Summary of Recent Results for Quarkonia Production in pp, pPb, PbPb with CMS

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On behalf of CMS collaboration
(Chonnam National University, Korea)

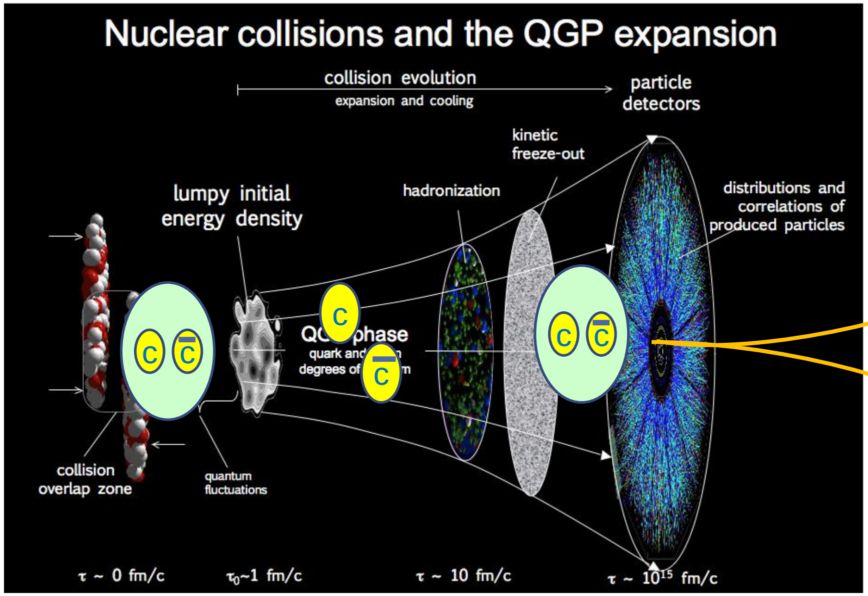
2019/01/10 XXV EPIPHANY @ Crocow, Poland

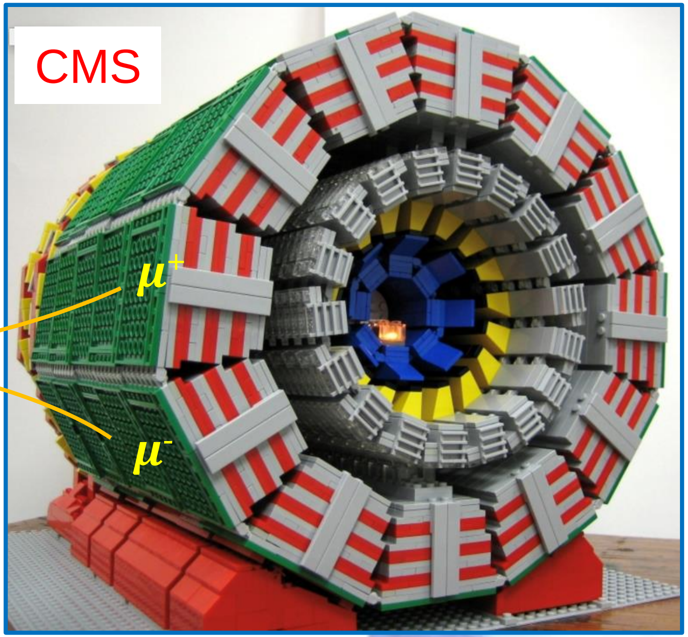
Quarkonia in Heavy ion Collisions

- Quarkonia : Excellent Probe for the Quark-Gluon-Plasma
  - Produced by hard scattering in the early stage of collisions

$$\tau_{formation}(q\bar{q}) \leq \tau_{formation}(QGP) < \tau_{life\ time}(QGP) < \tau_{decay\ time}(q\bar{q})$$

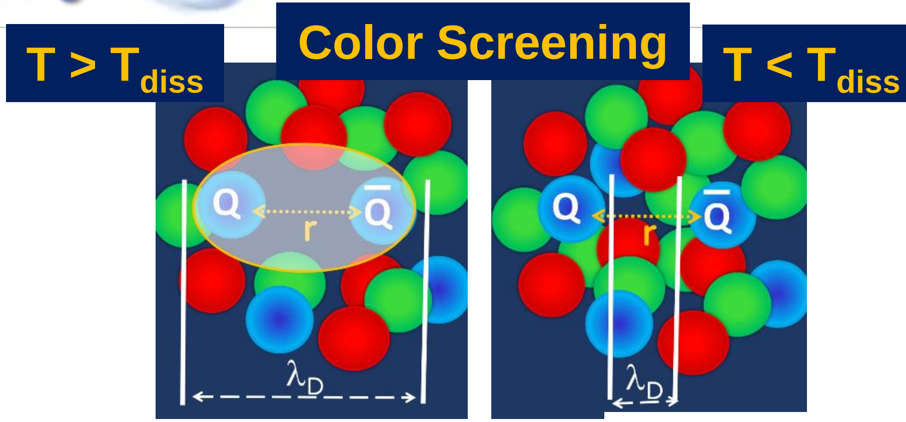
➠ expected to experience whole QGP evolution





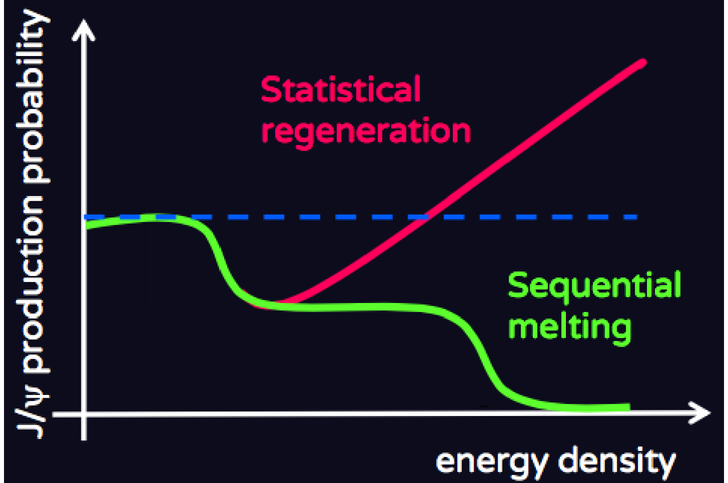
Quarkonia in Heavy ion Collisions

- **Quarkonia productions in heavy ion collisions are affected by**
  - **Color Screening** : melting depending on different temperatures and binding energies
    - ► **Sequential Melting**
  - **Parton energy loss** in medium
  - **Cold Nuclear Matter (CNM) Effects** : Nuclear PDFs, multiple scattering, comover break-up.. Etc
  - **Statistical Regeneration**



QWG 2017 R. Arnaldi

Central AA collisions	SPS 20 GeV	RHIC 200 GeV	LHC 2.76TeV
N_{ccbar}/event	~0.2	~10	~85



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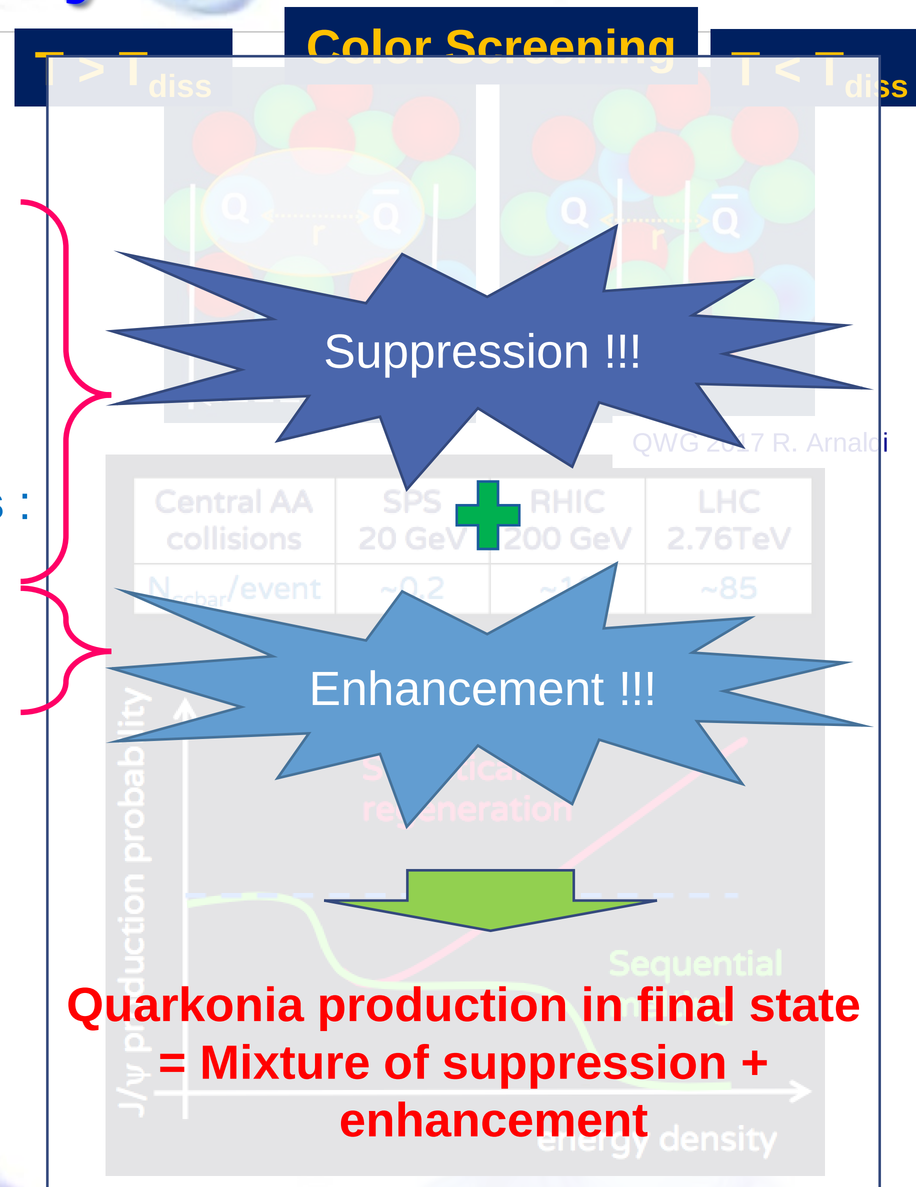
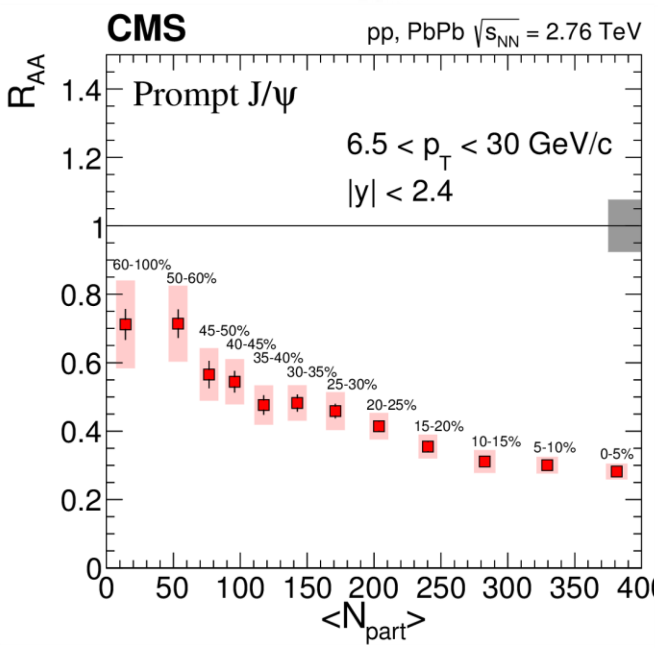
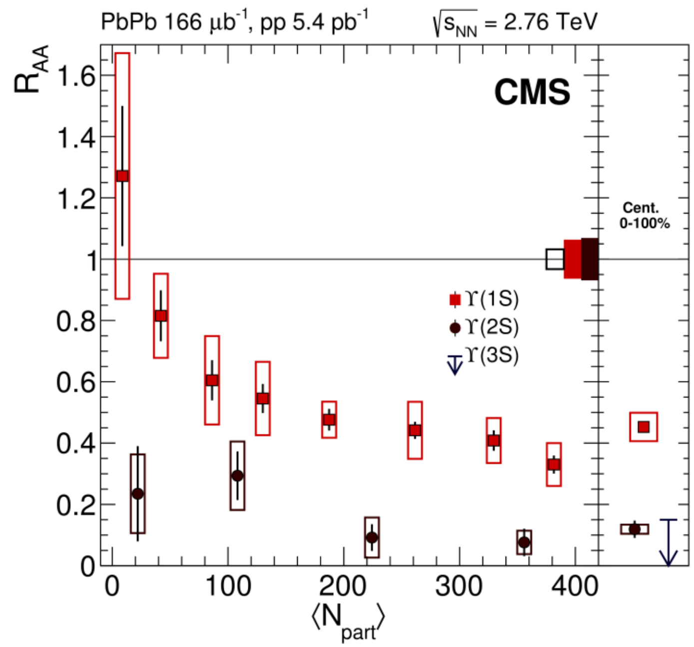


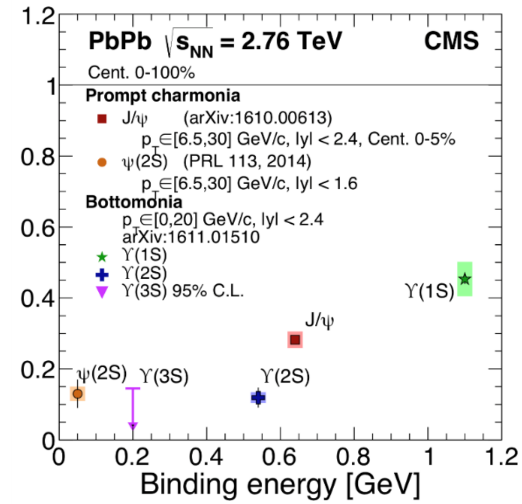
Quarkonia production in final state = Mixture of suppression + enhancement

Reminder from Run I

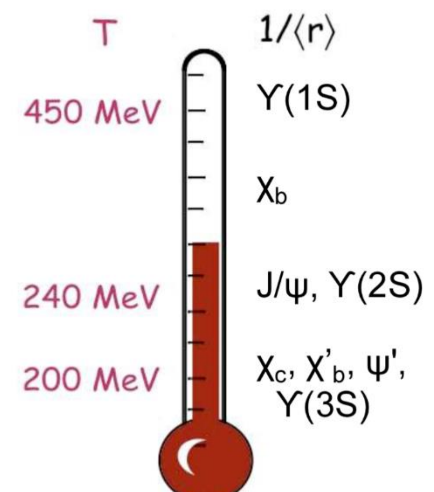
EPJC 77 (2017) 252
PRL 109 (2012) 222301







$$R_{AA} = \frac{\text{Yield}_{AA} / \langle N_{Coll} \rangle}{\text{Yield}_{pp}}$$



Charmonia	J/ψ	χ_c	ψ'(2S)
Mass(GeV)	3.10	3.53	3.69
ΔE (GeV)	0.64	0.20	0.05
T_d/T_c	2.1	1.16	1.12

Bottomonia	ϒ(1S)	ϒ(2S)	ϒ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
T_d/T_c	> 4.0	1.60	1.17

Mocsy, EPJC61 (2009) 705
BNL workshop in June

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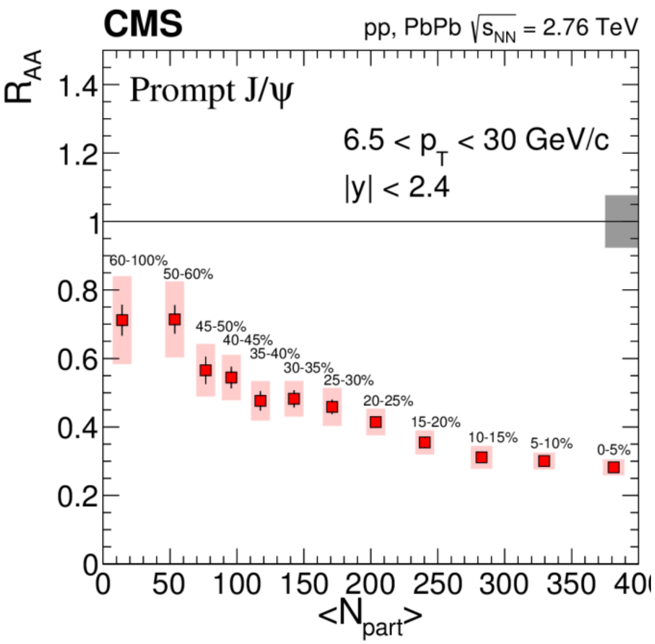
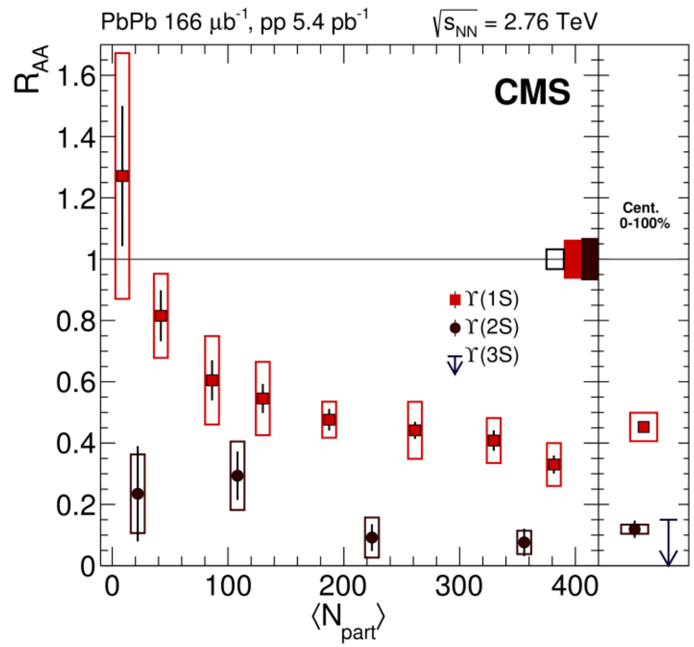
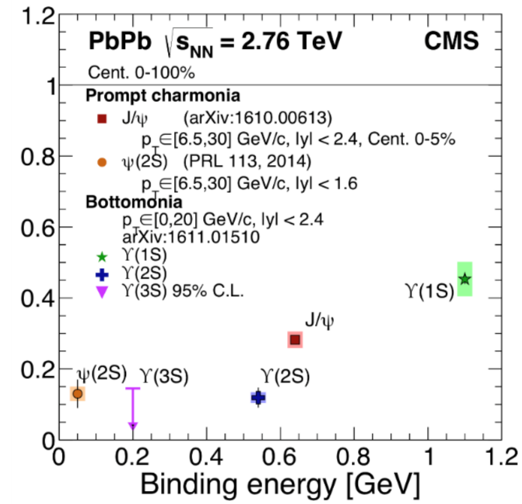




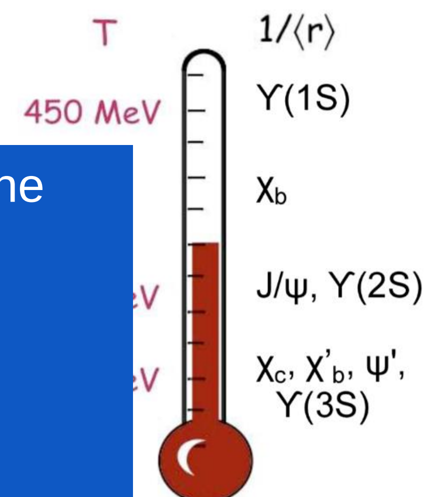


Yield$_{AA}$/⟨N$_{Coll}$⟩

Today contents will be made by the results with the 2015 data at 5.02 TeV.

- Charmonia in pPb & PbPb
- Bottomnoia in PbPb
- J/ψ Elliptic flow
- Summary & Outlook

Charmonia	J/ψ
Mass(GeV)	3.1
ΔE (GeV)	0.6
T_d/T_c	2.



