



**Сергей Петрушанко  
(for the CMS Collaboration)**



**НИИЯФ МГУ**

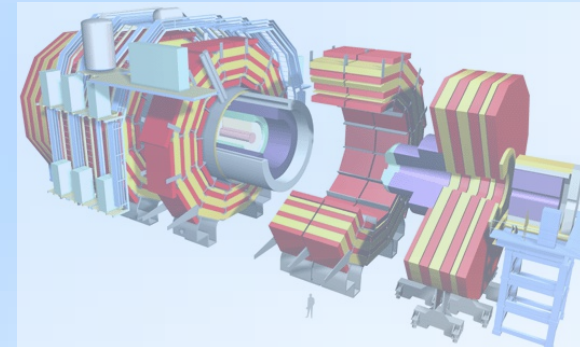
# **Heavy-ion Physics Results by the CMS Experiment**

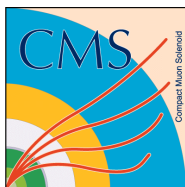
## **Результаты по физике тяжелых ионов в эксперименте CMS**



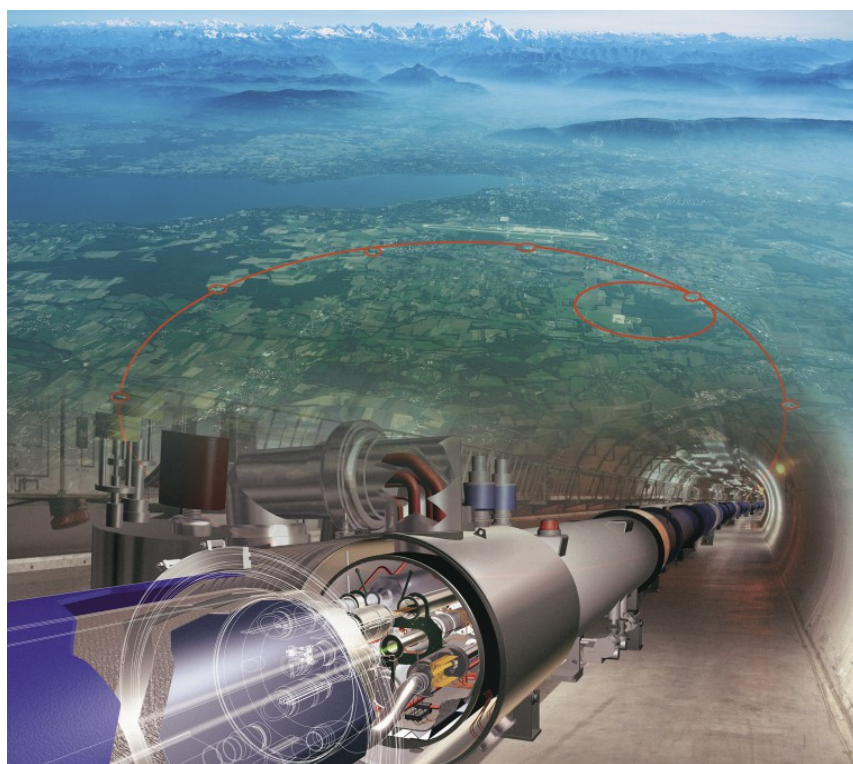
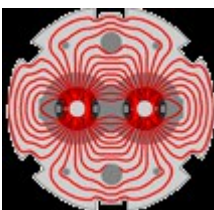
**LXXIV International Conference  
"Nucleus-2024: Fundamental  
Problems and Applications"**

**JINR, Dubna, Russia  
1 – 5 July 2024**

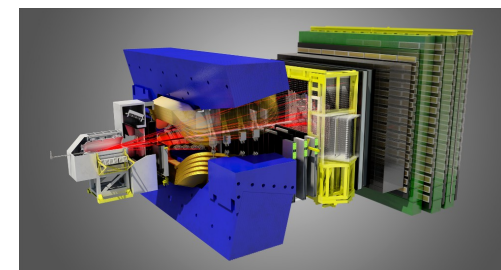




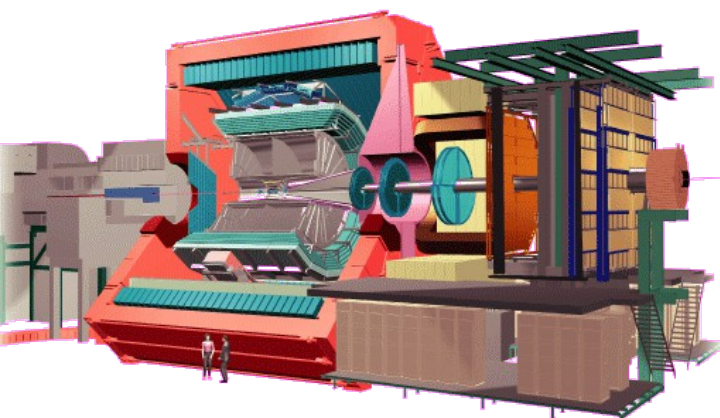
# Физика тяжелых ионов на LHC



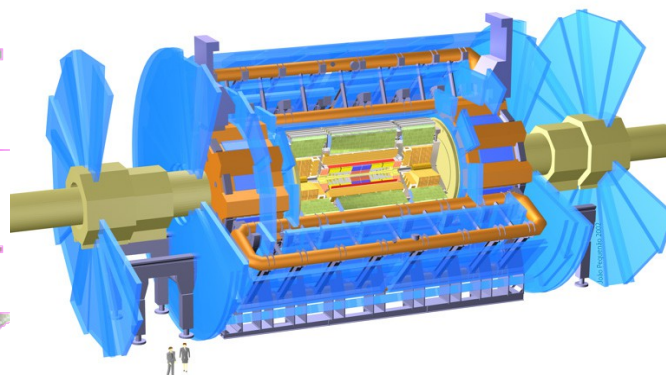
LHCb



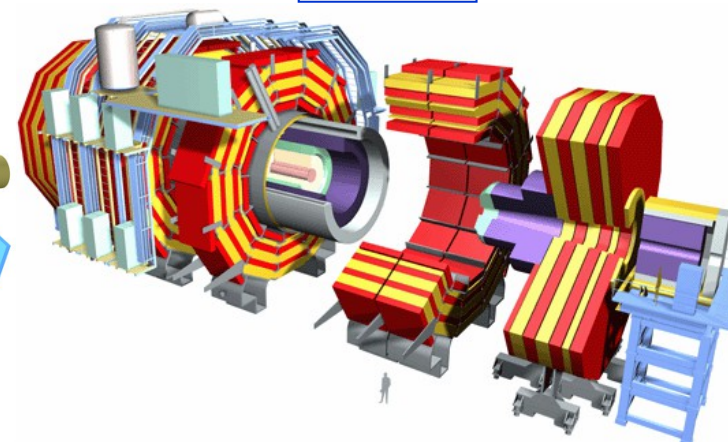
ALICE



ATLAS



CMS





# Компактный Мюонный Соленоид (CMS)



## 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 (100x150  $\mu\text{m}$ )  $\sim 1\text{m}^2 \sim 66\text{M}$  channels  
 Microstrips (80x180  $\mu\text{m}$ )  $\sim 200\text{m}^2 \sim 9.6\text{M}$  channels

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

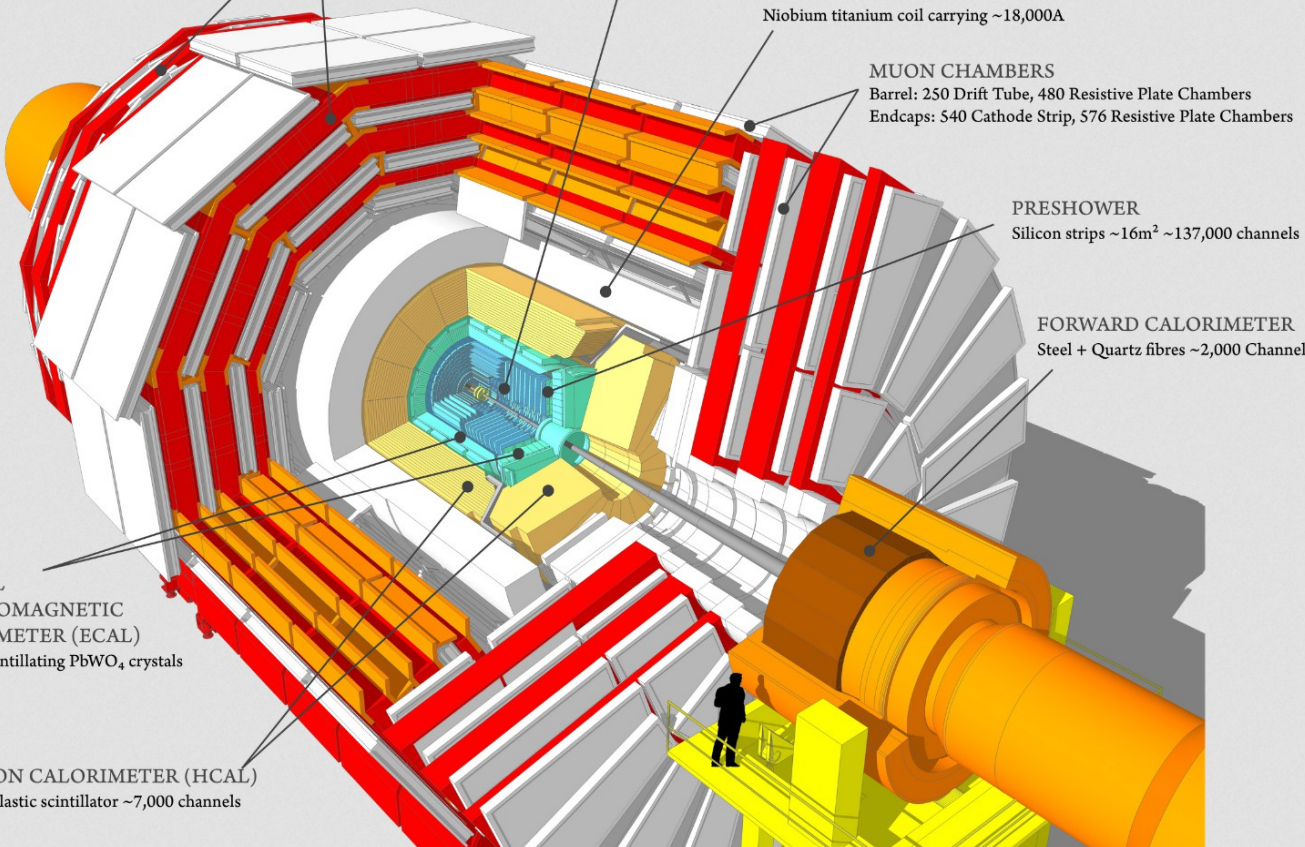
MUON CHAMBERS  
 Barrel: 250 Drift Tube, 480 Resistive Plate Chambers  
 Endcaps: 540 Cathode Strip, 576 Resistive Plate Chambers

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  $\text{PbWO}_4$  crystals

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



Магнитное поле: 3.8 Тесла

◆ Кремниевый трекер

$$|\eta| < 2.4$$

◆ Электромагнитный калориметр

$$|\eta| < 3.0$$

◆ Адронный калориметр

*центр + торец*

$$|\eta| < 3.0$$

+ HF-калориметр

$$|\eta| < 5.2$$

◆ Мюонные камеры

$$|\eta| < 2.4$$

+ Детектор CASTOR

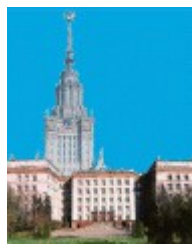
$$-5.2 < \eta < -6.6$$

+ Калориметр Zero-Degree

+ TOTEM



# CMS как эксперимент по тяжелым ионам: герметичность, разрешение, гибкий триггер и DAQ



## Калориметры: высокое разрешение и сегментация

- герметичность до  $|\eta| < 5.2$
- $-5.2 < \eta < -6.6$  CASTOR
- Zero-Degree калориметр

## Мюоны: $\mu$ от $Z^0$ , $J/\psi$ , $\Upsilon$

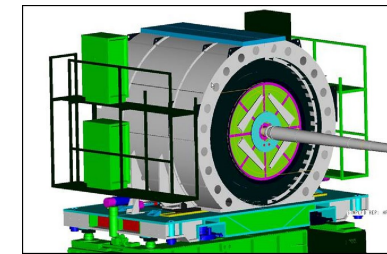
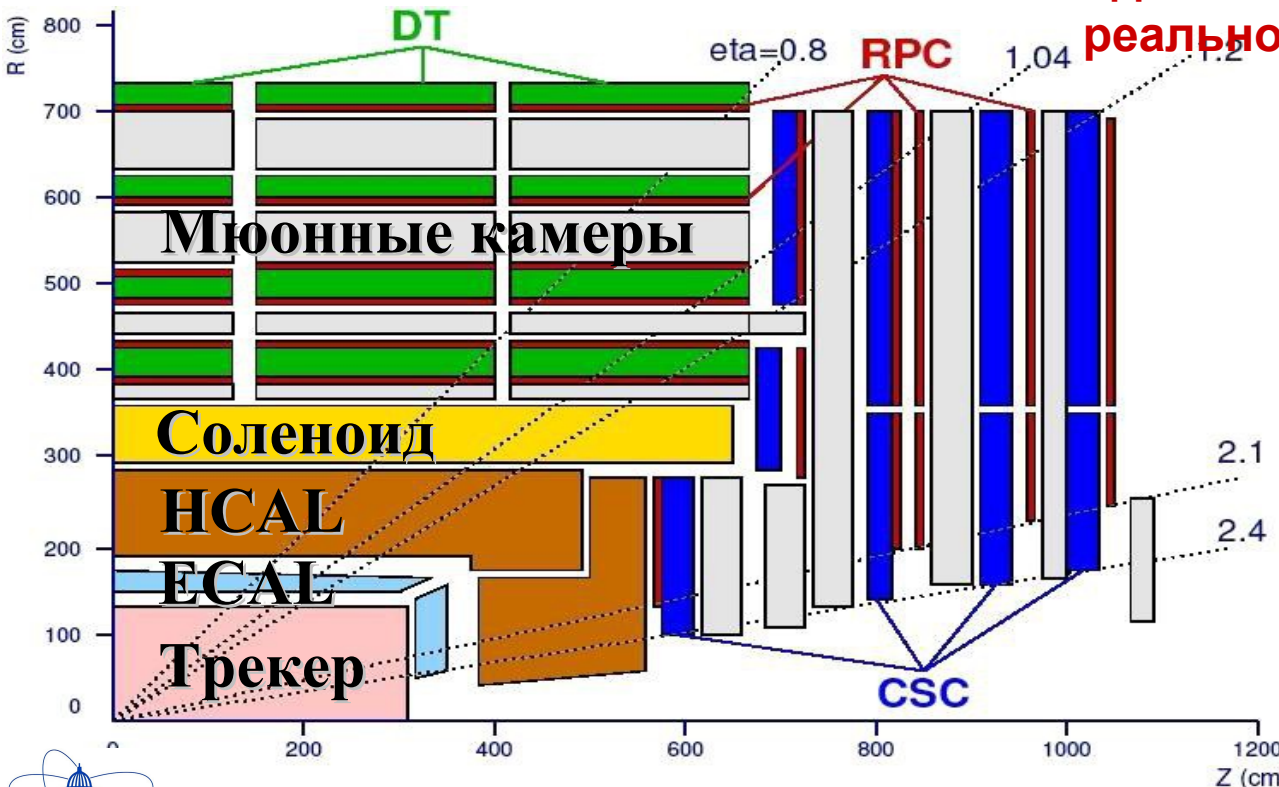
- широкое покрытие до  $|\eta| < 2.4$
- высокое разрешение масс димюонов

## Кремниевый детектор

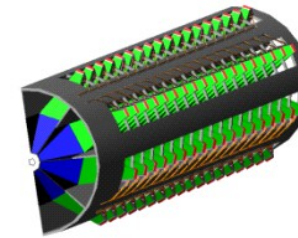
- высокая эффективность и чистота для треков с  $p_T > 1$  ГэВ/с
- загрузка пикселей:  $< 2\%$
- $\Delta p/p \approx 1-2\%$  для треков с  $p_T < 100$  ГэВ/с
- регистрация треков с низким  $p_T$

## Триггер и DAQ

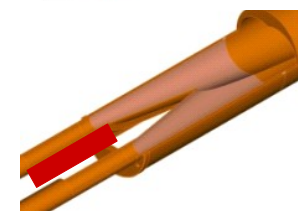
- Широкие возможности: AA и pp
- для тяжелых ионов: реконструкция в реальном времени для HLT



**HF**  
 $3 < |\eta| < 5.2$



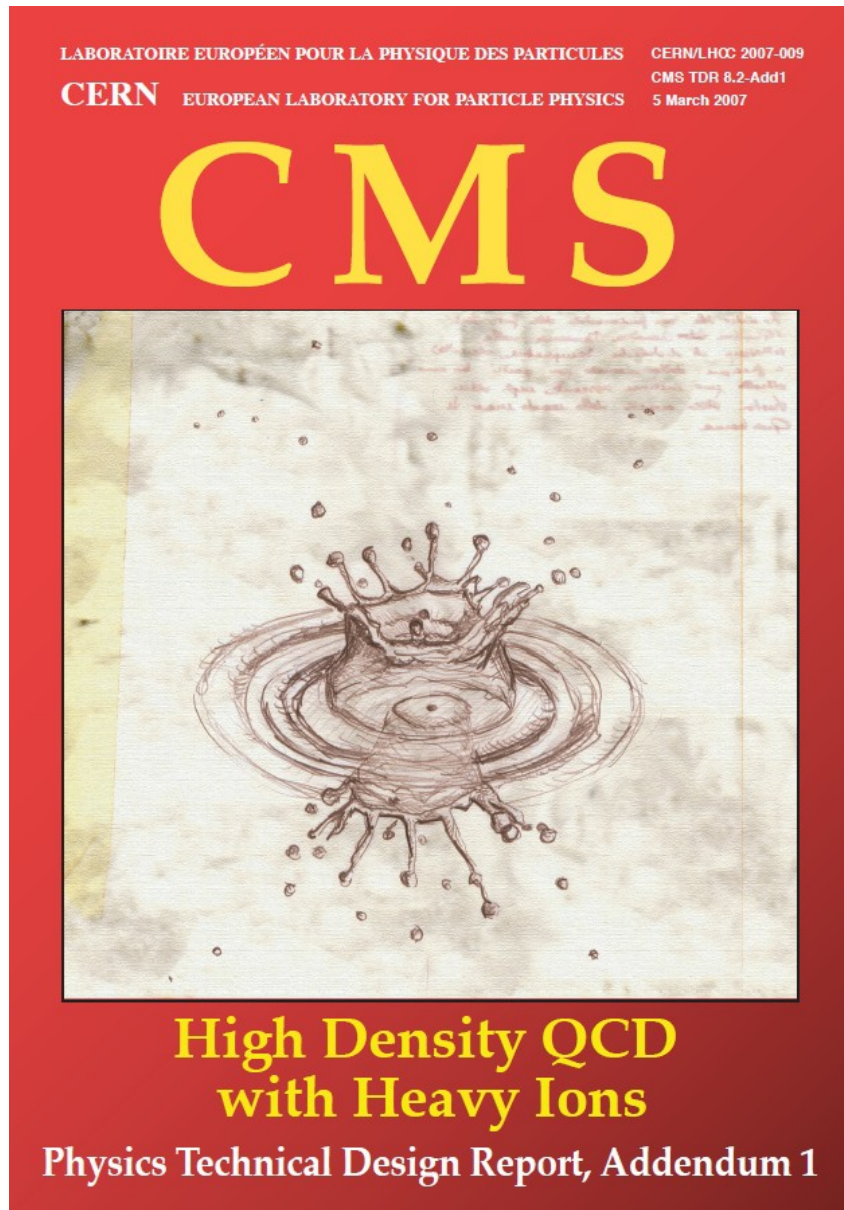
**CASTOR**  
 $-5.2 < \eta < -6.6$



**ZDC**  
( $z = \pm 140$  m,  
 $|\eta| > 8.2$  neutrals)



# Подготовка программы CMS по изучению физики тяжелых ионов

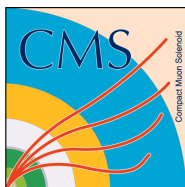


## The CMS Collaboration

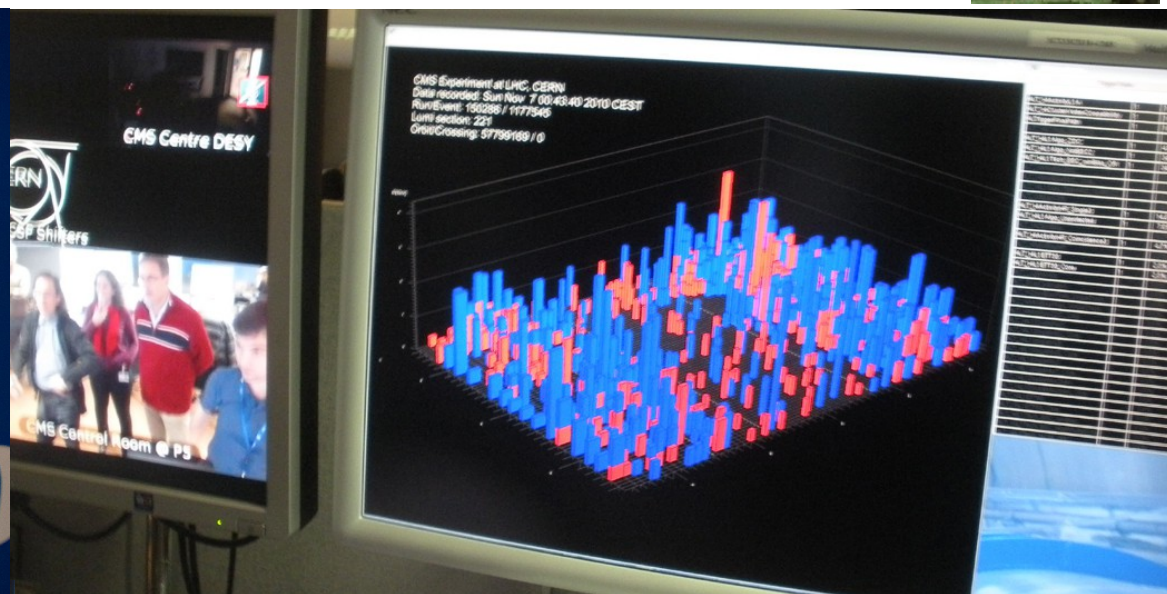
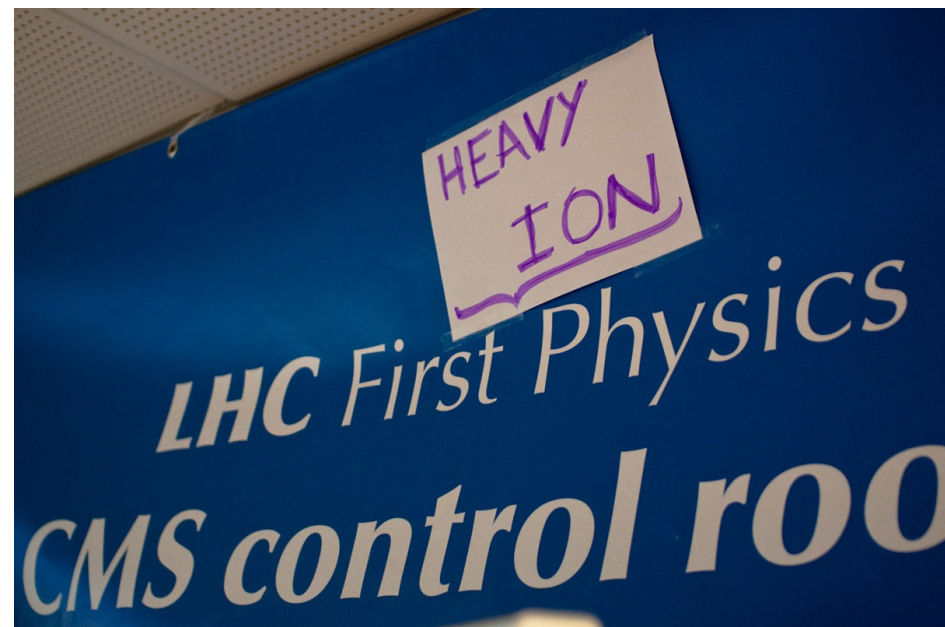
D. d'Enterria, M. Ballintijn,  
M. Bedjidian, D. Hofman,  
O. Kodolova, C. Loizides,  
I. P. Lokthin, C. Lourenco,  
C. Mironov, S. V. Petrushanko,  
C. Roland, G. Roland, F. Sikler  
and G. Veres (*editors*)

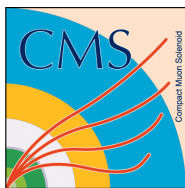
**"CMS Physics Technical Design  
Report: Addendum on High  
Density QCD with Heavy Ions"**

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



# 7 ноября 2010 года 0:27 Контрольная комната CMS





# CMS – статьи по физике тяжелых ионов



**136 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>



# Результаты по физике тяжелых ионов



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

- multiplicity
- energy
- flow, “ridge”, correlations, ...

