

Sergey Petrushanko (for CMS Collaboration)

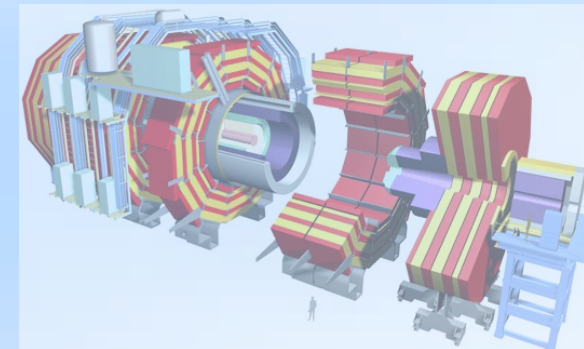


Skobeltsyn Institute of Nuclear Physics
Lomonosov Moscow State University

Heavy-ion Physics with CMS Detector

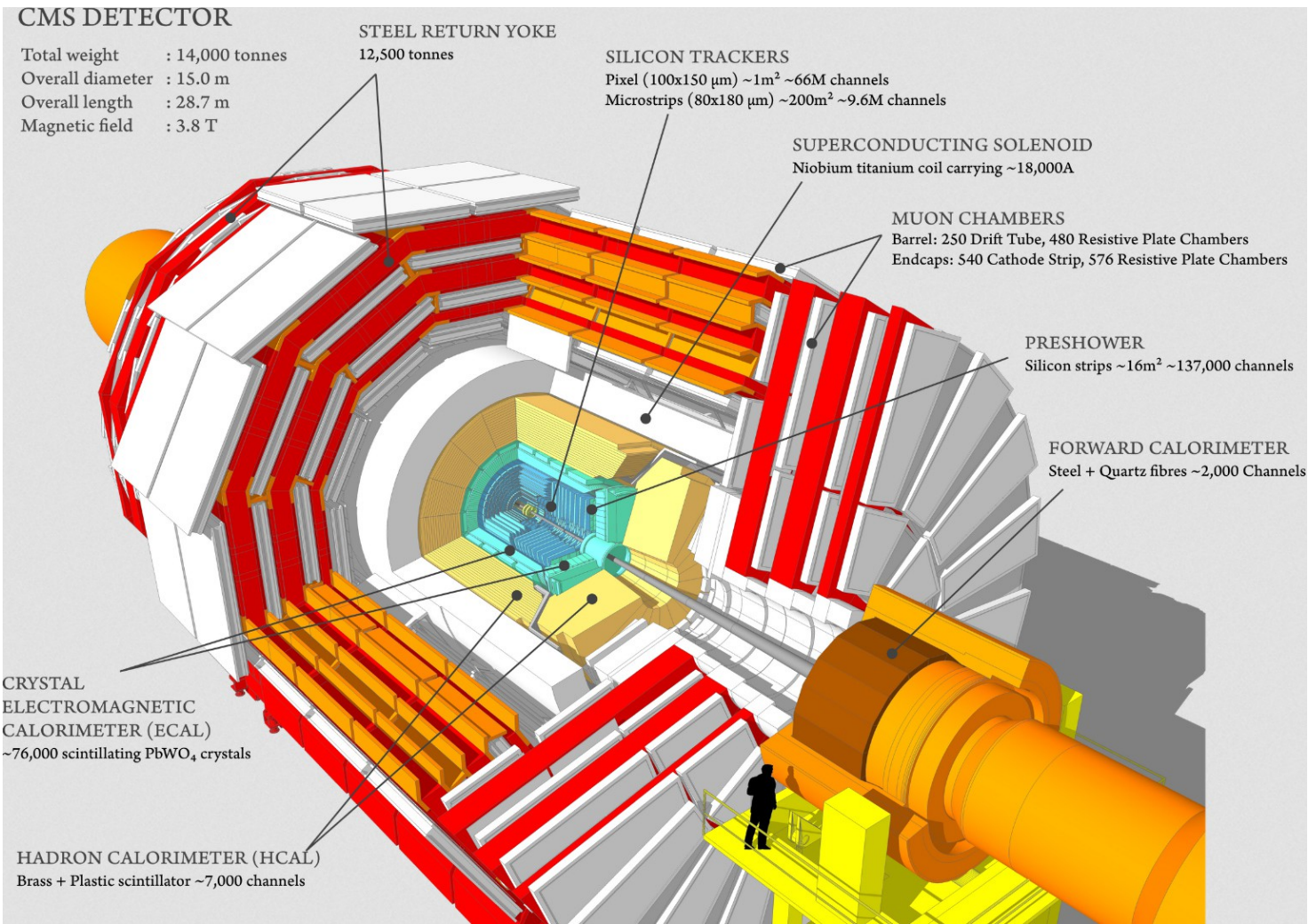
LXXII International Conference
*"Nucleus-2022: Fundamental
Problems and Applications"*

Lomonosov Moscow State University
Moscow, Russia
11 – 16 July 2022





CMS is a nice heavy-ion experiment



◆ Silicon Tracker

$$|\eta| < 2.4$$

◆ Electromagnetic Calorimeter

$$|\eta| < 3.0$$

◆ Hadron Calorimeter
barrel and endcap

$$|\eta| < 3.0$$

with HF-calorimeter up to

$$|\eta| < 5.2$$

◆ Muon Chambers

$$|\eta| < 2.4$$

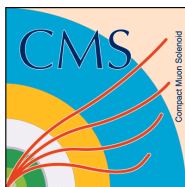
+ CASTOR detector

$$5.2 < |\eta| < 6.6$$

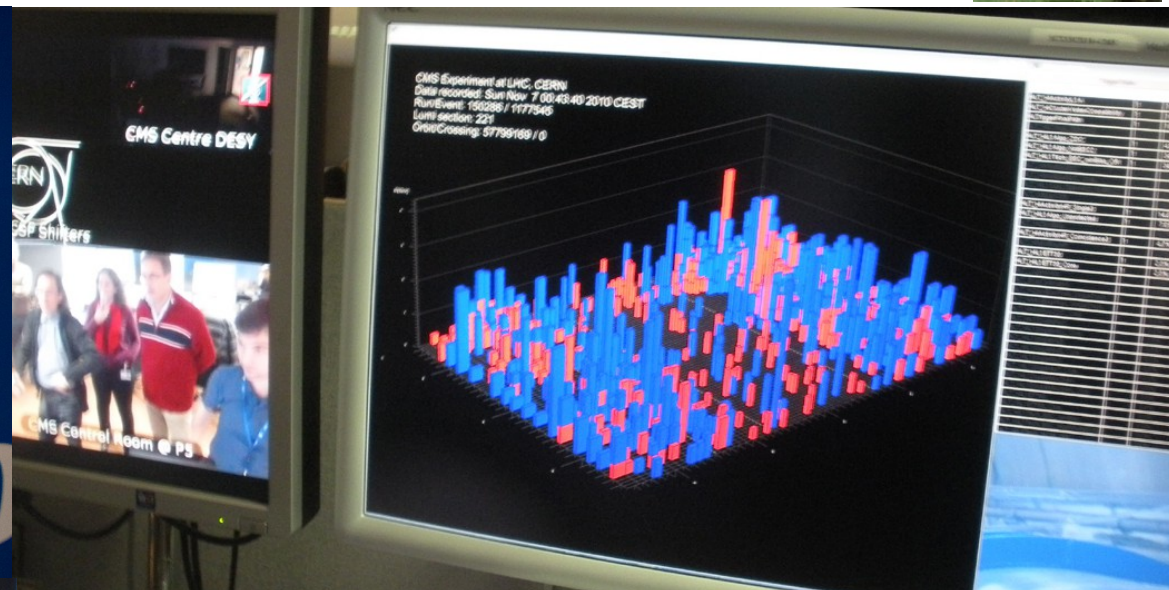
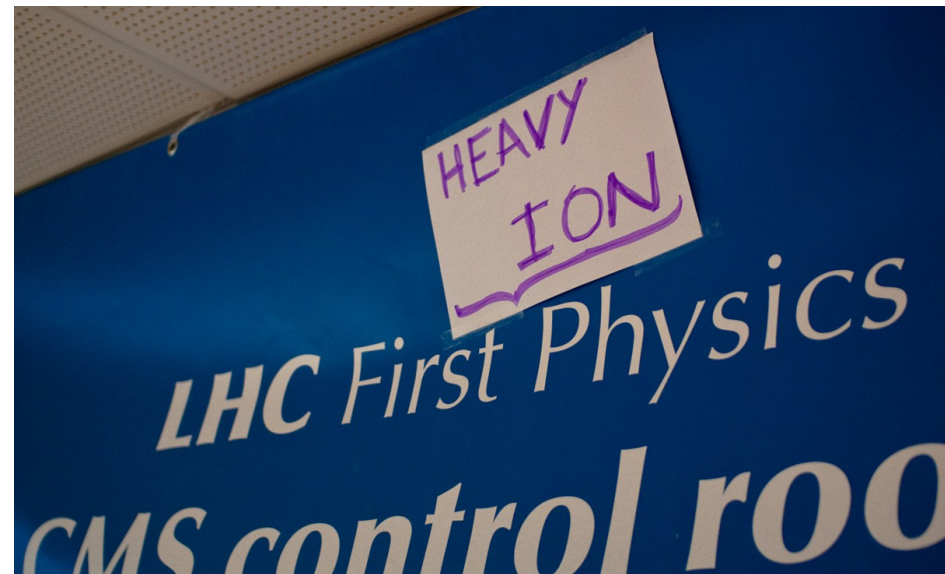
+ Zero-degree calorimeter

+ TOTEM

Magnetic field: 3.8 Tesla



November 7, 2010 0:27. CMS Control Room





CMS heavy-ion physics results



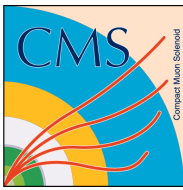
**118 published/submitted
Heavy-ion Physics CMS papers:**

<http://cms-results.web.cern.ch/cms-results/public-results/publications/HIN/index.html>

...and also > 100

Heavy-ion Physics CMS preliminary results (PAS):

<http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIN/index.html>



CMS heavy-ion physics results



- **Global picture of heavy-ion collisions**

- multiplicity,
- energy,
- flow, ...

Pb+Pb collisions

2010-11: 2.76 TeV 0.16/nb
2015-18: 5.02 TeV 1.7/nb

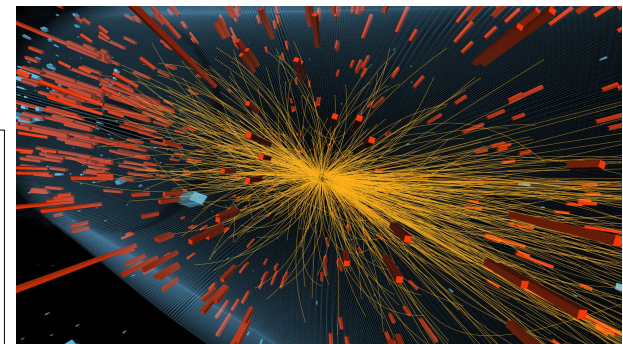
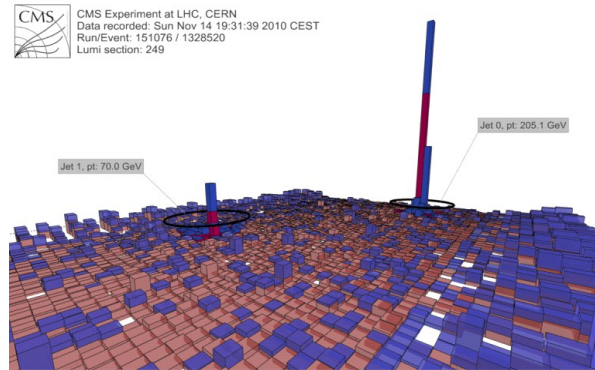
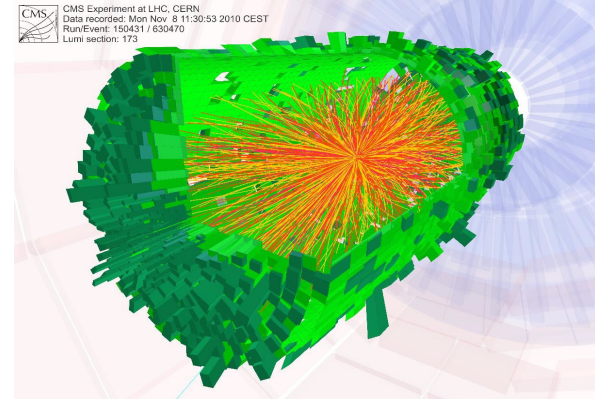
- **Hard probes**

- jets
- dimuons (quarkonia)
- charged hadrons R_{AA} , ...

- **p+p, p+Pb, Xe+Xe**

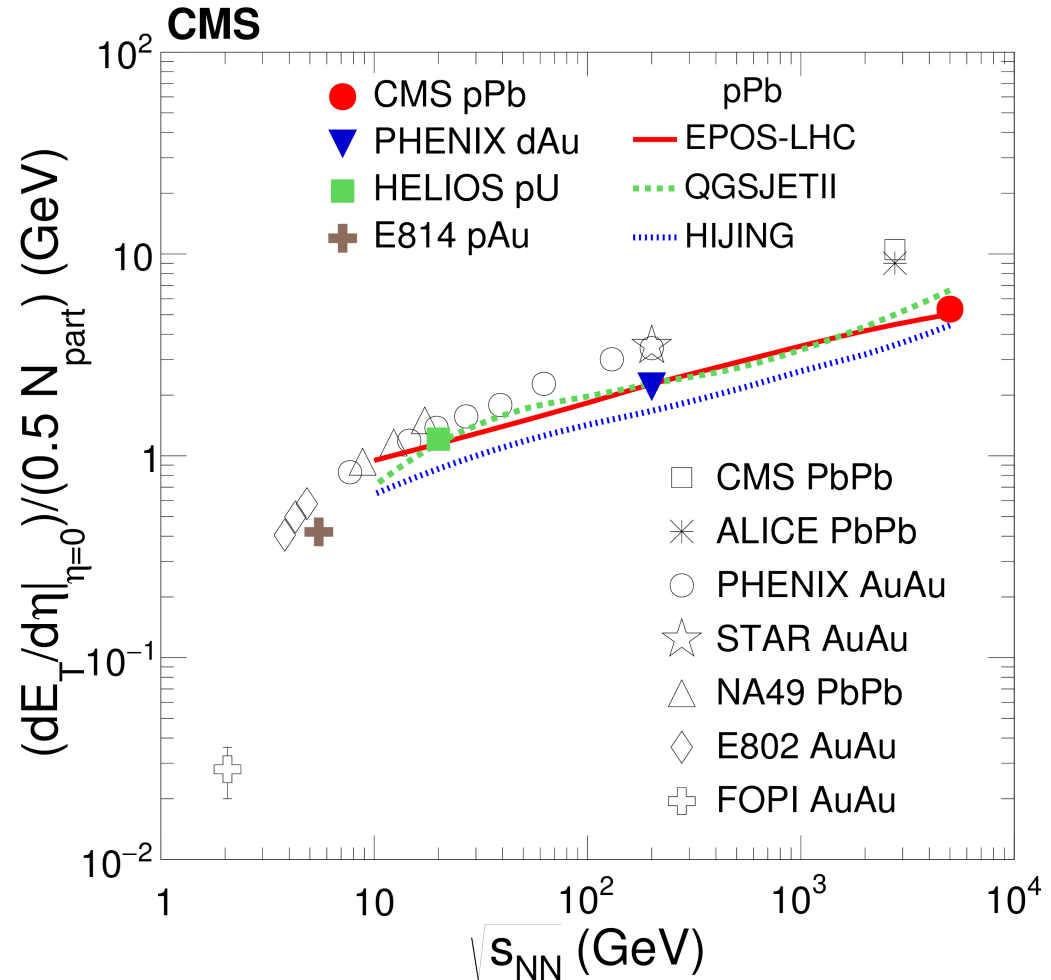
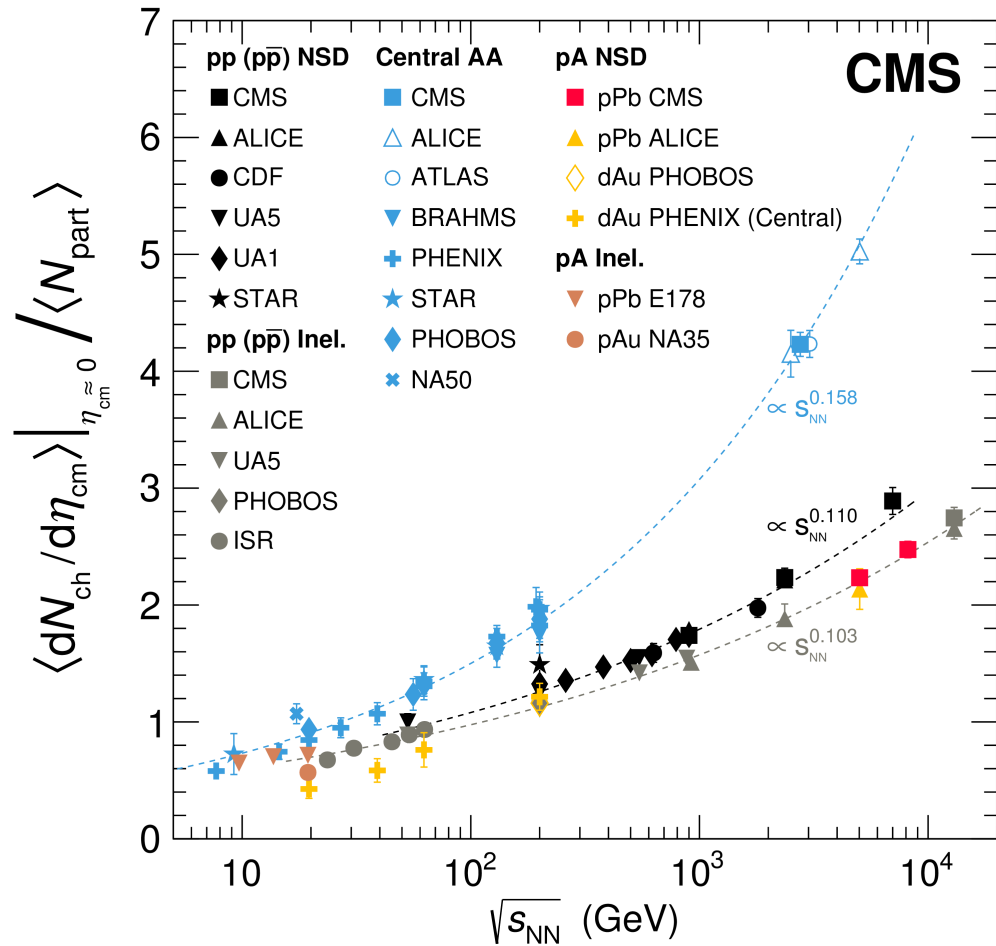
- correlations
- flow,
- jets, ...

p+p 2.76, 5.02, 7, 8, 13 TeV
p+Pb 5.02, 8.16 TeV
Xe+Xe 5.44 TeV





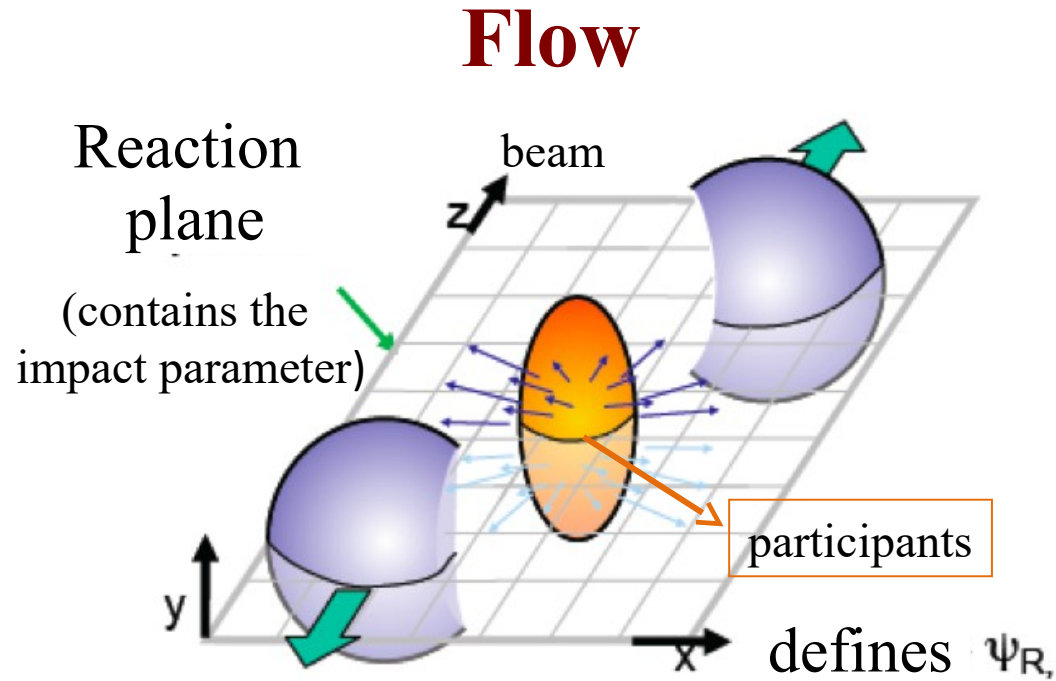
Charged particle multiplicity Transverse energy density



