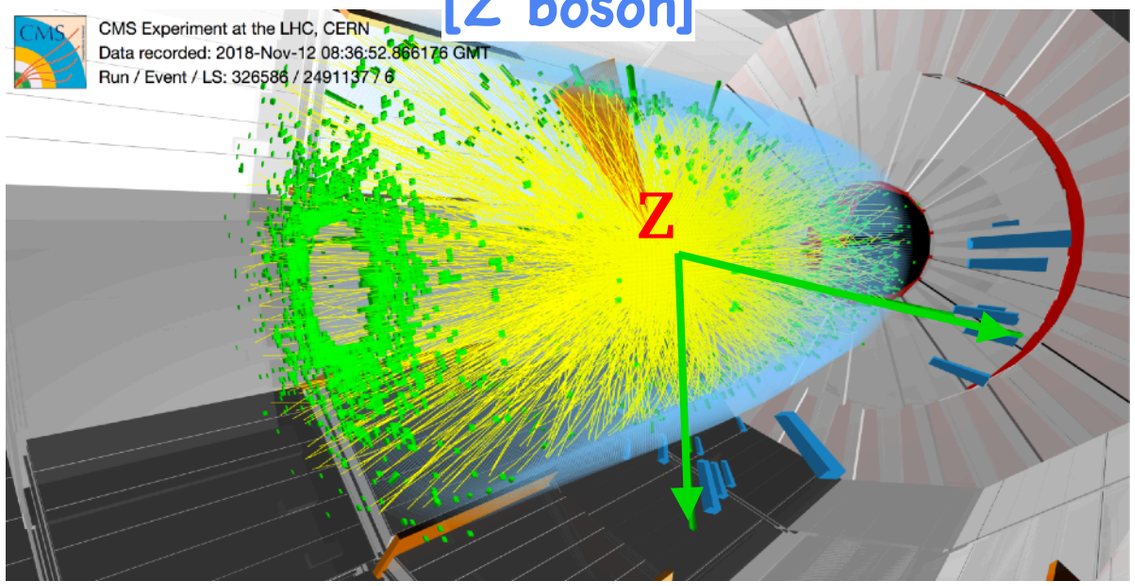
CMS Heavy-Ion Physics Results

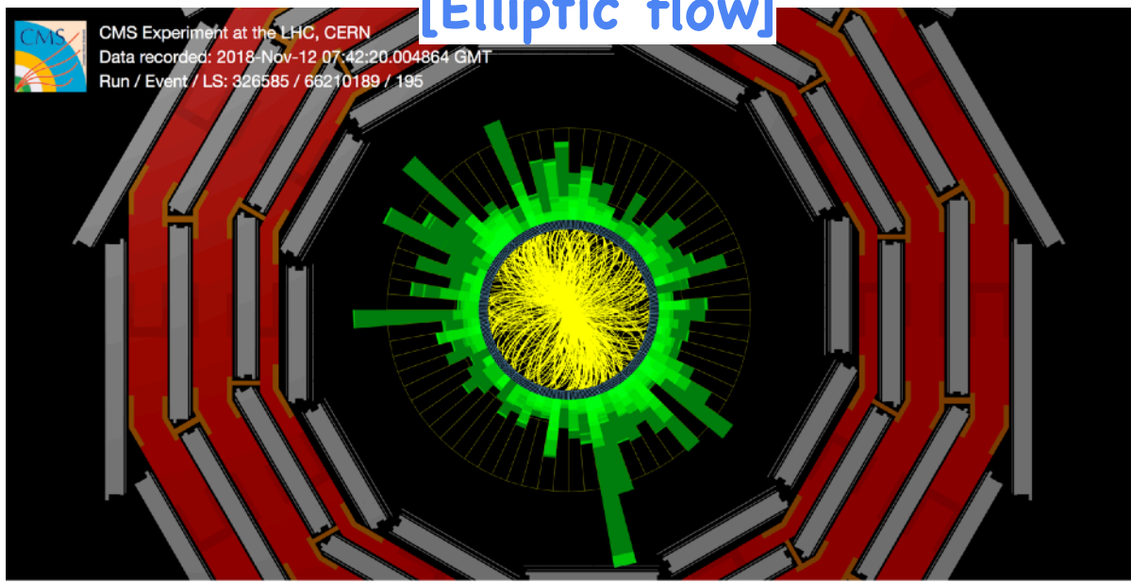
JaeBeom Park (Korea University)
- on behalf of CMS collaboration

Excited QCD 2022 @ Sicily (Italy)

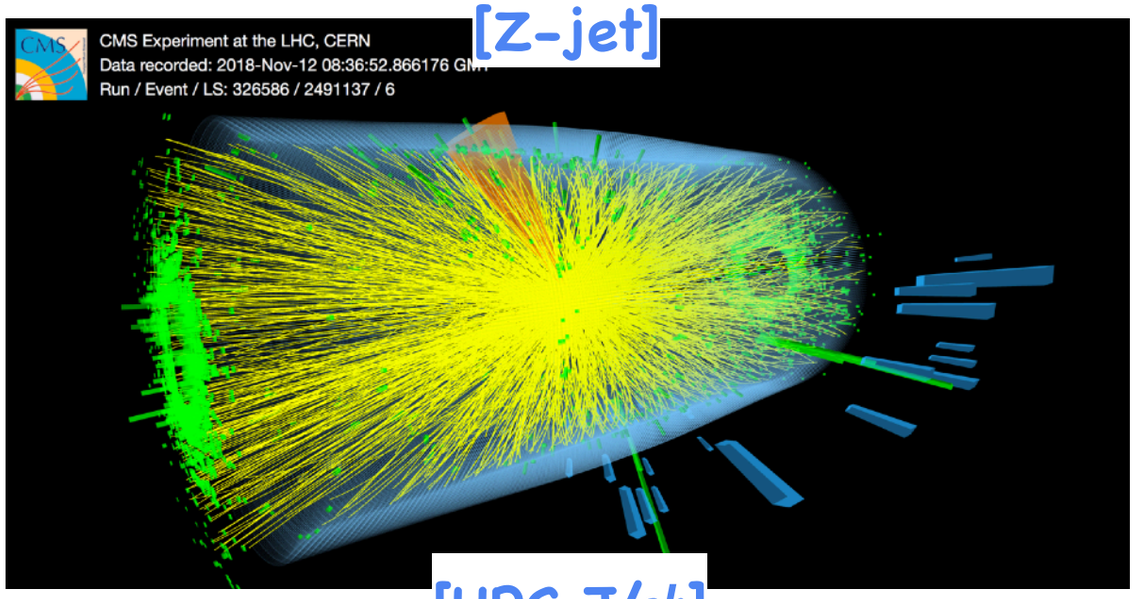
[Z boson]



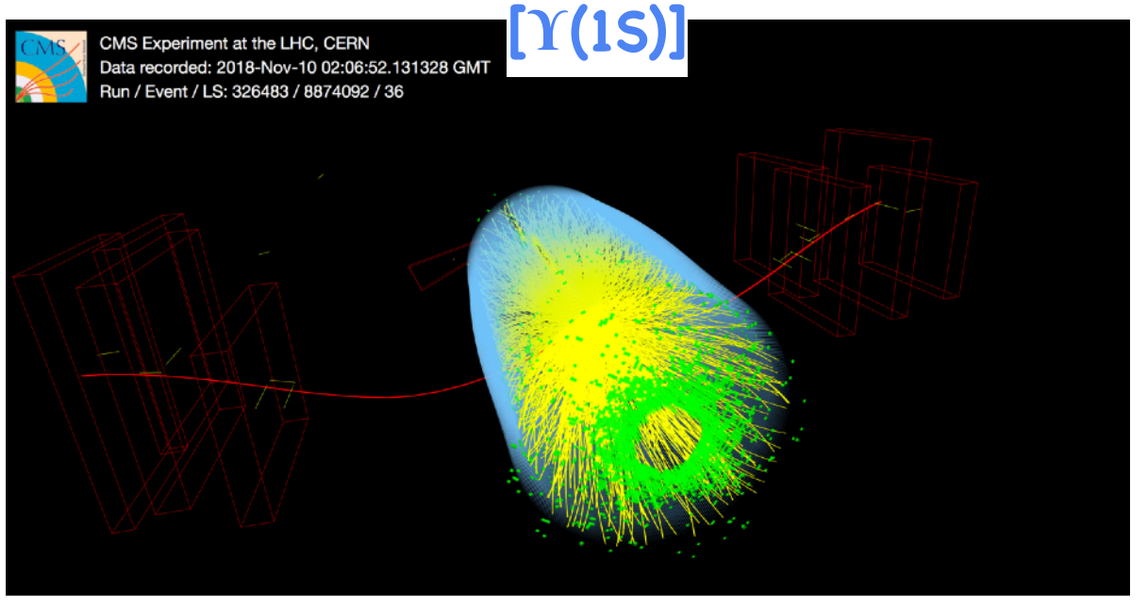
[Elliptic flow]



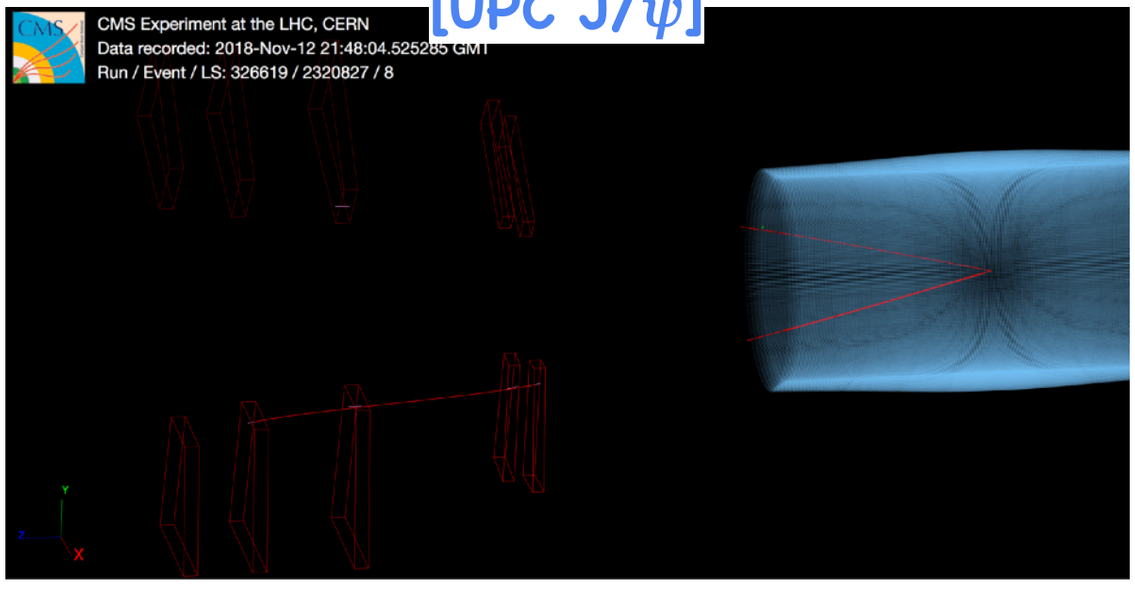
[Z-jet]



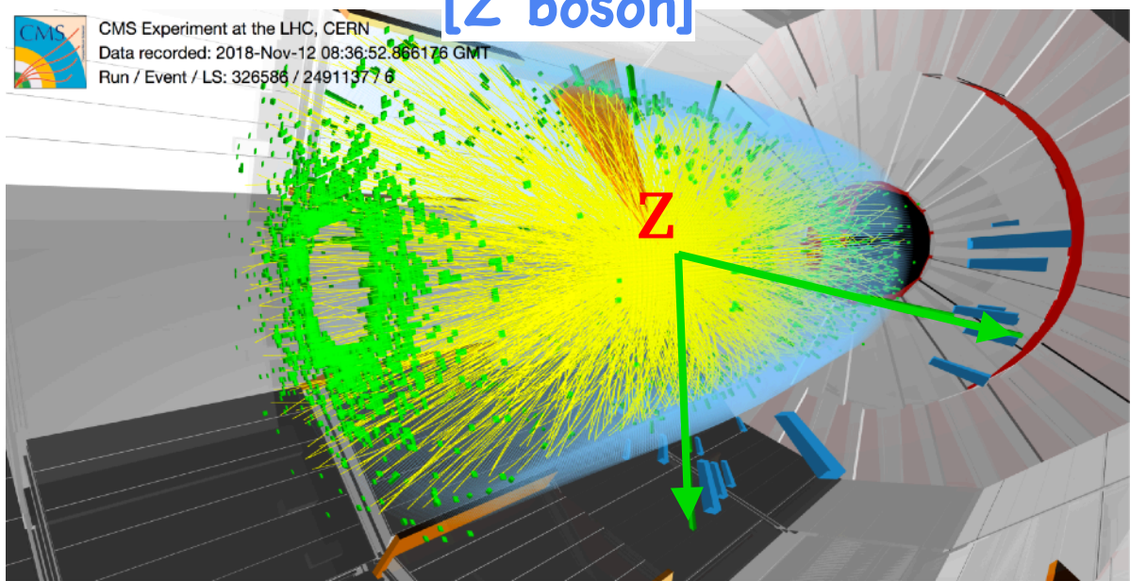
[Υ(1S)]



[UPC J/ψ]



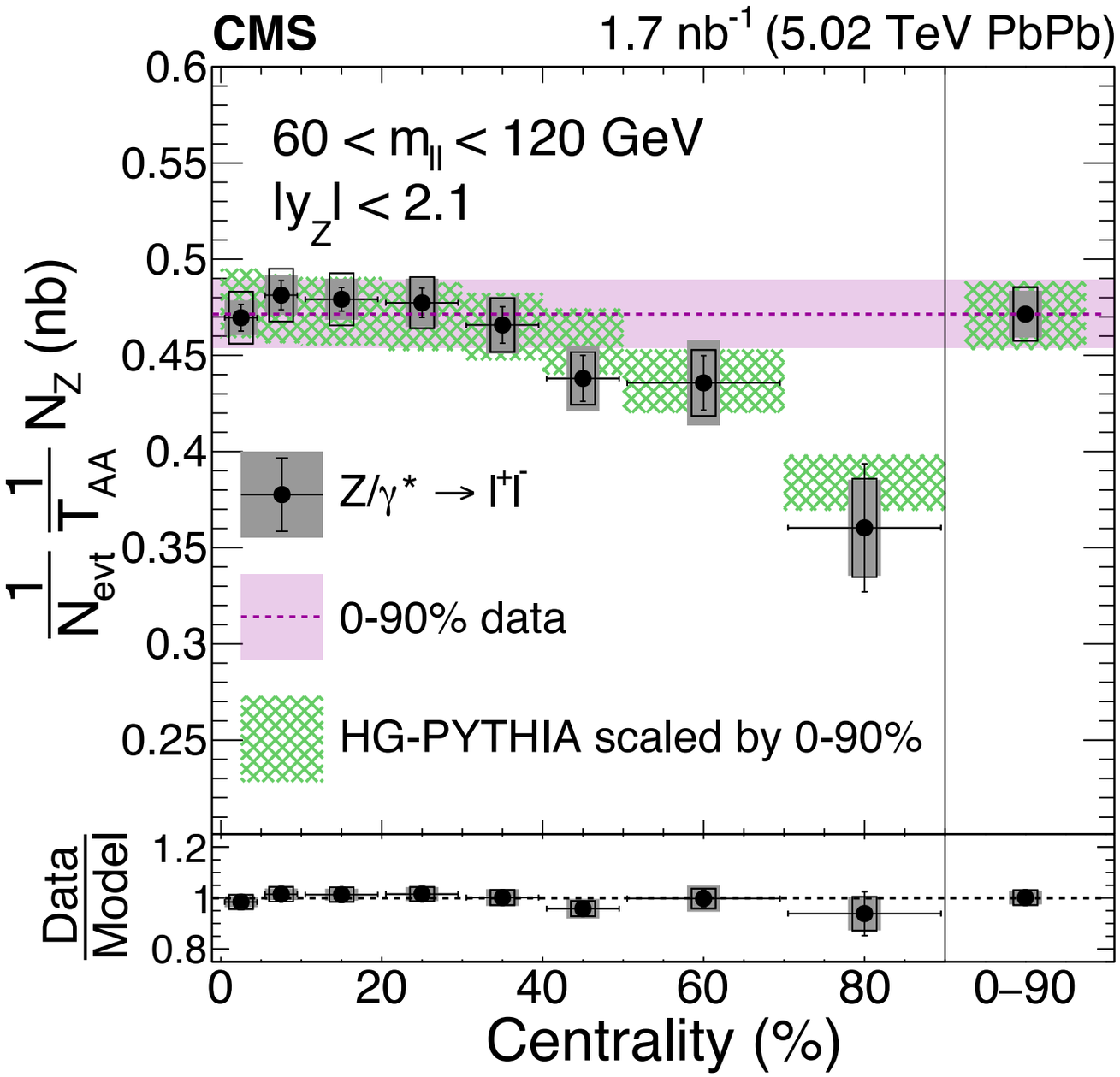
- Electroweak (EW) probes
- Flow/Correlations
- Jets
- Heavy Flavor (HF) & Quarkonia
- Ultraperipheral collisions (UPCs)



- EW probes
- Flow/Correlations
- Jets
- HF & Quarkonia
- Ultraperipheral collisions (UPCs)

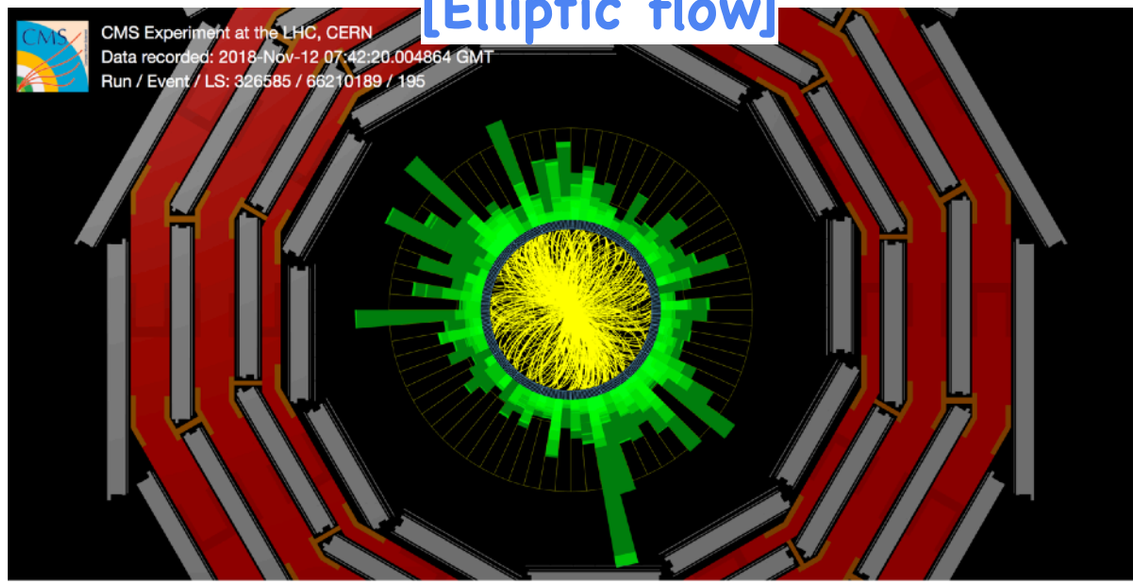
Initial state with Z bosons

[PRL 127 (2021) 102002]



- Deviation from flat centrality dependence
  : 2.2σ at 70-90%
- Qualitatively described by HG-PYTHIA
  - Initial geometry + event selection biases
- Suggestion to replace Glauber model with
  # of Z boson counting

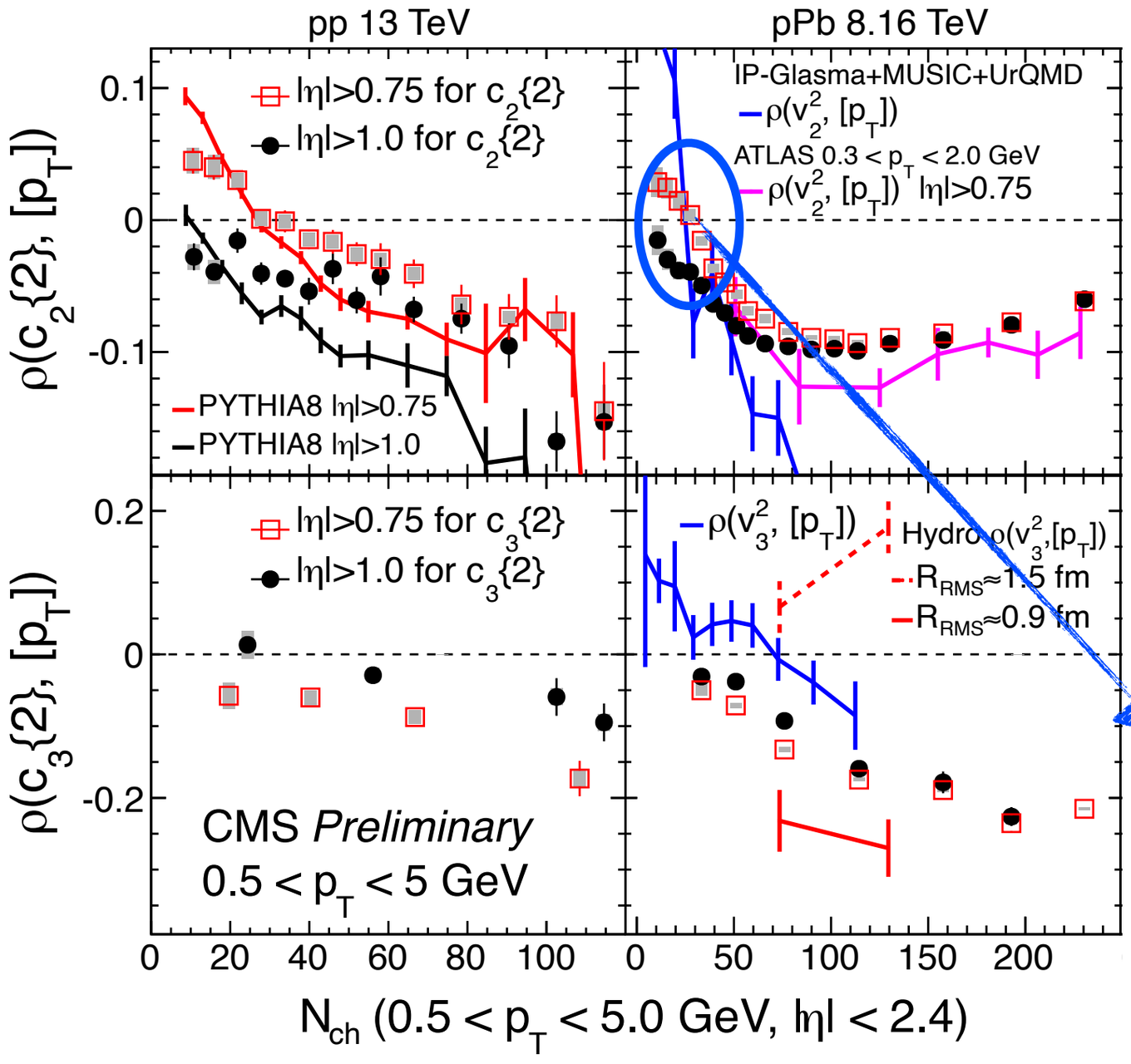
[Elliptic flow]



- EW probes
- Flow/Correlations
- Jets
- HF & Quarkonia
- Ultraperipheral collisions (UPCs)

Multiparticle cumulants

[CMS-PAS-HIN-21-012]



$$\rho(v_n^2, [p_T]) = \frac{\mathrm{cov}(v_n^2, [p_T])}{\sqrt{\mathrm{Var}(v_n^2)_{\mathrm{dyn}}}\sqrt{\mathrm{Var}([p_T])_{\mathrm{dyn}}}}$$

- □ small η gap
- ● large η gap

Reduction of non-flow effects

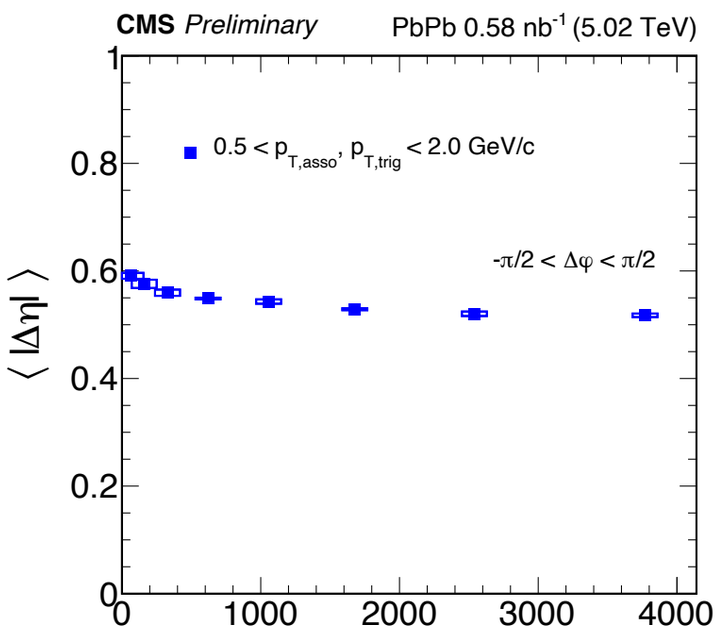
† IP-Glasma+MUSIC+UrQMD

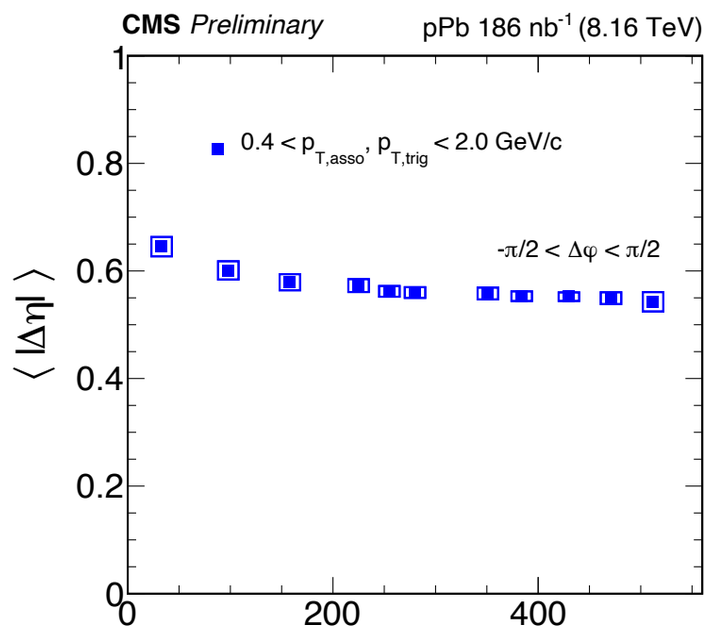
: Sign change predicted by CGC

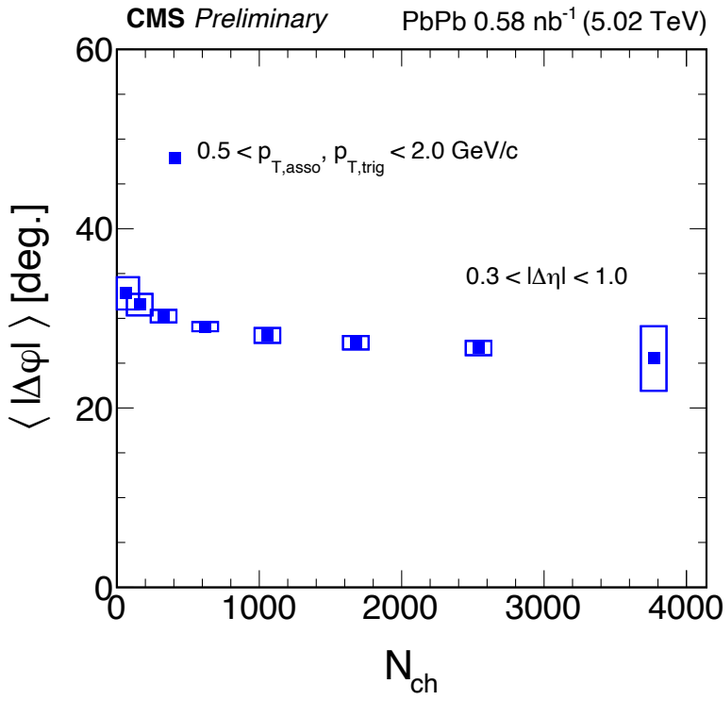
- No sign change with large η gap : Deviations from CGC predictions

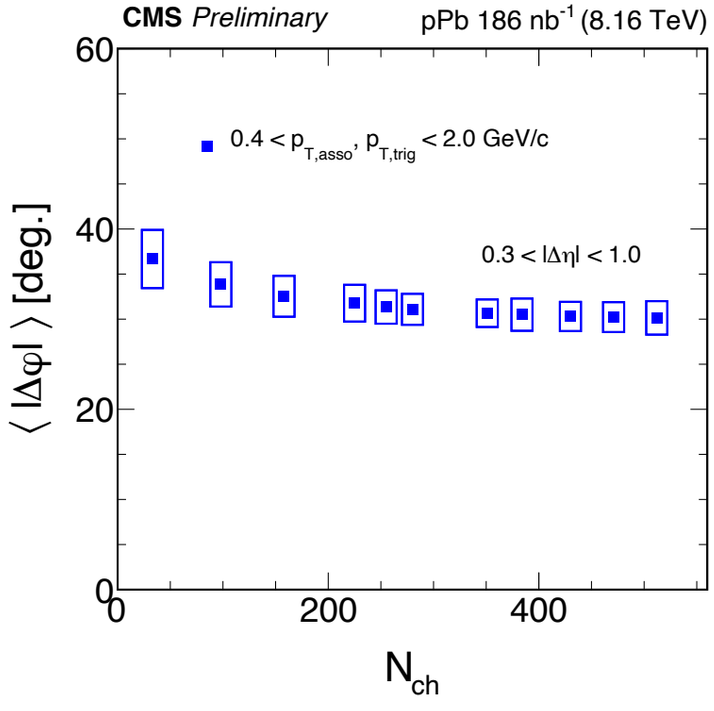
Charge balance function : low-p_T

[CMS-PAS-HIN-21-017]

