Quarkonium production in heavy-ion collisions from CMS

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  - Bottomonia in pPb collisions → **CMS-PAS HIN-13-003**
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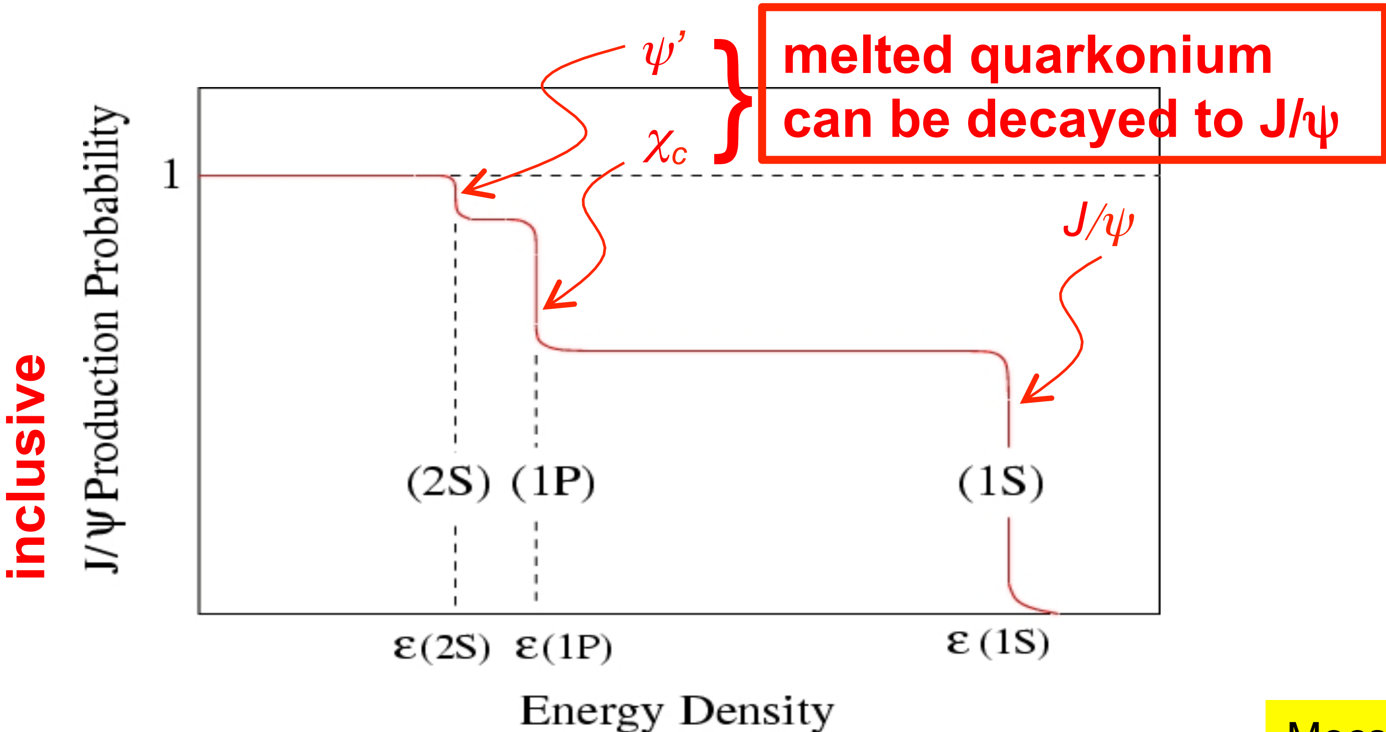
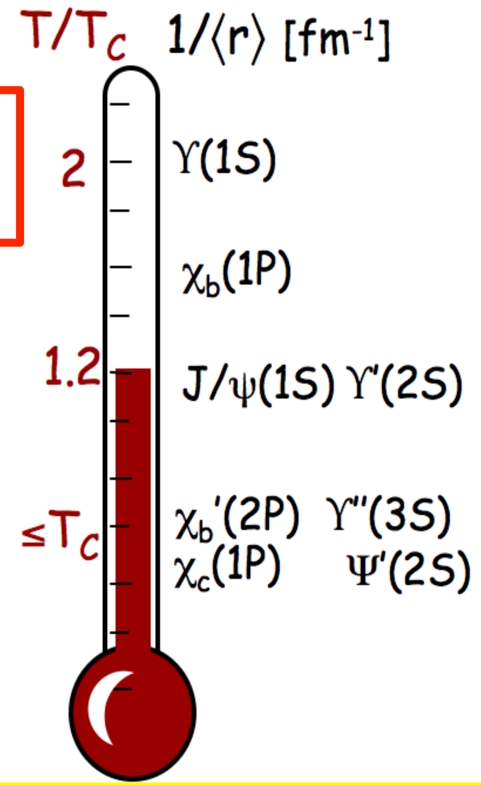
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

Theoretical motivation

From Matsui & Satz
PLB 178 (1986) 416

- Before Quark-Gluon Plasma, heavy quarks (charm, bottom) are produced.
- heavy quark + anti heavy quark → quarkonium
- In QGP, we expect the melting of quarkonia caused by Debye screening
- Use sequential melting of the quarkonia states as the thermometer of the hot and dense matter





Mocsy, EPJ C 61 (2009) 705

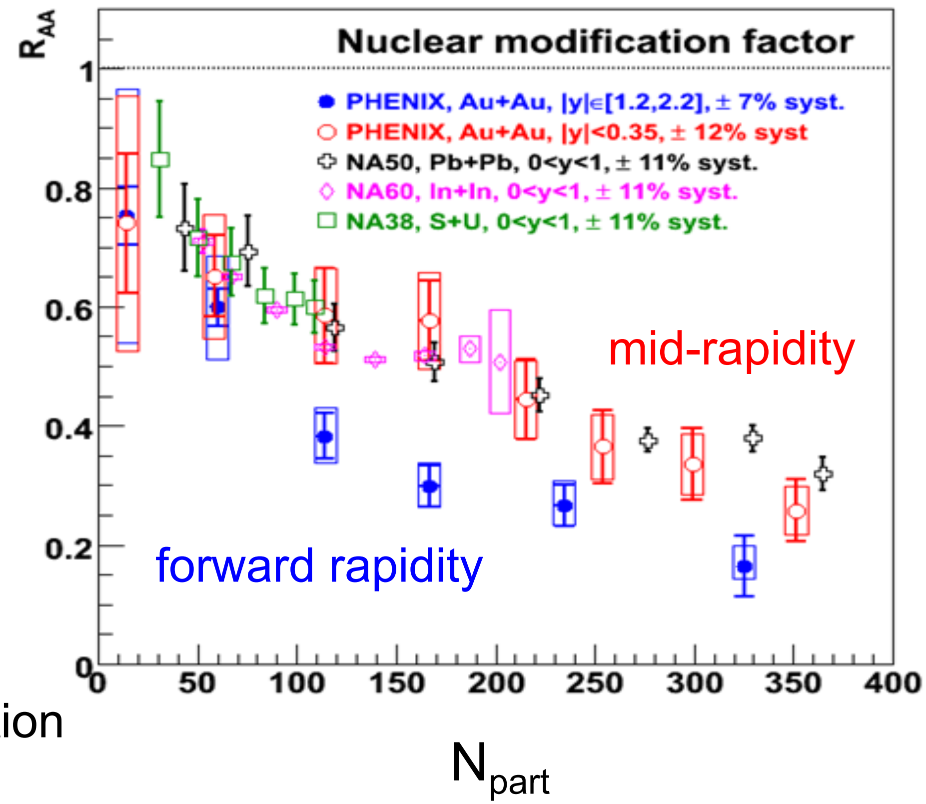
Experimental motivation

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

- **Nuclear Modification factor(R_{AA}) measurement**
  - Formula :

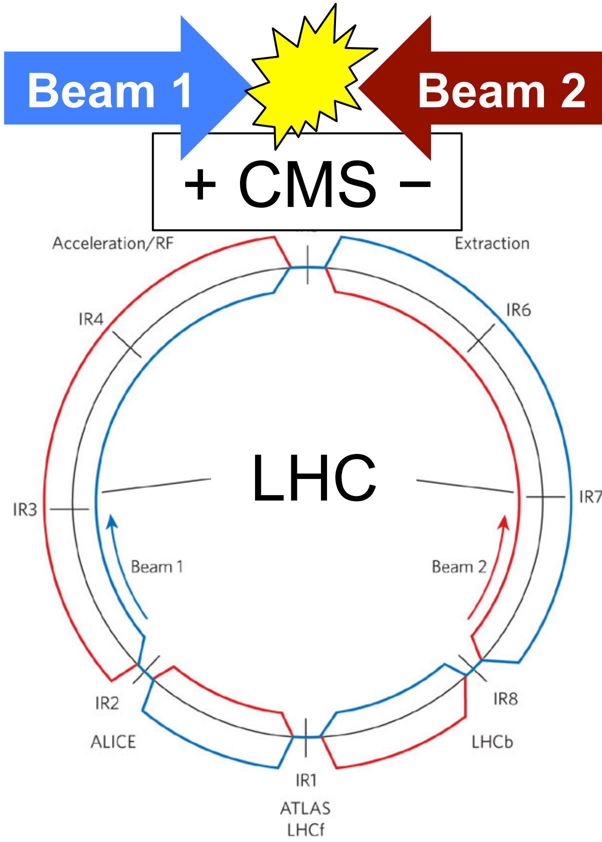
$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB} \varepsilon_{cent}} \frac{N_{PbPb}(Q\overline{Q})}{N_{pp}(Q\overline{Q})}$$

  - Indicator of suppression(R_{AA}<1) of enhancement(R_{AA}>1) of the particle in ion collision
- **Puzzles from SPS and RHIC**
  - Similar J/ψ suppression at SPS(< 20 GeV) and RHIC(200 GeV)
  - R_{AA}(forward) < R_{AA}(mid)
    - Suppression does not increase with local energy density
  - Possible answers
    - regeneration?
    - cold nuclear matter effects?
- **Now LHC is giving us the hint**
  - higher energy
    - PbPb@2.76 TeV, pPb@5.02 TeV
  - higher luminosity
  - more charm → possible to recombination
  - new probe : ϒ

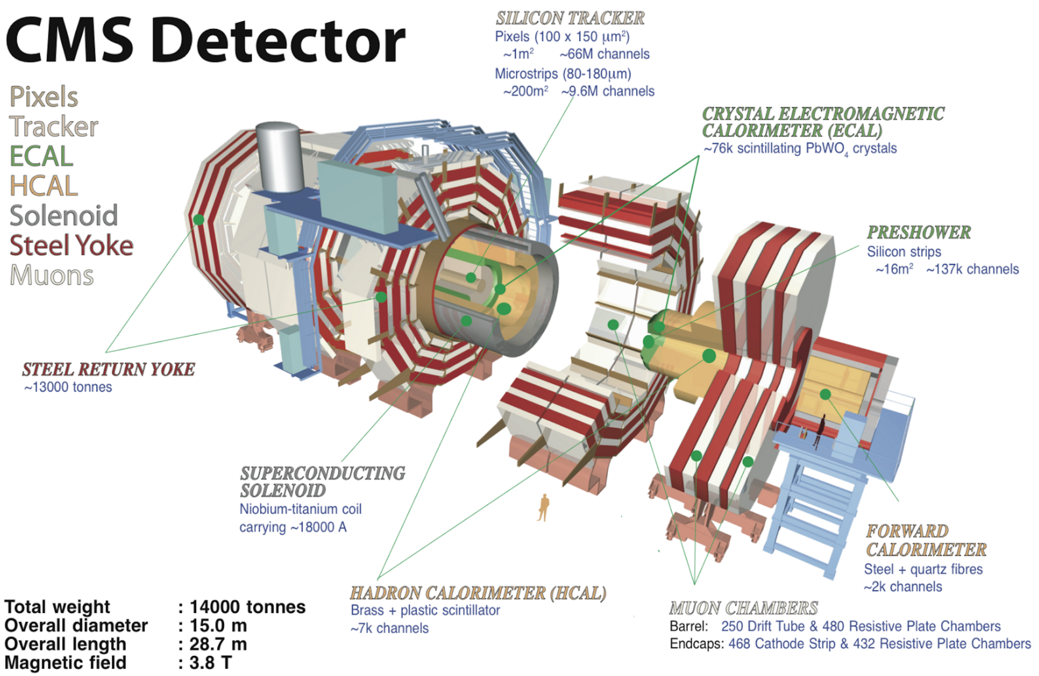


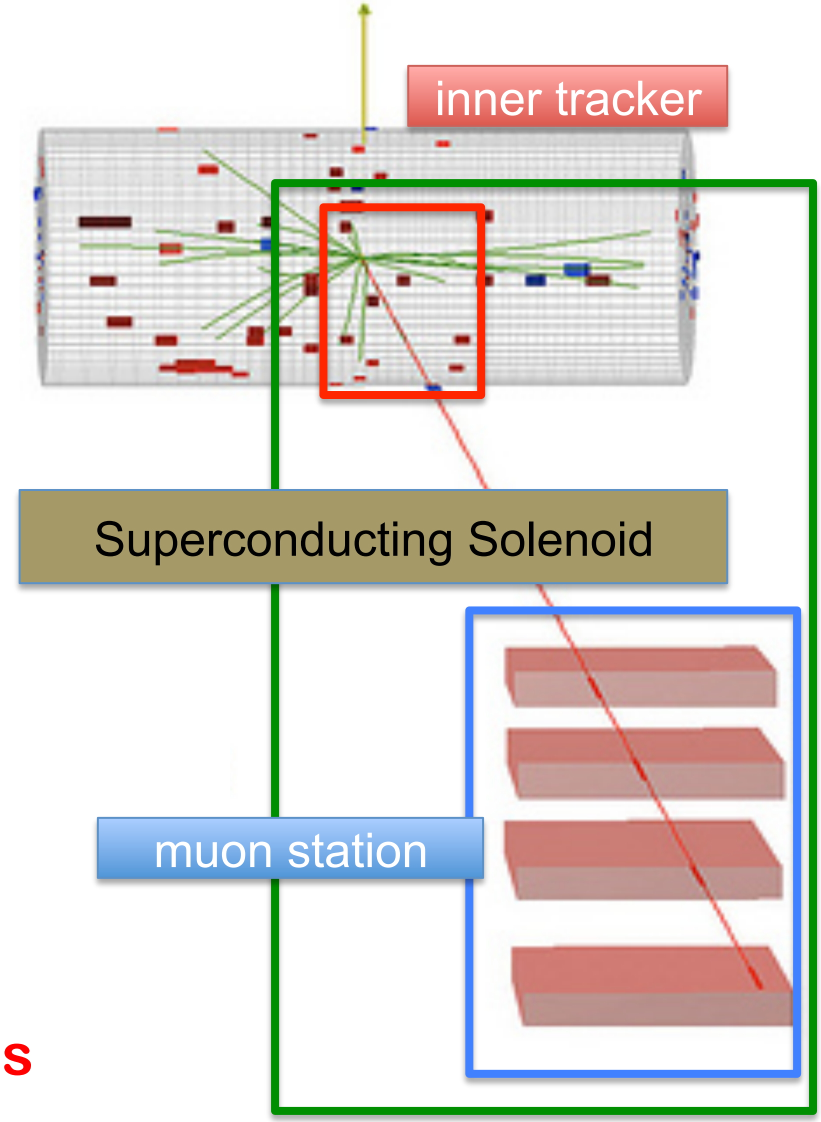
Summary of ion physics run from LHC

- Pb ion-Pb ion collisions (2010, 2011 – about one month/year)
  - Beam Energy : 2.76 TeV/nucleon pair
  - Integrated luminosity
    - 2010 : 7.28 μb^{-1}
    - 2011 : 157.6 μb^{-1} recorded
- proton-Pb ion collisions (2013. Jan. ~ Feb.)
  - Beam Energy : 5.02 TeV/nucleon
    - proton : 4 TeV, Pb ion : 1.58 TeV
  - Asymmetry collision, boosted to proton forward direction
  - Integrated luminosity : 31 nb^{-1}
  - Change beam circulation
    - 1^{st} (Beam1:proton, Beam2:Pb ion) collision
      - Jan. 20^{th} ~ 30^{th}
    - 2^{nd} (Beam1:Pb ion, Beam2:proton) collision
      - Feb. 2^{nd} ~ 10^{th}
- proton-proton collisions (2011 Mar., 2013. Feb. 11^{th} ~ 14^{th})
  - For the reference to PbPb data and partially to pPb data
  - Beam energy : 2.76 TeV/proton
  - Integrated luminosity
    - 2011 : 231 nb^{-1} (equivalent to 2010 PbPb data)
    - 2013 : 5.41 pb^{-1} (equivalent to 2011 PbPb data)



