

Sergey Petrushanko
(for CMS Collaboration)



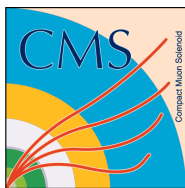
Skobeltsyn Institute of Nuclear Physics
Lomonosov Moscow State University

Recent Heavy-Ion Results by CMS Experiment

**6th International Conference on
Particle Physics and Astrophysics**

National Research Nuclear University
“MEPhI”, Moscow, Russia
29 November – 2 December 2022





CMS is a nice heavy-ion experiment



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}$) $\sim 1\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000\text{A}$

MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO_4 crystals

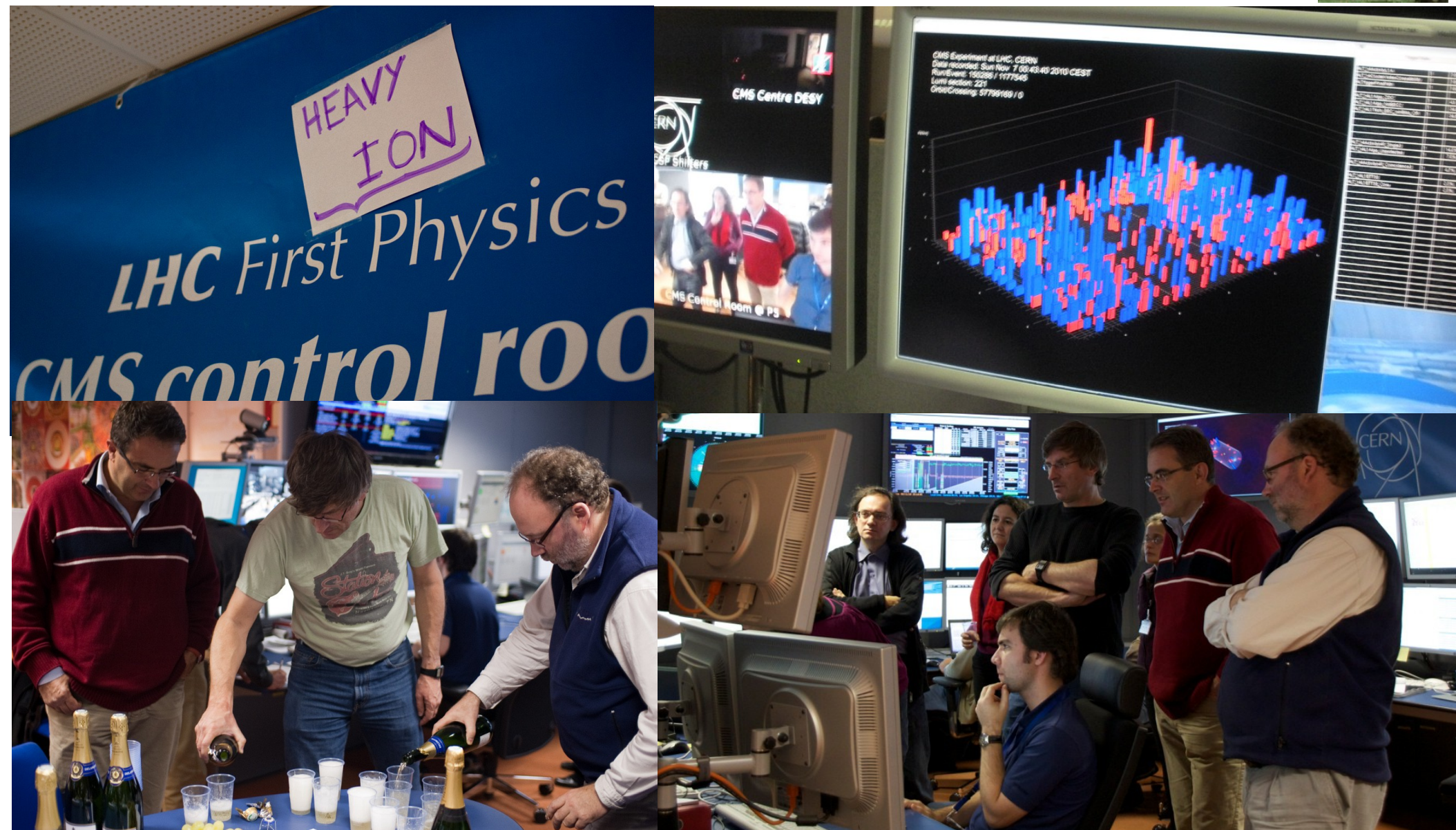
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels

- ◆ **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



**120 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**

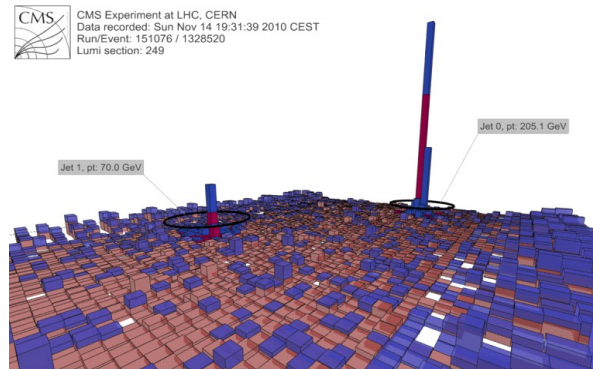
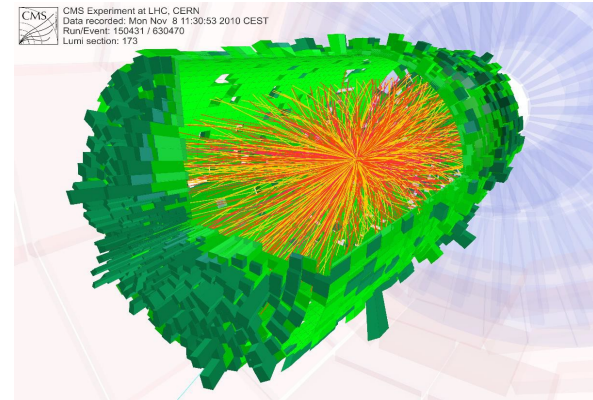
- multiplicity,
- energy,
- flow, ...

Pb+Pb collisions

2010-11: 2.76 TeV	0.16/nb
2015-18: 5.02 TeV	1.7/nb
2022-?: 5.36 TeV	...

- **Hard probes**

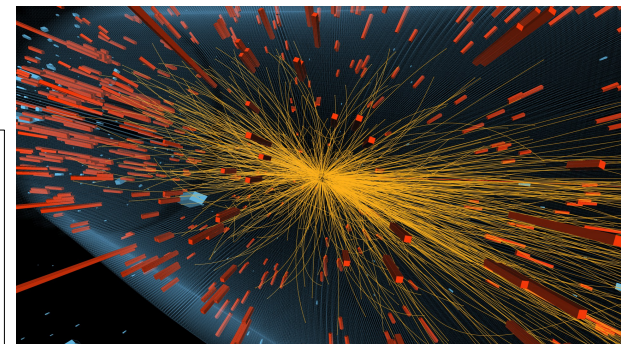
- jets
- dimuons (quarkonia)
- charged hadrons R_{AA} , ...



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

- correlations
- flow,
- jets, ...

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





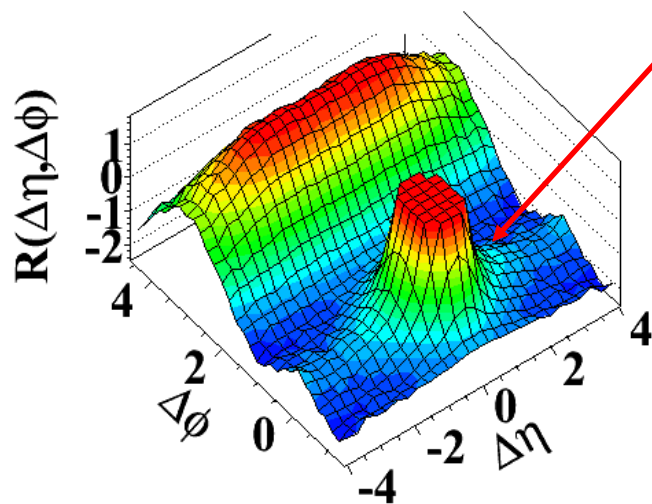
Correlations: “RIDGE” is everywhere...

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

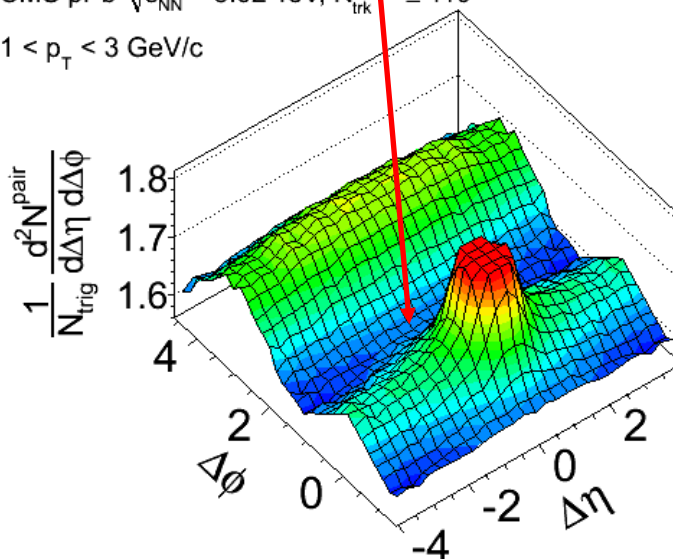
(d) $N > 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



JHEP 09 (2010) 091

p+Pb 5.02 TeV

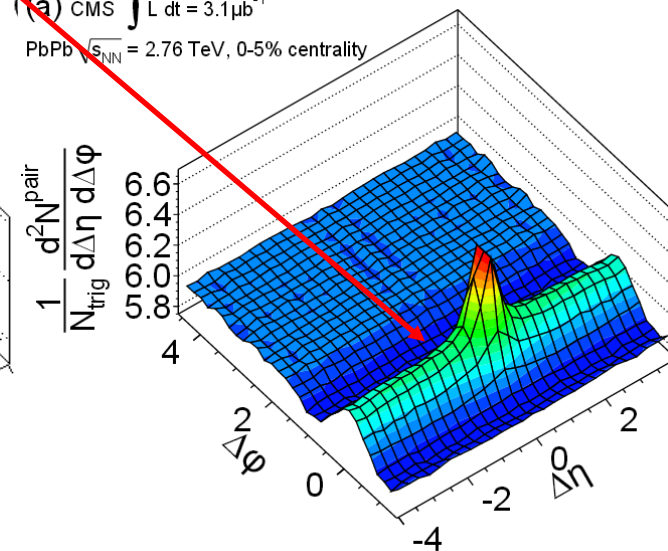
CMS pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, $N_{trk}^{offline} \geq 110$
 $1 < p_T < 3 \text{ GeV}/c$



PLB 718 (2013) 795

Pb+Pb 2.76 A TeV, 0-5%

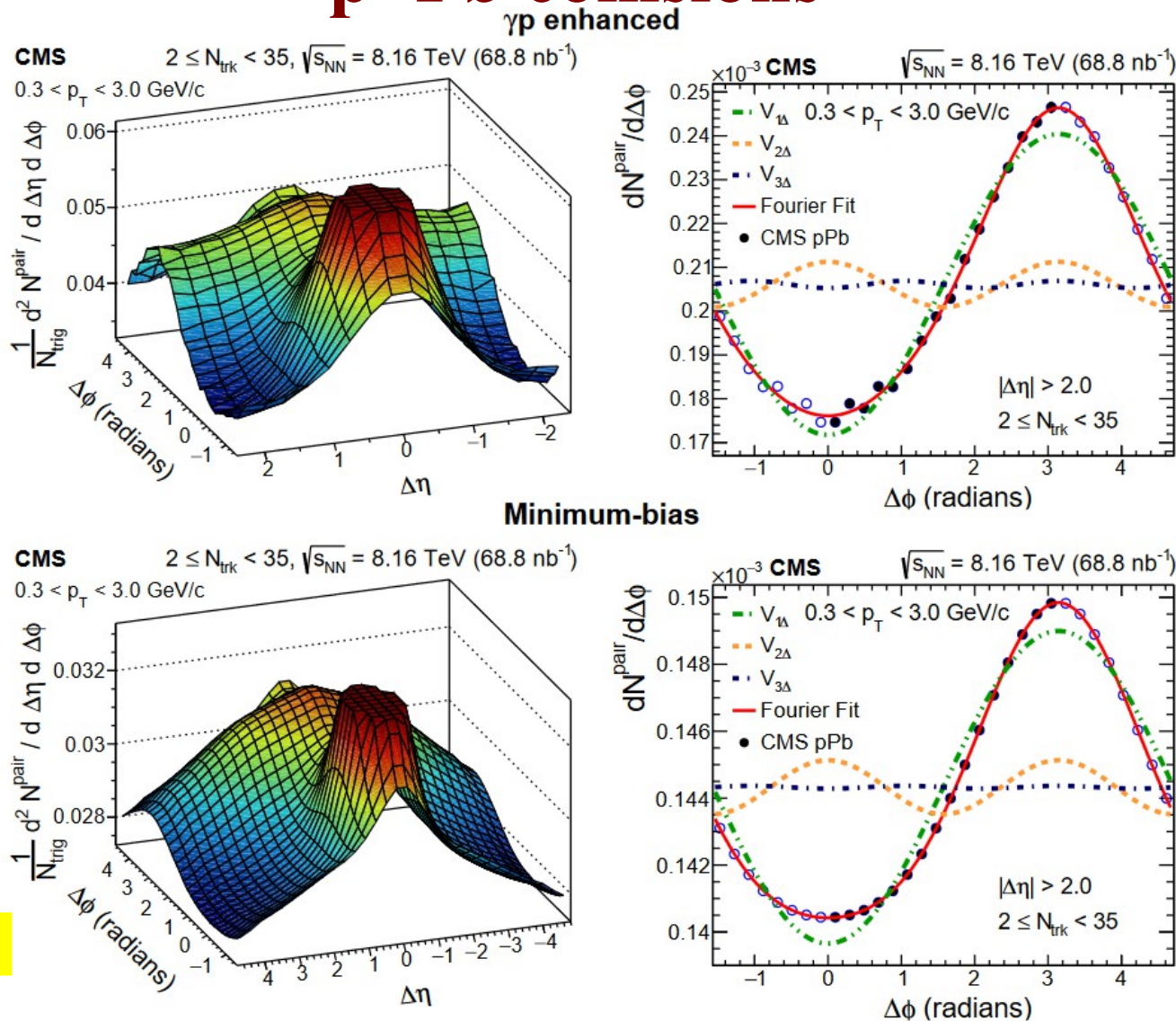
(a) CMS $\int L dt = 3.1 \mu\text{b}^{-1}$
PbPb $\sqrt{s_{NN}} = 2.76 \text{ TeV}$, 0-5% centrality



JHEP 07 (2011) 076



γp interactions within ultra-peripheral p+Pb collisions

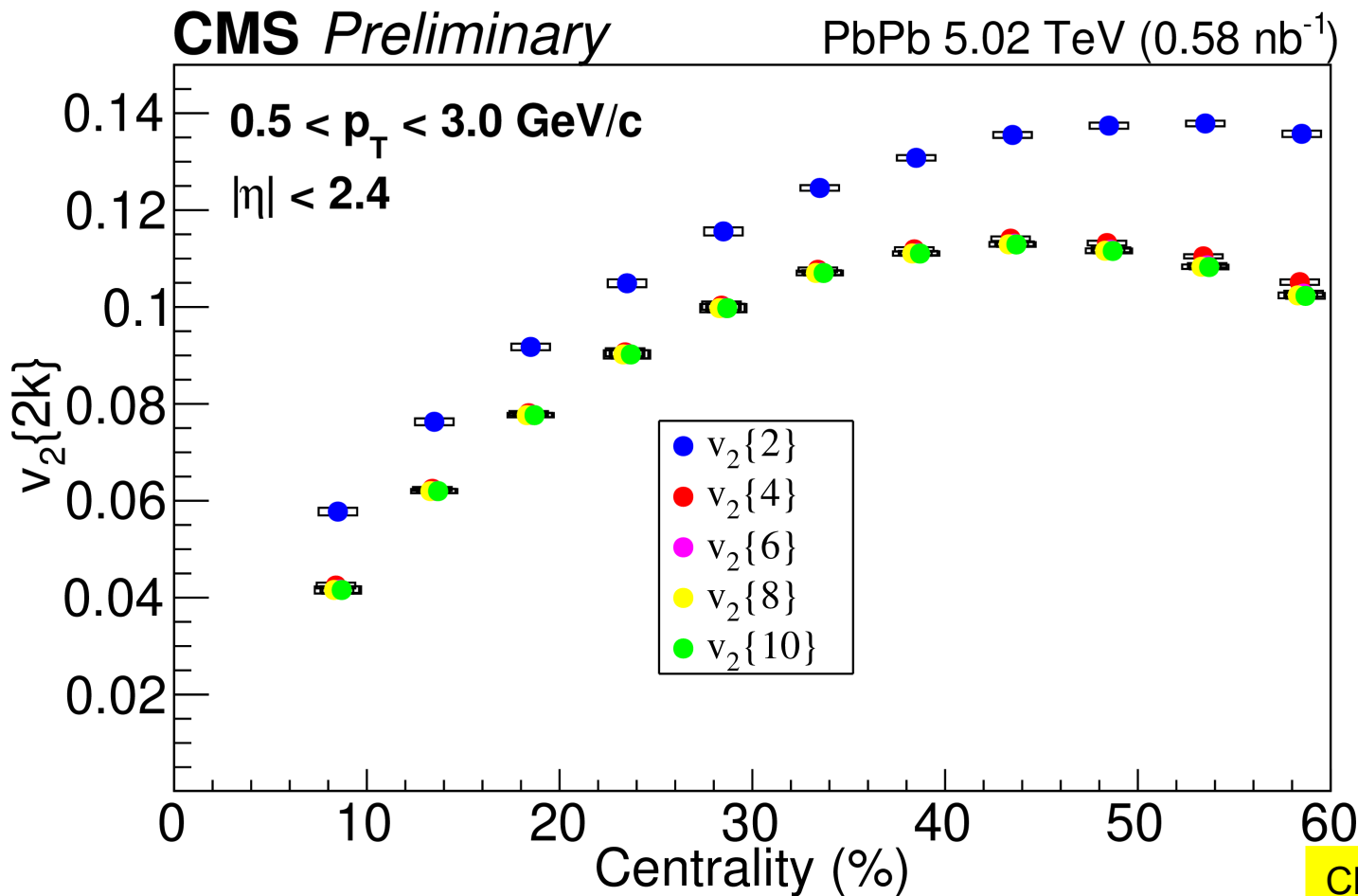


arXiv:2204.13486

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!