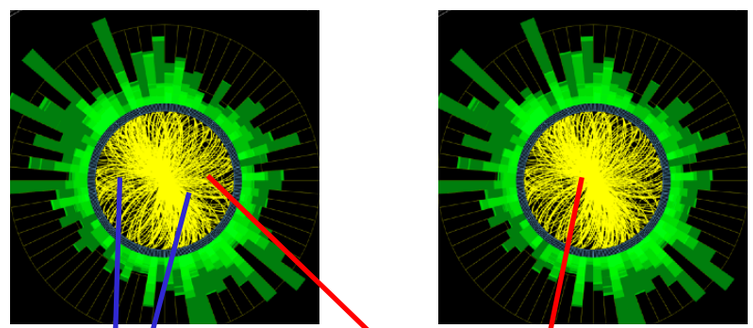








Event 1 Event 2



$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{same}}}{d\Delta\eta\Delta\varphi} \qquad M(\Delta\eta,\Delta\varphi) = \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{mix}}}{d\Delta\eta\Delta\varphi}$$

2D correlation : $C_2(\Delta\eta,\Delta\varphi) = M(0,0)\frac{S(\Delta\eta,\Delta\varphi)}{M(\Delta\eta,\Delta\varphi)}$

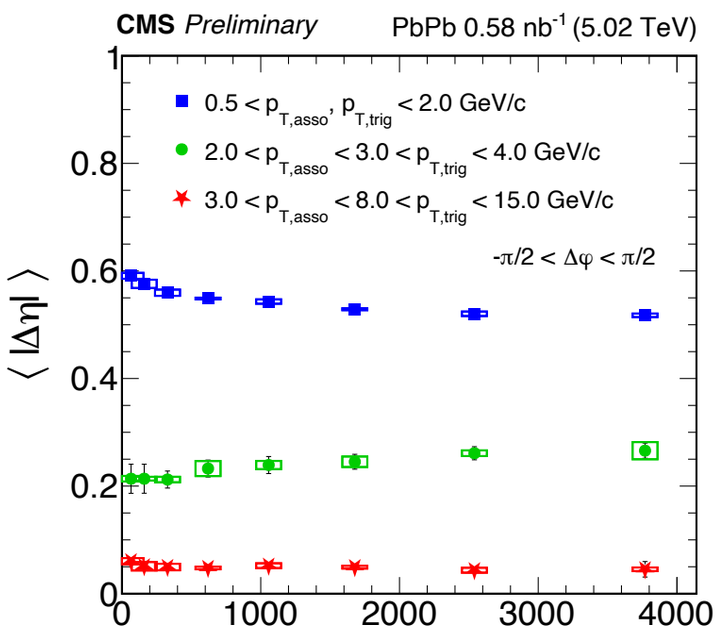
Balance function

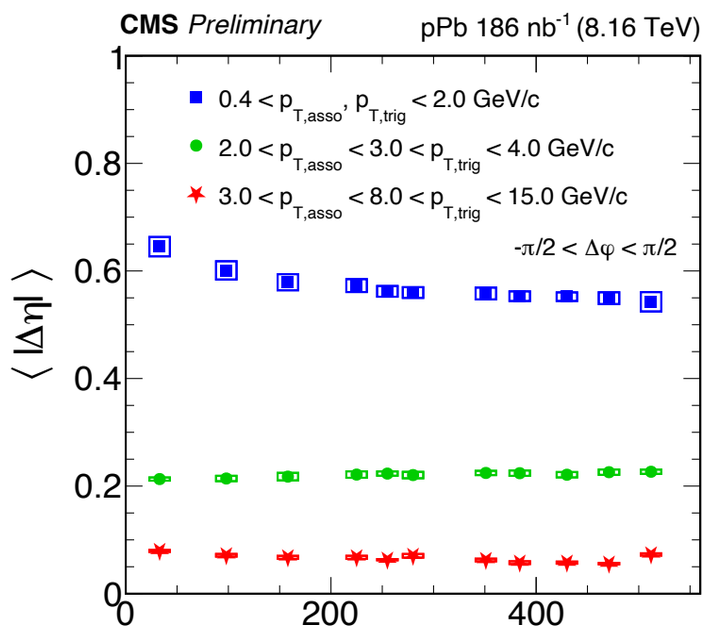
$$B(\Delta\eta,\Delta\varphi) = \frac{1}{2}[C_2(+,-) + C_2(-,+) - C_2(+,+) - C_2(-,-)]$$

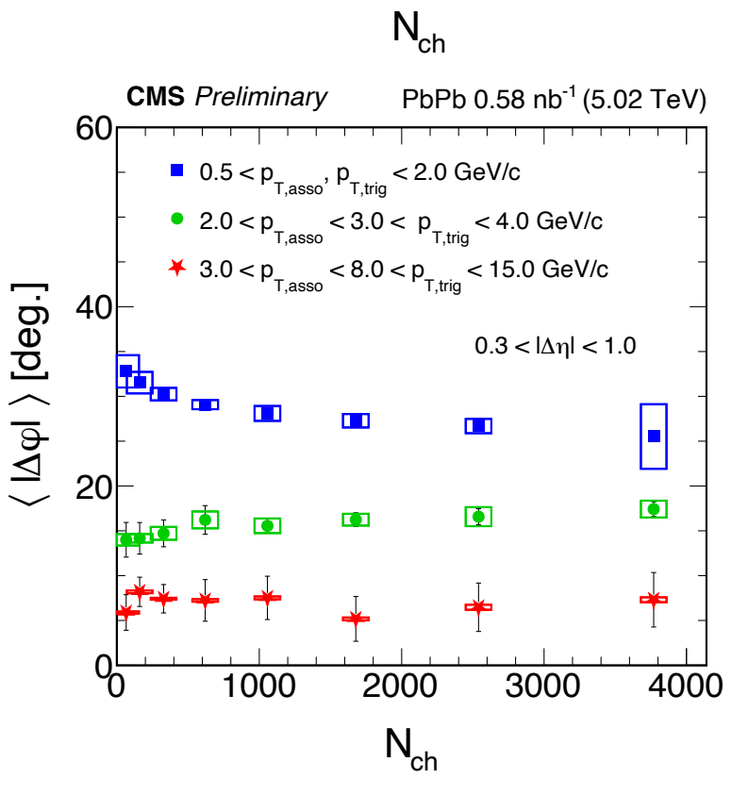
- $|\Delta\phi|$, $|\Delta\eta|$ decrease for low-p_T
  - Delayed hadronization
  - Radial flow

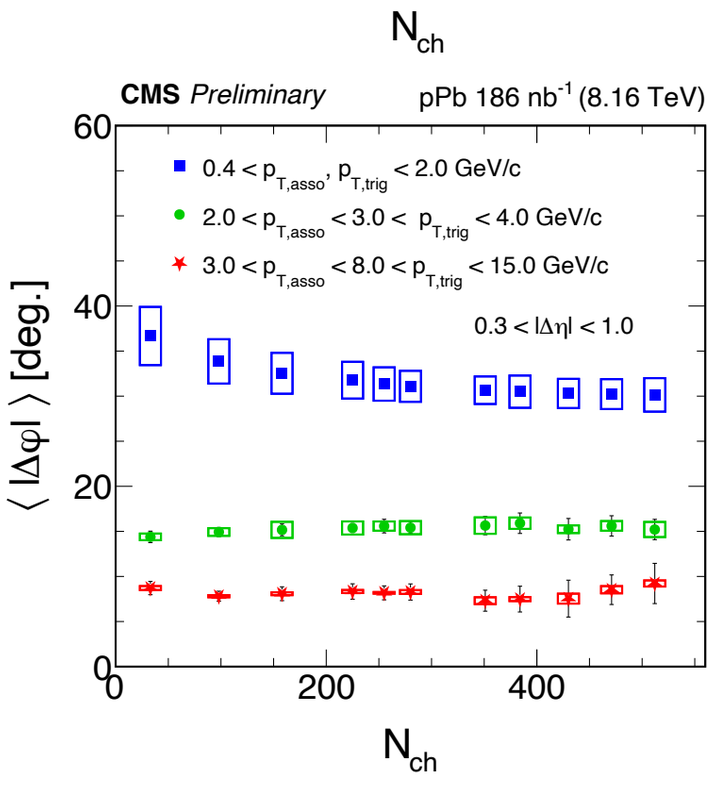
Charge balance function : high-p_T

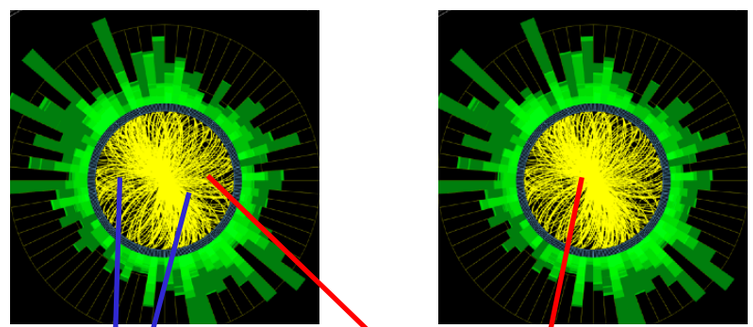
[CMS-PAS-HIN-21-017]











$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{same}}}{d\Delta\eta\Delta\varphi} \qquad M(\Delta\eta,\Delta\varphi) = \frac{1}{N_{\text{trig}}}\frac{d^2N^{\text{mix}}}{d\Delta\eta\Delta\varphi}$$

2D correlation : $C_2(\Delta\eta,\Delta\varphi) = M(0,0)\frac{S(\Delta\eta,\Delta\varphi)}{M(\Delta\eta,\Delta\varphi)}$

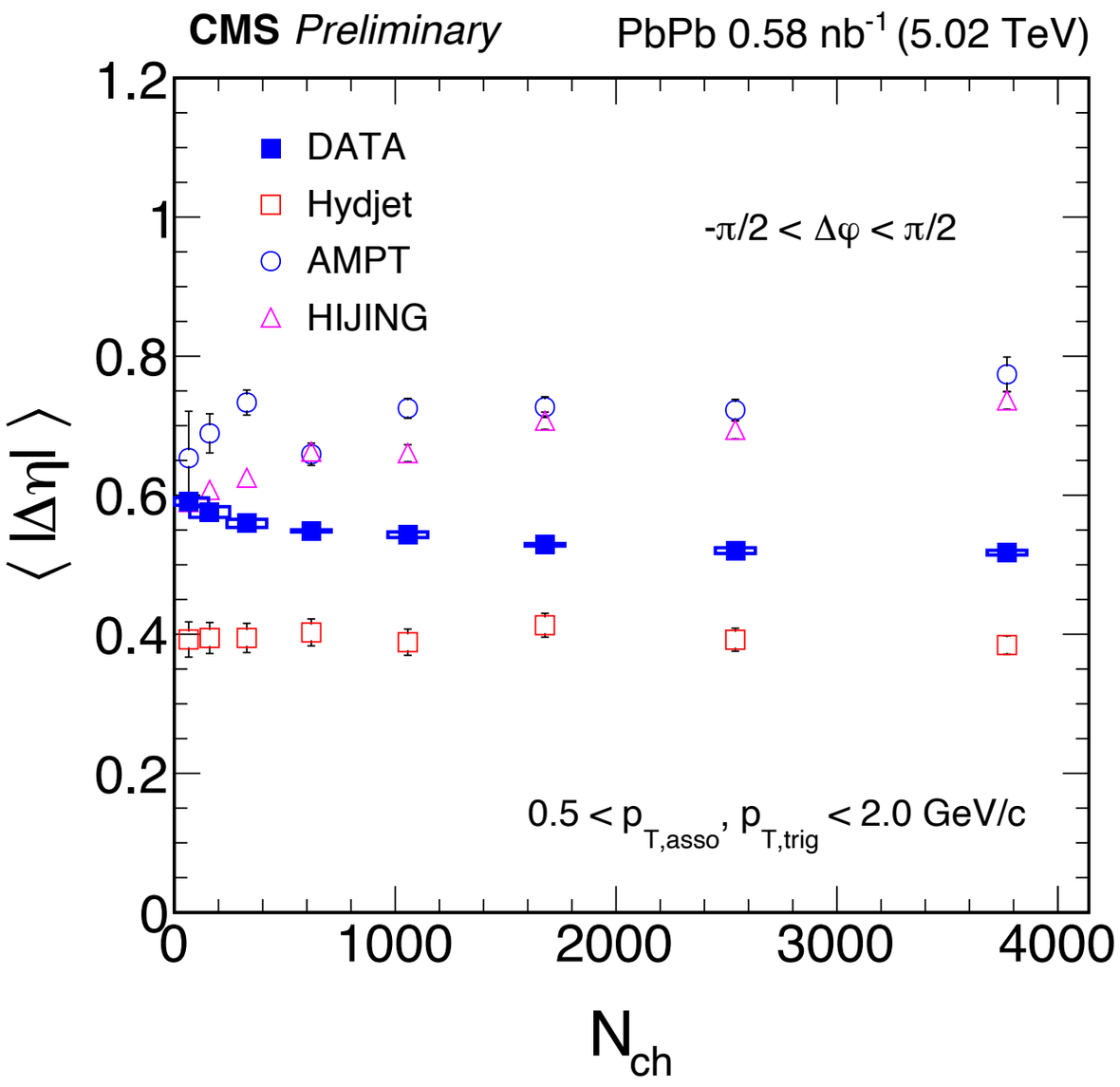
Balance function

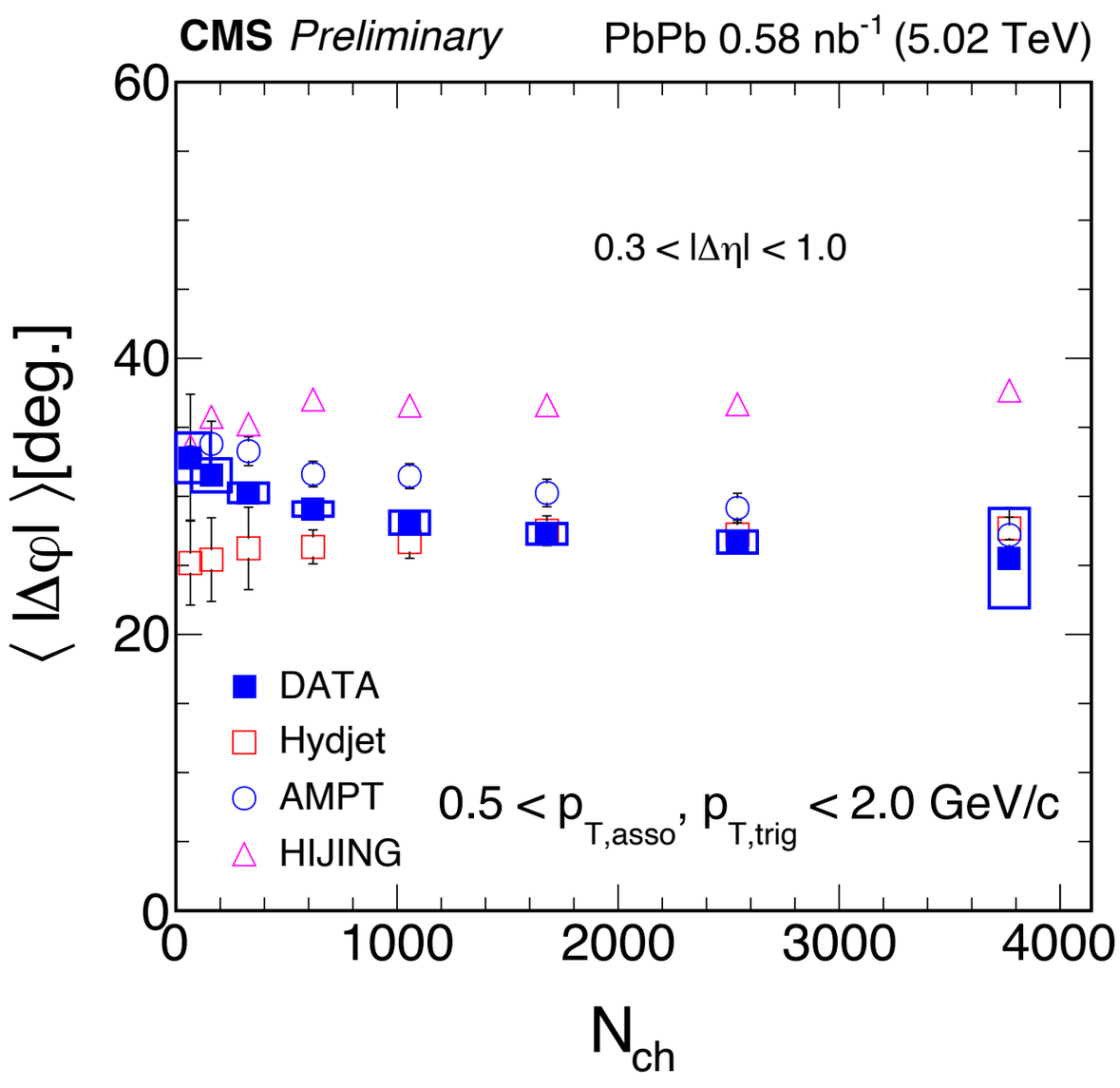
$$B(\Delta\eta,\Delta\varphi) = \frac{1}{2}[C_2(+,-) + C_2(-,+) - C_2(+,+) - C_2(-,-)]$$

- $|\Delta\phi|$, $|\Delta\eta|$ decrease for low-p_T
  - Delayed hadronization
  - Radial flow
- Constant trend for high-p_T particles
  - produced from initial hard scattering & jet fragmentation
  - stronger correlation with charge partners compared to low-p_T

Charge balance function vs models

[CMS-PAS-HIN-21-017]

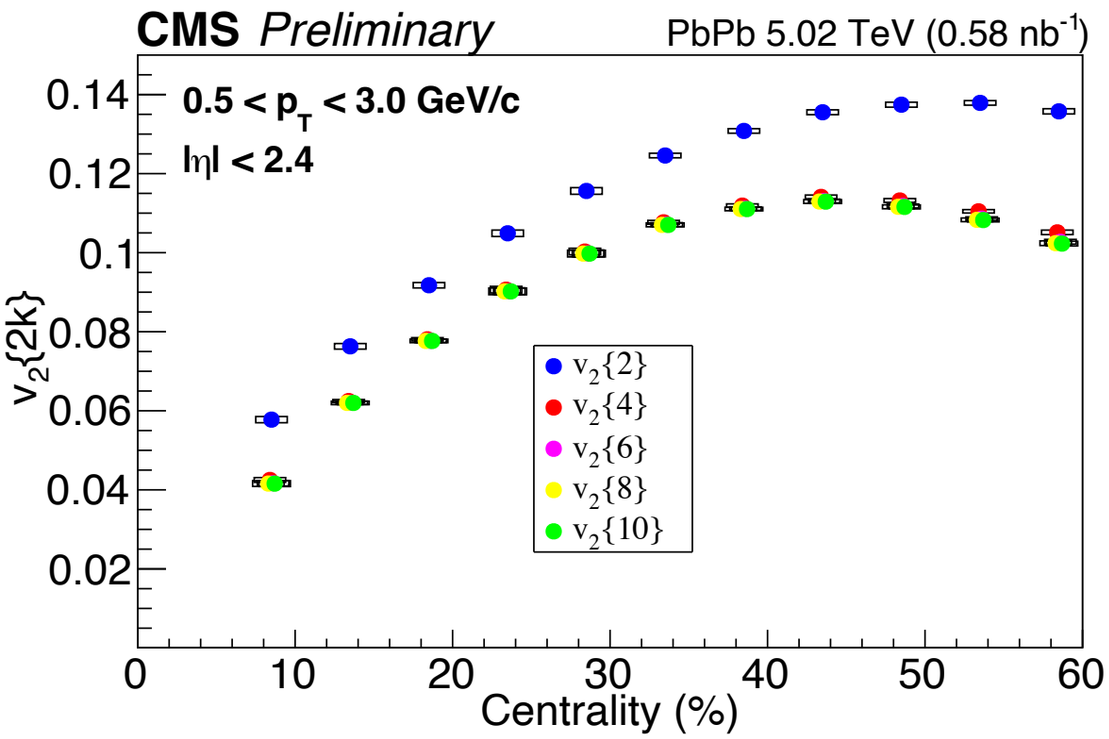


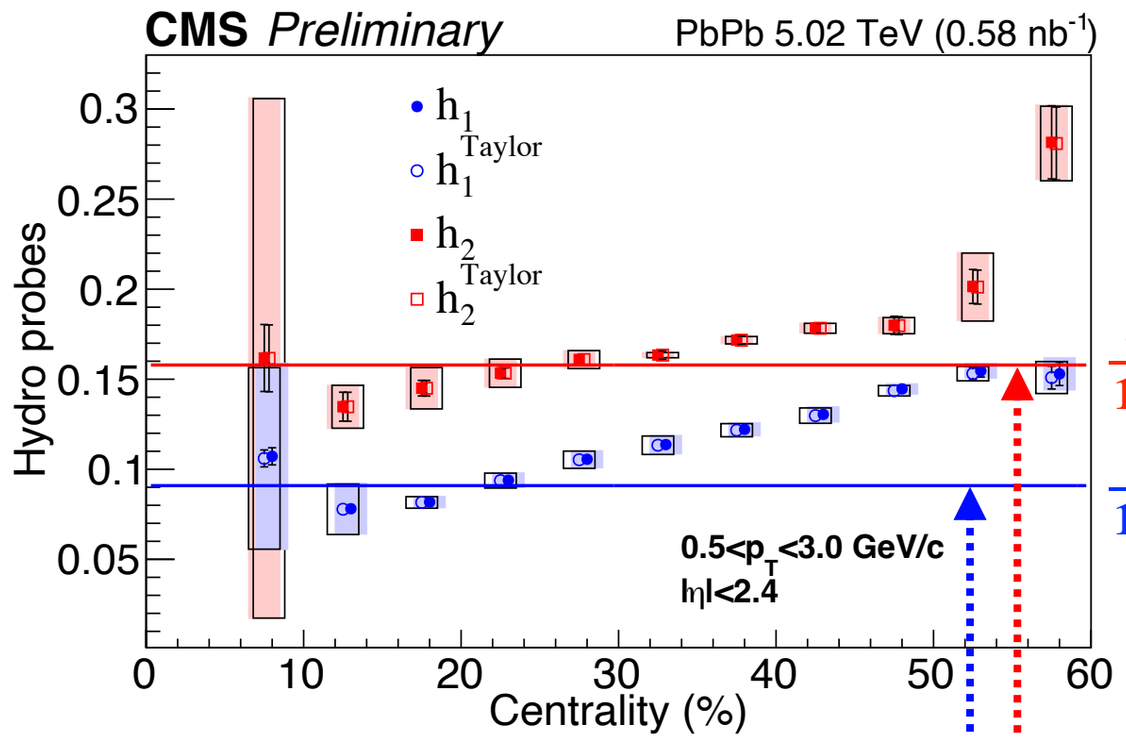


- Generators fail to reproduce results for $|\Delta\eta|$
- $|\Delta\phi|$ qualitatively described by AMPT — inclusion of collective effects

High-order cumulant $v_2\{10\}$

[CMS-PAS-HIN-21-011]





- $v_2\{2k\}$ (k=1,2, …) obtained up to $v_2\{10\}$ measured for the first time!
- Hydrodynamical probes h_1, h_2 : Constant only if high-order moments are negligible

$$h_1 = \frac{v_2\{6\} - v_2\{8\}}{v_2\{4\} - v_2\{6\}} \approx h_1^{\text{Taylor}} = \frac{1}{11} - \frac{1}{11}\frac{v_2\{4\}^2 - 12v_2\{6\}^2 + 11v_2\{8\}^2}{v_2\{4\}^2 - v_2\{6\}^2}$$

New probe! ← $$h_2 = \frac{v_2\{8\} - v_2\{10\}}{v_2\{6\} - v_2\{8\}} \approx h_2^{\text{Taylor}} = \frac{3}{19} - \frac{1}{19}\frac{3v_2\{6\}^2 - 22v_2\{8\}^2 + 19v_2\{10\}^2}{v_2\{6\}^2 - v_2\{8\}^2}$$

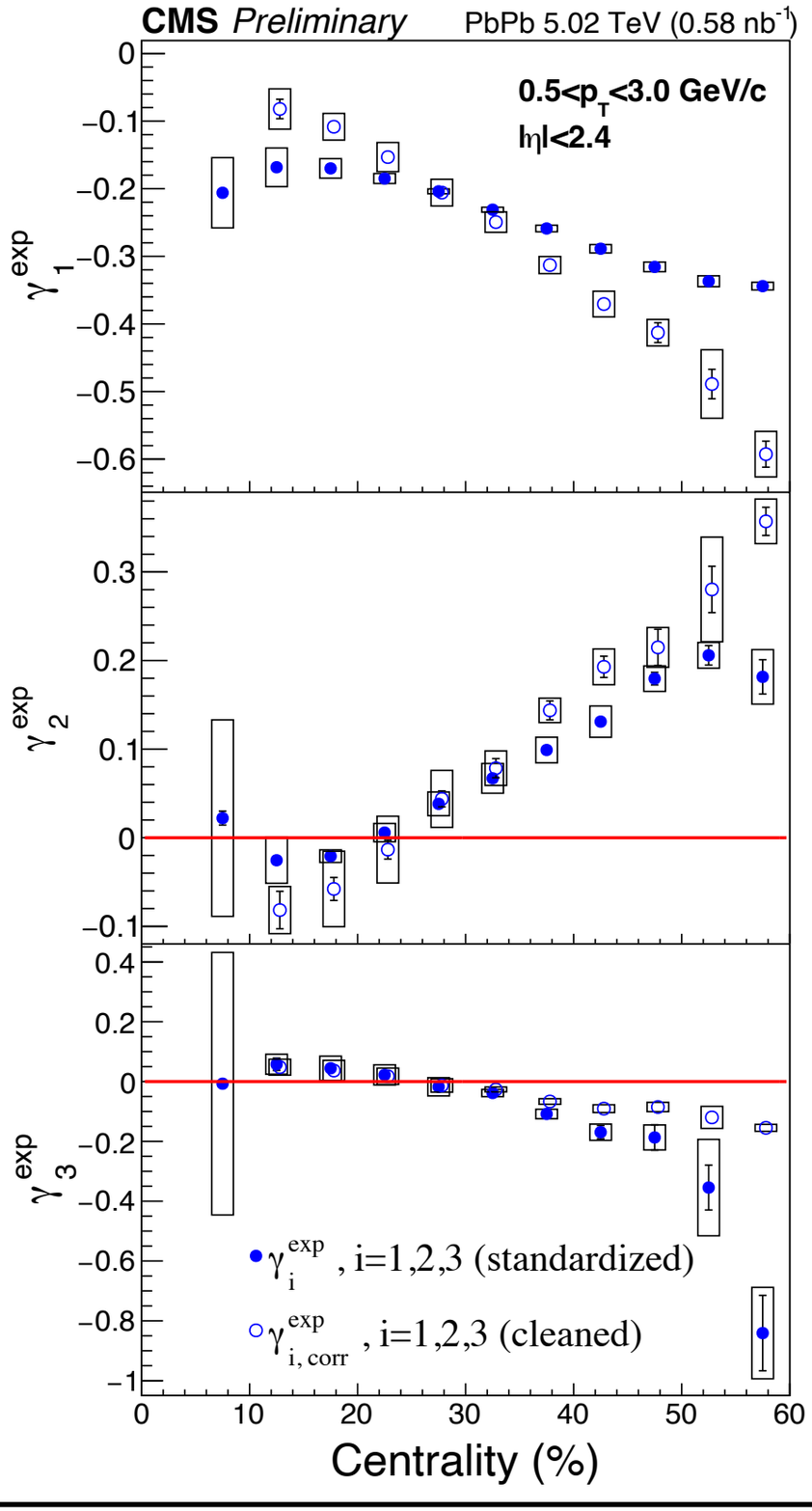
Higher-order moments

[CMS-PAS-HIN-21-011]

- Study for the origin of non-gaussian flow fluctuations
  - Skewness (γ_1^{exp}) : 3rd moment
  - Kurtosis (γ_2^{exp}) : 4th moment
  - Superskewness (γ_3^{exp}) : 5th moment

