Quarkonium Production in heavy-ion collisions at LHC

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HIM 2018 @ Korea University, 3rd July 2018

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Motivation

Charmonia in pPb, PbPb

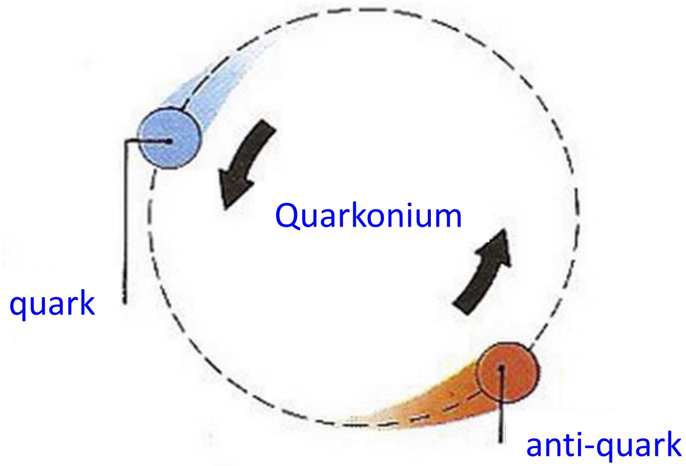
Bottomonia in pPb, PbPb

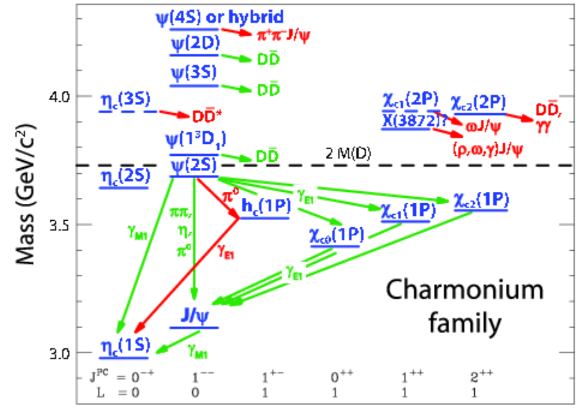
Elliptic Flow for J/ψ

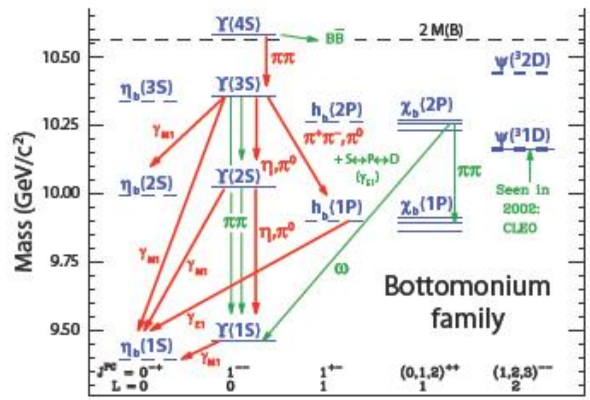
Summary

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) ...)





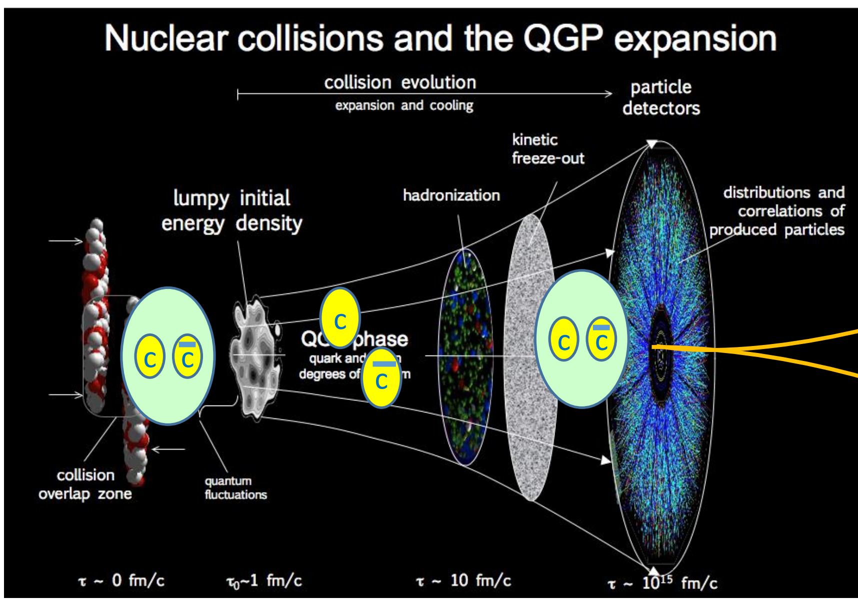


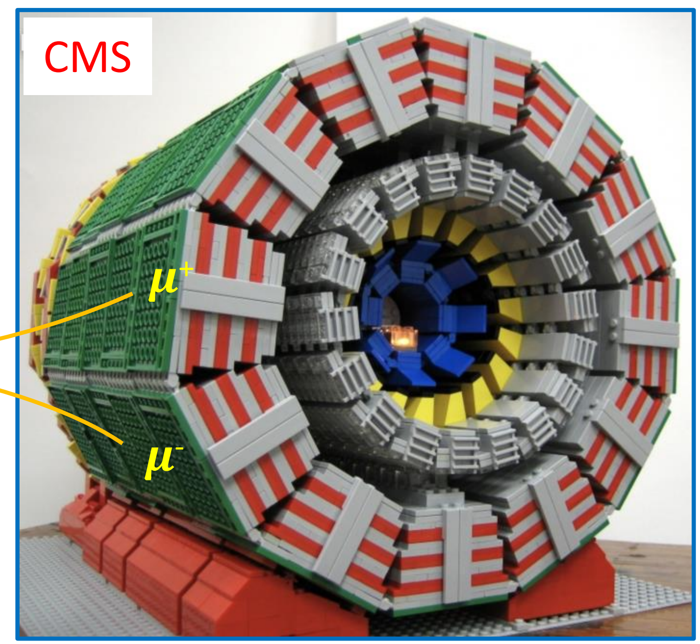
Quarkonia in Heavy ion Collisions

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

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

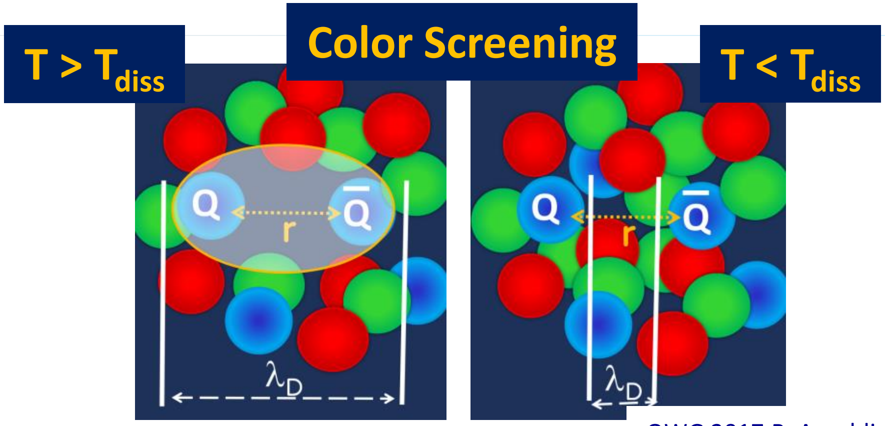
➠ expected to experience whole QGP evolution





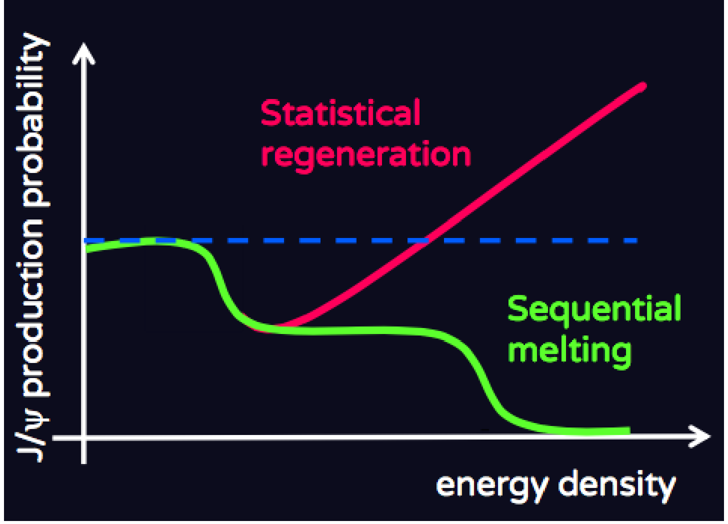
Quarkonia in Heavy ion Collisions

- **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 Effects (CNM)** : Nuclear PDFs, coherent energy loss, 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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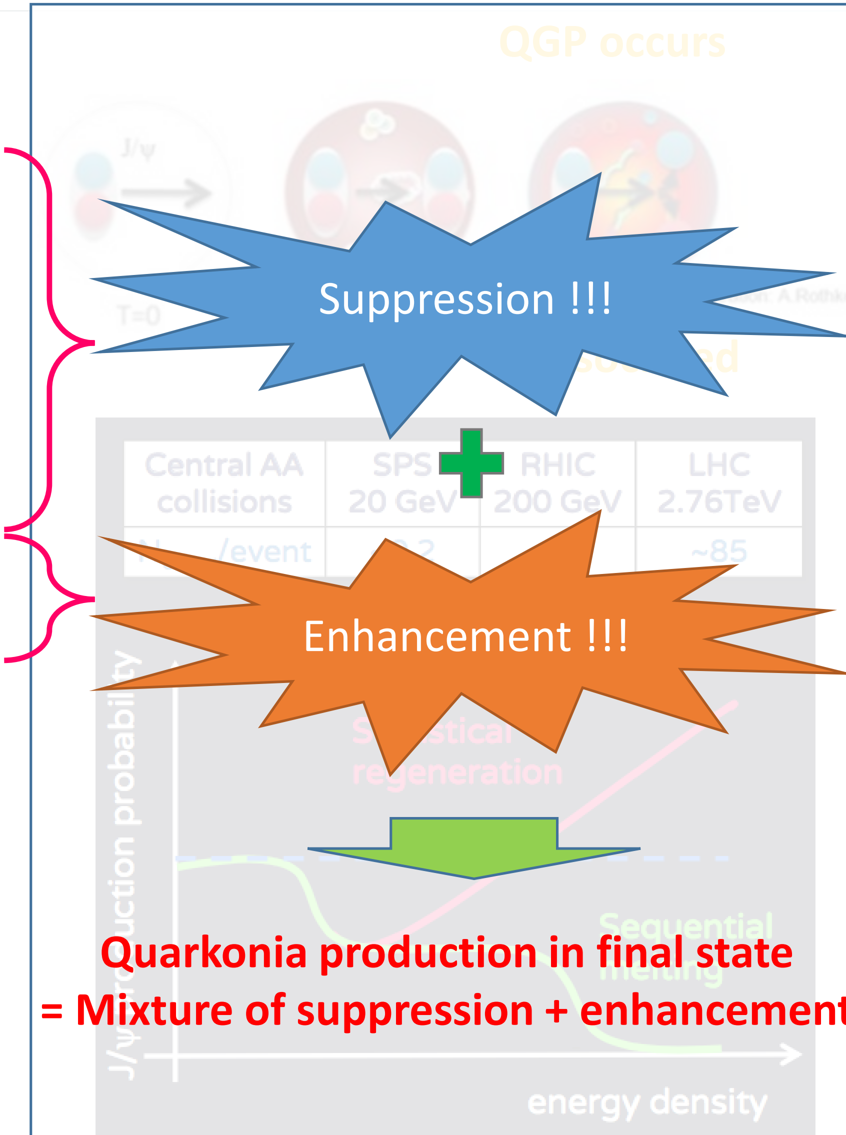
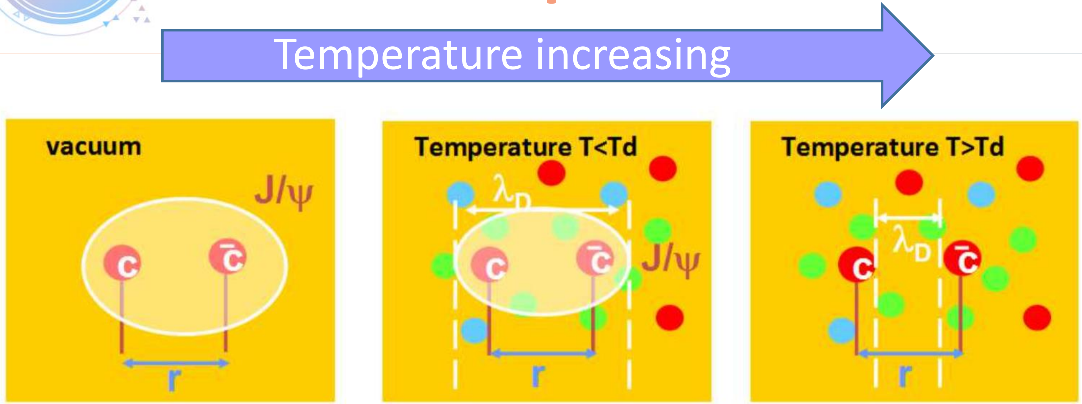
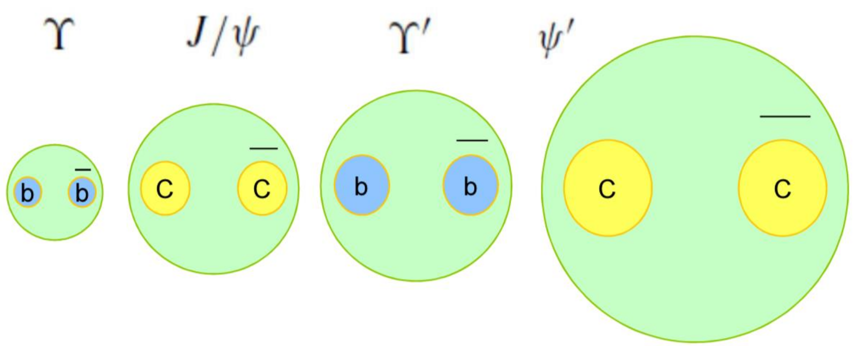
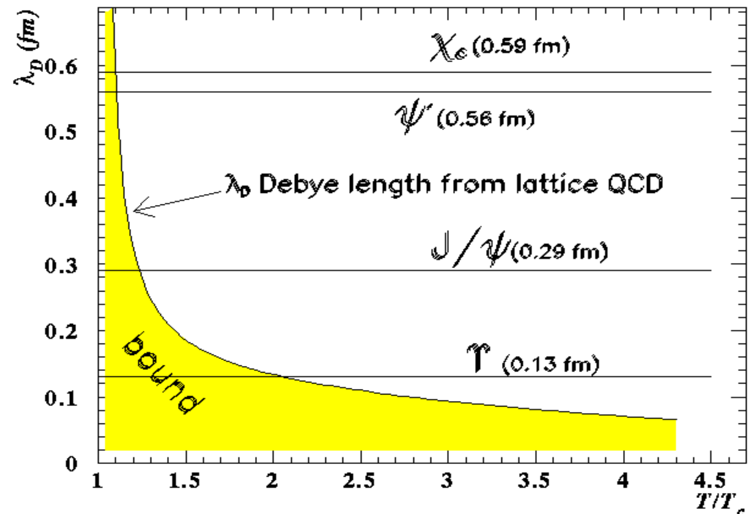


Sequential Melting

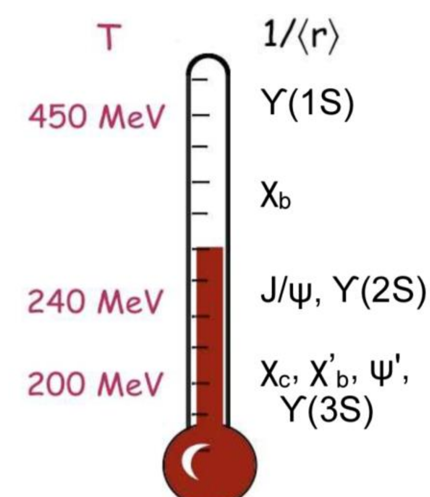






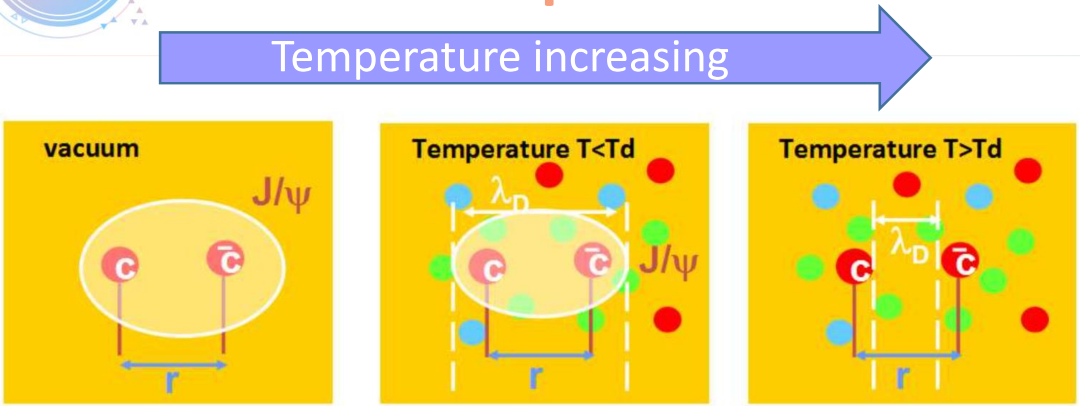
Charmonia	J/ψ	χ_c	ψ′(2S)
Mass(GeV)	3.10	3.53	3.69
ΔE (GeV)	0.64	0.20	0.05
T_d/T_c	2.1	1.16	1.12

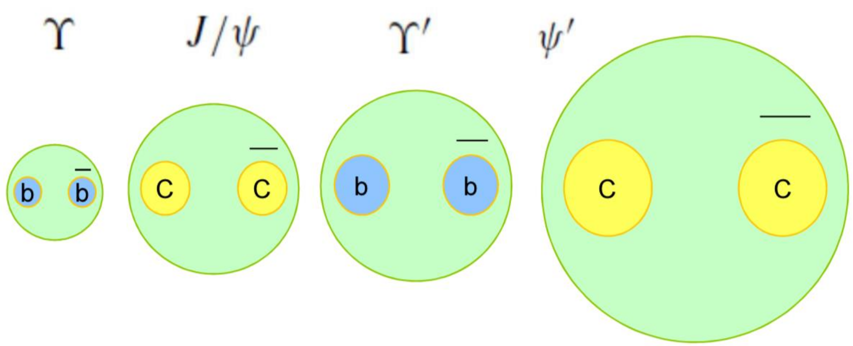
Bottomonia	Υ(1S)	Υ(2S)	Υ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
T_d/T_c	> 4.0	1.60	1.17

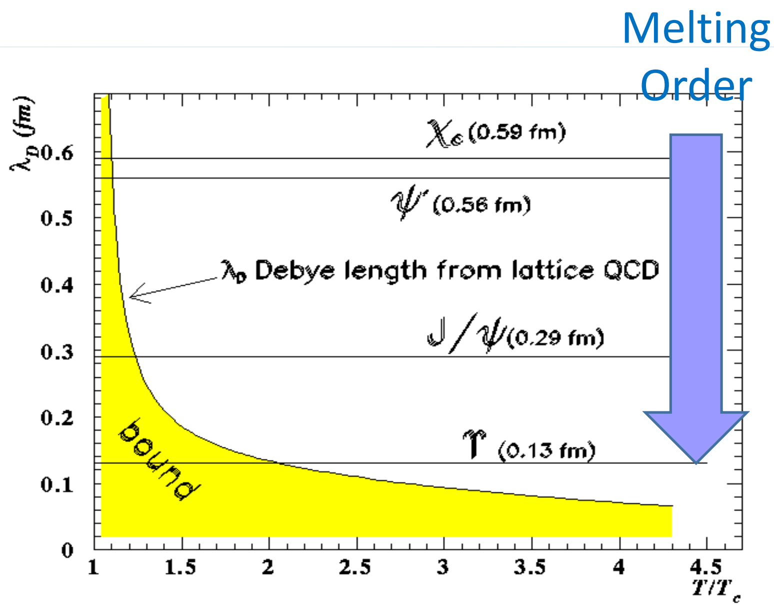


Mocsy, EPJC61 (2009) 705
BNL workshop in June

Sequential Melting







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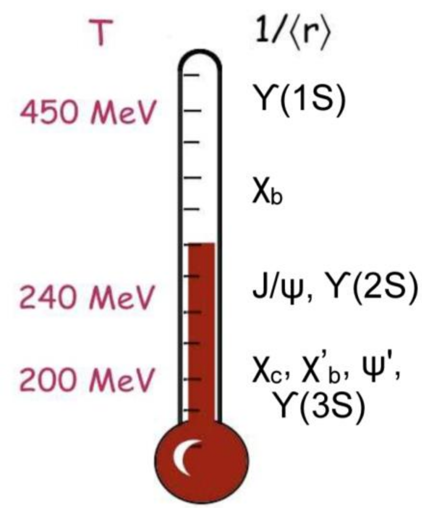
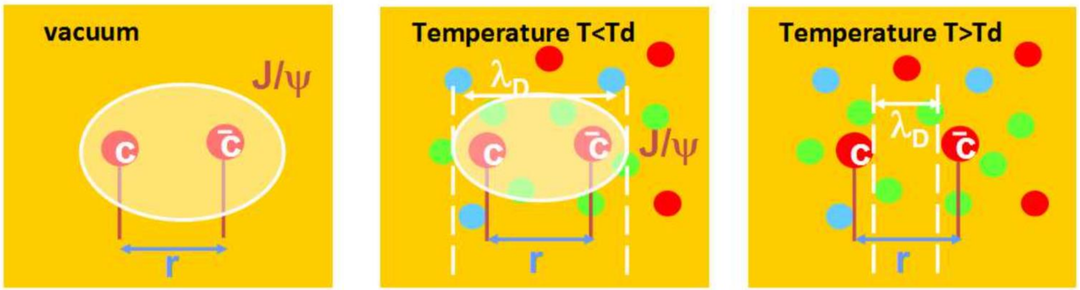


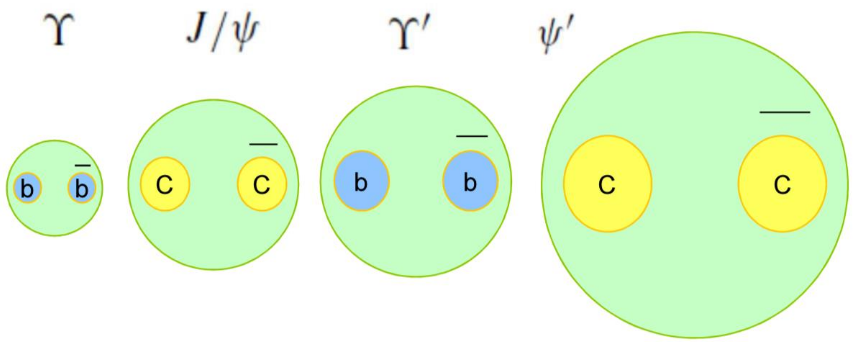
Mocsy, EPJC61 (2009) 705
BNL workshop in June

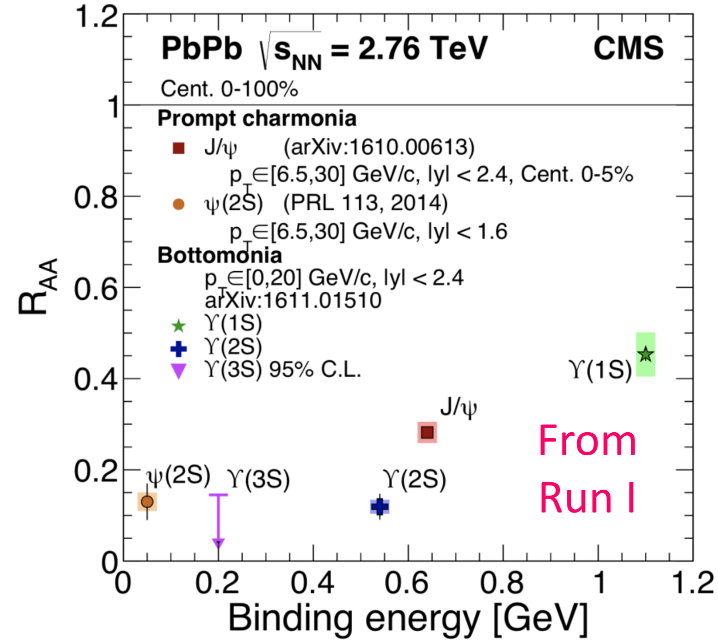
Sequential Melting

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

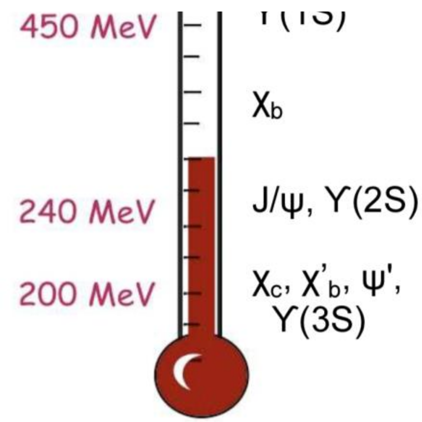
Temperature increasing







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



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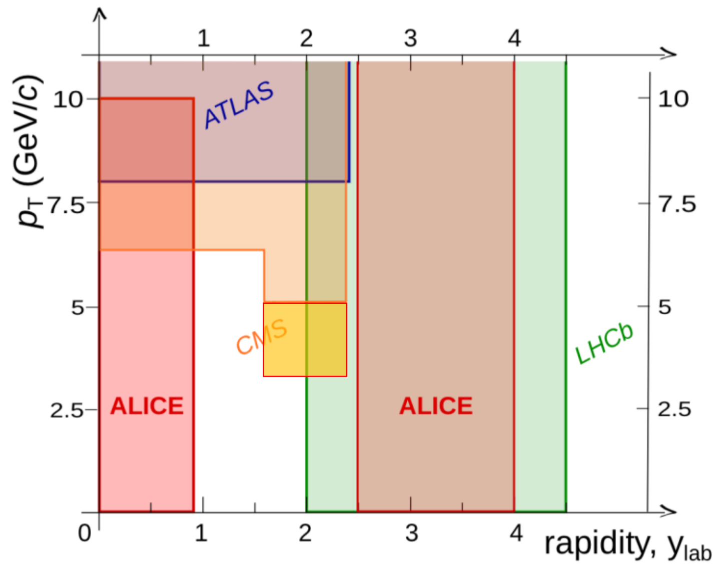
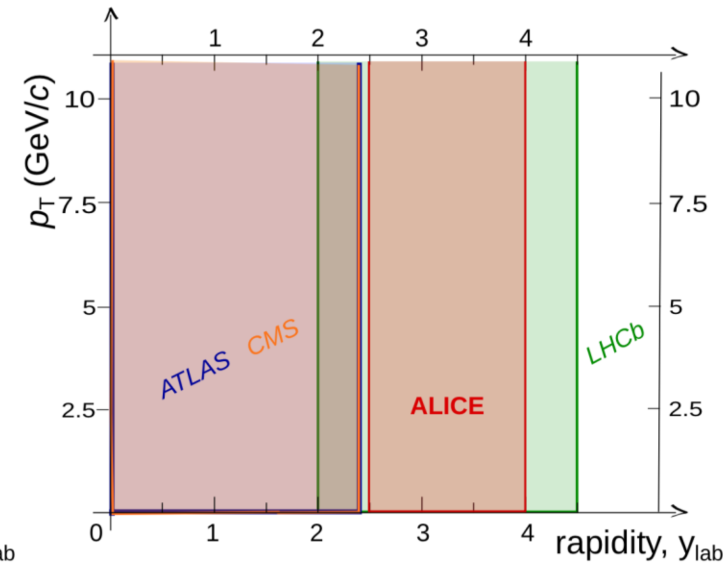
Mocsy, EPJC61 (2009) 705
BNL workshop in June

Quarkonia Acceptance

- **Complimentary acceptance for LHC detectors**

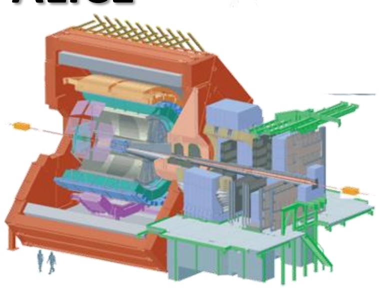
J/ψ



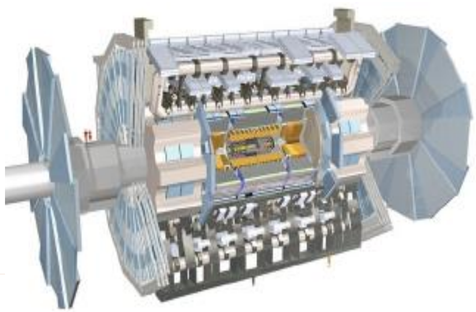


ϒ

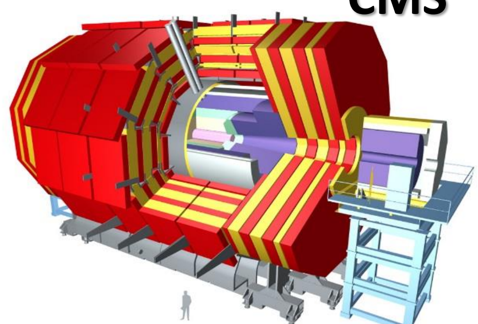
ALICE



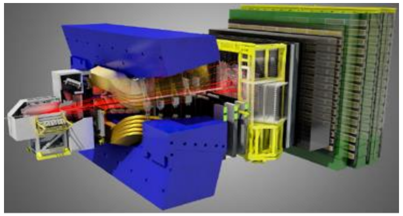
ATLAS



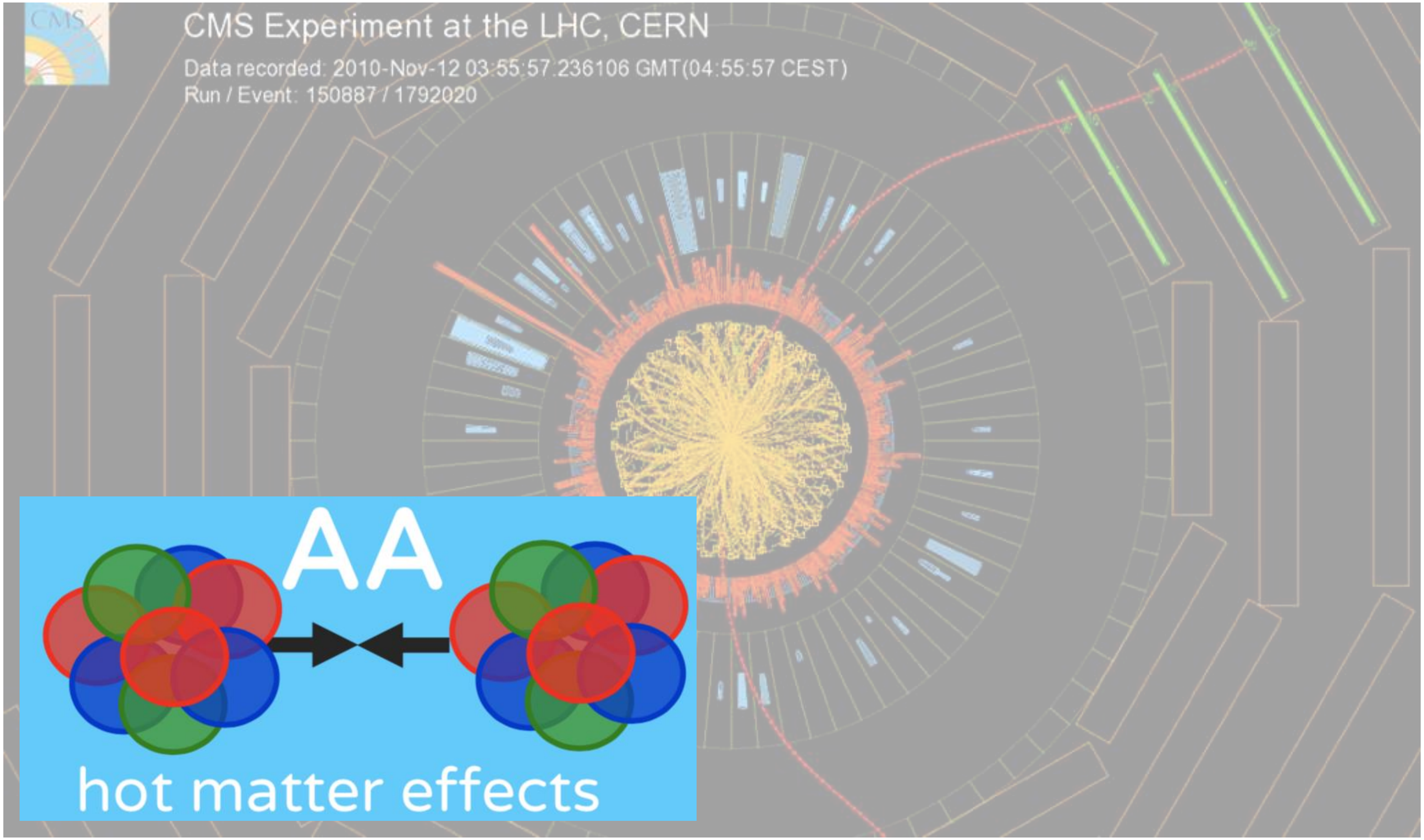
CMS



LHCb



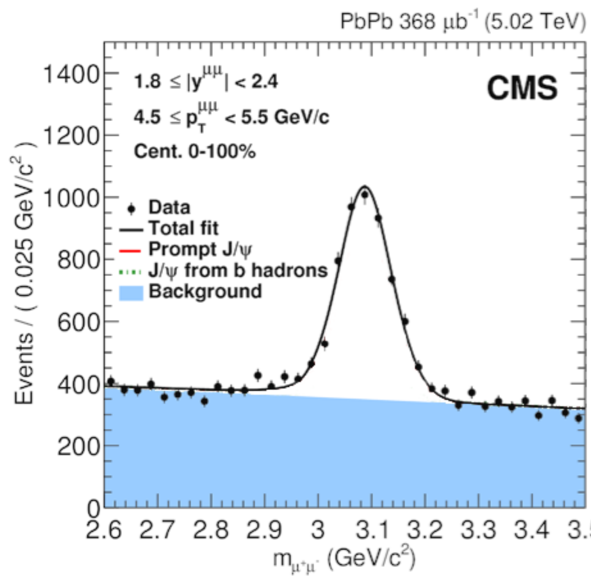
Charmonia in PbPb

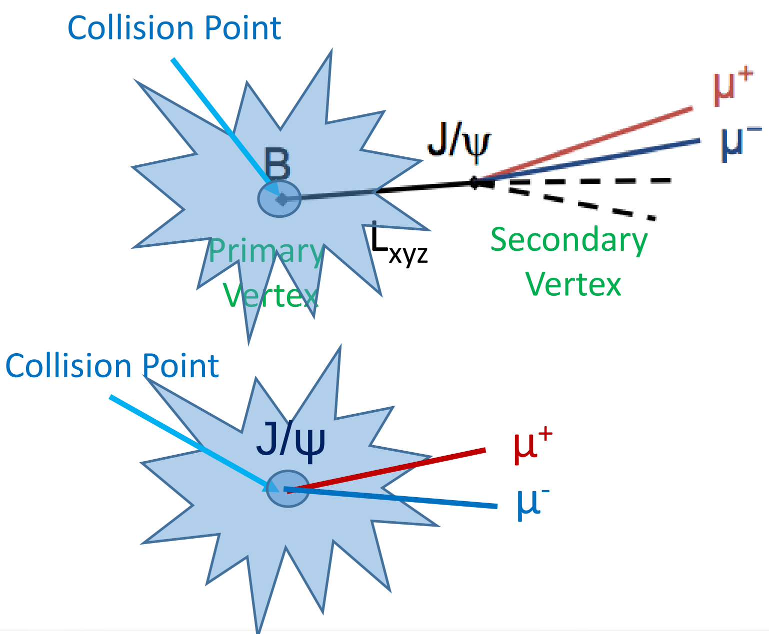


J/ψ : Signal Extraction

arXiv:1712.08959

Inclusive J/ψ





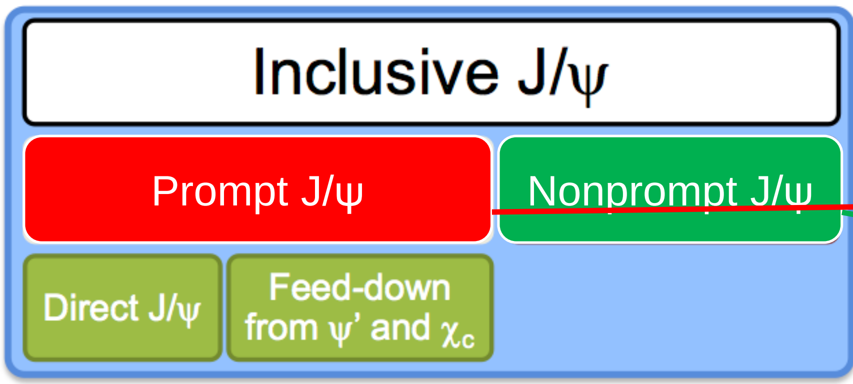
Nonprompt J/ψ

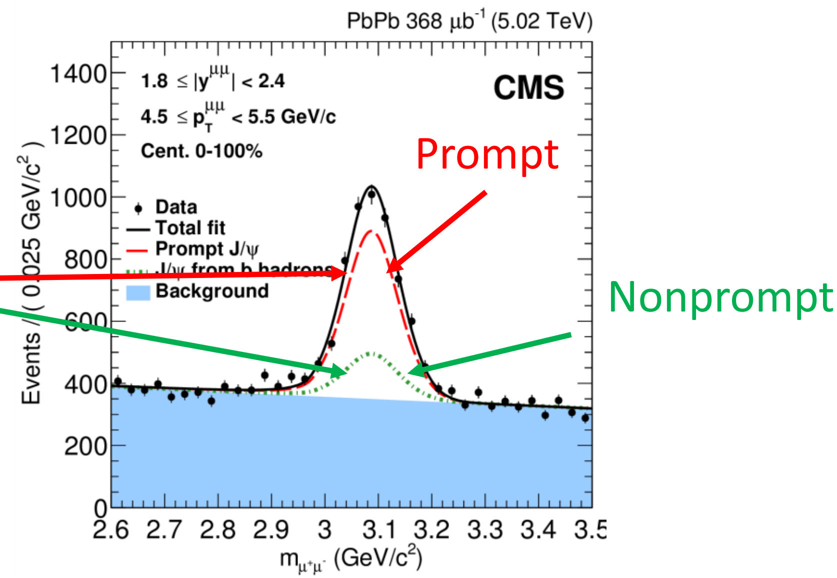
Prompt J/ψ

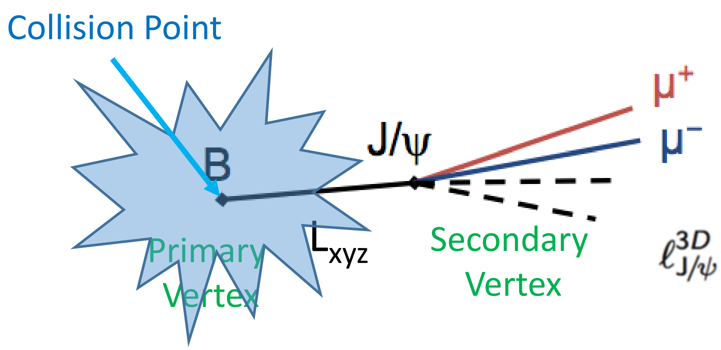
Inclusive J/ψ

J/ψ : Signal Extraction

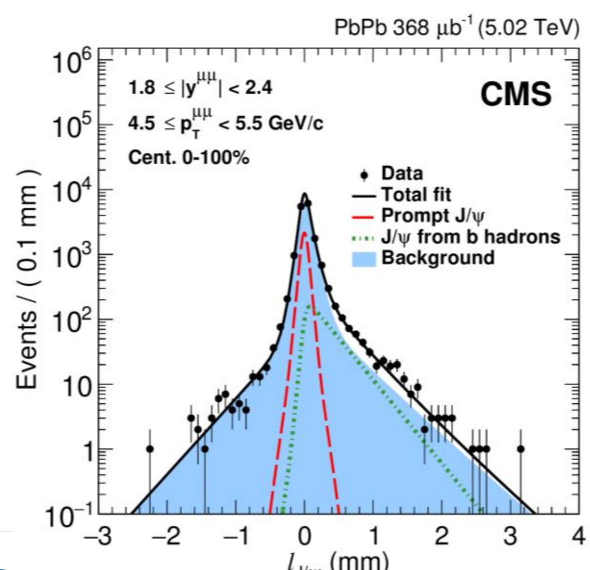
arXiv:1712.08959







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



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

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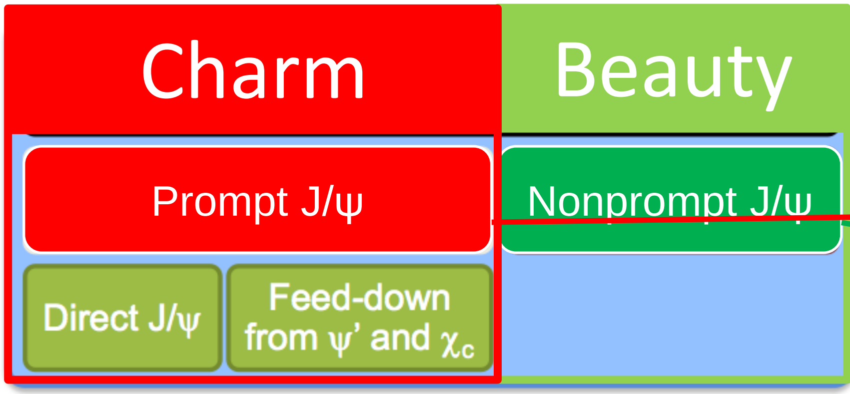