### Pb+Pb collisions

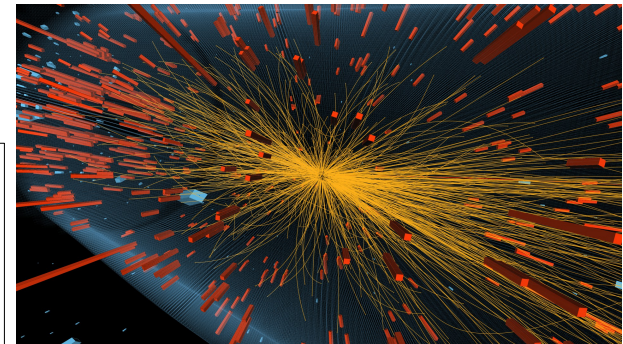
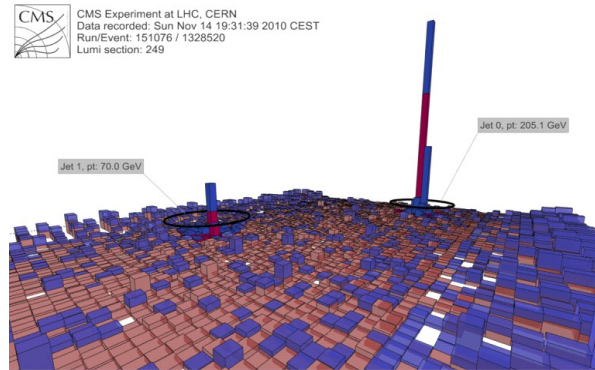
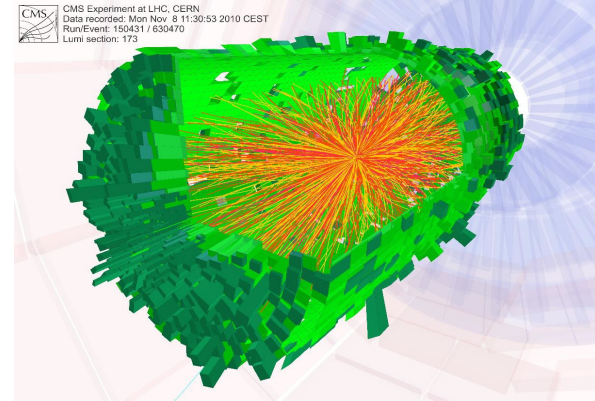
2010-11: 2.76 TeV 0.16/nb  
2015-18: 5.02 TeV 1.7/nb  
2023-... : 5.36 TeV ...

- **Hard probes**

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

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

- correlations
  - flow
  - jets, ...
- |              |                          |
|--------------|--------------------------|
| <b>p+p</b>   | 2.76, 5.02, 7, 8, 13 TeV |
| <b>p+Pb</b>  | 5.02, 8.16 TeV           |
| <b>Xe+Xe</b> | 5.44 TeV                 |







# “Ридж”-эффект в столкновениях протон-протон в эксперименте CMS

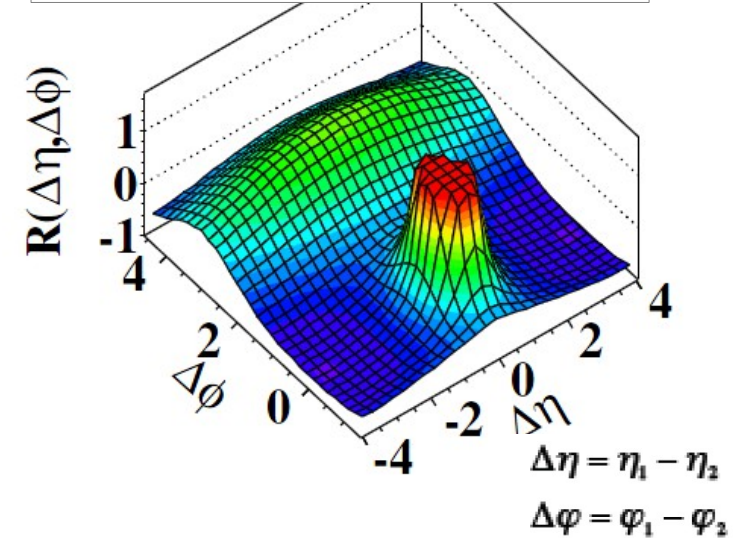


- Протон-протонные столкновения  $\sqrt{s} = 7$  ТэВ с высокой множественностью  $N > 110$ .
- Корреляционная функция для треков с поперечным импульсом в диапазоне от 1 до 3 ГэВ/с:

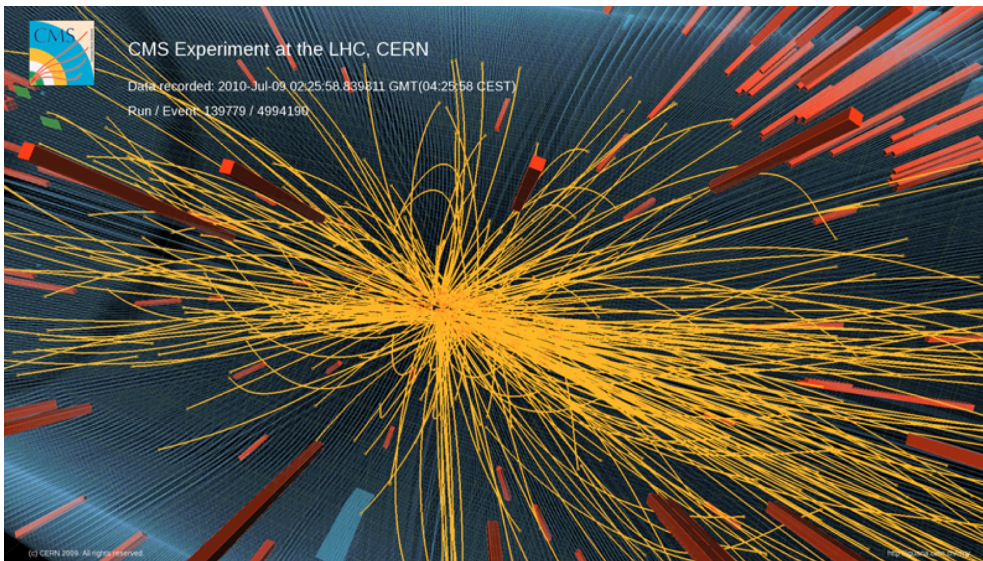
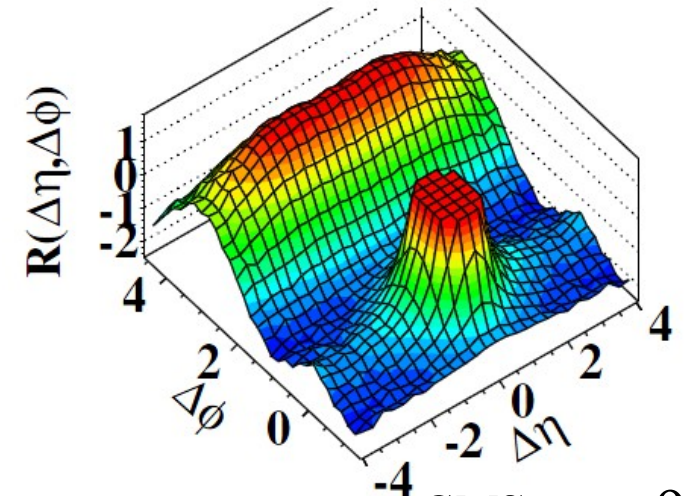
JHEP 09 (2010) 091

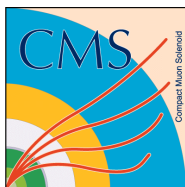
$$\left\{ \begin{aligned} S_N(\Delta\eta, \Delta\phi) &= \frac{1}{N(N-1)} \frac{d^2 N^{signal}}{d\Delta\eta d\Delta\phi} \\ B_N(\Delta\eta, \Delta\phi) &= \frac{1}{N^2} \frac{d^2 N^{bkg}}{d\Delta\eta d\Delta\phi} \end{aligned} \right.$$

все столкновения



столкновения с  $N > 110$





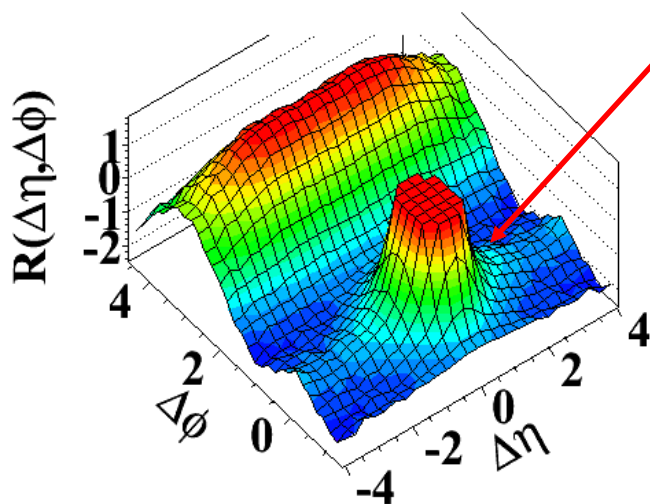
# “Ридж”-эффект — везде...

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

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

p+p 7 TeV

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

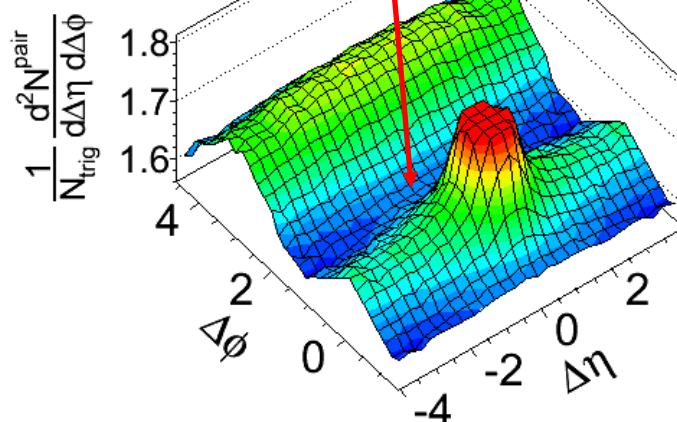


JHEP 09 (2010) 091

p+Pb 5.02 TeV

CMS pPb  $\sqrt{s_{NN}} = 5.02 \text{ TeV}, N_{trk}^{offline} \geq 110$

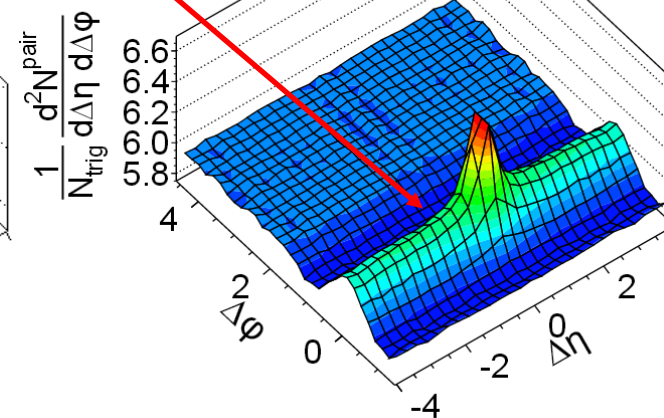
$1 < p_T < 3 \text{ GeV}/c$



PLB 718 (2013) 795

Pb+Pb 2.76 A TeV, 0-5%

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



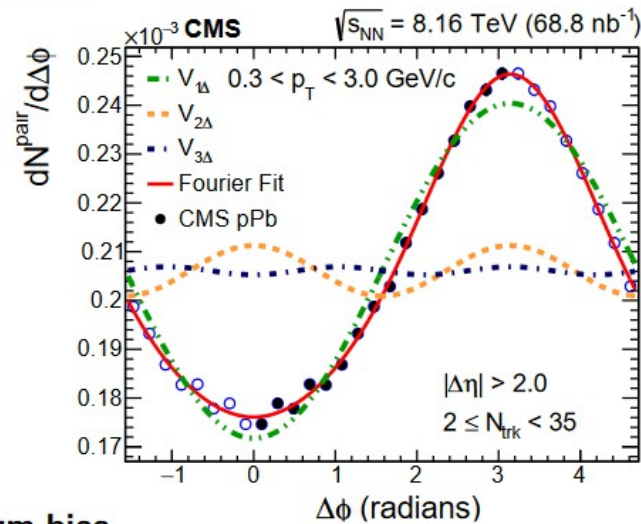
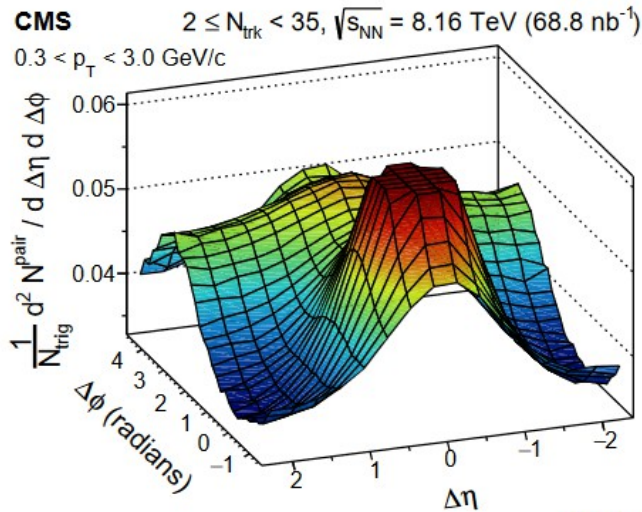
JHEP 07 (2011) 076



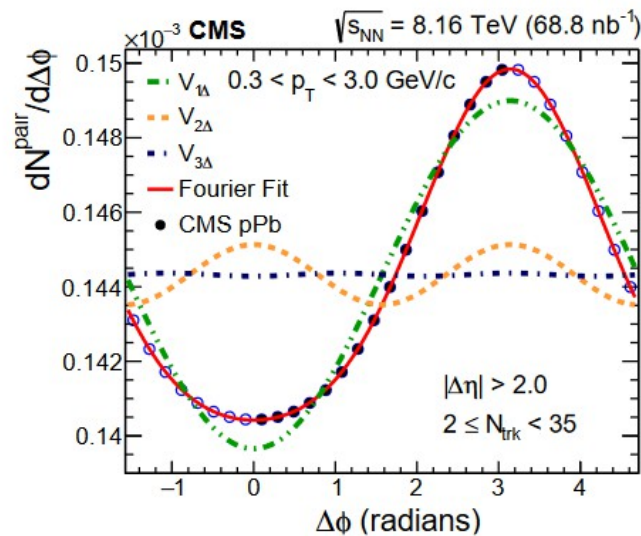
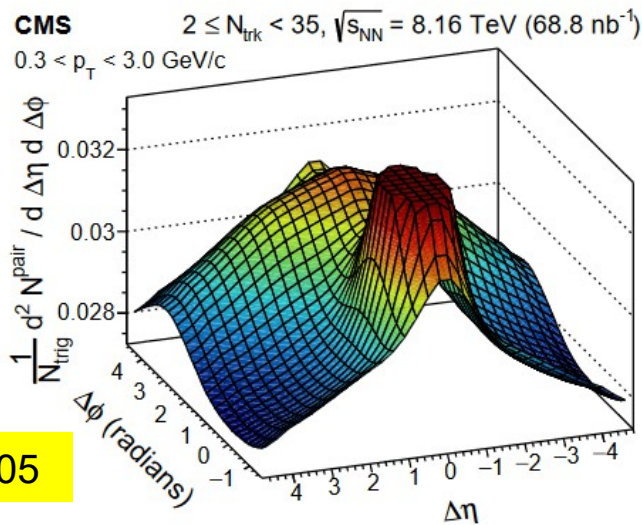
# $\gamma$ +p взаимодействия в ультра-периферических столкновениях p+Pb



$\gamma$ p enhanced



Minimum-bias



PLB 844 (2023) 137905

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

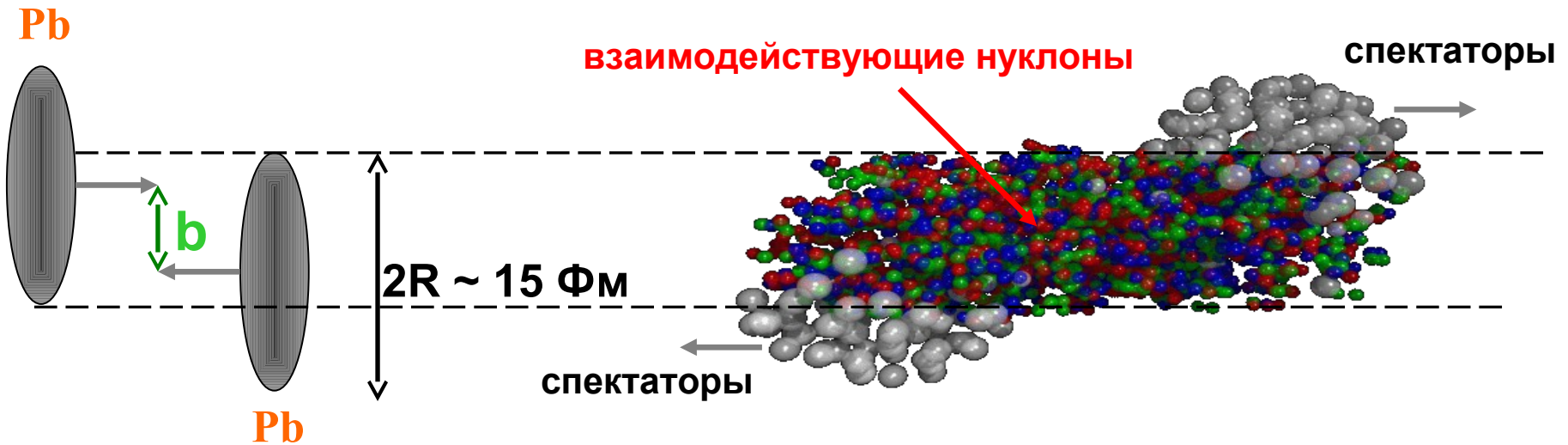
Сергей Петрушко (CMS Collaboration) Физика тяжелых ионов на CMS



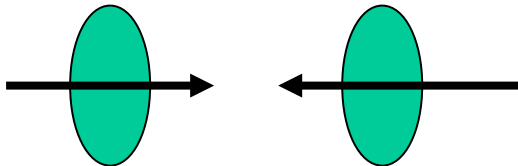
# Кварк-глюонная плазма



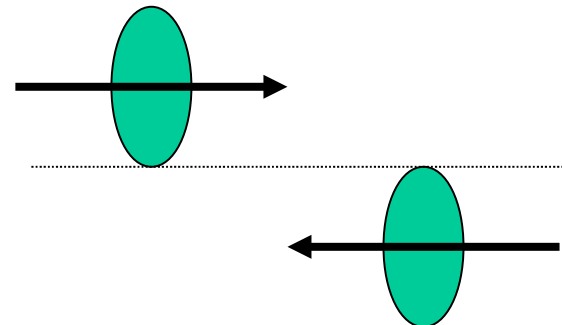
В релятивистских соударениях тяжелых ионов возможно формирование сверхплотного состояния КХД-материи в квазимакроскопических объемах (по сравнению с характерными адронными масштабами).



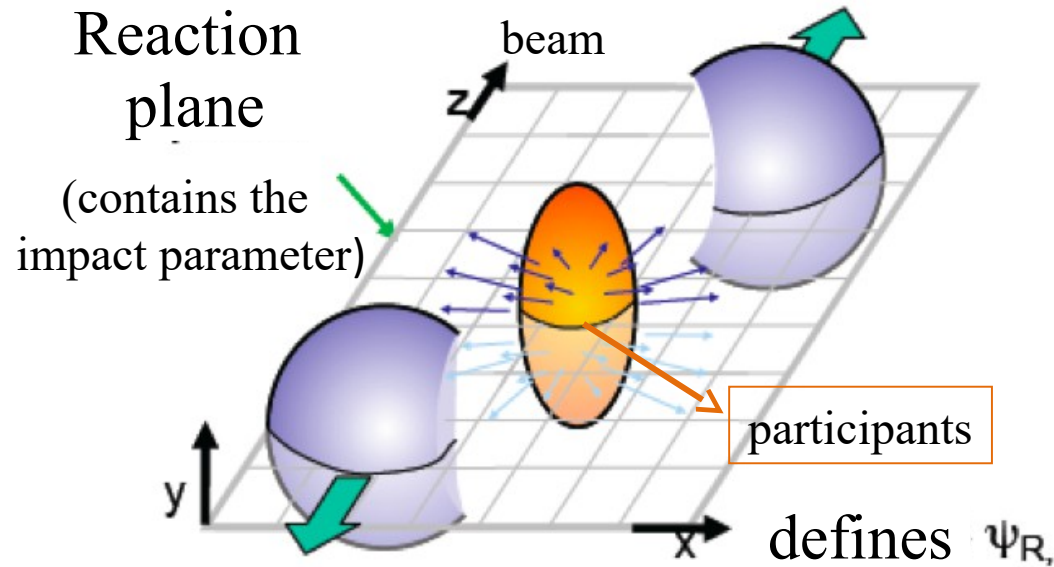
Центральные столкновения, прицельный параметр  $b = 0$



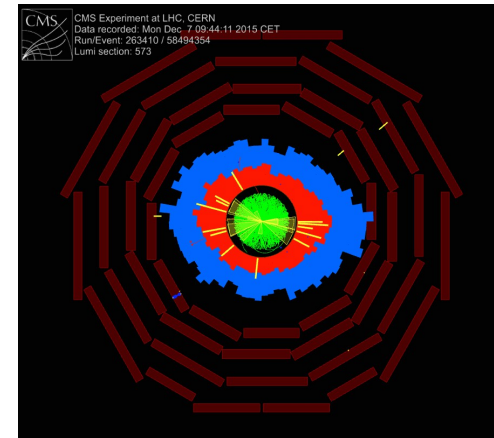
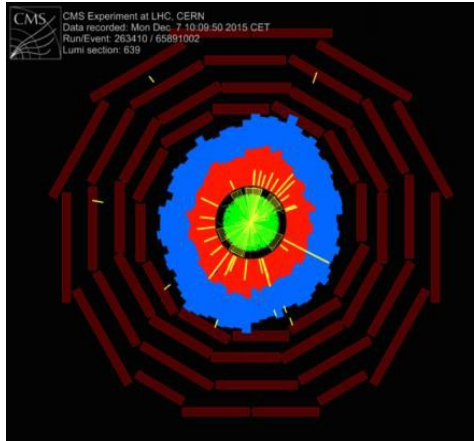
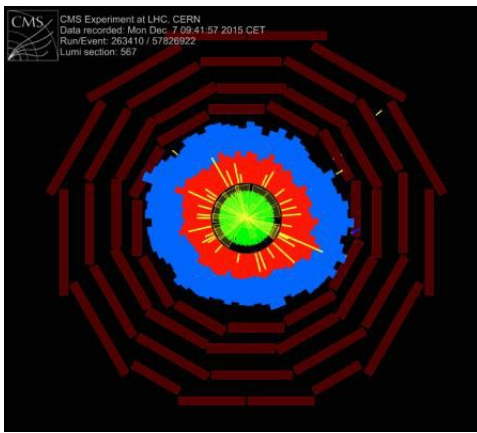
Периферические столкновения, прицельный параметр  $b \approx 2R$



# Азимутальная анизотропия



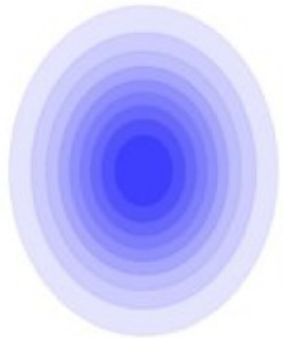
Non-central Pb+Pb “screen shots” from CMS Event Monitor:  
**Electromagnetic**, **Hadronic** Energy and **charged particles tracks**



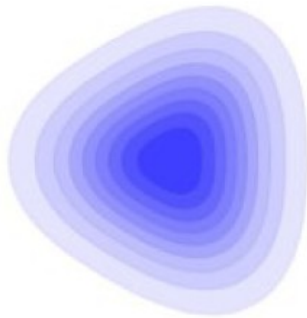
**Collective motion is observed in the event azimuthal distributions**

# Потоки гармоник $v_2, v_3 \dots$

Ненулевые гармоники  $v_2, v_3$  и т.д. несут информацию об условиях пространственно-временной эволюции ядерной материи и флуктуациях ее начального состояния.