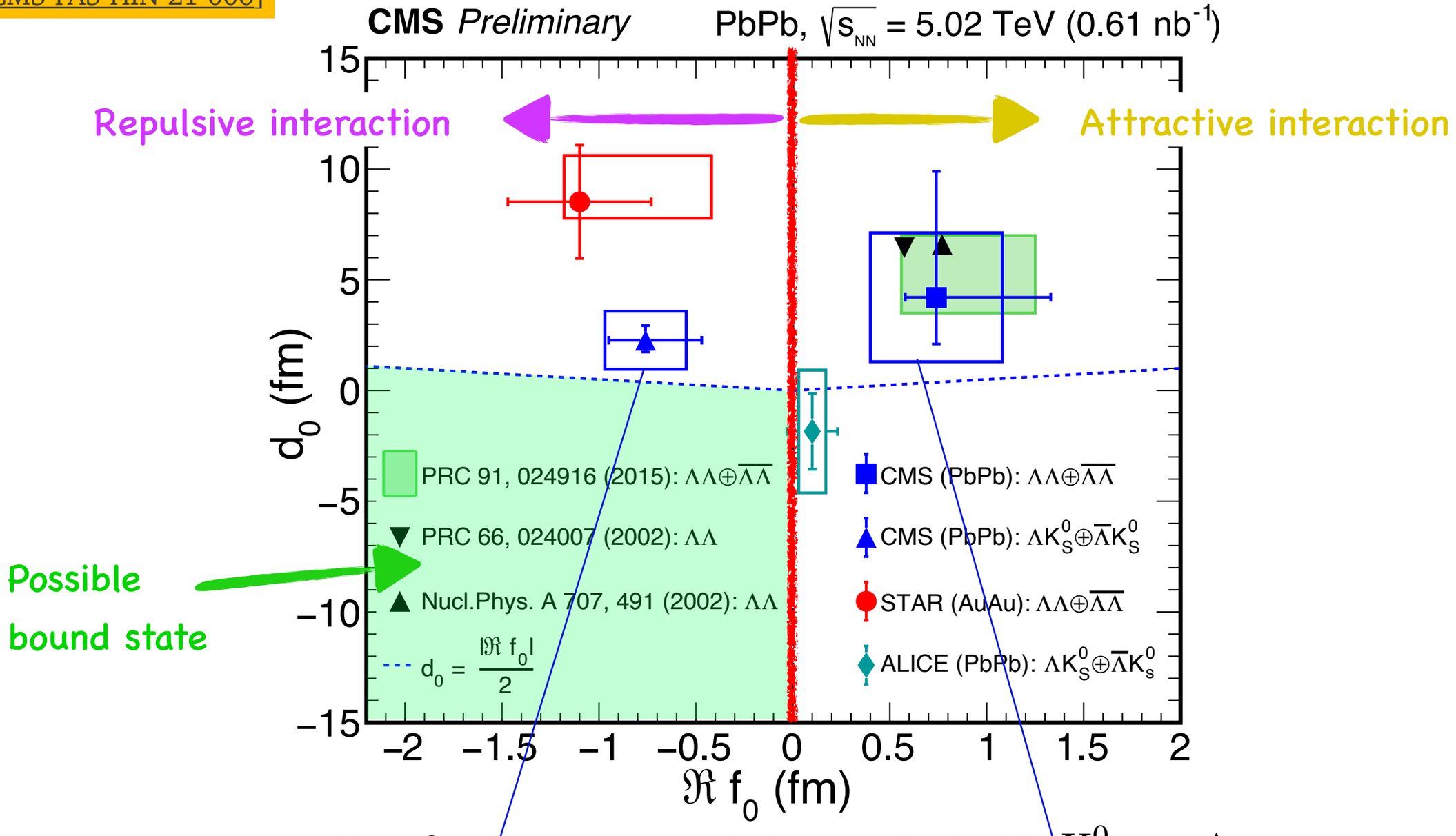
- Nonzero values for γ_1^{exp}, γ_2^{exp}, γ_3^{exp} in both standardized and cleaned (higher-order moments removed)

- Strong constraints to initial state geometry in hydrodynamical calculations



Femtoscopy of K^0_S and $\Lambda(\overline{\Lambda})$

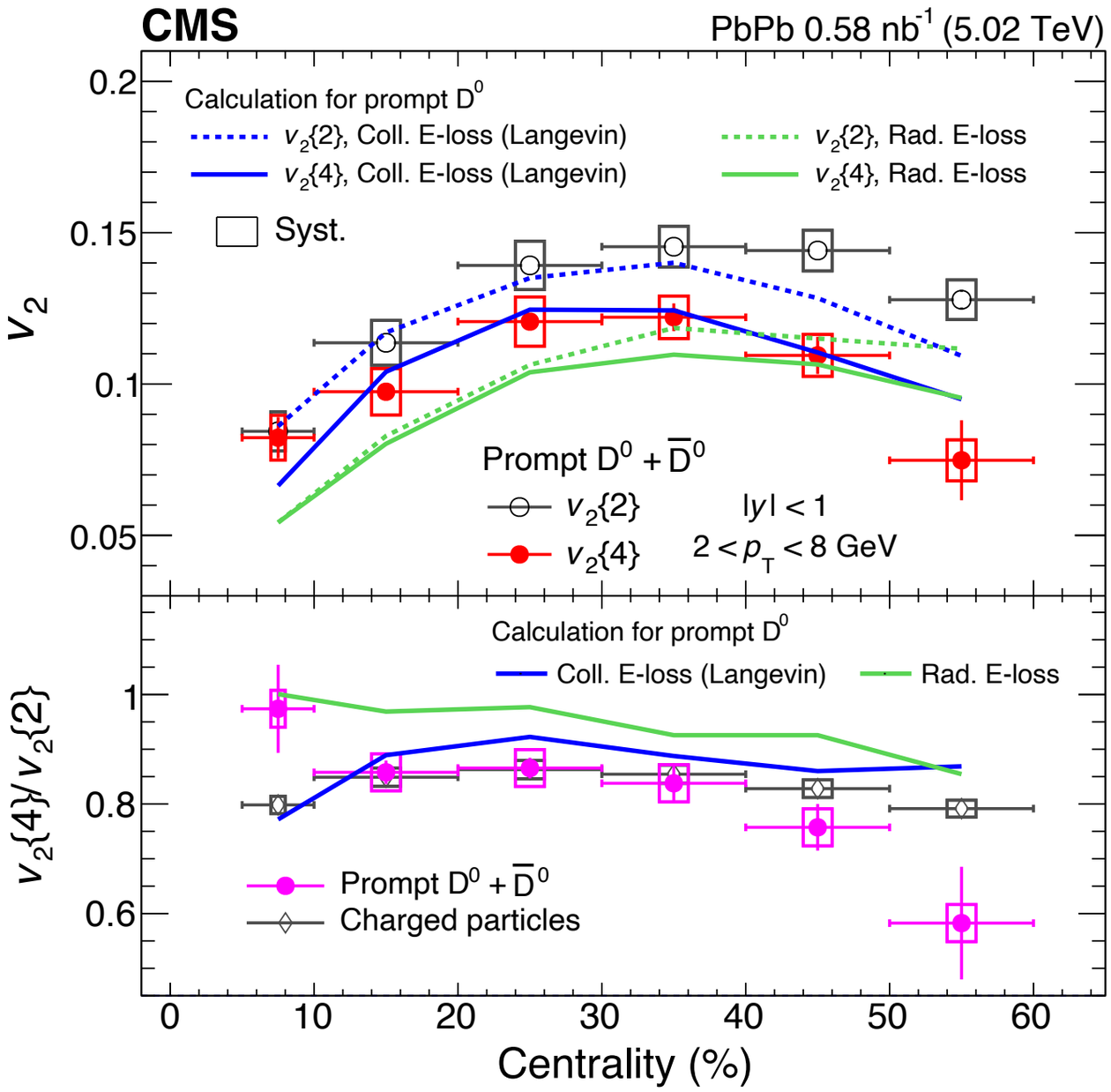
[CMS-PAS-HIN-21-006]



- Two-particle femtoscopic correlation studied with K^0_S and Λ
- Repulsive $\Lambda K^0_S \oplus \overline{\Lambda} K^0_S$ interaction
- No evidence for bound H-dibaryon in PbPb with $\Lambda\Lambda \oplus \overline{\Lambda\Lambda}$ correlation

E-by-E fluctuation via D^0 $v_2\{4\}$

[PRL 129 (2022) 022001]



Probing event-by-event fluctuation

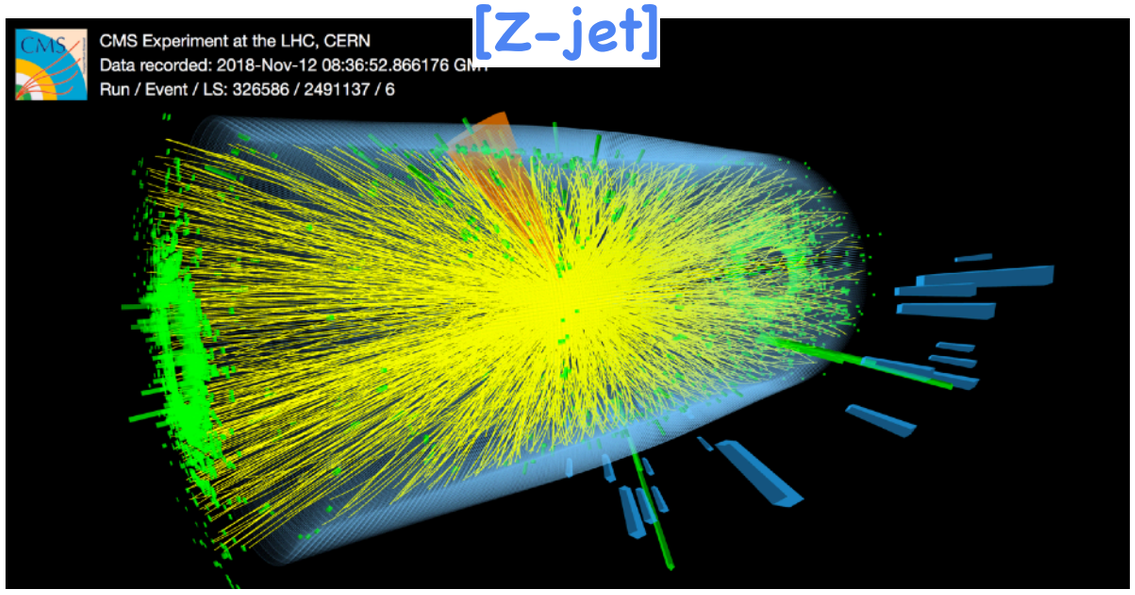
D+h

- $v_2\{2\}^2 \approx \langle v_2 \rangle^2 + \sigma^2$
- $v_2\{4\}^2 \approx \langle v_2 \rangle^2 - \sigma^2$

D+h+h+h

Flow *Fluctuation*

- $v_2\{4\}/v_2\{2\}$ as a discriminator of v_2 fluctuations
  - Similar trend as charged particles
    : fluctuations mainly from initial geometry?
  - Deviation in most-central & most-peripheral
    : Hint of additional fluctuations from E-loss
- Better described by collisional E-loss mechanisms

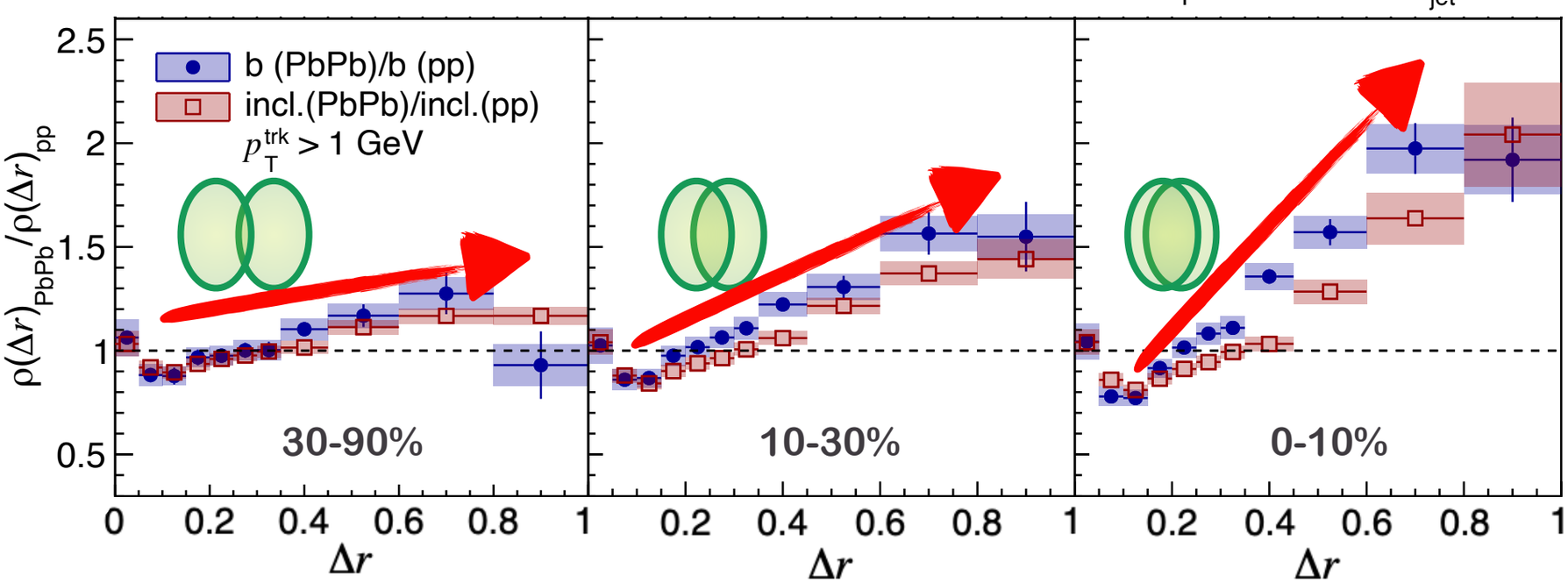


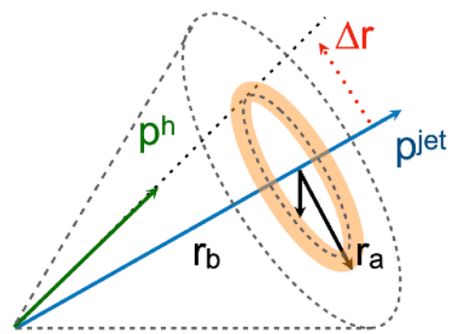
[Z-jet]

- EW probes
- Flow/Correlations
- Jets
- HF & Quarkonia
- Ultraperipheral collisions (UPCs)

b-jet shape in PbPb and pp (1)

[arXiv:2210.08547]

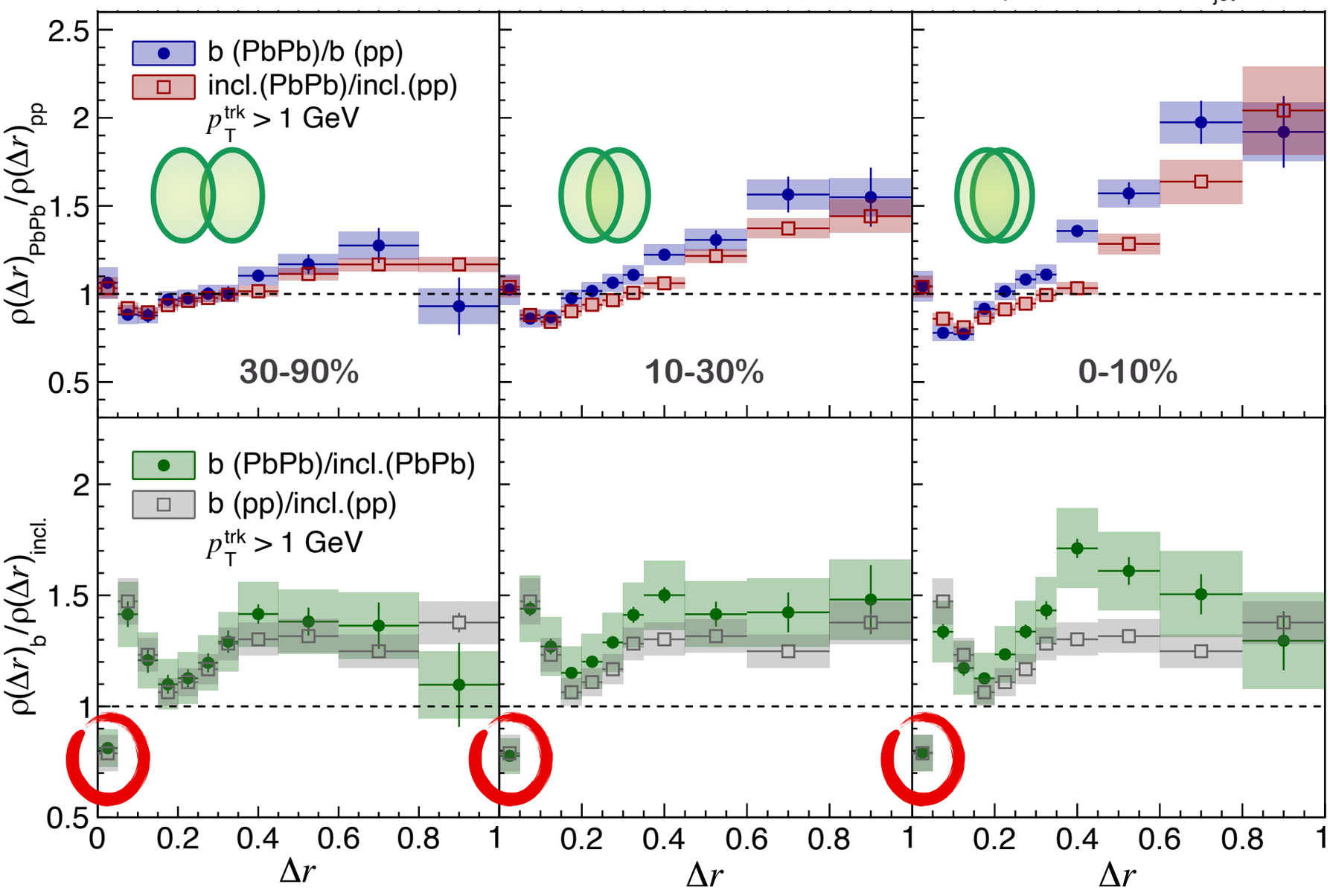


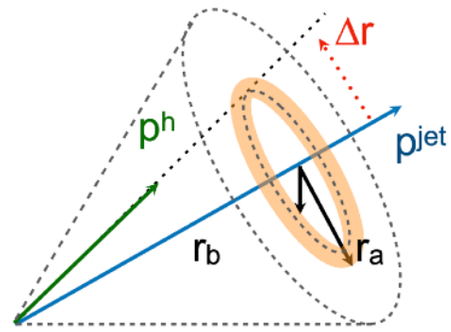


- Larger relative modification for b and inclusive jets at large Δr in central collisions

b-jet shape in PbPb and pp (2)

[arXiv:2210.08547]

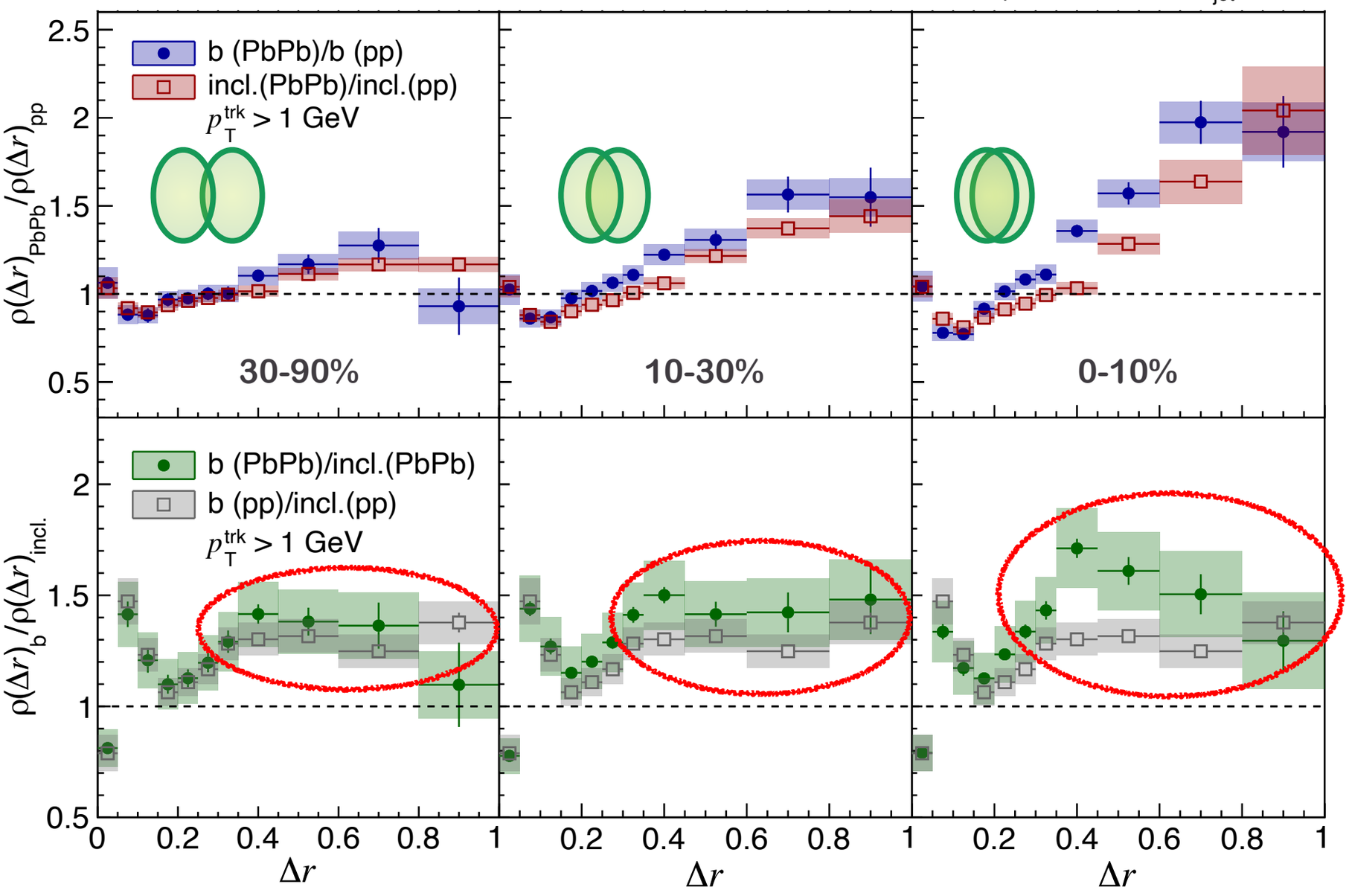


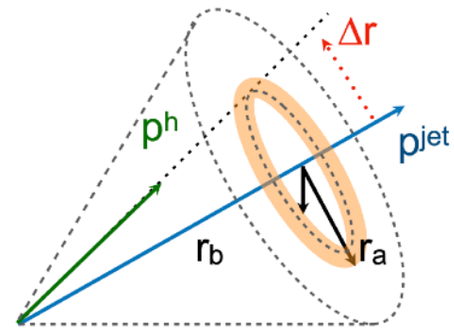


- Larger relative modification for b and inclusive jets at large Δr in central collisions
- Depletion at small Δr : suggestion of dead-cone effect for b jets

b-jet shape in PbPb and pp (3)

[arXiv:2210.08547]

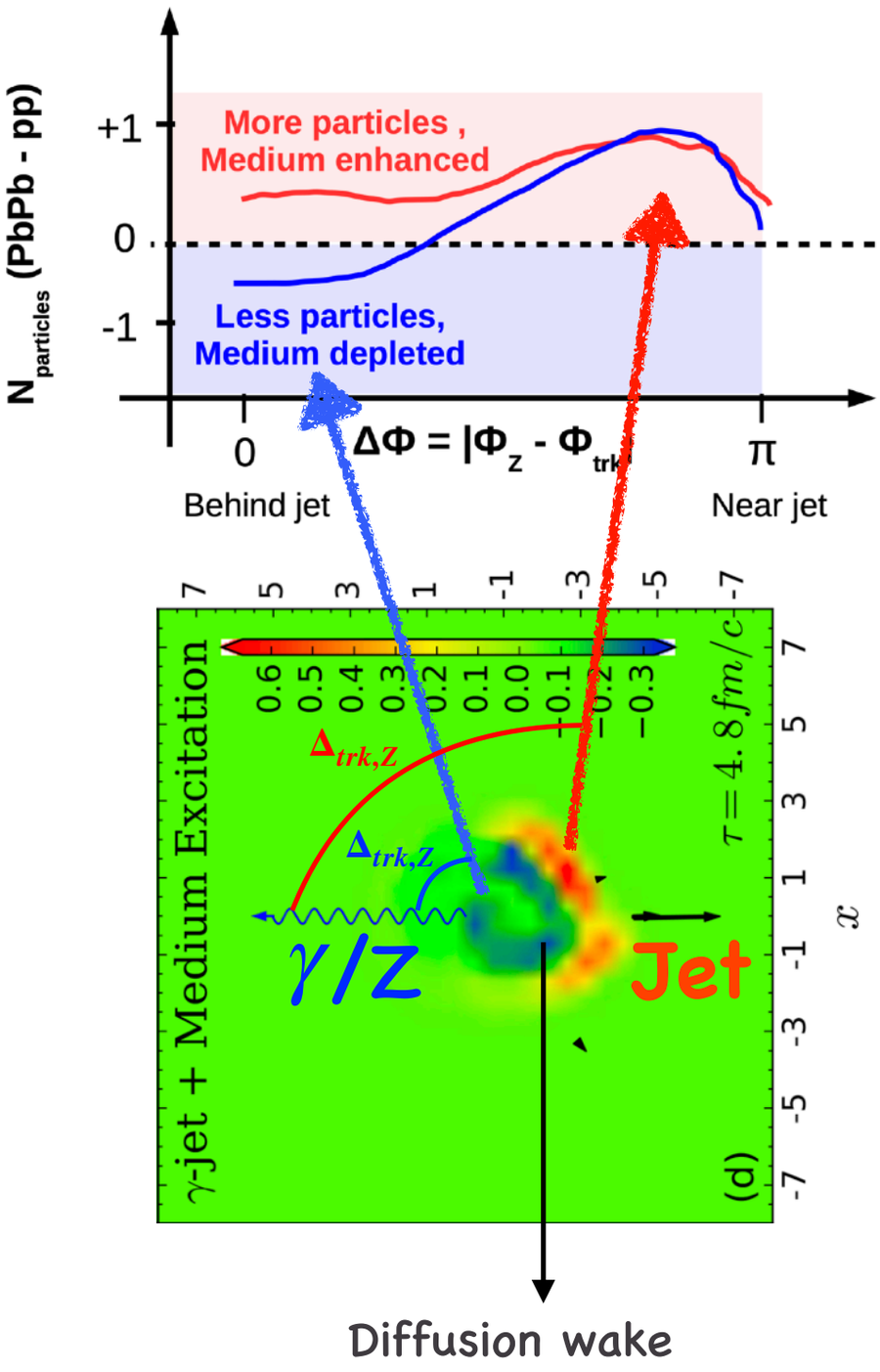




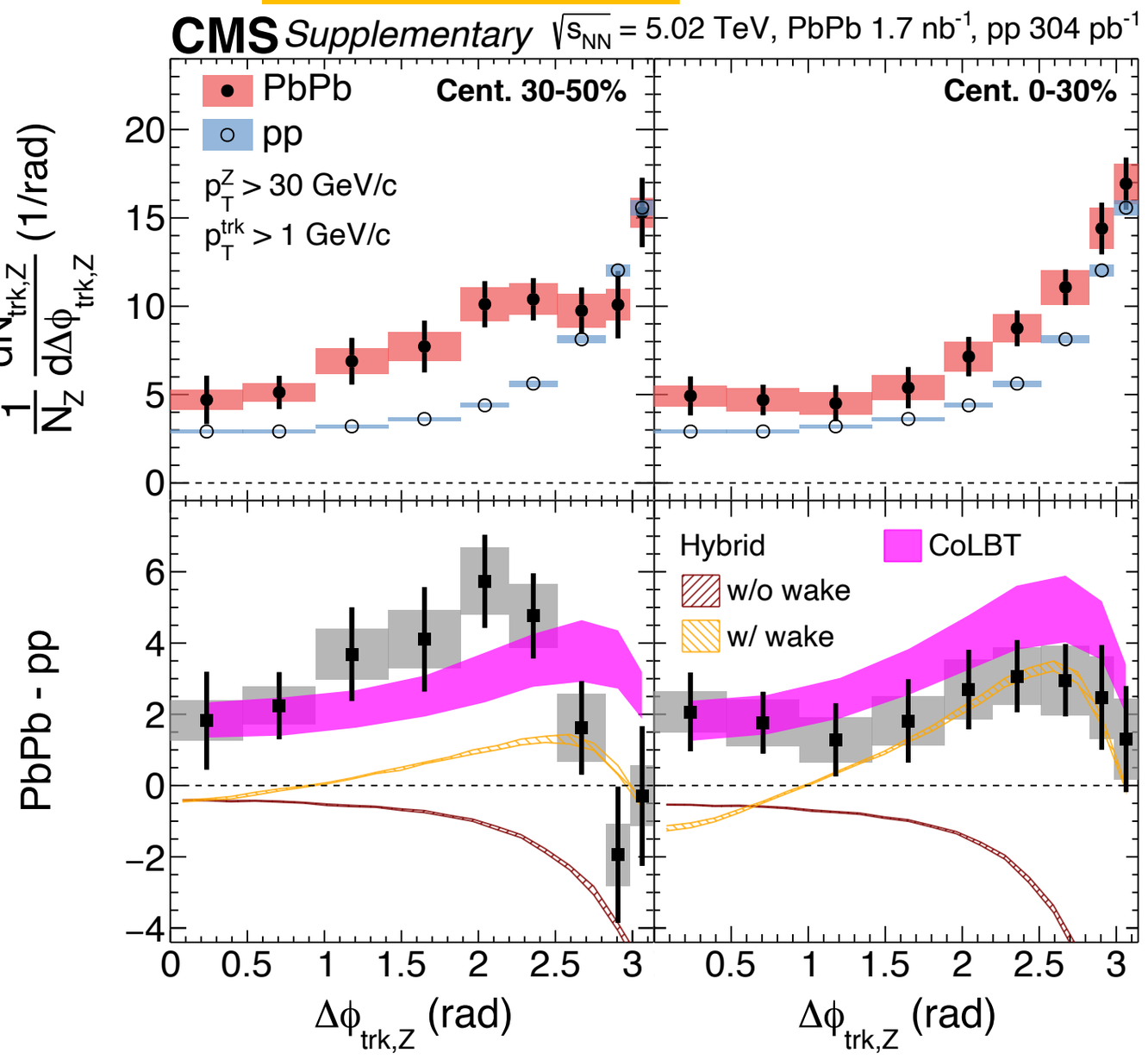
- Larger relative modification for b and inclusive jets at large Δr in central collisions
- Depletion at small Δr : suggestion of dead-cone effect for b jets
- Large Δr enhancement greater for b jets in PbPb : increased medium response for b quarks

Parton-Medium Interactions

[PLB 777 (2018) 86]



