LHC Run 3 and results for SQM from CMS

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HIM 2024/06 meeting

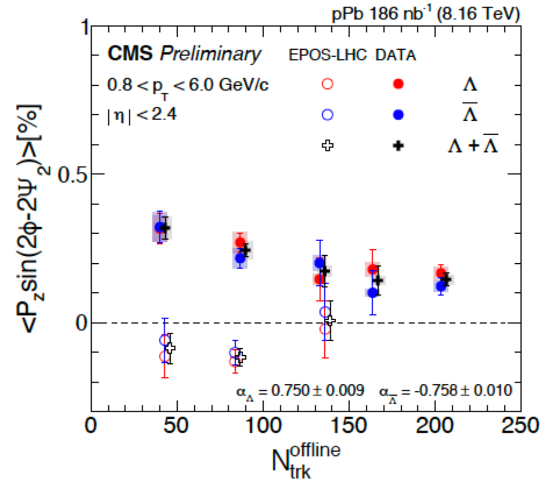
Jun. 21st. 2024, APCTP, Pohang

Summary of CMS talk@ SQM2024 (Jun. 3-7, 2024, Strasbourg, France)

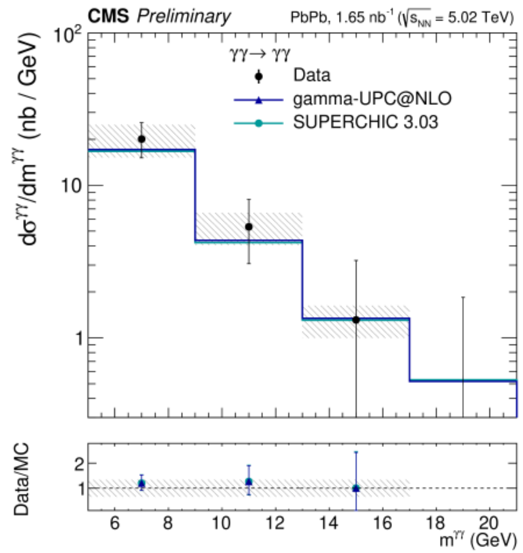
Section	Talk	Speaker
	Investigating bottom quark energy loss, hadronization, and B meson nuclear modification factors	Jhovanny Mejia Guisao
	Observation of double J/psi production in pPb collisions	Stefanos Leontsinis
	Detailed study of the production of Y mesons in PbPb collisions	Prabhat Ranjan Pujahari
	Probing a new regime of ultra-dense gluonic matter using high-energy photons	Pranjal Verma
	Measurement of the multiplicity dependence of charm hadron production in pPb collisions	Austin Baty
	Study of charm quark and QGP medium interactions via Lambda c and D0 production and collective flow	Soumik Chandra
	Measuring the speed of sound in the QGP	Michael Murray
	Measurement of strange particle femtoscopic correlations	Raghunath Pradhan
	Hyperon polarization along the beam direction in pPb collisions	Chenyan Li
	Using Multivariate Cumulants to Constrain the Initial State in PbPb collisions	Aryaa Dattamunsi
	Measurement of azimuthal anisotropy at high pT using subevent cumulants in pPb collisions	Rohit Kumar Singh
	Physics of heavy flavors and strangeness with a time-of-flight PID upgrade at CMS at the high-luminosity LHC	Zhenyu Chen

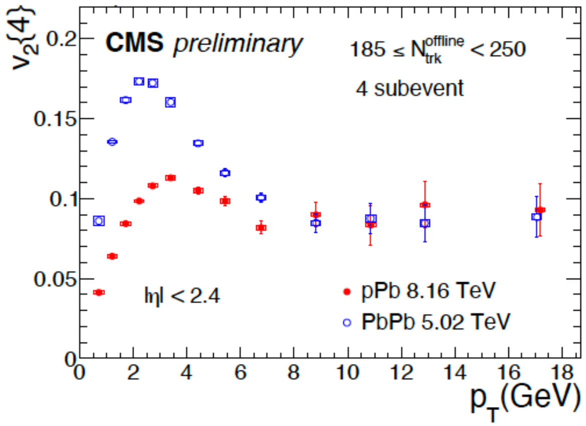
CMS summary

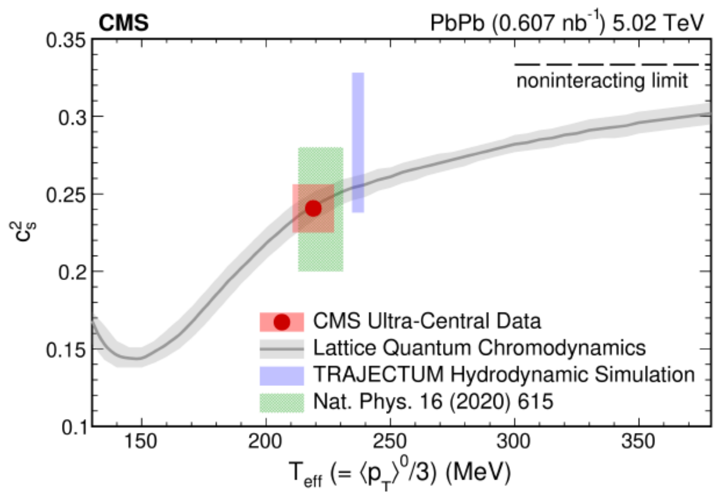
Summary

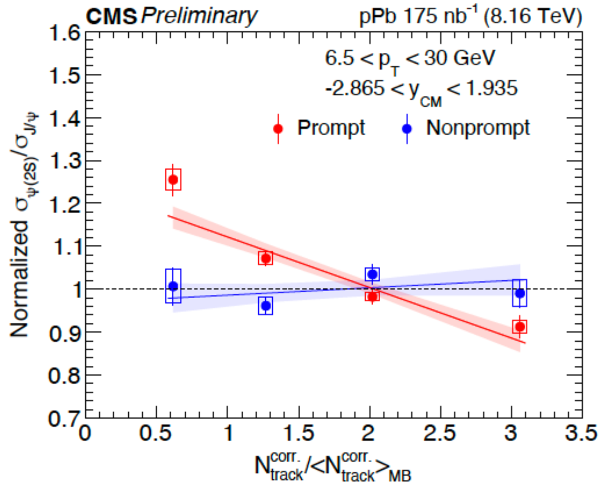


- J/ψ probing low-x parton densities
- Direct constraints on the QCD EoS
- In-medium behavior of heavy quarks
- Signs of medium effects in pPb systems
- First Run 3 results and more to come!









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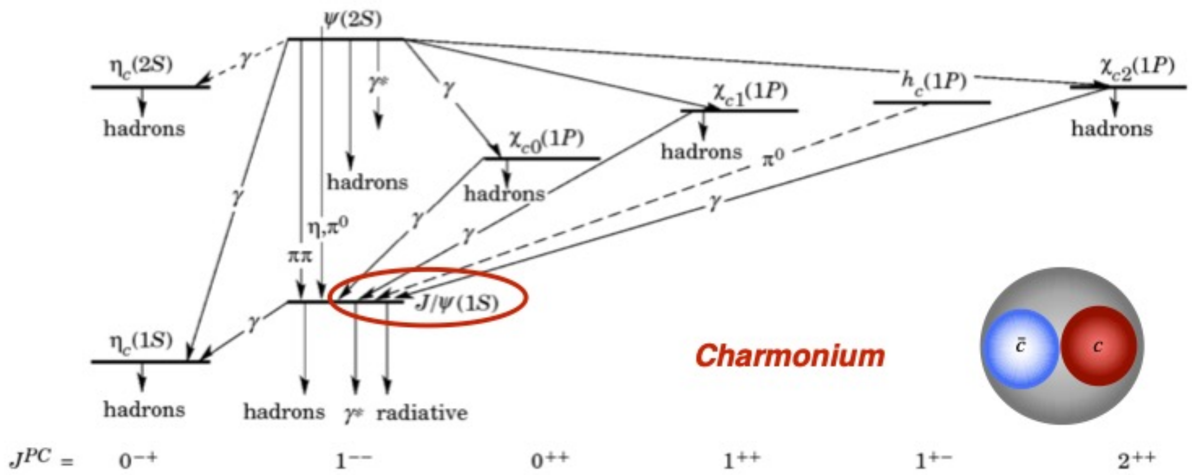
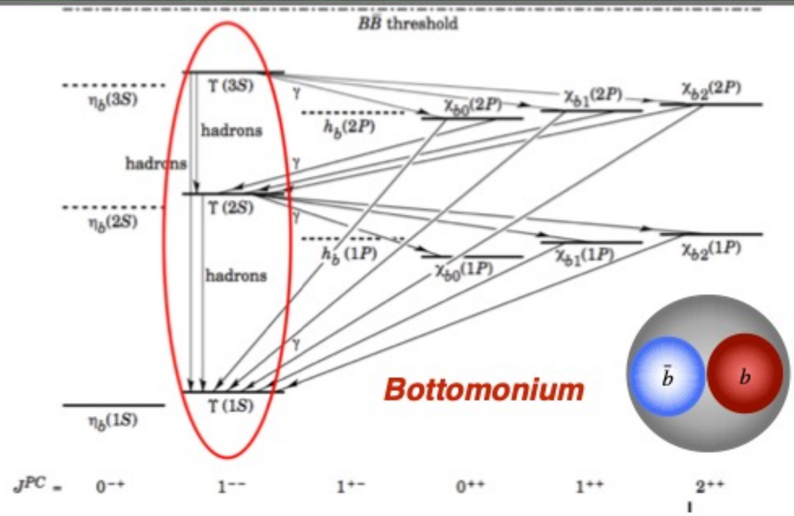
Measurement of the multiplicity dependence of charm hadron production in pPb collisions

Motivation of quarkonia study





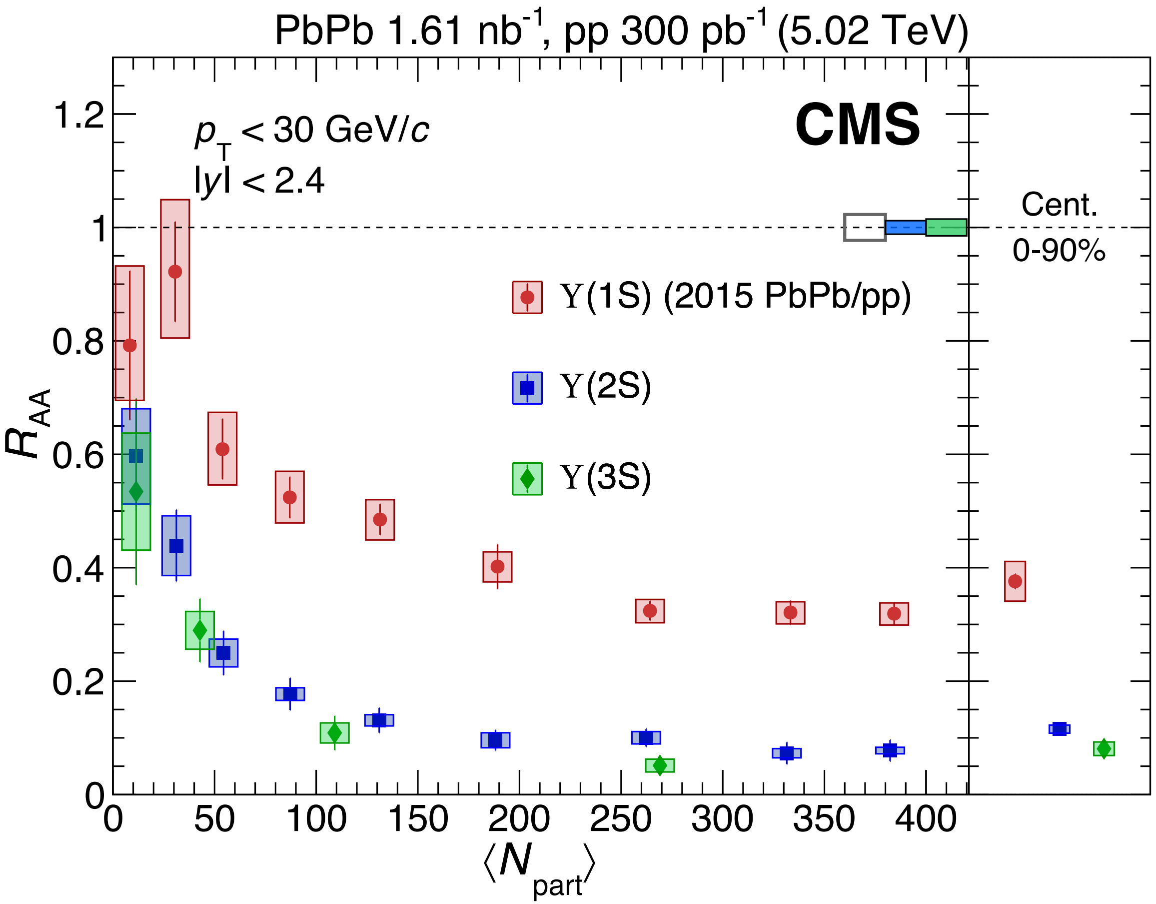
Why are they important ?

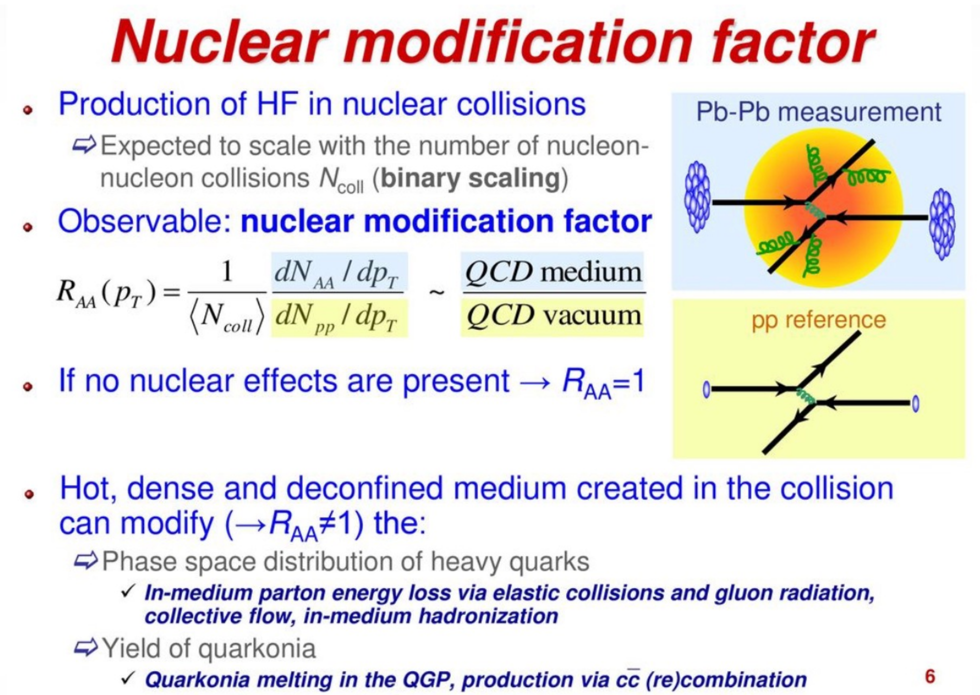
- ➡ Heavy quarks/quarkonoium are mostly produced in the early stage of heavy ion collisions
- ➡ Heavy quark -> scale separation -> Heavy Quark Effect Theory

Quarkonia suppression has been considered as a smoking gun of the QGP (Matsui, Satz at 1986, …)
From yield and distribution -> deduce in-medium properties and infer the fundamental interaction in QCD matter !

Suppression of quarkonia excited states

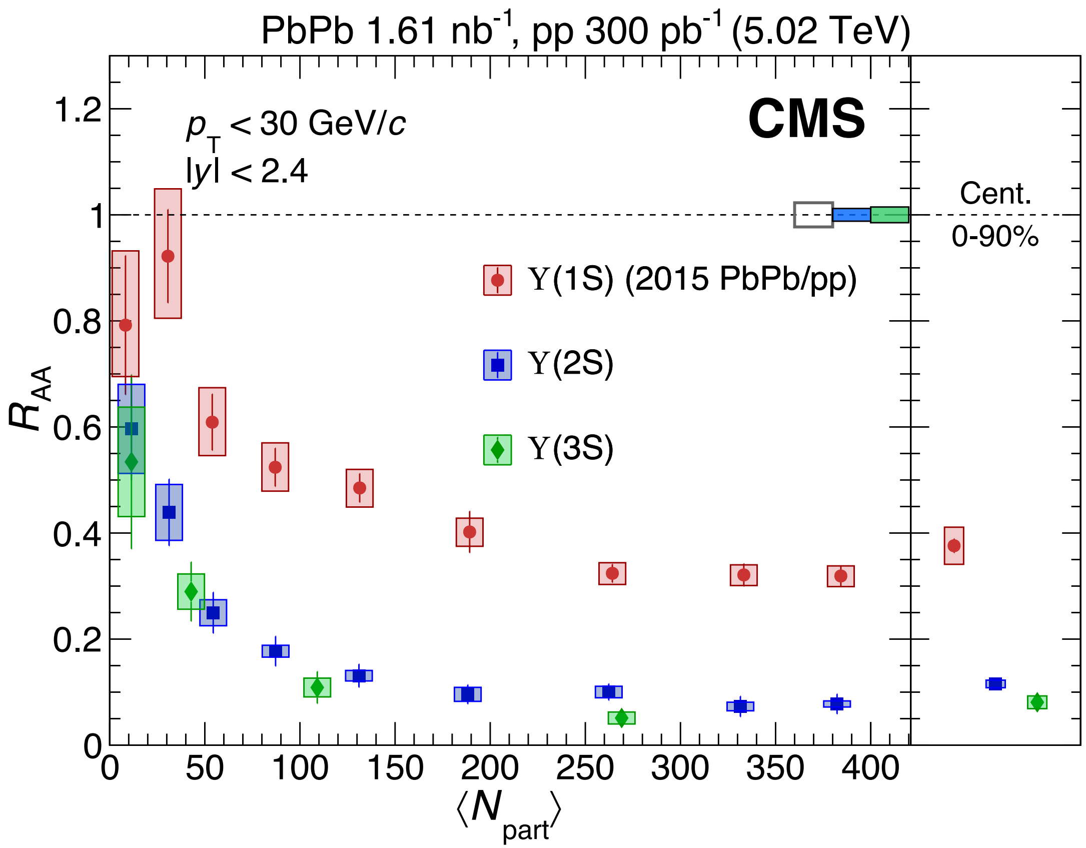
- **Quarkonia suppressed in AA collisions**

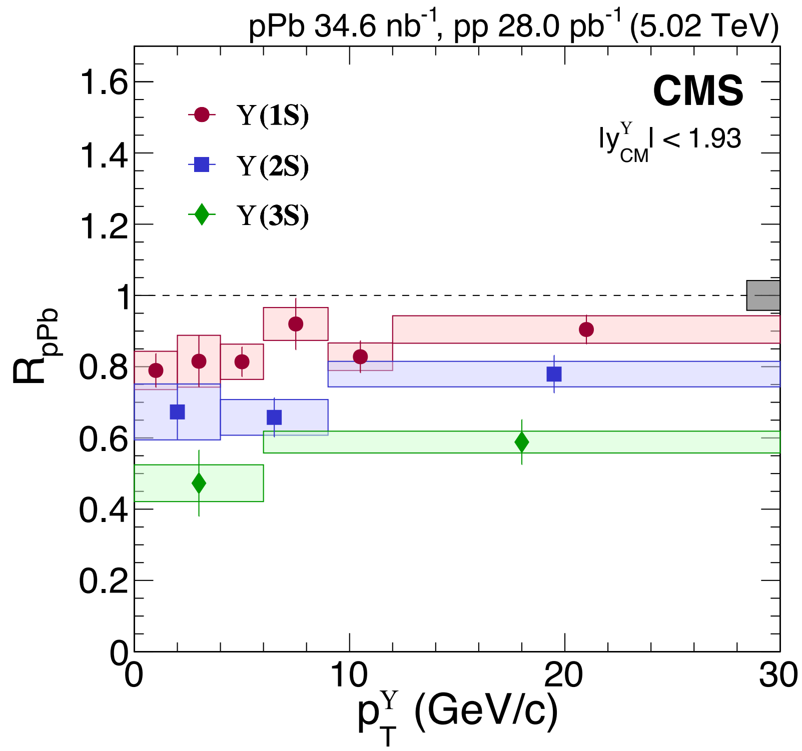




Suppression of quarkonia excited states

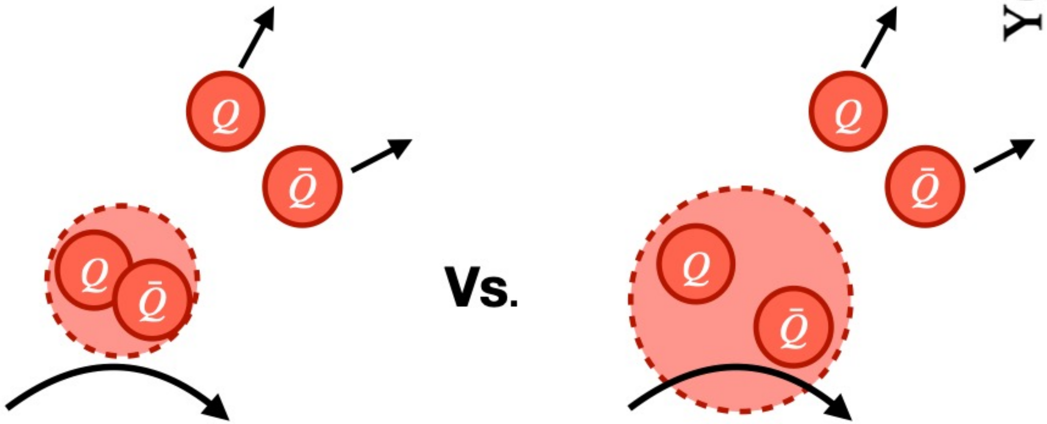
- **Quarkonia suppressed in AA collisions**
- **Suppression of excited states also seen in small systems**

