Final state interactions in heavy ion collisions with CMS and at the EIC

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(UIC)

Heavy Ions in the
EIC Era Workshop

August 20, 2024

Institute for Nuclear Theory
Seattle, Washington

Introduction

- Heavy ion collisions
  - Produce QGP
    - Sensitive to the initial state
    - Complex hydrodynamic-like behavior
    - Jet quenching
  - Study hadronization and hadron structure
- Small systems studies (pp, pPb data)
- Quasi-real photons for UPC studies

Introduction

- Heavy ion collisions
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    - Complex hydrodynamic-like behavior
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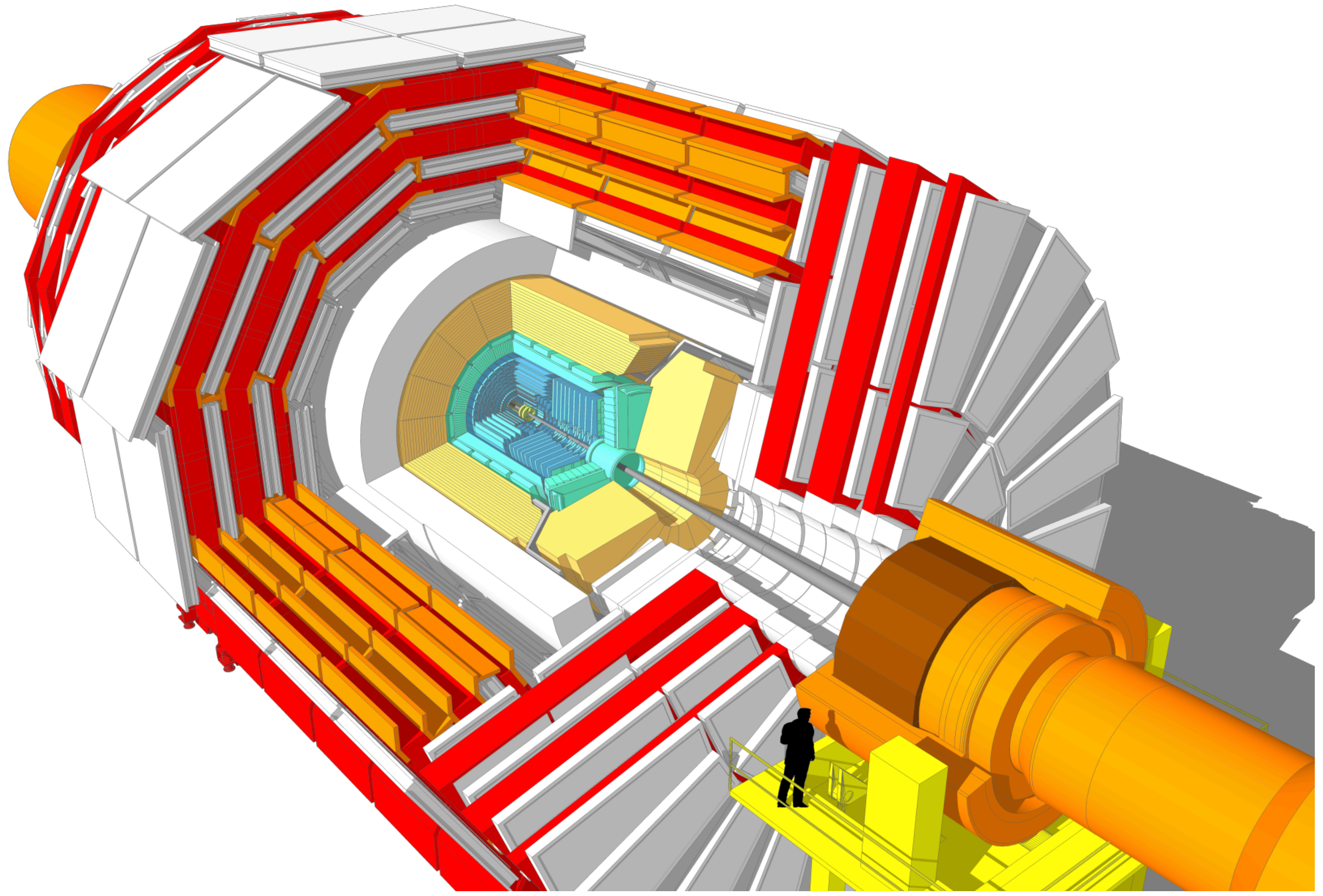
- Quasi-real photons for UPC studies

What will the CMS physics program look like in the future and how does it synergize with the EIC?

LHC and EIC timeline

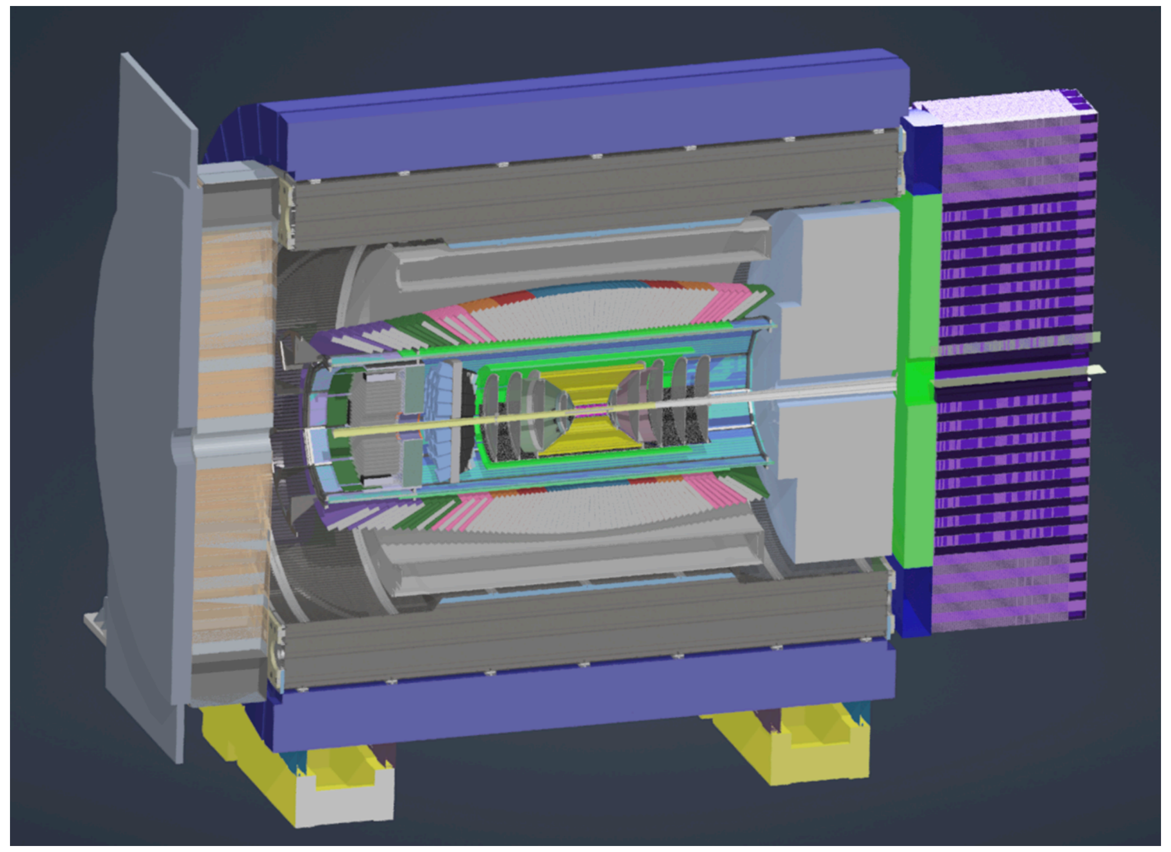
LHC Run 3

Fast detector+large acceptance
Full calorimetry, limited PID



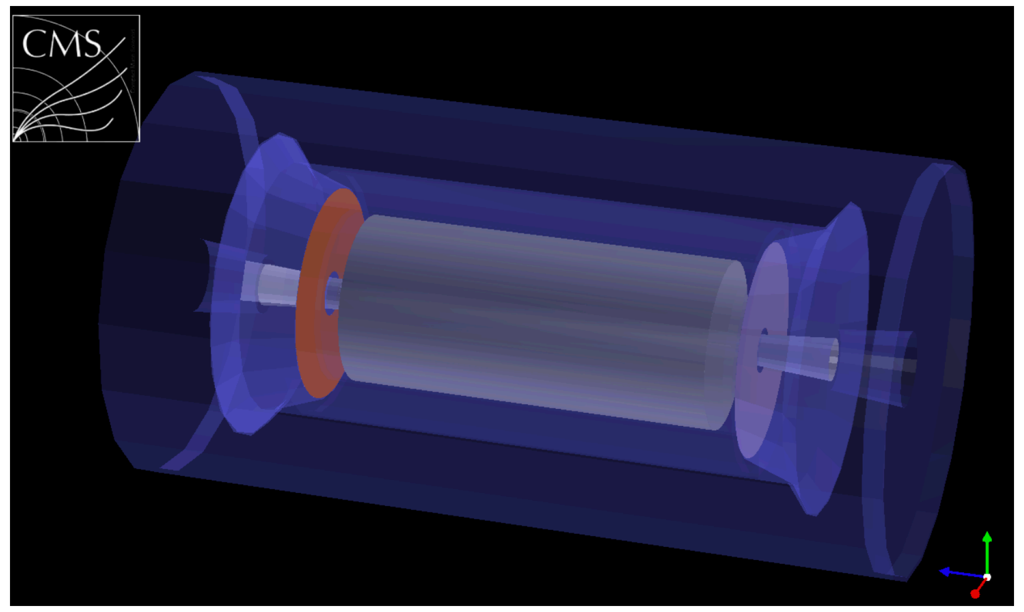
Electron-Ion Collider

ePIC



High-Luminosity LHC

CMS MTD



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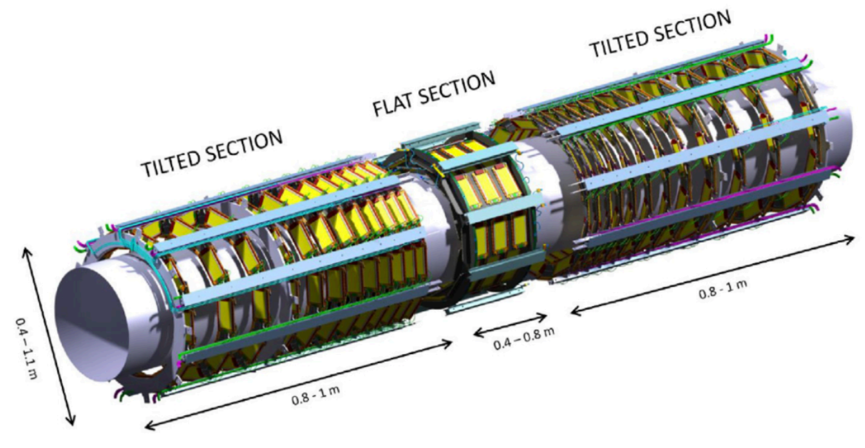
CMS Phase 2 tracker



Xe Pb

2023 ‘24 ‘25 ‘26 ‘27 ‘28 ‘29 ‘30 ‘31 ‘32 ‘33 ‘34 ‘35 2036

pp, PbPb, pO, OO

EIC (eA, ep)

R&D, Design

Construction

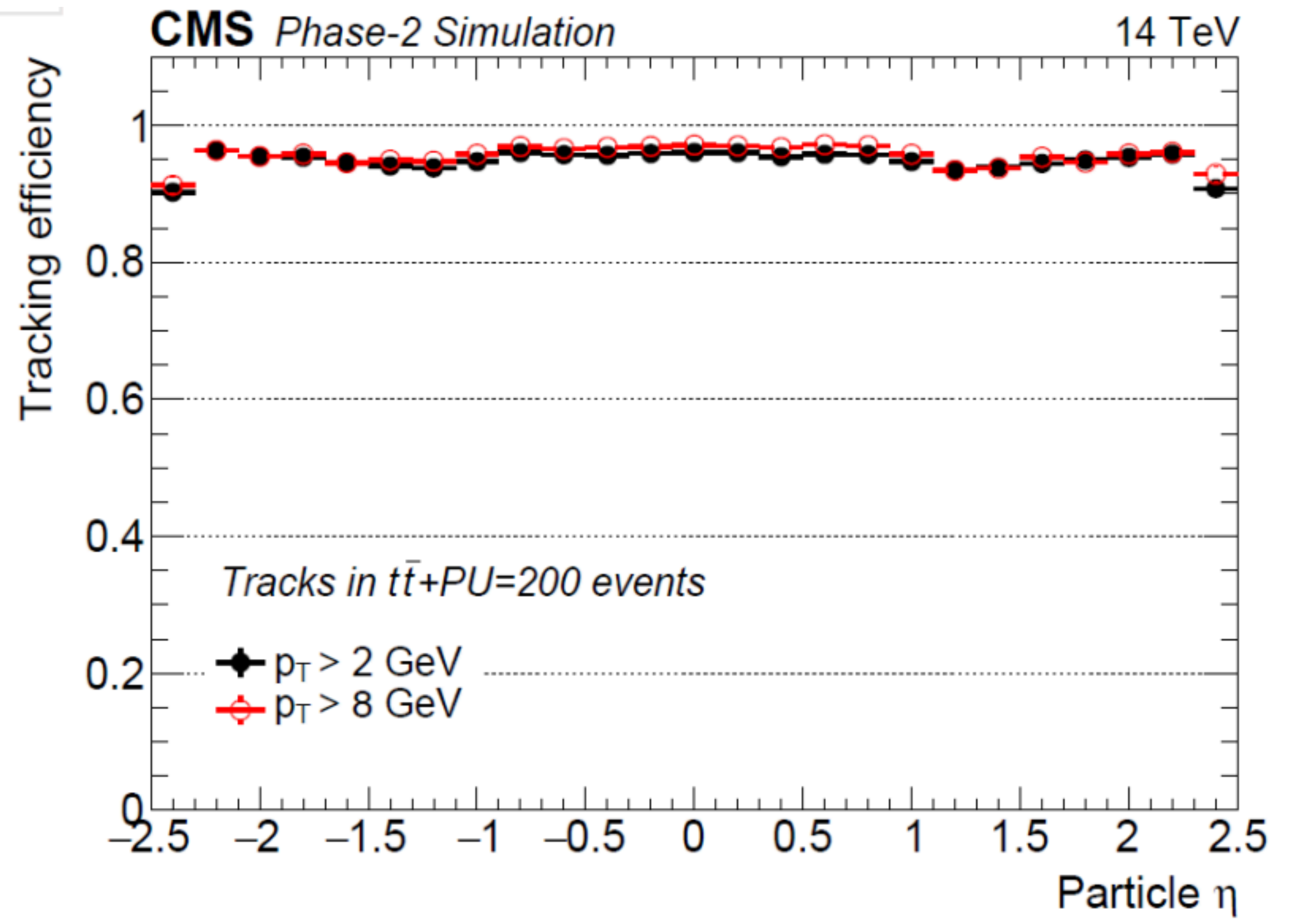
Run 4 (pp/pPb/PbPb)

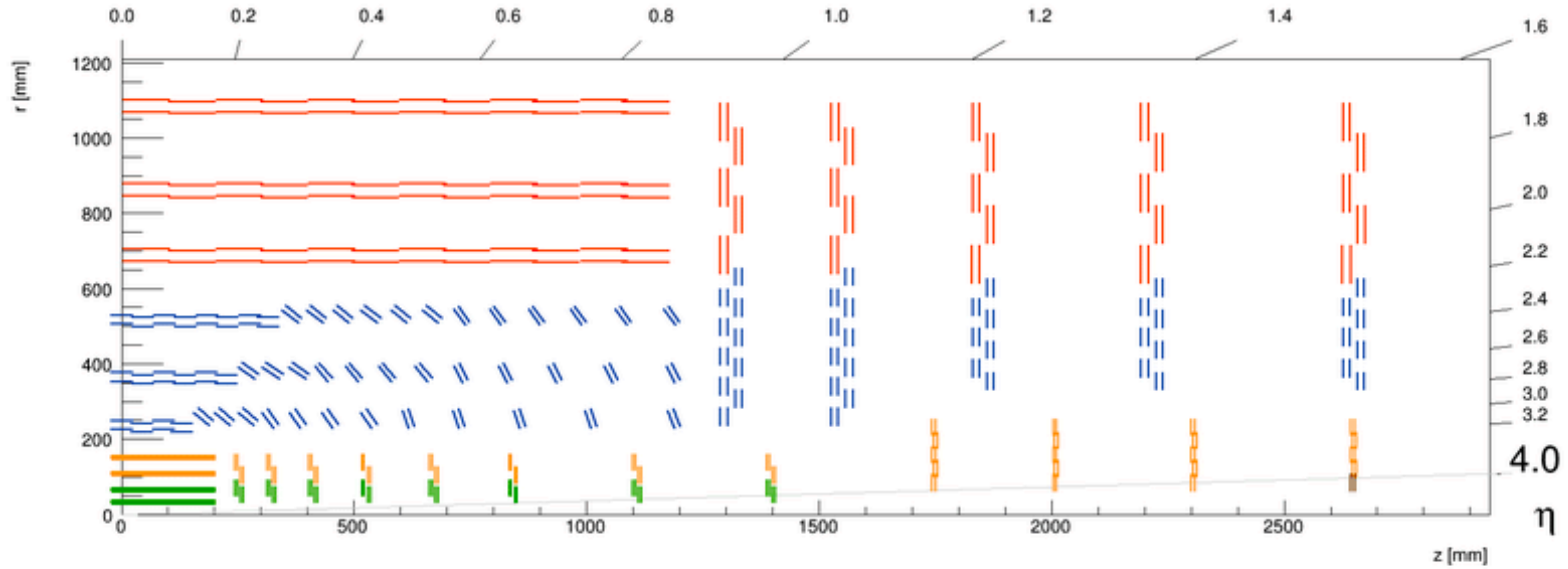
Run 5 (pA,AA)