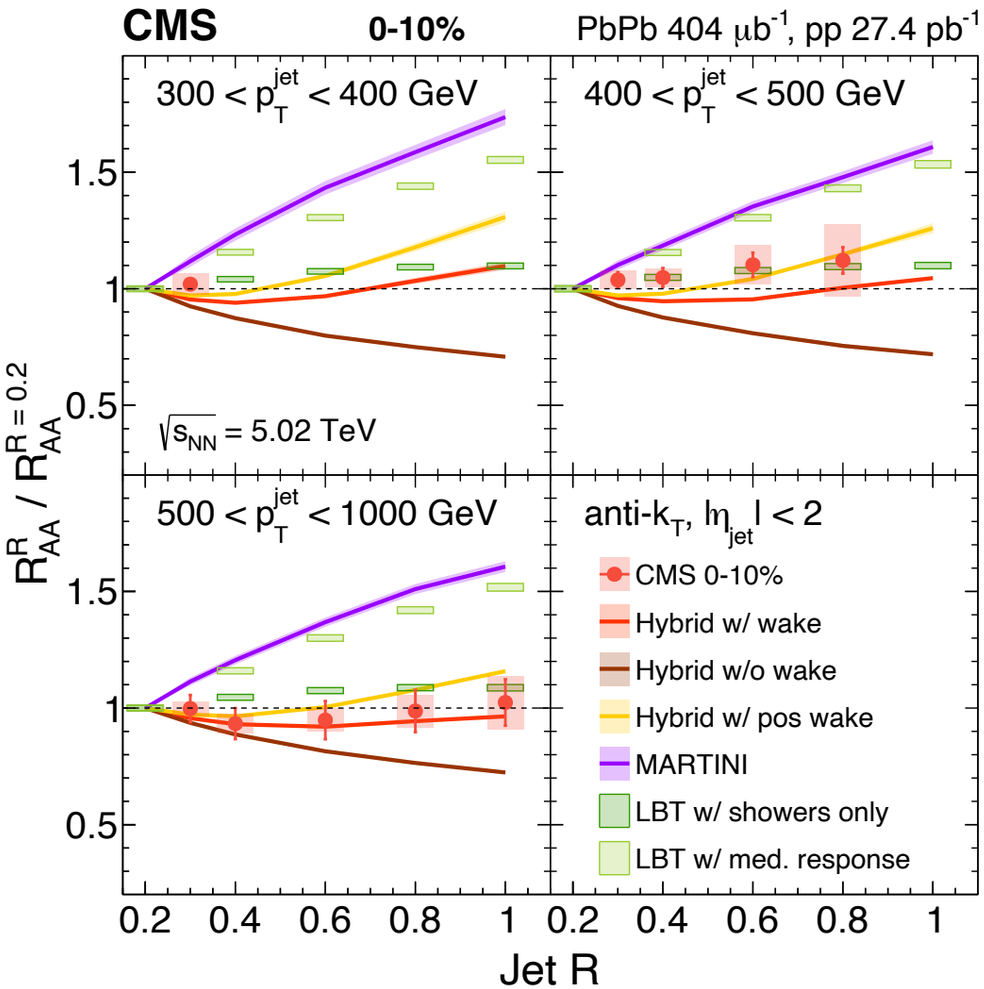
[PRL 128 (2022) 122301]

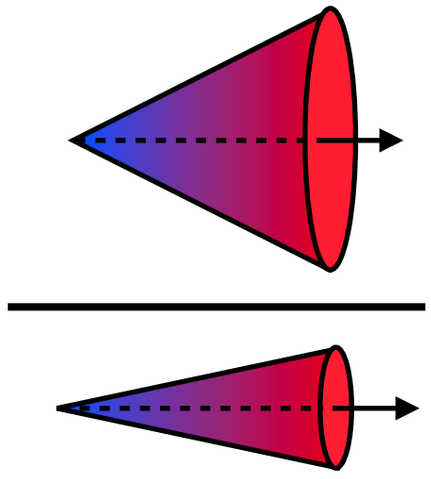


- Excess of particle yield in PbPb collisions
- No depletion at $\Delta\phi_{trk,Z} \sim 0$? Possible quenching of MPI
  → Strong constraints to medium-parton interaction models

Jet R_{AA} of large area

[JHEP05(2021)284]

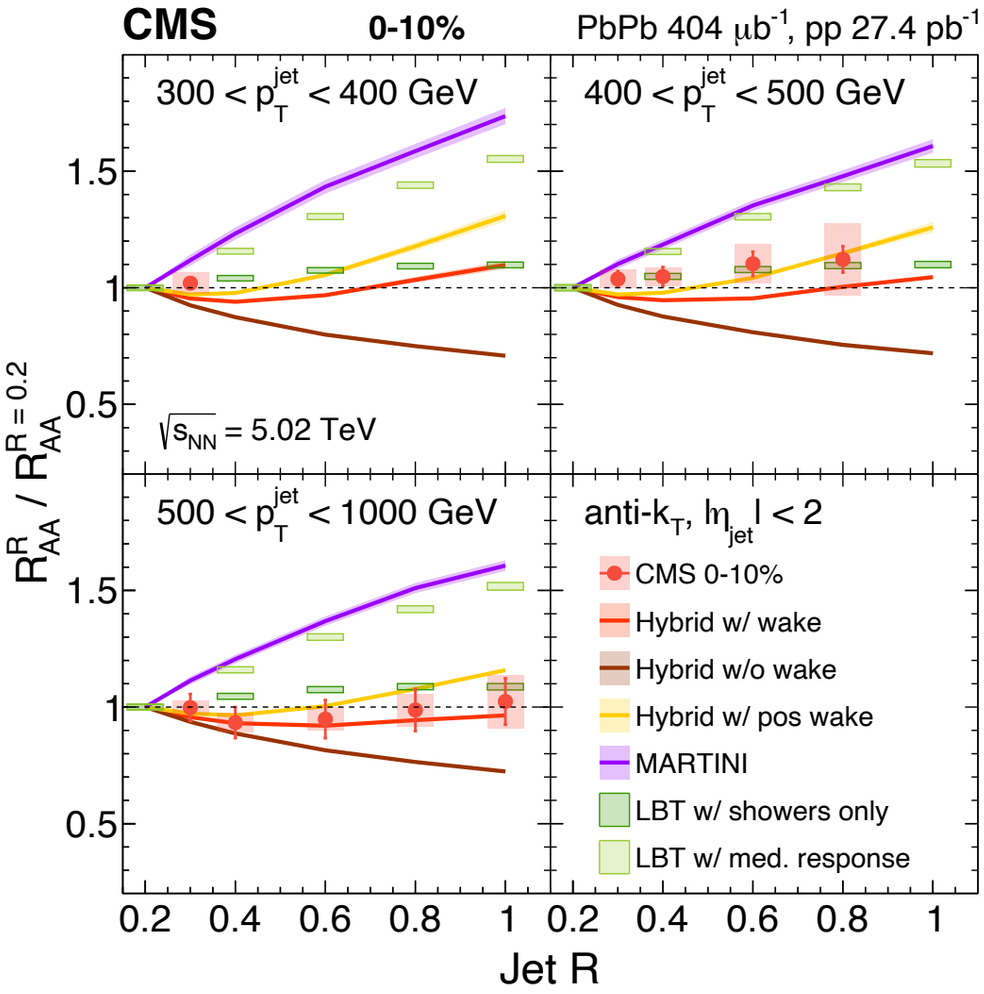


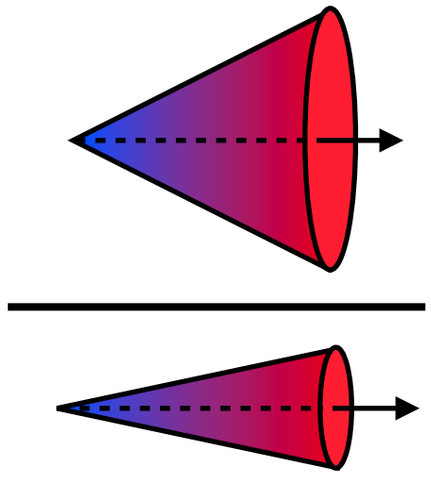


- Competing effects
  - Recovery of E-loss
  - Stronger suppression in wider cone

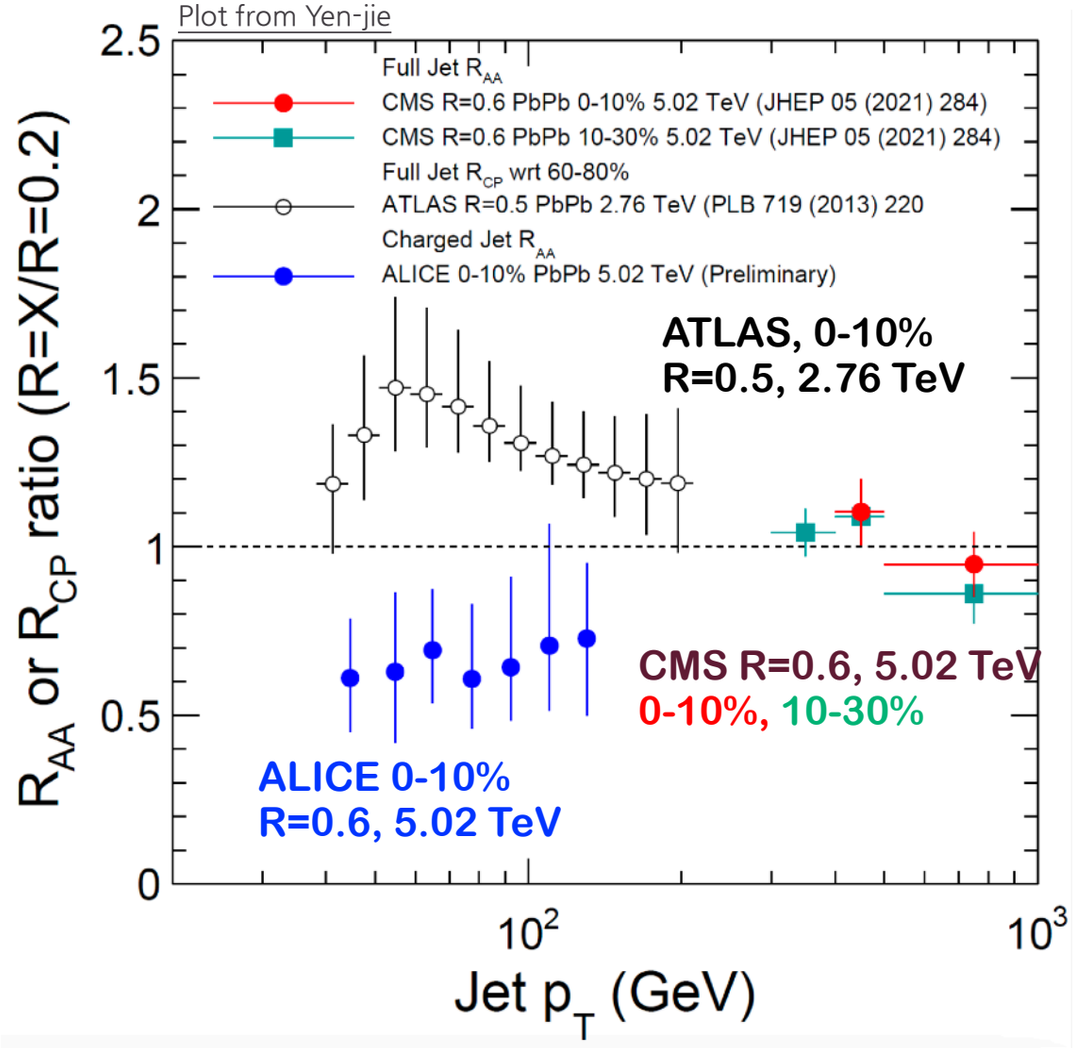
Jet R_{AA} of large area (low-p_T)

[JHEP05(2021)284]



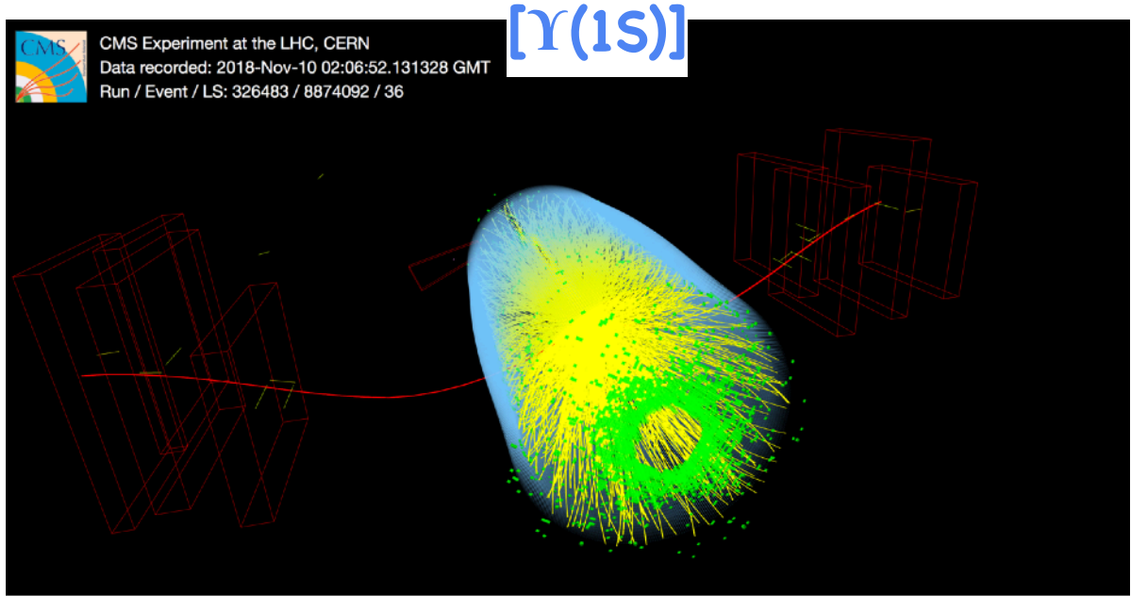


[ALICE preliminary] [PLB 719 (2013) 220]



- Competing effects
  - Recovery of E-loss
  - Stronger suppression in wider cone

- Caveat at lower-p_T @ LHC (ATLAS/ALICE)
  - sensitive to detailed jet reconstruction algorithm?

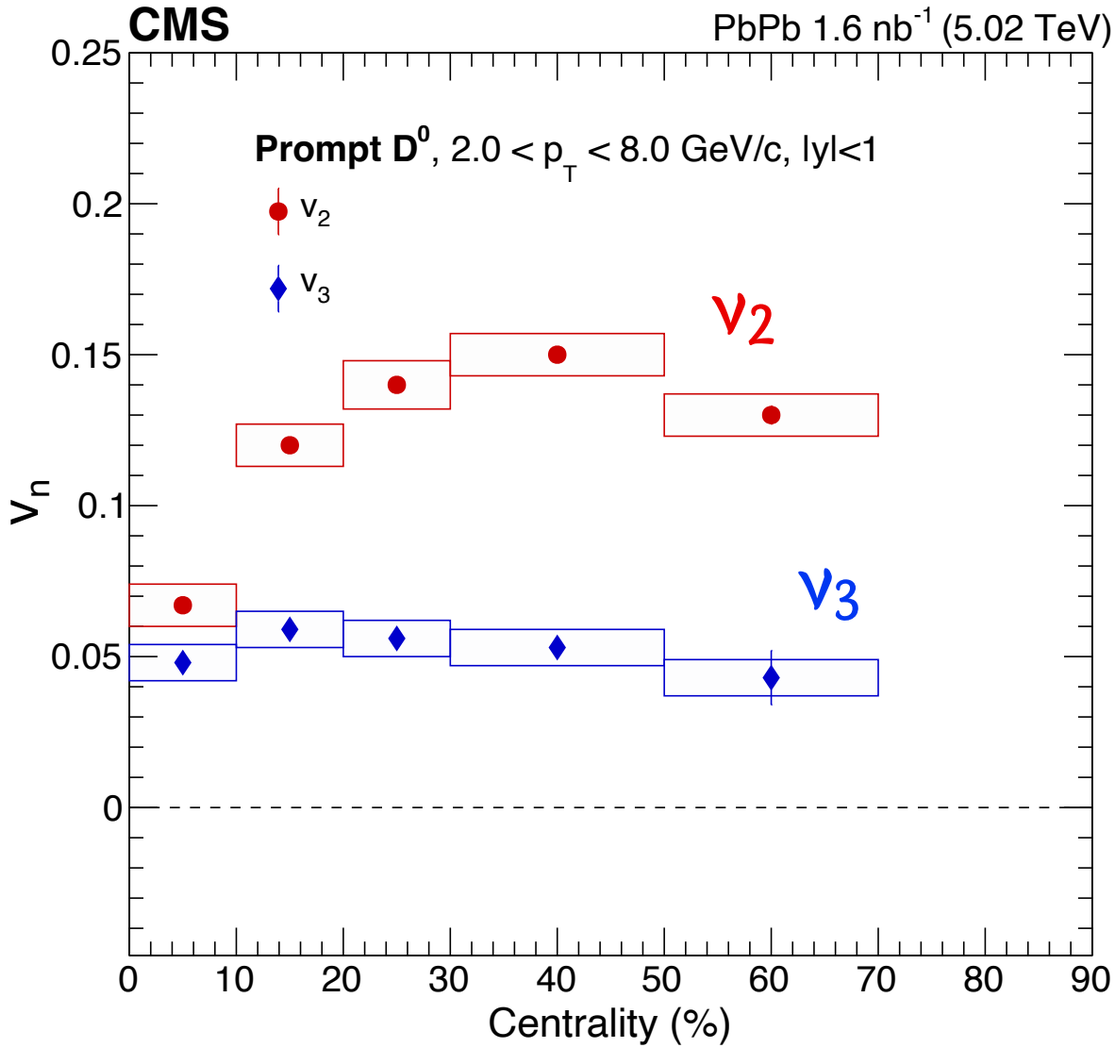


[Υ(1S)]

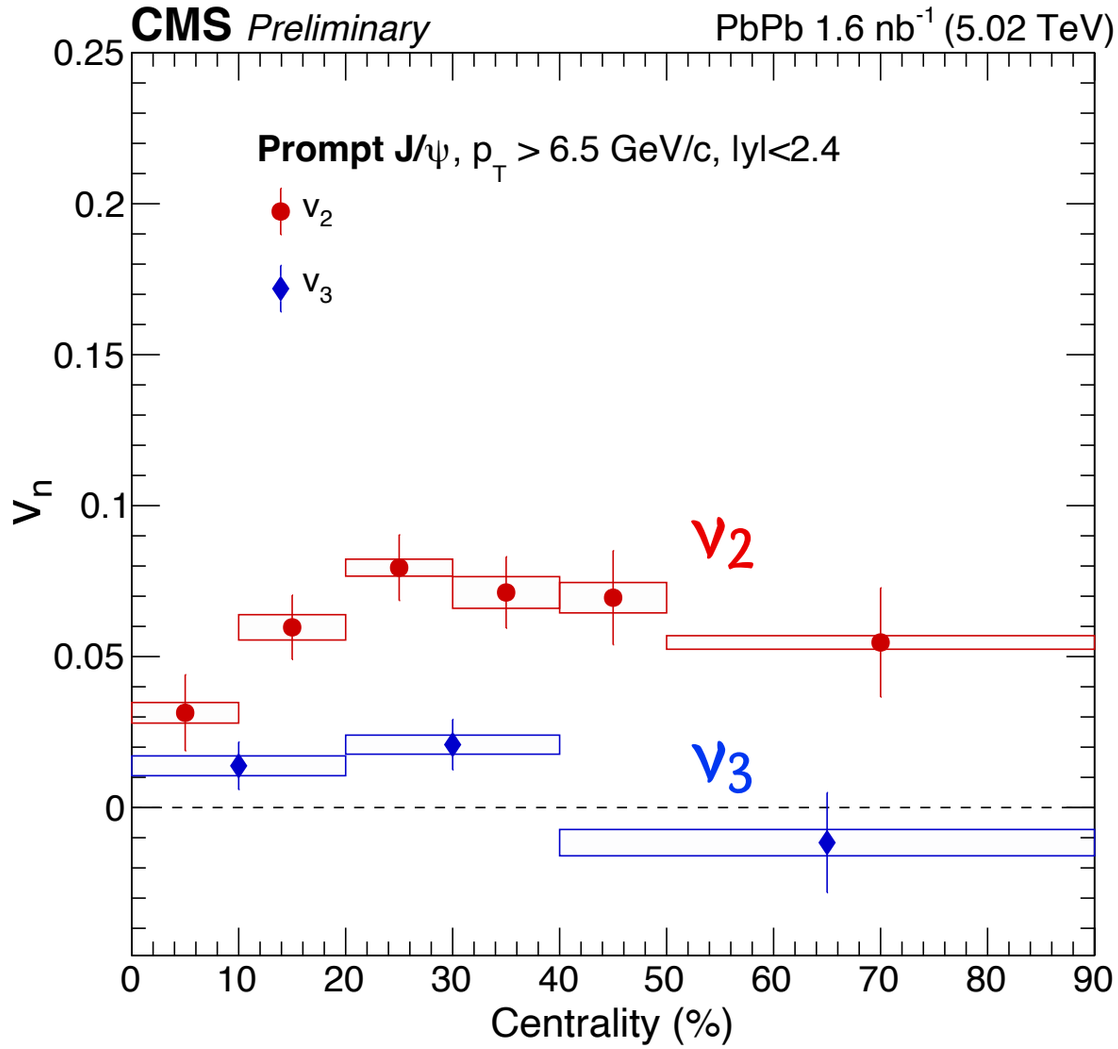
- EW probes
- Flow/Correlations
- Jets
- HF & Quarkonia
- Ultraperipheral collisions (UPCs)

Open vs hidden charm in PbPb

[PLB 816 (2021) 136253] **Prompt D^0**



Prompt J/ψ [CMS-PAS-HIN-21-008]

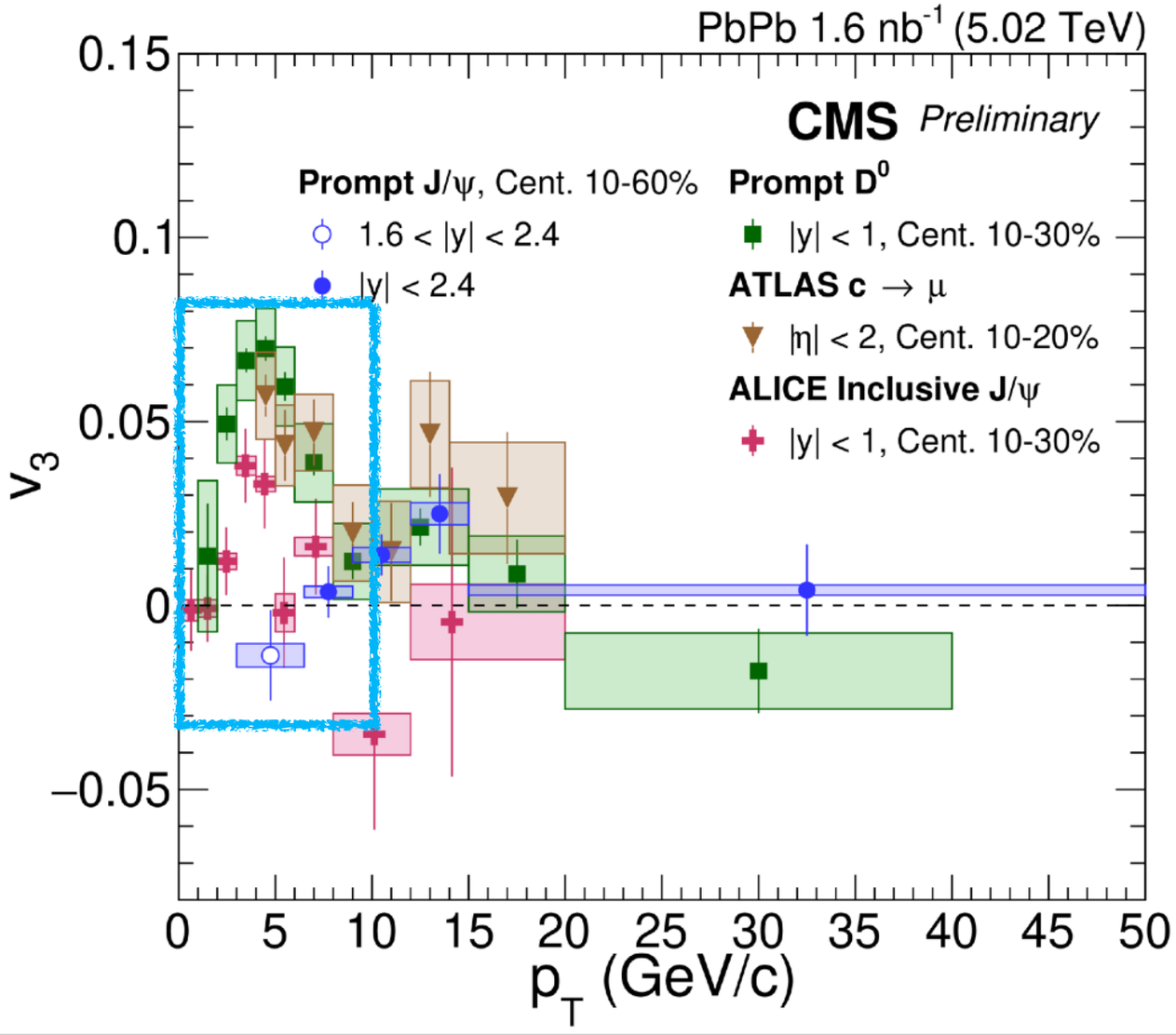


- v_2 maxima at mid-central collisions for D^0 & J/ψ –> hydrodynamical behavior
- D^0 v_3 > J/ψ v_3 : open charm less sensitive to initial geometry? N.B different p_T range

Charm v_3 in PbPb @ LHC

Prompt D⁰ | **c → μ**

Prompt J/ψ | **Inclusive J/ψ**



[CMS-PAS-HIN-21-008]

[PLB 816 (2021) 136253]

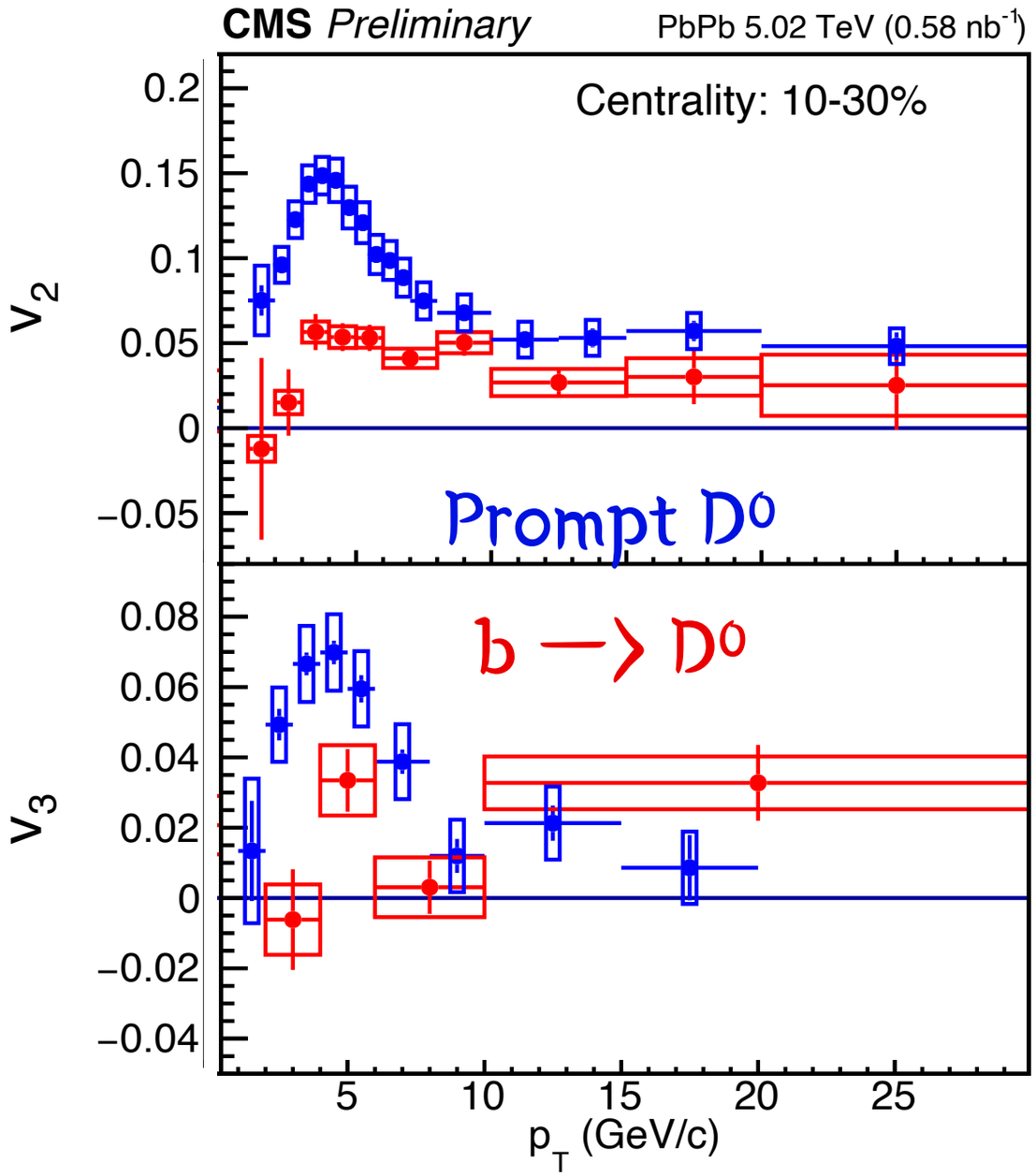
[JHEP 10 (2020) 141]

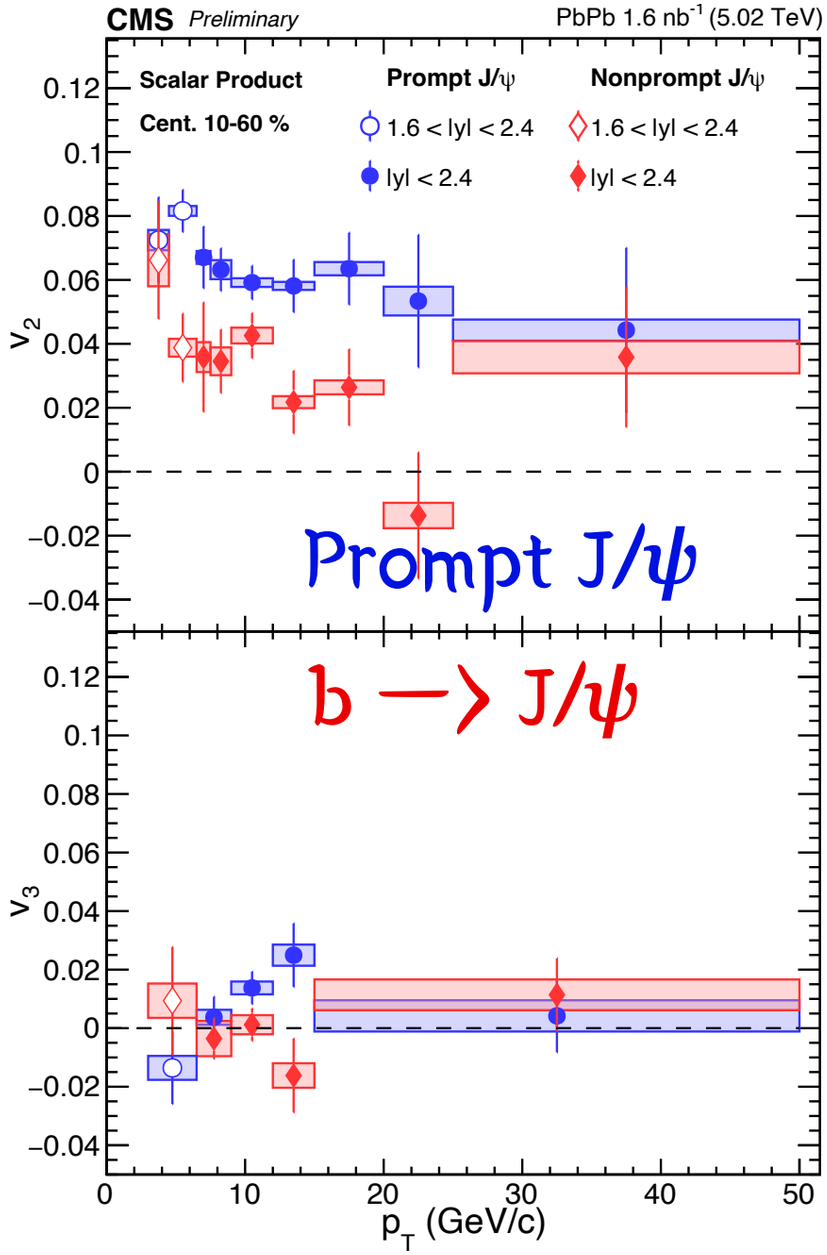
[PLB 807 (2020) 135595]

- Hint of larger v_3 for open charm than hidden charm mesons
- Not possible for a firm conclusion with current uncertainties..