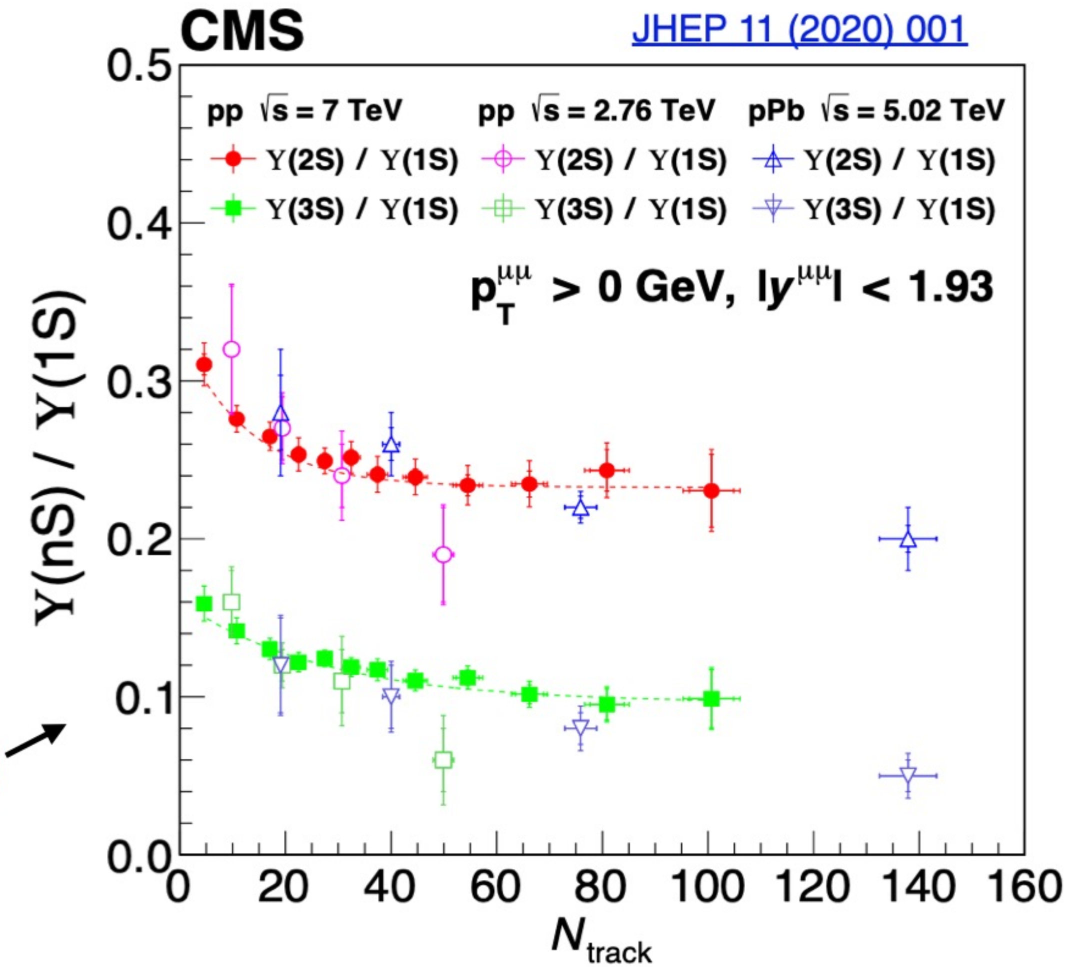




Suppression of quarkonia excited states

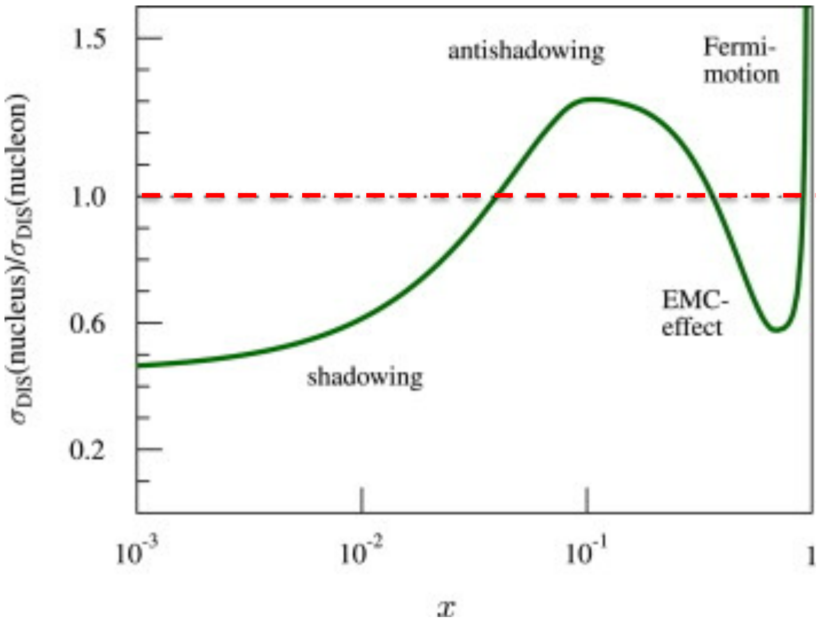
- **Quarkonia suppressed in AA collisions**
- **Suppression of excited states also seen in small systems**
- **Co-moving particles break up excited states more easily than ground states?**
  - **Studies of Υ(nS) support this picture**
  - **Suppression should scale with comover density**

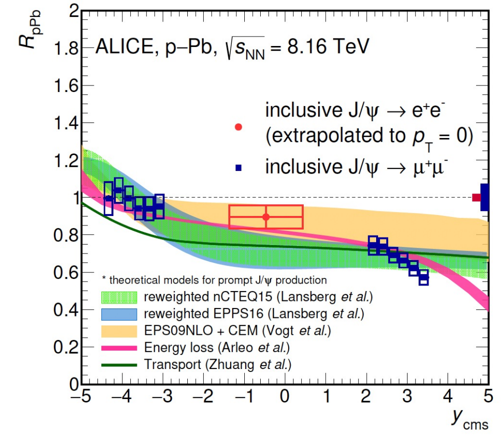




Cold nuclear matter effects

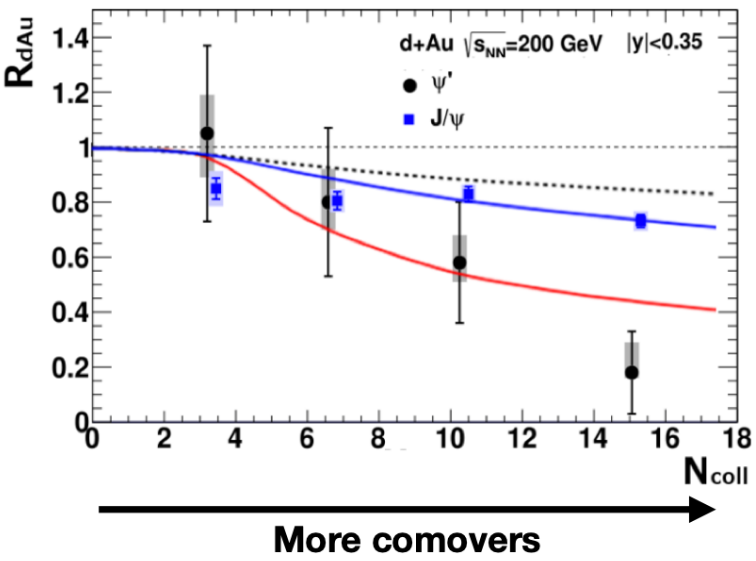
- **Nuclear PDFs (Parton Distribution Functions)**
- **Color Glass Condensate (CGC) – Gluon saturation**
  - high gluon occupation numbers can affect production
- **Cronin effect**
  - broadening of p_T spectra due to NN interactions in nucleus
- **Nuclear absorption**
  - disassociation of a bound state passing through a nucleus
- **Parton energy loss**
  - elastic scattering when moving through the nucleus before hard scattering
- <u>**Comover absorption**</u>
  - <u>hadrons propagating together with the bound state interact with it</u>



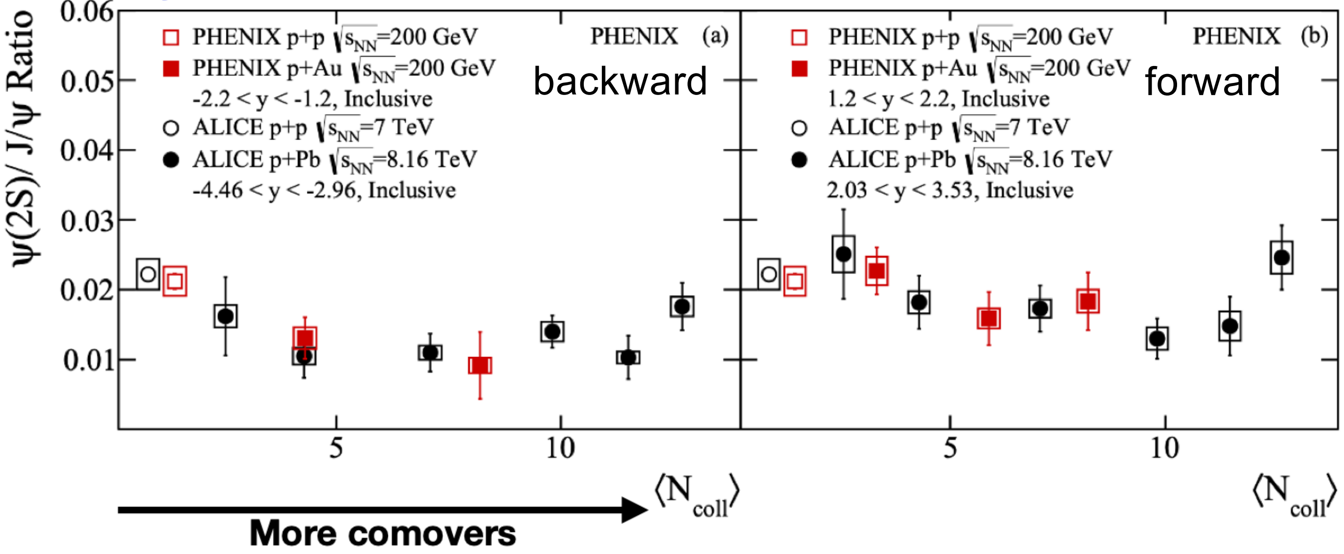


Charmonia and comover effect

PHENIX Phys. Lett. B 749 (2015) 98–103



Phys. Rev. C 105, 064912



- **What about charmonia? - weakly bound excited state**
  - **Should be more sensitive to comover effects**

- **Initial studies performed in pAu, dAu, pPb vs N_{col} inconclusive**

Recent measurement

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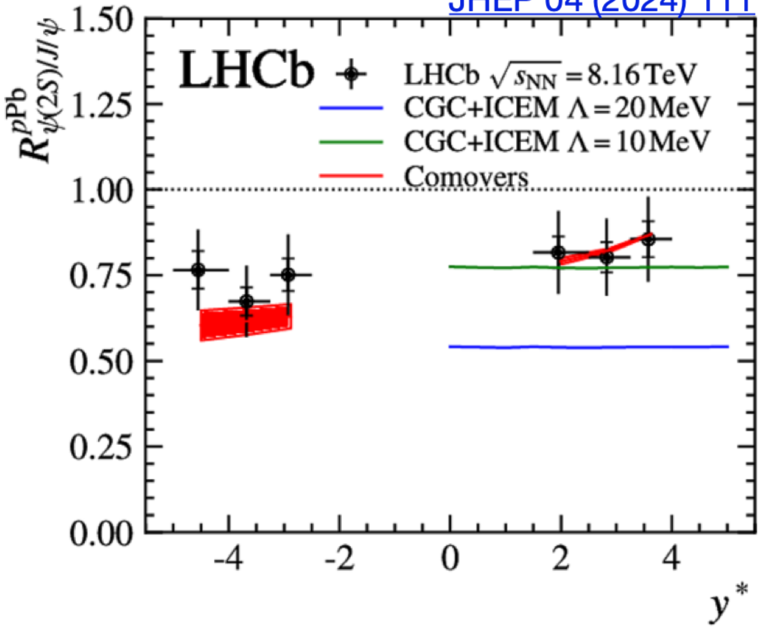

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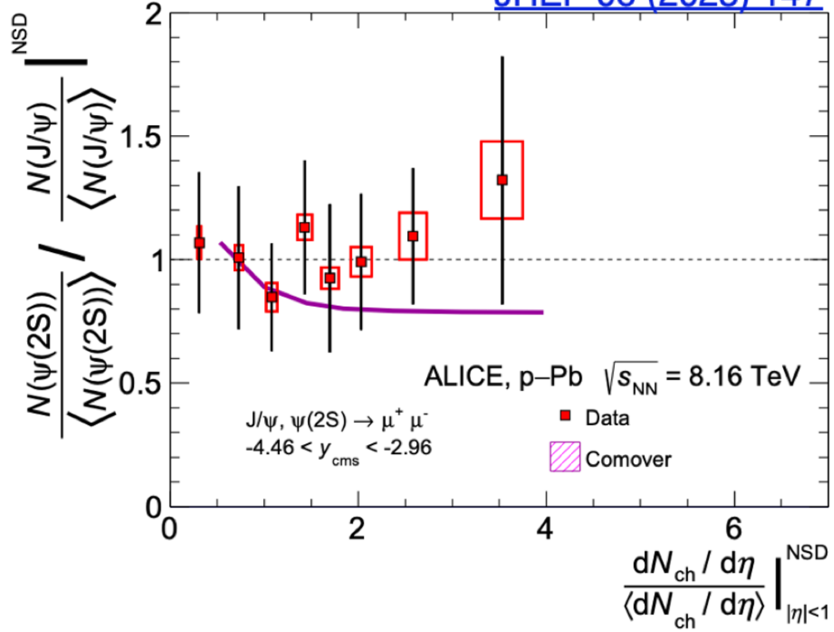
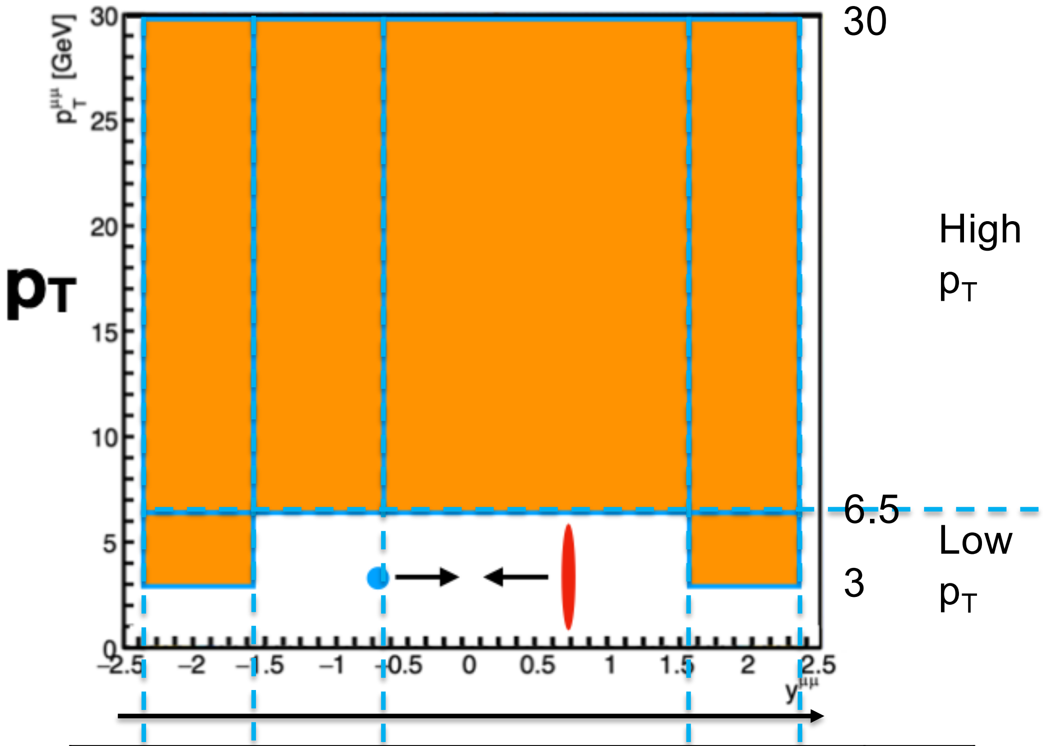


- **LHCb measurements - rapidity dependence of excited state suppression?**
- **ALICE measurements - study dependence on comover density directly**
- **Interpretation limited by large uncertainties in both cases**
  - **Comover effect expected only for prompt charmonia**
  - **Need prompt/non-prompt separation!**

Analysis range and observable of interest

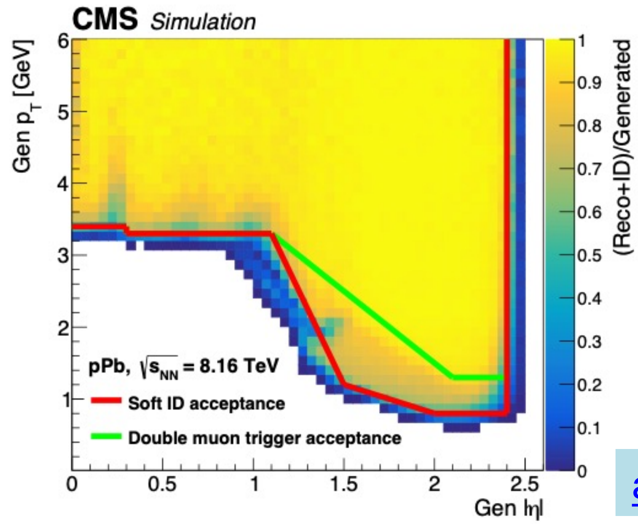


-2.865	-2	-1	1	1.935	y_{lab}
-2.4.	-1.535	-0.535	1.465	2.4	y_{CM}

Far backward | Backward | Mid-rapidity | Forward

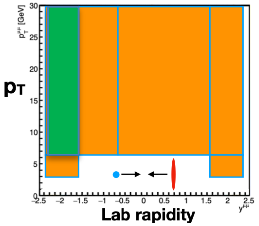
$$\text{Normalised } \sigma_{\psi(2S),n}/\sigma_{J/\psi,n} = \frac{\sigma_{\psi(2S),n}/\sigma_{J/\psi,n}}{\sum_n \sigma_{\psi(2S),n}/\sum_n \sigma_{J/\psi,n}}$$

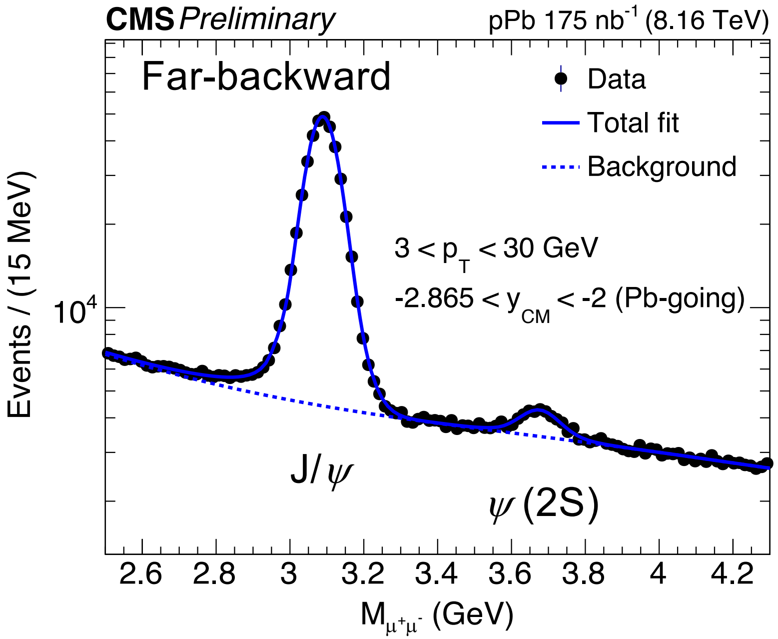
- **Normalized ratio cancels acceptance, shadowing effects**
- **Dimuon range is limited by the single muon acceptance**