CMS Phase 2 Tracker

CMS-TDR-014

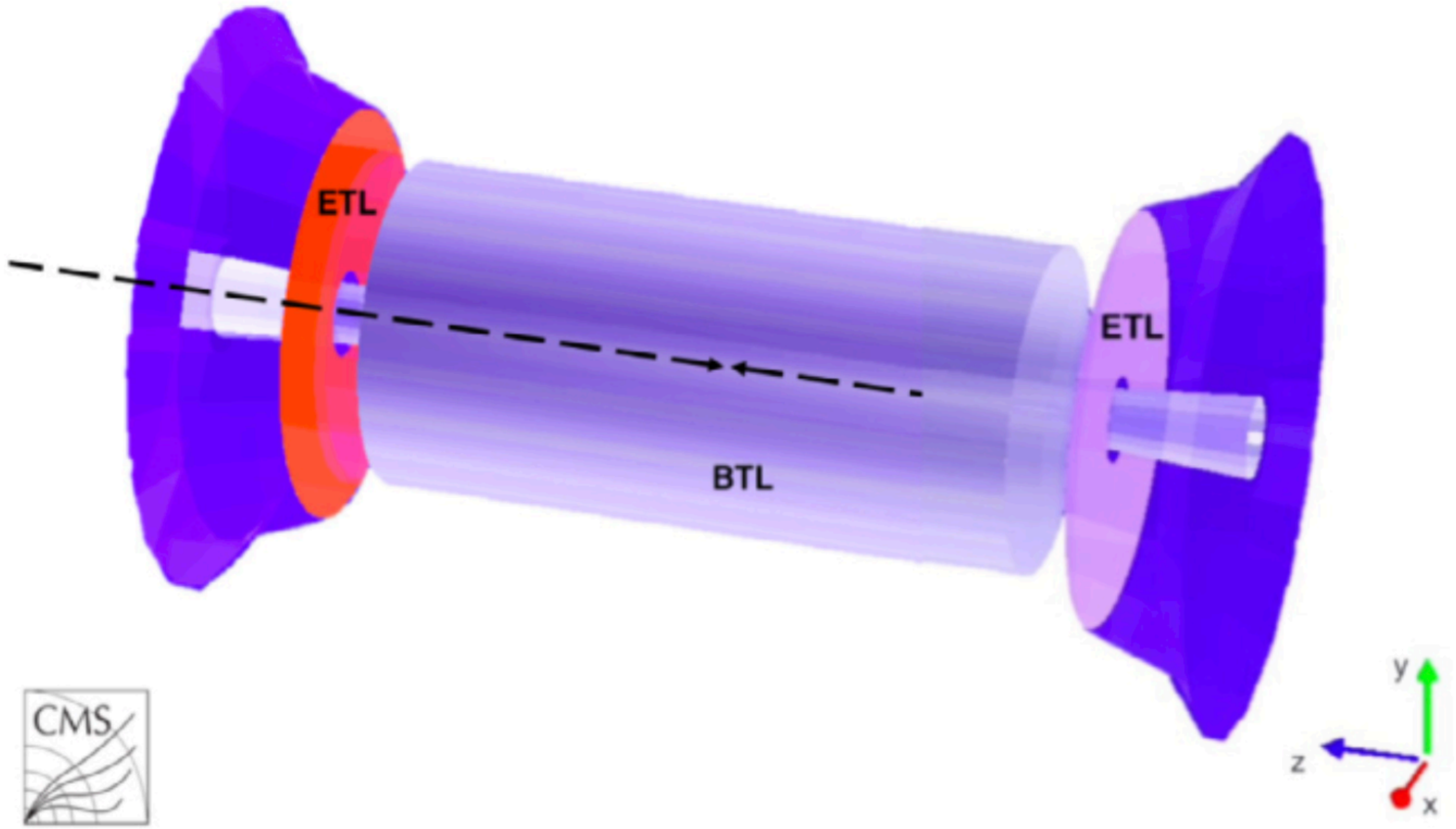
- **Lower material budget**
- $|\eta| < 4$ **coverage (currently 2.4)**
- **Better handling of barrel-end cap transition**
  - **Projective orientation of modules**
- **90% efficiency at 200 pileup in pp**
  - **Occupancy conditions similar to PbPb**
- **Better p_T and d_0 resolution, multiplicity determination**

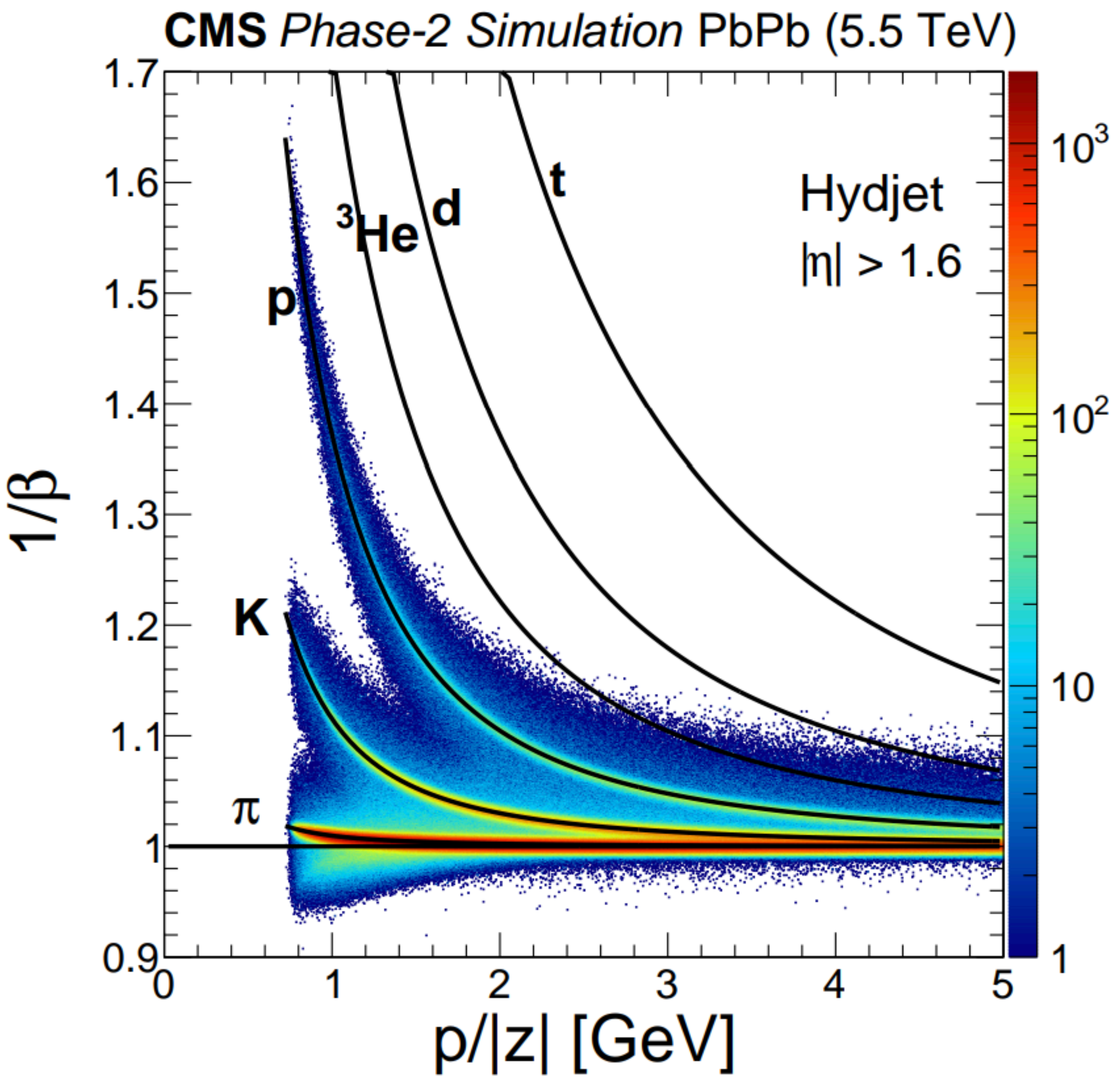




CMS MTD

- **Timing detector installed during Run 4**
- **Pileup mitigation in high-lumi pp**
- **New particle identification capabilities**
  - **Better reconstruction of strangeness, better heavy flavor, light nuclei, etc.**

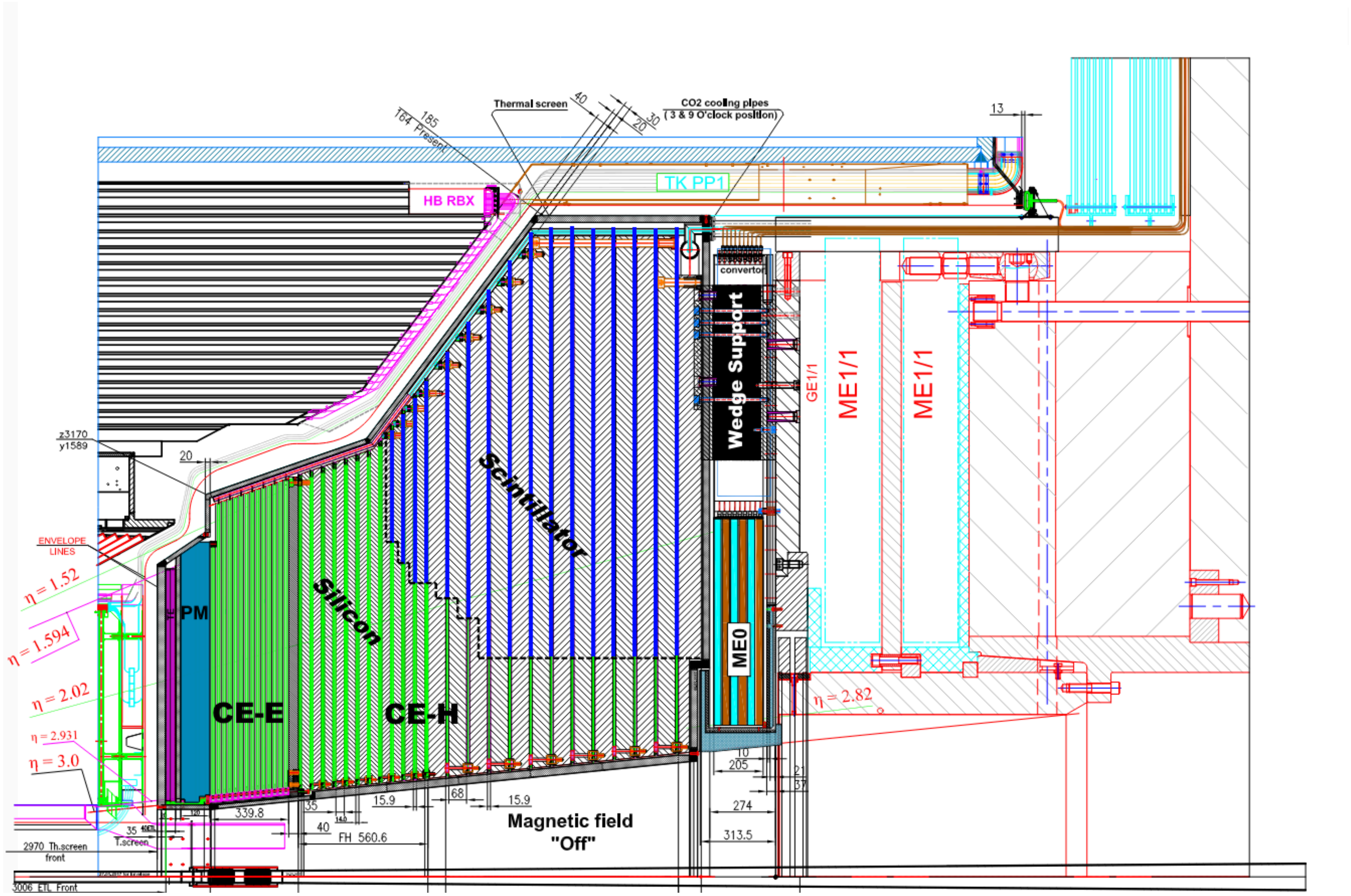




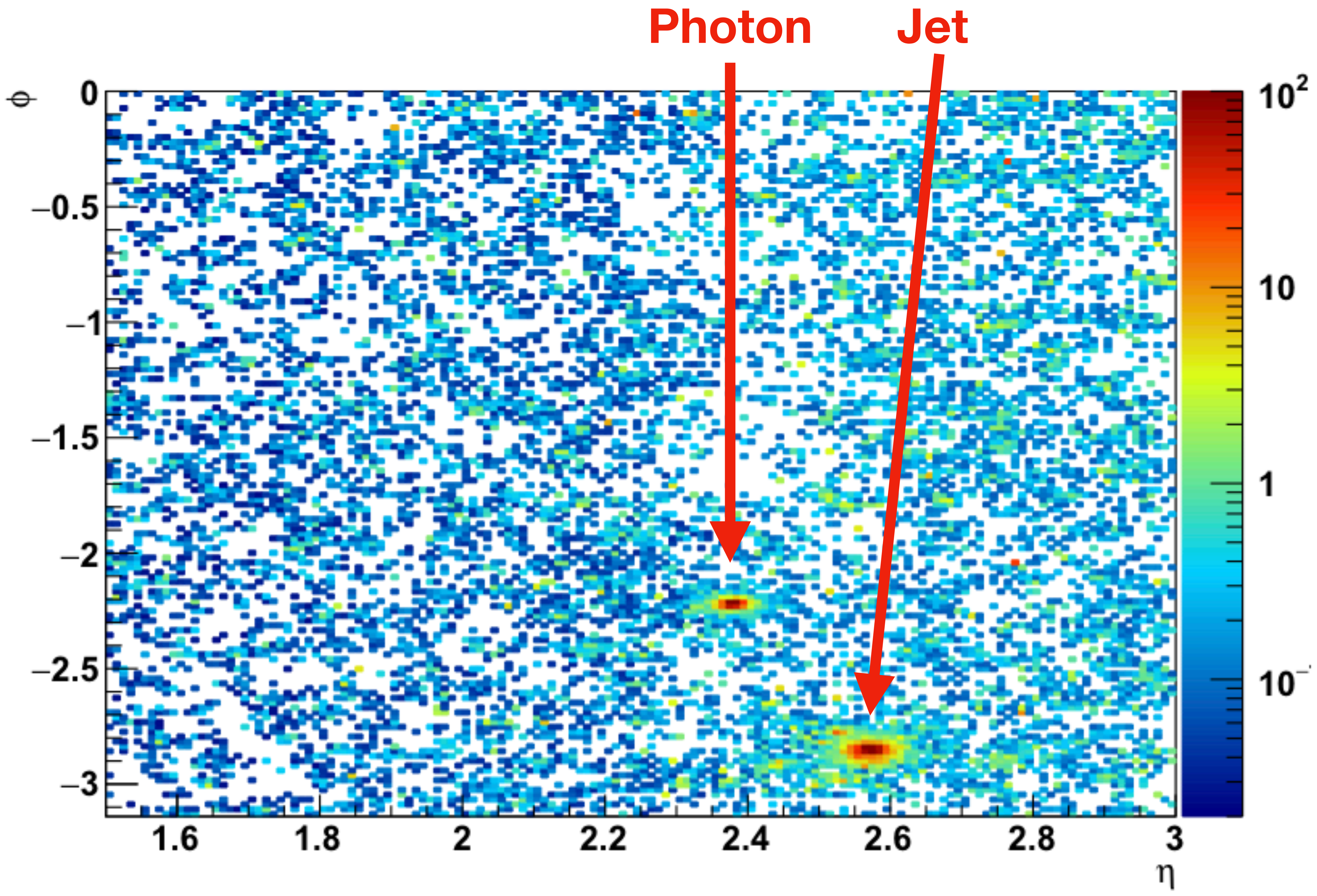
CMS-TDR-020

CMS Phase-2 Calorimetry (HGCAL)

- **Overhaul of endcap calorimetry with high-granularity calorimeters**
- **Exquisite reconstruction of full particle shower - improve single particle separation**
  - **Fully 4D - longitudinal and timing information also included**



CMS-TDR-019

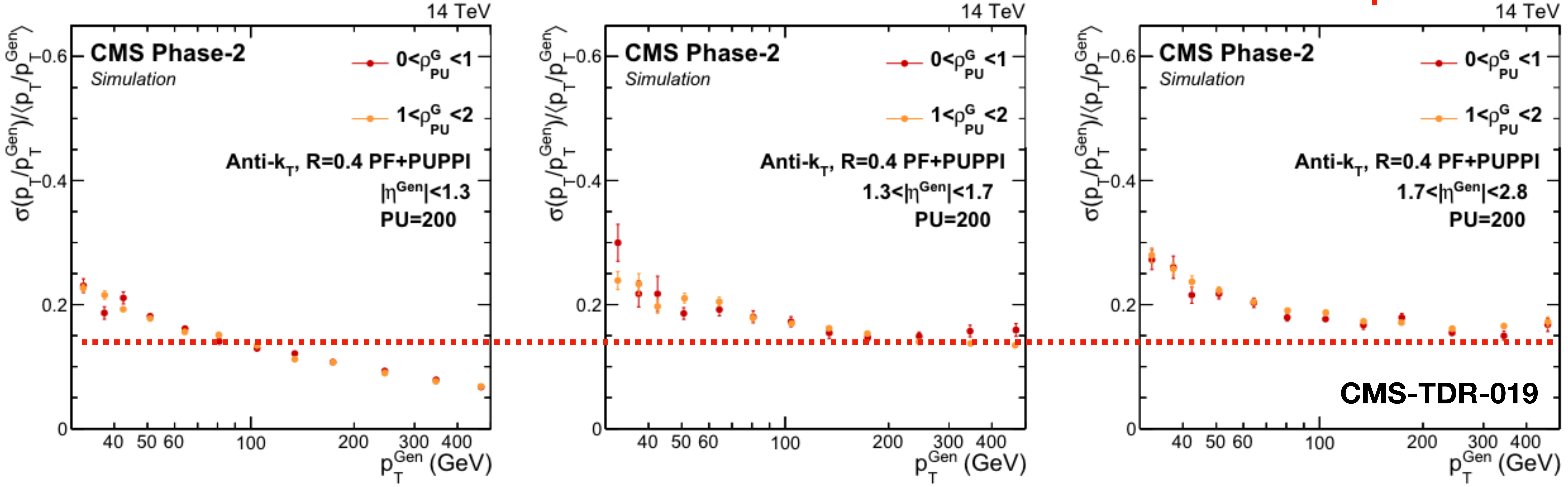


CMS Phase-2 Calorimetry (HGCAL)

- Overhaul of endcap calorimetry with high-granularity calorimeters
- Exquisite reconstruction of full particle shower - improve single particle separation
  - Fully 4D - longitudinal and timing information also included
- Jet resolutions in endcaps significantly improved
  - Comparable to barrel performance at lower p_T