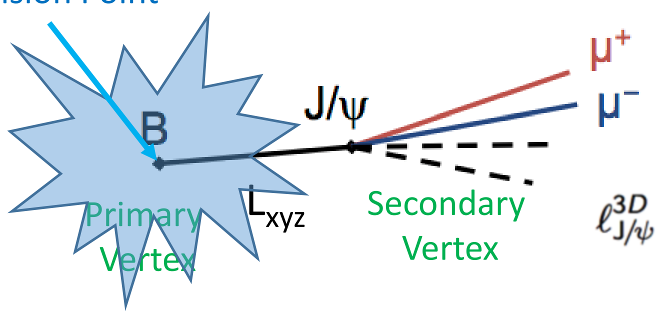

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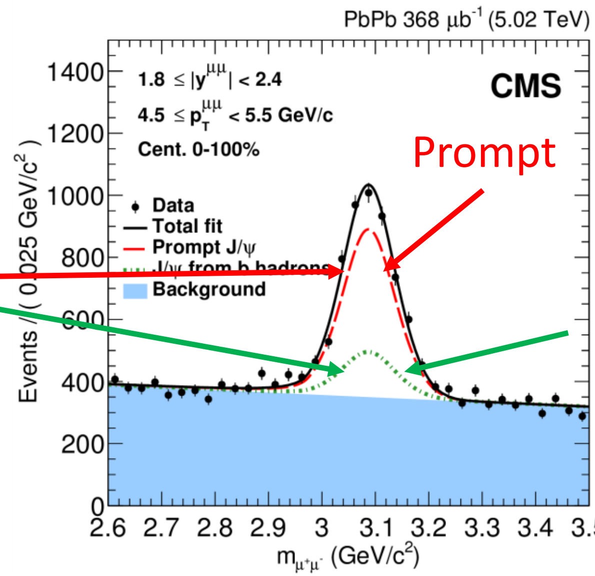

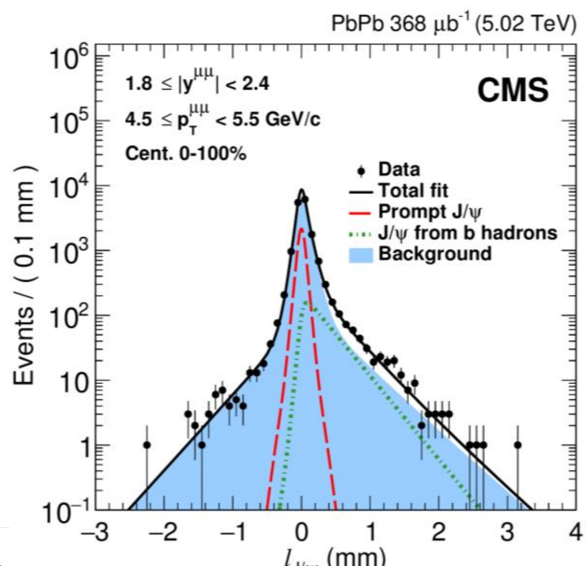

- Simultaneous two dimensional fit method
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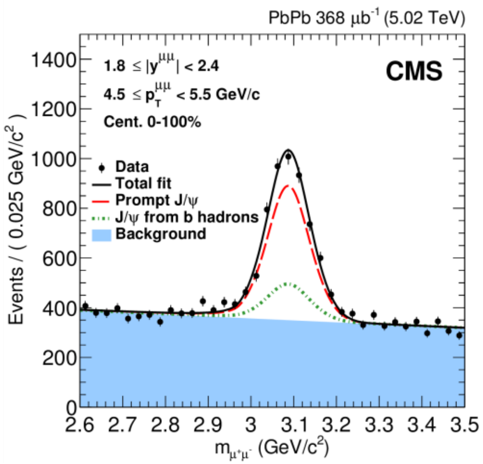
J/ψ Mass Distributions at LHC



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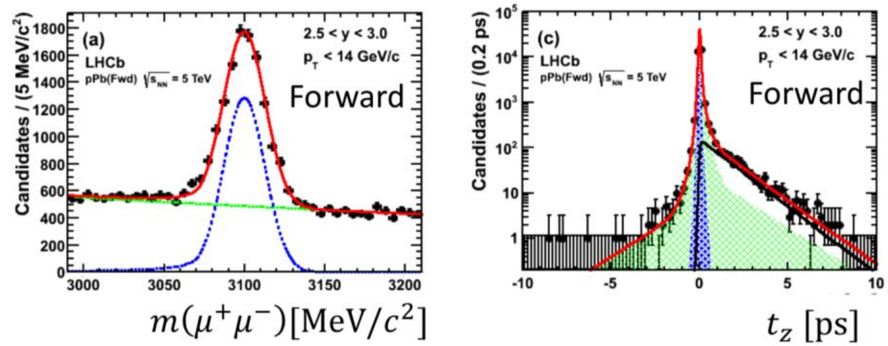
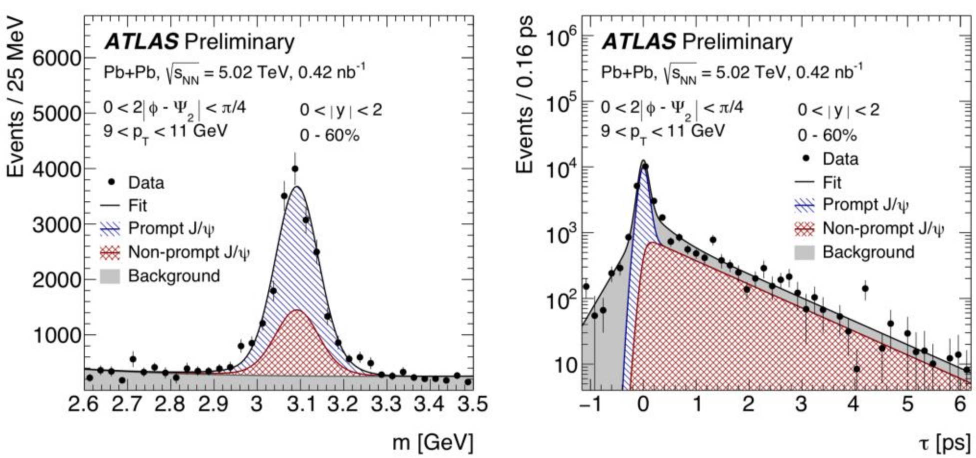
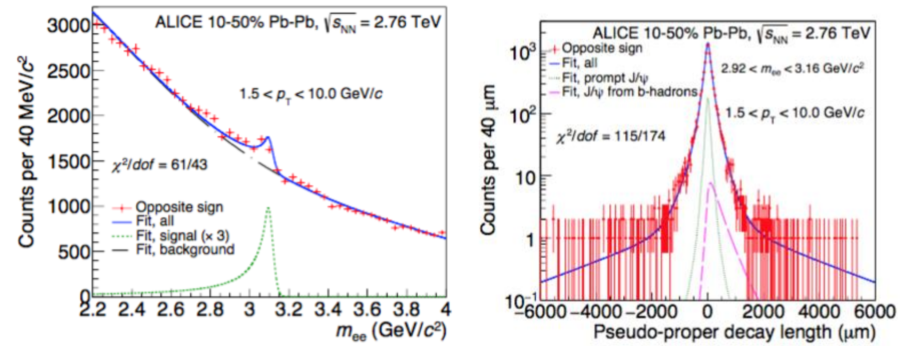


LHCb-CONF-2015-005

arXiv:1504.07151



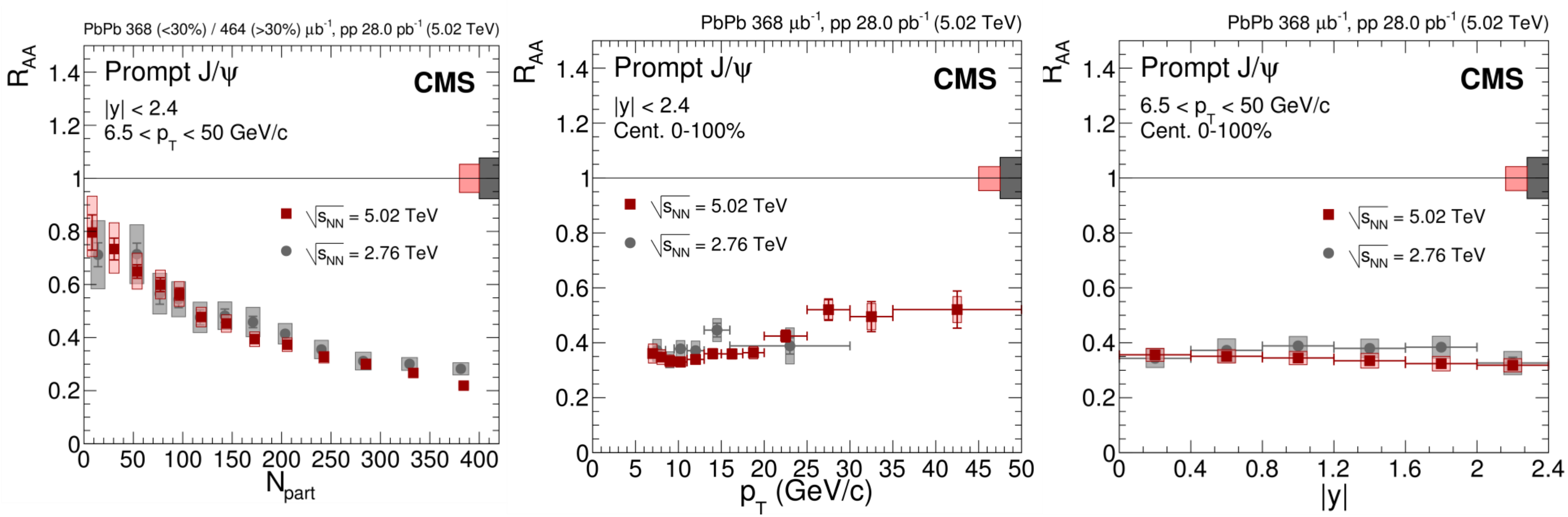
ATLAS-CONF-2018-013



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

CMS 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 and p_T dependences

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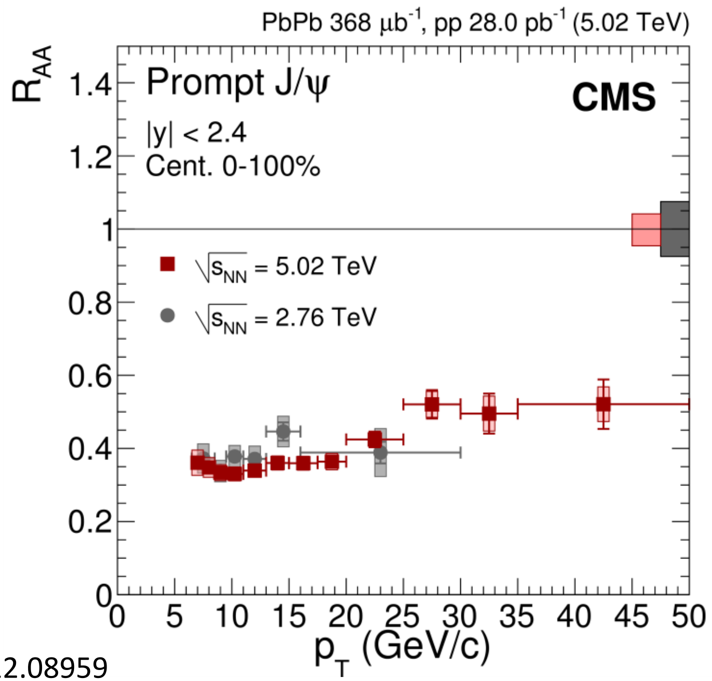

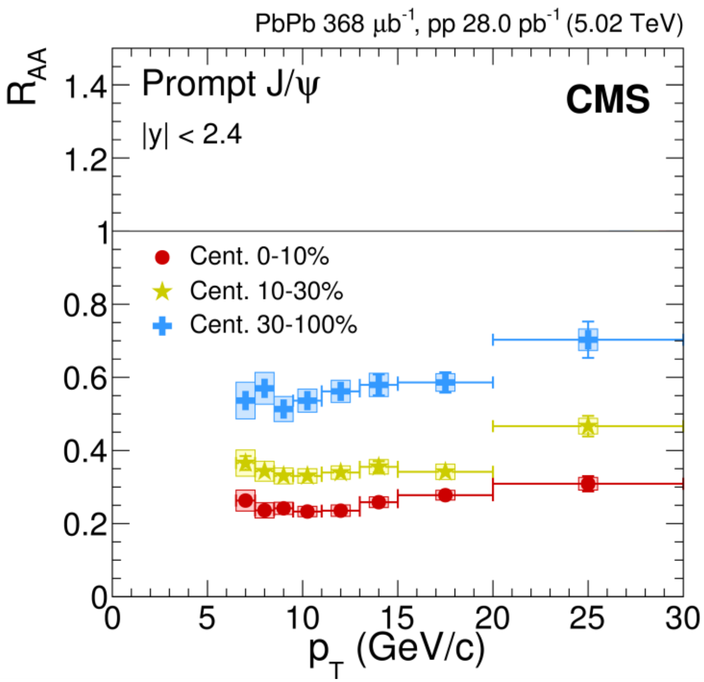

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- At high p_T, no strong collision energy dependence

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

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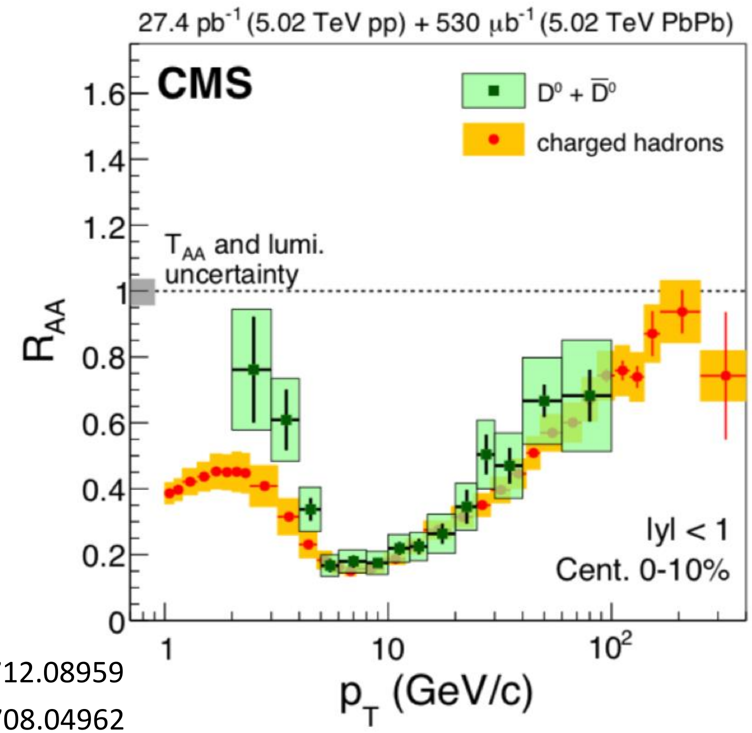
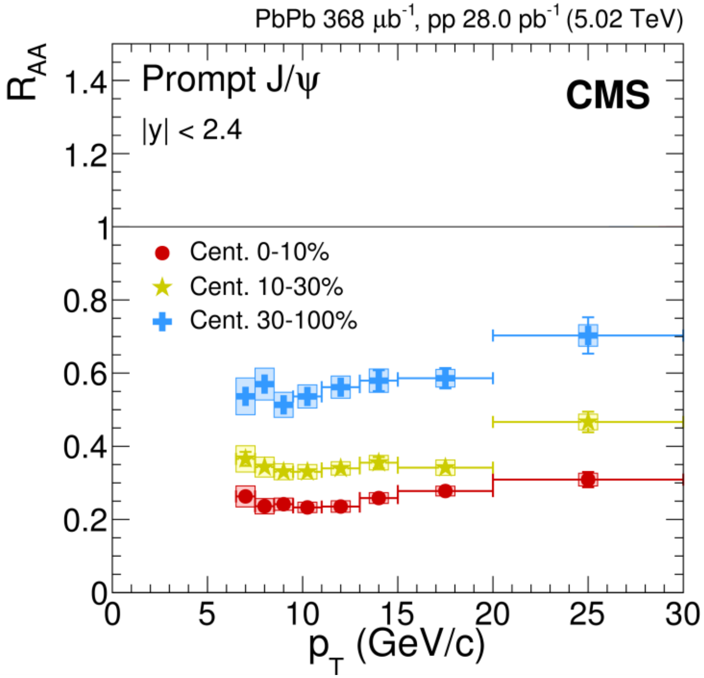


arXiv:1712.08959

arXiv:1708.04962



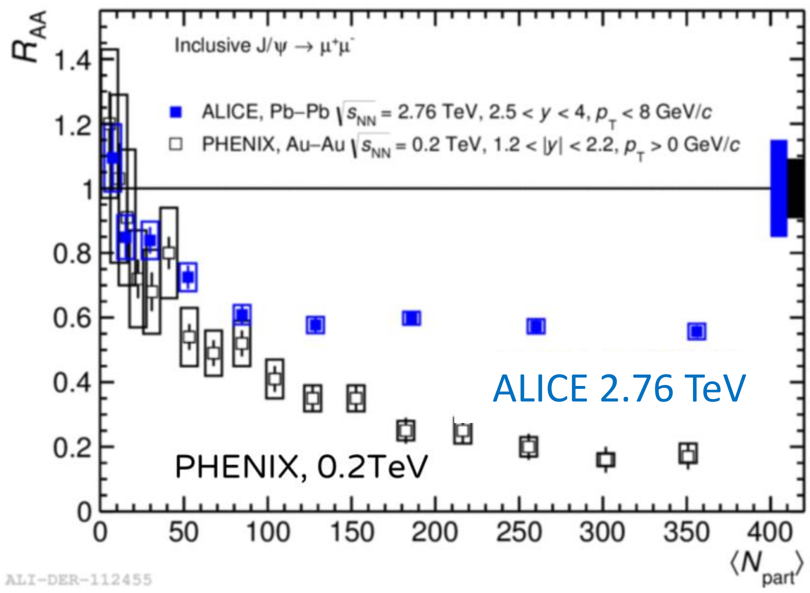
- At high p_T, no strong collision energy dependence

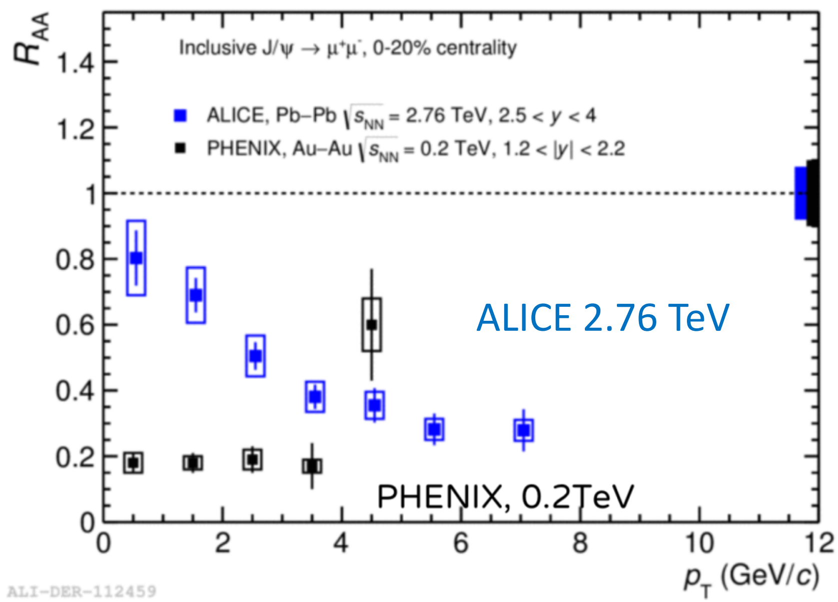
- Decrease suppression at higher p_T
- Similar trend of p_T depending on centrality (increasing trend at high p_T)

- Less suppressed at high p_T : energy loss contribution ?
  - Similar to D meson and charged hadron

ALICE Inclusive J/ψ at 2.76 TeV

JHEP 05 (2016) 179, PLB 734 (2014) 314, PRL 109 (2012) 072301



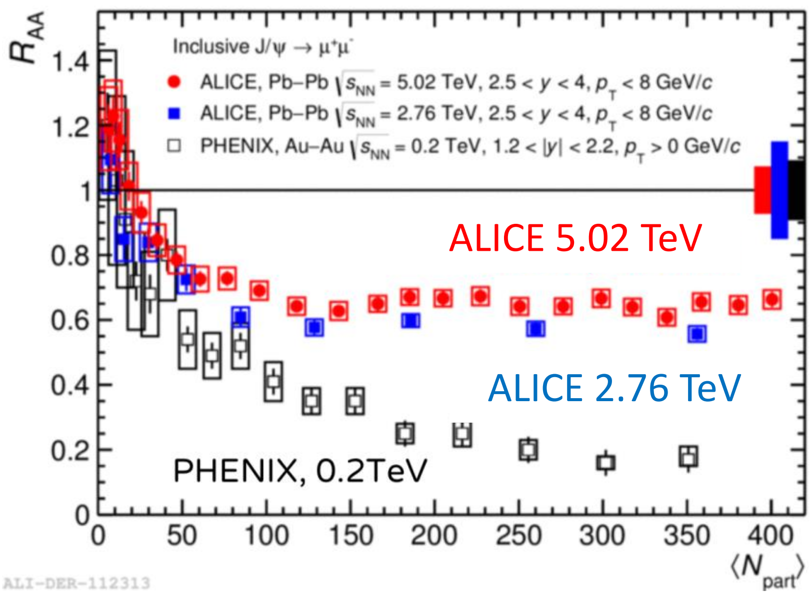


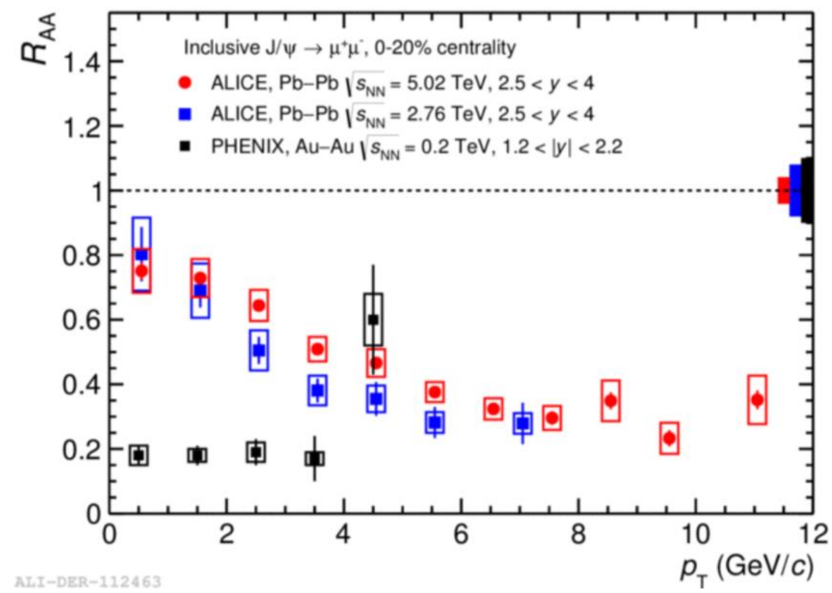
$$R_{AA} = \frac{\text{Yield}_{AA} / \langle N_{Coll} \rangle}{\text{Yield}_{pp}}$$

- Stronger centrality suppression at RHIC than LHC, in spite of larger energy at LHC
  - Hint of statistical regeneration ?
- At low p_T : very different p_T dependence

ALICE Inclusive J/ψ at 5.02 TeV

JHEP 05 (2016) 179, PLB 734 (2014) 314, PRL 109 (2012) 072301





PLB 766 (2017) 212

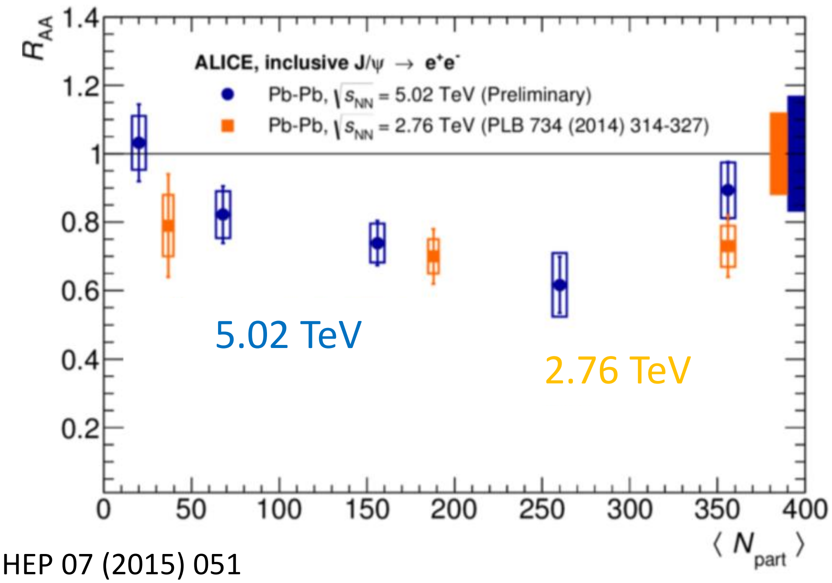
$$R_{AA} = \frac{\mathrm{Yield}_{AA}/\langle N_{Coll}\rangle}{\mathrm{Yield}_{pp}}$$

- Observed similar J/ψ suppression at both of 2.76 TeV and 5.02 TeV
  - Increased precision at 5.02 TeV
- But slightly higher for 5.02 TeV

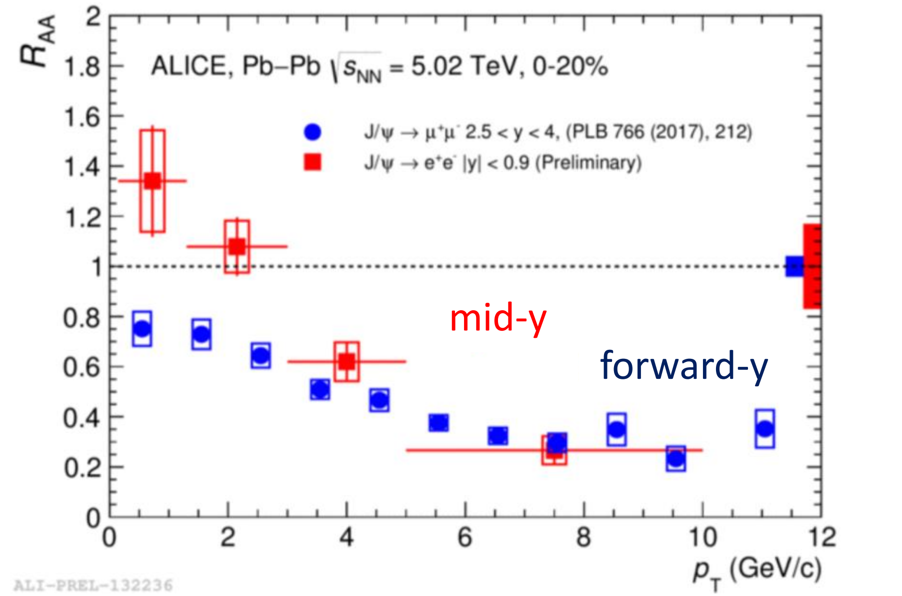
ALICE Inclusive J/ψ at 5.02 TeV

J/ψ to e^+e^- at mid-rapidity

JHEP 05 (2016) 179, PLB 734 (2014) 314, PRL 109 (2012) 072301



JHEP 07 (2015) 051

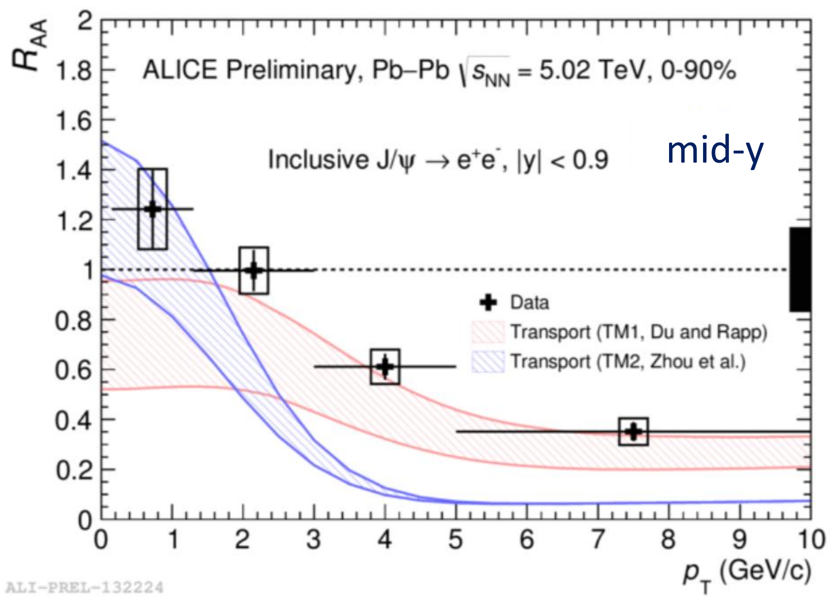


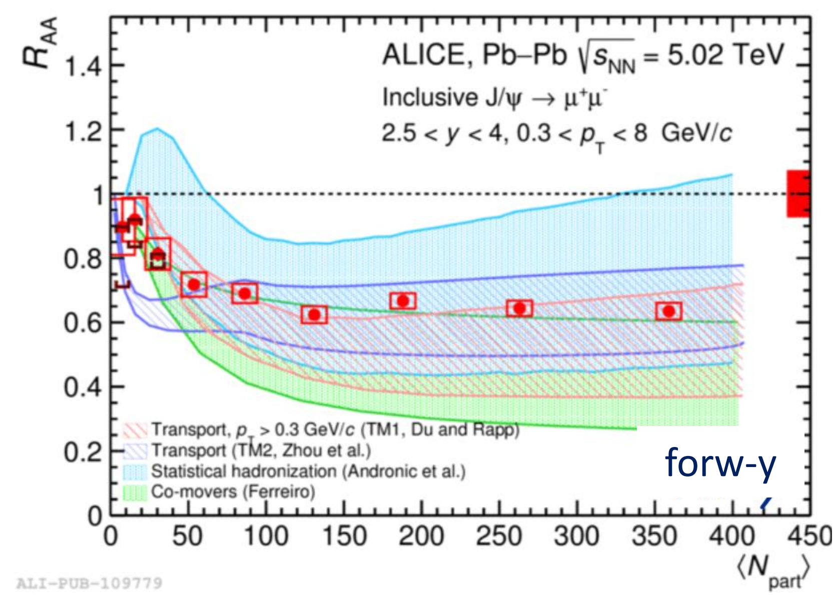
$$R_{AA} = \frac{\text{Yield}_{AA}/\langle N_{Coll}\rangle}{\text{Yield}_{pp}}$$

- No significant collision energy dependence at mid and forward rapidity
  - But hint of stronger regeneration effect on larger collision energy
- Enhanced at low p_T compared to forward rapidity

ALICE Inclusive J/ψ at 5.02 TeV

JHEP 07 (2015) 051





Transport models
Based on thermal rate eq. with continuous J/ψ dissociation and regeneration in QGP and hadronic phase
(NPA 859 (2011) 114, PRC 89 (2011) 05491)

Statistical hadronization
J/ψ produced at chemical freeze-out according to their statistical weight
(NPA 904 (2013) 535)

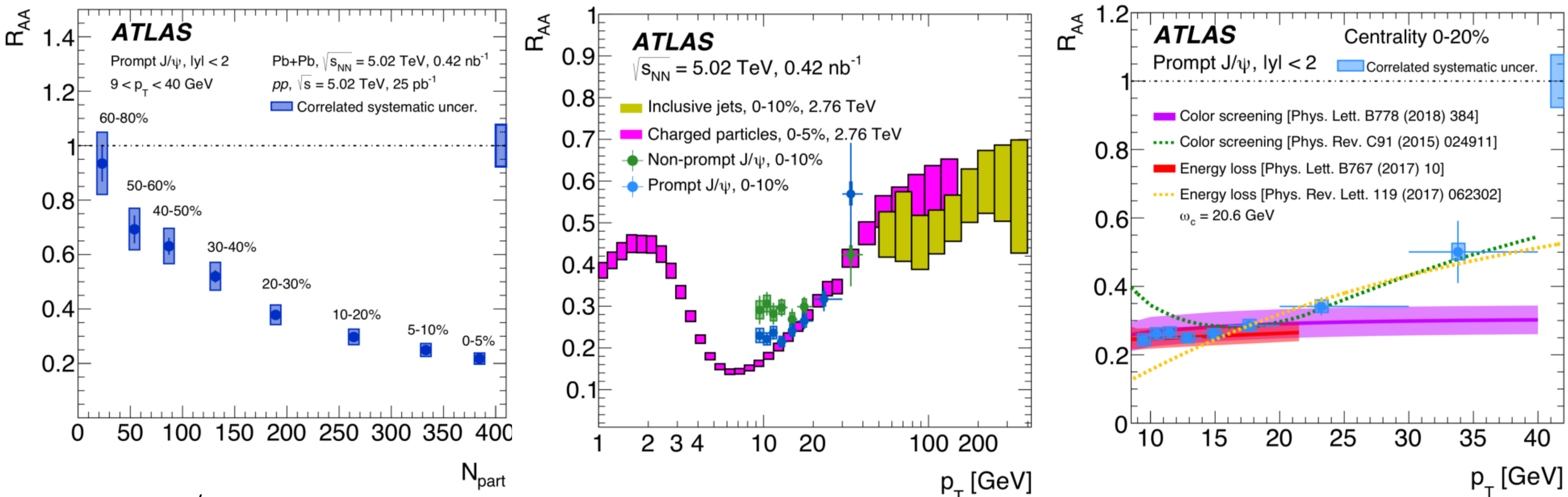
Comover model
J/ψ dissociated via interactions with partons - hadrons + regeneration contribution
(PLB 749 (2015) 98, PLB 731 (2014) 57)

- **All models fairly describe the data, as already in Run 1**
- **But large uncertainties associated**

QWG2017, Roberta Arnaldi's slide

ATLAS Prompt J/ψ R_{AA}

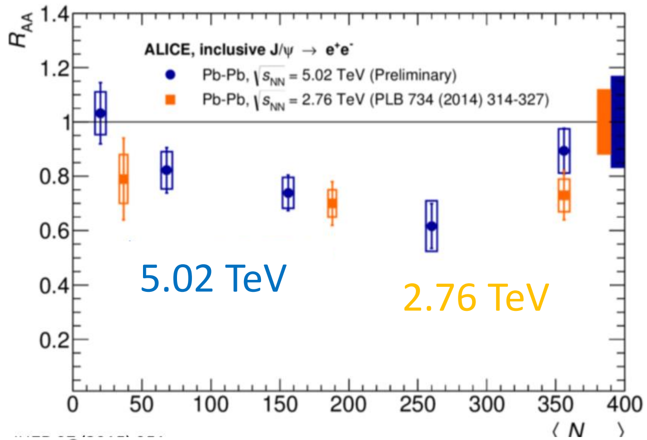
arXiv:1805.04077

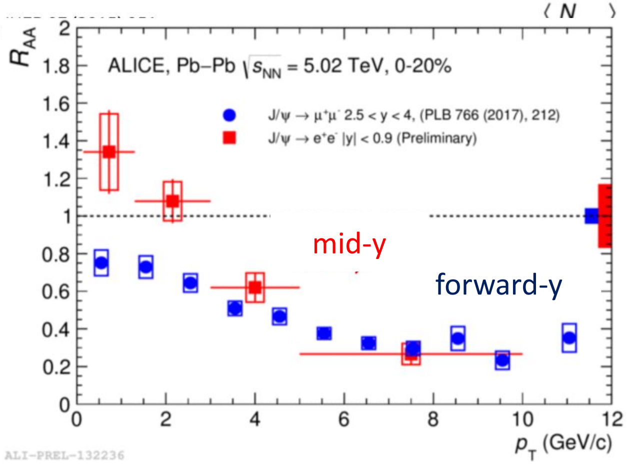


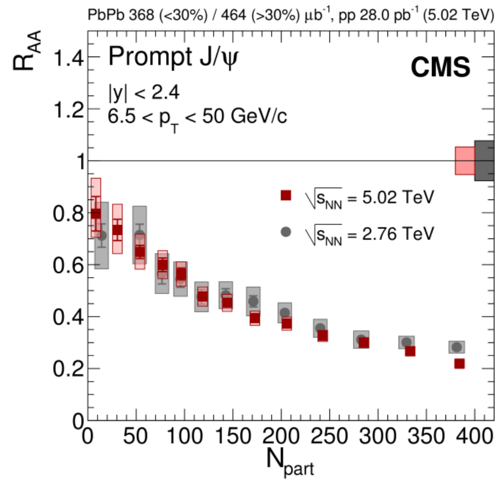
$$R_{AA} = \frac{\mathrm{Yield}_{AA}/\langle N_{Coll}\rangle}{\mathrm{Yield}_{pp}}$$

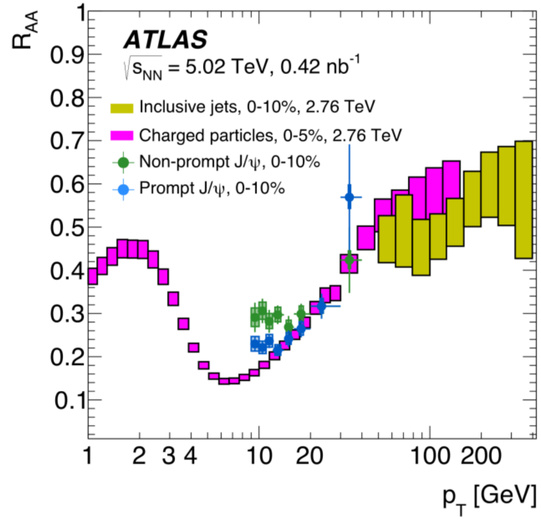
- Strong centrality dependence
- Suggestion of high p_T universality from the charged hadrons and jets
- Data is well described by different models : color screening vs energy loss scenarios

Brief Summary of J/ψ R_{AA}





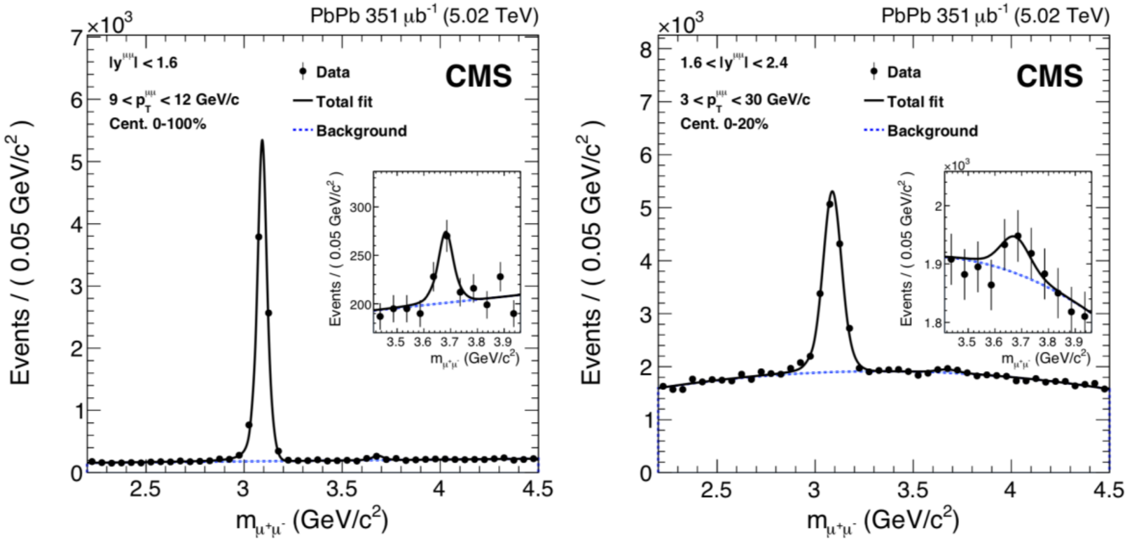




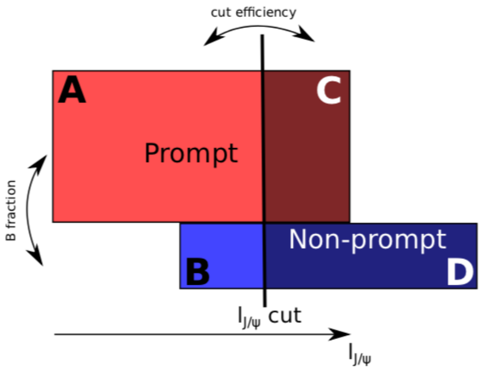
- Strong centrality dependence of suppression
- But no big difference between 2.76 TeV and 5.02 TeV
- At low p_T : regeneration effect would be more dominant
- At high p_T : energy loss would be more dominant effect than color screening

