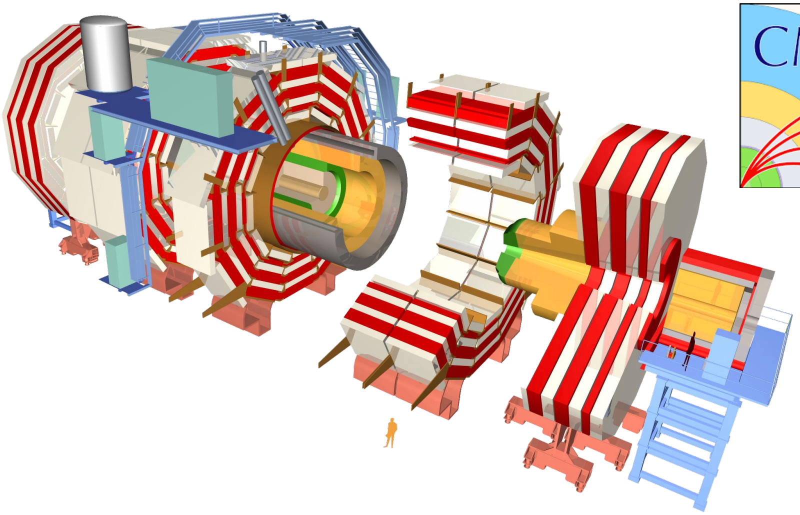
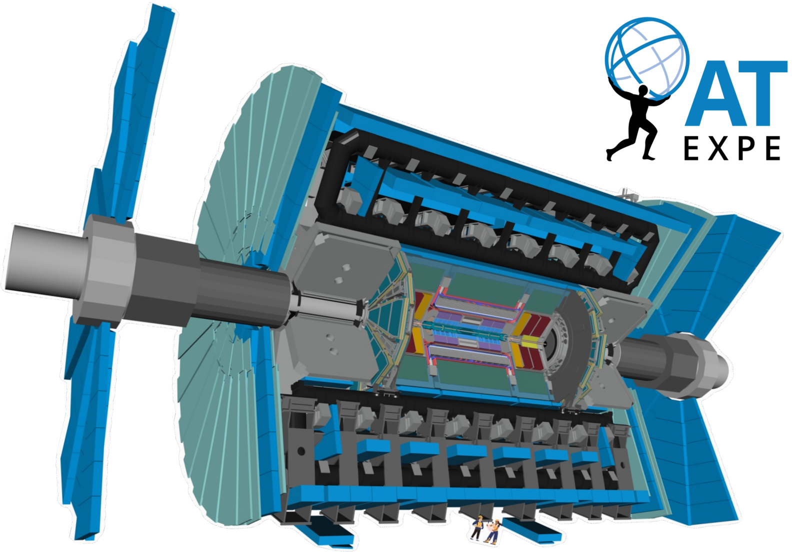
Speed of Sound in QGP and ATLAS/CMS Heavy Ion Summary

Zaochen Ye (叶早晨)

South China Normal University (华南师范大学)

Chinese Heavy Ion Teams at CMS and ATLAS





Chinese PI at CMS HI:

- Zhenyu Chen (**SDU**) – L3 **Convener** of Flow/Corr PInG
- Shuai Yang (**SCNU**) – L3 **Convener** of Dilepton PInG
- Zaochen Ye (**SCNU**) – L3 **Convener** of Fwd/UPC PInG
- Wangmei Zha (**USTC**)
- Jinlong Zhang (**SDU**)

Chinese PI at ATLAS HI:

- Xin Chen (**Tshinghua**)
- Qipeng Hu (**USTC**) – L2 **Convener** of HI
- Haifeng Li (**SDU**)
- Lei Zhang (**NJU**)

(sorted by last name)

Roughly 30-50 active members in each HIN groups

Heavy Ion Publications of CMS and ATLAS

Since CLHCP 2023:

☐ Published/accepted papers:

- **CMS:** **11** (**3** Phys. Rev. Lett., **2** Rep. Prog. Phys.)
- **ATLAS:** **5** (**3** Phys. Rev. Lett.)

CMS: ROPP 87 077801 (2024)
CMS: ROPP 87 107801 (2024)
CMS: PRL 133 142301 (2024)
CMS: PRL 133 022302 (2024)
CMS: PRL 131 262301 (2023)
....

☐ Under journal review:

- **CMS:** **7** (**2** Phys. Rev. Lett., **1** Phys. Rep., **1** Nat. Com.)
- **ATLAS:** **3** (**1** Phys. Rev. Lett.)

ATLAS: arXiv:2407.06413 (accepted by PRL)
ATLAS: PRL 132 202301 (2024)
ATLAS: PRL 132 102301 (2024)
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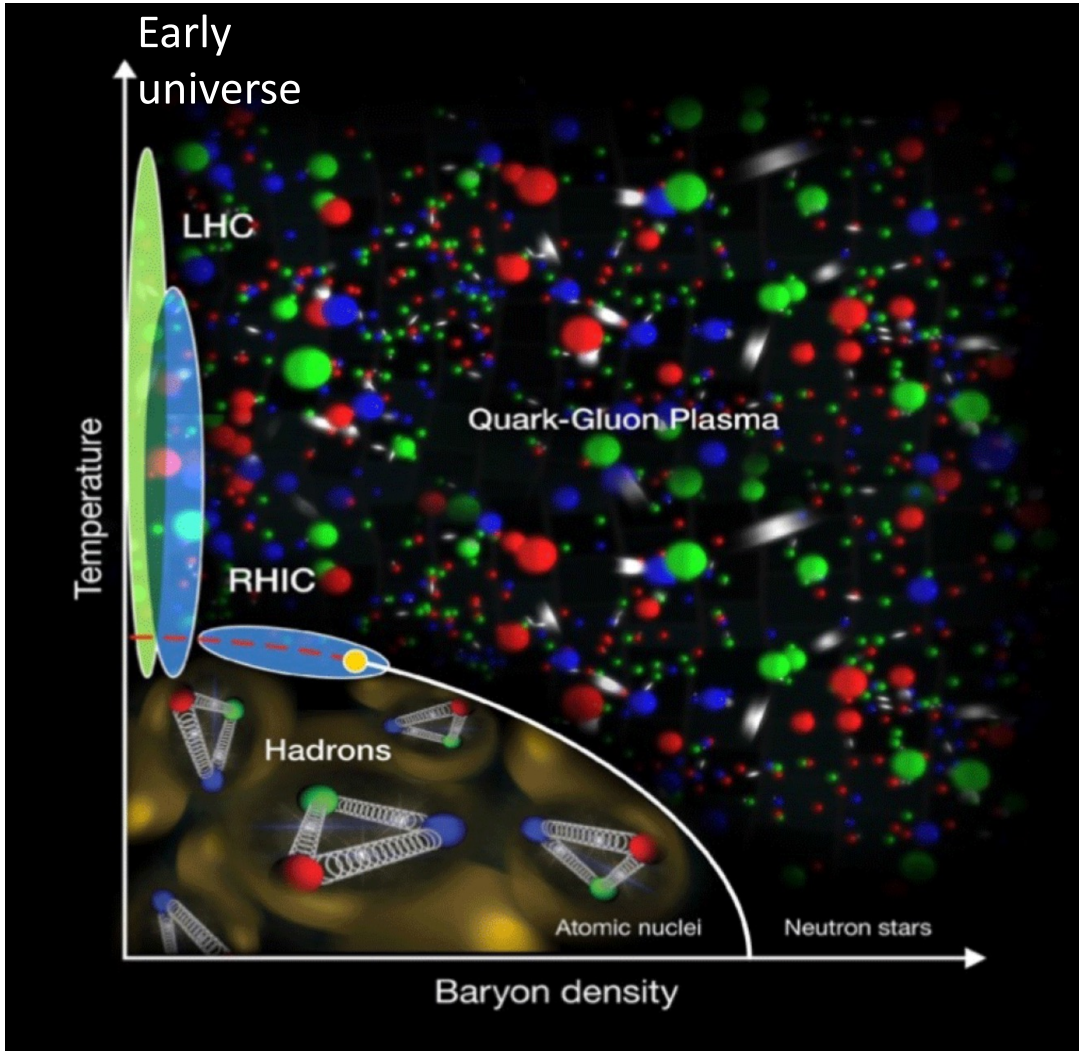
This talk present selected results from recent publications and preliminary

QCD Phase Diagram and Heavy Ion Collisions



- **QCD phase diagram:**
  - Describes phases of matter under various conditions of temperature (T) and chemical potential (μ_B)

- **Heavy-ion collisions** create extreme conditions:
  - Explore QCD diagram with different trajectories

- **Open questions:**
  - What's the d.o.f of the created QCD matter
  - What's the nature of phase transition?
    - 1st-order? Critical end point?
  - What is the equation of state (EoS) of QGP?

EoS and Thermodynamics

An EoS is a thermodynamic equation relating state variables ($\boldsymbol{p, E, S, V, T}$)

General form: $f(p, V, T) = 0$

Idea gas: $f(p, V, T) = pV - nRT = 0$

Ultra-relativistic fluid: $\boldsymbol{f(p, V, T) = p - \varepsilon c_s^2 = 0}$

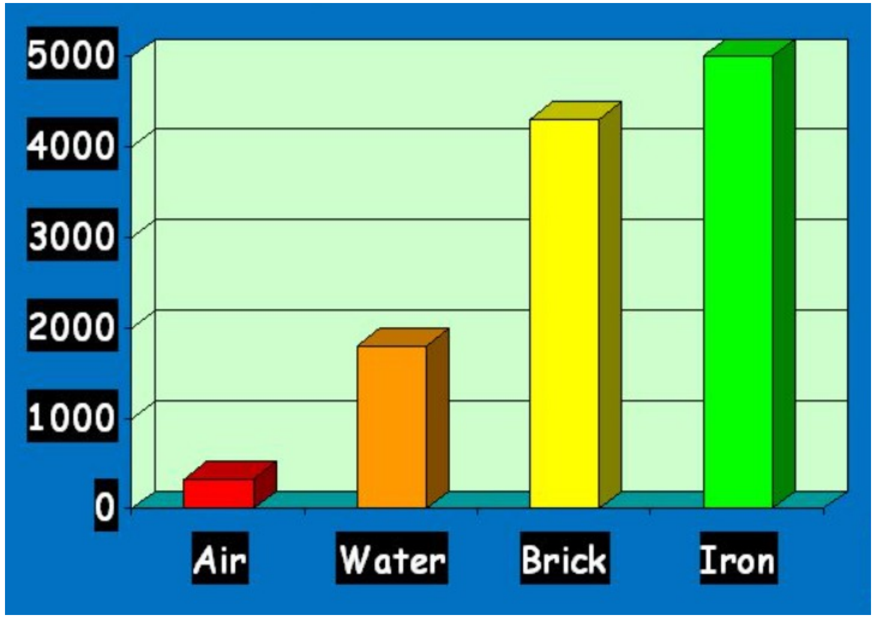
Number of independent variables depends on the substrances and phases of the system

Constrain EoS via Speed of Sound Measurement

Speed of sound tells how fast sound wave propagate

- Sensitive to **substance, stiffness, density and temperature**

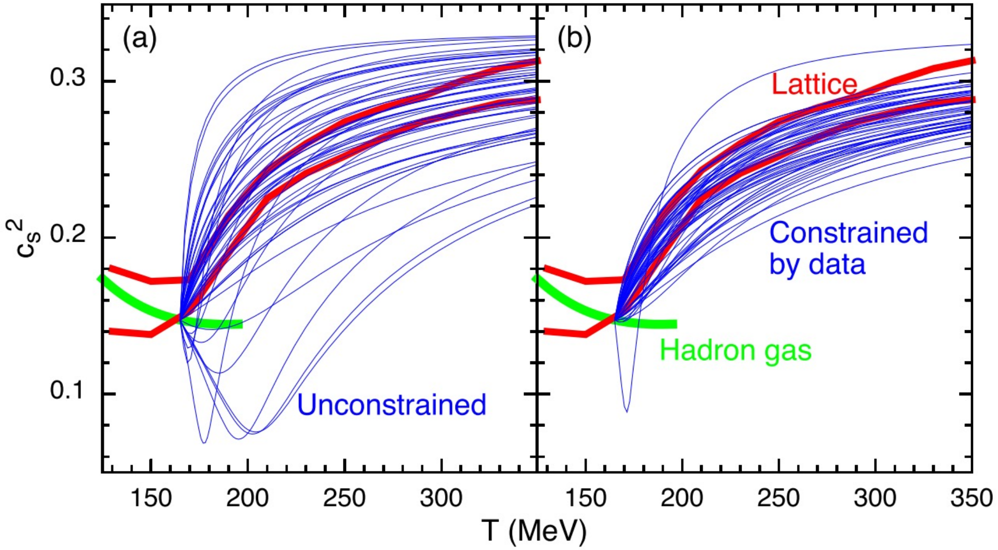
Speed of sound (m/s)



In QGP:

$$\boxed{c_s^2 = \frac{dP}{d\varepsilon}}$$

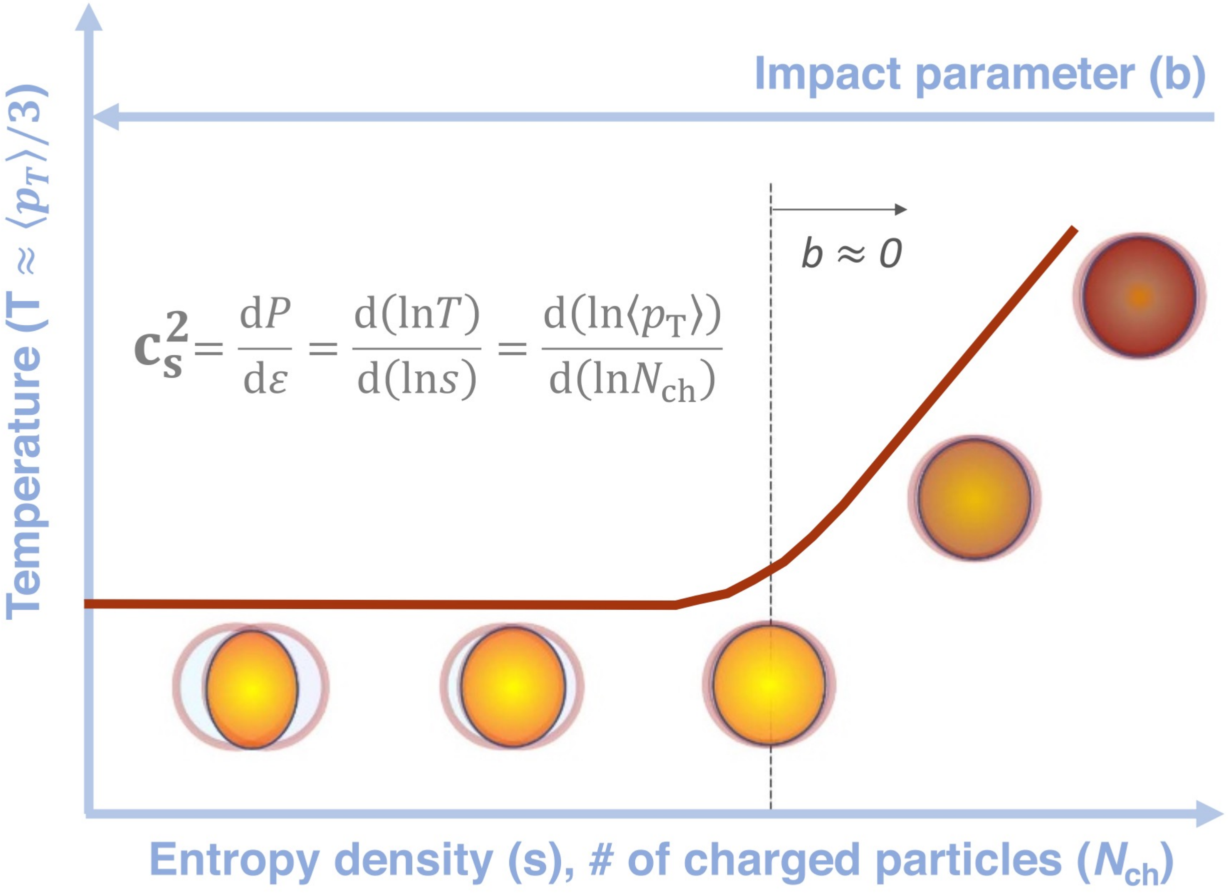
Extract by Bayesian fit to RHIC-LHC Data (PRL 114 202301 (2015))



- 14 free parameters
- Large uncertainties

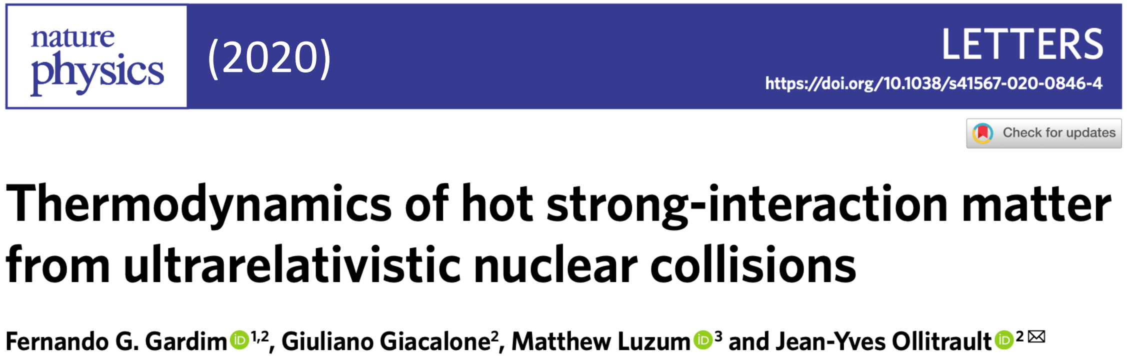
Precision measurement of speed of sound directly constrain the EoS

