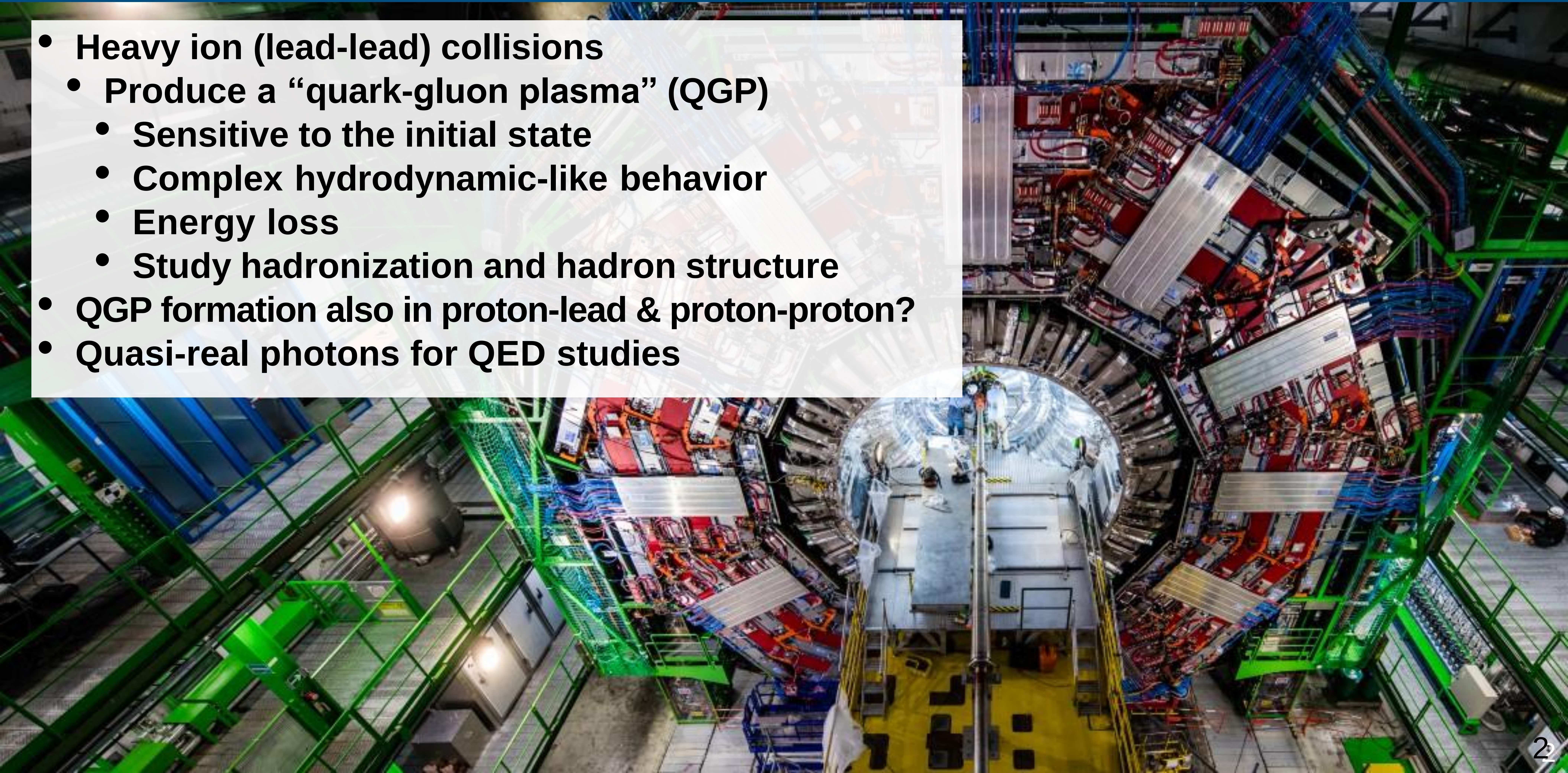
Overview of Recent CMS Results

Slides mostly from Austin Baty, Jelena Mijuskovic, and Giulia Negro

Introduction

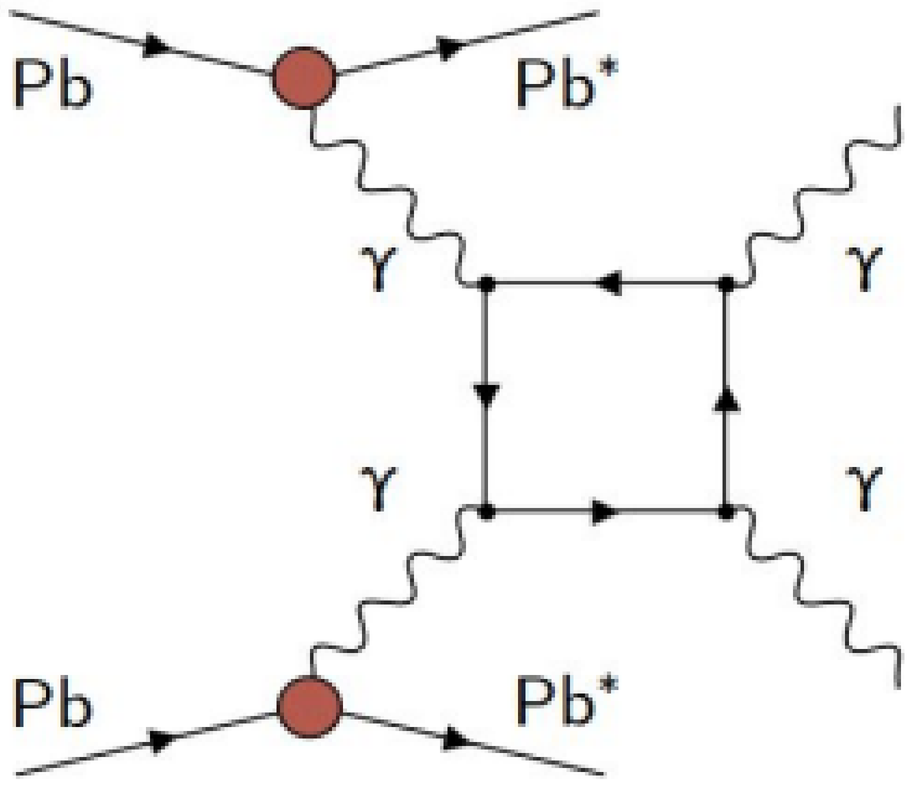
- **Heavy ion (lead-lead) collisions**
  - **Produce a “quark-gluon plasma” (QGP)**
    - **Sensitive to the initial state**
    - **Complex hydrodynamic-like behavior**
    - **Energy loss**
    - **Study hadronization and hadron structure**
- **QGP formation also in proton-lead & proton-proton?**
- **Quasi-real photons for QED studies**

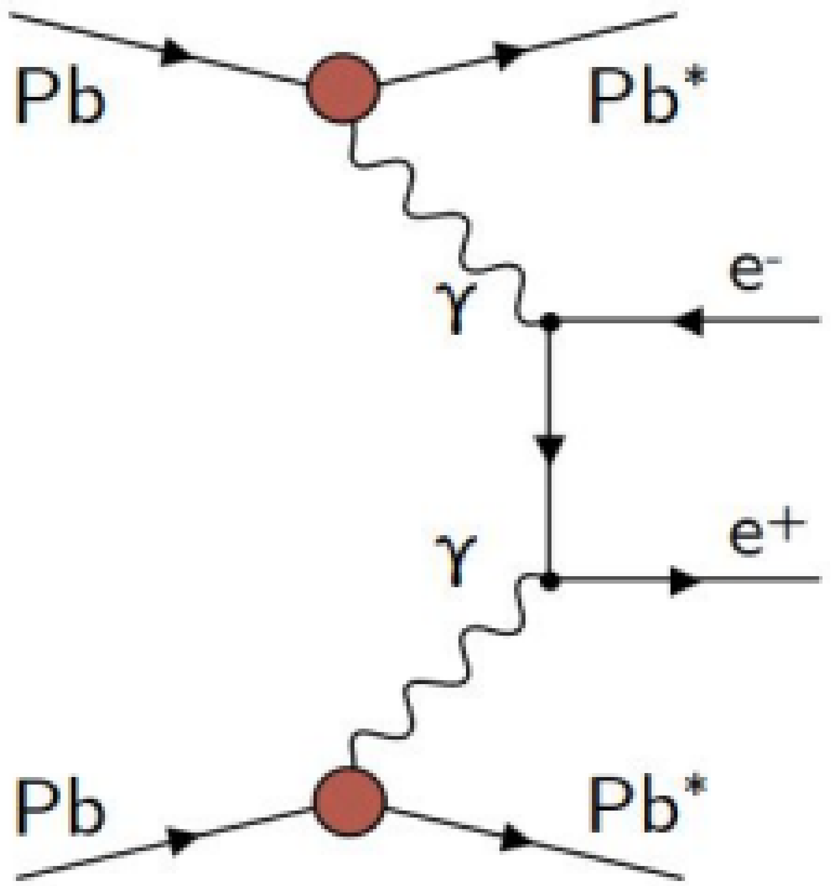


Measurements of light-by-light scattering, the Breit–Wheeler process

CMS-PAS-HIN-21-015

- At the LHC - γγ studied in proton-proton, proton-nucleus, and nucleus-nucleus UPCs





➢ γγ luminosities associated with PbPb UPCs - enhanced compared with similar pp or e^+e^- interaction

⇒ chance to study **light-by-light (LbL) scattering**

➢ Elastic LbL scattering- pure quantum mechanical process that proceeds at leading QED coupling α

- Photon-fusion processes with larger cross sections and well-known properties

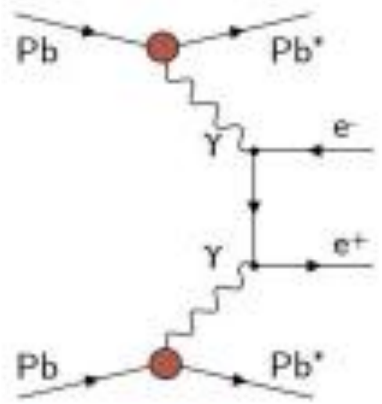
⇒ Study **Breit–Wheeler (B–W) process**

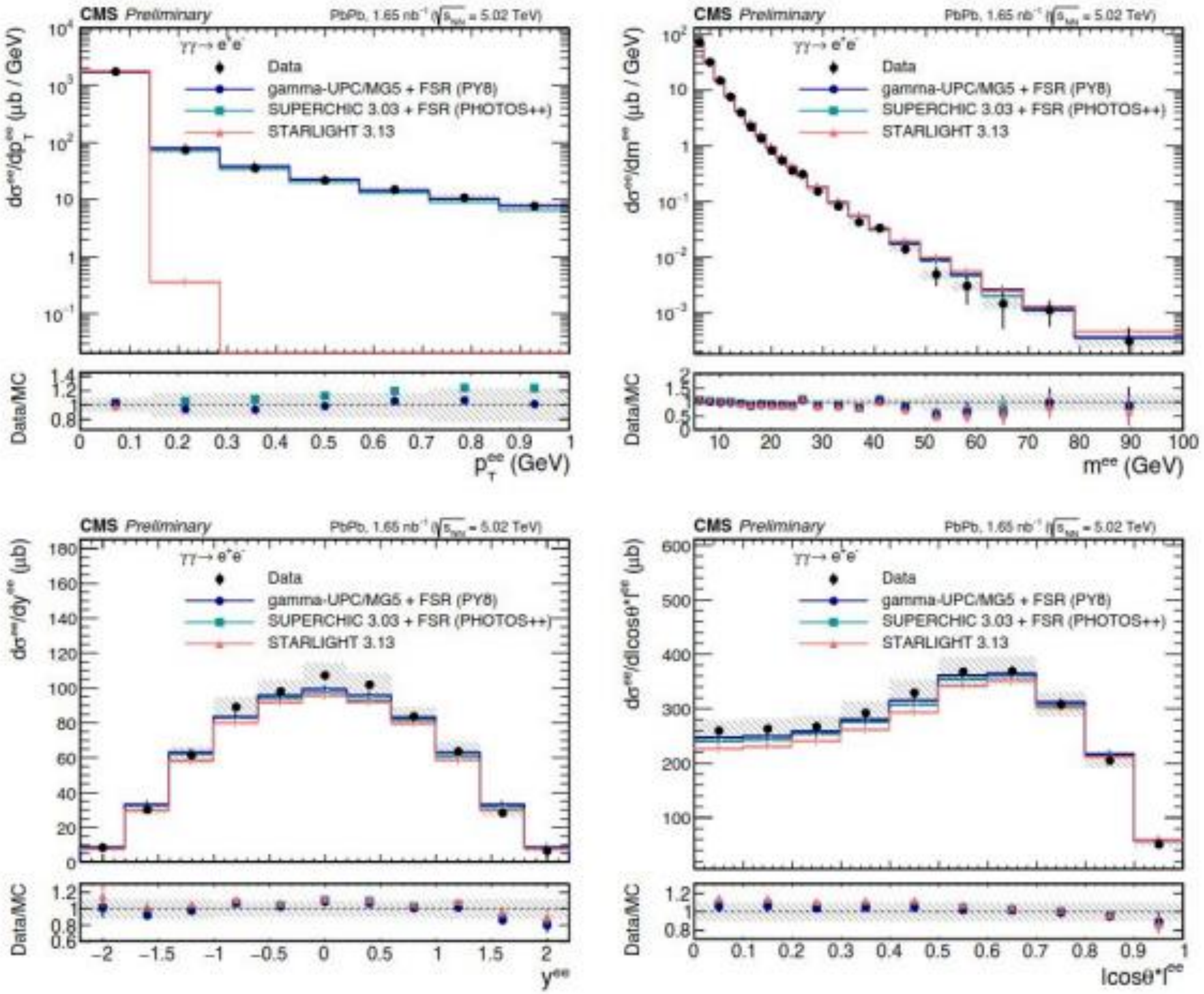
- "Standard candles" of the more elusive signals

Measurements of the Breit–Wheeler process

CMS-PAS-HIN-21-015

- The data collected in 2018 at a centre-of-mass energy per nucleon pair of 5.02 TeV, integrated luminosity of 1.647 nb^{-1}





- **B-W process** measured over m_{ee} = 5 - 100 GeV with ≈20 000 events observed

$$\sigma_{\rm fid}(\gamma\gamma \to e^+e^-) = 271.5 \pm 1.9\,({\rm stat}) \pm 18.3\,({\rm syst})\ \mu b$$

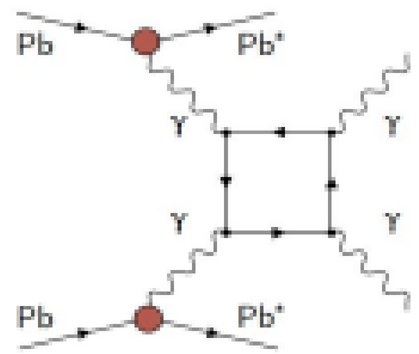
SuperChic 3.03+FSR: $\sigma_{fid}(\gamma\gamma\to e^+e^-) = 261\ \mu b$
Starlight 3.13: $\sigma_{fid}(\gamma\gamma\to e^+e^-) = 251\ \mu b$
gamma-UPC/MG5+FSR: $\sigma_{fid}(\gamma\gamma\to e^+e^-) = 265\ \mu b$

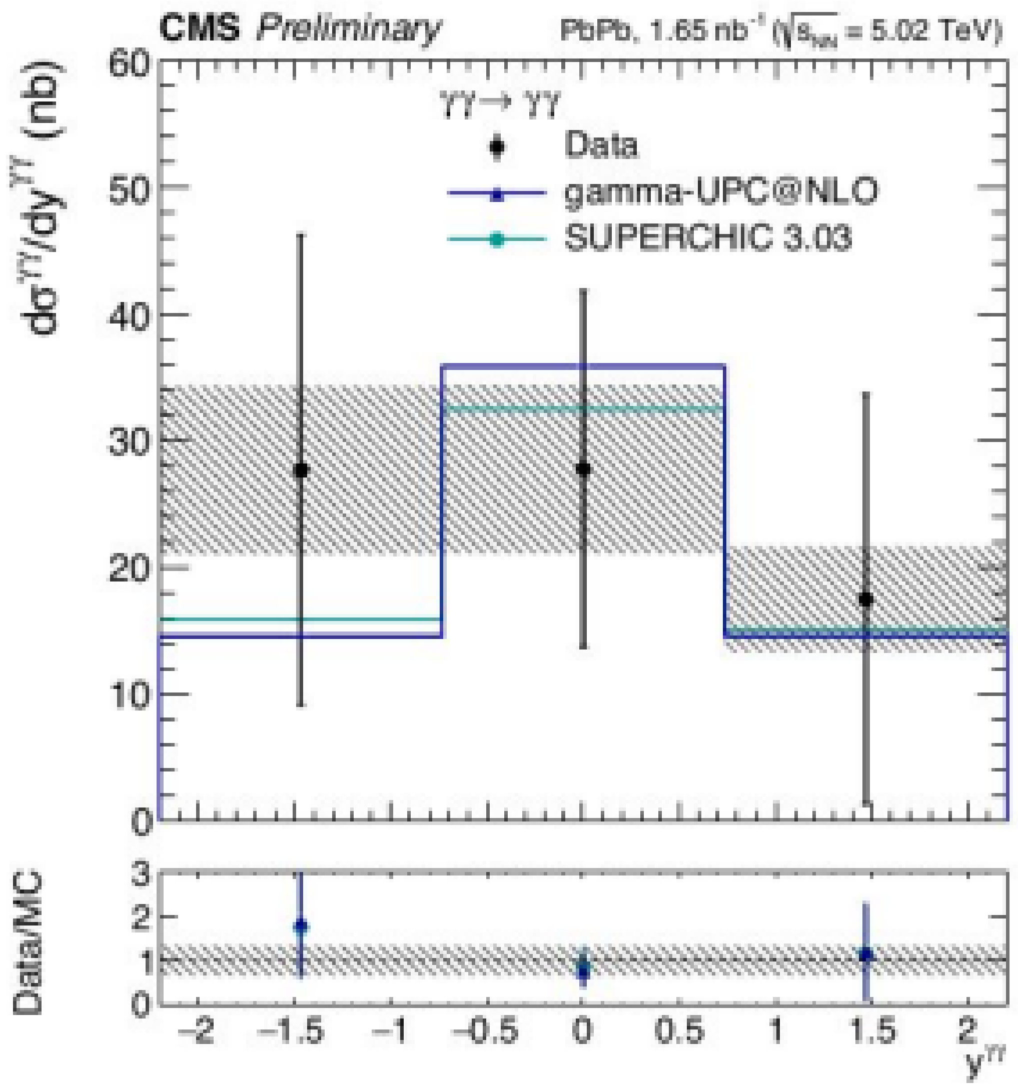
- Differential cross sections measured in data
  - ⇒ very good agreement between data and predictions with FSR

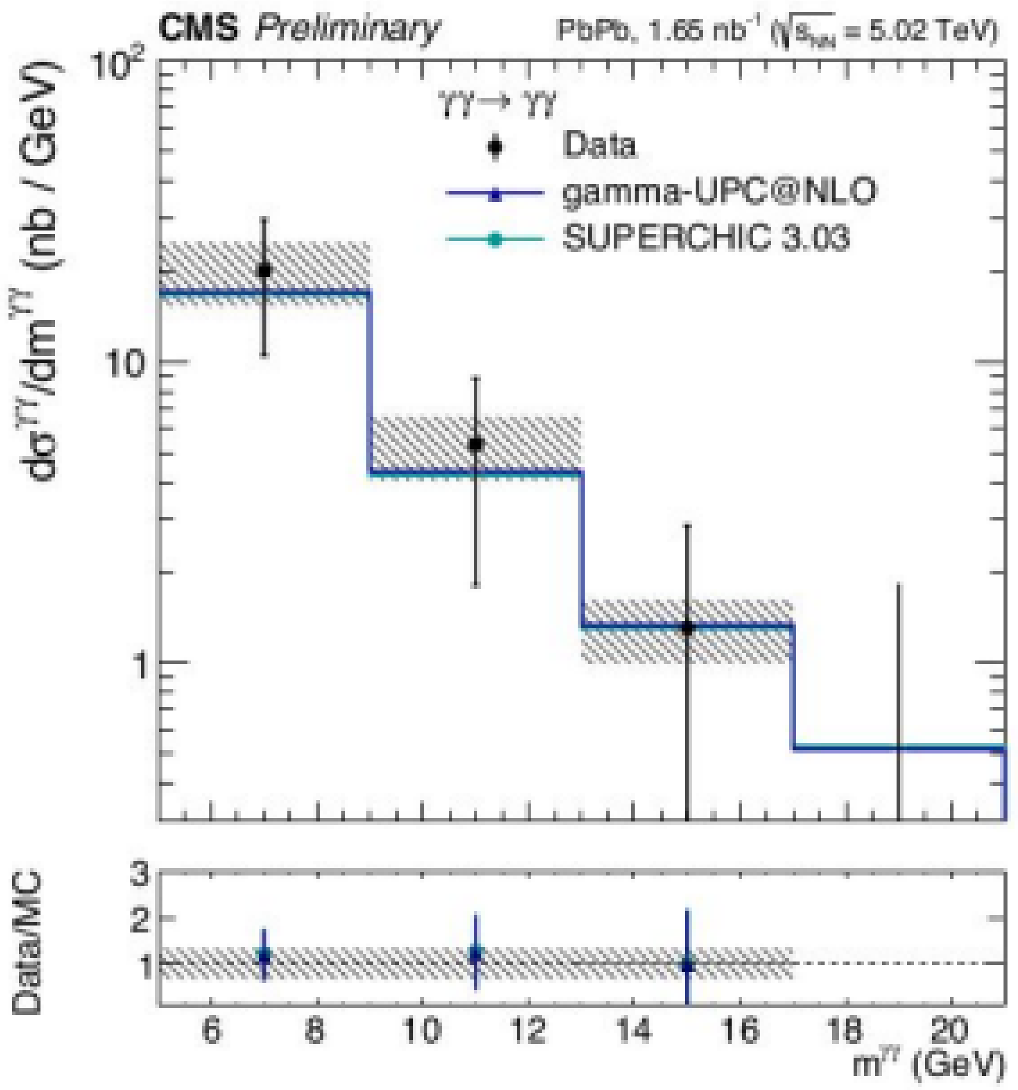
Measurements of light-by-light scattering

CMS-PAS-HIN-21-015

- The data collected in 2018 at a centre-of-mass energy per nucleon pair of 5.02 TeV, integrated luminosity of 1.647 nb^{-1}







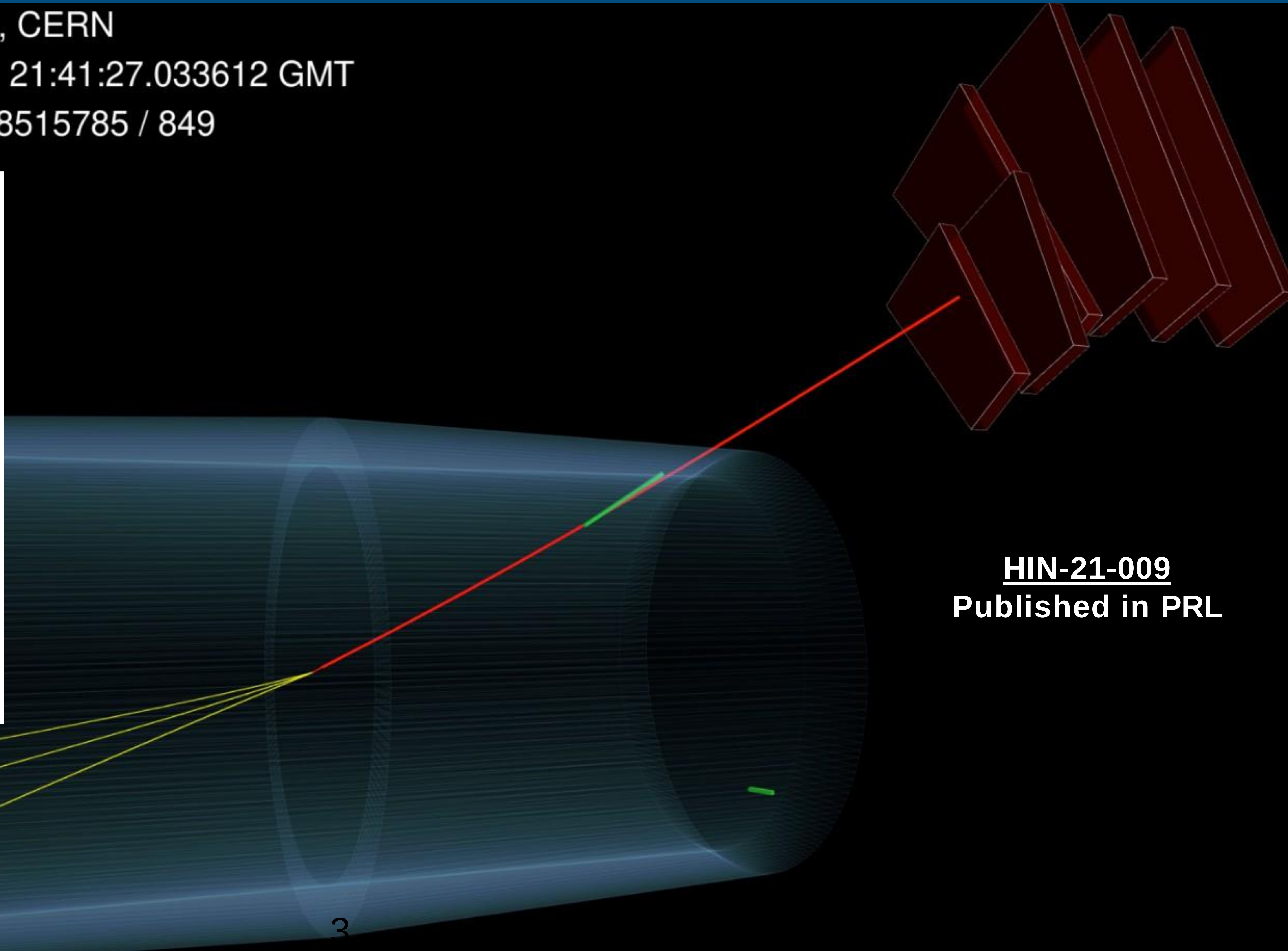
- **Light-by-light scattering** observed at 5.2σ (3.8 exp.) with 26 events

