Summary of heavy flavour dilepton in pp and PbPb at CMS

Dong Ho Moon
for CMS Collaboration
(Chonnam National University)

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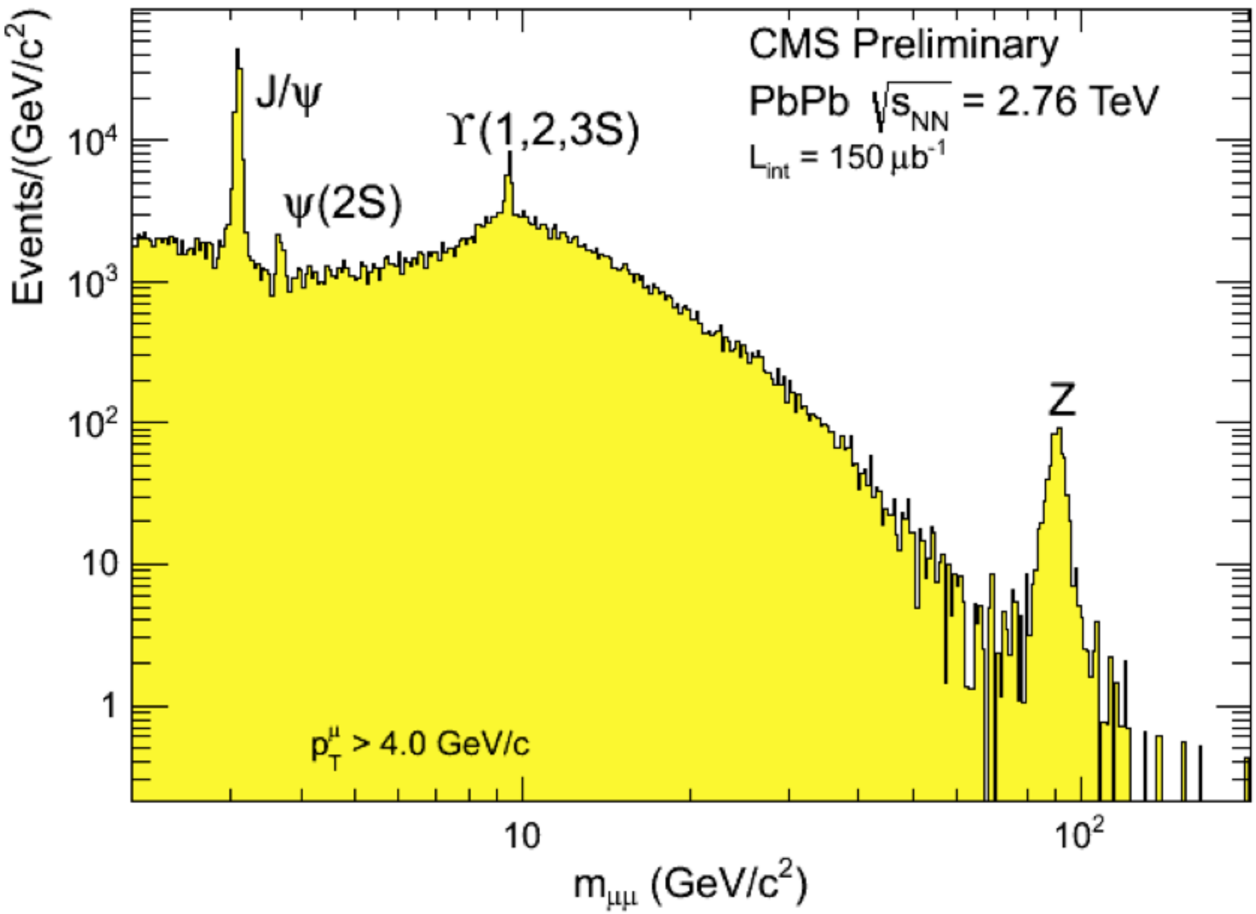
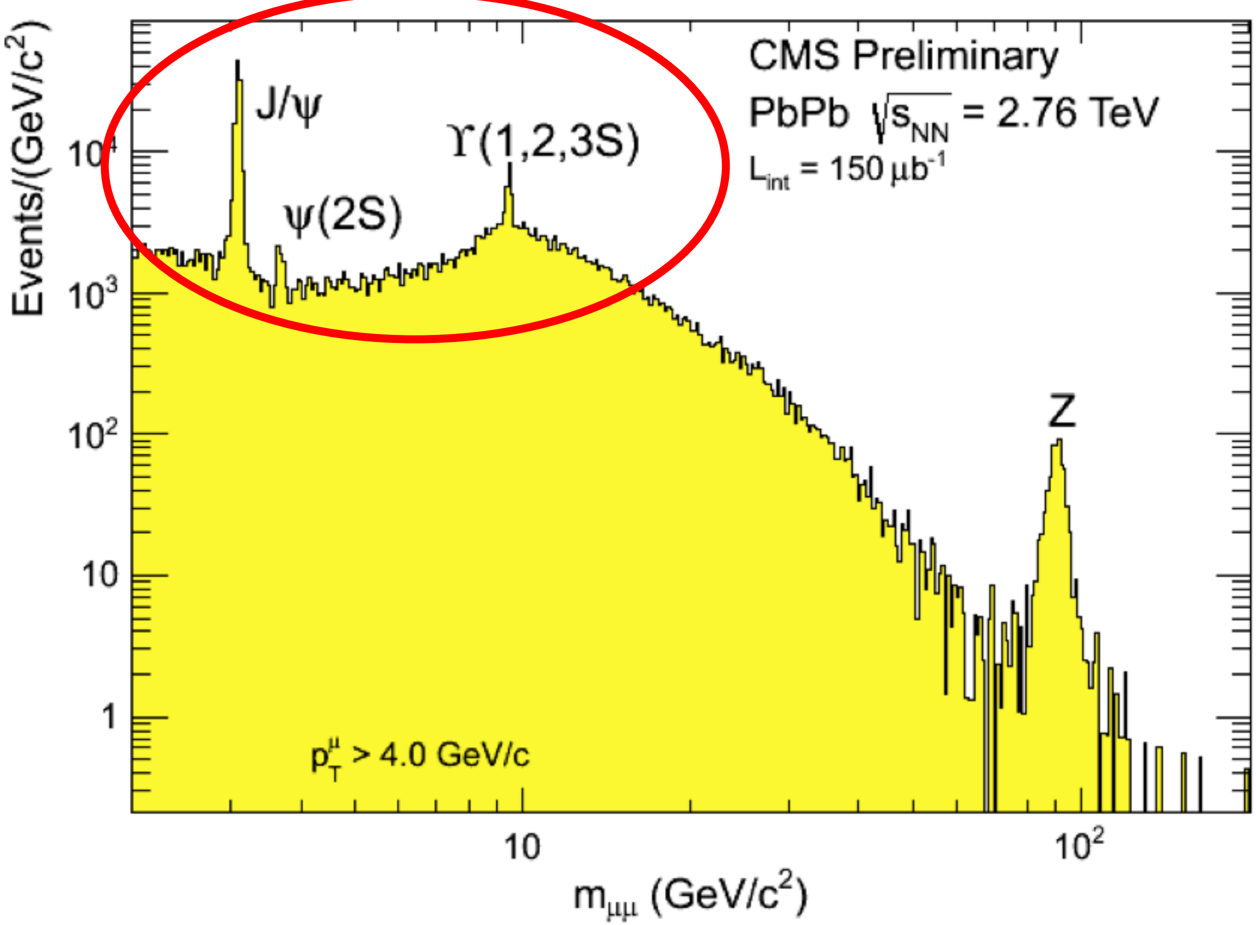
Hello ☺ (Yellow) Plot for PbPb in CMS



CMS HI-Dilepton group

- Z to mumu (or ee)
  - PRL 106 (2011) 212301
  - JHEP 03 (2015) 022
- Charmonia
  - J/ψ to mumu
  - ψ(2S) to mumu
    - JHEP 05 (2012) 063
    - CMS-PAS-12-014
    - PRL 113 (2014) 262301
    - CMS-PAS-12-001
- Bottomonia
  - ϒ(1,2,3S)
    - PRL 109 (2012) 222301
    - PRL 107 (2011) 052302
    - CMS-PAS-15-001

Hello ☺ (Yellow) Plot for PbPb in CMS



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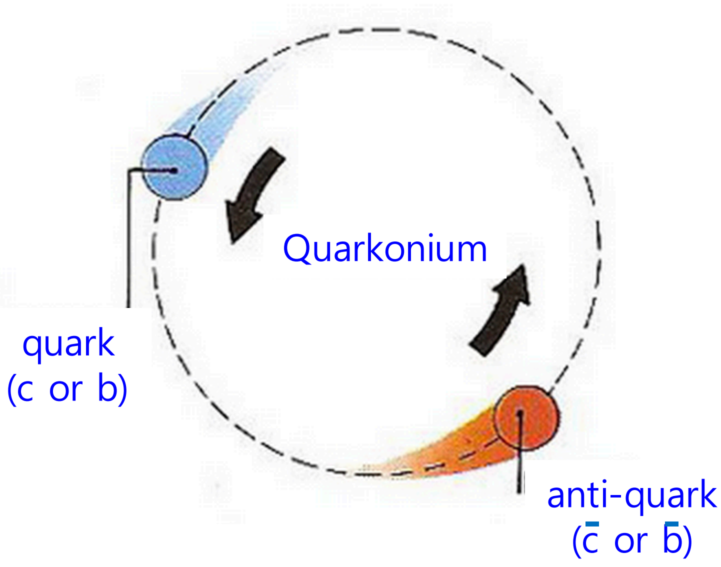
Quarkonia Measurement in Heavy-ion Collisions

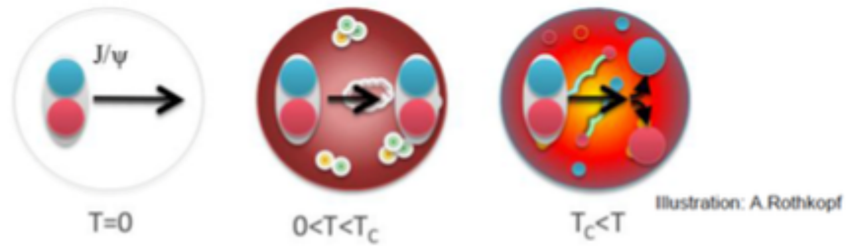
- **Quarkonia are wonderful probe of Quark-Gluon-Plasma (QGP)**
  - ➠ Produced in early stage of collisions with large momentum transfer in gluon-gluon fusion



Quarkonia Measurement in Heavy-ion Collisions

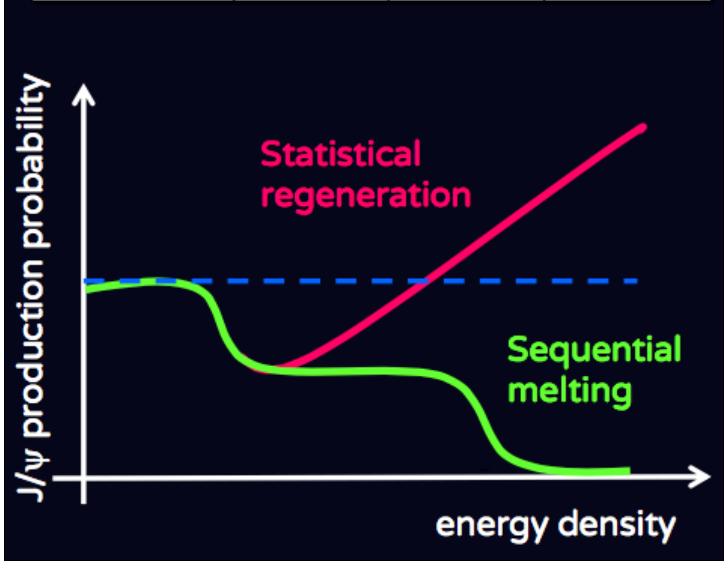
- **Quarkonia production in heavy-ion collisions**
  - ➠ **Color screening** : dissociated in the medium (***suppression***).
  - ➠ **Sequential melting** : different dissociation temperatures for different bound states (thermometer of medium)
  - ➠ **Energy loss** (landau damping)
  - ➠ **Regeneration** : heavy flavor quark production increases strongly with collision energy.

QGP occurs



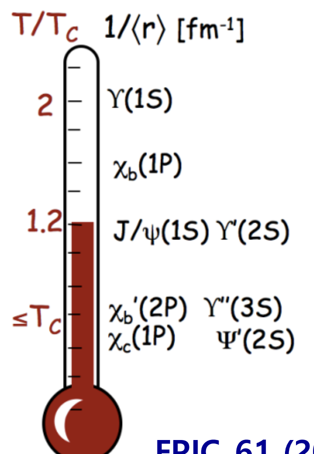
Disociated

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



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

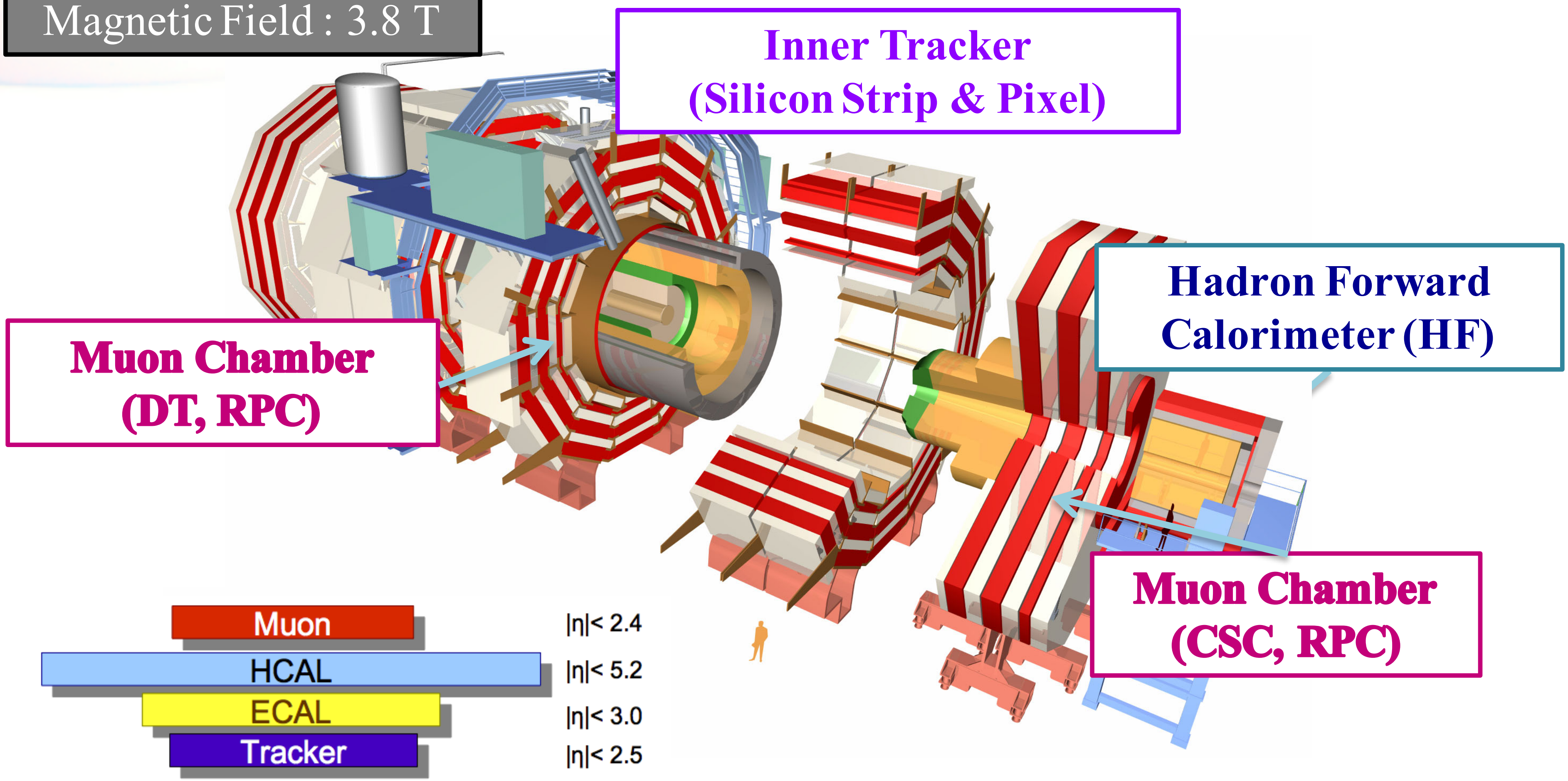
Bottomonia	Υ(1S)	Υ(2S)	Υ(3S)
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
T_d/T_c	> 4.0	1.60	1.17



EPJC 61 (2009) 705

CMS Detector

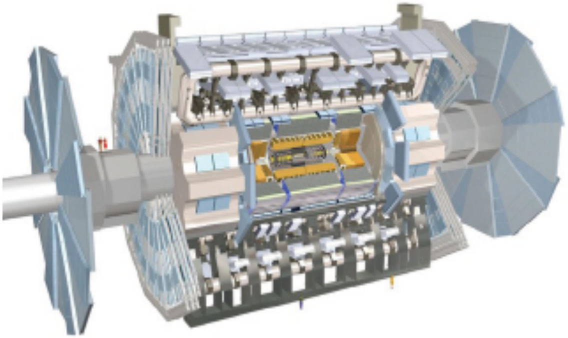
Magnetic Field : 3.8 T

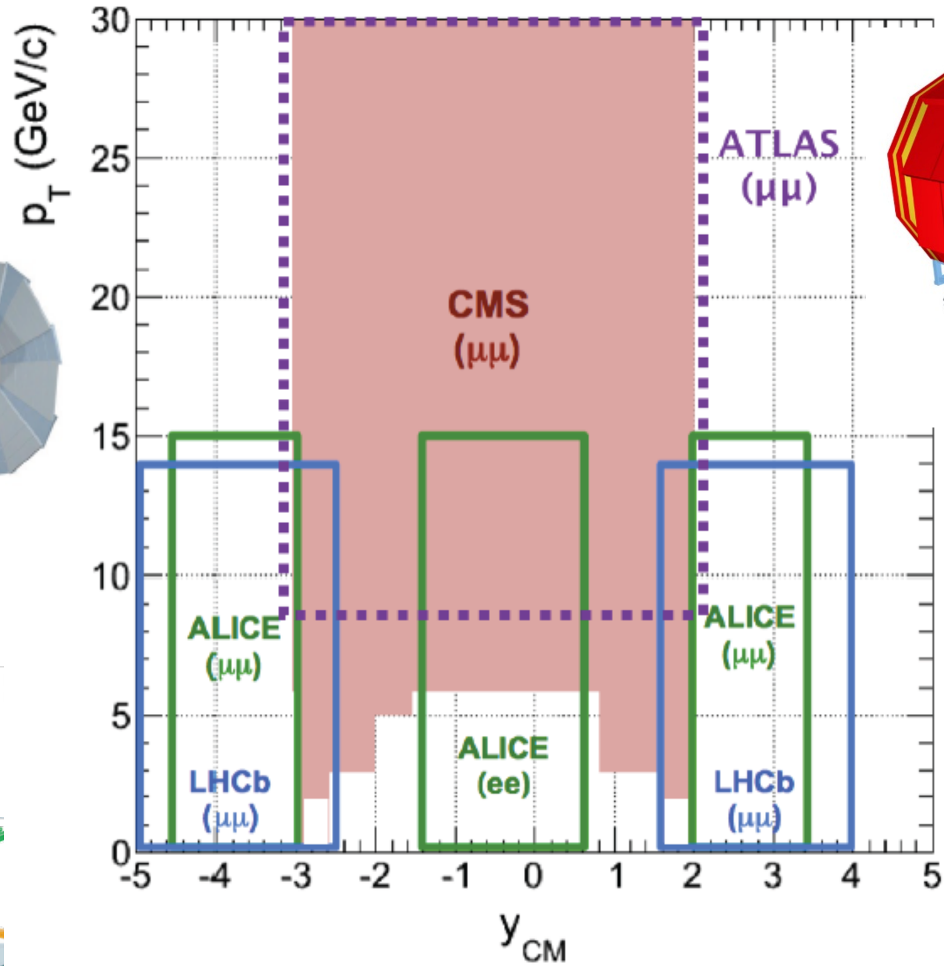


Quarkonia Acceptance

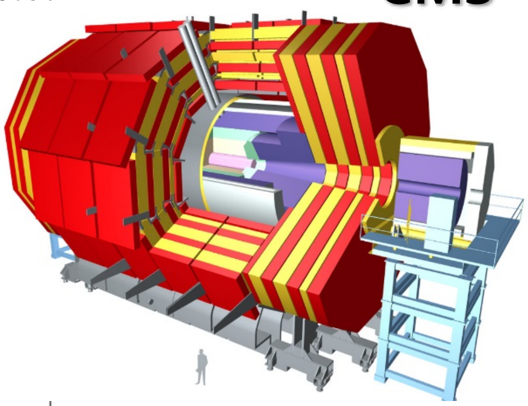
We are good friends !!!