CMS Prompt Charmonia

PRL 0118 (2017) no.16, 162301



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

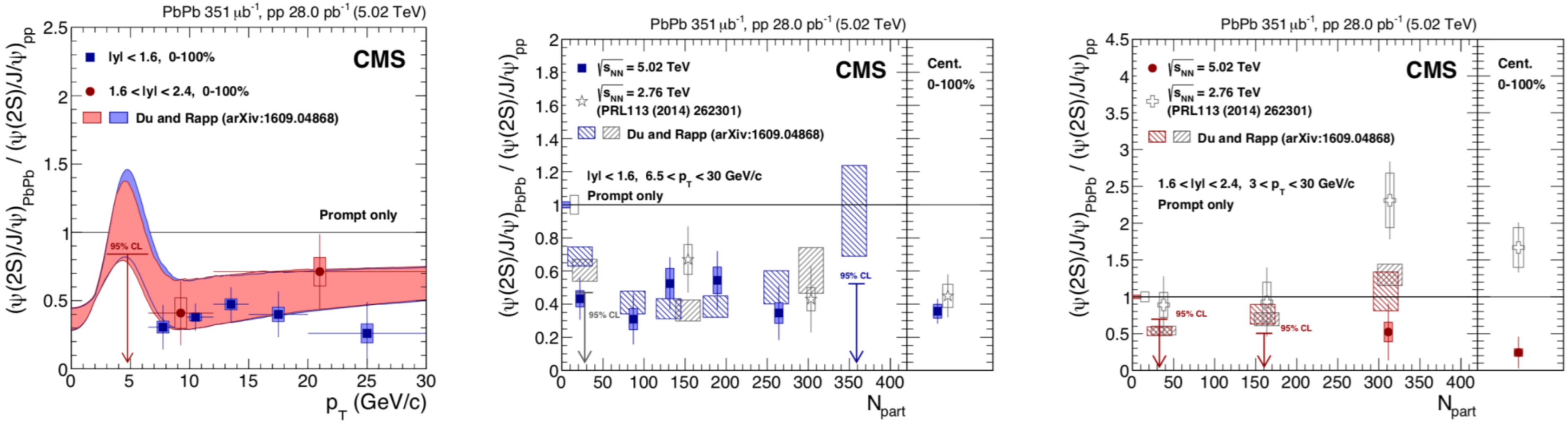


Simultaneous two dimensional fit method

- 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

CMS Prompt Charmonia

PRL 0118 (2017) no.16, 162301



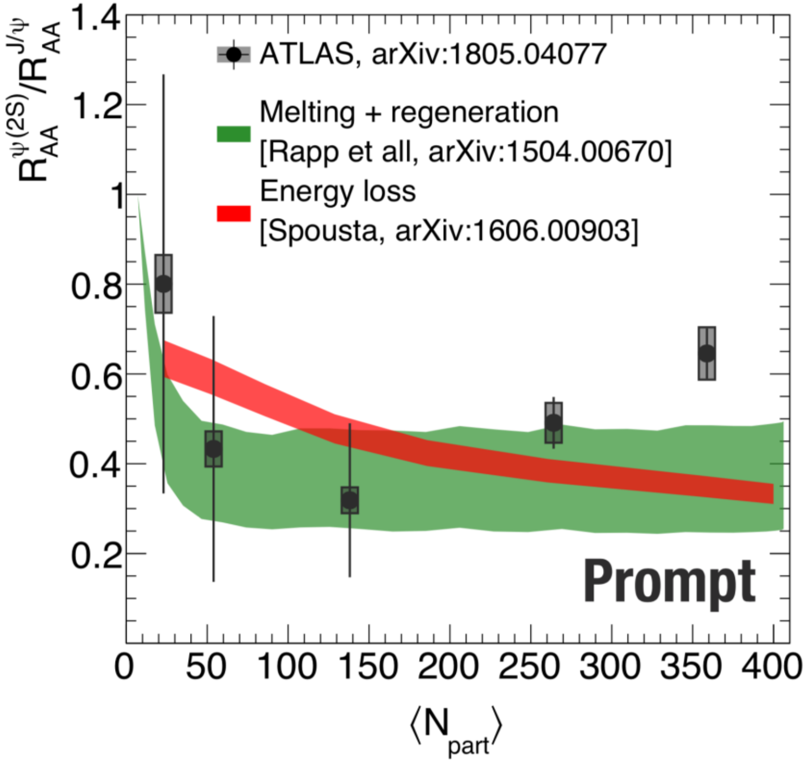
$$\text{Double Ratio (DR)} = \frac{[\psi(2S)/J/\psi]_{PbPb}}{[\psi(2S)/J/\psi]_{pp}} = \frac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}$$

- 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

ATLAS Prompt Charmonia

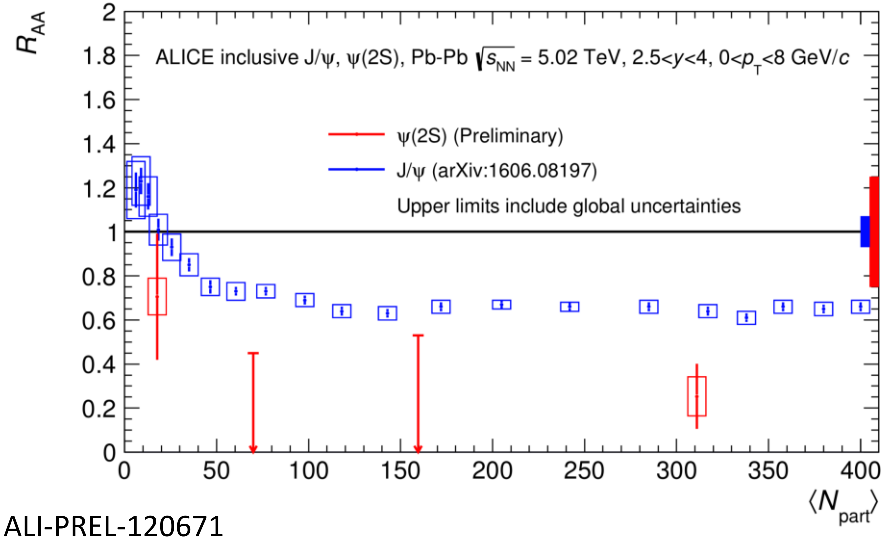
arXiv:1805.04077

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

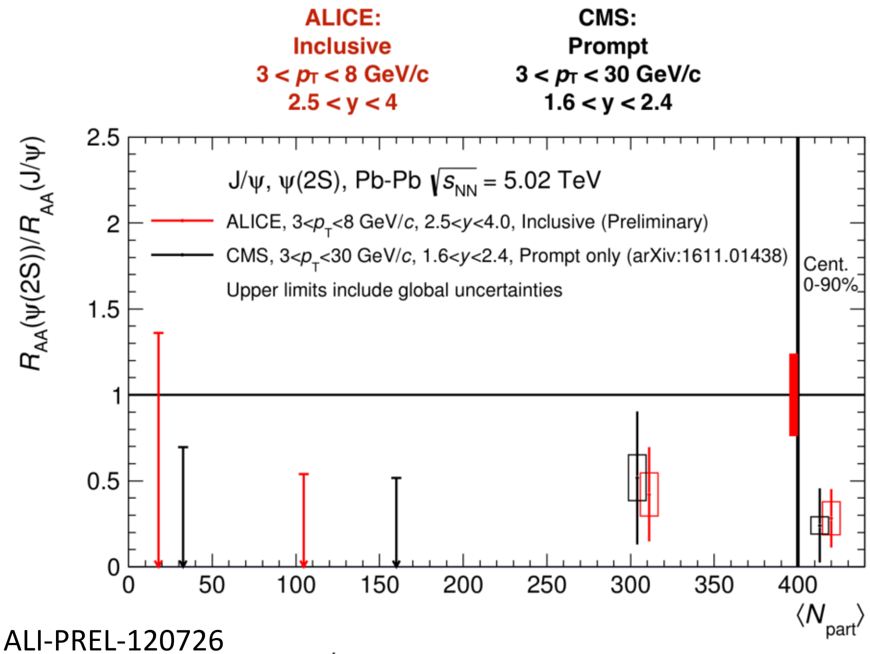


- DR is under unity : strong suppression of ψ(2S) with respect to J/ψ (sequential melting)
- Slightly increasing trend along increasing centrality
- Superimposing model results – data is well described under different scenarios
  - Sequential Melting + Color Regeneration
  - Energy loss
  - Tension in most central events

ALICE Inclusive Charmonia



ALI-PREL-120671



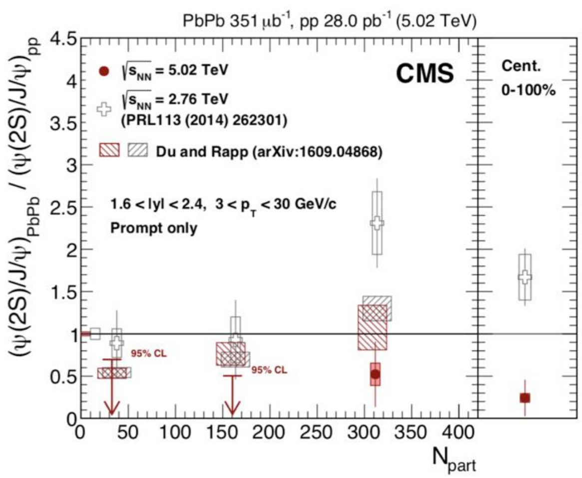
ALI-PREL-120726

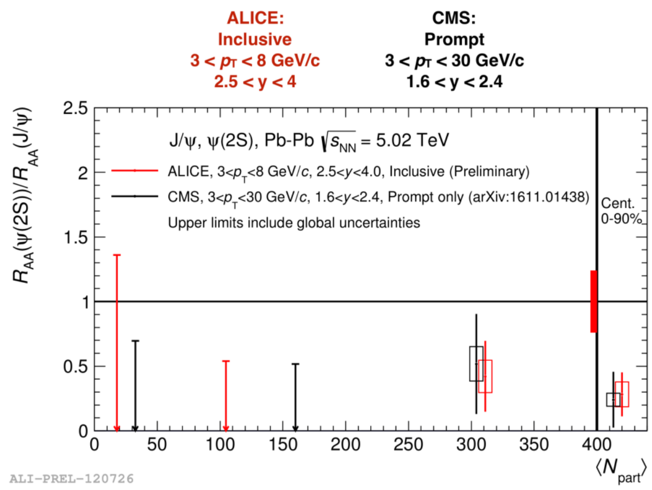
$$R_{AA} = \frac{\mathrm{Yield}_{AA}/\langle N_{Coll}\rangle}{\mathrm{Yield}_{pp}}$$

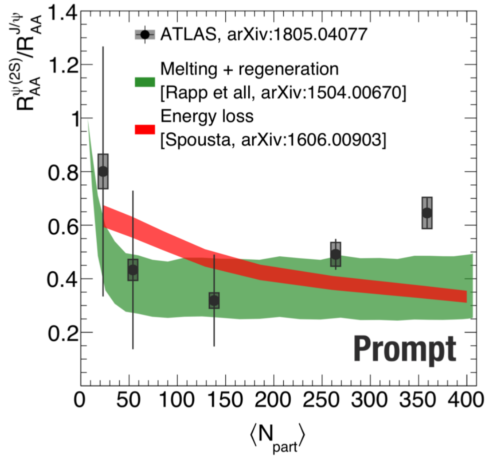
Double Ratio (DR) = $\dfrac{[\psi(2S)/J/\psi]_{PbPb}}{[\psi(2S)/J/\psi]_{pp}} = \dfrac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}$

- ψ(2S) more suppressed than J/ψ in semi-central and central collisions
- Results at 5.02 TeV compatible with those at 2.76 TeV
- Good agreement also with CMS results at 5.02 TeV

Brief Summary of ψ(2S)

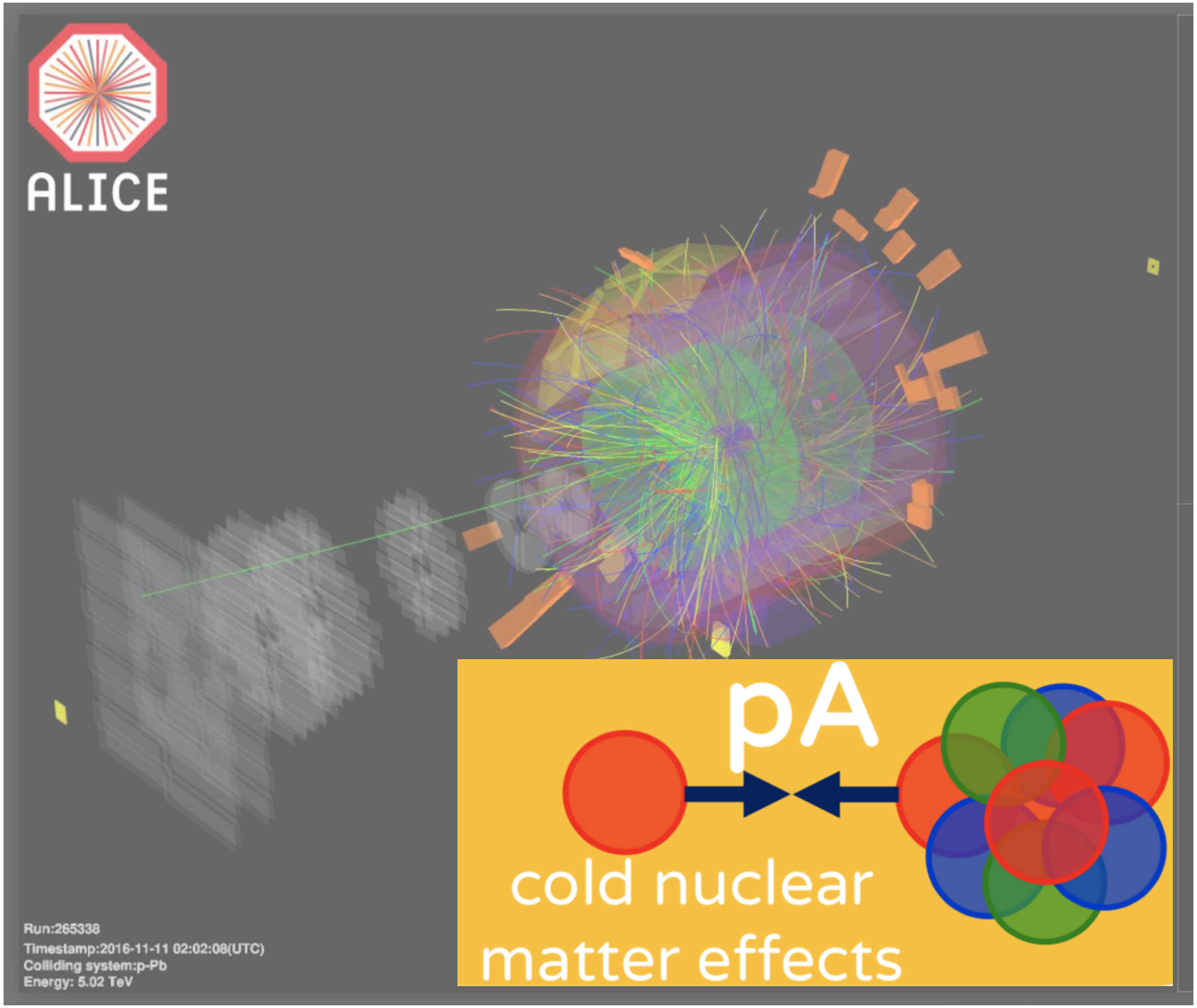






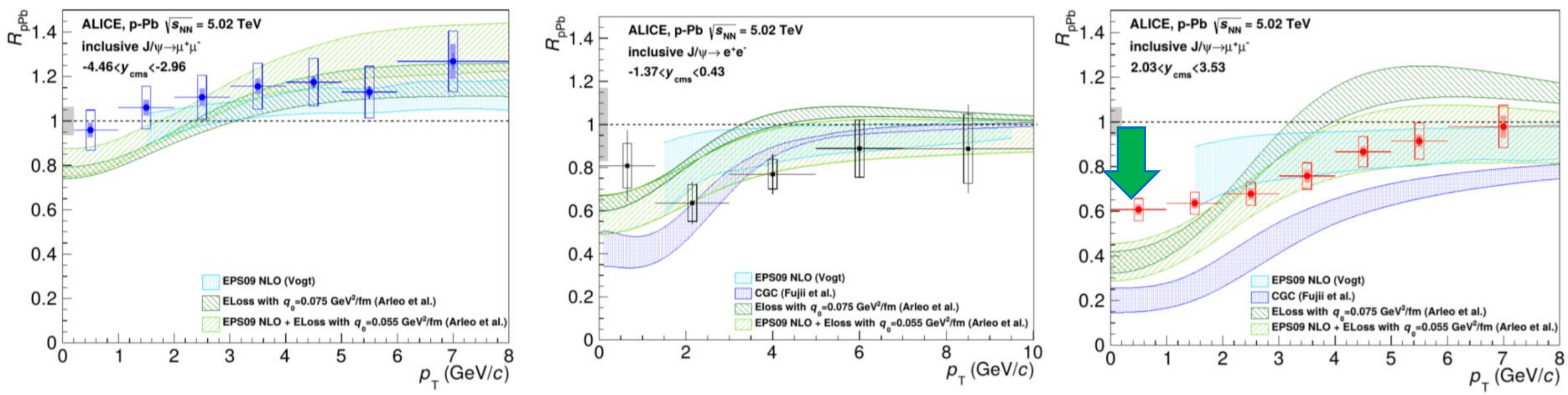
- ψ(2S) more suppressed than J/ψ as expected (sequential melting)
- Results at 5.02 TeV compatible with those at 2.76 TeV for ALICE
- Hint for a different behavior with energy for CMS (enhancement of low p_T disappeared at 5.02 TeV)
- Increasing trend along increasing centrality at 5.02 TeV in ATLAS

Charmonia in pPb



ALICE J/ψ in pPb

Backward   Forward



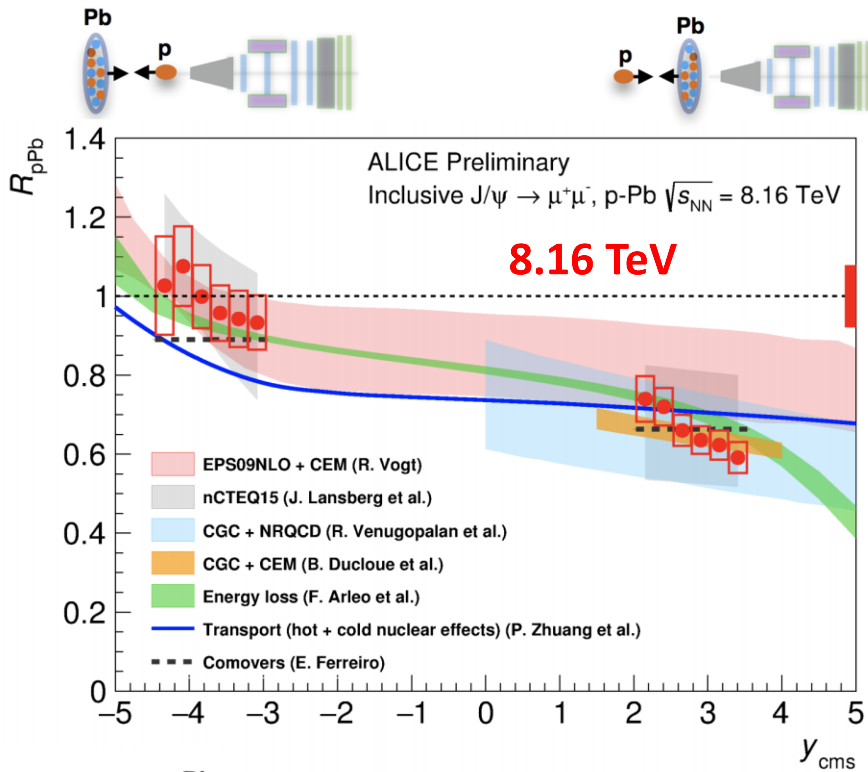
arXiv:1308.6726, arXiv:1506.07179, arXiv:1506.08808

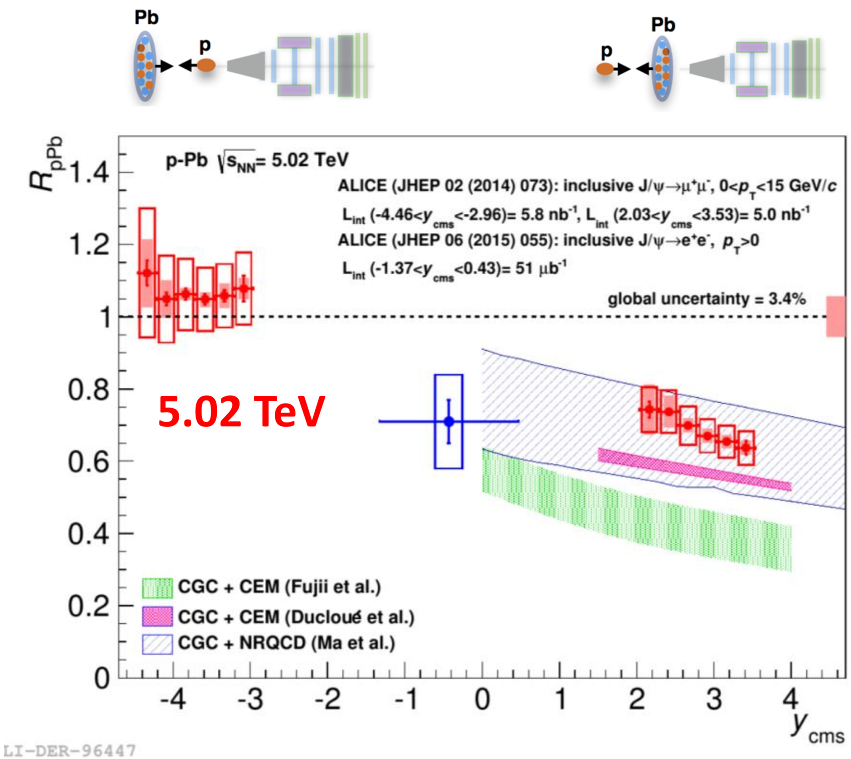
$$R_{\rm pPb} = \frac{1}{208}\frac{\sigma^{p+{\rm Pb}}}{\sigma^{pp}}$$

- 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

ALICE J/ψ in pPb

ALICE-PUBLIC-2017-001



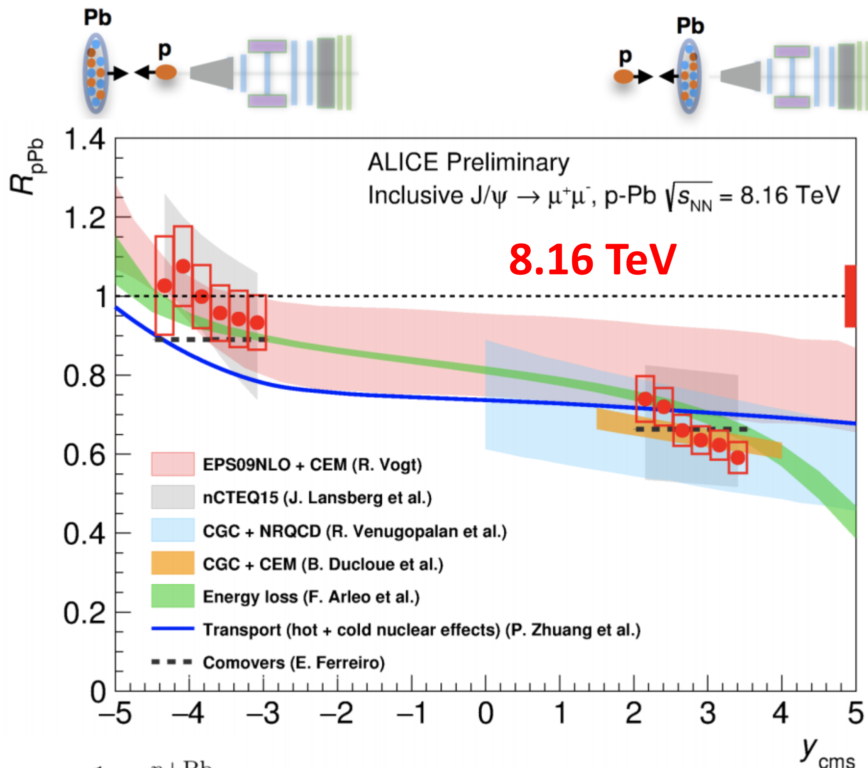


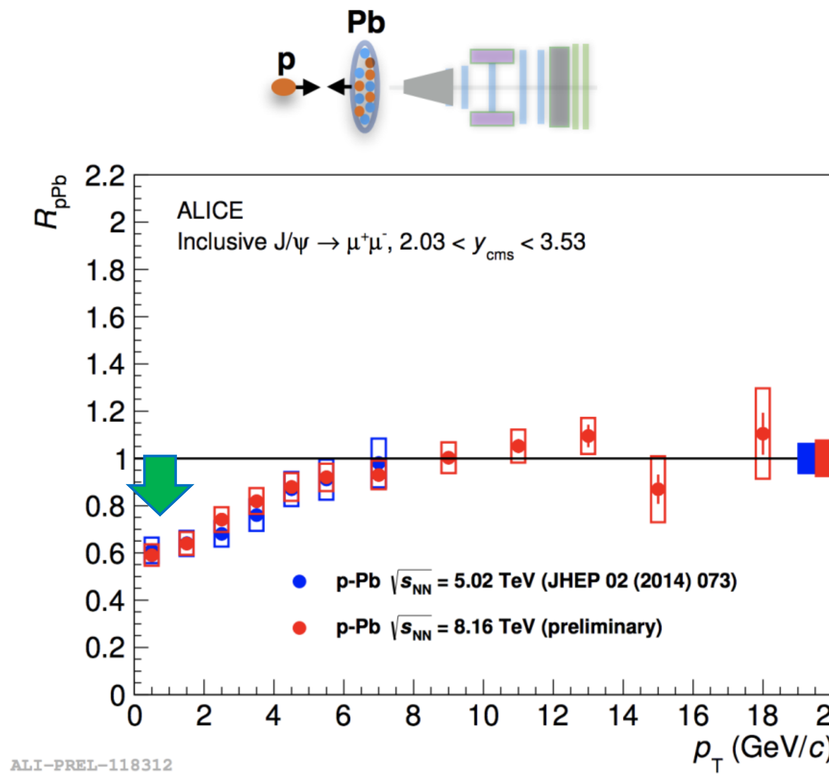
$$R_{\mathrm{pPb}} = \frac{1}{208}\frac{\sigma^{p+\mathrm{Pb}}}{\sigma^{pp}}$$

- Clear suppression at forward rapidity in both energies
- Different models (Shadowing, energy loss, CSC) can describe data well

ALICE J/ψ in pPb

ALICE-PUBLIC-2017-001



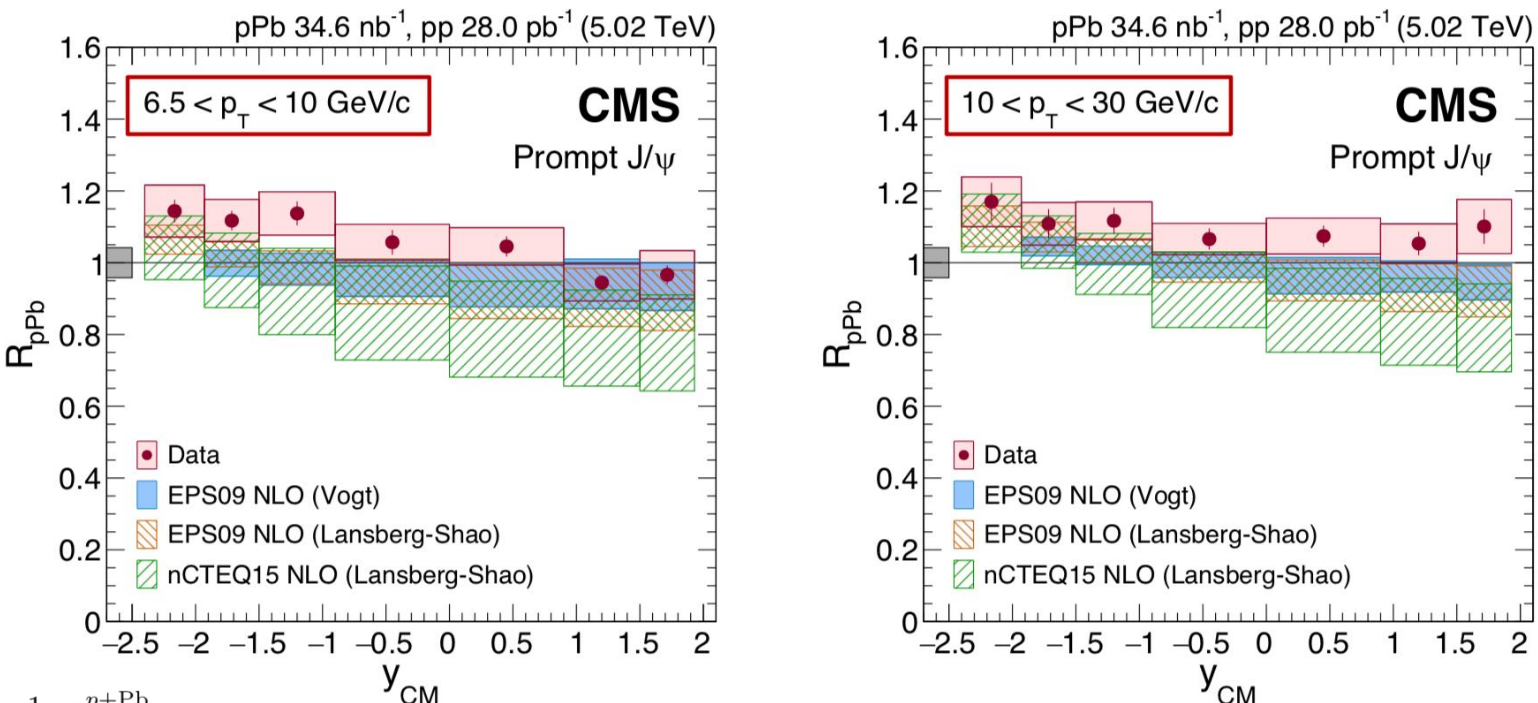


$$R_{\rm pPb} = \frac{1}{208}\frac{\sigma^{p+\rm Pb}}{\sigma^{pp}}$$

- Clear suppression at forward rapidity
- Different models (Shadowing, energy loss, CSC) can describe data well
- No energy dependence at all bins

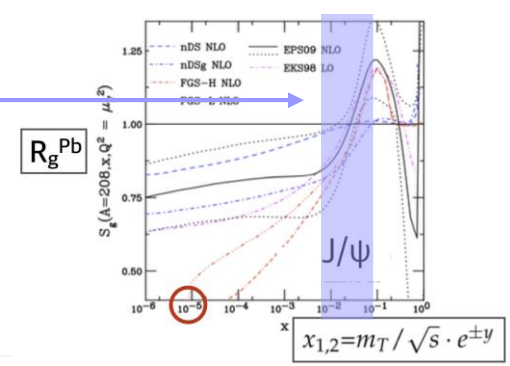
CMS Prompt J/ψ in pPb

EPJC 77 (2017) 269



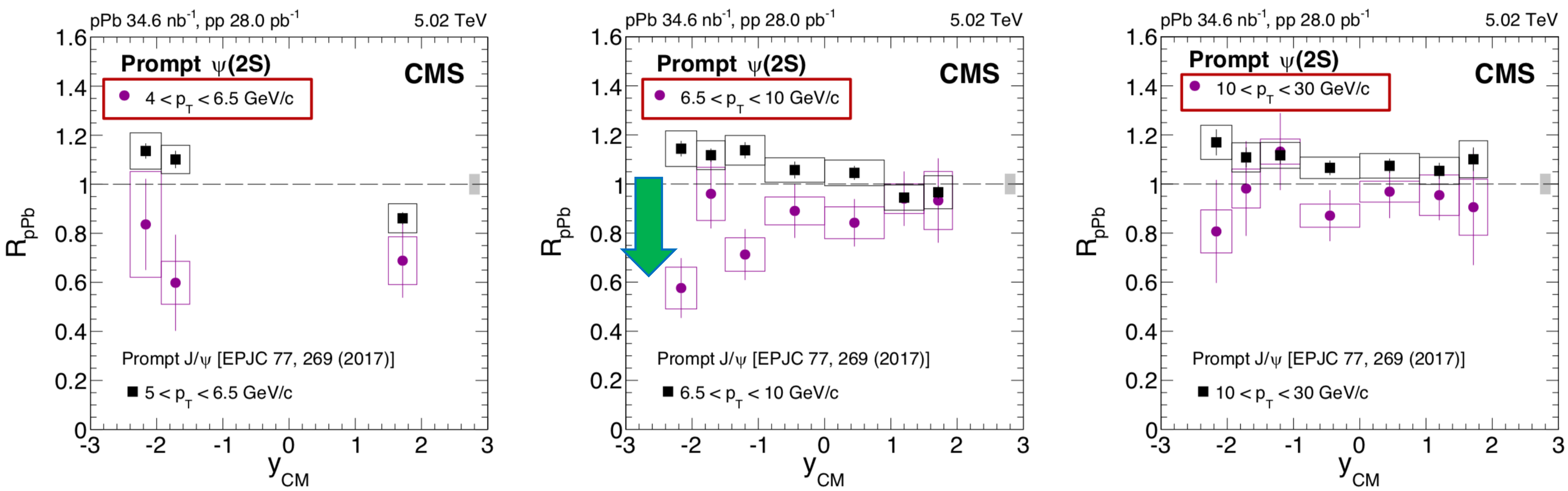
$$R_{\mathrm{pPb}} = \frac{1}{208}\frac{\sigma^{p+\mathrm{Pb}}}{\sigma^{pp}}$$

- 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



CMS Prompt ψ(2S) in pPb

arXiv:1805.0248

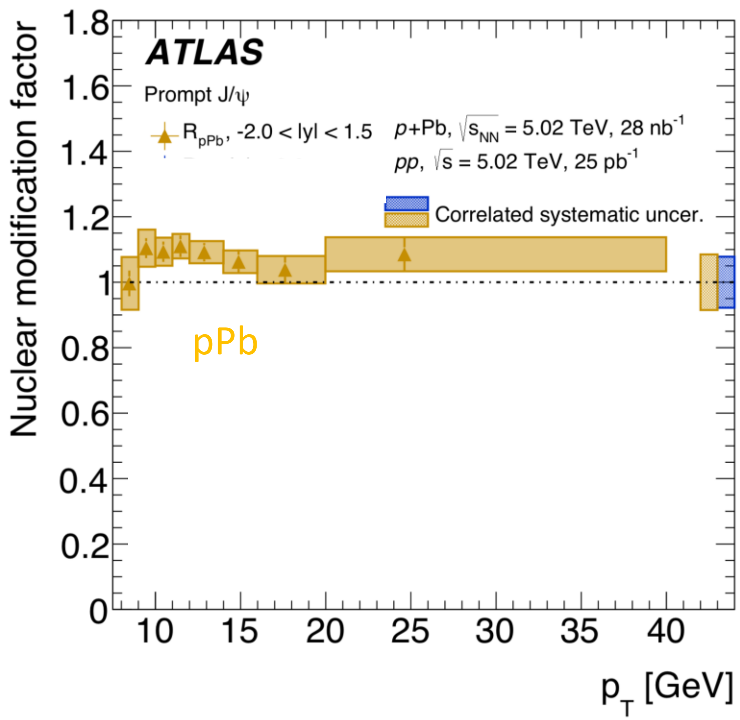


$$R_{\mathrm{pPb}} = \frac{1}{208} \frac{\sigma^{p+\mathrm{Pb}}}{\sigma^{pp}}$$

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

ATLAS Prompt J/ψ in pPb

arXiv:1709.03089

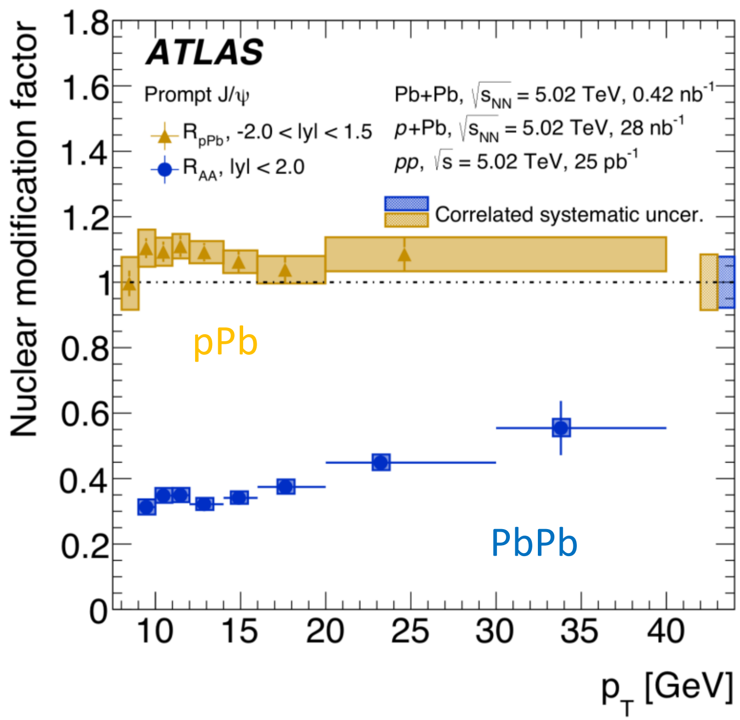


$$R_{\text{pPb}} = \frac{1}{208}\frac{\sigma^{p+\text{Pb}}}{\sigma^{pp}}$$

- No strong modification in pPb ($p_T > 8$ GeV/c) but above unity in most bins

ATLAS Prompt J/ψ in pPb

arXiv:1709.03089

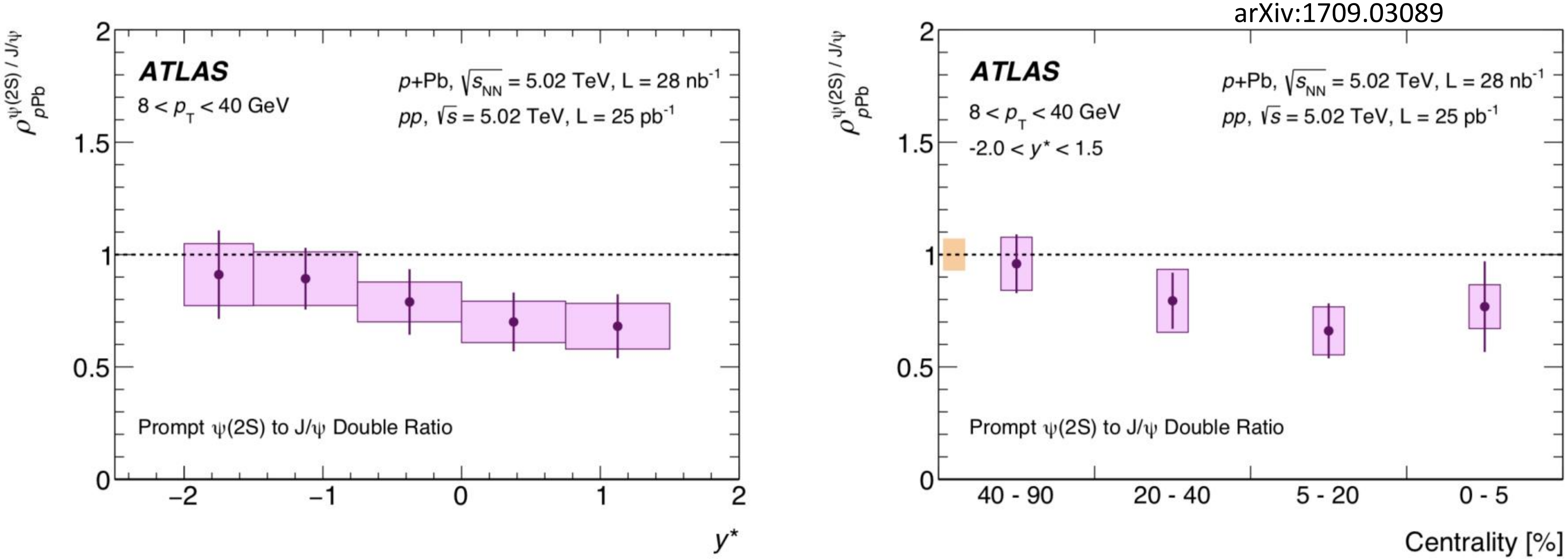


$$R_{\mathrm{pPb}} = \frac{1}{208}\frac{\sigma^{p+\mathrm{Pb}}}{\sigma^{pp}}$$

- No strong modification in pPb (p_T > 8 GeV/c) but above unity in most bins
- Can conclude strong suppression in PbPb dominated by QGP effect