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



$v_2\{2\} > v_2\{4\} \gtrsim v_2\{6\} \gtrsim v_2\{8\} \gtrsim v_2\{10\}$ ($v_2\{10\}$ is the first time ever)

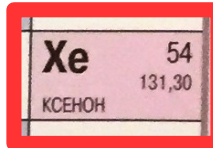
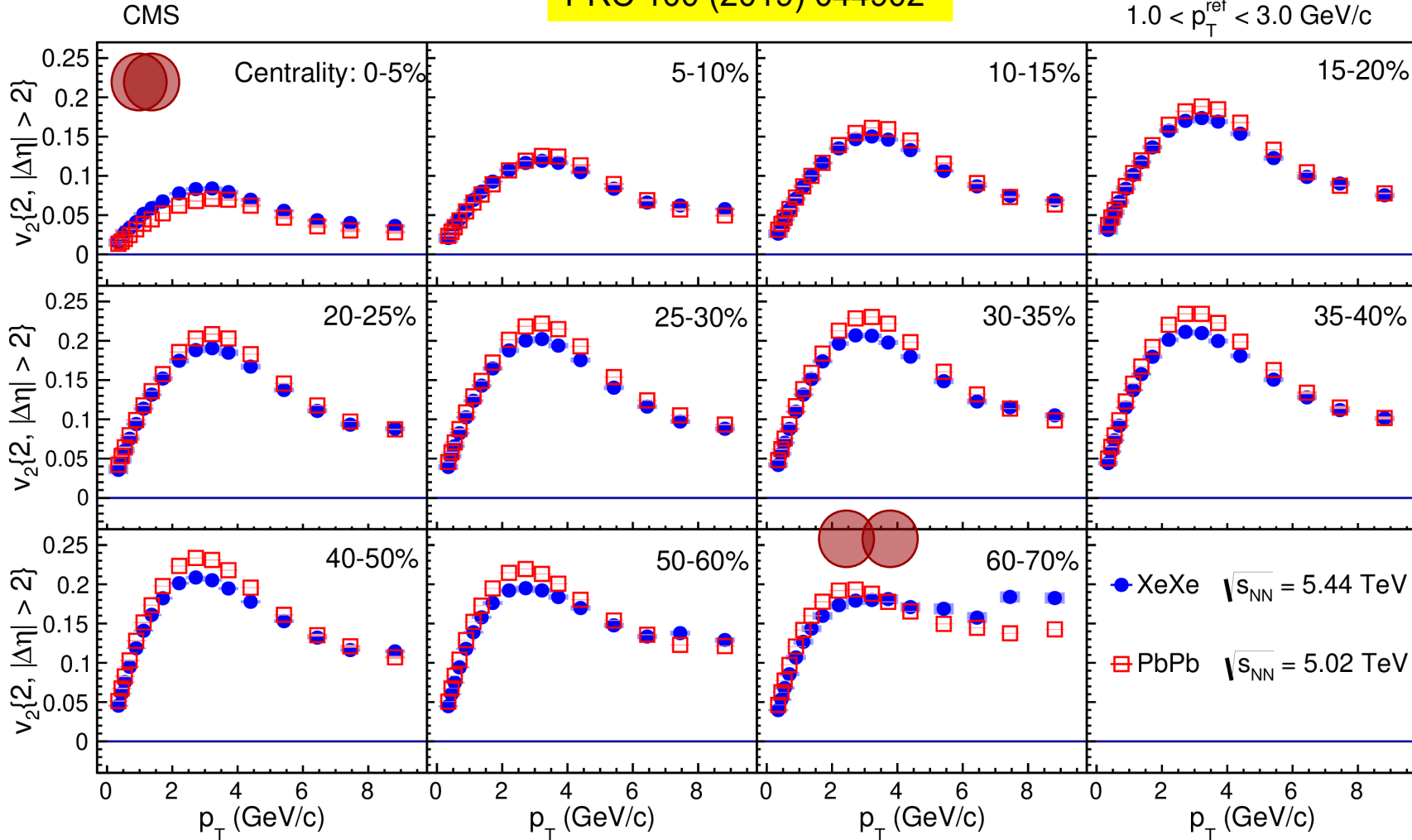
The subtle differences in the higher order harmonics allow for a precise determination of the underlying hydrodynamics and what condition prevail before the onset of hydrodynamics.

v_2 Xe+Xe vs. Pb+Pb

PRC 100 (2019) 044902

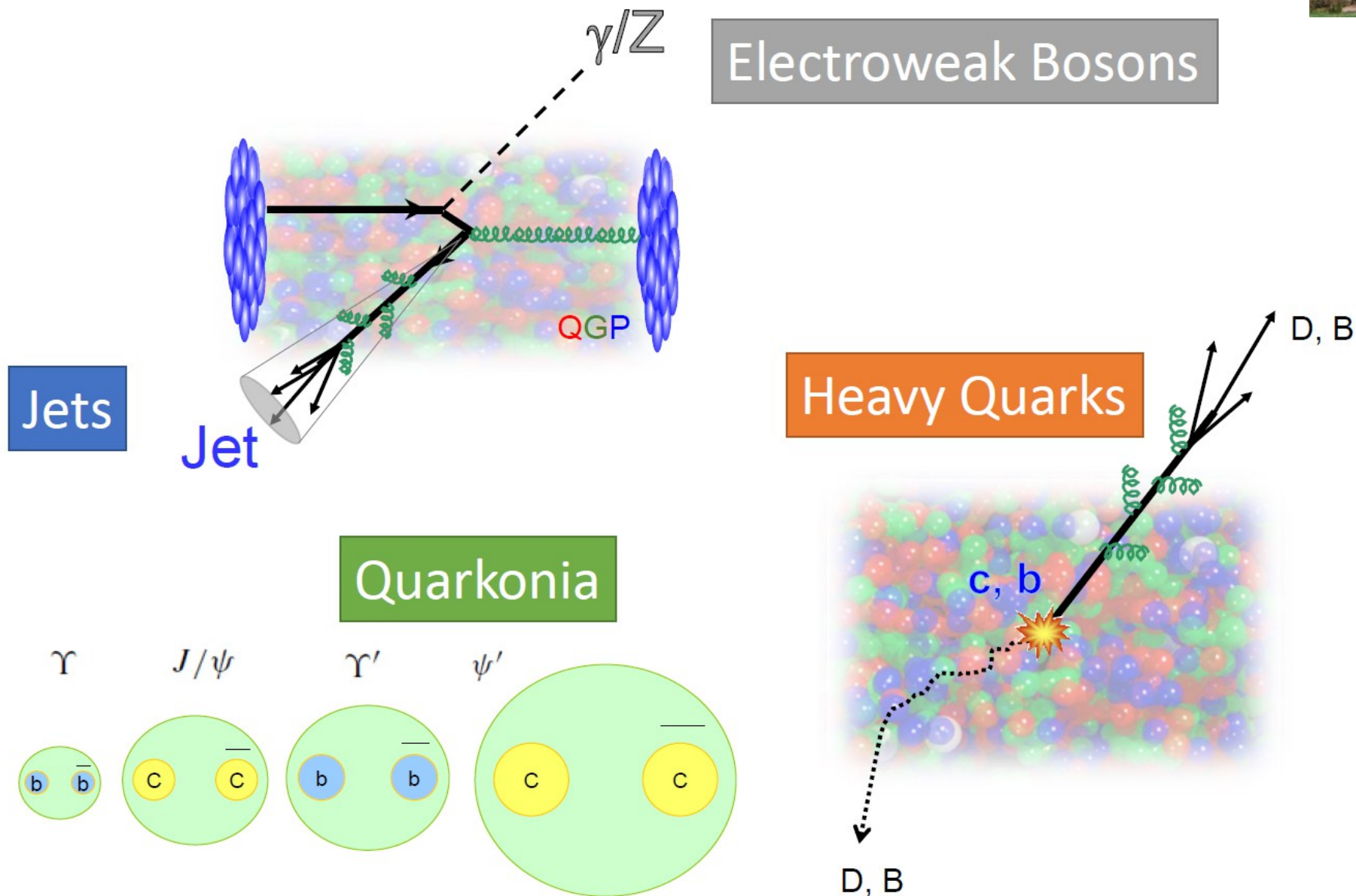


$1.0 < p_T^{\text{ref}} < 3.0 \text{ GeV/c}$

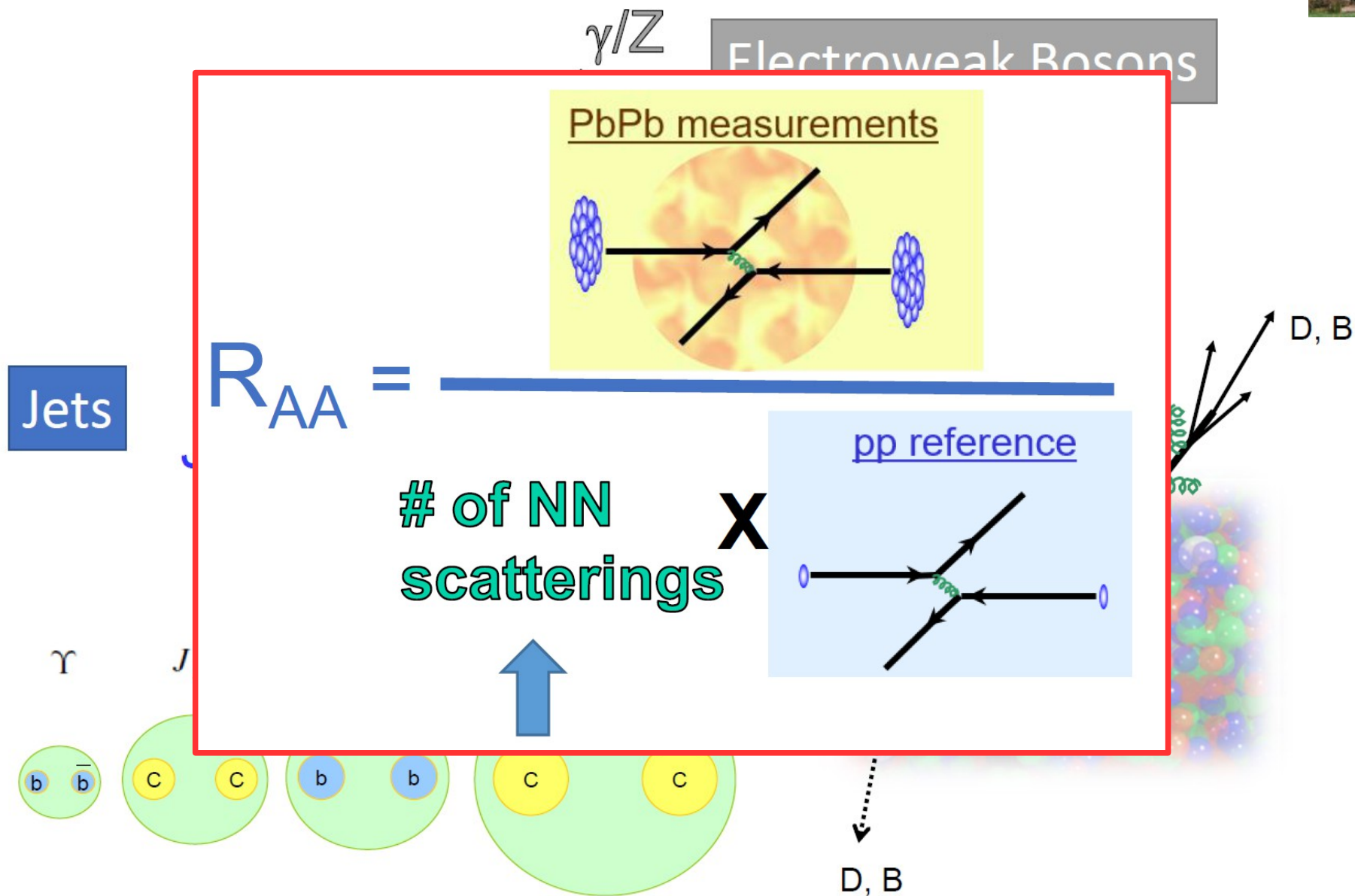


The magnitude of the v_2 coefficients for Xe+Xe collisions are larger than those found in Pb+Pb collisions for the most central collisions. This is attributed to a larger fluctuation component in the lighter colliding system.

Hard Probes for Quark-Gluon Plasma

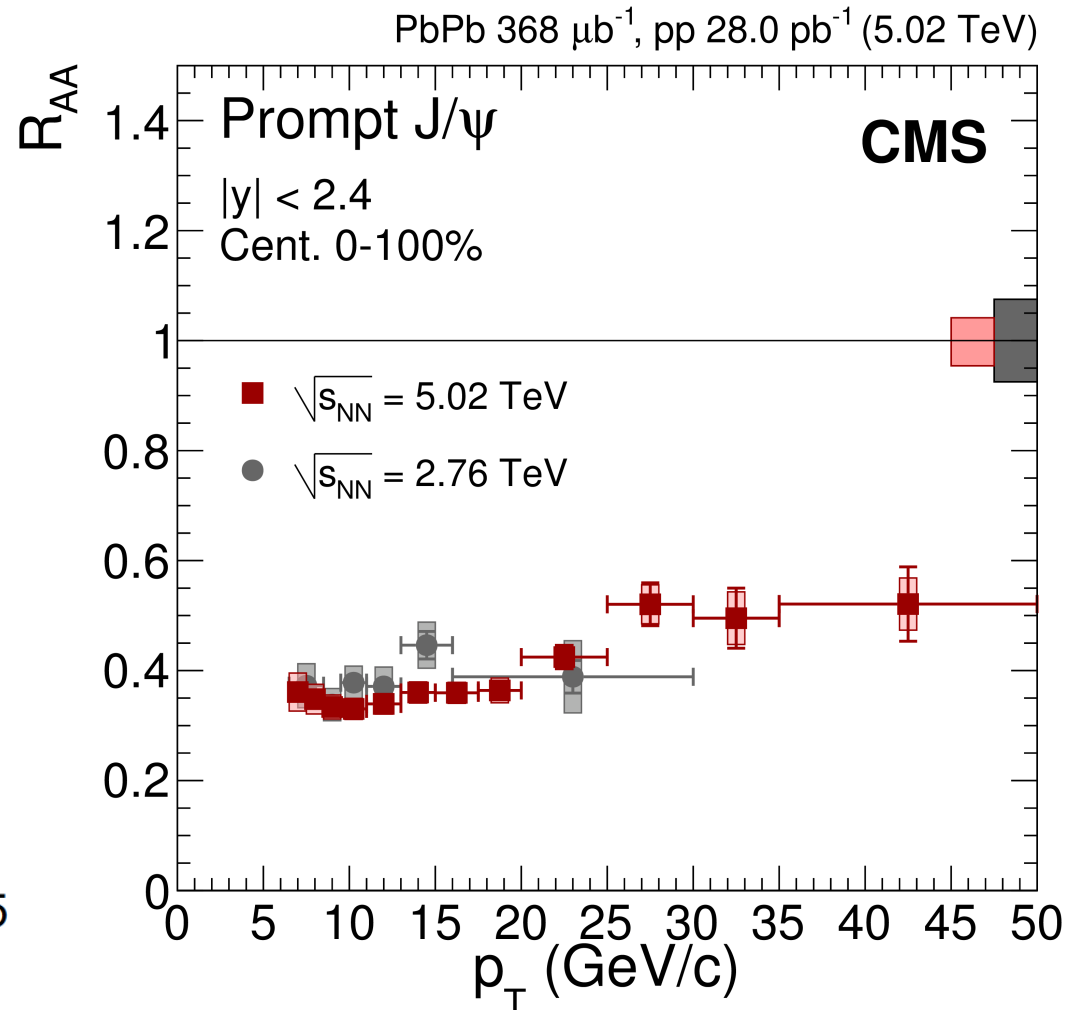
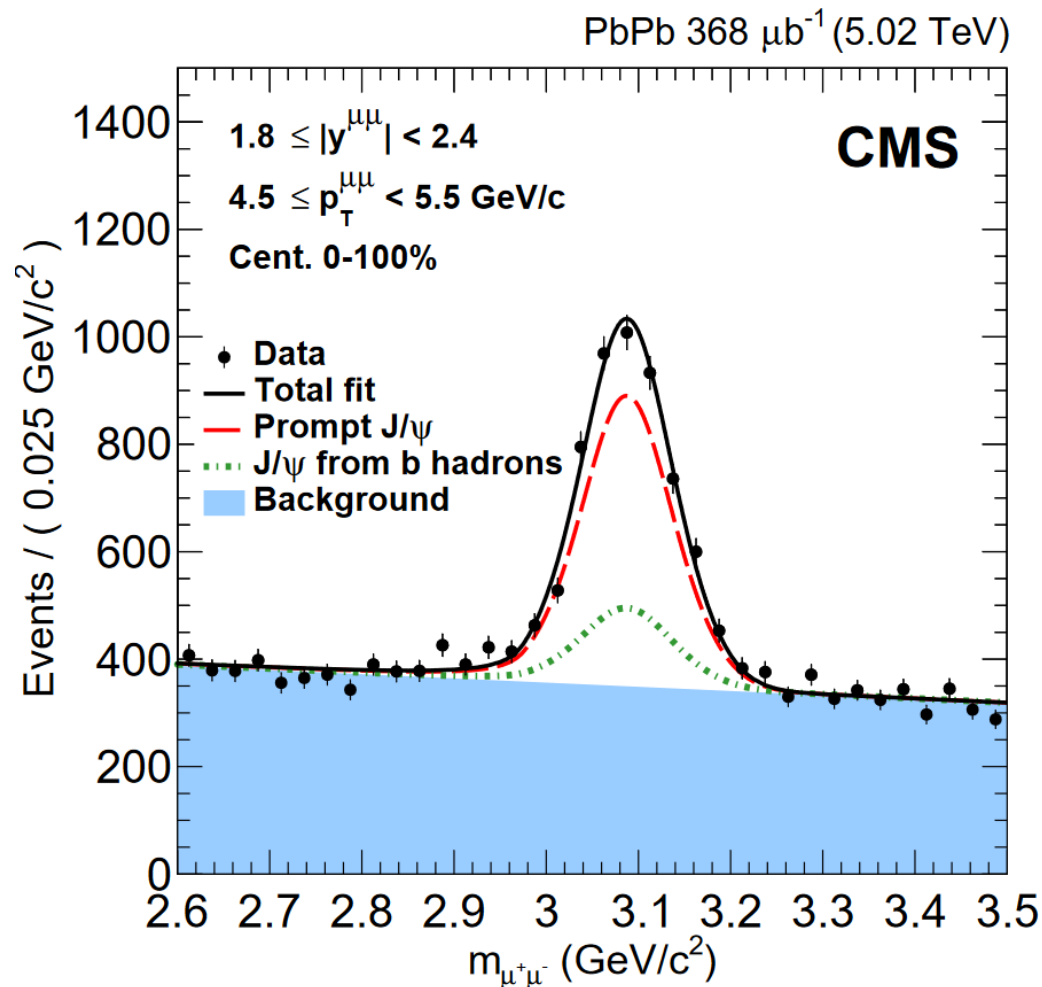


Hard Probes for Quark-Gluon Plasma



J/ψ suppression in Pb+Pb

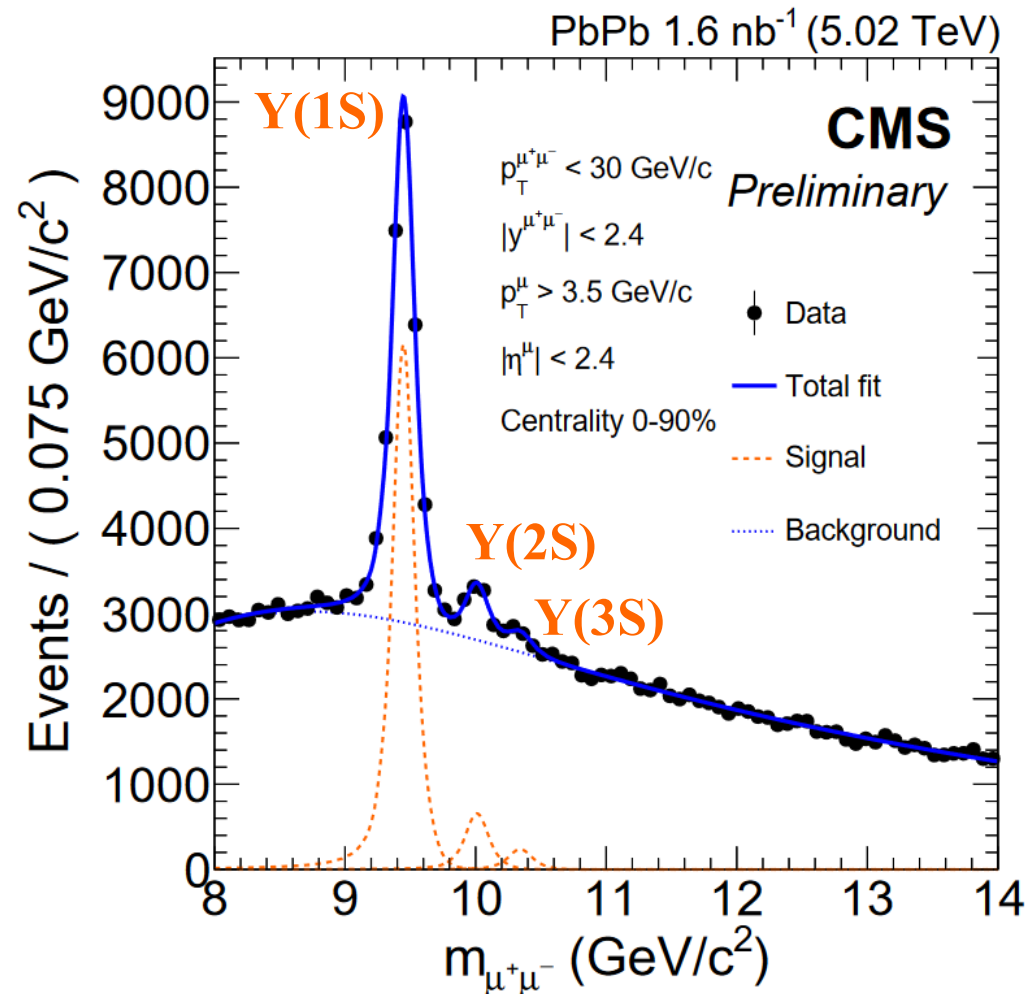
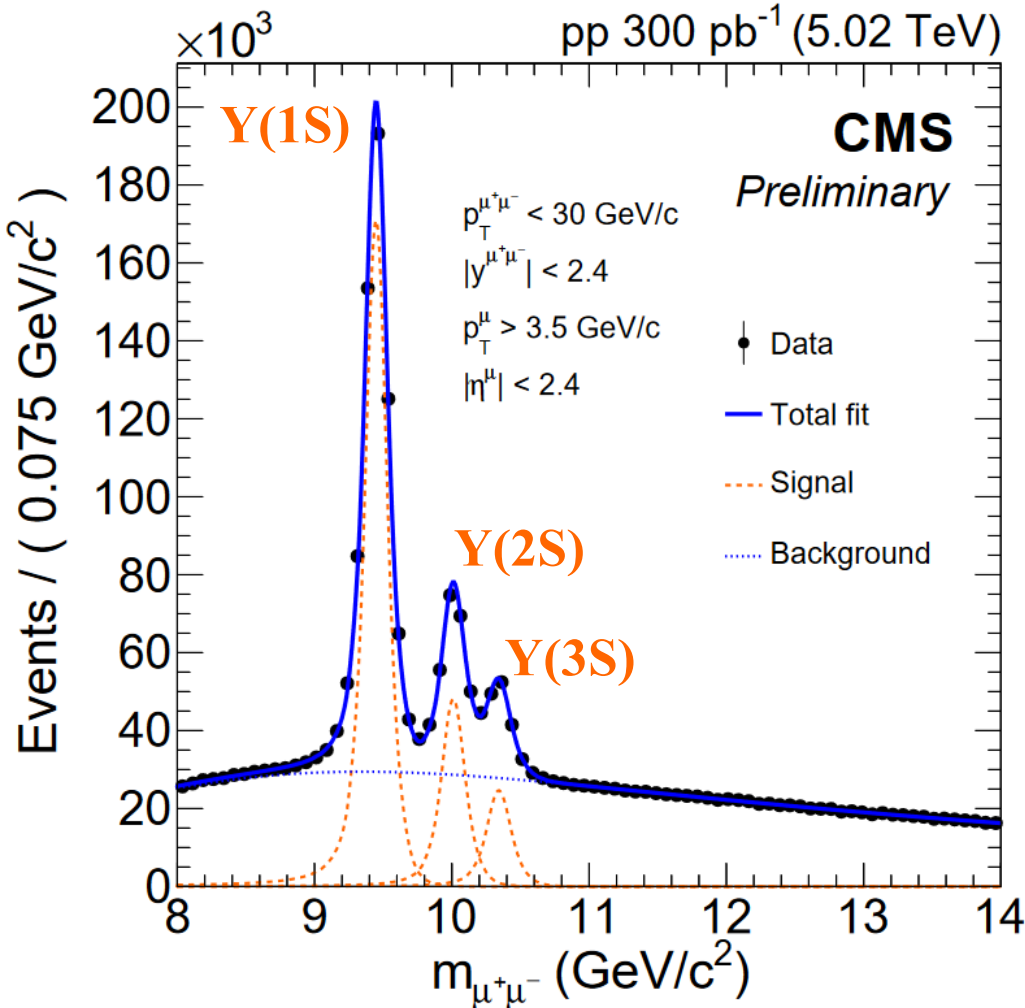
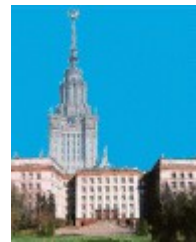
EPJ C 78 (2018) 509