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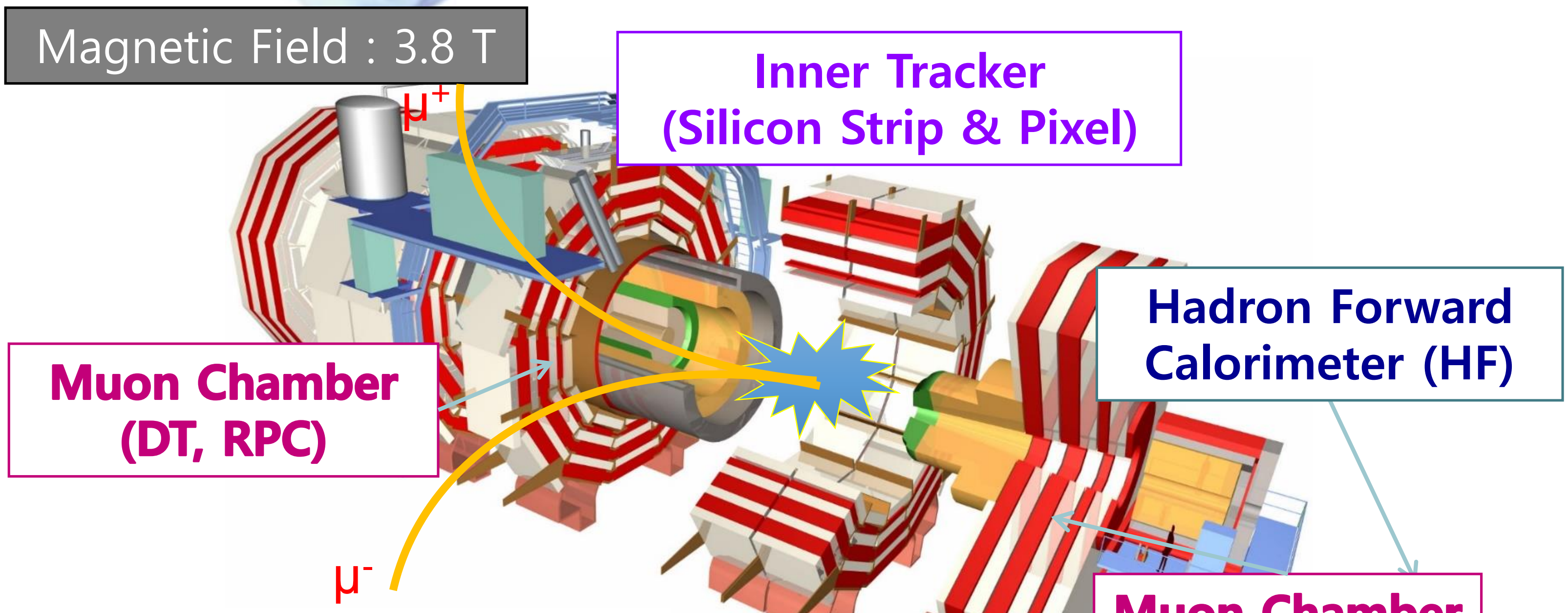
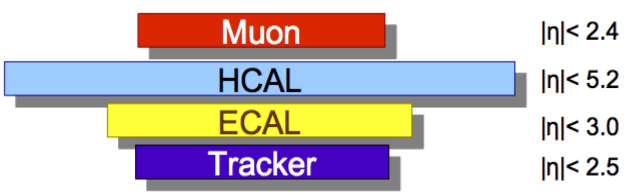
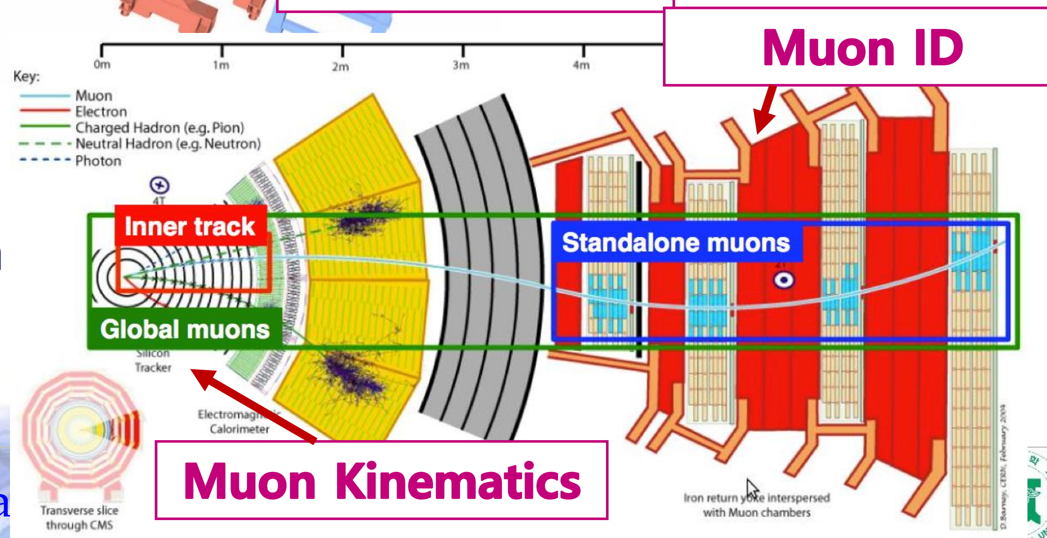
CMS Detector & Muon Reconstruction



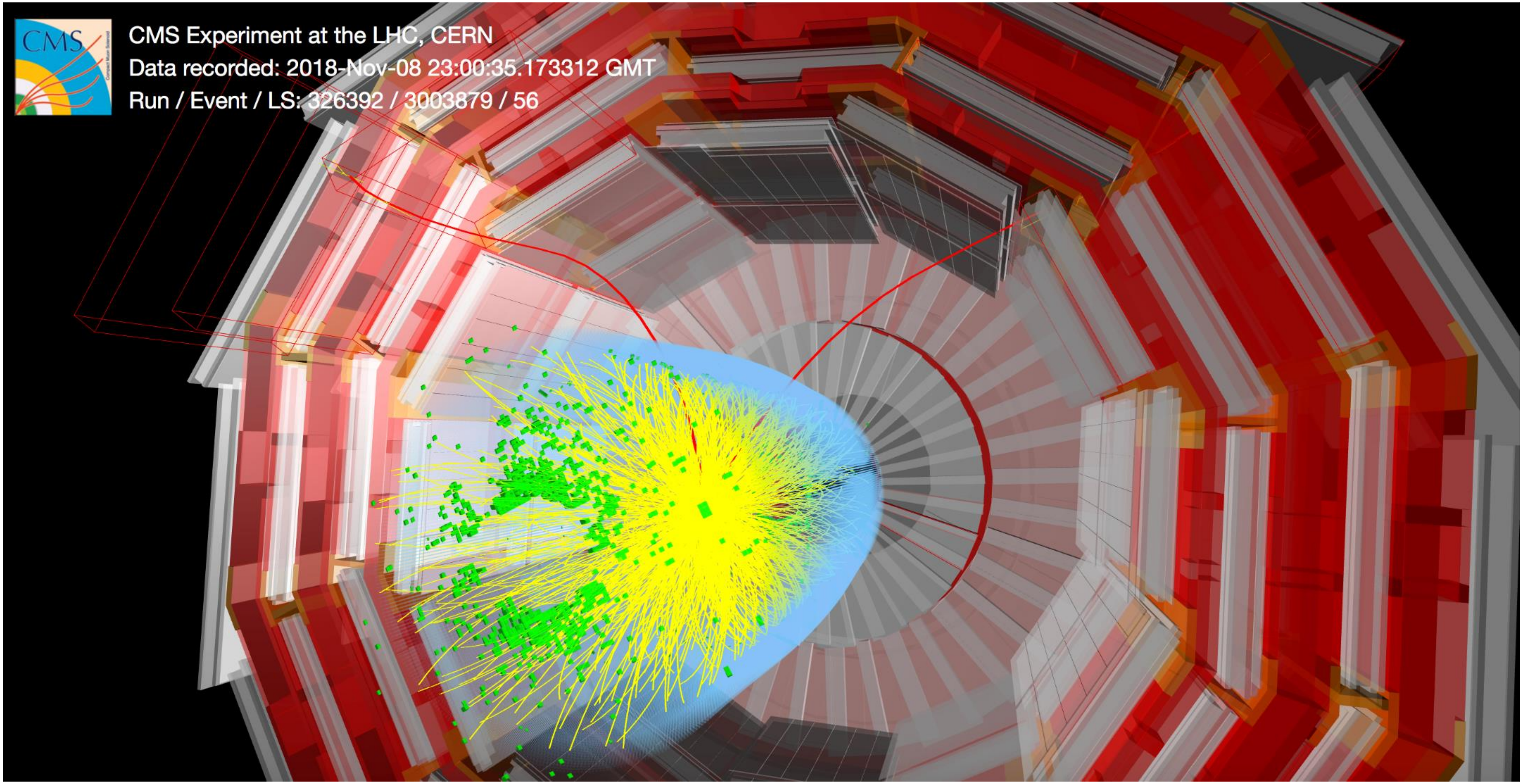




Excellent muon momentum resolution

- Overall resolution: 1~2 %

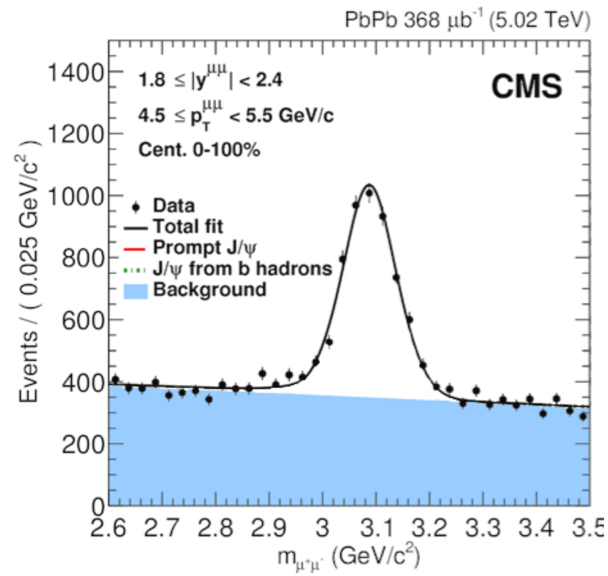
Charmonia in pPb & PbPb

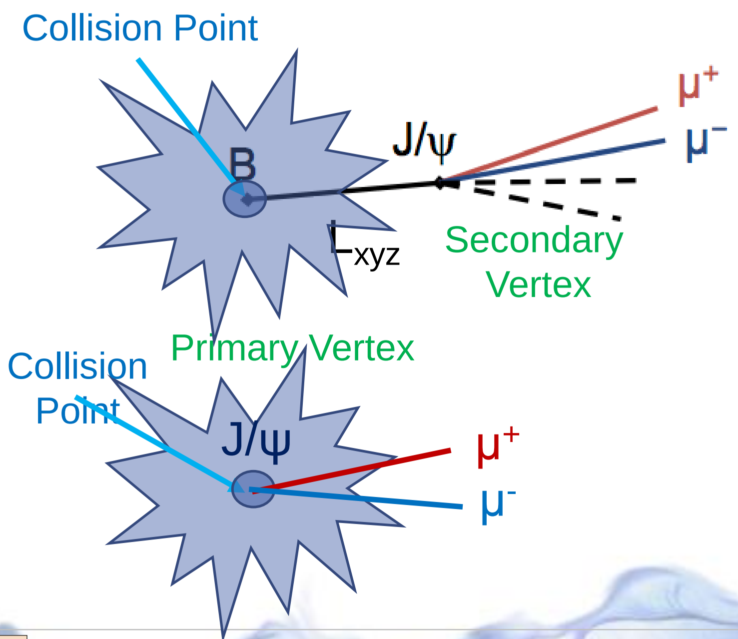


J/ψ : Signal Extraction

arXiv:1712.08959

Inclusive J/ψ





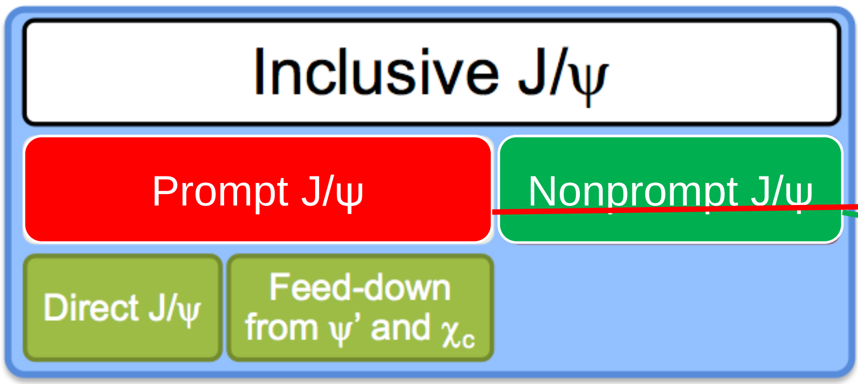
Nonprompt J/ψ

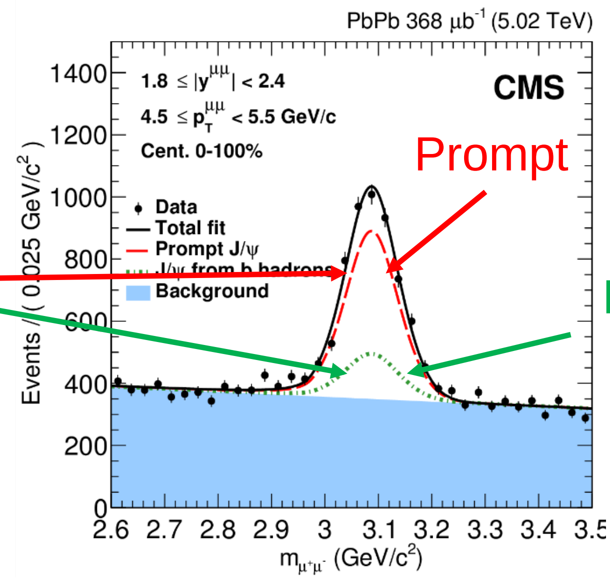
Prompt J/ψ

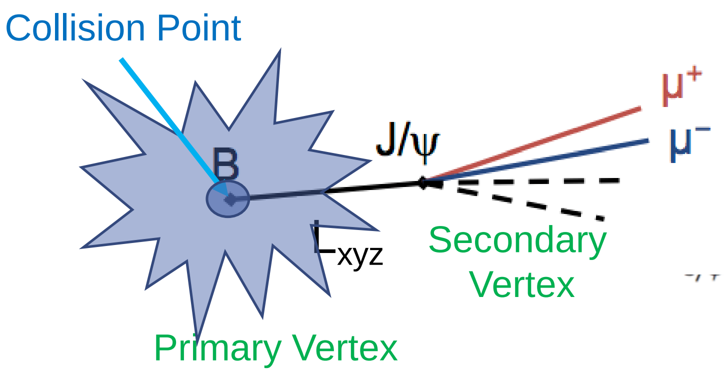
Inclusive J/ψ

J/ψ : Signal Extraction

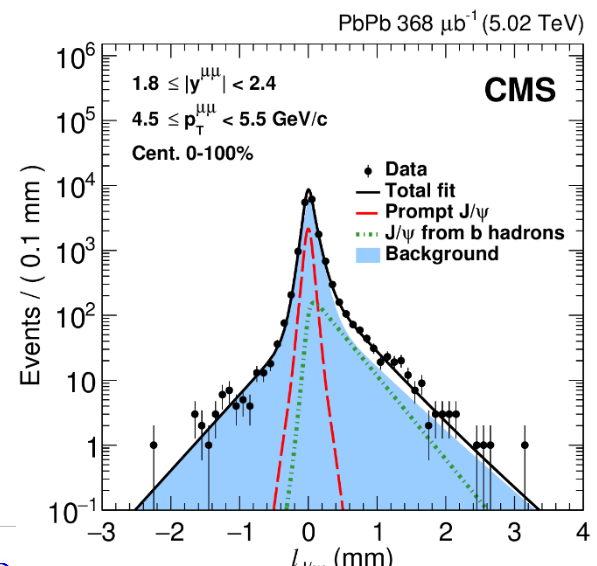
arXiv:1712.08959







$$= L_{xyz} \cdot \frac{m_{J/\psi}}{p_{\mu\mu}}$$



- Simultaneous two dimensional fit method
  - Mass + pseudo-proper decay length
- Separate prompt and nonprompt statistically bin-by-bin

J/ψ : Signal Extraction

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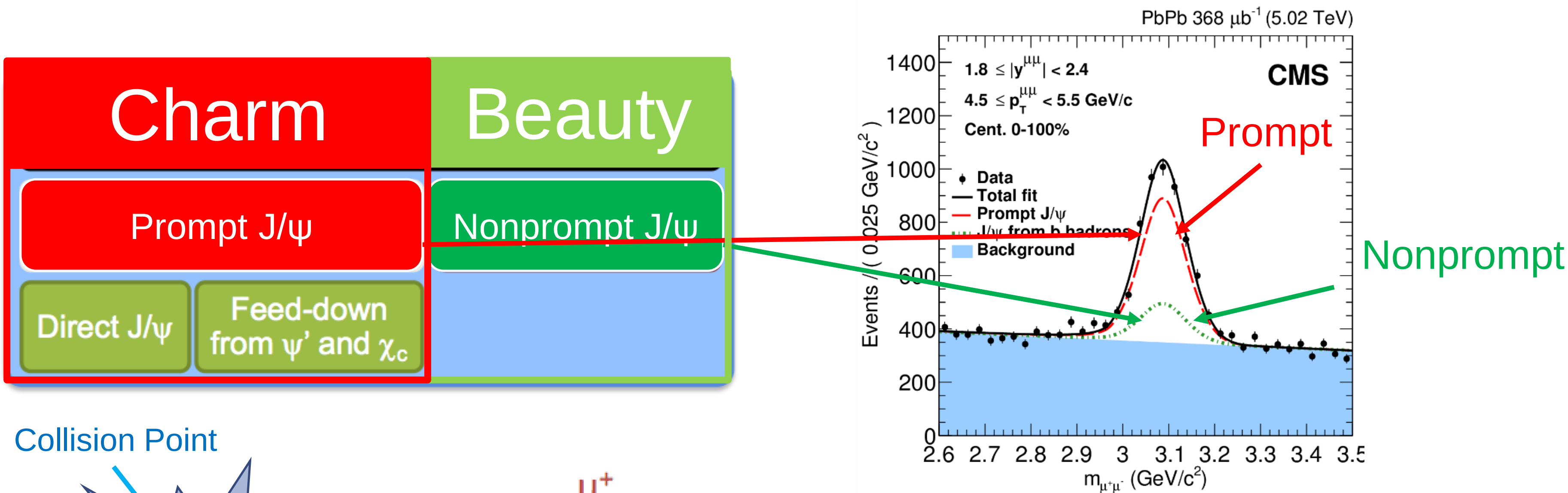
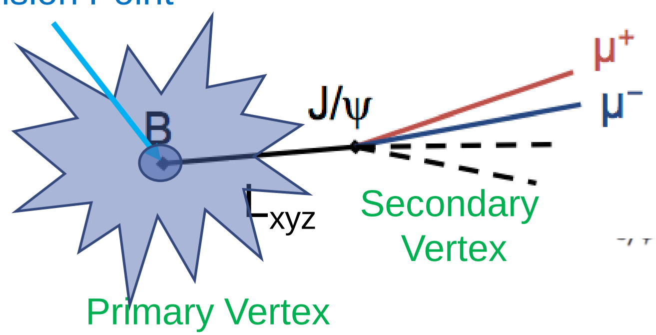
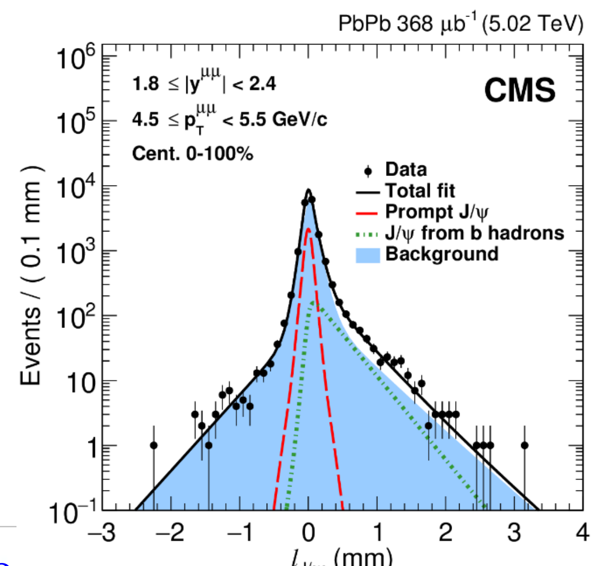




$$\ell_{J/\psi} = L_{xyz} \cdot \frac{m_{J/\psi}}{p_{\mu\mu}}$$



- Simultaneous two dimensional fit method
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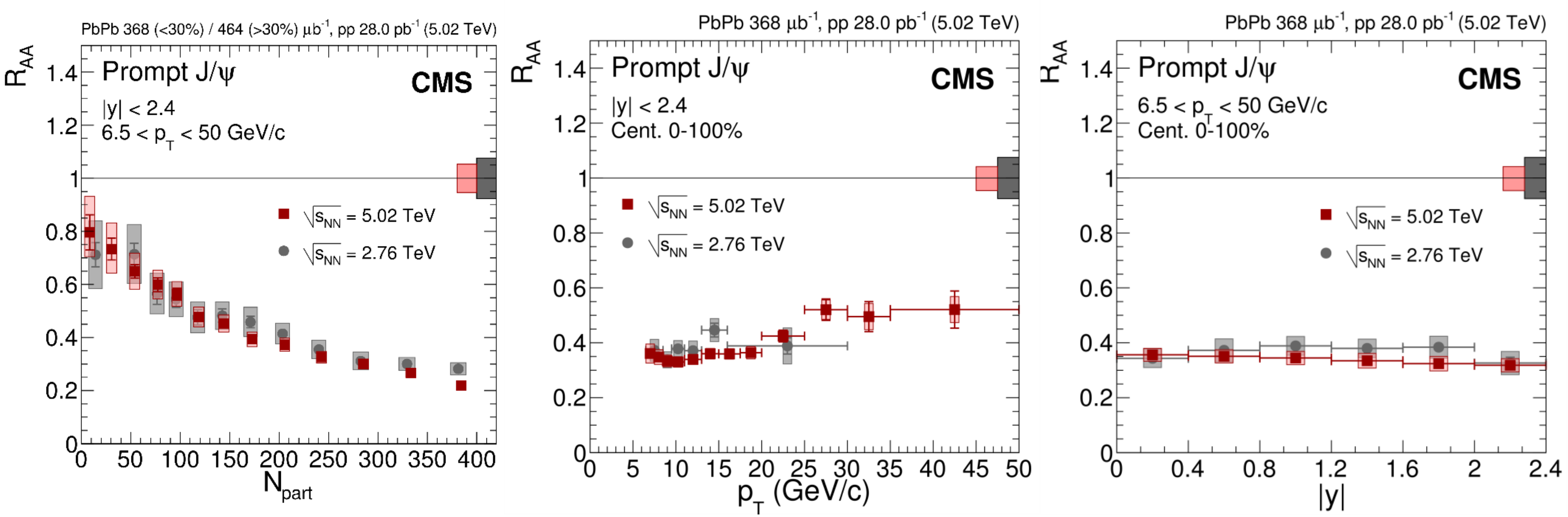
Prompt J/ψ : R_{AA}

$$R_{AA} = \frac{\text{Yield}_{AA}/\langle N_{Coll}\rangle}{\text{Yield}_{pp}}$$



arXiv:1712.08959

- Very similar suppression : no strong dependence on collision energy but slightly more suppressed in most central events at higher collision energy
  - R_{AA} (0-5 %) : ~20% more suppressed
    - 5.02 TeV : 0.219 ± 0.005 (stat.) ± 0.013 (syst.)
    - 2.76 TeV : 0.282 ± 0.010 (stat.) ± 0.023 (syst.)
  - No strong rapidity dependence and but increasing p_T dependence slightly

Prompt J/ψ : R_{AA}

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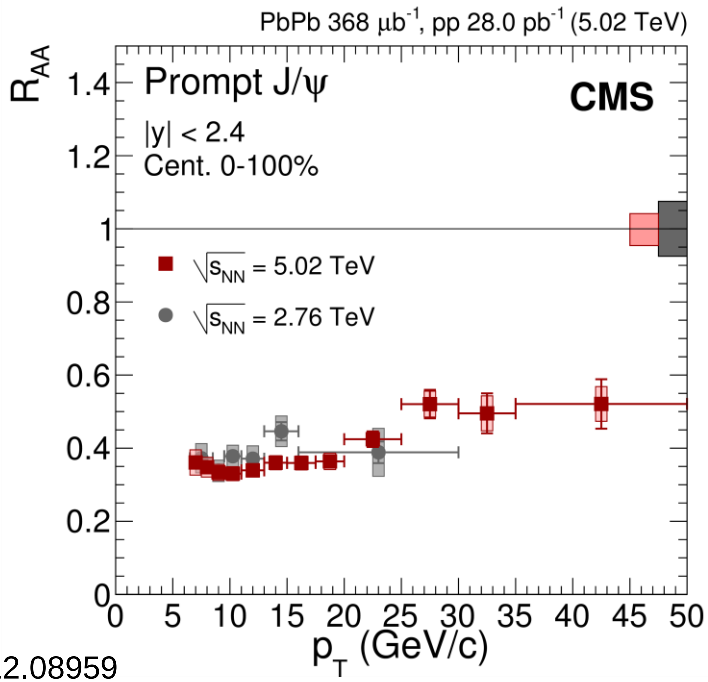

