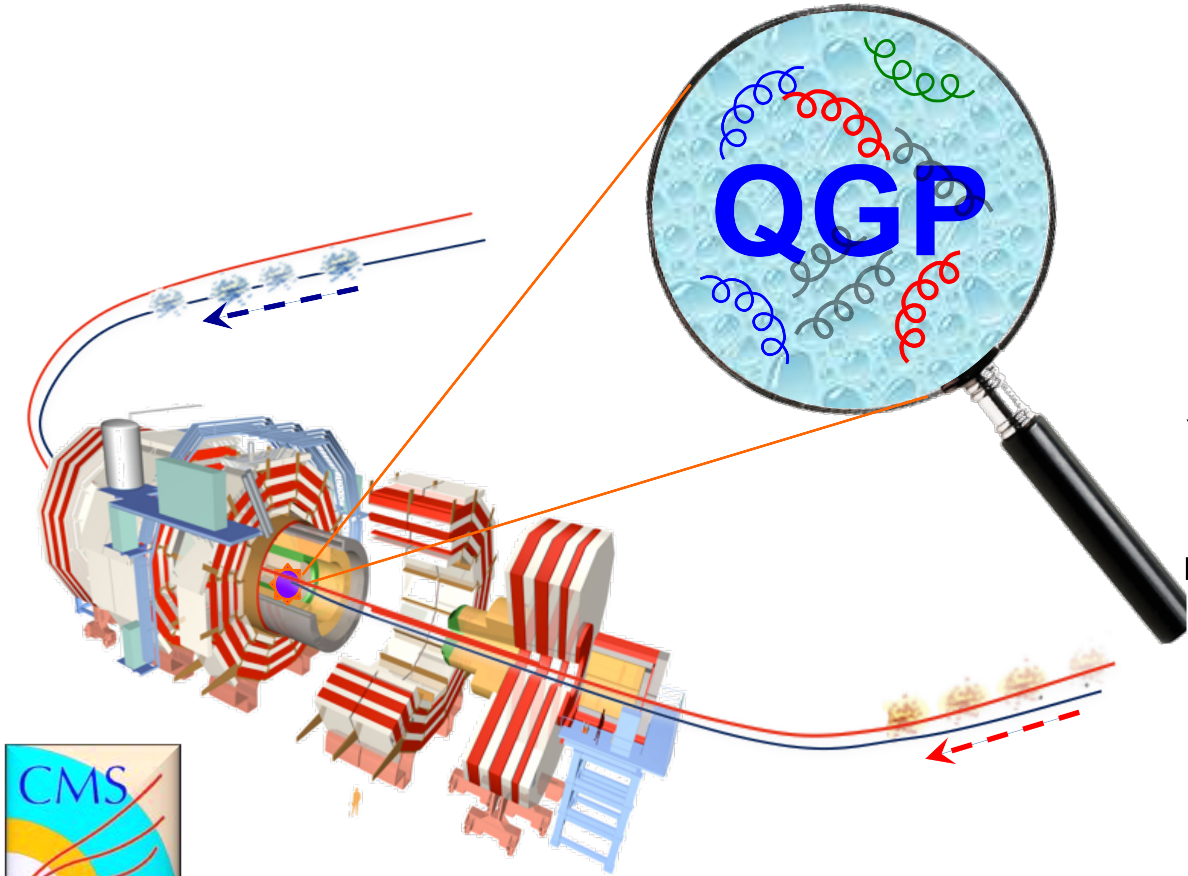
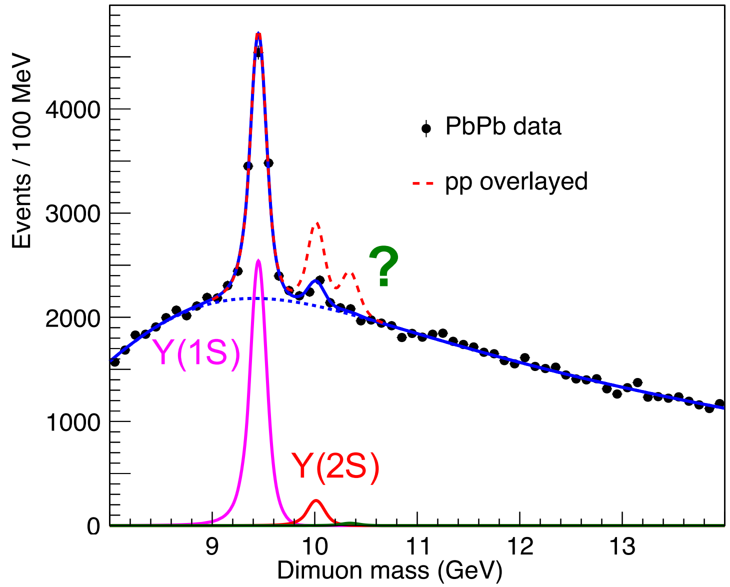
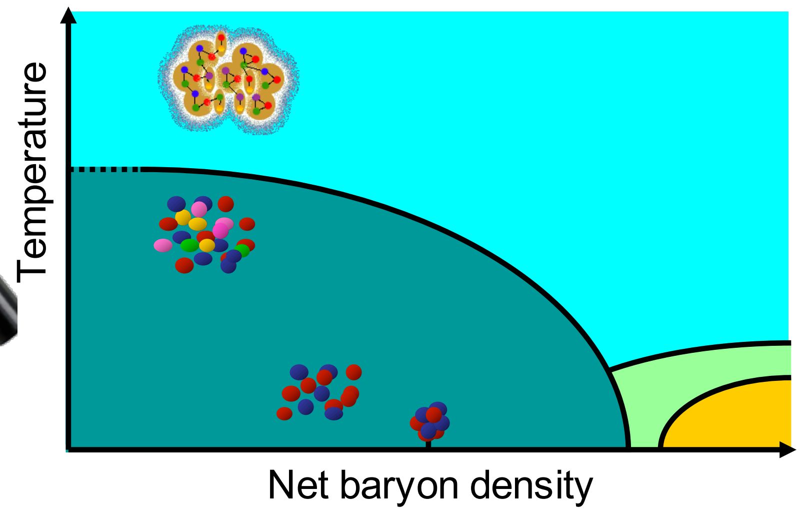
A penetrating look at Quark-Gluon Plasma physics

Probing the QCD phase transition with heavy quarkonia

Carlos Lourenço (CERN)
on behalf of CMS
Moriond QCD 2017







At the beginning there was… Helmut's An'Satz

"J/ψ suppression in nuclear collisions should provide
an unambiguous signature of QGP formation"

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
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and

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PLB 178 (1986) 416

Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

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Cited 2575 times ! (inspire)

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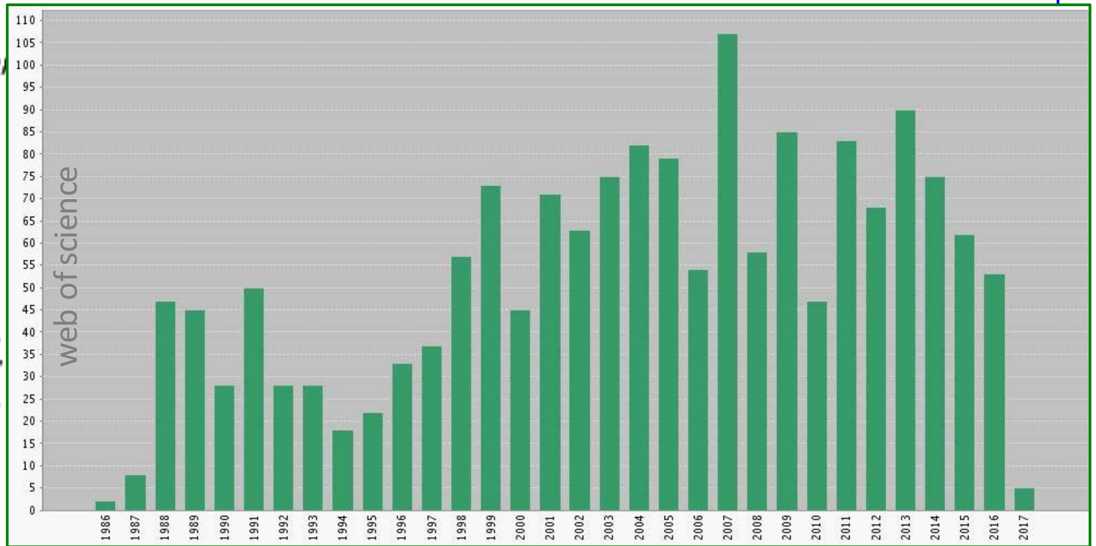

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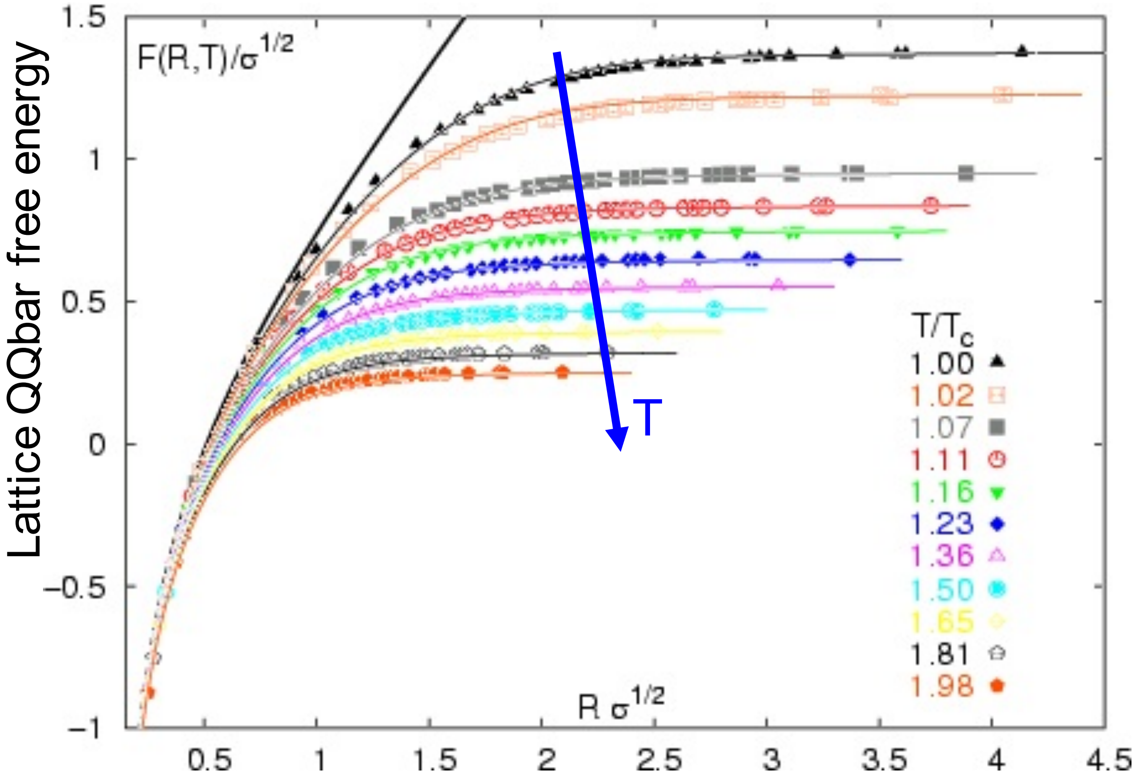
QGP formation melts heavy quarkonia

Screening the QCD potential dissolves
the charmonium and bottomonium states
into open charm or open beauty mesons



Different heavy quarkonium states have different binding energies
→ should dissolve at successive thresholds in the temperature of the medium
→ sequential suppression pattern provides a "thermometer" of the QCD matter