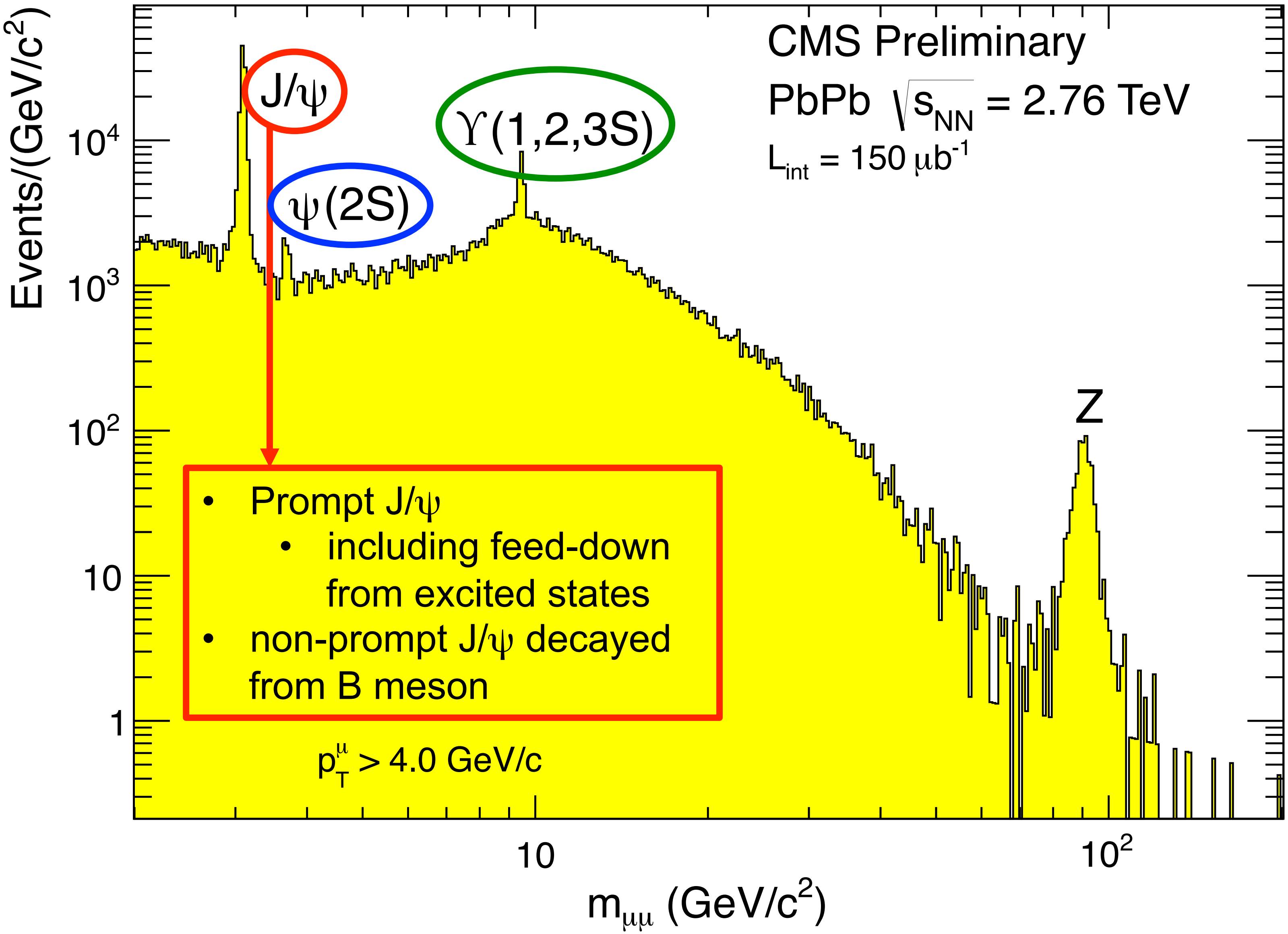
CMS muon reconstruction





- **Global muons reconstructed with information from inner tracker and muon stations, with additional quality cut**
- **For pPb analysis, use tracker muons like pp group analysis**

Quarkonium decayed to dimuon

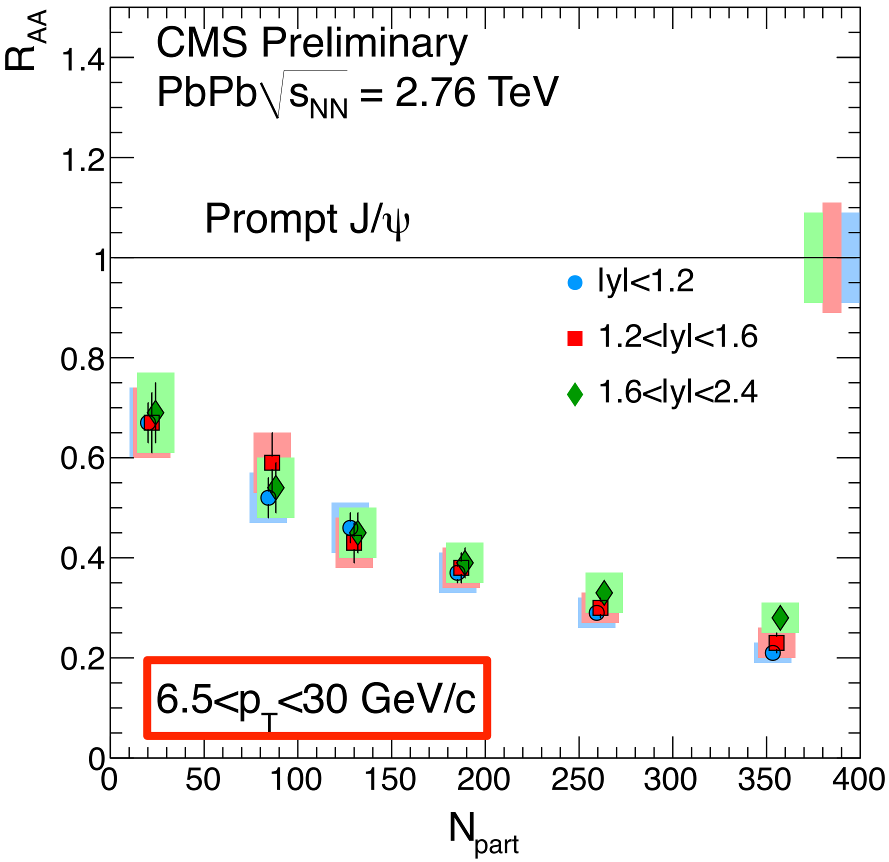


- Prompt J/ψ
  - including feed-down from excited states
- non-prompt J/ψ decayed from B meson

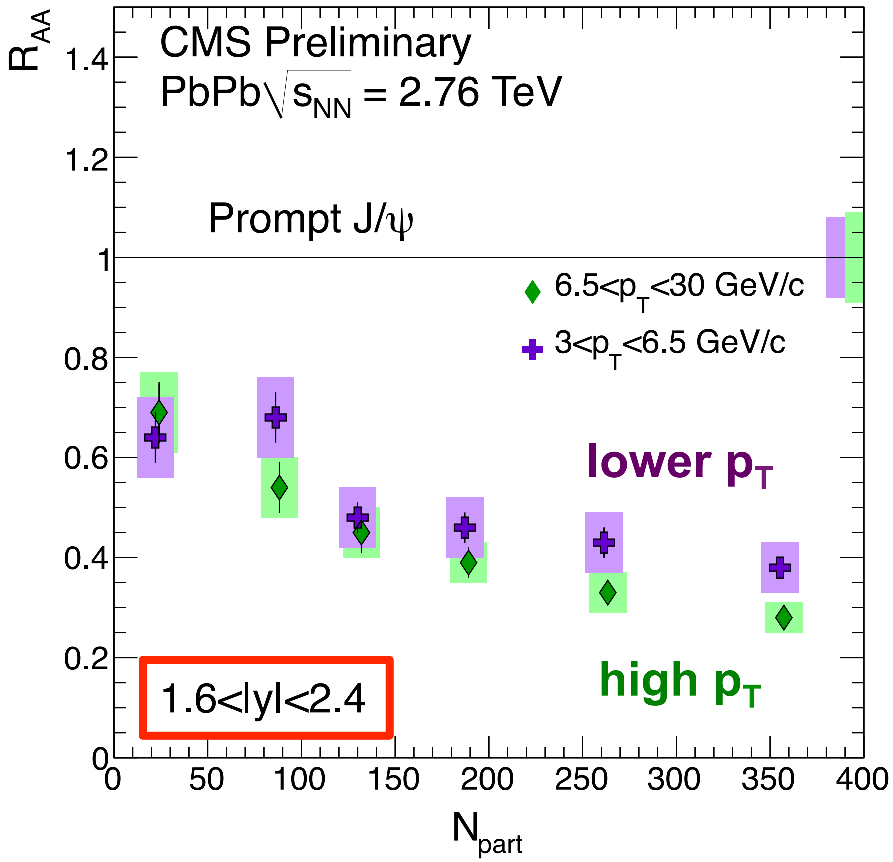
Prompt J/ψ R_{AA} : centrality dependence

CMS-PAS HIN-12-014

Rapidity dependence



p_T dependence



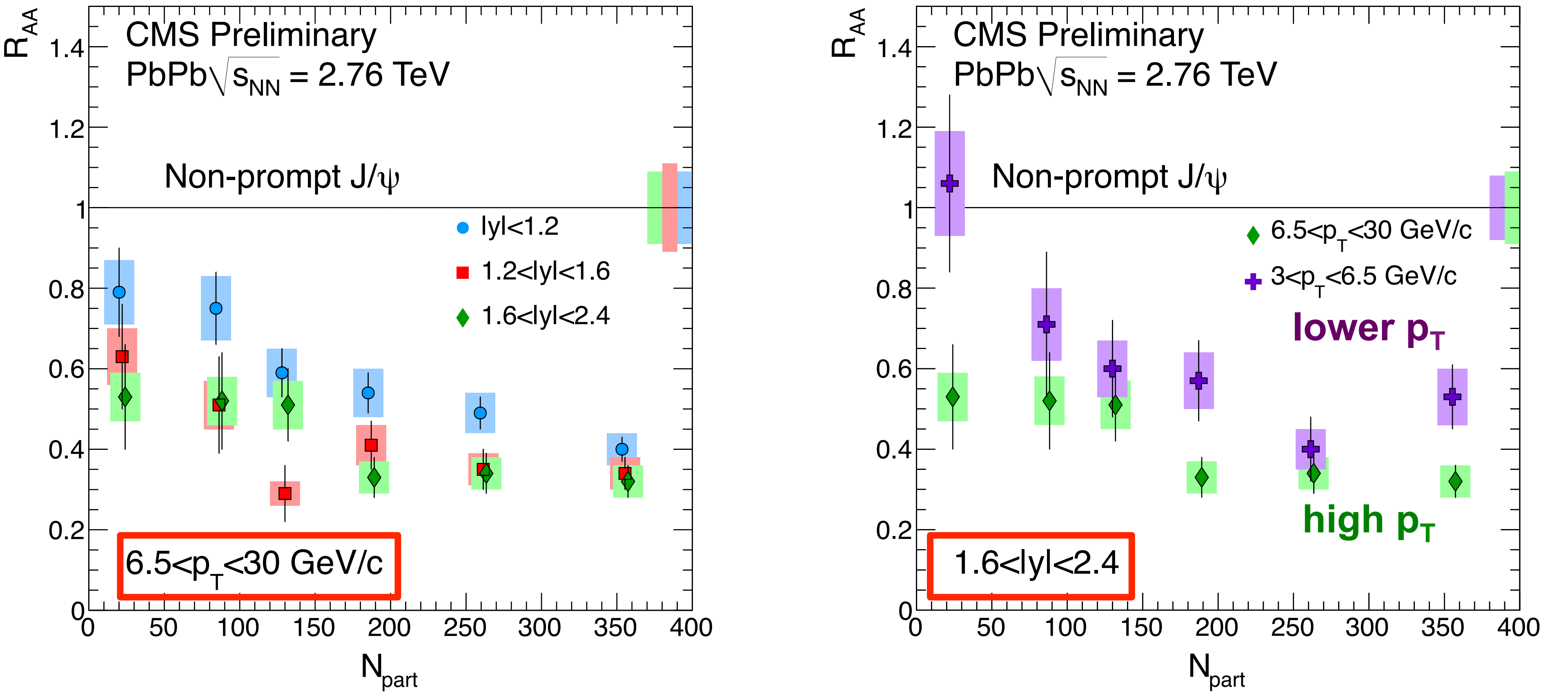
- Suppressed by factor 5 in most central collision
- Left : no strong dependence on rapidity at higher p_T region
- Right : at forward rapidity region, lower p_T J/ψ is slightly less suppressed in most central case.