Constrain EoS via Speed of Sound Measurement



$$c_s^2 = \frac{dP}{d\varepsilon} = \frac{d(\ln T)}{d(\ln s)} = \frac{d(\ln\langle p_T\rangle)}{d(\ln N_{ch})}$$

Measure the speed of sound in ultral-central collision (UCC)


nature physics (2020) LETTERS

https://doi.org/10.1038/s41567-020-0846-4

Check for updates

Thermodynamics of hot strong-interaction matter from ultrarelativistic nuclear collisions

Fernando G. Gardim[1,2], Giuliano Giacalone[2], Matthew Luzum[3] and Jean-Yves Ollitrault[2] ✉

Energy and **entropy** of fluid at freeze-out:

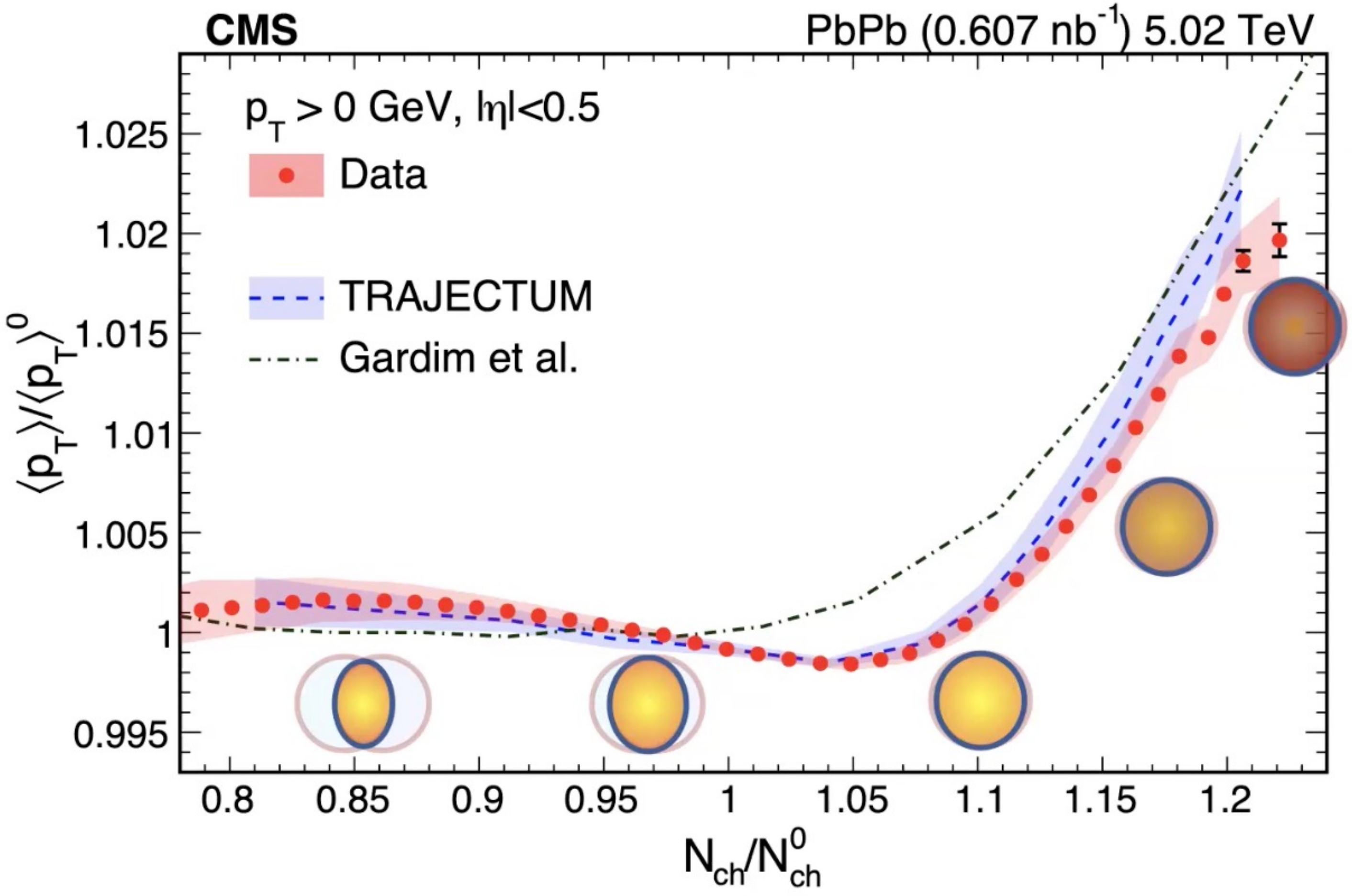
$$E = \int_{\mathrm{f.o.}} T^{0\mu} d\sigma_\mu = \epsilon(T_{\mathrm{eff}}) V_{\mathrm{eff}}$$

$$S = \int_{\mathrm{f.o.}} s u^\mu d\sigma_\mu = s(T_{\mathrm{eff}}) V_{\mathrm{eff}}$$

$$\frac{ds(T_{\mathrm{eff}})}{s(T_{\mathrm{eff}})} = \frac{dN_{\mathrm{ch}}}{N_{\mathrm{ch}}}, \qquad \frac{dT_{\mathrm{eff}}}{T_{\mathrm{eff}}} = \frac{d\langle p_t\rangle}{\langle p_t\rangle}$$

$$\boxed{c_s^2(T_{\mathrm{eff}}) \equiv \frac{dP}{d\varepsilon} = \left.\frac{s\,dT}{T\,ds}\right|_{T_{\mathrm{eff}}} = \frac{d\ln\langle p_t\rangle}{d\ln(dN_{\mathrm{ch}}/d\eta)}}$$

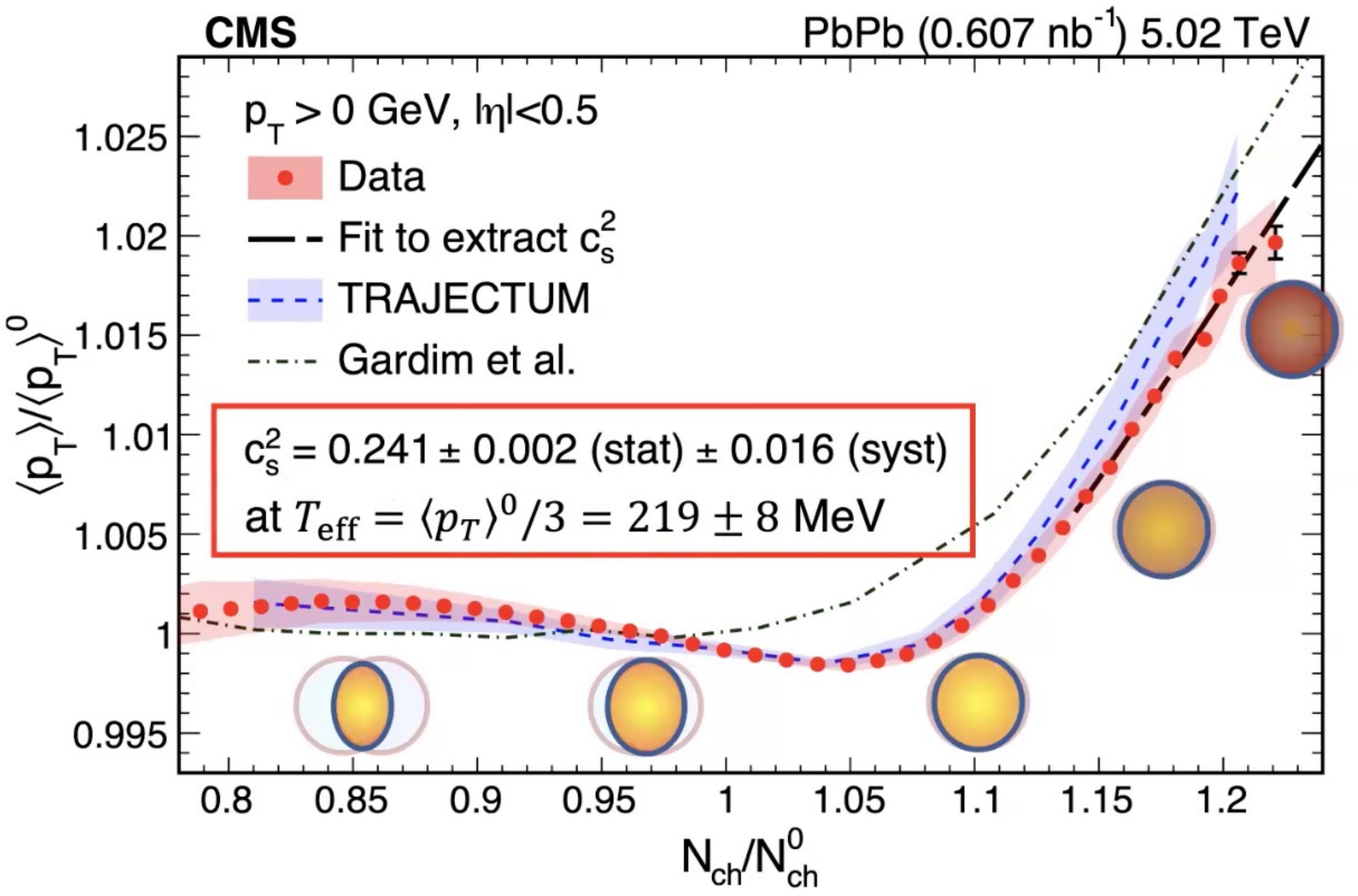
Normalized "$<p_T>$ vs. N_{ch}"



CMS: Rep. Prog. Phys. 87 077801 (2024)

- **Data shows very clear rising trend in UCC**
- TRAJECTUM model calculation with (EoS from lQCD, Hydrodynamic simulations) **perfectly predicted the data**

Extraction of Speed of Sound of QGP



CMS: Rep. Prog. Phys. 87 077801 (2024)

The c_s^2 extracted by fitting:

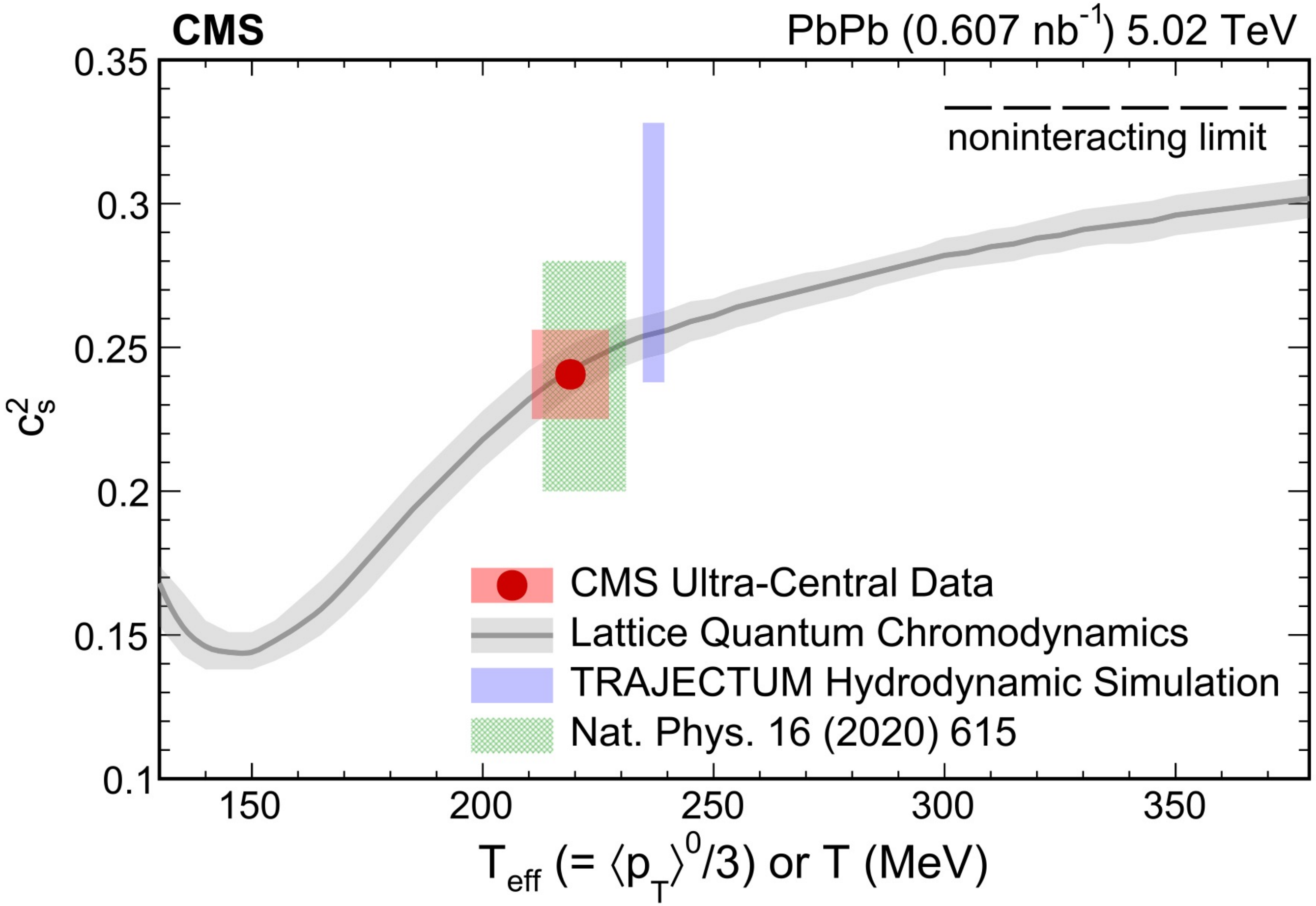
$$\langle p_{\rm T}\rangle^{\rm norm} = \left(\frac{N_{\rm ch}^{\rm norm}}{\langle \overline{N_{\rm ch}^{\rm knee}} \,|\, N_{\rm ch}^{\rm norm}\rangle}\right)^{\boxed{c_s^2}}$$

$$\langle \overline{N_{\rm ch}^{\rm knee}} \,|\, N_{\rm ch}^{\rm norm}\rangle = N_{\rm ch}^{\rm norm} - \sigma\sqrt{\frac{2}{\pi}}\,\frac{\exp\left(-\frac{(N_{\rm ch}^{\rm norm}-\overline{N_{\rm ch}^{\rm knee}})^2}{2\sigma^2}\right)}{\mathrm{erfc}\left(\frac{N_{\rm ch}^{\rm norm}-\overline{N_{\rm ch}^{\rm knee}}}{\sqrt{2}\sigma}\right)}$$

Sound travels in QGP at LHC
with ~ 50% c in vacuum!

Breaking the exist record 💎 by a factor of ~20000

Constrain EoS in UCC



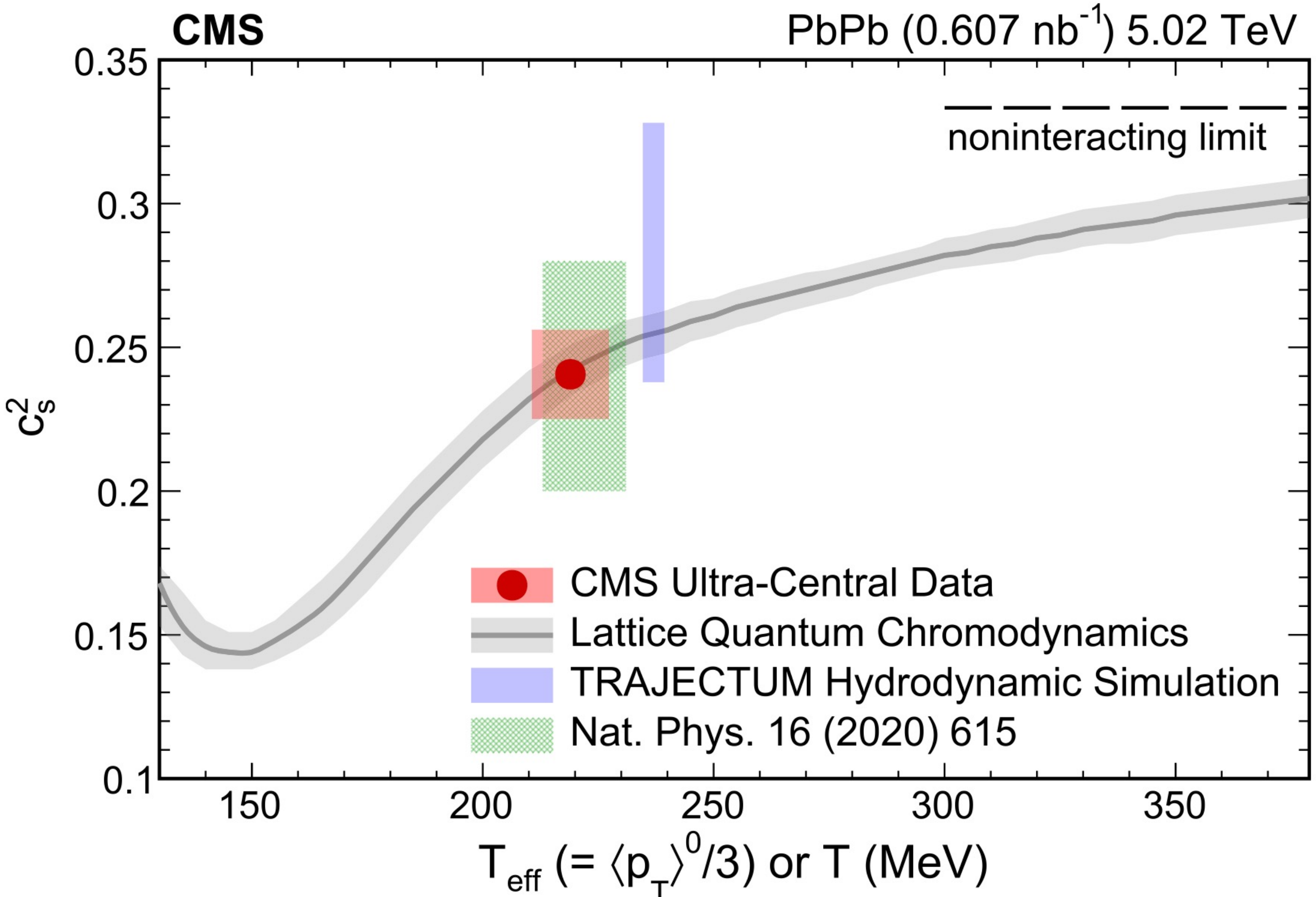
CMS: Rep. Prog. Phys. 87 077801 (2024)

Precise determination of speed of sound of hot medium created in PbPb UCC:

- Agrees with LQCD, where a deconfined phase is predicted
  - → **strong evidence that QGP is formed**

- Provide the **best direct experimental constraints on the EOS** of hot QCD medium at **QGP** phase

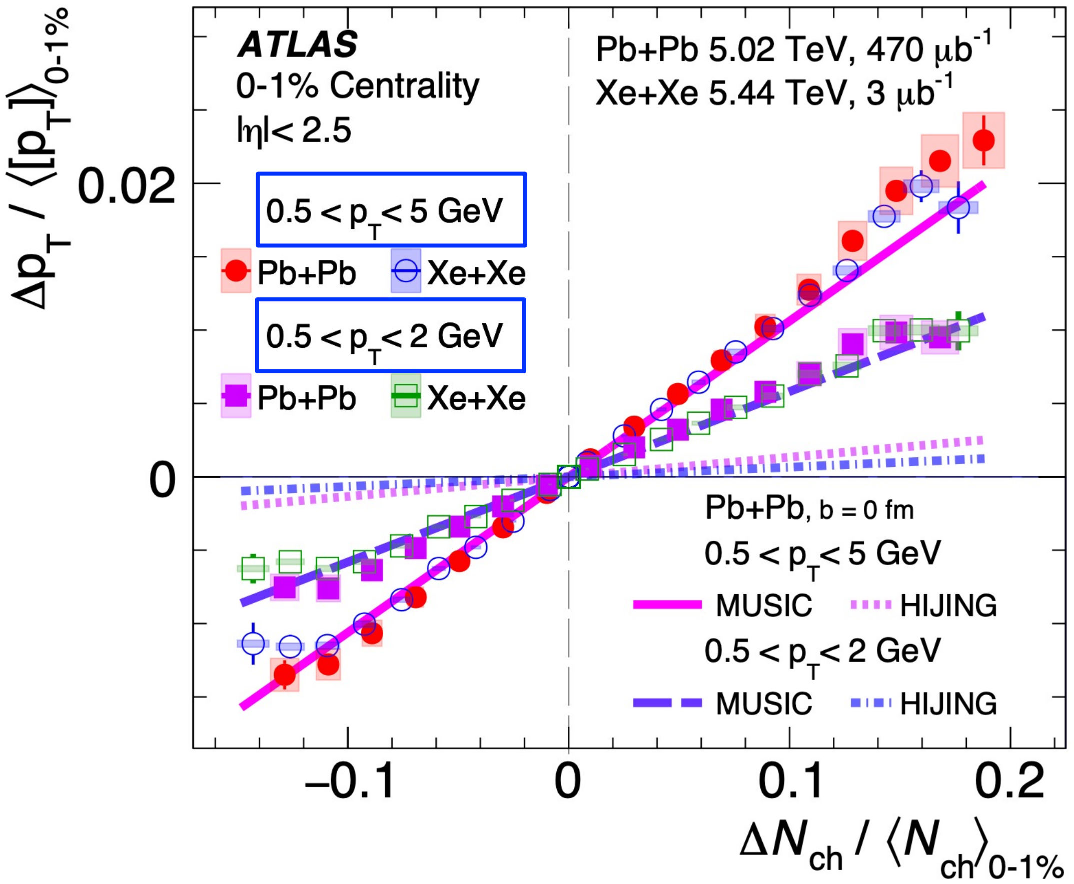
Constrain EoS in UCC



CMS: Rep. Prog. Phys. 87 077801 (2024)

$$c_s^2 \approx 0.23 \text{ with } T_{\text{eff}} \approx 222 \text{ MeV}$$

$$c_s^2(T_{\text{eff}}) \propto \frac{d\ln(\langle[p_{\text{T}}]\rangle)}{d\ln(N_{\text{ch}})} \approx \frac{\Delta p_{\text{T}}/\langle[p_{\text{T}}]\rangle}{\Delta N_{\text{ch}}/\langle N_{\text{ch}}\rangle}$$



ATLAS **Xe+Xe/Pb+Pb** data are well described by MUSIC model where: $c_s^2 \approx 0.23$ and $T_{eff} = 222\ MeV$

Consistent with CMS extracted values

Study Geometric/Intrinsic Fluctuations in UCC

Initial conditions of heavy ion collisions vary event-by-event due to fluctuations

Geometric fluctuations:
Transverse size R

At fixed N_{ch}, R (b) fluctuates

Intrinsic fluctuations:
Nucleon and parton positions, energy density, entropy

At fixed R(b), N_{ch} fluctuates

In UCC (b→0), R and N_{part} reach maximum values, **geometric fluctuations are suppressed**

→ excellent environment to study the intrinsic fluctuations.

$$\langle [p_{\mathrm{T}}] \rangle$$

Avg Mean

$$k_2 = \frac{\langle c_2 \rangle}{\langle [p_{\mathrm{T}}] \rangle^2}$$

Norm. Variance

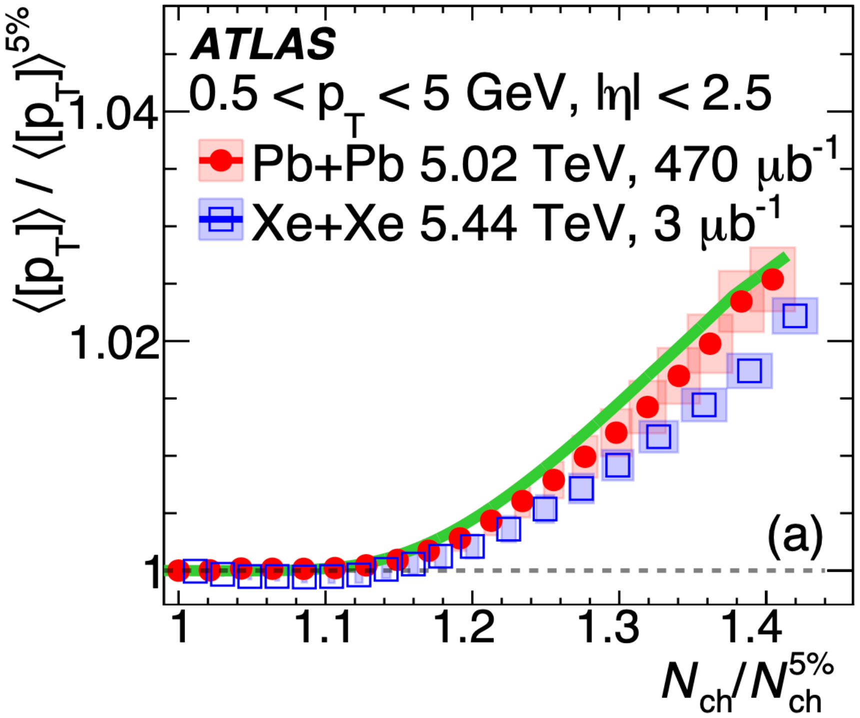
$$k_3 = \frac{\langle c_3 \rangle}{\langle [p_{\mathrm{T}}] \rangle^3}$$

Norm. Skewness

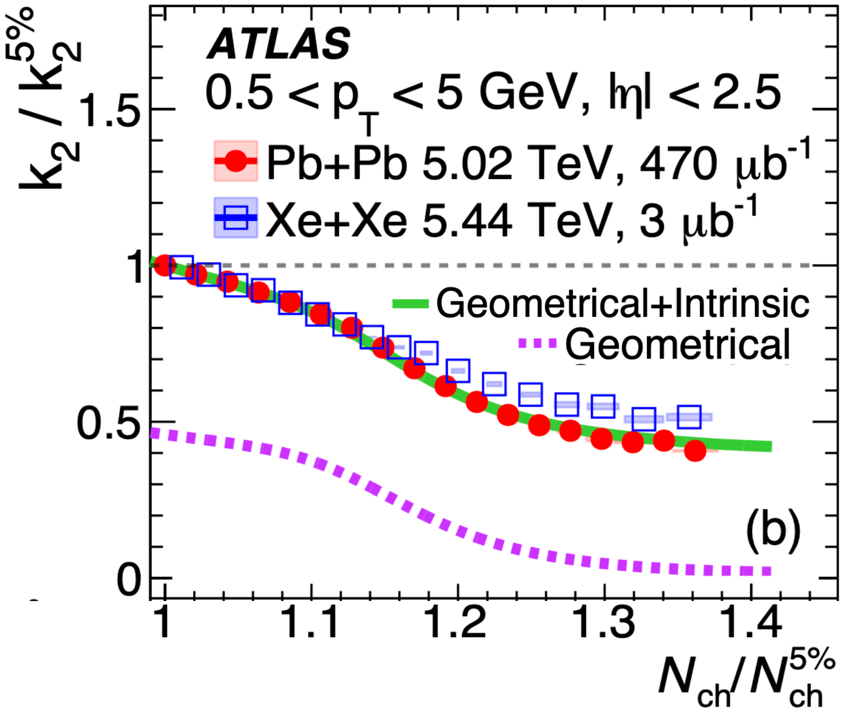
Study mean, variance and skewness of $[p_T]$ in UCC can explore the intial-state variations.

Study Geometric/Intrinsic Fluctuations in UCC

Norm. Mean

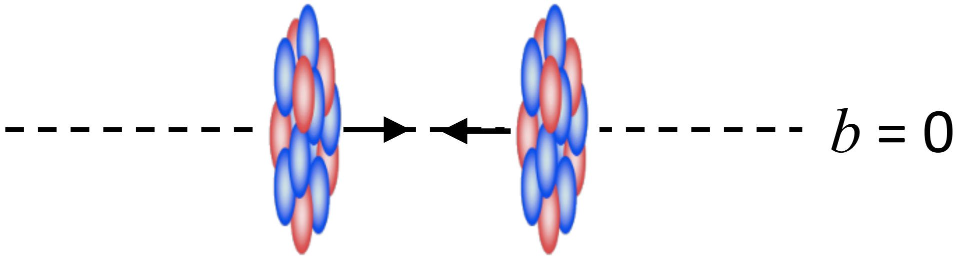


Norm. Variance

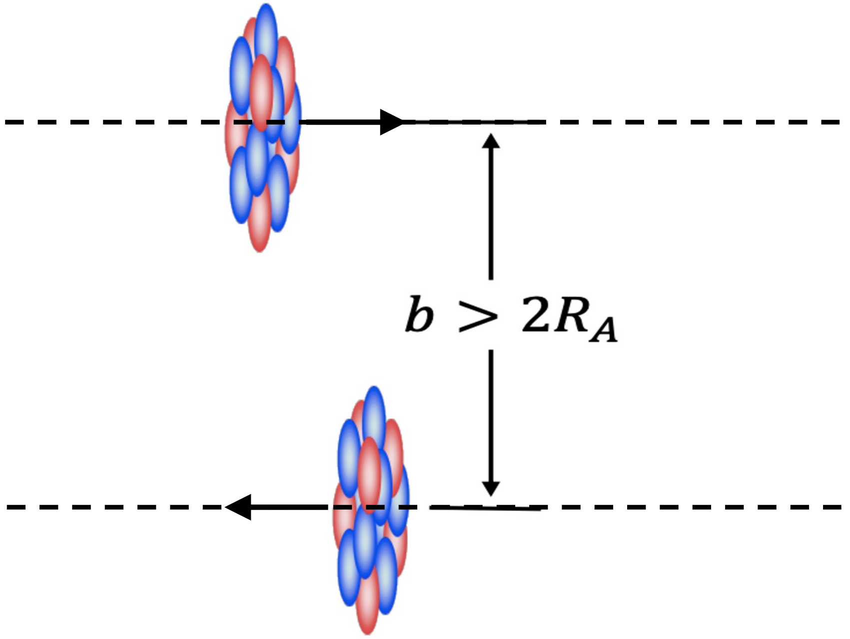


- **Similar rising** <[pT]> trend for Pb+Pb and Xe+Xe collisions
- **Variance** (k_2) **decrease with multiplicity**, model calculations have to include **both geometric and intrinsic fluctuations**
  - → Decreasing variance of geometrical fluctuations at b → 0
  - **→ Rising <[pT]> is driven by intrinsic fluctuations**

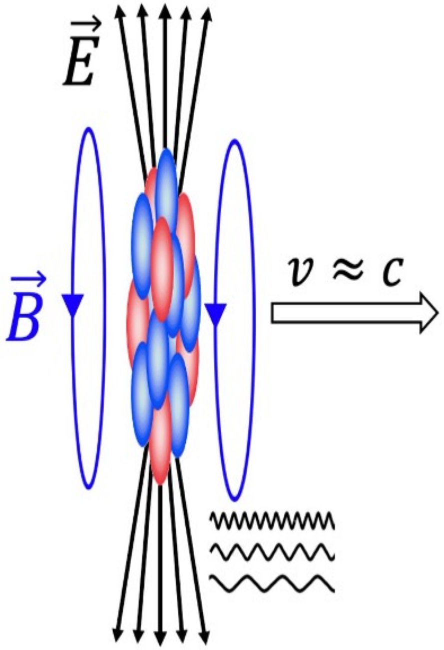
Ultra-Central Collision (UCC)



Ultra-Peripherial Collision (UPC)

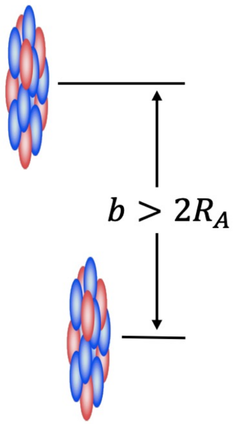


Ultra-Peripheral Collision (UPC)

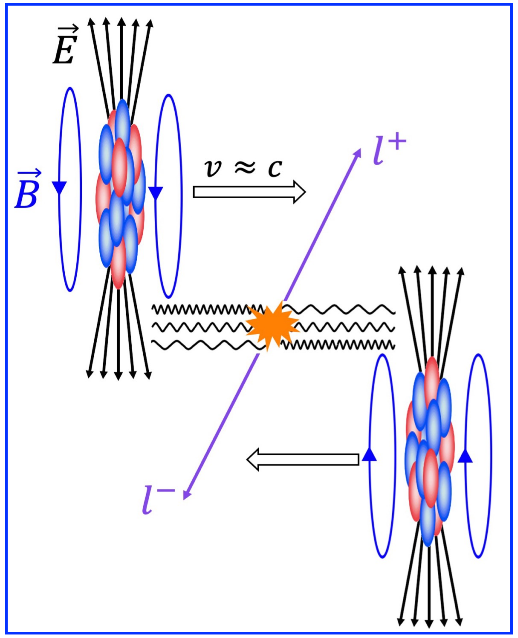


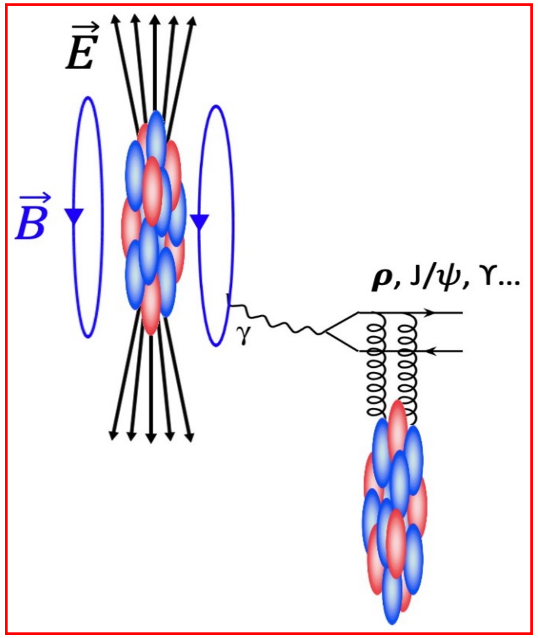
- **Lorentz contracted EM fields → flux of quasi-real photons ($Q^2<\hbar^2/R^2$).**
- **The photon flux ∝ Z^2.**
- **Photon kinematics: $p_T < \hbar/R_A$ ~ 30 MeV (E_{max} ~ 80 GeV) at LHC.**

UPC:



Heavy ion collider is also a Photon-Photon and Photon-Ion collider !!!





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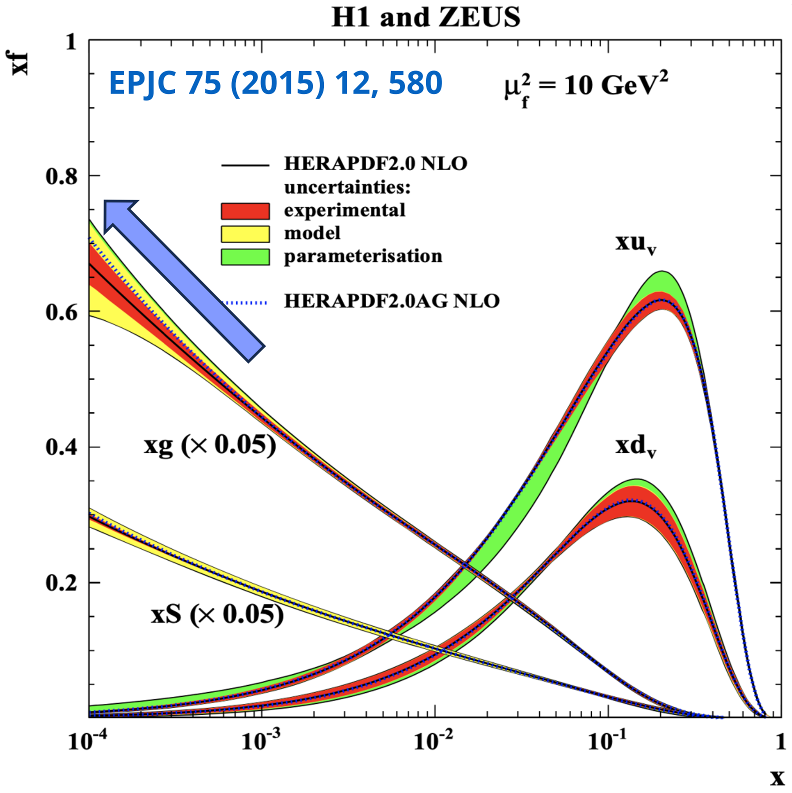
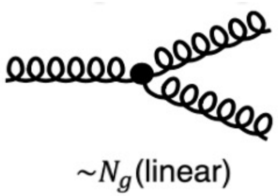
- **Exam QED at extreme field**
- **Investigate nuclear structure**
- **Search for new physics**

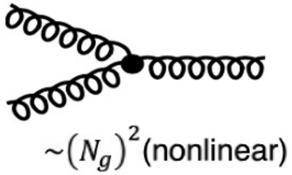
Search for Gluon Saturation in Heavy Nucleus

Gluons are found be increasingly dominant constituents of nucleus and nucleons

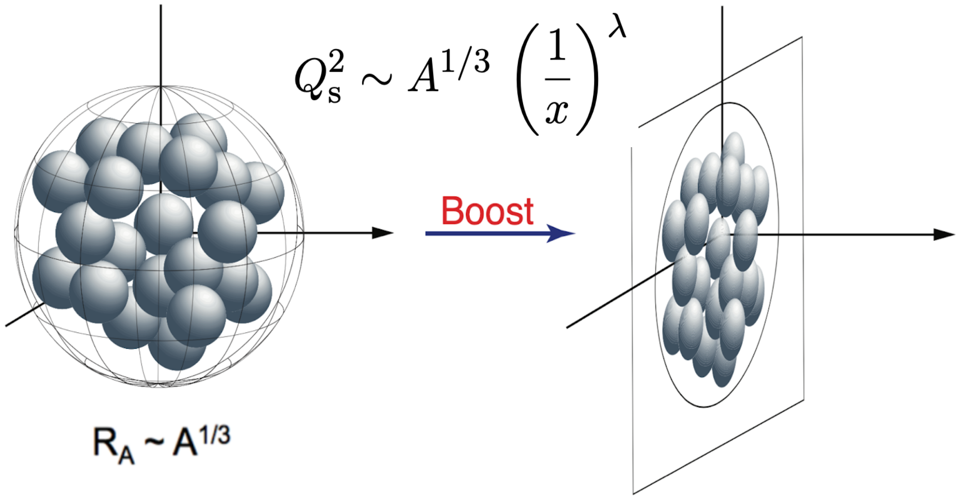




Gluon saturation?



Gluon density is **enhanced** in **nucleus**

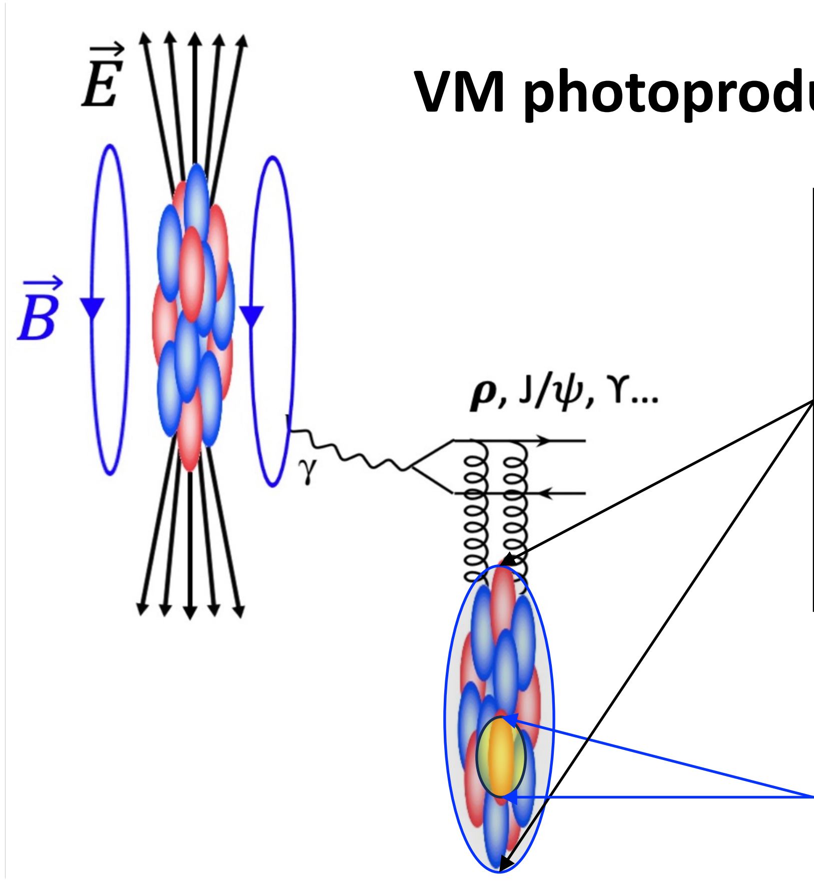


$$Q_s^2 \sim A^{1/3} \left(\frac{1}{x}\right)^{\lambda}$$

- **Gluon saturation is expected to be more easily reached in heavy nuclei**

Vector Meson Photoproduction in UPCs

VM photoproduction is sensitive to the gluonic structure of target nucleus



Coherent photoproduction:

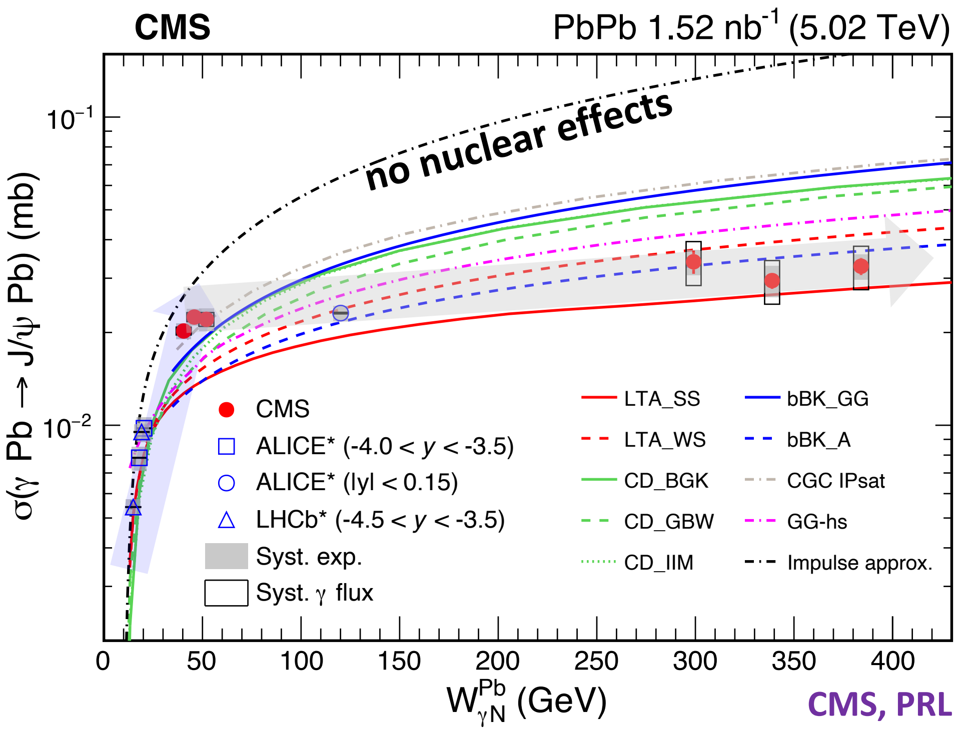
- Photon **interact with entire nucleus**
- **Target** nucleus remains **intact**
- VM $\langle p_T \rangle$ ~ **50 MeV**
- Probing the **averaged gluon density**

Incoherent photoproduction:

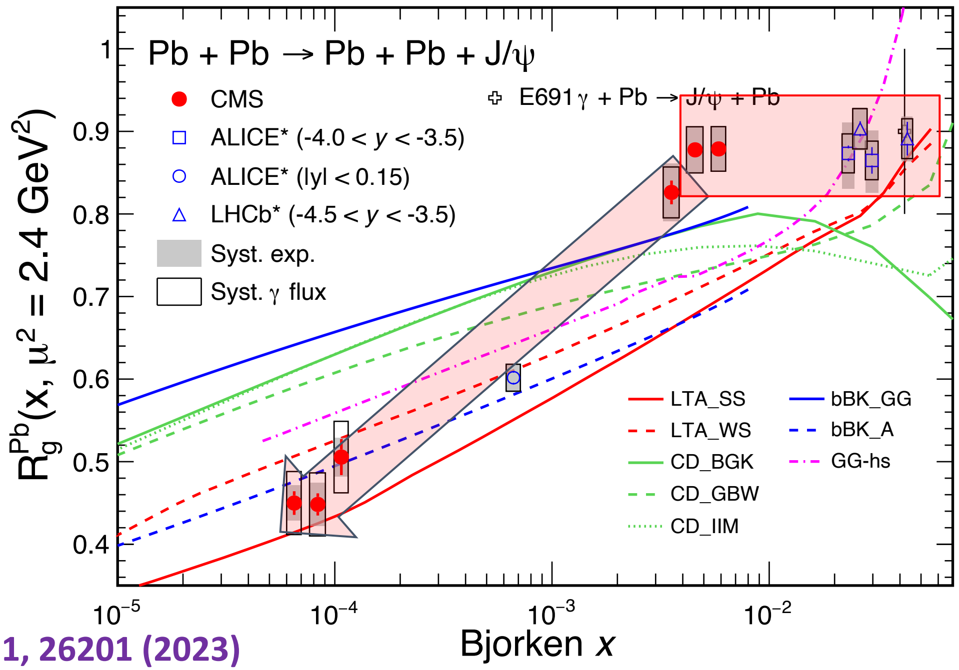
- Photon interact with **individual nucleon** or **sub-nucleon**
- **Target** nucleus usually **breaks**
- VM $\langle p_T \rangle$ ~ **500 MeV**
- Probing the **local gluon density and fluctuations**

$$\sigma \propto [xG(x,Q^2)]^2$$

Coherent J/Ψ Photoproduction



$$R_g^A = \left(\frac{\sigma^{exp}_{\gamma A \to J/\psi A}}{\sigma^{IA}_{\gamma A \to J/\psi A}}\right)^{1/2}$$



CMS, PRL 131, 26201 (2023)

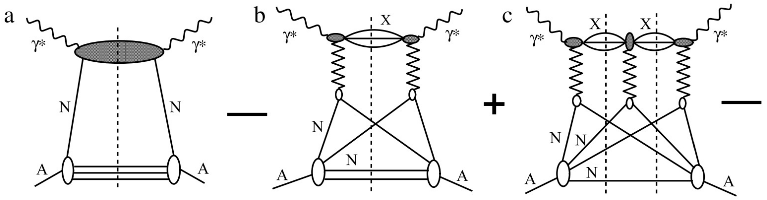
Strongly saturated cross section

Strongly suppressed gluon density

Gluon Saturation?

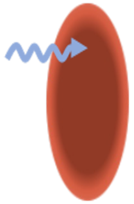
F. Gelis et al. Annu. Rev. Nucl. Part. Sci. 60 (2010) 463

Nuclear shadowing?



V. Guzey et al. EPJC 74 (2014) 2942

Black Disk Limit?



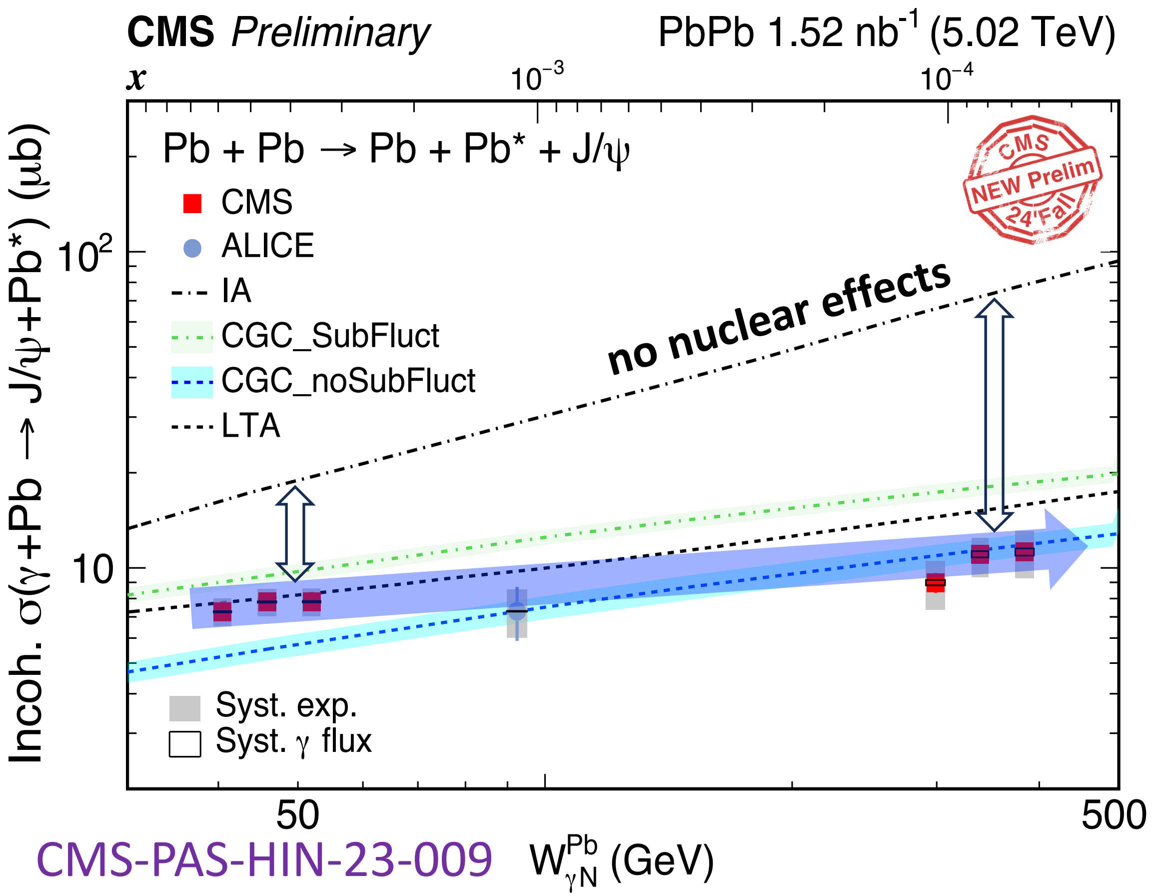
$$\hat{\sigma}^{\text{inel}}_{\text{PQCD}} \leq \hat{\sigma}_{\text{black}} = \pi R^2_{\text{target}}$$

L. Frankfurt et al. PRL 87 (2001)192301

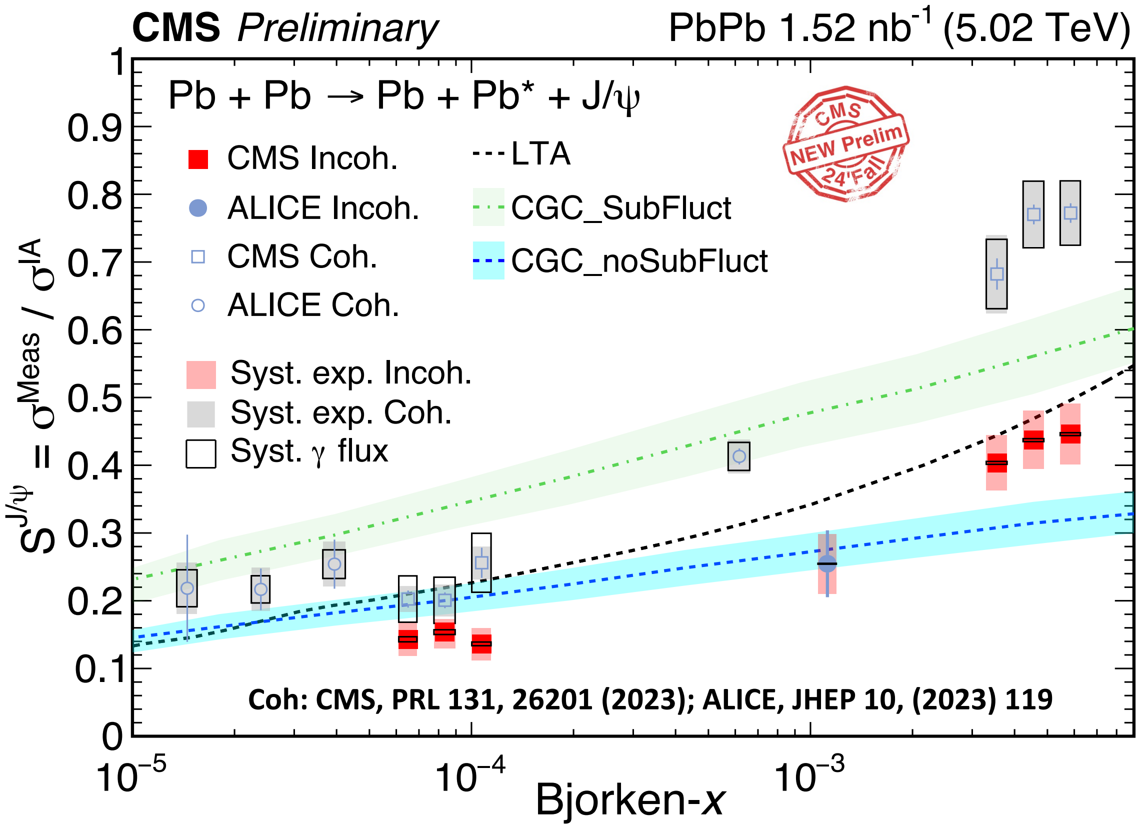
L. Frankfurt et al. PLB 537 (2002) 51

...?

Incoherent J/Ψ Photoproduction



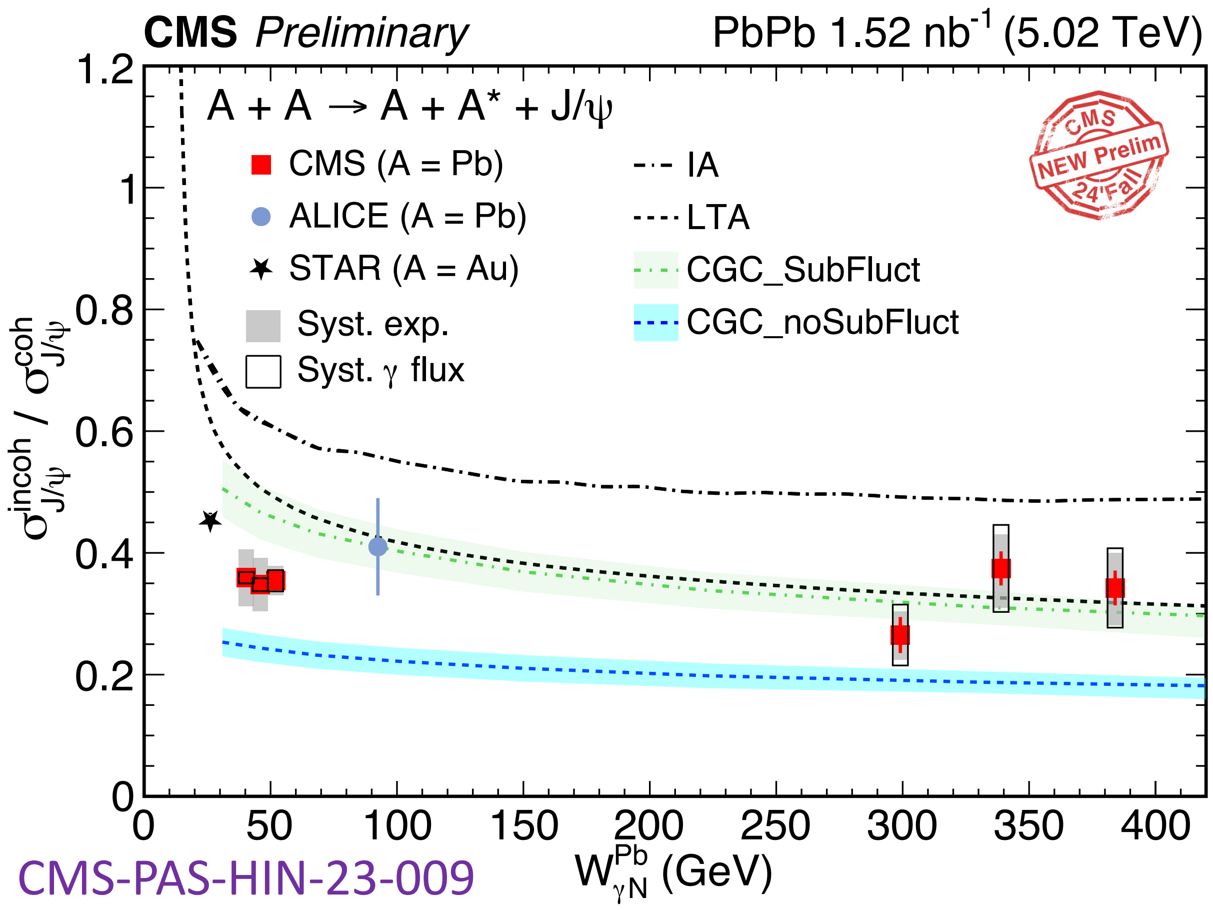
CMS-PAS-HIN-23-009



First energy-dependent measurement of incoherent J/Ψ Photoproduction

- **Strong suppression** for all W or x values**, is more suppressed than coherent**
- **Suppression factor decrease toward lower x, eventually flattens out**

Cross Section Ratio of Incoh/Coh



CMS-PAS-HIN-23-009

- No clear W dependent (40<W<400 GeV)
  - Not support Black Disk Limit is reached
  - Coh and Incoh has similar W dependence
- LTA and CGC with Sub-N fluctuation qualitatively describe data trend

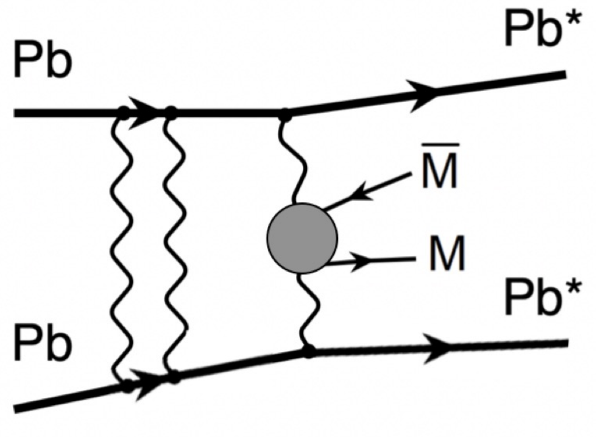
Theoretical uncertainties from VM wave function, nuclear density, nuclear form factor, free nucleon PDFs, photon flux, and J/Ψ formation probability **are largely canceled.**

→

Cleanest test for examining theoretical assumptions on nuclear effects: saturation or nuclear shadowing...

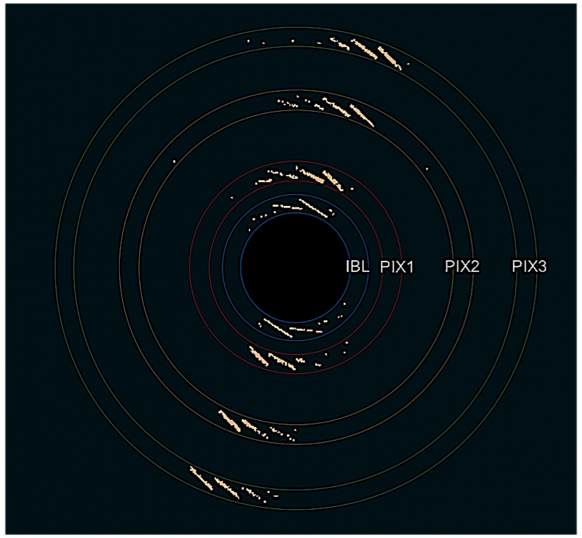
Magnetic Monopole Search in UPCs

Magnetic monopole, postulated by Paul Dirac in 1931, its existence would complete the sysm. btw electricity and magnetism



Advantages in UPCs:

Strongest B field (10^{16} T), large Z and clean event



ATLAS: arxiv:408.11035

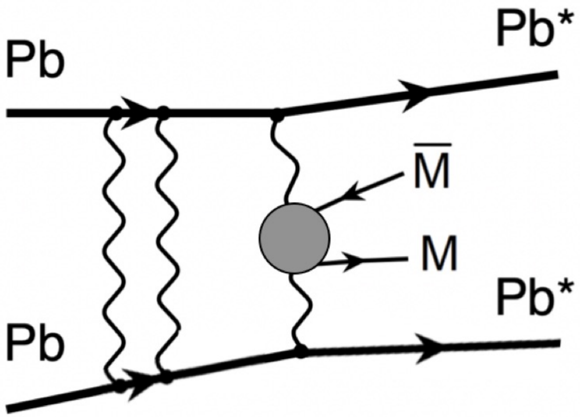
Submitted to PRL

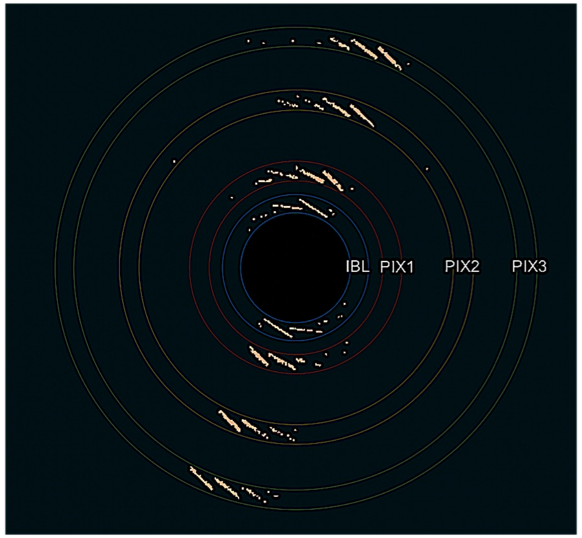
Expected signals

- Highly ionizing particles, large energy deposits in detectors
- Unique trajectories: bend along the direction of magnetic field

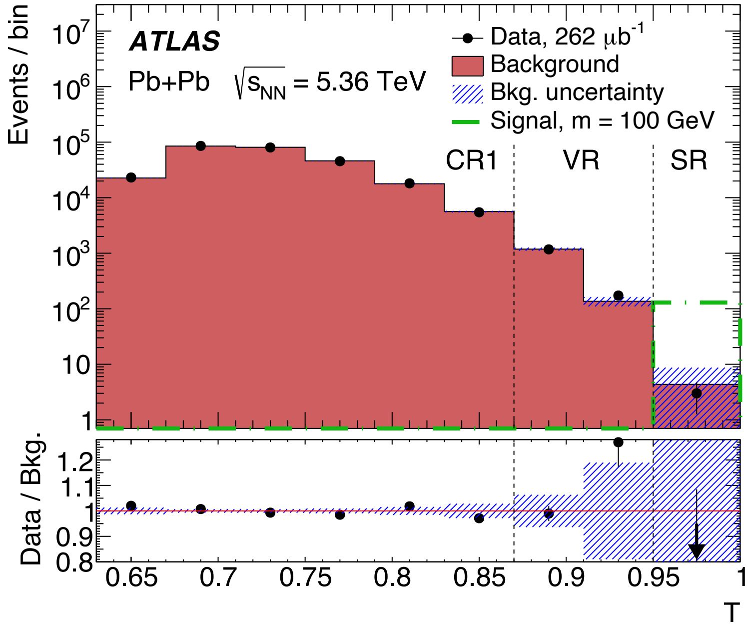
Magnetic Monopole Search in UPCs

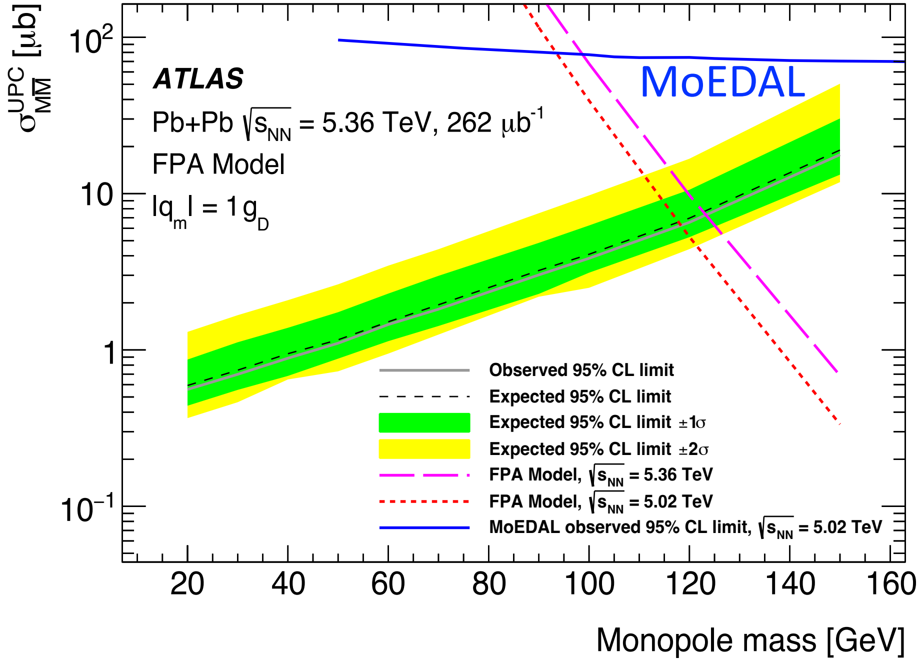
Magnetic monopole, postulated by Paul Dirac in 1931, its existence would complete the sysm. btw electricity and magnetism





ATLAS: arxiv:408.11035
Submitted to PRL

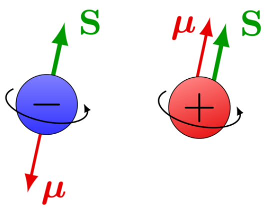




First search for magnetic monopole in UPCs:

- Only **3** events in SR, **consistent with background** estimate (4 ± 4)
- Set **best limits**, **~8** times better than dedicated MoEDAL experiment [Nature 602 63 (2022)] for **masses at 20-120 GeV**

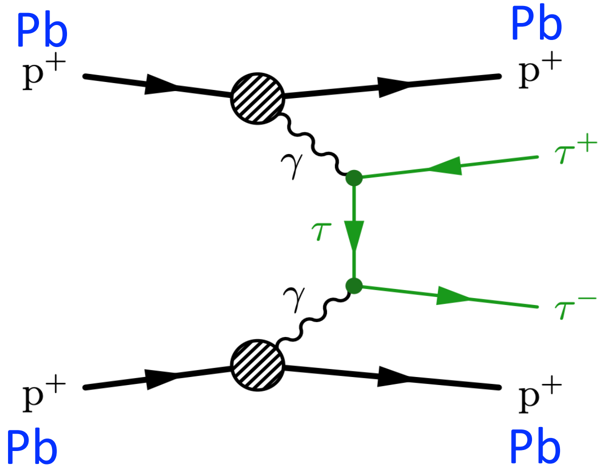
Measurement of **Tau g-2** Factor in UPCs



$$\boldsymbol{\mu} = g\frac{e}{2m}\mathbf{S}$$

Anomalous magnetic moment

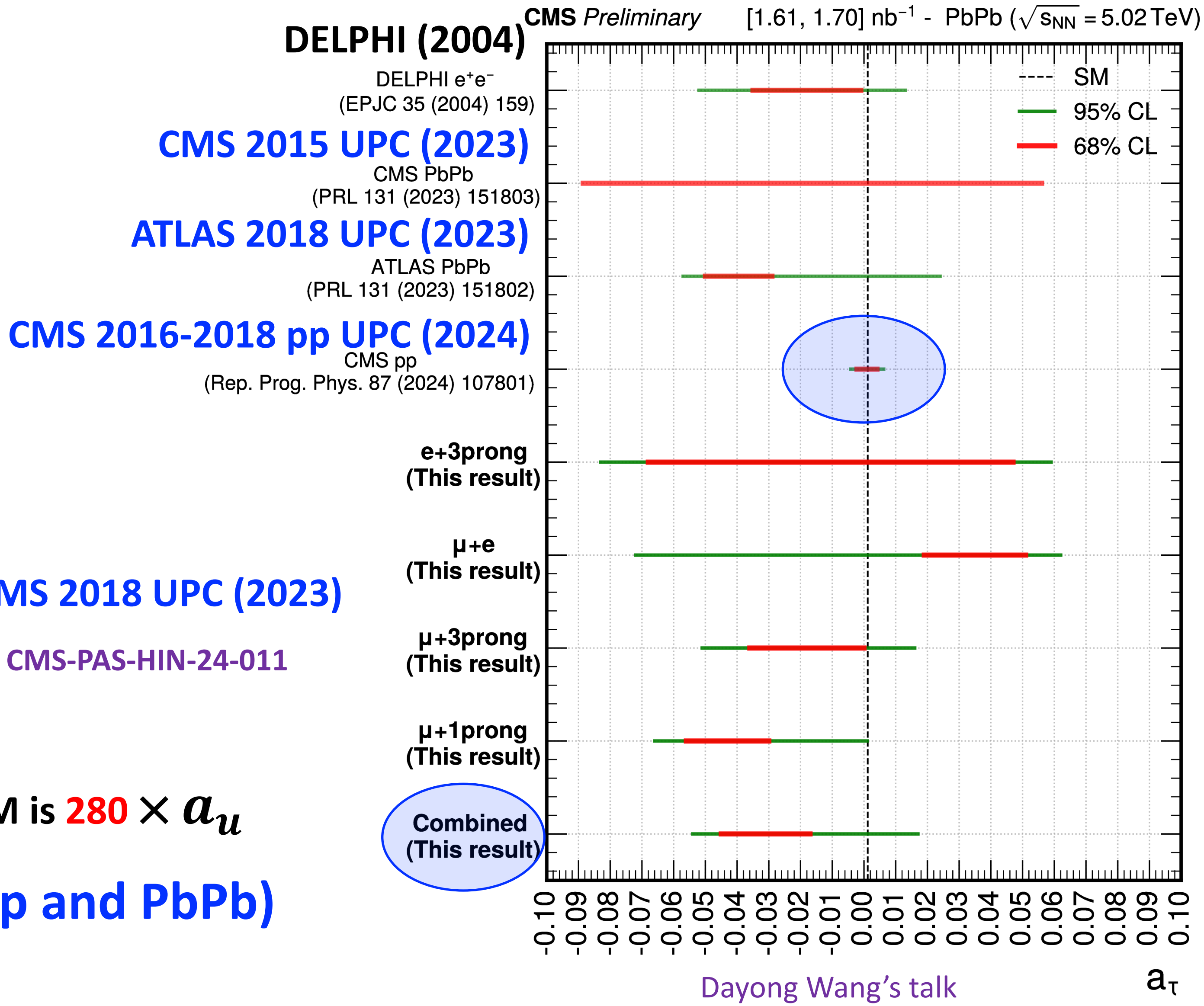
$$a_\tau = \frac{(g-2)_\tau}{2}$$



CMS NEW Prelim 24'Fall

CMS 2018 UPC (2023)

CMS-PAS-HIN-24-011

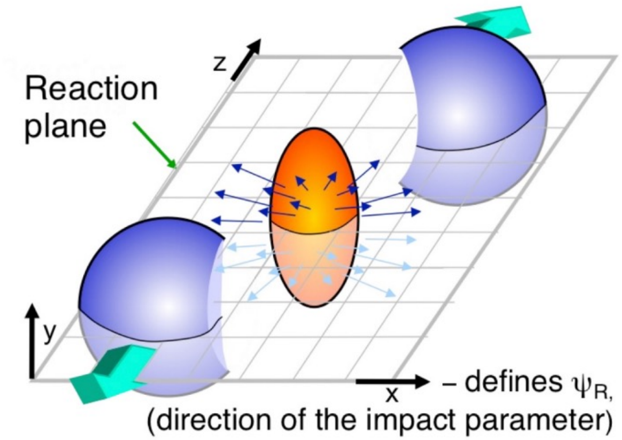


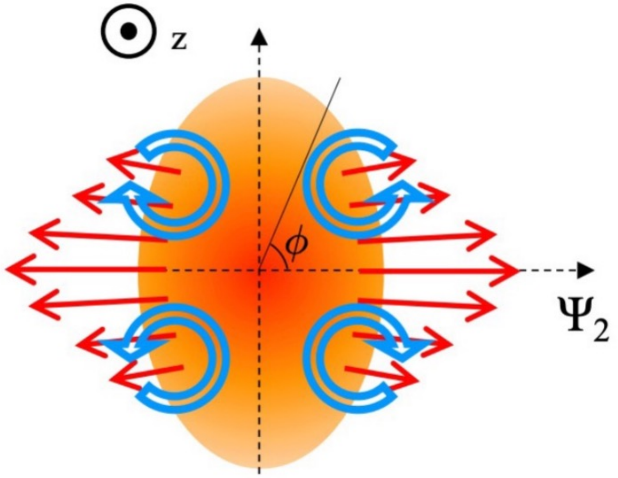
Dayong Wang's talk
(Friday 11:05)

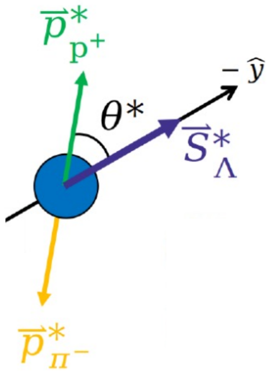
If **BSM** effects scale with m_l^2, deviation of $\boldsymbol{a_\tau}$ **from SM is** 280 $\times\, \boldsymbol{a_u}$

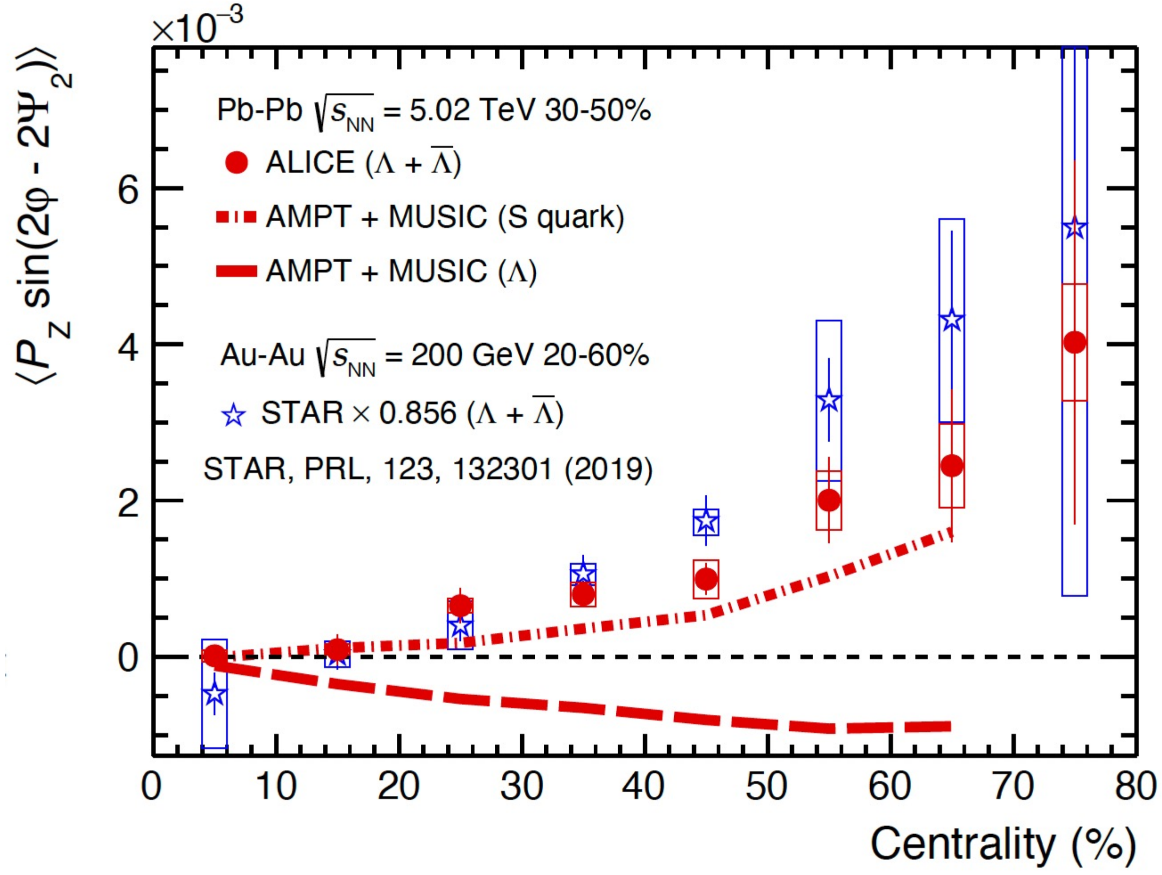
UPC data from ATLAS (Pb+Pb), CMS (p+p and PbPb) are consistent with SM

Origin of Hyperon Polarization Along Beam Direction



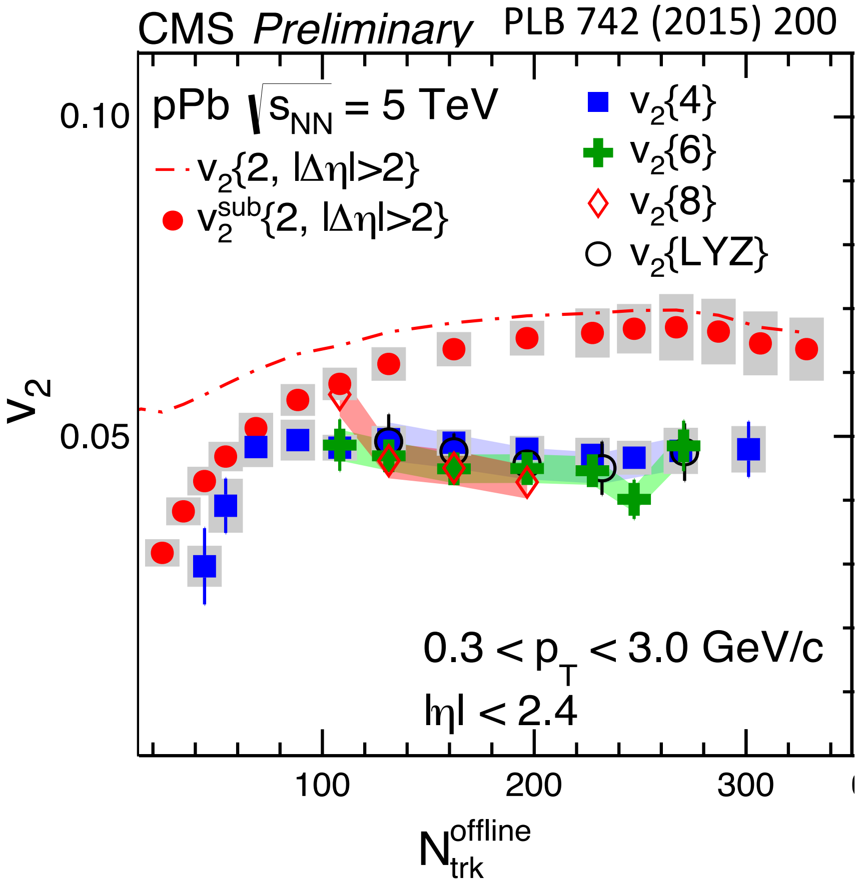


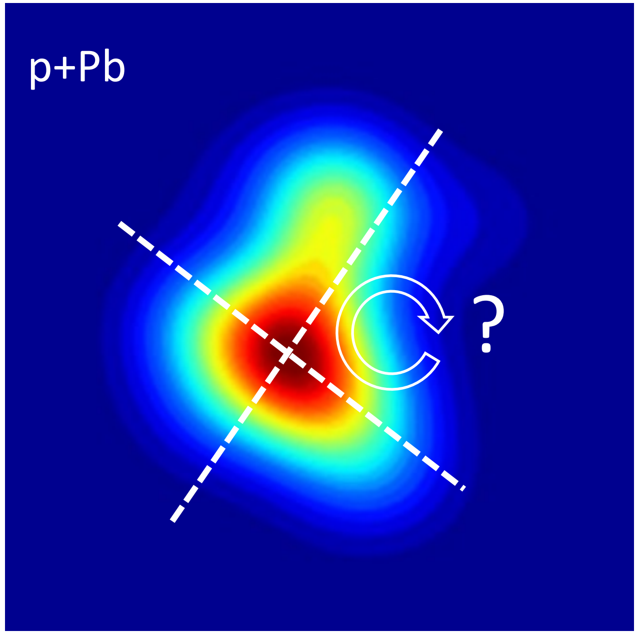




Simple expectation of vorticity from the anisotropic expansion of QGP?

P_z in Small System?

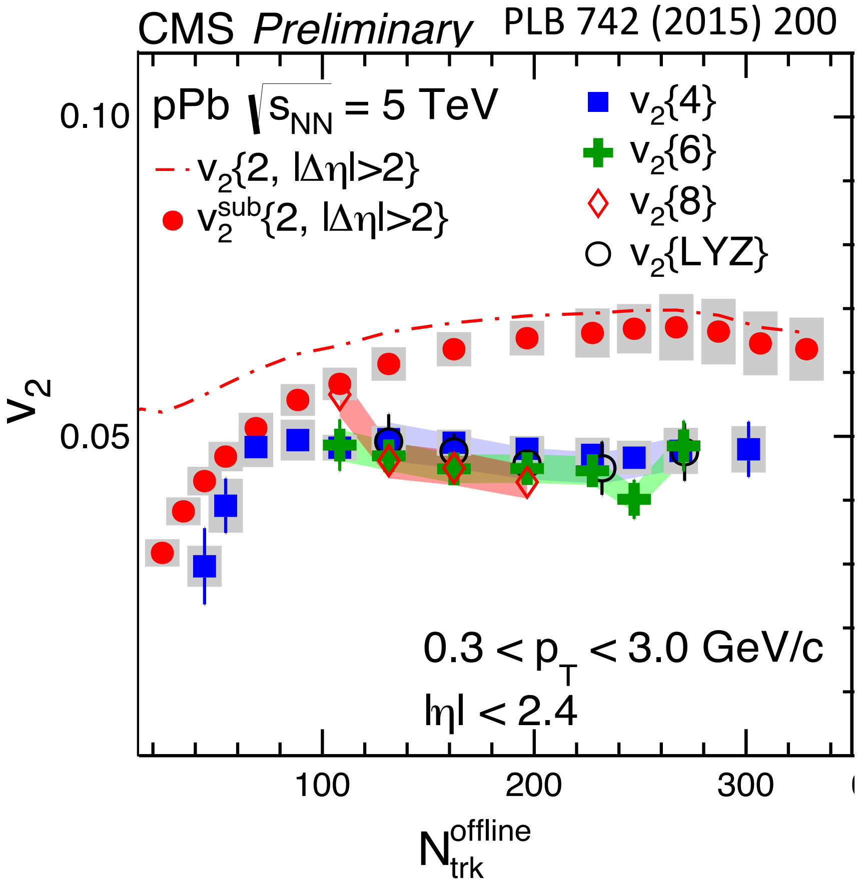


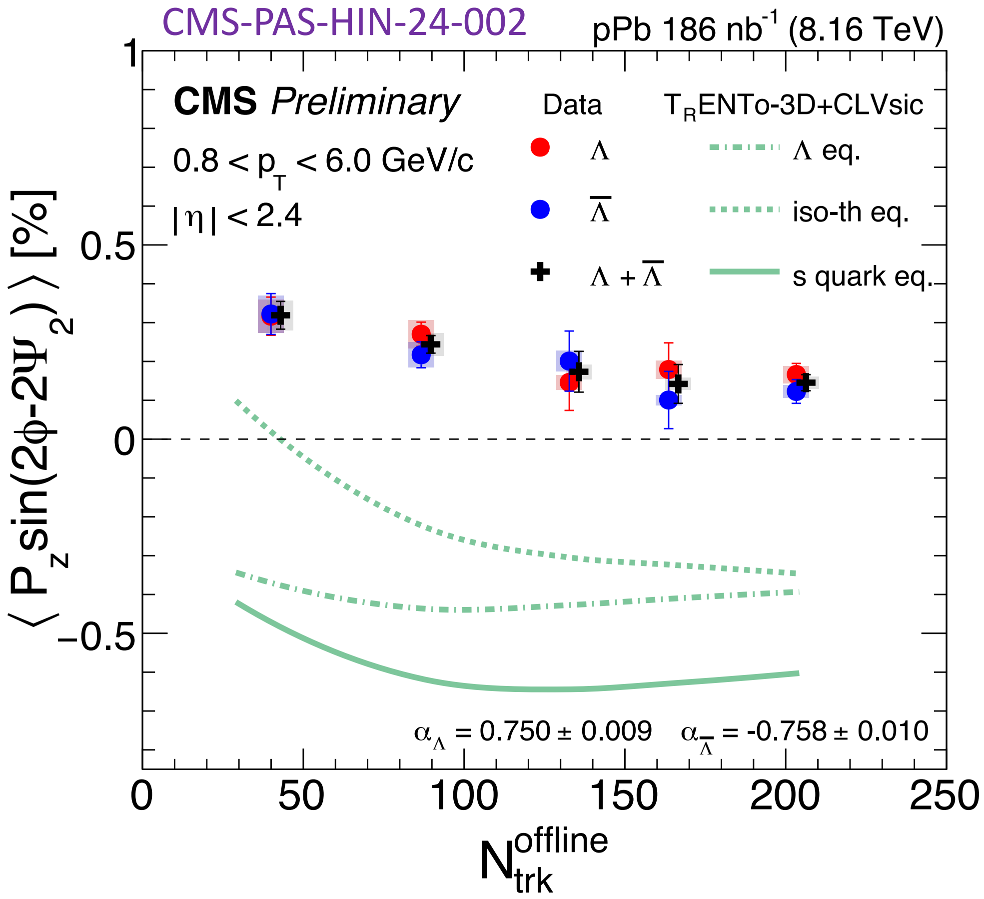


Features of QGP droplets observed in small but dense systems

Can we see hyperon polarization P_z there? → **A test of QGP formation & mechanisms for the P_z**

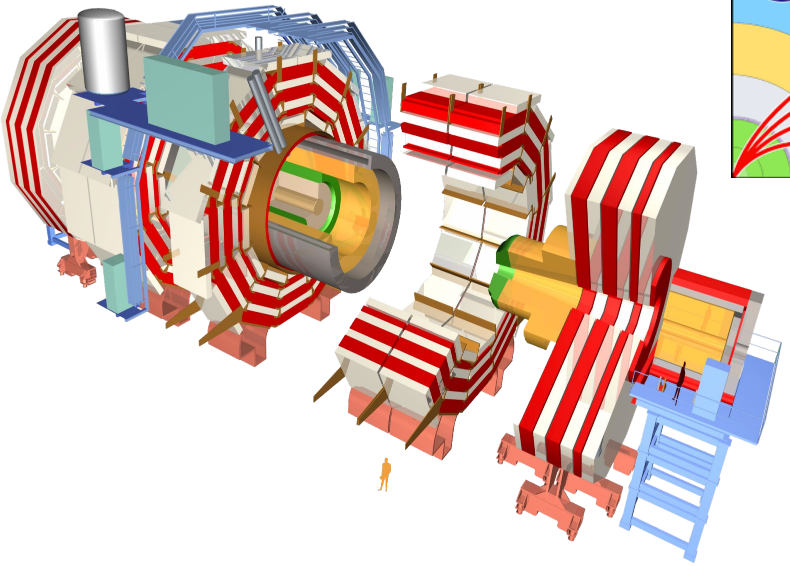
P_z in Small System?

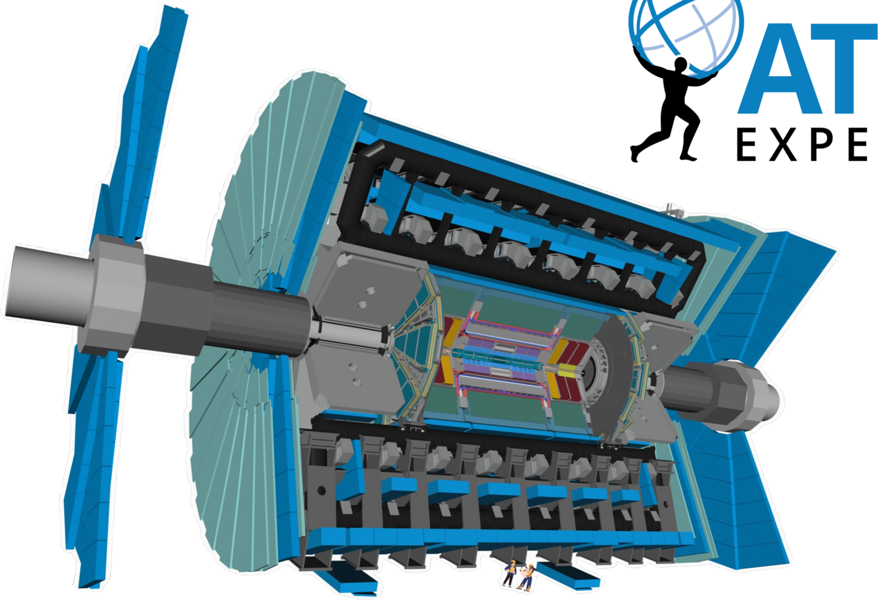




- **P_z decrease with multiplicity**, **opposite trend of v_2**
- Not captured by hydro. (negative P_z), similar behavior as in AA collisions
  - Other mechanisms are needed

Summary



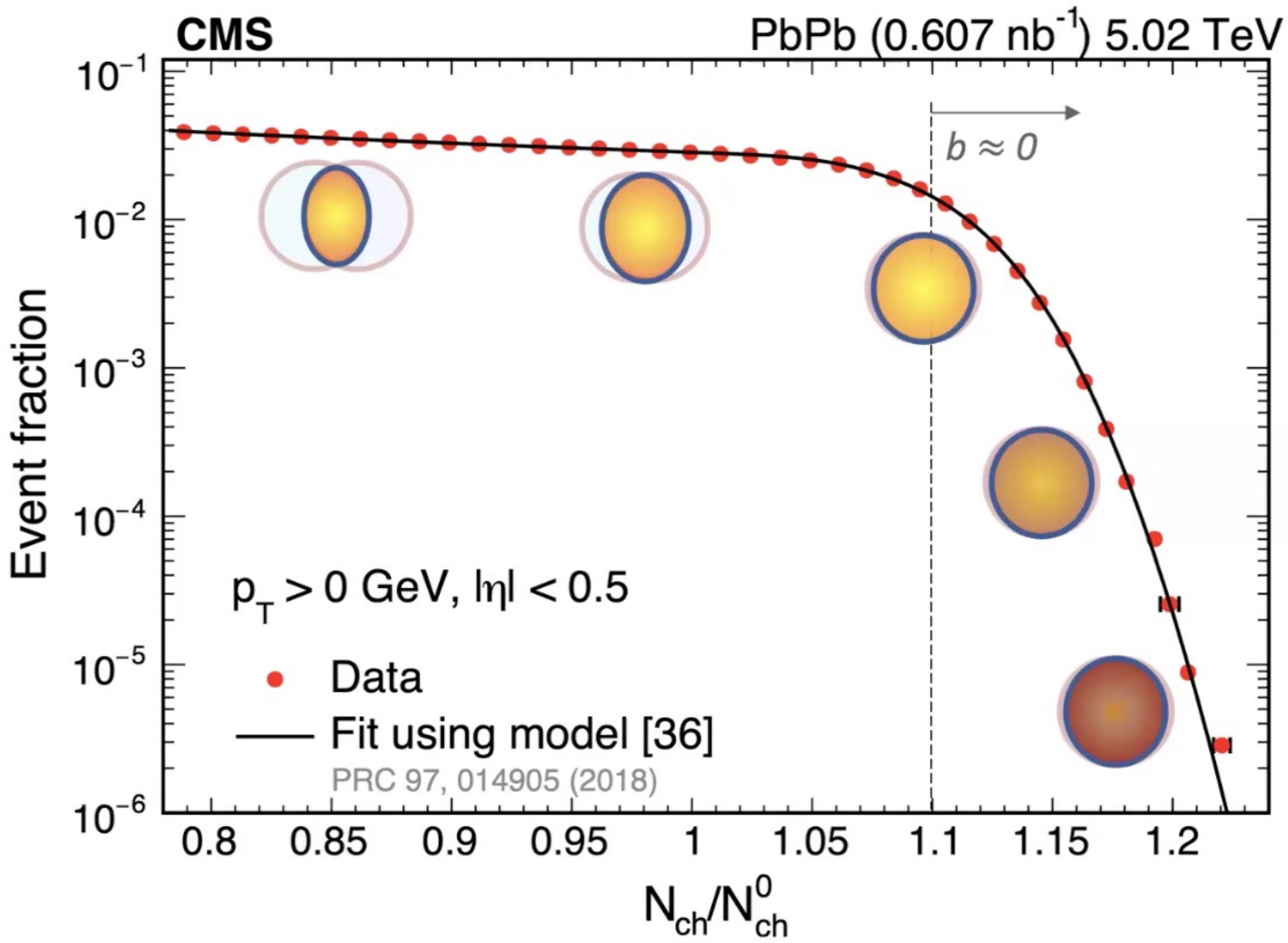


Chinese team are making significant contributions at CMS and ATLAS Heavy Ion Program

More new results from Run3 are coming soon!

Backup Slides

Multiplicity Fluctuation in UCC

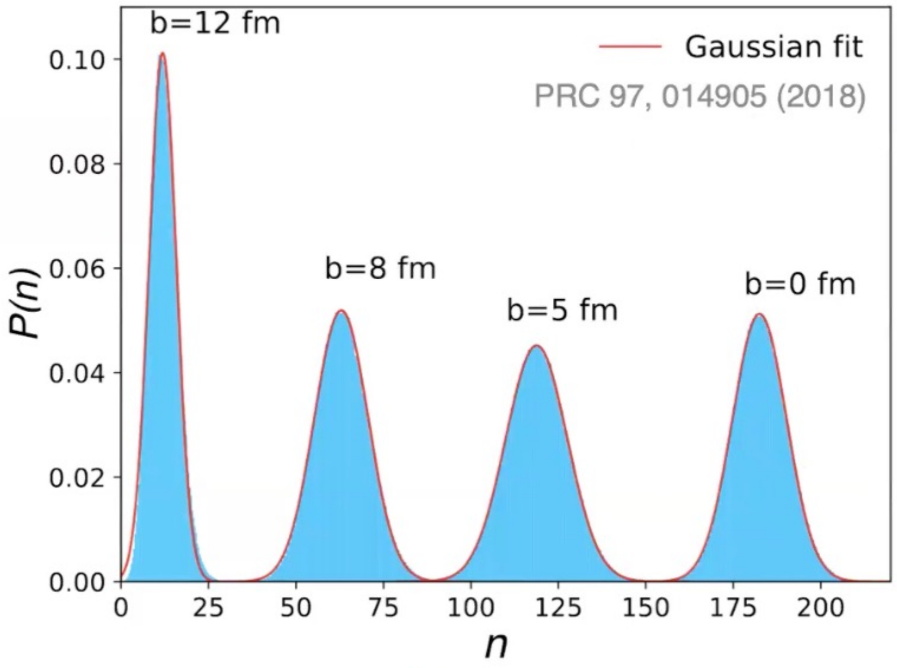


Excellent description by the model fit!

Fit by $P(n) = \int_0^1 P(n|c_b)\,dc_b$, where

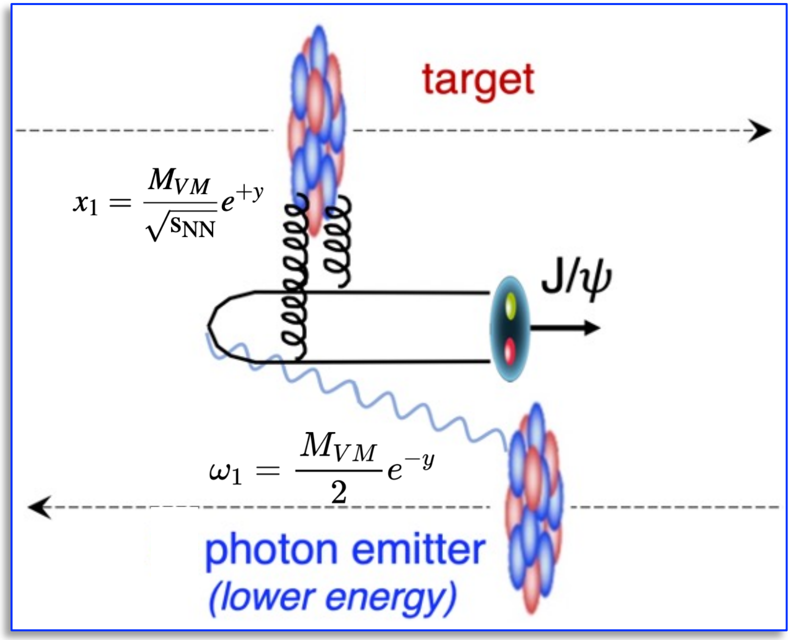
$$P(n|c_b) = \frac{\eta(c_b)}{\sigma(c_b)\sqrt{2\pi}} \exp\left(-\frac{(n-\bar{n}(c_b))^2}{2\sigma(c_b)^2}\right)$$

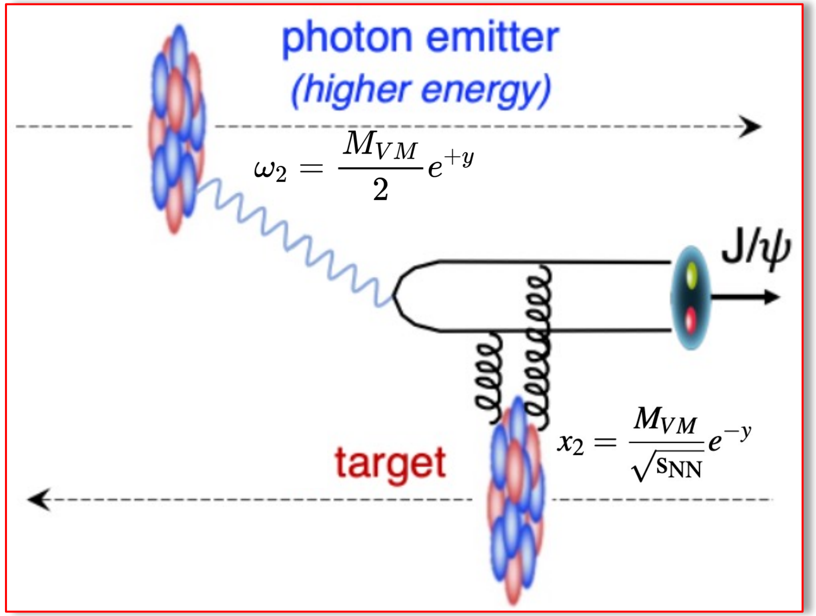
– multiplicity distribution at fixed b



Fitted values: $N_{ch}^{knee} = 1.1$, $\sigma = 0.027$

“Two-way Ambiguity” in A-A UPCs





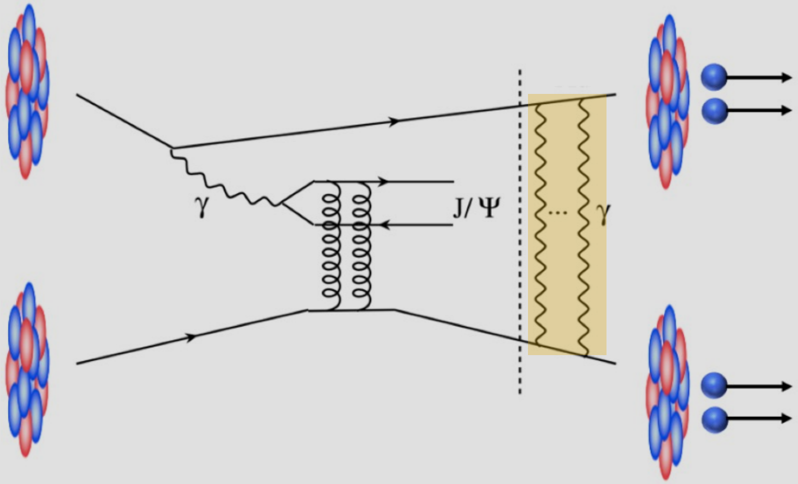
$$\frac{d\sigma_{AA\rightarrow AA'J/\psi}}{dy} = N_{\gamma/A}(\omega_1)\cdot\boxed{\sigma_{\gamma A\rightarrow J/\psi A'}(\omega_1)} + N_{\gamma/A}(w_2)\cdot\boxed{\sigma_{\gamma A\rightarrow J/\psi A'}(w_2)}$$

what we measure

- This ambiguity exists for both **coherent** and **incoherent** processes

Solution Based on Forward Neutrons

V. Guzey, M. Strikman, M. Zhalov, EPJC (2014) 72 2942

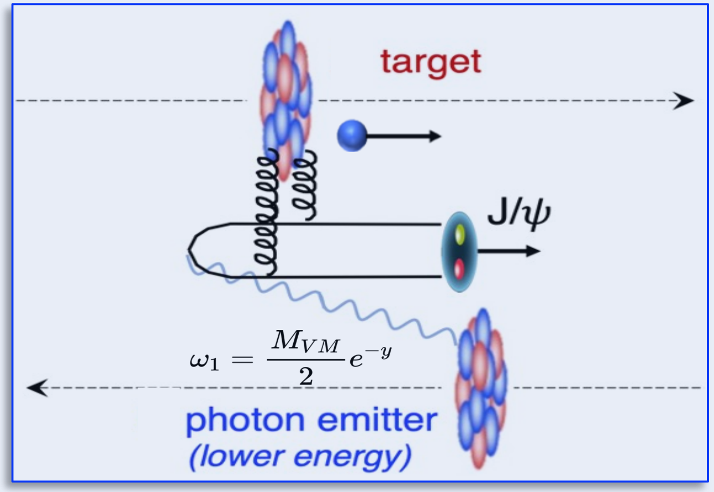


$$\frac{d\sigma^{0nXn}_{AA\to AA'J/\psi}}{dy} = \boxed{N^{0nXn}_{\gamma/A}(\omega_1)} \cdot \sigma_{\gamma A\to J/\psi A'(\omega_1)} + \boxed{N^{0nXn}_{\gamma/A}(w_2)} \cdot \sigma_{\gamma A\to J/\psi A'(w_2)}$$

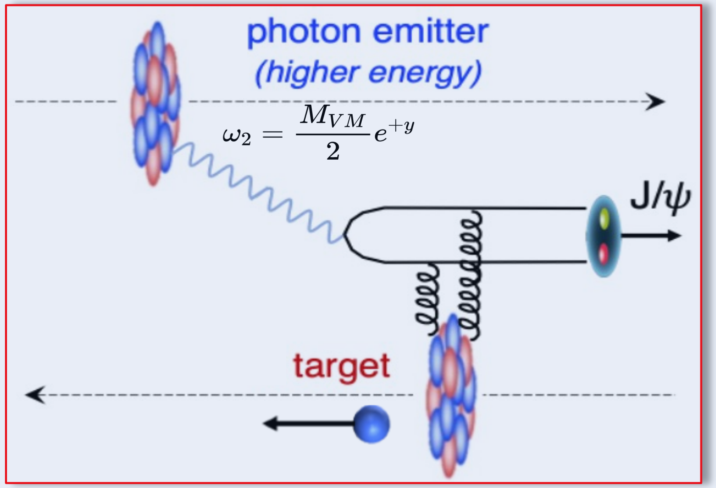
from theoretical calculation

$$\frac{d\sigma^{XnXn}_{AA\to AA'J/\psi}}{dy} = \boxed{N^{XnXn}_{\gamma/A}(\omega_1)} \cdot \sigma_{\gamma A\to J/\psi A'(\omega_1)} + \boxed{N^{XnXn}_{\gamma/A}(w_2)} \cdot \sigma_{\gamma A\to J/\psi A'(w_2)}$$

Coh. J/Psi at ω_1 and ω_2 are solved by making use of neutrons induced by EMD process



J/Psi-Xn (Same Direction)



J/Psi-Xn (Opposite Direction)

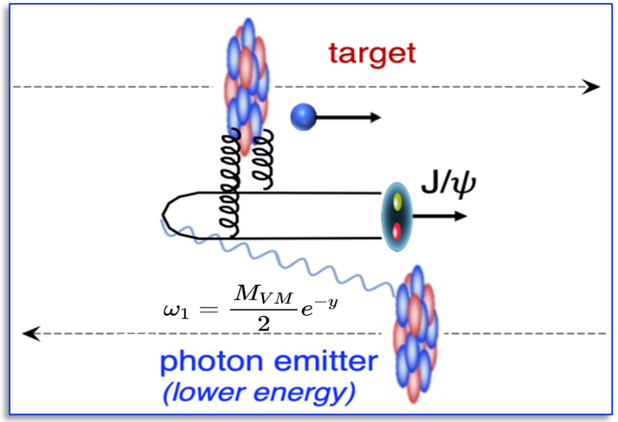
Incoh. J/Psi production itself has ~85% chance to induce the forward neutrons → Detecting these neutrons will identify the target nucleus and solve the two-way ambiguity

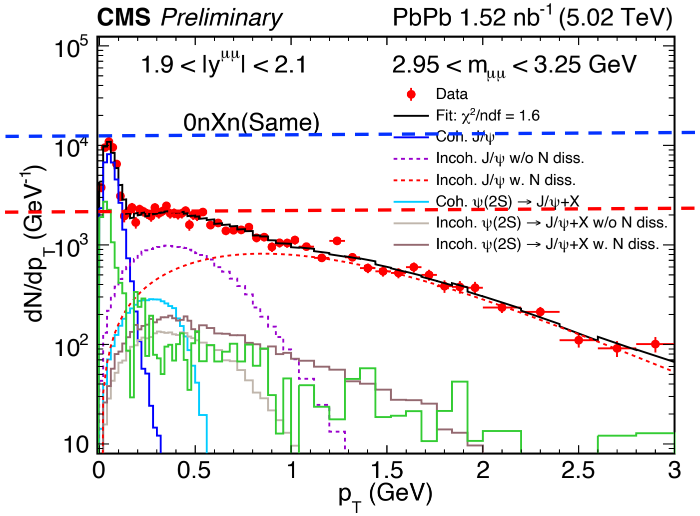
Example of Signal Extraction (**0nXn**)

Low-W

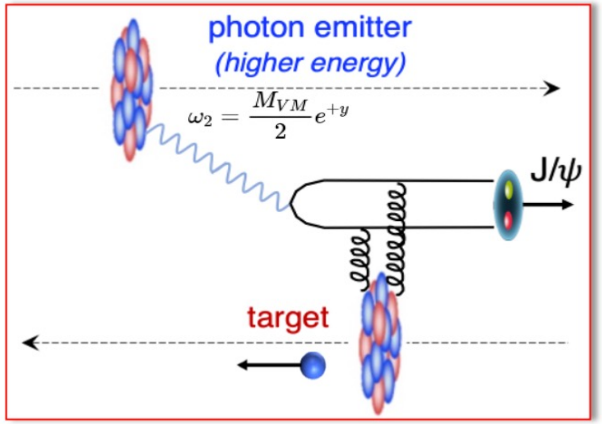
-y

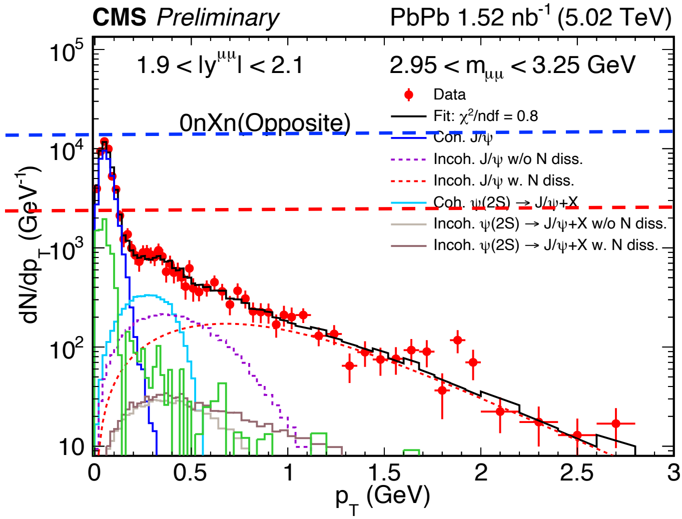
J/Ψ-Xn (Same Direction)





J/Ψ-Xn (Opposite Direction)



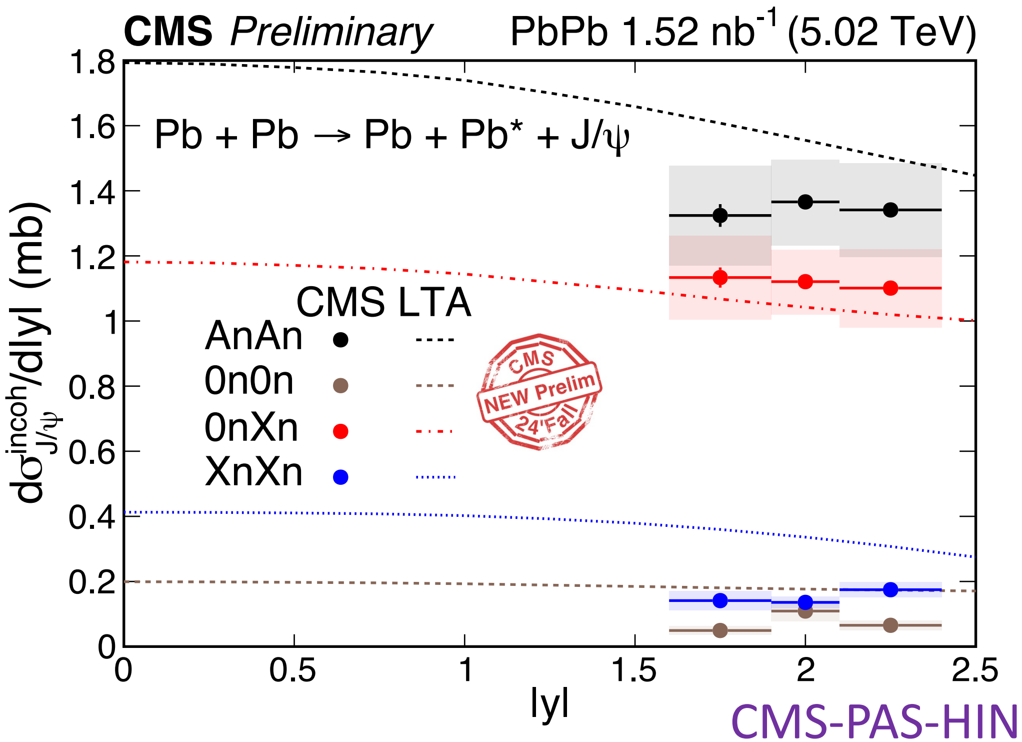


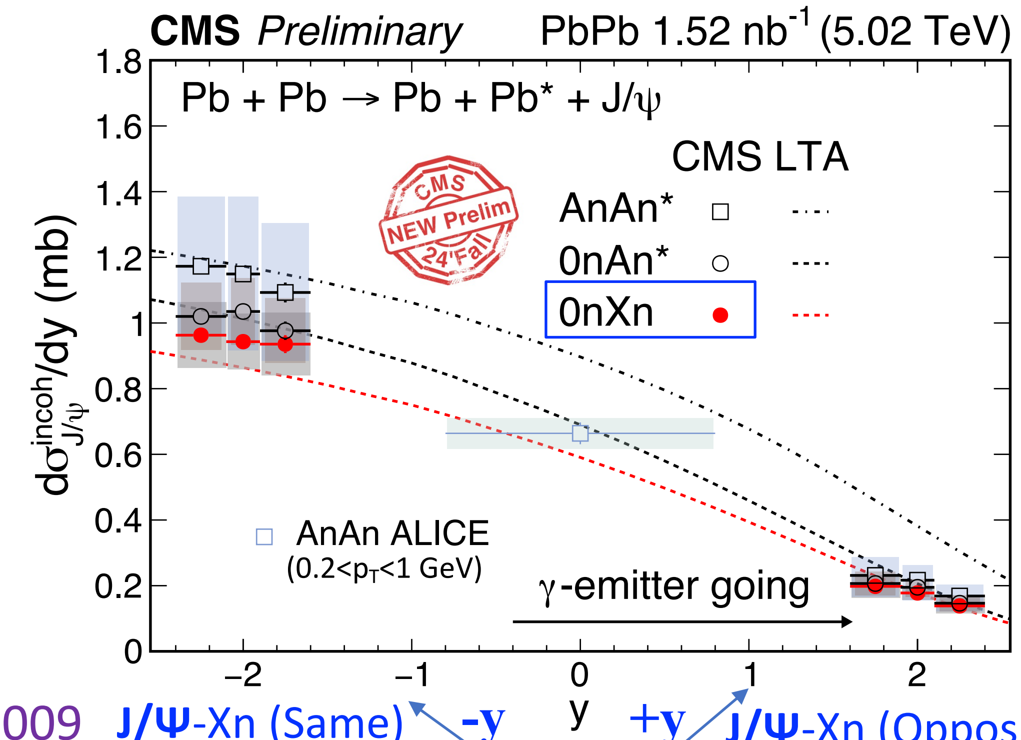
High-W

+y

- **No correlation** between forward neutrons and coh. production
- **Strong correlation** between forward neutrons and incoh. production

Total InCoh. J/Ψ Photoproduction Cross Section





CMS-PAS-HIN-23-009

J/Ψ-Xn (Same) **-y** **+y** **J/Ψ**-Xn (Opposite)

LTA: V. Guzey et al. PRC 108 (2023) 024904, PRC 99 (2019) 015201
ALICE: PRL 132, 162302 (2024)

$$\frac{d\sigma^{0nAn*}_{PbPb\to PbPb'\,J/\psi}(y)}{dy} = \frac{d\sigma^{0nXn}_{PbPb\to PbPb'\,J/\psi}(y)}{dy} + \frac{d\sigma^{0n0n}_{PbPb\to PbPb'\,J/\psi}(y)}{dy}$$

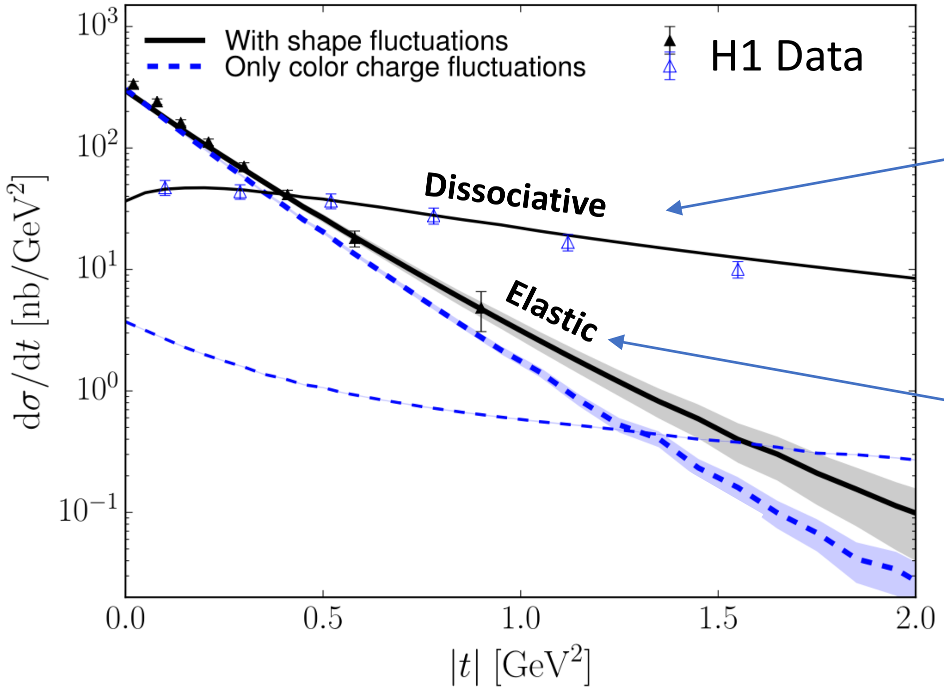
- 0nXn events: Data at (**-y**) are **5-6 times** of data at (**+y**) ➔ **Strong incoh. J/Ψ – Xn correlation**

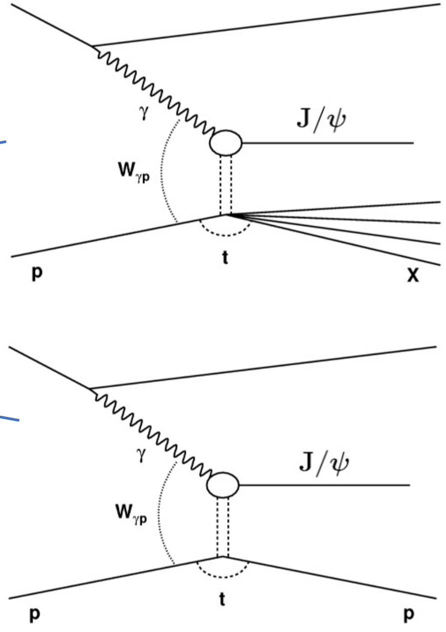
Relative fractions at (+y) and (-y) in 0n0n are asummed to be same as what measured in 0nXn events

Probing Fluctuating Gluonic Structure via γ+p

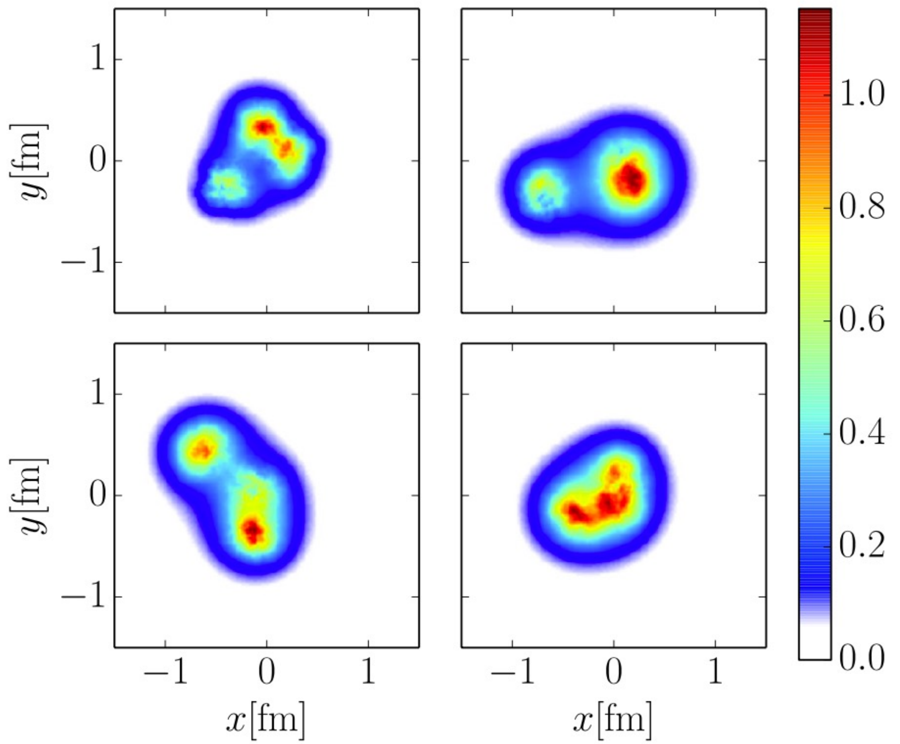
CGC IPsat considering the **fluctuations** of **geometry** (shape and size), **energy density, local saturation scale** and **color charge**, successfully describe the HERA data

J/Ψ Photoproduction off proton at HERA





Rep. Prog. Phys. **83** (2020) 082201



CGC Ipsat is impact parameter dependent saturation model under the Color-Glass Condensate framework.