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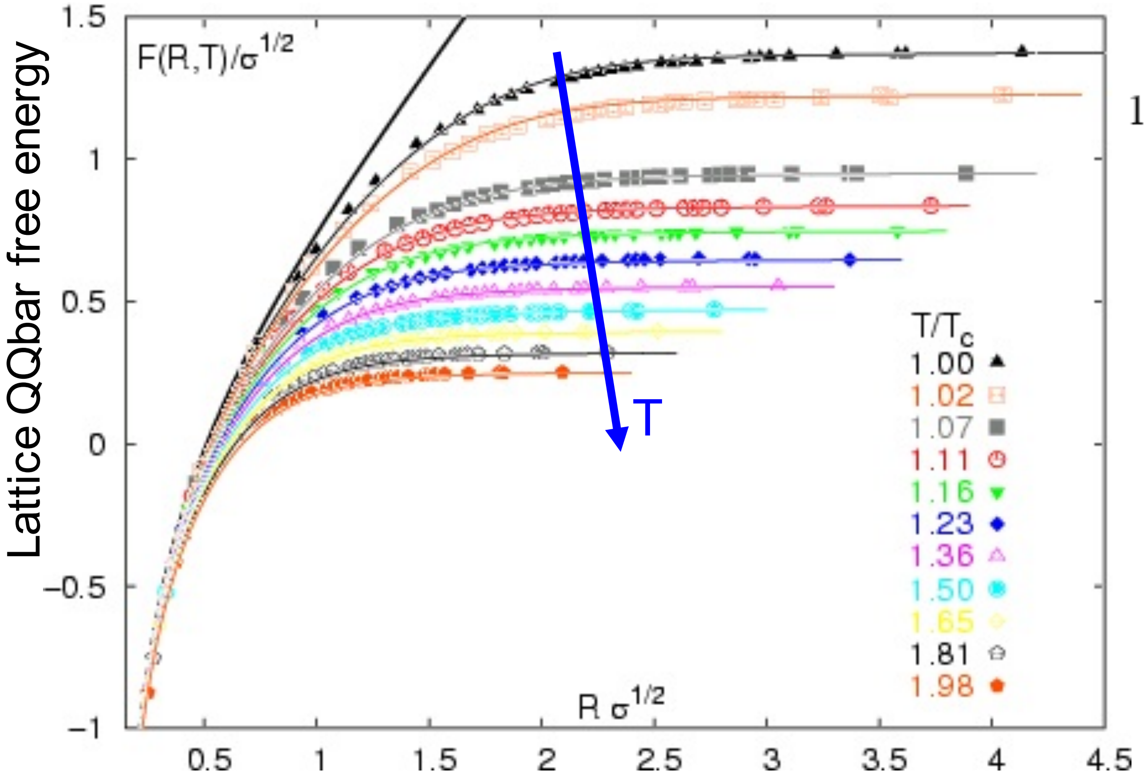

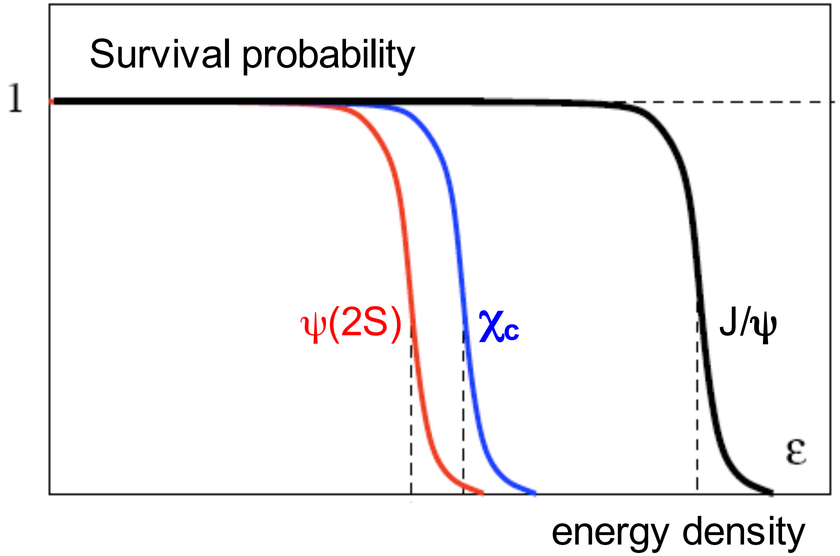

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The theory dream: sequential quarkonium melting

Take a box of QCD matter and continuously increase its energy density, while measuring the population of several charmonium and bottomonium states; when certain *critical* thresholds are crossed, *sudden* drops in the yields are seen, first for the ψ(2S), χ_c, Y(3S) and χ_b(2P), then for the more strongly bound states

	J/ψ	χ_c	ψ(2S)	Y(1S)	χ_b(1P)	Y(2S)	χ_b(2P)	Y(3S)
T_d / T_c	2.10	1.16	1.12	> 4	1.76	1.60	1.19	1.17

Values for illustration purposes

By comparing with each other the suppression patterns of several states, we probe the predicted sequential quarkonium melting and confirm (or exclude) the observation of critical behaviour

The P-wave quarkonia can be studied through their feed-down effects on the suppression trend of the ground states

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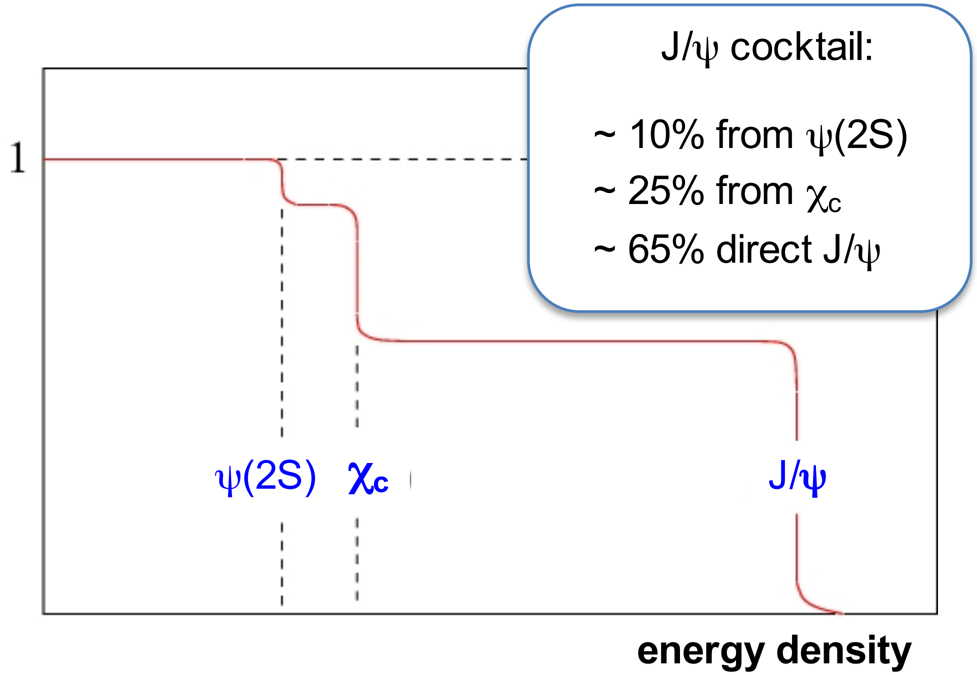

From the theory heaven to the experimental hall

The χ states cannot be detected via radiative decays ($\rightarrow$ J/ψ + γ) in HI collisions; too many background photons (from π^0 decays)

The excited S-wave states have very small yields;
the ψ(2S) peak is ~50 times smaller than the J/ψ peak in the dimuon decay channel

To measure all the five S-wave states, we need
- a very efficient dimuon trigger: ☺
- a very good dimuon mass resolution: ☺
- a very large integrated luminosity: ☹

Quarkonia are affected by the medium where they are born (nuclear PDFs, etc) and which they traverse towards the detectors (energy loss, absorption, etc): the observations reflect a convolution of the QGP *signal* with a complex cocktail of "cold nuclear matter" *background* effects

Different collision energies, rapidity and p_T ranges, backgrounds, efficiencies, etc, can conspire to cancel or enhance some trends, potentially triggering misleading interpretations: we must remain critical

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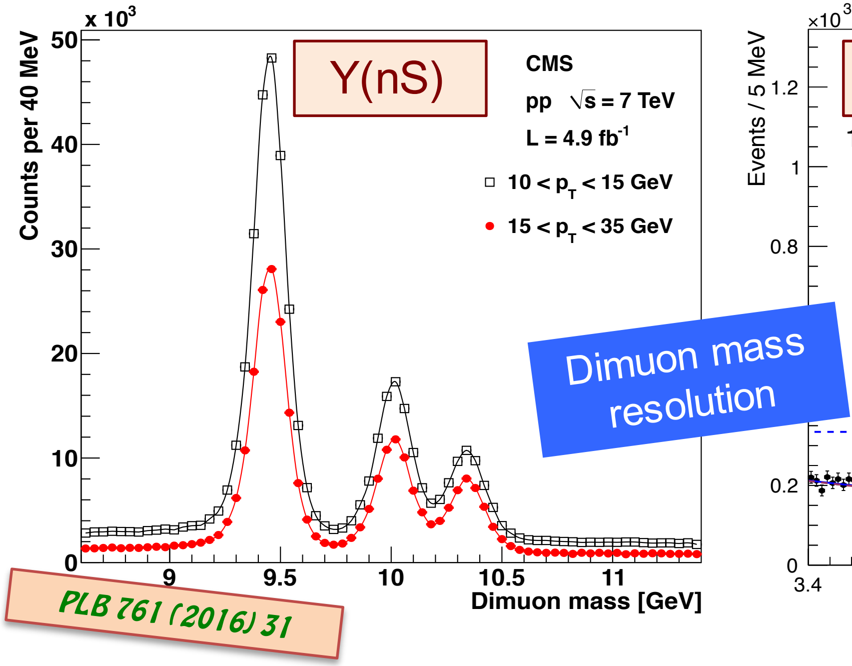
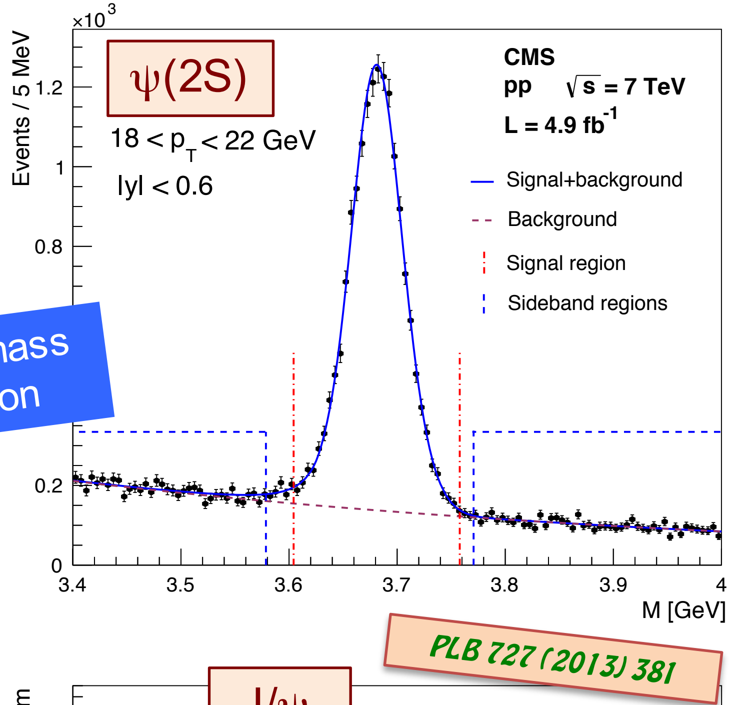
Excellent dimuon performance for quarkonium studies