non-prompt J/ψ R_{AA} : centrality dependence

CMS-PAS HIN-12-014

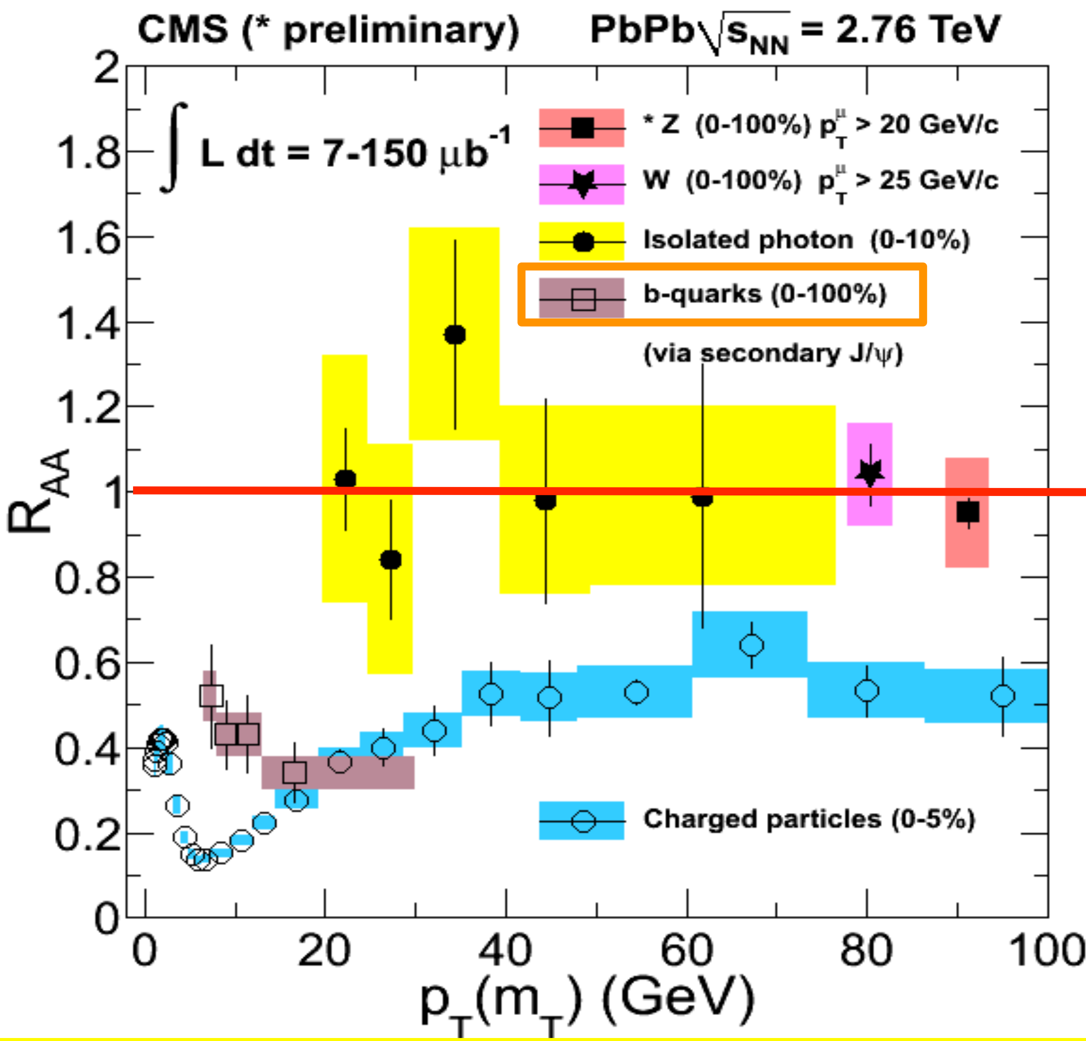
Rapidity dependence

p_T dependence



- Left : In all rapidity bins at high p_T region, centrality dependent suppression is shown.
- Right : In the forward region, lower p_T J/ψ has strong centrality dependence and less suppressed than high p_T J/ψ

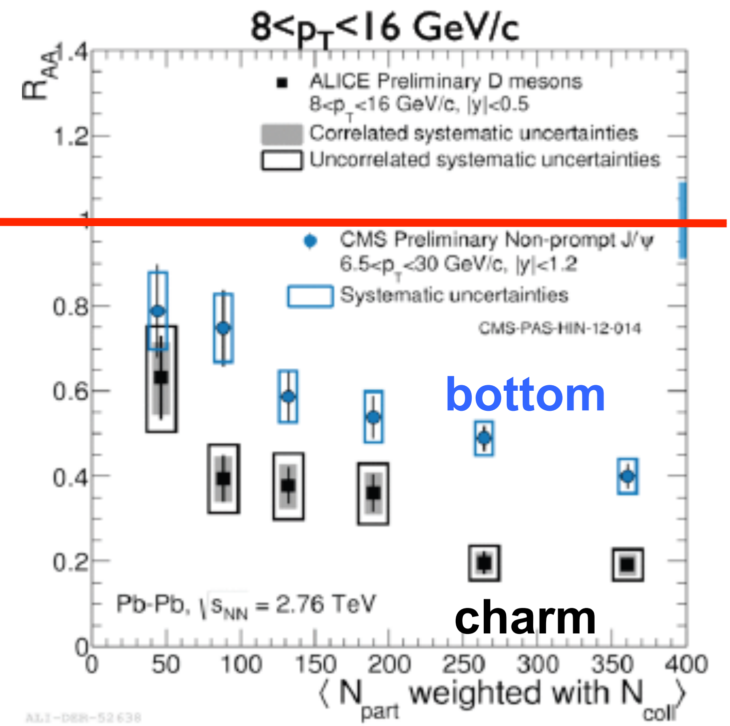
b-quark R_{AA} compared with other particles



CMS Highlights from Gunther Roland@QM12

In central collisions

$R_{AA}^{charm} < R_{AA}^{bottom}$



ALICE : E.Bruna's slide@SQM2013
CMS : CMS-PAS HIN-12-014

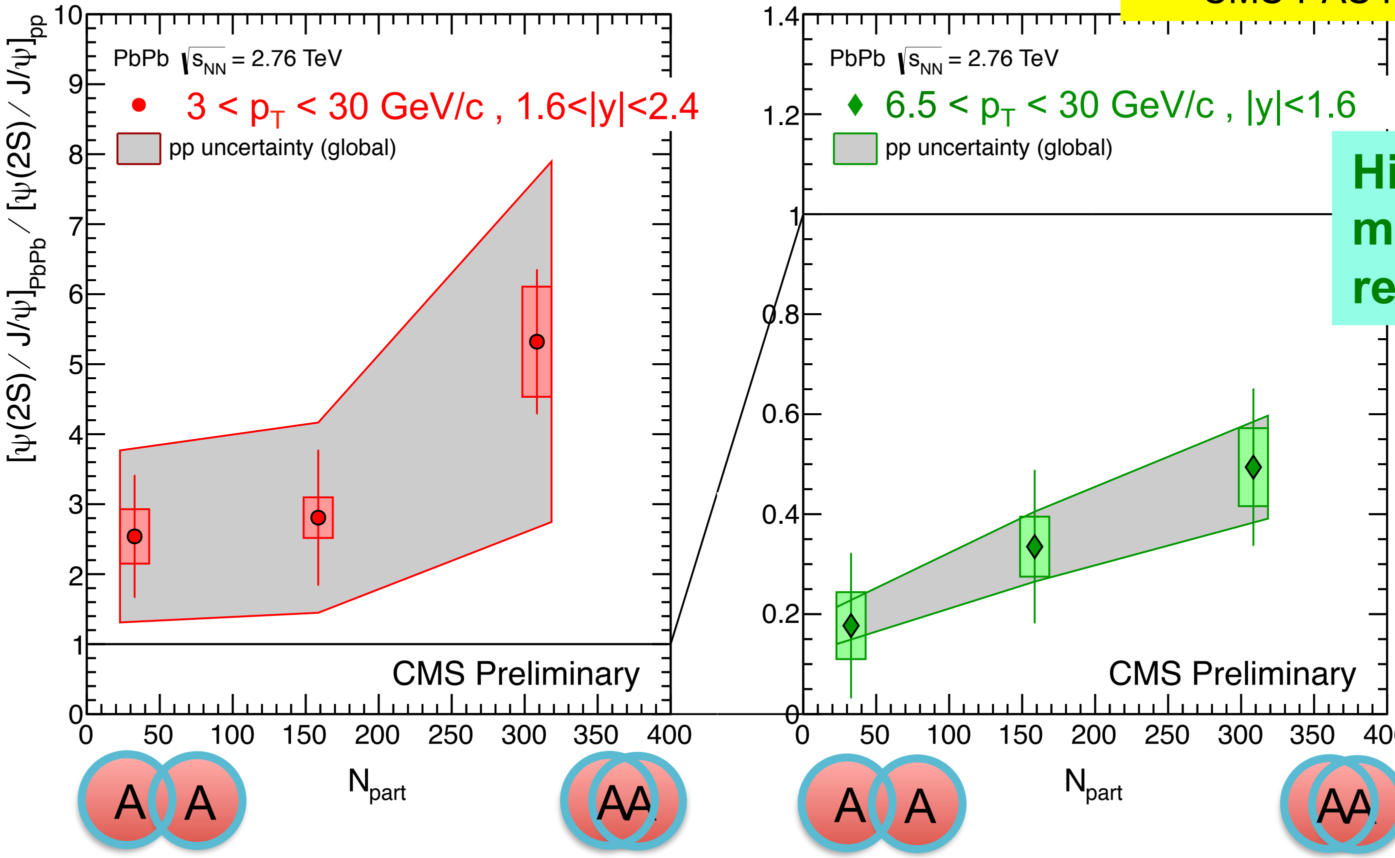
- Directly measuring the b-quark energy loss in the medium
- b-quark is suppressed distinctly

ψ (2S) double ratios and R_{AA} : centrality dependence

CMS-PAS HIN-12-007

Lower-p_T, forward region

High-p_T, mid-rapidity region



$$\frac{N_{\psi(2S)}/N_{J/\psi}|_{PbPb}}{N_{\psi(2S)}/N_{J/\psi}|_{pp}} = \frac{R_{AA}(\psi(2S))}{R_{AA}(J/\psi)}$$

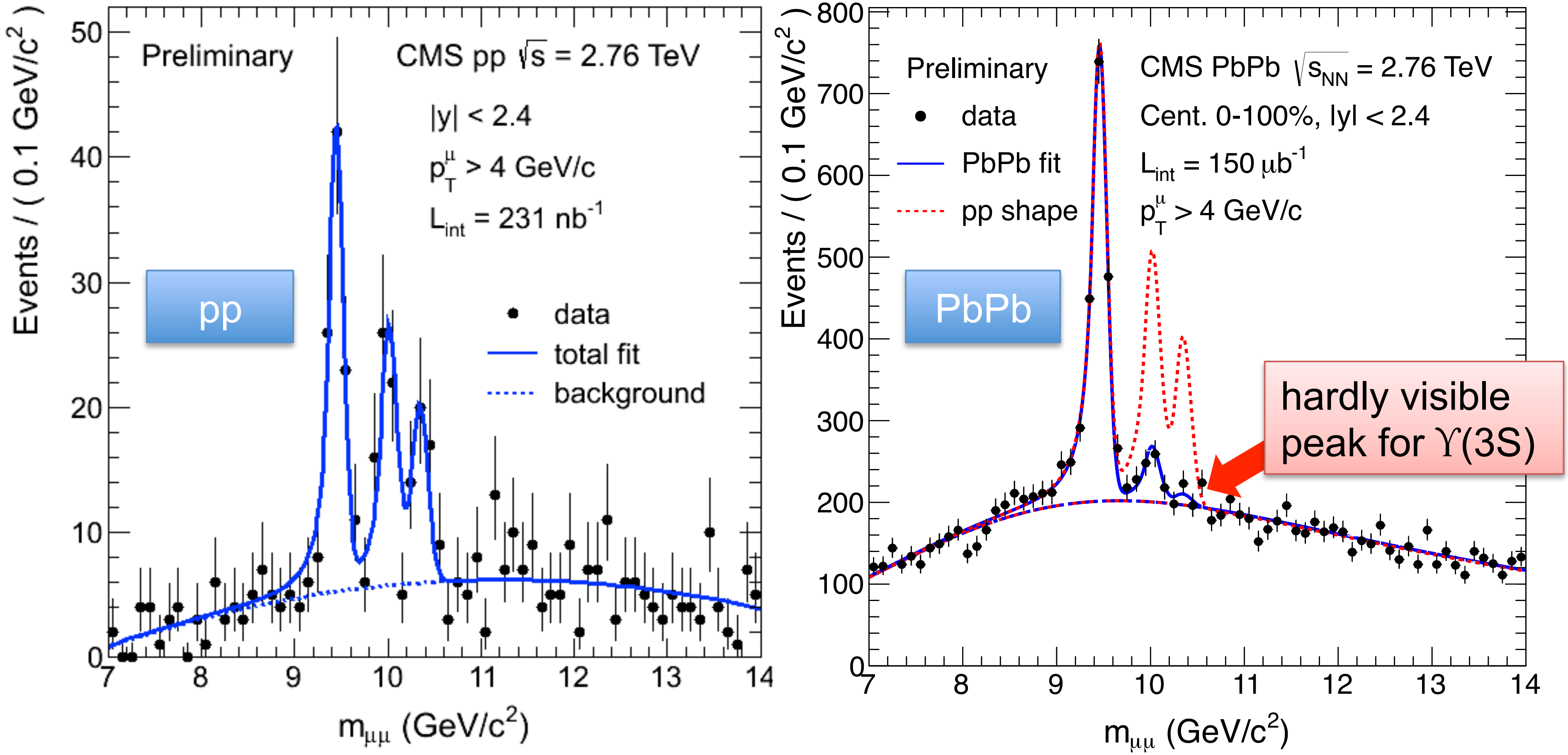
$$R_{AA}^{0-100\%}(\psi(2S)) = 1.54 \pm 0.32(\mathrm{stat}) \pm 0.22(\mathrm{syst}) \pm 0.76(\mathrm{pp})$$

limited by low statistics from 2011 pp data

$$R_{AA}^{0-100\%}(\psi(2S)) = 0.11 \pm 0.03(\mathrm{stat}) \pm 0.02(\mathrm{syst}) \pm 0.02(\mathrm{pp})$$

- Will be updated with 2013 pp data

Υ(nS)’ s mass distributions

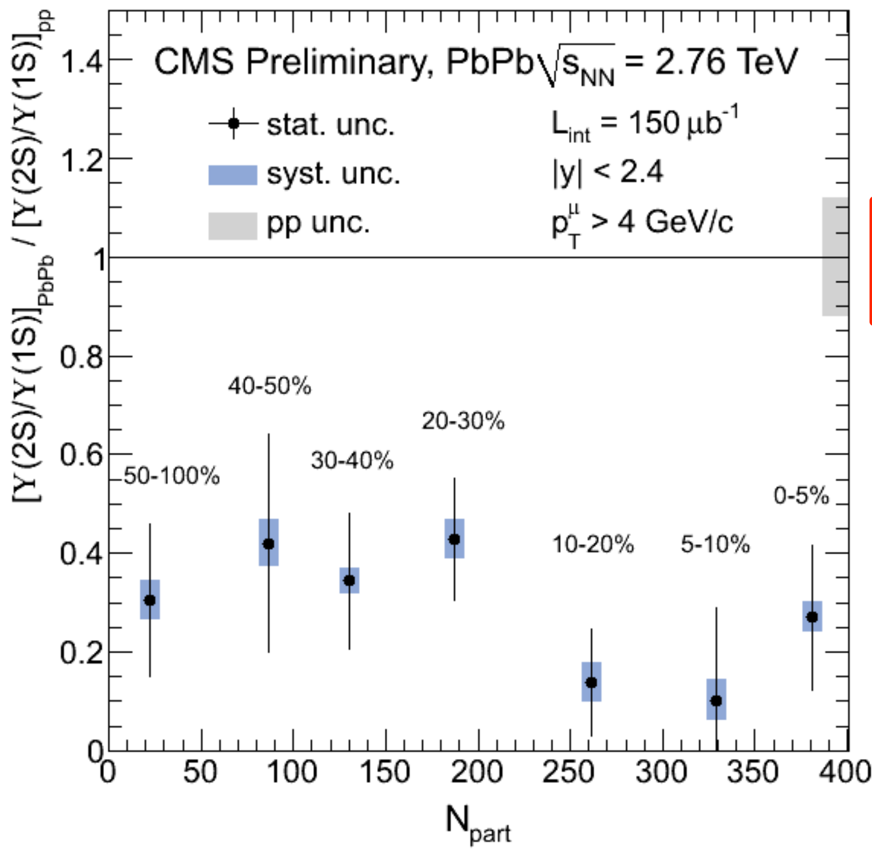


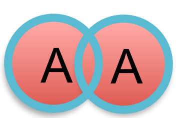
- Ratios not corrected for acceptance and efficiency.
- In PbPb, the excited states suppressed relative to the ground state.

