



Sergey Petrushanko (for CMS Collaboration)



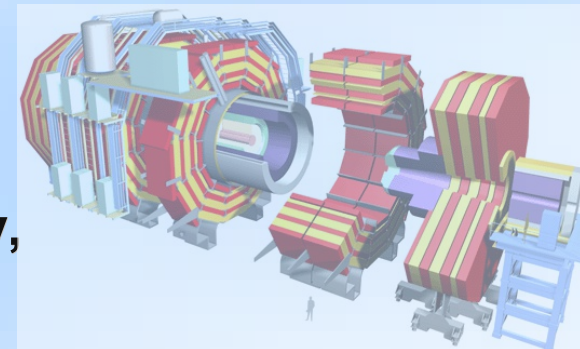
Skobeltsyn Institute of Nuclear Physics
Lomonosov Moscow State University

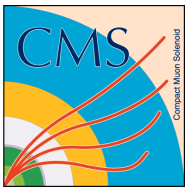
Latest results on heavy-ion physics with the CMS detector



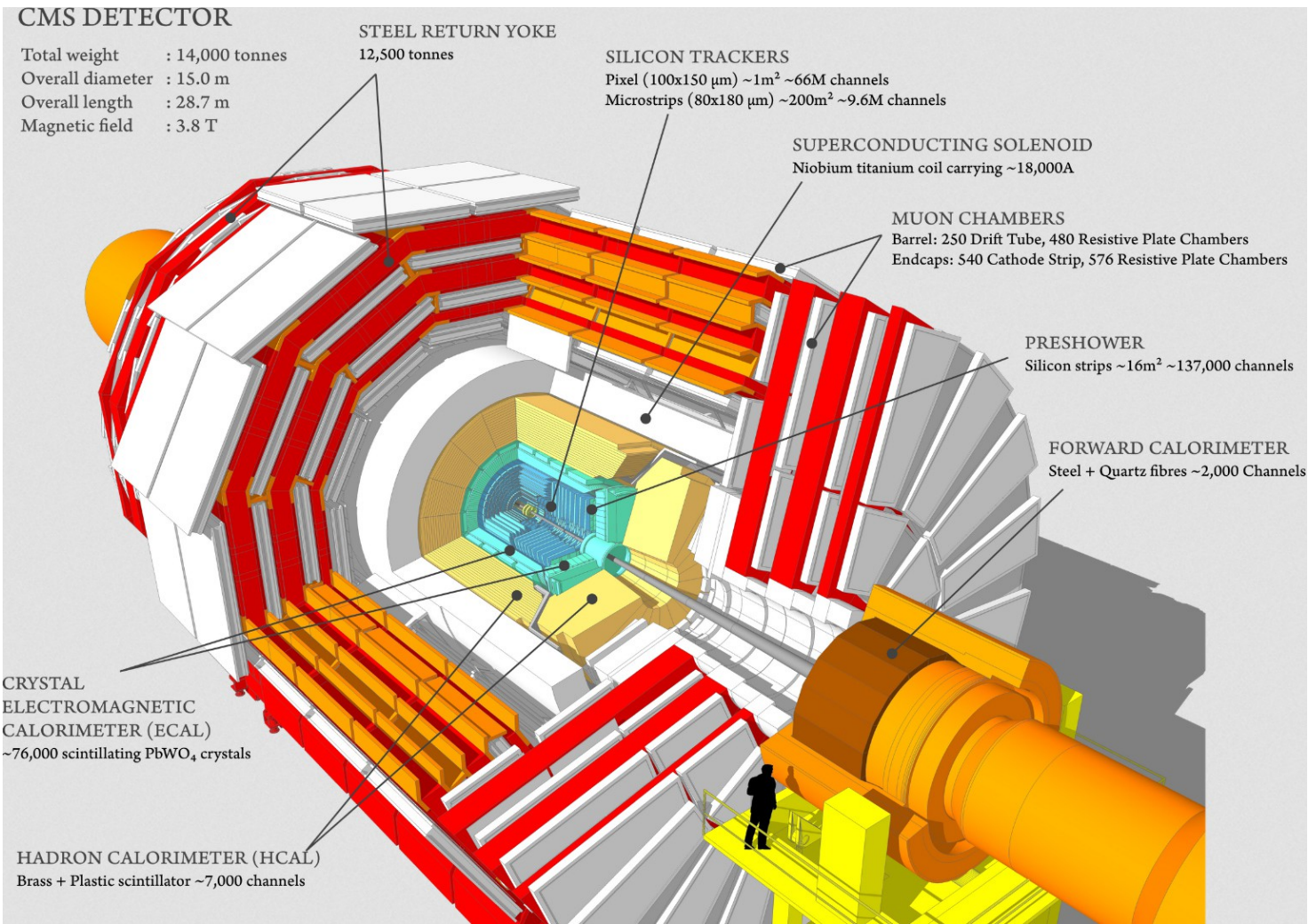
21st Lomonosov Conference
on Elementary Particle Physics

Lomonosov Moscow State University,
Moscow, Russia
24 – 30 August 2023





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

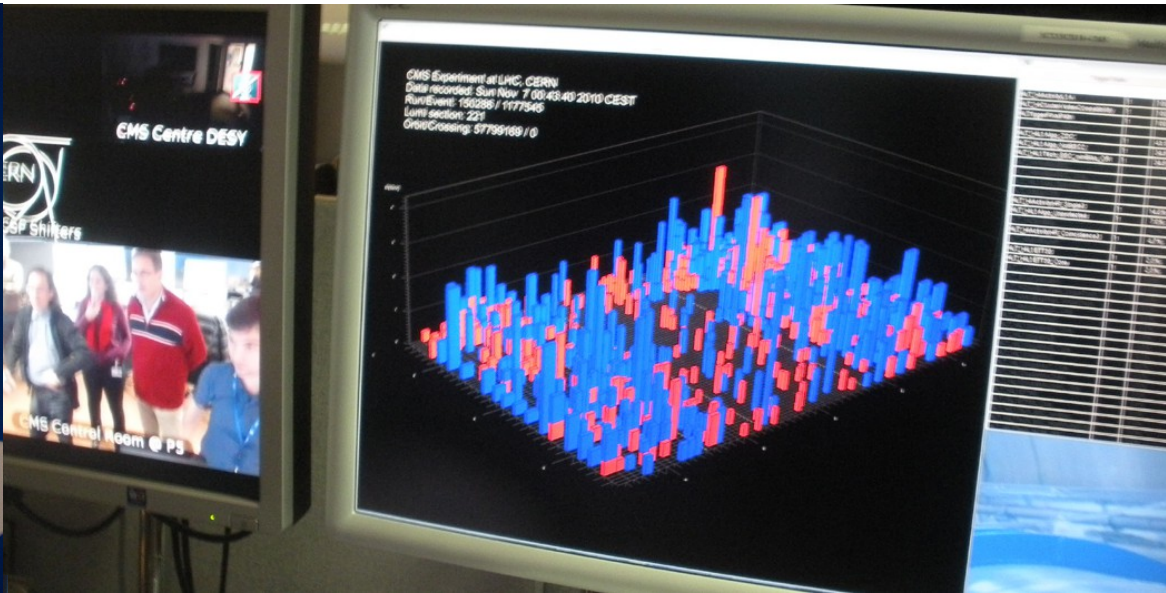
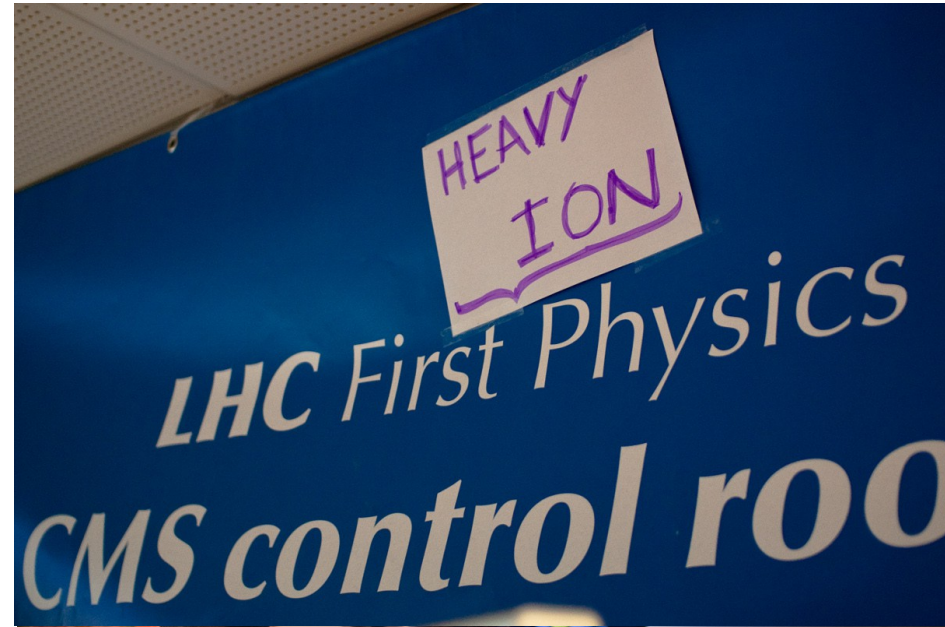
+ TOTEM

Magnetic field: 3.8 Tesla





November 7, 2010 0:27. CMS Control Room





CMS heavy-ion physics results



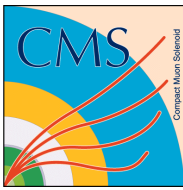
**129 published/submitted
Heavy-ion Physics CMS papers:**

<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**

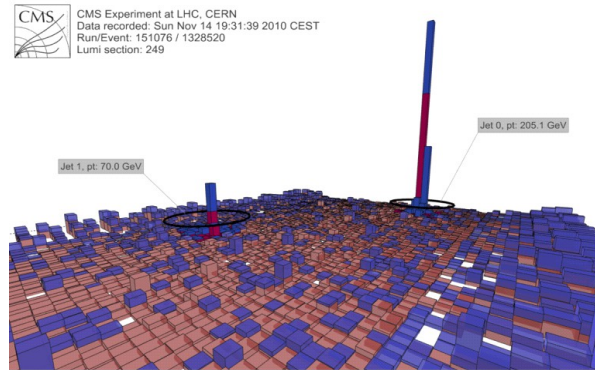
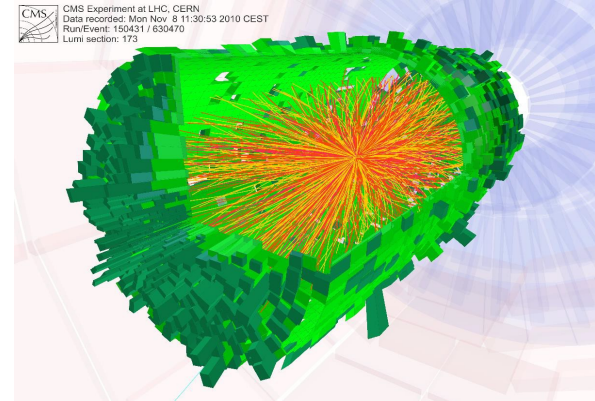
- multiplicity,
- energy,
- flow, ...

Pb+Pb collisions

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

- **Hard probes**

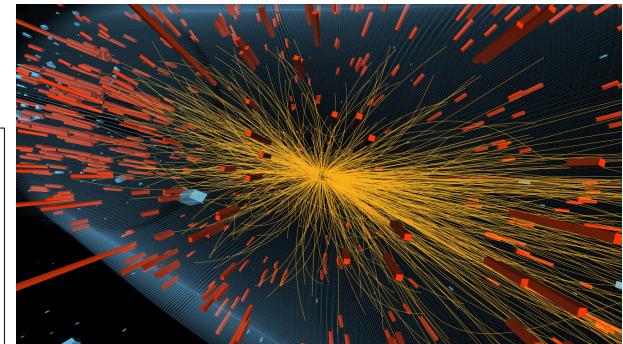
- jets
- dimuons (quarkonia)
- charged hadrons R_{AA} , ...



- **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





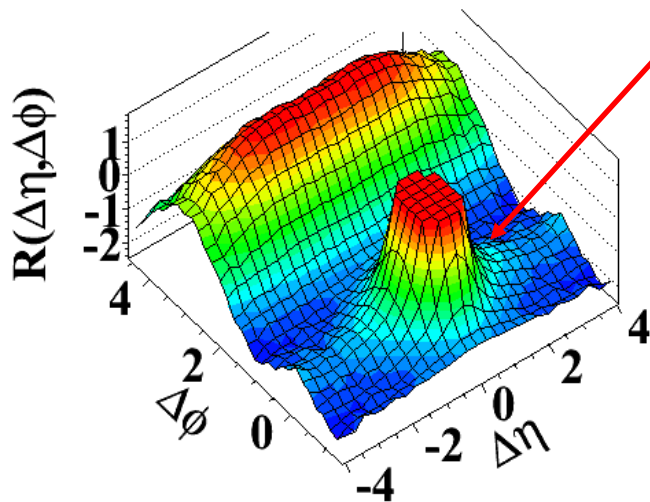
Correlations: “RIDGE” is everywhere..

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

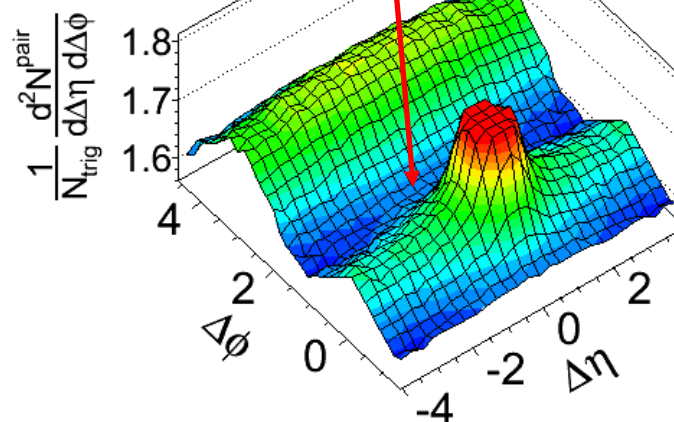
(d) $N > 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



JHEP 09 (2010) 091

p+Pb 5.02 TeV

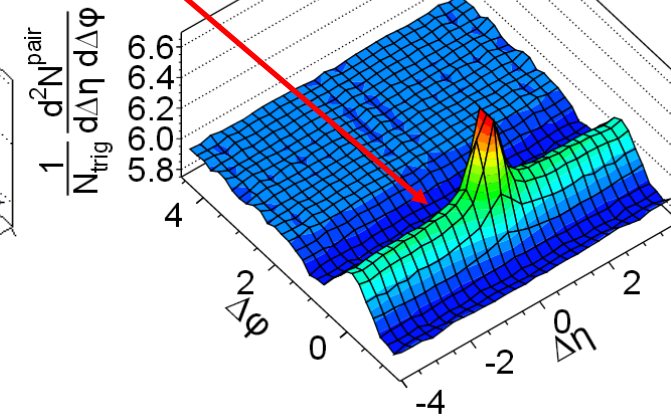
CMS pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, $N_{\text{trk}}^{\text{offline}} \geq 110$
 $1 < p_T < 3 \text{ GeV}/c$