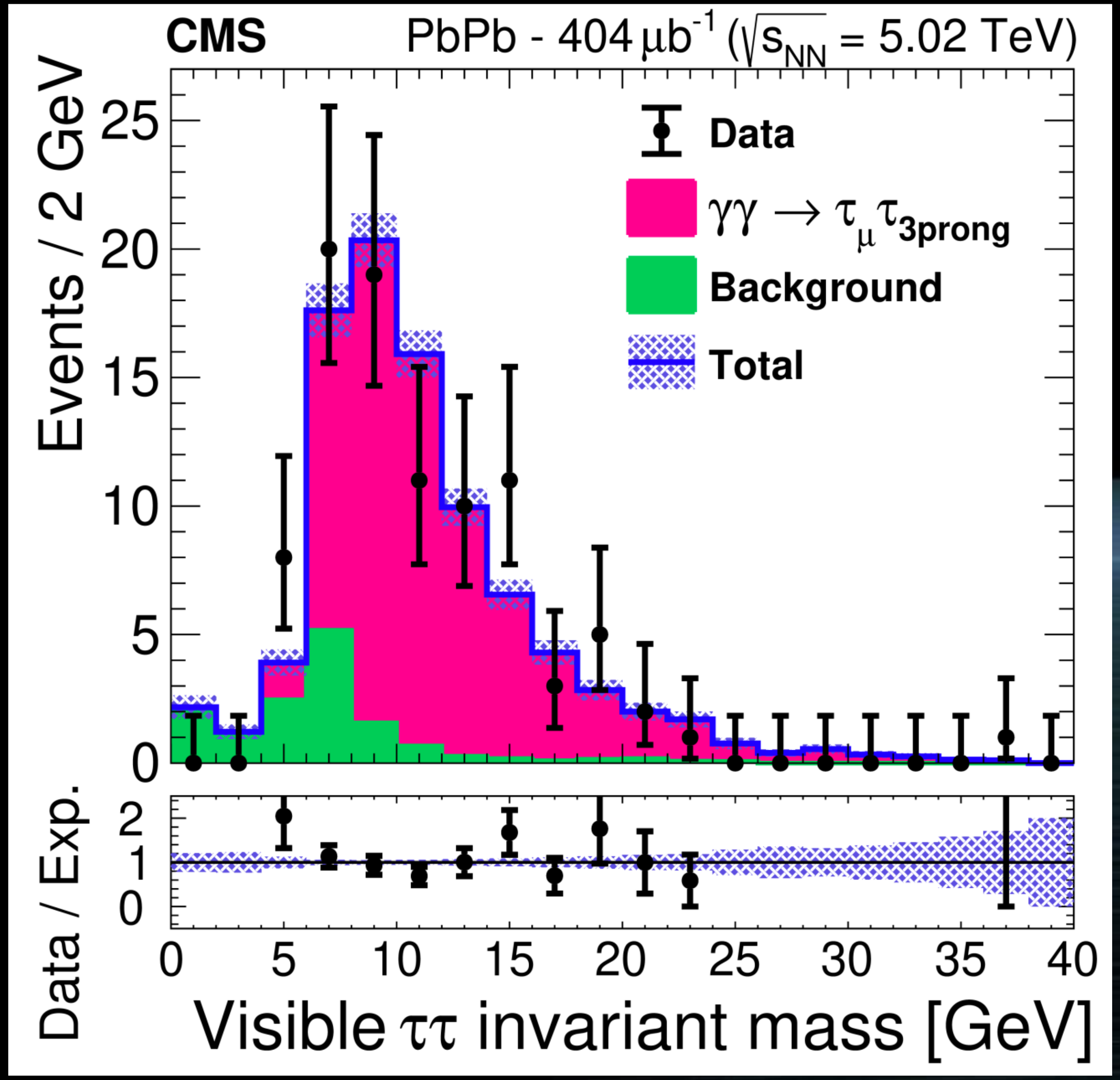
$$\sigma_{\text{fid}}(\gamma\gamma \to \gamma\gamma) = \frac{N^{\gamma\gamma,\text{data}} - N^{\gamma\gamma,\text{bkg}}}{C^{\gamma\gamma}\mathcal{L}_{\text{int}}} = 107 \pm 33\,(\text{stat}) \pm 20\,(\text{syst})\,\text{nb}$$

gamma-UPC/MG5+FSR: $\sigma_{\text{fid}}(\gamma\gamma\to\gamma\gamma) = 95.4 \pm 2.0\ \mu\text{b}$

- Differential cross sections measured in data
  ⇒ agreement between both predictions and the unfolded data within experimental uncertainties

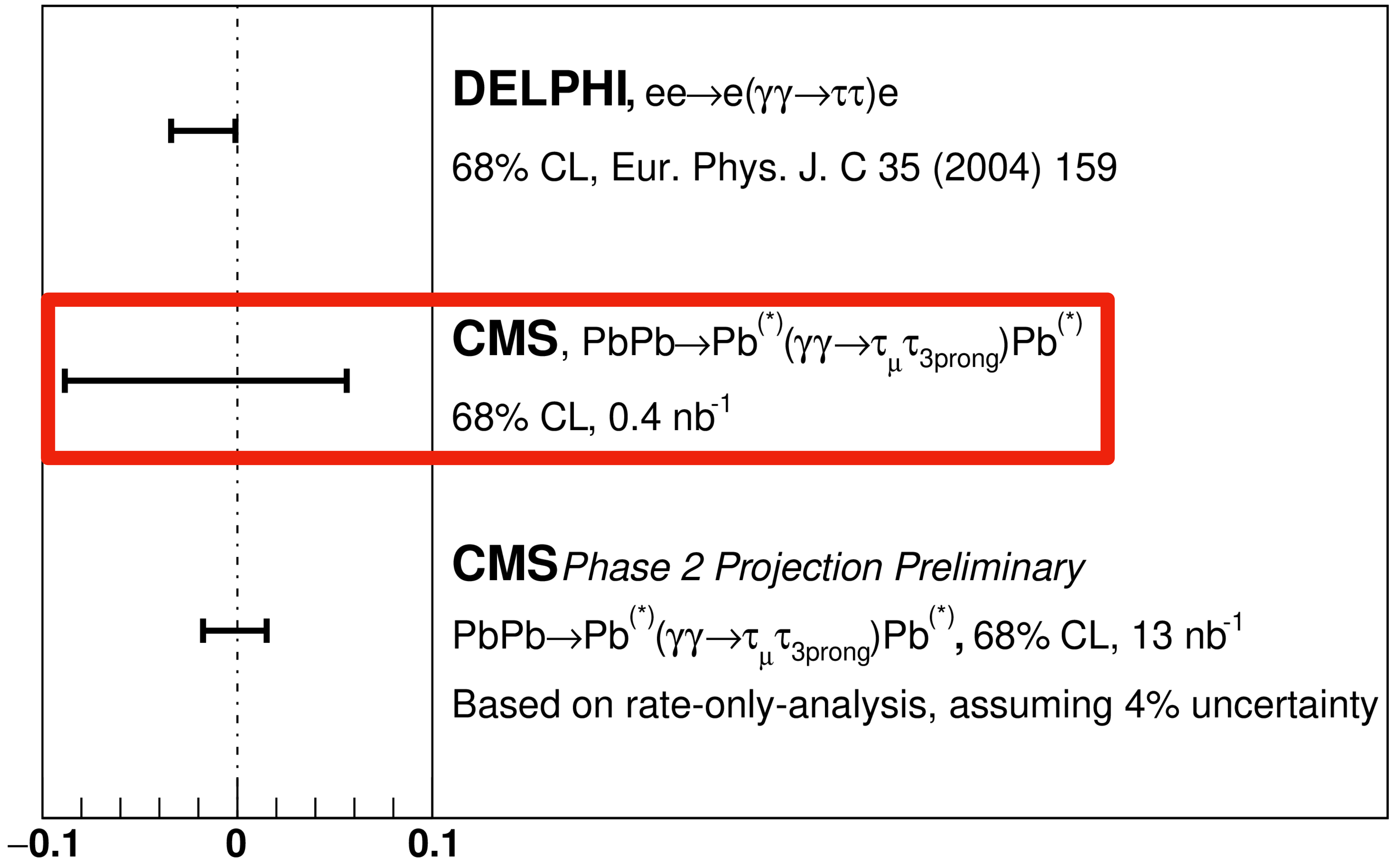
Observation of γγ→ττ





HIN-21-009
Published in PRL

Tau g-2



$a_\tau = (g - 2)/2$

See Matthew Michael's talk!

Projected sensitivity with more data

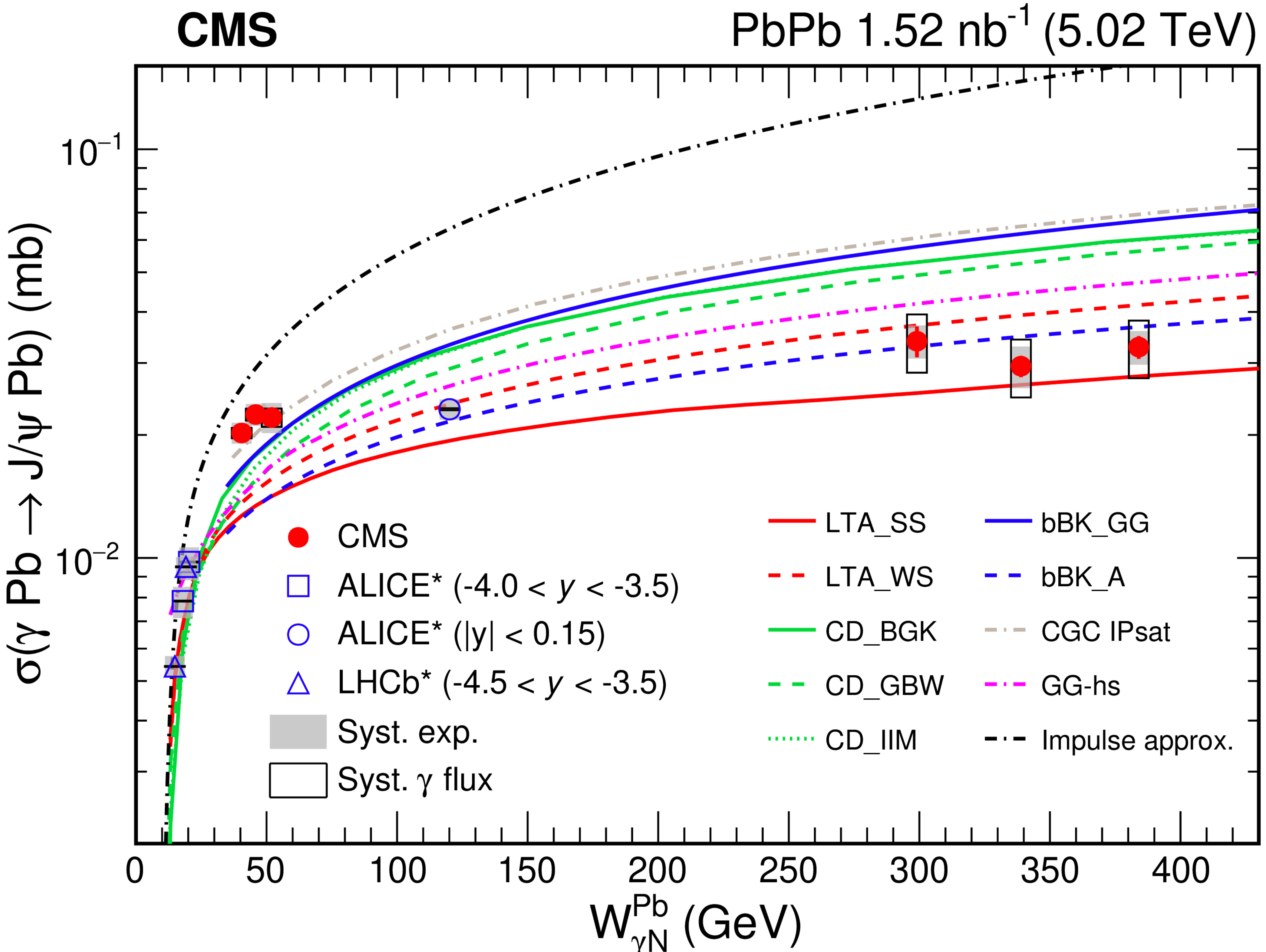
HIN-21-009
Published in PRL

Probing gluon nPDF at low x

- **Models cannot describe data across all $W_{\gamma N}^{Pb}$**
- **Evidence of gluon saturation?**

HIN-22-022 Published in PRL

Luis talk



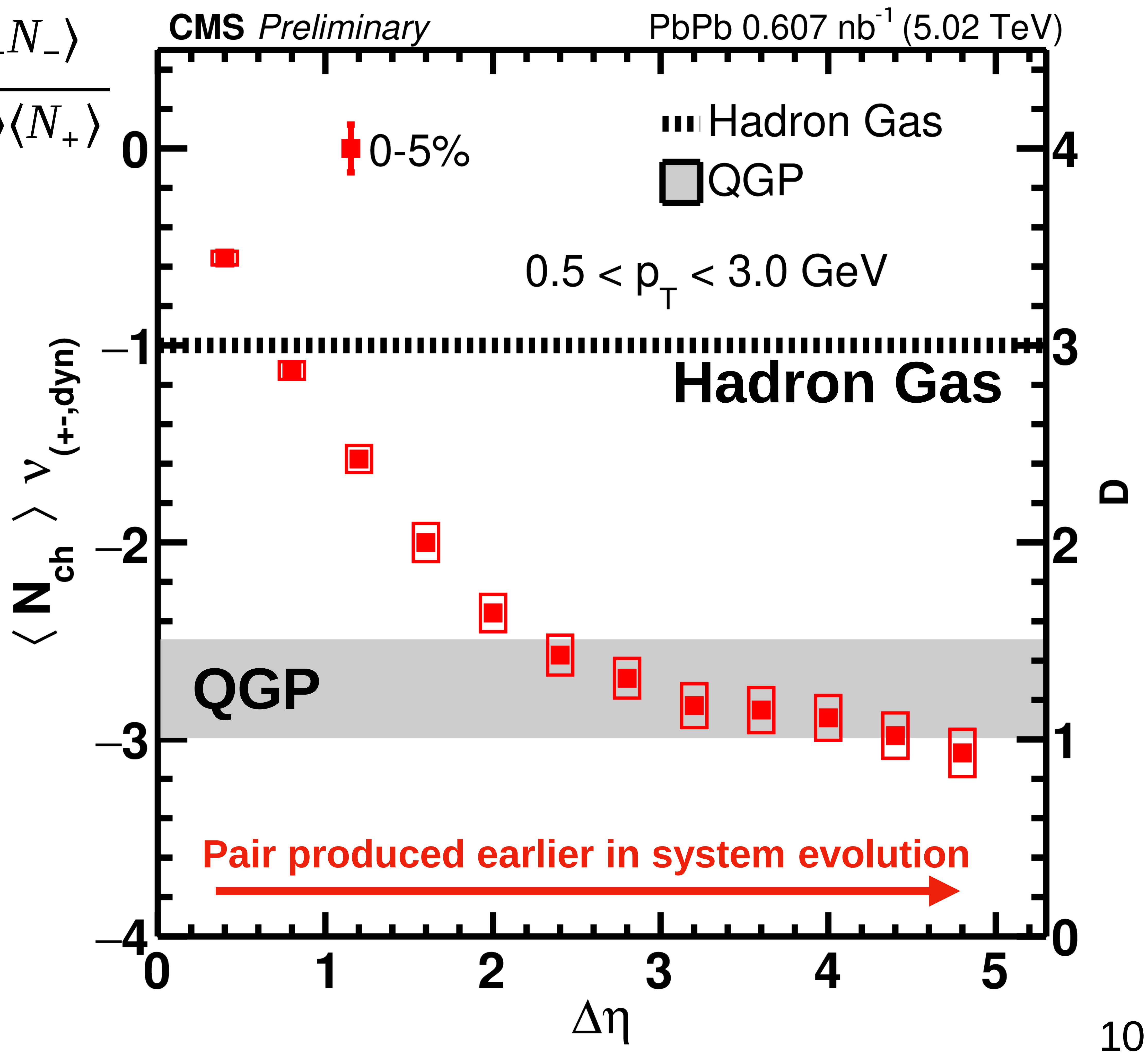
QGP Degrees of Freedom

Net charge fluctuations in PbPb

$$\nu_{(+-,\mathrm{dyn})} = \frac{\langle N_+(N_+ - 1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_- - 1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_+ N_-\rangle}{\langle N_-\rangle\langle N_+\rangle}$$

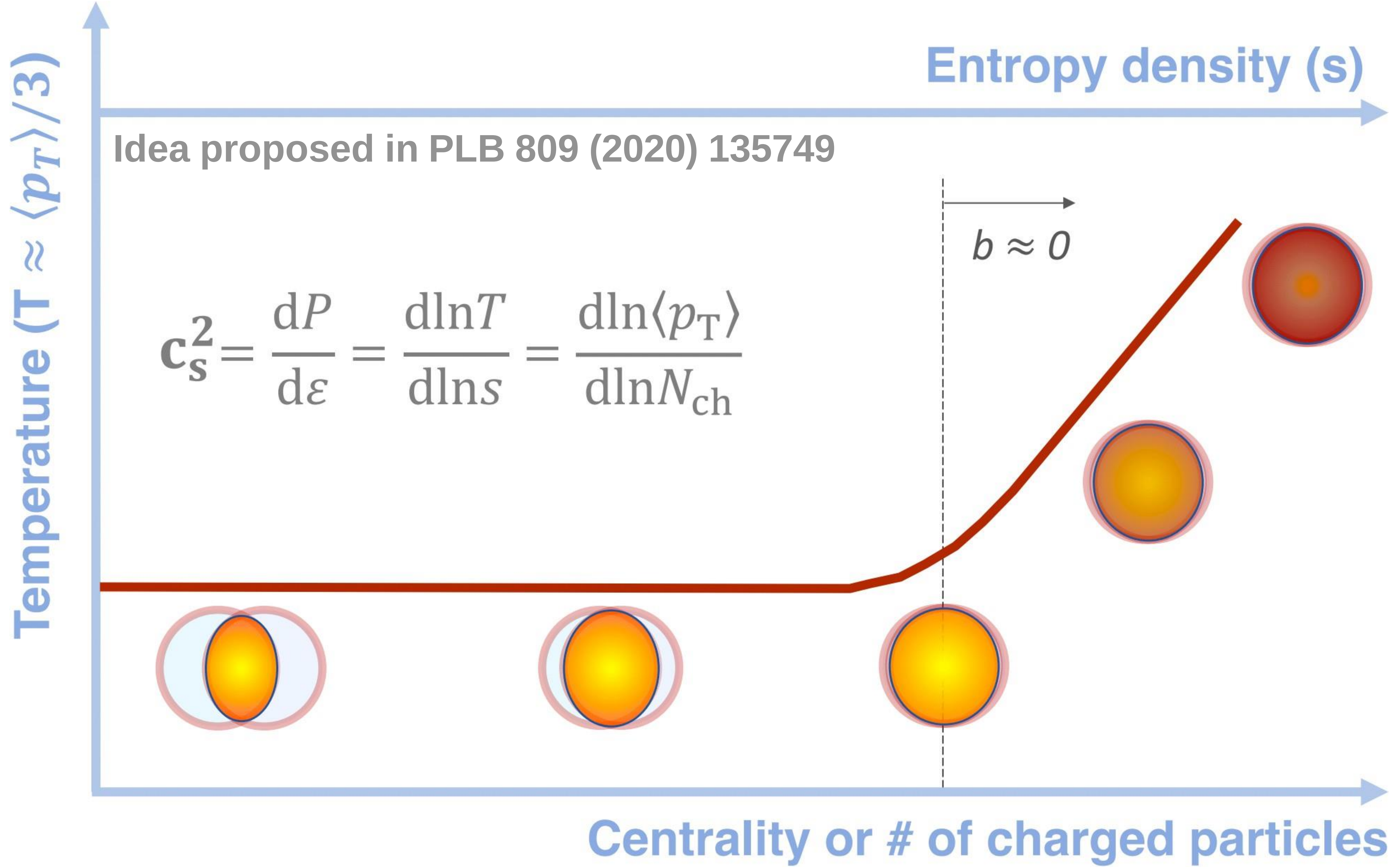
- **Net charge fluctuations vs. $\Delta\eta$ of particle pairs**
- **Consistent with predictions for QGP at large $\Delta\eta$**

CMS PAS HIN-22-005



Speed of Sound in QGP

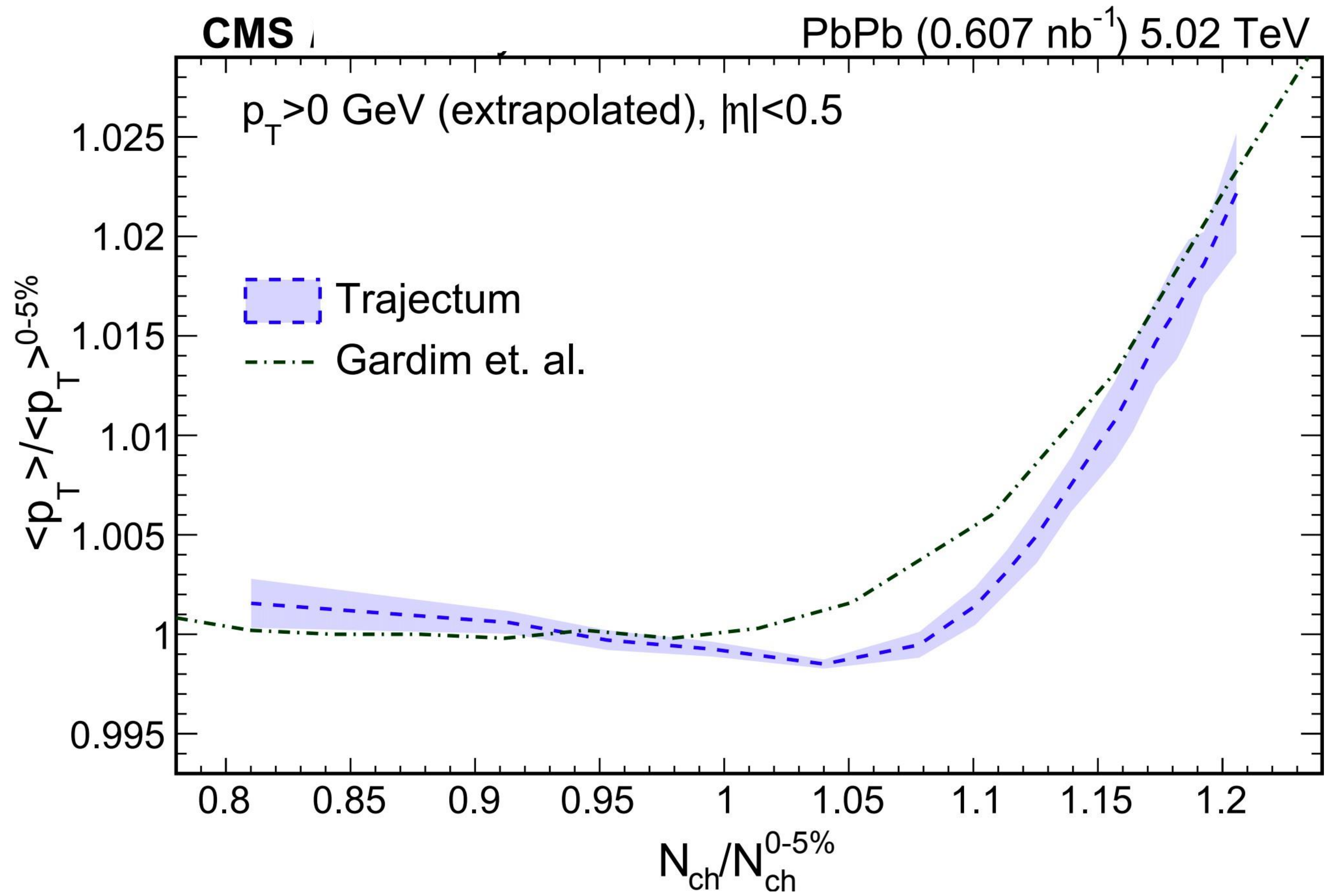
- **QGP speed of sound can be extracted from measurements of <p_T> vs N_{ch}**