Barrel

Endcaps

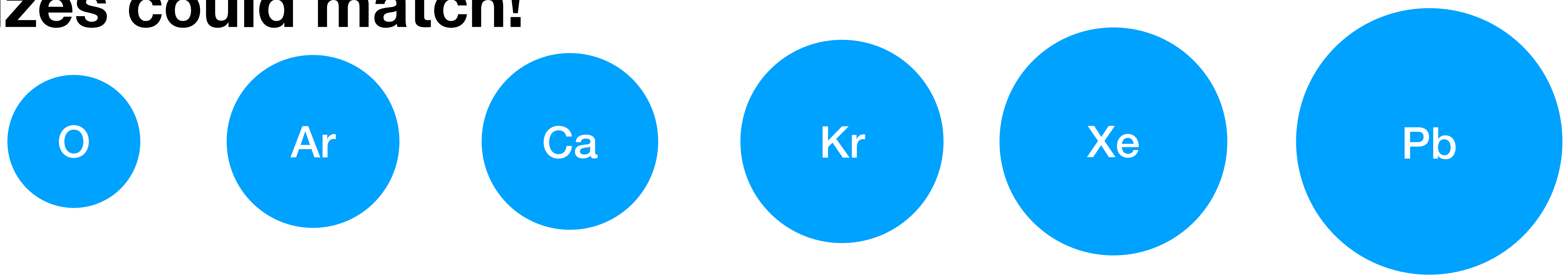


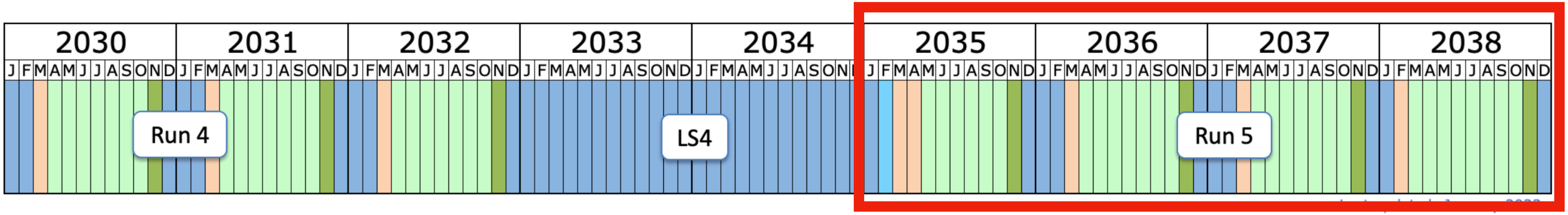
LHC Run 5 and Beyond

- **Many different ion species proposed**
- **Higher energy**
- **Higher nucleon-nucleon luminosities**
  - **More jets, heavy flavor, EWK bosons**
- **Enables LHC 'system size scan'**

- **Taking data concurrently with EIC!**
  - **pA system sizes could match!**

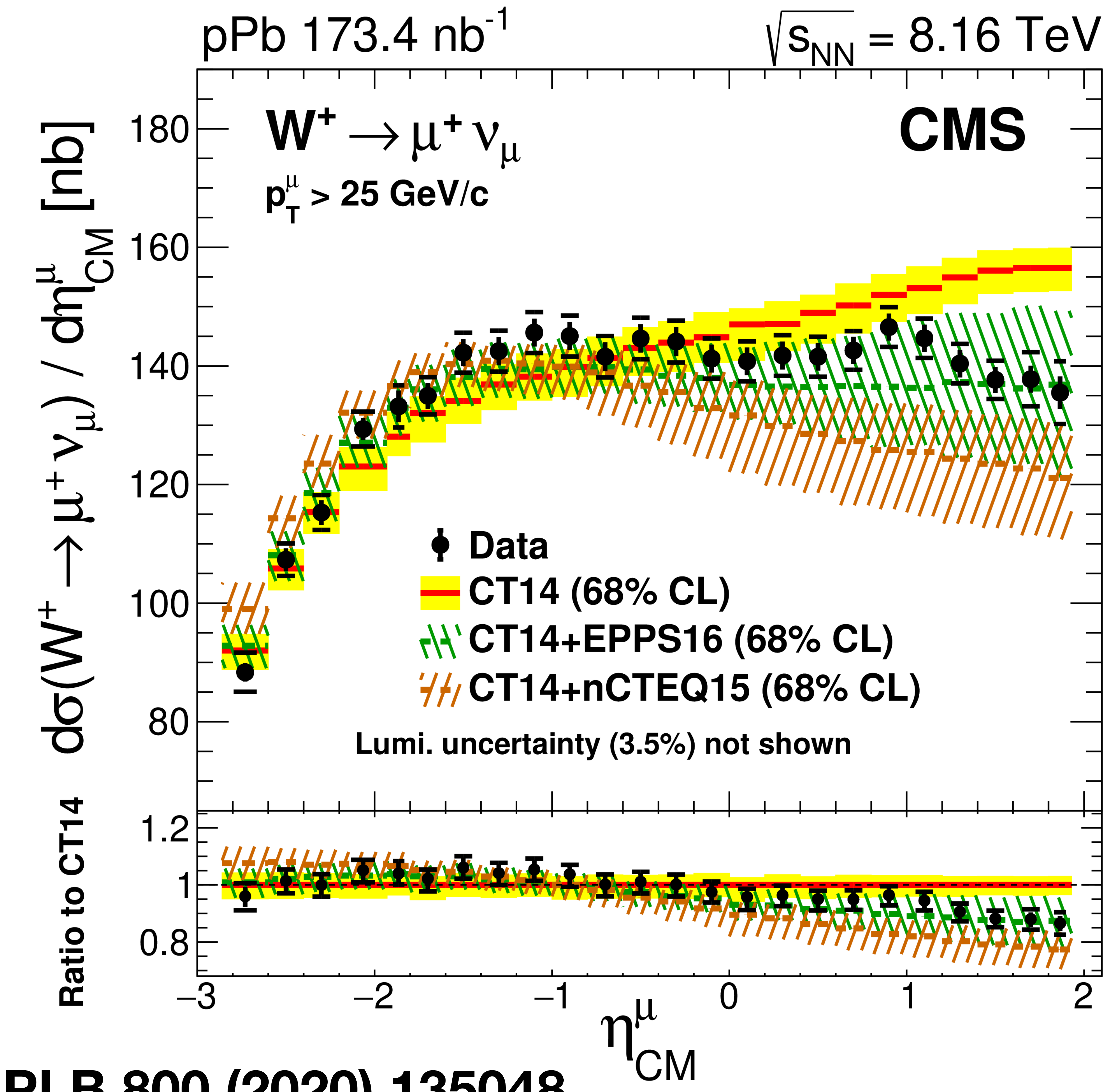
	$^{16}O^{8+}$	$^{40}Ar^{18+}$	$^{40}Ca^{20+}$	$^{78}Kr^{36+}$	$^{129}Xe^{54+}$	$^{208}Pb^{82+}$
γ	3760.	3390.	3760.	3470.	3150.	2960.
$\sqrt{s_{NN}}$/TeV	7.	6.3	7.	6.46	5.86	5.52
σ_{had}/b	1.41	2.6	2.6	4.06	5.67	7.8
σ_{BFPP}/b	2.36×10^{-5}	0.00688	0.0144	0.88	15.	280.
σ_{EMD}/b	0.0738	1.24	1.57	12.2	51.8	220.
σ_{tot}/b	1.48	3.85	4.18	17.1	72.5	508.
N_b	6.24×10^9	1.85×10^9	1.58×10^9	6.53×10^8	3.56×10^8	1.9×10^8
ϵ_{xn}/μm	2.	1.8	2.	1.85	1.67	1.58
f_{IBS}/(m Hz)	0.0662	0.0894	0.105	0.13	0.144	0.167
W_b/MJ	68.9	45.9	43.6	32.5	26.5	21.5
$L_{AA0}/cm^{-2}s^{-1}$	1.46×10^{31}	1.29×10^{30}	9.38×10^{29}	1.61×10^{29}	4.76×10^{28}	1.36×10^{28}
$L_{NN0}/cm^{-2}s^{-1}$	3.75×10^{33}	2.06×10^{33}	1.5×10^{33}	9.79×10^{32}	7.93×10^{32}	5.88×10^{32}

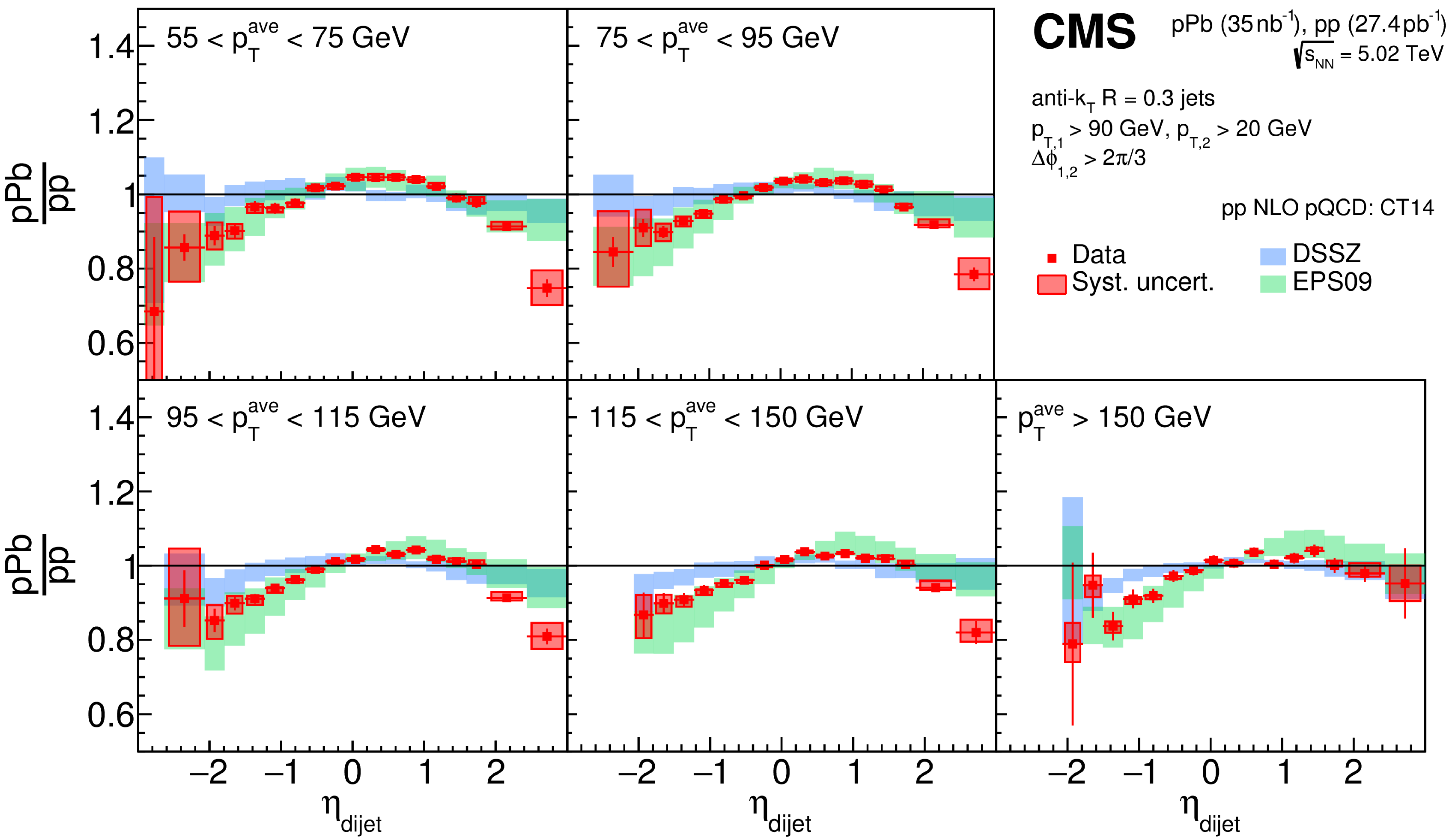




Initial State - Studies of nPDFs

- **Strong constraints on nPDFs from CMS data - obvious synergy with EIC**
- **Potential to explore small-ion nPDFs in Run 5, but statistics hungry**
- **Expanded acceptance for leptons, jets will help stats + (Q^2,x) coverage**



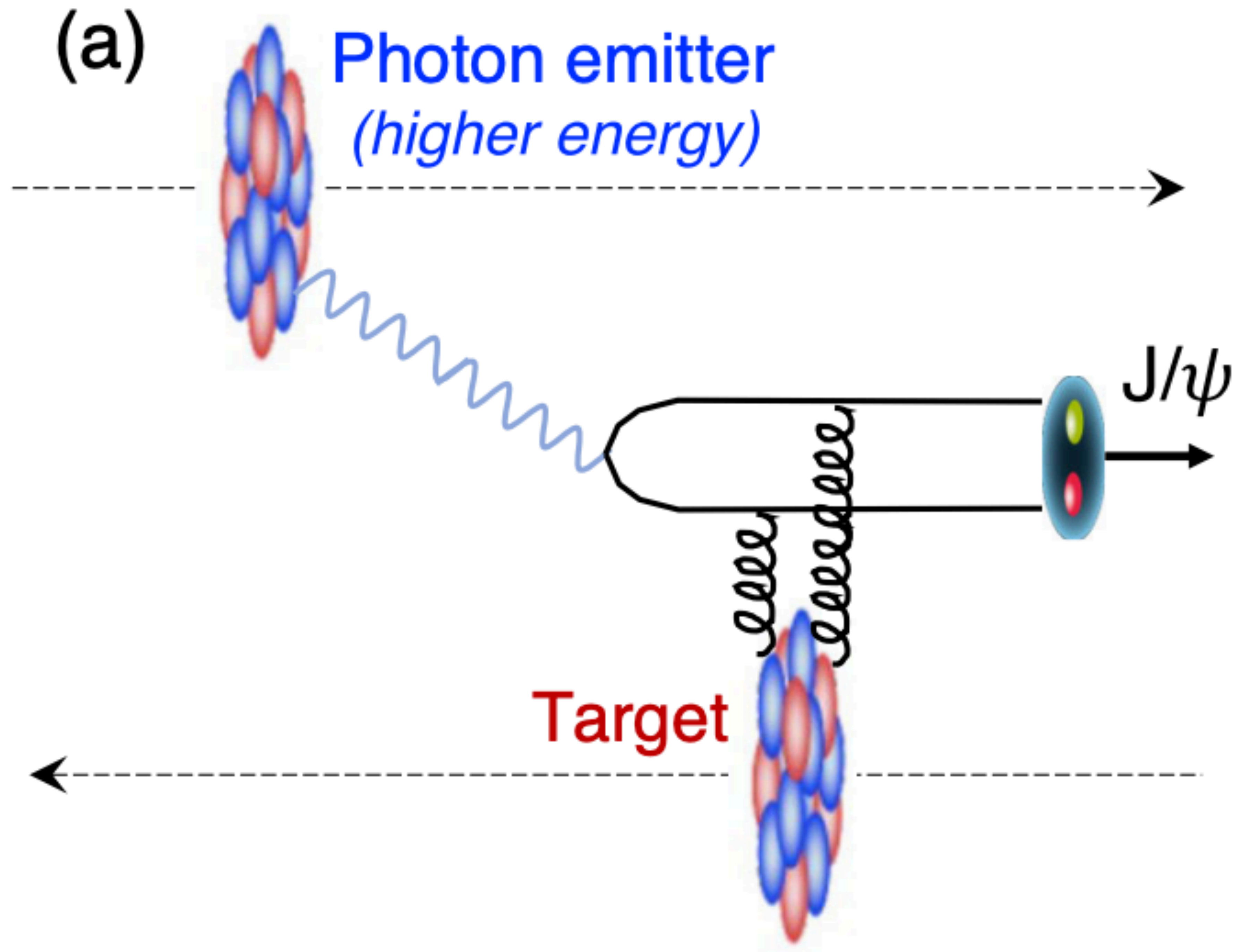


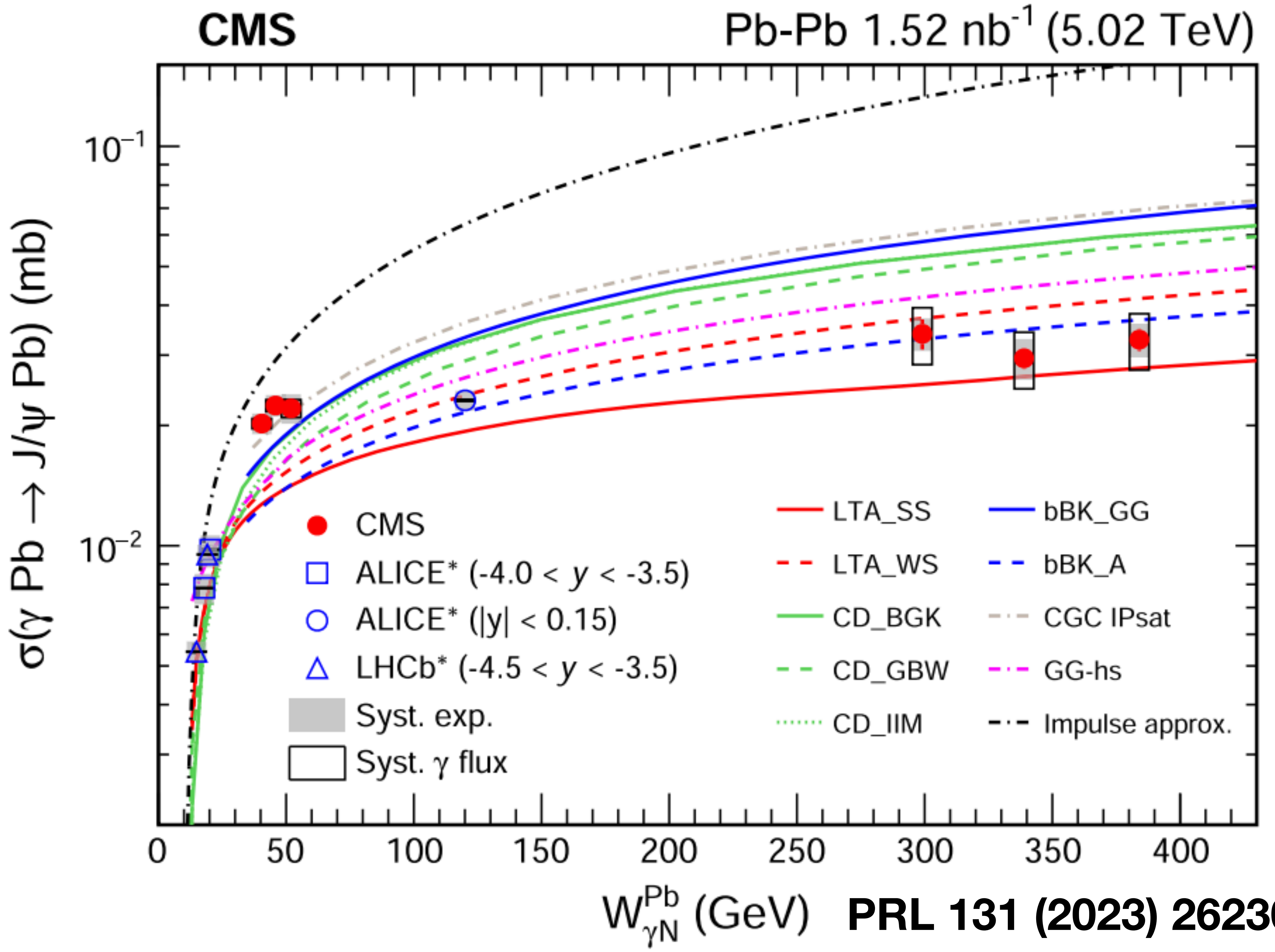
PLB 800 (2020) 135048

PRL 121 (2018) 062002

UPCs - testbed for EIC physics

- **Clear synergy between CMS UPC program and EIC**
- **Probes of low-x/saturation physics that will be core aspect of EIC program**
- **See Gian-Michele's Talk on Monday for more**