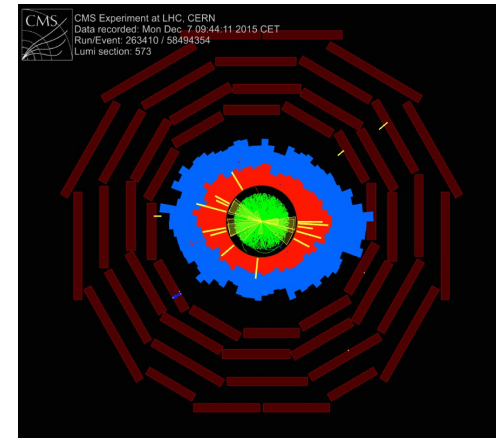
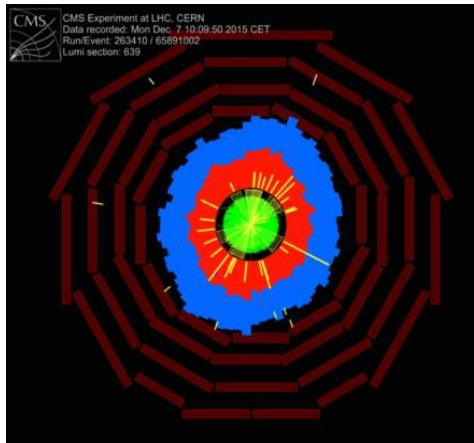
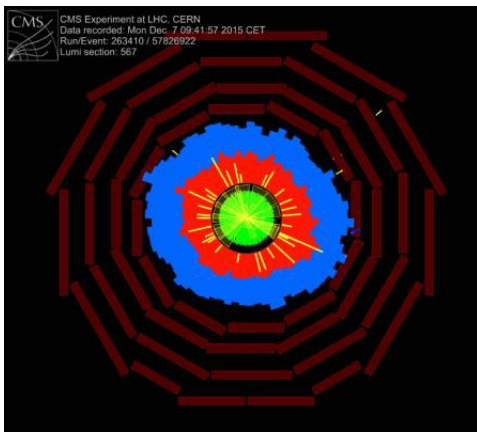
JHEP 01 (2018) 045 • \sqrt{s} dependence:

PRC 100 (2019) 024902

- p+p, p+Pb, Pb+Pb follow power law



Non-central Pb+Pb “screen shots” from CMS Event Monitor: **Electromagnetic**, **Hadronic** Energy and **charged particles tracks**



Collective motion is observed in the event azimuthal distributions



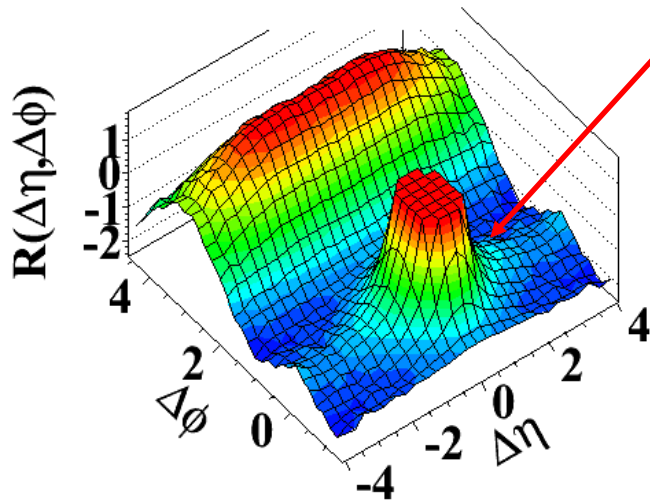
Correlations: “RIDGE” is everywhere...

Long-range ($2 < |\Delta\eta| < 4$), near-side ($\Delta\phi \approx 0$)

angular correlations were observed in high multiplicity p+p and p+Pb collisions (as well as in Pb+Pb)

p+p 7 TeV

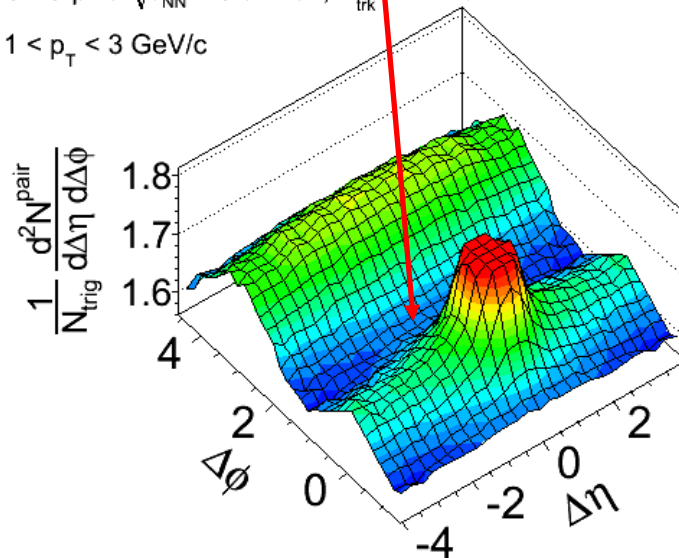
(d) $N > 110, 1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



JHEP 09 (2010) 091

p+Pb 5.02 TeV

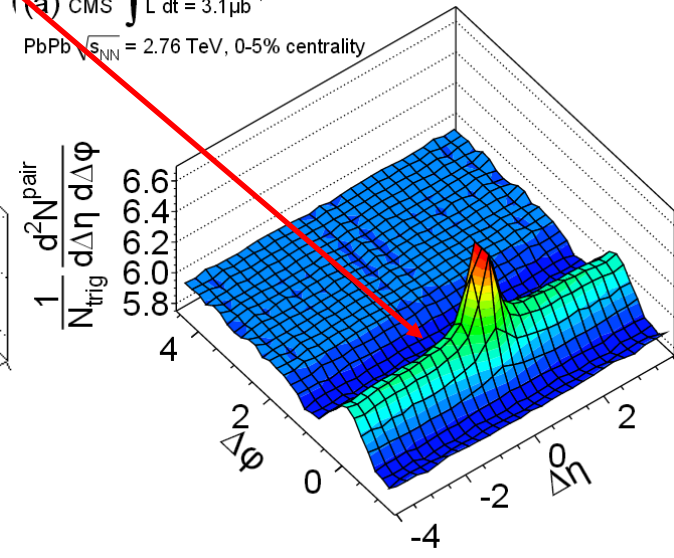
CMS pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}, N_{trk}^{offline} \geq 110$
 $1 < p_T < 3 \text{ GeV}/c$



PLB 718 (2013) 795

Pb+Pb 2.76 A TeV, 0-5%

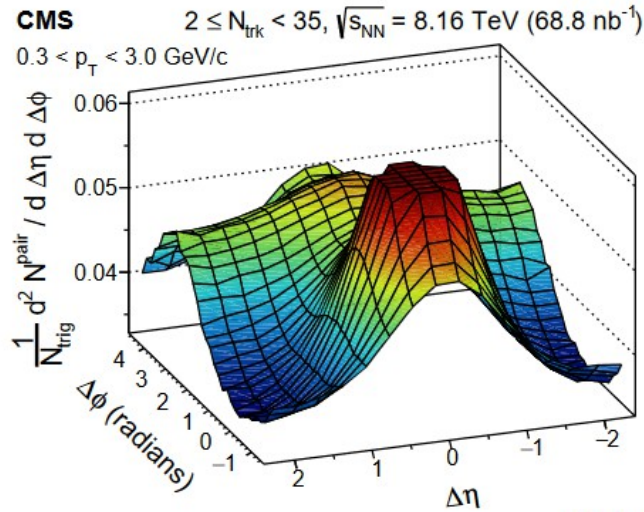
(a) CMS $\int L dt = 3.1 \mu\text{b}^{-1}$
PbPb $\sqrt{s_{NN}} = 2.76 \text{ TeV}, 0\text{-}5\%$ centrality



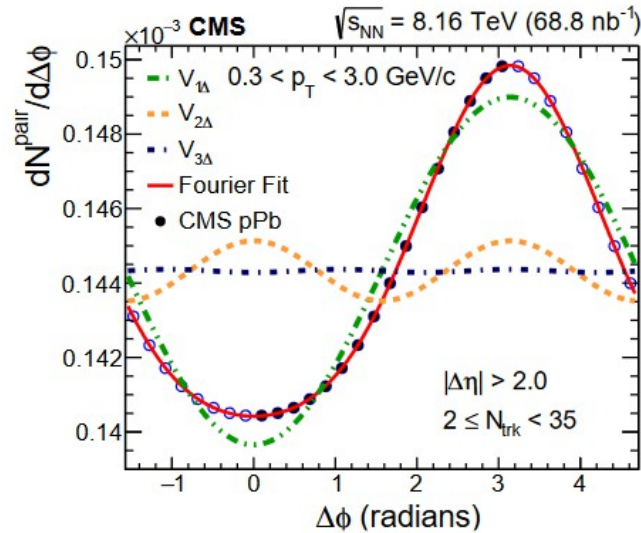
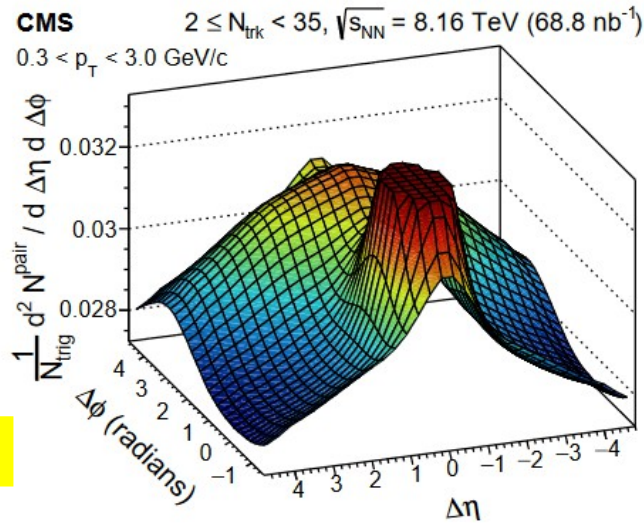
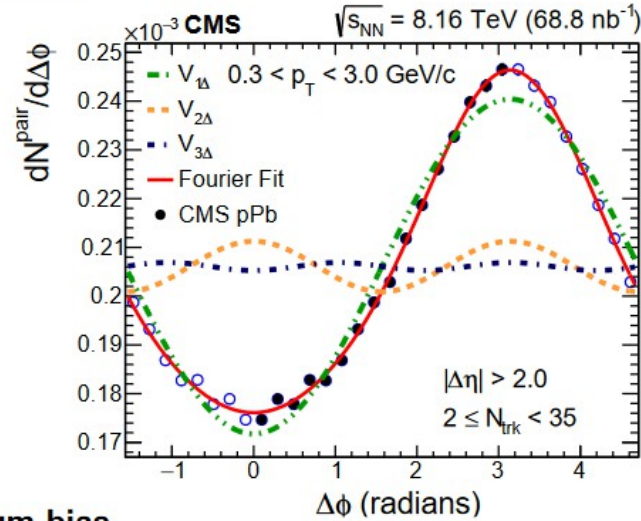
JHEP 07 (2011) 076



γp interactions within ultra-peripheral p+Pb collisions



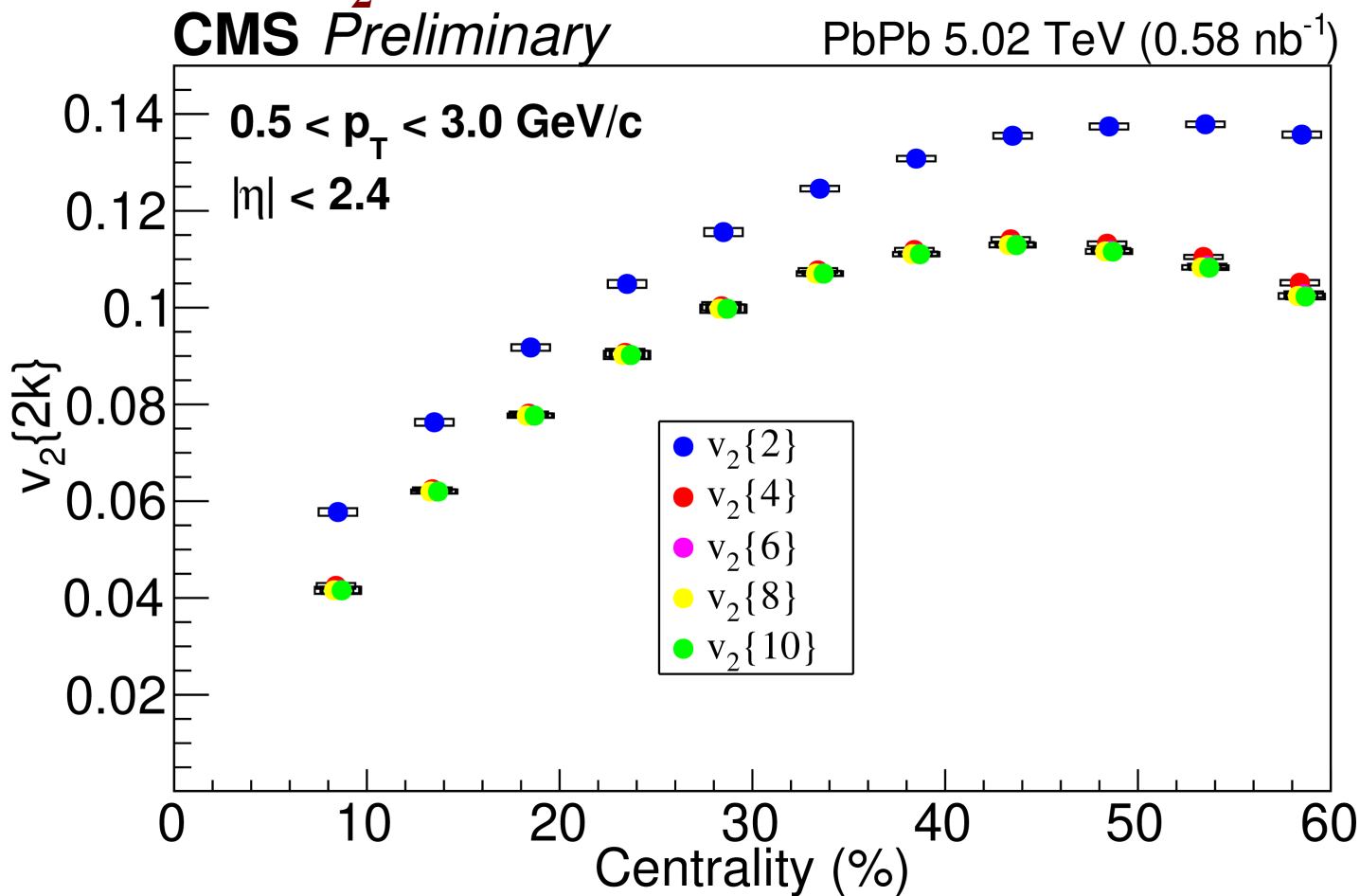
Minimum-bias



arXiv:2204.13486

The single particle flow coefficient $v_2(p_T)$ is larger for γp -enhanced events than for minimum-bias collisions. But we don't see “ridge” here!

The cumulants of the elliptic flow $v_2\{2k\}$ in Pb+Pb collisions



$$v_2\{2\} > v_2\{4\} \gtrsim v_2\{6\} \gtrsim v_2\{8\} \gtrsim v_2\{10\}$$

CMS-PAS-HIN-21-010

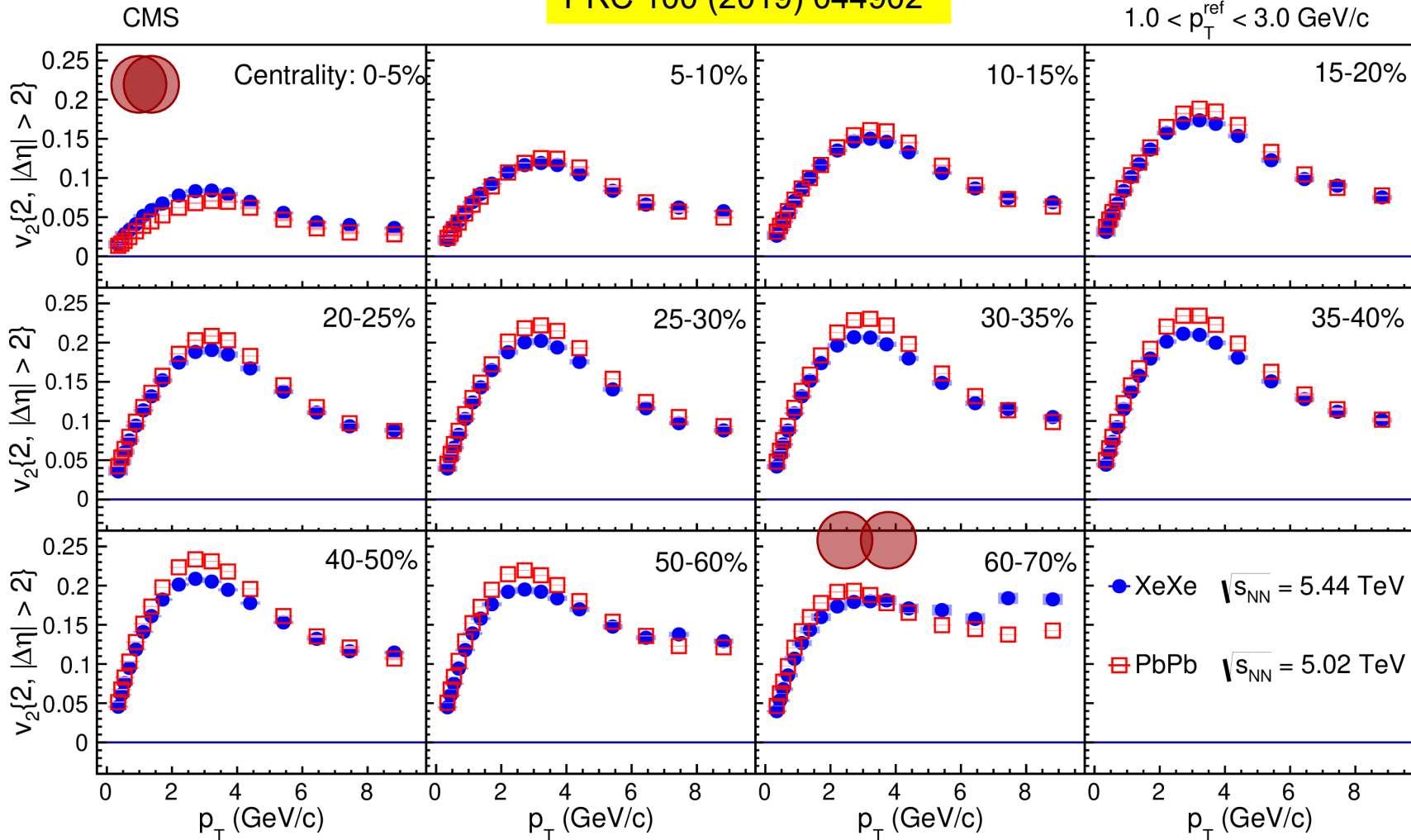
The subtle differences in the higher order harmonics allow for a precise determination of the underlying hydrodynamics and what condition prevail before the onset of hydrodynamics.

