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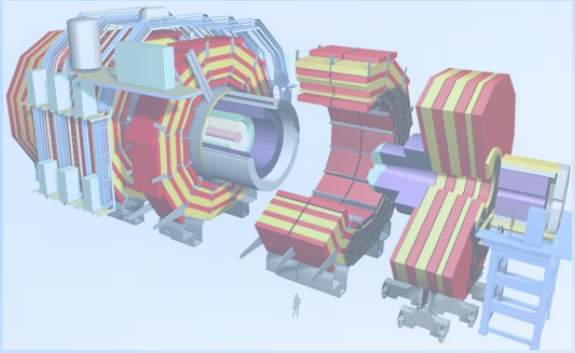
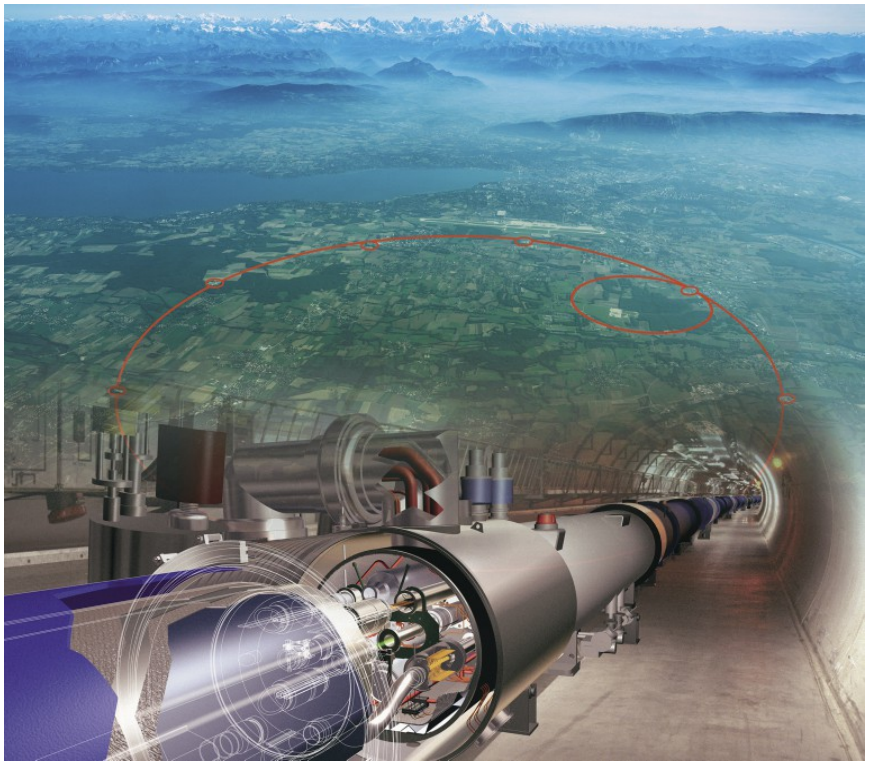
New results on heavy-ion collisions by the CMS detector at the LHC

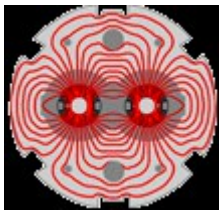
22nd Lomonosov Conference
on Elementary Particle Physics

Lomonosov Moscow State University,
Moscow, Russia
21 – 27 August 2025

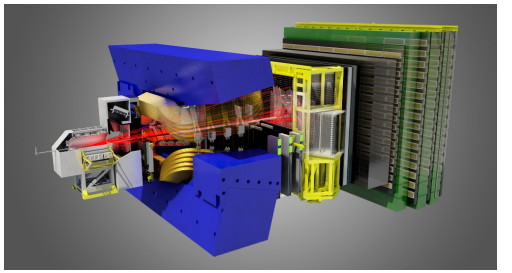


Heavy-ion physics at the LHC

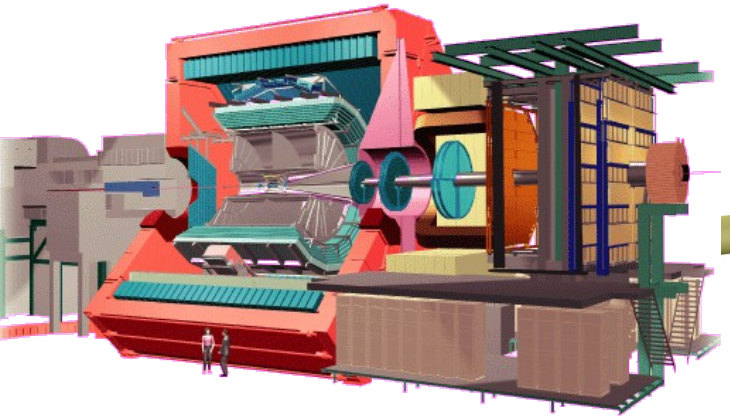




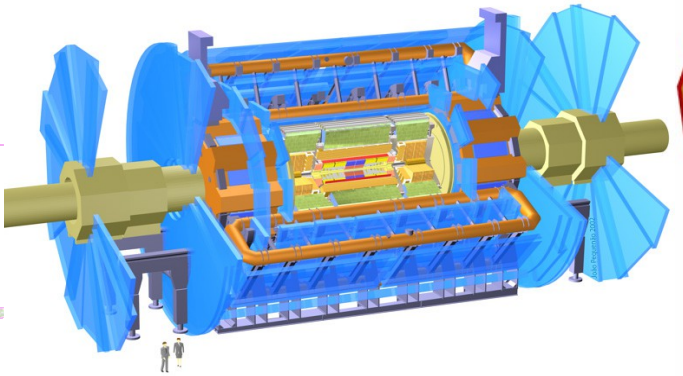
LHCb



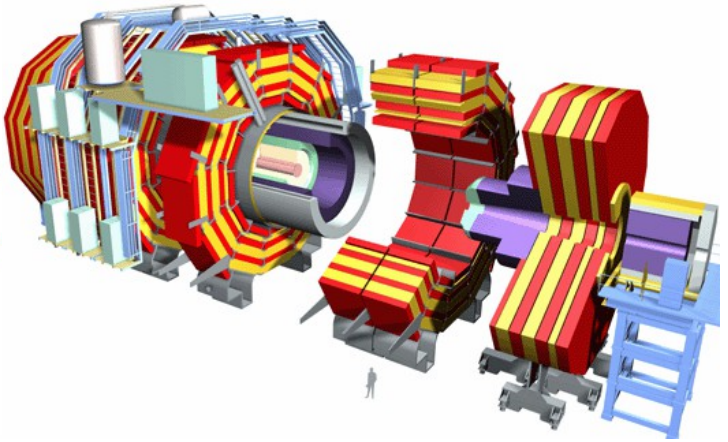
ALICE



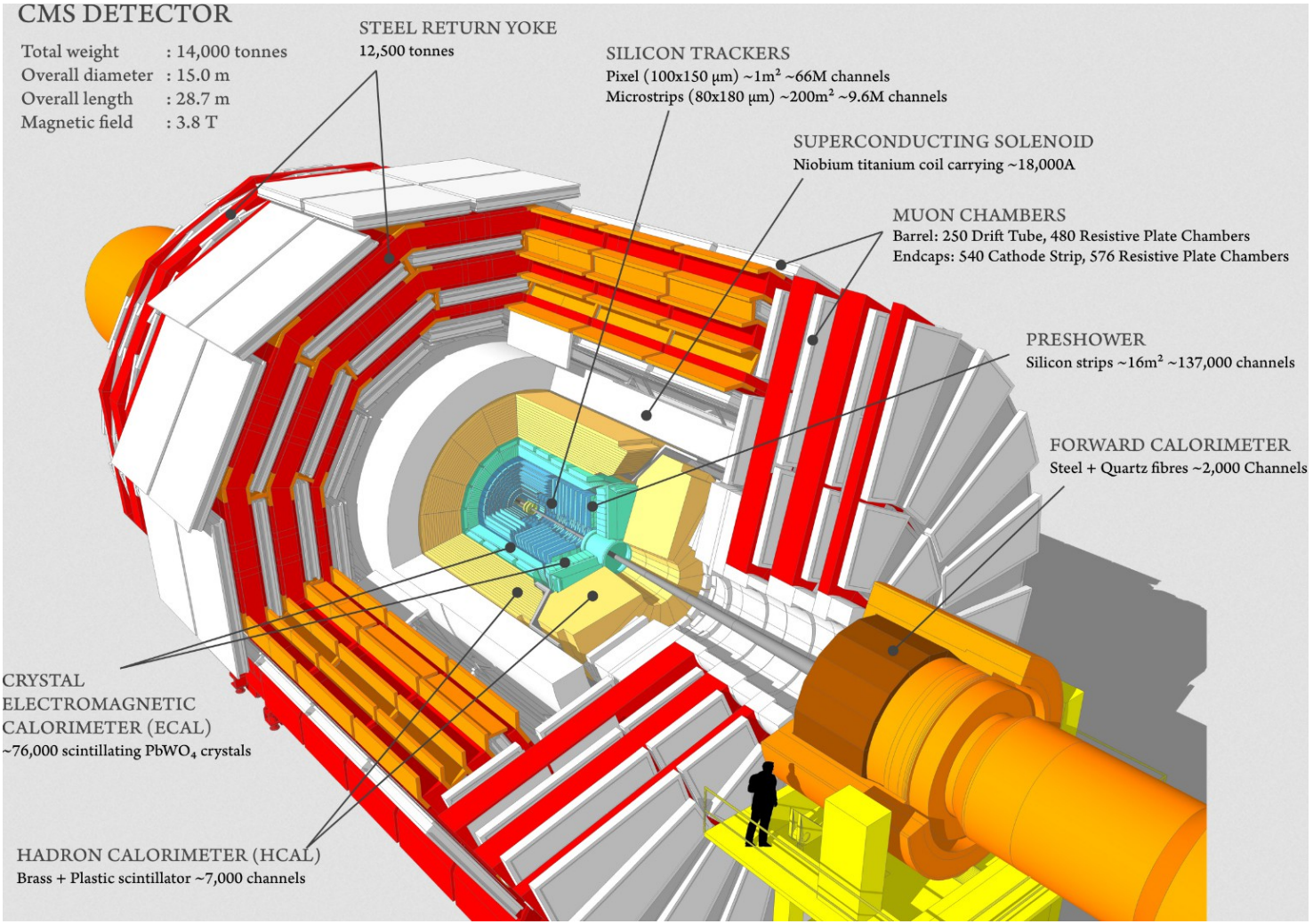
ATLAS



CMS



CMS is a nice heavy-ion experiment

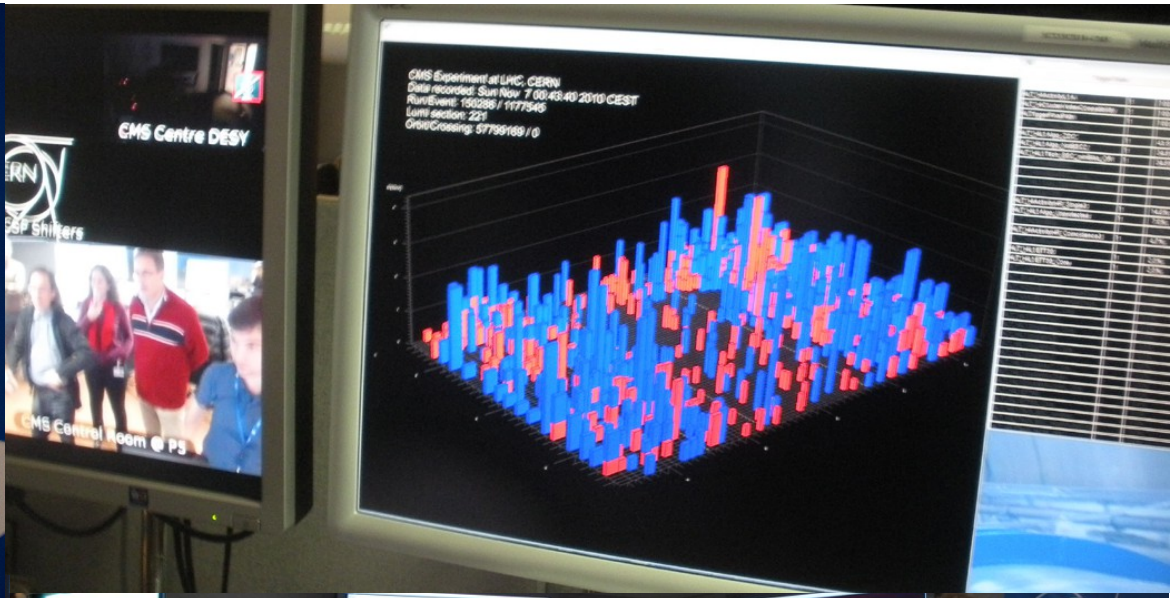


Magnetic field: 3.8 Tesla

- **Silicon Tracker**
  $|\eta| < 2.4$ (< 3.0 after 2017)
- **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

November 7, 2010 0:27. CMS Control Room



CMS heavy-ion physics results

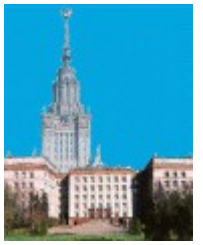
153 published/submitted
Heavy-ion Physics CMS papers:

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

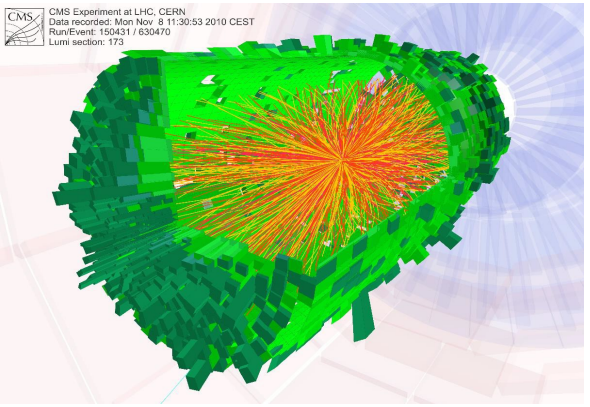
…and also > 100
Heavy-ion Physics CMS preliminary results (PAS):

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

CMS heavy-ion physics results



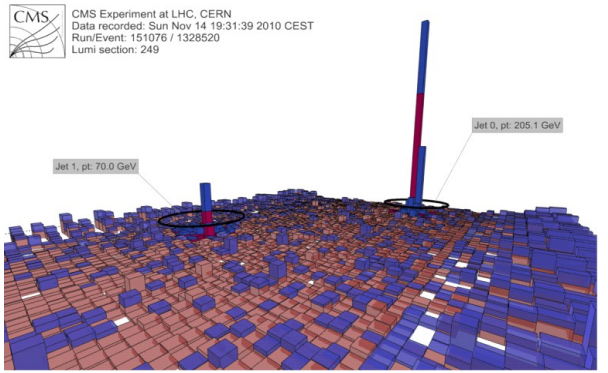
- **Global picture of heavy-ion collisions**
  - multiplicity,
  - energy,
  - flow, ...



Pb+Pb collisions

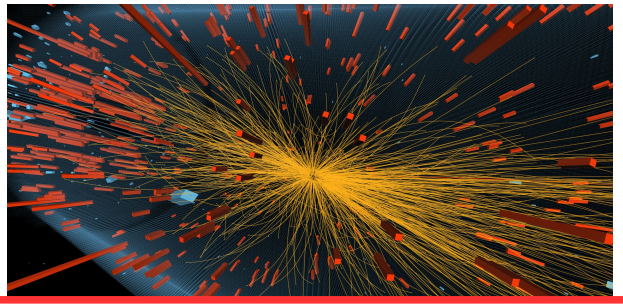
2010-11: 2.76 TeV 0.16/nb
2015-18: 5.02 TeV 1.7/nb
2023-26 : 5.36 TeV ...

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



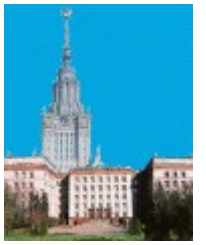
- **p+p, p+Pb, Xe+Xe**
  - correlations
  - flow,
  - jets, ...

p+p 2.76, 5.02, 7, 8, 13, 13.6 TeV
p+Pb 5.02, 8.16 TeV
Xe+Xe 5.44 TeV



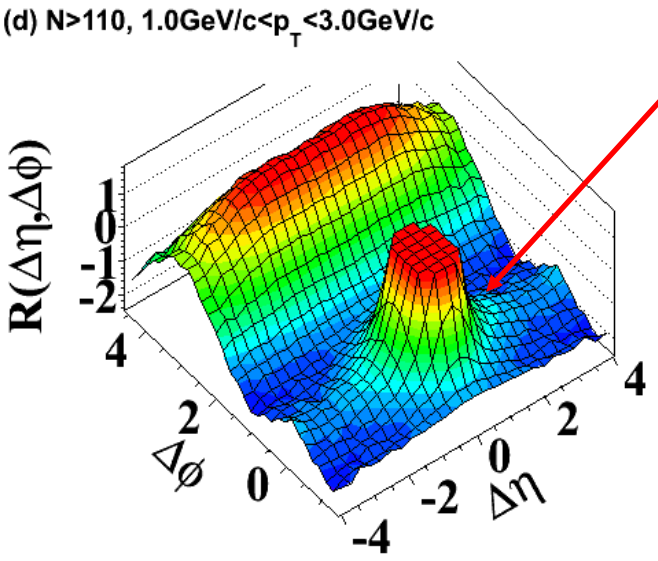
NEW! p+O, O+O, Ne+Ne – July 2025

Correlations: “RIDGE” is everywhere...