ATLAS Prompt ψ(2S) in pPb

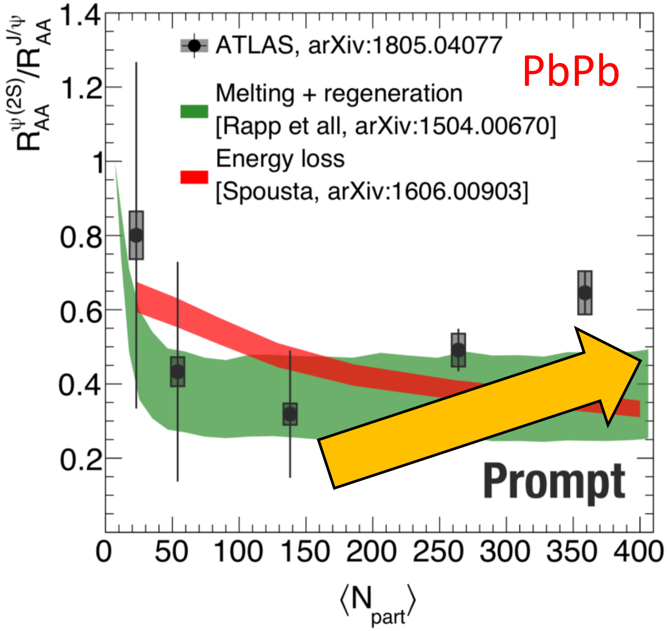
arXiv:1709.03089



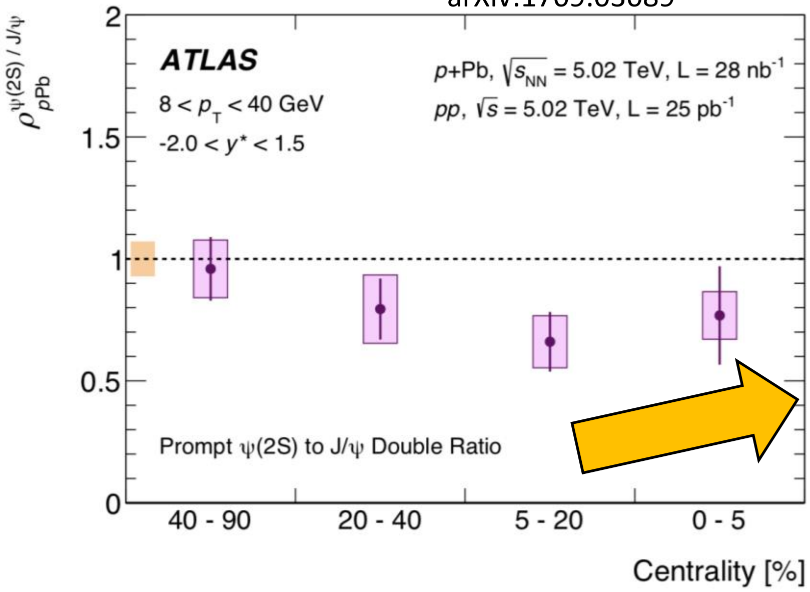
Double Ratio (DR) = $\frac{[\psi(2S)/J/\psi]_{PbPb}}{[\psi(2S)/J/\psi]_{pp}} = \frac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}$

- 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)

ATLAS Prompt ψ(2S) in pPb



arXiv:1709.03089

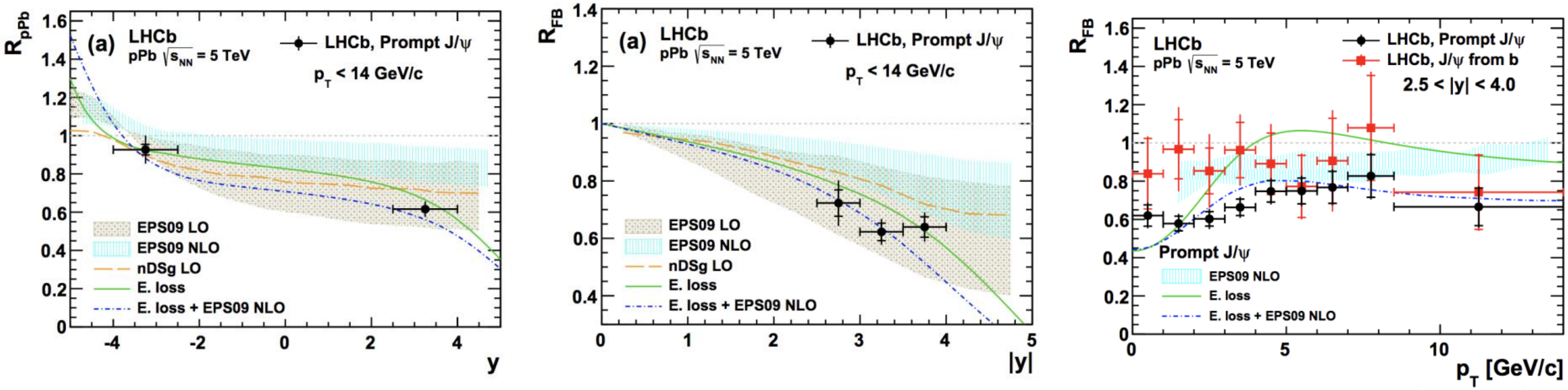


- ψ(2S) is more suppressed than J/ψ (maybe same reason with CMS?)
- Slightly more suppression at forward rapidity and in more central events
- But still big error bar (need more statistics)
- Similar increasing trend in more central events at both of PbPb and pPb (is this effect from CNM ? not from QGP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

LHCb Prompt J/ψ in pPb

$$R_{\mathrm{FB}}(p_{\mathrm{T}}, y) = \frac{d^2\sigma(p_{\mathrm{T}}, +y)/dp_{\mathrm{T}}dy}{d^2\sigma(p_{\mathrm{T}}, -y)/dp_{\mathrm{T}}dy}$$

JHEP 02 (2014) 072

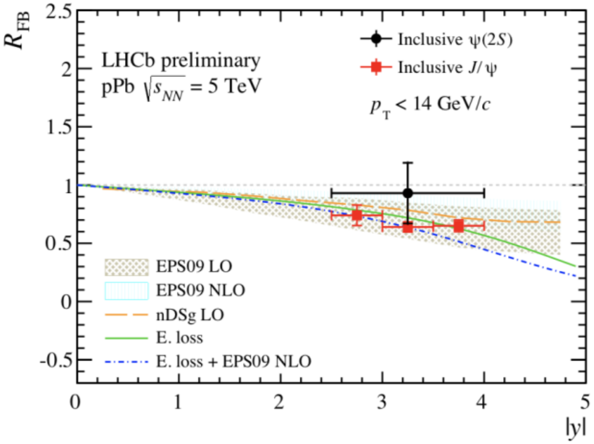


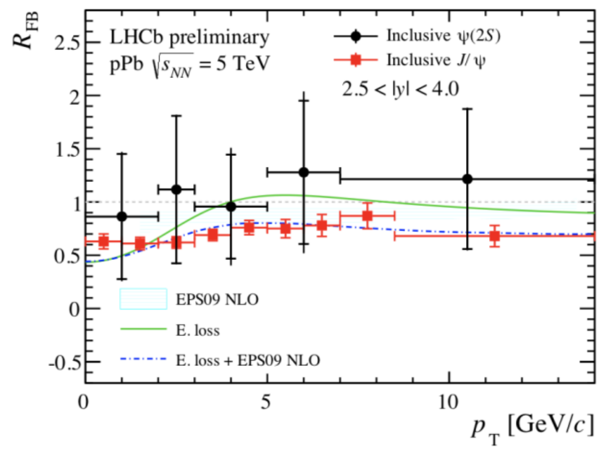
- More suppression at forward rapidity
- Clear p_T dependence : increasing trend (starting from 0.6 of R_{FB})

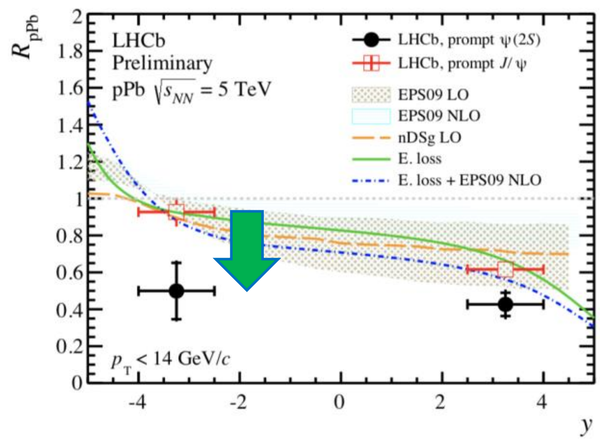
LHCb Prompt ψ(2S) in pPb

$$R_{\mathrm{FB}}(p_{\mathrm{T}}, y) = \frac{d^2\sigma(p_{\mathrm{T}}, +y)/dp_{\mathrm{T}}dy}{d^2\sigma(p_{\mathrm{T}}, -y)/dp_{\mathrm{T}}dy}$$

LHCb-CONF-2015-005





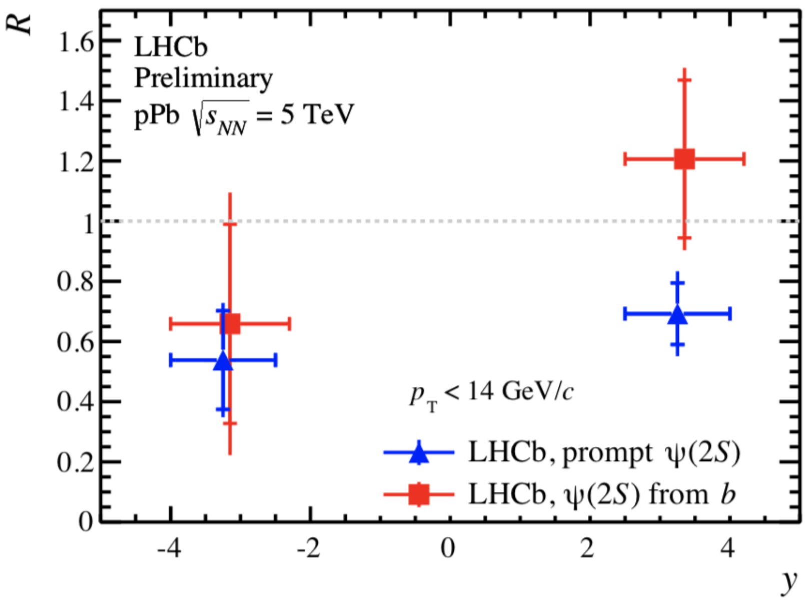


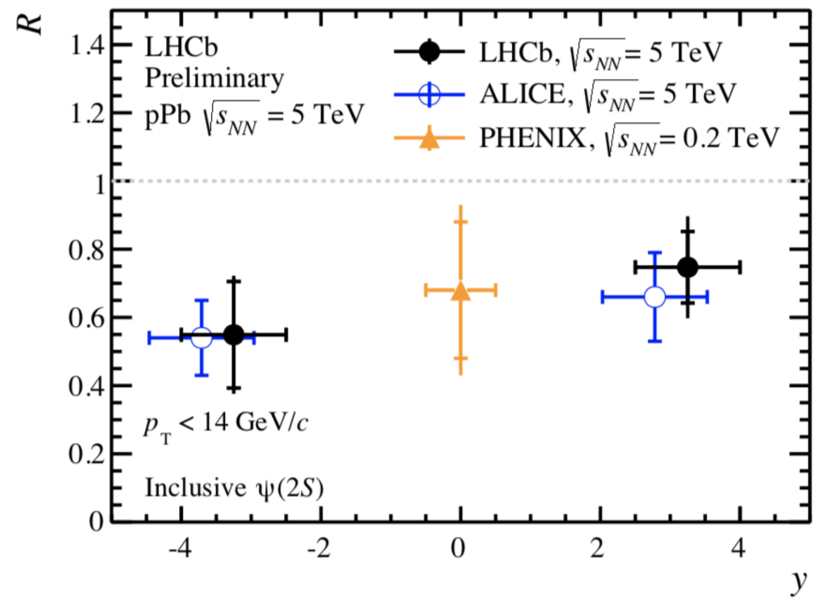
$$R_{\mathrm{pPb}} = \frac{1}{208}\frac{\sigma^{p+\mathrm{Pb}}}{\sigma^{pp}}$$

- R_{FB}
  - No significant suppression and dependence on rapidity and p_T
  - Large error bar (need more data)
- R_{pPb}
  - More suppression than prompt J/ψ
  - Theoretical calculations underestimate prompt ψ(2S) suppression

LHCb Prompt ψ(2S) in pPb

LHCb-CONF-2015-005

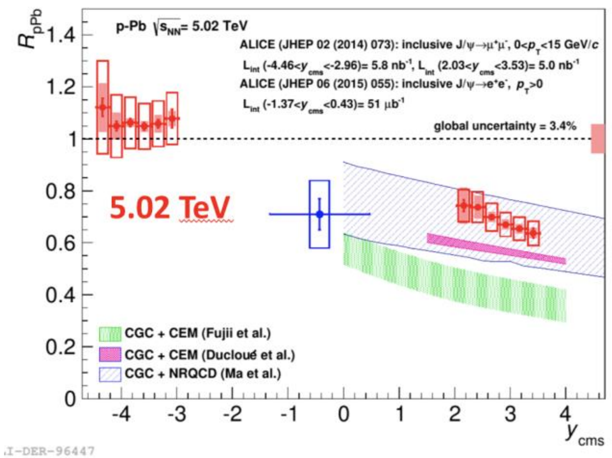


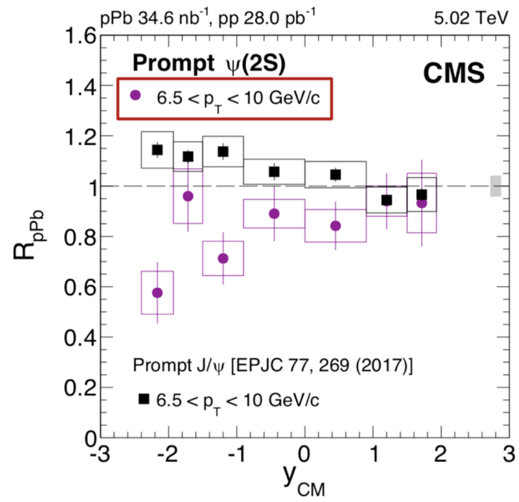


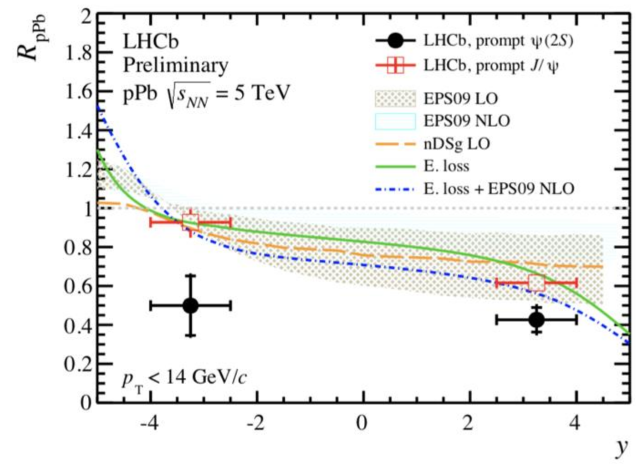
Double Ratio (DR) = $\frac{[\psi(2S)/J/\psi]_{PbPb}}{[\psi(2S)/J/\psi]_{pp}} = \frac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}$

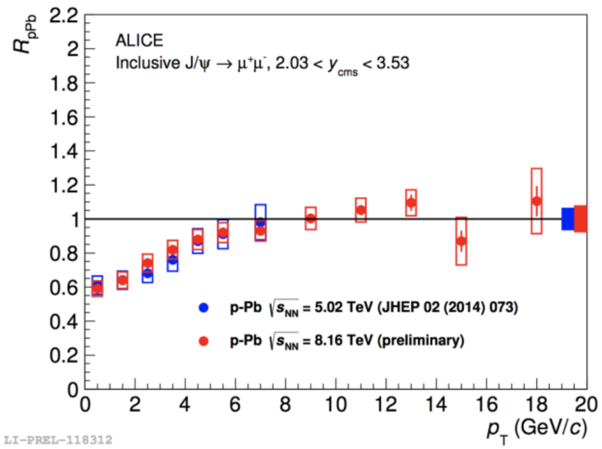
- Double Ratio (R) = R_{AA}(ψ(2S)/R_{AA}(J/ψ)
  - More suppression than J/ψ at all bins of rapidity
  - Consistent with ALICE

Brief Summary of Charmonia in pPb



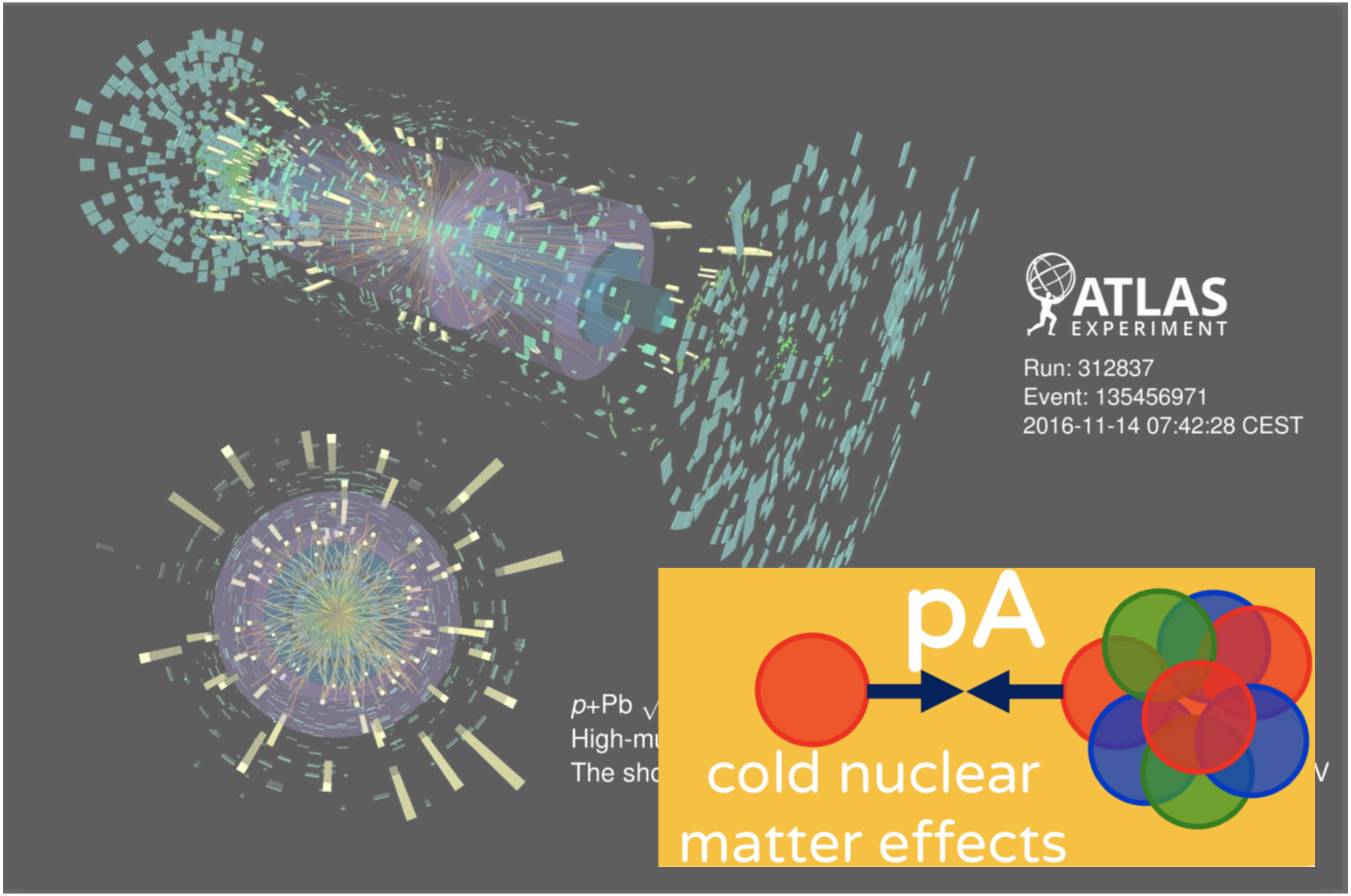




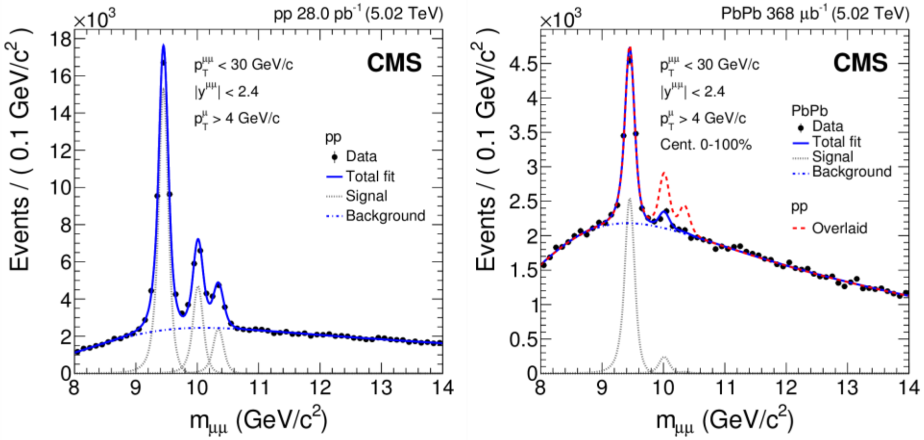


- Common behavior but understandable
  - Charmonia suppression at forward rapidity
  - Specially in low p_T
  - ψ(2S) is more suppressed than J/ψ (less tightly bound state)
- Why ?
  - Backward suppression for ψ(2S) in CMS, LHCb, ALICE : not sure yet

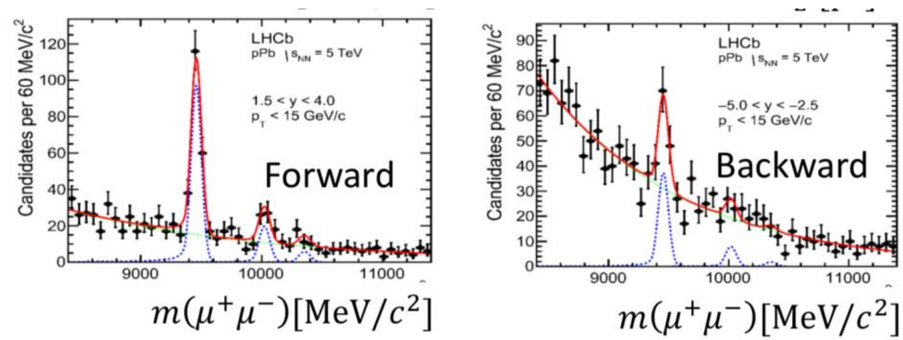
Bottomonia in pPb



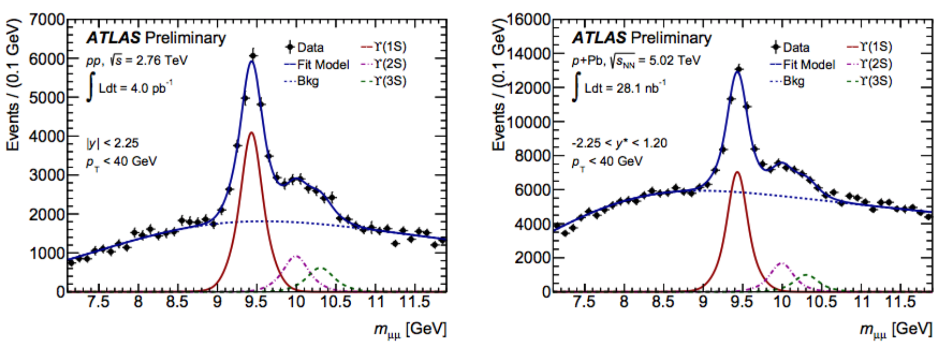
Υ Mass Distributions at LHC



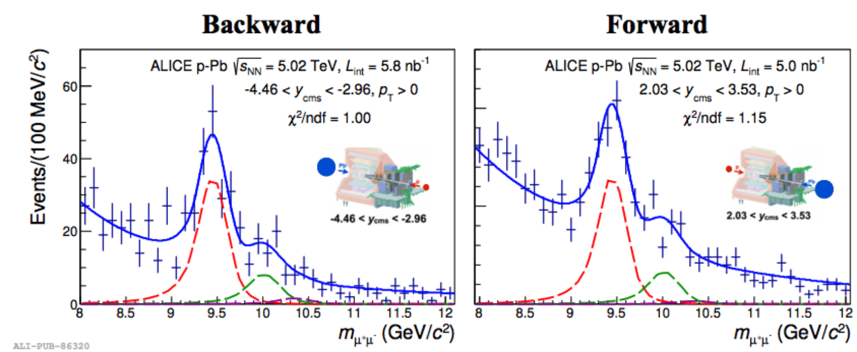
PRL 109 (2012) 222301



JHEP 07 (2014) 094



ATLAS-CONF-2015-050

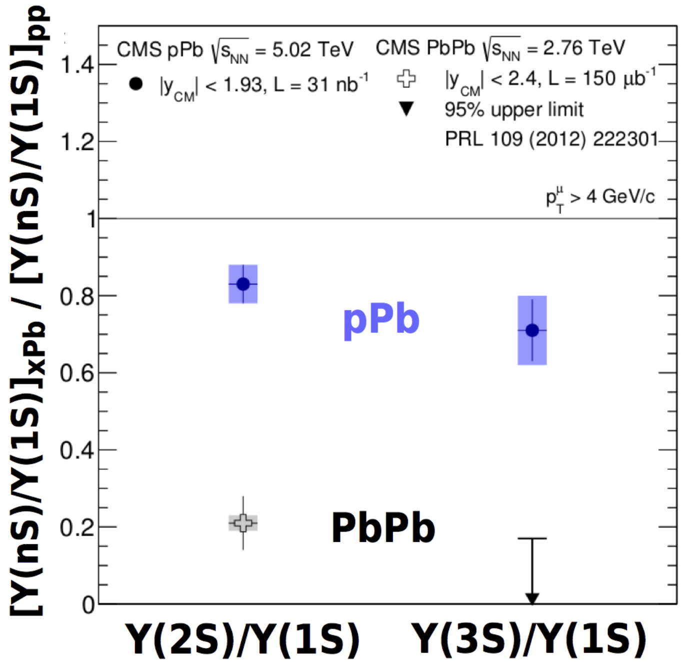


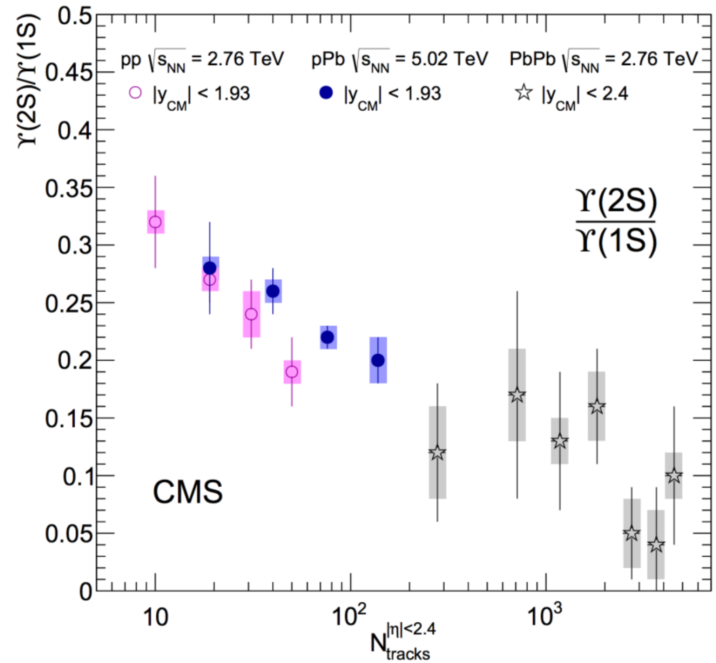
PLB 740 (2015) 105

CMS Υ(nS) in pPb

$$DR = \frac{R_{pPb}(\Upsilon(nS))}{R_{pPb}(\Upsilon(1S))}$$

PRL 109 (2012) 222301

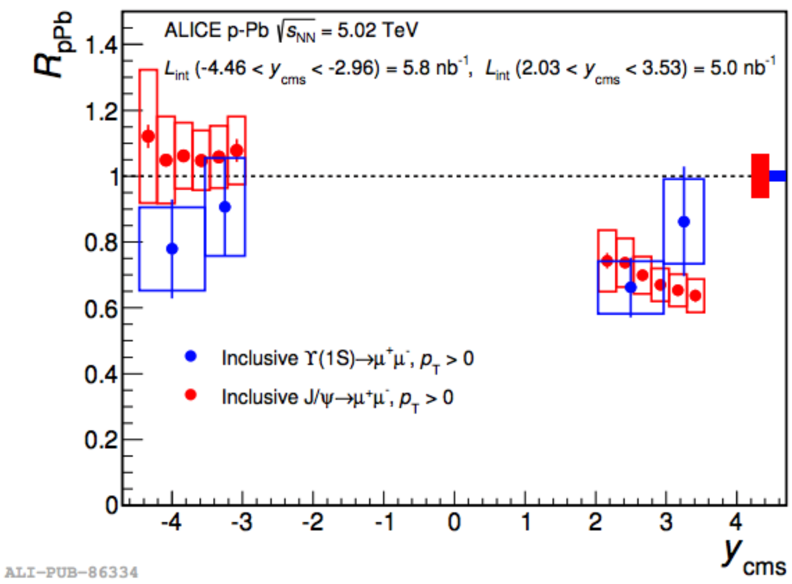


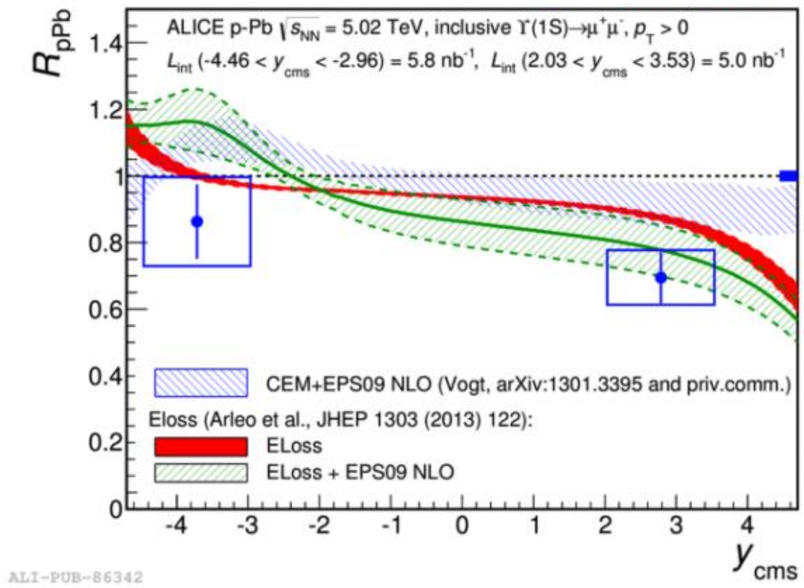


- Indication of initial suppression in pPb
- Y(nS)/Y(1S) has clear dependence on N^{trks} for pp & pPb & PbPb

ALICE Υ in pPb

PLB 740 (2015) 105

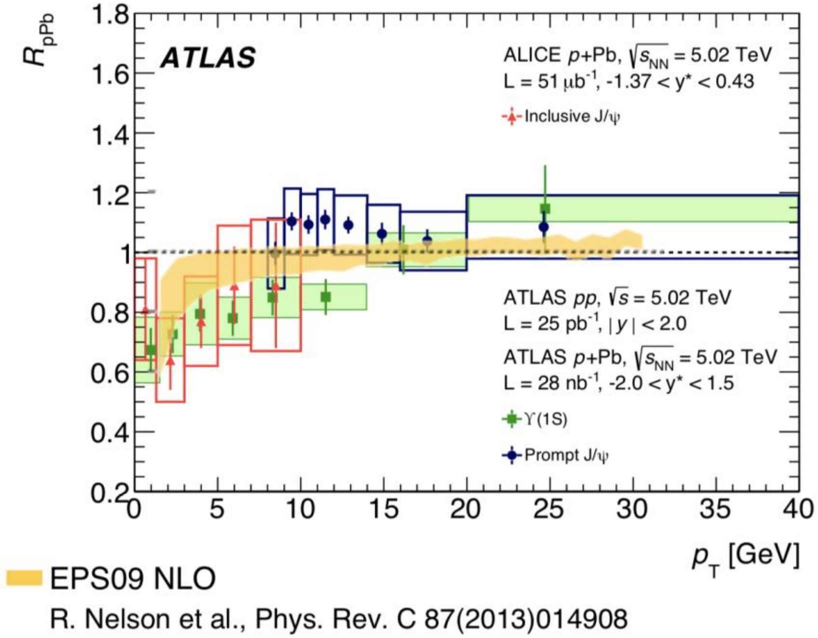


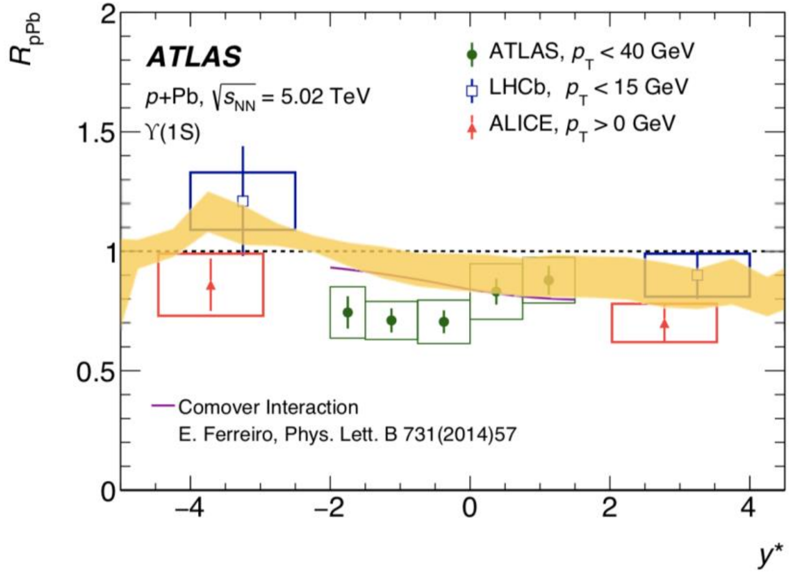


- Consistent with no suppression at backward rapidity
- Indication of suppression at forward rapidity, similar to J/ψ one

Υ in ATLAS

arXiv:1709.03089, JHEP 02 (2014) 972, JHEP 06 (2015) 055, JHEP 02 (2014) 073

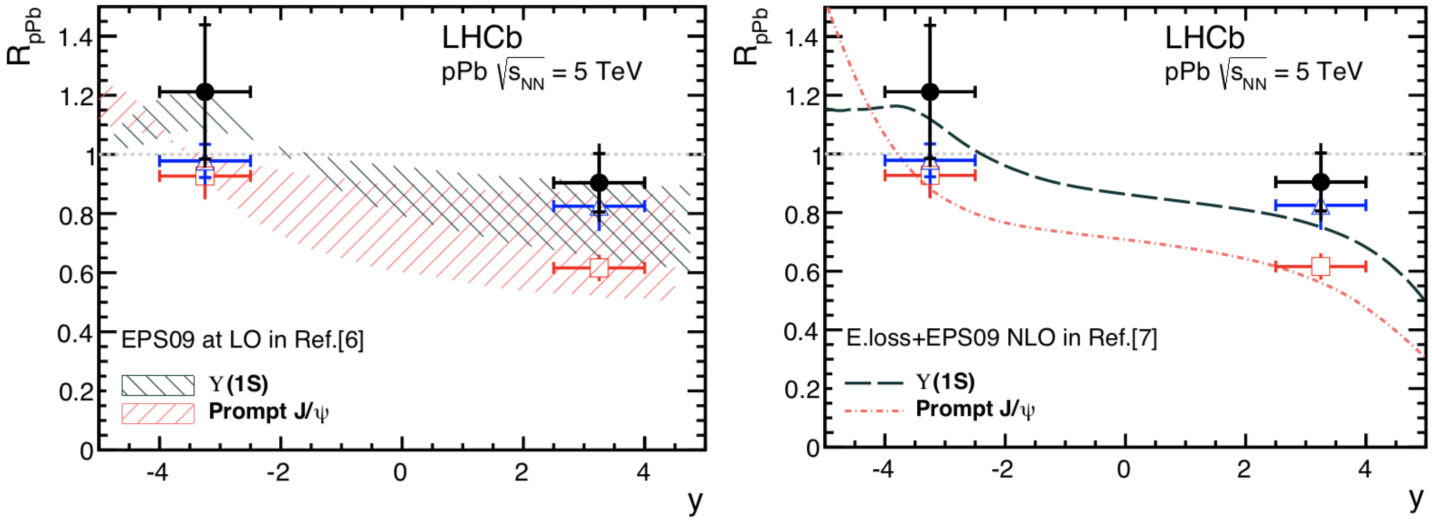




- Υ(1S) is found to be suppressed at low p_T
- Difference between Υ(1S) and J/ψ R_{pPb} in 10 < p_T < 15 GeV/c
- Co-mover interaction and EPS09 give a rough interpretation of the observables

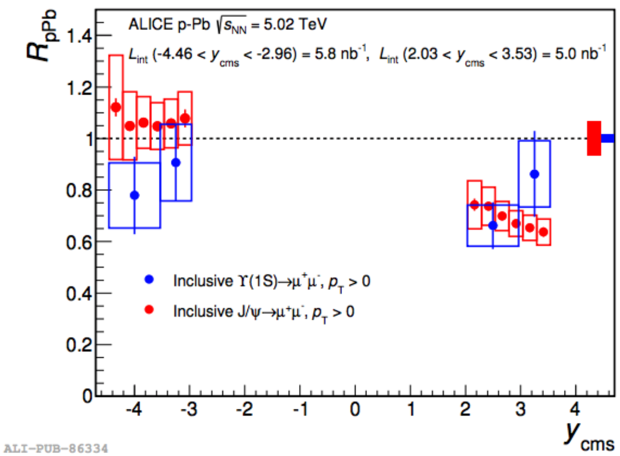
LHCb Υ in pPb

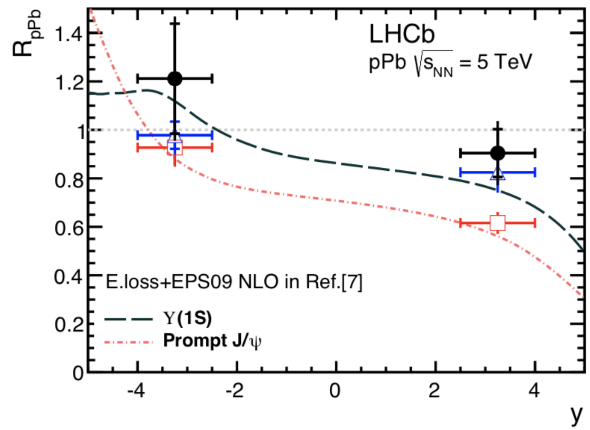
JHEP 07 (2014) 094

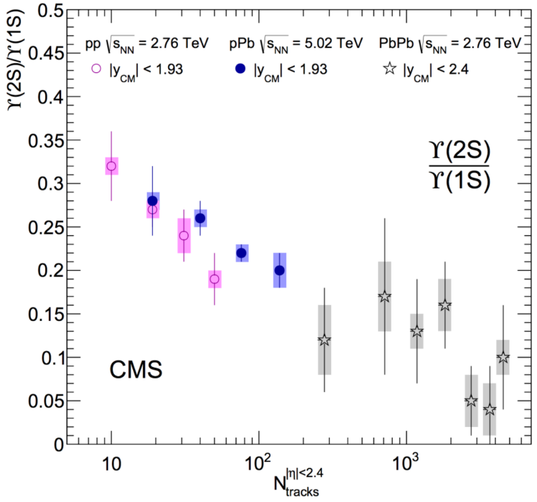


- More suppression at forward rapidity as expected
- Models (shadowing, energy loss) reproduce data well within uncertainties