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

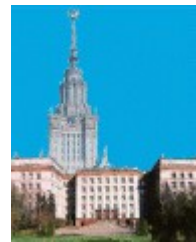
Upsilon suppression in Pb+Pb

CMS-PAS-HIN-21-007

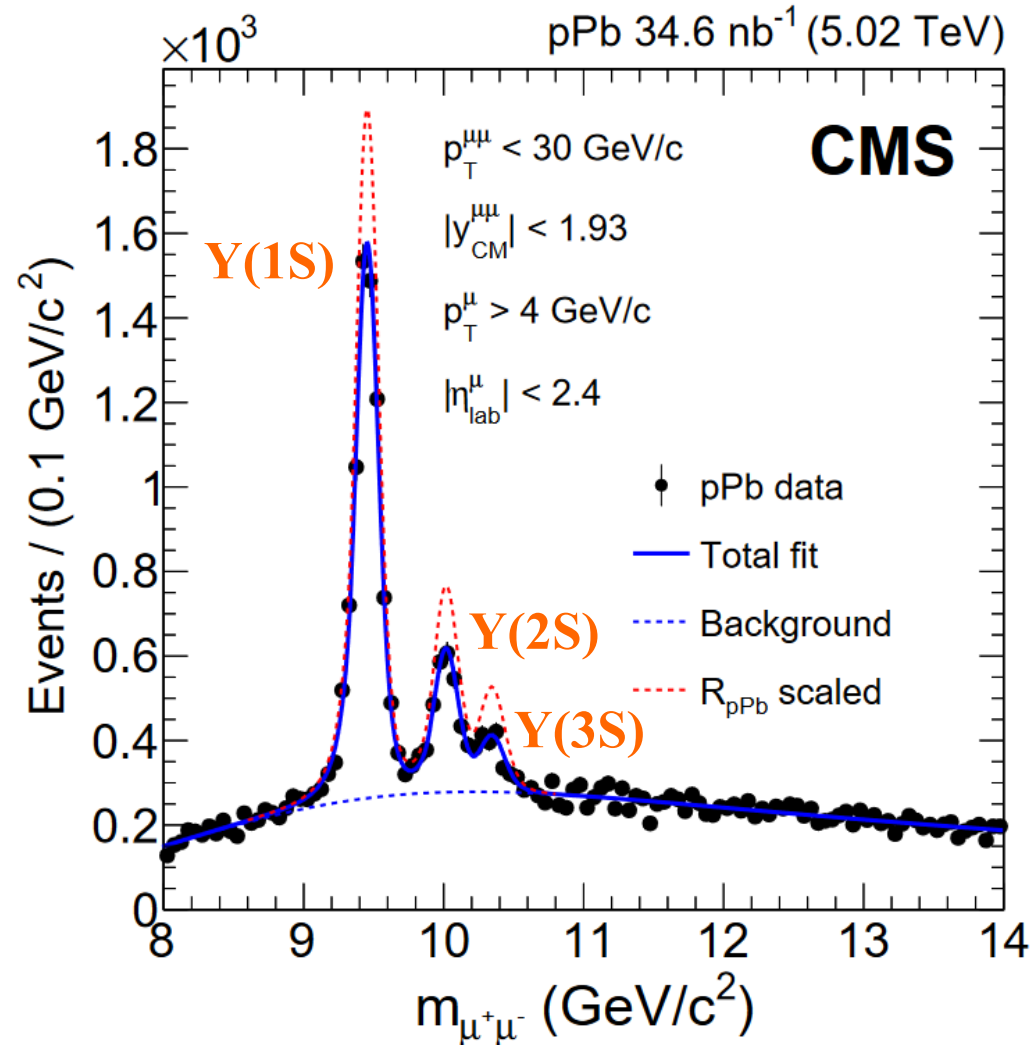
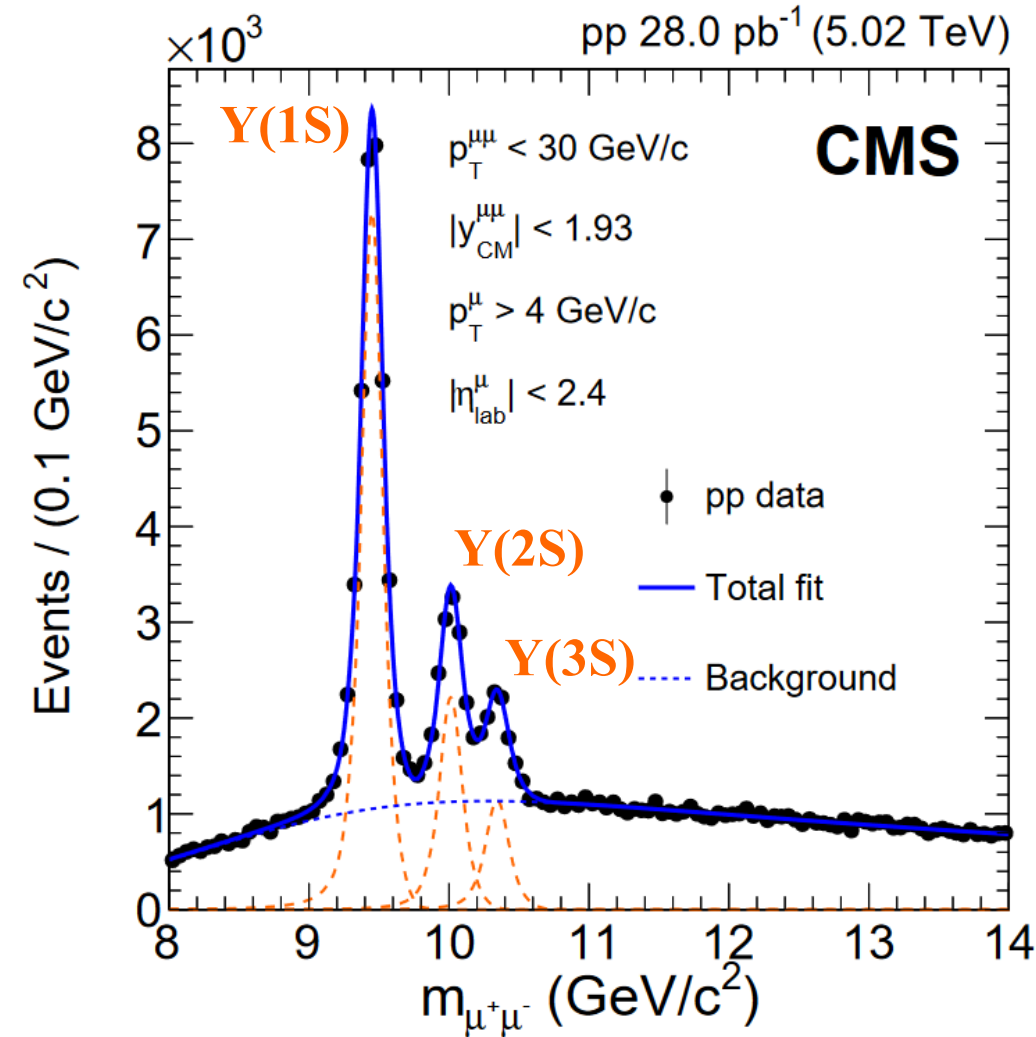


- Observation of sequential suppression of Y family in Pb+Pb.
- First observation of Y(3S) in heavy-ion collisions! ($\sigma > 5$)

Upsilon suppression in p+Pb



PLB 835 (2022) 137397

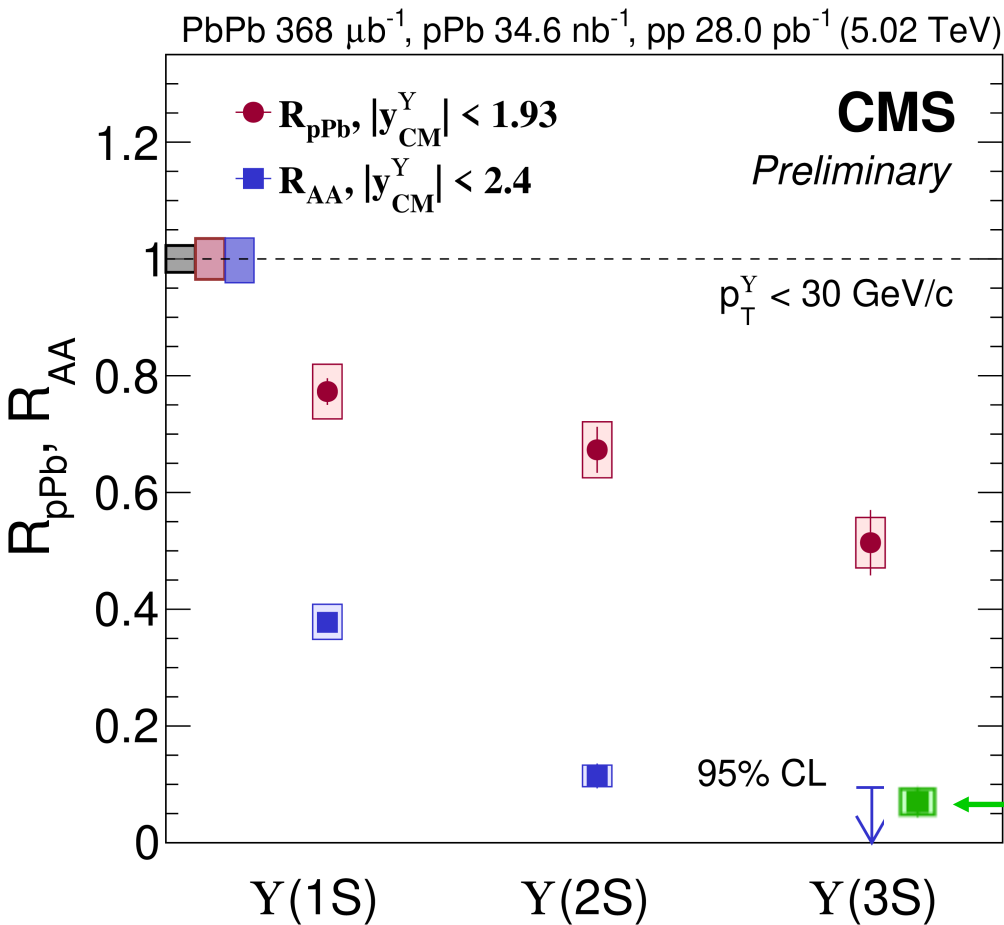


All Y states are found to be suppressed in p+Pb collisions compared to p+p collisions.



Upsilon suppression in p+Pb and Pb+Pb

PLB 835 (2022) 137397 & 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

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

New result for $\Upsilon(3\text{S})$

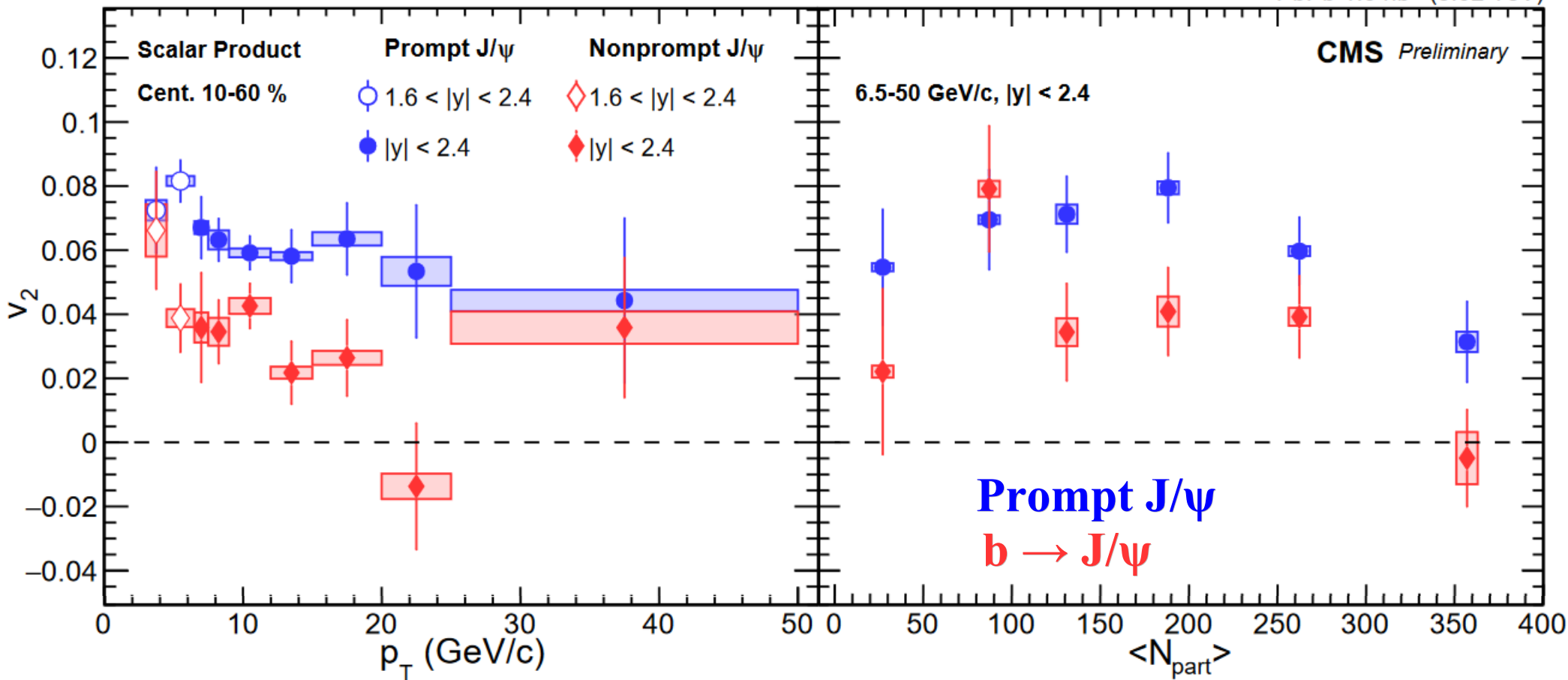


v_2 of J/ψ in Pb+Pb collisions

CMS-PAS-HIN-21-008



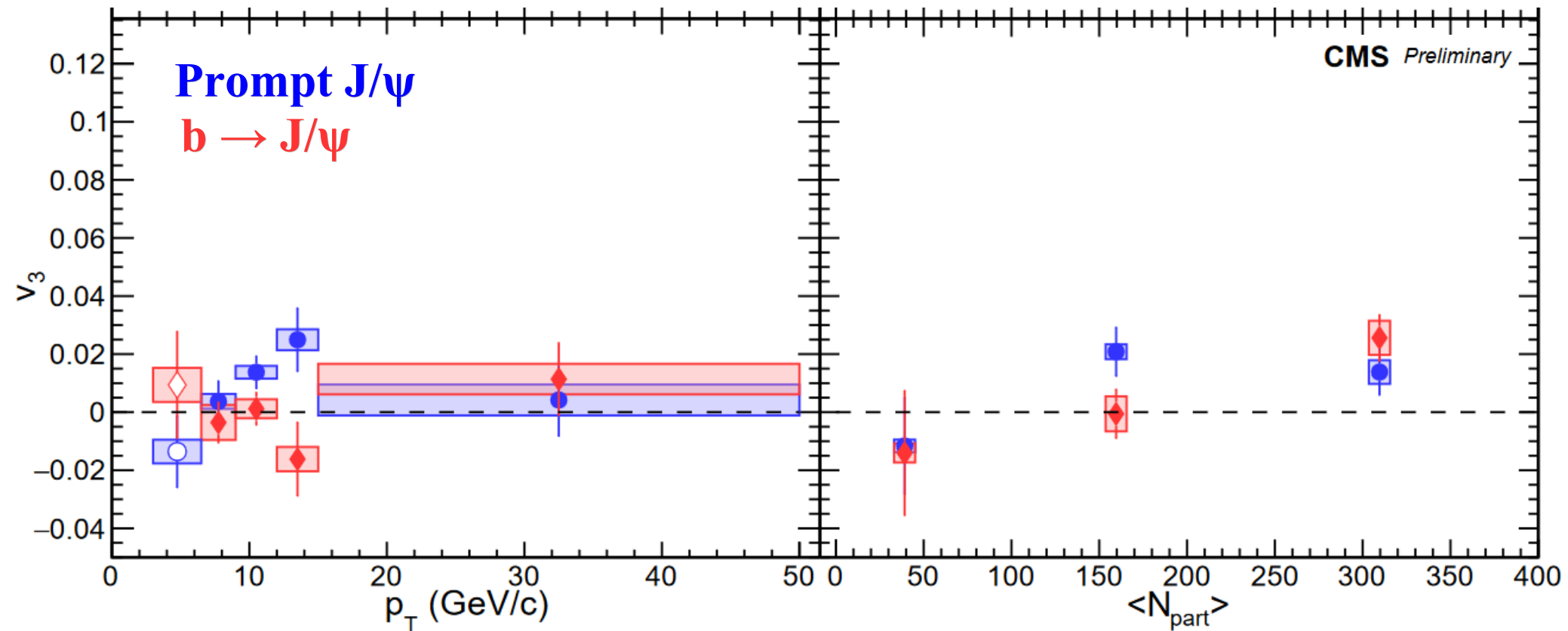
PbPb 1.6 nb⁻¹ (5.02 TeV)