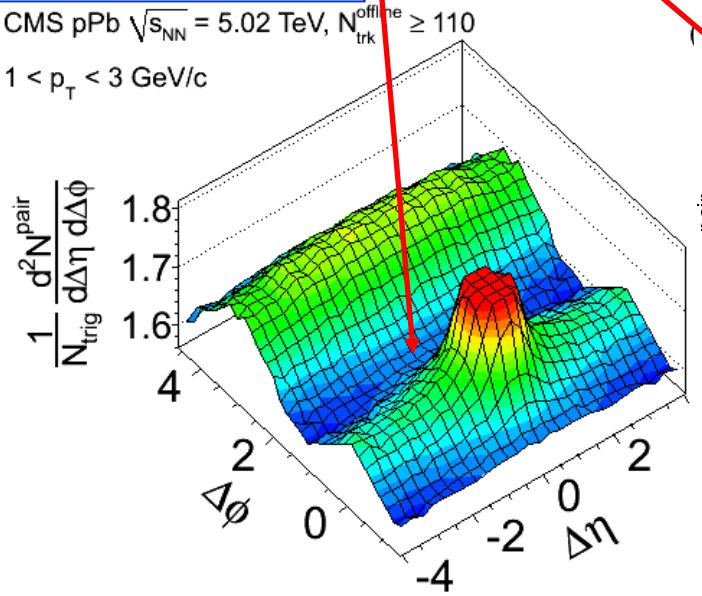
Long-range ($2 < |\Delta\eta| < 4$), near-side ($\Delta\phi \approx 0$)
angular correlations were observed in high multiplicity p+p and p+Pb collisions (as well as in Pb+Pb)

p+p 7 TeV



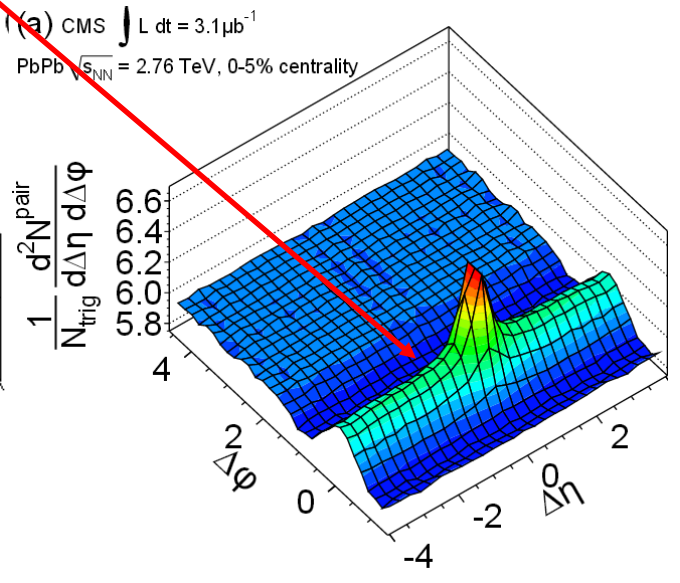
JHEP 09 (2010) 091

p+Pb 5.02 TeV



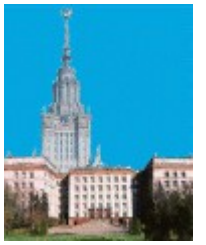
PLB 718 (2013) 795

Pb+Pb 2.76 A TeV, 0-5%

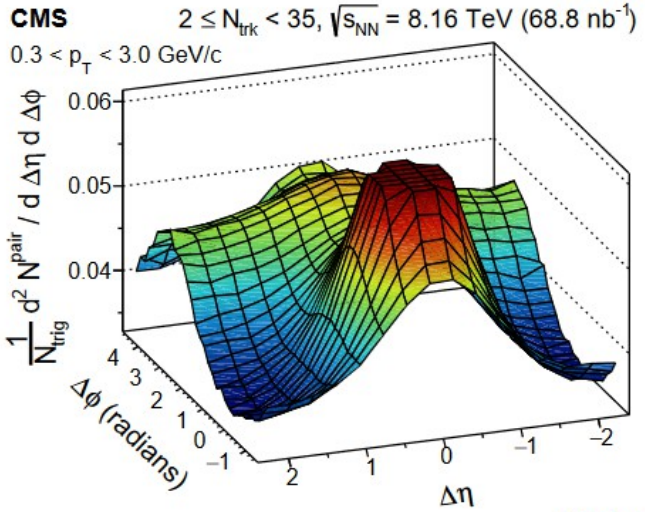


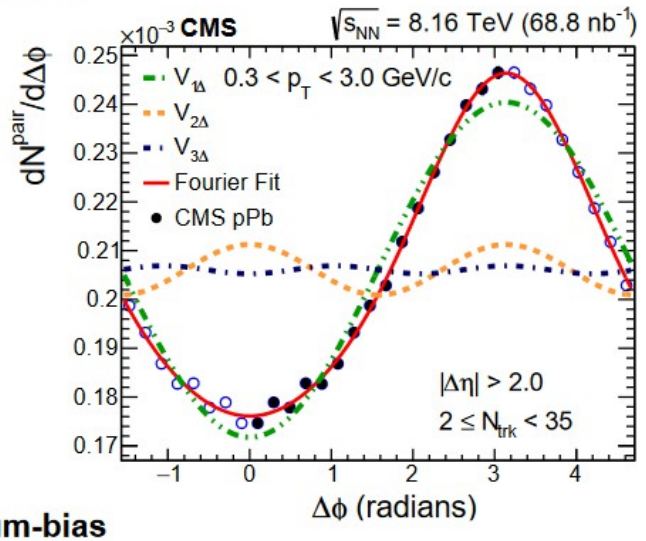
JHEP 07 (2011) 076

γp interactions within ultra-peripheral p+Pb collisions

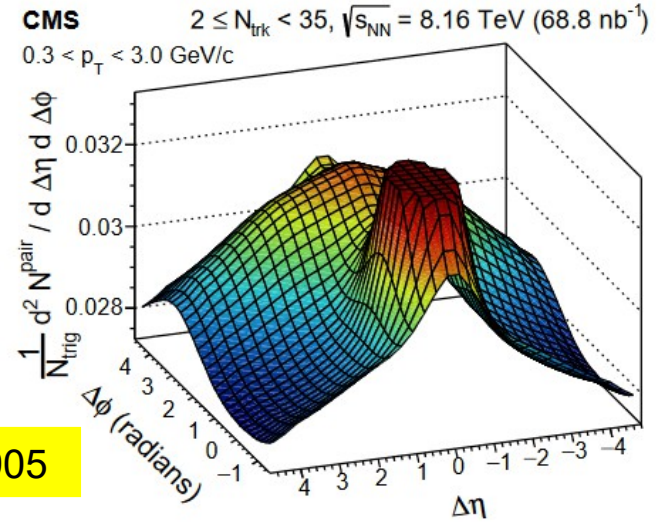


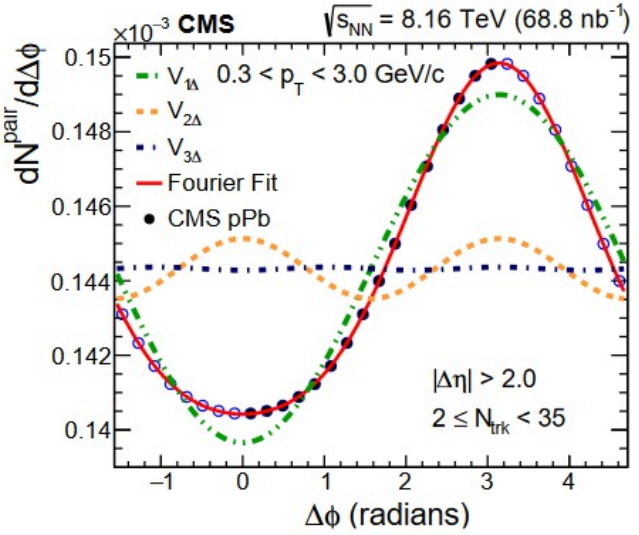
γp enhanced





Minimum-bias

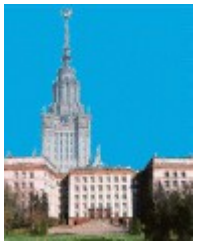




PLB 844 (2023) 137905

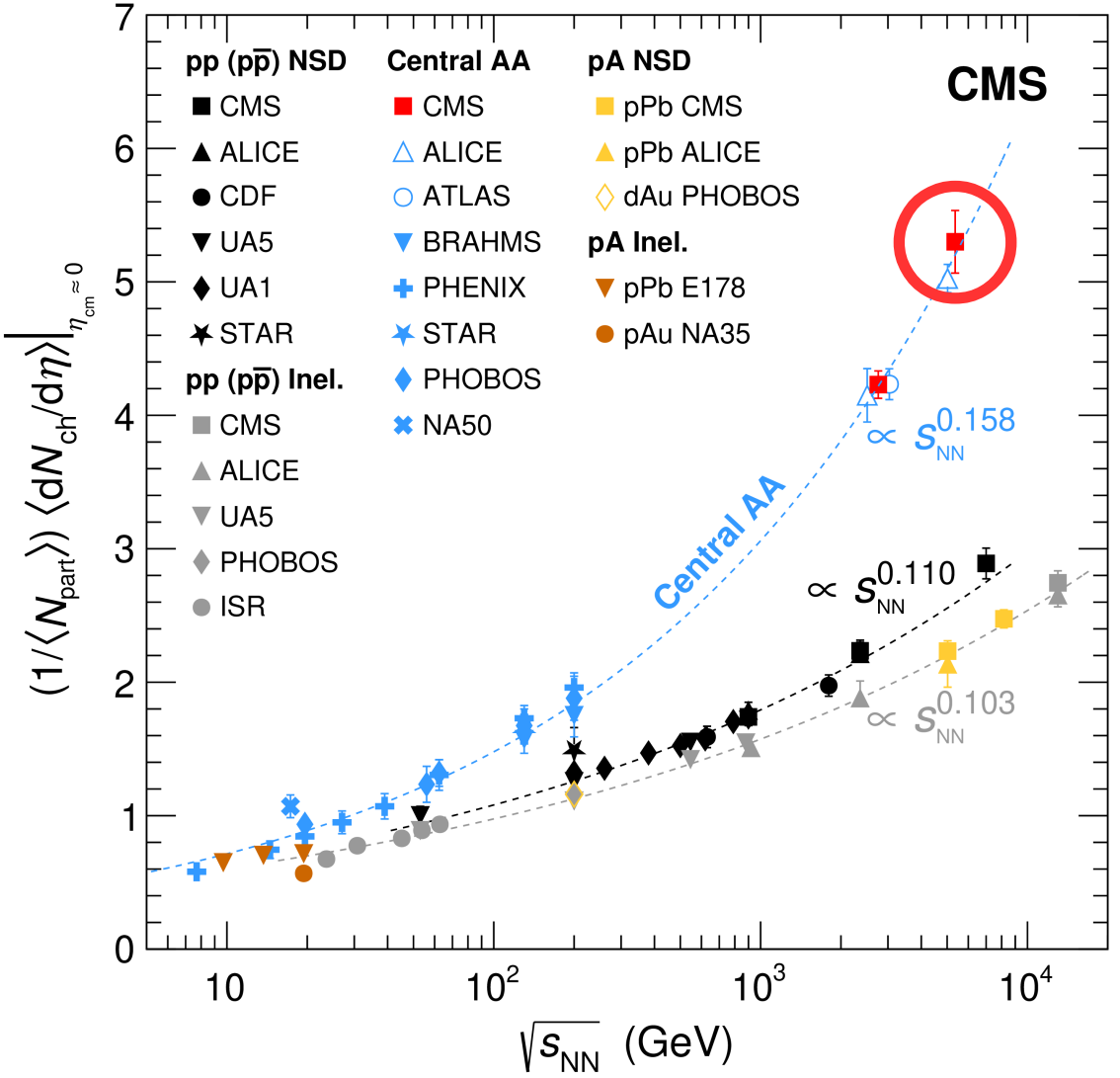
The single particle flow coefficient $v_2(p_T)$ is larger for γp-enhanced events than for minimum-bias collisions. But we don't see "ridge" here!

Charged particle multiplicity CMS results Run 3



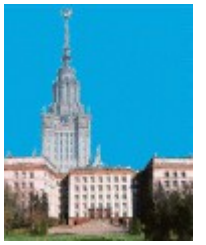
5.36 TeV Pb+Pb data from 2022 test heavy-ion run

$\sqrt{s_{NN}}$ dependence consistent with power law calculated using lower energies



PLB 861 (2025) 139279

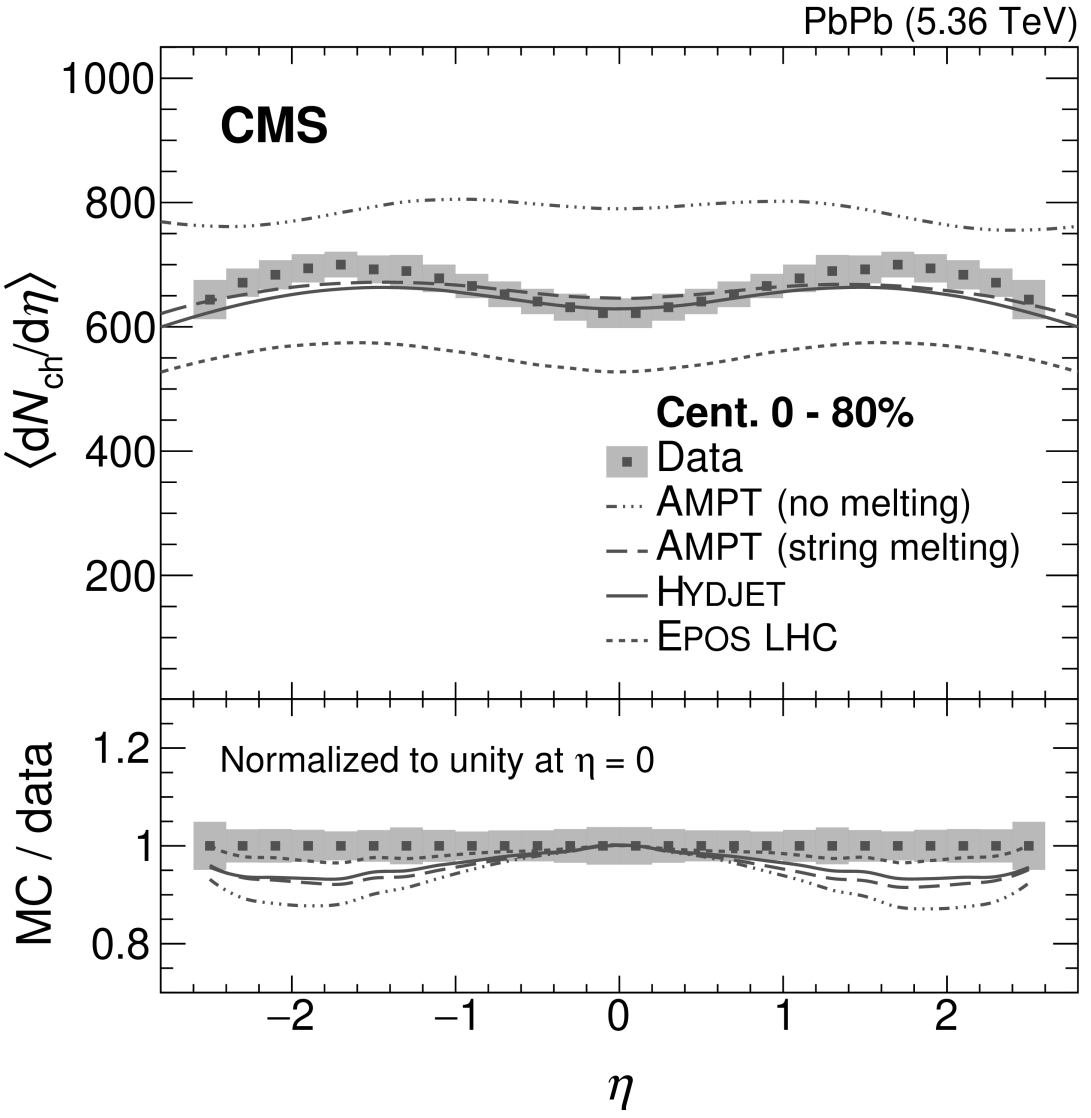
$dN_{ch}/d\eta$
CMS results Run 3



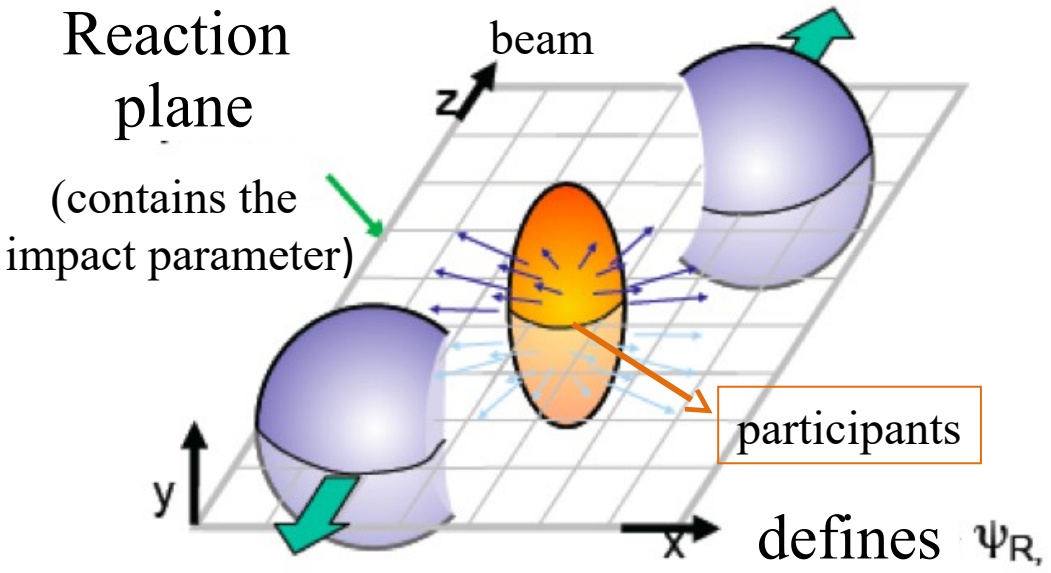
5.36 TeV Pb+Pb data from 2022 test heavy-ion run

Monte Carlo generators try to predict both magnitude and shape of $dN_{ch}/d\eta$

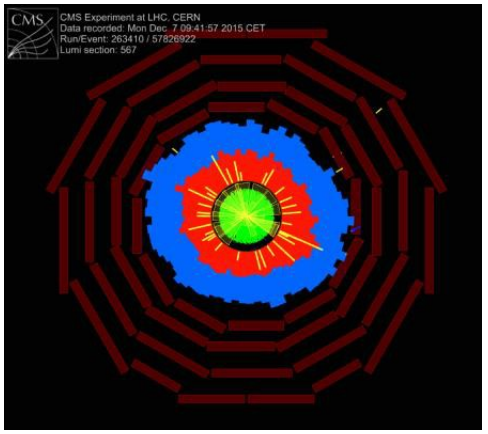
PLB 861 (2025) 139279

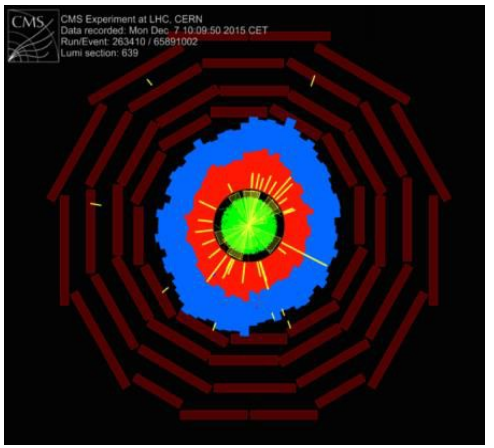


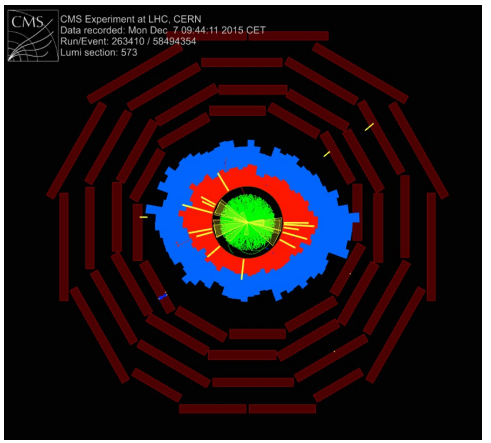
Flow



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



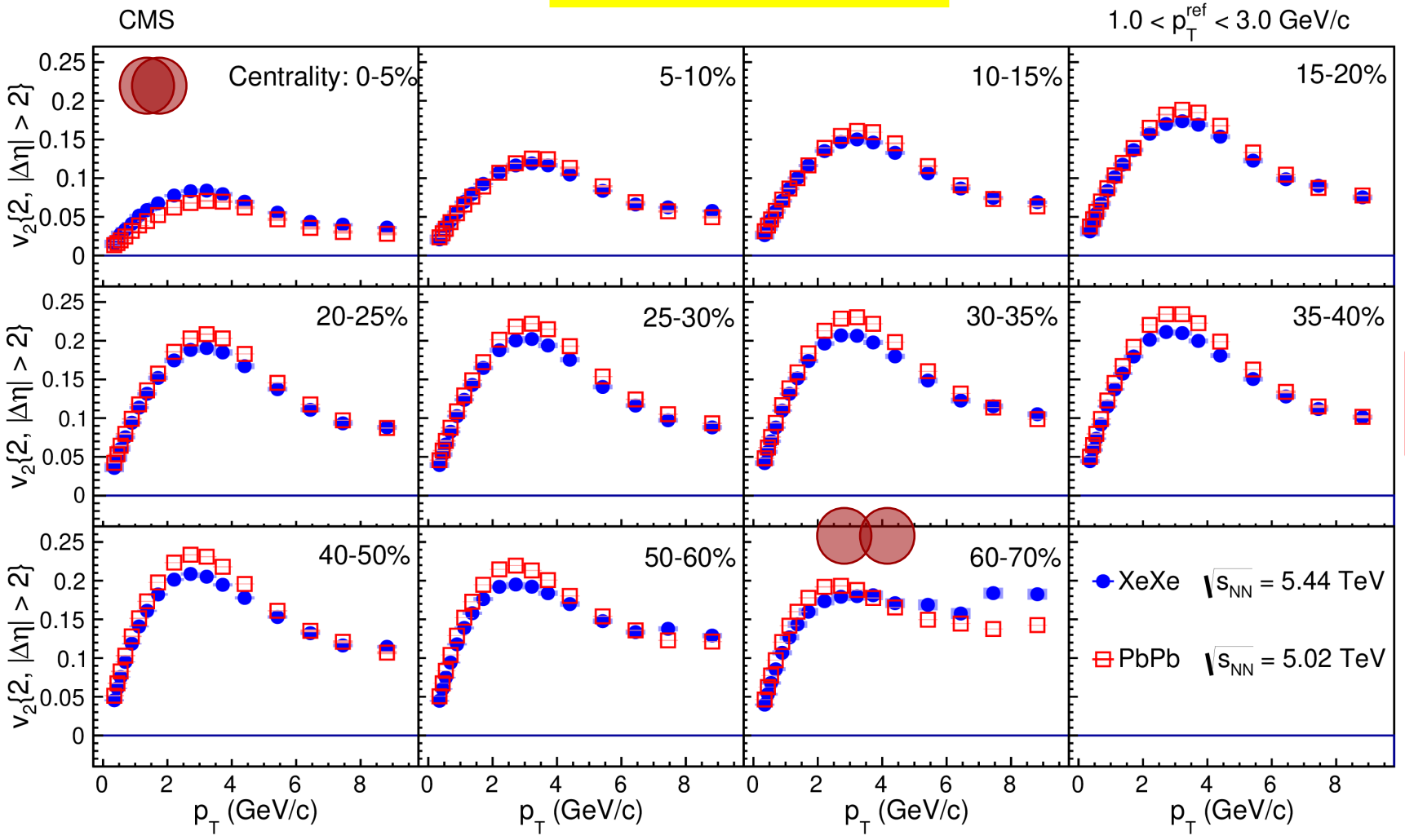


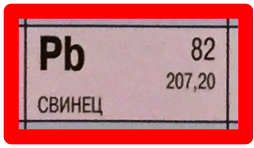


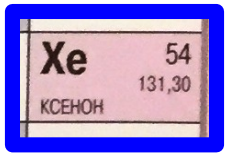
Collective motion is observed in the event azimuthal distributions