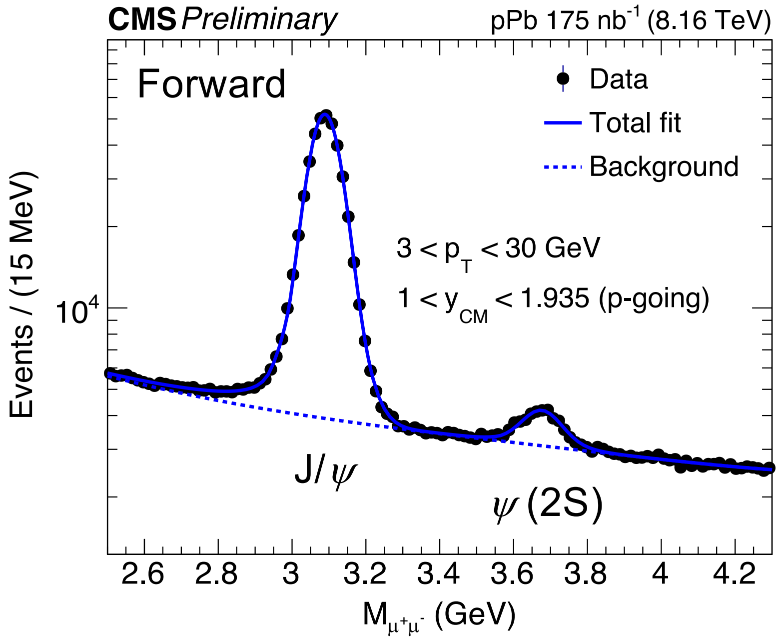


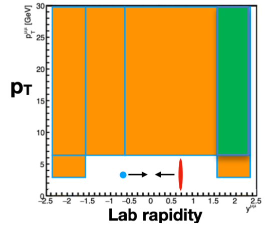
arXiv:2404.17377

Invariant mass peak



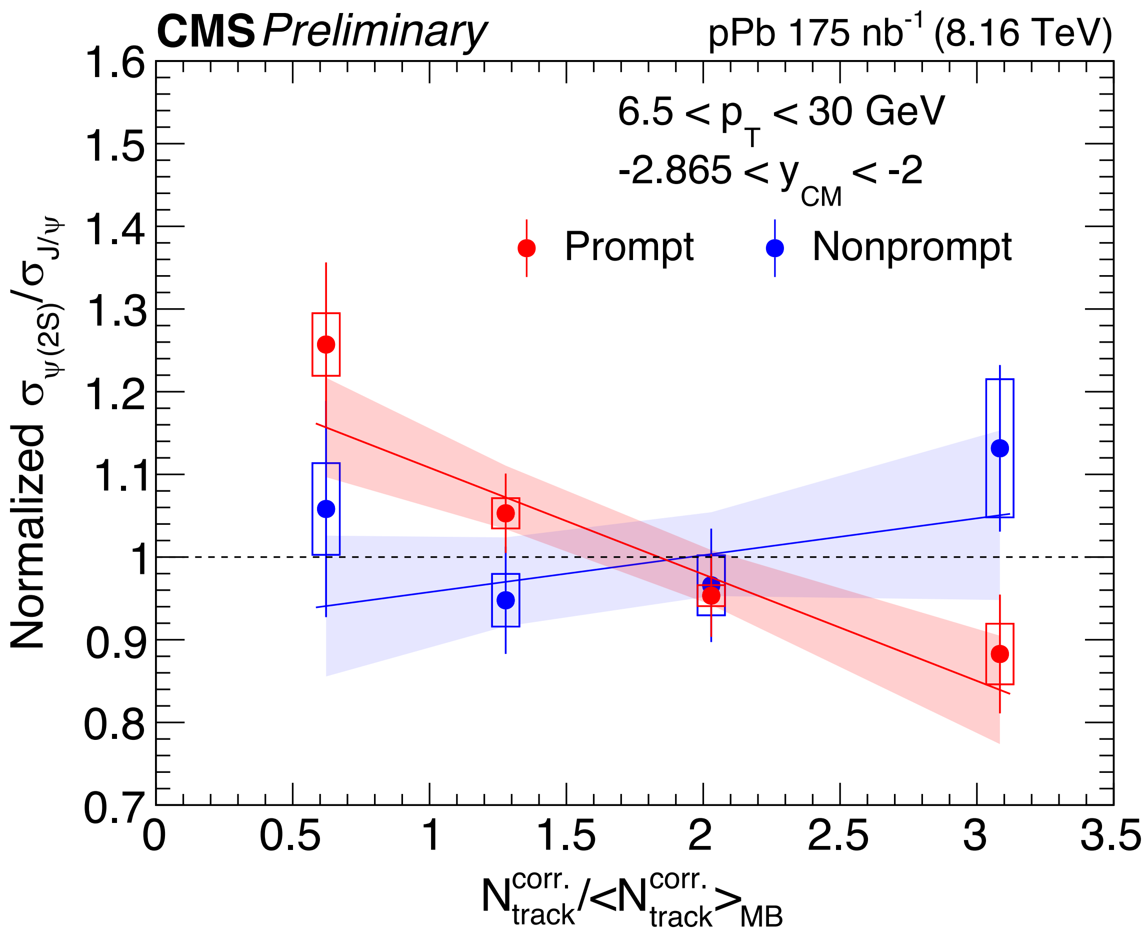


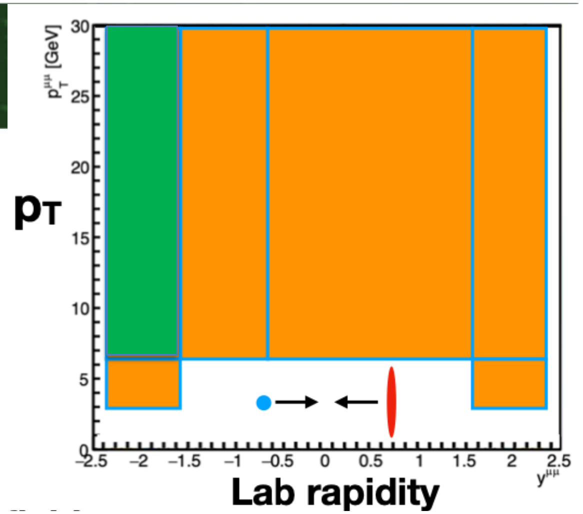




- **Clear J/ψ and ψ(2S) peaks in both forward/backward regions**
- **Analysis mainly limited by statistics**
- **Separation of prompt and nonprompt components with proper decay length**

Normalised ratio (Far-backward) High p_T

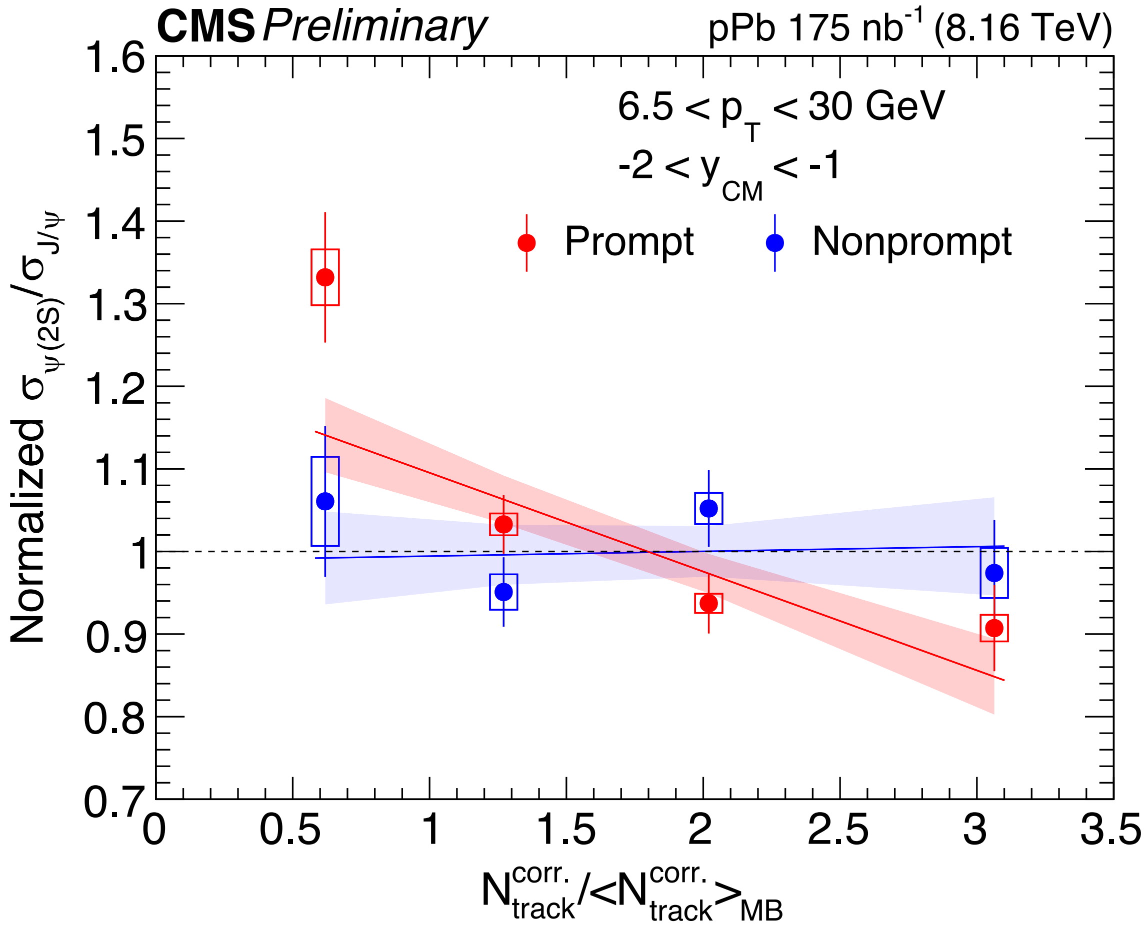


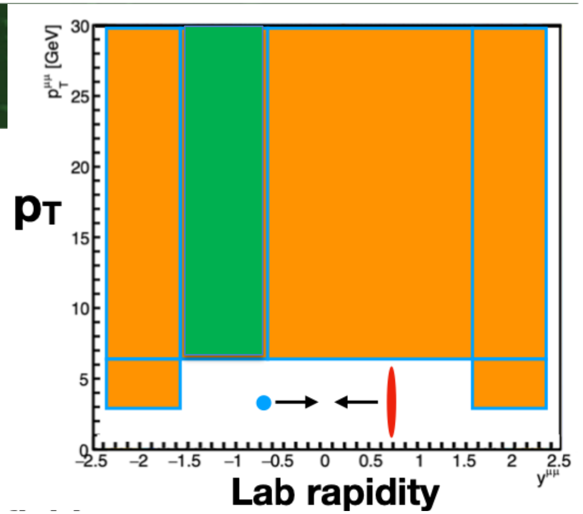


$$\text{Normalised } \sigma_{\psi(2S),n}/\sigma_{J/\psi,n} = \frac{\sigma_{\psi(2S),n}/\sigma_{J/\psi,n}}{\sum_n \sigma_{\psi(2S),n}/\sum_n \sigma_{J/\psi,n}}$$

- **Clear slope for prompt data**
- **No slope for nonprompt data**

Normalised ratio (Backward) High p_T





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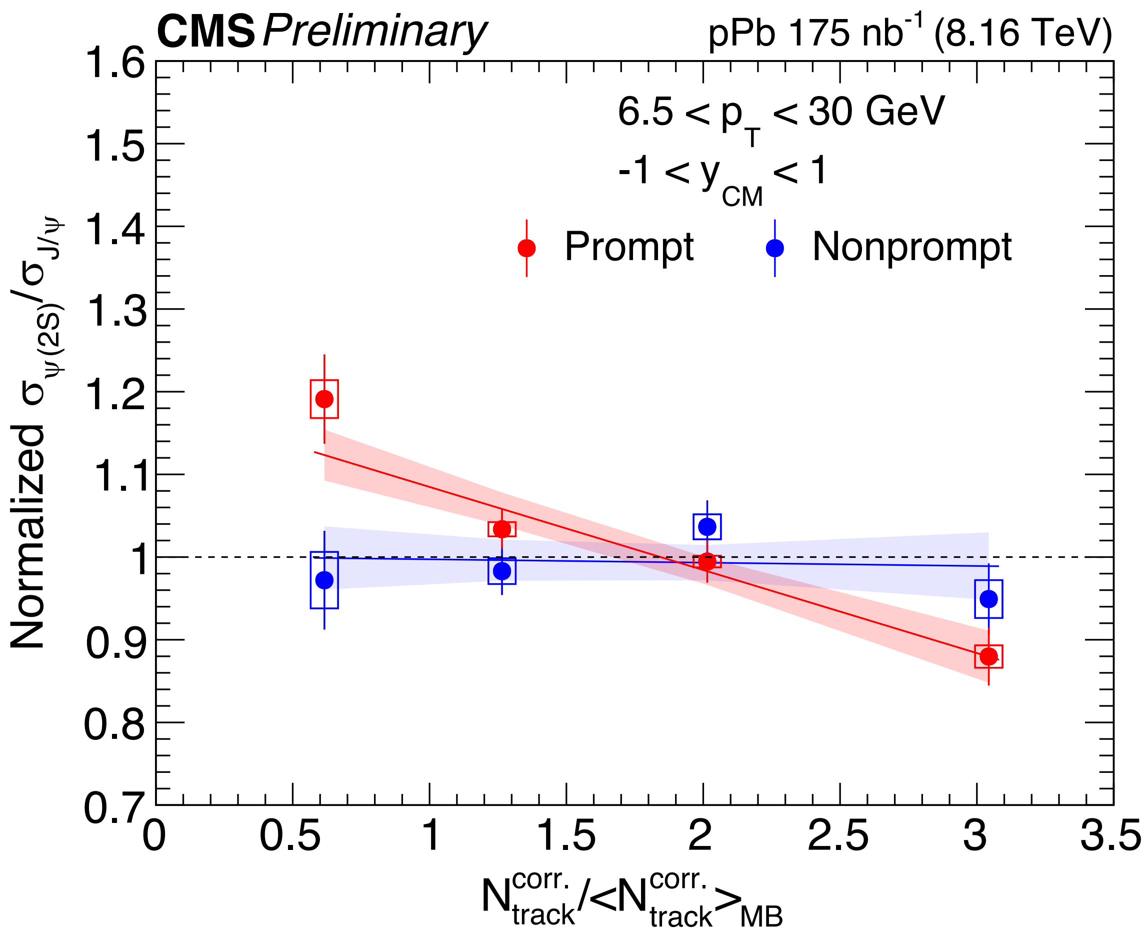
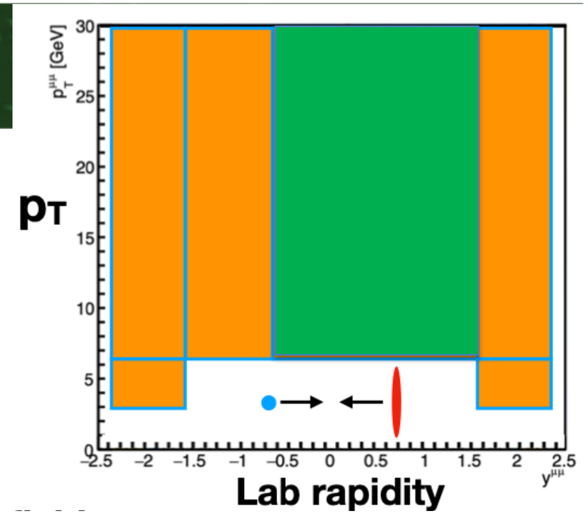
- **Clear slope for prompt data**
- **No slope for nonprompt data**

Normalised ratio (Mid-rapidity) High p_T





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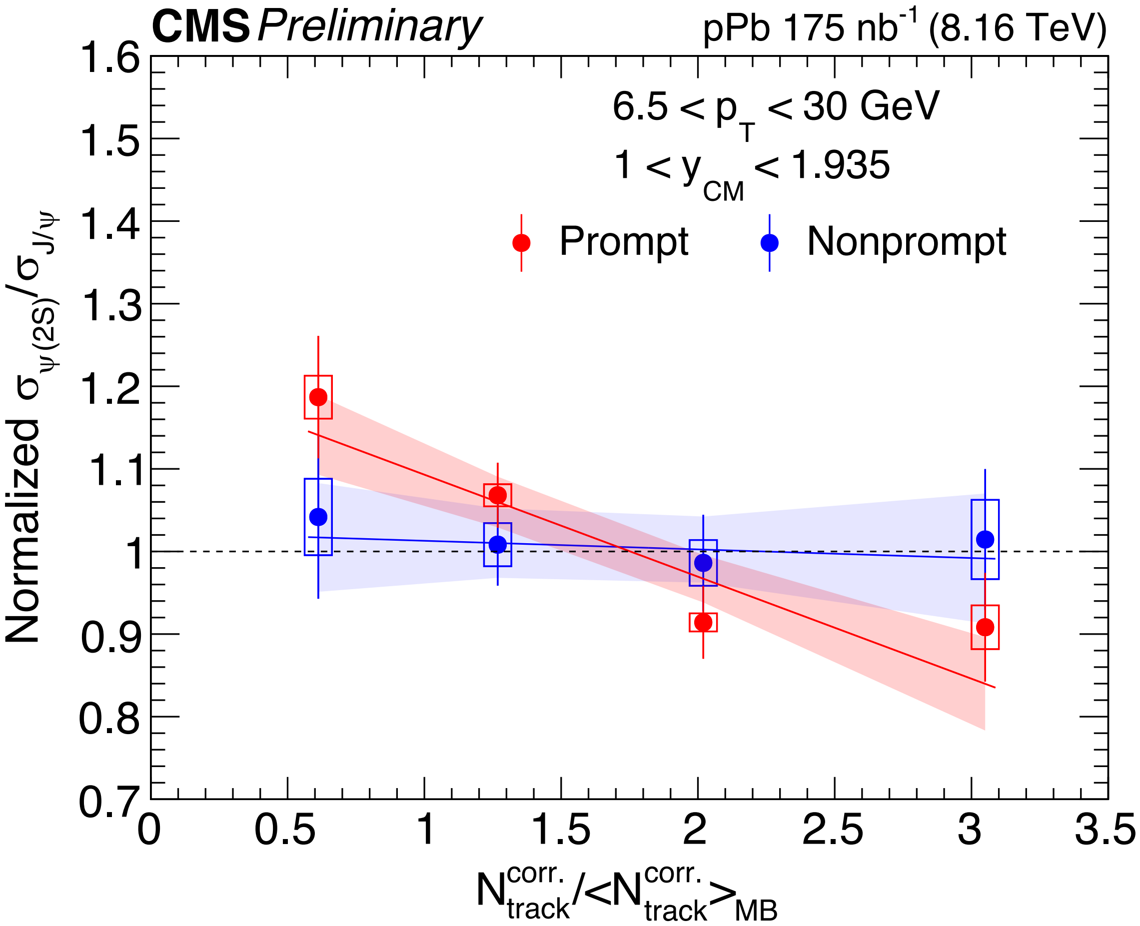
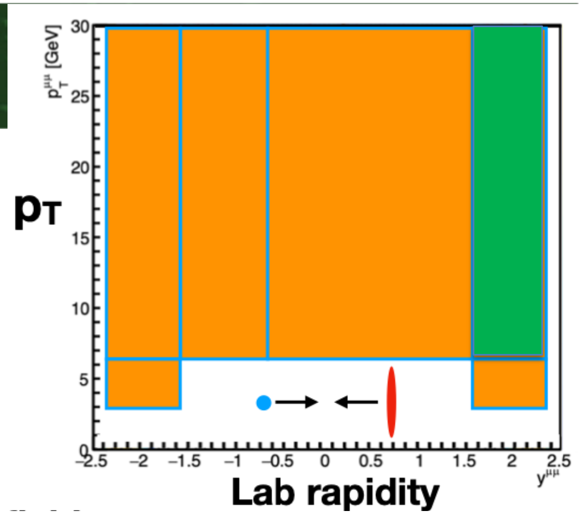
- **Clear slope for prompt data**
- **No slope for nonprompt data**

Normalised ratio (Forward) High p_T





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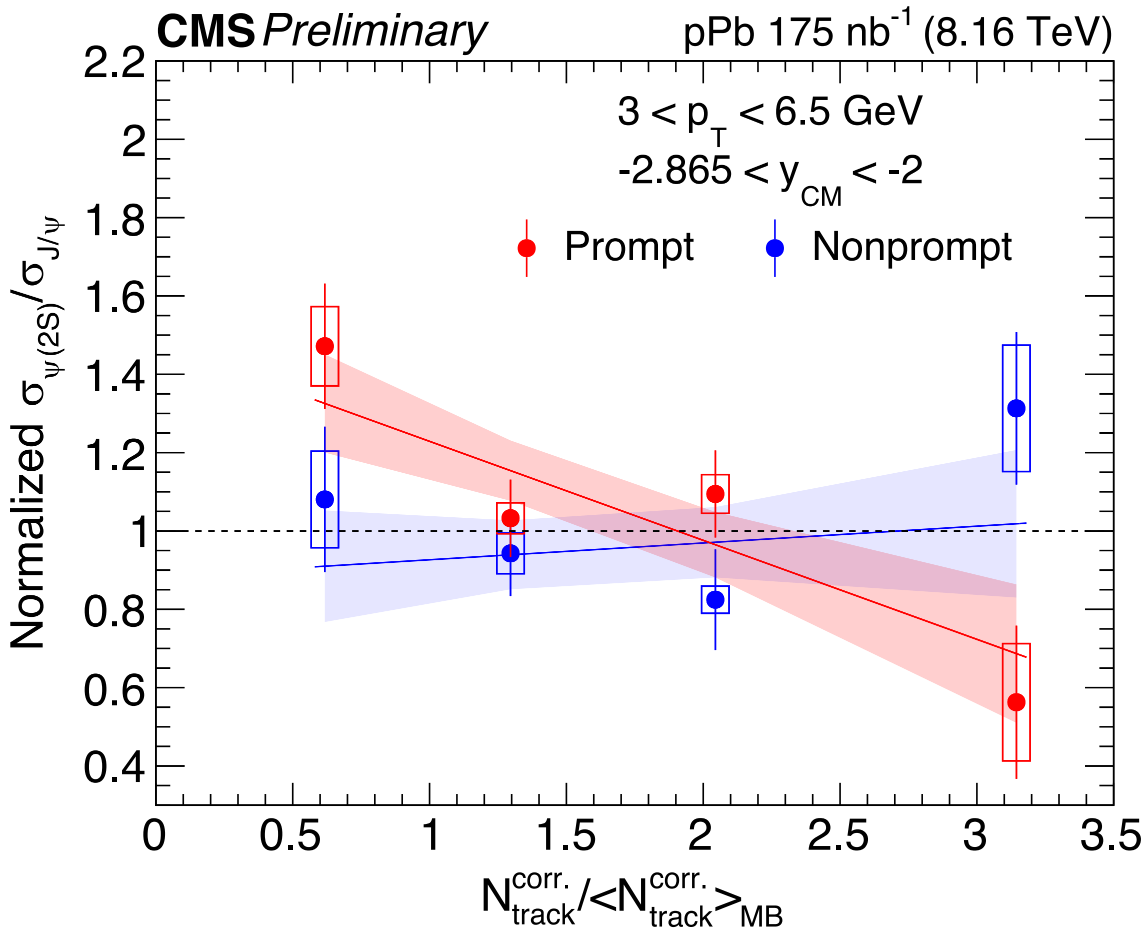
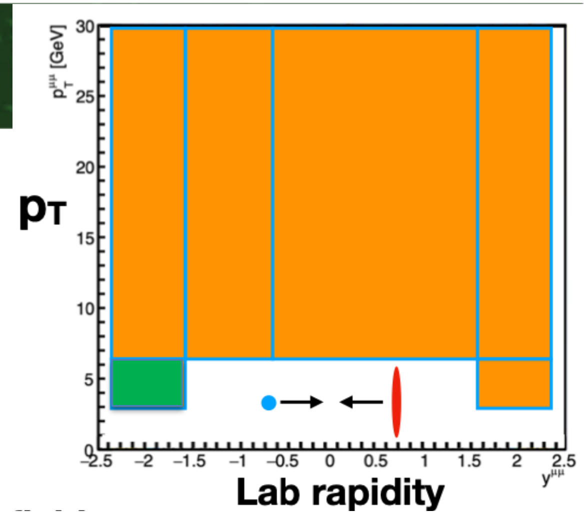
- **Clear slope for prompt data**
- **No slope for nonprompt data**