- 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

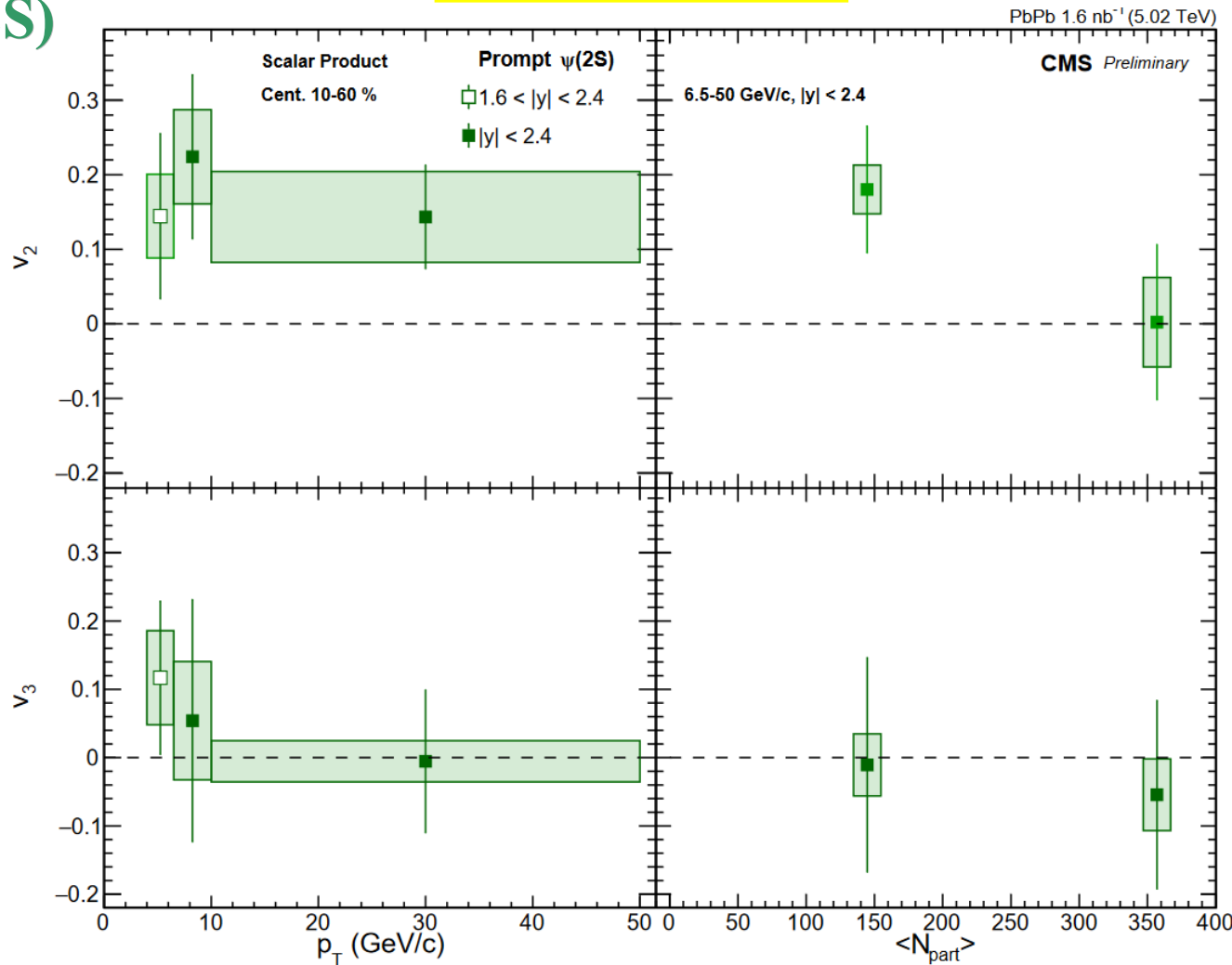


- First measurement of v_3 for prompt and non-prompt J/ψ separately
- no significant non-zero v_3 (J/ψ)

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

CMS-PAS-HIN-21-008

Prompt $\psi(2S)$

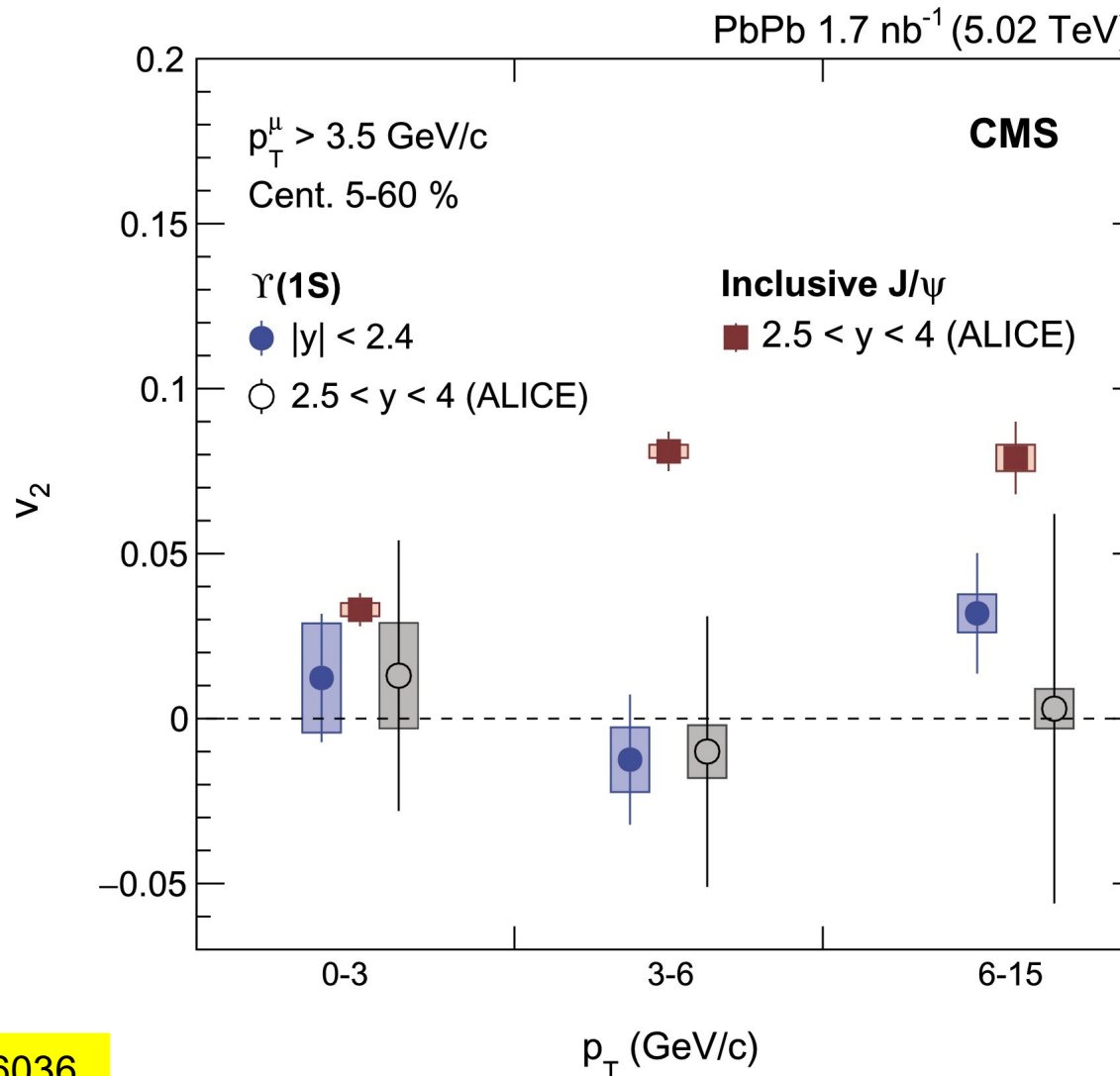


- First measurements for prompt $\psi(2S)$!
- v_2 is non-zero in $p_T = 4 - 50$ GeV/c, v_3 is close to zero

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

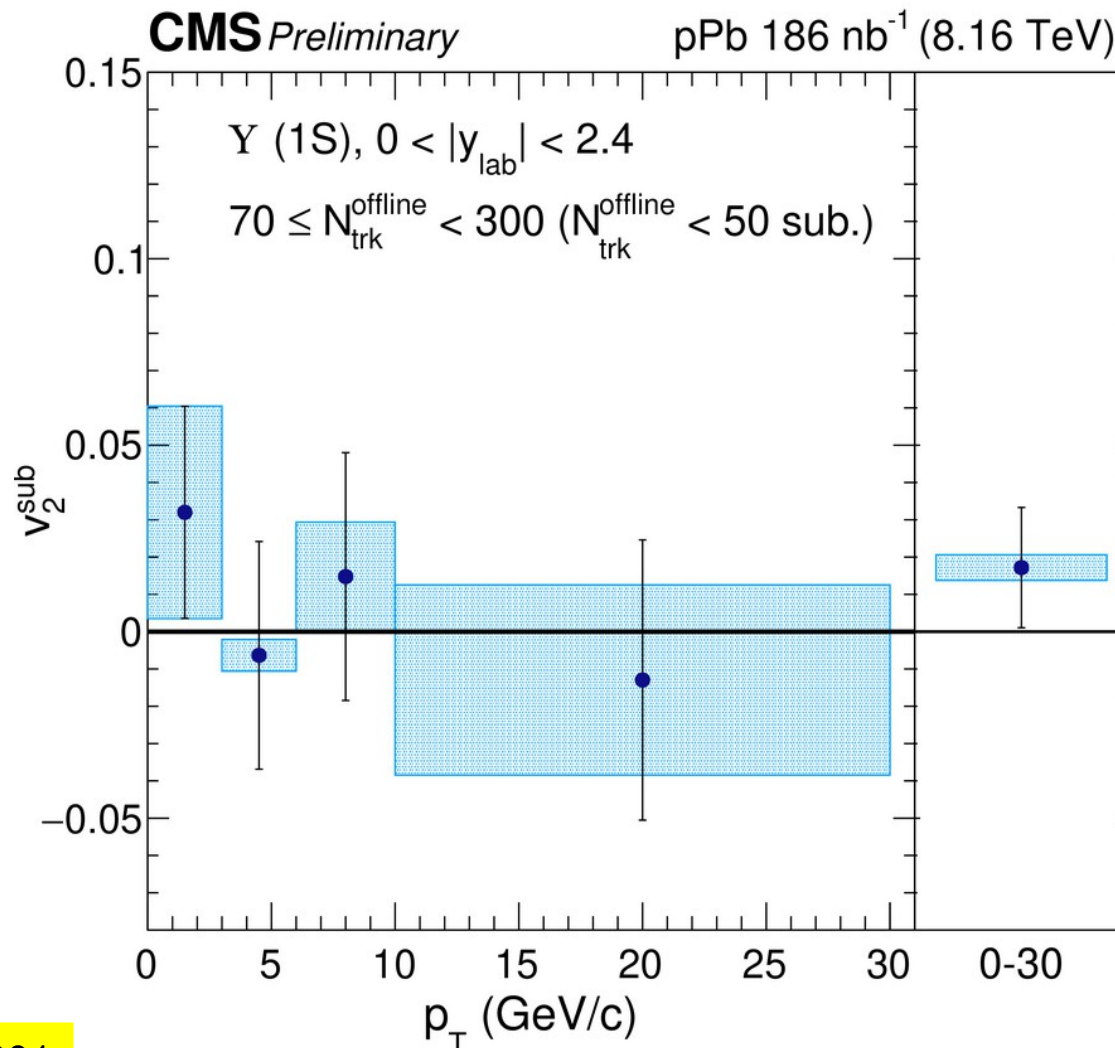
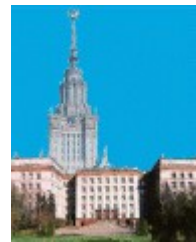


PLB 813 (2021) 136036

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

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

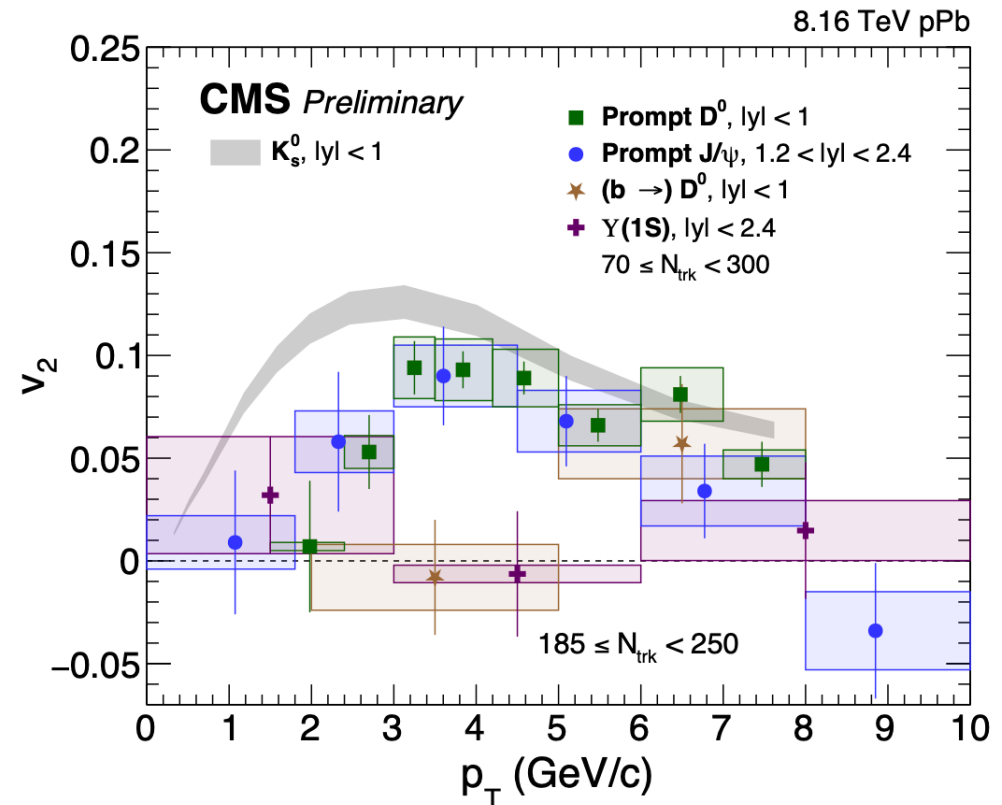
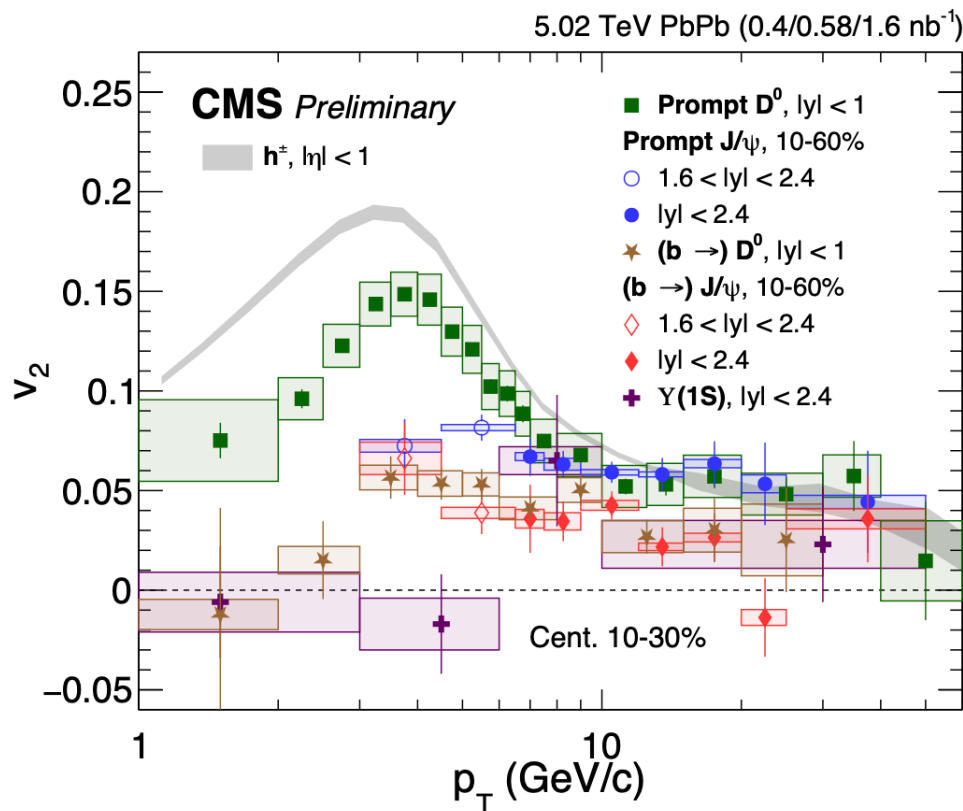
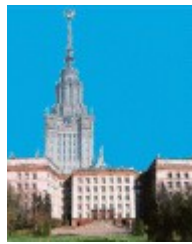


CMS-PAS-HIN-21-001

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

Sergey Petrushanko (CMS Collaboration) Heavy-Ions Results

CMS Heavy Flavor v_2 Zoo

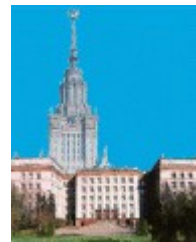


**Abundant physics behind these
high precision and unique measurements from the CMS!**

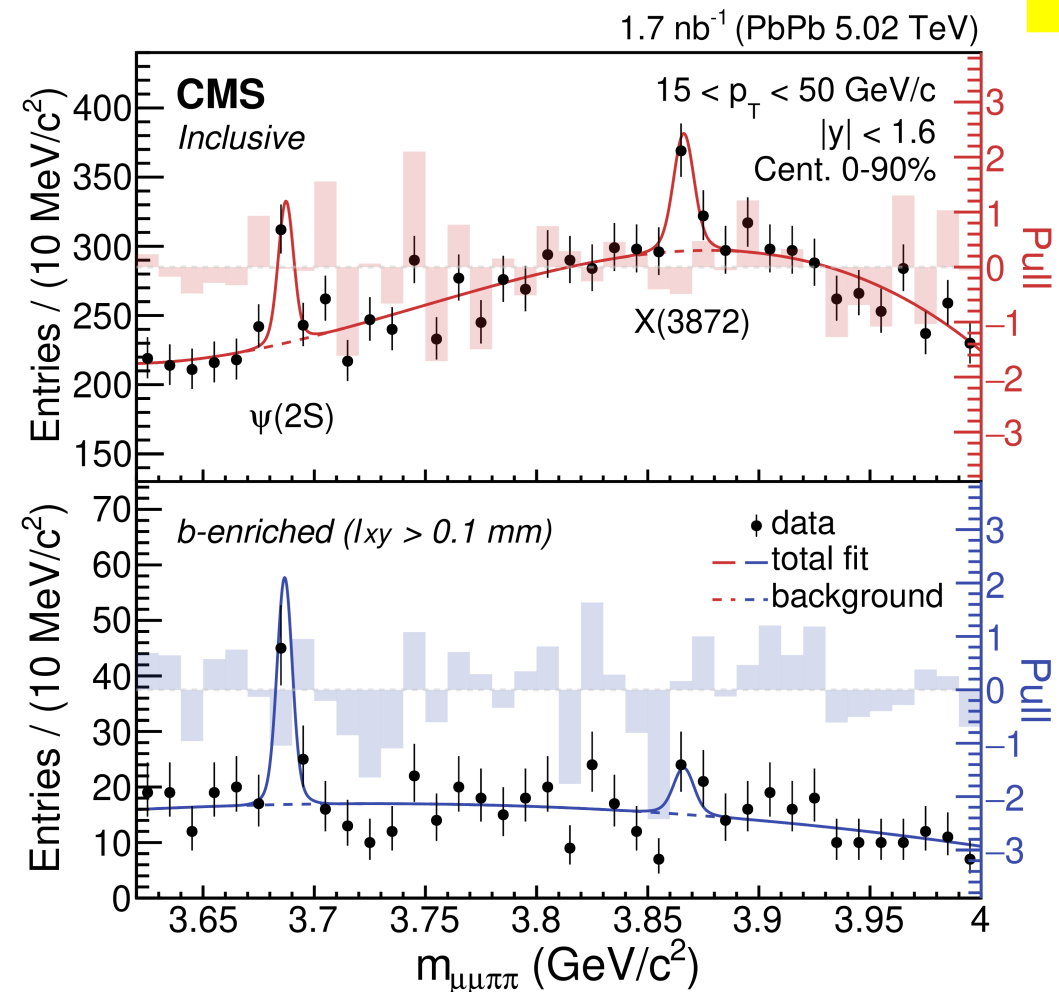
Reference



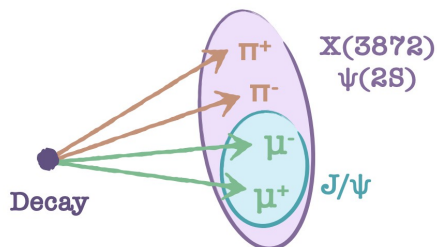
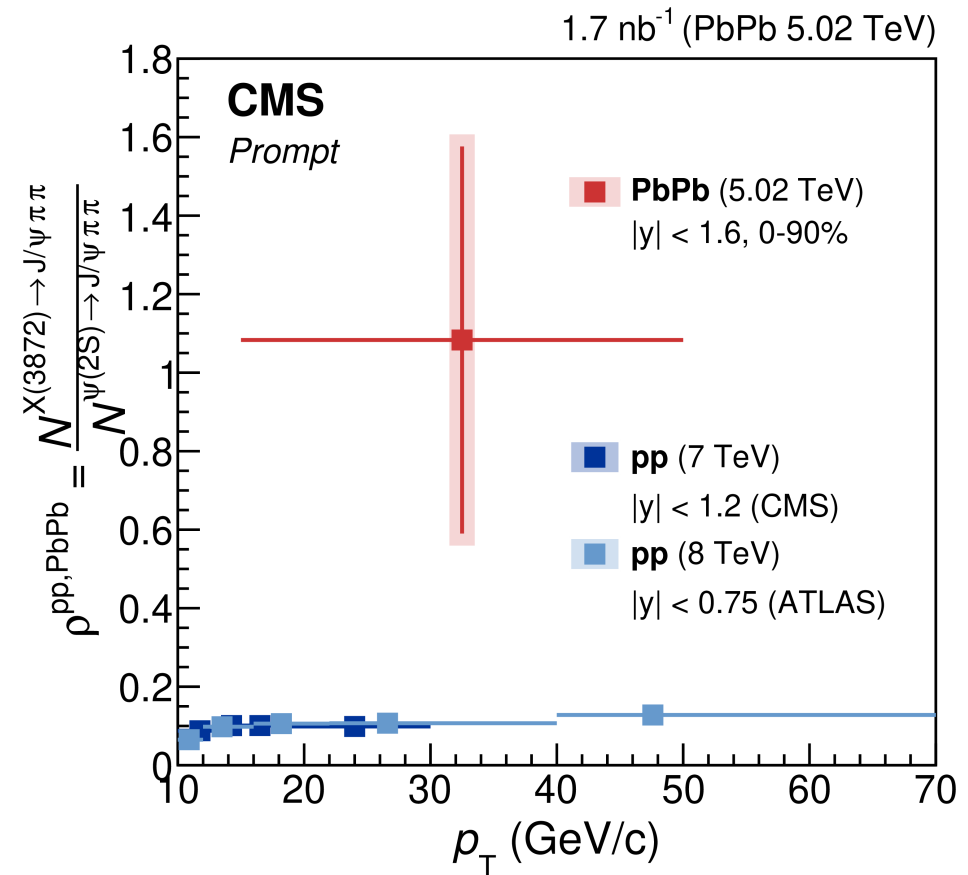
First evidence of X(3872) in Pb+Pb