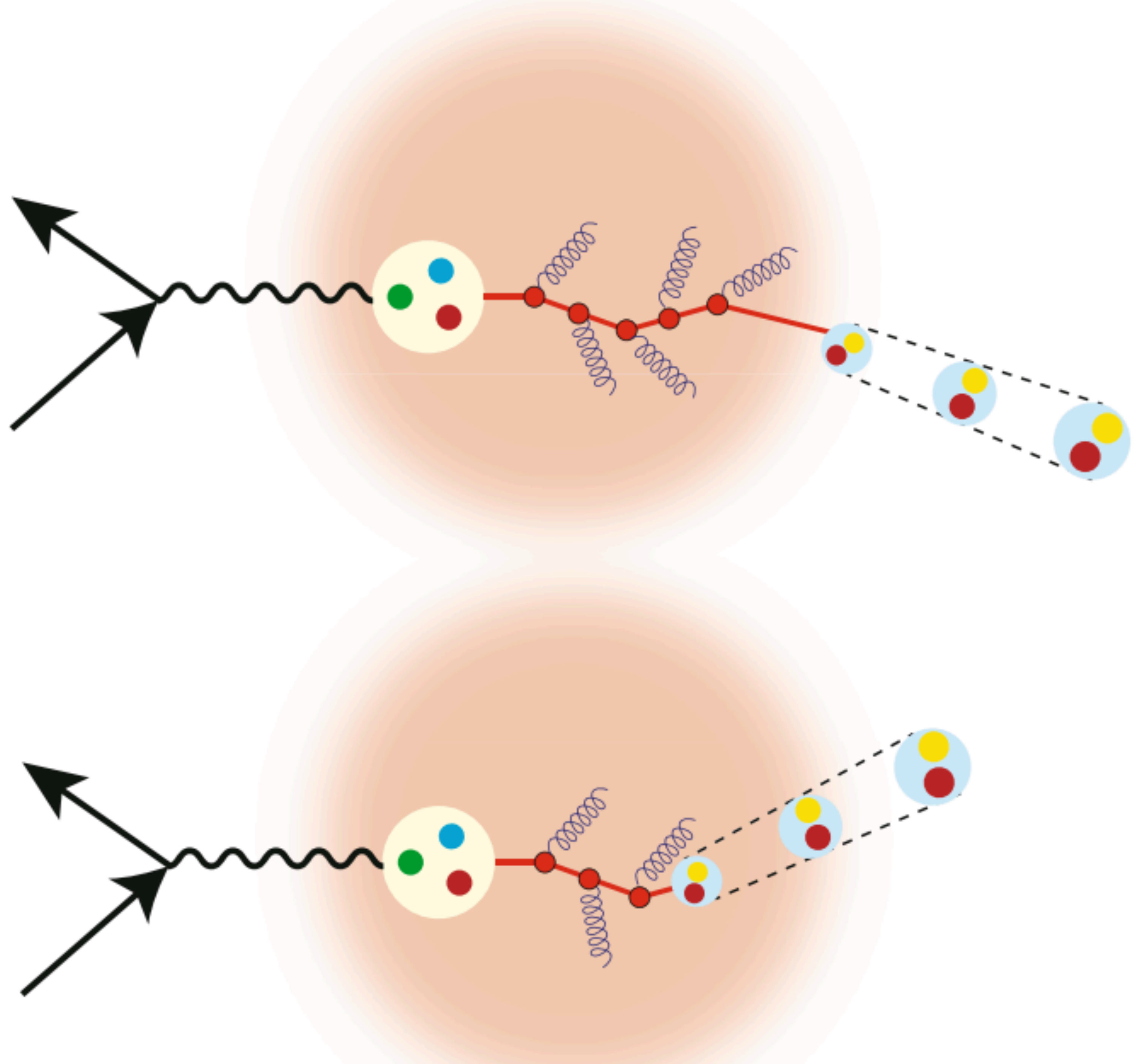


PRL 131 (2023) 262301

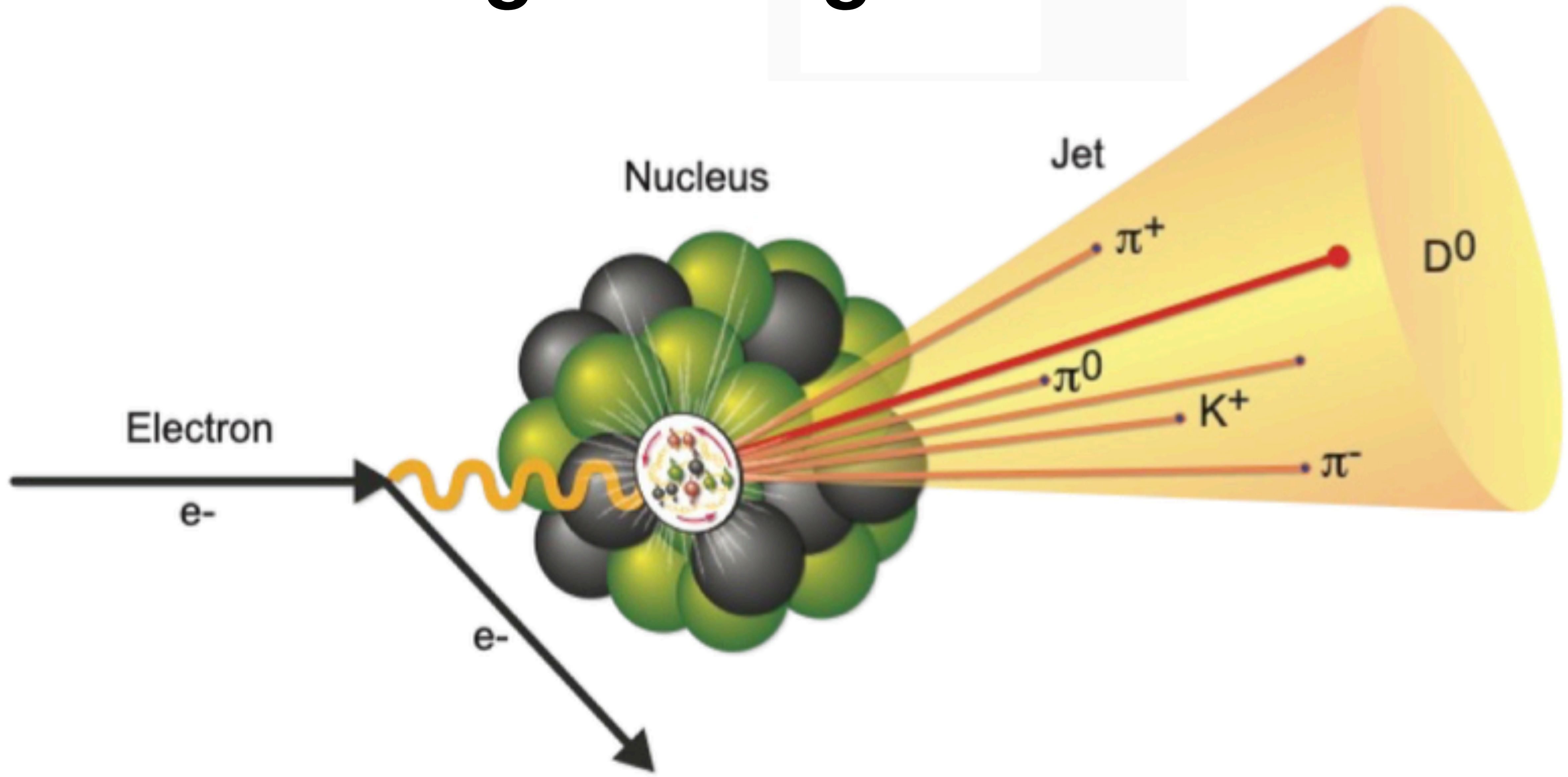
Final-State effects

- Complementarity of LHC/EIC extends far beyond initial state (particularly for pA)
  - Modification of hadronization in high-density QCD environments
  - Passage of particles/jets through cold nuclear matter
  - Helping understand QGP-like effects in pA collisions

Hadronization Studies



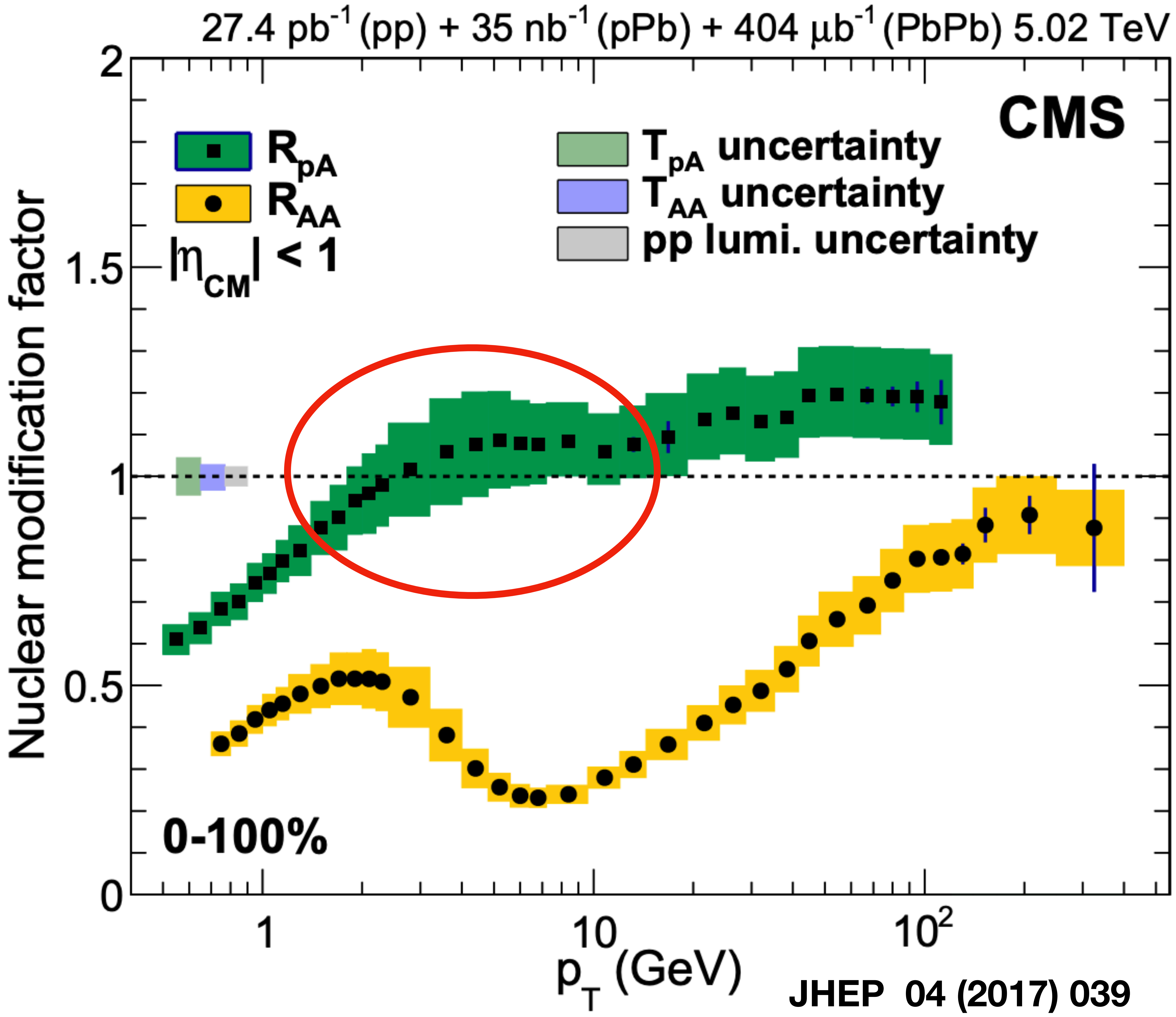
Passage through CNM



Eur. Phys. J. A (2016) 52: 268

Light hadron studies

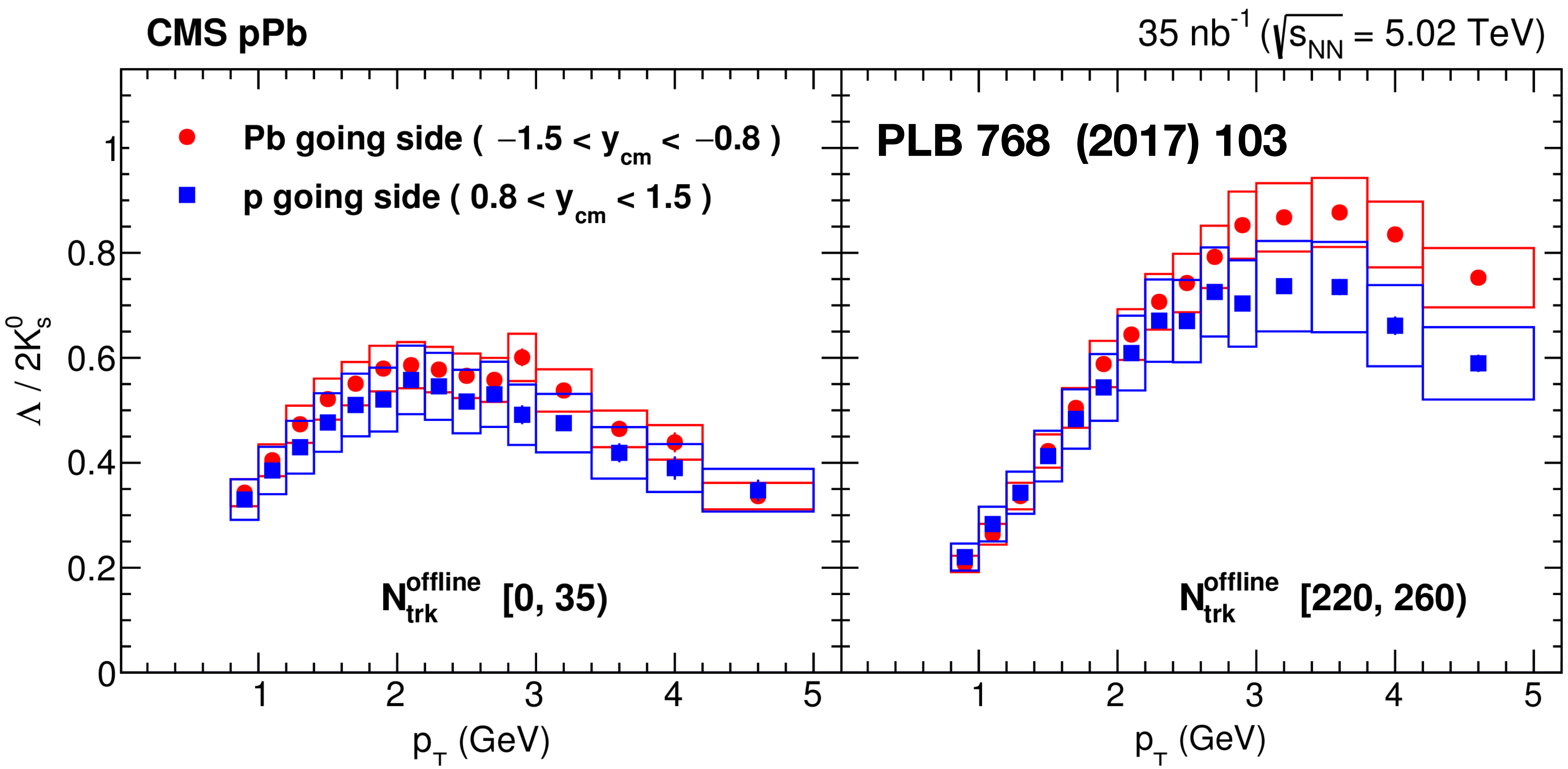
- **Intermediate p_T region of pA sensitive to final-state effects**
  - **CNM effects - EIC will test**
  - **Hydrodynamic flow?**
  - **Cronin effect, etc.**
- **Run 4: Explore over 8 units of eta**
  - **p/K/pi separation by MTD (6 units)**
- **Run 5+: test different ion sizes**
  - **'25 pO run will be interesting peek**



