Quarkonium results in heavy-ion collisions with CMS

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On behalf of the CMS collaboration

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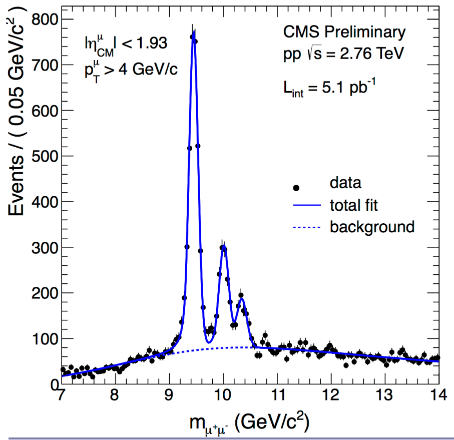

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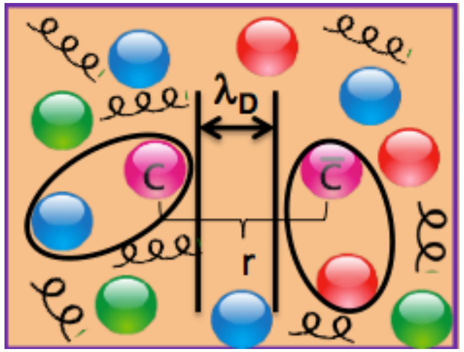
Outline

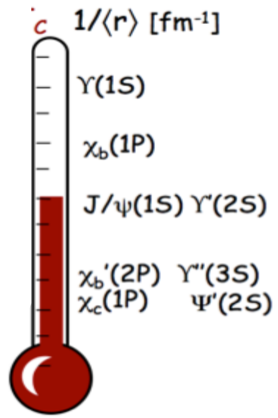
- Introduction
- Charmonium
  - J/ψ in PbPb and pPb
  - ψ (2S) in PbPb
- Bottomonium
  - Υ(1S), Υ(2S), Υ(3S) in PbPb and pPb
- Conclusion

Physics motivation

- Quarkonia as a probe of deconfinement via colour screening
  - If $\lambda_D(T) < r$ → screening
    → melting of the bound state
    → yields suppressed
  - → *Matsui and Satz, PLB 178 (1986) 416*



- Sequential suppression of the quarkonium states
  - Screening at different T for different states → sequential melting
  - → *Digal, Petreczky, Satz, PRD 64 (2001) 0940150*

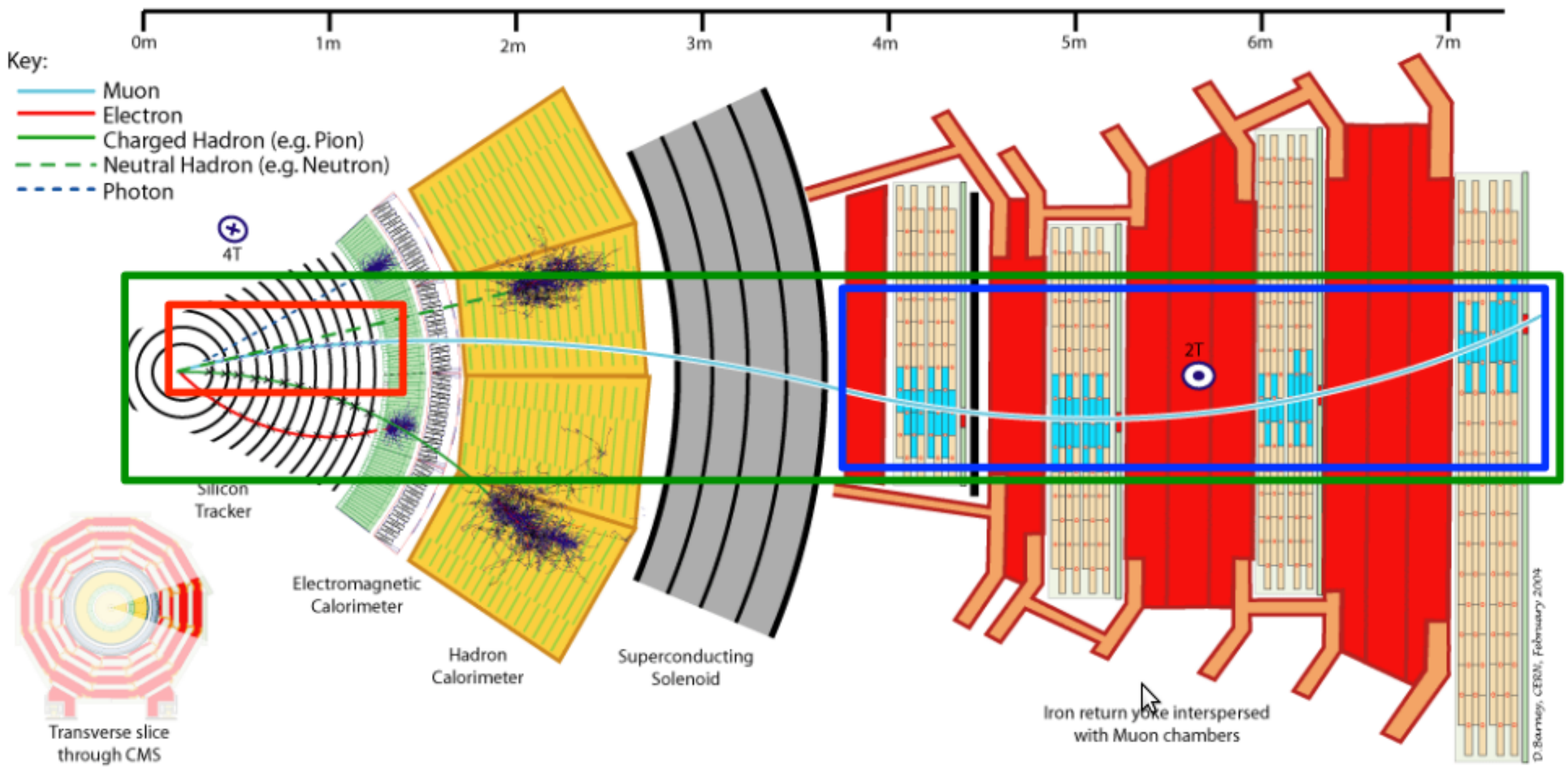


- Enhancement via (re)generation of quarkonia, due to the large heavy-quark multiplicity
  - → *Andronic, Braun-Munzinger, Redlich, Stachel, PLB 571(2003) 36*
  - → *R. L. Thews, M. Schroedter, and J. Rafelski, Phys. Rev. C63, 054905 (2001)*

- Cold Nuclear Matter effects (CNM effects), such as nuclear absorption and gluon shadowing

Muons in CMS

CMS detector

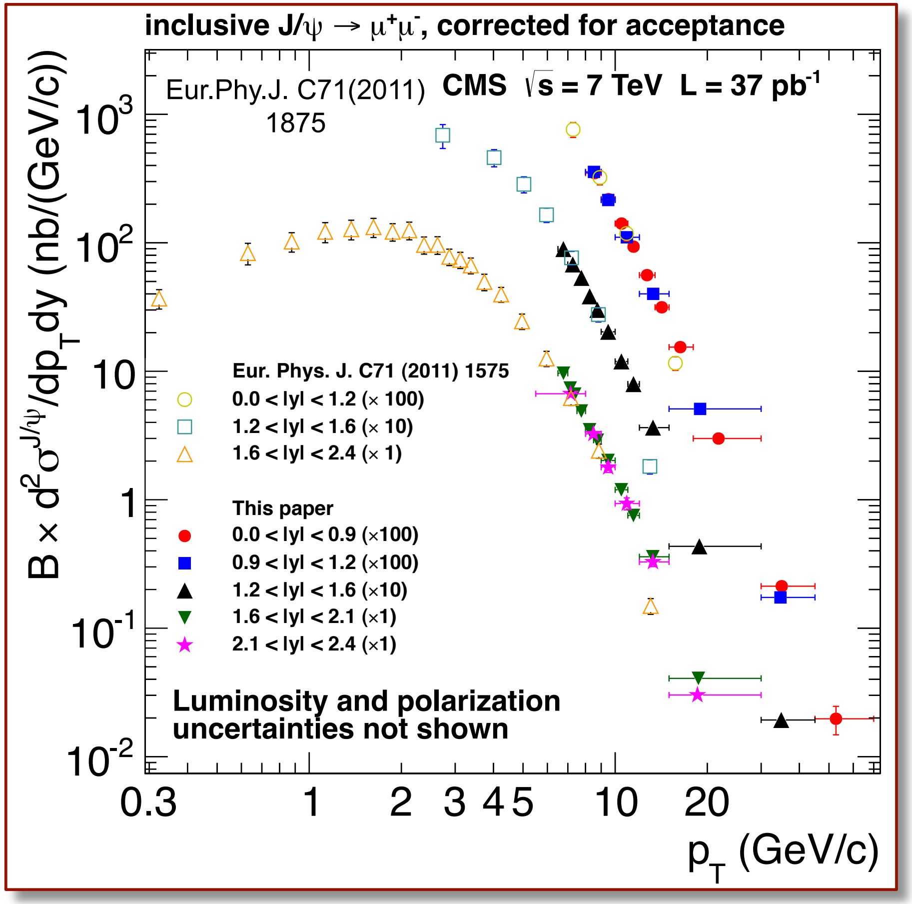


- Muon reconstruction: silicon tracker + muon subdetectors
  - Tracker p_T resolution: 1-2% up to p_T ~ 100 GeV/c:
    - separation of quarkonium states
    - displaced tracks for heavy-flavour measurements

Υ and J/ψ acceptance

CMS detector

	1.6<|y|<2.4	1.2<|y|<1.6	|y|<1.2
Υ p_T in pp	> 0 GeV/c		
J/ψ p_T in pp	> 0 GeV/c	> 2 GeV/c	> 6.5 GeV/c
J/ψ p_T in PbPb	> 3 GeV/c	> 5.5 GeV/c	> 6.5 GeV/c

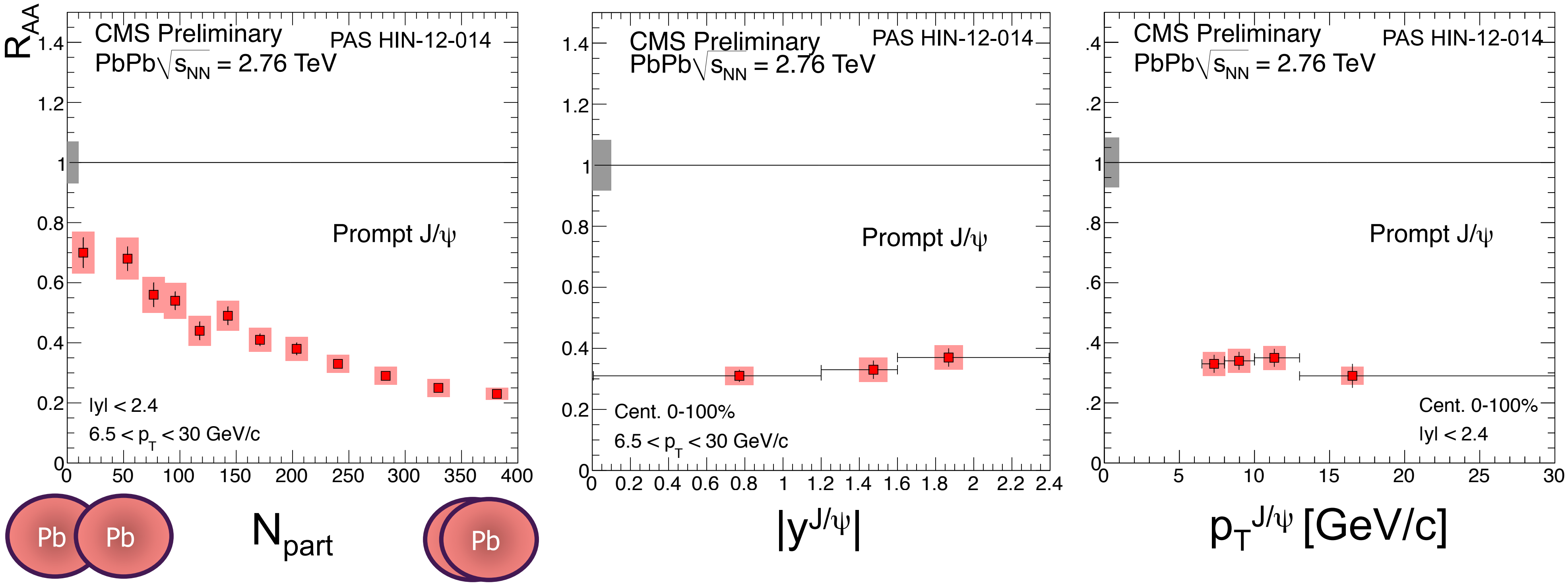


- CMS can measure J/ψ down to ~ 0 p_T in the forward region 1.6<|y|<2.4 (in pp collisions for now)