PRL 128 (2022) 032001



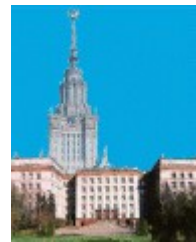
Comparison to ψ(2S)



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

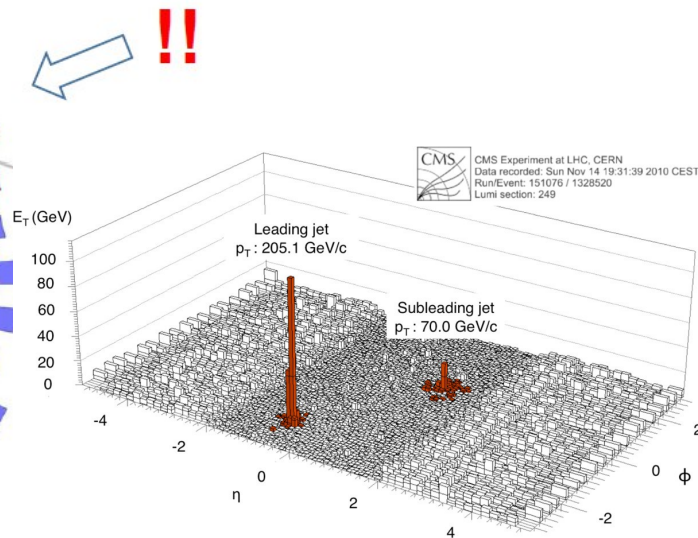
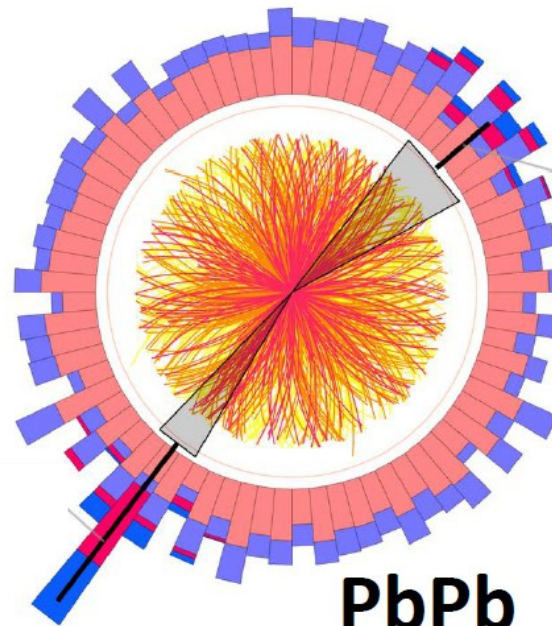
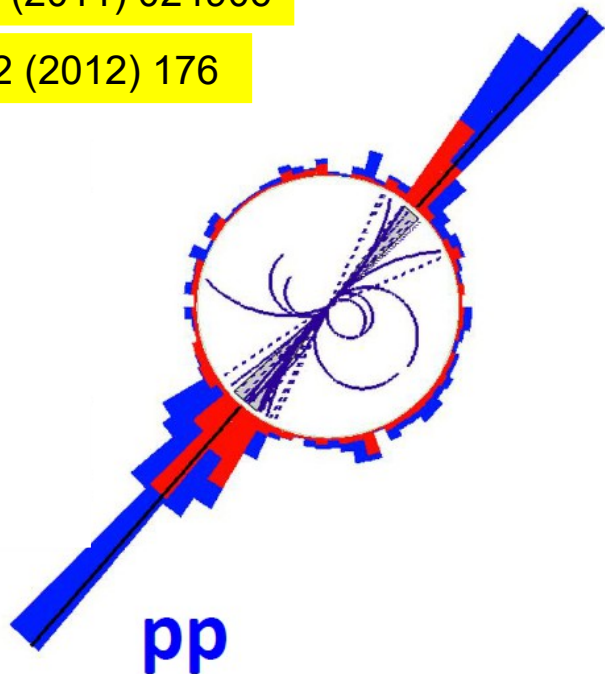


Jet quenching in Pb+Pb

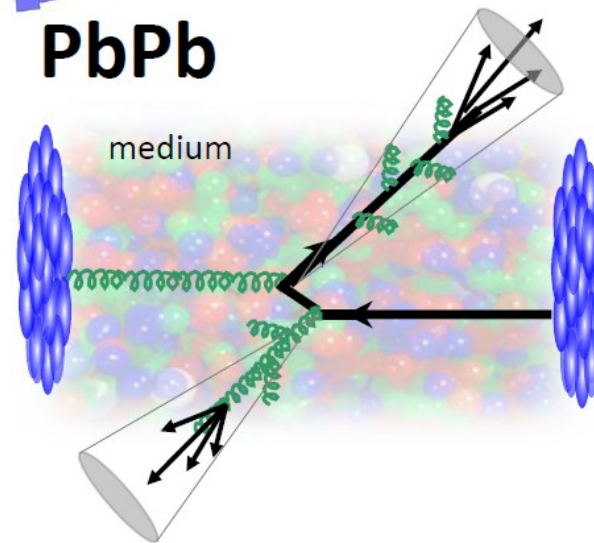


PRC 84 (2011) 024906

PLB 712 (2012) 176

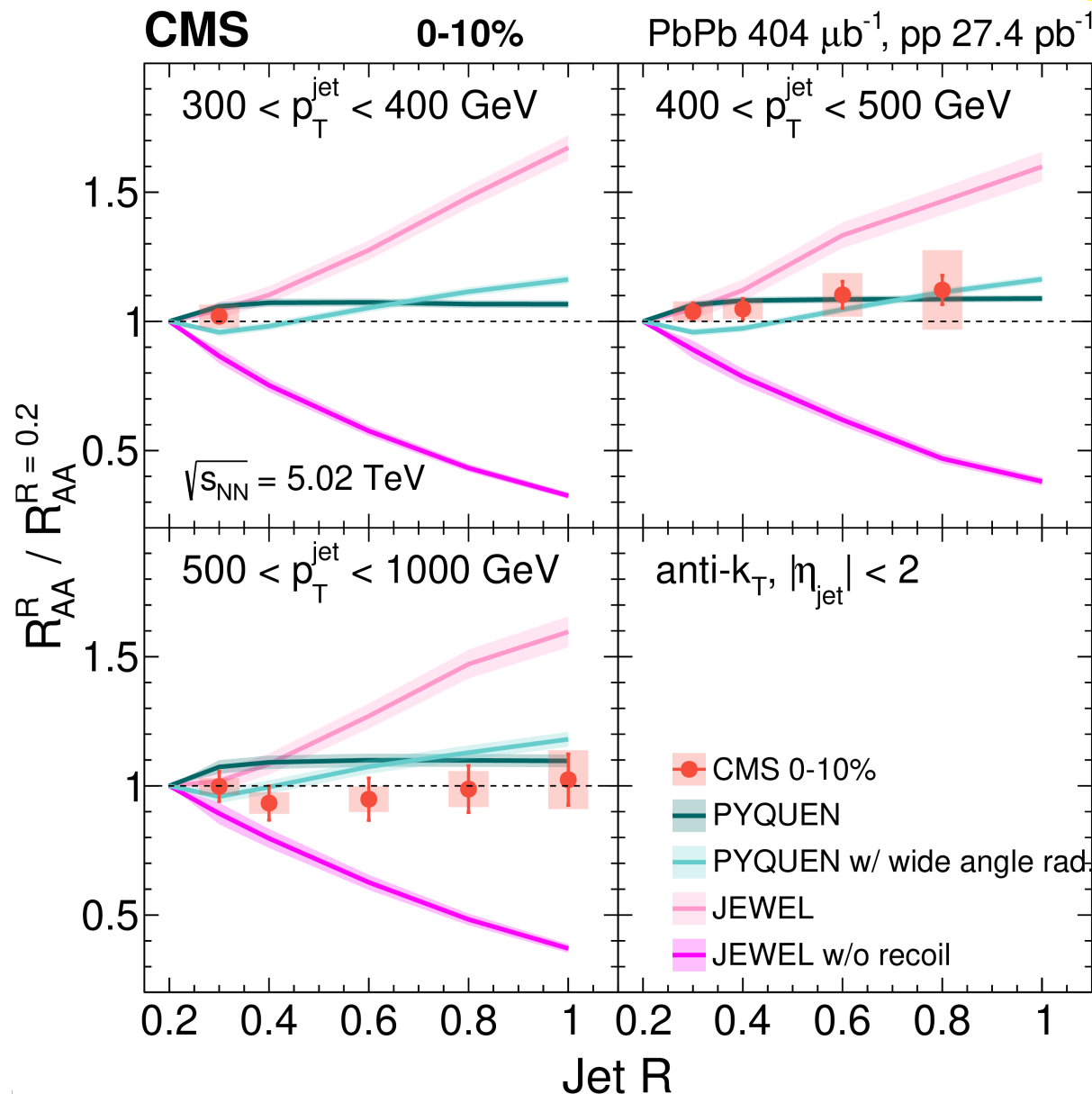


- Asymmetric dijets observed more frequently in PbPb collisions
- The stopping power (dE/dx) of the Quark Soup is **Incredibly Strong**



Jet radius scan

JHEP 05 (2021) 284



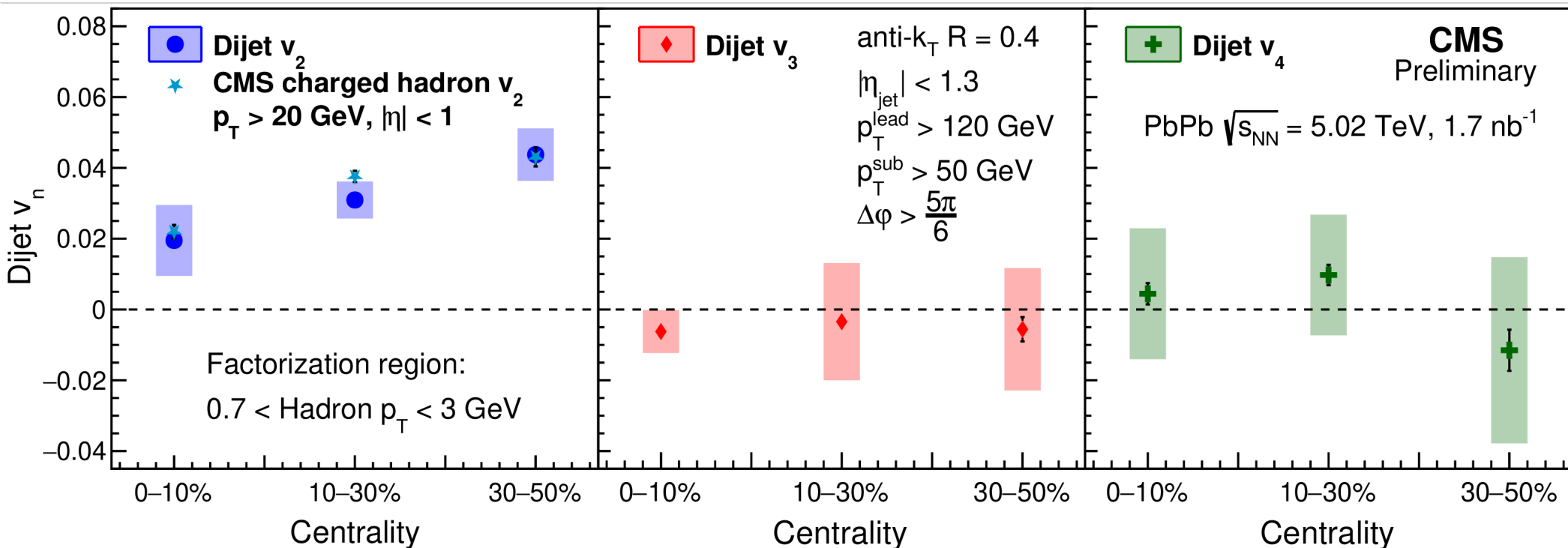
- Sensitive to balance between increasing radiative sources and recovering re-distributed energy

- Enables simultaneous comparisons of model calculations across jet radii

- First time at CMS: no radius dependence of jet energy loss in central Pb+Pb collisions for $400 \text{ GeV} < p_T^{\text{jet}}$. (Also for $400 < p_T^{\text{jet}} < 500 \text{ GeV}$)

Azimuthal anisotropy of di-jets in Pb+Pb

arXiv:2210.08325

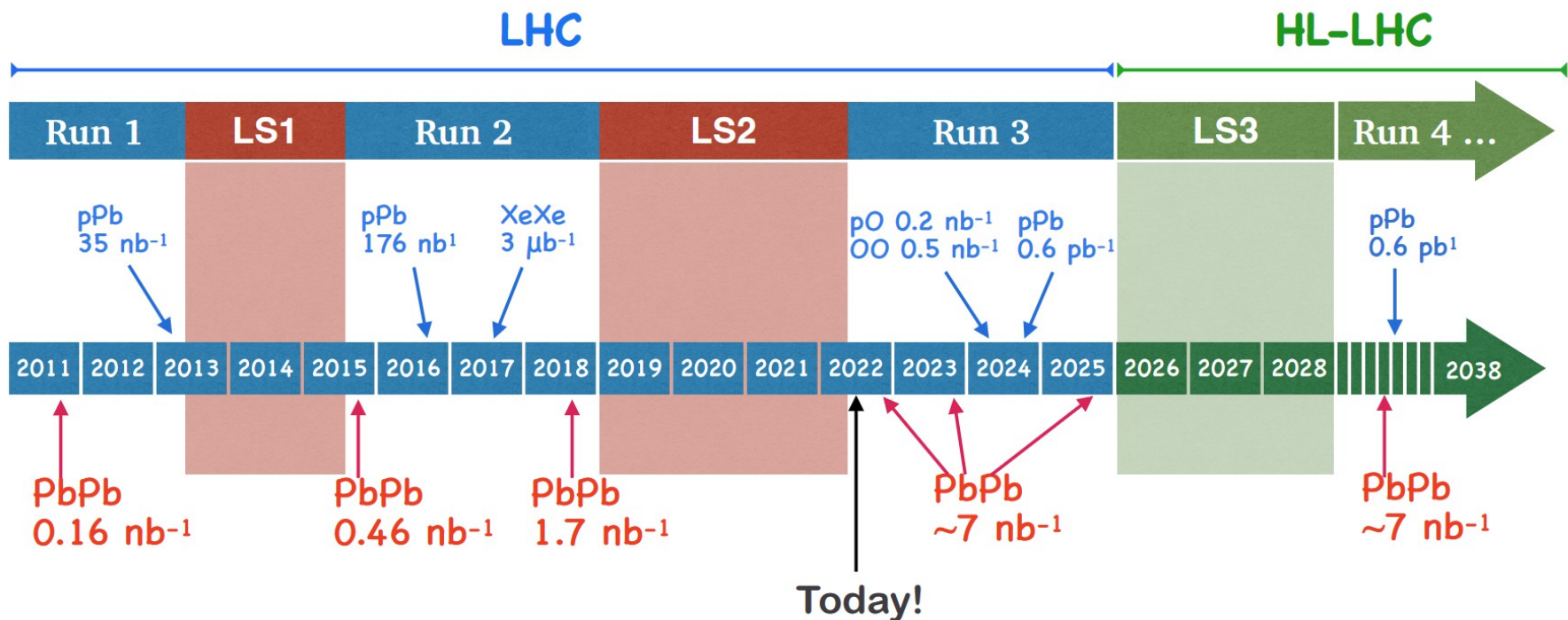


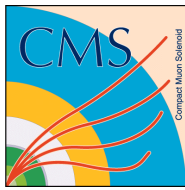
- v_2, v_3, v_4 of the di-jets in Pb+Pb were measured for the first time
- Di-jets v_2 is compatible with v_2 of high pt hadrons
- Di-jets v_3 and v_4 are consistent with zero

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!





