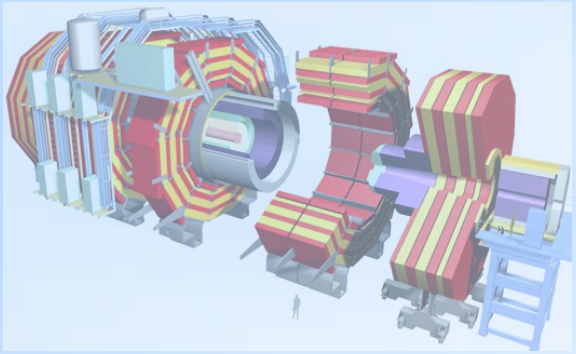
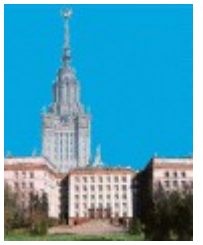
Sergey Petrushanko
(for CMS Collaboration)
SINP MSU Russia

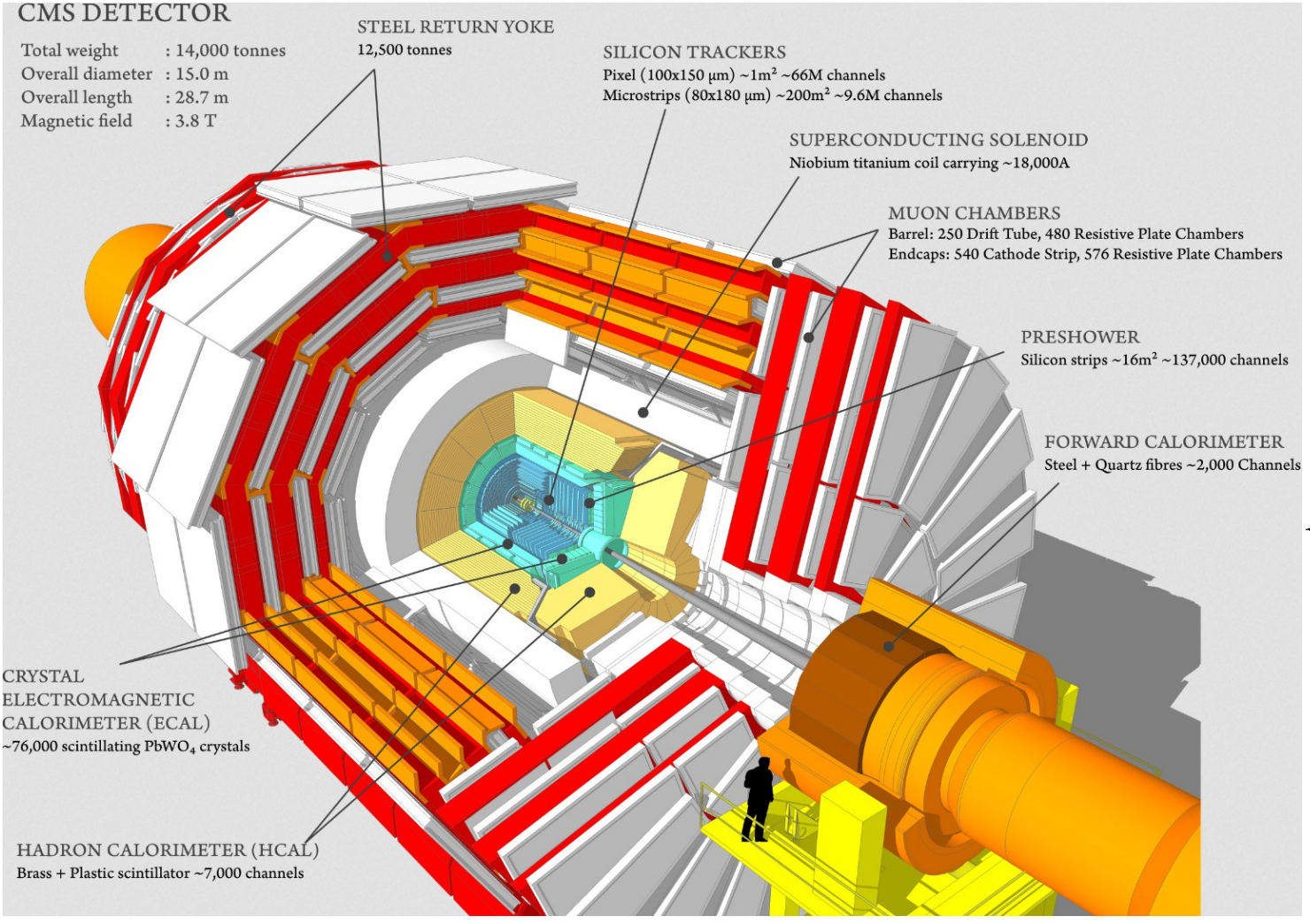
Heavy-ion Physics at CMS

20th Lomonosov Conference
on Elementary Particle Physics
Moscow, Russia
19-22 August 2021



CMS is a nice heavy-ion experiment



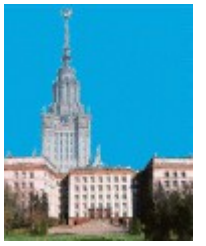


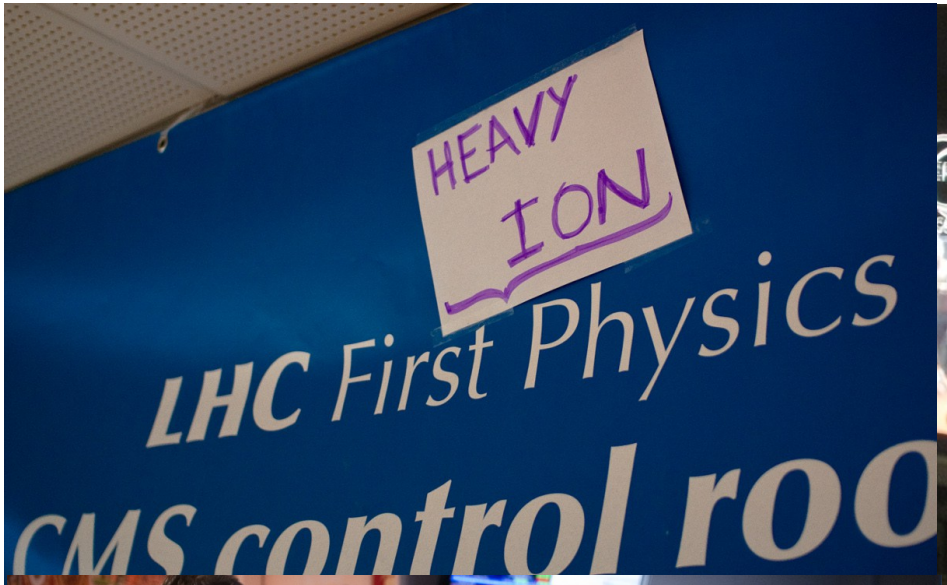
- **Silicon Tracker**
  $|\eta| < 2.4$
- **Electromagnetic Calorimeter**
  $|\eta| < 3.0$
- **Hadron Calorimeter**
  barrel and endcap
  $|\eta| < 3.0$
  with HF-calorimeter up to
  $|\eta| < 5.2$
- **Muon Chambers**
  $|\eta| < 2.4$

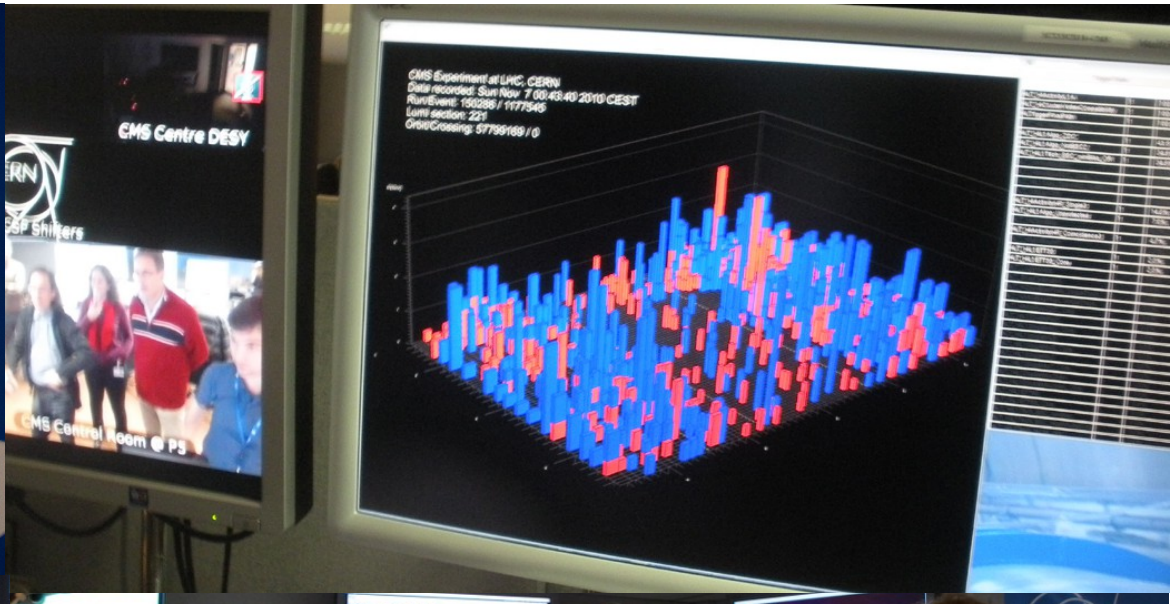
+ CASTOR detector
$5.2 < |\eta| < 6.6$
+ Zero-degree calorimeter
+ TOTEM

Magnetic field: 3.8 Tesla

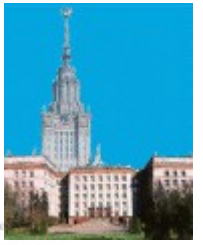
November 7, 2010 0:27. CMS Control Room.







CMS heavy-ion physics results



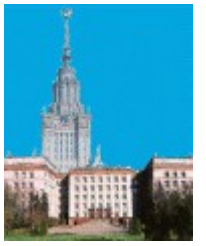
110 published/submitted
Heavy-ion Physics CMS papers:

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

…and also
Heavy-ion Physics CMS preliminary results:

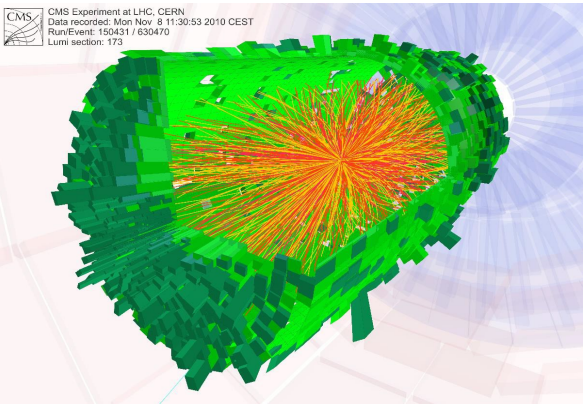
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIN/index.html

CMS heavy-ion results

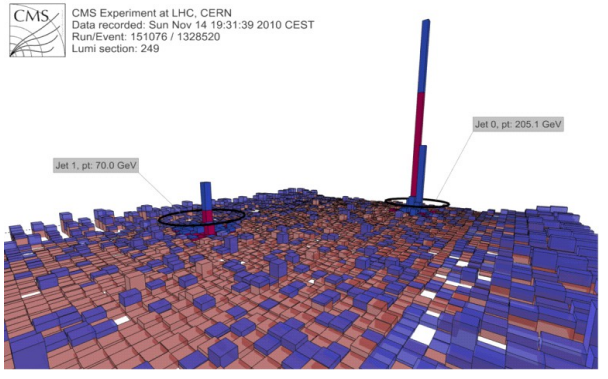


- **Global picture of heavy-ion collisions**
  - multiplicity,
  - energy,
  - flow, ...

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

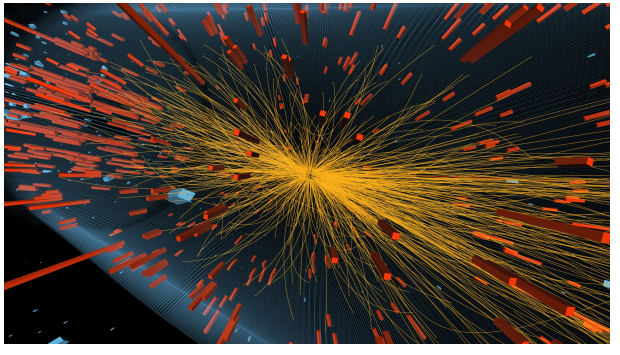


- **Hard probes**
  - jets
  - dimuons
  - charged hadrons R_{AA}, ...

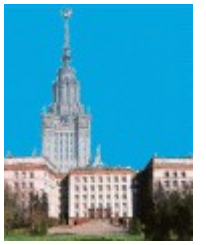


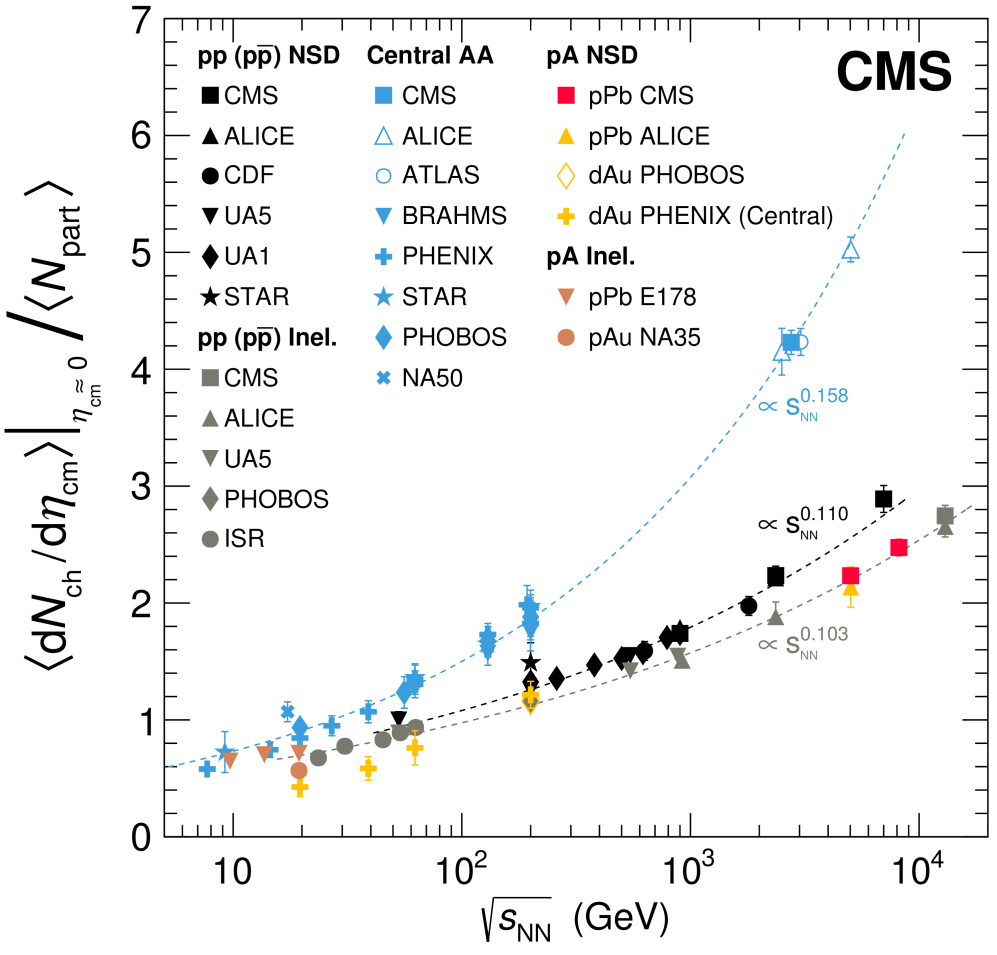
- **p+p, p+Pb, Xe+Xe**
  - correlations
  - flow,
  - jets, ...