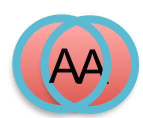
PRL 109 (2012) 222301

Υ (nS) / Υ (1S) Double ratio

Υ(2S) / Υ(1S)







PRL 109 (2012) 222301

- **Measured Υ(2S) double ratio vs. centrality**
  - centrality integrated:

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

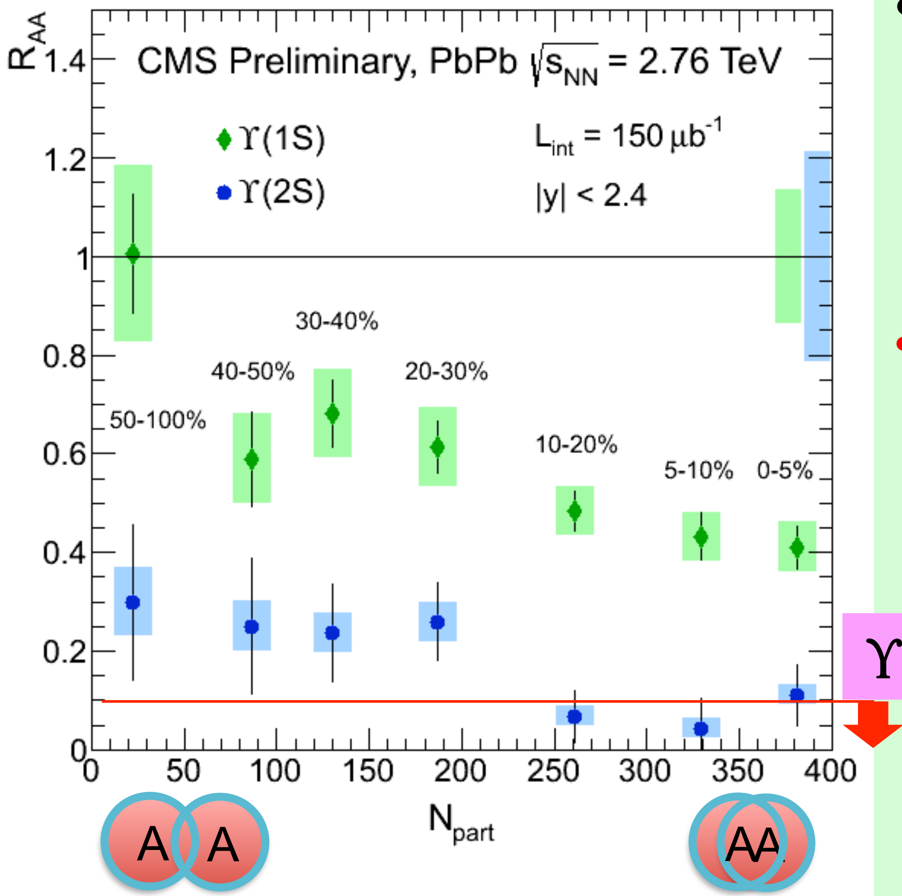
  - no strong centrality dependence
- **Upper limit on Υ(3S)**
  - peak at PbPb is hard to distinguish : set the upper limit
  - centrality integrated:

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

$$< 0.17 \text{ at } 95\% \text{ C.L.}$$

Υ(nS) R_{AA}

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



- first results on Υ(2S) R_{AA}
- Υ(1S) suppression is consistent with suppression of excited state only considering ~50% feed down
- **Sequential suppression of the Υ(nS) states in order of their binding energy**
  - **Υ(1S) R_{AA} > Υ(2S) R_{AA} > Υ(3S) R_{AA}**

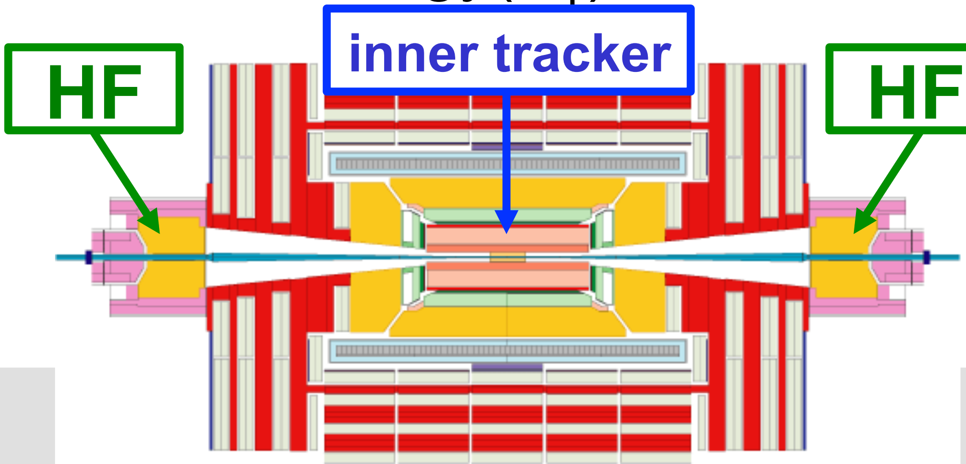
Υ(3S) R_{AA} (95% C.L.)

$$\begin{aligned}
R_{AA}(\Upsilon(1S)) &= 0.56 \pm 0.08\,(\text{stat.}) \pm 0.07\,(\text{syst.}) \\
R_{AA}(\Upsilon(2S)) &= 0.12 \pm 0.04\,(\text{stat.}) \pm 0.02\,(\text{syst.}) \\
R_{AA}(\Upsilon(3S)) &= 0.03 \pm 0.04\,(\text{stat.}) \pm 0.01\,(\text{syst.}) \\
&< 0.10 \quad (95\%\ \text{C.L.})\,.
\end{aligned}$$

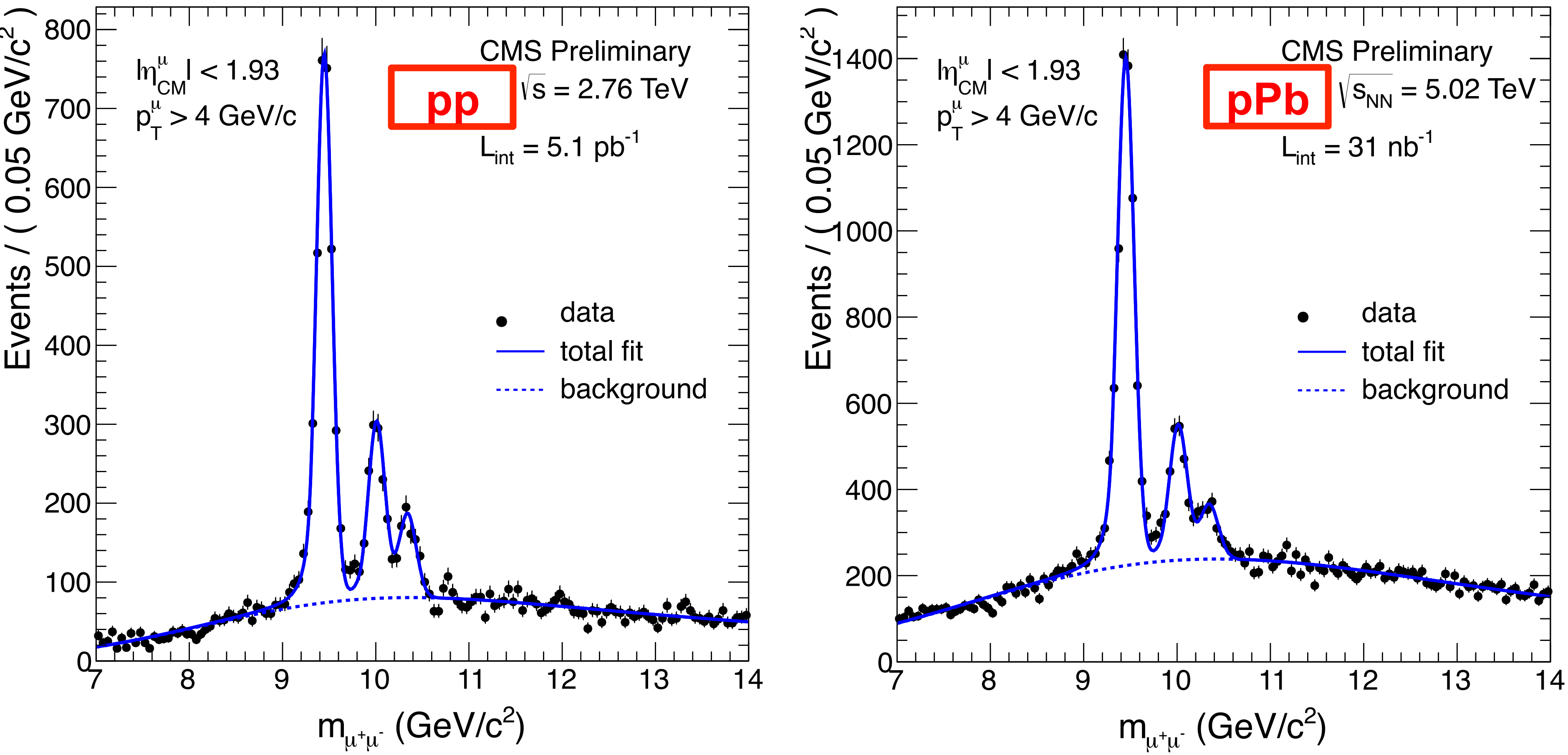
PRL 109 (2012) 222301

Remark for pPb bottomonia analysis

- Because of asymmetry collision, for rapidity need to consider boosted shift (about 0.47)
- muon's η and dimuon's rapidity in lab CM frame(y_{CM}) in (-1.93,1.93) is selected.
  - for proton going to - η : $-2.4 < \eta < 1.47$
  - for proton going to + η : $-1.47 < \eta < 2.4$
- Binning in 2 event-activity variables
  - corrected N_{track} in inner tracker ($|\eta|<2.4$, pT>0.4 GeV/c)
  - raw transverse energy(E_T) measured in HF ($4<|\eta|<5.2$)



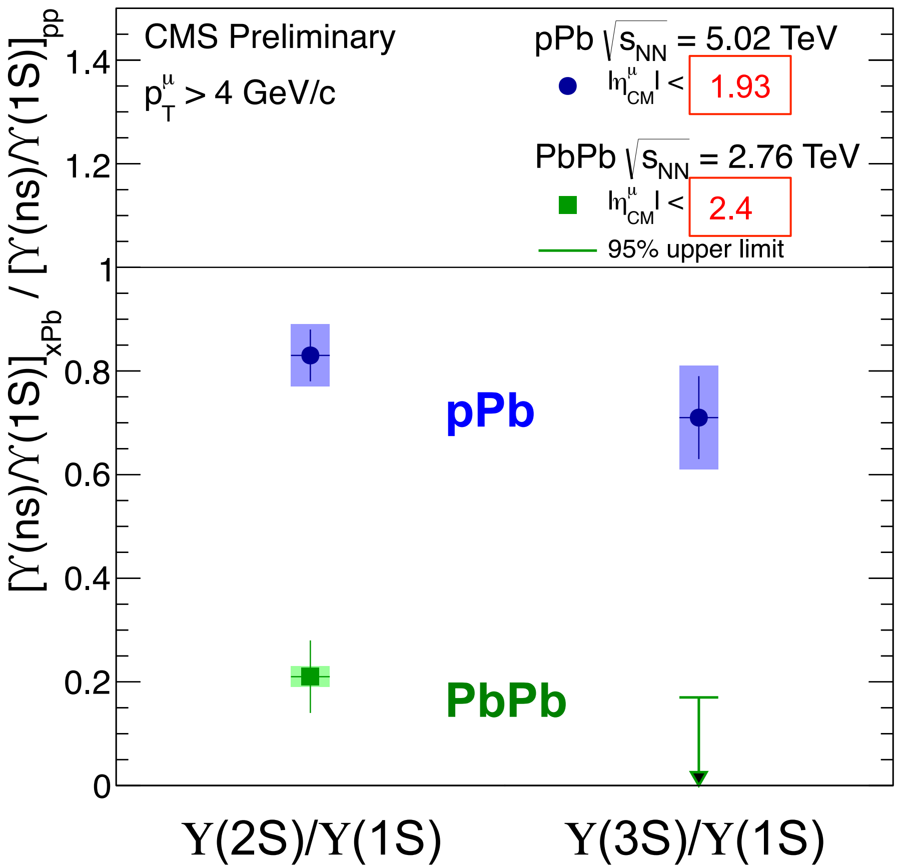
dimuon mass distributions from 2013 data



CMS-PAS HIN-13-003

- Signal extraction in pp, pPb and PbPb same procedure
  - Using unbinned maximum log likelihood fit
  - Signal : 3 Crystal-Ball functions (Gaussian with low-side tail regarding Final State Radiation)
  - Background : error function × exponential (all parameters were free)

Double ratio (Υ(nS) / Υ(1S))



- PbPb / pp : using 2011 pp dataset
- pp 2.76 TeV reference is used for pPb 5.02 TeV data, but have checked that the single ratios with Υ(2S) and Υ(3S) don't change from 2.76 to 7 TeV.