ATLAS

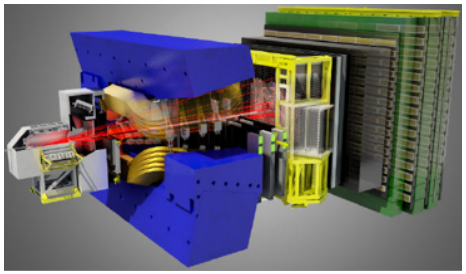




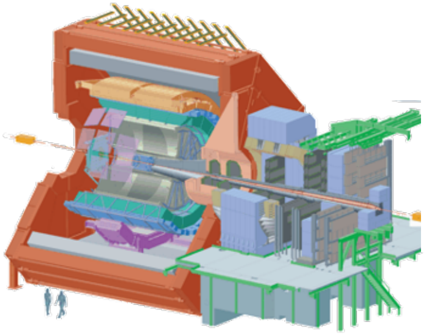
CMS



LHCb

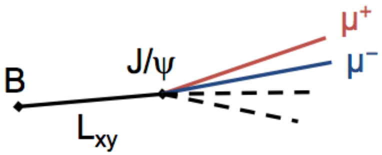


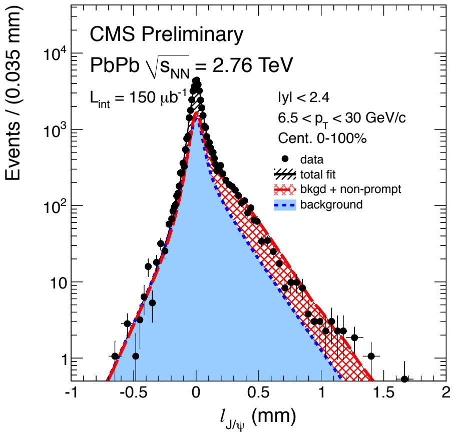
ALICE

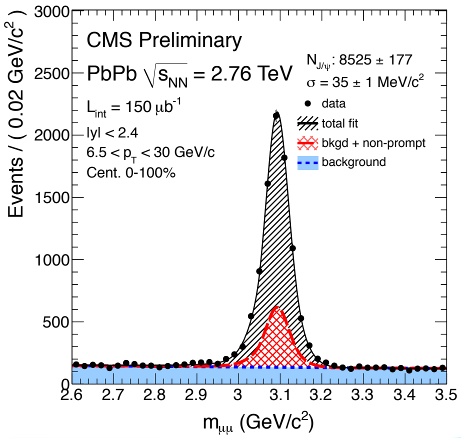


- Complimentary acceptance for LHC detectors

Charmonia in PbPb collisions



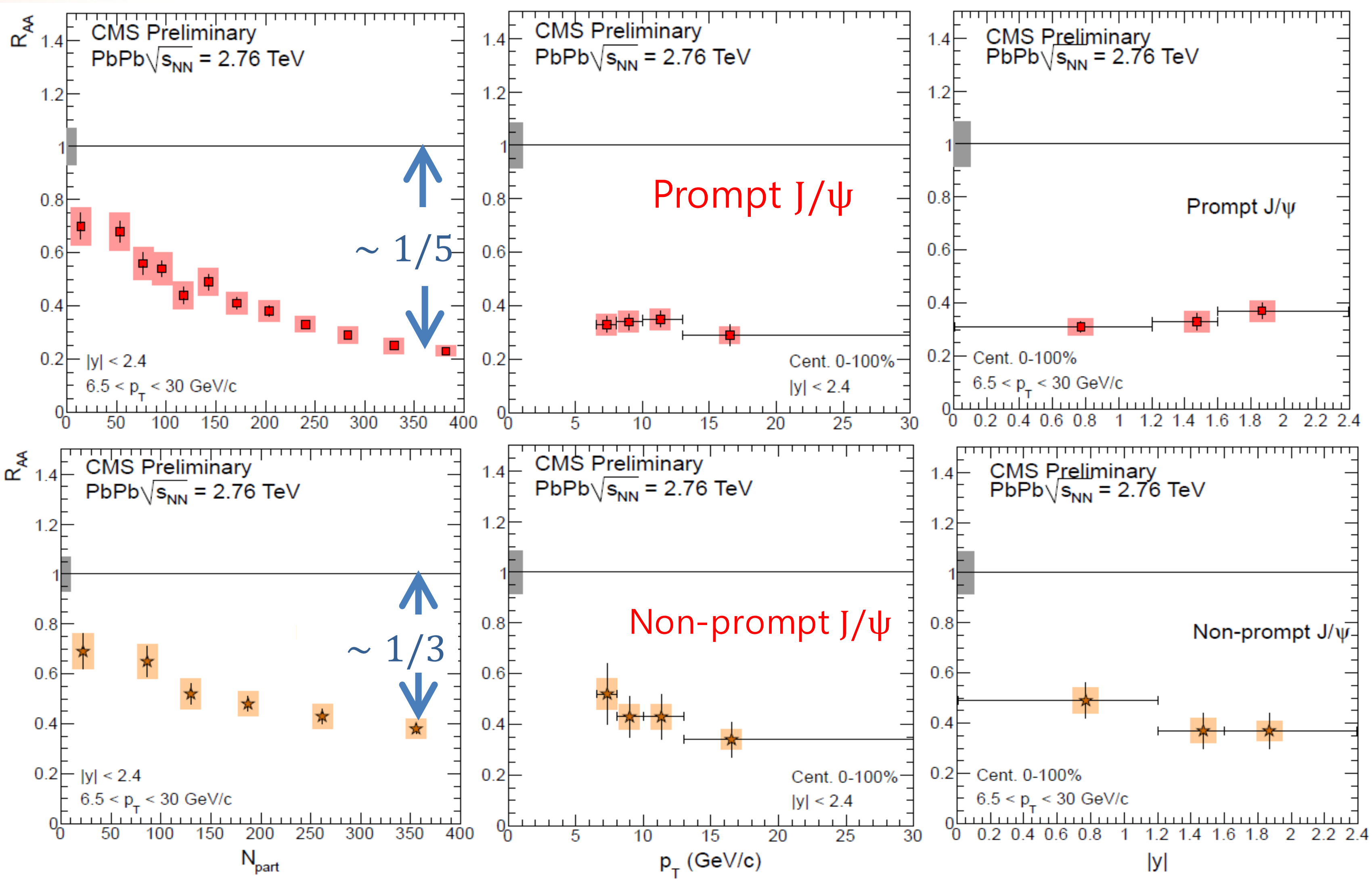




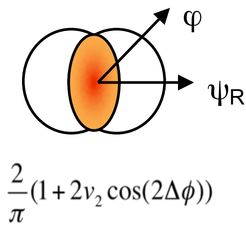
$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}}{N_{pp}} \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}}$$

Charmonia in PbPb

CMS-PAS-12-014



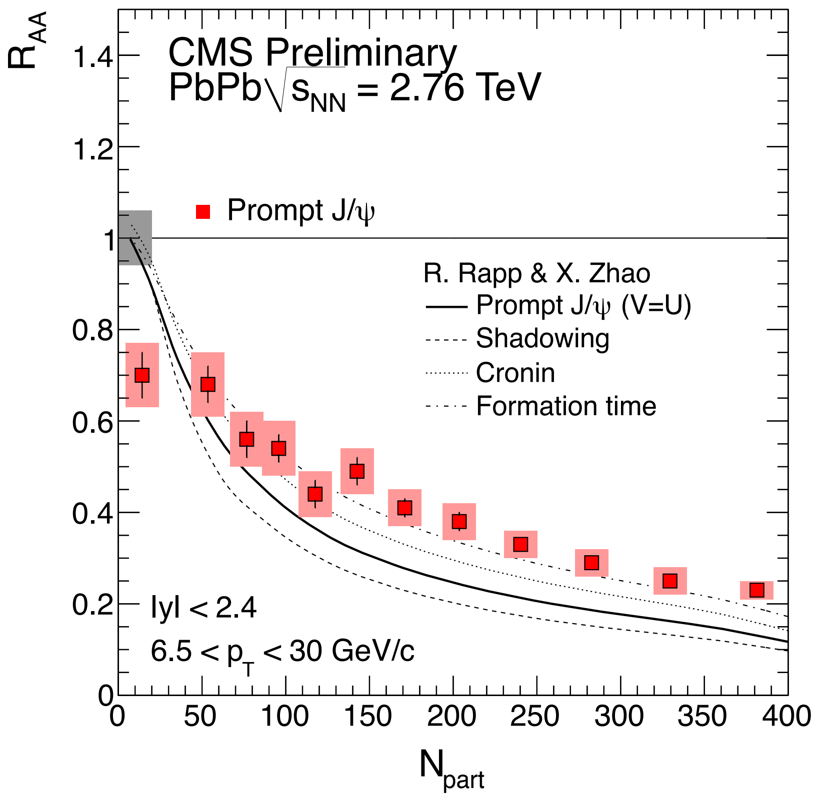
Charmonia in PbPb

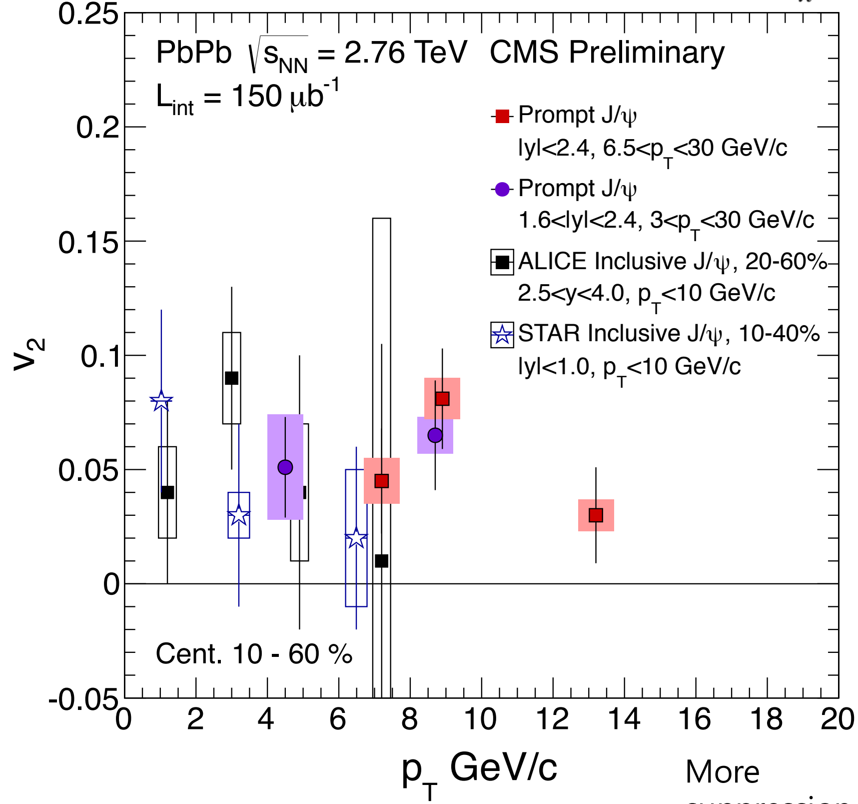


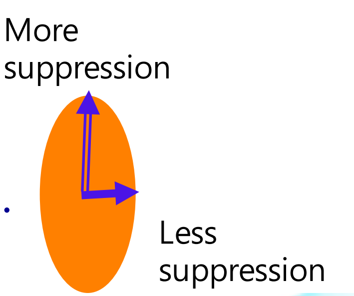
CMS-HIN-PAS-12-001
Phys. Rev. Lett. 111, 052301 (2013)
Phys. Rev. Lett. 111, 162301 (2013)

Prompt J/ψ

Model, NPA 859, 114 (2011)

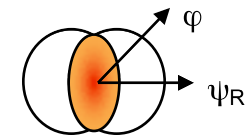






- Model describes data well within error bar.
- Observed non-zero v_2 of prompt J/ψ up to high p_T (~ 30 GeV/c).
- Low p_T : thermalized charm quark regeneration effect.
- High p_T : hint of path-length dependence.

Charmonia in PbPb

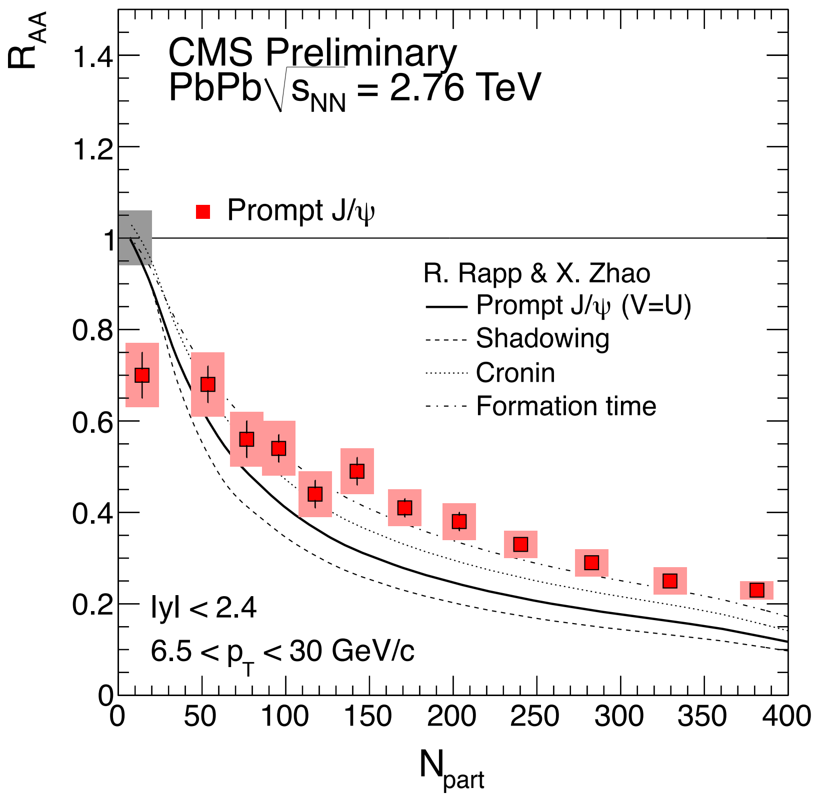


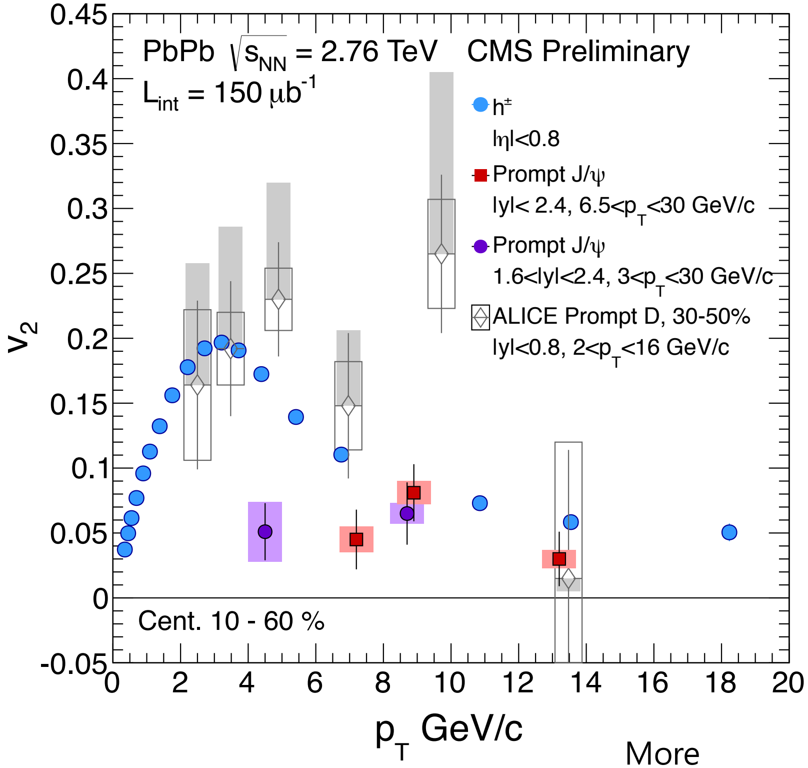
CMS-HIN-PAS-12-001
Phys. Rev. Lett. 111, 052301 (2013)
Phys. Rev. Lett. 111, 162301 (2013)

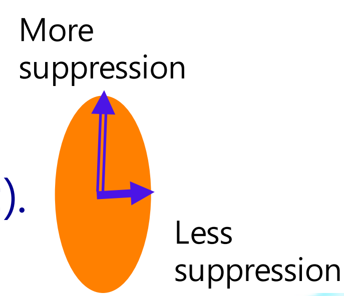
$$\frac{2}{\pi}(1+2v_2\cos(2\Delta\phi))$$

Prompt J/ψ

Model, NPA 859, 114 (2011)







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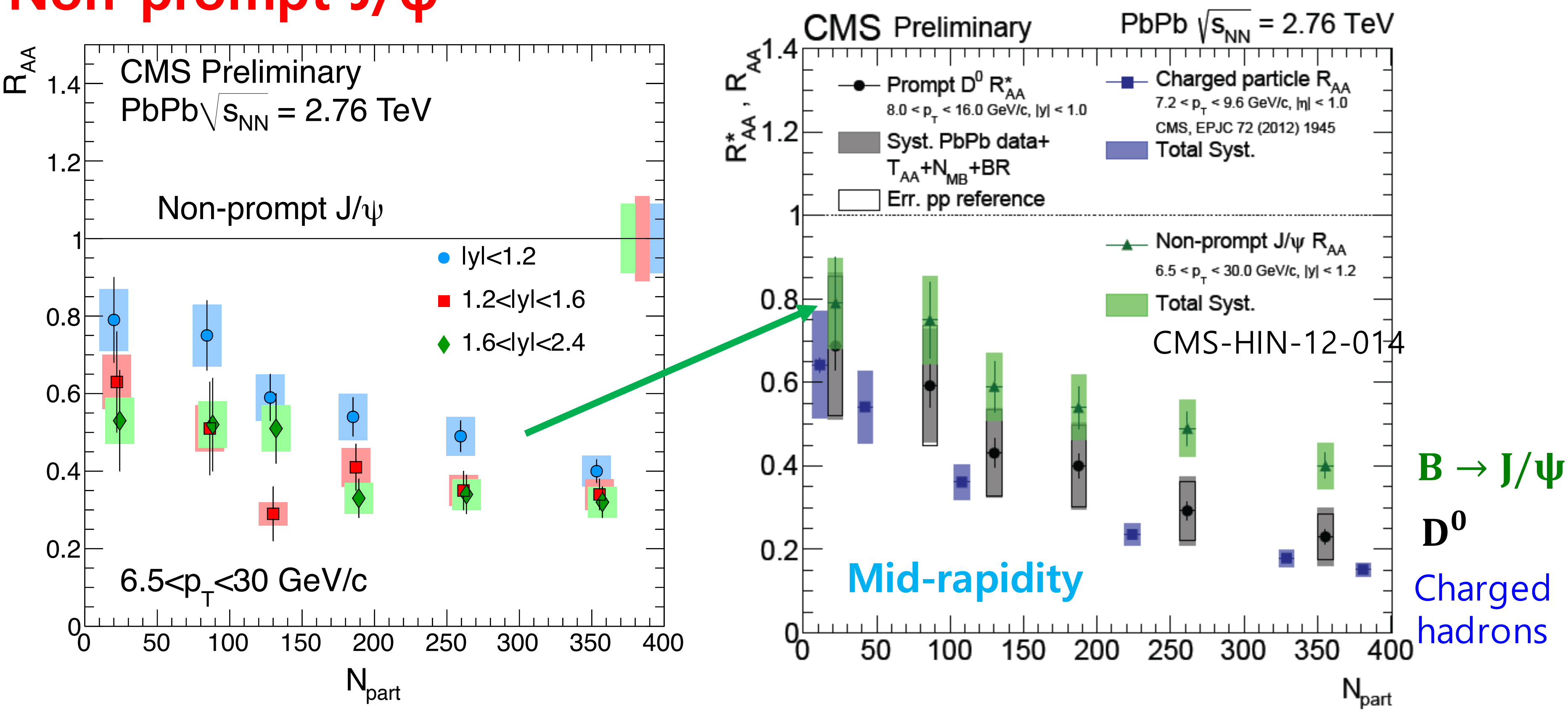
Charmonia in PbPb

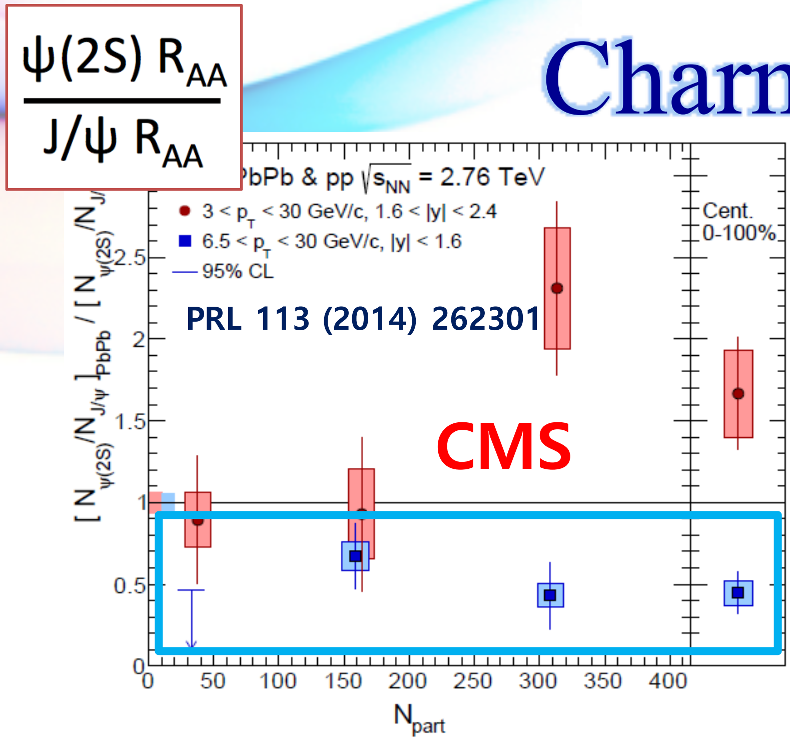
Non-prompt J/ψ

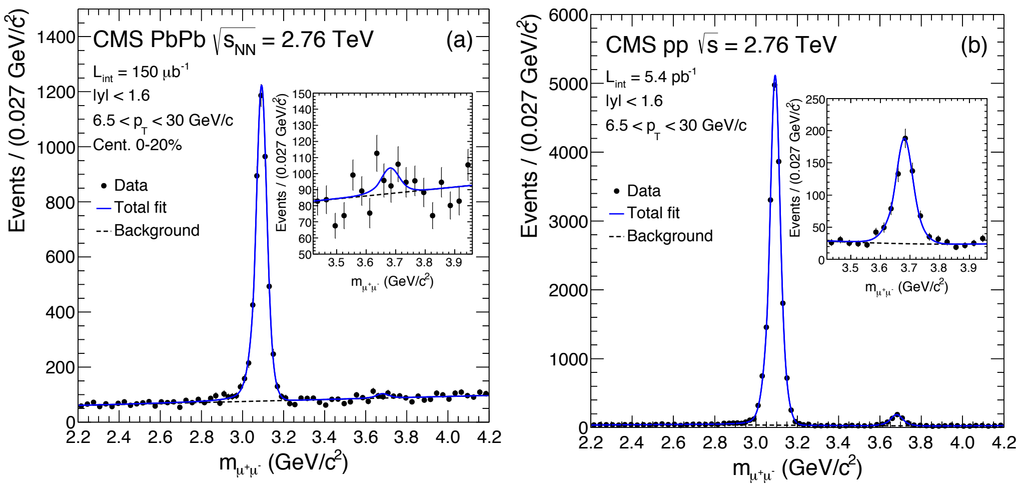


CMS-PAS-12-014

- Mass ordering R_{AA}(B) > R_{AA}(D) : predicted by dead cone effect.