Charm vs bottom in PbPb

[PLB 816 (2021) 136253]



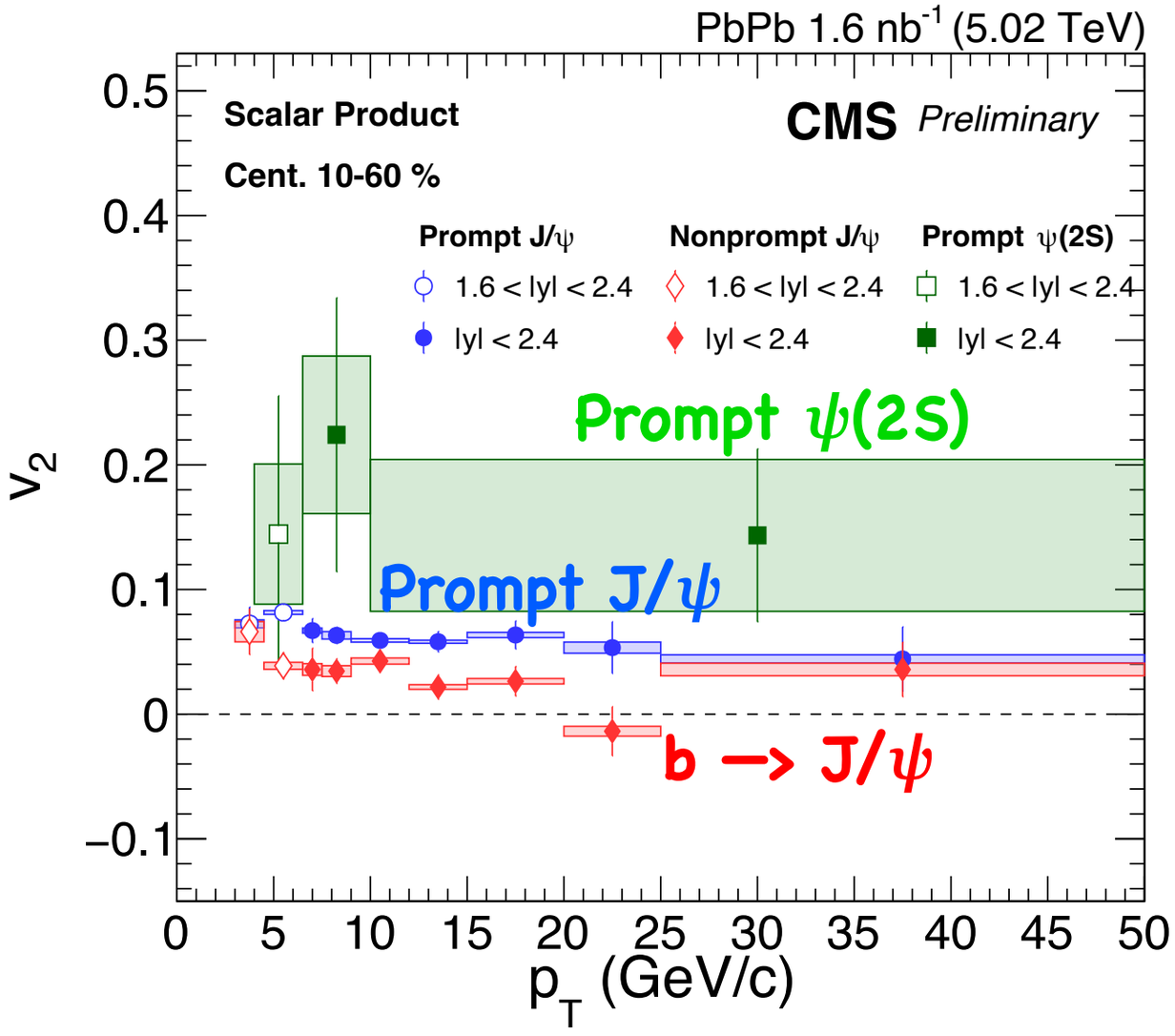


[CMS-PAS-HIN-21-008]

- Prompt D^0, J/ψ v_2 > b —> D^0, J/ψ v_2 : different in-medium effects for charm and bottom
- Prompt D^0 v_3 > b —> D^0 v_3 ⟷ Not seen with J/ψ
  : different b-quark medium effect transfer for open vs hidden charm? b/c of different p_T region?

Charmonia in PbPb

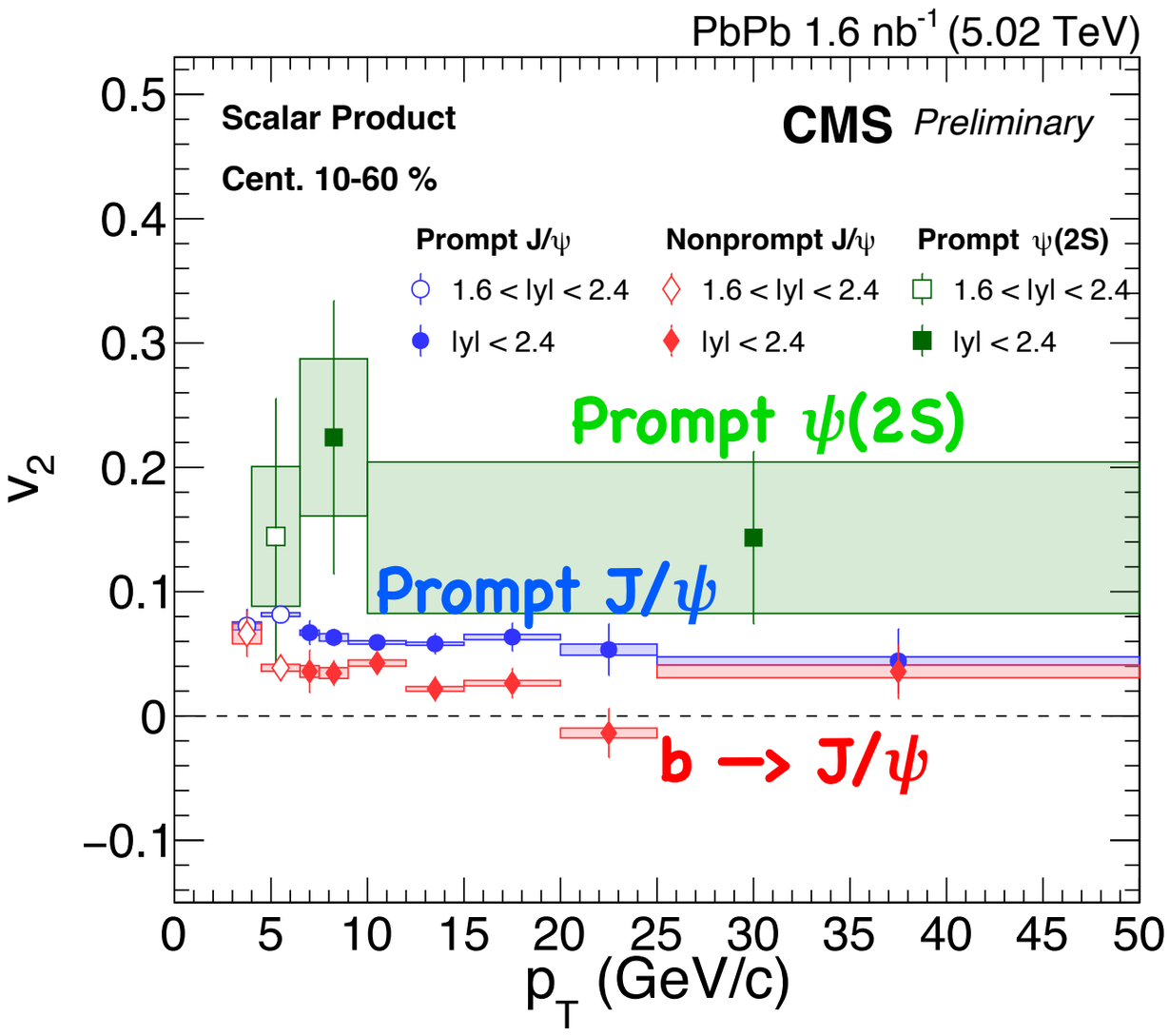
[CMS-PAS-HIN-21-008]



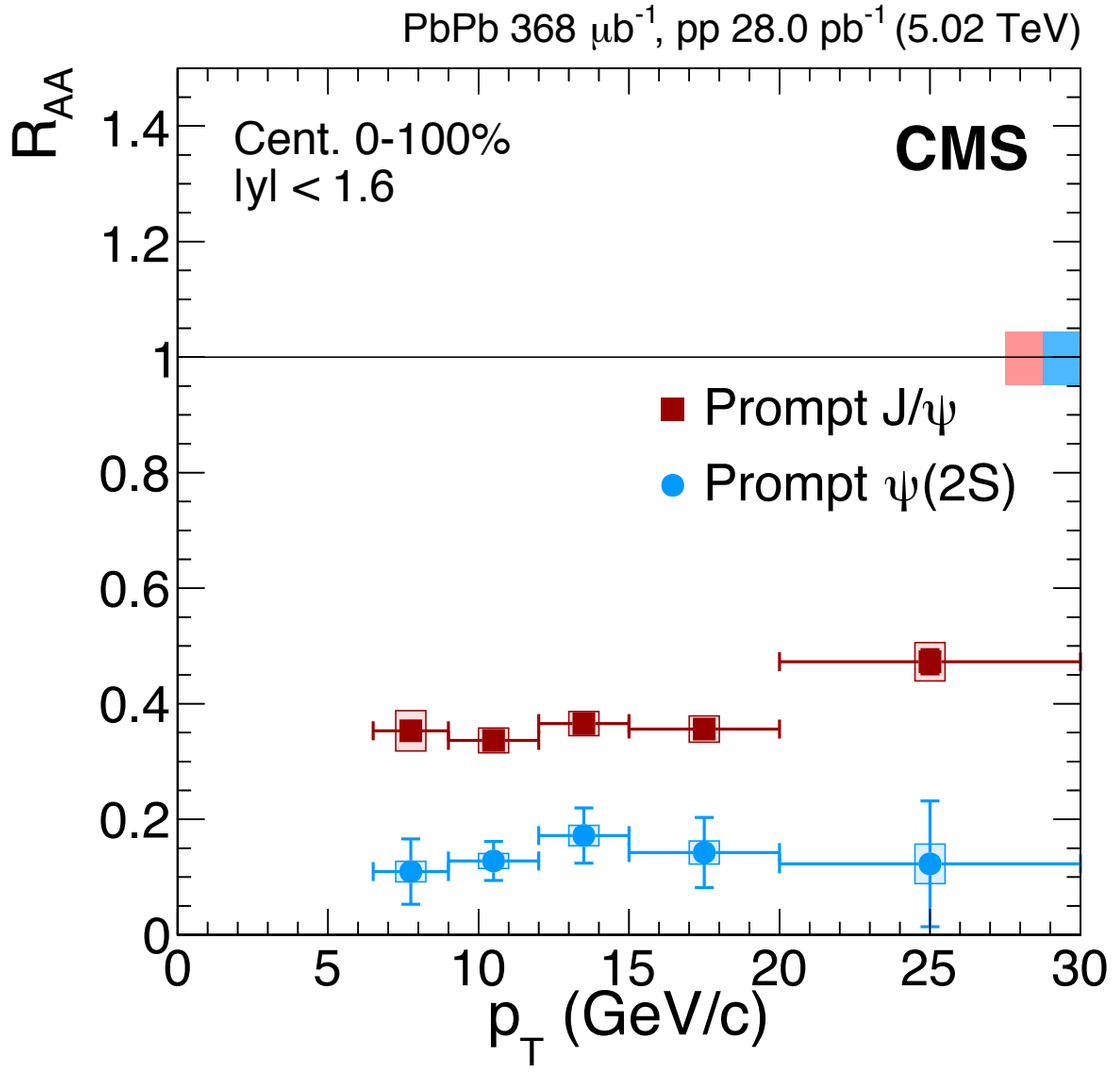
- Hint of $v_2(\psi(2S)) > v_2(J/\psi)$: recombination? path-length E. loss? Jet-fragmentation?

Charmonia in PbPb

[CMS-PAS-HIN-21-008]



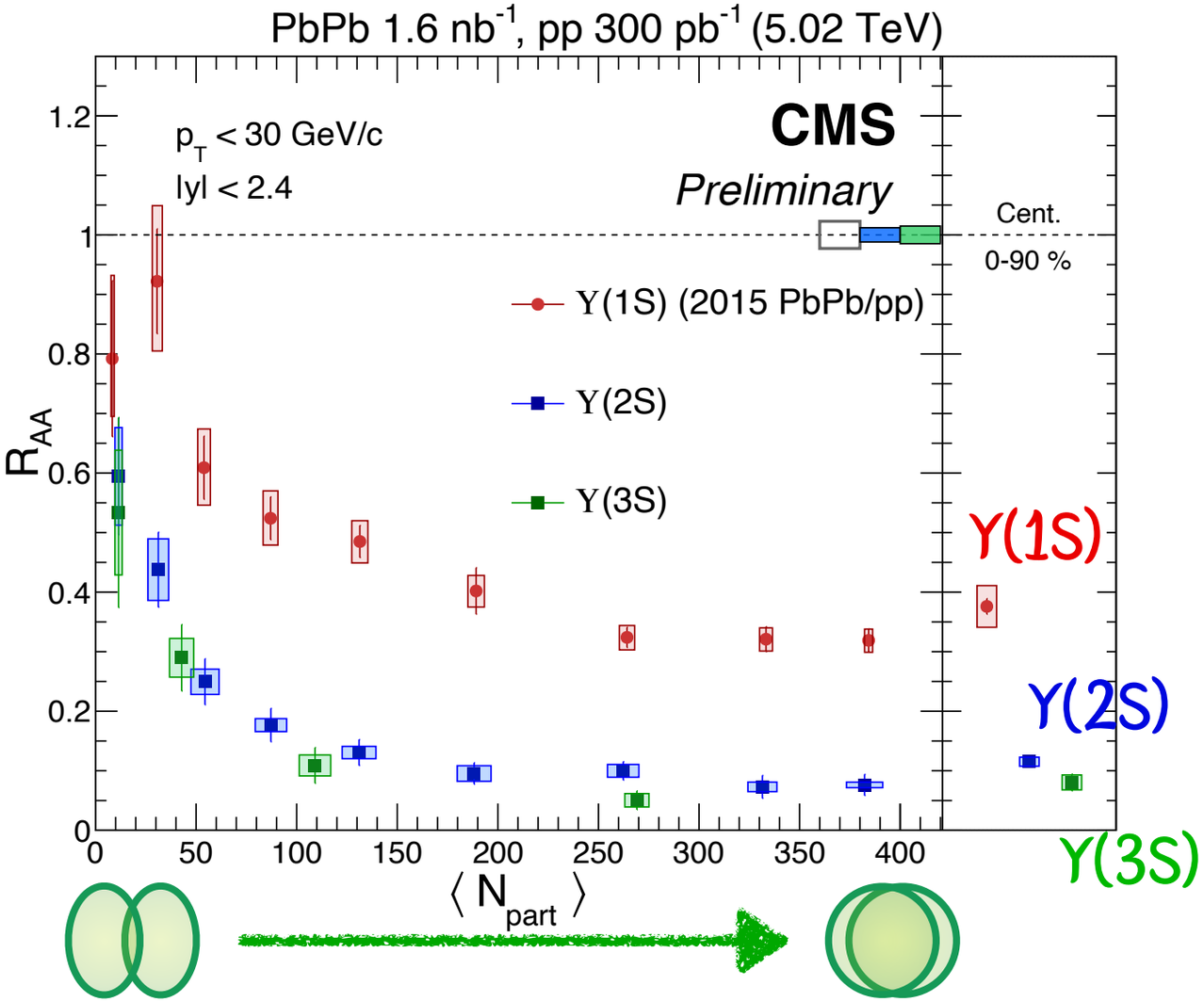
[EPJC 78 (2018) 509]



- Hint of $v_2(\psi(2S)) > v_2(J/\psi)$: recombination? path-length E. loss? Jet-fragmentation?
- Still larger suppression than J/ψ at high-p_T : $R_{AA}(J/\psi) > R_{AA}(\psi(2S))$

Bottomonia in PbPb

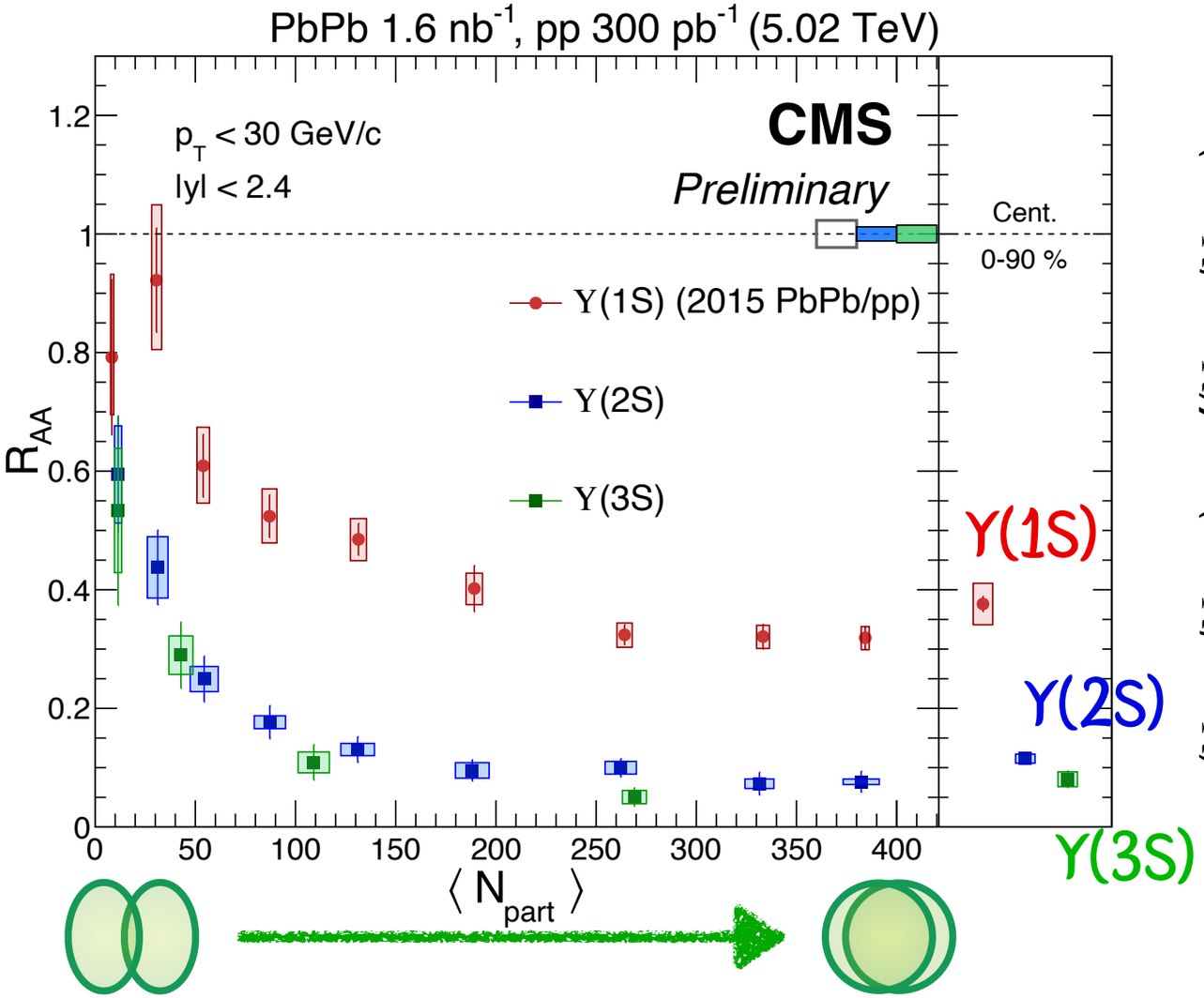
[CMS-PAS-HIN-21-007]

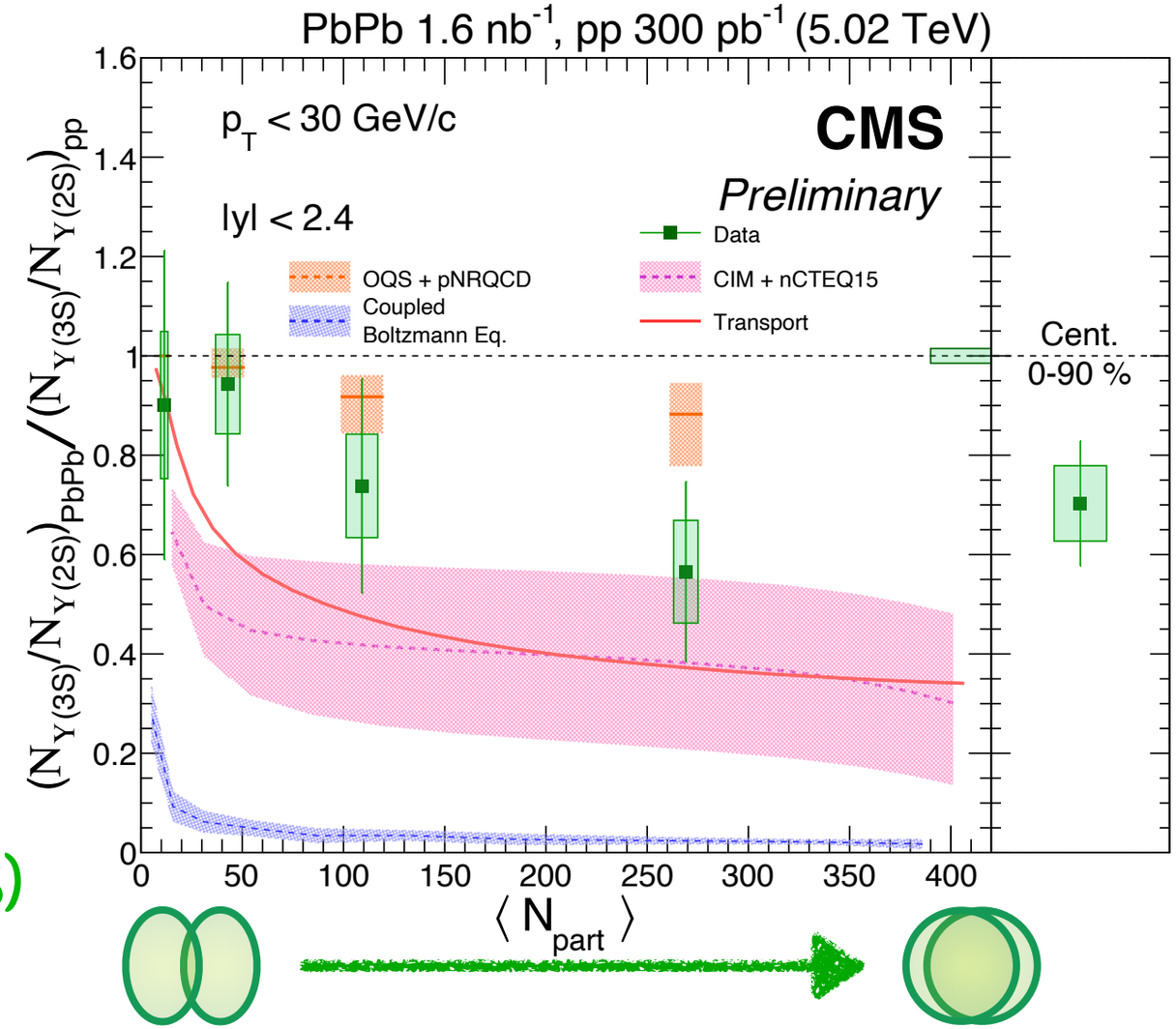


- Observation of Υ(3S) in PbPb! (> 5σ)
- Clear quantification of Υ(1,2,3S) sequential suppression
  $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$

Bottomonia in PbPb

[CMS-PAS-HIN-21-007]





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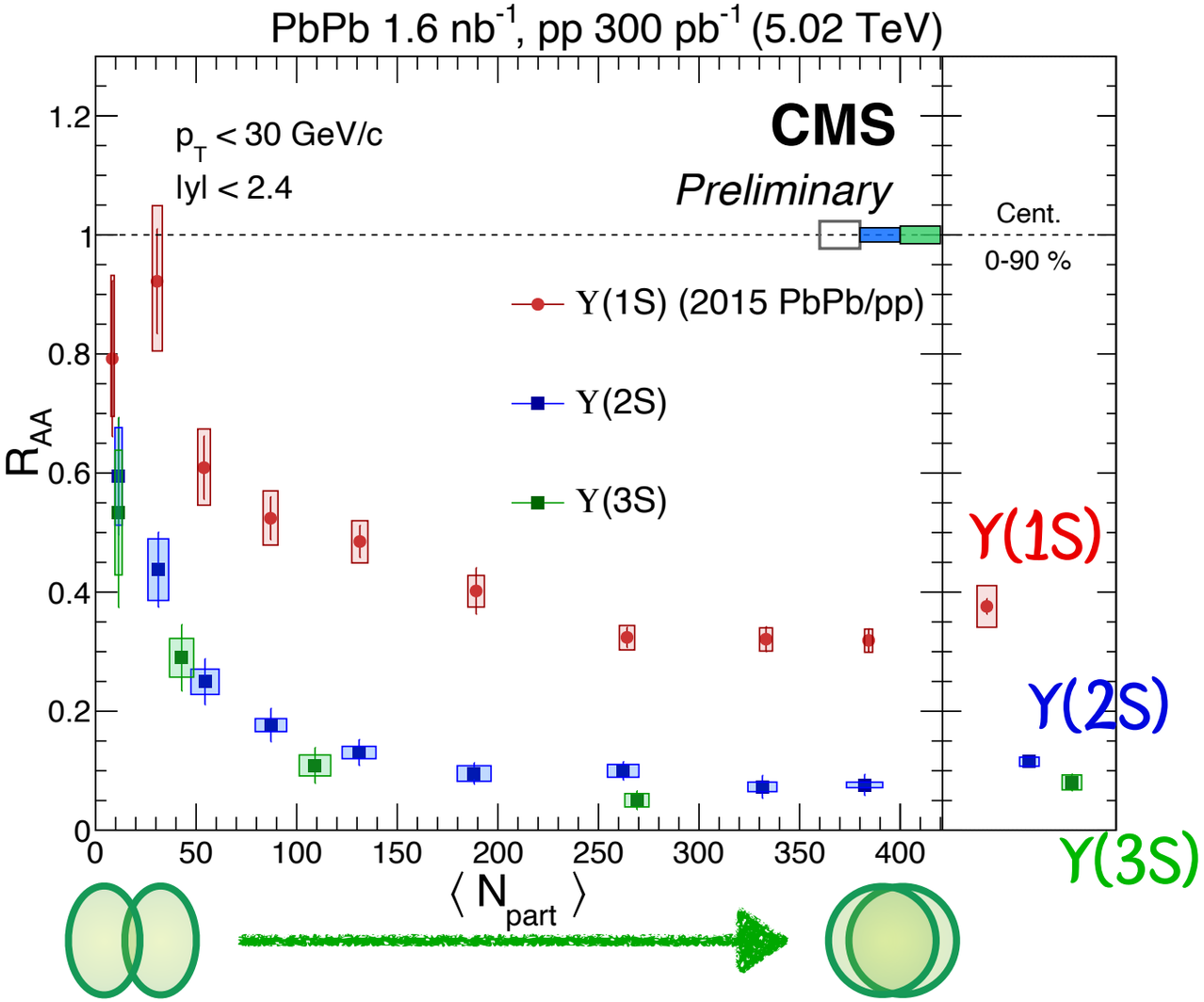
- Clear quantification of Υ(1,2,3S) sequential suppression
  $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$