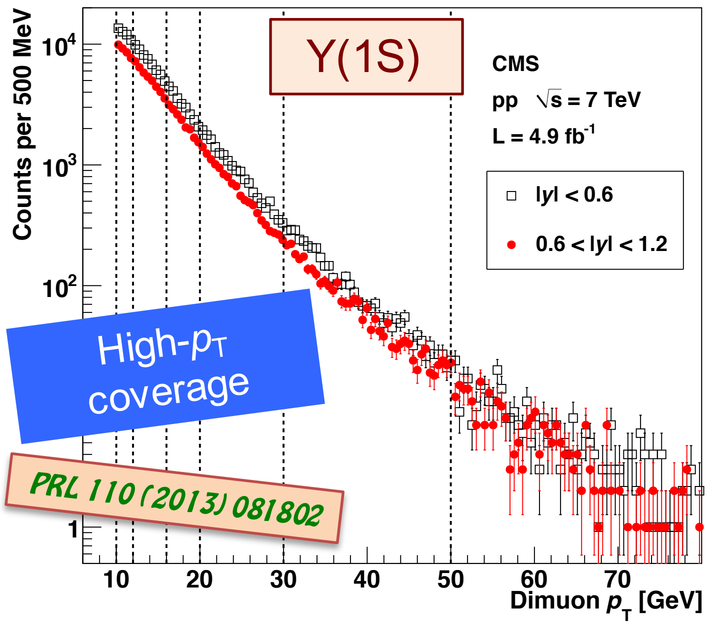
Huge silicon tracker

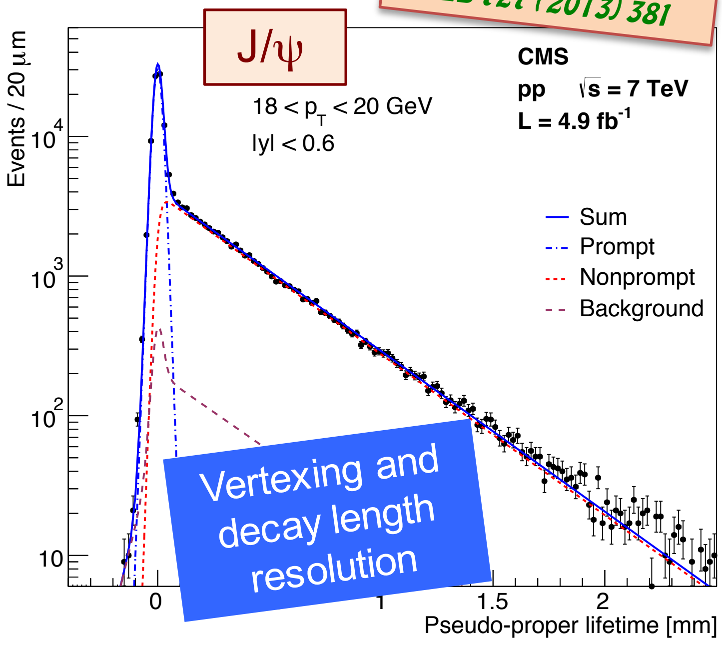
Very strong B field

Broad acceptance

Flexible muon trigger

Powerful DAQ





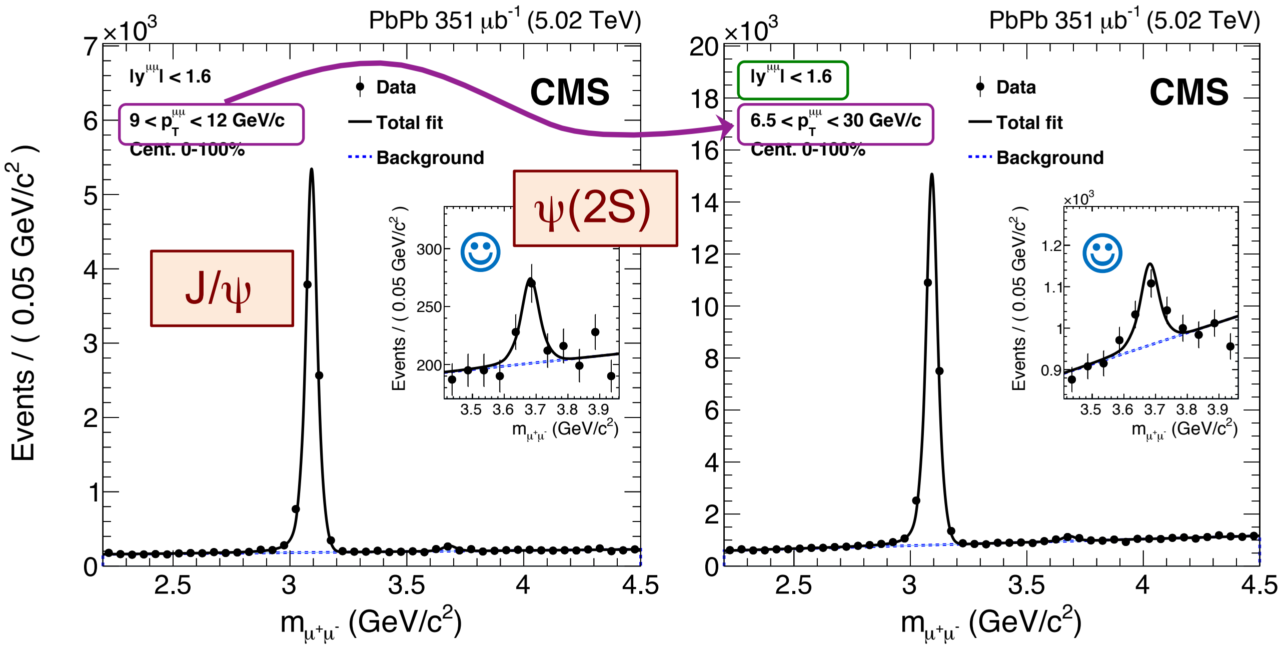
Note: In this talk we always address *prompt charmonia*, after subtraction of the B decays term, using the dimuon "lifetime"

Heavy-ion data: more challenging conditions

The CMS experiment is just as good for Pb-Pb as for pp data but the event samples are much smaller and the backgrounds are much larger

The J/ψ peak is always well above the underlying dimuon continuum

The ψ(2S) peak is harder to see, especially at forward rapidity (worse resolution) and low p_T (larger background)



HIN-16-004

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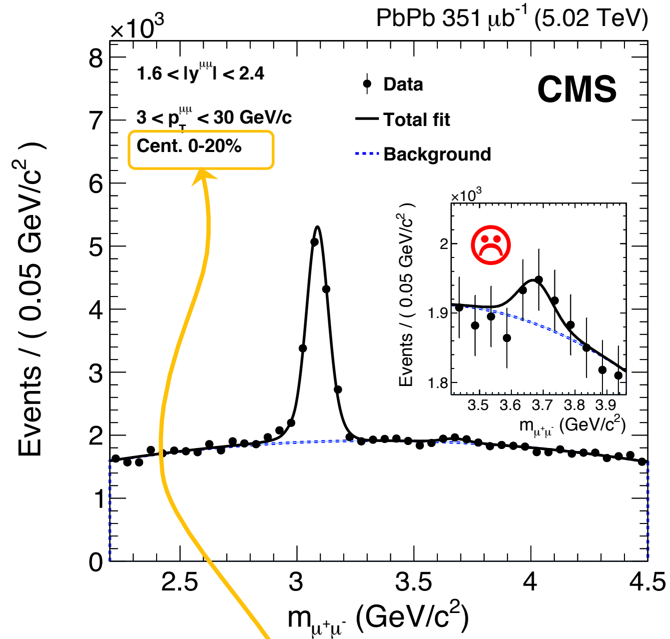
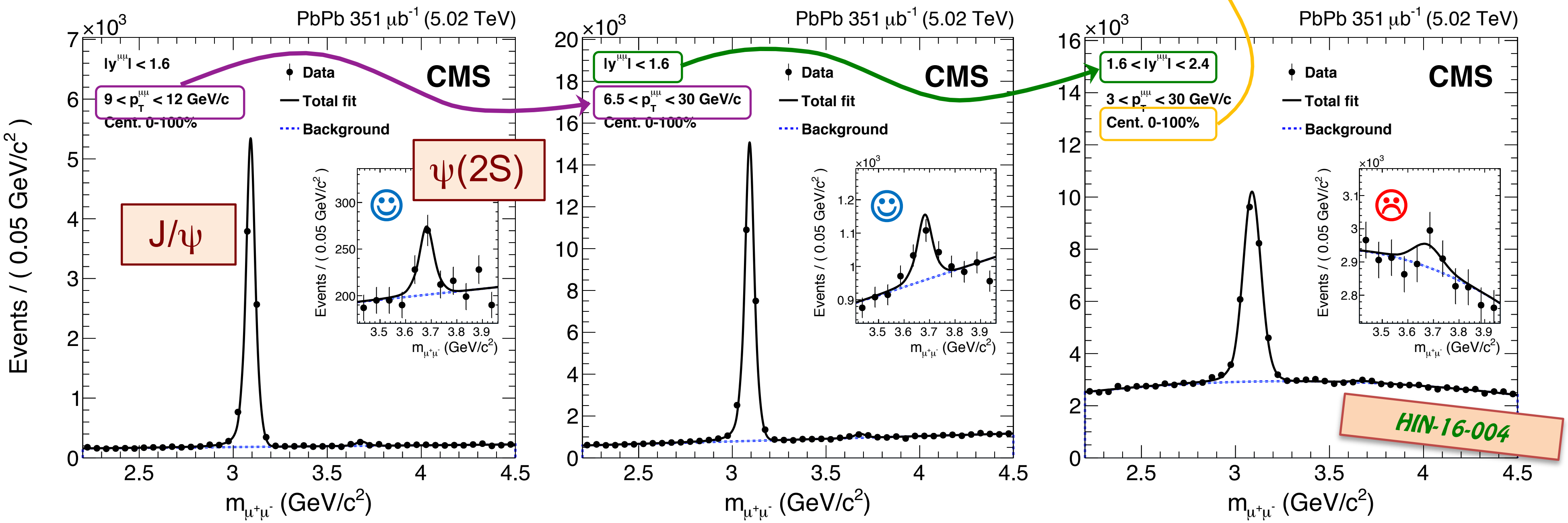




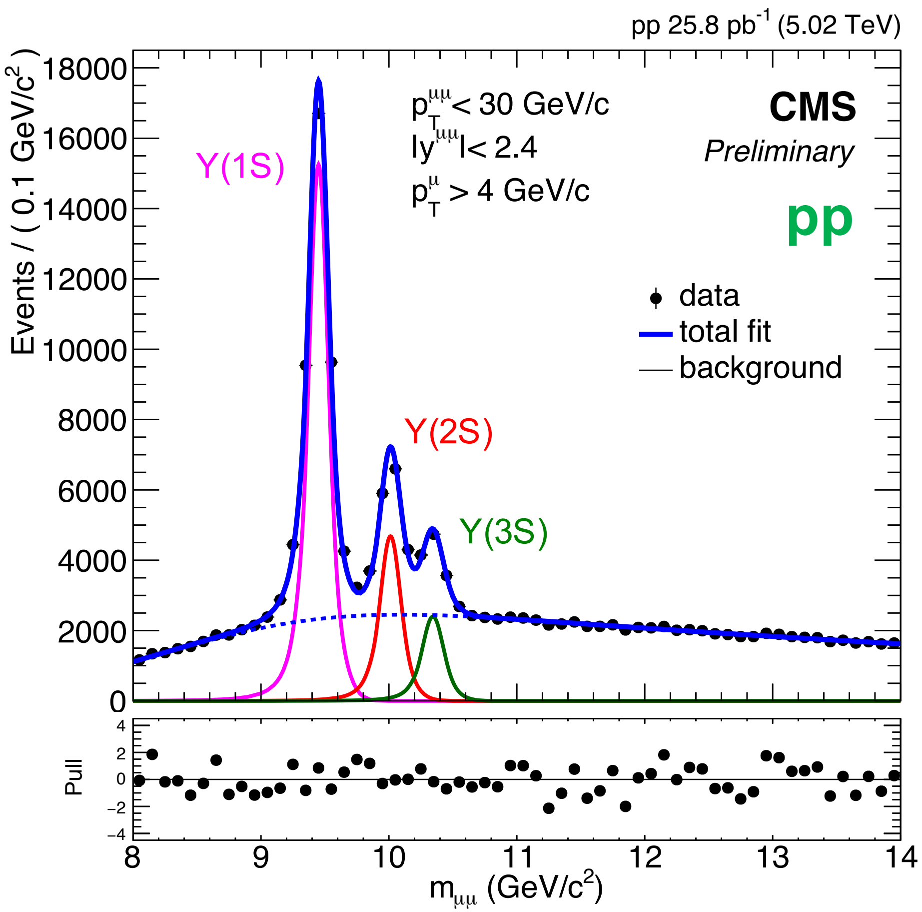
From charm to beauty: just as challenging