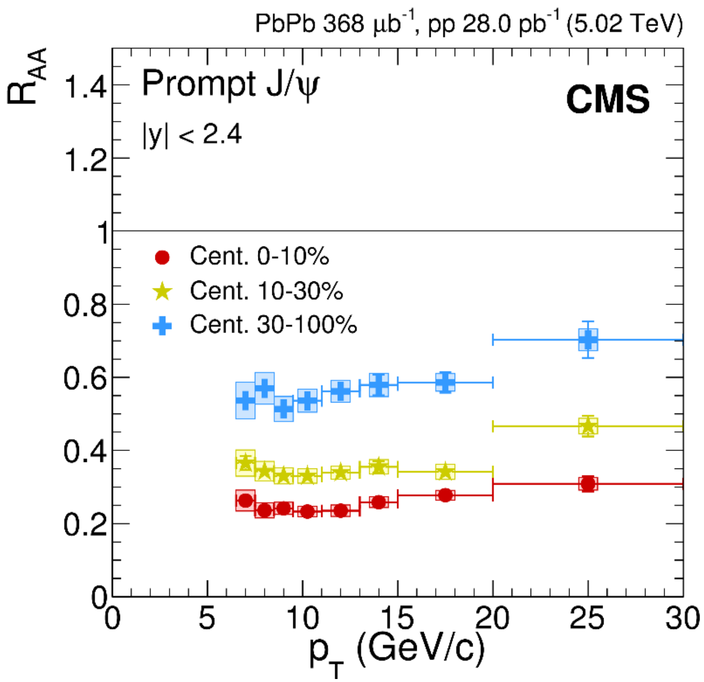

arXiv:1712.08959

- At high p_T, no strong collision energy dependence

- Decrease suppression at higher p_T
- Similar trend of p_T depending on centrality (increasing trend at high p_T)

Prompt J/ψ : R_{AA}

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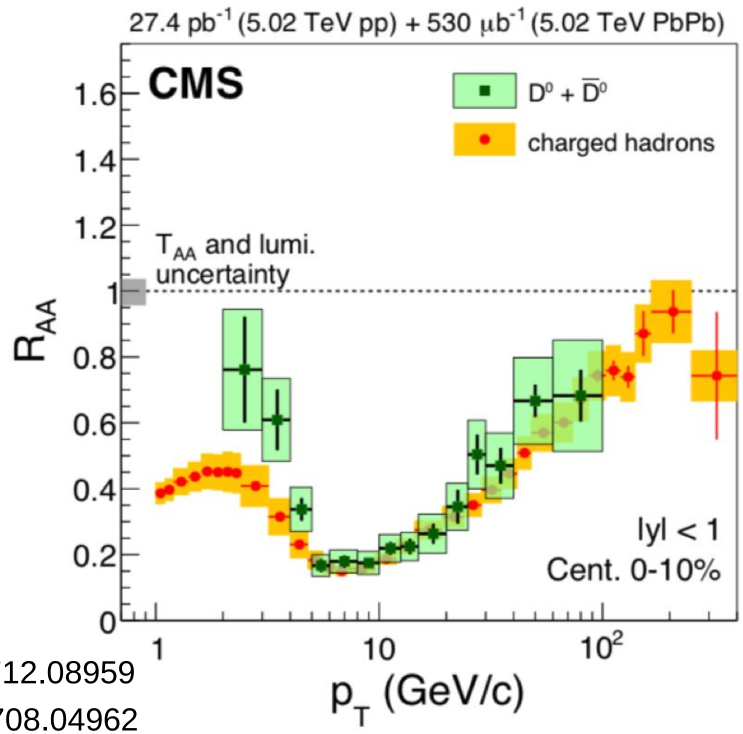
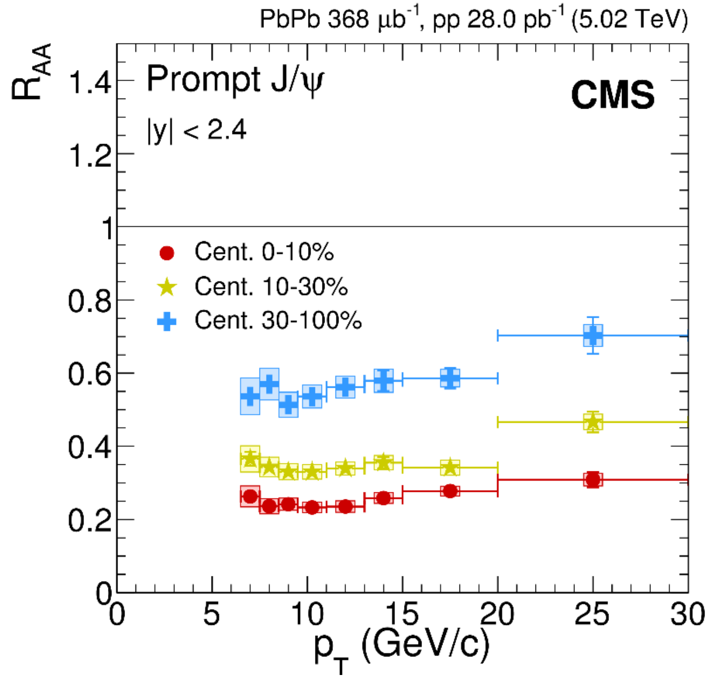


arXiv:1712.08959

arXiv:1708.04962



- At high p_T, no strong collision energy dependence
- Decrease suppression at higher p_T
- Similar trend of p_T depending on centrality (increasing trend at high p_T)
- Less suppressed at high p_T : more energy loss contribution ?
  - Similar to D meson and charged hadron

Prompt J/ψ : R_{AA}

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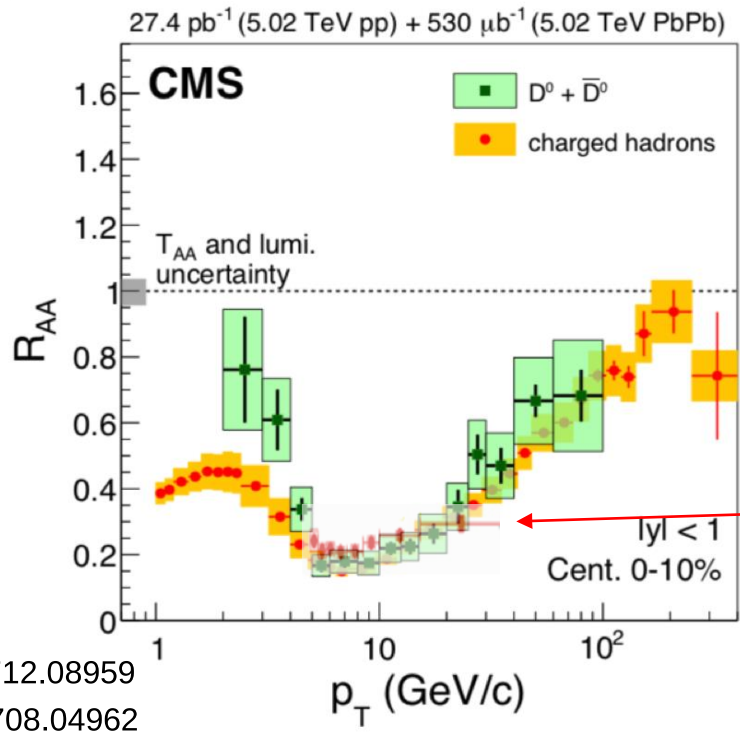

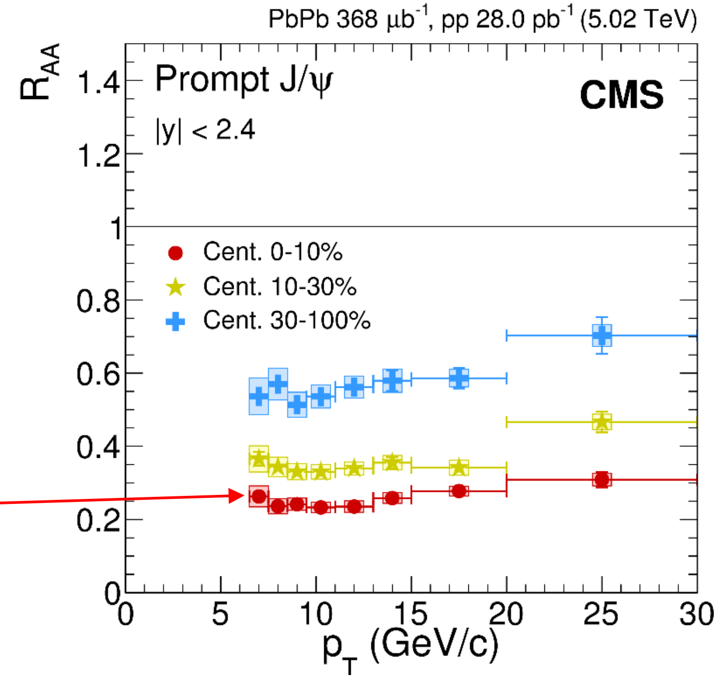

arXiv:1712.08959

arXiv:1708.04962

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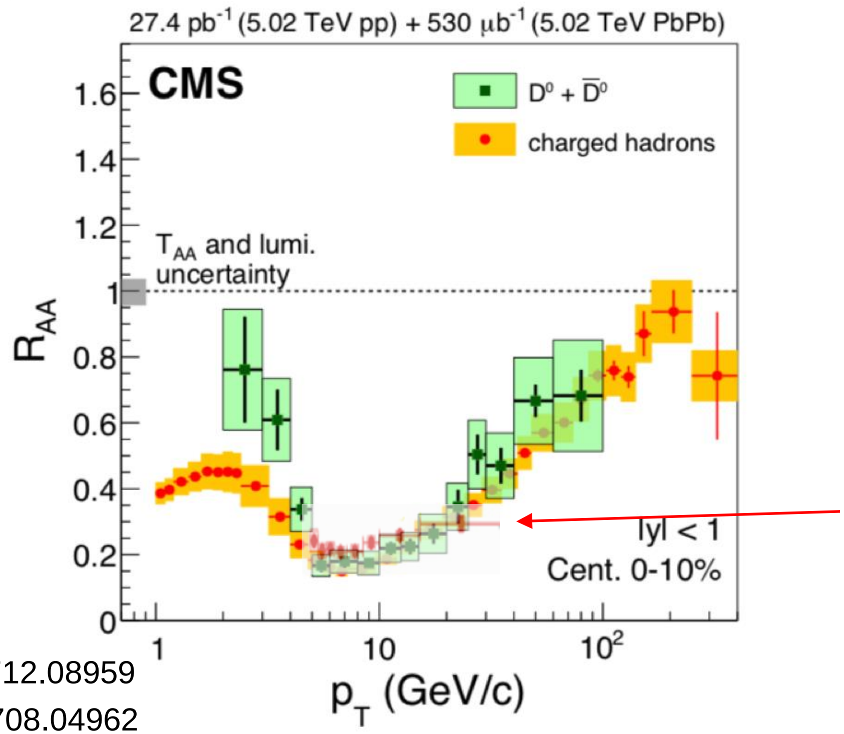

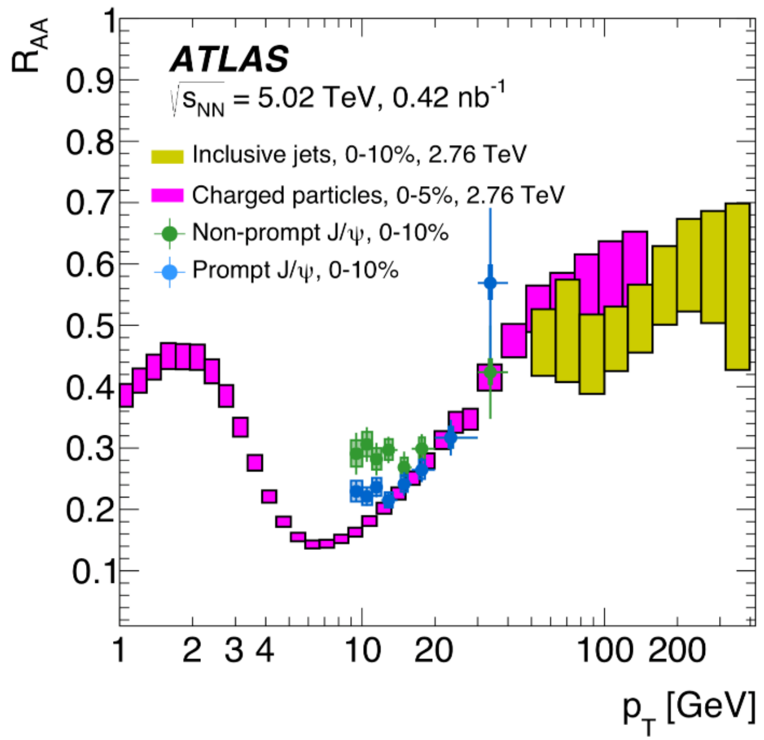

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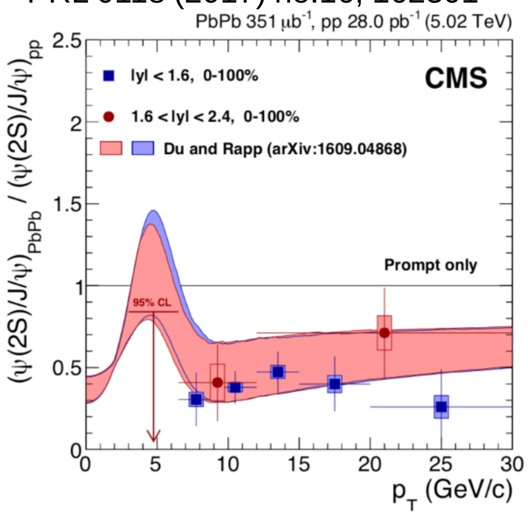
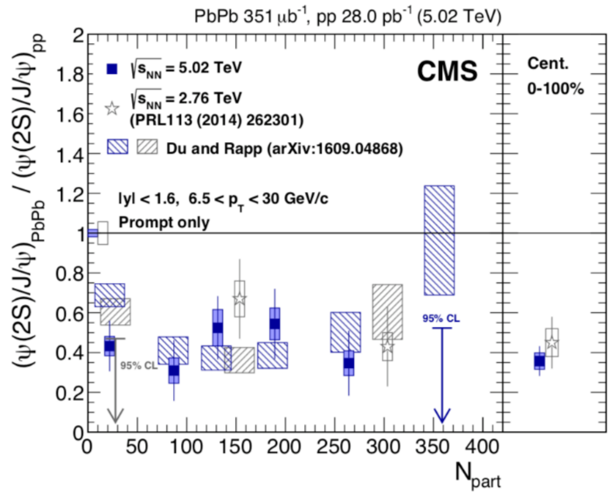
- Decrease suppression at higher p_T
- Similar trend of p_T depending on centrality (increasing trend at high p_T)
- Less suppressed at high p_T : more energy loss contribution ?
  - Similar to D meson and charged hadron
  - Agreed with ATLAS (energy loss vs color screening at high p_T ?)

Prompt ψ(2S) : Double Ratio

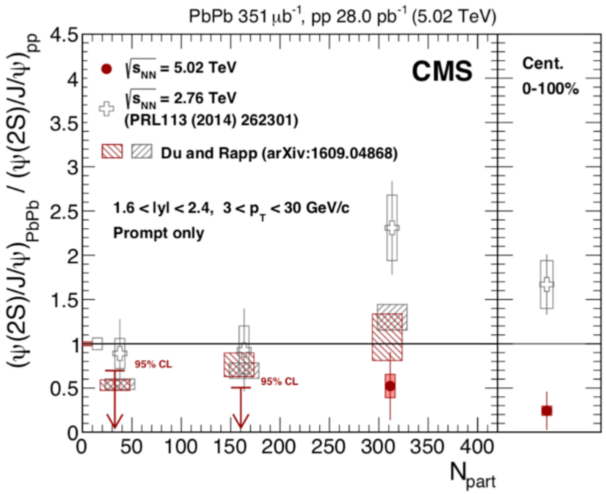
PRL 0118 (2017) no.16, 162301



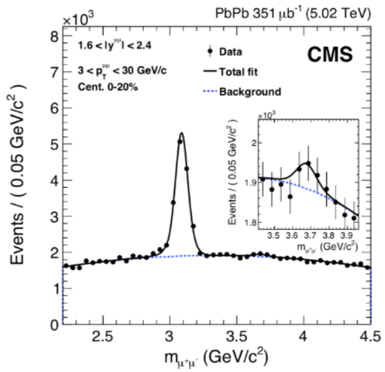
$|y|<1.6$, $6.5 < p_T < 30$ GeV/c



$1.6<|y|<2.4$, $3 < p_T < 30$ GeV/c



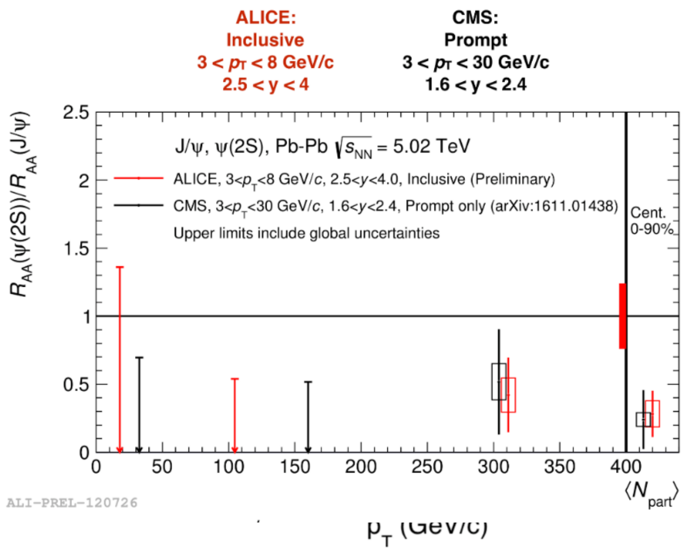
$$\text{Double Ratio (DR)} = \frac{[\psi(2S)/J/\psi]_{PbPb}}{[\psi(2S)/J/\psi]_{pp}} = \frac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}$$

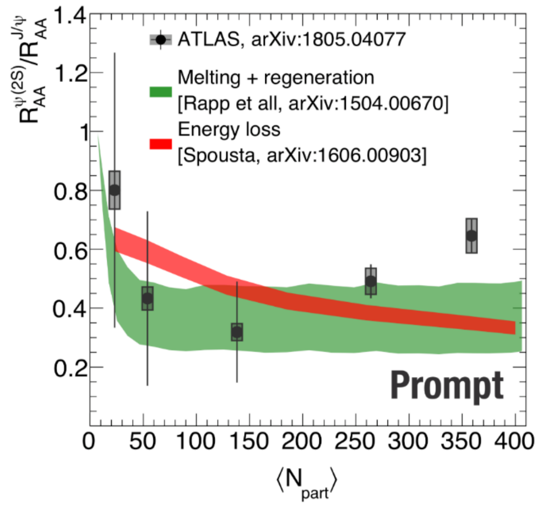


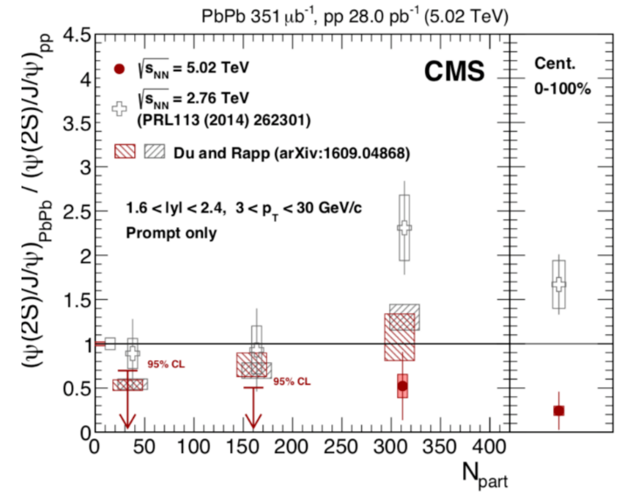
- Double Ratio (DR)
  : relative behavior of excited state compared to the ground state
- ψ(2S) more suppressed than J/ψ : sequential melting
- No significant dependence on p_T
- Hint for a different behavior with energy
- X. Du and R. Rapp: ψ(2S) regenerated later than J/ψ in the fireball evolution

Prompt ψ(2S) : Double Ratio

arXiv:1805.04077







$$\text{Double Ratio (DR)} = \frac{[\psi(2S)/J/\psi]_{PbPb}}{[\psi(2S)/J/\psi]_{pp}} = \frac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}$$

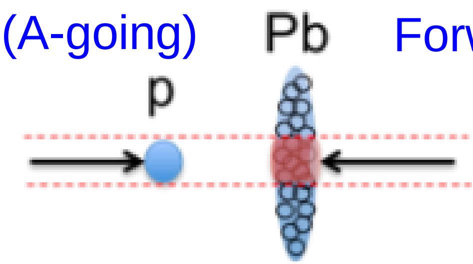
- Good agreement with CMS and ALICE but slightly different observation in ATLAS (increasing at most central collisions but theory couldn't follow)
- 2018 Data will be helpful to understand what is going on

- No significant dependence on p_T
- Hint for a different behavior with energy
- X. Du and R. Rapp: ψ(2S) regenerated later than J/ψ in the fireball evolution

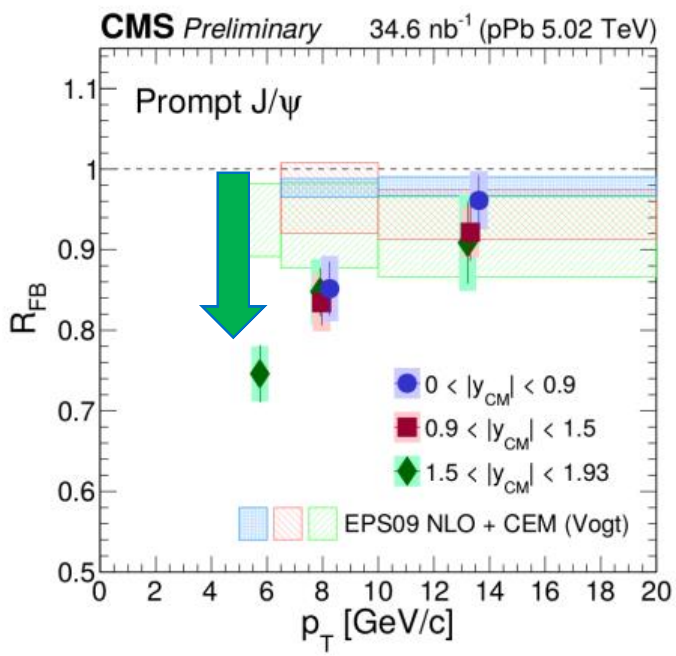
Prompt J/ψ in pPb

Backward (A-going) Forward (p-going)

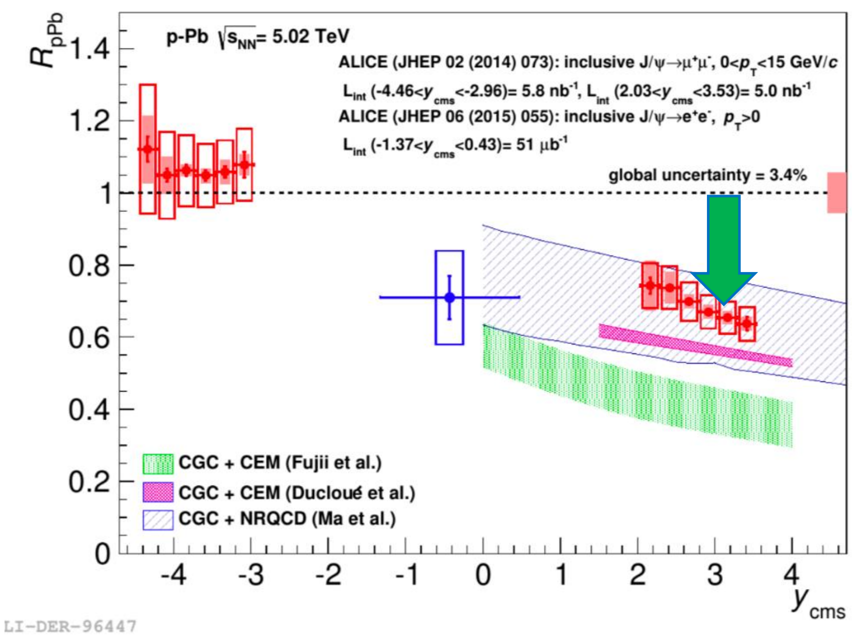
$$R_{FB} = \frac{\text{Yield at Forward}}{\text{Yield at Backward}}$$