PLB 718 (2013) 795

Pb+Pb 2.76 A TeV, 0-5%

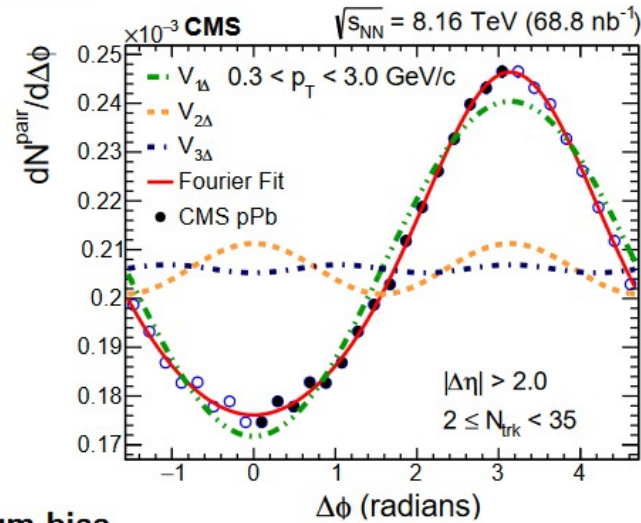
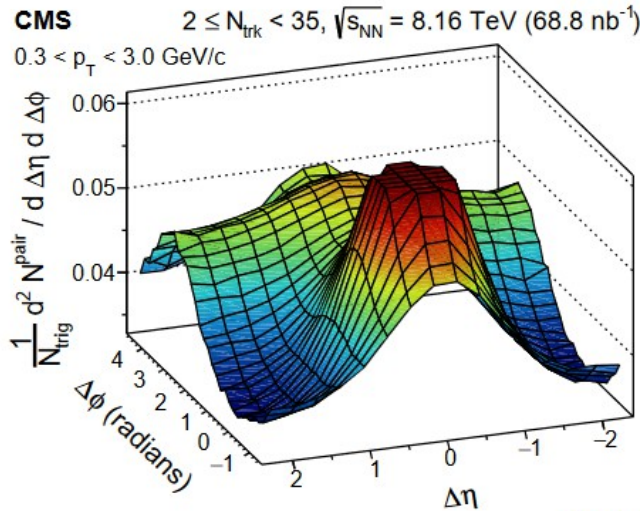
(a) CMS $\int L dt = 3.1 \mu\text{b}^{-1}$
PbPb $\sqrt{s_{NN}} = 2.76 \text{ TeV}$, 0-5% centrality



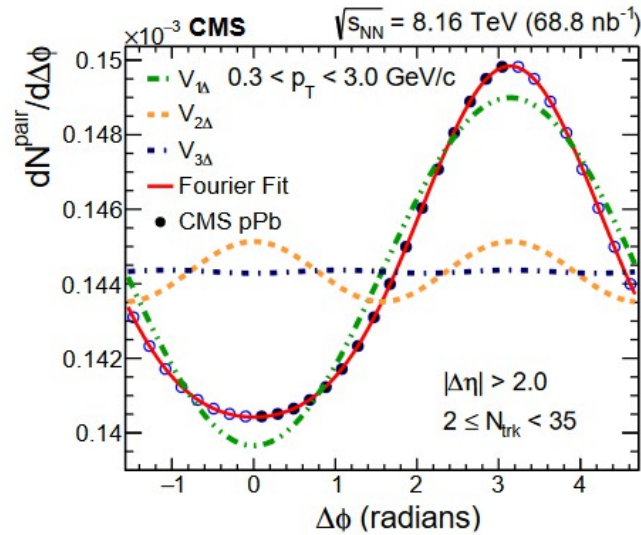
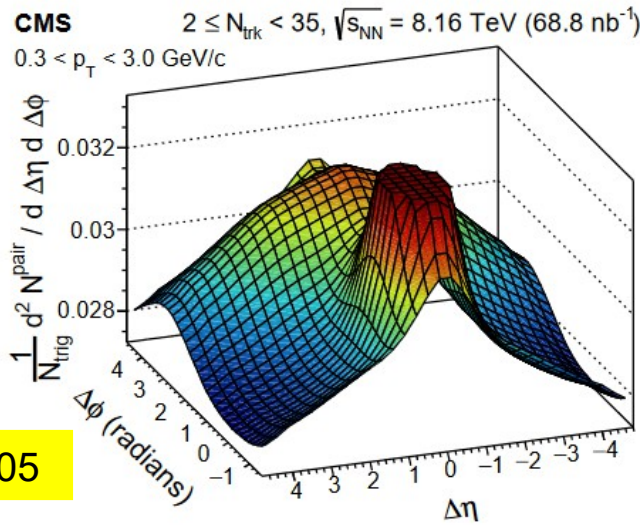
JHEP 07 (2011) 076



γp interactions within ultra-peripheral p+Pb collisions



Minimum-bias

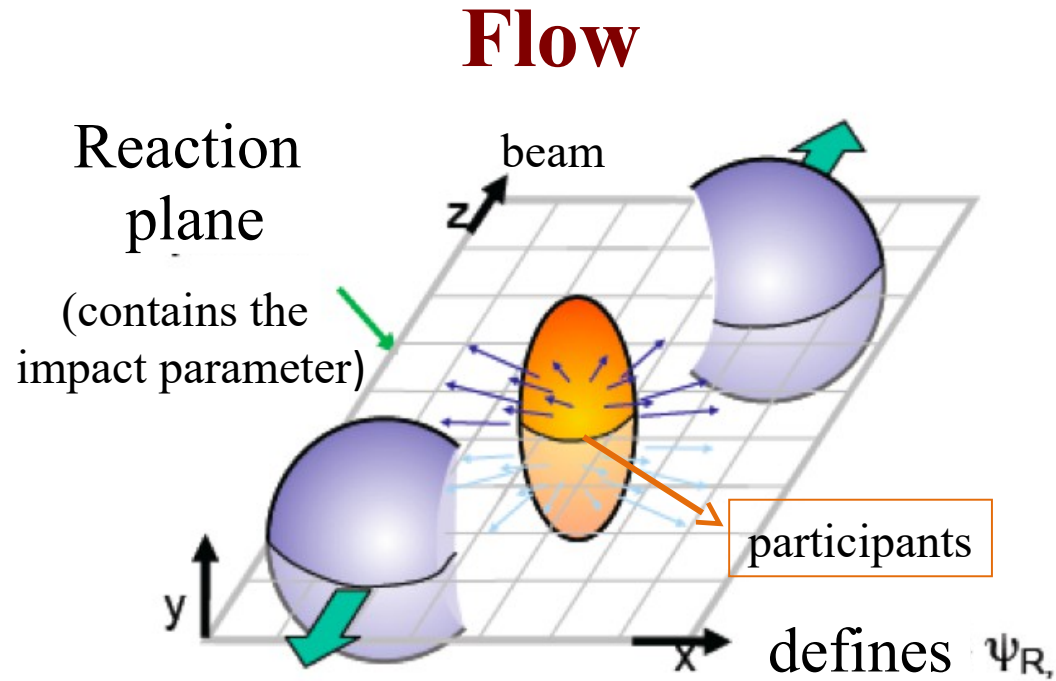


PLB 844 (2023) 137905

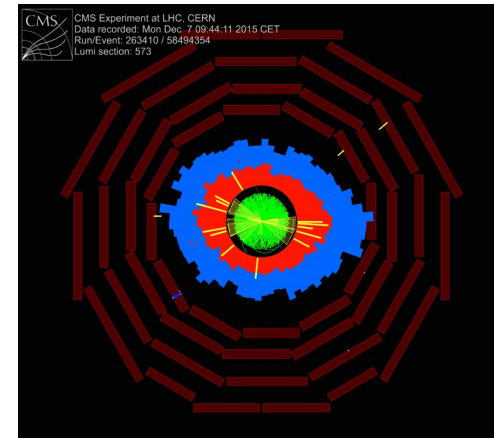
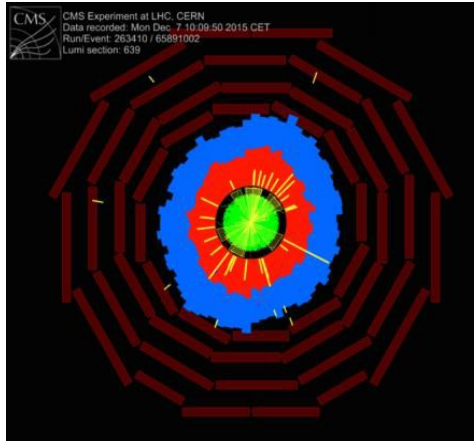
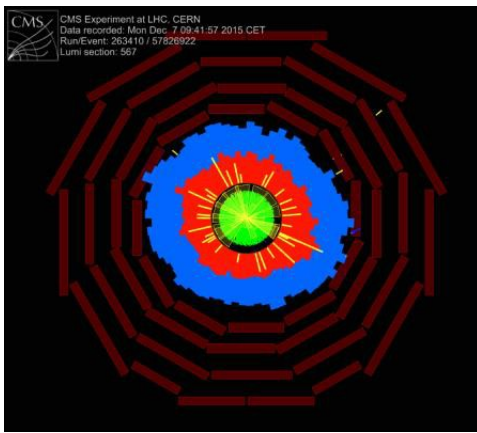
The single particle flow coefficient $v_2(p_T)$ is larger for γp -enhanced events than

for minimum-bias collisions. But we **don't see "ridge"** here!





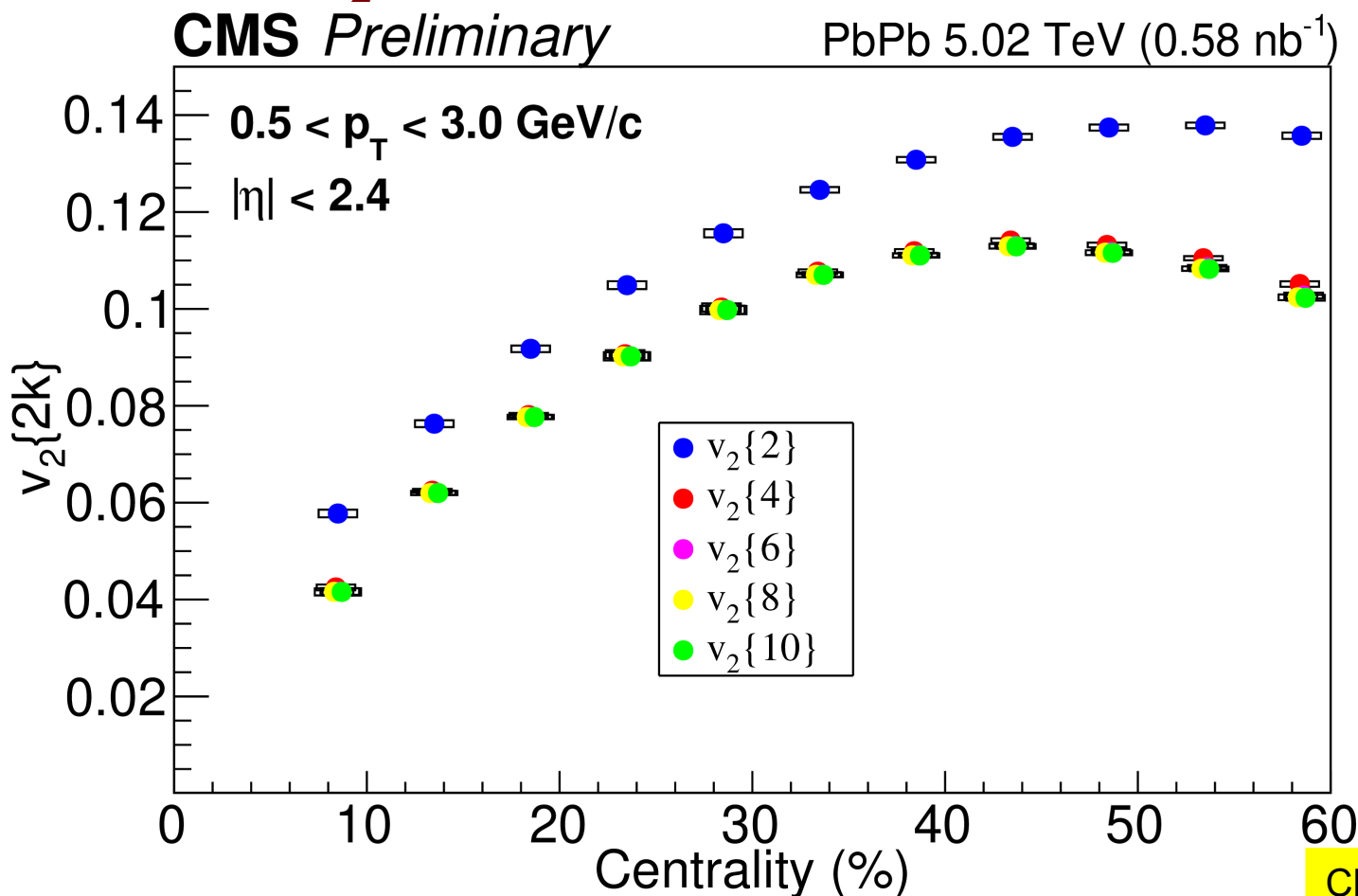
Non-central Pb+Pb “screen shots” from CMS Event Monitor: **Electromagnetic**, **Hadronic** Energy and **charged particles tracks**



Collective motion is observed in the event azimuthal distributions



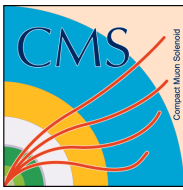
The cumulants of the elliptic flow $v_2\{2k\}$ in Pb+Pb collisions



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



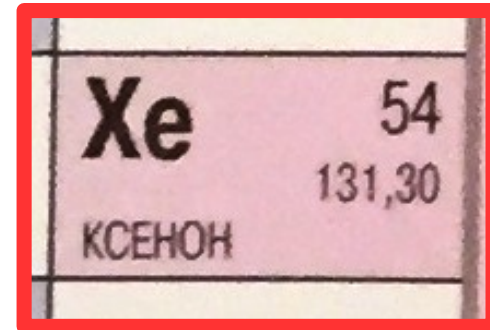
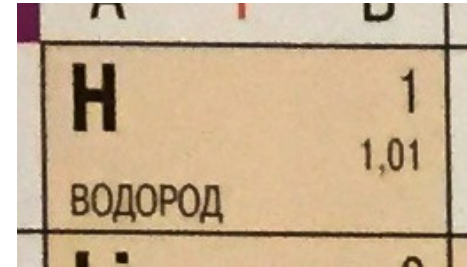


Xe+Xe as a "bridge" between p and Pb



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	B VIII	A																	
1	1	H 1 ВОДОРОД						(H)									He 2 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																			
	7	Ag 47 СЕРЕБРО	Cd 48 КАДМИЙ	In 49 ИНДИЙ	Sn 50 ОЛОВО	Sb 51 СУРЬМА	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																			
	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** 104 АКТИНИЙ	Rf 106 РЕЗЕРФОРДИЙ	Db 107 ДУБИНИЙ	Sg 108 СИБОРГИЙ	Bh 109 БОРИЙ																			
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 ЛЮТЕЦИЙ												
**АКТИНОИДЫ		Th 90 ТОРИЙ	Pa 91 ПРОТАКТИНИЙ	U 92 УРАН	Np 93 НЕПТУНИЙ	Pu 94 ПУЛТОНИЙ	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	