v_2 Xe+Xe vs. Pb+Pb



PRC 100 (2019) 044902

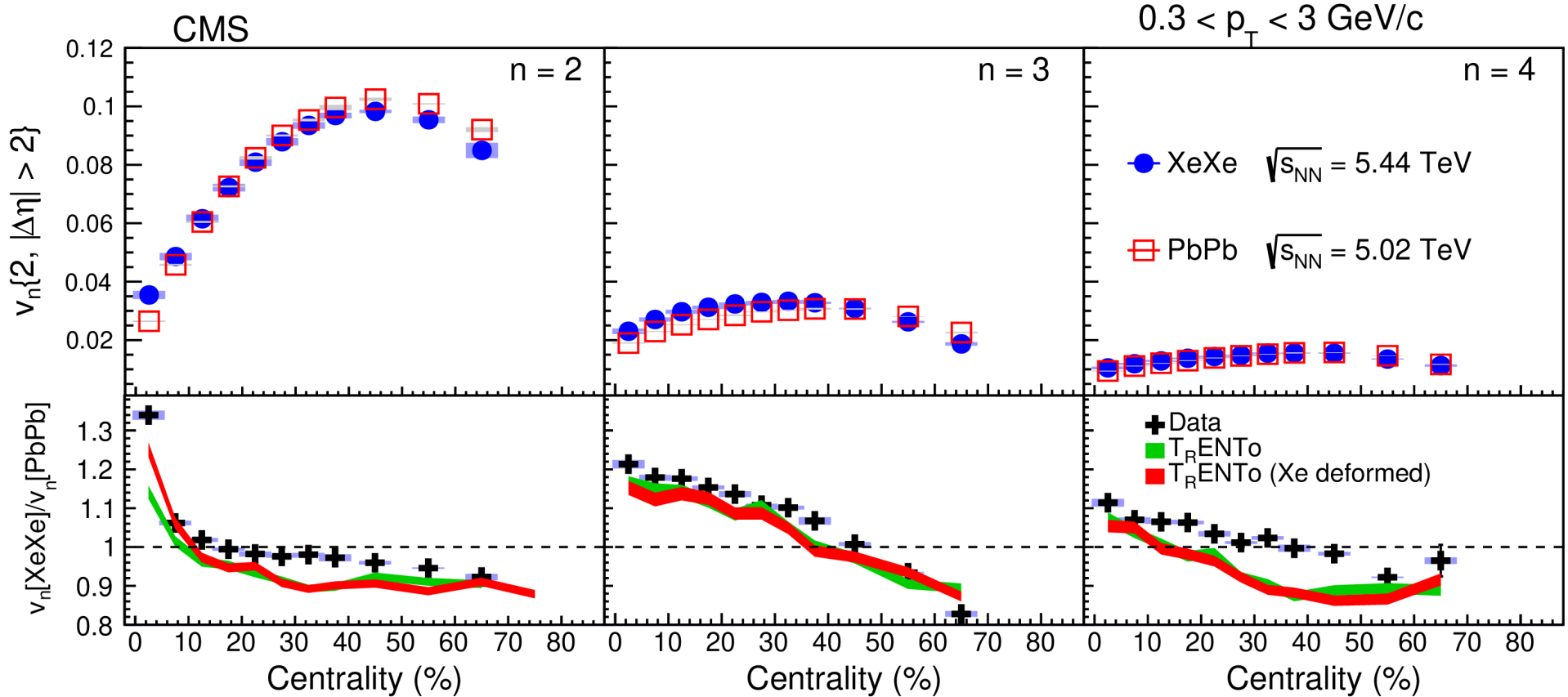
$1.0 < p_T^{\text{ref}} < 3.0 \text{ GeV/c}$



The magnitude of the v_2 coefficients for Xe+Xe collisions are larger than those found in Pb+Pb collisions for the most central collisions. This is attributed to a larger fluctuation component in the lighter colliding system.

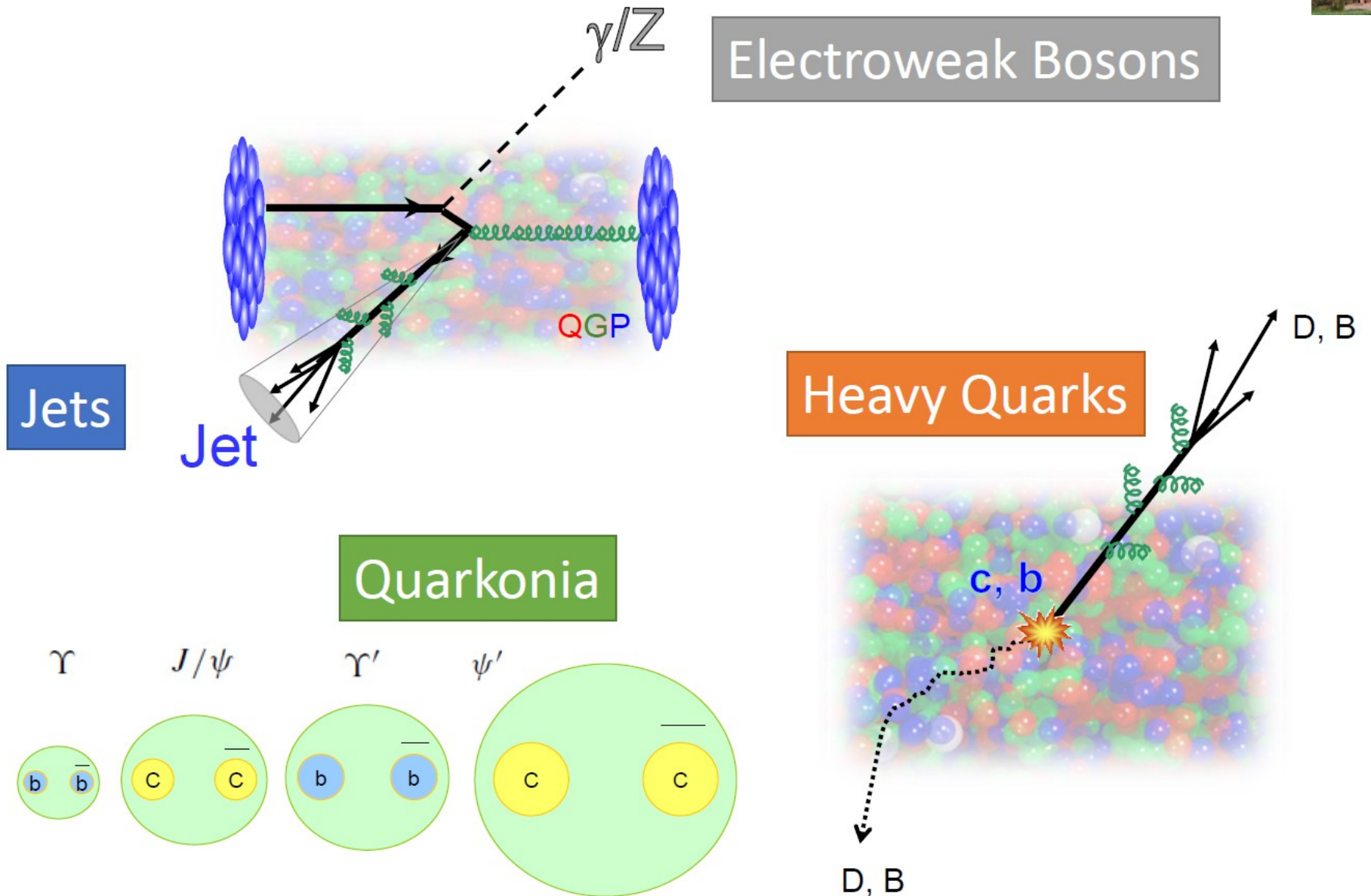
$v_{2,3,4}$ Xe+Xe vs. Pb+Pb

PRC 100 (2019) 044902

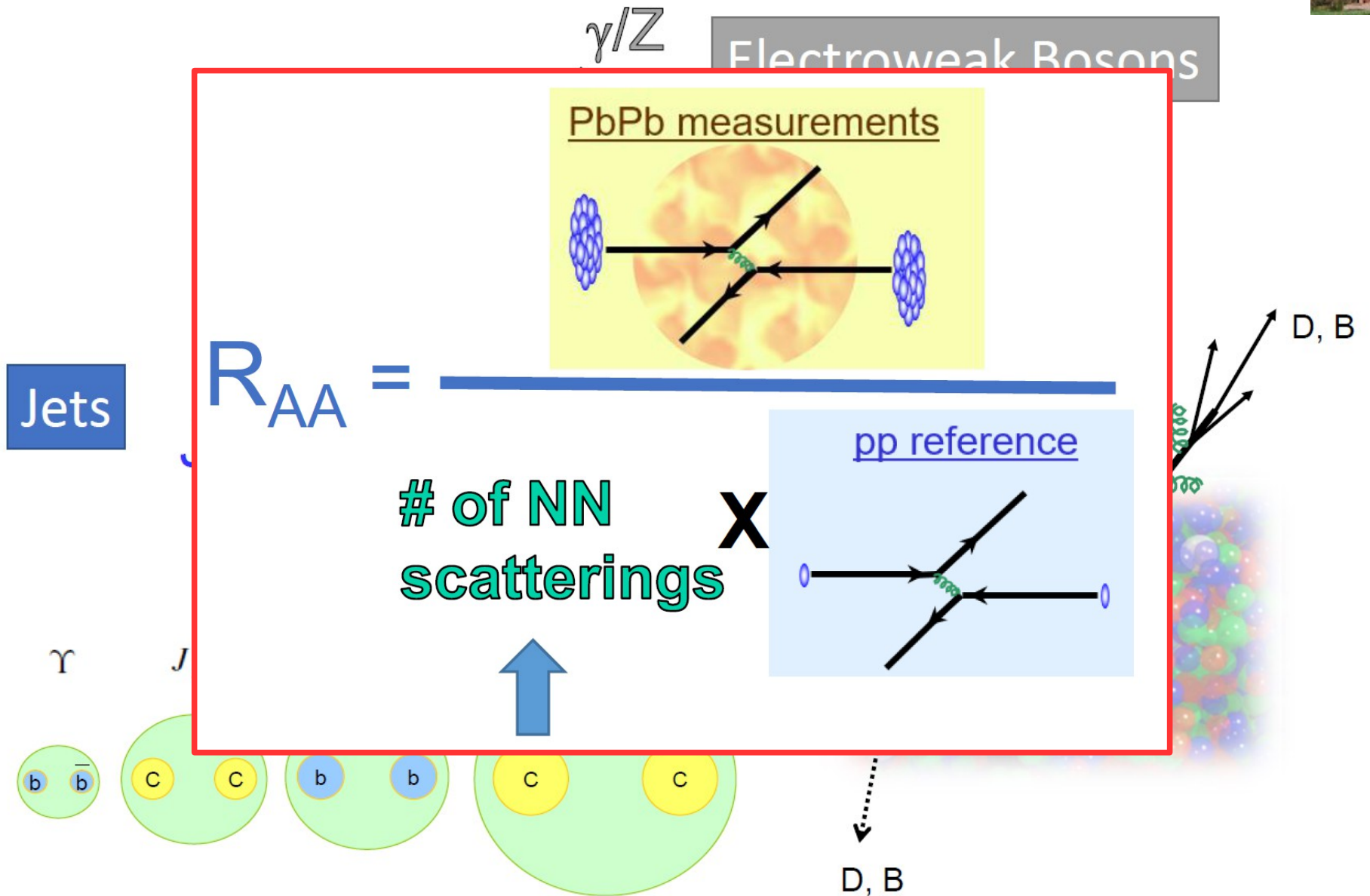


Hydrodynamic models that consider the Xe nuclear deformation are able to better describe the $v_2[\text{XeXe}]/v_2[\text{PbPb}]$ ratio in central collisions than those assuming a spherical Xe shape.

Hard Probes for Quark-Gluon Plasma



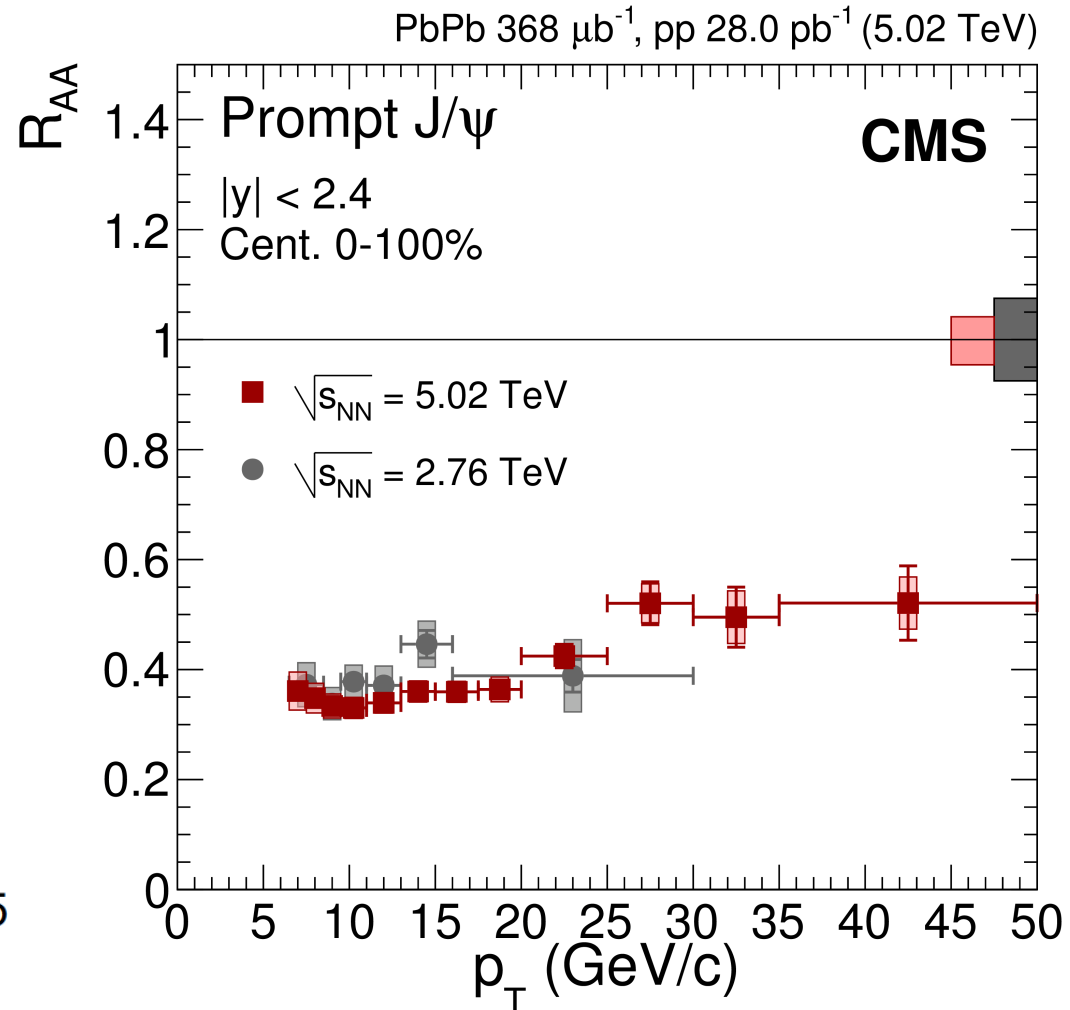
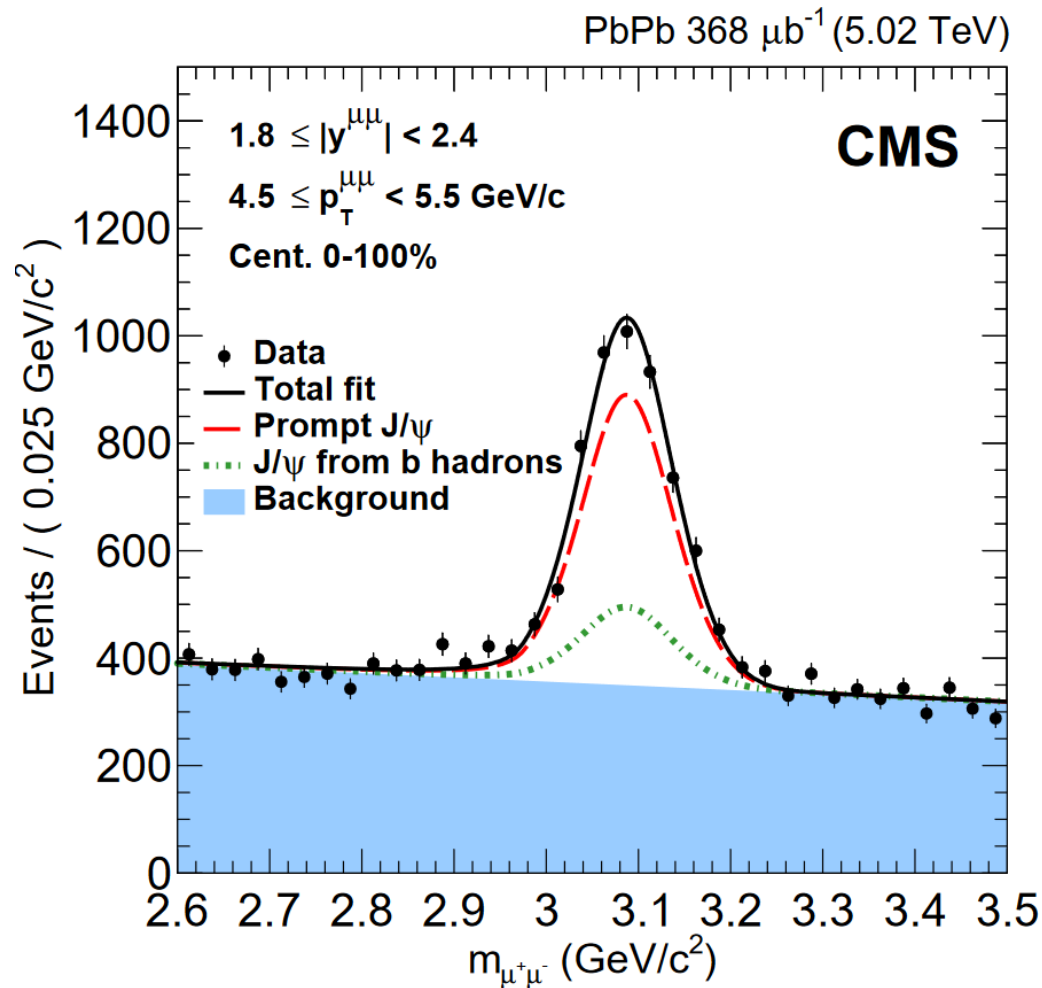
Hard Probes for Quark-Gluon Plasma



