

Сергей Петрушанко (CMS Collaboration)

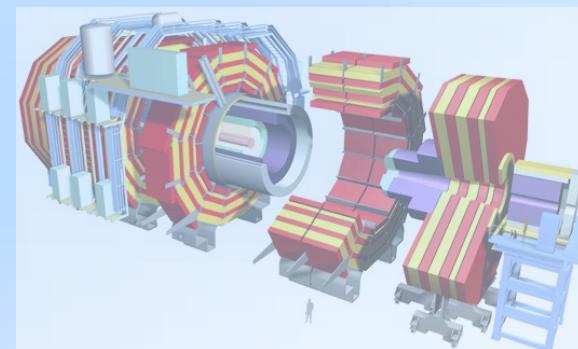


Лаборатория сильных взаимодействий
ОЭФВЭ НИИЯФ МГУ

**Физика тяжелых ионов
на установке
Компактный мюонный соленоид (CMS)
ускорителя
Большой адронный коллайдер (LHC)**

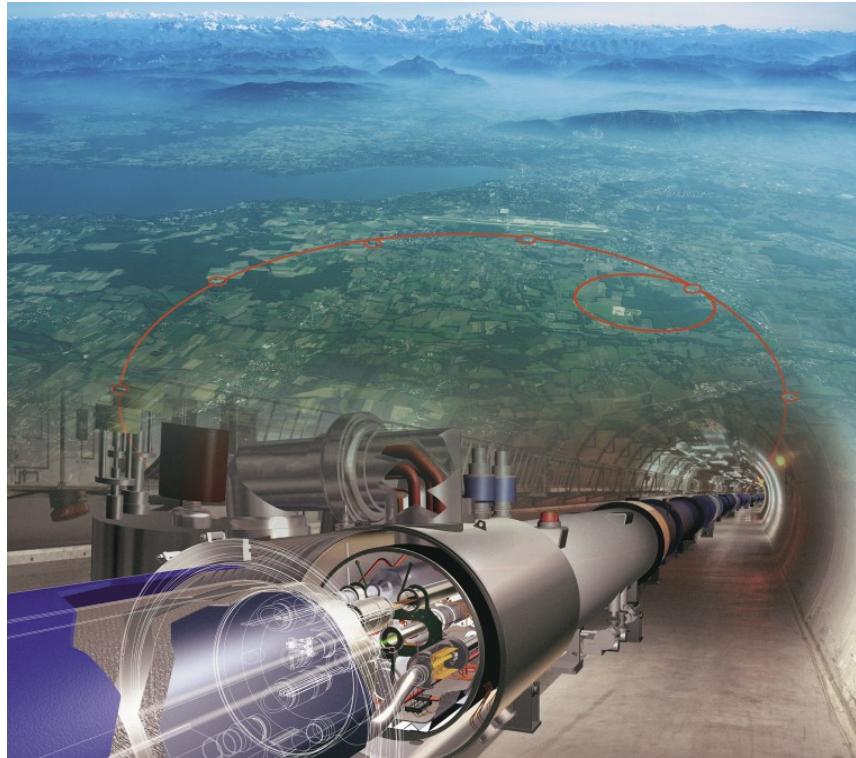
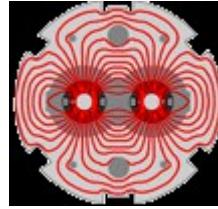


Семинар
ОЭПВАЯ НИИЯФ МГУ
2 ноября 2023 года

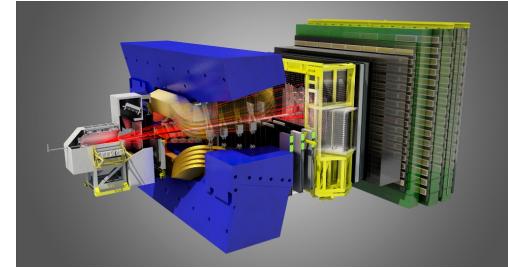




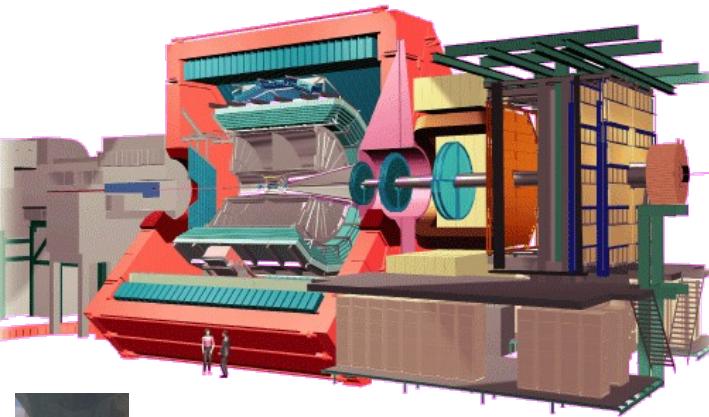
Физика тяжелых ионов на LHC



LHCb



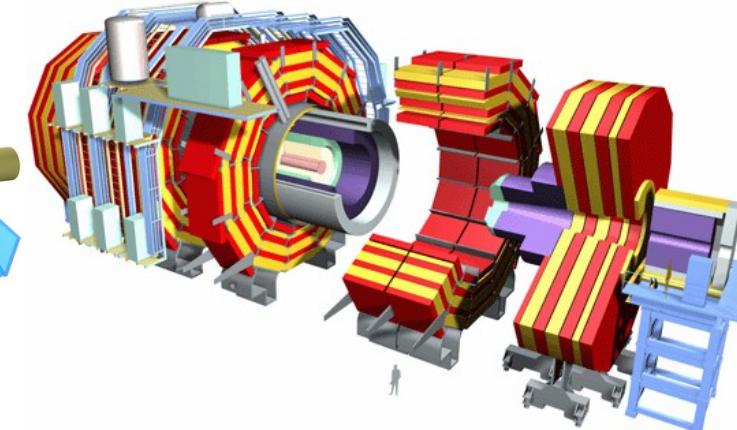
ALICE



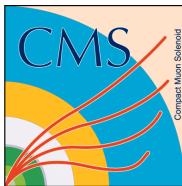
ATLAS



CMS



Сергей Петрушанко (CMS Collaboration) Физика тяжелых ионов на 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 ($100 \times 150 \mu\text{m}$) $\sim 1\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

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

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

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

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

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

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

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

$|\eta| < 2.4$

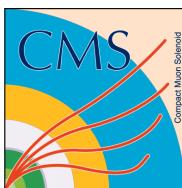
+ Детектор CASTOR

$-5.2 < \eta < -6.6$

+ Калориметр Zero-Degree

+ TOTEM





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

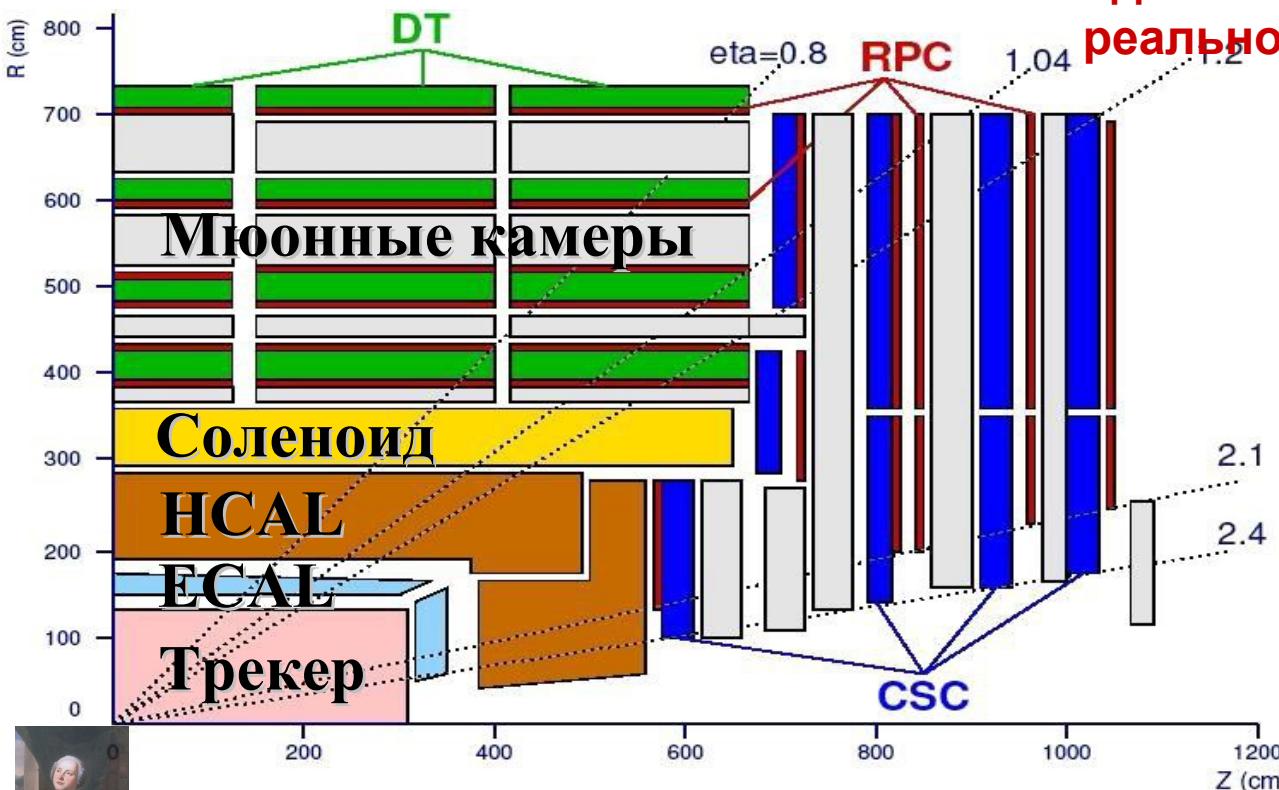


Калориметры: высокое разрешение и сегментация

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

Мюоны: μ от Z^0 , J/ψ , Υ

- 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

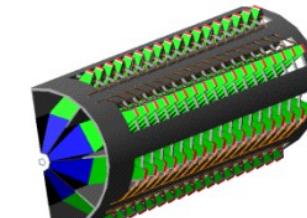
Триггер и DAQ

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



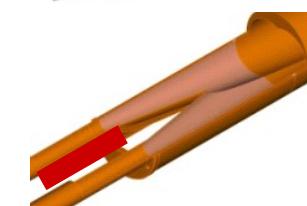
HF

$3 < |\eta| < 5.2$



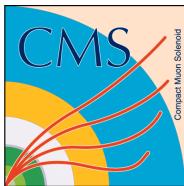
CASTOR

$-5.2 < \eta < -6.6$



ZDC

$(z = \pm 140$ м,
 $|\eta| > 8.2$ neutrals)



Подготовка программы CMS по изучению физики тяжелых ионов



LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN/LHCC 2007-009
CMS TDR 8.2-Add1
5 March 2007

CMS

High Density QCD
with Heavy Ions

Physics Technical Design Report, Addendum 1

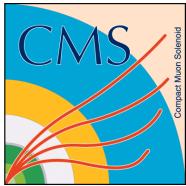
The CMS Collaboration

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*)

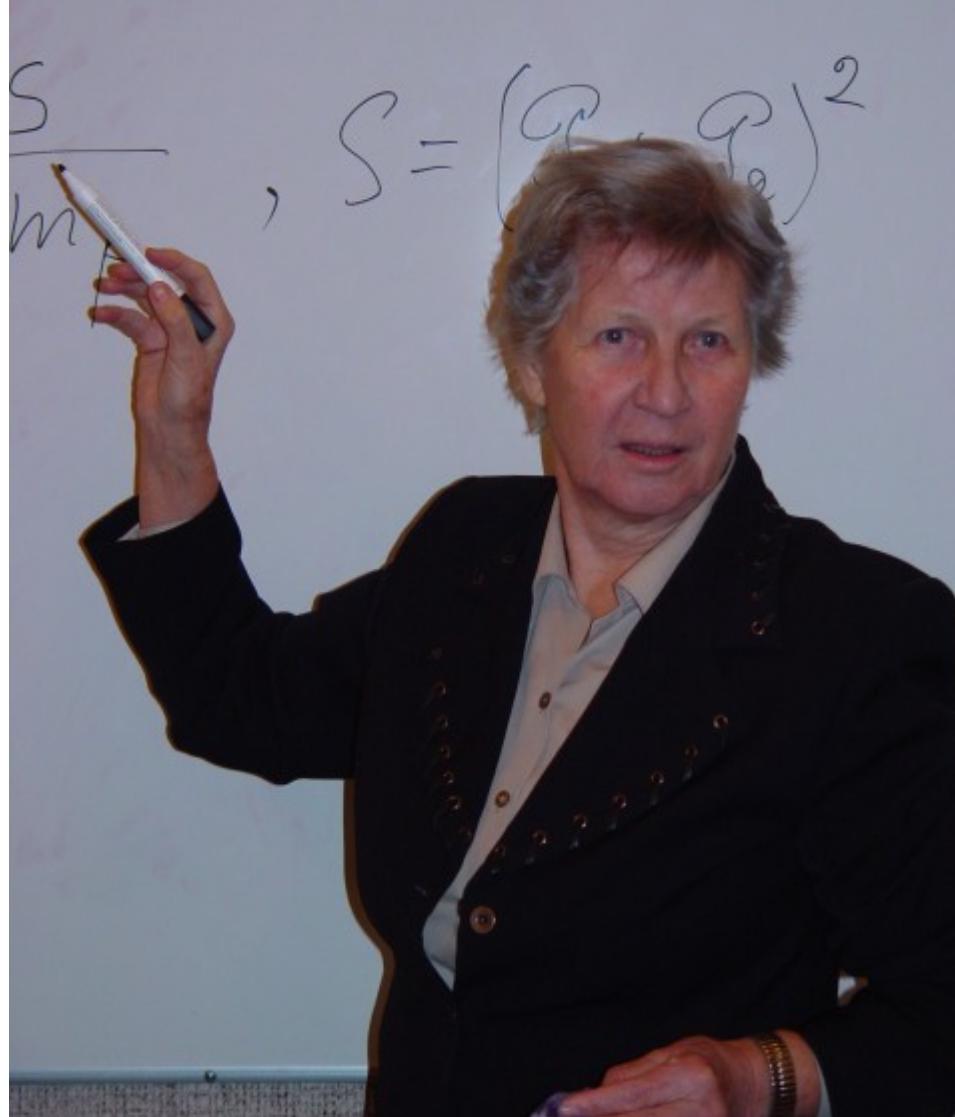
"CMS Physics Technical Design
Report: Addendum on High
Density QCD with Heavy Ions"

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



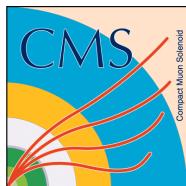


Людмила Ивановна САРЫЧЕВА (1926 – 2011)



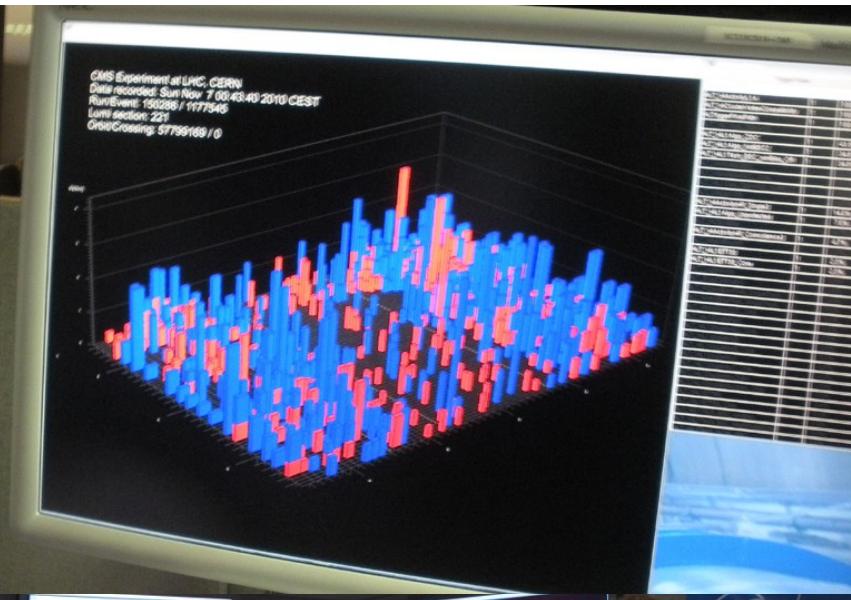
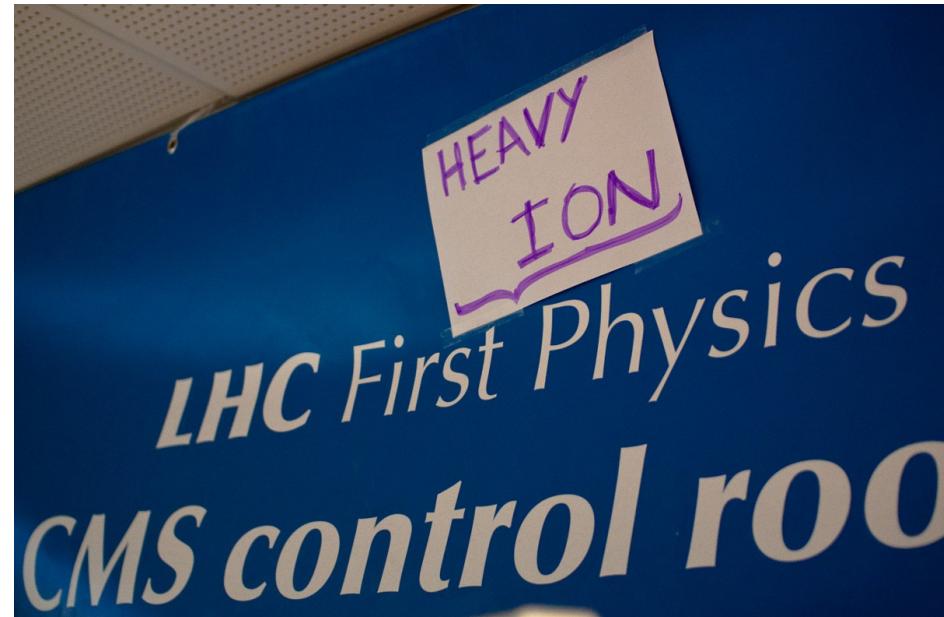
Сергей Петрушанко (CMS Collaboration) Физика тяжелых ионов на CMS





7 ноября 2010 года 0:27

Контрольная комната CMS



Сергей Петрушанко (CMS Collaboration) Физика тяжелых ионов на CMS



CMS – статьи по физике тяжелых ионов



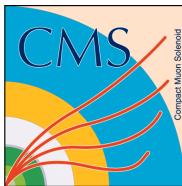
130 published/submitted
Heavy-ion Physics CMS papers:

<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>

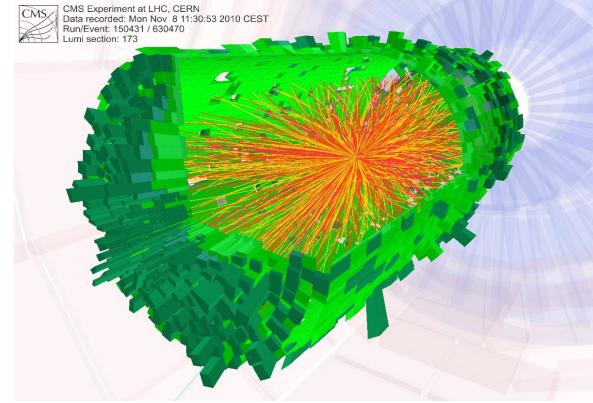


Результаты по физике тяжелых ионов

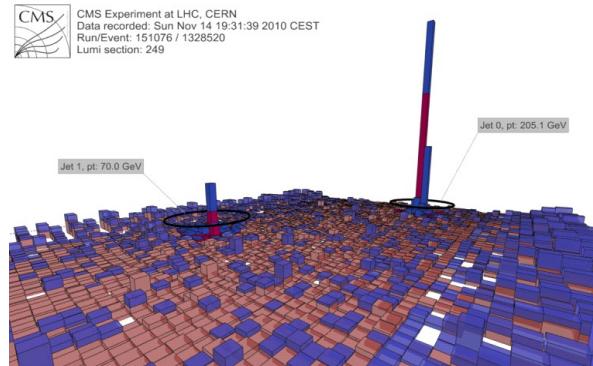


- Global picture of heavy-ion collisions
 - multiplicity
 - energy
 - flow, “ridge”, correlations,? ...

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

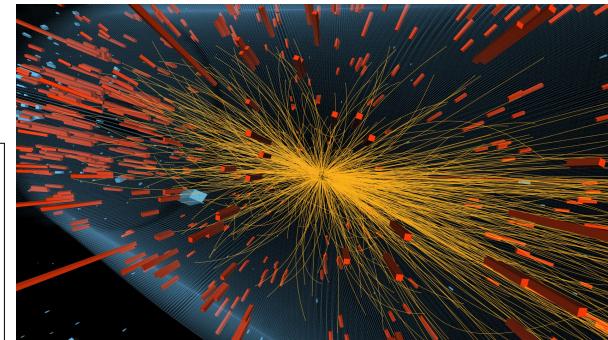


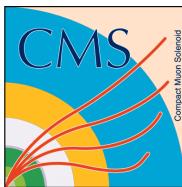
- Hard probes
 - jets
 - dimuons (quarkonia)
 - charged hadrons R_{AA} , ...



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

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





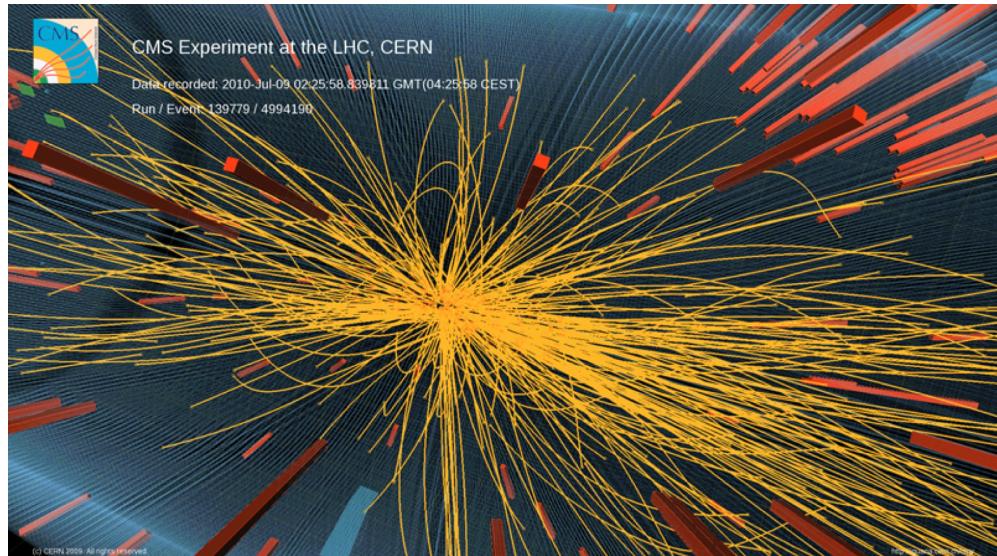
“Ридж”-эффект в столкновениях протон-протон в эксперименте CMS



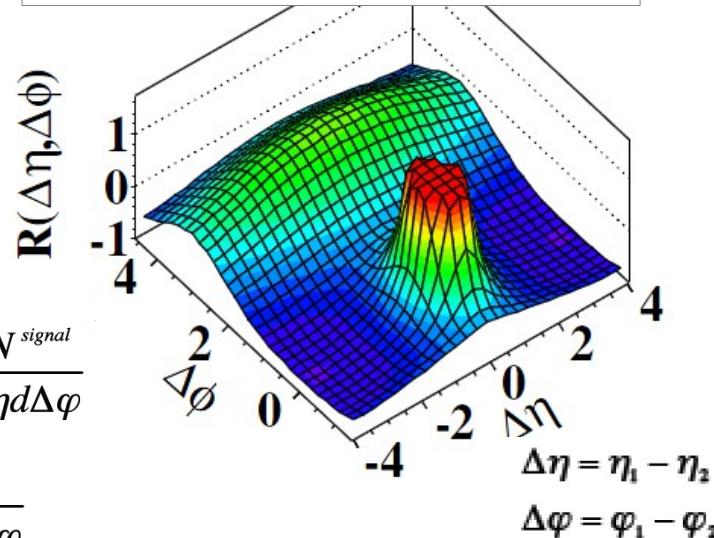
- Протон-протонные столкновения $\sqrt{s} = 7$ ТэВ с высокой множественностью $N > 110$.
- Корреляционная функция для треков с поперечным импульсом в диапазоне от 1 до 3 ГэВ/с:

JHEP 09 (2010) 091

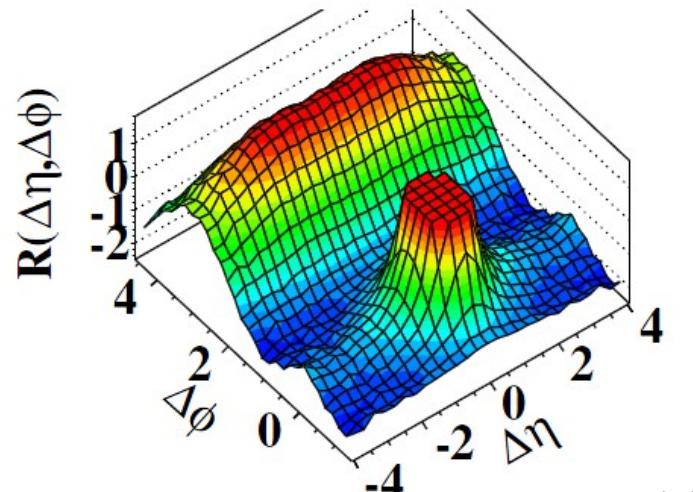
$$\left\{ \begin{array}{l} S_N(\Delta\eta, \Delta\varphi) = \frac{1}{N(N-1)} \frac{d^2 N^{signal}}{d\Delta\eta d\Delta\varphi} \\ B_N(\Delta\eta, \Delta\varphi) = \frac{1}{N^2} \frac{d^2 N^{bkg}}{d\Delta\eta d\Delta\varphi} \end{array} \right.$$