- Propose a new observable : Υ(3S)/Υ(2S) double ratio
- Strong constraints on models

Bottomonia in PbPb and pPb

[CMS-PAS-HIN-21-007]



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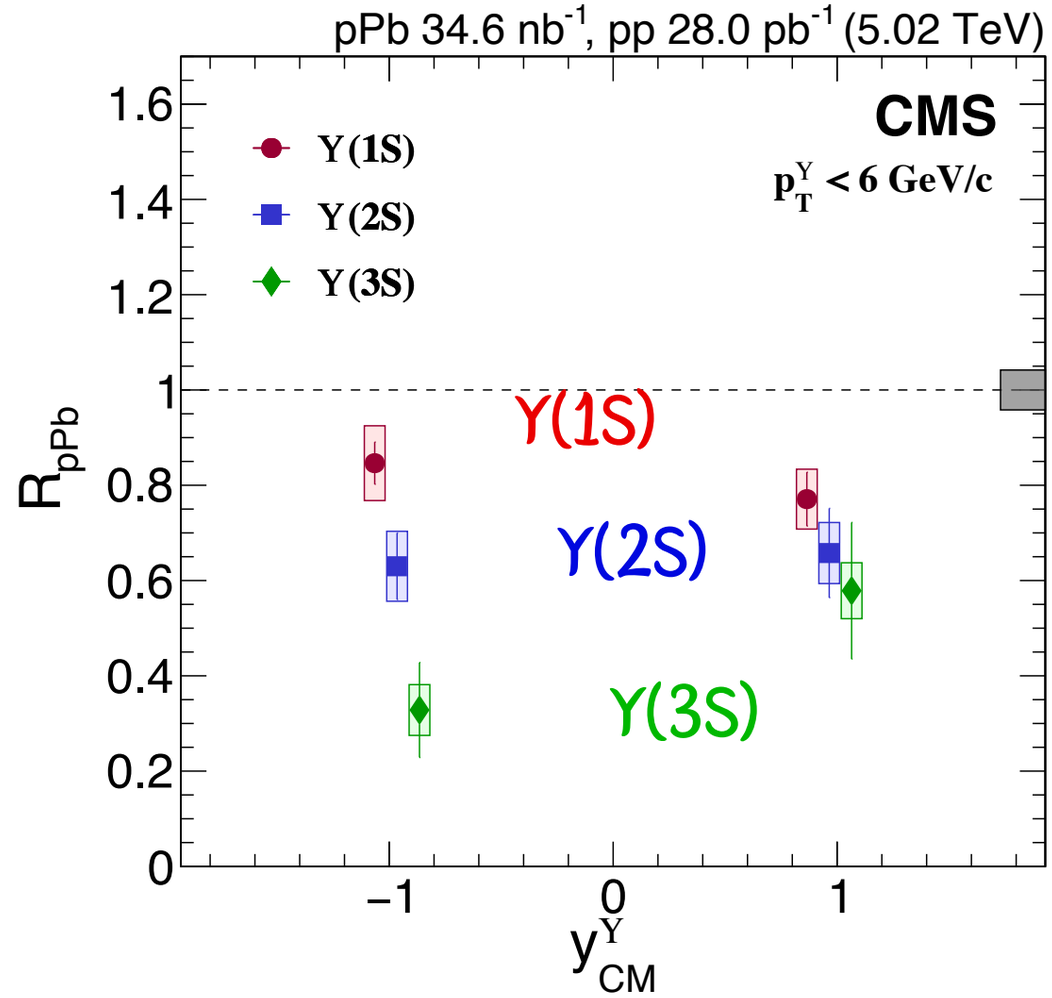
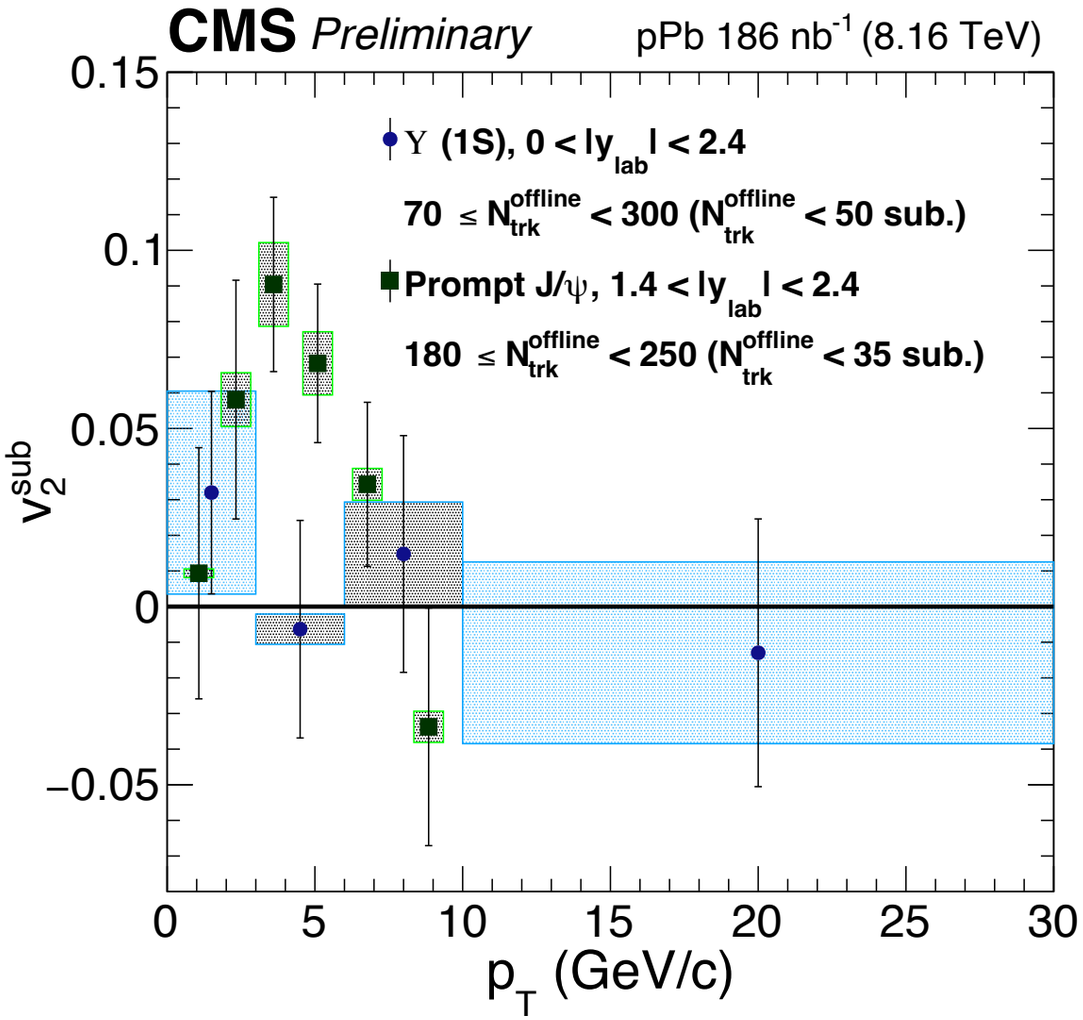
[PLB 835 (2022) 137397]



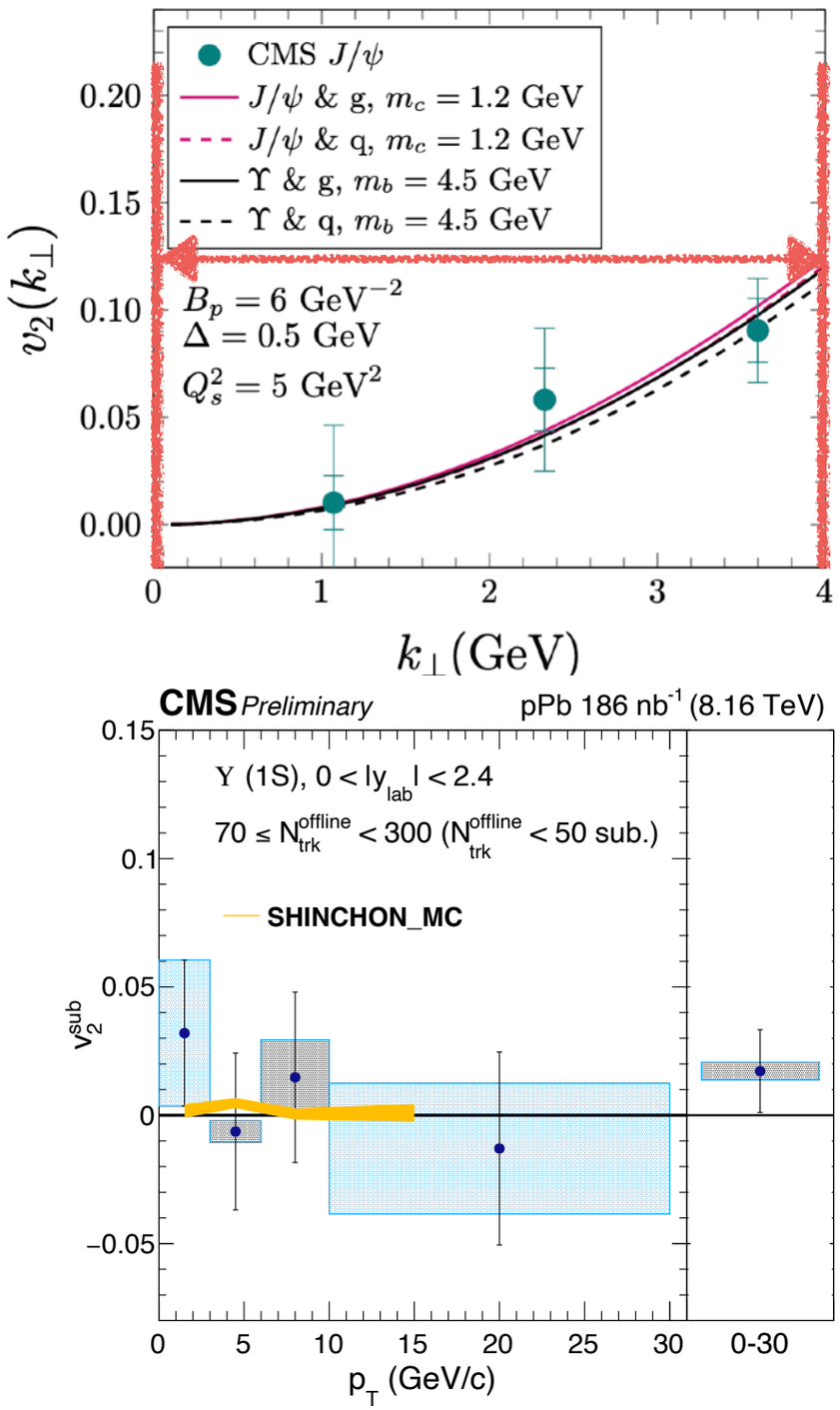
- Sequential suppression also in pPb!
- Cold or hot medium final state effect?

Y(1S) v_2 in pPb

[CMS-PAS-HIN-21-001]

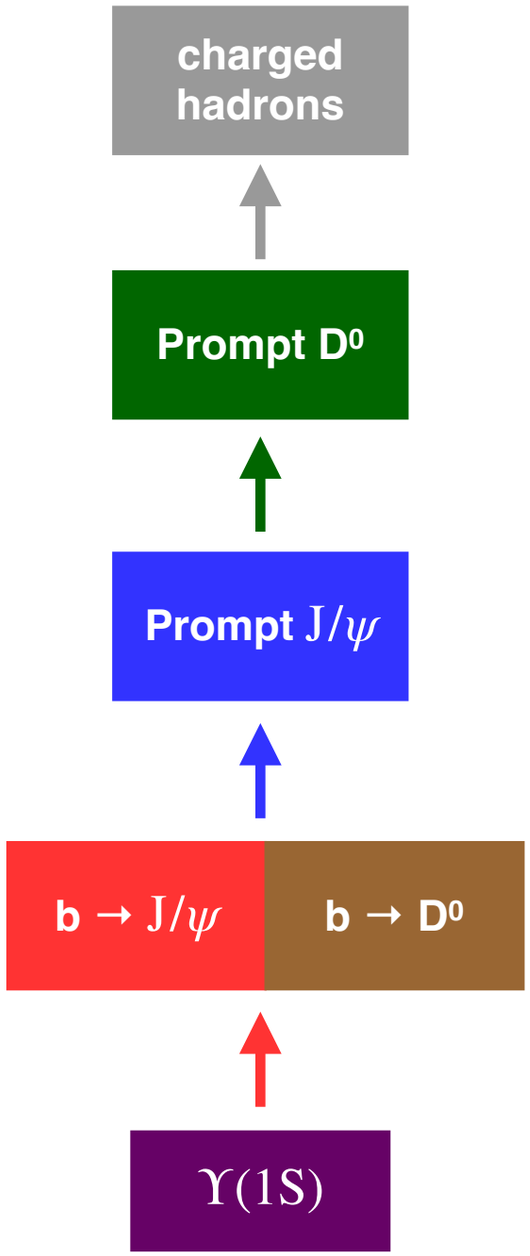


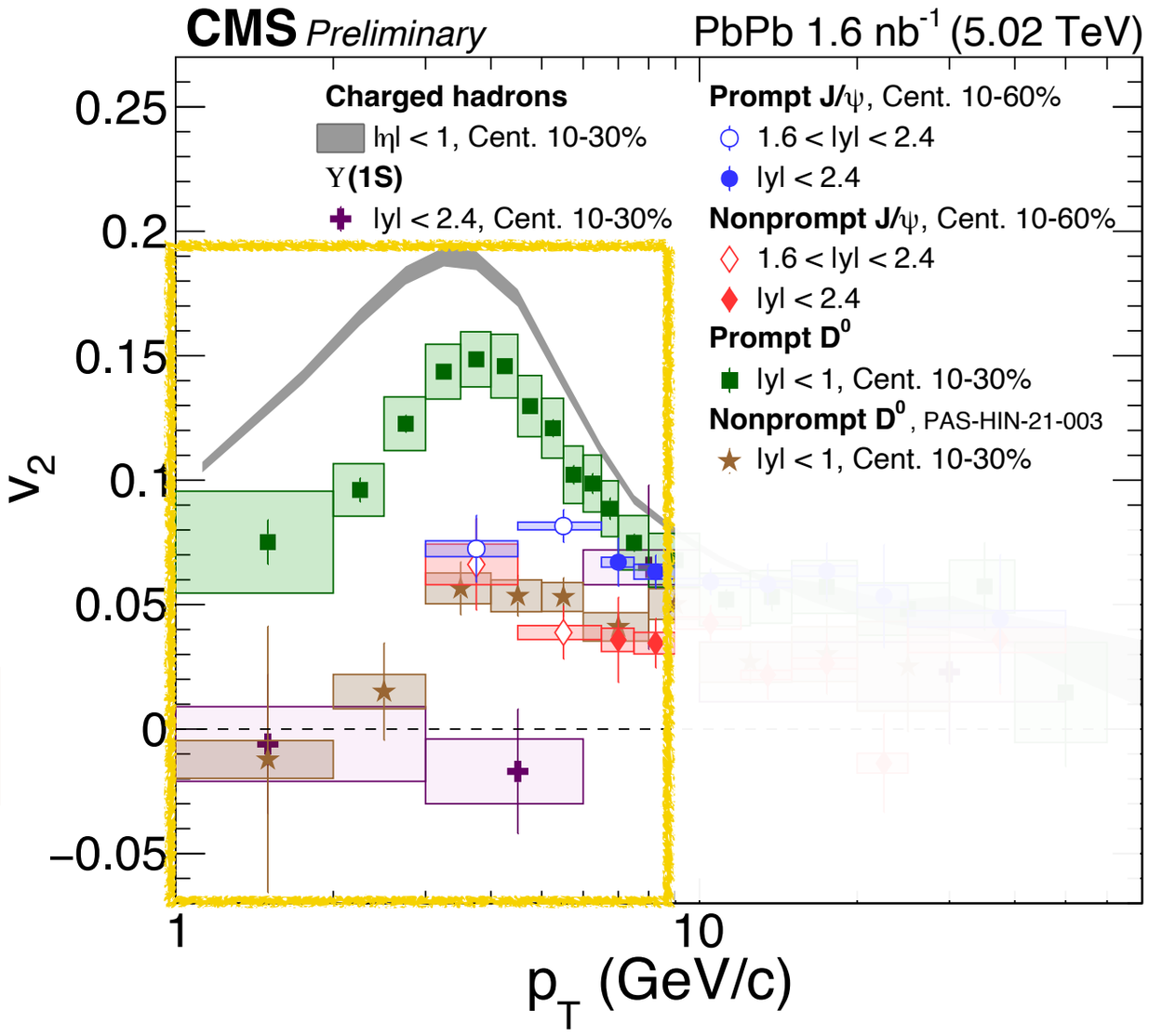
[PRD 102 (2020) 034010]



- Smaller v_2 of Υ(1S) in pPb than J/ψ!
- Deviation from LO CGC predictions
  - Caveat of LO only + large data unc.
- Small v_2 predicted by dissociation-only picture

CMS HF v_2 Zoo : PbPb





[CMS-PAS-HIN-21-003]

[CMS-PAS-HIN-21-008]

[PLB 816 (2021) 136253]

[PLB 819 (2021) 136385]

[PLB 776 (2017) 195]

- Low-p_T : light > open charm > hidden charm > open beauty > hidden beauty

CMS HF v_2 Zoo : PbPb

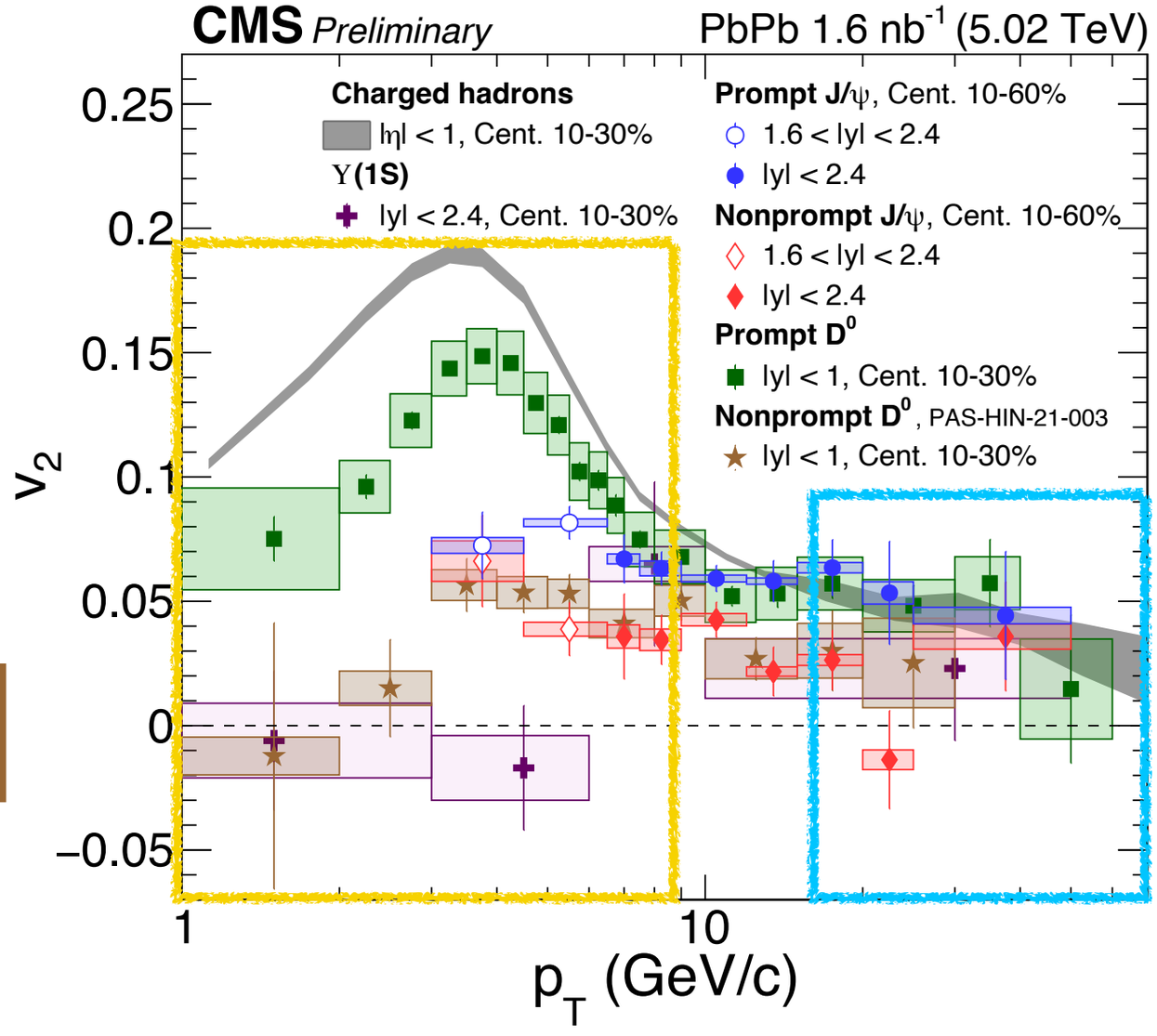
charged hadrons

Prompt D^0

Prompt J/ψ

$b \to J/\psi$ | $b \to D^0$

$\Upsilon(1S)$



[CMS-PAS-HIN-21-003]

[CMS-PAS-HIN-21-008]

[PLB 816 (2021) 136253]

[PLB 819 (2021) 136385]

[PLB 776 (2017) 195]

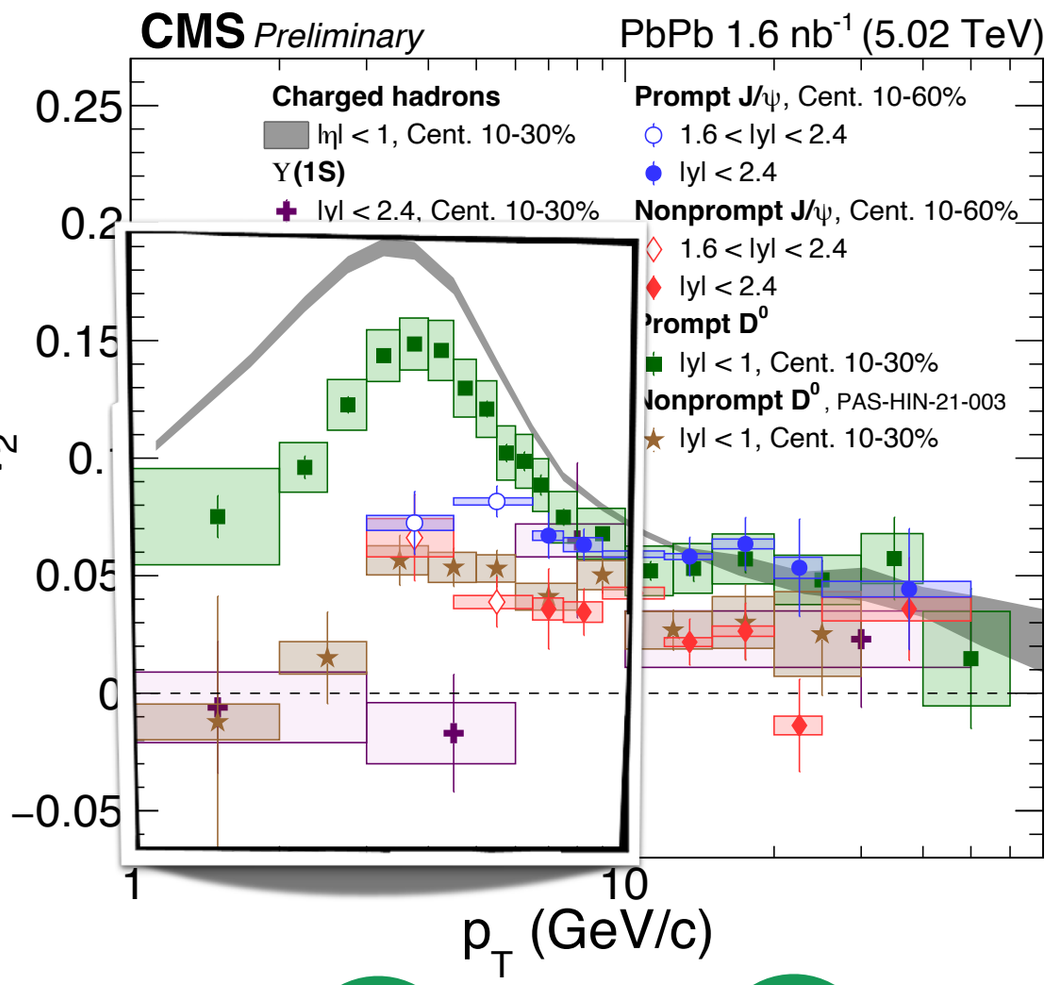
charged hadrons ≈ Prompt D^0 ≈ Prompt J/ψ

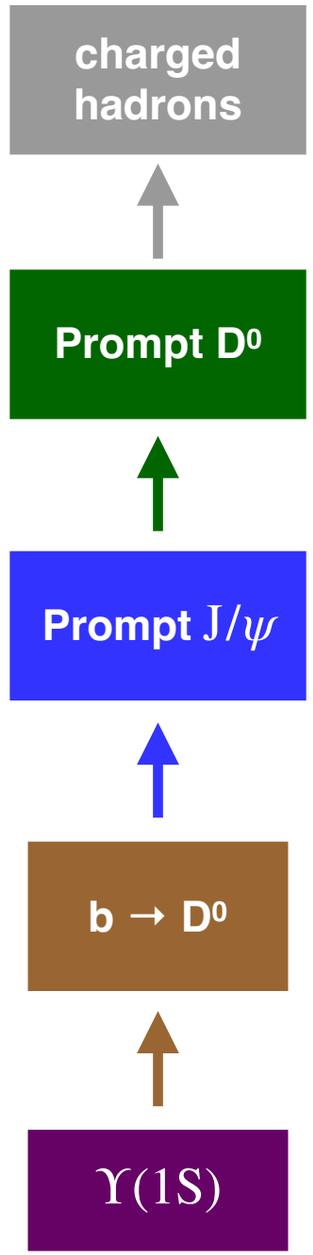
≈ $b \to J/\psi$ ≈ $b \to D^0$ ≈ $\Upsilon(1S)$

- Low-p_T : light > open charm > hidden charm > open beauty > hidden beauty
- High-p_T : converge for all hadron species

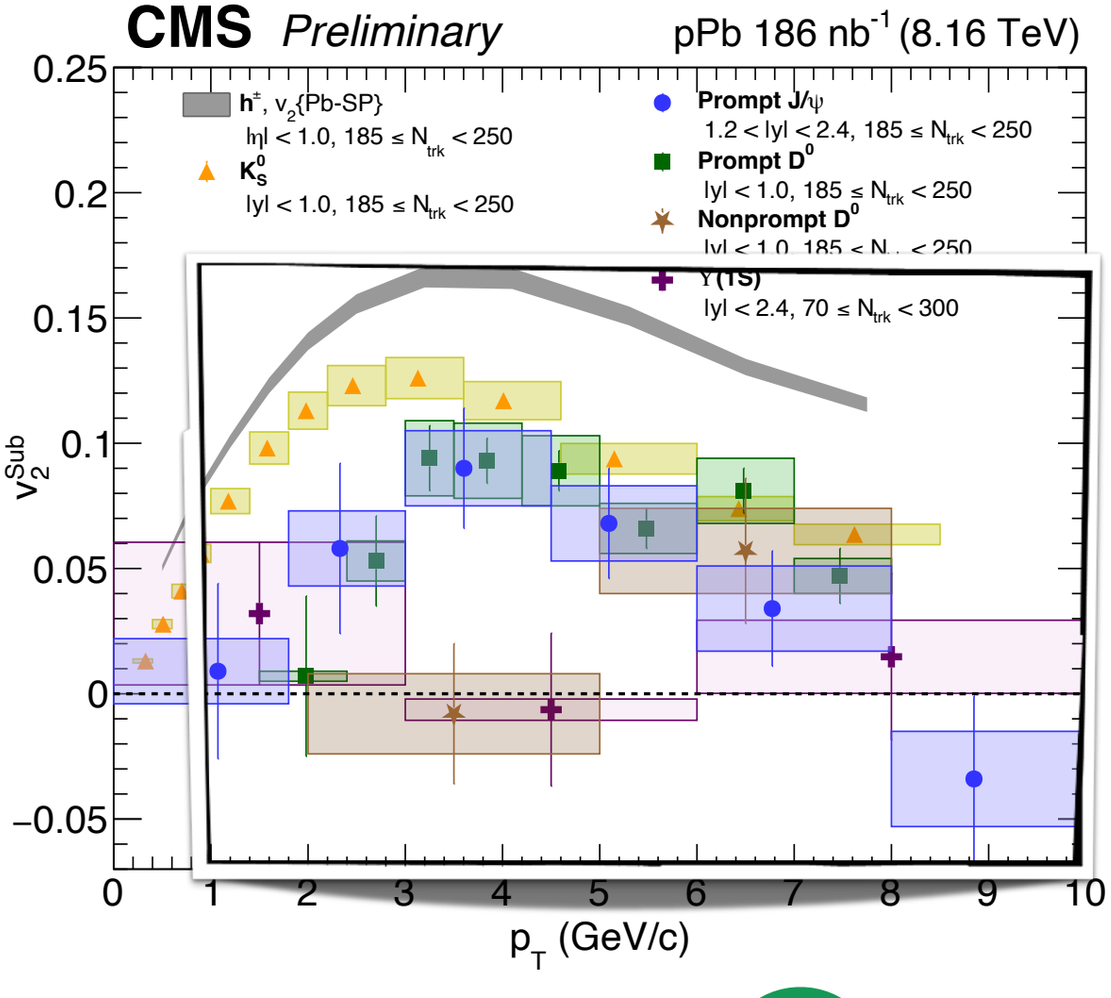
CMS HF v_2 Zoo : PbPb & pPb

[CMS-PAS-HIN-21-008]