v_2 vs. p_T in Xe+Xe and Pb+Pb

PRC 100 (2019) 044902



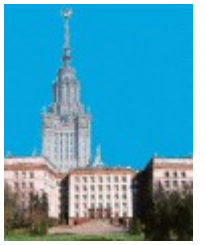


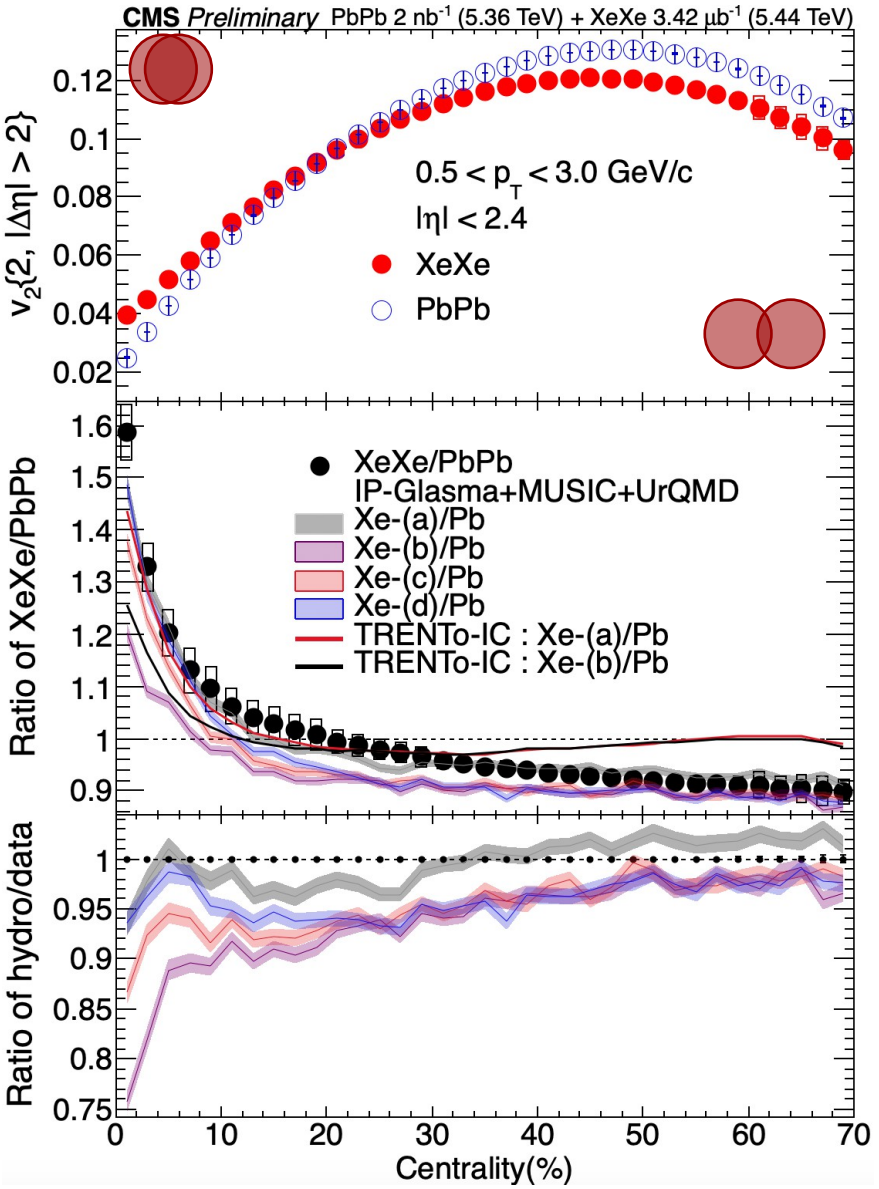


The magnitude of the v_2 coefficients for Xe+Xe collisions are larger than those found in Pb+Pb collisions for the most central collisions.

Integral v_2 in Xe+Xe and Pb+Pb

CMS-PAS-HIN-24-004

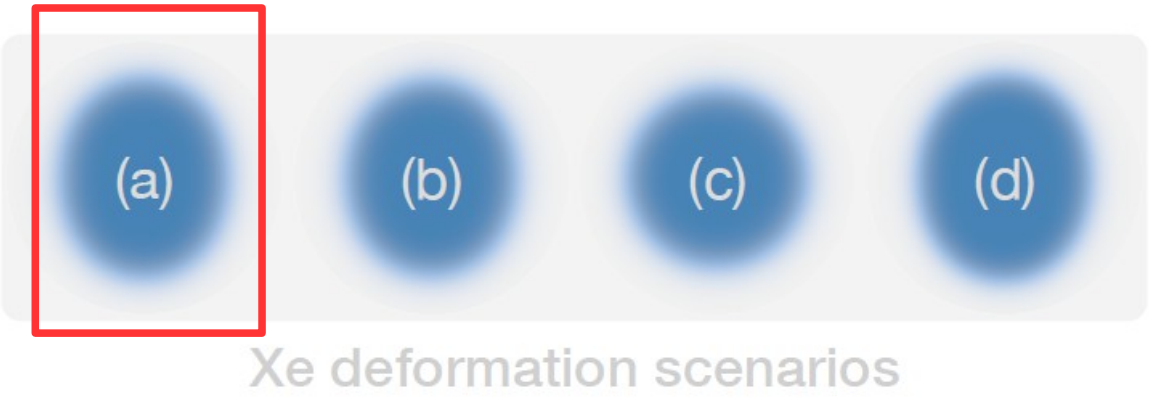




v_2(XeXe) > v_2(PbPb) till ~20% centrality

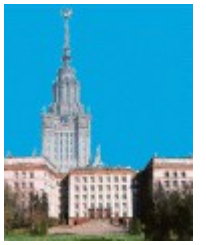
- Sensitivity to elliptical deformation of Xe nucleus

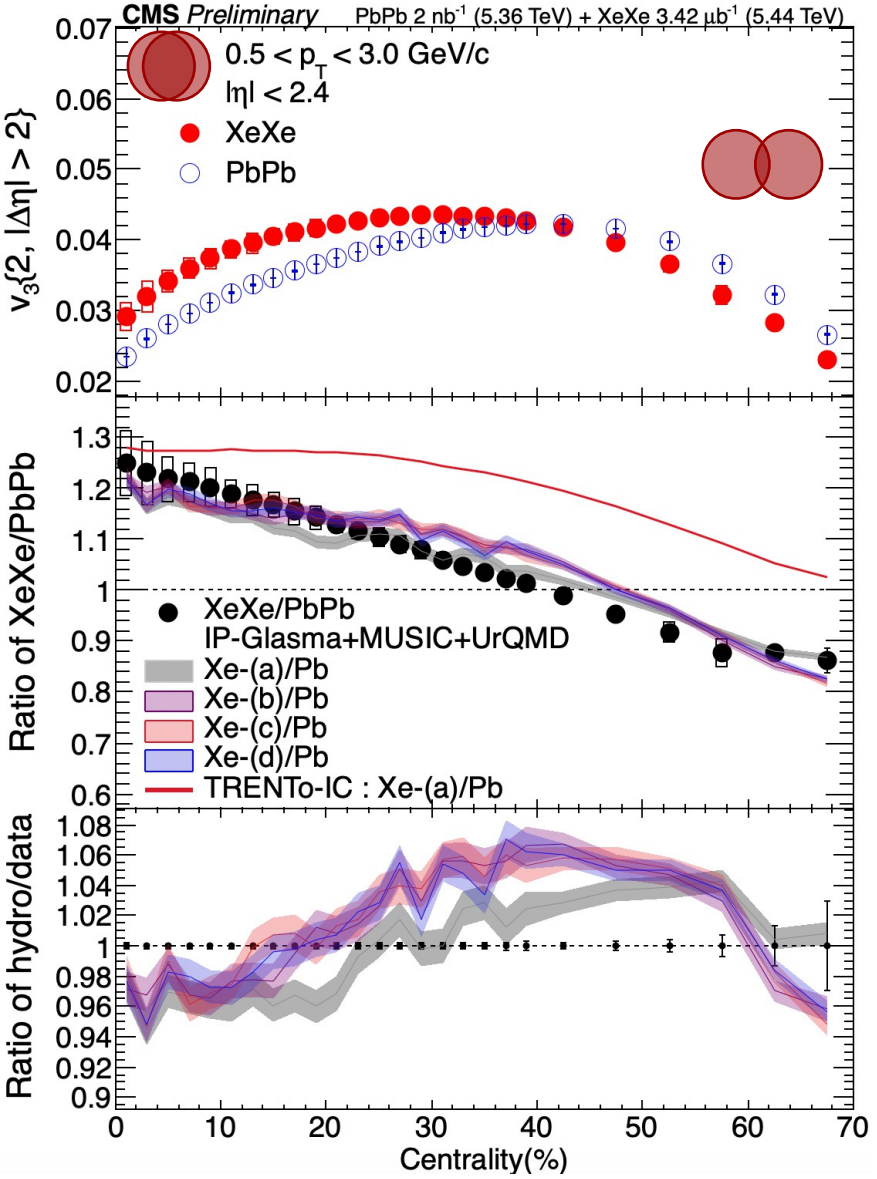
Best match of final-state IP-Glasma+MUSIC+UrQMD hydrodynamic prediction with parameter **set (a)**



Integral v_3 in Xe+Xe and Pb+Pb

CMS-PAS-HIN-24-004

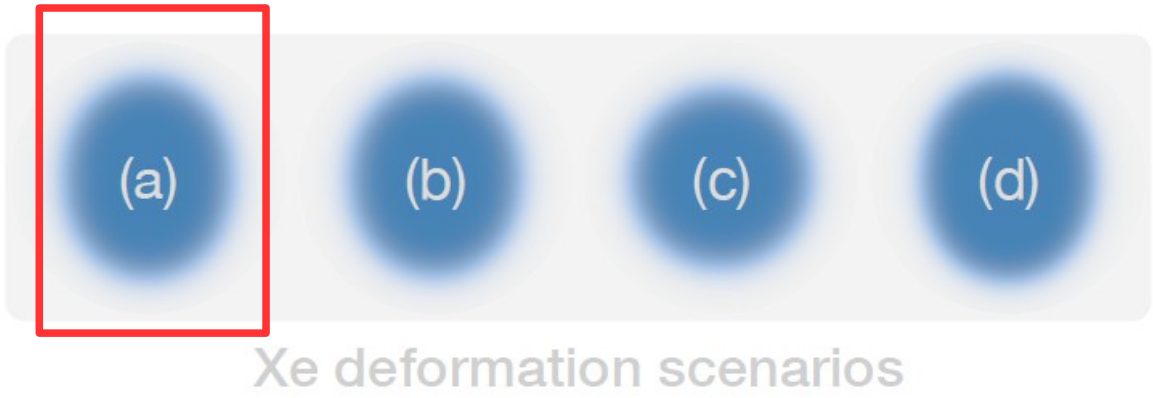




v_3(XeXe) > v_3(PbPb) till ~40% centrality

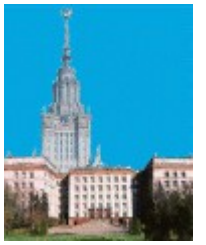
- Sensitivity to elliptical deformation of Xe nucleus

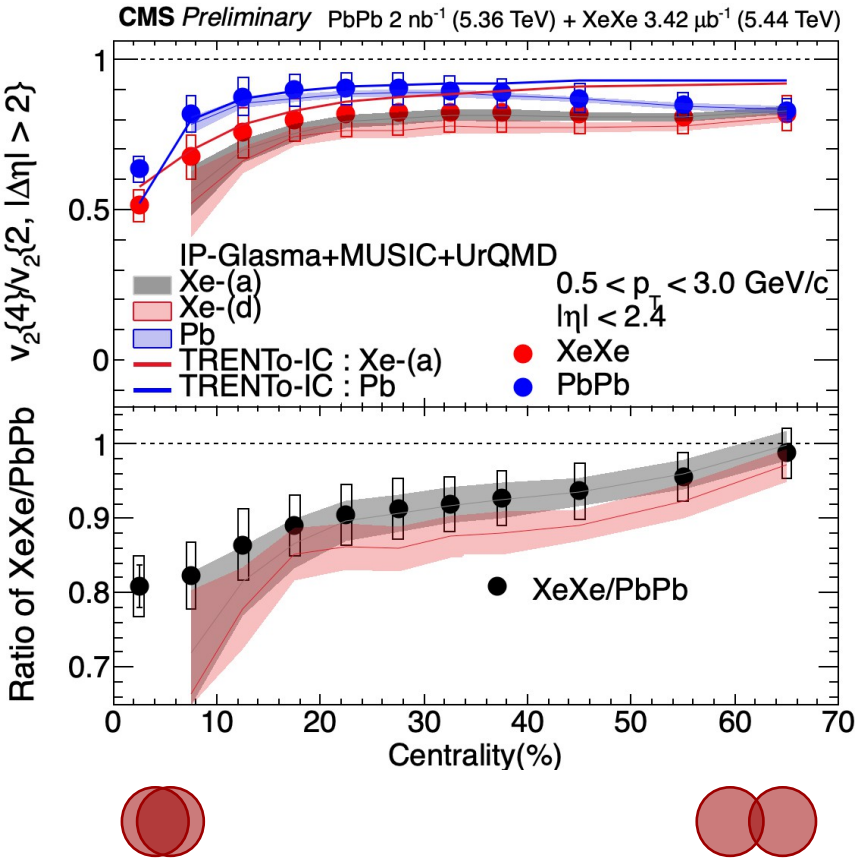
Best match of final-state IP-Glasma+MUSIC+UrQMD hydrodynamic prediction with parameter **set (a)**



$v_2\{4\}$ / $v_2\{2\}$ Xe+Xe and Pb+Pb

CMS-PAS-HIN-24-004

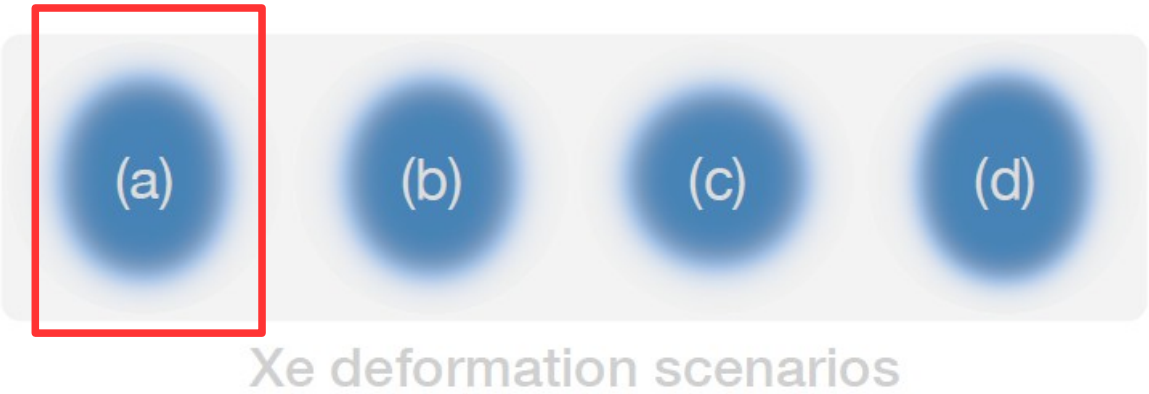




$v_2\{4\}/v_2\{2\}(\mathrm{XeXe}) < v_2\{4\}/v_2\{2\}(\mathrm{PbPb})$

- greater flow fluctuations for XeXe
- largest deviation in most central region

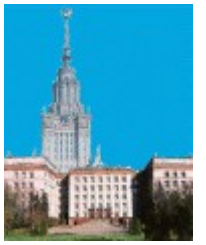
Best match of final-state IP-Glasma+MUSIC+UrQMD hydrodynamic prediction with parameter **set (a)**

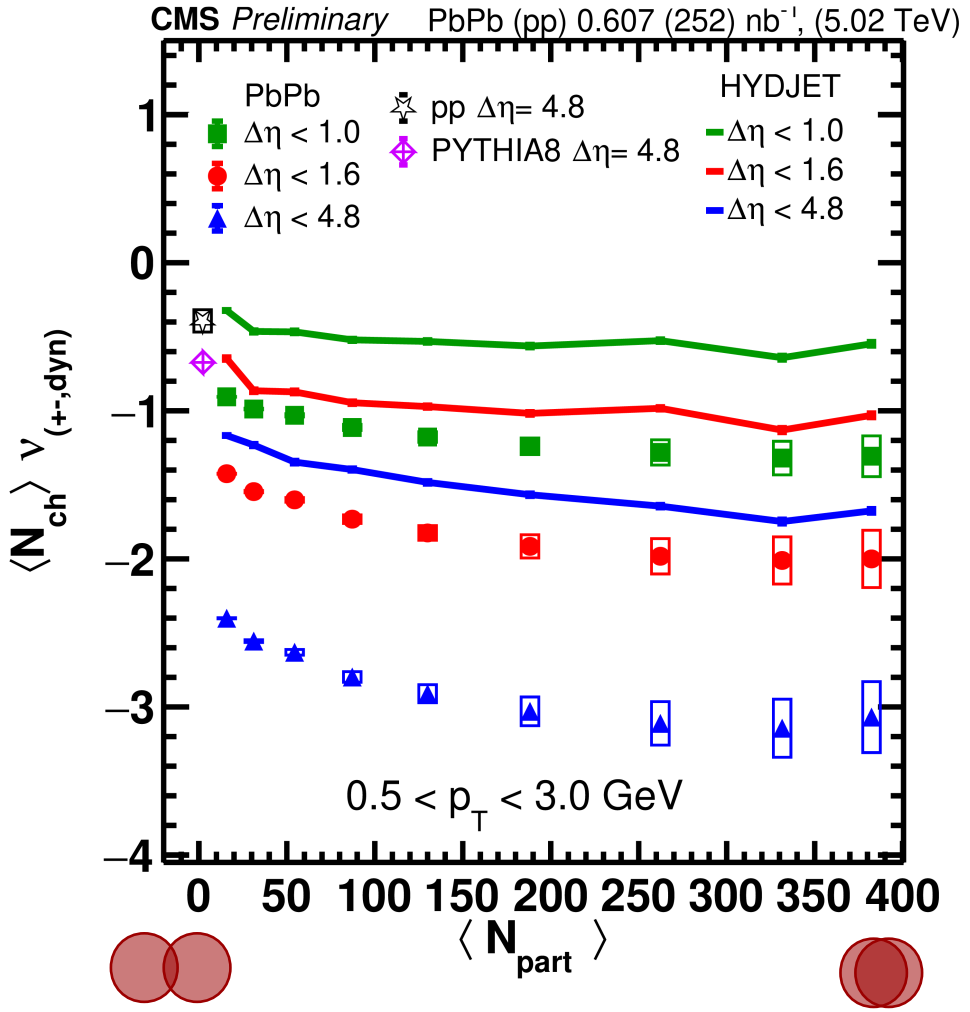


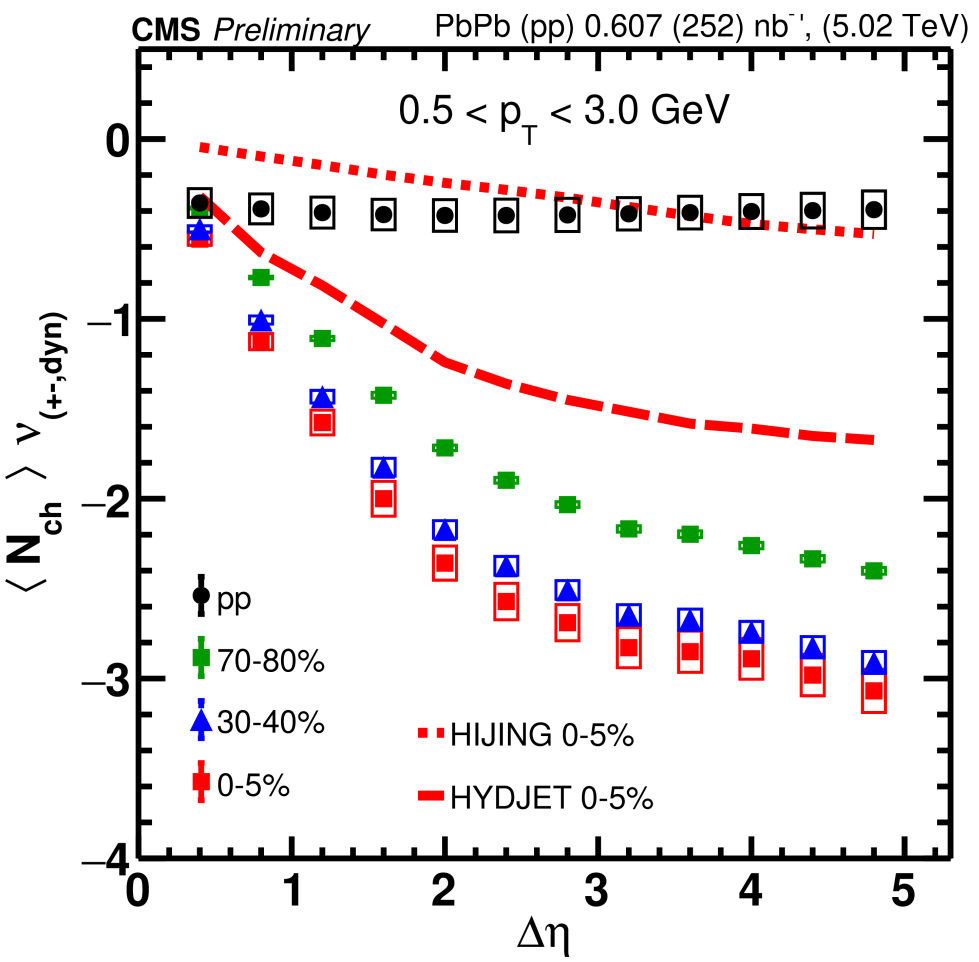
See talk by Danila Myagkov on comparison with HYDJET++ model