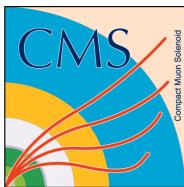


все столкновения



столкновения с $N > 110$





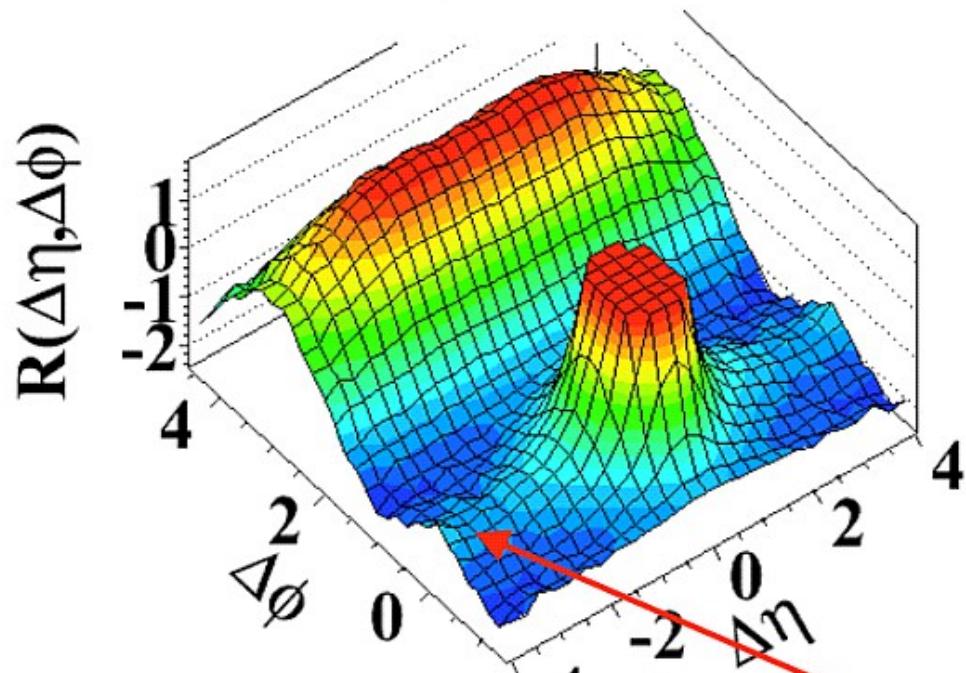
“Ридж”-эффект

на ускорителях LHC и RHIC



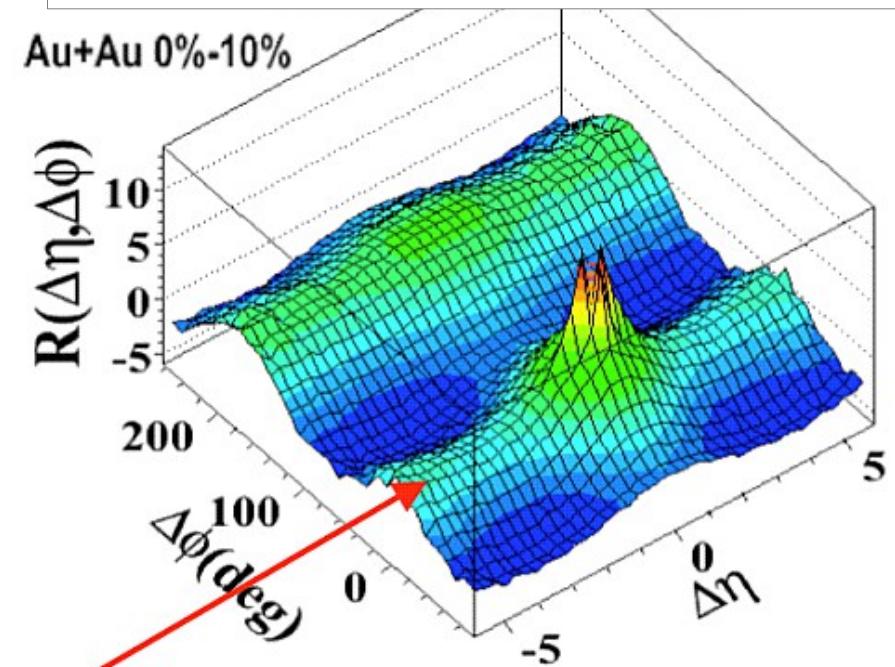
JHEP 09 (2010) 091

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



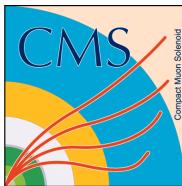
LHC pp 7 ТэВ

RHIC AuAu 200 ГэВ



Подобный эффект наблюдался ранее в столкновениях Au+Au на коллайдере RHIC при энергии $\sqrt{s} = 200$ ГэВ на пару нуклонов в тех же диапазонах поперечного импульса.





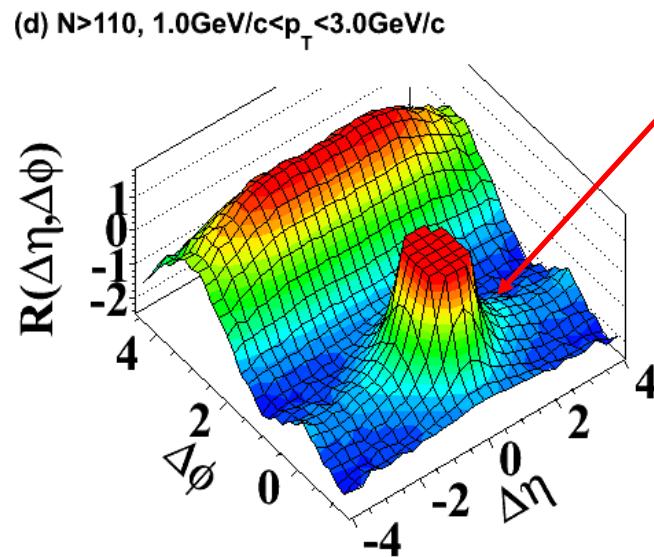
“Ридж”-эффект — везде...



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

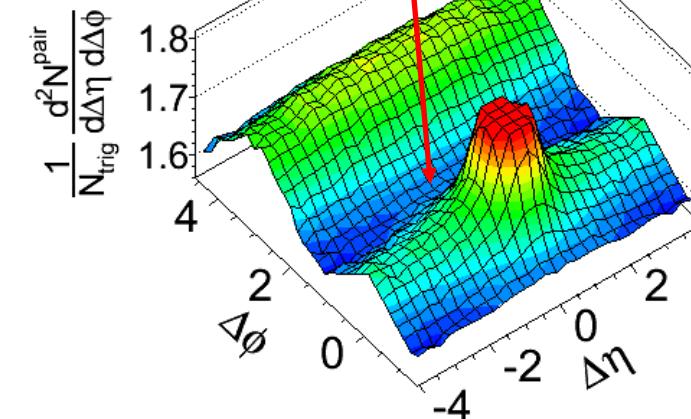
angular correlations were observed in high multiplicity p+p and p+Pb collisions (as well as in Pb+Pb)

p+p 7 TeV



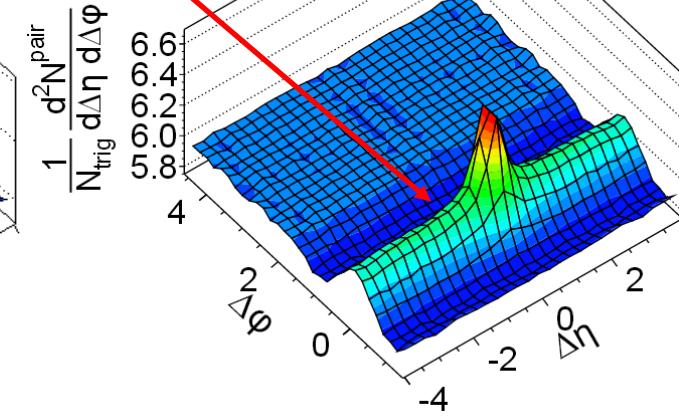
p+Pb 5.02 TeV

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



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

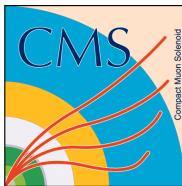


JHEP 09 (2010) 091

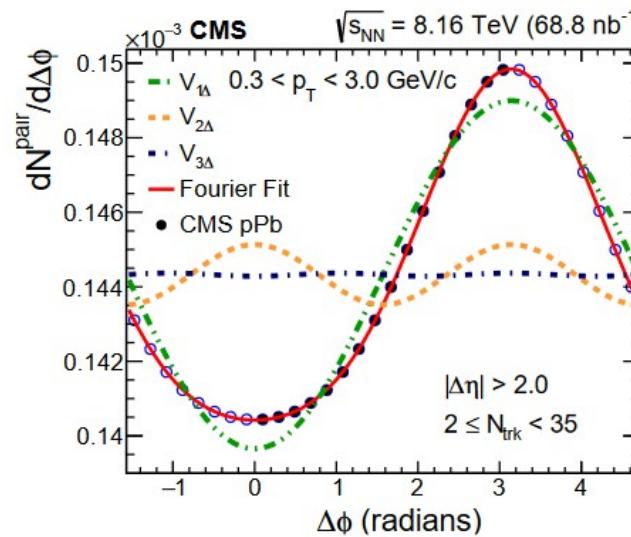
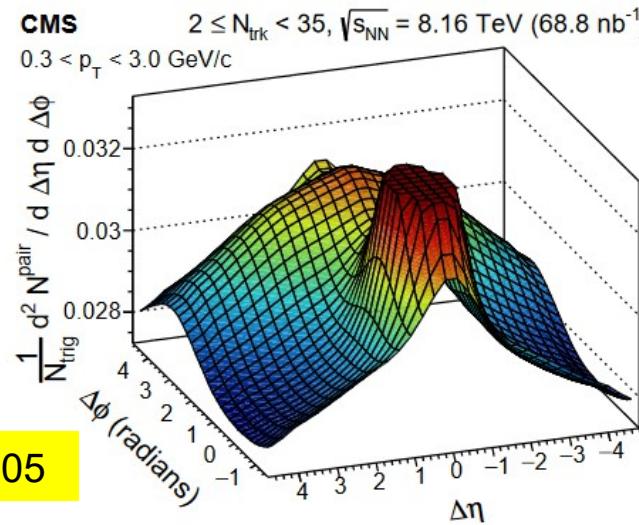
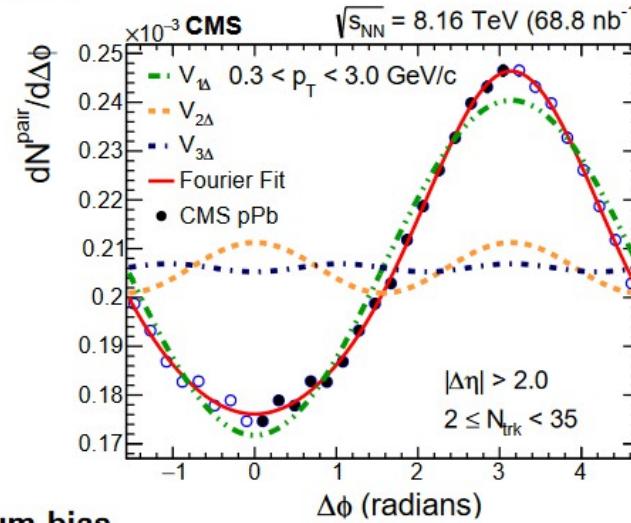
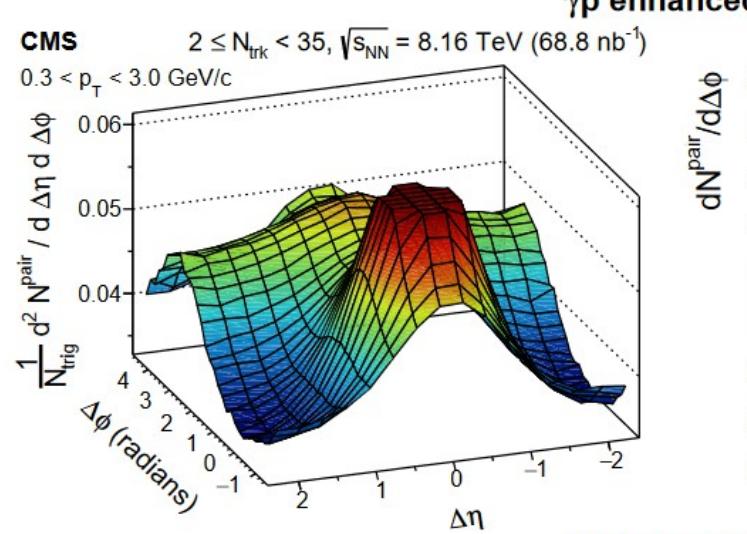
PLB 718 (2013) 795

JHEP 07 (2011) 076





$\gamma+p$ взаимодействия в ультрапериферических столкновениях $p+Pb$

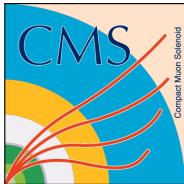


PLB 844 (2023) 137905

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!

Сергей Петрушинко (CMS Collaboration) Физика тяжелых ионов на CMS

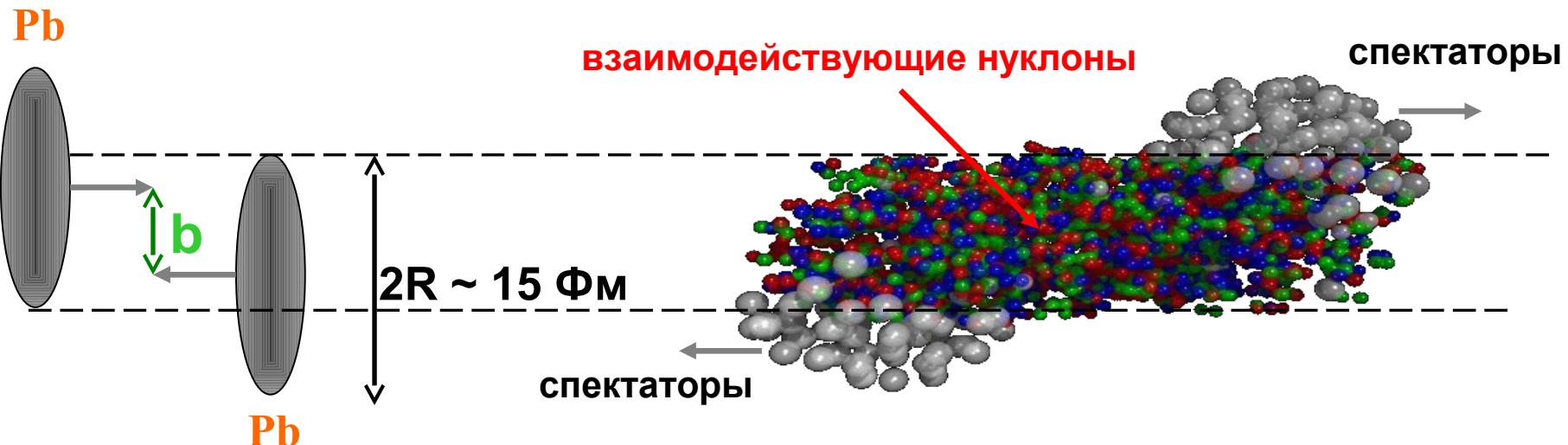




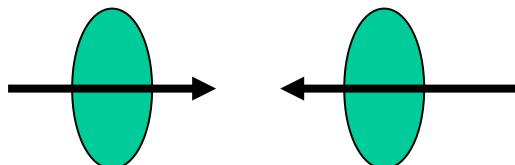
Кварк-глюонная плазма



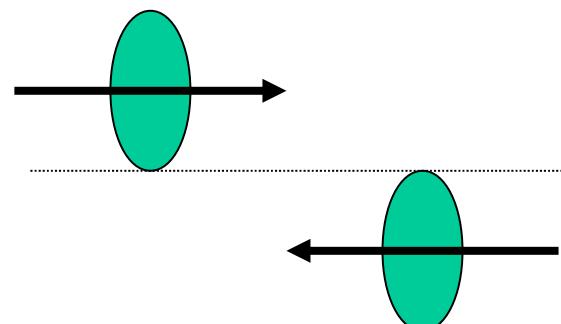
В релятивистских соударениях тяжелых ионов возможно формирование сверхплотного состояния КХД-материи в квазимакроскопических объемах (по сравнению с характерными адронными масштабами).

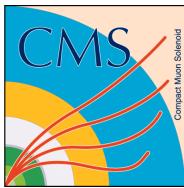


Центральные столкновения,
прицельный параметр $b = 0$



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

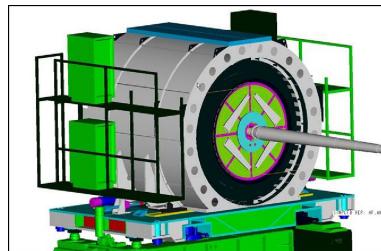




Определение центральности – HF-калориметр установки CMS



HF-калориметр установки CMS: радиационно-стойкий калориметр, основанный на регистрации **черенковского света** в кварцевом волокне, внедренном в **стальной поглотитель**.

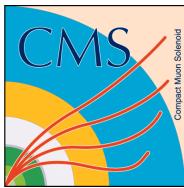


HF
 $3 < |\eta| < 5.2$

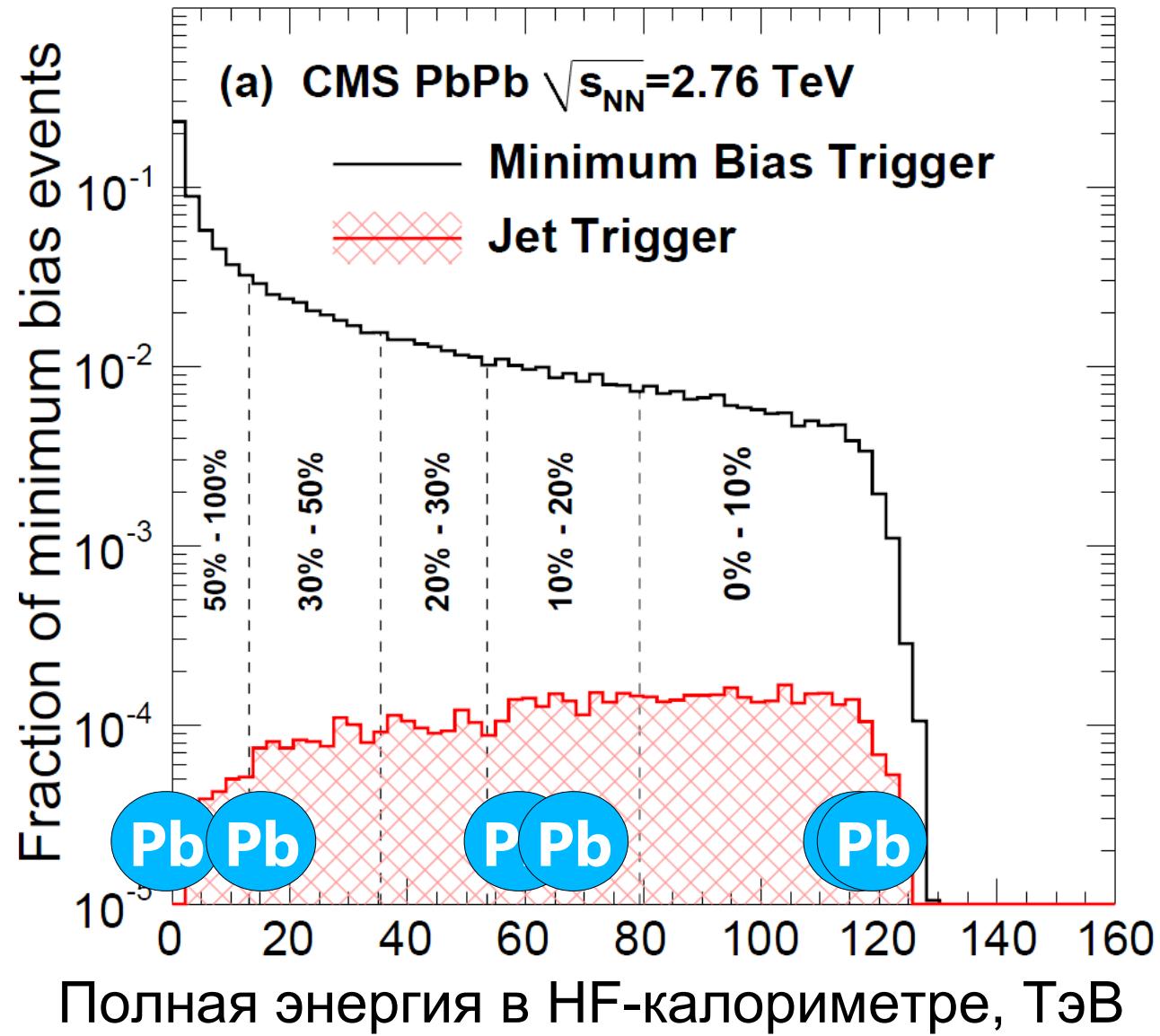


Сергей Петрушанко (CMS Collaboration) Физика тяжелых ионов на CMS





Определение центральности Pb+Pb

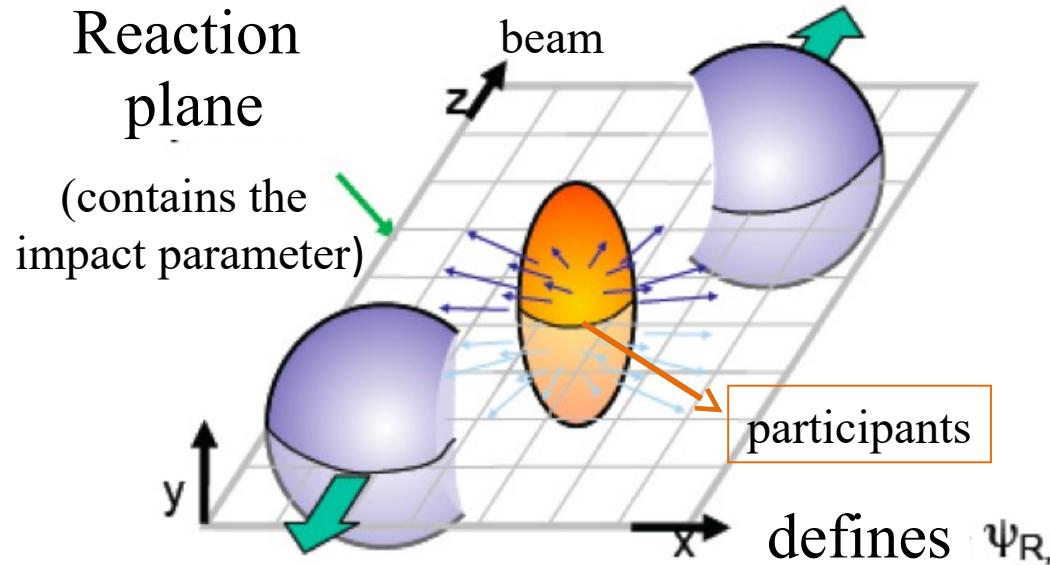


JHEP 08 (2011) 141

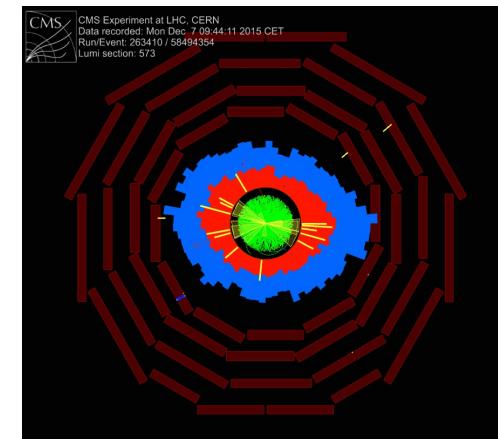
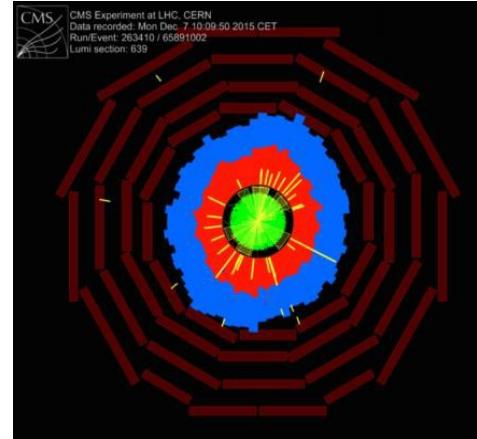
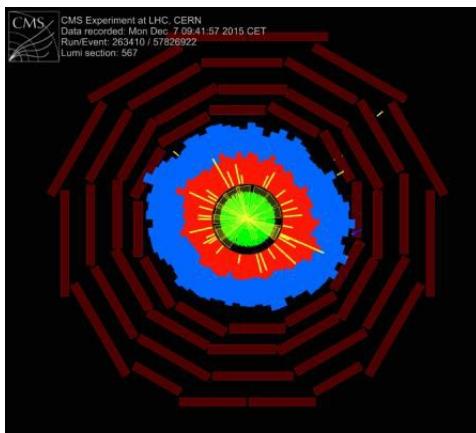




Азимутальная анизоропия

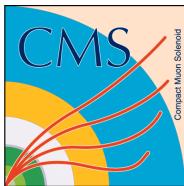


Non-central Pb+Pb “screen shots” from CMS Event Monitor:
Electromagnetic, Hadronic Energy and charged particles tracks



Collective motion is observed in the event azimuthal distributions

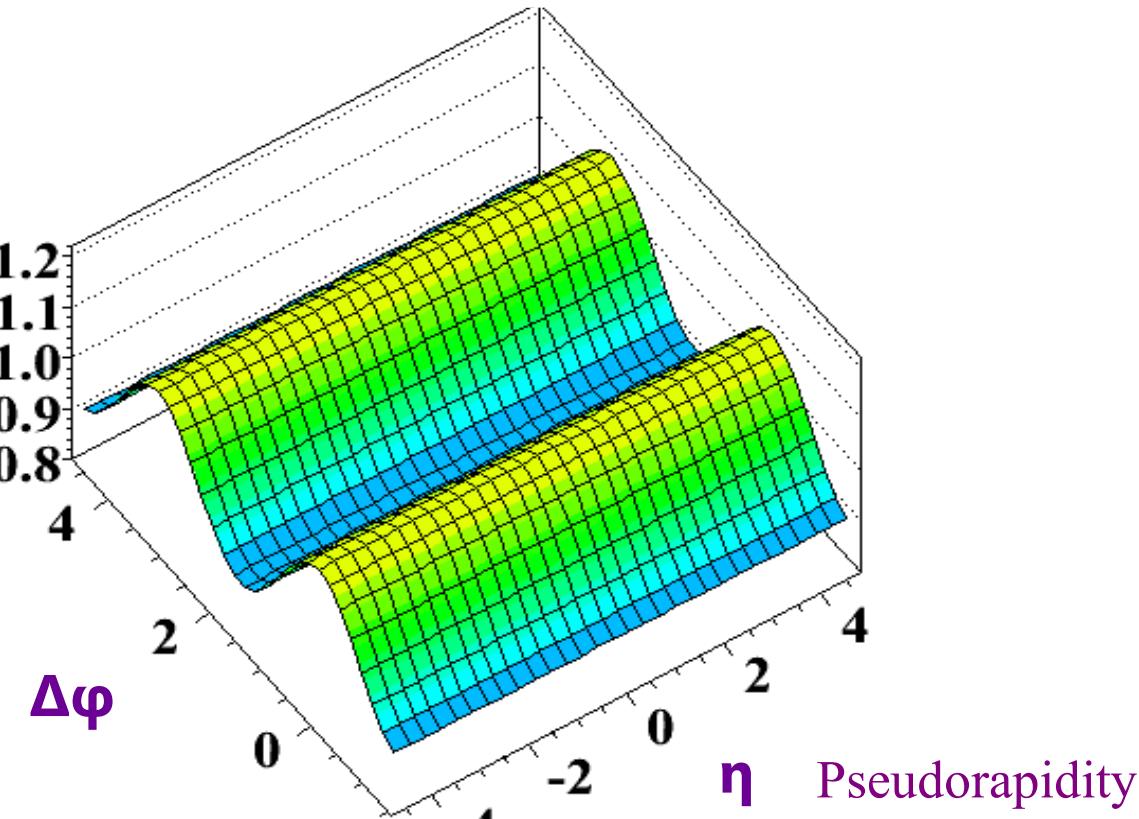




Азимутальная анизоропия



Azimuthal angle related
to the reaction plane



$$\frac{dN}{d\phi}(\varphi_p) = N_0 (1 + 2v_1 \cos(\varphi_p - \Psi_R) + 2v_2 \cos 2(\varphi_p - \Psi_R) + \dots)$$

Ψ_R – azimuthal angle of the reaction plane

Elliptic flow $v_2 = <\cos 2(\varphi - \Psi_R)>$

$$\varphi = \tan^{-1}(p_y/p_x)$$





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 флюктуациях ее начального состояния.