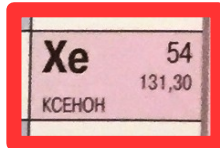
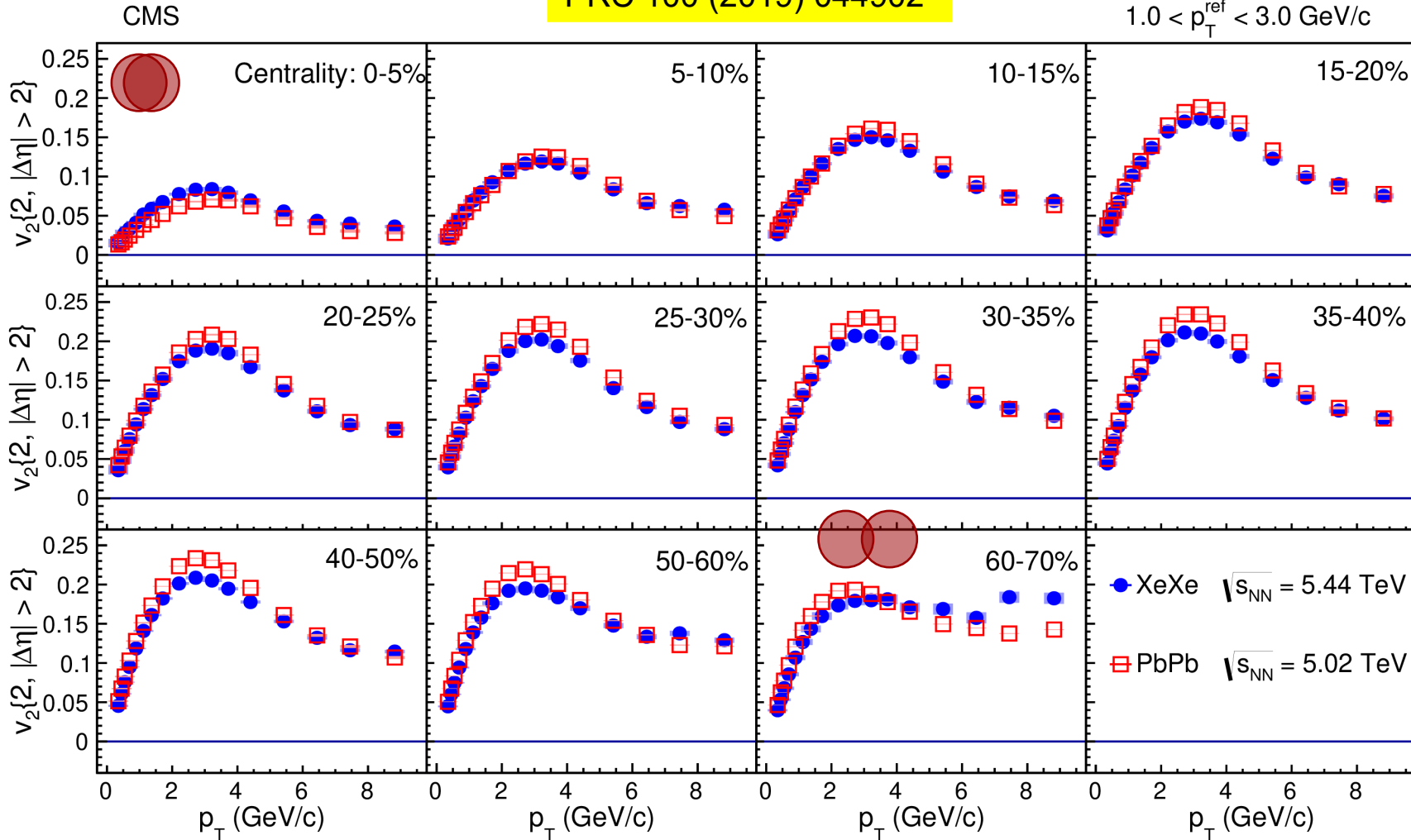


v_2 Xe+Xe vs. Pb+Pb



PRC 100 (2019) 044902

$1.0 < p_T^{\text{ref}} < 3.0$ 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.



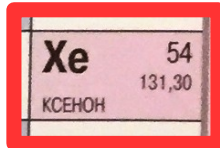
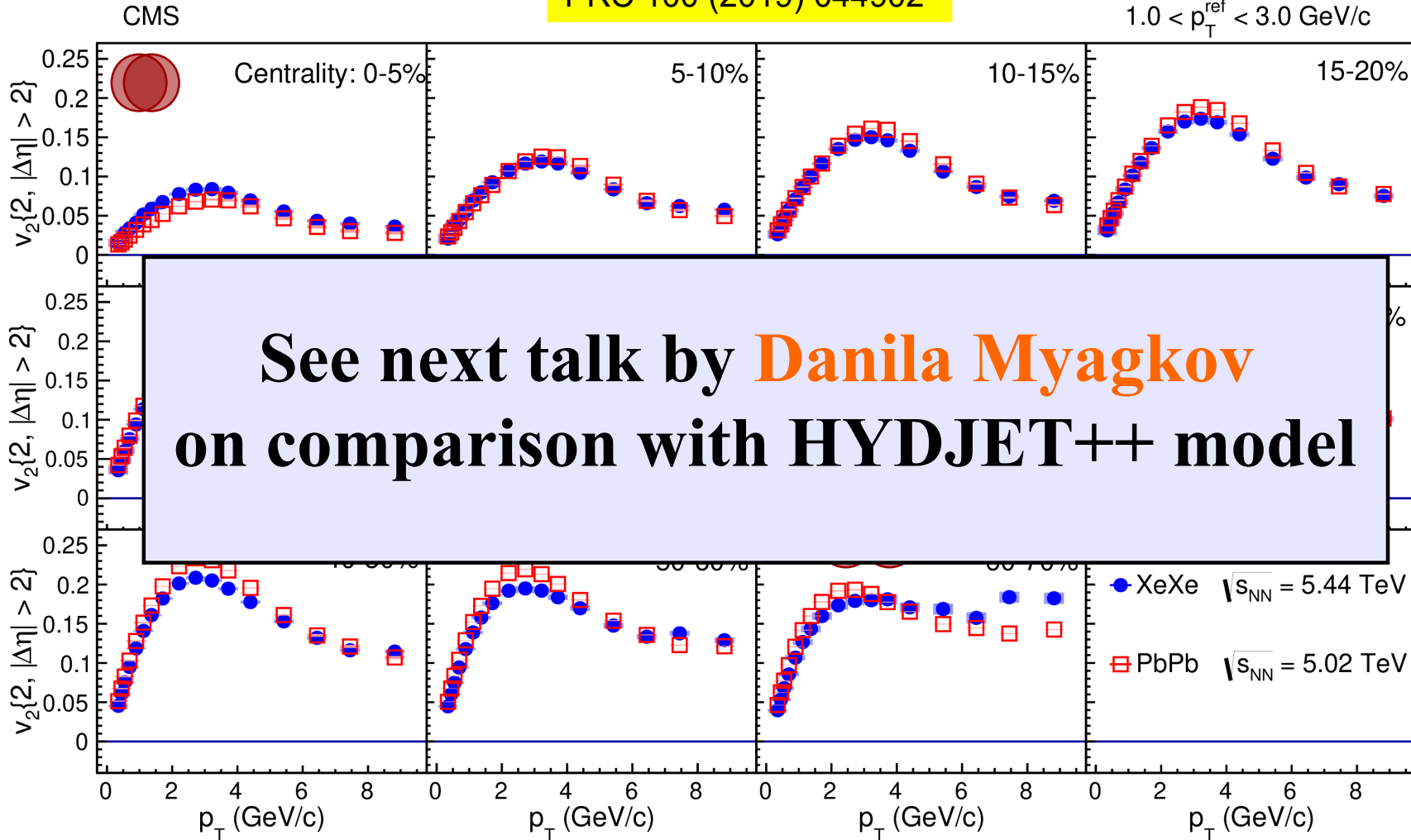


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PRC 100 (2019) 044902

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

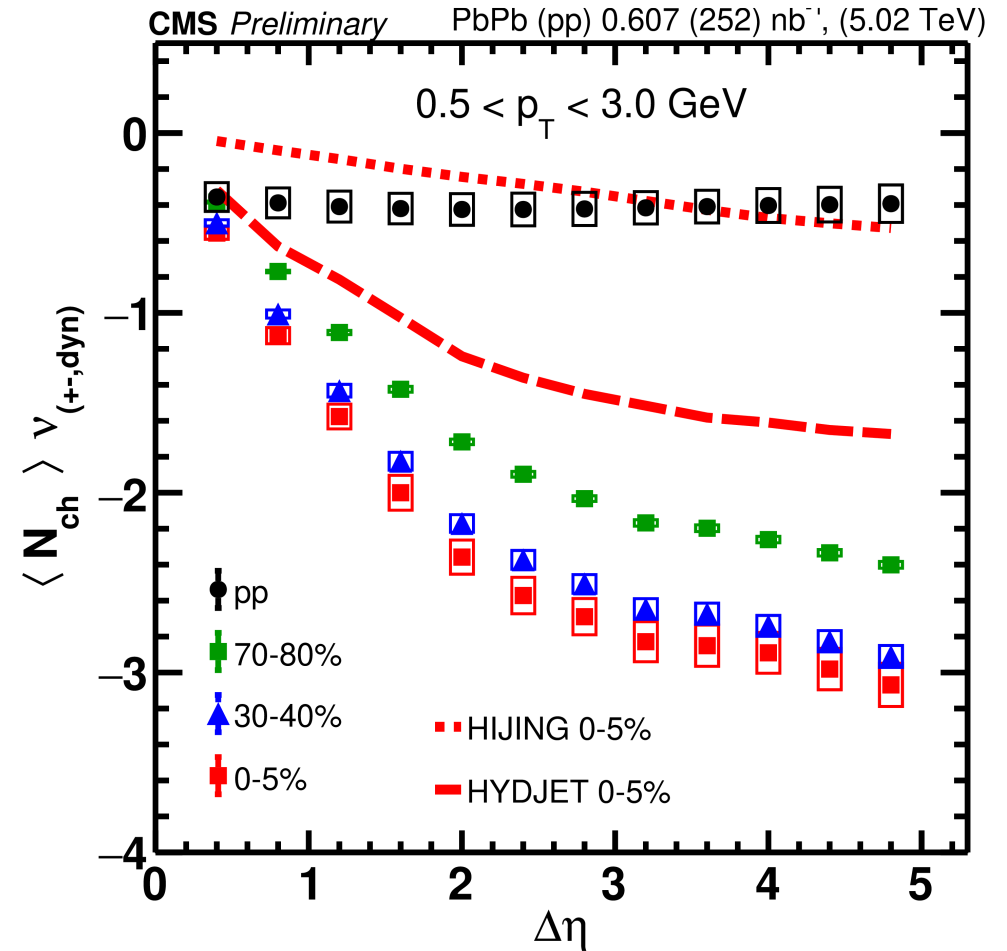
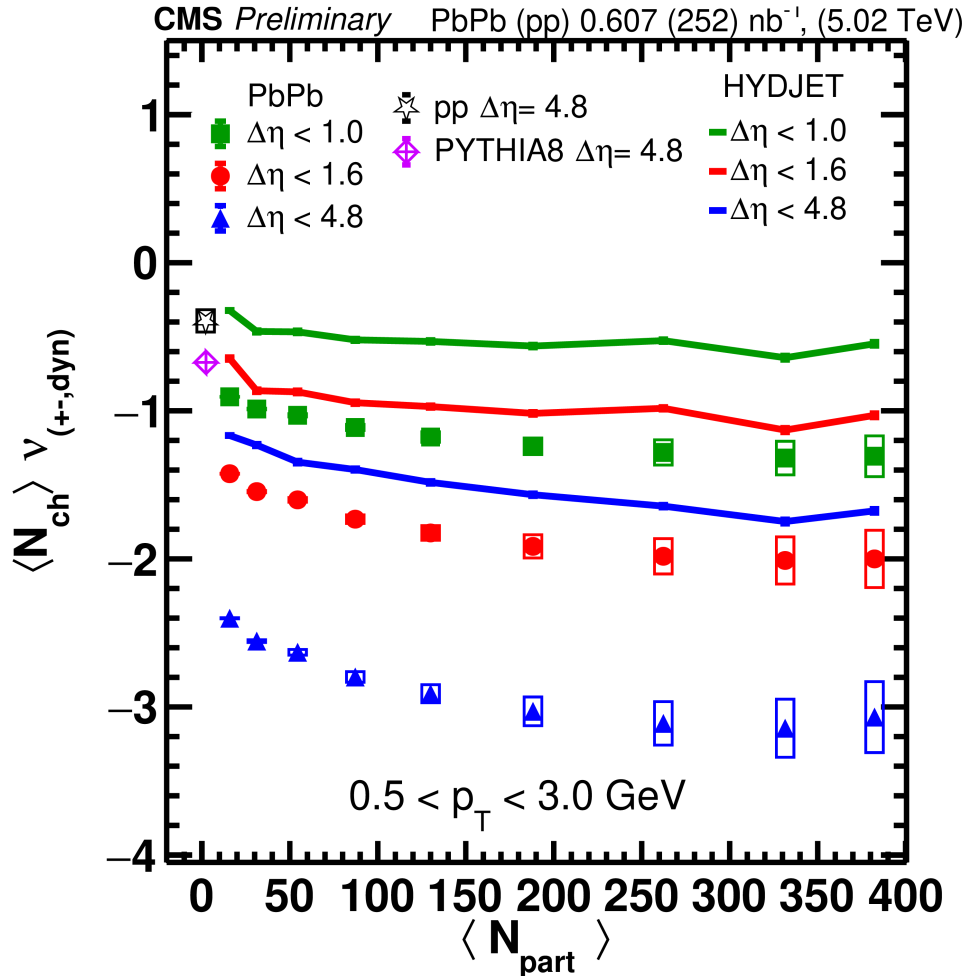


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CMS-PAS-HIN-22-005



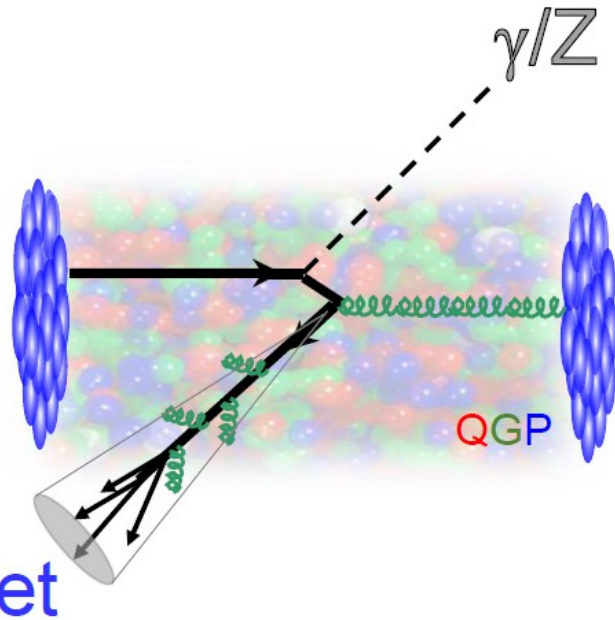
Net-charge fluctuations differ between QGP and hadron gas phase
We see the signature of QGP