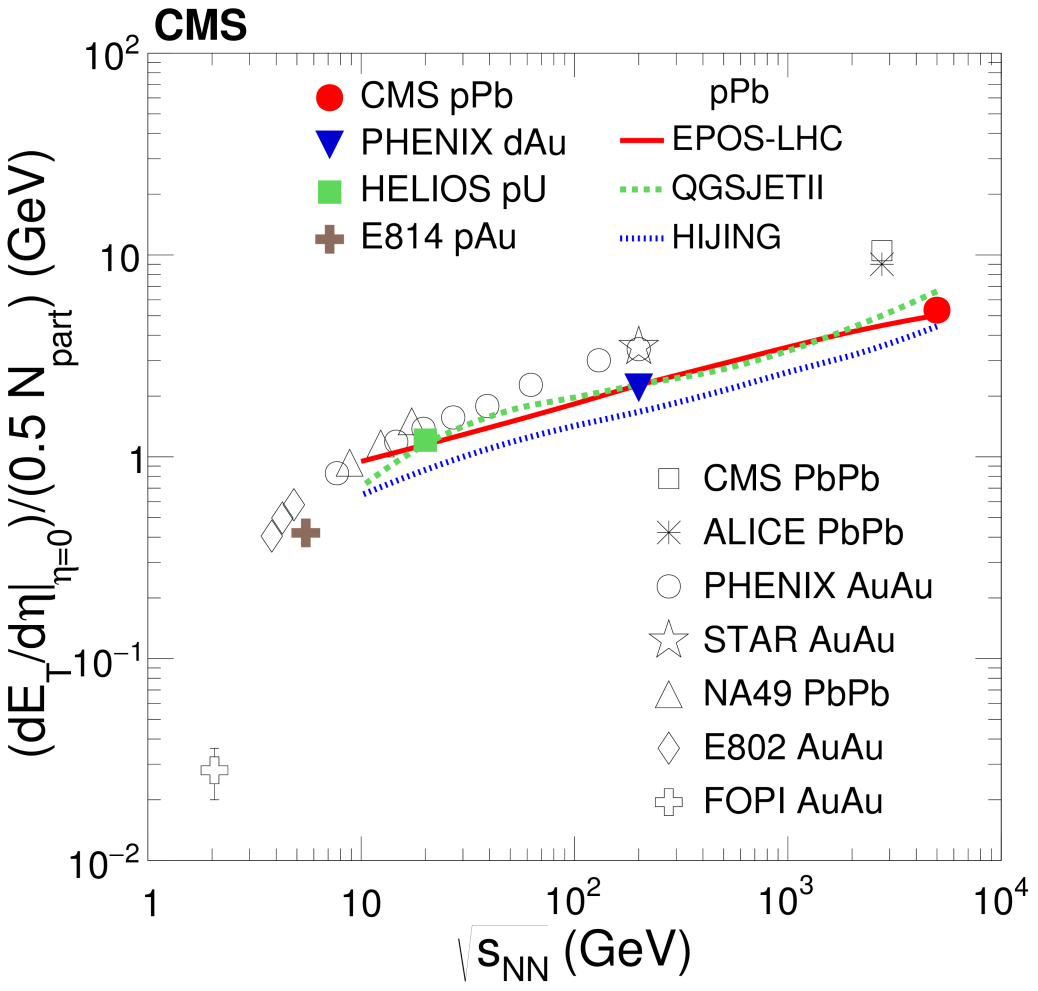
p+p 2.76, 5.02, 7, 8, 13 TeV
p+Pb 5.02, 8.16 TeV
Xe+Xe 5.44 TeV



Charged particle multiplicity
Transverse energy density



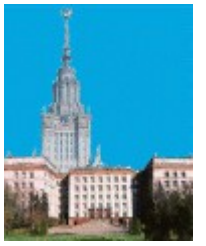




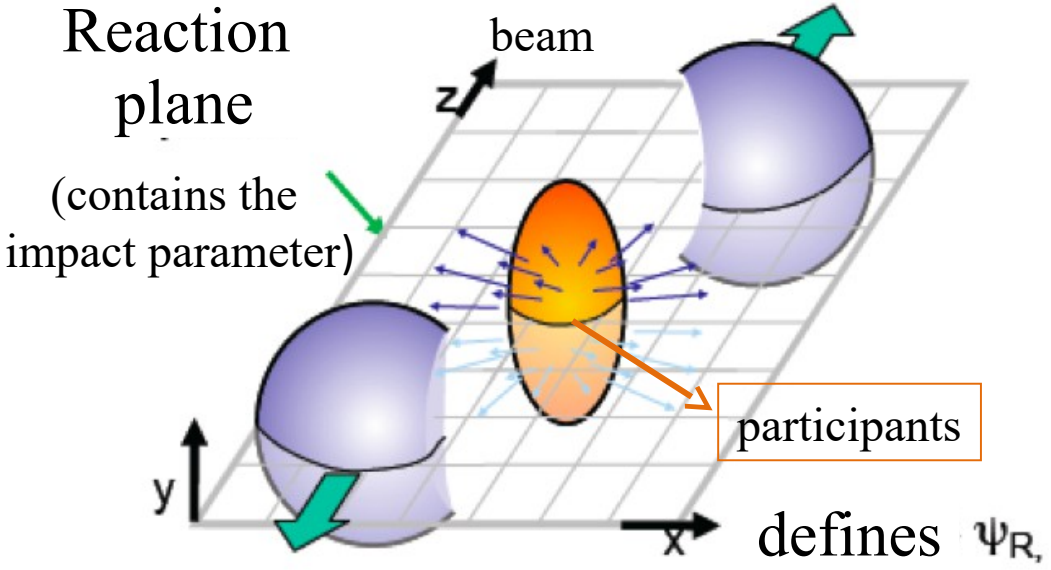
JHEP 01 (2018) 045

PRC 100 (2019) 024902

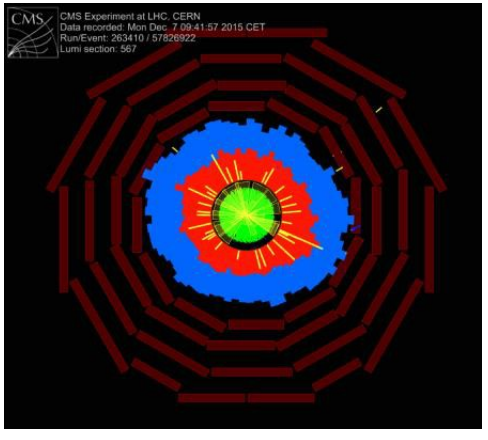
- √s dependence:
  - p+p, p+Pb, Pb+Pb follow power law

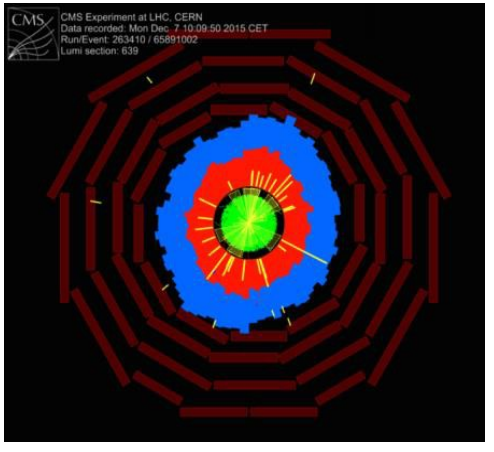


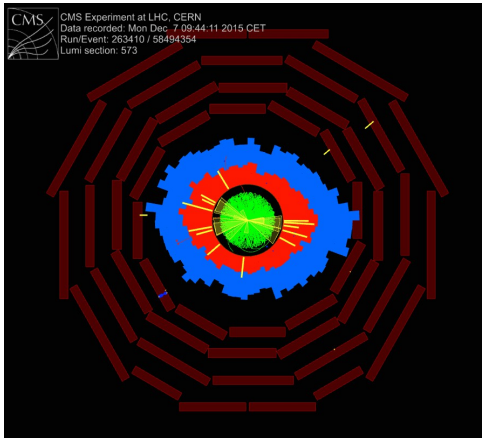
Flow



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

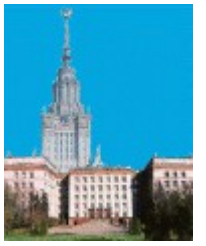






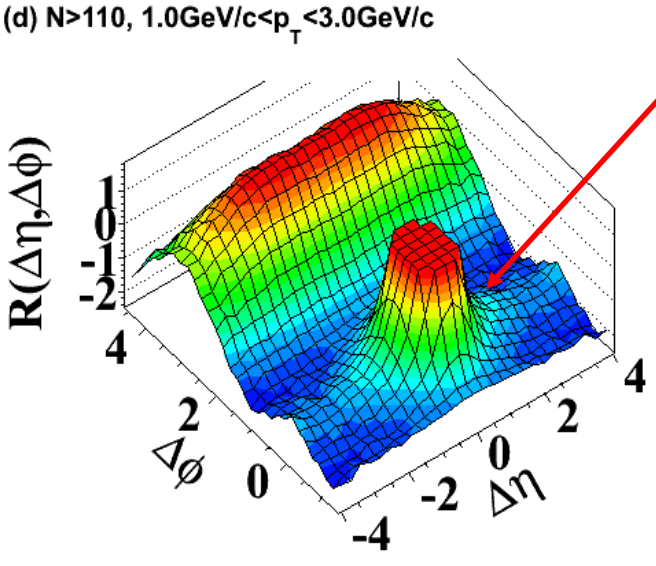
Collective motion is observed in the event azimuthal distributions

Correlations: "RIDGE" everywhere...



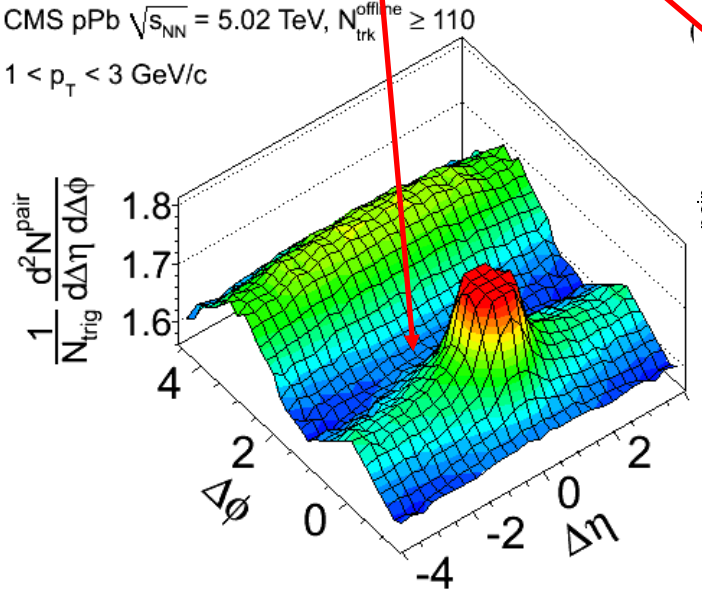
Long-range ($2 < |\Delta\eta| < 4$), near-side ($\Delta\phi \approx 0$)
angular correlations were observed in high multiplicity p+p and p+Pb collisions (as well as in Pb+Pb)