- pPb/pp < 1
  - hint of additional effects on the excited states compared to the ground state in pPb collisions with a significance < 3σ
- pPb/pp > PbPb/pp
  - suggestion of additional final effects that affect more the excited states than the ground state

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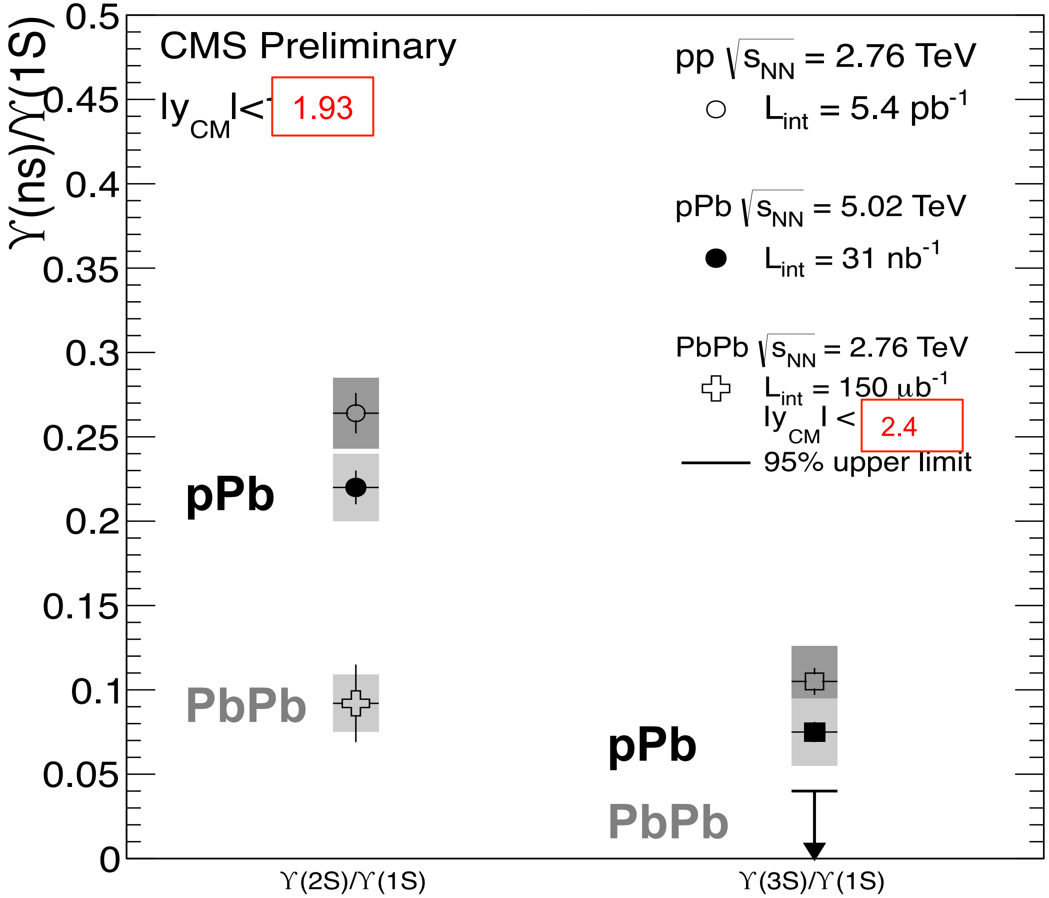
Single ratio (Υ(nS) / Υ(1S))



- pp : 2013 larger dataset
- Fully corrected with acceptance×efficiency

- pPb > PbPb with non-overlapped error bar
  - hint the presence of additional effects on excited states compared to ground state

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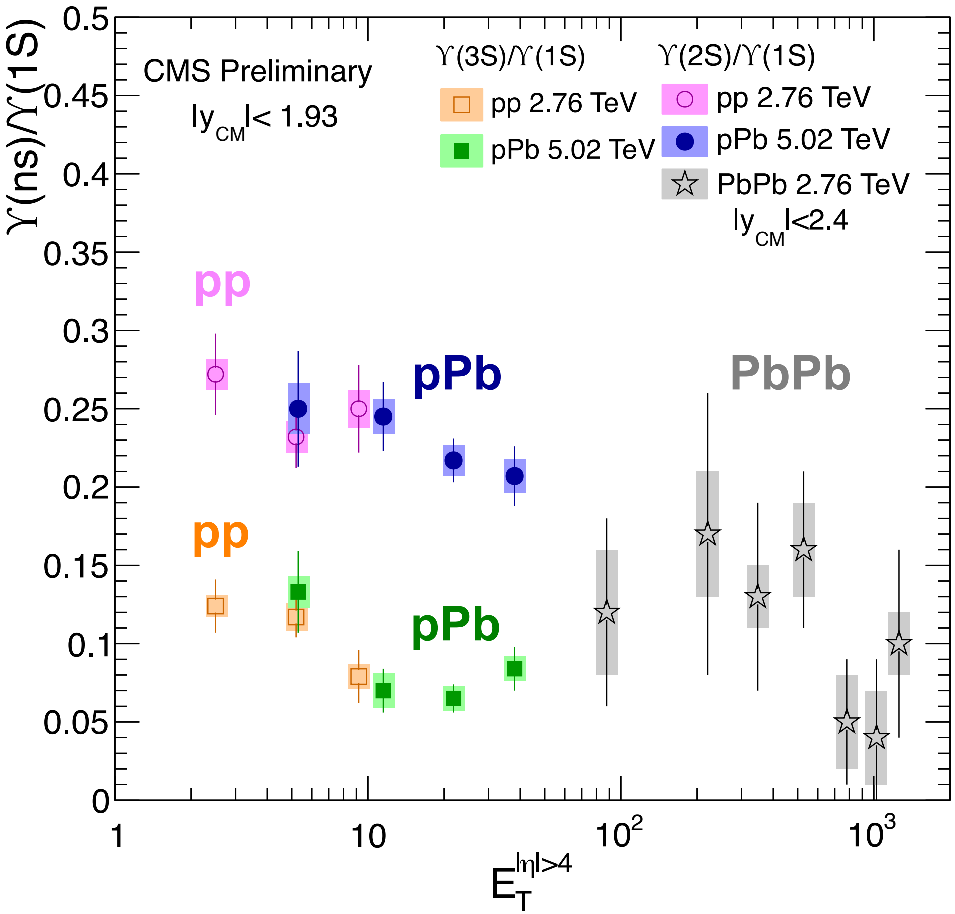
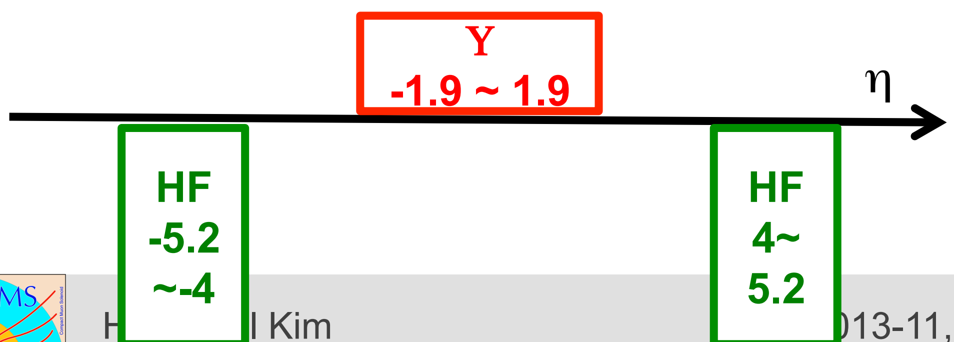
Υ(nS)/Υ(1S) vs event activity variables





E_T dependence

- All the single ratios in PbPb are below points in pPb within huge uncertainties in PbPb.
- Within uncertainties(bigger in PbPb), single ratios in all cases show the weaker dependence on E_T

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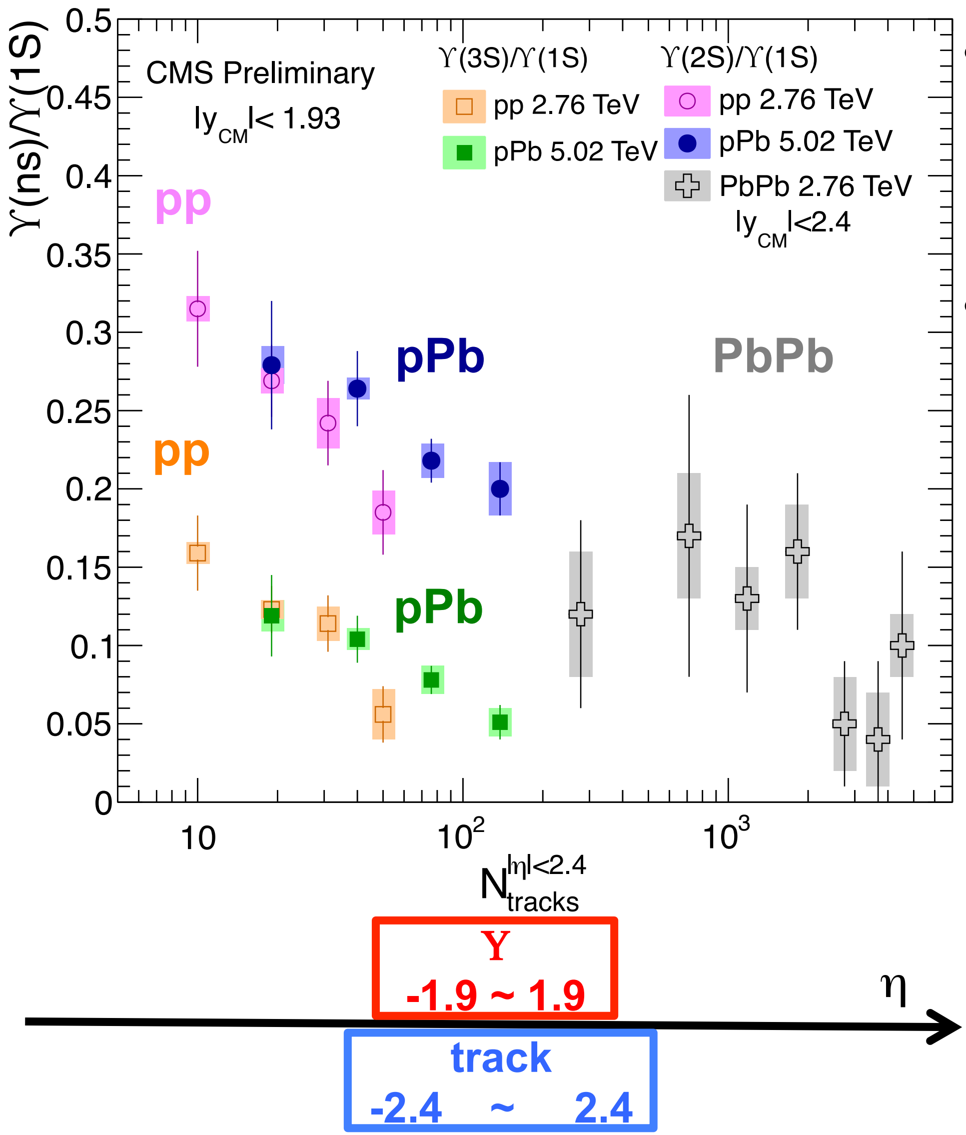
Υ(nS)/Υ(1S) vs event activity variables

N_{tracks} dependence



- All the single ratios in PbPb are below points in pPb within huge uncertainties.(like E_T in HF case)
- Within uncertainties, single ratios in pp and pPb cases show the significant decreasing dependence on N_{tracks}
  - In PbPb is expected, but in pp is not expected(we expected flat on N_{tracks})
  - Two possibilities of interpretation
    - Υ affects the multiplicity?
    - the multiplicity affects the Υ?

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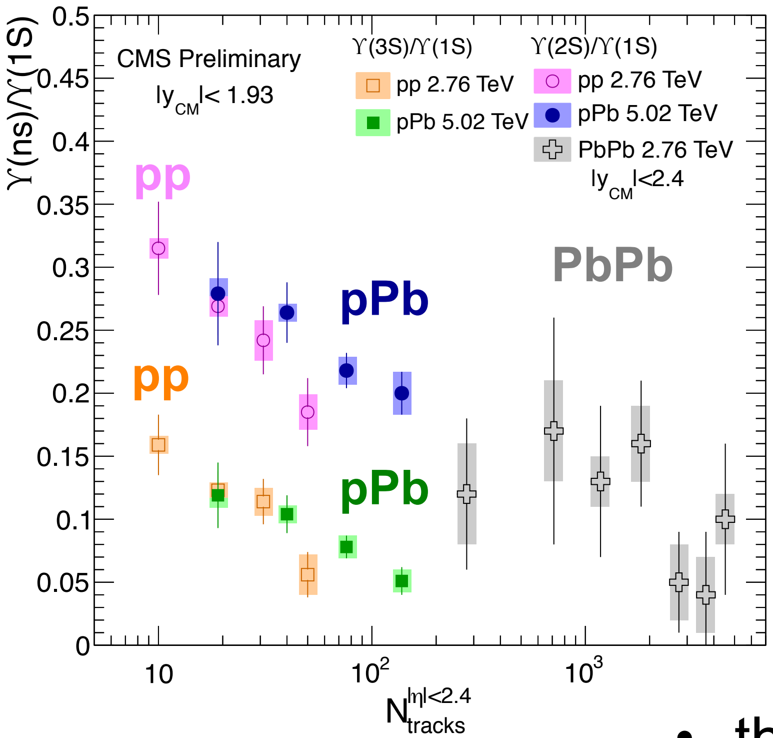
Υ(nS)/Υ(1S) vs event activity variables

N_{tracks} dependence



- Υ affects the multiplicity?
  - N_{tracks} in Υ(1S) events – N_{tracks} in Υ(2S or 3S) events = ~2 extra tracks
    - Same in pPb and pp, despite of different average no. of tracks (10 in pp, 41 in pPb)
    - expected due to feed-down from higher states, such as Υ(2S) → Υ(1S) + $\pi^+\pi^-$
    - can affect to low N_{tracks} bin
- the multiplicity affects the Υ?
  - Υ(2S or 3S) is more interacting with the surrounding environment than Υ(1S) which is the most tightly bounded.

