithm uses vertex constraint
  - Smaller efficiency for non-prompt than for prompt J/ψ
  - Effect increases with p_T
- Efficiencies from Monte Carlo
  - Simulate signal with "realistic" PYTHIA
  - Embed signal in min. bias event simulated with HYDJET (also in data)
  - Validated MC by comparing efficiencies measured with "Tag & Probe" in MC and data

CMS HIN-10-006
JHEP 05 (2012) 063

Tag & Probe





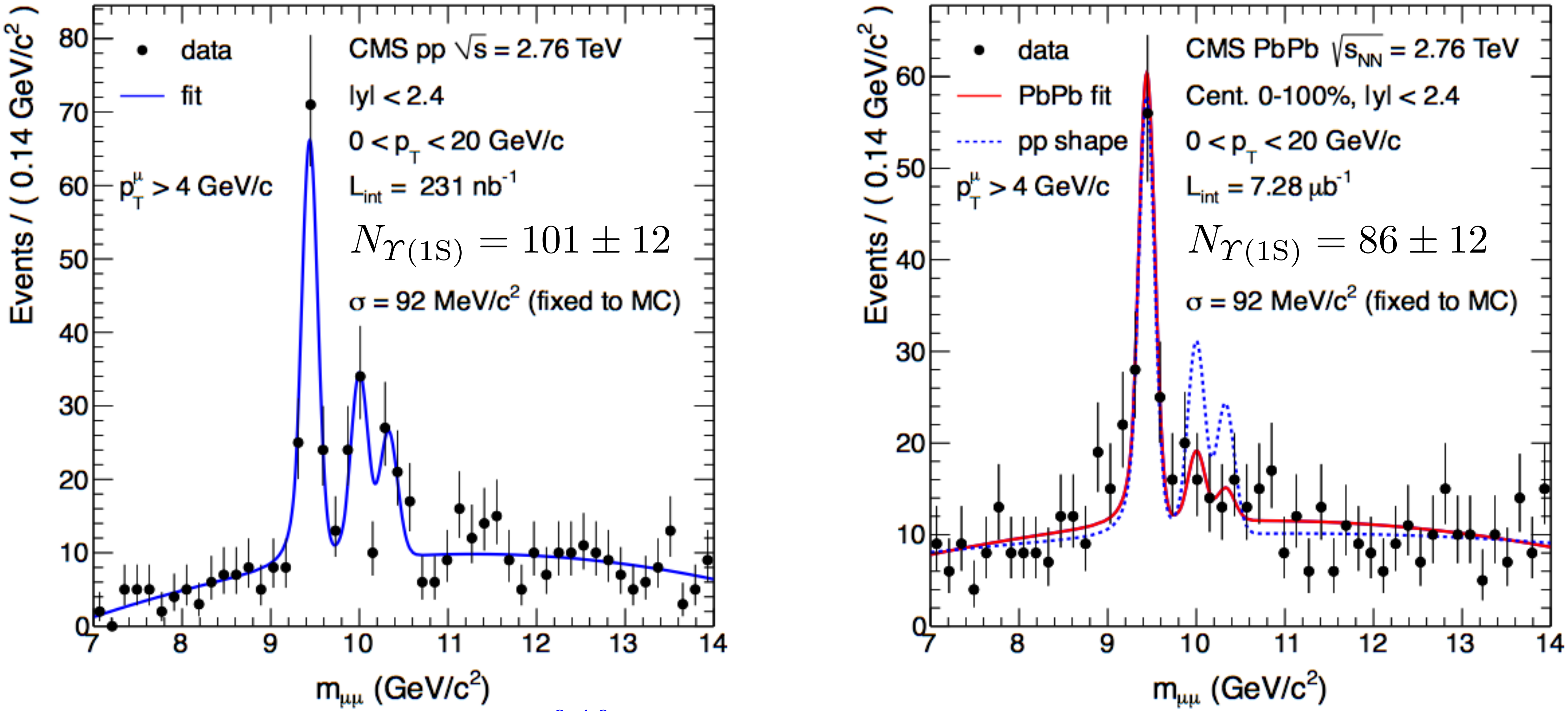
CMS PAS
HIN-10-006

Tracking efficiency:

- Tag: high quality muon
- Probe: track in the muon station
- Passing Probe:
  - Probe that is also reconstructed as global muon (i.e. with a track in the Si-tracker)
- Reconstruct J/ψ peak in passing probe-tag pairs and in failing probe-tag pairs
- Simultaneous fit to passing and failing probes allows us to measure the efficiency of the inner track reconstruction
- Agreement within stat. uncertainty of data
  → 14% systematic uncertainty on data/MC agreement

Bottomonia: with 2010 data

pp | PbPb



$\Upsilon(2S+3S)/\Upsilon(1S)|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$ $\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