Charmonia in PbPb

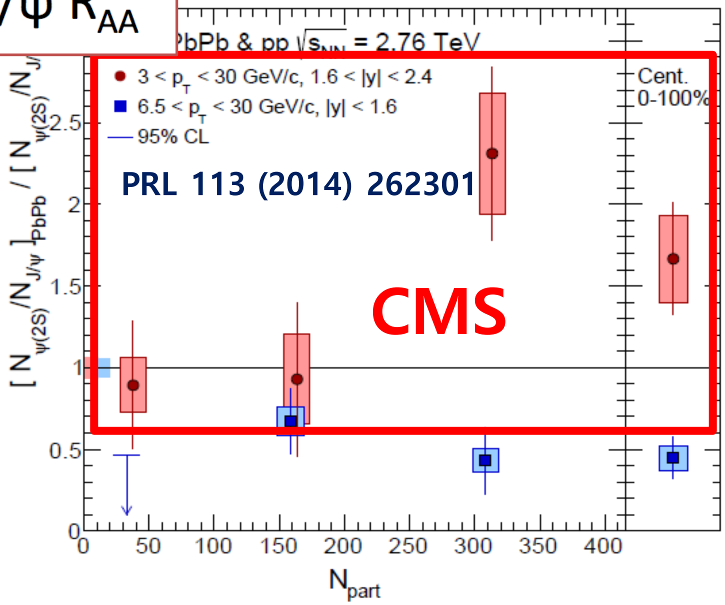


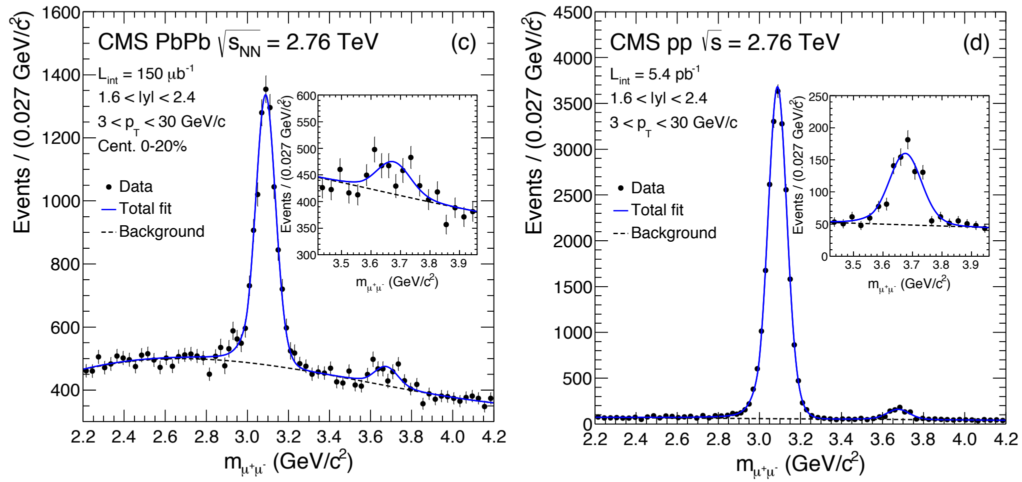


- For $6.5 < p_T < 30$ GeV/c in $|y| < 1.6$, $R_{\psi(2S)}$ in central (20%) PbPb is ~2 times smaller than that in pp.

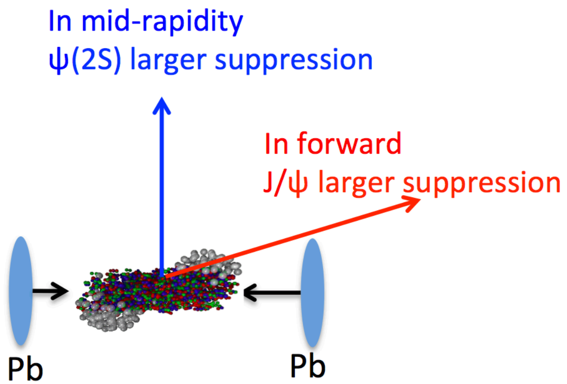
Charmonia in PbPb

$$\frac{\psi(2S)\ R_{AA}}{J/\psi\ R_{AA}}$$



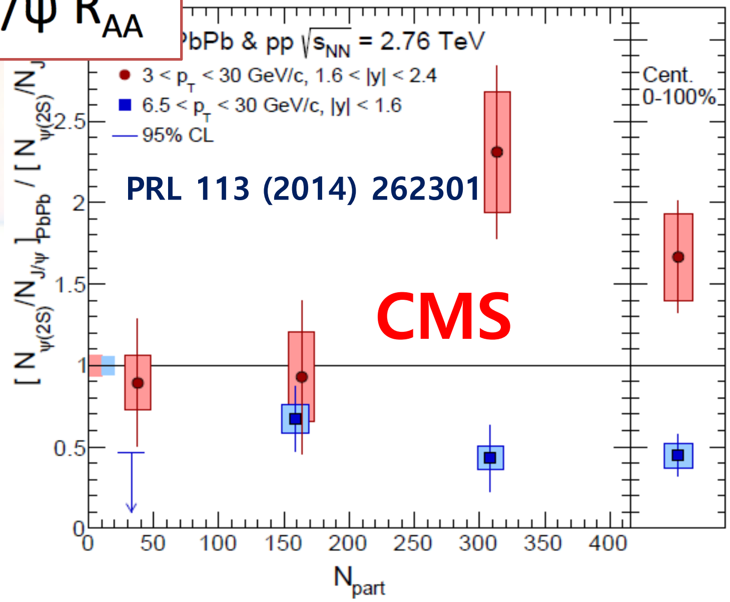


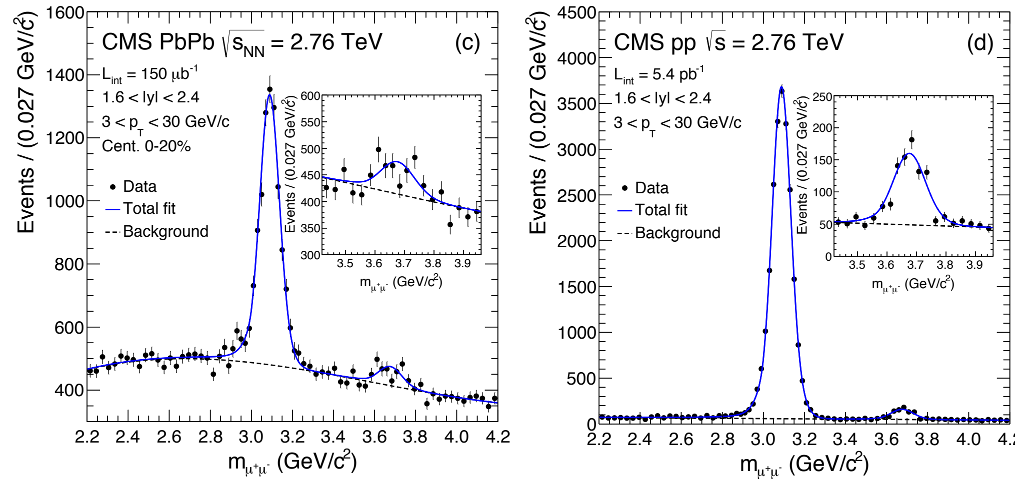
- For $3<p_T<30$ GeV/c in $1.6 < |y| < 2.4$, $R_{\psi(2S)}$ in central (20%) PbPb is ~ 5 times larger than that in pp with larger systematic error.
- For $6.5<p_T<30$ GeV/c in $|y| < 1.6$, $R_{\psi(2S)}$ in central (20%) PbPb is ~2 times smaller than that in pp.

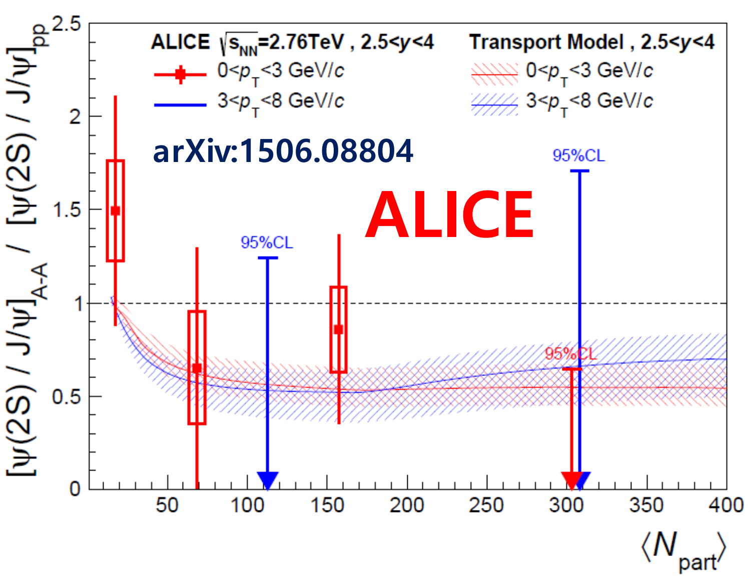


$$\frac{\psi(2S)\ R_{AA}}{J/\psi\ R_{AA}}$$

Charmonia in PbPb

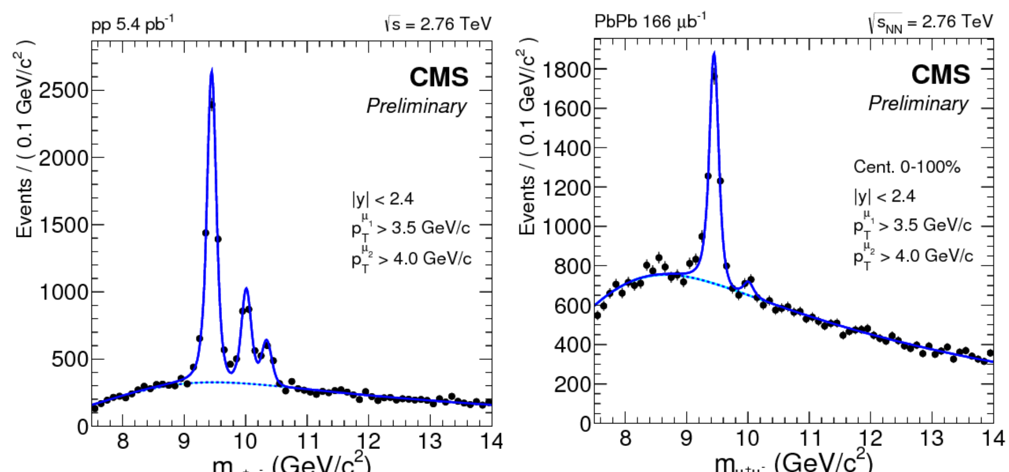




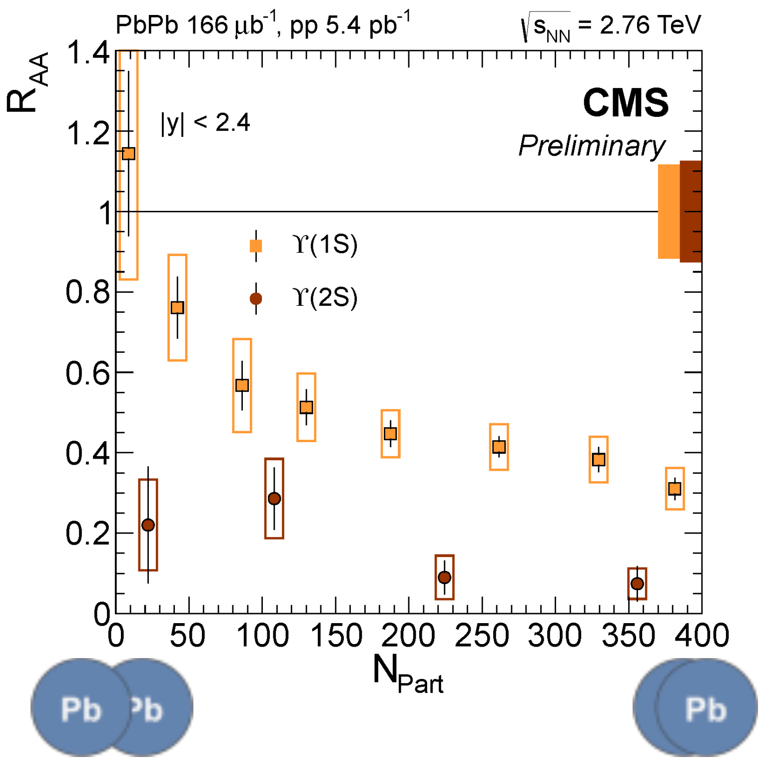


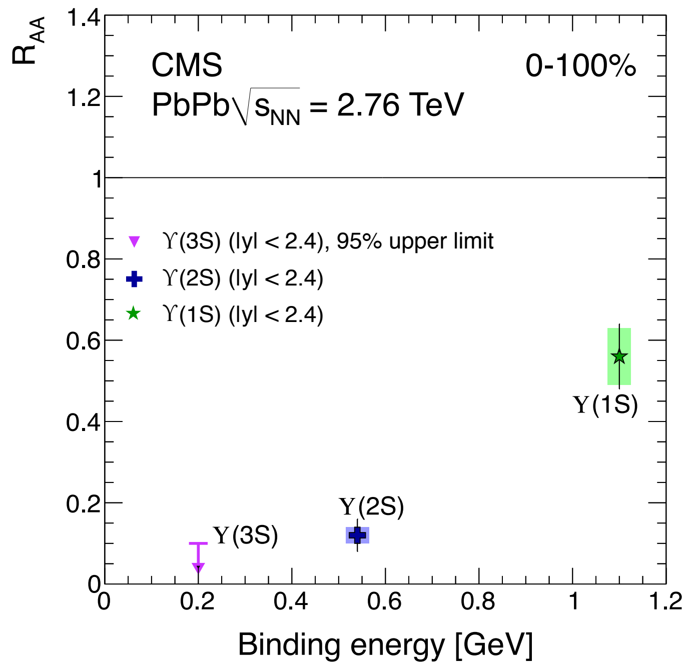
- For $3<p_T<30$ GeV/c in $1.6 < |y| < 2.4$, $R_{\psi(2S)}$ in central (20%) PbPb is ~ 5 times larger than that in pp with larger systematic error.
- For $6.5<p_T<30$ GeV/c in $|y| < 1.6$, $R_{\psi(2S)}$ in central (20%) PbPb is ~2 times smaller than that in pp.
- Indication of ψ(2S) being less suppressed than J/ψ (<2σ effect) at low p_T in the most central events: Need more J/ψ statistics during LHC Run II.

Bottomonia in PbPb collisions



Bottomonia in PbPb at CMS





JHEP 1205 (2012) 063

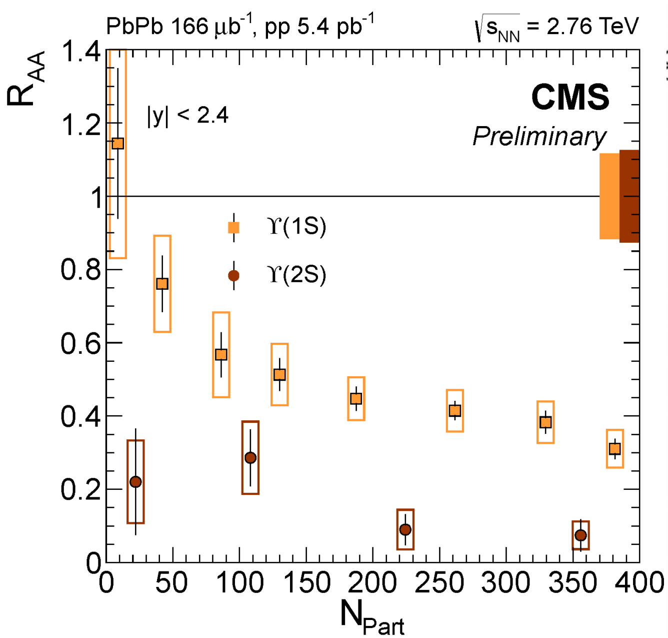
CMS PAS-15-001

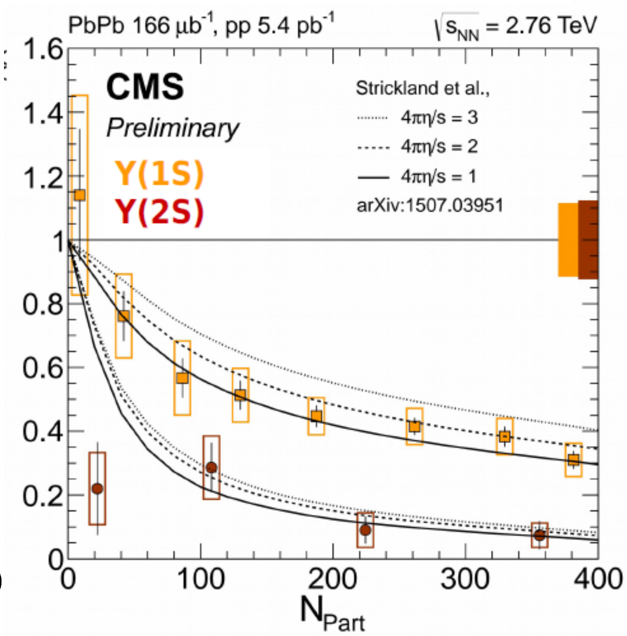
$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}}{N_{pp}} \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}}$$

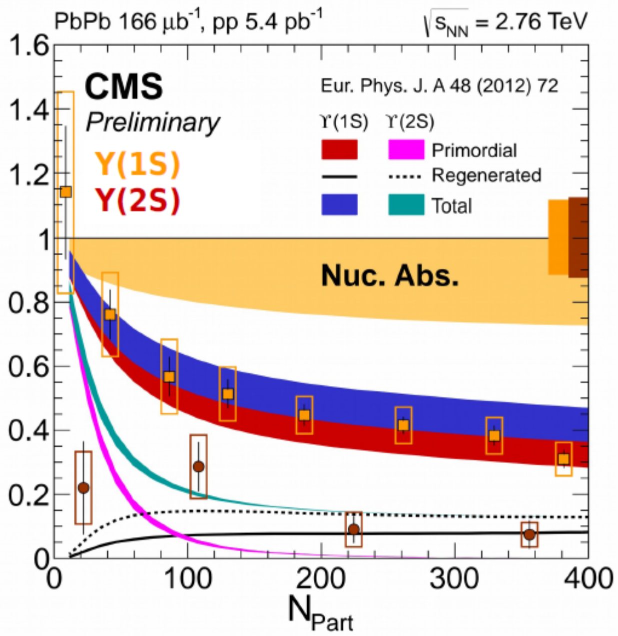
- Significant suppression of ϒ (1S, 2S, 3S) at PbPb collisions.
- Expected hierarchy in the suppression of the states with different binding energies.

Bottomonia in PbPb

CMS PAS-15-001





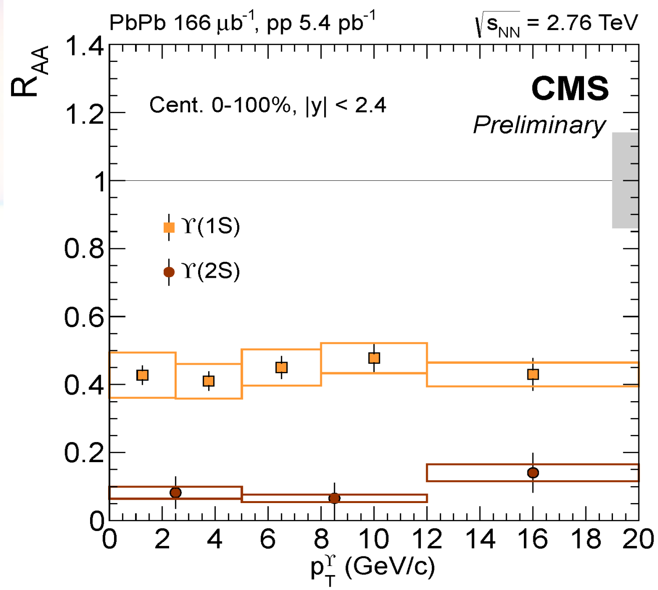


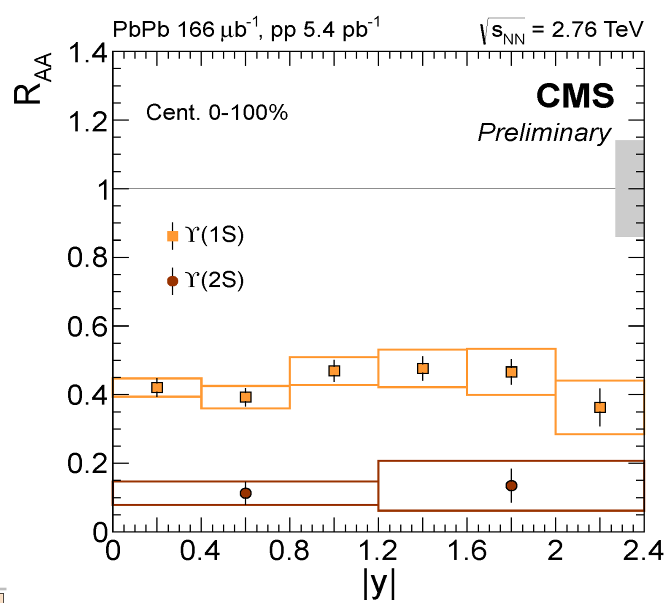
- Centrality integrated results: Υ states suppressed sequentially (0-100%)
  - $R_{AA}[\Upsilon(1S)] = 0.425 \pm 0.029 \pm 0.070$
  - $R_{AA}[\Upsilon(2S)] = 0.116 \pm 0.028 \pm 0.022$
  - $R_{AA}[\Upsilon(3S)] < 0.14$ at 95% CL

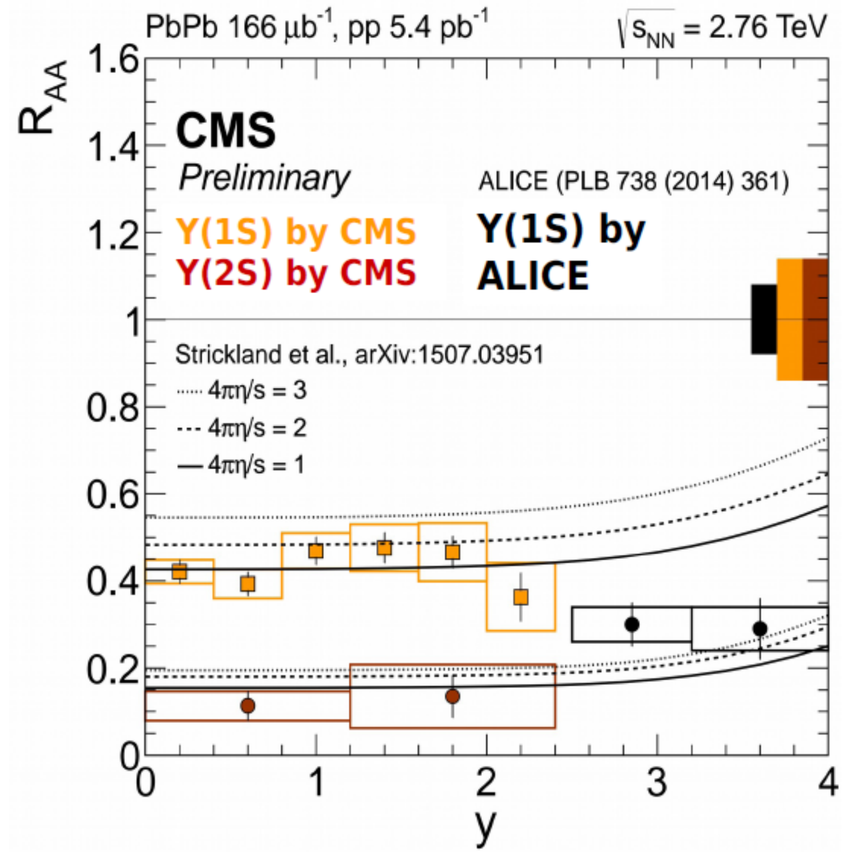
- Anisotropic hydrodynamic model for thermal suppression of bottomonia
  - 2 temperatures along y, 3 shear viscosities, no CNM, no regeneration, …
- Transport model taking into account CNM and regeneration.