Net-charge fluctuation in Pb-Pb collisions

CMS-PAS-HIN-22-005

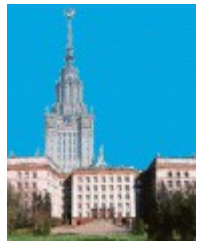




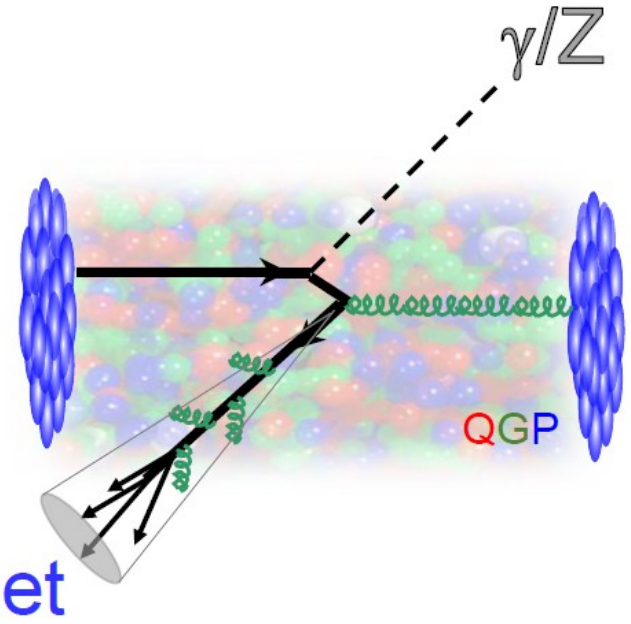


Net-charge fluctuations differ between QGP and hadron gas phase
We see the signature of QGP