J/ψ suppression in Pb+Pb

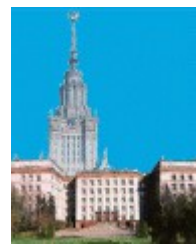


EPJ C 78 (2018) 509

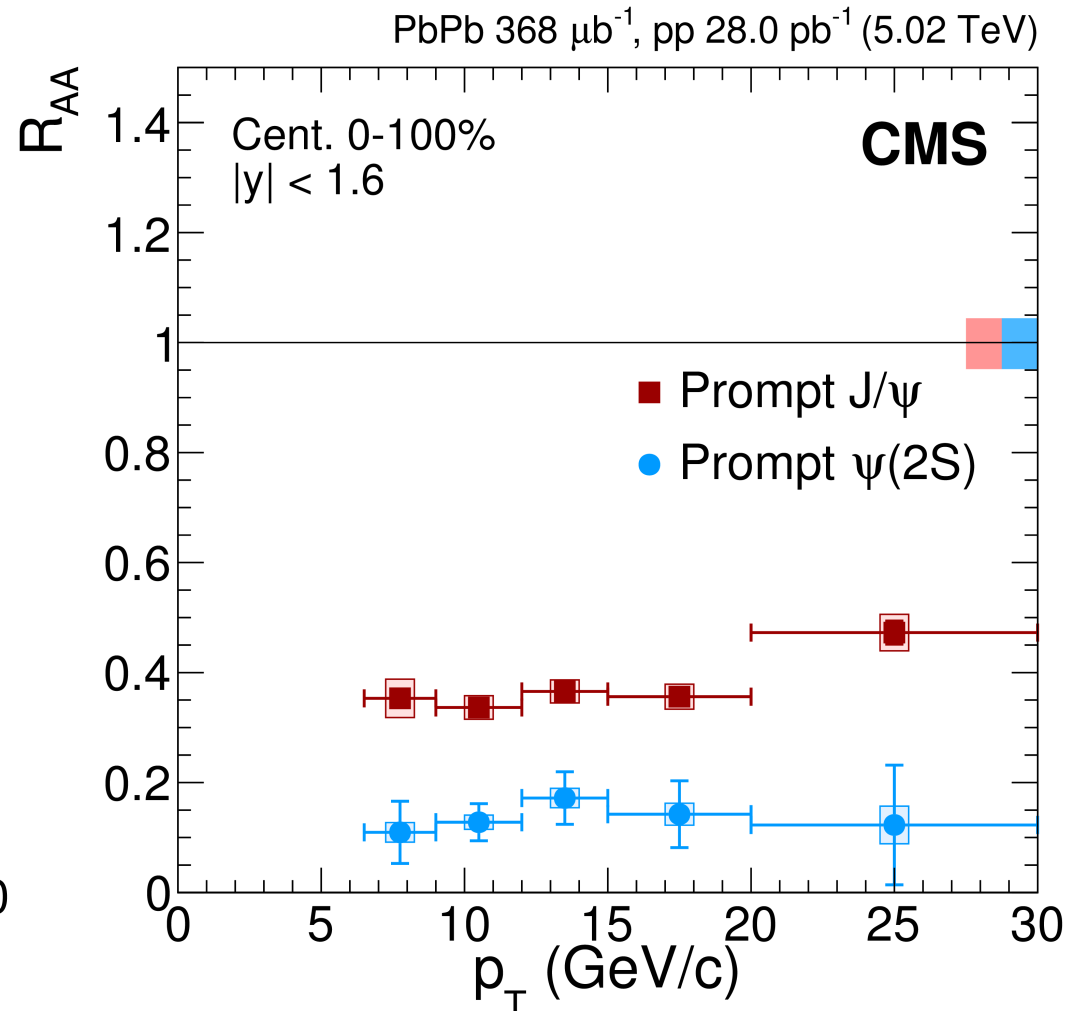
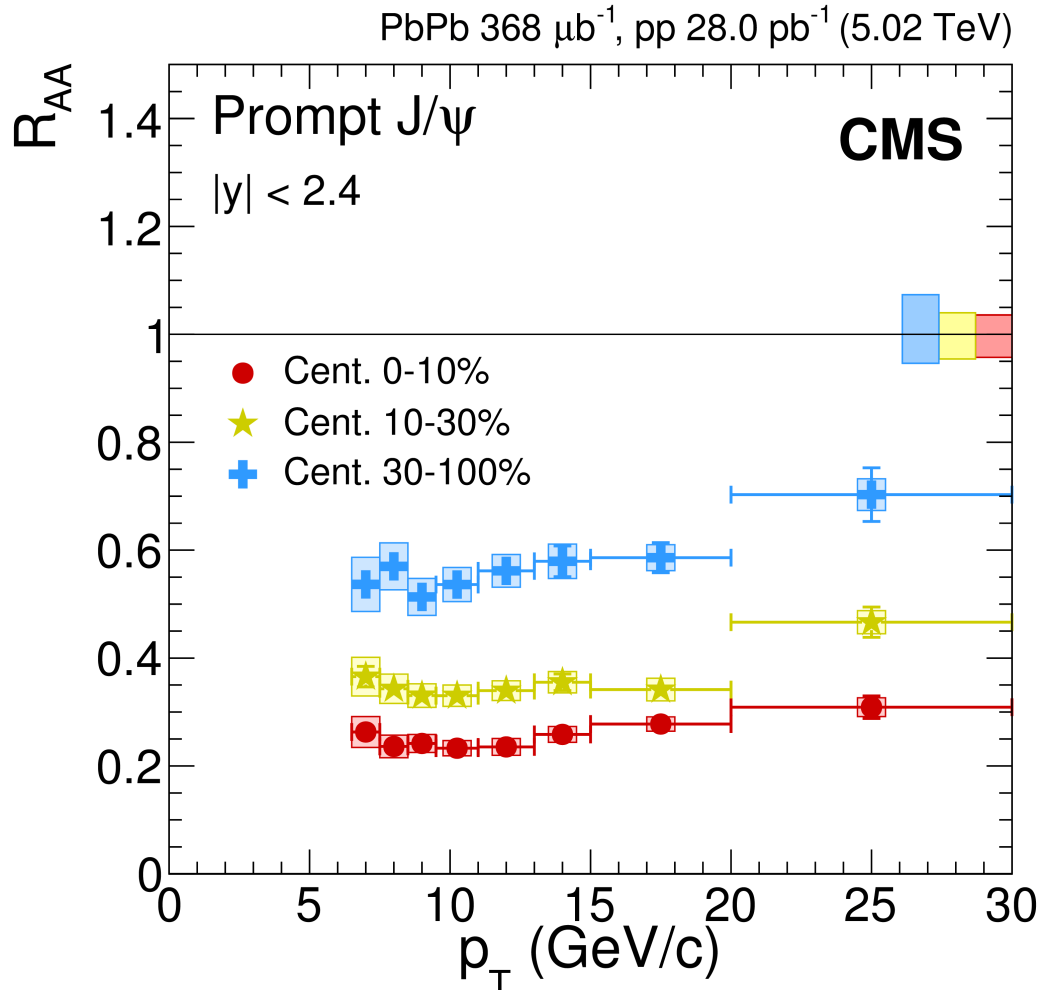


**J/ψ mesons are observed to be suppressed
(similarly in 2.76 and 5.02 TeV)**

J/ψ and ψ(2S) suppression in Pb+Pb



EPJ C 78 (2018) 509

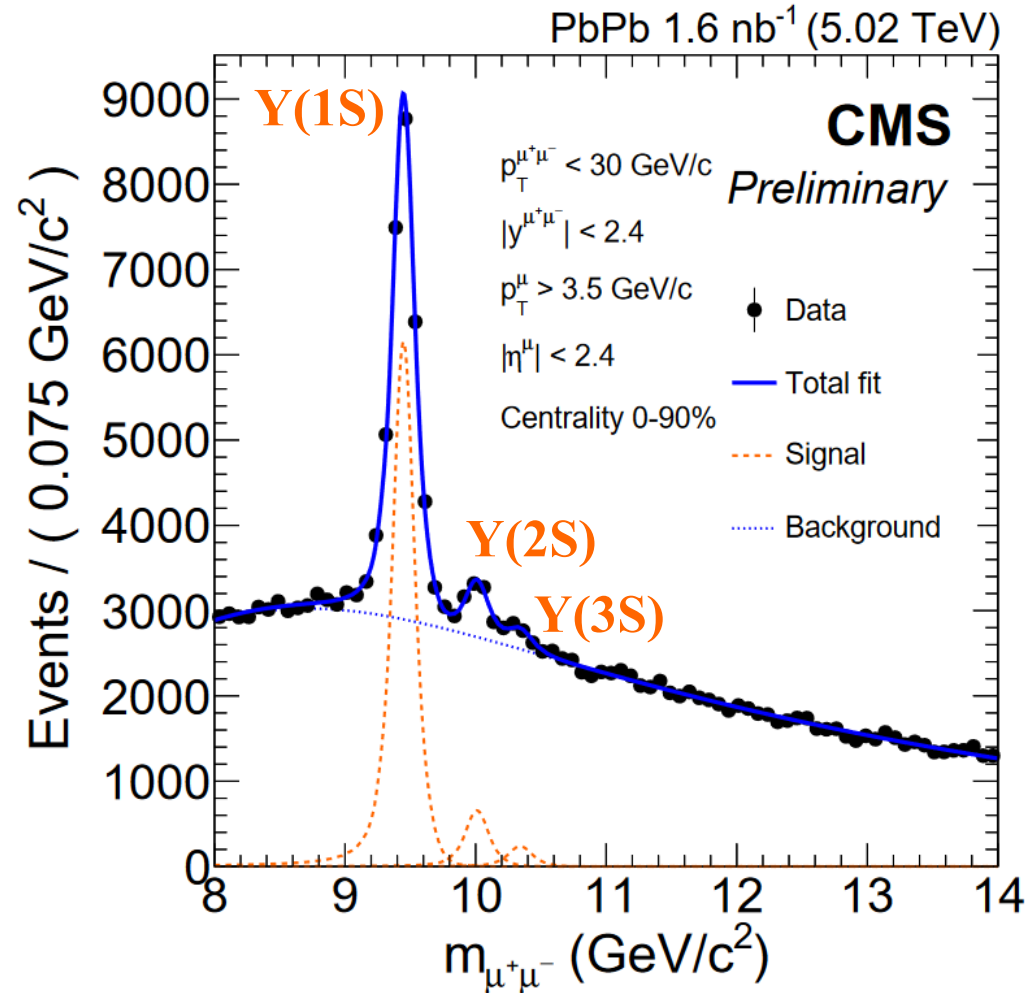
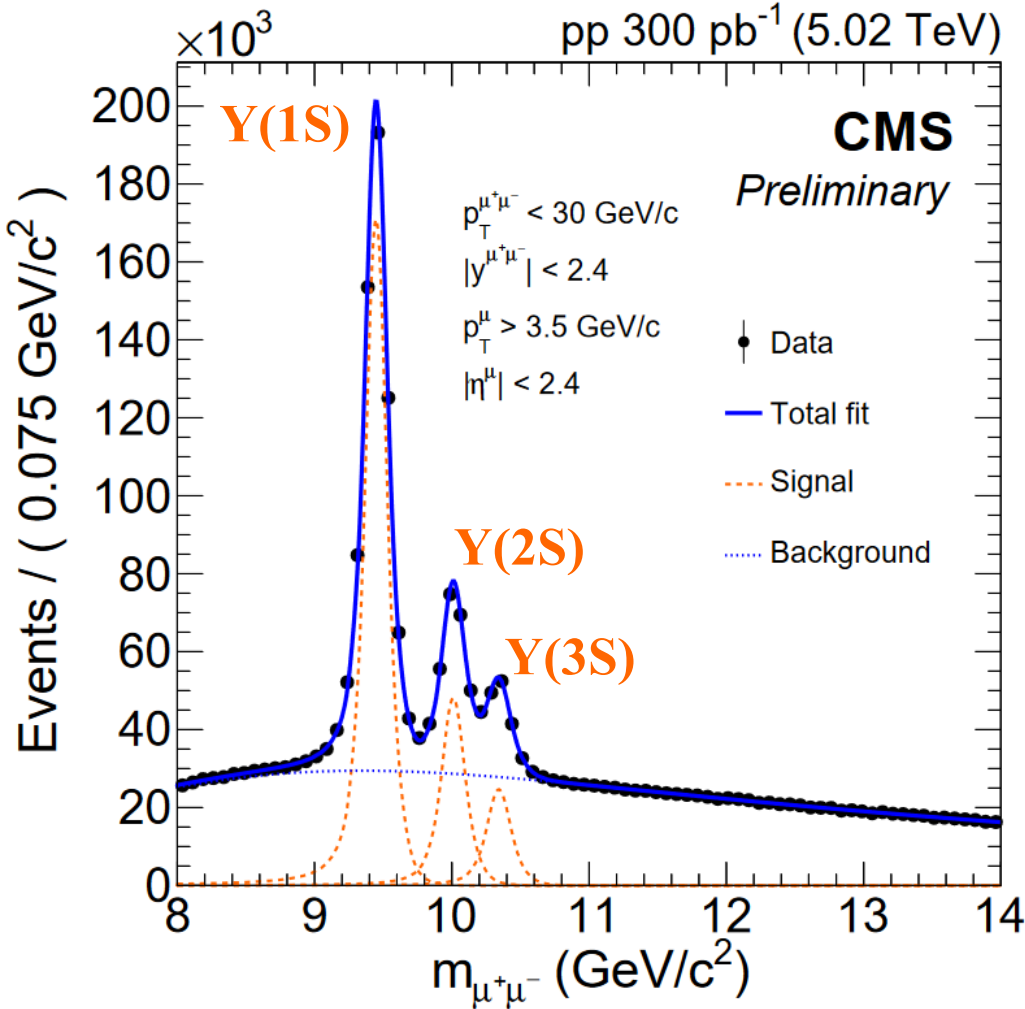


- **Increasing suppression for increasing centrality**
- **ψ(2S) is more suppressed than the J/ψ meson**

Upsilon suppression in Pb+Pb



CMS-PAS-HIN-21-007

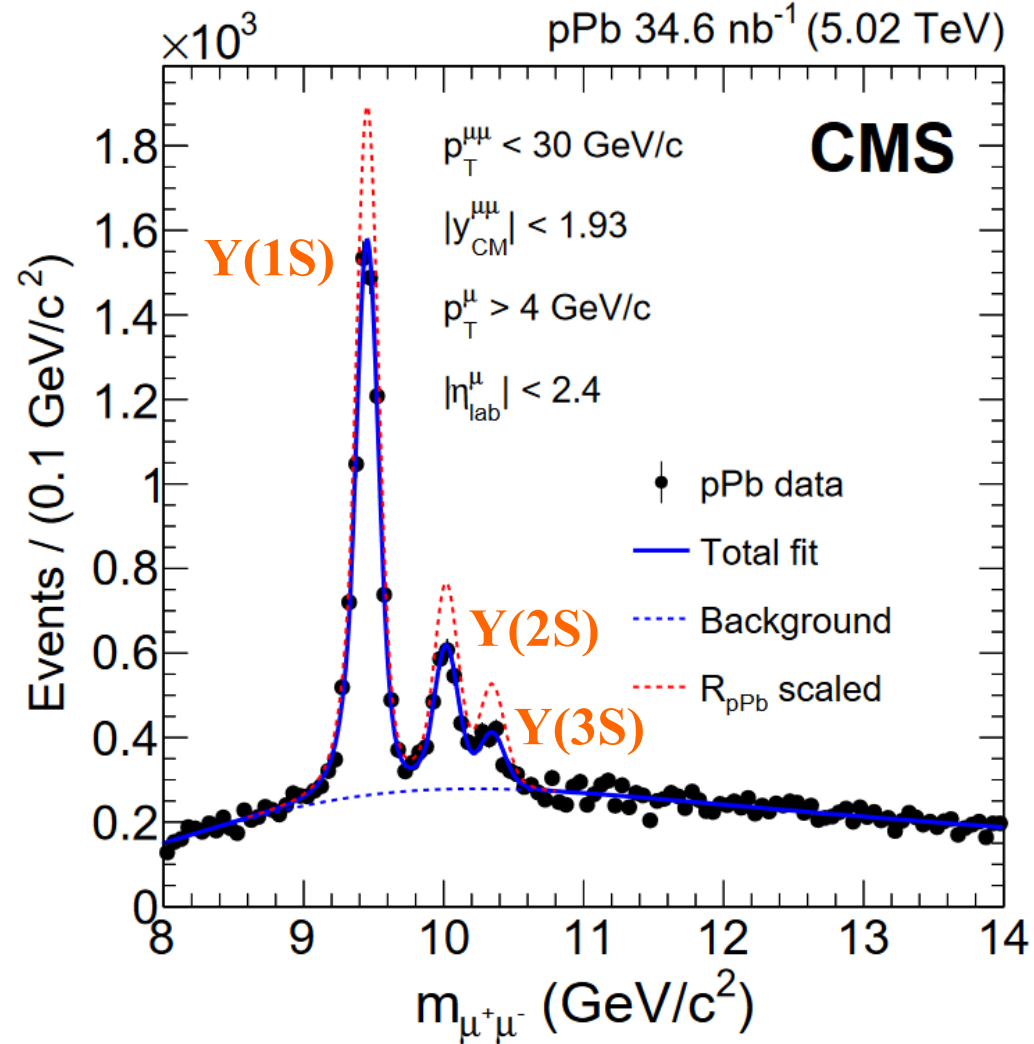
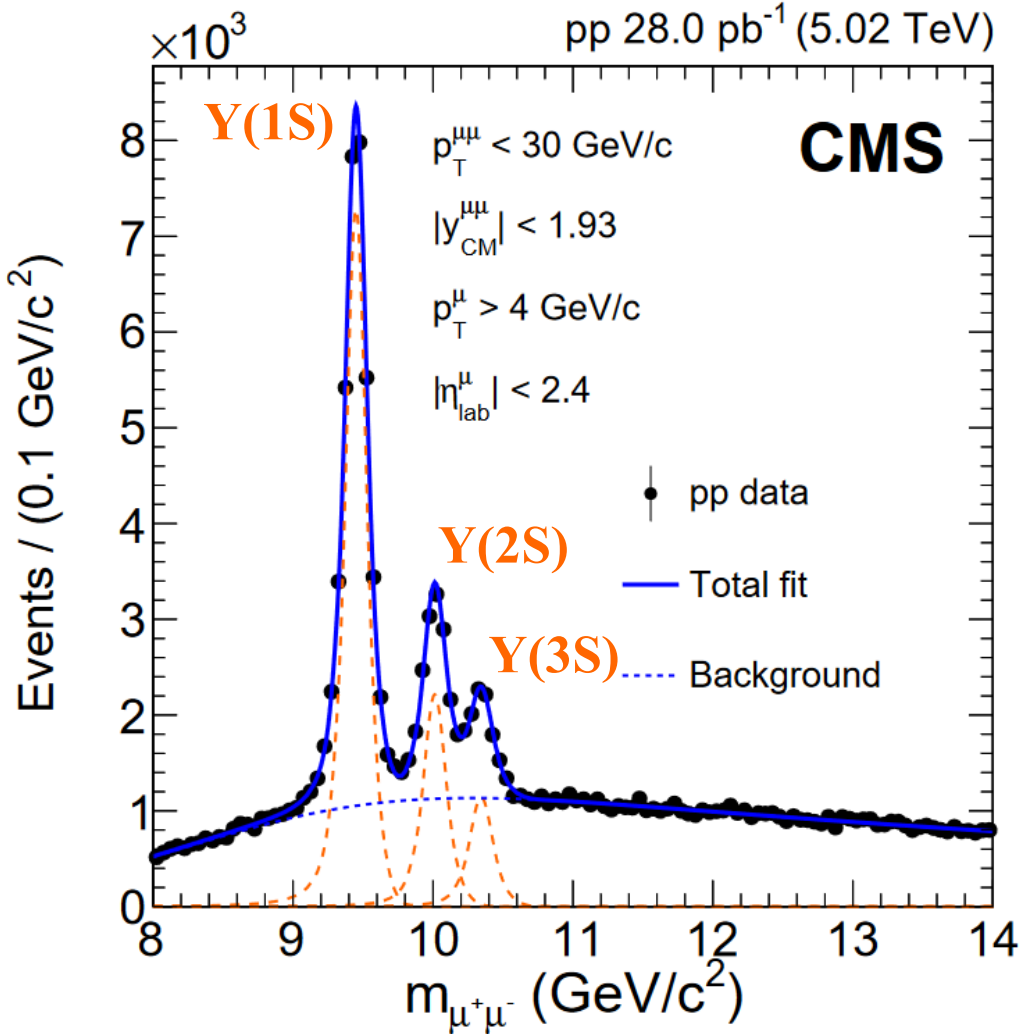


- **Observation of sequential suppression of Y family in Pb+Pb.**
- **First observation of Y(3S) in heavy-ion collisions! ($\sigma > 5$)**

Upsilon suppression in p+Pb



arXiv:2202.11807



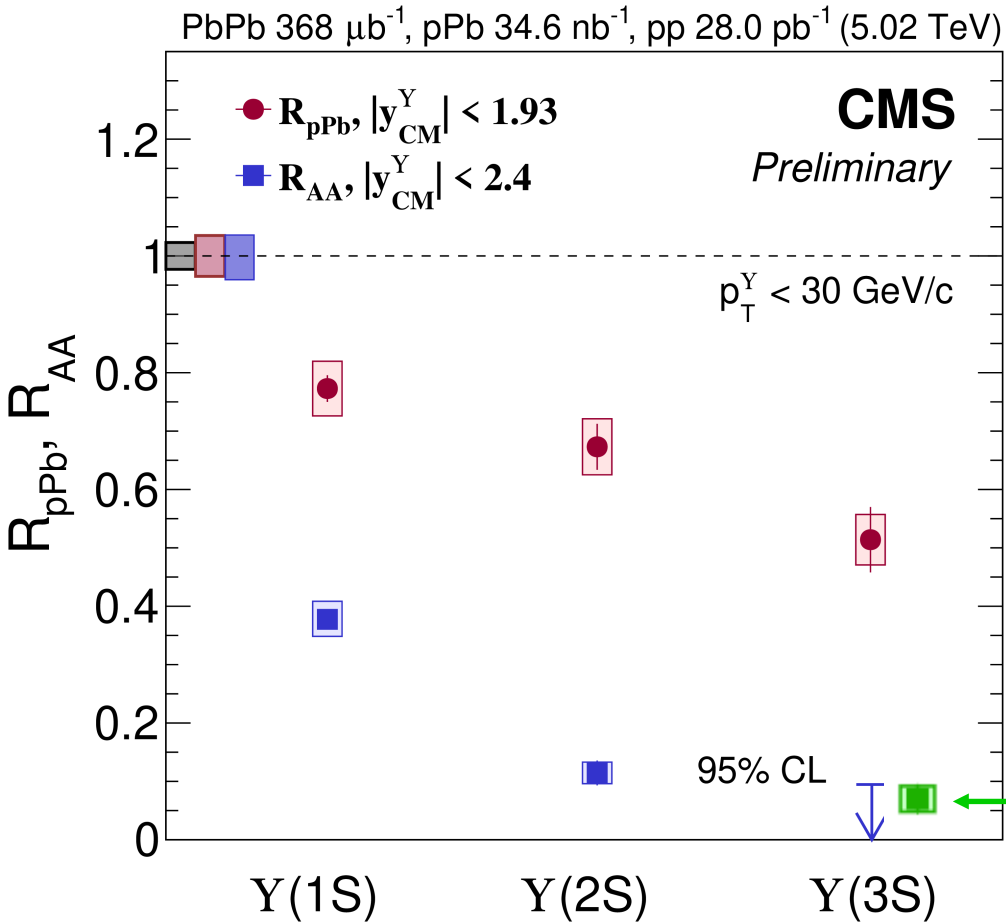
All Y states are found to be suppressed in p+Pb collisions compared to p+p collisions.