Bottomonia in PbPb

CMS PAS-15-001

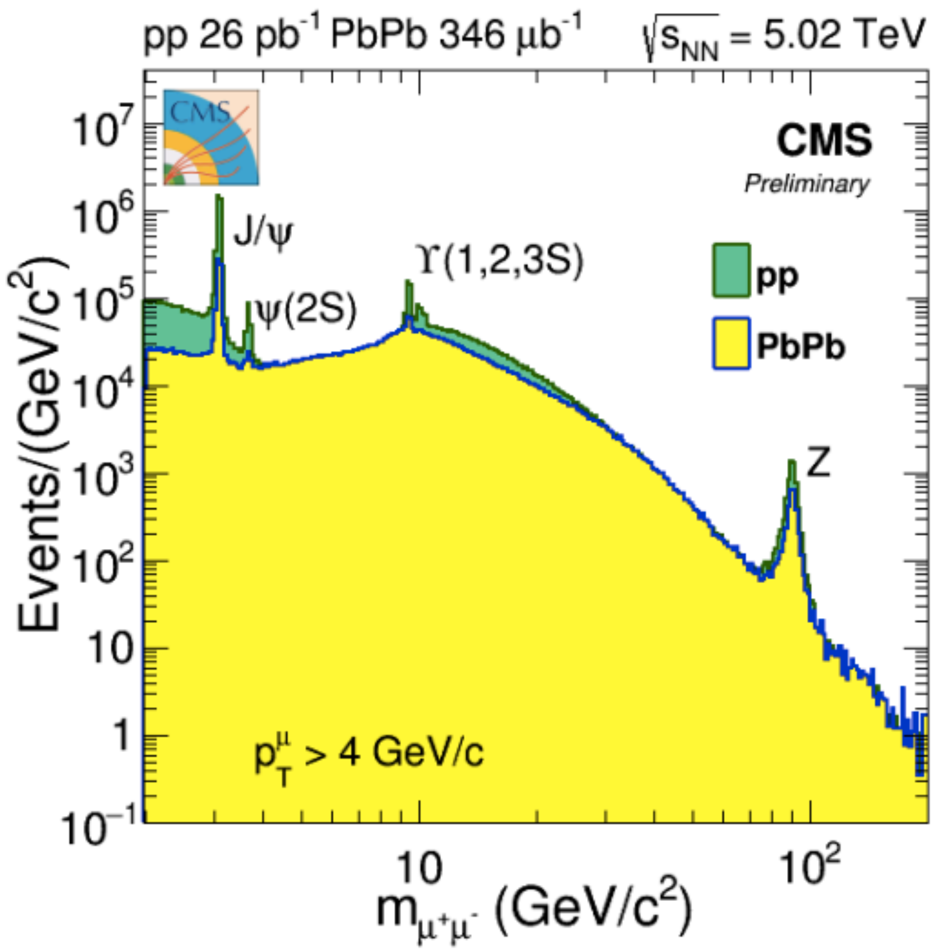


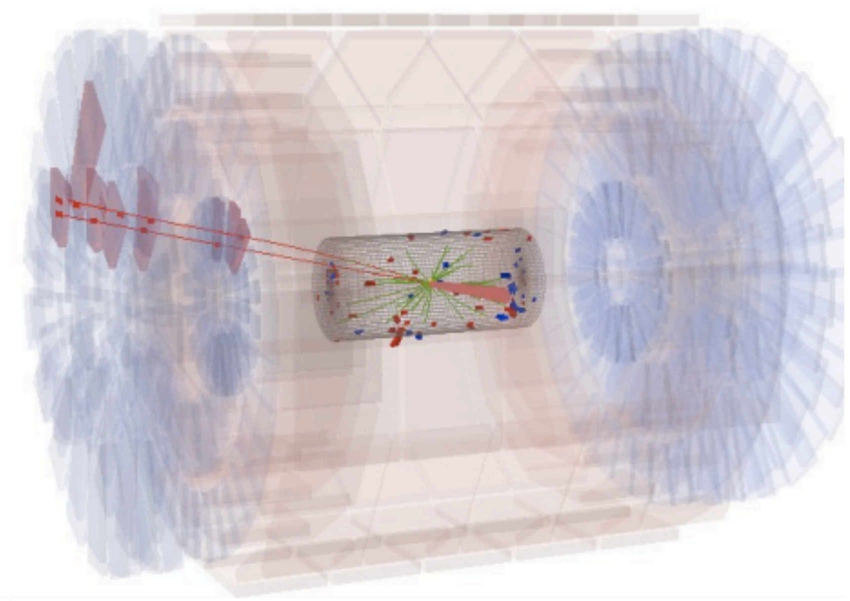




- ϒ suppression does not strongly depend on kinematics.
- Anisotropic hydro model cannot reproduce the forward data.

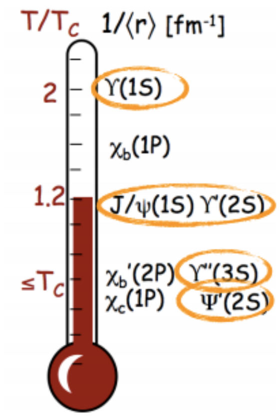
Run II Results Coming Soon !!!

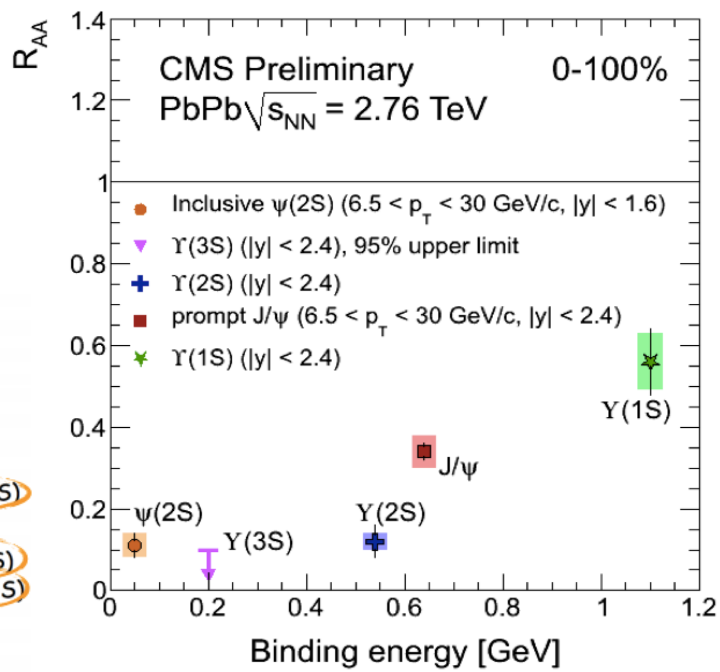


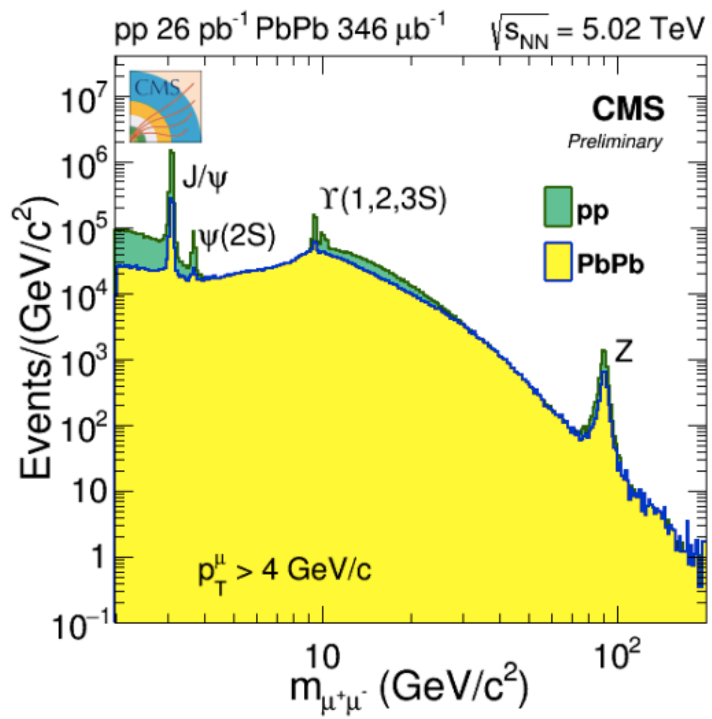


Summary

- Charmonia and Bottomonia in PbPb are suppressed sequentially along their binding energies with respect to pp collisions.
  - R_{AA}s : $\Upsilon(1S)$ > J/ψ* > $\Upsilon(2S)$,$\psi(2S)$* > $\Upsilon(3S)$ (* high p_T)
- New results are coming soon (Maybe HP 2016) !!!



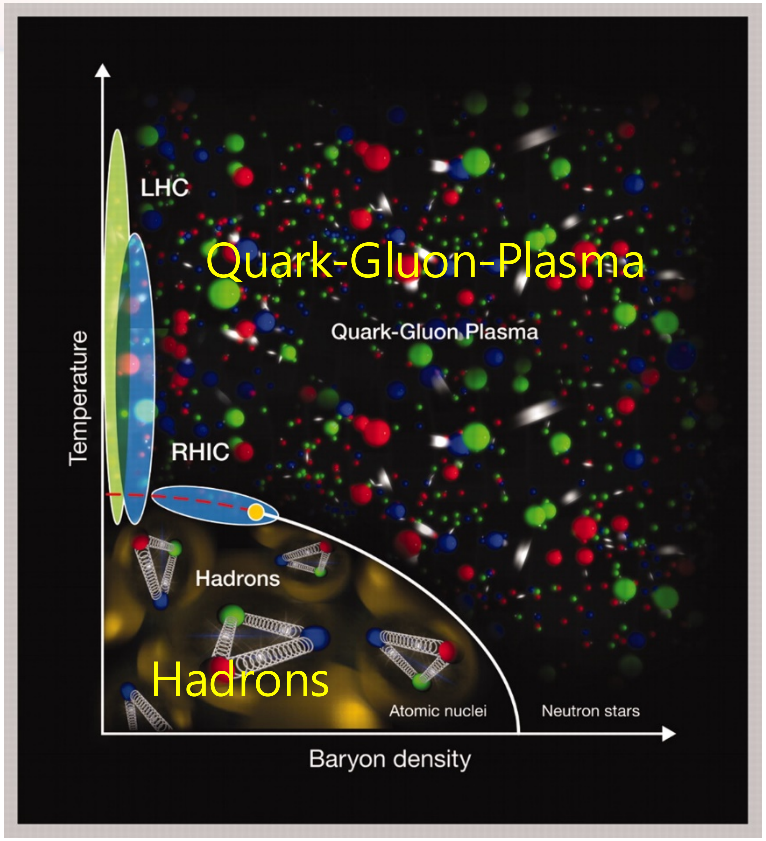




THANK YOU!!!

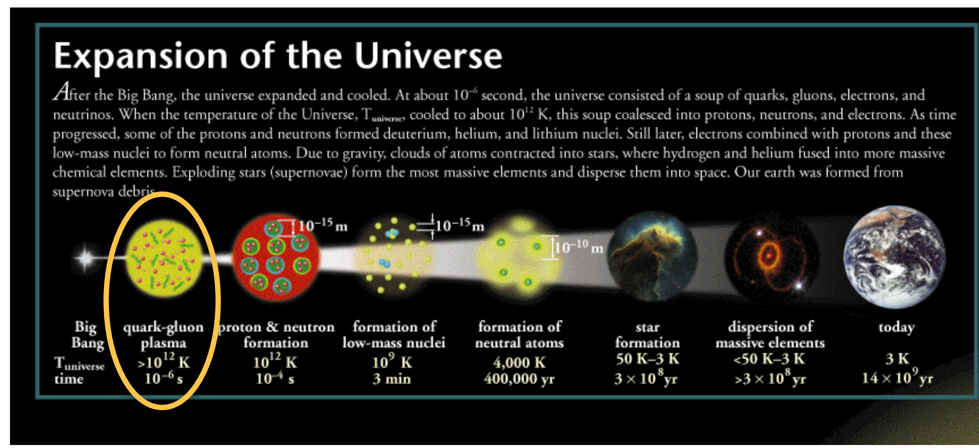
Quark-Gluon-Plasma (QGP)

❖ QCD phase diagram



What is Quark-Gluon-Plasma ?

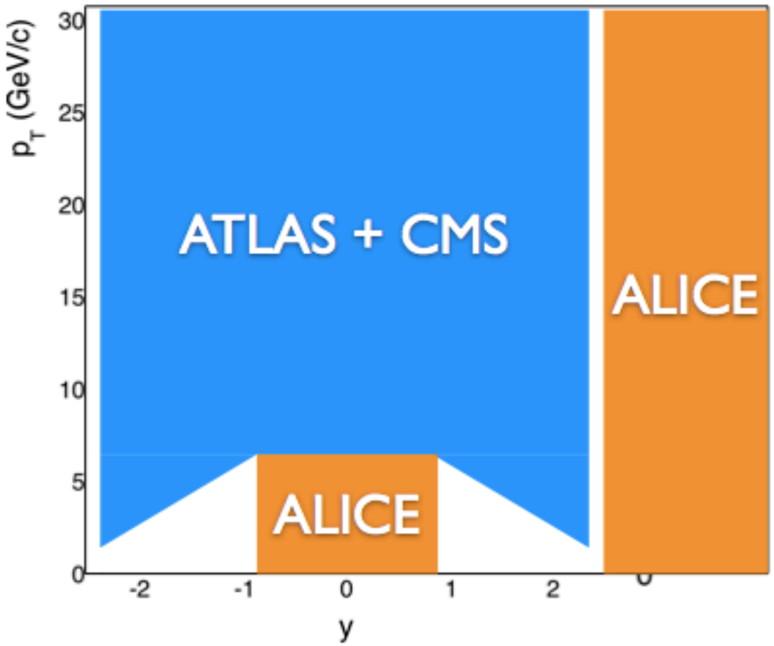
- A phase of Quantum Chromodynamics (QCD)
- Consist of asymptotically free quarks and gluons
- Exist at extremely high temperature and density
- Live in only a few milliseconds after Big Bang

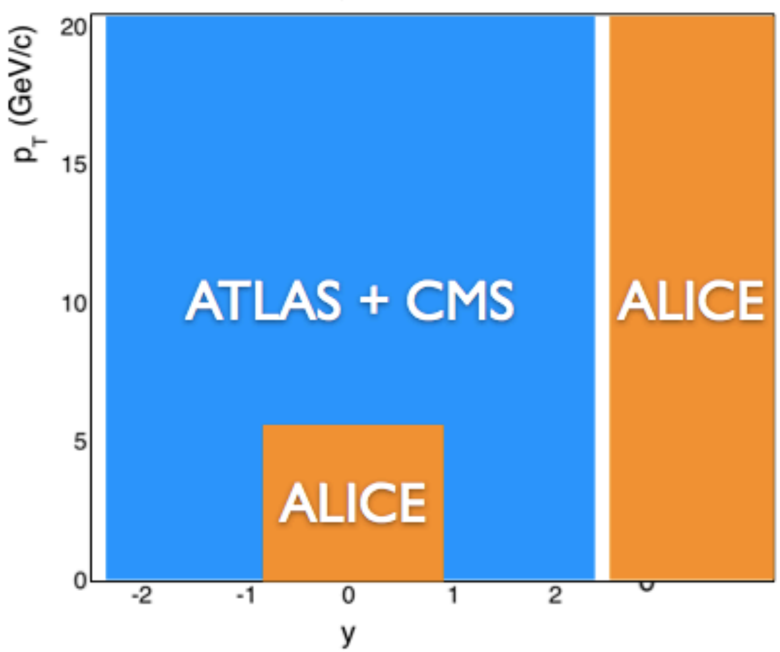


T_c (Critical temperature)
: 150~200 MeV(Lattice QCD)

- Exploring QGP means exploring our early of universe

Quarkonia Acceptance

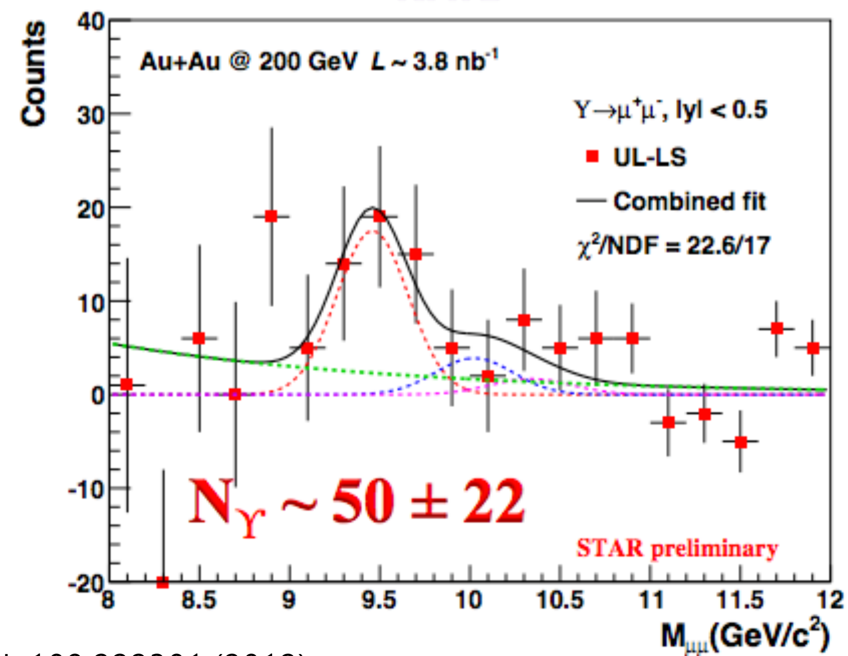




- ALICE: acceptance for $p_T > 0$
  - midrapidity: no absorber and low magnetic field
  - forward rapidity: longitudinal boost
- ATLAS and CMS: Muons need to overcome strong magnetic field and energy loss in the absorber
  - minimum total momentum p~3–5 GeV/c to reach the muon stations
  - Limits J/ψ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

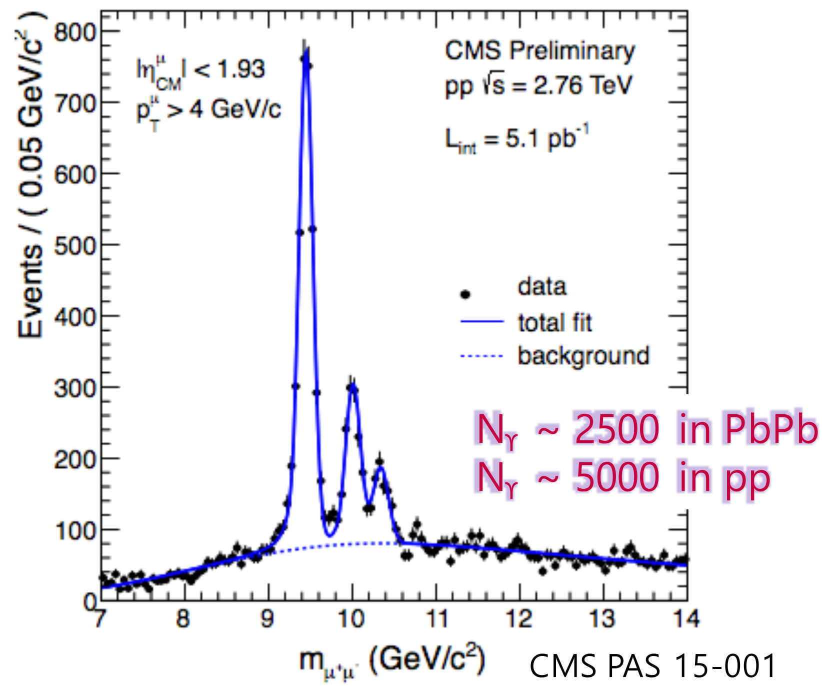
Quarkonia Measurement in pp, pPb and PbPb