$n = 2$

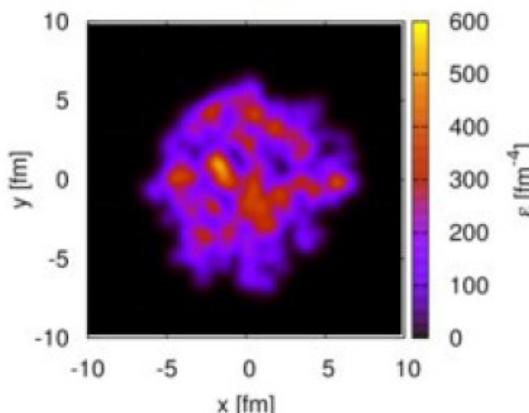
$n = 3$

$n = 4$

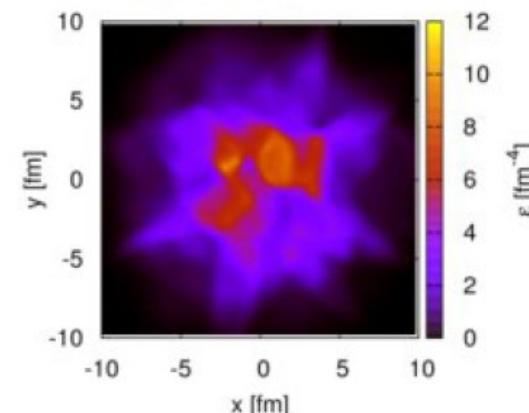
$n = 5$

$n = 6$

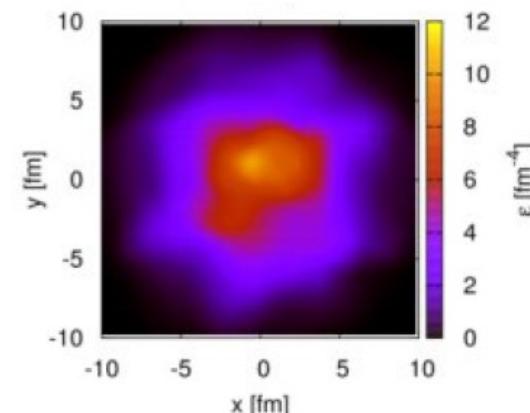
Начальная
стадия

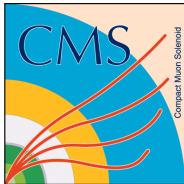


Идеальная
гидродинамика



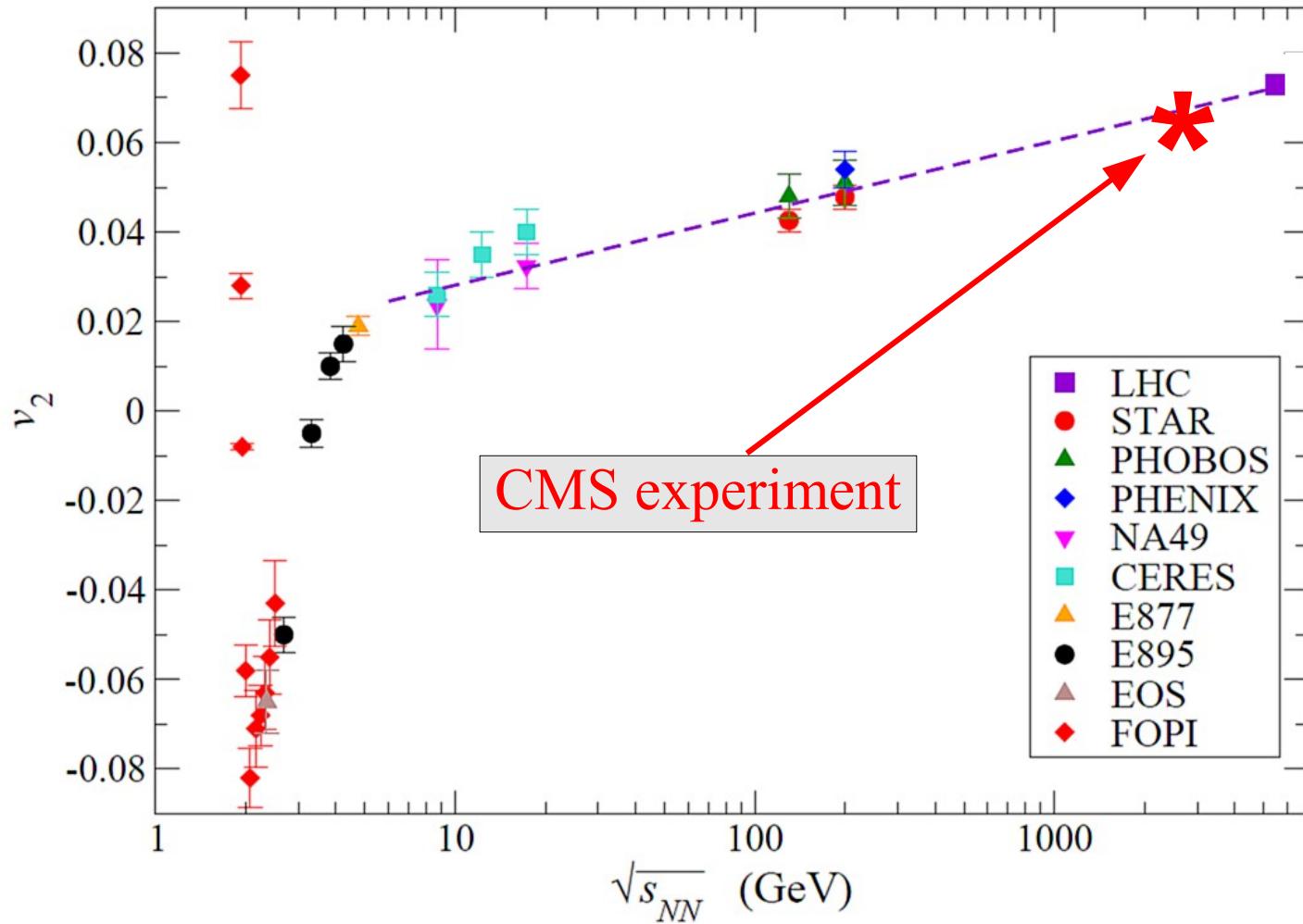
Гидродинамика
с вязкостью



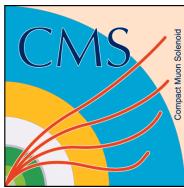


Интегральная v_2 –

предсказание и результат для LHC

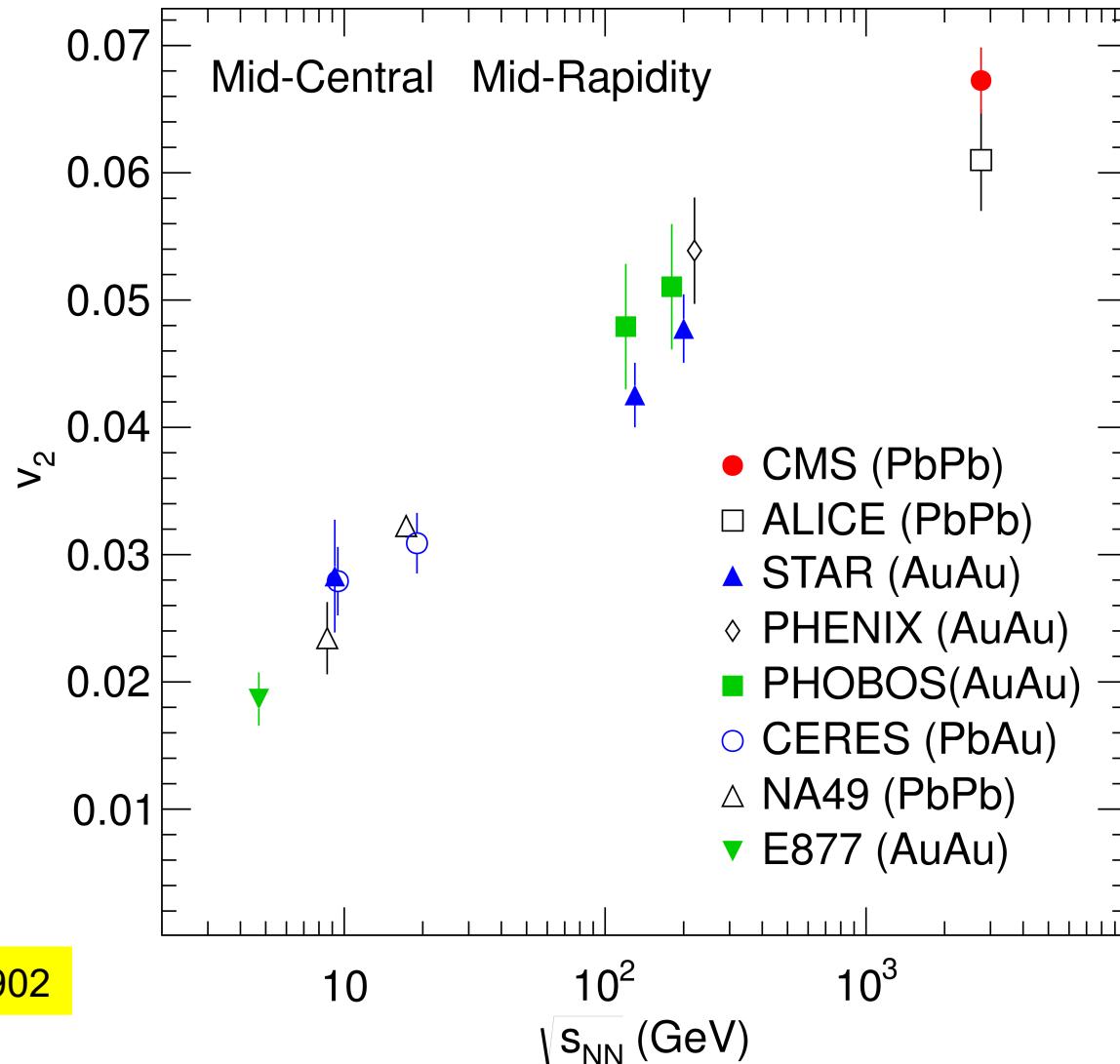


Alessandro B et al., 2006 J. Phys. G: Nucl. Part. Phys. 32 1295



Интегральная v_2 –

результат для LHC от CMS

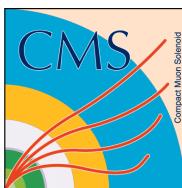


PRC 87 (2013) 014902

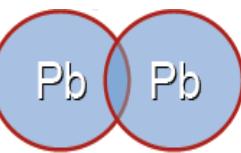
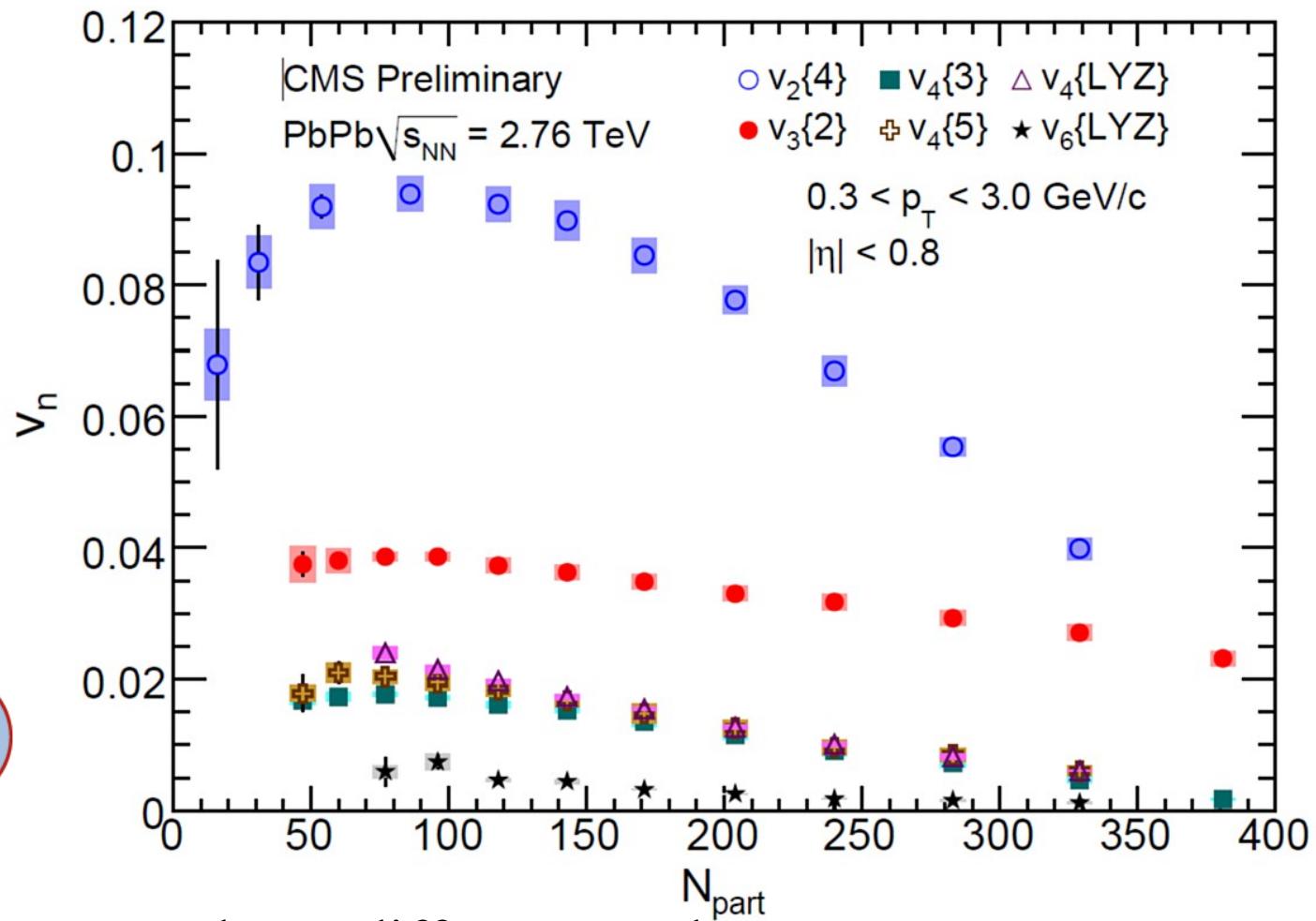
15-30% increase in integral v_2 from top RHIC energy to LHC



Сергей Петрушанко (CMS Collaboration) Физика тяжелых ионов на CMS



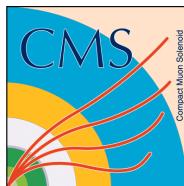
Зависимости v_n от центральности



v_n vs N_{part} shows different trends:

- **even harmonics** have similar centrality dependence:
decreasing $\rightarrow 0$ with increasing N_{part}
- v_3 has weak centrality dependence, finite for central collisions





Xe+Xe как “мост” между p+p и Pb+Pb



ПЕРИОДИЧЕСКАЯ СИСТЕМА ЭЛЕМЕНТОВ Д. И. МЕНДЕЛЕЕВА

		ГРУППЫ ЭЛЕМЕНТОВ																											
ПЕРИОДЫ	РЯДЫ	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														(H)												
		ВОДОРОД																											
2	2	Li	3	Be	4	B	5	C	6	N	7	O	8	F	9								He	2					
		ЛИТИЙ	6,94	БЕРИЛЛИЙ	9,01	БОР	10,81	УГЛЕРОД	12,01	АЗОТ	14,01	КИСЛОРОД	16,00	ФТОР	19,00								ГЕЛИЙ	4,00					
3	3	Na	11	Mg	12	Al	13	Si	14	P	15	S	16	Cl	17								Ne	10					
		НАТРИЙ	22,99	МАГНИЙ	24,31	АЛЮМИНИЙ	26,98	КРЕМНИЙ	28,09	ФОСФОР	30,97	СЕРА	32,06	ХЛОР	35,45								НЕОН	20,18					
4	4	K	19	Ca	20	Sc	21	Ti	23	V	24	Cr	25	Mn	26	Fe	27	Co	28	Ni									
		КАЛИЙ	39,10	КАЛЬЦИЙ	40,08	СКАНДИЙ	44,96	ТИТАН	50,94	ВАНДИЙ	52,00	ХРОМ	54,94	МАРГАНЕЦ	55,85	ЖЕЛЕЗО	58,93	КОБАЛЬТ	58,70	НИКЕЛЬ									
5	5	29	Cu	30	Zn	Ga	31	Ge	32	As	33	Se	34	Br	35								Kr	36					
		63,55	МЕДЬ	65,39	ЦИНК	ЦИНК	69,72	ГЕРМАНИЙ	72,59	МЫШЬЯК	74,92	СЕЛЕН	78,96	БРОМ	79,90								КРИПТОН	83,80					
6	6	Rb	37	Sr	38	Y	39	Zr	41	Nb	42	Mo	43	Tc	44	Ru	45	Rh	46	Pd									
		РУБИДИЙ	85,47	СТРОНИЙ	87,62	ИТРИЙ	88,91	ЦИРКОНИЙ	91,22	НИОБИЙ	92,91	МОЛИБДЕН	95,94	ТЕХНЕЦИЙ	98,91	РУТЕНИЙ	102,91	РОДИЙ	106,42	ПАЛЛАДИЙ									
7	7	47	Ag	48	Cd	In	49	Sn	50	Sb	51	Te	52	I	53								Xe	54					
		107,87	СЕРЕБРО	112,41	КАДМИЙ	ИНДИЙ	114,82	ОЛОВО	118,71	СУРЬМА	121,75	ТЕЛЛУР	127,60	ЙОД	128,90								КСЕНОН	131,30					
8	8	Cs	55	Ba	56	La*	57	Hf	73	Ta	74	W	75	Re	76	Os	77	Ir	78	Pt									
		ЦЕЗИЙ	132,91	БАРИЙ	137,33	ЛАНТАН	138,91	ГАФНИЙ	178,49	ТАНТАЛ	183,84	ВОЛЬФРАМ	186,21	РЕННИЙ	190,23	ОСМИЙ	192,22	ИРИДИЙ	195,09	ПЛАТИНА									
9	9	79	Au	80	Hg	Tl	81	Pb	82	Bi	83	Po	84	At	85								Rn	86					
		196,97	ЗОЛОТО	200,59	РТУТЬ	ТАЛЛИЙ	204,38	СВИНЦ	207,20	ВИСМУТ	208,98	ПОЛОНИЙ	[209]	АСТАТ	[210]								РАДОН	[222]					
7	10	Fr	87	Ra	88	Ac**	89	Rf	104	Db	106	Sg	107	Bh	108	Hs	109	Mt	110	Ds									
		ФРАНЦИЙ	[223]	РАДИЙ	[226]	АКТИНИЙ	[227]	РЕЗЕРФОРДИЙ	[261]	ДУБНИЙ	[263]	СИБОРГИЙ	[262]	БОРИЙ	[265]	ГАССИЙ	[268]	МЕЙНТЕРИЙ	[271]	ДАРМШТАДТИЙ									
ВЫСШИЕ ОКСИДЫ		R ₂ O		RO		R ₂ O ₃		RO ₂		R ₂ O ₅		R ₂ O ₃		R ₂ O ₇		МОЛЮБДЕНЫЙ						RO ₄							
ЛЕТУЧИЕ ВОДОРОДНЫЕ СОЕДИНЕНИЯ								RH ₄		RH ₃		H ₂ R		HR															
*ЛАНТАНОИДЫ		Ce	58	Pr	59	Nd	60	Pm	61	Sm	62	Eu	63	Gd	64	Tb	65	Dy	66	Ho	67	Er	68	Tm	69	Yb	70	Lu	71
		ЦЕРИЙ	140,12	ПРАЗЕОДИМ	140,91	НЕОДИМ	144,24	ПРОМЕТИЙ	[145]	САМАРИЙ	150,36	ЕВРОПИЙ	151,96	ГАДОЛИНИЙ	157,25	ТЕРБИЙ	158,93	ДИСПРОЗИЙ	162,50	ГОЛЬМИЙ	164,93	ЭРБИЙ	167,26	ТУЛИЙ	168,93	ИТЕРБИЙ	173,04	ЛОТЕЦИЙ	174,97
***АКТИНОИДЫ		Th	90	Pa	91	U	92	Np	93	Pu	94	Am	95	Cm	96	Bk	97	Cf	98	Es	99	Fm	100	Md	101	No	102	Lr	103
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	As		
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			

A	B	1	1,01
ВОДОРОД			

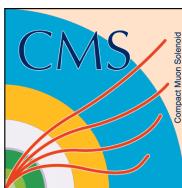
Xe	54	131,30
КСЕНОН		

Pb	82	207,20
СВИНЕЦ		



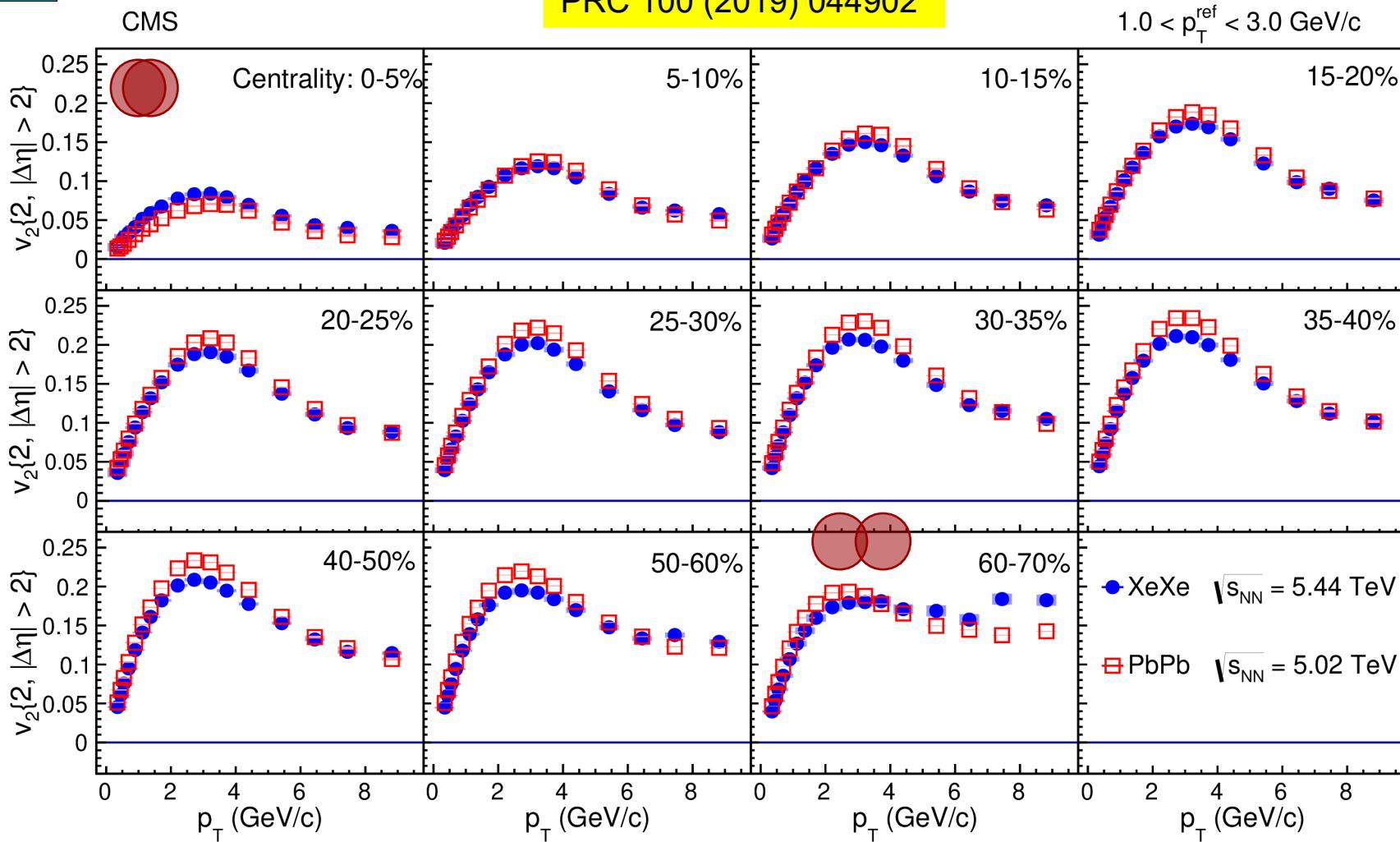
Сергей Петрушанко (CMS Collaboration) Физика тяжелых ионов на CMS



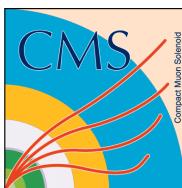


v_2 Xe+Xe vs. Pb+Pb

PRC 100 (2019) 044902

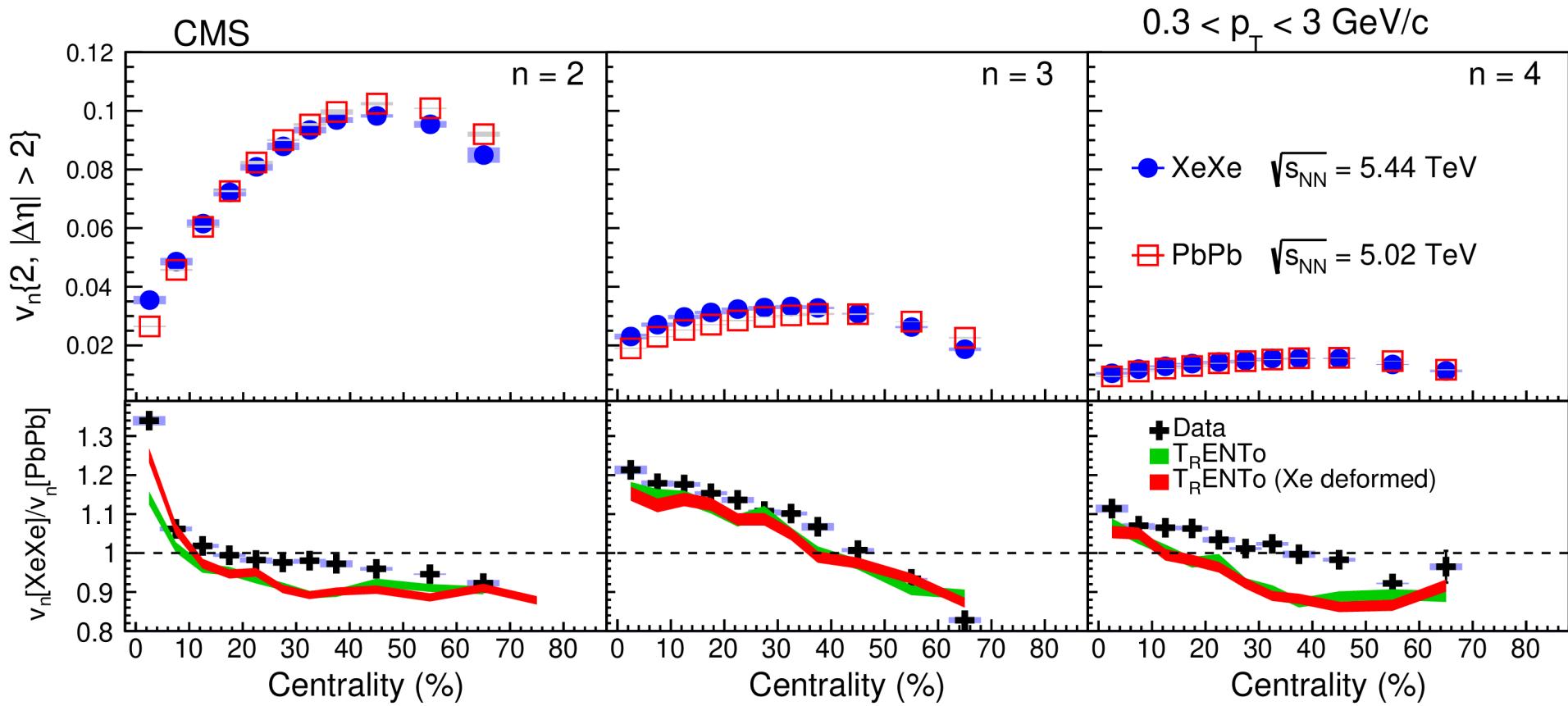


The magnitude of the v_2 coefficients for Xe+Xe collisions are larger than those found in Pb+Pb collisions for the most central collisions. This is attributed to a larger fluctuation component in the lighter colliding system.