Hard Probes for Quark-Gluon Plasma

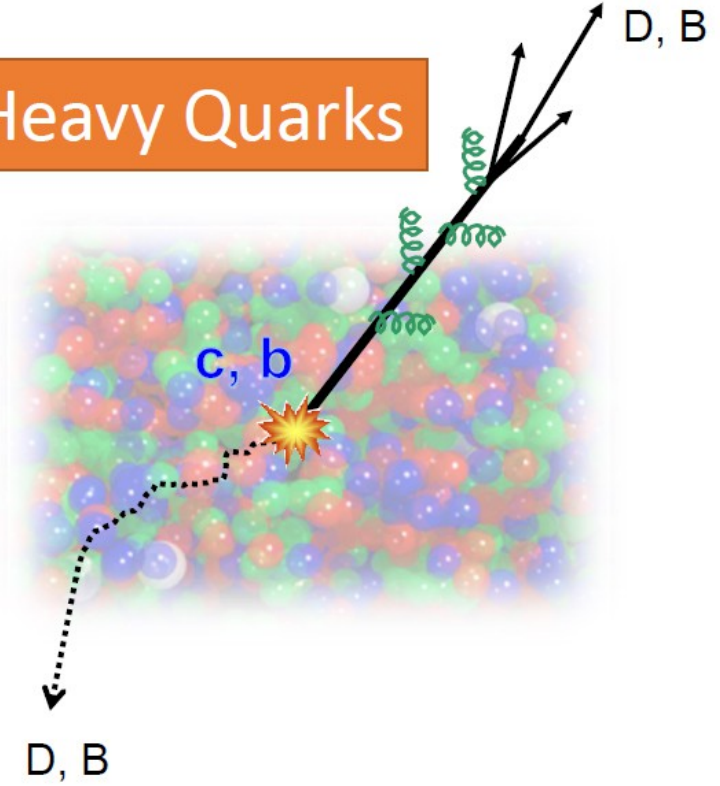


Electroweak Bosons

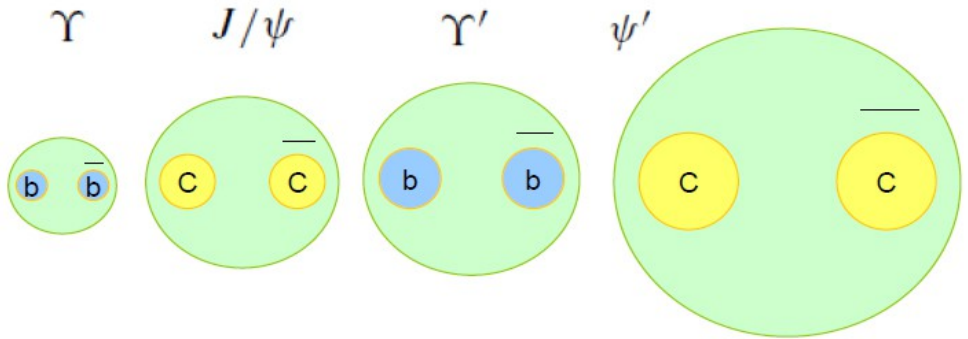


Jets

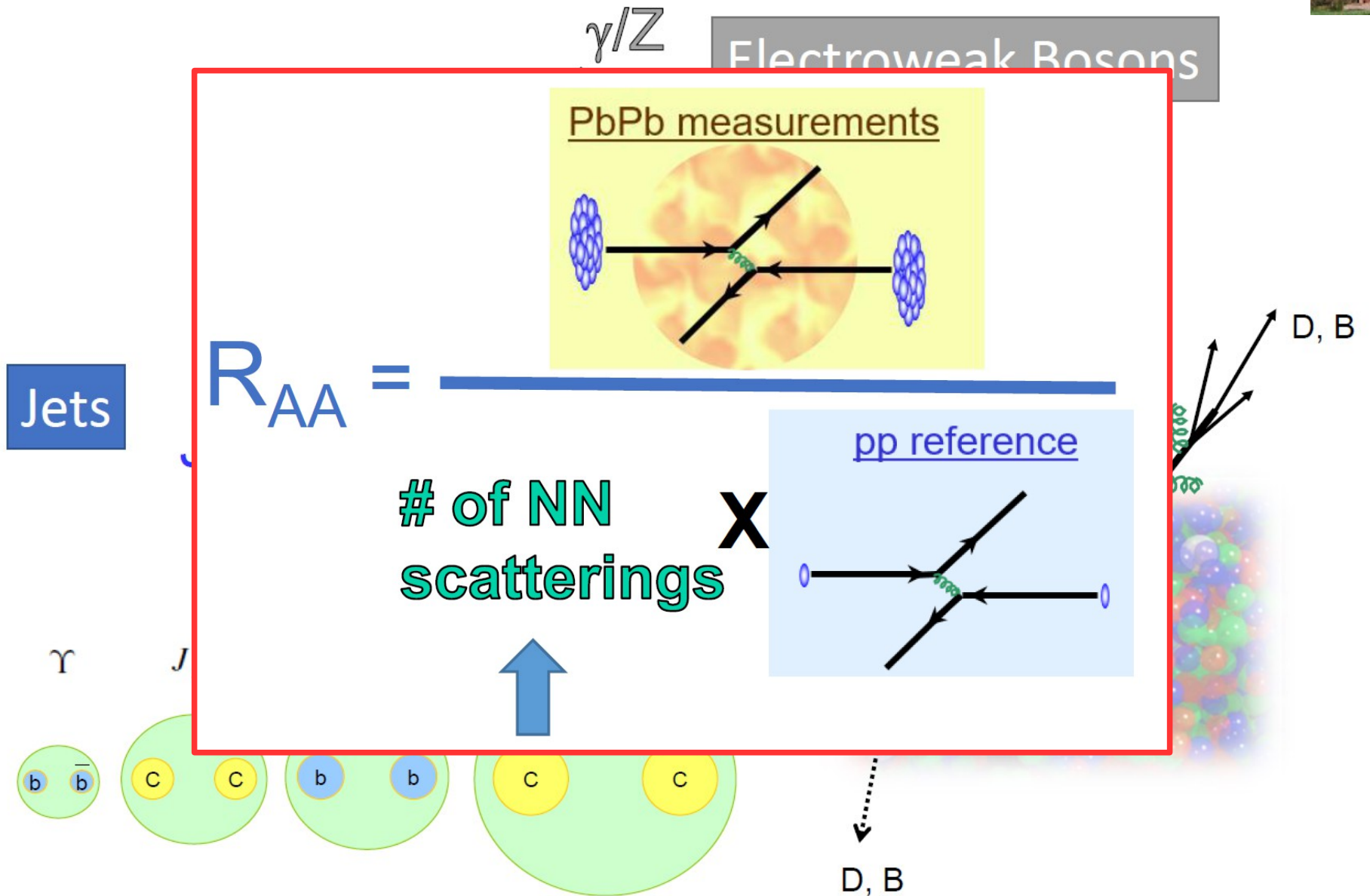
Heavy Quarks



Quarkonia



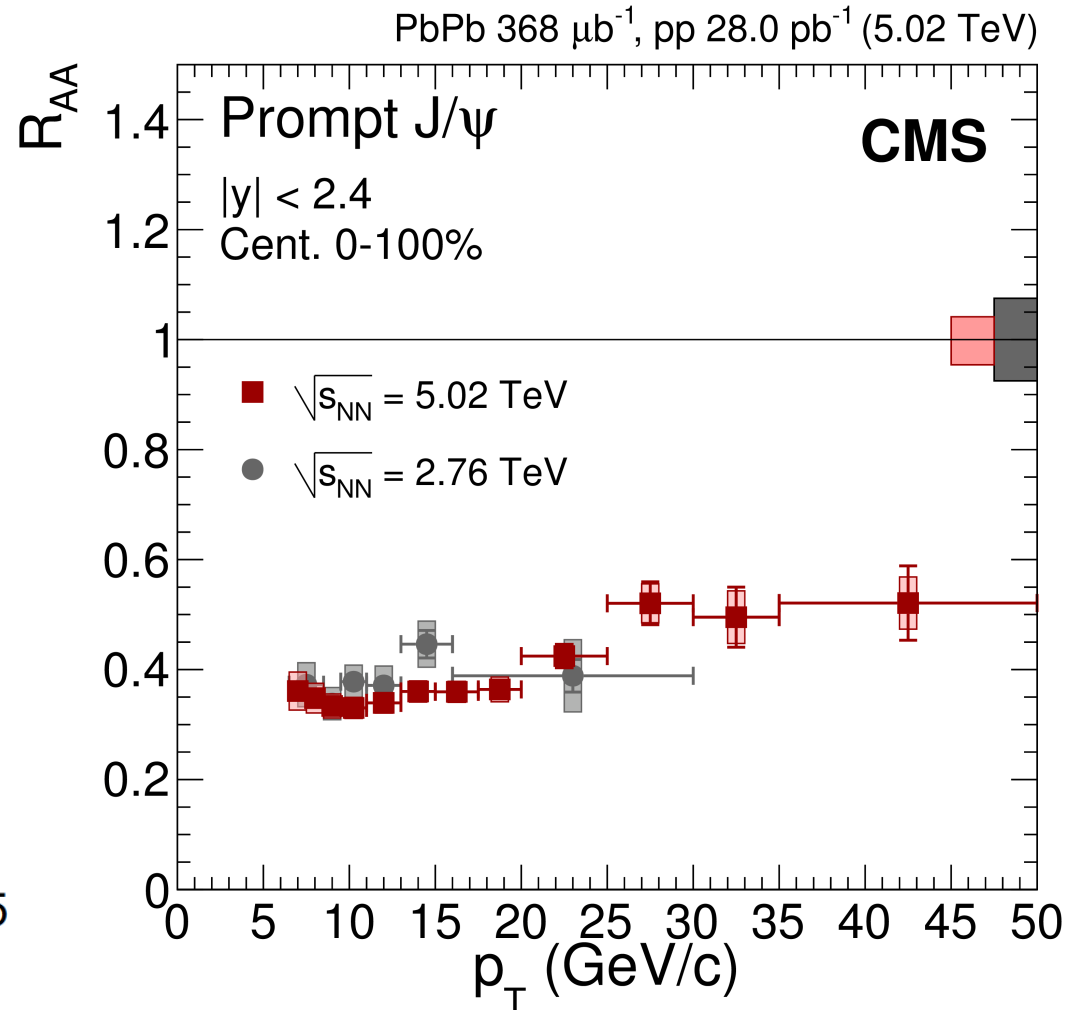
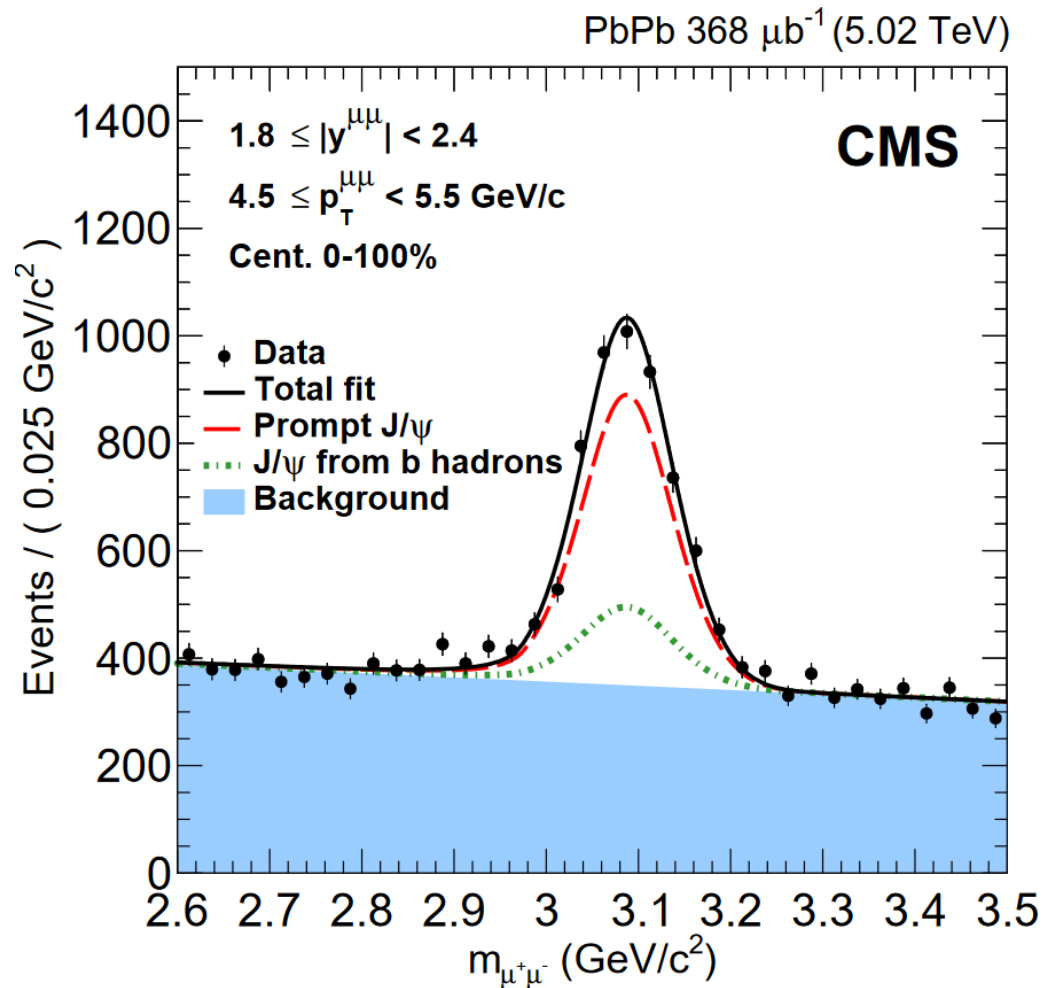
Hard Probes for Quark-Gluon Plasma



J/ψ suppression in Pb+Pb



EPJ C 78 (2018) 509



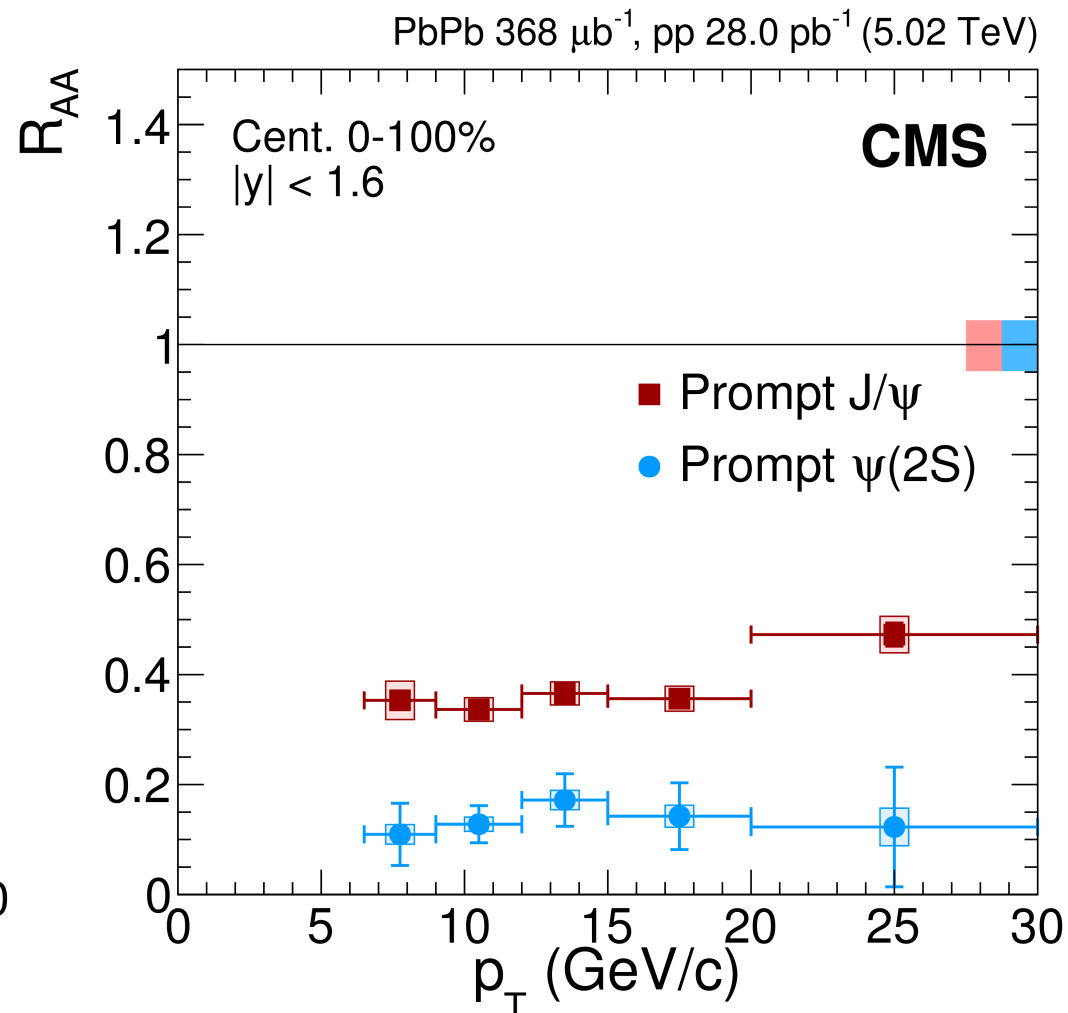
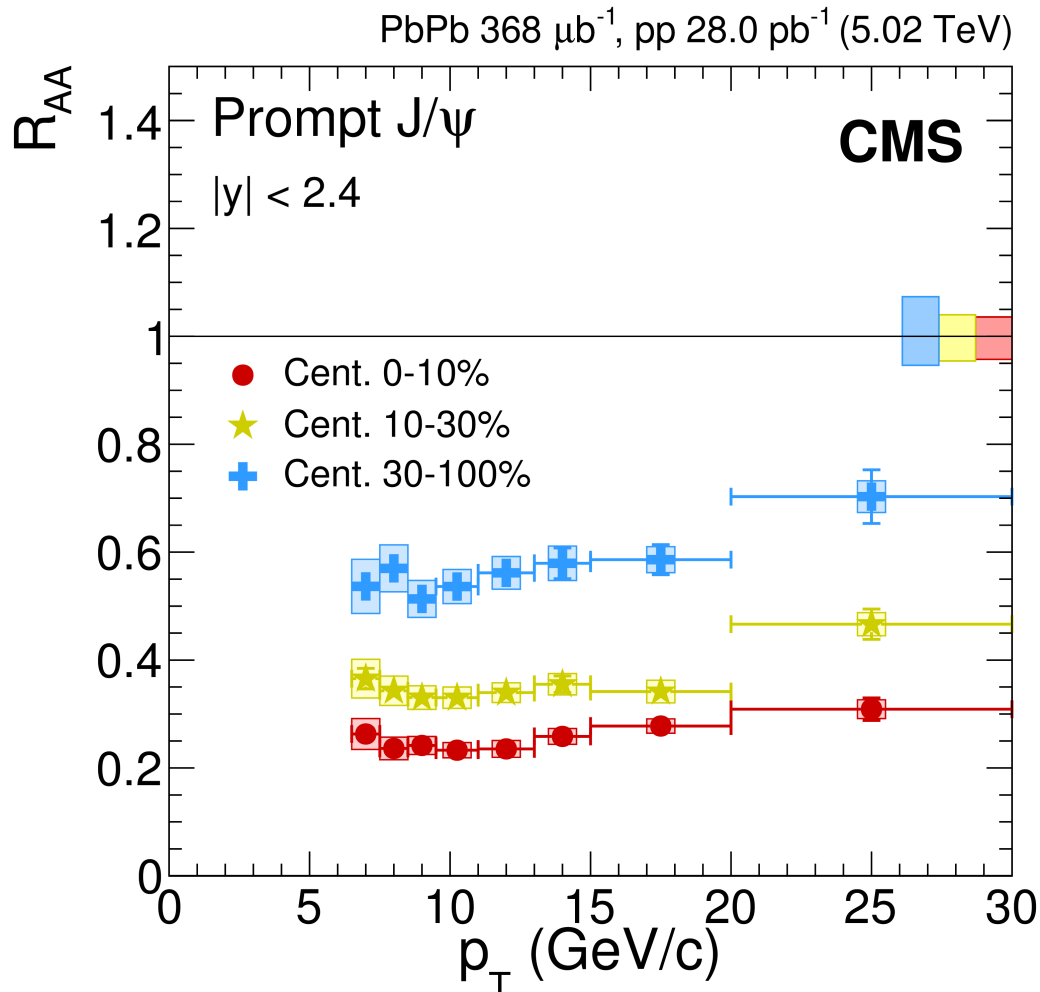
**J/ψ mesons are observed to be suppressed
(similarly in 2.76 and 5.02 TeV)**