RHIC



PRL 109 222301 (2012)

LHC

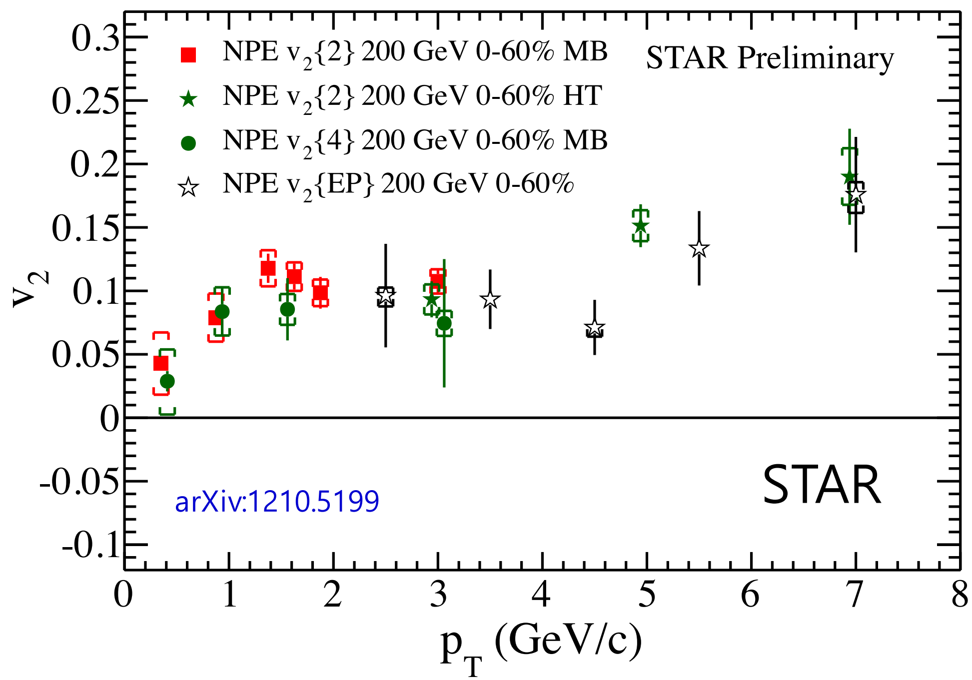


CMS PAS 15-001

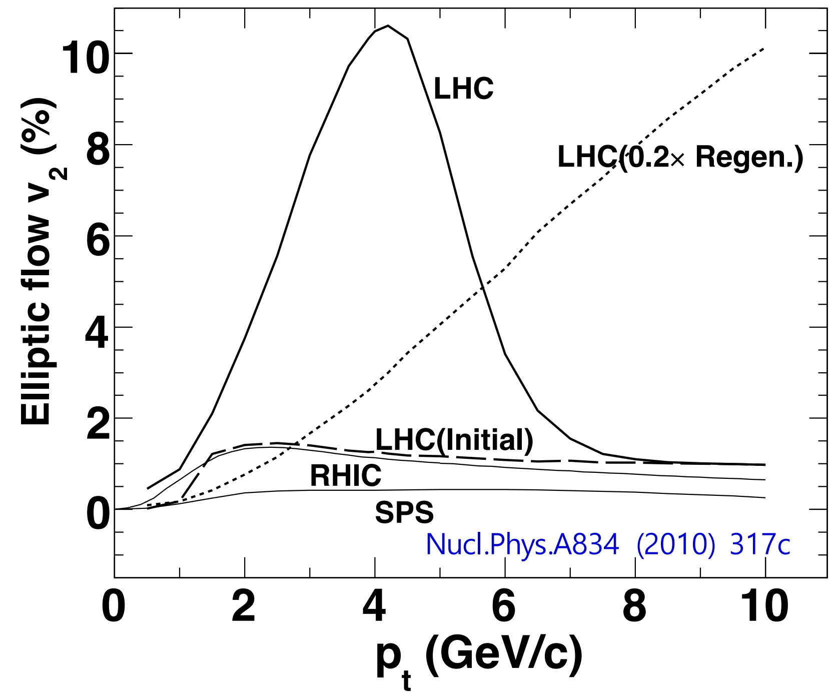
- **Quarkonia** (heavy flavor (charm, bottom) quark-antiquark bound states)
  - Large momentum transfer required to produce by hard gluon-gluon fusion at early stage of collisions : good probe of initial and final state of evolution of extremely hot and dense matter created in high energy heavy-ion collisions
- **Bottomonia** ($b\bar{b}$ bound state : ϒ (1S, 2S, 3S), X_b …) have been actively used as new possible probes since 2010 LHC era.

NPE v_2 at RHIC and prediction of J/ψ v_2 at LHC

NPE (Non Photonic Electron) v_2



Prediction of elliptic flow of J/ψ



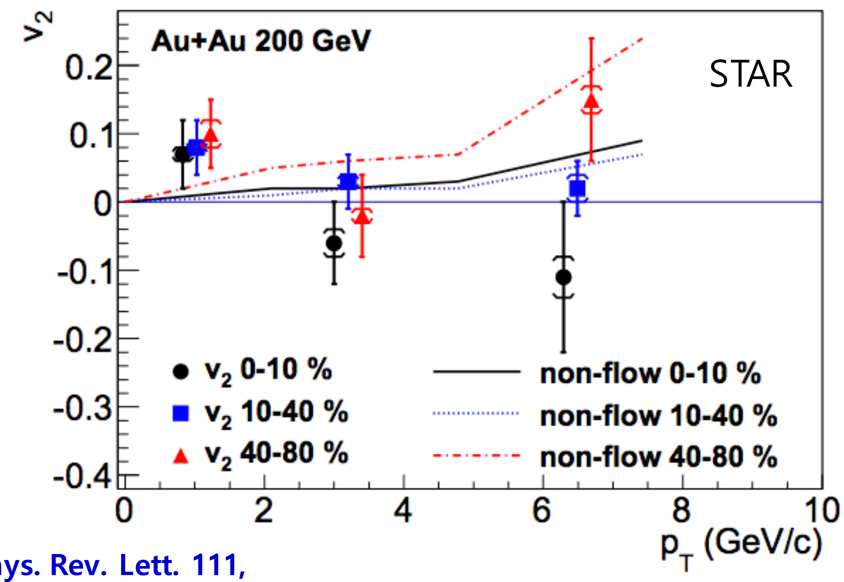
NPE has significant elliptic flow (v_2).
It should be inherited to quarkonia,
which indicates the existence
non-zero v_2 of quarkonia

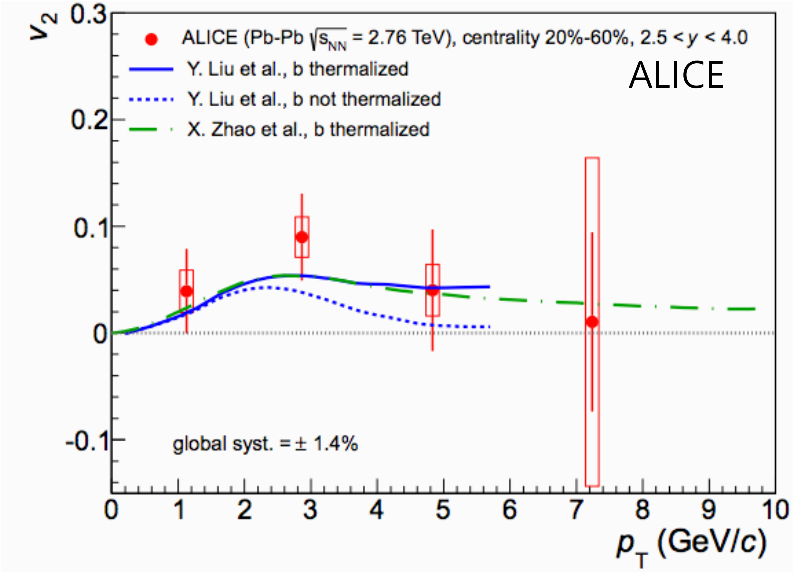
Significant elliptic flow (v_2) may b
e
expected at LHC energy
due to the significant
contribution of regenerated J/ψ

J/ψ Azimuthal Anisotropy at RHIC and LHC

- STAR and ALICE measured inclusive J/ψ v_2

Phys. Rev. Lett. 111, 102301 (2013)





Phys. Rev. Lett. 111, 052301 (2013)

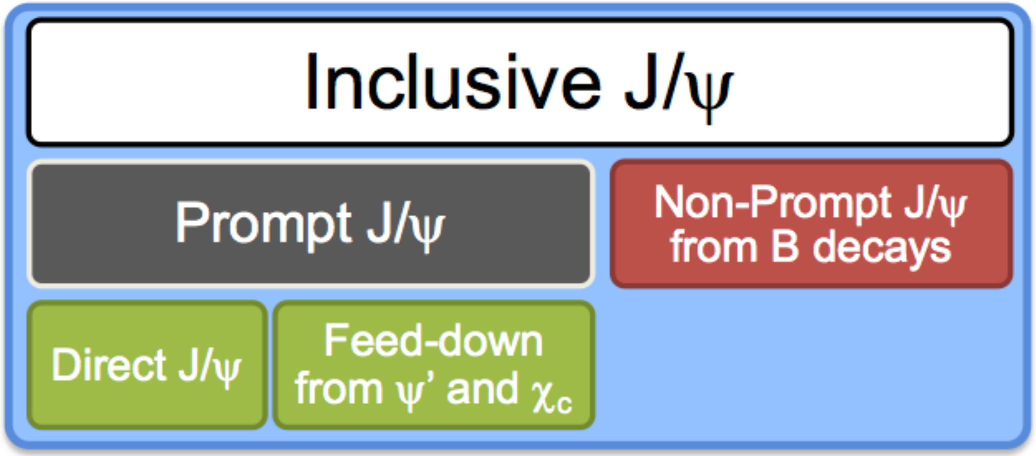
STAR measured compatible zero v_2 from 2 GeV/c in whole p_T region.

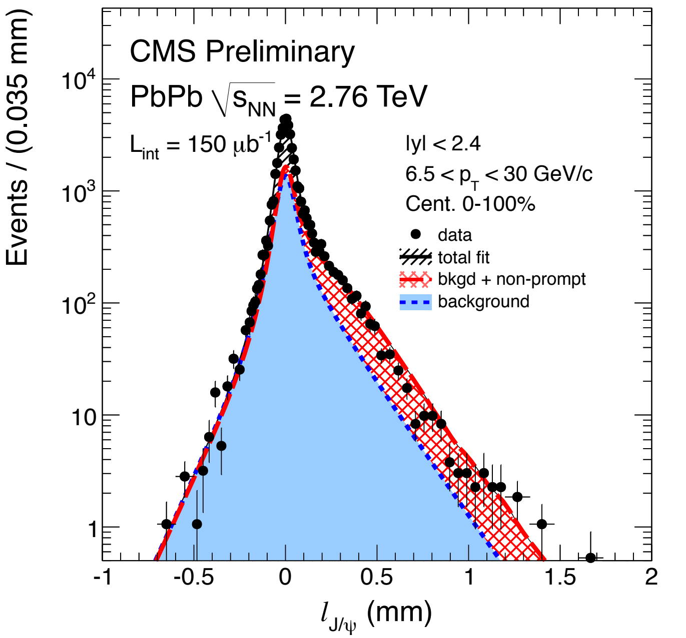
ALICE observed non-zero v_2 in 2 - 4 GeV/c region. Data covers both of b-contribution models.

CMS challenge:

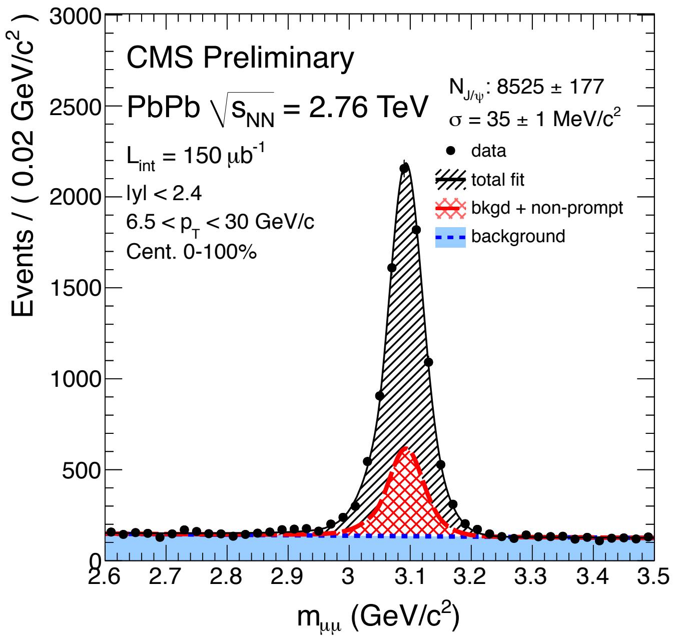
1) Prompt and non-prompt J/ψ separation
2) Extend high p_T region

Prompt & Non-prompt J/ψ Separation

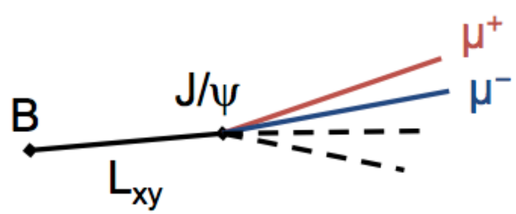




- Reconstruct opposite sign muon vertex
- 2-D unbinned maximum likelihood fit of dimuon mass and pseudo-proper decay length ($l_{J/\psi}$)

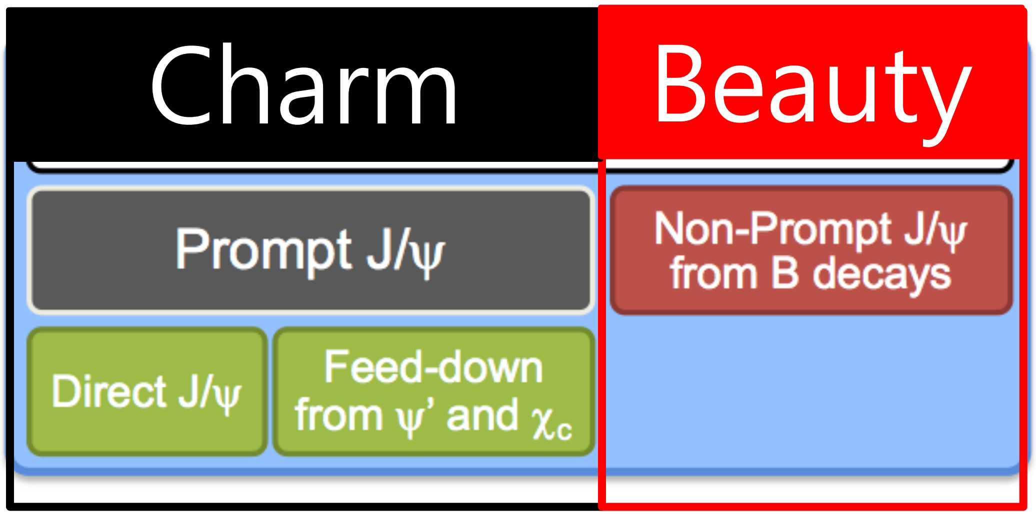


$$\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$



CMS-PAS-HIN-12-014

Prompt & Non-prompt J/ψ Separation



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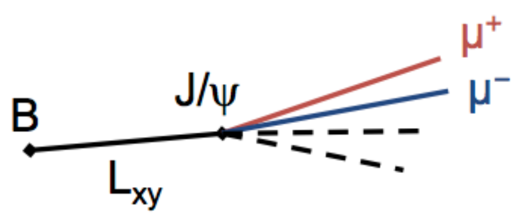
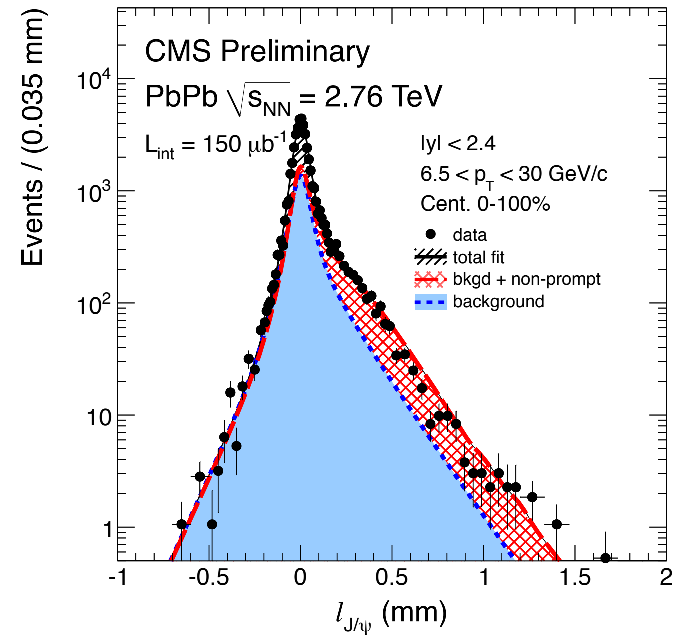
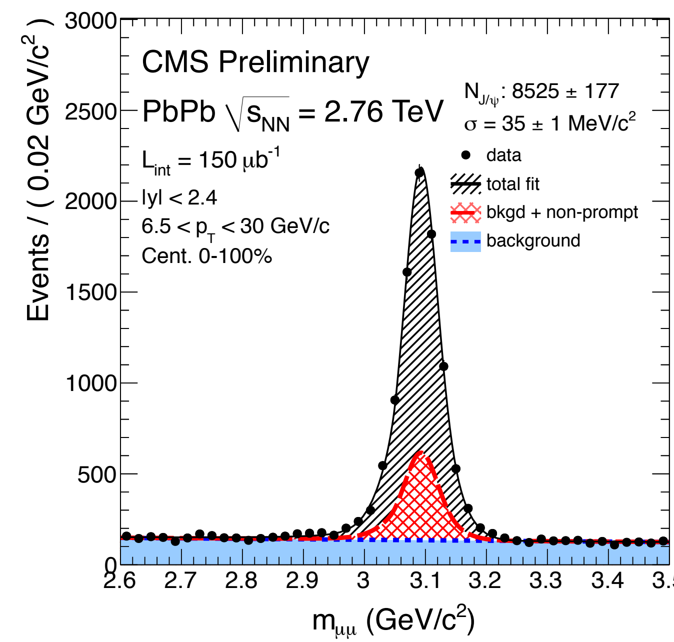
$$\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$

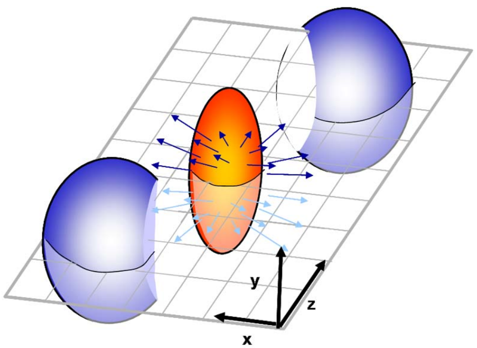


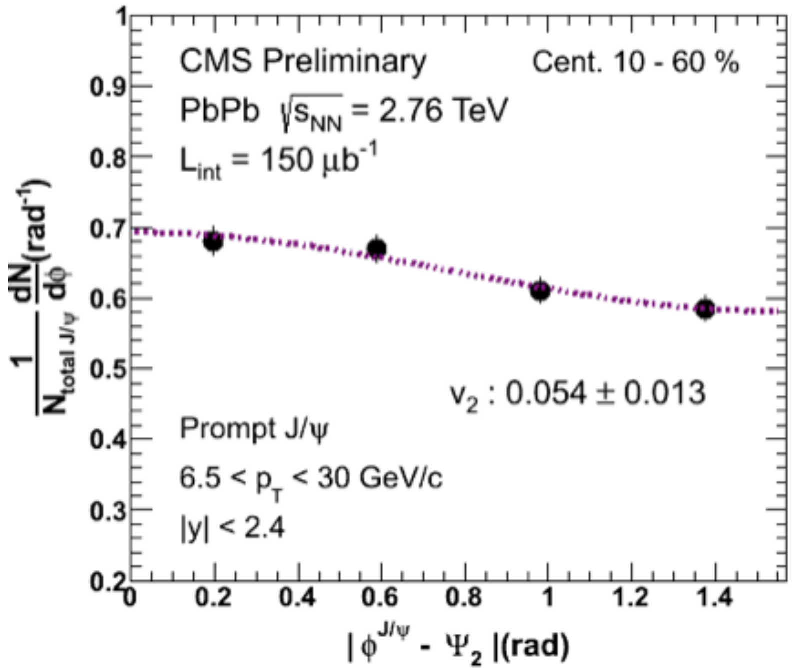
CMS-PAS-HIN-12-014

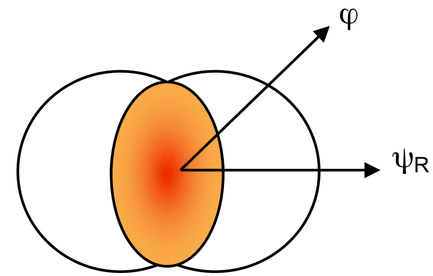




J/ψ Azimuthal Anisotropy in CMS







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

CMS-PAS-HIN-12-001

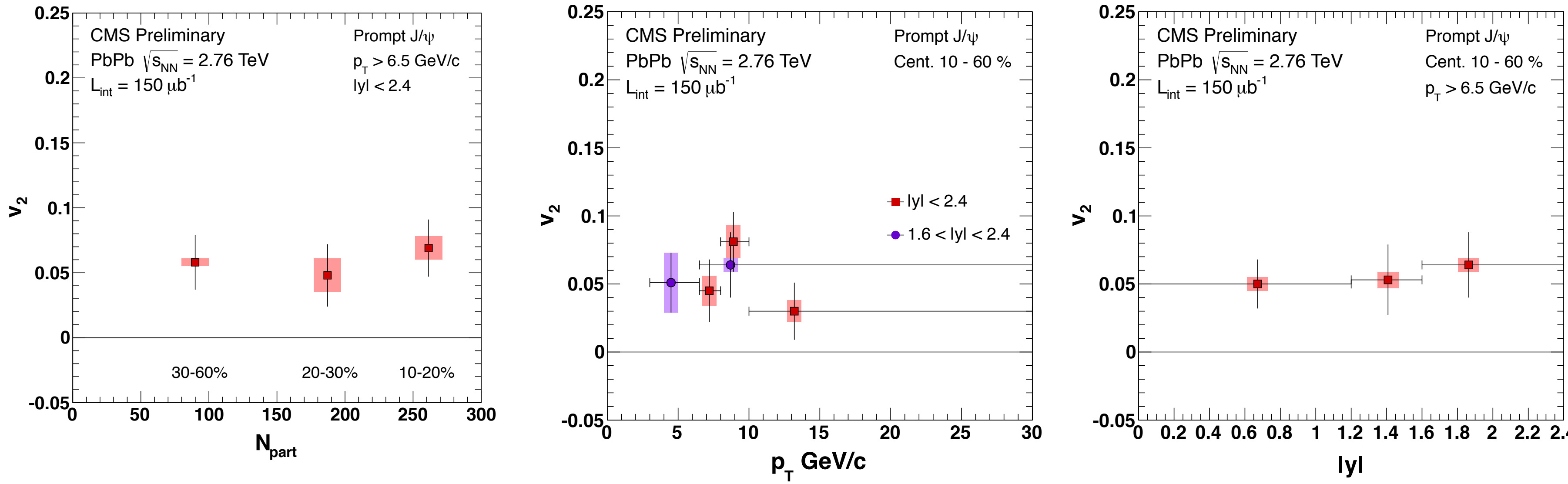
- Event plane method
- Integrated v_2 for Prompt J/ψ (p_T > 6.5 GeV/c)
  - ➠ 0.054 ± 0.013 (stat.) ± 0.006 (syst.) in |y| < 2.4, 10-60 %
  - ➠ significant (3.8σ) v_2 at high-p_T prompt J/ψ