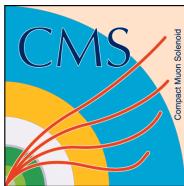
$v_{2, 3, 4}$ Xe+Xe vs. Pb+Pb

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.





HYDJET и HYDJET++ Монте-Карло генераторы соударений



HYDJET

(HYDrodynamics + JETs)

event generator to simulate heavy ion event as merging of two independent components (**soft** hydro-type part + **hard** multi-partonic state)

<http://cern.ch/lokhtin/hydro/hydjet.html>
(*latest version 1.9*)

I.Lokhtin, A.Snigirev, Eur. Phys. J. C 46 (2006) 2011

HYDJET++

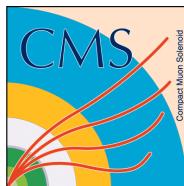
continuation of HYDJET

(improved **soft** component including full set of thermal resonance production
+ identical to HYDJET **hard** component)

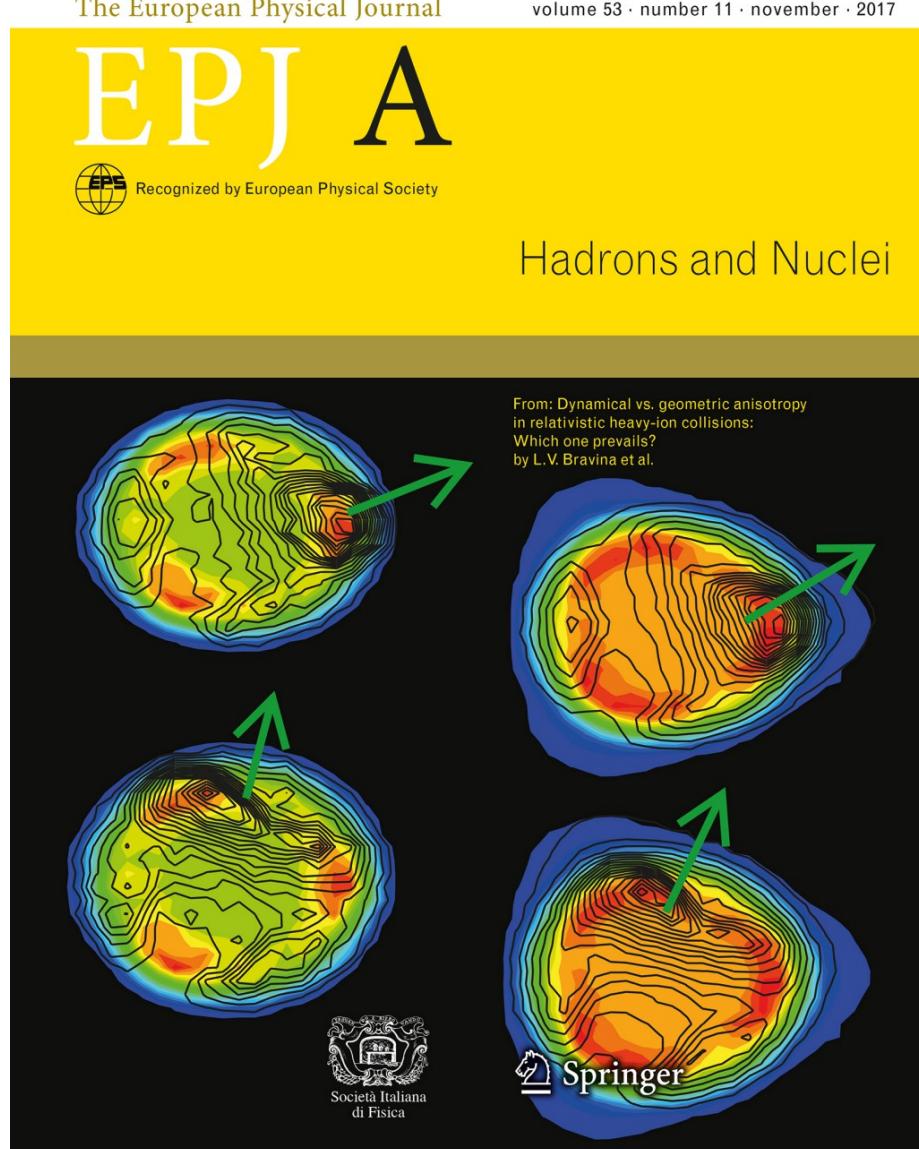
<http://cern.ch/lokhtin/hydjet++>
(*latest version 2.4*)

*I.Lokhtin, L.Malinina, S.Petrushanko, A.Snigirev, I.Arsene, K.Tywoniuk,
Comp.Phys.Comm. 180 (2009) 779*





HYDJET++ на обложке Eur. Phys. J. A

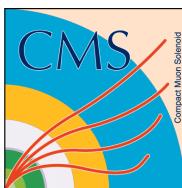


L.V. Bravina, I.P. Lokhtin,
L.V. Malinina, S.V. Petrushanko,
A.M. Snigirev, E.E. Zabrodin

**“Dynamical vs. geometric
anisotropy in relativistic
heavy-ion collisions: Which
one prevails?”**

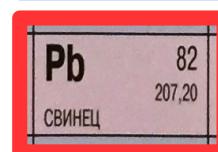
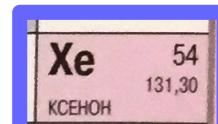
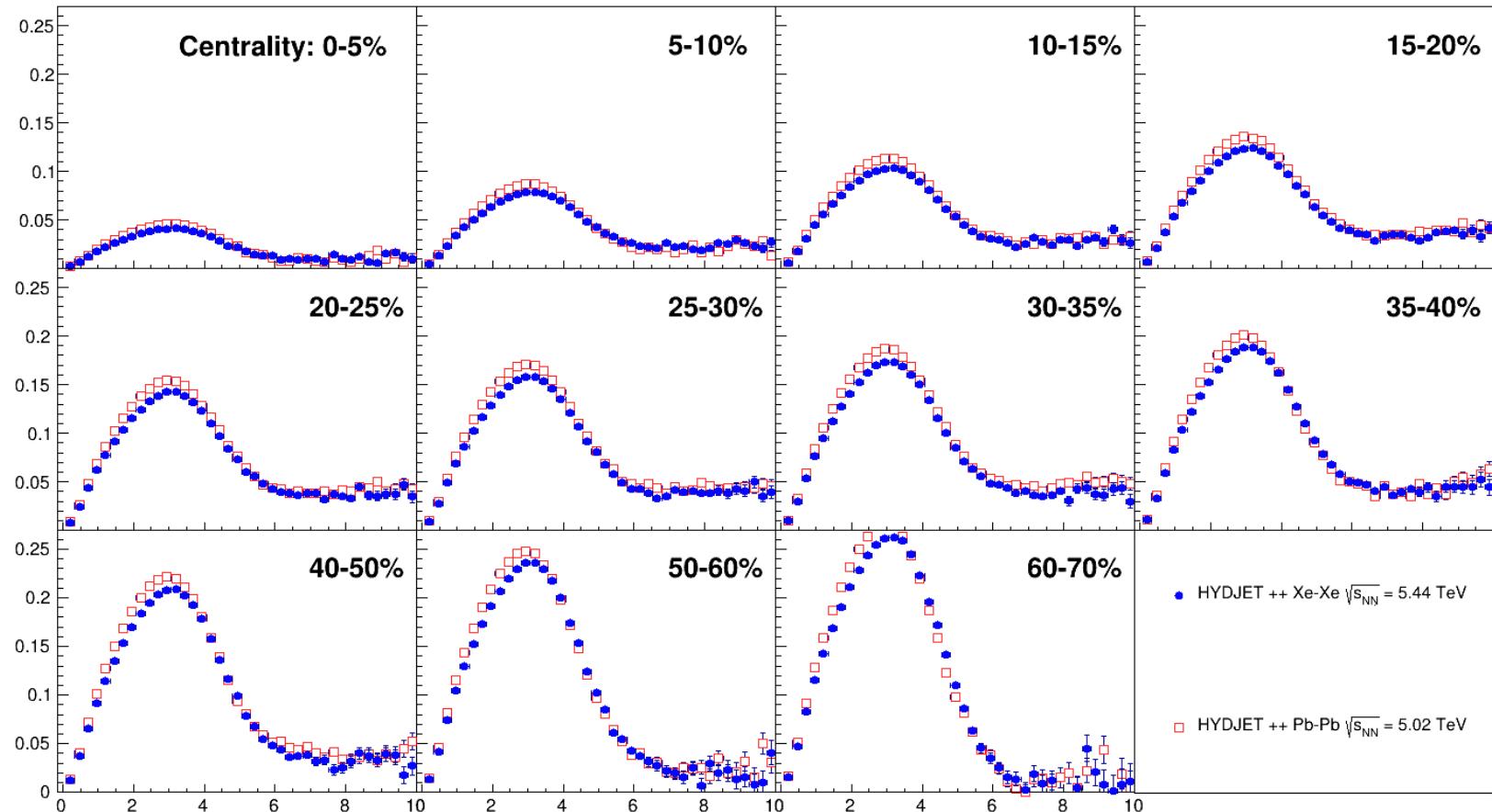
Eur. Phys. J. A 53 (2017) 219.





v_2 Xe+Xe vs. Pb+Pb (HYDJET++ генератор)

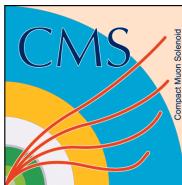
Д.Мягков, С.Петрушанко. Учен. зап. физ. фак-та Моск. ун-та. 2023. № 3. 2330205



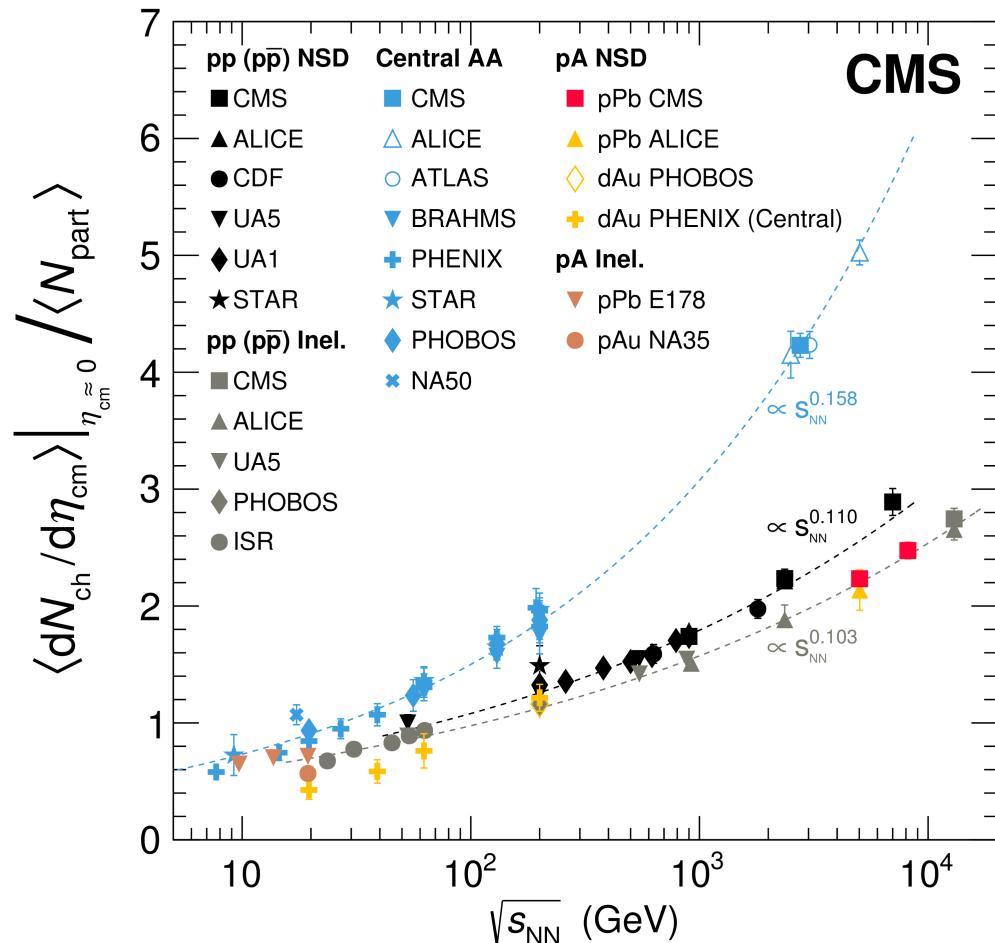
In hydrodynamic model HYDJET++
<http://cern.ch/lokhtin/hydjet++>

Xe+Xe v_2 are higher than Pb+Pb v_2 for all centralities.





Множественность заряженных частиц Плотность поперечной энергии

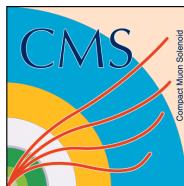


JHEP 01 (2018) 045

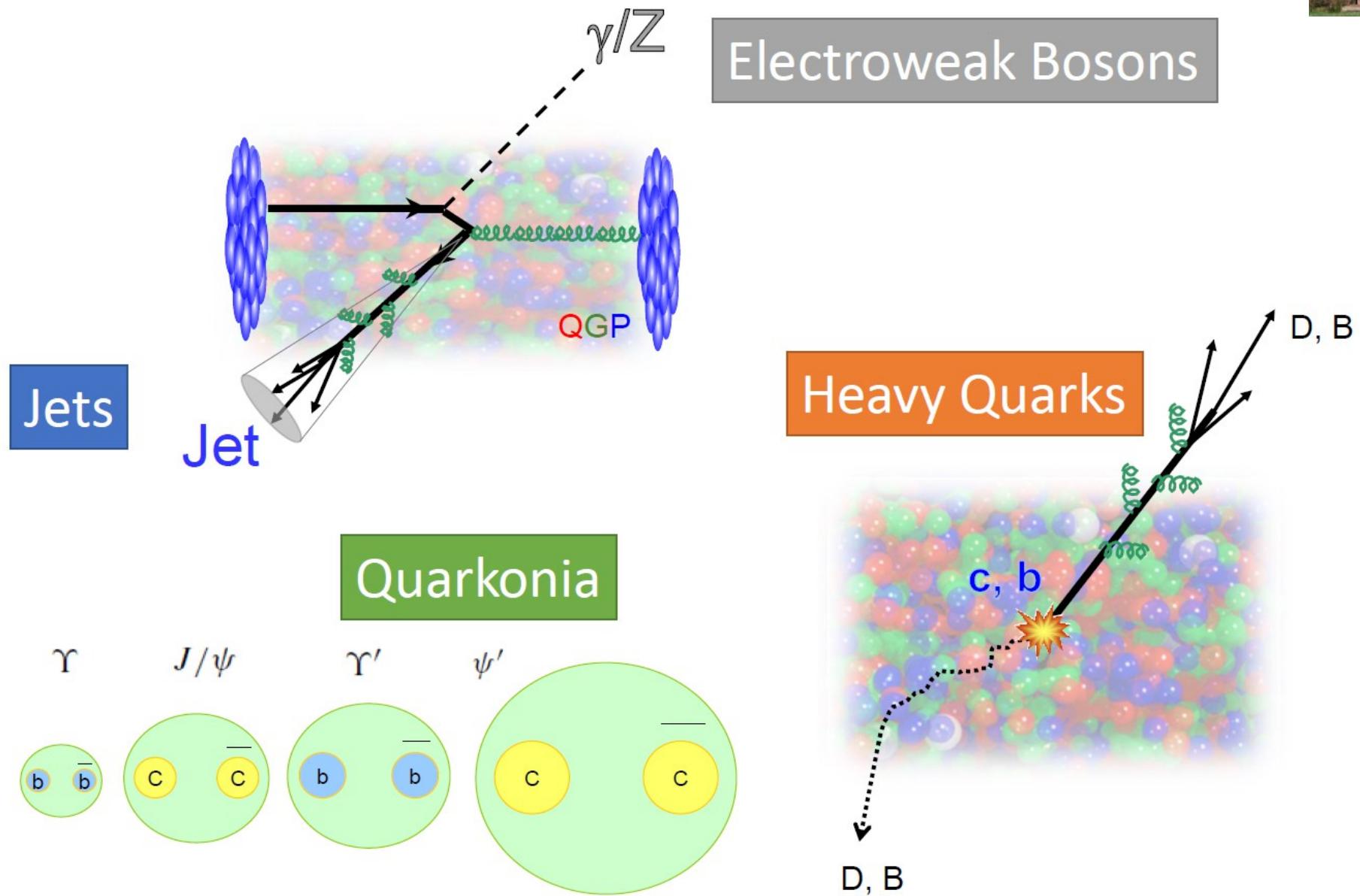
\sqrt{s} dependence

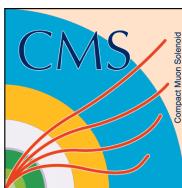
$p+p$, $p+Pb$ and $Pb+Pb$ follow power law