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



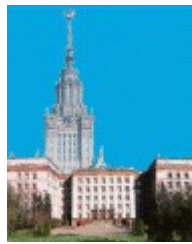
EPJ C 78 (2018) 509



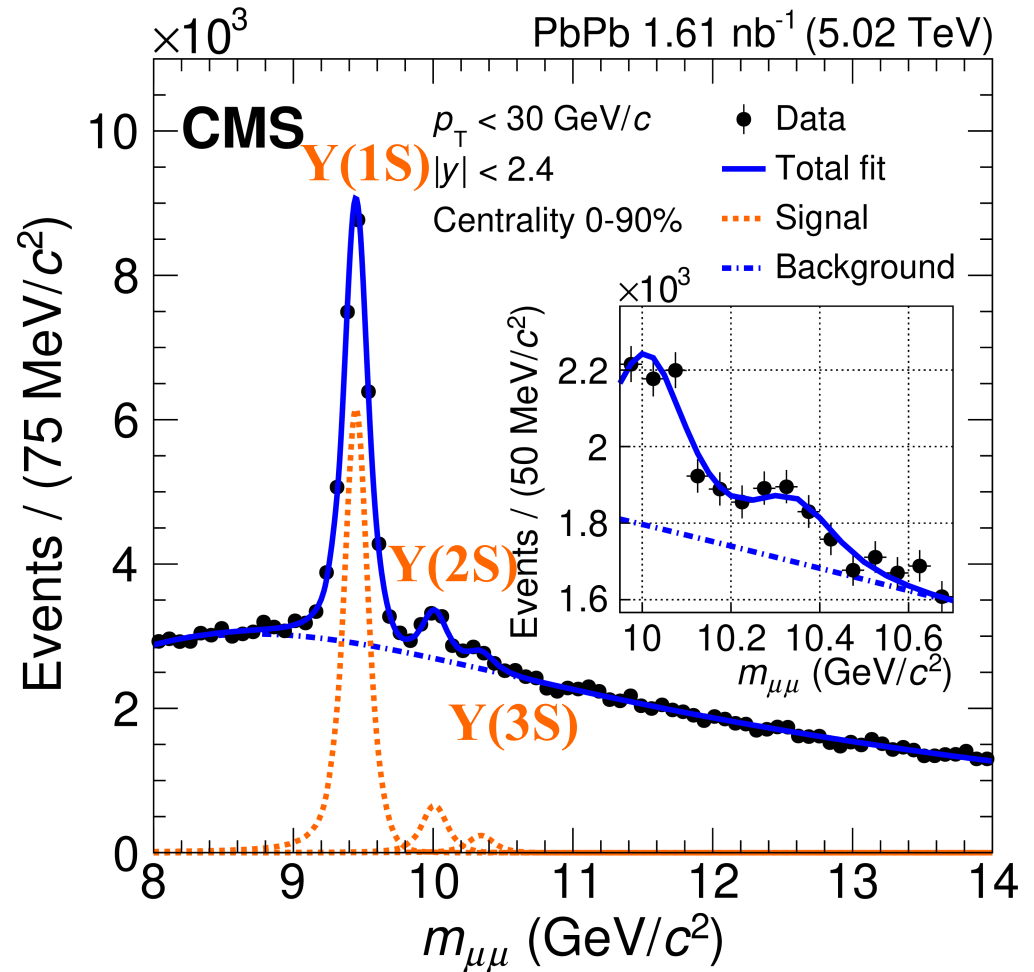
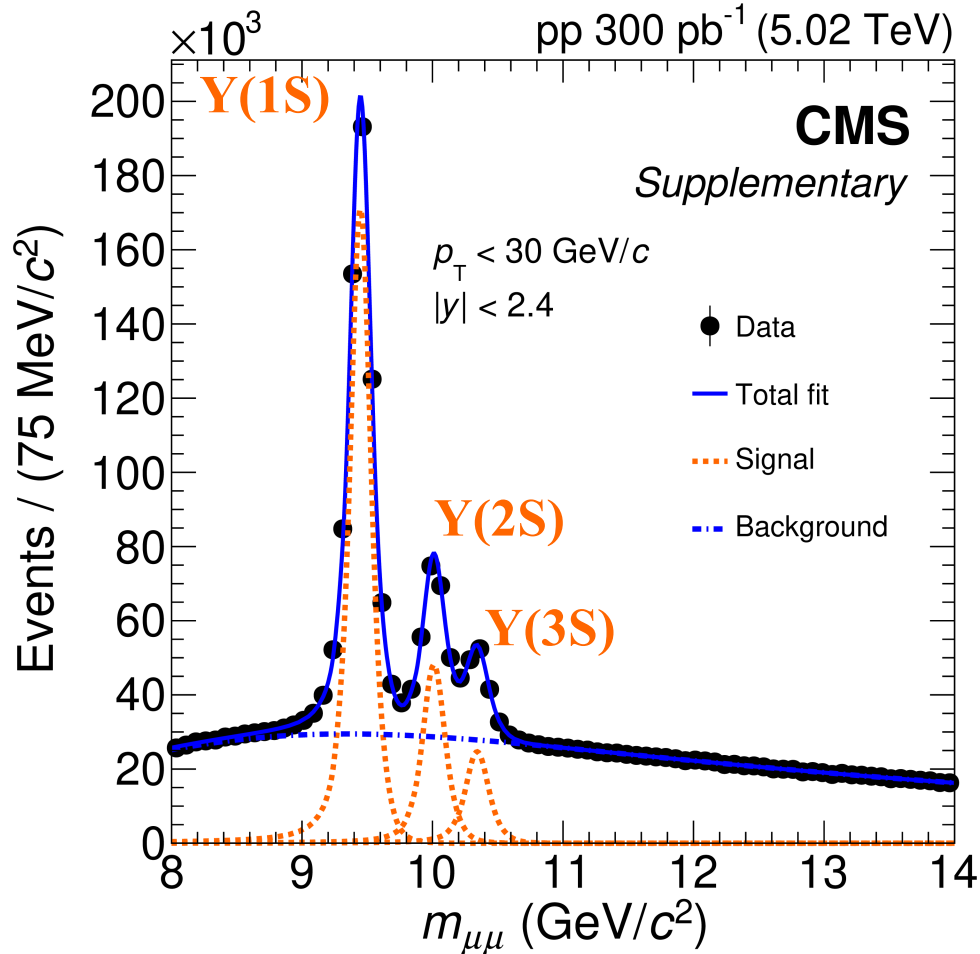
- Increasing suppression for increasing centrality
- $\psi(2S)$ is more suppressed than the J/ ψ meson



Upsilon suppression in Pb+Pb

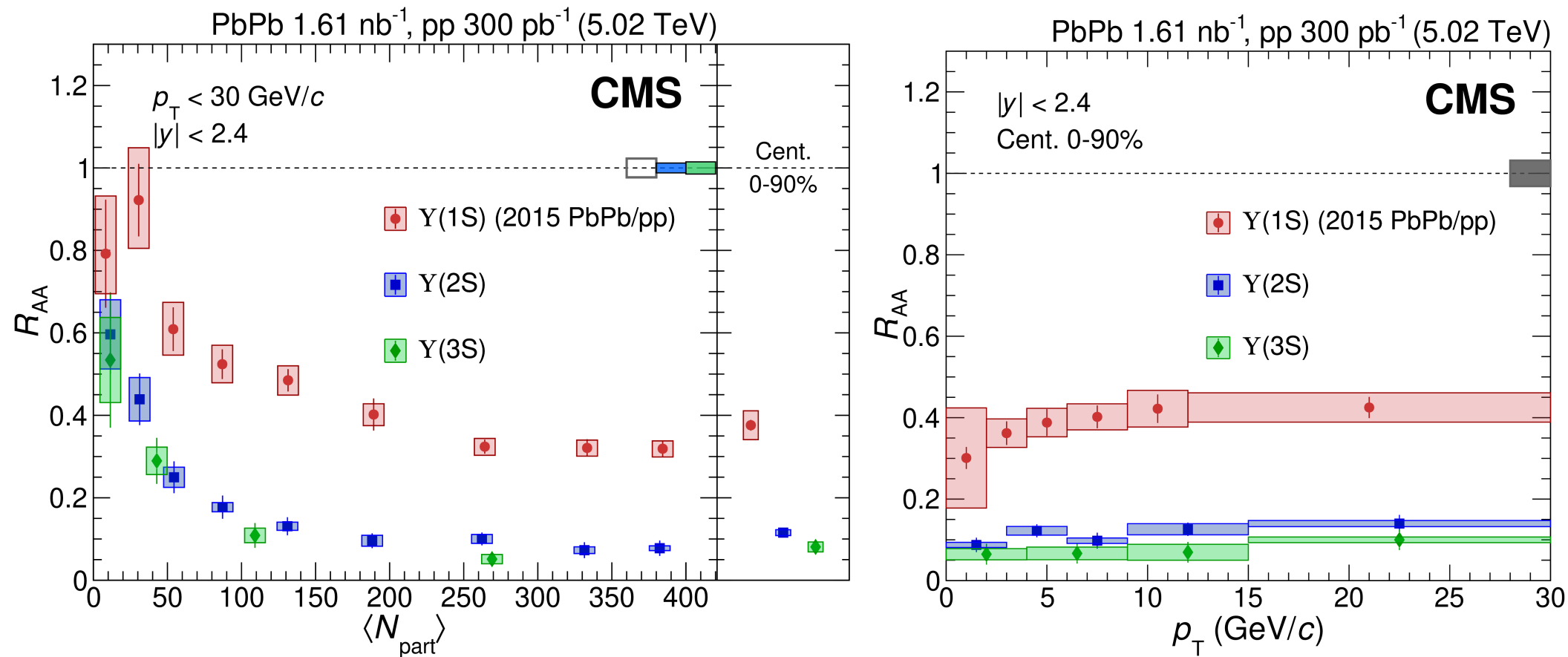


arXiv:2303.17026



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





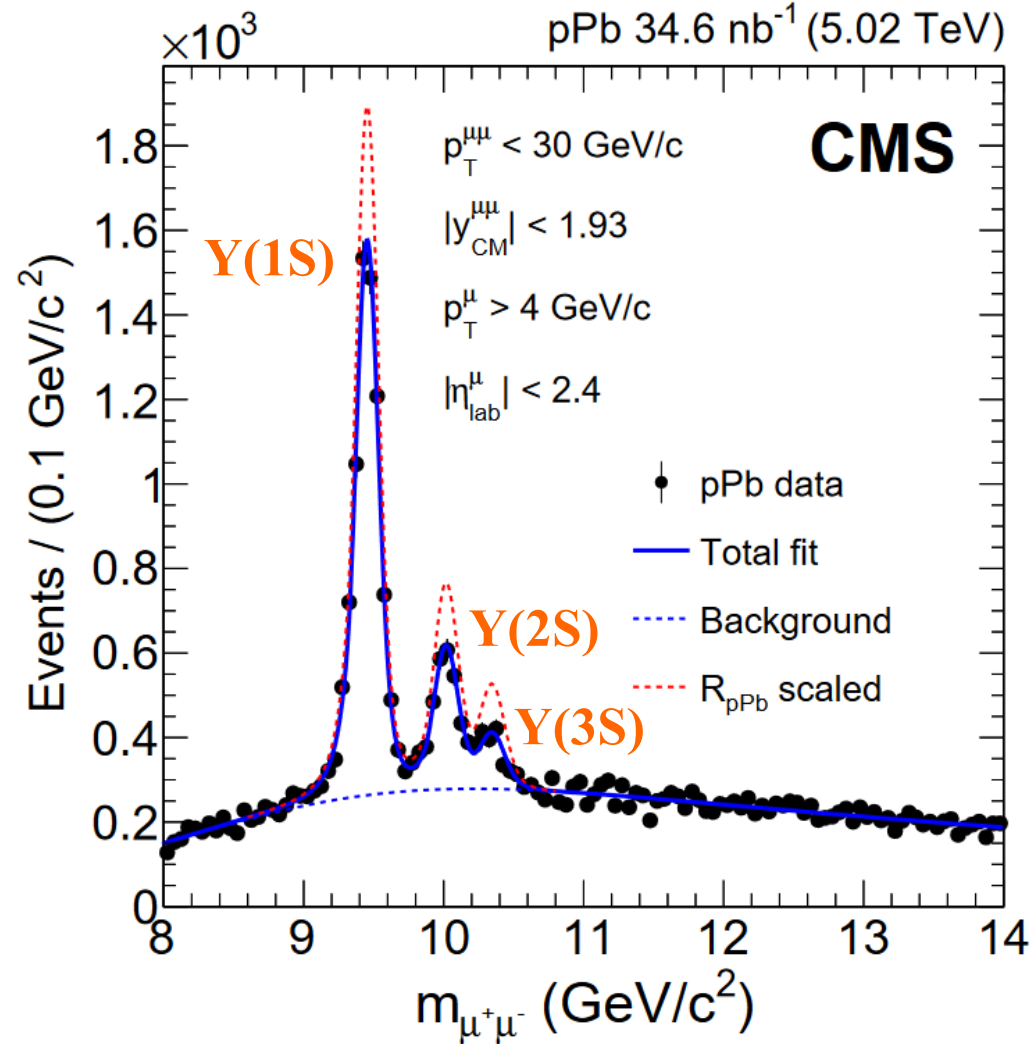
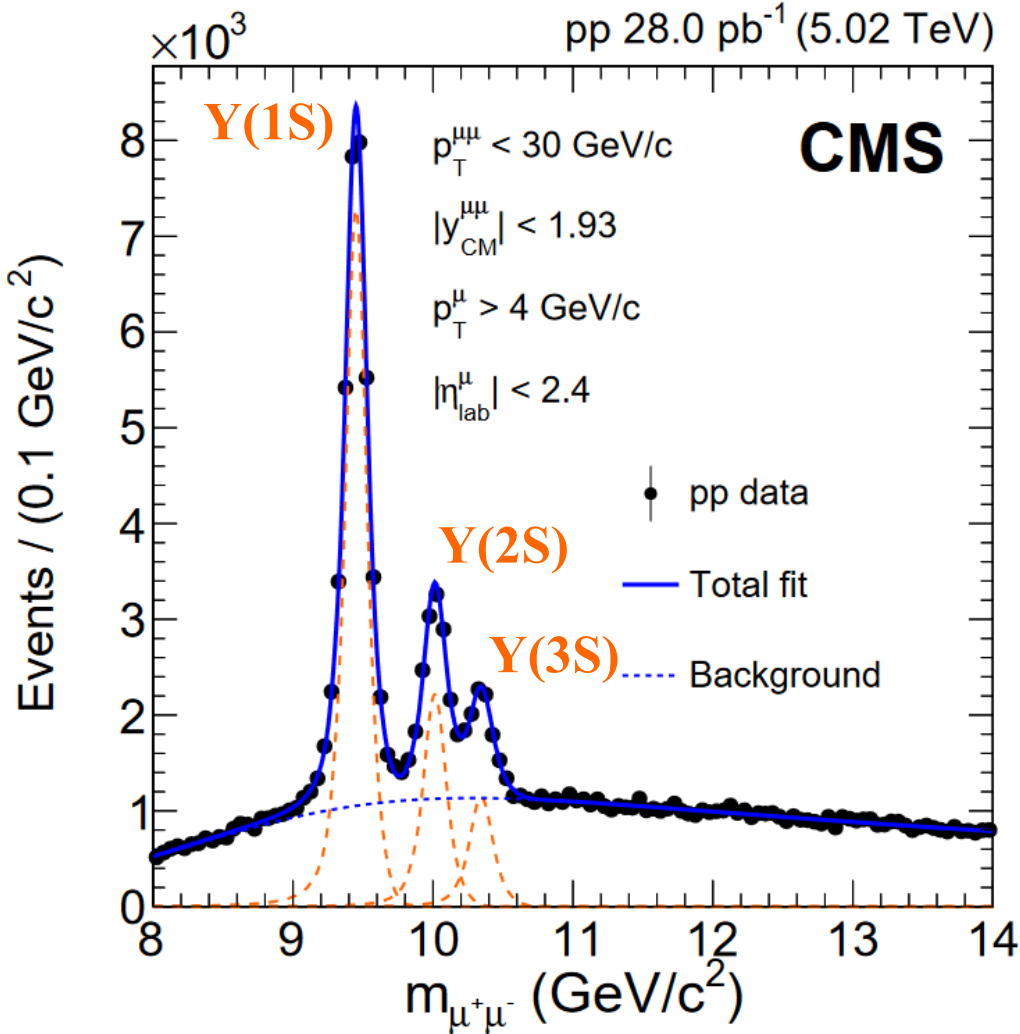
- R_{AA} is decreasing with numbers of participants of Pb+Pb collision.
- Slightly increasing with p_T ?