p+p 7 TeV



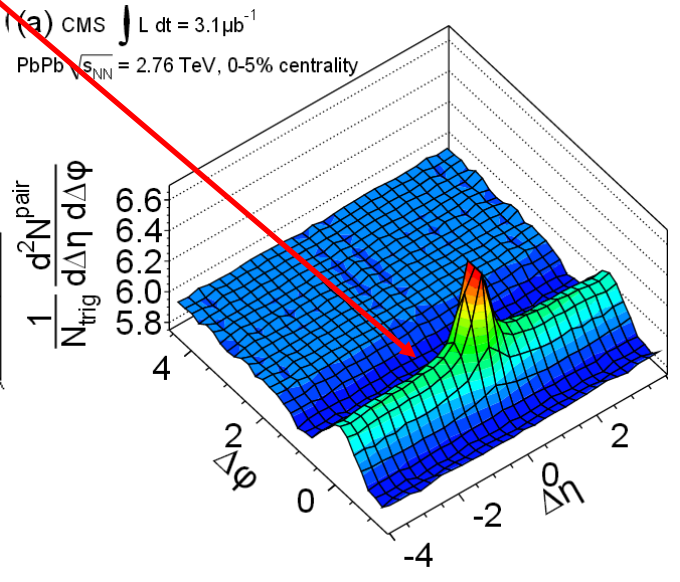
JHEP 09 (2010) 091

p+Pb 5.02 TeV



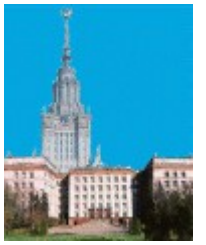
PLB 718 (2013) 795

Pb+Pb 2.76 A TeV, 0-5%

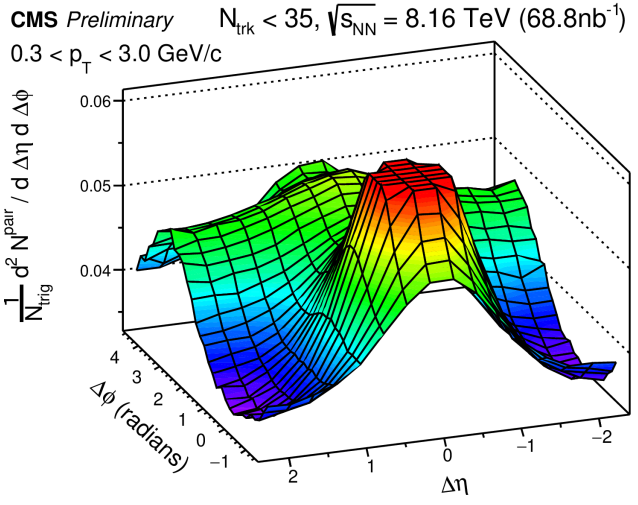


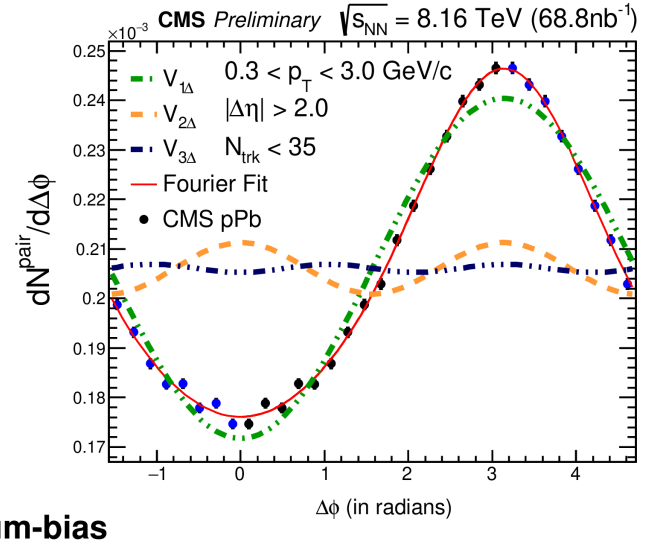
JHEP 07 (2011) 076

γp interactions within ultra-peripheral p+Pb collisions

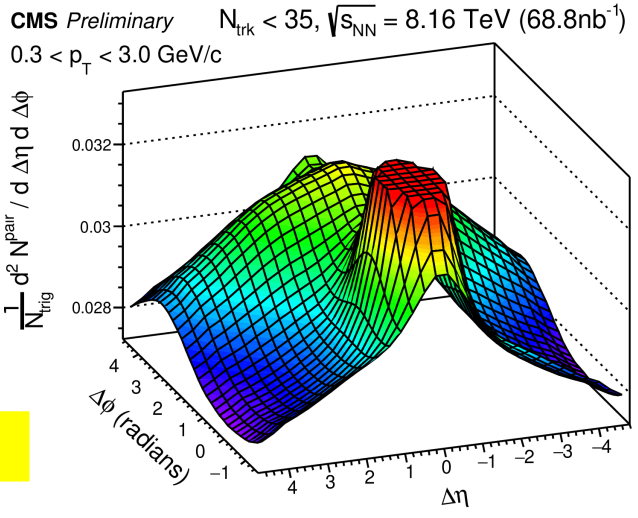


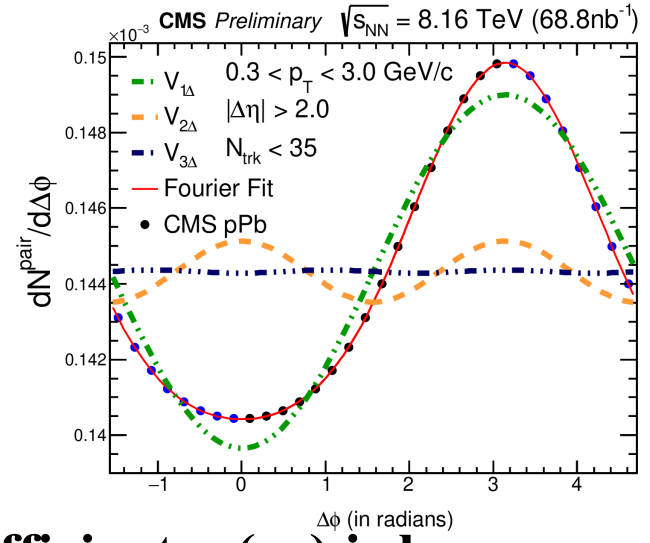
γp enhanced





Minimum-bias

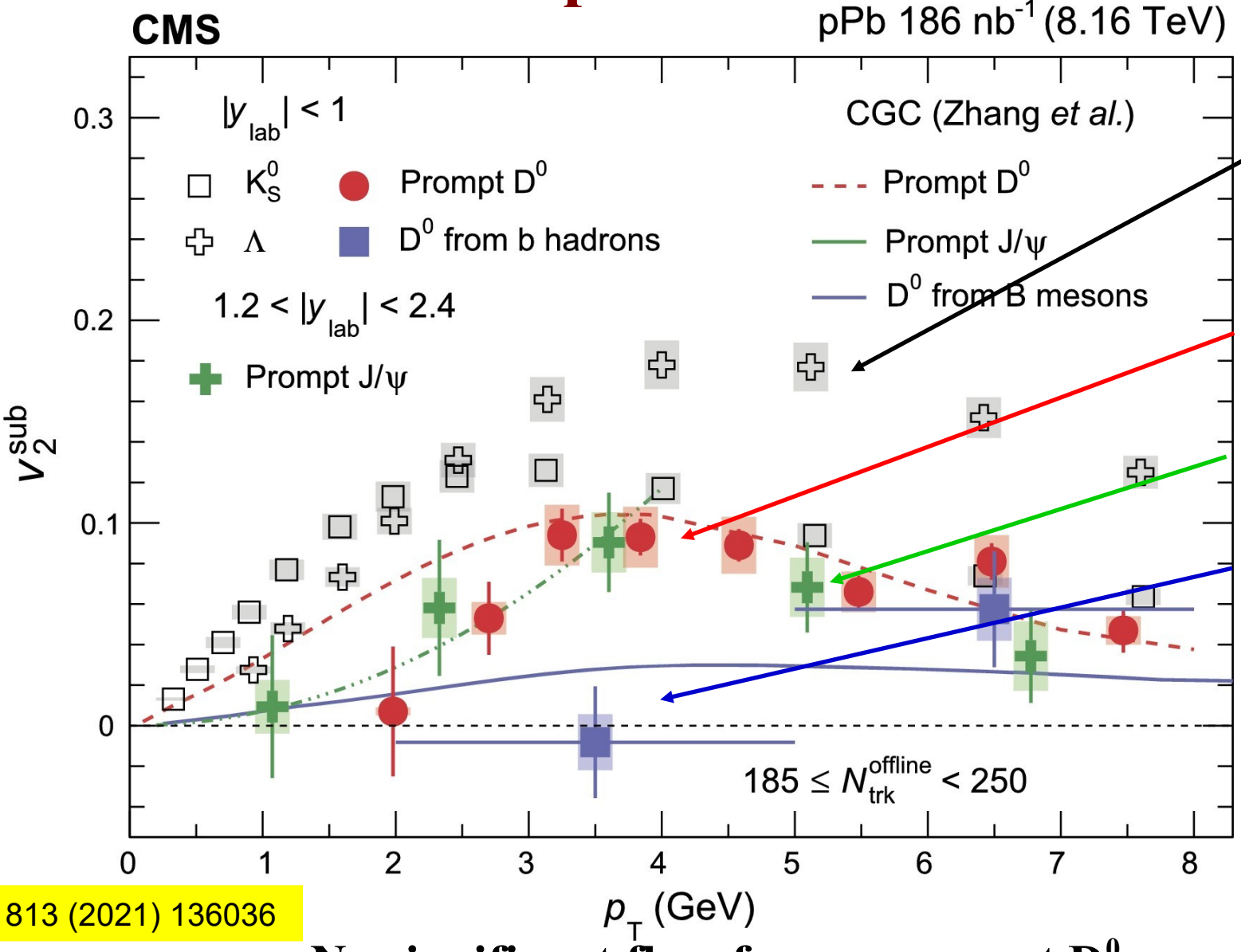




CMS-PAS-HIN-18-008

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

Charm and beauty long-range correlations in p+Pb collisions



Theory

Open charm

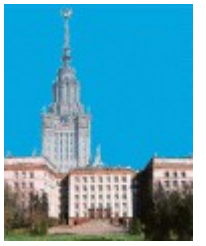
Hidden charm

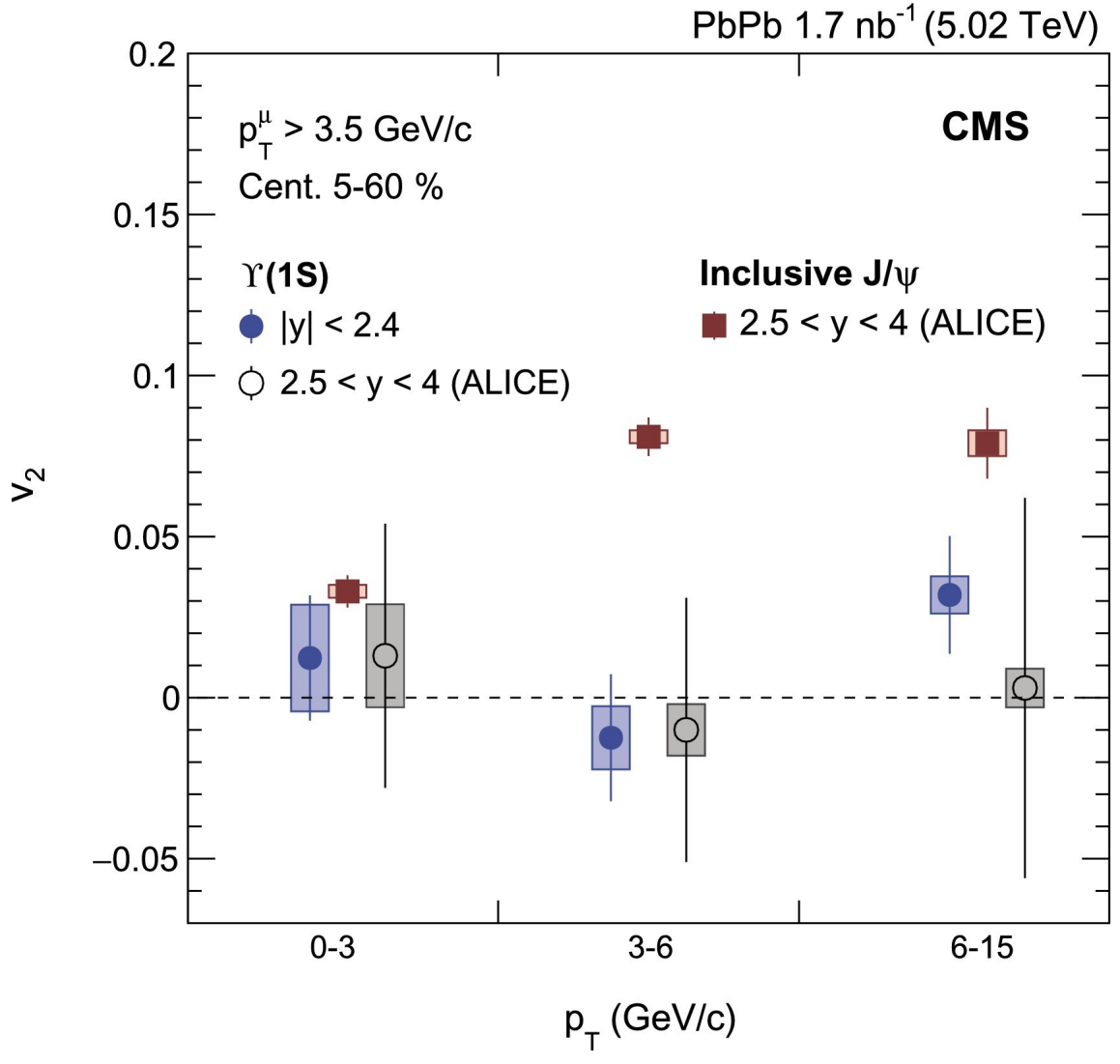
Open beauty

PLB 813 (2021) 136036

No significant flow for nonprompt D^0

Measurement of v_2 of Υ in Pb+Pb collisions

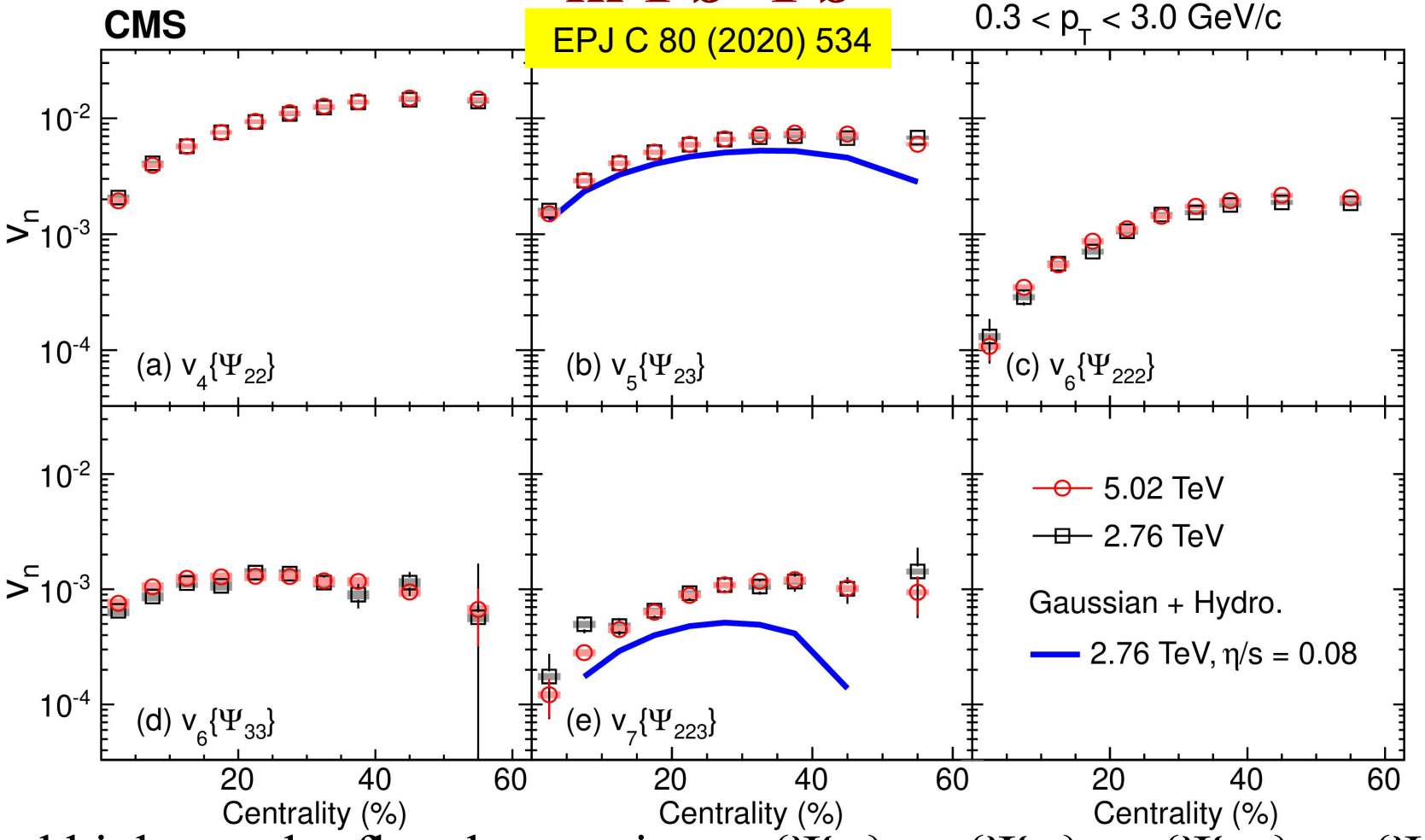




PLB 813 (2021) 136036

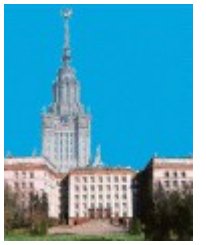
In contrast to the J/ψ mesons, no azimuthal anisotropy is observed for the Υ mesons.

Mixed higher-order anisotropic flow in Pb+Pb



The mixed higher-order flow harmonics, $v_4\{\Psi_{22}\}$, $v_5\{\Psi_{23}\}$, $v_6\{\Psi_{222}\}$, $v_6\{\Psi_{33}\}$, and $v_7\{\Psi_{223}\}$ all have a qualitatively similar p_T dependence. Viscous hydrodynamic calculation with Glauber initial conditions and shear viscosity doesn't provide a simultaneous description.