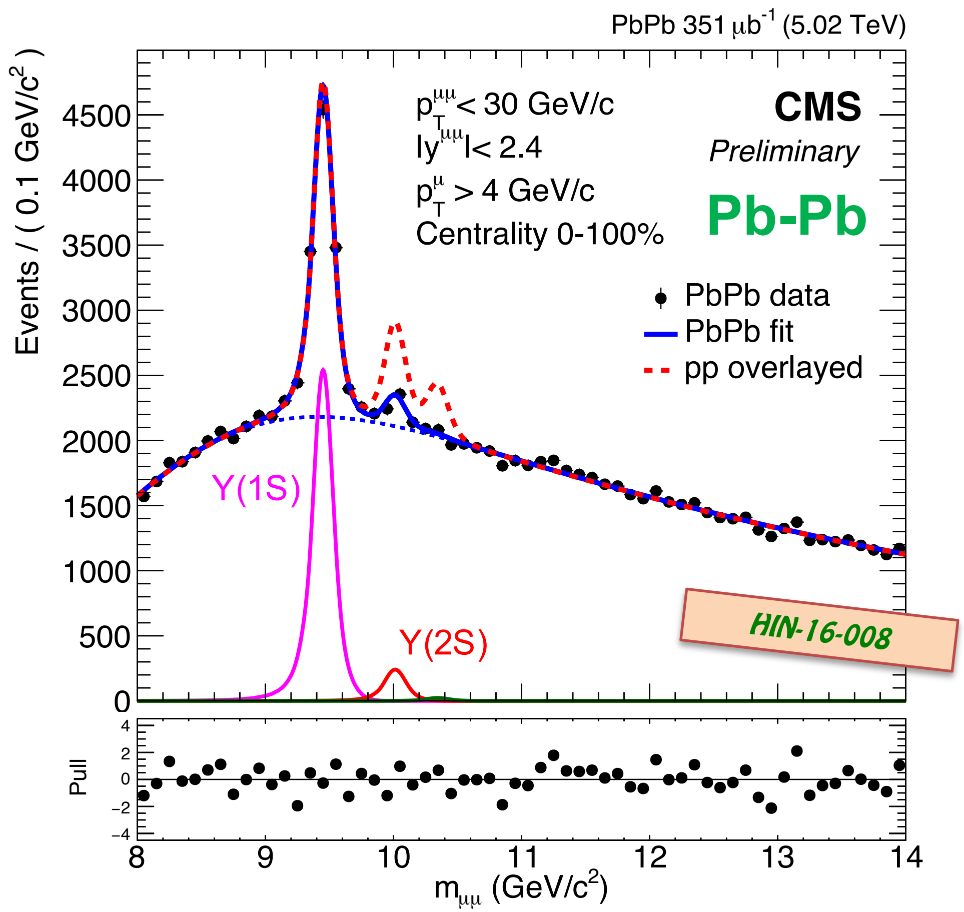
The Υ(1S) peak is always easy to identify, well above the underlying dimuon continuum

The Υ(2S) peak is harder to see…
and, so far, we have no sign of the Υ(3S) in the Pb-Pb data samples !

Note: the NN collision integrated luminosity is only ~ 1.7 times larger in pp than in Pb-Pb :

$(25.8\ pb^{-1} / 351\ \mu b^{-1}) / 208^2 = 1.7$





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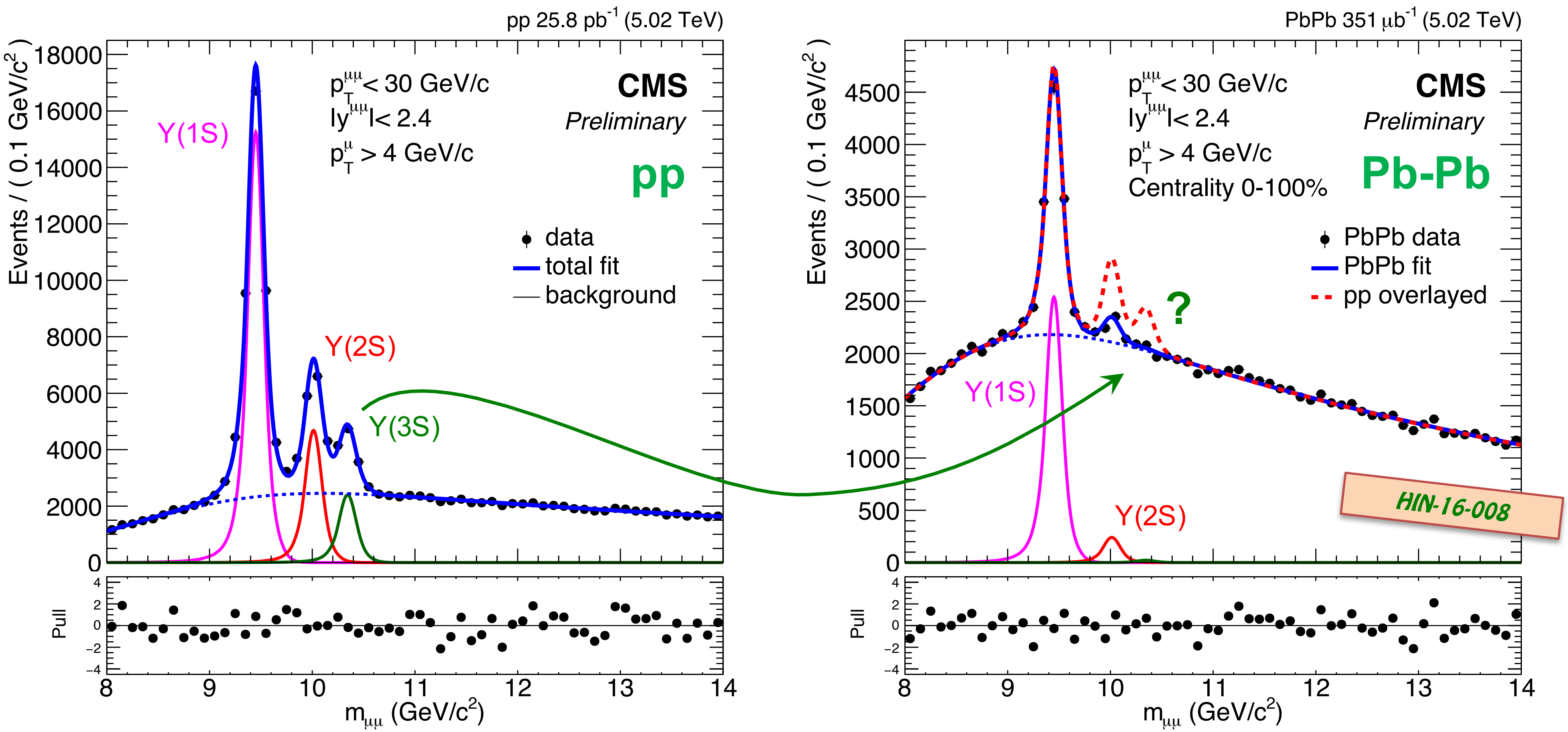

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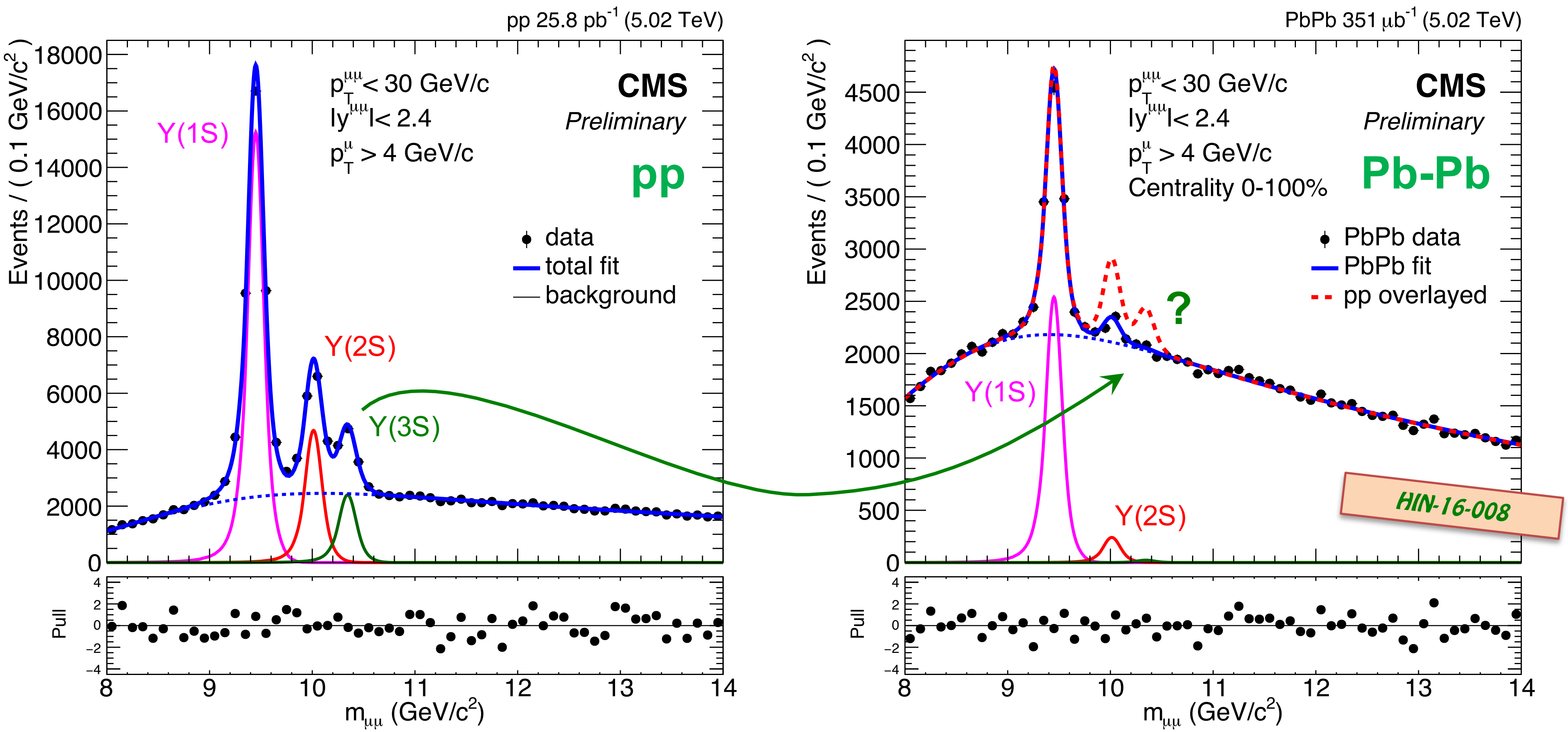
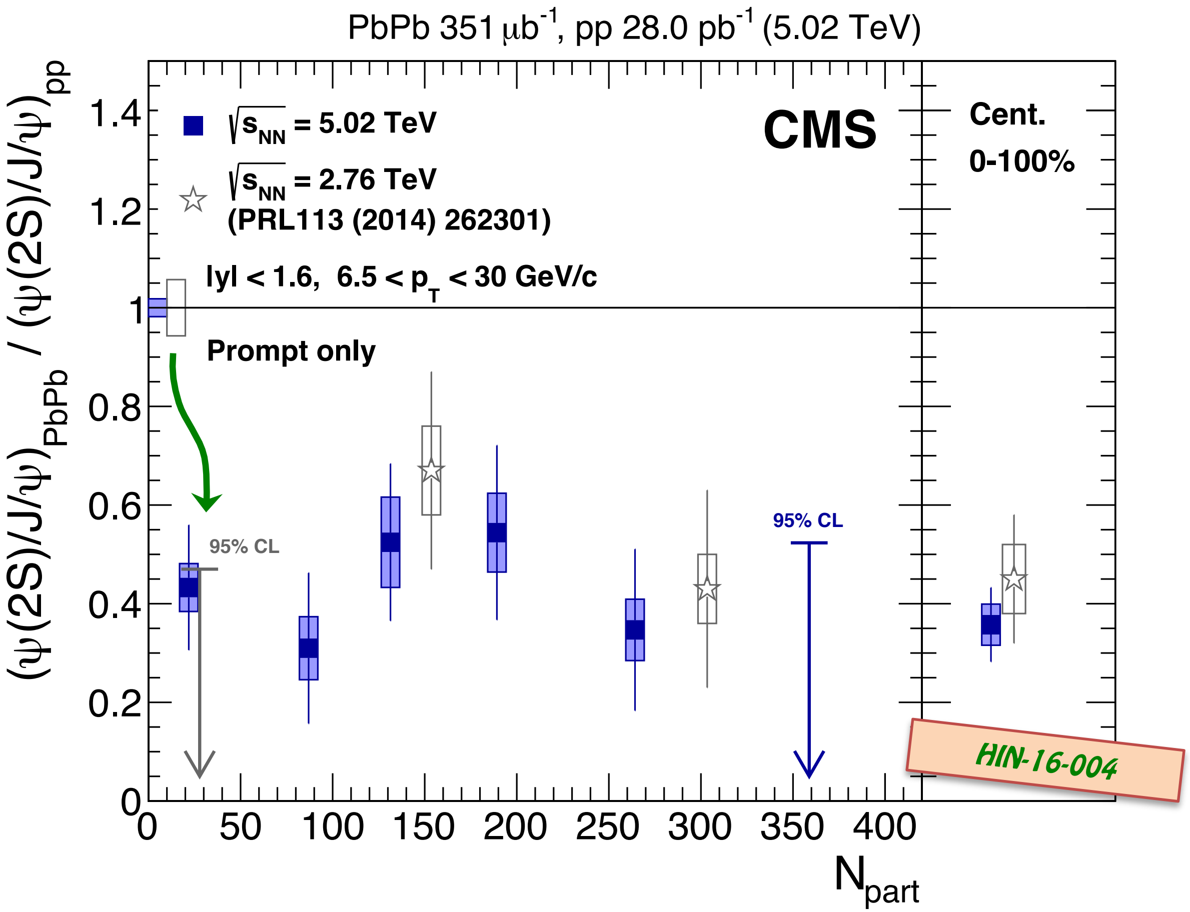