Upsilon suppression in p+Pb



PLB 835 (2022) 137397



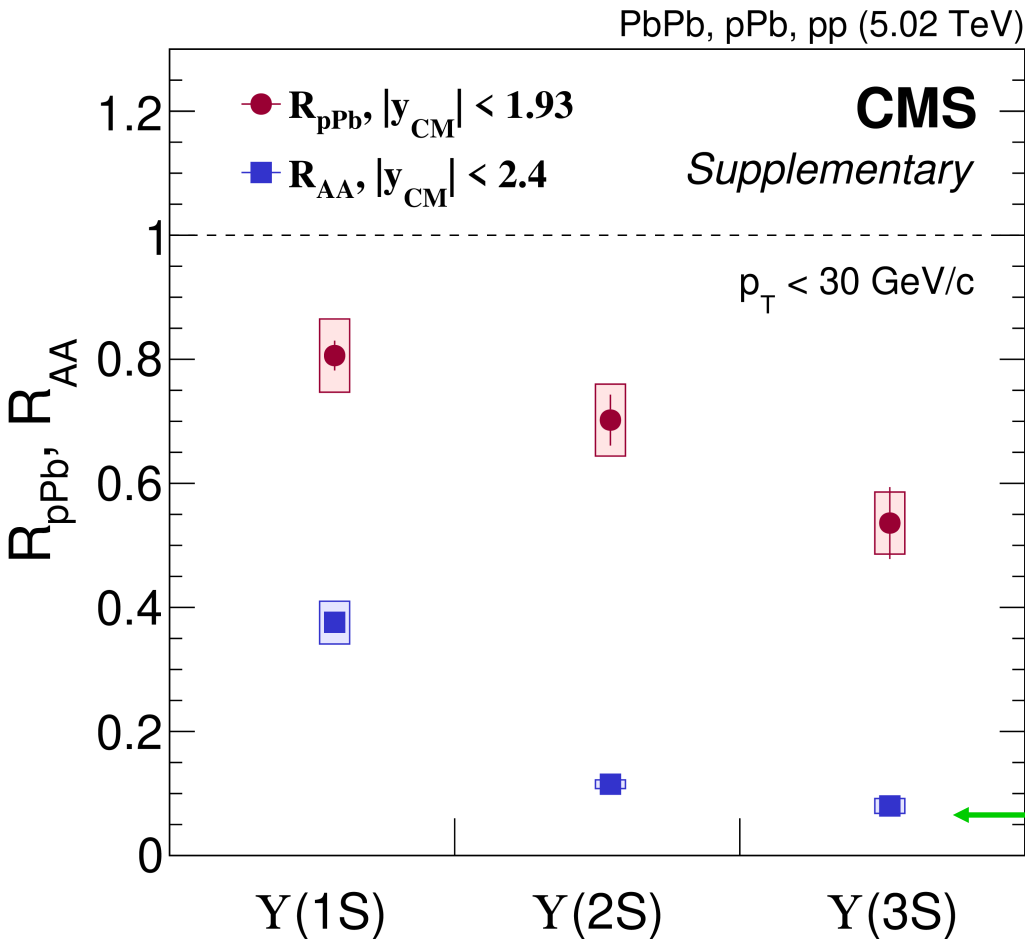
All Y states are found to be suppressed in p+Pb collisions compared to p+p collisions.



Upsilon suppression in p+Pb and Pb+Pb



arXiv:2303.17026



Ordered in binding energy

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

Largest suppression is in Pb+Pb

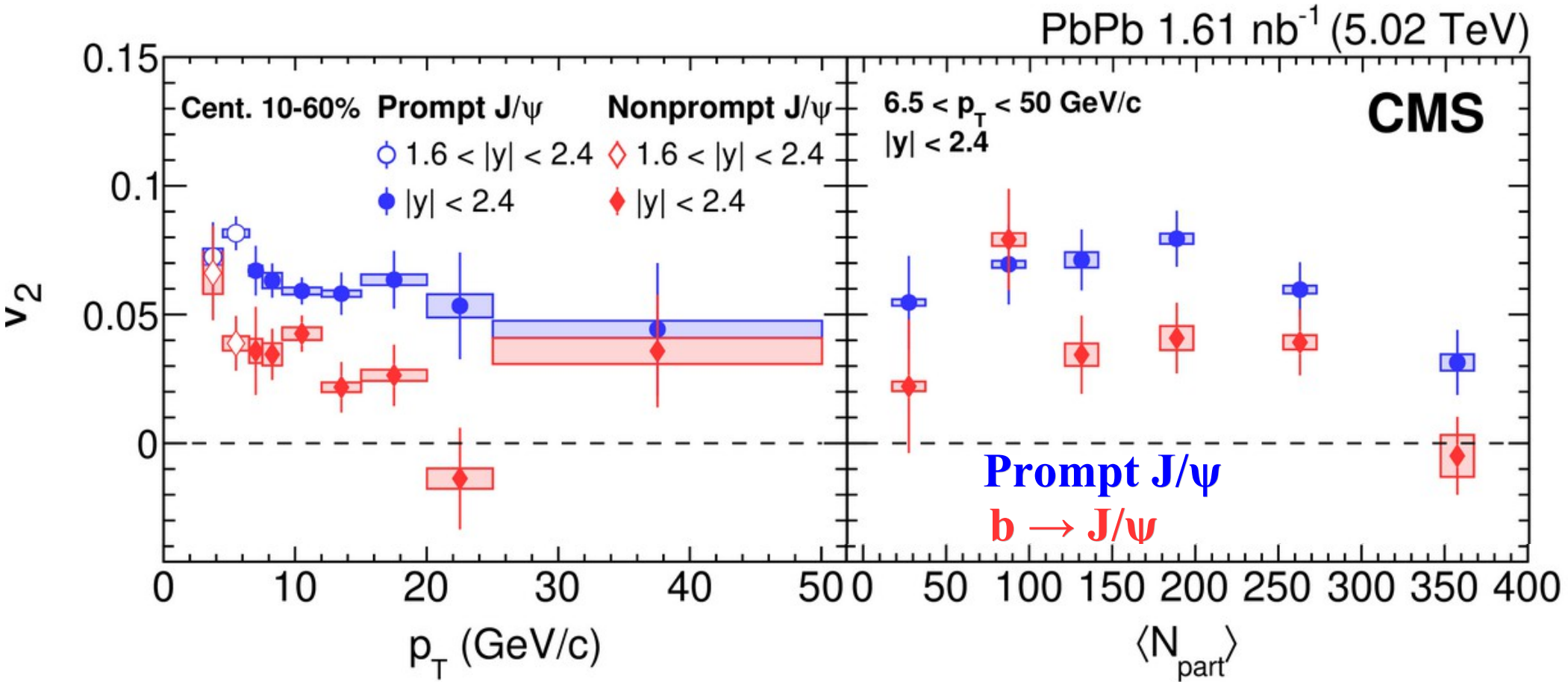
$R_{pPb} > R_{pPb}$

New result for $\Upsilon(3S)$



v_2 of J/ψ in Pb+Pb collisions

arXiv:2305.16928

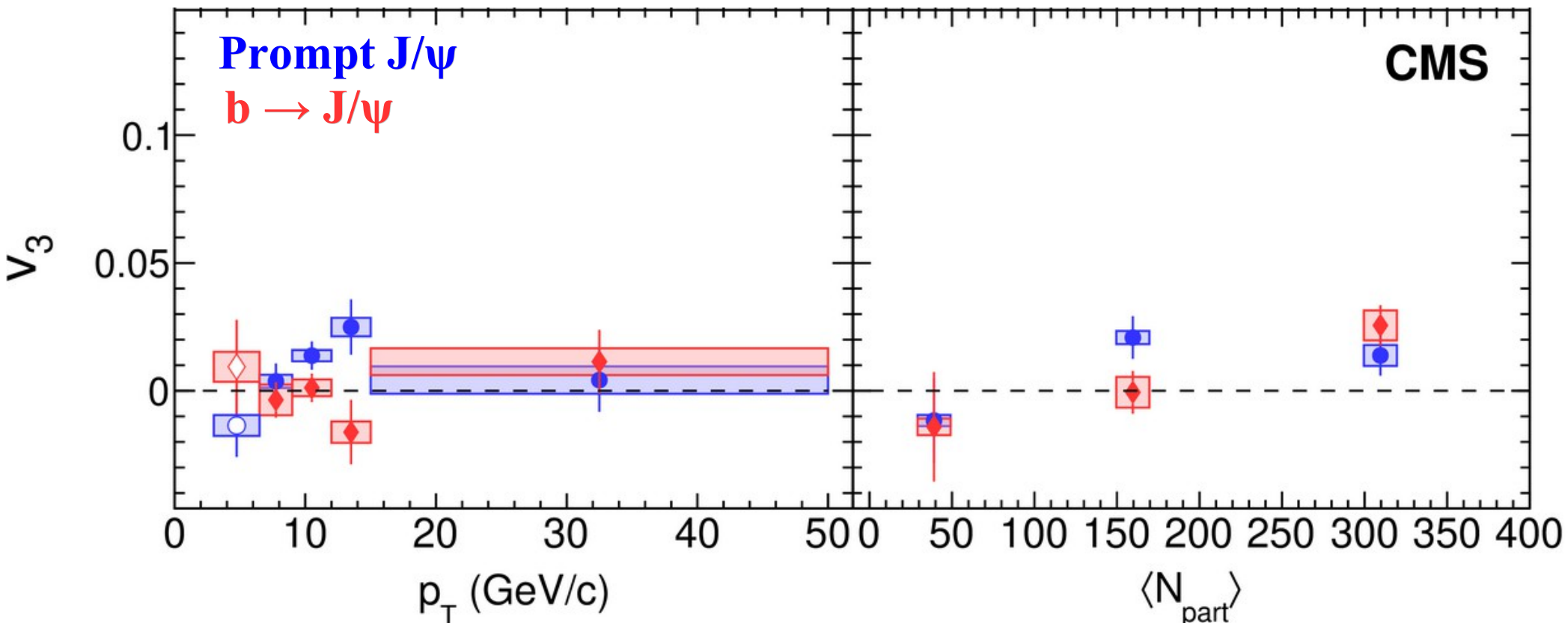
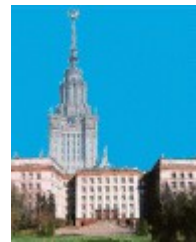


- Large v_2 of J/ψ up to $p_T = 50 \text{ GeV}/c$
- $v_2(b \rightarrow J/\psi) < v_2(\text{prompt } J/\psi)$