Stronger CNM Effect



EPJC 77 (2017) 269

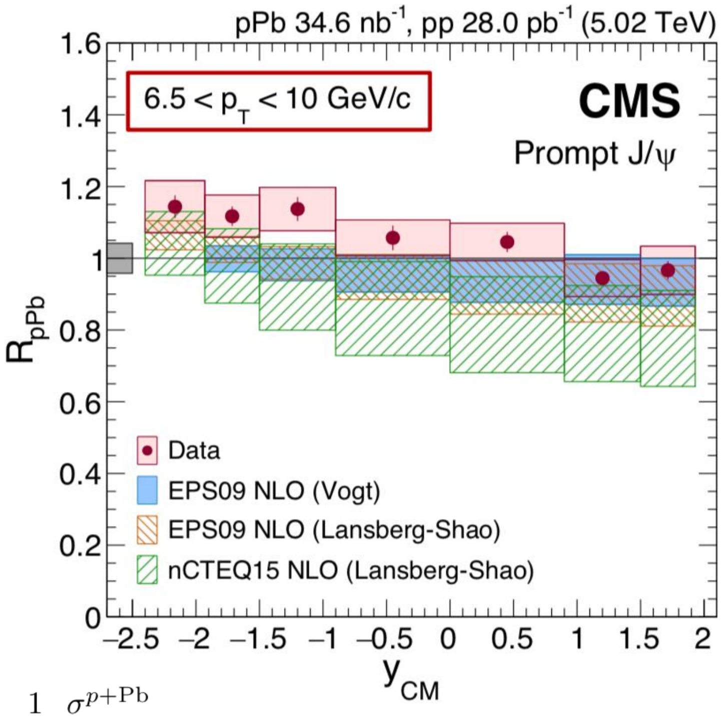


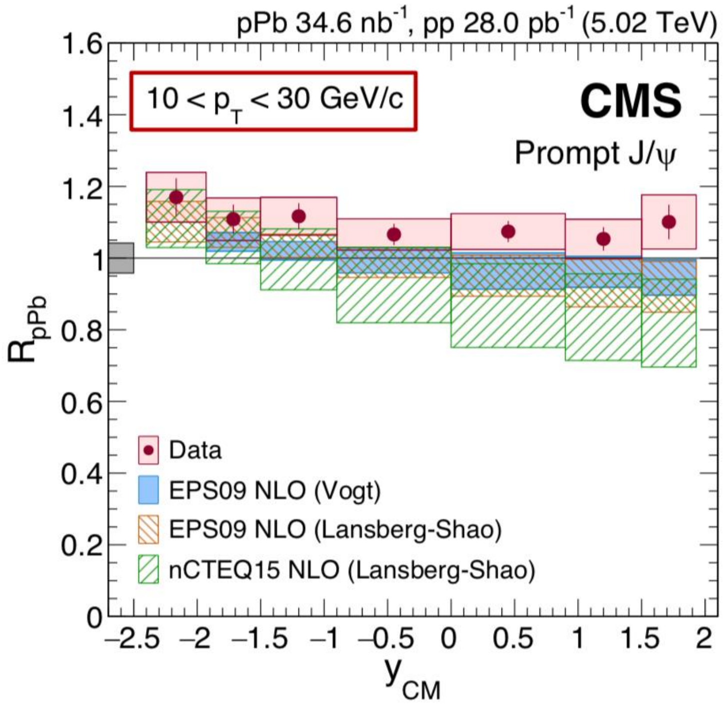
JHEP 02 (2014) 073

Strong forward and lower p_T region suppression

Prompt J/ψ in pPb

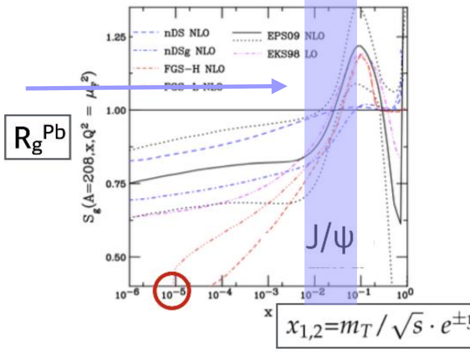
EPJC 77 (2017) 269





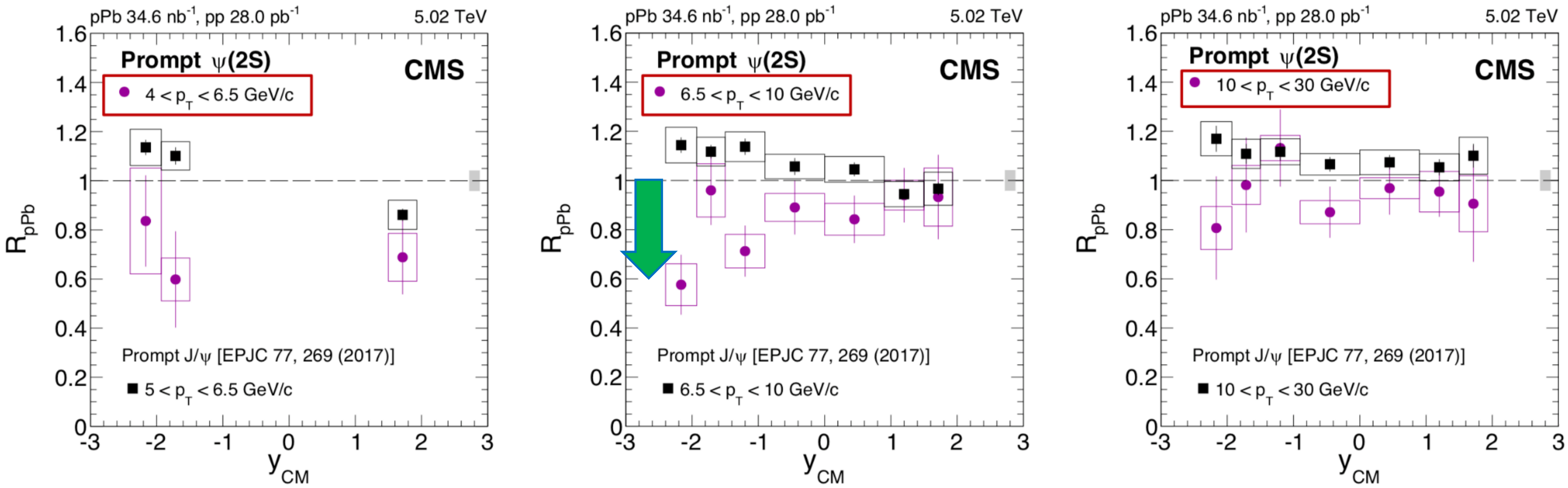
$$R_{\mathrm{pPb}} = \frac{1}{208}\frac{\sigma^{p+\mathrm{Pb}}}{\sigma^{pp}}$$

- Prompt J/ψ R_{pPb} above unity in most bin : anti-shadowing ?
  - Slightly more enhancement in backward (Pb going side)
  - More enhancement in high p_T
- nPDF calculations slightly lower than data



Prompt ψ(2S) in pPb

arXiv:1805.0248

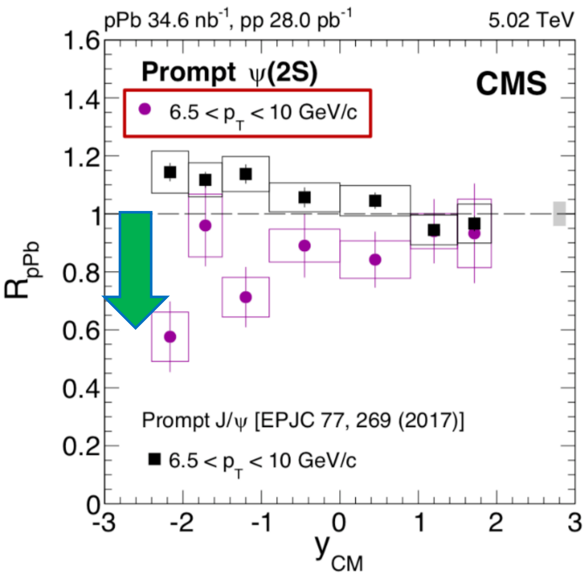


$$R_{\rm pPb} = \frac{1}{208}\frac{\sigma^{p+{\rm Pb}}}{\sigma^{pp}}$$

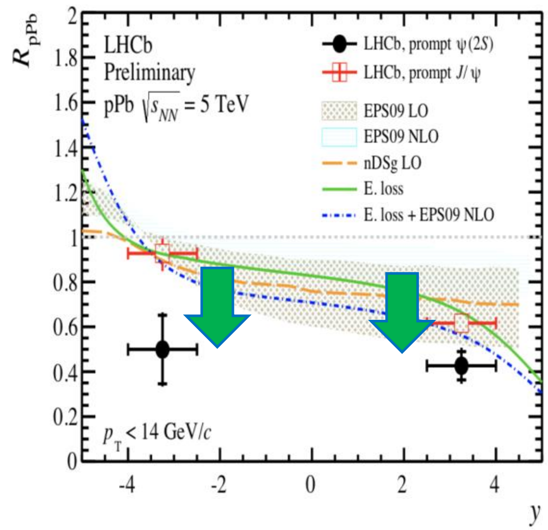
- Expecting to see similar effects from nPDF for J/ψ and ψ(2S)
- Hint for a different modification in the data (in Pb going direction)
- Is the more fragile ψ(2S) affected by final state effect ?

Prompt ψ(2S) in pPb

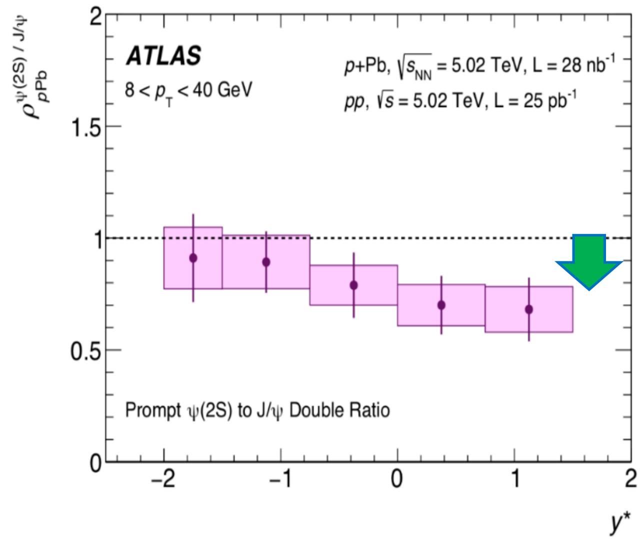
arXiv:1805.0248



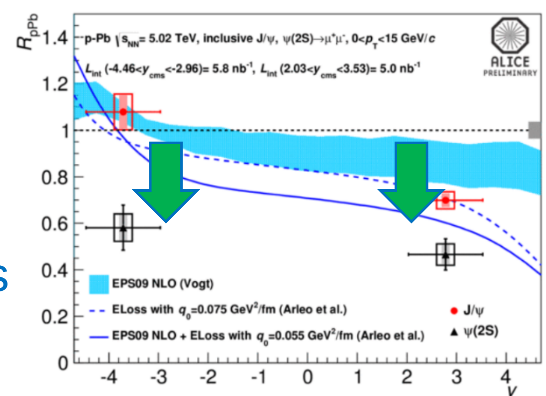
LHCb-CONF-2015-005



arXiv:1709.03089



$$R_{\mathrm{pPb}} = \frac{1}{208}\frac{\sigma^{p+\mathrm{Pb}}}{\sigma^{pp}}$$

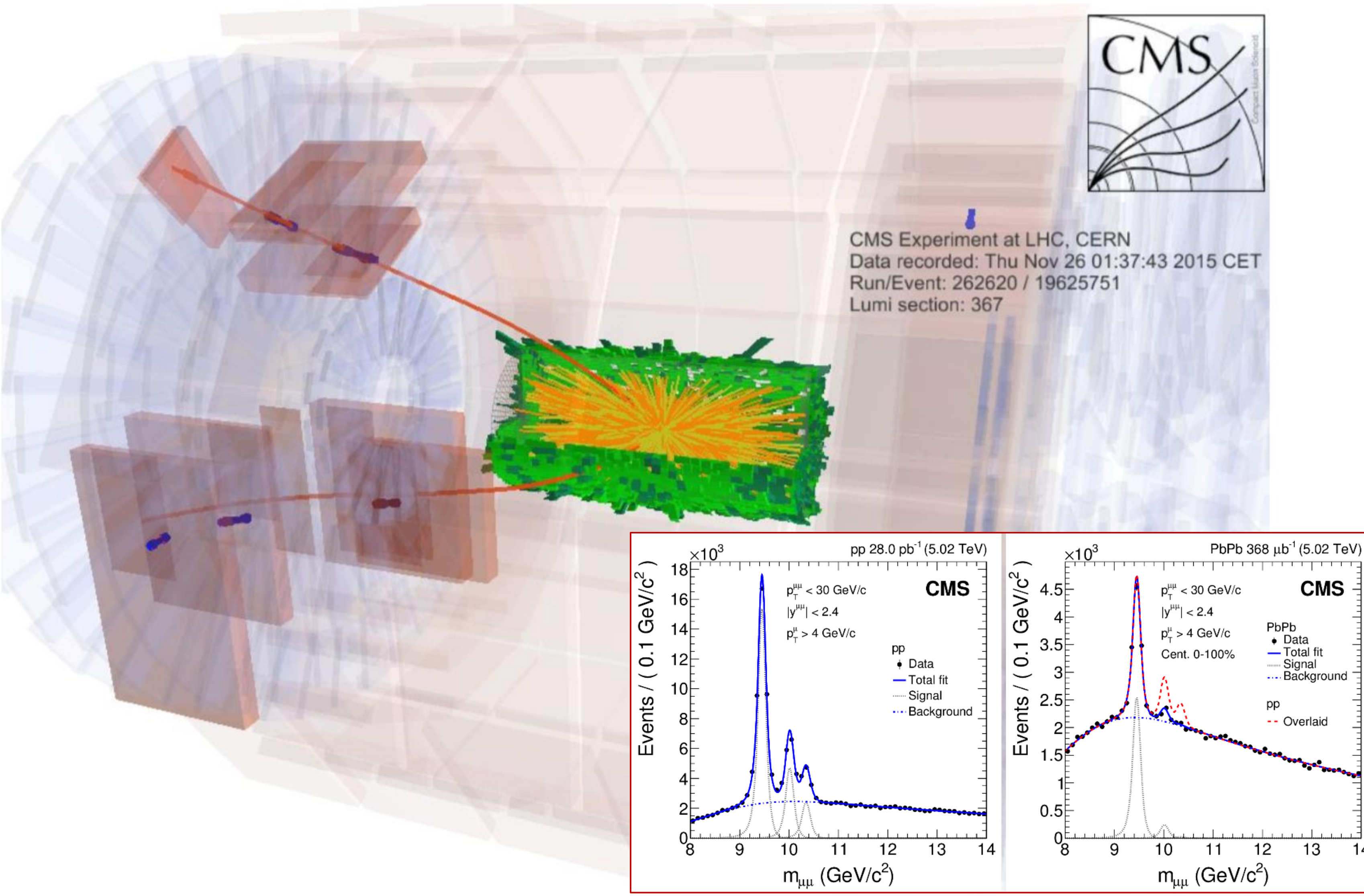


JHEP 12 (2014) 073

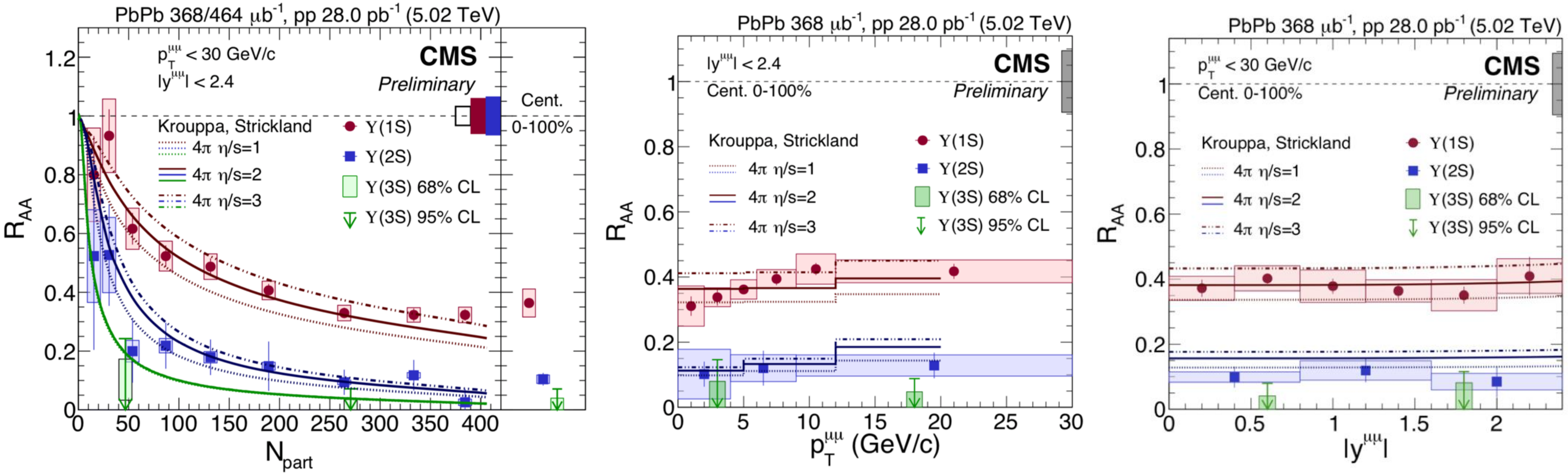
- Expecting to see s … or J/ψ and ψ(2S)
- Hint for a different … n the Pb going direction)
- Is the more fragile … ate effect ?

- Complicated results : ALICE, LHCb showed same results but backward suppression in CMS and forward suppression in ATLAS.
- Not possible to get strong conclusion due to the large error bar, 2018 data will give us more clear conclusion.

Bottomonia in PbPb



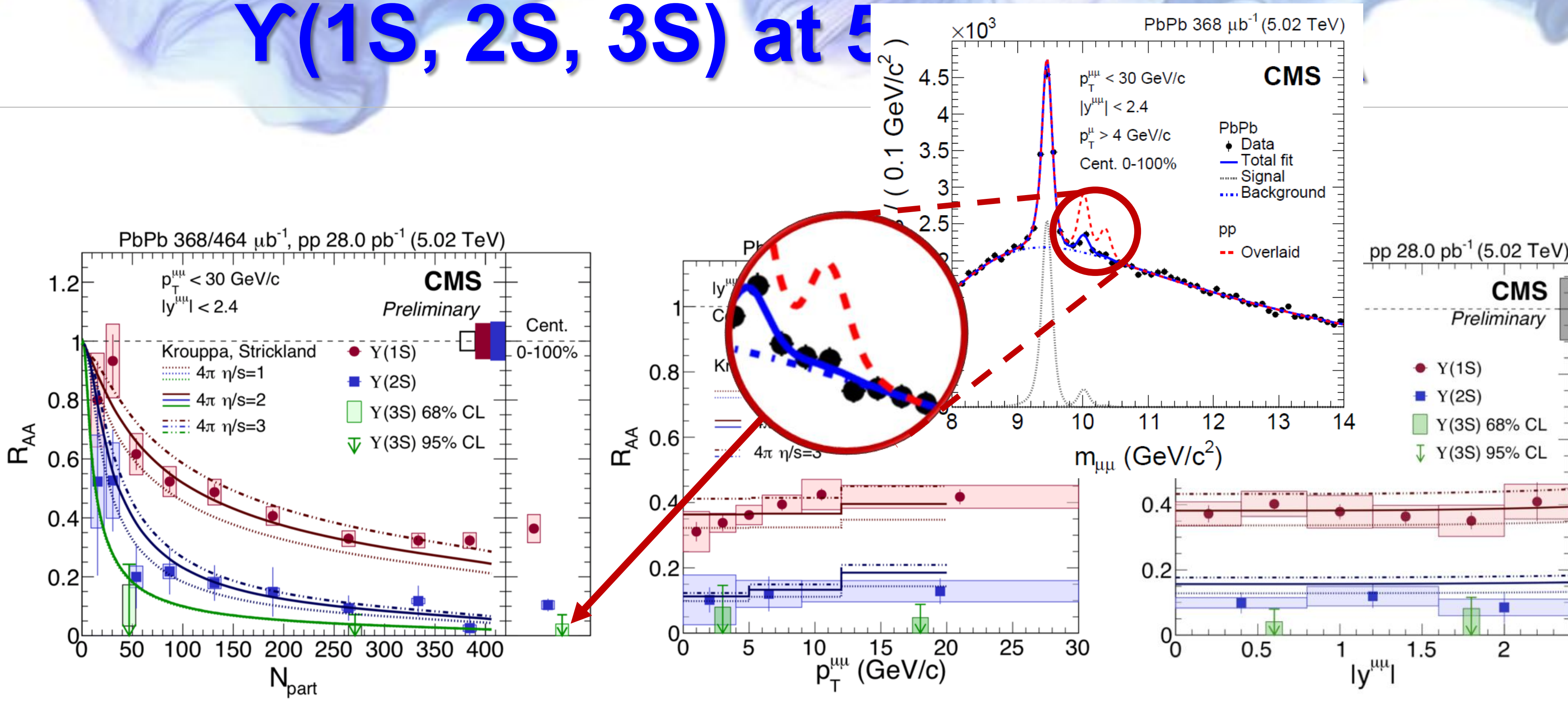
Υ(1S, 2S, 3S) at 5.02 TeV : R_{AA}



arXiv:1805.09215

- Increasing suppression along the centralities
- 'Clear' ordering : $R_{AA}(\Upsilon(3S)) < R_{AA}(\Upsilon(2S)) < R_{AA}(\Upsilon(1S))$
- Also hydrodynamic model with 3 temperatures (Krouppa & Strickland) describe well data within uncertainty ($4\pi\eta/s$ = {1, 2, 3}, T_0 = {641, 632, 629} MeV)

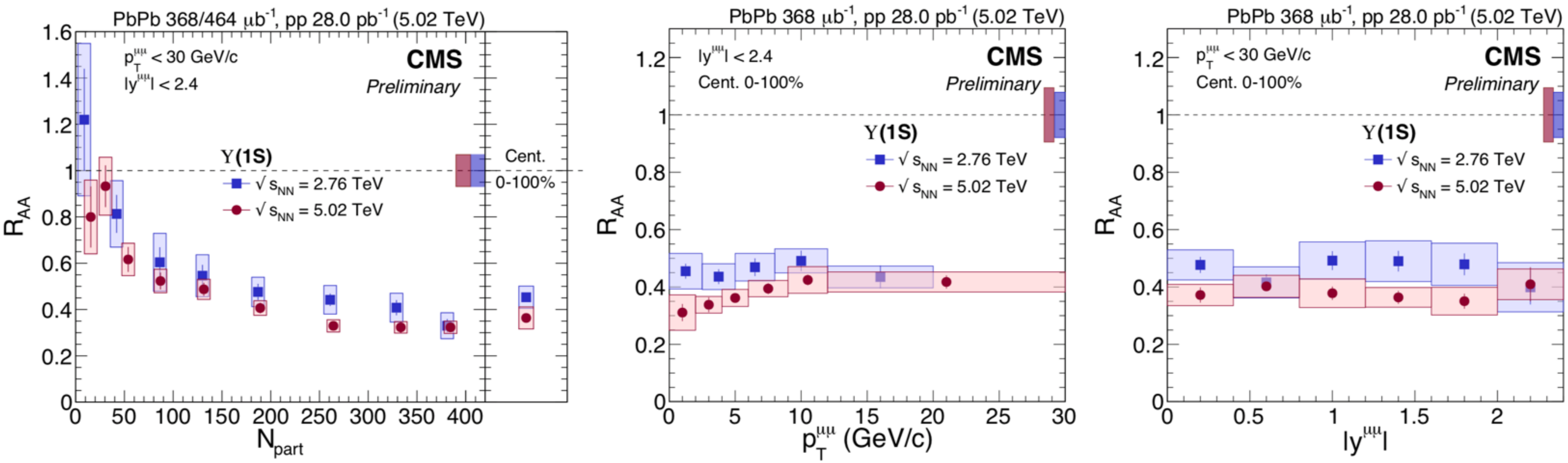
Υ(1S, 2S, 3S) at 5



arXiv:1805.09215

- Increasing suppression along the centralities
- 'Clear' ordering : R_{AA}(Υ(3S)) < R_{AA}(Υ(2S)) < R_{AA}(Υ(1S))
- Also hydrodynamic model with 3 temperatures (Krouppa & Strickland) describe well data within uncertainty ($4\pi\eta/s$ = {1, 2, 3}, T_0 = {641, 632, 629} MeV)
- Complete melting of 3S
  - 3S yet to be seen in PbPb collisions at the LHC (maybe in 2018 data?)