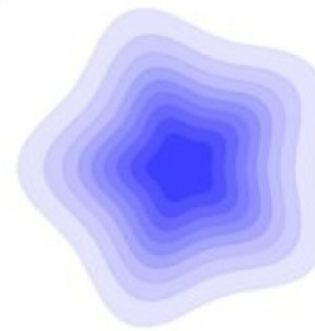
$n = 2$



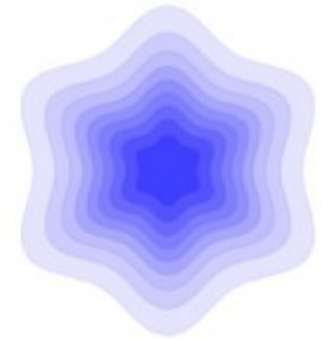
$n = 3$



$n = 4$

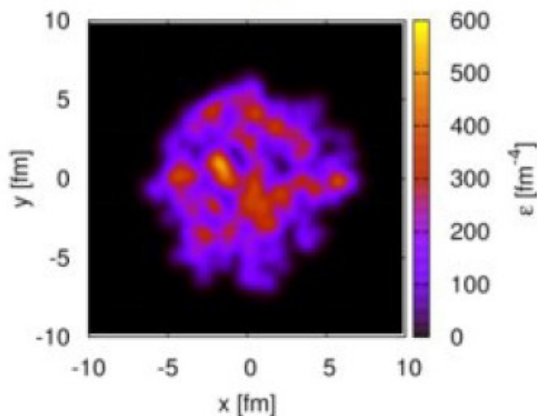


$n = 5$

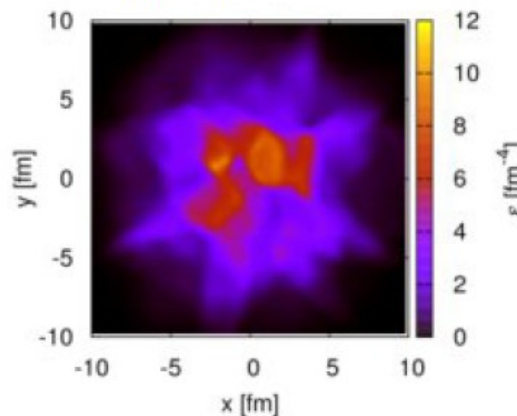


$n = 6$

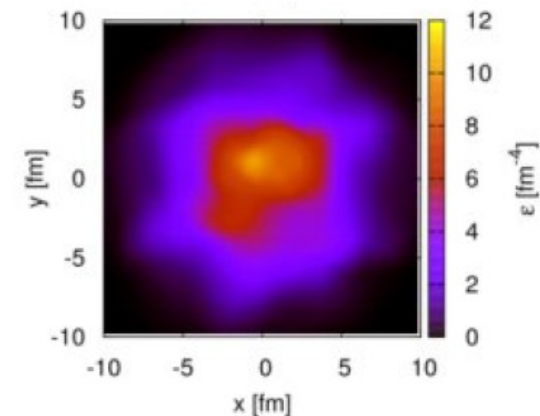
Начальная стадия



Идеальная гидродинамика

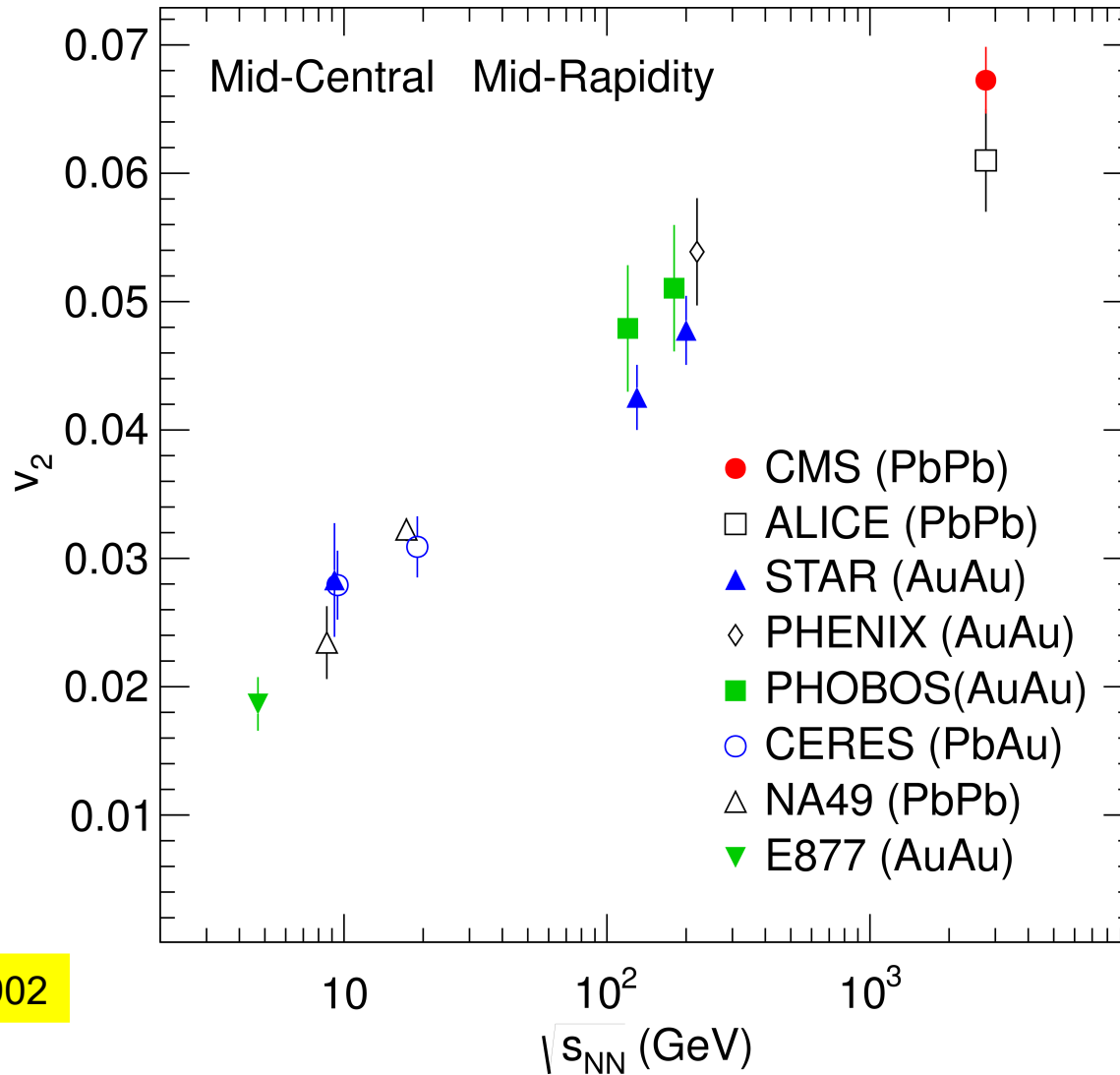


Гидродинамика с вязкостью





# Интегральная $v_2$ – результат для ЛНС от CMS

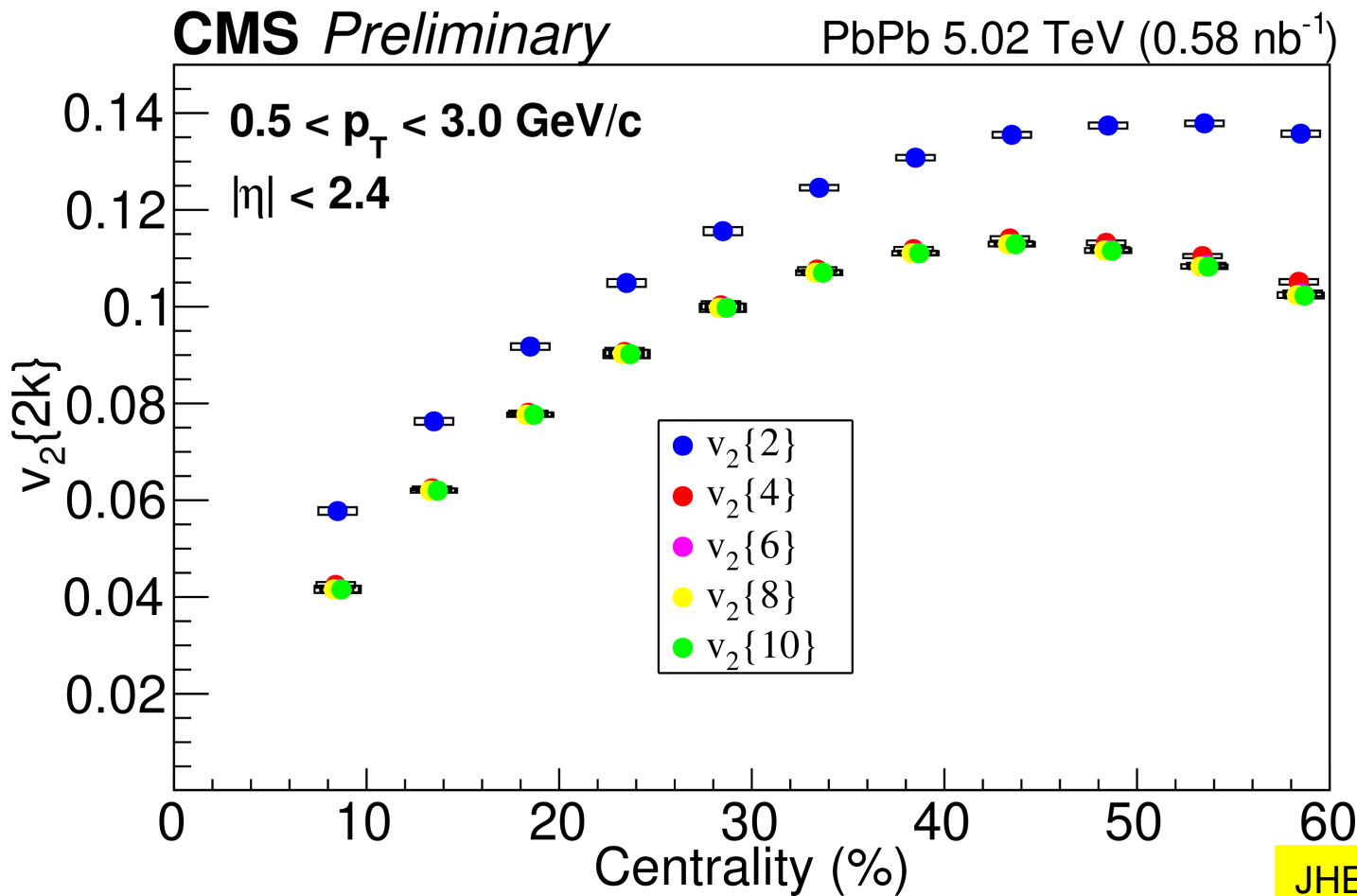


PRC 87 (2013) 014902

15-30% increase in integral  $v_2$  from top RHIC energy to LHC



# Кумулянты эллиптического потока $v_2\{2k\}$ в Pb+Pb соударениях



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

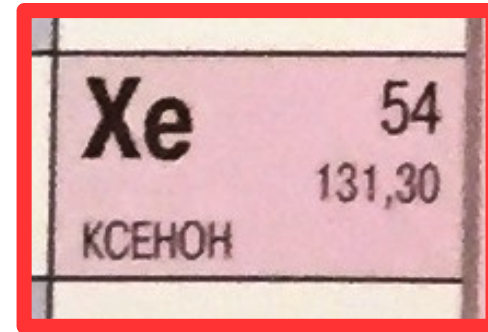
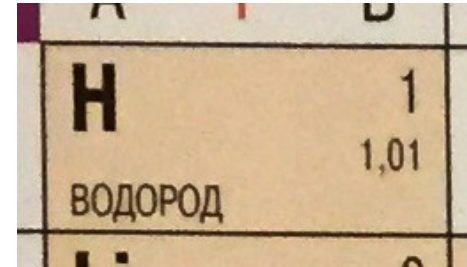


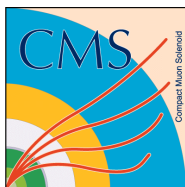
# Хе+Хе как “мост” между р+р и Рb+Рb



## 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	<b>H</b> 1 ВОДОРОД							(H)								<b>He</b> 2 ГЕЛИЙ 4,00										
2	2	<b>Li</b> 3 ЛИТИЙ 6,94	<b>Be</b> 4 БЕРИЛЛИЙ 9,01	<b>B</b> 5 БОР 10,81	<b>C</b> 6 УГЛЕРОД 12,01	<b>N</b> 7 АЗОТ 14,01	<b>O</b> 8 КИСЛОРОД 16,00	<b>F</b> 9 ФТОР 19,00									<b>Ne</b> 10 НЕОН 20,18										
3	3	<b>Na</b> 11 НАТРИЙ 22,99	<b>Mg</b> 12 МАГНИЙ 24,31	<b>Al</b> 13 АЛЮМИНИЙ 26,98	<b>Si</b> 14 КРЕМНИЙ 28,09	<b>P</b> 15 ФОСФОР 30,97	<b>S</b> 16 СЕРА 32,06	<b>Cl</b> 17 ХЛОР 35,45									<b>Ar</b> 18 АРГОН 39,95										
4	4	<b>K</b> 19 КАЛИЙ 39,10	<b>Ca</b> 20 КАЛЬЦИЙ 40,08	<b>Sc</b> 21 СКАНДИЙ 44,96	<b>Ti</b> 22 ТИТАН 47,90	<b>V</b> 23 ВАНАДИЙ 50,94	<b>Cr</b> 24 ХРОМ 52,00	<b>Mn</b> 25 МАРГАНЕЦ 54,94	<b>Fe</b> 26 ЖЕЛЕЗО 55,85	<b>Co</b> 27 КОБАЛЬТ 58,93	<b>Ni</b> 28 НИКЕЛЬ 58,70																
	5	<b>Cu</b> 29 МЕДЬ 63,55	<b>Zn</b> 30 ЦИНК 65,39	<b>Ga</b> 31 ГАЛЛИЙ 69,72	<b>Ge</b> 32 ГЕРМАНИЙ 72,59	<b>As</b> 33 МЫШЬЯК 74,92	<b>Se</b> 34 СЕЛЕН 78,96	<b>Br</b> 35 БРОМ 79,90										<b>Kr</b> 36 КРИПТОН 83,80									
5	6	<b>Rb</b> 37 РУБИДИЙ 85,47	<b>Sr</b> 38 СТРОНЦИЙ 87,62	<b>Y</b> 39 ИТРИЙ 88,91	<b>Zr</b> 40 ЦИРКОНИЙ 91,22	<b>Nb</b> 41 НИОБИЙ 92,91	<b>Mo</b> 42 МОЛИБДЕН 95,94	<b>Tc</b> 43 ТЕХНЕЦИЙ 98,91	<b>Ru</b> 44 РУТЕНИЙ 101,07	<b>Rh</b> 45 РОДИЙ 106,42	<b>Pd</b> 46 ПАЛЛАДИЙ 106,42																
	7	<b>Ag</b> 47 СЕРЕБРО 107,87	<b>Cd</b> 48 КАДМИЙ 112,41	<b>In</b> 49 ИНДИЙ 114,82	<b>Sn</b> 50 ОЛОВО 118,71	<b>Sb</b> 51 СУРЬМА 121,75	<b>Te</b> 52 ТЕЛЛУР 127,60	<b>I</b> 53 ЙОД 126,90										<b>Xe</b> 54 КСЕНОН 131,30									
6	8	<b>Cs</b> 55 ЦЕЗИЙ 132,91	<b>Ba</b> 56 БАРИЙ 137,33	<b>La*</b> 57 ЛАНТАН 138,91	<b>Hf</b> 72 ГАФНИЙ 178,49	<b>Ta</b> 73 ТАНТАЛ 180,95	<b>W</b> 74 ВОЛЬФРАМ 183,84	<b>Re</b> 75 РЕНИЙ 186,21	<b>Os</b> 76 ОСМИЙ 190,23	<b>Ir</b> 77 ИРИДИЙ 192,22	<b>Pt</b> 78 ПЛАТИНА 195,09																
	9	<b>Au</b> 79 ЗОЛОТО 196,97	<b>Hg</b> 80 РУТУТЬ 200,59	<b>Tl</b> 81 ТАЛЛИЙ 204,38	<b>Pb</b> 82 СВИНЕЦ 207,20	<b>Bi</b> 83 ВИСМУТ 208,98	<b>Po</b> 84 ПОЛОНИЙ [209]	<b>At</b> 85 АСТАТ [210]											<b>Rn</b> 86 РАДОН [222]								
7	10	<b>Fr</b> 87 ФРАНЦИЙ [223]	<b>Ra</b> 88 РАДИЙ [226]	<b>Ac**</b> 89 АКТИНИЙ [227]	<b>Rf</b> 104 РЕЗЕРФОРДИЙ [261]	<b>Db</b> 105 ДУБИНИЙ [262]	<b>Sg</b> 106 СИБОРИЙ [263]	<b>Bh</b> 107 БОРИЙ [262]	<b>Hs</b> 108 ГАССИЙ [265]	<b>Mt</b> 109 МЕЙТТЕРИЙ [268]	<b>Ds</b> 110 ДАРМШТАДТИЙ [271]																
ВЫСШИЕ ОКСИДЫ		R <sub>2</sub> O		RO		R <sub>2</sub> O <sub>3</sub>		RO <sub>2</sub>		R <sub>2</sub> O <sub>5</sub>		RO <sub>3</sub>		R <sub>2</sub> O <sub>7</sub>		RO <sub>4</sub>											
ЛЕТУЧИЕ ВОДОРОДНЫЕ СОЕДИНЕНИЯ						RH <sub>4</sub>		RH <sub>3</sub>		H <sub>2</sub> R		HR															
*ЛАНТАНОИДЫ		<b>Ce</b> 58 ЦЕРИЙ 140,12	<b>Pr</b> 59 ПРАЗЕОДИМ 140,91	<b>Nd</b> 60 НЕОДИМ 144,24	<b>Pm</b> 61 ПРОМЕТИЙ [145]	<b>Sm</b> 62 САМАРИЙ 150,36	<b>Eu</b> 63 ЕВРОПИЙ 151,96	<b>Gd</b> 64 ГАДОЛИНИЙ 157,25	<b>Tb</b> 65 ТЕРБИЙ 158,93	<b>Dy</b> 66 ДИСПРОЗИЙ 162,50	<b>Ho</b> 67 ГОЛЬМИЙ 164,93	<b>Er</b> 68 ЭРБИЙ 167,26	<b>Tm</b> 69 ТУЛИЙ 168,93	<b>Yb</b> 70 ИТТЕРБИЙ 173,04	<b>Lu</b> 71 ЛЮТЕЦИЙ 174,97												
**АКТИНОИДЫ		<b>Th</b> 90 ТОРИЙ 232,03	<b>Pa</b> 91 ПРОТАКТИНИЙ 231,04	<b>U</b> 92 УРАН 238,03	<b>Np</b> 93 НЕПТУНИЙ [237]	<b>Pu</b> 94 ПЛУТОНИЙ [244]	<b>Am</b> 95 АМЕРИЦИЙ [243]	<b>Cm</b> 96 КЮРИЙ [247]	<b>Bk</b> 97 БЕРКЛИЙ [247]	<b>Cf</b> 98 КАЛИФОРНИЙ [251]	<b>Es</b> 99 ЭЙНШТЕЙНИЙ [252]	<b>Fm</b> 100 ФЕРМИЙ [257]	<b>Md</b> 101 МЕНДЕЛЕВИЙ [258]	<b>No</b> 102 НОБЕЛИЙ [259]	<b>Lr</b> 103 ЛОУРЕНСИЙ [262]												
РЯД АКТИВНОСТИ МЕТАЛЛОВ		Li	Cs	Rb	K	Ba	Sr	Ca	Na	Mg	Be	Al	Mn	Zn	Cr	Fe	Cd	Co	Ni	Sn	Pb	H <sub>2</sub>	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 <sub>2</sub>	Sb	Cu	Hg	Ag	Pt	Au	