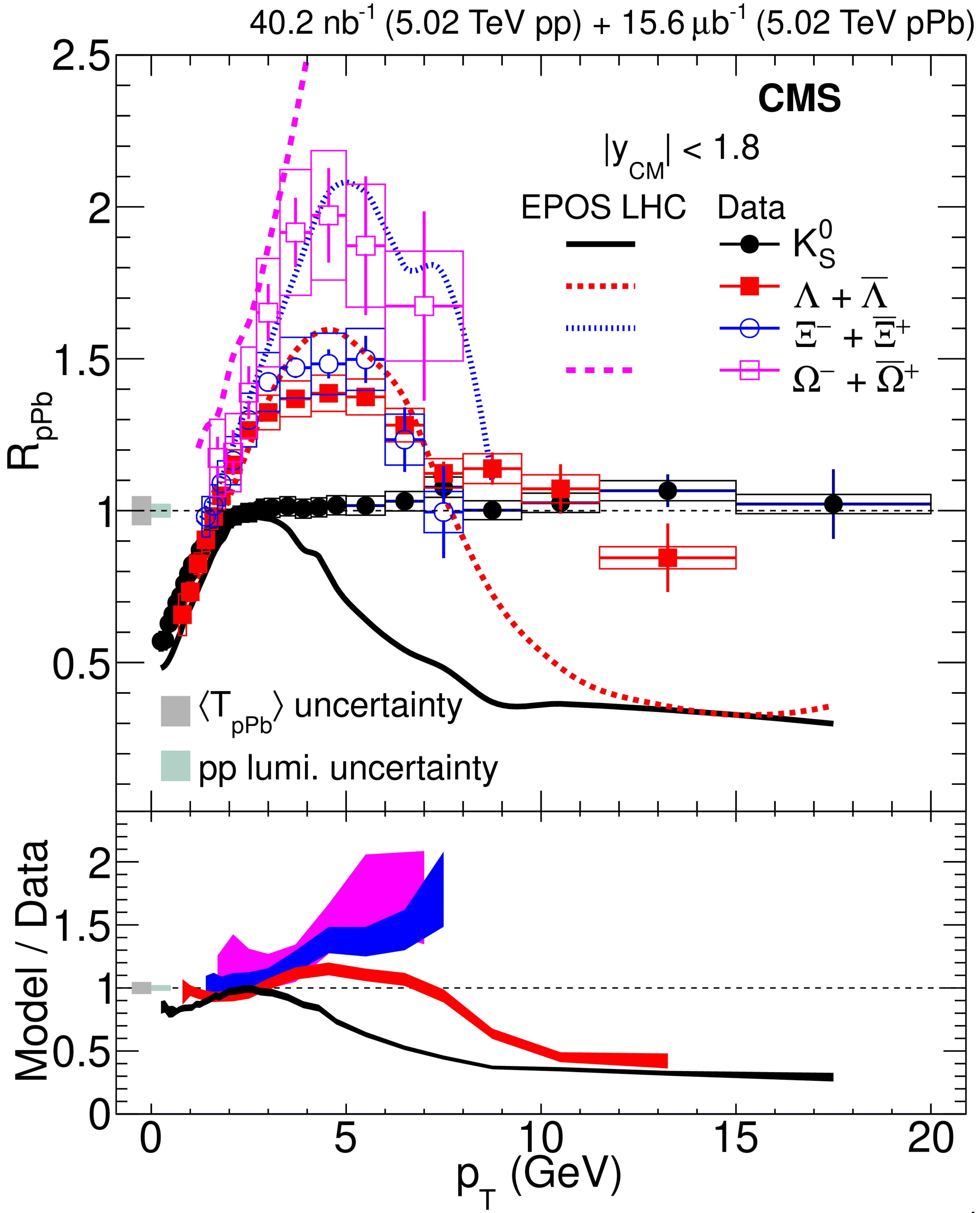
JHEP 04 (2017) 039

Strange Hadrons

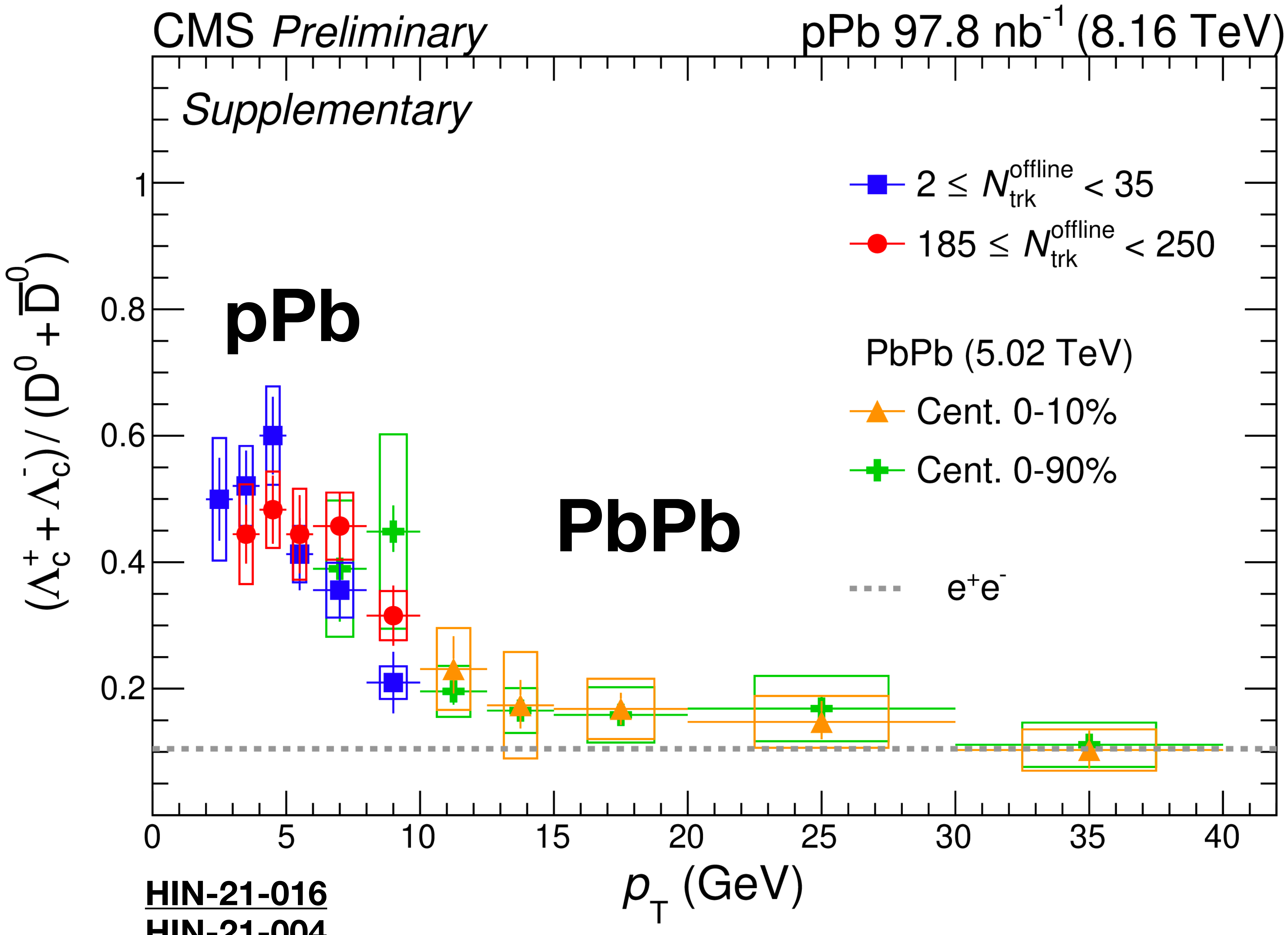
- **Run 4: Strange hadron efficiency drastically improved**
- **Study strangeness and baryon/meson ratios** $|\eta| < 8$
  - **Run 5+: Same effect for smaller ions?**
- **EIC - to what extent can CNM play a role here?**



PRC 101 (2020) 064906



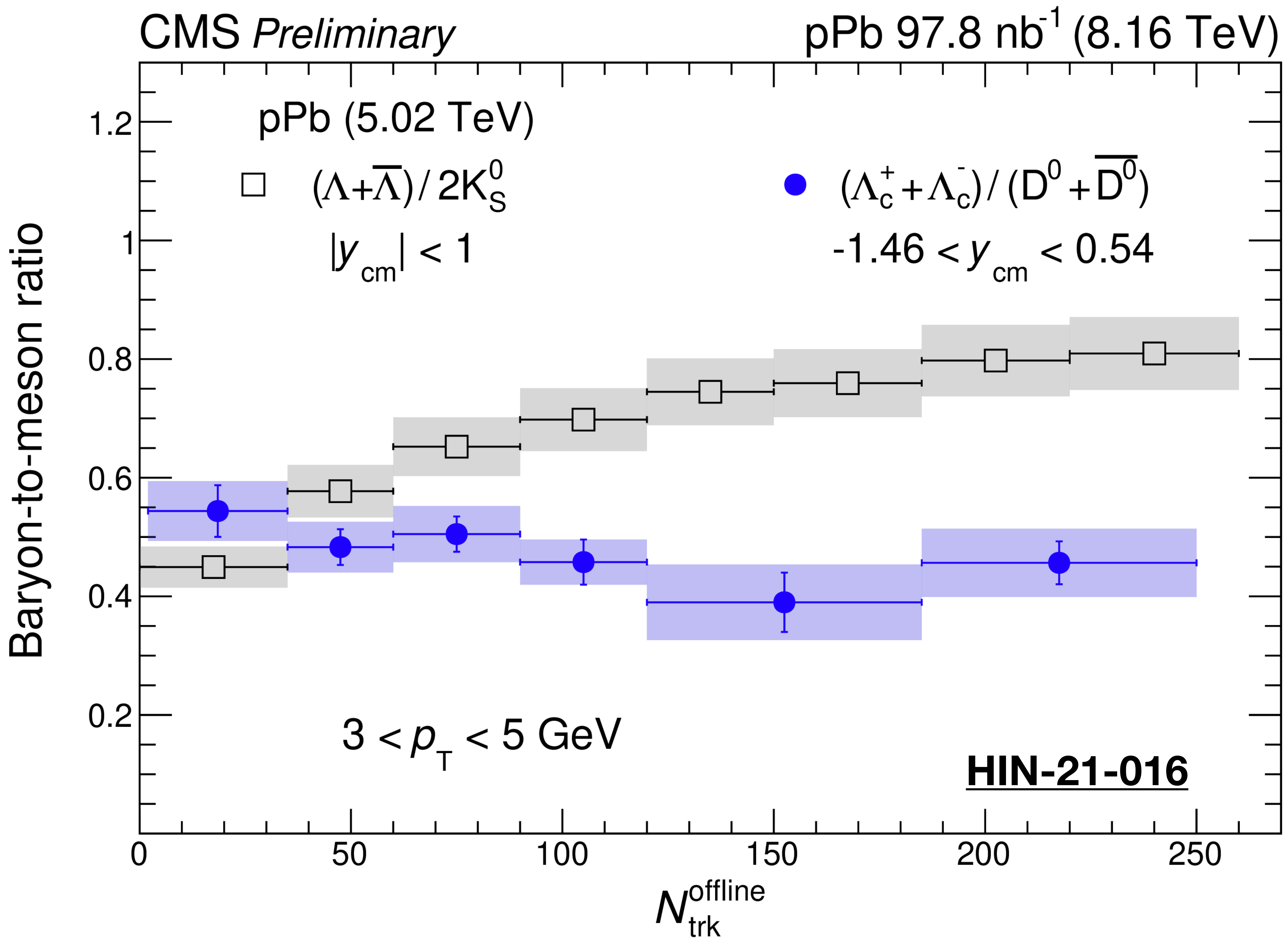
Heavy Flavor hadronization: Λ_c^+/D^0



HIN-21-016
HIN-21-004

- **Low-p_T behavior higher than e^+e^- baseline?**
- **Presence of hadron in initial state affects hadronization?**
- **Can check with EIC!**
- **Precision will improve with MTD + acceptance increase**

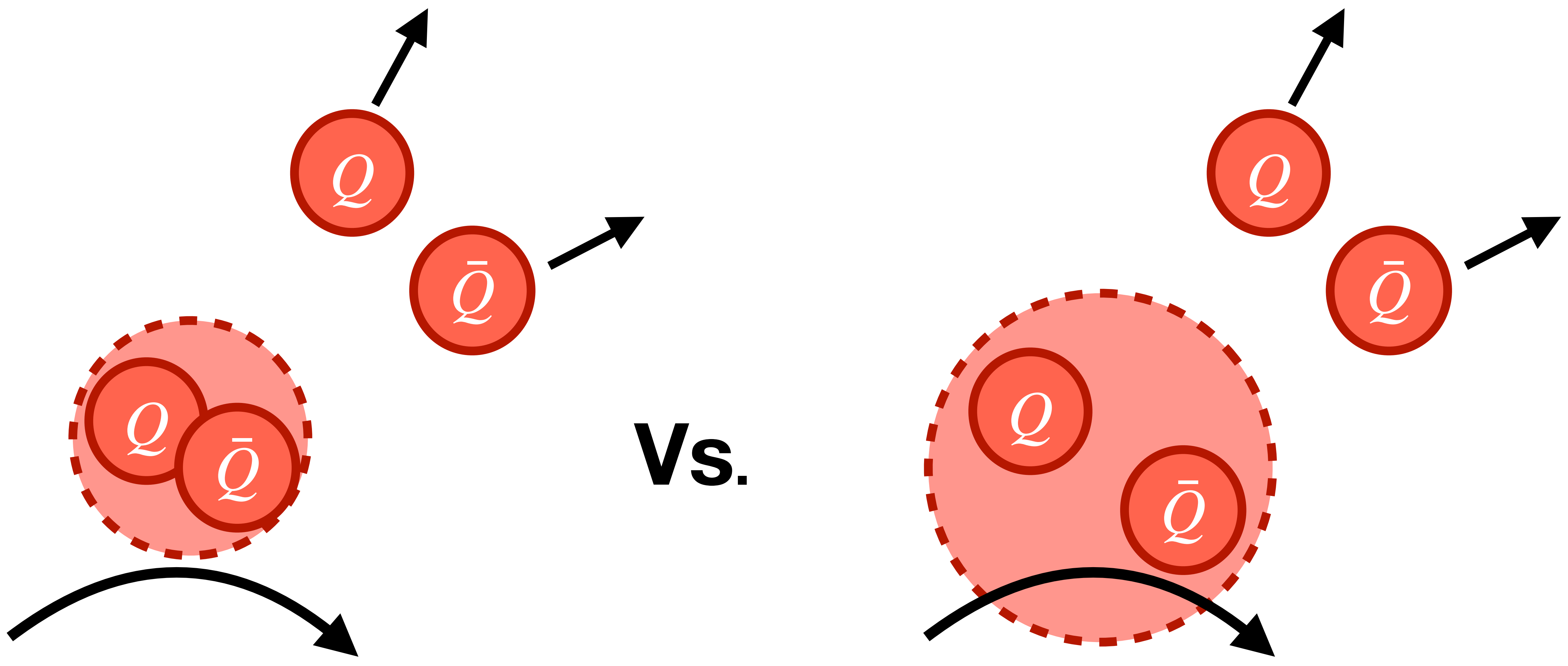
Baryon to Meson Ratio vs. multiplicity

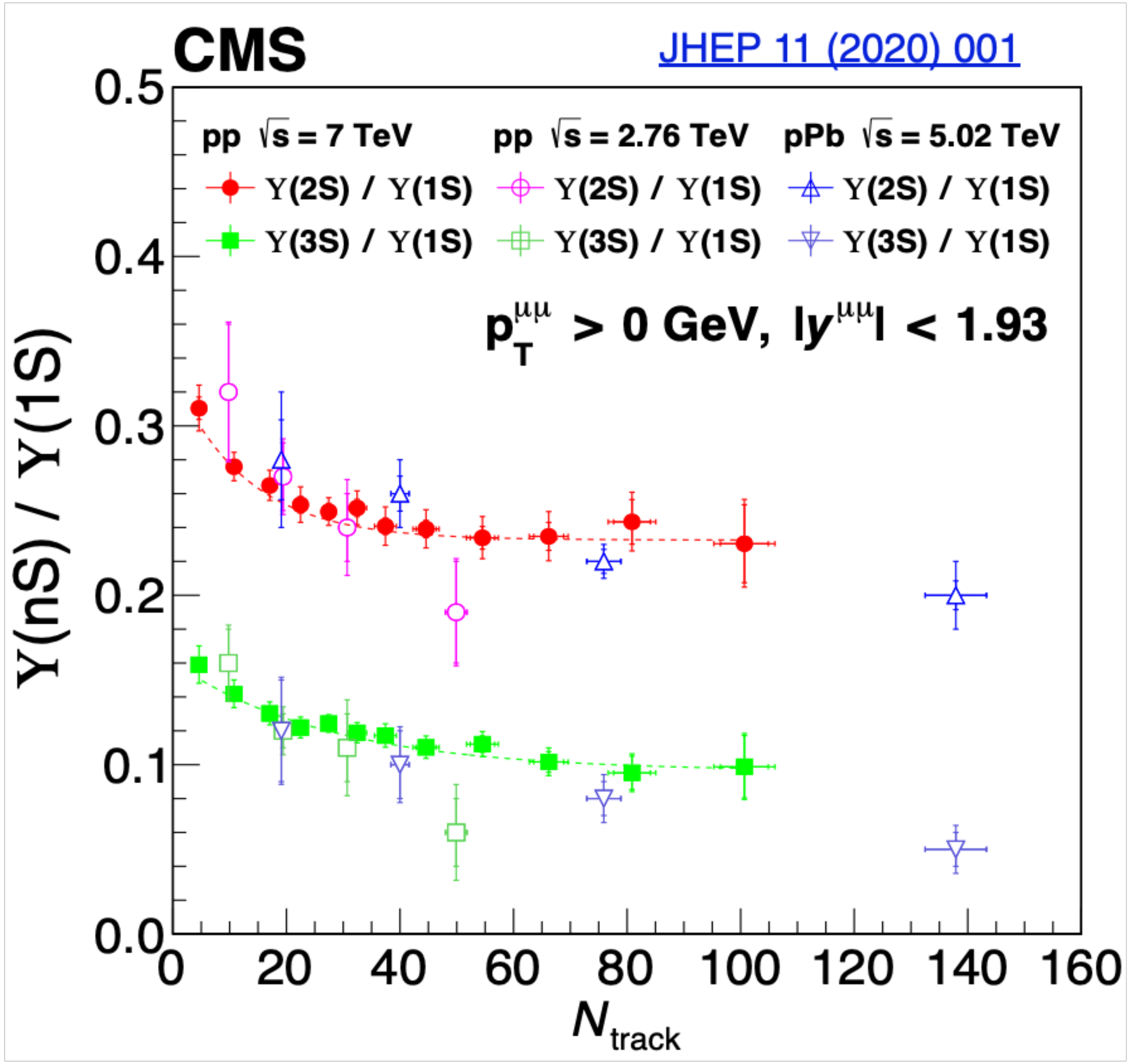


- **Comparison of charm and strange baryon-to-meson ratio**
  - **Trends differ in low multiplicity limit - could be probed with EIC multiplicities**

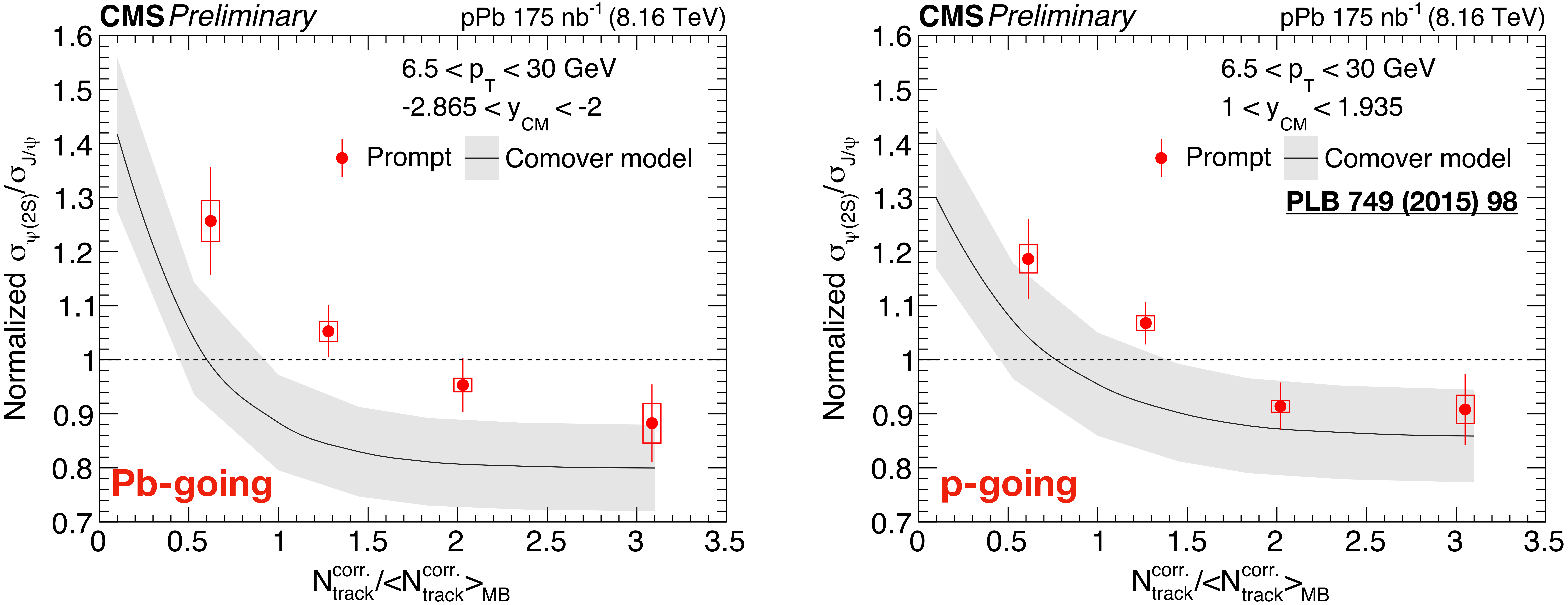
Suppression of quarkonia excited states

- Suppression of quarkonia excited states seen in small systems
- Co-moving particles break up excited states more easily than ground states?
    - Studies of Υ(nS) support this picture
    - Suppression should scale with comover density