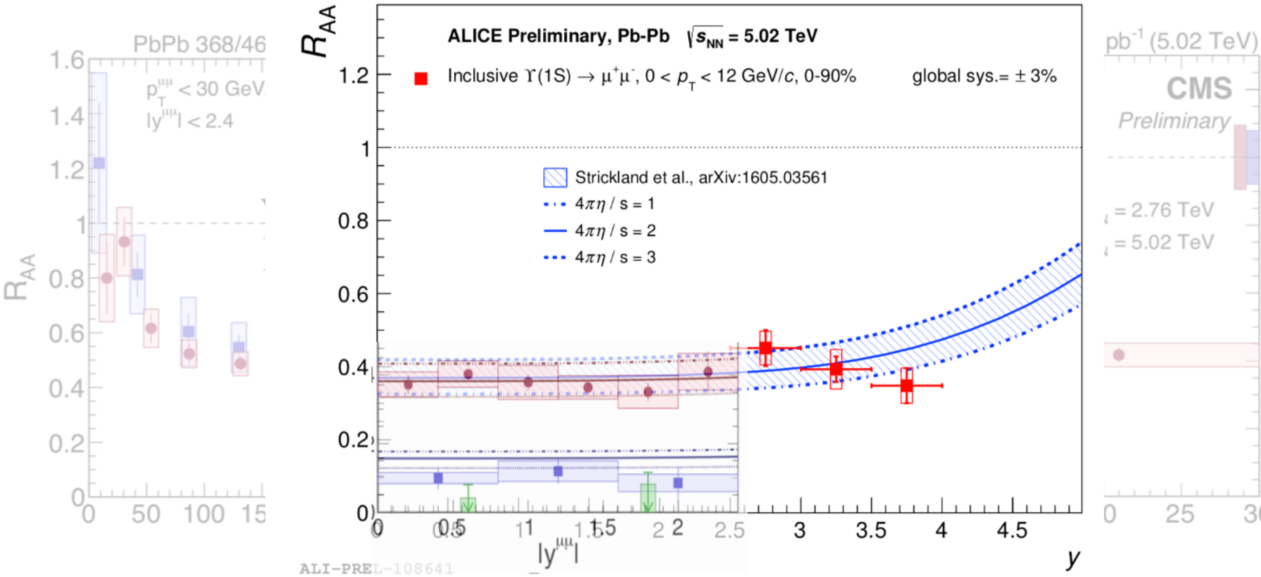
Energy Dependence of ϒ(1S) : R_{AA}



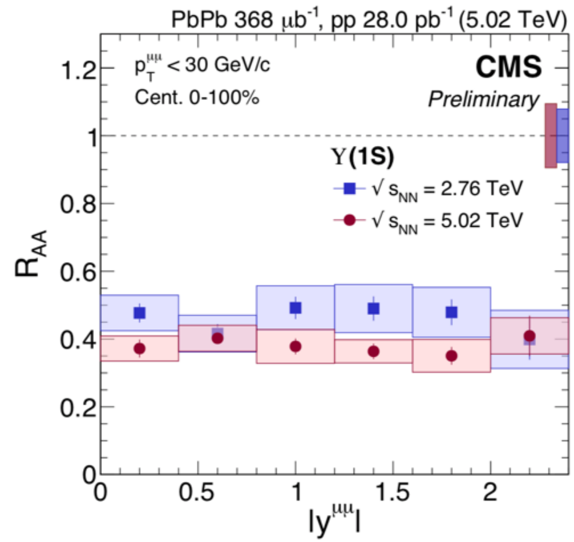
arXiv:1805.09215

- Indication of larger suppression of ϒ(1S) at higher collision energy
- No significant dependence on rapidity but hint of more suppression in low p_T region at 5.02 TeV than 2.76 TeV

Energy Dependence of ϒ(1S, 2S, 3S) : R_{AA}



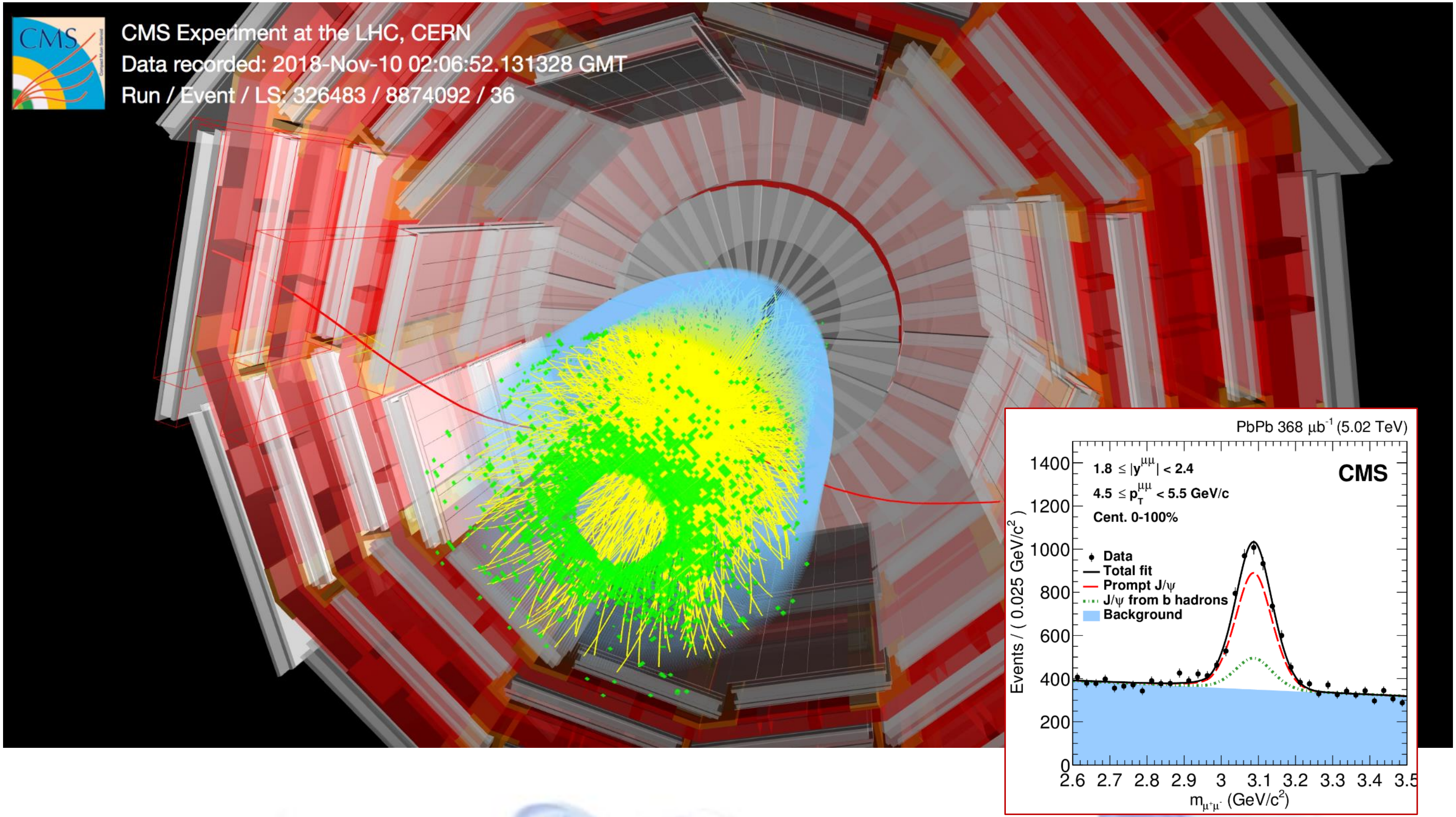
arXiv:1805.04387



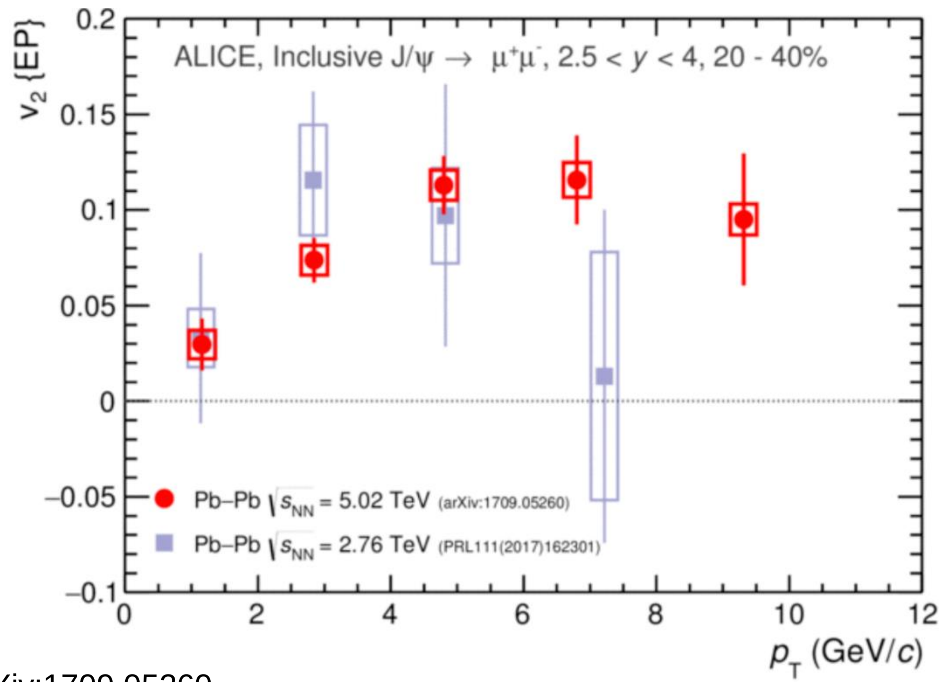
arXiv:1805.09215

- Indication of larger suppression of ϒ(1S) at higher collision energy
- No significant dependence on rapidity but hint of more suppression in low p_T region at 5.02 TeV than 2.76 TeV
- Stricklaland Thermal anisotropic hydrodynamical model reproduce ALICE results within uncertainties but tension in forward rapidity (increasing or decreasing)

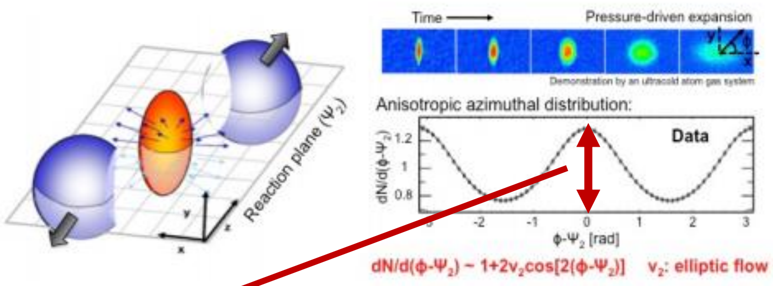
J/ψ Elliptic flow



J/ψ Elliptic flow in PbPb



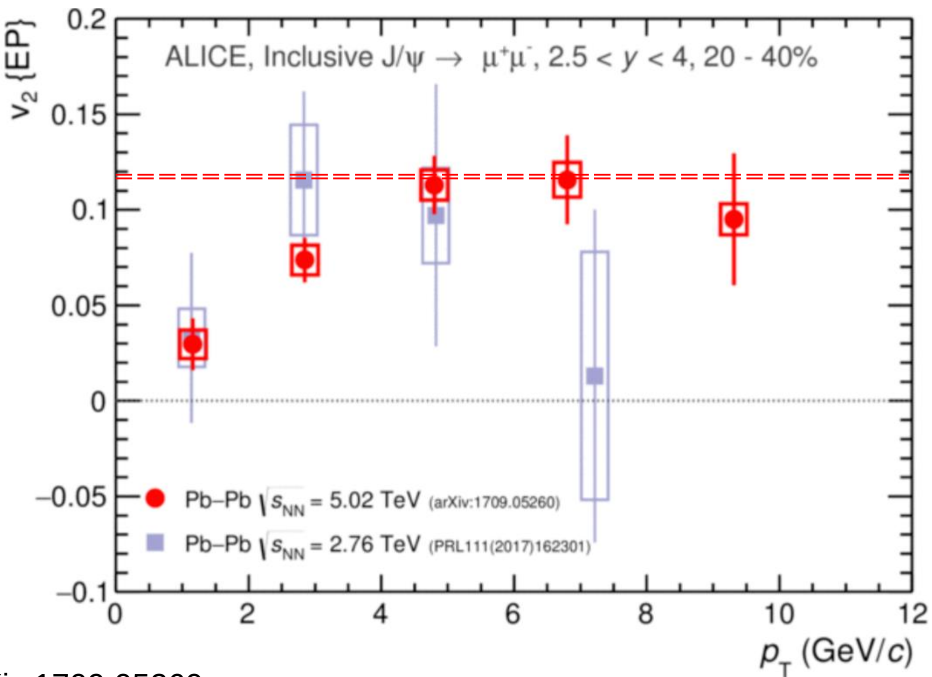
arXiv:1709.05260



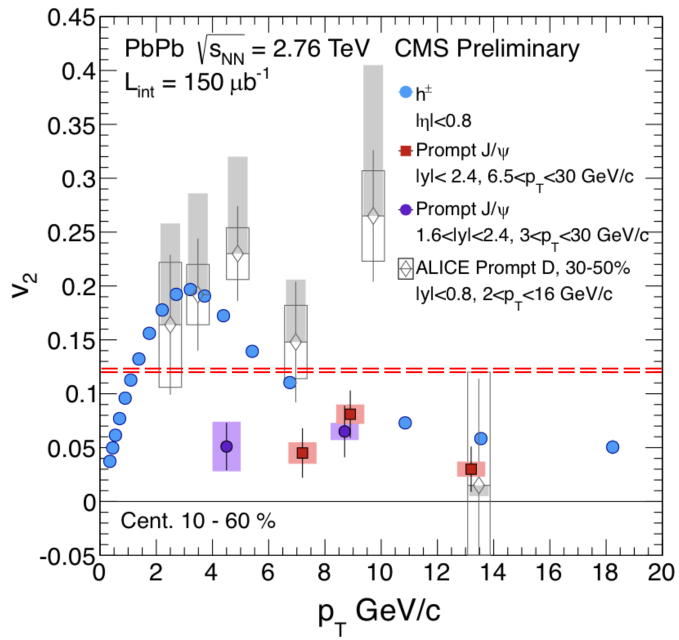
$v_2 = \langle \cos 2(\phi_{particle} - \Psi_{EP}) \rangle$

- Indication of non-zero flow (2.7σ) at 2.76 TeV
- Evidence for non-zero flow (7σ) in p_T 4-6 GeV/c at 5.02 TeV

J/ψ Elliptic flow in PbPb

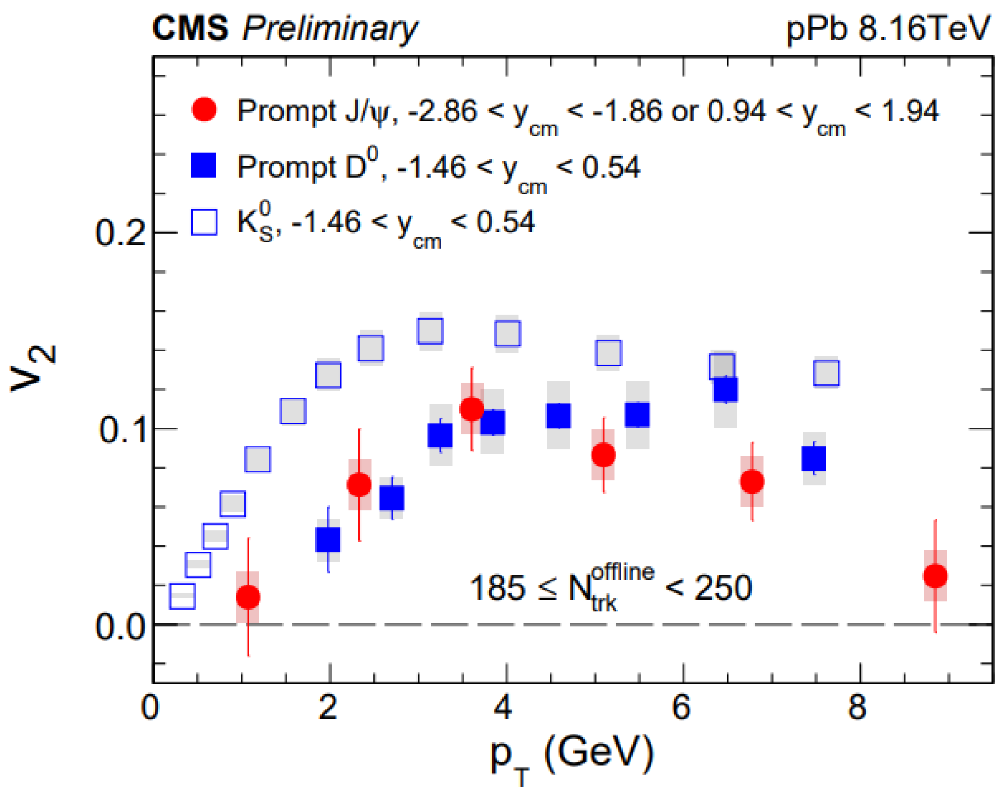


arXiv:1709.05260



- Available precise measurements in low p_T at ALICE and in high p_T at CMS
- Clear p_T dependence in low p_T and still non-zero flow in high p_T
- Interpretation : thermalized charm quark inherited to J/ψ in low p_T (hint of regeneration) but path-length dependence in high p_T.

J/ψ Elliptic flow in pPb

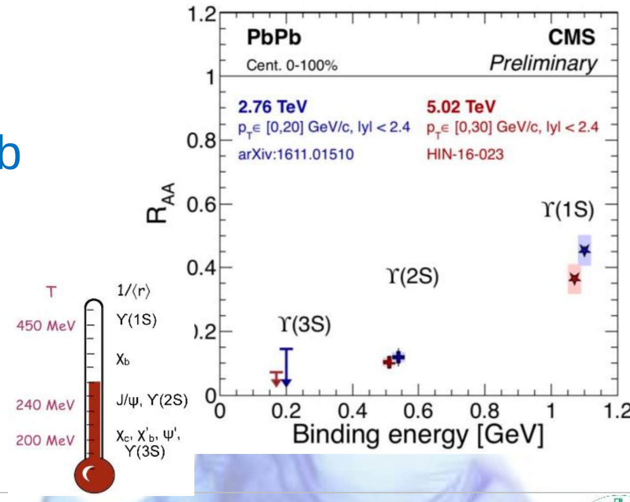


CMS-PAS-HIN-18-010

- Observed significant positive J/ψ v_2 even in pPb
- Measured in events with $N^{trk} > 185$ (only in high multiplicity events)
- Don't understand yet exactly but can imagine that D and prompt J/ψ should have same reason

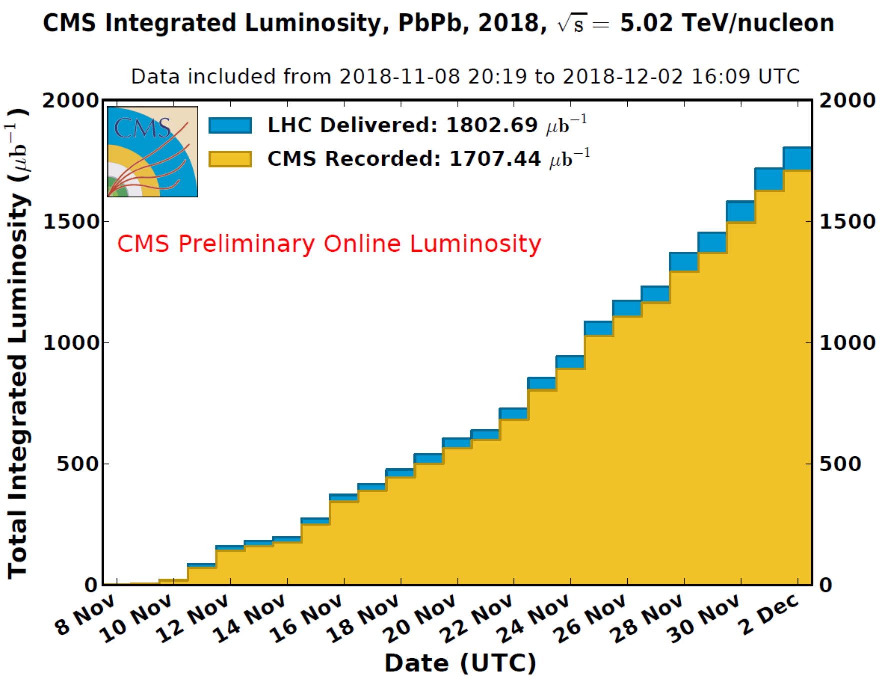
Summary

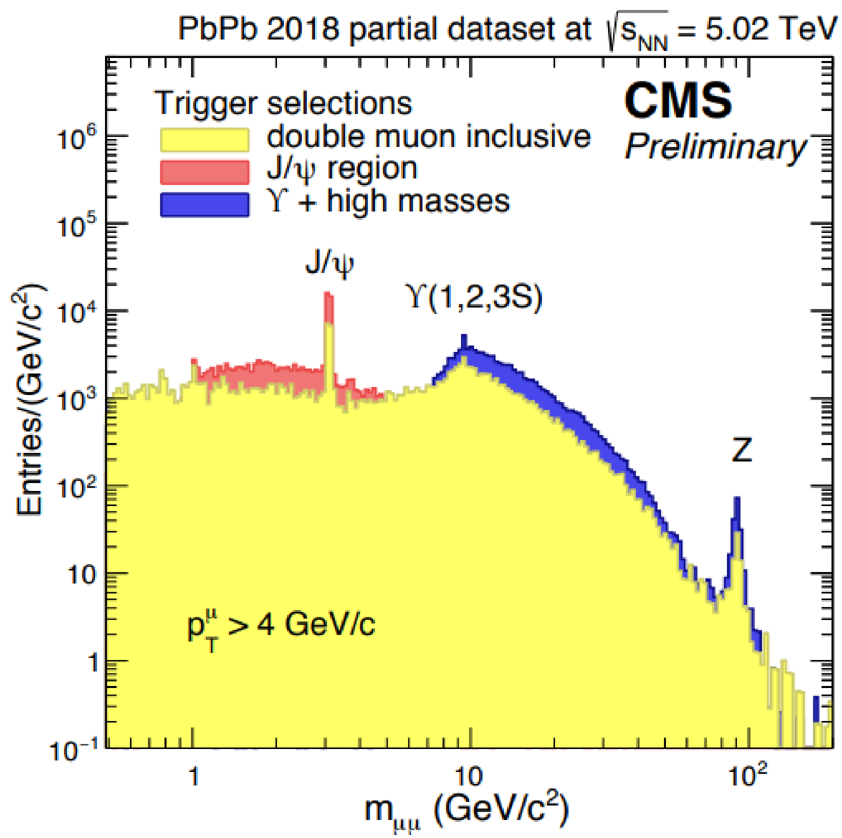
- **Chamoina in pPb & PbPb**
  - Strong suppression along with centralities
  - Energy loss would be more dominant in high p_T region than color screening
  - ψ(2S) is more suppressed than J/ψ at backward rapidity in pPb but not sure exact reason, yet
- **Bottomonia in PbPb**
  - Observed sequential suppression as expected
  - Indication of larger suppression of ϒ(1S) at 5.02 TeV than 2.76 TeV
  - Still no sign of ϒ(3S), yet
- **Elliptic flow for J/ψ**
  - Observed non-zero flow in PbPb and even in pPb
  - No significant dependence on collision energy
  - Similar size of v_2 observed in pPb and PbPb



Outlook

- PbPb Data taking in 2018 at 5.02 TeV
  - 1.7 nb^{-1} : ~ 4 x 2015 PbPb data, ~ 10 x 2011 PbPb data
- Exciting results are coming soon !!! Please stay tuned.