PRC 100 (2019) 024902

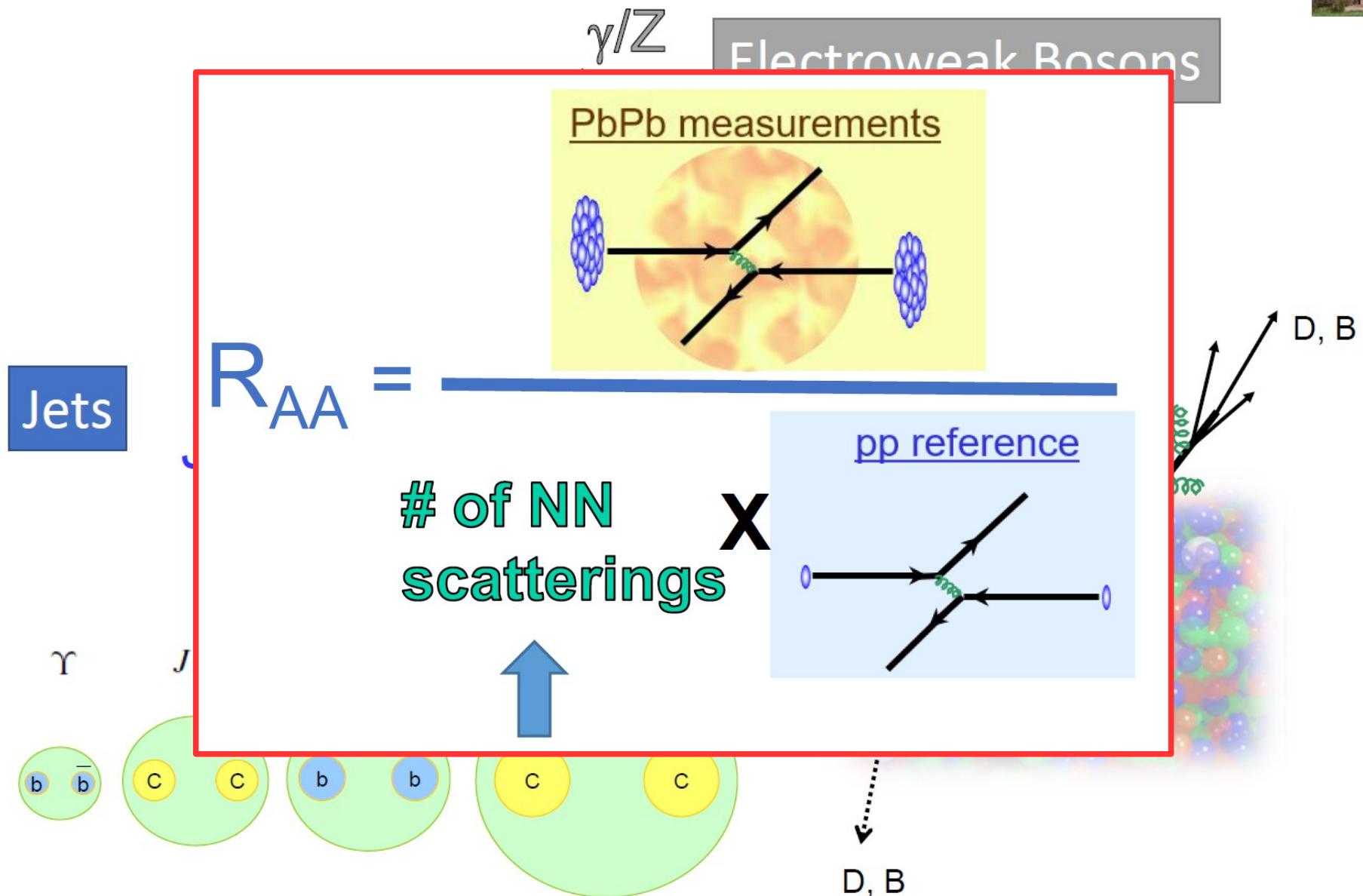


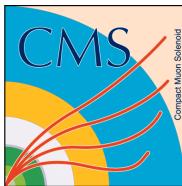
Жесткие тесты кварк-глюонной плазмы





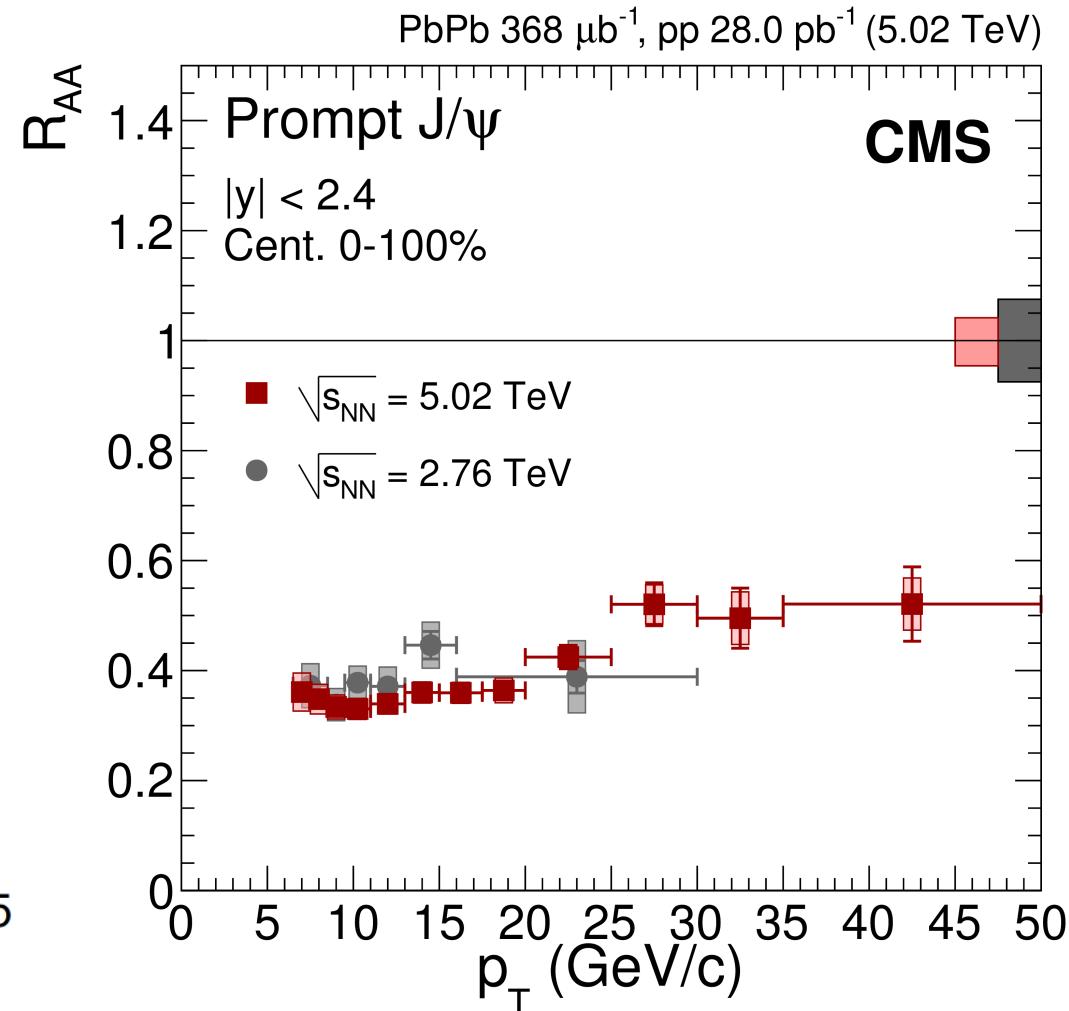
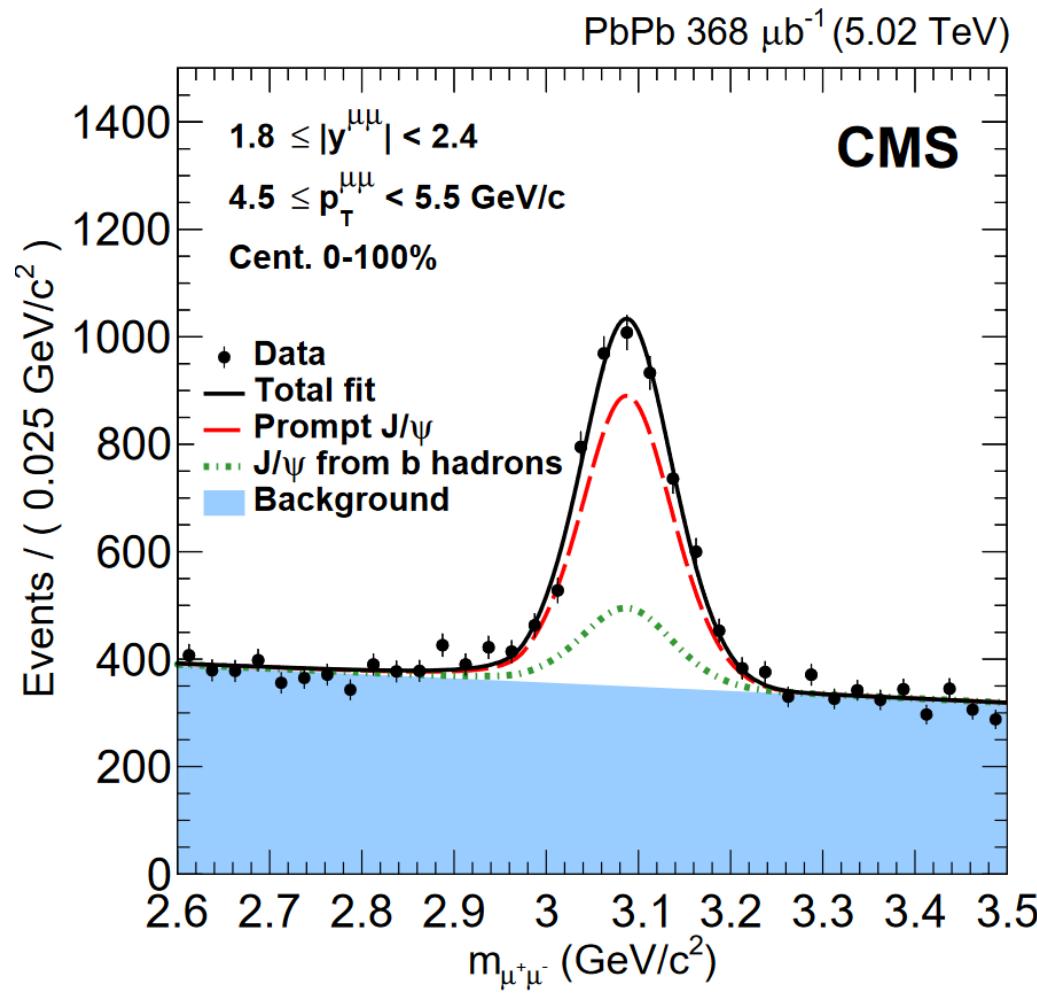
Жесткие тесты кварк-глюонной плазмы





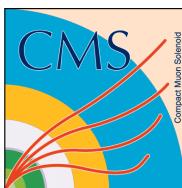
Подавление J/ψ в Pb+Pb

EPJ C 78 (2018) 509



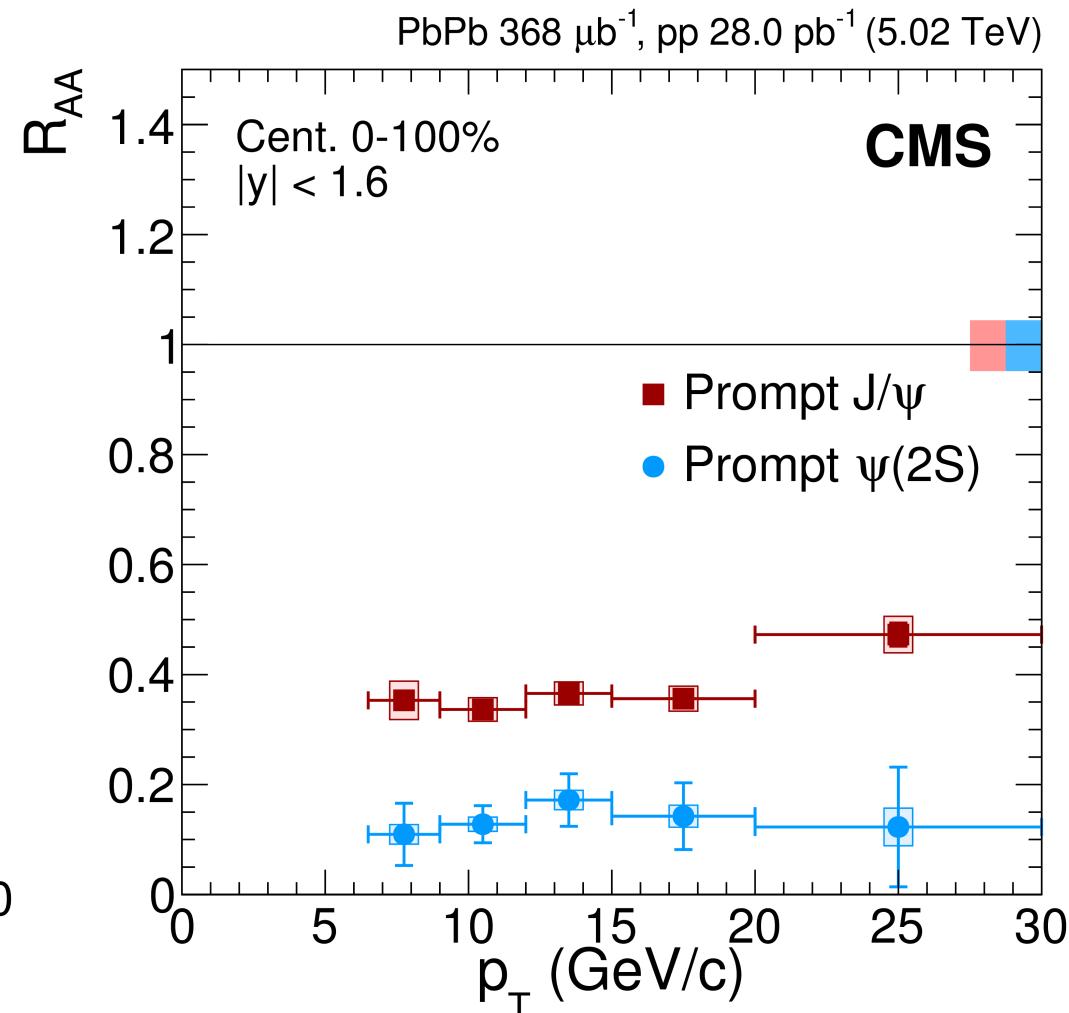
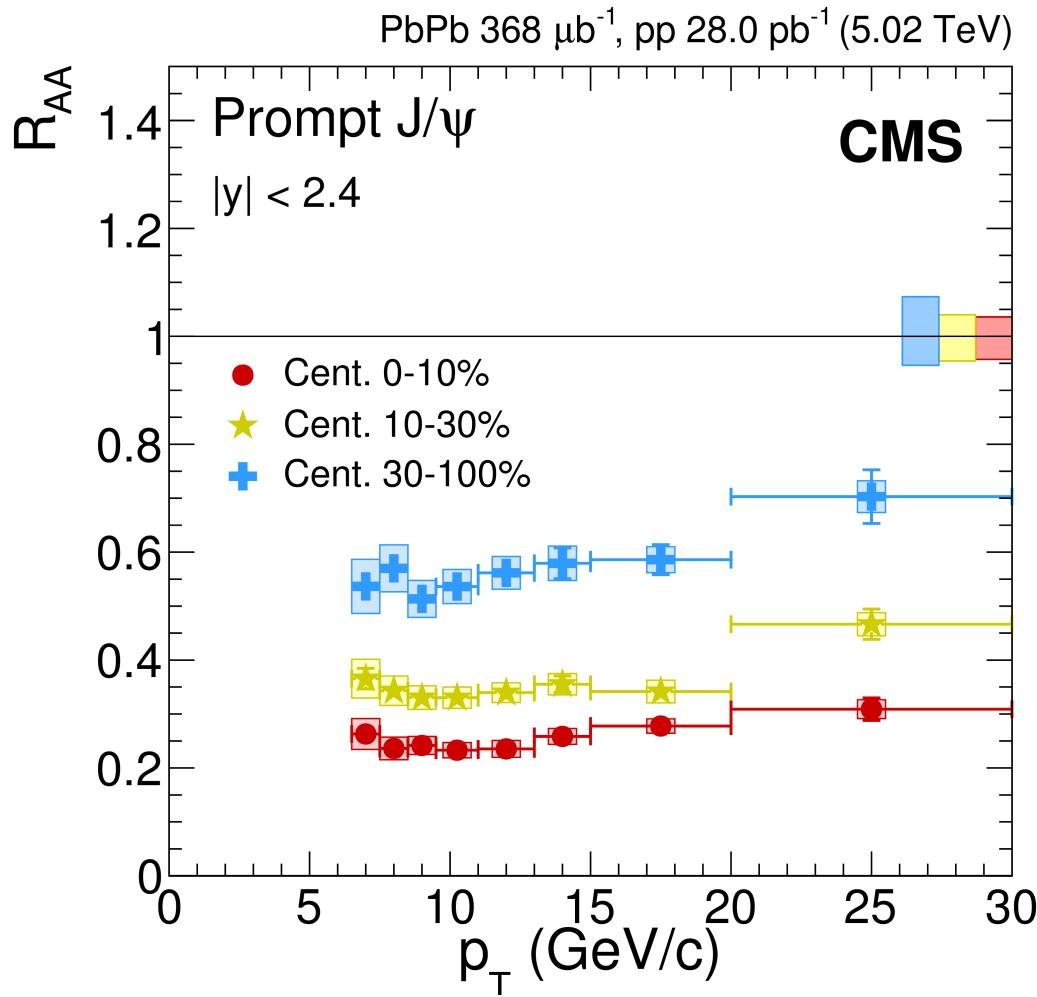
J/ψ mesons are observed to be suppressed
(similarly in 2.76 and 5.02 TeV)





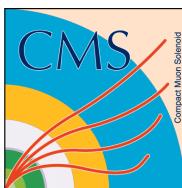
Подавление J/ψ и ψ(2S) в Pb+Pb

EPJ C 78 (2018) 509



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

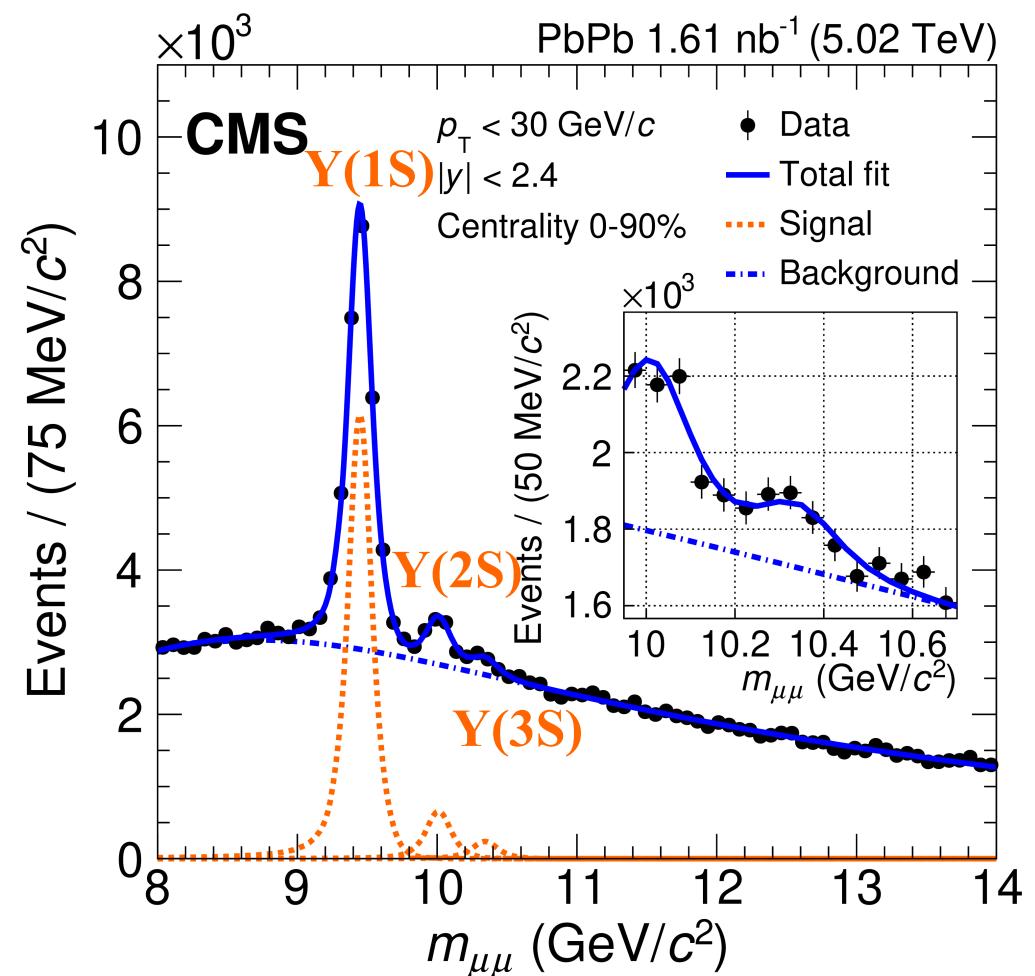
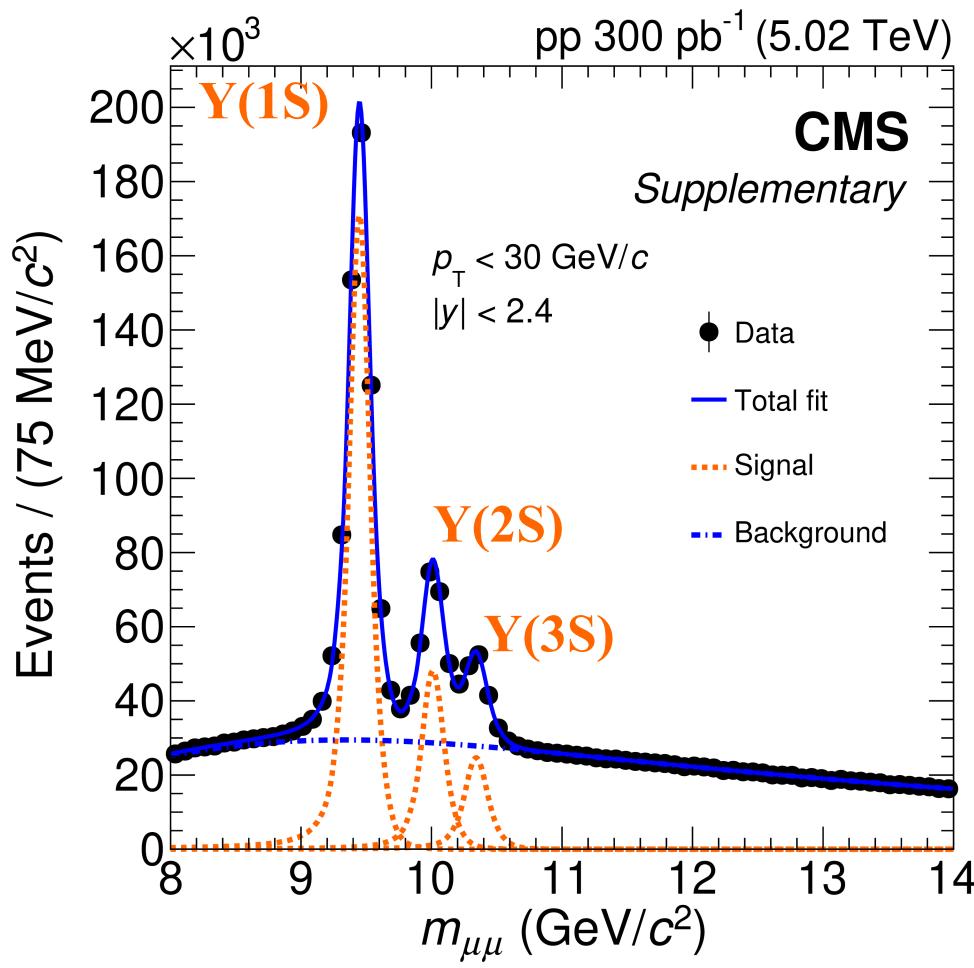




Подавление Y в Pb+Pb

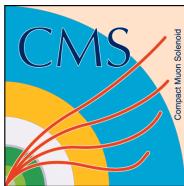


arXiv:2303.17026



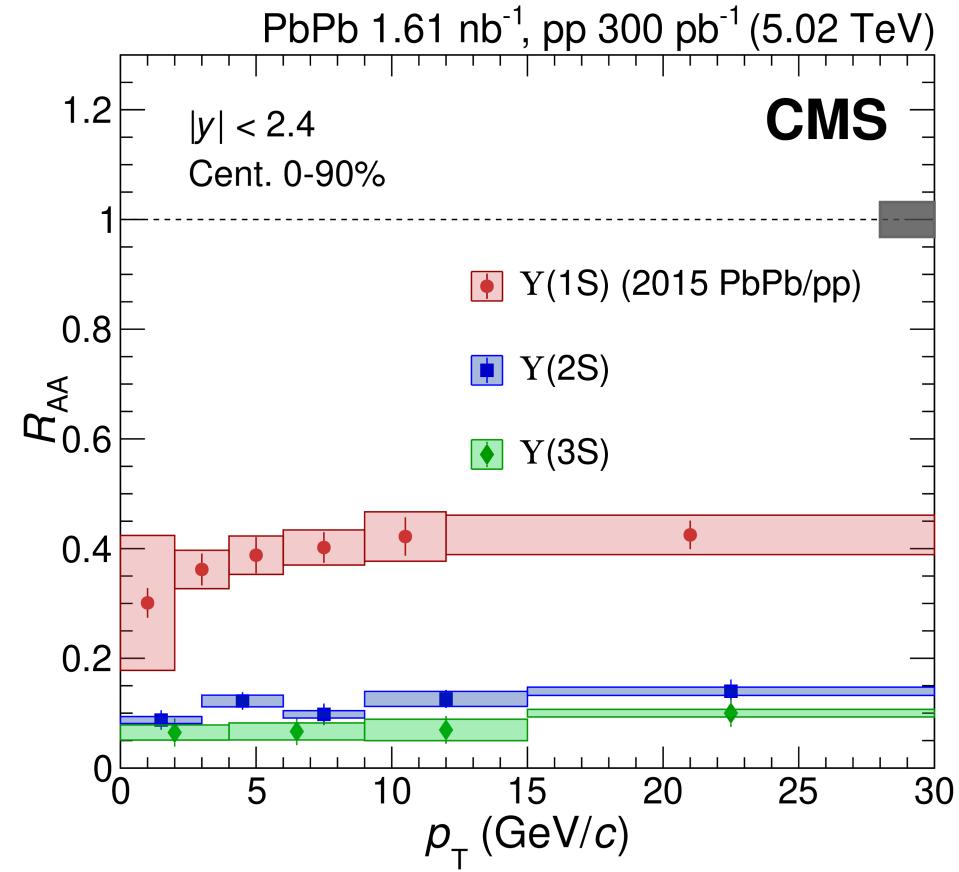
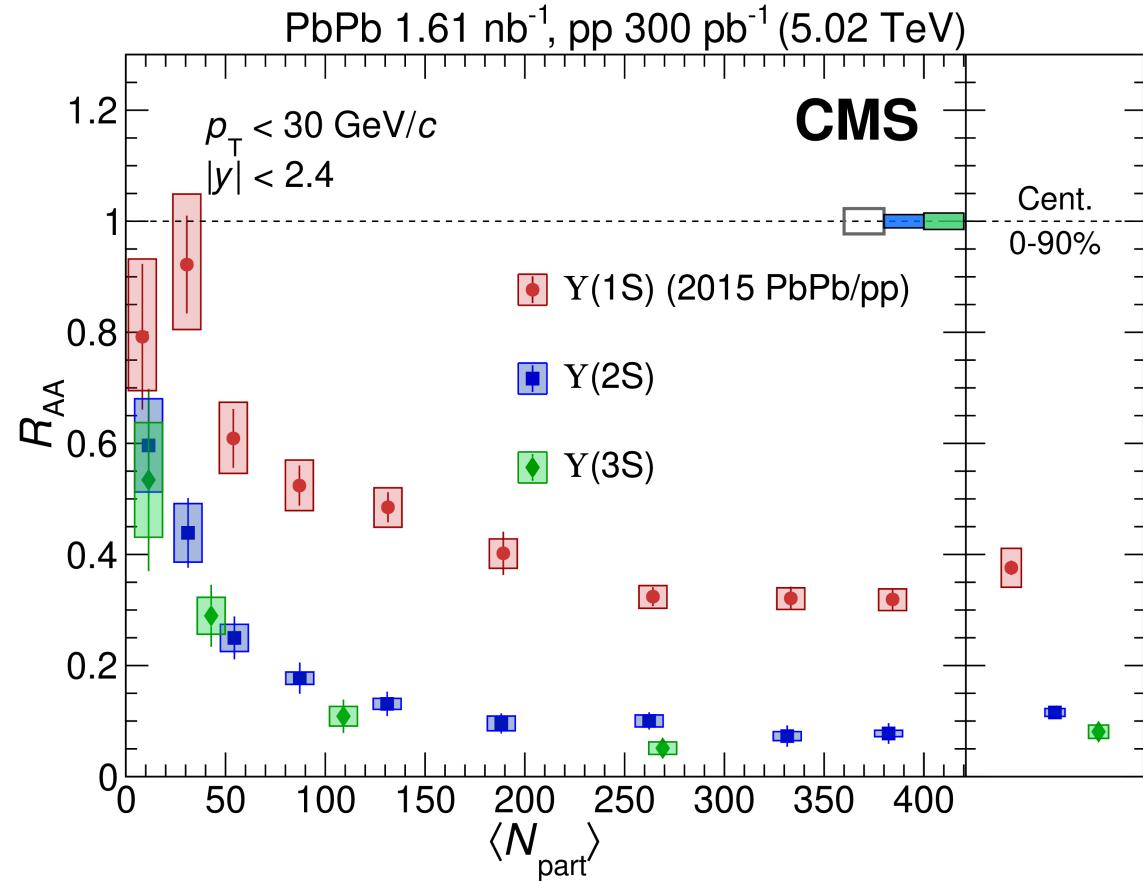
- Observation of sequential suppression of Y family in Pb+Pb.
 - First observation of Y(3S) in heavy-ion collisions! ($\sigma > 5$)