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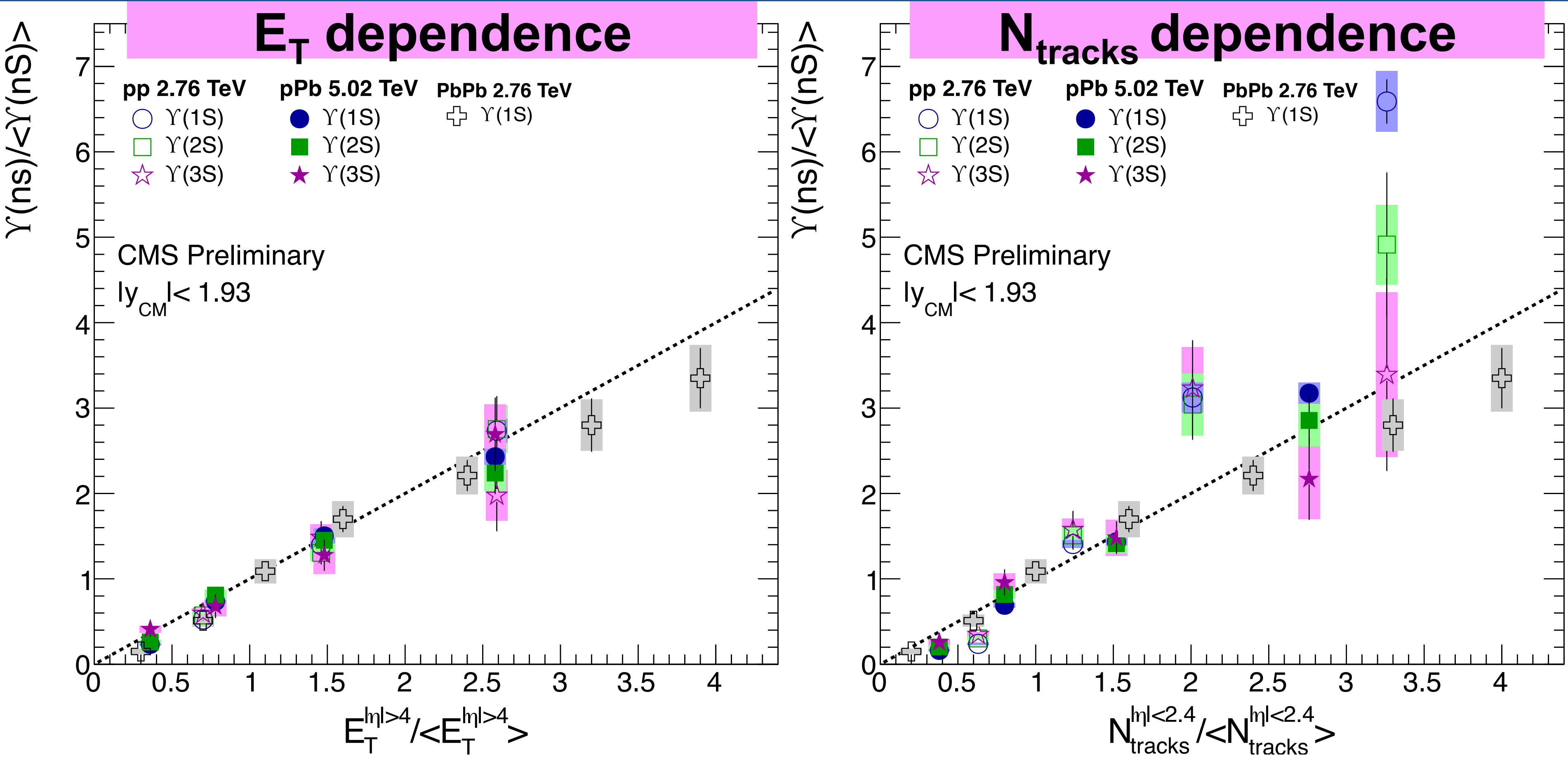
Self-normalized ratios Υ(nS)/<Υ(nS)>



- Left : all the points on the line with slope 1 despite of different collision conditions and average E_T
- Right : less coherent behavior, variation depend on species in large activity events
- more Υ(nS) in event with more multiplicity in pp collisions can be interpreted as a sign of multi-parton interactions.

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Summary

- Suppression of prompt and non-prompt J/ψ in PbPb is observed, but for ψ(2S) need more pp data.
- In PbPb collisions, sequential suppression of Υ(nS) is shown.
- pPb data give us the hint of the additional effects on Υ(2S,3S) than on Υ(1S).
- Within uncertainties, Υ(nS)/Υ(1S) in pp and pPb cases show the significant decreasing dependence on N_{tracks}.
- $\Upsilon(nS)/<\Upsilon(nS)>$ increasing with increasing N_{tracks} in pp, pPb and PbPb.

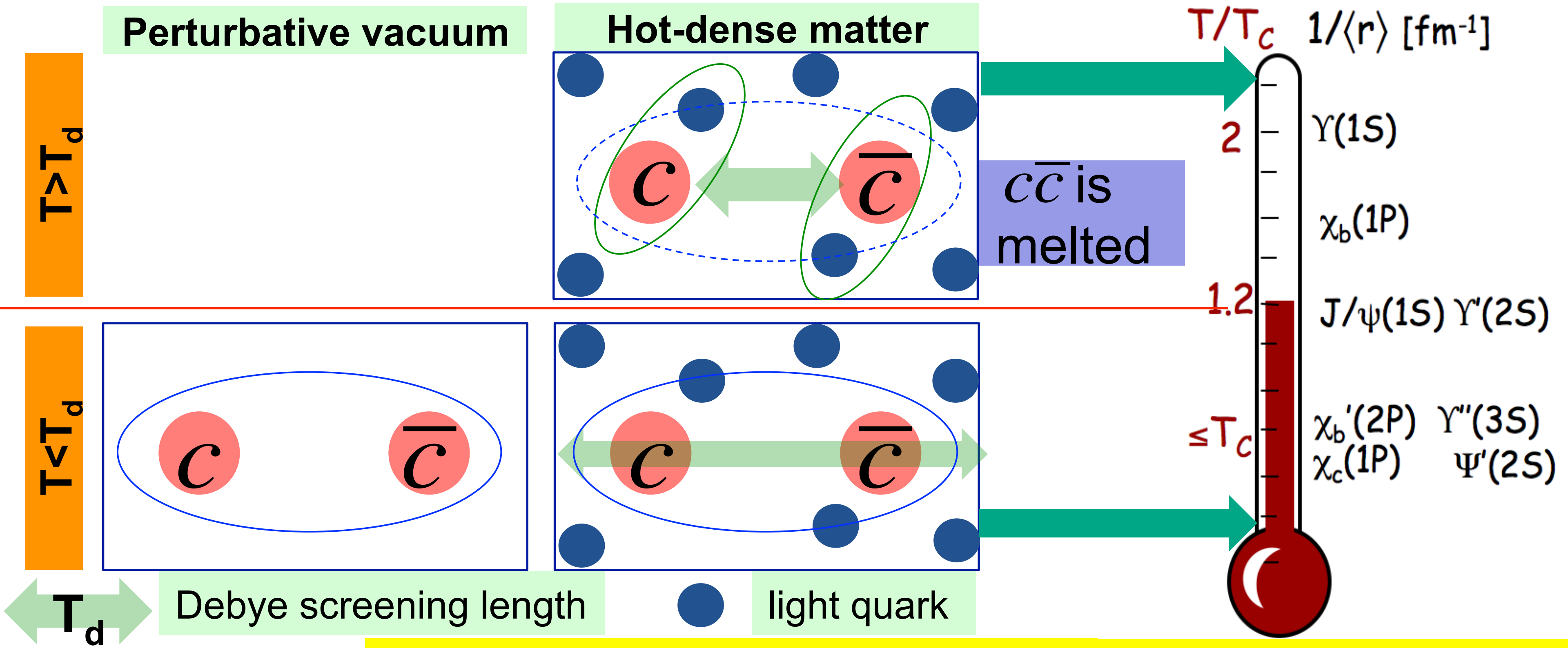
BACK UP

Quarkonia family

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

H.Satz Slides from INT/Seattle June 18, 2009

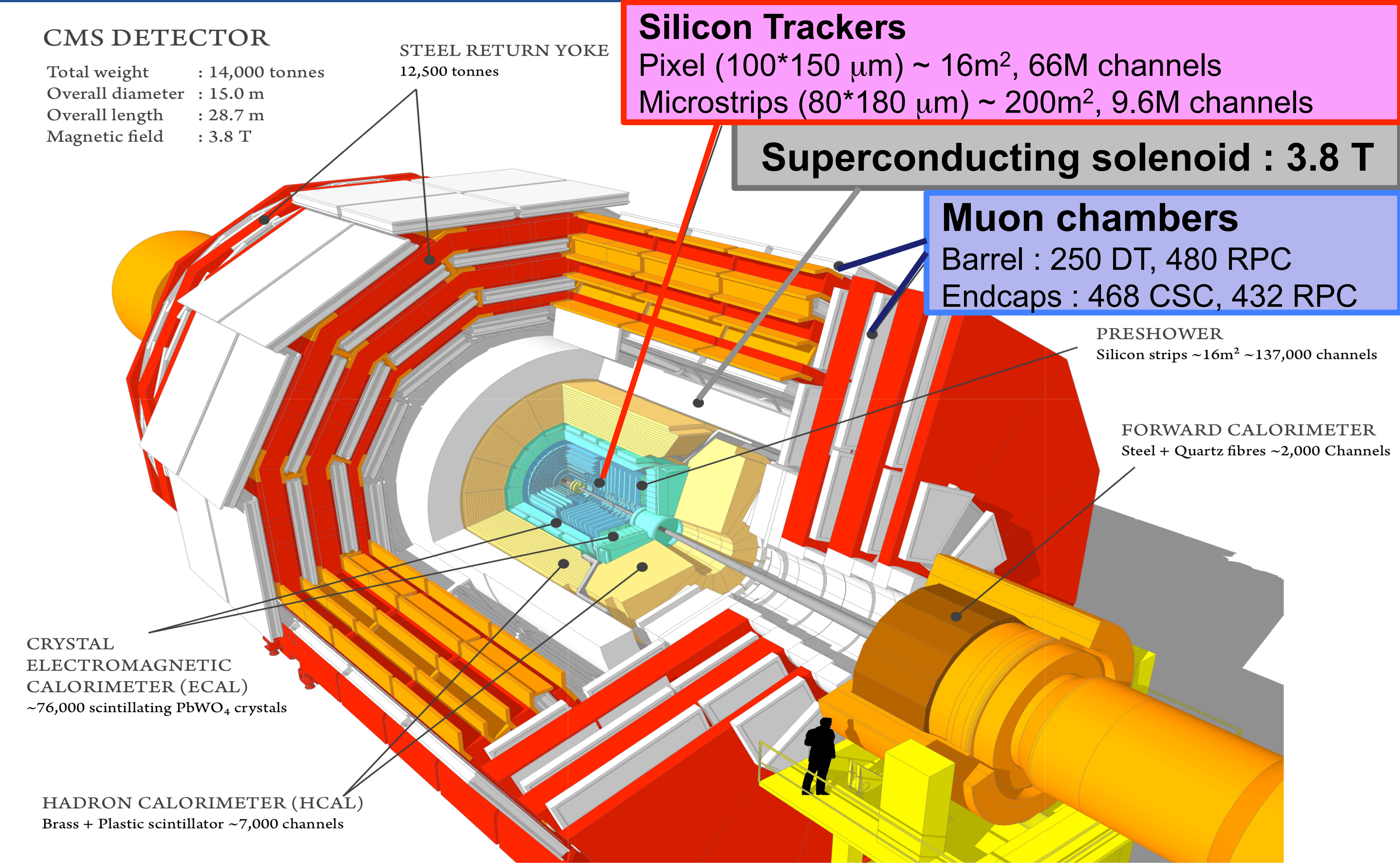
Cartoon for Debye screening



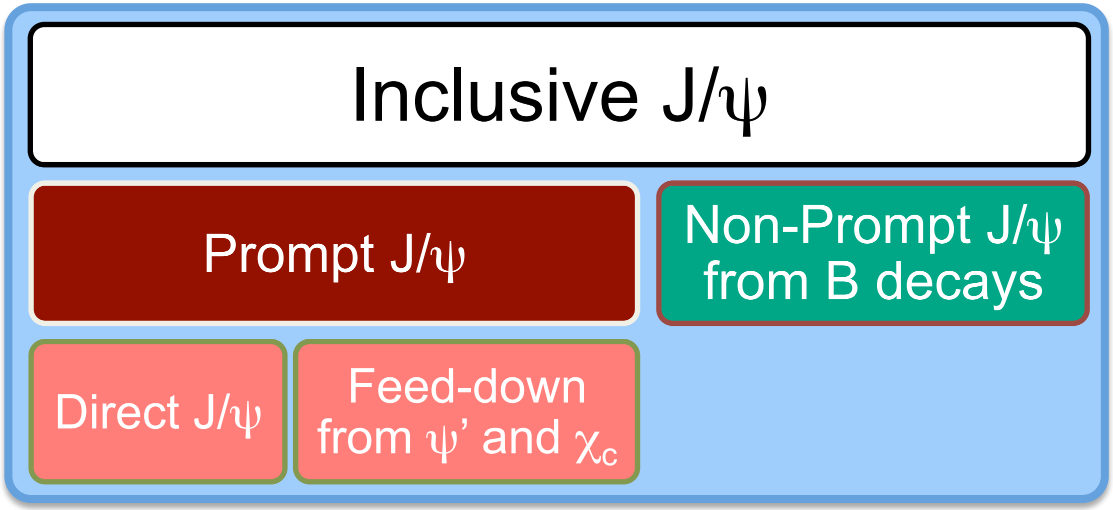
E. Scomparin, CERN seminar (06/11/2012)

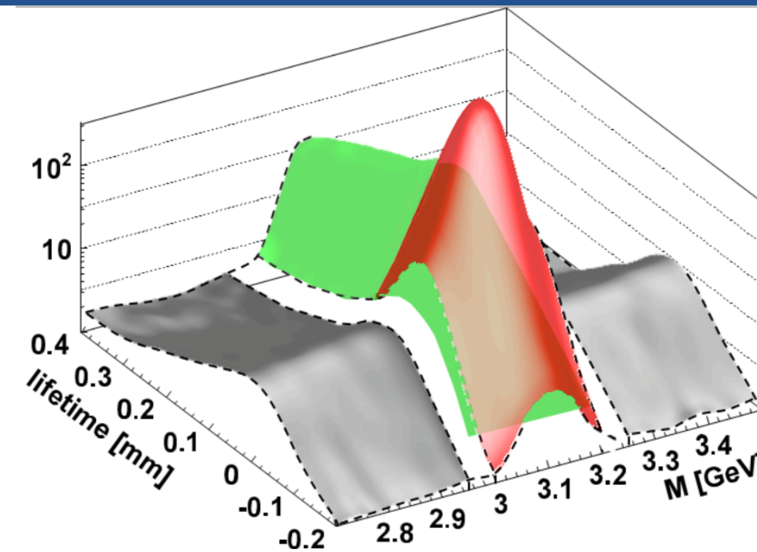
Mocsy, EPJ C 61 (2009) 705

CMS detector



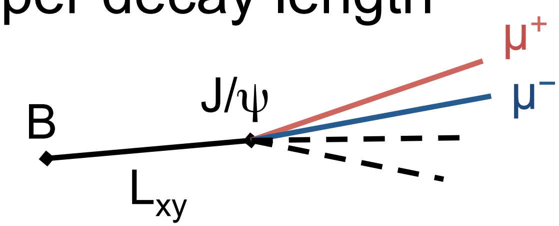
Prompt, non-prompt J/ψ signal extraction