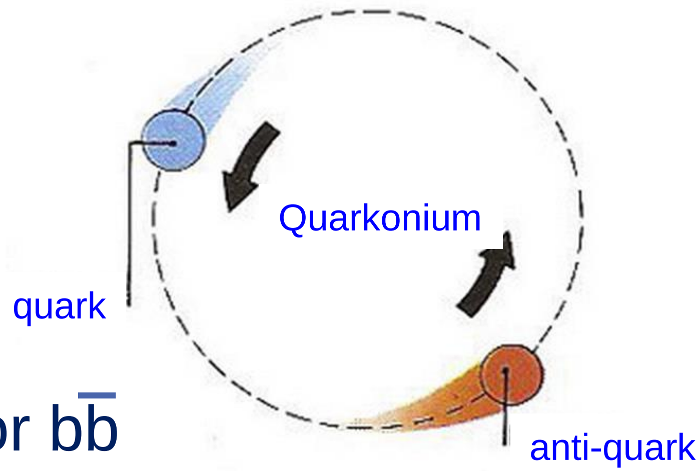


Thank You Very Much
for your attention !

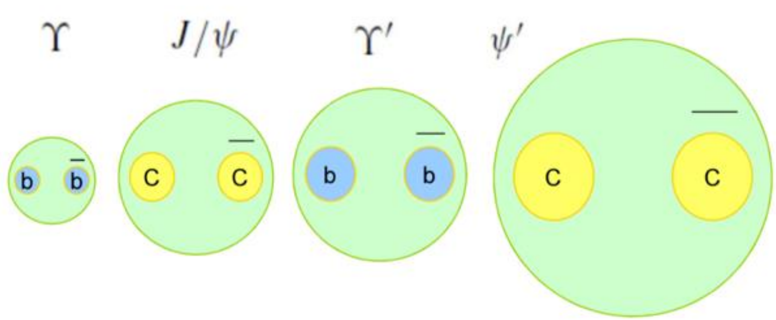
Back Up

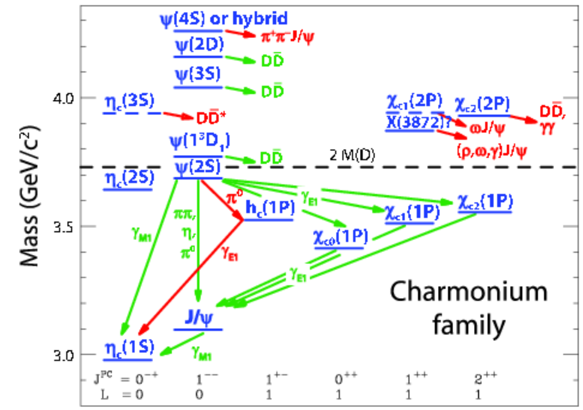
What is "Quarkonia" ?

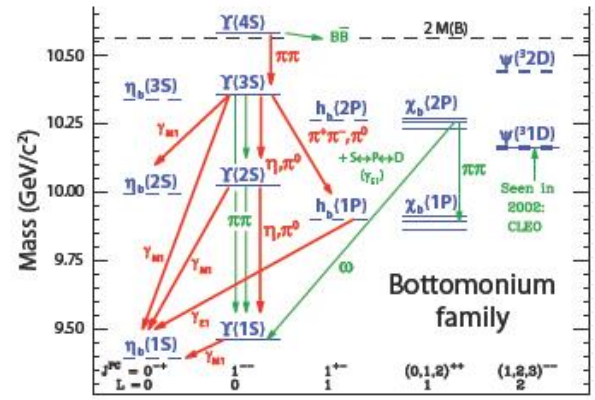
- **Quarkonia** : plural of quarkonium (heavy flavor quarks : c, b)
  - Charmonia : bound state of charm and anti-charm (J/ψ, ψ'(2S), χ_c(1P) ...)
  - Bottomonia : bound state of bottom and anti-bottom (ϒ(1S, 2S, 3S), χ_b(1P) ...)



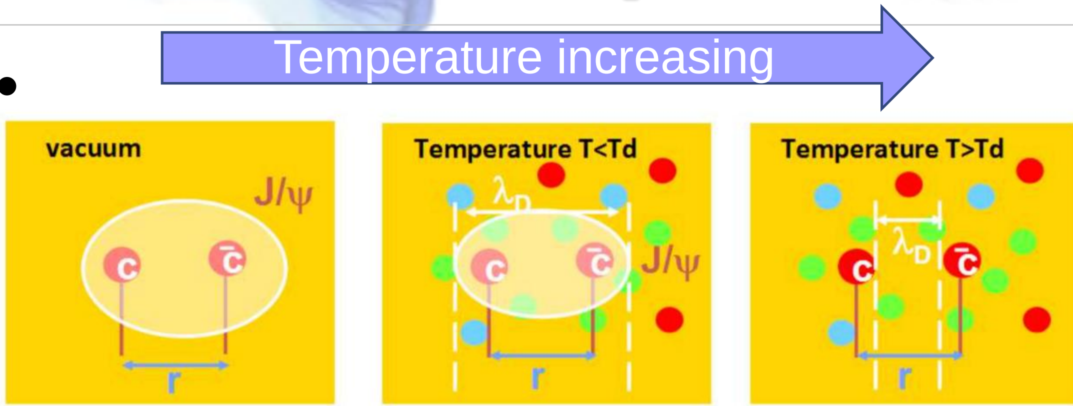
$c\bar{c}$ or $b\bar{b}$



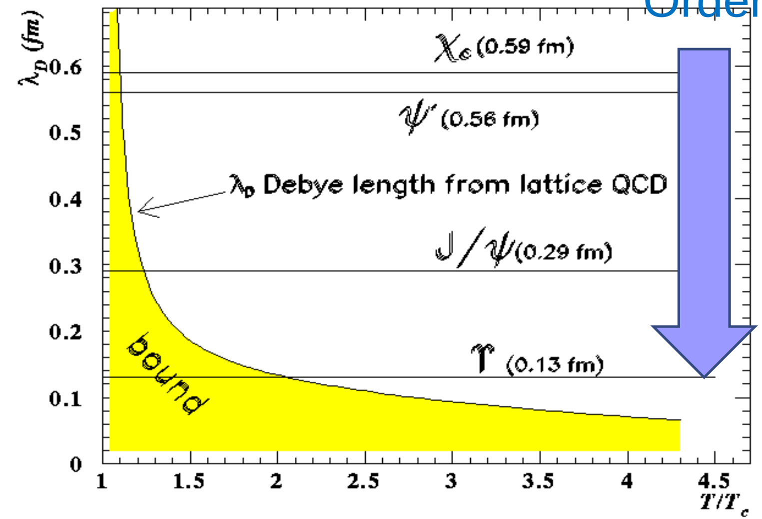


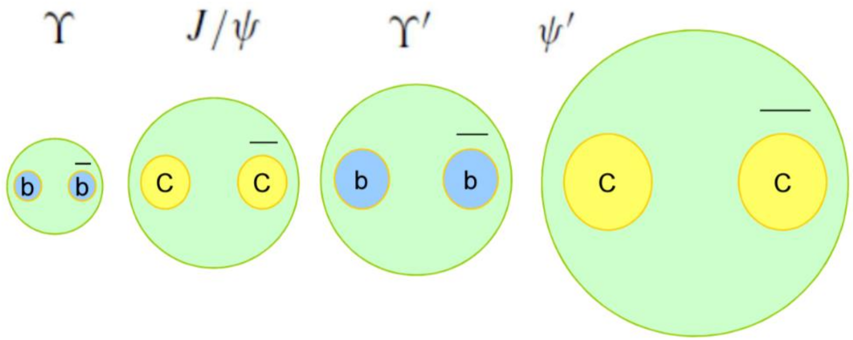


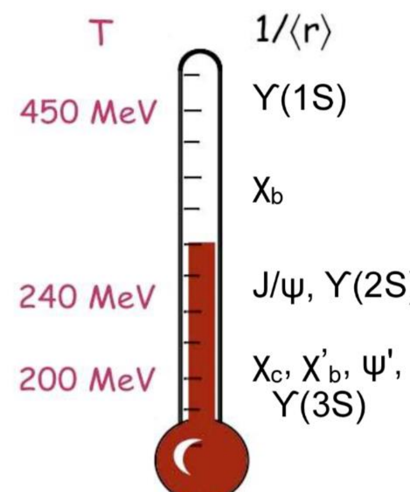
Sequential Melting



Melting Order







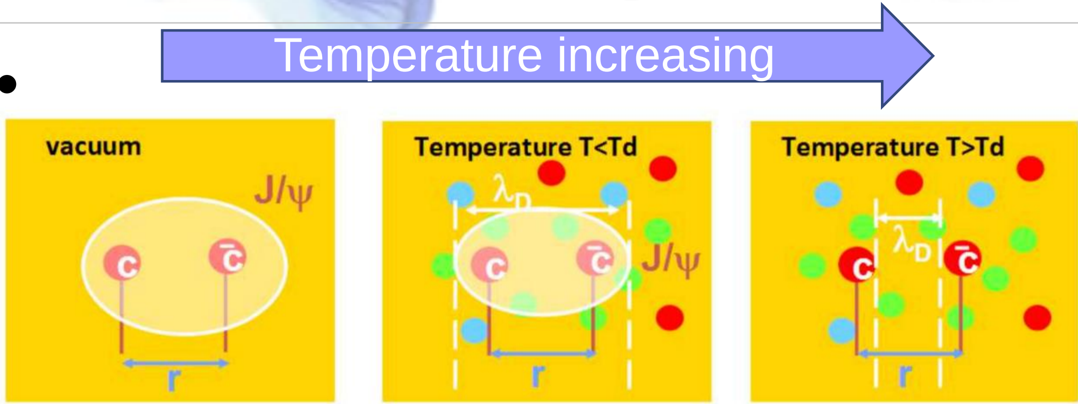
Charmonia	J/ψ	χ_c	ψ'(2S)
Mass(GeV)	3.10	3.53	3.69
ΔE (GeV)	0.64	0.20	0.05
T_d/T_c	2.1	1.16	1.12

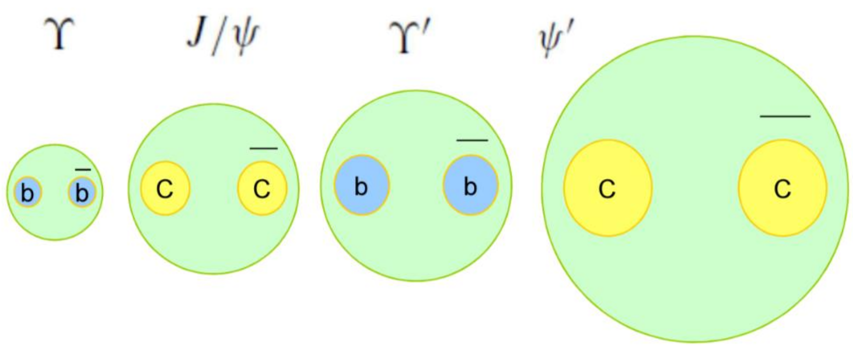
Bottomonia	Υ(1S)	Υ(2S)	Υ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
T_d/T_c	> 4.0	1.60	1.17

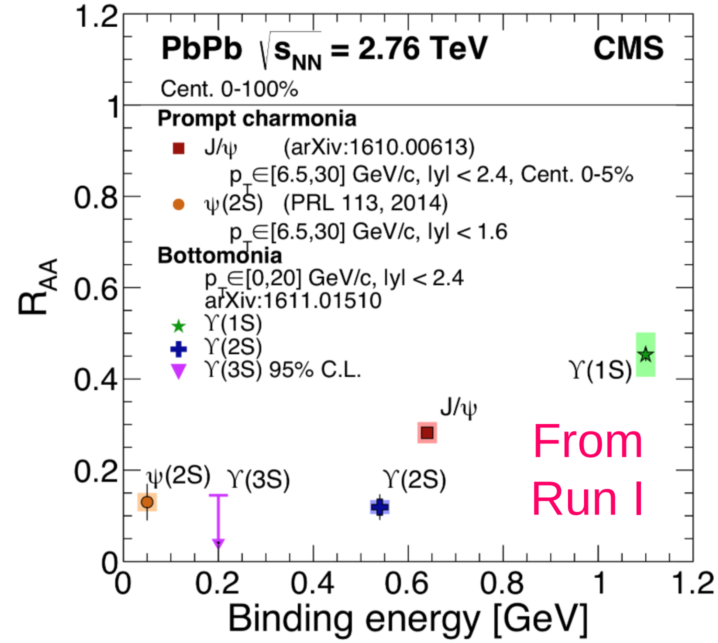
Mocsy, EPJC61 (2009) 705 BNL workshop in June

Sequential Melting

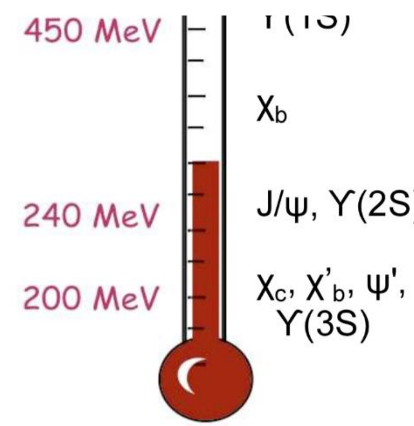
EPJC 77 (2017) 252
PRL 109 (2012) 222301







$$R_{AA} = \frac{\mathrm{Yield}_{AA}/\langle N_{Coll}\rangle}{\mathrm{Yield}_{pp}}$$



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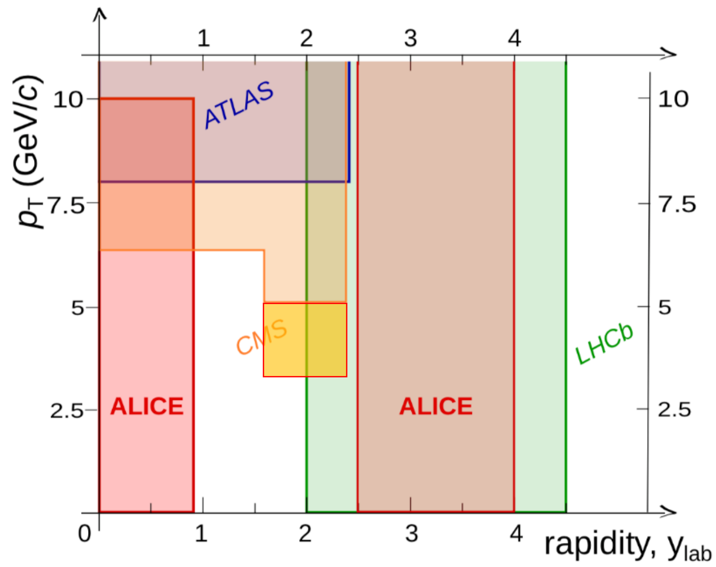
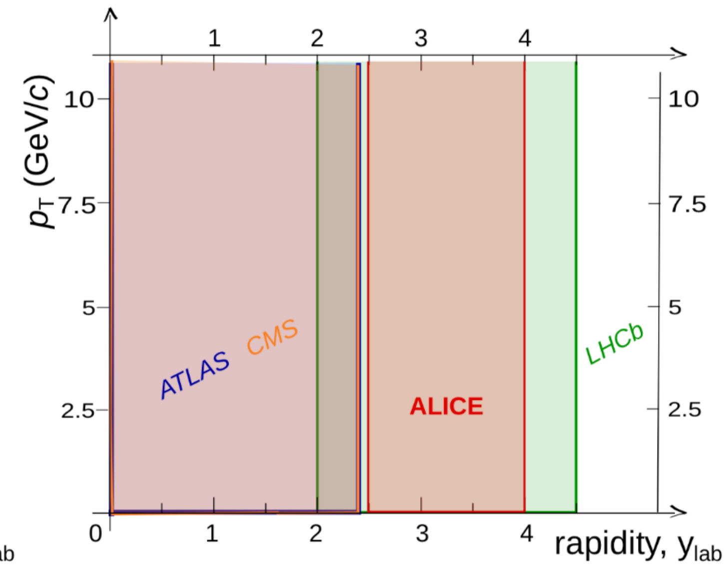
Mocsy, EPJC61 (2009) 705 BNL workshop in June