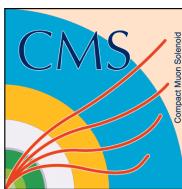
Подавление Y в Pb+Pb

arXiv:2303.17026



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

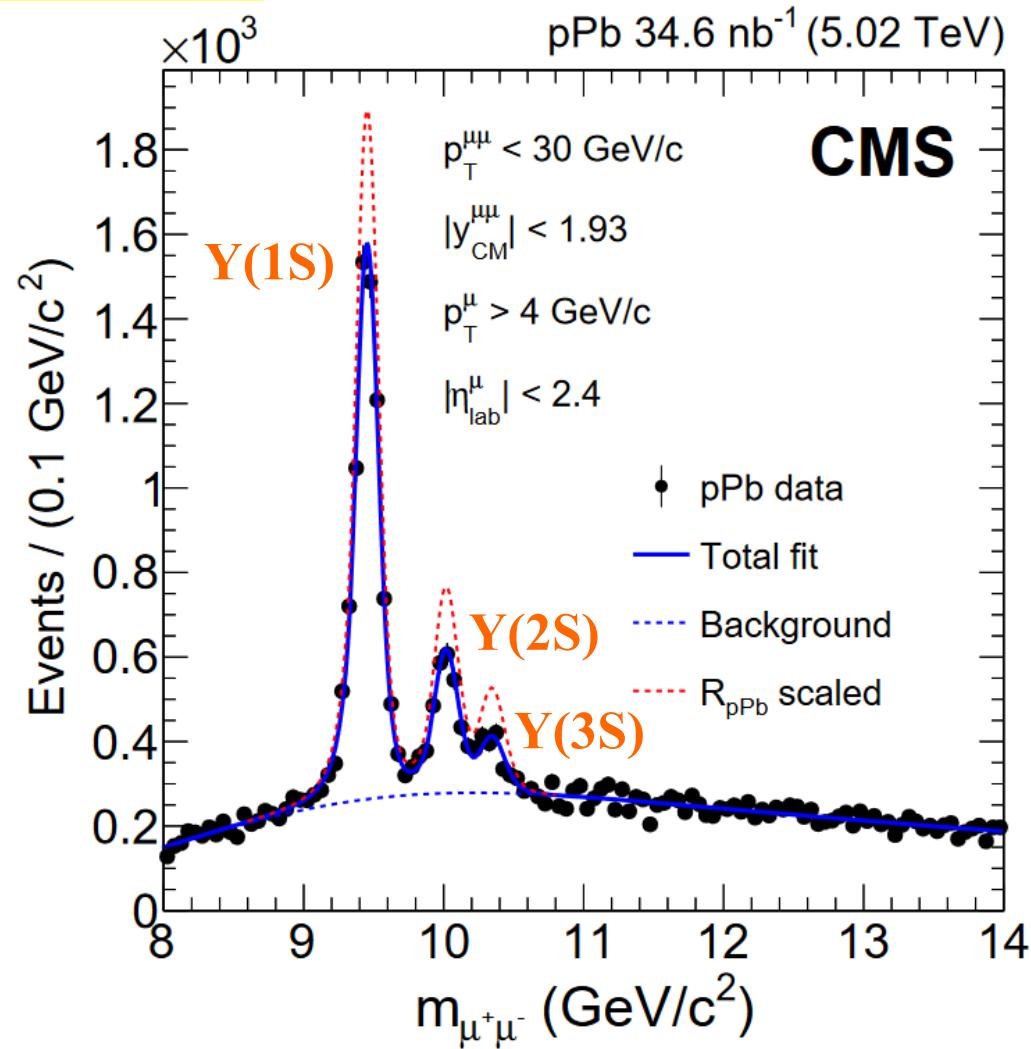
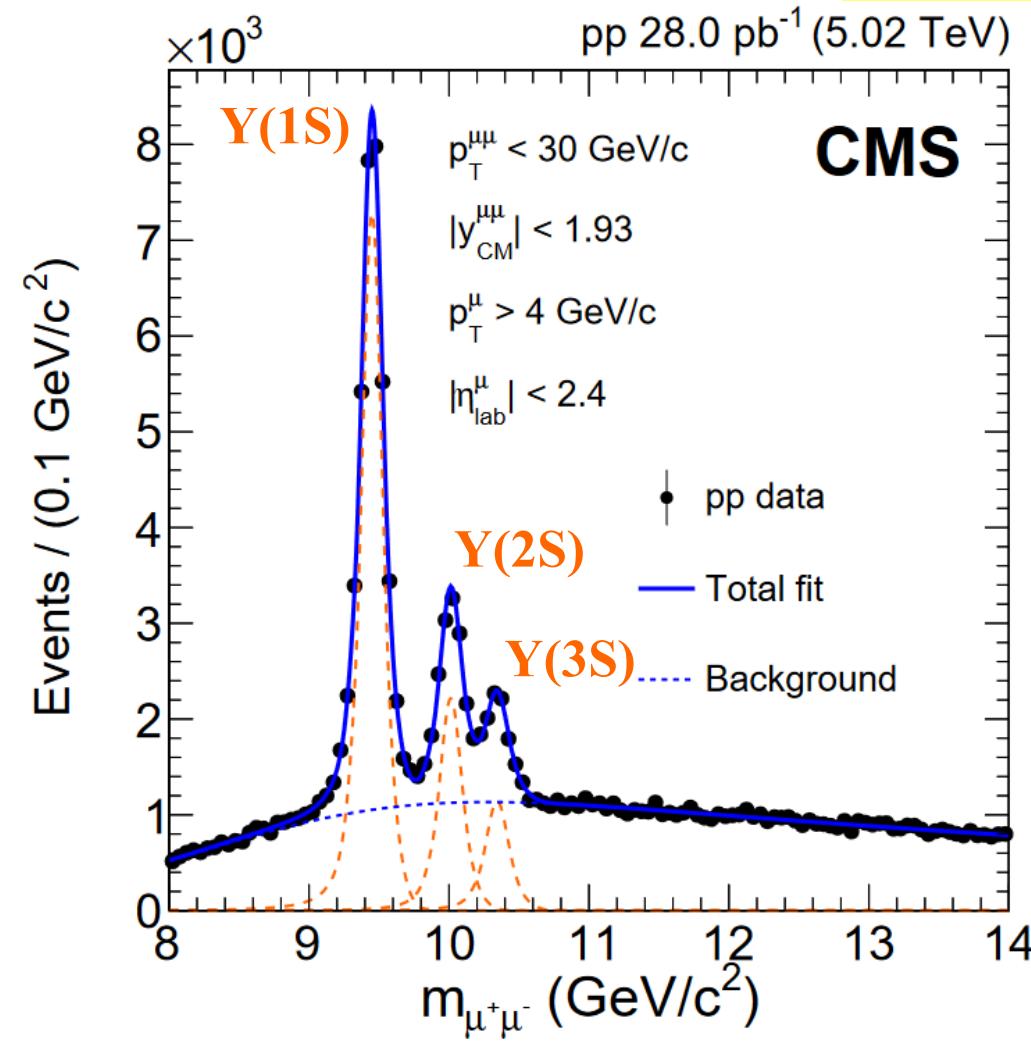




Подавление Y в p+Pb

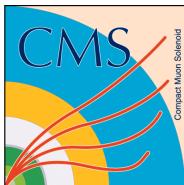


PLB 835 (2022) 137397



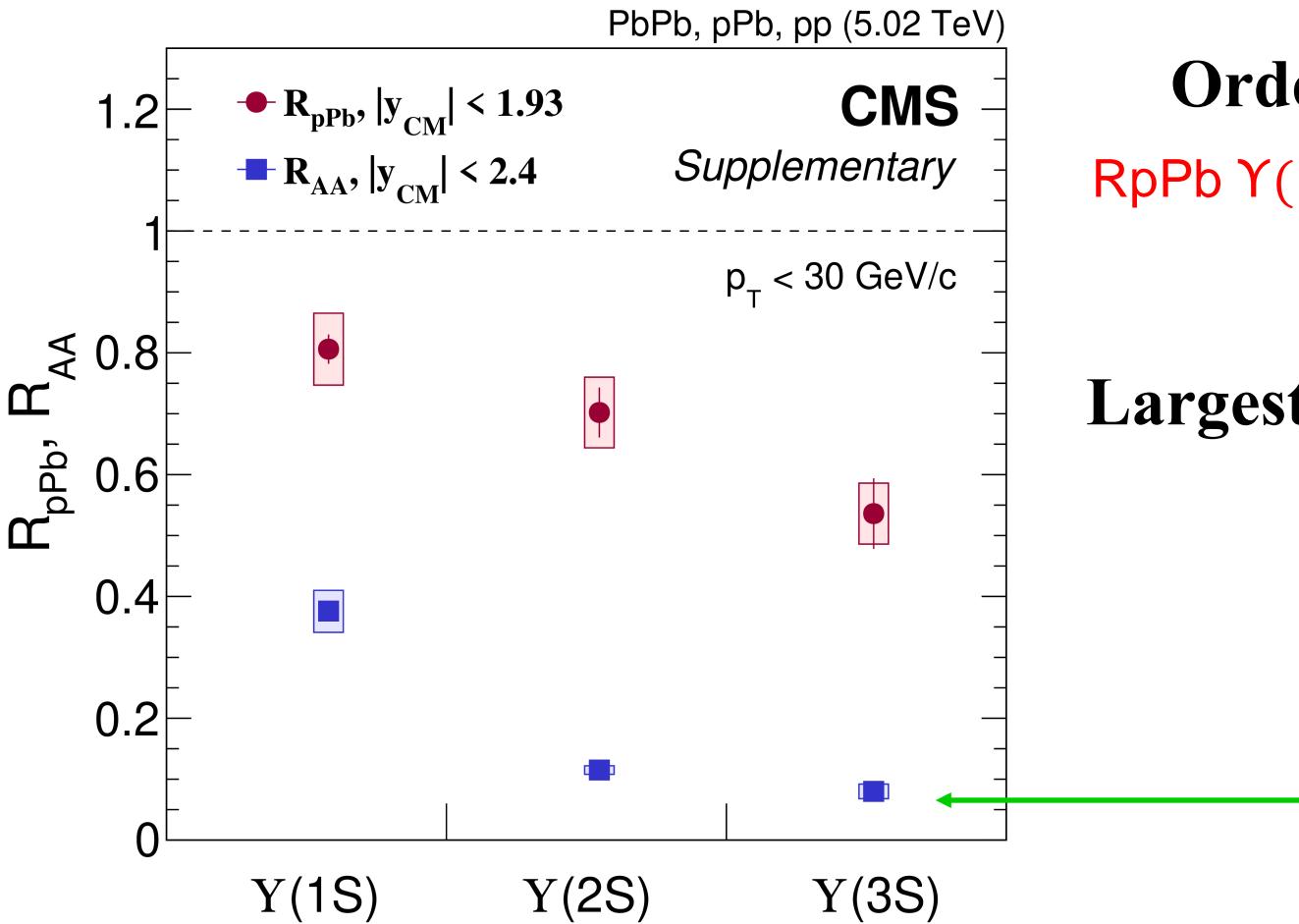
All Y states are found to be suppressed in p+Pb collisions compared to p+p collisions.





Подавление Y в p+Pb и Pb+Pb

arXiv:2303.17026



Ordered in binding energy

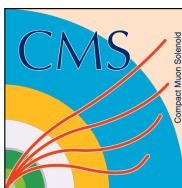
$R_{pPb} \ U(1S) > R_{pPb} \ U(2S) > R_{pPb} \ U(3S)$

Largest suppression is in Pb+Pb

$R_{pPb} > R_{pbPb}$

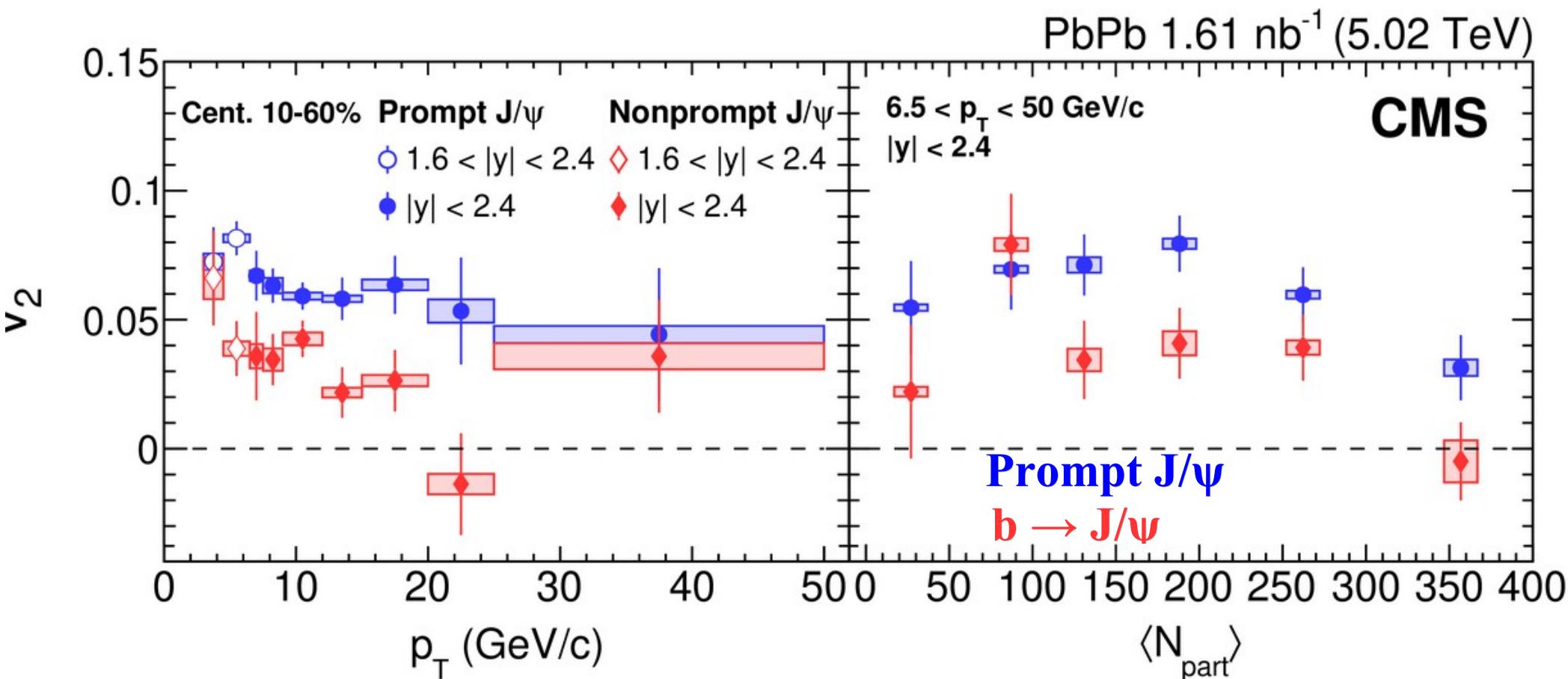
New result for $U(3S)$





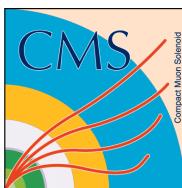
v_2 J/ ψ в Pb+Pb

arXiv:2305.16928



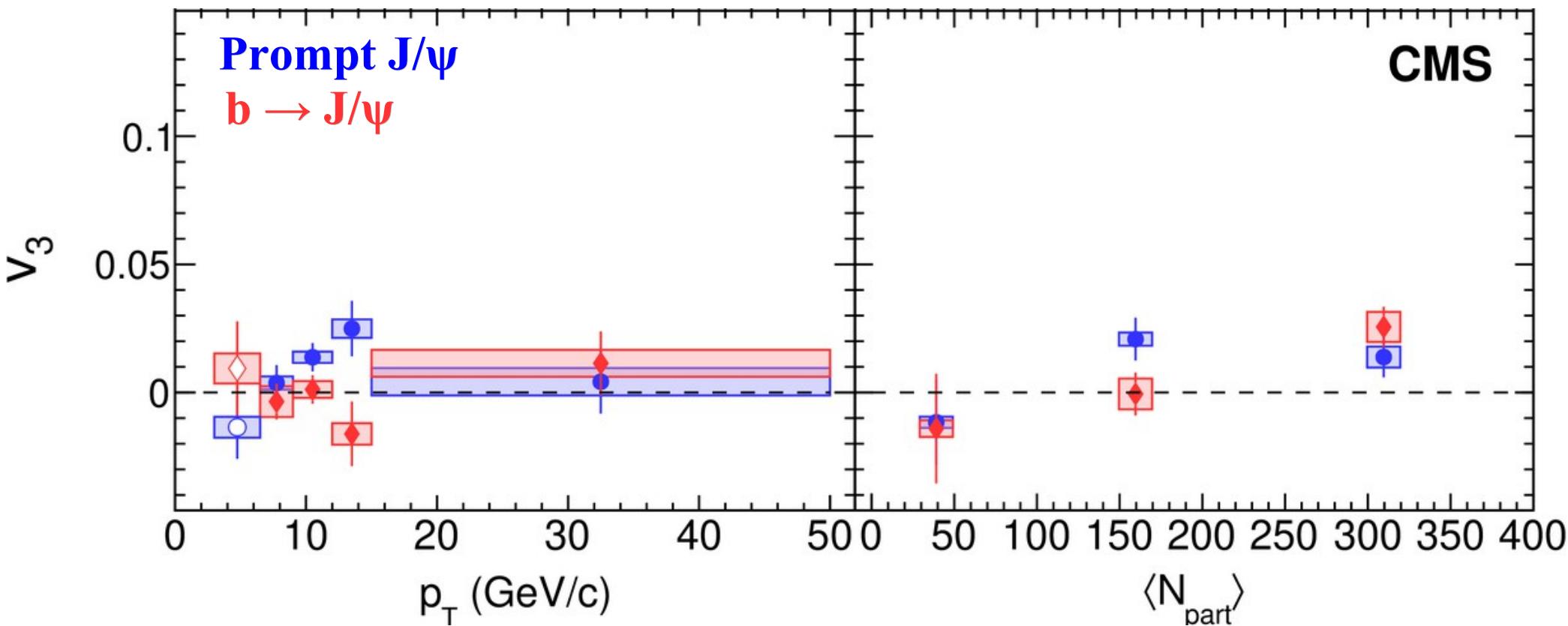
- Large v_2 of J/ ψ up to $p_T = 50 \text{ GeV}/c$
 - $v_2(b \rightarrow J/\psi) < v_2(\text{prompt } J/\psi)$





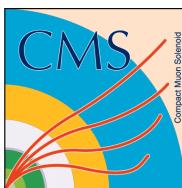
v_3 J/ ψ в Pb+Pb

arXiv:2305.16928



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



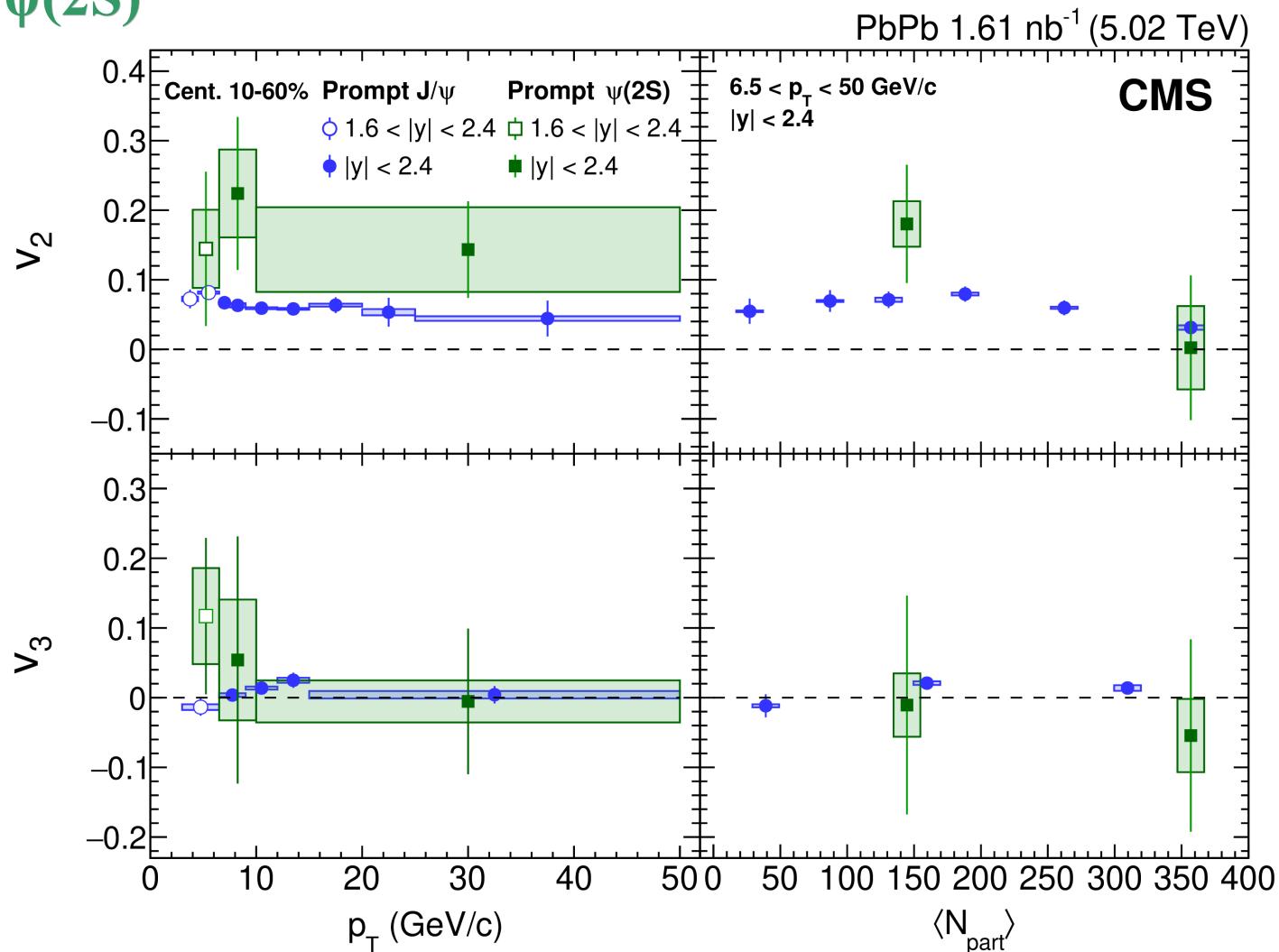


v_2 и $v_3 \psi(2S)$ в Pb+Pb

arXiv:2305.16928



Prompt $\psi(2S)$

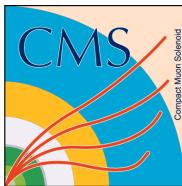


- First measurements for prompt $\psi(2S)$!

- v_2 is non-zero in $p_T = 4 - 50 \text{ GeV}/c$, v_3 is close to zero

Сергей Петрушинко (CMS Collaboration) Физика тяжелых ионов на CMS

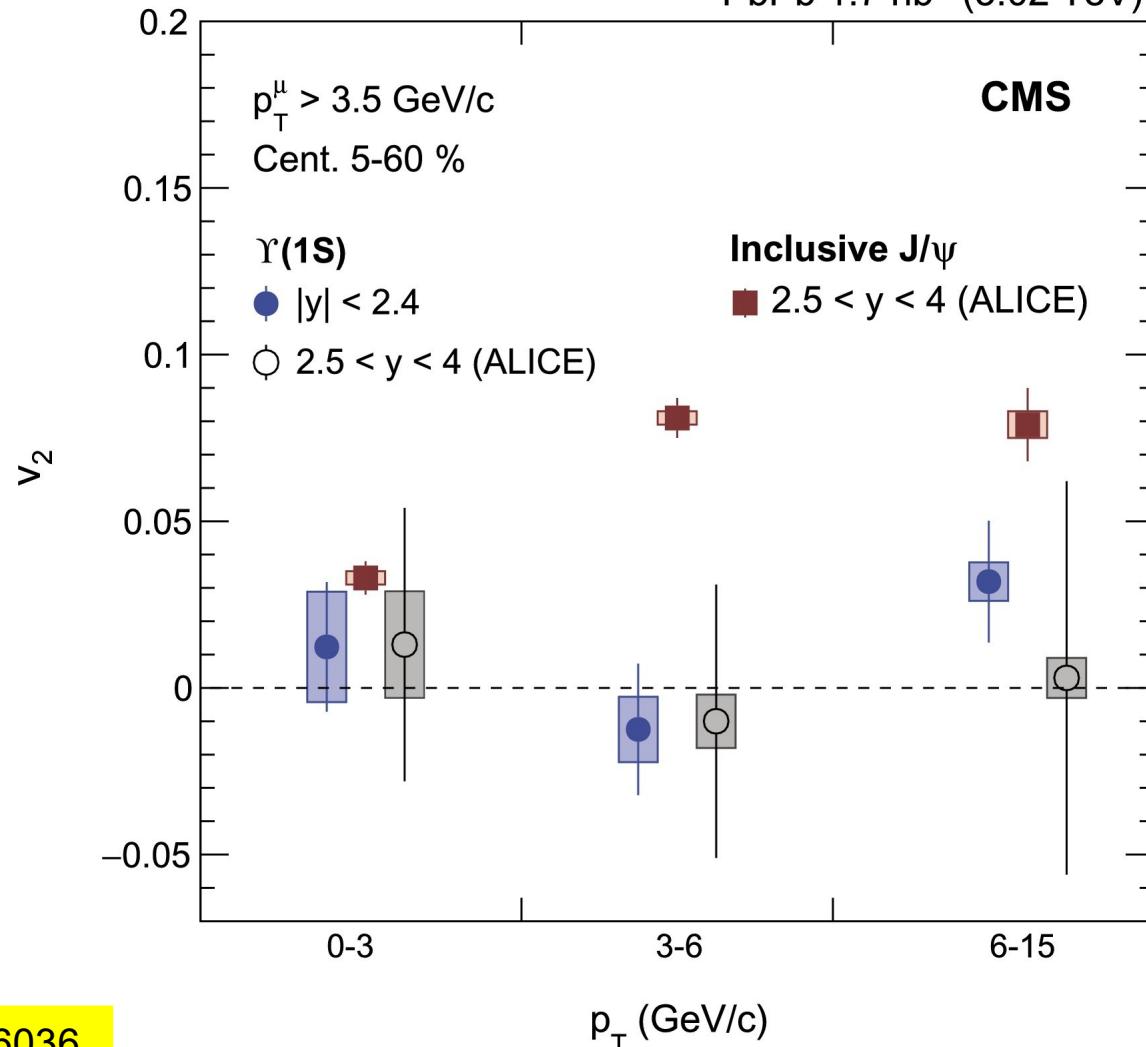




v_2 Y(1S) в Pb+Pb



PbPb 1.7 nb⁻¹ (5.02 TeV)

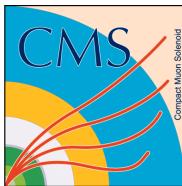


PLB 813 (2021) 136036

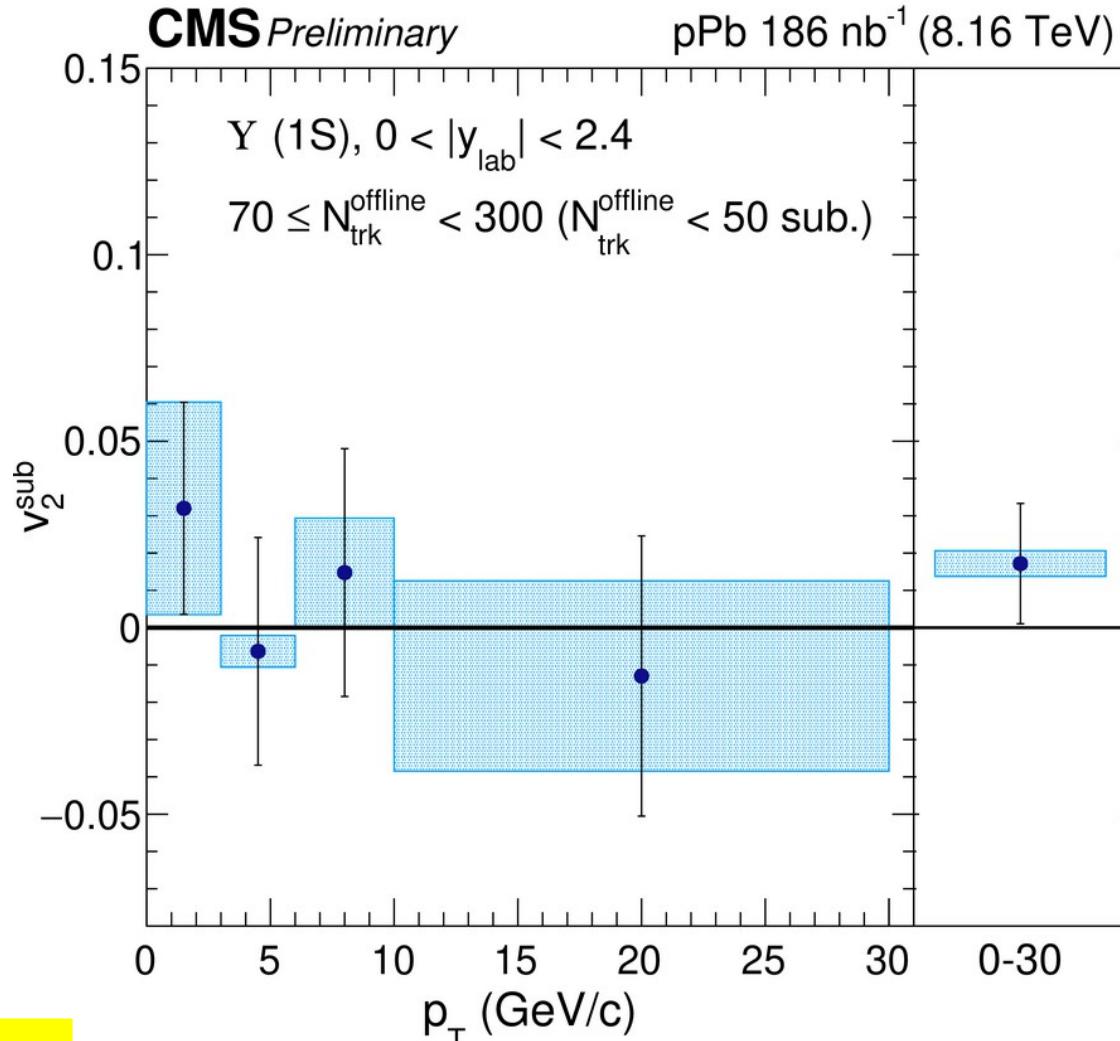
In contrast to the J/ψ mesons,
no azimuthal anisotropy is observed for the $\Upsilon(1\text{S})$ in Pb+Pb...