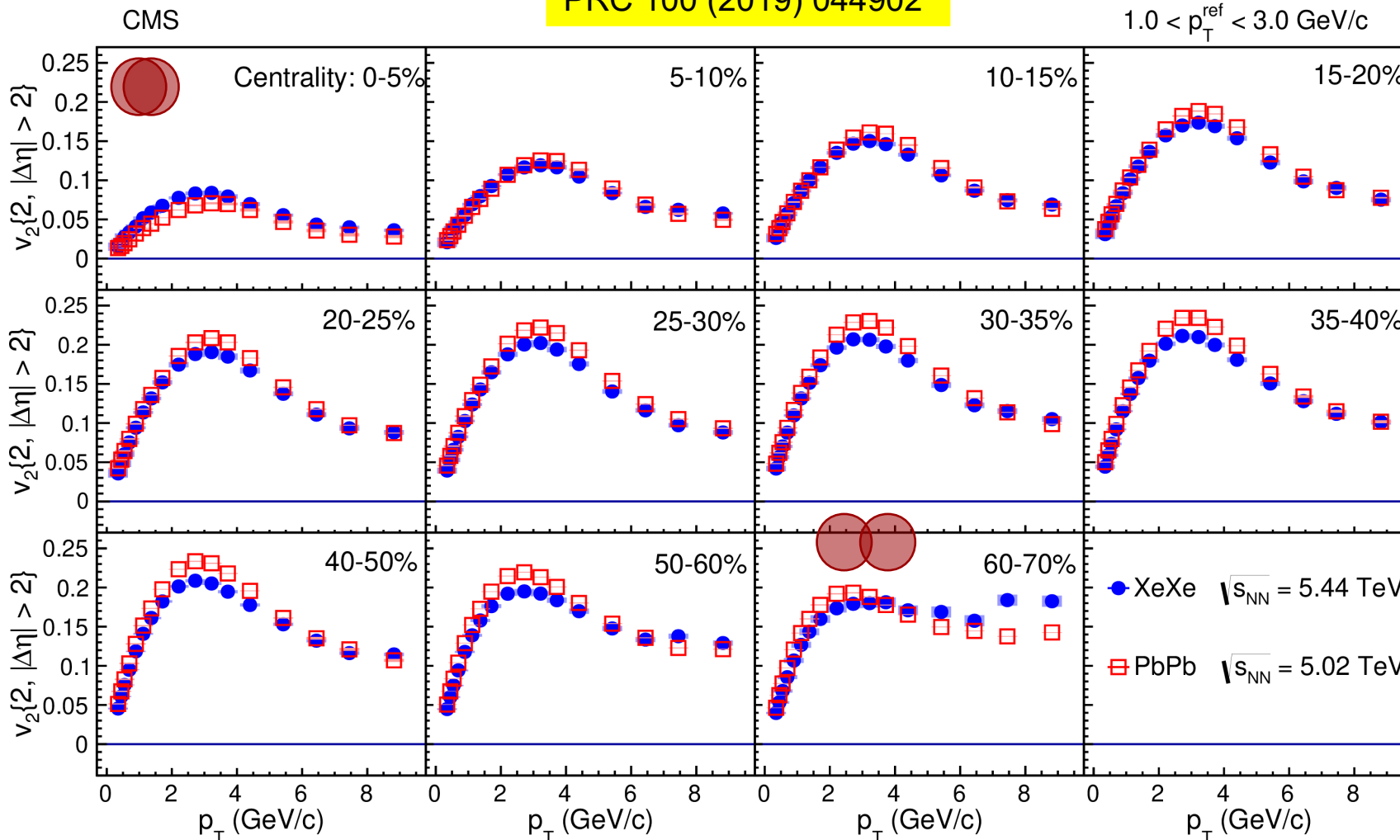


# $v_2$ Xe+Xe vs. Pb+Pb



PRC 100 (2019) 044902

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



<b>Xe</b>	54
КСЕНОН	131,30

<b>Pb</b>	82
СВИНЕЦ	207,20

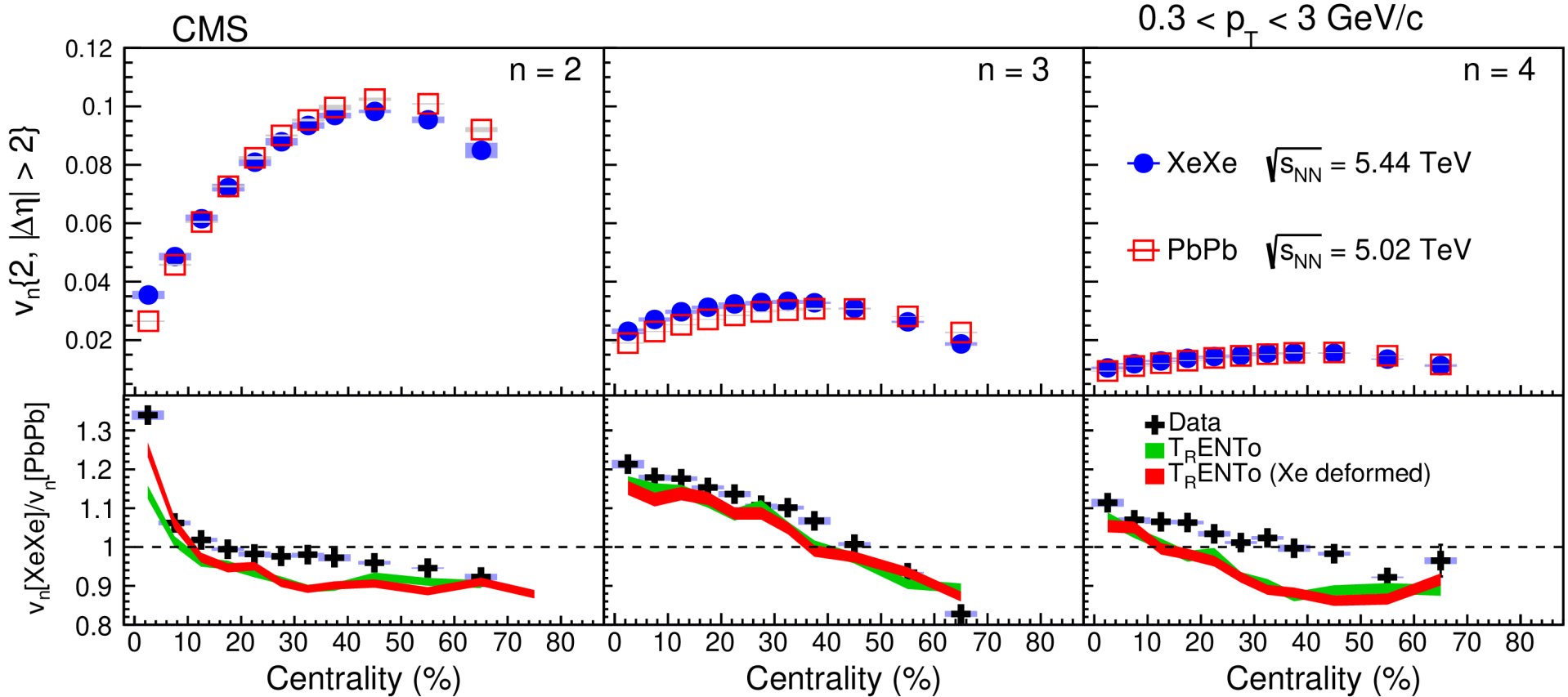
The magnitude of the  $v_2$  coefficients for Xe+Xe collisions are larger than those found in Pb+Pb collisions for the most central collisions. This is attributed to a larger fluctuation component in the lighter colliding system.

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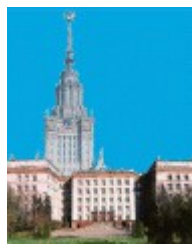
# $v_{2,3,4}$ Xe+Xe vs. Pb+Pb

PRC 100 (2019) 044902

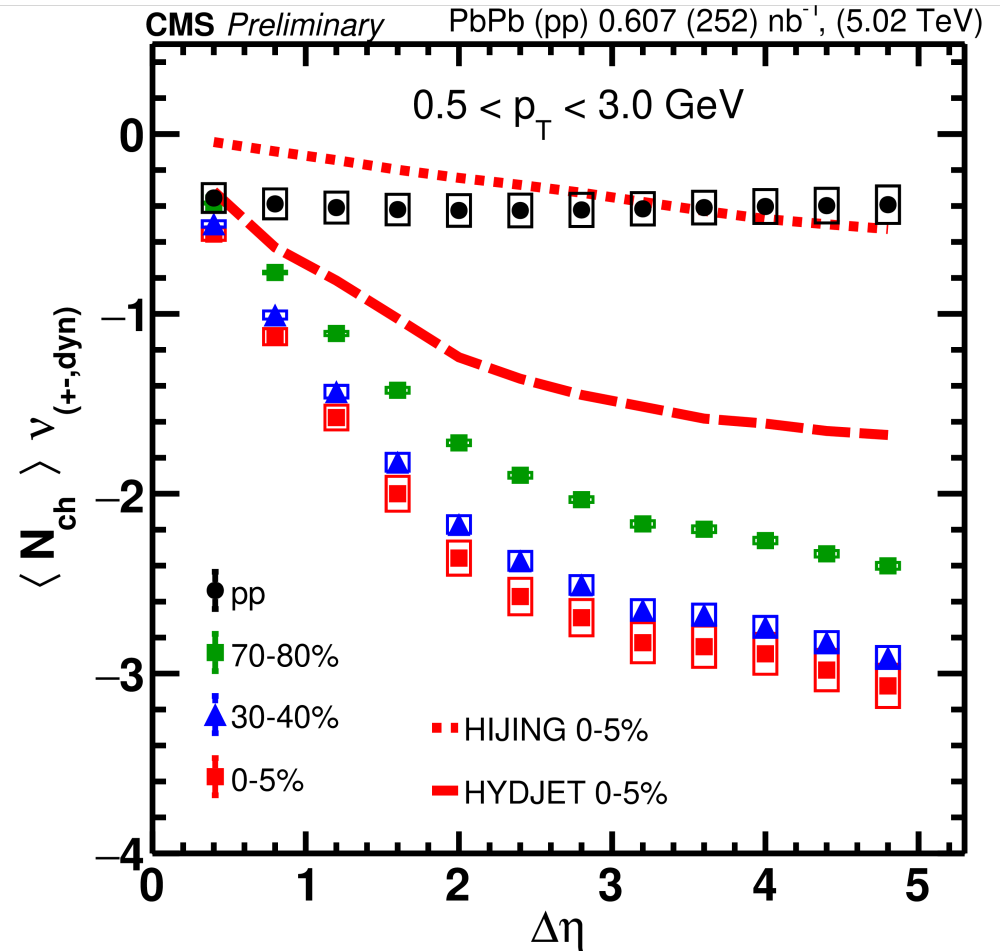
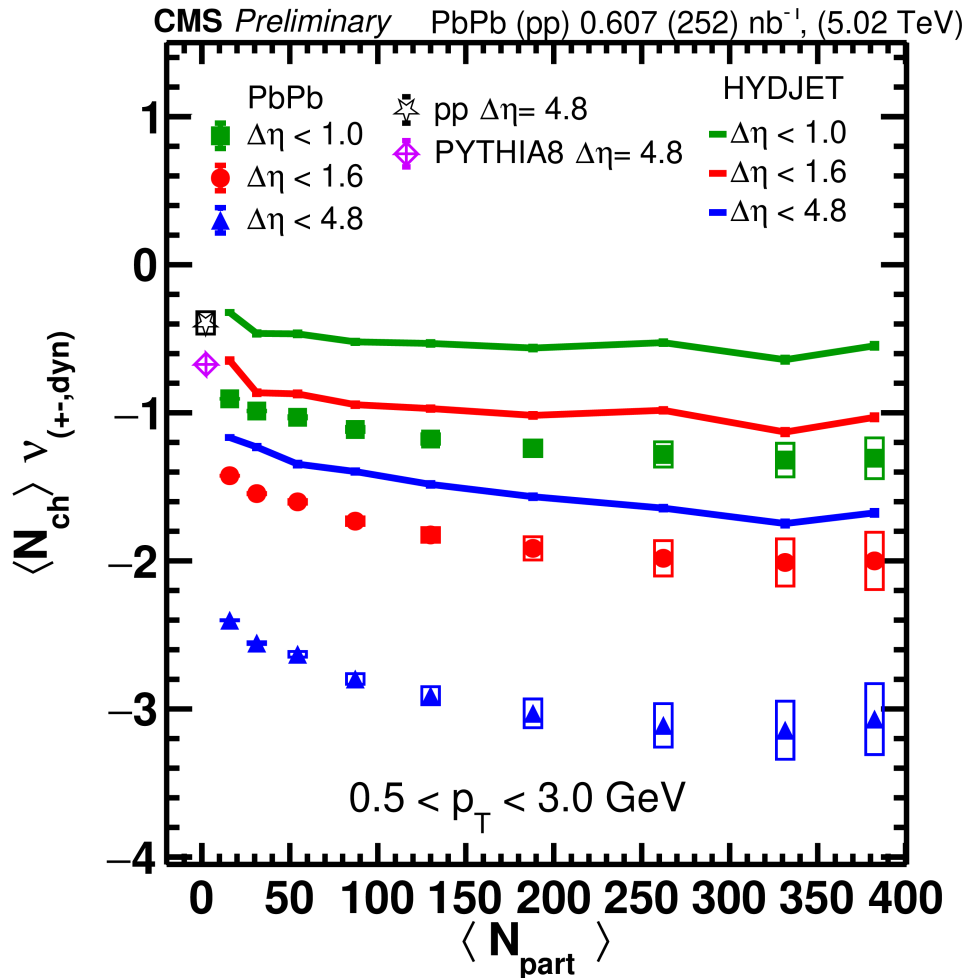


Hydrodynamic models that consider the Xe nuclear deformation are able to better describe the  $v_2[\text{XeXe}]/v_2[\text{PbPb}]$  ratio in central collisions than those assuming a spherical Xe shape.

# Зарядовые флуктуации в Pb-Pb соударениях

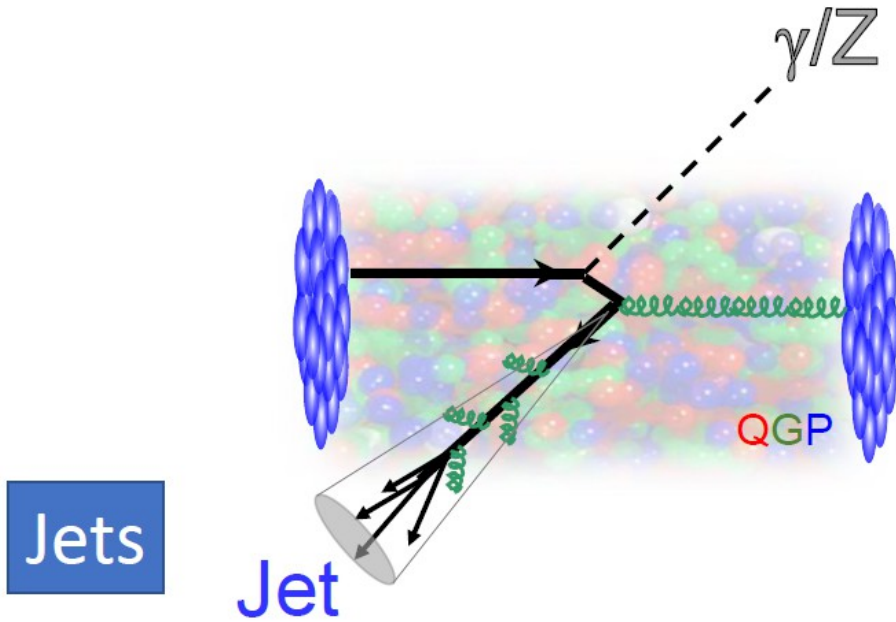


CMS-PAS-HIN-22-005



Net-charge fluctuations differ between QGP and hadron gas phase.  
 Increasing centrality approaches QGP prediction faster.

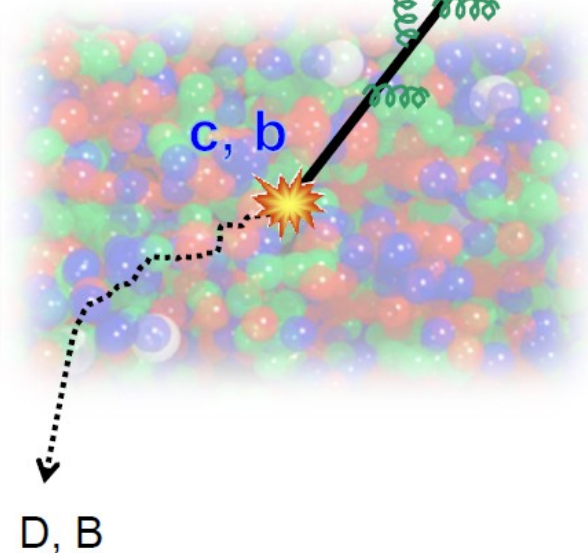
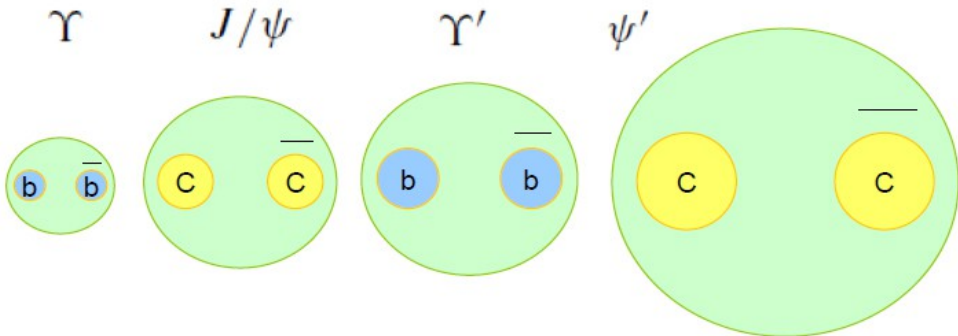
# Жесткие тесты кварк-глюонной плазмы



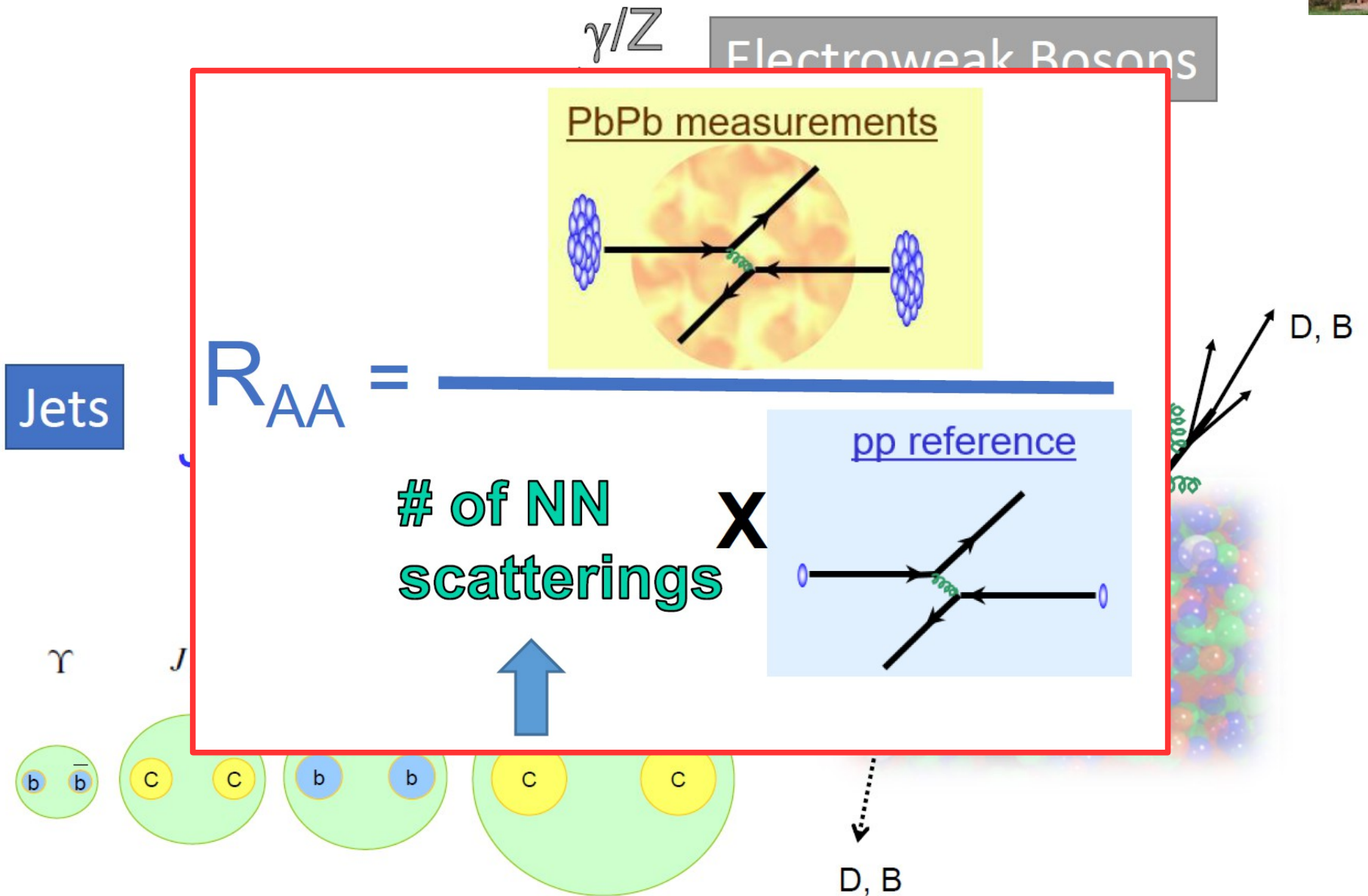
Electroweak Bosons



Quarkonia

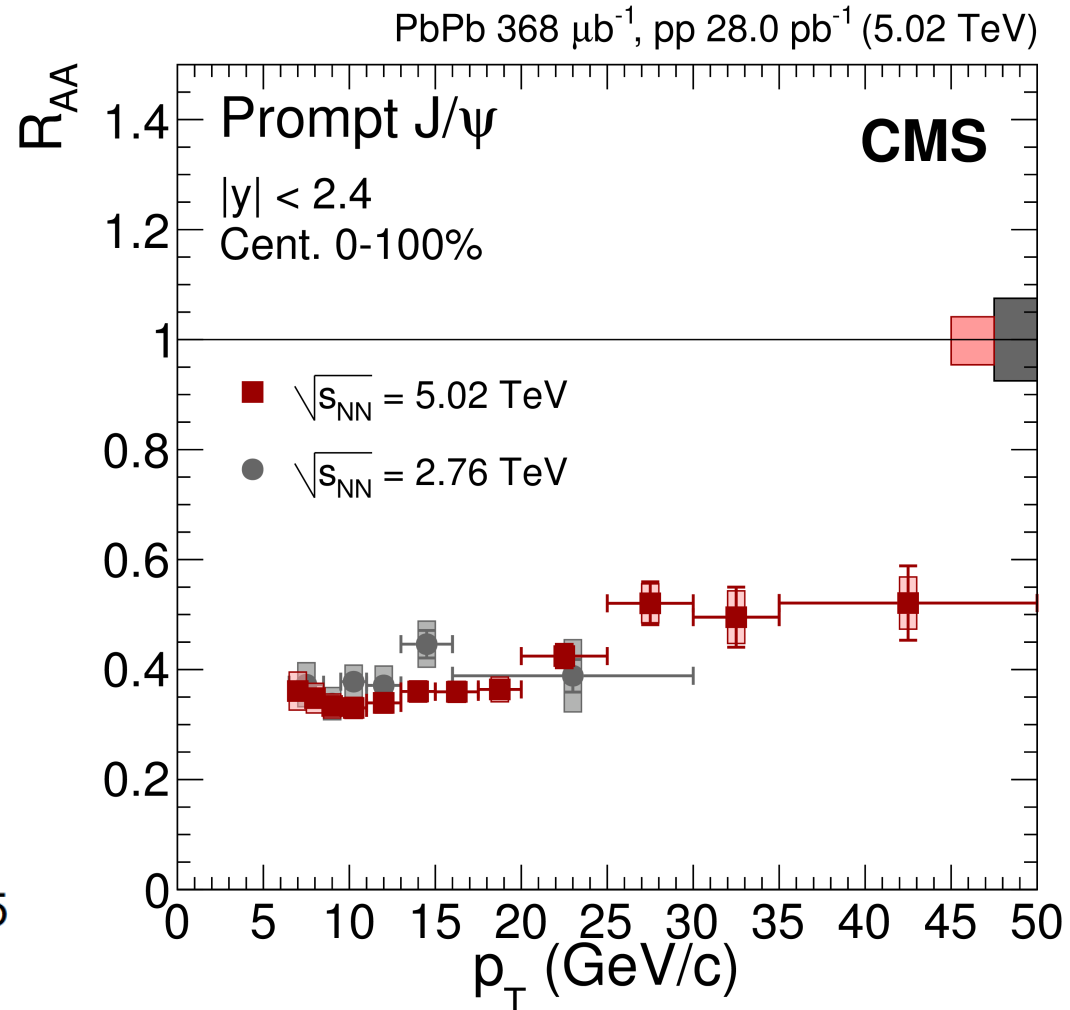
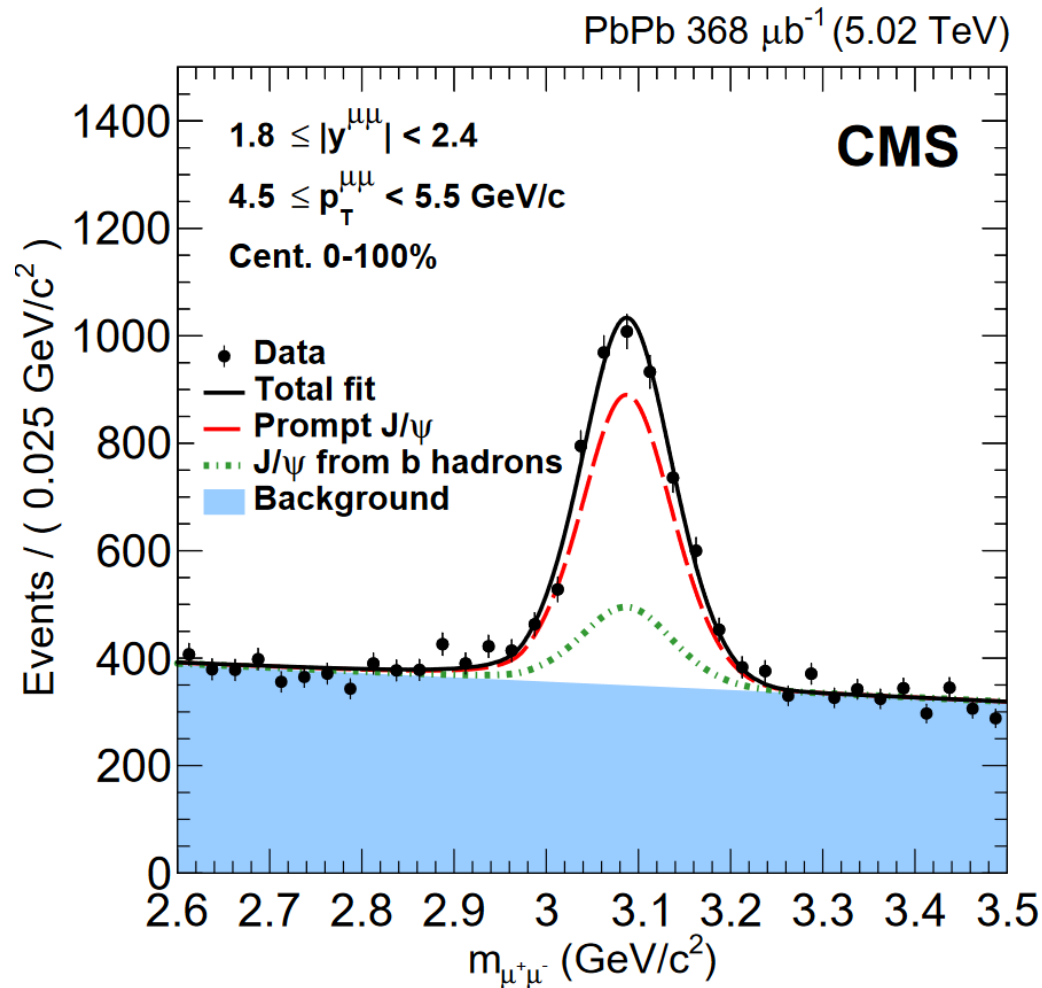