Hard Probes for Quark-Gluon Plasma



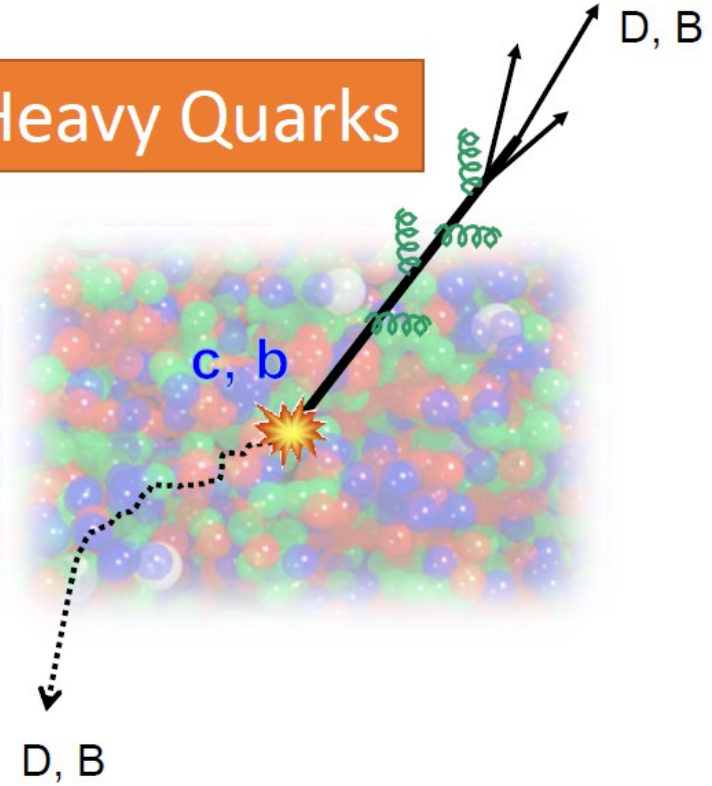
Electroweak Bosons



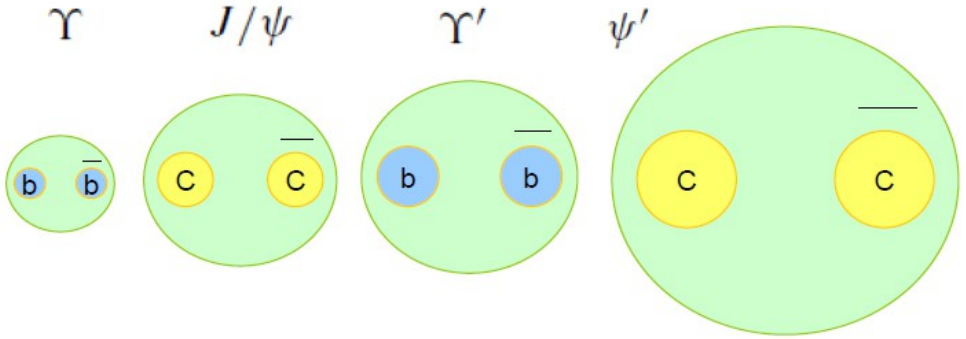
Jets

Jet

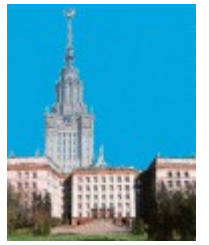
Heavy Quarks

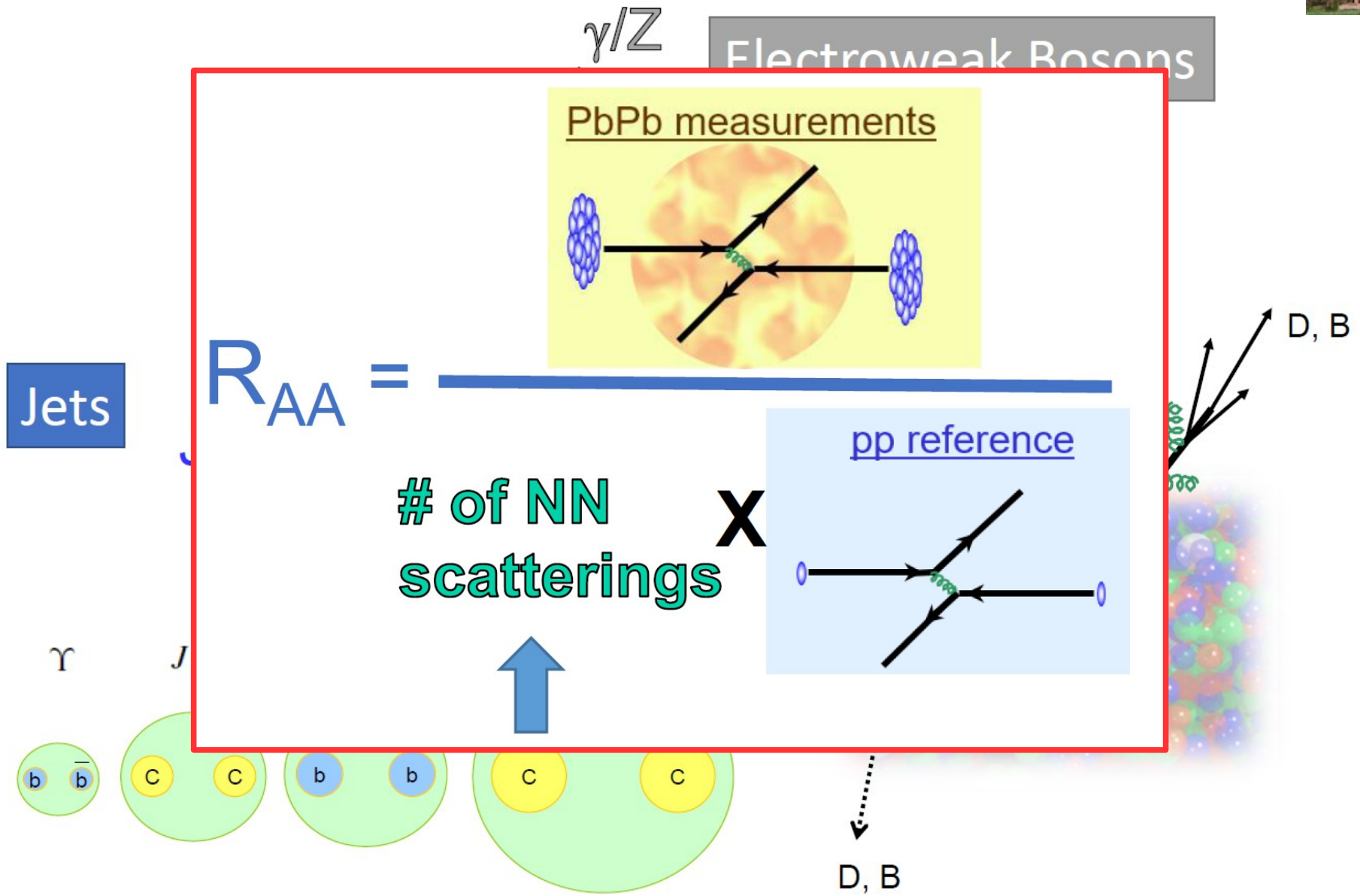


Quarkonia



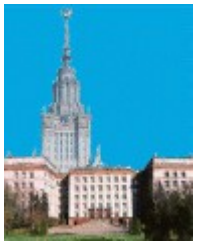
Hard Probes for Quark-Gluon Plasma

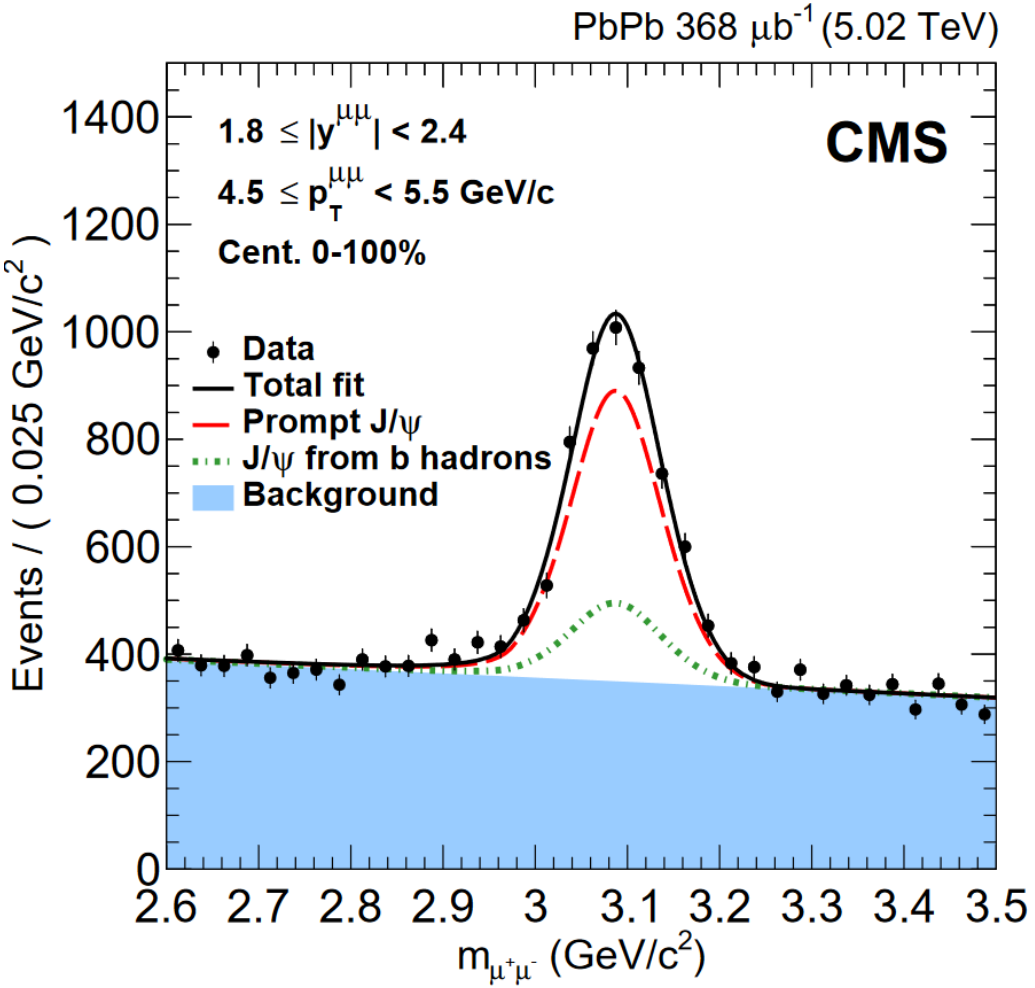


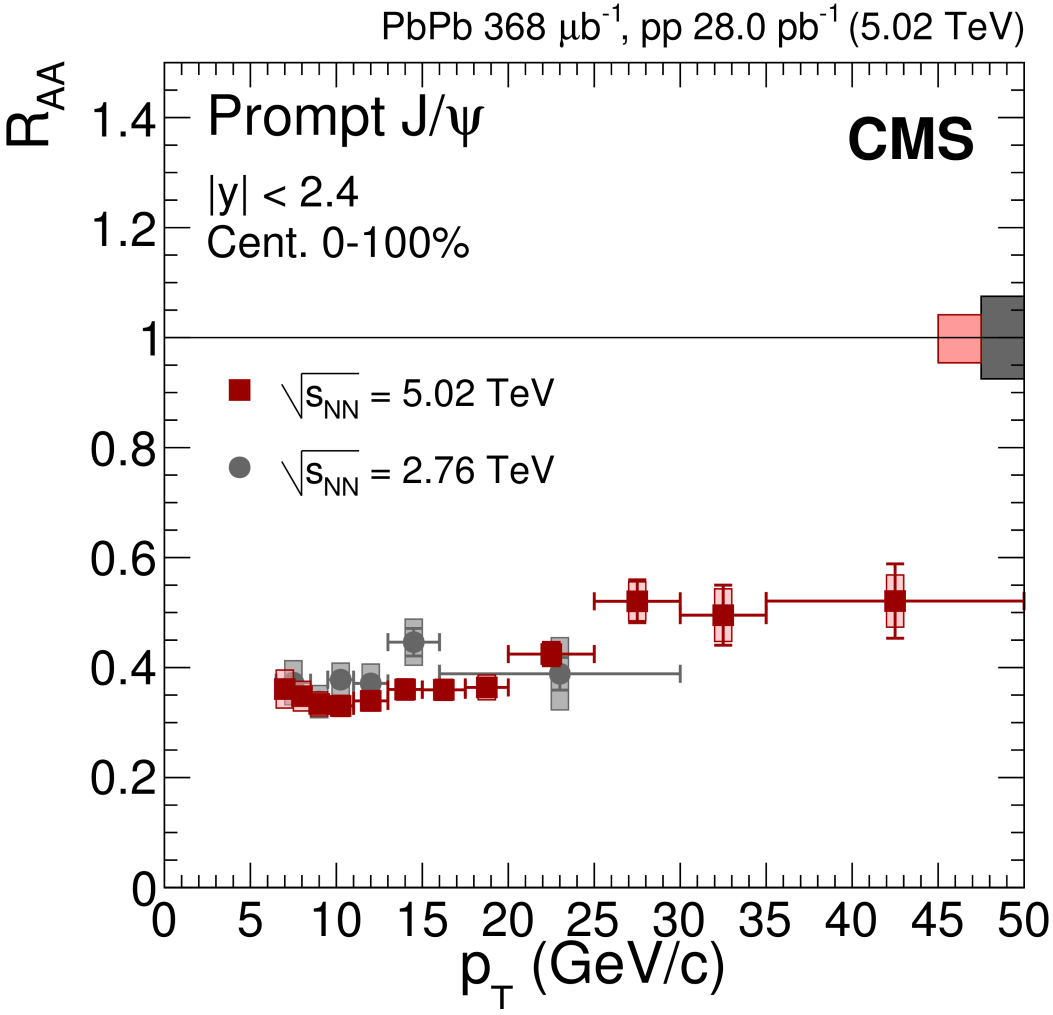


J/ψ suppression in Pb+Pb

EPJ C 78 (2018) 509

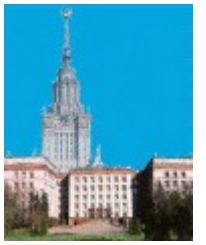




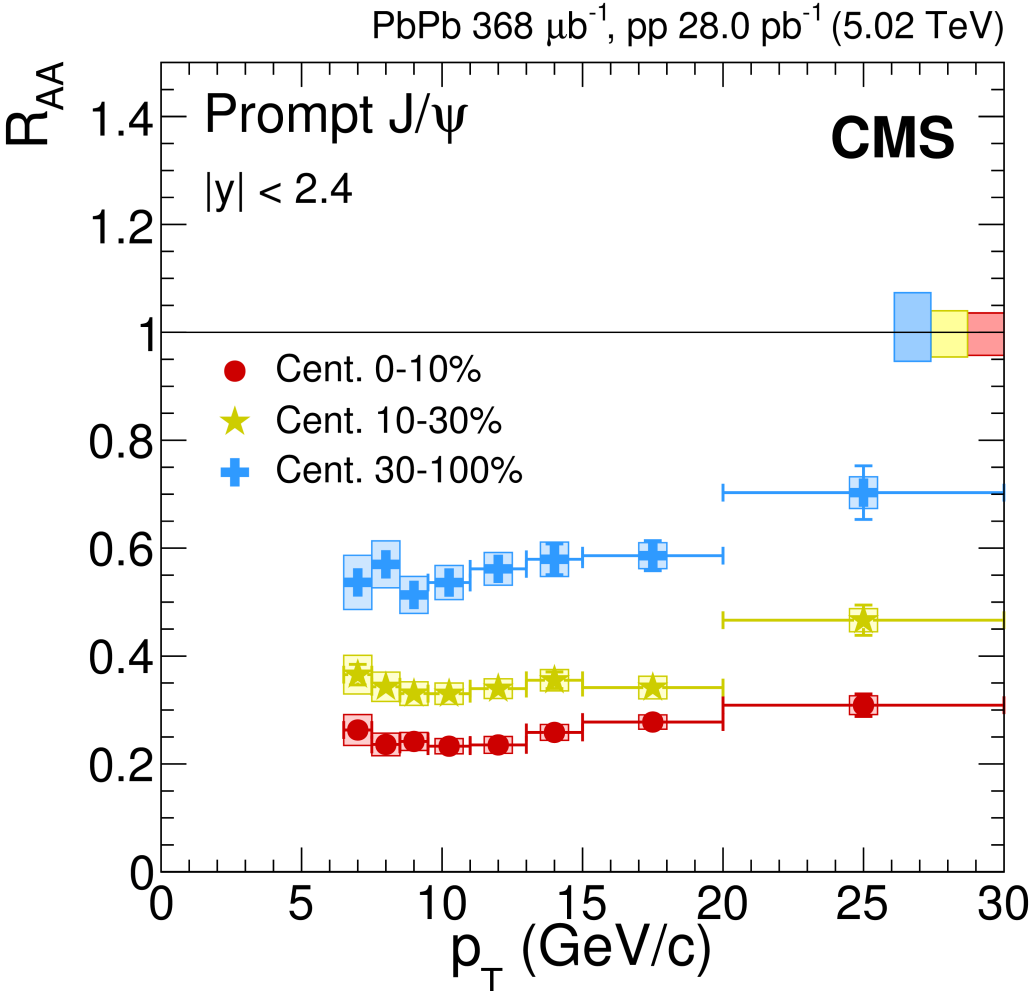


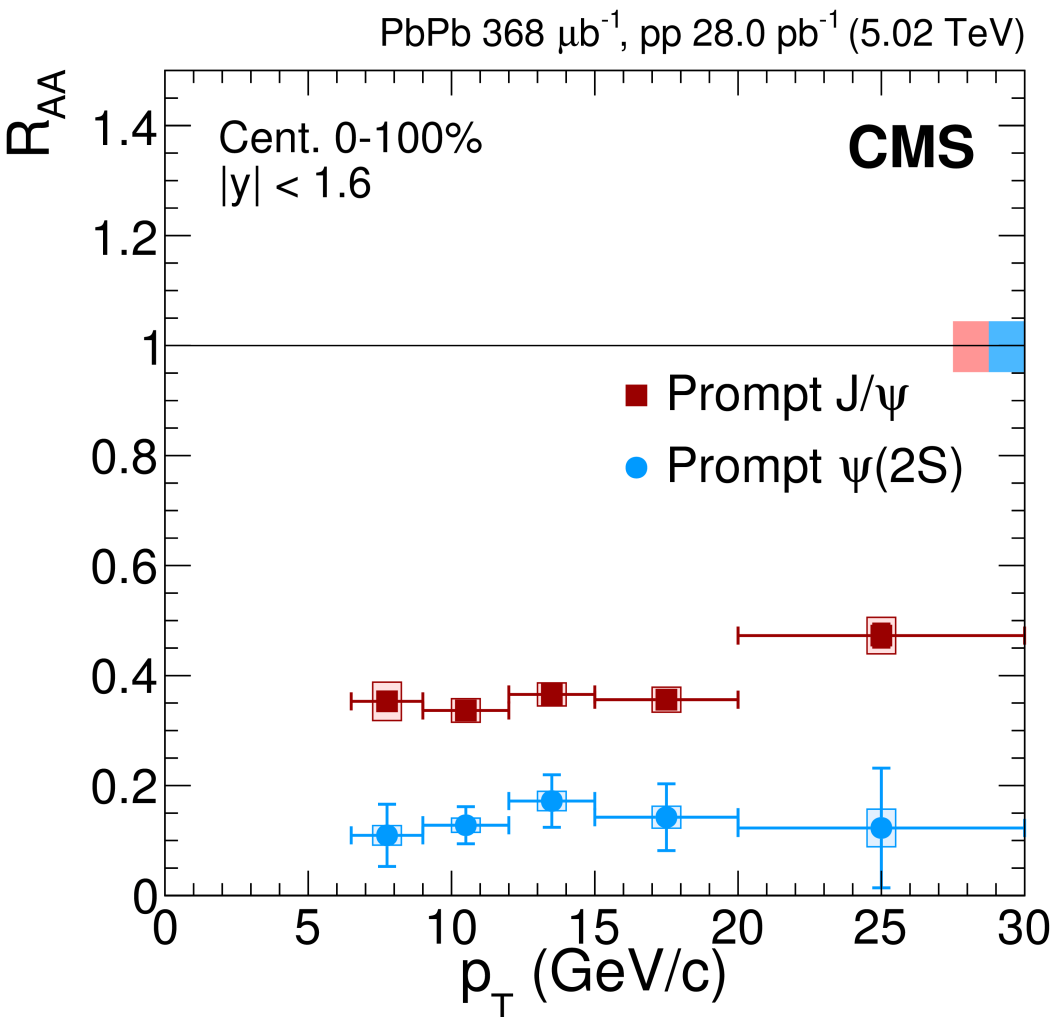
J/ψ mesons are observed to be suppressed (similarly in 2.76 and 5.02 TeV)

J/ψ and ψ(2S) suppression in Pb+Pb



EPJ C 78 (2018) 509

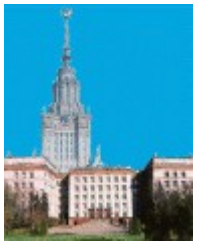


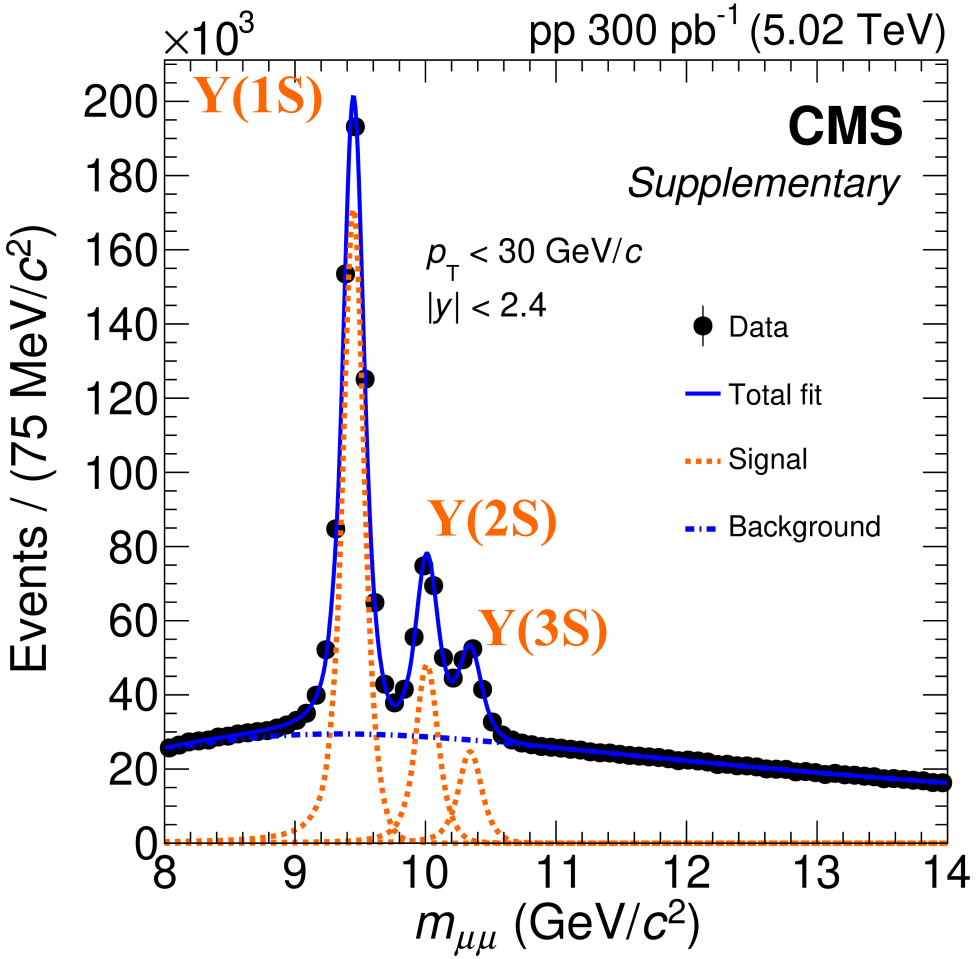


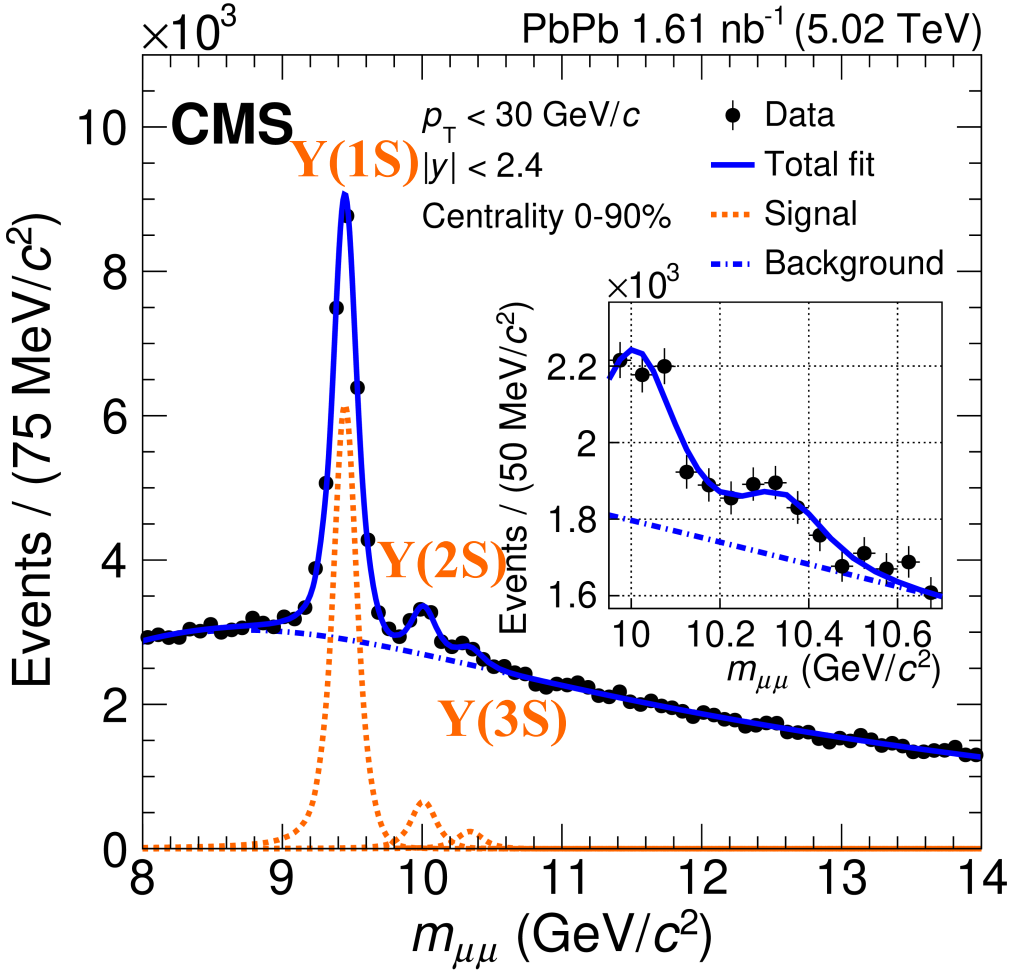
- **Increasing suppression for increasing centrality**
- **ψ(2S) is more suppressed than the J/ψ meson (different binding energies)**

Upsilon suppression in Pb+Pb

PRL 133 (2024) 022302



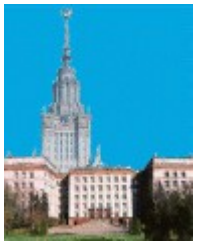


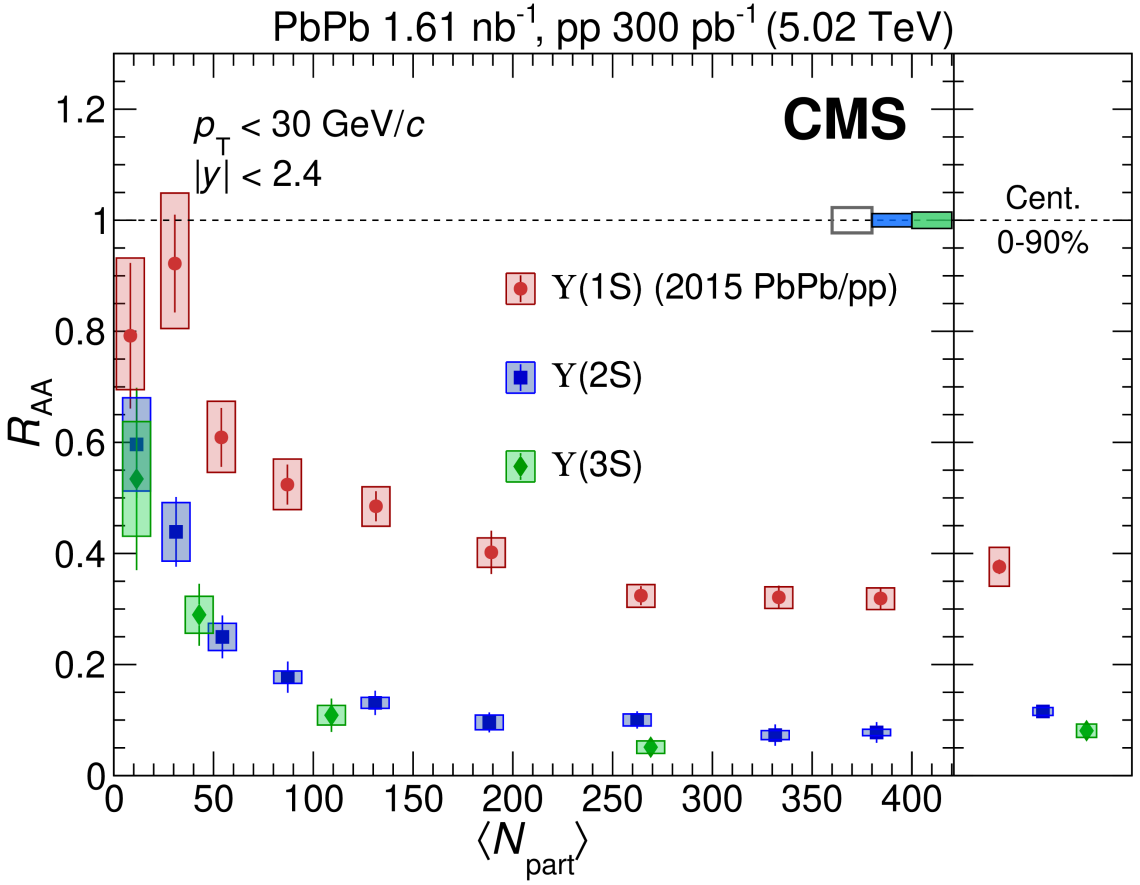


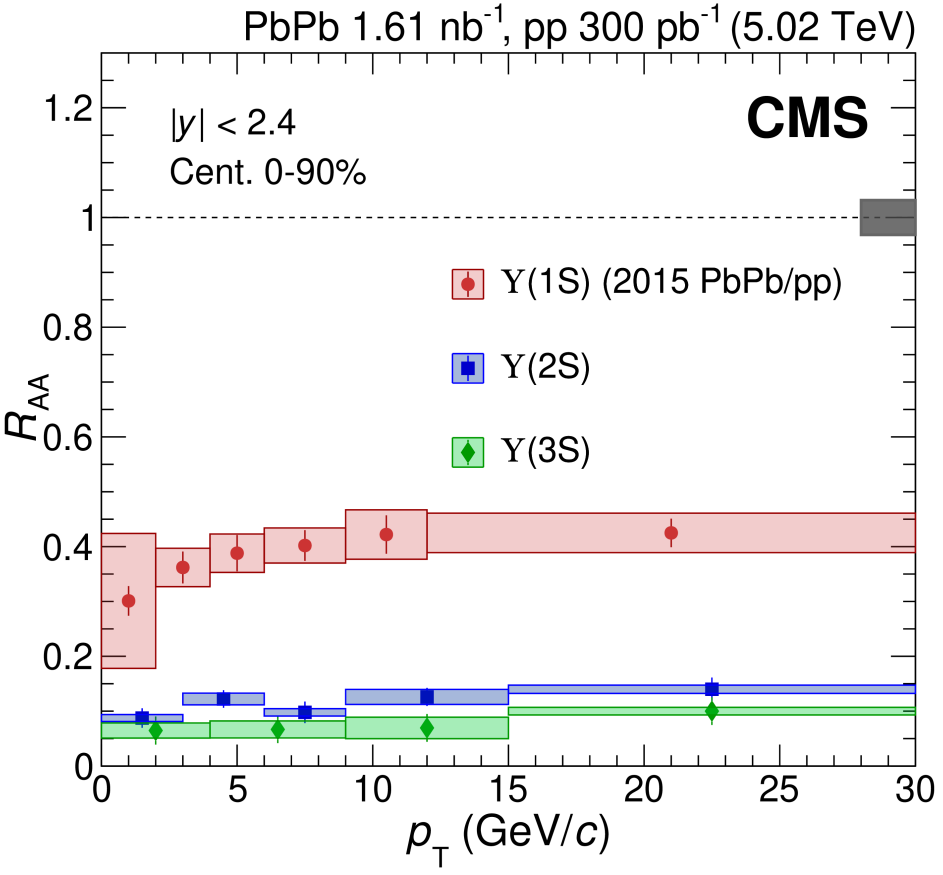
- **Observation of sequential suppression of Y family in Pb+Pb.**
- **First observation of Y(3S) in heavy-ion collisions! (σ > 5)**