Quarkonia Acceptance

- Complimentary acceptance for LHC detectors

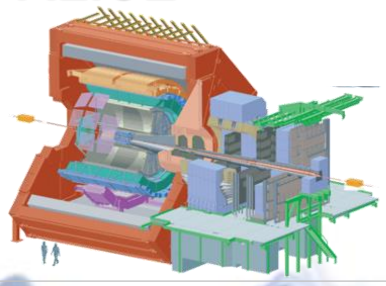
J/ψ



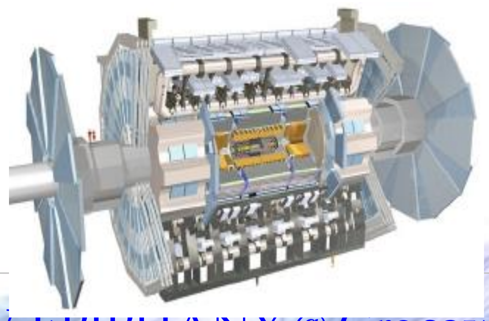


Υ

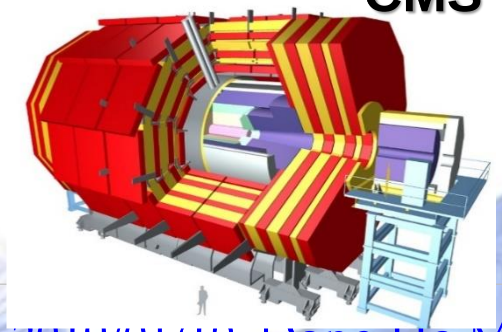
ALICE



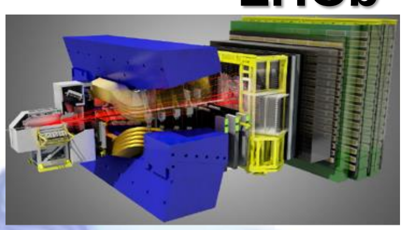
ATLAS



CMS

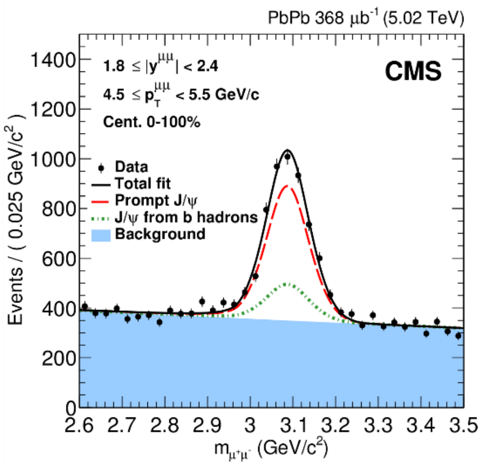


LHCb

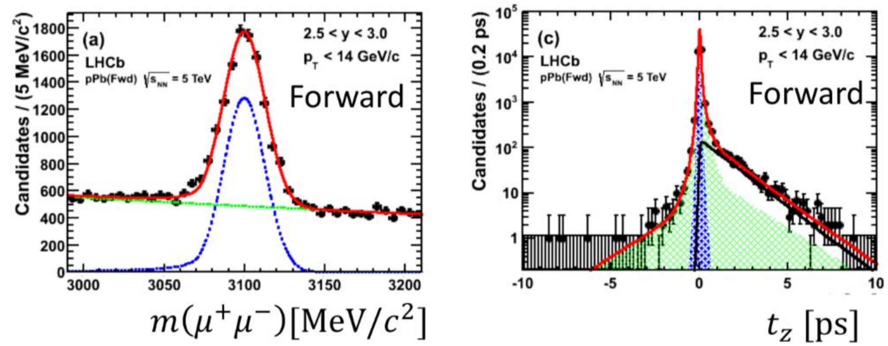


J/ψ Mass Distributions at LHC

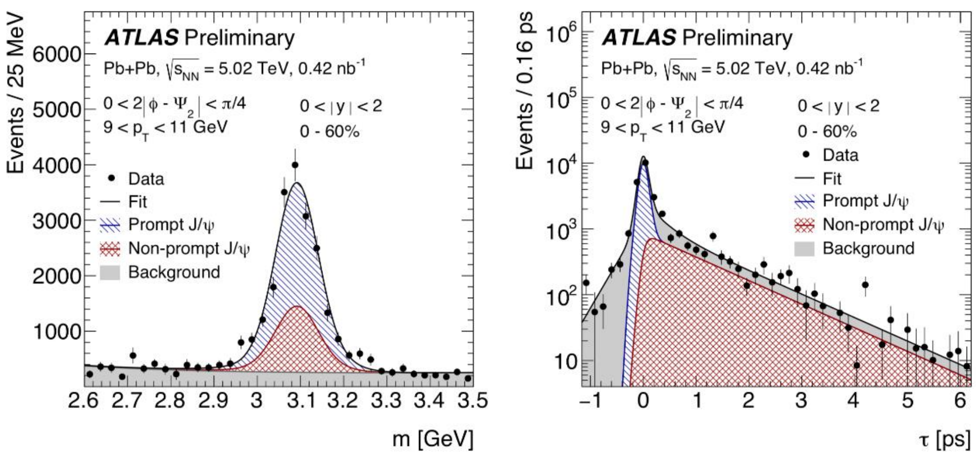
-



arXiv:1712.08959

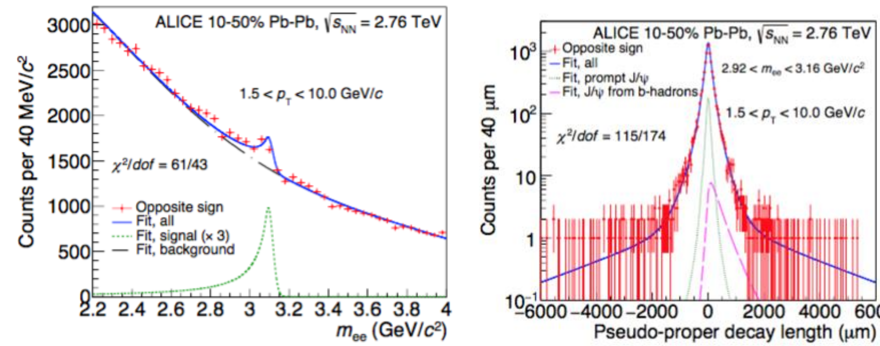


LHCb-CONF-2015-005



ATLAS-CONF-2018-013

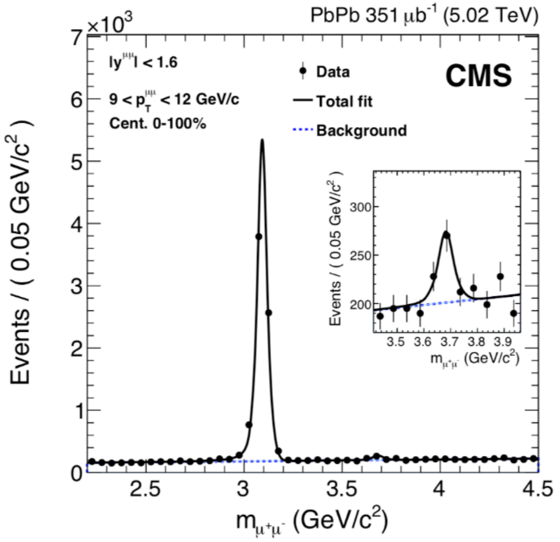
arXiv:1504.07151

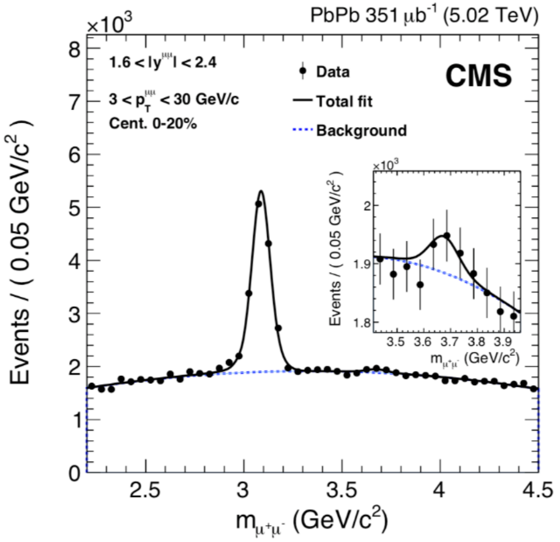


Note : electron-electron can be only separated (at mid-rapidity)

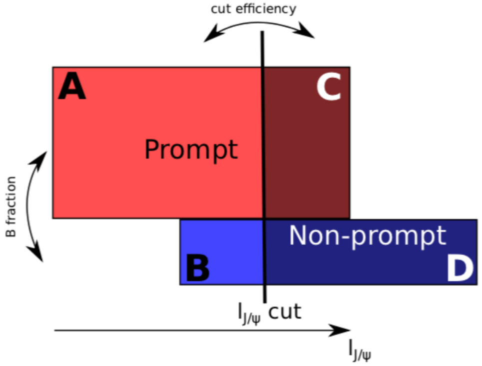
CMS Prompt Charmonia

PRL 0118 (2017) no.16, 162301





$$\ell^{3D}_{J/\psi} = L_{xyz} \cdot \frac{m_{J/\psi}}{p_{\mu\mu}}$$



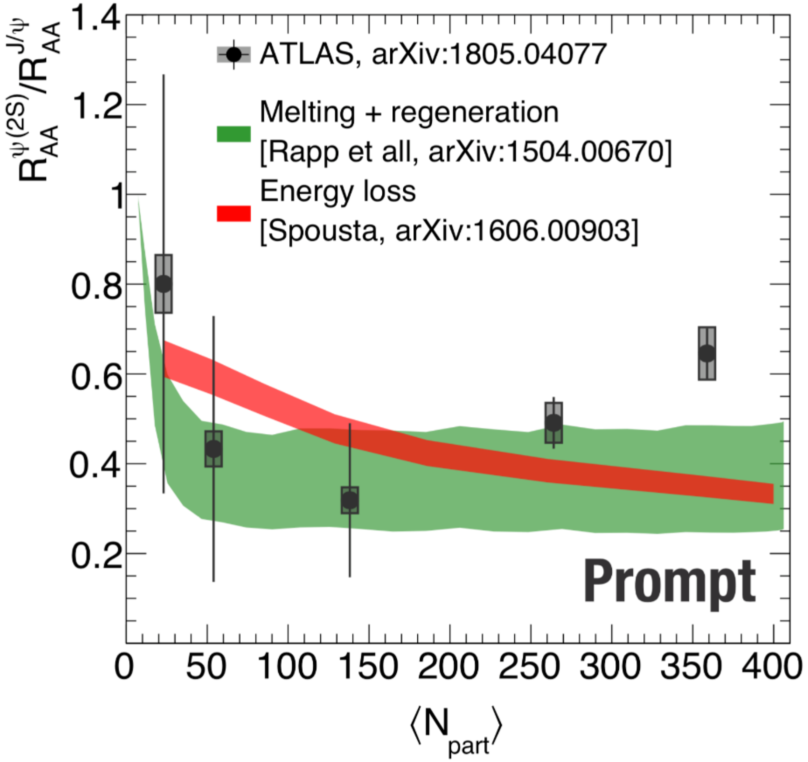
Simultaneous two dimensional fit method

- Mass + pseudo-proper decay length
- For ψ(2S), extra cut applied for rejecting non-prompt components using a cut on $l_{J/\psi}$ due to small S/B
- Data-driven correction for the non-prompt contamination in the low $l_{J/\psi}$ region

ATLAS Prompt Charmonia

- arXiv:1805.04077

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

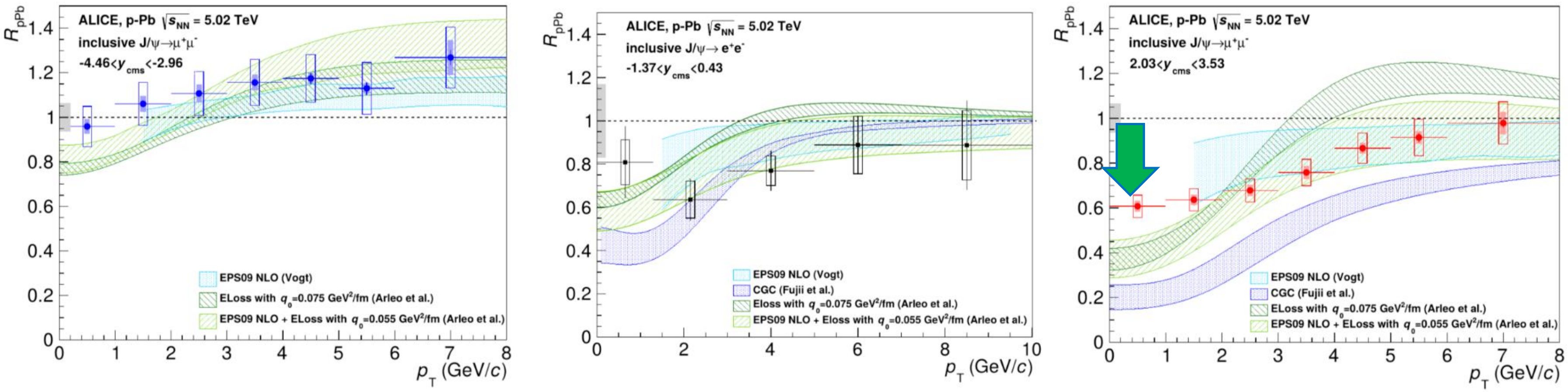


- DR is under unity : strong suppression of ψ(2S) with respect to J/ψ (sequential melting)
- Slightly increasing trend along increasing centrality

- Superimposing model results – data is well described under different scenarios
  - Sequential Melting + Color Regeneration
  - Energy loss
  - Tension in most central events

ALICE J/ψ in pPb

Backward Forward



arXiv:1308.6726, arXiv:1506.07179, arXiv:1506.08808

$$R_{\rm pPb} = \frac{1}{208}\frac{\sigma^{p+{\rm Pb}}}{\sigma^{pp}}$$

- Strong modifications at forward rapidity
- p_T dependence : gradually approaching to unity (starting from 0.6 of R_{pPb})
- nPDF, energy loss and CGC models describe well data within uncertainties

Υ Mass Distributions at LHC

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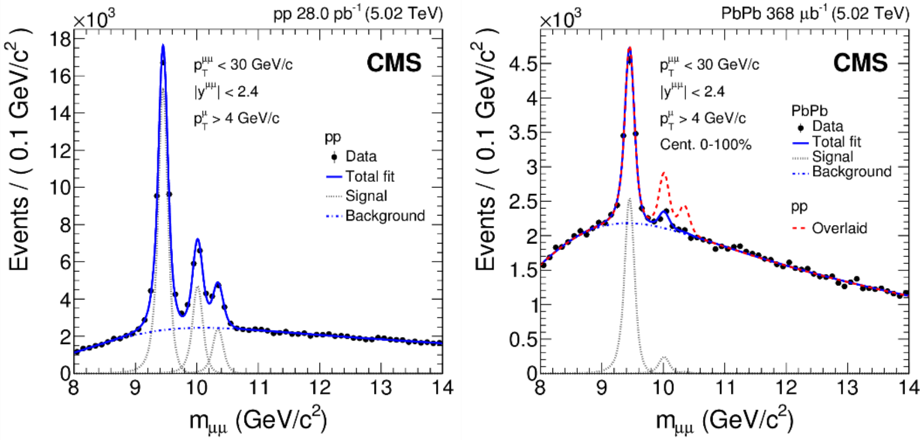
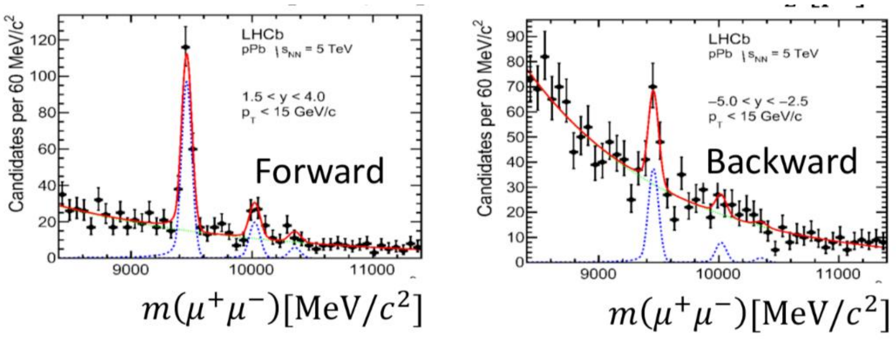
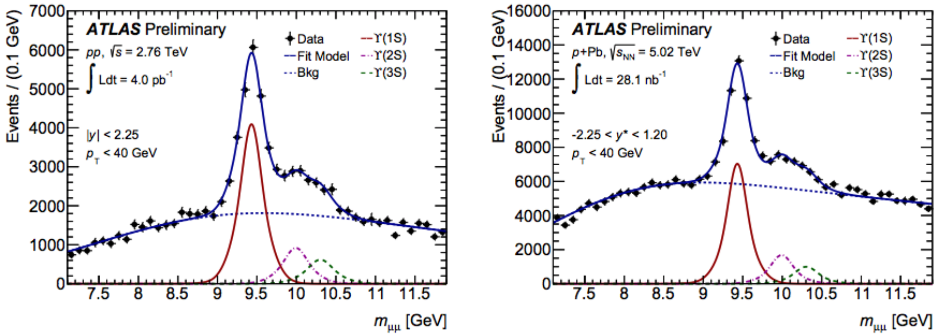
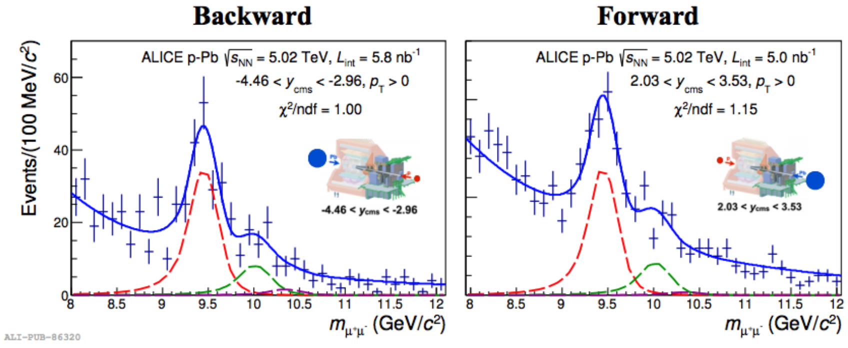




JHEP 07 (2014) 094

PRL 109 (2012) 222301





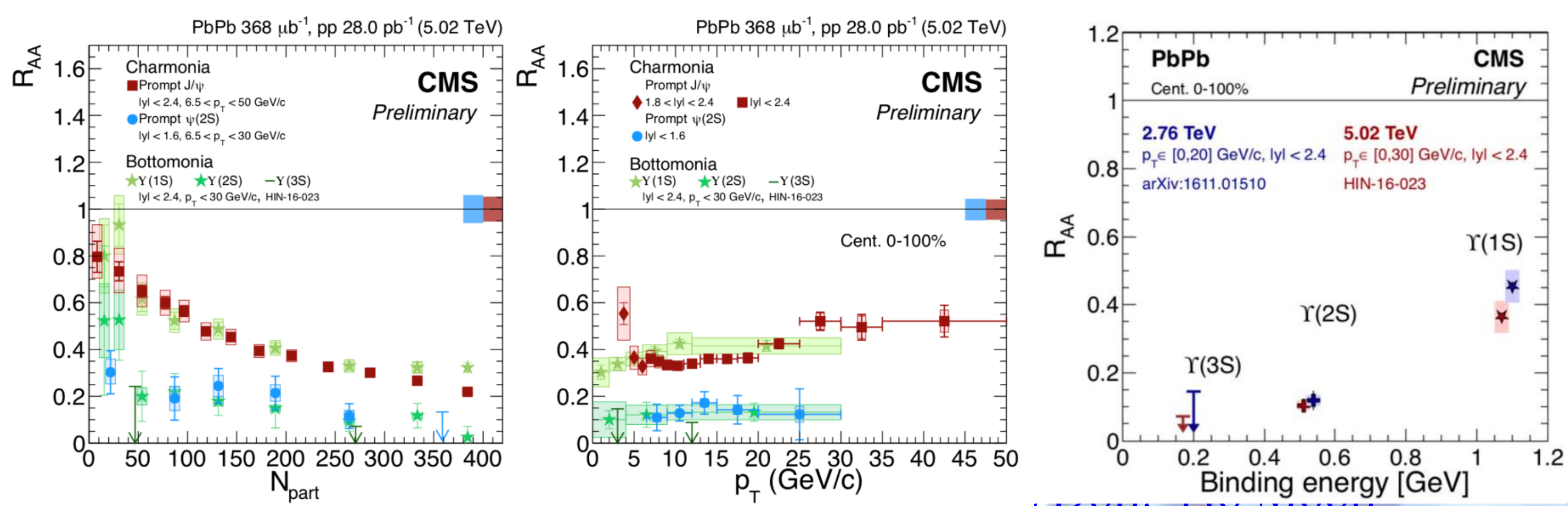
PLB 740 (2015) 105

ATLAS-CONF-2015-050

Summary

- **In pPb**
  - Indication of initial suppression for all of quarkonia
  - More suppression at forward rapidity and low p_T region
  - ψ(2S) is more suppressed than J/ψ at backward rapidity but not sure exact reason

- **In PbPb**
  - Observed sequential suppression as expected
  - Indication of larger suppression of Υ(1S) at 5.02 TeV than 2.76 TeV in CMS but slightly opposite trend is observed in ALICE
  - Still no sign of Υ(3S)



ATLAS Prompt ψ(2S) in pPb

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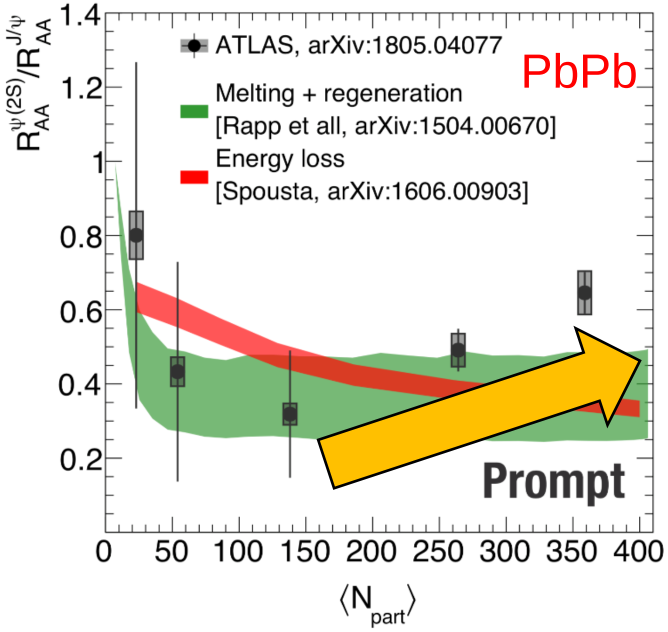
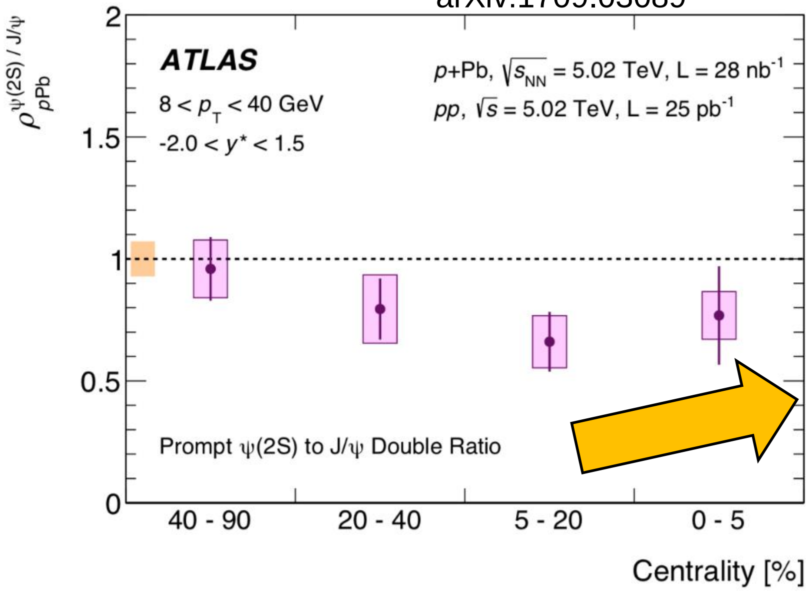


arXiv:1709.03089



- ψ(2S) is more suppressed than J/ψ (maybe same reason with CMS?)
- Slightly more suppression at forward rapidity and in more central events
- But still big error bar (need more statistics)
- Similar increasing trend in more central events at both of PbPb and pPb (is this effect from CNM ? not from QGP ?)