# Жесткие тесты кварк-глюонной плазмы



# Подавление $J/\psi$ в Pb+Pb

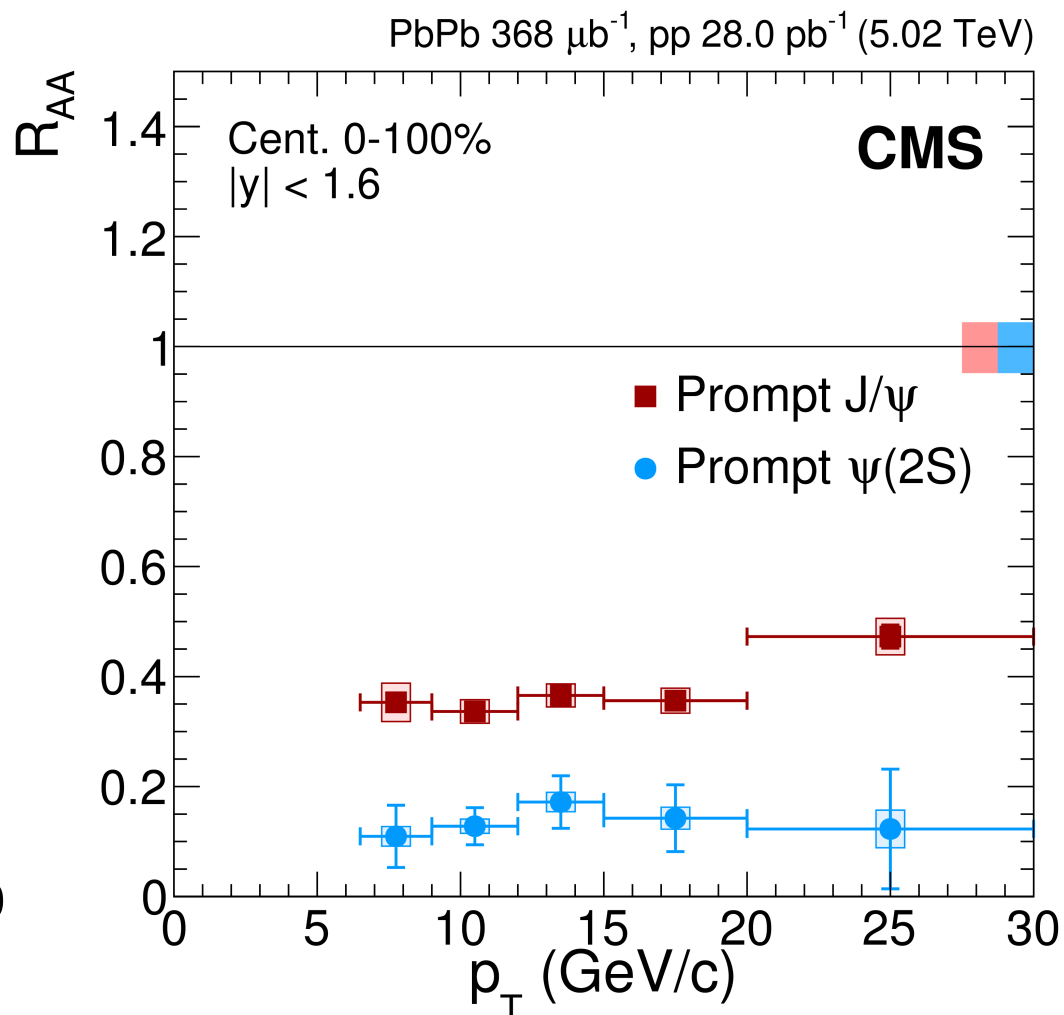
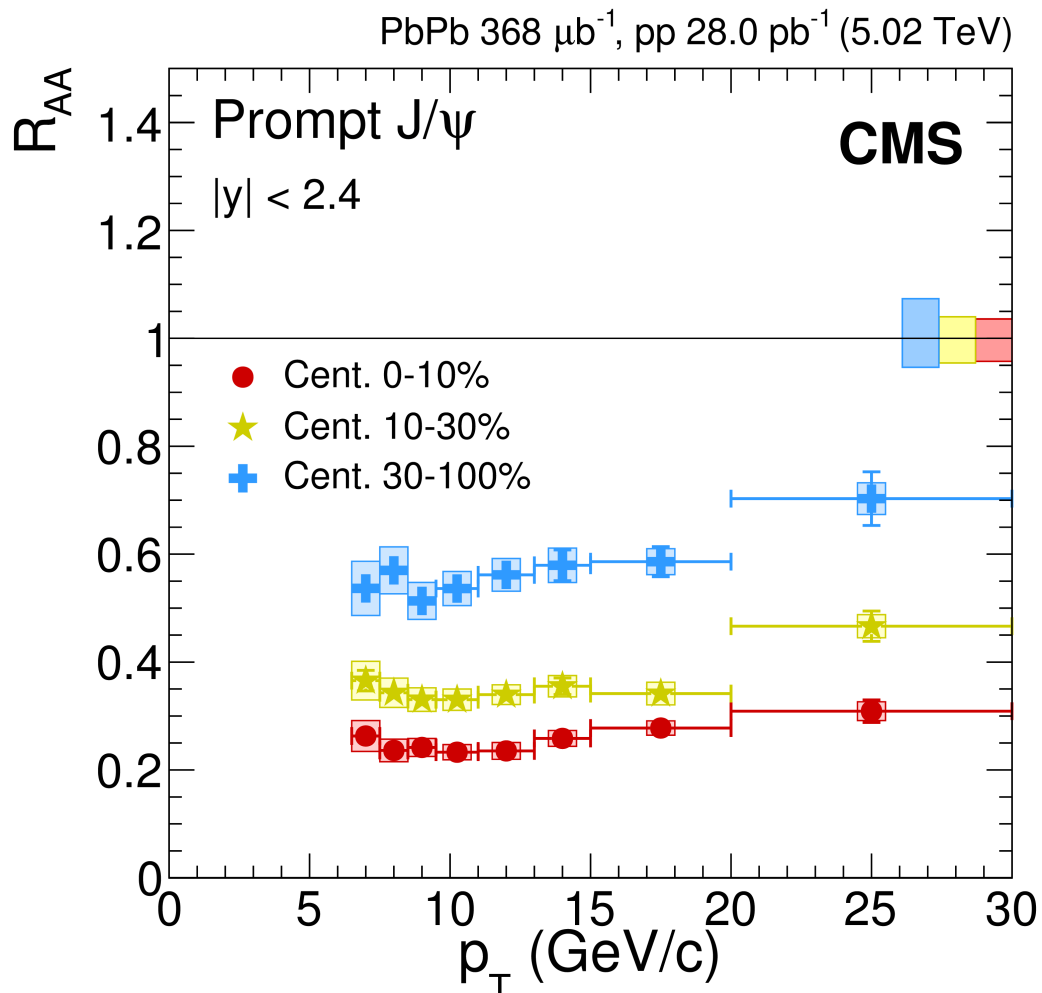
EPJ C 78 (2018) 509



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

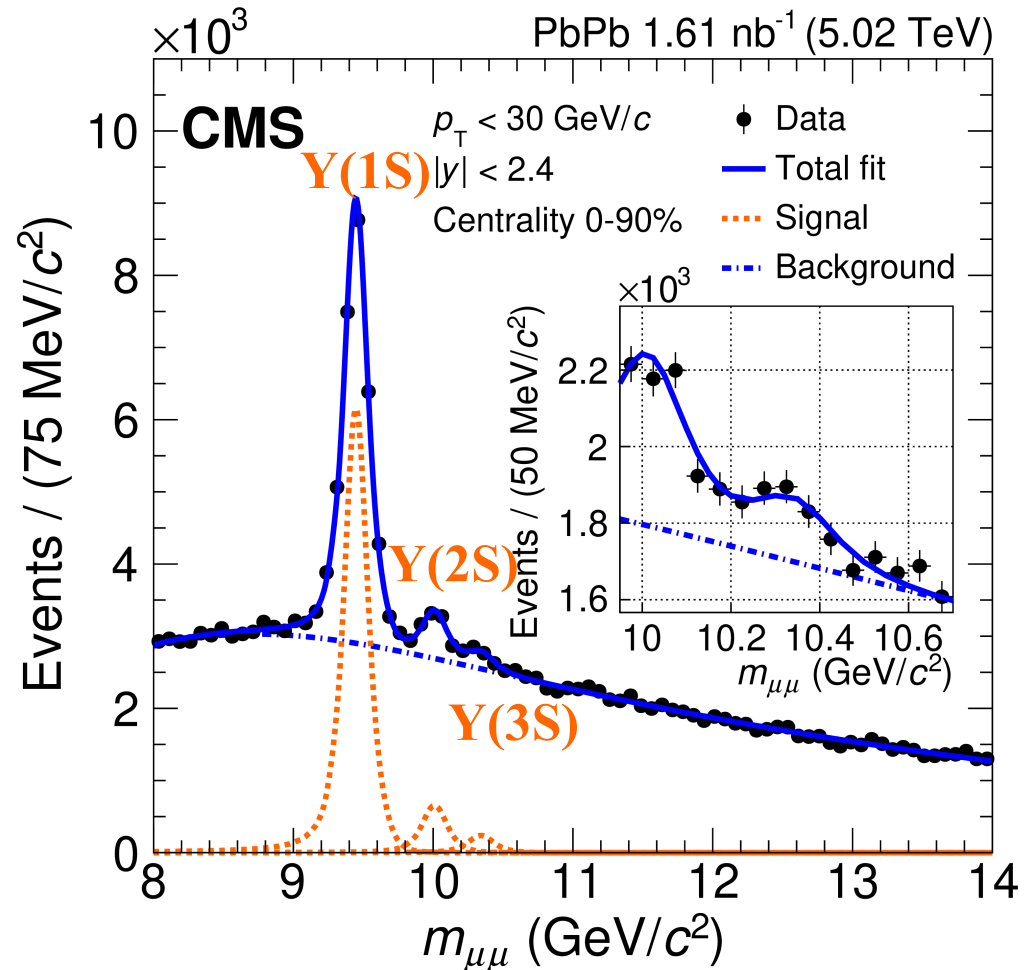
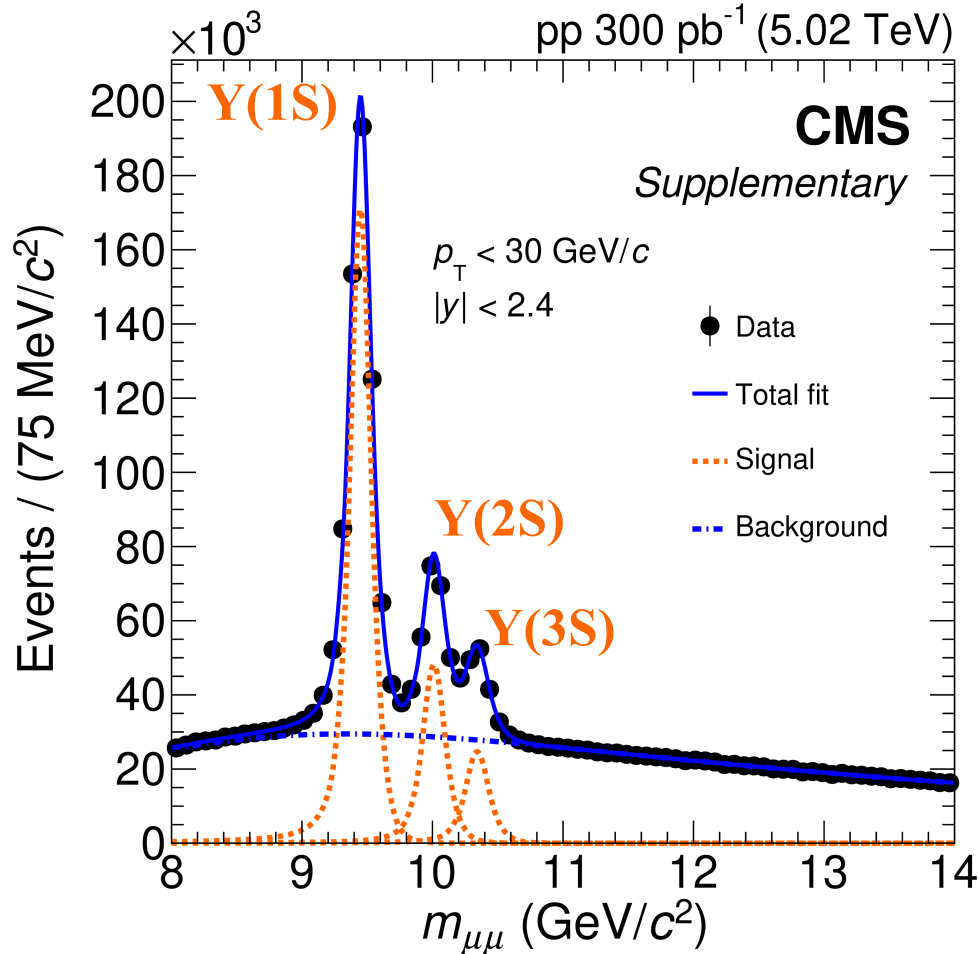
# Подавление $J/\psi$ и $\psi(2S)$ в Pb+Pb

EPJ C 78 (2018) 509



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

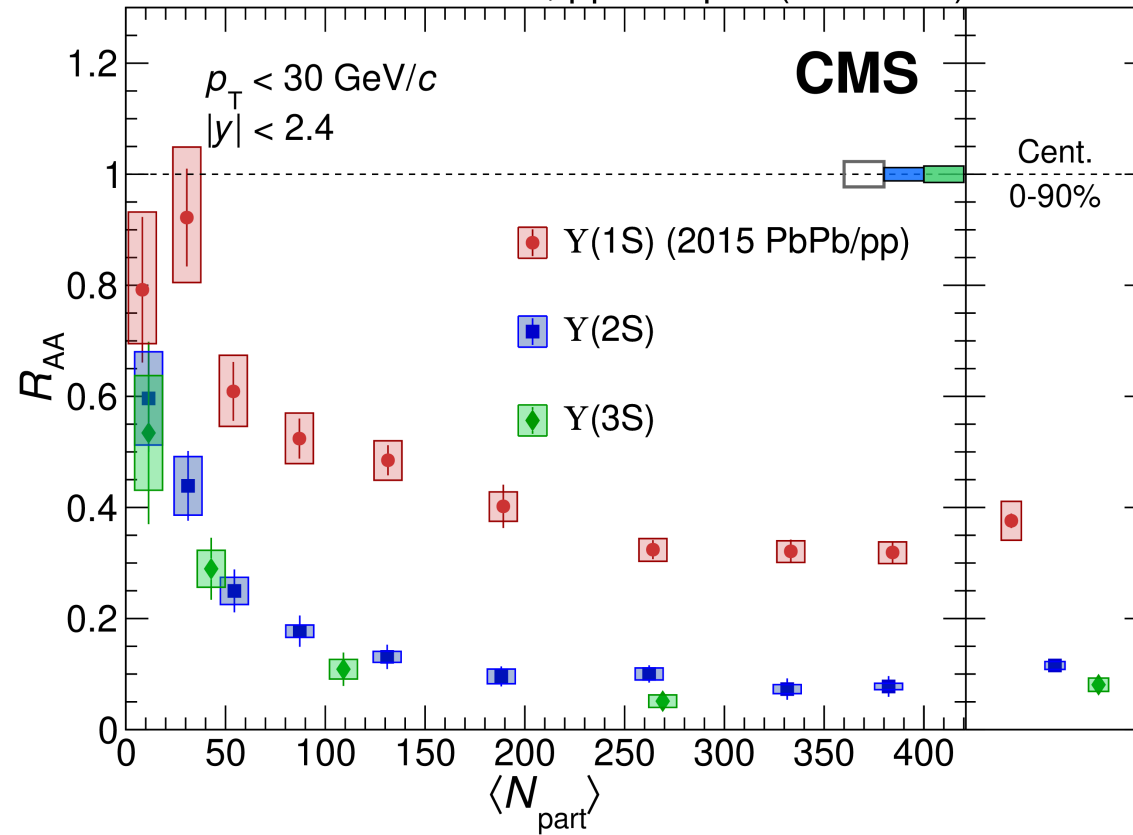




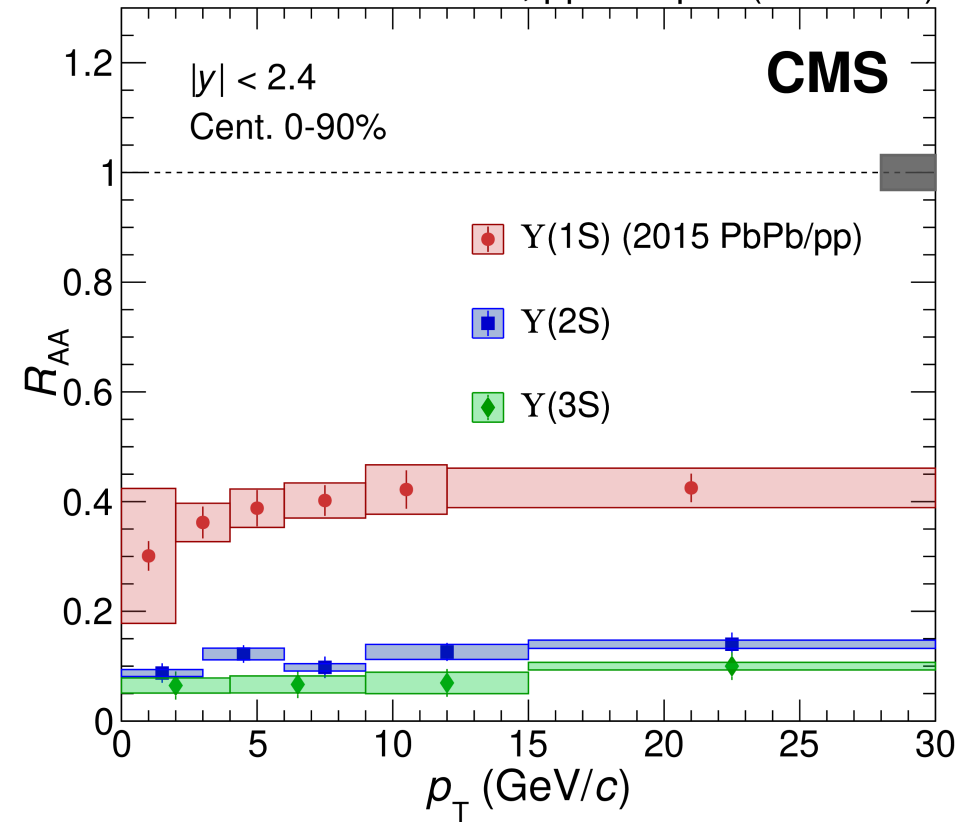
- **Observation of sequential suppression of  $\Upsilon$  family in Pb+Pb.**
- **First observation of  $\Upsilon(3S)$  in heavy-ion collisions! ( $\sigma > 5$ )**



PbPb 1.61 nb<sup>-1</sup>, pp 300 pb<sup>-1</sup> (5.02 TeV)



PbPb 1.61 nb<sup>-1</sup>, pp 300 pb<sup>-1</sup> (5.02 TeV)