Upsilon suppression Pb+Pb

PRL 133 (2024) 022302

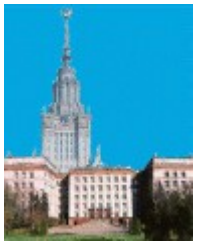




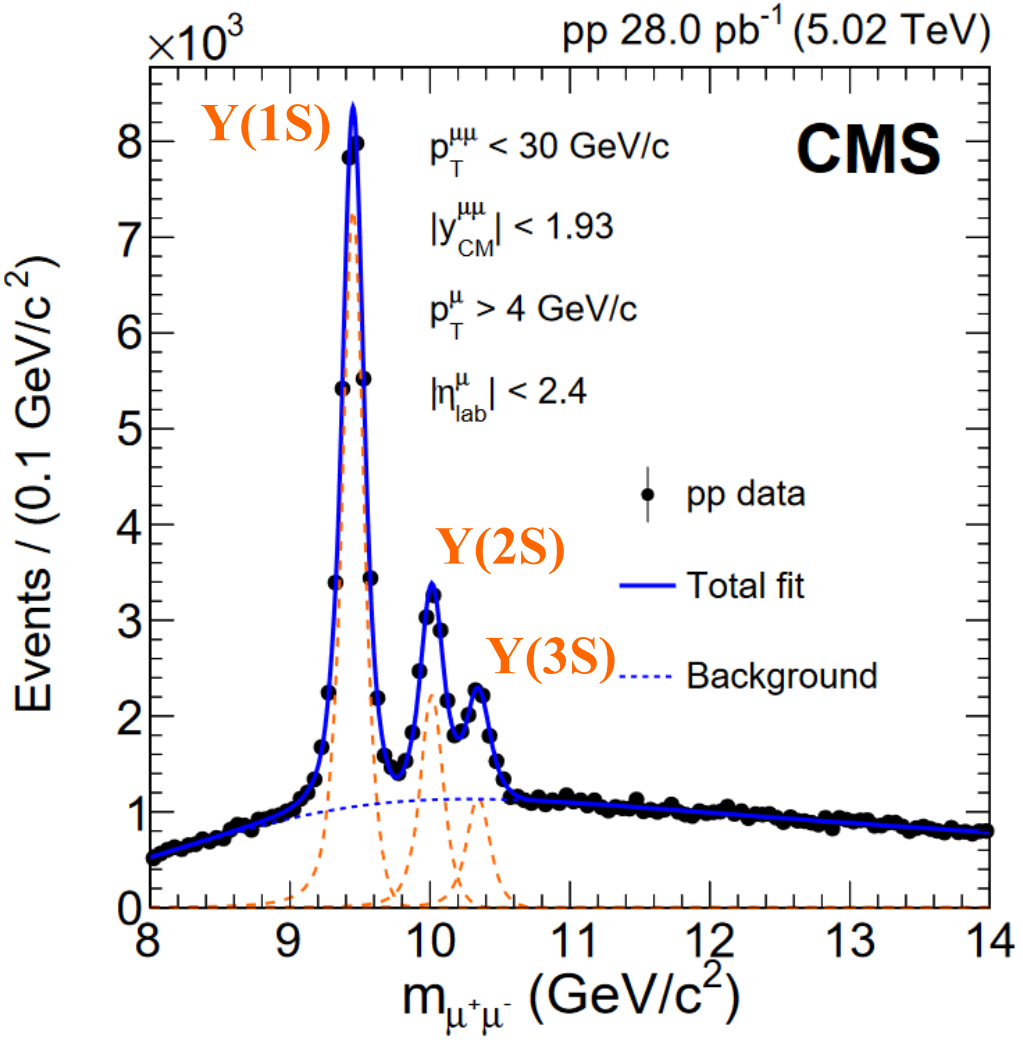


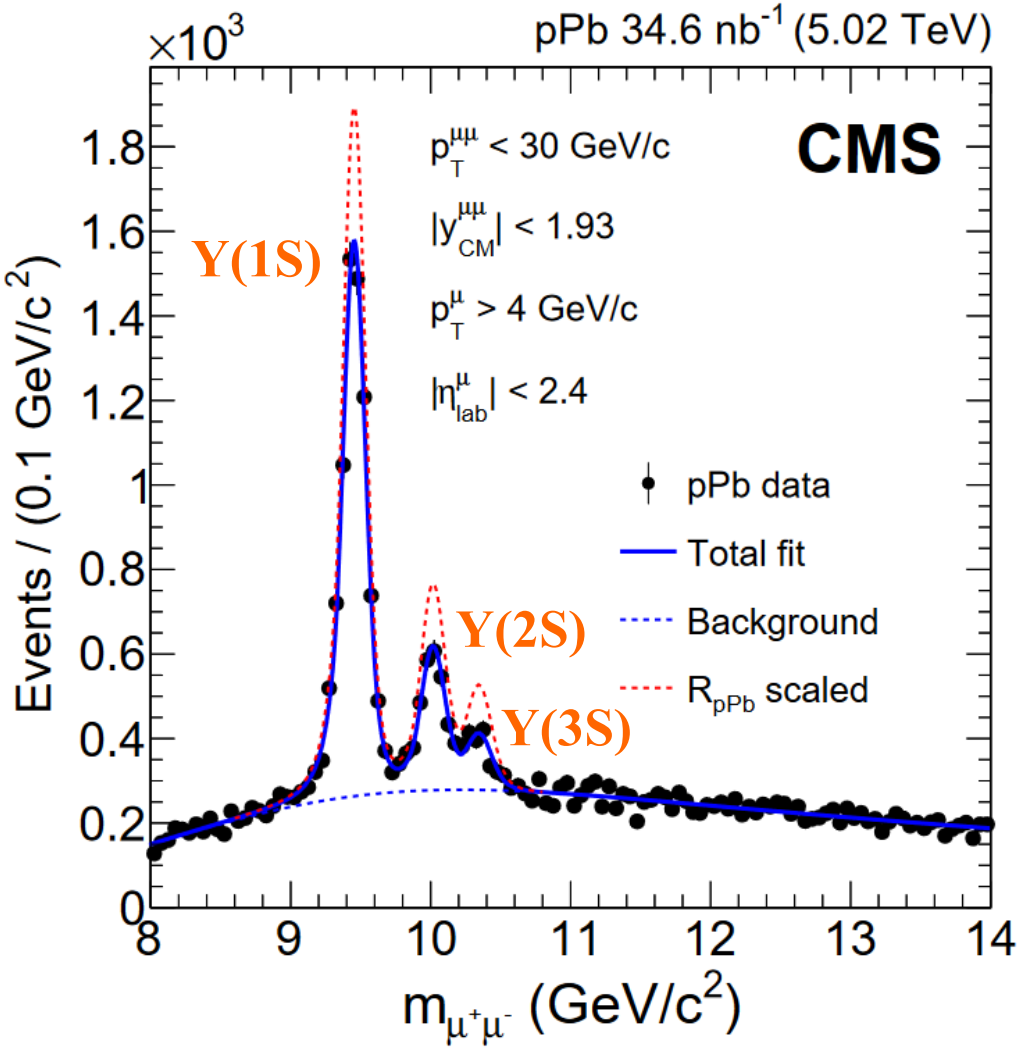
- **R_{AA} is decreasing with numbers of participants of Pb+Pb collision.**
- **Slightly increasing with p_T?**

Upsilon suppression in p+Pb



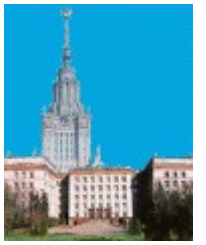
PLB 835 (2022) 137397



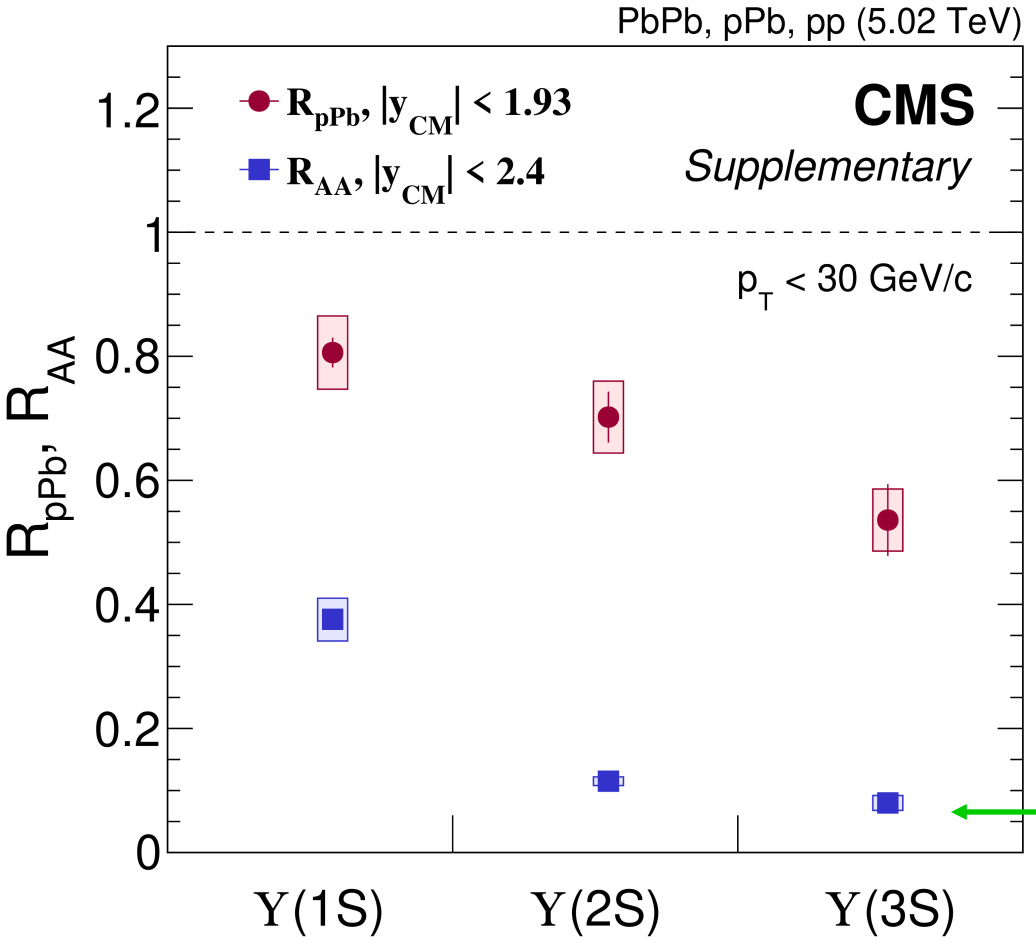


All Y states are found to be suppressed in p+Pb collisions compared to p+p collisions.

Upsilon suppression in p+Pb and Pb+Pb



PRL 133 (2024) 022302



Ordered in binding energy

RpPb Υ(1S) > RpPb Υ(2S) > RpPb Υ(3S)

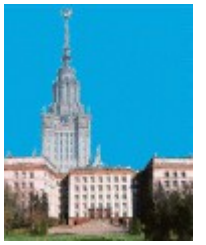
Largest suppression is in Pb+Pb

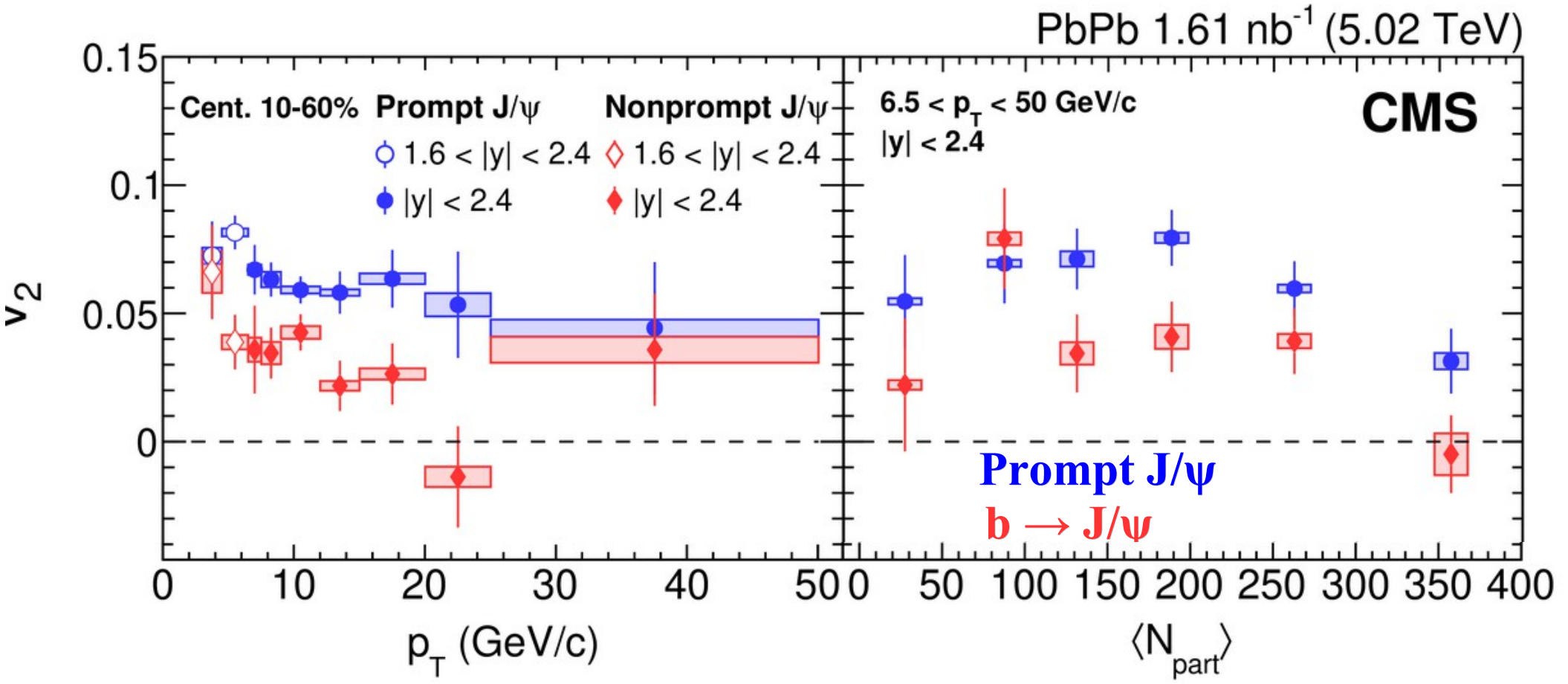
$R_{pPb} > R_{PbPb}$

New result for Y(3S)

v_2 of J/ψ in Pb+Pb collisions

JHEP 10 (2023) 115

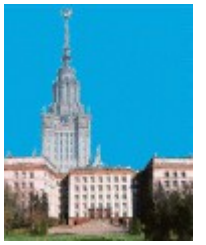


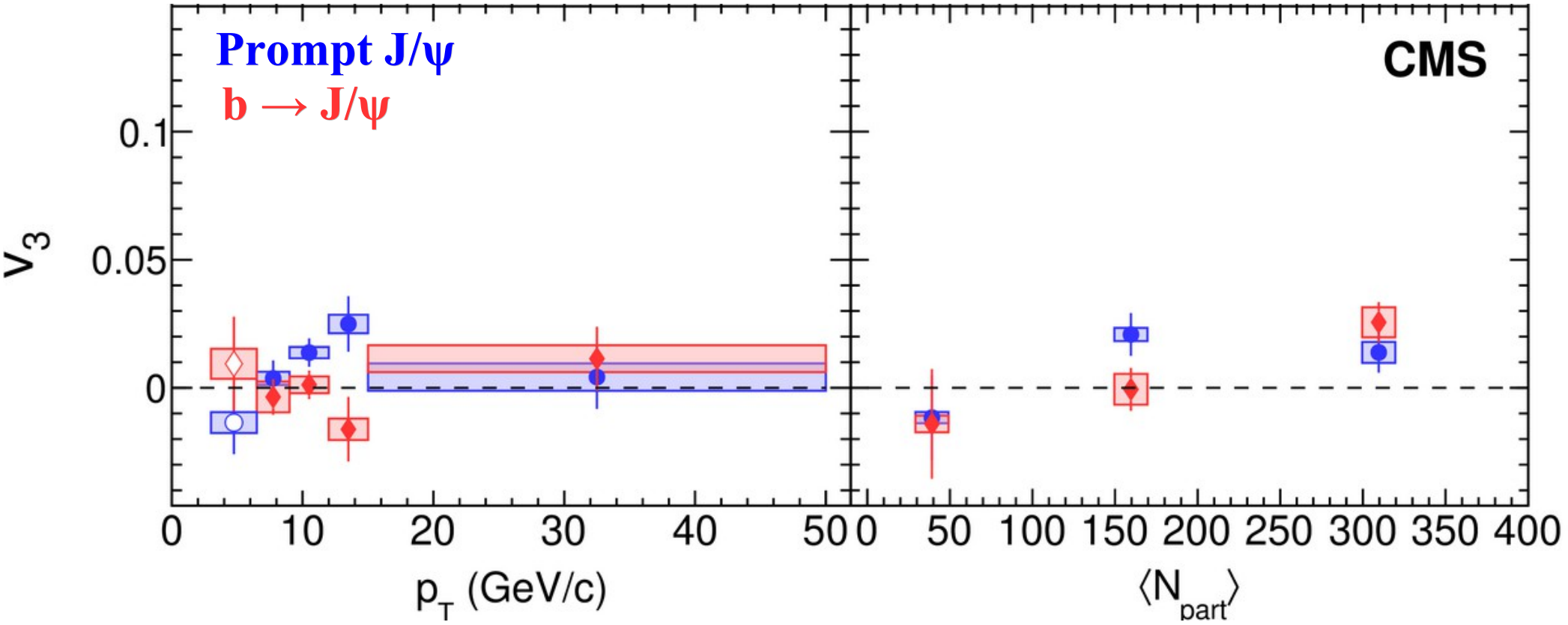


- Large v_2 of J/ψ up to p_T = 50 GeV/*c*
  - v_2 (b → J/ψ) < v_2(prompt J/ψ)

v_3 of J/ψ in Pb+Pb collisions

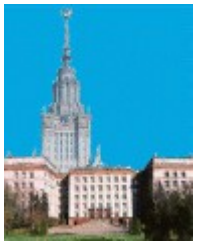
JHEP 10 (2023) 115





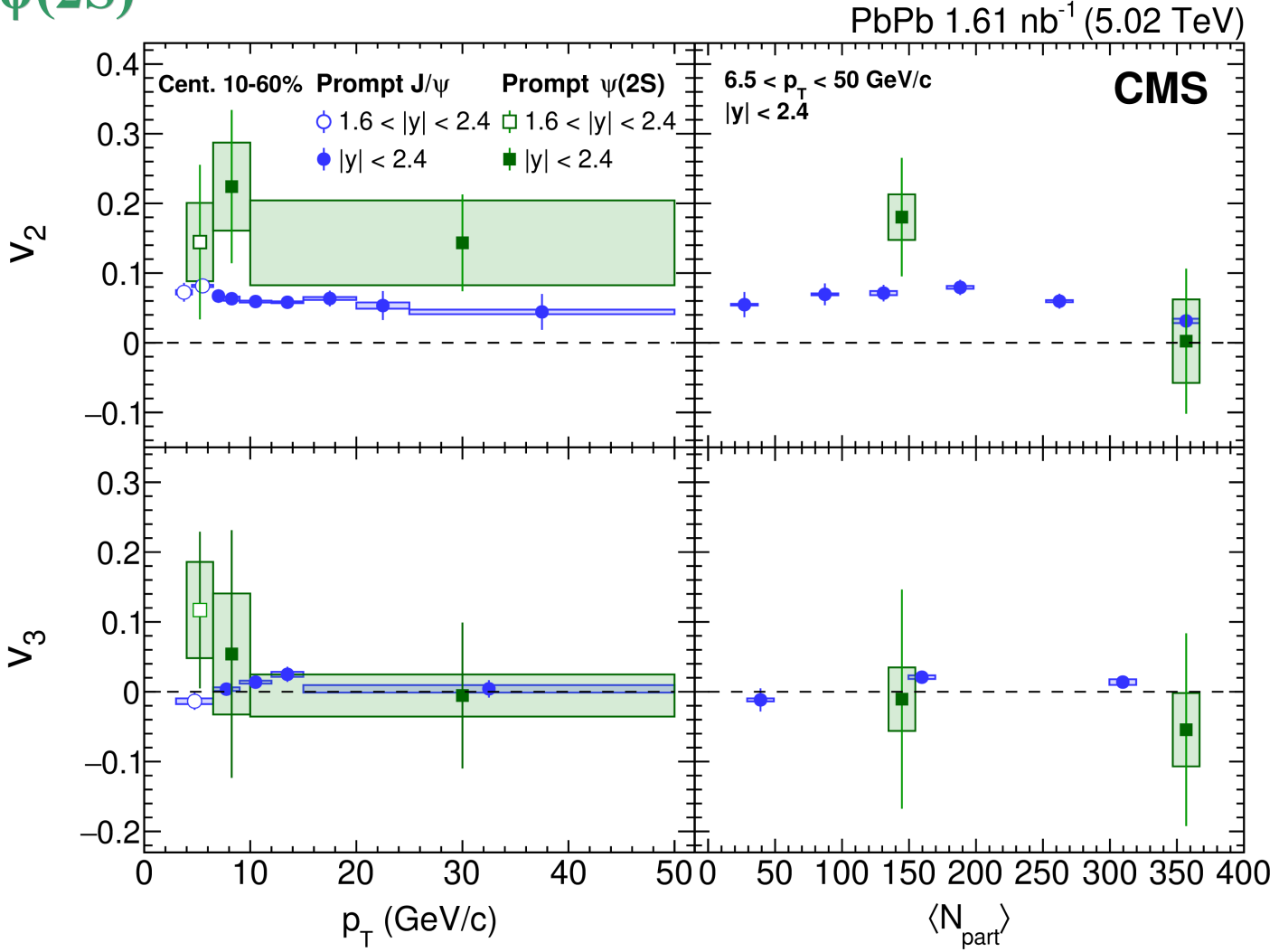
- **First measurement of v_3 for prompt and non-prompt J/ψ separately**
- **no significant non-zero v_3 (J/ψ)**

v_2 and v_3 of ψ(2S) in Pb+Pb collisions



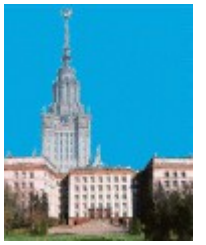
JHEP 10 (2023) 115

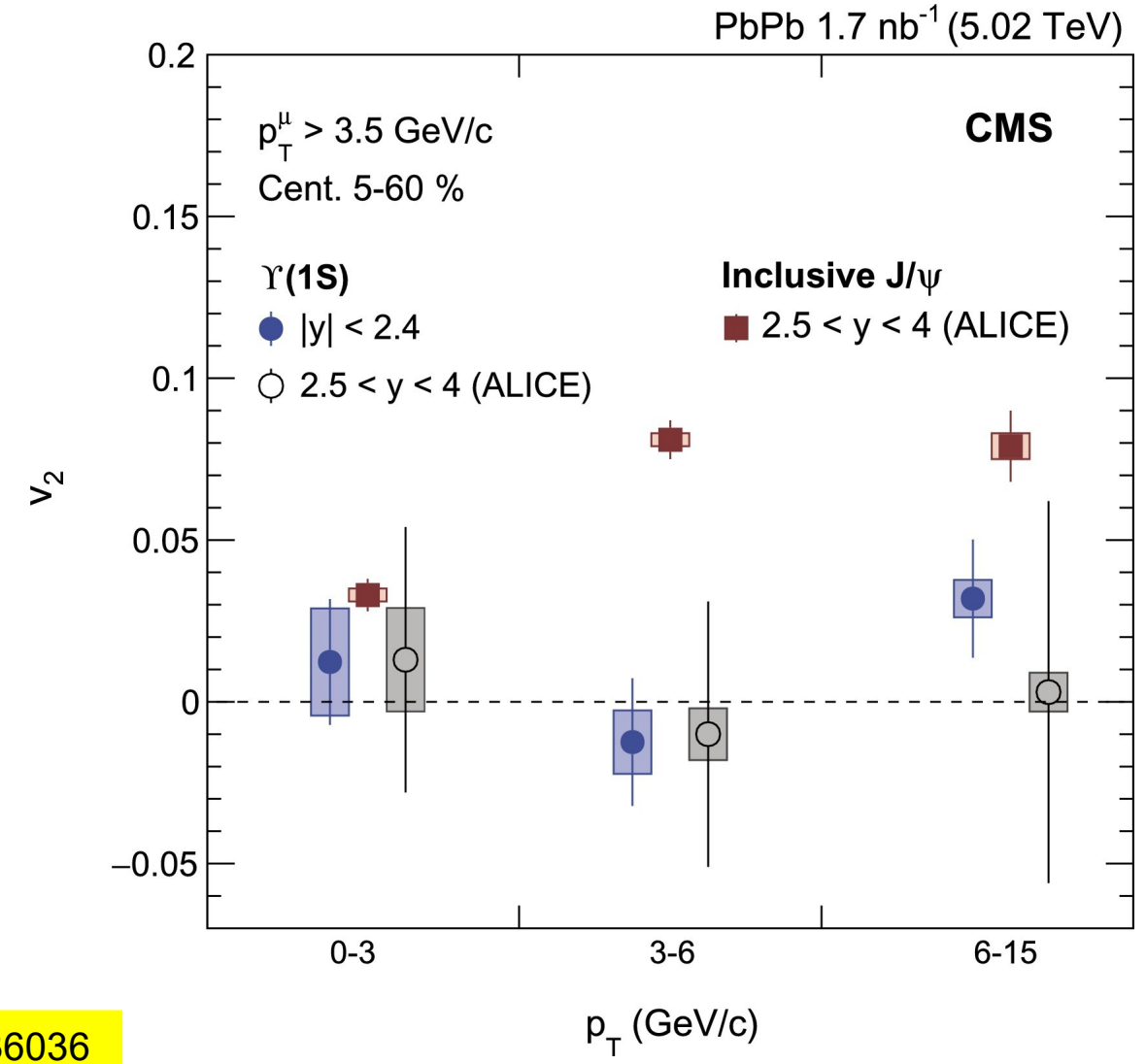
Prompt ψ(2S)