Brief Summary of Υ in pPb

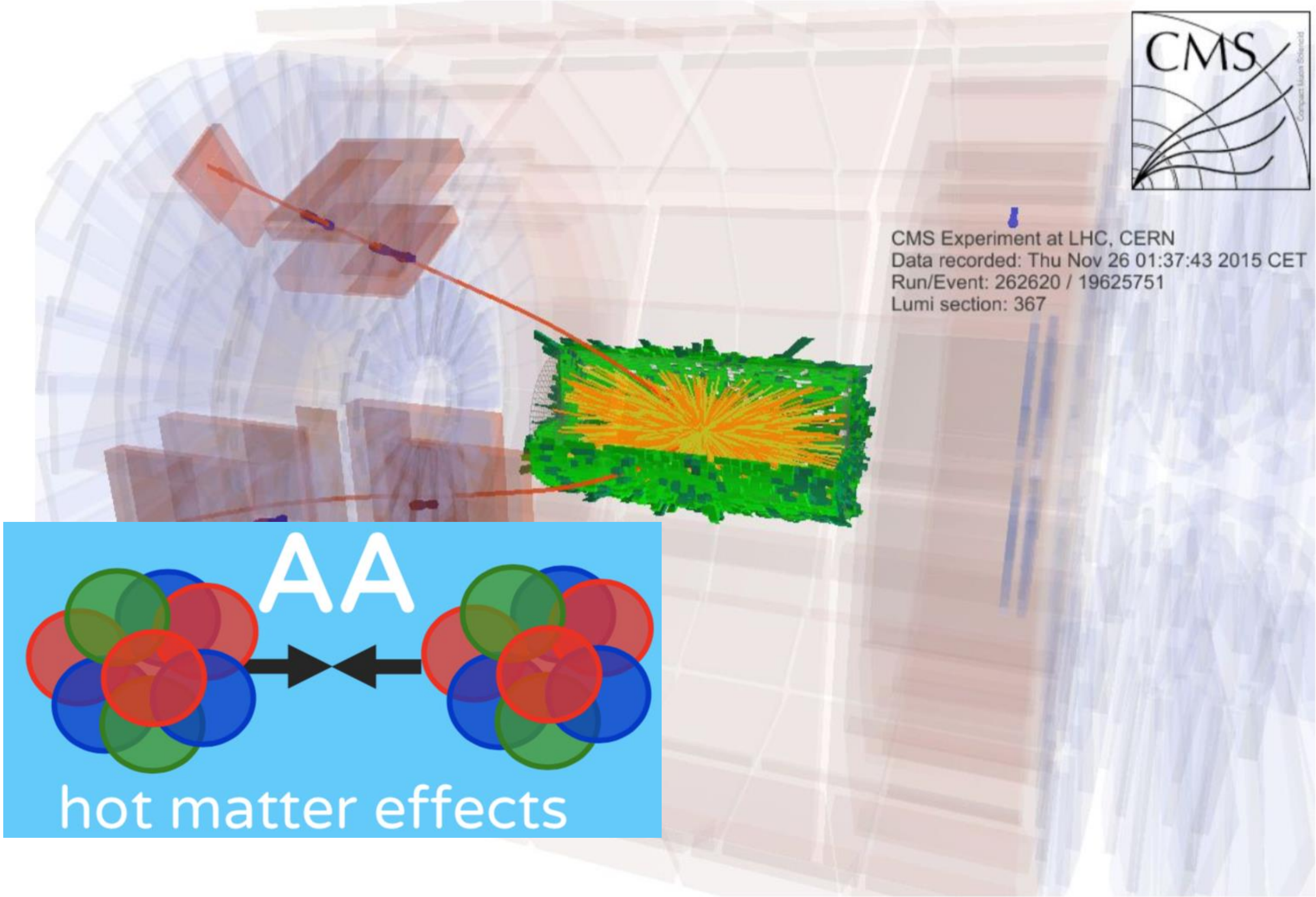




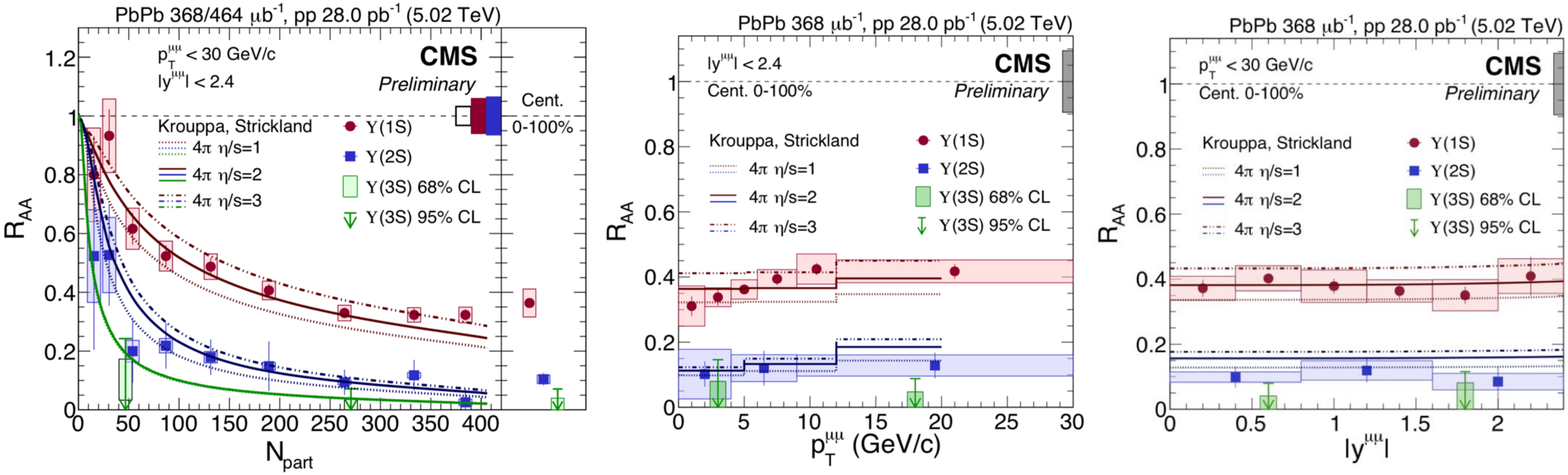


- No big surprises : very similar to J/ψ trend (forward and low p_T suppression)
- Beautiful scaling of multiplicity for Double Ratio of Y(nS) but large error in PbPb (maybe coming Run would be helpful to answer)

Bottomonia in PbPb



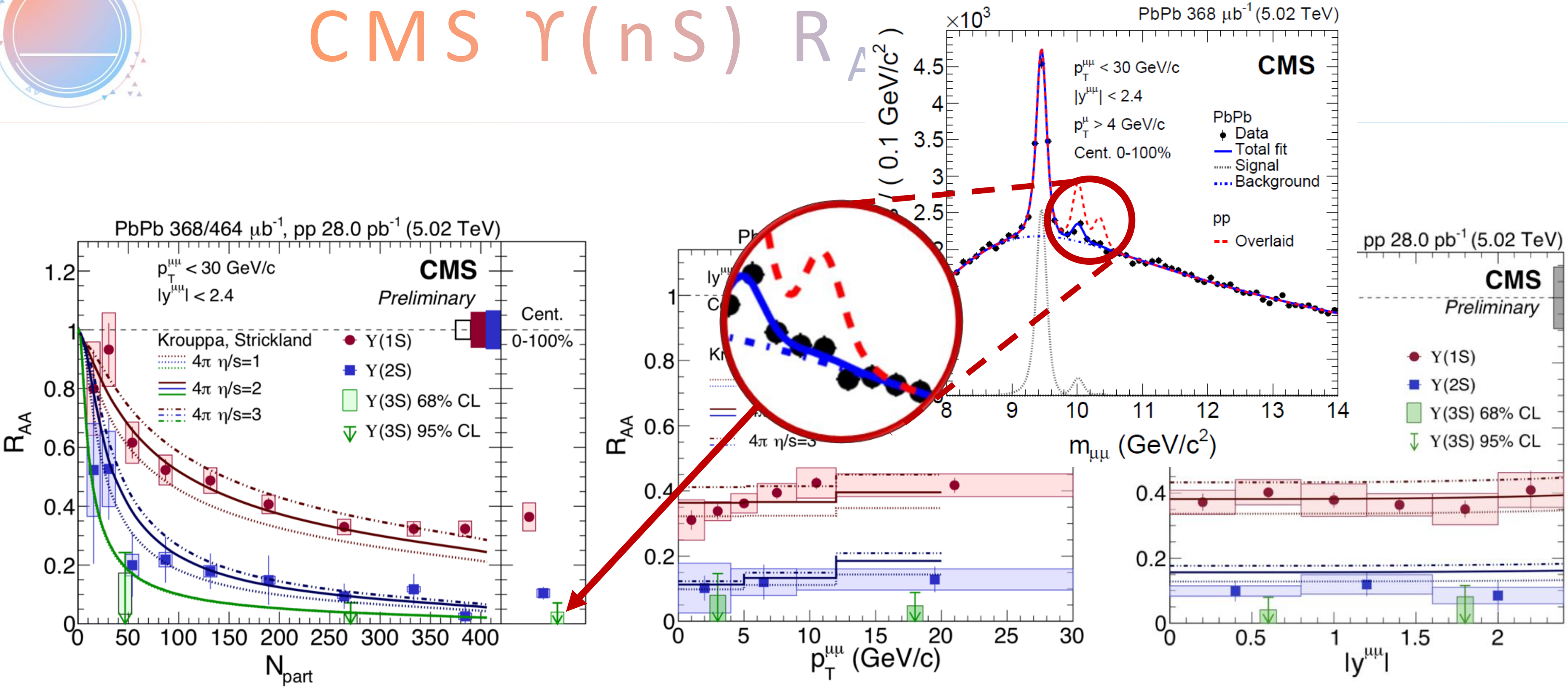
CMS Υ(nS) R_{AA} in PbPb



CMS-PAS-HIN-16-023

- 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**πη**/s = {1, 2, 3}, T_0 = {641, 632, 629} MeV)

CMS ϒ(nS) R_{AA}



CMS-PAS-HIN-16-023

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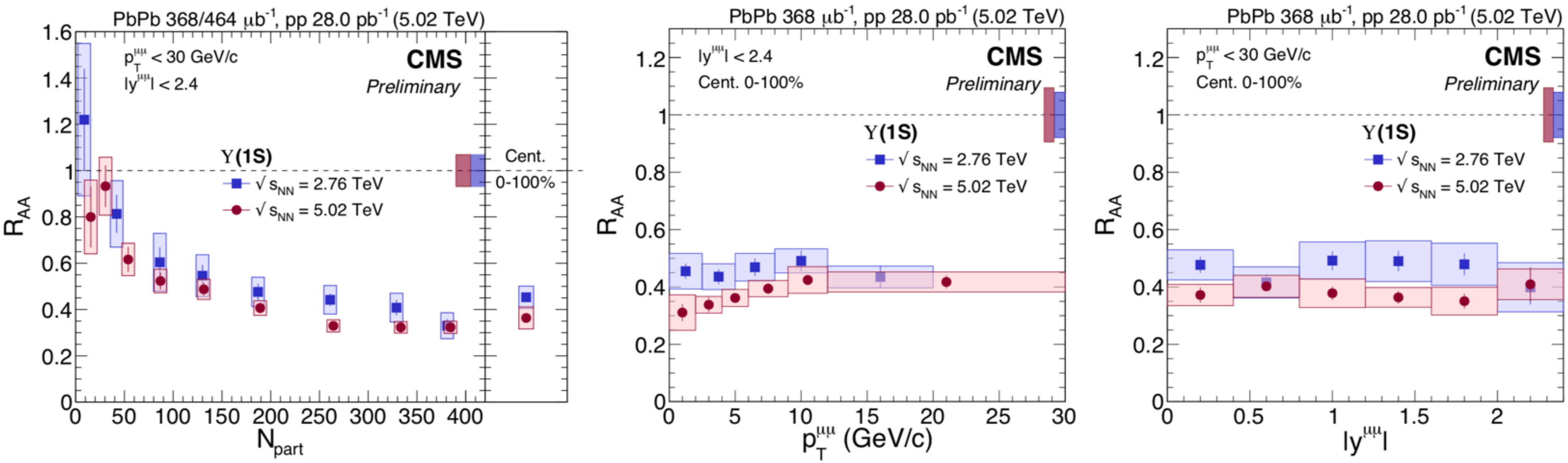
- Also hydrodynamic model with 3 temperatures (Krouppa at al.) describe well data within uncertainty ($4\pi\eta/s$ = {1, 2, 3}, T_0 = {641, 632, 629} MeV)
- Complete melting of 3S
  - 3S yet to be seen in PbPb collisions at the LHC

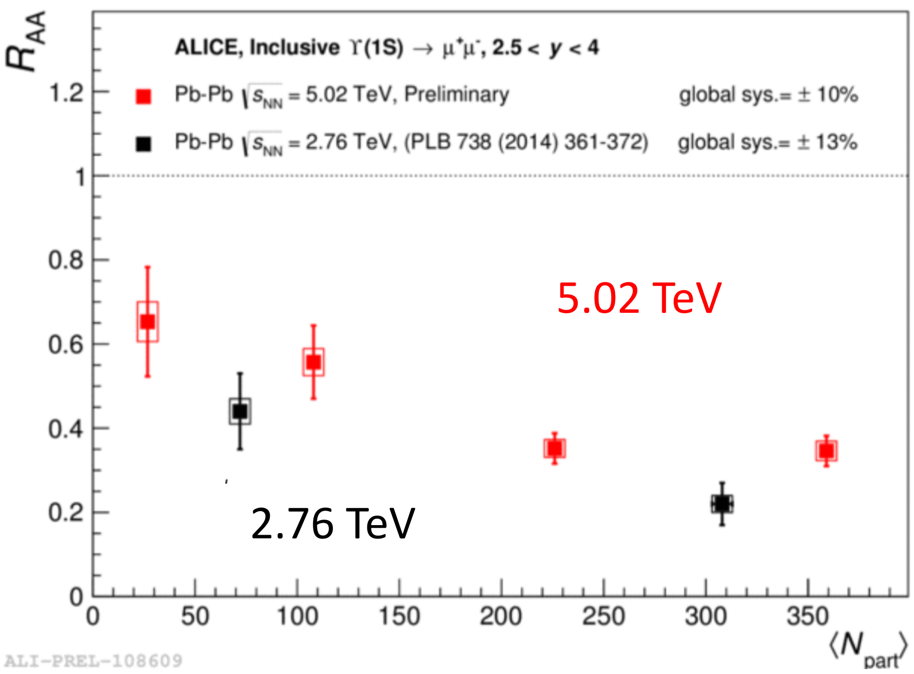
CMS Υ(nS) R_{AA} in PbPb



CMS-PAS-HIN-16-023

- 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

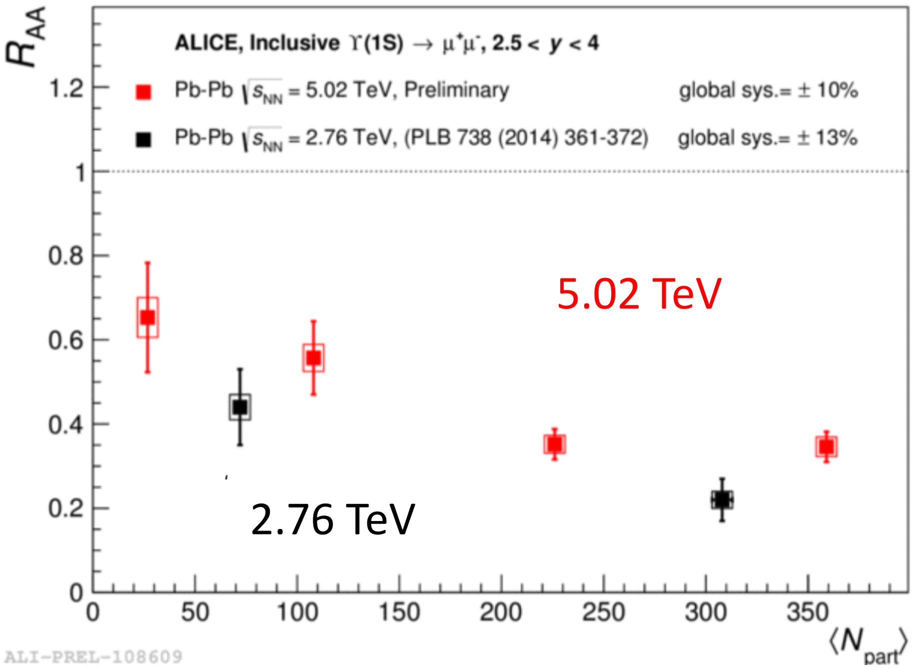
ALICE $\Upsilon(nS)$ R_{AA} in PbPb

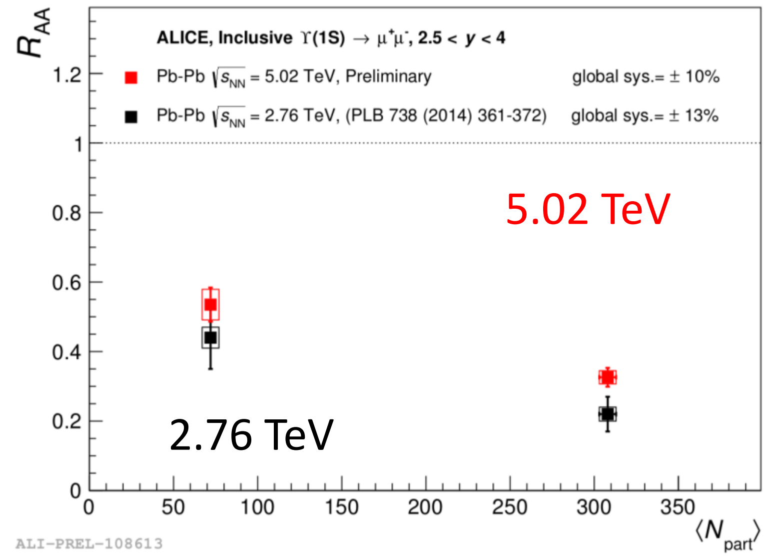


arXiv:1805.04387

- Similar suppression of $\Upsilon(1S)$ in both energies within uncertainties

ALICE $\Upsilon(nS)$ R_{AA} in PbPb

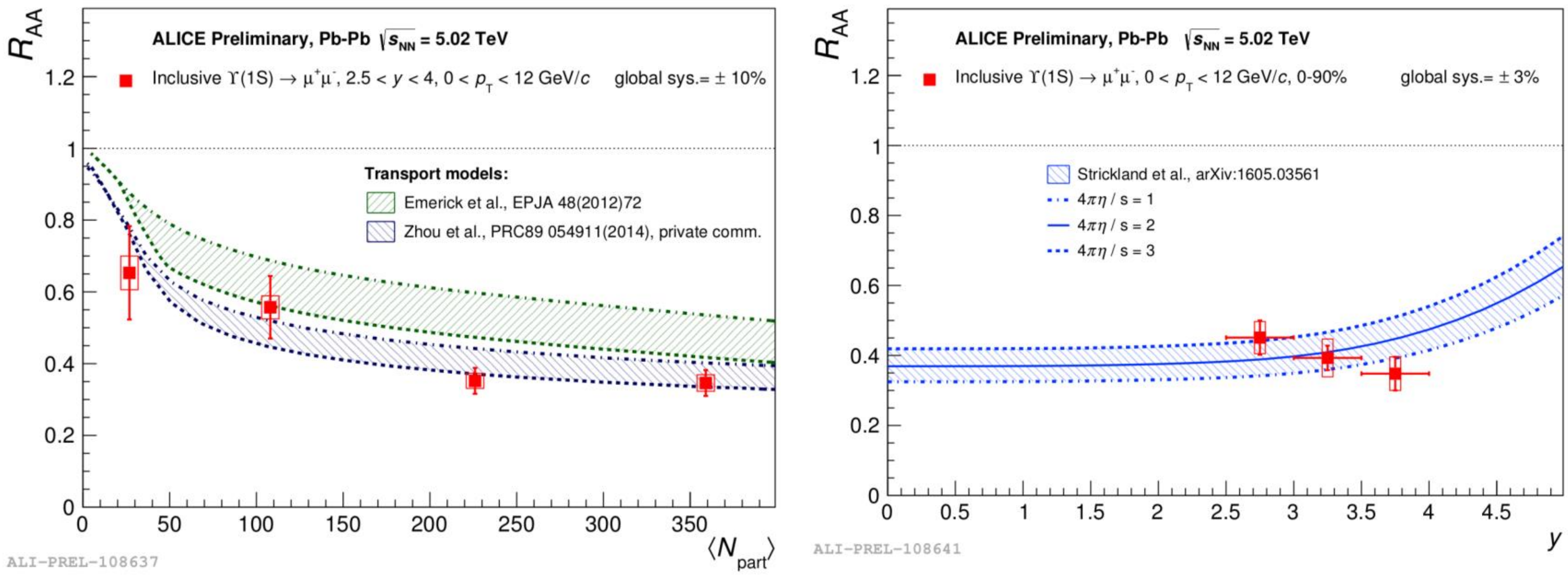




arXiv:1805.04387

- Similar suppression of $\Upsilon(1S)$ in both energies within uncertainties
- But at most central bin, $\Upsilon(1S)$ is less suppressed in 5.02 TeV than 2.76 TeV (could be upsilon regeneration?) differently from CMS

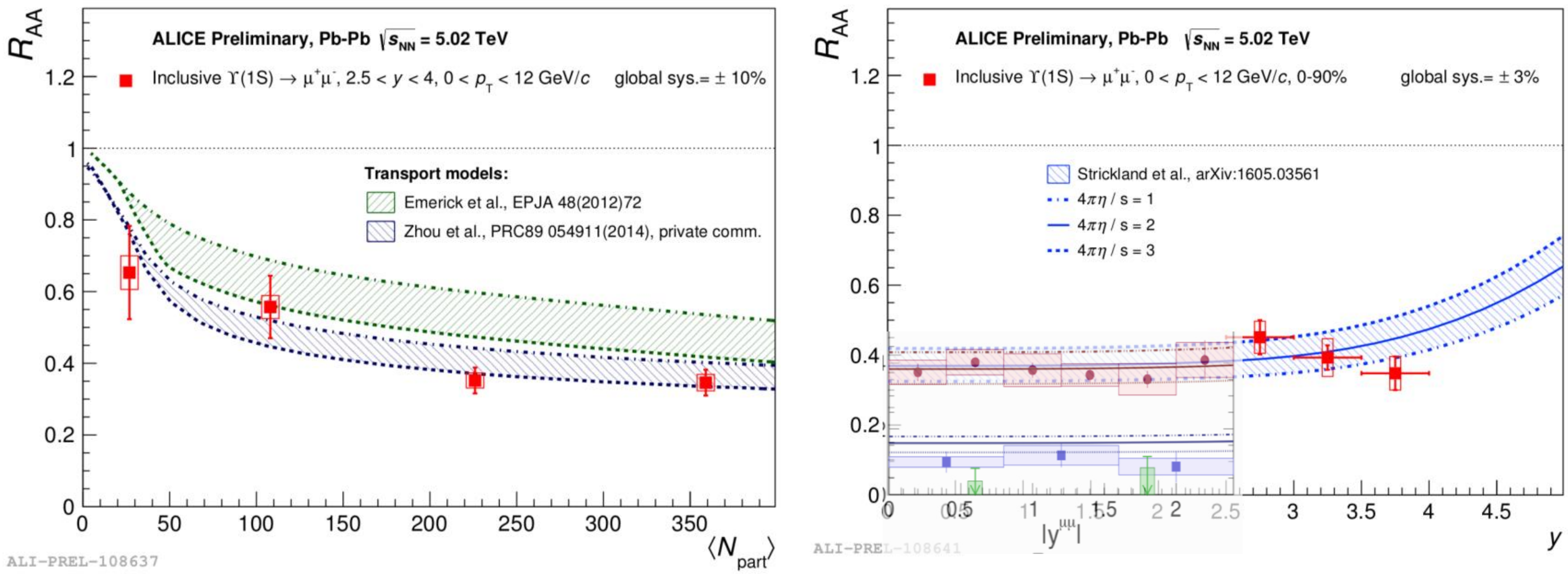
ALICE Υ(nS) R_{AA} in PbPb



arXiv:1805.04387

- Transport and anisotropic hydrodynamical models qualitatively describe the centrality
- Stricklaland Thermal anisotropic hydrodynamical model reproduce data within uncertainties but tension in forward rapidity

ALICE Υ(nS) R_{AA} in PbPb



arXiv:1805.04387

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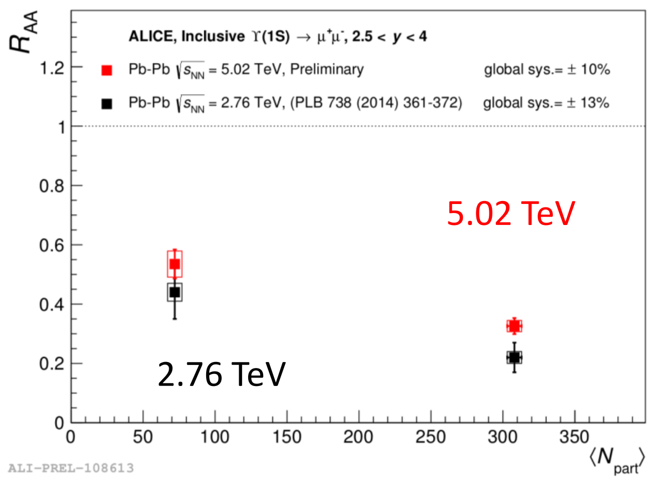
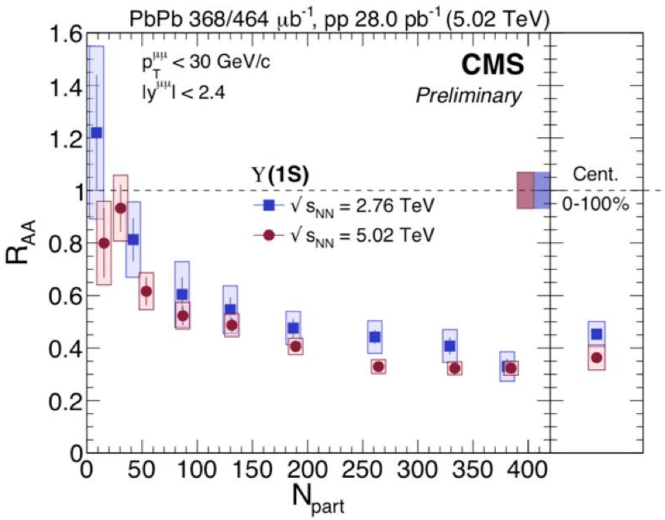
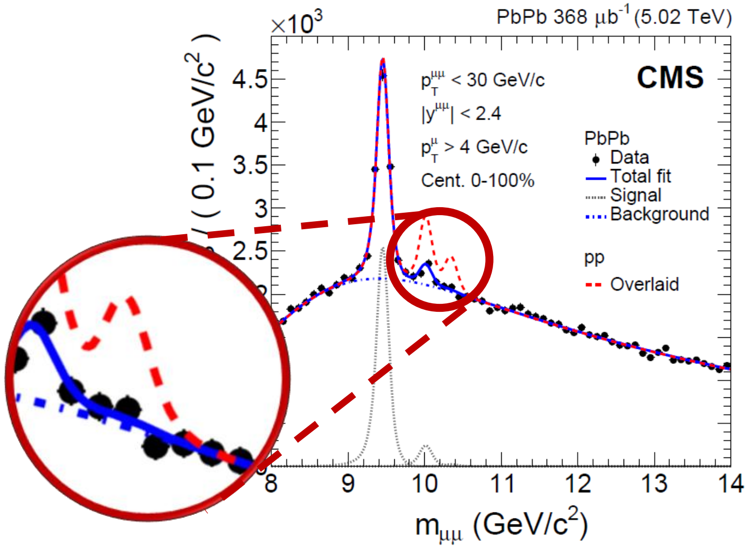
Brief Summary of Υ(nS) R_{AA} in PbPb

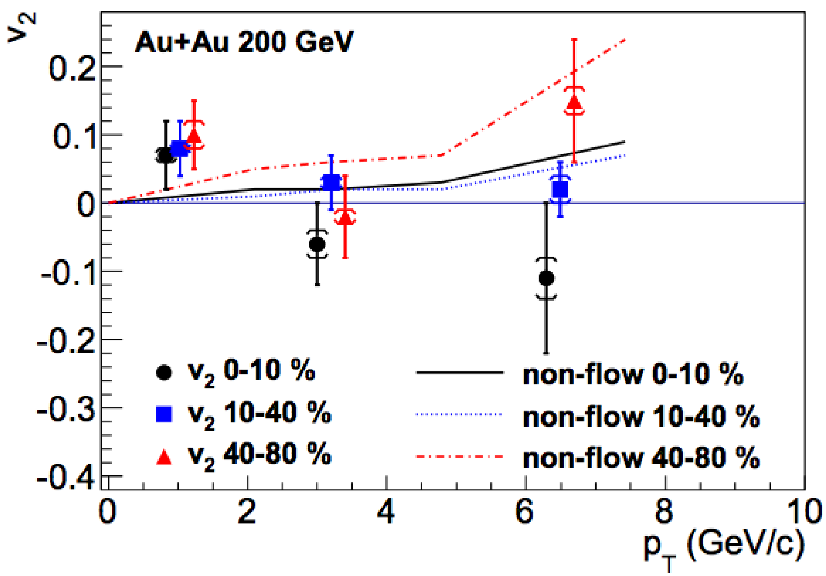


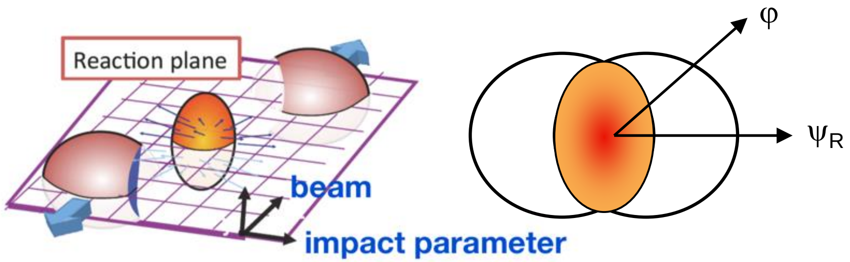




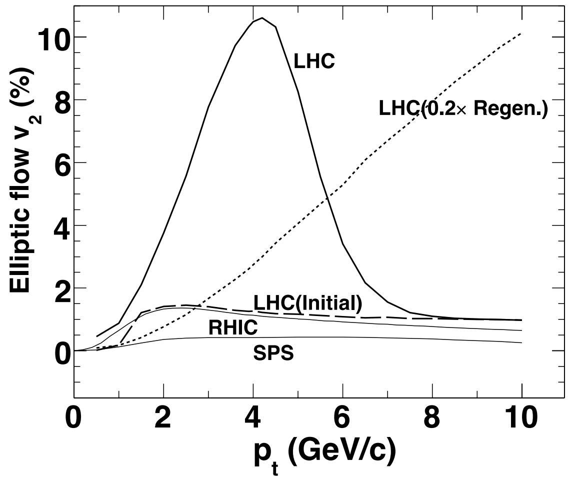
- Υ(1S) similar suppression but
  - R_{AA} at 5.02 TeV is less suppressed in ALICE
  - R_{AA} at 5.02 TeV is more suppressed in CMS
- Υ(3S) still not visible at PbPb collisions
  - Insufficient statistics ?
  - Complete melting at 5.02 TeV ?

J/ψ Elliptic flow



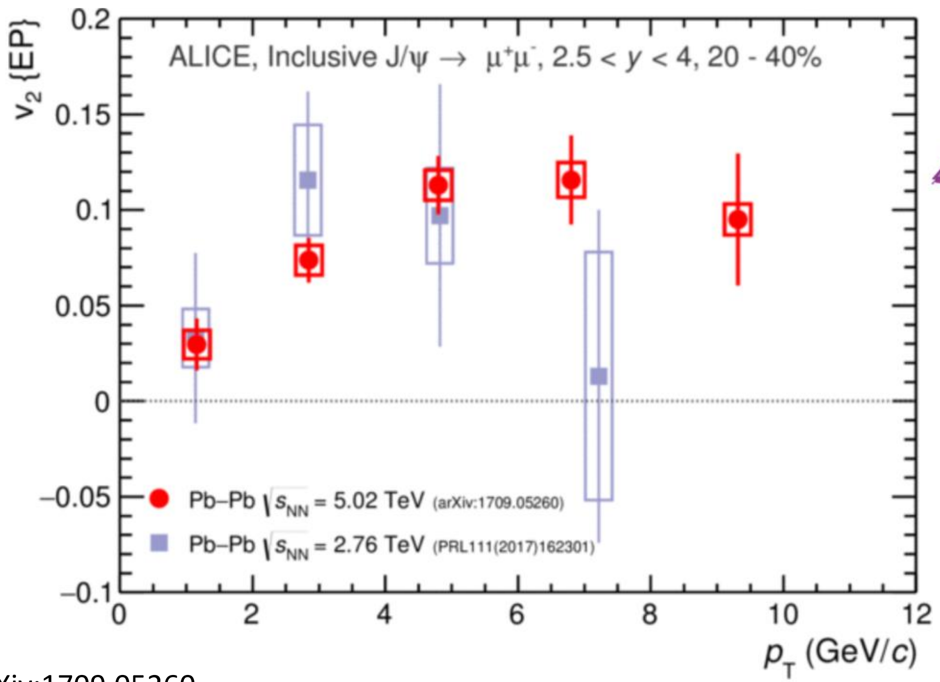


$v_2 = \langle \cos 2(\phi_{particle} - \Psi_{EP}) \rangle$

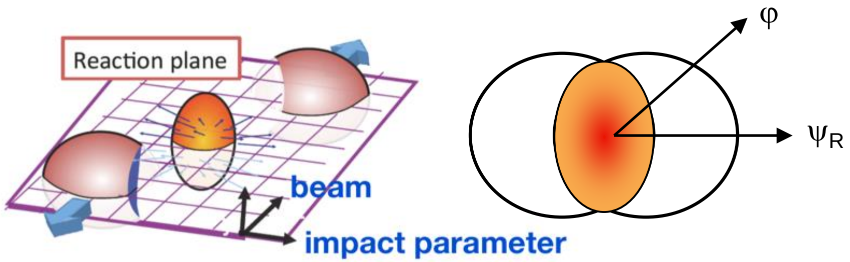


- Almost zero flow at RHIC
- But significant elliptic flow (v_2) may be expected at LHC energy due to the significant contribution of regenerated J/ψ
  - Good regeneration signal

J/ψ Elliptic flow



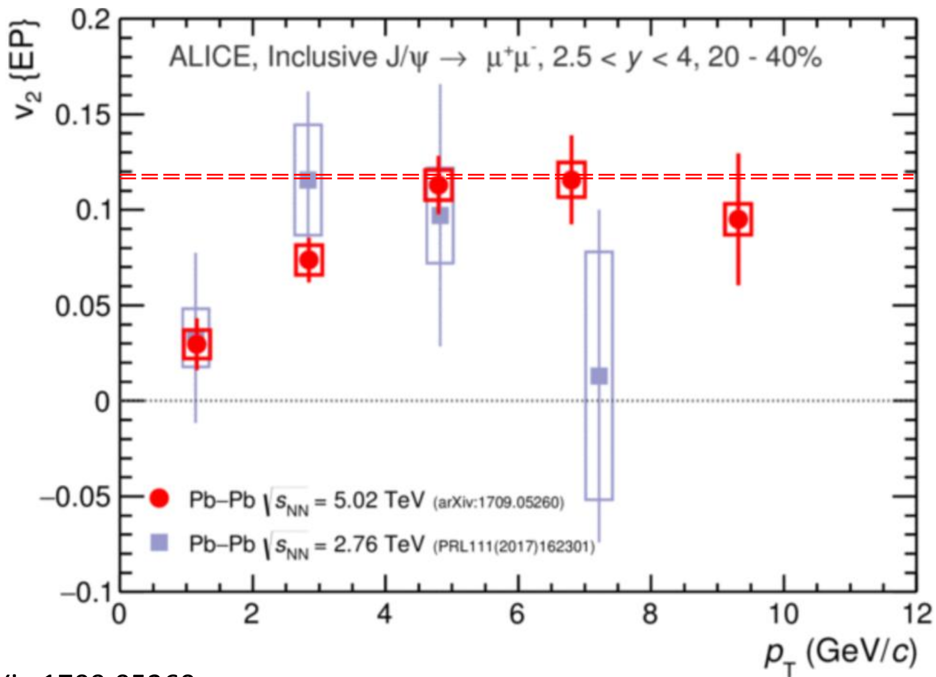
arXiv:1709.05260



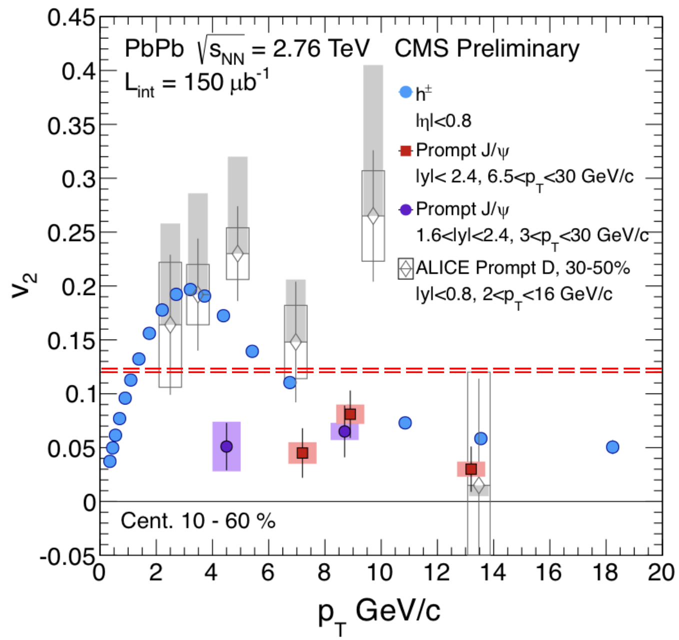
$v_2 = \langle \cos 2(\phi_{particle} - \Psi_{EP}) \rangle$

