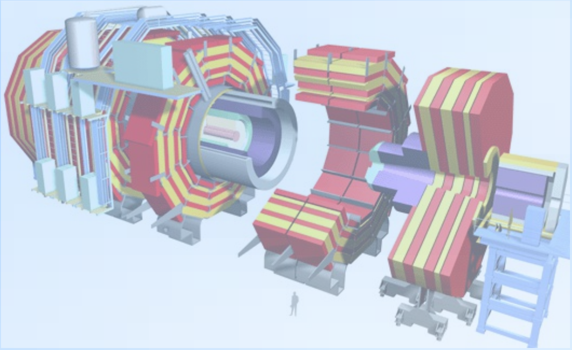
Сергей Петрушанко
(for the CMS Collaboration)

НИИЯФ МГУ

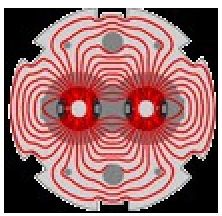
Heavy-ion Physics Results by the CMS Experiment

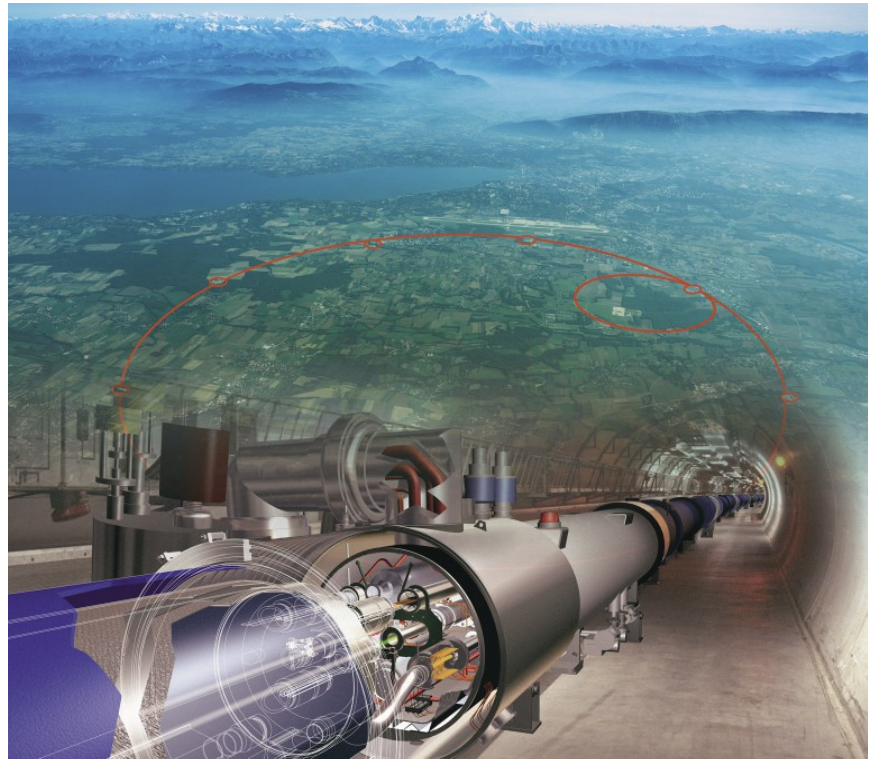
Результаты по физике тяжелых ионов в эксперименте CMS

LXXIV International Conference
"Nucleus-2024: Fundamental Problems and Applications"
JINR, Dubna, Russia
1 – 5 July 2024

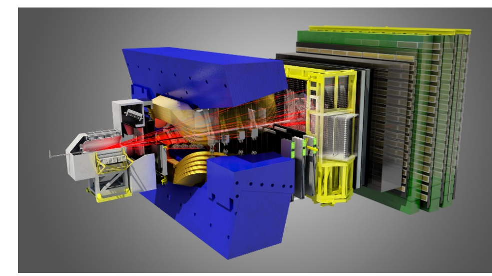


Физика тяжелых ионов на LHC





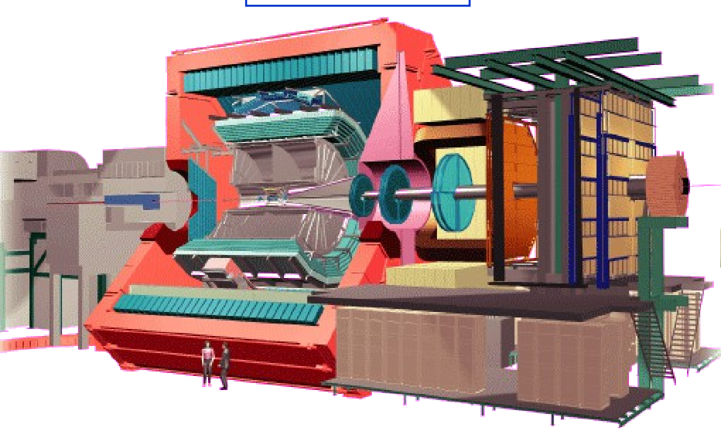
LHCb

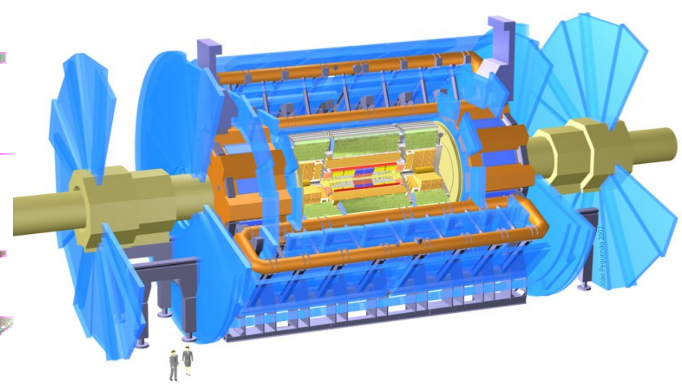


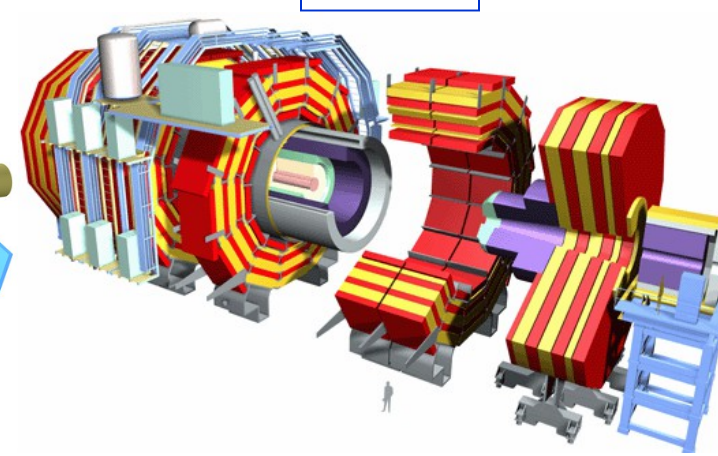
ALICE

ATLAS

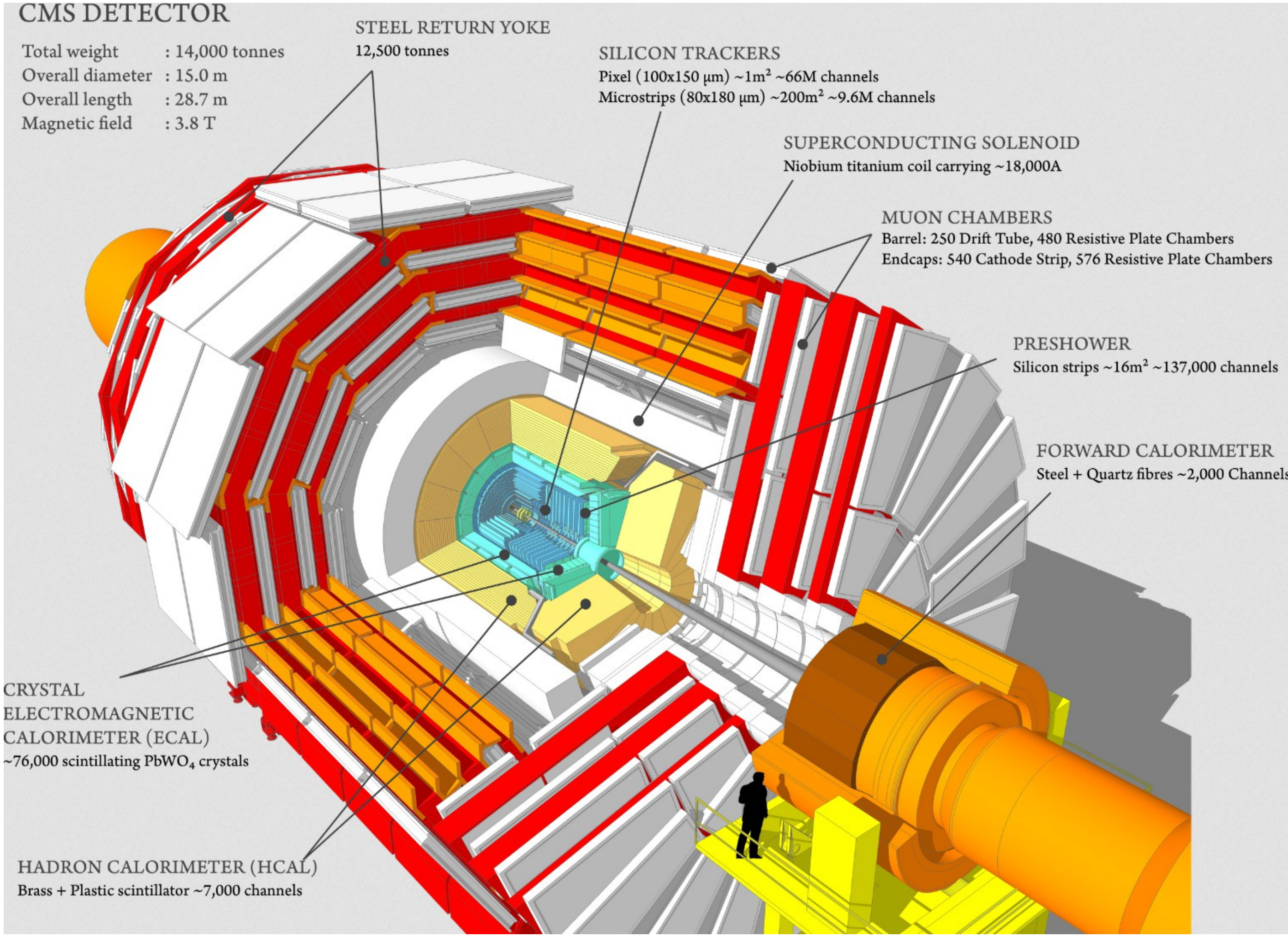
CMS







Компактный Мюонный Соленоид (CMS)



- **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

Магнитное поле: 3.8 Тесла

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

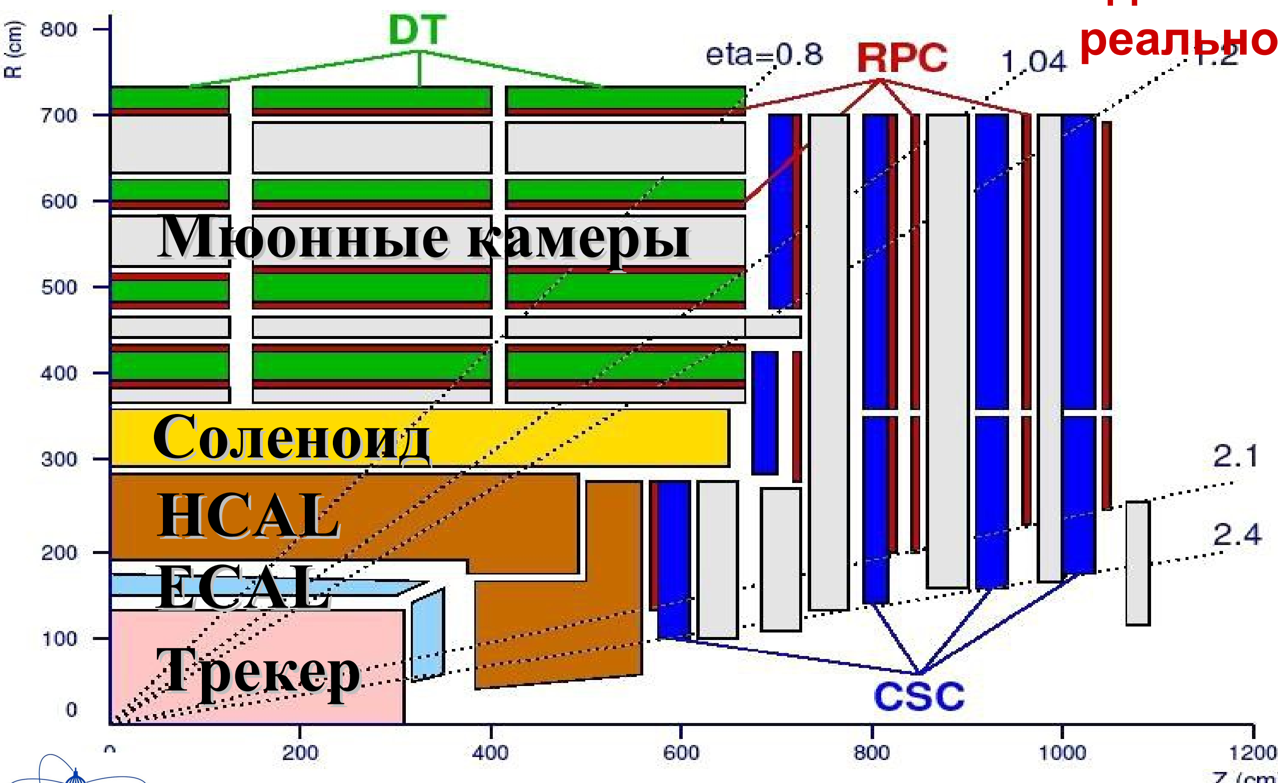
- широкое покрытие до $|\eta| < 2.4$
- высокое разрешение масс димюонов

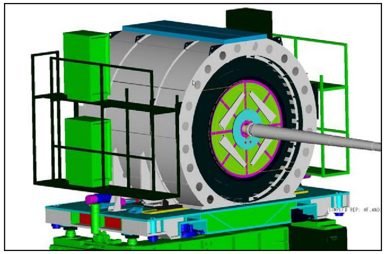
Кремниевый детектор

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

Триггер и DAQ

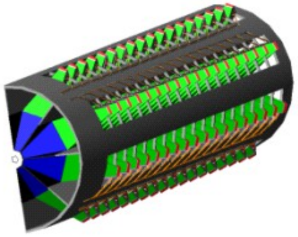
- Широкие возможности: AA и pp
- для тяжелых ионов: реконструкция в реальном времени для HLT





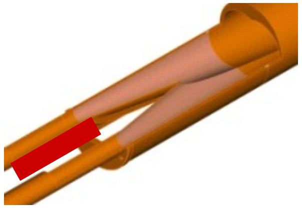
HF

$3 < |\eta| < 5.2$



CASTOR

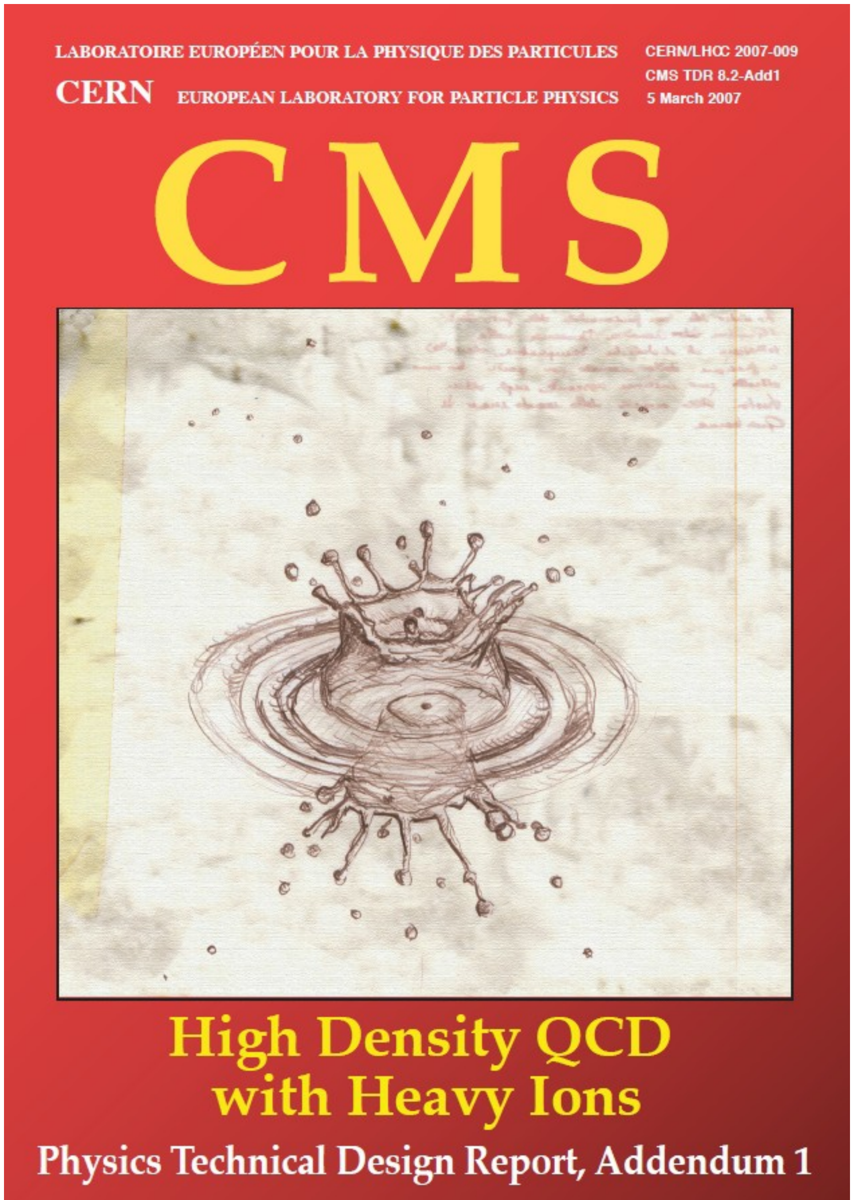
$-5.2 < \eta < -6.6$



ZDC

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

Подготовка программы CMS по изучению физики тяжелых ионов



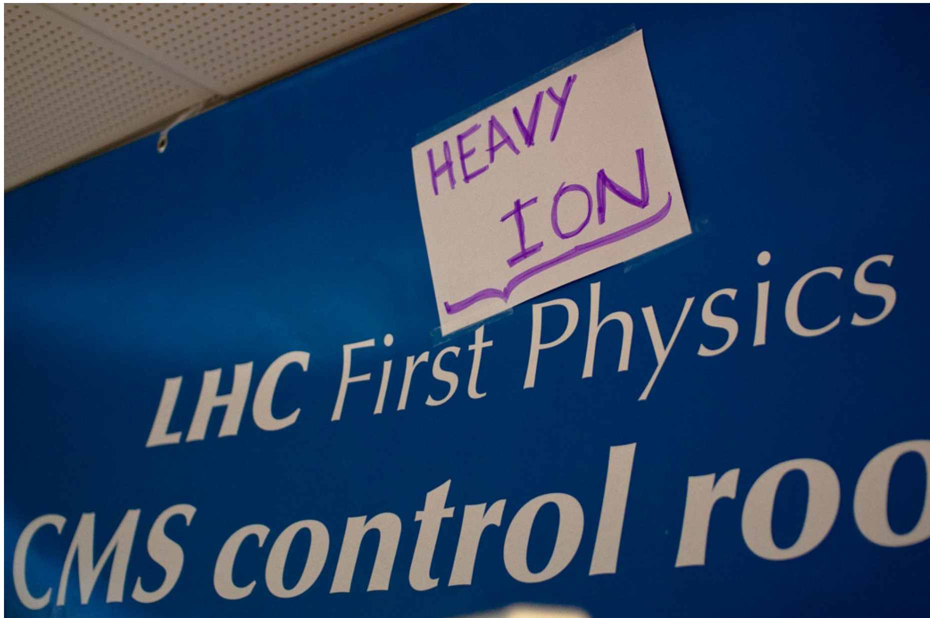
The CMS Collaboration

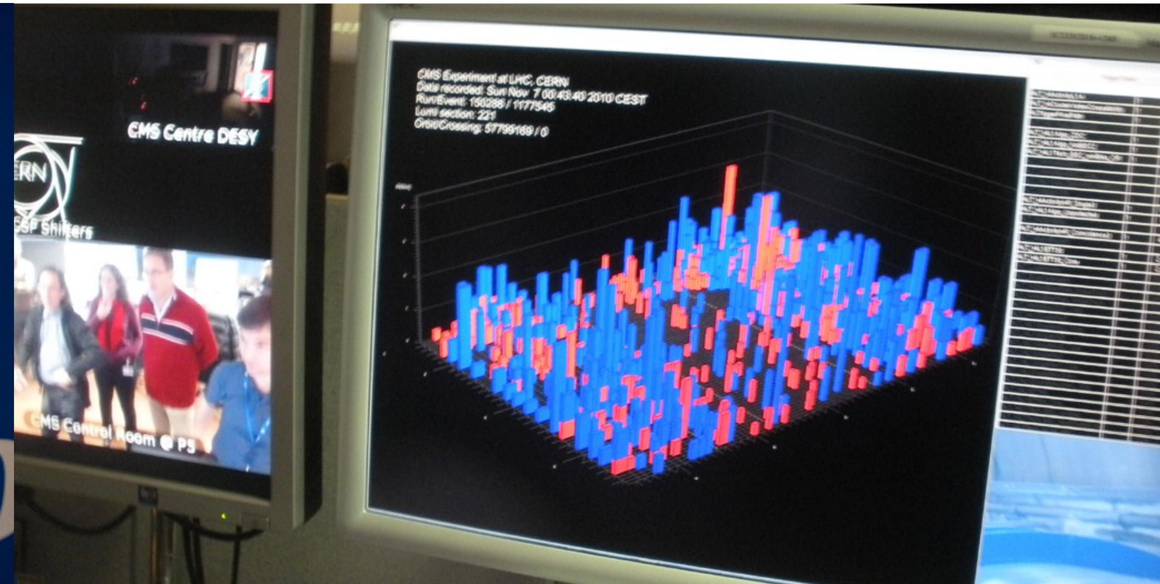
D. d'Enterria, M. Ballintijn, M. Bedjidian, D. Hofman, O. Kodolova, C. Loizides, I. P. Lokthin, C. Lourenco, C. Mironov, S. V. Petrushanko, C. Roland, G. Roland, F. Sikler and G. Veres *(editors)*

"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:

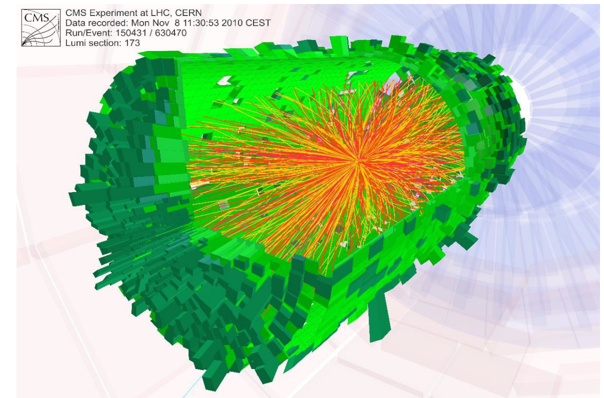
http://cms-results.web.cern.ch/cms-results/public-results/publications/HIN/index.html

…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

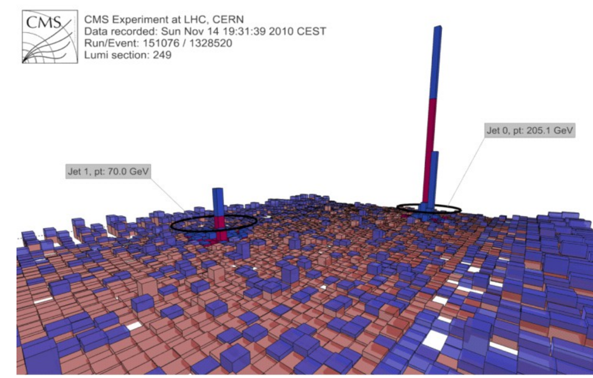
- **Global picture of heavy-ion collisions**
  - multiplicity
  - energy
  - flow, “ridge”, correlations, ...