J/ψ Azimuthal Anisotropy in CMS

- Systematic uncertainties

	Systematic uncertainties (%)
Yield extraction	1 - 20
Efficiency corrections	0 - 42
Event plane determination	3.5
Total	12 - 46

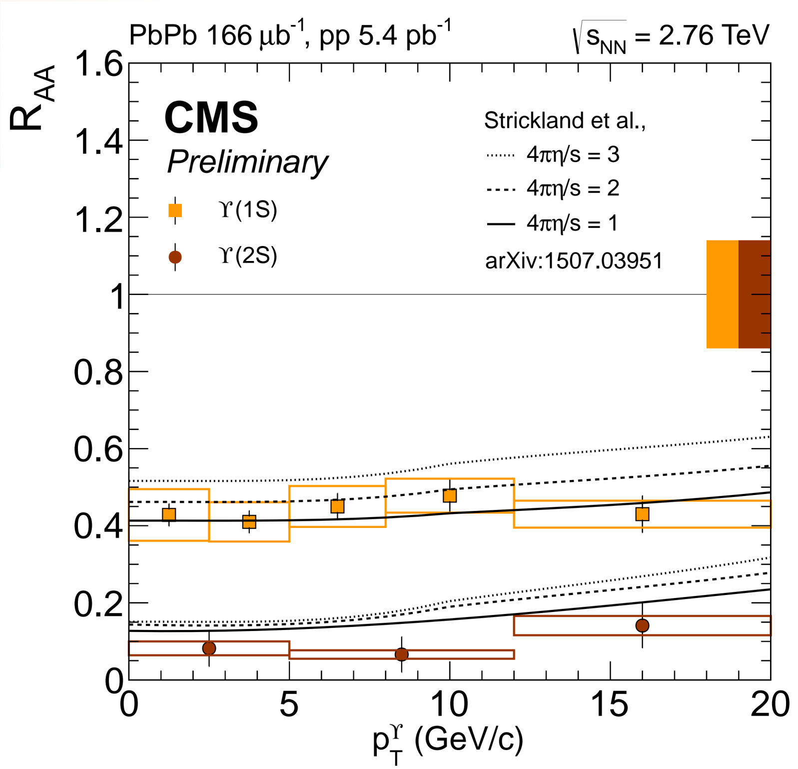
J/ψ Azimuthal Anisotropy in CMS



CMS-PAS-HIN-12-001

- No strong dependences of centrality, p_T, rapidity
- Low p_T (3-6.5 GeV/c) measured in forward (1.6<|y|<2.4)

R_{AA} p_T dependence

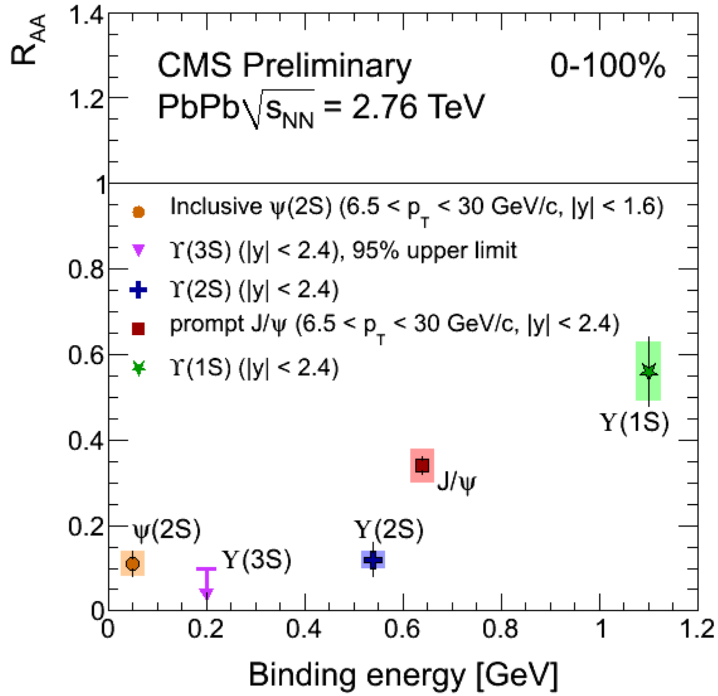


CMS PAS 15-001

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

- No strong dependence for p_T in the measured region.
- ϒ(1S) is described well but some tension with ϒ(2S).

R_{AA} vs binding energy



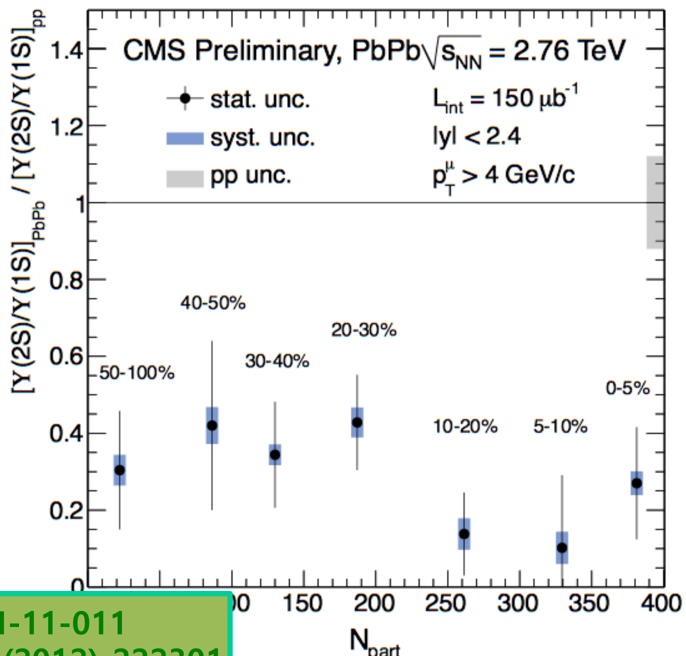
state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
mass [GeV]	3.10	3.53	3.68	9.46	9.99	10.02	10.26	10.36
ΔE [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
ΔM [GeV]	0.02	-0.03	0.03	0.06	-0.06	-0.06	-0.08	-0.07
r_0 [fm]	0.50	0.72	0.90	0.28	0.44	0.56	0.68	0.78

Table 3: Quarkonium Spectroscop

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN12014

Results from PbPb Collisions

Double Ratio



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

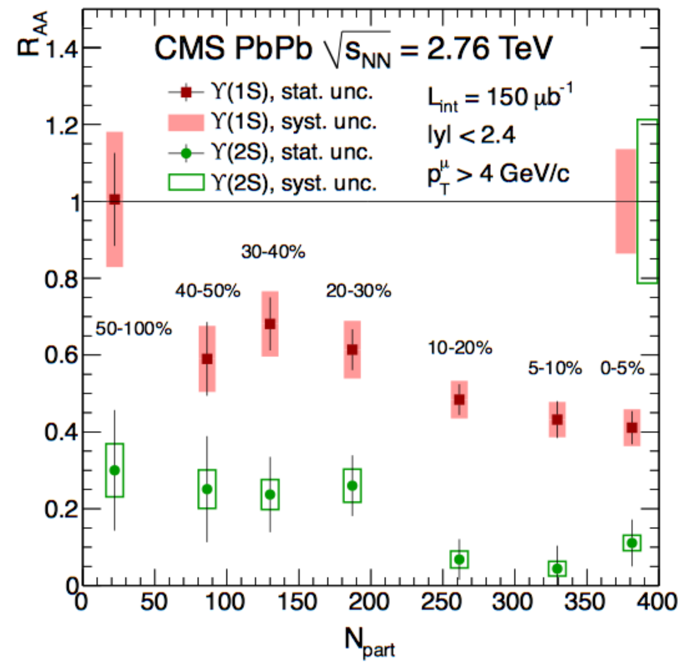
$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{\text{PbPb}}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07(\text{stat}) \pm 0.02(\text{syst}),$$

$$\frac{\Upsilon(3S)/\Upsilon(1S)|_{\text{PbPb}}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}} = 0.06 \pm 0.06(\text{stat}) \pm 0.06(\text{syst})$$

$$< 0.17(95\%\text{CL}).$$

Υ(2S) and Υ(3S) are more suppressed than Υ(1S)

R_{AA}



$$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08(\text{stat}) \pm 0.07(\text{syst}),$$

$$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04(\text{stat}) \pm 0.02(\text{syst}),$$

$$R_{AA}(\Upsilon(3S)) = 0.03 \pm 0.04(\text{stat}) \pm 0.01(\text{syst})$$

$$< 0.10(95\%\text{CL}).$$

Υ(3S) are more suppressed than Υ(2S).

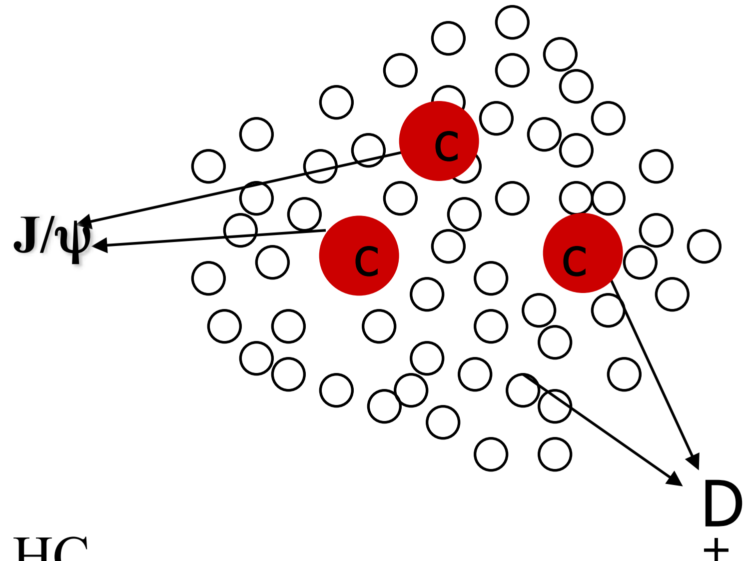
Ordering: $R_{AA}(\Upsilon(3S)) < R_{AA}(\Upsilon(2S)) < R_{AA}(\Upsilon(1S))$

The life of Quarkonia in the Medium can be Complicated

- Observed J/ψ is a mixture of direct production+feeddown (R. Vogt: Phys. Rep. 310, 197 (1999)).
  - All J/ψ ~ 0.6J/ψ(Direct) + ~0.3 χ_c + ~0.1ψ'
  - B meson feed down.
    - Important to disentangle different component

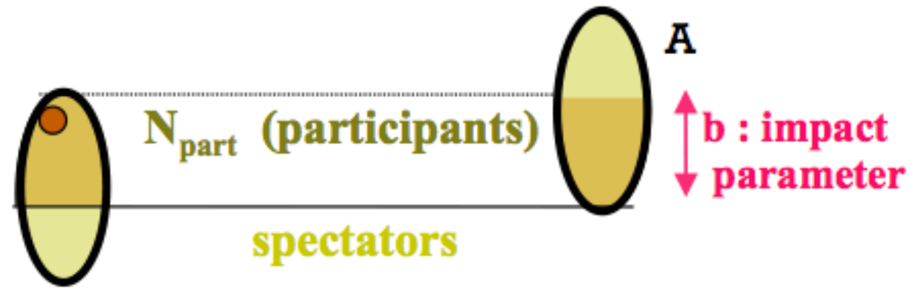
- Suppression and enhancement in the "cold" nuclear medium
  - Nuclear Absorption, Gluon shadowing, initial state energy loss, Cronin effect and gluon saturation (CGC)
  - Study p+A collisions

- Hot/dense medium effect
  - J/ψ, ϒ dissociation, i.e. suppression
  - Recombination, i.e. enhancement
  - Study different species, e.g. J/psi, ϒ
  - Study at different energy, i.e. RHIC, LHC



+ How do we quantify medium effects ?

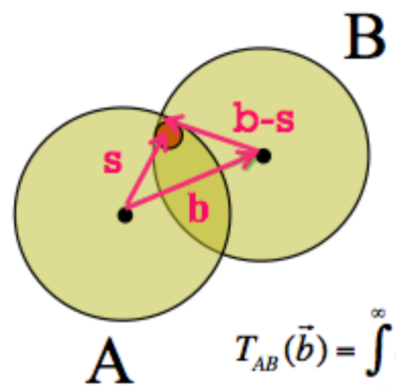
- N_{part} : number of nucleons which undergo at least one collision



- N_{coll} : number of n+n collisions taking place in A+B collision
- Modification nuclear factor $R_{AA} = \dfrac{1/N_{evnts} d^2N^Z/dydp_T}{<T_{AB}> d^2\sigma_{pp}/dydp_T}$

quantifies the effect of the medium on a particle production

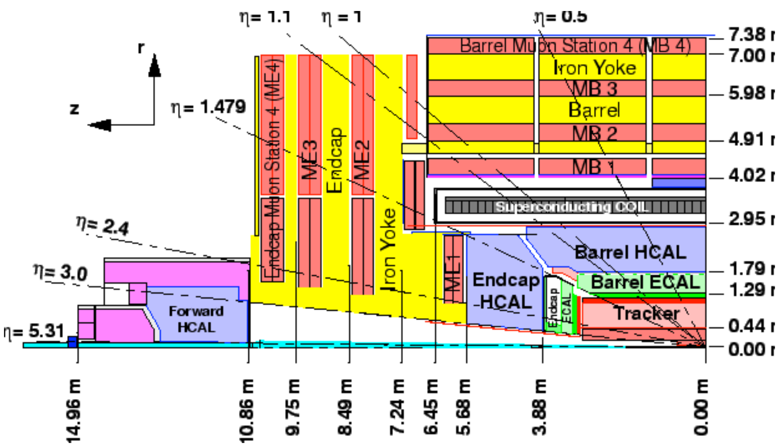
- To compare measured PbPb yields to theoretical pp cross sections, we need T_{AB} : nuclear overlap function
  - In absence of medium effects
    - $R_{AA} = 1$ for perturbative probes
  - T_{AB} is proportional to N_{coll}
    - 30-100% : $T_{AB} = 1.45 \pm 0.18$ mb^{-1}
    - 10-30% : $T_{AB} = 16.6 \pm 0.7$ mb^{-1}
    - 0-10% : $T_{AB} = 23.2 \pm 1.0$ mb^{-1}

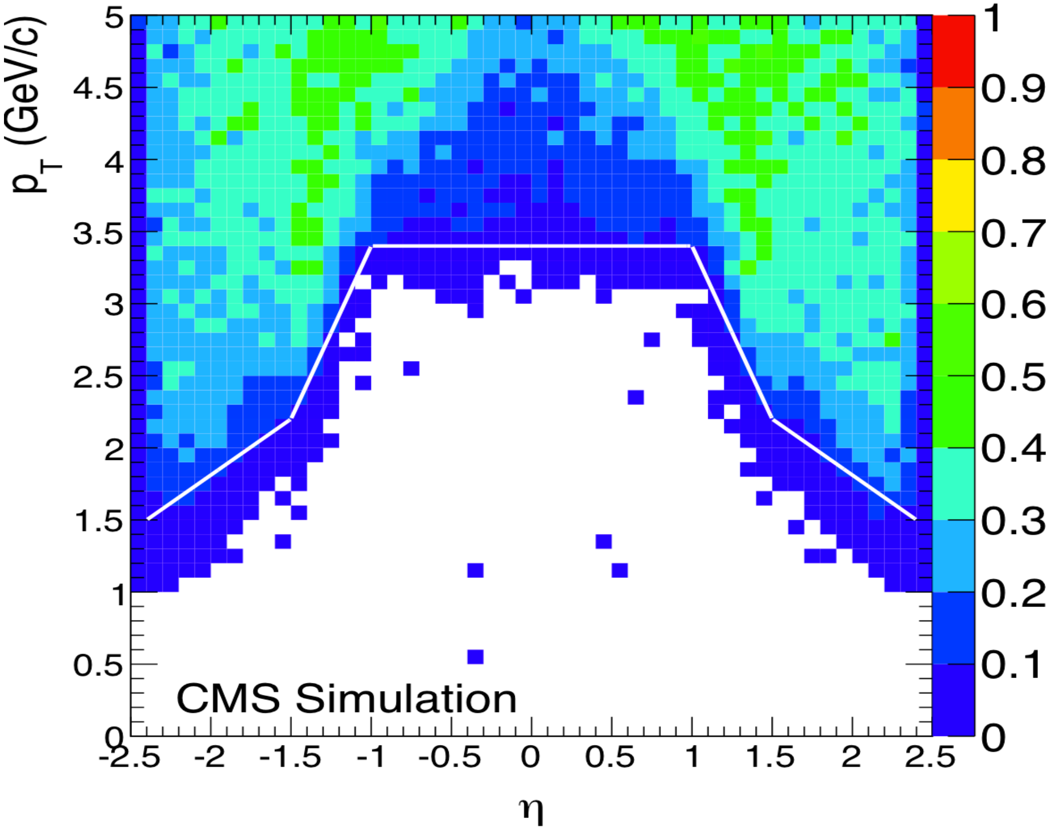


$$T_{AB}(\vec{b}) = \int_{-\infty}^{\infty} d\vec{s}\, T_A(\vec{s})T_B(\vec{b}-\vec{s})$$

Lamia, B. "Observation of Z Boson Production in Heavy Ion Collisions at CMS" Moriond QCD and High Energy Interactions, 2011

Single Muon Acceptance





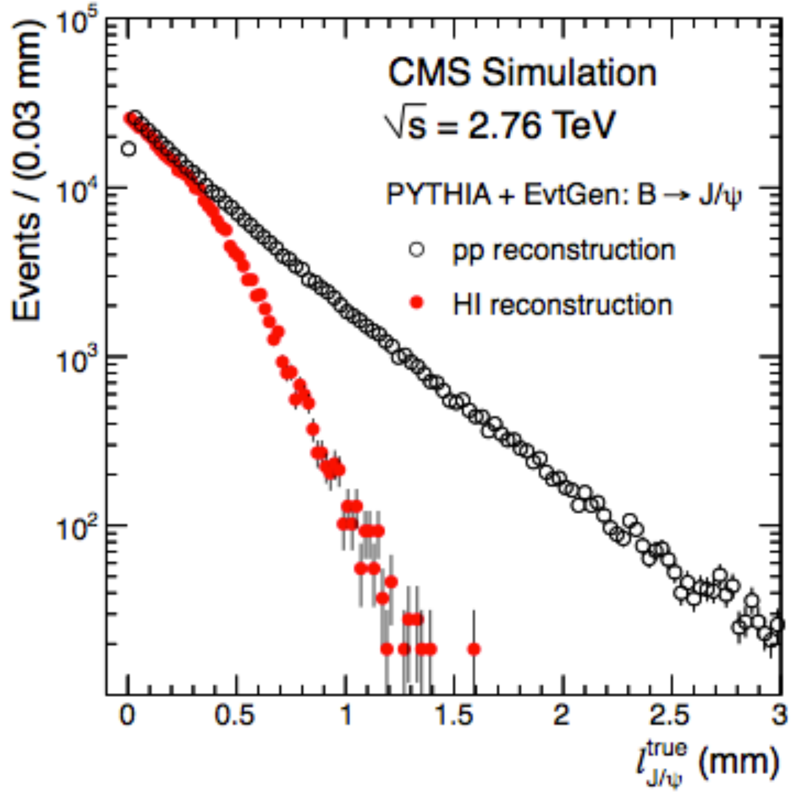
✔ Acceptance definition: Range of p_T and eta of reconstructable muon (RecoMu/GenMu ≥ 10%)