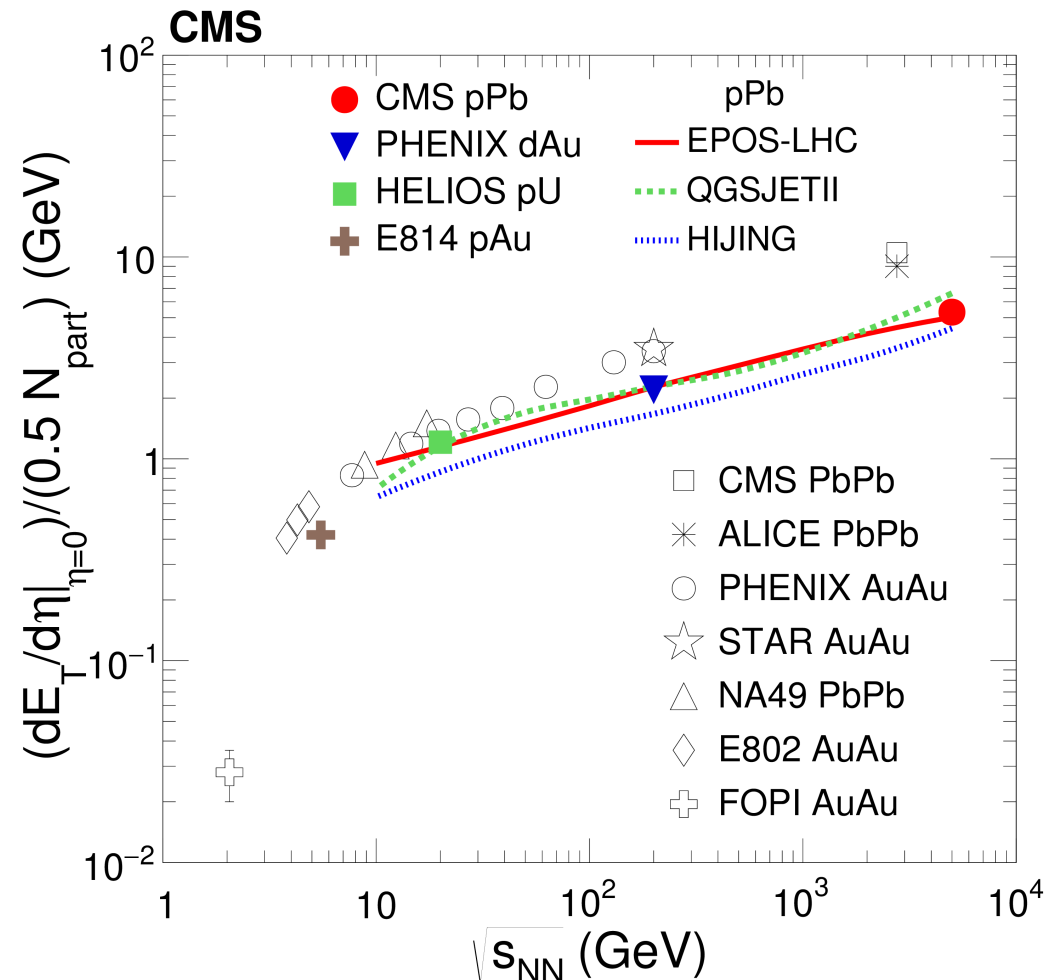
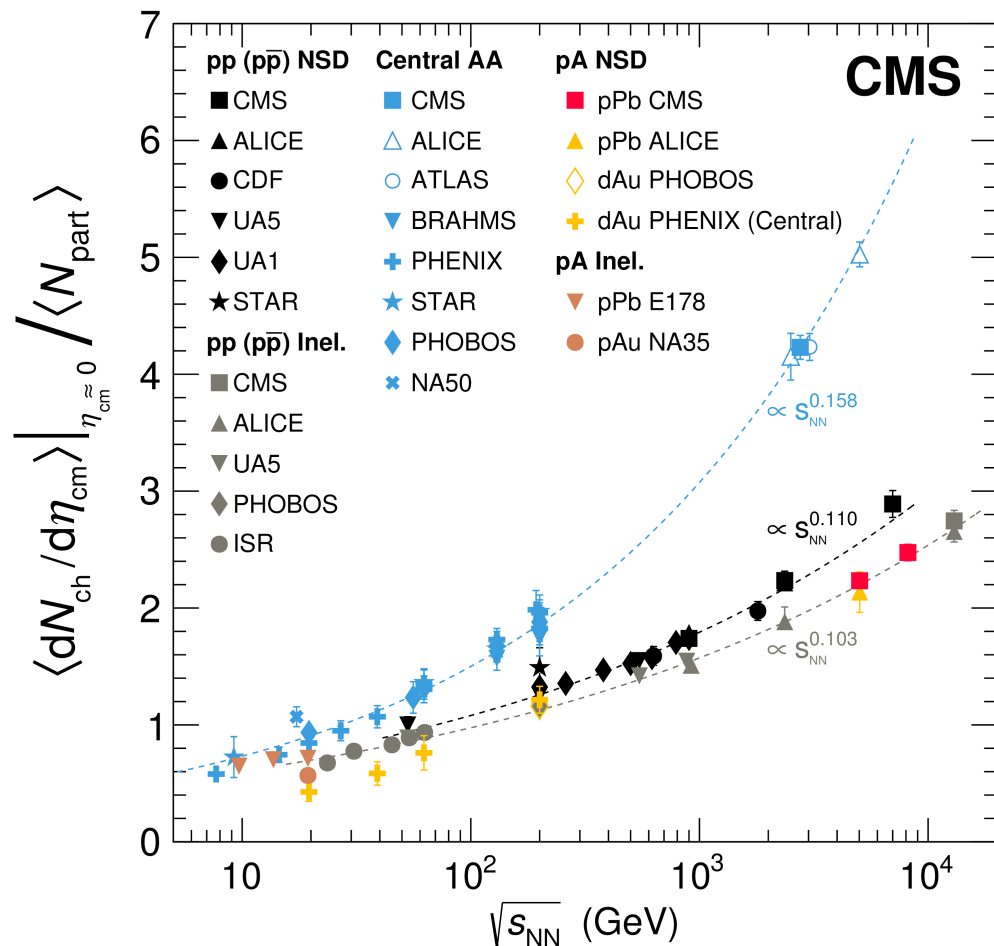
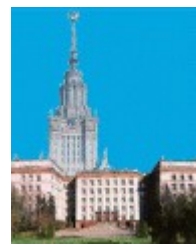
BACK UP



Sergey Petrushanko (CMS Collaboration) Heavy-Ions Results



Charged particle multiplicity Transverse energy density



JHEP 01 (2018) 045

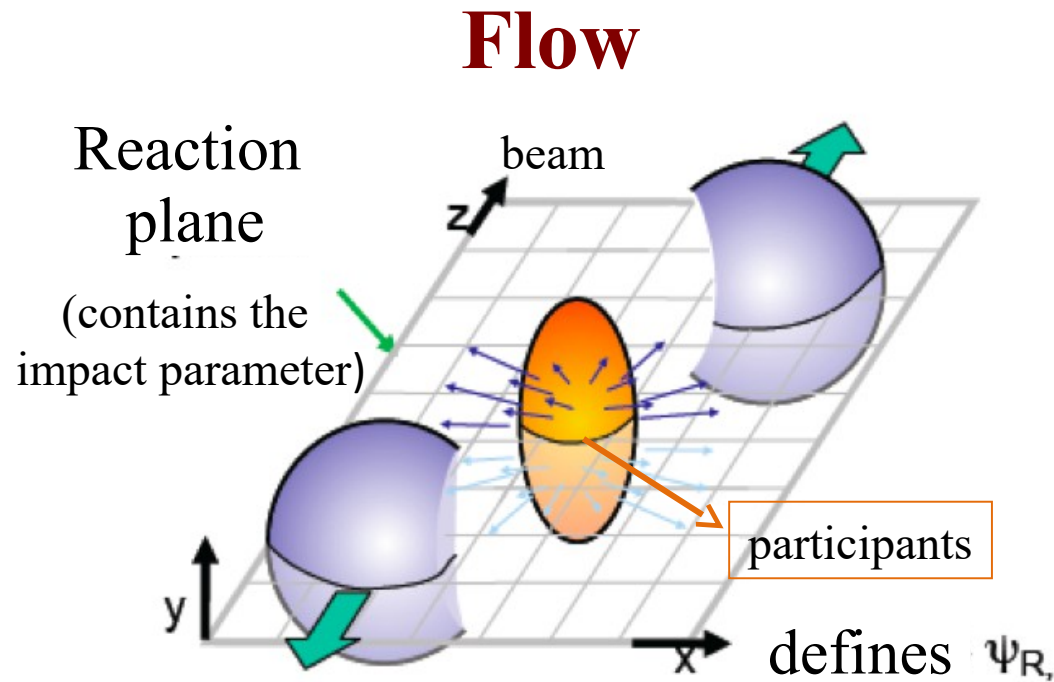
• \sqrt{s} dependence:

• p+p, p+Pb, Pb+Pb follow power law

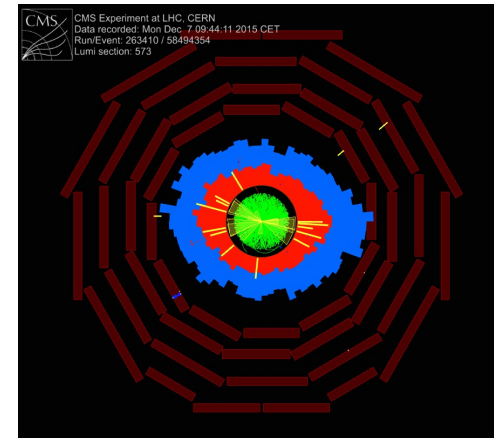
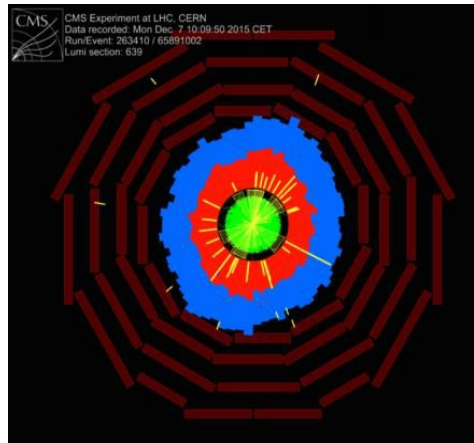
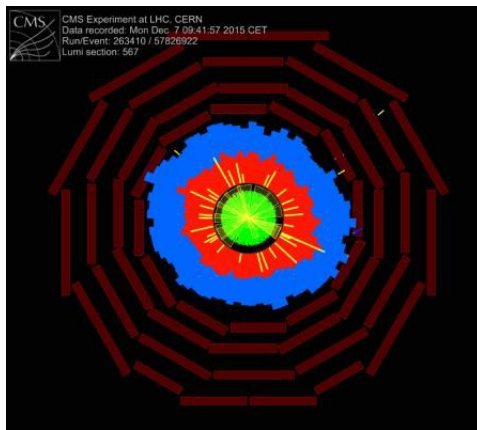
PRC 100 (2019) 024902

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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

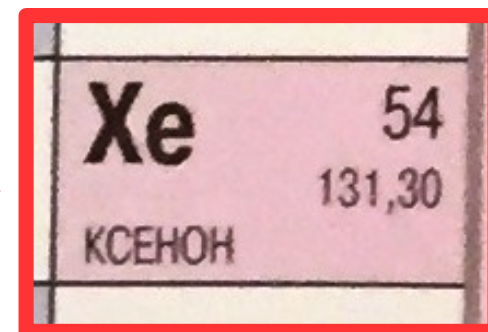
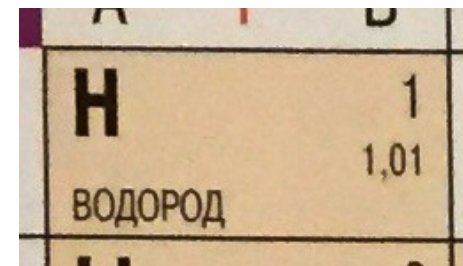
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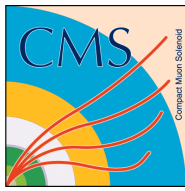
Xe+Xe as a “bridge” between p and Pb



ПЕРИОДИЧЕСКАЯ СИСТЕМА ЭЛЕМЕНТОВ Д. И. МЕНДЕЛЕЕВА

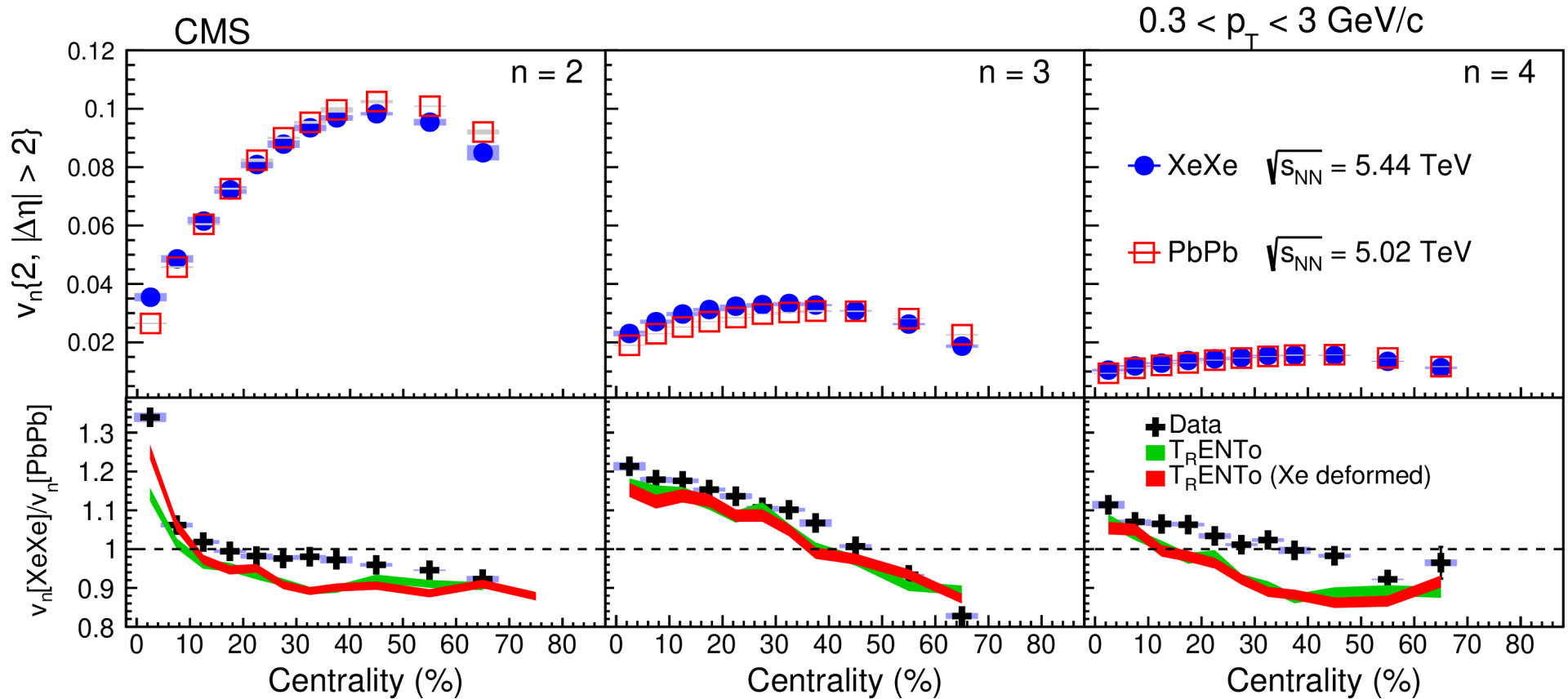
ПЕРИОДЫ	РЯДЫ	ГРУППЫ ЭЛЕМЕНТОВ																
		A I B	A II B	A III B	A IV B	A V B	A VI B	A VII B	VIII				A					
1	1	H 1 ВОДОРОД															(H)	 <div>МЕНДЕЛЕЕВ Дмитрий Иванович (8.11.1834–2.11.1907) Русский ученый-энциклопедист. В 1869–1871 гг. изложил основы учения о периодичности, открыл периодический закон и разработал периодическую систему химических элементов. На основе системы впервые предсказал (1870) существование и свойства нескольких еще не открытых элементов.</div> He 4 ГЕЛИЙ
2	2	Li 3 ЛИТИЙ	Be 4 БЕРИЛЛИЙ	B 5 БОР	C 6 УГЛЕРОД	N 7 АЗОТ	O 8 КИСЛОРОД	F 9 ФТОР					Ne 10 НЕОН					
3	3	Na 11 НАТРИЙ	Mg 12 МАГНИЙ	Al 13 АЛЮМИНИЙ	Si 14 КРЕМНИЙ	P 15 ФОСФОР	S 16 СЕРА	Cl 17 ХЛОР					Ar 18 АРГОН					
4	4	K 19 КАЛИЙ	Ca 20 КАЛЬЦИЙ	Sc 21 СКАНДИЙ	Ti 22 ТИТАН	V 23 ВАНАДИЙ	Cr 24 ХРОМ	Mn 25 МАРГАНЕЦ	Fe 26 ЖЕЛЕЗО	Co 27 КОБАЛЬТ	Ni 28 НИКЕЛЬ							
	5	Cu 29 МЕДЬ	Zn 30 ЦИНК	Ga 31 ГАЛЛИЙ	Ge 32 ГЕРМАНИЙ	As 33 МЫШЬЯК	Se 34 СЕЛЕН	Br 35 БРОМ					Kr 36 КРИПТОН					
5	6	Rb 37 РУБИДИЙ	Sr 38 СТРОНЦИЙ	Y 39 ИТРИЙ	Zr 40 ЦИРКОНИЙ	Nb 41 НИОБИЙ	Mo 42 МОЛИБДЕН	Tc 43 ТЕХНЕЦИЙ	Ru 44 РУТЕНИЙ	Rh 45 РОДИЙ	Pd 46 ПАЛЛАДИЙ							
	7	Ag 47 СЕРЕБРО	Cd 48 КАДМИЙ	In 49 ИНДИЙ	Sn 50 ОЛОВО	Sb 51 СВУРМА	Te 52 ТЕЛЛУР	I 53 ЙОД					Xe 54 КСЕНОН					
6	8	Cs 55 ЦЕЗИЙ	Ba 56 БАРИЙ	La* 57 ЛАНТАН	Hf 72 ГАФНИЙ	Ta 73 ТАНТАЛ	W 74 ВОЛЬФРАМ	Re 75 РЕНИЙ	Os 76 ОСМИЙ	Ir 77 ИРИДИЙ	Pt 78 ПЛАТИНА							
	9	Au 79 ЗОЛОТО	Hg 80 РУТУТЬ	Tl 81 ТАЛЛИЙ	Pb 82 СВИНЕЦ	Bi 83 ВИСМУТ	Po 84 ПОЛОНИЙ	At 85 АСТАТ					Rn 86 РАДОН					
7	10	Fr 87 ФРАНЦИЙ	Ra 88 РАДИЙ	Ac** 89 АКТИНИЙ	Rf 104 РЕЗЕРФОРДИЙ	Db 105 ДУБНИЙ	Sg 106 СГБЕРГИЙ	Bh 107 БОРИЙ	Hs 108 ГАСИЙ	Mt 109 МЕЙТТЕРИЙ	Ds 110 ДАРМШТАДТИЙ							
ВЫСШИЕ ОКСИДЫ		R ₂ O	RO	R ₂ O ₃	RO ₂	R ₂ O ₅	RO ₃	R ₂ O ₇					RO ₄					
ЛЕТУЧИЕ ВОДОРОДНЫЕ СОЕДИНЕНИЯ					RH ₄	RH ₃	H ₂ R	HR										
*ЛАНТАНОИДЫ		Ce 58 ЦЕРИЙ	Pr 59 ПРАЗЕОДИМ	Nd 60 НЕОДИМ	Pm 61 ПРОМЕТИЙ	Sm 62 САМАРИЙ	Eu 63 ЕВРОПИЙ	Gd 64 ГАДОЛИНИЙ	Tb 65 ТЕРБИЙ	Dy 66 ДИСПРОЗИЙ	Ho 67 ГОЛЬМИЙ	Er 68 ЭРБИЙ	Tm 69 ТУЛИЙ	Yb 70 ИТТЕРБИЙ	Lu 71 ЛУТЕЦИЙ			
**АКТИНОИДЫ		Th 90 ТОРИЙ	Pa 91 ПРОТАКТИНИЙ	U 92 УРАН	Np 93 НЕПТУНИЙ	Pu 94 ПУТОНИЙ	Am 95 АМЕРИЦИЙ	Cm 96 КУРИЙ	Bk 97 БЕРКЛИЙ	Cf 98 КАЛИФОРНИЙ	Es 99 ЭЙНШТЕЙНИЙ	Fm 100 ФЕРМИЙ	Md 101 МЕНДЕЛЕВИЙ	No 102 НОБЕЛИЙ	Lr 103 ЛОУРЕНСИЙ			
РЯД АКТИВНОСТИ МЕТАЛЛОВ		Li Cs Rb K Ba Sr Ca Na Mg Be Al Mn Zn Cr Fe Cd Co Ni Sn Pb H ₂ Cu Hg Ag Pt Au																
РЯД НАПРЯЖЕНИЙ МЕТАЛЛОВ		Li Rb K Ba Sr Ca Na Mg Al Mn Zn Cr Fe Cd Co Ni Sn Pb H ₂ Sb Cu Hg Ag Pt Au																