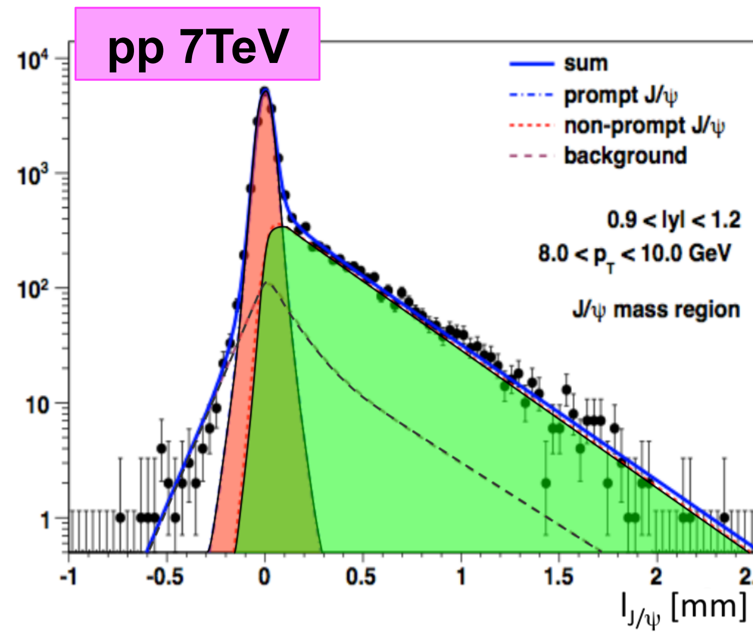




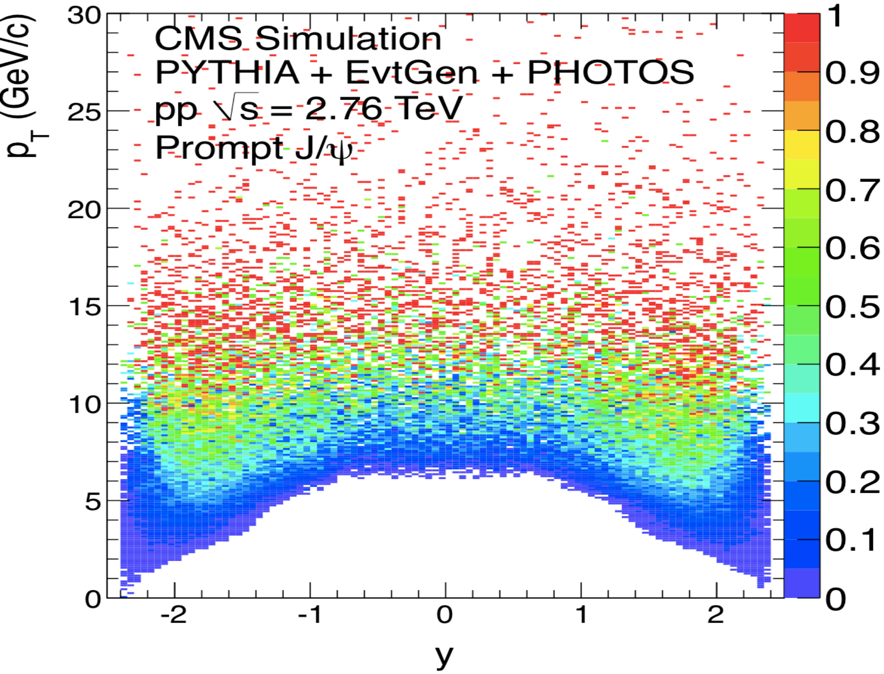
- **Reconstruct $\mu^+\mu^-$ vertex**
- **Separation of prompt and non-prompt J/ψ**
  - by 2D simultaneous fit of $\mu^+\mu^-$ mass and pseudo-proper decay length

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



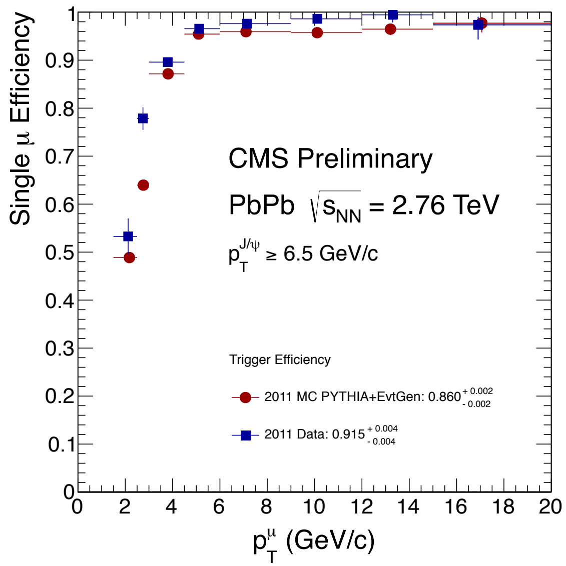


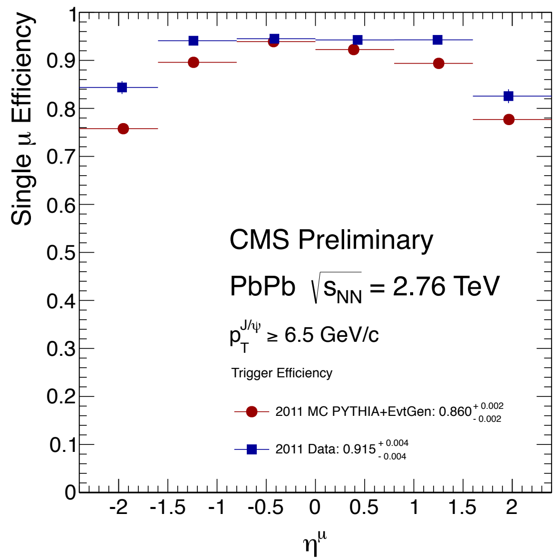
J/ψ's acceptance and efficiency



- Because of the magnetic field and energy loss (2~3 GeV) in the iron yoke, Global muons need minimum p_μ to reach the muon stations

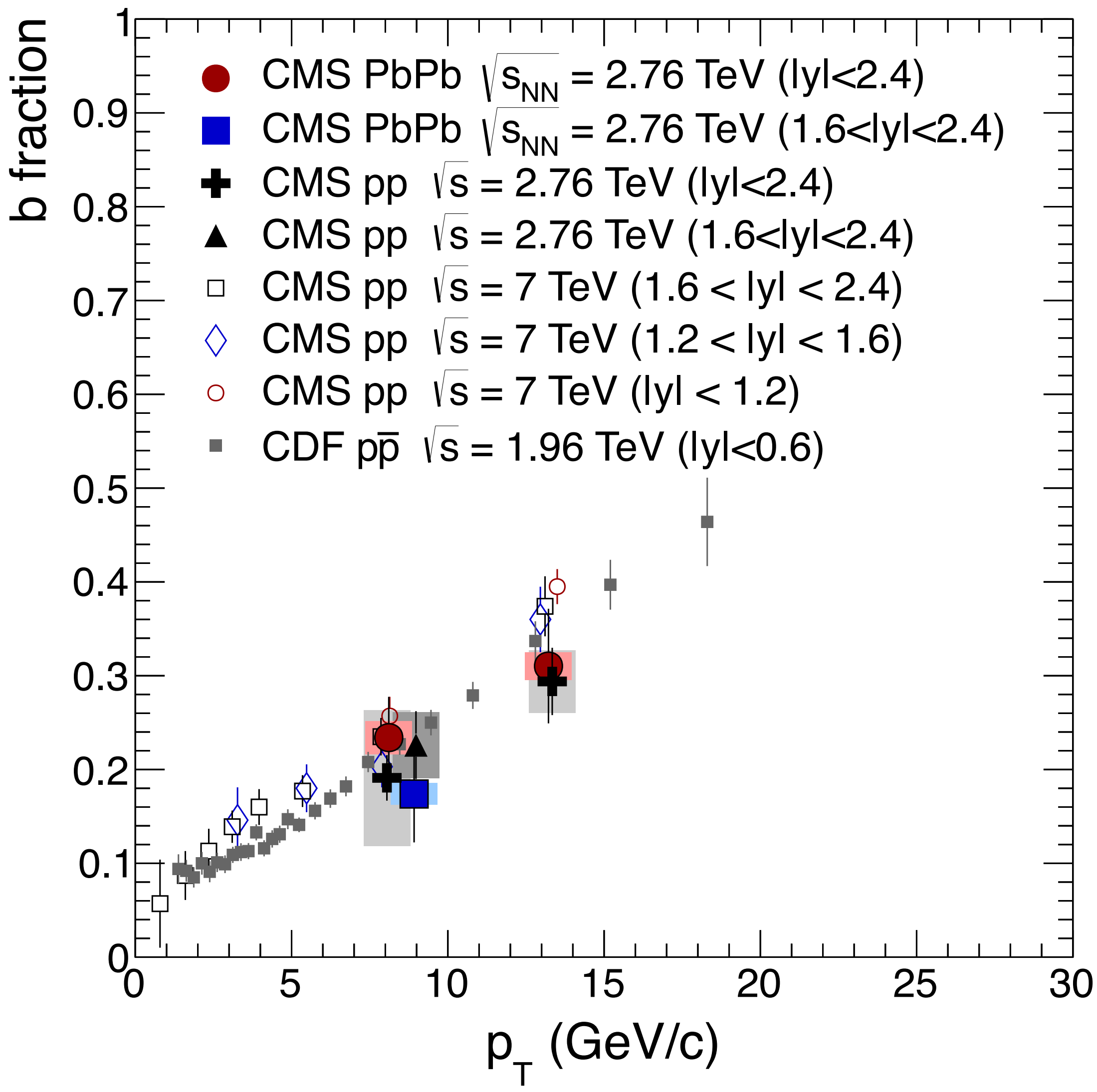
  (3~5 GeV, depending on η)
- Limits J/ψ acceptance
  - mid-rapidity: $p_{T,\,J/\psi}$>6.5 GeV/c
  - forward: $p_{T,\,J/\psi}$>3 GeV/c





- Efficiencies are evaluated with MC
- Crosschecked with tag-and-probe method in data and MC

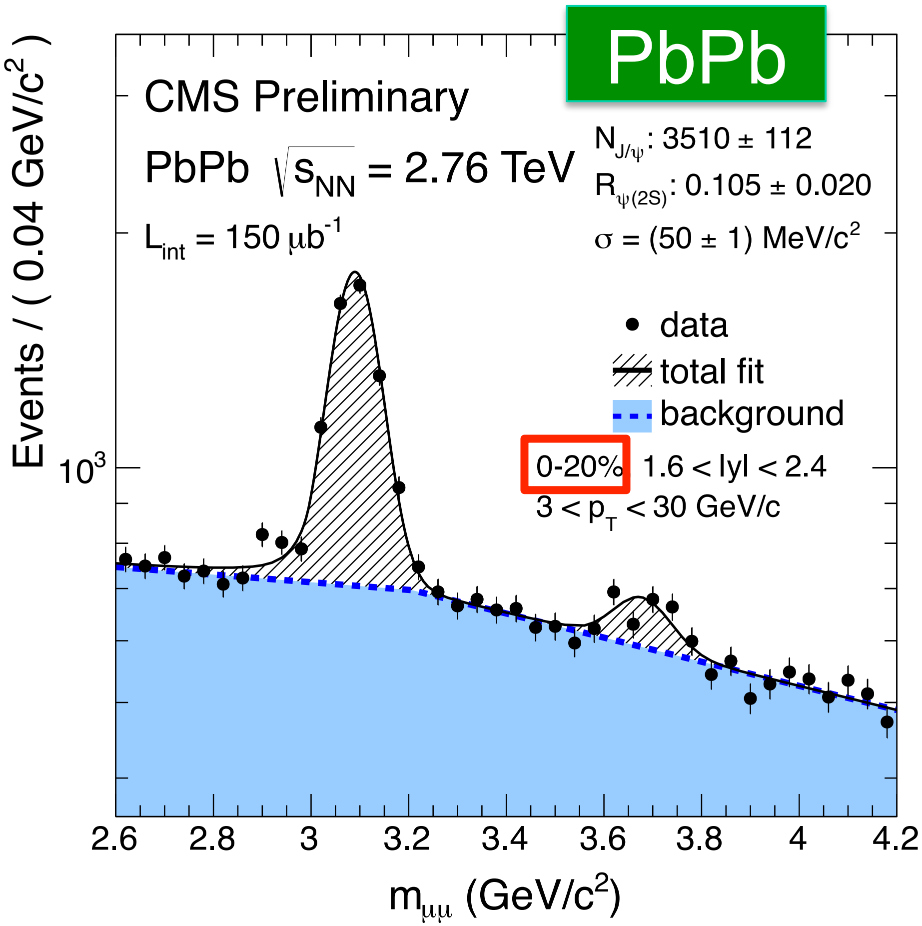
b fraction of J/ψ production

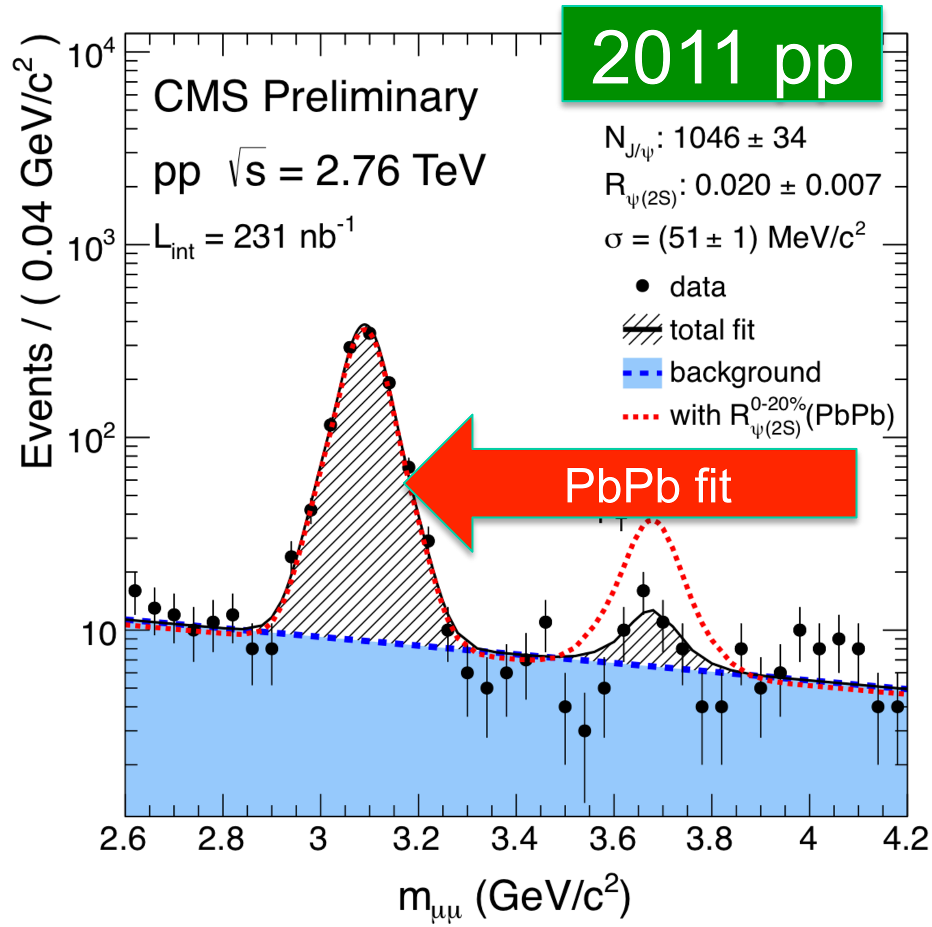


$\psi(2S)$ in pp & PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

Lower-p_T, forward region (p_T>3 GeV/c and 1.6<|y|<2.4)