Speed of Sound in QGP

- **Hydrodynamic models predict rising slope at large N_{ch}**

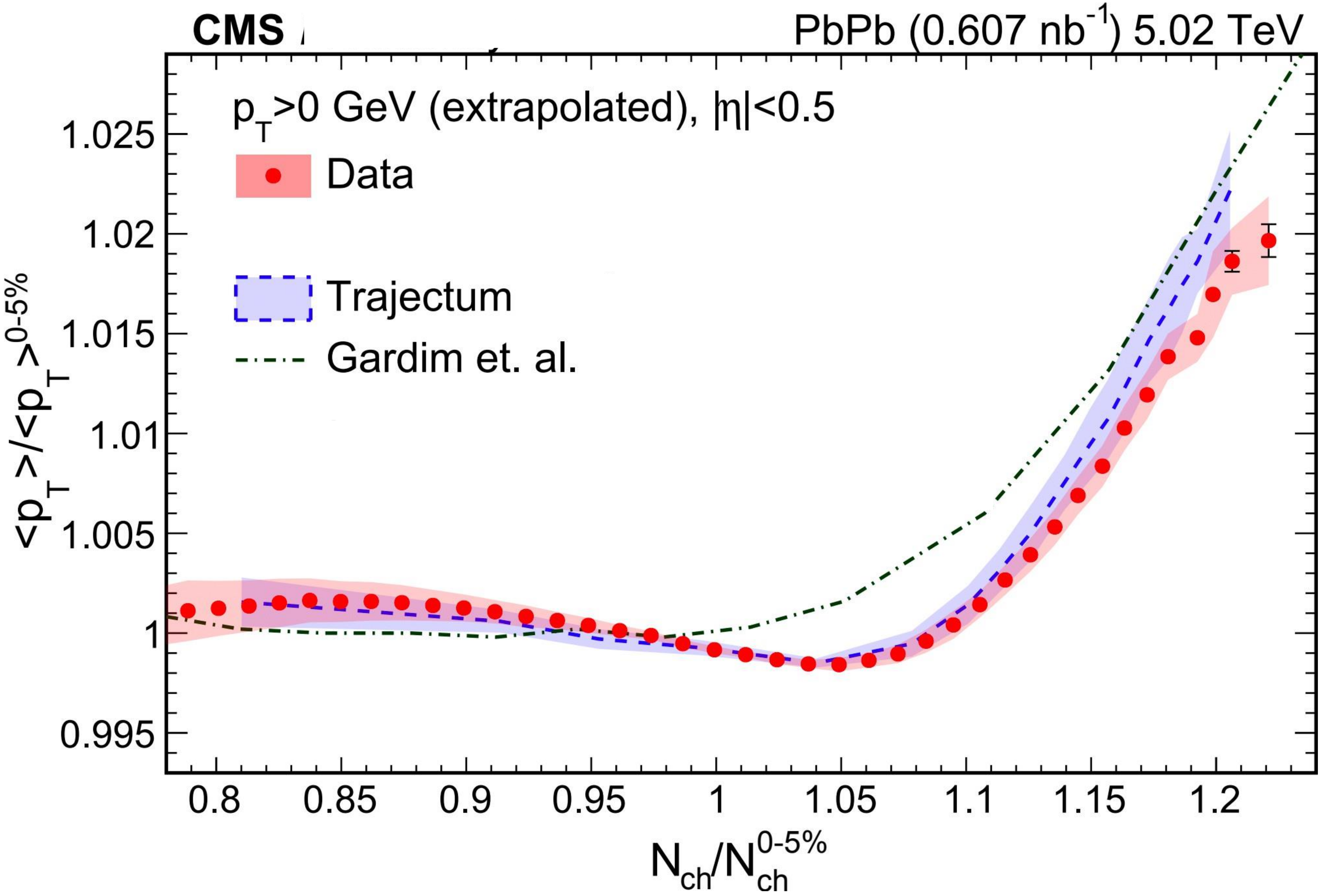
HIN-23-003 Accepted by ROPP



Speed of Sound in QGP

- **Slope of data matches models closely!**

HIN-23-003 Accepted by ROPP



Speed of Sound in QGP

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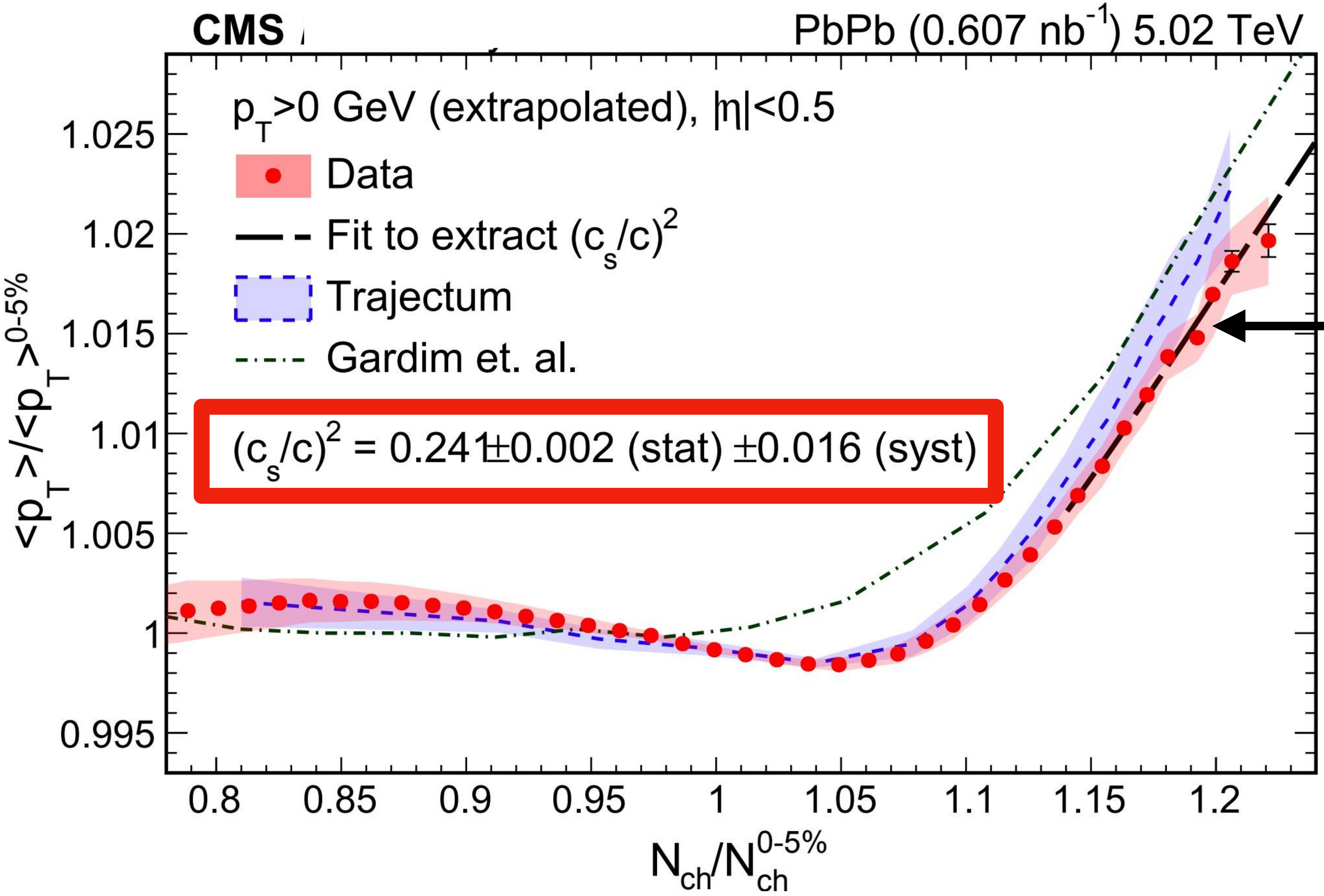
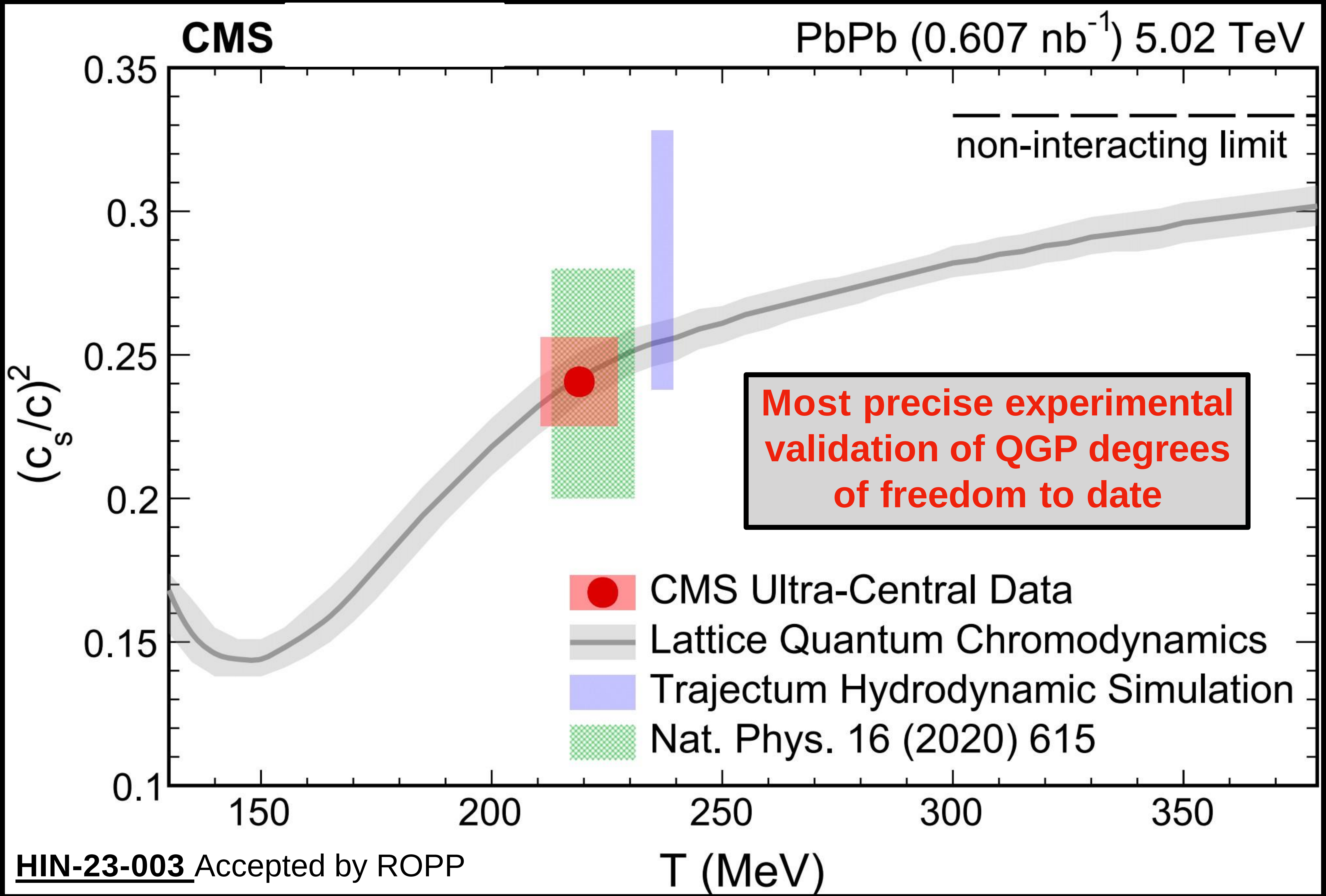
HIN-23-003 Accepted by ROPP



Fit slope to get c_s^2

Constraining QCD Equation of State

- Slope of d



HIN-23-003 Accepted by ROPP

- Fit slope to get c_s^2

PAS HIN-23-003

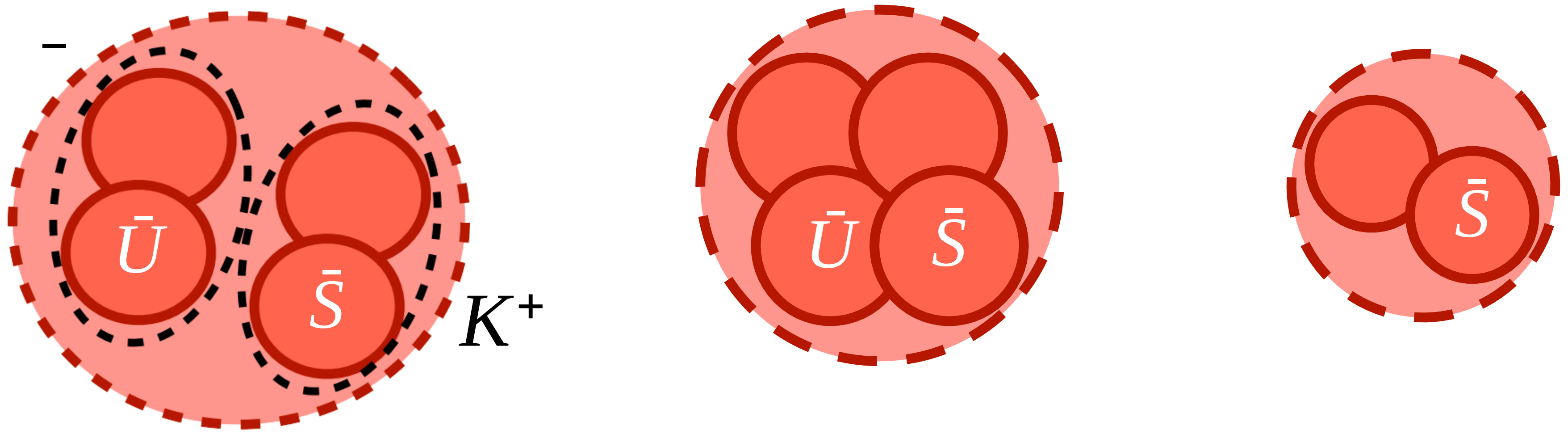
Cesar
rnardes's talk
Wed. 15:40,
Ballroom C

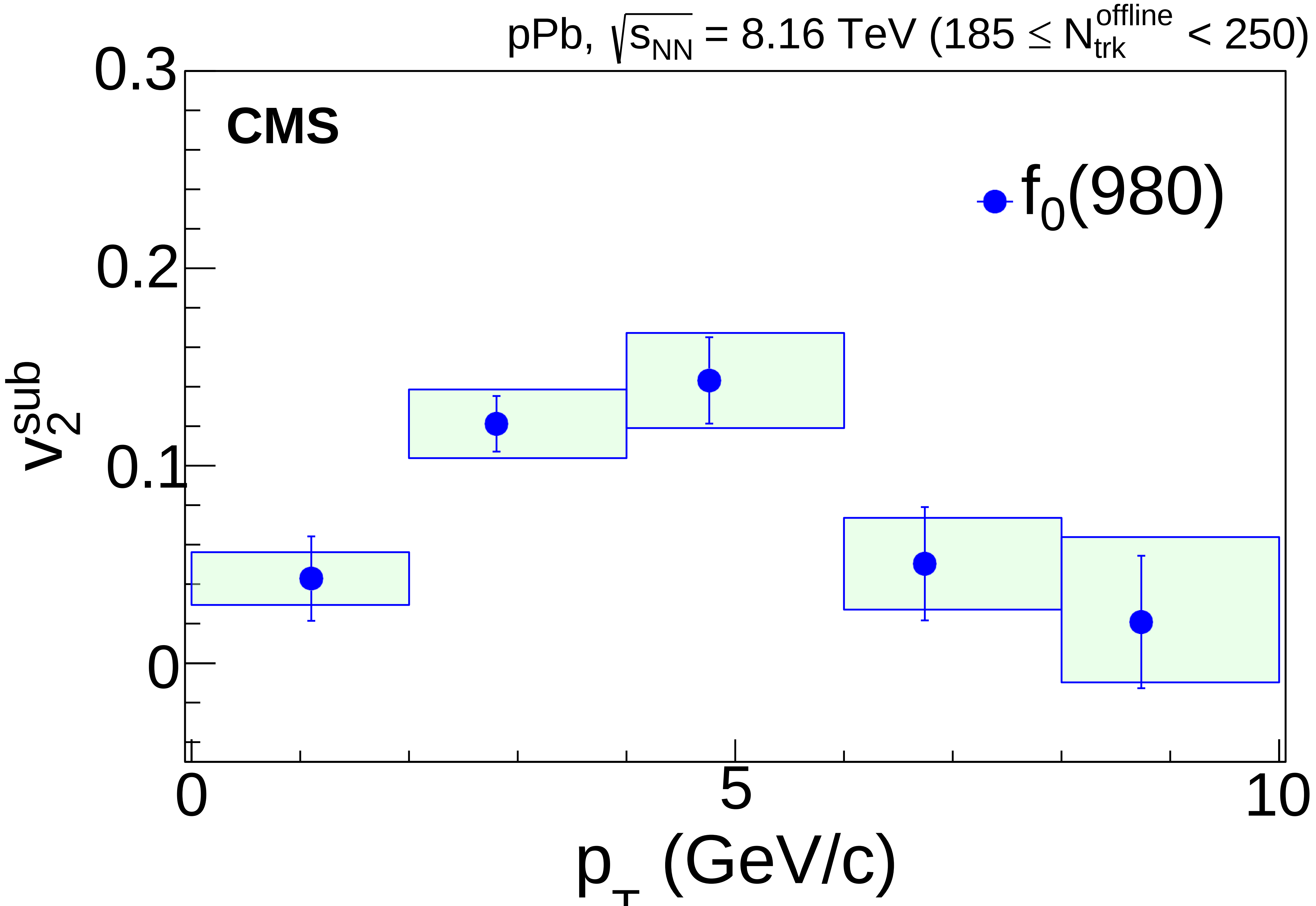
Hadronization and Heavy Flavor

v_2 of f_0(980) in pPb

- **v_2 of $f_0(980)$ measured in pPb**

- **Inner structure unknown**
  - **Diquark**
  - **Tetraquark**
  - **K-K molecule**

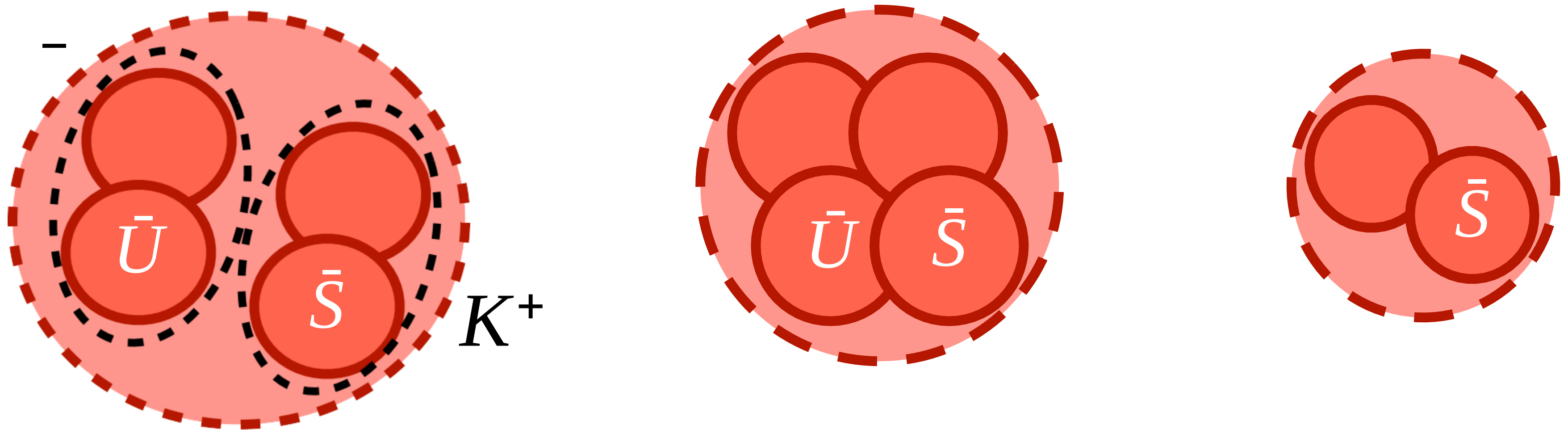


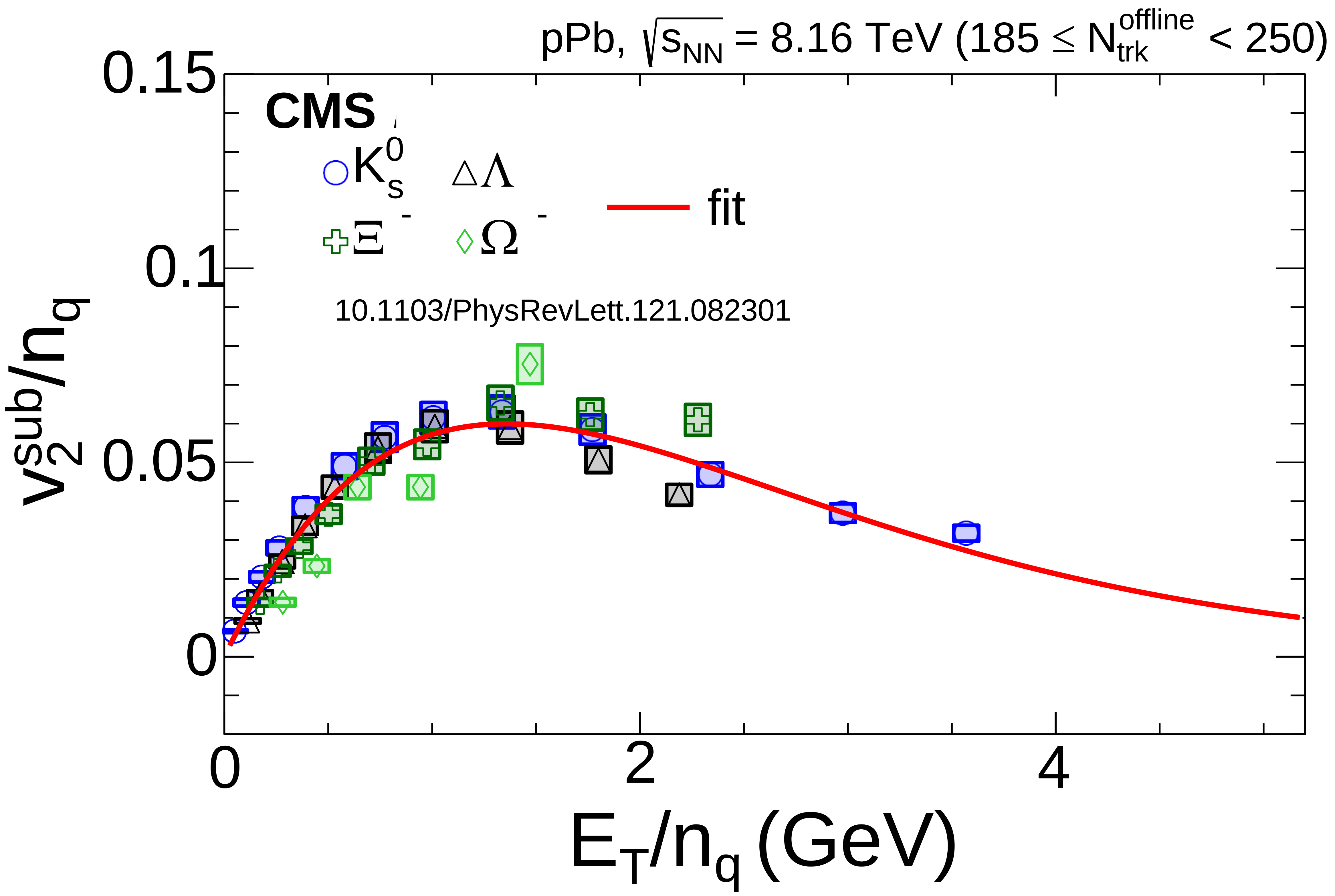


Constituent Scaling of v_2

- v_2 of $f_0(980)$ measured in pPb
- Inner structure unknown
  - Diquark
  - Tetraquark
  - K-K molecule
- Use constituent quark scaling to extract number of quarks