Pb+Pb collisions

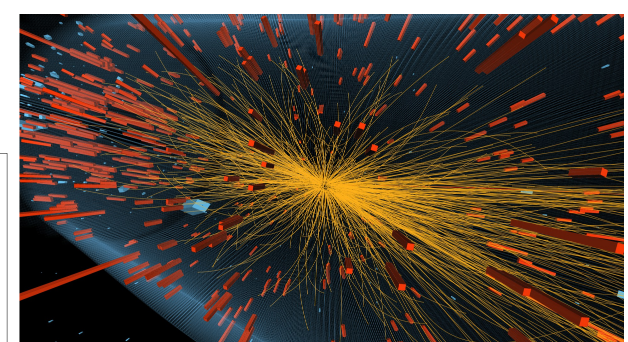
2010-11:	2.76 TeV	0.16/nb
2015-18:	5.02 TeV	1.7/nb
2023-... :	5.36 TeV	...

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



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

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

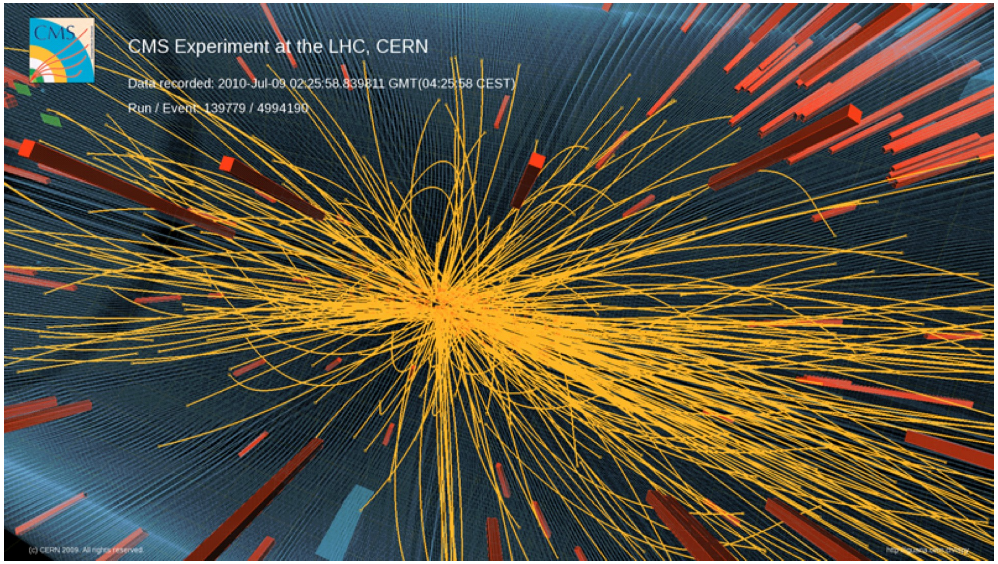


“Риджˮ-эффект в столкновениях протон-протон в эксперименте CMS

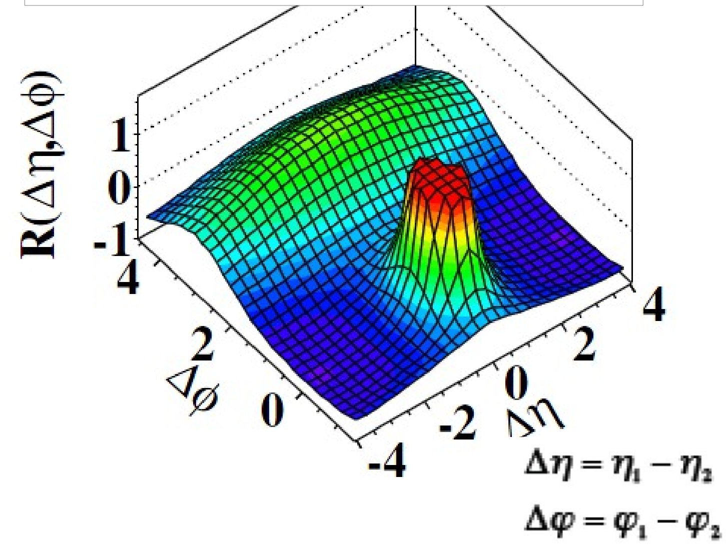
- Протон-протонные столкновения **√s = 7 ТэВ** с высокой множественностью **N > 110**.
- Корреляционная функция для треков с поперечным импульсом в диапазоне **от 1 до 3 ГэВ/*c***:

$$\begin{cases} S_N(\Delta\eta,\Delta\varphi) = \dfrac{1}{N(N-1)} \dfrac{d^2N^{signal}}{d\Delta\eta d\Delta\varphi} \\ B_N(\Delta\eta,\Delta\varphi) = \dfrac{1}{N^2} \dfrac{d^2N^{bkg}}{d\Delta\eta d\Delta\varphi} \end{cases}$$

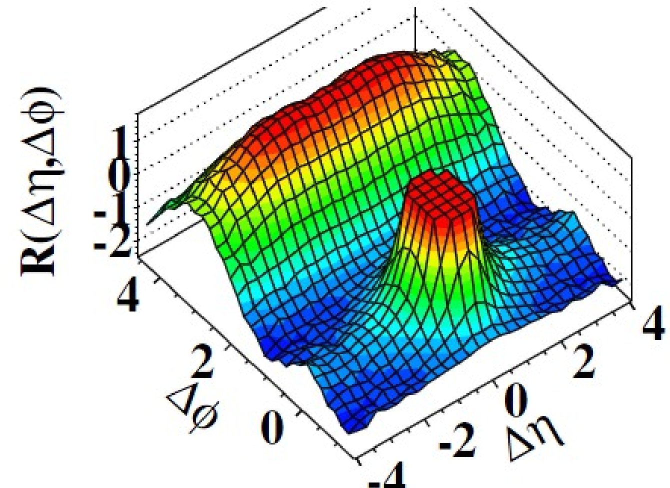
JHEP 09 (2010) 091



все столкновения



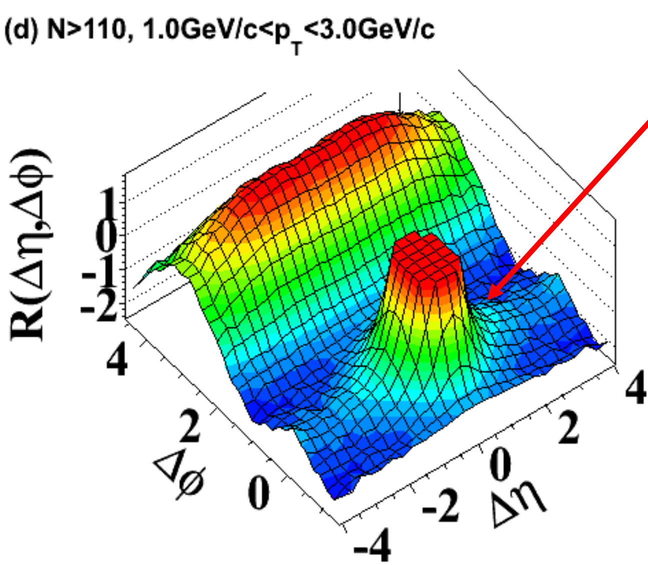
столкновения с **N>110**



“Ридж”-эффект — везде...

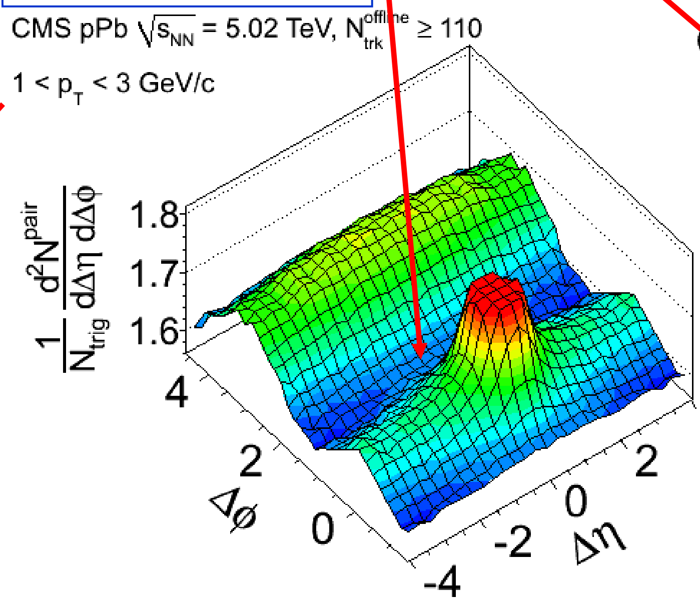
Long-range (2 < |Δη| < 4), near-side (Δϕ ≈ 0) angular correlations were observed in high multiplicity p+p and p+Pb collisions (as well as in Pb+Pb)

p+p 7 TeV



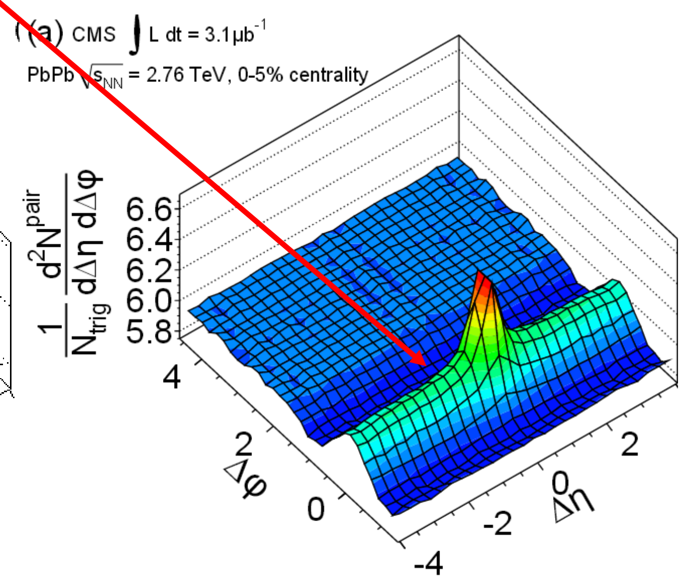
JHEP 09 (2010) 091

p+Pb 5.02 TeV



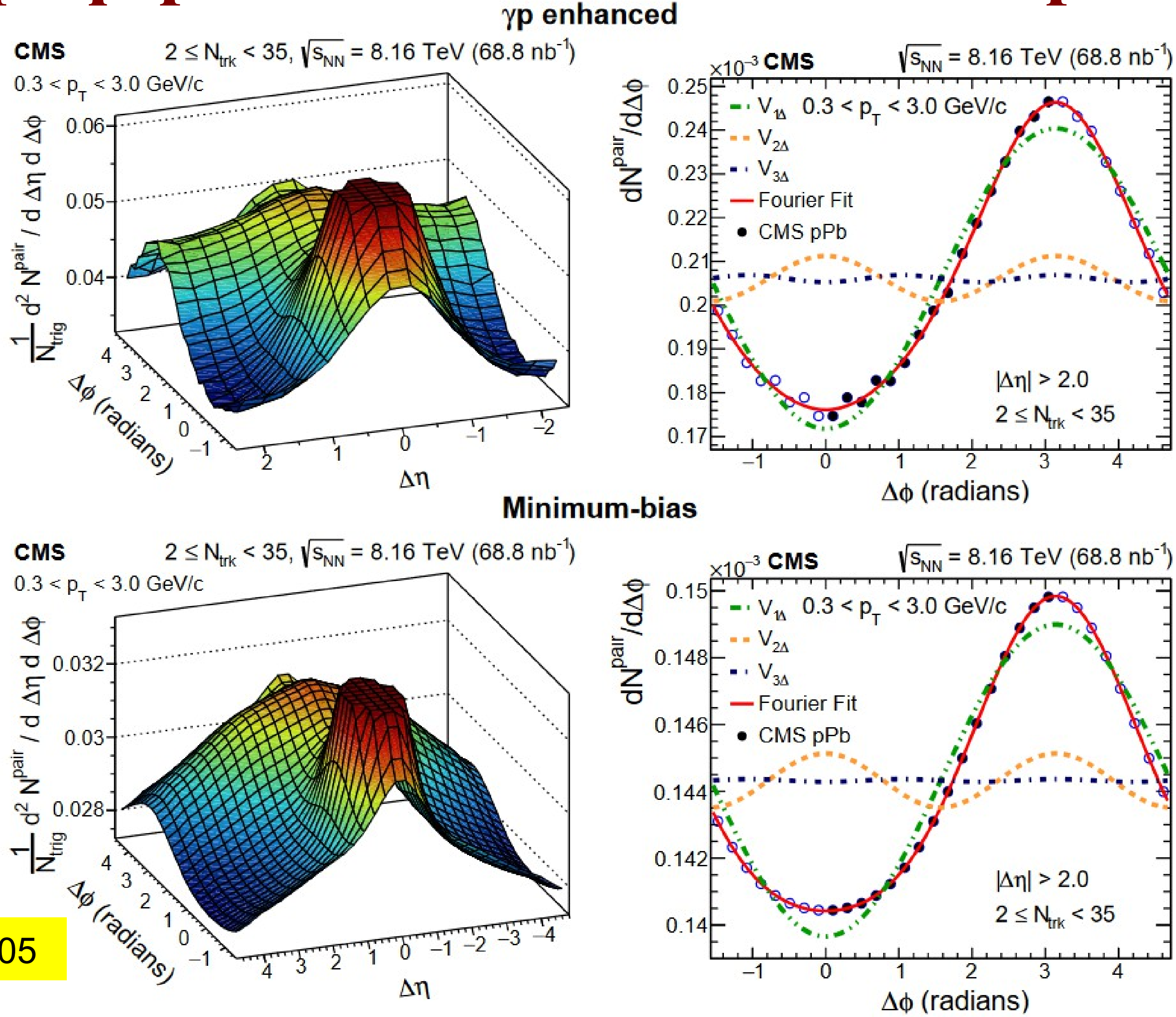
PLB 718 (2013) 795

Pb+Pb 2.76 A TeV, 0-5%



JHEP 07 (2011) 076

γ+p взаимодействия в ультра-периферических столкновениях p+Pb

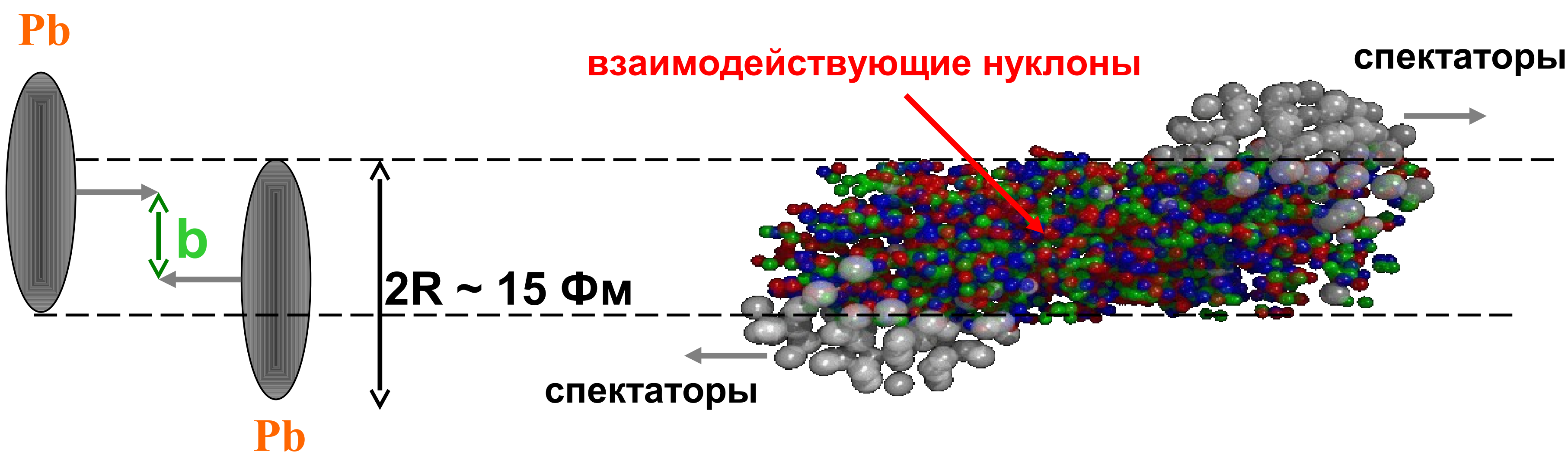


PLB 844 (2023) 137905

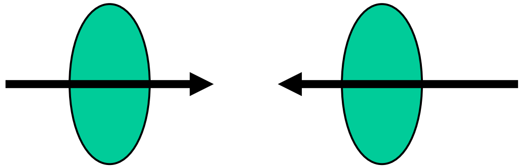
The single particle flow coefficient $v_2(p_T)$ is larger for γp-enhanced events than for minimum-bias collisions. But we don't see “ridge” here!

Кварк-глюонная плазма

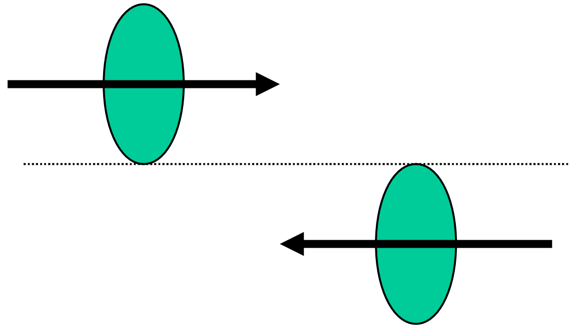
В релятивистских соударениях тяжелых ионов возможно формирование сверхплотного состояния КХД-материи в квазимакроскопических объемах (по сравнению с характерными адронными масштабами).