Xe+Xe as a “bridge” between p and Pb



ПЕРИОДИЧЕСКАЯ СИСТЕМА ЭЛЕМЕНТОВ Д. И. МЕНДЕЛЕЕВА

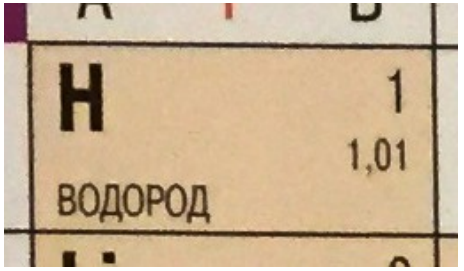
ПЕРИОДЫ	РЯДЫ	ГРУППЫ ЭЛЕМЕНТОВ																
		A I B	A II B	A III B	A IV B	A V B	A VI B	A VII B	B VIII									A
1	1	H 1 ВОДОРОД						(H)										He 2 4,00 ГЕЛИЙ
2	2	Li 3 6,94 ЛИТИЙ	Be 4 9,01 БЕРИЛЛИЙ	B 5 10,81 БОР	C 6 12,01 УГЛЕРОД	N 7 14,01 АЗОТ	O 8 16,00 КИСЛОРОД	F 9 19,00 ФТОР										Ne 10 20,18 НЕОН
3	3	Na 11 22,99 НАТРИЙ	Mg 12 24,31 МАГНИЙ	Al 13 26,98 АЛЮМИНИЙ	Si 14 28,09 КРЕМНИЙ	P 15 30,97 ФОСФОР	S 16 32,06 СЕРА	Cl 17 35,45 ХЛОР										Ar 18 39,95 АРГОН
4	4	K 19 39,10 КАЛИЙ	Ca 20 40,08 КАЛЬЦИЙ	21 Sc 44,96 СКАНДИЙ	22 Ti 47,90 ТИТАН	23 V 50,94 ВАНАДИЙ	24 Cr 52,00 ХРОМ	25 Mn 54,94 МАРГАНЕЦ	26 Fe 55,85 ЖЕЛЕЗО	27 Co 58,93 КОБАЛЬТ	28 Ni 58,70 НИКЕЛЬ							
	5	29 Cu 63,55 МЕДЬ	30 Zn 65,39 ЦИНК	Ga 31 69,72 ГАЛЛИЙ	Ge 32 72,59 ГЕРМАНИЙ	As 33 74,92 МЫШЬЯК	Se 34 78,96 СЕЛЕН	Br 35 79,90 БРОМ										Kr 36 83,80 КРИПТОН
5	6	Rb 37 85,47 РУБИДИЙ	Sr 38 87,62 СТРОНЦИЙ	39 Y 88,91 ИТТРИЙ	40 Zr 91,22 ЦИРКОНИЙ	41 Nb 92,91 НИОБИЙ	42 Mo 95,94 МОЛИБДЕН	43 Tc 98,91 ТЕХНЕЦИЙ	44 Ru 101,07 РУТЕНИЙ	45 Rh 102,91 РОДИЙ	46 Pd 106,42 ПАЛЛАДИЙ							
	7	47 Ag 107,87 СЕРЕБРО	48 Cd 112,41 КАДМИЙ	In 49 114,82 ИНДИЙ	Sn 50 118,71 ОЛОВО	Sb 51 121,75 СУРЬМА	Te 52 127,60 ТЕЛЛУР	I 53 126,90 ЙОД										Xe 54 131,30 КСЕНОН
6	8	Cs 55 132,91 ЦЕЗИЙ	Ba 56 137,33 БАРИЙ	57 La* 138,91 ЛАНТАН	72 Hf 178,49 ГАФНИЙ	73 Ta 180,95 ТАНТАЛ	74 W 183,84 ВОЛЬФРАМ	75 Re 186,21 РЕНИЙ	76 Os 190,23 ОСМИЙ	77 Ir 192,22 ИРИДИЙ	78 Pt 195,09 ПЛАТИНА							
	9	79 Au 196,97 ЗОЛОТО	80 Hg 200,59 РТУТЬ	Tl 81 204,38 ТАЛЛИЙ	Pb 82 207,20 СВИНЕЦ	Bi 83 208,98 ВИСМУТ	Po 84 [209] ПОЛОНИЙ	At 85 [210] АСТАТ										Rn 86 [222] РАДОН
7	10	Fr 87 [223] ФРАНЦИЙ	Ra 88 [226] РАДИЙ	89 Ac** [227] АКТИНИЙ	104 Rf [261] РЕЗЕРФОРДИЙ	105 Db [262] ДУБНИЙ	106 Sg [263] СИБОРГИЙ	107 Bh [262] БОРИЙ	108 Hs [265] ГАССИЙ	109 Mt [268] МЕЙТНЕРИЙ	110 Ds [271] ДАРМШТАДТИЙ							
ВЫСШИЕ ОКСИДЫ		R_2O	RO	R_2O_3	RO_2	R_2O_5	RO_3	R_2O_7	RO_4									
ЛЕТУЧИЕ ВОДОРОДНЫЕ СОЕДИНЕНИЯ					RH_4	RH_3	H_2R	HR										

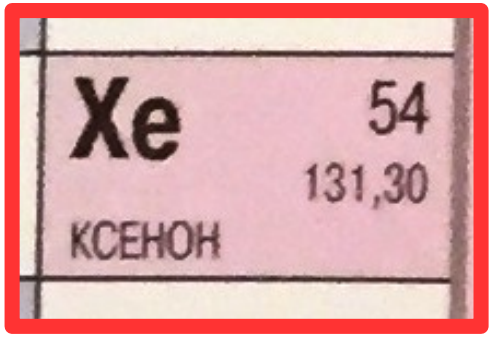
МЕНДЕЛЕЕВ Дмитрий Иванович (8.II.1834–2.II.1907)

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.

*ЛАНТАНОИДЫ	Ce 58 140,12 ЦЕРИЙ	Pr 59 140,91 ПРАЗЕОДИМ	Nd 60 144,24 НЕОДИМ	Pm 61 [145] ПРОМЕТИЙ	Sm 62 150,36 САМАРИЙ	Eu 63 151,96 ЕВРОПИЙ	Gd 64 157,25 ГАДОЛИНИЙ	Tb 65 158,93 ТЕРБИЙ	Dy 66 162,50 ДИСПРОЗИЙ	Ho 67 164,93 ГОЛЬМИЙ	Er 68 167,26 ЭРБИЙ	Tm 69 168,93 ТУЛИЙ	Yb 70 173,04 ИТТЕРБИЙ	Lu 71 174,97 ЛЮТЕЦИЙ
**АКТИНОИДЫ	Th 90 232,03 ТОРИЙ	Pa 91 231,04 ПРОТАКТИНИЙ	U 92 238,03 УРАН	Np 93 [237] НЕПТУНИЙ	Pu 94 [244] ПЛУТОНИЙ	Am 95 [243] АМЕРИЦИЙ	Cm 96 [247] КЮРИЙ	Bk 97 [247] БЕРКЛИЙ	Cf 98 [251] КАЛИФОРНИЙ	Es 99 [252] ЭЙНШТЕЙНИЙ	Fm 100 [257] ФЕРМИЙ	Md 101 [258] МЕНДЕЛЕВИЙ	No 102 [259] НОБЕЛИЙ	Lr 103 [262] ЛОУРЕНСИЙ

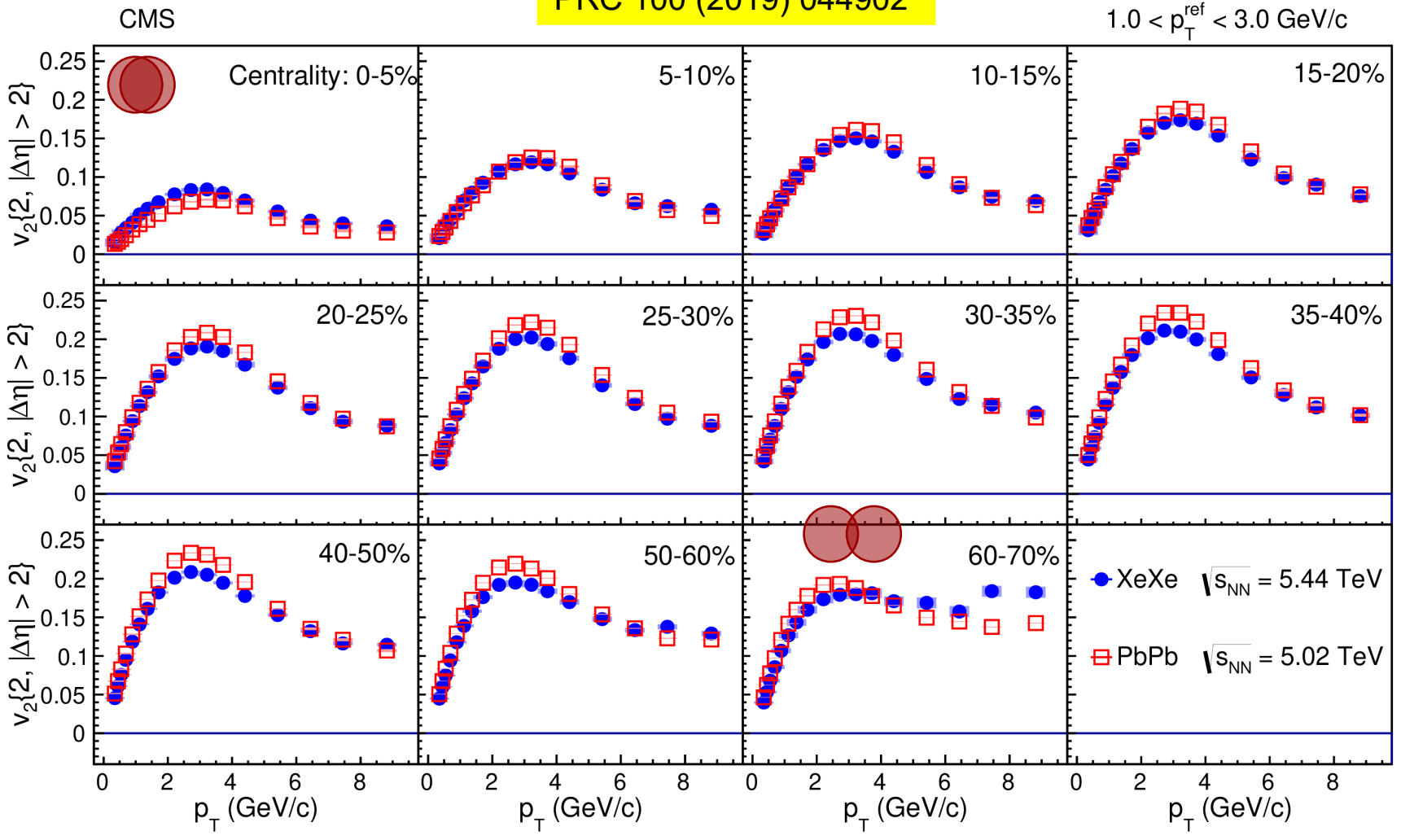
РЯД АКТИВНОСТИ МЕТАЛЛОВ	Li	Cs	Rb	K	Ba	Sr	Ca	Na	Mg	Be	Al	Mn	Zn	Cr	Fe	Cd	Co	Ni	Sn	Pb	H_2	Cu	Hg	Ag	Pt	Au
РЯД НАПРЯЖЕНИЙ МЕТАЛЛОВ	Li	Rb	K	Ba	Sr	Ca	Na	Mg	Al	Mn	Zn	Cr	Fe	Cd	Co	Ni	Sn	Pb	H_2	Sb	Cu	Hg	Ag	Pt	Au	





v_2 Xe+Xe vs. Pb+Pb

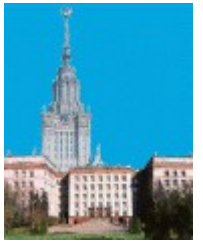
PRC 100 (2019) 044902

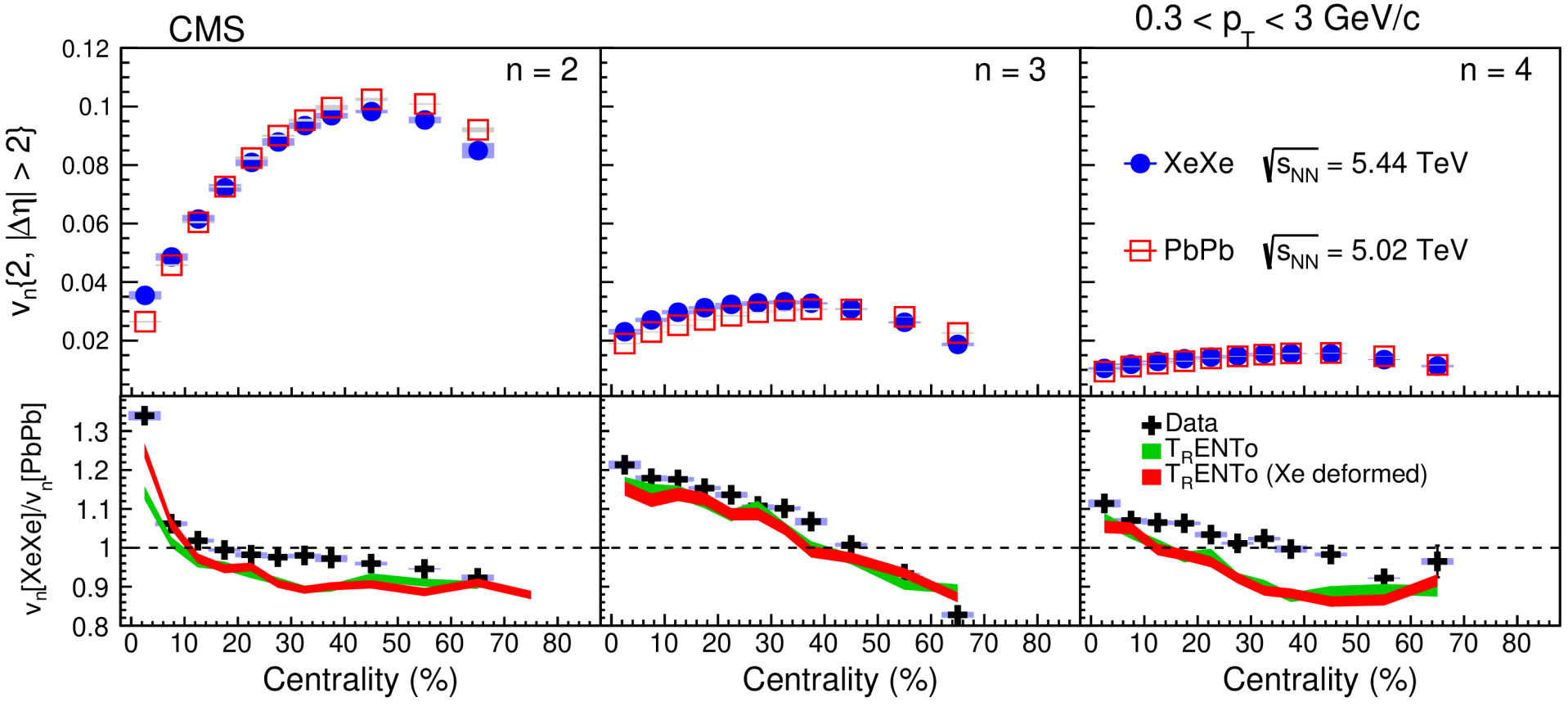


The magnitude of the v_2 coefficients for Xe+Xe collisions are larger than those found in Pb+Pb collisions for the most central collisions. This is attributed to a larger fluctuation component in the lighter colliding system.