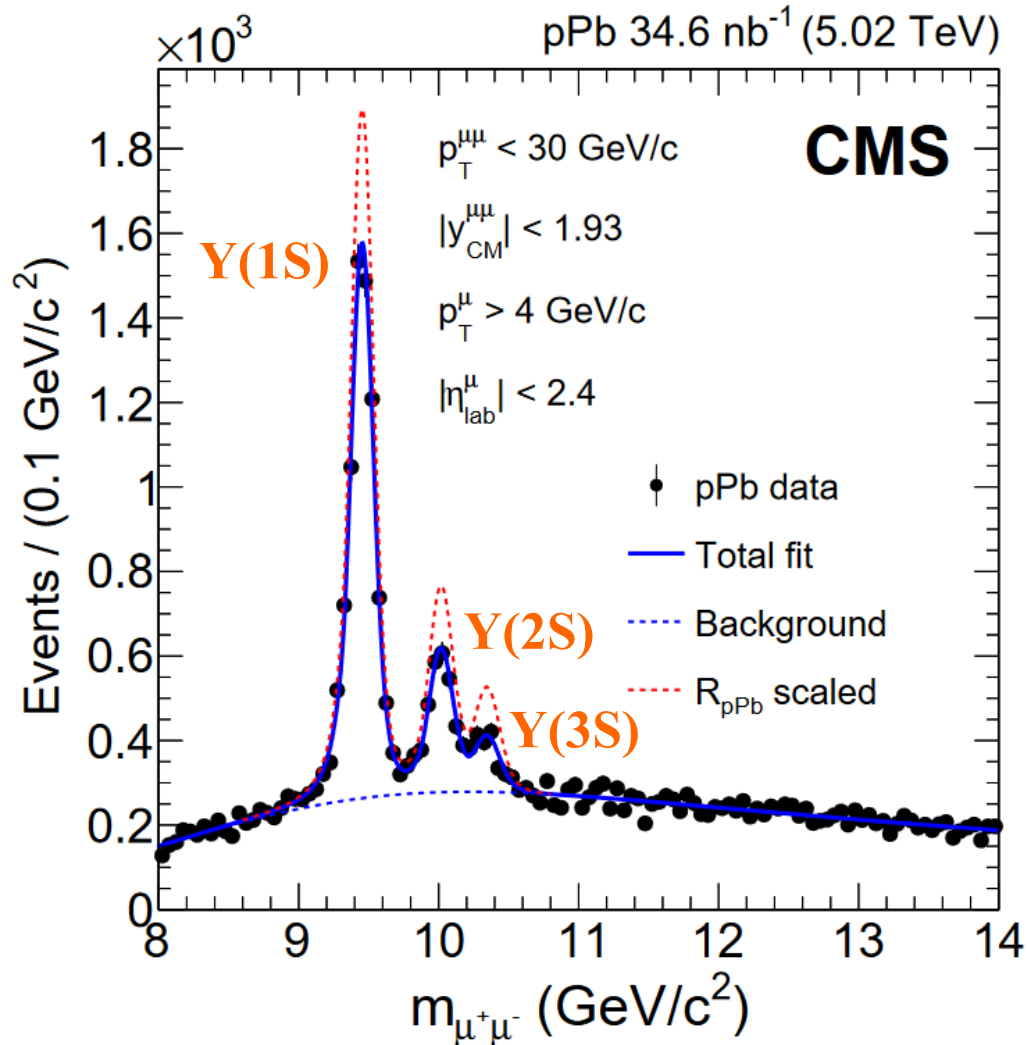
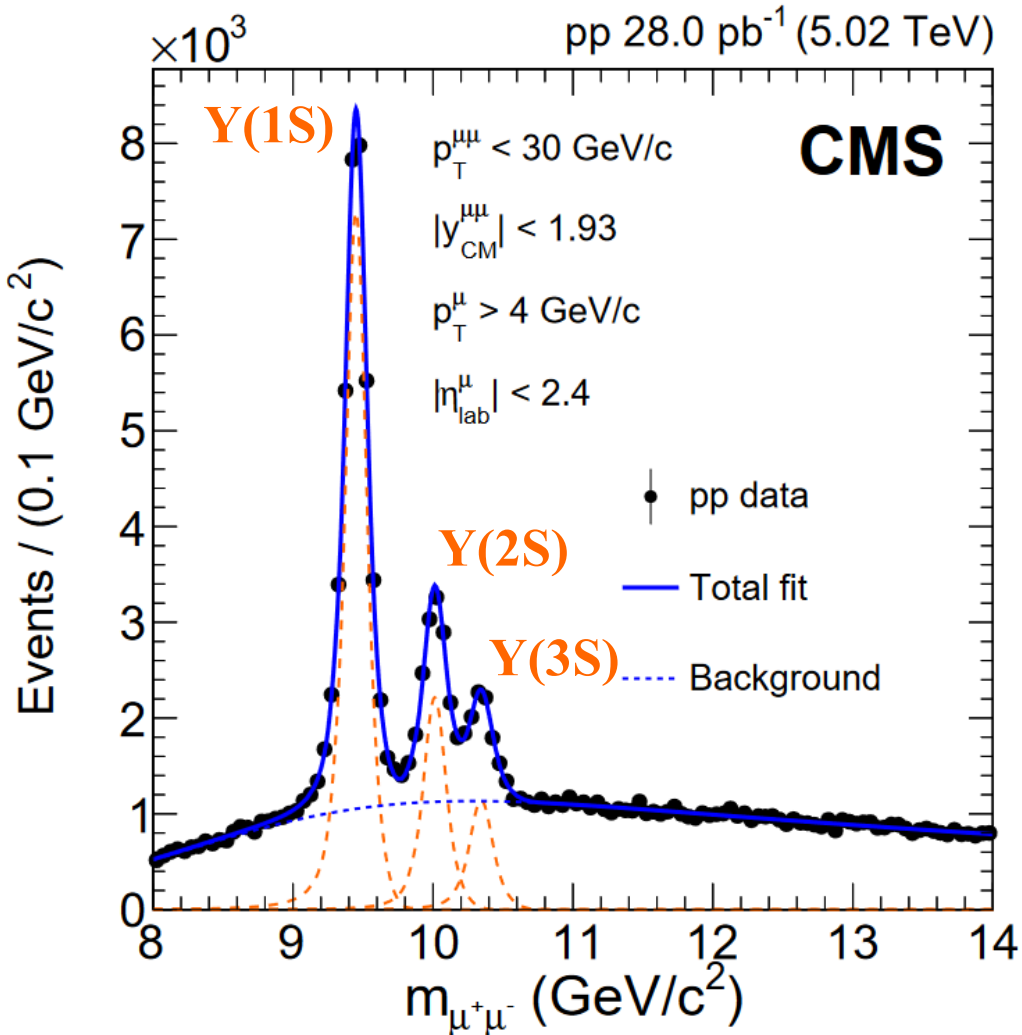


- $R_{AA}$  is decreasing with numbers of participants of Pb+Pb collision.
- Slightly increasing with  $p_T$  ?

# Подавление $\Upsilon$ в $p+Pb$



PLB 835 (2022) 137397

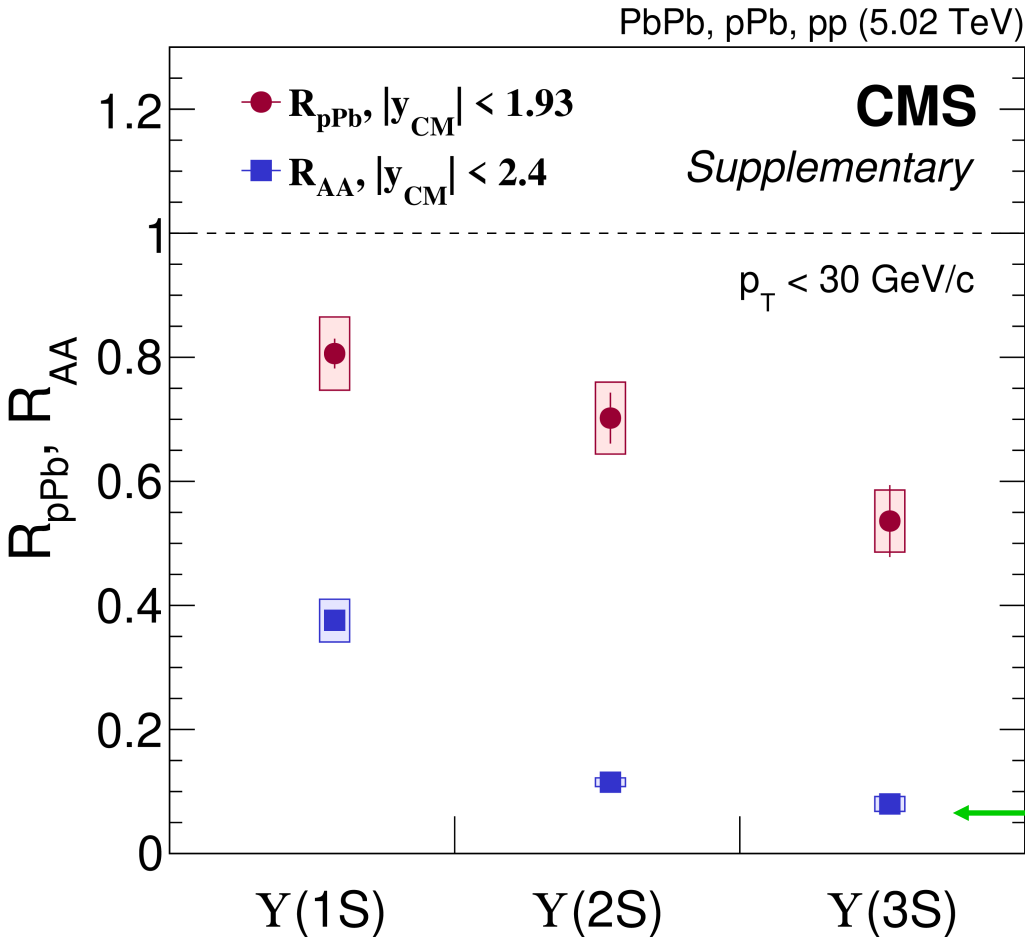


**All  $\Upsilon$  states are found to be suppressed in  $p+Pb$  collisions compared to  $p+p$  collisions.**



# Подавление $\Upsilon$ в $p+Pb$ и $Pb+Pb$

arXiv:2303.17026



**Ordered in binding energy**

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

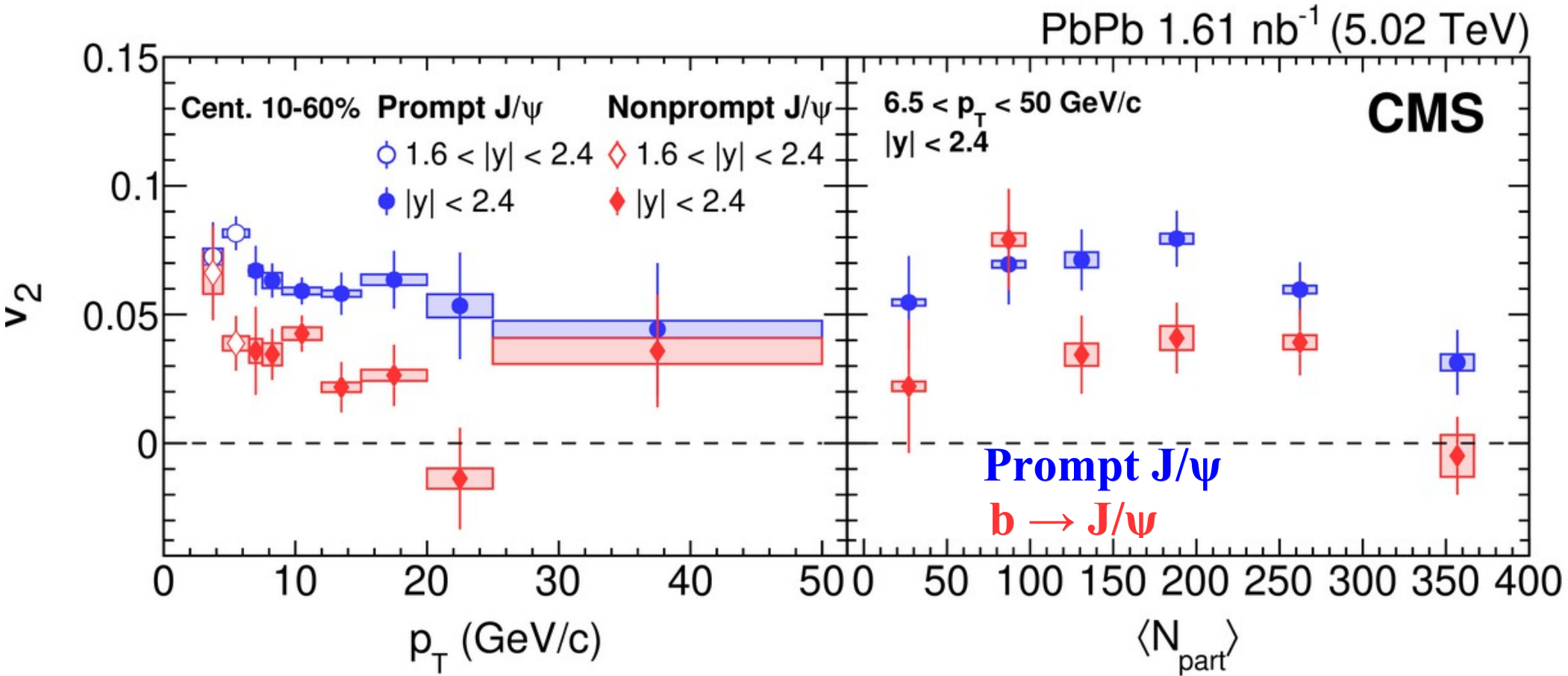
**Largest suppression is in Pb+Pb**

$R_{pPb} > R_{pPb}$

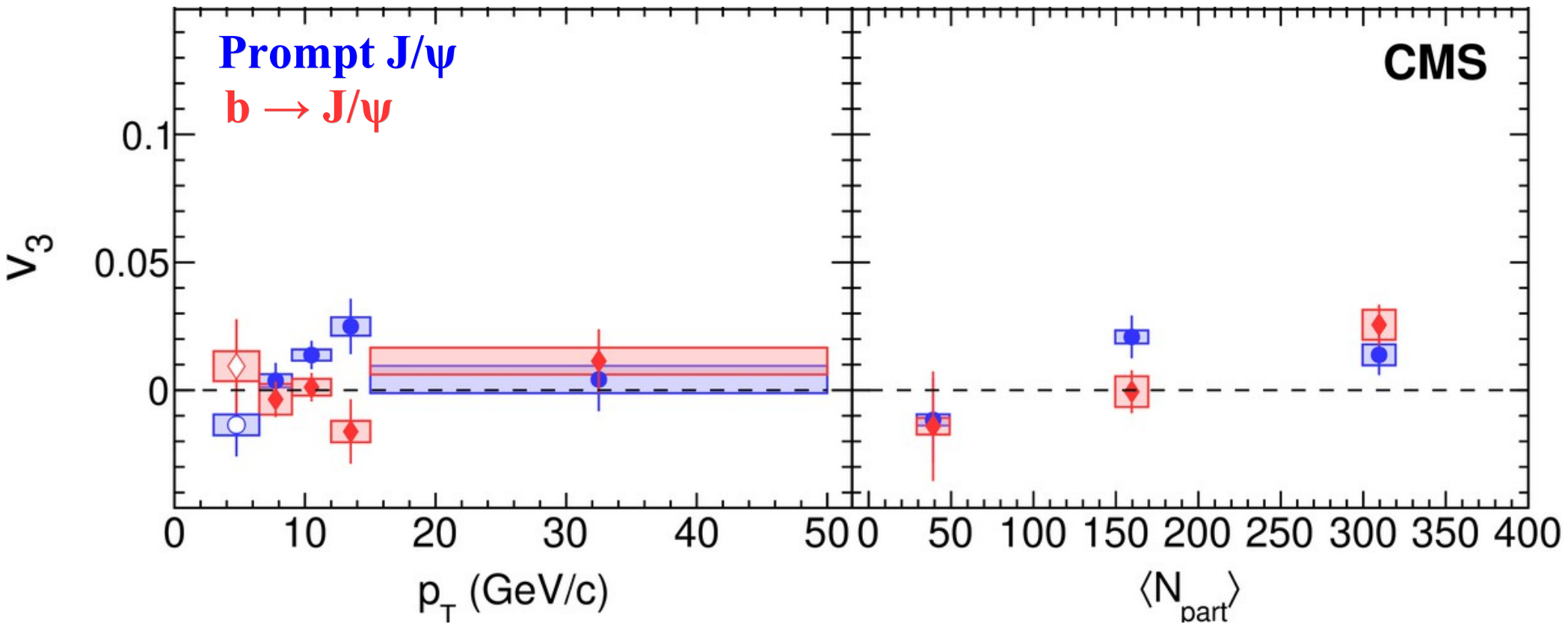
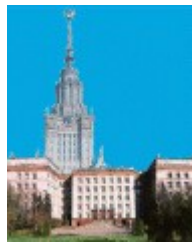
**New result for  $\Upsilon(3S)$**

# $v_2$ J/ $\psi$ в Pb+Pb

JHEP 10 (2023) 115



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



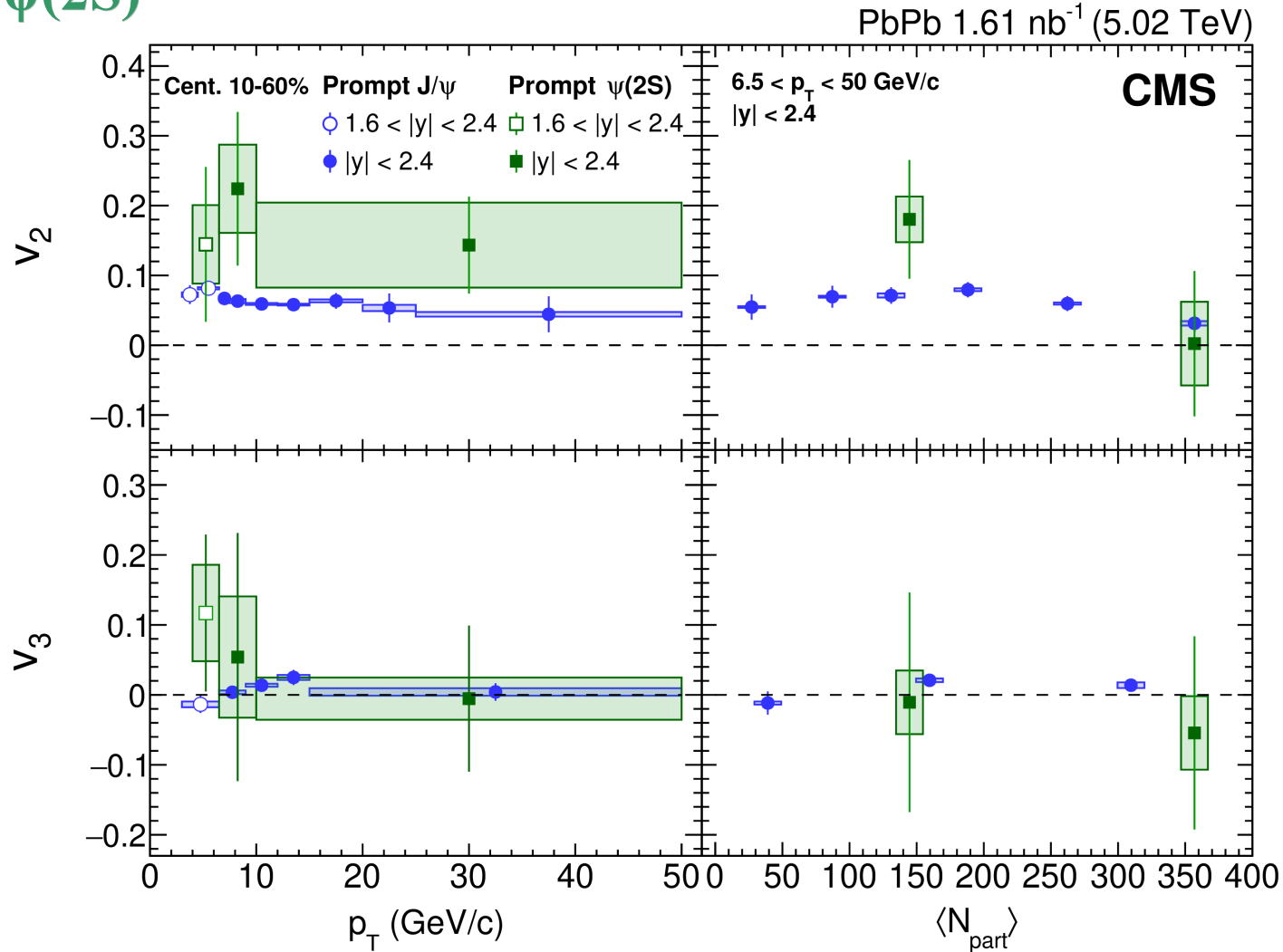
- First measurement of  $v_3$  for prompt and non-prompt J/ $\psi$  separately
- no significant non-zero  $v_3$  (J/ $\psi$ )

# $v_2$ и $v_3$ $\psi(2S)$ в Pb+Pb

JHEP 10 (2023) 115



## Prompt $\psi(2S)$

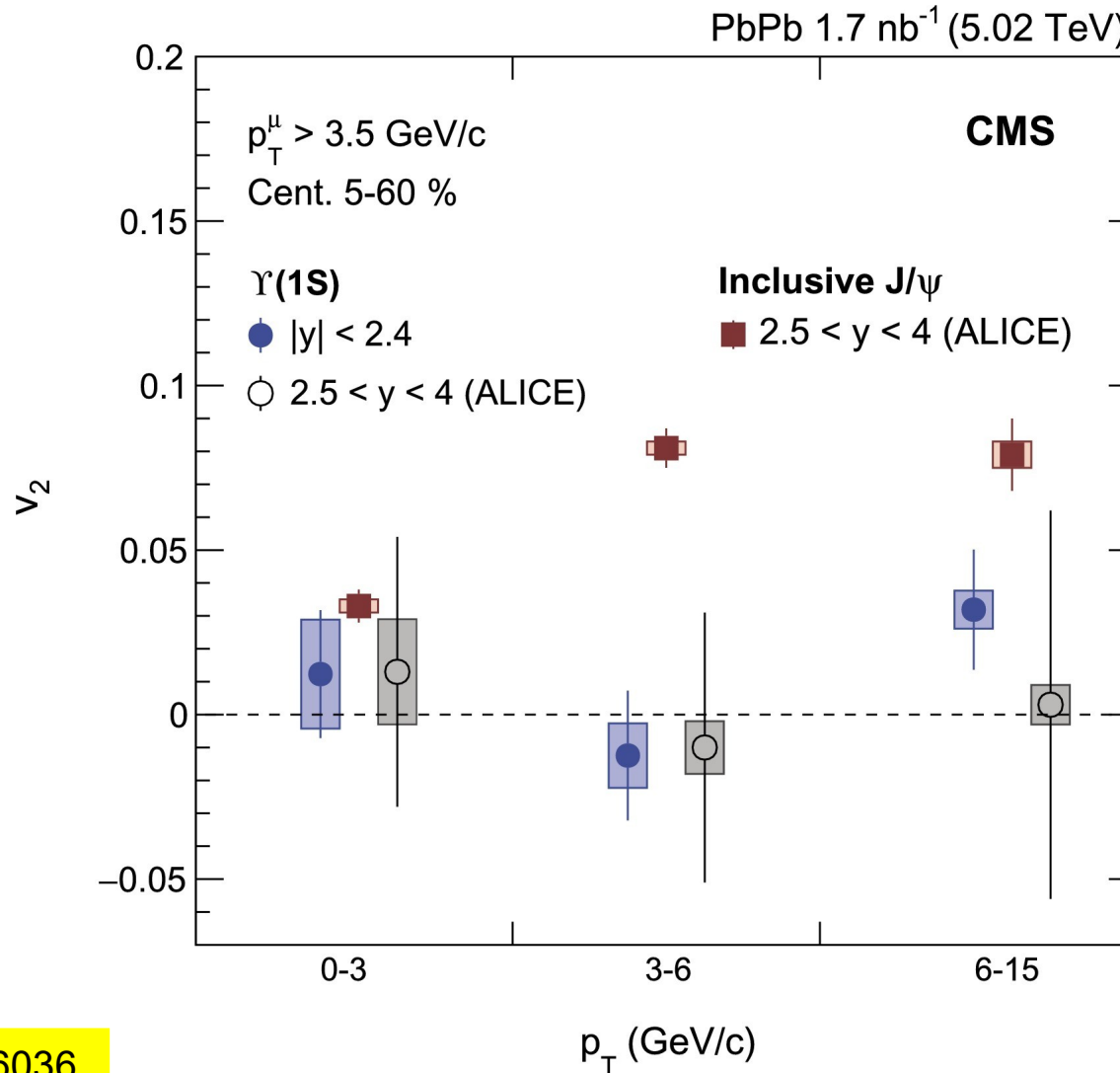


• **First measurements for prompt  $\psi(2S)$  !**

•  $v_2$  is non-zero in  $p_T = 4 - 50$  GeV/c,  $v_3$  is close to zero

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# $v_2$ $\Upsilon(1S)$ в Pb+Pb