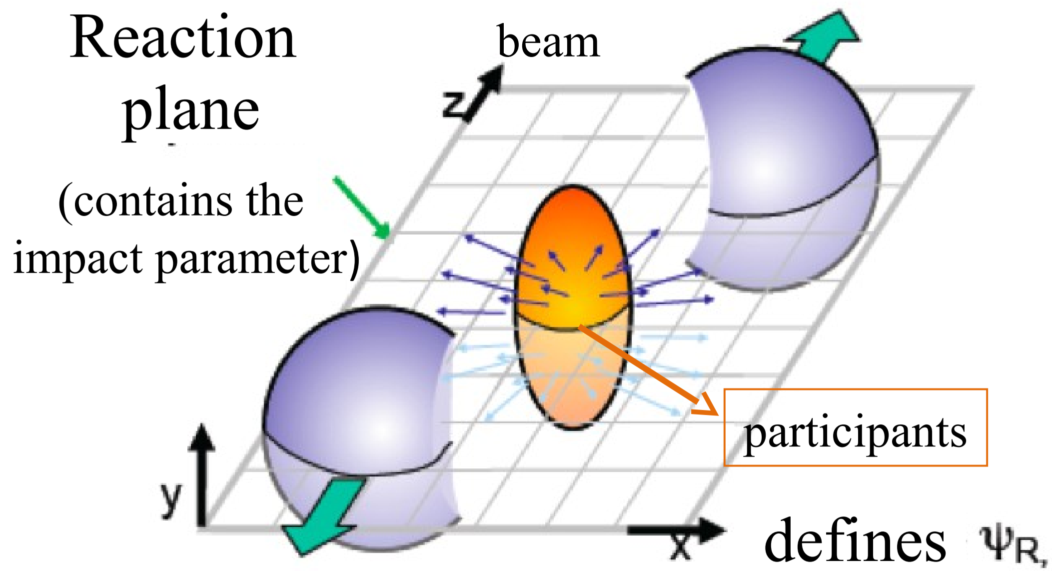
Центральные столкновения,
прицельный параметр b = 0



Периферические столкновения,
прицельный параметр b ≈ 2R

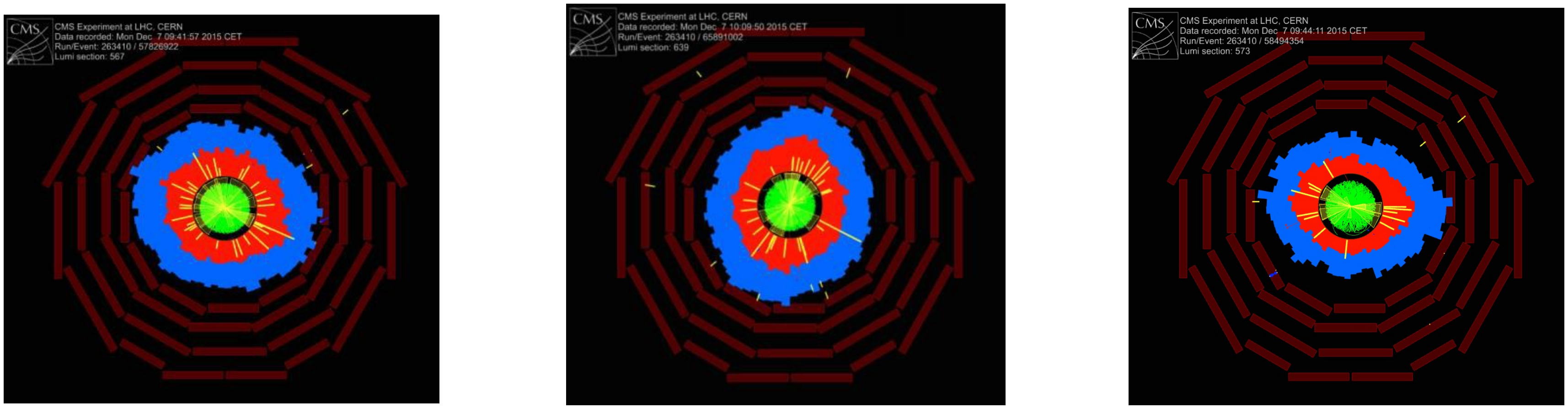


Азимутальная анизотропия



Non-central Pb+Pb “screen shots” from CMS Event Monitor:

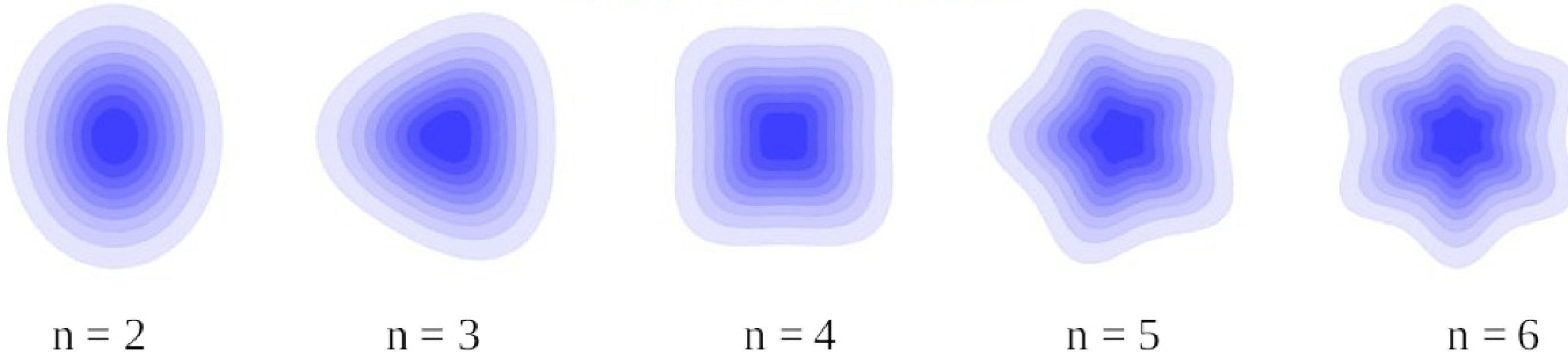
Electromagnetic, **Hadronic** **Energy** and **charged particles tracks**

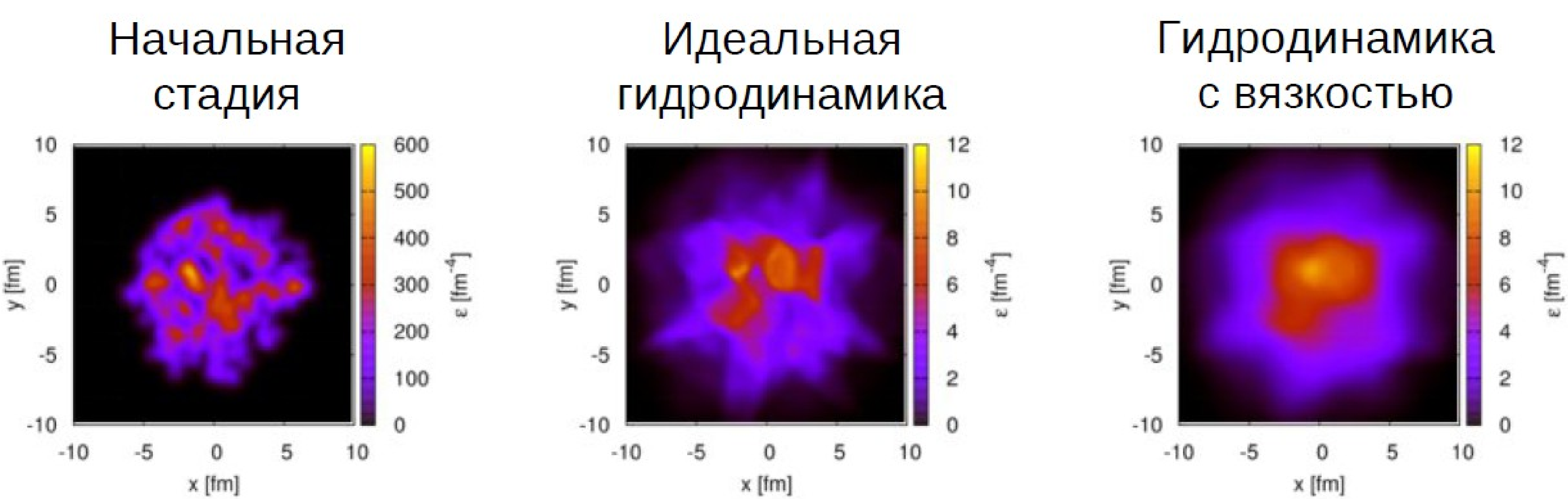


Collective motion is observed in the event azimuthal distributions

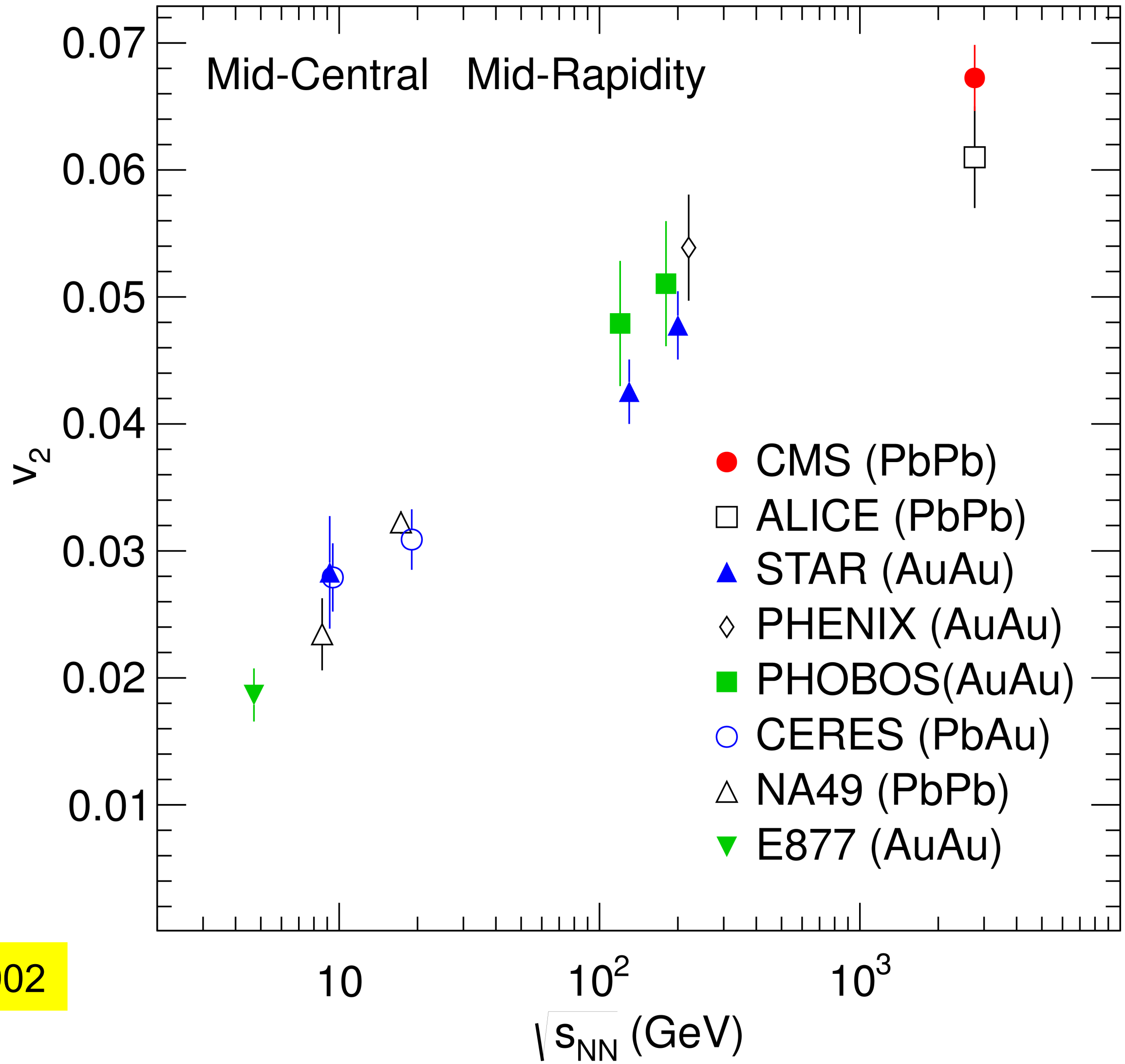
Потоки гармоник v_2, v_3 ...

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





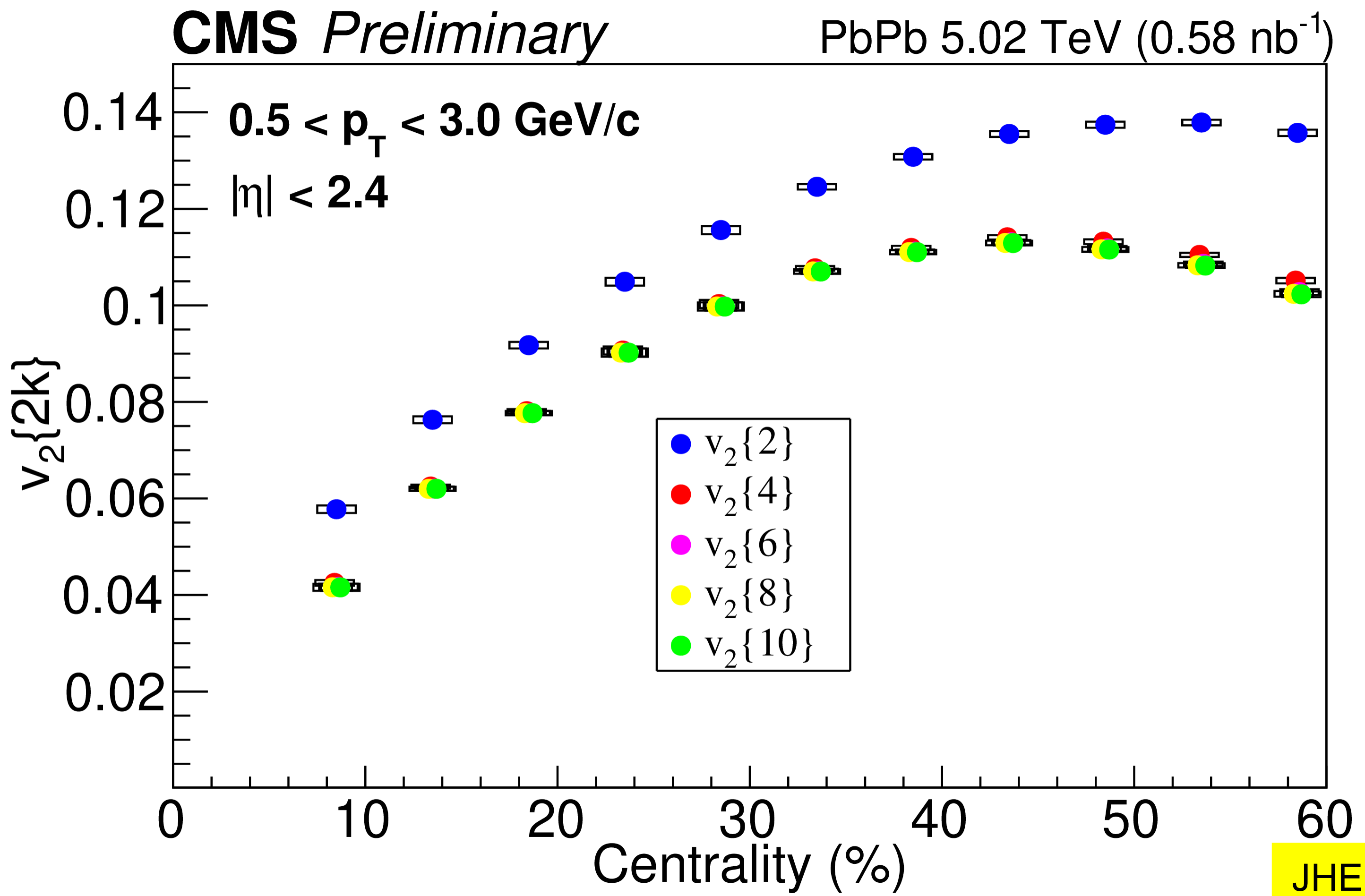
Интегральная v_2 – результат для LHC от CMS



PRC 87 (2013) 014902

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

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

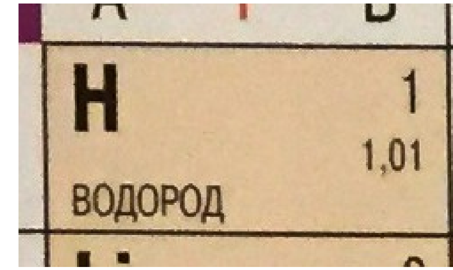


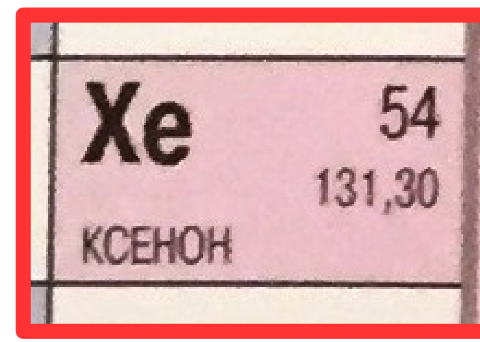
JHEP 02 (2024) 106

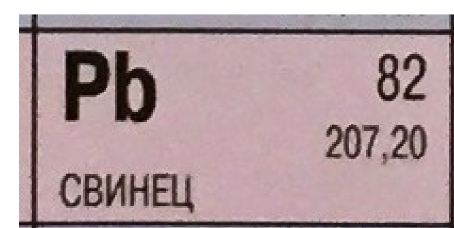
$v_2\{2\} > v_2\{4\} \gtrsim v_2\{6\} \gtrsim v_2\{8\} \gtrsim v_2\{10\}$ ($v_2\{10\}$ is the first time ever)

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

Xe+Xe как “мост” между p+p и Pb+Pb

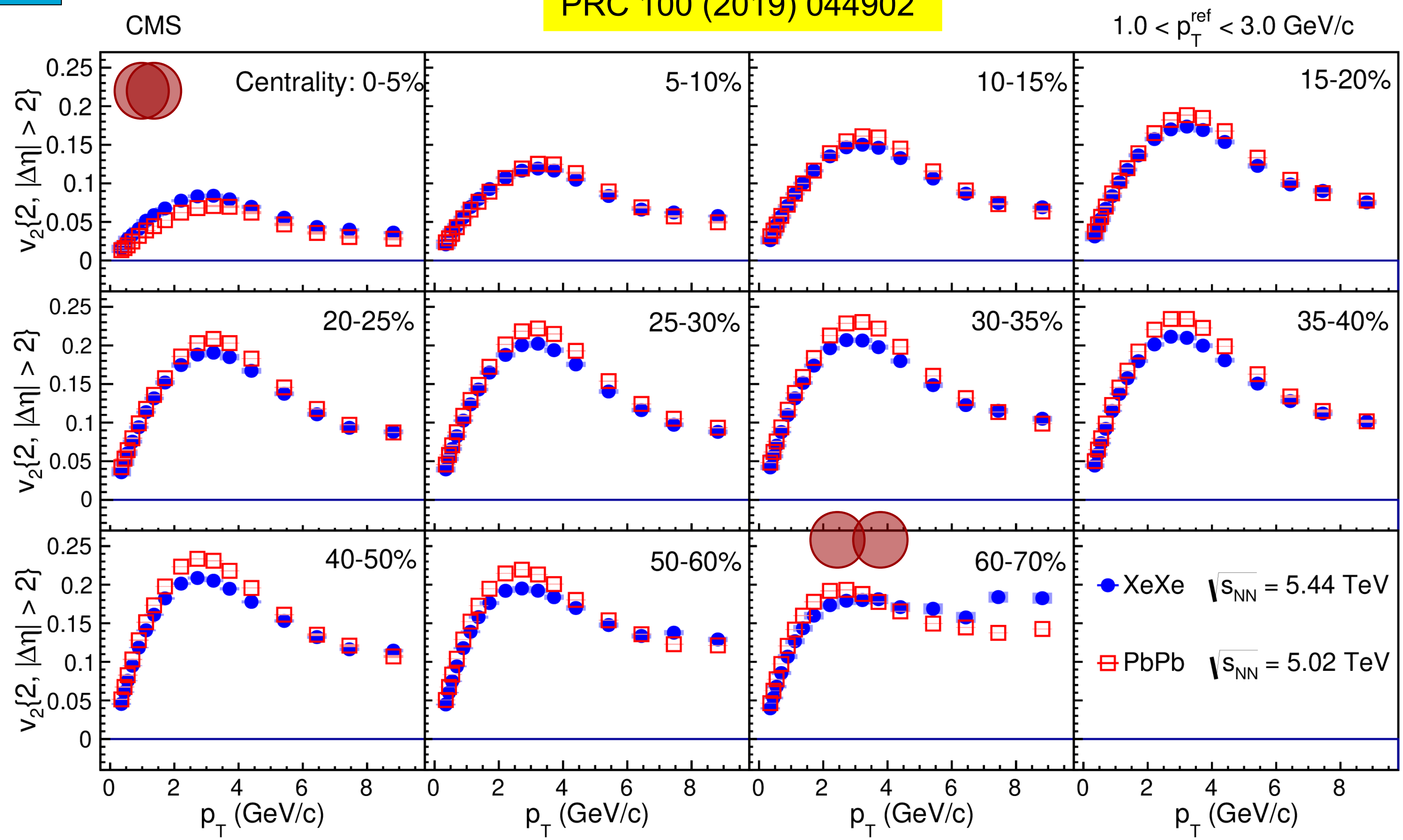


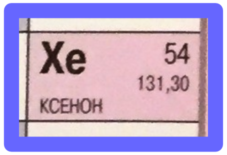


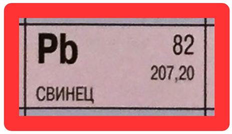


v_2 Xe+Xe vs. Pb+Pb

PRC 100 (2019) 044902



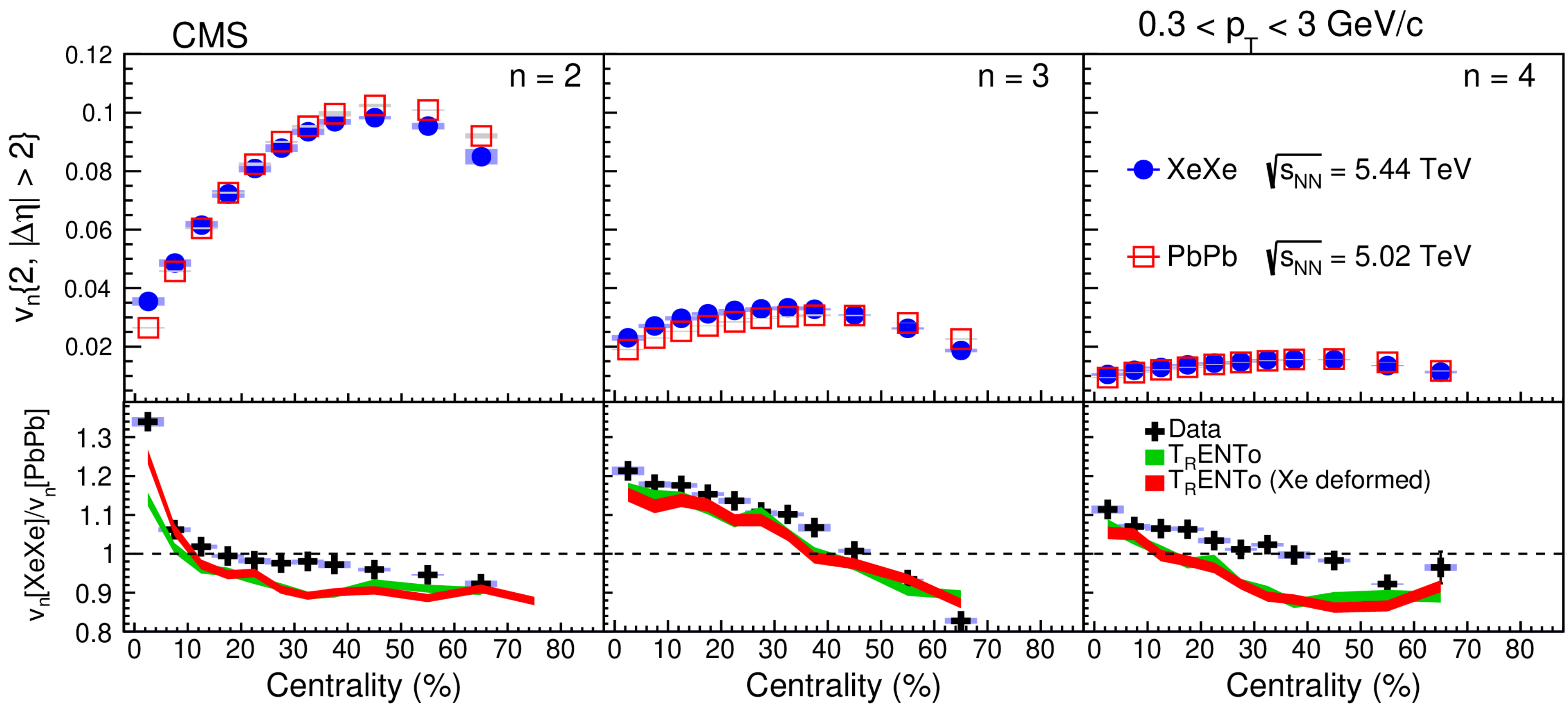




The magnitude of the v_2 coefficients for Xe+Xe collisions are larger than those found in Pb+Pb collisions for the most central collisions. This is attributed to a larger fluctuation component in the lighter colliding system.