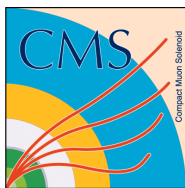
$v_{2,3,4}$ Xe+Xe vs. Pb+Pb

PRC 100 (2019) 044902



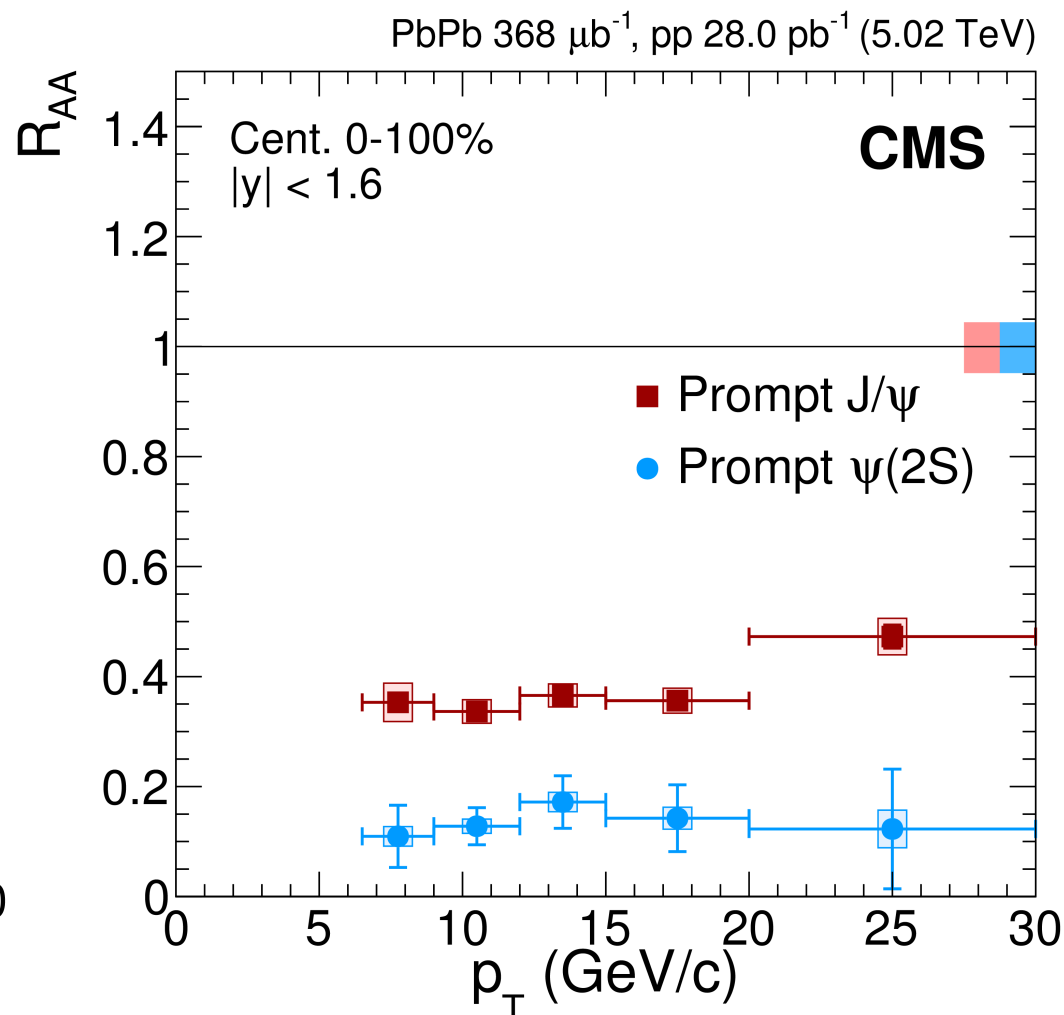
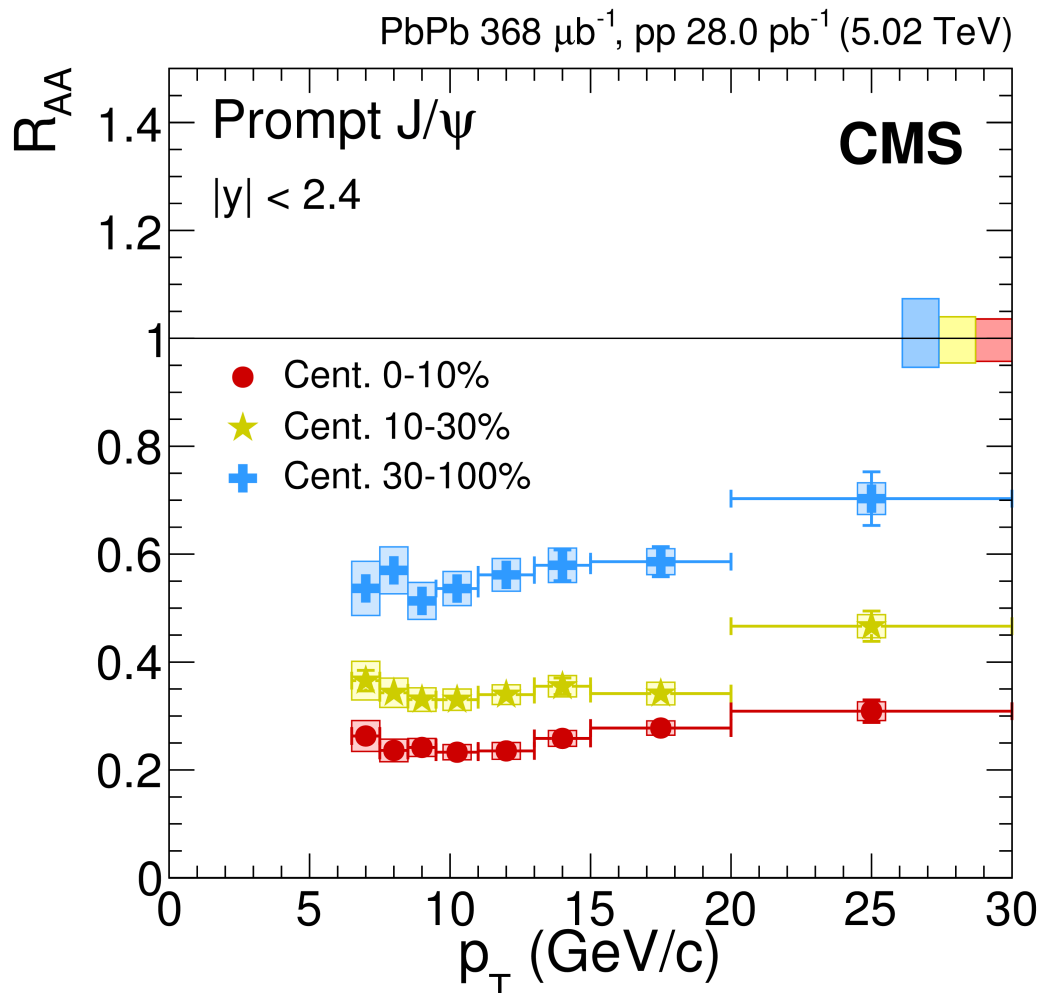
Hydrodynamic models that consider the Xe nuclear deformation are able to better describe the $v_2[\text{XeXe}]/v_2[\text{PbPb}]$ ratio in central collisions than those assuming a spherical Xe shape.





J/ ψ and $\psi(2S)$ suppression in Pb+Pb

EPJ C 78 (2018) 509



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

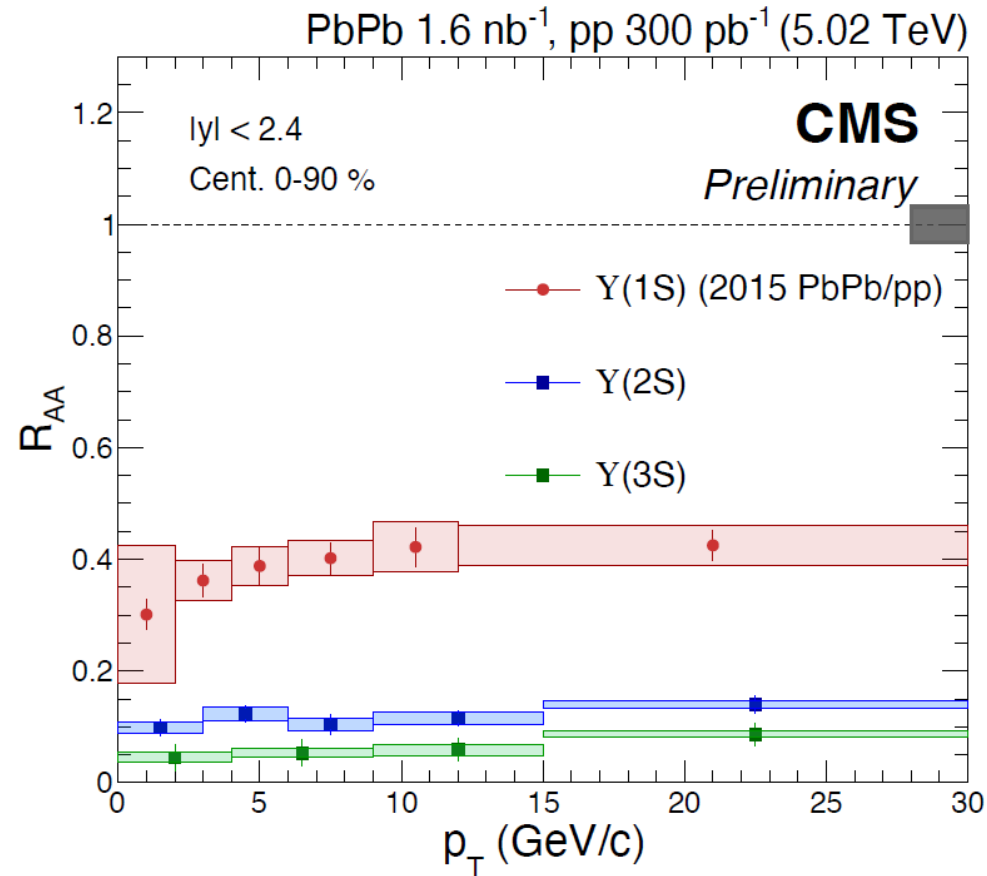
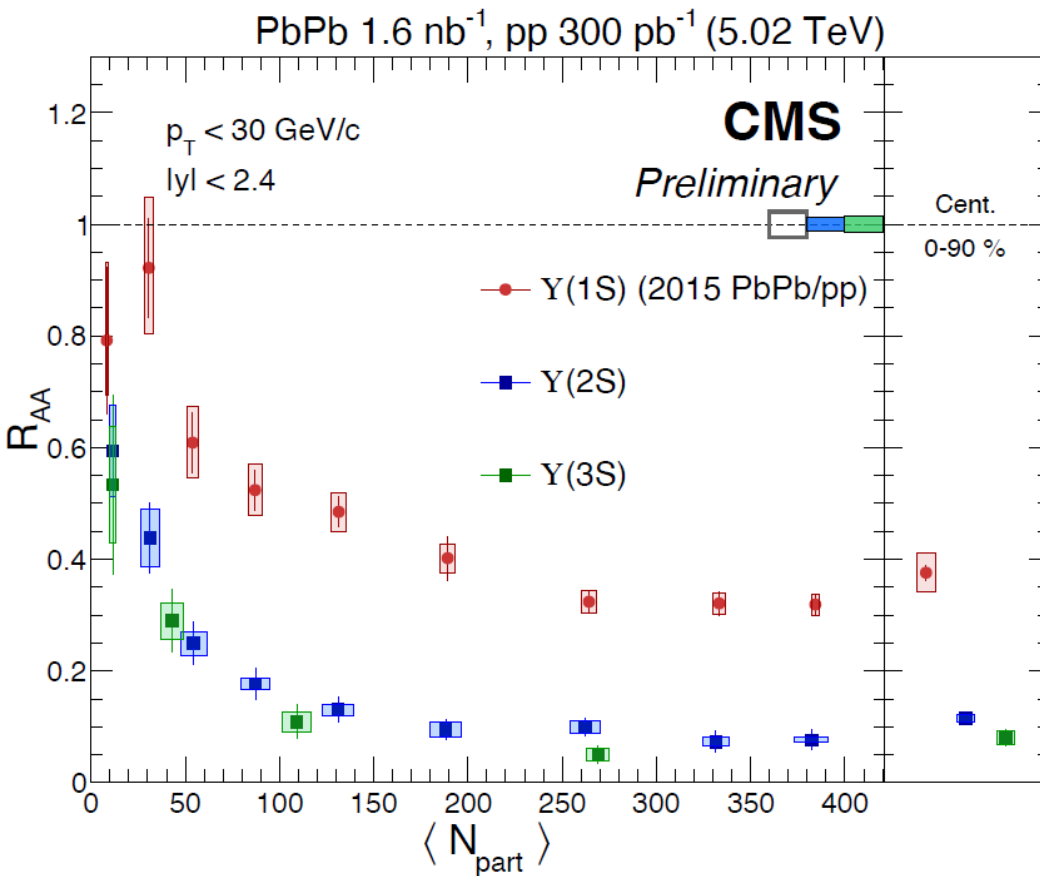
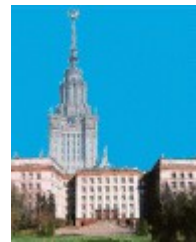
Sergey Petrushanko (CMS Collaboration) Heavy-Ions Results





Upsilon suppression Pb+Pb

CMS-PAS-HIN-21-007



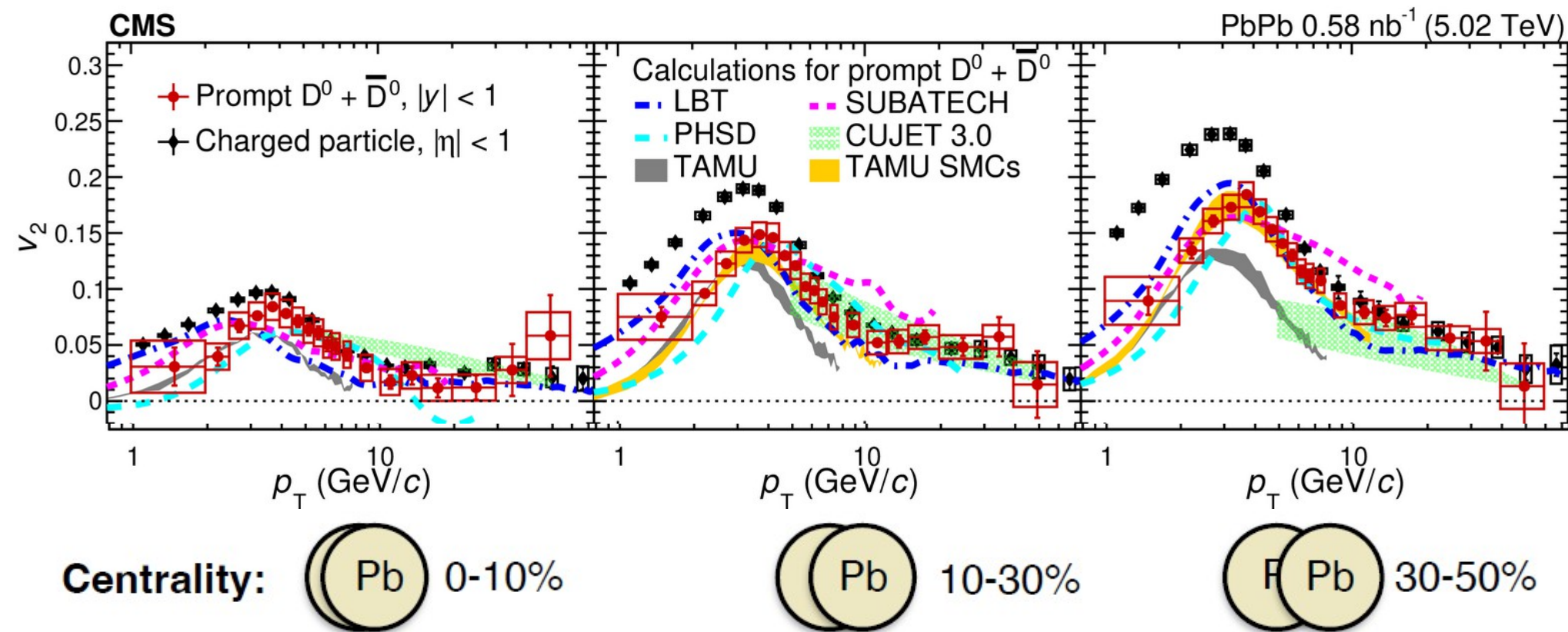
- R_{AA} is decreasing with numbers of participants of Pb+Pb collision.
- Slightly increasing with p_T ?



Sergey Petrushanko (CMS Collaboration) Heavy-Ions Results

Prompt D^0 flow in Pb+Pb collisions

PLB 816 (2021) 136253

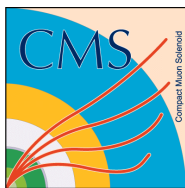


The elliptic flow of prompt D^0 has similar pattern to that of charged hadrons.

CMS-PAS-HIN-21-003

– also confirmed for the multiparticle correlations.

Sergey Petrushanko (CMS Collaboration) Heavy-Ions Results

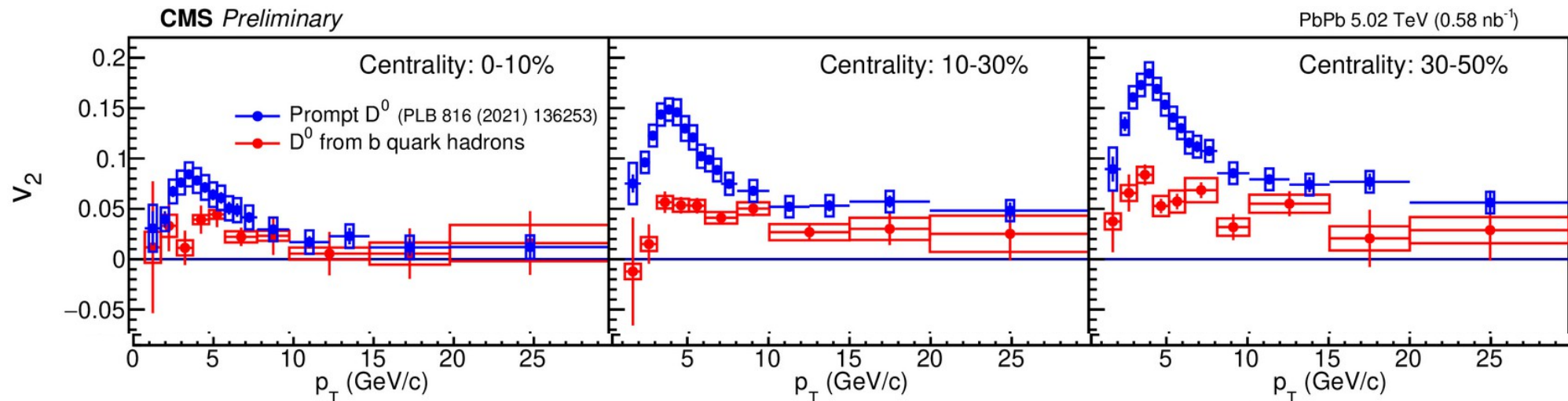


Prompt vs. non-prompt D^0 flow in Pb+Pb collisions



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

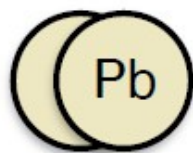
CMS Preliminary



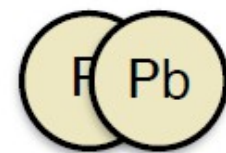
Centrality:



0-10%



10-30%



30-50%

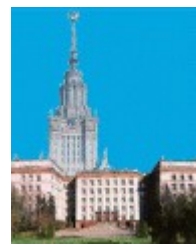
The elliptic flow of prompt D^0
larger than non-prompt D^0 (from b quarks hadrons)