Charmonia

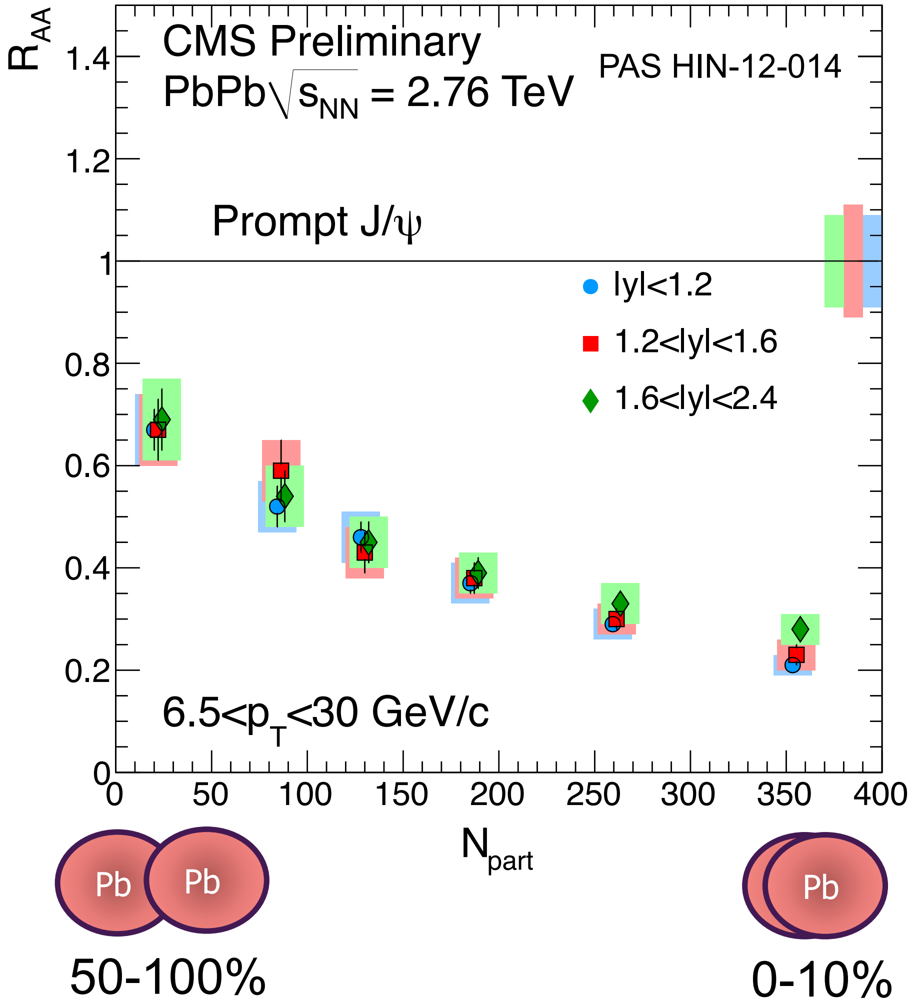
R_{AA} prompt J/ψ

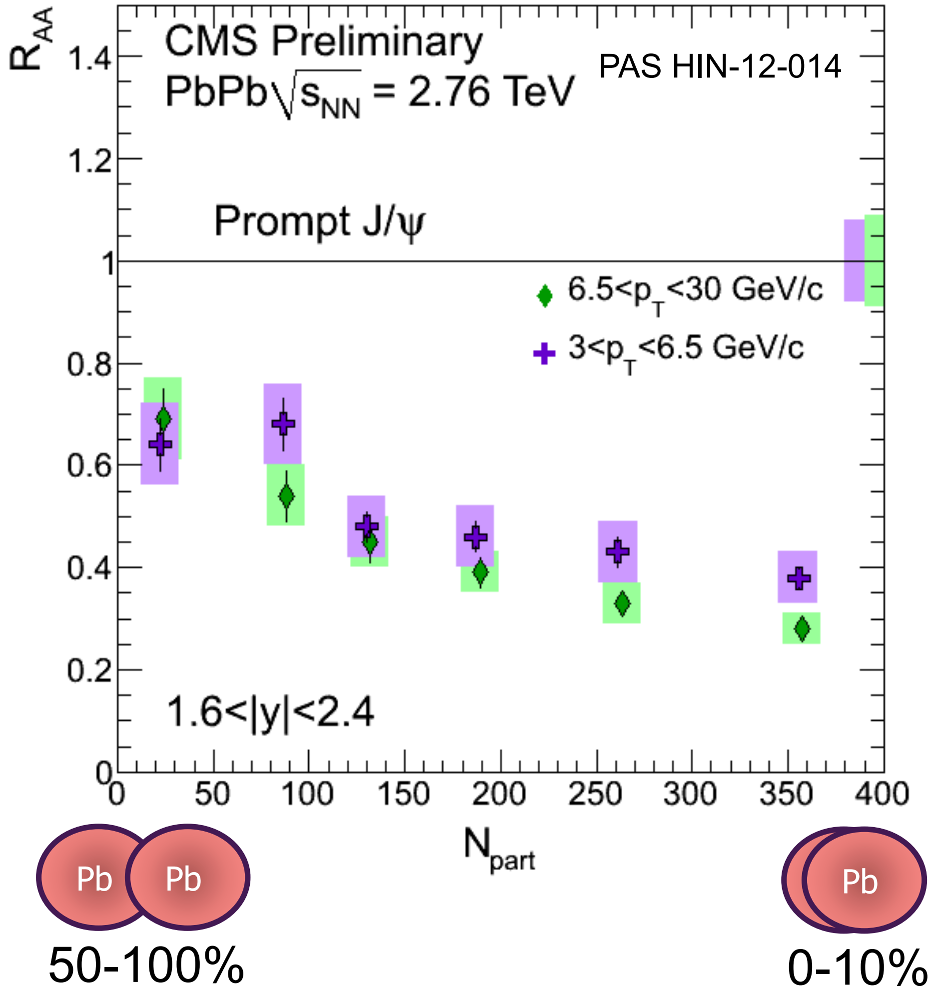
- Nuclear modification factor $$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}}{N_{pp}} \cdot \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}}$$



- No significant dependence for R_{AA} vs. rapidity and p_T
- R_{AA} vs. centrality:
  - 0-5% factor ~5 suppression → R_{AA} = 0.20 ± 0.03 (stat.) ± 0.01 (syst.)
  - 60-100% factor ~1.4 suppression

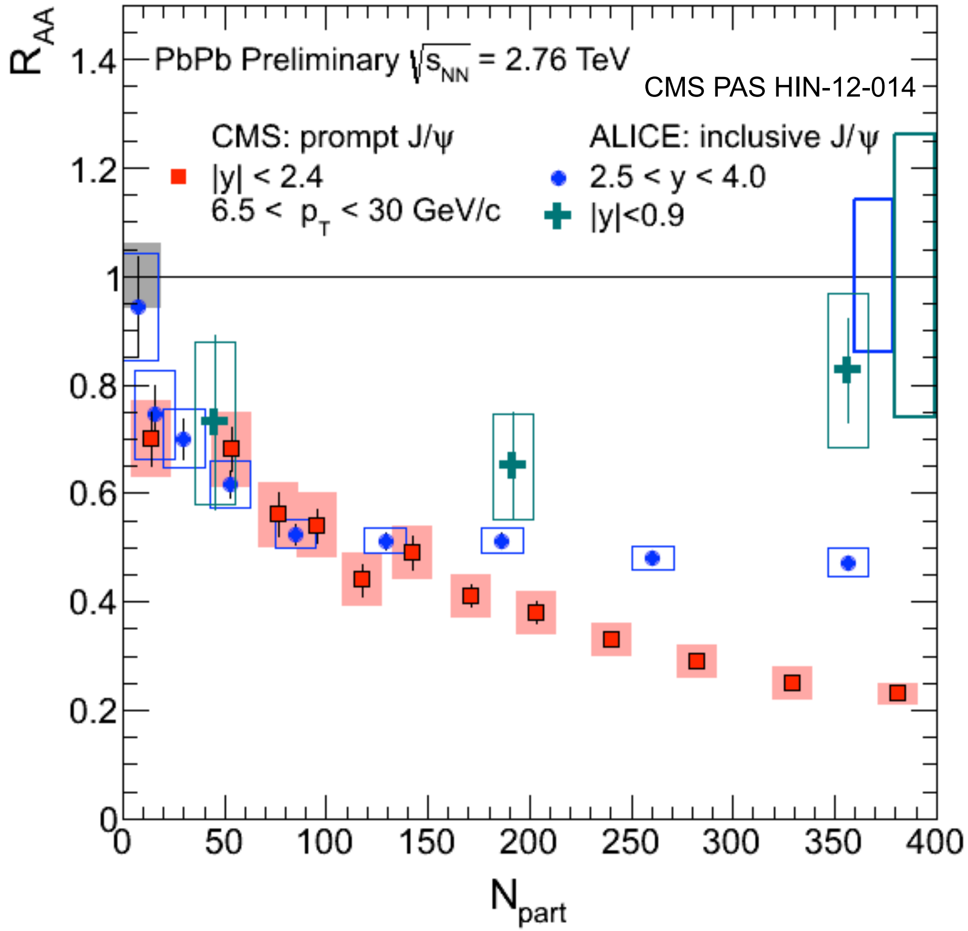
R_{AA} prompt J/ψ





- $6.5 < p_T < 30$ GeV/c
  - no rapidity dependence
- Prompt J/ψ with $3 < p_T < 6.5$ GeV/c slightly less suppressed than the ones with $6.5 < p_T < 30$ GeV/c

R_{AA} prompt J/ψ CMS vs. ALICE



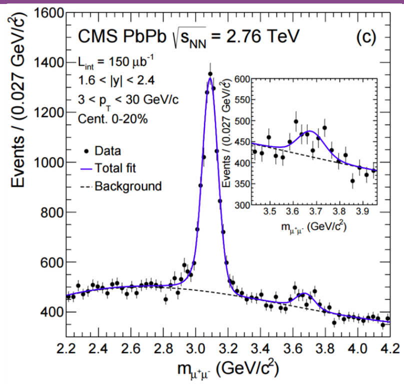
- Less suppression seen for low p_T J/ψ (ALICE) compared to high p_T J/ψ (CMS)
- Sign of (re)generation for low p_T J/ψ

J/ψ vs. ψ(2S) in PbPb

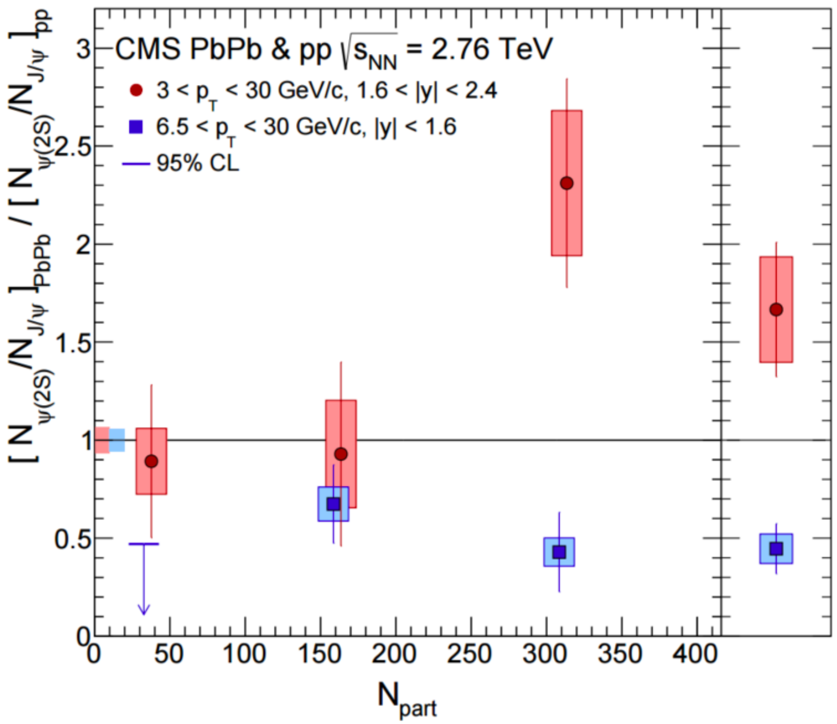
PRL113 (2014) 262301

- Double ratio:

$$\frac{[\frac{\psi(2S)}{J/\psi}]_{AA}}{[\frac{\psi(2S)}{J/\psi}]_{pp}} = \frac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}$$



R_{AA} (0-100%)	ψ(2S)	J/ψ
$3 < p_T < 30$ GeV/c $1.6 < \|y\| < 2.4$	0.67 ± 0.16 ± 0.11 ± 0.07	0.40 ± 0.05 ± 0.02 ± 0.03
$6.5 < p_T < 30$ GeV/c $\|y\| < 1.6$	0.13 ± 0.04 ± 0.02 ± 0.01	0.28 ±0.04 ±0.02

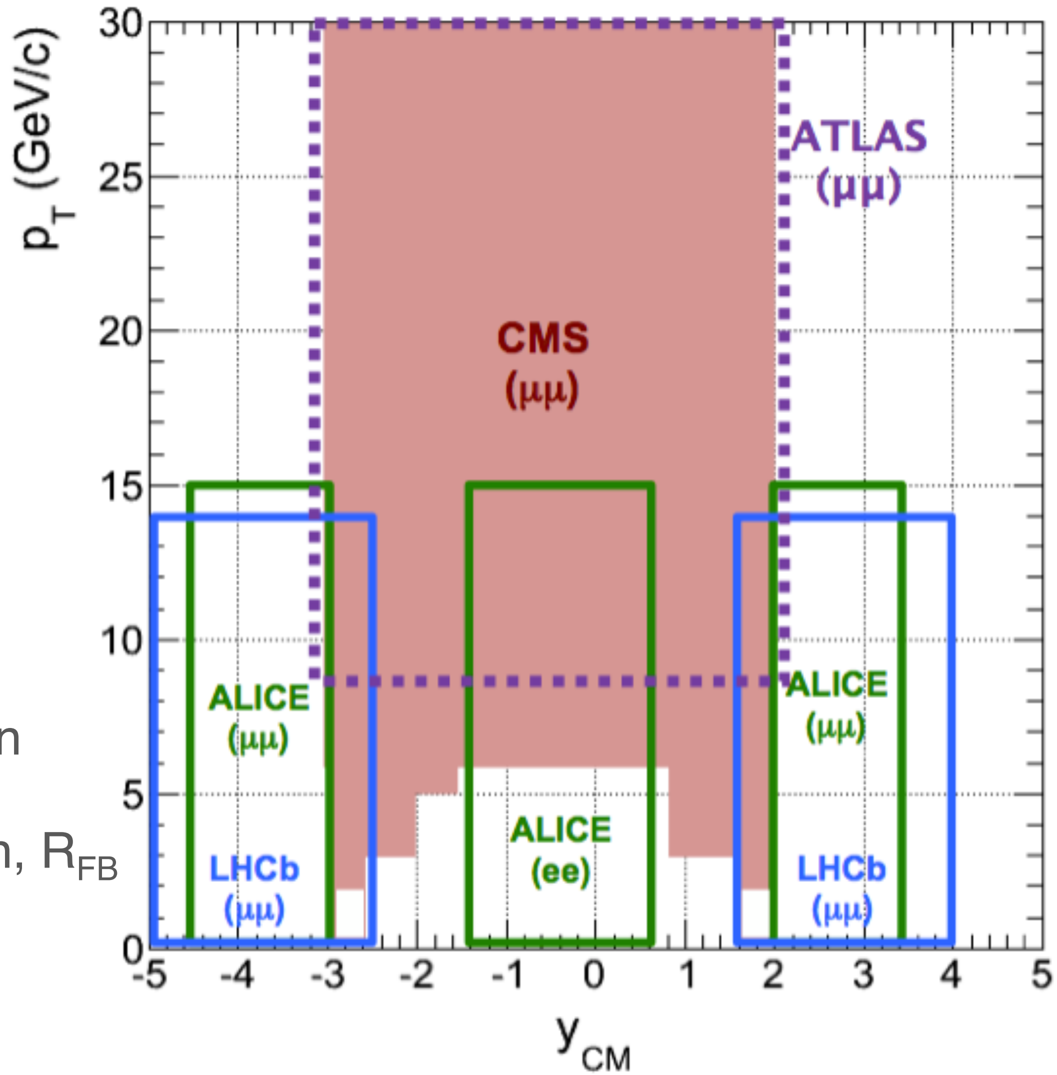


- **At high-p_T** (6.5<pT<30GeV/c, |y|<1.6): **R_{AA}(ψ (2S)) < R_{AA}(J/ψ)**
  - Consistent with a sequential melting scenario
- **At intermediate-p_T: R_{AA}(ψ(2S)) > R_{AA}(J/ψ)**
  - Presence of sequential recombination (?)
- More statistics will reduce uncertainties and allow stronger statements

J/ψ in pPb

New

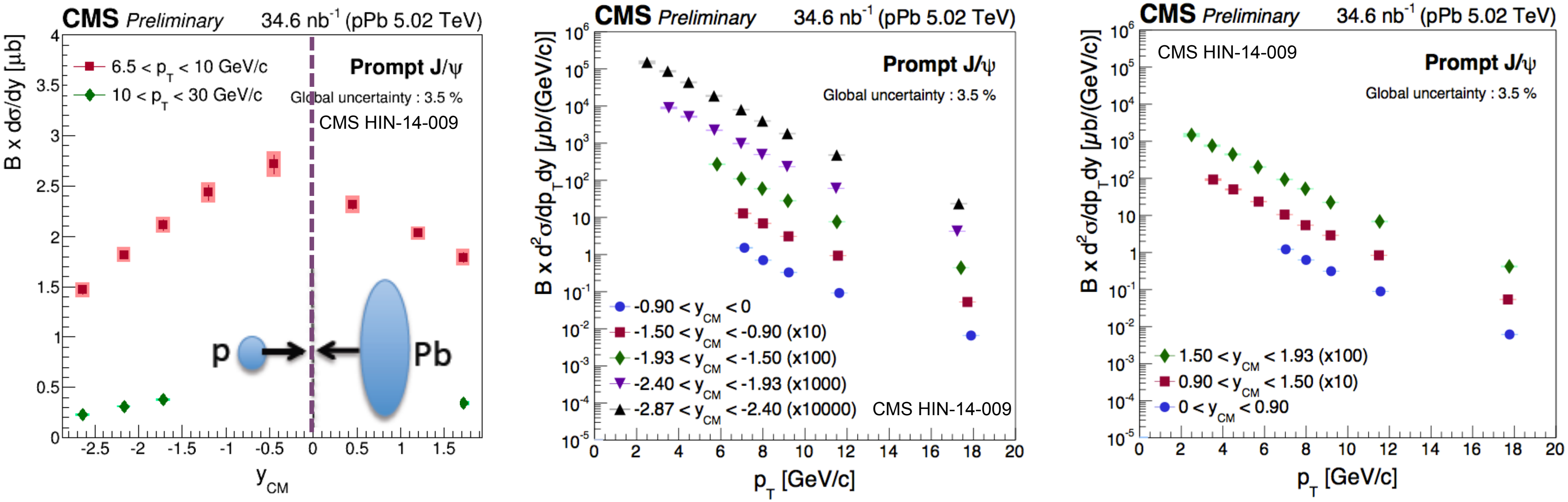
- In pA collisions at 5 TeV, CMS is probing small x-regions
  - CMS coverage
    - $-2.87 < y_{CM} < 1.93$
    - $2 < p_T < 30$ GeV/c
  - $x_{1,2} = \frac{\sqrt{m^2_{J/\psi} + p_{T}{}^2_{J/\psi}}}{\sqrt{s}} \cdot e^{\pm y}$
    - $x \sim 10^{-4} - 10^{-2}$