Charmonia Measurements

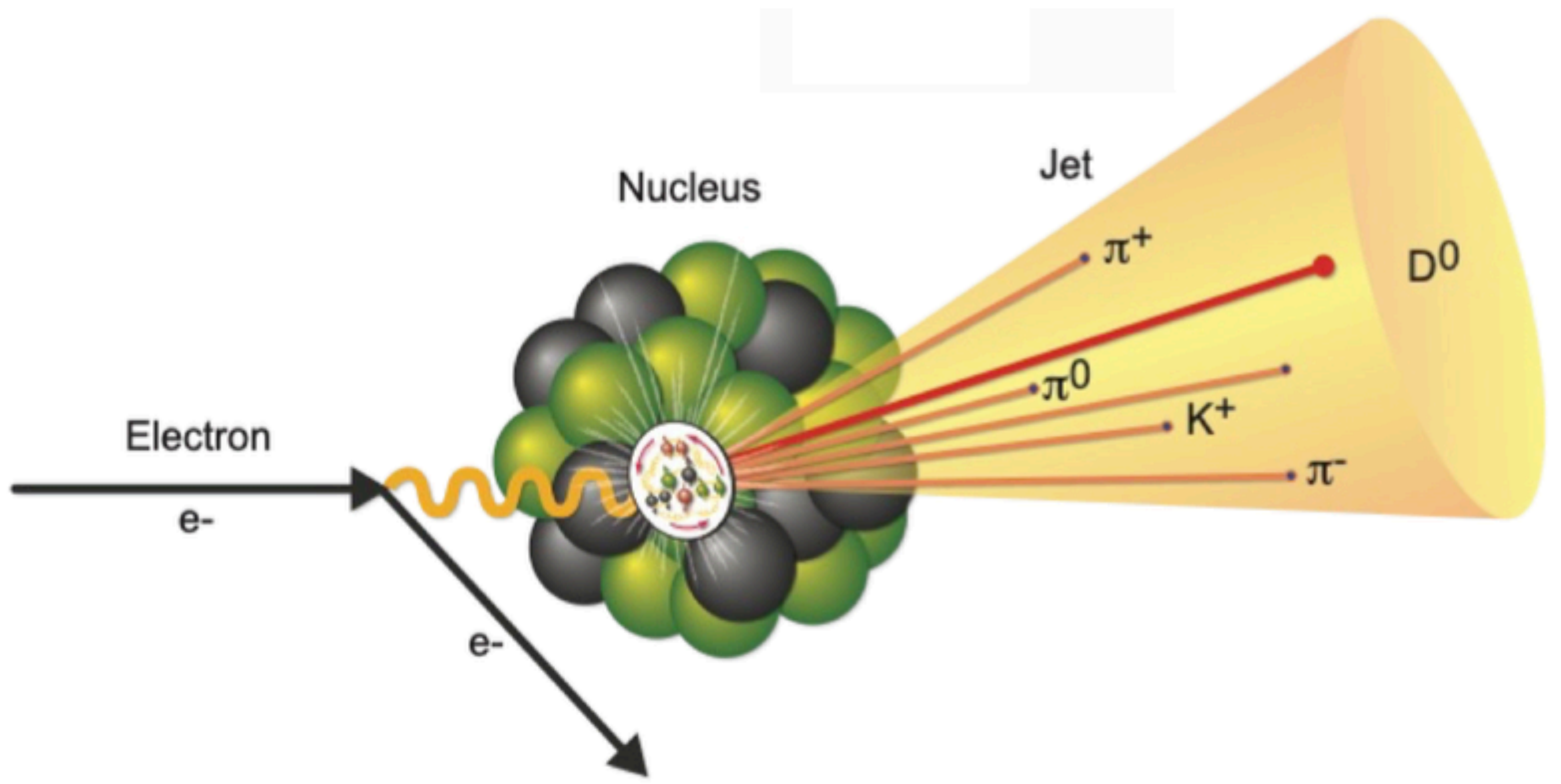


$$\text{Normalised } \sigma_{\psi(2S),n} / \sigma_{J/\psi,n} = \frac{\sigma_{\psi(2S),n} / \sigma_{J/\psi,n}}{\sum_n \sigma_{\psi(2S),n} / \sum_n \sigma_{J/\psi,n}}$$

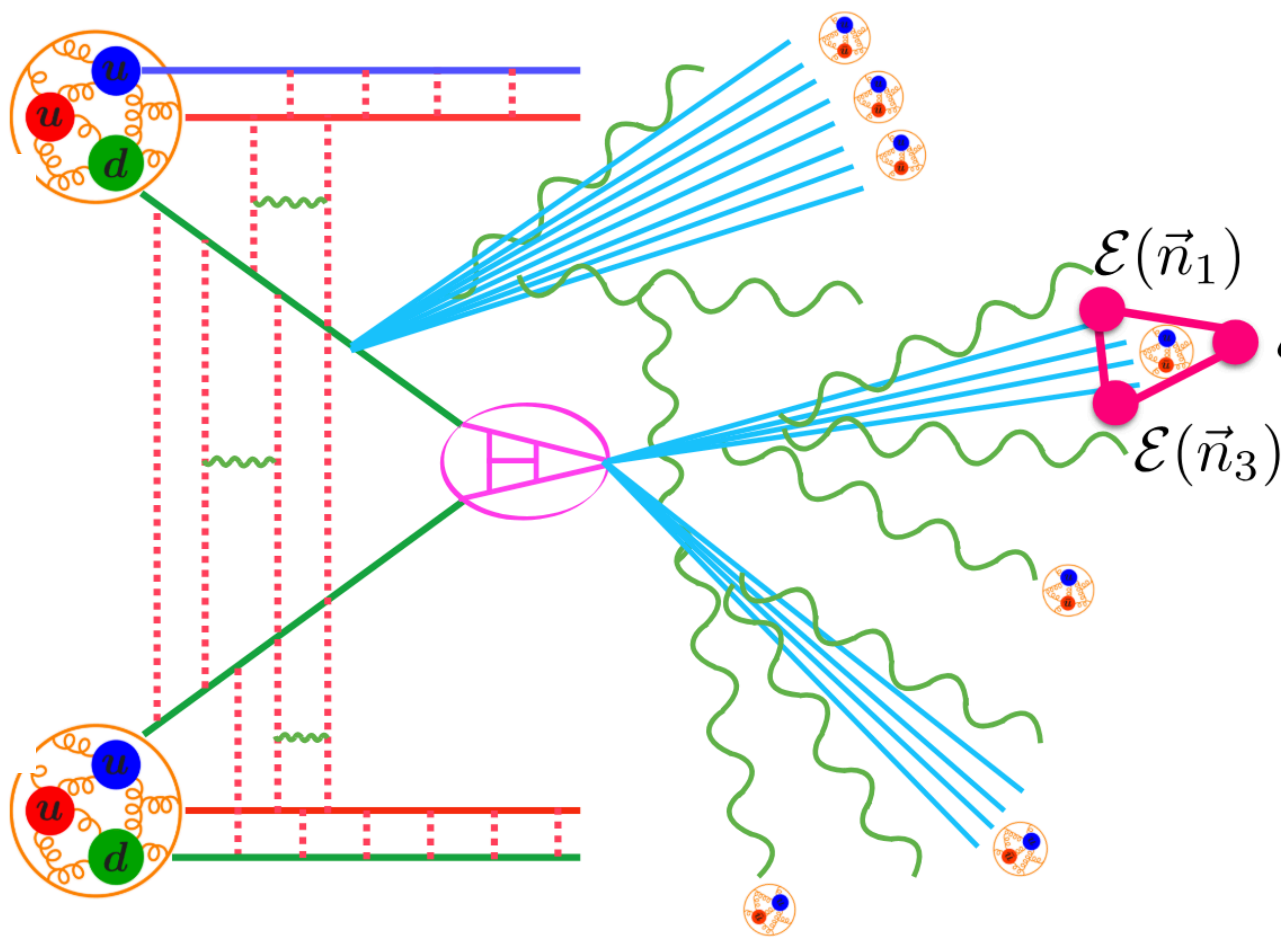
- **Model includes comover interactions**
- **Reasonable agreement with model**
- **“Extra” multiplicity quickly generates suppression - study at EIC**

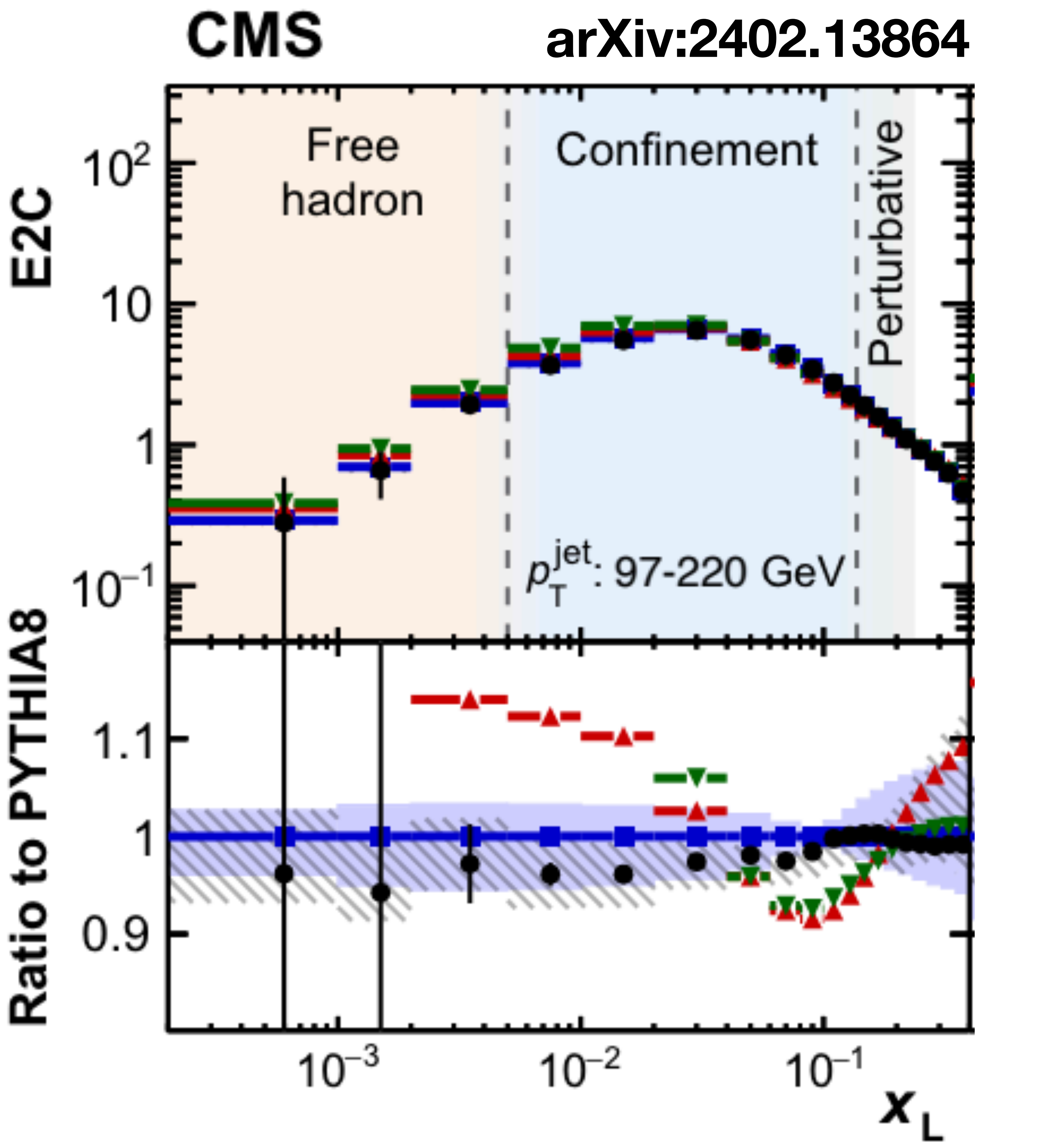
CMS-HIN-24-001

Energy-Energy Correlators



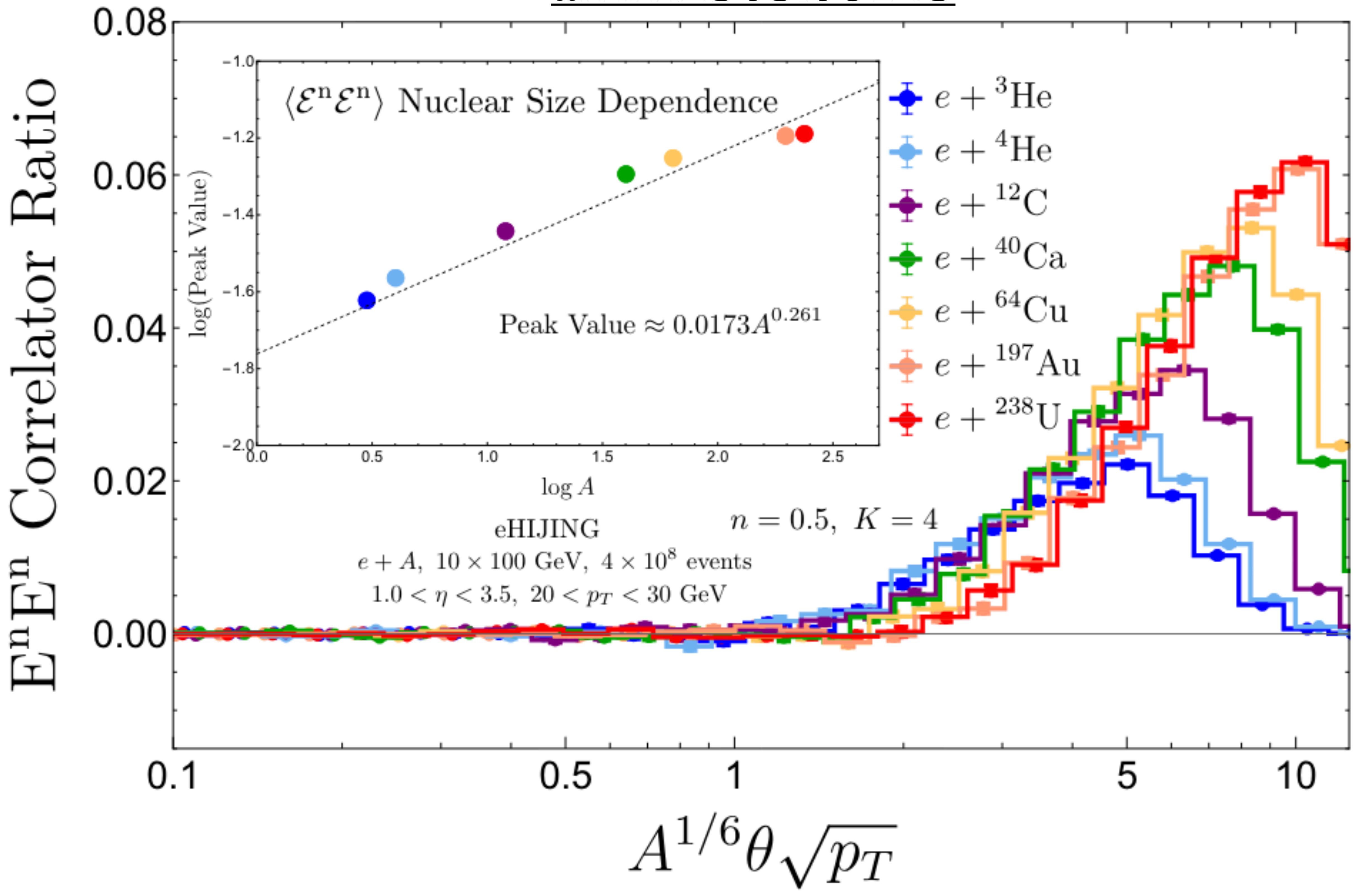
Phys. Rev. D 102, 054012 (2020)