Сергей Петрушинко (CMS Collaboration) Физика тяжелых ионов на CMS





v_2 Y(1S) в p+Pb

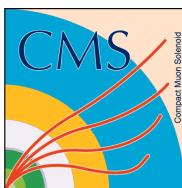


CMS-PAS-HIN-21-001

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

Сергей Петрушинко (CMS Collaboration) Физика тяжелых ионов на CMS





Регистрация струй в Pb+Pb на CMS



CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249

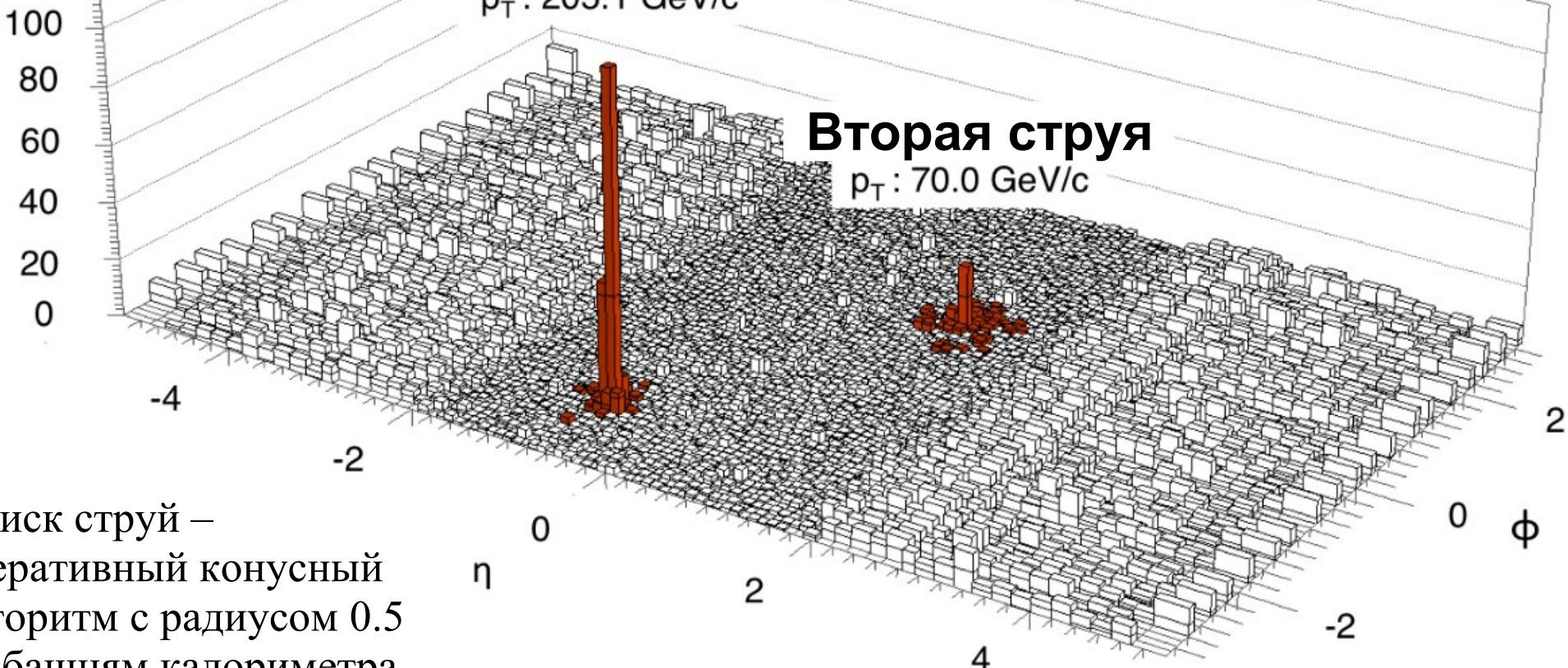
E_T (GeV)

Лидирующая струя

p_T : 205.1 GeV/c

Вторая струя

p_T : 70.0 GeV/c

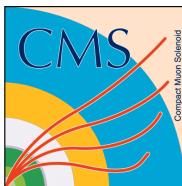


Поиск струй –
итеративный конусный
алгоритм с радиусом 0.5
по башням калориметра,
с учетом фона.

O.Kodolova, I.Vardanian, A.Nikitenko et al.,
Eur.Phys.J. C50, 117 (2007)



Сергей Петрушанко (CMS Collaboration) Физика тяжелых ионов на CMS

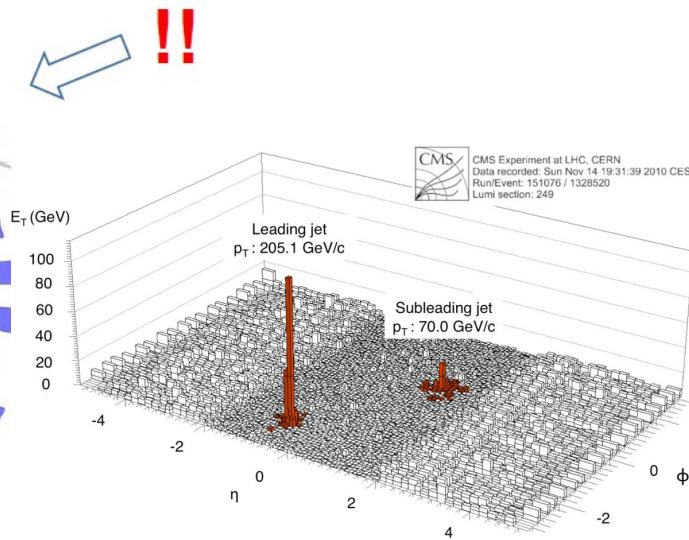
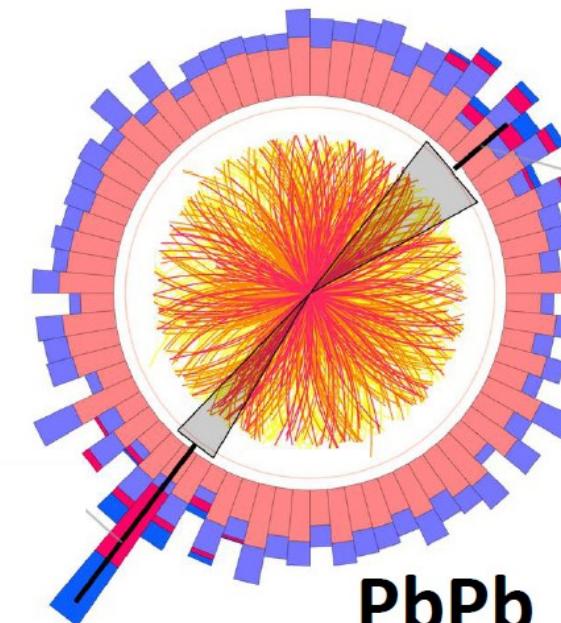
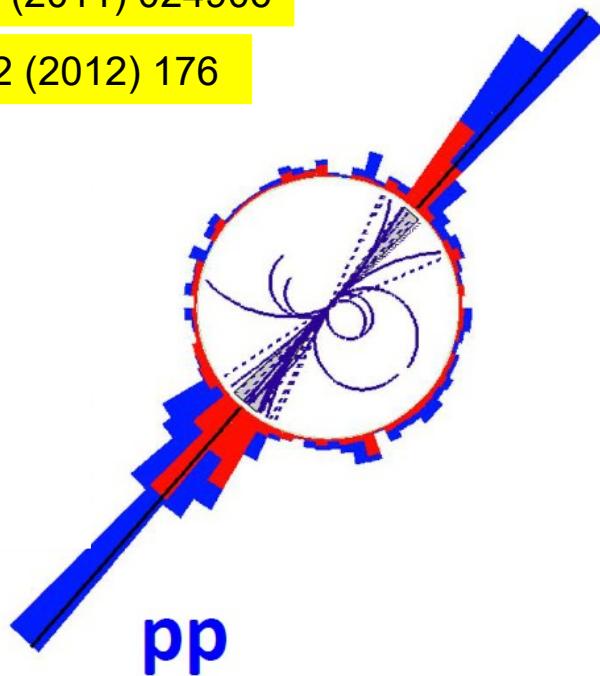


“Jet quenching” (“гашение” струй) в Pb+Pb

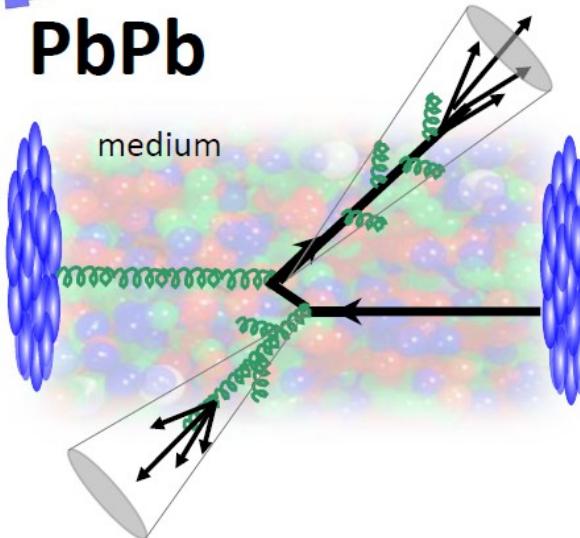


PRC 84 (2011) 024906

PLB 712 (2012) 176

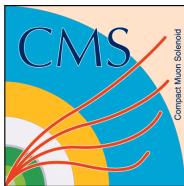


PbPb



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





Отбор событий для наблюдения эффекта “гашения струй”



Отбор двухструйных событий Pb+Pb

$$- |\eta_{\text{jet}}| < 2$$

Лидирующая струя – Leading jet $p_T > 120 \text{ GeV}/c$

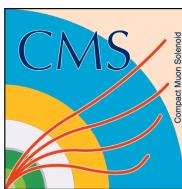
Вторая струя – Subleading jet $p_T > 50 \text{ GeV}/c$

$$- \Delta\phi_{1,2} > 2\pi/3$$

Коэффициент степени анизотропии рождения струй:

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

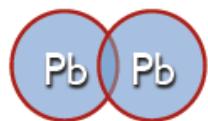




Доля событий, для которых $A_J < 0.15$

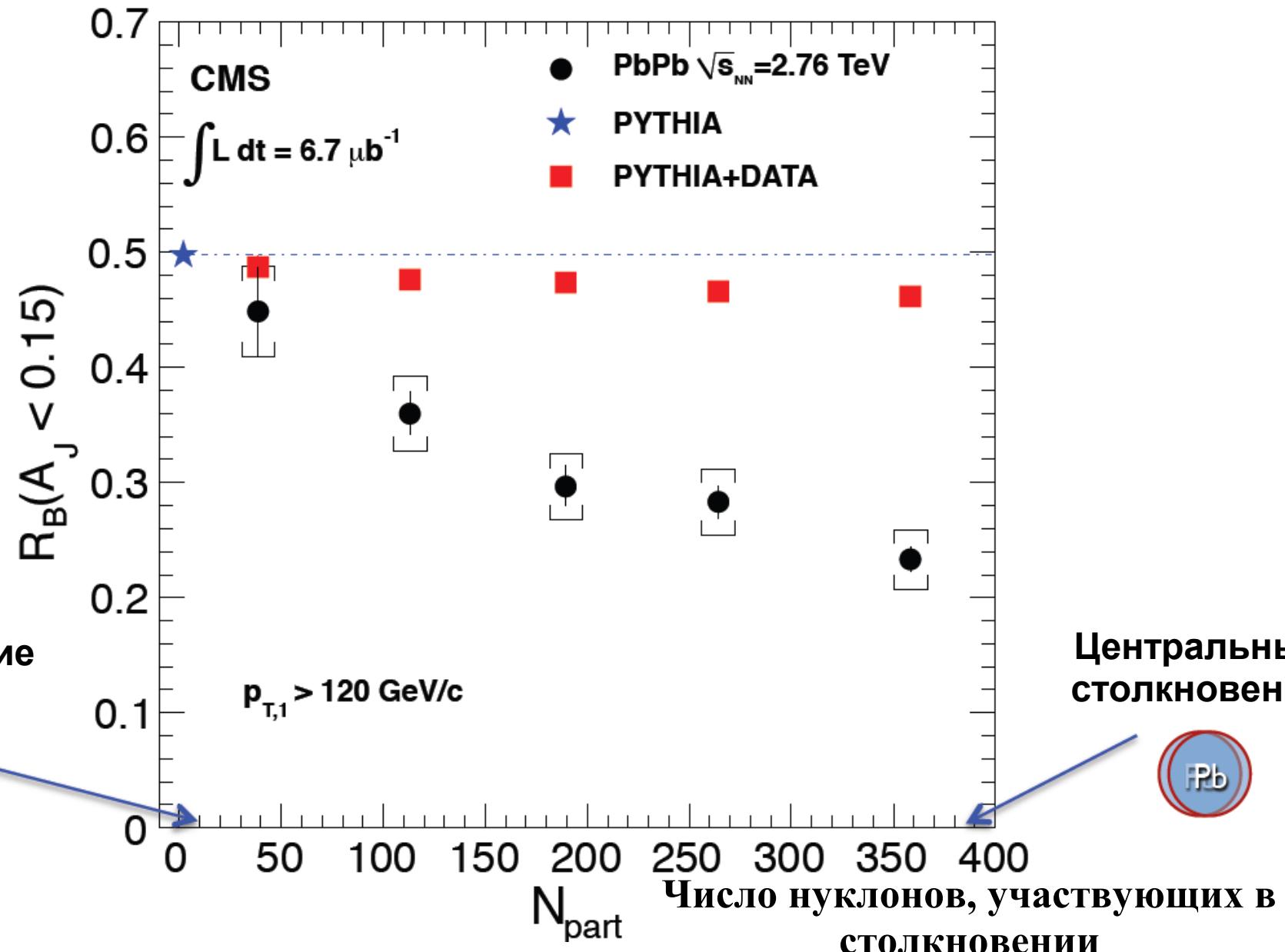


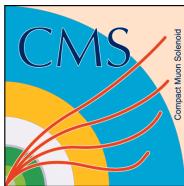
Периферийские
столкновения



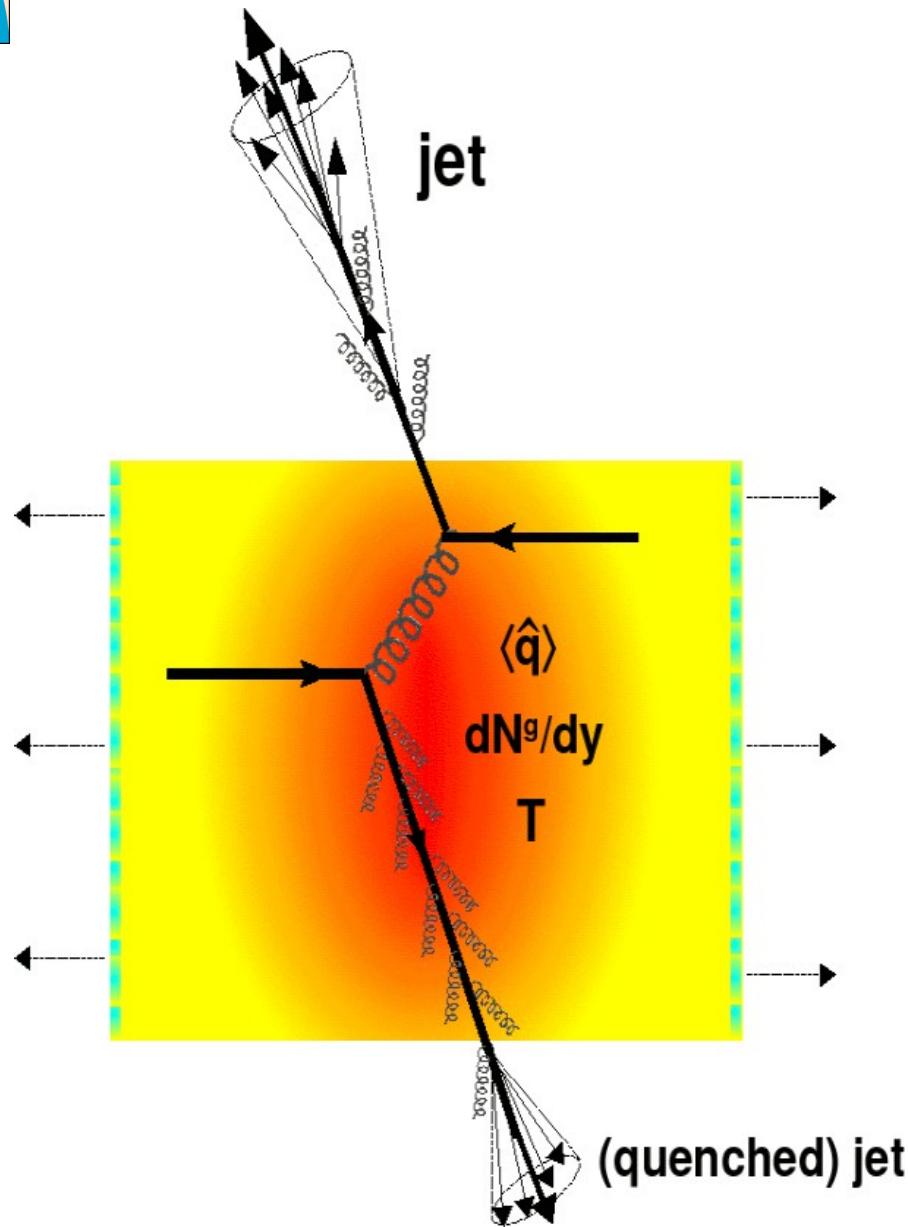
$p_{T,1} > 120 \text{ GeV/c}$

Центральные
столкновения



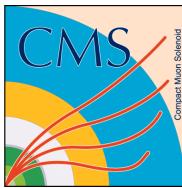


Эффект “гашения” струй



Одно из возможных объяснений эффекта “гашения” струй при энергии LHC –
энергетические потери
партонов в плотном
веществе КГП

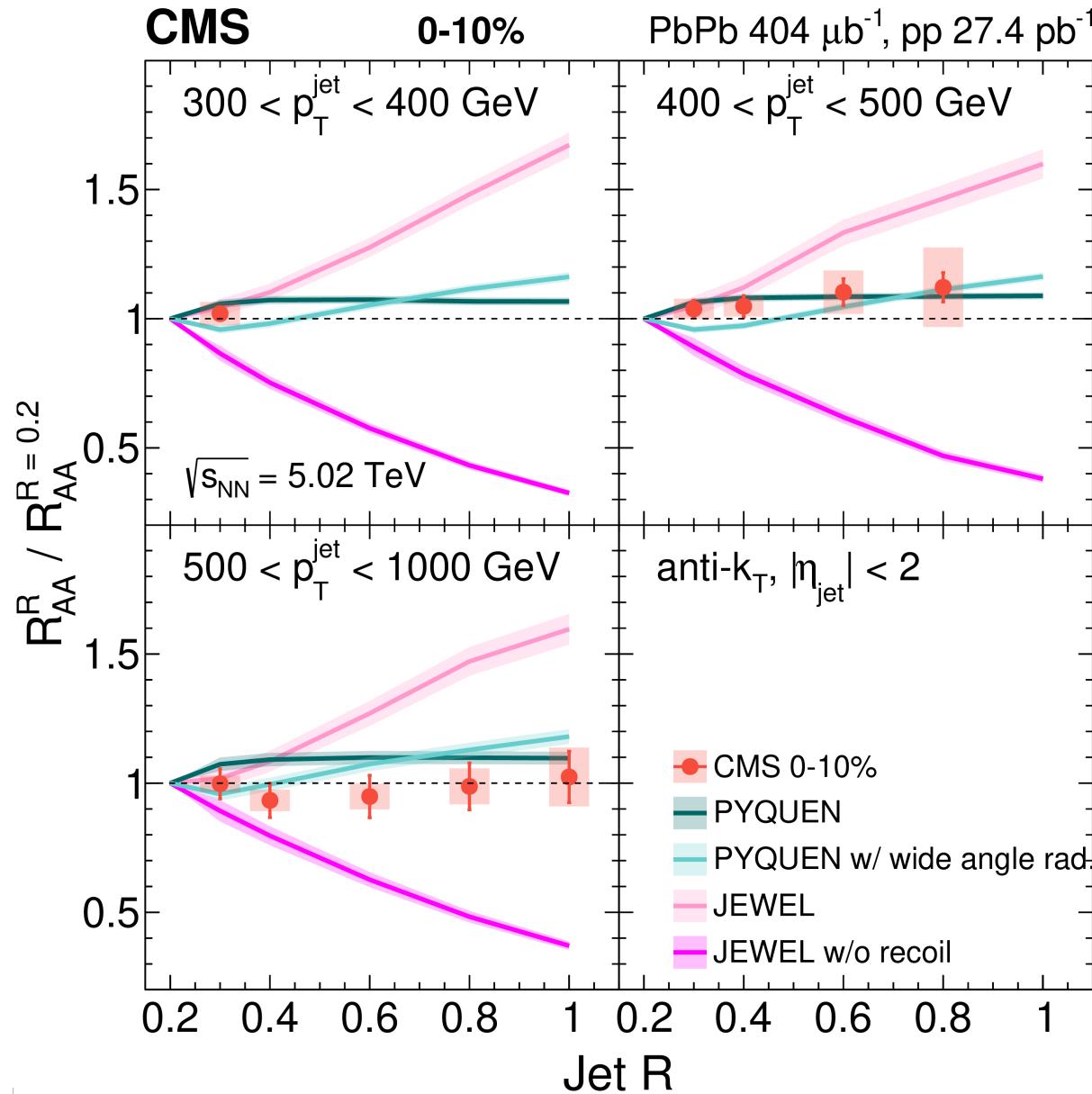




Сканирование по ширине струй

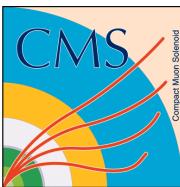


JHEP 05 (2021) 284



- 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 $400 \text{ GeV}/c < p_T \text{ jet} < 500 \text{ GeV}/c$ (Also for $400 < p_T \text{ jet} < 500 \text{ GeV}/c$)

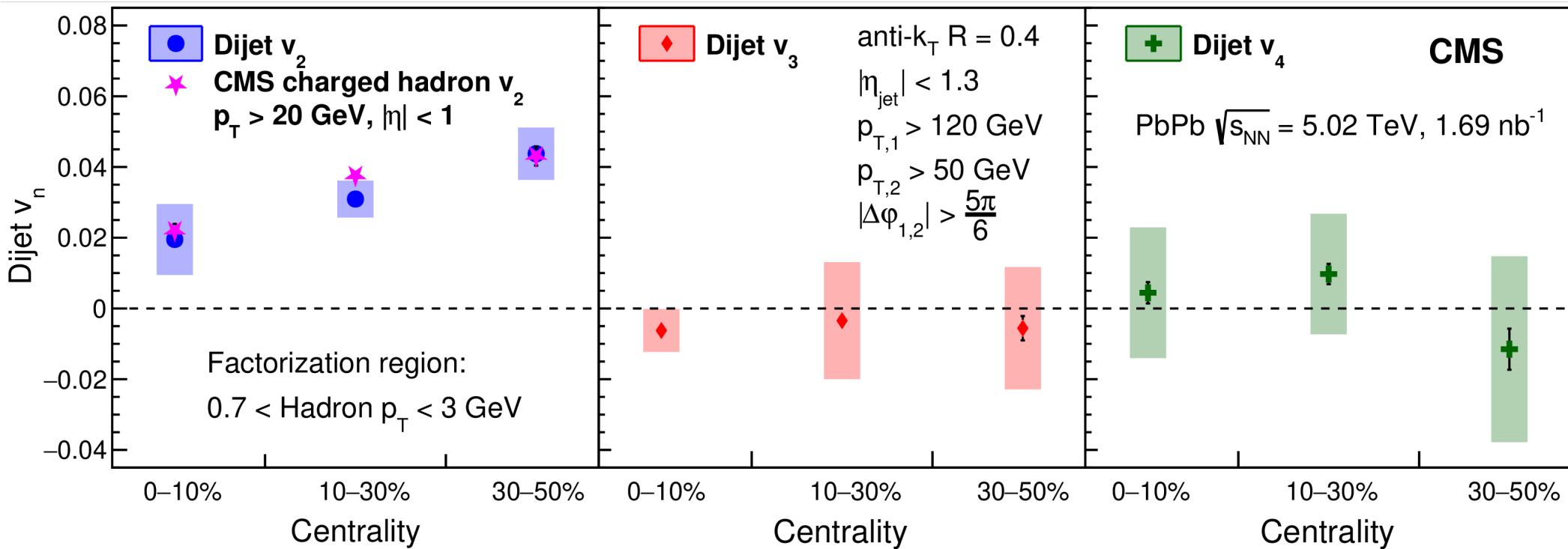




Азимутальная анизотропия двойных струй в Pb+Pb

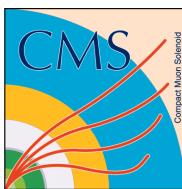


JHEP 07 (2023) 139



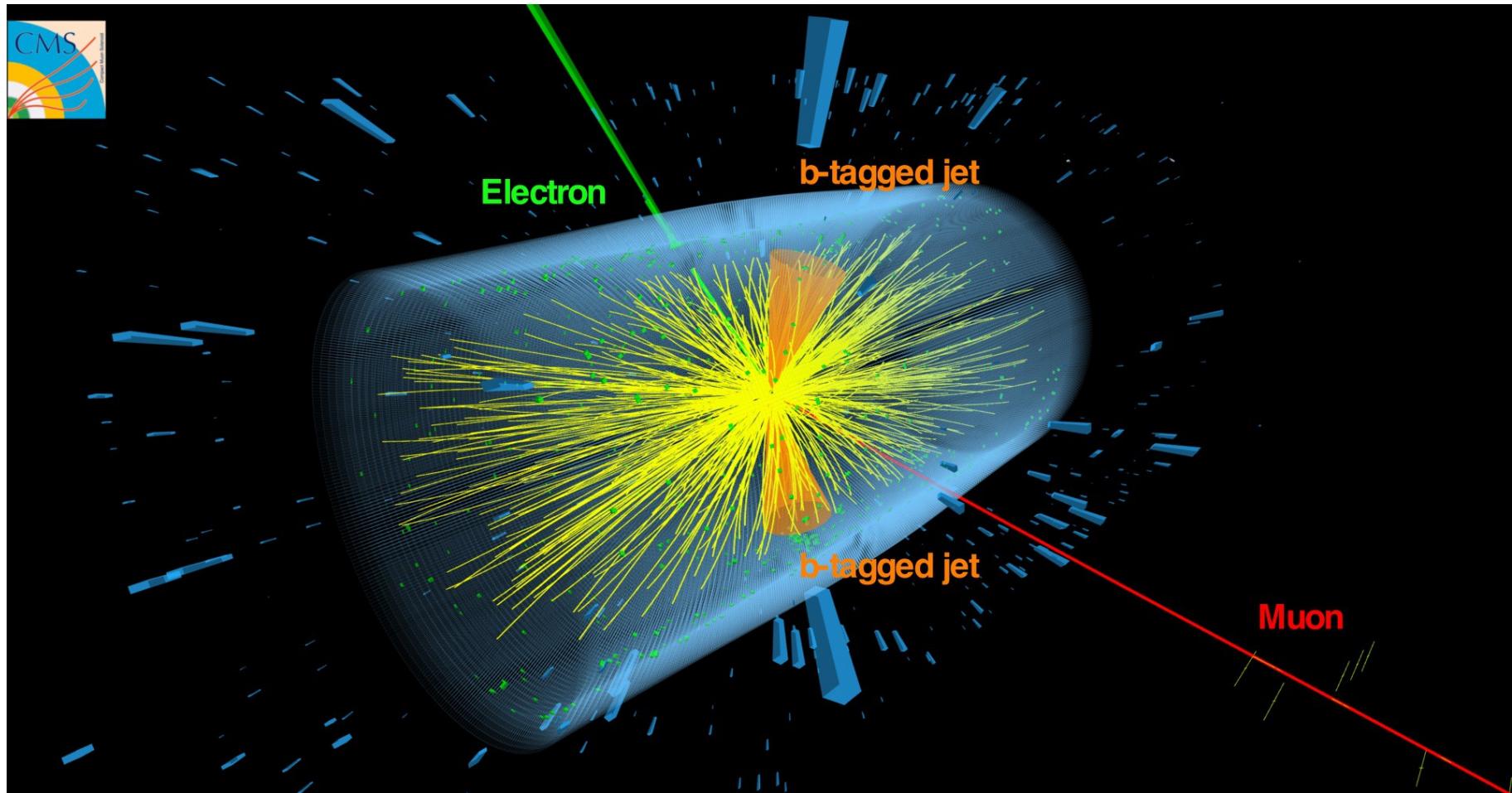
- v_2 , v_3 and v_4 of the di-jets in Pb+Pb were measured for the first time
 - Di-jets v_2 is compatible with v_2 of high p_T hadrons
 - Di-jets v_3 and v_4 are consistent with zero





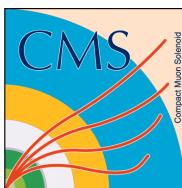
Первое наблюдение топ кварка в Pb+Pb

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.