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

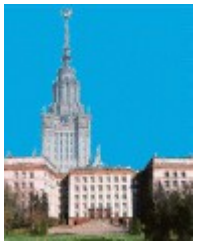
PRC 100 (2019) 044902



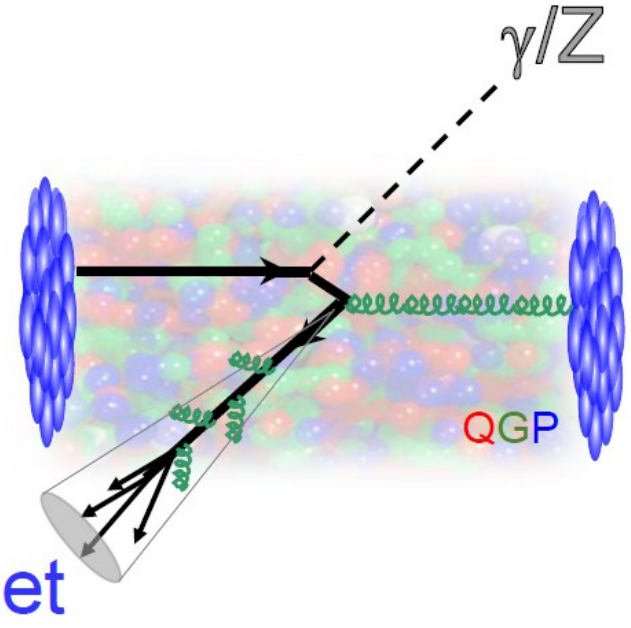


Hydrodynamic models that consider the Xe nuclear deformation are able to better describe the v_2[XeXe]/v_2[PbPb] ratio in central collisions than those assuming a spherical Xe shape.