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

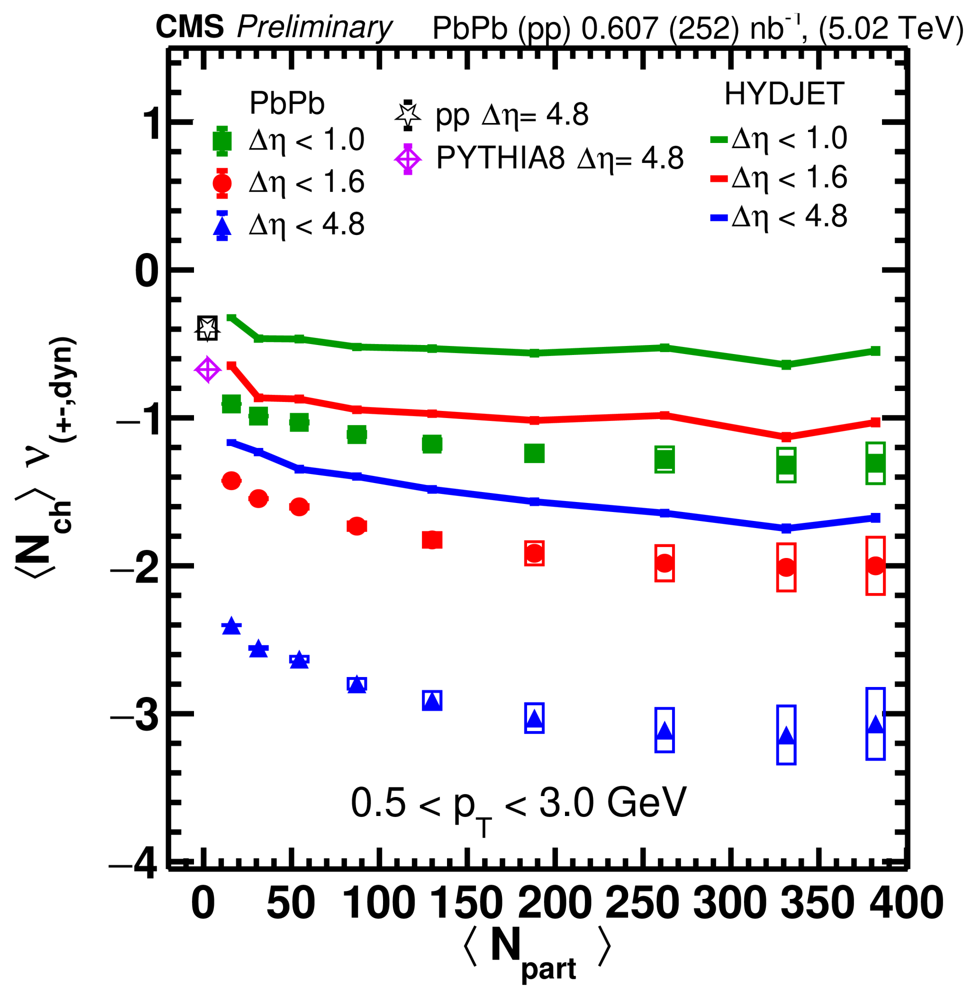
PRC 100 (2019) 044902

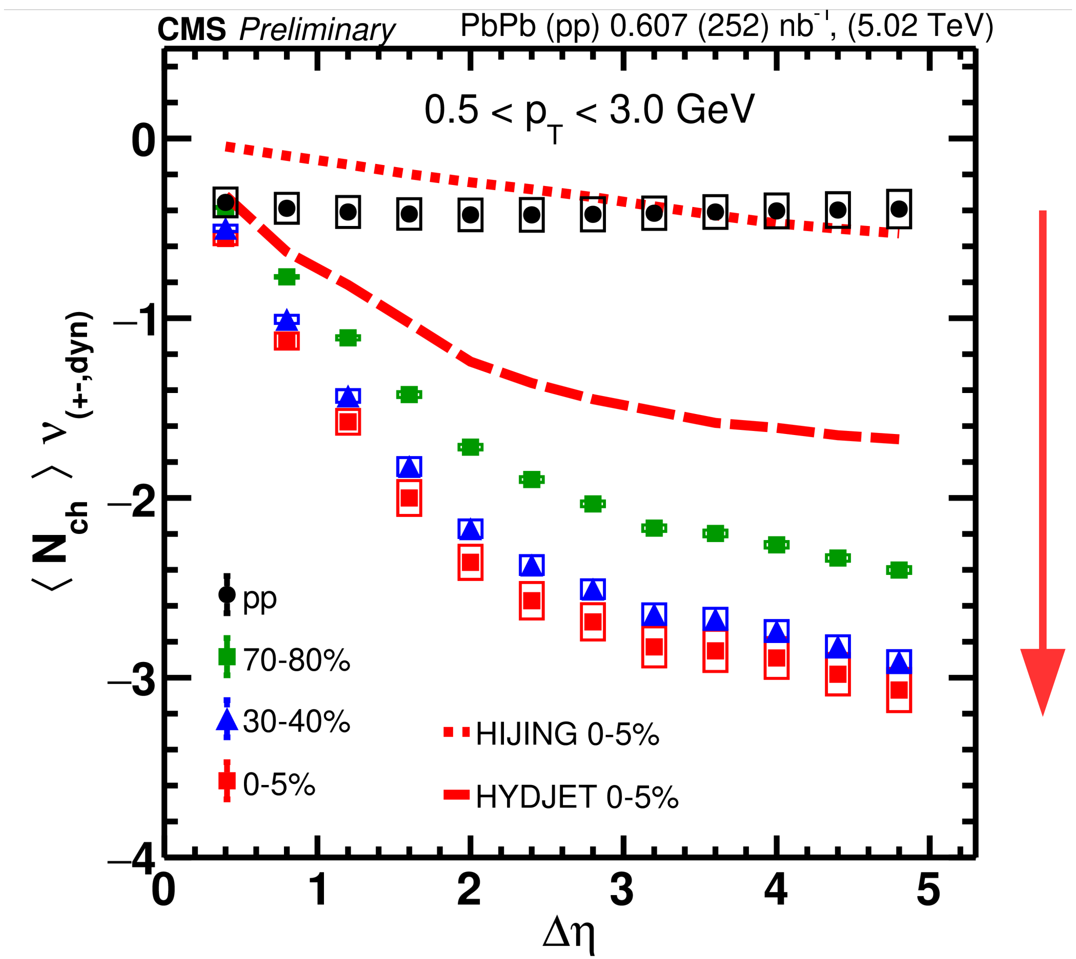


Hydrodynamic models that consider the Xe nuclear deformation are able to better describe the v_2[XeXe]/v_2[PbPb] ratio in central collisions than those assuming a spherical Xe shape.

Зарядовые флуктуации в Pb-Pb соударениях

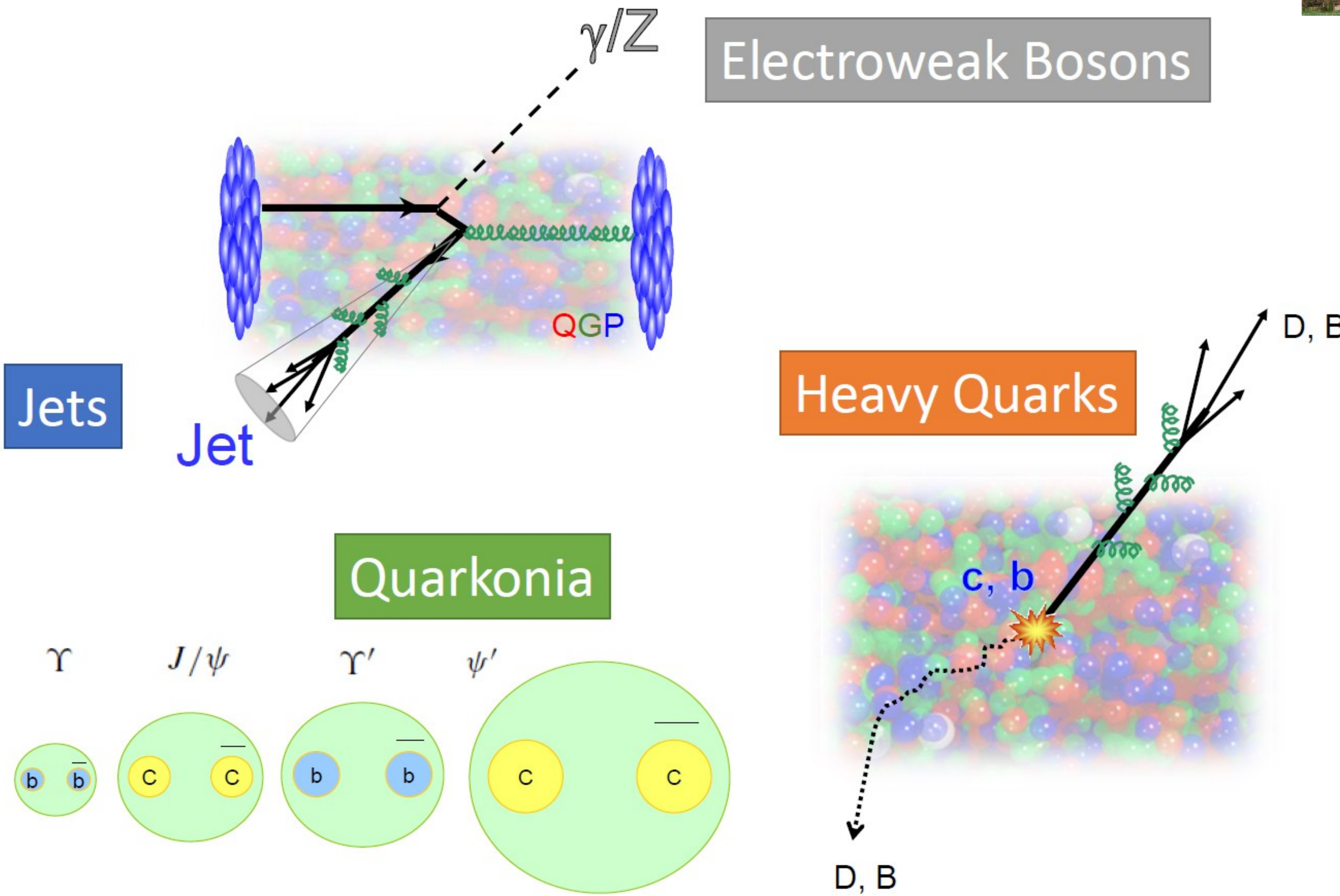
CMS-PAS-HIN-22-005



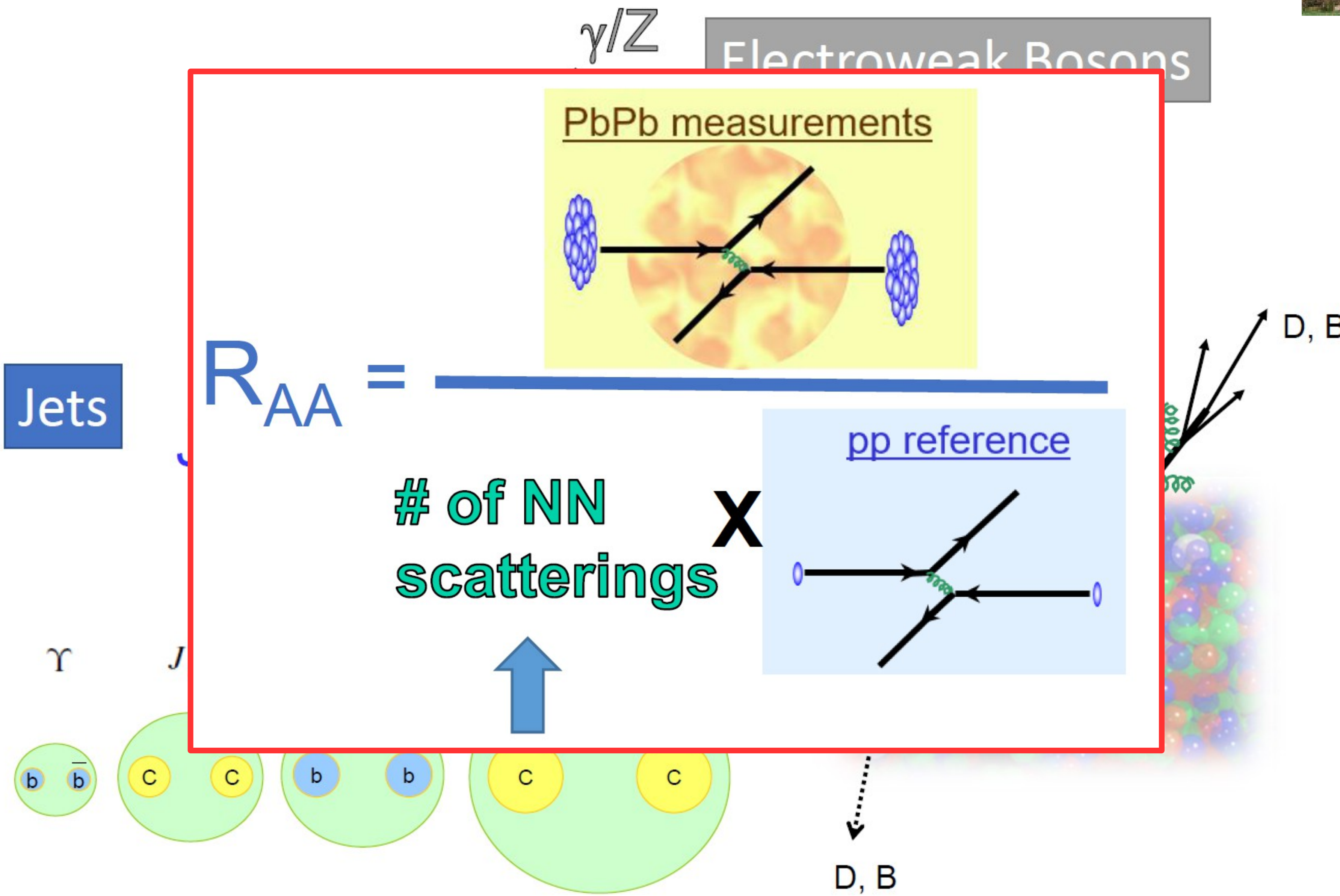


Net-charge fluctuations differ between QGP and hadron gas phase.
Increasing centrality approaches QGP prediction faster.