Normalised ratio (Far-backward) Low p_T





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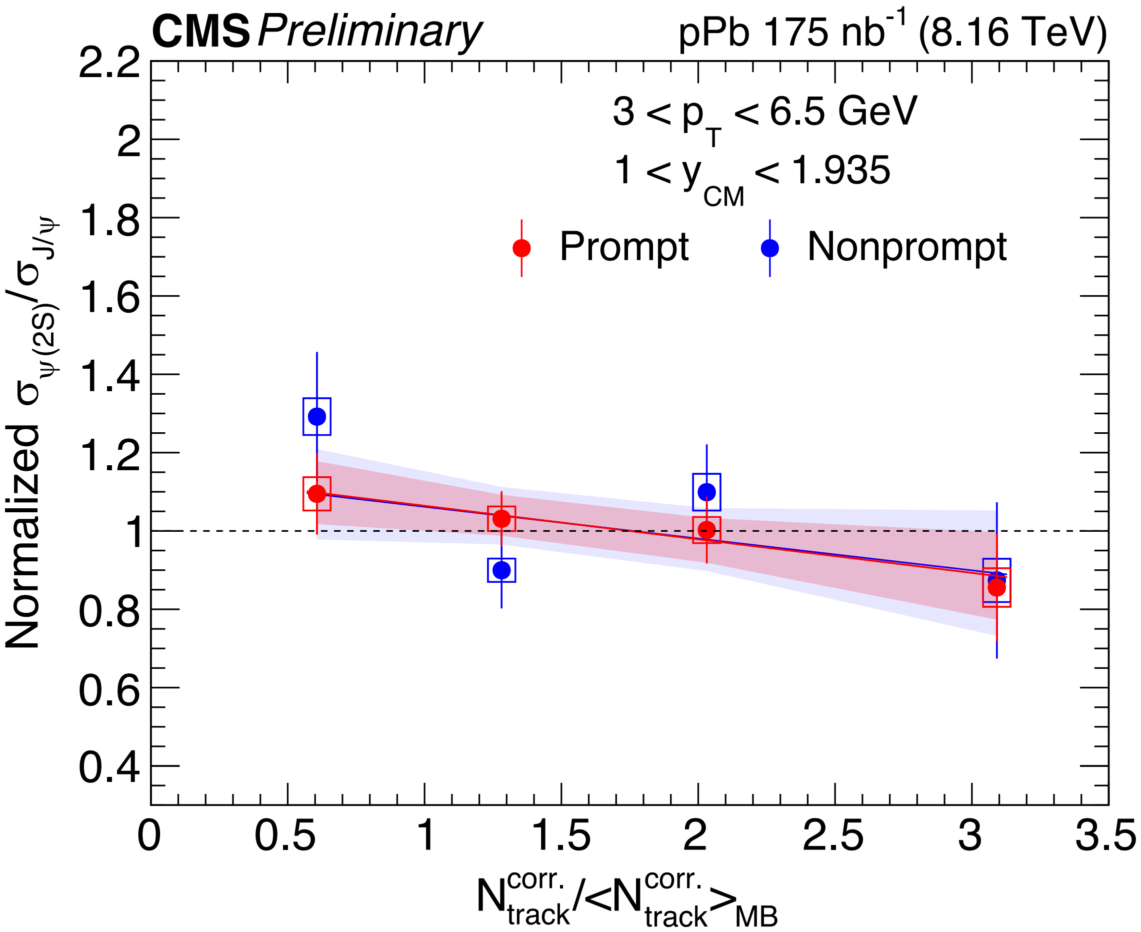
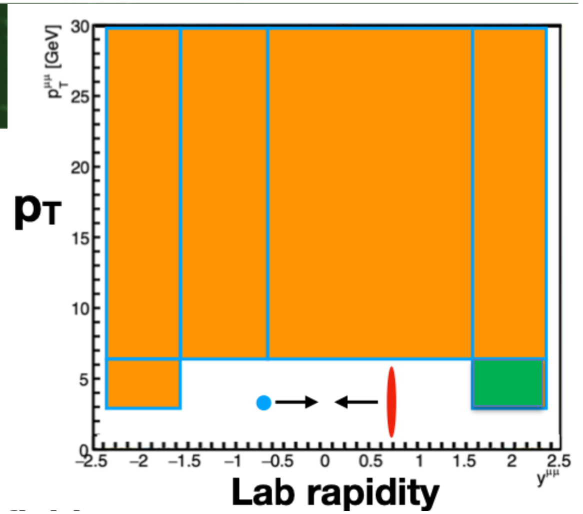
- **Clear slope for prompt data**
- **No slope for nonprompt data**

Normalised ratio (Forward) Low p_T





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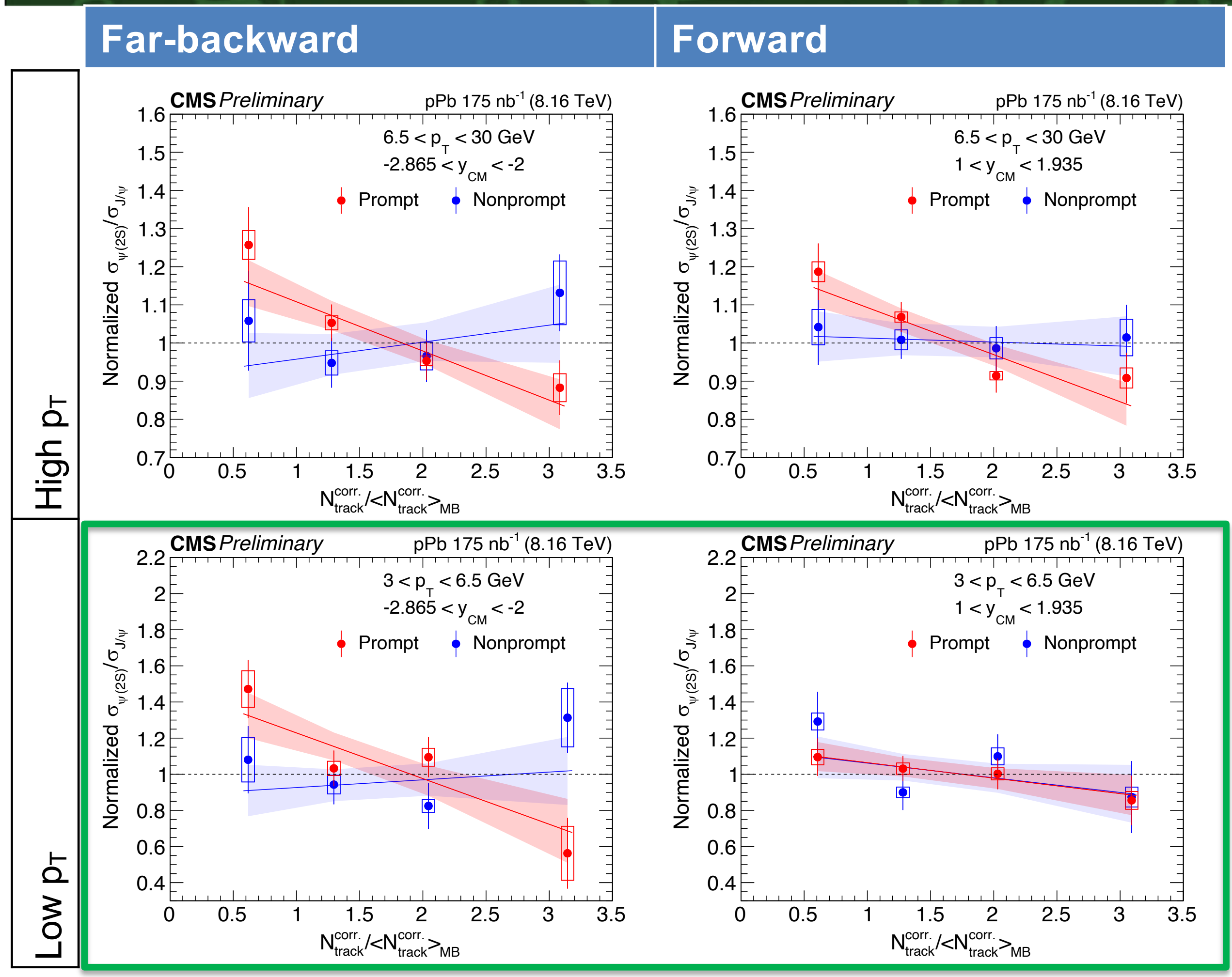
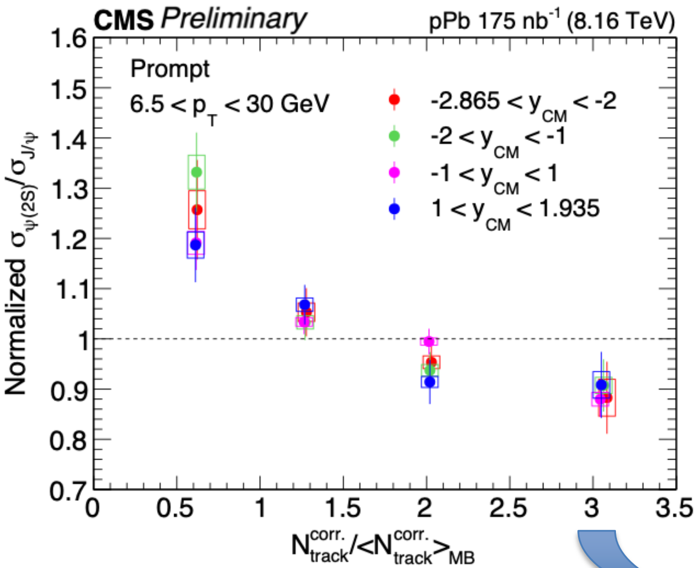
- **Clear slope for prompt data**
- **No slope for nonprompt data**

High p_T vs. Low p_T

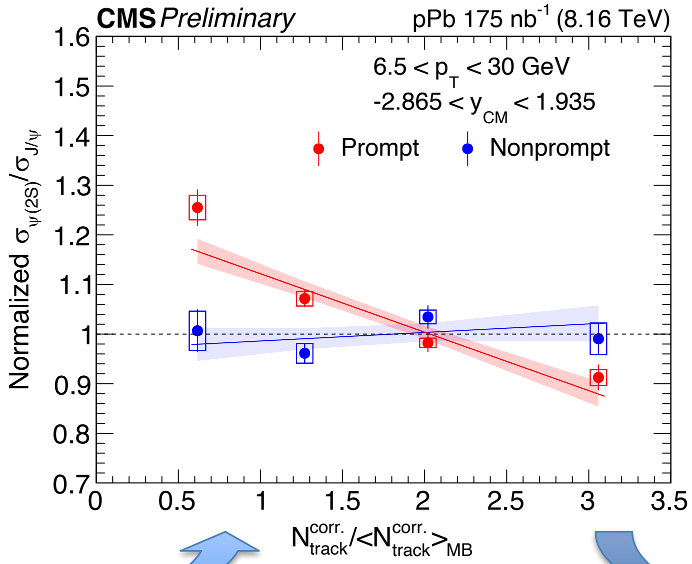


- **Hint of stronger dependence for prompt in Pb-going side than in p-going side**
  - Limited by statistical precision

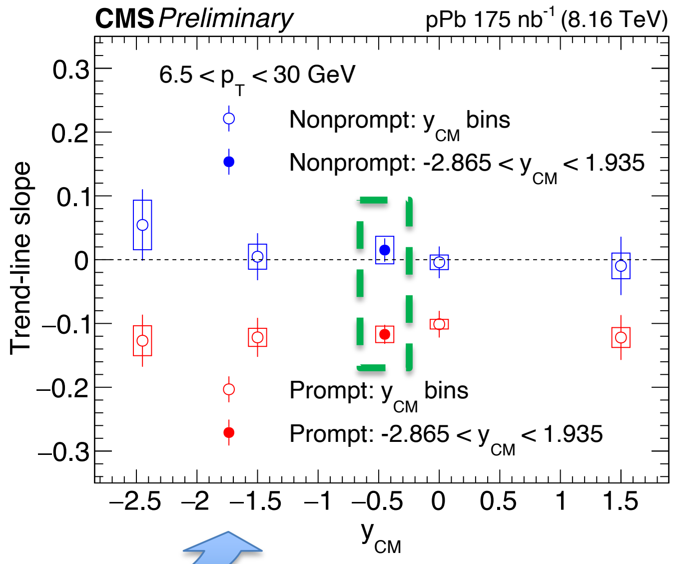
Combined high-p_T results



Dependence similar for all rapidities



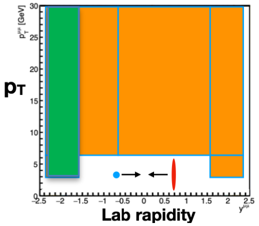
Combine all regions



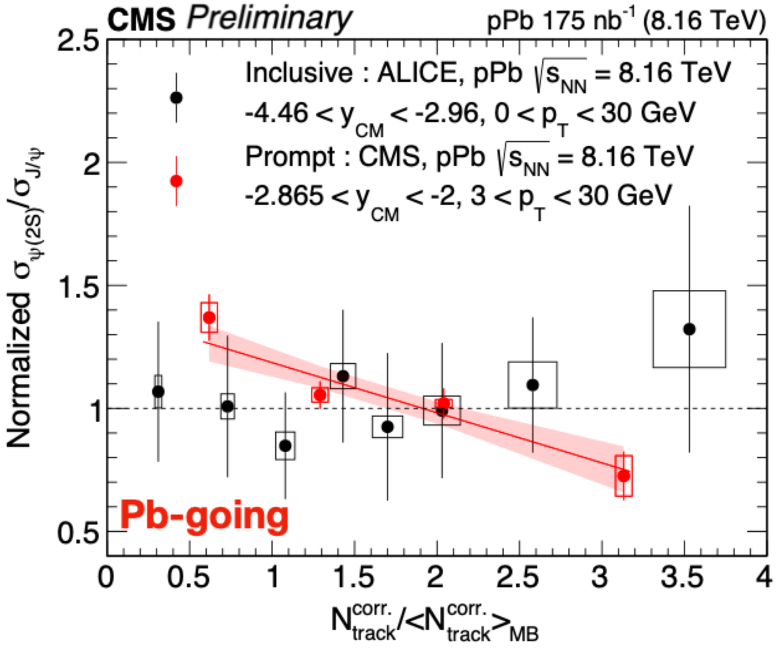
Add slope for inclusive y_{CM} bin

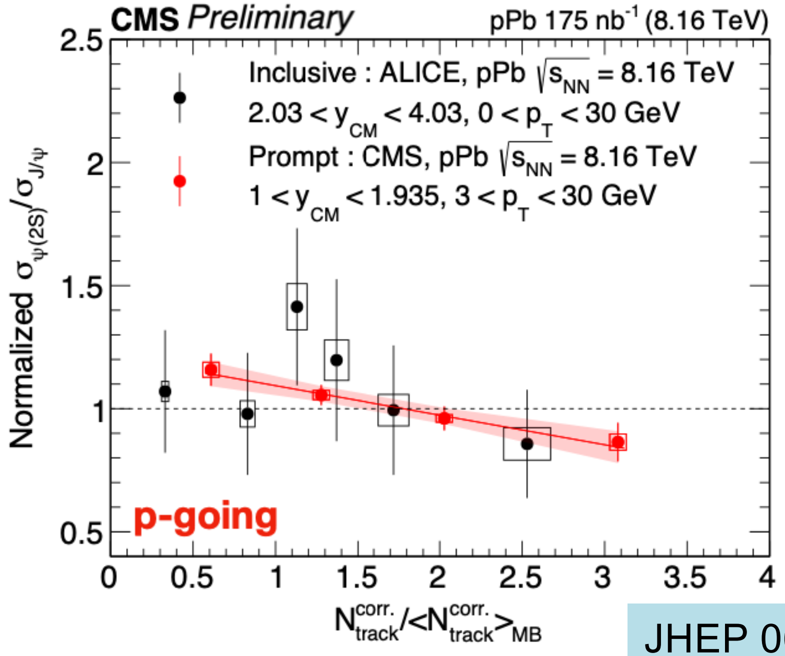
- **5.9σ deviation fron flat line for prompt**
- **Observation of multiplicity dependence of $\sigma_{\psi(2S)} / \sigma_{J/\psi}$ in pPb**
- **No clear rapidity dependence**
- **Nonprompt measurements consistent with zero**

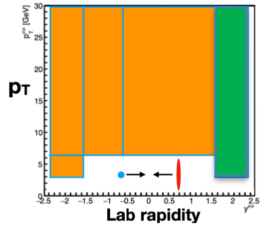
Comparison to ALICE results



Far-backward







Forward

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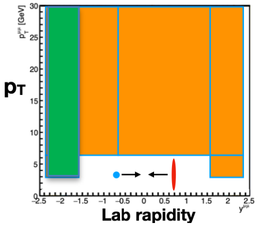
- **CMS prompt data vs. ALICE inclusive data (prompt + nonprompt)**
- **y_{CM} and p_T ranges slightly different but results are consistent within uncertainties**

Comparison to theory



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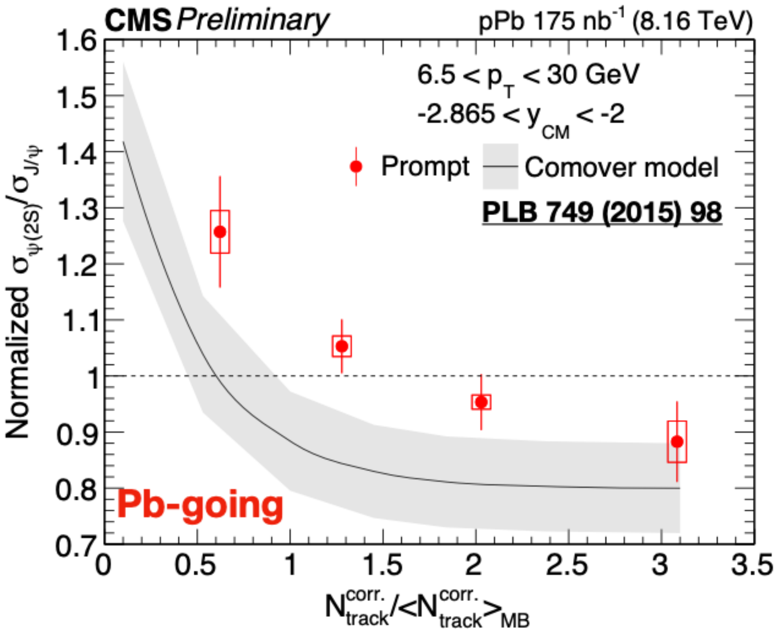
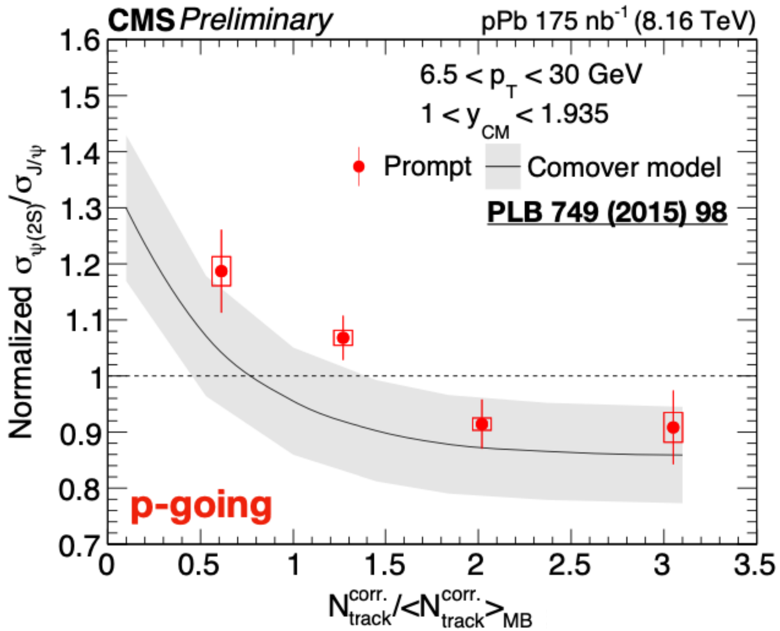
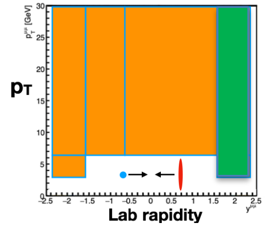