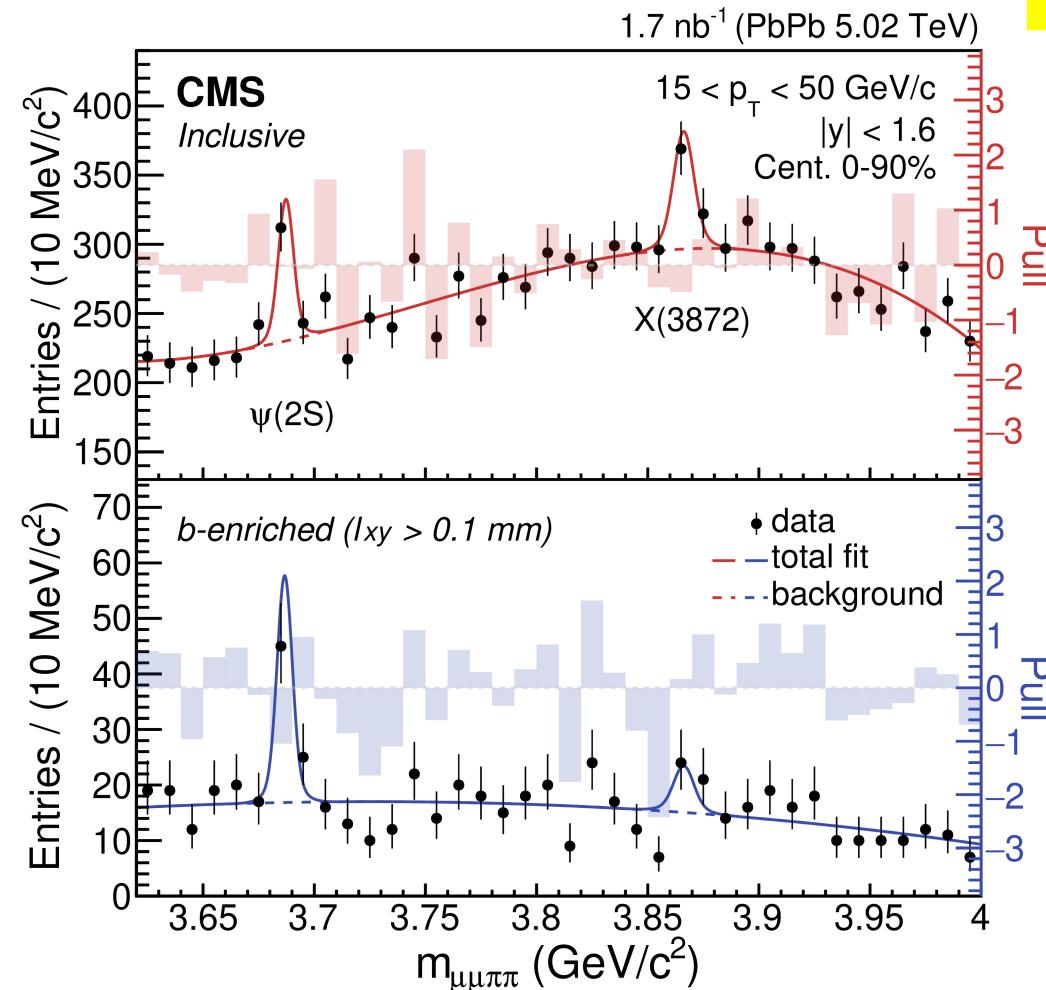




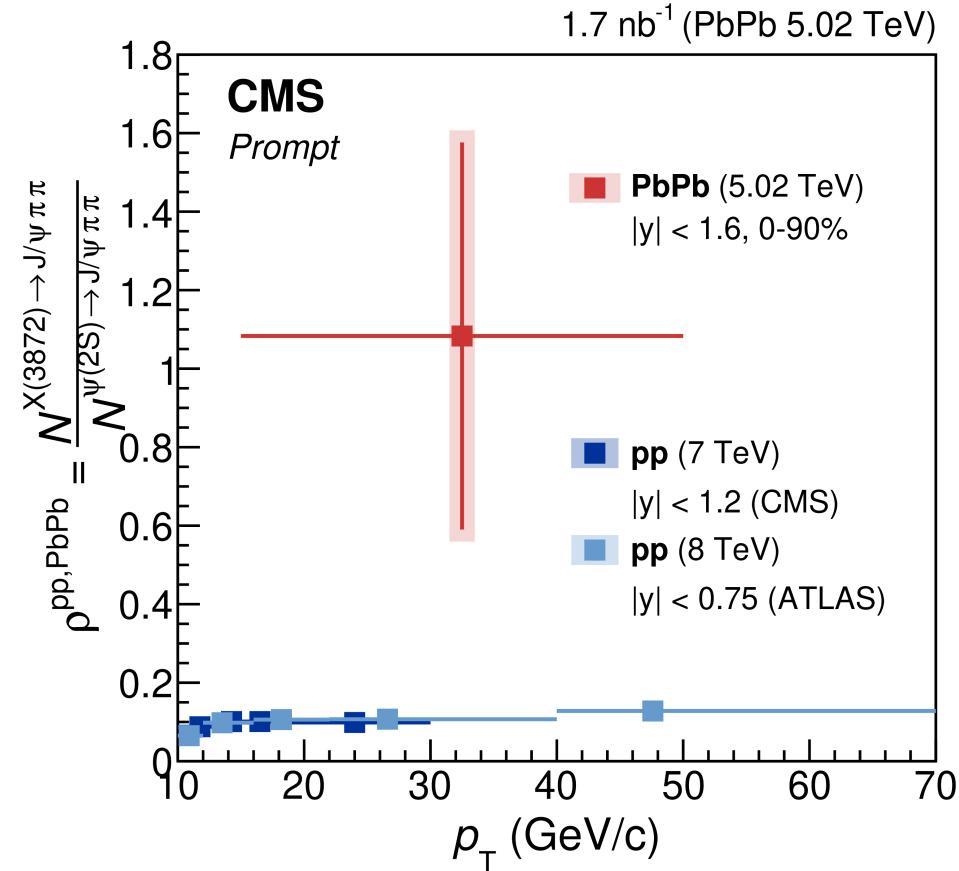
Рождение X(3872) в Pb+Pb



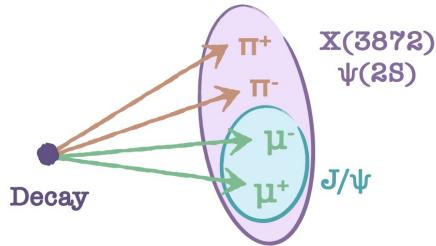
PRL 128 (2022) 032001

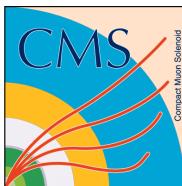


Comparison to $\psi(2S)$



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

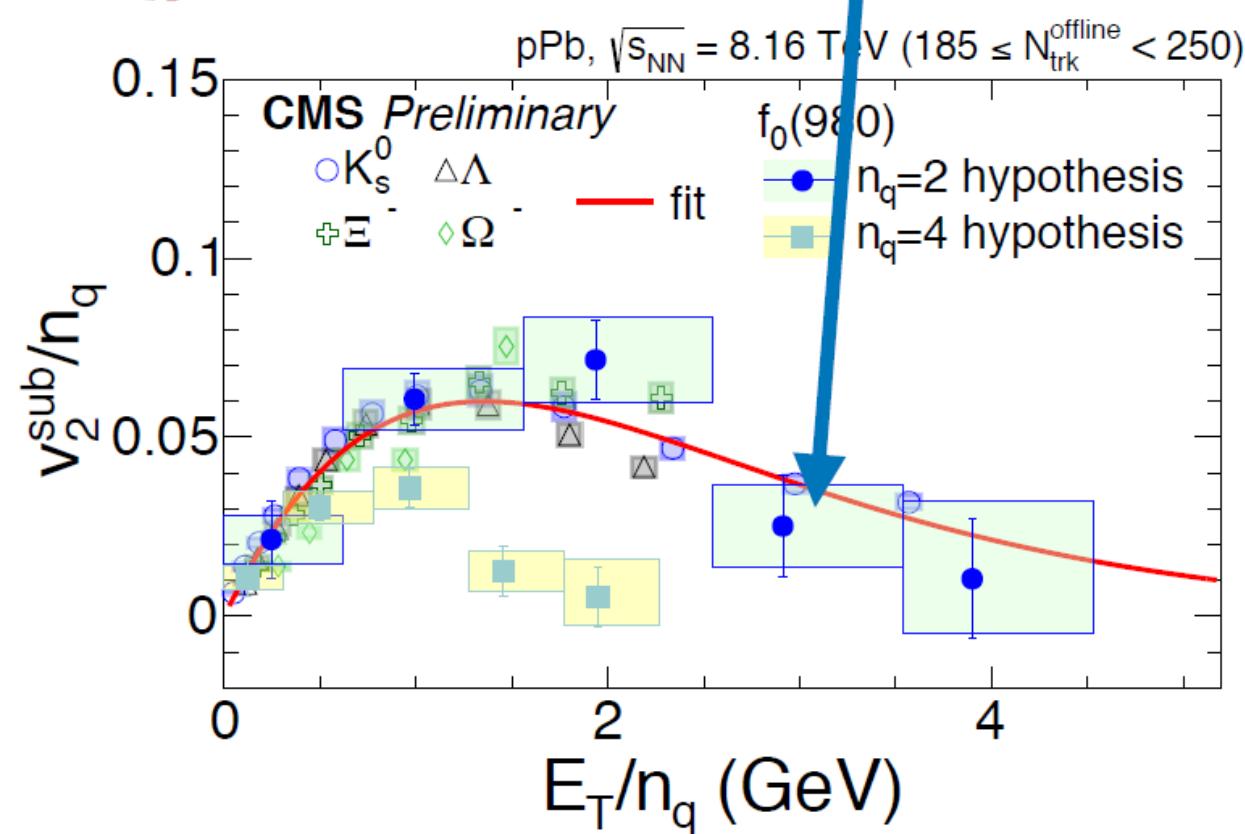
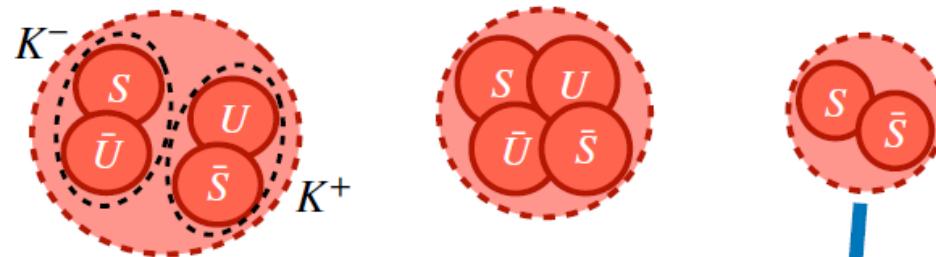
CMS PAS HIN-20-002

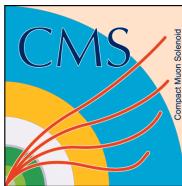


v_2 of $f_0(980)$ measured in $p+Pb$

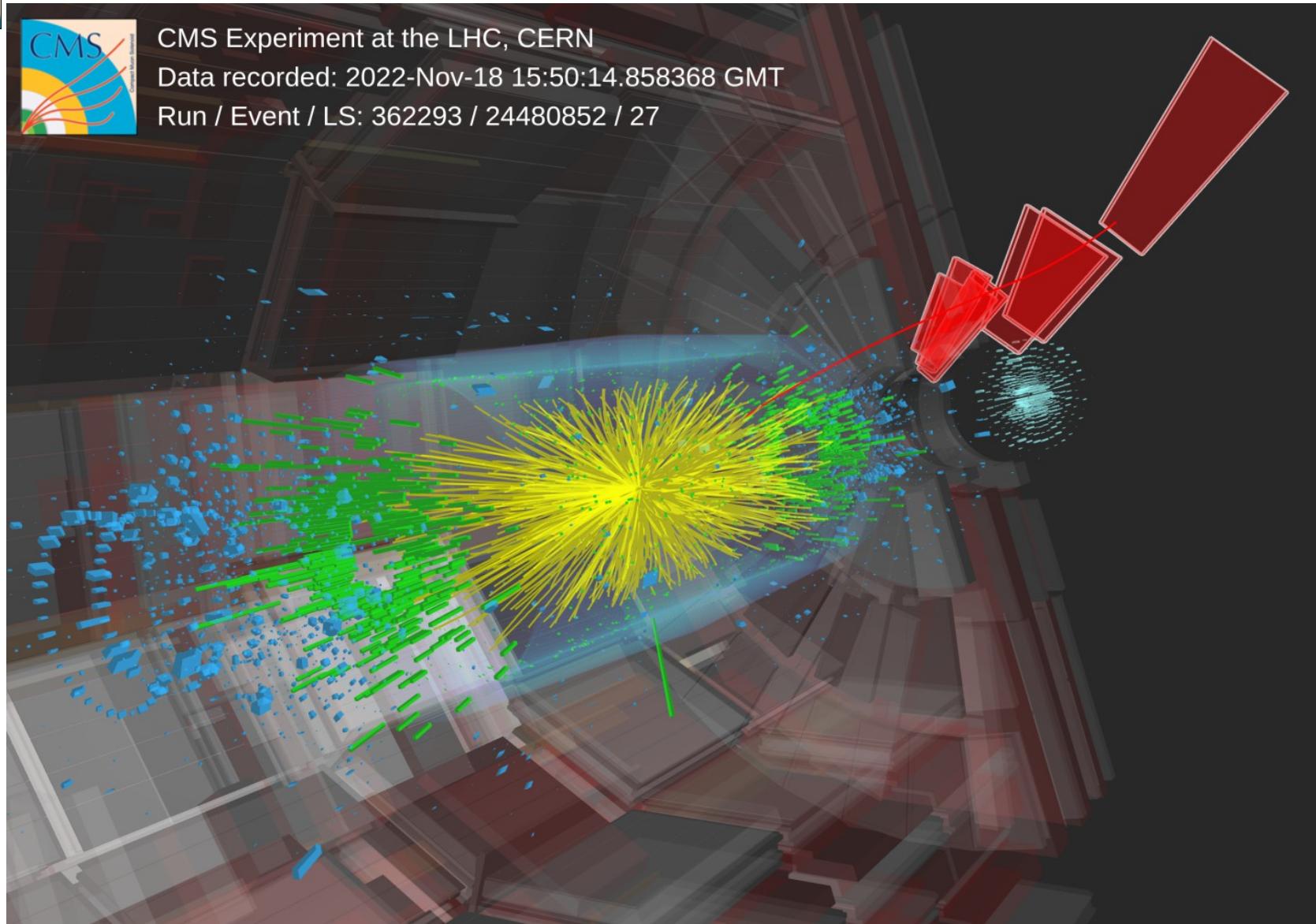
Inner structure unknown:

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





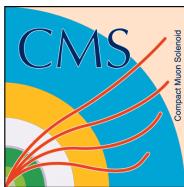
Run 3 начался в июле 2022 года



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



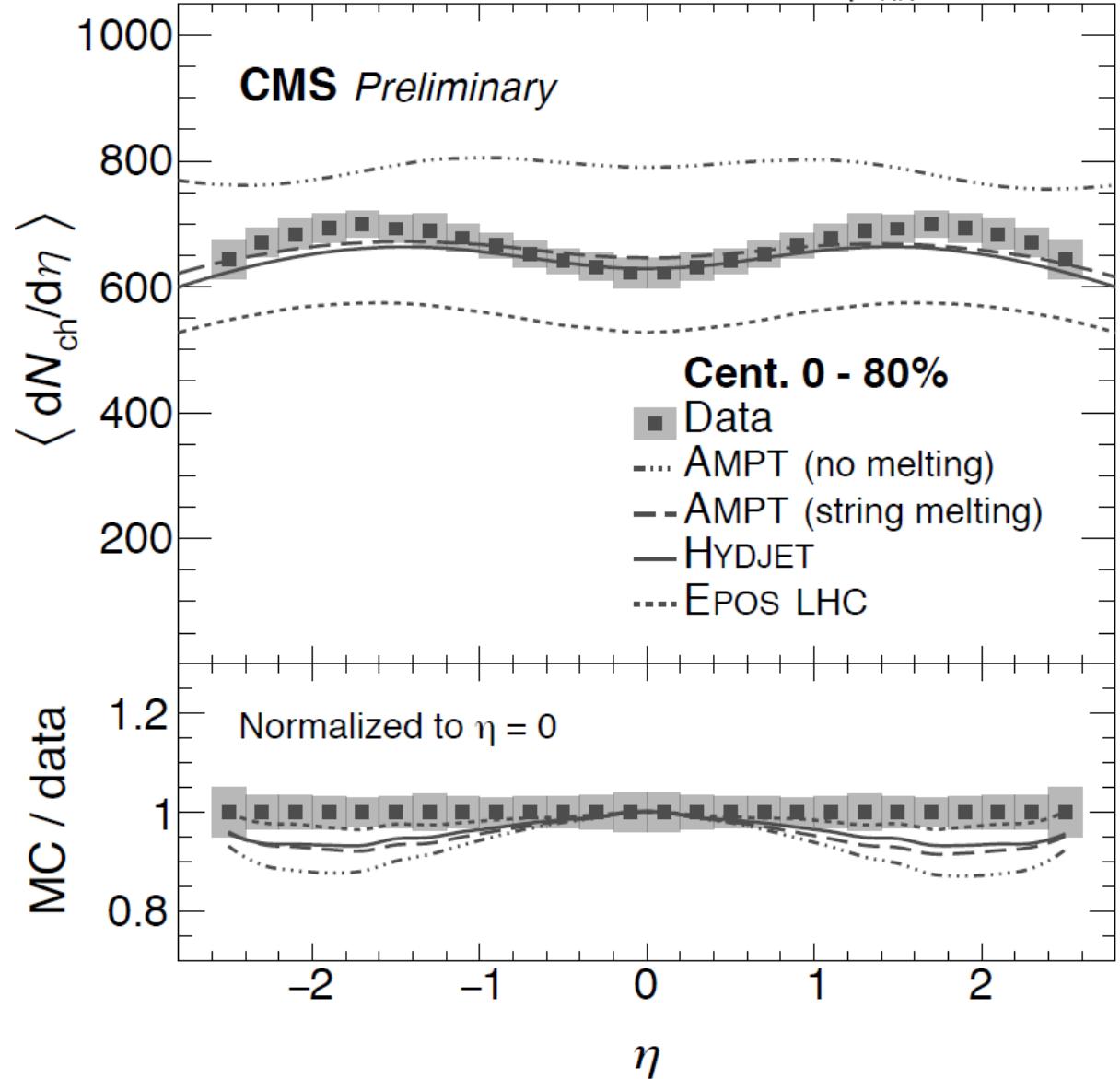
CMS Run 3 – $dN_{ch}/d\eta$

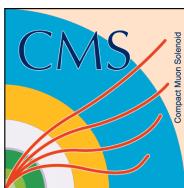
CMS PAS HIN-23-007

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

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

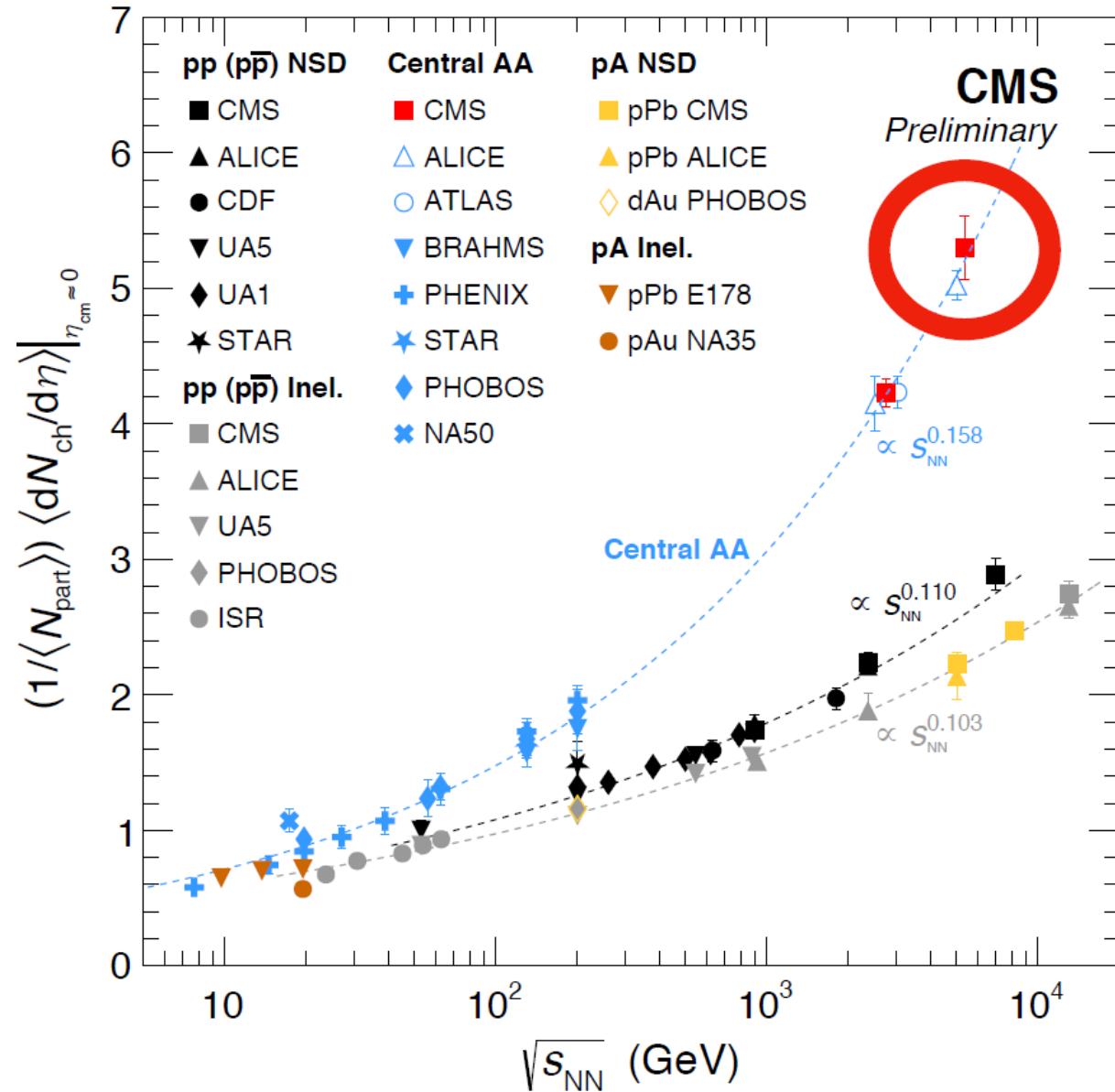
CMS Run 3 – $dN_{ch}/d\eta$

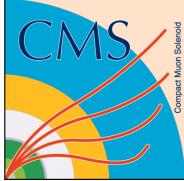


CMS PAS HIN-23-007

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!





Жизнь – это то, что случается с нами, пока мы строим планы на будущее. (Джон Леннон)