Upsilon suppression in p+Pb and Pb+Pb



arXiv:2202.11807 & CMS-PAS-HIN-21-007



Ordered in binding energy

$R_{\text{pPb}} \Upsilon(1\text{S}) > R_{\text{pPb}} \Upsilon(2\text{S}) > R_{\text{pPb}} \Upsilon(3\text{S})$

Largest suppression is in Pb+Pb

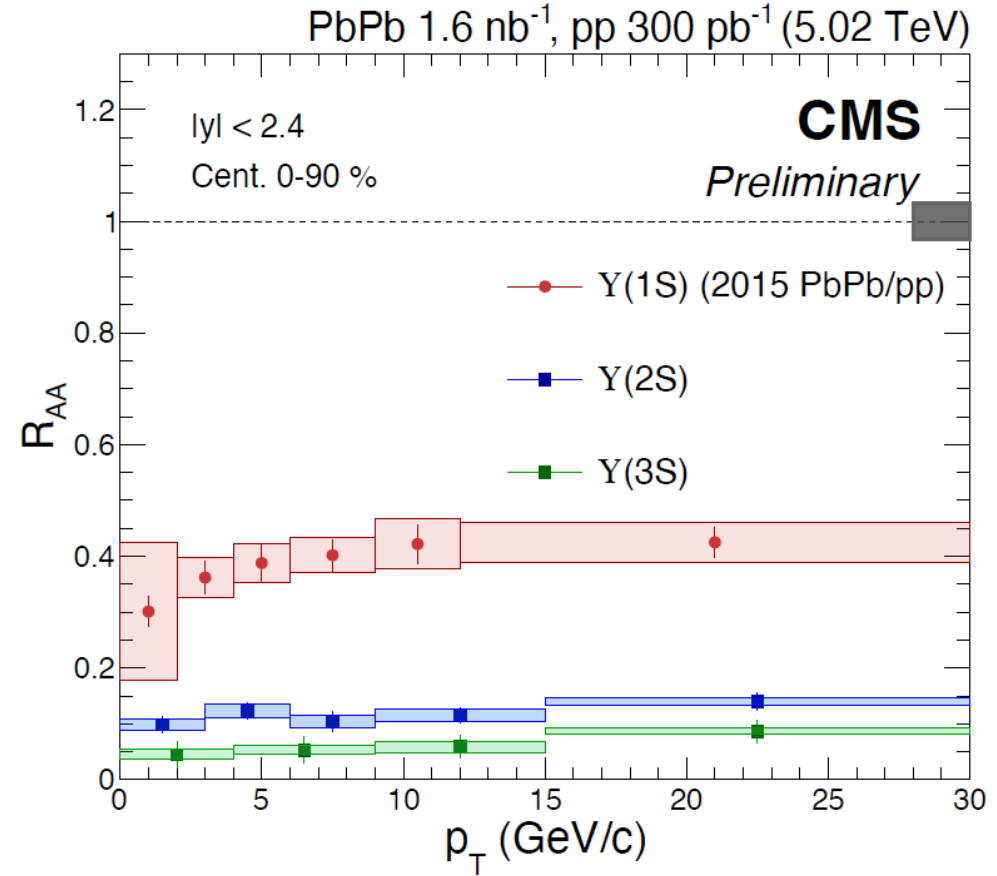
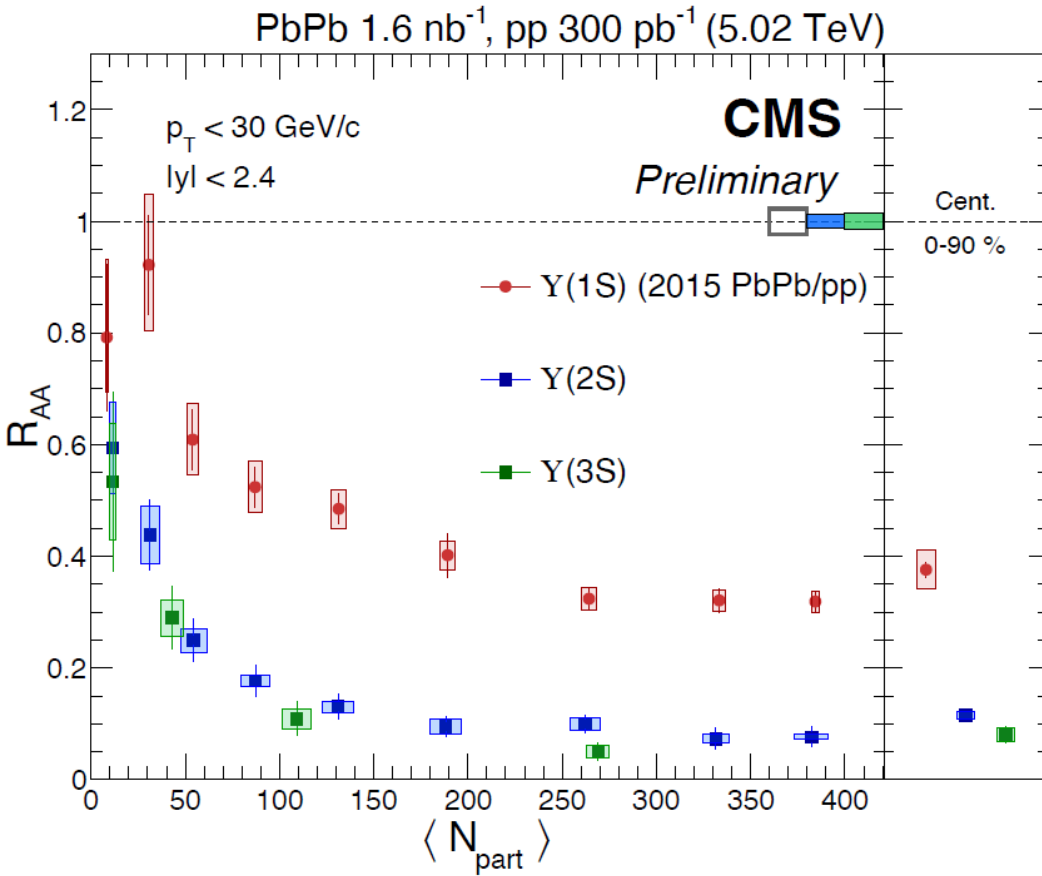
$R_{\text{pPb}} > R_{\text{pPb}}$

New result for Y(3S)

Upsilon suppression Pb+Pb



CMS-PAS-HIN-21-007



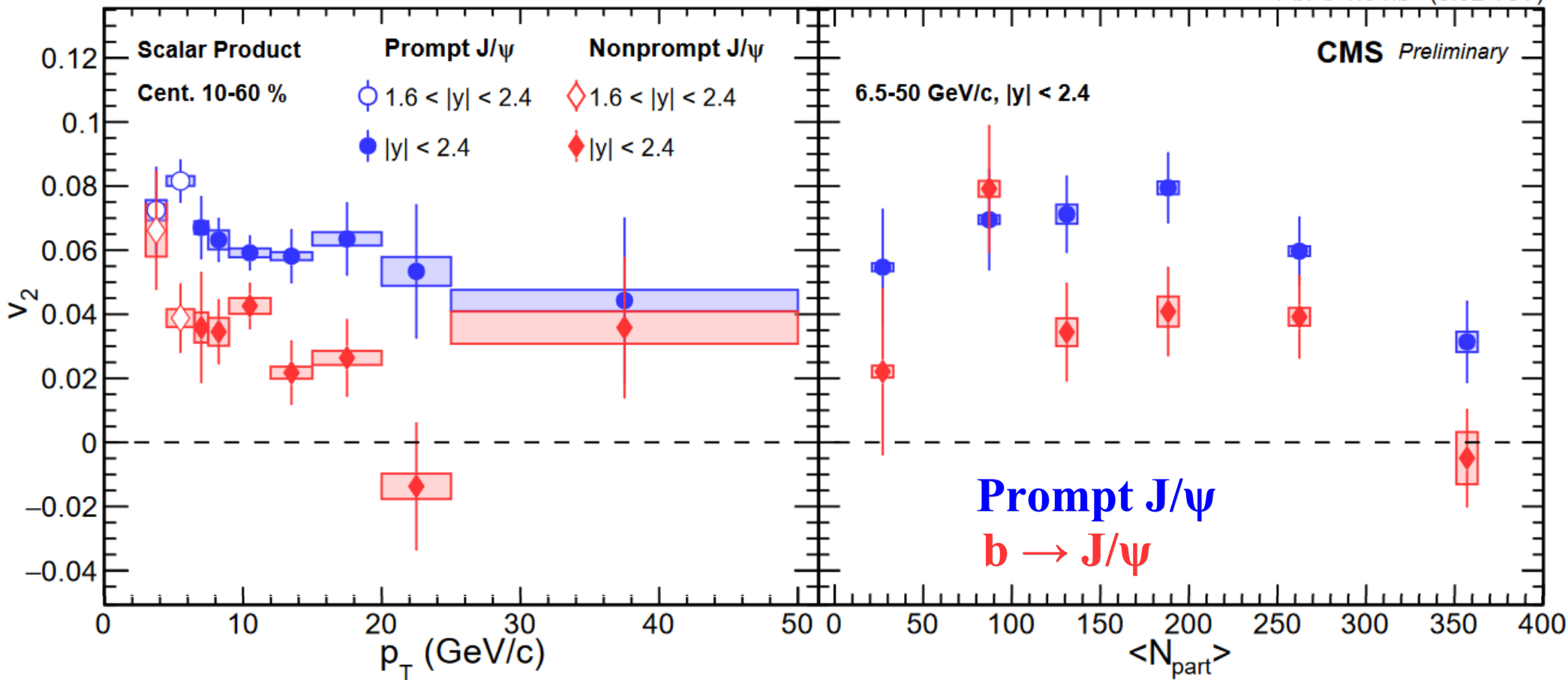
- R_{AA} is decreasing with numbers of participants of Pb+Pb collision.
- Slightly increasing with p_T ?

v_2 of J/ψ in Pb+Pb collisions

CMS-PAS-HIN-21-008



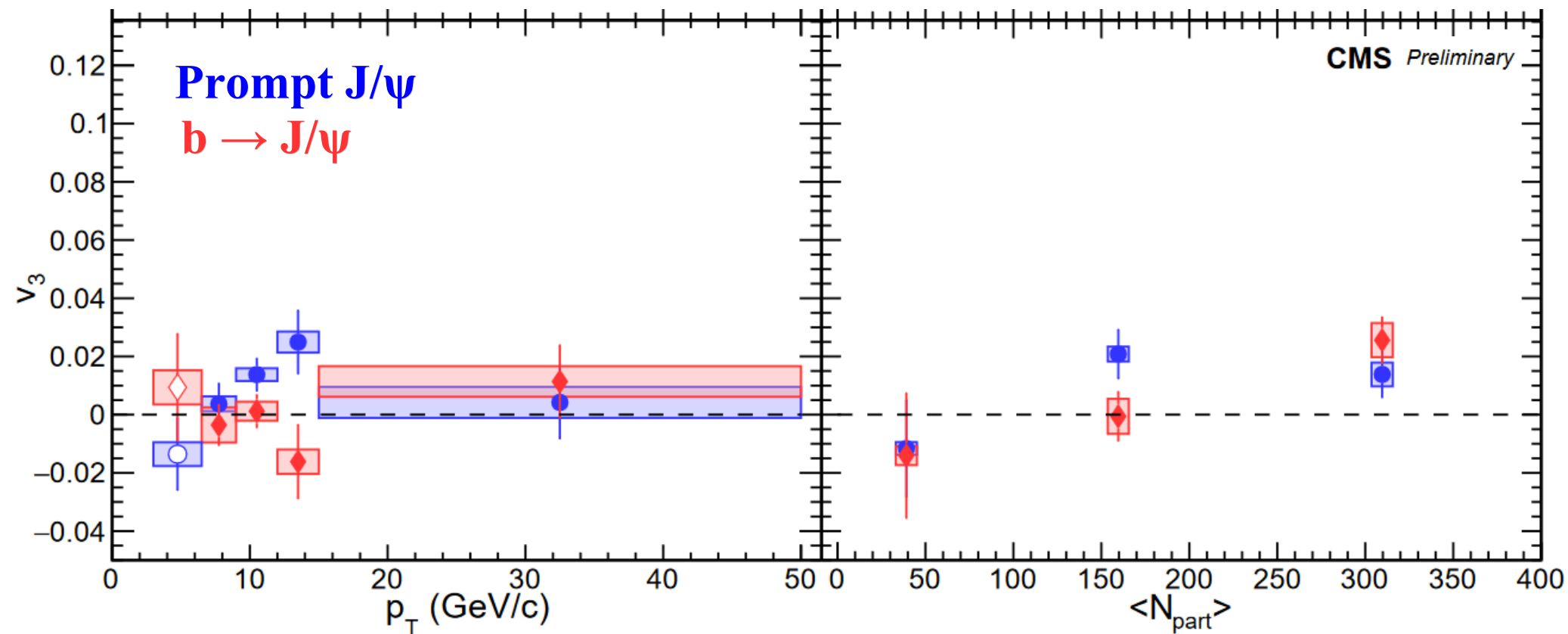
PbPb 1.6 nb⁻¹ (5.02 TeV)



- Large v_2 of J/ψ up to $p_T = 50$ GeV/c
- $v_2(b \rightarrow J/\psi) < v_2(\text{prompt } J/\psi)$

v_3 of J/ψ in Pb+Pb collisions

CMS-PAS-HIN-21-008



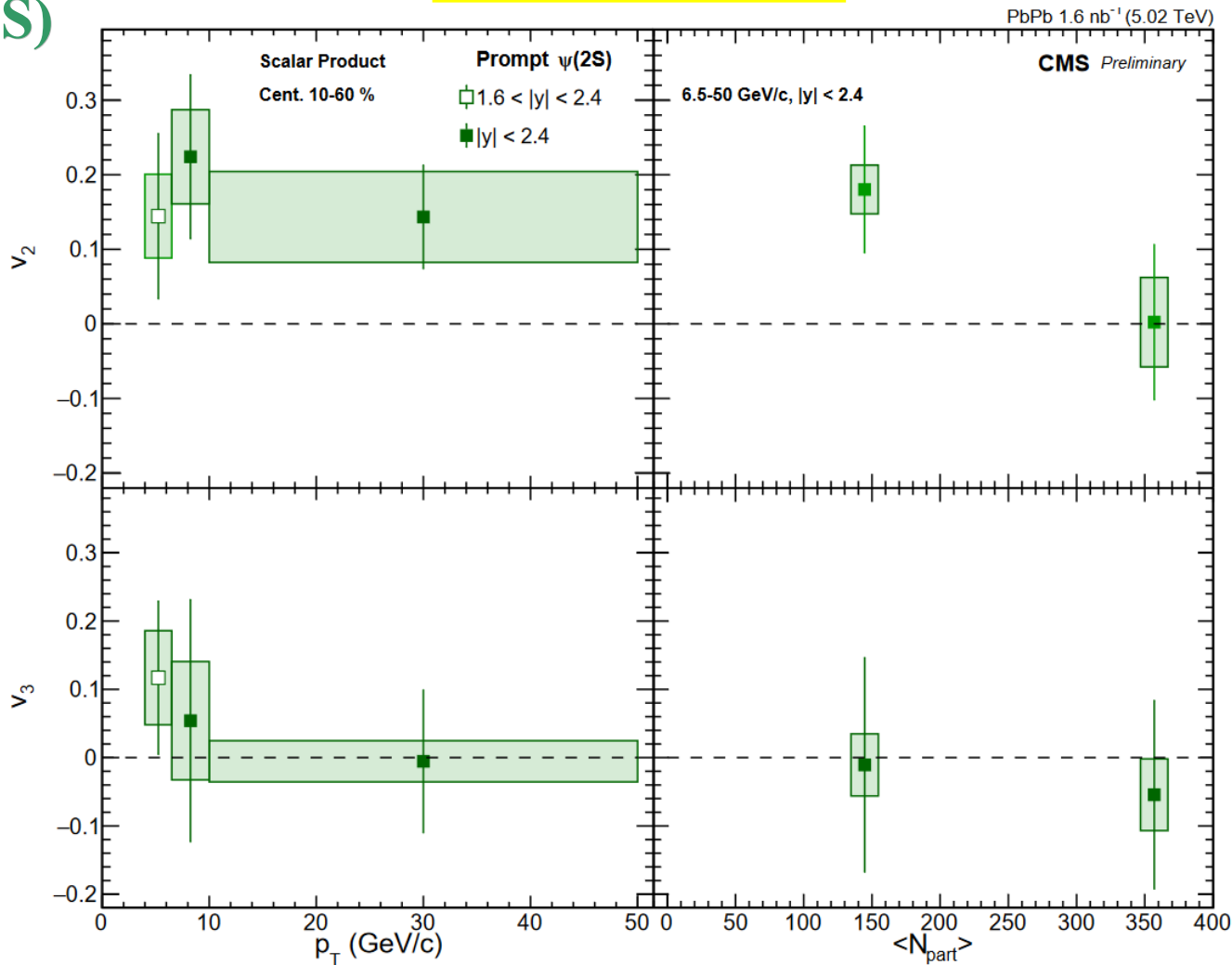
- First measurement of v_3 for prompt and non-prompt J/ψ separately
- no significant non-zero v_3 (J/ψ)