Жесткие тесты кварк-глюонной плазмы

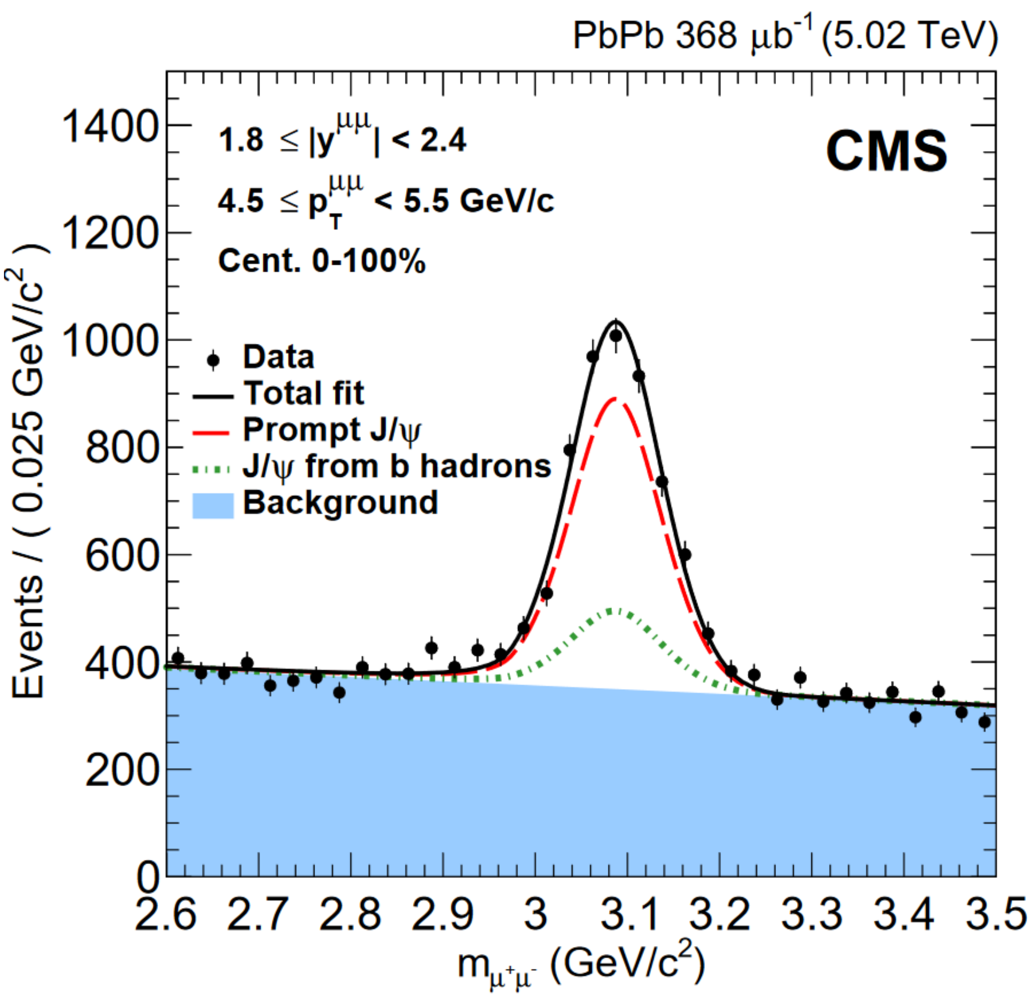


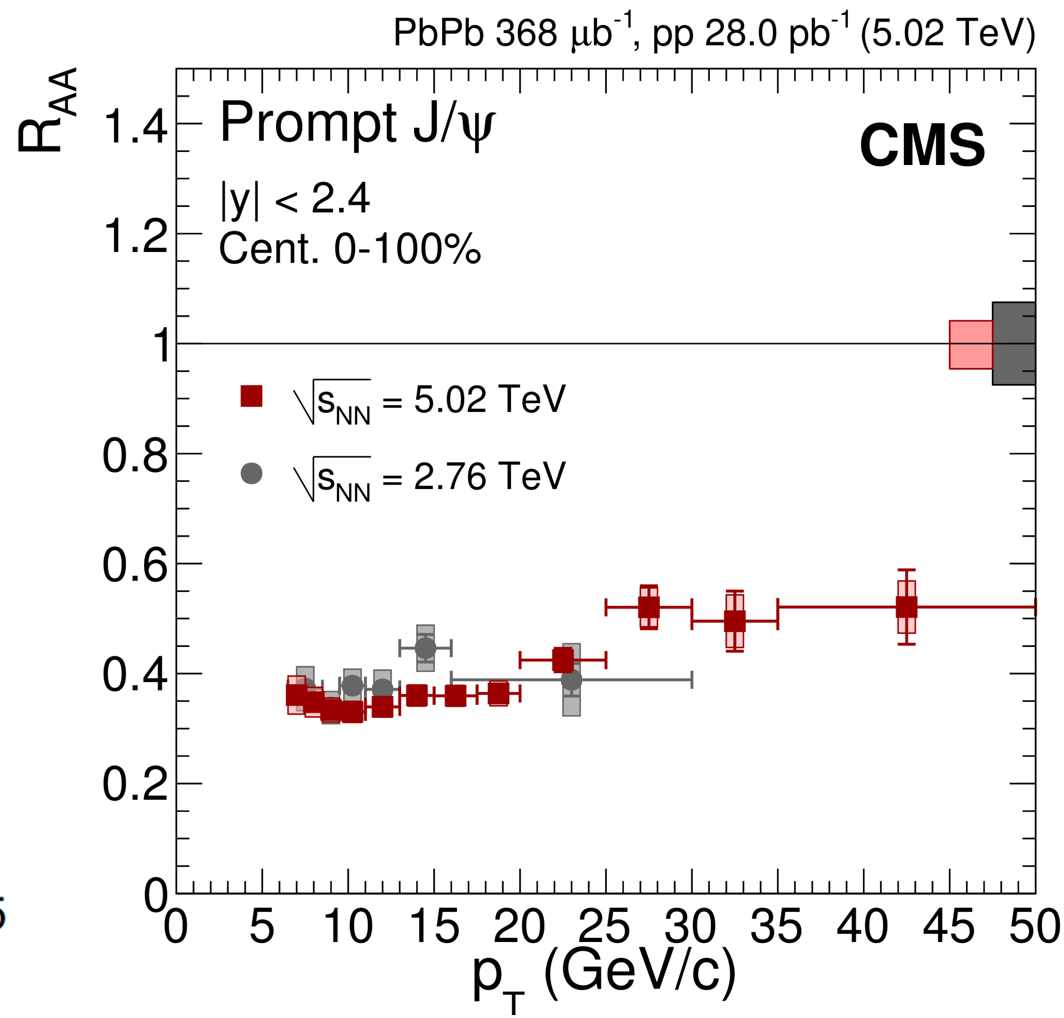
Жесткие тесты кварк-глюонной плазмы



Подавление J/ψ в Pb+Pb

EPJ C 78 (2018) 509

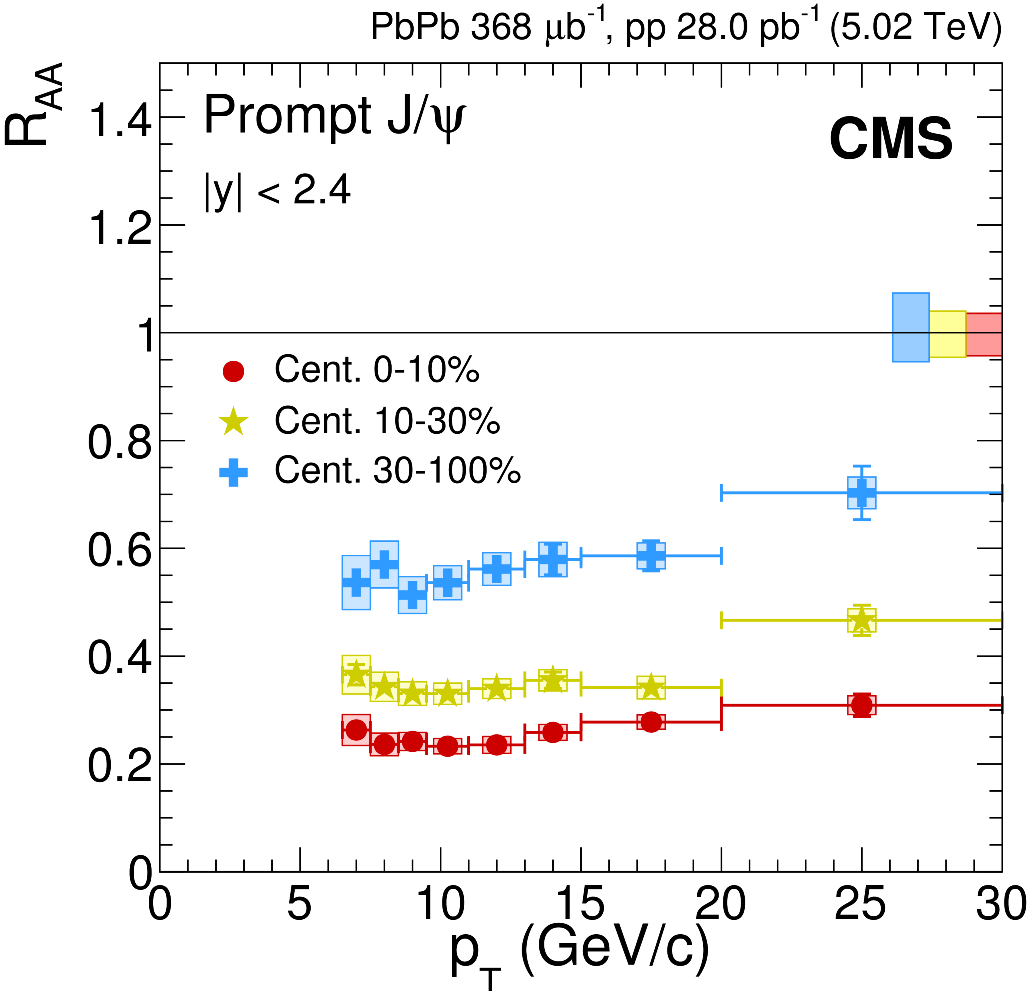


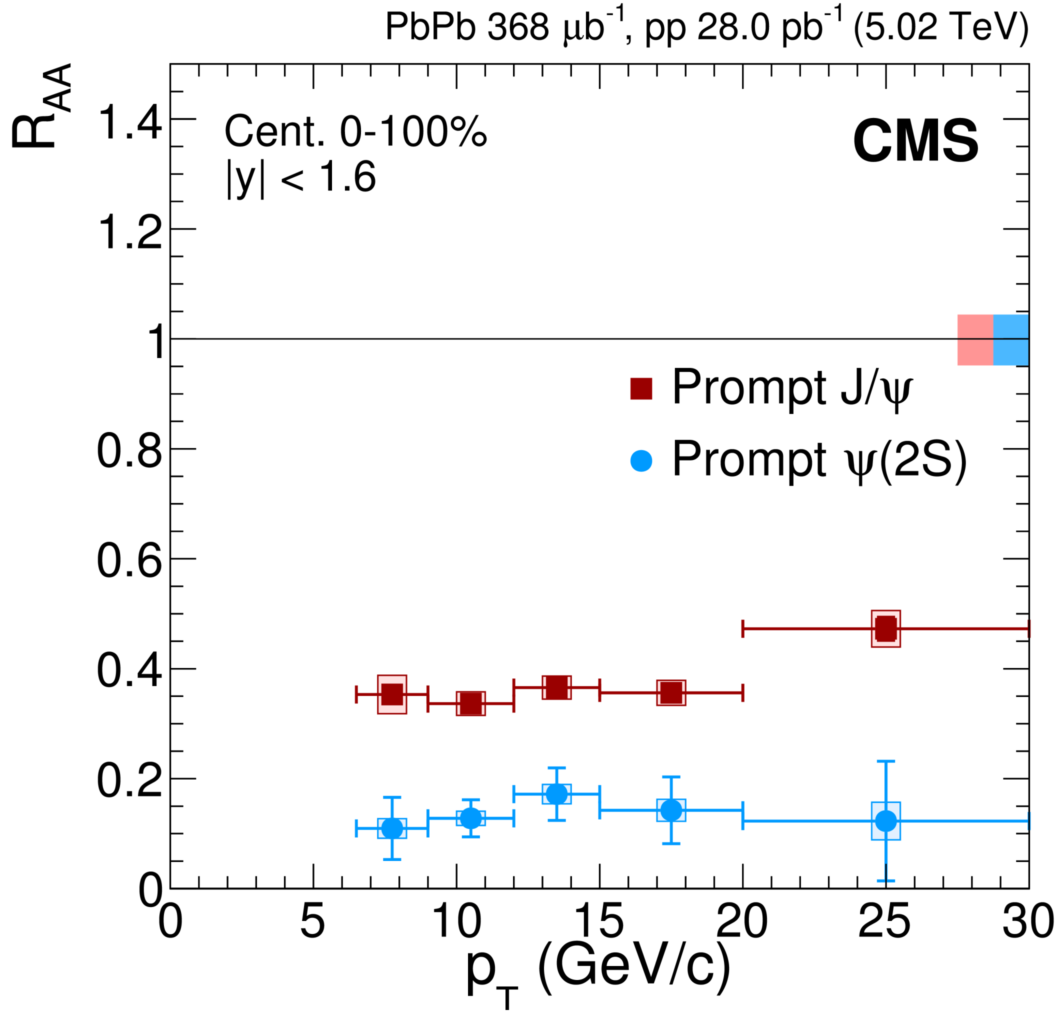


J/ψ mesons are observed to be suppressed (similarly in 2.76 and 5.02 TeV)

Подавление J/ψ и ψ(2S) в Pb+Pb

EPJ C 78 (2018) 509

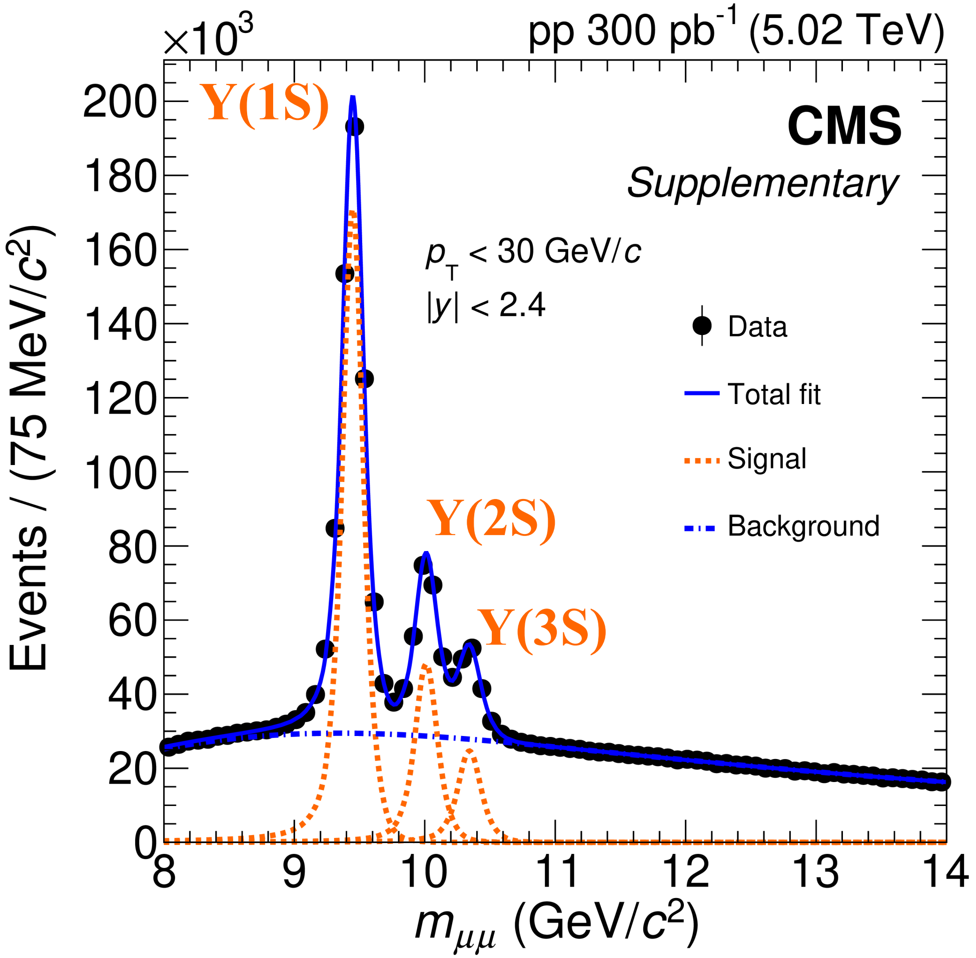


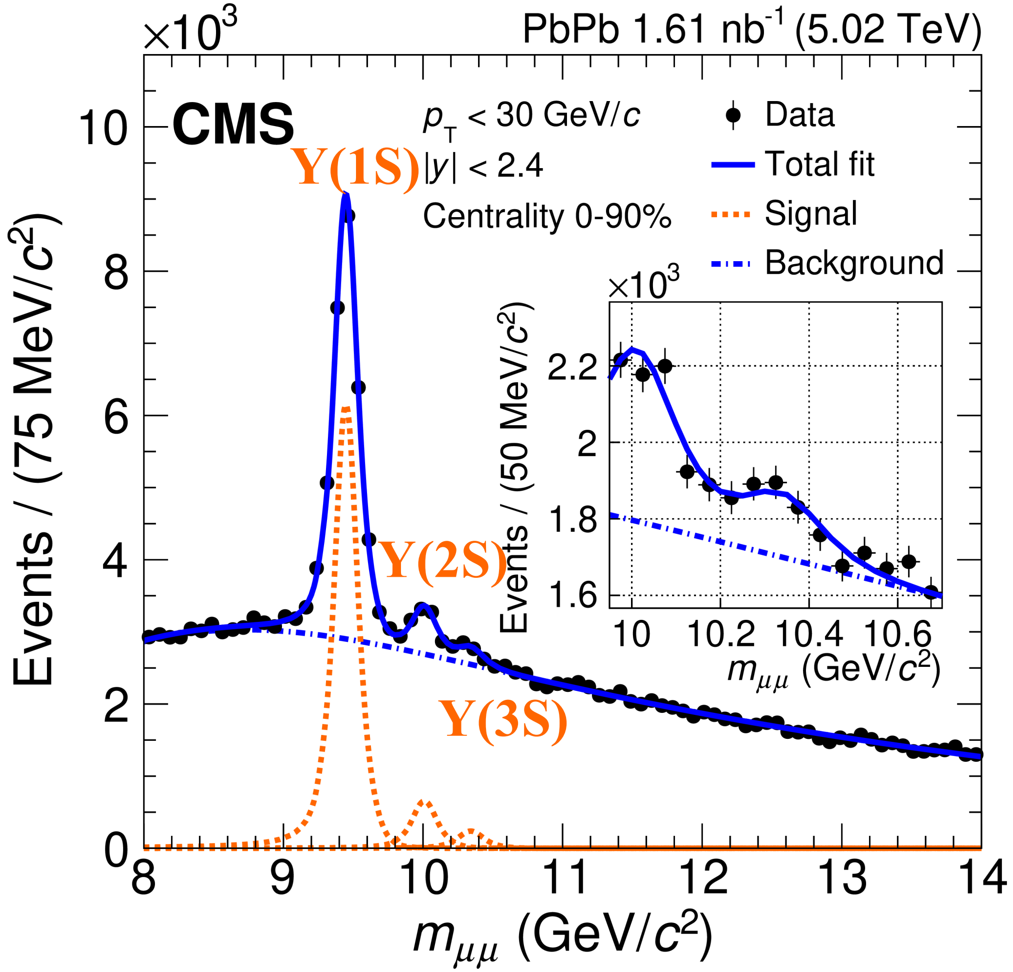


- **Increasing suppression for increasing centrality**
- **ψ(2S) is more suppressed than the J/ψ meson**

Подавление Υ в Pb+Pb

arXiv:2303.17026

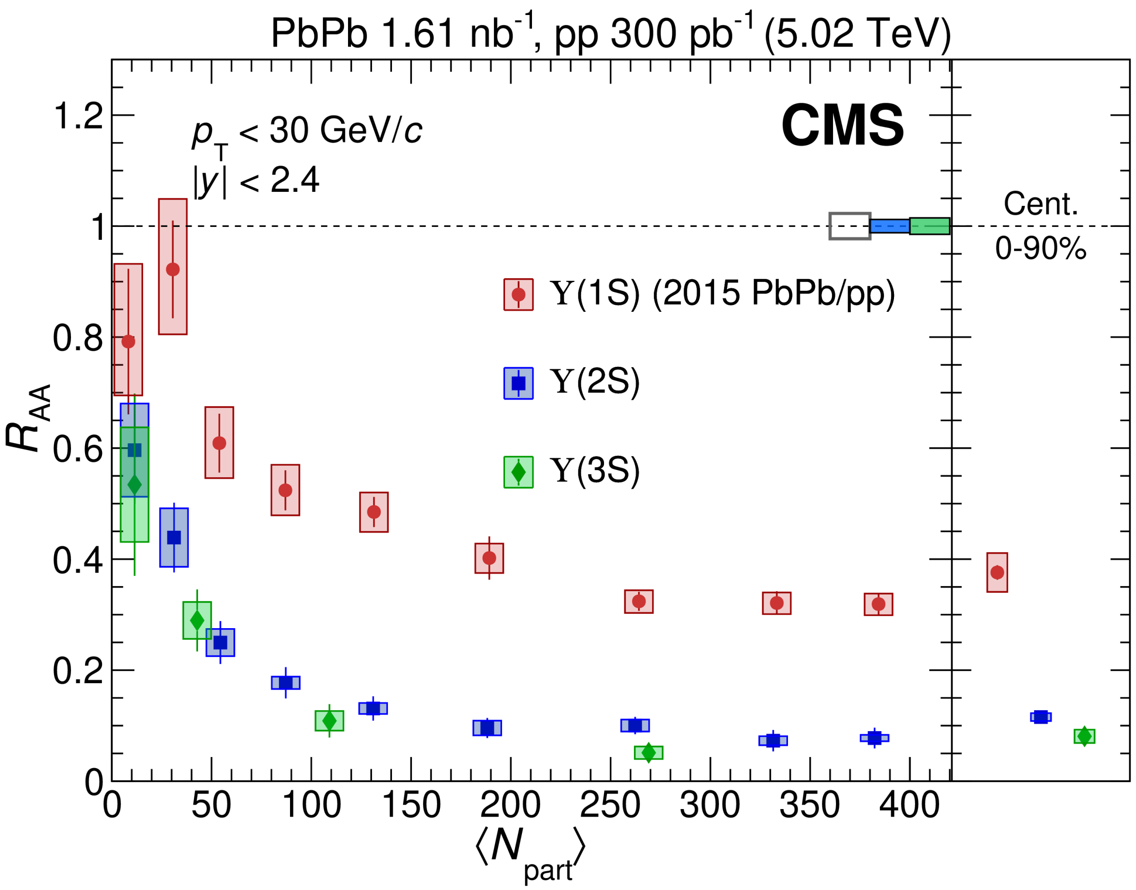


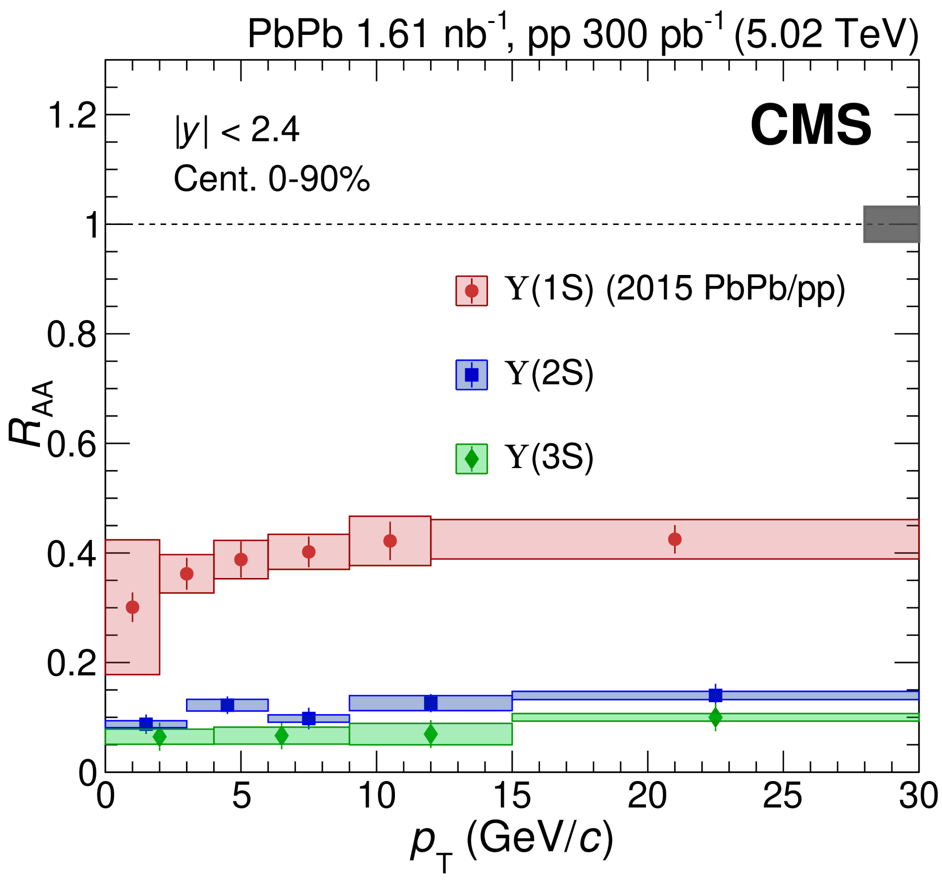


- **Observation of sequential suppression of Υ family in Pb+Pb.**
  - **First observation of Υ(3S) in heavy-ion collisions! (σ > 5)**

Подавление Υ в Pb+Pb

arXiv:2303.17026

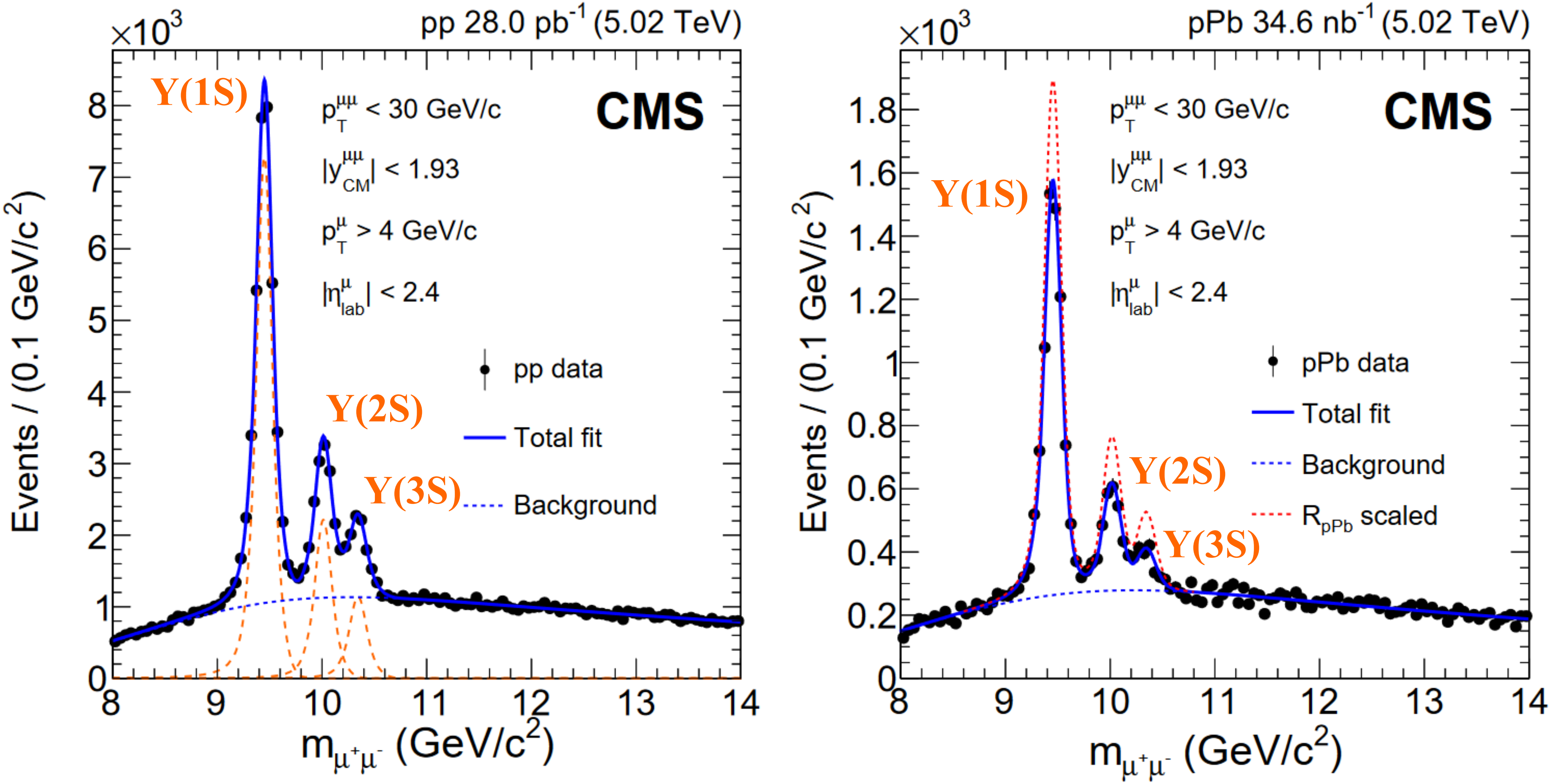




- R_{AA} is decreasing with numbers of participants of Pb+Pb collision.
    - Slightly increasing with p_T ?