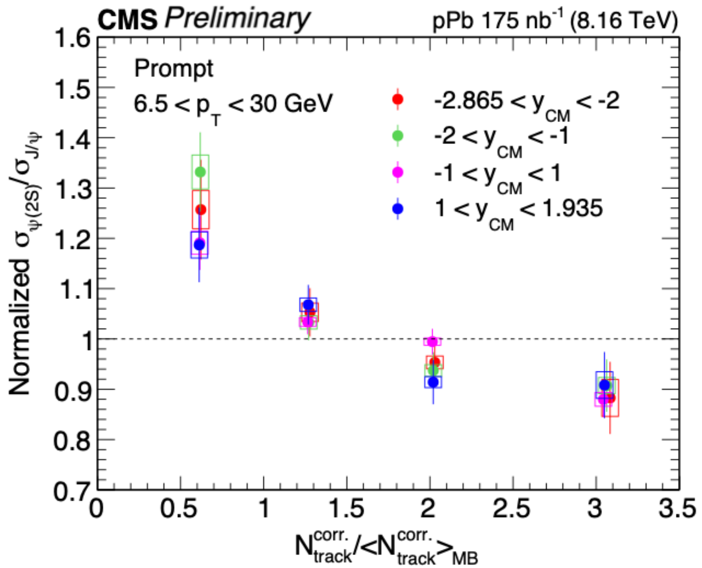


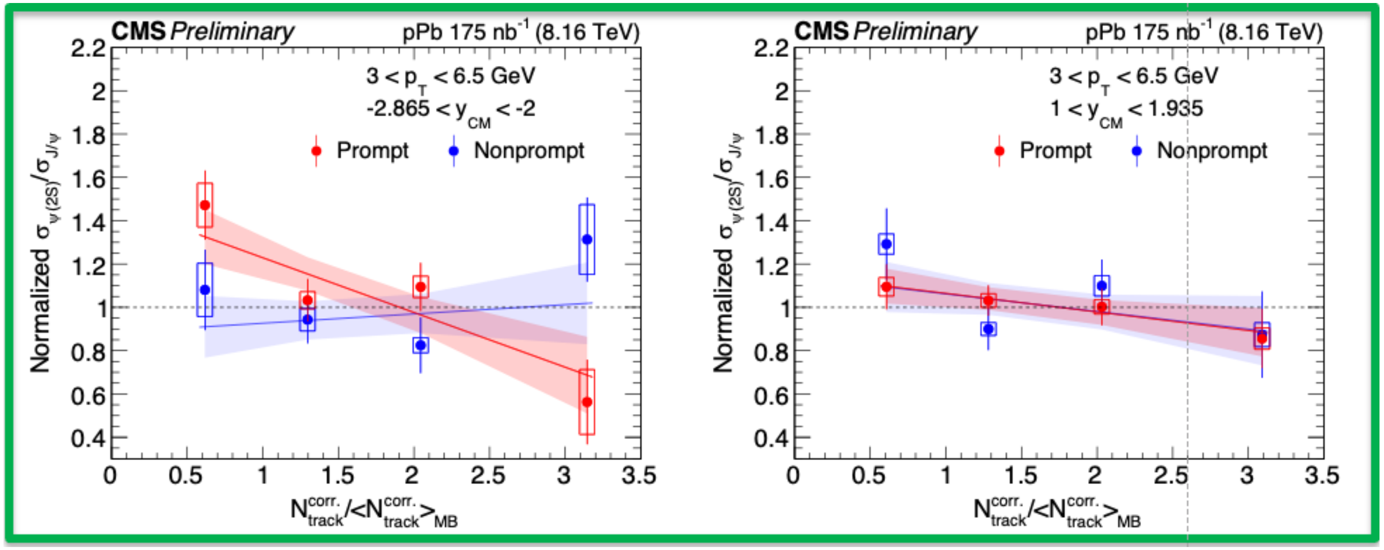
Forward

- **Comparison to model including comover interactions**
- **Reasonable agreement in p-going side**
- **Less suppression in Pb-going side compared to model**

Partial summary

- First observation of multiplicity-dependence of prompt $\sigma_{\psi(2S)} / \sigma_{J/\psi}$ in pPb
- Nonprompt ratio consistent with unity
- Hint of rapidity dependence at lower p_T
- Supports picture where suppression increases with comover density
- Data constrain hadronization models of charm hadrons in small systems



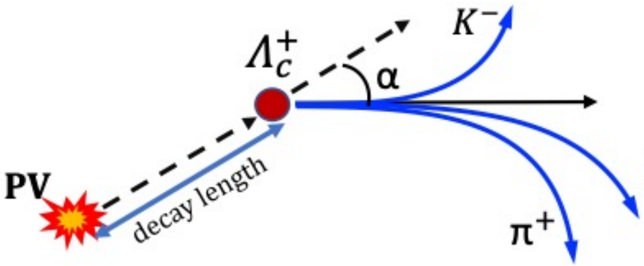


Several results for quarkonia and Heavy flavors

Reconstruction of Λ_c (lambda c) and D^0

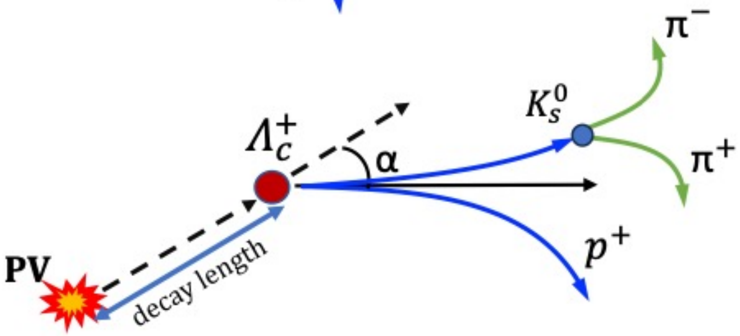
- ❖ Λ_c^+ reconstruction
  - ➢ $\Lambda_c^+ \to p^+K^-\pi^+$ (BR ~ 6.23%)

    $p\overline{K^*}(892) \to pK^-\pi^+$ 1.31%
    $\Delta^{++}K^- \to pK^-\pi^+$ 1.08%
    $\Lambda(1520)\pi^+ \to pK^-\pi^+$ 0.49%
    Non resonance = 3.5%

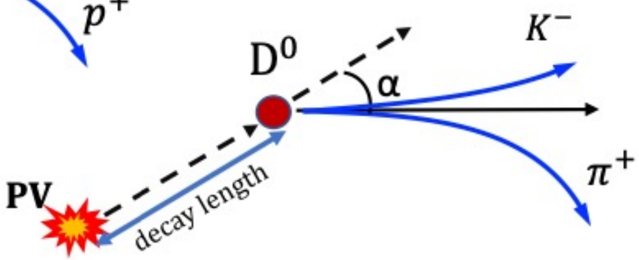


- ❖ PID (dE/dx) used for proton identification for Λ_c^+ in pPb

- ❖ Λ_c^+ reconstruction (pPb)
  - ➢ $\Lambda_c^+ \to K_S^0 p$ (BR ~ 1.59%)
    - ➢ $K_S^0 \to \pi^+\pi^-$ (BR ~ 69.20%)

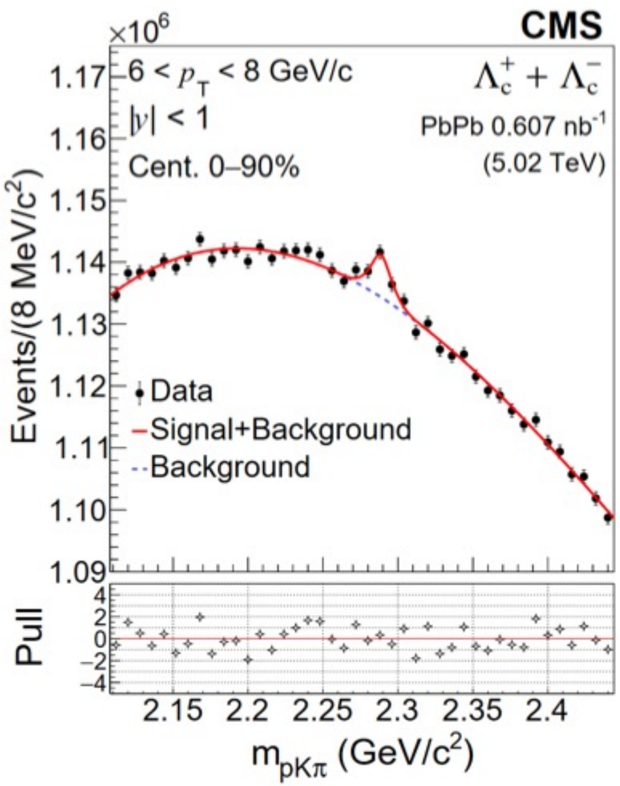


- ❖ D^0 reconstruction
  - ➢ $D^0 \to K^-\pi^+$ (BR ~ 3.94%)

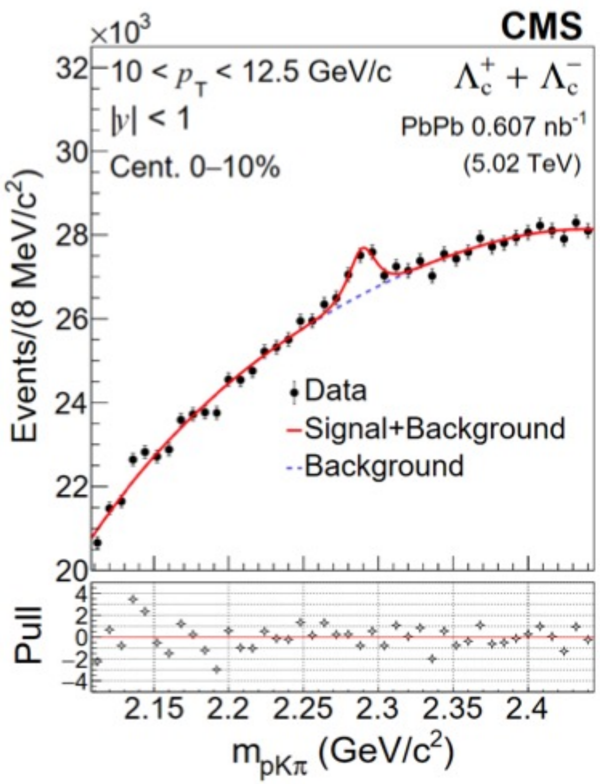


- ❖ All possible combinations of three (two) charged tracks in an event are considered for pp and PbPb

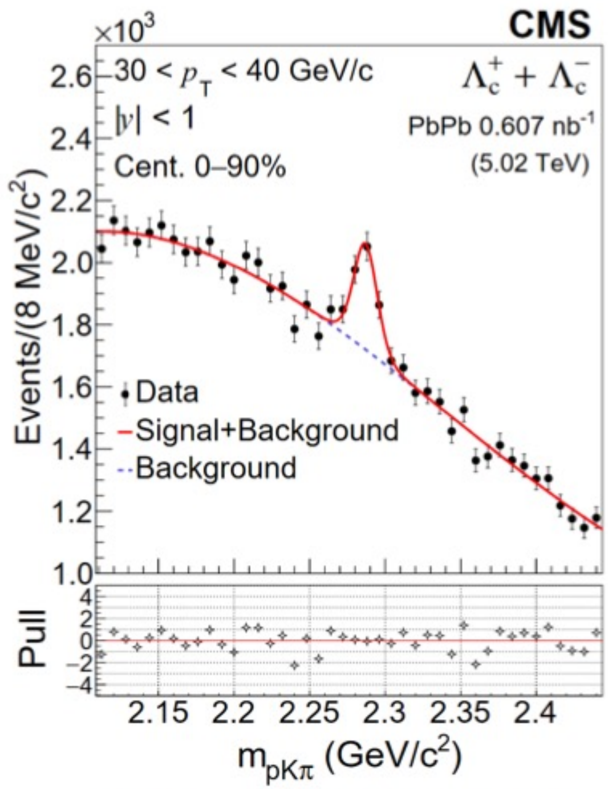
Mass distribution of Λ_c in PbPb



Low p_T in PbPb (0-90%)



Low p_T in PbPb (0-10%)



High p_T in PbPb (0-90%)

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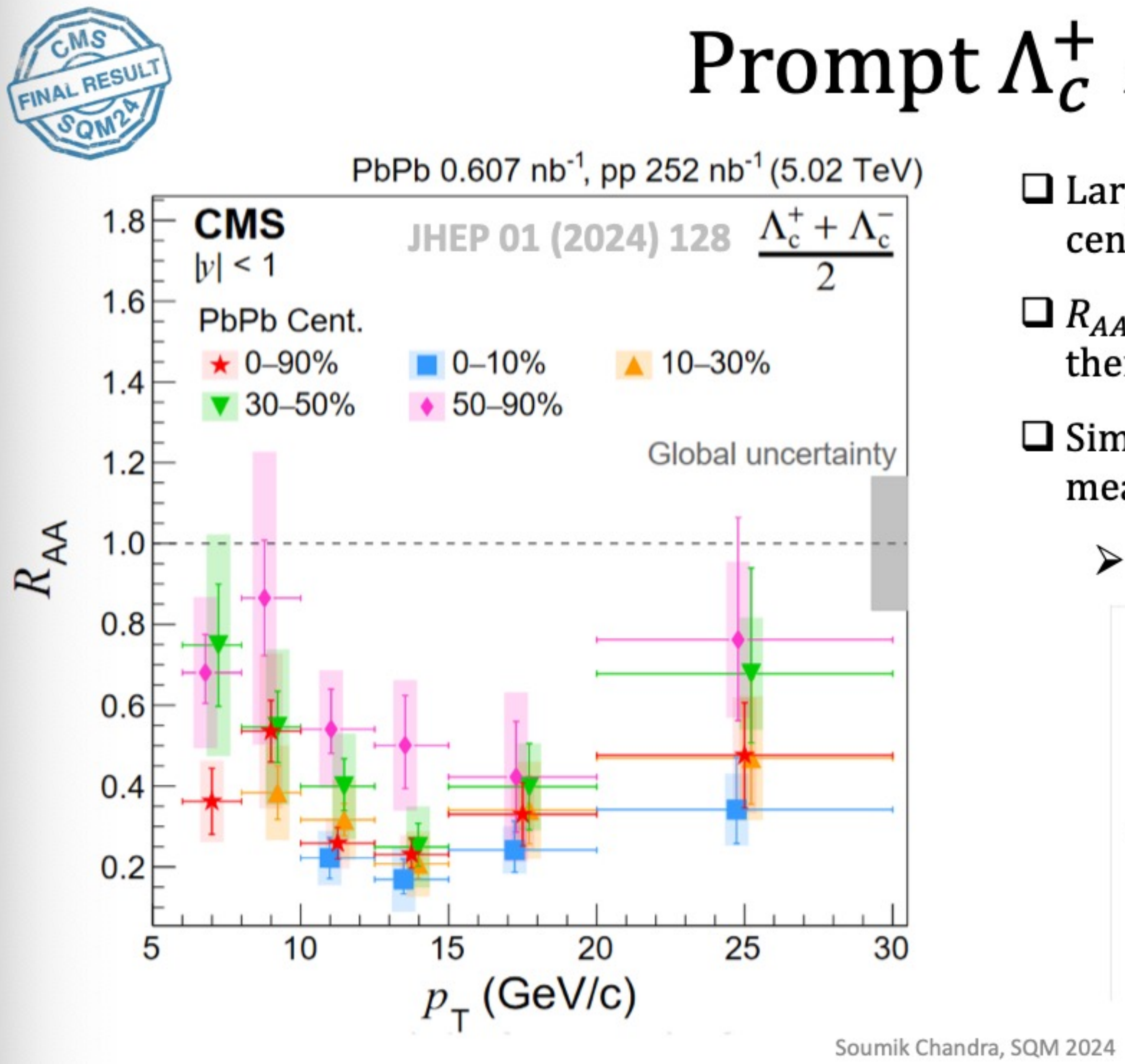
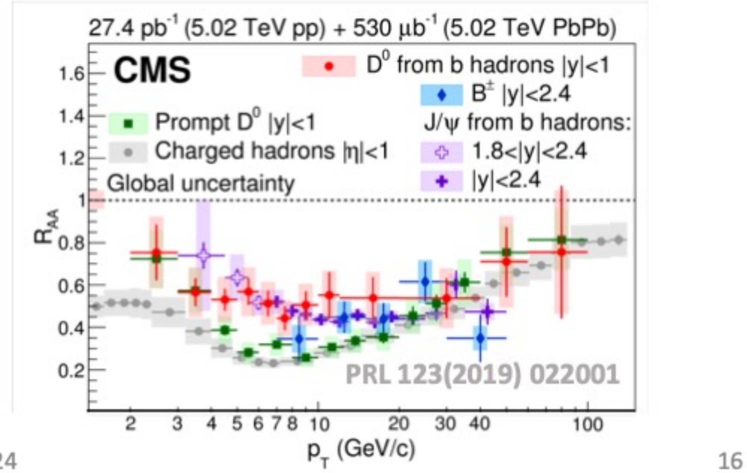
Prompt Λ_c^+ R_{AA}

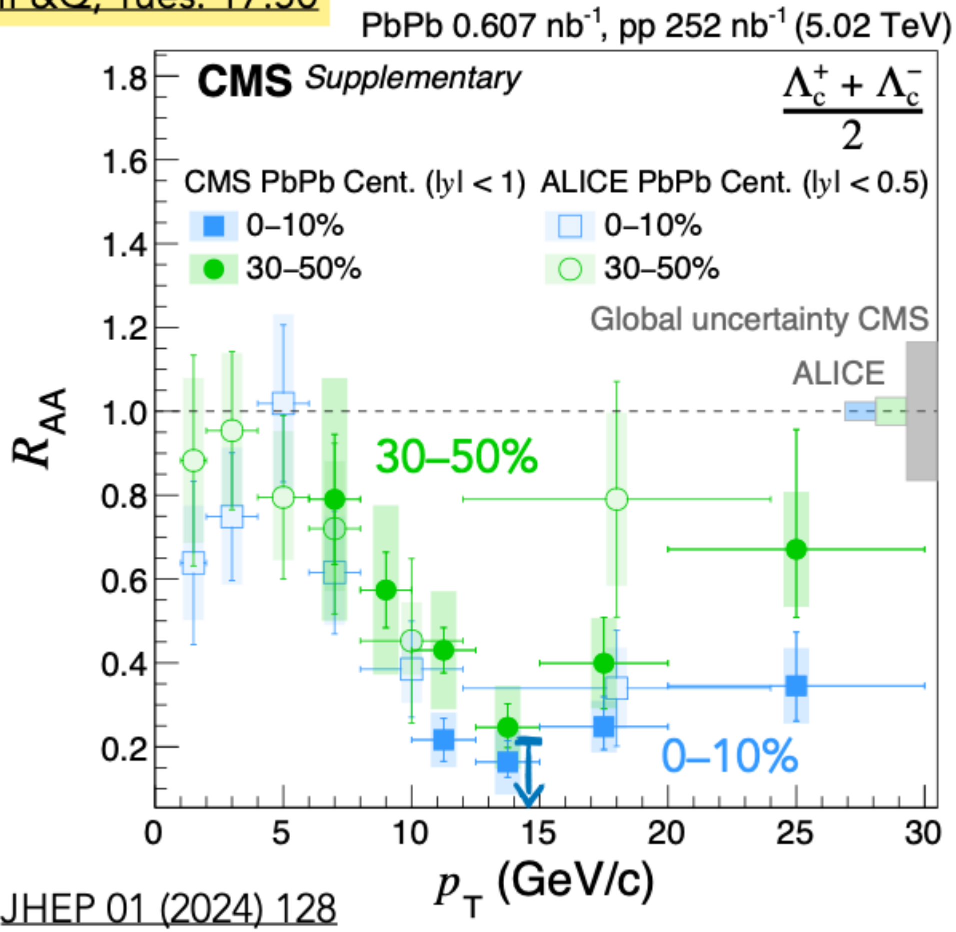


- ❑ Larger suppression of Λ_c^+ production for central PbPb collisions
- ❑ R_{AA} decreases from low p_T up to ~14 GeV/c, then increases for higher p_T
- ❑ Similar trend to other heavy flavor measurements. but larger than D^0
  - ➢ D^0 R_{AA} minimum at p_T ~ 9 GeV/c