v_2 and v_3 of $\psi(2S)$ in Pb+Pb collisions



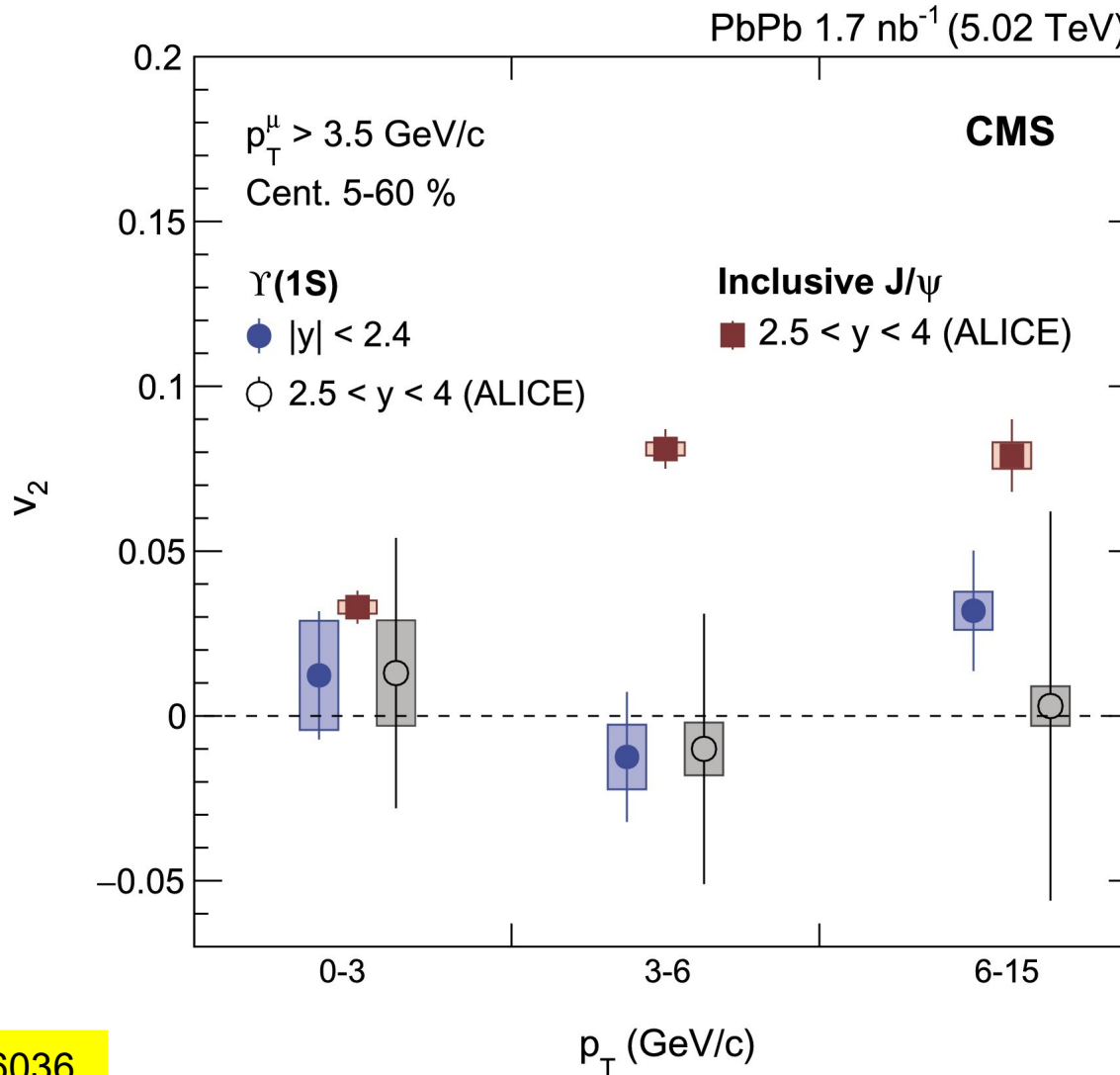
CMS-PAS-HIN-21-008

Prompt $\psi(2S)$



- First measurements for prompt $\psi(2S)$!
- v_2 is non-zero in $p_T = 4 - 50$ GeV/c, v_3 is close to zero

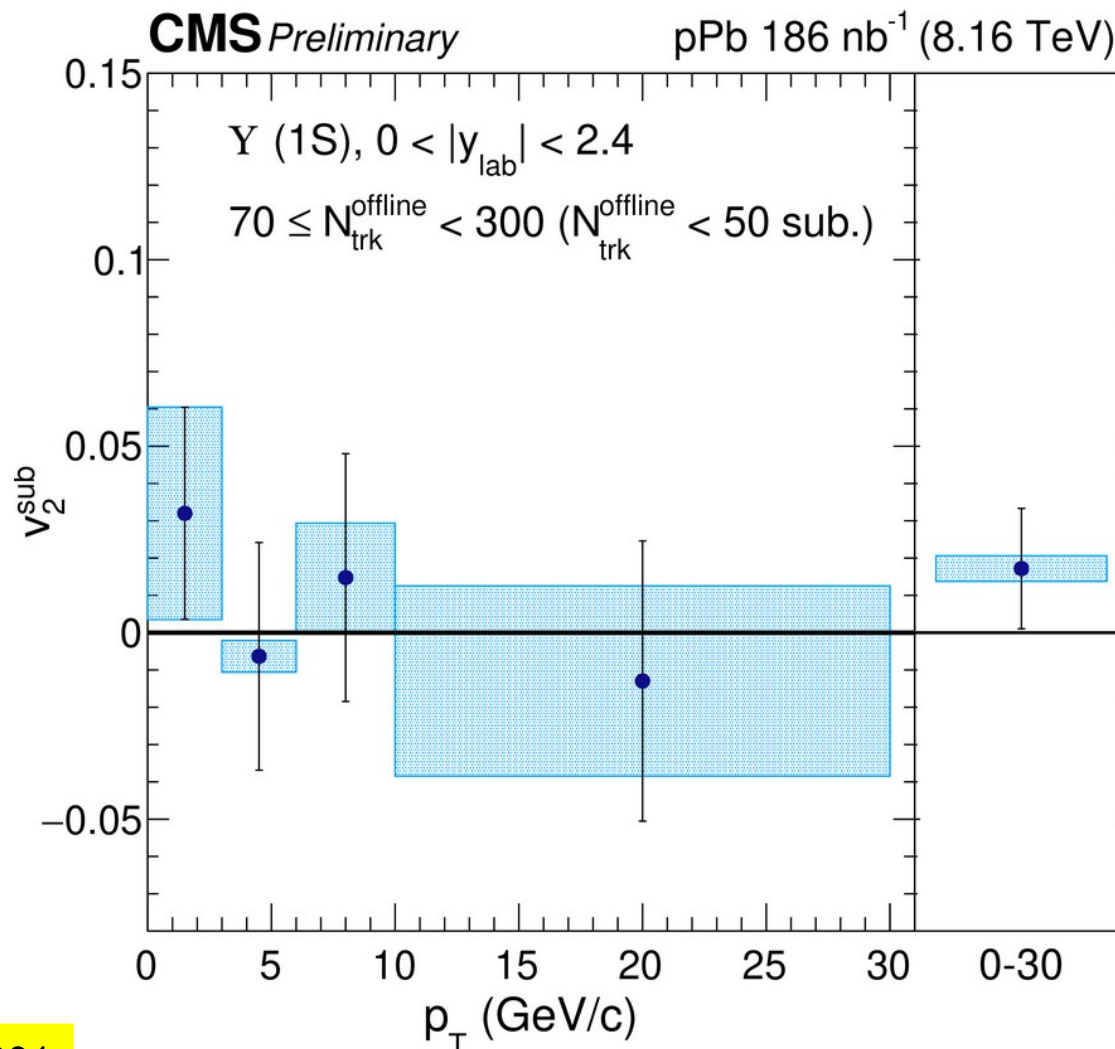
v_2 of $\Upsilon(1S)$ in Pb+Pb collisions



PLB 813 (2021) 136036

**In contrast to the J/ψ mesons,
no azimuthal anisotropy is observed for the $\Upsilon(1S)$ in Pb+Pb...**

v_2 of $Y(1S)$ in p+Pb collisions



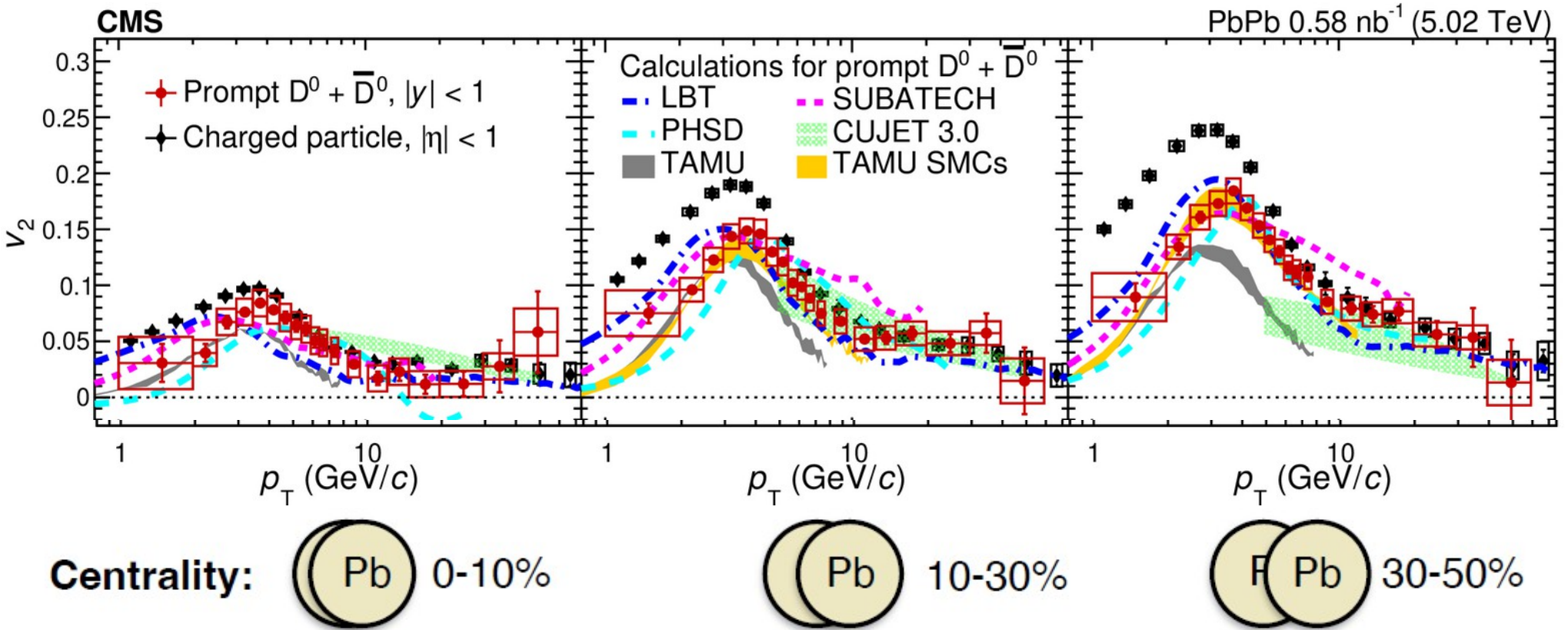
CMS-PAS-HIN-21-001

... and also no azimuthal anisotropy for the $Y(1S)$ in p+Pb !

Prompt D^0 flow in Pb+Pb collisions



PLB 816 (2021) 136253



The elliptic flow of prompt D^0 has similar pattern to that of charged hadrons.

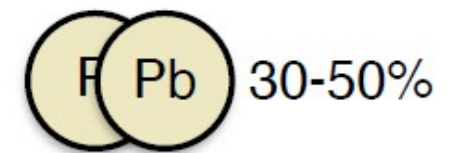
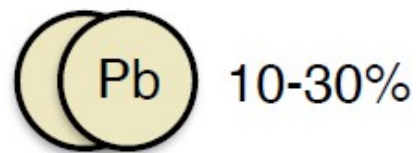
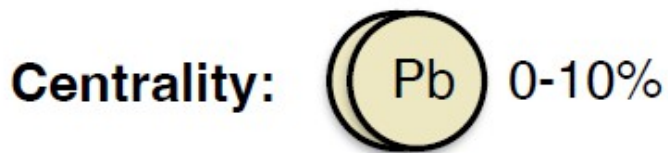
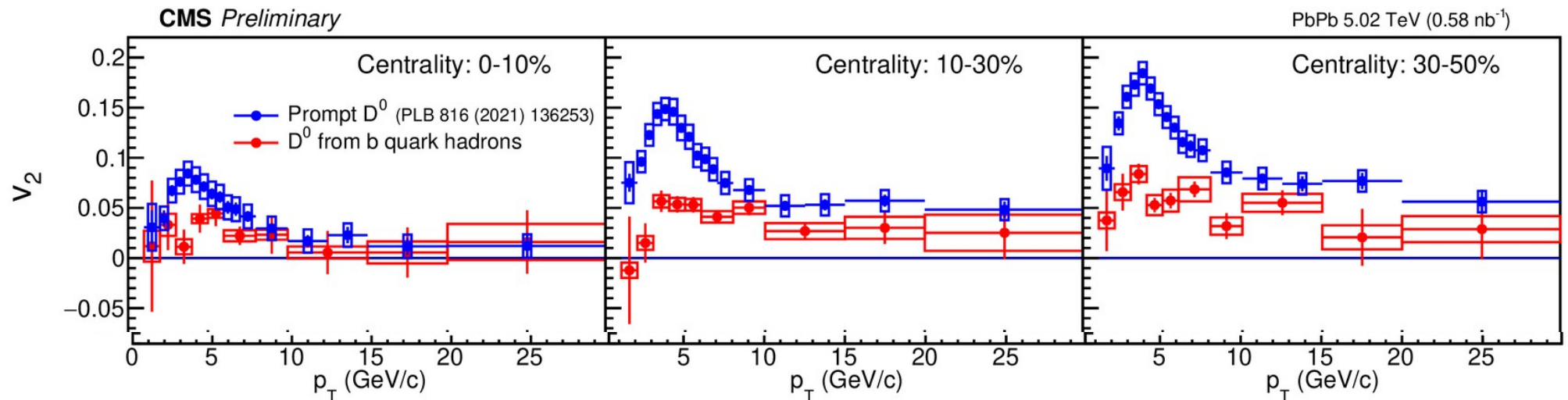
CMS-PAS-HIN-21-003

– also confirmed for the multiparticle correlations.

Prompt vs. non-prompt D^0 flow in Pb+Pb collisions

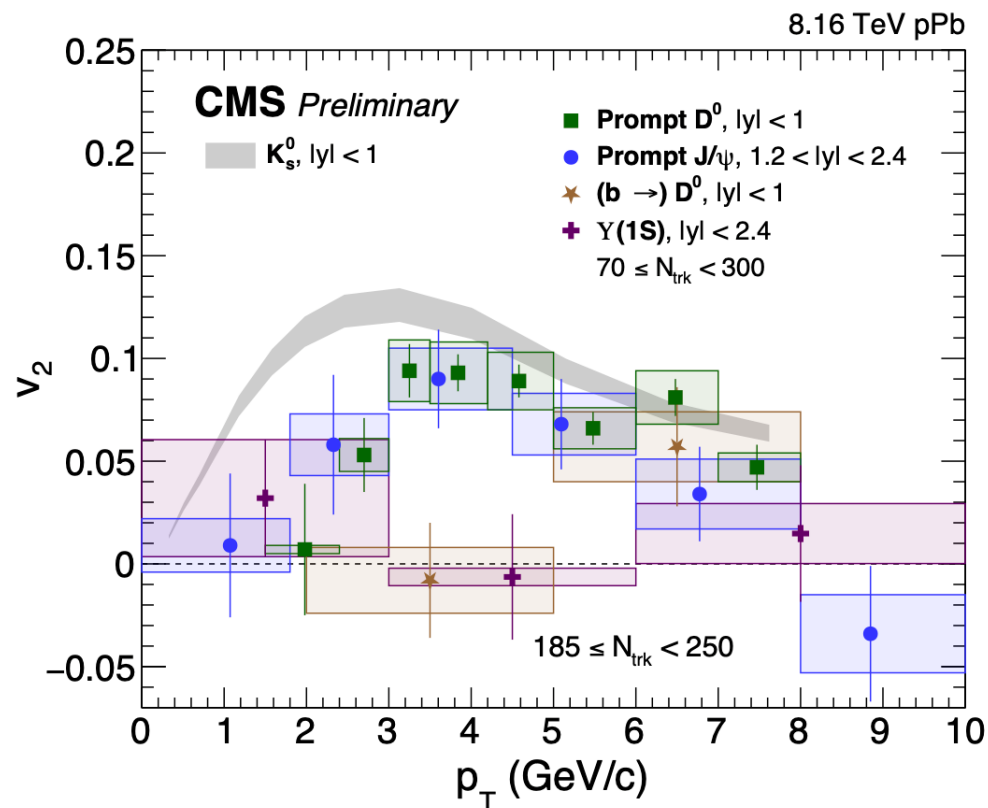
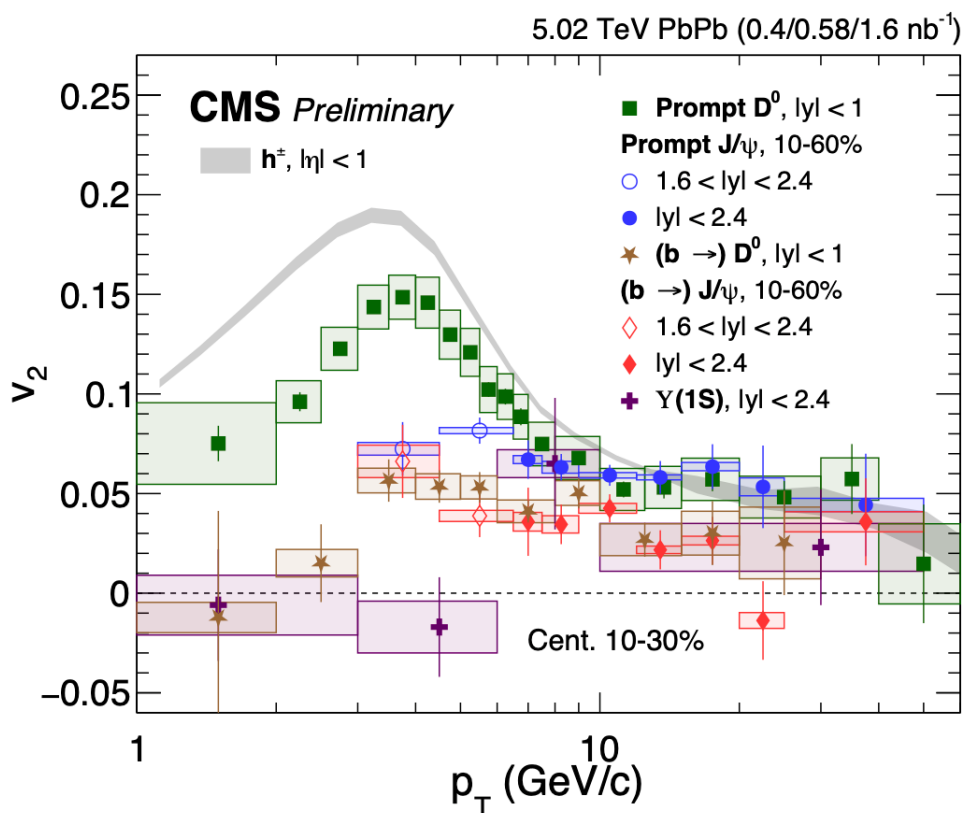


PLB 816 (2021) 136253 & CMS-PAS-HIN-21-003



The elliptic flow of prompt D^0 larger than non-prompt D^0 (from b quarks hadrons)