Sergey Petrushanko (CMS Collaboration) Heavy-Ions Results

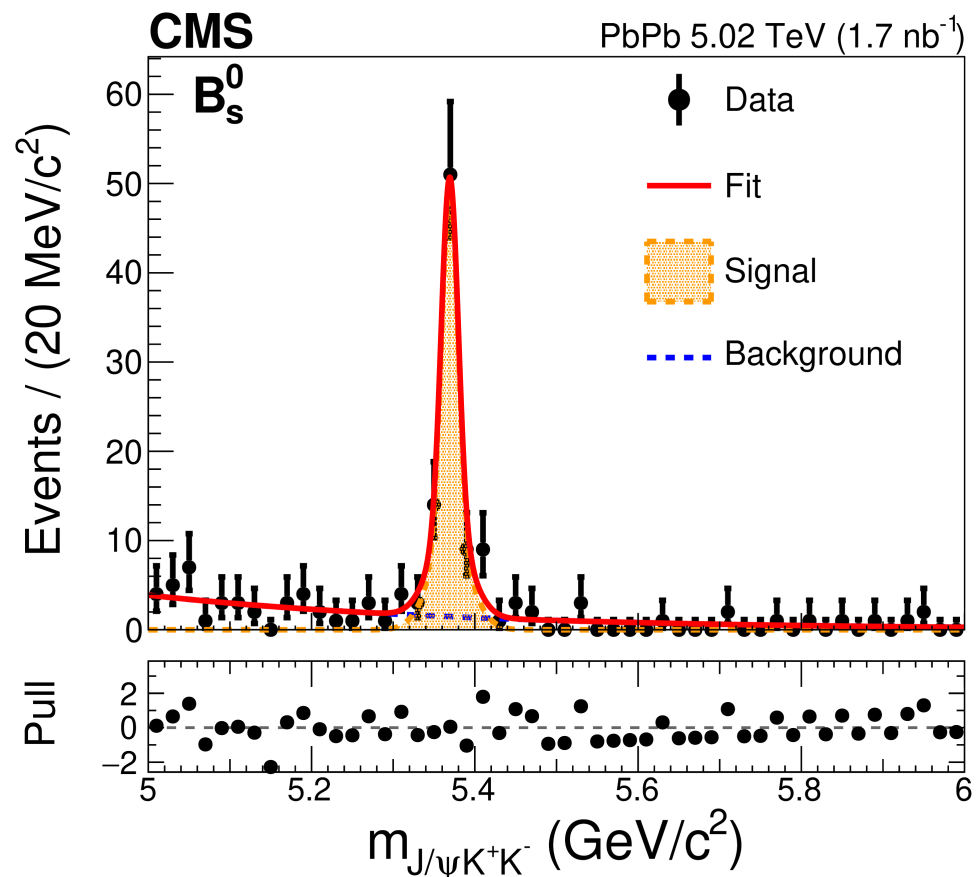
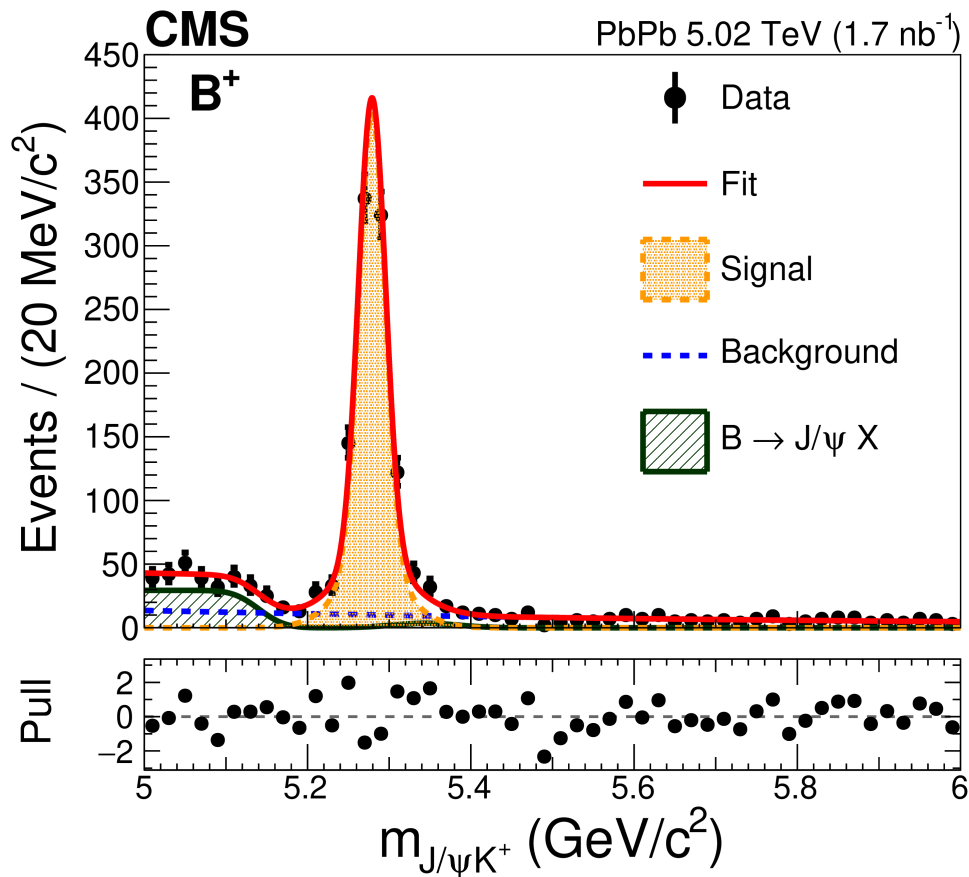




Measurement of B_s^0 and B^+ meson in Pb+Pb collisions



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

Sergey Petrushanko (CMS Collaboration) Heavy-Ions Results

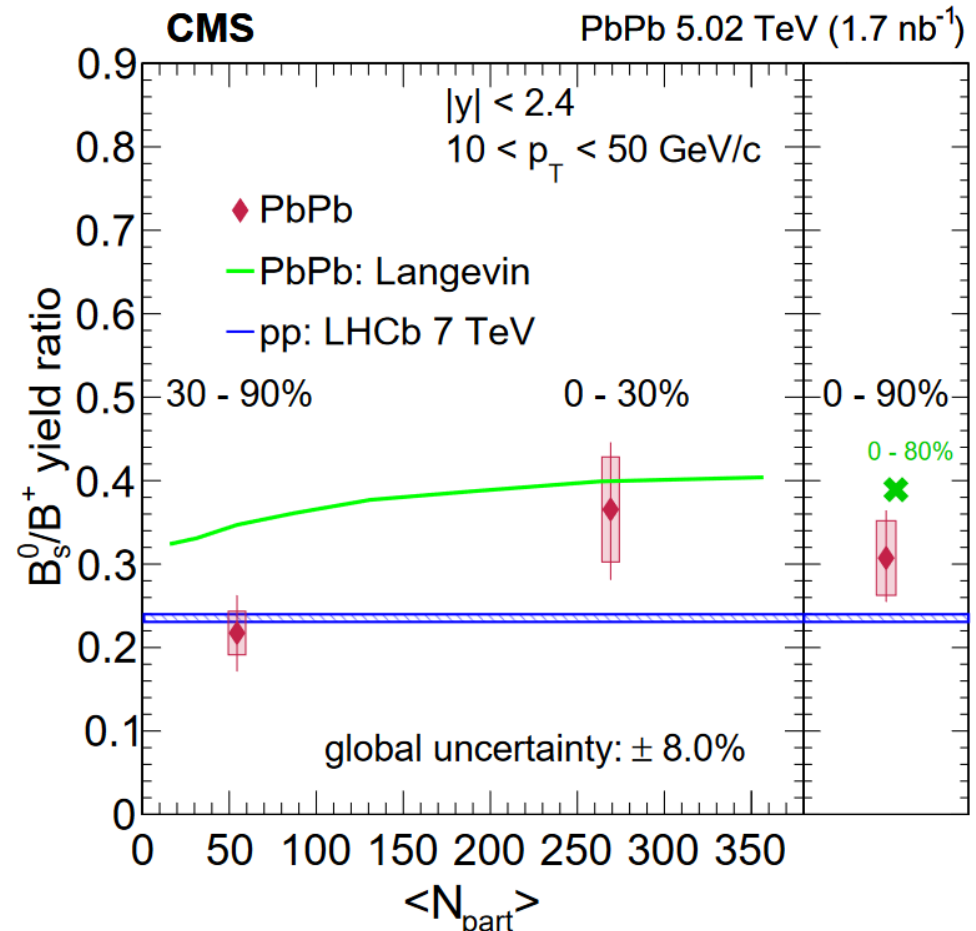
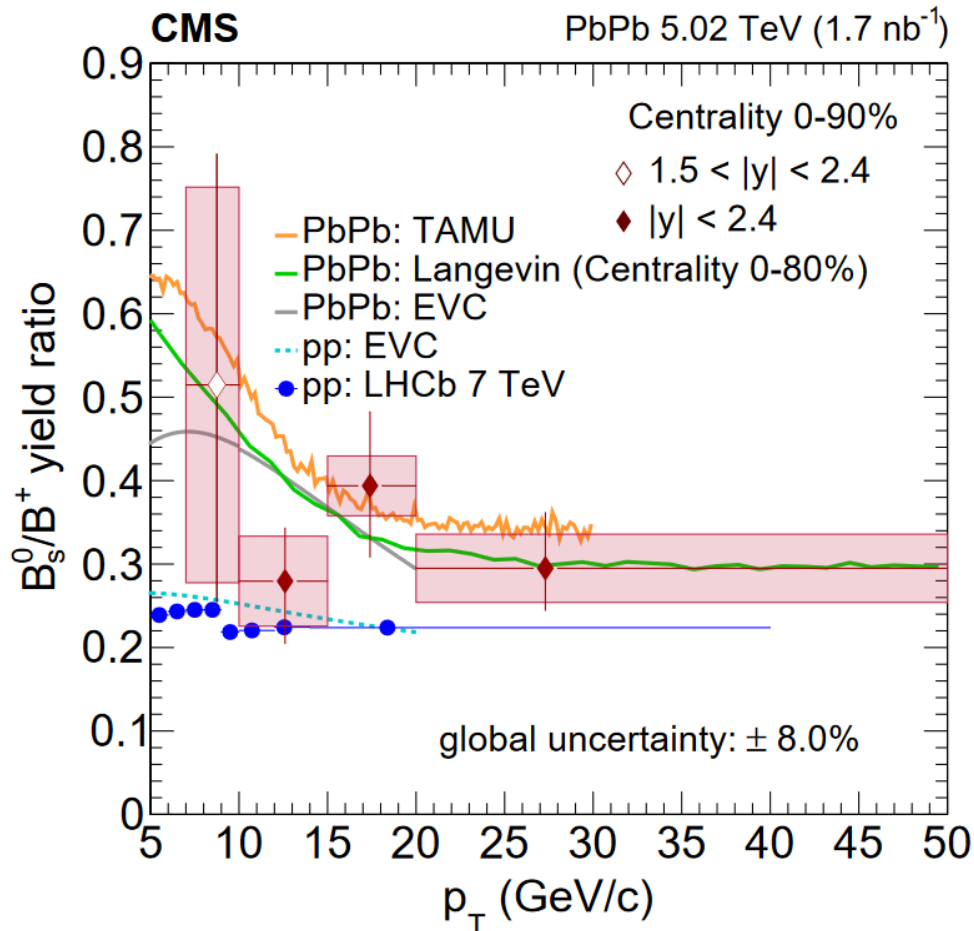




Measurement of B_s^0 and B^+ meson in Pb+Pb collisions



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

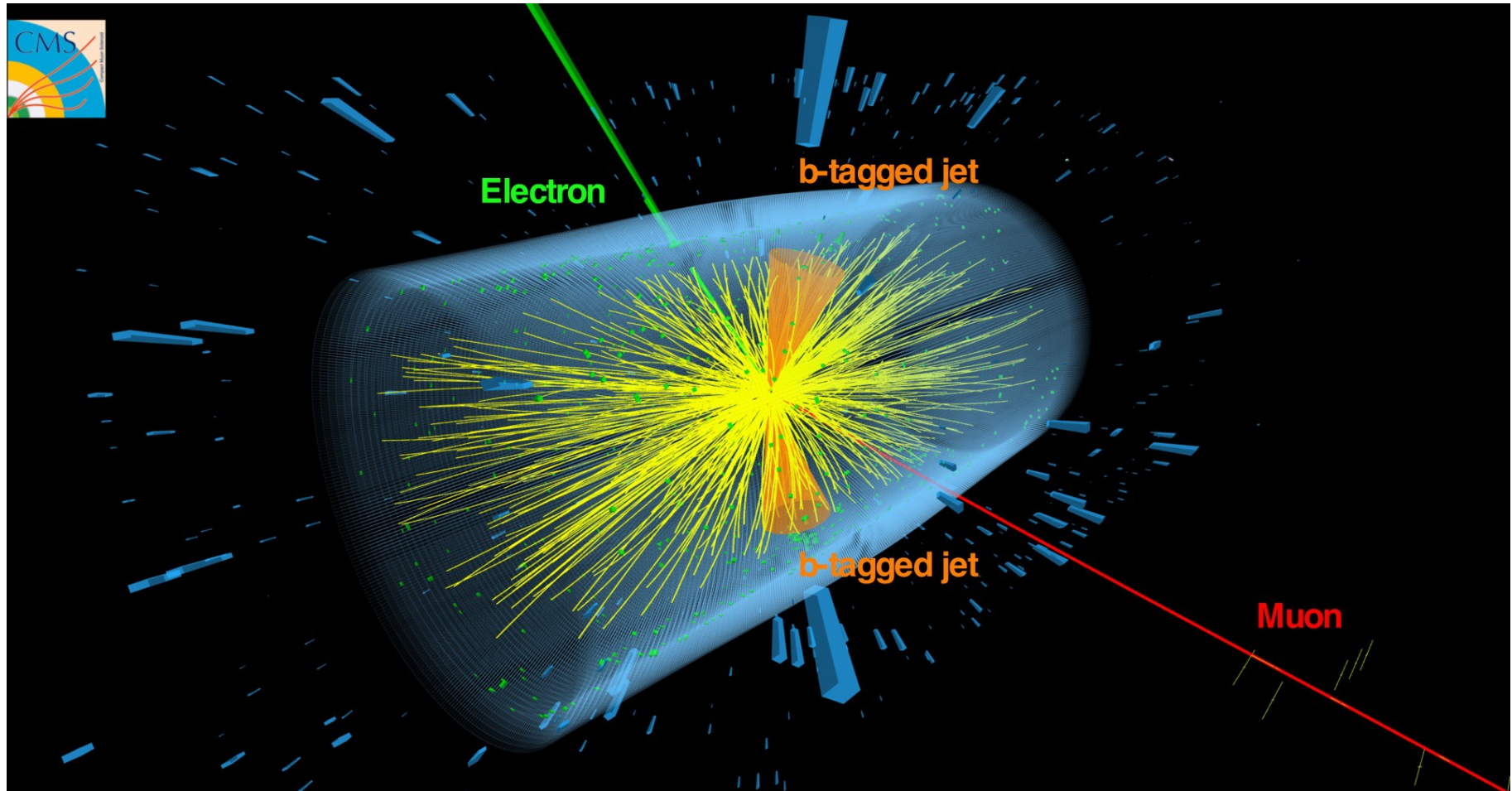
Sergey Petrushanko (CMS Collaboration) Heavy-Ions Results





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

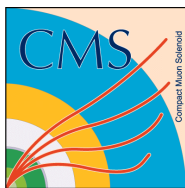
PRL 125 (2020) 222001



**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.**

Sergey Petrushanko (CMS Collaboration) Heavy-Ions Results





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

PRL 125 (2020) 222001



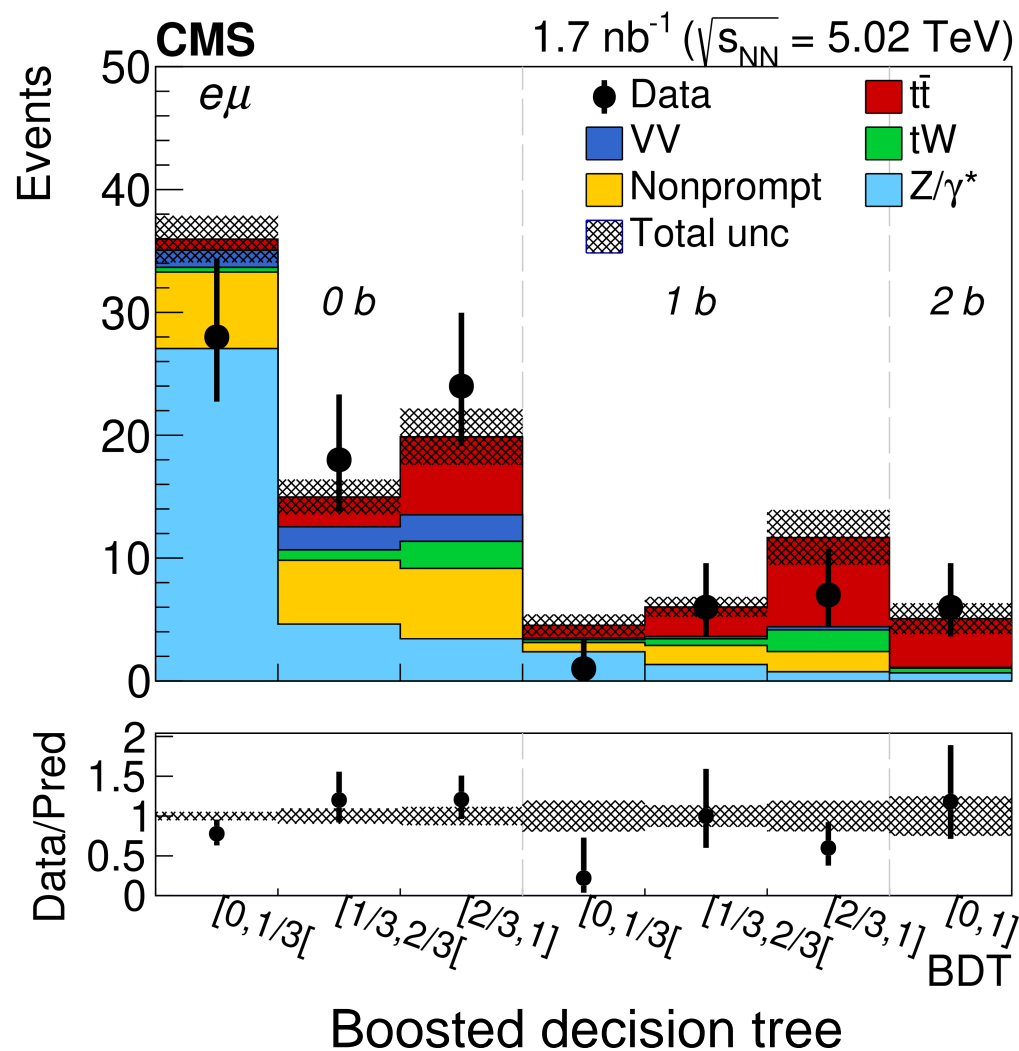
4.0 σ significance

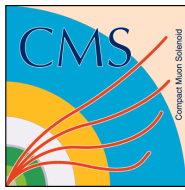
Consistent with pQCD

- 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.





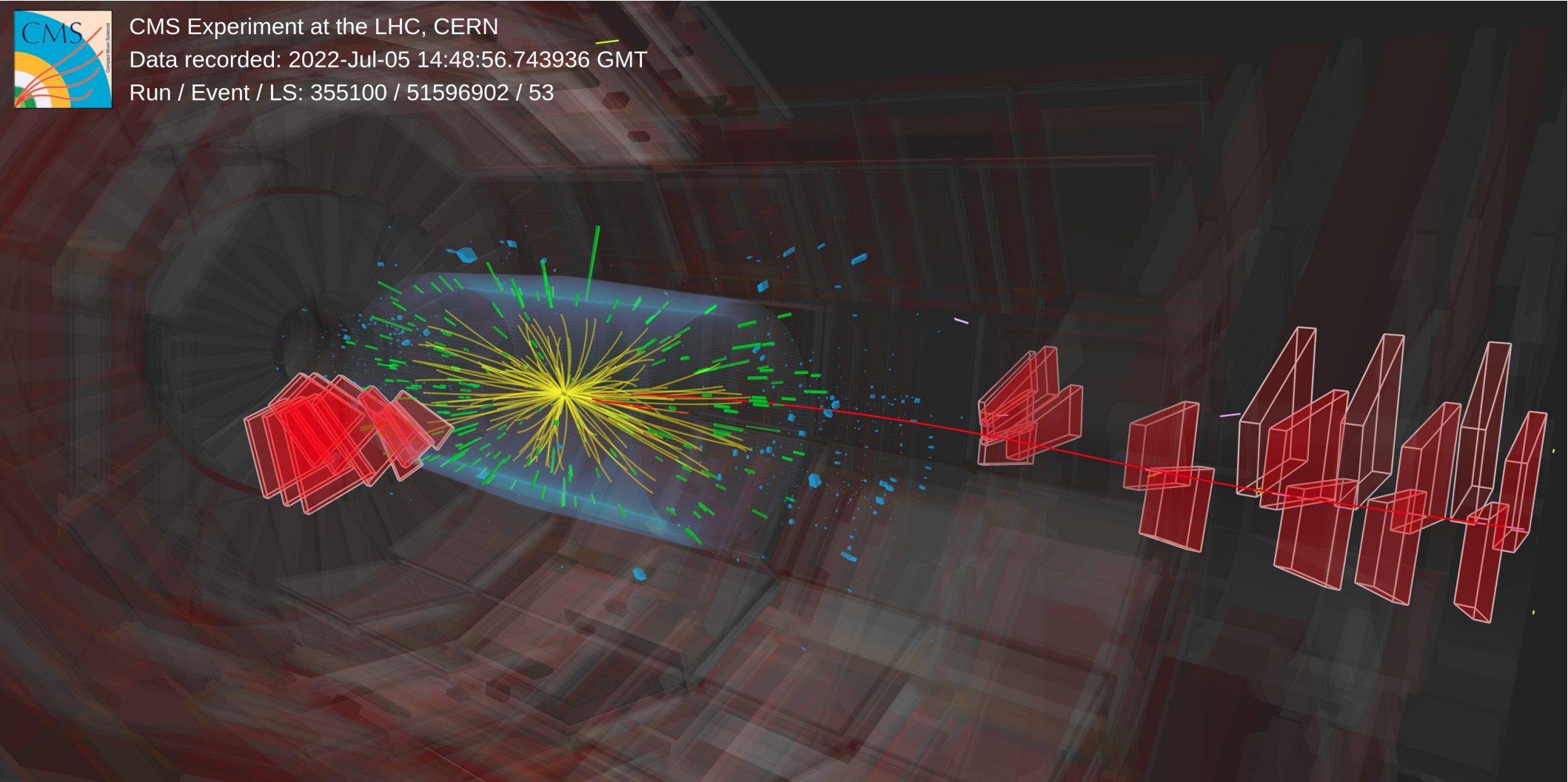
Run 3 was started !



CMS Experiment at the LHC, CERN

Data recorded: 2022-Jul-05 14:48:56.743936 GMT

Run / Event / LS: 355100 / 51596902 / 53



Sergey Petrushanko (CMS Collaboration) Heavy-Ions Results