Hard Probes for Quark-Gluon Plasma

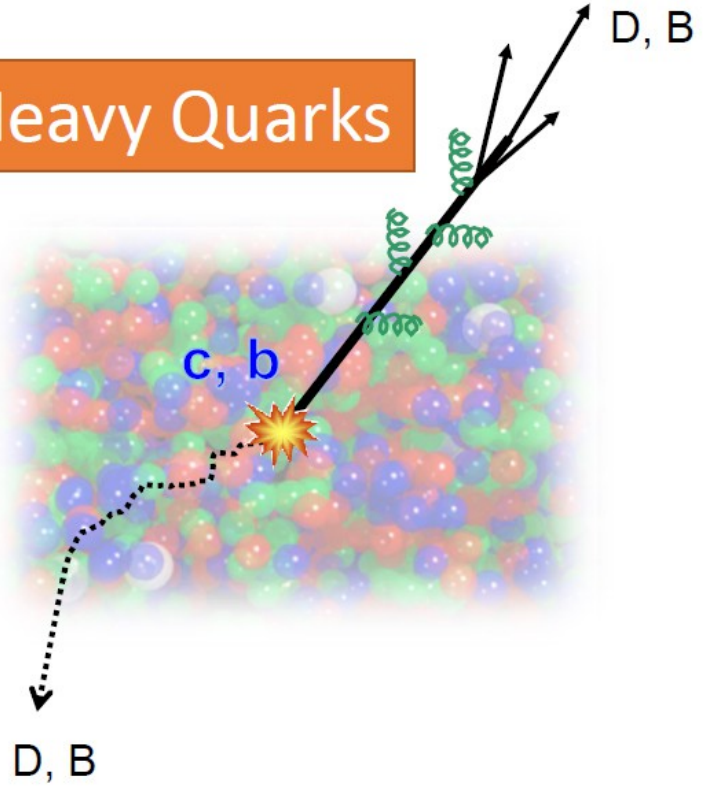


Electroweak Bosons

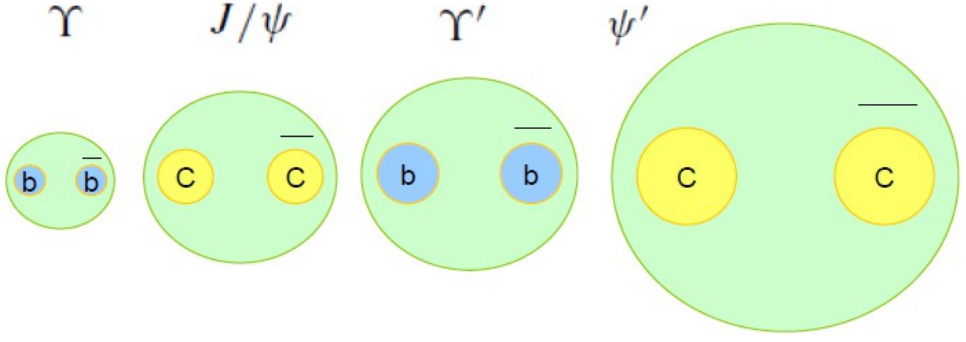


Jets

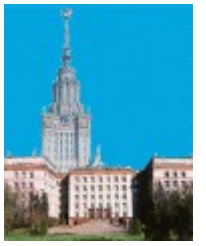
Heavy Quarks

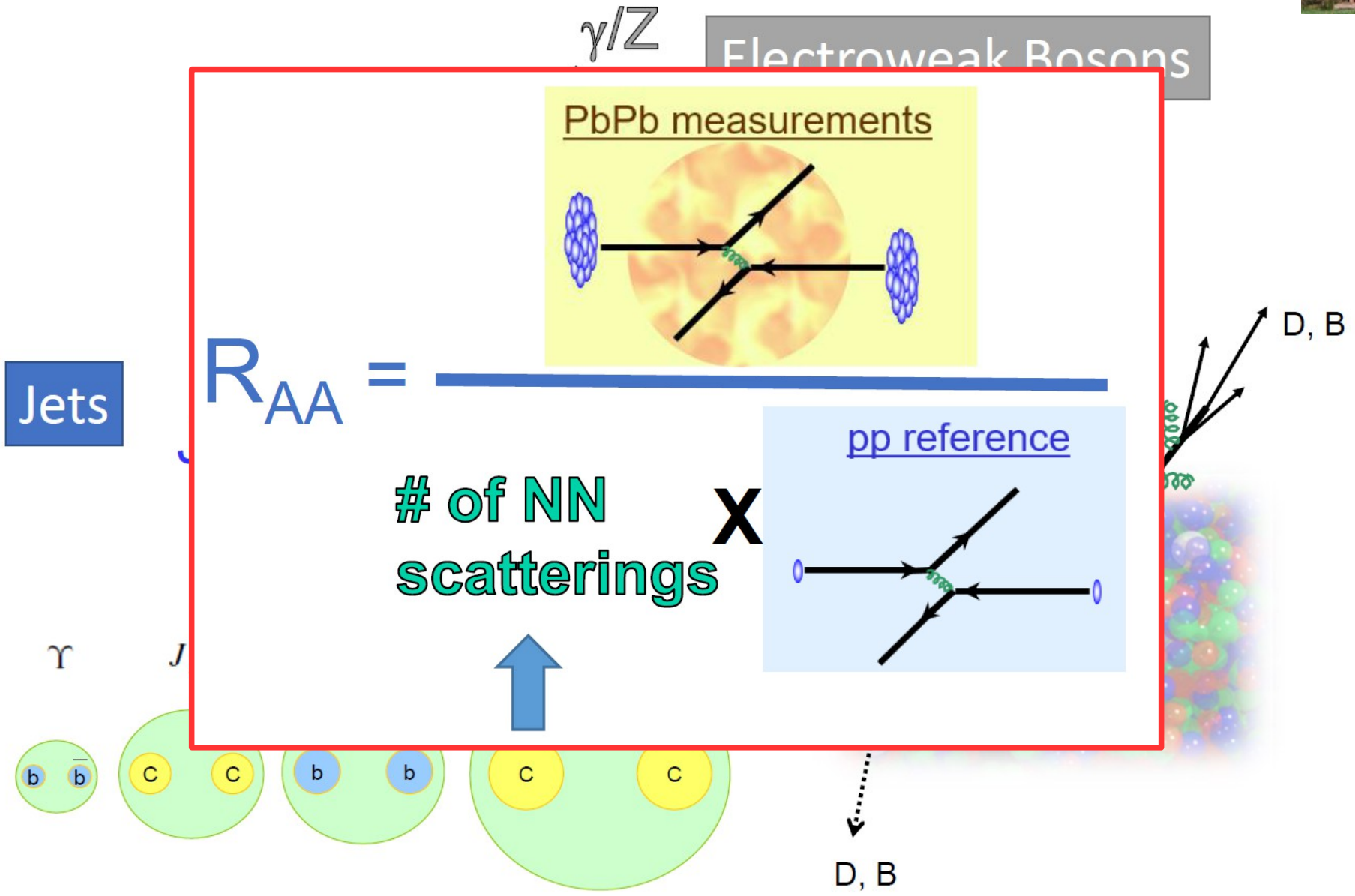


Quarkonia

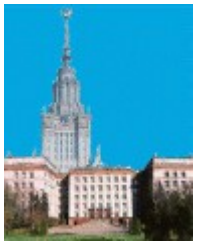


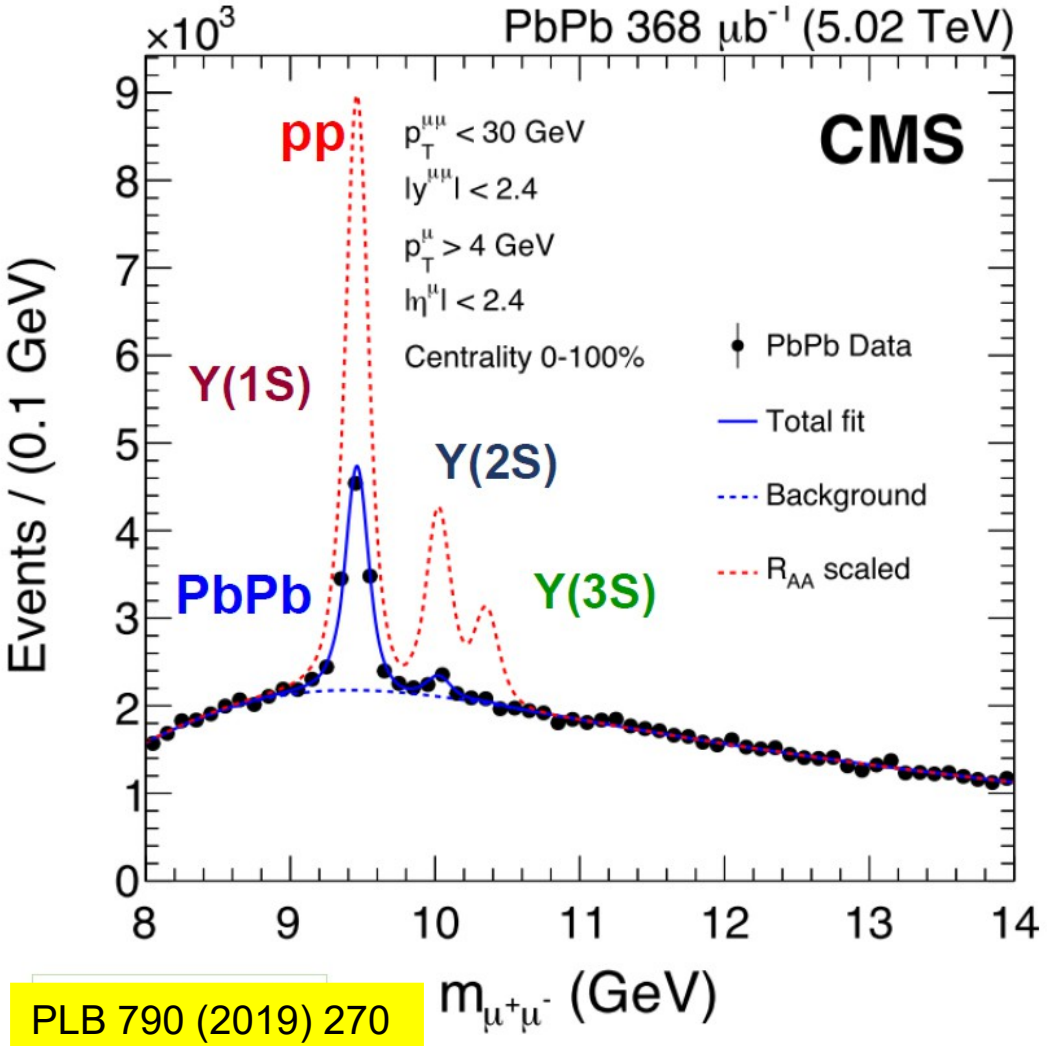
Hard Probes for Quark-Gluon Plasma

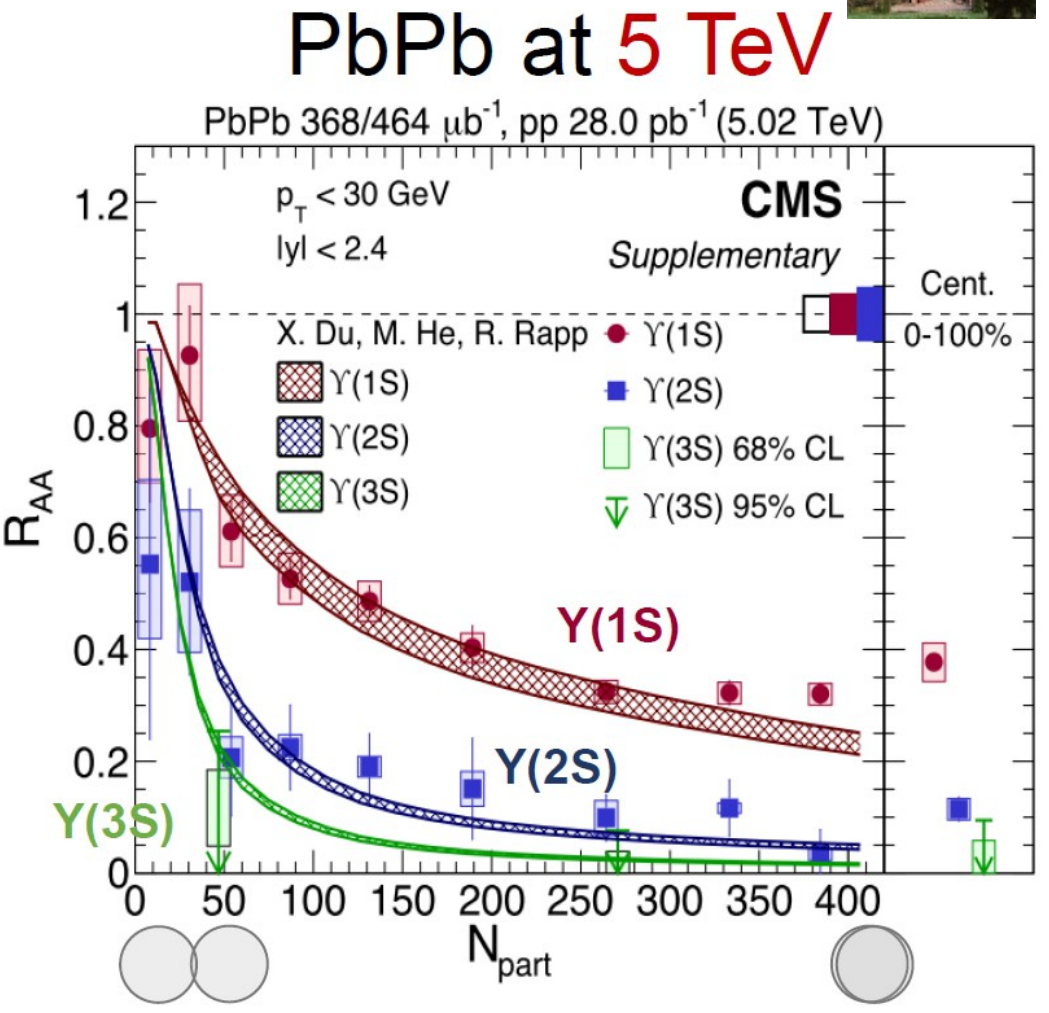




Upsilon suppression in Pb+Pb







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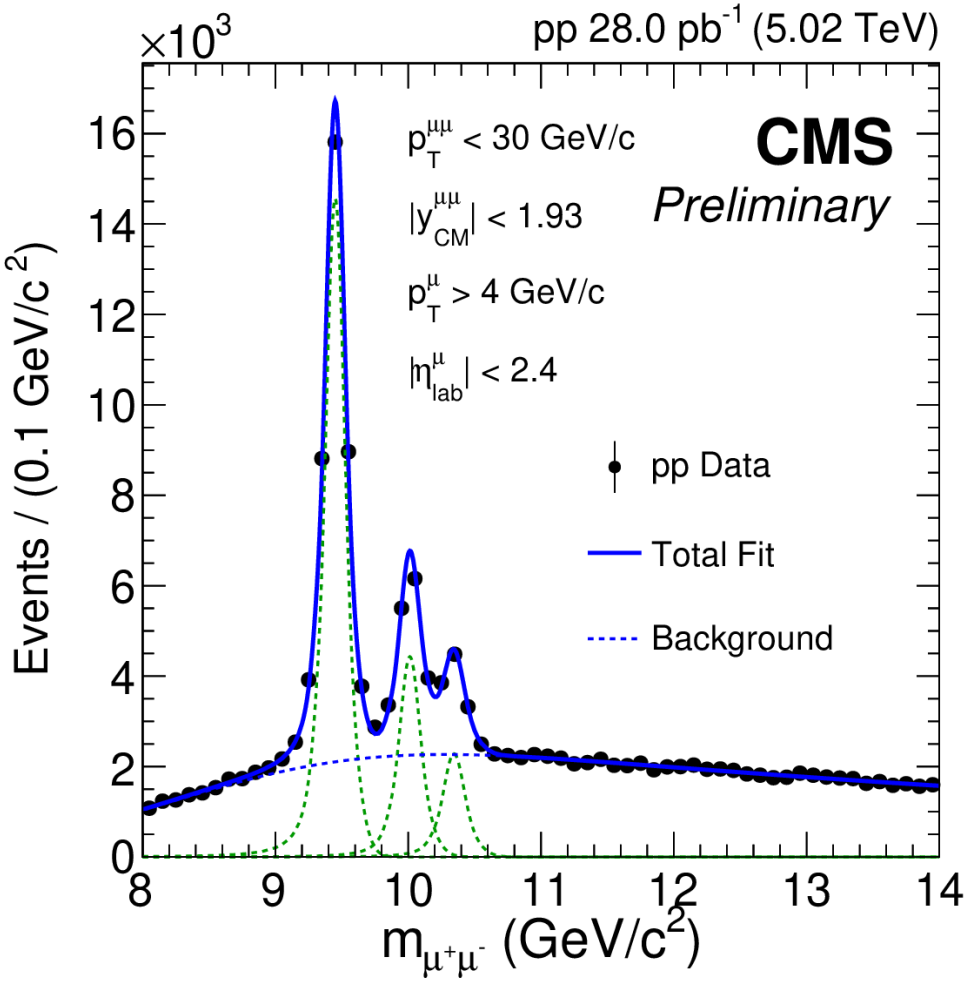
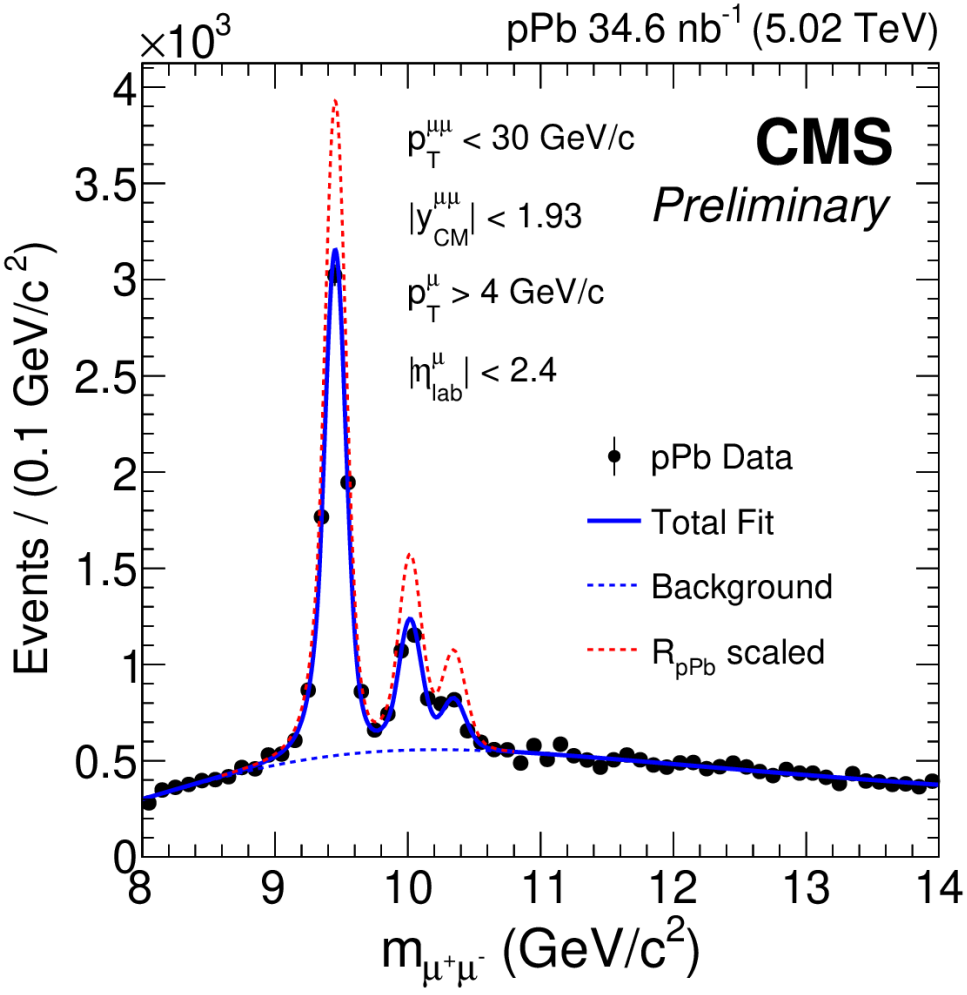
- Observation of sequential suppression of Y family.
- No any sign of Y(3S) in the high statistics 2015 data.

Upsilon suppression in p+Pb

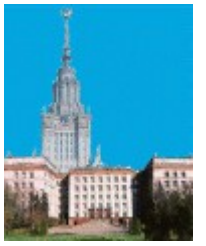
CMS-PAS-HIN-18-005



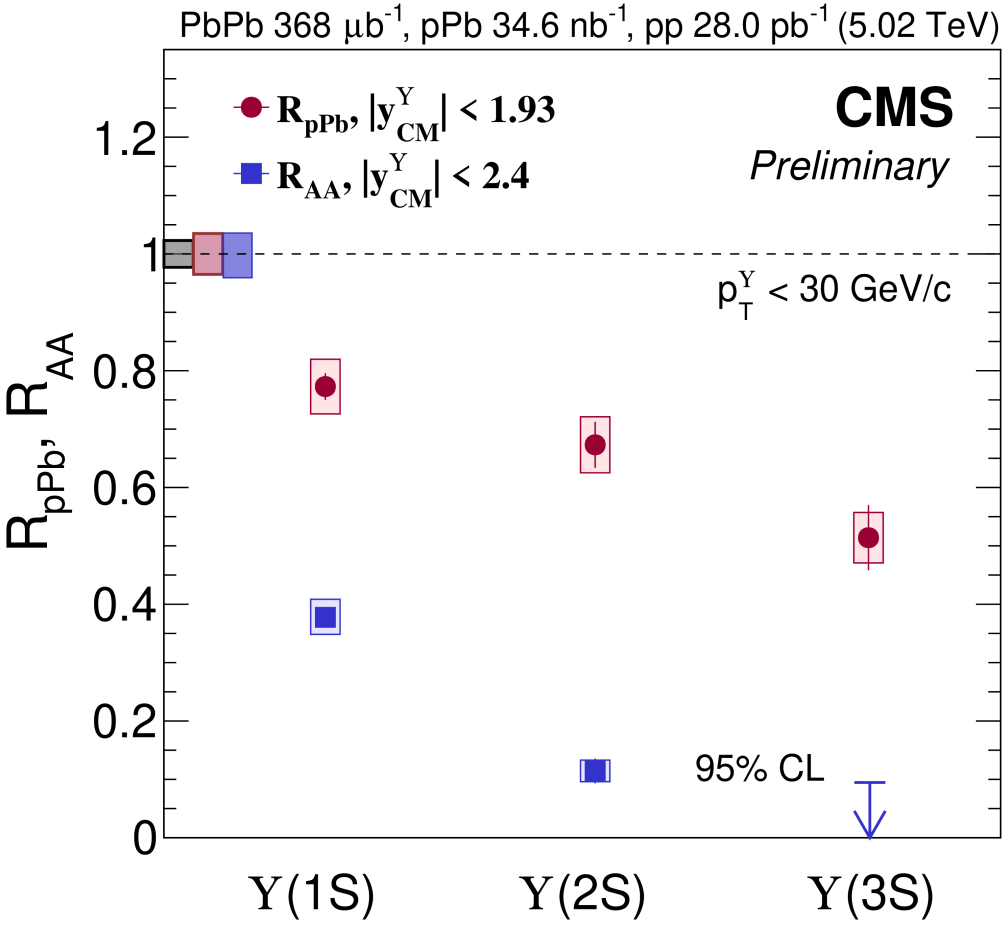


All Y states are found to be suppressed in p+Pb collisions compared to p+p collisions.

Upsilon suppression in p+Pb and Pb+Pb



CMS-PAS-HIN-18-005



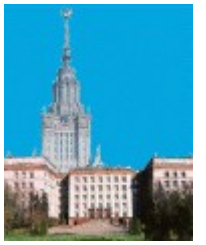
Ordered in binding energy

RpPb Υ(1S) > RpPb Υ(2S) > RpPb Υ(3S)

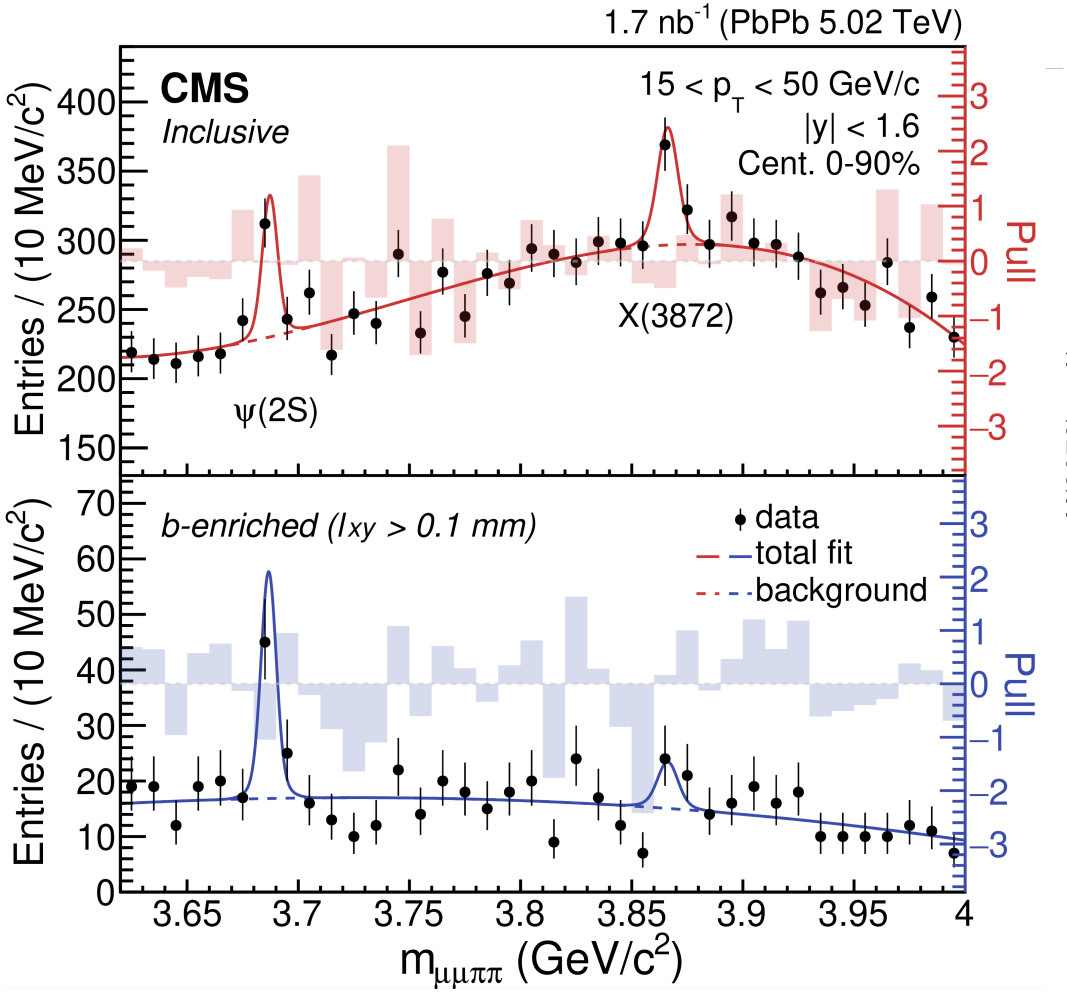
Largest suppression in Pb+Pb

$R_{pPb} > R_{PbPb}$

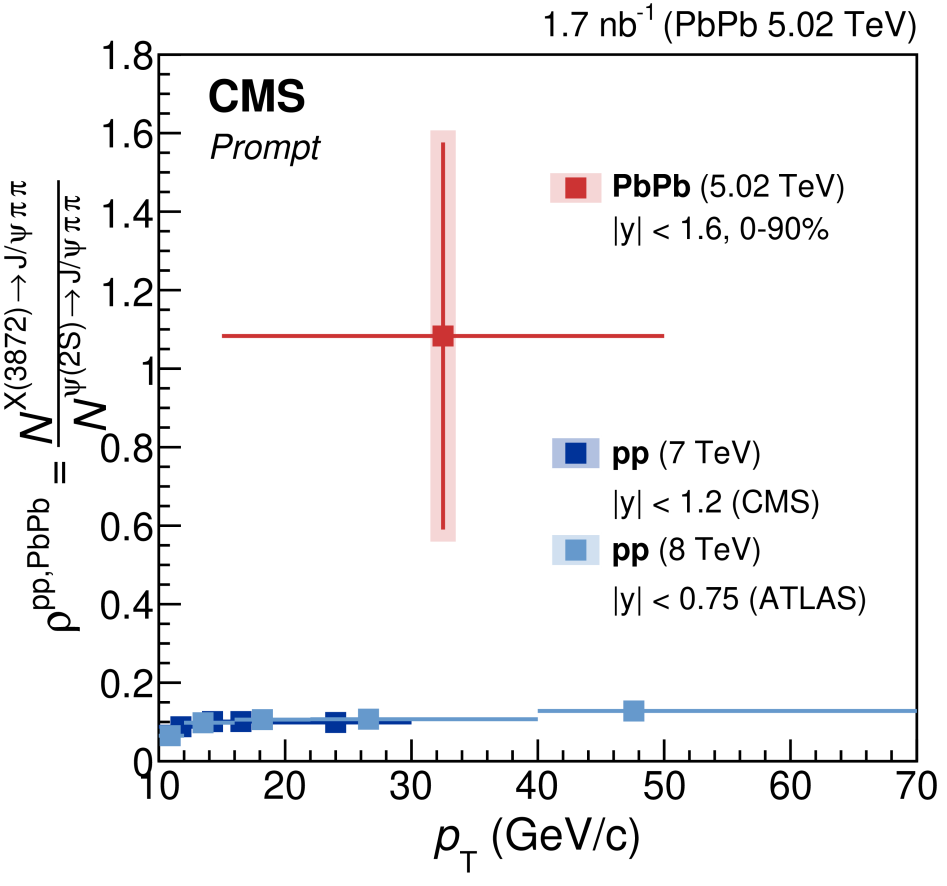
First evidence of X(3872) in Pb+Pb

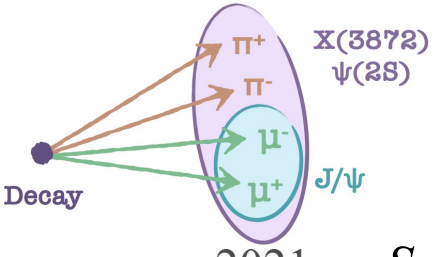


arXiv:2102.13048



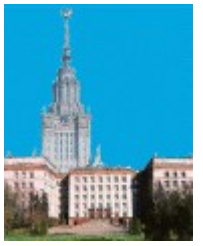
Comparison to ψ(2S)