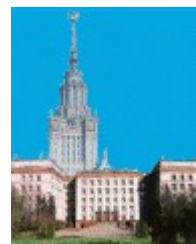
CMS Heavy Flavor v_2 Zoo



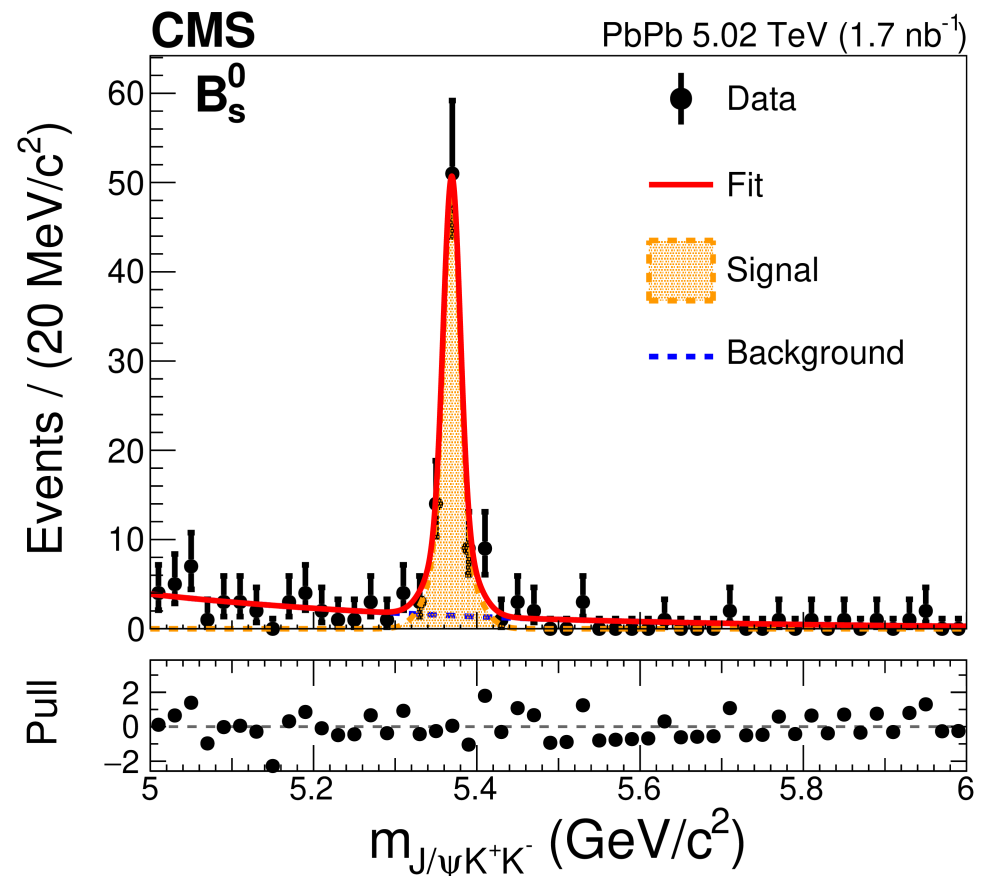
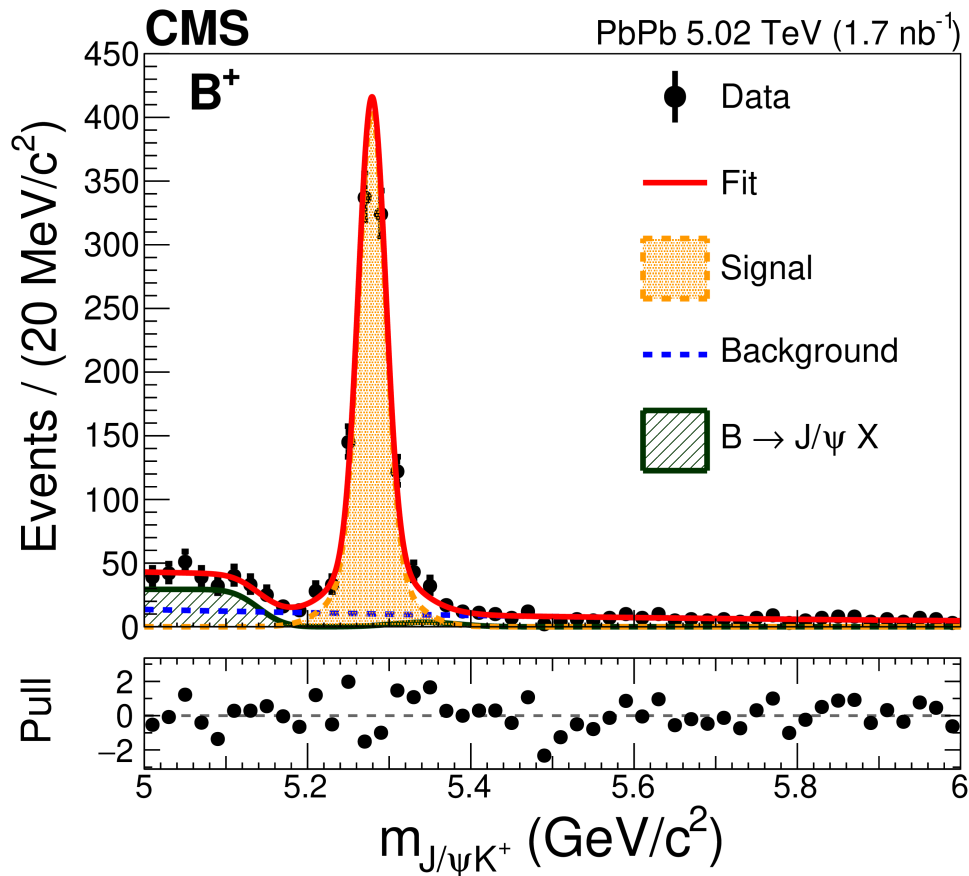
**Abundant physics behind these
high precision and unique measurements from the CMS!**

Reference

Measurement of B_s^0 and B^+ meson in Pb+Pb collisions

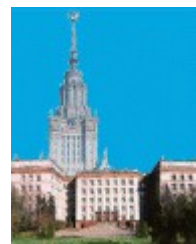


PLB 829 (2022) 137062

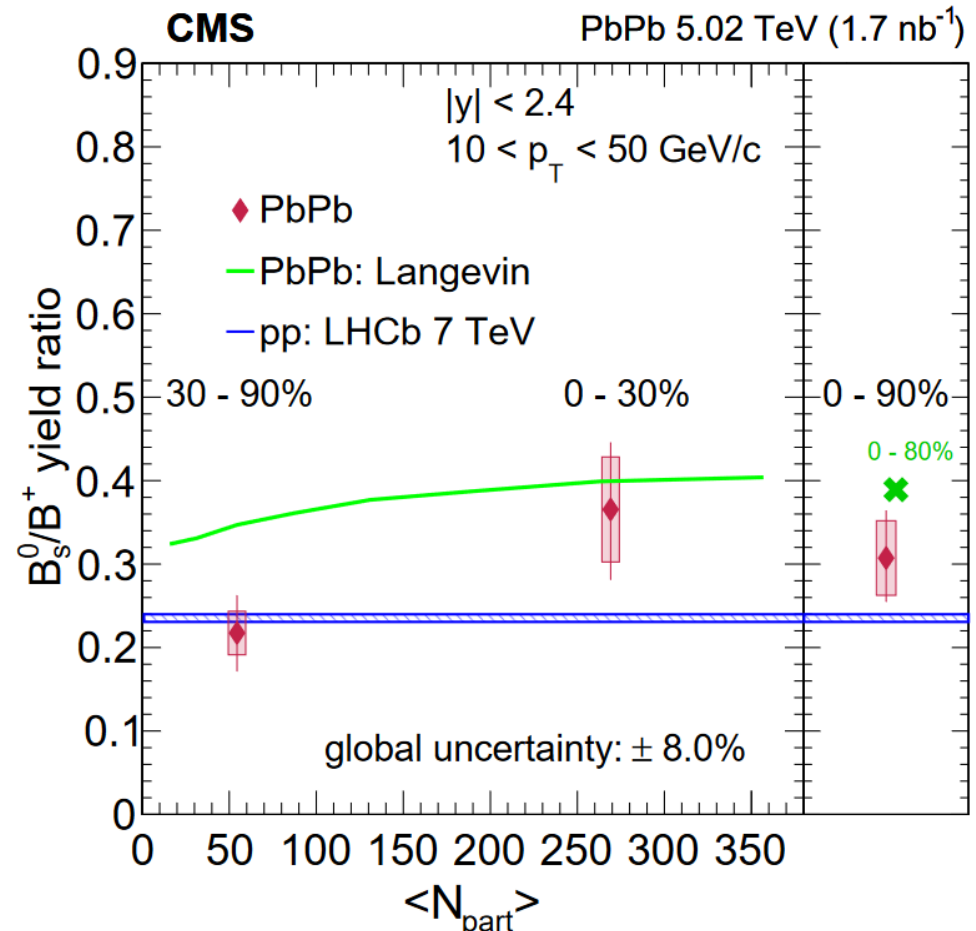
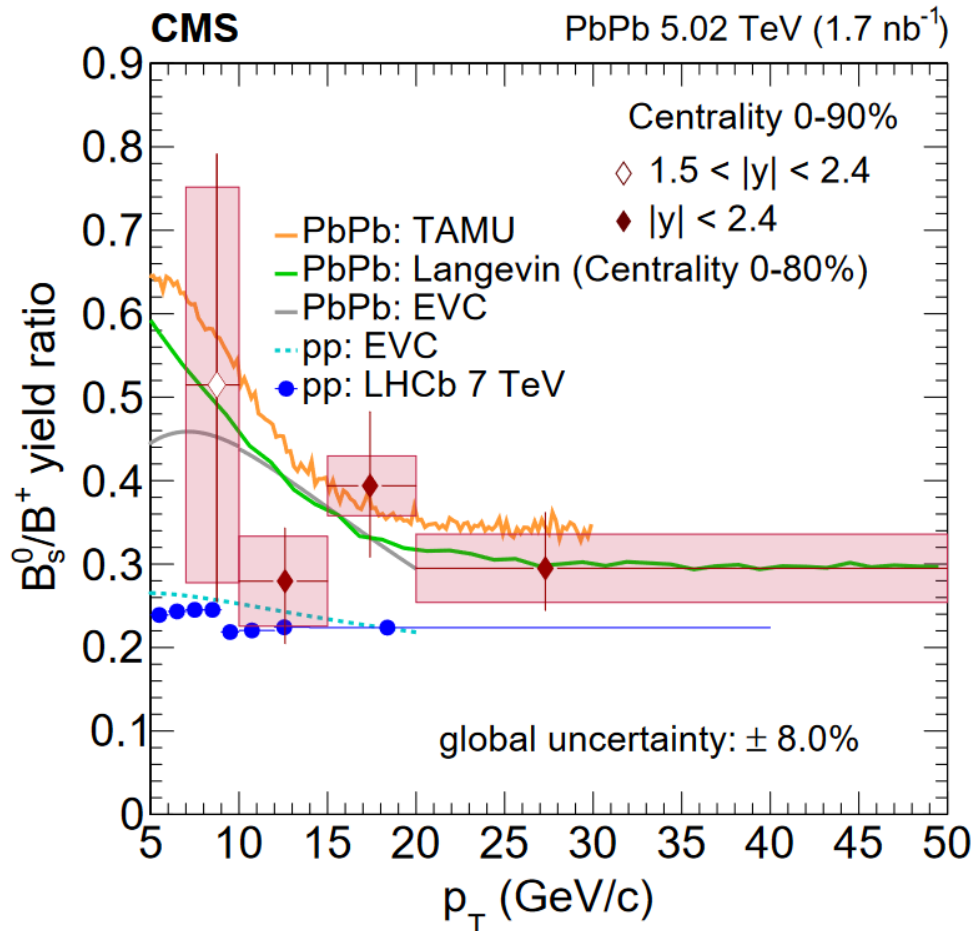


The B_s^0 meson is observed with a statistical significance in excess of 5 standard deviations for the first time in nucleus-nucleus collisions

Measurement of B_s^0 and B^+ meson in Pb+Pb collisions



PLB 829 (2022) 137062



- No significant p_T -dependence of B_s^0/B^+ ratio
- Model predictions in reasonably well agreement with data

- B_s^0/B^+ ratio in Pb+Pb compatible with measurements in pp



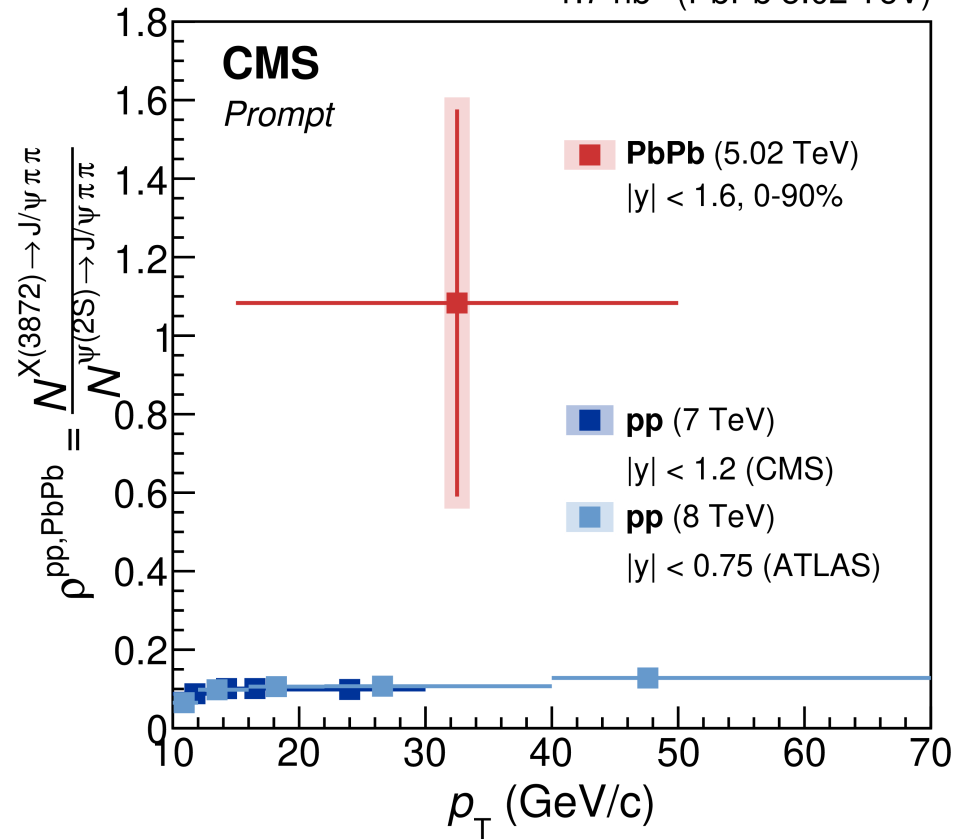
First evidence of X(3872) in Pb+Pb



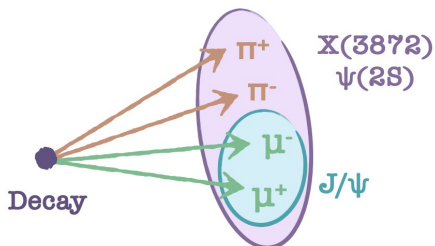
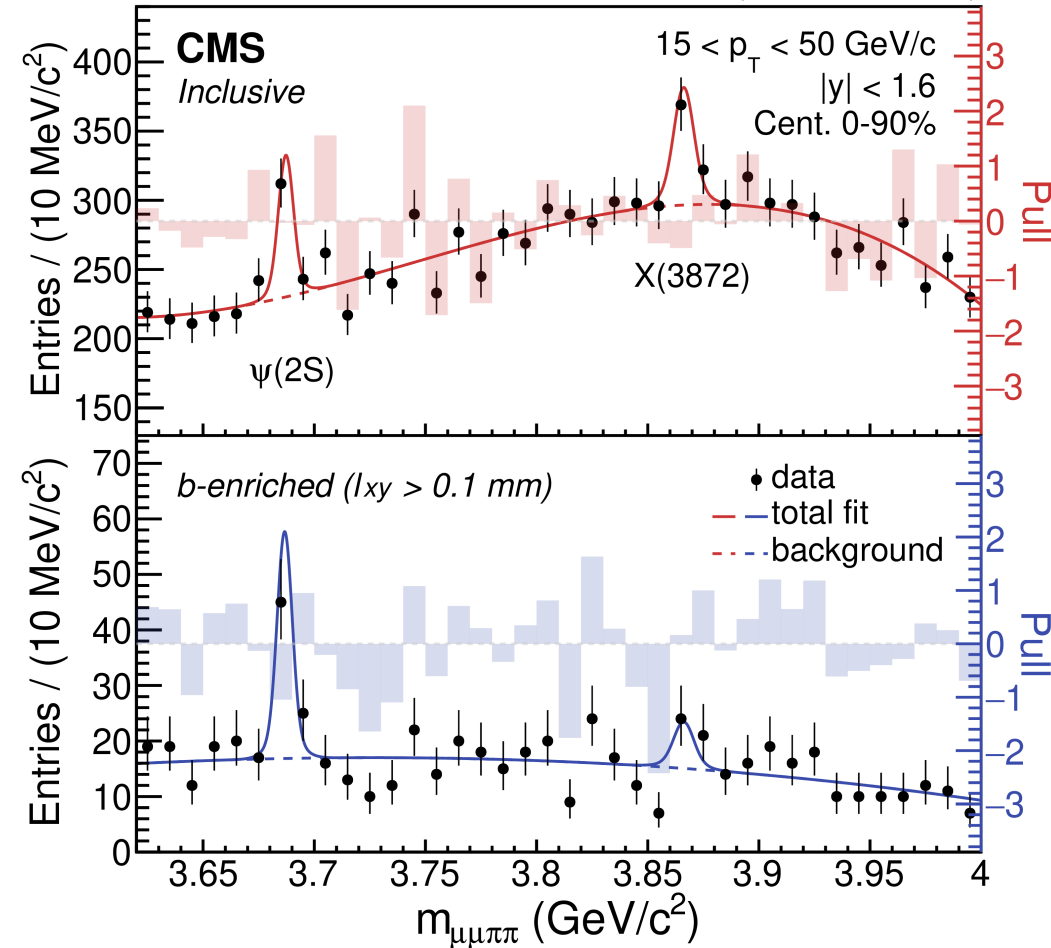
PRL 128 (2022) 032001

Comparison to $\psi(2S)$

1.7 nb⁻¹ (PbPb 5.02 TeV)



1.7 nb⁻¹ (PbPb 5.02 TeV)



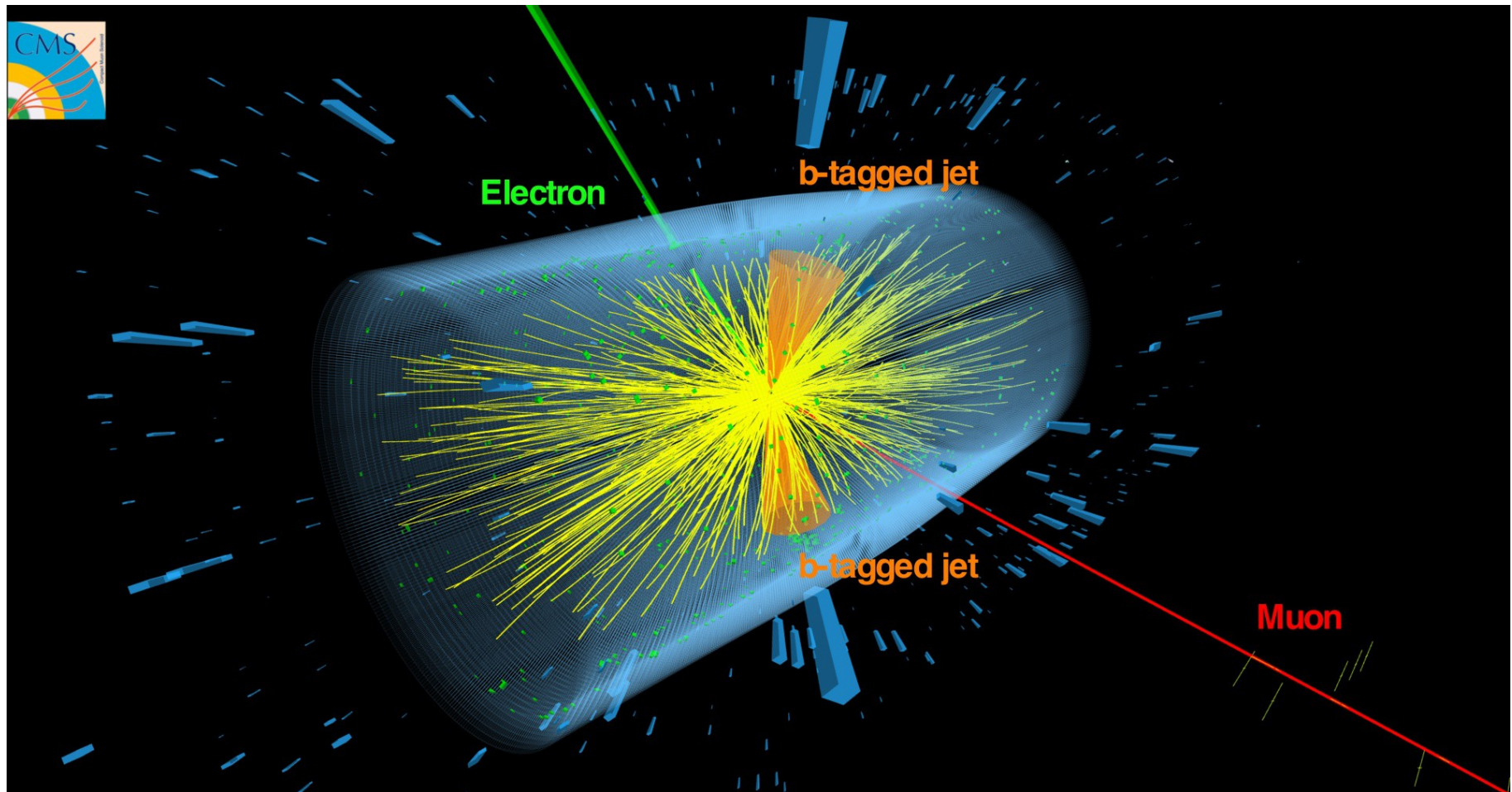
Result provides a unique experimental input to the theory, towards elucidating the production mechanism and the nature of the X(3872).