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



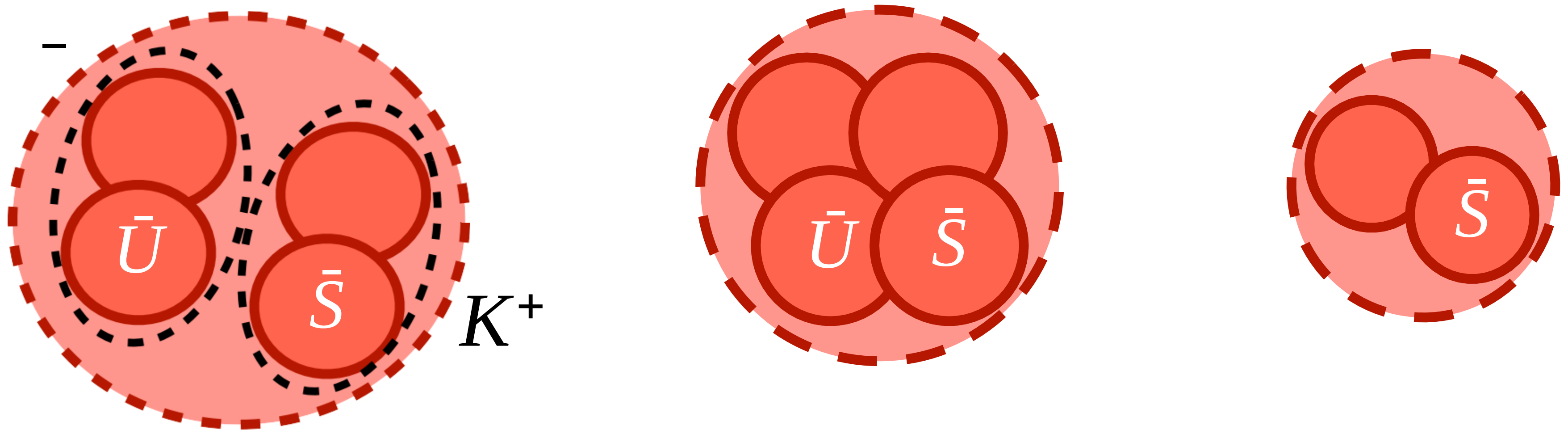


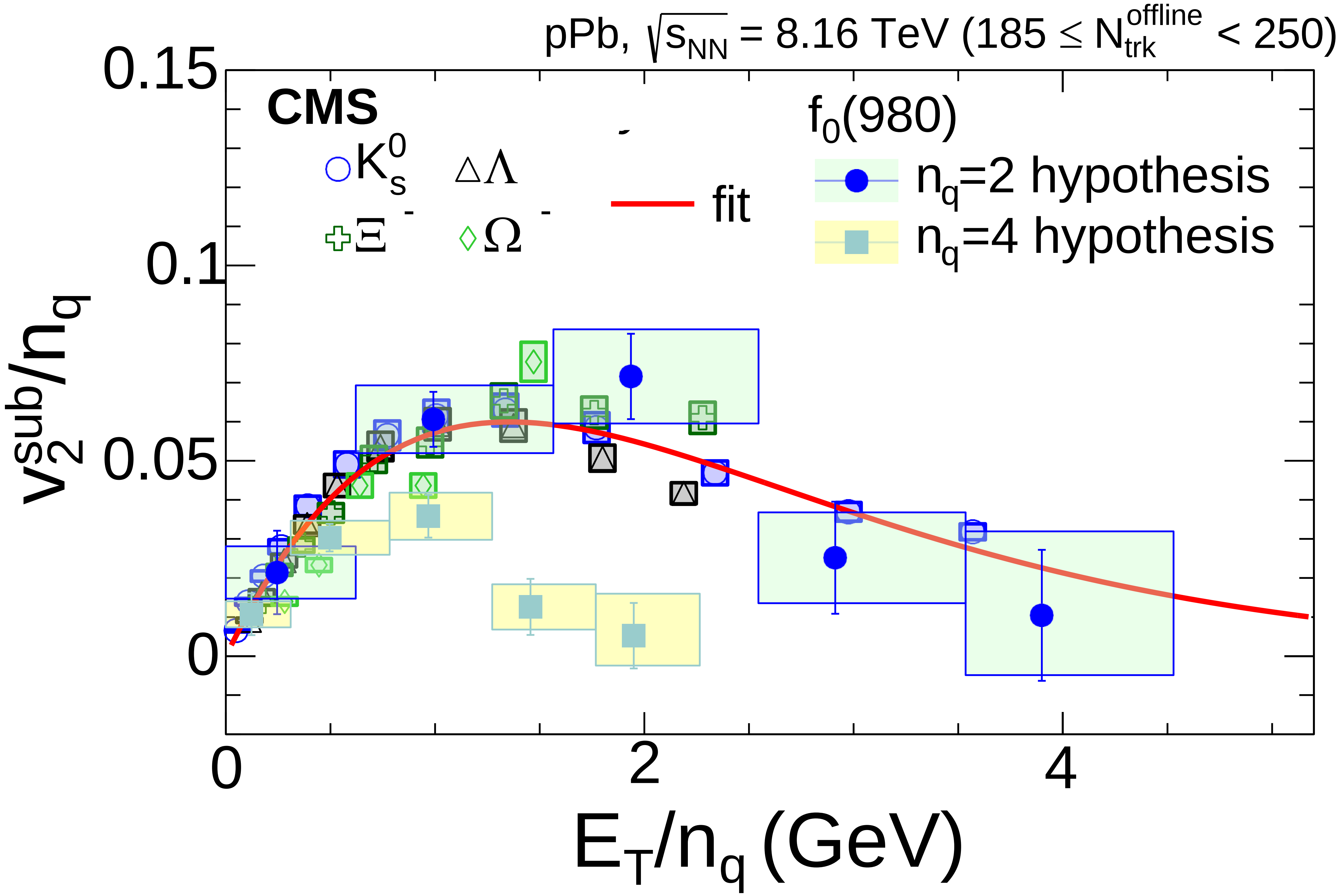
CMS HIN-20-002 Submitted to Nat Commun

$f_0(980)$ Quark Content

- **v_2 of $f_0(980)$ measured in pPb**
- **Inner structure unknown**
  - **Diquark**
  - **Tetraquark**
  - **K-K molecule**
- **Use constituent quark scaling to extract number of quarks**

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





f_0(980) Quark Content

- v_2 of $f_0(980)$ measured in pPb
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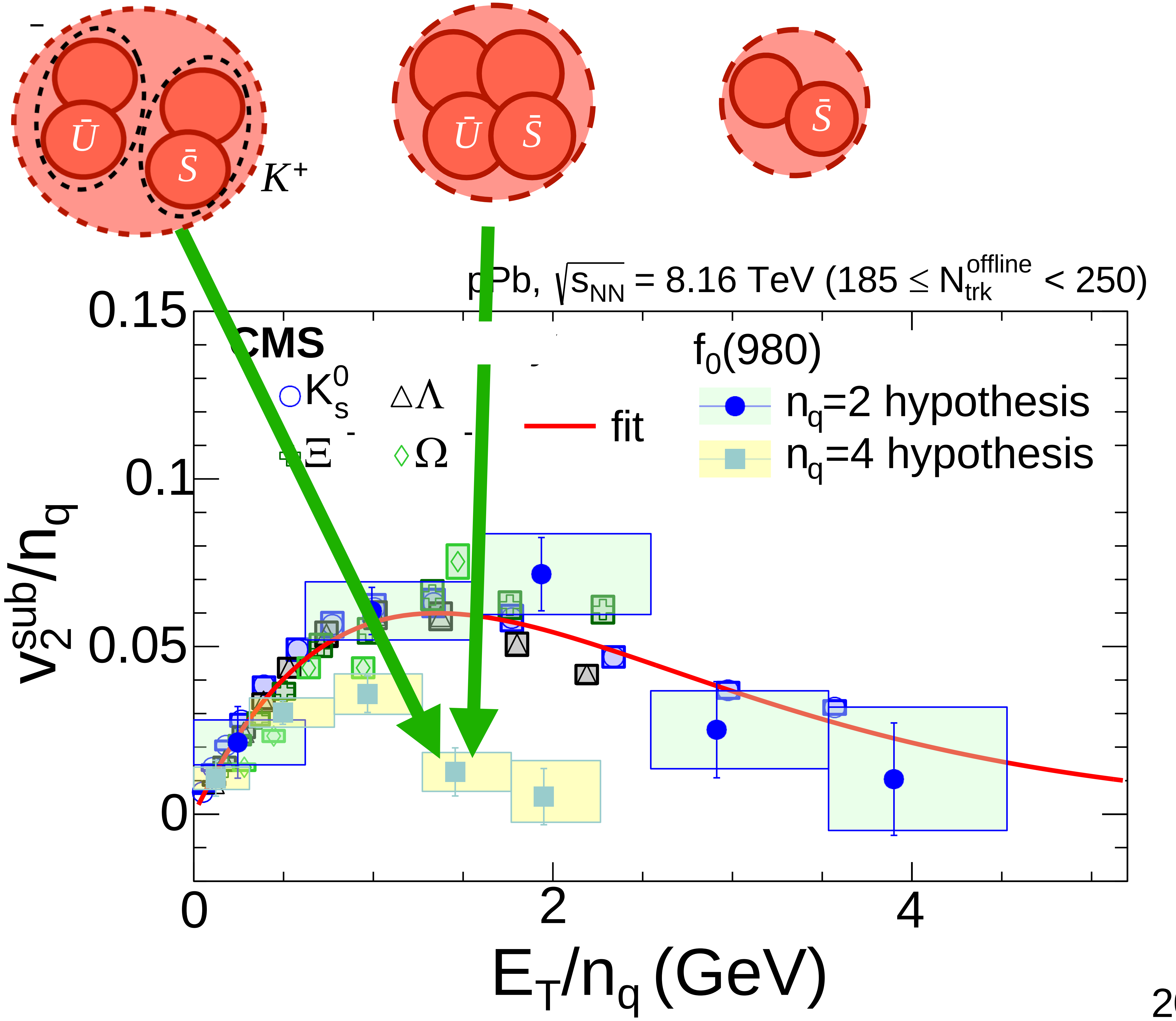
$$v_2(E_T)/n_q = v_{2,q}(E_T/n_q)$$

- n_q = 4 excluded at ≥3.1

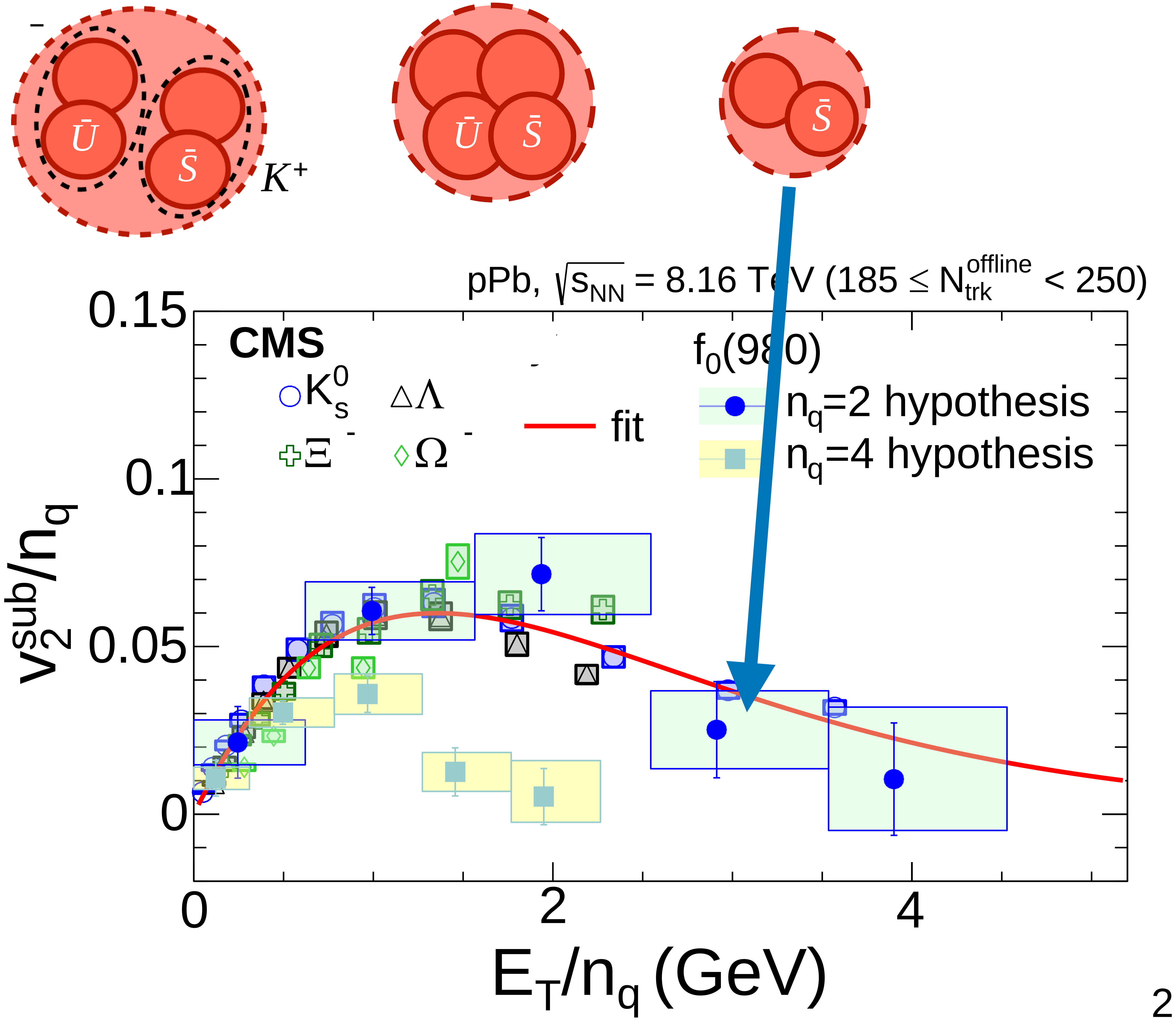


f_0(980) Quark Content

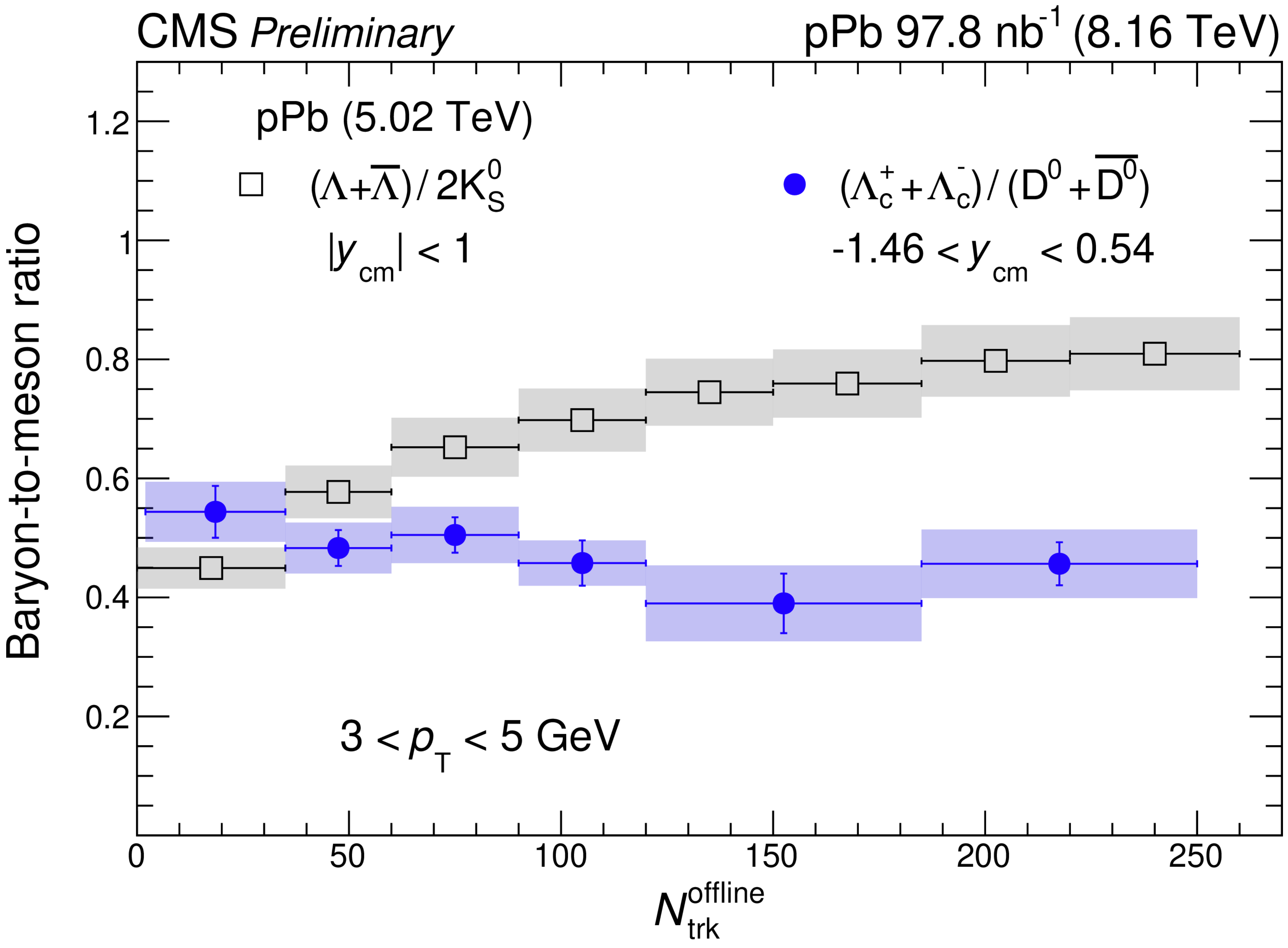
- **v_2 of $f_0(980)$ measured in pPb**
- **Inner structure unknown**
  - **Diquark**
  - **Tetraquark**
  - **K-K molecule**
- **Use constituent quark scaling to extract number of quarks**

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

- **$n_q = 4$ excluded at ≥3.1**
- **$n_q = 2$ favored**



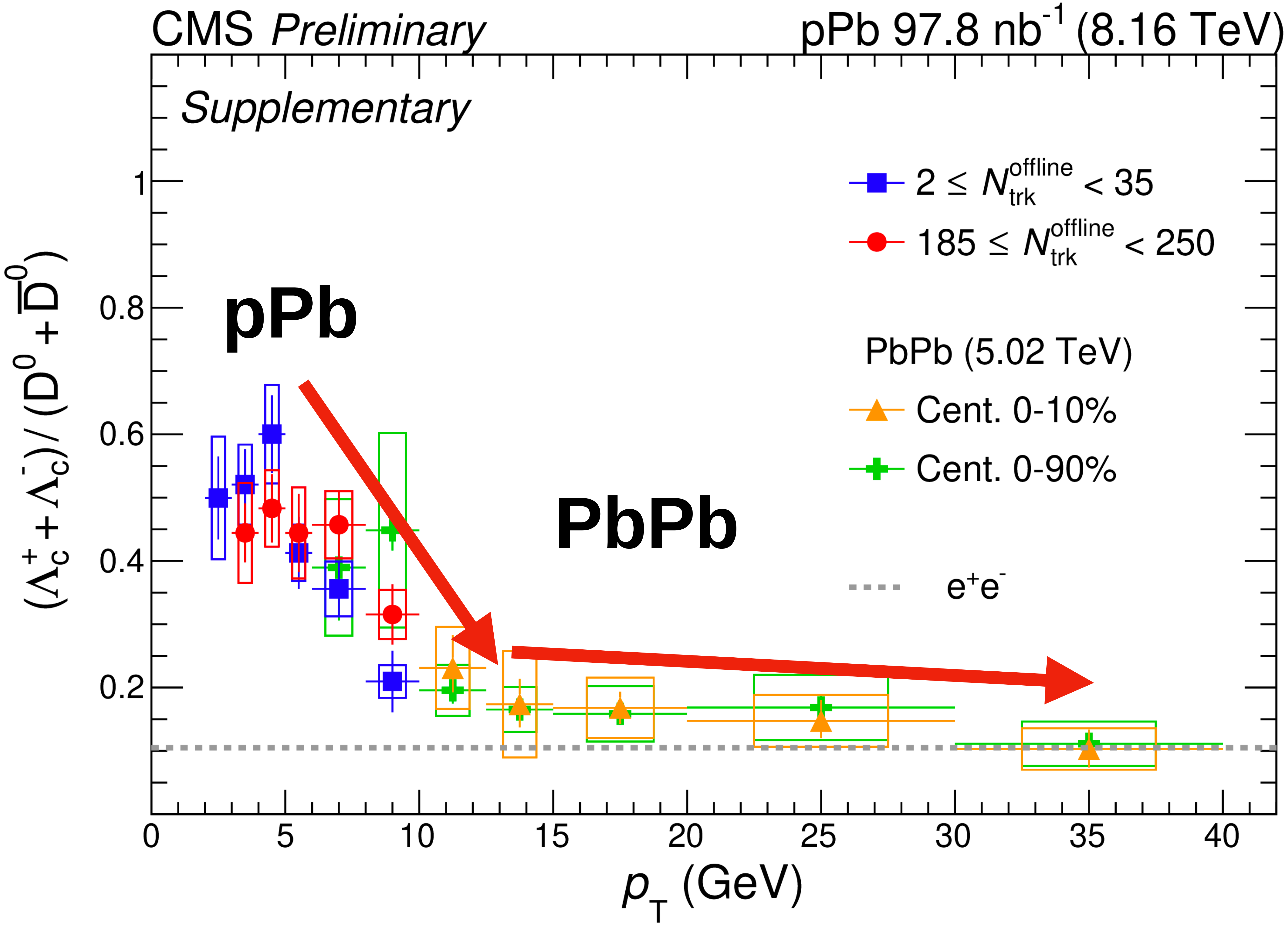
Λ_c^+/D^0 Ratio vs. pPb multiplicity



CMS PAS HIN-21-016

- **Comparison of charm and strange baryon-to-meson ratio**
  - **Multiplicity-dependence not observed in charm sector**

Λ_c^+/D^0 Compilation



- **Similar trend vs p_T regardless of multiplicity in pPb and PbPb**
- **High-p_T behavior close to e^+e^- baseline**