Подавление Υ в p+Pb

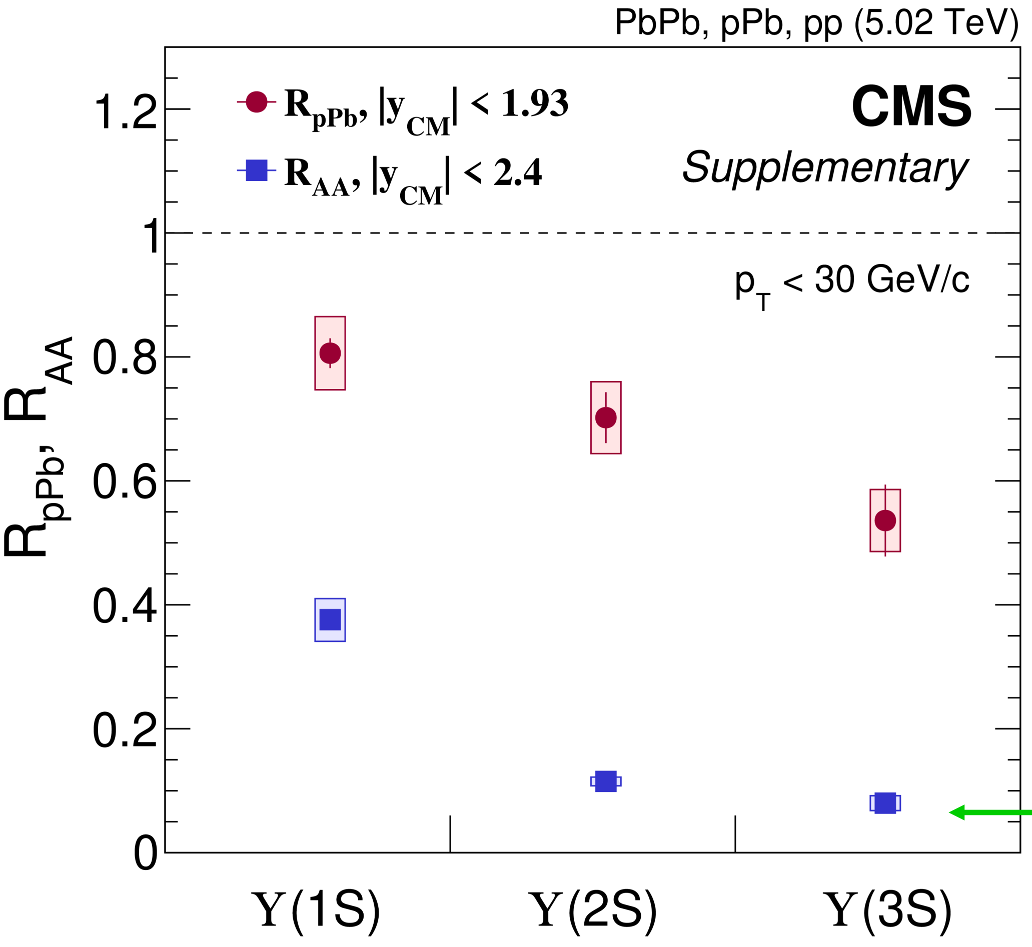
PLB 835 (2022) 137397



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

Подавление Υ в p+Pb и Pb+Pb

arXiv:2303.17026



Ordered in binding energy

RpPb Υ(1S) > RpPb Υ(2S) > RpPb Υ(3S)

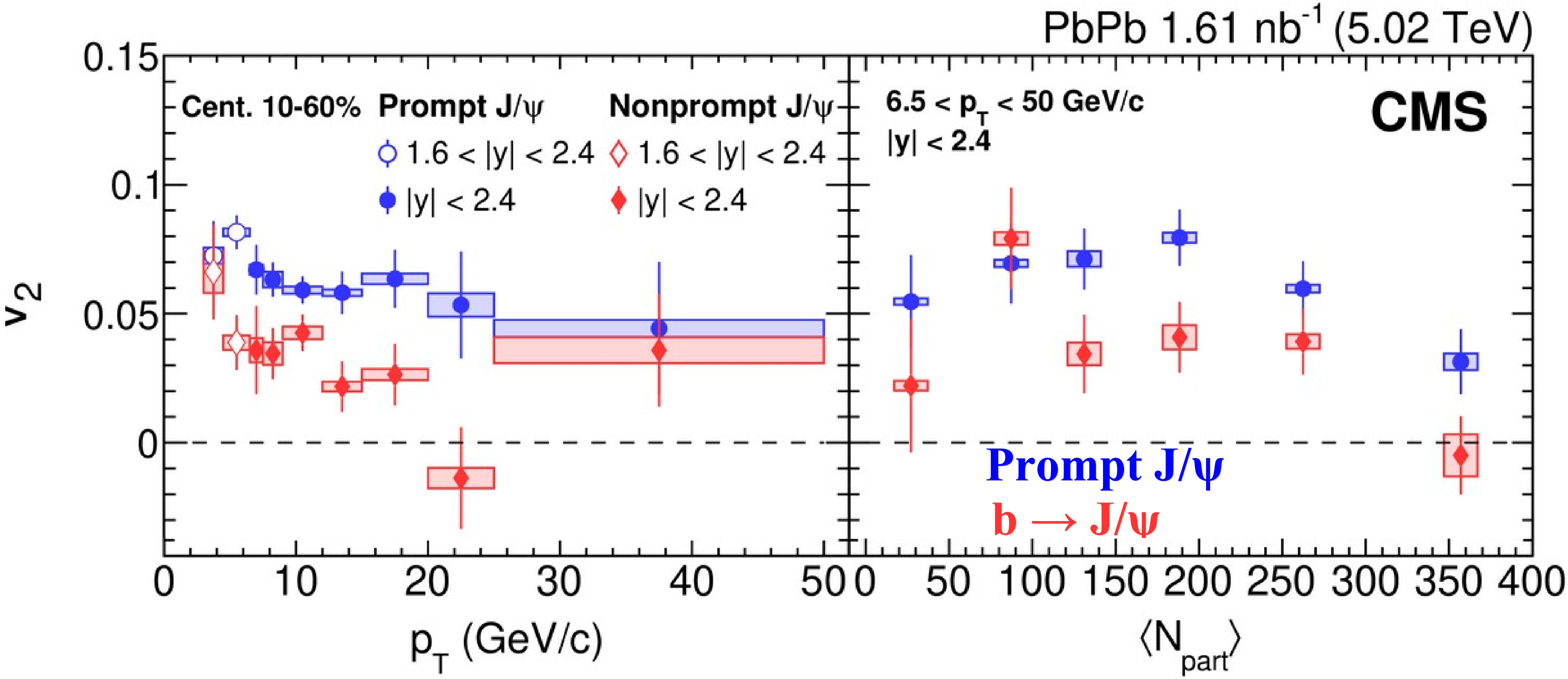
Largest suppression is in Pb+Pb

$R_{pPb} > R_{PbPb}$

New result for Υ(3S)

v_2 J/ψ в Pb+Pb

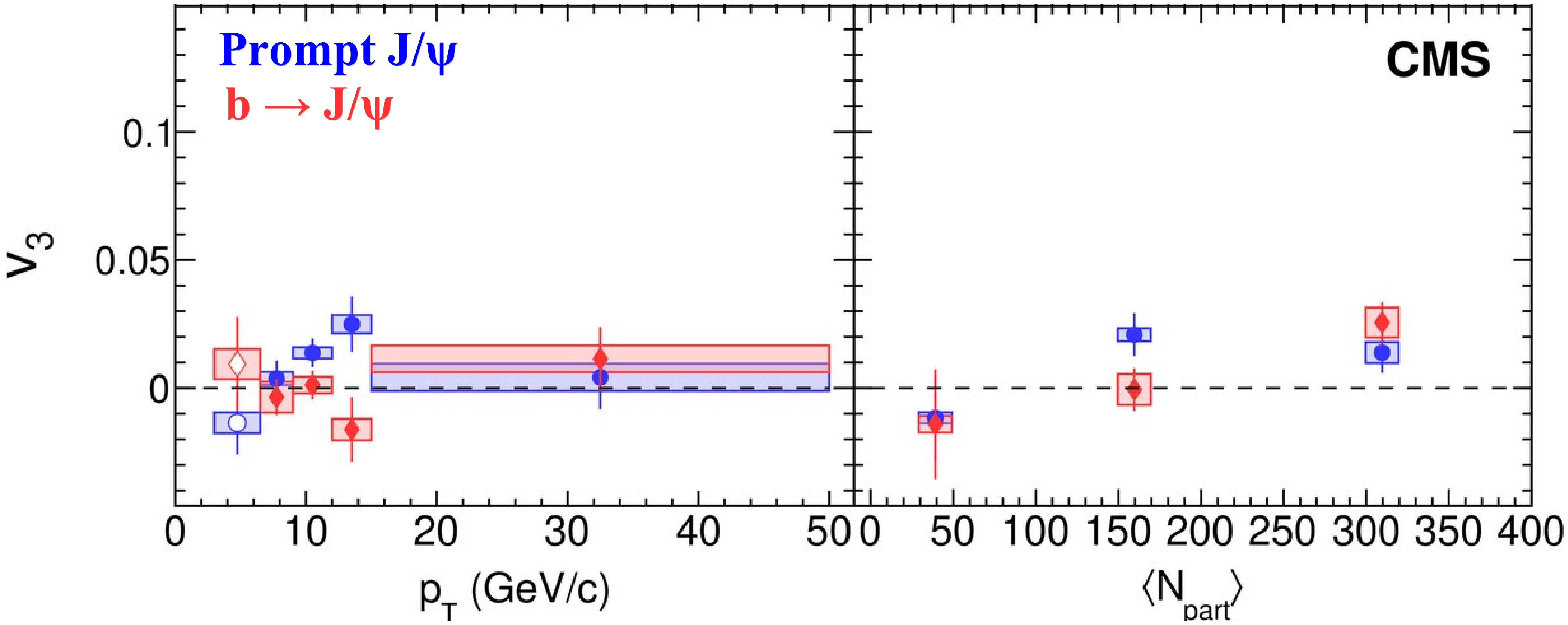
JHEP 10 (2023) 115



- Large v_2 of J/ψ up to p_T= 50 GeV/*c*
- v_2 (b → J/ψ) < v_2(prompt J/ψ)

v_3 J/ψ в Pb+Pb

JHEP 10 (2023) 115

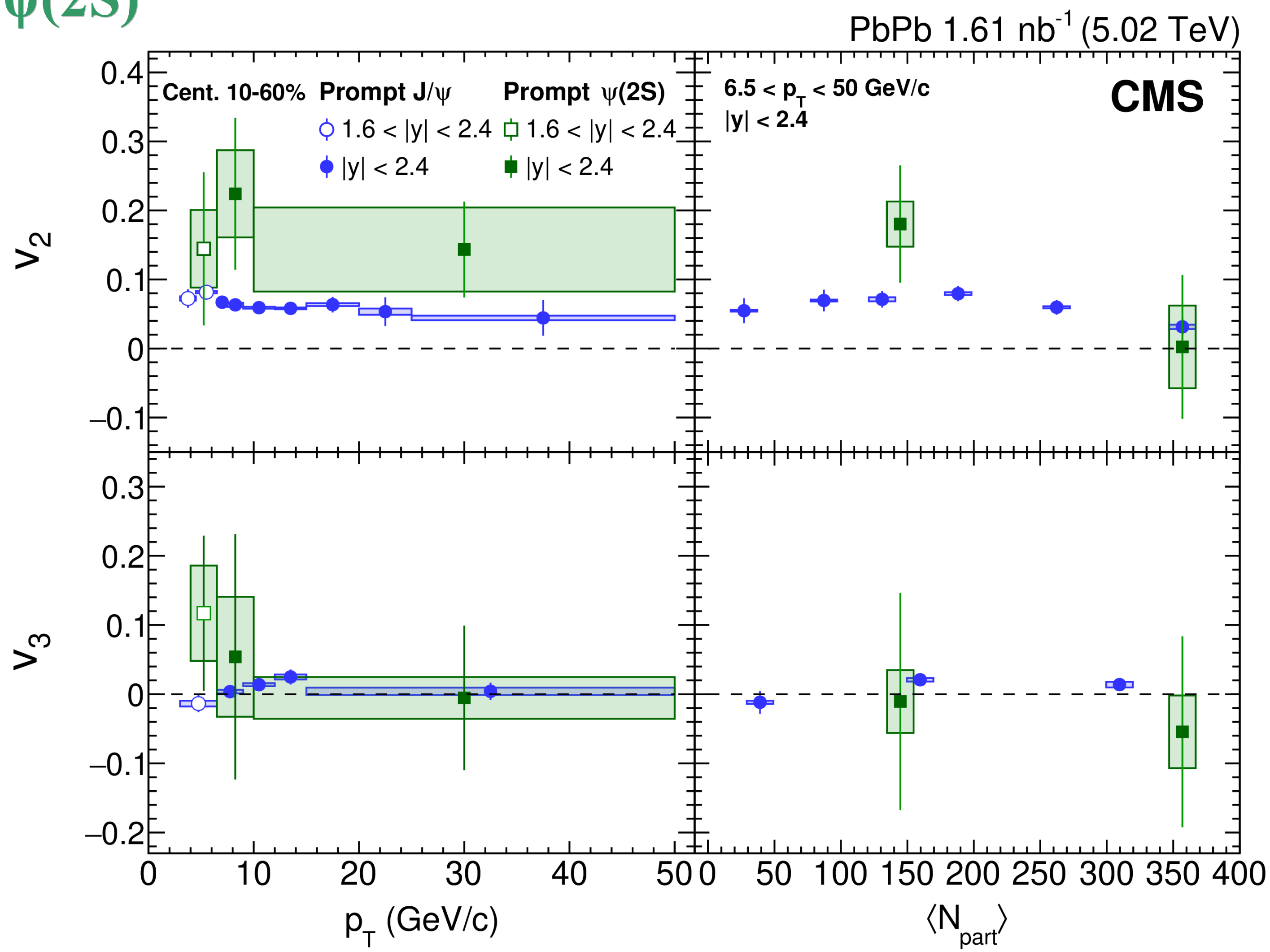


- **First measurement of v_3 for prompt and non-prompt J/ψ separately**
- **no significant non-zero v_3 (J/ψ)**

v_2 и v_3 ψ(2S) в Pb+Pb

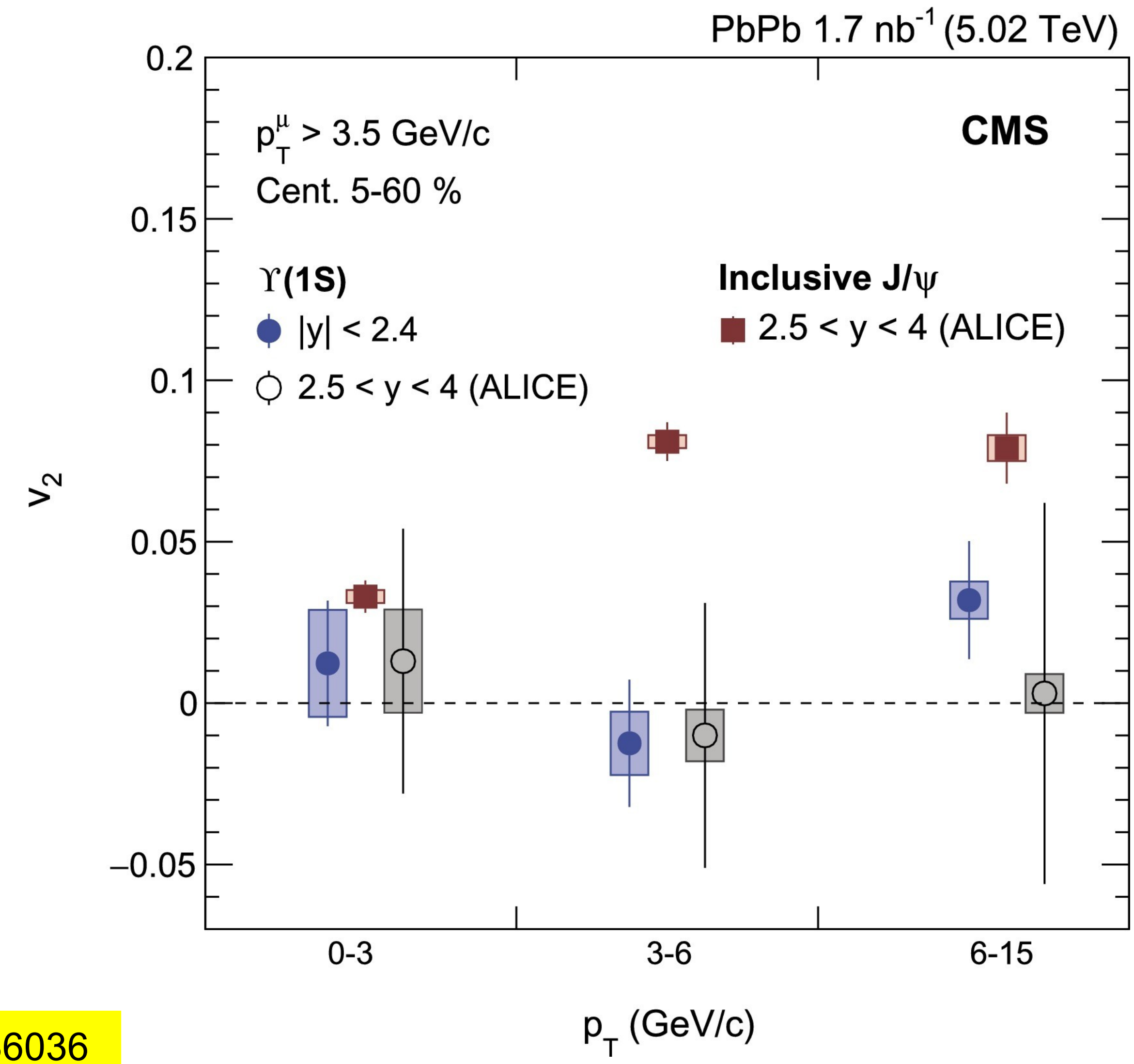
JHEP 10 (2023) 115

Prompt ψ(2S)