- Measure Υ(2S+3S) production relative to Υ(1S) production
- Simultaneous fit to pp and PbPb data at 2.76 TeV

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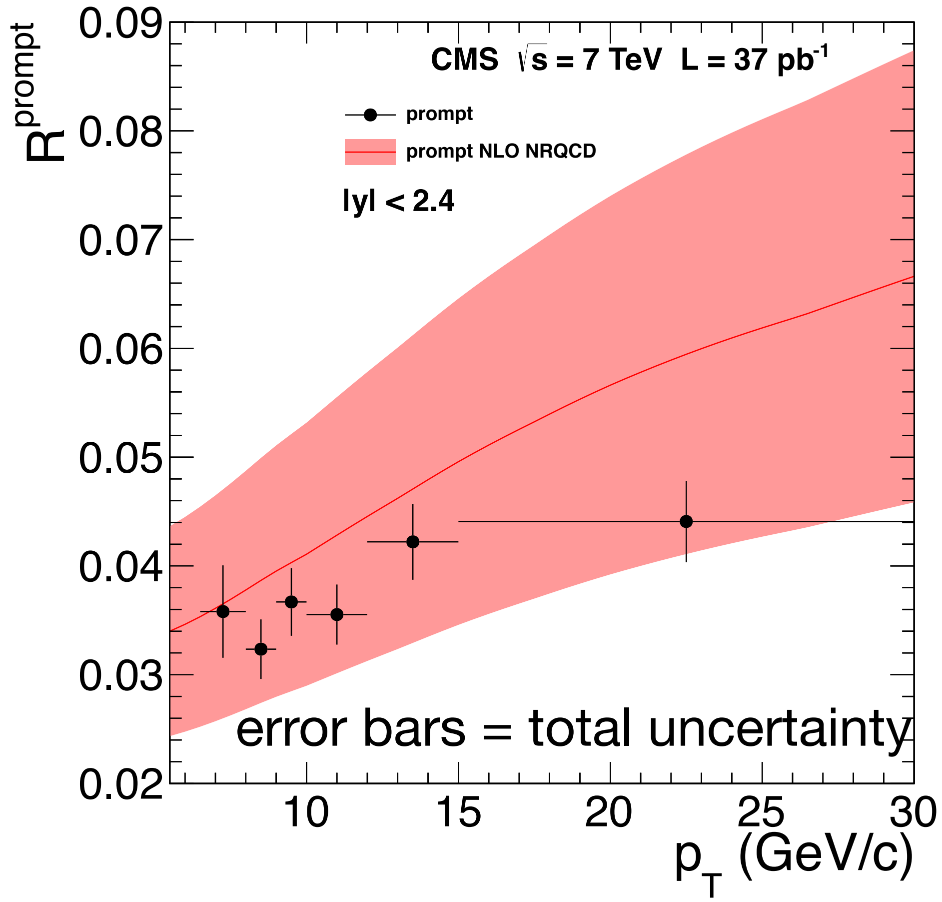
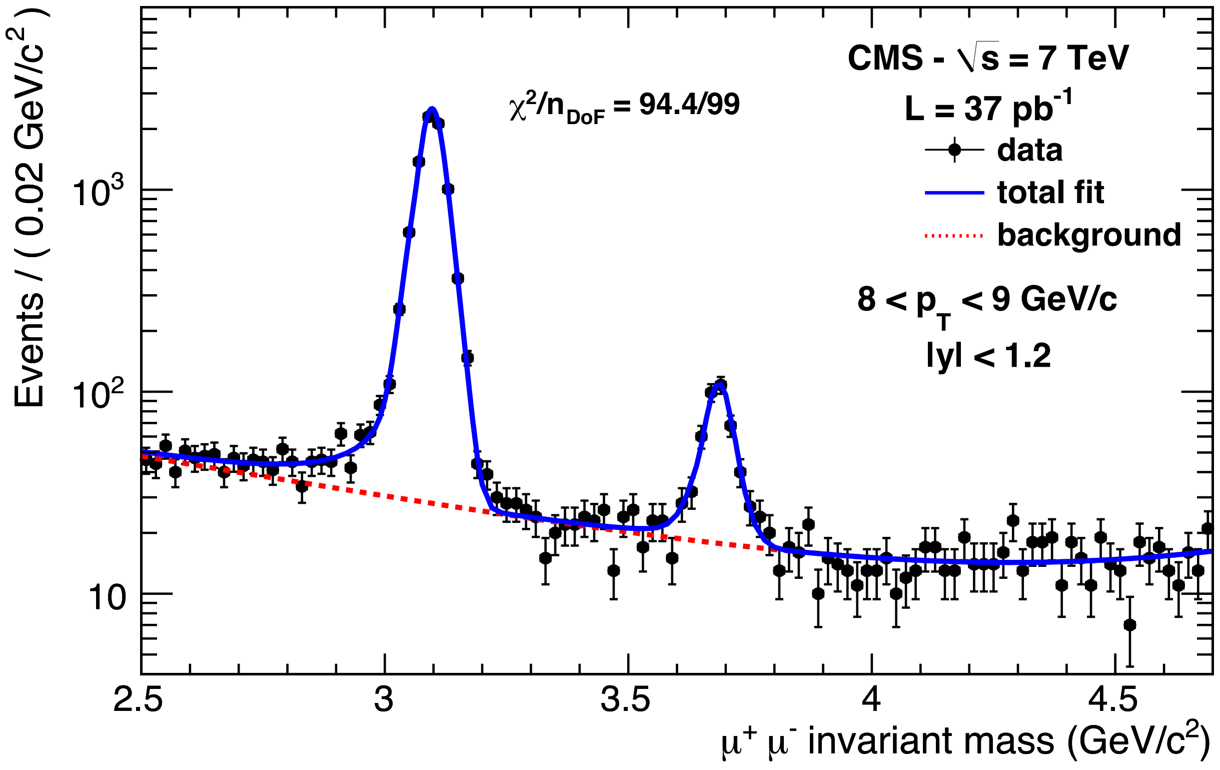
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Probability to obtain measured value, or lower, if the real double ratio is