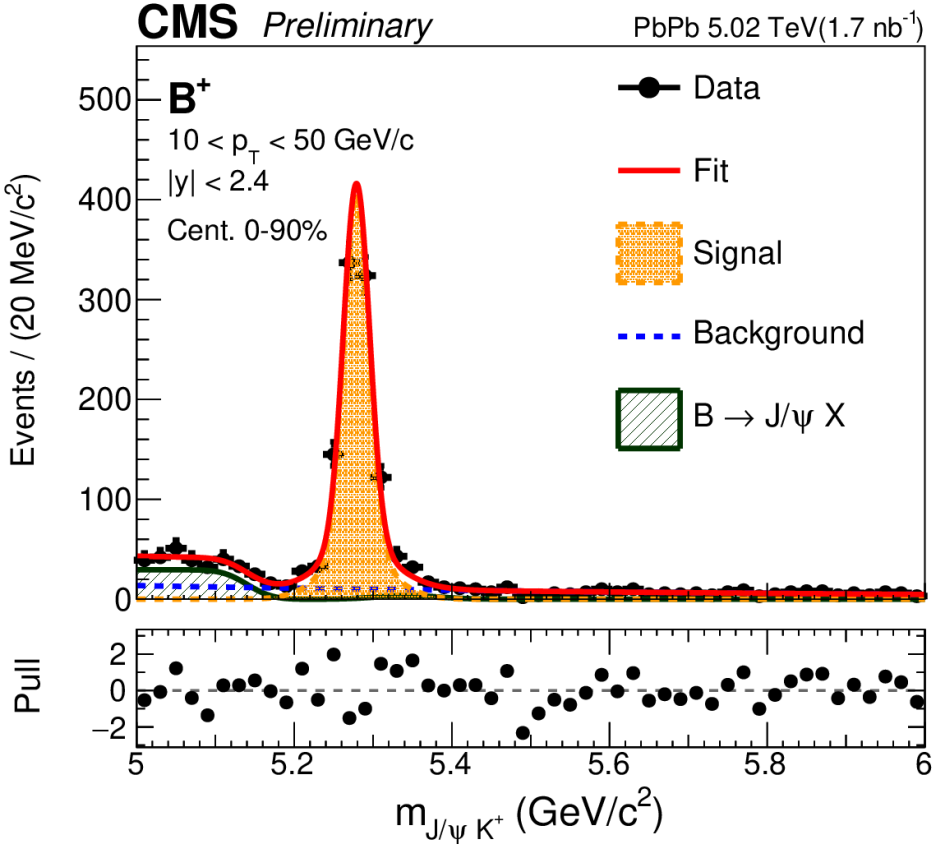


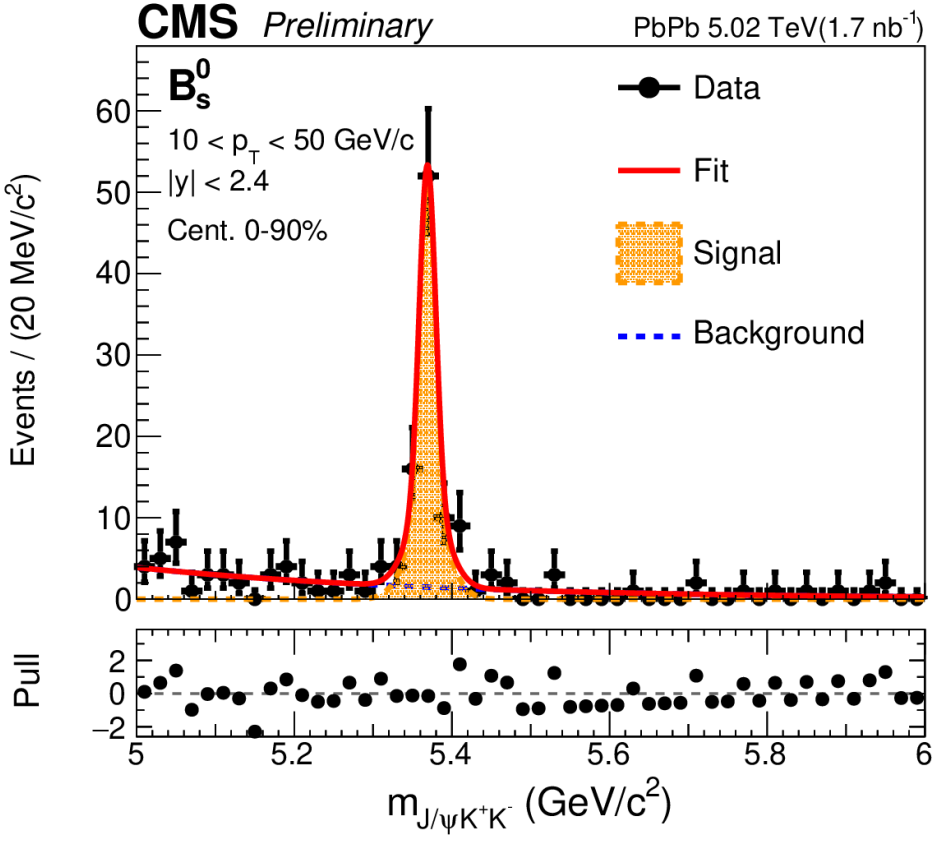
Result provides a unique experimental input to the theory, towards elucidating the production mechanism and the nature of the X(3872).

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



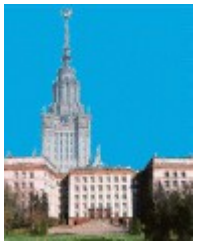
CMS-PAS-HIN-19-011



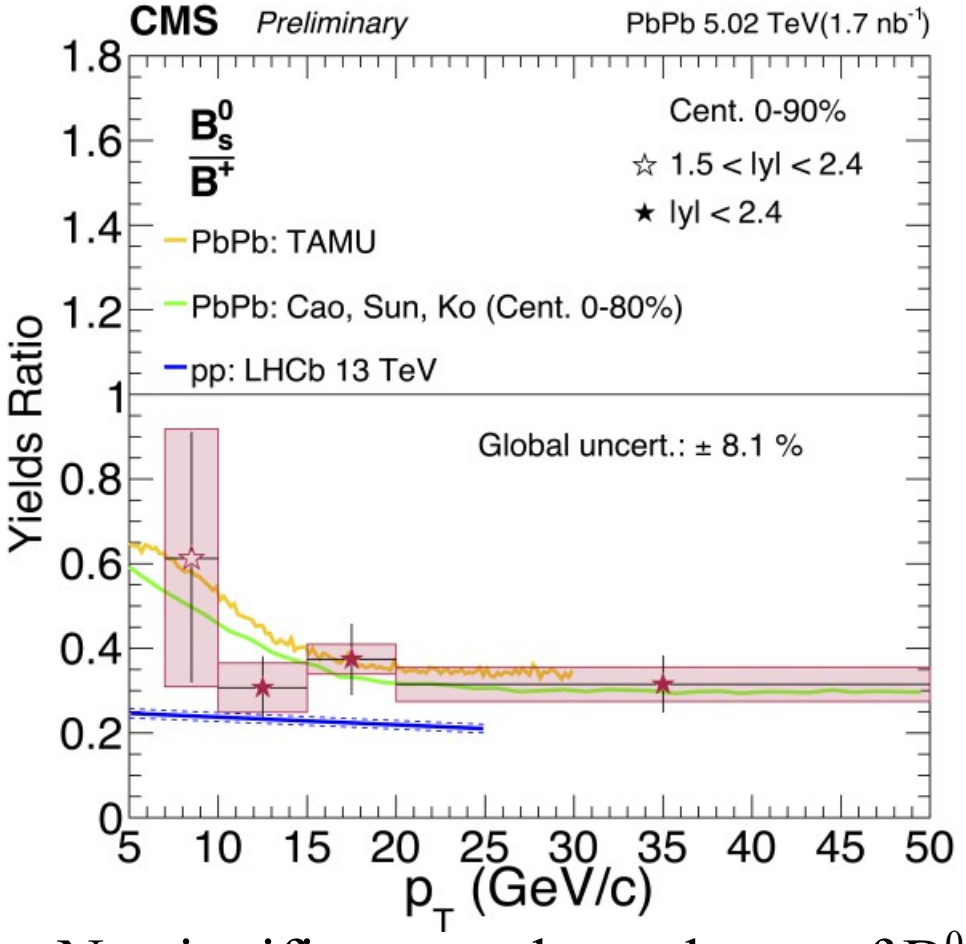


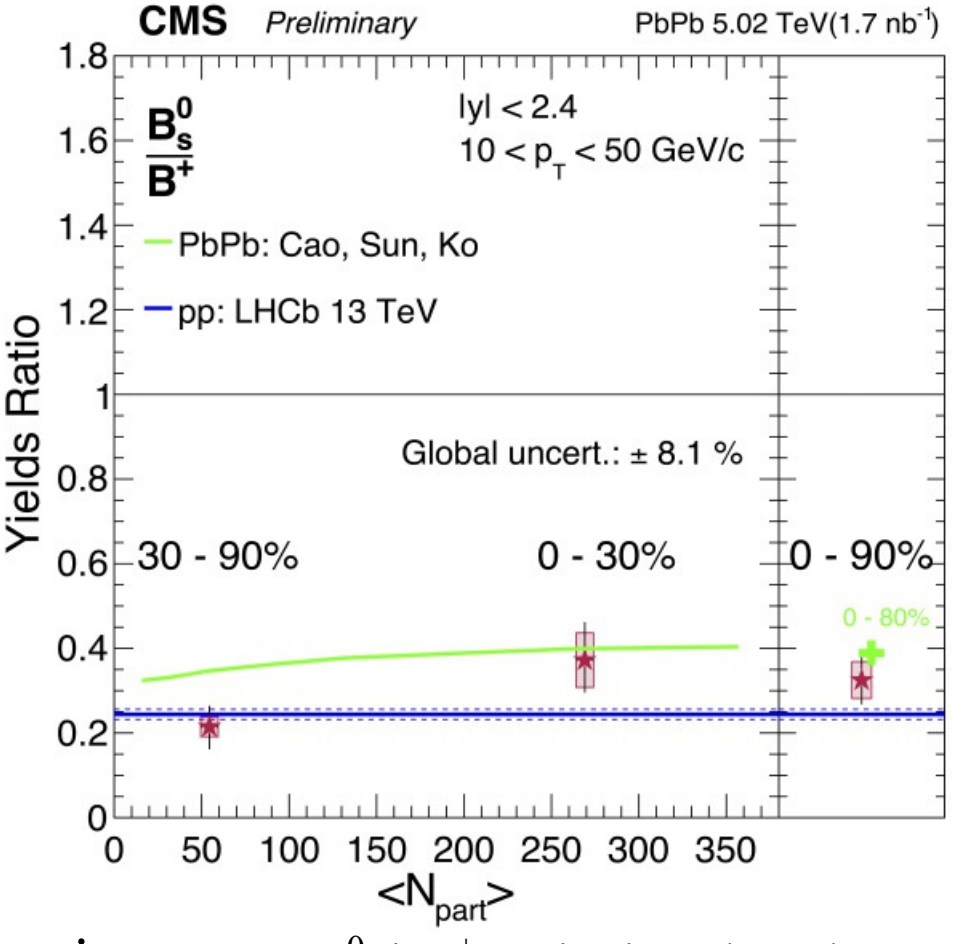
The B^0_s meson is observed with a statistical significance in excess of 5 standard deviations for the first time in nucleus-nucleus collisions

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



CMS-PAS-HIN-19-011

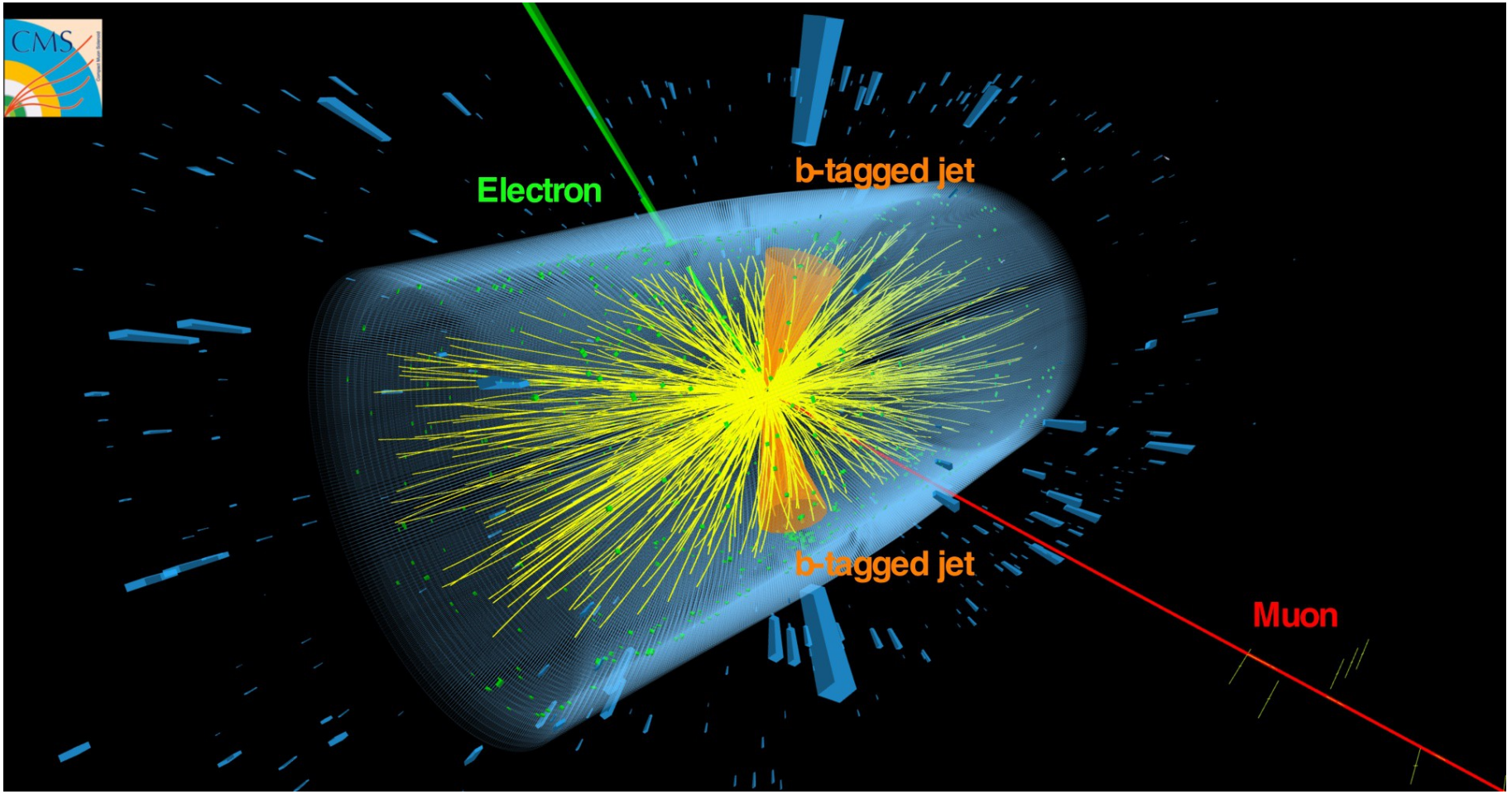




- No significant p_T-dependence of B^0_s / B^+ ratio
  - Model predictions in reasonably well agreement with data
- B^0_s / B^+ ratio in Pb+Pb compatible with measurements in pp

The first search for top using Pb+Pb collisions

PRL 125 (2020) 222001

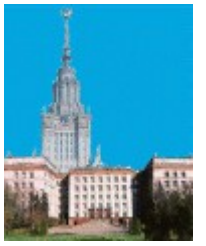


Using either charged leptons only or charged leptons + b jets. The measured cross sections are compatible with expectations from scaled proton-proton data and QCD predictions.