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

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

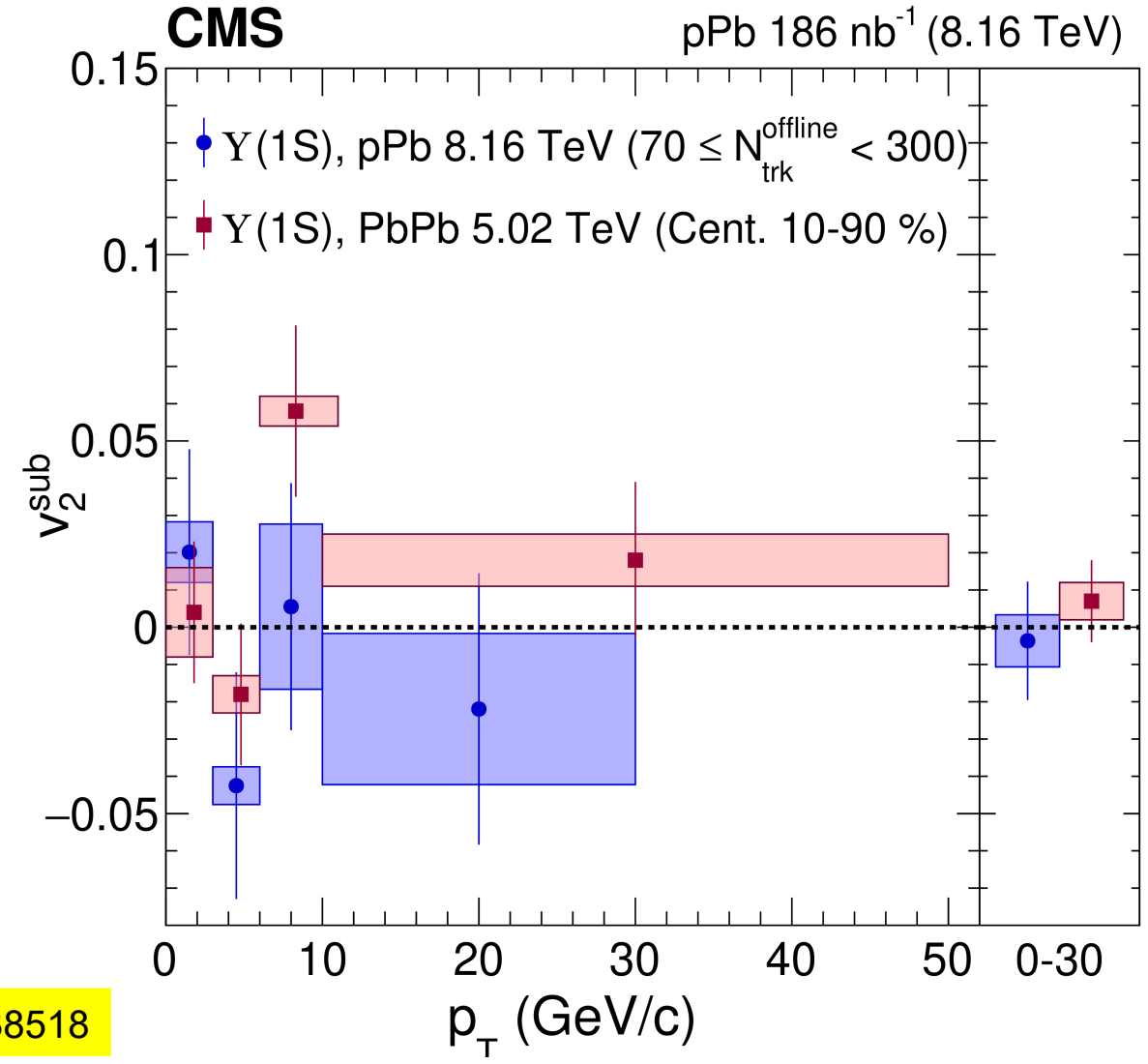




PLB 813 (2021) 136036

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

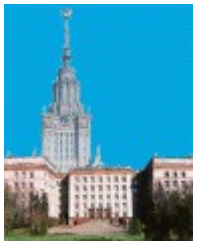
v_2 of Y(1S) in p+Pb collisions



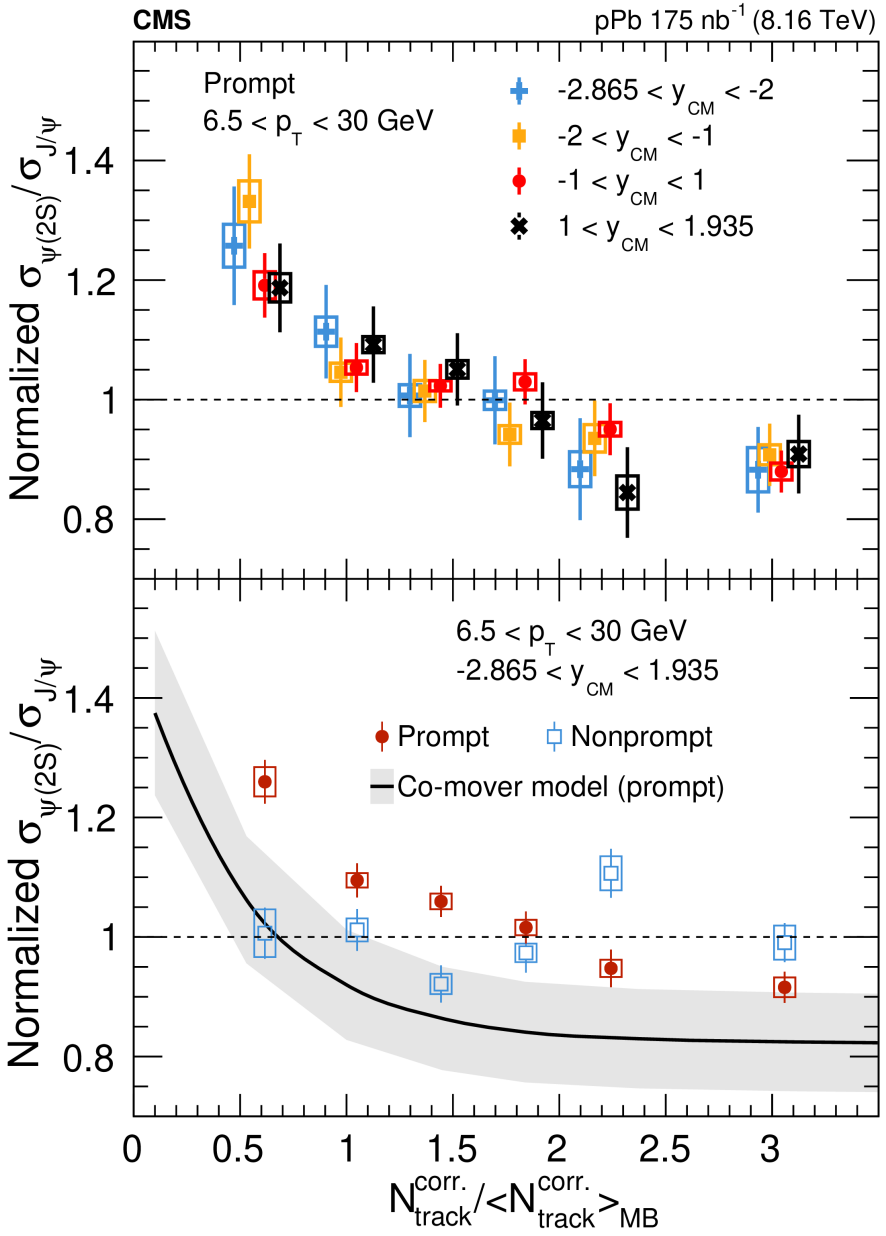
PLB 850 (2024) 138518

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

ψ(2S)/J/ψ vs multiplicity in p+Pb collisions

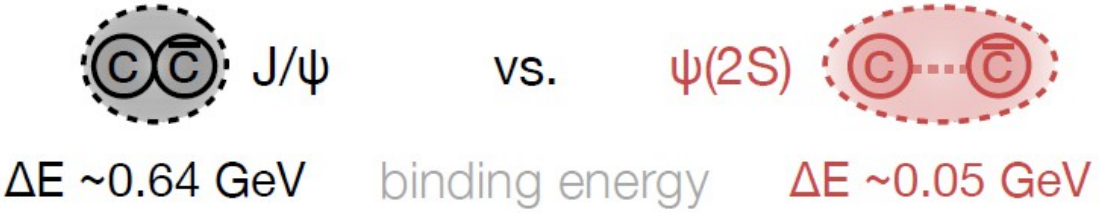


arXiv:2503.02139



Significant multiplicity dependence of prompt ψ(2S)/J/ψ in pPb

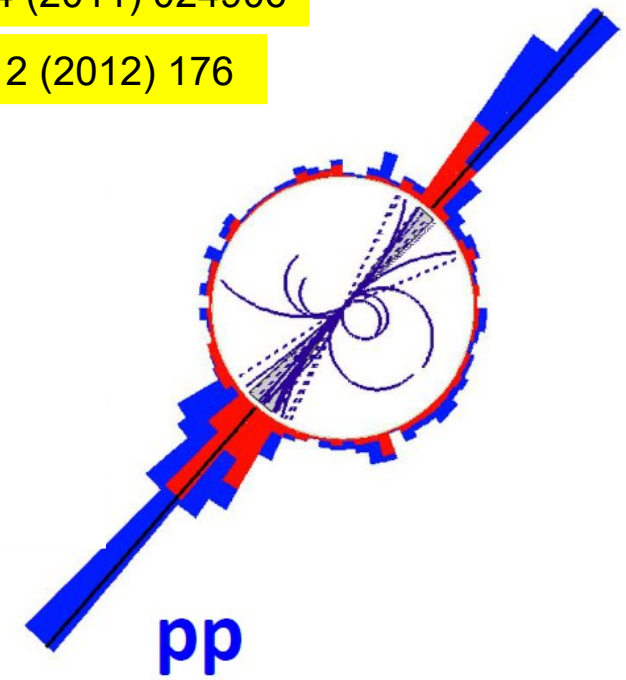
Weaker bound state ψ(2S) easier to be destroyed in color dense environments

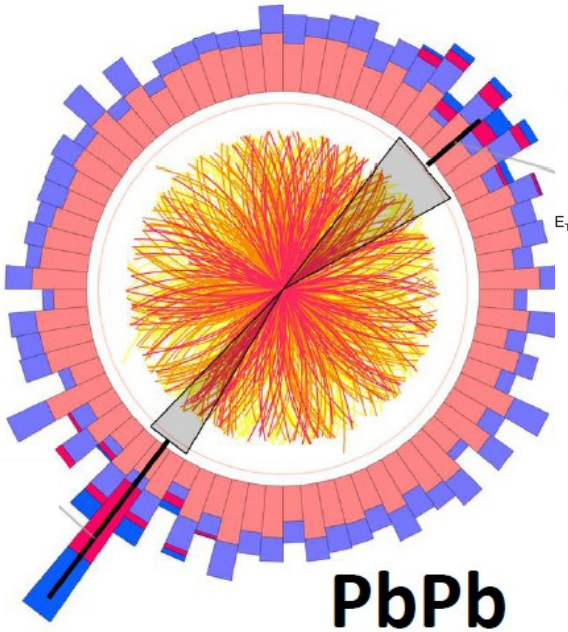


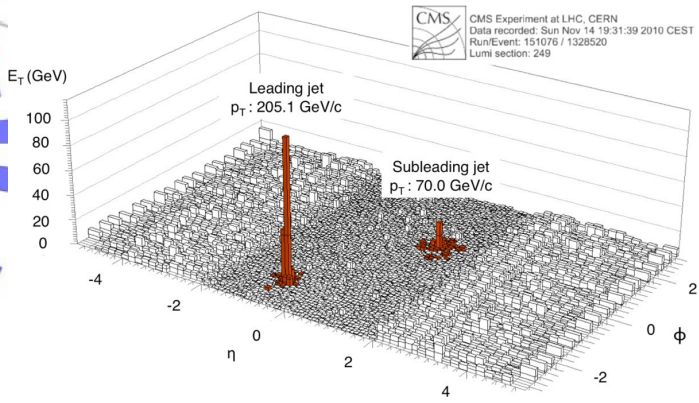
Jet quenching in Pb+Pb

PRC 84 (2011) 024906

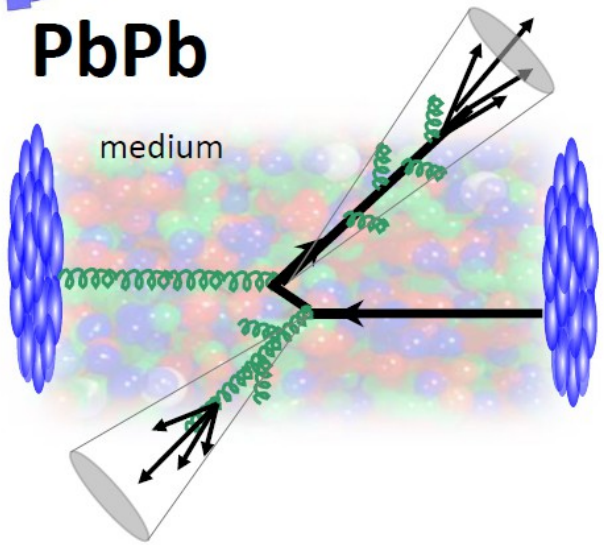
PLB 712 (2012) 176





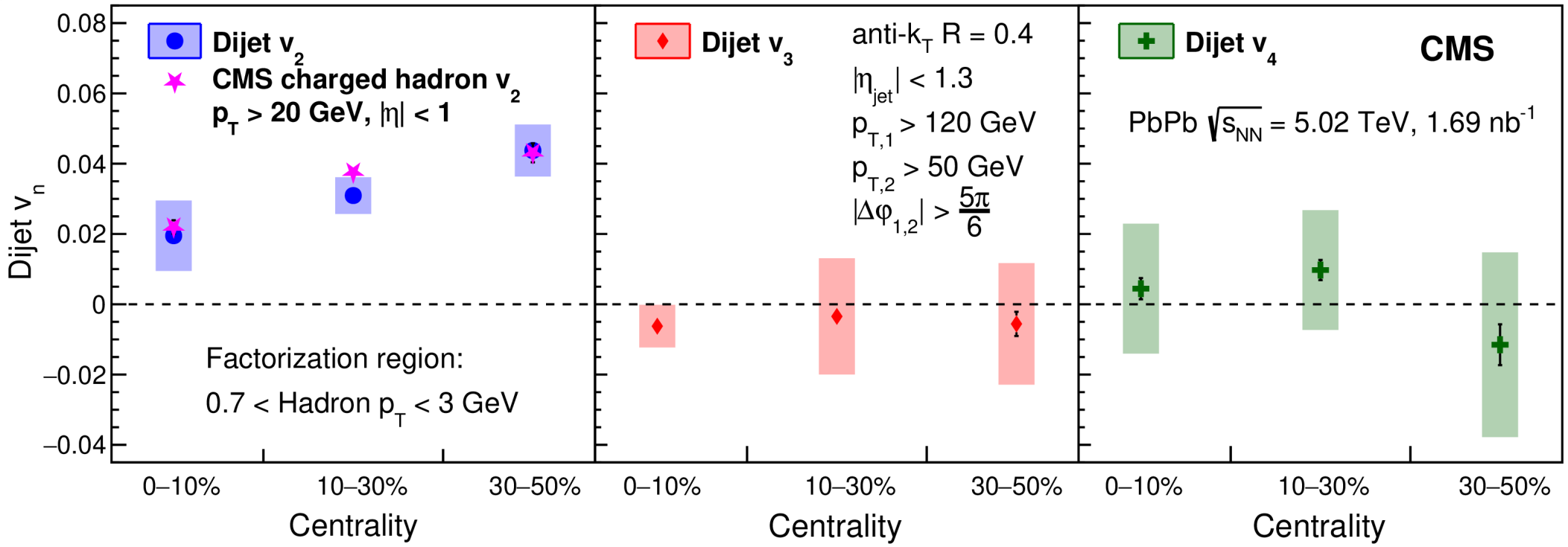


- Asymmetric dijets observed more frequently in PbPb collisions
- The stopping power (dE/dx) of the Quark Soup is **Incredibly Strong**



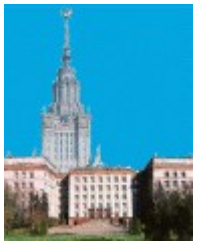
Azimuthal anisotropy of di-jets in Pb+Pb