The centrality dependence of the ψ double ratio

We would expect the ψ(2S) to be more suppressed than the J/ψ, once we exceed a certain medium temperature (collision centrality)

But even the most peripheral Pb-Pb collisions probed by CMS are already very effective at melting the excited state



Double ratio:

$$\frac{[\,(2S)\,/\,(1S)\,]_{PbPb}}{[\,(2S)\,/\,(1S)\,]_{pp}}$$

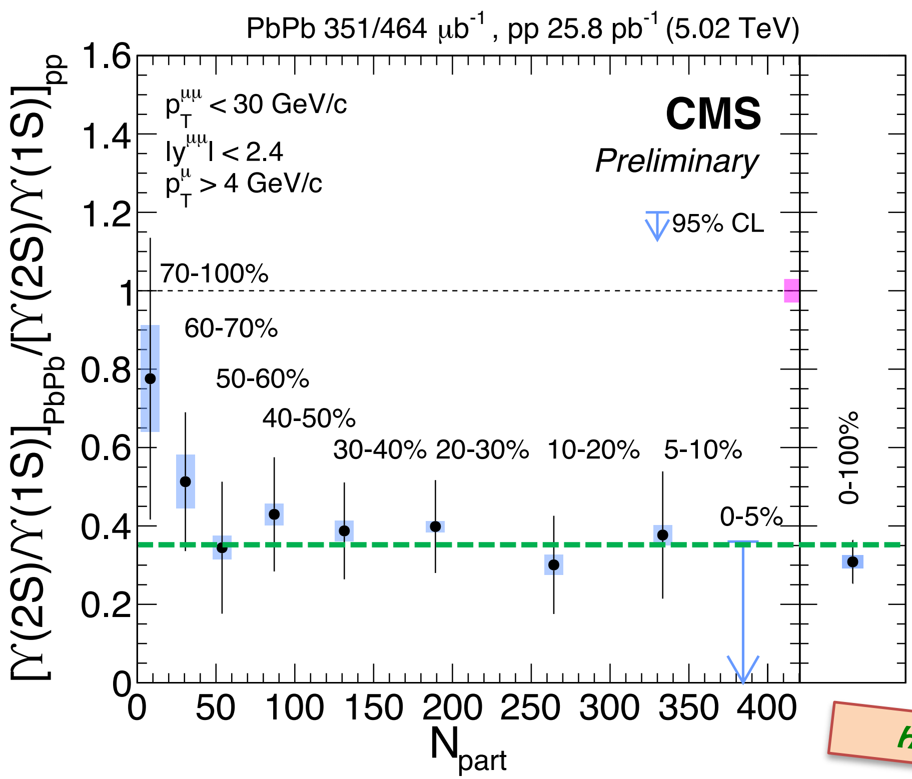
Note:
Charmonium states that bind quarks from different NN interactions should not add much yield for p_T > 6.5 GeV

The centrality dependence of the Υ double ratios

The Υ(2S) / Υ(1S) double ratio has been measured in 9 centrality bins, including three bins in the peripheral 50 to 100% percentile range

As in the ψ(2S) case, the Υ(2S) double ratio is essentially flat, at around 0.35, and the drop from pp to Pb-Pb occurs at very peripheral collisions

The Υ(3S) / Υ(1S) double ratio is not significantly higher than zero, even in the most peripheral bin



HIN-16-008

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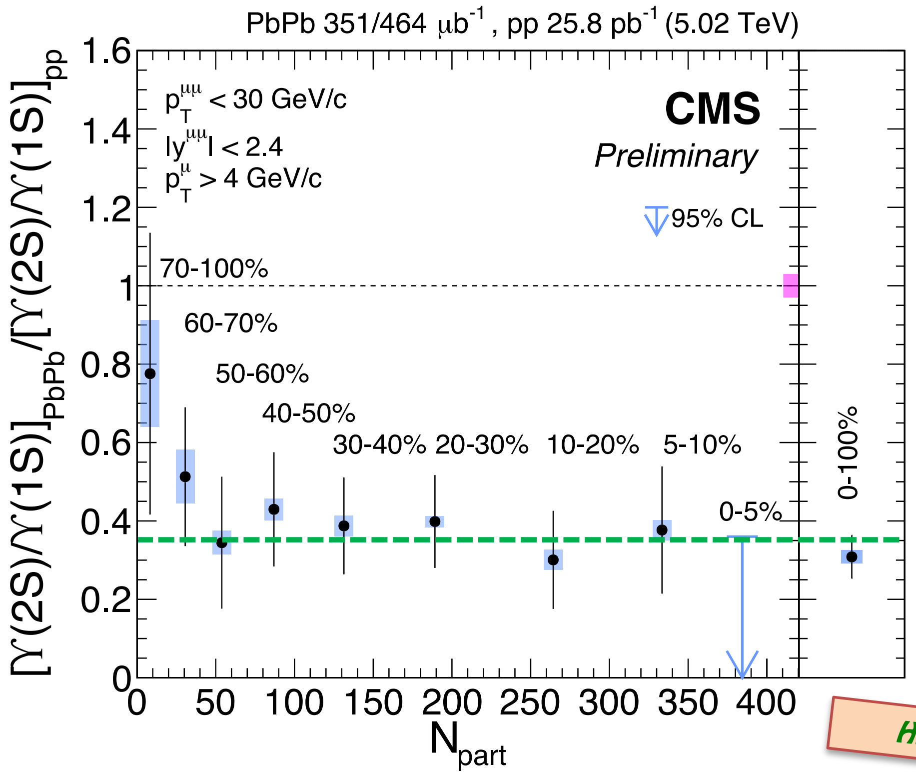

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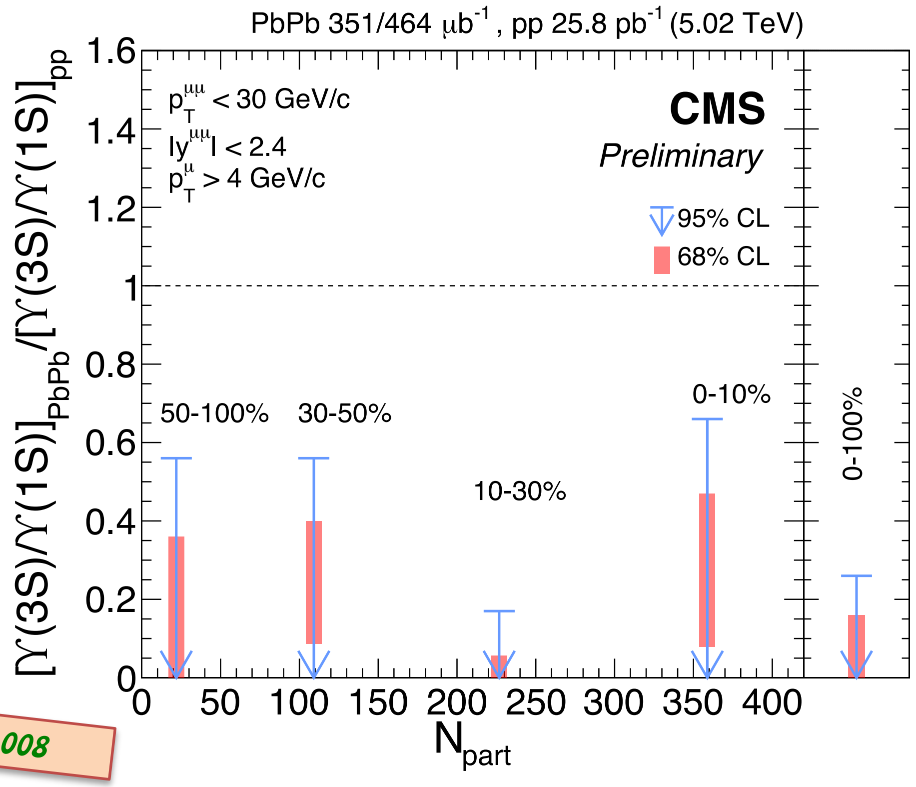
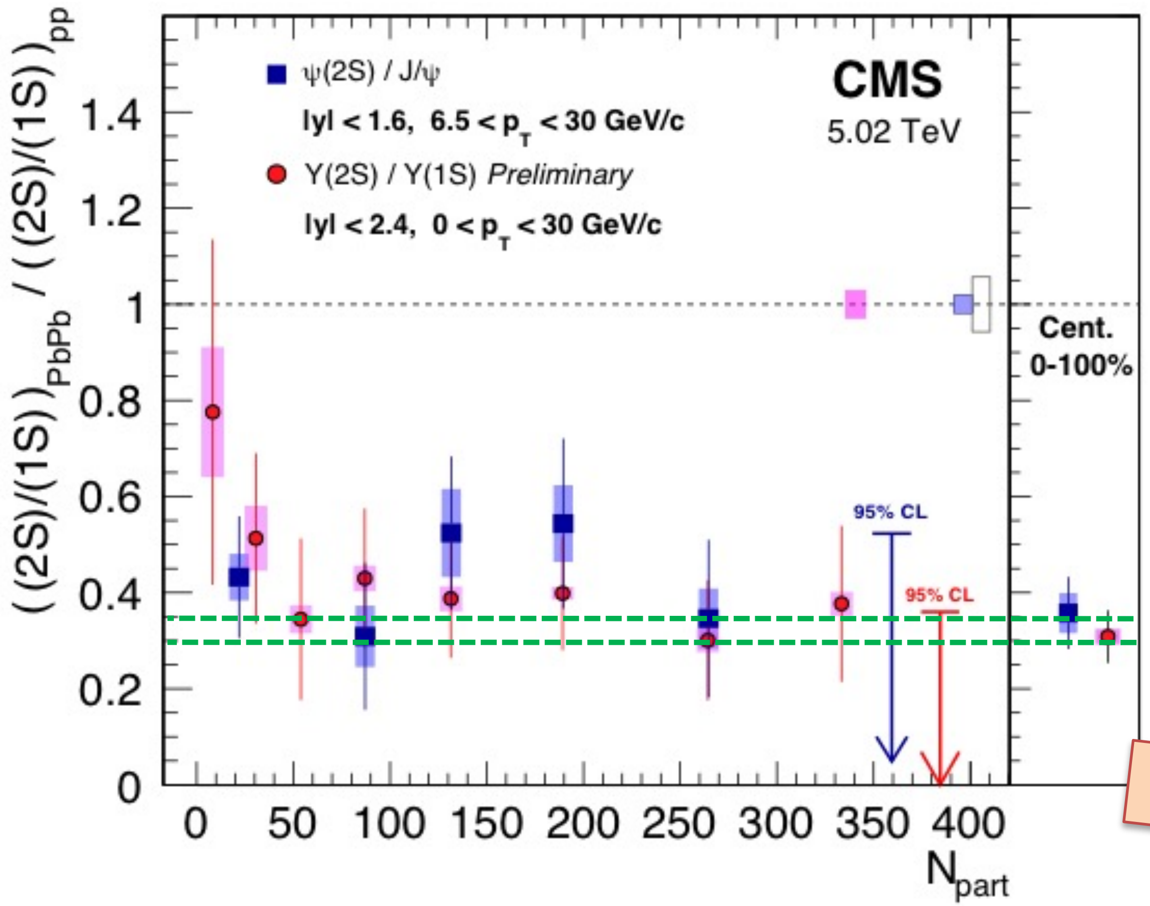


The centrality dependence of the ψ and Υ double ratios

The 2S/1S double ratios have very similar trends in the two families

With respect to the ground states, 65% of the ψ(2S) and 70% of the Υ(2S) mesons are no longer produced in Pb-Pb collisions…
a huge drop from the pp level



HIN-16-004
HIN-16-008

Can we distinguish 2S suppression from 1S enhancement ?