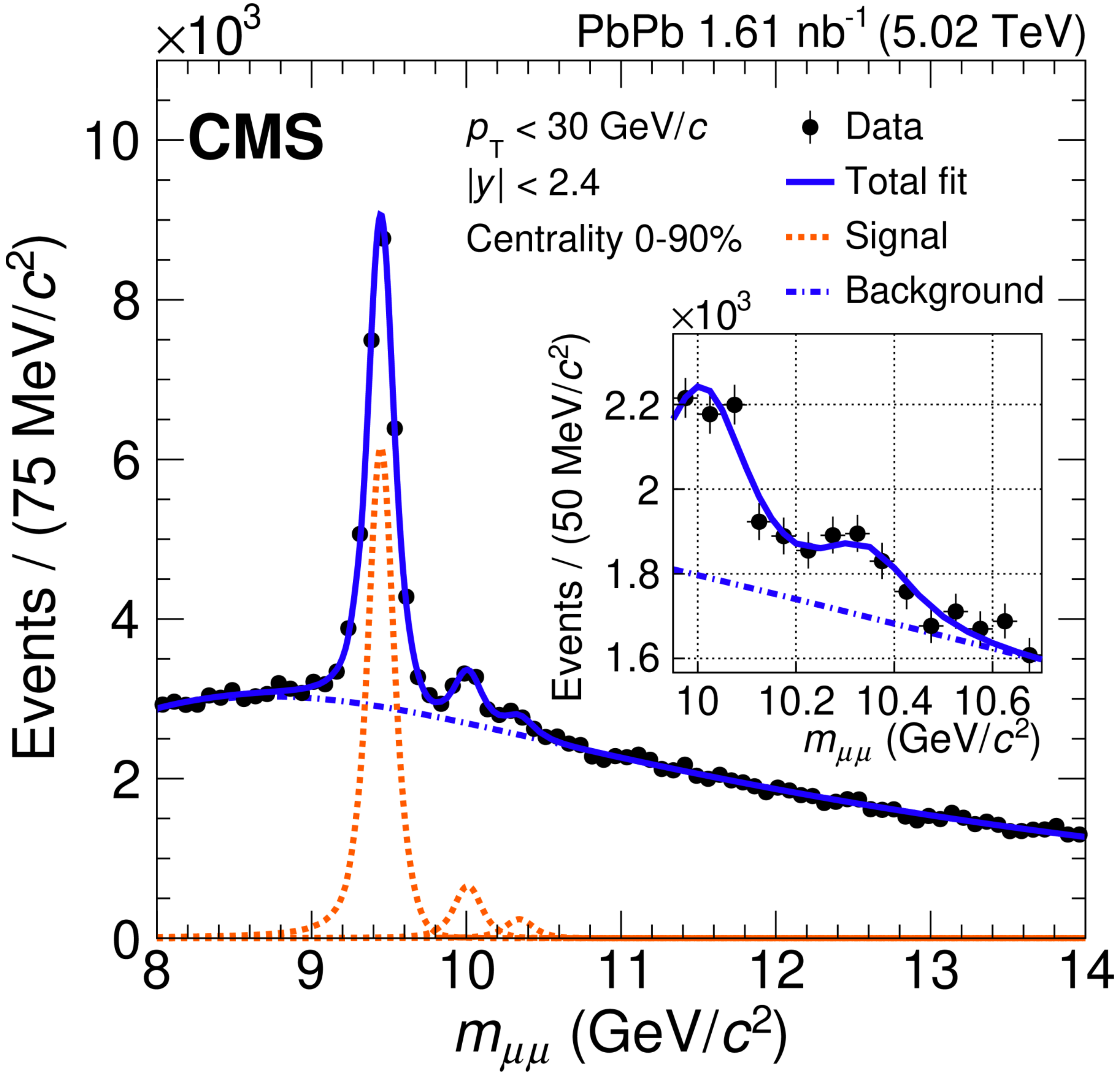
CMS PAS HIN-21-016

HIN-21-004 Published in JHEP

Observation of $\Upsilon(3S)$

- **First observation of $\Upsilon(3S)$ in AA collisions**

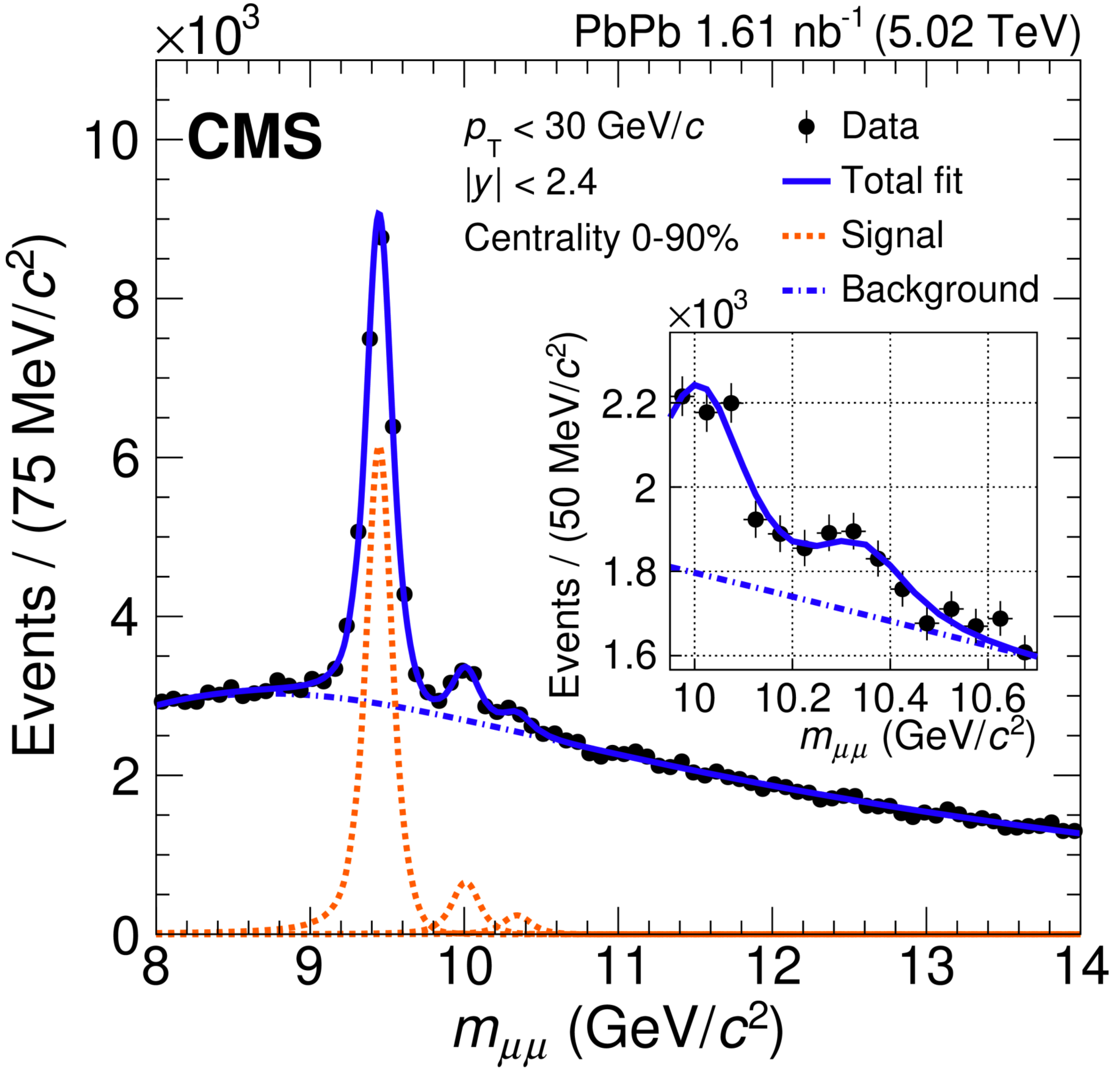
HIN-21-007 Submitted to PRL

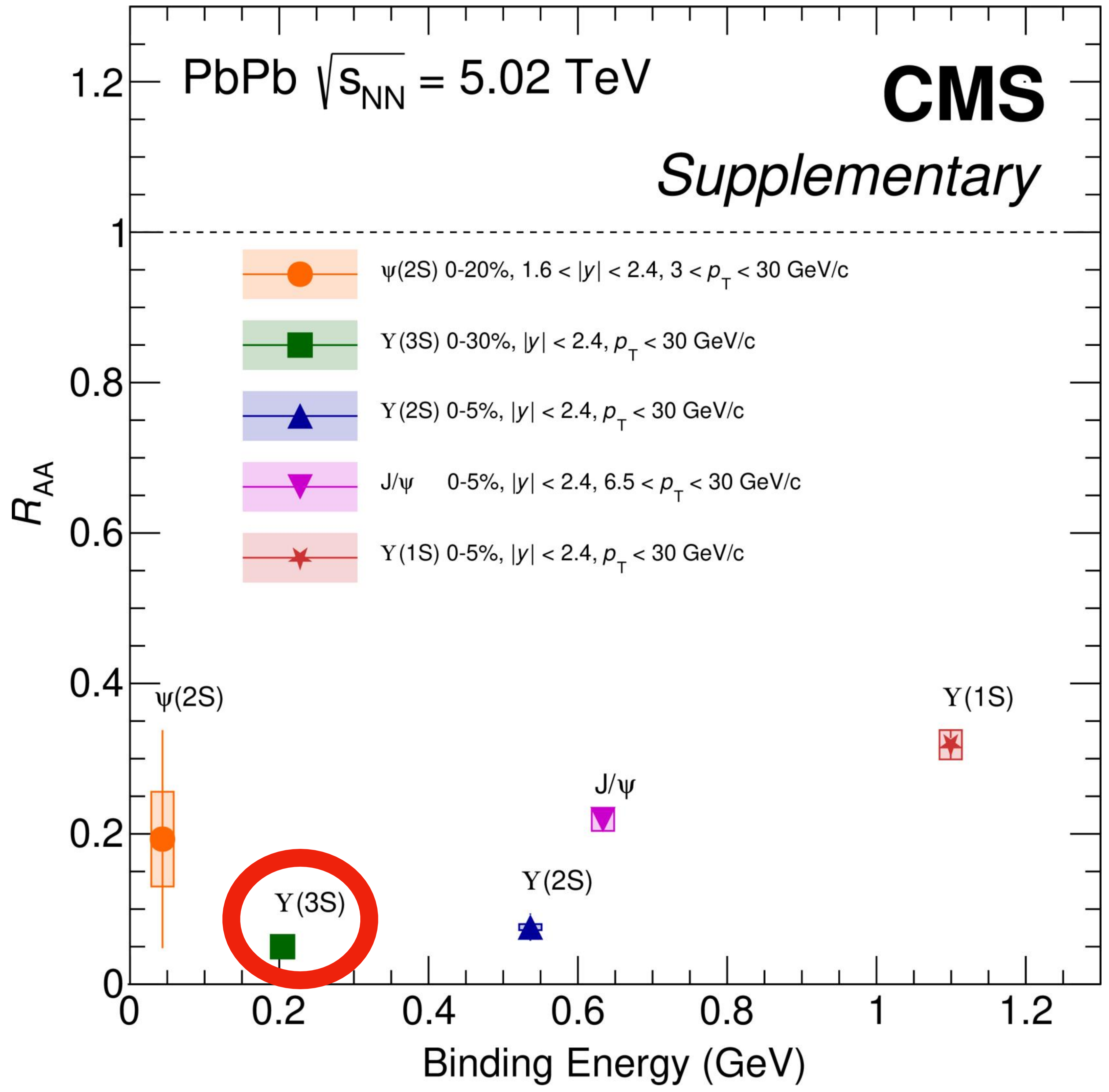


5 vector quarkonia states

HIN-21-007 Submitted to PRL

- First observation of $\Upsilon(3S)$ in AA collisions
- Stronger suppression at low binding energies

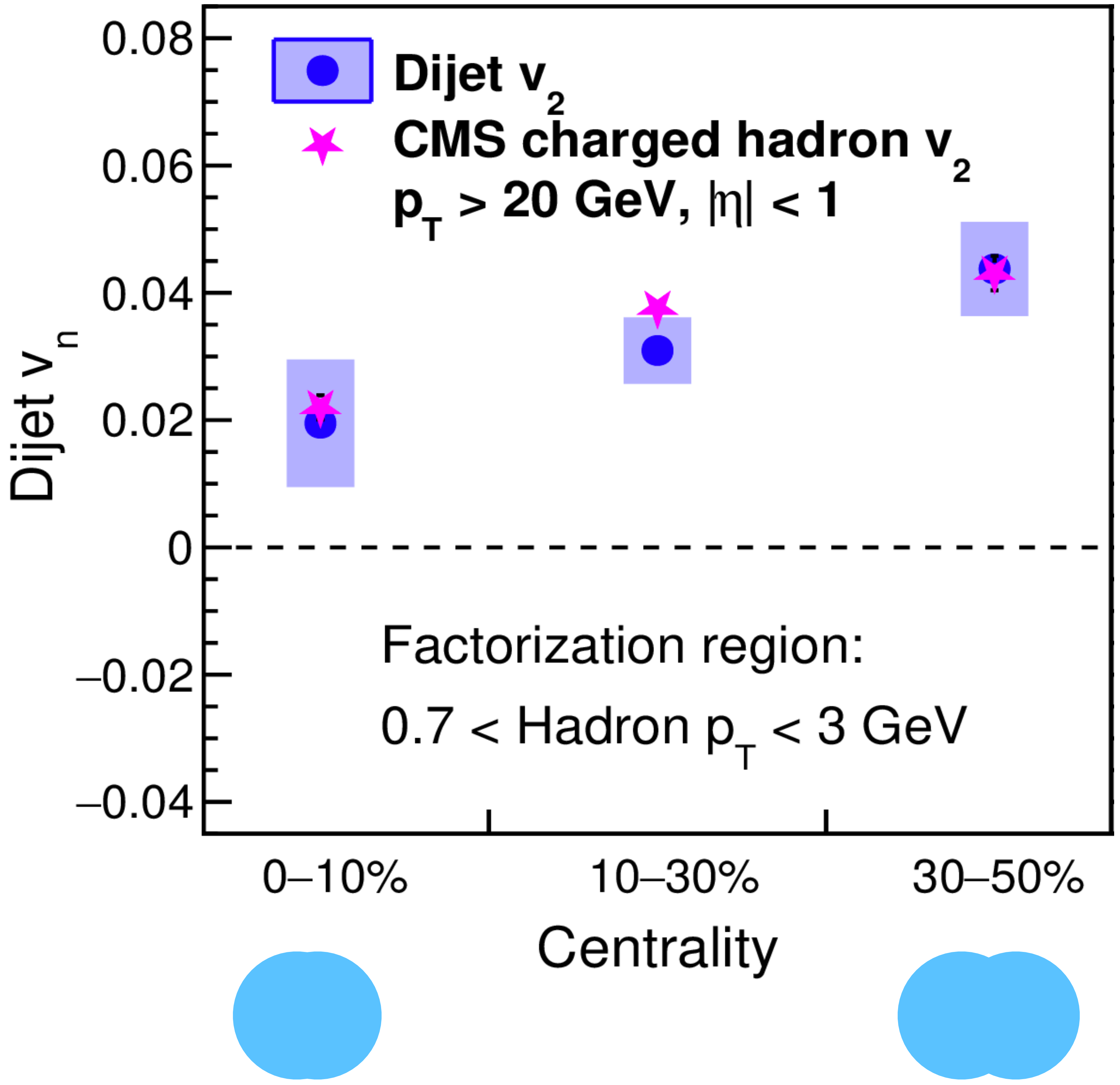


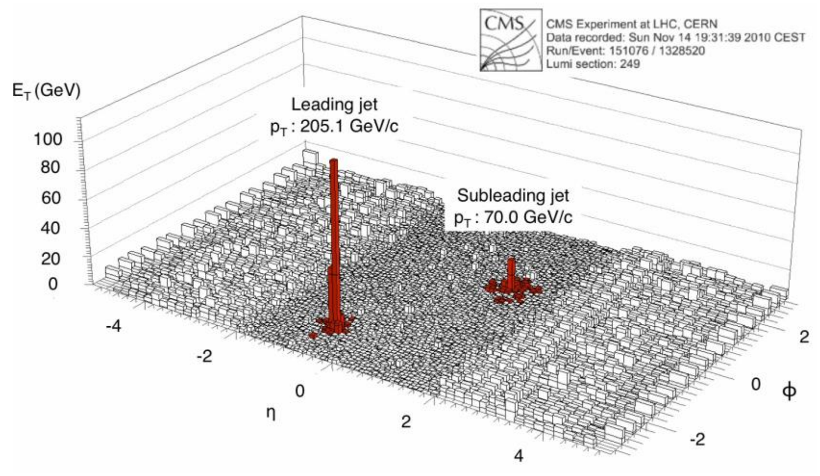


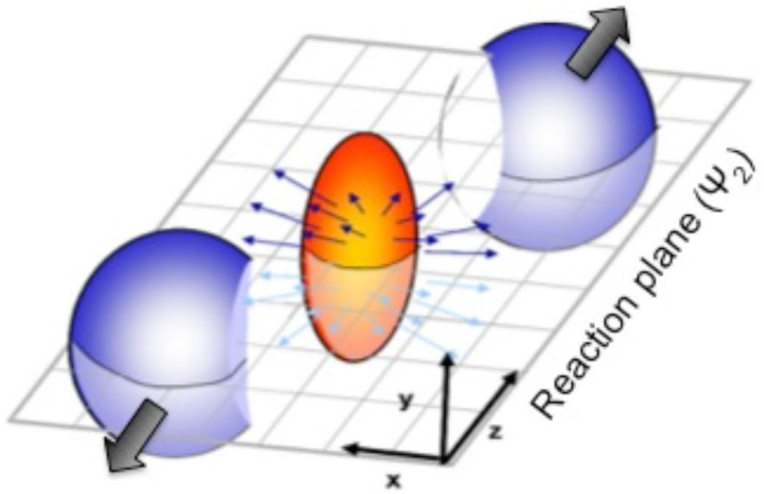
Jet Quenching and Substructure

Dijet v_2 in PbPb

- **Positive dijet v_2 - jet yields correlated with initial elliptic geometry**



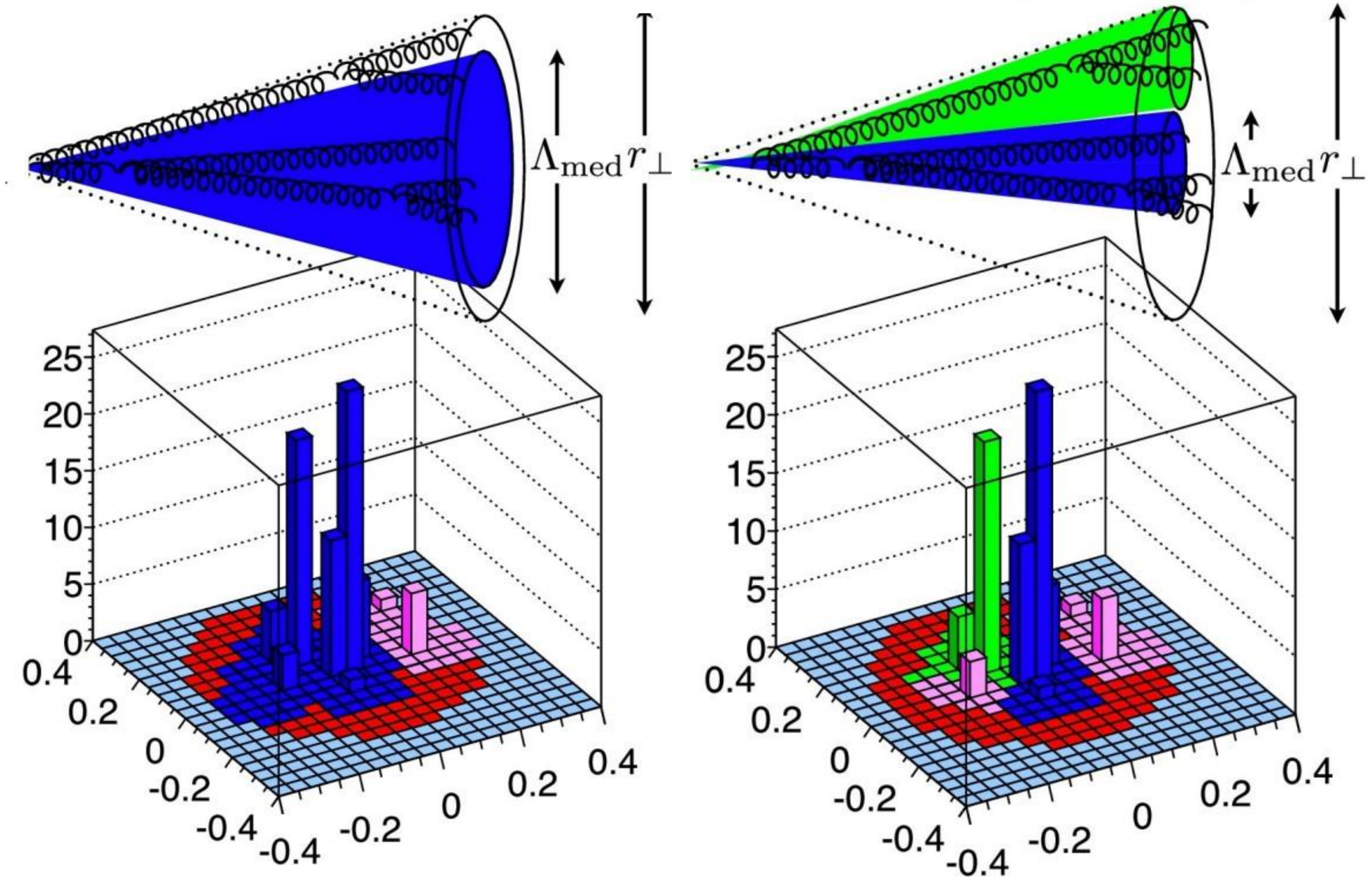




JHEP 07 (2023) 139

How many particles can QGP separate at once?

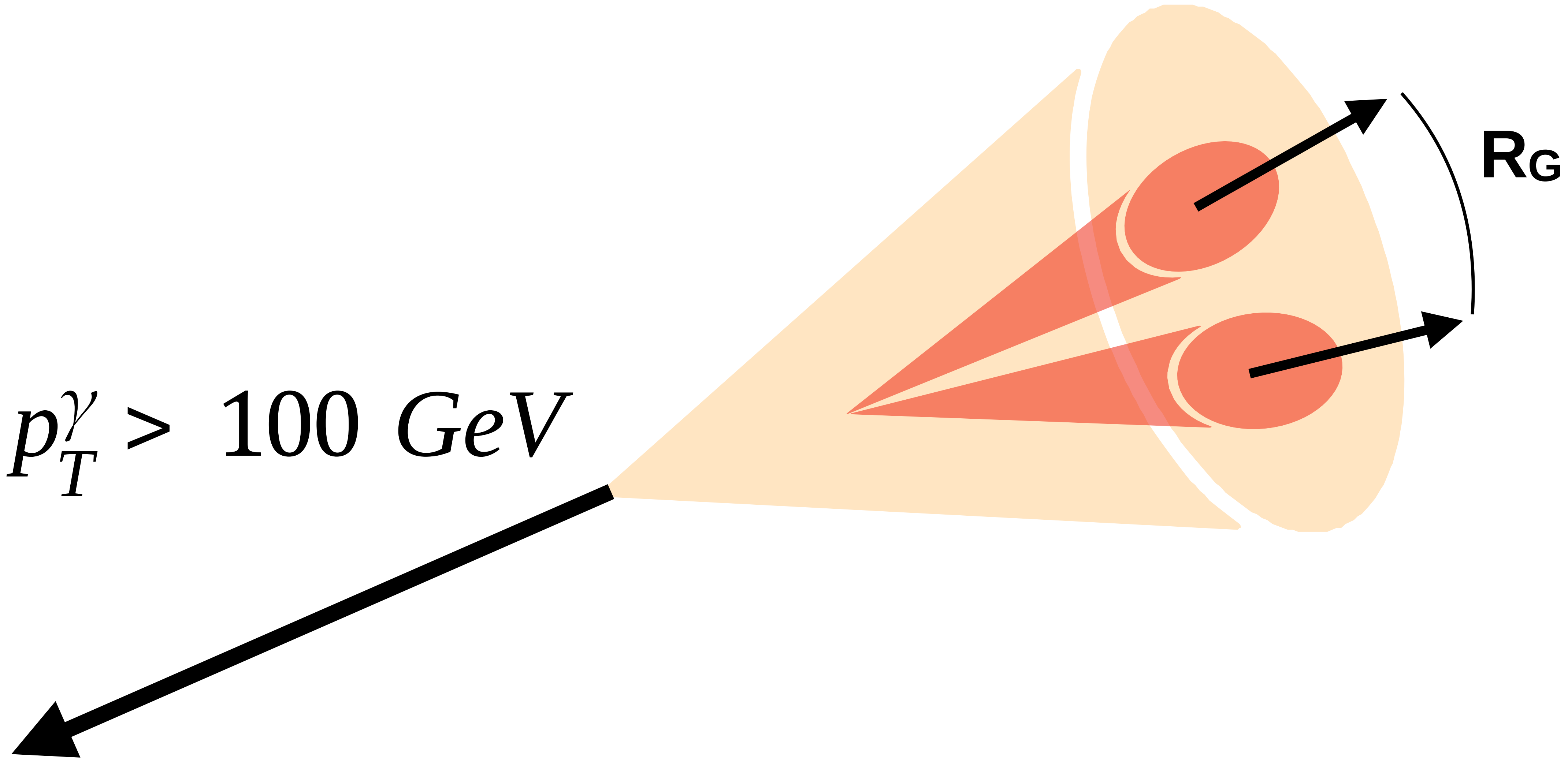
J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, arXiv:1210.7765

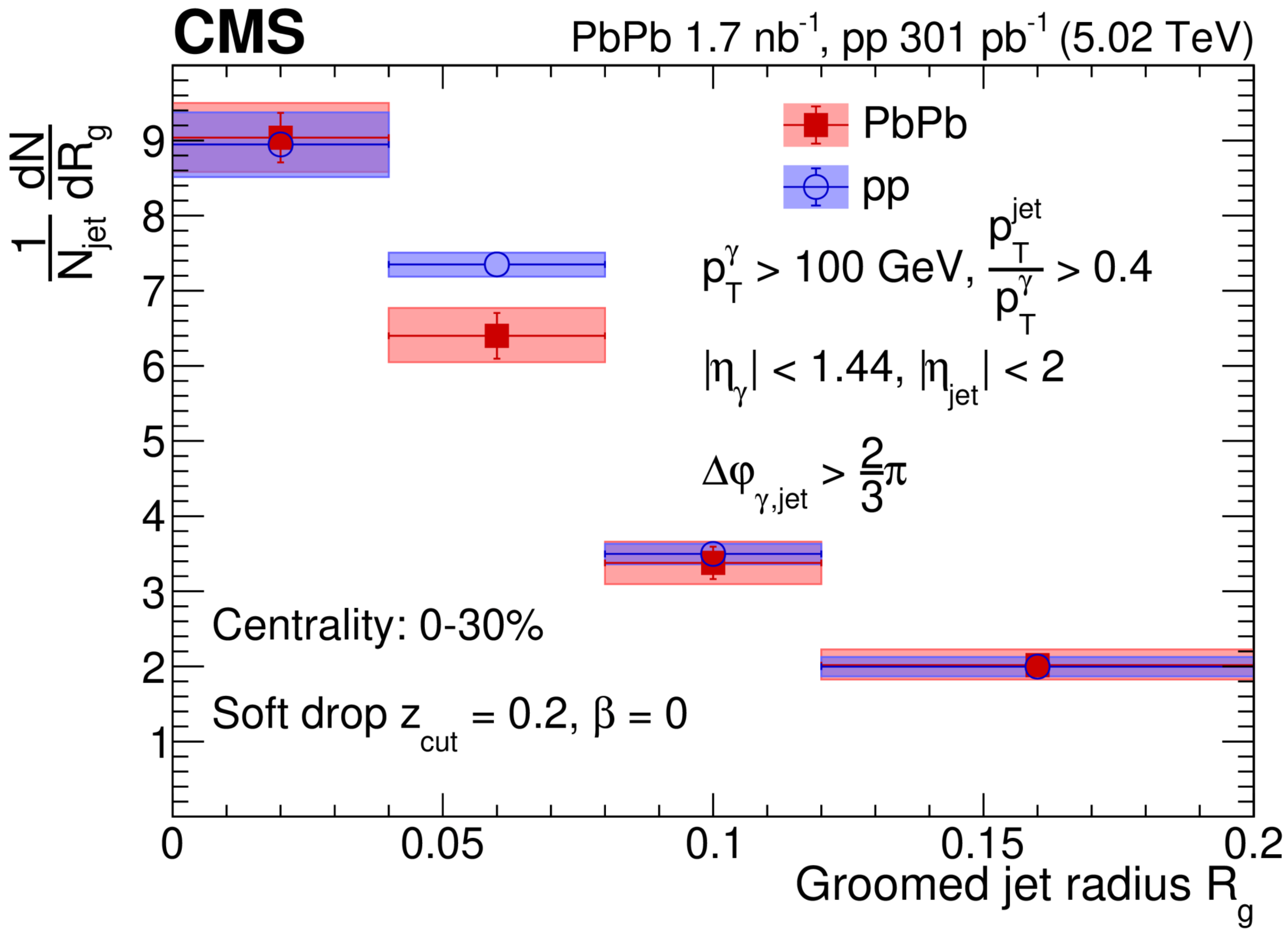


- **Simple picture so far: there is a scale that separates two configurations**

Interpretation not that simple as initially thought

CMS HIN-23-001 Submitted to PLB





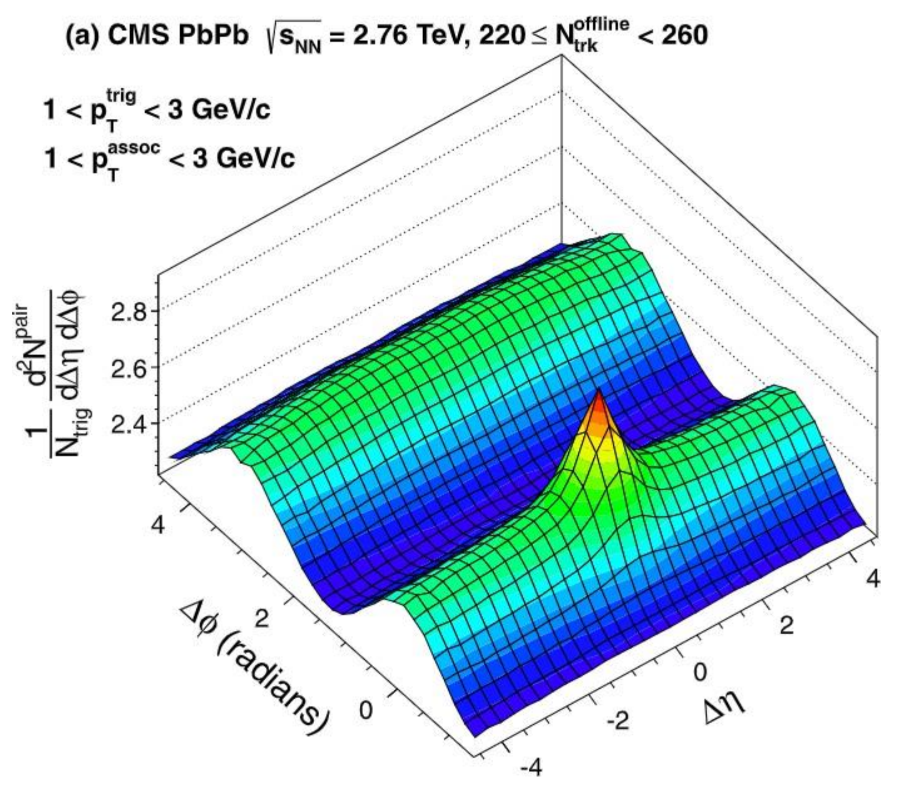
- **Found out with a photon recoil**
- **No actual modification seen…**