The first search for **top** using **Pb+Pb** collisions



PRL 125 (2020) 222001

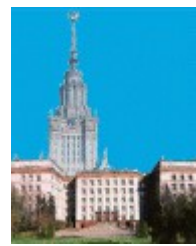


**Using either charged leptons only or charged leptons + b jets.
The measured cross sections are compatible with expectations from
scaled proton-proton data and QCD predictions.**



The first search for top using Pb+Pb collisions

PRL 125 (2020) 222001

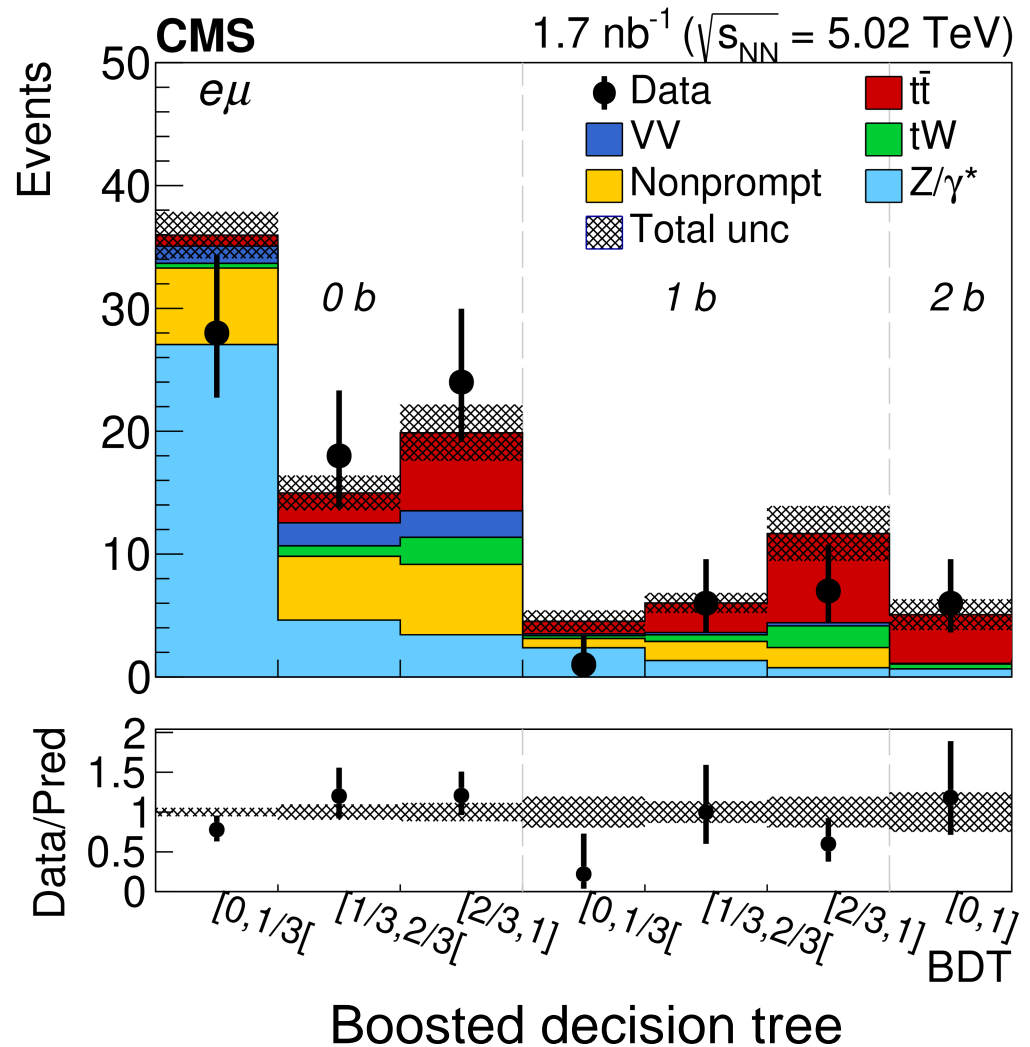


4.0 σ significance
Consistent with pQCD

- Top quarks can probe both the initial and final state
- Probing the QGP formation?

Both dilepton multivariate & b-jet counting analyses

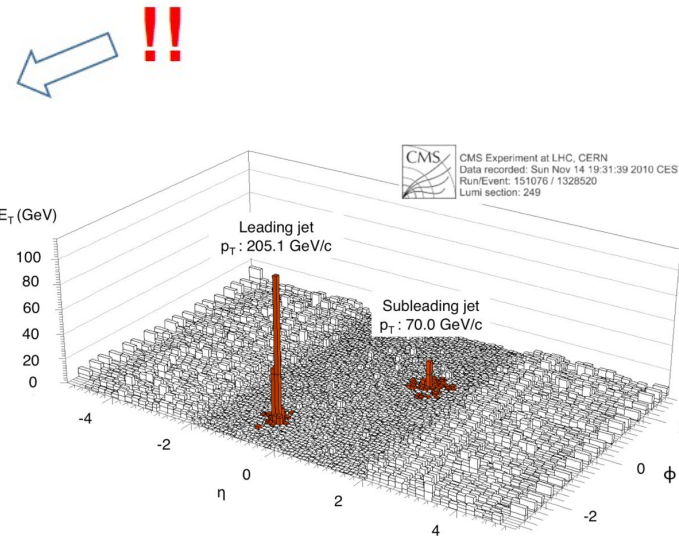
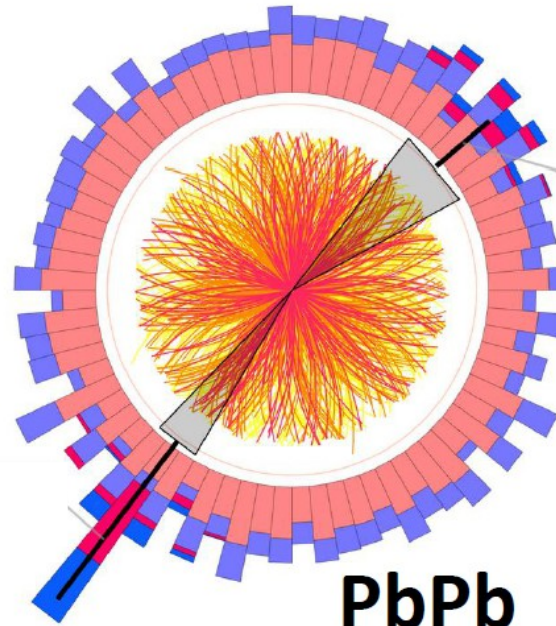
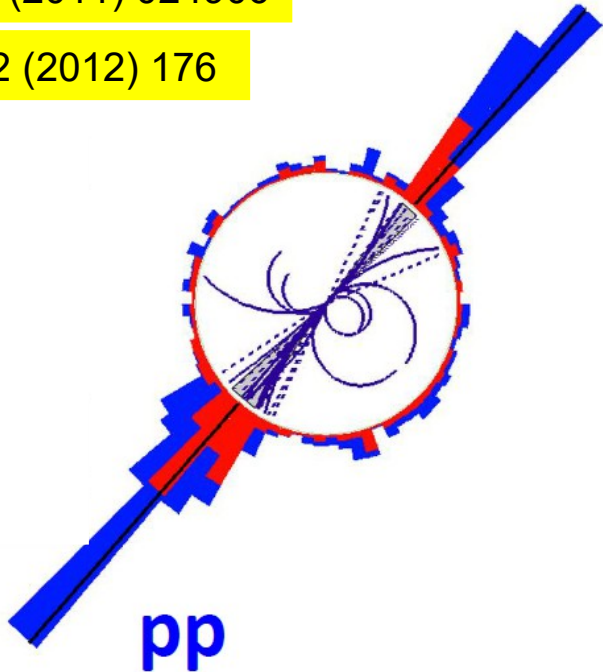
The observed significance of the top signal against the background-only hypothesis amounts to 3.8 and 4.0 standard deviations in the two methods.



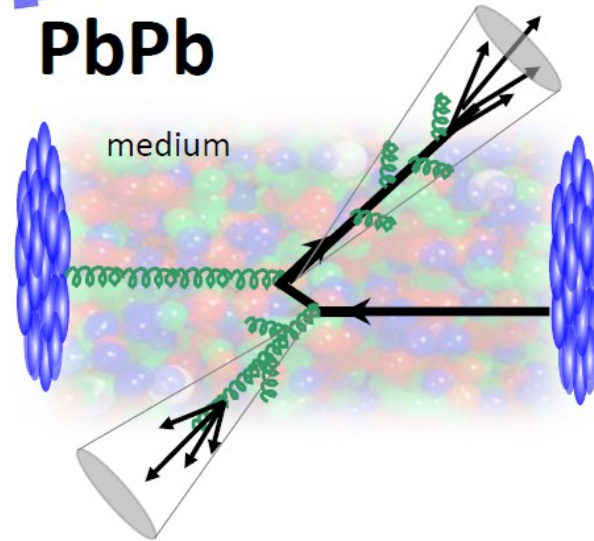
Jet quenching in Pb+Pb



PRC 84 (2011) 024906
 PLB 712 (2012) 176

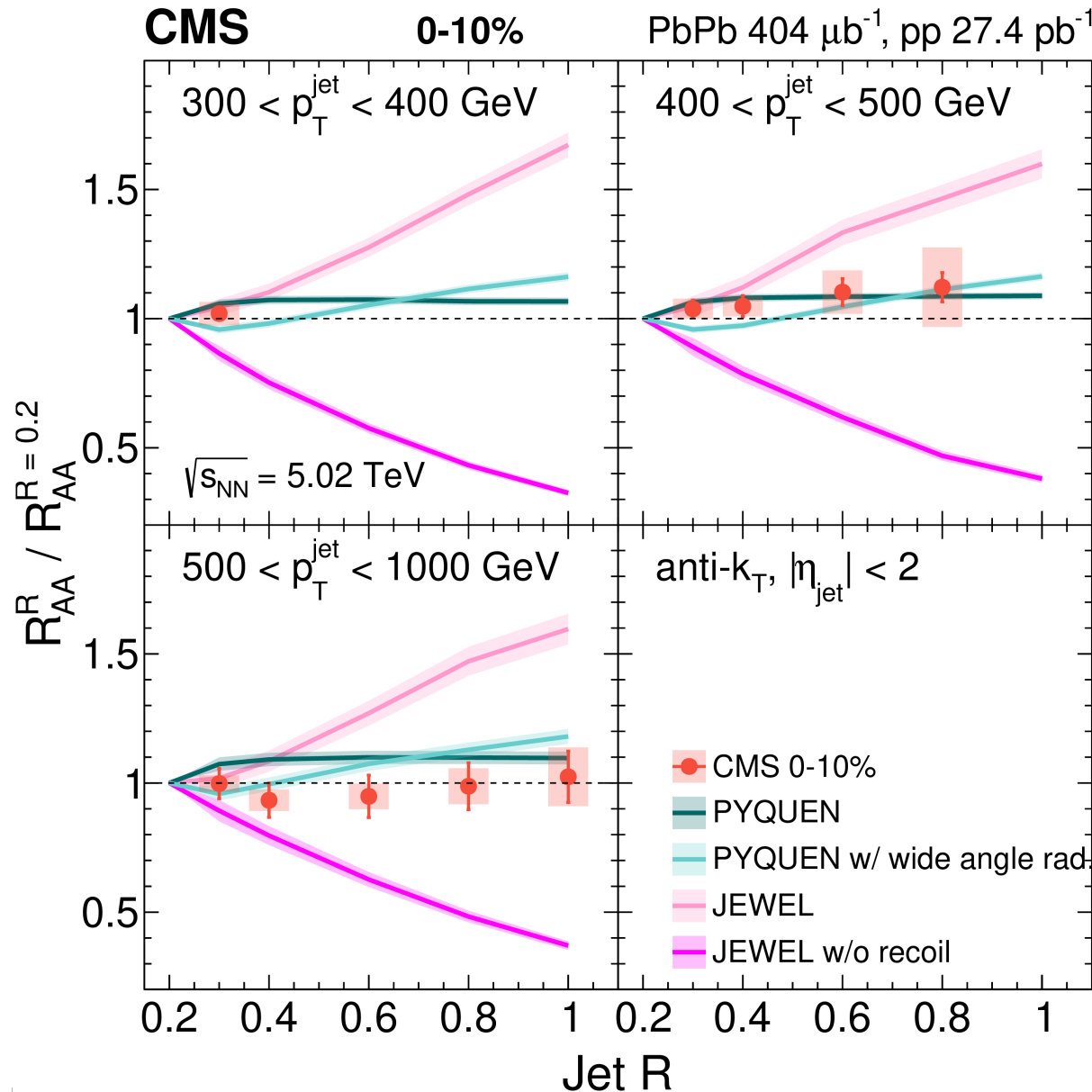


- Asymmetric dijets observed more frequently in PbPb collisions
- The stopping power (dE/dx) of the Quark Soup is **Incredibly Strong**



Jet radius scan

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- Sensitive to balance between increasing radiative sources and recovering re-distributed energy

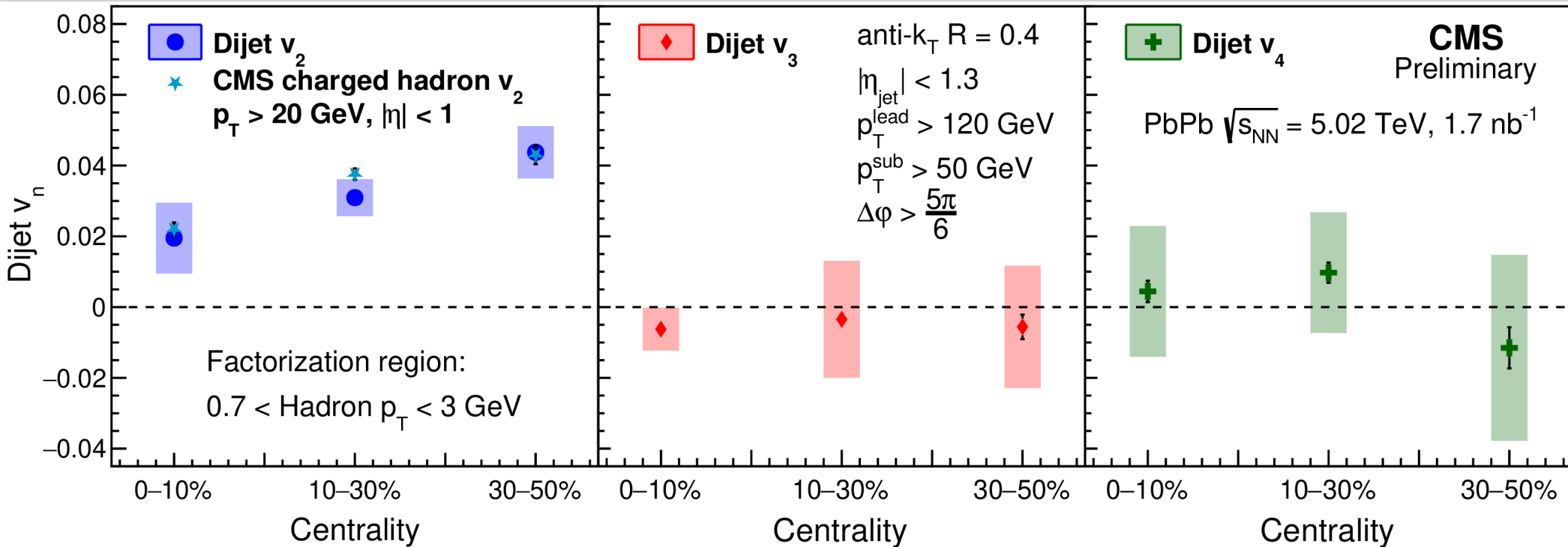
- Enables simultaneous comparisons of model calculations across jet radii

- First time at CMS it was observed no radius dependence to jet energy loss in central Pb+Pb for $500 \text{ GeV} < p_{\text{T}}^{\text{jet}} < 1 \text{ TeV}$

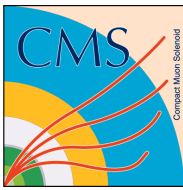
Azimuthal anisotropy of di-jets in Pb+Pb



CMS-PAS-HIN-21-002



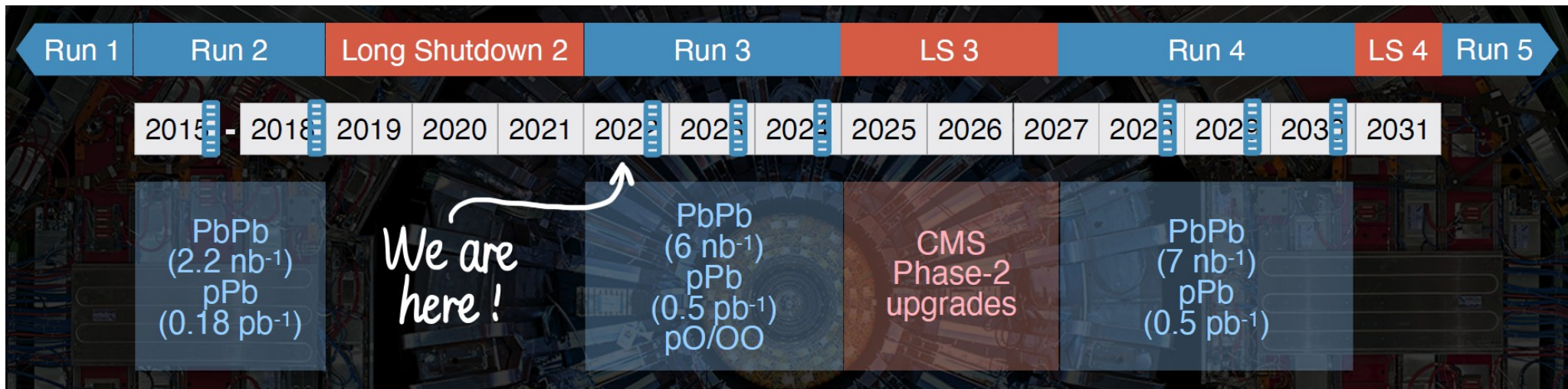
- v_2, v_3, v_4 of the di-jets in Pb+Pb were measured for the first time
- Di-jets v_2 is compatible with v_2 of high pt hadrons
- Di-jets v_3 and v_4 are consistent with zero



CMS Summary for Heavy-Ions



- Many interesting heavy-ion physics results with the CMS detector in p+p, p+Pb, Pb+Pb and Xe+Xe...
- Future heavy-ion program at the LHC (Run 3 and 4) with the upgraded CMS detector will provide more exciting opportunities! Stay tuned!





Run 3 was started !



CMS Experiment at the LHC, CERN
Data recorded: 2022-Jul-05 14:48:56.743936 GMT
Run / Event / LS: 355100 / 51596902 / 53