Yes, with single ratios :

$R_{AA} \sim (nS)_{PbPb} / (nS)_{pp}$

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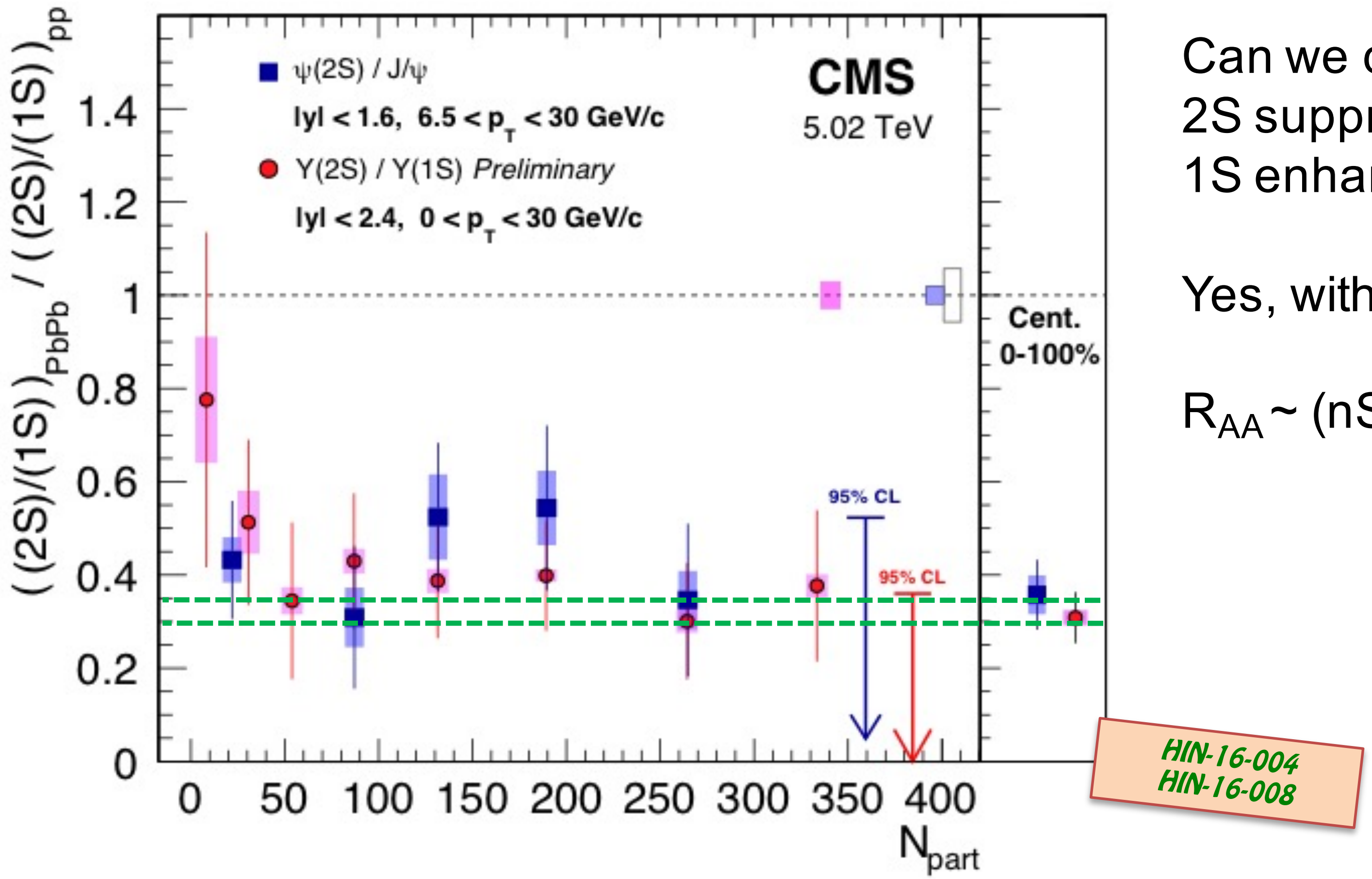

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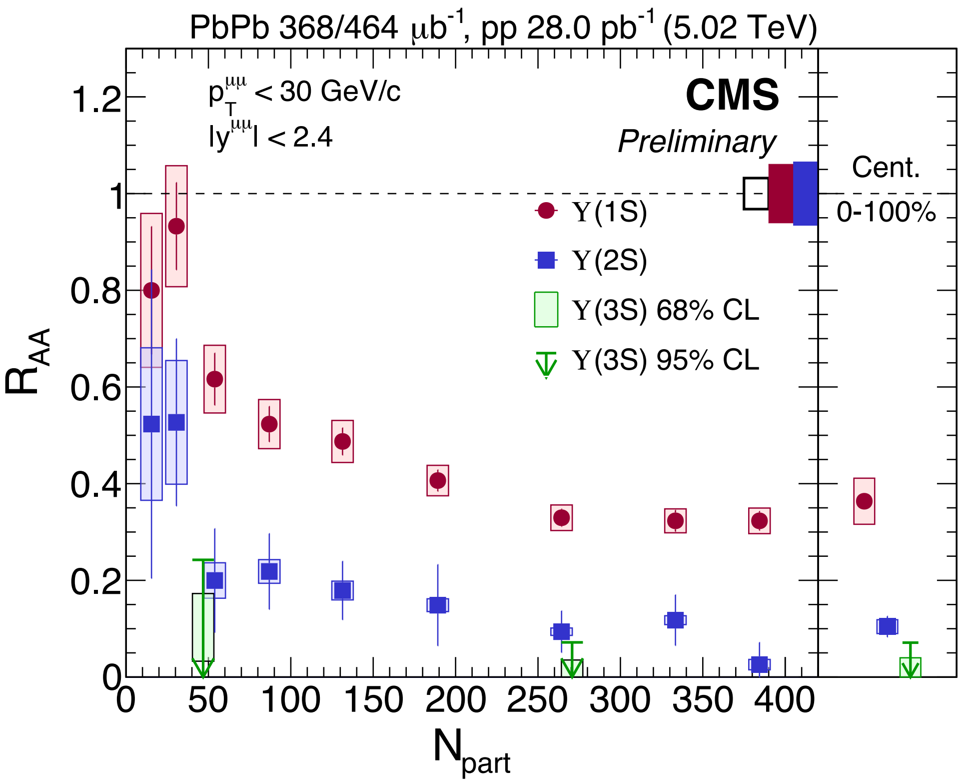
The centrality dependence of Upsilon suppression

The Υ(1S) and Υ(2S) R_{AA} have roughly parallel trends, with the most peripheral Υ(1S) R_{AA} being close to 1

The Υ(1S) data suggests that the higher energy collisions lead to a stronger suppression: R_{AA}(5.02 TeV) < R_{AA}(2.76 TeV)

An indication that the energy increase results in a hotter medium



HIN-16-023

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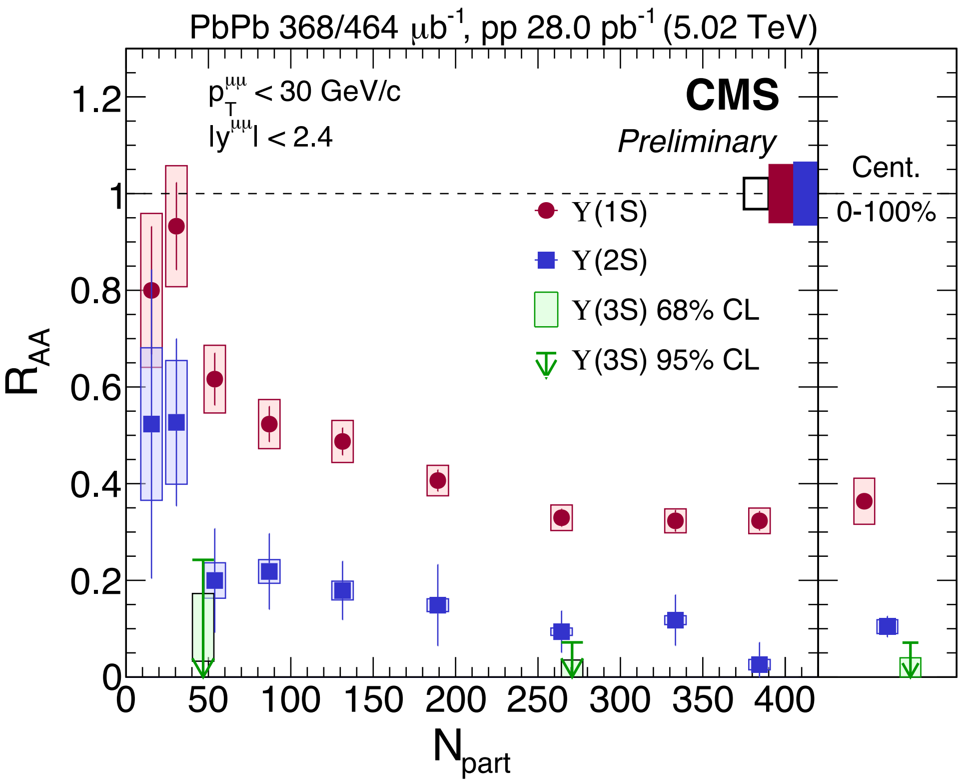
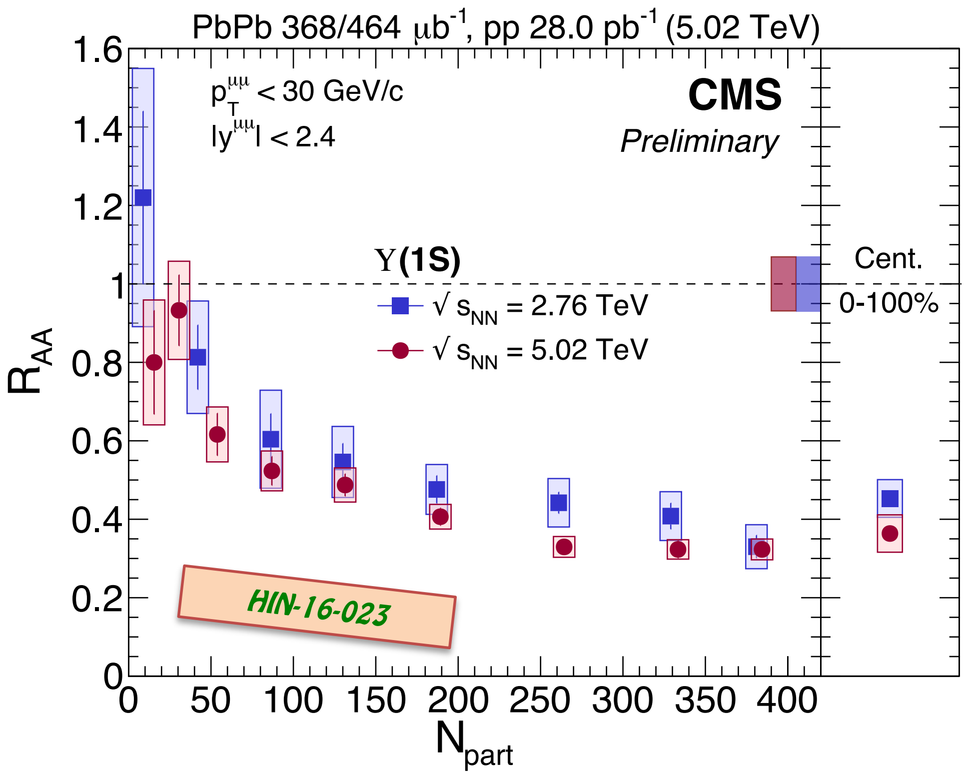
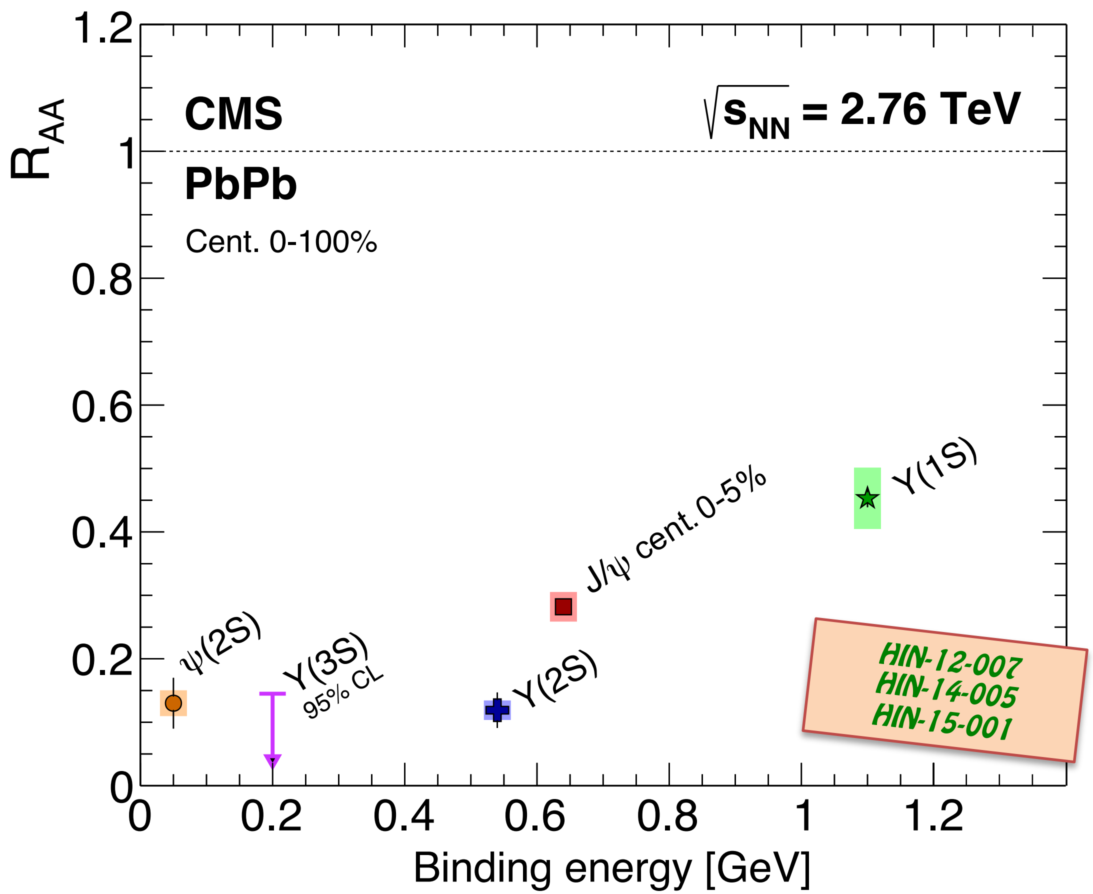