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

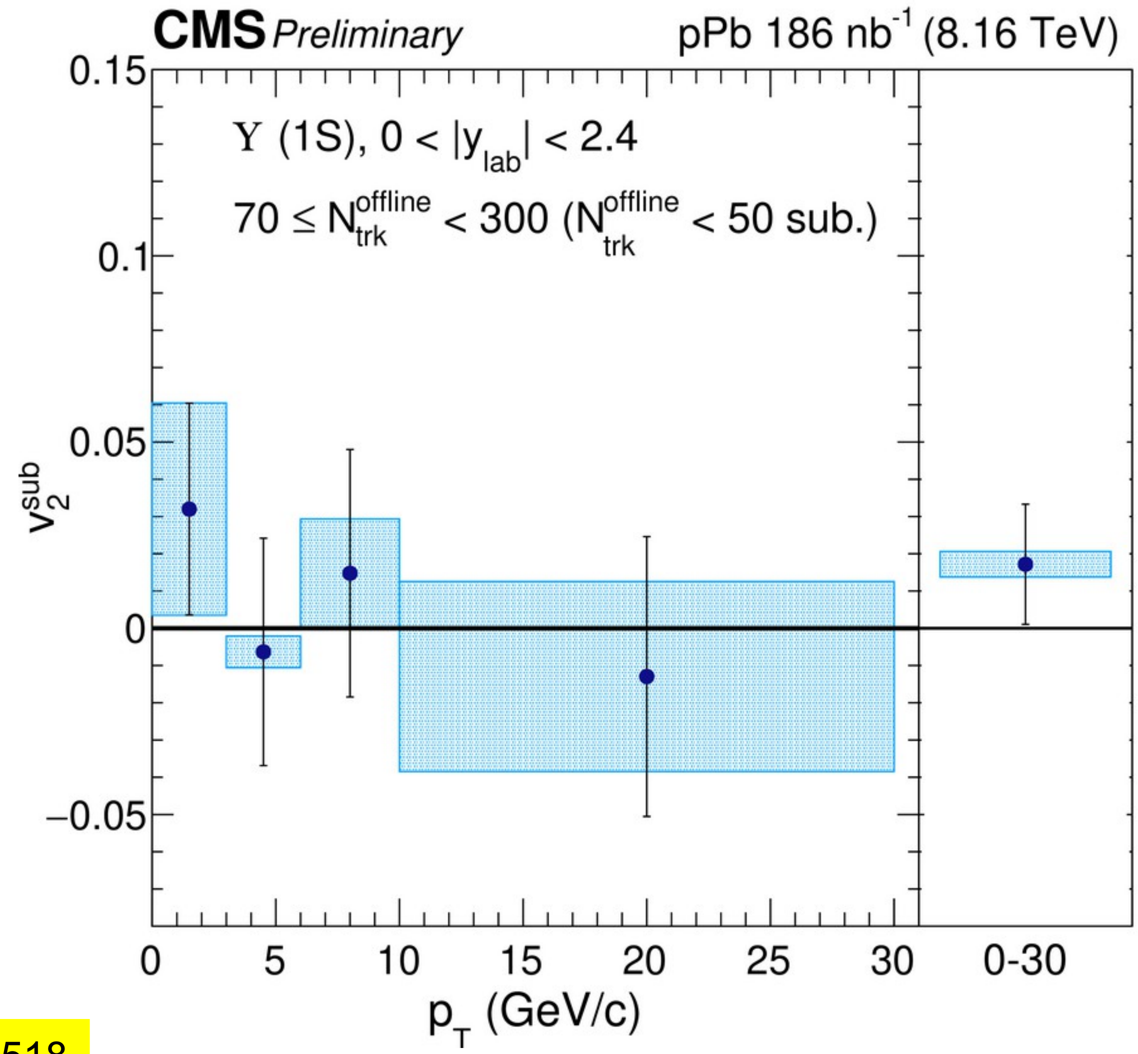
v_2 Υ(1S) в Pb+Pb



PLB 813 (2021) 136036

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

v_2 Υ(1S) в p+Pb

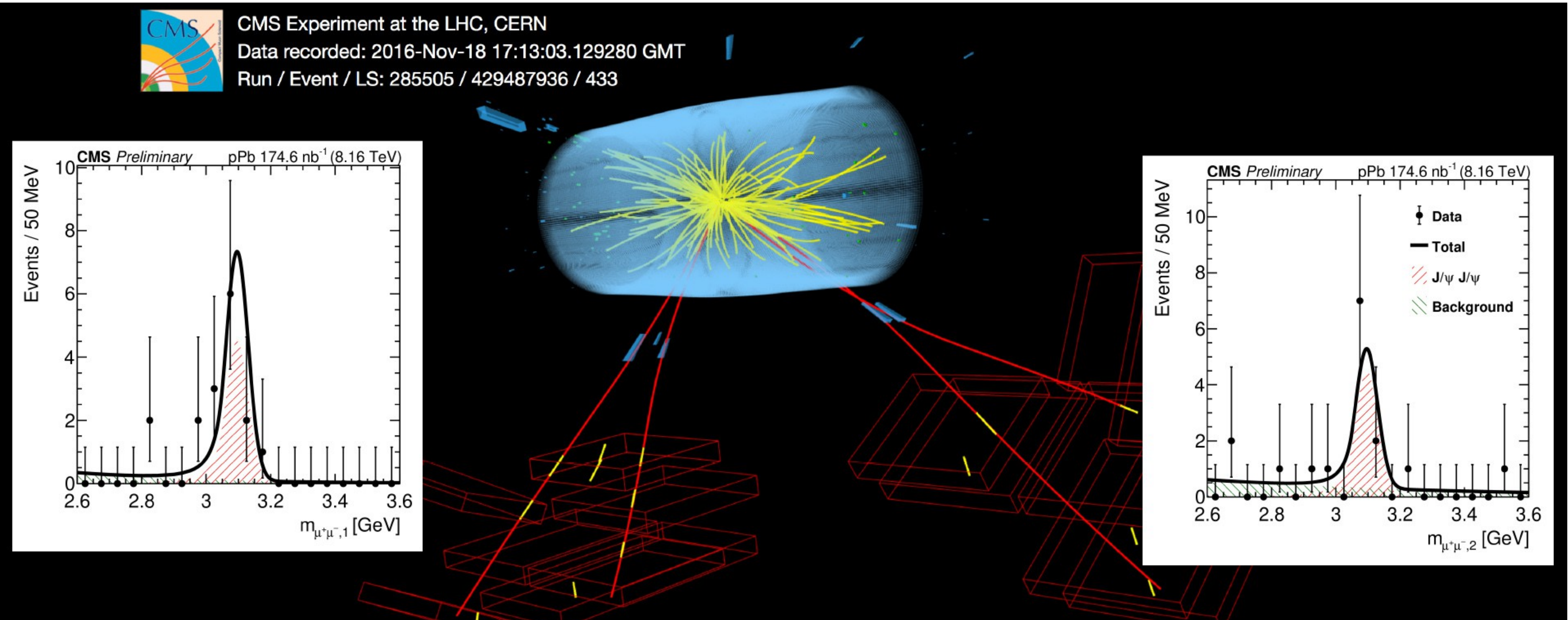


PLB 850 (2024) 138518

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

Рождение двух J/ψ в p+Pb

CMS-PAS-HIN-23-013



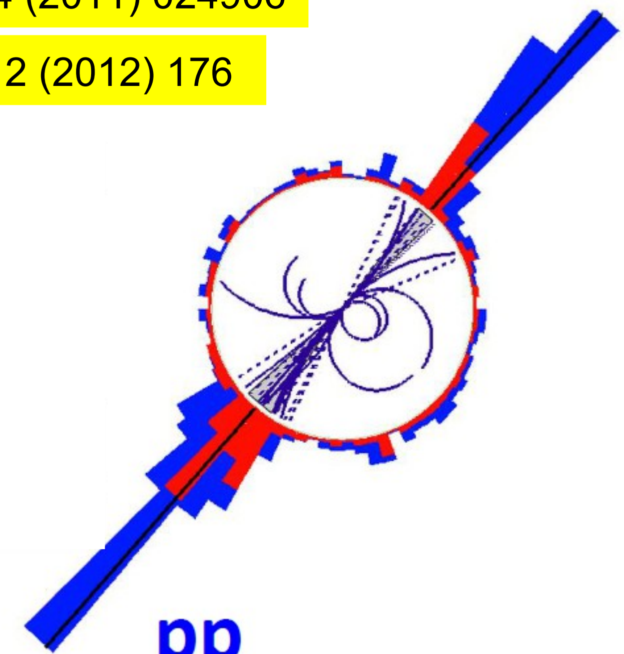
$N(J/\psi\ J/\psi \to 2\ \mu^+\mu^-) = 8.5 \pm 3.4$ events

$\sigma_{fiducial}(pPb \to J/\psi\ J/\psi) = 22.0 \pm 8.9\ (stat) \pm 1.5\ (syst)$ nb

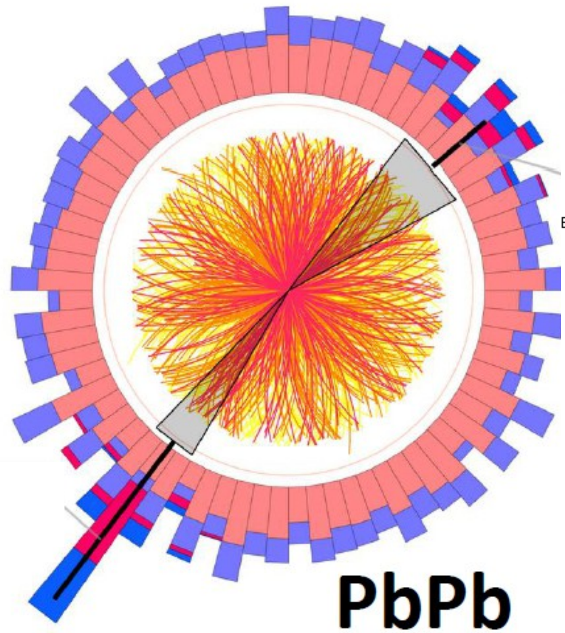
“Jet quenching” (“гашение” струй) в Pb+Pb

PRC 84 (2011) 024906

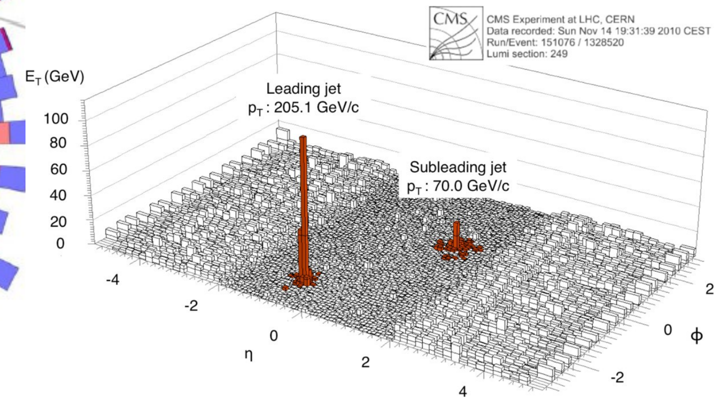
PLB 712 (2012) 176



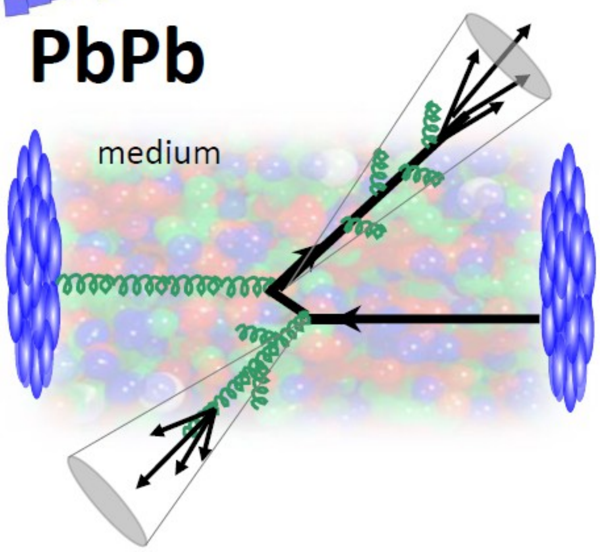
pp



!!



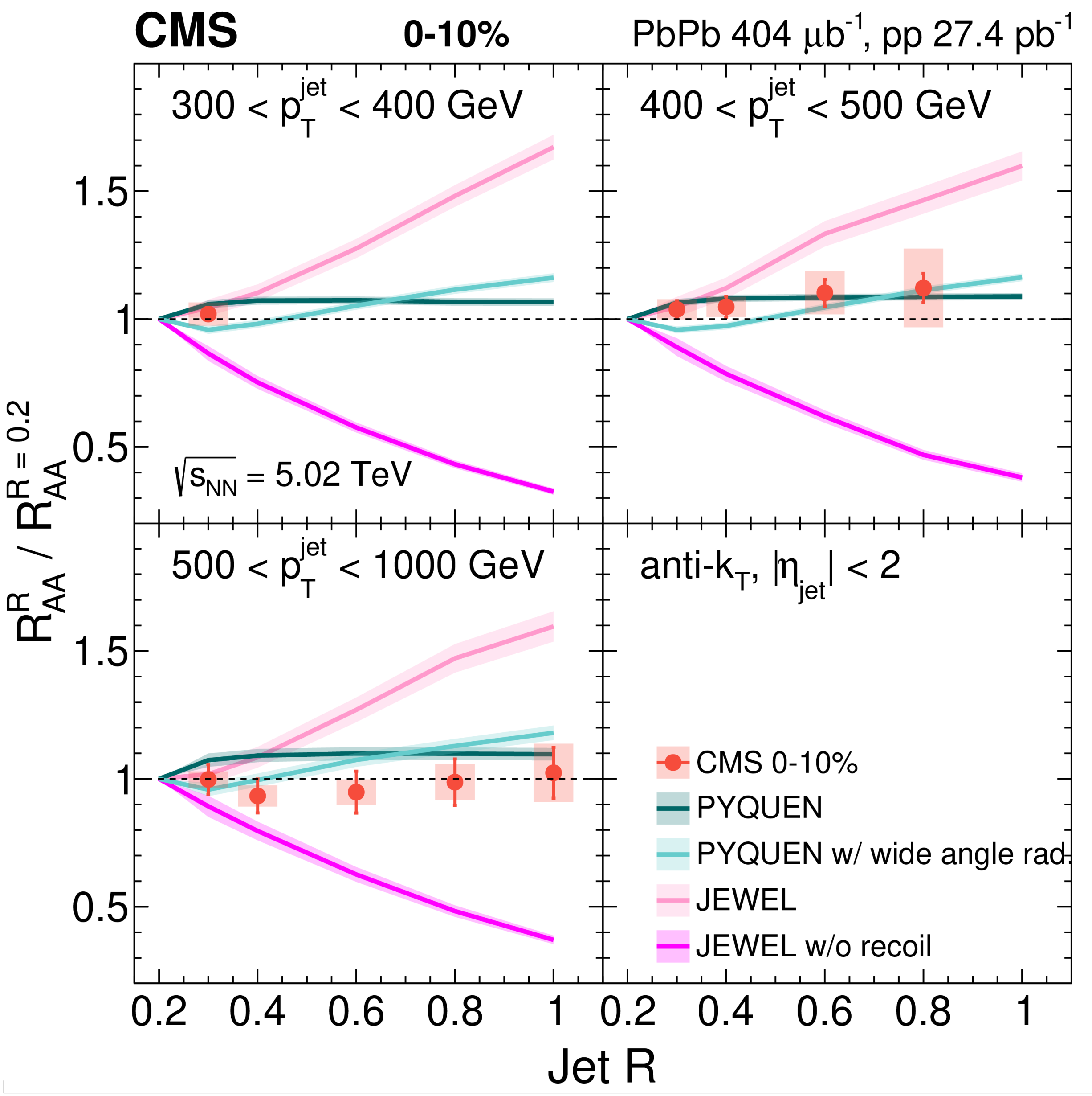
PbPb



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

Сканирование по ширине струй

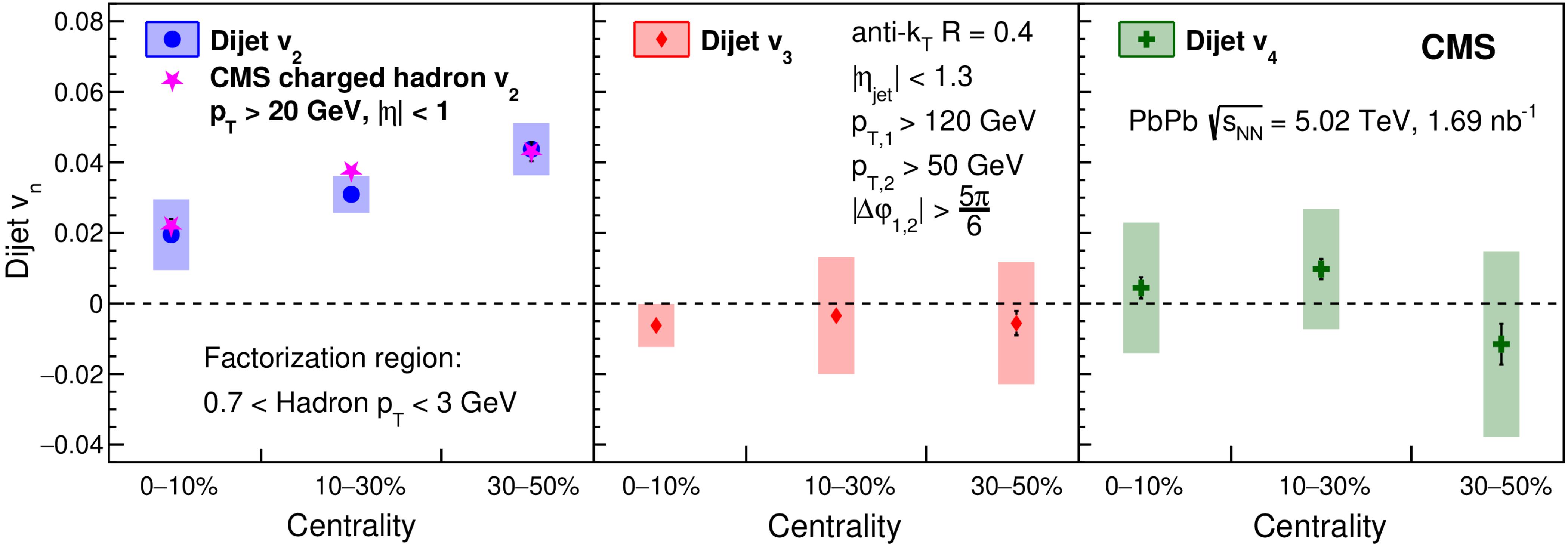
JHEP 05 (2021) 284



- 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 GeV/*c* < p_T jet. (Also for 400 < p_T jet < 500 GeV/*c*)