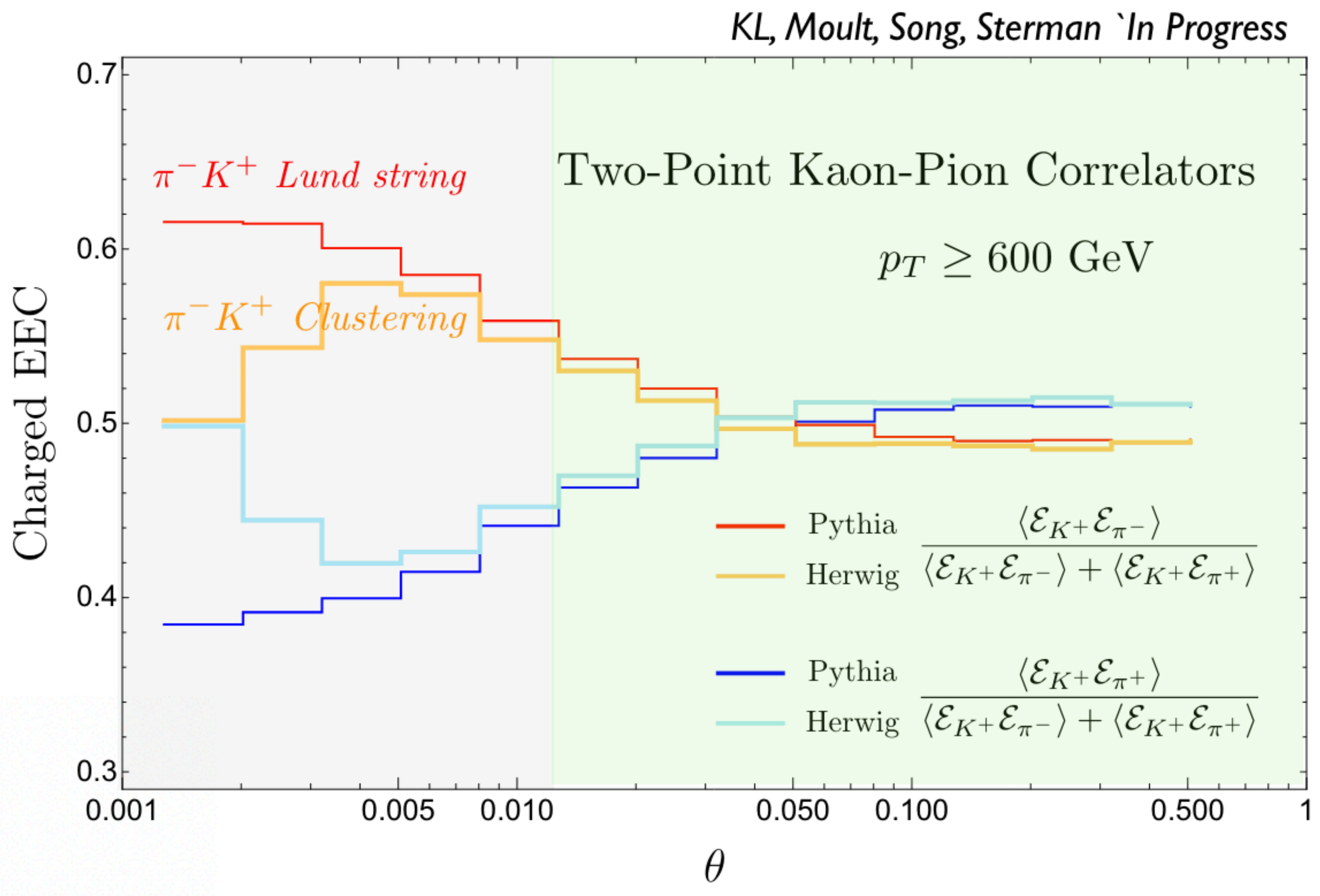


- **EECs provide distinct separation of scales that allow probing different stages of jet**
- **Theoretically well-controlled (used for α_s extractions)**
- **Interactions with nuclear matter (hot or cold) will modify distinct regions**

EECs at the EIC and LHC



Kyle Lee's Presentation at 2024 EICUG Meeting (LeHigh University)

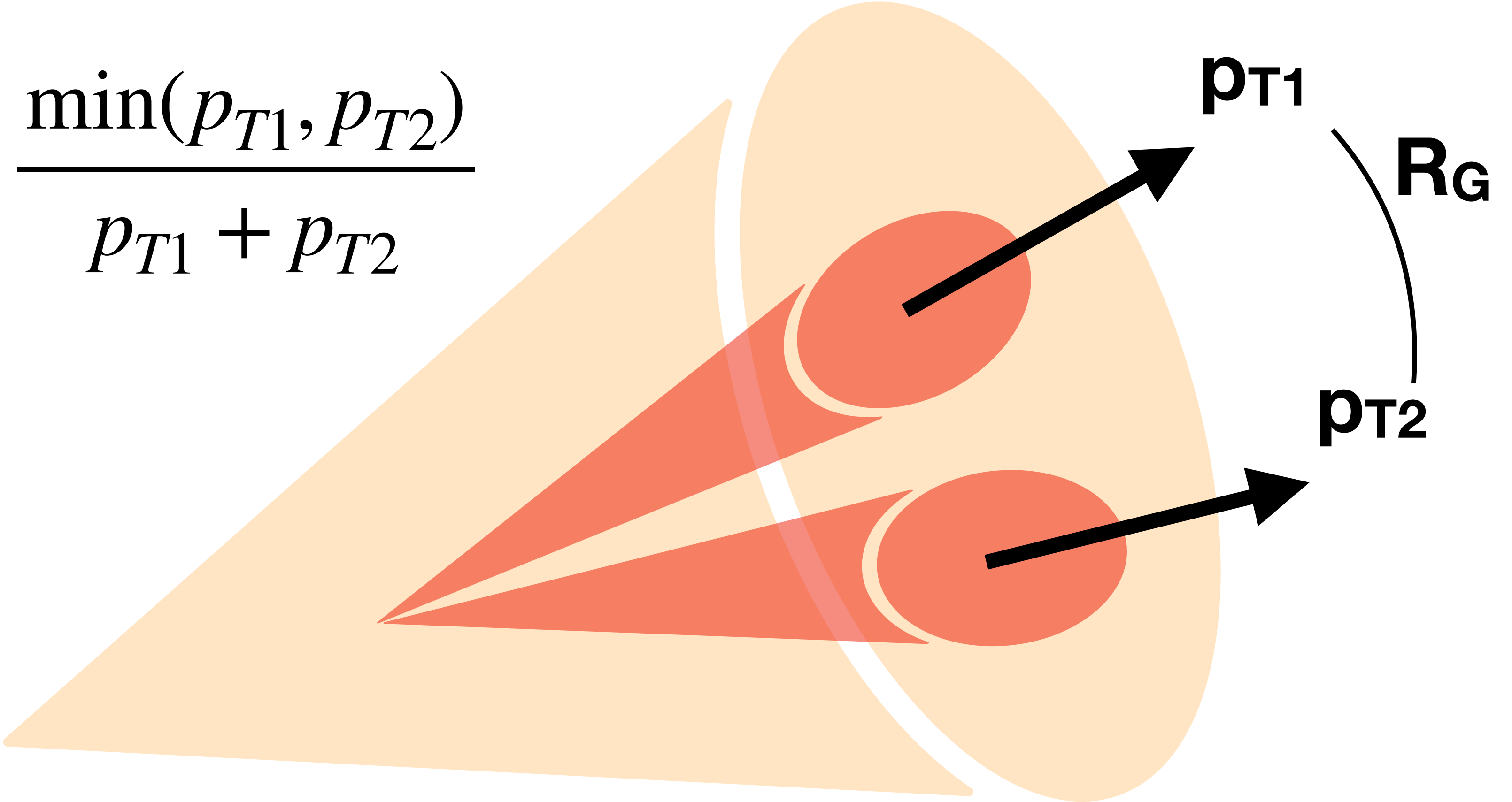


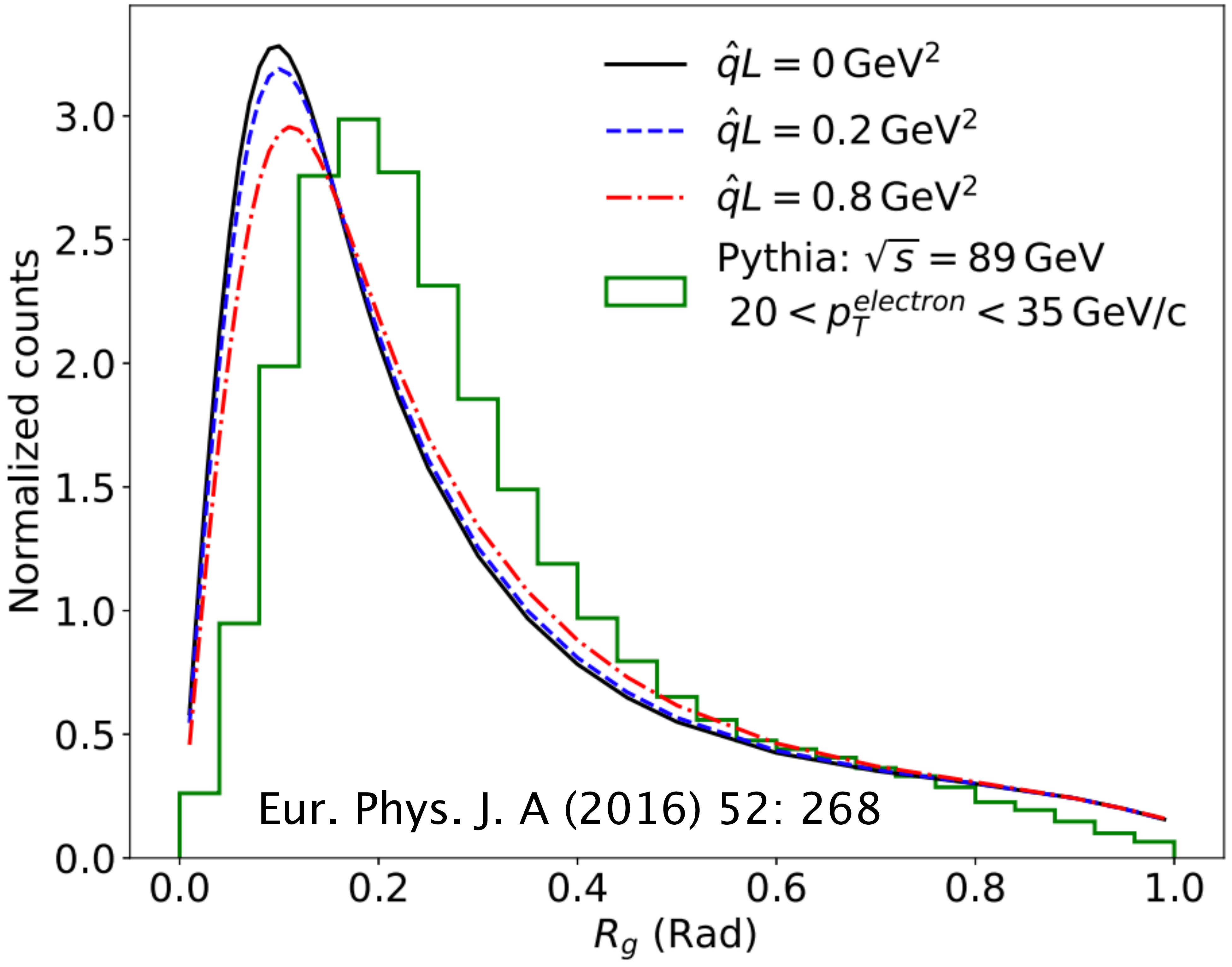
- **EEC ratios could be sensitive to CNM effects/ion size - testable in pA during Run 5?**
  - **HGCAL useful in trying to match p_T range as closely as possible**
- **EECs with PID (i.e. CMS MTD!) could give insight into hadronization**

Groomed jet properties

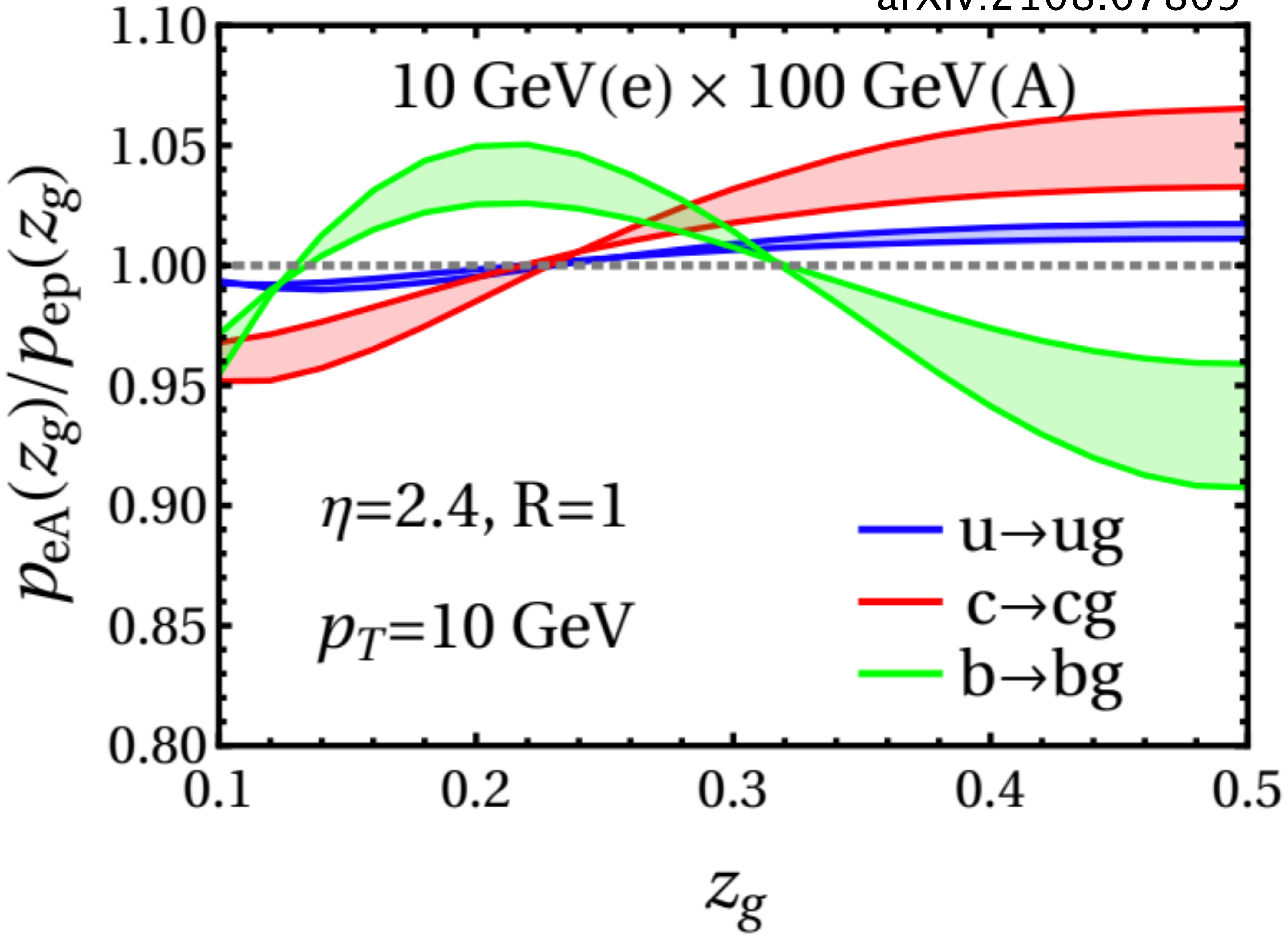
- **Groomed jet radius sensitive to $\hat{q}$**
  - **Momentum broadening from interactions with CNM**
- **Momentum sharing sensitive to jet flavor**
  - **Can study effect of quark mass on shower/interactions**