[CMS-PAS-HIN-21-001]

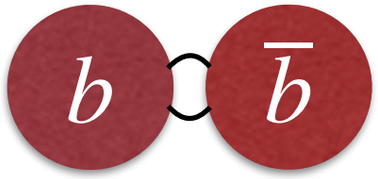


- Hierarchy also in pPb! light > open charm ≈ hidden charm > open beauty ≥ hidden beauty
  - Note in pPb Prompt D0 v_2 ≈ J/ψ v_2 — different behavior than in PbPb

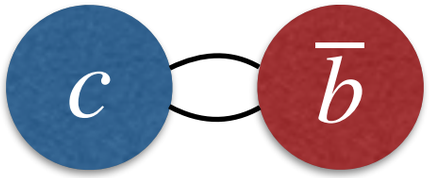
B_c mesons in PbPb

[PRL 128 (2022) 252301]

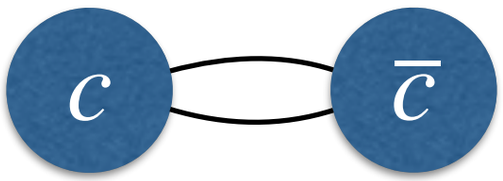
Binding energy hierarchy



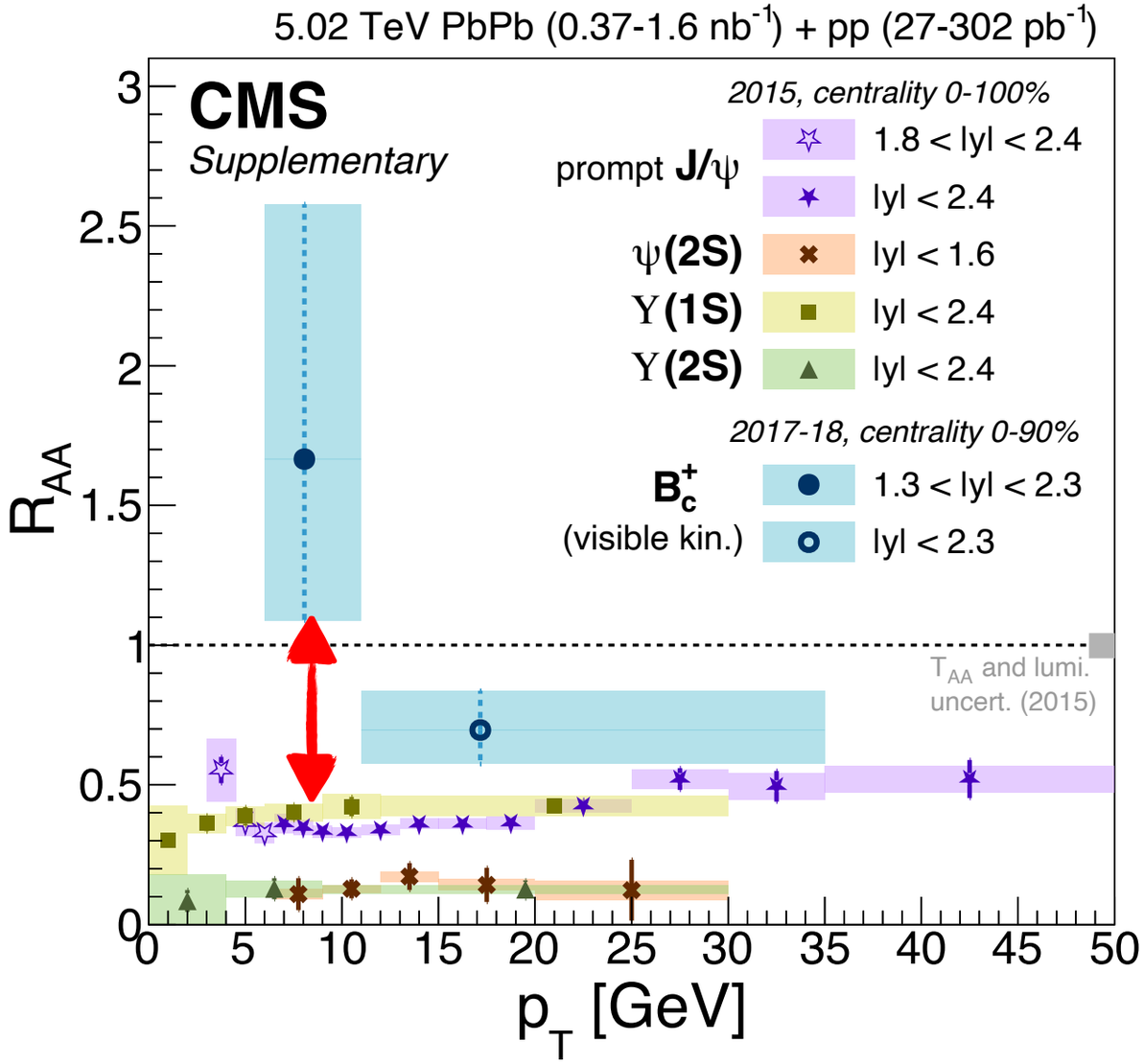
$\Upsilon(1S)$ 1.1 GeV



B_c^+ 0.87 GeV



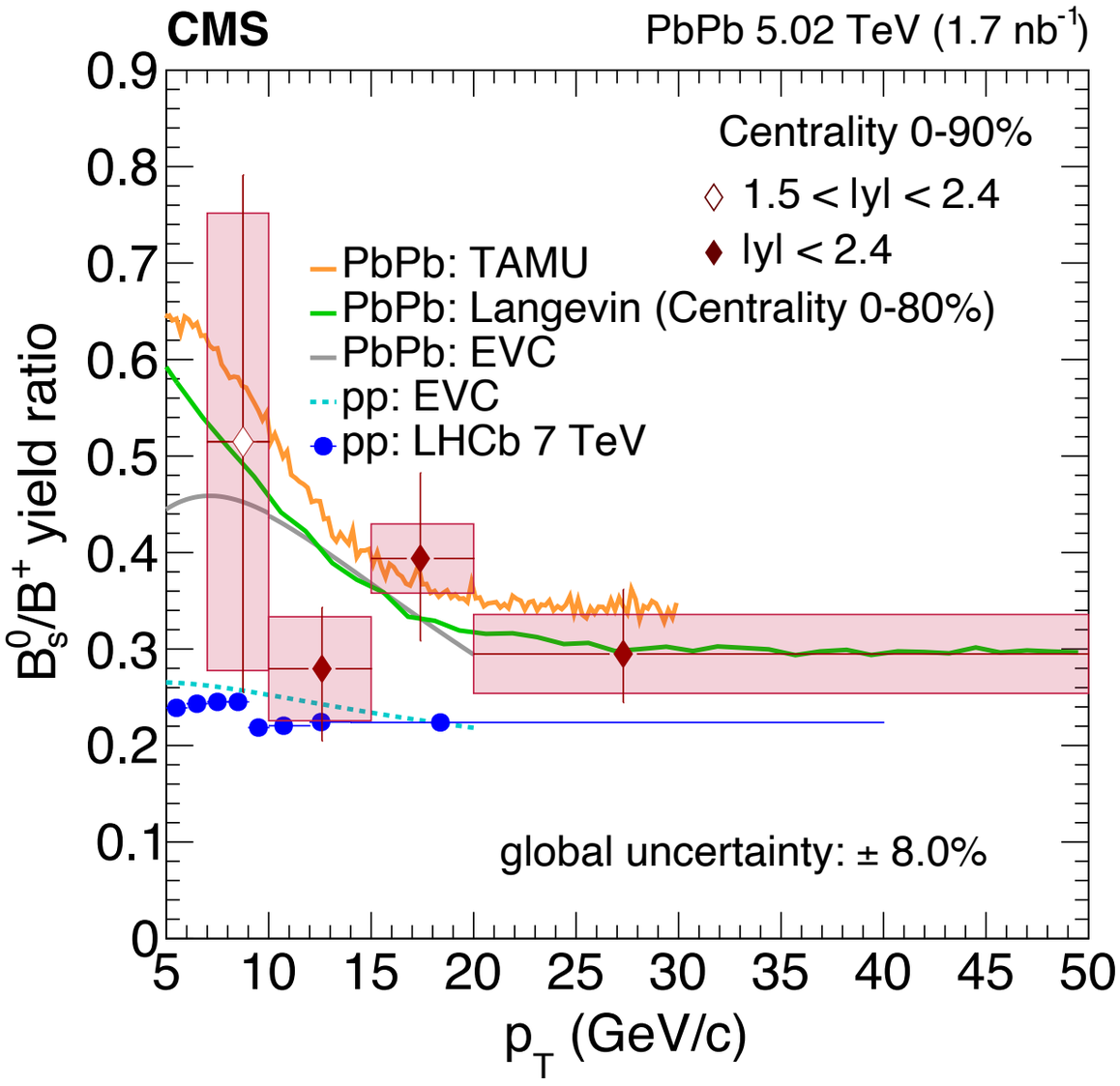
J/ψ 0.63 GeV

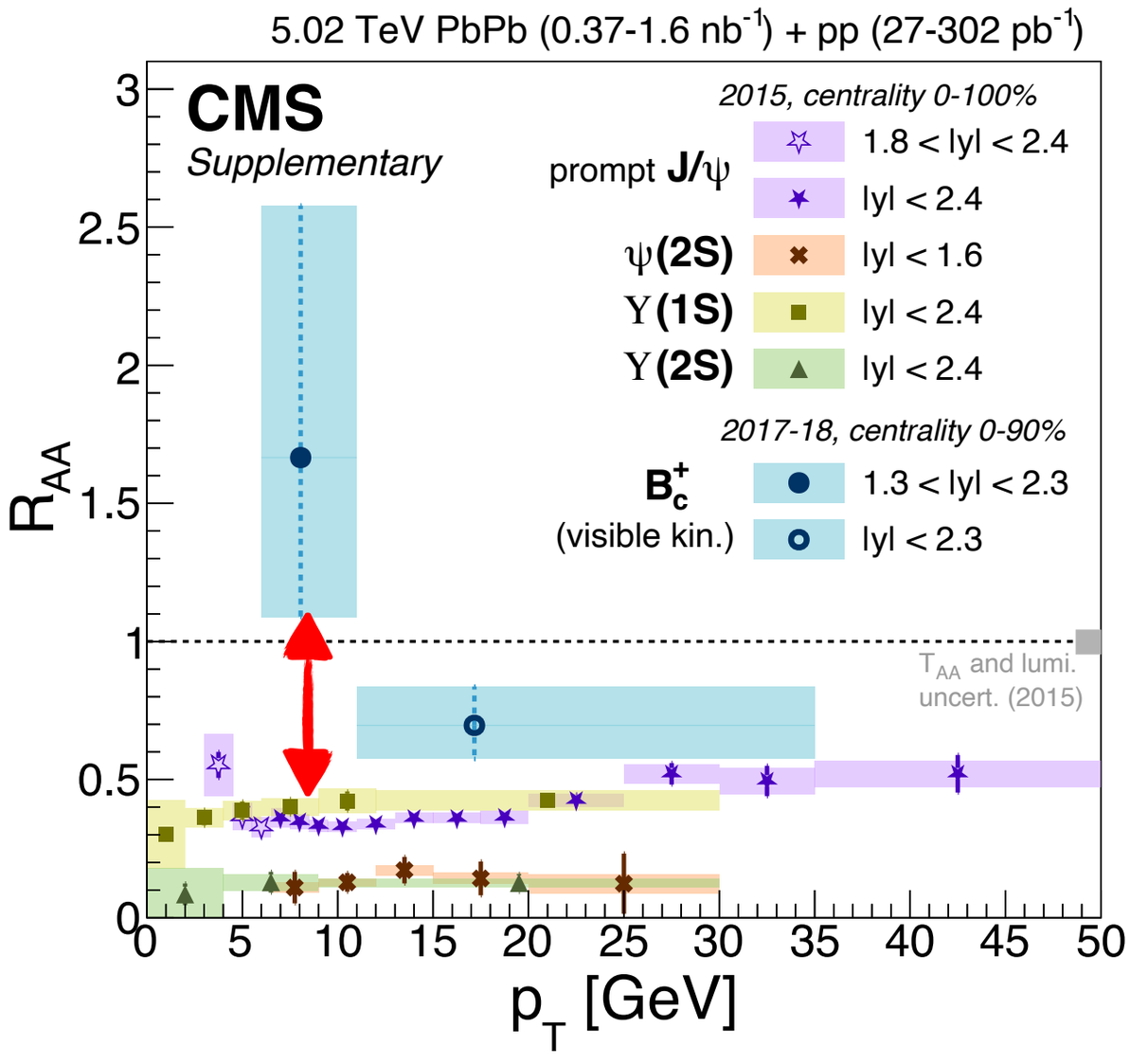


- Binding energy : J/ψ < B_c < $\Upsilon(1S)$ —> novel probe for recombination?

B_c and B_s mesons in PbPb

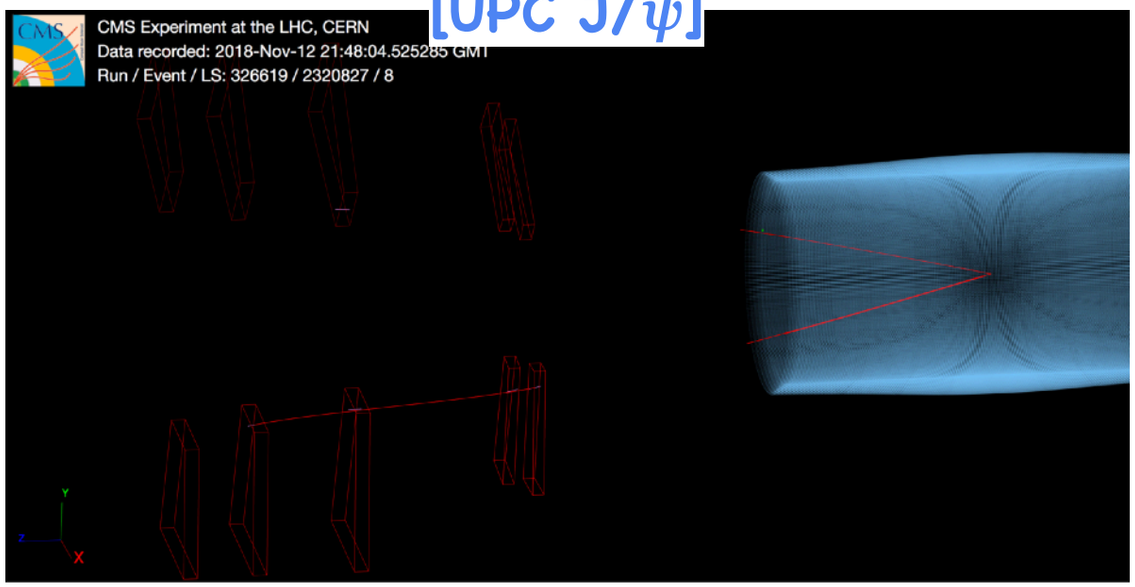
[PRL 128 (2022) 252301] [PLB 829 (2022) 137062]





- Binding energy : J/ψ < B_c < Υ(1S) —> novel probe for recombination?
- Low-p_T enhancement suggested by models for B_s : not confirmed with current precision —> Future prospects for Run3+Run4 data analysis

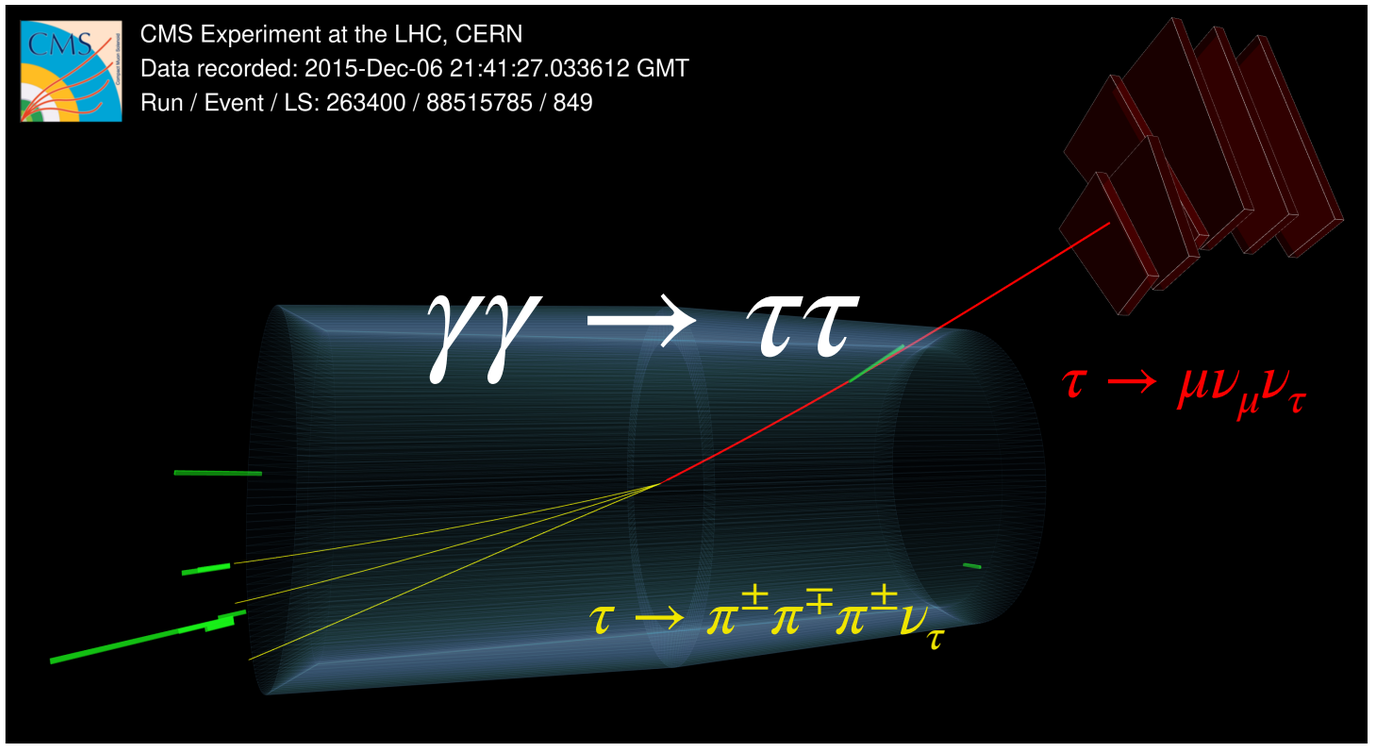
[UPC J/ψ]

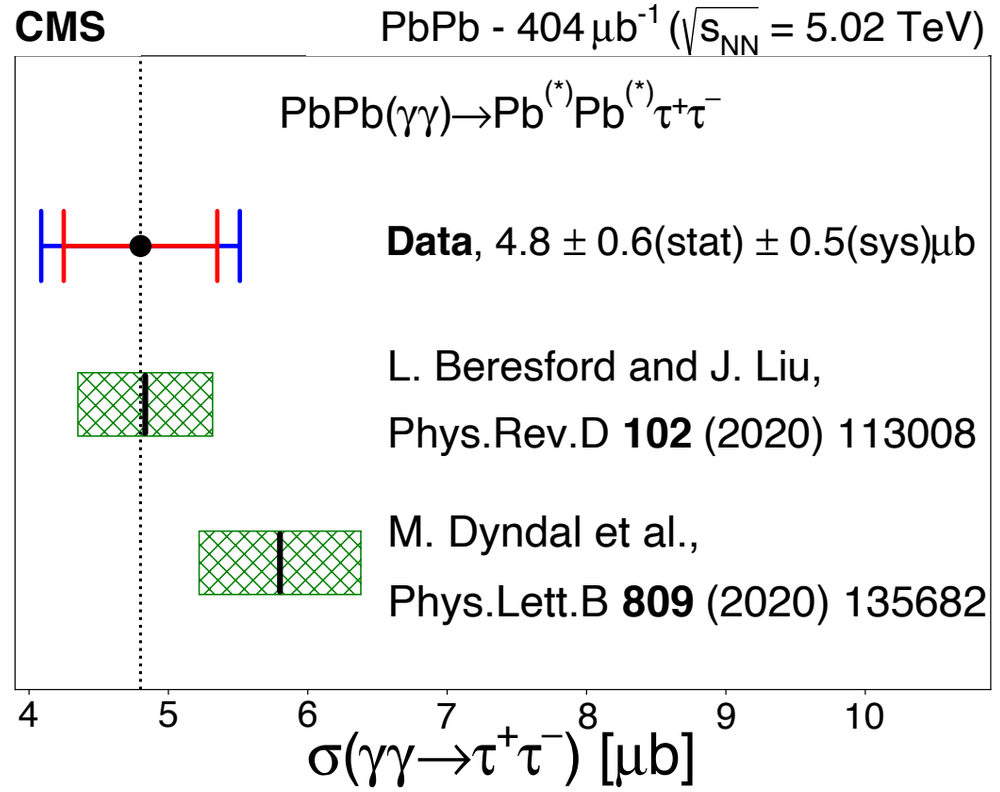


- EW probes
- Flow/Correlations
- Jets
- HF & Quarkonia
- Ultraperipheral collisions (UPCs)

$\gamma\gamma \rightarrow \tau\tau$ in PbPb UPC

[arXiv:2206.05192]



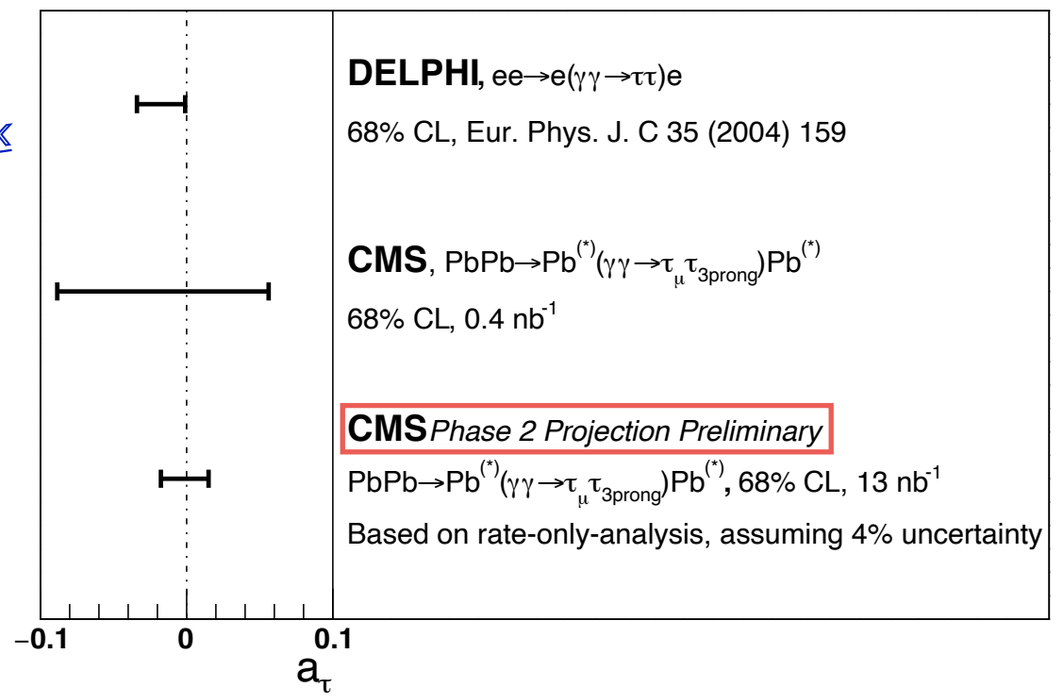


- **Observation of $\gamma\gamma \rightarrow \tau\tau$**
  - Significance $> 5\sigma$ (77±12)

see details in talk from David : link

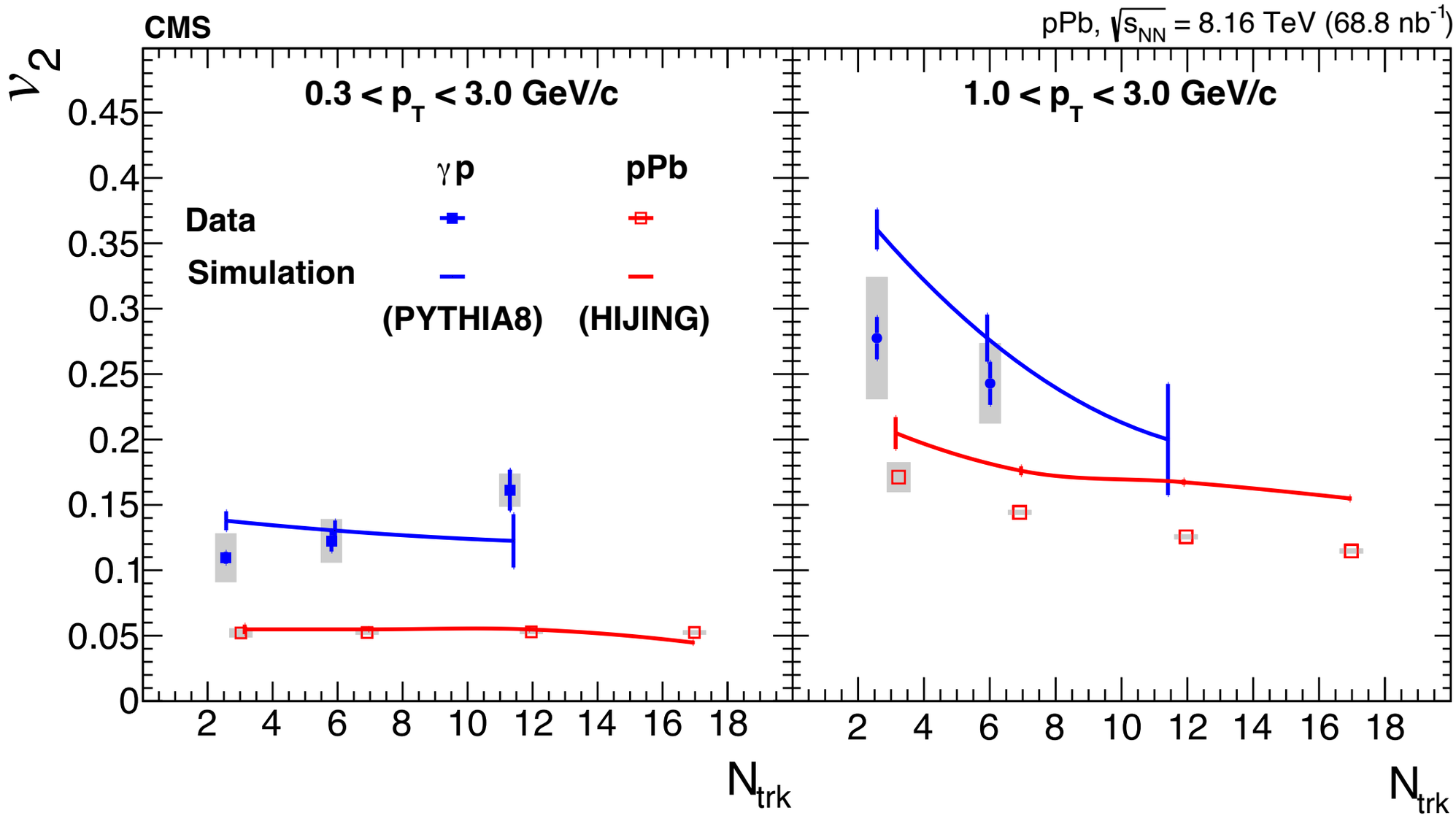
- **Cross section scales with Z^4**

- **Study of anomalous magnetic moment** $a_\tau = \frac{(g-2)_\tau}{2}$
  - Strong constraint with Run3+Run4 data



Flow in γp interaction in pPb

[arXiv:2204.13486]



- Search for elliptic flow in γp interactions in pPb UPC events
- Overall comparable with calculations without collectivity (slight deviation at higher-p_T)

Summary

☑ EW

- ➡ Z boson yields to constrain the initial state

➡ CMS HI Run2 publications

➡ CMS HI Run2 preliminary

☑ Flow/correlations

- ➡ Investigation of the flow origin using multiparticle cumulant
- ➡ Particle production mechanism with charge balance function
- ➡ High-order cumulant ~$v_2\{10\}$ for new hydrodynamic probes
- ➡ Femptoscopic studies for strong force interactions and H-dibaryon search in AA

☑ Jets

- ➡ b-jet shape for QGP medium effect of bottom quarks
- ➡ Detailed jet profile for energy redistribution in wide angle
- ➡ Z boson as non-modified probe to study jet quenching

☑ HF & Quarkonia

- ➡ Many “firsts” measurements (Y(3S), B_c, $\psi(2S)$ & b-> D flow, etc.) providing new insight to theory models
- ➡ Precision measurements of R_{AA} and v_2 for open/hidden heavy flavor

☑ UPC

- ➡ First constraints on g-2 of τ
- ➡ UPC offering smallest system at LHC to study collectivity

back-up

Recent of Run2 results

Recent Run2 results : link

☑ UPC

- τ lepton pair in PbPb : [arXiv:2206.05192]
- dijet azimuthal correlation in PbPb : [arXiv:2205.00045]
- v_2 in γp interactions in pPb : [arXiv:2204.13486]