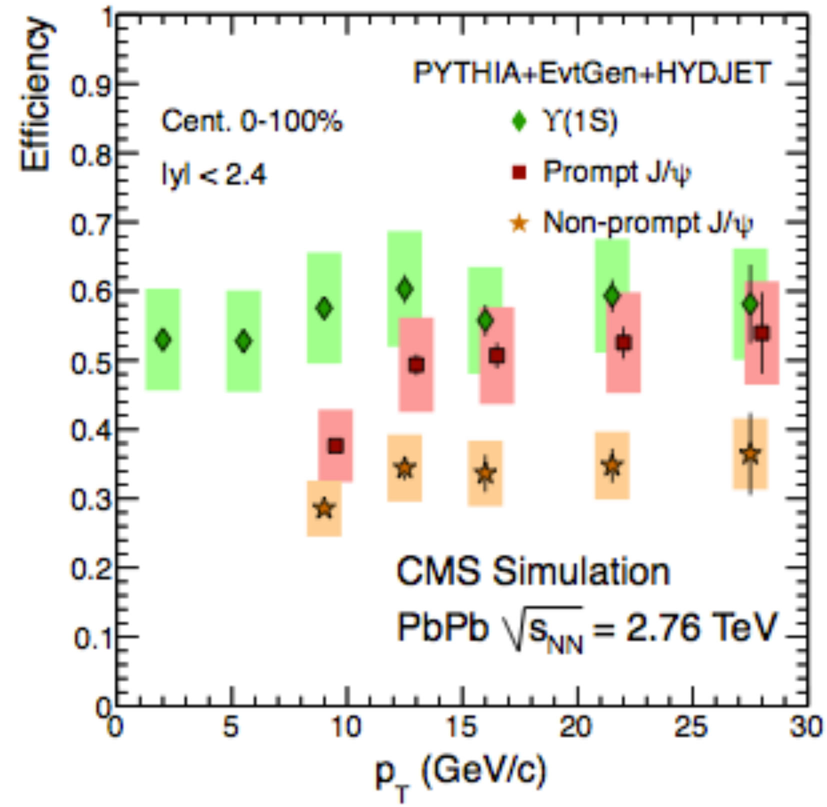
$$|\eta^\mu| < 1.0 \rightarrow p_T^\mu > 3.4\ \mathrm{GeV}/c$$

$$1.0 \leq |\eta^\mu| < 1.6 \rightarrow p_T^\mu > 5.8 - 2.4 \times |\eta^\mu|\ \mathrm{GeV}/c$$

$$1.6 \leq |\eta^\mu| < 2.4 \rightarrow p_T^\mu > 3.3667 - 7/9 \times |\eta^\mu|\ \mathrm{GeV}/c$$

Reconstruction Efficiency



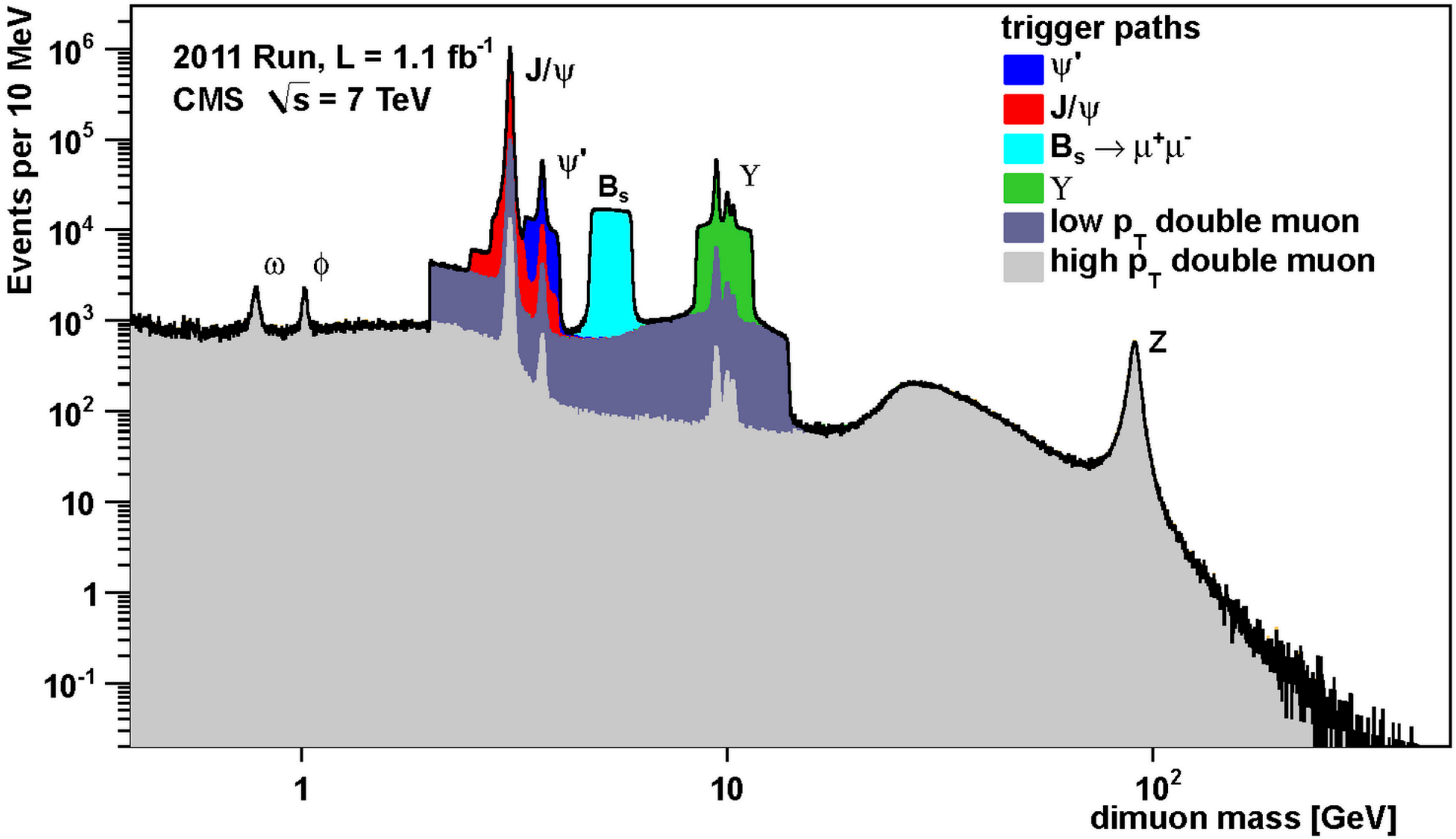


Binding Energy of Quarkonia

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
radius [fm]	0.25	0.36	0.45	0.14	0.22	0.28	0.34	0.39

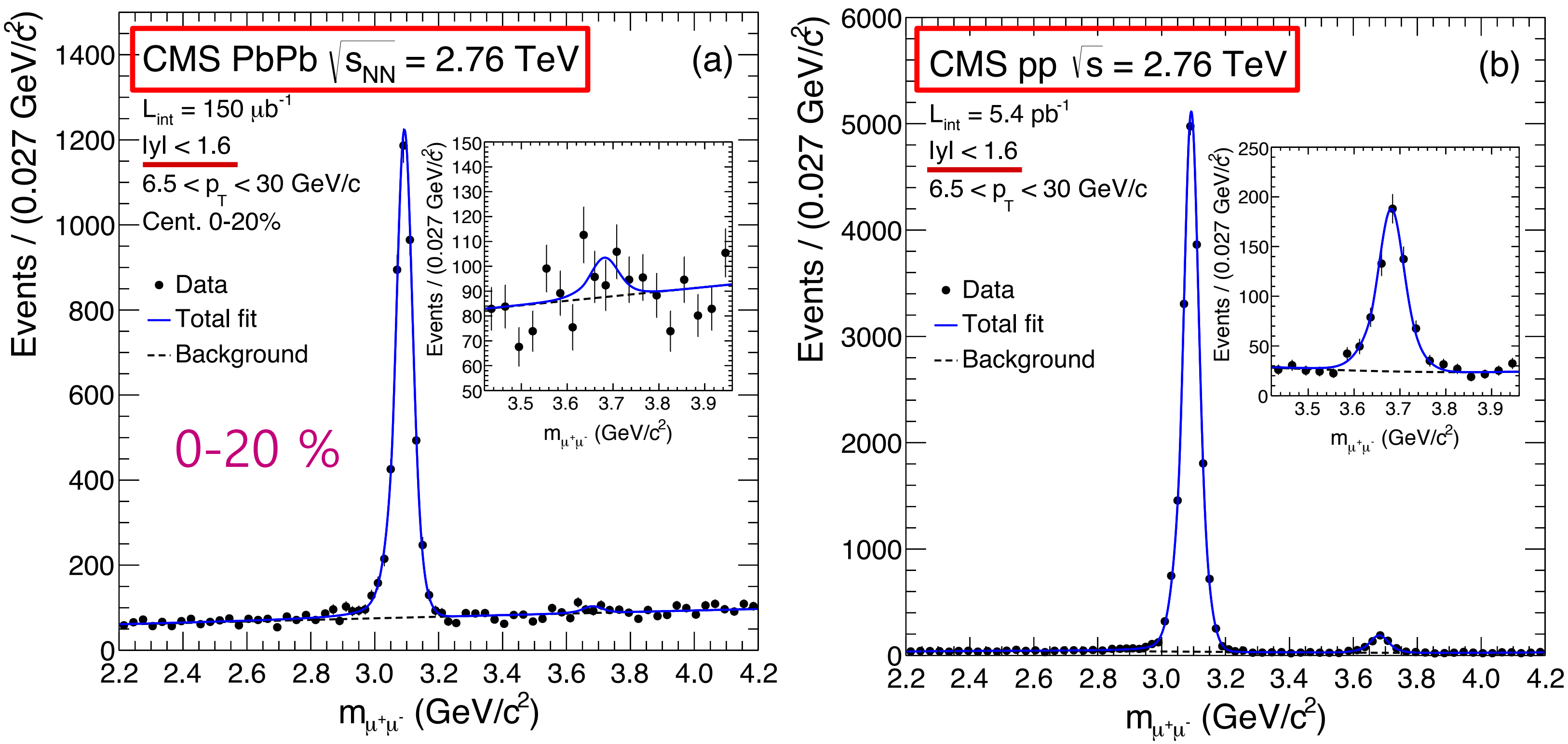
pp DiMuon

•


2011 Run, L = 1.1 fb^{-1}
CMS $\sqrt{s}$ = 7 TeV
J/ψ
ψ'
B_s
Υ
ω
φ
Z
trigger paths
ψ'
J/ψ
$B_s \to \mu^+\mu^-$
Υ
low p_T double muon
high p_T double muon
Events per 10 MeV
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
1
10
10^2
dimuon mass [GeV]

Prompt ψ(2S) in mid-rapidity (high p_T)

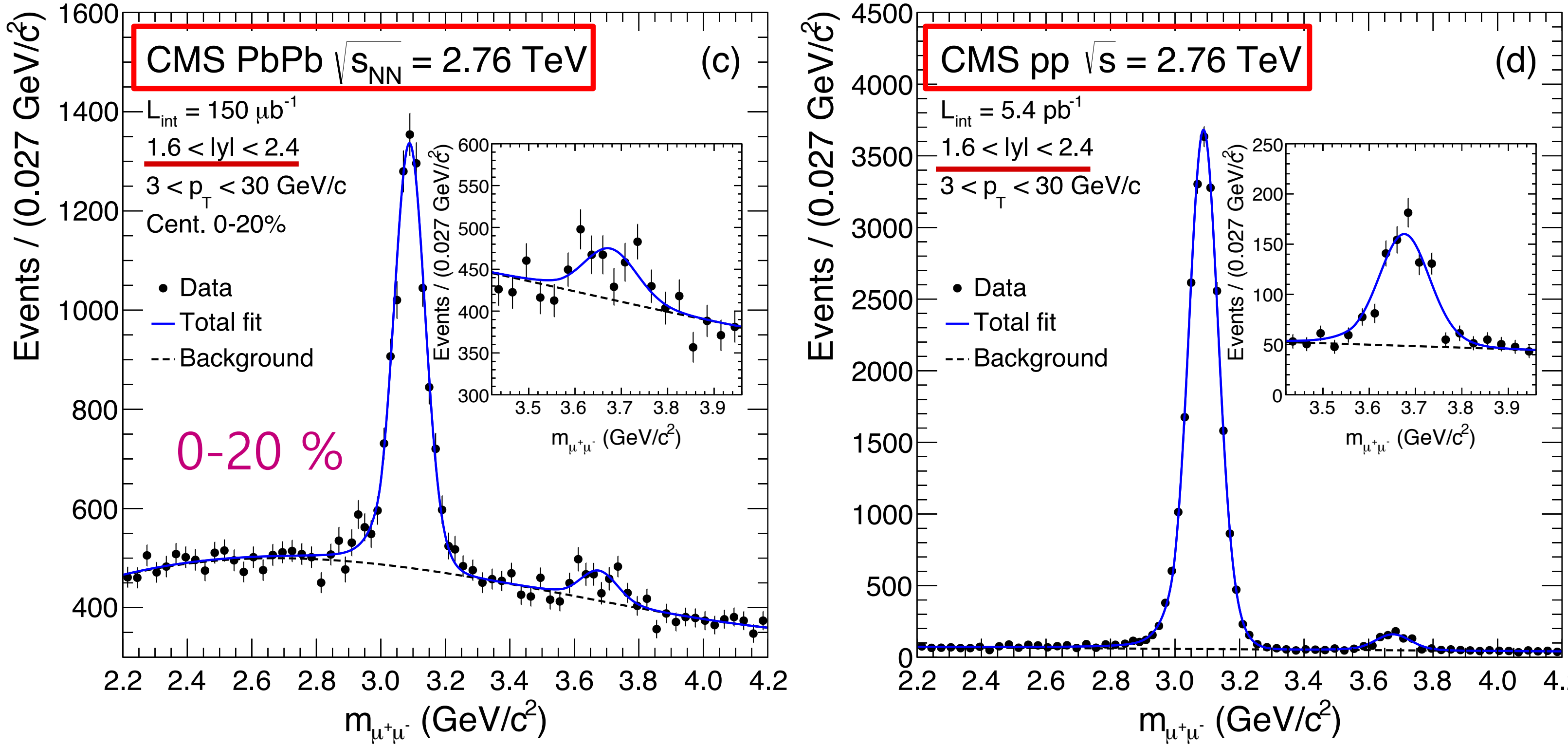
PRL 113 (2014) 262301



- In high p_T (mid-rapidity): ψ(2S) in PbPb is smaller than in pp with respect to the J/ψ as seen with 2010 pp data.

Prompt ψ(2S) in forward rapidity (low p_T)

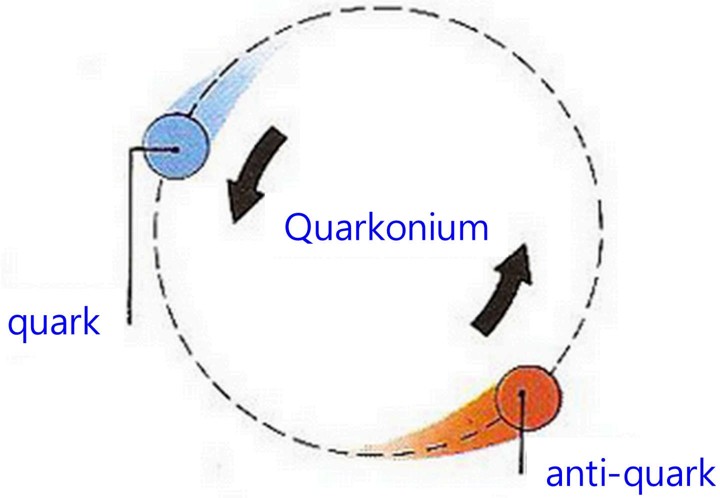
PRL 113 (2014) 262301



- In low p_T (forward-rapidity): ψ(2S) in PbPb is higher(or less) ?? than in pp with respect to J/ψ, yet.

Quarkonia Measurements

- **Quarkonia** : plural of quarkonium (c, b)
  - Charmonia : bound state of charm and anti-charm (J/ψ, $\psi'(2S)$, $\chi_c(1P)$ etc..)
  - Bottomonia : bound state of bottom and anti-bottom ($\Upsilon(1S, 2S, 3S)$, $\chi_b(1P)$ etc..)



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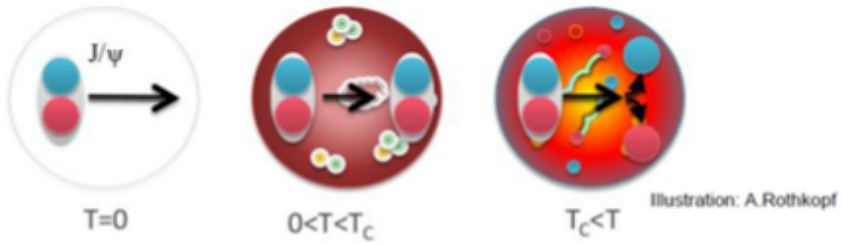

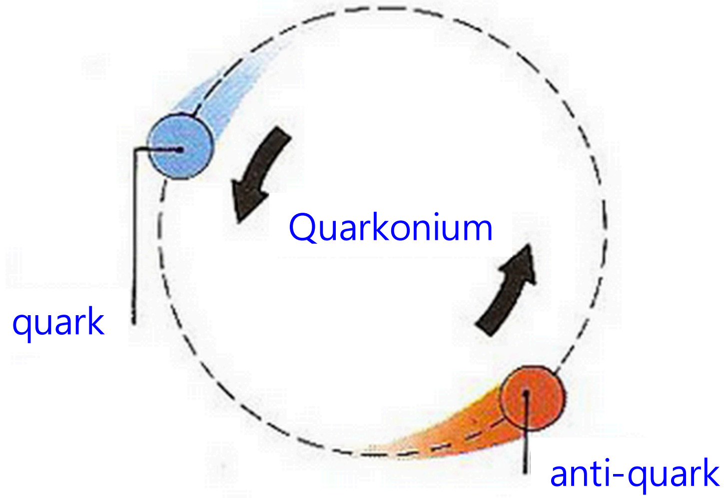

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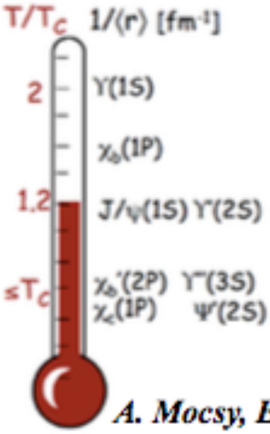
ΔE (GeV)	0.64	0.20	0.05
T_d/T_c	2.1	1.16	1.12

state	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
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



A. Mocsy, EPJC61 (2009) 705

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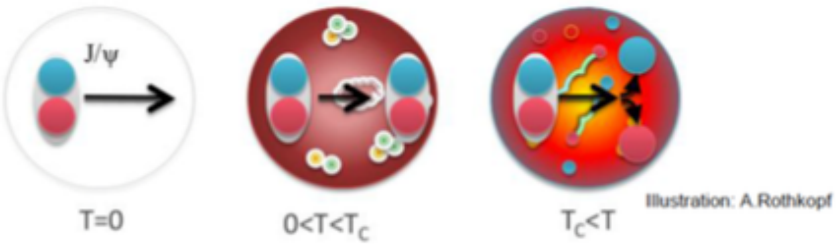

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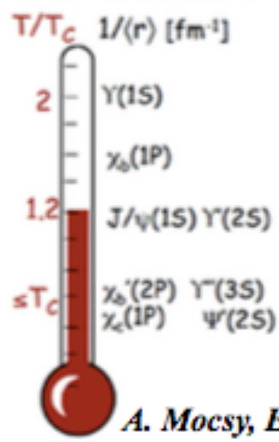
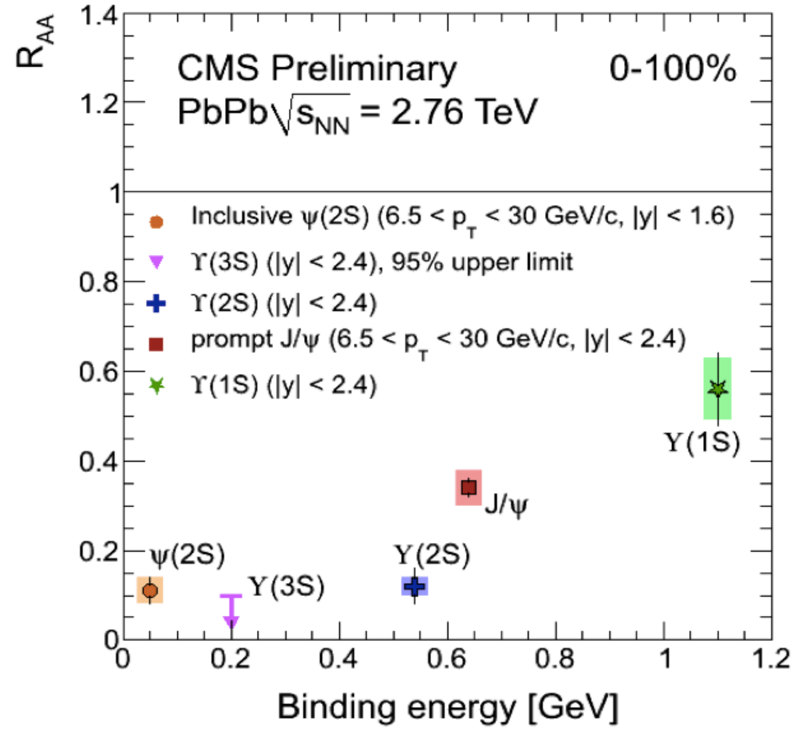


A. Mocsy, EPJC61 (2009) 705



CMS-PAS-HIN-12-014
PRL 109 (2012) 222301

Quarkonia Measurement in pp, pPb and PbPb

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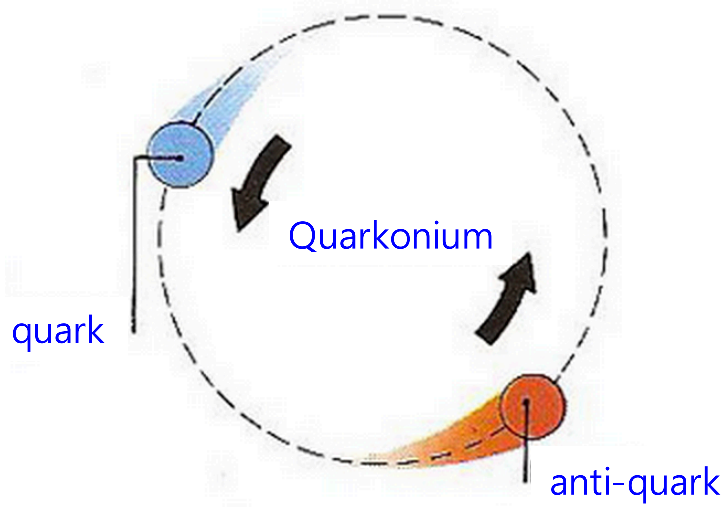