Prompt Λ_c^+ R_{AA}

Soumik Chandra
HF&Q, Tues. 17:50



JHEP 01 (2024) 128

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- R_{AA} decreases from low p_T up to ~14 GeV/c, then increases for higher p_T
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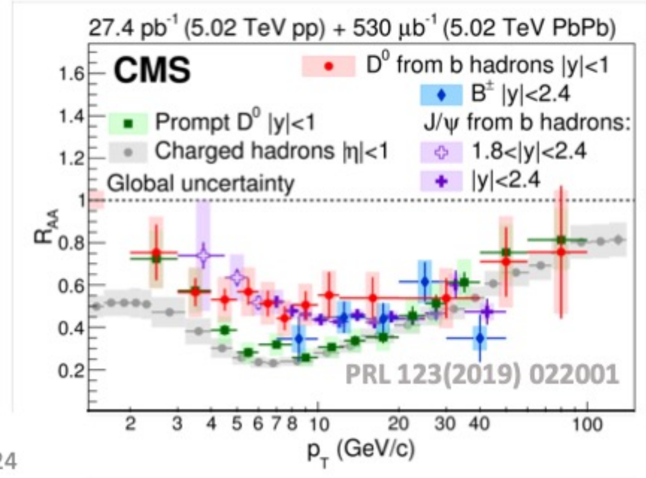
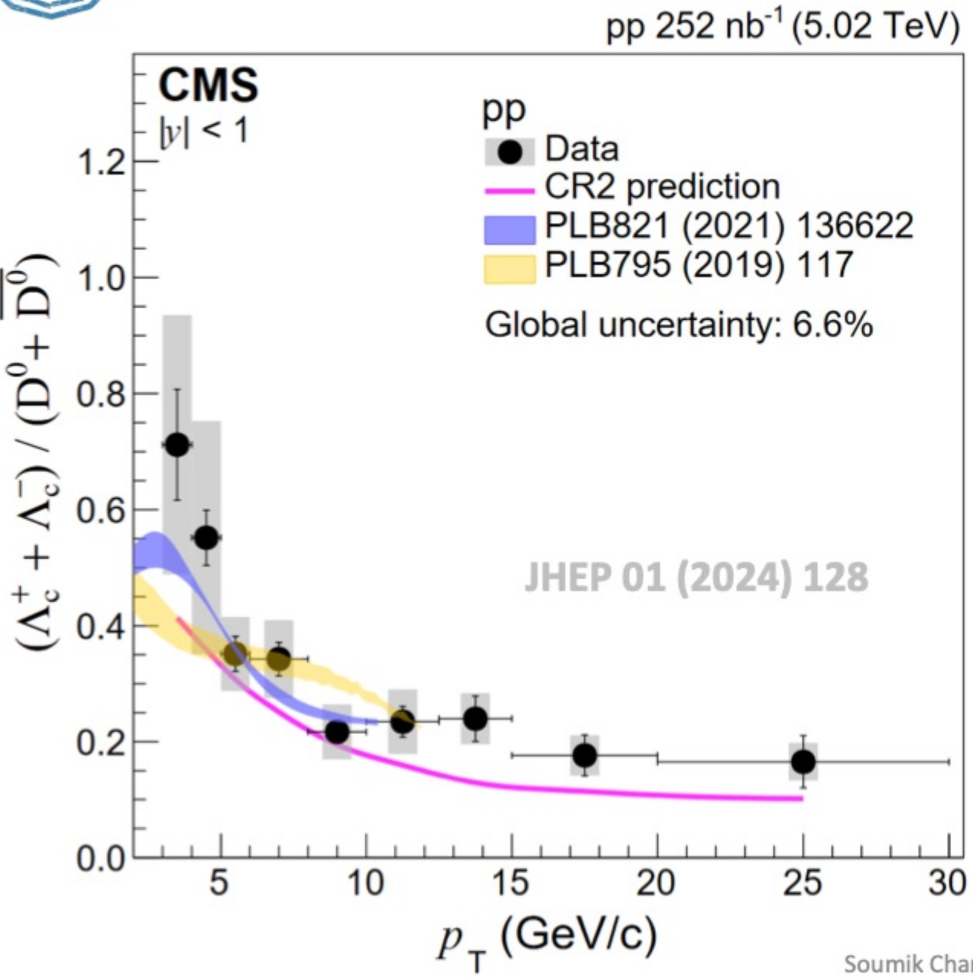
  - D^0 R_{AA} minimum at $p_T \sim 9$ GeV/c



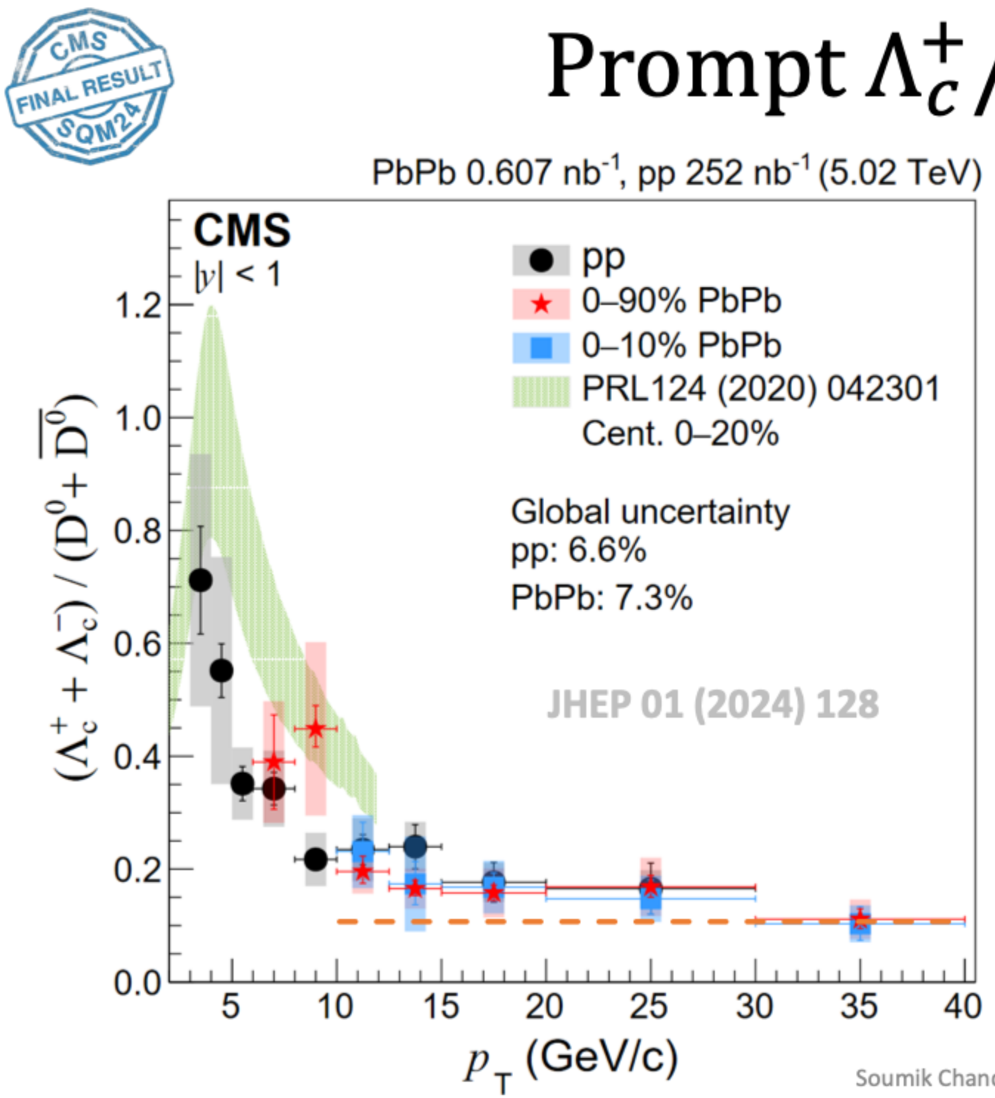
Prompt Λ_c^+/D^0 in pp



- PYTHIA8+CR2 predictions consistent with pp data for $p_T < 10$ GeV/c, systematically lower for p_T range 10-30 GeV/c.
- Catania model including both coalescence and fragmentation consistent with data for $p_T < 10$ GeV/c.
- TAMU model using statistical hadronization approach and including excited charmed baryon states beyond the PDG describes the data reasonably

Soumik Chandra, SQM 2024 19

Prompt Λ_c^+/D^0 in PbPb



ucd / uc

- Λ_c^+/D^0 ratio for PbPb is consistent with pp data for $p_T > 10$ GeV/c.
  - Coalescence process does not play a significant role for high p_T
- Model for PbPb collisions (0-20% centrality) consistent with data for p_T 10-12.5 GeV/c
  - Four-momentum conserving recombination mechanisms
  - Excited charm baryon states beyond PDG.
- Ratio consistent with e^+e^- for higher p_T region

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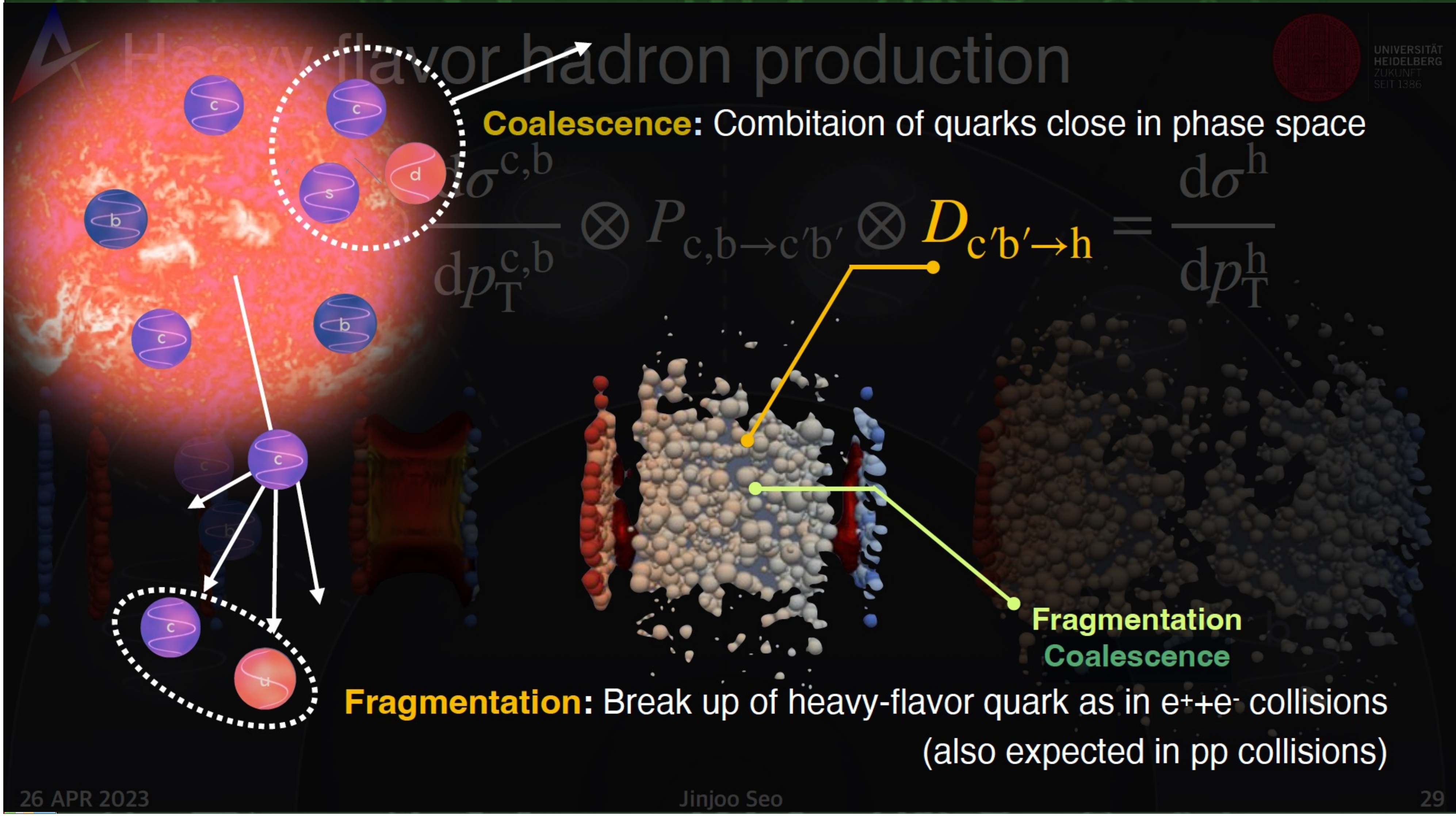
No significant contribution from coalescence

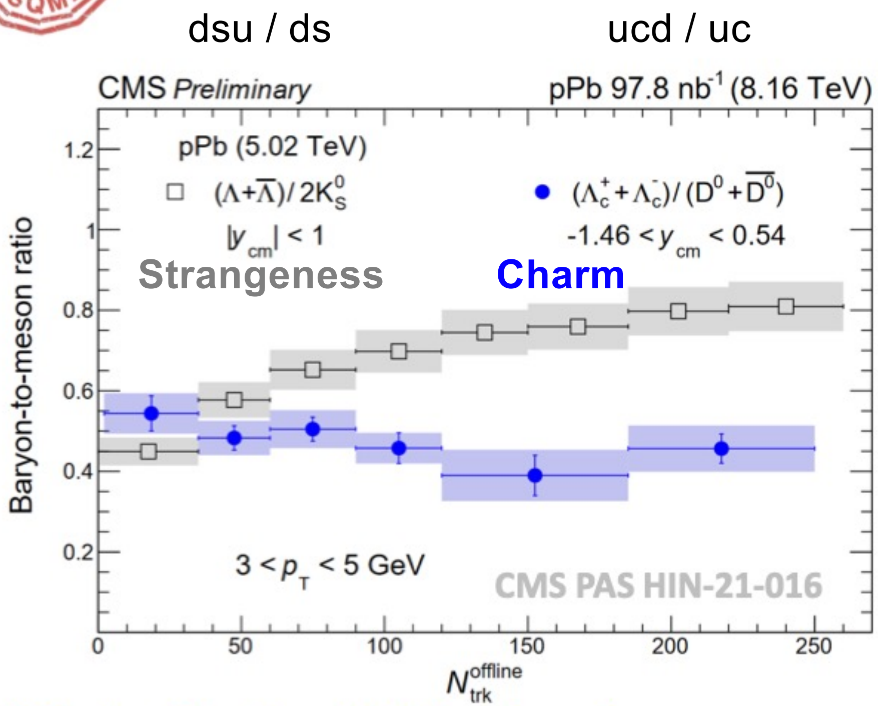
21

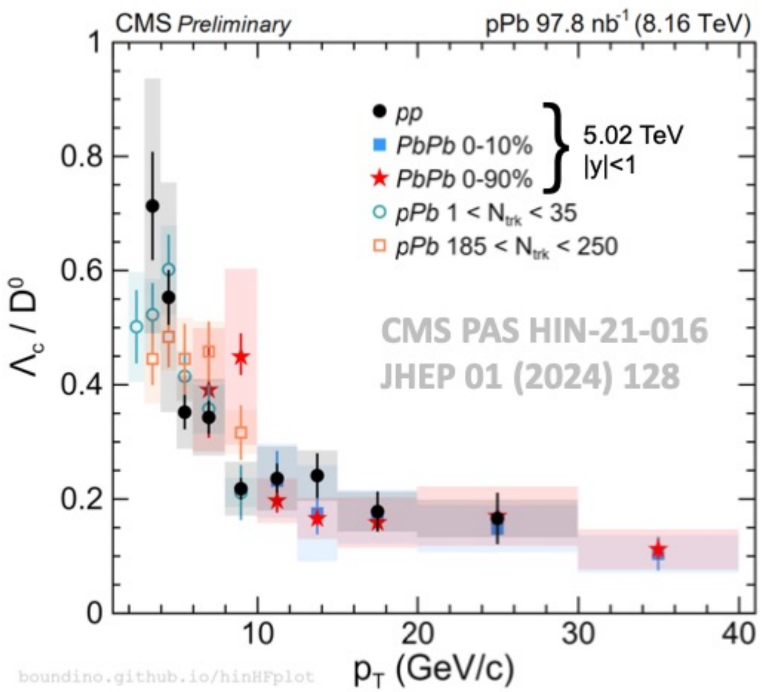
Coalescence? Fragmentation?



Jinjoo Seo's slide

Prompt Λ_c^+/D^0 ratio in pPb





- No significant multiplicity dependence
  - Differs from strange quark trend
- Coalescence process saturates early for charm quark with multiplicity

- Λ_c^+/D^0 ratio decreases with increasing p_T
- Consistent with pp and PbPb results

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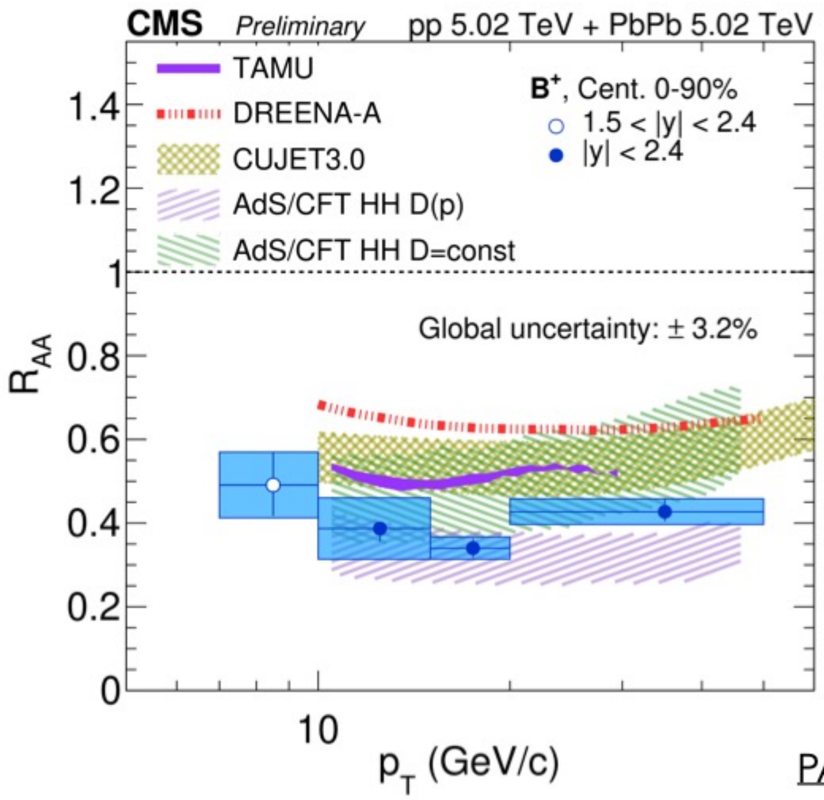
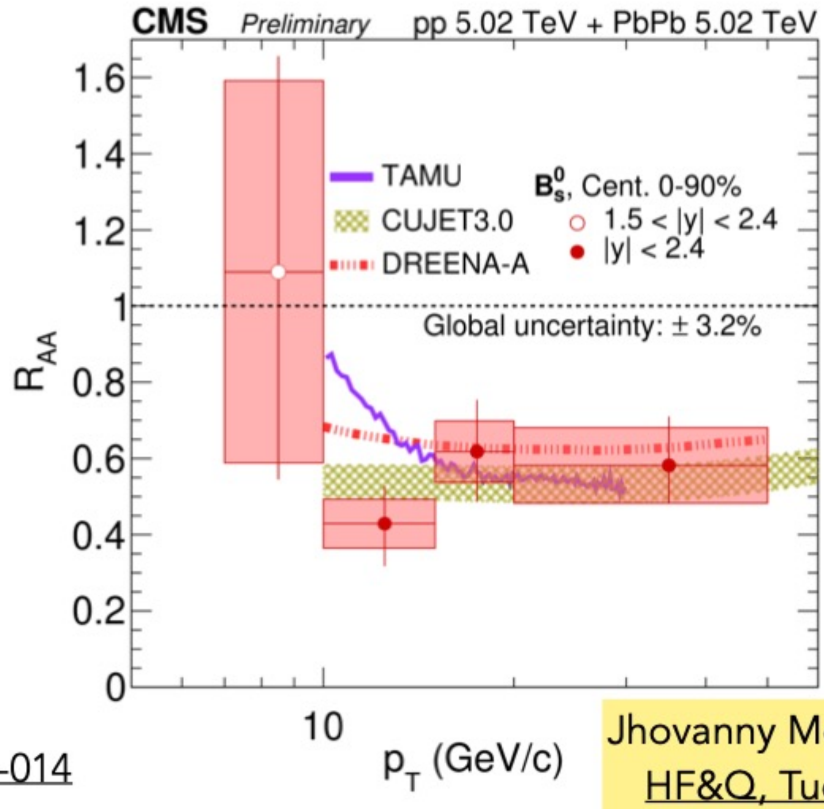
In-medium energy loss of beauty quarks