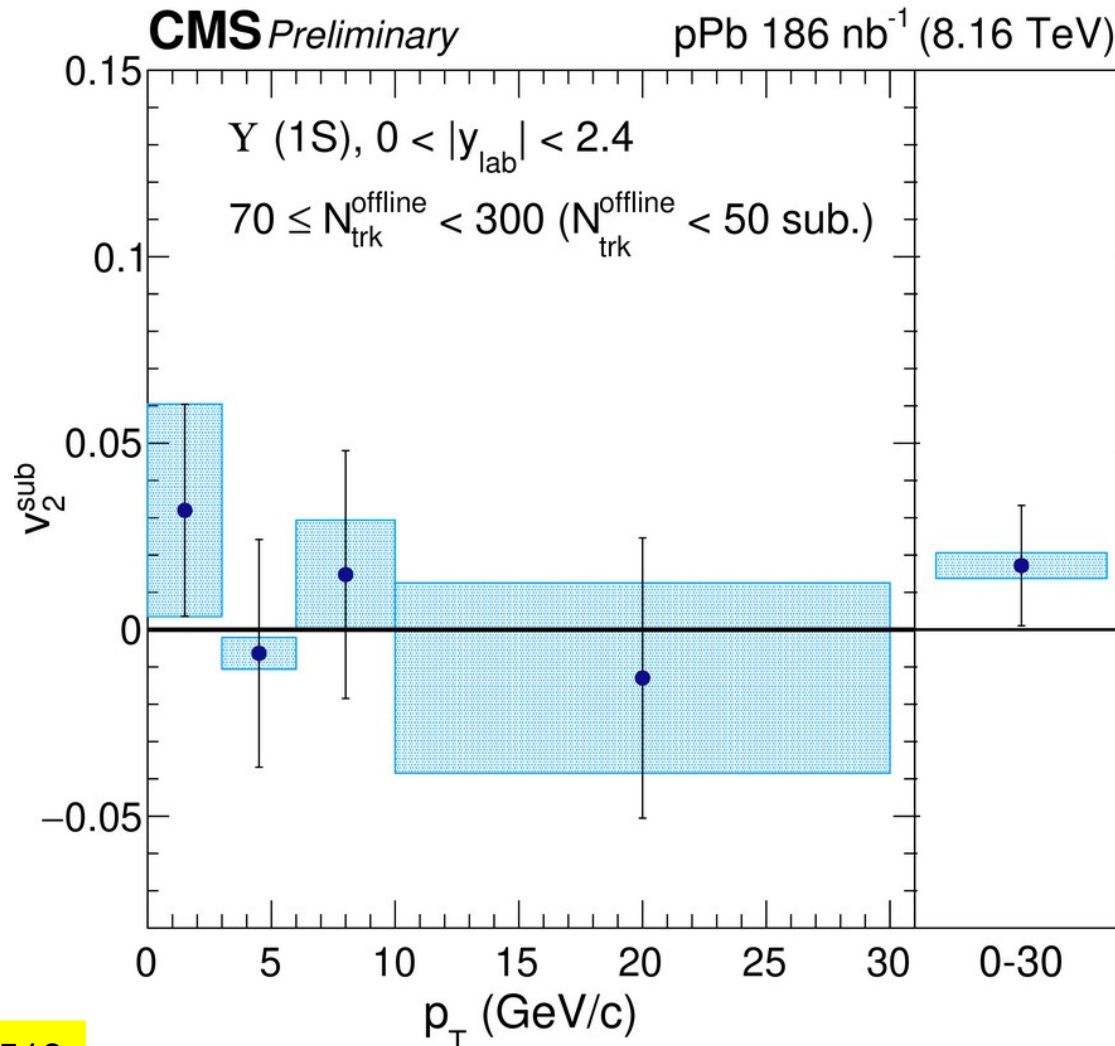
PLB 813 (2021) 136036

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

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# $v_2$ Y(1S) в p+Pb



PLB 850 (2024) 138518

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



# Рождение двух J/ψ в p+Pb



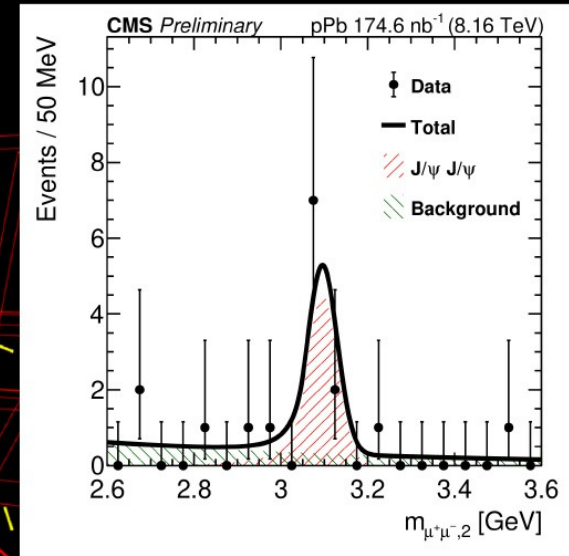
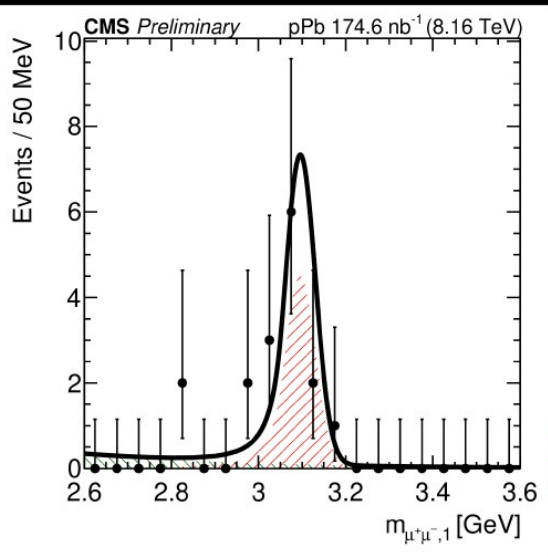
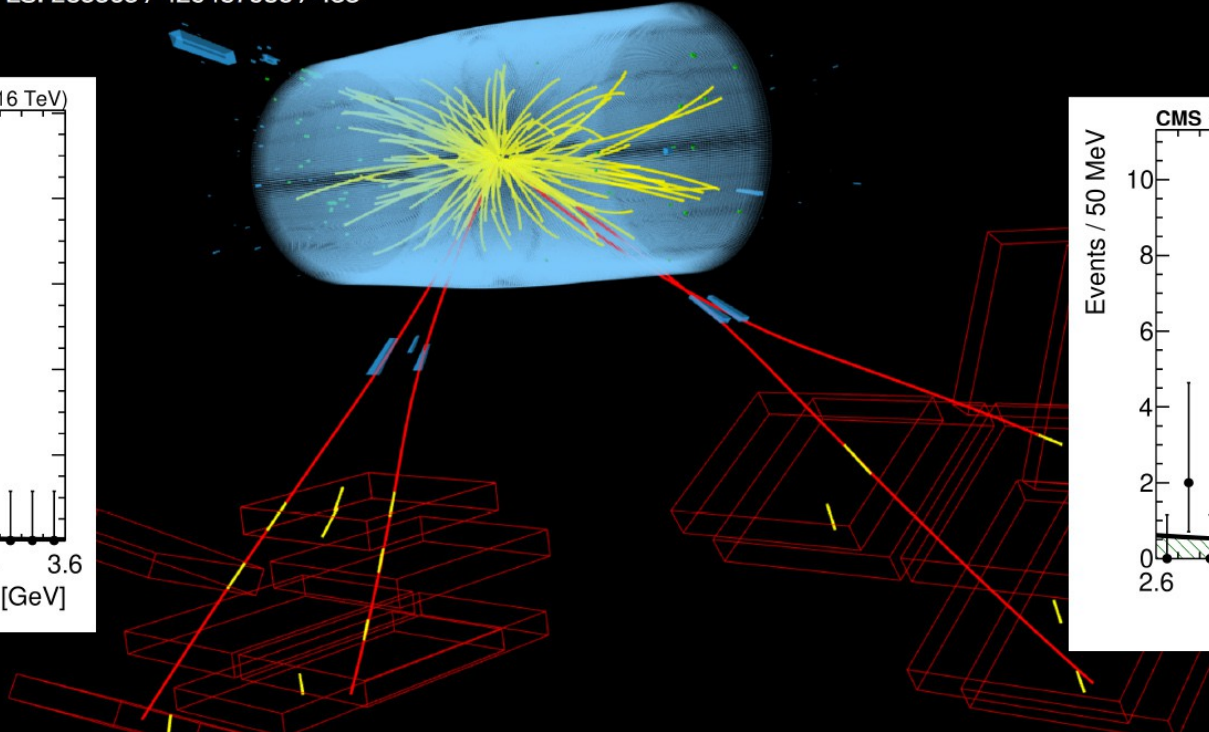
CMS-PAS-HIN-23-013



CMS Experiment at the LHC, CERN

Data recorded: 2016-Nov-18 17:13:03.129280 GMT

Run / Event / LS: 285505 / 429487936 / 433



$$N(J/\psi J/\psi \rightarrow 2 \mu^+\mu^-) = 8.5 \pm 3.4 \text{ events}$$

$$\sigma_{\text{fiducial}}(p\text{Pb} \rightarrow J/\psi J/\psi) = 22.0 \pm 8.9 \text{ (stat)} \pm 1.5 \text{ (syst) nb}$$

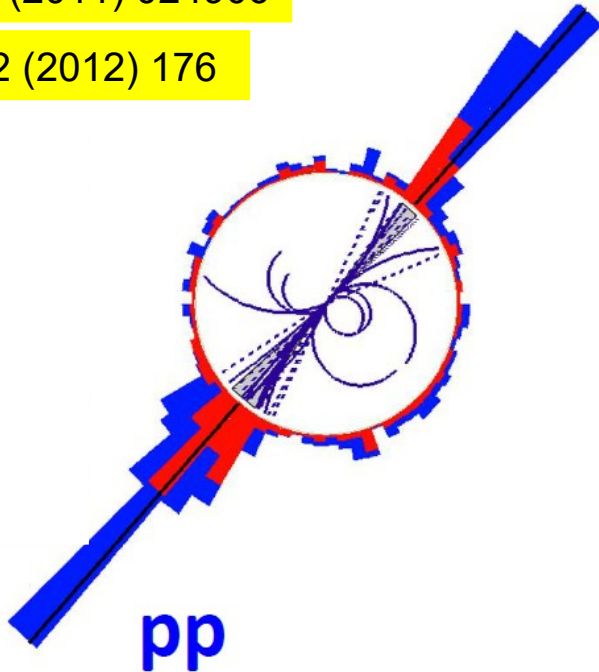


# “Jet quenching” (“гашение” струй) в Pb+Pb

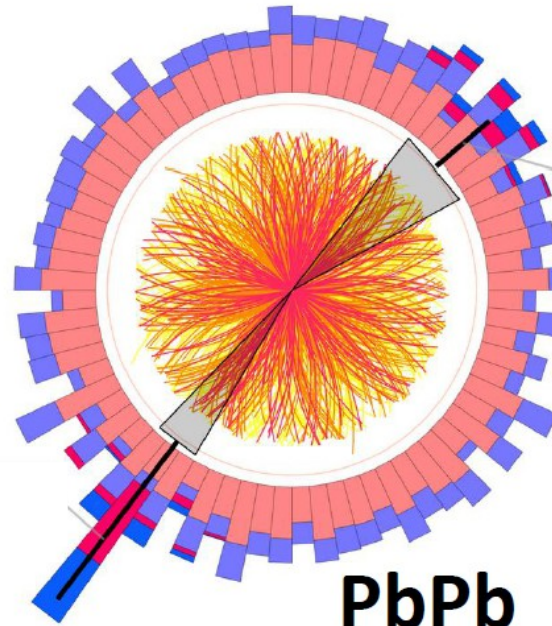


PRC 84 (2011) 024906

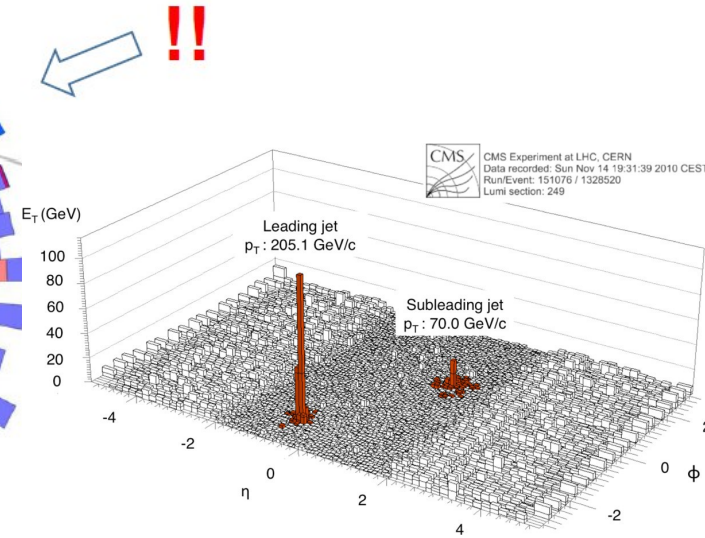
PLB 712 (2012) 176



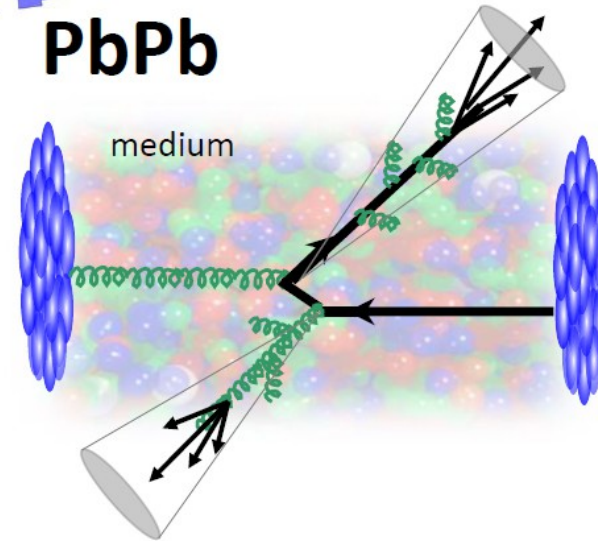
pp



PbPb



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



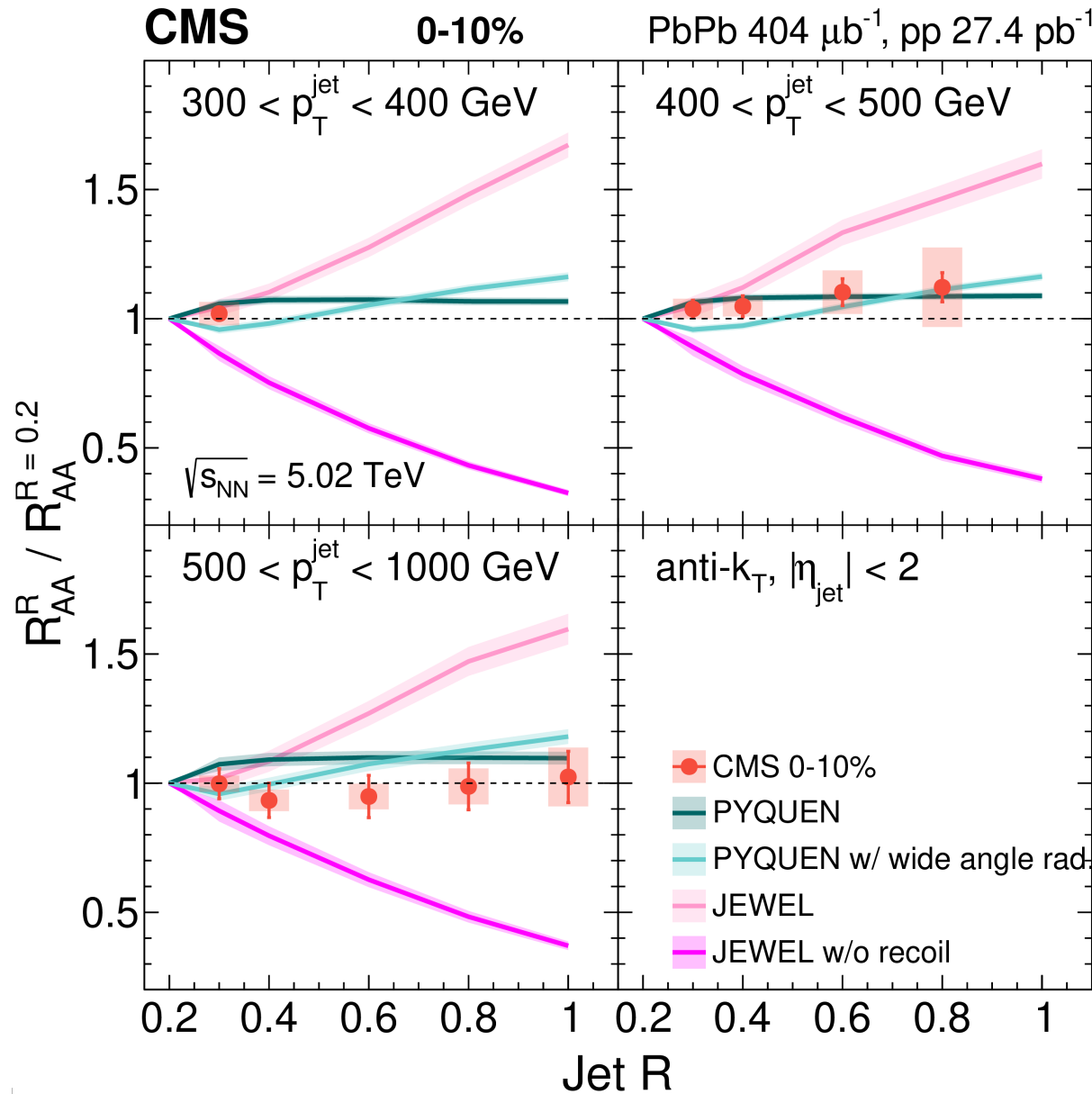
medium



# Сканирование по ширине струй



JHEP 05 (2021) 284

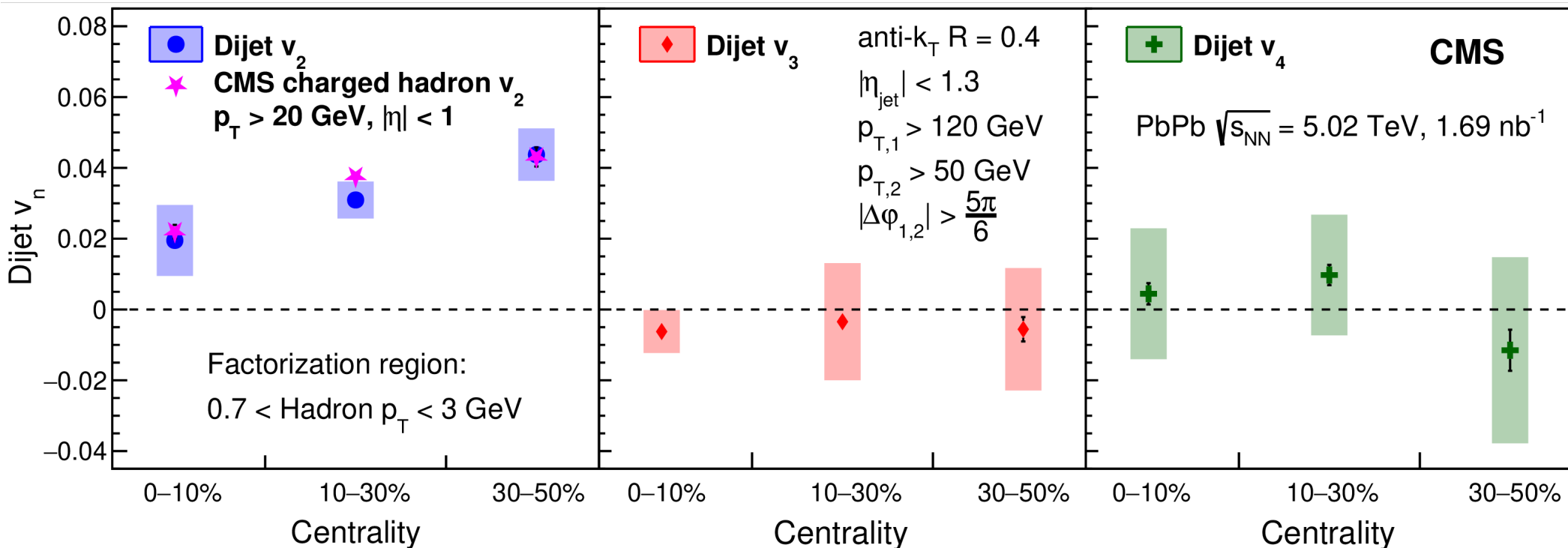


- Sensitive to balance between increasing radiative sources and recovering re-distributed energy
- Enables simultaneous comparisons of model calculations across jet radii
- First time at CMS: no radius dependence of jet energy loss in central Pb+Pb collisions for  $400 \text{ GeV}/c < p_T \text{ jet}$ . (Also for  $400 < p_T \text{ jet} < 500 \text{ GeV}/c$ )

# Азимутальная анизотропия двух-струйных событий в Pb+Pb



JHEP 07 (2023) 139



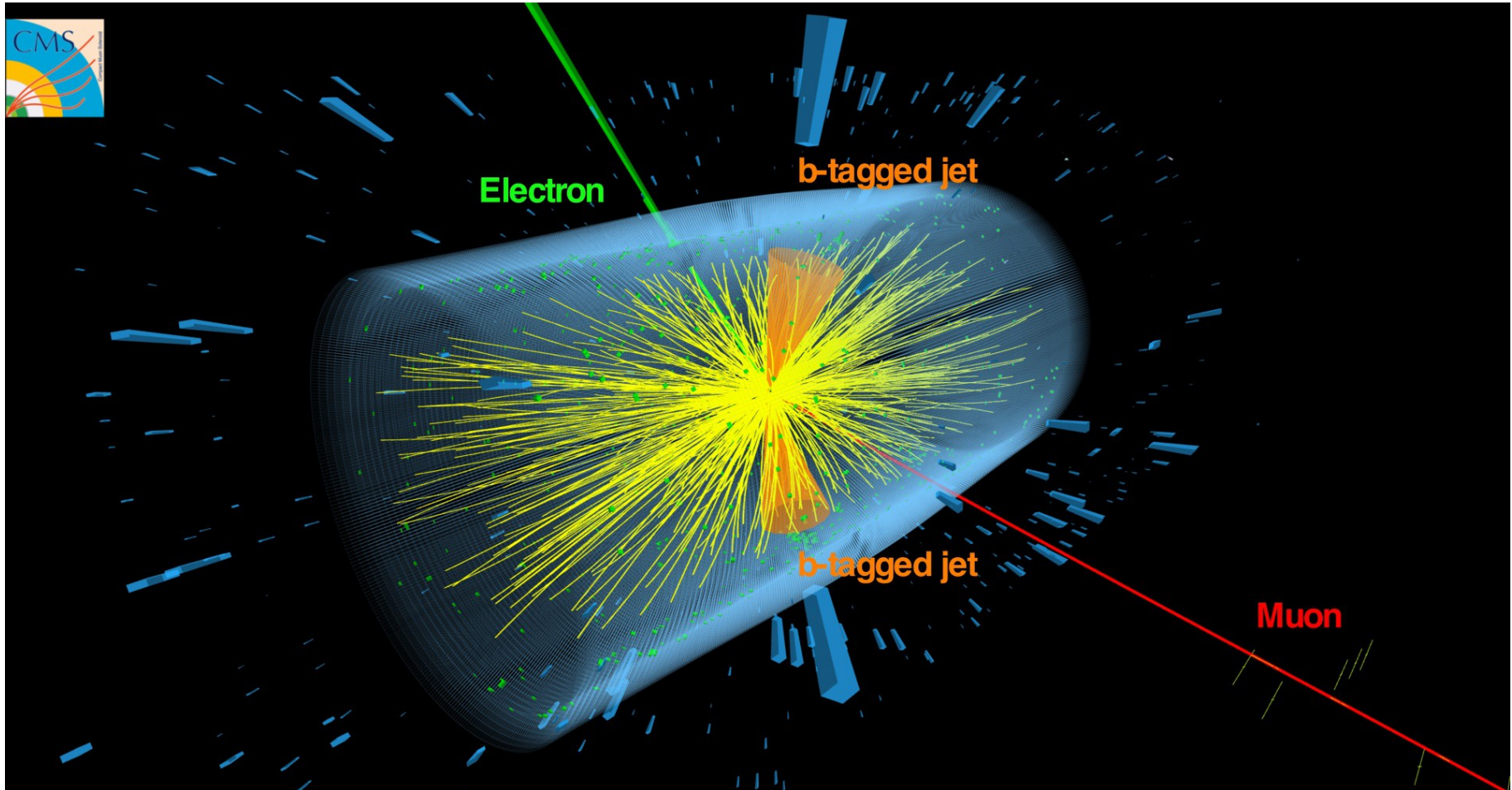
- $v_2$ ,  $v_3$  and  $v_4$  of the di-jets in Pb+Pb were measured for the first time
- Di-jets  $v_2$  is compatible with  $v_2$  of high  $p_T$  hadrons
- Di-jets  $v_3$  and  $v_4$  are consistent with zero