JHEP 07 (2023) 139



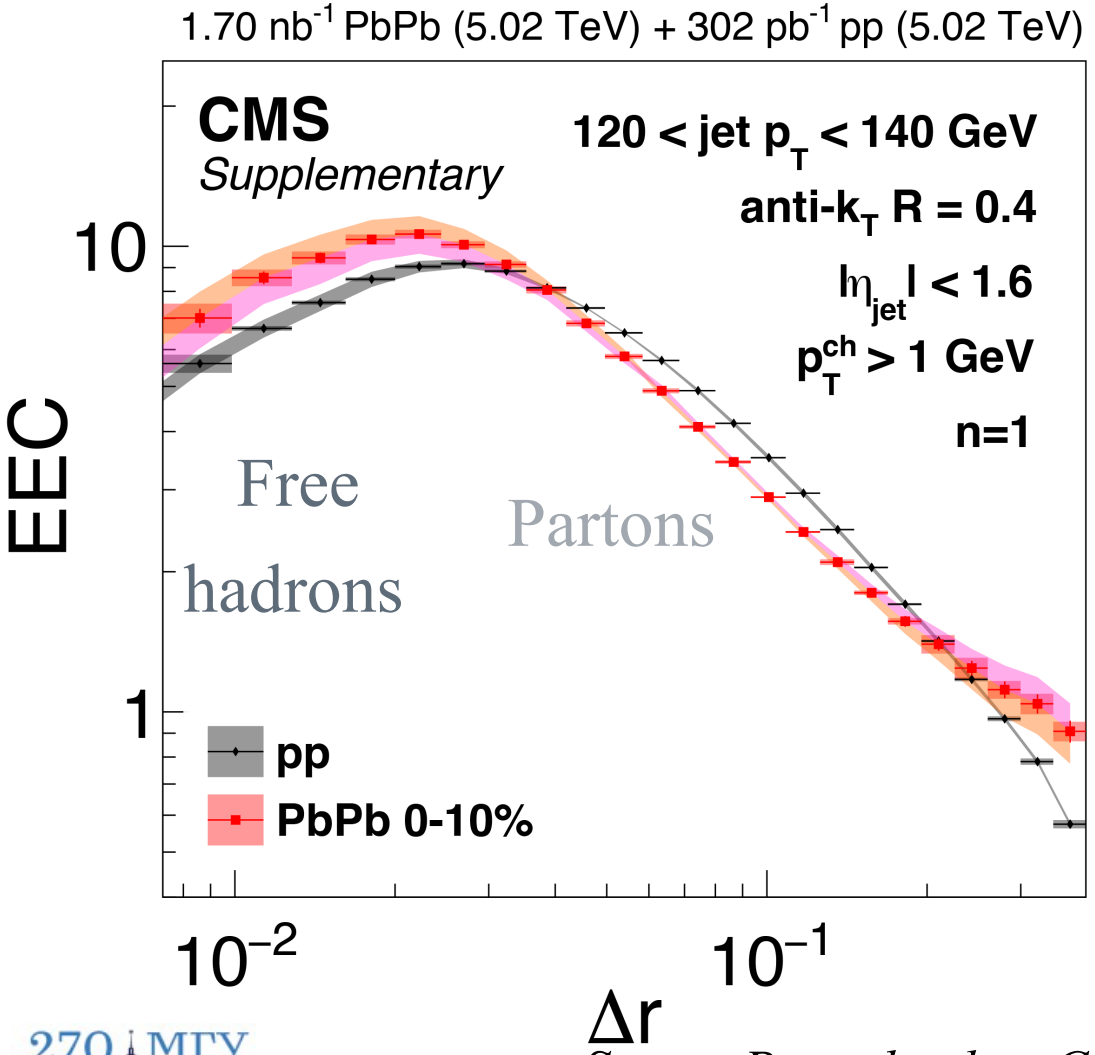
- v_2, v_3 and v_4 of the di-jets in Pb+Pb were measured for the first time
- Di-jets v_2 is compatible with v_2 of high p_T hadrons
- Di-jets v_3 and v_4 are consistent with zero

First measurement of energy-energy correlator of jets in Pb+Pb



arXiv:2503.19993

angular distance $\Delta r_{ij} = \sqrt{\Delta\phi_{ij}^2 + \Delta\eta_{ij}^2}$ weight $w_{ij} = p_{T,i}p_{T,j}$



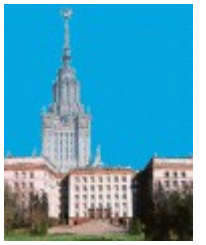
First jet energy-energy correlator measurement in heavy-ion collisions

Different scales of jet evolution reflected in angles

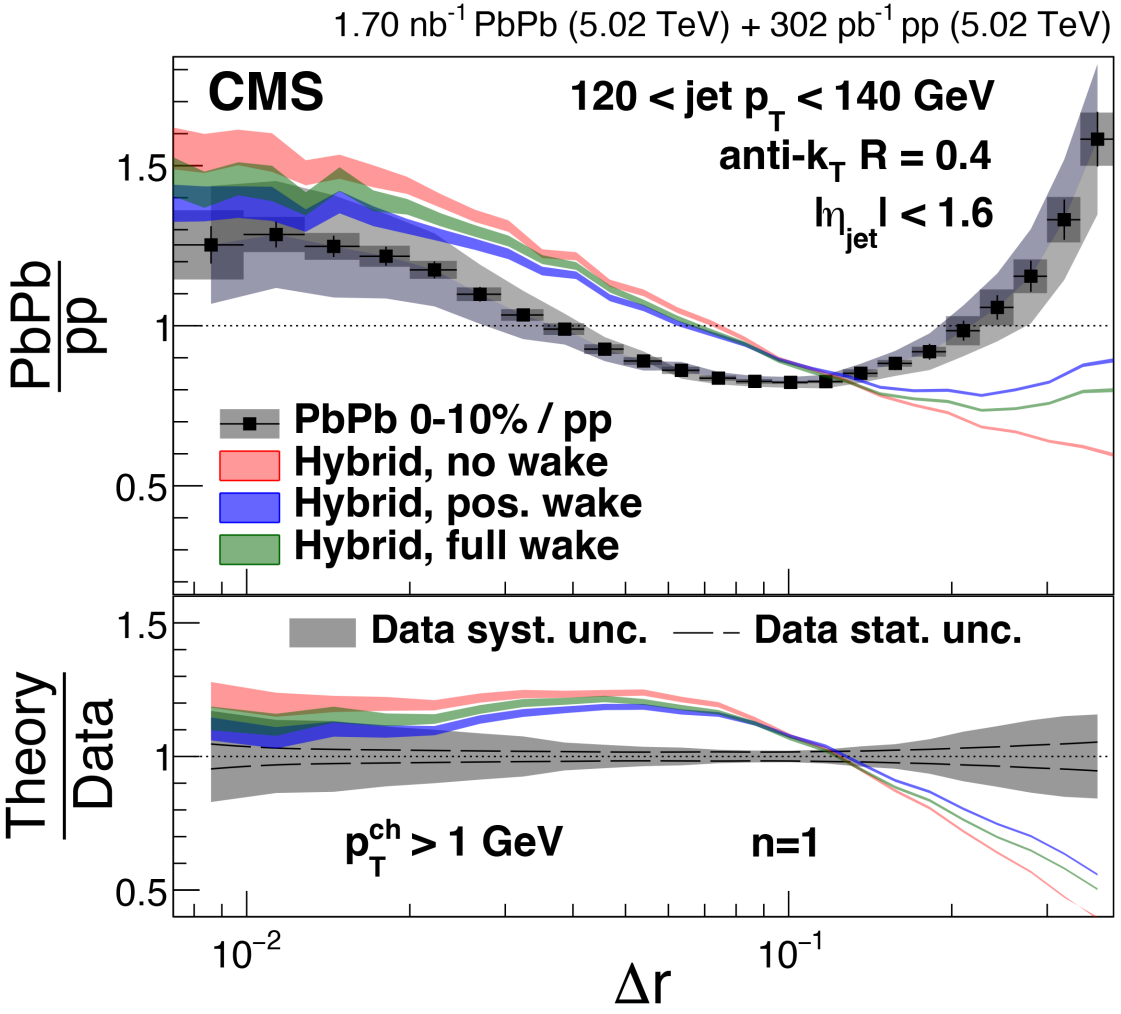
Similar peak shapes in PbPb

Additional scales in medium, e.g. color decoherence angle

First measurement of energy-energy correlator of jets in Pb+Pb



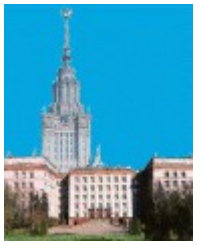
arXiv:2503.19993



Reveal different QGP effects on angular scales

- Intermediate Δr sensitive to medium induced parton shower modification
- Medium response mostly at large Δr EEC PbPb / pp

Nice overview of (almost) all CMS heavy-ion results



Phys. Rept. 1115 (2025) 219

Physics Reports 1115 (2025) 219–367

Contents lists available at ScienceDirect

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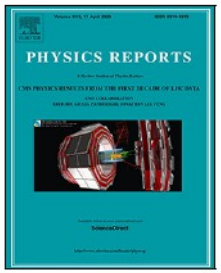
journal homepage: www.elsevier.com/locate/physrep



Overview of high-density QCD studies with the CMS experiment at the LHC

The CMS Collaboration [1]

CERN, Geneva, Switzerland

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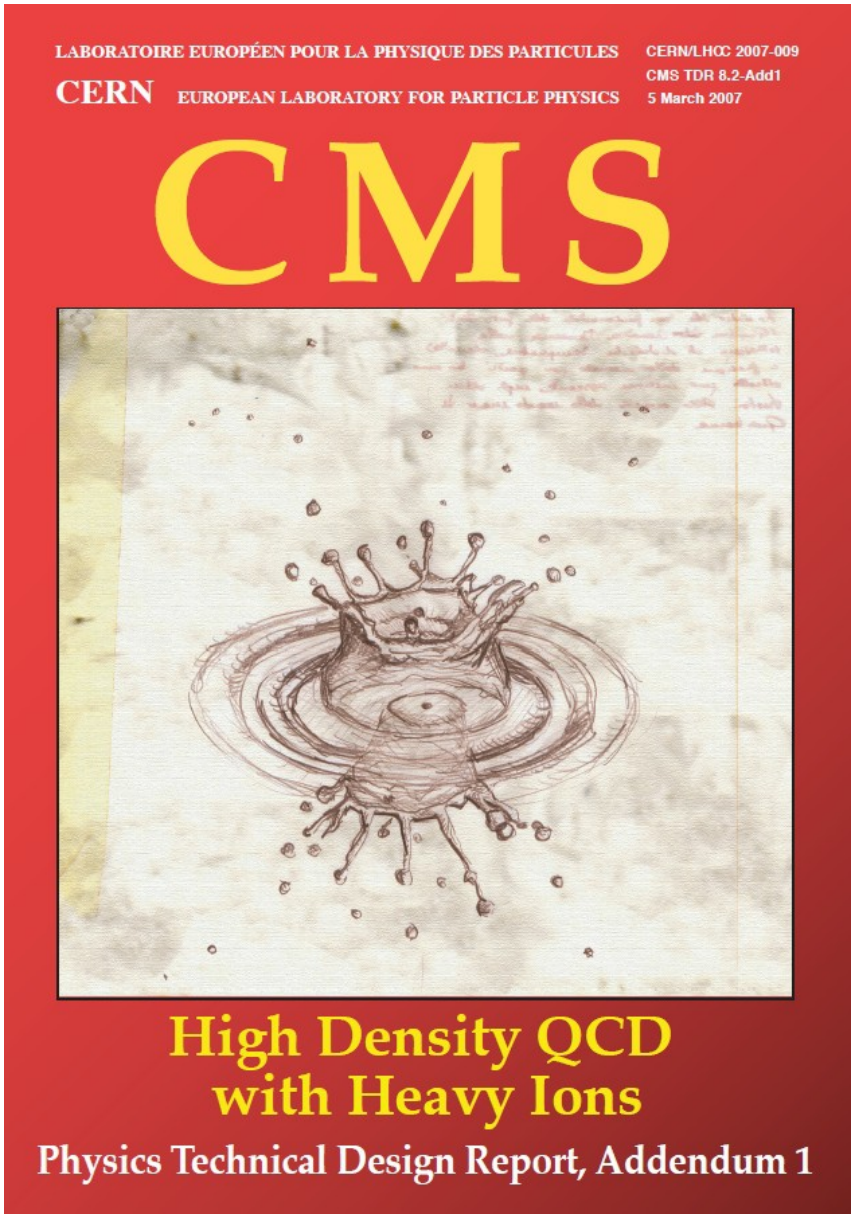
Dataset link: CMS data preservation, re-use and open access policy

ABSTRACT

We review key measurements performed by CMS in the context of its heavy ion physics program, using event samples collected in 2010–2018 with several collision systems and energies. These studies provide detailed macroscopic and microscopic probes of the quark-gluon plasma (QGP) created at the LHC energies, a medium characterized by the highest temperature and smallest baryon-chemical potential ever reached in the laboratory. Numerous observables related to high-density quantum chromodynamics (QCD) were studied, leading to some of the most impactful and qualitatively novel results in the 40-year history of the field. Using a dedicated high-multiplicity trigger in the first

Preparation of the CMS heavy-ion program



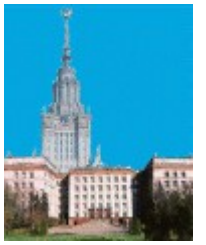
The CMS Collaboration

D. d'Enterria, M. Ballintijn, M. Bedjidian, D. Hofman, O. Kodolova, C. Loizides, I. P. Lokthin, C. Lourenco, C. Mironov, S. V. Petrushanko, C. Roland, G. Roland, F. Sikler and G. Veres *(editors)*

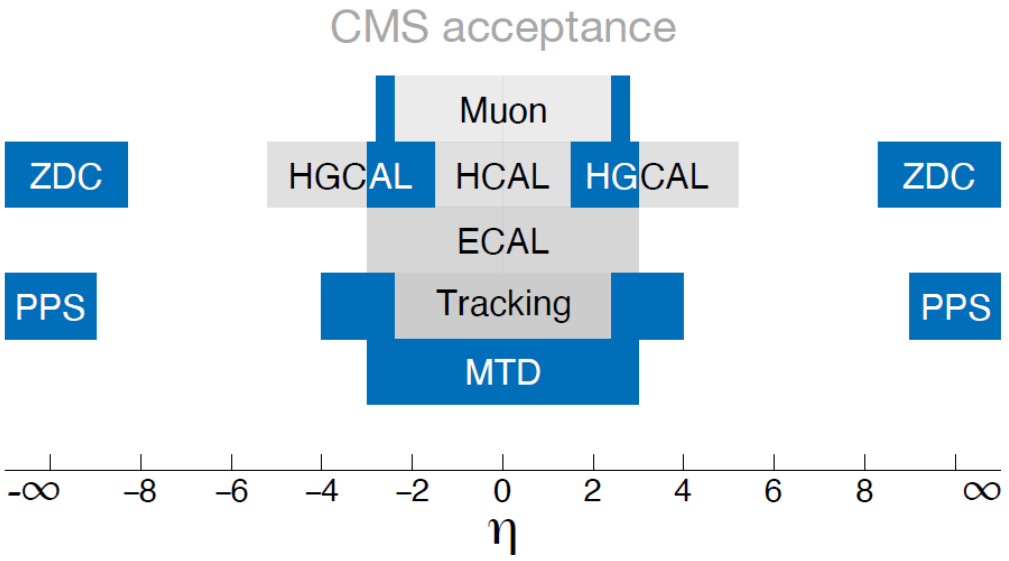
"CMS Physics Technical Design Report: Addendum on High Density QCD with Heavy Ions"

J. Phys. G 34, 2307-2455 (2007)

CMS Phase 2 Upgrade
Greater heavy-ion detector



From Run 4



Expand trigger and DAQ bandwidth

- L1 trigger 50 kHz → **750 kHz**
- DAQ throughput 20 GB/s → **60 GB/s**

  Save all hadronic events with higher luminosity

  Big UPC datasets with tracking in L1 trigger

Full coverage $0 < \phi < 2\pi$ for all units

Even wider acceptance

- Inner tracker $|\eta| < 2.4$ → **$|\eta| < 4$**
- Muon detector $|\eta| < 2.4$ → **$|\eta| < 2.8$**

Higher precision

- Tracker pixel 100x150 → **50x50 μm²**
- High granularity end-cap HGCAL

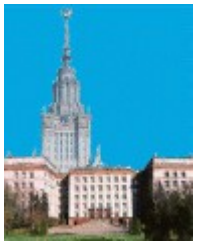
Forward detector

- ZDC tagging neutron → **Radiation hard**
- **PPS** tagging out-going proton

Timing info

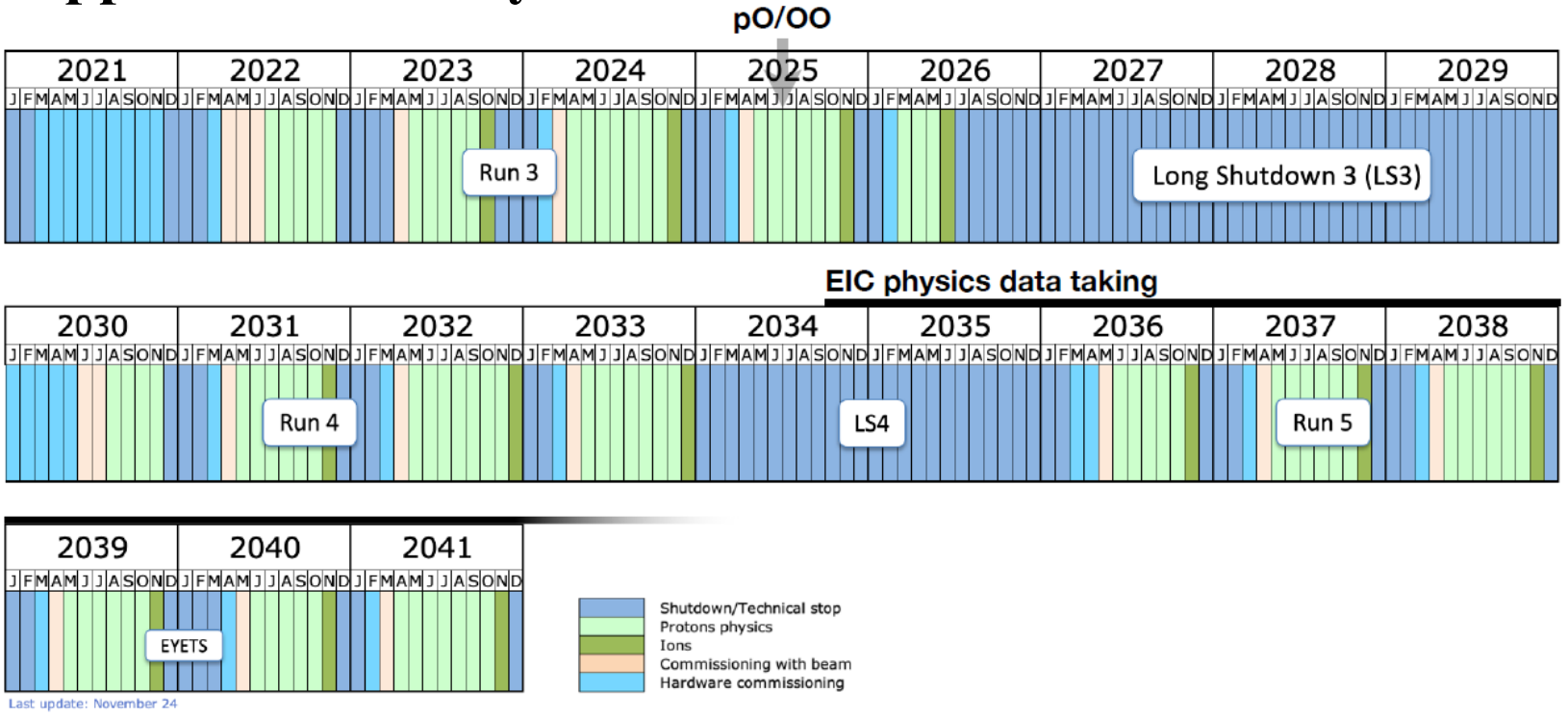
- MTD as **TOF for charged hadron PID**
- End-cap HGCAL with timing

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... (and O+O, Ne+Ne waiting to come)**

- **Future heavy-ion program at the LHC (Run 3 and 4) with the upgraded CMS detector will provide more exciting opportunities! Stay tuned with the CMS!**



My Alma Mater!
Happy Birthday!!!

РОССИЙСКАЯ ФЕДЕРАЦИЯ
г.Москва
Московский государственный университет имени М.В.Ломоносова

ДИПЛОМ
С ОТЛИЧИЕМ
АВС 0076938

Решением Государственной аттестационной комиссии
от 22 января 1999 года
Петрушанко Сергею Владимировичу

ПРИСУЖДЕНА КВАЛИФИКАЦИЯ
ФИЗИК
по специальности "Физика"

Председатель Государственной аттестационной комиссии
Ректор
м.п.

ДИПЛОМ
КАНДИДАТА НАУК
КТ № 086283
Москва 17 января 2003 г.

Решением
диссертационного совета
Московского гос. университета
им. М. В. Ломоносова
от 10 октября 2002 г. № 5
Петрушанко Сергею Владимировичу
ПРИСУЖДЕНА УЧЕНАЯ СТЕПЕНЬ
КАНДИДАТА
физико-математических наук
Председатель диссертационного совета
Ученый секретарь диссертационного совета