Updated B^+ measurement more precise than calculations uncertainties at high p_T



PAS HIN-21-014

Updated B_s measurement consistent with different model approaches



Jhovanny Mejia Guisao
HF&Q, Tues. 09:50

Energy loss : Beauty vs. Lighter flavors

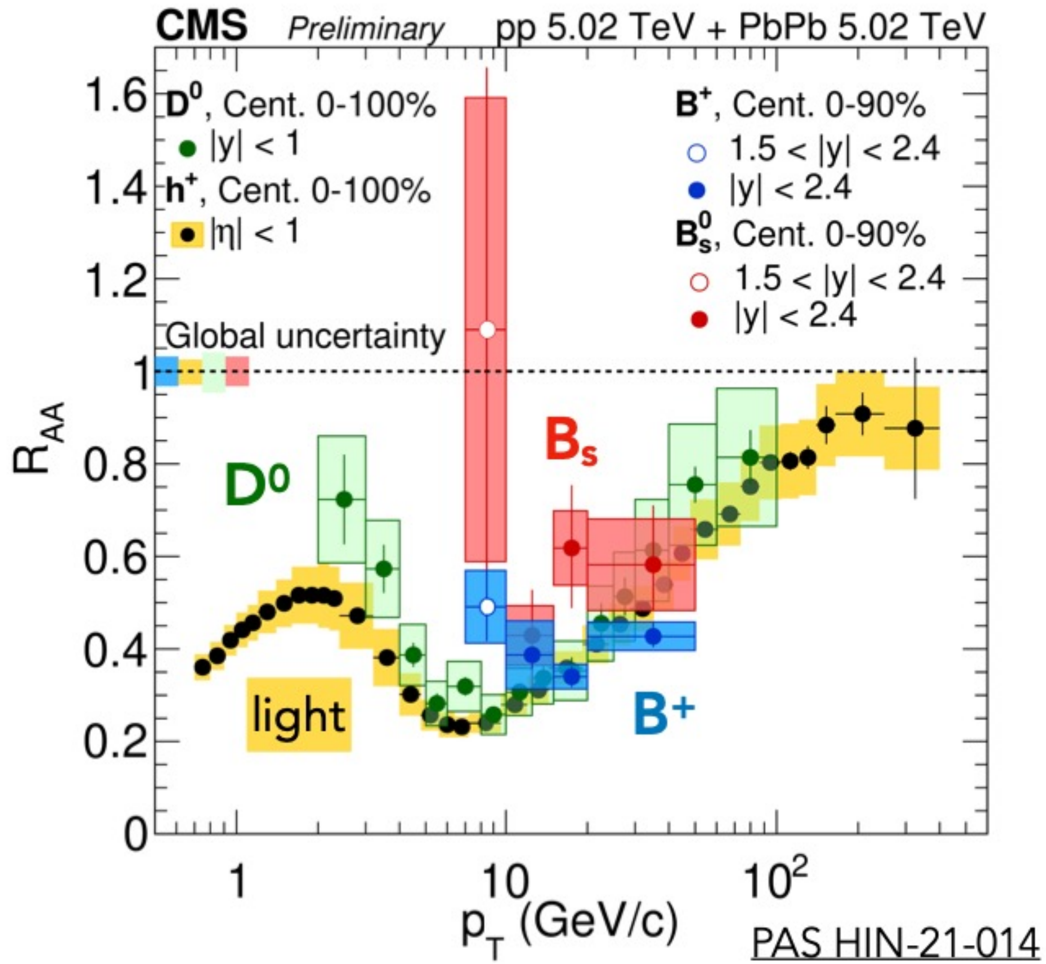
Suppression of B^+ and B_s similar to lighter hadrons at high p_T

☛ mass/flavor-dependence of parton energy loss

R_{AA} of fully-reconstructed hadrons from light to beauty flavor from CMS

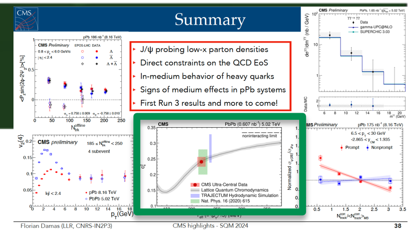
Jhovanny Mejia Guisao

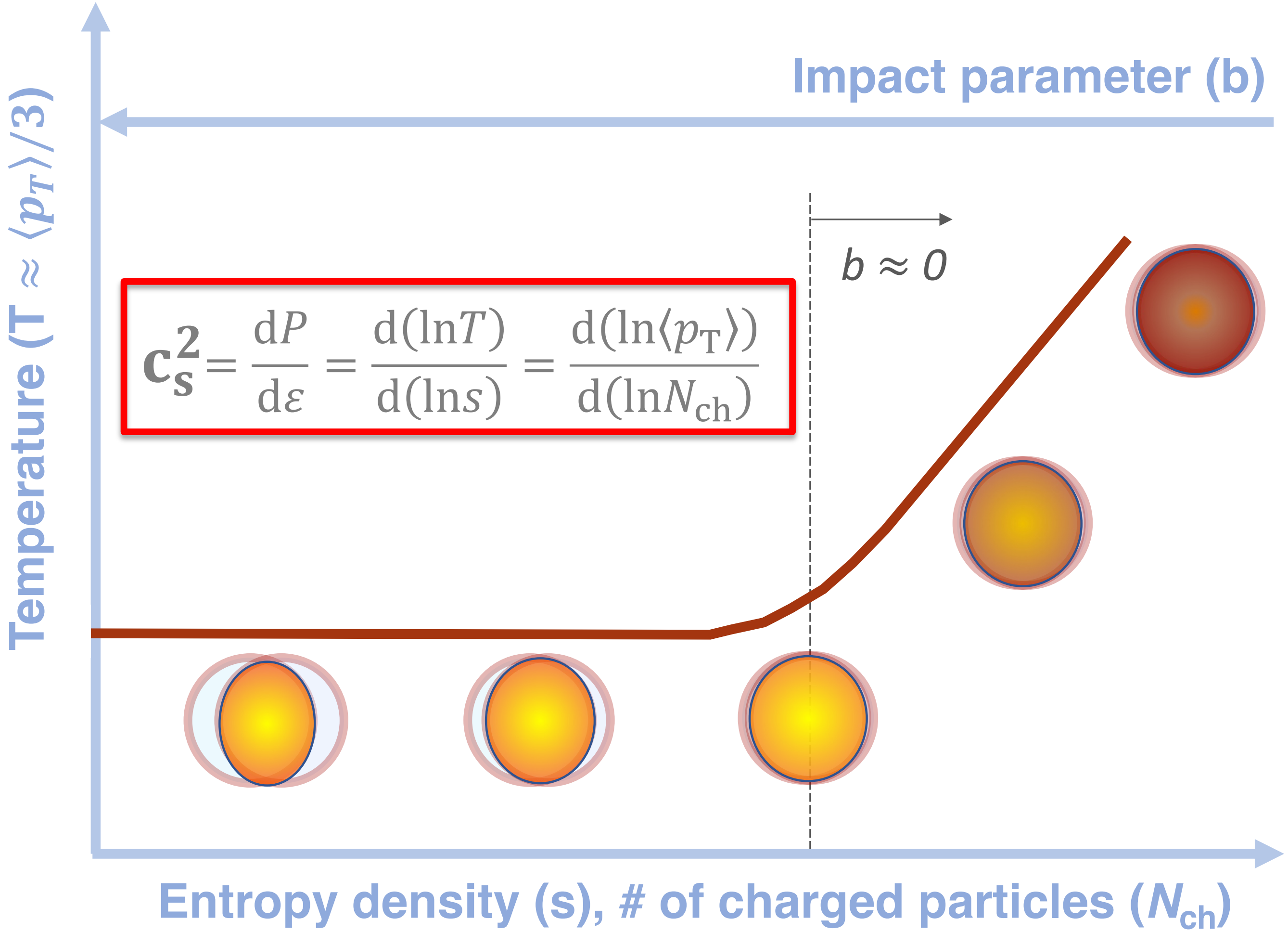
HF&Q, Tues. 09:50



Measuring the speed of sound in the QGP with CMS

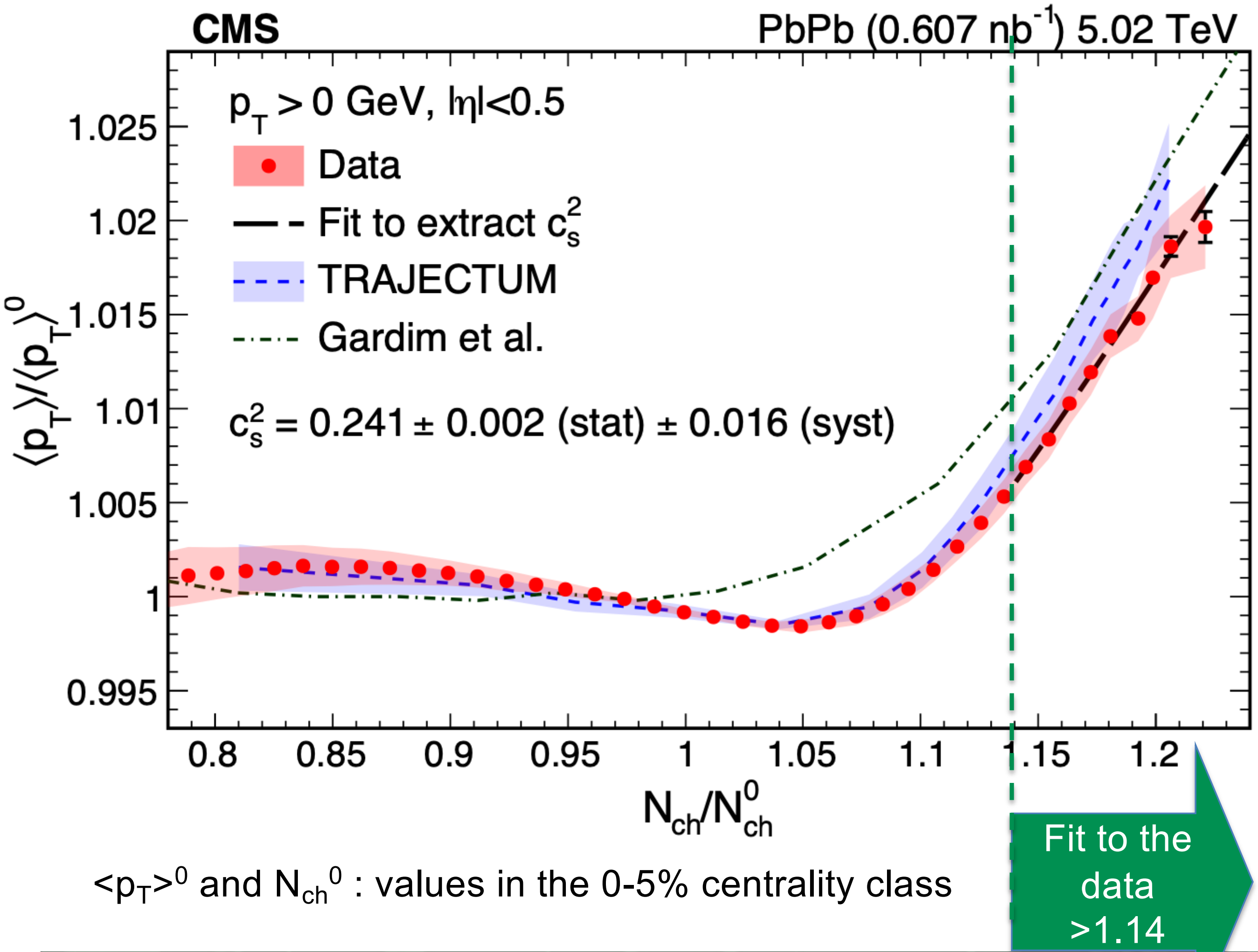
Measuring the speed of sound in the QGP with CMS



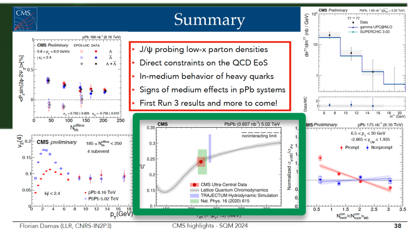


- **Speed of sound depends on relation of pressure to energy density**
  - Sound travels faster in stiffer materials
- **C_s is measured by the multiplicity and p_T**

Measuring the speed of sound in the QGP with CMS

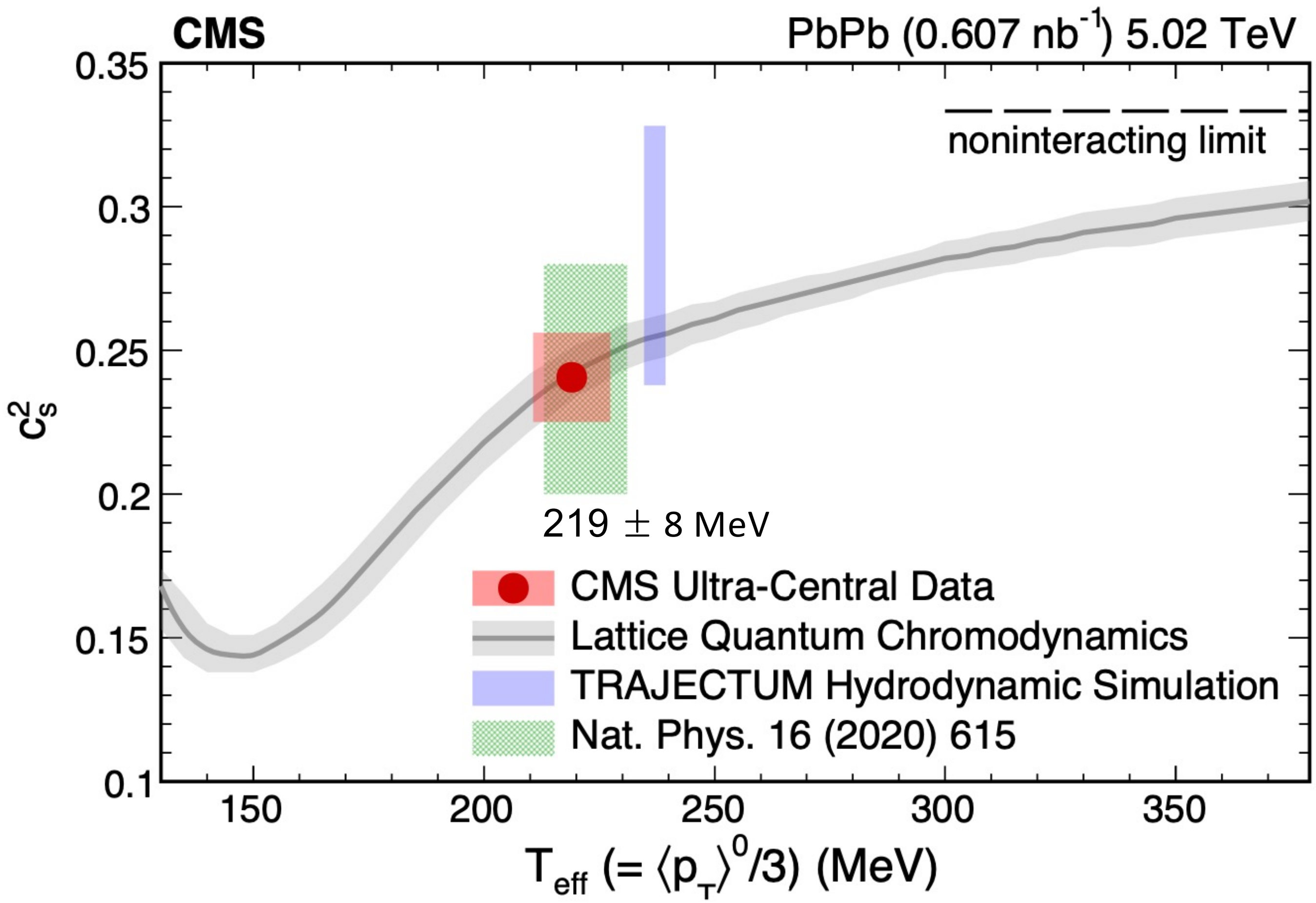


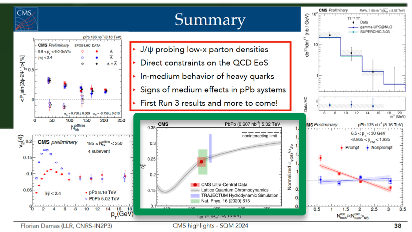
$\langle p_T \rangle^0$ and N_{ch}^0 : values in the 0-5% centrality class



- **Correlation between average p_T of charged particles and charged-particle multiplicity**
- **Steep rising trend matching the hydrodynamic model predictions (TRAJECTUM, By Gardim et al.)**

Measuring the speed of sound in the QGP with CMS





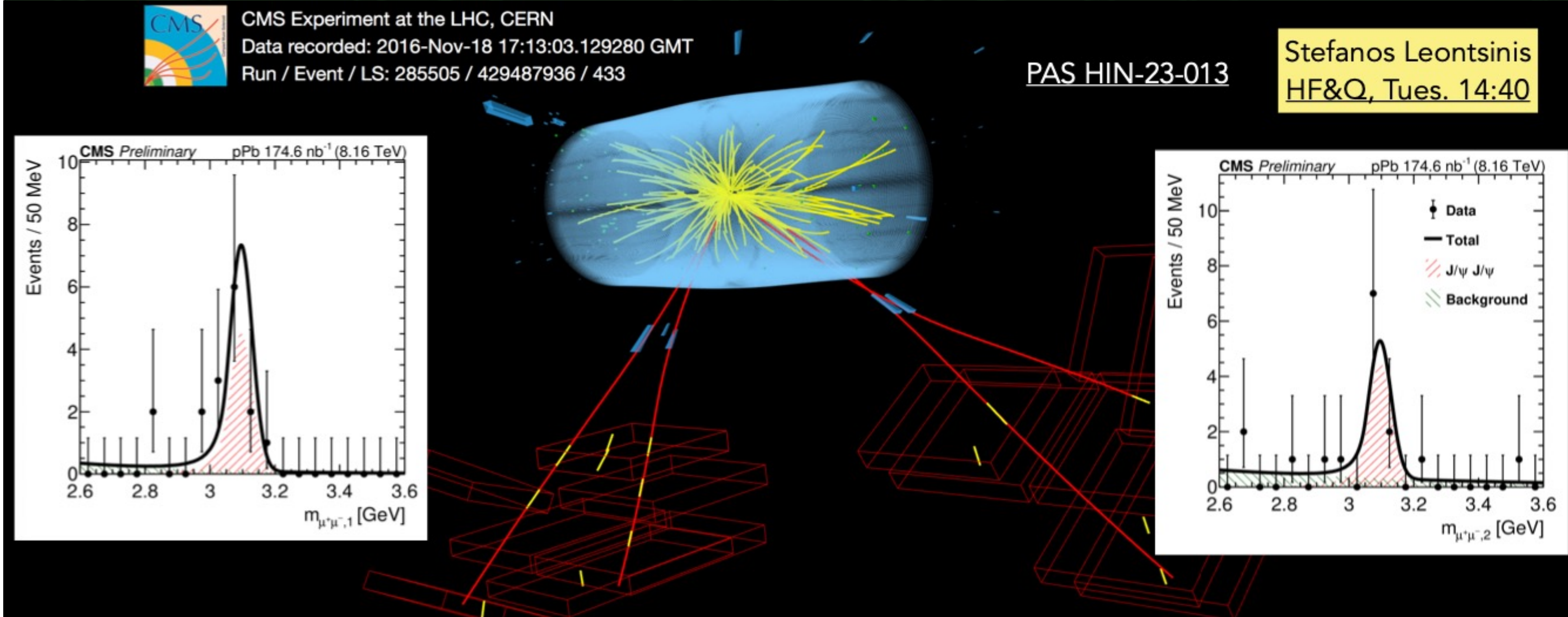
The dashed line at the value of 1/3 corresponds to the upper limit for noninteracting, massless gas (``ideal gas'') systems

T_{eff} : the initial temperature that a uniform fluid at rest would have if it possessed the same amount of energy and entropy as the QGP fluid does when it reaches its freeze-out state, the point at which the quarks become bound into hadrons

- C_s^2 as a function of the effective temperature (T_{eff})
- **CMS Data** in good agreement with lattice QCD, hydrodynamic model (TRAJECTUM), and ALICE data
- It would be very interesting to look at lower energy data to map the temperature dependence of the speed of sound

Observation of double J/ψ production in pPb collisions

Observation of double J/ψ production in pPb



PAS HIN-23-013

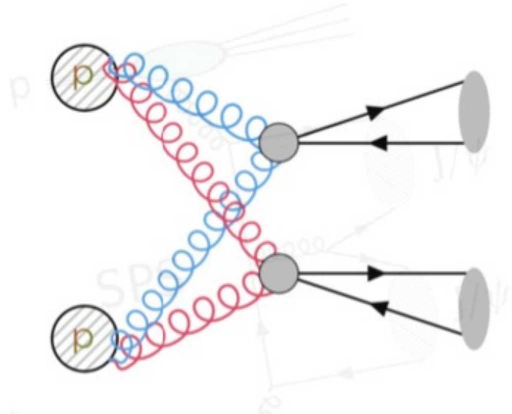
Stefanos Leontsinis
HF&Q, Tues. 14:40

$N(J/\psi\ J/\psi \rightarrow 2\ \mu^+\mu^-) = 8.5 \pm 3.4$ events

$\sigma_{fiducial}(pPb \rightarrow J/\psi\ J/\psi) = 22.0 \pm 8.9\ (stat) \pm 1.5\ (syst)$ nb

Introduction of the study

- High-energy collisions at LHC -> multiple interactions of protons and nuclei's underlying partonic constituents such as quarks and gluons
- Multiple Parton Interactions (MPI) -> simultaneous production of several particles with large p_T
- n high p_T particle production probability id proportional to the nth-product of the probabilities to independently produce each of them
- two high p_T particle production in double-parton scattering – square of SPS probabilities