PAS CMS-HIN-12-007





$R_{\psi(2S)} = N_{\psi(2S)} / N_{J/\psi}$

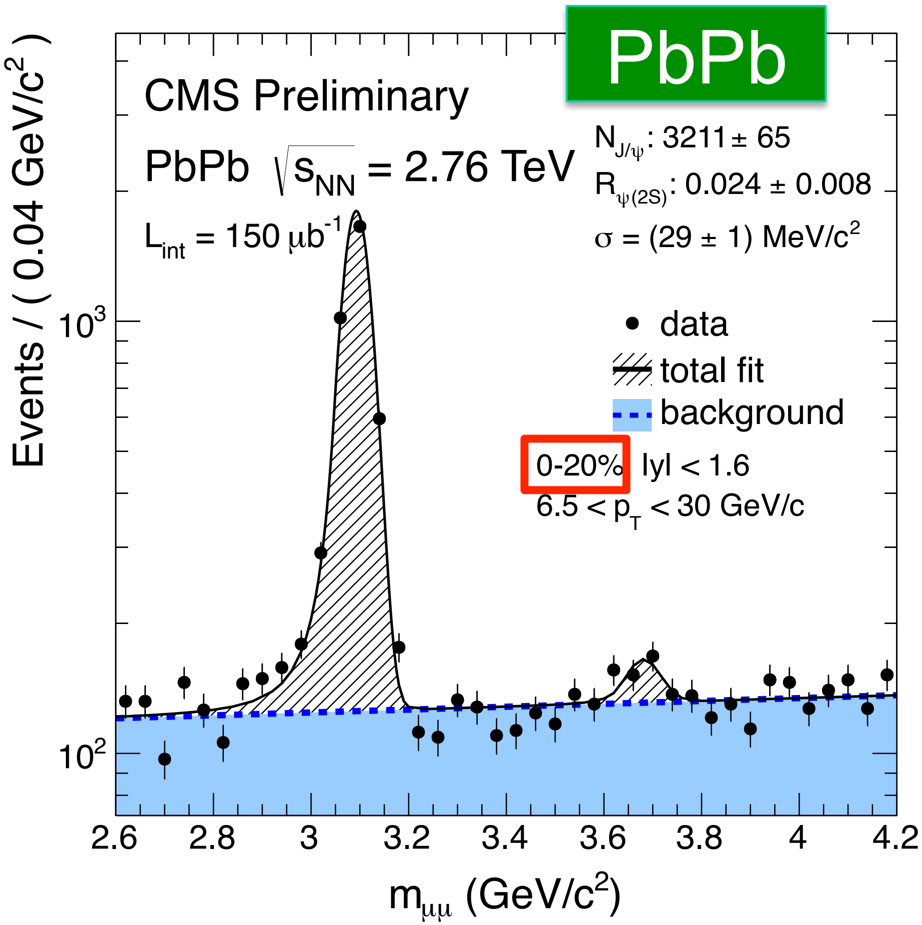
$R_{\psi(2S)}^{PbPb} \sim$ **5** $\times R_{\psi(2S)}^{pp}$

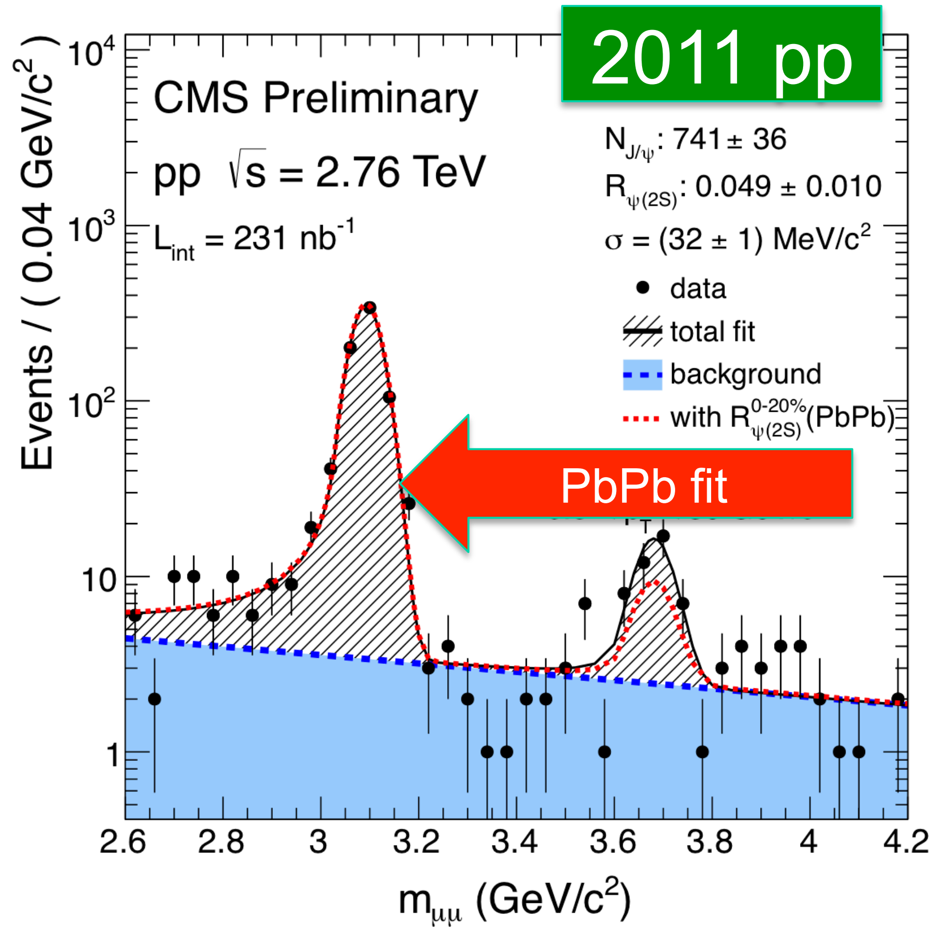
limited by pp statistics

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

High-p_T, mid-rapidity region ($p_T > 6.5$ GeV/c and $|y| < 1.6$)

PAS CMS-HIN-12-007

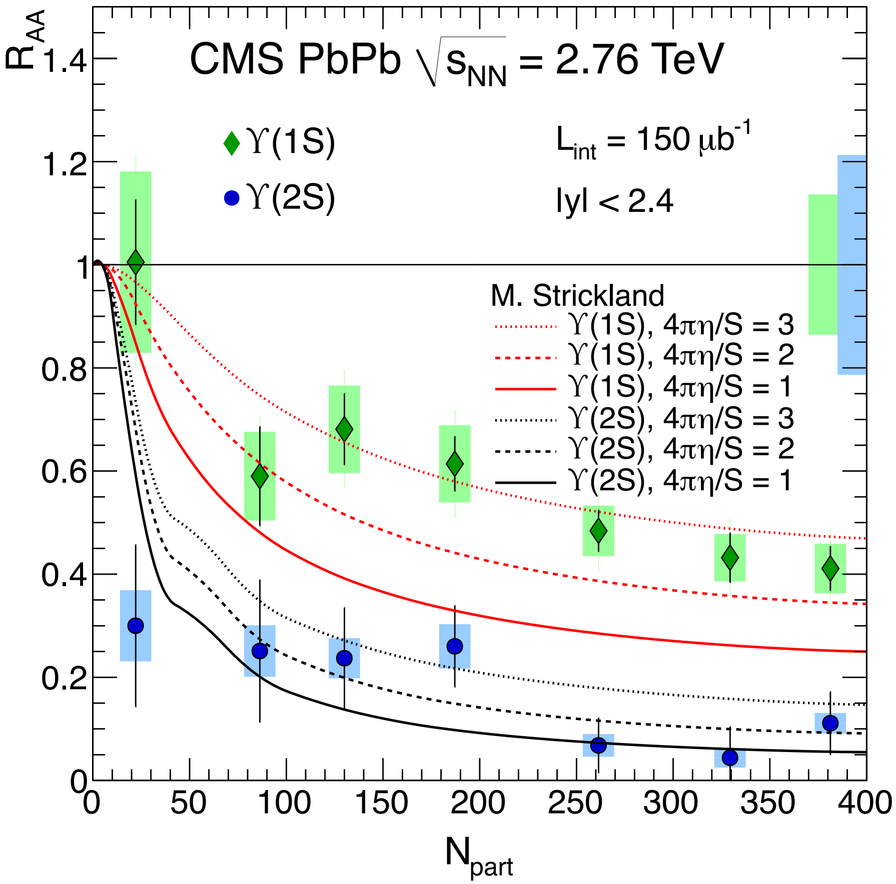


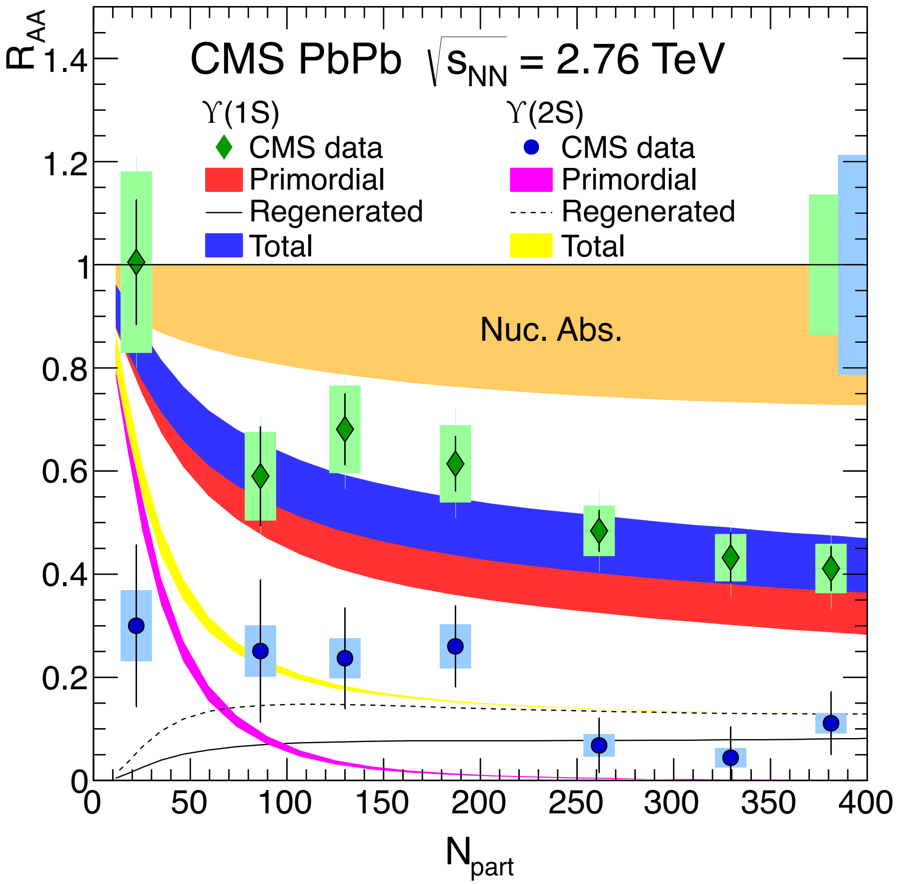


$R_{\psi(2S)} = N_{\psi(2S)} / N_{J/\psi}$

$R_{\psi(2S)}^{PbPb} \sim$ **0.5** $\times R_{\psi(2S)}^{pp}$

Υ(1S) and Υ (2S) R_{AA} : theory comparison





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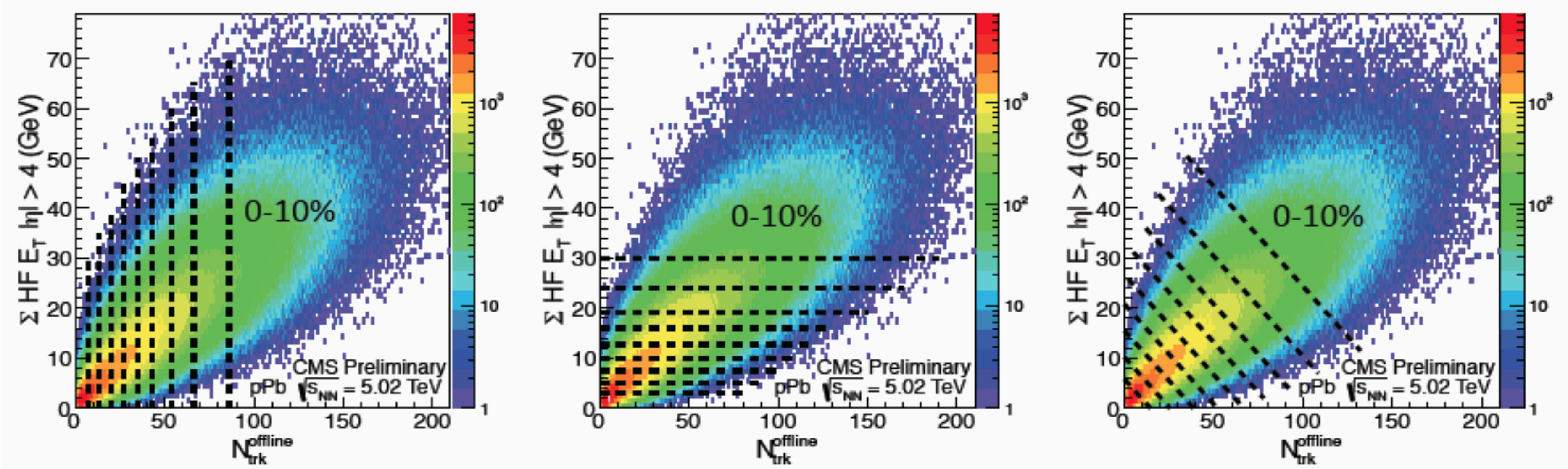
Υ(1S) and Υ(2S) results are consistent with the theoretical model within uncertainties

<N$_{coll}$> from different methods agree well

Defining centrality from different methods:



- Slicing multiplicity and ΣHF E_T |η|>4 means selecting very different events (e.g. 0-10% in the plots), but <N$_{coll}$> are the same
- The real difficulties of centrality determination are about how to define centrality in real data (which η range to use?) for an analysis and study possible biases