Quarkonia Measurement in pp, pPb and PbPb

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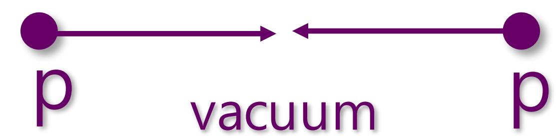
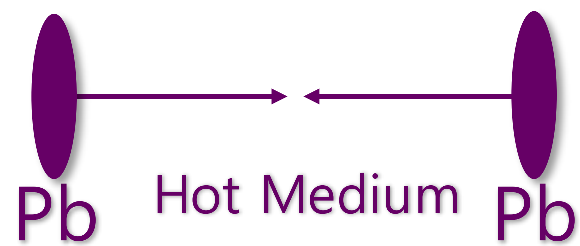
- **pp collisions**
  — Cross section, understanding polarization



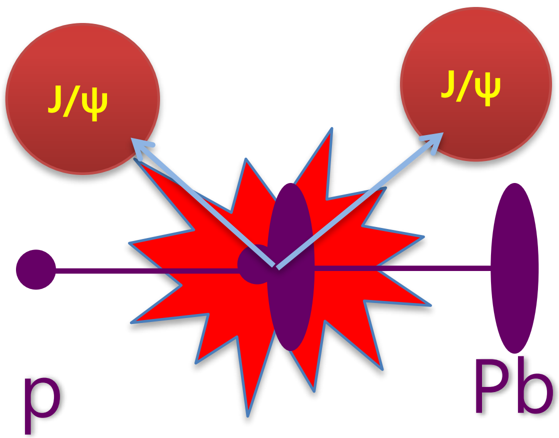
- **PbPb collisions**
  — Exploring new nuclear matter known as Quark-Gluon-Plasma (QGP)
  — Characterize and quantify the properties of QGP
  — Observed strong quarkonia suppression



- **pPb collisions**
  — Create Cold Nuclear Matter (CNM)
  — Understanding initial state effect on production
  — Examine pure suppression from observation in PbPb collisions

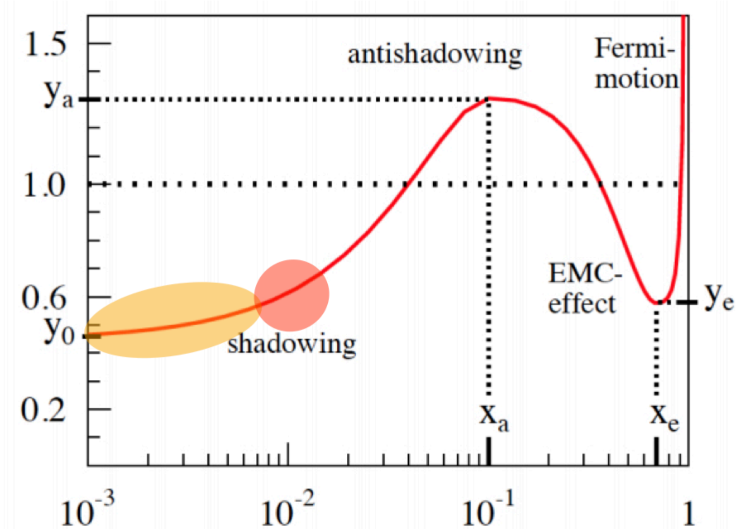
Quarkonia Measurement in pPb Collisions

- **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**



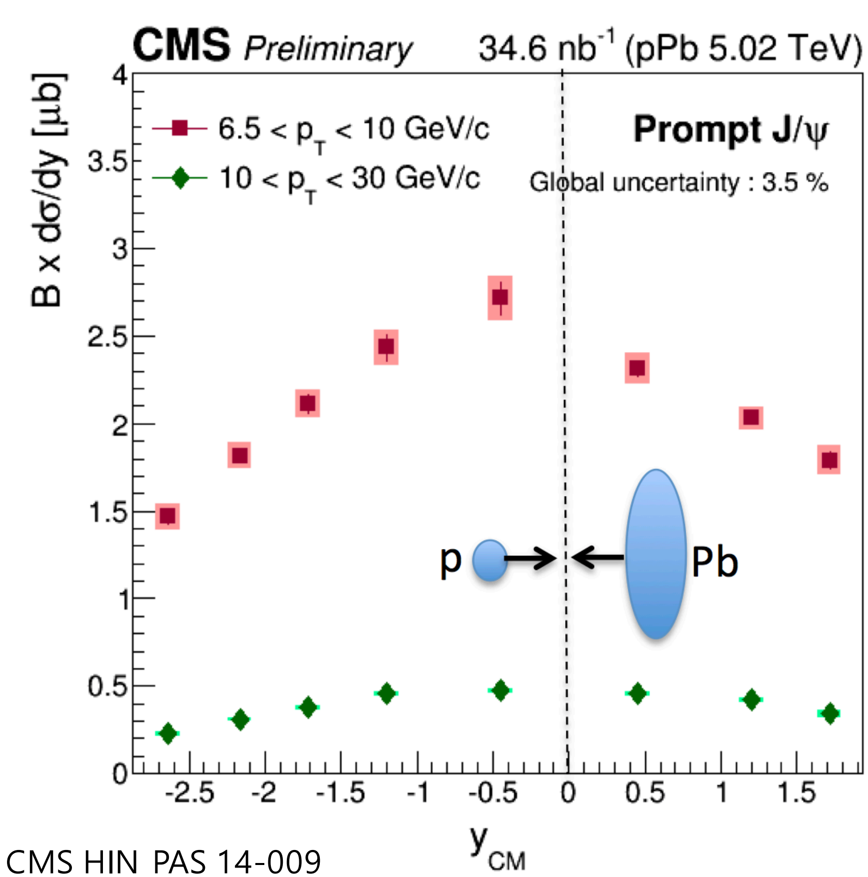
Forward **Backward**

Illustration of nPDF fit
JHEP 0904 (2009) 065



x of parton in Pb
[In log scale]

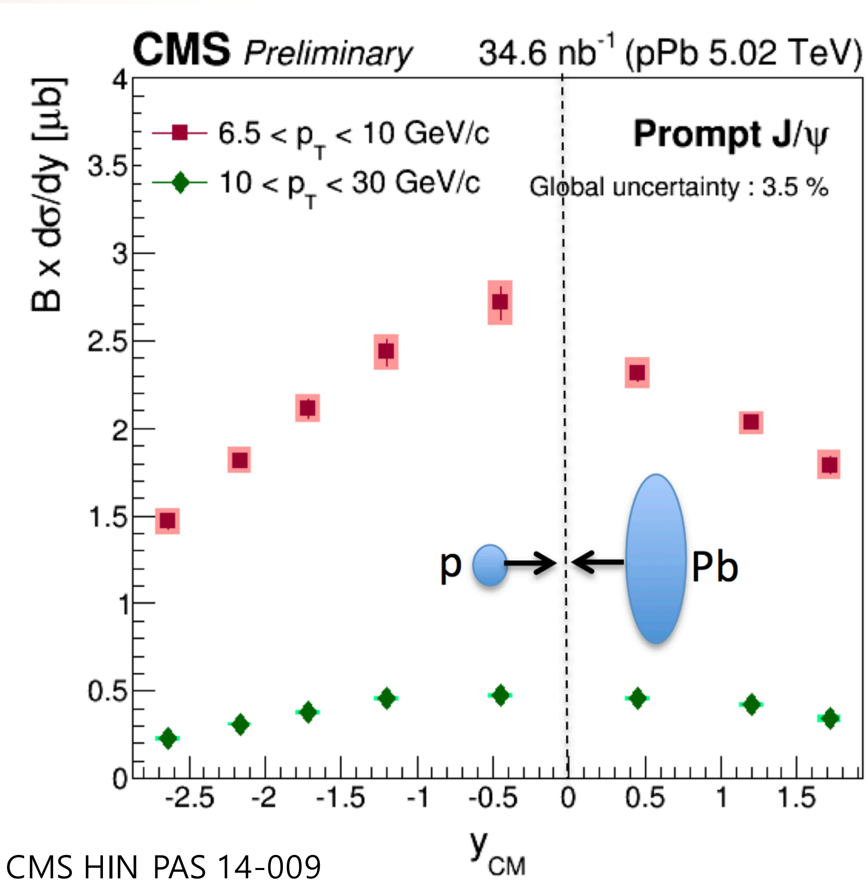
Charmonia in pPb



CMS HIN PAS 14-009

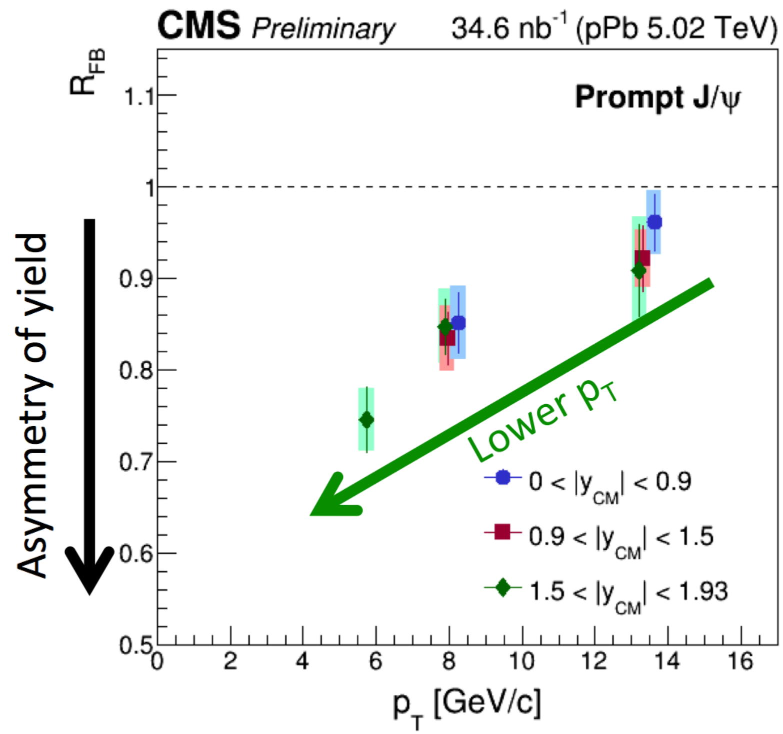
$$R_{FB}(p_T, y) = \frac{\text{Yield in } (p_T, +y)}{\text{Yield in } (p_T, -y)}$$

Charmonia in pPb



CMS HIN PAS 14-009

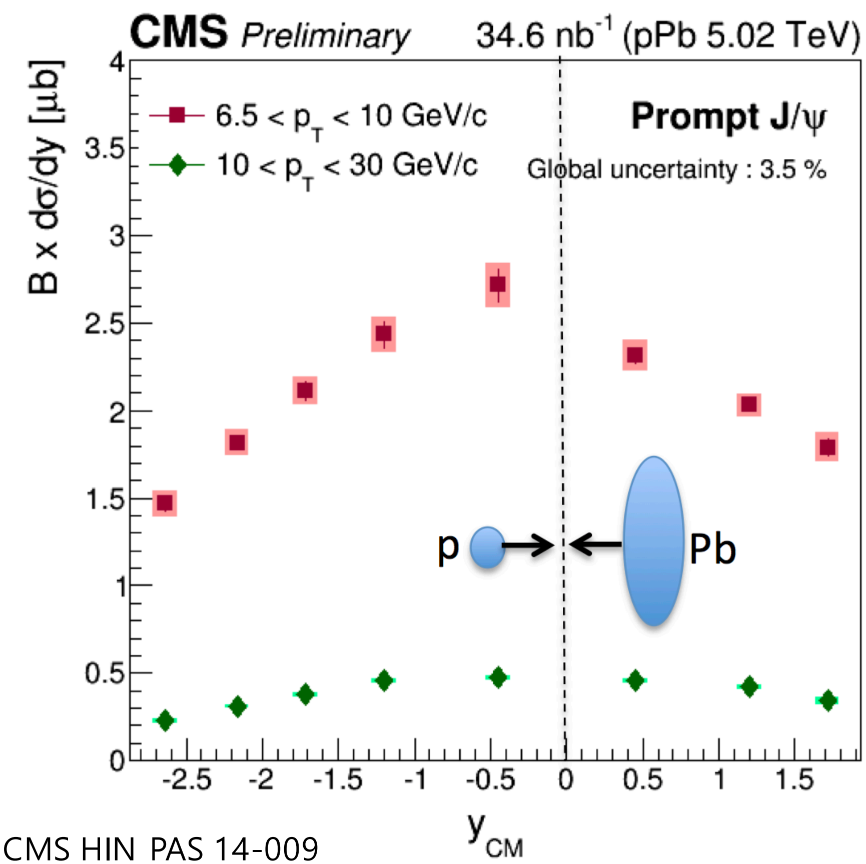
$$R_{FB}(p_T, y) = \frac{\text{Yield in } (p_T, +y)}{\text{Yield in } (p_T, -y)}$$



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

Charmonia in pPb

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



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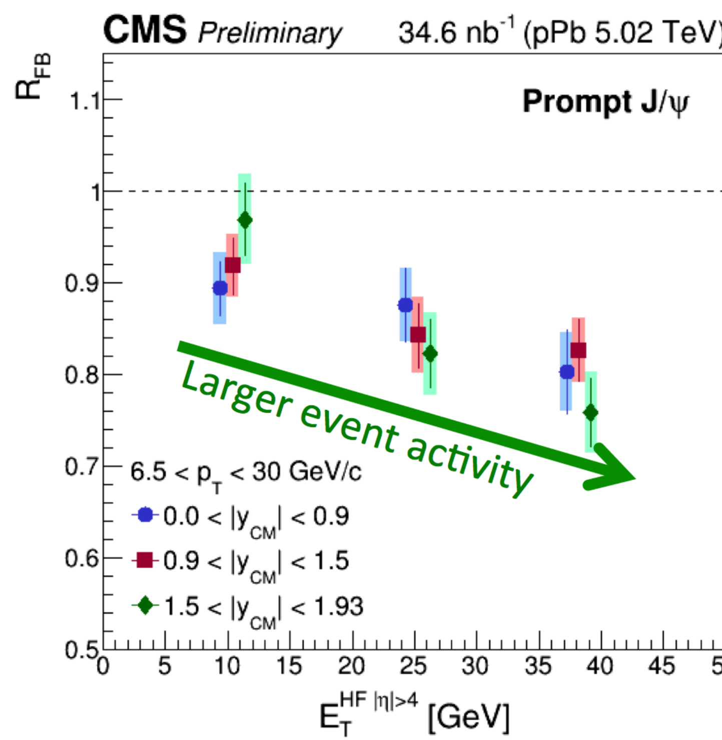
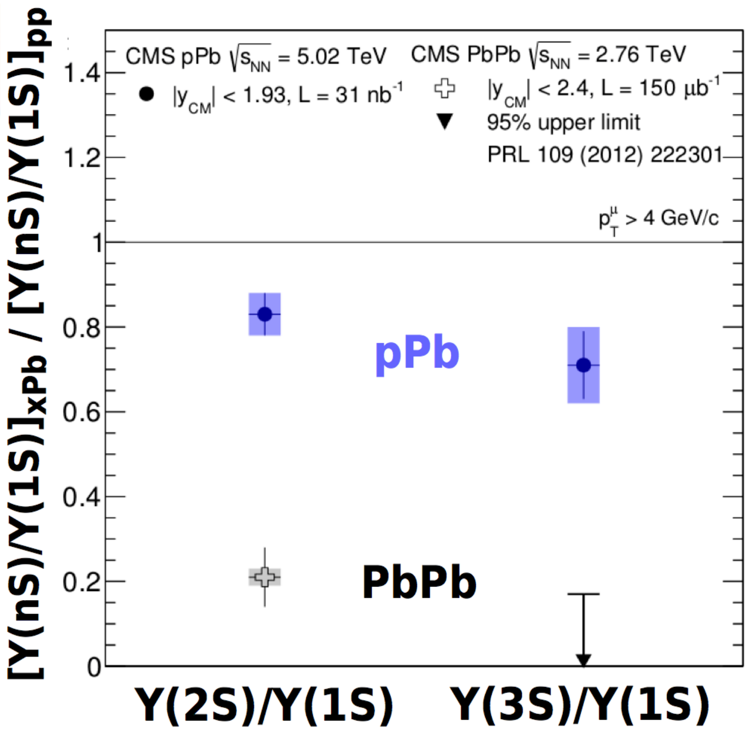
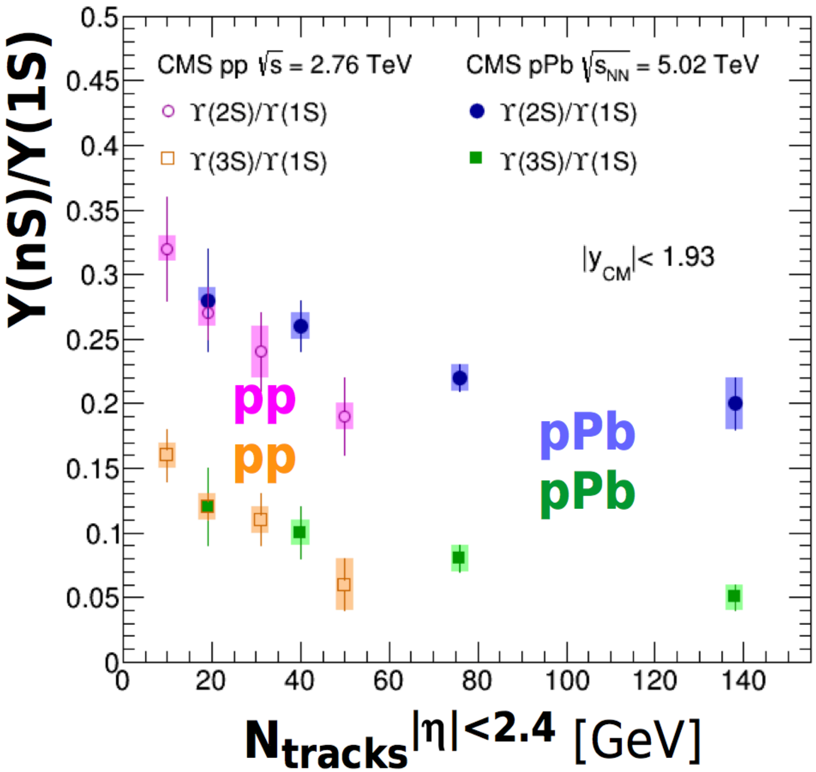


- Clear dependence of event activity : more suppression for forward in larger event activity
- No strong dependence on |y|

Bottomonia in pPb

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



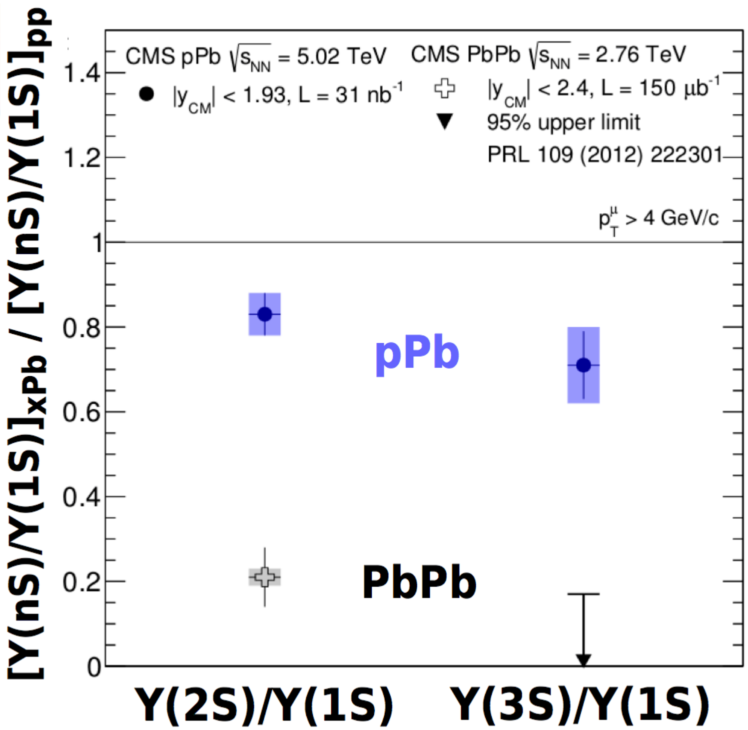


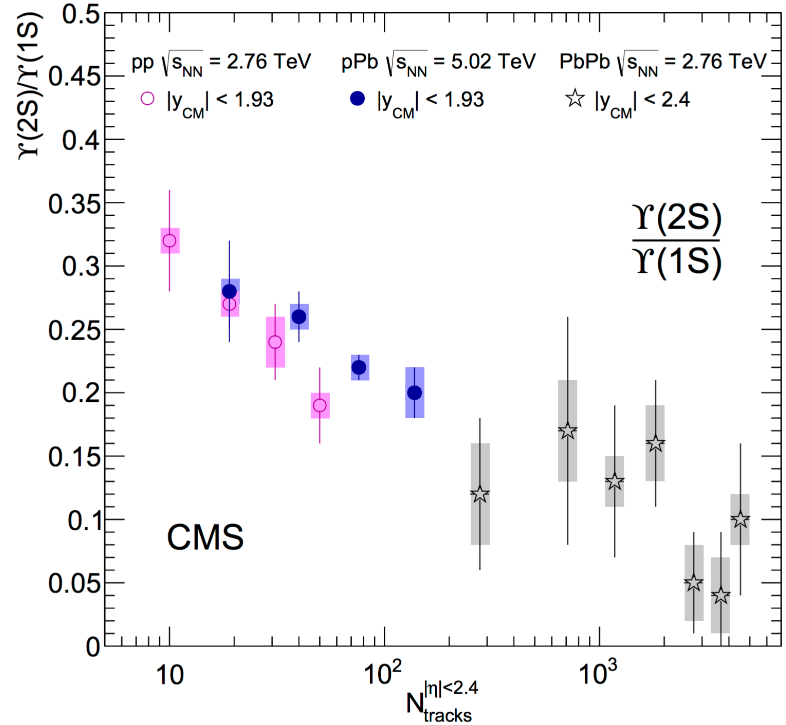
PRL 109 (2012) 222301

- Indication of initial suppression in pPb
- Υ(nS)/Υ(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