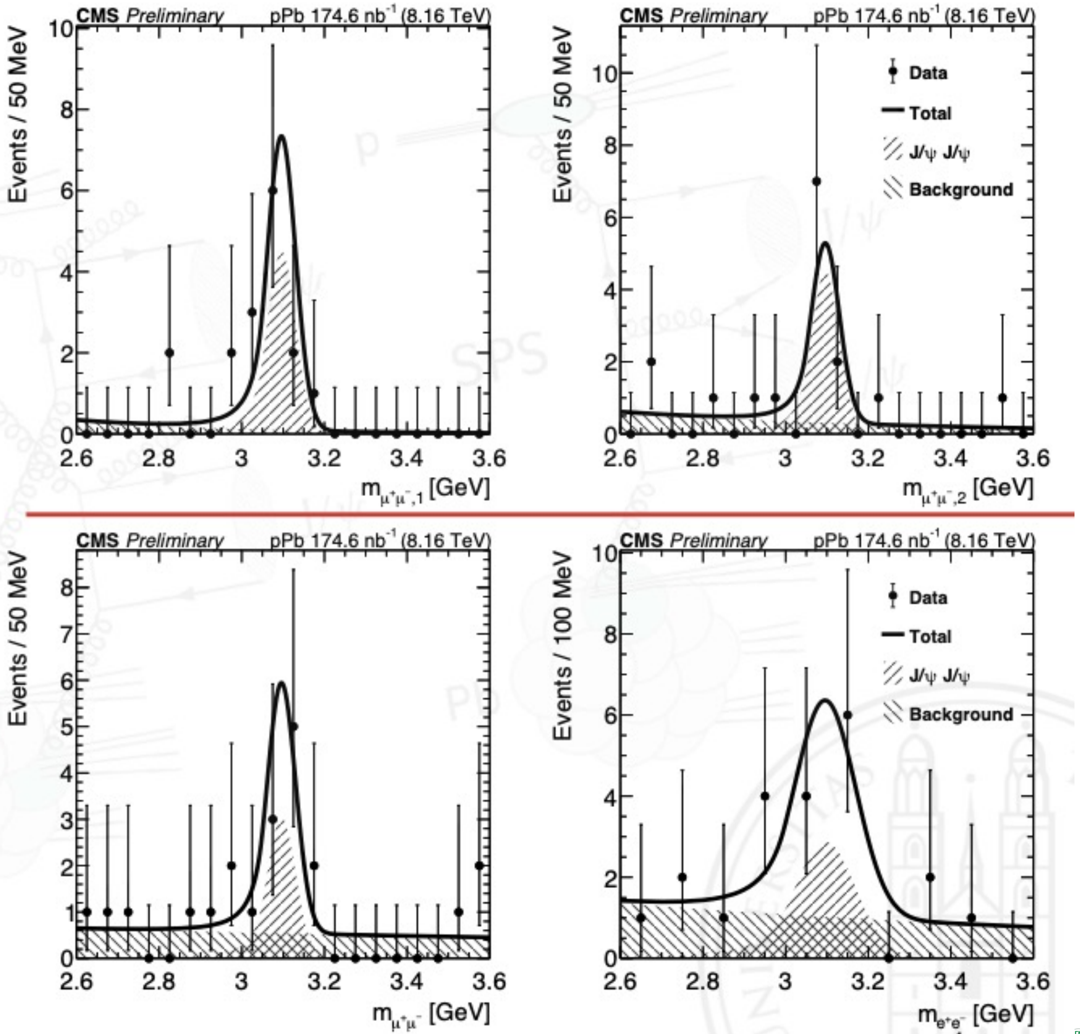


Signal extraction

Fiducial requirement		
For all muons	$p_T > 3.4\,\text{GeV}$	for $0 < \lvert\eta\rvert < 0.3$
	$p_T > 3.3\,\text{GeV}$	for $0.3 < \lvert\eta\rvert < 1.1$
	$p_T > 5.5\text{–}2.0\lvert\eta\rvert\,\text{GeV}$	for $1.1 < \lvert\eta\rvert < 2.1$
	$p_T > 1.3\,\text{GeV}$	for $2.1 < \lvert\eta\rvert < 2.4$
For the two J/ψ mesons	$p_T > 6.5\,\text{GeV}$ and $\lvert y\rvert < 2.4$	

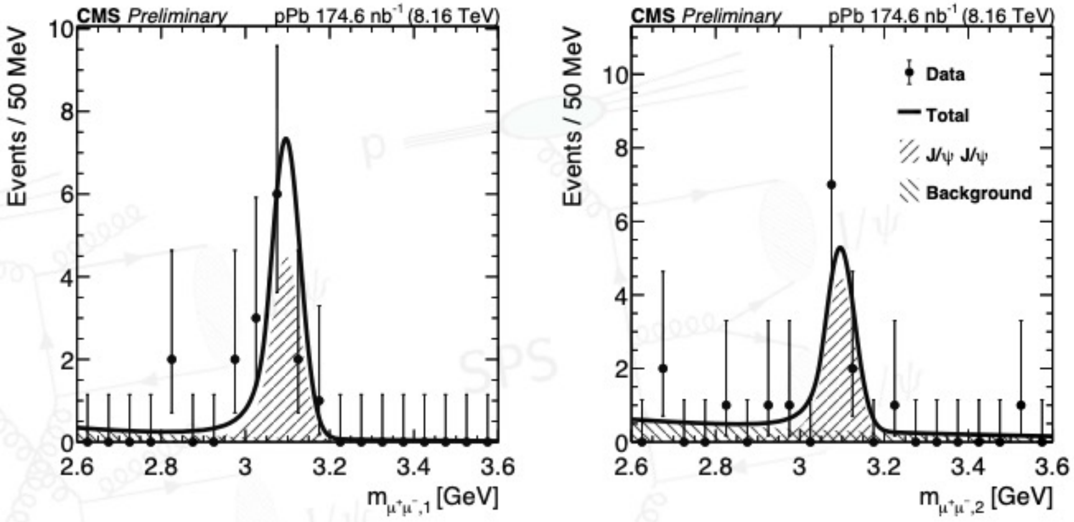
- Yield extraction
  - 2D unbinned extended ML fit
    - crystal ball function for signal
    - exponential for background
- μμ+μμ channel
  - **$N_{J/\psi J/\psi}$ = 8.5 ± 3.4** and 4.9σ significance
- μμ+ee channel
  - **$N_{J/\psi J/\psi}$ = 5.7 ± 4.0** and 2.3σ significance
- Total significance of 5.3σ

8.16 TeV – 174.6 nb^{-1}



Cross section measurement and systematics

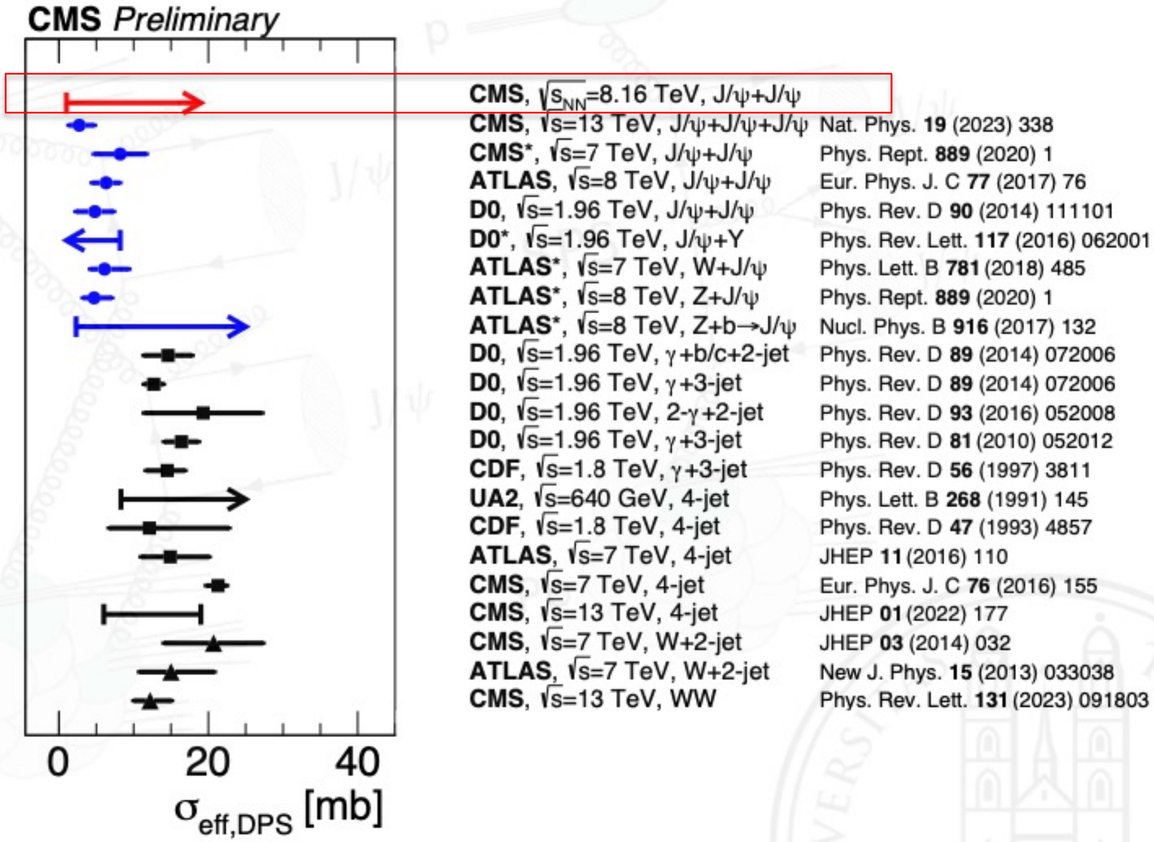
- Measured fiducial cross section to be determined from single-J/ψ MC-based efficiency in (p_T,y) plane
  - $\sigma(\mathrm{pPb} \to \mathrm{J}/\psi \mathrm{J}/\psi + X) = N_{\mathrm{sig}}/(\epsilon \mathscr{L}_{\mathrm{int}} \mathscr{B}^2_{\mathrm{J}/\psi \to \mu\mu})$
  - considering **only J/ψ→μμ J/ψ→μμ mode**
- $N_{\mathrm{sig}}/\varepsilon = \Sigma_i N^i_{\mathrm{sig}}/\varepsilon^i$
  - N^i_{sig} is the per event signal weight
  - $\epsilon^i = \epsilon^i_{\mu\mu,1}\epsilon^i_{\mu\mu,2}$ is the product of the two J/ψ efficiencies
  - $\epsilon = 62.1\ \%$



Source of uncertainty	$\sigma(\mathrm{pPb} \to \mathrm{J}/\psi \mathrm{J}/\psi + \mathrm{X})$
J/ψ meson signal shape	4.0%
Dimuon continuum background shape	2.5%
Luminosity	3.5%
Branching fraction	1.1%
Scale factors	1.3%
Total	6.1%

Partial summary

- **First observation of the associated production of two J/ψ mesons in pPb** at $\sqrt{s_{NN}}$ = 8.16 TeV and measurement of the fiducial cross sections
  - $\sigma_{SPS}^{pPb\to J/\psi J/\psi+X} = 16.5 \pm 10.8\,(stat) \pm 0.1\,(syst)\,nb$
  - $\sigma_{DPS}^{pPb\to J/\psi J/\psi+X} = 5.4 \pm 6.2\,(stat) \pm 0.4\,(syst)\,nb$
  - extraction of σ_{eff} lower limit
    - $\sigma_{eff} > 1.0\,mb$ at 95% CL
- Future pPb data will provide more accurate σ_{eff} extractions that can help clarify the observed span of σ_{eff} in pp collisions.

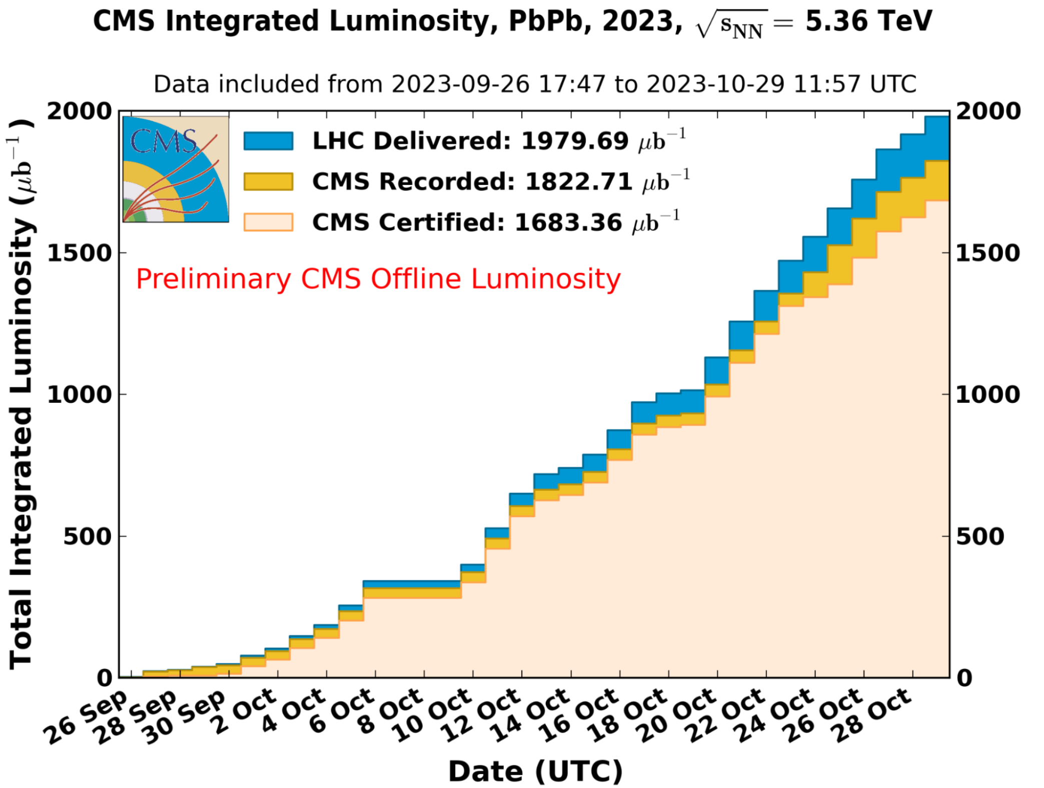


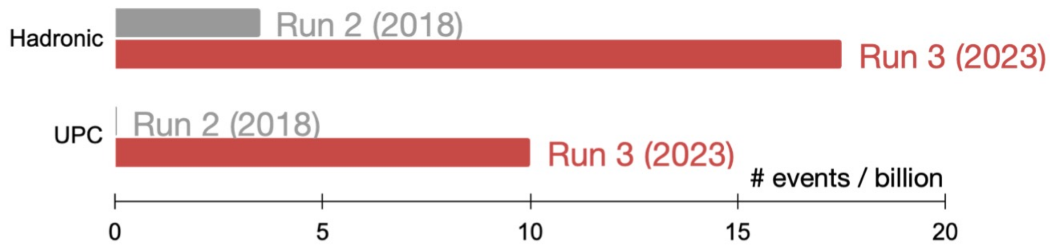
CMS NEW RESULT SQM24

CMS-PAS-HIN-23-013

CMS Run3

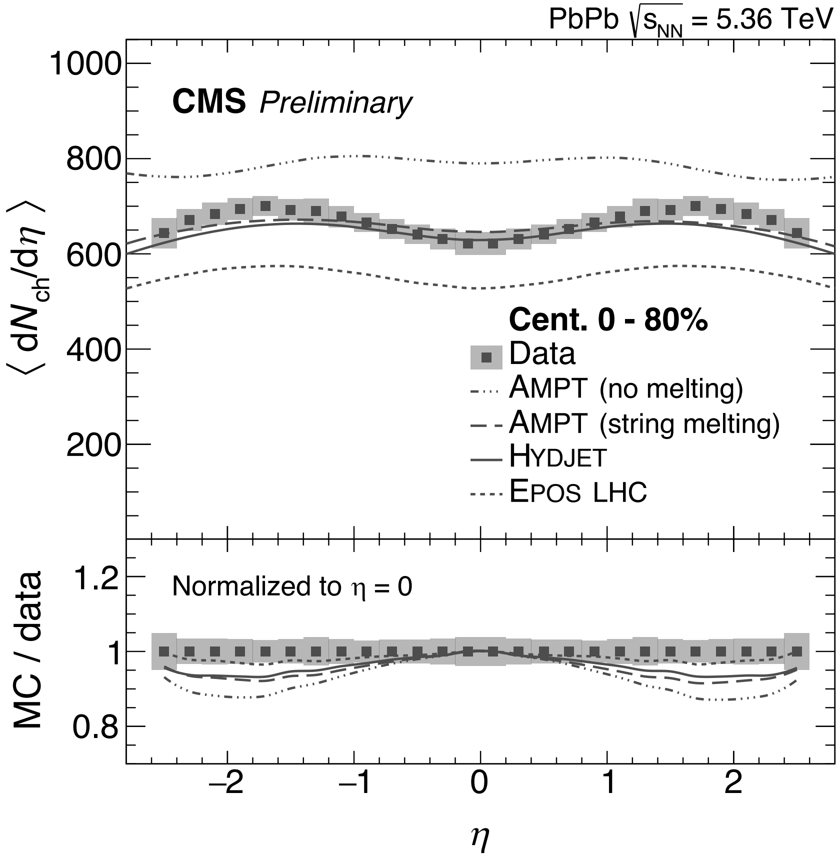
Successful start of HI run 3 period

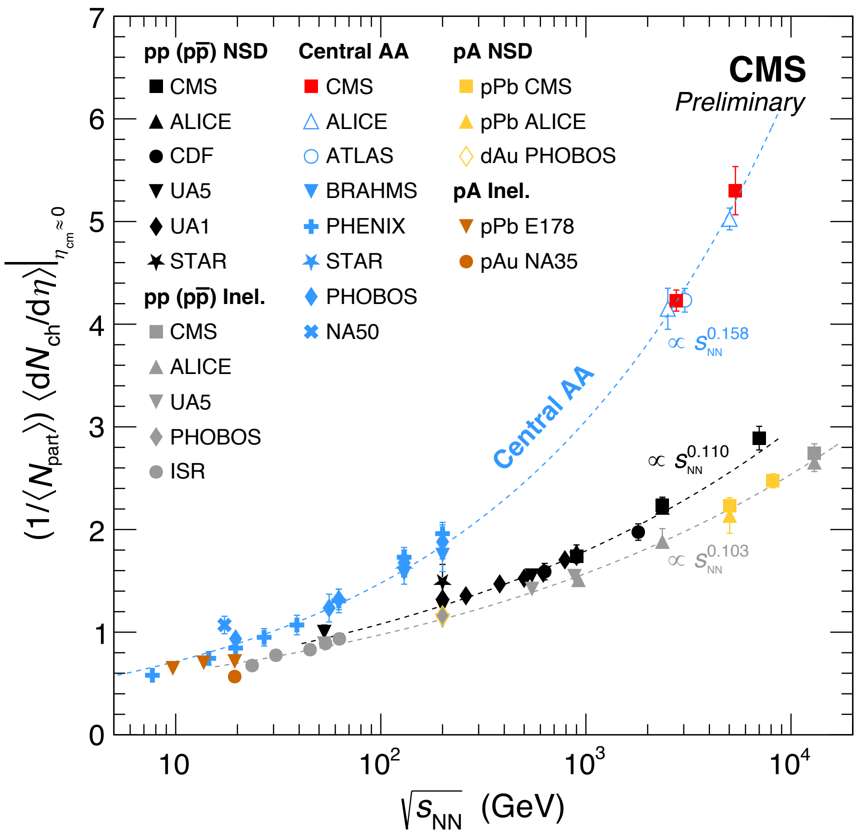




- **5.36 TeV PbPb**
- **1.683 nb^{-1} data is certified**
- **In 2023, larger statistics of hadronic and UPC data**
  - Expect more precise measurement for UPC

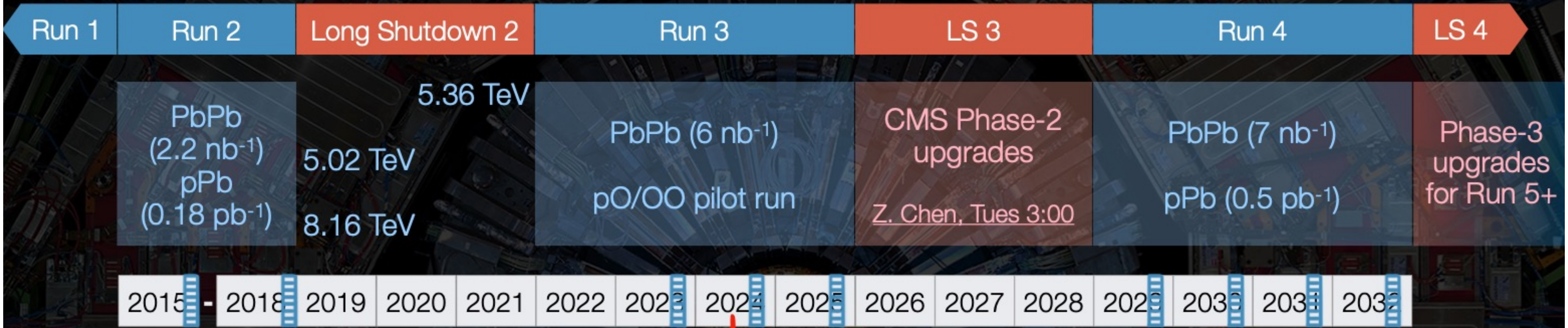
First results from run3 PbPb data (2022 test run, not 2023)





- **Event generators not describing the data accurately**
  - important input to tune MC for Run 3

Flow of LHC heavy ion program



Timeline updated from Jing Wang's overview @ SQM 2022

Overview of results from Runs 1 & 2 available now! (submitted to Physics Reports)

Detailed studies to draw a comprehensive picture of HIC

- Conditions of the system in the initial state
- Emerging properties and medium-induced effects
- Collectivity features in small collision systems
- Nature of exotic hadrons and rare phenomena

SQM 2026 @ UCLA

March 23-27, 2026 (+March 22 student's day)

For coming HP, CMS is preparing interesting results
Stay tuned!