☑ Flow/Correlations

- strange hadron correlations in pPb and PbPb : [arXiv:2205.00080]
- charge balance function in pPb and PbPb : [CMS-PAS-HIN-21-017]
- femtoscopy of K^0_S and $\Lambda(\overline{\Lambda})$ in PbPb : [CMS-PAS-HIN-21-006]
- higher moments using high-order cumulants in PbPb : [CMS-PAS-HIN-21-010]
- Lévy parameter of BEC in PbPb : [CMS-PAS-HIN-21-011]
- Correlator of $c_n\{2\}$ & $\langle p_T \rangle$ in small systems : [CMS-PAS-HIN-21-012]
- Charm quark dynamics via multiparticle correlations in PbPb : [PRL 129 (2022) 022001]

☑ Jets

- b-jet shape in PbPb : [arXiv:2210.08547]
- dijet v_n in PbPb : [arXiv:2210.08325]
- Z boson tagged parton-medium interaction in PbPb : [PRL 128 (2022) 122301]
- jet spectra for large area in PbPb : [JHEP 05 (2021) 284]

Recent of Run2 results

Recent Run2 results : link

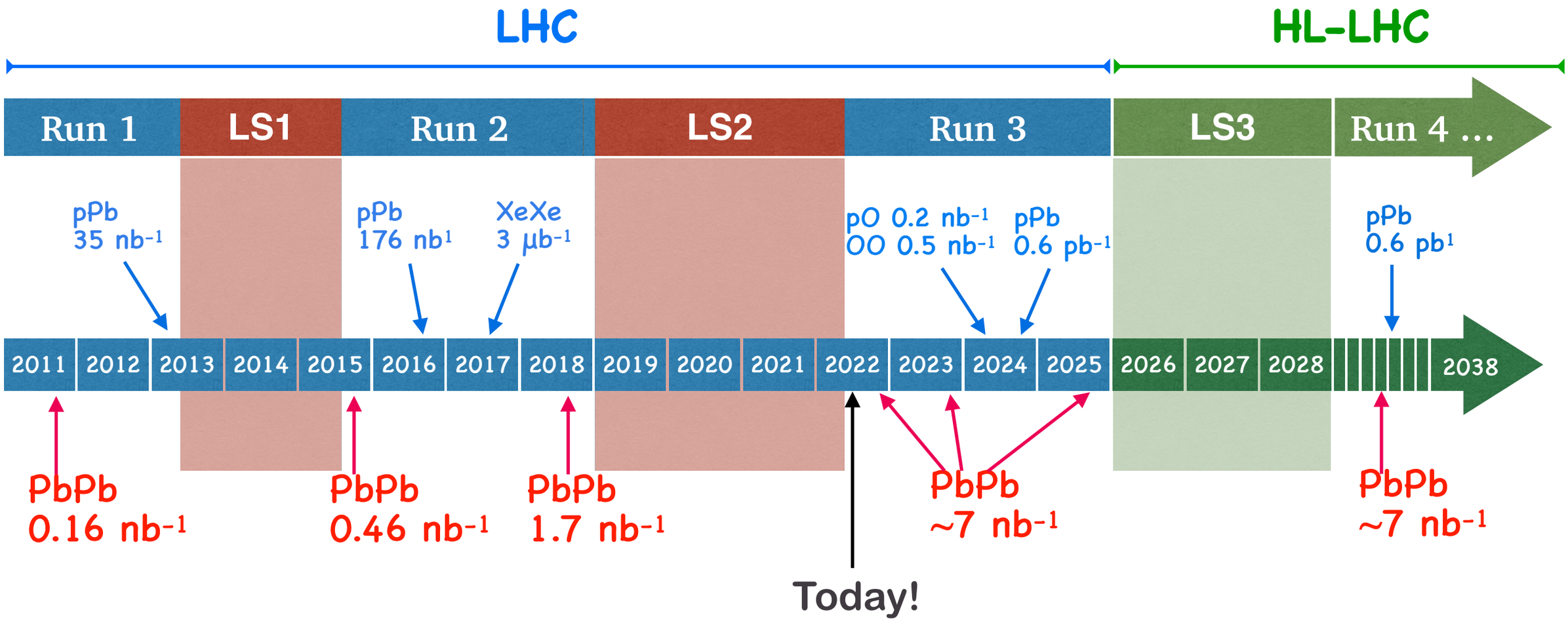
☑ **Heavy flavor and quarkonia**

- Y R_{pPb} in pPb : [arXiv:2202.11807]
- Observation of B_c^+ in PbPb : [PRL 128 (2022) 252301]
- Observation of B_S^0 in PbPb : [PLB 829 (2022) 137062]
- J/ψ jet fragmentation in PbPb and pp : [PLB 825 (2021) 136842]
- Evidence of X(3872) in PbPb : [PRL 128 (2022) 032001]
- Prompt and nonprompt D^0 in pp and pPb : [PLB 813 (2021) 136036]
- Y(1S) & Y(2S) v_2 in PbPb : [PLB 819 (2021) 136385]
- Azimuthal anisotropy of nonprompt D^0 in PbPb : [CMS-PAS-HIN-21-003]
- Y(1S) v_2 in pPb : [CMS-PAS-HIN-21-001]
- Observation of Y(3S) in PbPb : [CMS-PAS-HIN-21-007]
- Azimuthal anisotropy for J/ψ and ψ(2S) in PbPb : [CMS-PAS-HIN-21-008]

☑ **EW probes**

- Initial state constraints with Z boson yields and v_2 in PbPb : [PRL 127 (2021) 102002]
- Drell-Yan dimuon in pPb : [JHEP 05 (2021) 182]

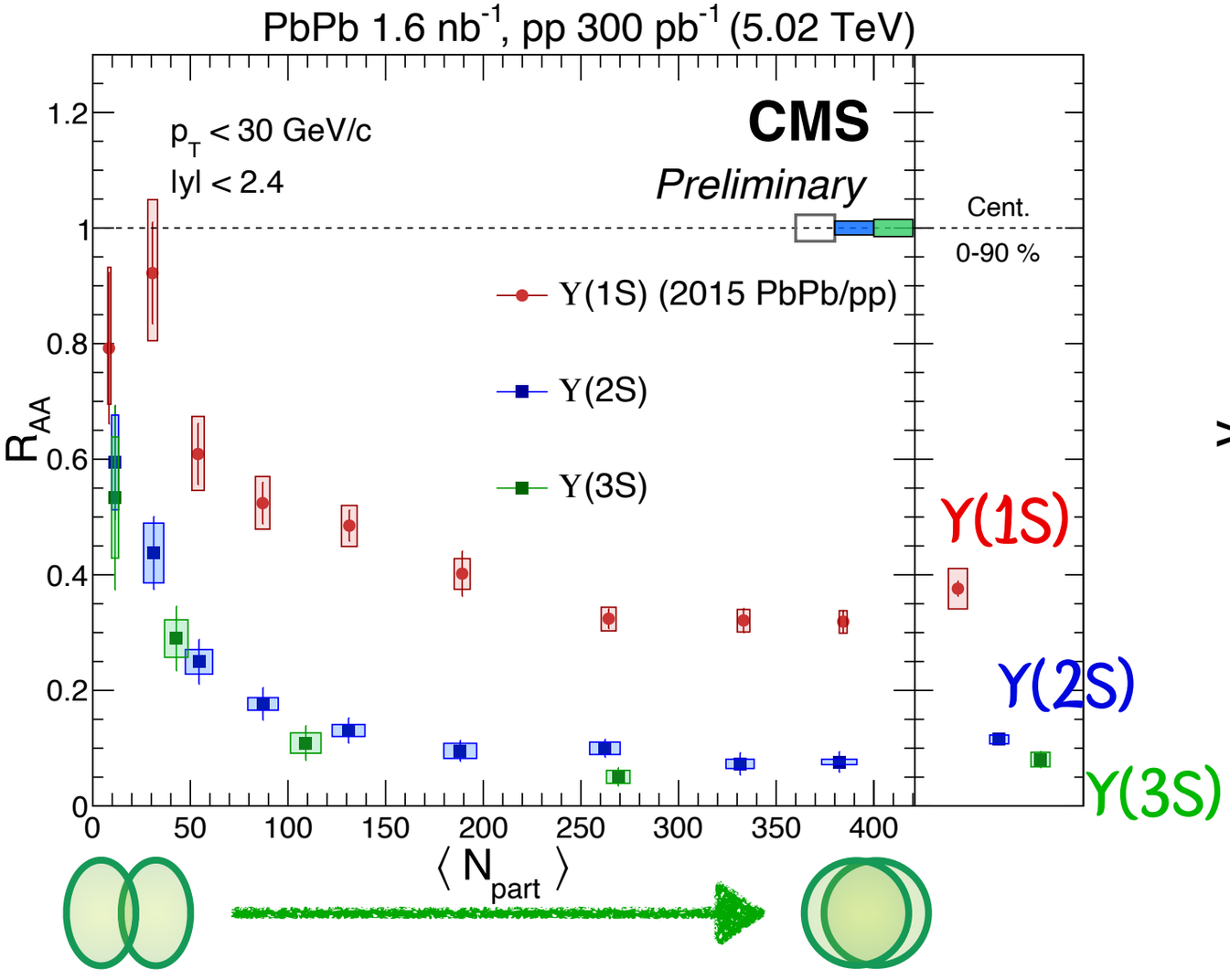
CMS Heavy Ion Program



- HI program at LHC : Successful data taking since the first PbPb data in 2011!
- Significant contributions to the QGP research field with Run1 + Run2
- 5-7x increased HI data with Run3 + Run4

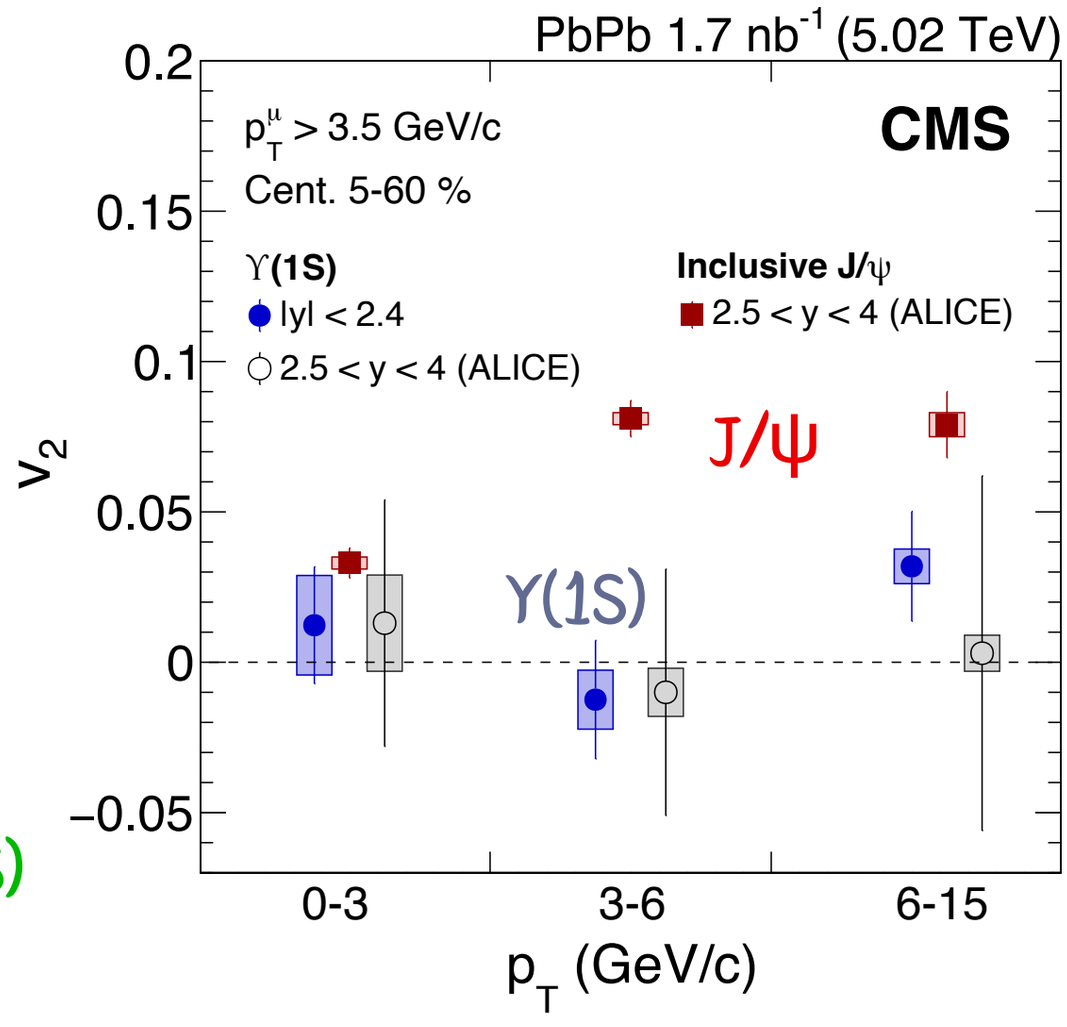
Bottomonia in PbPb

[CMS-PAS-HIN-21-007]



- Observation of Υ(3S) in PbPb! (> 5σ)
- Clear quantification of Υ(1,2,3S) sequential suppression
  R_{AA}(Υ(1S)) > R_{AA}(Υ(2S)) > R_{AA}(Υ(3S))

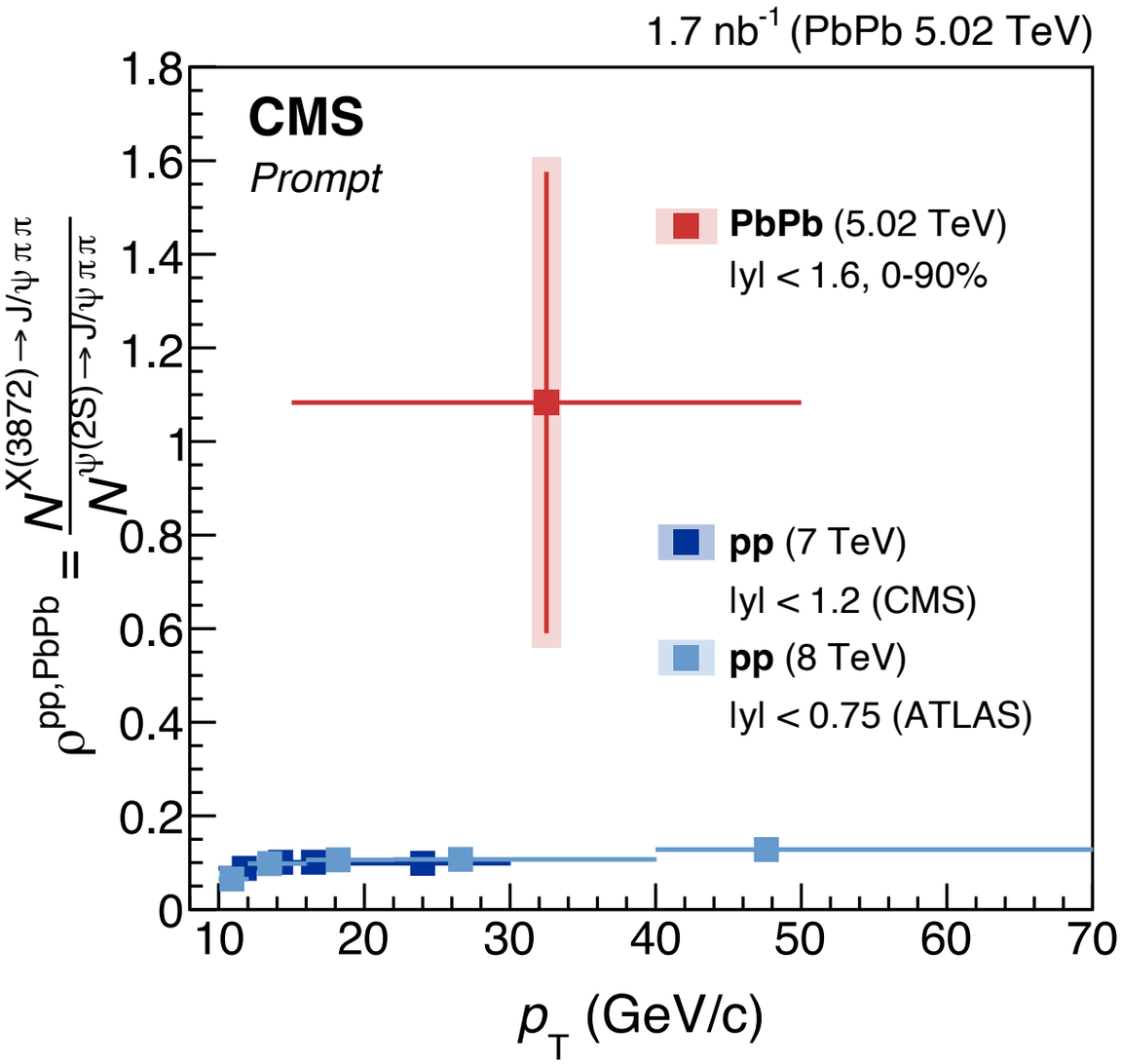
[PLB 819 (2021) 136385]



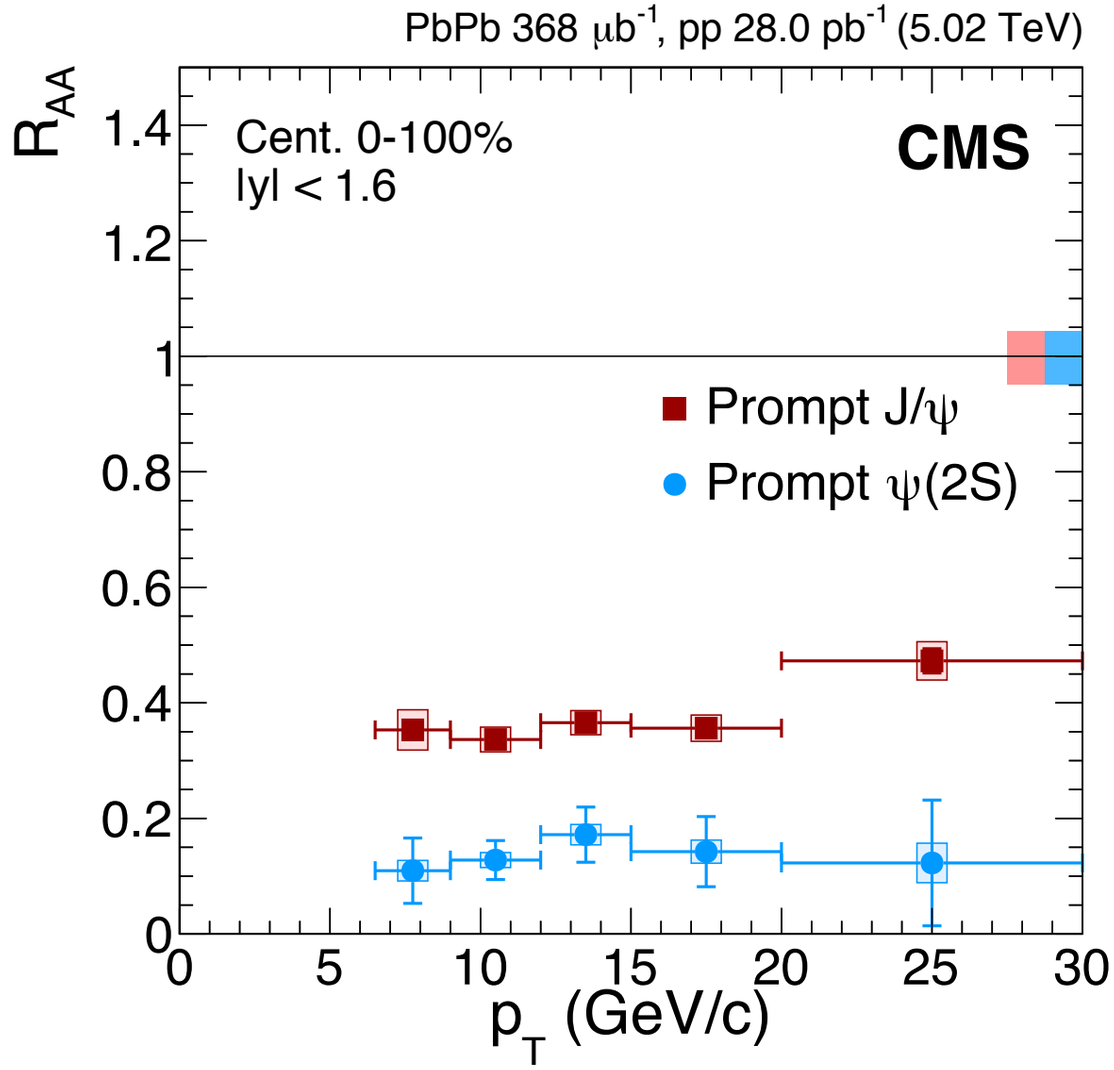
- Υ(1S) $v_2 \approx 0$ for PbPb
- Non-zero v_2 for J/ψ

X(3872) in PbPb

[PRL 128 (2022) 032001]



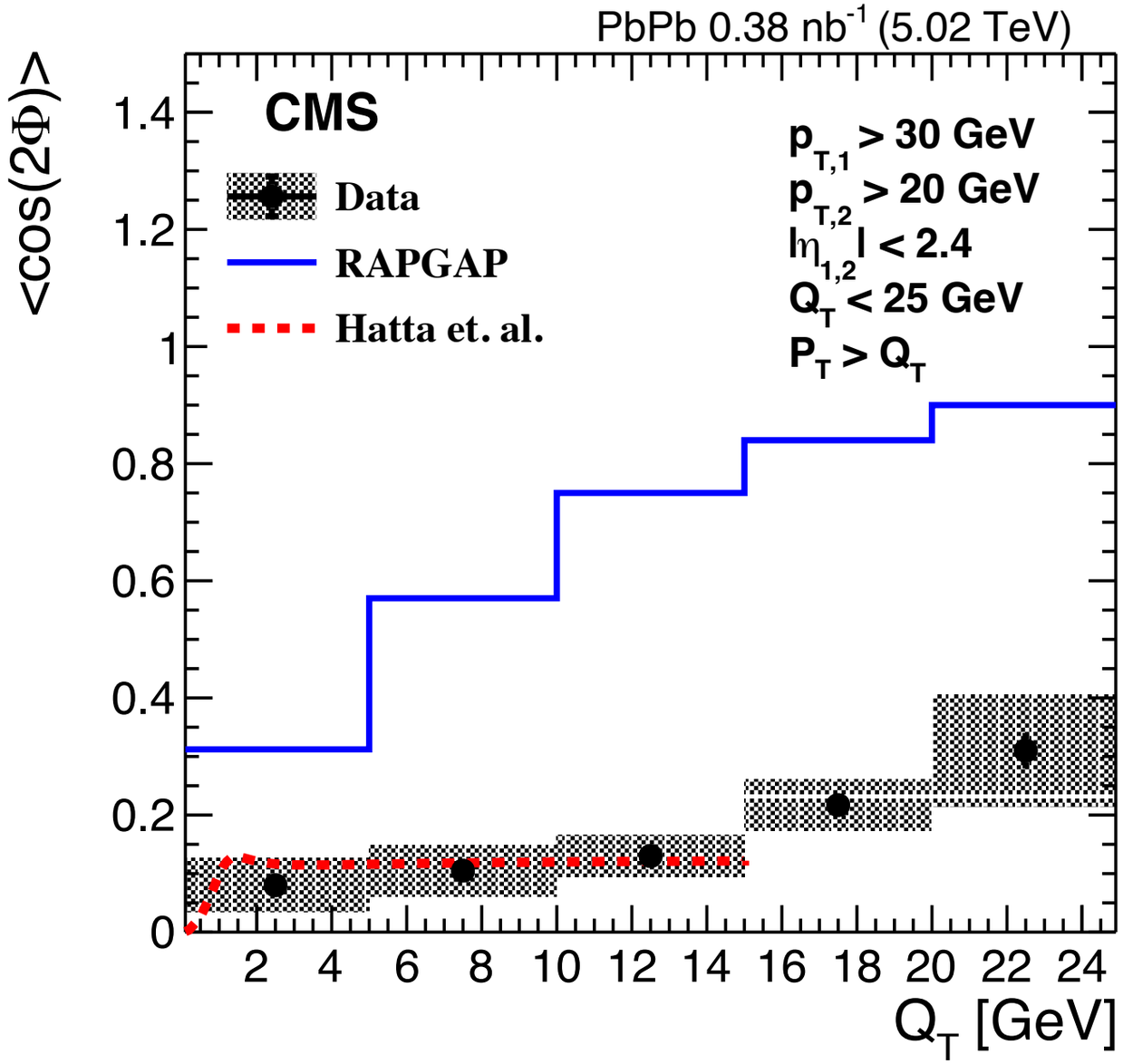
[EPJC 78 (2018) 509]

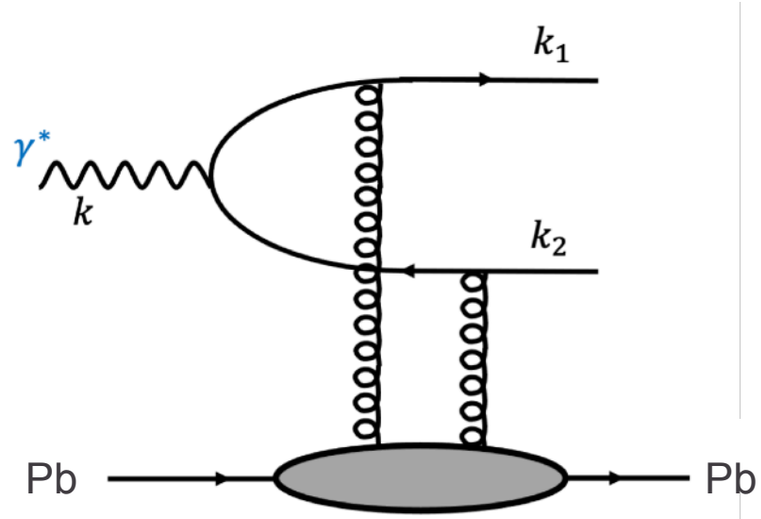


- Evidence of X(3872) in PbPb — hint of different ratio w.r.t pp
- Caveat of large suppression for ψ(2S) in PbPb : $R_{AA} \approx 0.1$

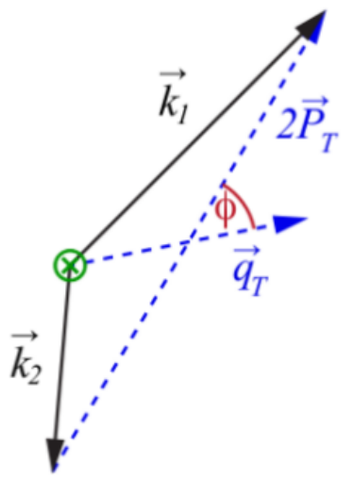
UPC dijet azimuthal anisotropy

[arXiv:2205.00045]





Dijet azimuthal anisotropy
— sensitive probe to gluon Wigner distribution

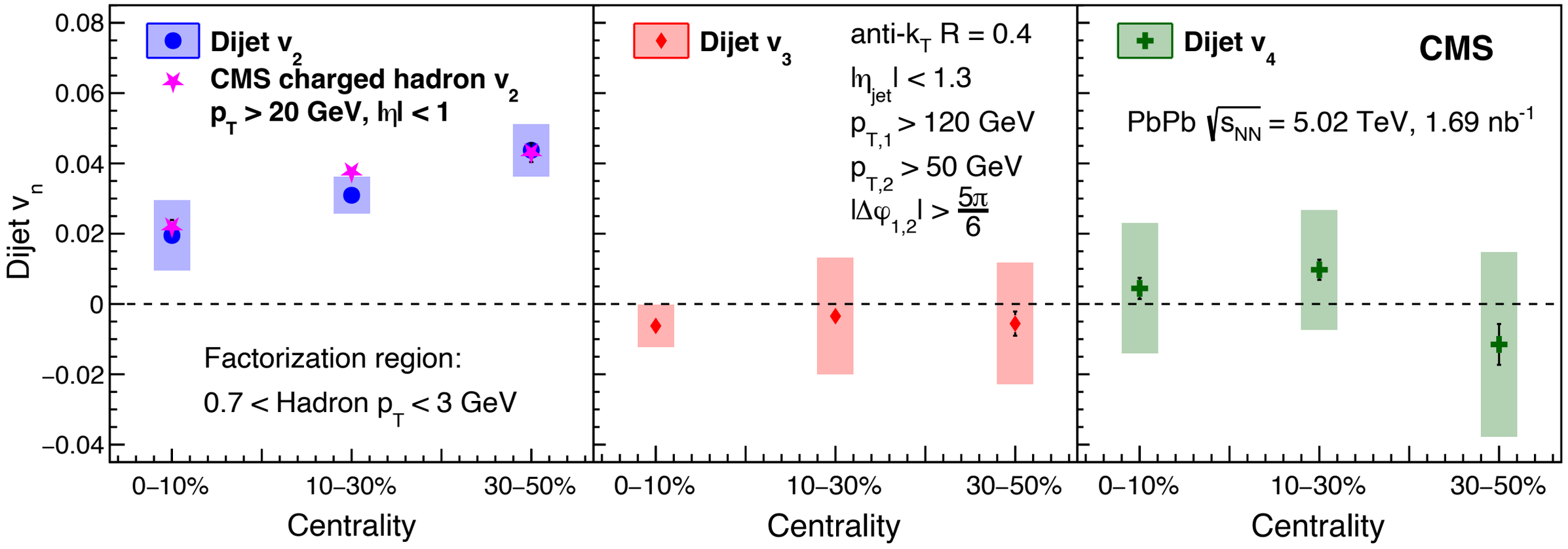


Two jets
Q_T = vector sum
P_T = vector difference

- First measurement of UPC dijets <cos(2ϕ)> in PbPb
- Overestimation of ep expectation (RAPGAP) / deviation of soft-gluon radiation at high Q_T?

Dijet v_n in PbPb

[arXiv:2210.08325]



- *Positive v_2* increasing up to centrality 50% –> Sensitive to initial geometry
- v_3 & v_4 ≈ 0 –> No impact from initial state geometry & medium density fluctuation