Collectivity in small systems

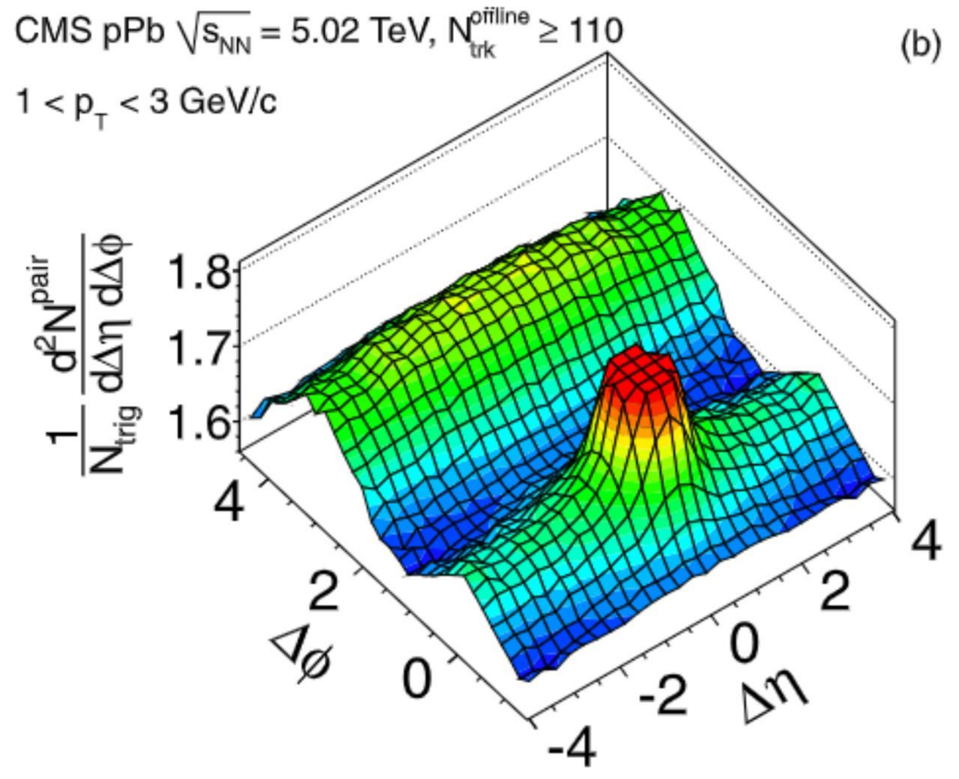
Systems smaller than pp?

PLB 724 (2013) 213
PLB 718 (2013) 795
PLB 765 (2017) 193

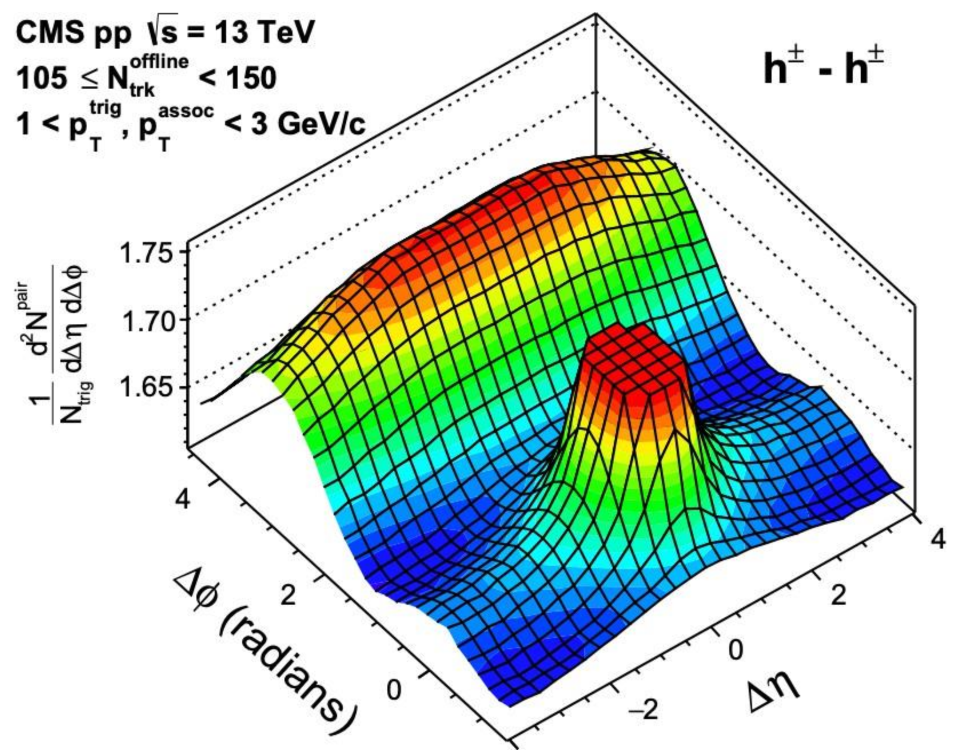
PbPb



pPb



High-multiplicity pp

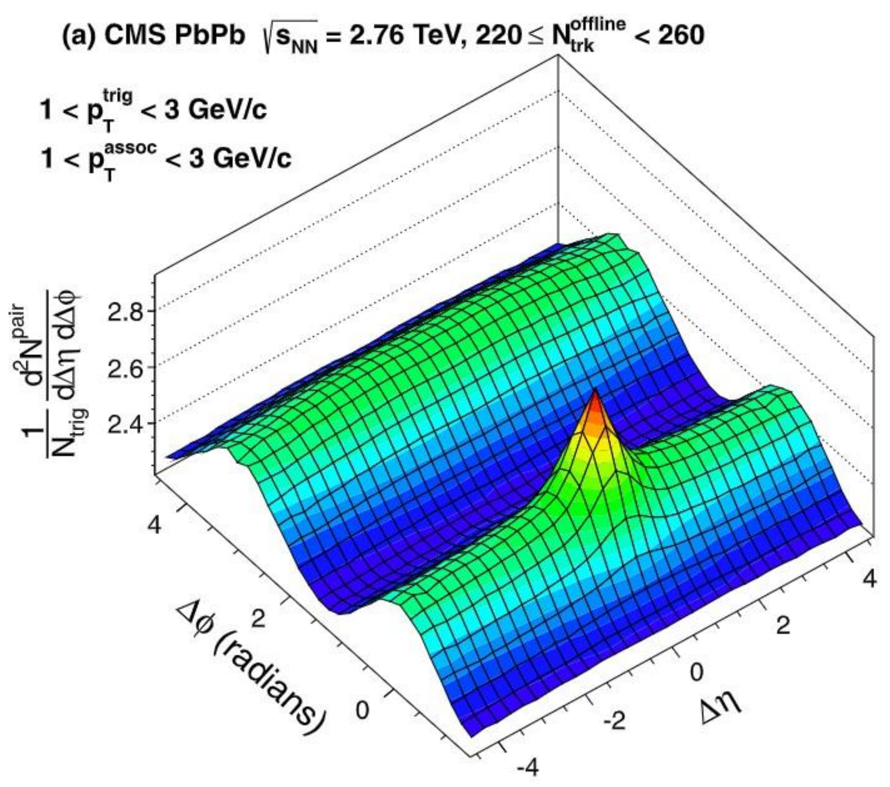


???

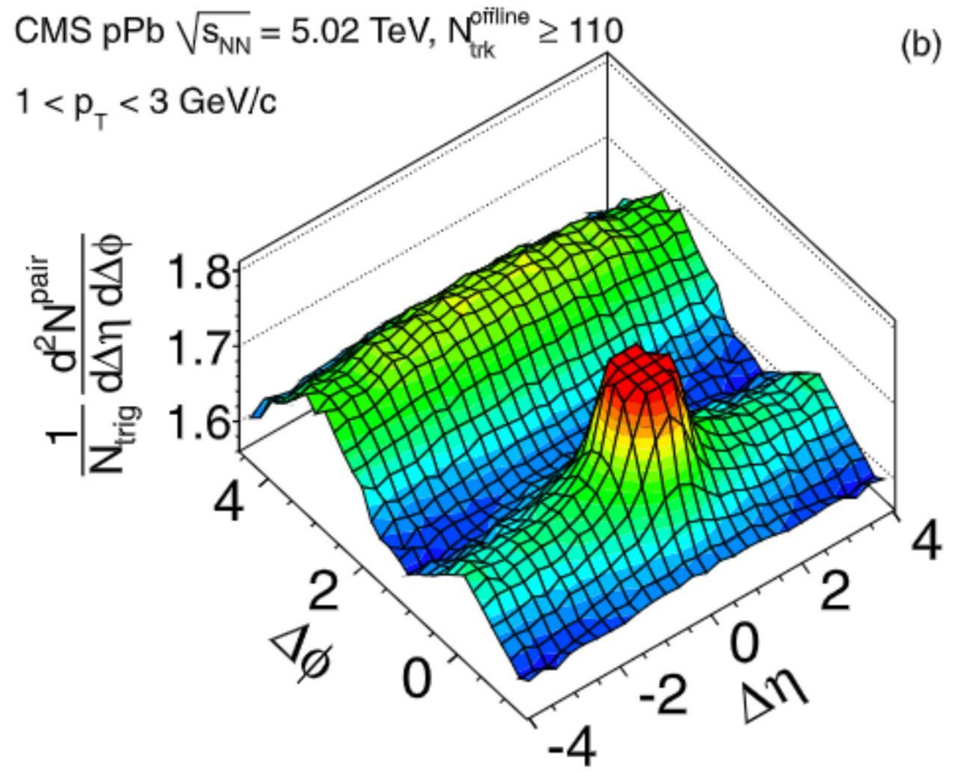
Search for flow in individual jets

PLB 724 (2013) 213
PLB 718 (2013) 795
PLB 765 (2017) 193

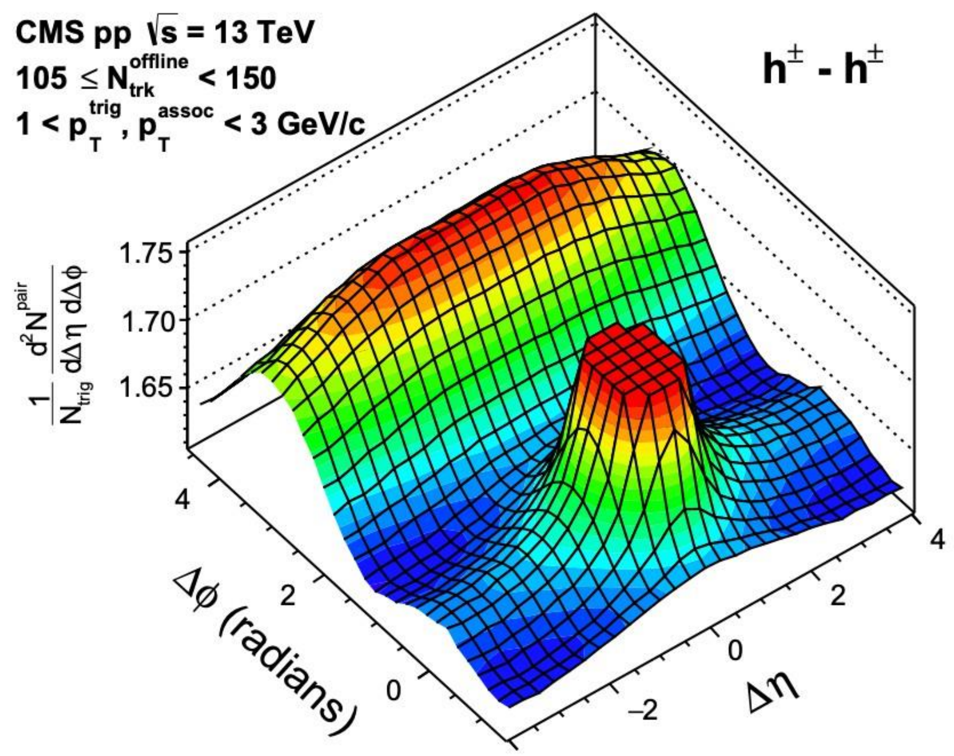
PbPb



pPb



High-multiplicity pp



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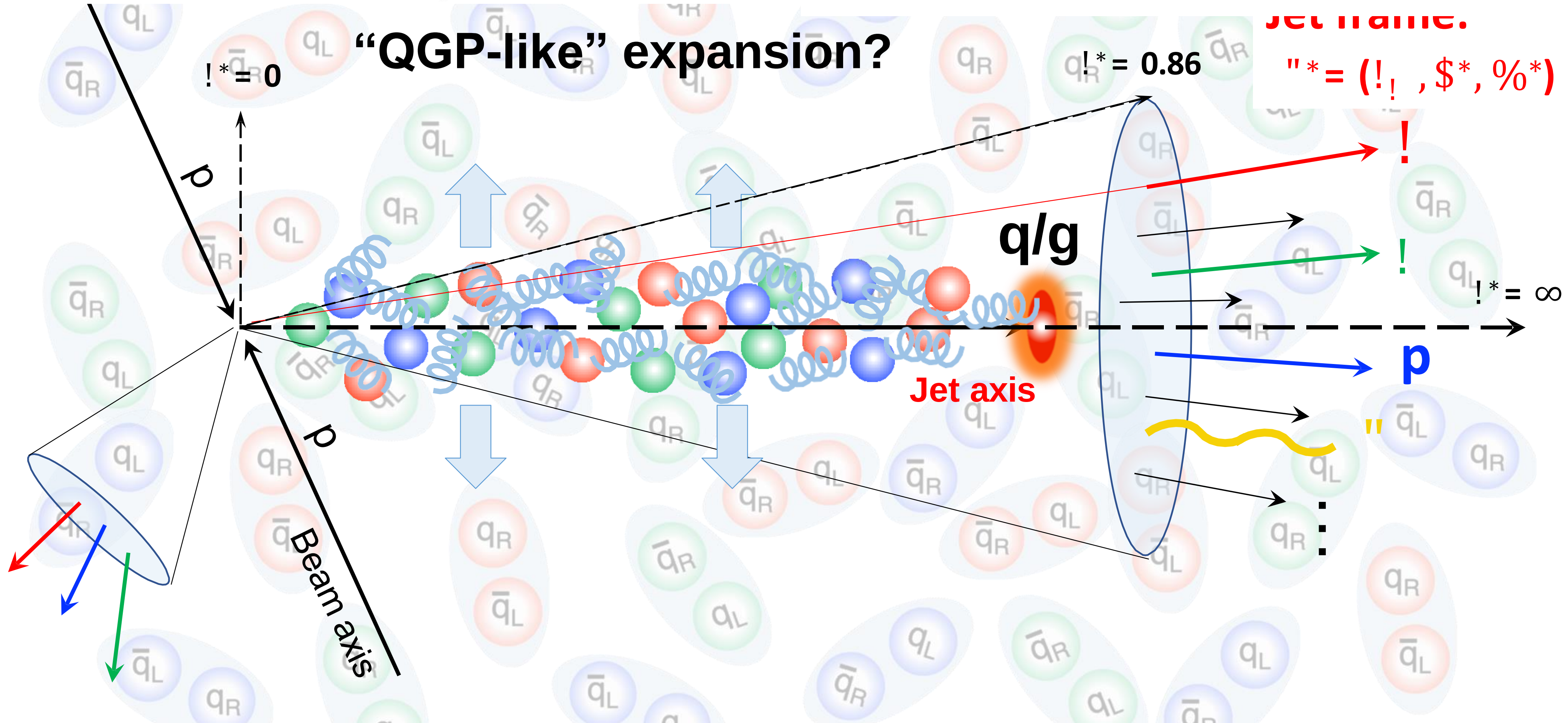
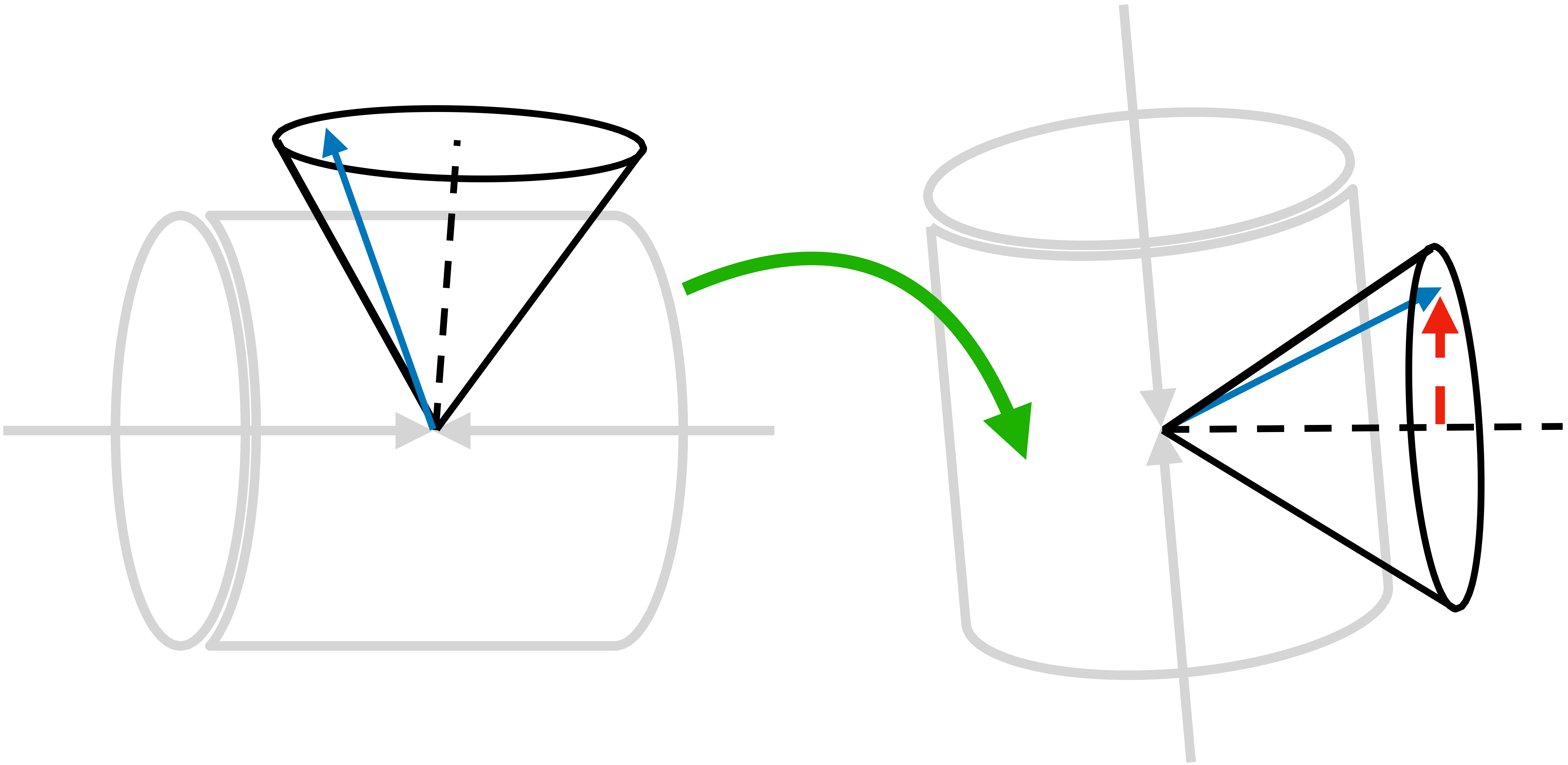


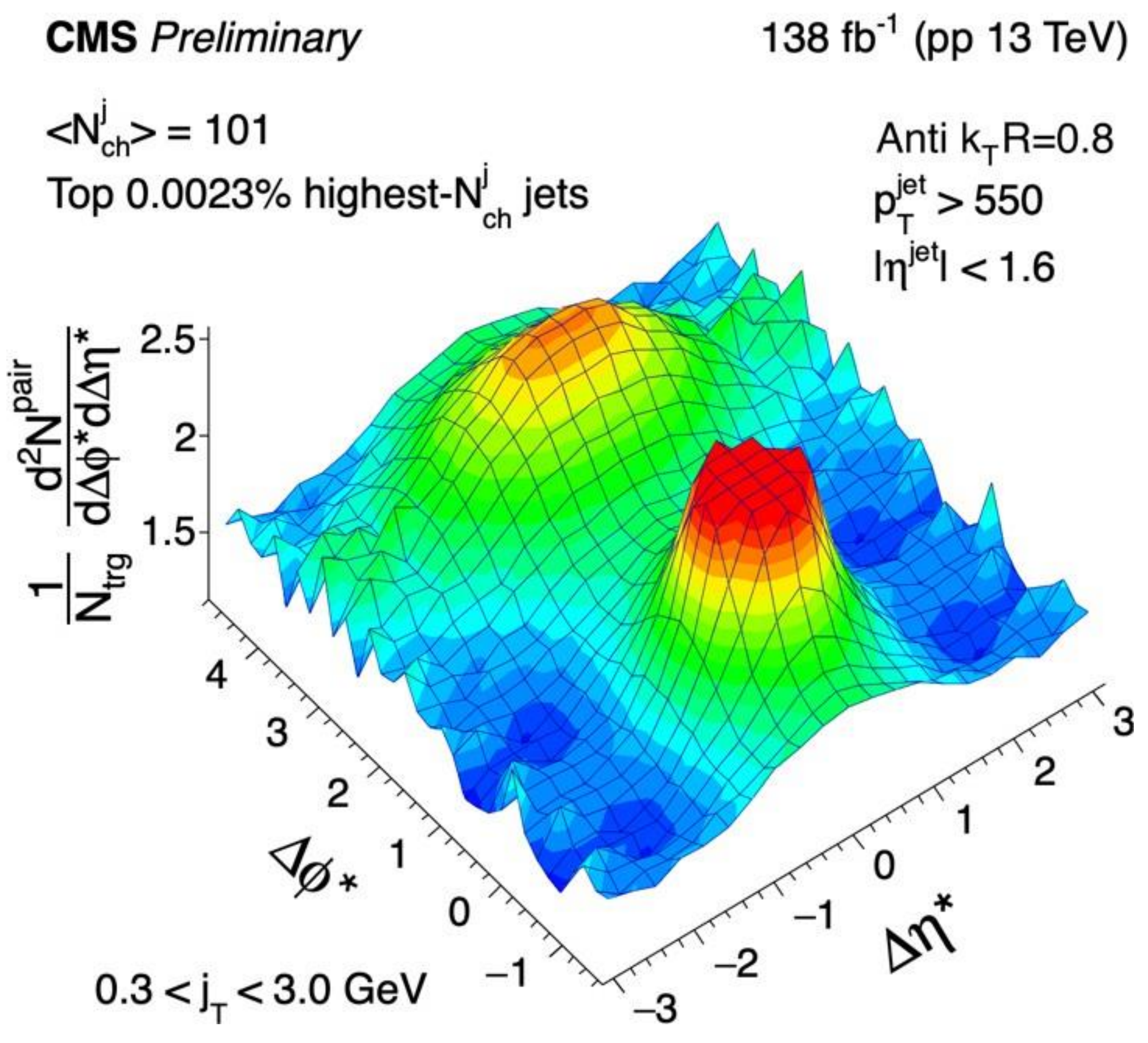
What if a QGP-like state is formed by a parton fragmenting to many particles?