v_3 of J/ψ in Pb+Pb collisions

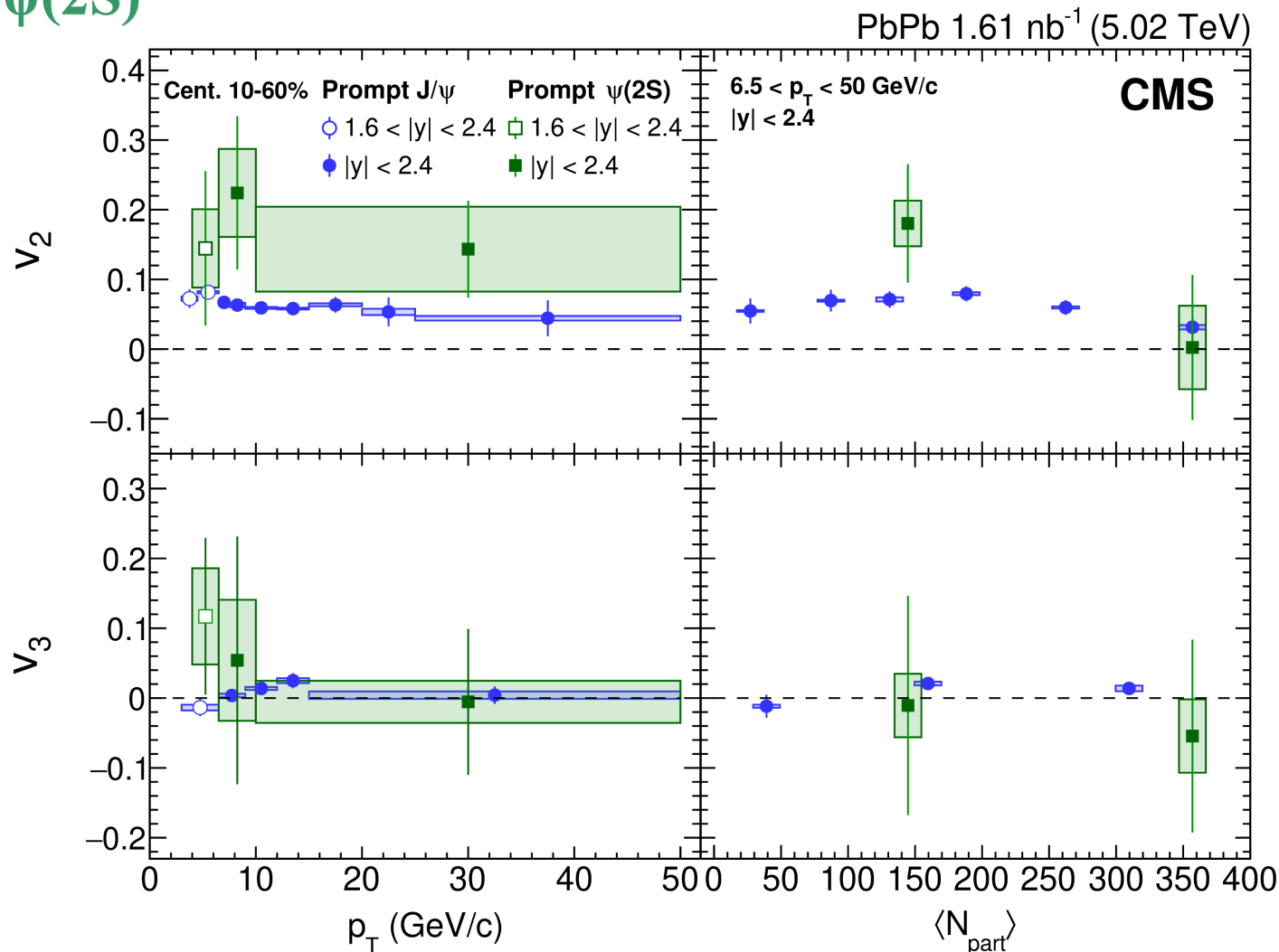
arXiv:2305.16928



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



Prompt $\psi(2S)$

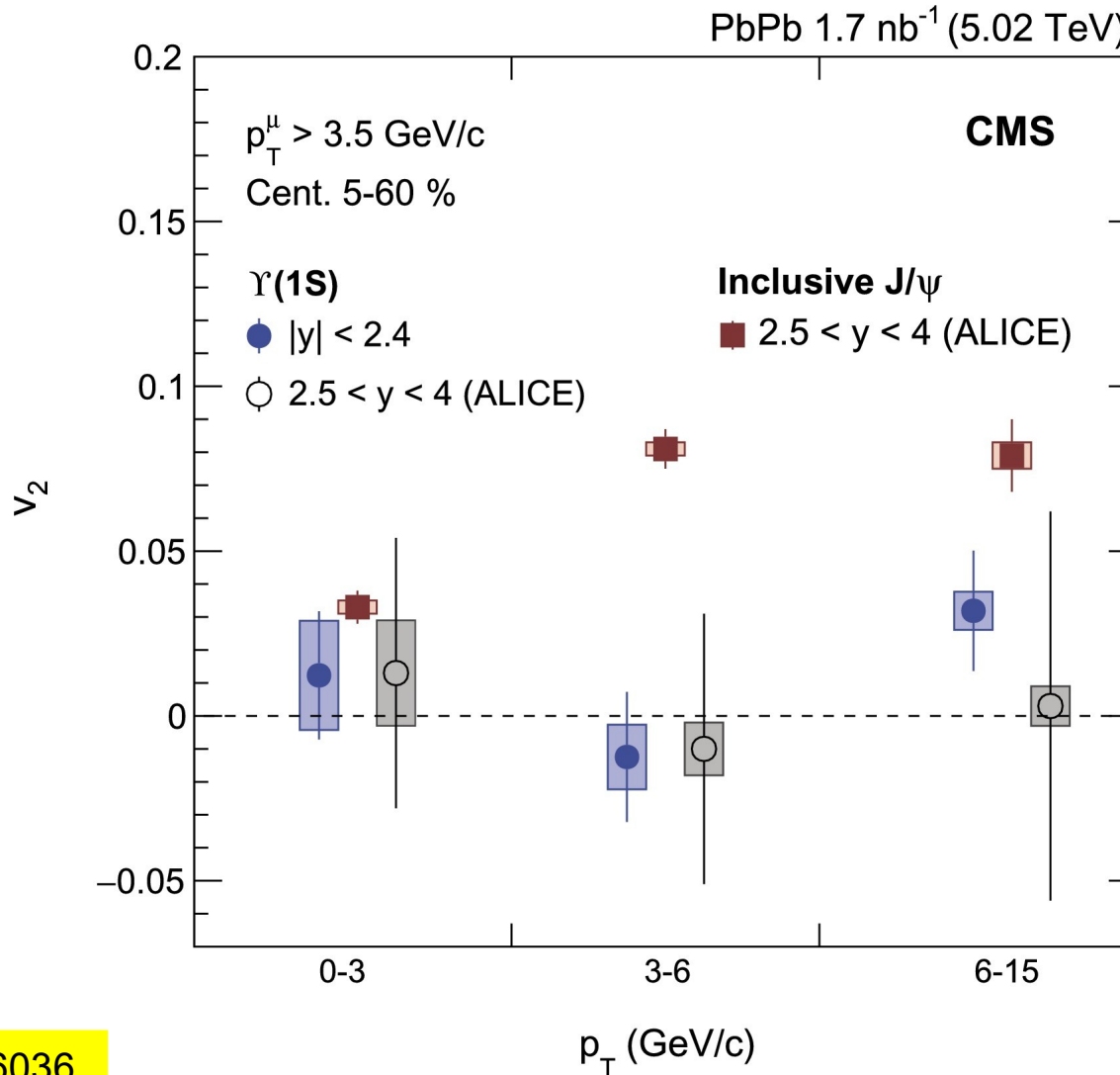


• **First measurements for prompt $\psi(2S)$!**

• **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

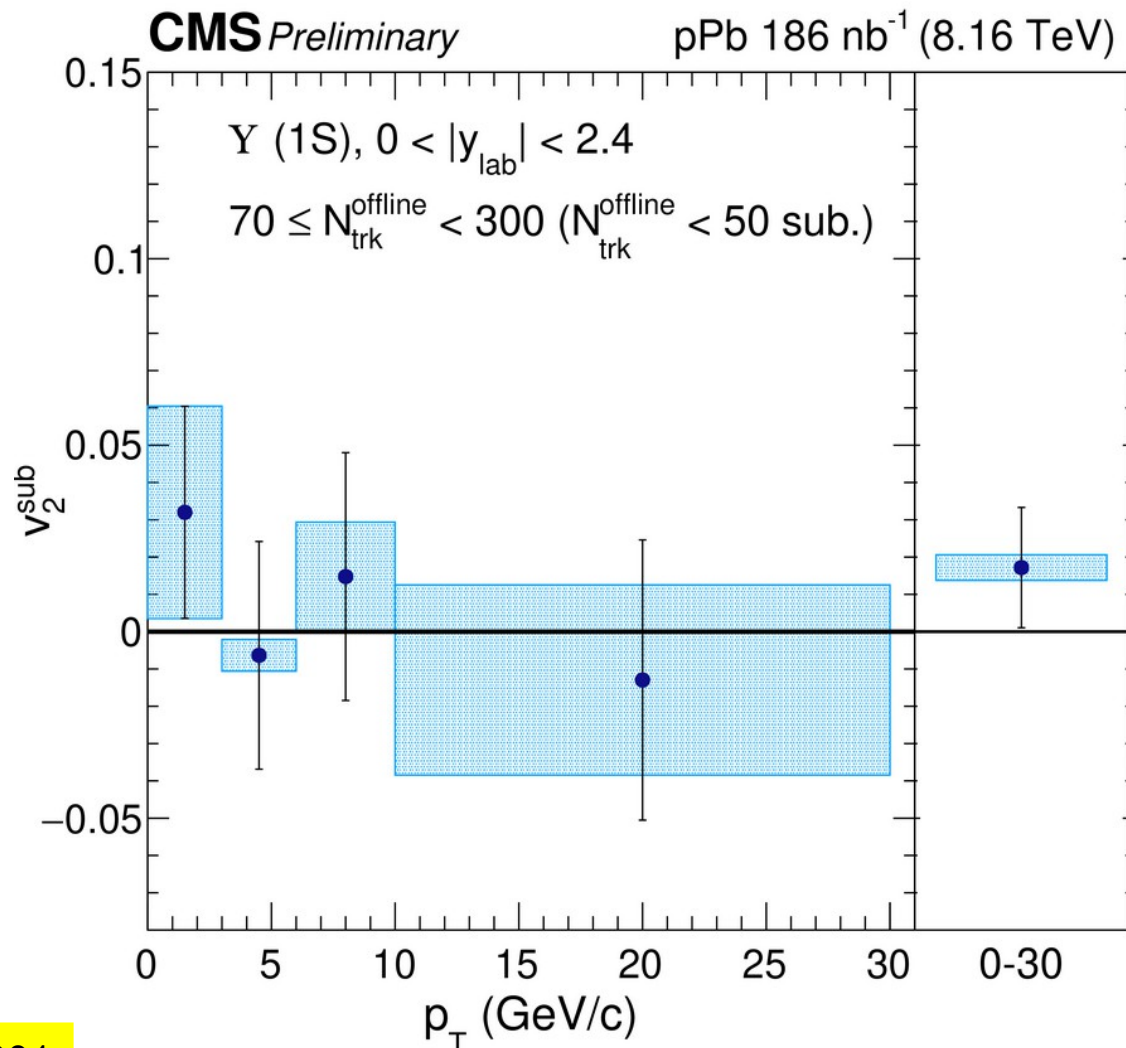


PLB 813 (2021) 136036

**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 !





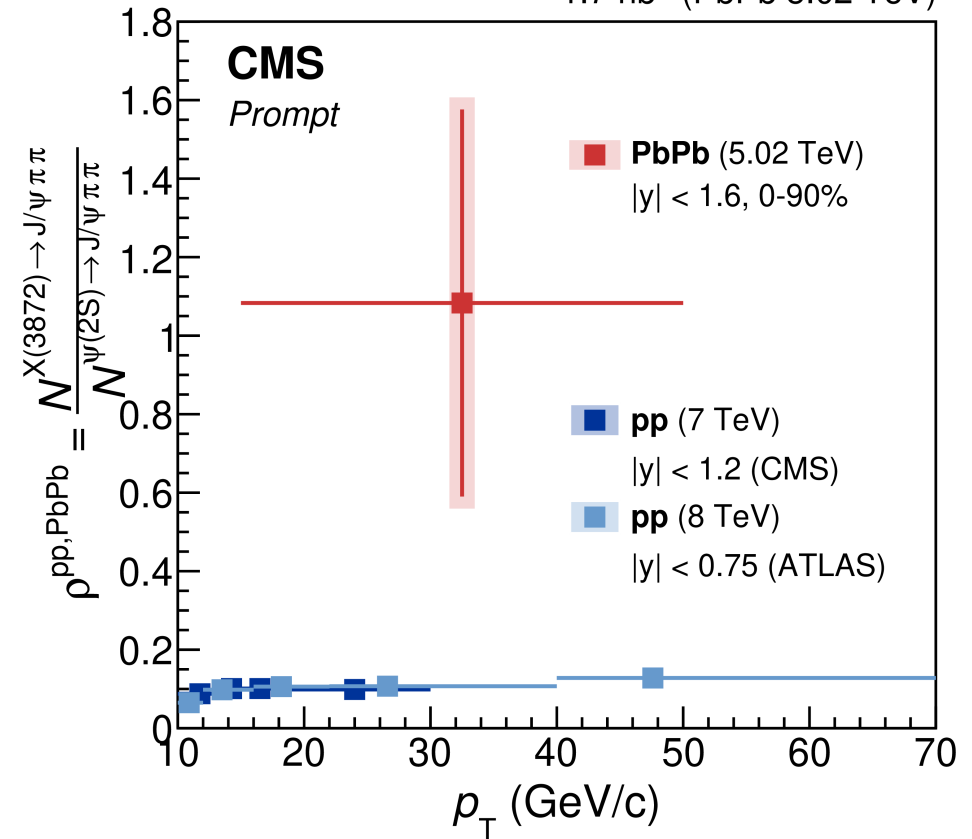
First evidence of X(3872) in Pb+Pb



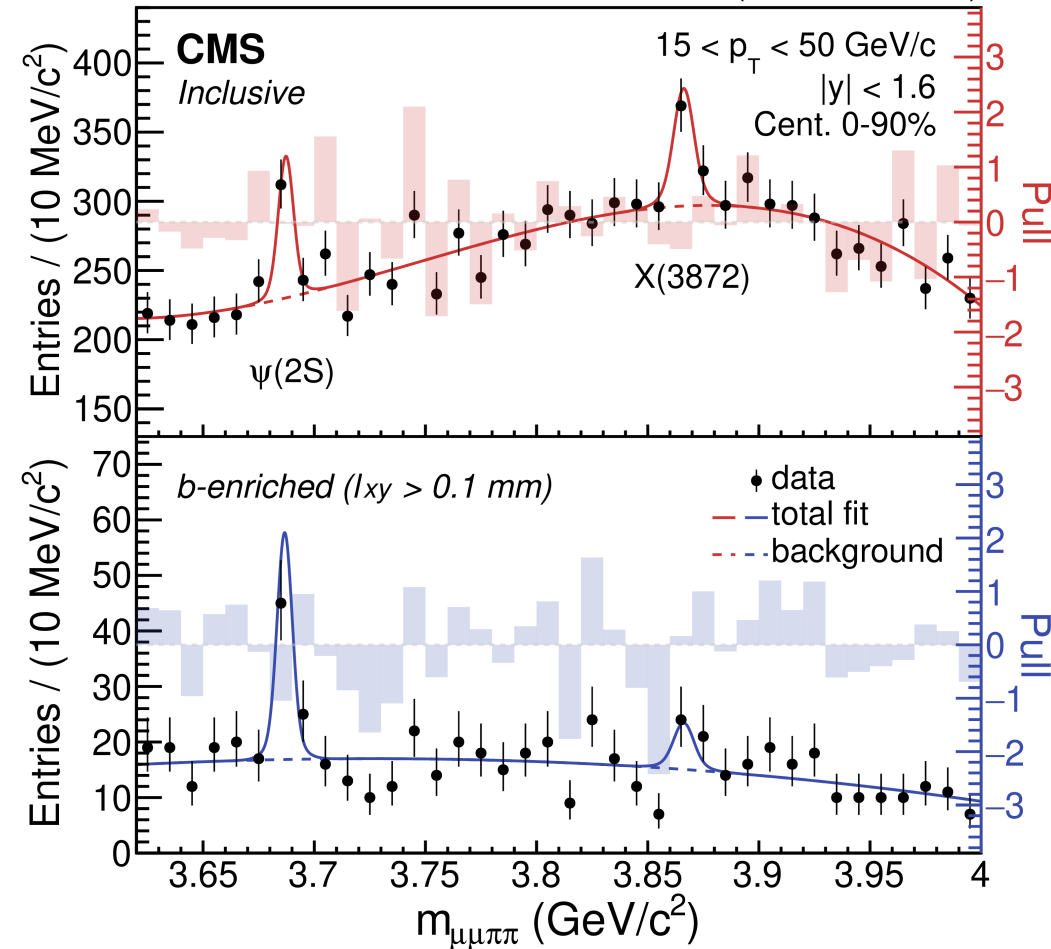
PRL 128 (2022) 032001

Comparison to $\psi(2S)$

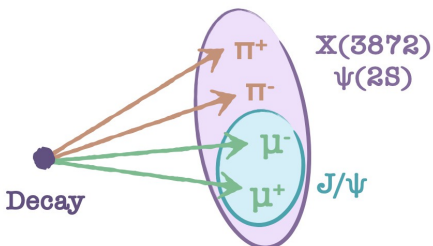
1.7 nb⁻¹ (PbPb 5.02 TeV)