- 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

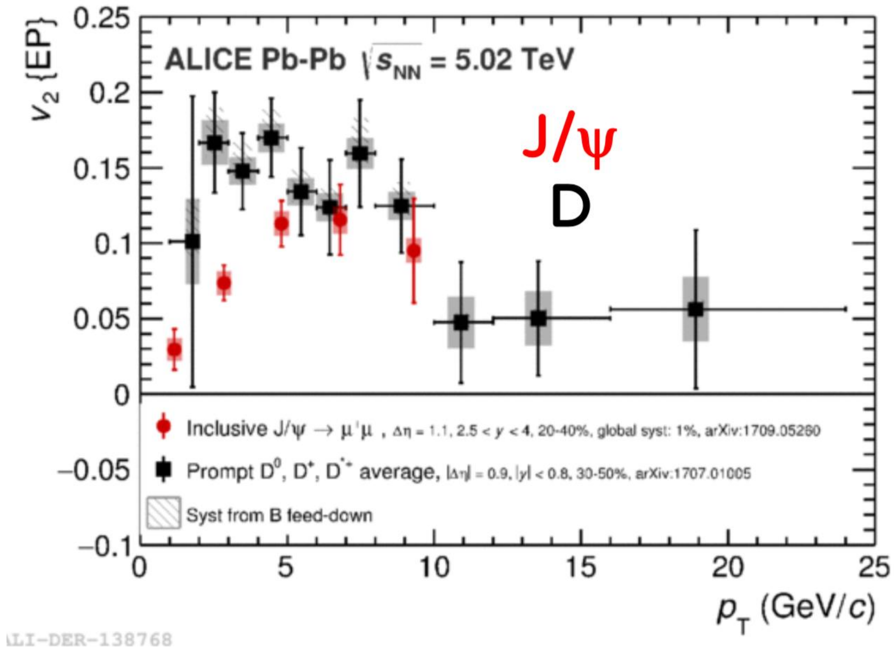


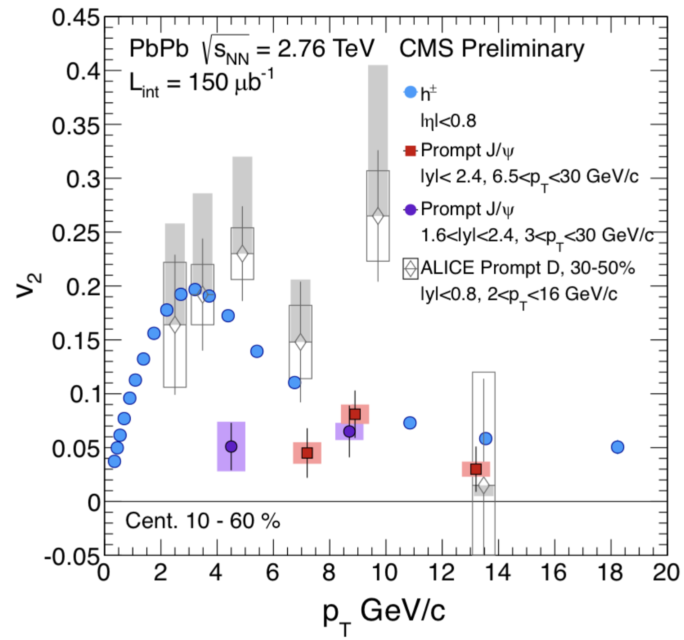
arXiv:1709.05260



- 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

J/ψ Elliptic flow

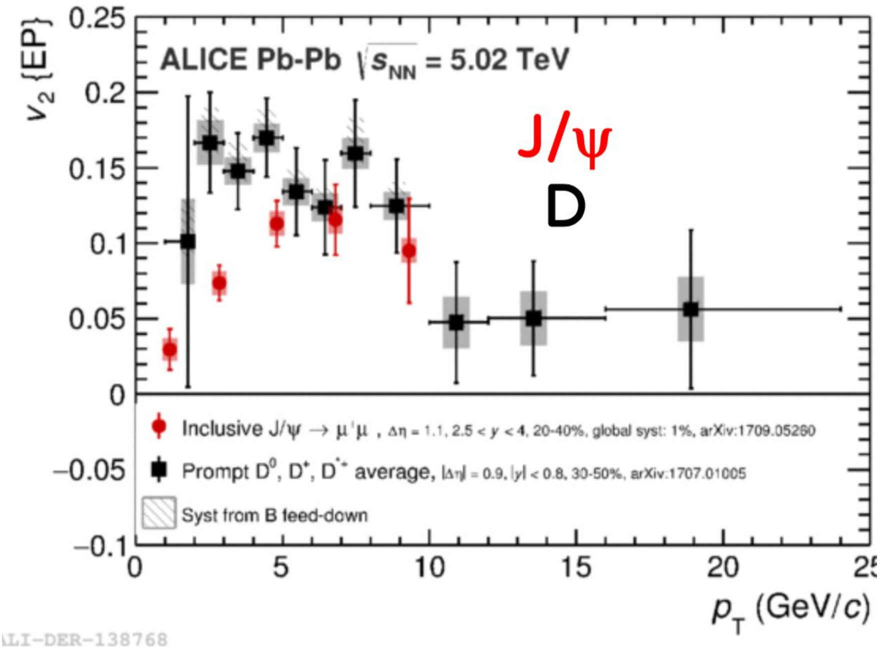


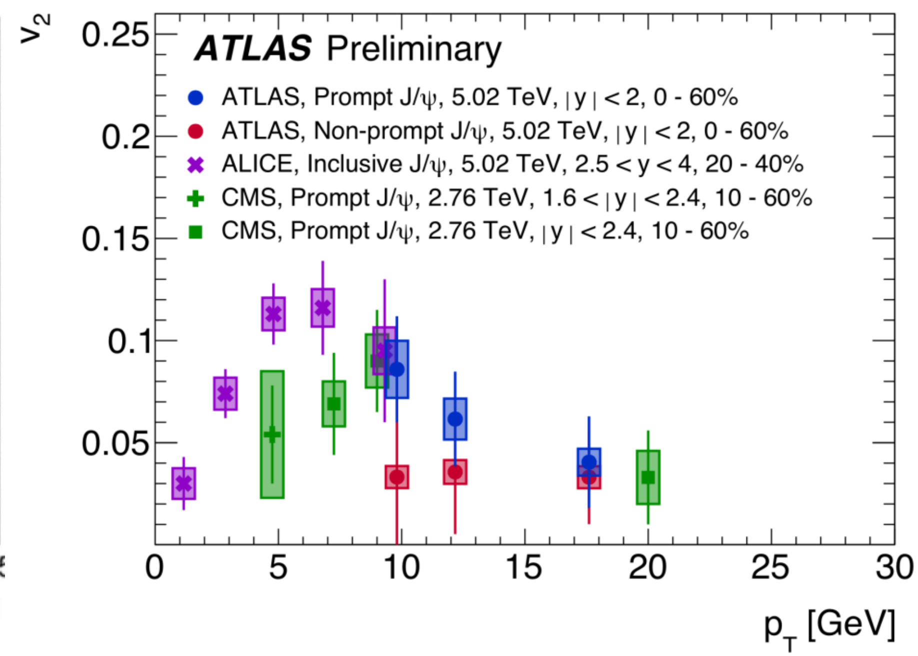


arXiv:1709.05260

- 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
    - 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

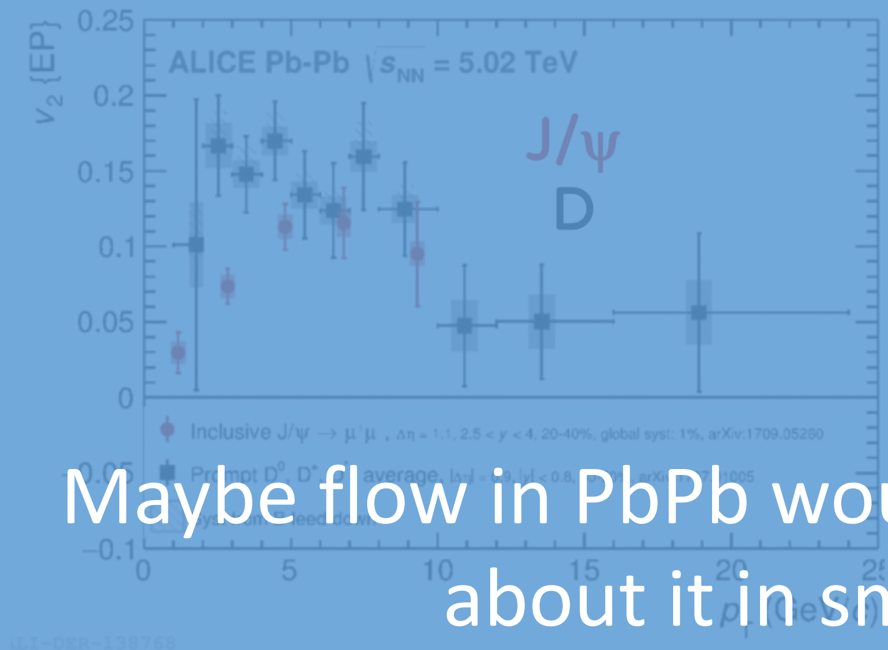


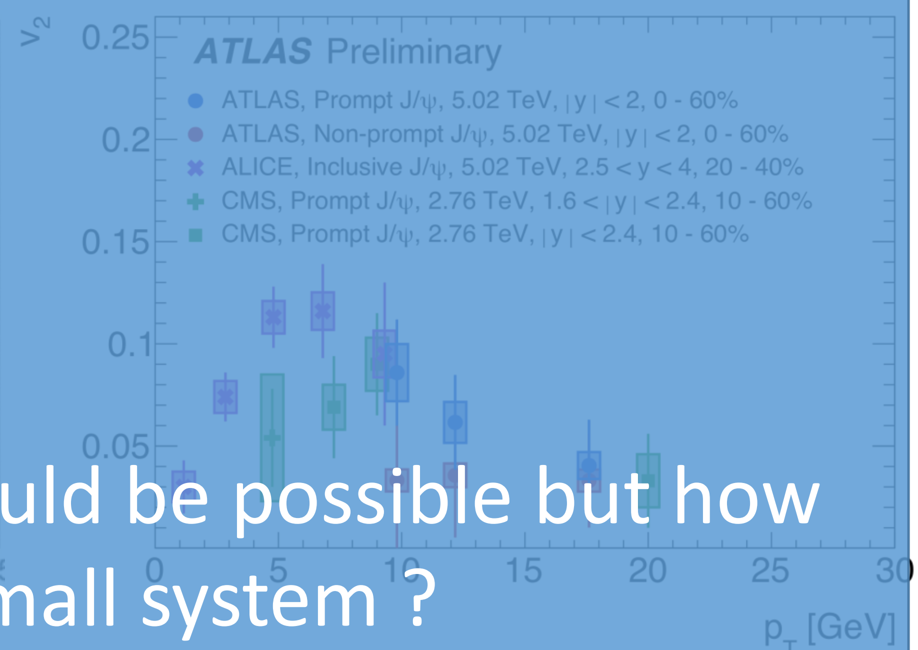


arXiv:1709.05260

- 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

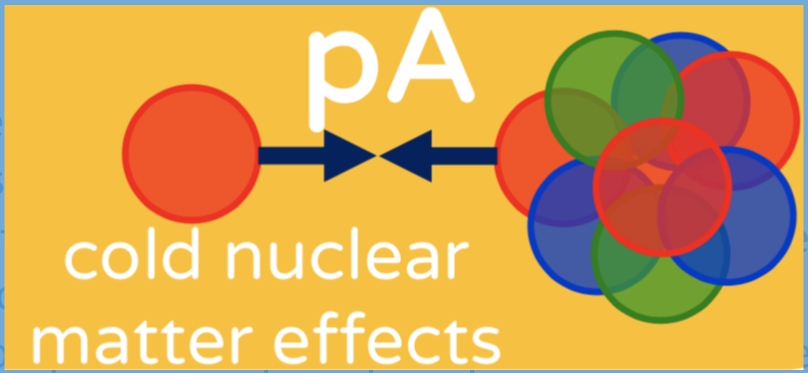




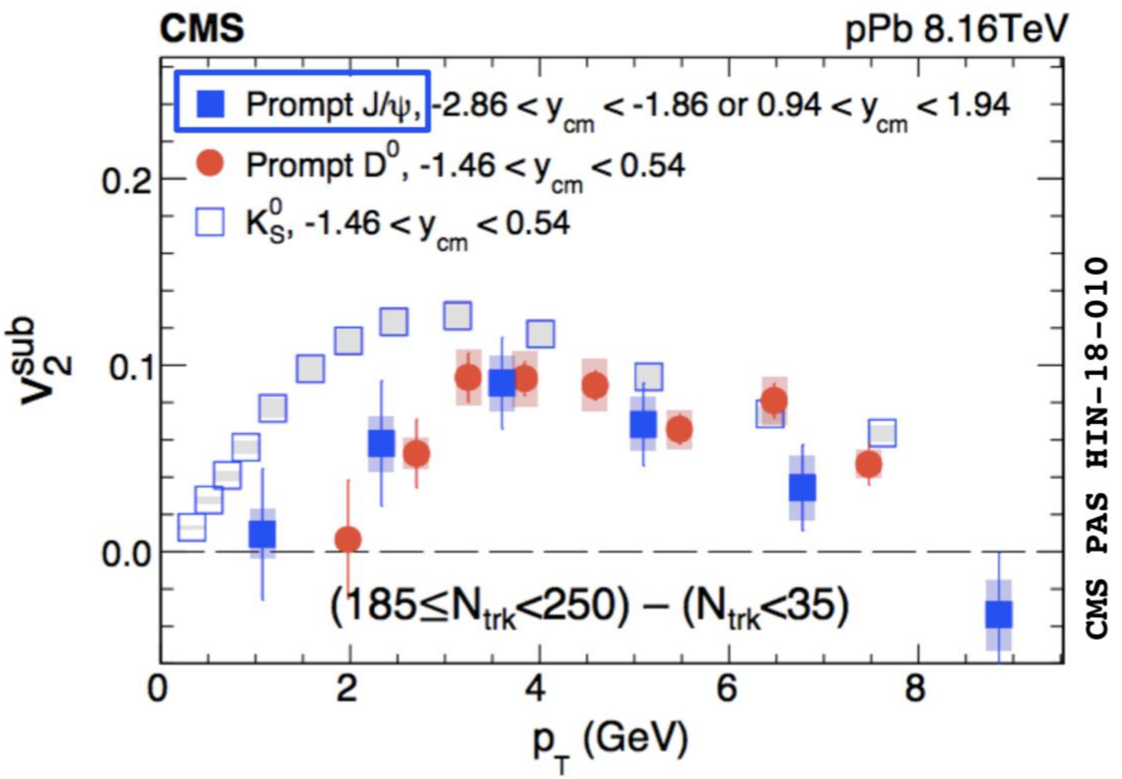
Maybe flow in PbPb would be possible but how about it in small system ?

arXiv:1709.05260

- Similar flow observe
  - Charm quarks s
  - Comparison be … insights on the properties of fl
- ATLAS measured pro … eV (for the first time)
  - Prompt J/ψ's flow is larger than nonprompt J/ψ's one



J/ψ Eliptic flow

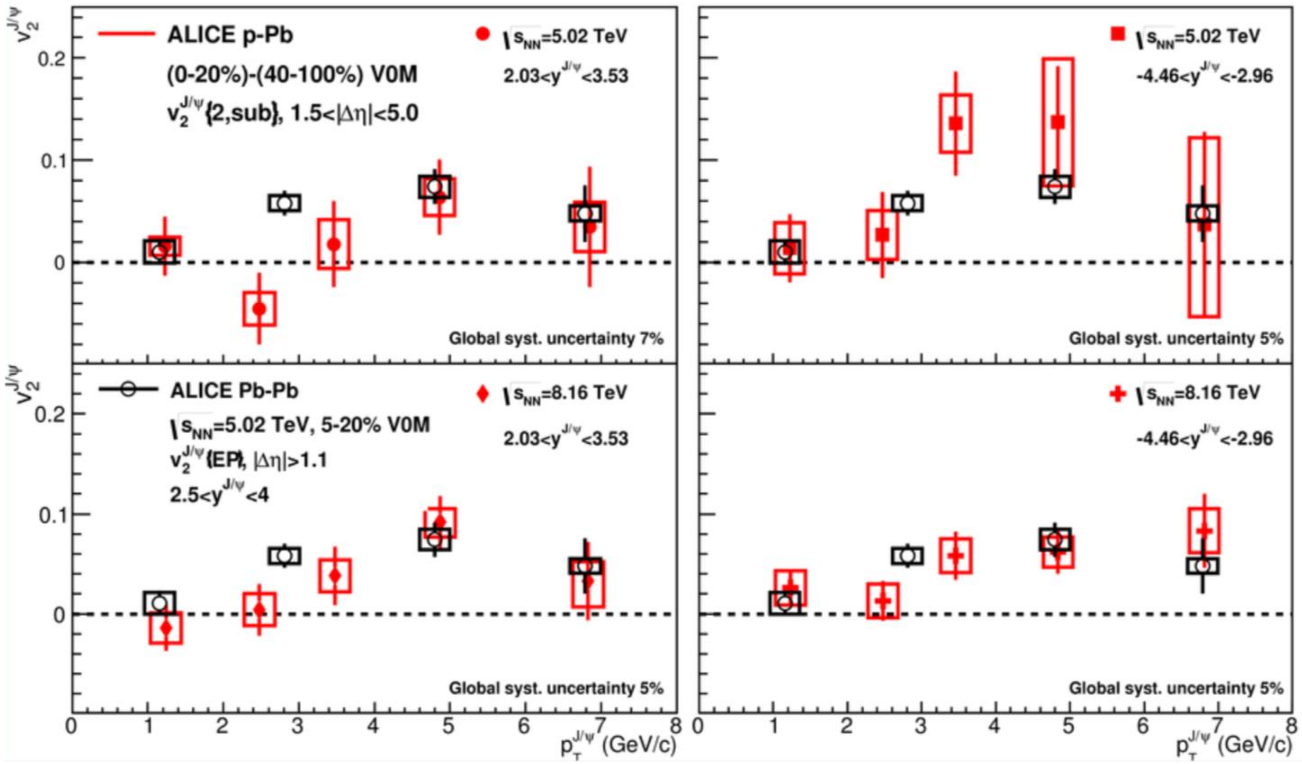


CMS-PAS-HIN-18-010

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

J/ψ Eliptic flow

Forward **Backward**

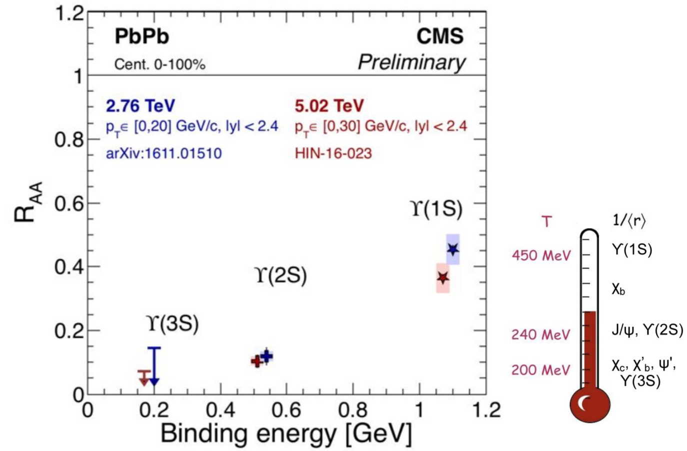


arXiv:1709.06807, 1709.05260

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

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)
- **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



Summary

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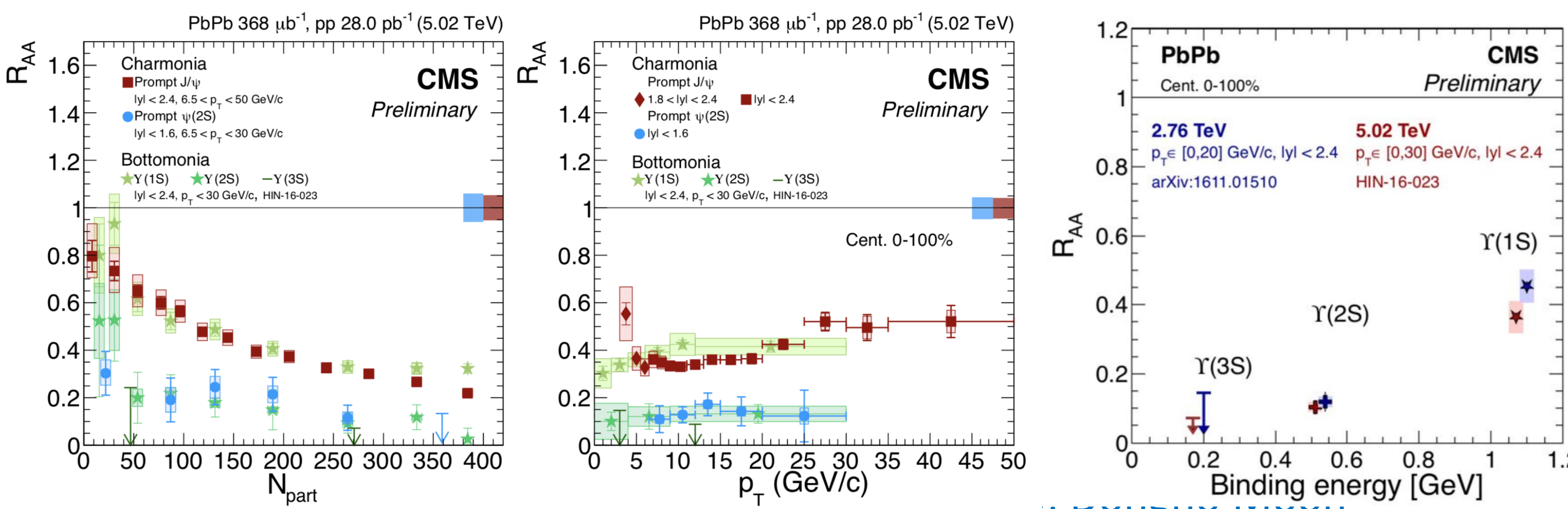
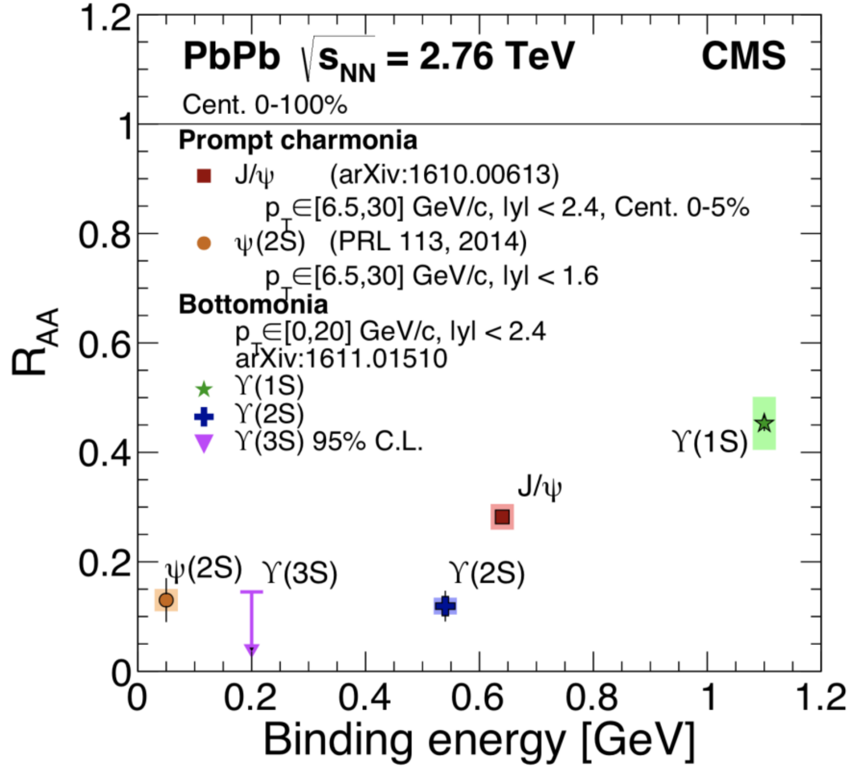
-



Thank you very much for your attention !!!

Backup

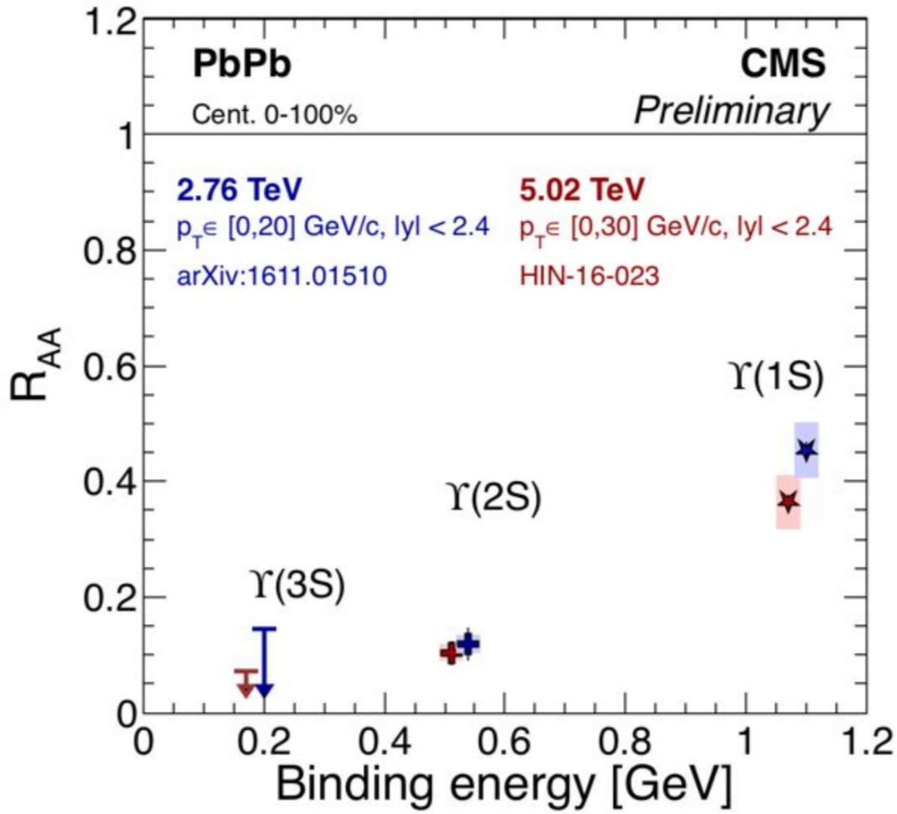
R_{AA} vs binding energy



state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

Table 3: Quarkonium Spectroscopy from Non-Relativistic Potential Theory [9]

R_{AA} vs binding energy



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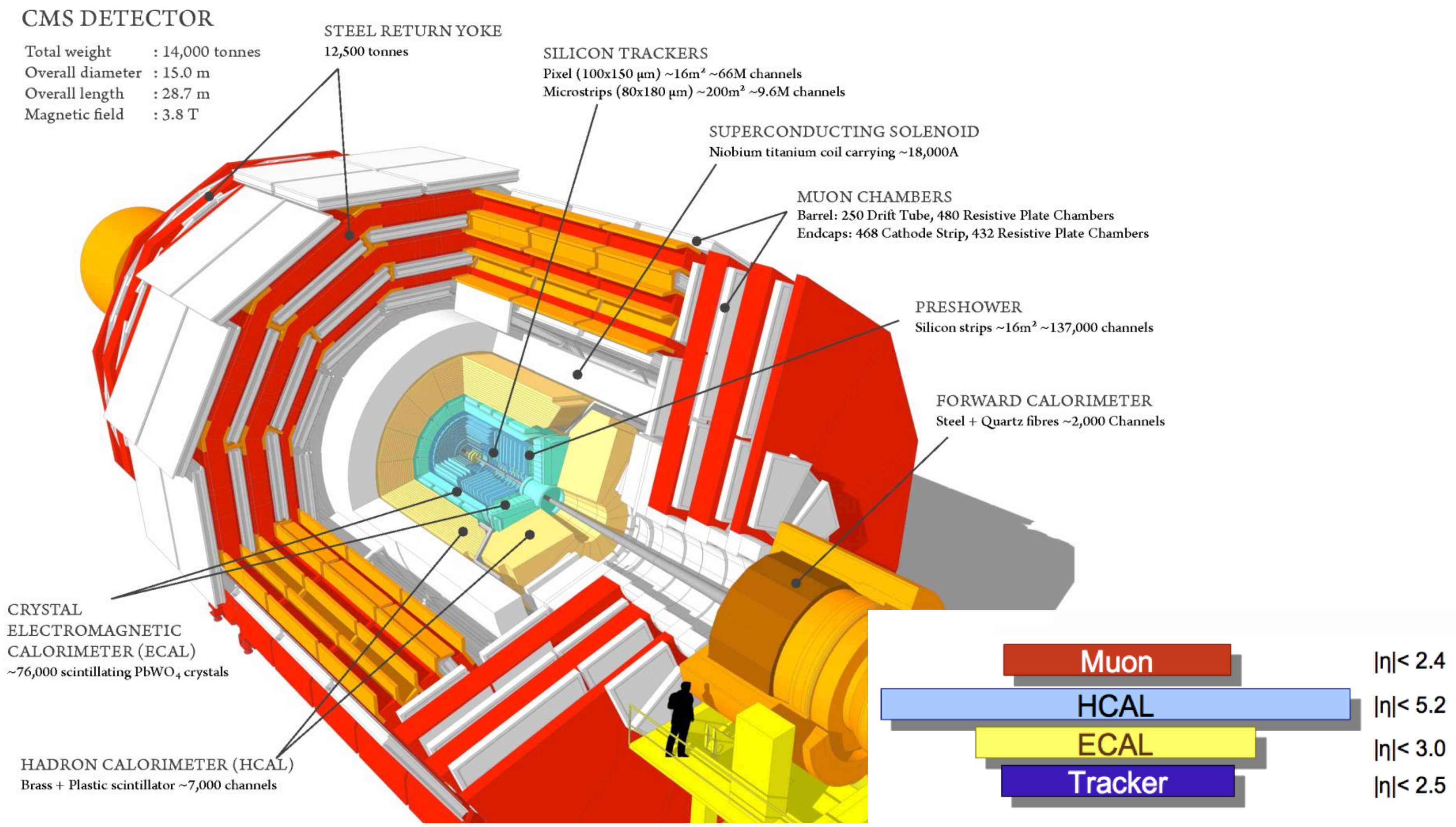
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

Table 3: Quarkonium Spectroscopy from Non-Relativistic Potential Theory [9]

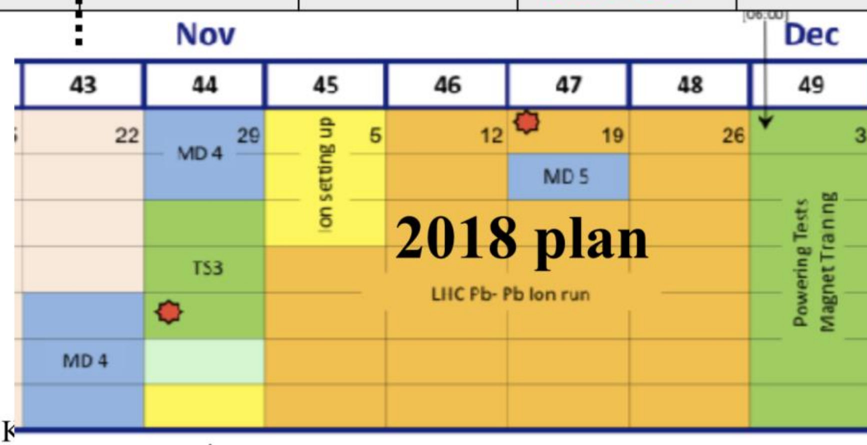
CMS Detector



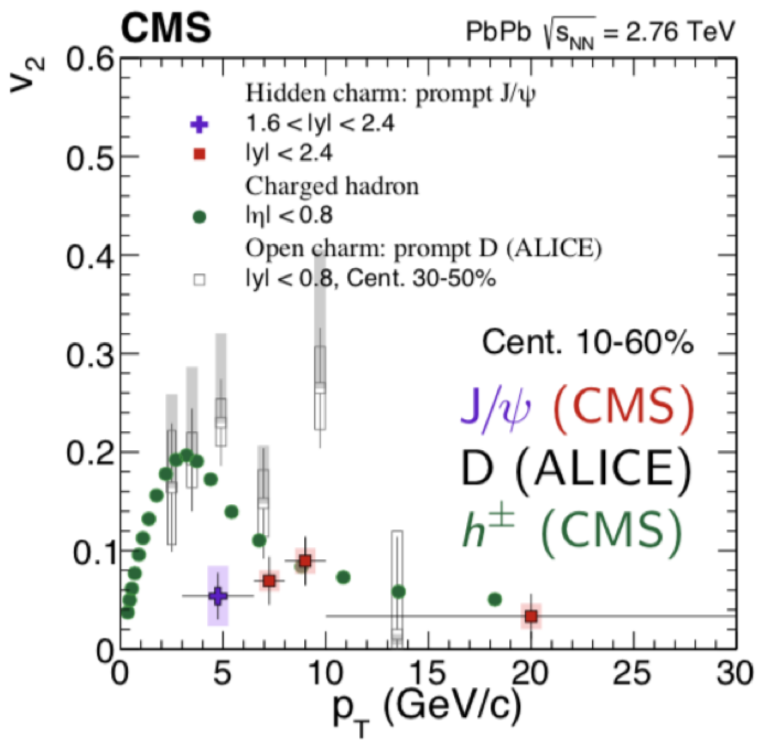
CMS Data Taking

	Run 1			Run 2			
	2010	2011	2013	2015	2016	2017	2018
pp		2.76 TeV 230n nb^{-1}	2.76 TeV 5.4 pb^{-1}	5.02 TeV 28 pb^{-1}		5.02 TeV 276 pb^{-1}	
pPb			5.02 TeV 34.6 nb^{-1}		8.16 TeV 185 nb^{-1}		
PbPb	2.76 TeV 7.3 ub^{-1}	2.76 TeV 166 ub^{-1}		5.02 TeV 0.5 nb^{-1}			*5.02 TeV ~1.5nb^{-1}*
XeXe						5.44 TeV 3.47 ub^{-1}	

- Much more data in Run 2
- New physics territory and precise measurement
- Still hungry of statistics



J/ψ flow at 2.76 TeV



EPJC 77 (2017) 252

- Comparing hidden charm (Prompt J/ψ, CMS) to open Cham (D, ALICE)
  - Smaller v_2 in low p_T but similar v_2 in high p_T
  - Mass ordering in low p_T, path-length dependence in high p_T

J/ψ at 5.02 TeV in pPb

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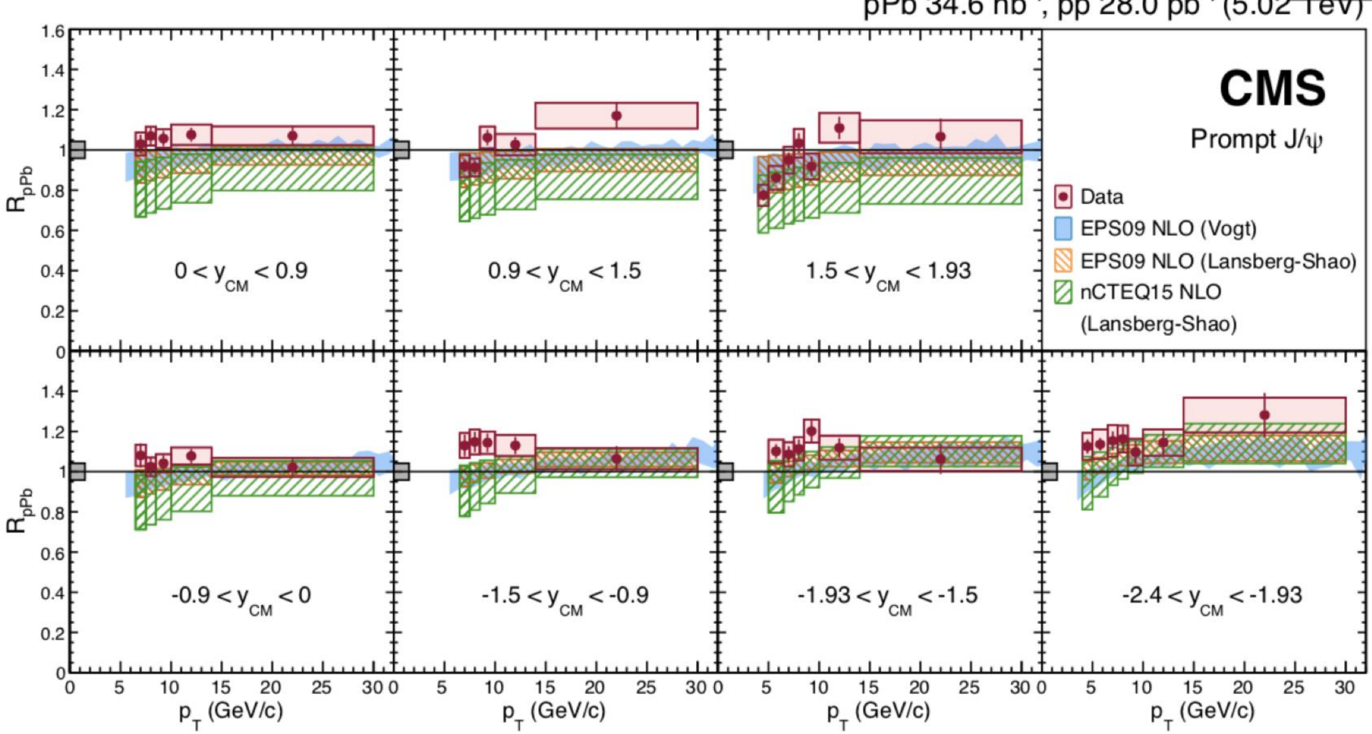


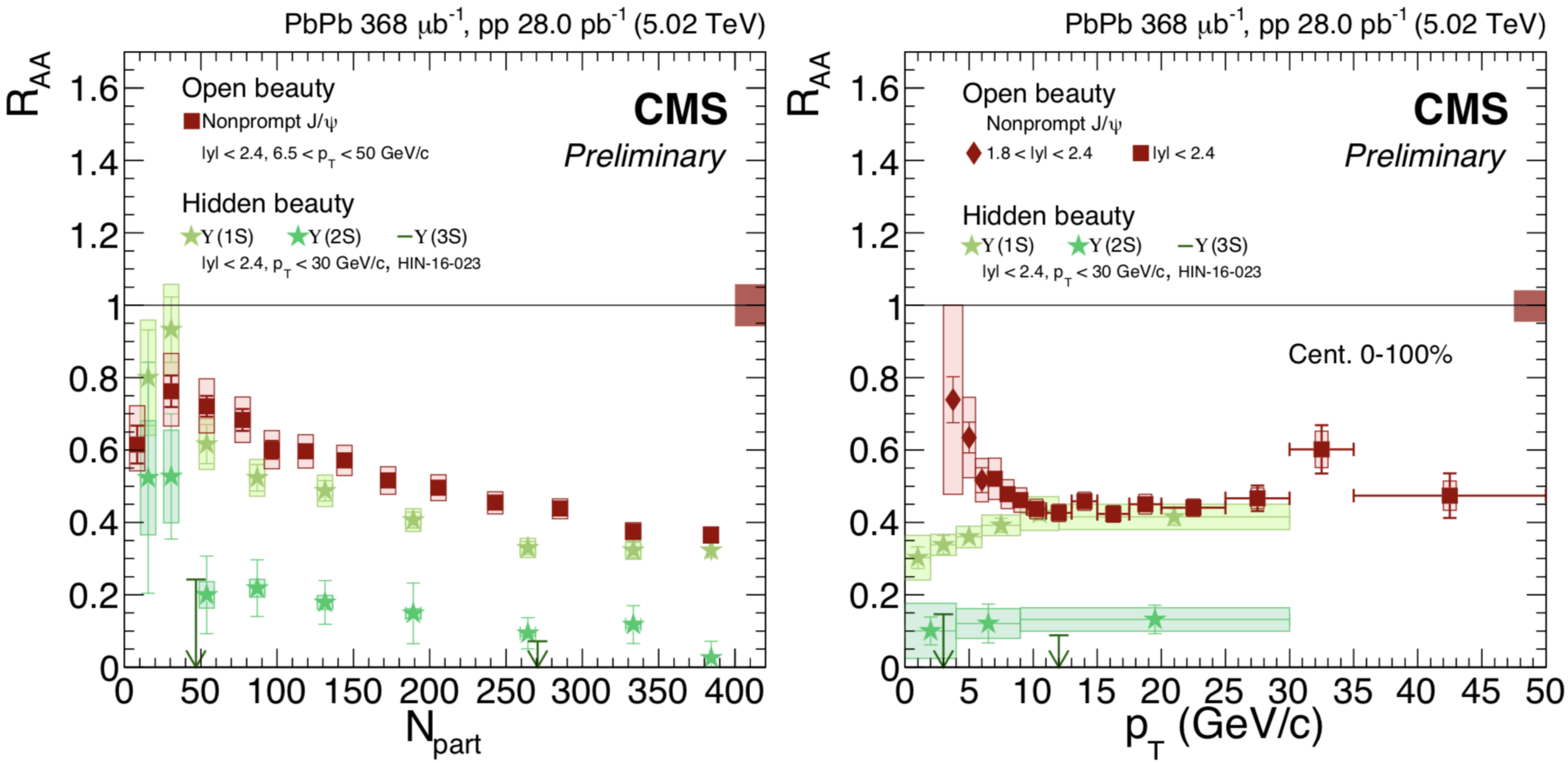
- Prompt J/ψ R_{pA} above unity in most bins
- Suppression only in the most forward bin (1.5 < y_{CM} < 1.93) for p_T < 7.5 GeV/c
- nPDF calculations slightly lower than data

- Coherent Energy Loss

  – Nuclear transverse momentum broadening of the heavy quark pair induces coherent gluon radiation, arising from the interference between emission amplitudes off the initial projectile parton and the final color octet quark pair. This coherent medium-induced radiation leads to an average induced energy loss proportional to the quarkonium energy [18]. The consequences of coherent energy loss are quarkonium suppression (respectively, enhancement) at large positive (respectively, large negative) values of the rapidity and at all center-of-mass energies of the p–A collision.