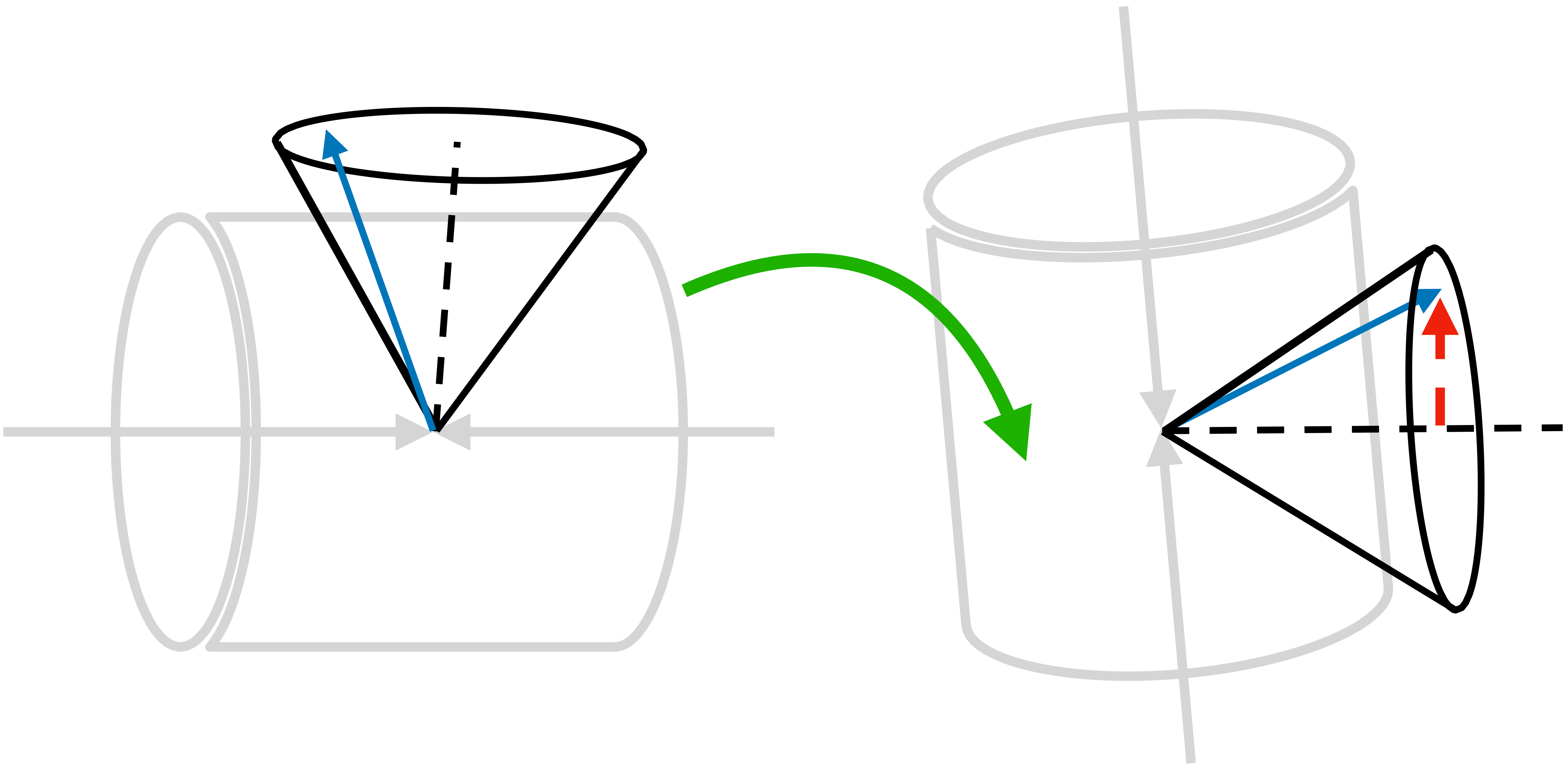
Rotated reference frame



- ***In rotated reference frame,*** **calculate two particle correlation using jet constituents**

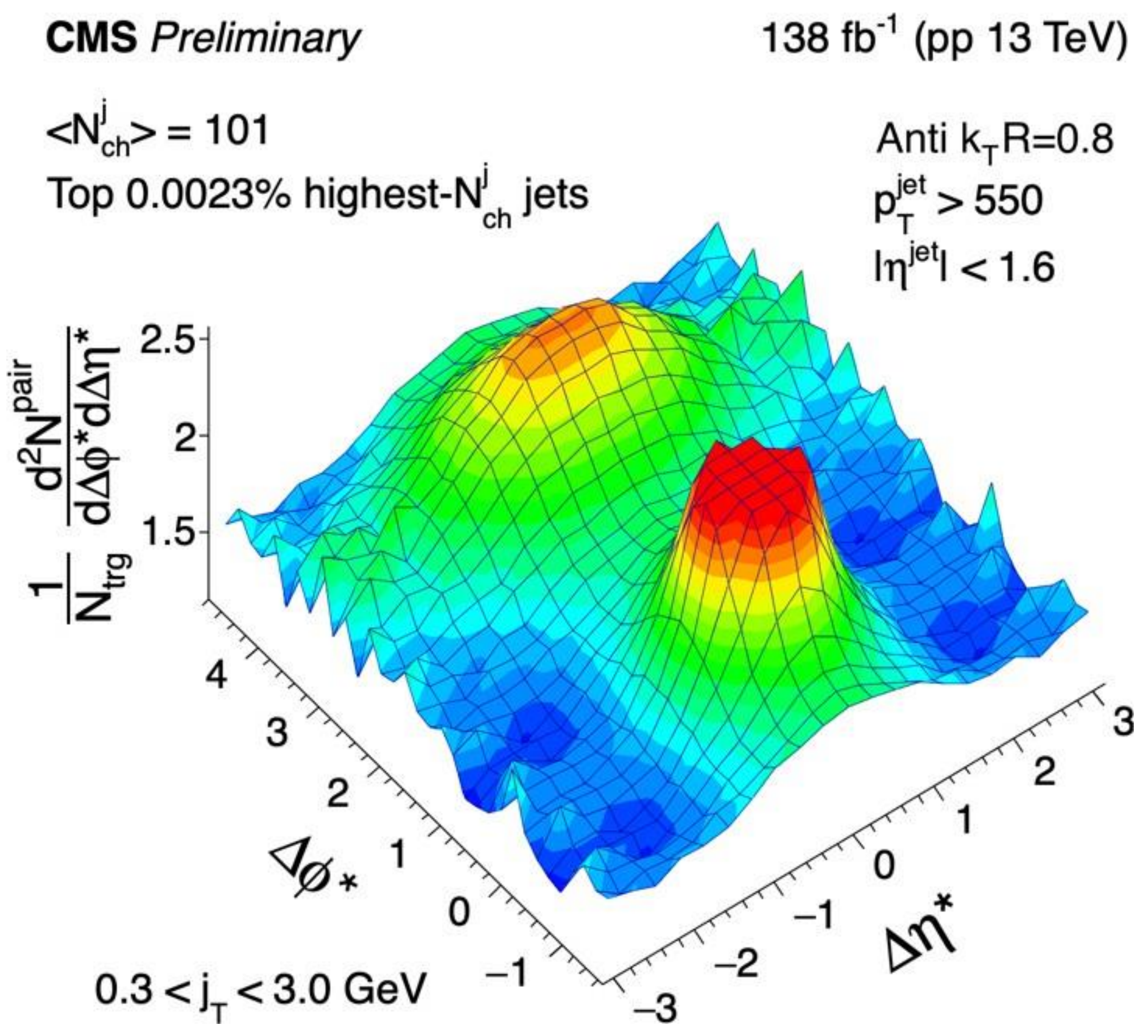
Two particle correlation

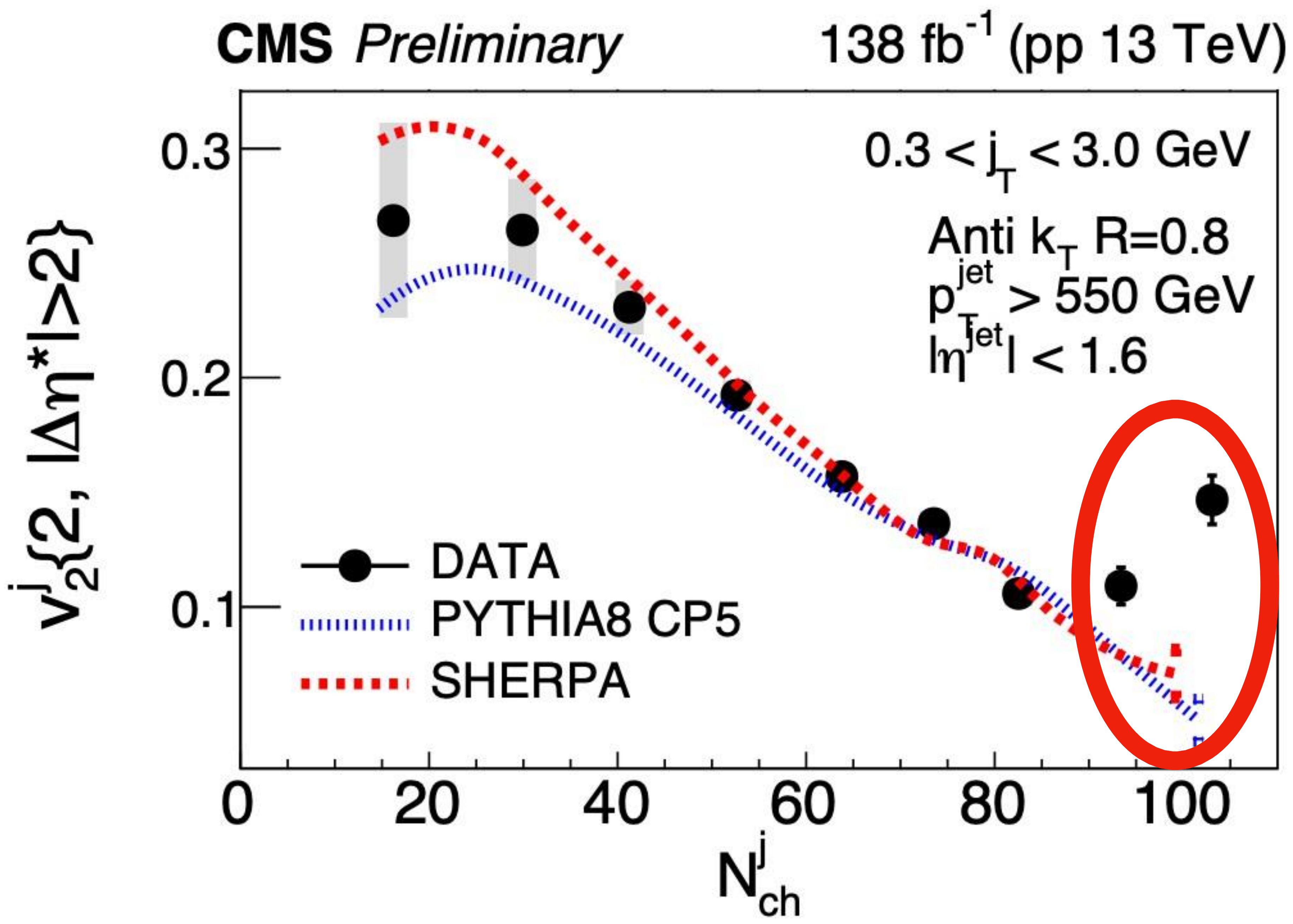




- *In rotated reference frame,* **calculate two particle correlation using jet constituents**

In-jet v_2 with respect to the jet axis



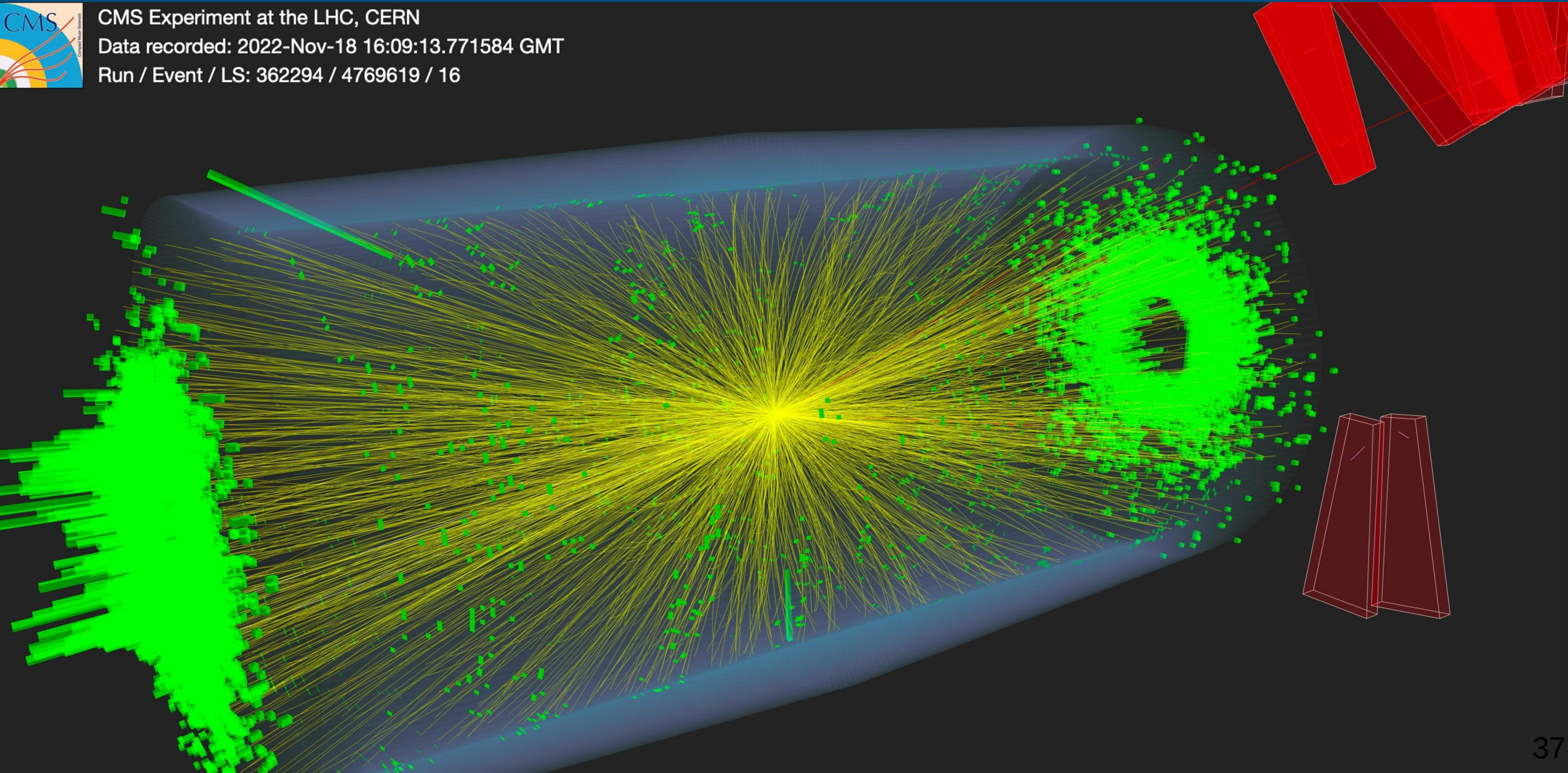


- *In rotated reference frame,* **calculate two particle correlation using jet constituents**
- **v_2 well described by MC for N_{ch}^{jet}<80**
- **Upward trend seen for N_{ch}^{jet}>80**
  - **Potential sign of collectivity in jets?**

CMS HIN-23-013 Submitted to PRL

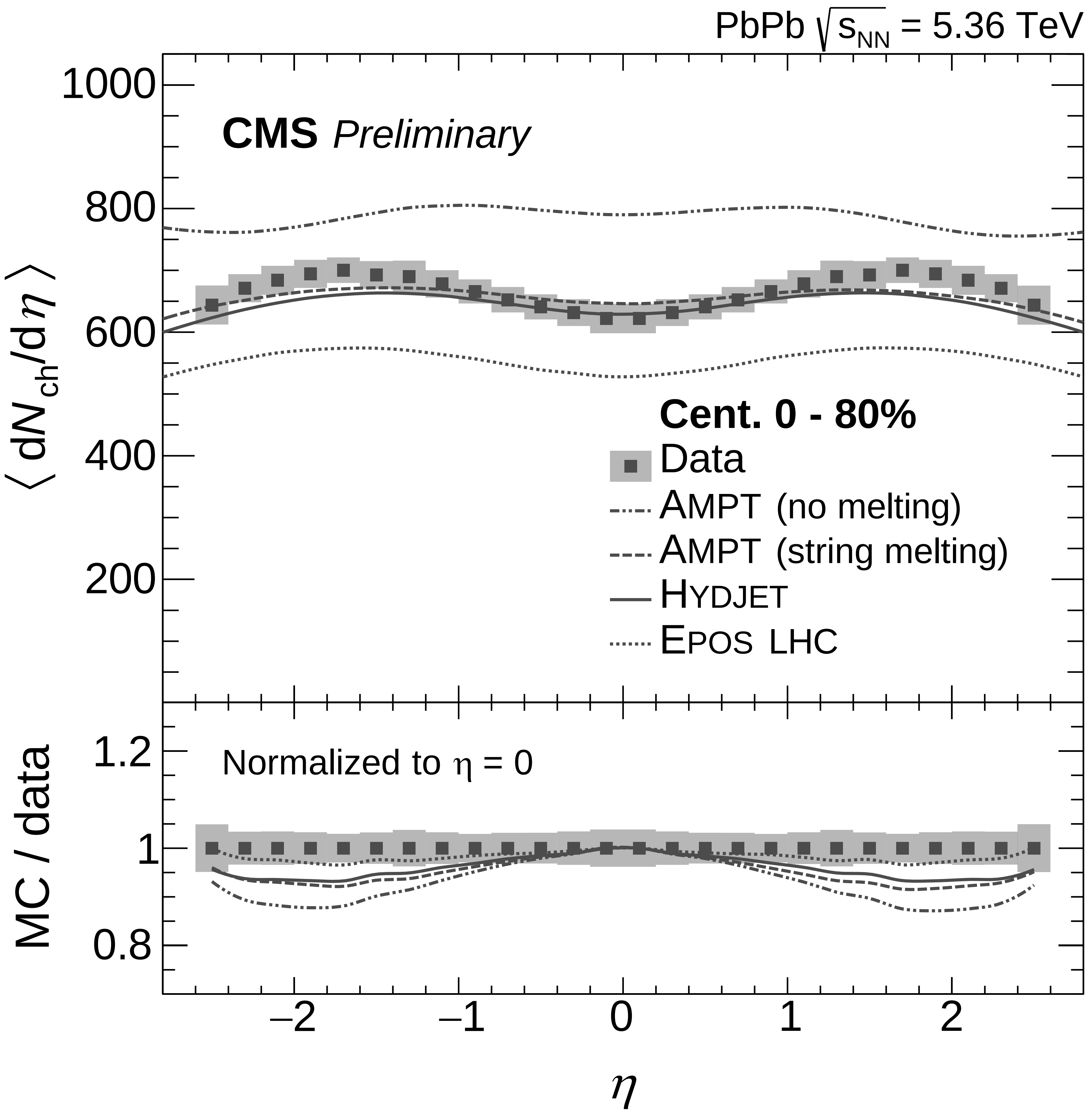
Looking Towards LHC Run 3 & 4

5.36 TeV PbPb Collisions!



First CMS HI Run 3 result - $dN_{ch}/d\eta$

- **5.36 TeV data from 2022 test run**
- **Challenging for MC generators to predict both magnitude and shape of $dN_{ch}/d\eta$**



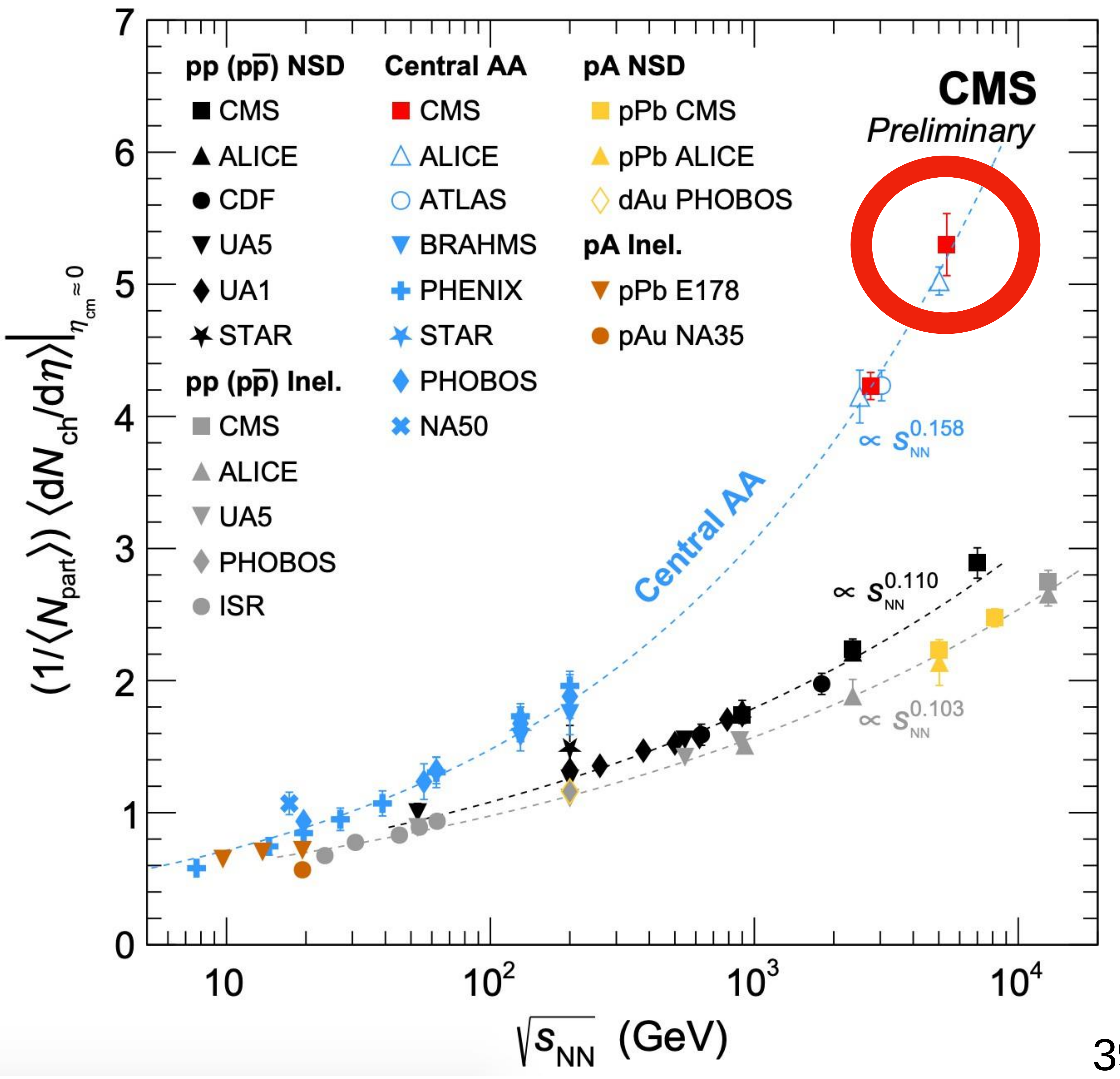
CMS PAS HIN-23-007

First CMS Run 3 result - $dN_{ch}/d\eta$

- **5.36 TeV data from 2022 test run**
- **Challenging for MC generators to predict both magnitude and shape of $dN_{ch}/d\eta$**

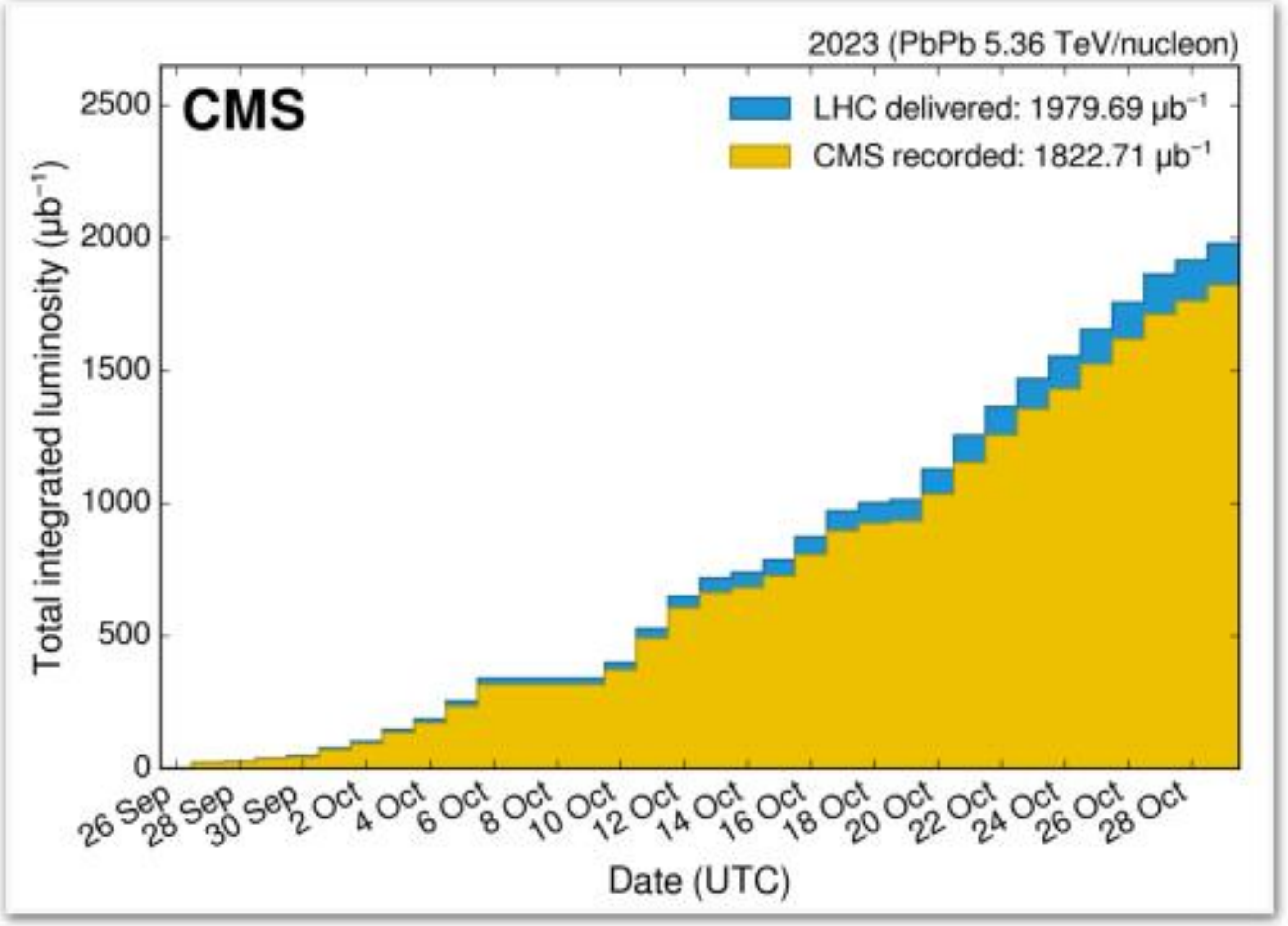
- $\sqrt{s_{NN}}$ **dependence consistent with power law calculated using lower energies**

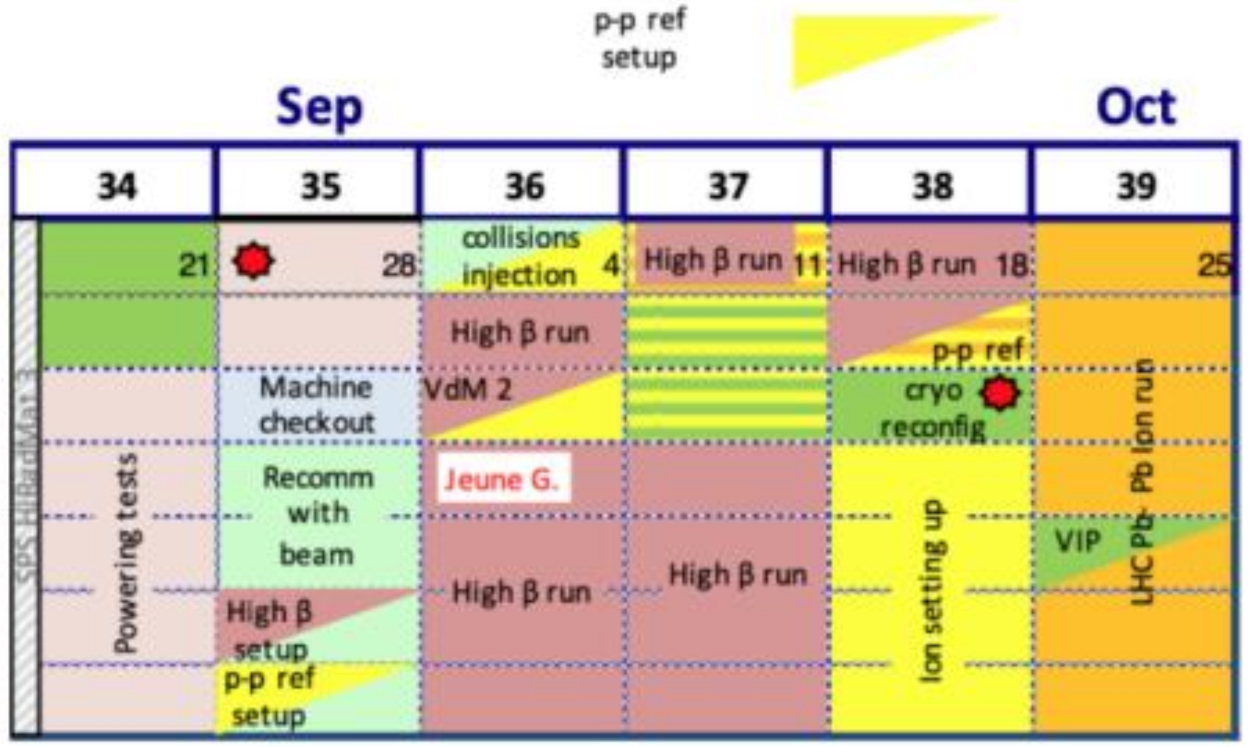
CMS PAS HIN-23-007

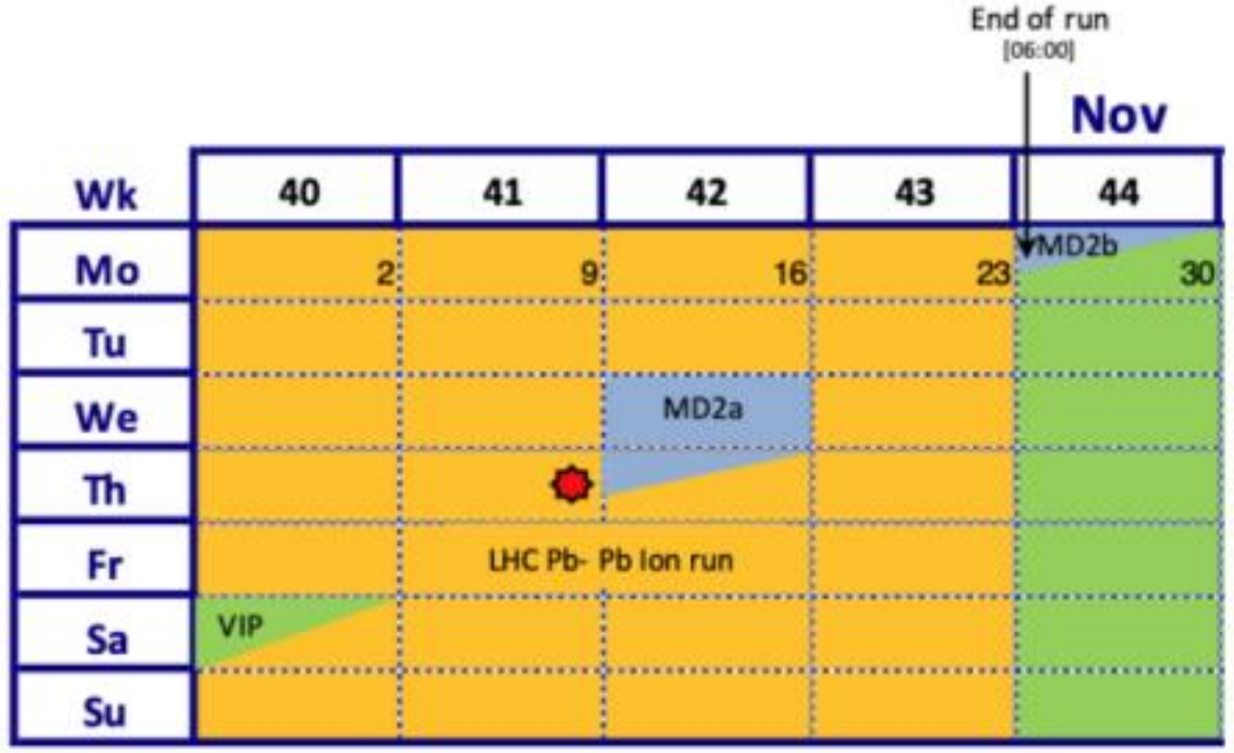


Heavy Ion

- **~5 weeks of PbPb data-taking @5.36 TeV in 2023**
  - ~1.98 nb^{-1} delivered by LHC (1.8 nb^{-1} in 2018)
  - ~1.82 nb^{-1} recorded by CMS (1.7 nb^{-1} in 1018)
  - efficiency by luminosity: ~91%
- **Smooth operation of the CMS detector**
- **Collected nearly all hadronic statistic**
  - ~17 billion Minimum Bias (MB) events
- **Also collected ~10 billion Ultra Peripheral Collisions (UPC) events**



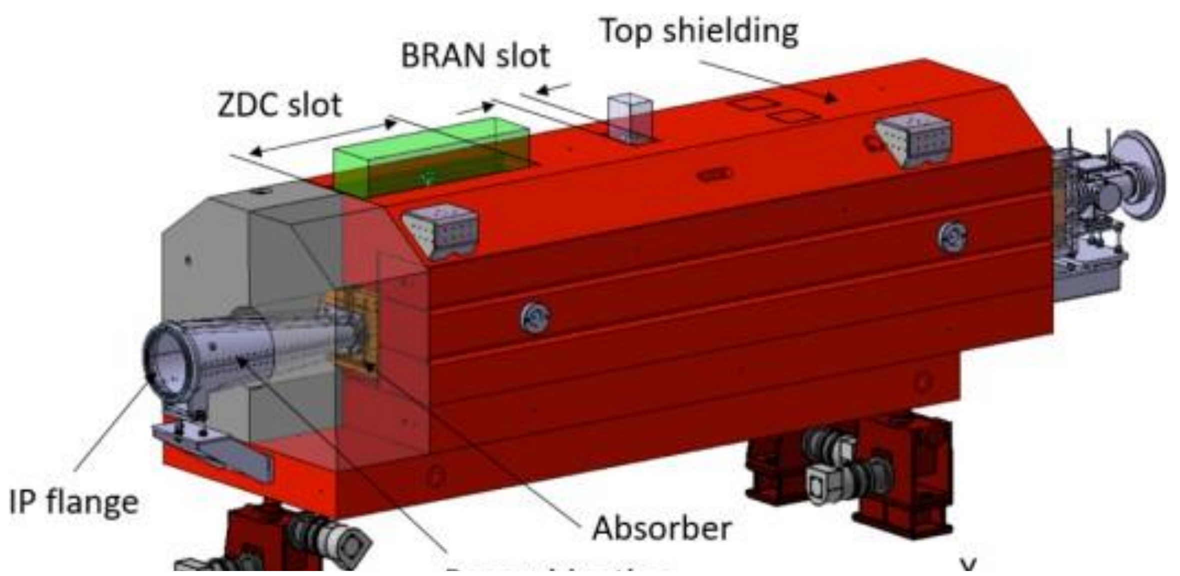


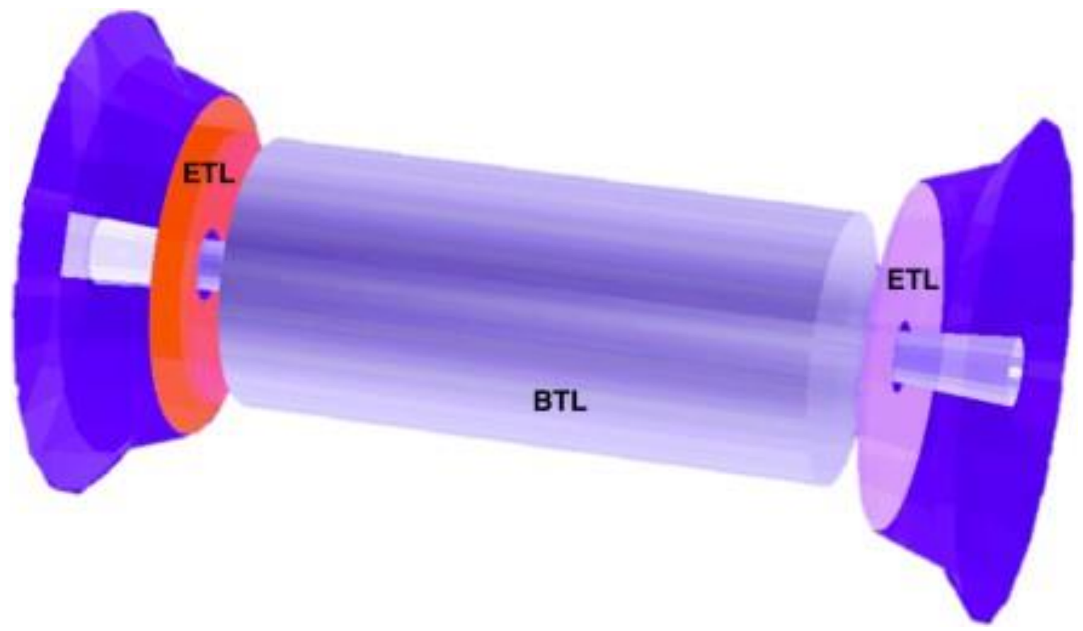


Ready for large 5.36 TeV data sets!

Run 4 upgrades

- **Adding PID and pileup rejection with MIP Timing Detector**
- **Research on rad-hard ZDCs for HL-LHC**





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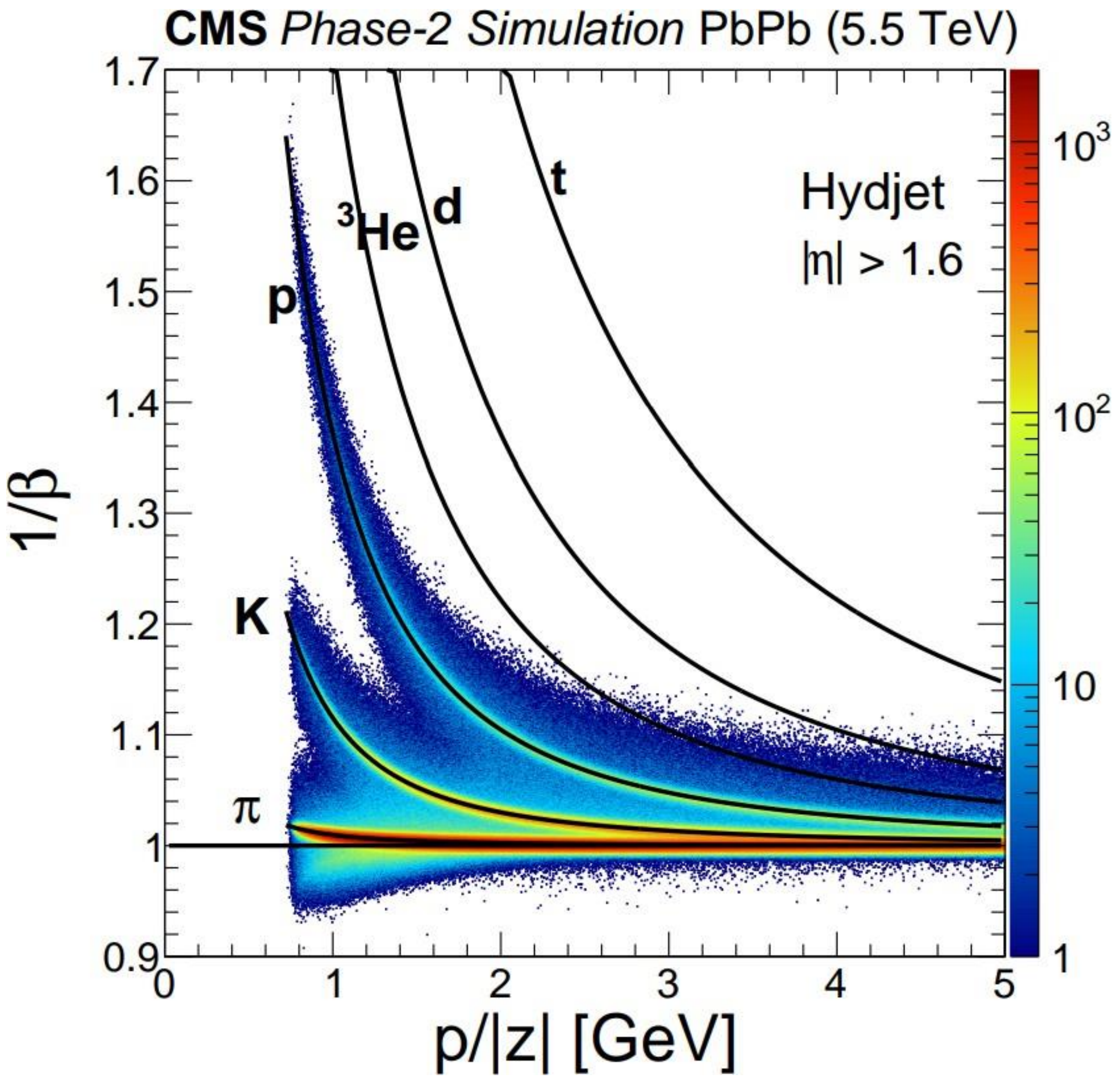
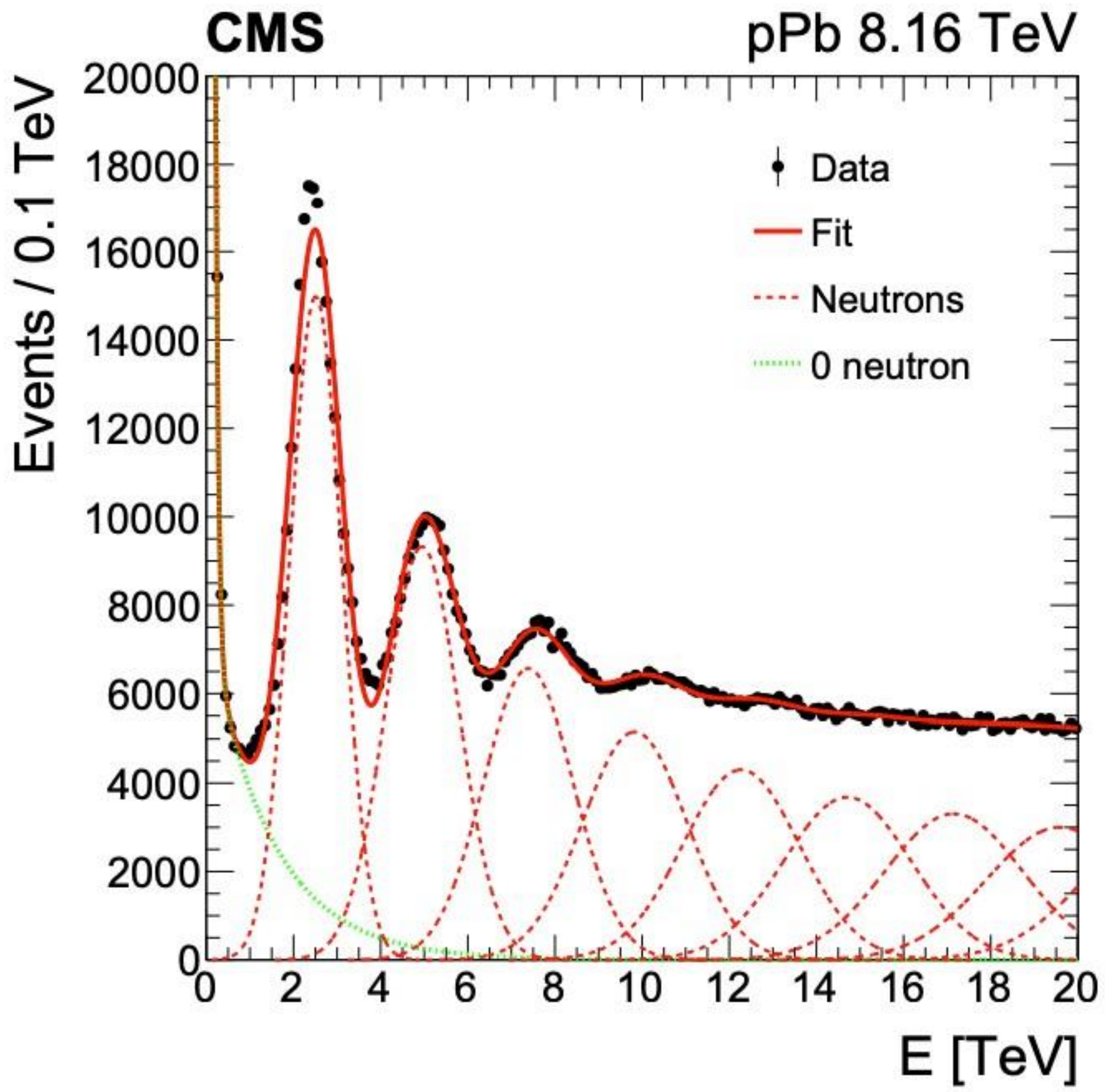
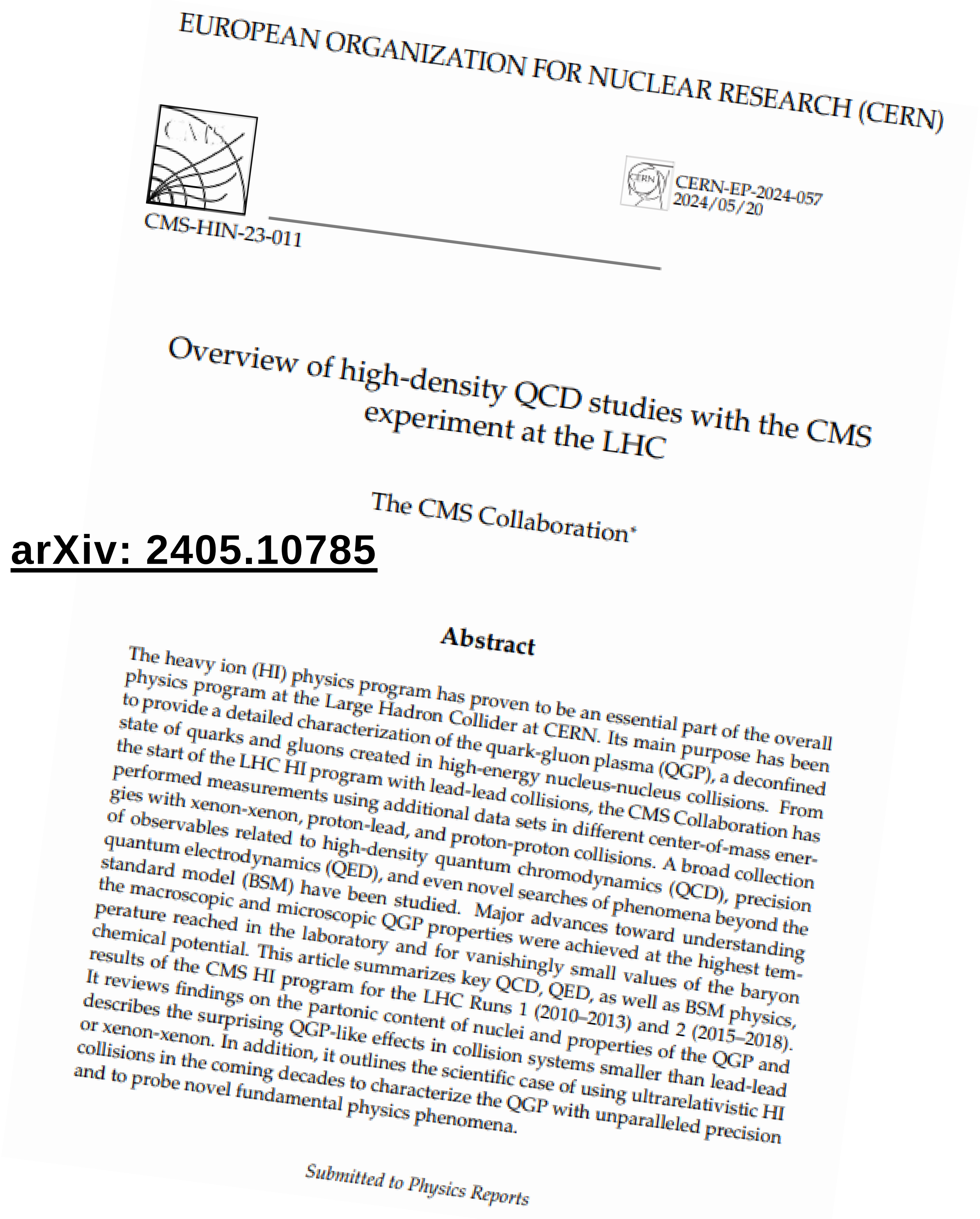




Celebration instead of Summary

- **Comprehensive overview of high-density QCD studies**
- **Since the start of the LHC HI program in all collision systems**
- **Major advances toward understanding the macroscopic and microscopic QGP properties**
- **Surprising QGP-like effects in smaller systems**
- **Precision QED as well as BSM physics searches**
- **Strengthens the scientific case of using HI collisions in the coming decade**


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS-HIN-23-011

CERN-EP-2024-057
2024/05/20

Overview of high-density QCD studies with the CMS experiment at the LHC

The CMS Collaboration*

Abstract

The heavy ion (HI) physics program has proven to be an essential part of the overall physics program at the Large Hadron Collider at CERN. Its main purpose has been to provide a detailed characterization of the quark-gluon plasma (QGP), a deconfined state of quarks and gluons created in high-energy nucleus-nucleus collisions. From the start of the LHC HI program with lead-lead collisions, the CMS Collaboration has performed measurements using additional data sets in different center-of-mass energies with xenon-xenon, proton-lead, and proton-proton collisions. A broad collection of observables related to high-density quantum chromodynamics (QCD), precision quantum electrodynamics (QED), and even novel searches of phenomena beyond the standard model (BSM) have been studied. Major advances toward understanding the macroscopic and microscopic QGP properties were achieved at the highest temperature reached in the laboratory and for vanishingly small values of the baryon chemical potential. This article summarizes key QCD, QED, as well as BSM physics, results of the CMS HI program for the LHC Runs 1 (2010–2013) and 2 (2015–2018). It reviews findings on the partonic content of nuclei and properties of the QGP and describes the surprising QGP-like effects in collision systems smaller than lead-lead or xenon-xenon. In addition, it outlines the scientific case of using ultrarelativistic HI collisions in the coming decades to characterize the QGP with unparalleled precision and to probe novel fundamental physics phenomena.

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