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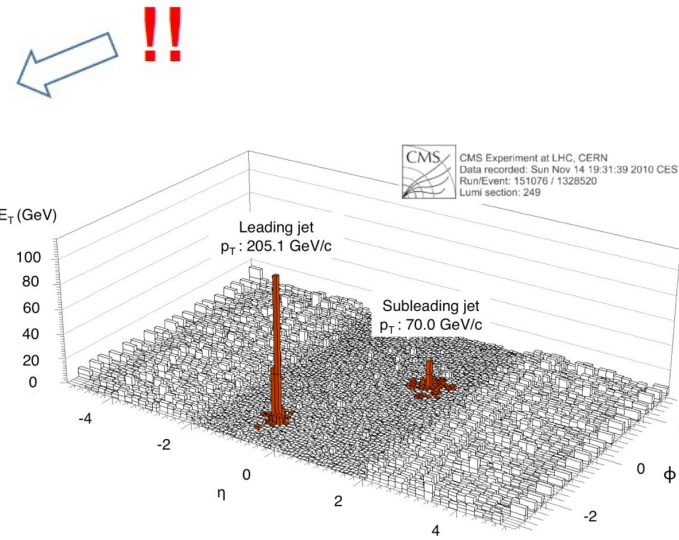
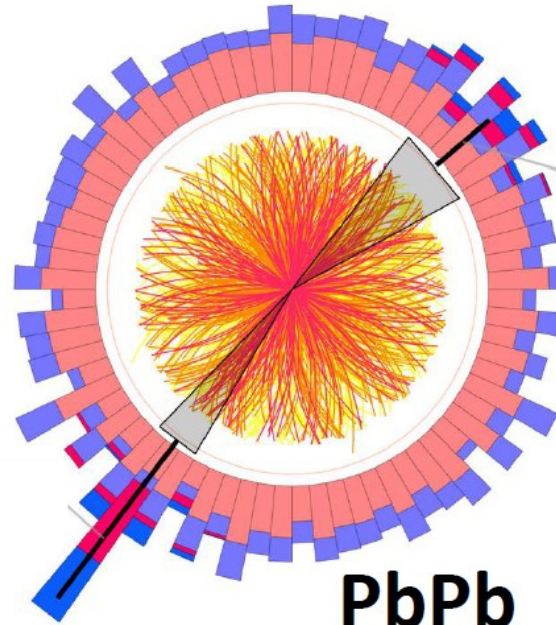
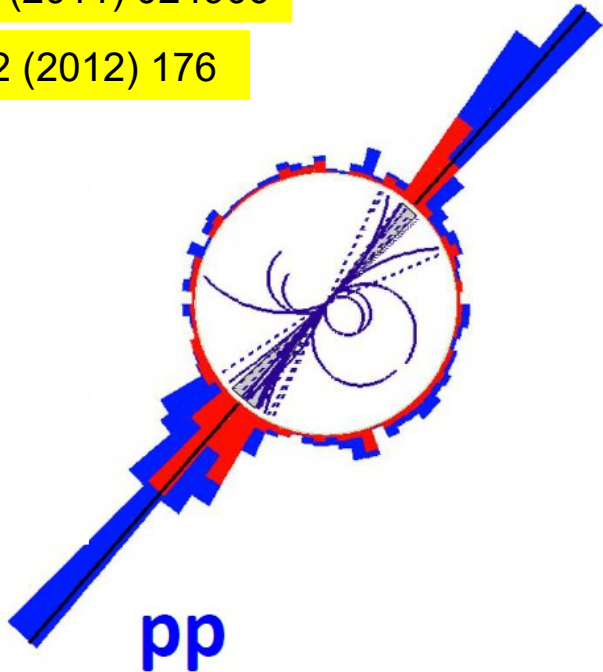
Result provides a unique experimental input to the theory, towards elucidating the production mechanism and the nature of the X(3872).



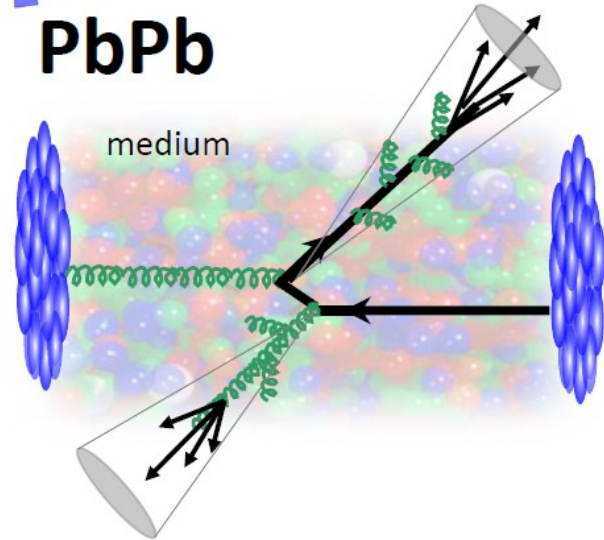
Jet quenching in Pb+Pb



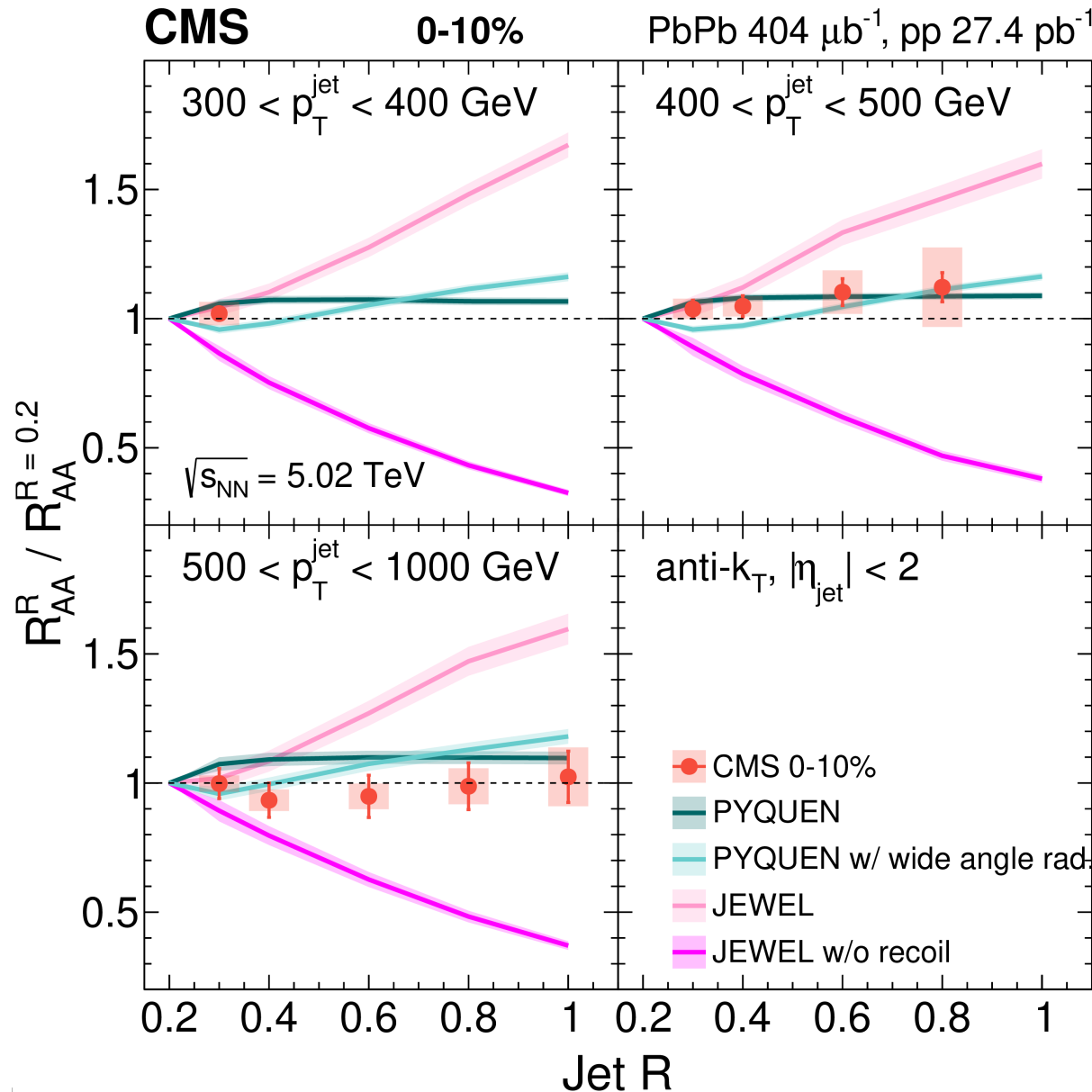
PRC 84 (2011) 024906
 PLB 712 (2012) 176



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



Jet radius scan



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

- Enables simultaneous comparisons of model calculations across jet radii

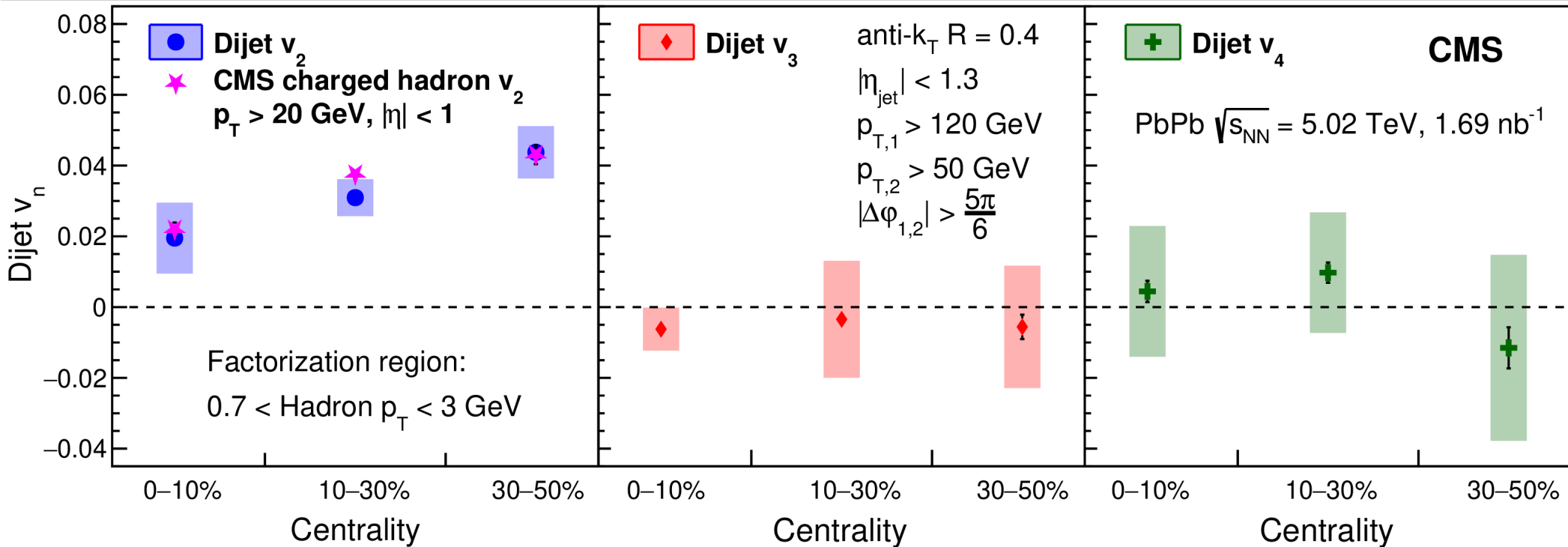
- First time at CMS: no radius dependence of jet energy loss in central Pb+Pb collisions for $400 \text{ GeV} < p_T \text{ jet}$. (Also for $400 < p_T \text{ jet} < 500 \text{ GeV}$)



Azimuthal anisotropy of di-jets in Pb+Pb

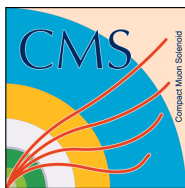


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- v_2, v_3 and v_4 of the di-jets in Pb+Pb were measured for the first time
- Di-jets v_2 is compatible with v_2 of high p_T hadrons
- Di-jets v_3 and v_4 are consistent with zero



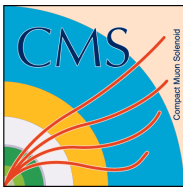


CMS Summary for Heavy-Ions

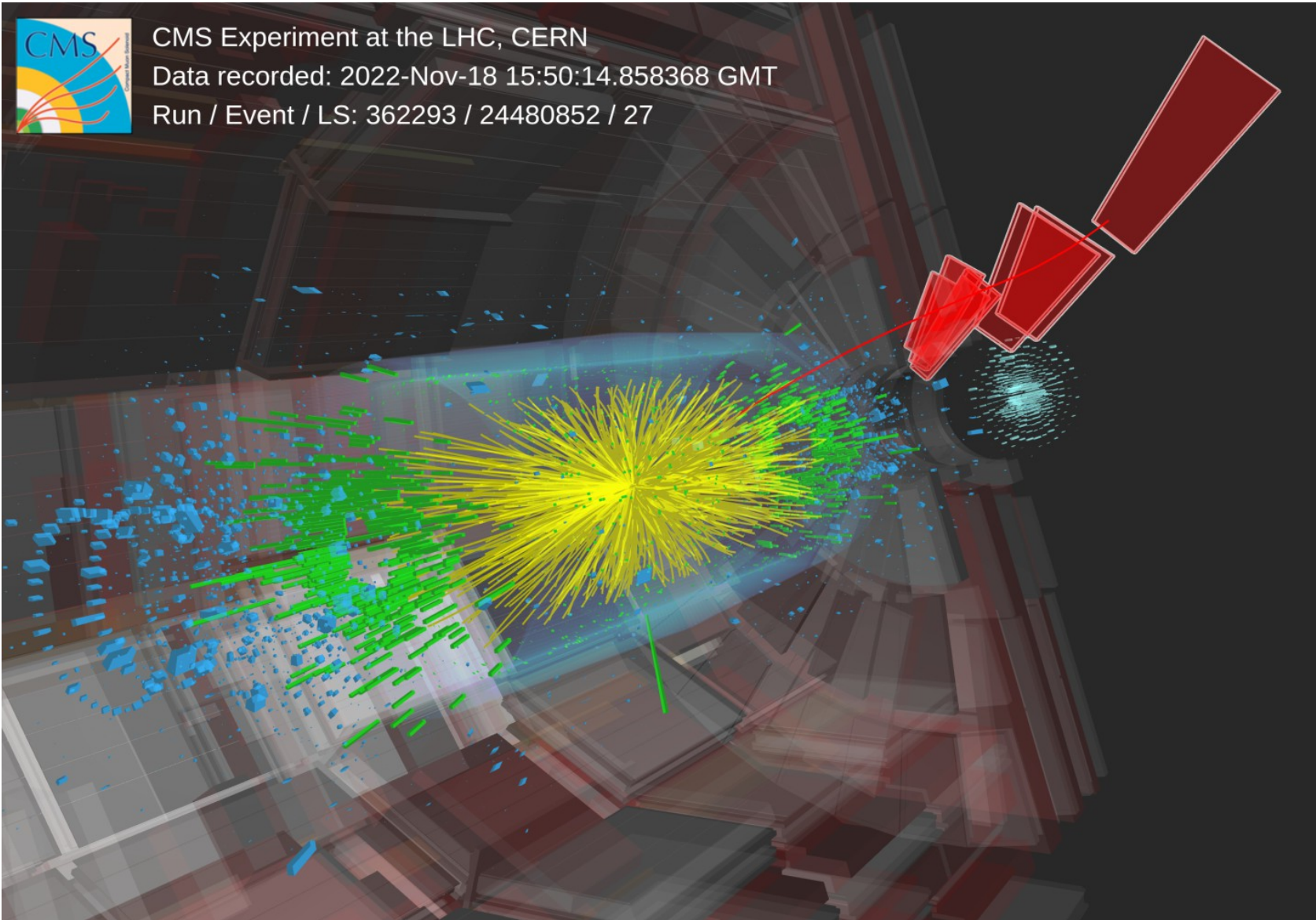


- **Many interesting heavy-ion physics results with the CMS detector in p+p, p+Pb, Pb+Pb and Xe+Xe...**
- **Future heavy-ion program at the LHC (Run 3 and 4) with the upgraded CMS detector will provide more exciting opportunities! Stay tuned!**





Run 3 was started in July 2022



**One of the first Pb-Pb collisions during Run 3 in CMS detector.
Lead beams traveled for 3 days (17-19 November 2022) in the LHC !**