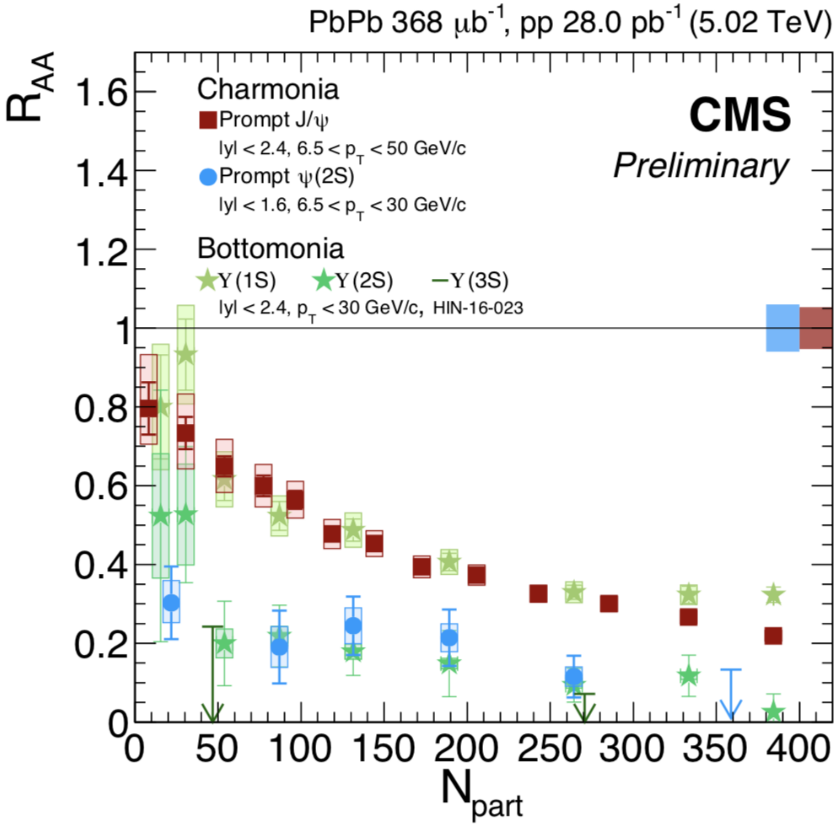
Open vs Hidden Beauty

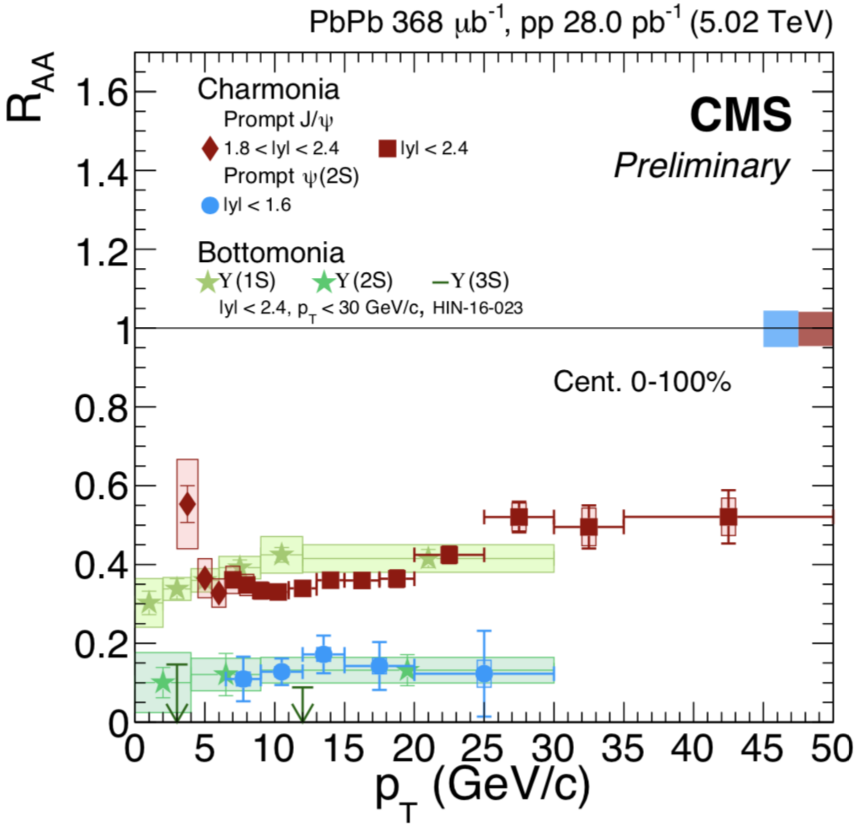
-



Hidden Charm vs Bottom

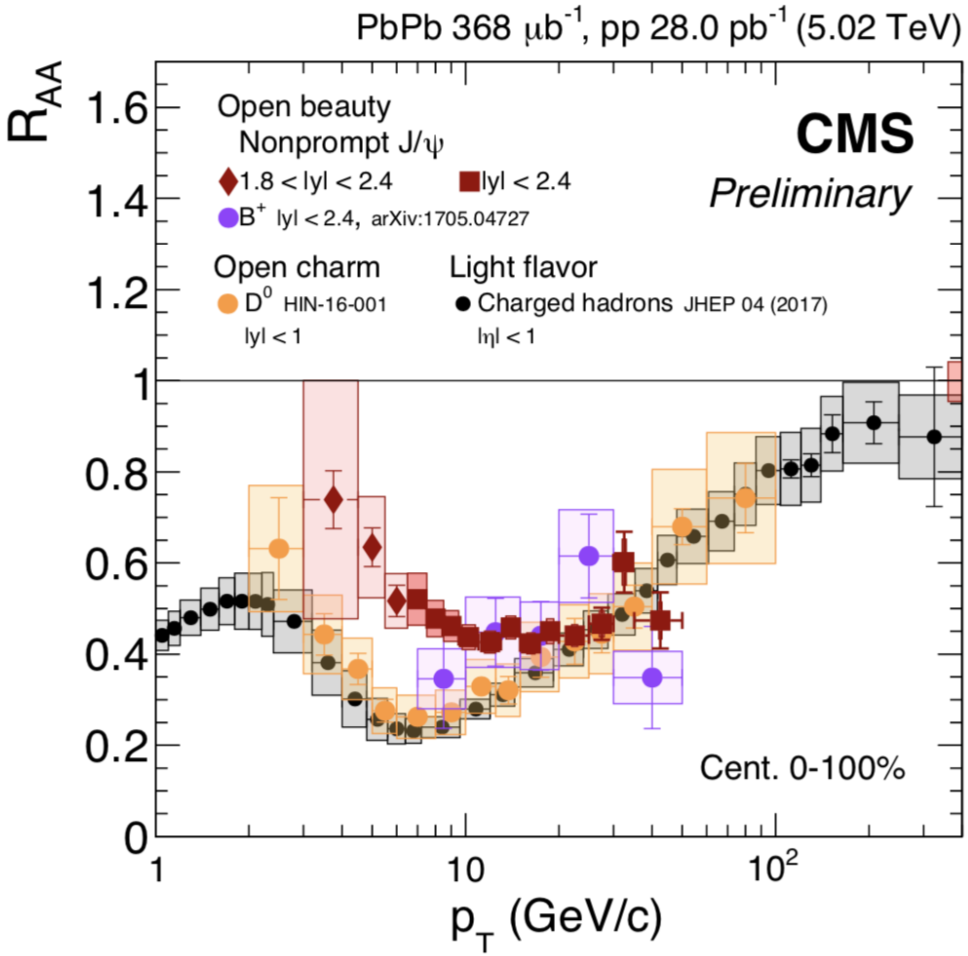
•





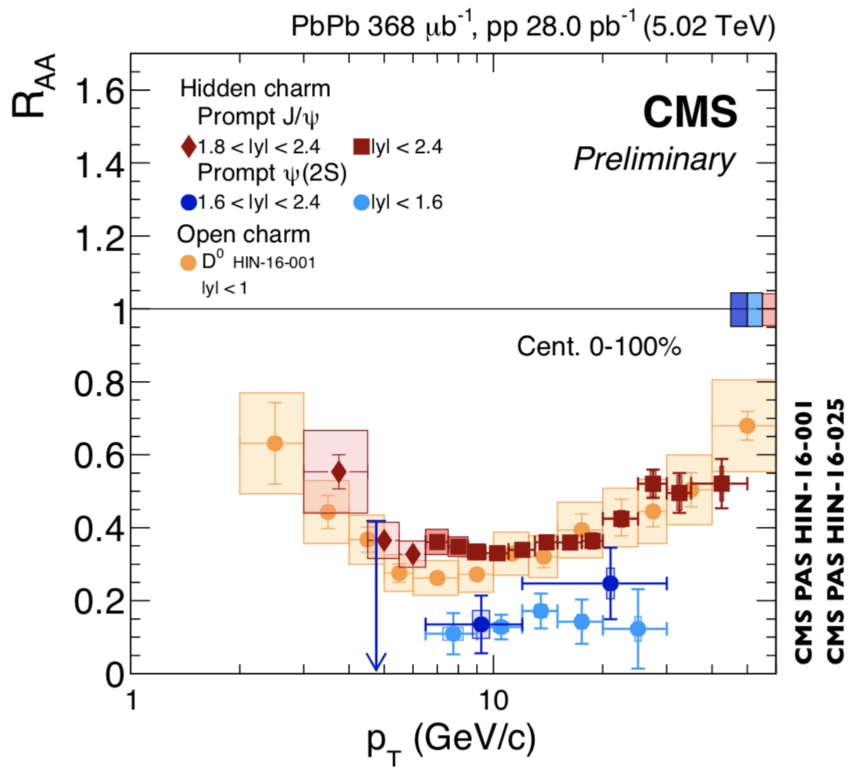
Flavor Dependence of E_{loss}

-



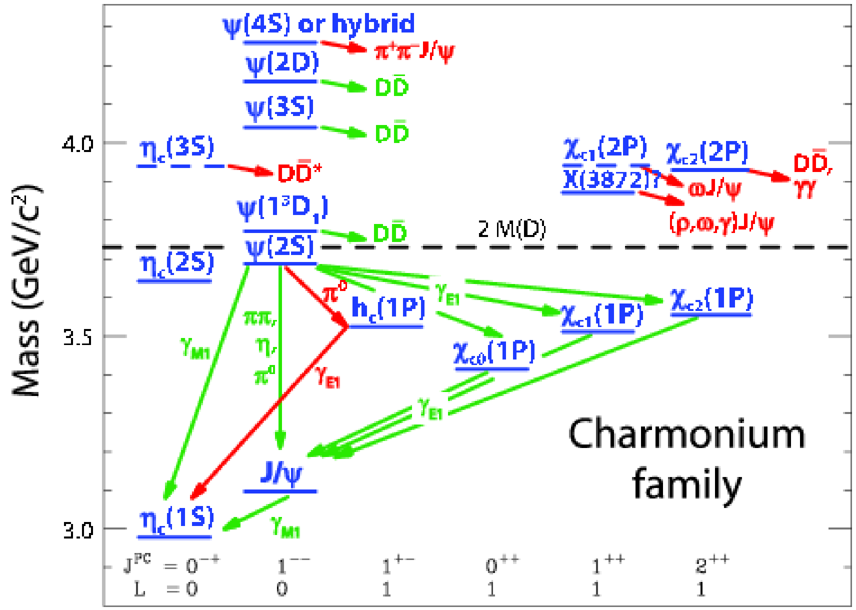
Flavor Dependence of E_{loss}

-



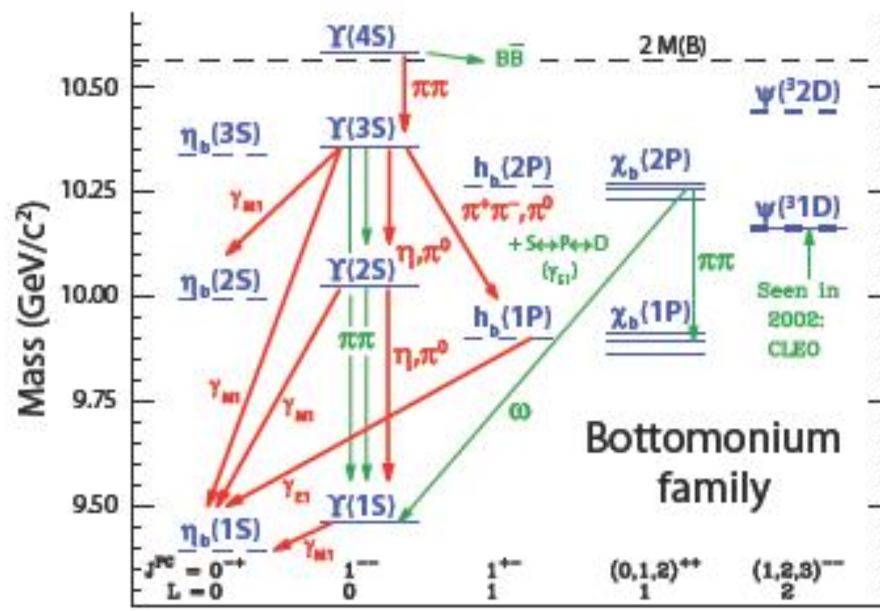
- Open charm suppression from energy loss (E_{loss}) of charm in QGP
- Similarity between prompt J/ψ and D^0 R_{AA}:
  E_{loss} contribution to charmonia suppression ?
- However, ψ(2S) still more suppressed up to p_T = 30 GeV/c

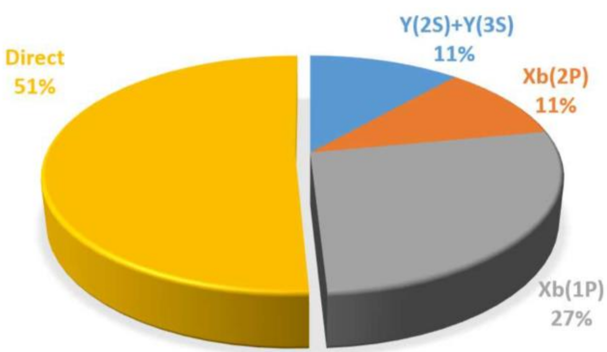
Quakonia Feed-down Fraction



J/ψ = 0.6 J/ψ + 0.3 X_c + 0.1 ψ(2S)

ϒ(1S) = 0.5 ϒ(1S) + 0.11 (ϒ(2S)+ ϒ(3S))
+ 0.11X_b(2P) + 0.27 X_b(1P)

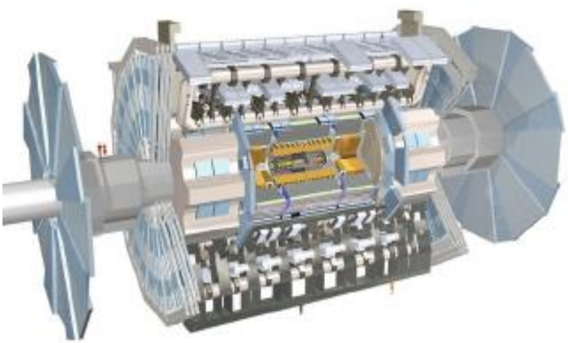




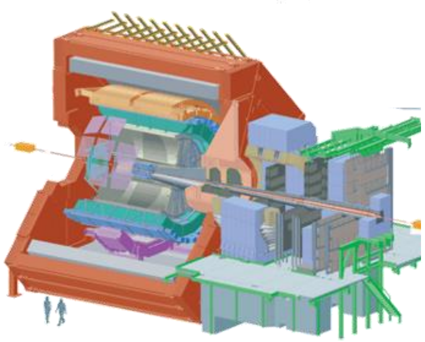
Quarkonia Acceptance

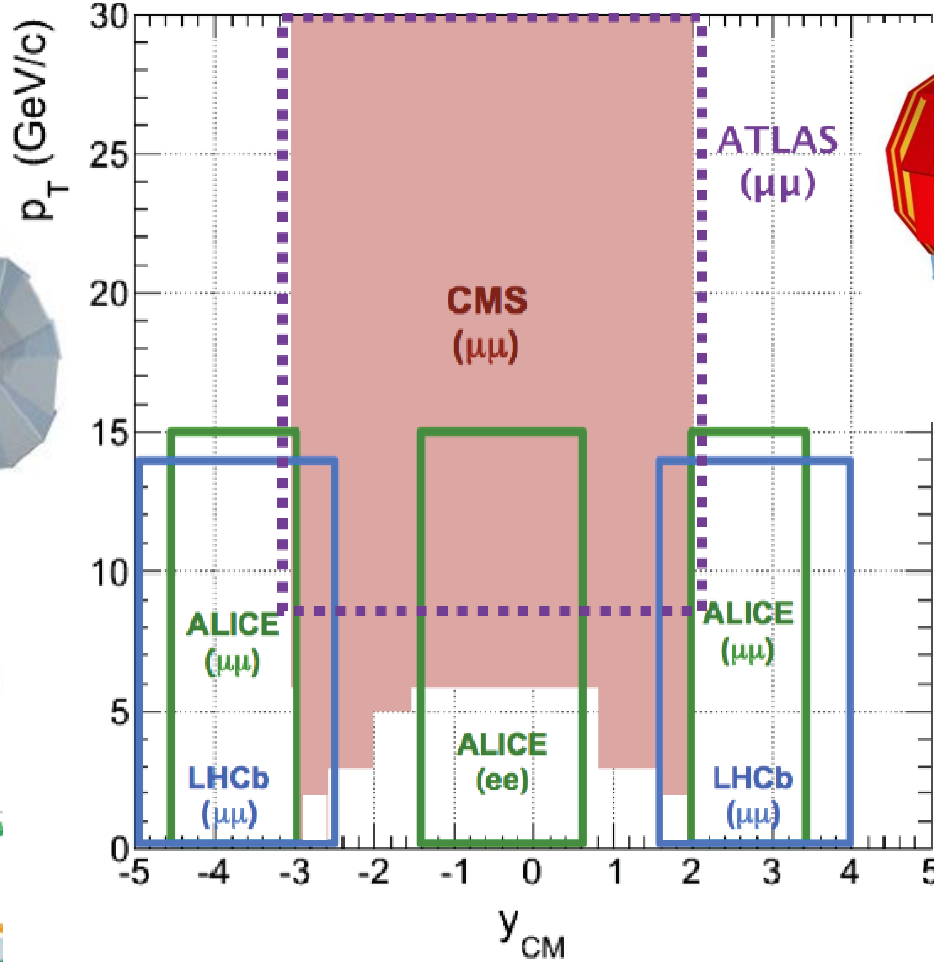
We are good friends !!!

ATLAS

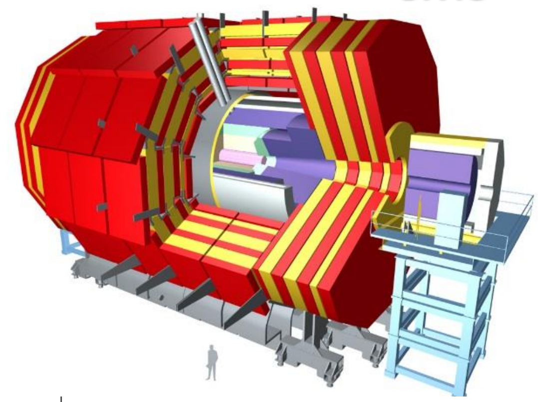


ALICE

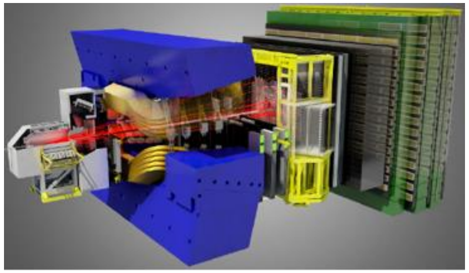




CMS

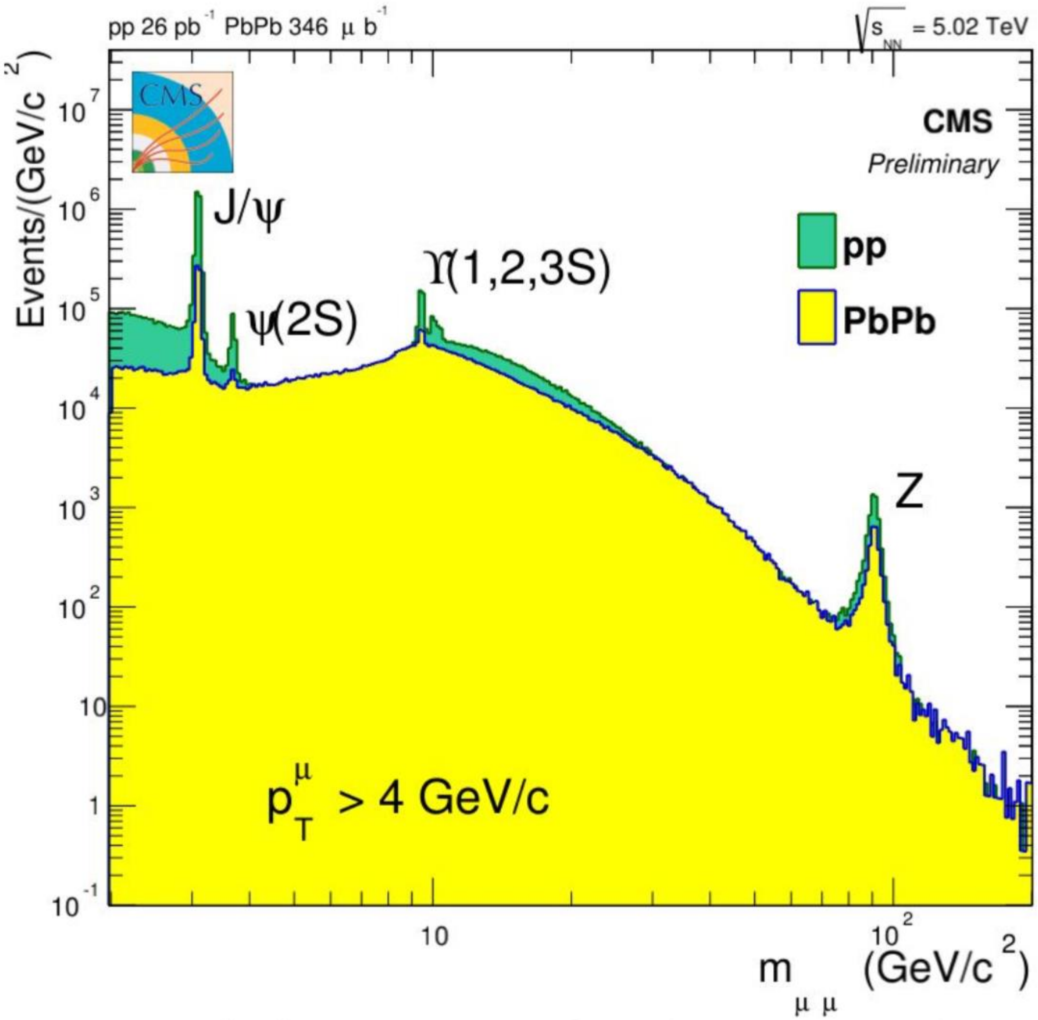


LHCb



- **Complimentary acceptance for LHC detectors**

Hello Yellow Plot 2015 Data



ALICE Detector

A Large Ion Collider Experiment

ALI

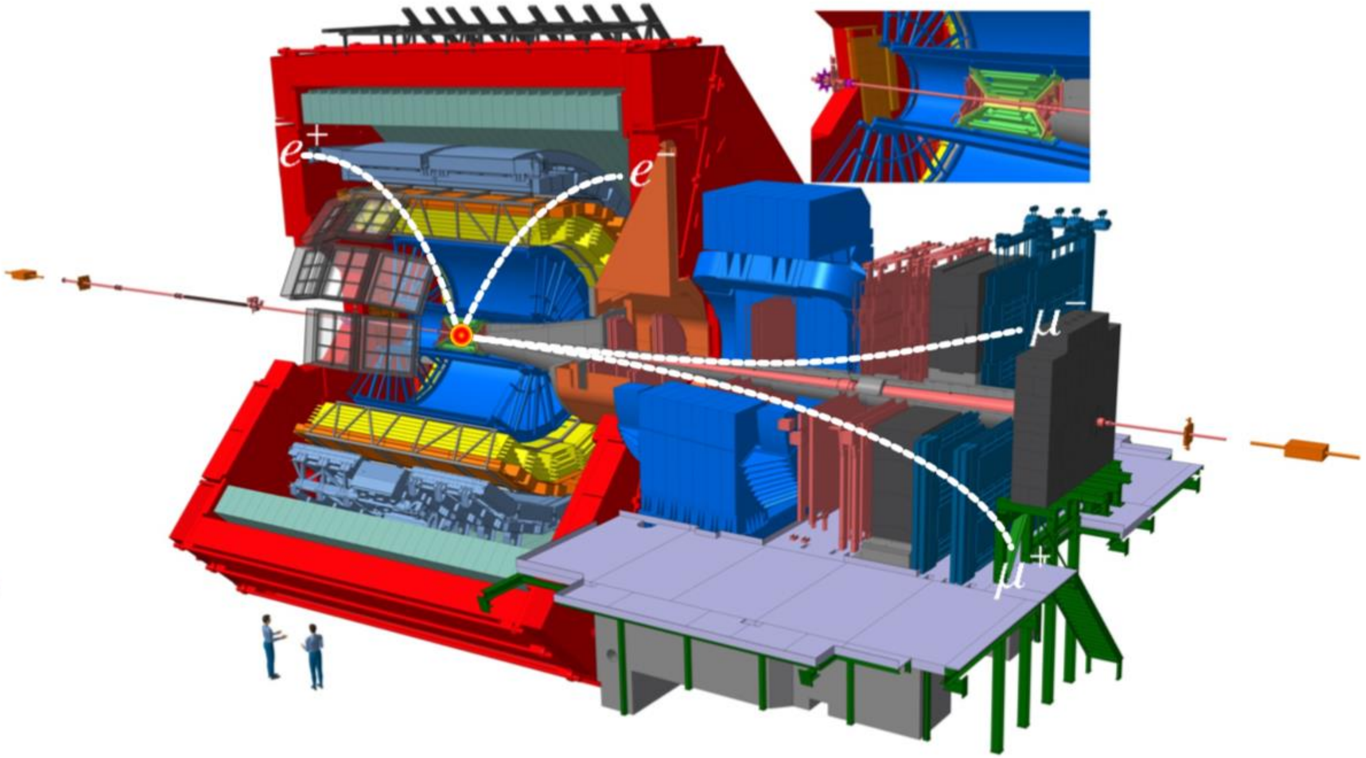
Quarkonium measurements with ALICE

Mid-rapidity:

- $Q\bar{Q} \rightarrow e^{+}e^{-}$
- $|y_{Lab}| < 0.9$
- tracking + PID
  - ITS, TPC, TOF, TRD

Forward rapidity:

- $Q\bar{Q} \rightarrow \mu^{+}\mu^{-}$
- $2.5 < y_{Lab} < 4$
- tracking + trigger
  - muon spectrometer



Quarkonia Measurement in pPb Collisions

- Cold Nuclear Matter
  - Quarkonia productions are sensitive to gluon PDF
  - Initial state effects : nPDF (Nuclear Shadowing), Comover break-up, energy loss due to multiple scattering … etc

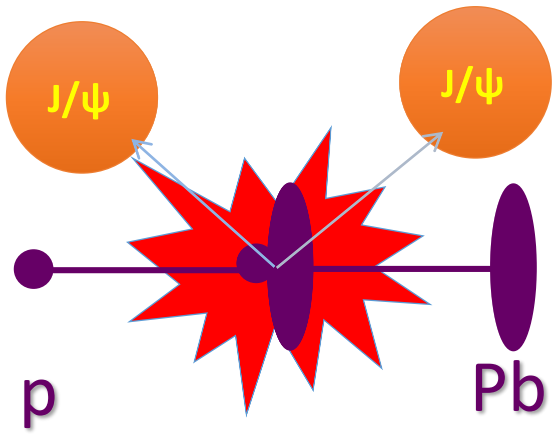
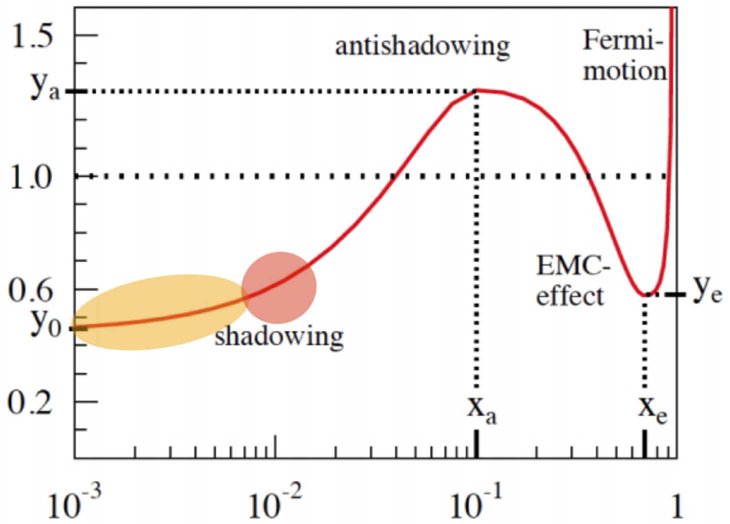


Illustration of nPDF fit
JHEP 0904 (2009) 065



x of parton in Pb
[In log scale]

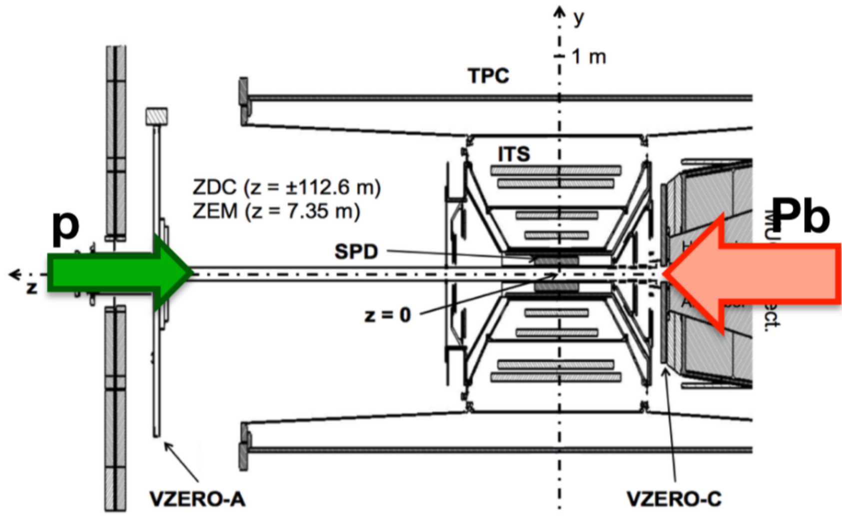
Event **multiplicity/centrality** classes are defined based on the amplitude measured in the **V0 scintillators**, placed at $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C)

$\langle dN_{ch}/d\eta \rangle$ is measured in $|\eta| < 0.5$
→ avoid "auto-biases" in multiplicity determination

In **Pb-Pb** the Glauber model is used to relate the V0A&V0C ("V0M") amplitude* distribution to the geometry of the collision.

At $\sqrt{s_{NN}} = 2.76$ TeV
0-5%: $\langle \mathbf{dN_{ch}/d\eta} \rangle = \mathbf{1601 \pm 60}$
$\langle \mathbf{N_{part}} \rangle = \mathbf{328.8 \pm 3.1}$
70-80%: $\langle \mathbf{dN_{ch}/d\eta} \rangle = \mathbf{35 \pm 2}$
$\langle \mathbf{N_{part}} \rangle = \mathbf{15.8 \pm 0.6}$

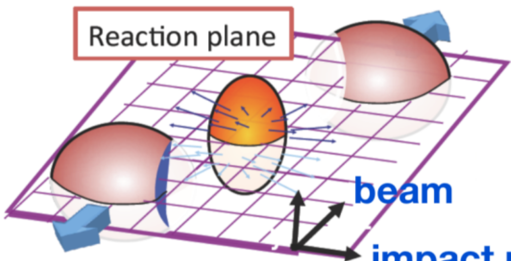
(*alternatively, multiplicity of spectators in the Zero Degree Calorimeters or number of tracks in the Silicon Pixel Detector or the Time Projection Chamber)



In **p-Pb** collisions, V0A (Pb side) is used:
at $\sqrt{s_{NN}} = 5.02$ TeV
0-5%: $\langle \mathbf{dN_{ch}/d\eta} \rangle = \mathbf{45 \pm 1}$
60-80%: $\langle \mathbf{dN_{ch}/d\eta} \rangle = \mathbf{9.8 \pm 0.2}$

In **pp** collisions, V0A&V0C ("V0M") us used:
at $\sqrt{s} = 7$ TeV
0-0.95%: $\langle \mathbf{dN_{ch}/d\eta} \rangle = \mathbf{21.3 \pm 0.6}$
48-68%: $\langle \mathbf{dN_{ch}/d\eta} \rangle = \mathbf{3.90 \pm 0.14}$

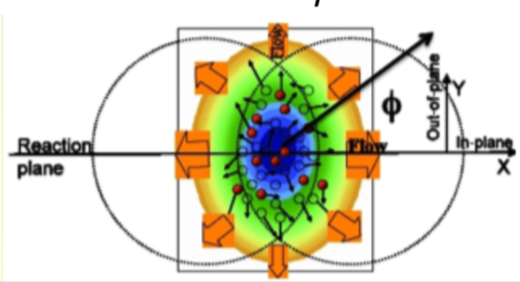
Elliptic flow (azimuthal anisotropy)



Study **azimuthal distribution** of produced particles w.r.t. the reaction plane (Ψ_{RP})

Anisotropic flow: v_2

$$\frac{dN}{d\varphi} = \frac{N_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2v_2\cos[2(\varphi - \Psi_{RP})] + \ldots\right)$$



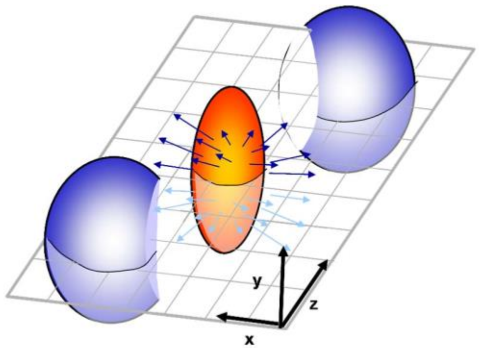
Initial **spatial** anisotropy —via re-scatterings→ **momentum** anisotropy of particle emission

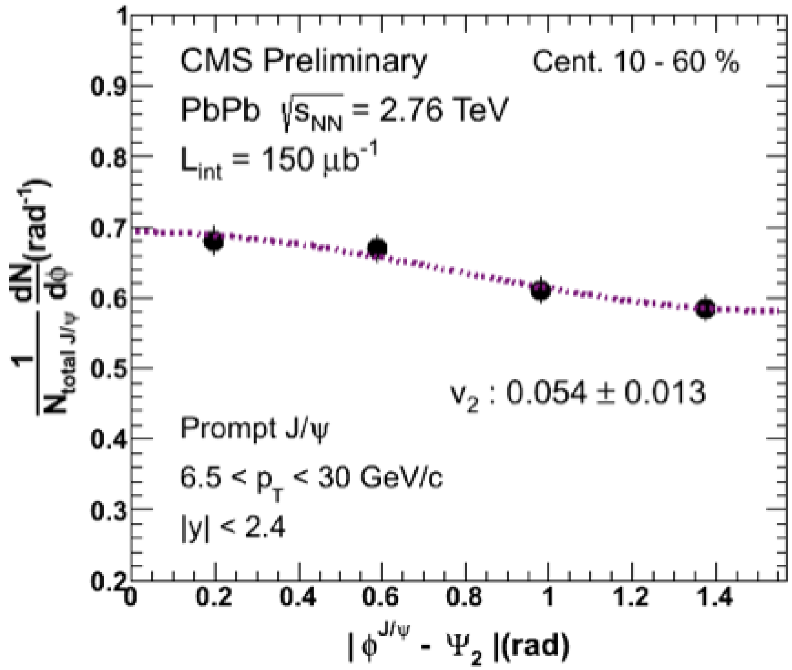
The **anisotropy** is quantified via a **Fourier expansion** in azimuthal angle (φ) with respect to the reaction plane (Ψ_{RP})

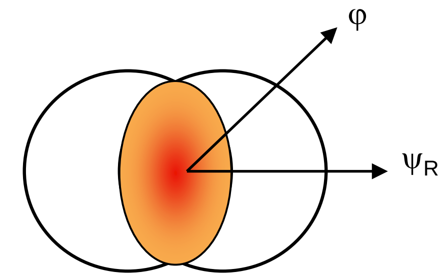
$v_2 > 0$
- → Thermalization/collective motion (at low p_T)
- → Path length dependence of energy loss (at high p_T)

v_2+ R_{AA}: complementary information → improve sensitivity to relative contribution of collisional and radiative energy losses and to coalescence

J/ψ Azimuthal Anisotropy in CMS





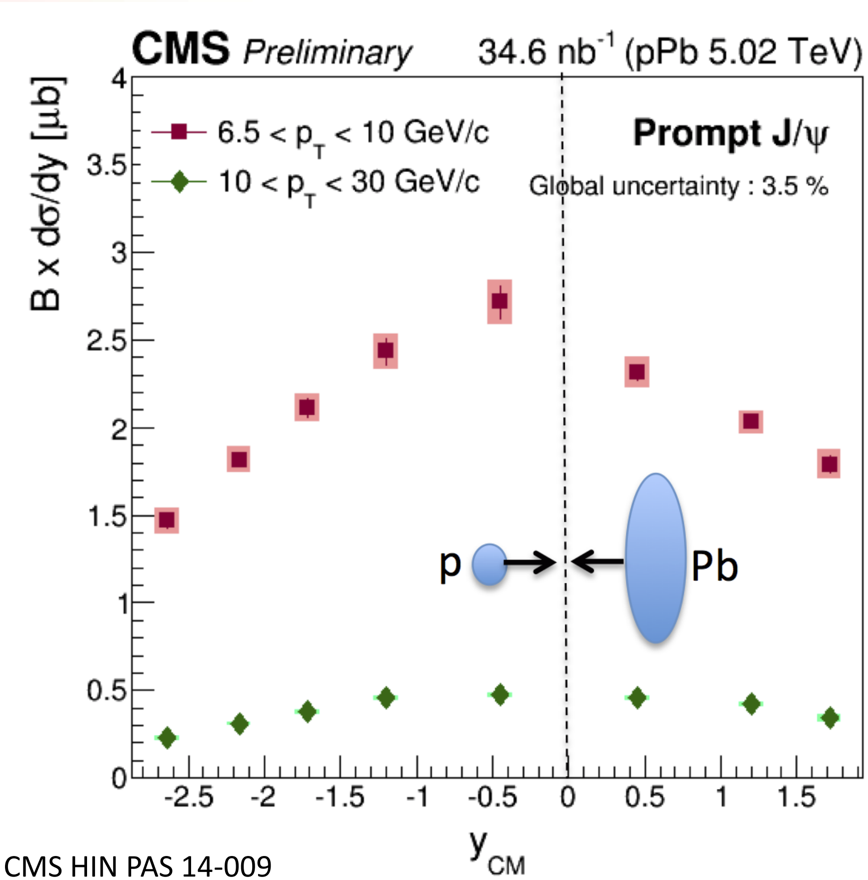


$$\frac{2}{\pi}(1+2v_2\cos(2\Delta\phi))$$

CMS-PAS-HIN-12-001

- Event plane method
- Integrated v_2 for Prompt J/ψ (p_T > 6.5 GeV/c)
  - ➠ 0.054 ± 0.013 (stat.) ± 0.006 (syst.) in |y| < 2.4, 10-60 %
  - ➠ significant (3.8σ) v_2 at high-p_T prompt J/ψ

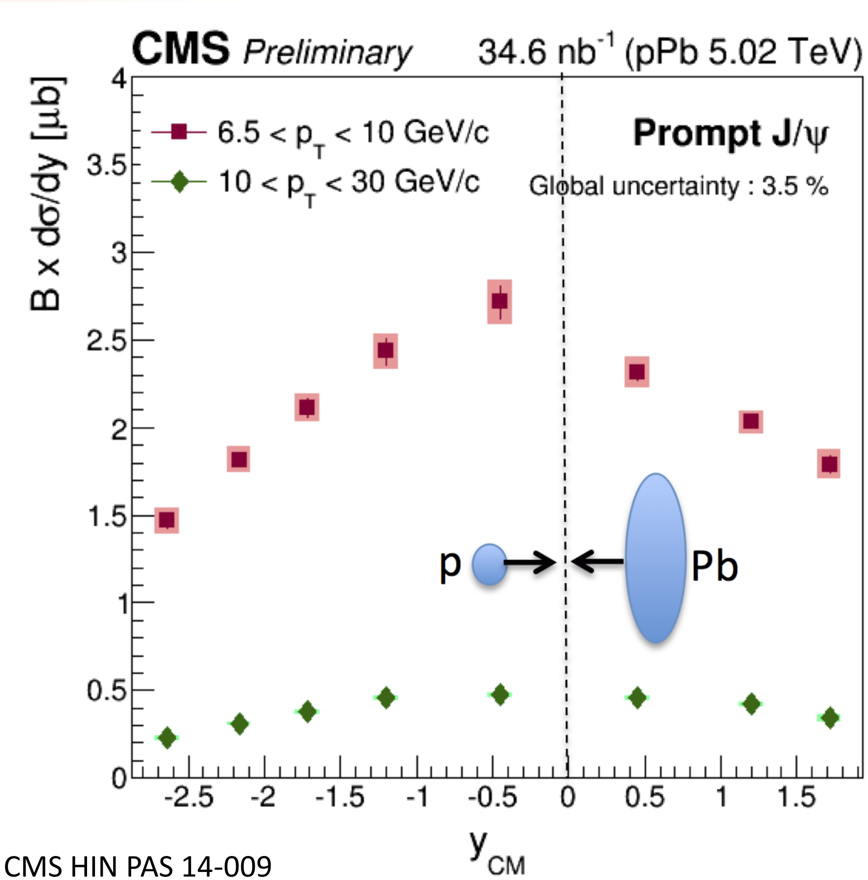
Charmonia in pPb



CMS HIN PAS 14-009

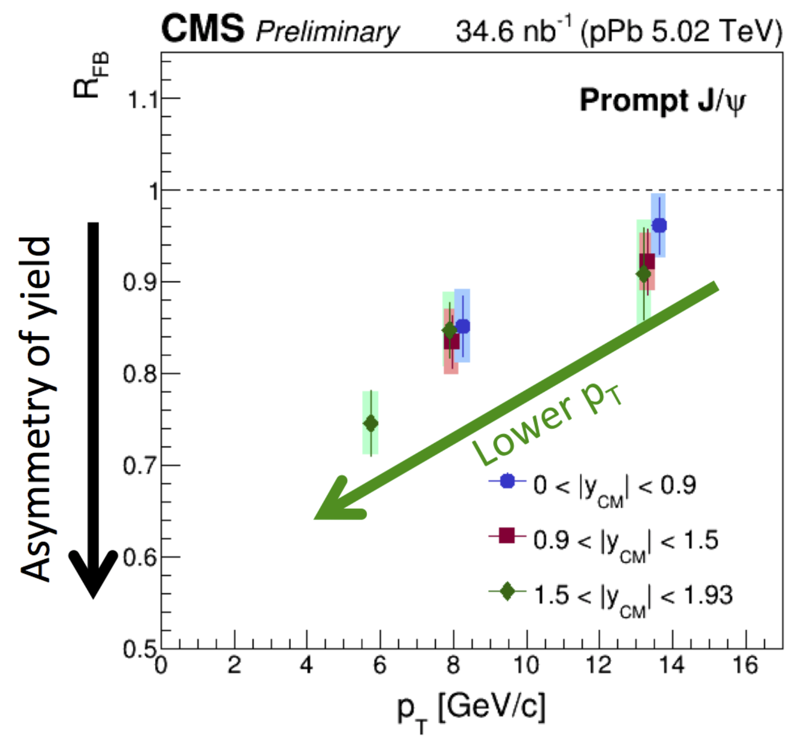
$$R_{FB}(p_T, y) = \frac{\text{Yield in } (p_T, +y)}{\text{Yield in } (p_T, -y)}$$