- Will be presented:
  - Forward, backward cross section
  - Nuclear effects in J/ψ production, R_{FB}
  - p_T-dependent R_{FB}
  - Event-activity dependent R_{FB}

J/ψ in pPb cross section vs. p_T

New



Backward (Pb going direction) **Forward** (p going direction)

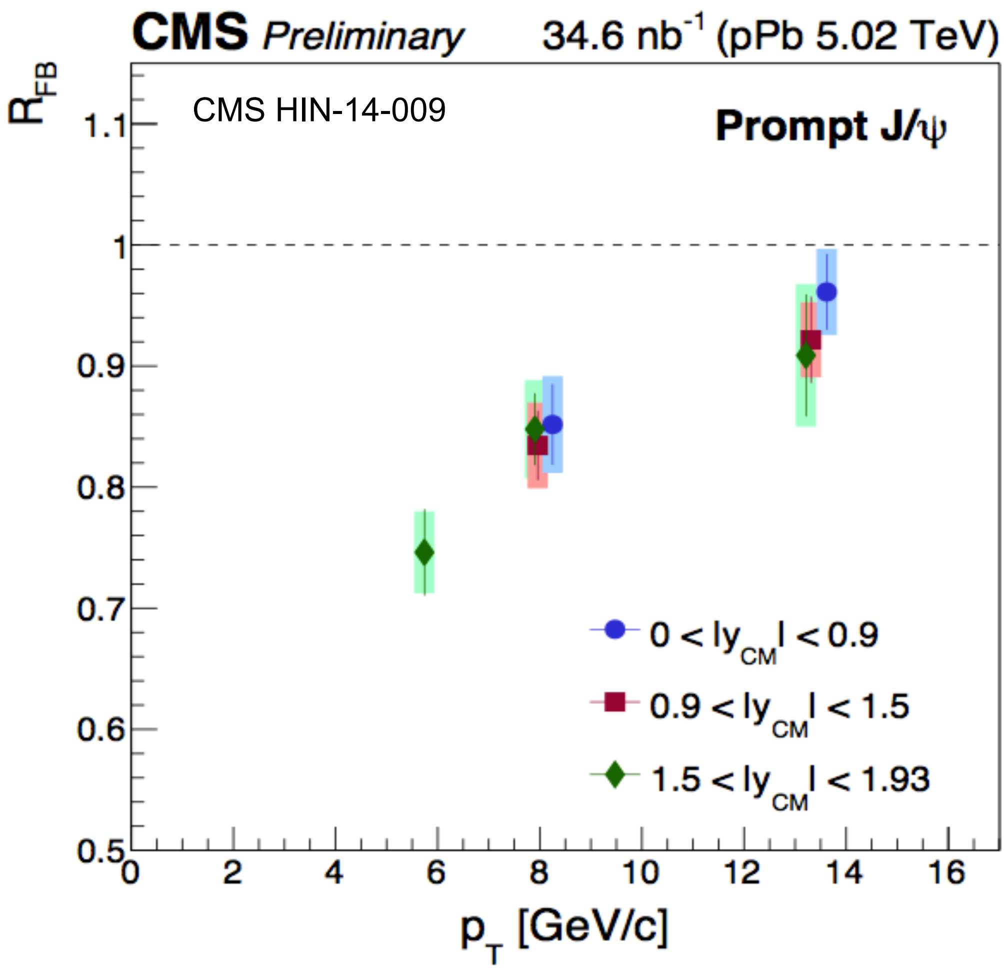
- Cross sections measured as a function of rapidity and p_T
- Modification of nPDF can be probed by comparing the corrected yields of the p-going direction and the Pb-going direction

J/ψ in pPb: R_{FB}

New

$$R_{FB}(p_T, y) = \frac{d^2\sigma(p_T, y > 0)/dp_T dy}{d^2\sigma(p_T, y < 0)/dp_T dy}$$

- R_{FB} vs. p_T : strong dependence
  - increasing with p_T consistently for 3 rapidity bins
- R_{FB} vs. rapidity:
  - at this high p_T, no strong rapidity dependence



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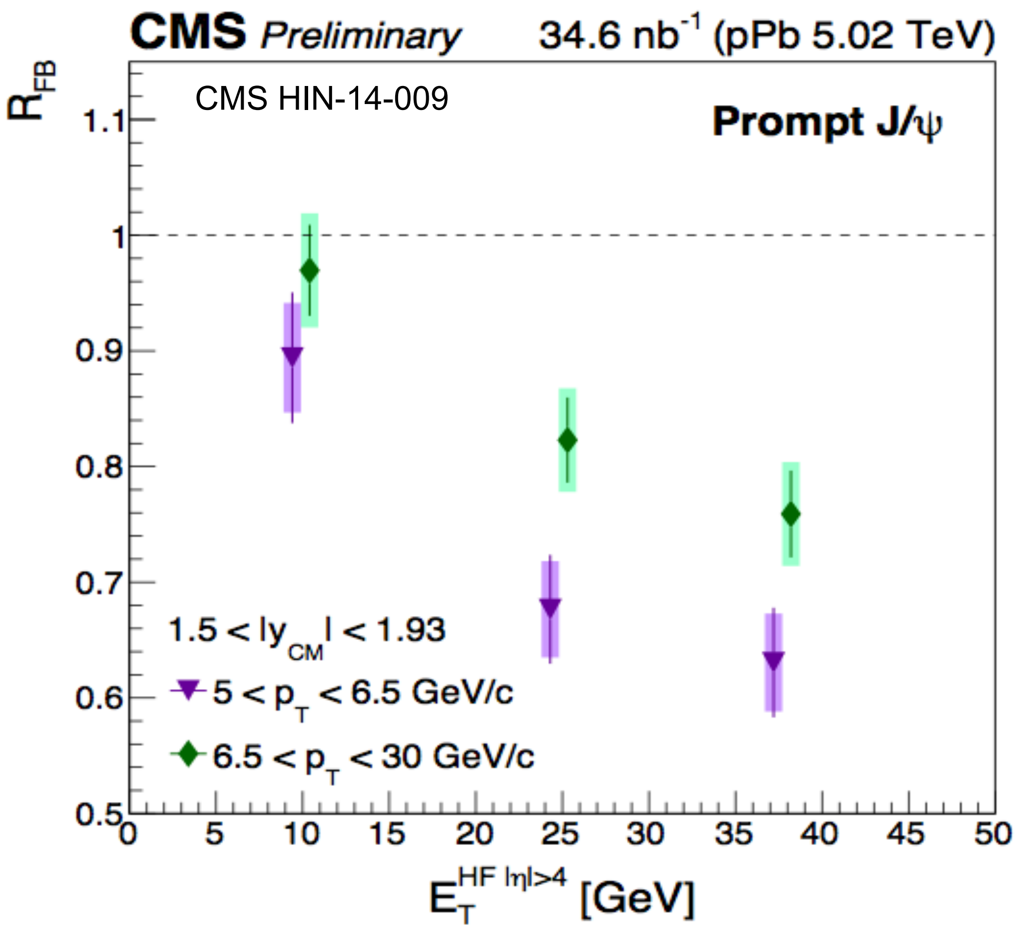
event activity dependence of R_{FB}

New

- At large J/ψ rapidities in two p_T bins:
  - Decreasing R_{FB} with increasing event activity
    - More pronounced at low p_T



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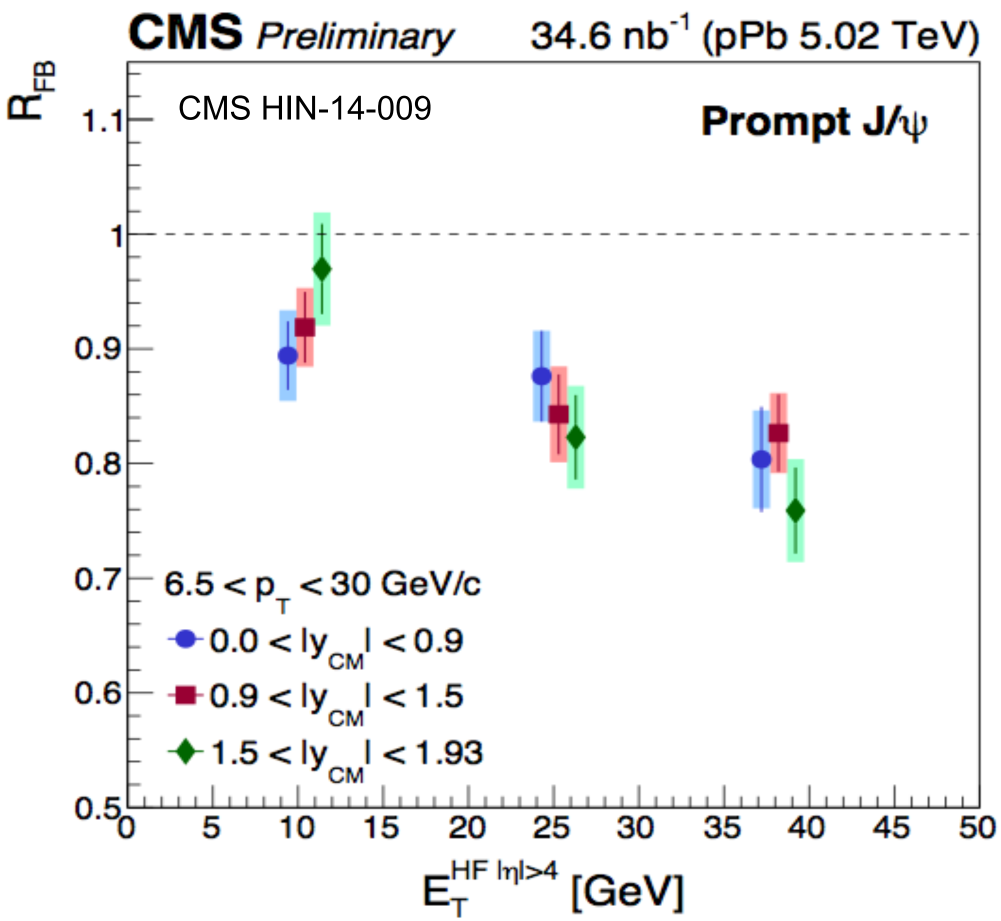
event activity dependence of R_{FB}

New

- Looking at high-p_T only:
  - Event activity dependence still clear
  - No significant rapidity dependence for the R_{FB} at high p_T



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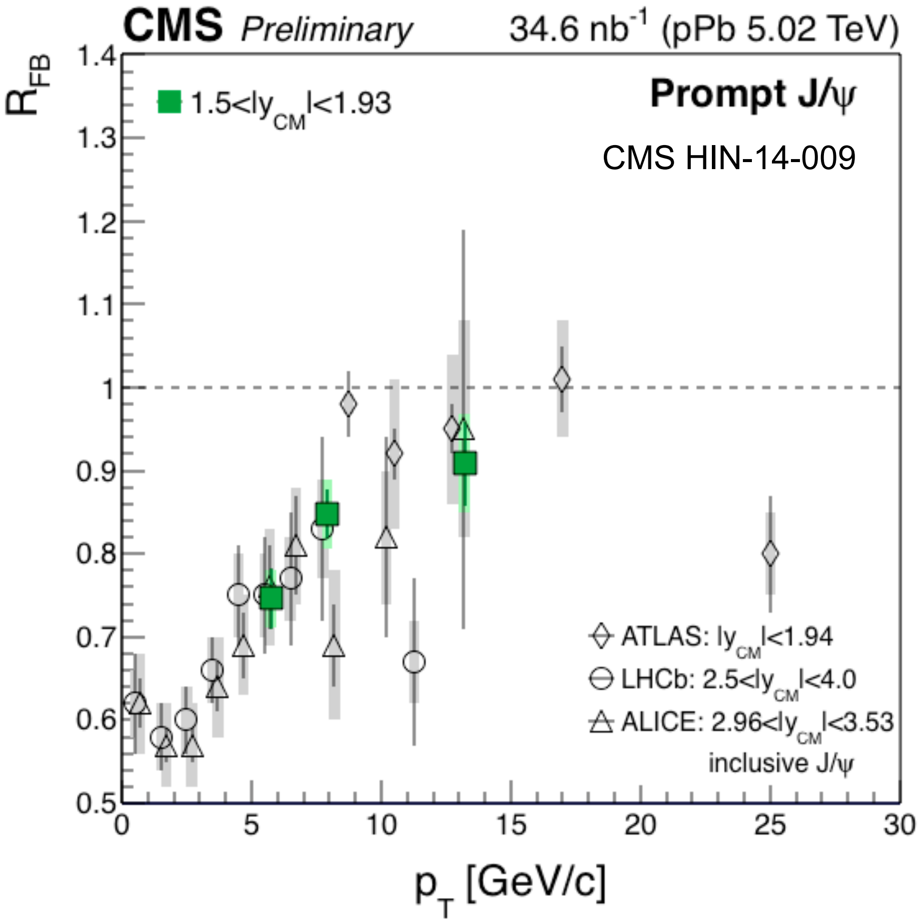
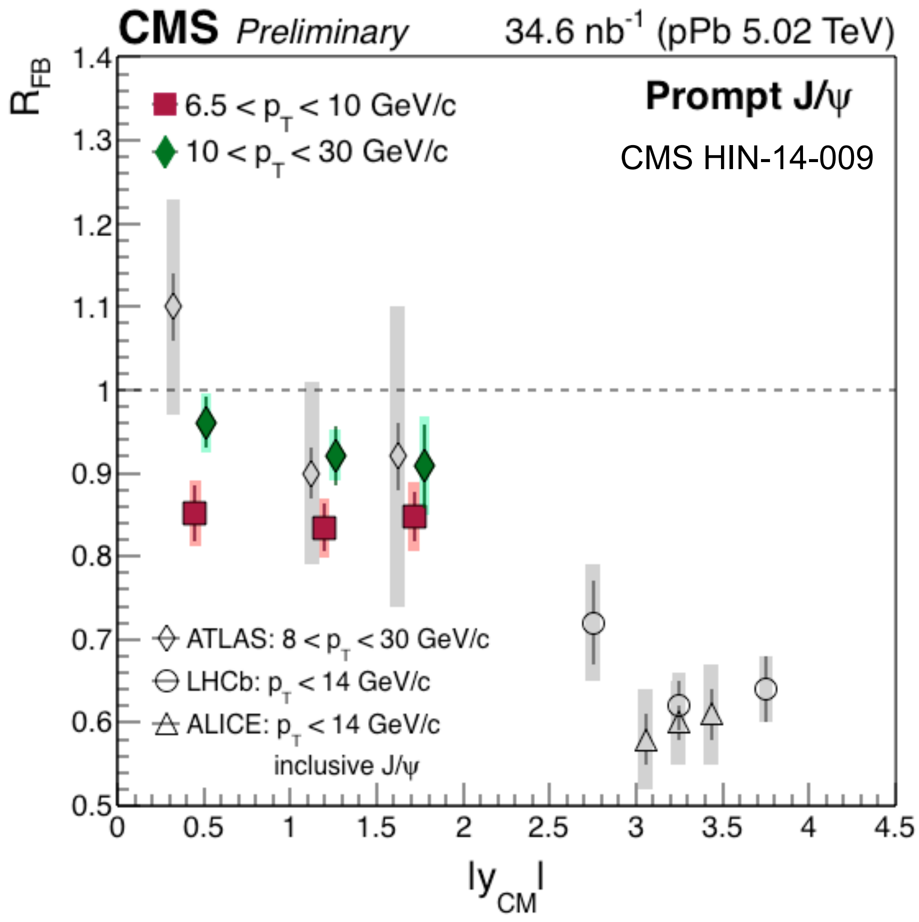
Comparaison with other experiments

New





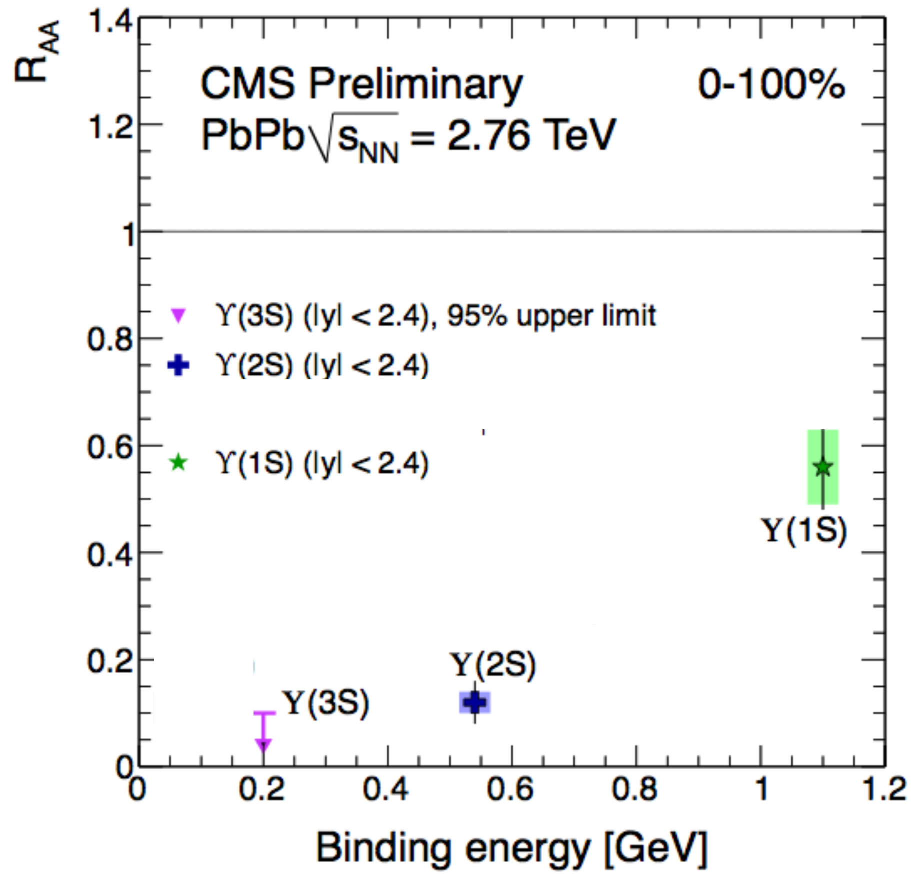
- A good agreement between the 4 LHC experiments for the R_{FB} vs. p_T and rapidity

Bottomonia

Bottomonia with CMS

- Υ states are suppressed in PbPb collisions
- Centrality dependent, stronger suppression for excited states
- Ordered with assumed binding energies

- With a larger reference at the same energy collisions
  - A precise mapping of the kinematics of the suppression in Υ is possible



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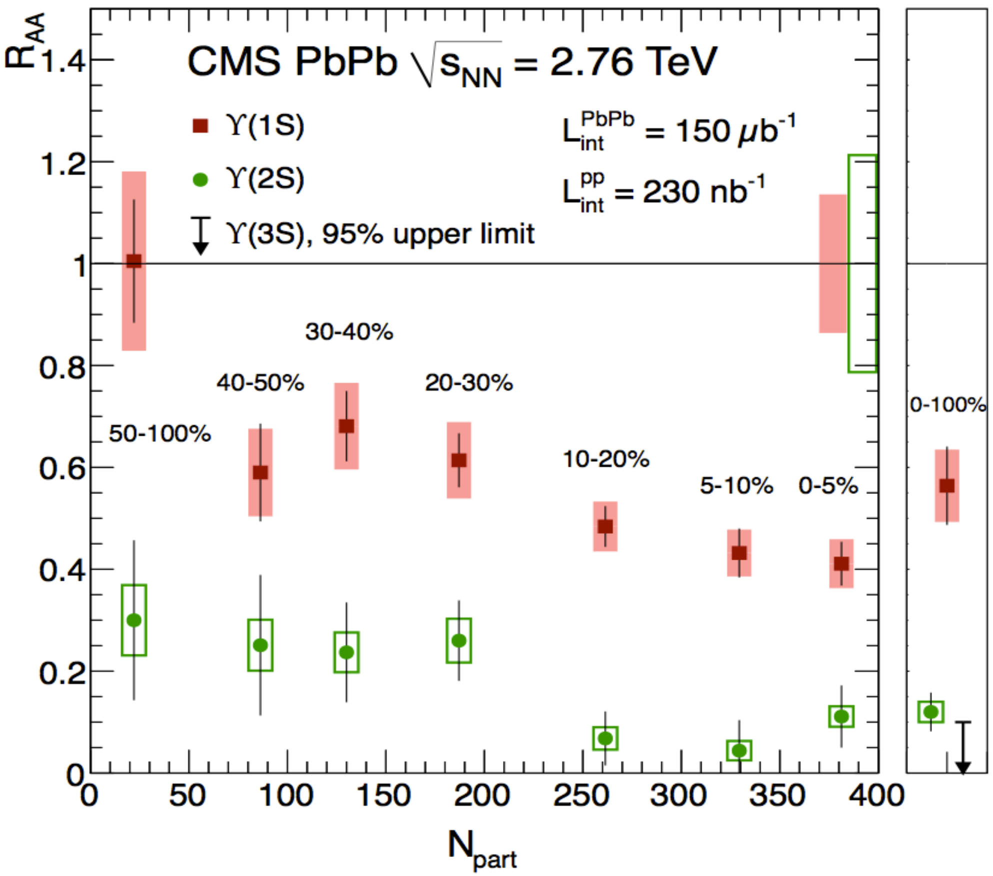
Υ R_{AA} vs. Centrality

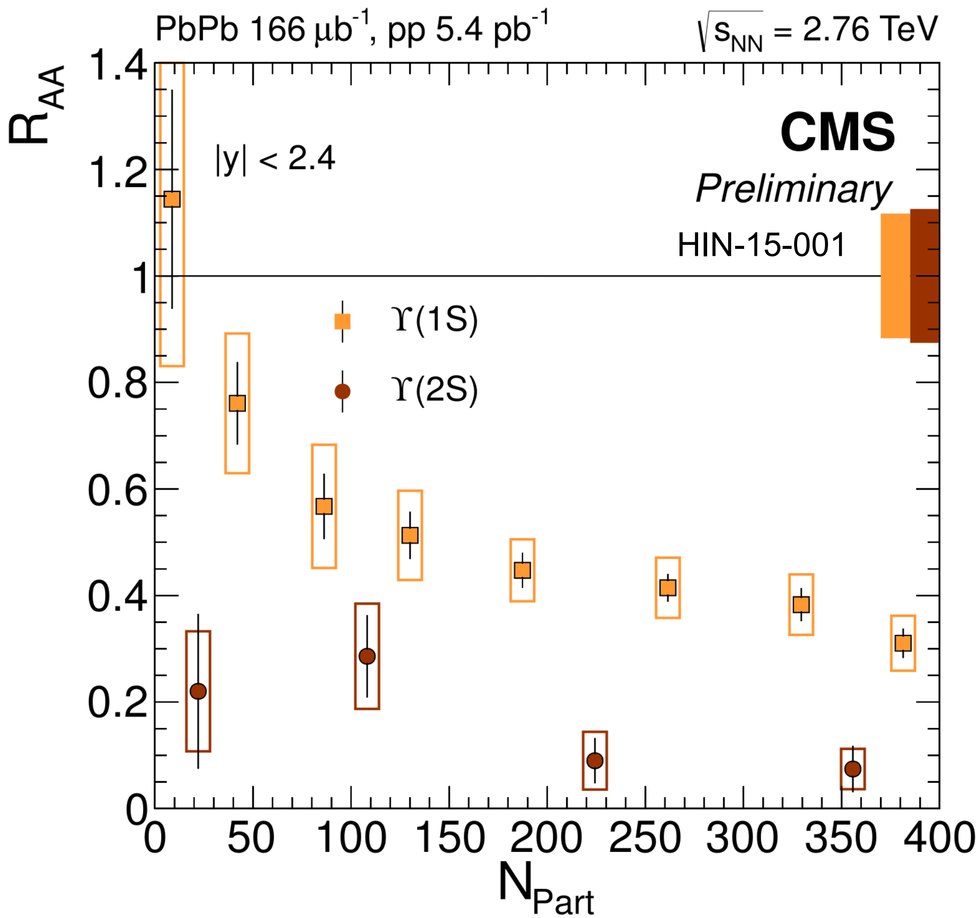
New

- Improvements:
  - pp reference x 20
  - Bigger, more precise PbPb sample
  - Reduced stat. uncertainties

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

PRL 109 (2012) 222301

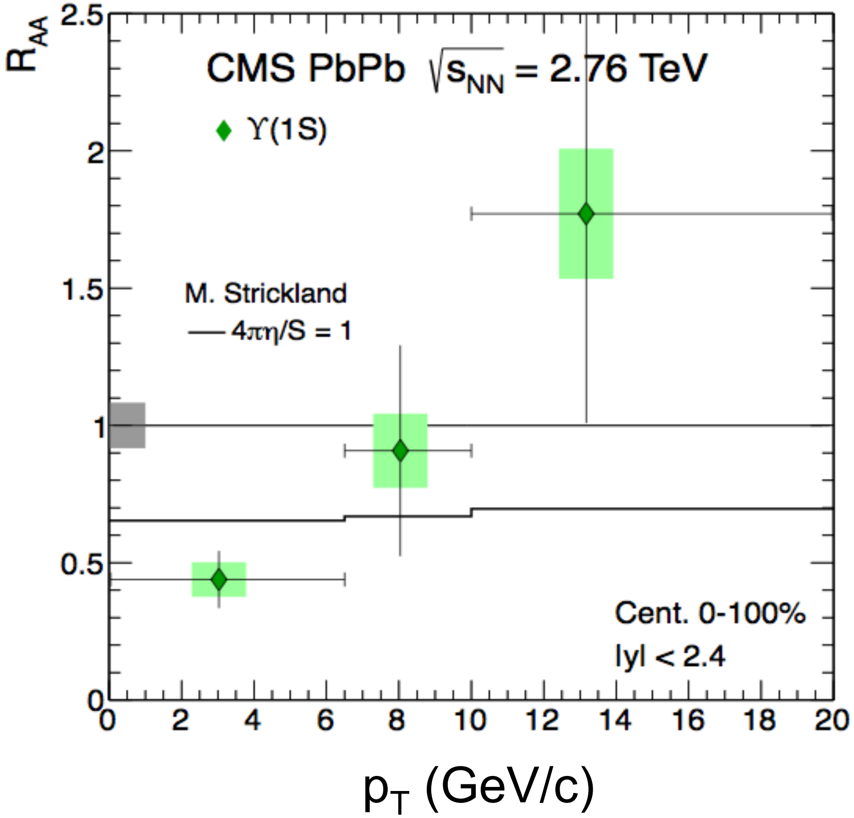




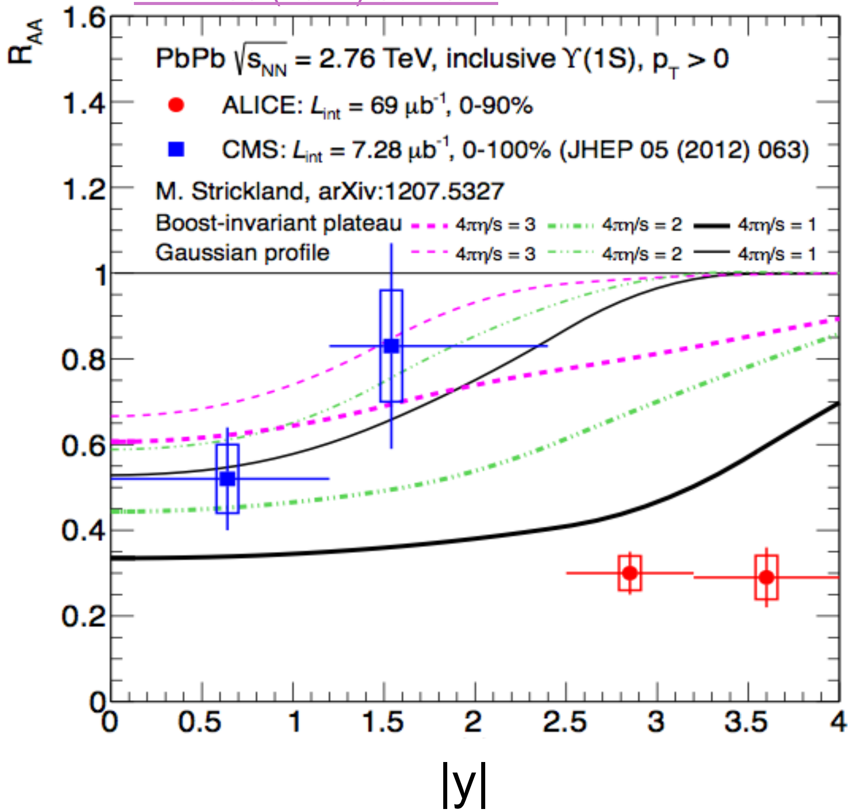
Υ R_{AA} vs. p_T and rapidity

- Questioning since the last CMS results:
  - Is the Υ suppression dependent on p_T and rapidity ?
  - No suppression at high-p_T?
  - At forward rapidities, ALICE sees $R_{AA} \approx 0.30$ (in $2.5 < y < 4$)
- Responses with ~20 times more pp data and an improved PbPb reconstruction

JHEP 1205 (2012) 063



PLB 738 (2014) 361-372



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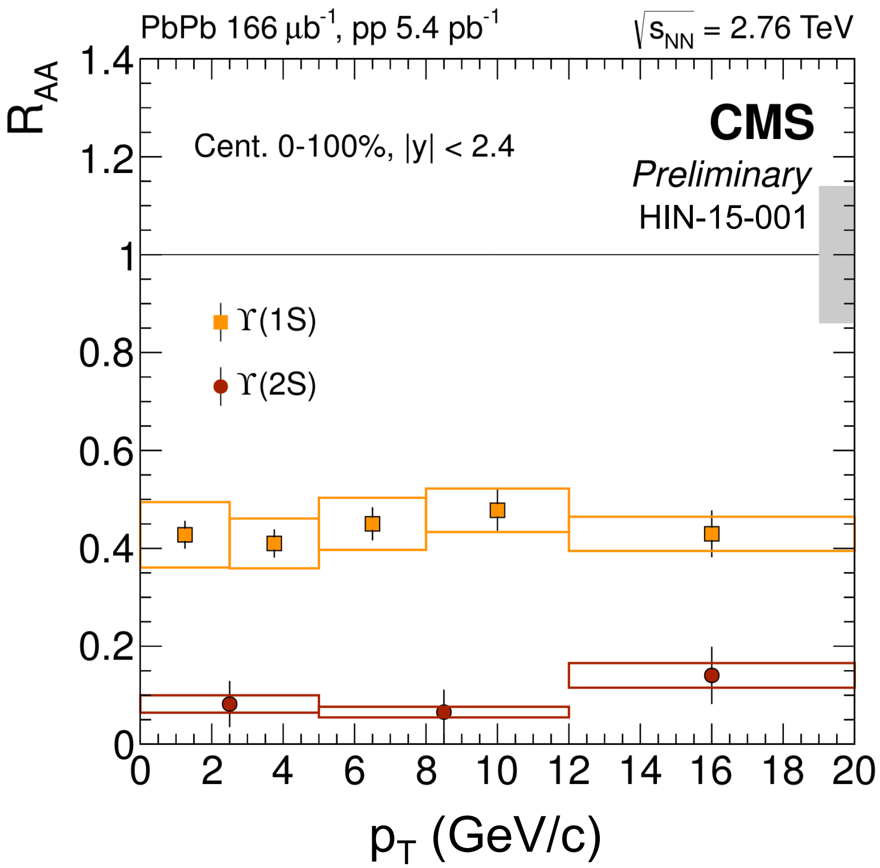
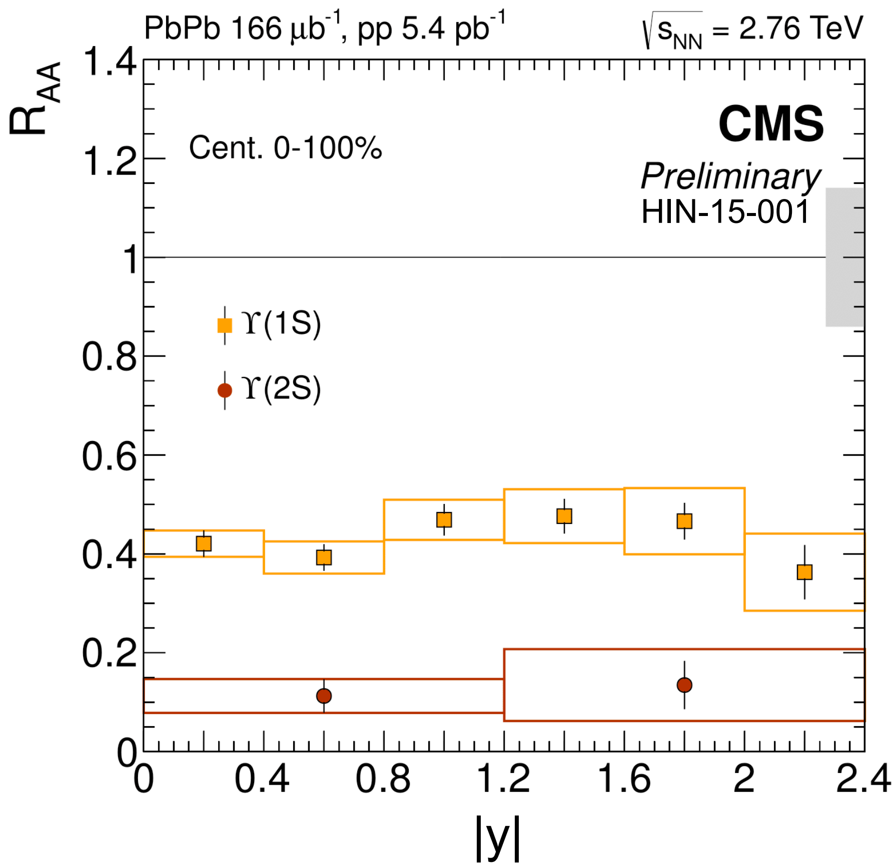
Υ R_{AA} vs. p_T and rapidity

New

- The suppression is constant over the analysis range
- Will help to constrain theoretical models





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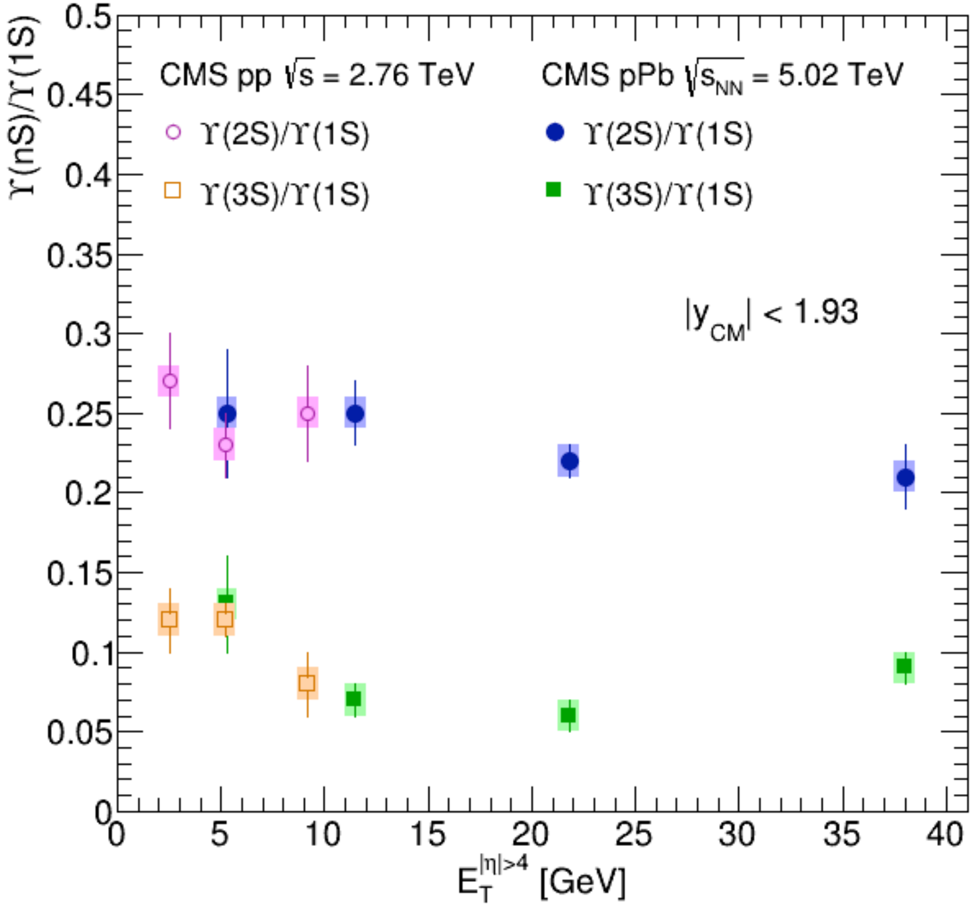
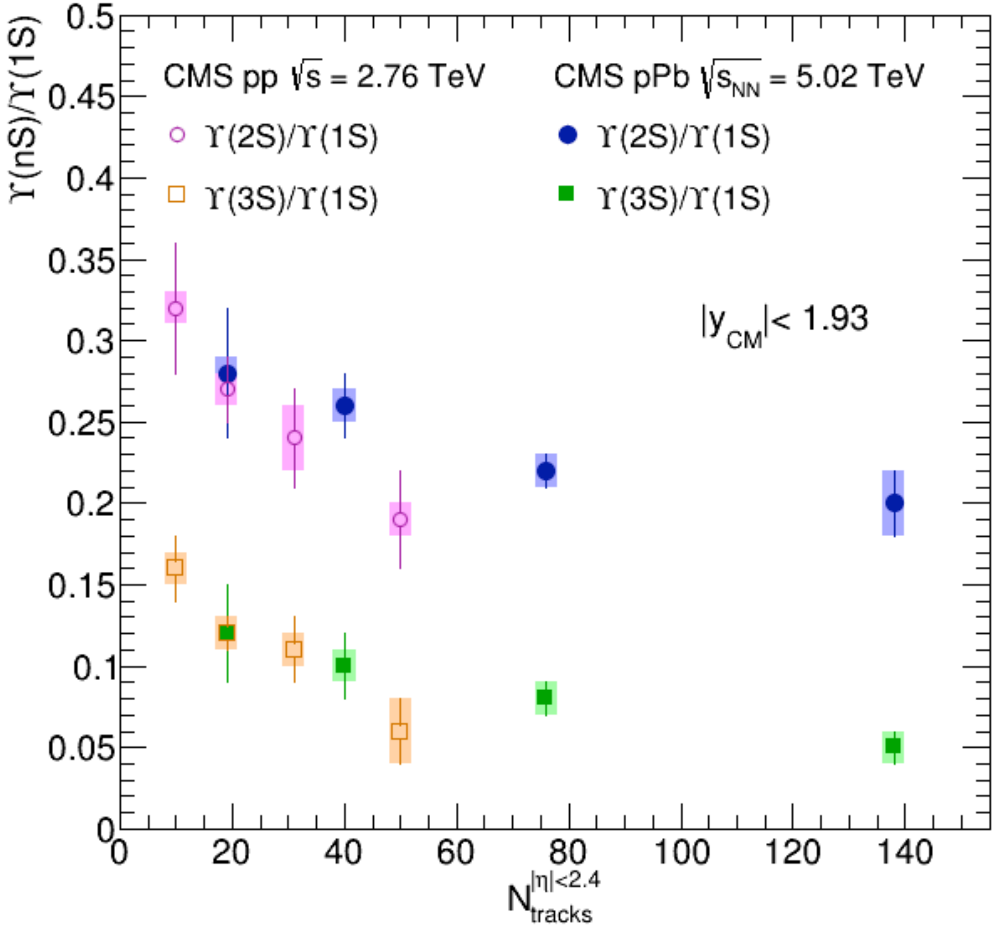
Υ(nS)/ Υ (1S) event activity dependence

PRL 109 (2012) 222301

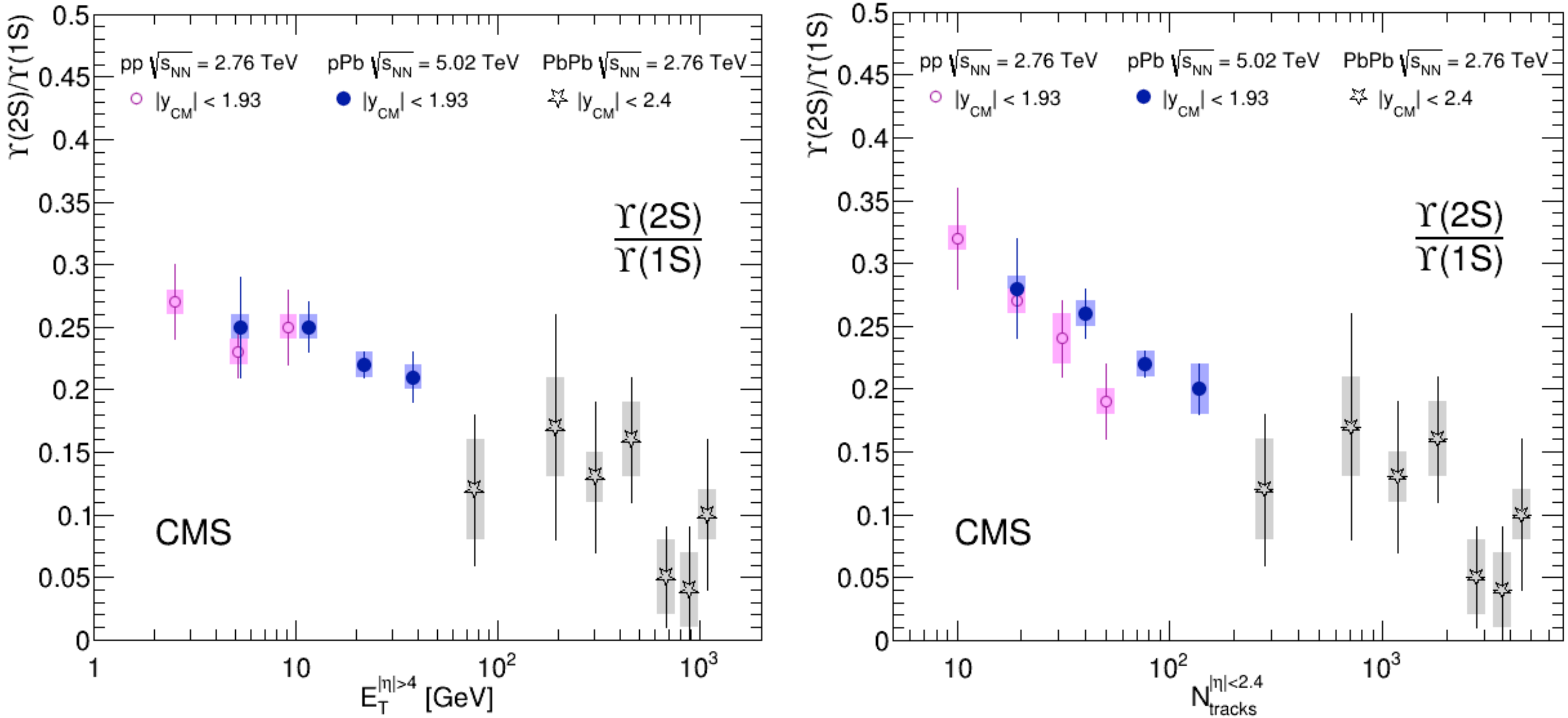




- Υ(nS)/Υ (1S) decrease with increase of charged-particle multiplicity in both pp and pPb: reflect an influence of the particles on the Υ and/or reflect a different multiplicity associated with the Υ states production

ϒ(2S)/ϒ (1S) system dependence

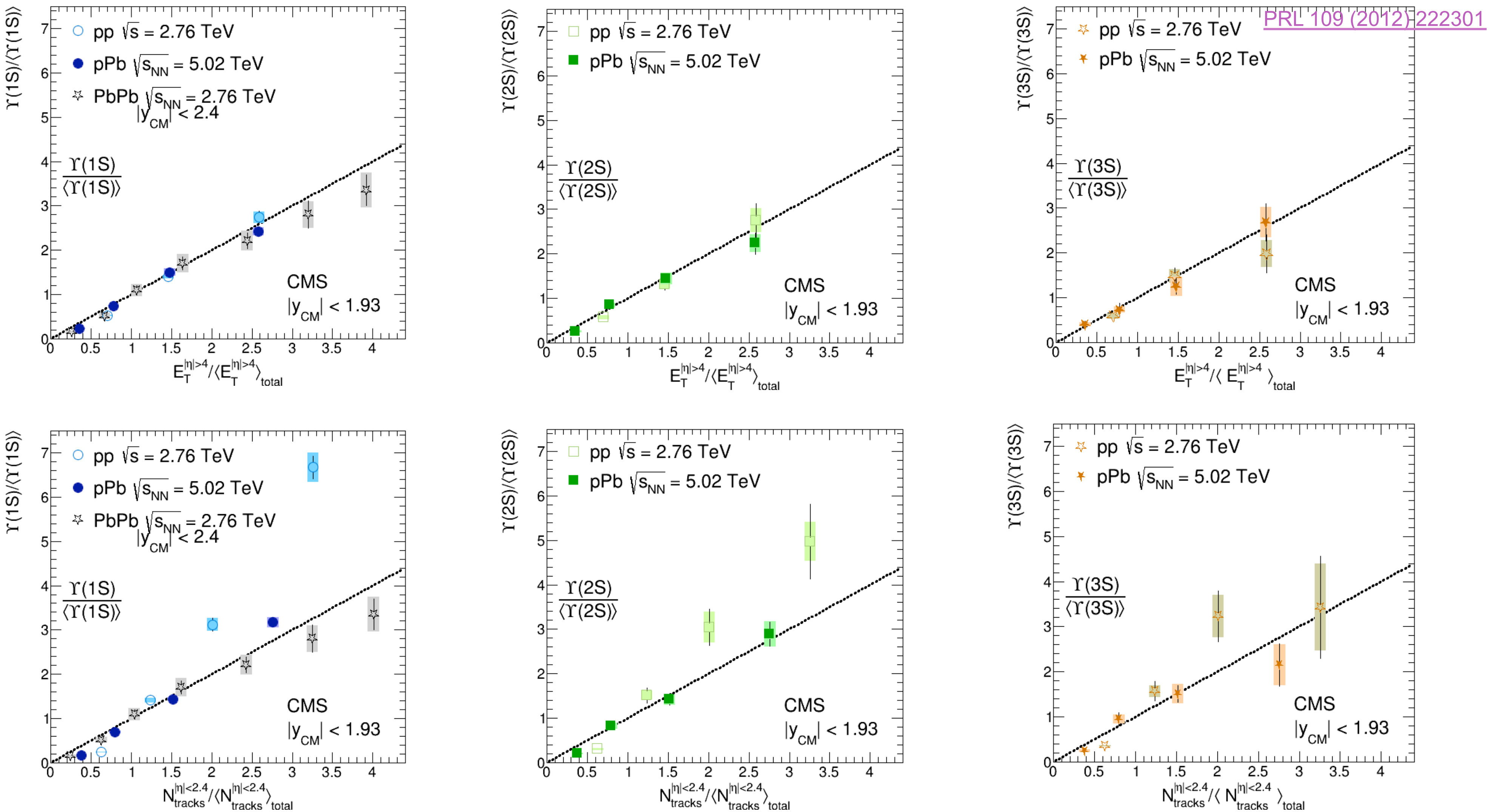
PRL 109 (2012) 222301



- No significant dependence for PbPb results as function of N_{tracks} and $E_T|\eta>4$, but we have large uncertainties (more PbPb data needed)

Self-normalized ratios

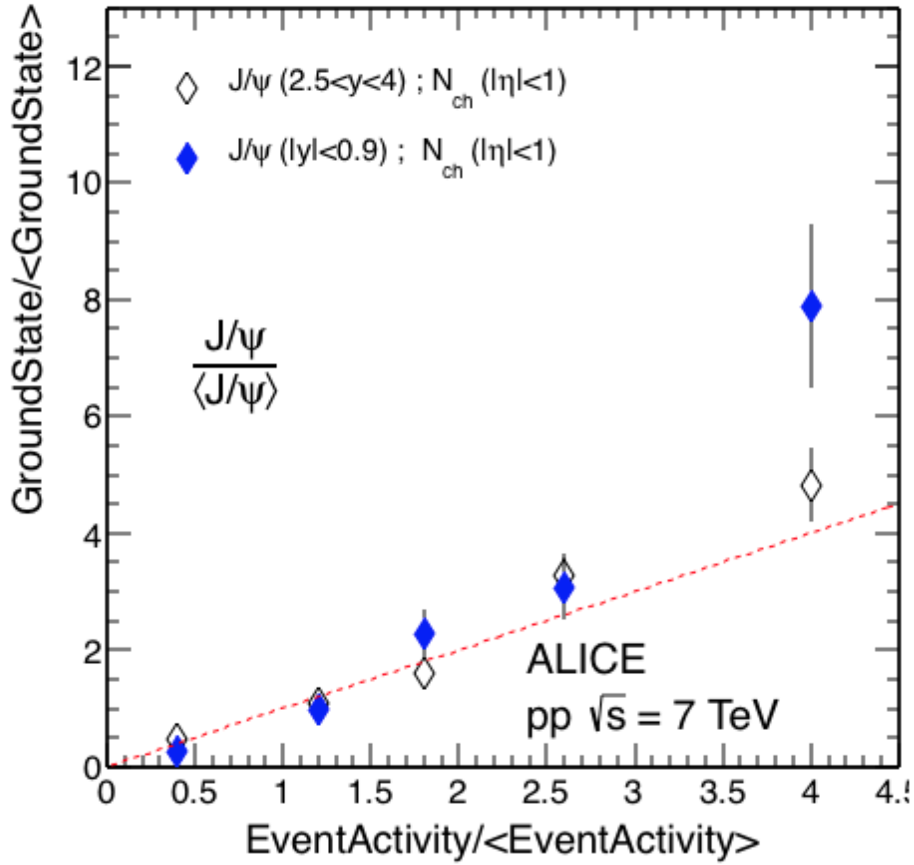
PRL 109 (2012) 222301



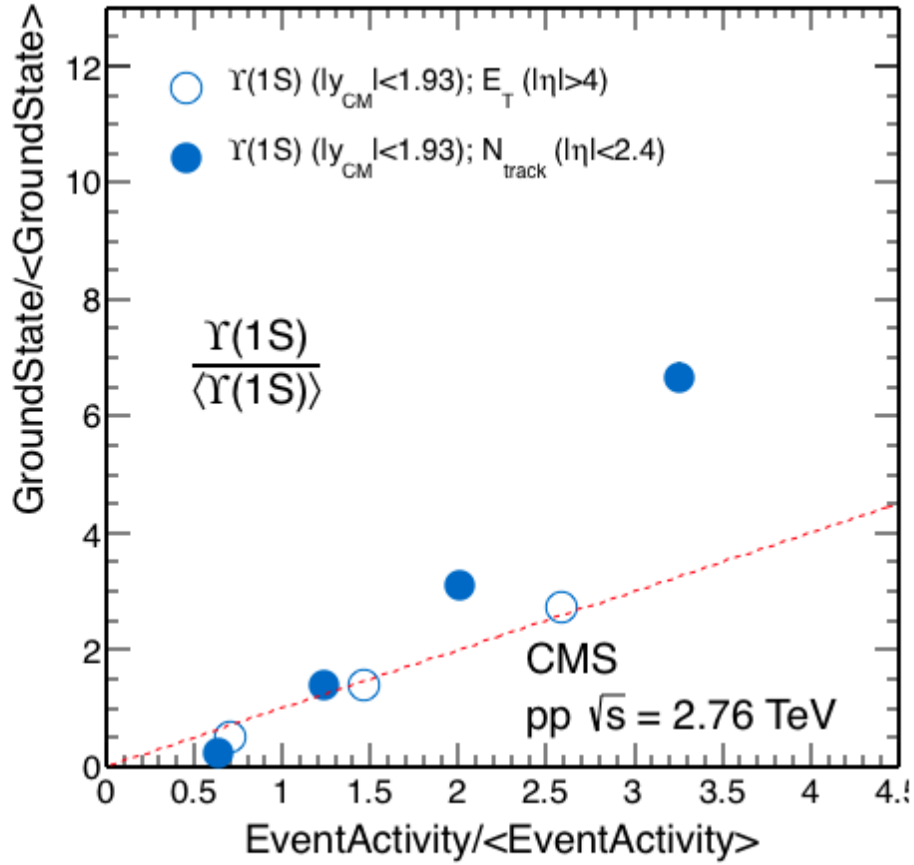
- Different $<E_T>$: 3.5 (pp), 14.7 (pPb), 760 GeV(PbPb)
- N_{Track}: less coherent behaviour
- pp: multi-parton interaction ?

Self-normalized ratios

Phys.Lett. B712 (2012) 165-175



PRL 109 (2012) 222301



- Similar trend measured by ALICE for J/ψ in pp at 7TeV
- Activity-dependent analysis of the copious pp data at 7 TeV may give a better understanding of the ϒ states

Summary

- PbPb
  - J/ψ more suppressed in central compared to peripheral events
  - low p_T J/ψ less suppressed than high p_T J/ψ
  - There is a sequential suppression for Υ states in order of binding energies
  - No p_T dependence for relatively high p_T Υ, as well as no rapidity dependence

- pPb
  - For the J/ψ
    - Nuclear effects seen in pPb prompt J/ψ production ($R_{FB} < 1$)
    - R_{FB} is clearly dependent on J/ψ transverse momentum
    - Large event activity affects more the forward-backward ratio
  - For the Υ
    - Υ(nS)/< Υ(nS)>: increase with increasing event activity in pp, pPb and PbPb
    - Detailed understanding of Υ states requires more PbPb data, and activity-dependent analysis of pp data at 7 TeV

  - All our public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

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Back-up

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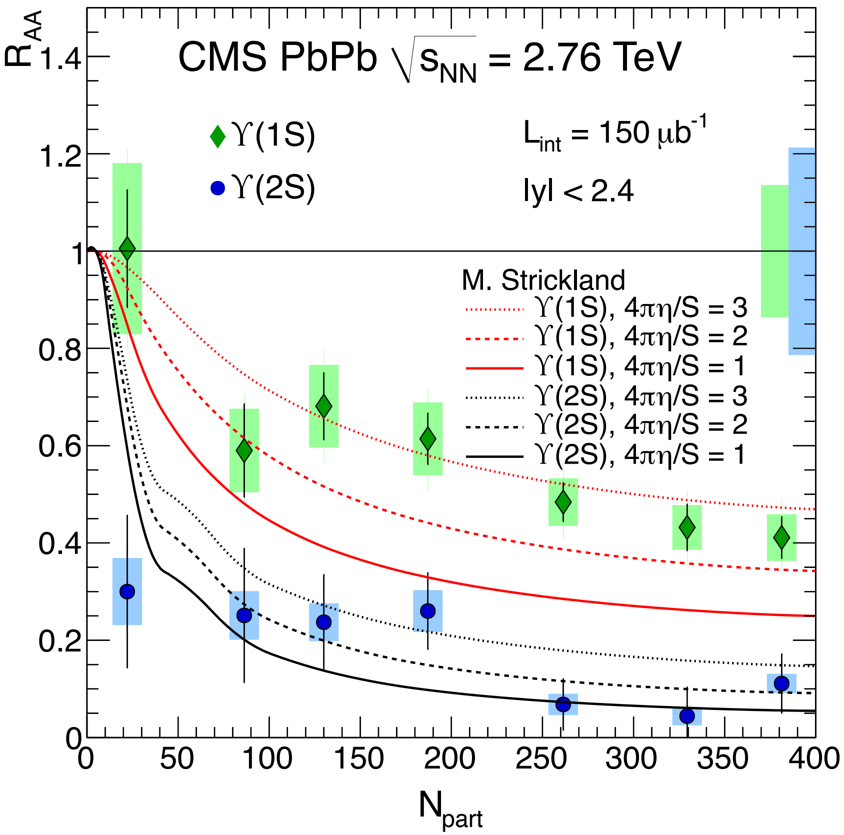
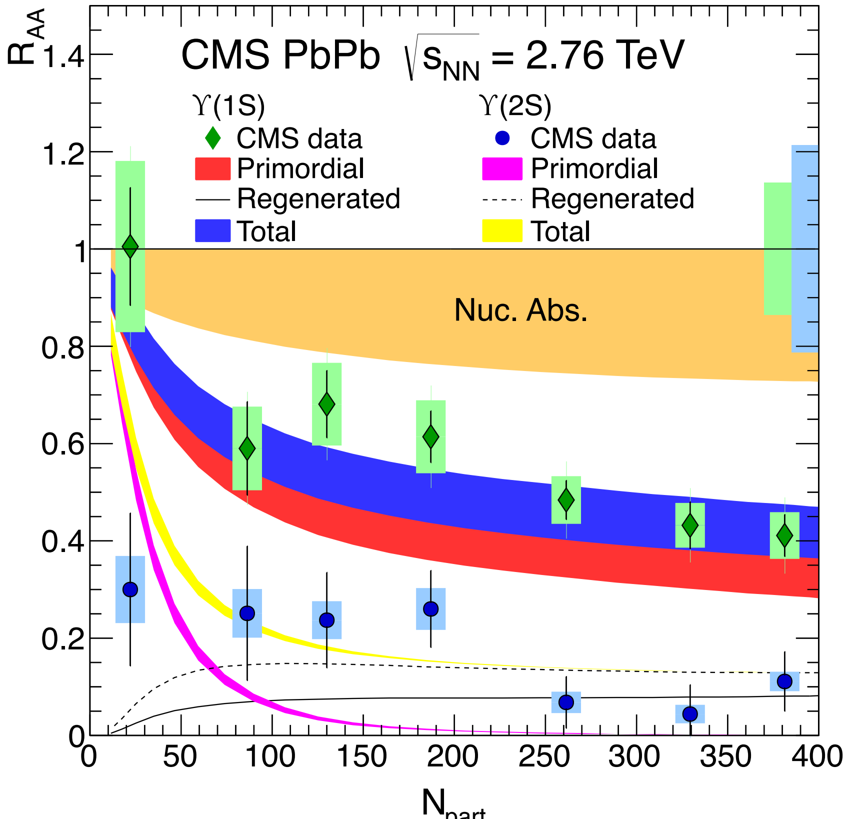
Data vs. Theory

bottomonium



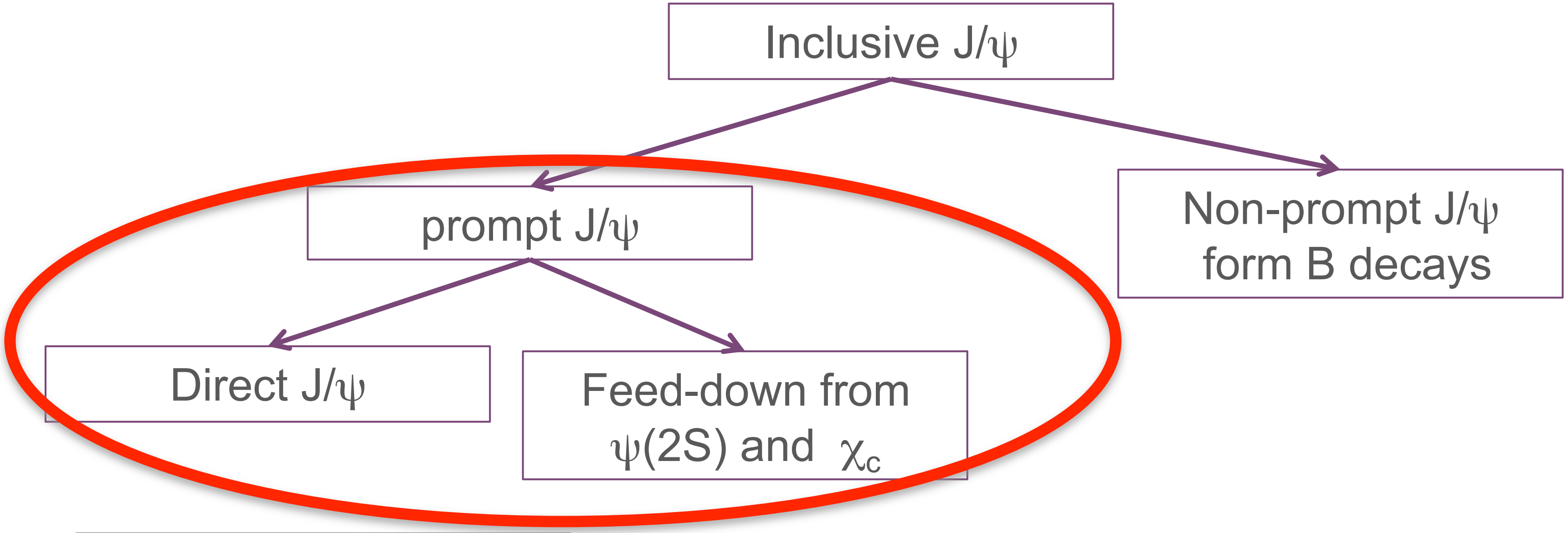
Strickland arXiv:1207.5327v2

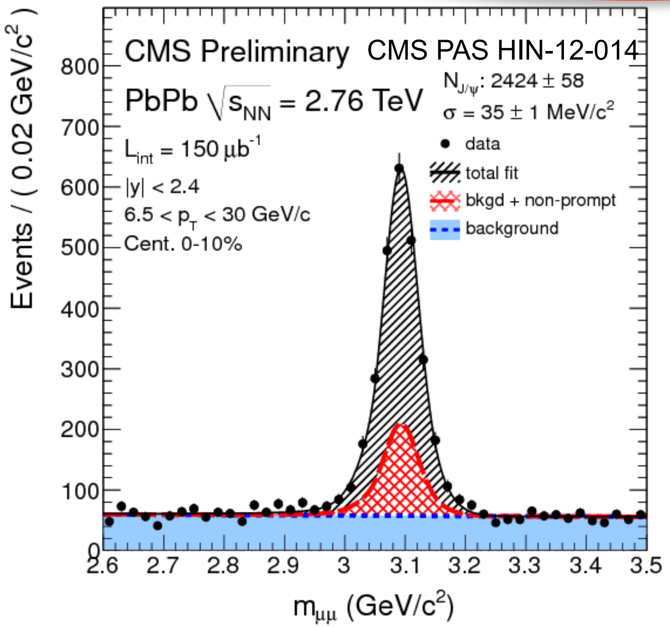


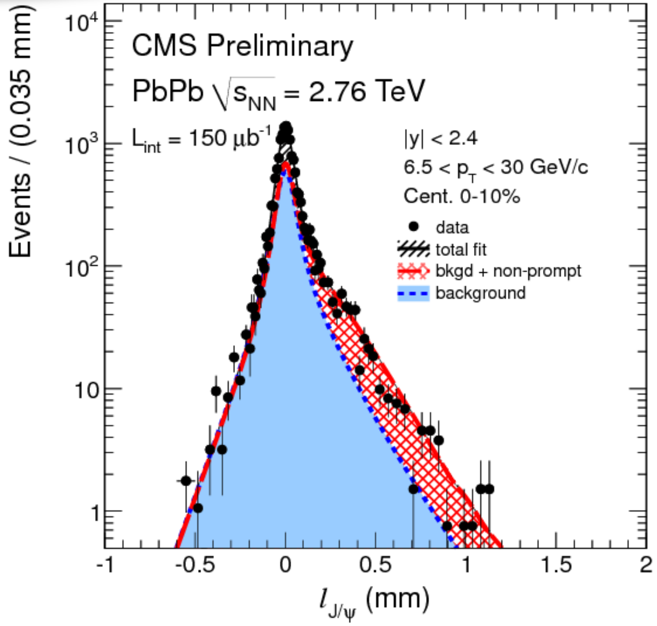
Rapp et al. Eur.Phys. J. A48 (2012) 72

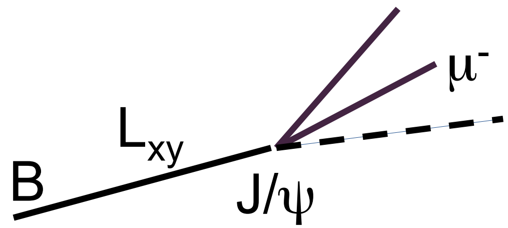
- Strickland: some tension to describe Υ(1S) and Υ(2S) simultaneously with the same η/S value
- Rapp: regeneration and nuclear absorption could be significant also for bottomonia

J/ψ separation



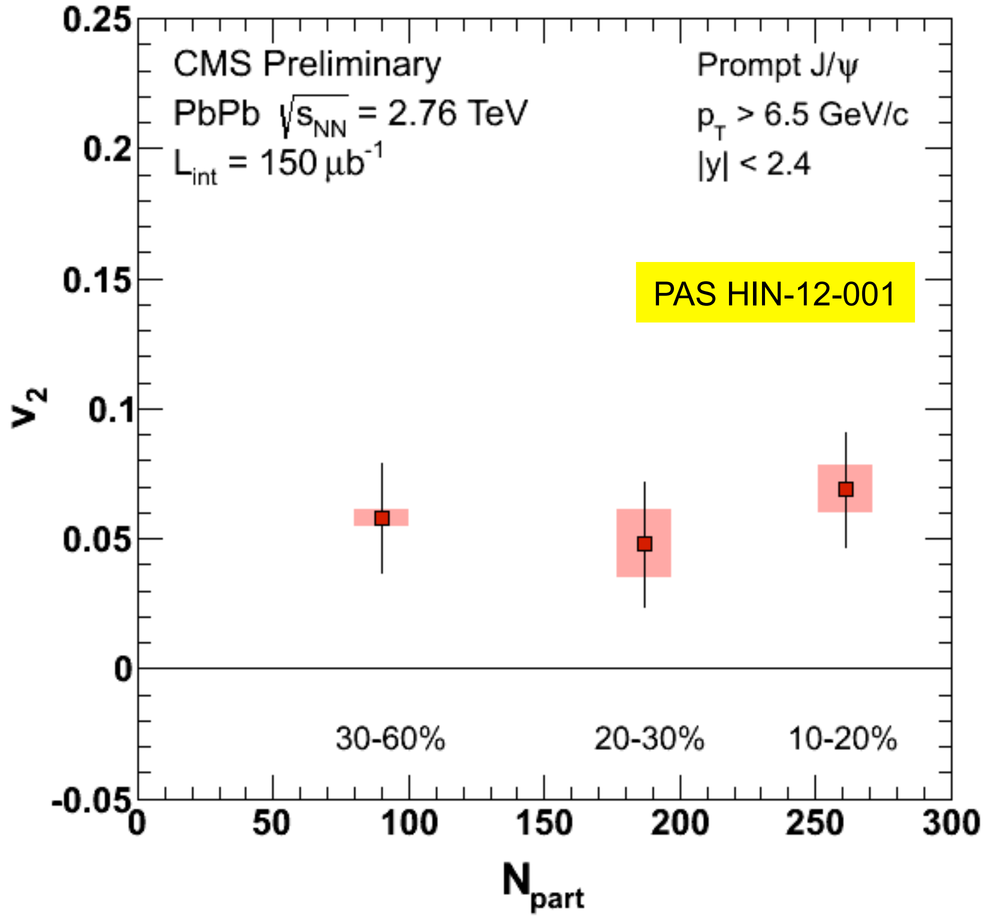


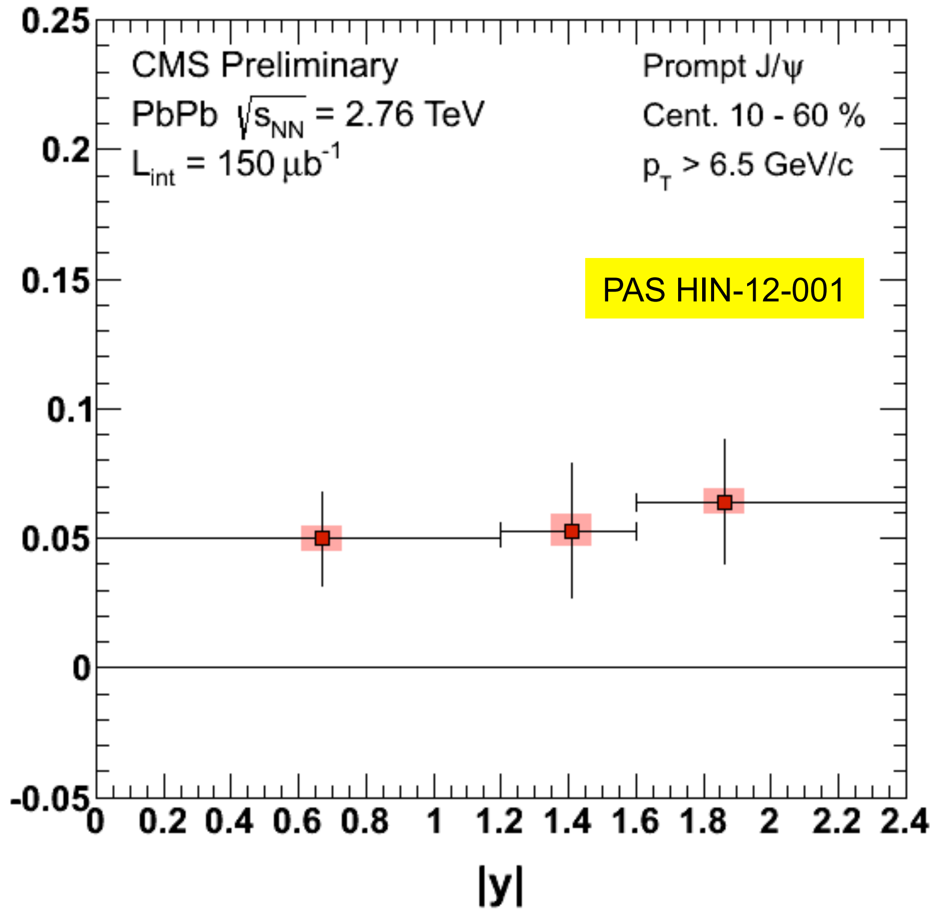




$$\ell_{J/\psi} = L_{xy}\frac{m_{J/\psi}}{p_T}$$

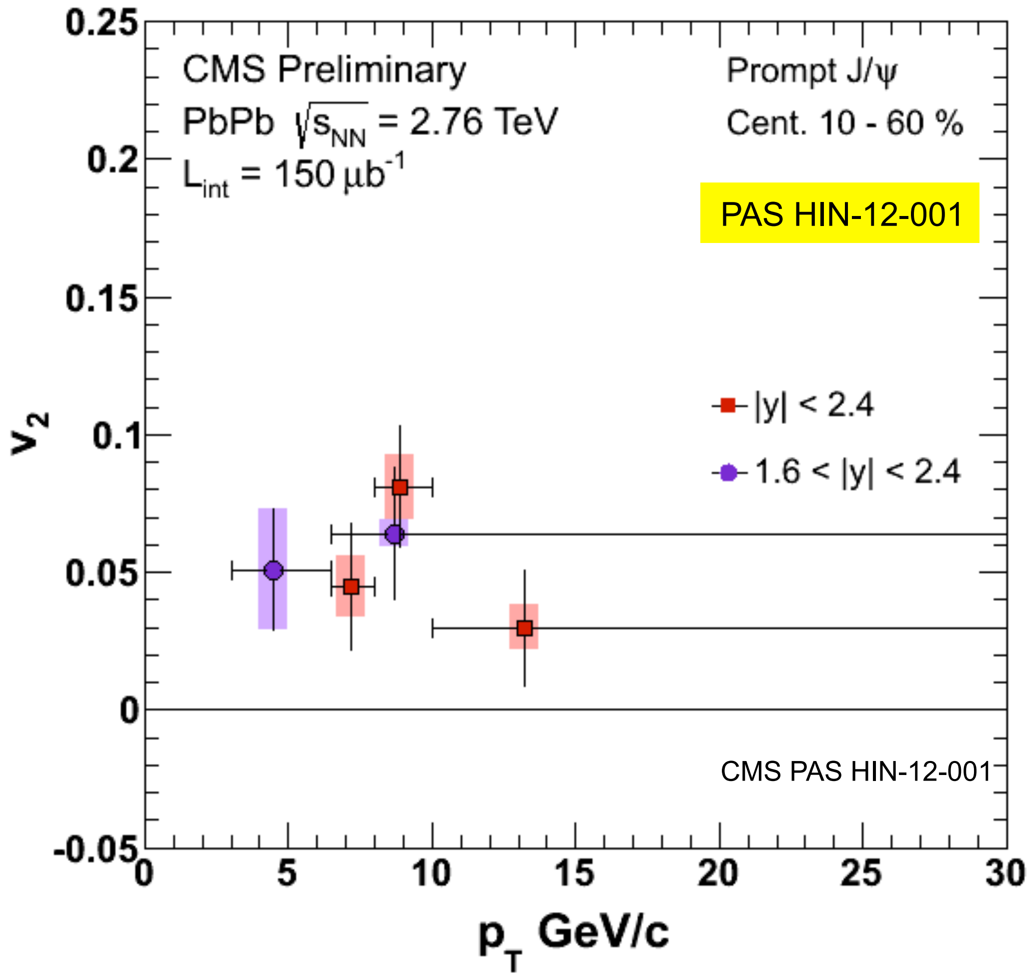
prompt J/ψ: v_2 vs. N_{part} and |y|





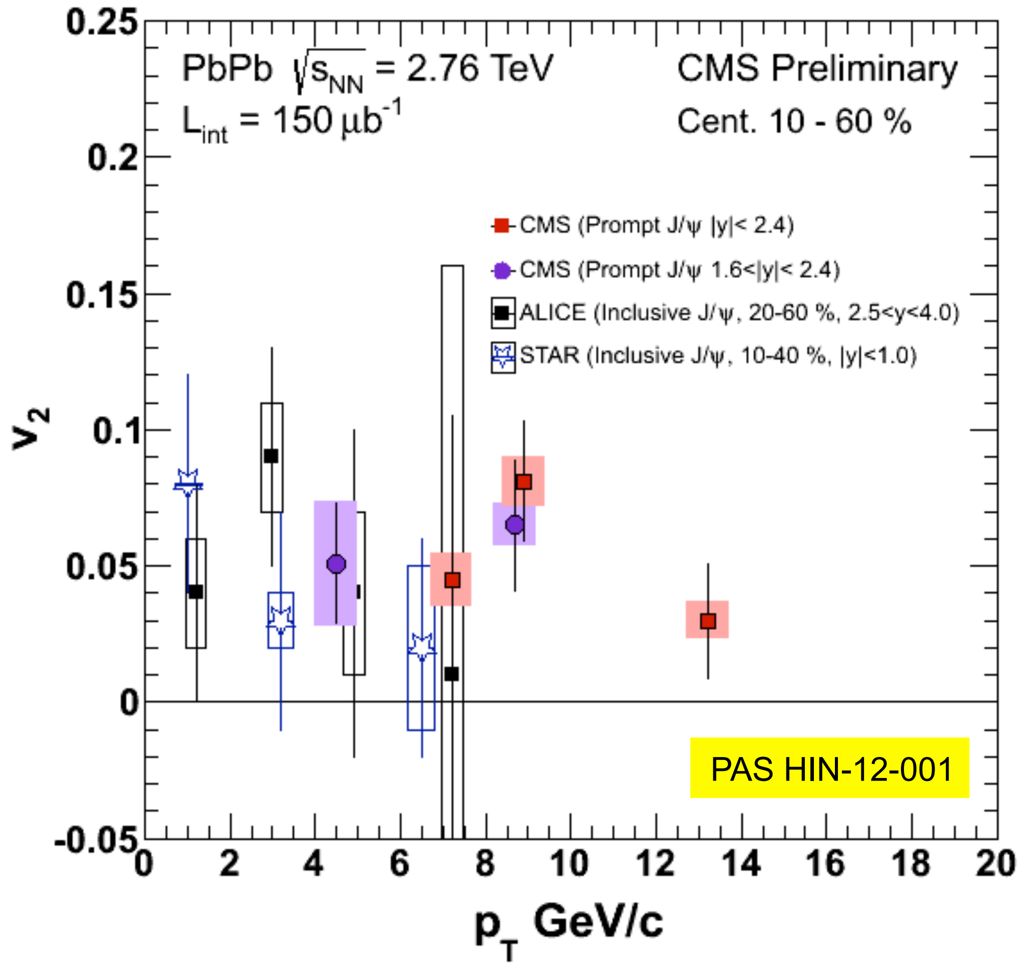
- Non zero v_2 for prompt J/ψ vs. centrality and vs. rapidity
- In [10-60%] and for $6.5 < p_T < 30$ GeV/c: $v_2 = 0.054 \pm 0.013 \pm 0.006$ with a 3.8σ significance

prompt J/ψ: v_2 vs. p_T



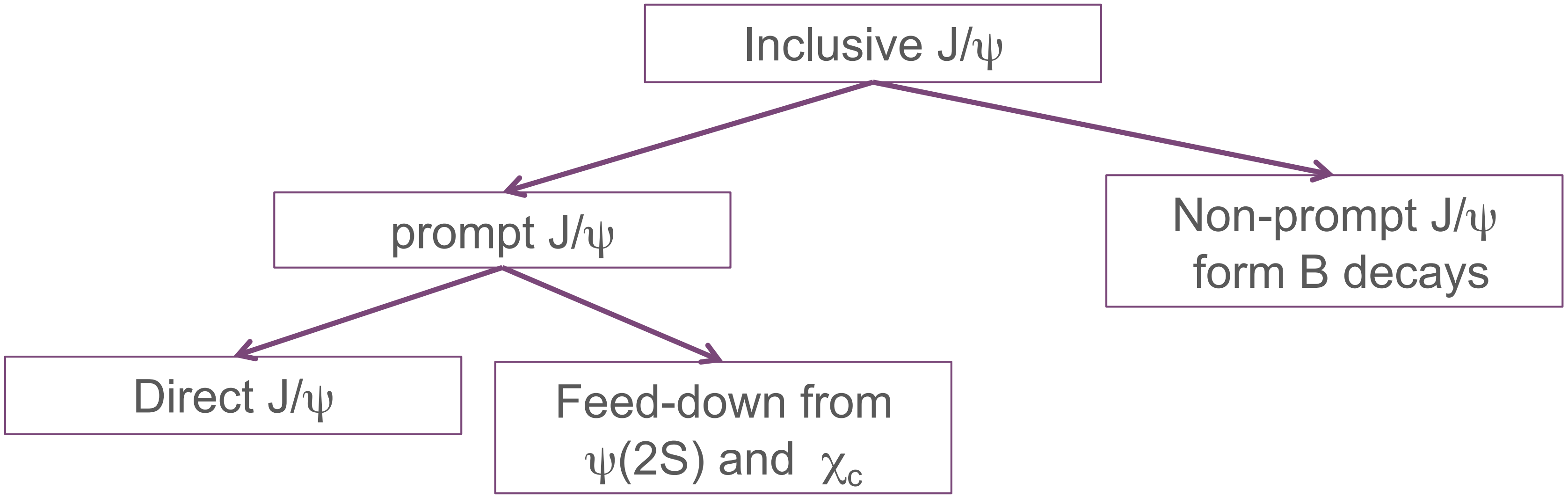
- Non zero v_2 for prompt J/ψ vs. p_T

prompt J/ψ: v_2 vs. p_T



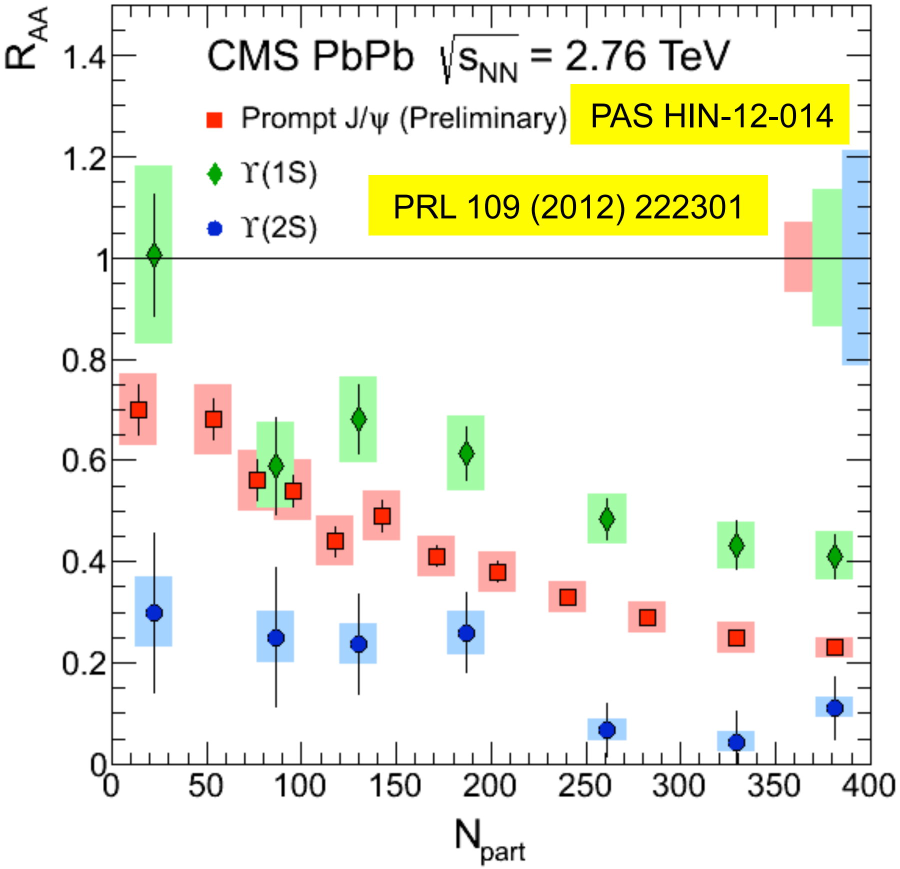
- v_2 of prompt J/ψ measured by CMS at 2.76 TeV is complementary to ALICE results (p_T < 10 GeV/c and 2.5< |y|< 4)
- STAR results at 0.2 TeV are consistent with zero in 2 < p_T < 10 GeV/c

J/ψ separation



ϒ(1S), ϒ(2S), ϒ(3S) in PbPb

- PbPb vs. pp: R_{AA}



- Clear suppression of ϒ(2S)

- ϒ(1S) suppression consistent with excited state suppression (~50% feed down)

- [0-100%]:

R_{AA}(ϒ(1S)) = 0.56 ± 0.08 (stat.) ± 0.07 (syst.)
R_{AA}(ϒ(2S)) = 0.12 ± 0.04 (stat.) ± 0.02 (syst.)
R_{AA}(ϒ(3S)) < 0.1 (at 95% C.L.)

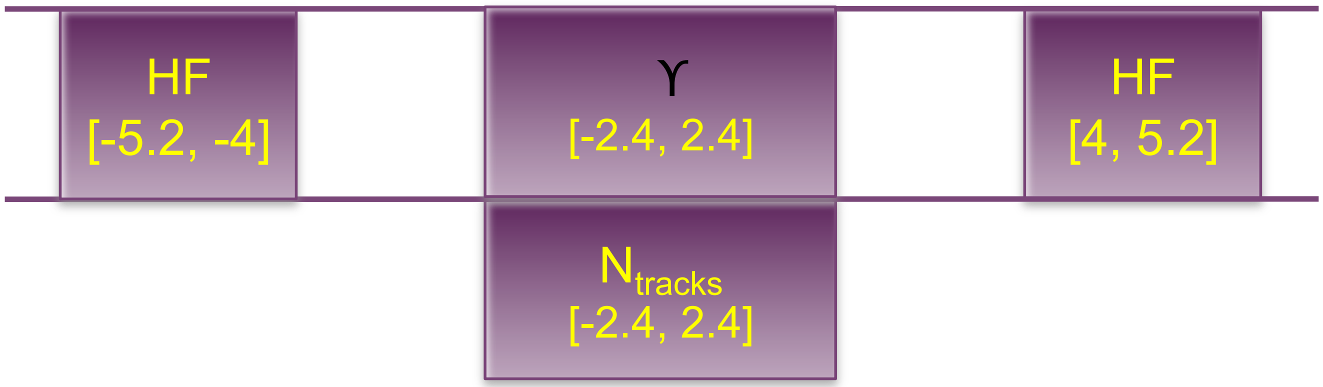
- Sequential suppression of the three states in order of their binding energy

pPb collisions

- pPb collisions: understand Cold Nuclear Matter (CNM) effect from QGP
- pPb asymmetric collisions (~0.47 rapidity boost)
  - analysis window $|y_{CM}<1.93|$

System	Pb p		
LAB	-2.4	-0.47	1.5
Collision (CM)	-1.9	0.00	1.9

- Binning in 2 event-activity variables:
  - $N_{track}^{|\eta|<2.4}$ corrected, p_T>400 MeV/c
  - $E_T^{|\eta|>4}$ raw transverse energy measured in HF



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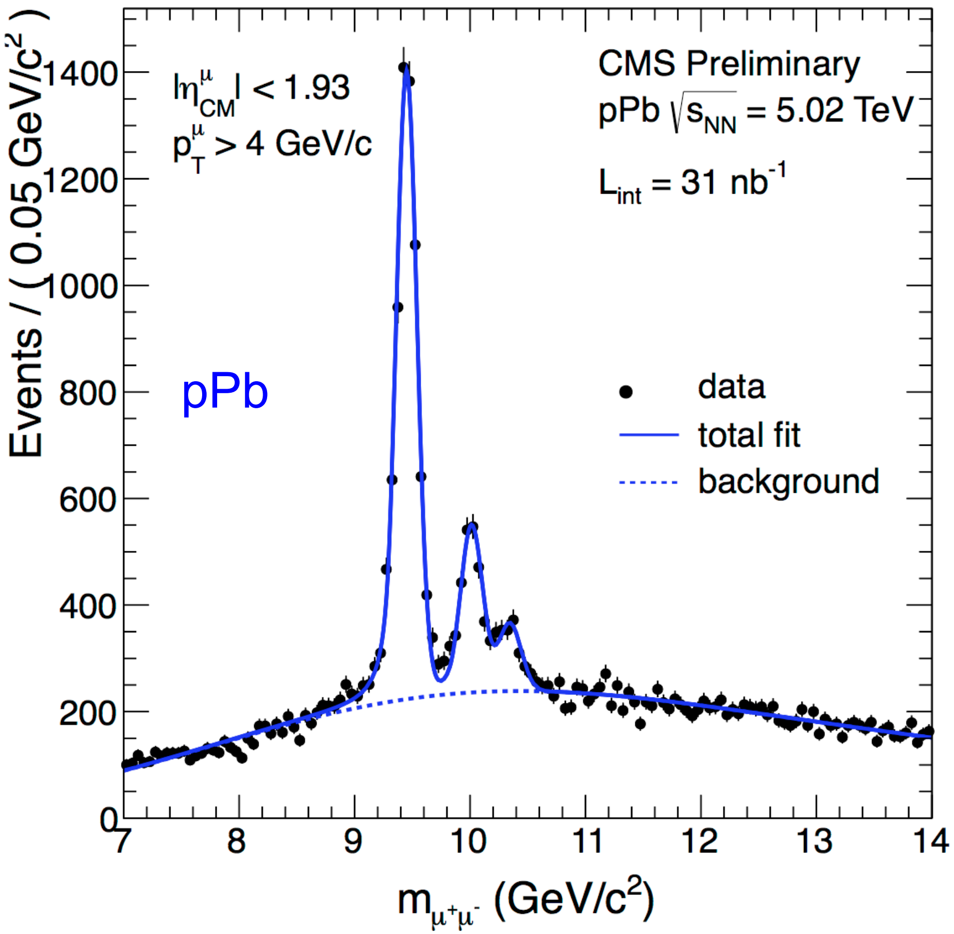
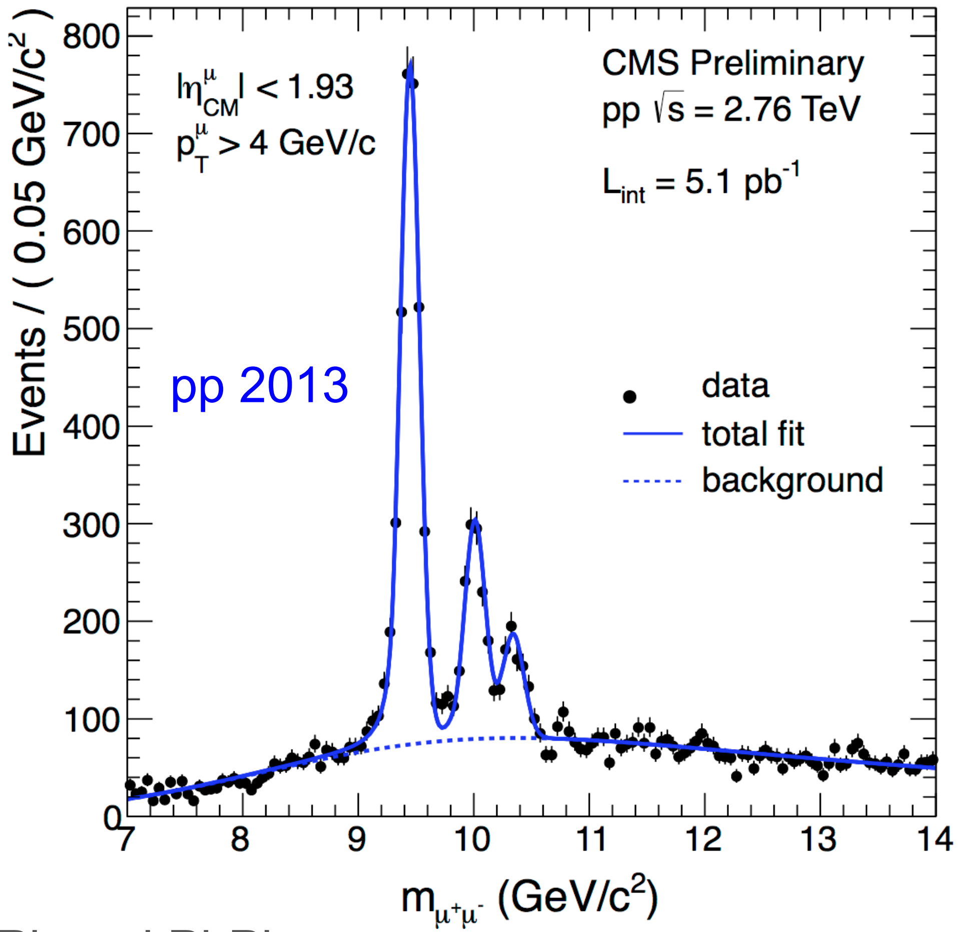
Y(1S), Y(2S), Y(3S) in pPb

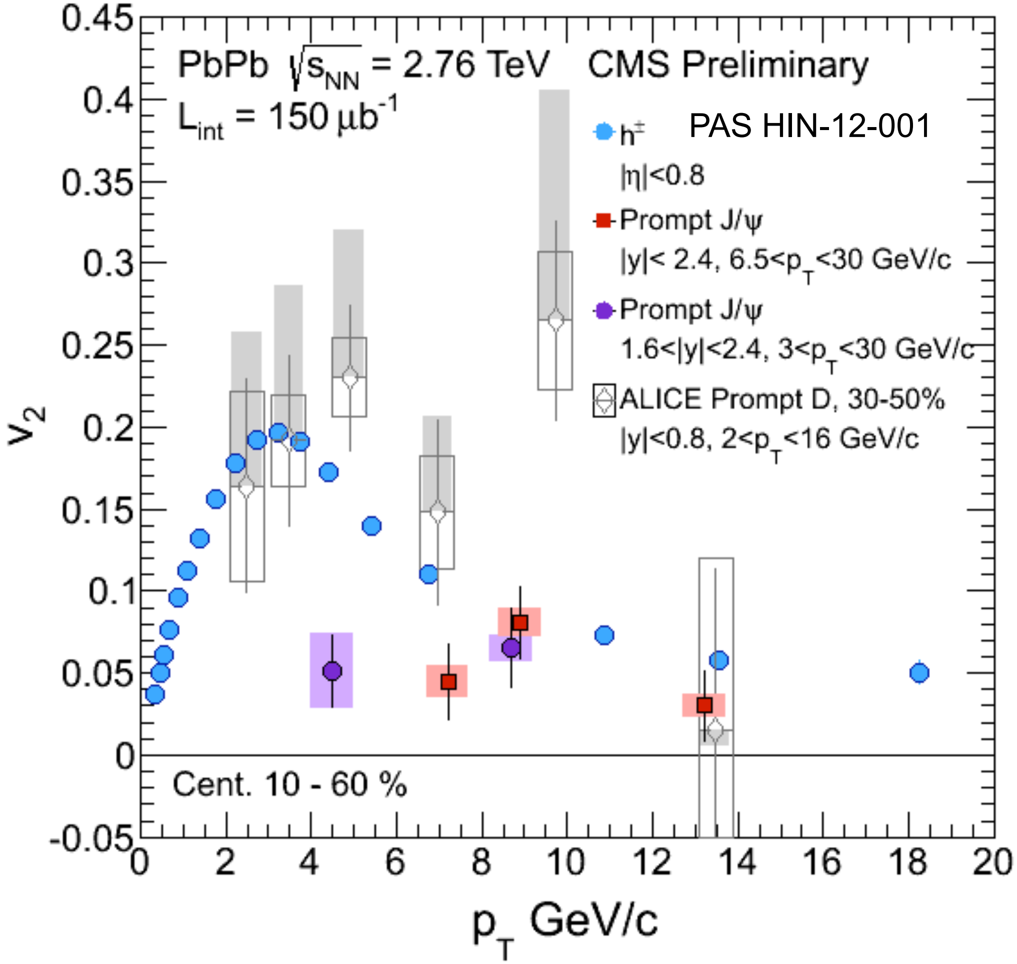
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN13003





- Signal extraction same procedure in pp, pPb and PbPb:
- Unbinned maximum log likelihood with 1S, 2S/1S, 3S/1S variables in the fit
  - Signal: 3 Crystal-Ball functions
  - Background: errorFunction x exponential (all background parameters free)

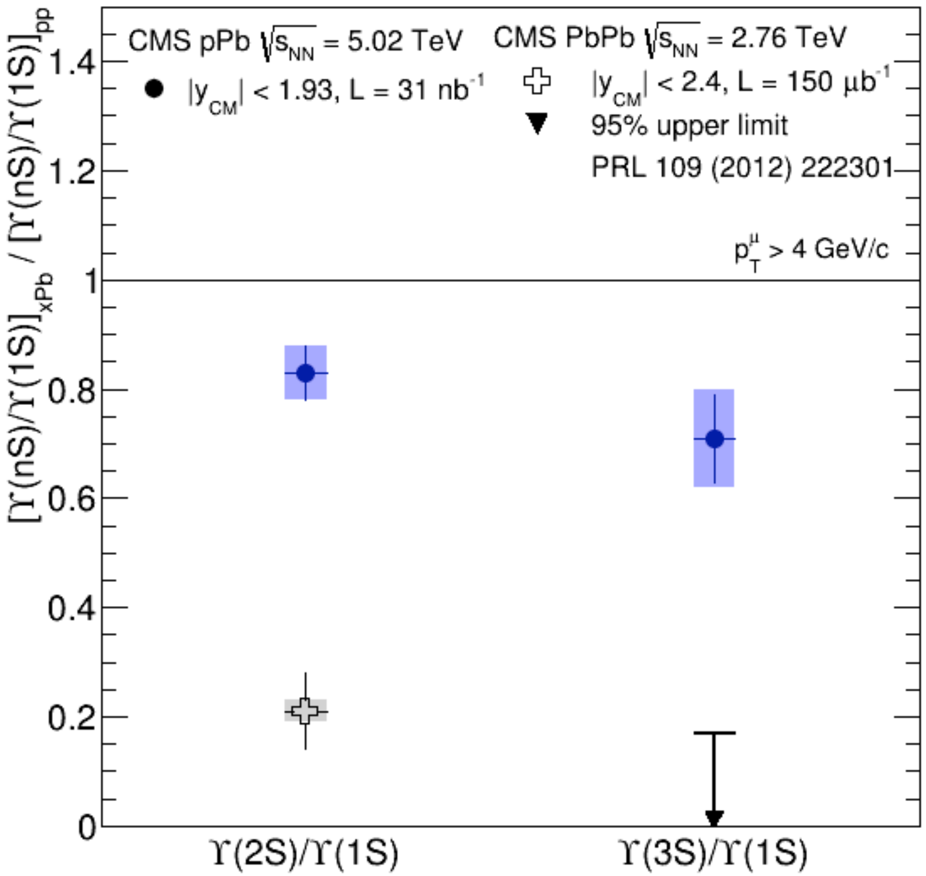
prompt J/ψ: v_2 vs. p_T



- At low p_T: v_2 prompt J/ψ < v_2 charged hadrons and v_2 D mesons (ALICE)
- At high p_T 8 < p_T < 10 GeV/c: similar v_2 for prompt J/ψ and charged hadrons

→ Path-length dependence of partonic energy loss in a deconfined medium ?

Integrated measurement



- pPb vs. PbPb: additional final-state effects in PbPb that affect the excited states more than the ground state
- pPb vs. pp: excited states suppressed more than the ground state in pPb compared to pp collisions (significance < 3 σ)