Азимутальная анизотропия двух-струйных событий в Pb+Pb

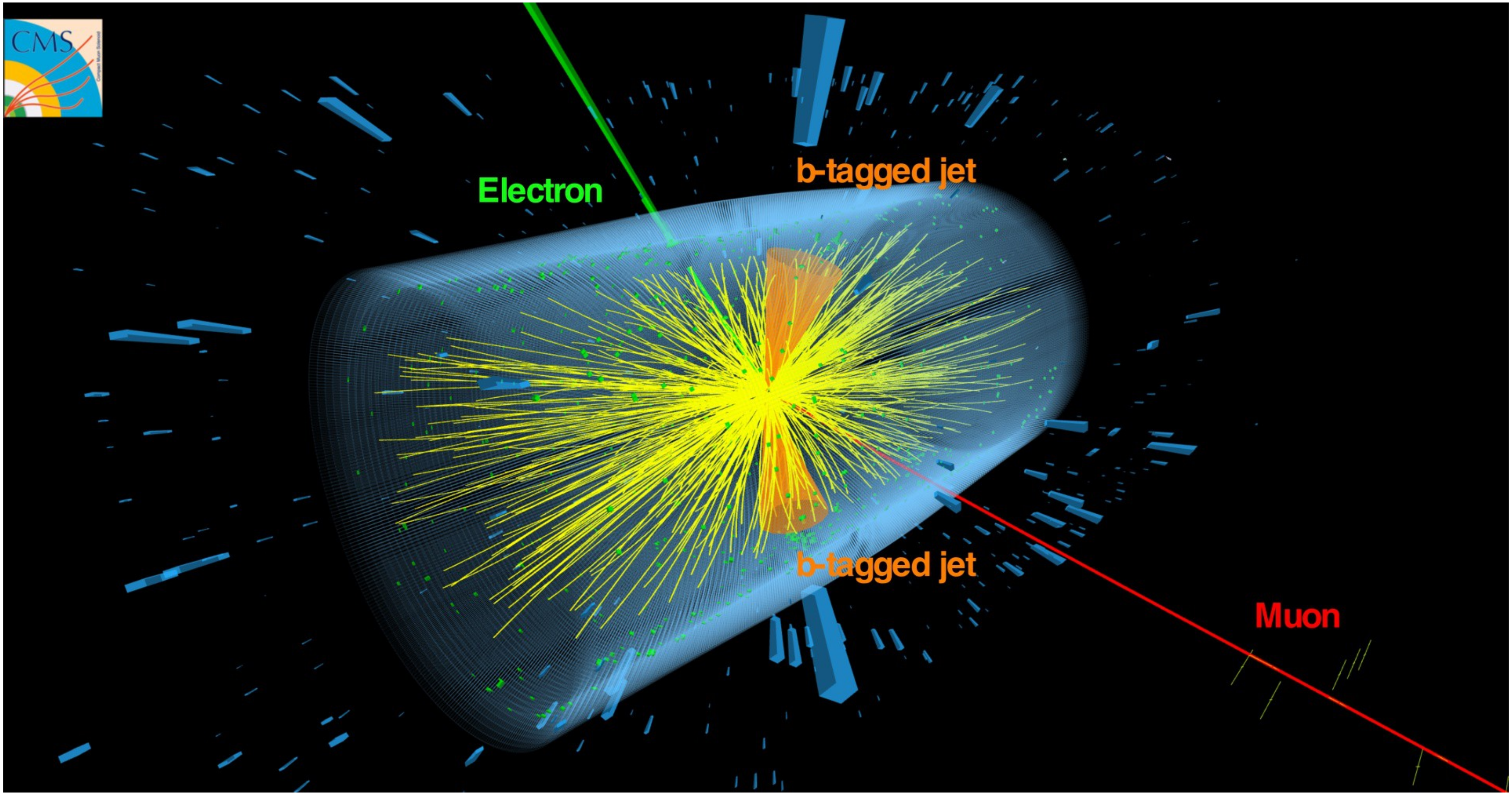
JHEP 07 (2023) 139



- 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

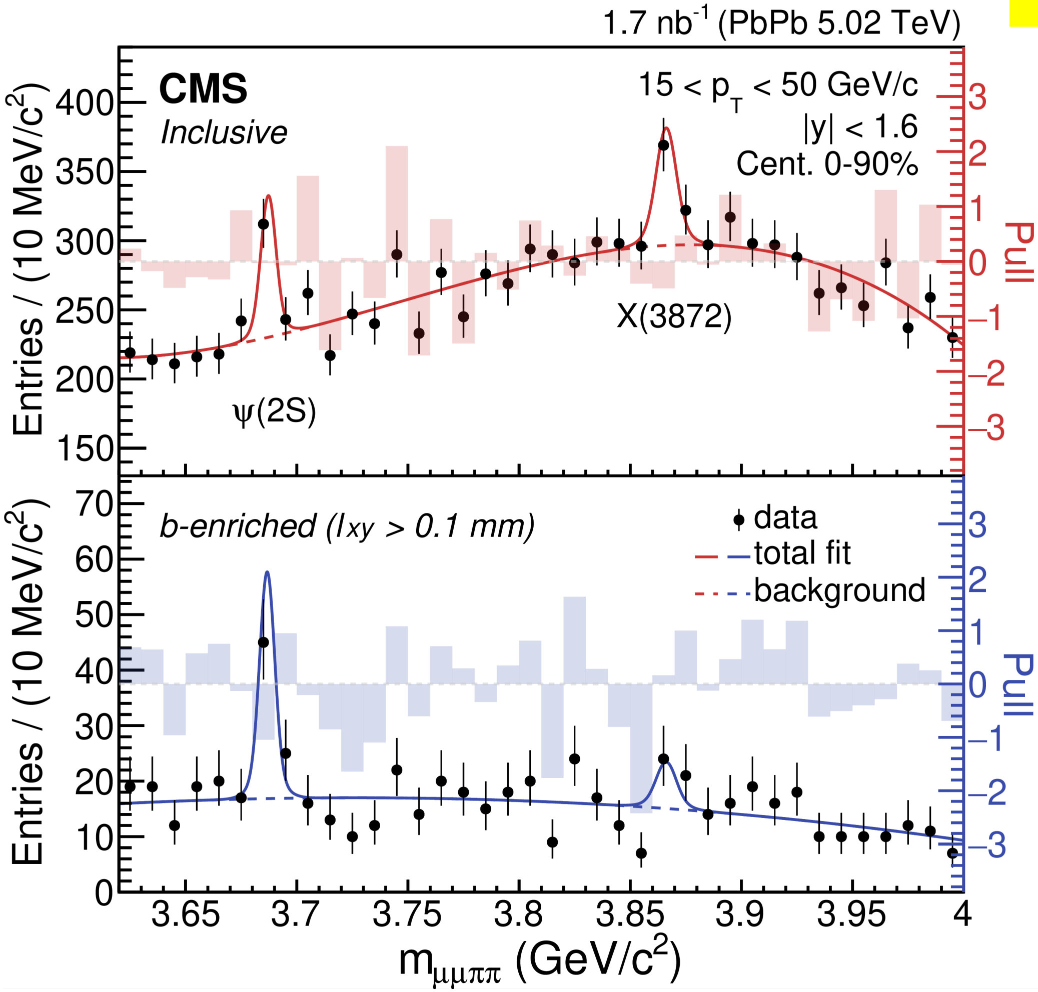
PRL 125 (2020) 222001



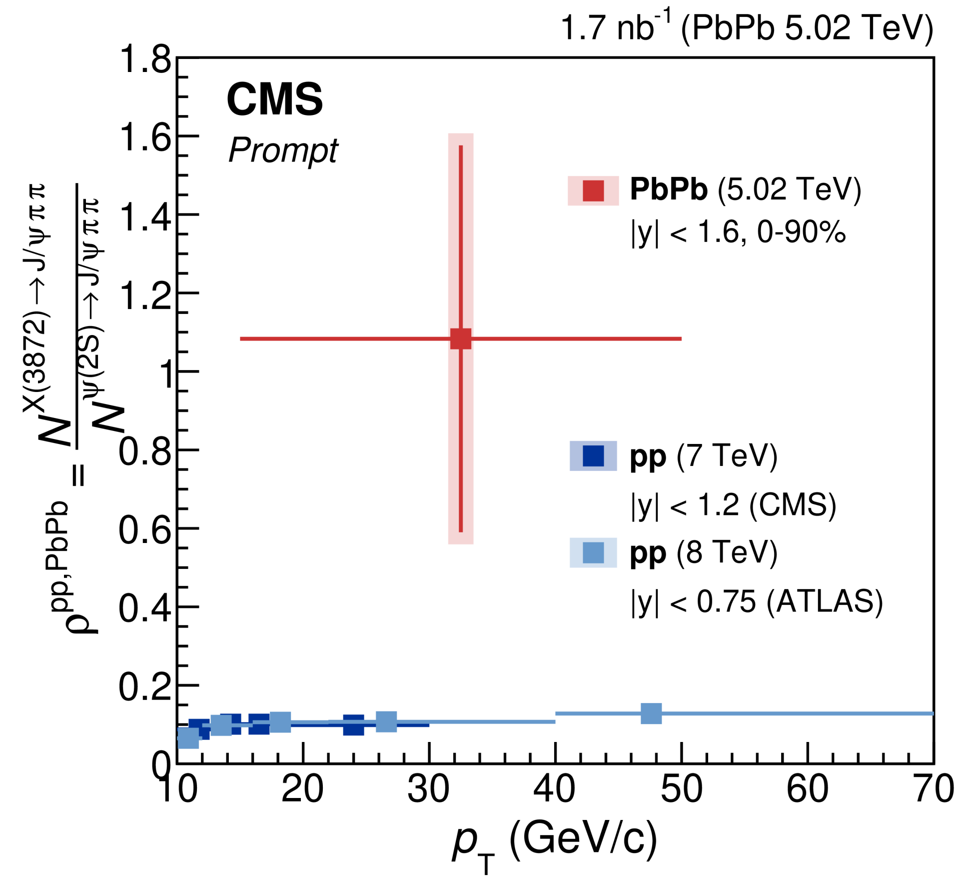
Using either charged leptons only or charged leptons + b jets.
The measured cross sections are compatible with expectations from scaled proton-proton data and QCD predictions.

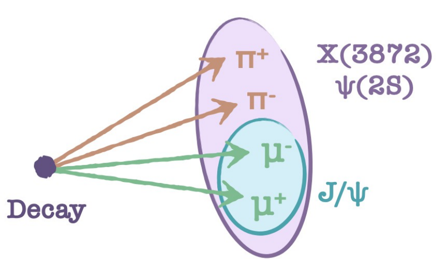
Рождение X(3872) в Pb+Pb

PRL 128 (2022) 032001



Comparison to ψ(2S)





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:

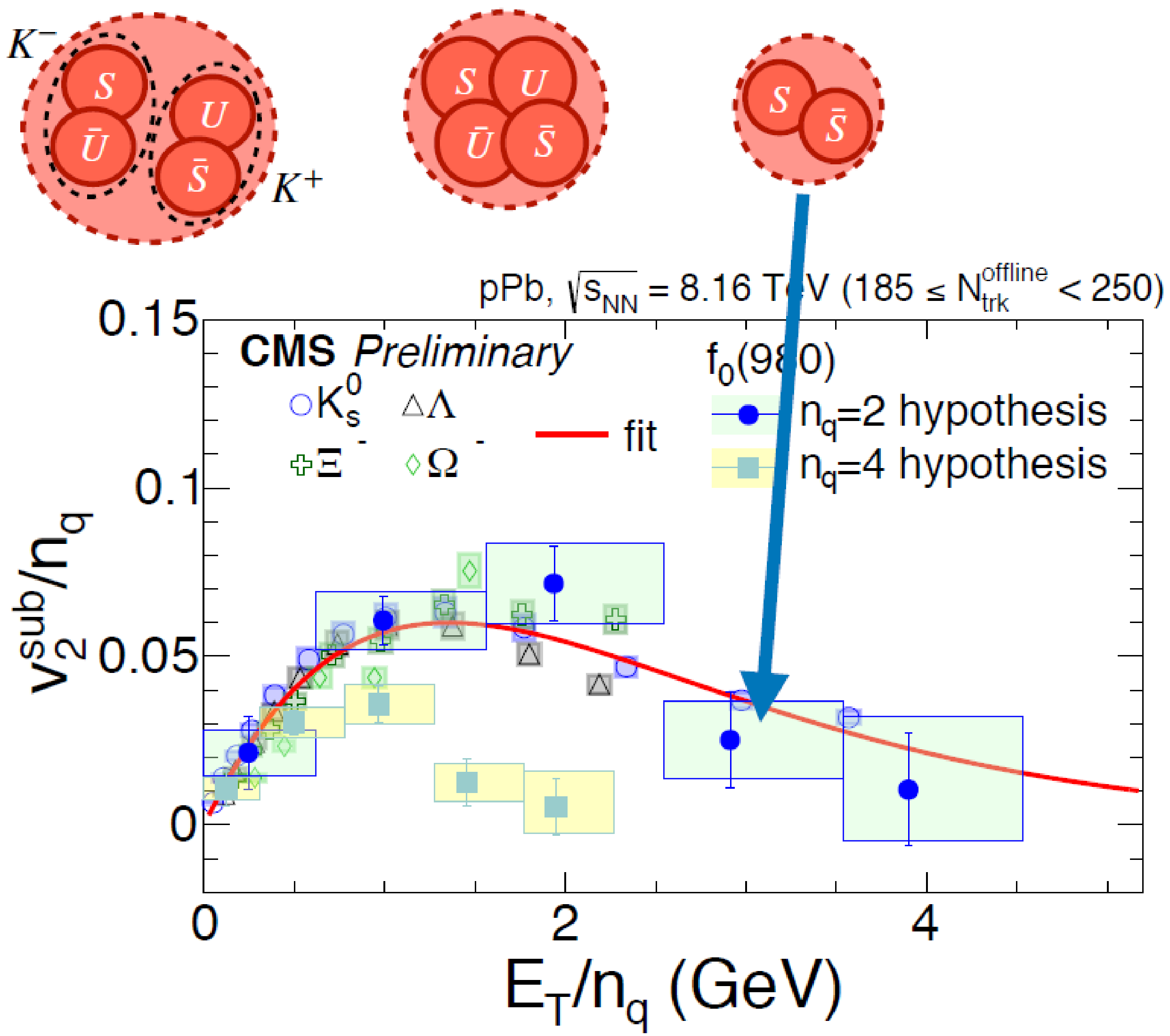
- K^-K^+ molecule
- Tetraquark
- Diquark

Use constituent quark scaling to extract number of quarks

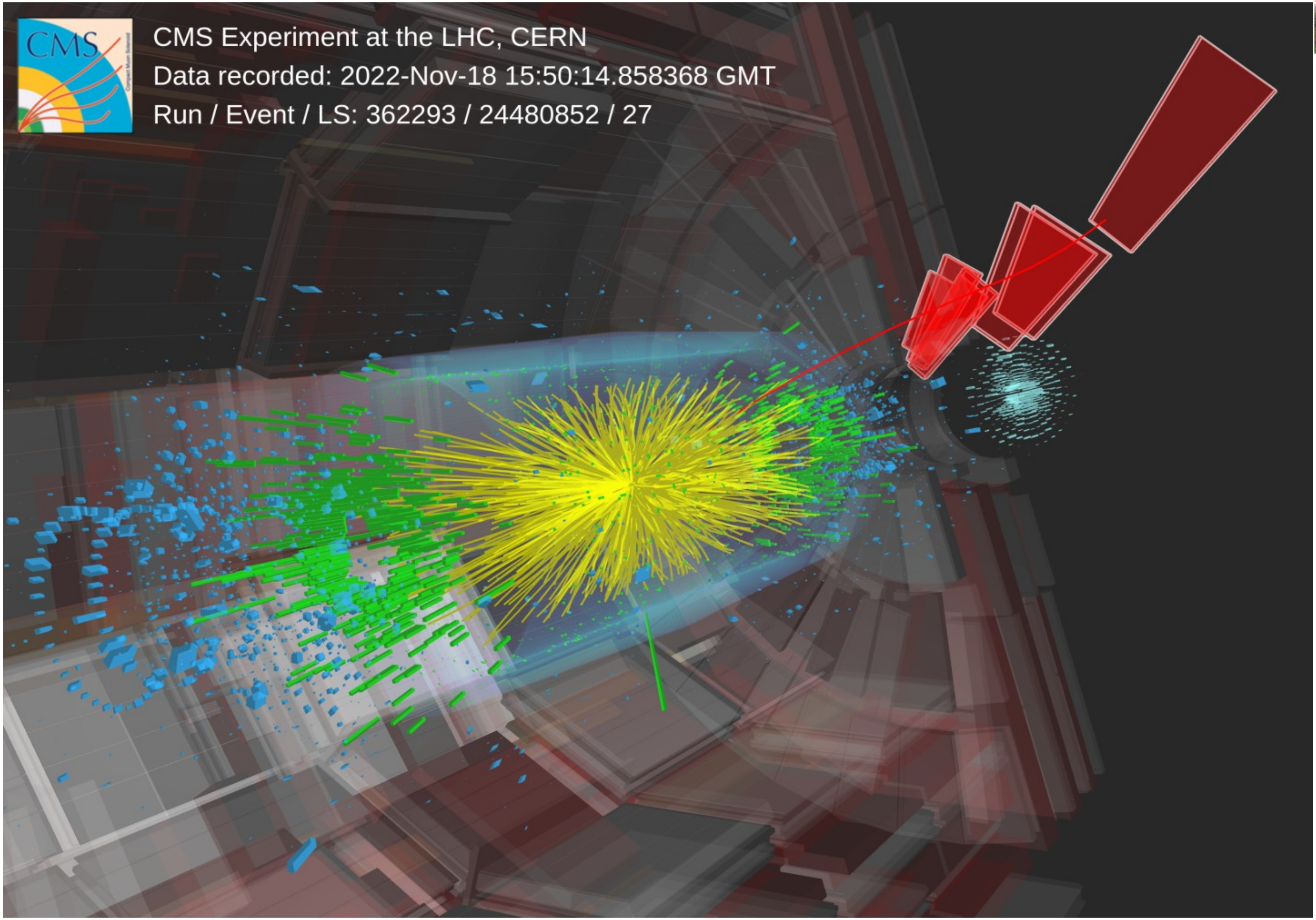
$$v_2(E_T)/n_q = v_{2,q}(E_T/n_q)$$

n_q = 4 excluded at σ > 3.1

n_q = 2 favored



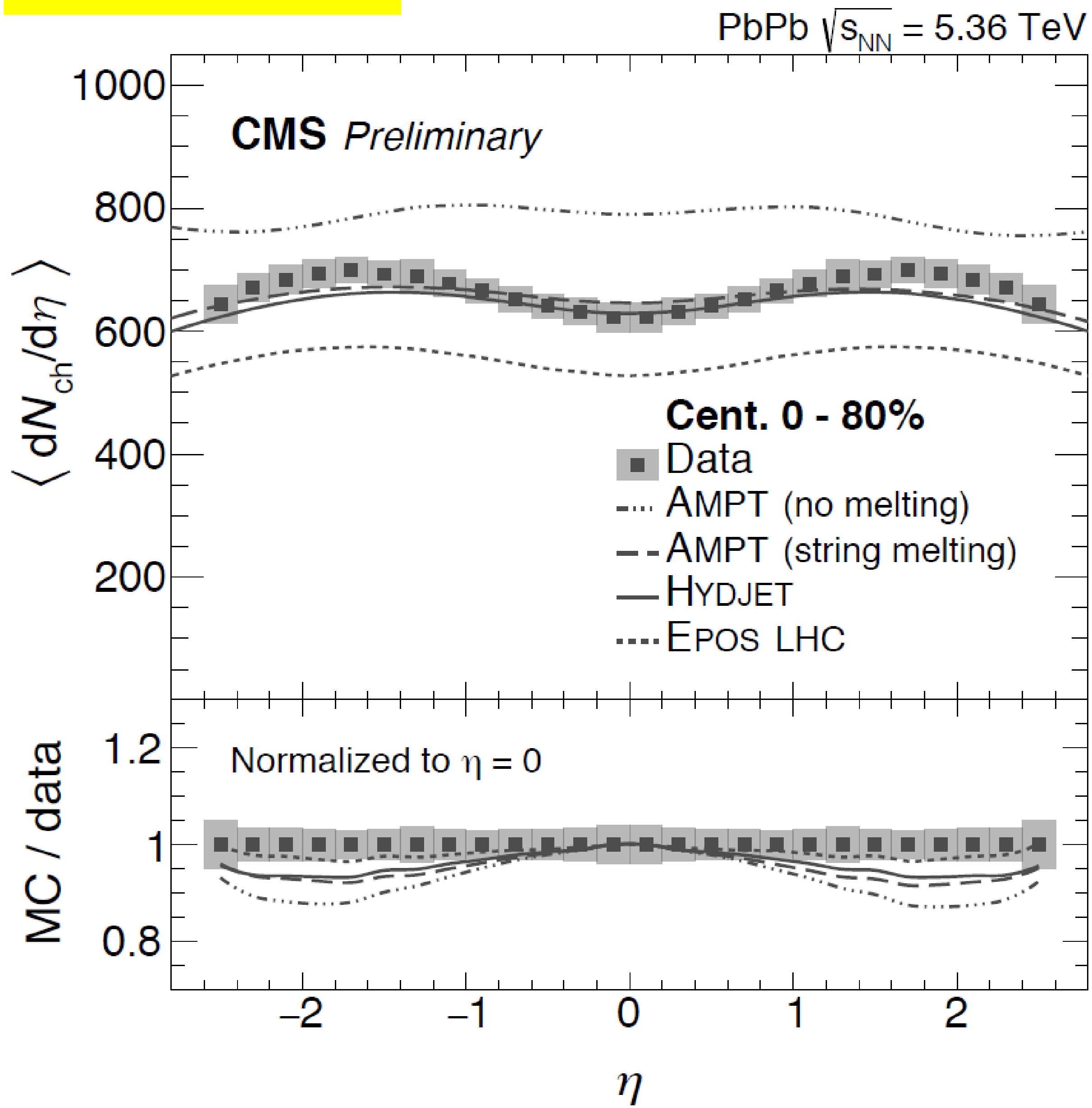
Run 3 начался в июле 2022 года



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 !

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

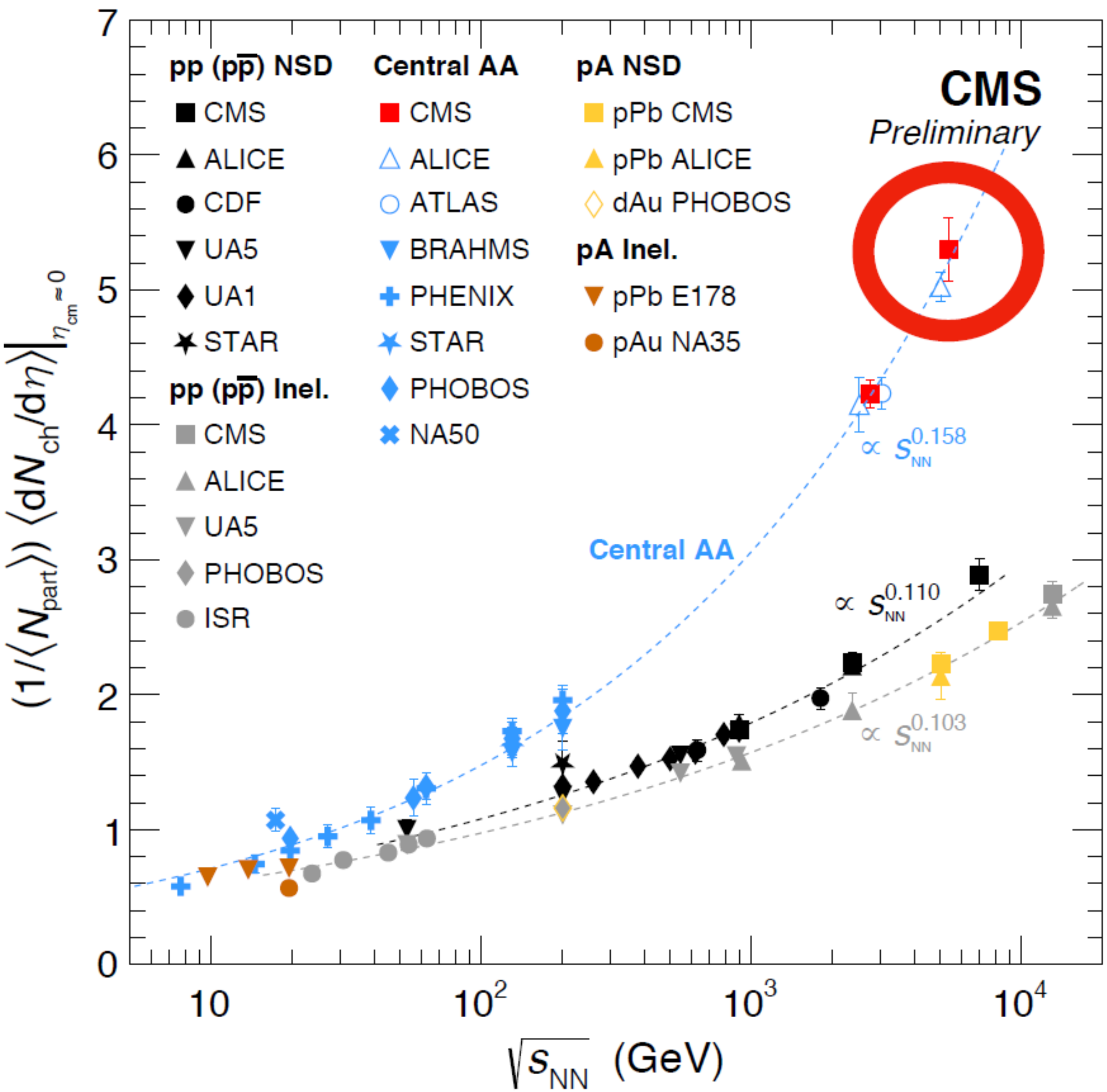
Monte Carlo generators try to predict both magnitude and shape of $dN_{ch}/d\eta$

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!**