Charmonia in pPb



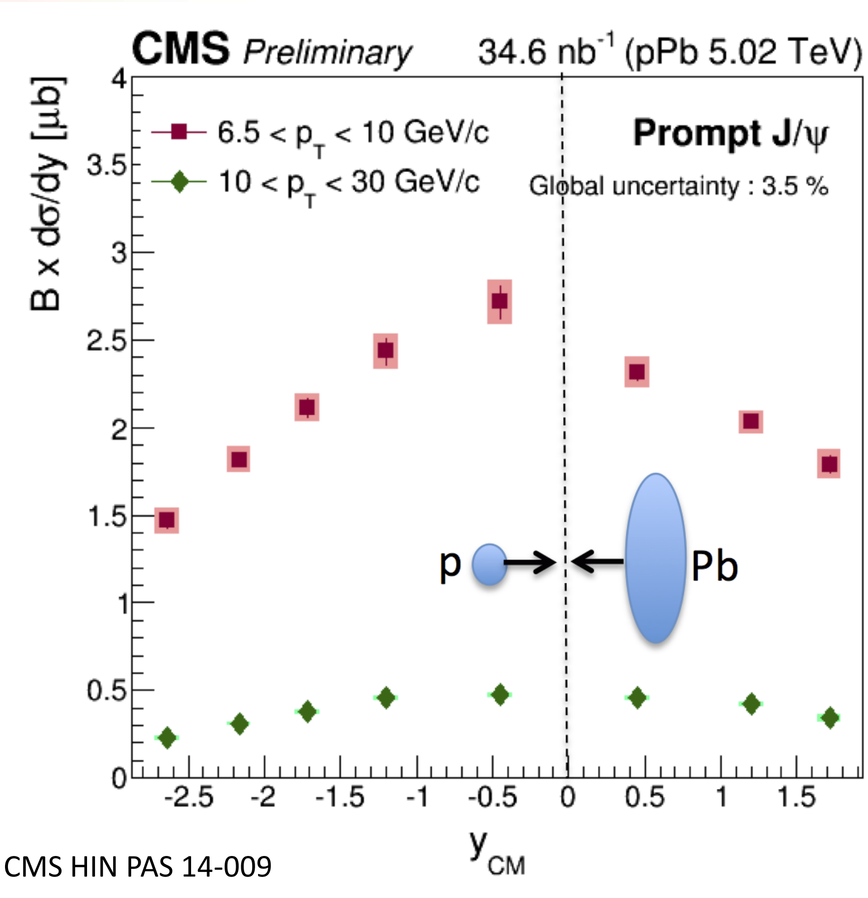
CMS HIN PAS 14-009

$$R_{FB}(p_T, y) = \frac{\text{Yield in } (p_T, +y)}{\text{Yield in } (p_T, -y)}$$



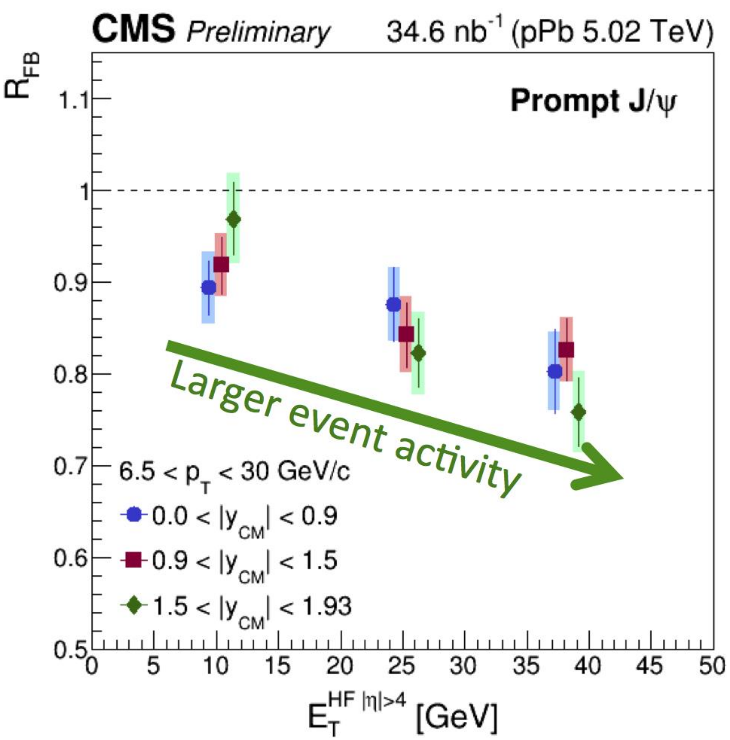
- Clear dependence of p_T : more suppression for forward in lower p_T
- No strong dependence on |y|

Charmonia in pPb



CMS HIN PAS 14-009

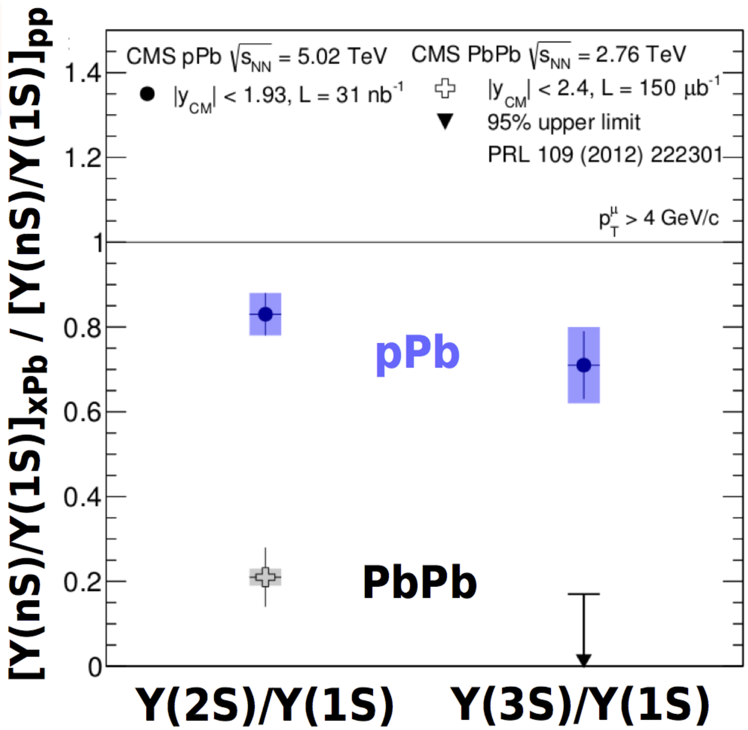
$$R_{FB}(p_T, y) = \frac{\text{Yield in } (p_T, +y)}{\text{Yield in } (p_T, -y)}$$

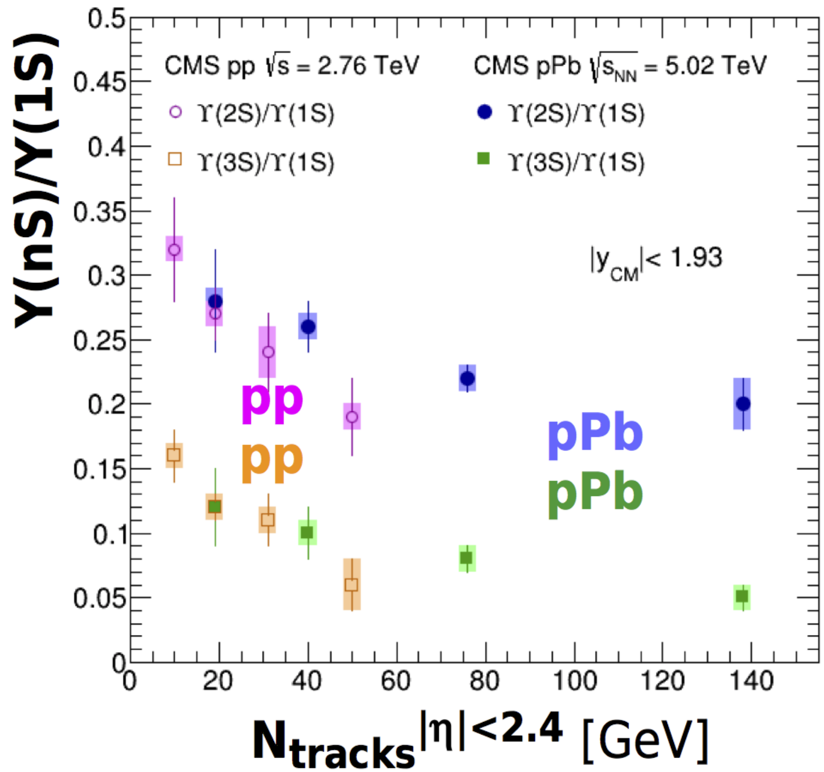


- Clear dependence of event activity : more suppression for forward in larger event activity
- No strong dependence on |y|

Bottomonia in pPb

$$\frac{R_{pPb}(\Upsilon(nS))}{R_{pPb}(\Upsilon(1S))}$$



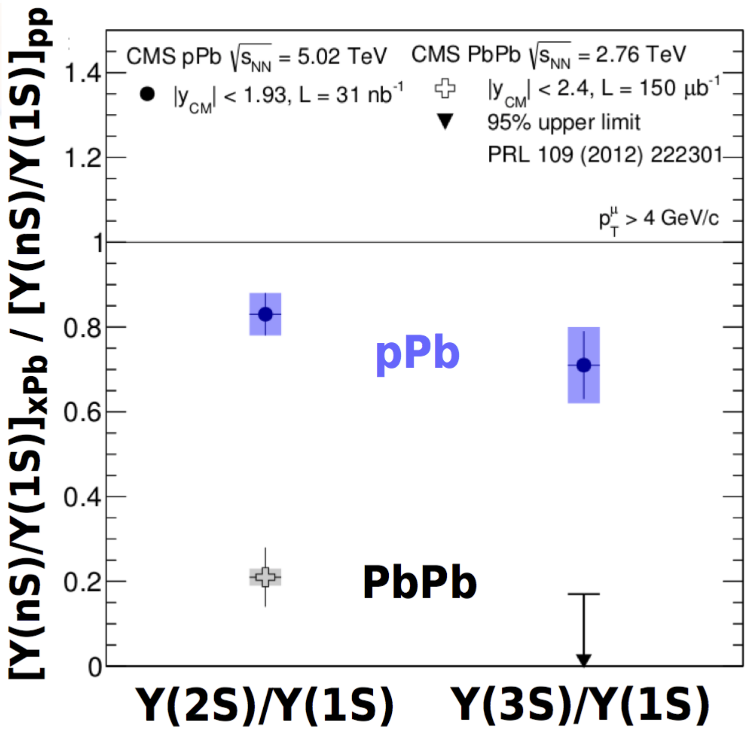


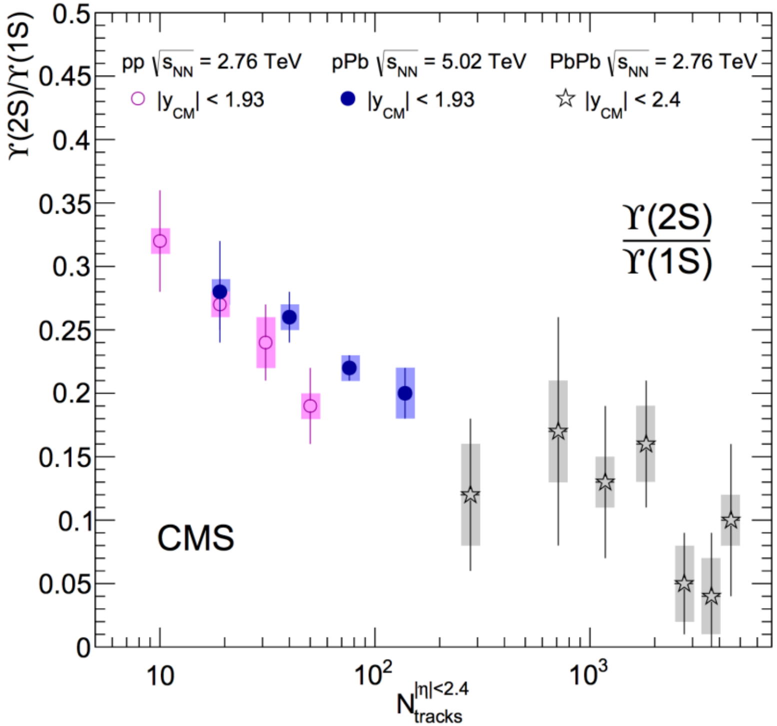
PRL 109 (2012) 222301

- Indication of initial suppression in pPb
- Y(nS)/Y(1S) has clear dependence on N_{trks} for pp & pPb

Bottomonia in pPb

$$\frac{R_{pPb}(\Upsilon(nS))}{R_{pPb}(\Upsilon(1S))}$$



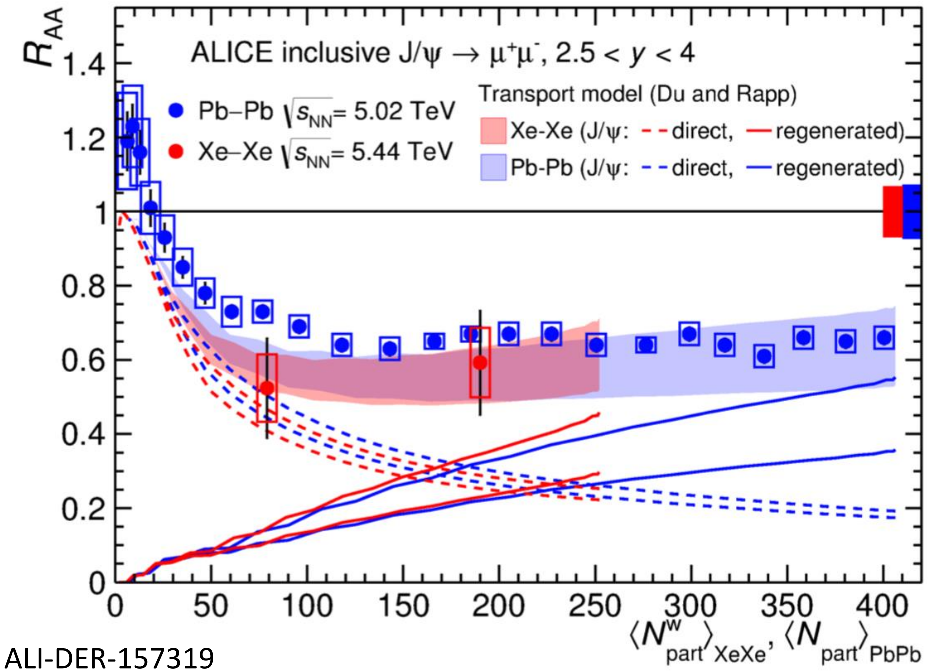


PRL 109 (2012) 222301

- Indication of initial suppression in pPb
- Y(nS)/Y(1S) has clear dependence on N_{trks} for pp & pPb & PbPb

ALICE Inclusive J/ψ: R_{AA}

Xe-Xe



ALI-DER-157319

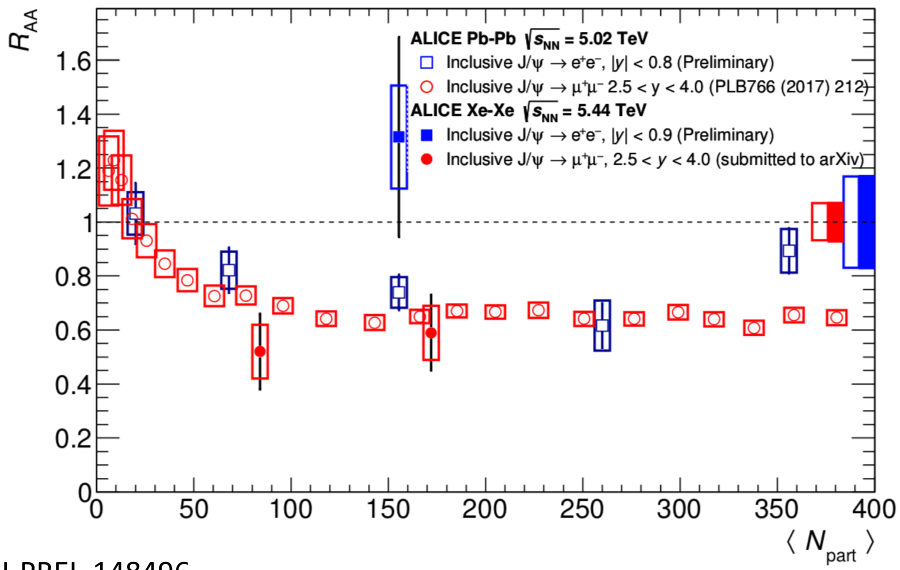
At forward rapidity:

- A_{Xe} = 129, $\mathscr{L}_{int} \approx$ 0.34 μb^{-1}
- A_{Pb} = 208 , $\mathscr{L}_{int} \approx$ 225 μb^{-1}
- $N_{J/\psi}$ = 241 ± 47(stat.) ± 26(syst.)
- R_{AA} results of Xe–Xe and Pb–Pb agree within uncertainties

➔ Similar $\sqrt{s_{NN}}$ and ⟨N_{part}⟩ lead to similar relative contributions of suppression/regeneration

ALICE Inclusive J/ψ: R_{AA}

Xe-Xe

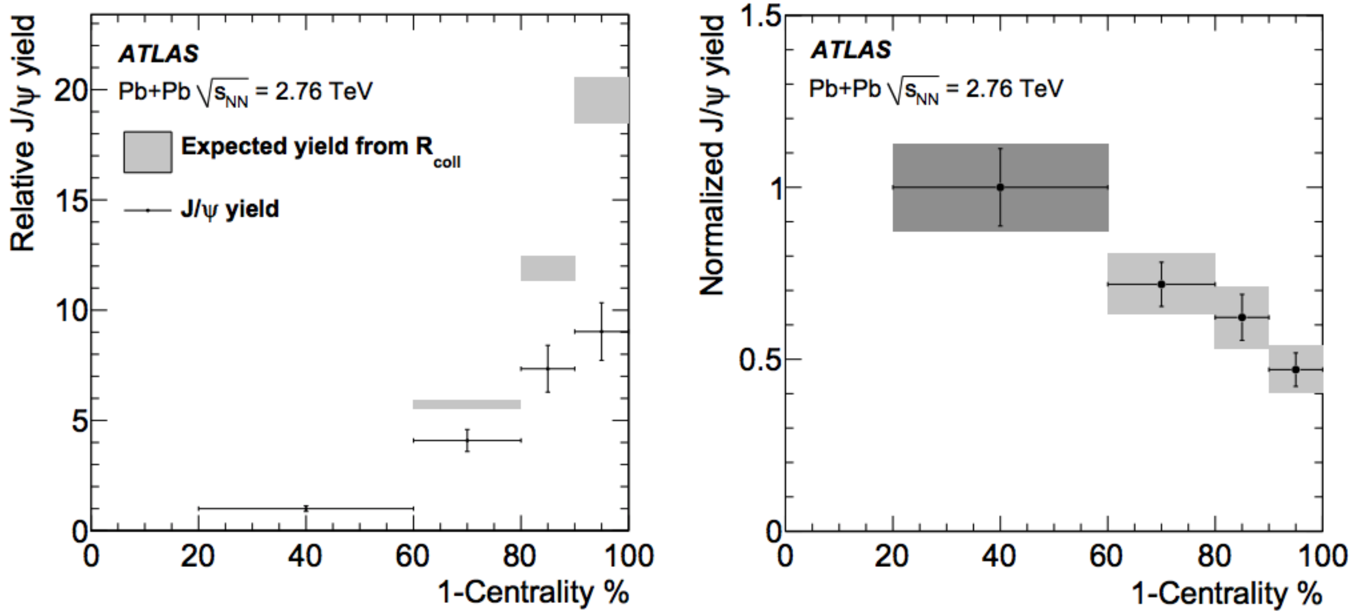


ALI-PREL-148496

<u>At mid-rapidity:</u>

- A_{Xe} = 129 , $\mathscr{L}_{int} \approx 0.25\ \mu b^{-1}$
- A_{Pb} = 208 , $\mathscr{L}_{int} \approx 13\ \mu b^{-1}$
- $N_{J/\psi}$ = 340 ± 89(stat.) ± 14(syst.)
- R_{AA} consistent with unity within large stat. and syst. uncertainties

ATLAS J/ψ: R_{AA}

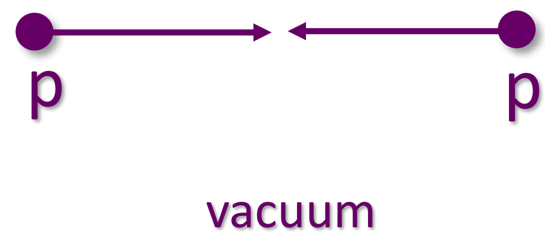


ALI-PREL-148

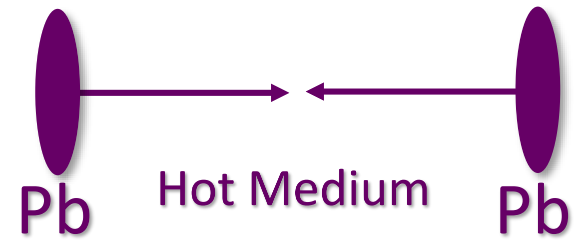
Figure 3: (left) Relative J/ψ yield as a function of centrality normalized to the most peripheral bin (black dots with errors). The expected relative yields from the (normalized) number of binary collisions ($R_{\rm coll}$) are also shown (boxes, reflecting 1σ systematic uncertainties). (right) Value of R_{cp}, as described in the text, as a function of centrality. The statistical errors are shown as vertical bars while the grey boxes also include the combined systematic errors. The darker box indicates that the 40-80% bin is used to set the scale for all bins, but the uncertainties in this bin are not propagated into the more central ones.

Three Collision System

- **pp collisions**
  - Reference to understand pA and AA data
  - Still ongoing to understand exact production mechanism (Color Octet vs. Color Singlet)



- **PbPb collisions**
  - Exploring new nuclear matter known as Quark-Gluon-Plasma (QGP)
  - Characterize and quantify the properties of QGP



- **pPb collisions**
  - Create Cold Nuclear Matter (CNM)
    - Nucler modification of gluon PDF (nPDF) : shadowing, saturation, CGC …
  - Understanding initial state effect on production
  - Examine pure suppression from observation in QGP

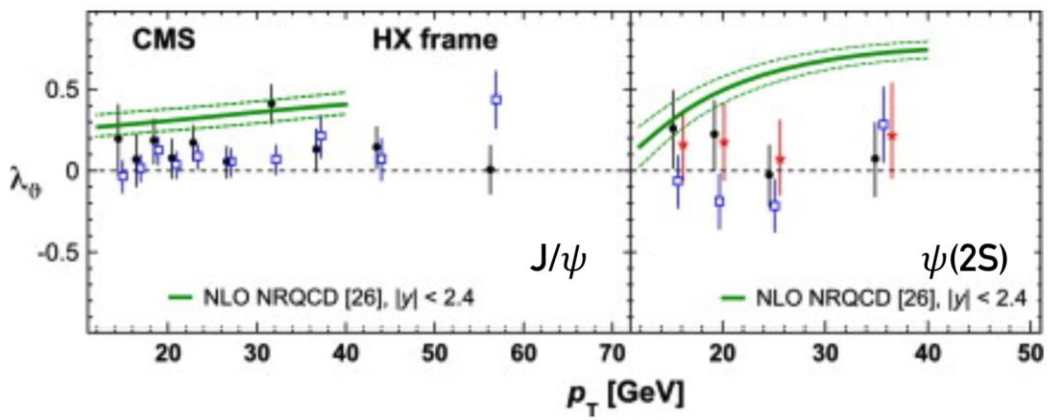
Quarkonium in pp collisions

CEM (Color Evaporation Model)

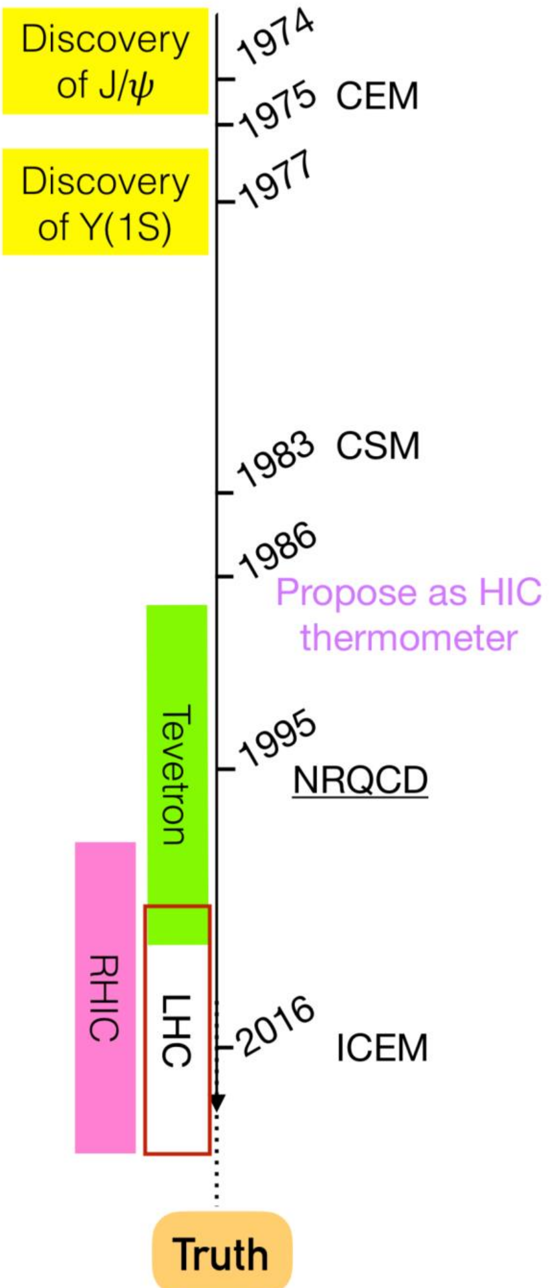
CSM (Color Singlet Model)

NRQCD (Nonrelativistic QCD)

ICEM (Improved Color Evaporation Model)
[Ma, Vogt 1609.06042]



- No consistency descriptions of cross section and polarization

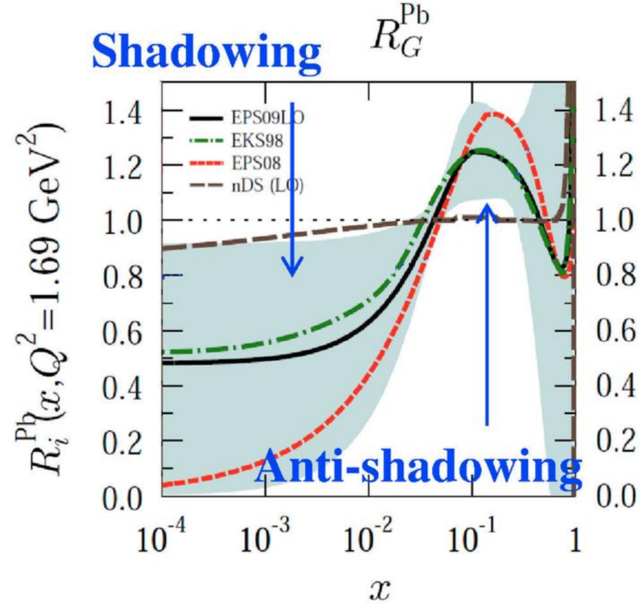


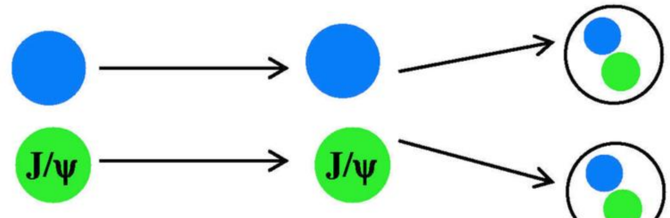
CMS: *PLB*, 727(2013)381
NRQCD: *PRL*, 110(2013)042002

Quarkonia in *p*Pb Collisions

Ferreiro et al., PRC 81(2010) 064911
Eskola et al., Eur.Phys.J. C9 (1999) 61-68
Eskola. et al., JHEP 0807 (2008) 102
Eskola et al., JHEP 0904 (2009) 065
De Florian et al., PRD69 (2004) 074028

- Cold Nuclear Matter effects
  - Initial state:
    - Modification of nuclear PDF
    - Gluon saturation
  - Multiple scattering of partons in the nucleus
  - Final state:
    - nuclear absorption (negligible at LHC energy)
    - Co-mover effect
      - Break-up of quarkonium by co-moving hadrons outside of nuclear remnant
      - study via $\psi(2S)$

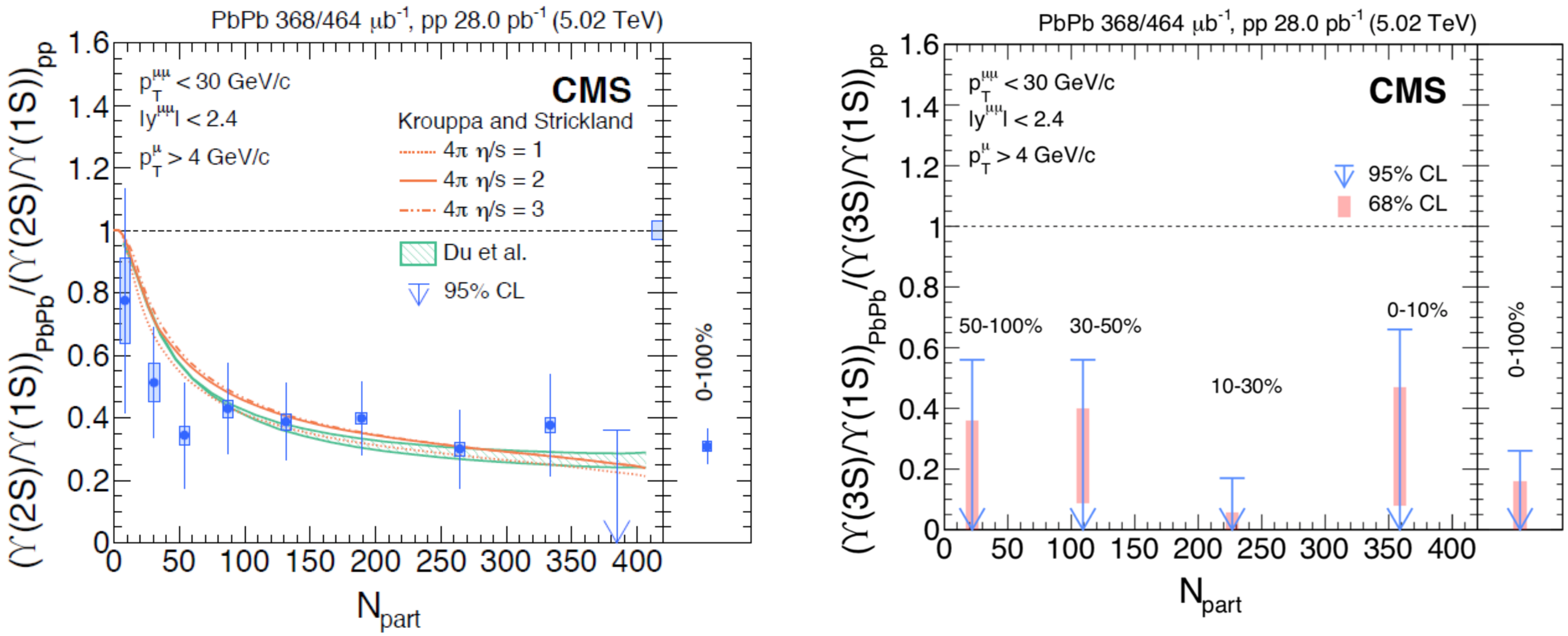




Ferreiro et al., Eur.Phys. J. C61 (2009) 859–864
Ferreiro et al., PLB680 (2009) 50–55
Ferreiro, et al., PRC81 (2010) 064911

Co-mover effect

Double Ratio for ϒ(nS)

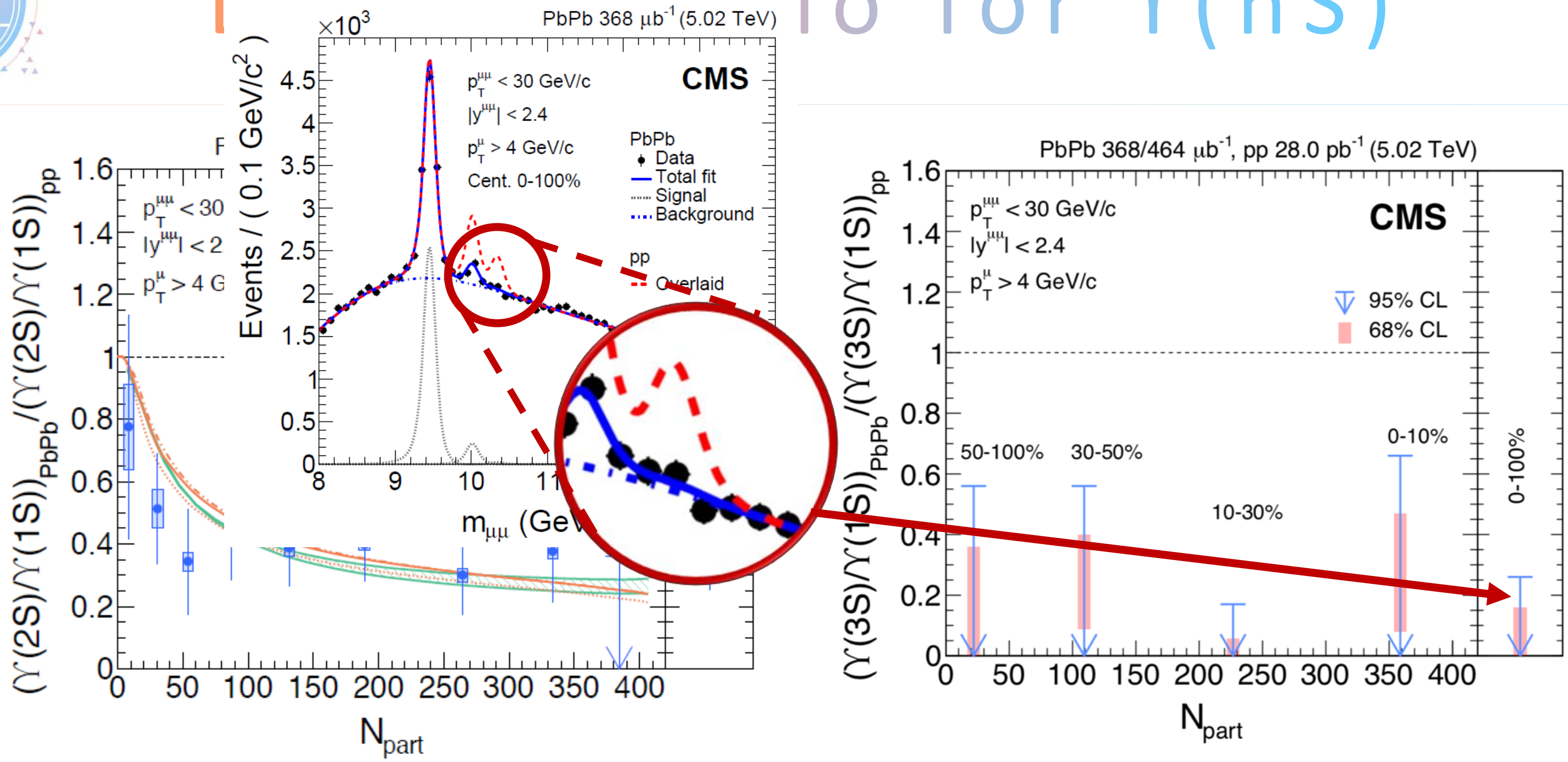


Double Ratio (DR) = $\frac{[\Upsilon(nS)/\Upsilon(1S)]_{PbPb}}{[\Upsilon(nS)/\Upsilon(1S)]_{pp}} = \frac{R_{AA}(\Upsilon(nS))}{R_{AA}(\Upsilon(1S))}$

Submitted to PRL
arXiv:1706.05984

- Suppression of ϒ(2S) w.r.t. ϒ(1S) and trend looks ~flat in centrality > 40 %
  - Upper limit assigned with 95% CL at most central event (0-5%)
- Strong suppression of ϒ(3S) w.r.t. ϒ(1S) in all centralities
- 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)

Double Ratio for ϒ(nS)

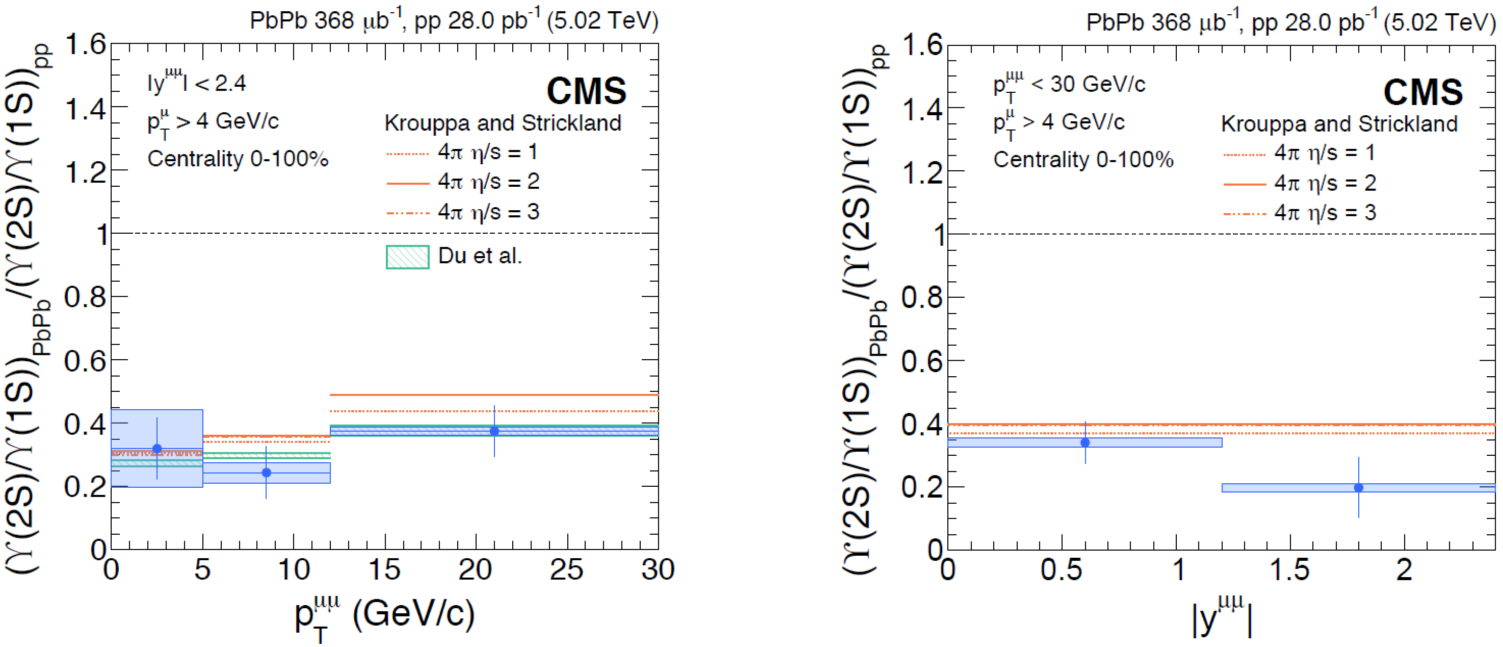


$$\text{Double Ratio (DR)} = \frac{[\Upsilon(nS)/\Upsilon(1S)]_{PbPb}}{[\Upsilon(nS)/\Upsilon(1S)]_{pp}} = \frac{R_{AA}(\Upsilon(nS))}{R_{AA}(\Upsilon(1S))}$$

Submitted to PRL
arXiv:1706.05984

- Complete melting of 3S
  - 3S yet to be seen in PbPb collisions at the LHC

Υ(2S): Differential double ratio



Double Ratio (DR) = $\frac{[\Upsilon(nS)/\Upsilon(1S)]_{PbPb}}{[\Upsilon(nS)/\Upsilon(1S)]_{pp}} = \frac{R_{AA}(\Upsilon(nS))}{R_{AA}(\Upsilon(1S))}$

Submitted to PRL
arXiv:1706.05984

- No strong dependence on p_T and rapidity but
- Possible stronger relative suppression in forward region (large stat. uncertainties) , not expected by theoretical model