# Первое наблюдение **top** кварка в Pb+Pb



PRL 125 (2020) 222001



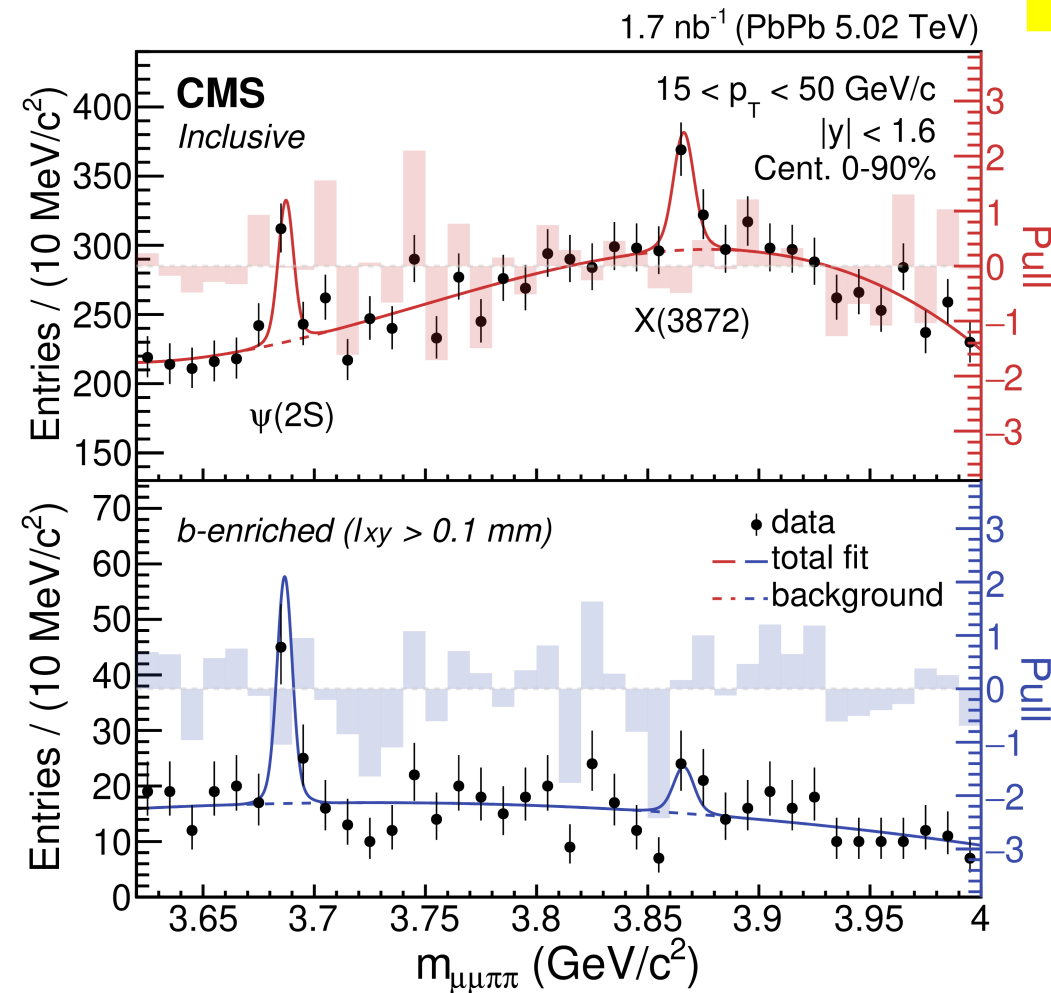
**Using either charged leptons only or charged leptons + b jets.  
The measured cross sections are compatible with expectations from  
scaled proton-proton data and QCD predictions.**



# Рождение X(3872) в Pb+Pb

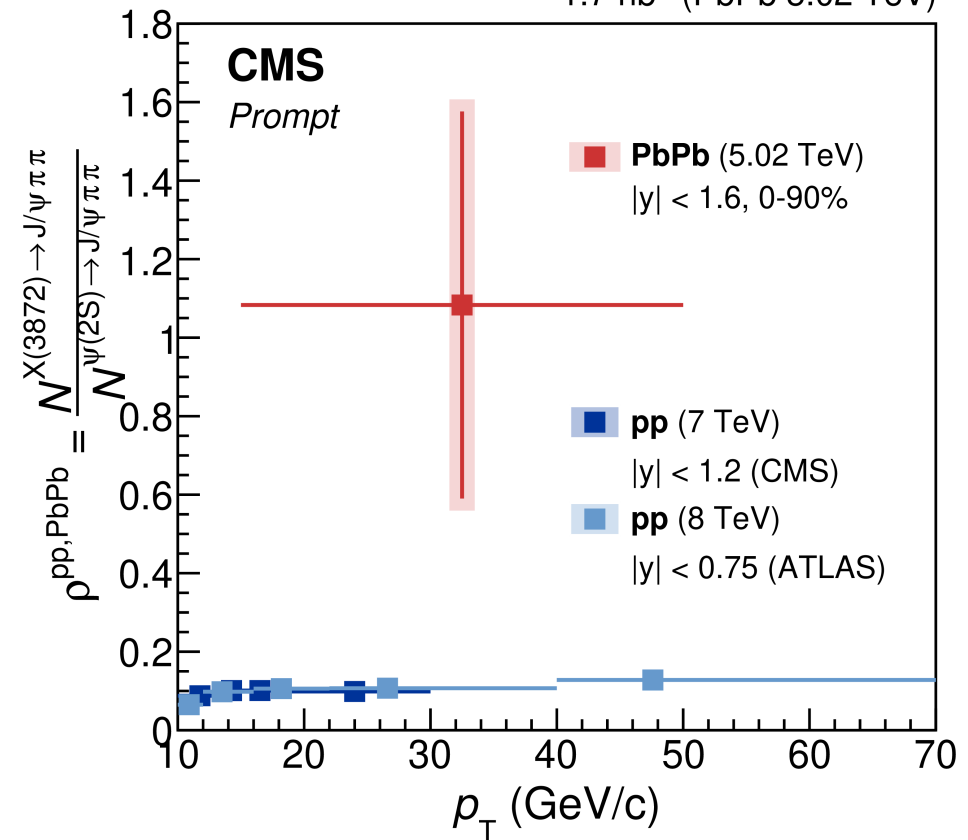


PRL 128 (2022) 032001

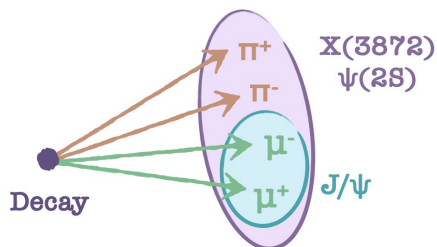


## Comparison to ψ(2S)

1.7 nb<sup>-1</sup> (PbPb 5.02 TeV)



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





# $f_0(980)$ в p+Pb столкновениях

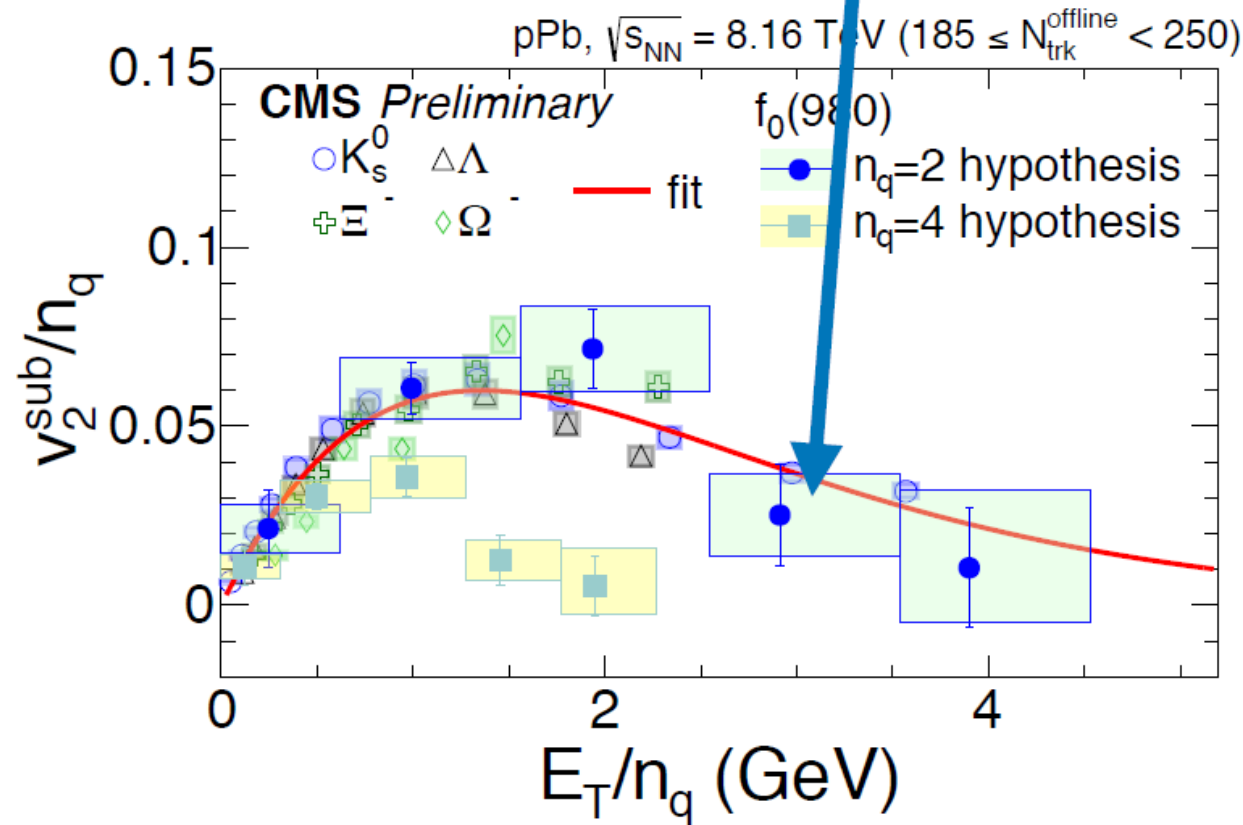
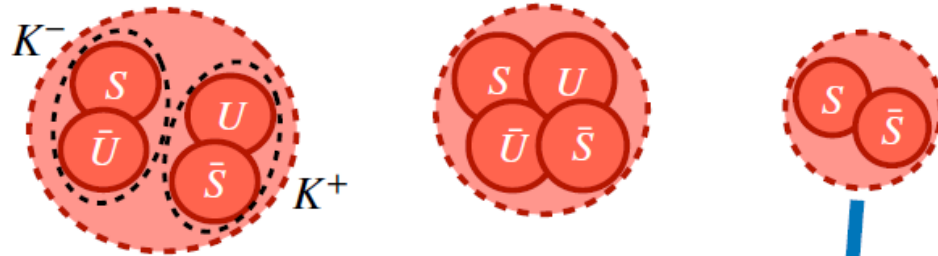


arXiv:2312.17092

$v_2$  of  $f_0(980)$  measured in p+Pb

Inner structure unknown:

- $K^-K^+$  molecule
- Tetraquark
- Diquark



Use constituent quark scaling to extract number of quarks

$$v_2(E_T)/n_q = v_{2,q}(E_T/n_q)$$

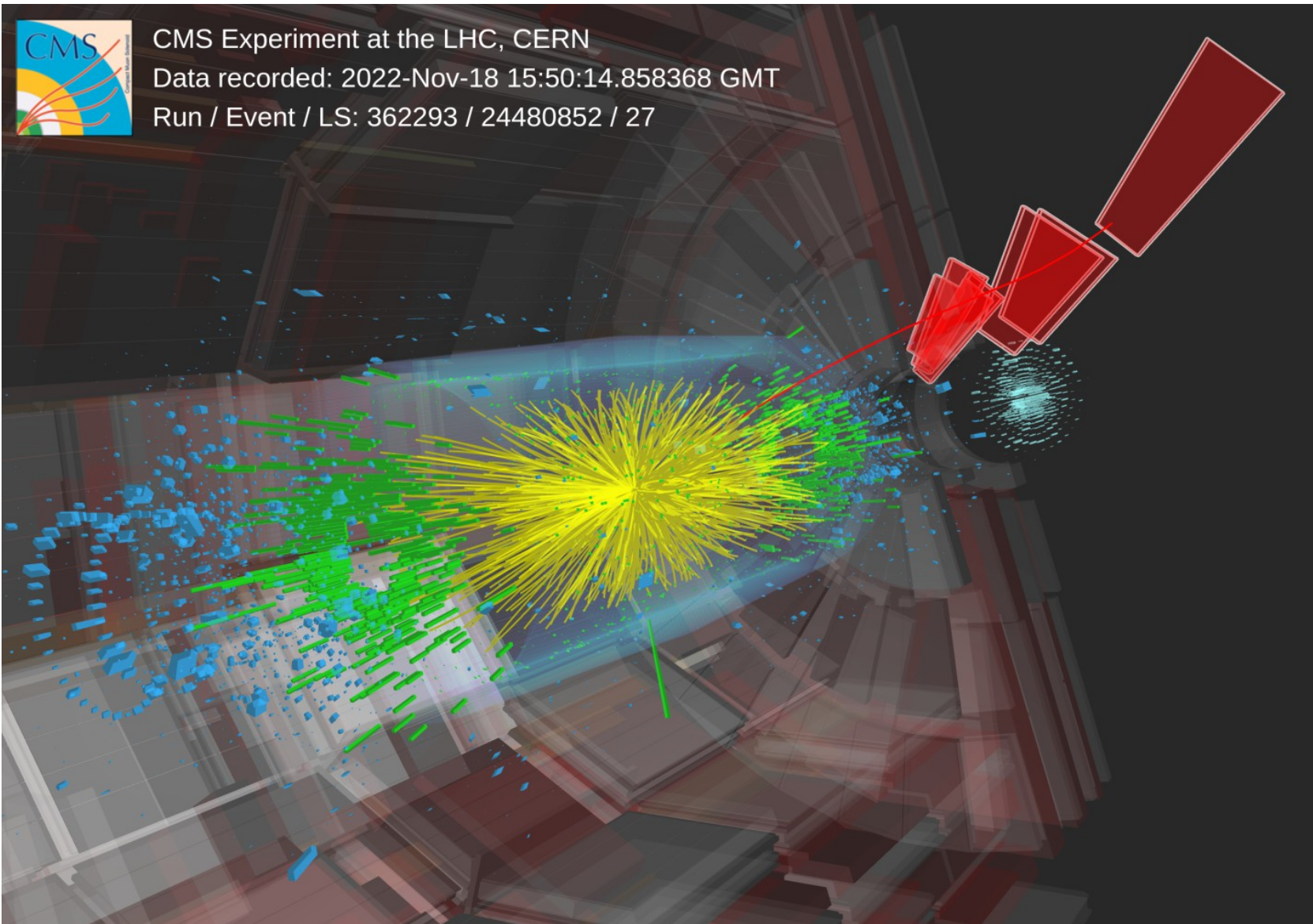
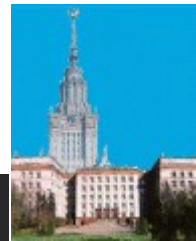
$n_q = 4$  excluded at  $\sigma > 3.1$

$n_q = 2$  favored



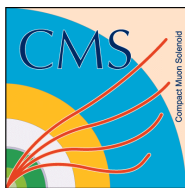


# Run 3 начался в июле 2022 года



**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 !**

*Сергей Петрушанко (CMS Collaboration) Физика тяжелых ионов на CMS*



# Первые результаты по тяжелым ионам

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

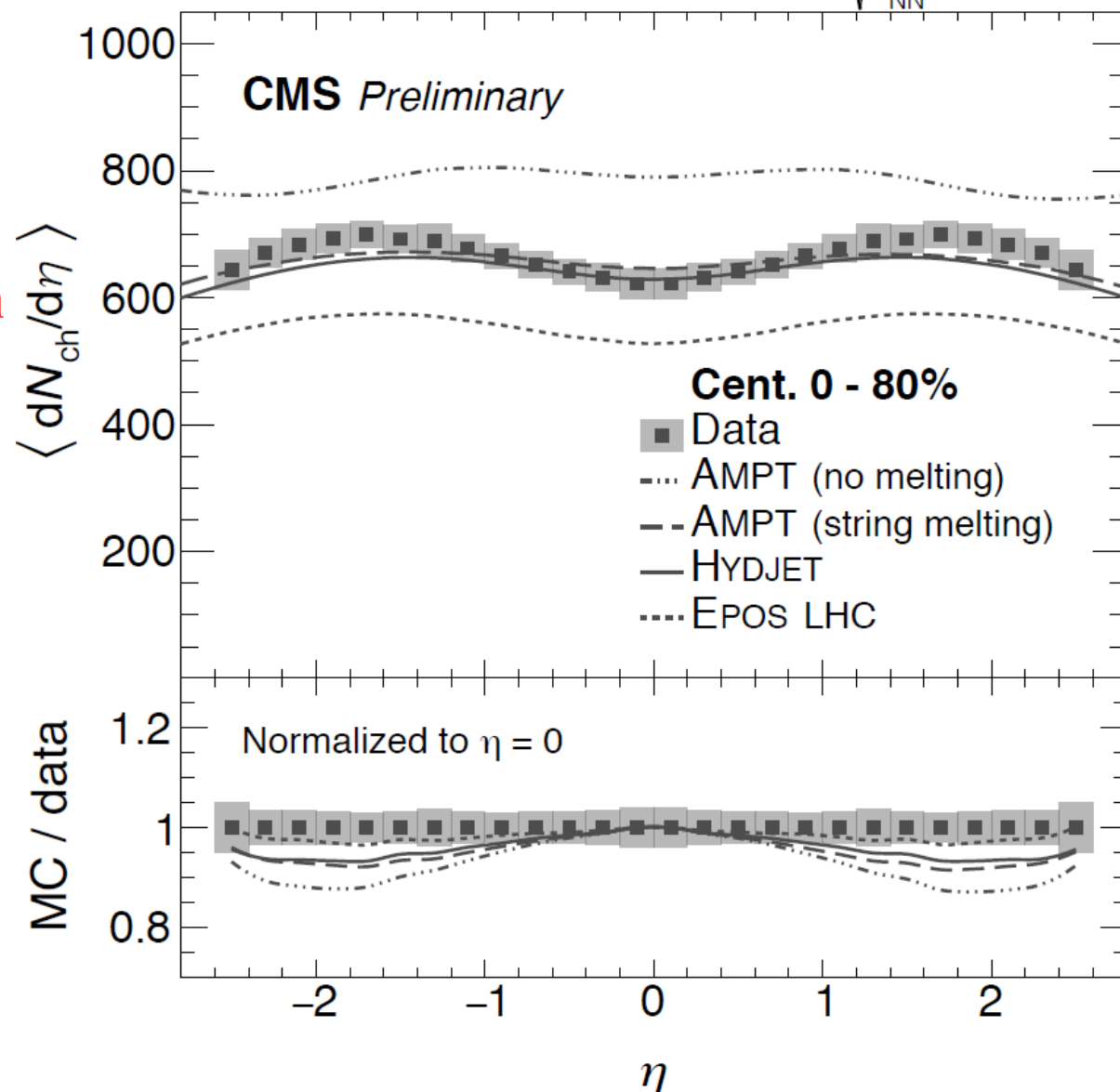


CMS PAS HIN-23-007

PbPb  $\sqrt{s_{NN}} = 5.36$  TeV

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

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





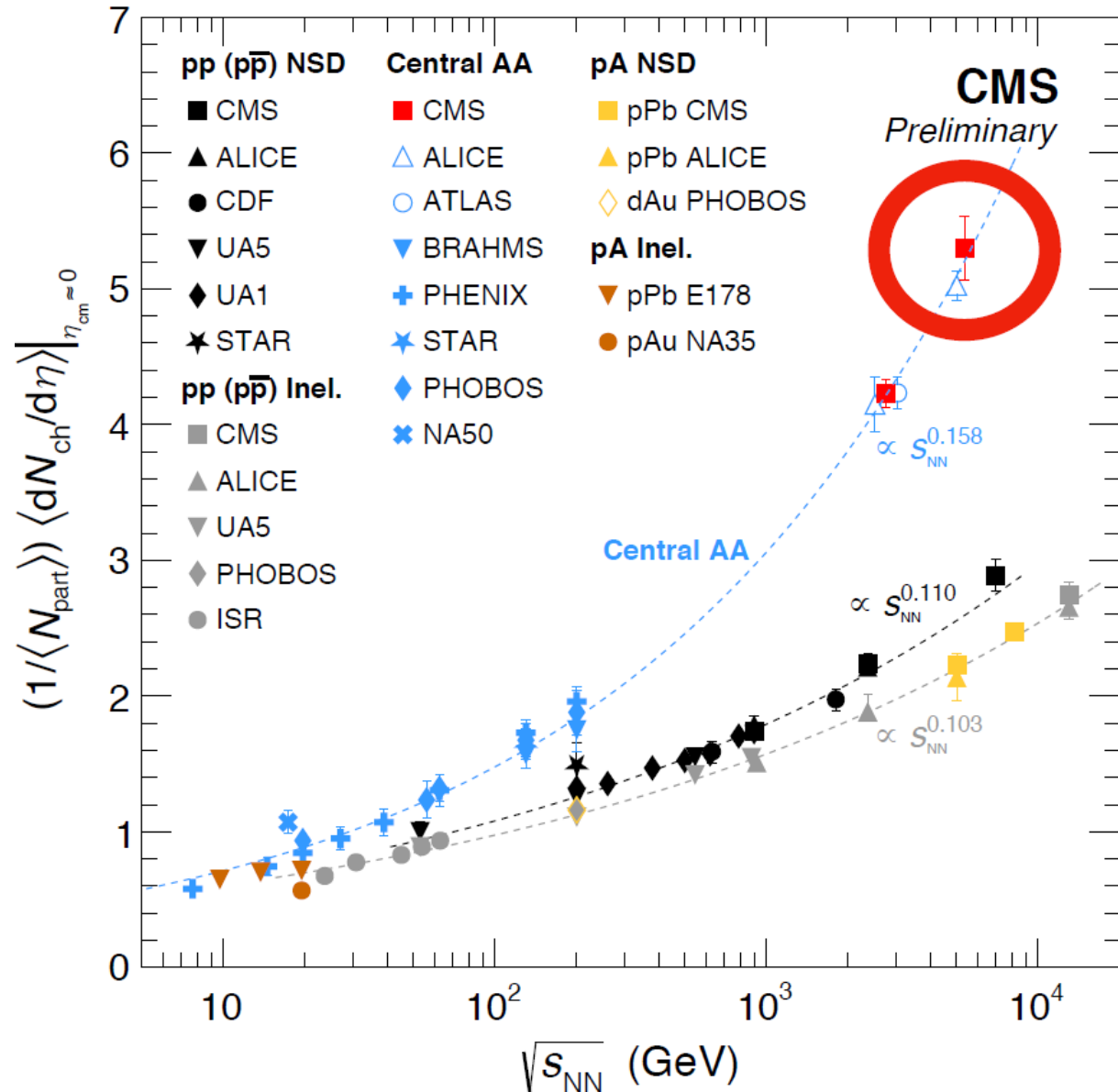
# Первые результаты по тяжелым ионам CMS Run 3 $v_2$



CMS PAS HIN-23-007

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

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





# ЗАКЛЮЧЕНИЕ



- **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!**