$\sigma_{t\bar{t}} = 2.54^{+0.84}_{-0.74}$ and $2.03^{+0.71}_{-0.64}$ μb

The first search for top using Pb+Pb collisions

PRL 125 (2020) 222001



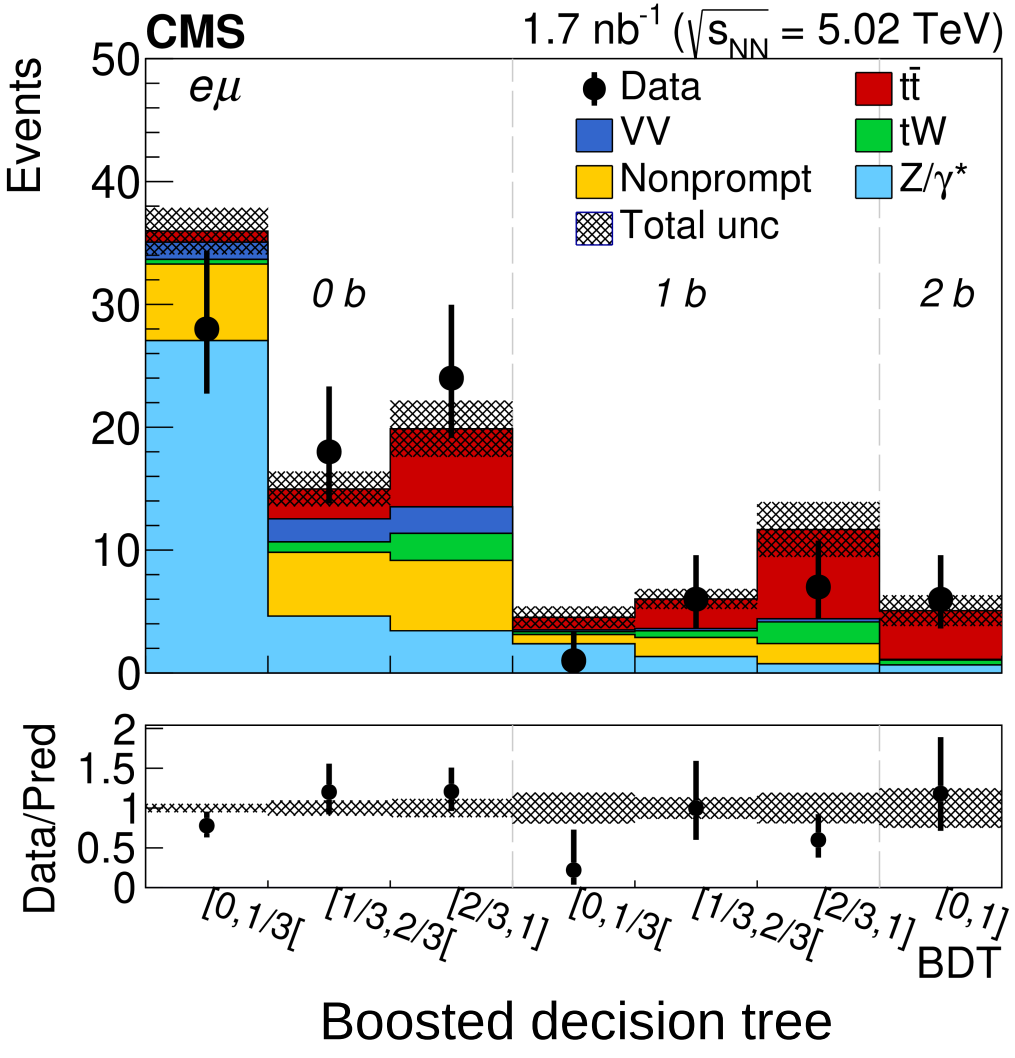
4.0 σ significance

Consistent with pQCD

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

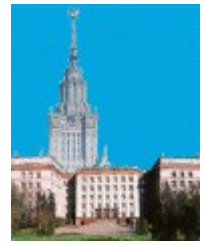
Both dilepton multivariate & b-jet counting analyses

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.



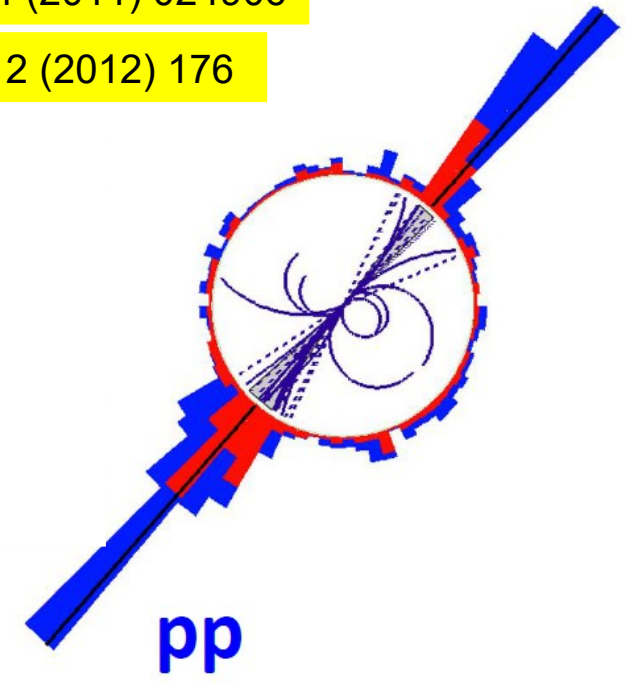
Boosted decision tree

Jet quenching in Pb+Pb

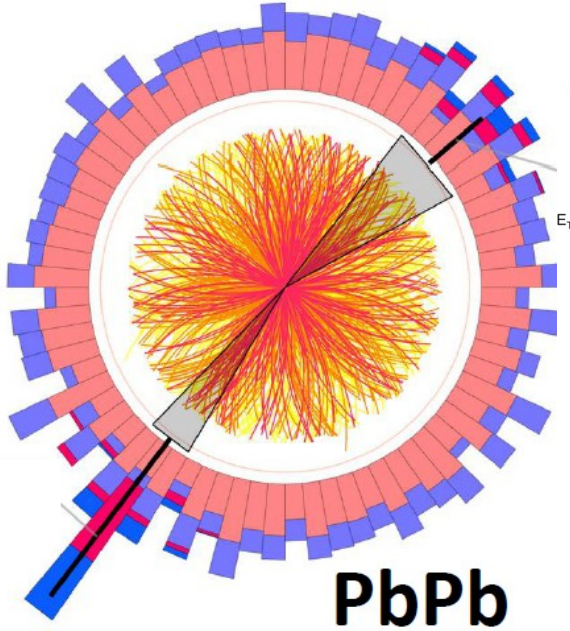


PRC 84 (2011) 024906

PLB 712 (2012) 176



pp



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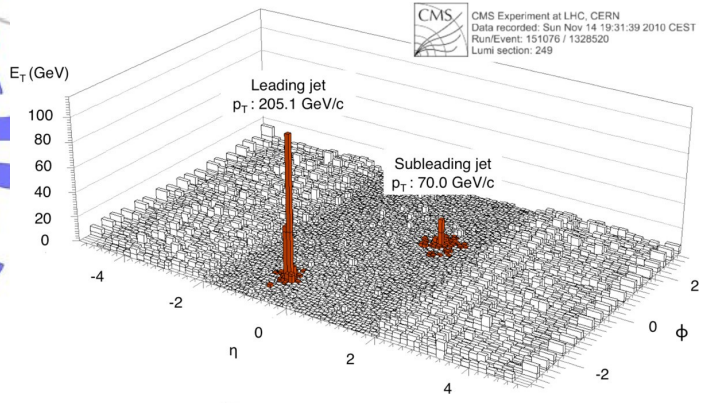
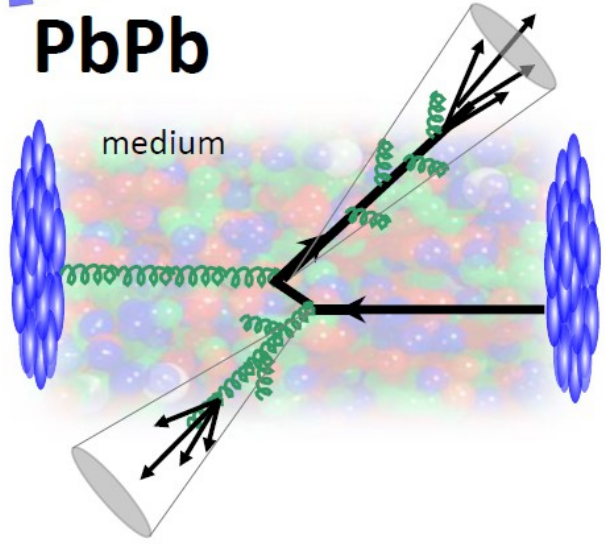


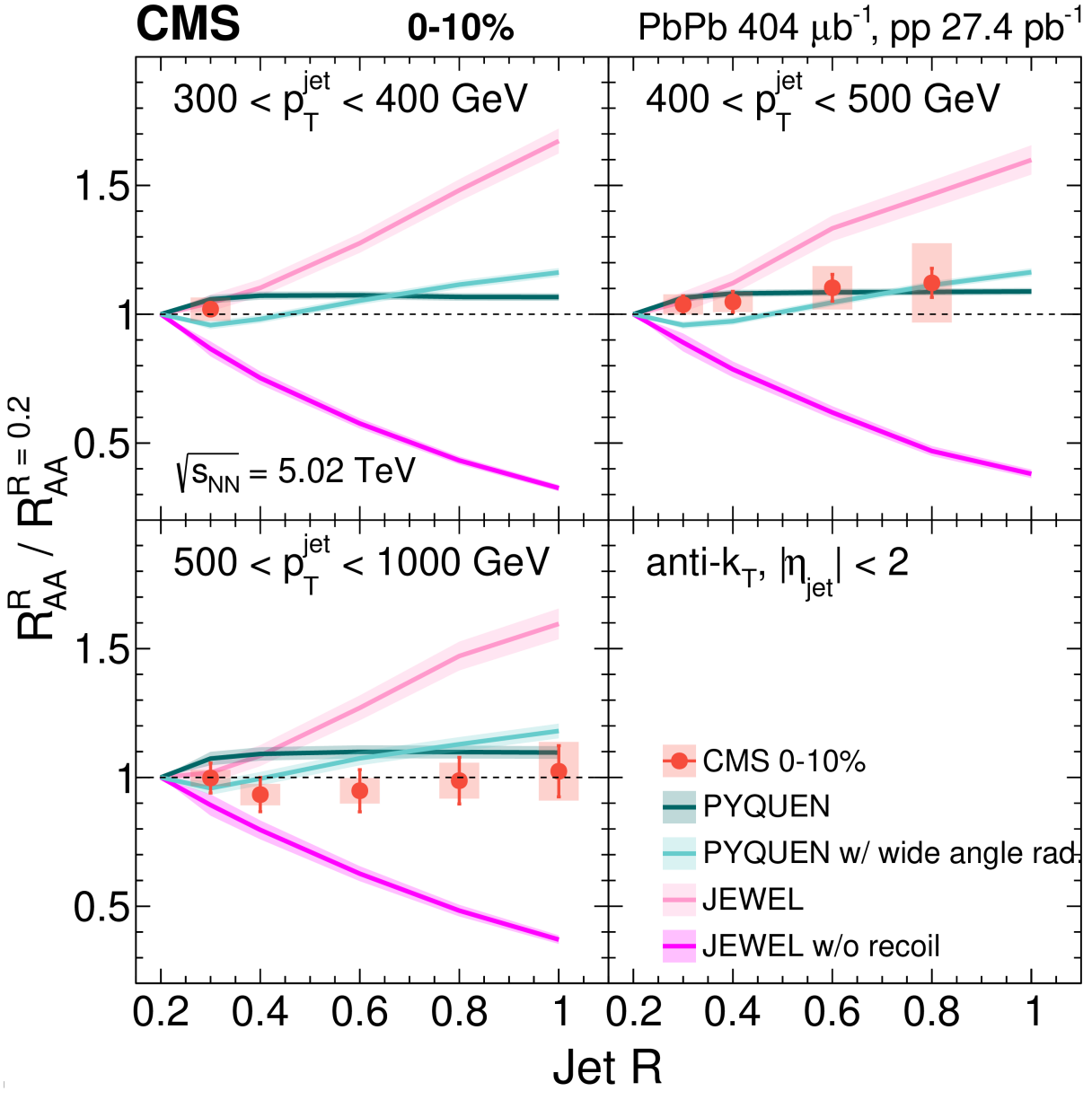
PbPb

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



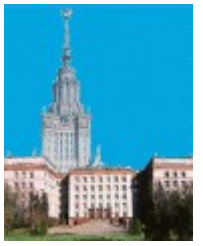
Jet radius scan

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
- CMS observes no radius dependence to jet energy loss in central Pb+Pb for 500 GeV < p_T jet <1 TeV

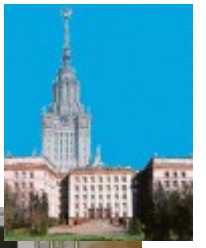
CMS Summary for Heavy-Ions



- **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 tunned!**

Two years ago... LOMONOSOV 2019



THANK YOU! СПАСИБО!

SEE YOU! УВИДИМСЯ!