Sequential quarkonium suppression?

To see how the Pb-Pb to pp suppression level (R_{AA}) depends on the binding energy, we need to account for the feed-down contributions of the other onia; only the ψ(2S) is *not* affected by feed-down decays

Maybe none of the *directly produced* Υ(1S) are suppressed and we are seeing a strong suppression of the Υ(2S), Υ(3S) and χ_b(nP) yields



The most loosely bound state, the ψ(2S), shows the strongest suppression among the directly produced quarkonia

ψ(2S): |y| < 1.6, p_T > 6.5 GeV, HIN-12-007

J/ψ: |y| < 2.4, p_T > 6.5 GeV, HIN-14-005

Υ(nS): |y| < 2.4, p_T > 0 GeV, HIN-15-001

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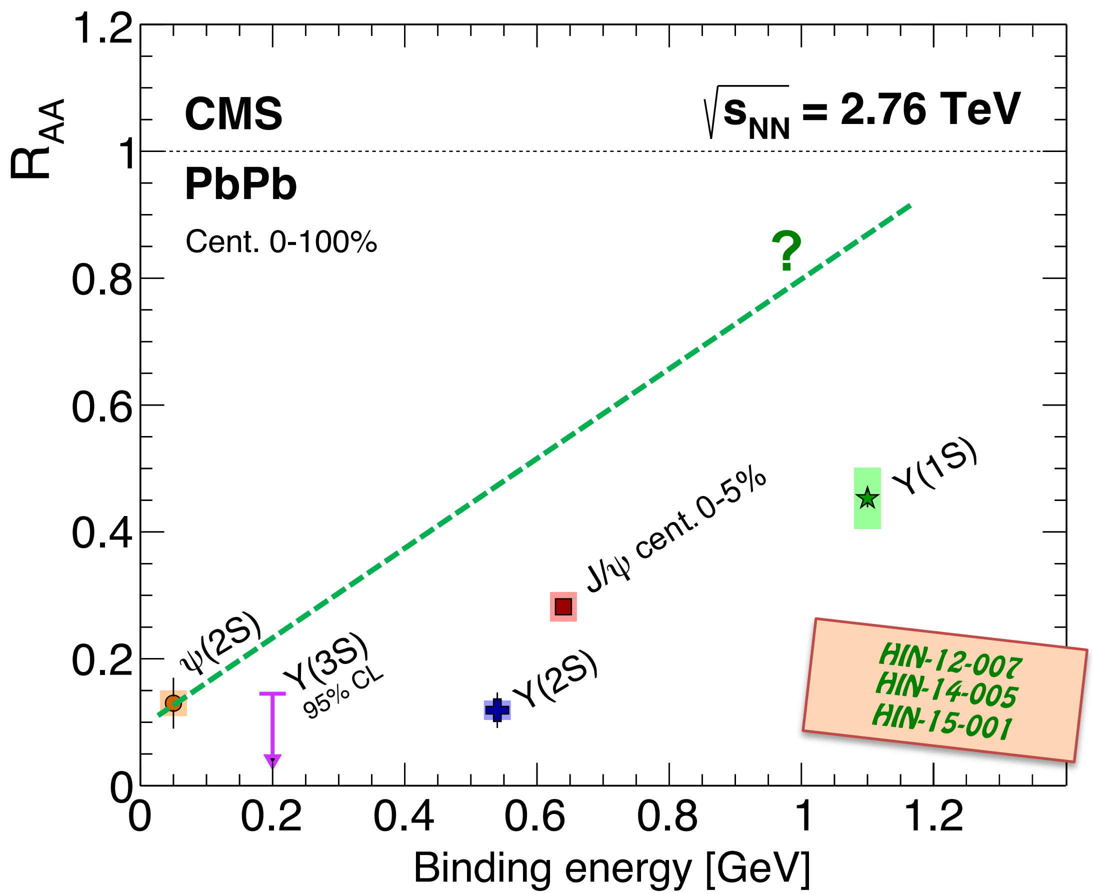

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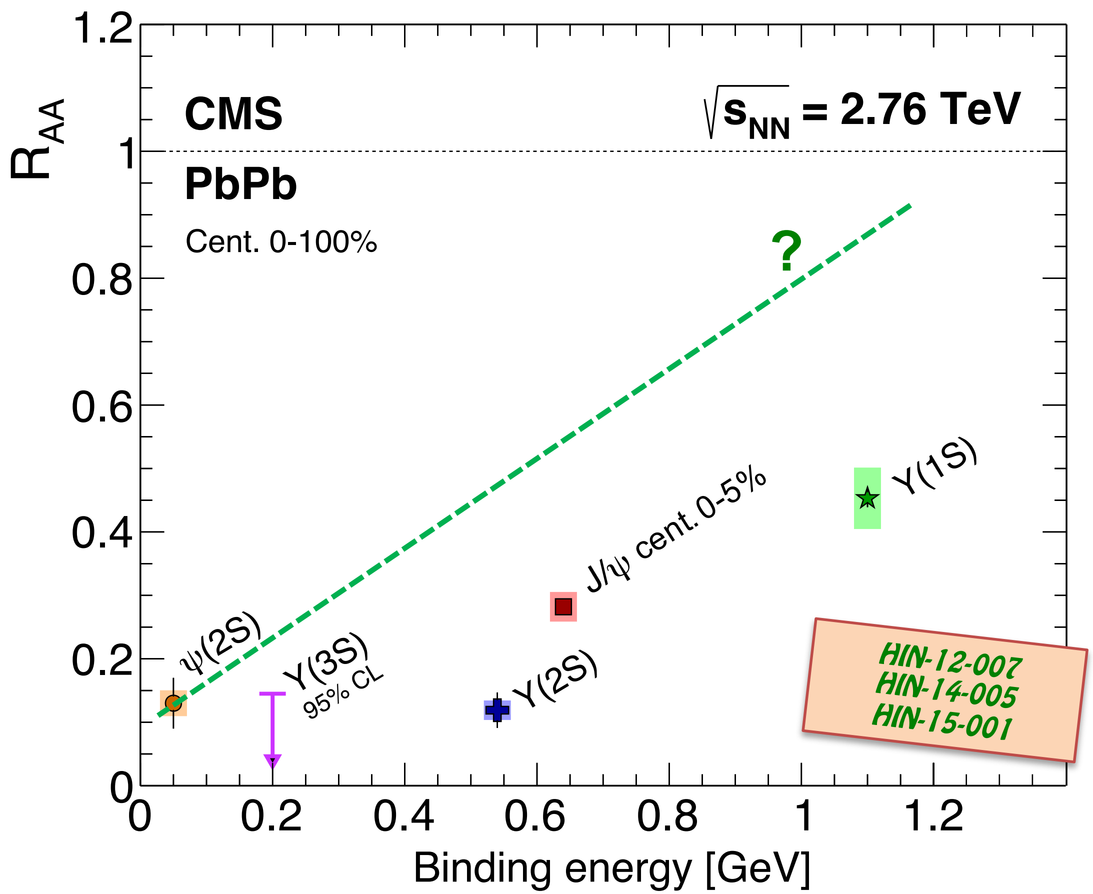

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A polarized look at quarkonium suppression

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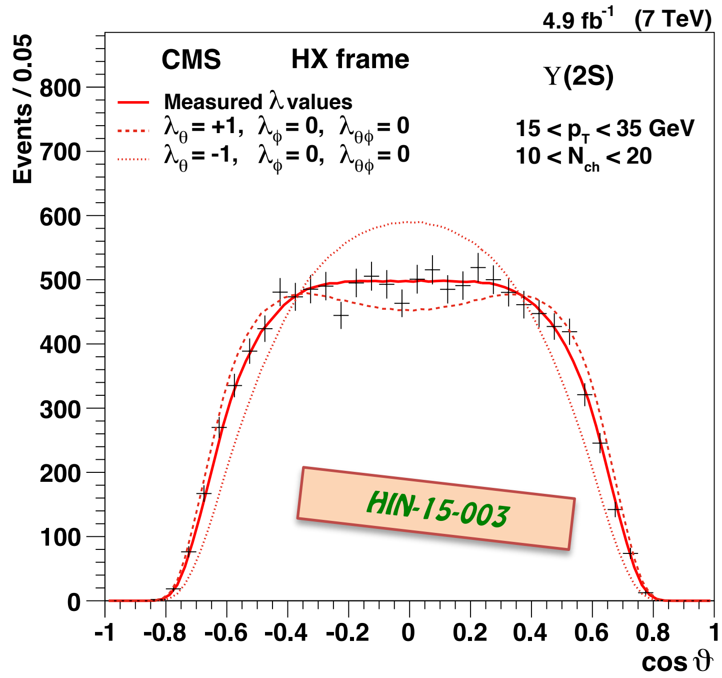

Polarization also provides important insights into quarkonium production mechanisms (vs. medium)

CMS measured the Y(nS) polarizations in pp vs. N_{ch}
No strong variations have been seen

The interpretation of the Y(1S) results is blurred by potential effects of the unknown feed-down contributions