J/ψ Elliptic flow

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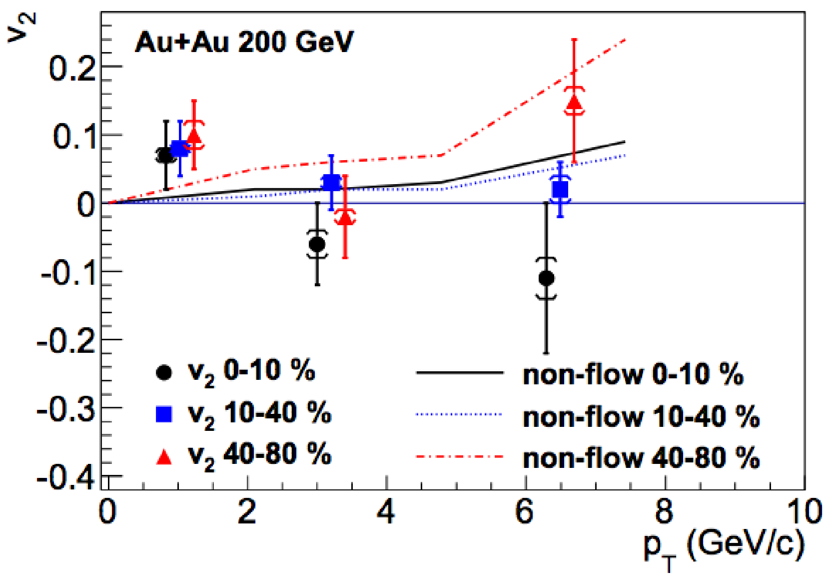
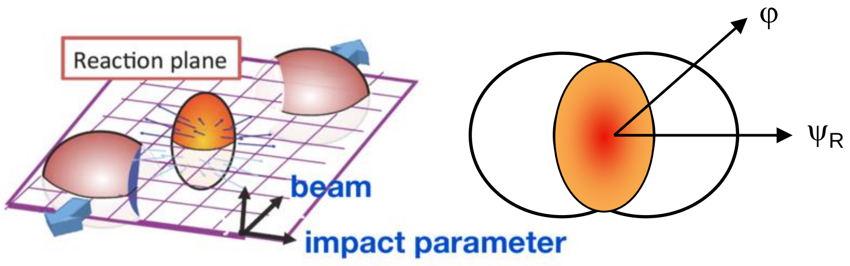
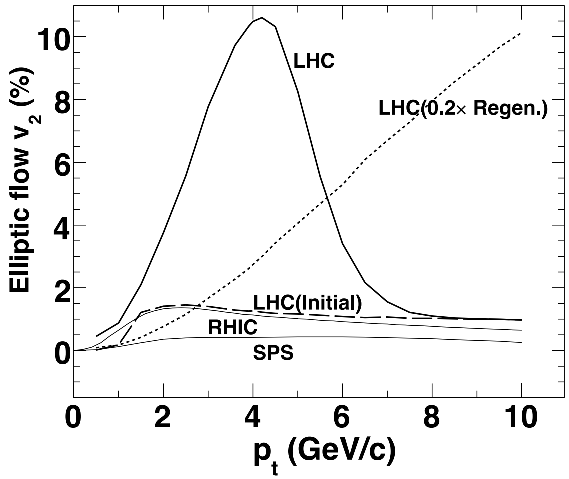




$v_2 = \langle \cos 2(\phi_{particle} - \Psi_{EP}) \rangle$



- Almost zero flow at RHIC
- But significant elliptic flow (v_2) may be expected at LHC energ y due to the significant contribut ion of regenerated J/ψ
  - Good regeneration signal

J/ψ Elliptic flow

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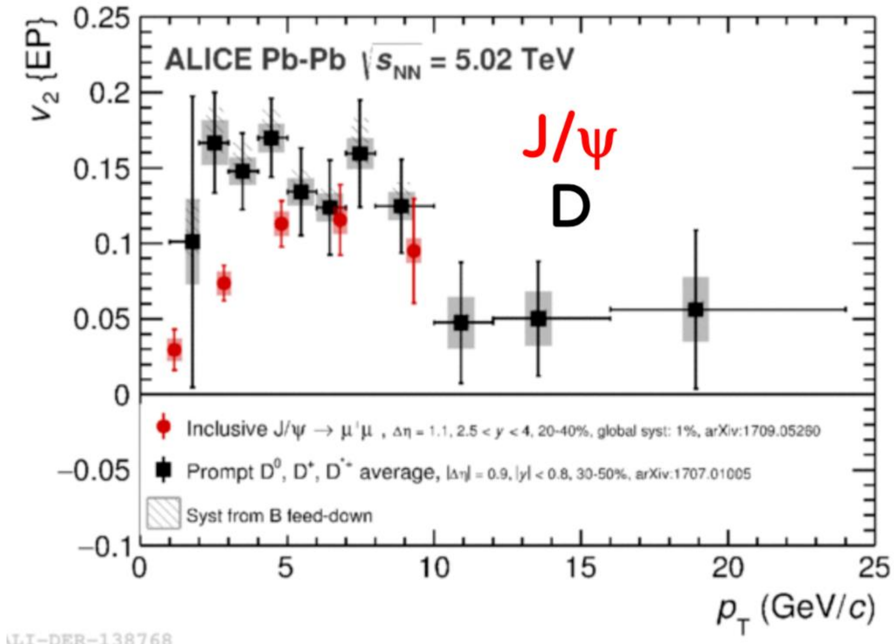
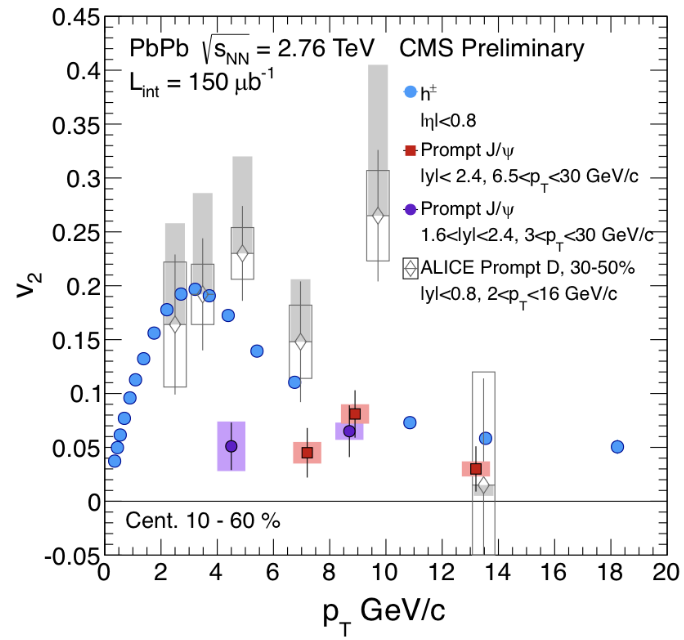
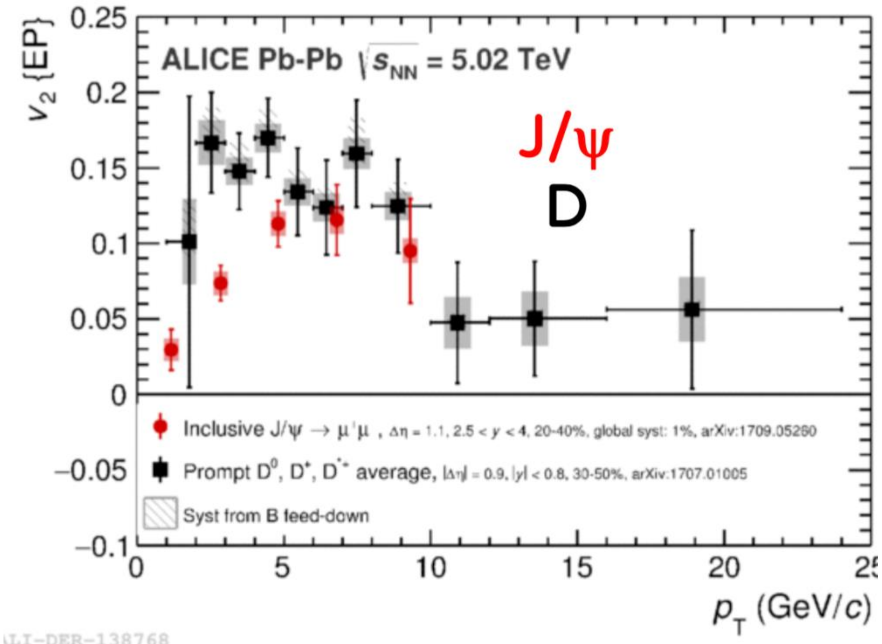


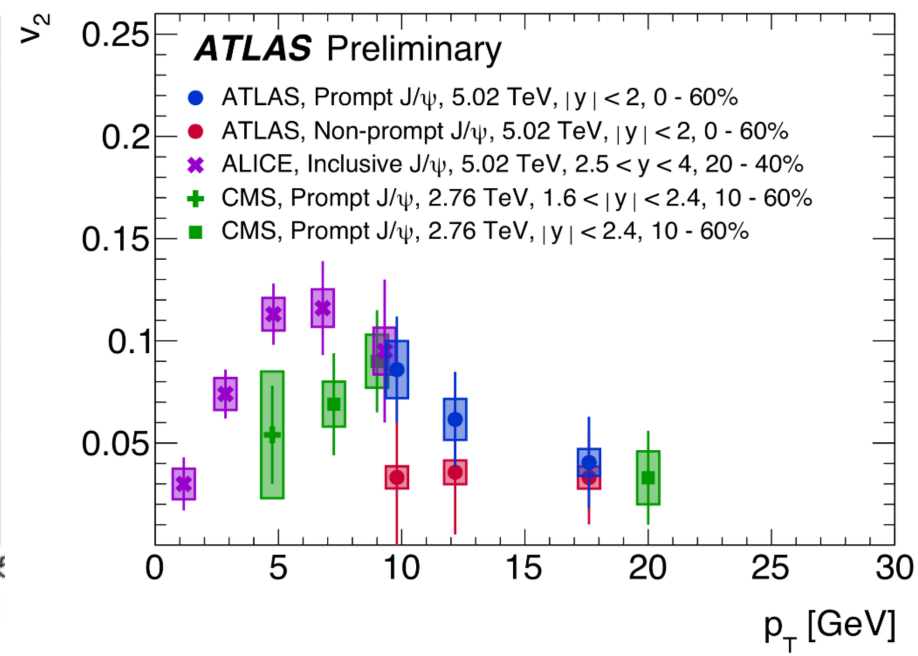


arXiv:1709.05260

- Similar flow observed for open charm
  - Charm quarks strongly interact with medium
  - Comparison between J/ψ and D meson flow can provide insights on the properties of flow of heavy vs light quarks
    - At low p_T : light quark ≈ c+light quark > c+c quark
    - At high p_T : light quark ≈ c+light quark ≈ c+c quark

J/ψ Elliptic flow





arXiv:1709.05260

- Similar flow observed for open charm
  - Charm quarks strongly interact with medium
  - Comparison between J/ψ and D meson flow can provide insights on the properties of flow of heavy vs light quarks
- ATLAS measured prompt and nonprompt J/ψ's flow at 5.02 TeV
  - Prompt J/ψ's flow is larger than nonprompt J/ψ's one

J/ψ Eliptic flow

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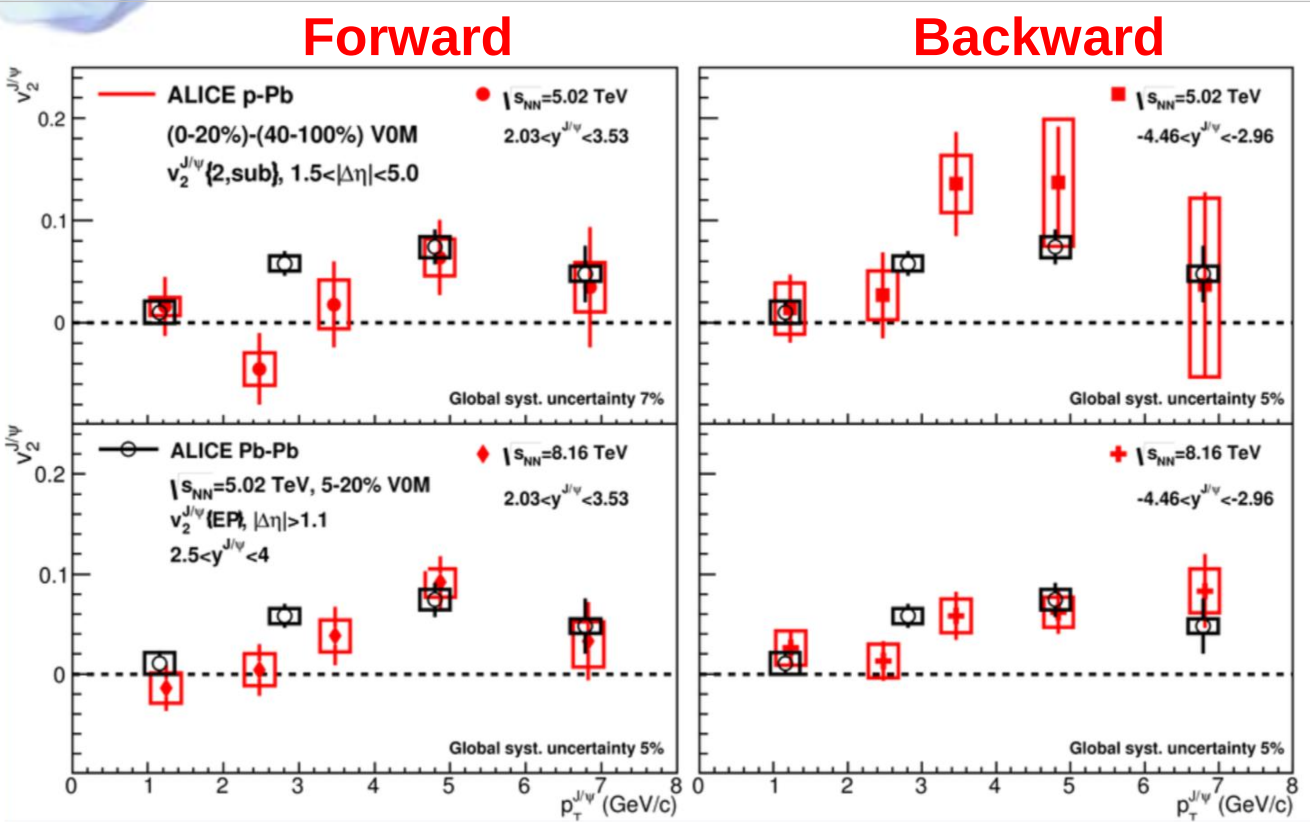
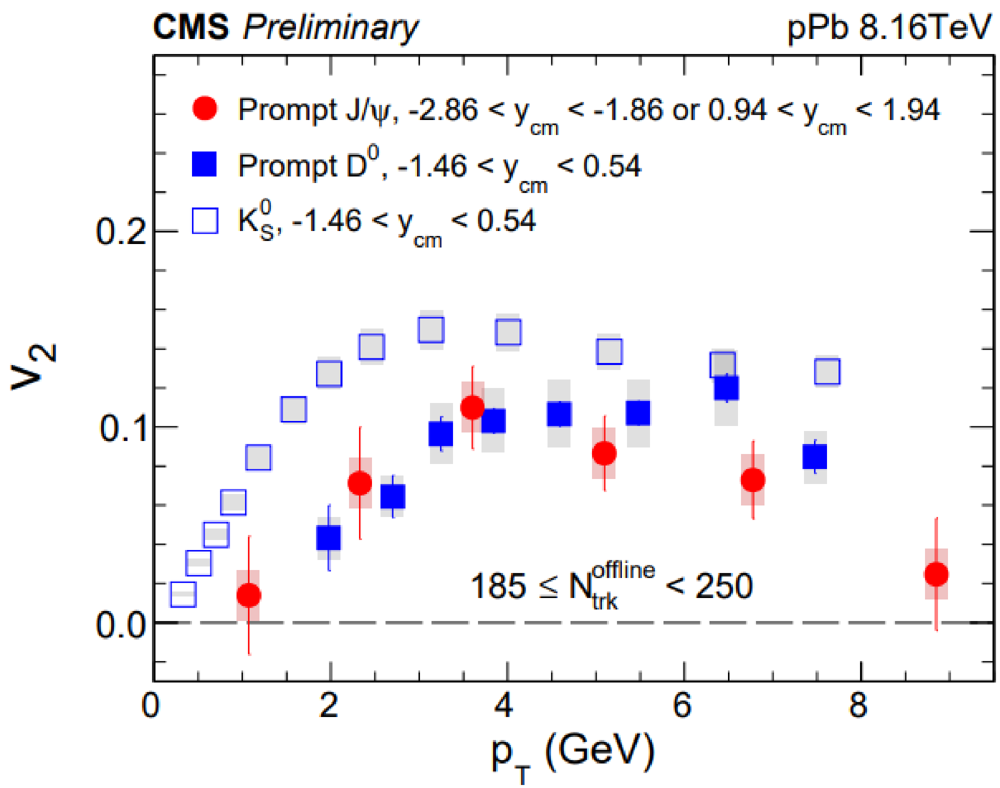


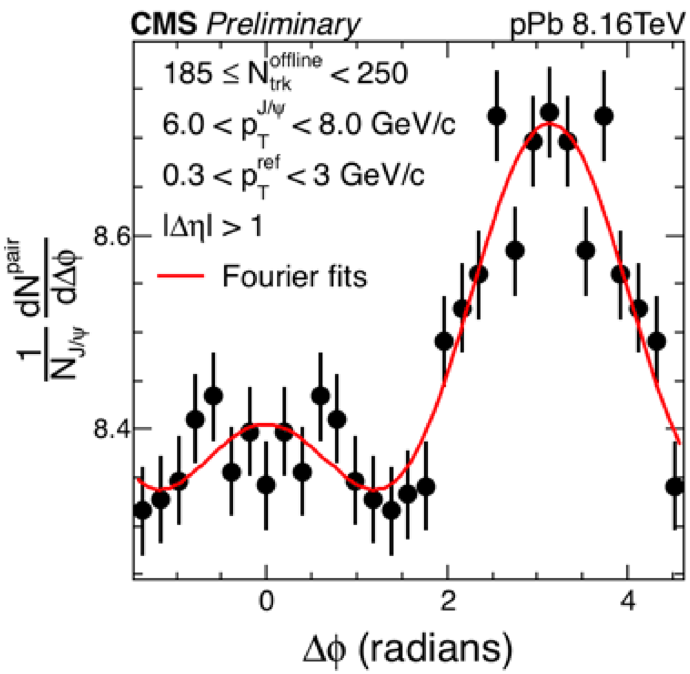
arXiv:1709.06807, 1709.05260

- Non-zero v_2 in p_T > 3 GeV/c
- No significant collision system dependence
- Similar size of v_2 in PbPb

J/ψ Elliptic flow in pPb

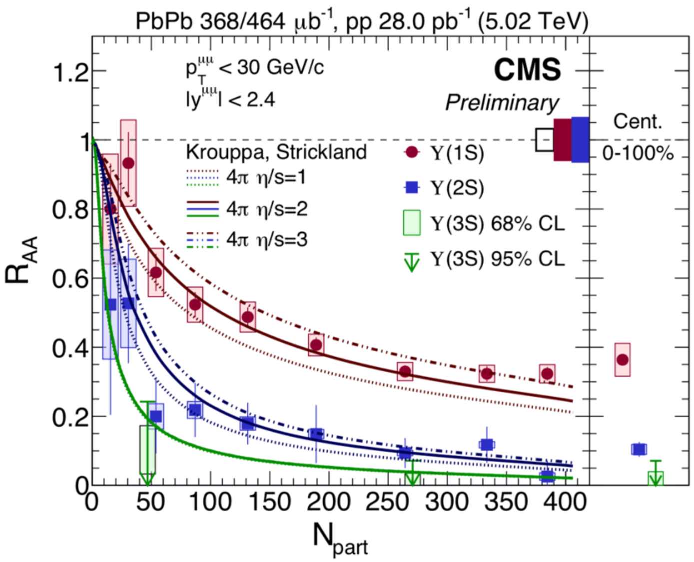
CMS-PAS-HIN-18-010

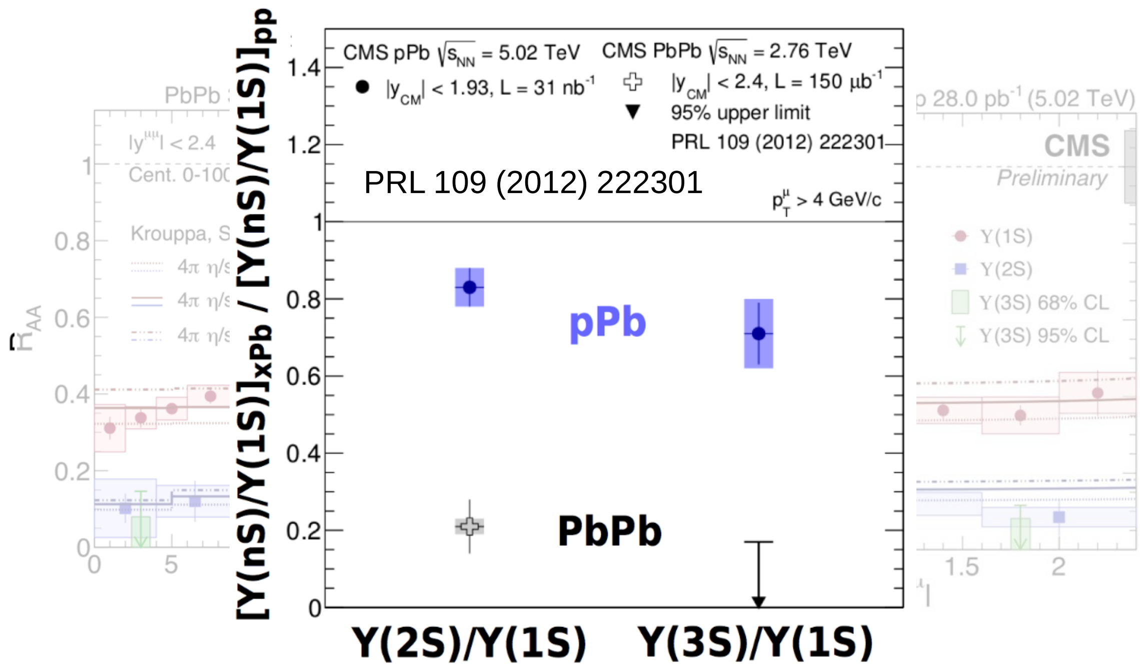




- Observed significant positive J/ψ v_2 even in pPb
- Measured in events with N^{trk} > 185 (only in high multiplicity events)

Υ(1S, 2S, 3S) at 5.02 TeV : R_{AA}

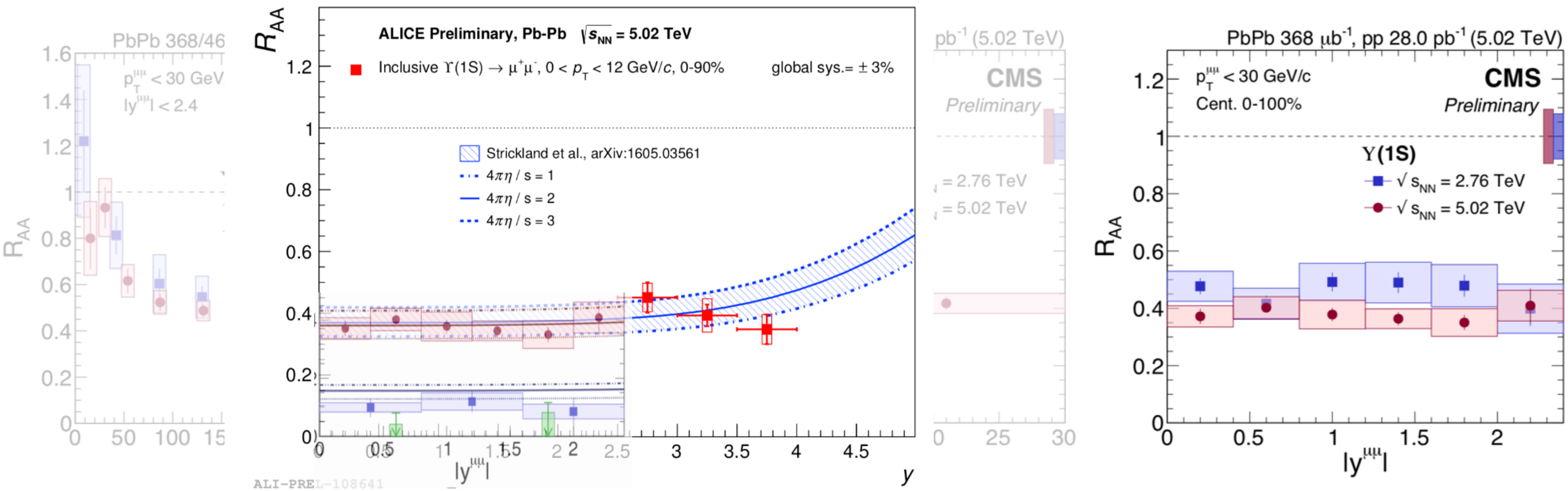




arXiv:1805.09215

- Increasing suppression along the centralities
- 'Clear' ordering : R_{AA}(Υ(3S)) < R_{AA}(Υ(2S)) < R_{AA}(Υ(1S))
- Also hydrodynamic model with 3 temperatures (Krouppa at al.) describe well data within uncertainty ($4\pi\eta/s$ = {1, 2, 3}, T_0 = {641, 632, 629} MeV)
- When interpreting this, don't forget the CNM effects as seen in pPb results.

Energy Dependence of Υ(1S, 2S, 3S) : R_{AA}



arXiv:1805.04387

arXiv:1805.09215

- Indication of larger suppression of Υ(1S) at higher collision energy
- No significant dependence on rapidity but hint of more suppression in low p_T region at 5.02 TeV than 2.76 TeV
- Stricklaland Thermal anisotropic hydrodynamical model reproduce ALICE results within uncertainties but tension in forward rapidity (increasing or decreasing)