ψ(2S) in pp at √s = 7 TeV





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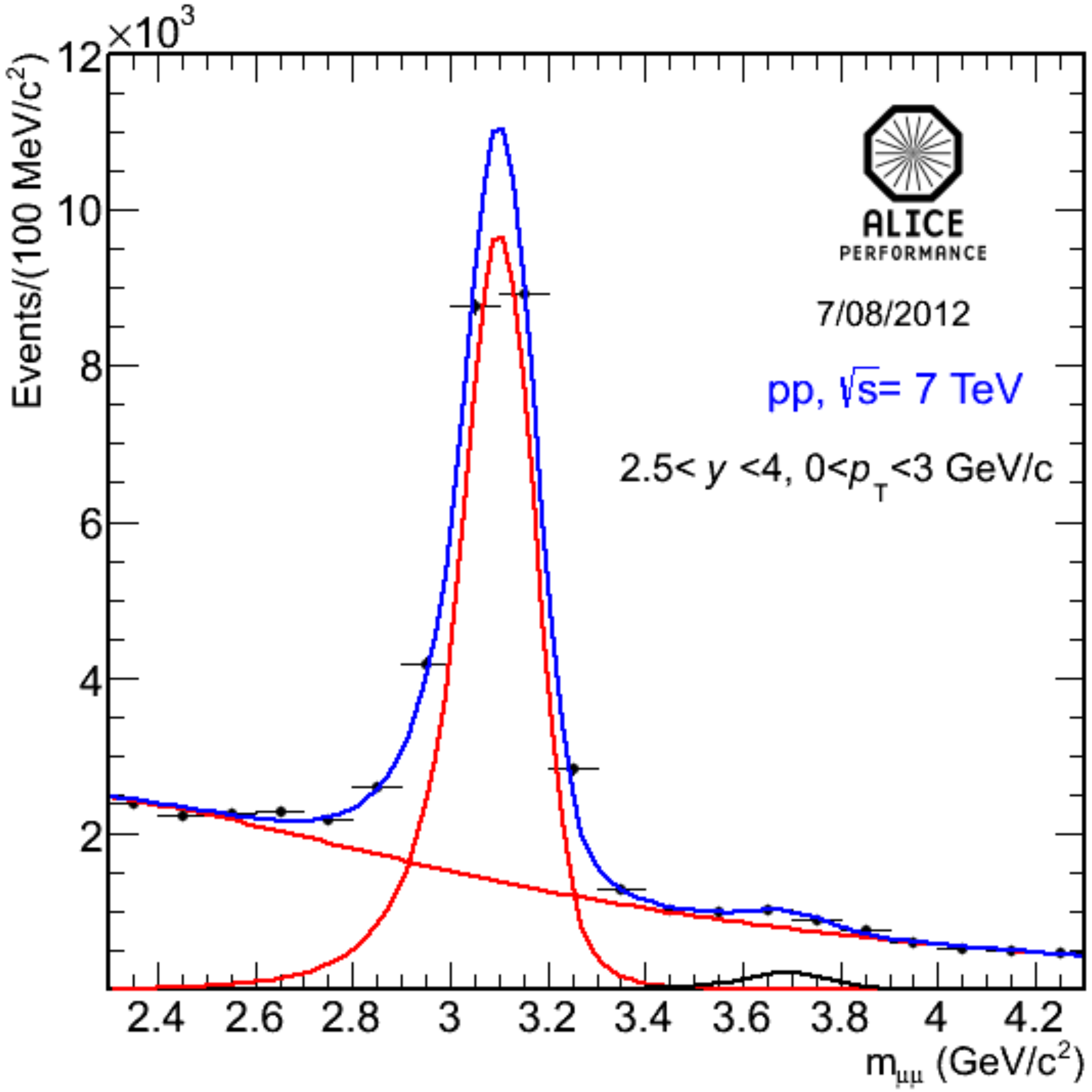
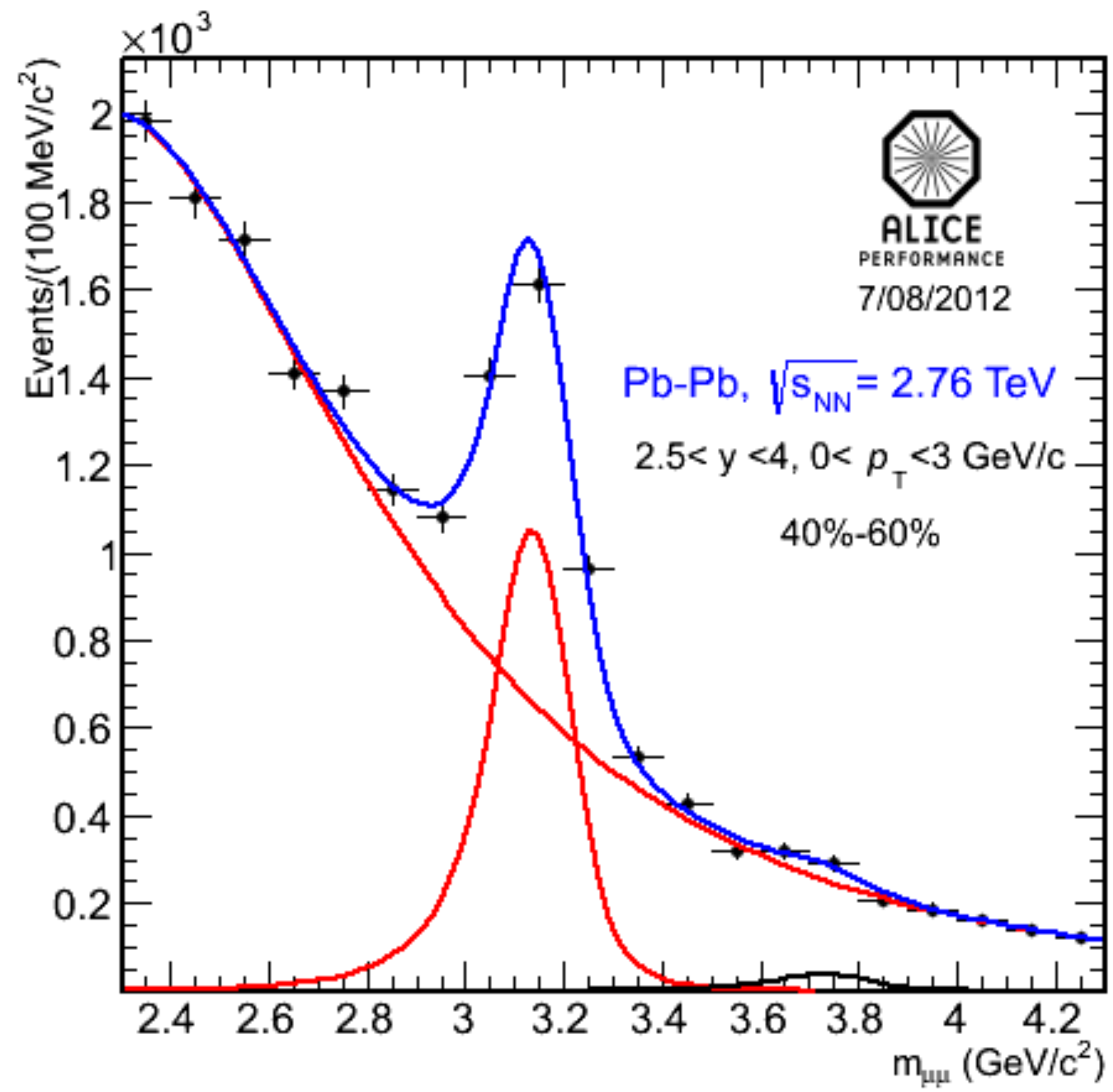
- CMS measured ψ(2S) cross section in pp at √s = 7 TeV
- ψ(2S) / J/ψ cross-section ratio ~0.035 for p_T > 6.5 GeV/c
- Uncertainties on theory larger than experimental uncertainties

ALICE: ψ(2S)





- PbPb: Signal/Background (at 3σ around the ψ(2S)) varies between 0.01 and 0.3 from central to peripheral collisions