The feed-down free ψ(2S) provides cleaner data; the analysis is ongoing

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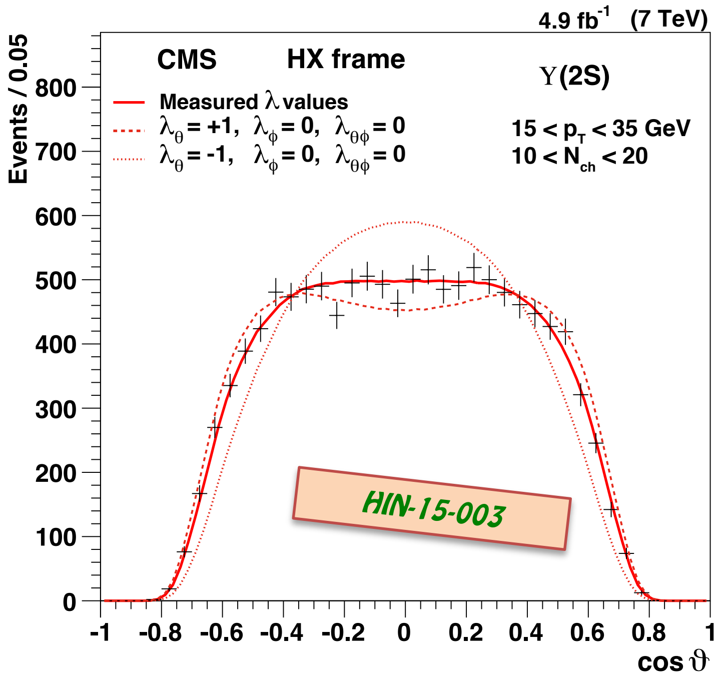

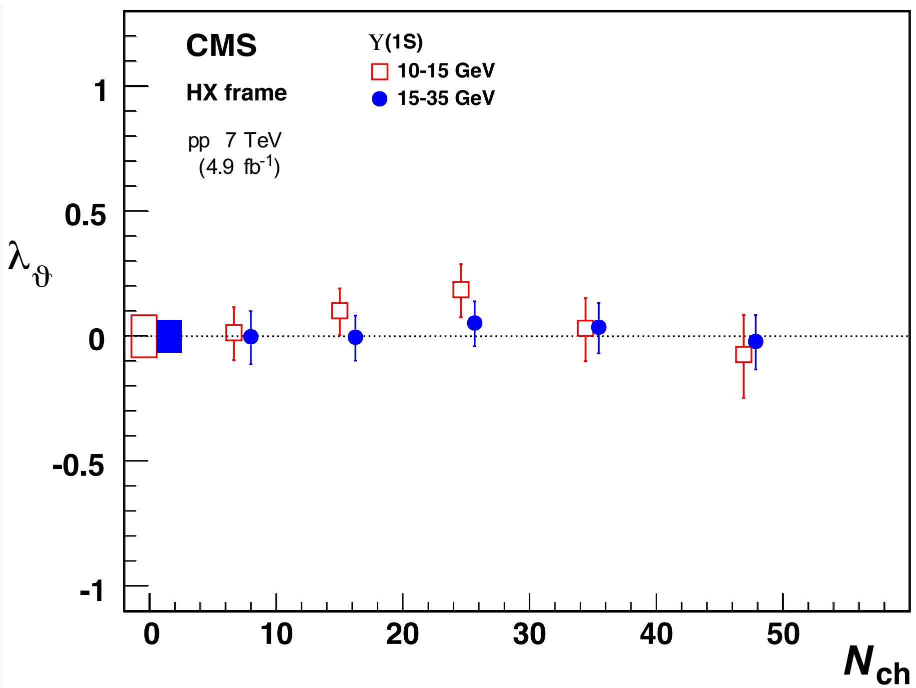

The interpretation of the Υ(1S) results is blurred by potential effects of the unknown feed-down contributions

The feed-down free ψ(2S) provides cleaner data; the analysis is ongoing

A polarized look at quarkonium suppression

If quarkonia would be produced more transversely polarized in Pb-Pb than in pp, we would see onia suppression; the acceptance corrections assume same polarizations for all states and collisions

Polarization also provides important insights into quarkonium production mechanisms (vs. medium)

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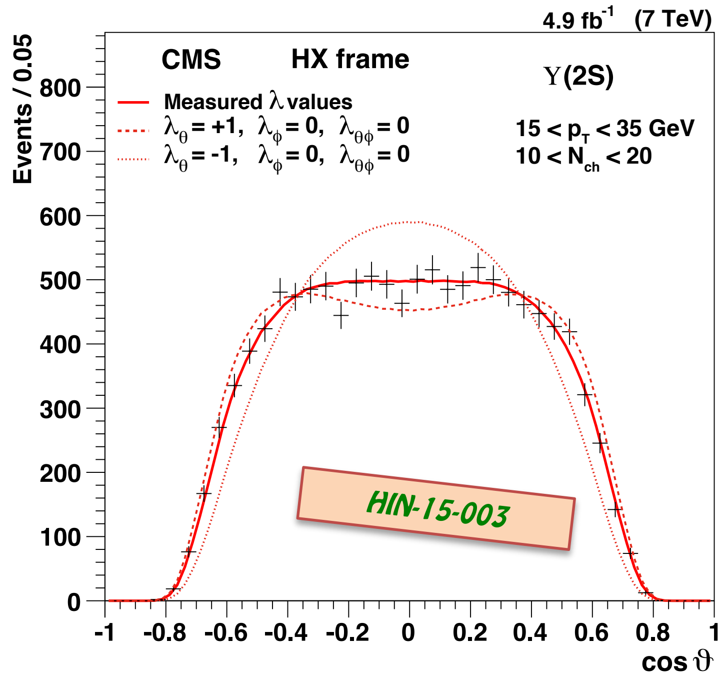

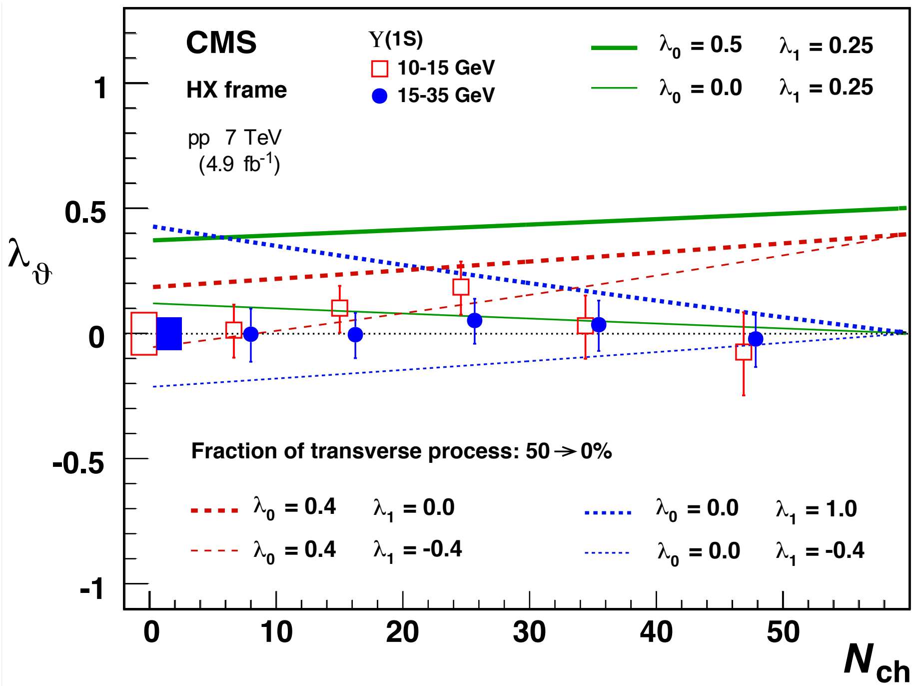

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Summary

Sequential quarkonium suppression in heavy ion collisions is a non-trivial signature of the phase transition from confined to deconfined QCD matter

Evidence beyond reasonable doubt requires very large event samples (statistics) and careful analysis procedures (systematics) to overcome many experimental challenges

The $\psi(2S)$ and $\Upsilon(3S)$ states are especially interesting; data on P-wave production would also be very valuable (in pp and Pb-Pb) but identifying the photons is hard…

The most peripheral Pb-Pb collisions seem to deserve further attention…

Summary and take home messages

Sequential quarkonium suppression in heavy ion collisions is a non-trivial signature of the phase transition from confined to deconfined QCD matter

Evidence beyond reasonable doubt requires very large event samples (statistics) and careful analysis procedures (systematics) to overcome many experimental challenges

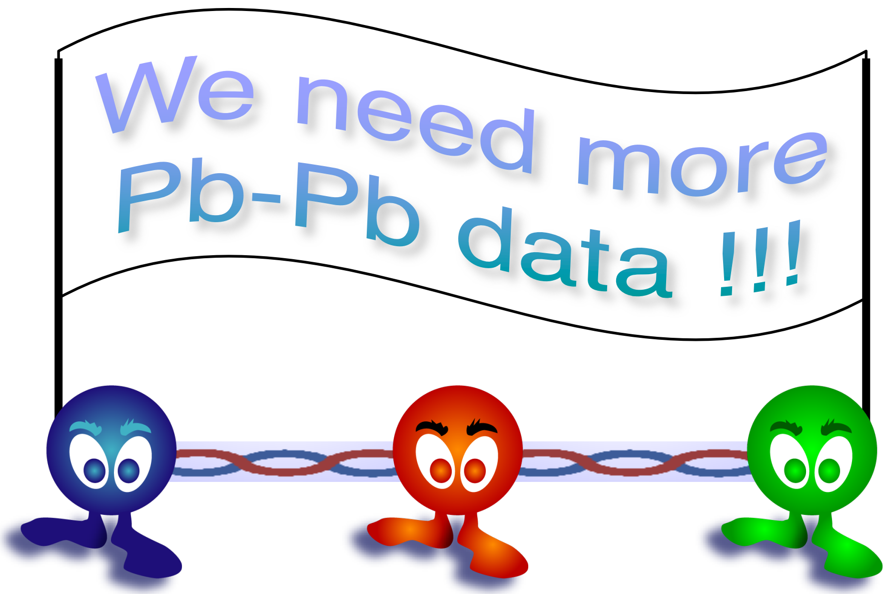
The ψ(2S) and Y(3S) states are especially interesting; data on P-wave production would also be very valuable (in pp and Pb-Pb) but identifying the photons is hard…

The most peripheral Pb-Pb collisions seem to deserve further attention…

Finding the needle is not enough;
we need many needles,
especially for the excited states

We are doing the "Ultra Trail Mont Blanc"
and we need to stay on the path, focused,
collecting data, one event after another

Just when we are about to find the answer...
let's not change the question



Further reading on CMS quarkonium measurements

CMS publications on quarkonium physics mentioned in these slides :

- ***HIN-16-004***: arXiv:1611.01438 ; accepted by PRL
  "Relative modification of prompt ψ(2S) and J/ψ yields from pp to PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV"
- ***HIN-16-008***: PAS: http://cds.cern.ch/record/2217909
  "Strong suppression of Y excited states in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV"
- ***HIN-16-023***: PAS: http://cds.cern.ch/record/2244680
  "Measurement of Nuclear Modification Factors of Y(nS) Mesons in PbPb Collisions at $\sqrt{s_{NN}}$ = 5.02 TeV"
- ***HIN-12-007***: arXiv:1410.1804 ; PRL 113 (2014) 262301
  "Measurement of prompt ψ(2S) to J/ψ yield ratios in PbPb and pp collisions at $\sqrt{s_{NN}}$ = 2.76 TeV"
- ***HIN-14-005***: arXiv:1610.00613 : submitted to EPJC
  "Suppression and azimuthal anisotropy of prompt and nonprompt J/ψ prod. in PbPb colls. at $\sqrt{s_{NN}}$ = 2.76 TeV"
- ***HIN-15-001***: arXiv:1611.01510 : submitted to PLB
  "Suppression of Y(1S), Y(2S) and Y(3S) production in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV"
- ***HIN-15-003***: arXiv:1603.02913 : Phys. Lett. B 761 (2016) 31
  "Y(nS) polarizations versus particle multiplicity in pp collisions at $\sqrt{s}$ = 7 TeV"

Other interesting publications can be found through these Twiki pages:

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsBPH