CMS Overview

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Rencontres QGP France
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Bagnoles de l'Orne, France

HI Physics Programs at CMS

A variety of probes sensitive to different structures of QGP

[High p_T]
Jets, photons

[Dileptons]
Onia, EW

QGP

[Forward]
UPC

Spectra
Open HF

Flow
Correlation

[LLR is among major contributors]

HI Physics Programs at CMS

The Road: From Past to Future

Run 1	Run 2	Long Shutdown 2	Run 3	LS 3	Run 4	LS 4
	PbPb ($2.2\ nb^{-1}$) pPb ($0.18\ pb^{-1}$)	5.02 TeV 8.16 TeV 5.36 TeV	PbPb ($6\ nb^{-1}$) pPb ($0.5\ pb^{-1}$) pO/OO	CMS Phase-2 upgrades	PbPb ($7\ nb^{-1}$) pPb ($0.5\ pb^{-1}$)	

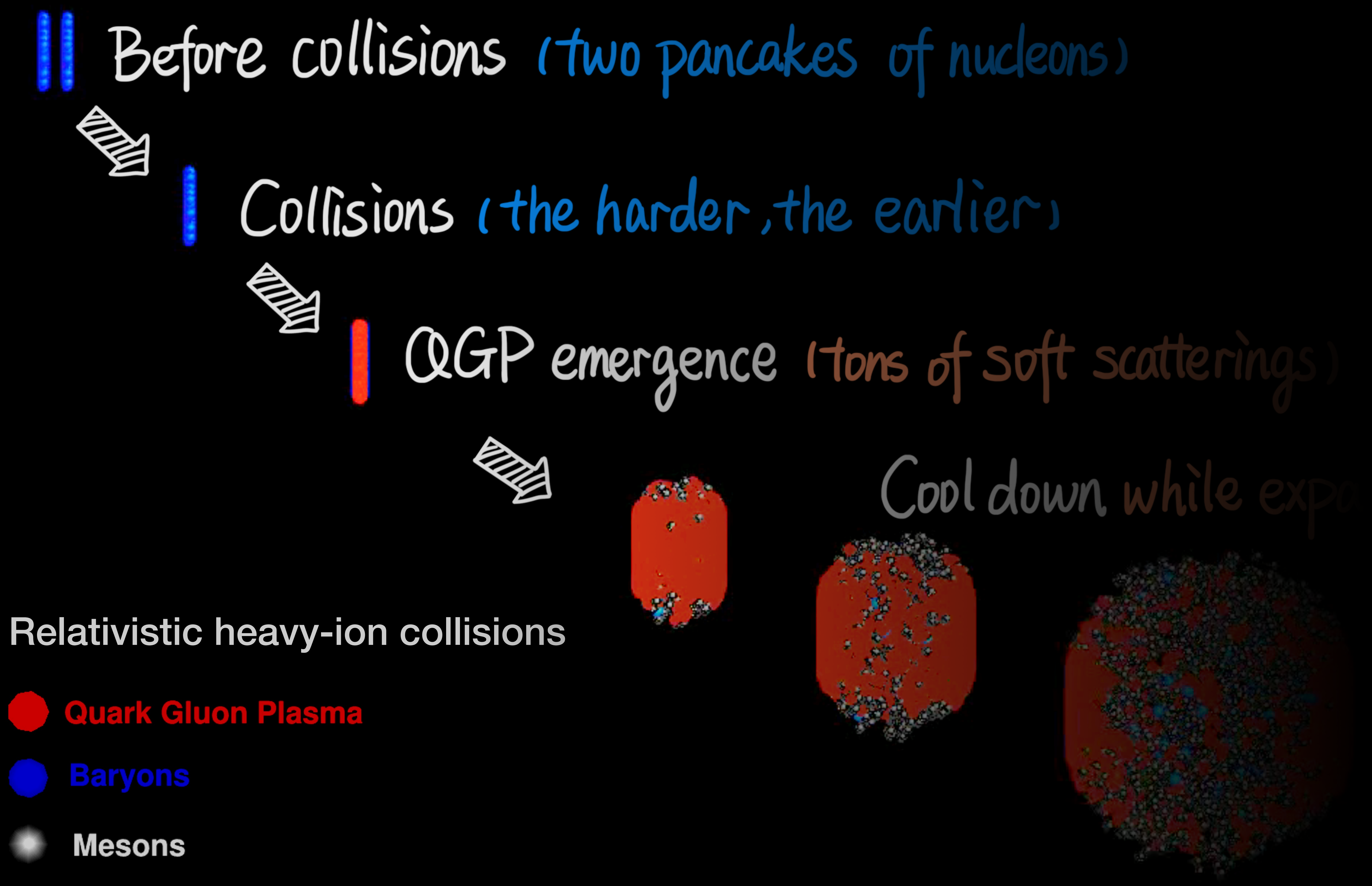
2015 -	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032

We are here !

[QGP-France'21]
[QGP-France'22]
[CMS HIN Public results]

- Only focus on new results since QGP-France'22
- Remind past success on the related topics to highlight new messages on top of what we had learnt

nPDF and Initial States



Yen-Jie Lee, Andre S. Yoon and Wit Busza

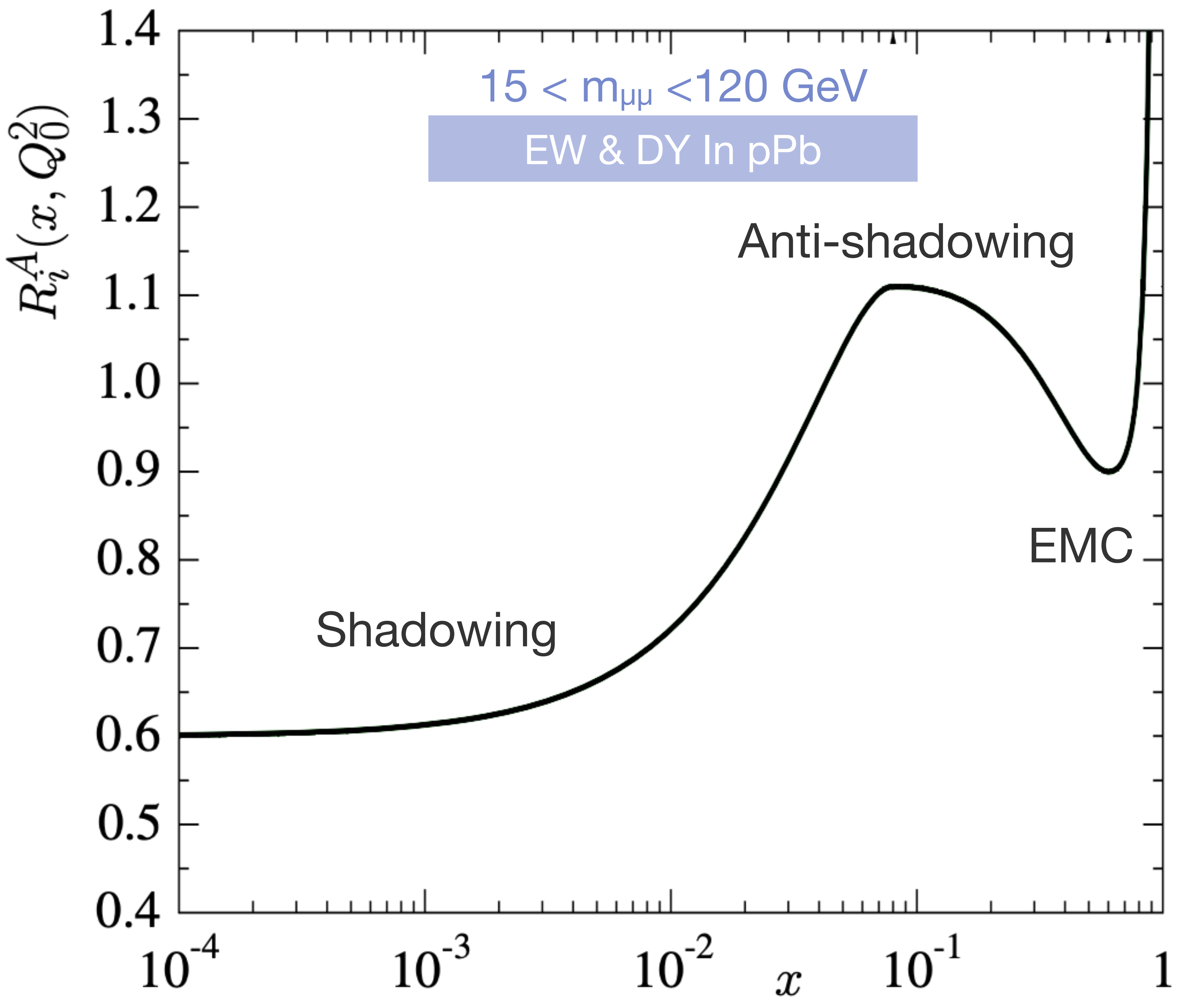
What is the nuclear matter like before QGP emergence?

Important input to models

Constrain nPDF Past Success

Quark distribution

- EW bosons & DY in pPb [PLB 2020] [JHEP 2021] [PRL 2021]
  - Significant shadowing & slight anti-shadowing



Probes sensitive to different x,Q^2 in global fits

Constrain nPDF Past Success

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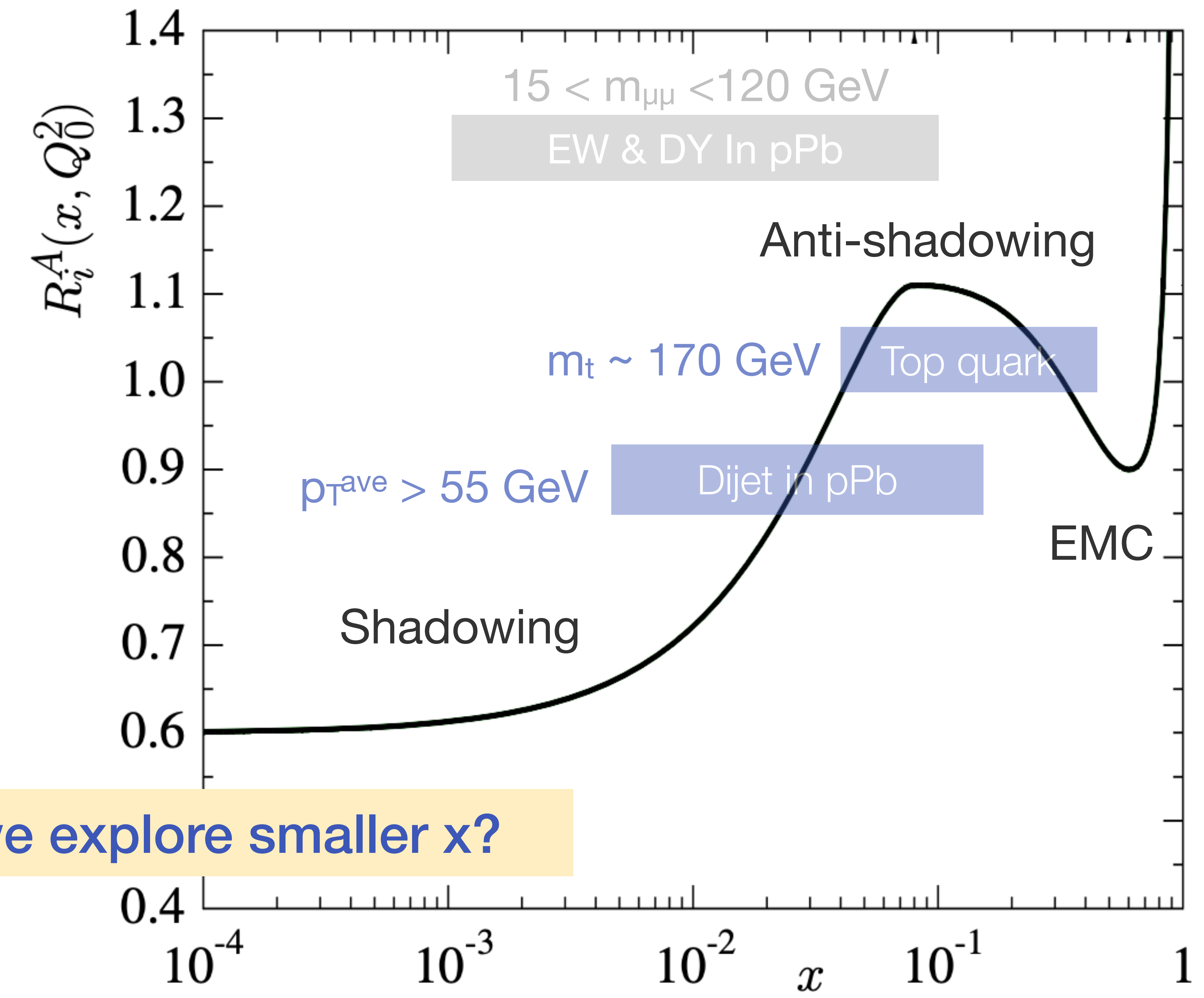
Gluon distribution

- Top quark in pPb [PRL 2017]
  - Agrees with NNLO pQCD + nPDF calculations
- Dijet in pPb [PRL 2018]
  - Strong evidence for (anti-) shadowing & hint of EMC
  - Significantly reduced uncertainty
  - Included in EPPS21 and nNNPDF3.0



Can we explore smaller x?

Probes sensitive to different x,Q^2 in global fits

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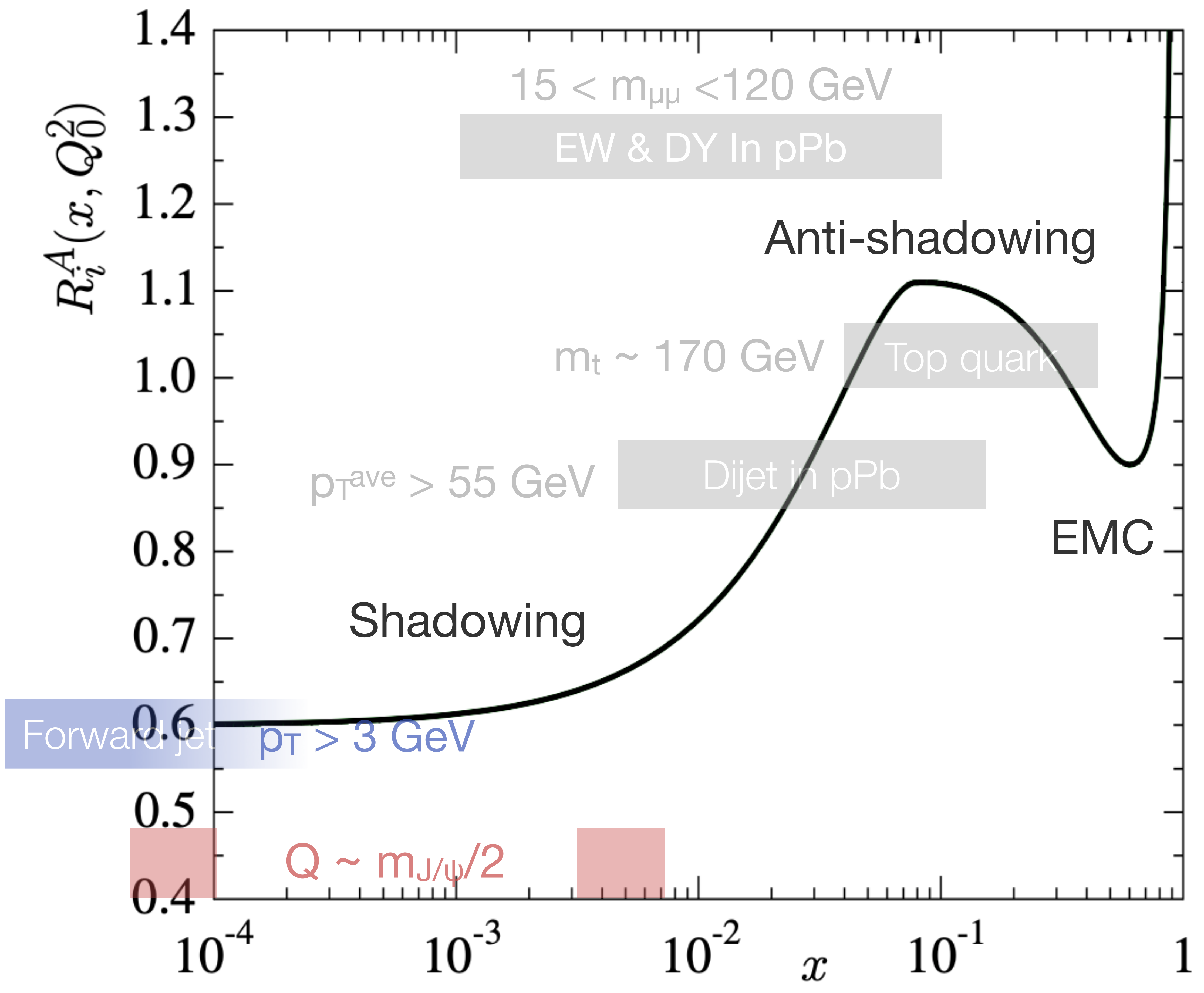
  - Included in EPPS21 and nNNPDF3.0
- Forward jet in pPb [JHEP 2019]
  - -6.6<η<-5.2 constrain saturation models
- Coherent J/ψ in PbPb UPC **New!** [arXiv:2303.16984]

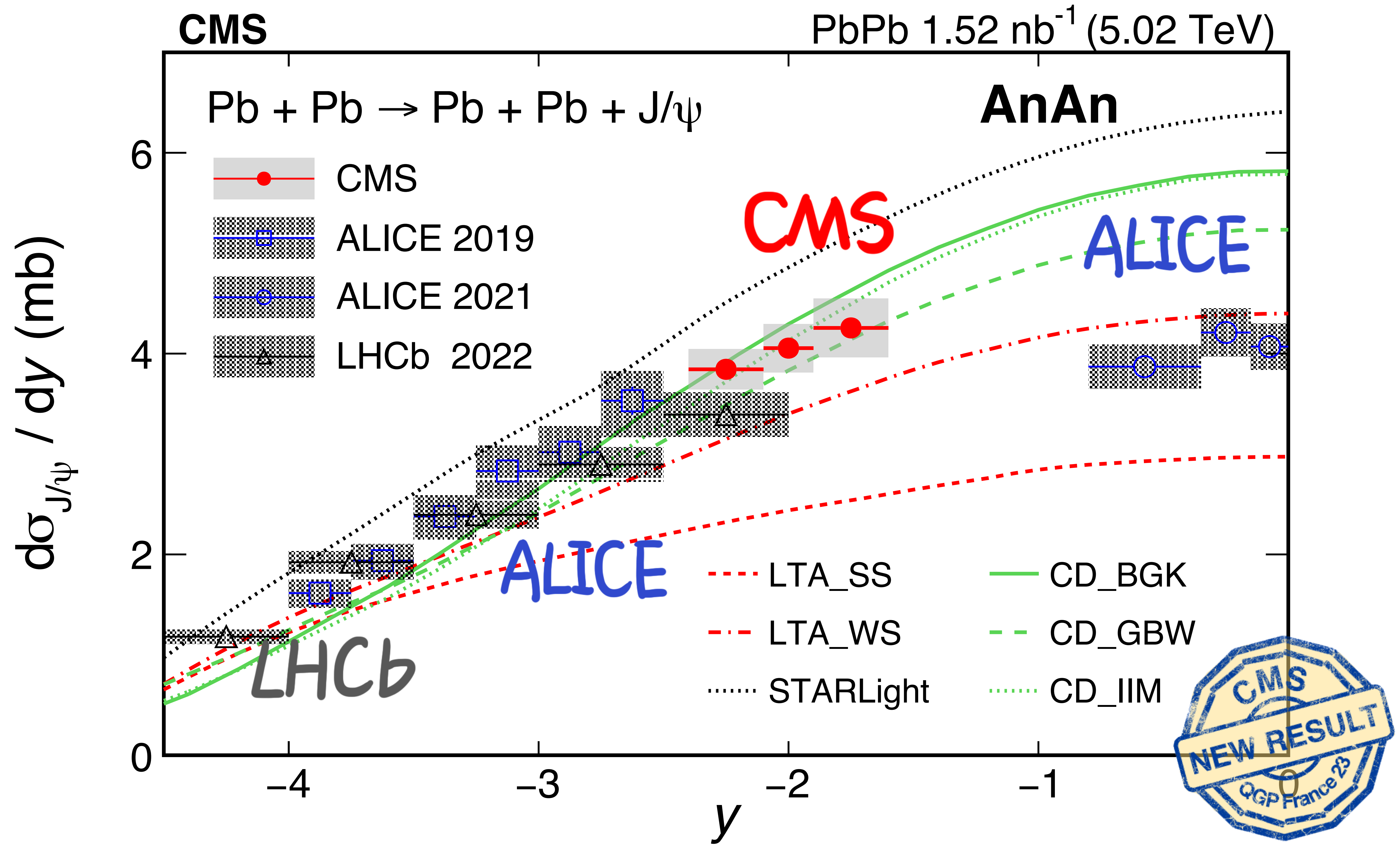
Can we directly see gluon saturation?



Probes sensitive to different x,Q^2 in global fits

New Small-x Reach Coherent J/ψ in PbPb UPC

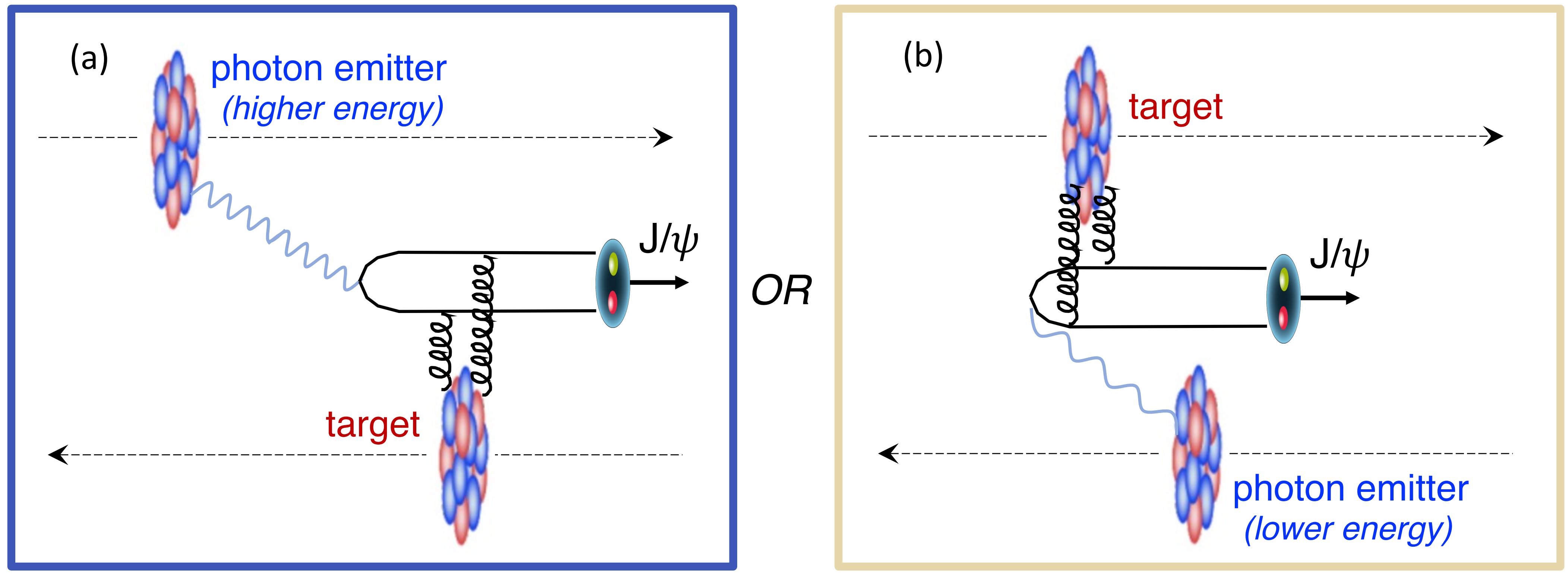
γ + Pb → J/ψ + Pb



x_1~10^{-5} or x_2~10^{-2}

x ~10^{-3}

- J/ψ photoproduction directly probes gluonic structure of nucleus and nucleon
- Both Pb ions can serve as photon sources
  - Mixed contributions from low (large x) and high (small x) photon energy at specific y



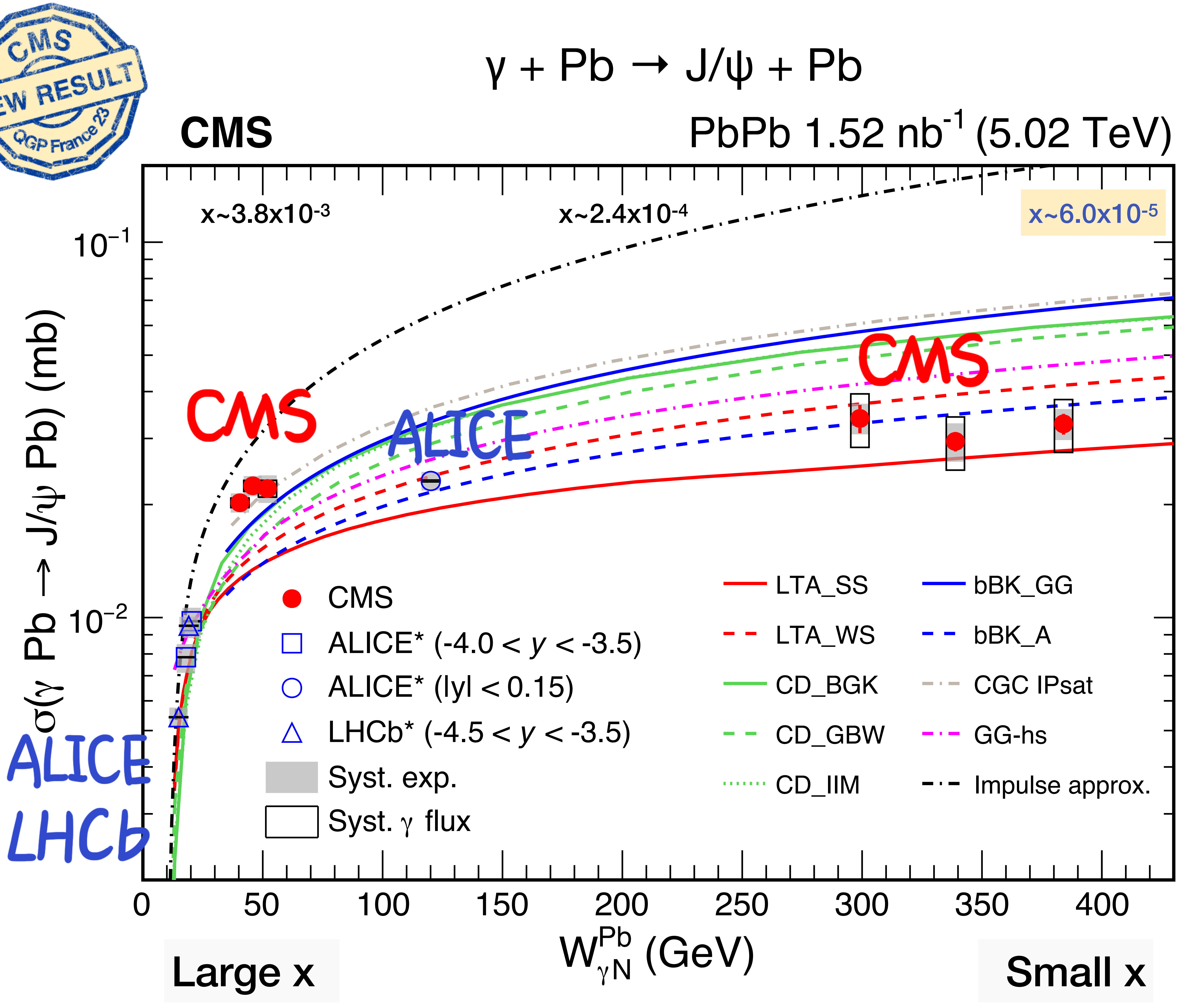
Small-x (want)

Large-x (dominant)

$$x = \frac{M_{J/\psi}}{\sqrt{s_{NN}}} e^{\mp y}$$

arXiv:2303.16984

New Small-x Reach Coherent J/ψ in PbPb UPC

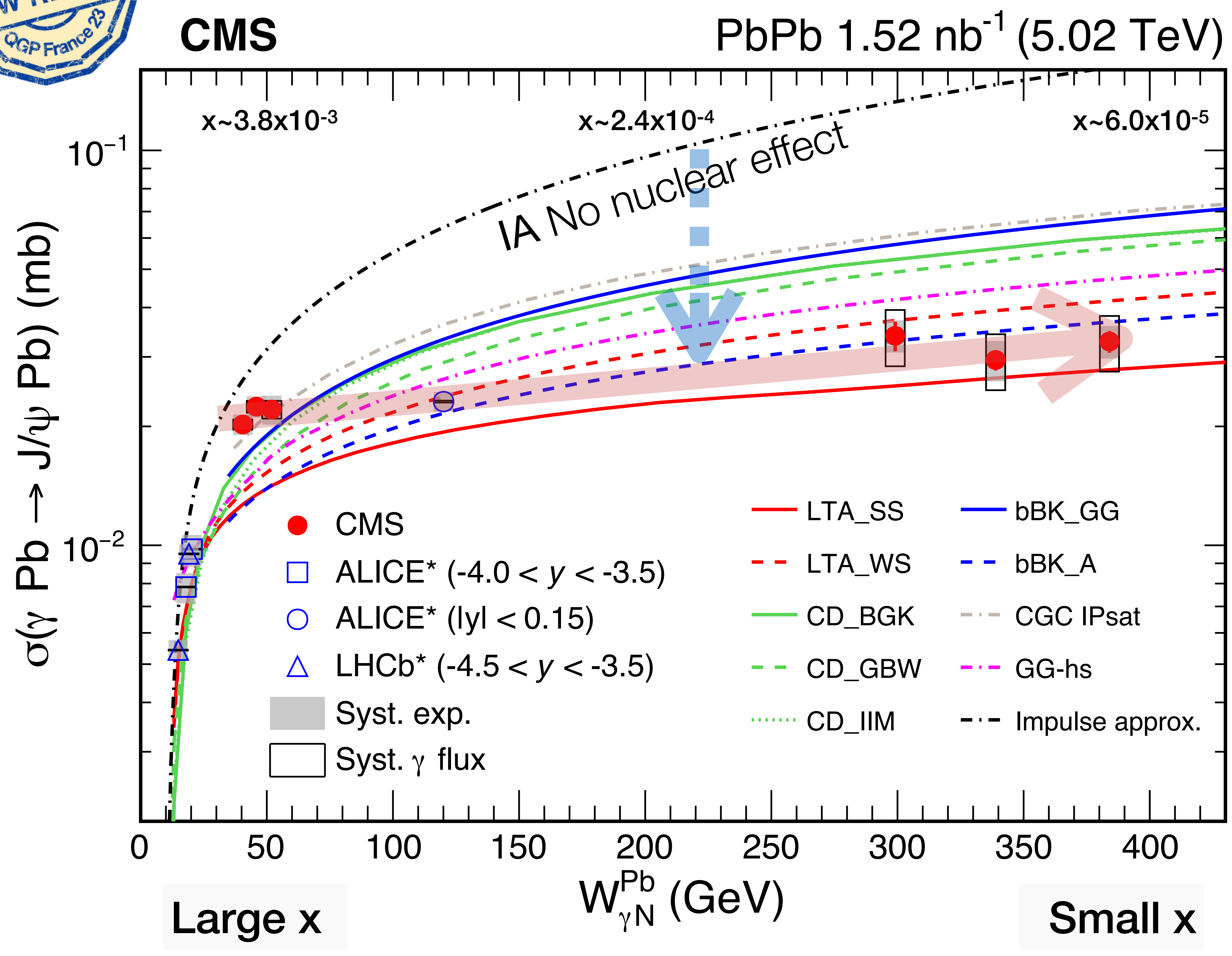


arXiv:2303.16984

- First unfolding of contributions from small-x and large-x
  - Vary neutron emission classes
  - Access gluon structure down to $x \sim 6 \times 10^{-5}$

New Small-x Reach Coherent J/ψ in PbPb UPC

γ + Pb → J/ψ + Pb



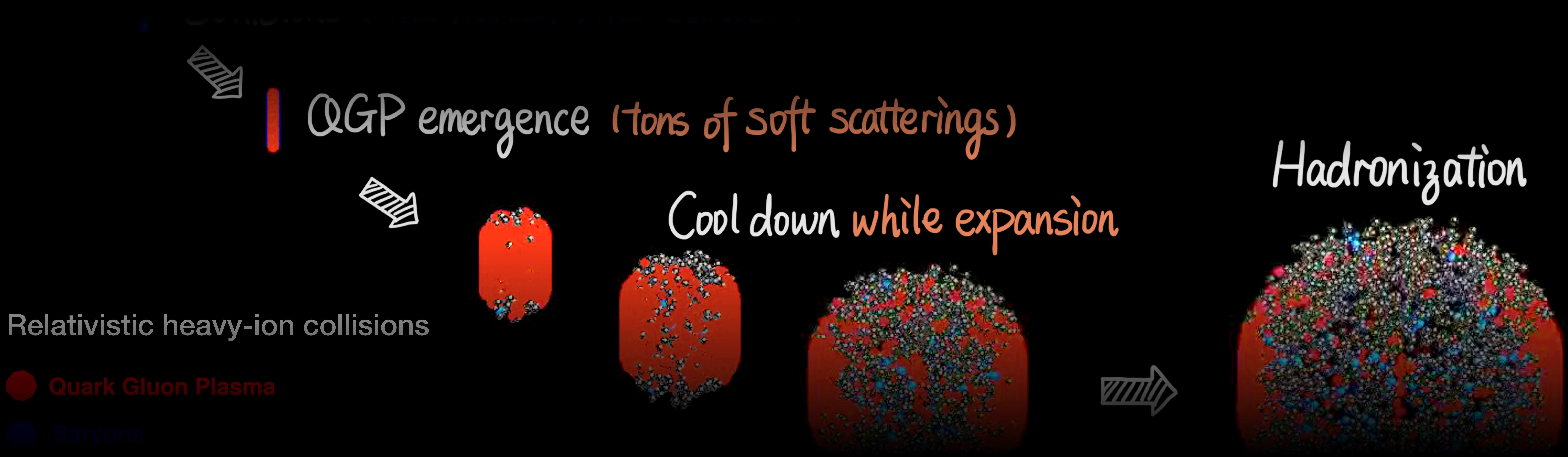
arXiv:2303.16984

- Strong nuclear effects
  - Suppression from Impulse approximation
- Flat cross-section for W > 40 GeV

  *Recent ALICE result [arXiv] is less flat
  - σ(γ p→J/ψ p) kept increasing to x ~ 10^{-5}
    - Saturation scale $Q_s^2 \sim A^{1/3}$
  - Gluon saturation?
    - Gluon splitting ⇌ recombination
  - Black disk limit?
    - Geometric limit of scattering probability

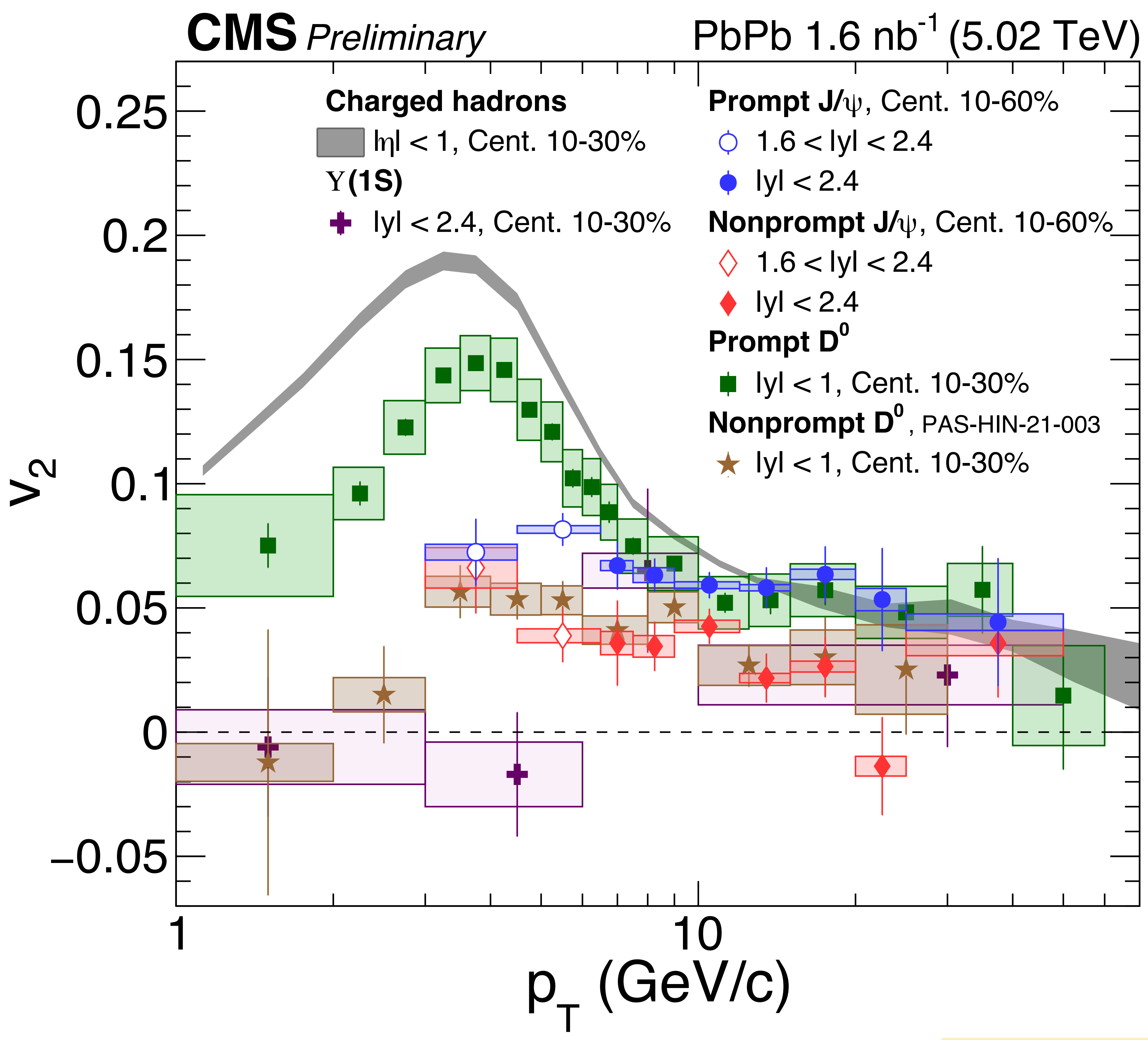
Onset of Quark Gluon Plasma

Under what condition does QGP emerge ?

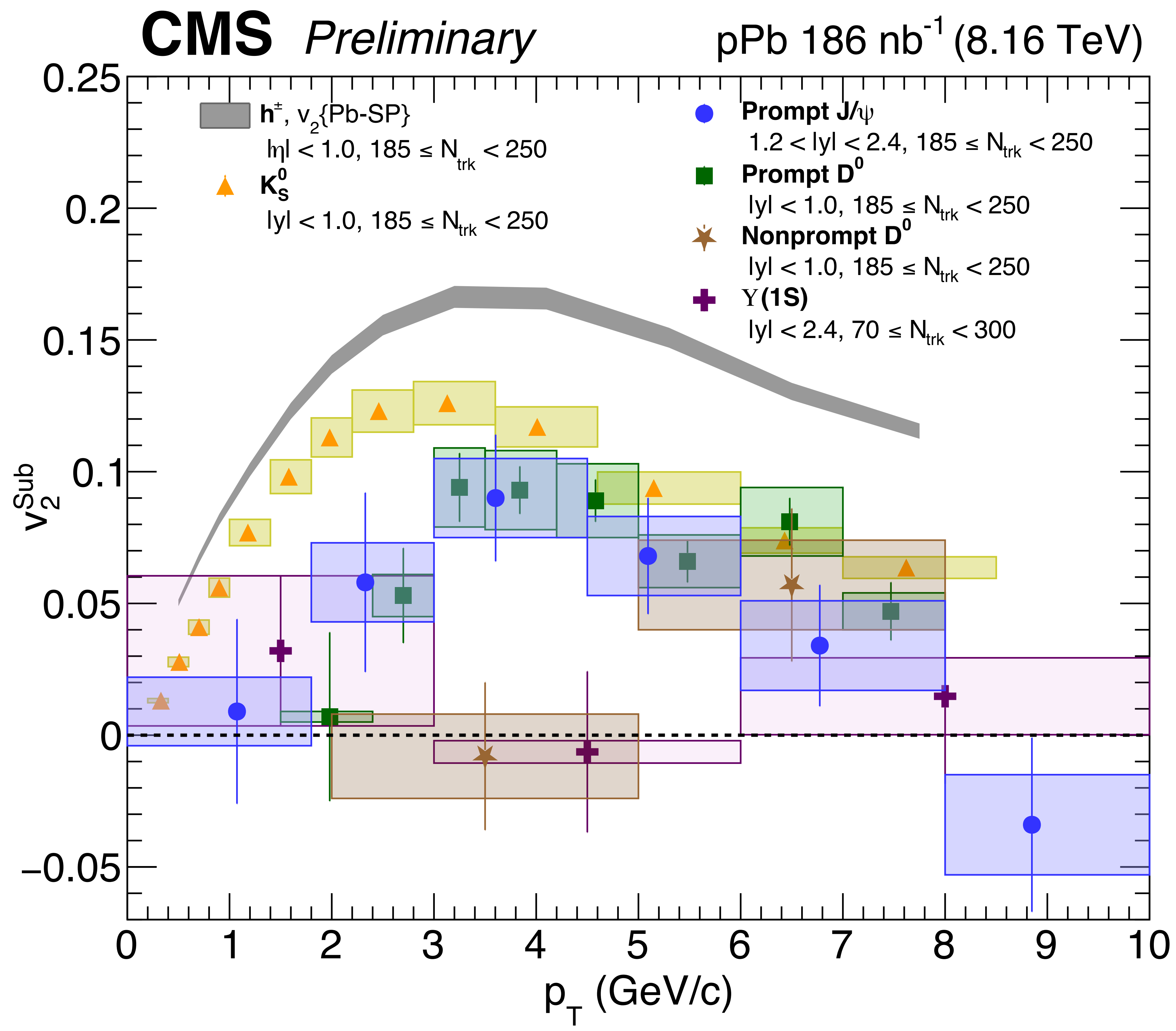


Collectivity Search Large to Small Systems

PbPb



High-multiplicity pPb



✔ Flow signal well established in PbPb for various flavors

What is the small limit of onset of collectivity?

✔ Almost everything flows in high-multiplicity pPb as well

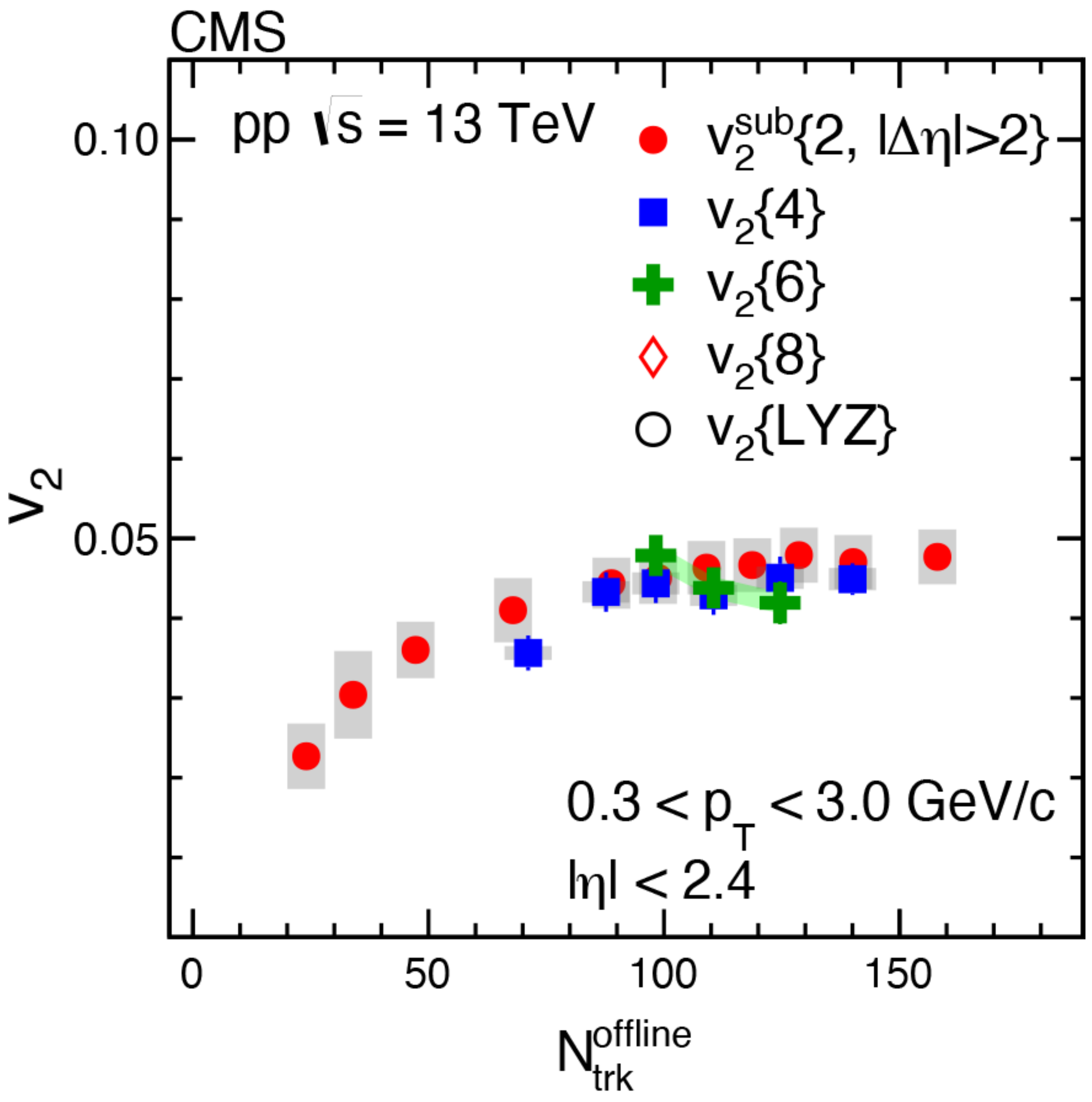
arXiv:2305.16928

CMS-PAS-HIN-21-001

Collectivity Search Large to Small Systems

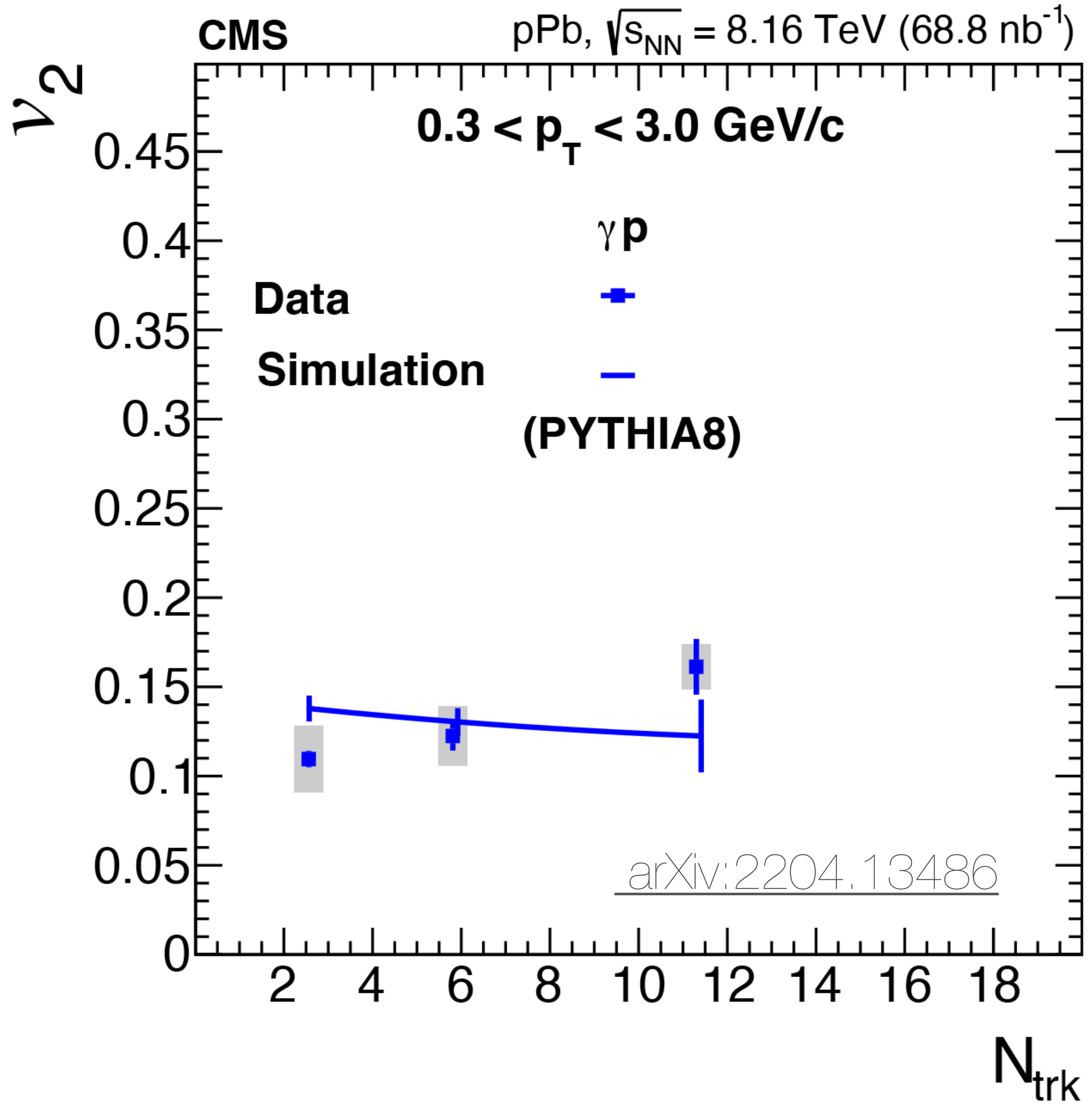
PLB 765 (2017) 193

pp



✔ Similar flow signal in pp after non-flow subtraction

γp (pPb UPC)



✘ PYTHIA8 describes the v_2 data at low multiplicity

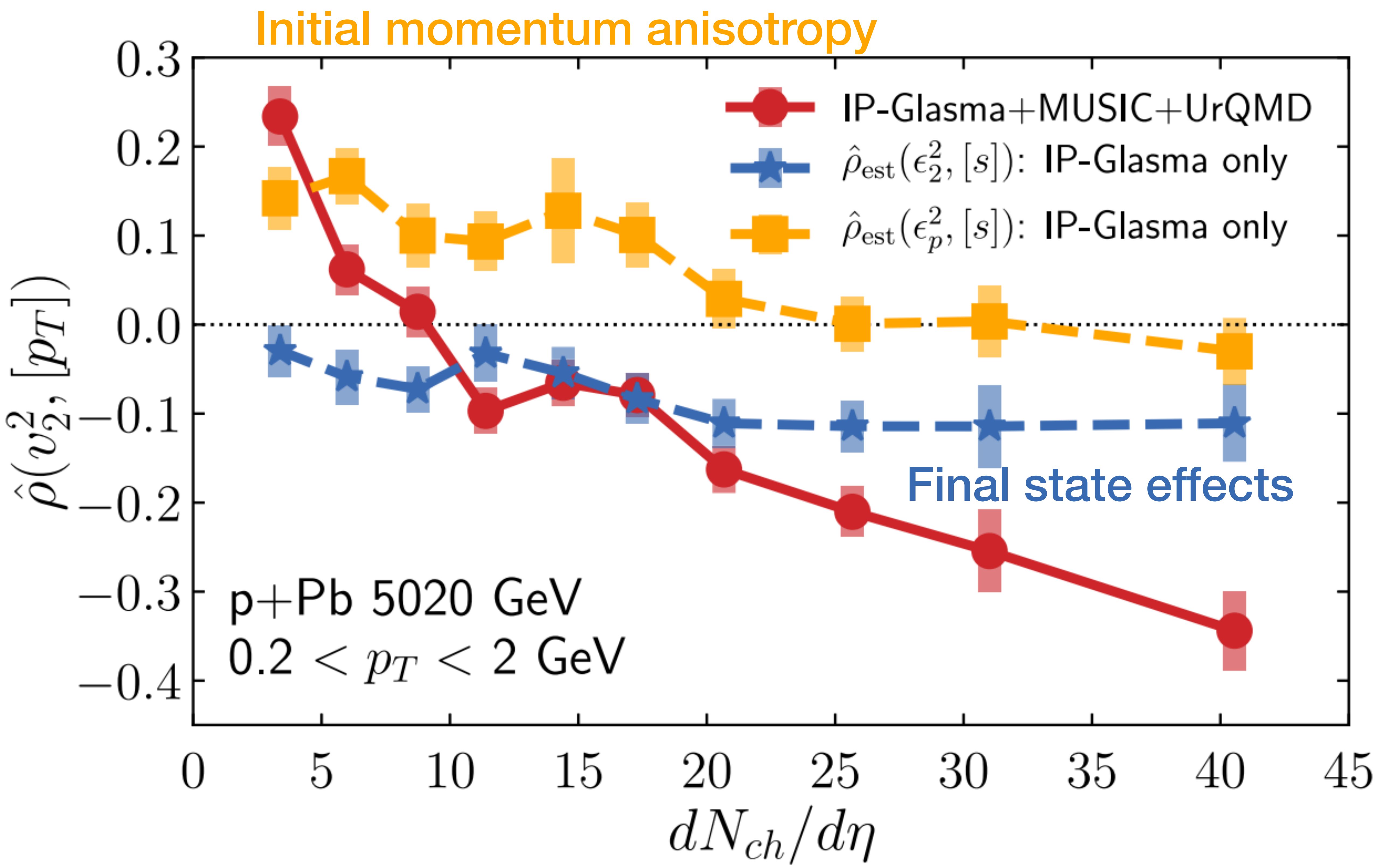
Possible interpretations of collectivity in small systems

- Final state effects driven by mini-QGP
- Single or few scatterings (e.g. AMPT, PYTHIA with Rope)
- Initial momentum anisotropy (e.g. CGC)

Can we separate these origins?

Collectivity Origin [p_T]-Cumulant Correlation

Mean p_T-v_2 correlation

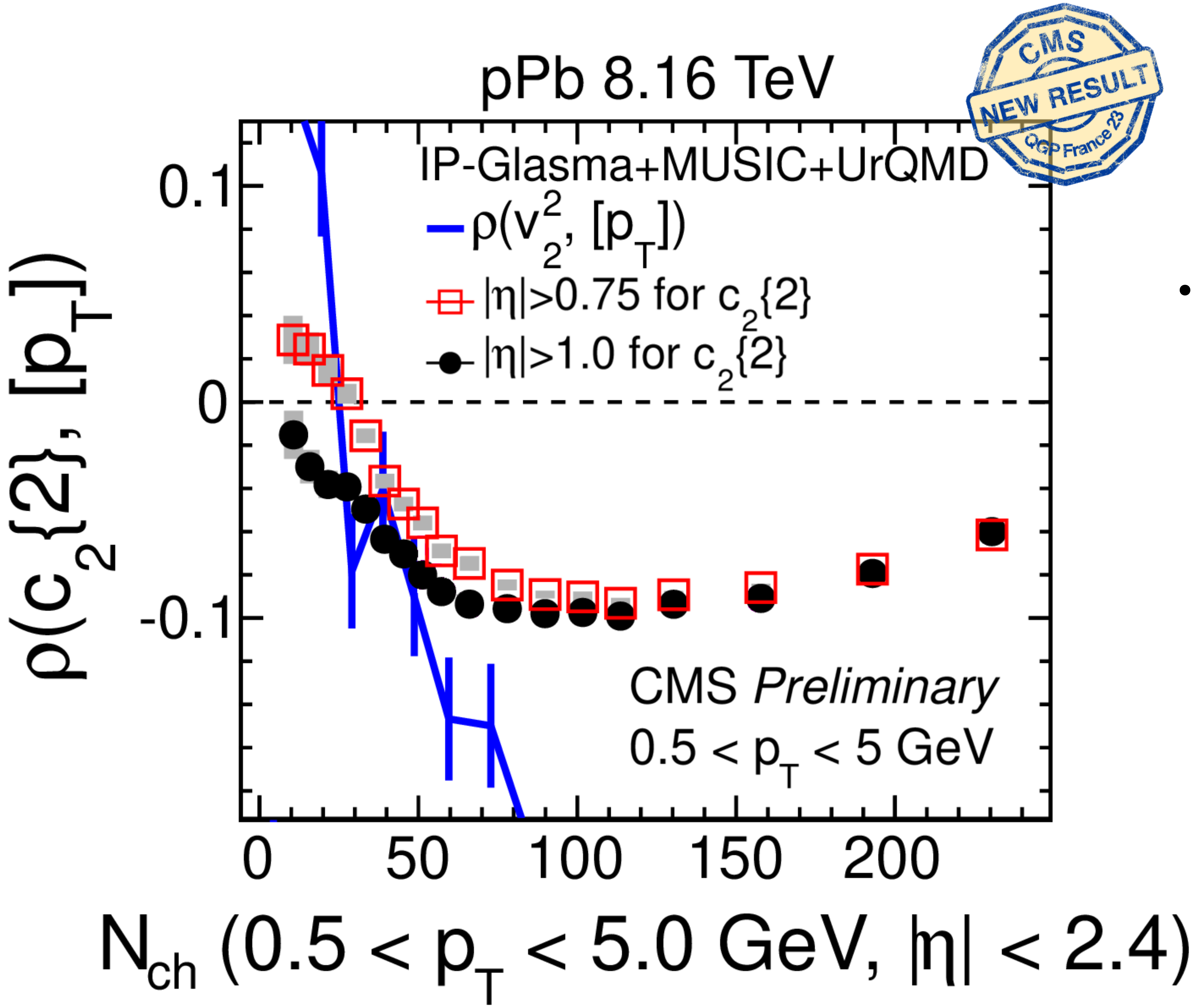


- v_n-mean p_T correlation vs. multiplicity reflects different initial state effects
- Sign-change predicted as signature of initial momentum anisotropy of CGC distinguished from initial geometry anisotropy+final state interactions

Let's see if data says there is initial momentum anisotropy!

PRL 125 (2020) 192301

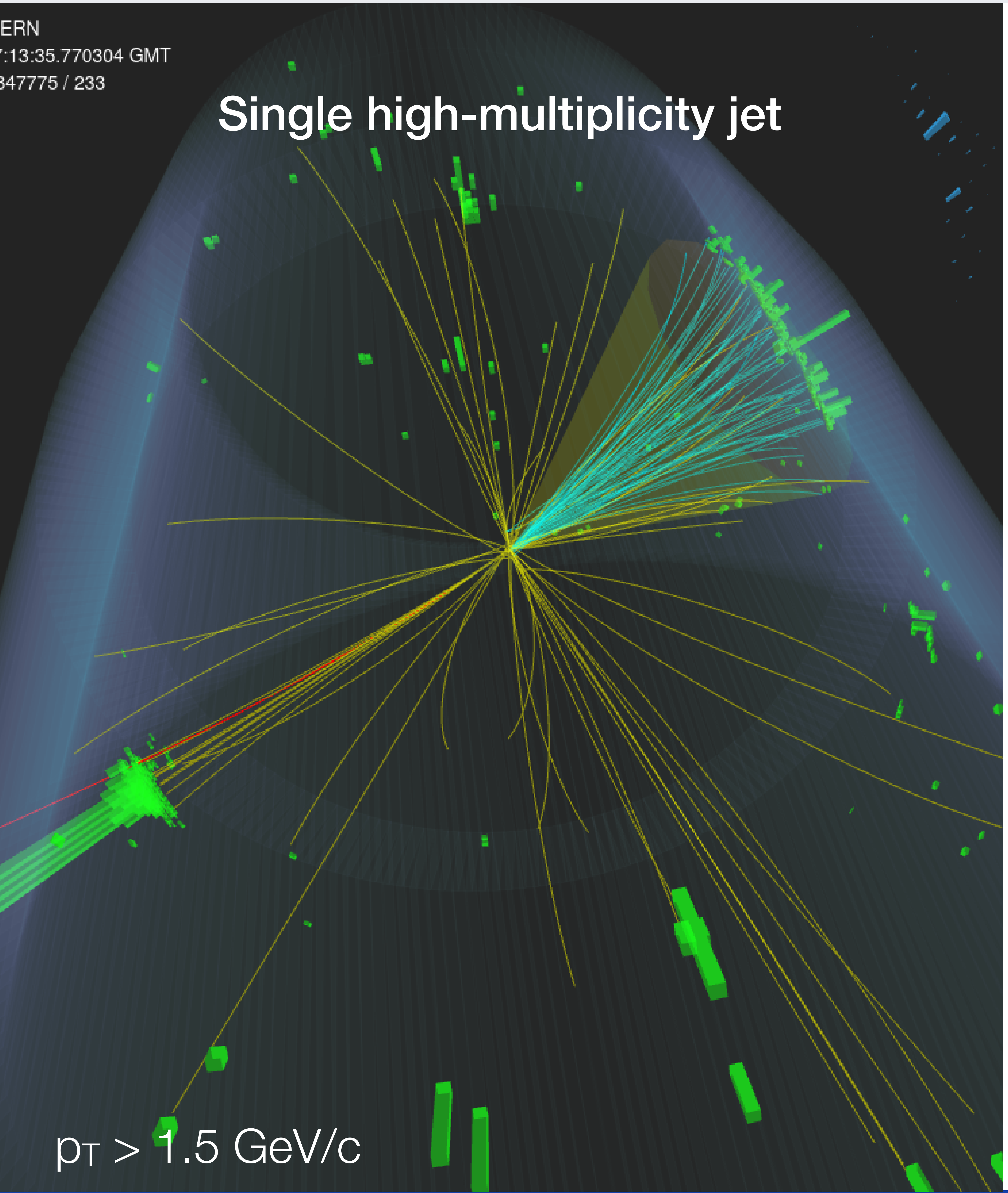
Collectivity Origin $[p_T]$-Cumulant Correlation



- Sign change with narrower η gap but no sign change with wider η gap
  - Sensitive to nonflow contribution?
  - Initial momentum correlation is relatively short-range?
  - Also depends on p_T kinematic cuts

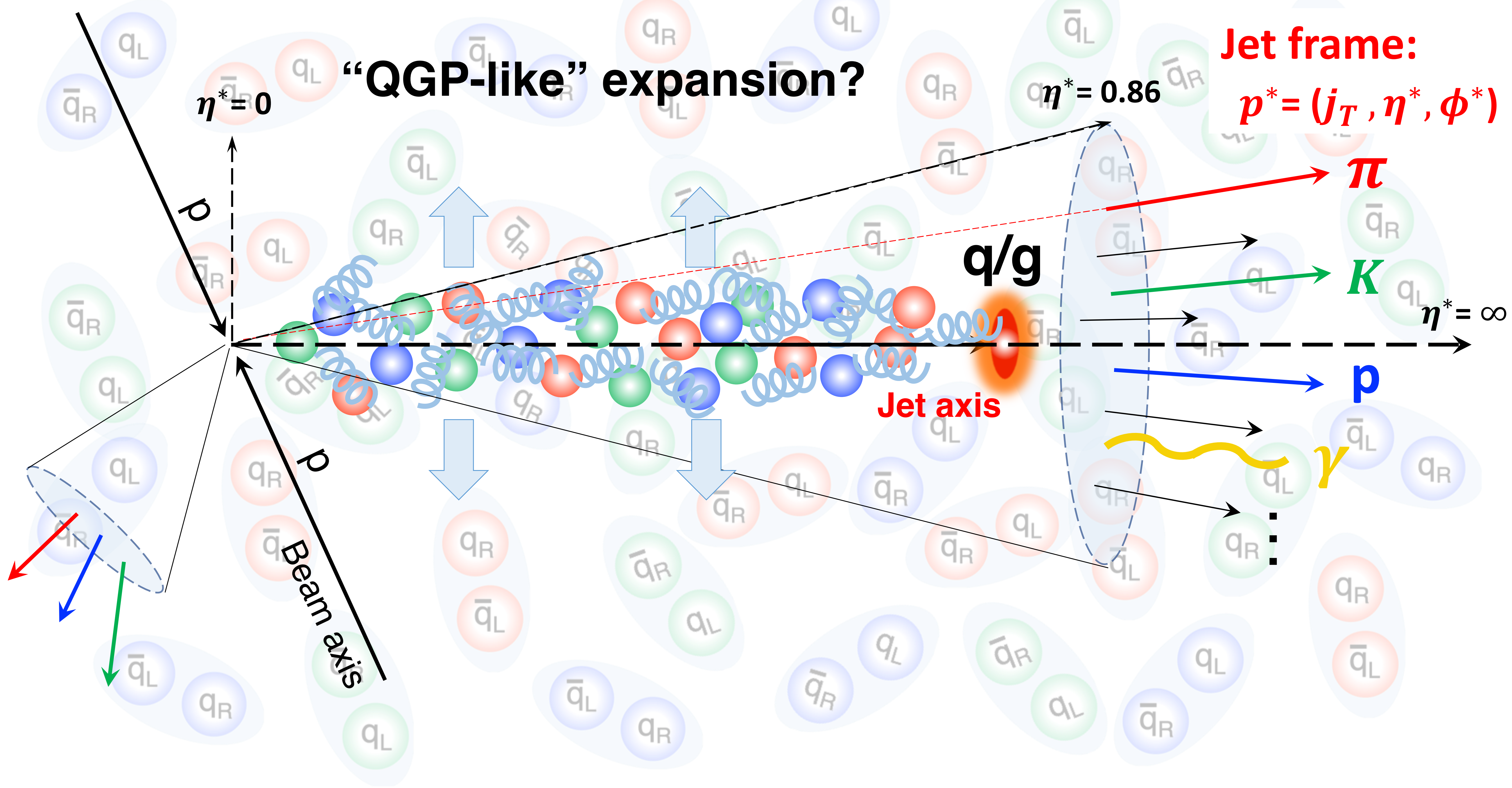
CMS-PAS-HIN-21-012

New Collectivity Search in High-mult. Jets in pp



Can we find a small but not dilute system?

Dynamics of a "single-parton" in the vacuum



- Search collectivity in single high-multiplicity jets in pp

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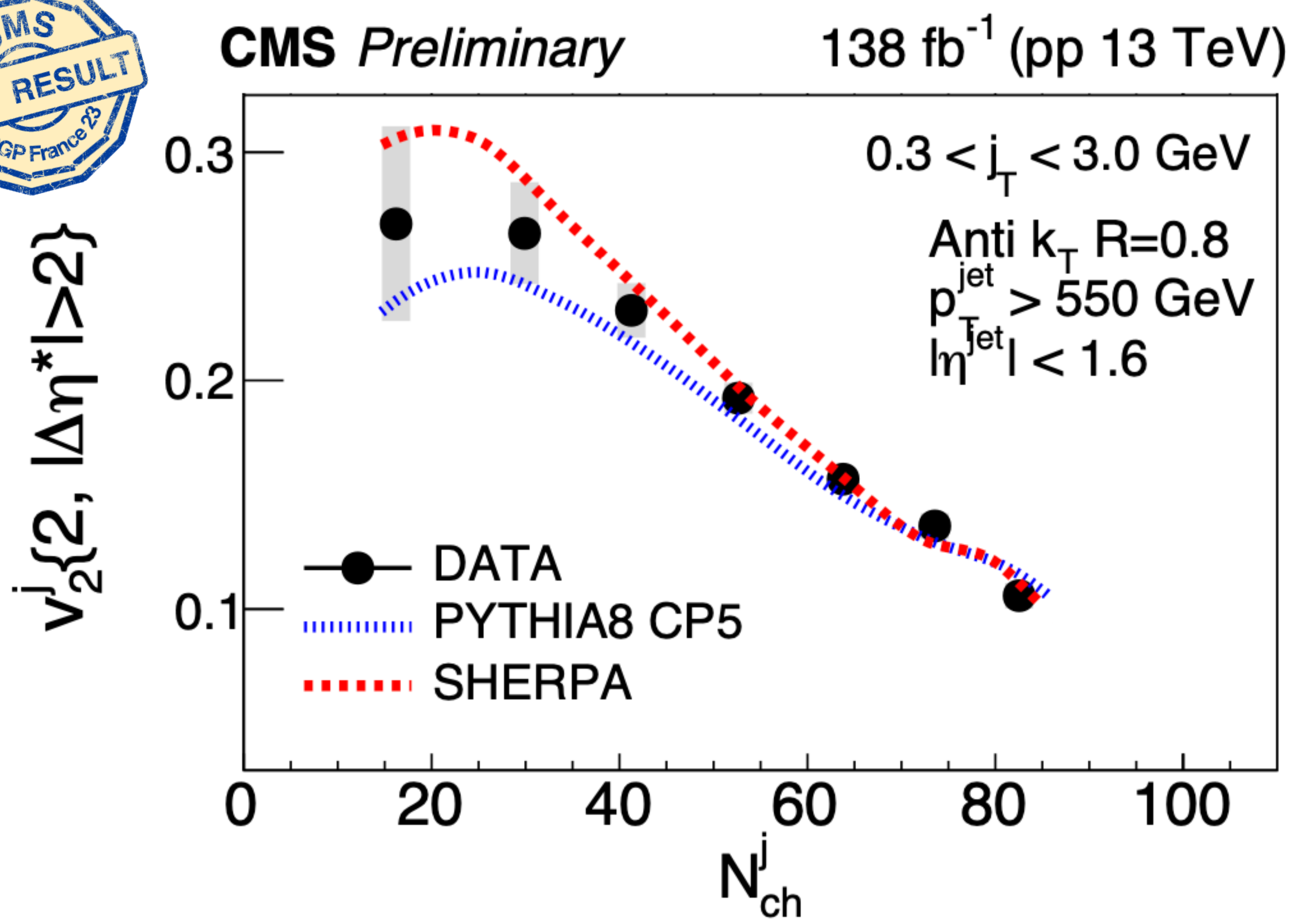
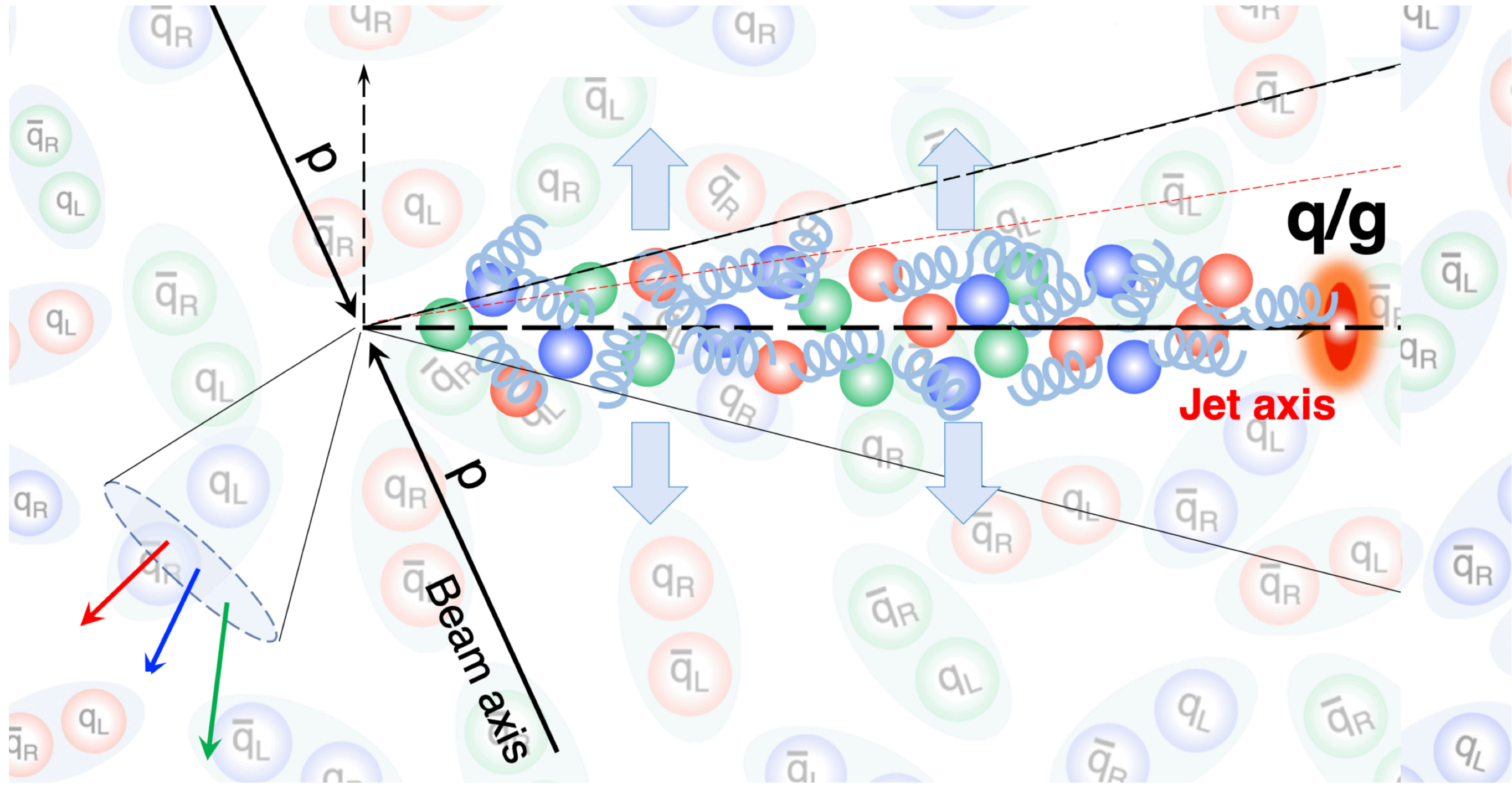
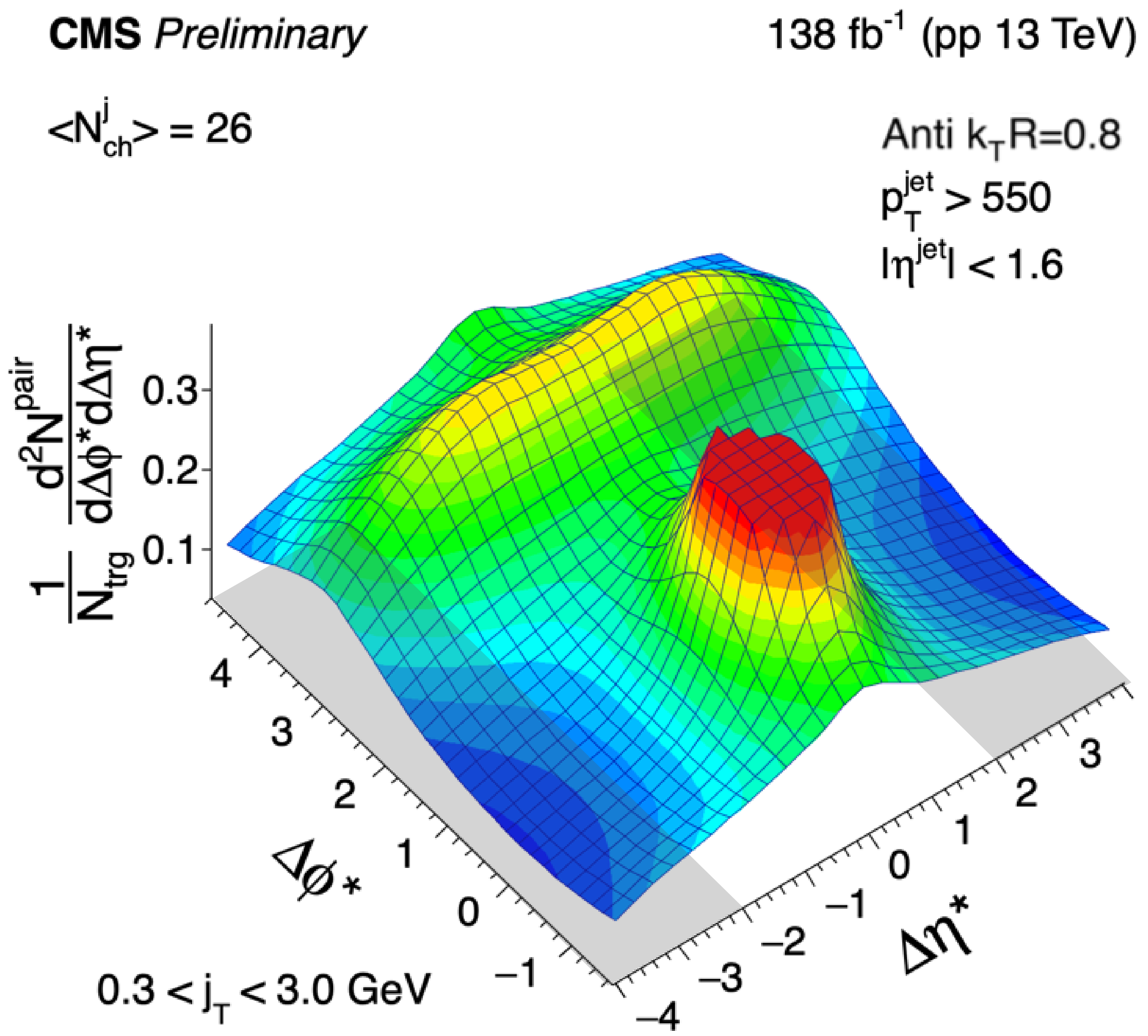
New Collectivity Search in High-mult. Jets in pp

Long range correlation in jet axis frame





Low multiplicity jets



- $N^{j}_{ch} < 90$: PYTHIA8 and SHERPA can effectively describe the data

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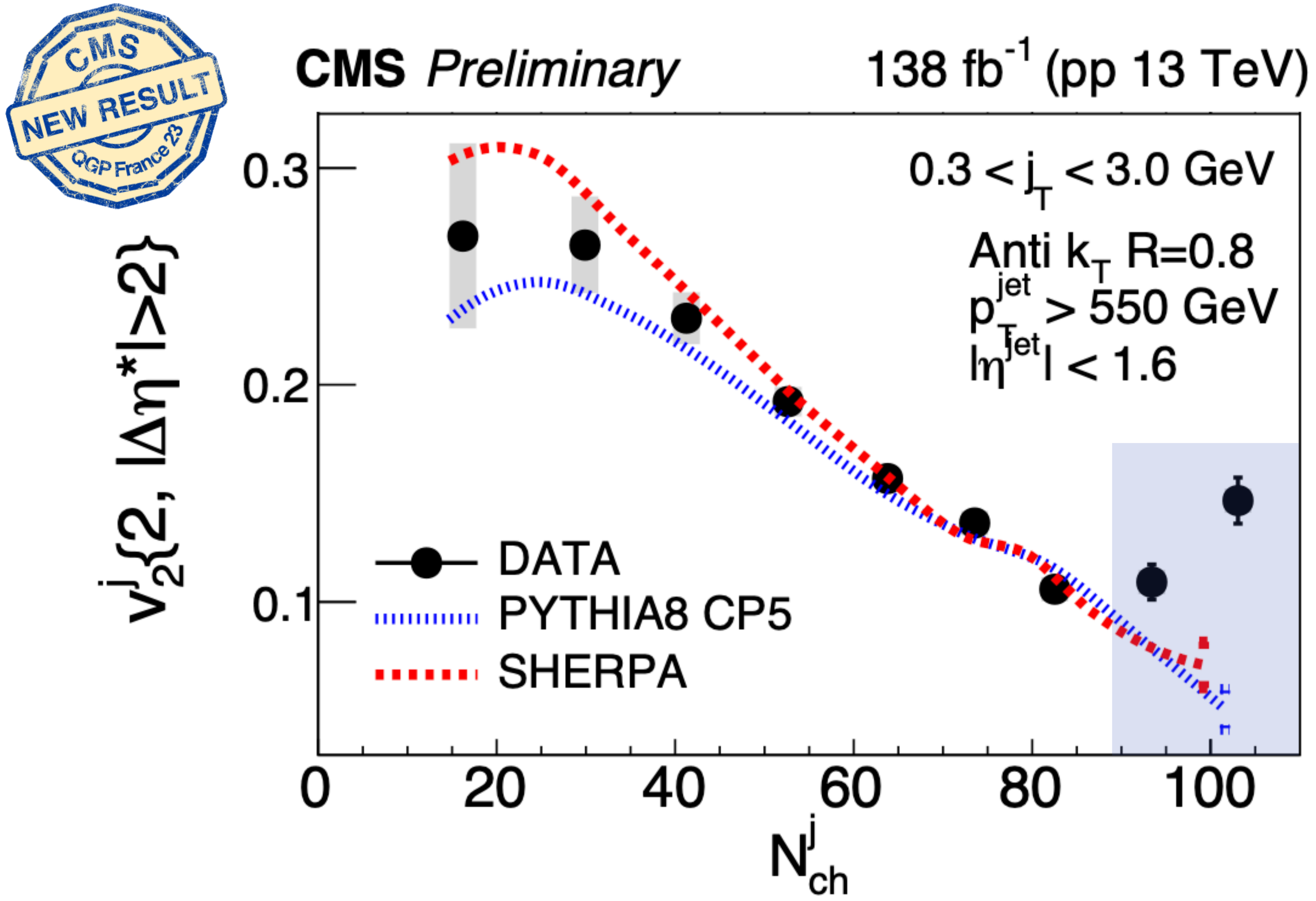
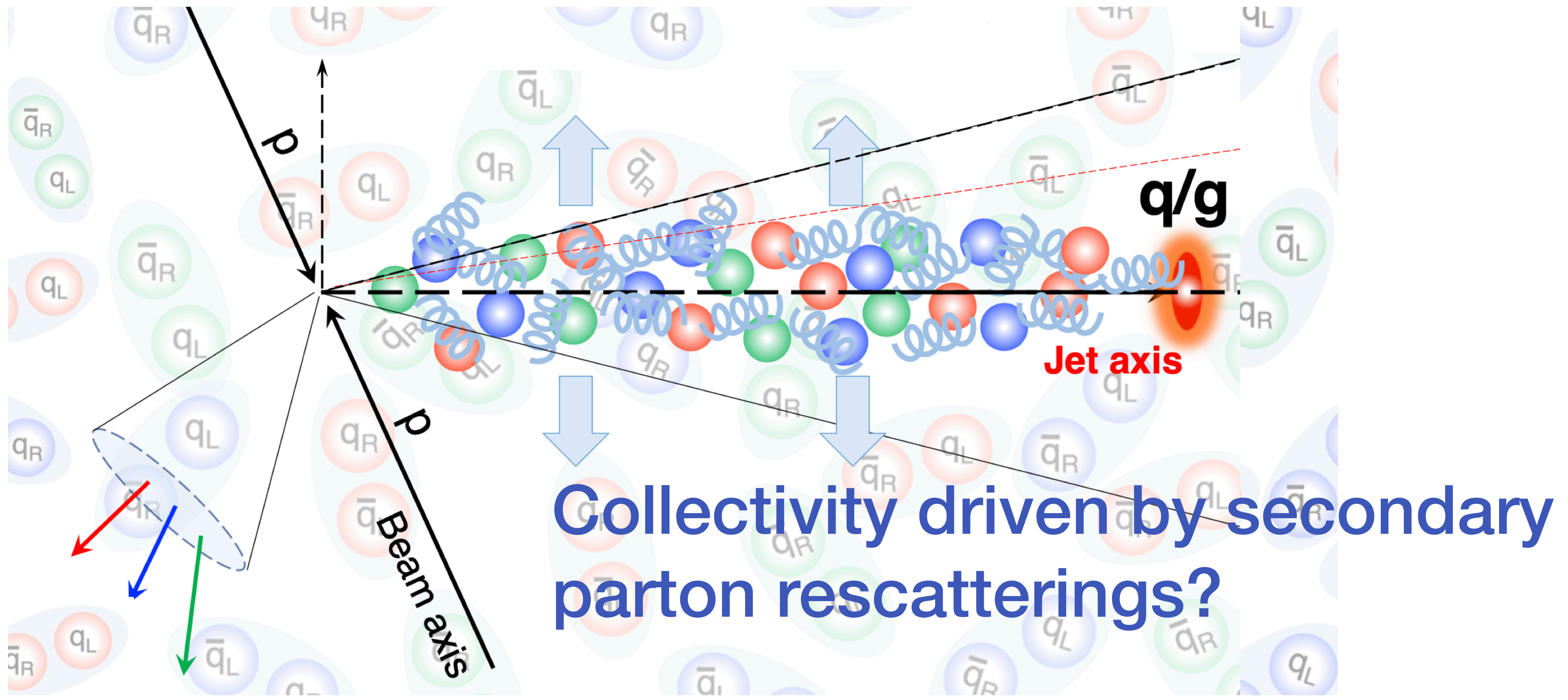
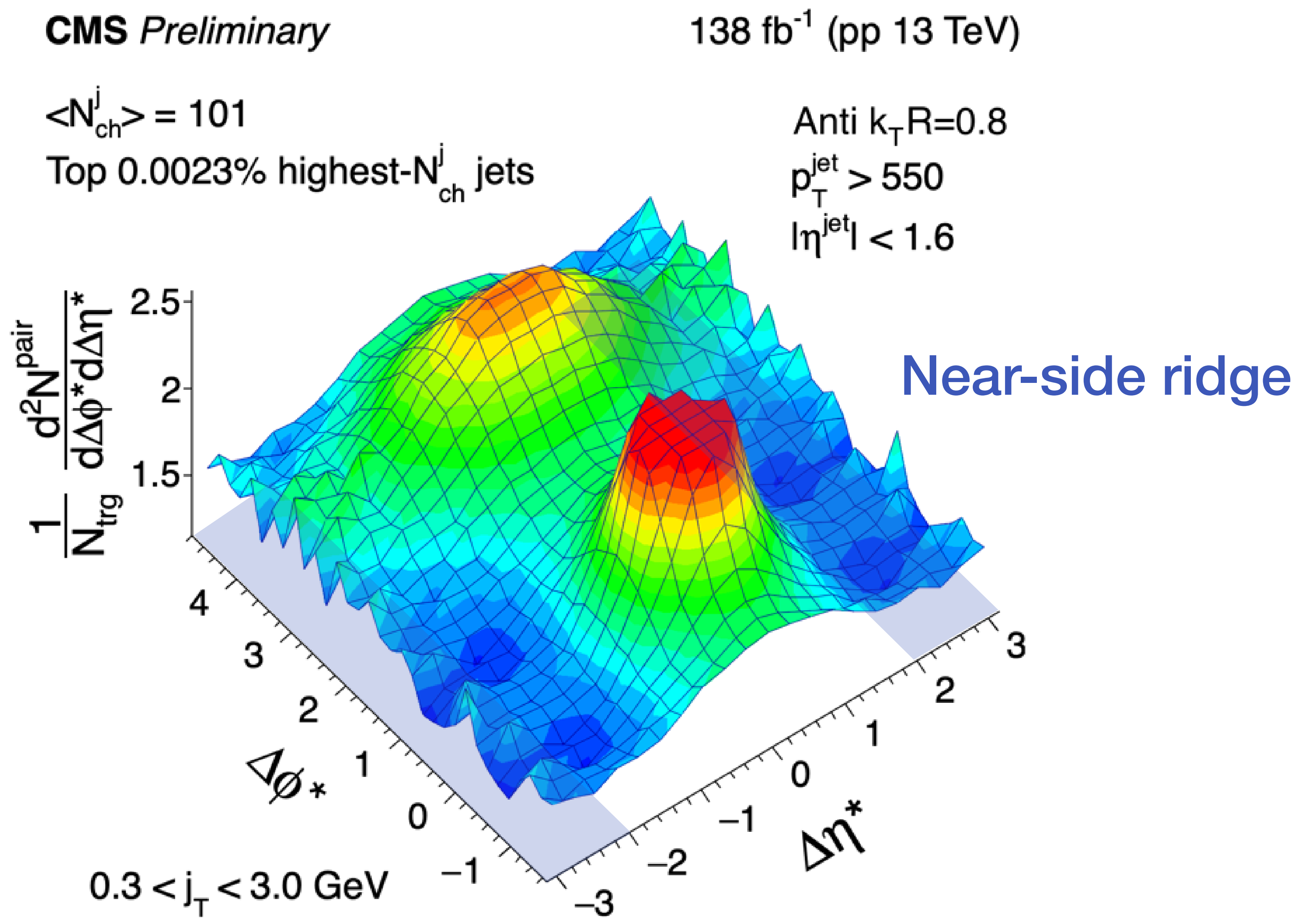
Long range correlation in jet axis frame





High multiplicity jets



- $N^j_{ch} < 90$: PYTHIA8 and SHERPA can effectively describe the data
- $N^j_{ch} > 90$: data v_2 deviates from the decreasing trend in MC

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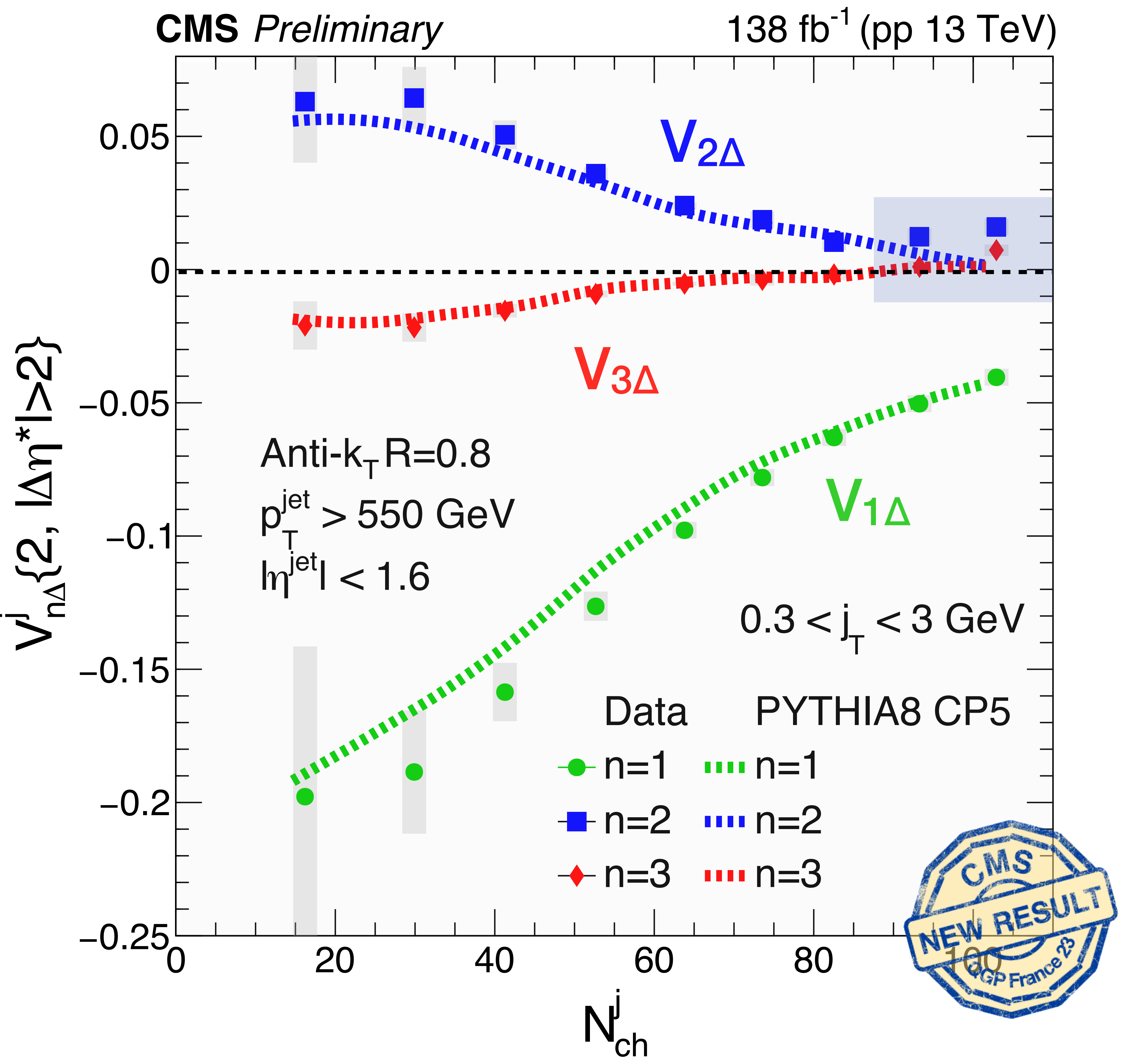
New Collectivity Search in High-mult. Jets in pp

Two-particle correlation Fourier coefficients



- Features @ small N^{j}_{ch} consistent with short-range few-body correlations captured by PYTHIA8
  - Magnitudes decrease
  - Negative odd $V_{n\Delta}$
- Features @ large N^{j}_{ch} different deviated from PYTHIA8
  - $V_{2\Delta}$ increases
  - Positive $V_{3\Delta}$

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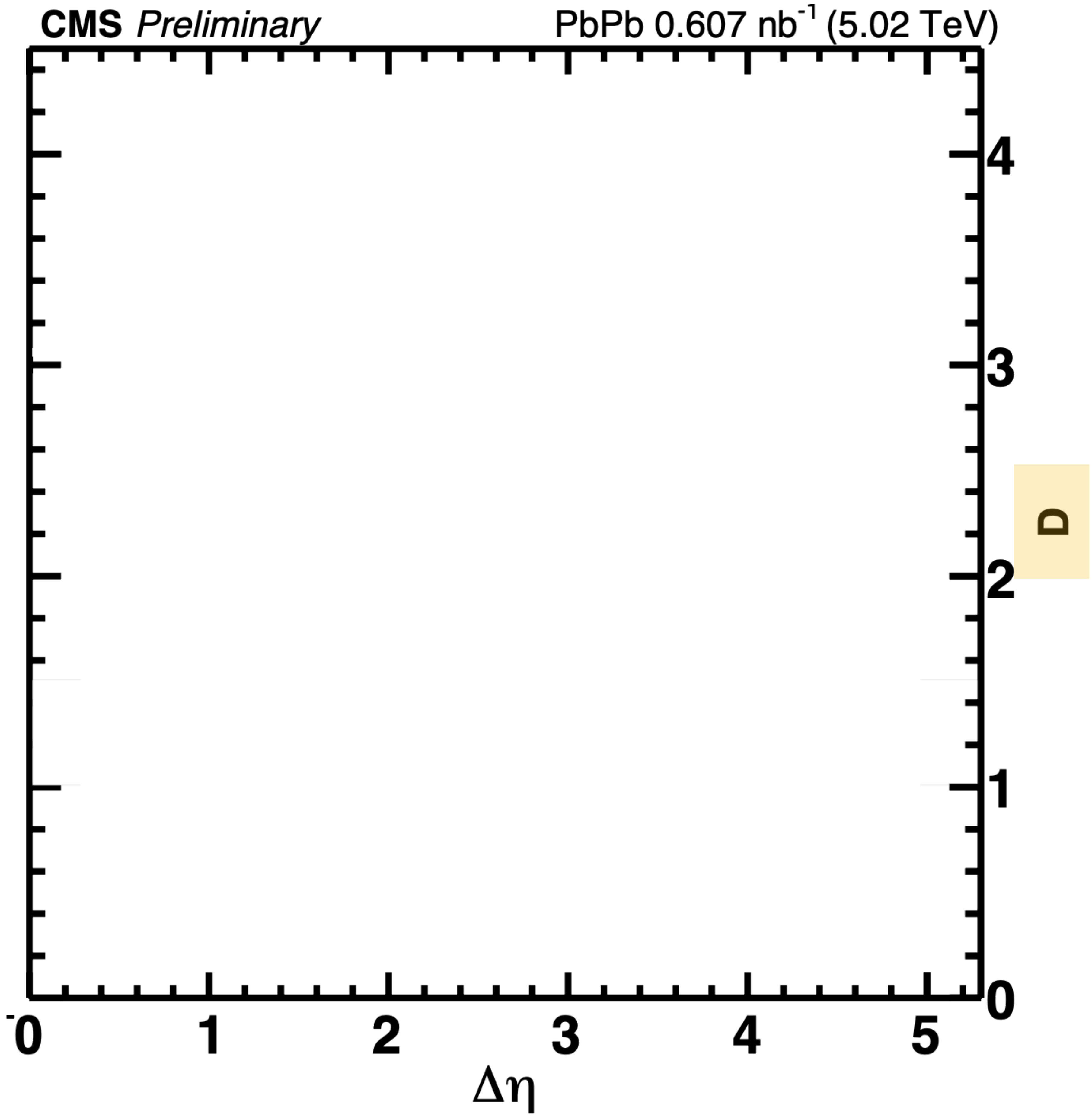
QGP Emergence Net Charge Fluctuations

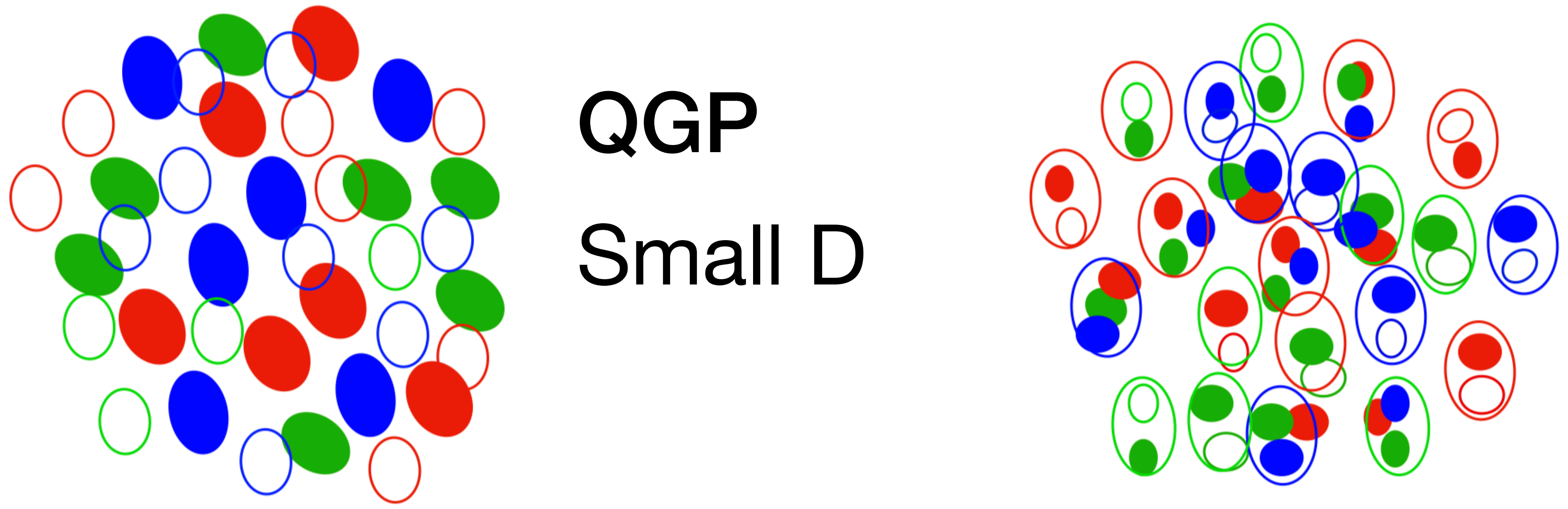


Theory

- Smaller net charge fluctuation in QGP than hadron gas
- Quantified by

  Variance of the net charge scaled by total charge

$$D = 4\frac{\langle \Delta Q^2 \rangle}{\langle N_{ch} \rangle}, \quad Q = N_+ - N_-$$



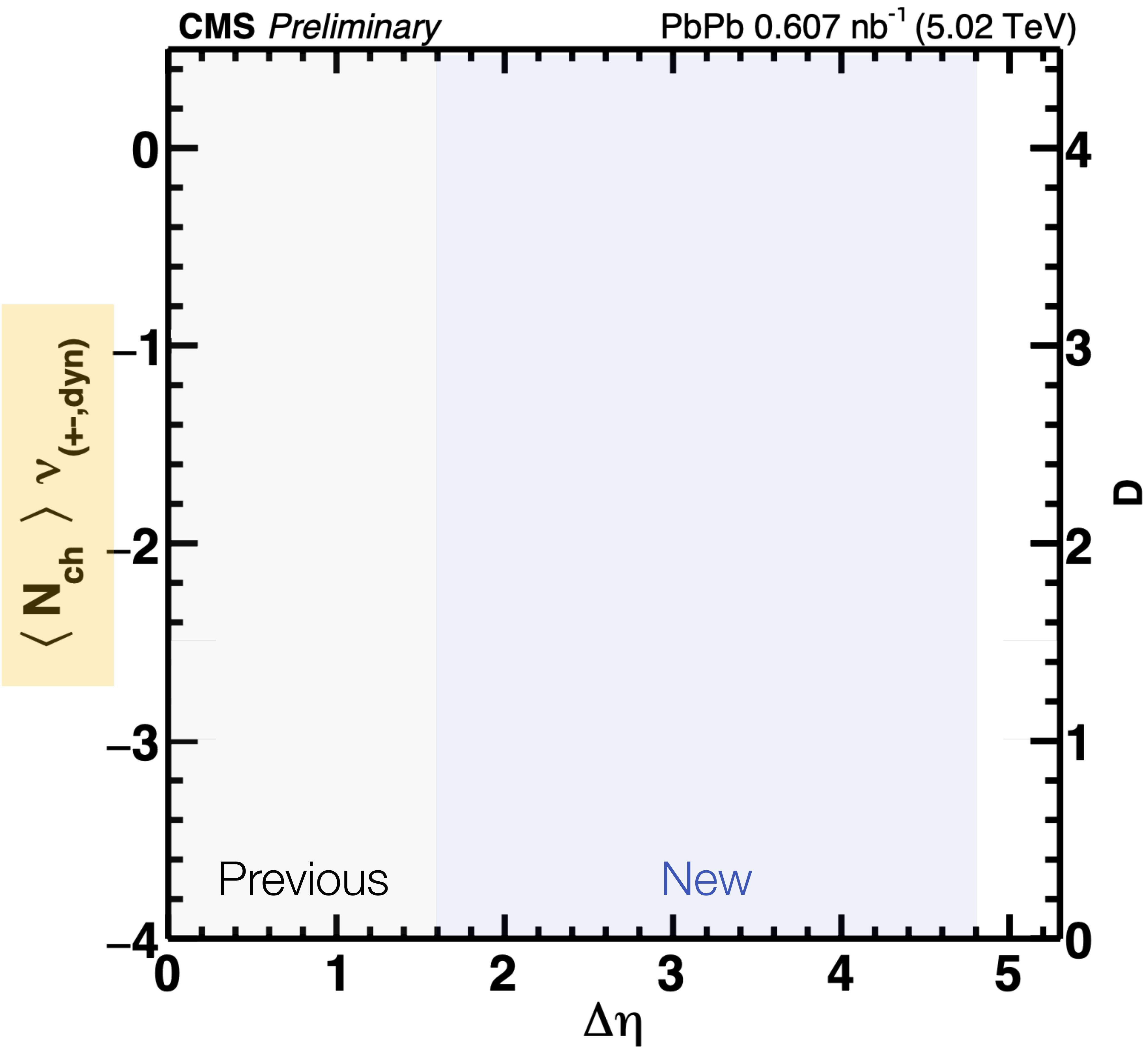
$q = \pm\frac{1}{3}, \pm\frac{2}{3}$

$q = \pm 1, \pm 2$

Net charge fluctuations tell which phase they originate from

CMS-PAS-HIN-22-005

QGP Emergence Net Charge Fluctuations



Theory

- Smaller net charge fluctuation in QGP than hadron gas
- Quantified by $D = 4\langle \Delta Q^2\rangle / \langle N_{ch}\rangle$

  Variance of the net charge scaled by total charge

Experimental observable

- Dynamical net charge fluctuation measure

$$\nu_{+-,dyn} = \left\langle \left(\frac{N_+}{\langle N_+\rangle} - \frac{N_-}{\langle N_-\rangle} \right)^2 \right\rangle - \nu_{+-,stat}$$

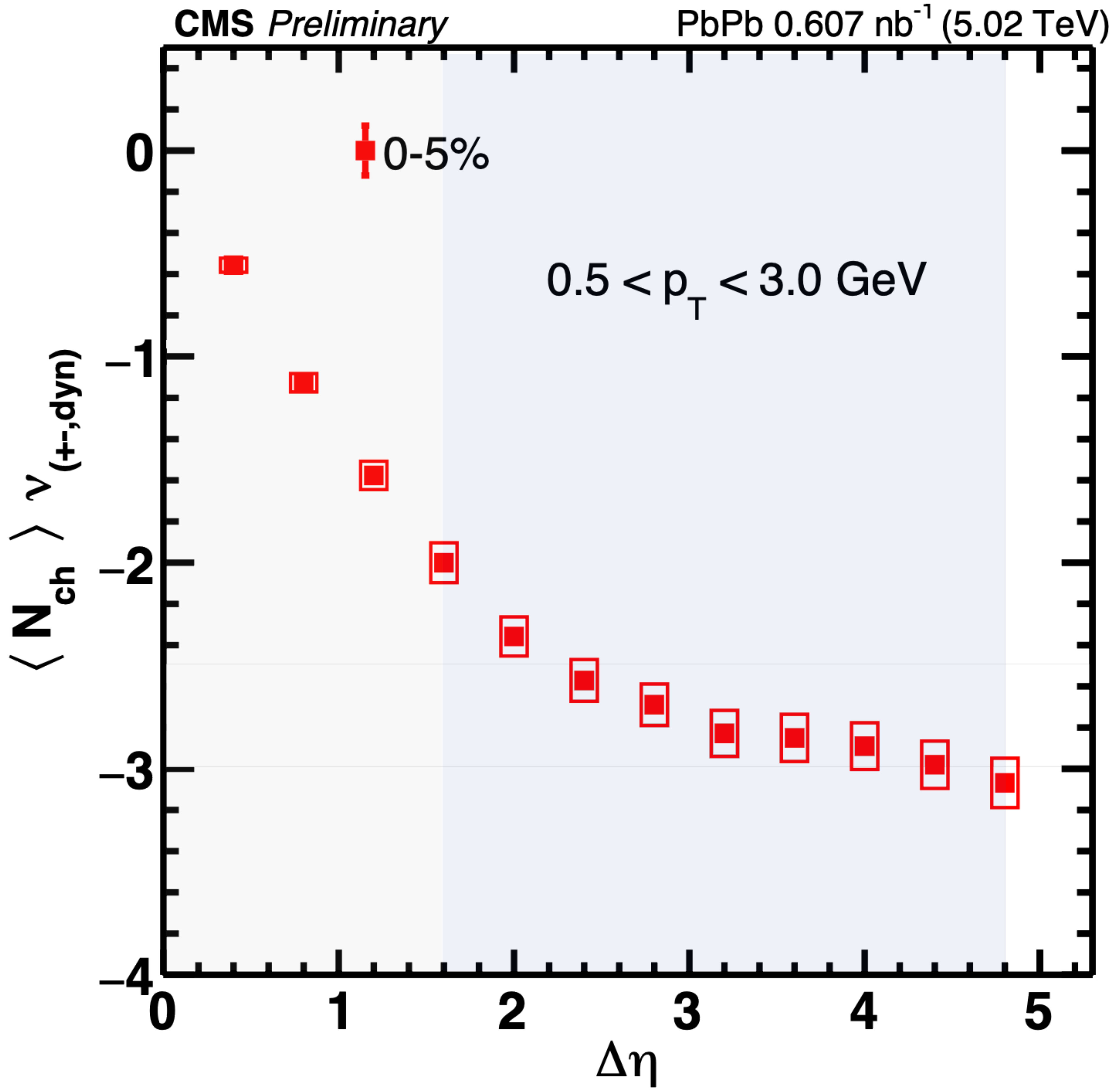
Poisson stat limit

- Robust observable minimally affected by efficiency
- Depends on η width in which the events are sampled
  - Large Δη reduces sensitivity to confounding effects
  - Measurement to Δη = 4.8 New!

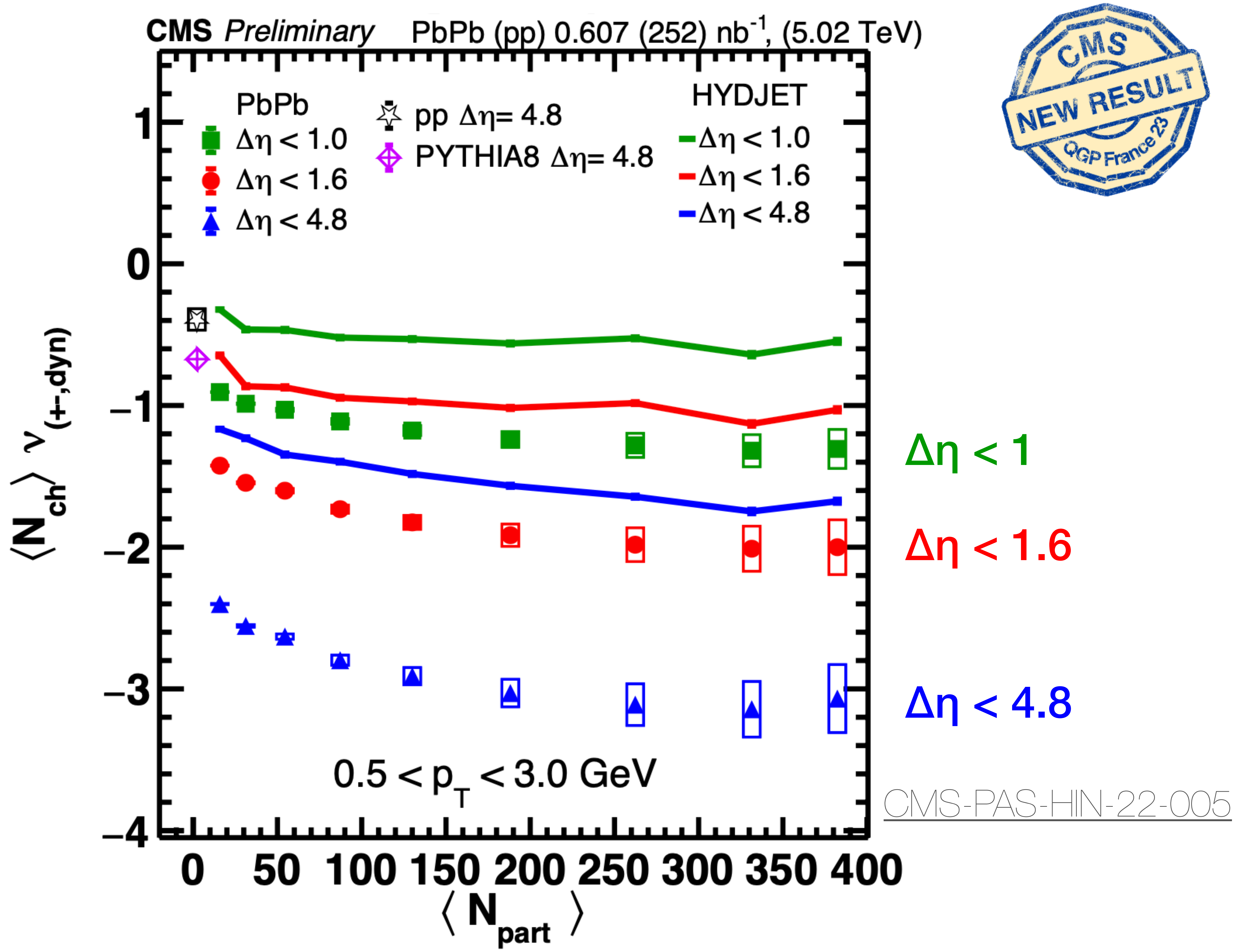
CMS-PAS-HIN-22-005

QGP Emergence Net Charge Fluctuations

vs. η width



vs. centrality



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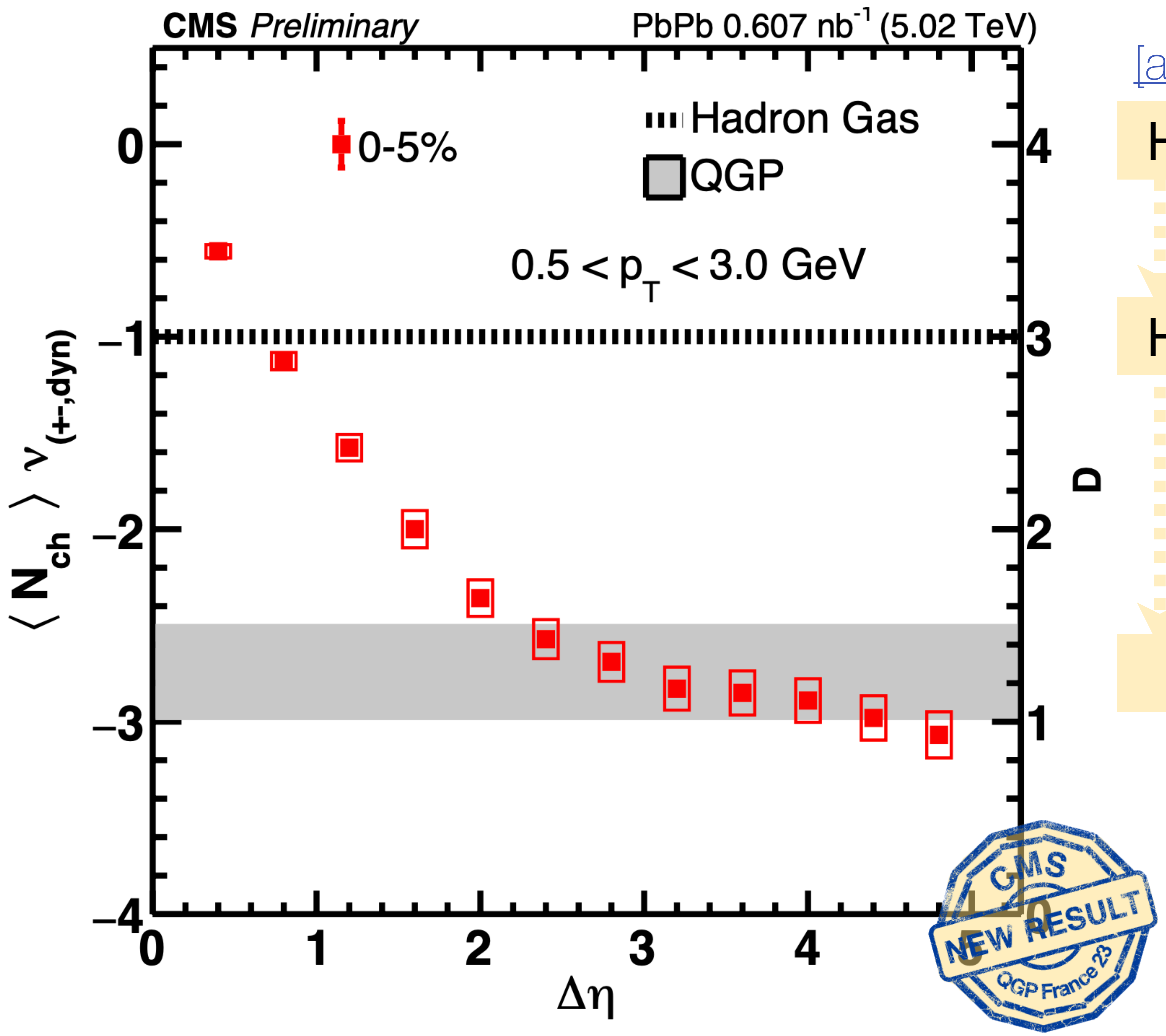
- Negative values
- Fluctuations decreases with increase of Δη

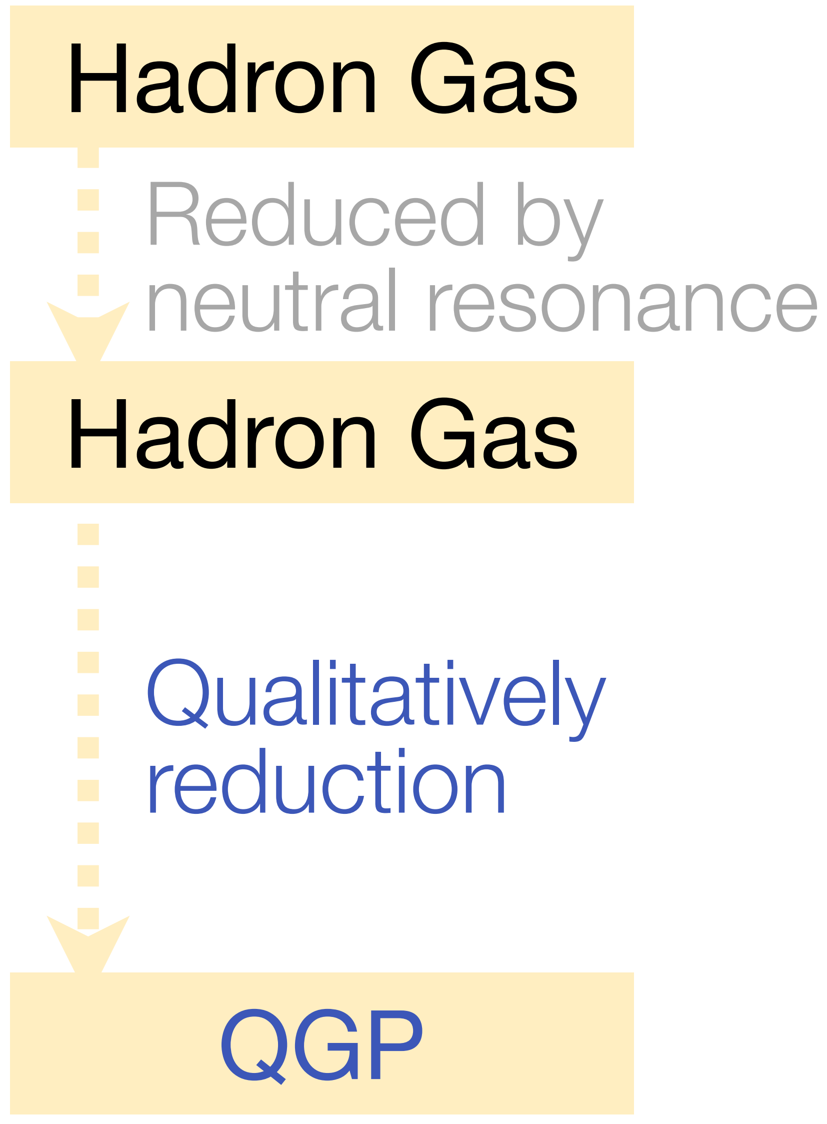
- Fluctuations decrease to central events
- HIJING and HYDJET can not explain data data well

QGP Emergence Net Charge Fluctuations



Net charge fluctuations

[arXiv:0304012]



- Interpretation of data is tricky
  Hadronization, resonance, diffusion, rescatterings, …
- Some complication (e.g. diffusion) is suppressed by the wide η range

Small Δη window
- Consistent with previous measurements by ALICE

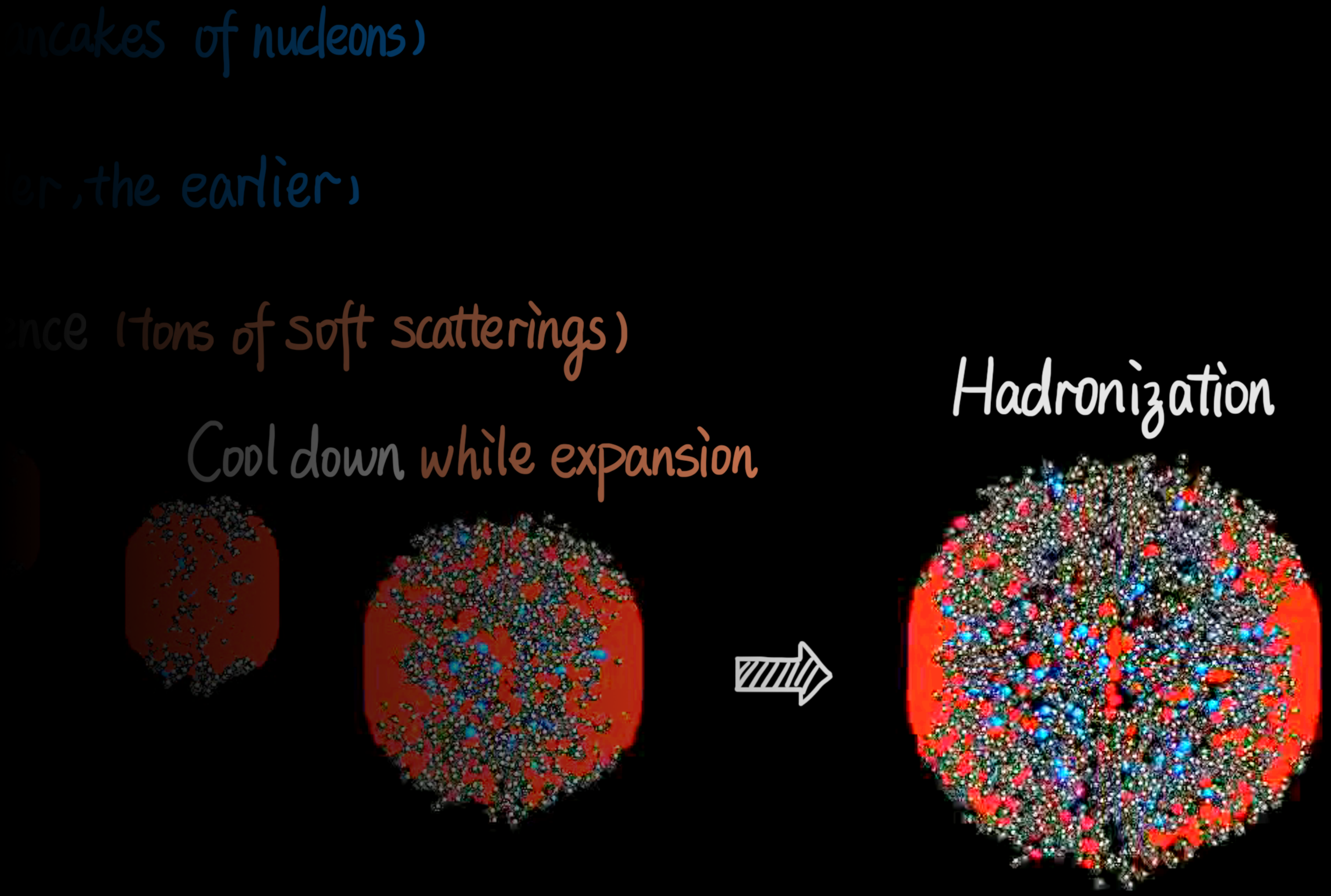
Large Δη window
- Consistent with prediction of QGP by specific model

CMS-PAS-HIN-22-005

Hadronization & Hadron Rescatterings

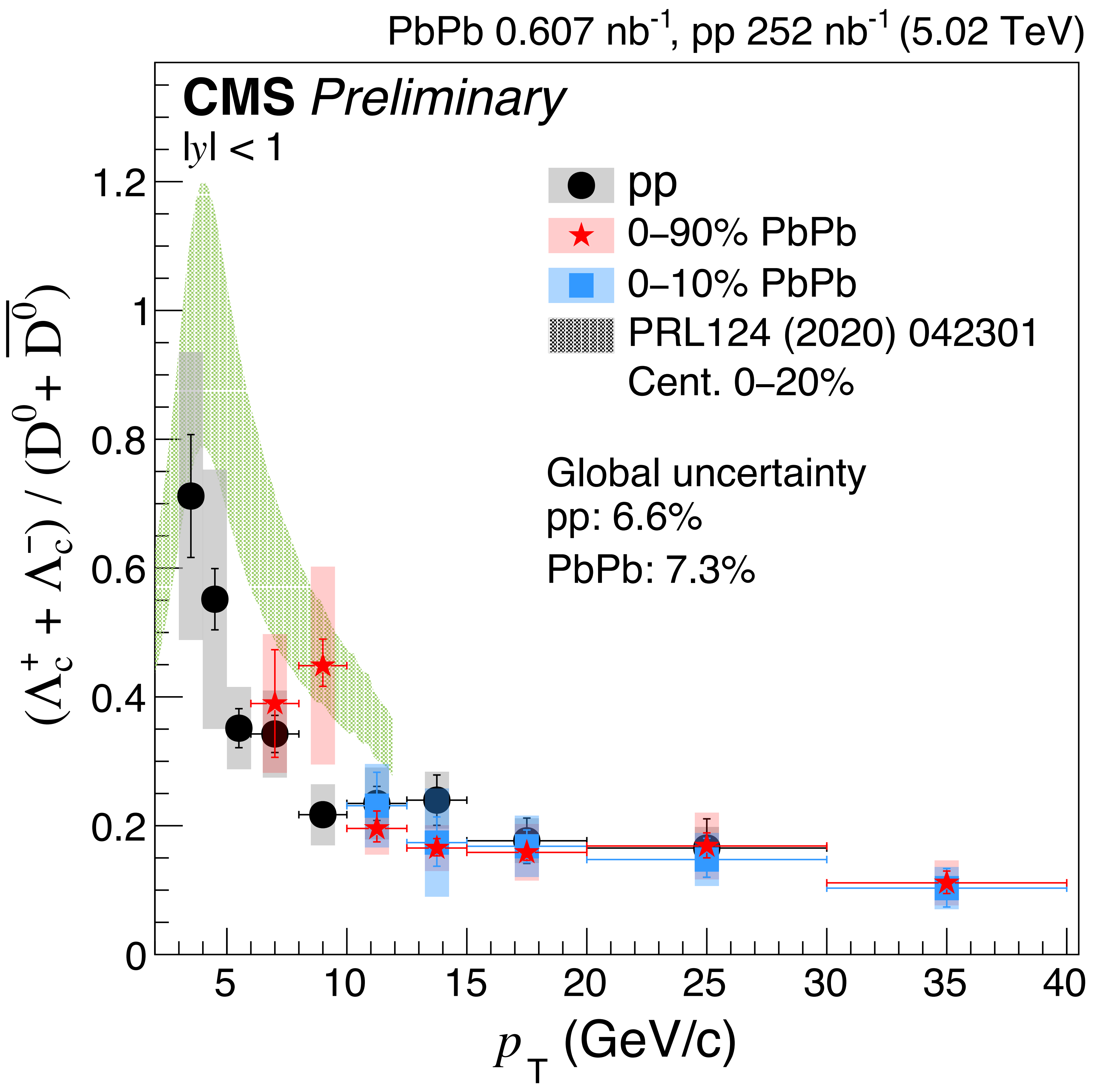
How are hadrons produced and interacting?

Major restriction/uncertainty in phenomenological models



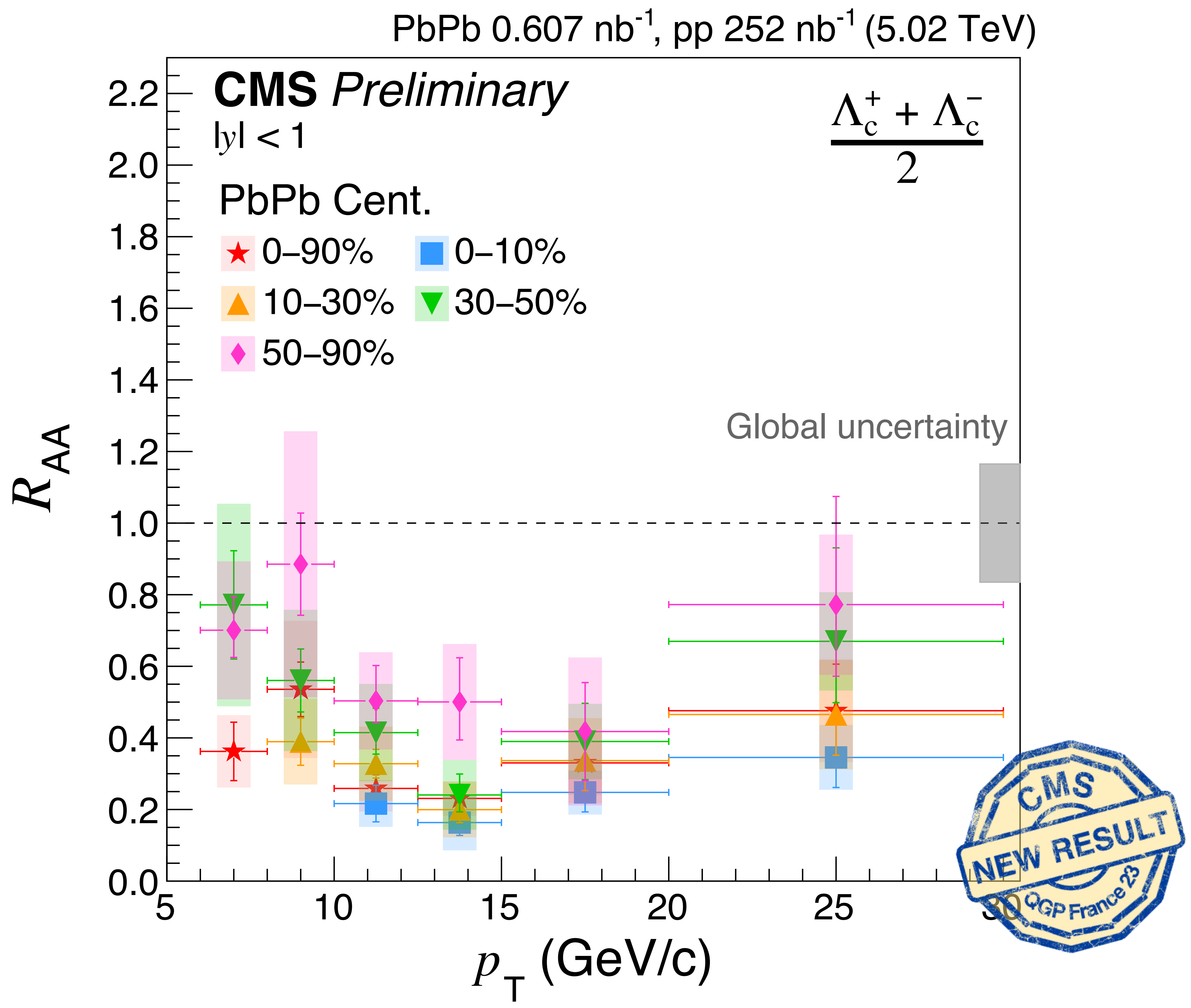
HF Hadronization Λ_c in pp and PbPb

Λ_c/D^0



- Significant enhancement at low p_T in pp

Λ_c R_{AA}



- Λ_c R_{AA} minimum point shift to higher p_T than D^0 possibly because of coalescence

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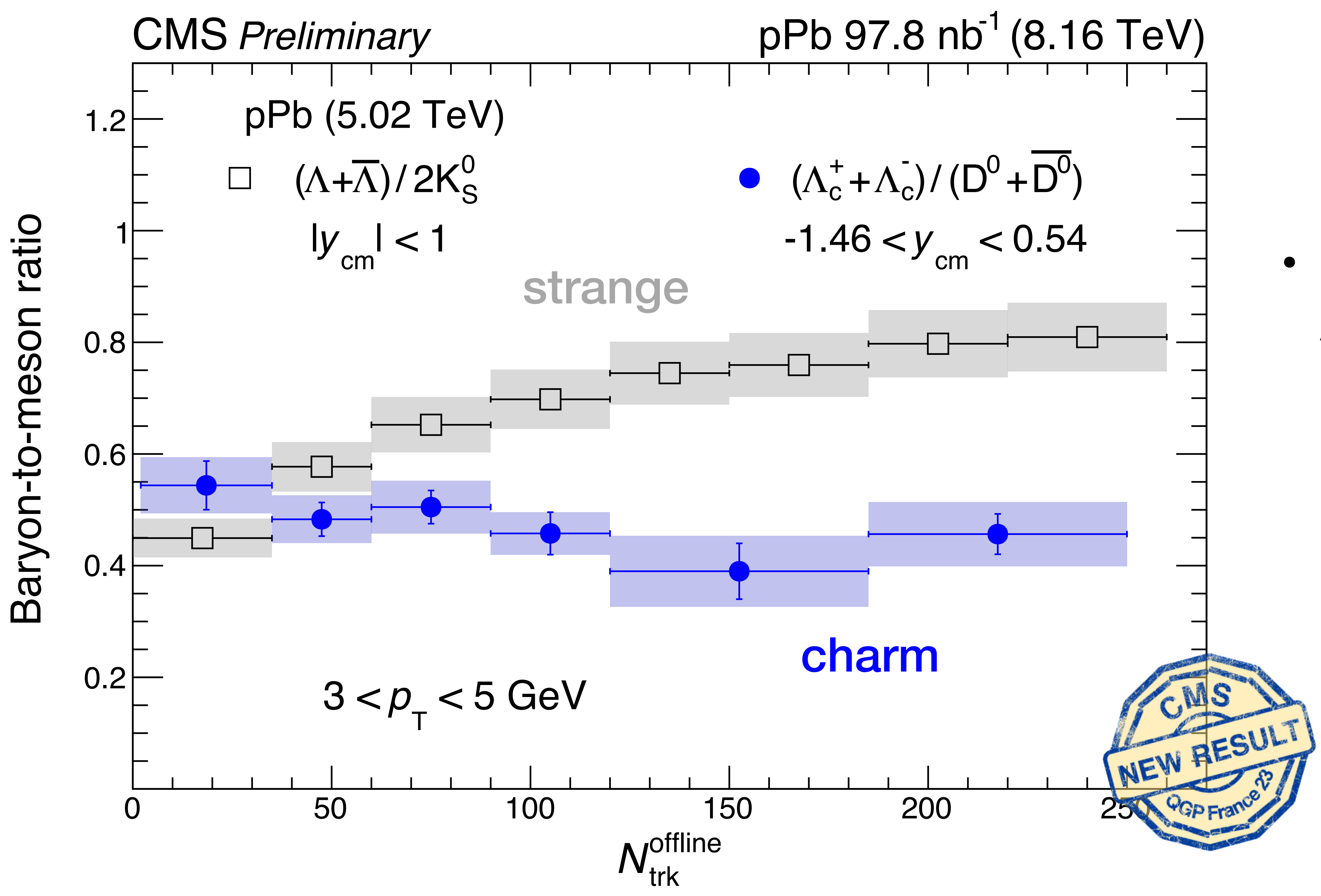
HF Hadronization Λ_c in pPb

Λ_c/D^0 vs. multiplicity in pPb

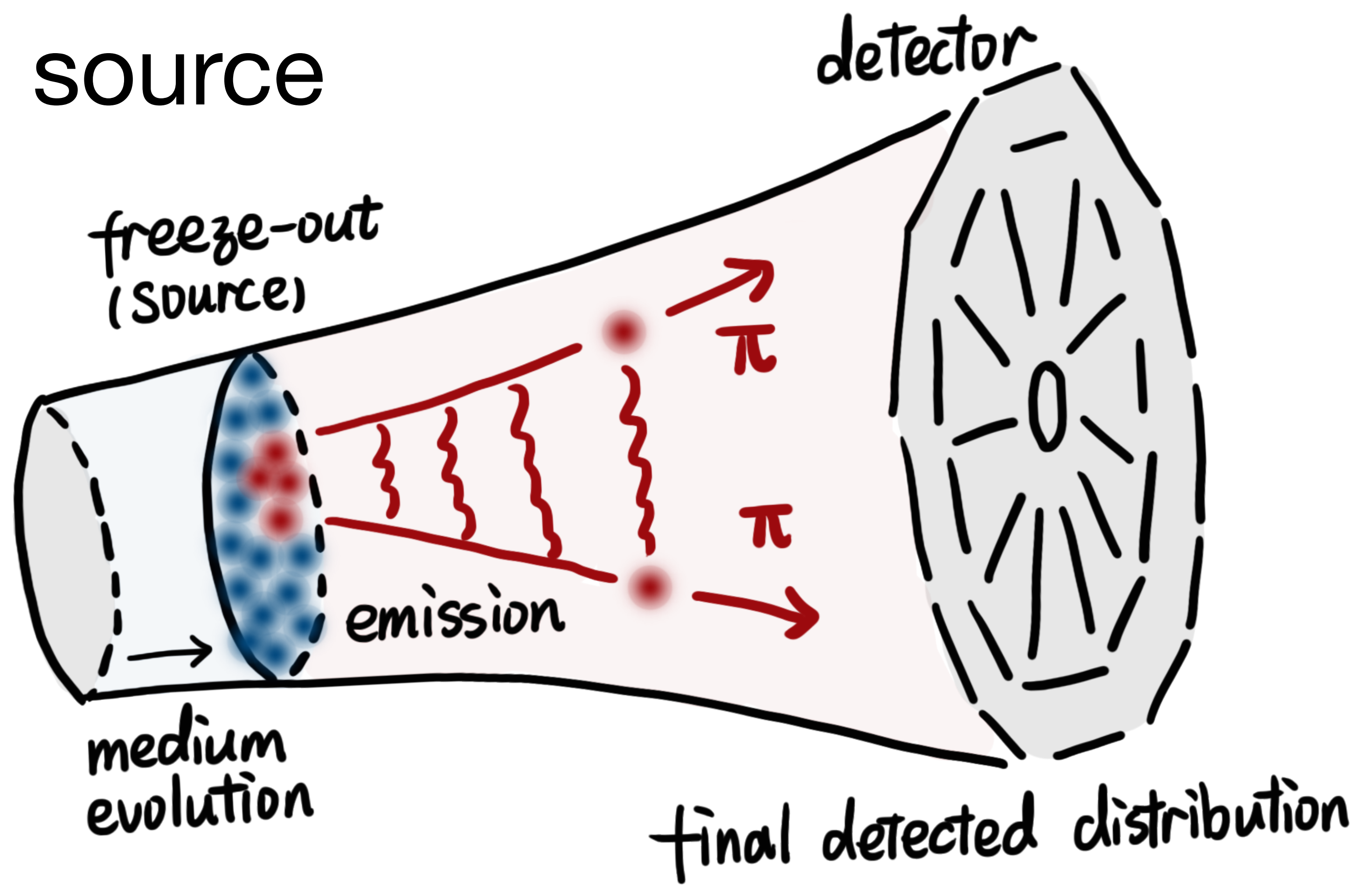


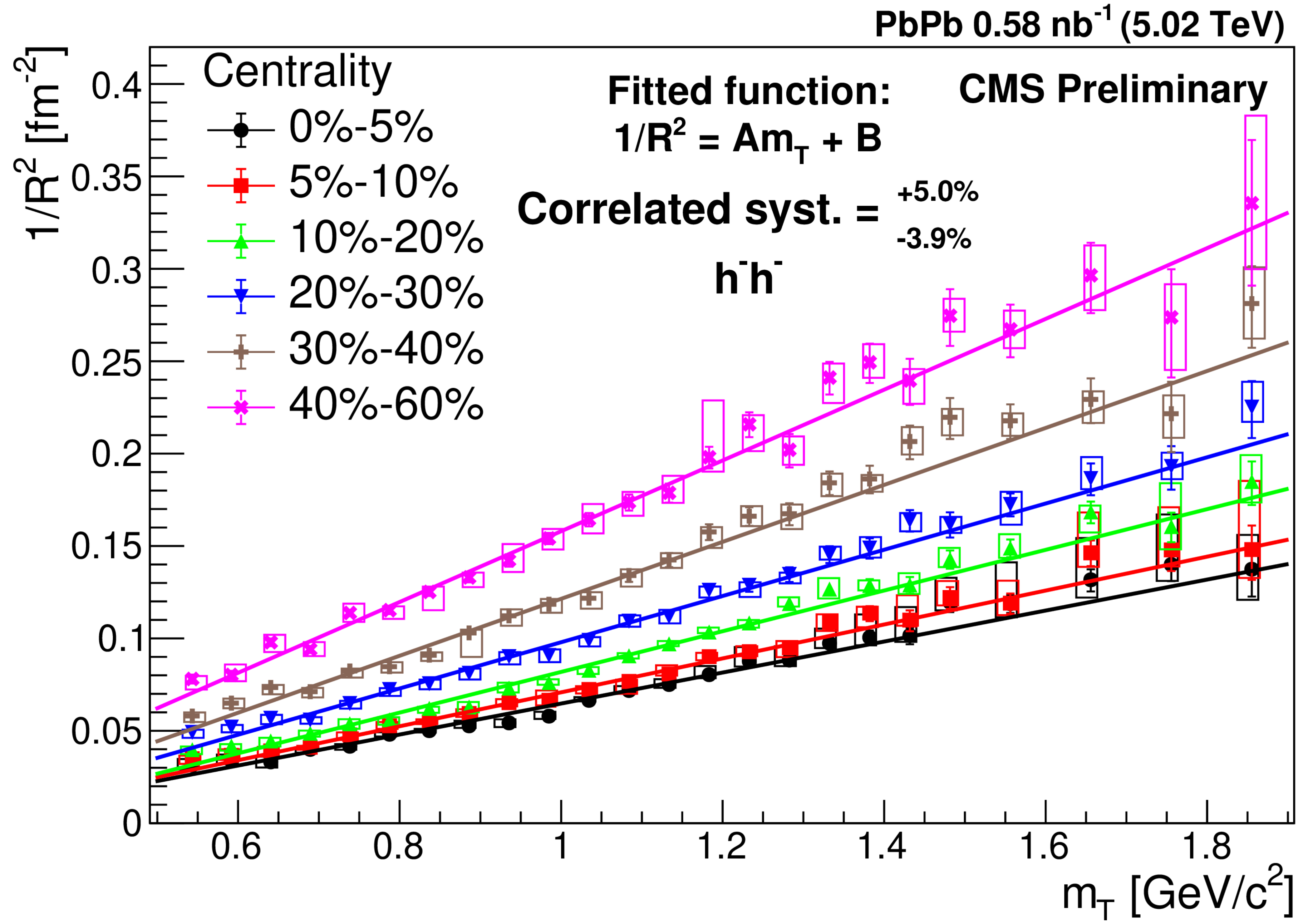
- (Surprising) weak multiplicity dependence of Λ_c/D^0 in pPb
  contrary to
  - Increasing Λ_c/D^0 vs. multiplicity in pp & PbPb
  - Increasing Λ/K_s vs. multiplicity in pPb

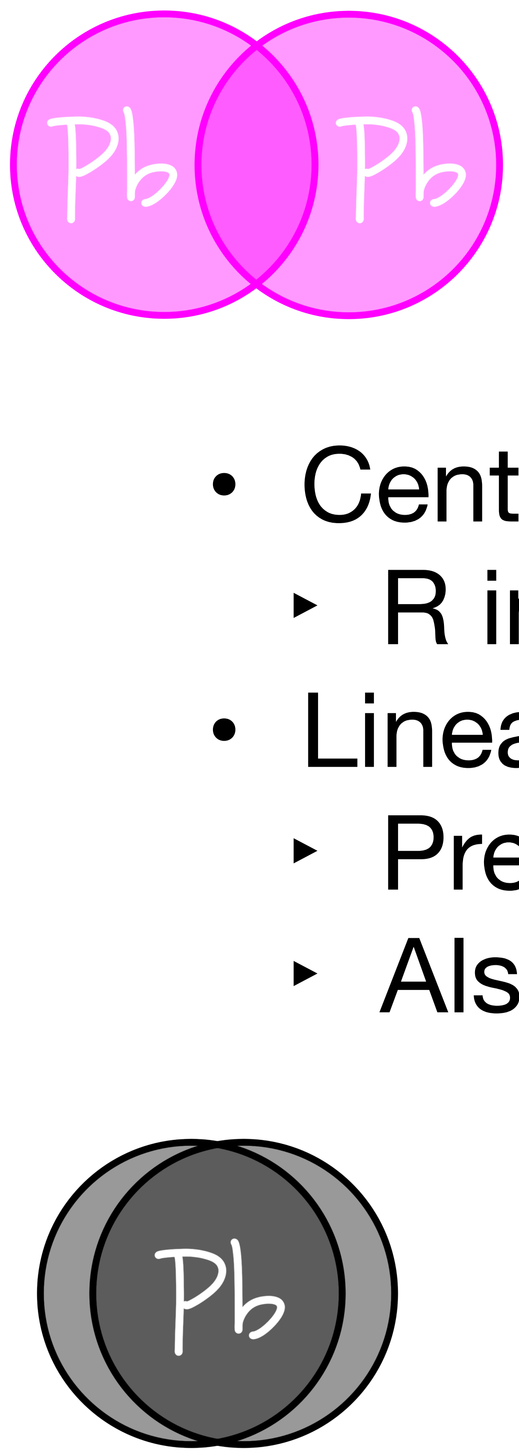
CMS-PAS-HIN-21-016

Femtoscopy h± - h± Correlation

- Use final state particle correlations to probe the particle emitting source
- Parameterization: Lévy-type source & core-halo model
  - Source shape: α ➜ non-Gaussian behavior
  - Spacial scale: R
  - Core-halo ratio: λ



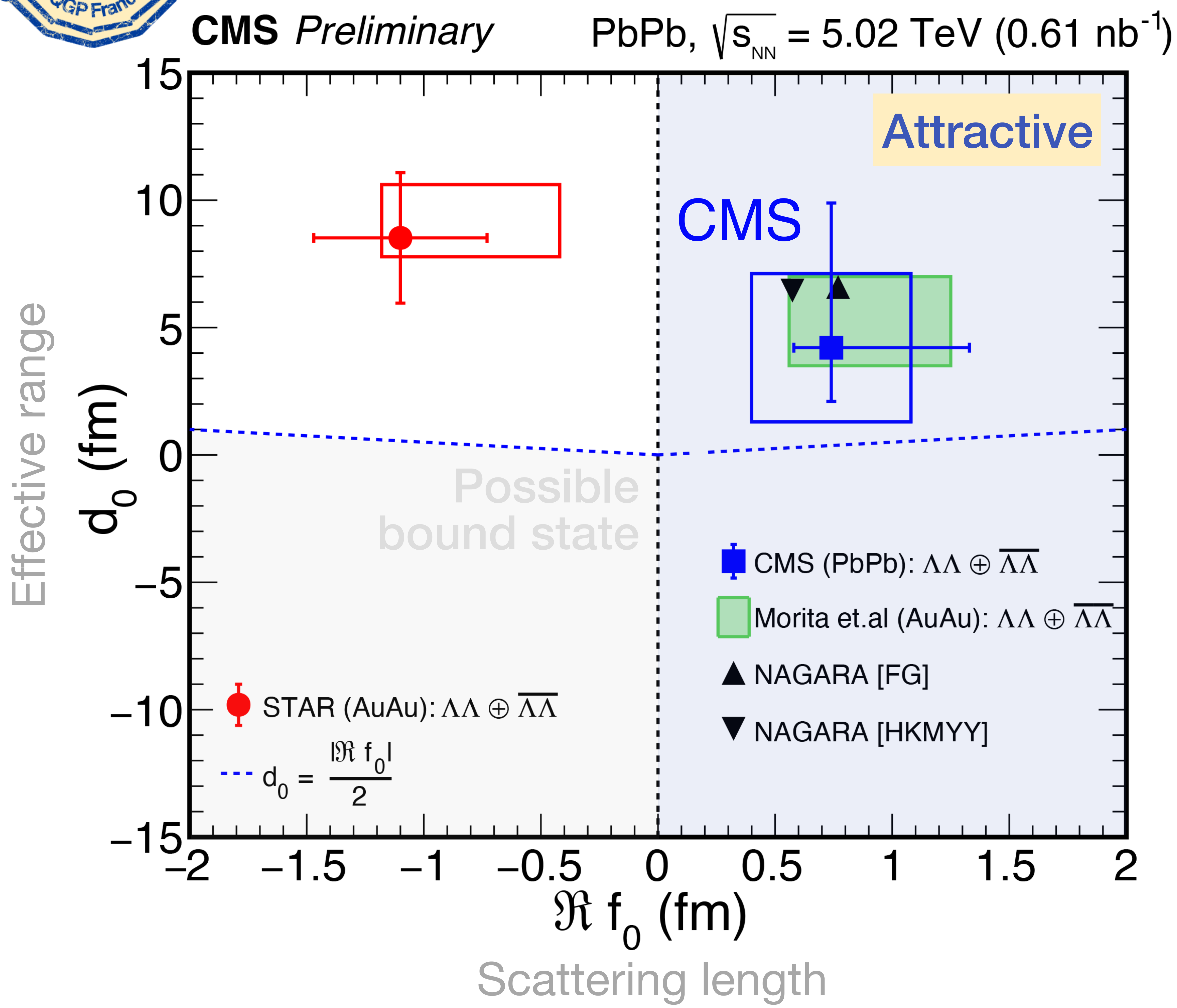




- Centrality dependence
  - R indeed reflects the spatial scale of system
- Linear scaling $1/R^2 = Am_T + B$
  - Predicted by hydrodynamics for Gaussian source
  - Also holds for Lévy source

arXiv:2306.11574

Scattering parameters: Λ-Λ

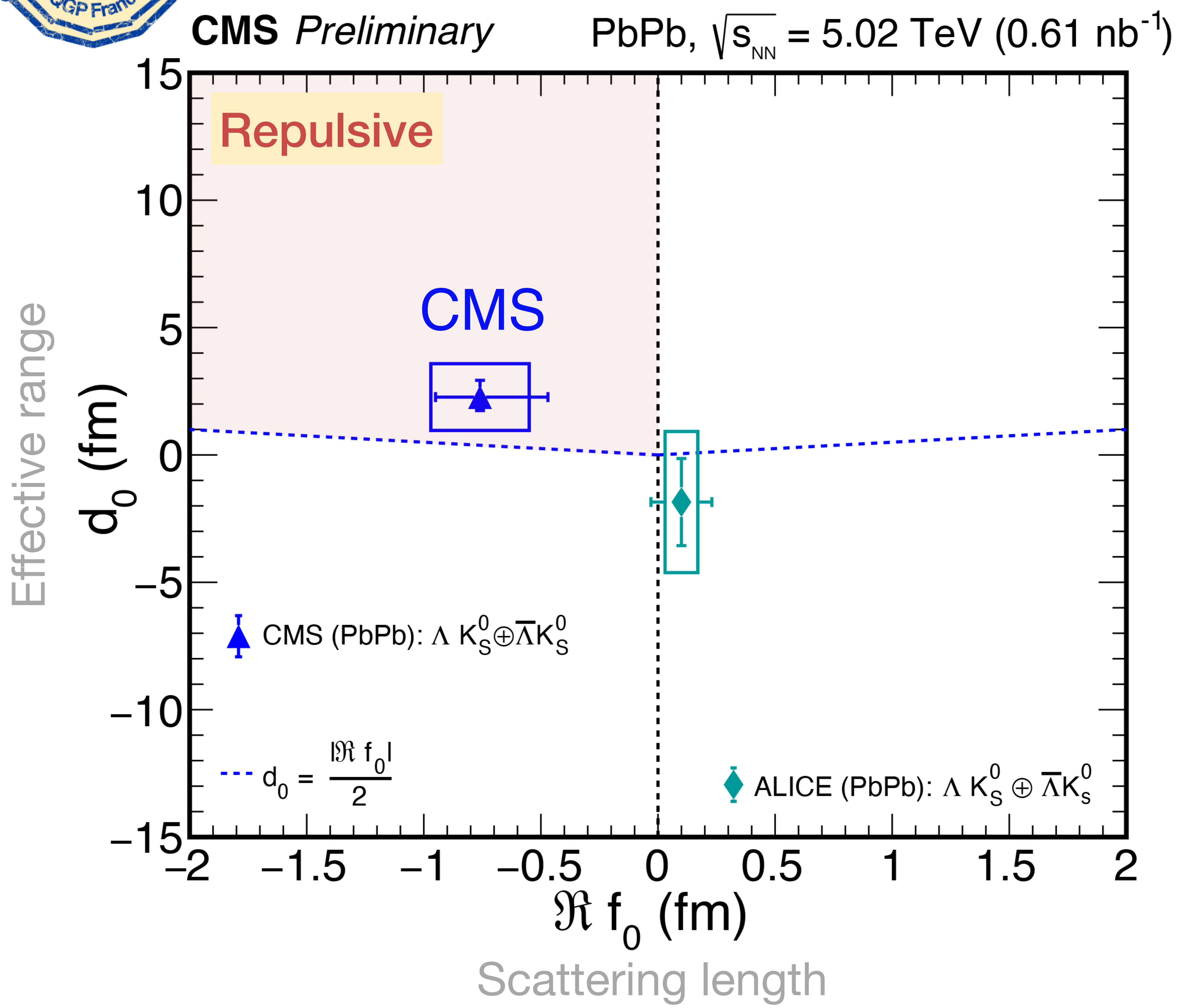


- $\Lambda\Lambda \oplus \overline{\Lambda\Lambda}$: $\Re f_0 > 0$
  - Indicates attractive interaction
  - Suggests non-existence of bound states of two Λ baryons

arXiv:2301.05290

Femtoscopy Hadron Rescattering

Scattering parameters: Λ-K_s^0

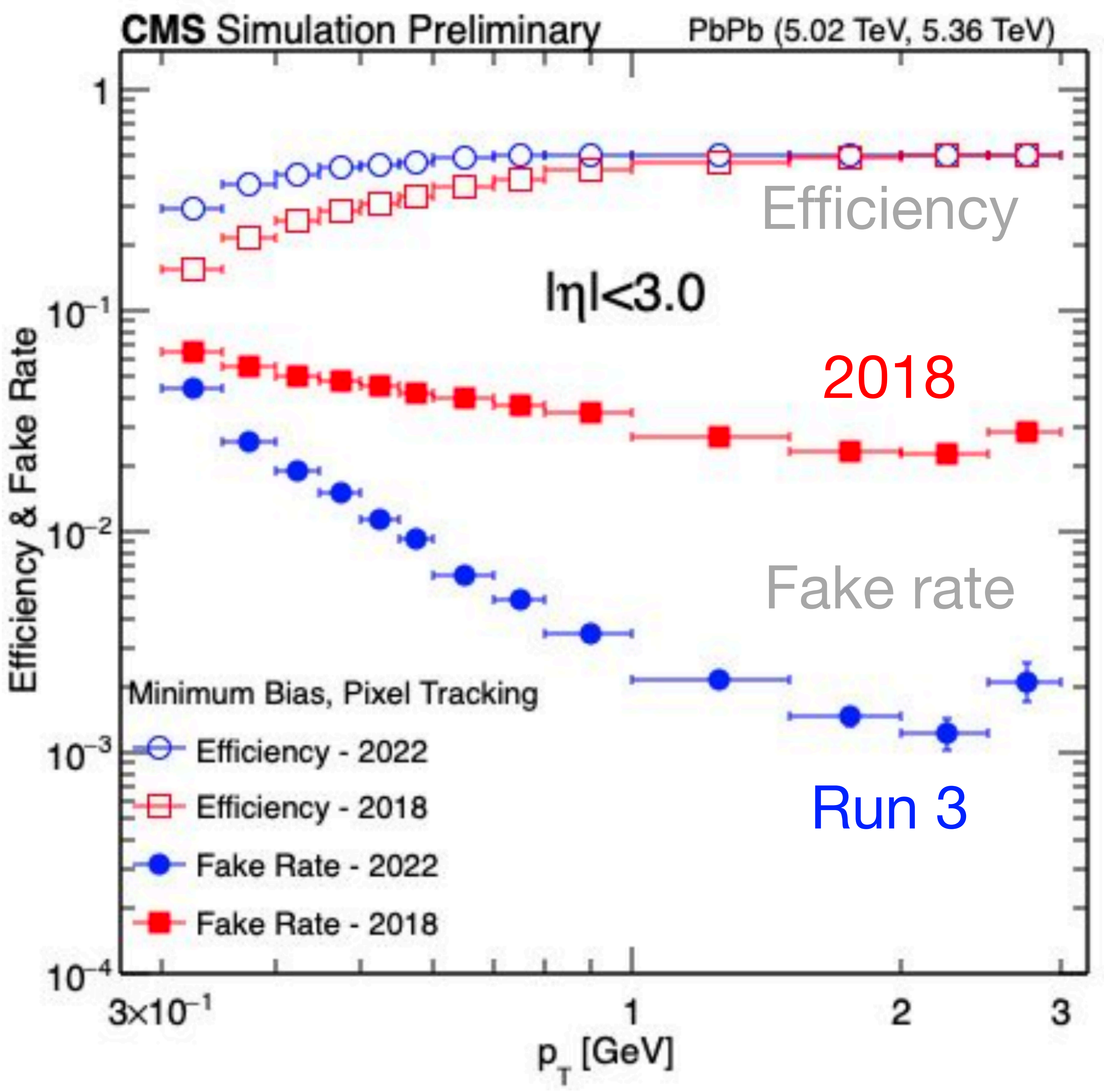


- $\Lambda\Lambda \oplus \overline{\Lambda\Lambda}$: $\Re f_0 > 0$
  - Indicates attractive interaction
  - Suggests non-existence of bound states of two Λ baryons
- $\Lambda K_s^0 \oplus \bar{\Lambda} K_s^0$: Negative $\Re f_0 < 0$
  - Indicates repulsive interaction

arXiv:2301.05290

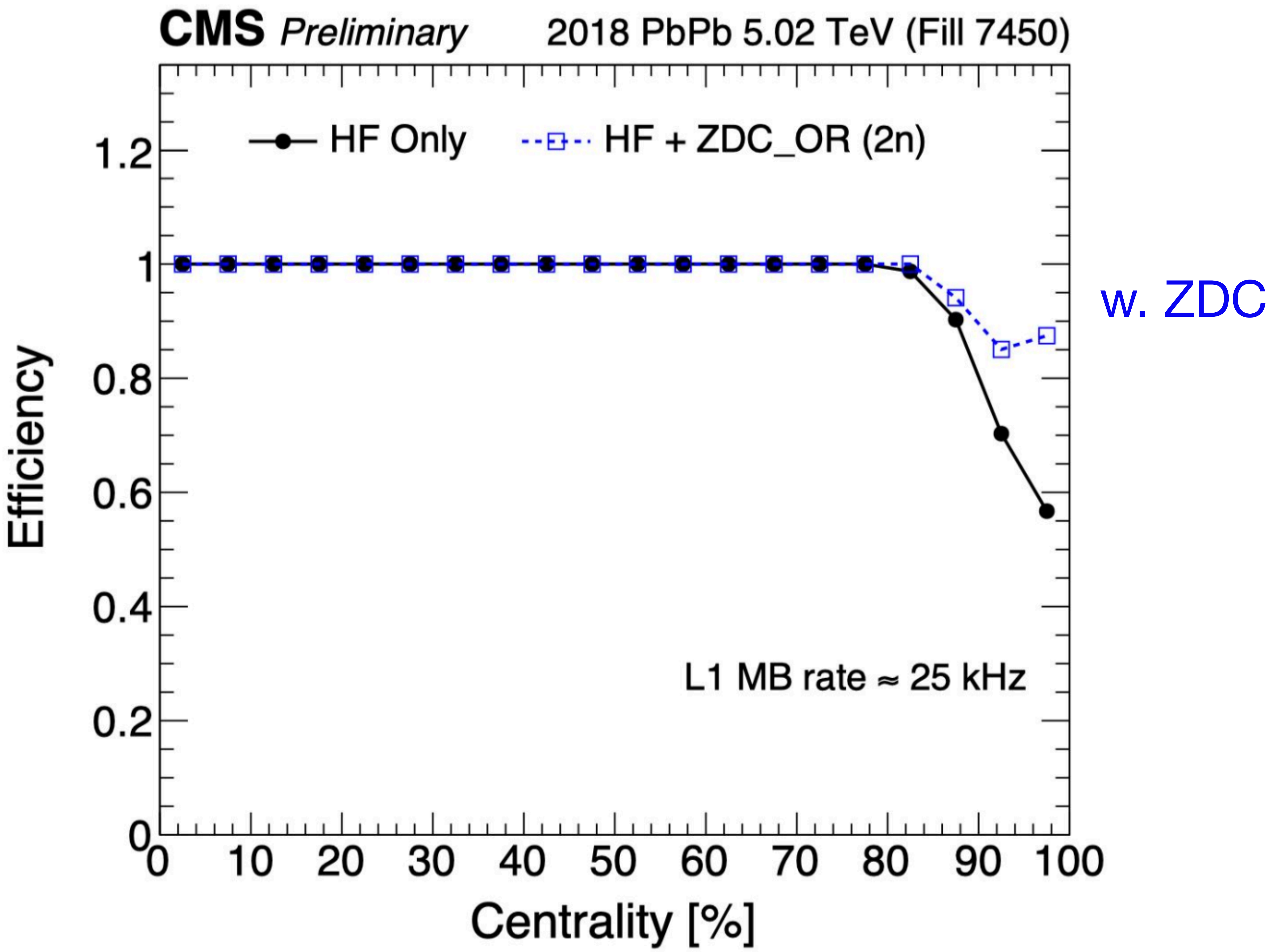
Get Ready for Run 3

Pixel tracking



- Better fitting method and detector condition improves low p_T tracking

Minbias trigger



- ZDC improves MB trigger at peripheral
- Collect higher rate of MB events

CMS-DP-2023/011

Summary

CMS still giving exciting new physics messages 4 years after run 2!

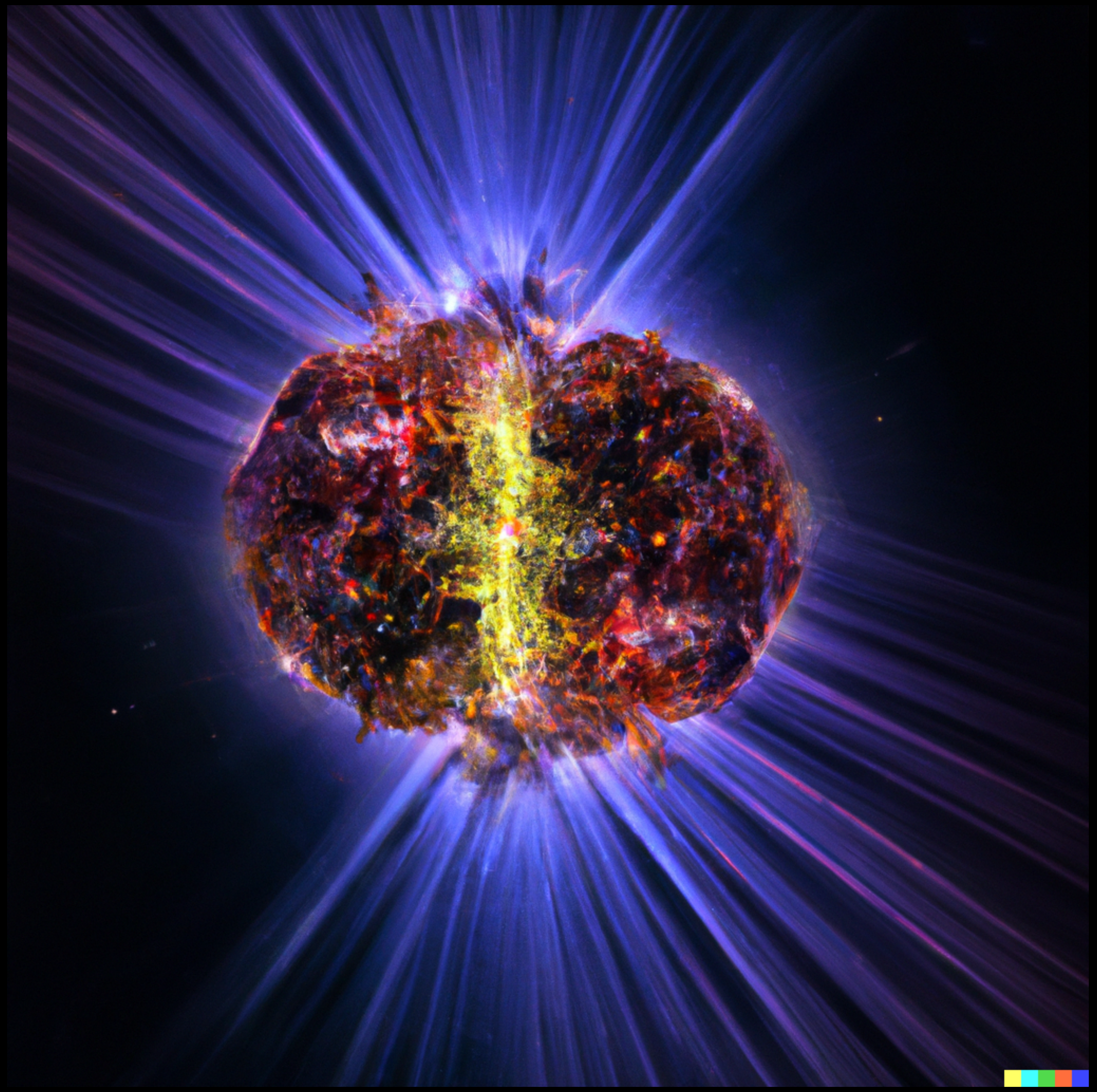
- nPDF constraints with various probes in (anti) shadowing and EMC regime
  - **Saturation behavior at $x \sim 10^{-5}$ via coherent J/ψ production in PbPb UPC**
- Collectivity observed in PbPb, pPb, pp for light and heavy flavors but not in γp
  - **Mean p_T-v_n correlation measured to search initial momentum anisotropy by CGC**
  - **Collectivity evidence in single high-multiplicity jets in pp**
- Net charge fluctuations decrease as η window increases within mid rapidity
  - **D param. consistent with QGP phase predicted by (model dep) lattice in large Δη**
- Baryon to meson ratio increases vs. multiplicity for light to heavy flavor in pp and AA
  - **Weak multiplicity dependence of Λ_c/D^0 in pPb**

[Saeahram] [Cristian] [Bharadwaj] [Lida] [Florian]

Even more are coming before QM…

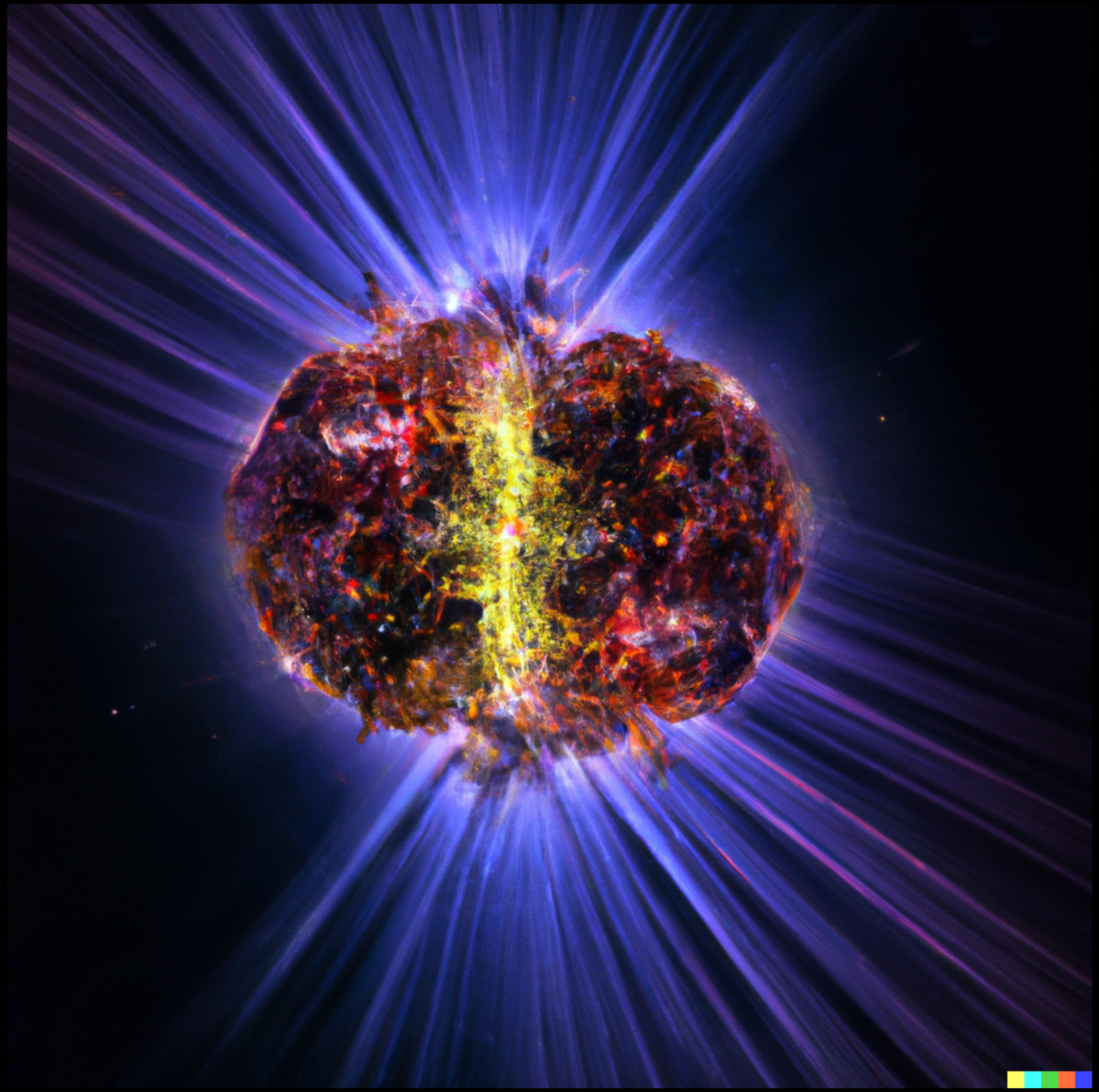
I Asked AI to Imagine…

Heavy-ion collisions

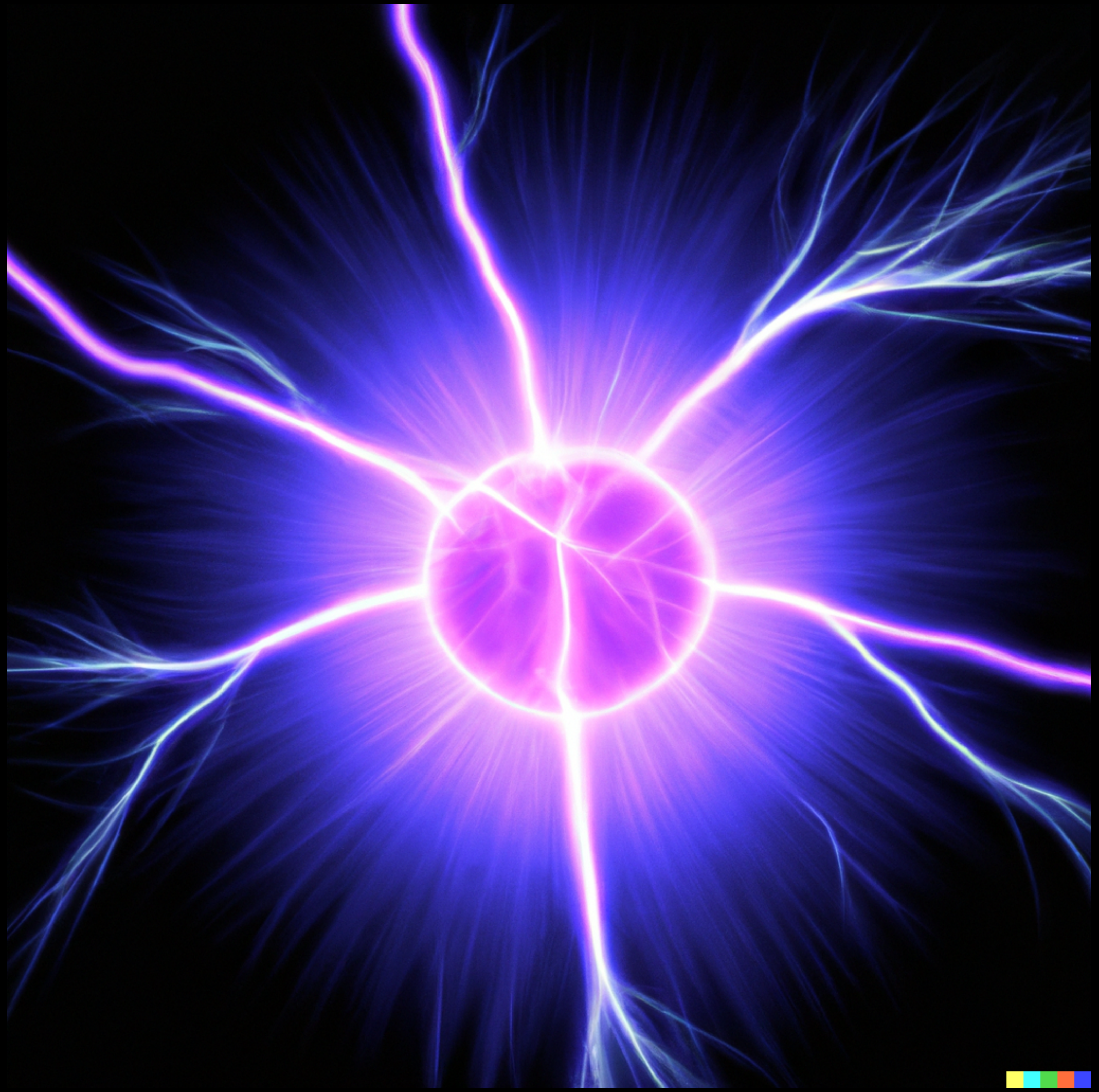


I Asked AI to Imagine...

Heavy-ion collisions



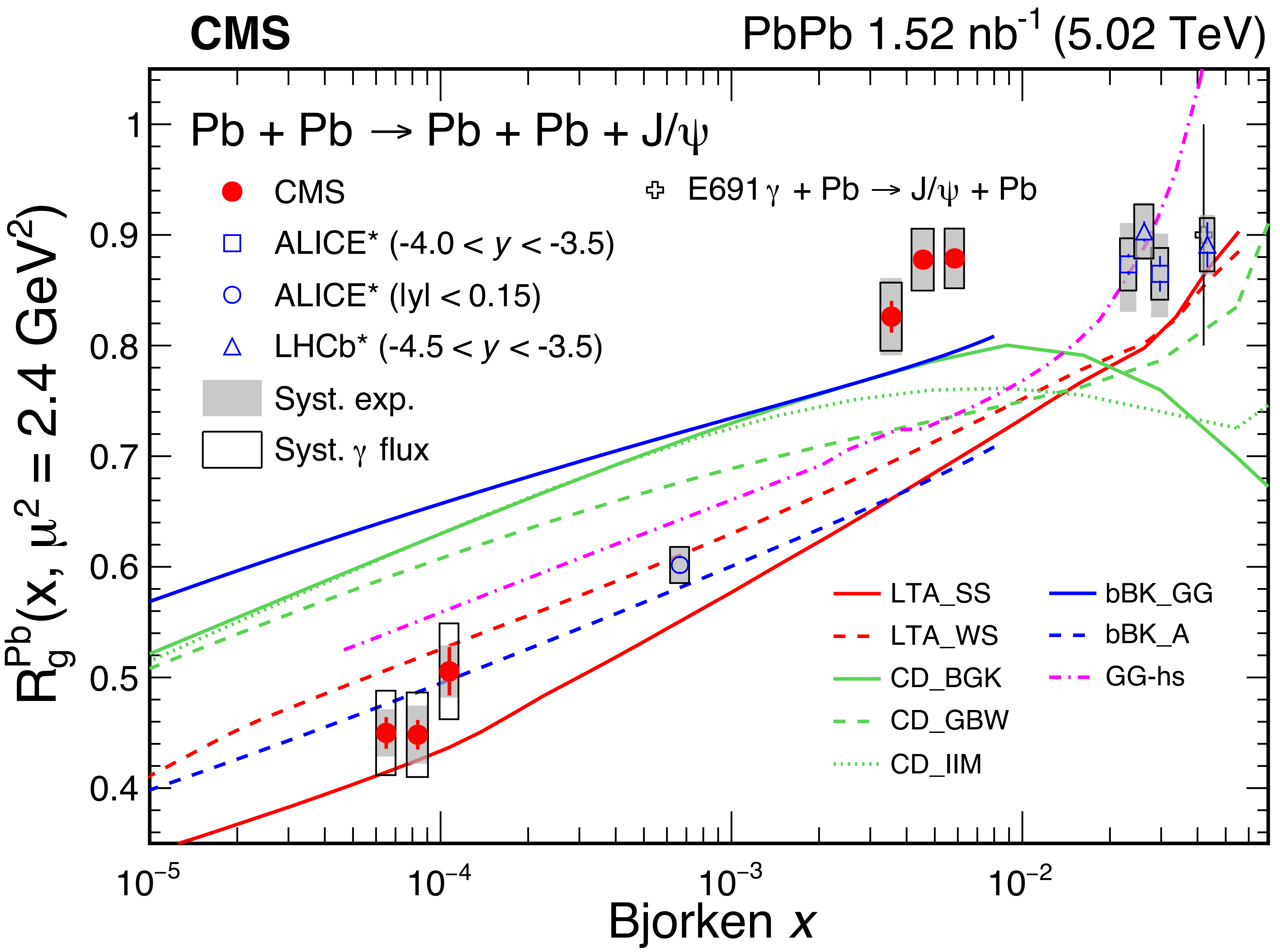
Quark-gluon plasma



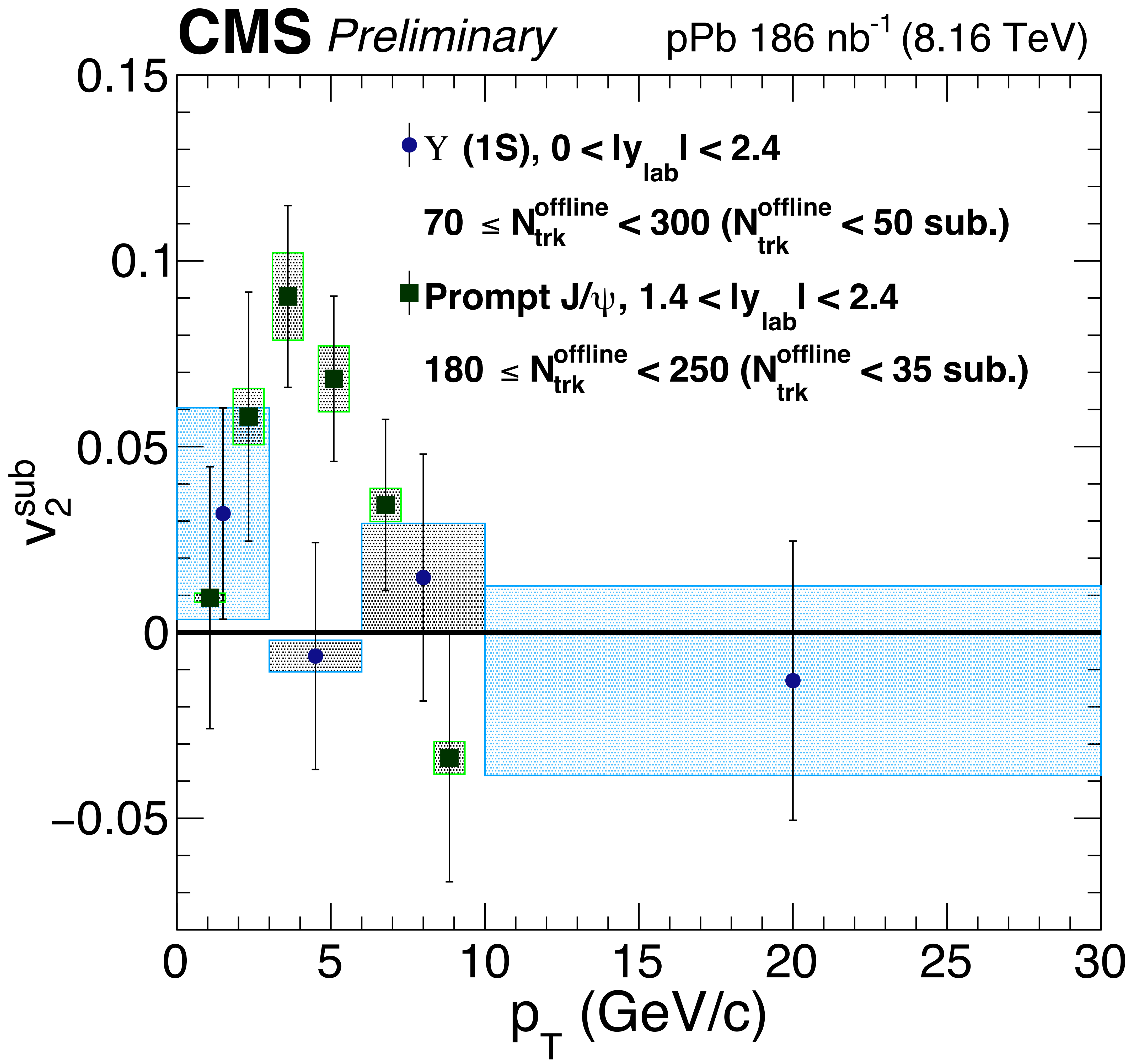
A long way to go to understand quarks and gluons


Isabelle
Thanks for your attention!

New Small-x Reach Coherent J/ψ in PbPb UPC



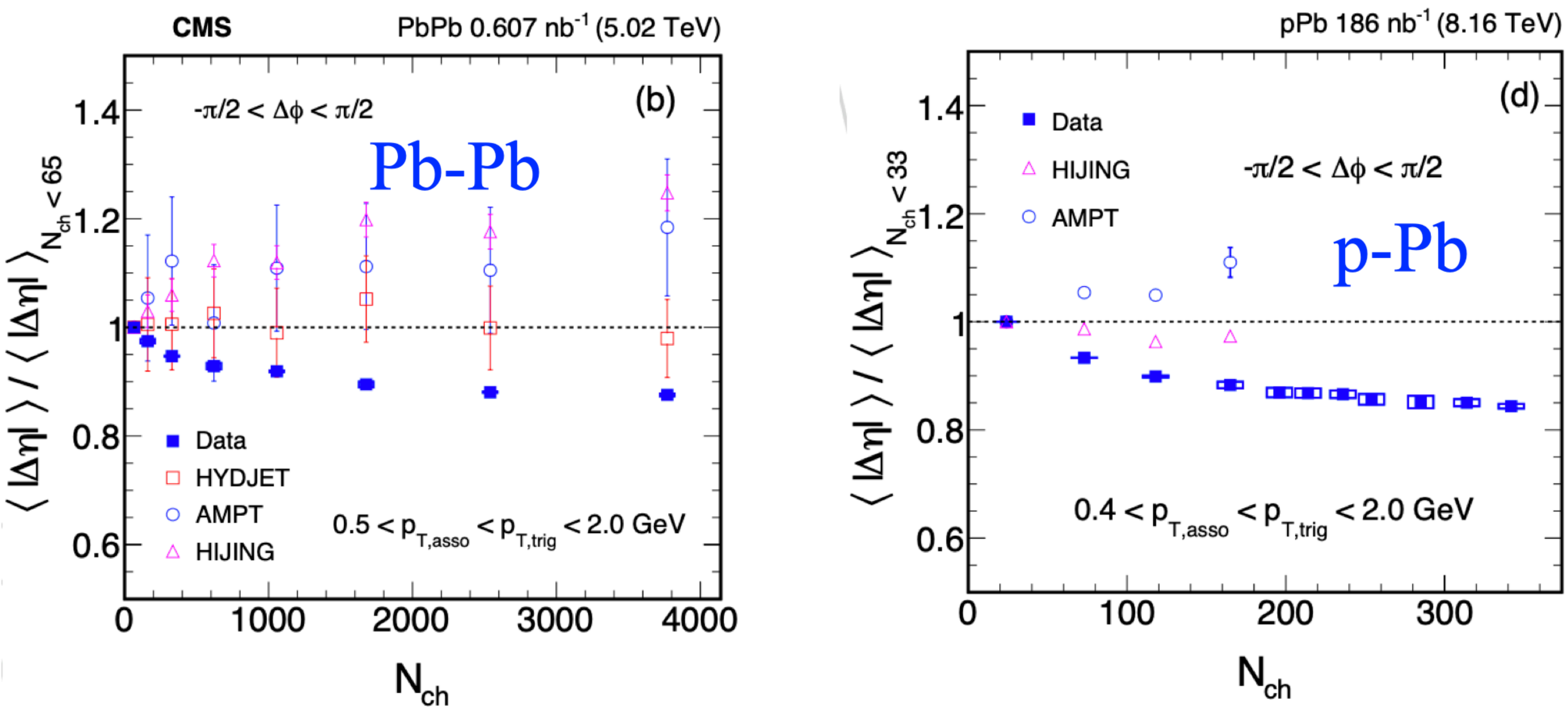
Collectivity Origin Y(1S) vs. J/ψ in pPb



- Initial momentum anisotropy in CGC predicts similar v_2 for J/ψ and Y
- Medium final state effects will lead to smaller v_2 for Y

CMS-PAS-HIN-21-001

Collectivity Origin Charge Balance Function in pPb



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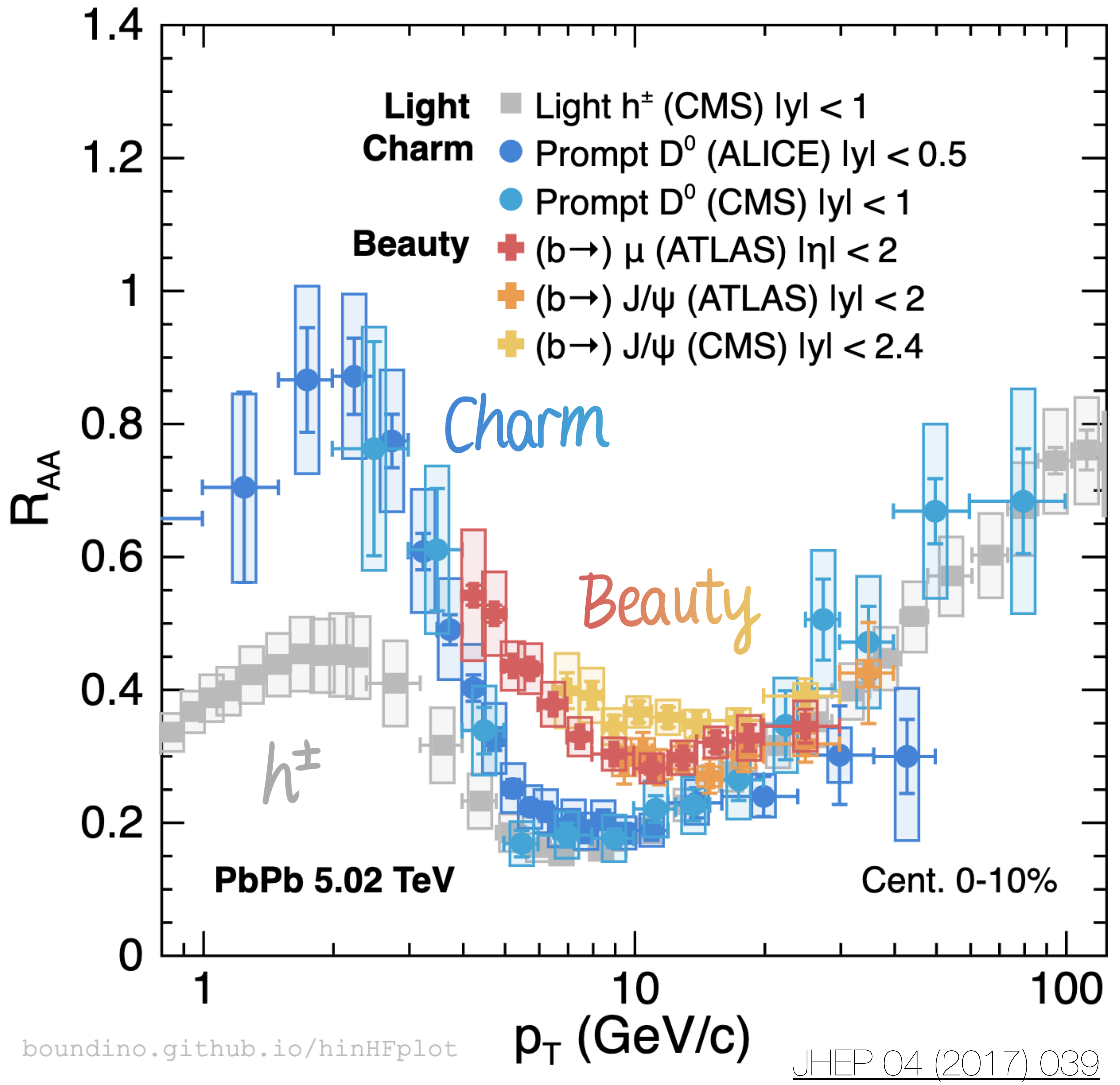
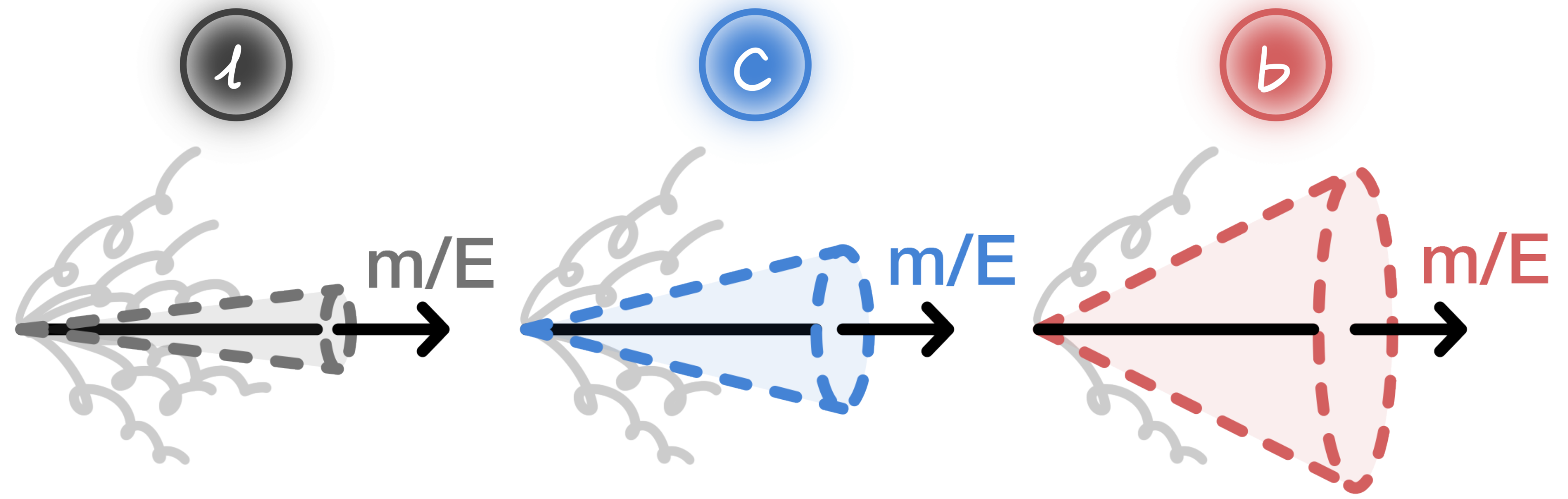
Flavor Dependence of Energy Loss

RAA vs. Flavors



boundino.github.io/hinHFplot

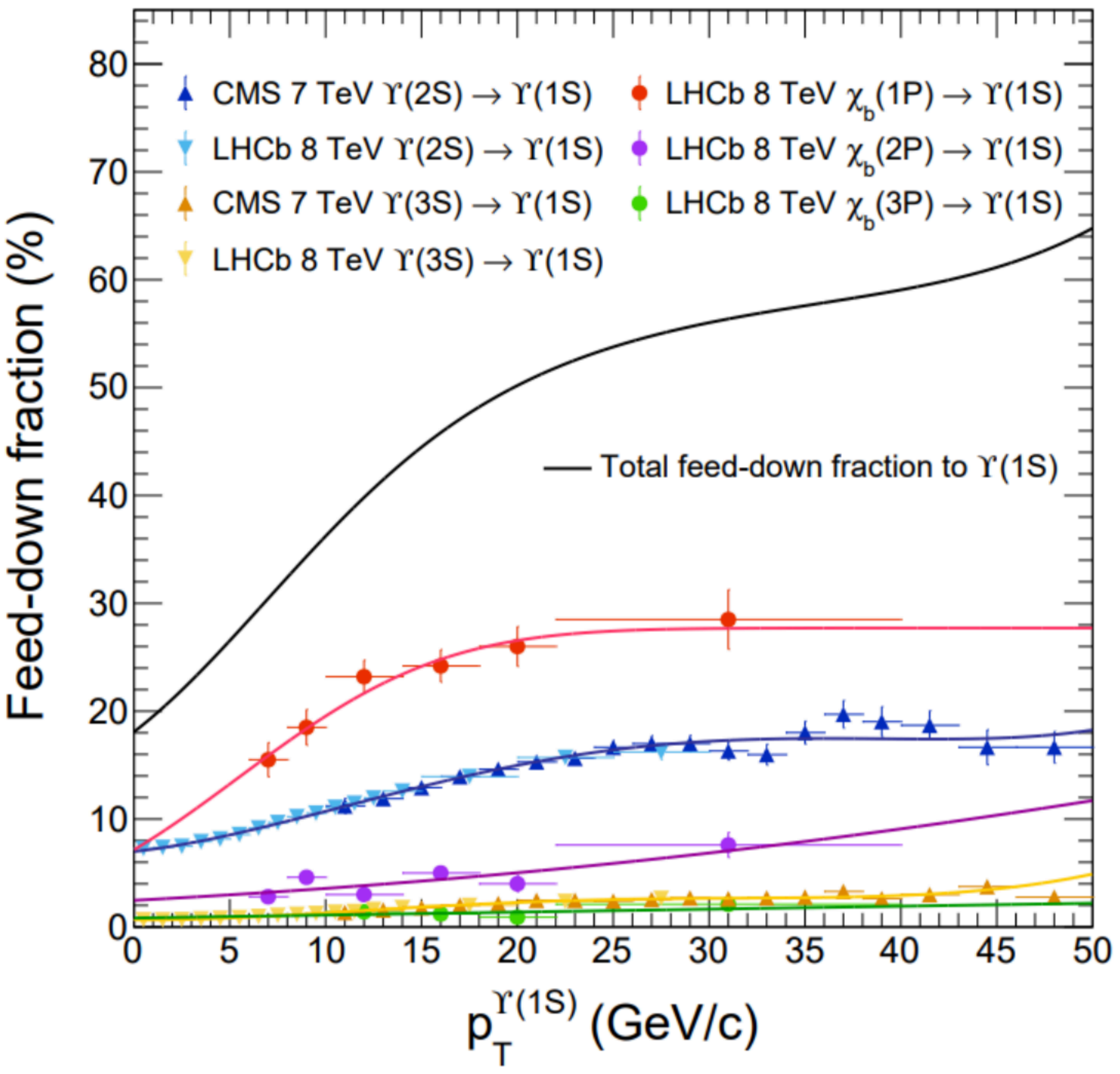
- Interplay of multiple effects
- (One is) Dead cone effect
  - Radiation is suppressed inside $\theta < m/E$
  - Energy loss $\Delta E_l > \Delta E_c > \Delta E_b$

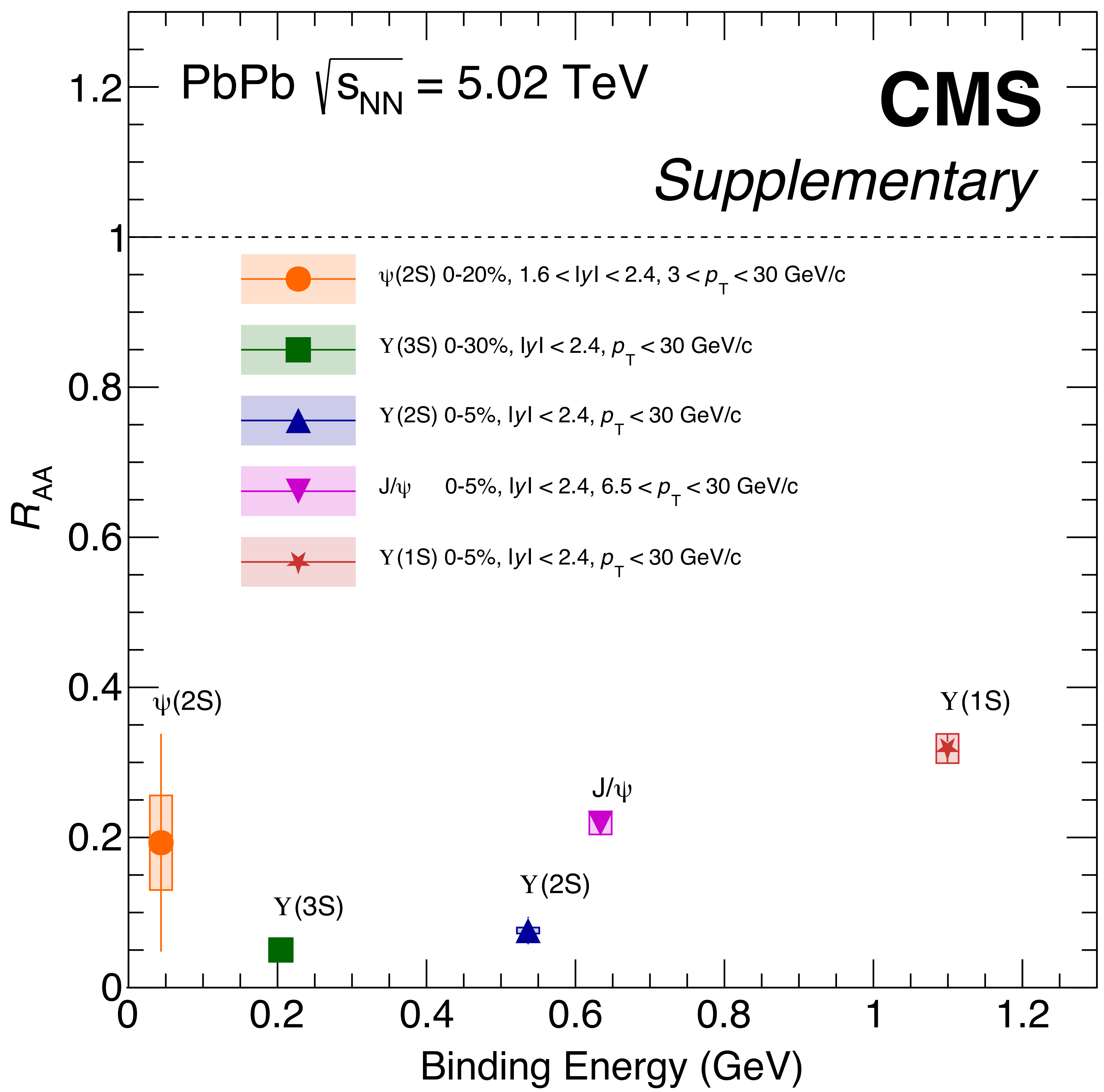


Larger energy loss ➜ Smaller energy loss

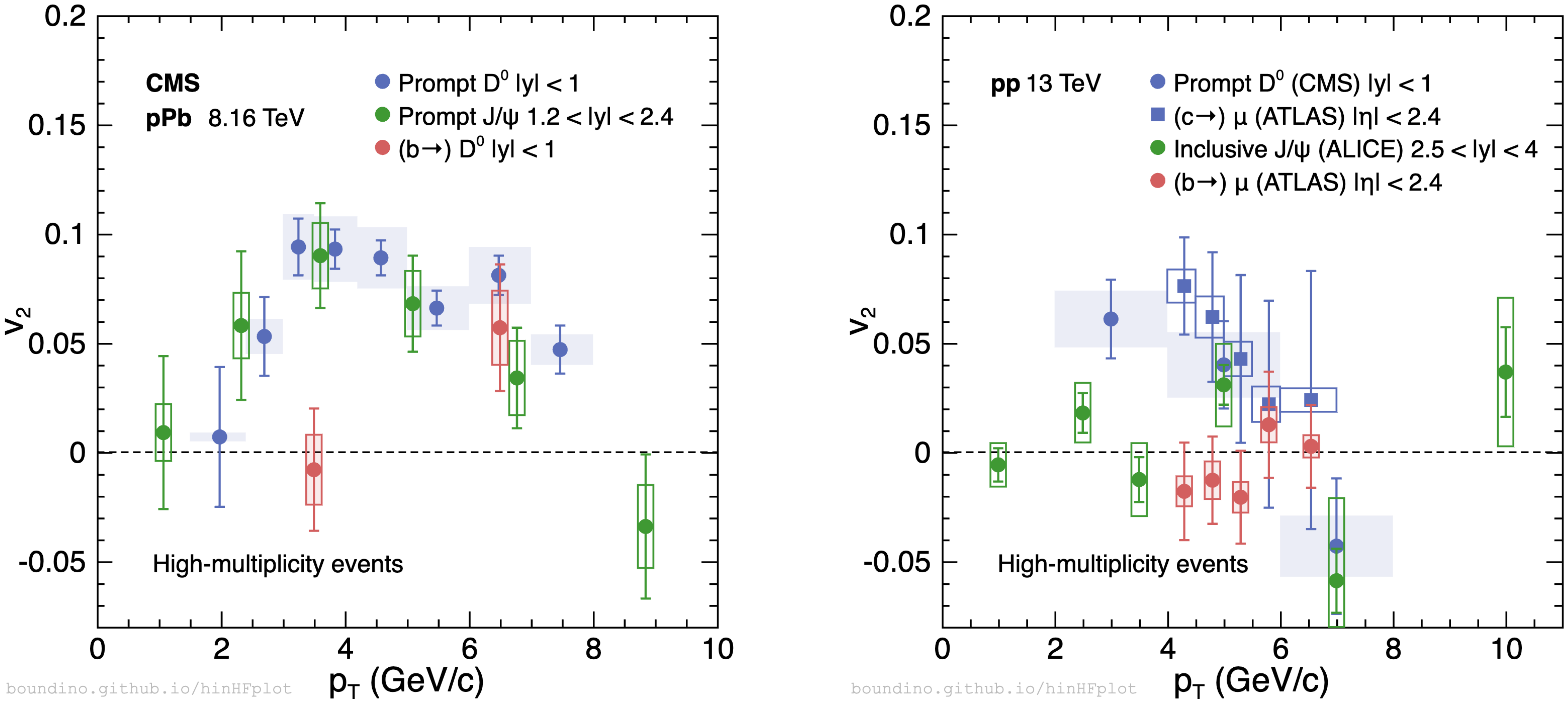
JHEP 04 (2017) 039 EPJC 78 (2018) 509
PLB 829 (2022) 137077 EPJC 78 (2018) 762

Feed-Down, Binding Energy

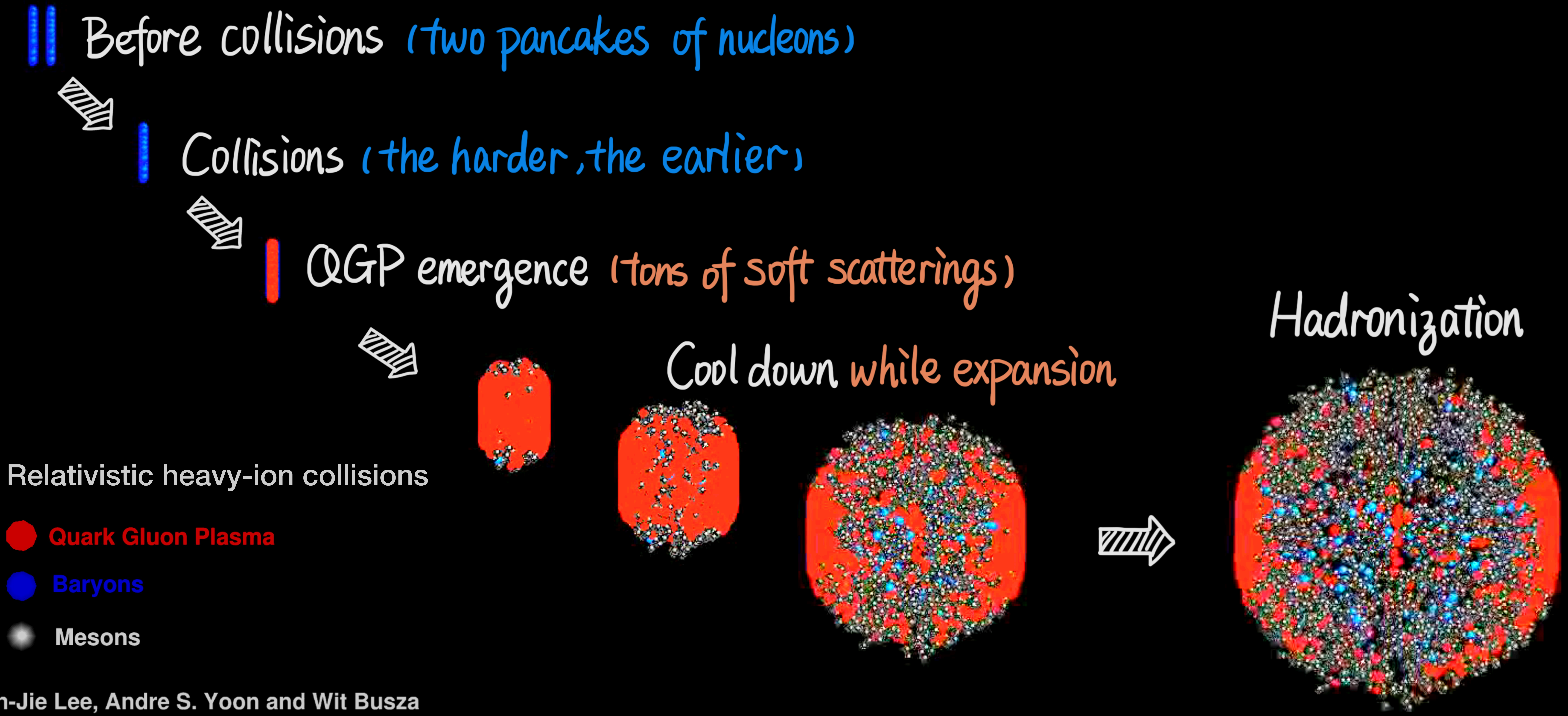




Azimuthal Anisotropy in pp and pA



Heavy-Ion Collisions



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