$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

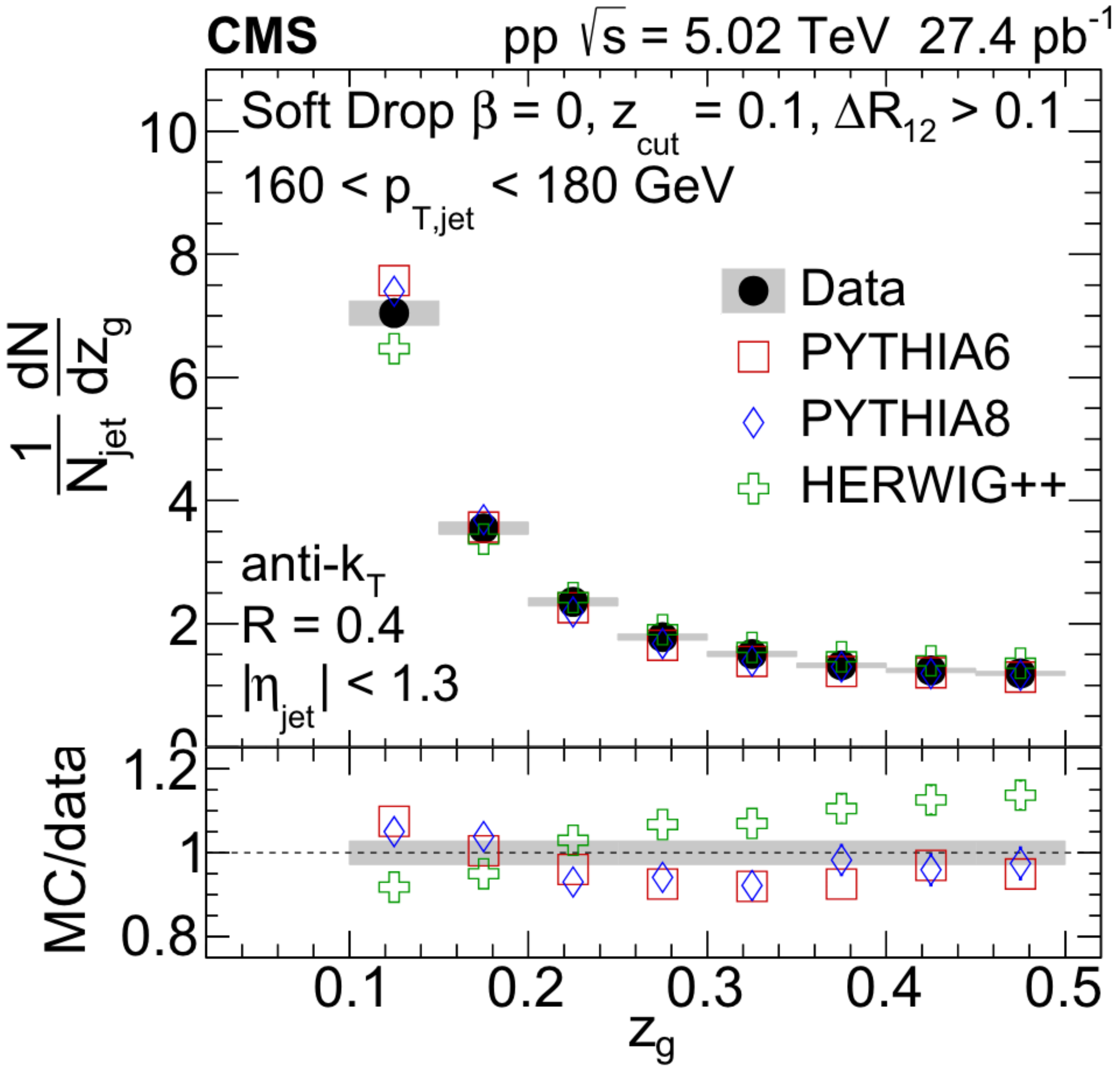




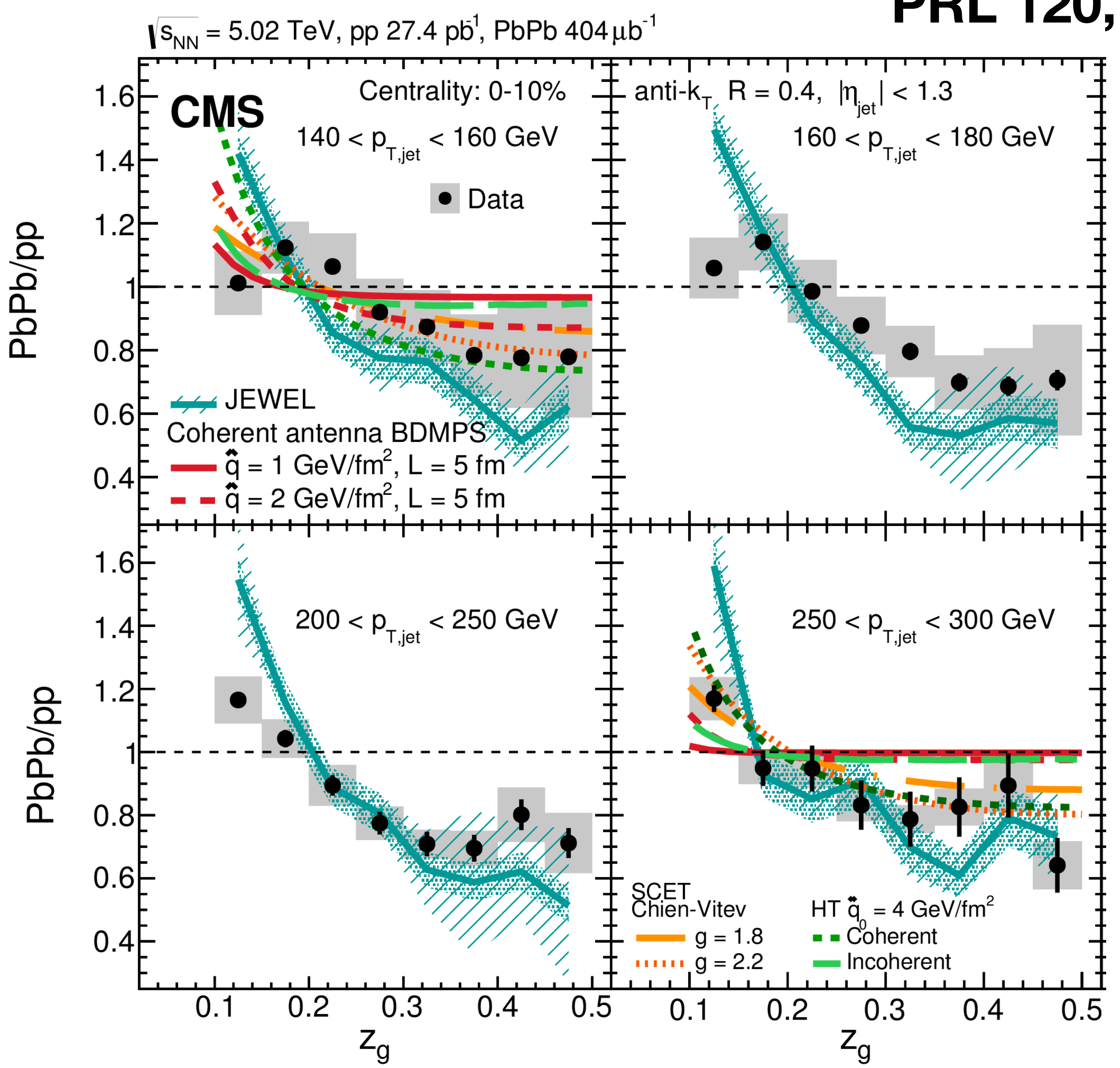
arXiv:2108.07809



Groomed jets at the LHC



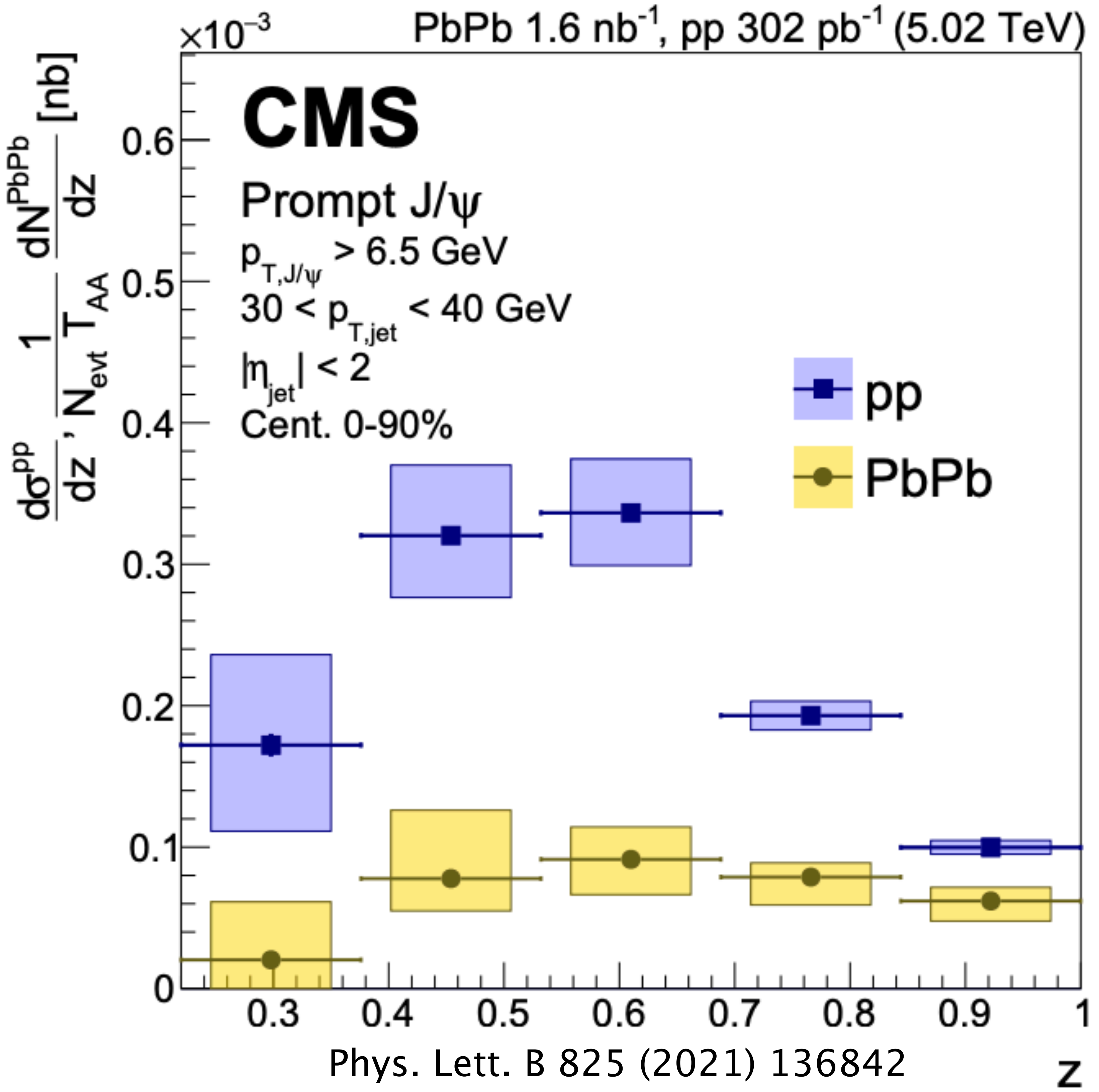
PRL 120, 142302 (2018)



- **Can we observe groomed jet modifications in pA collisions?**
  - **HGCAL + tracker should allow flavor-tagged studies at lower p_T**
- **Potential for much development here with grooming settings, etc.**

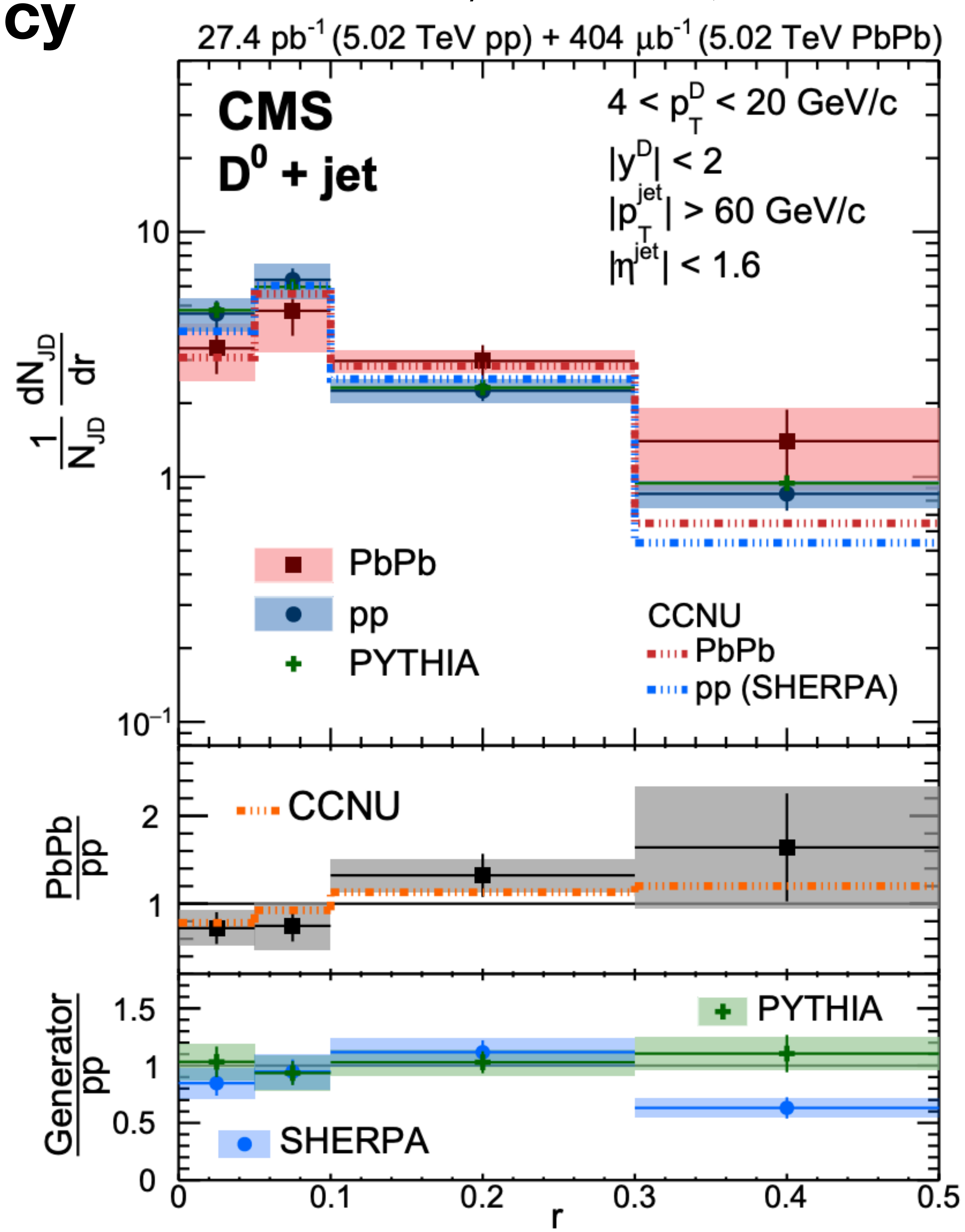
Jet + Heavy Flavor Hadrons

- **Phase 2 upgrades will greatly boost stats/efficiency for jets containing HF hadrons**
- **Study interplay of jet shower with HF production**
- **Many studies can be done with Run 4+5 pA data**



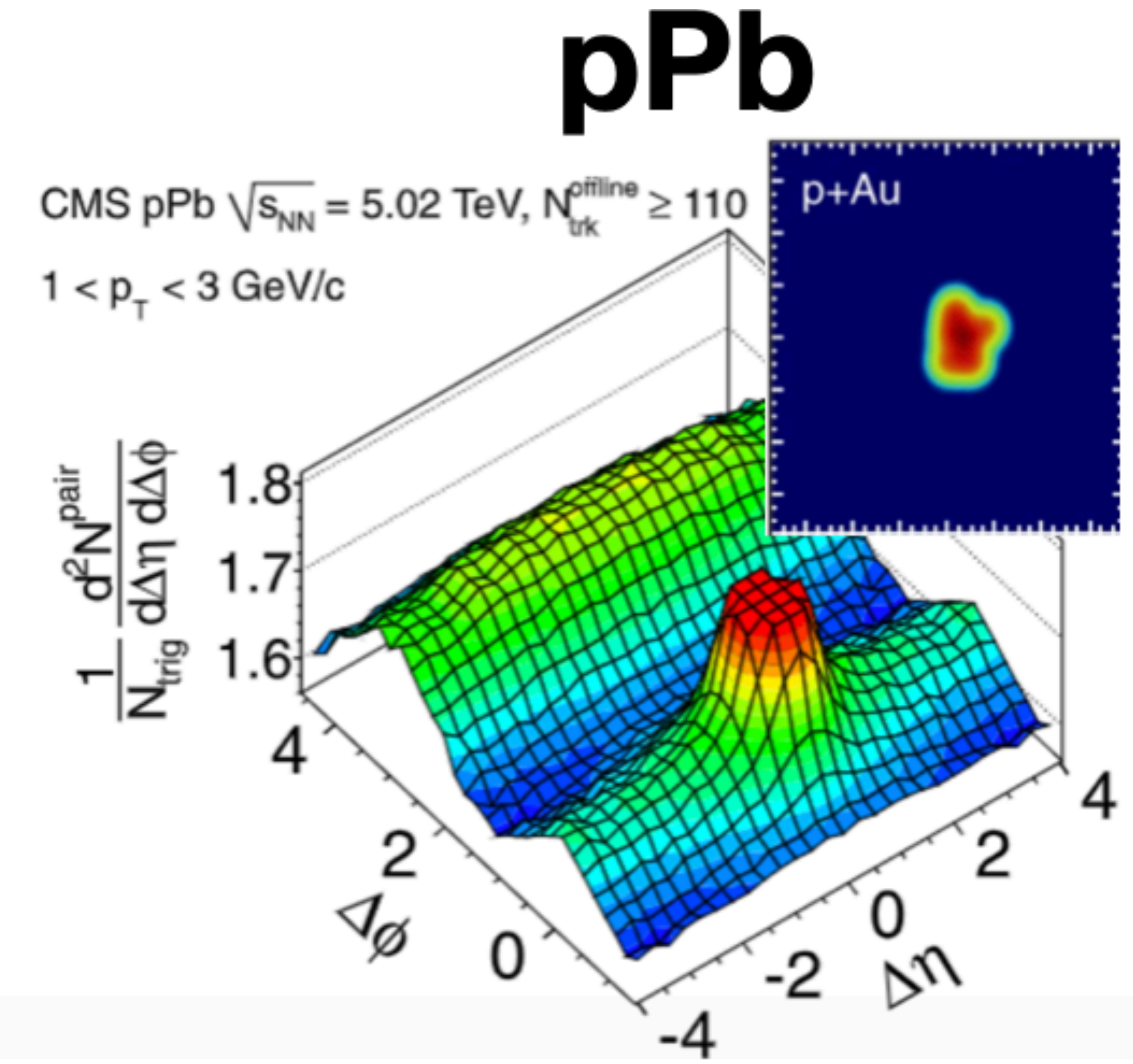
Phys. Lett. B 825 (2021) 136842

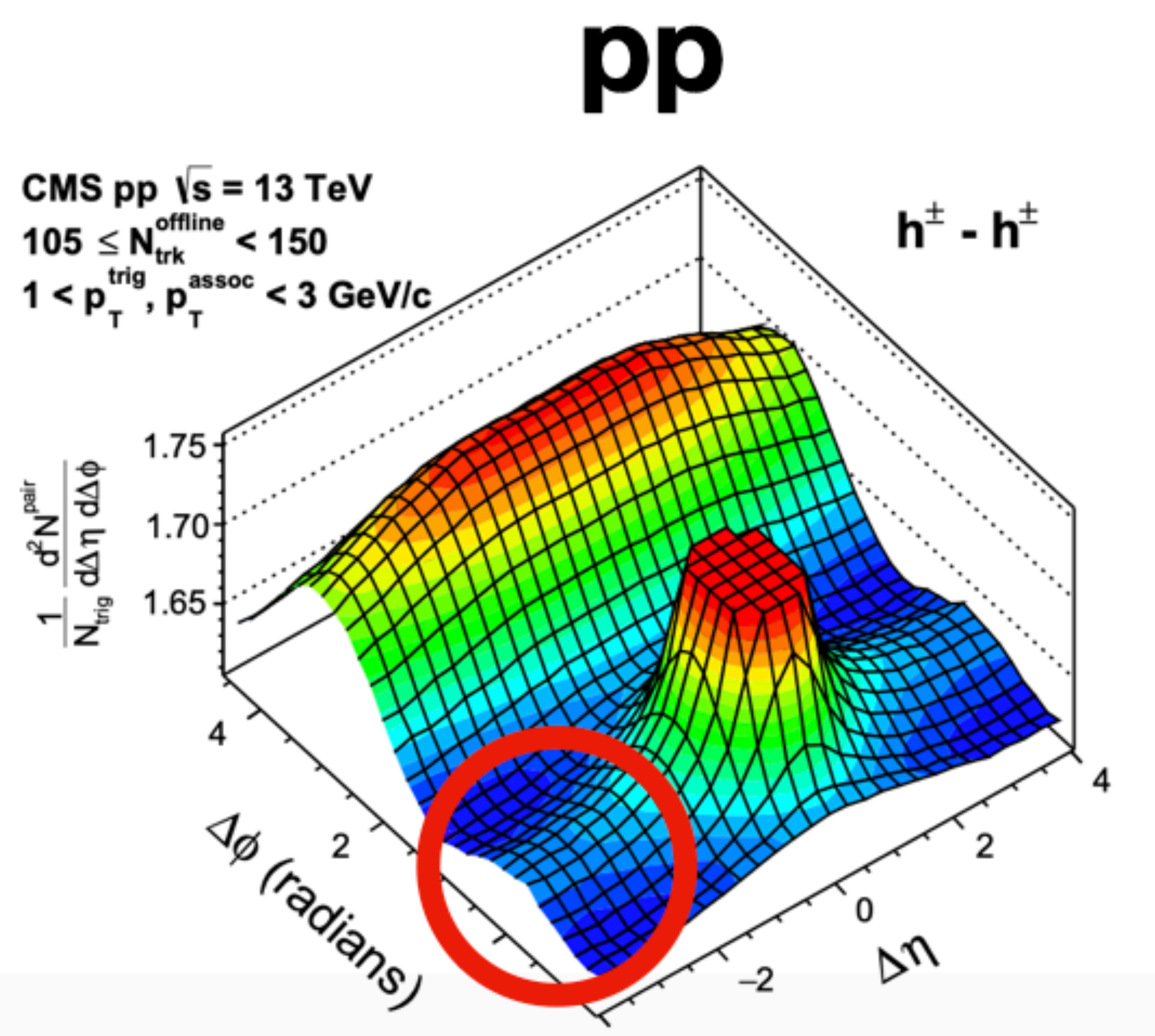
Phys. Rev. Lett. 125, 102001 (2020)



QGP-like final-state effects

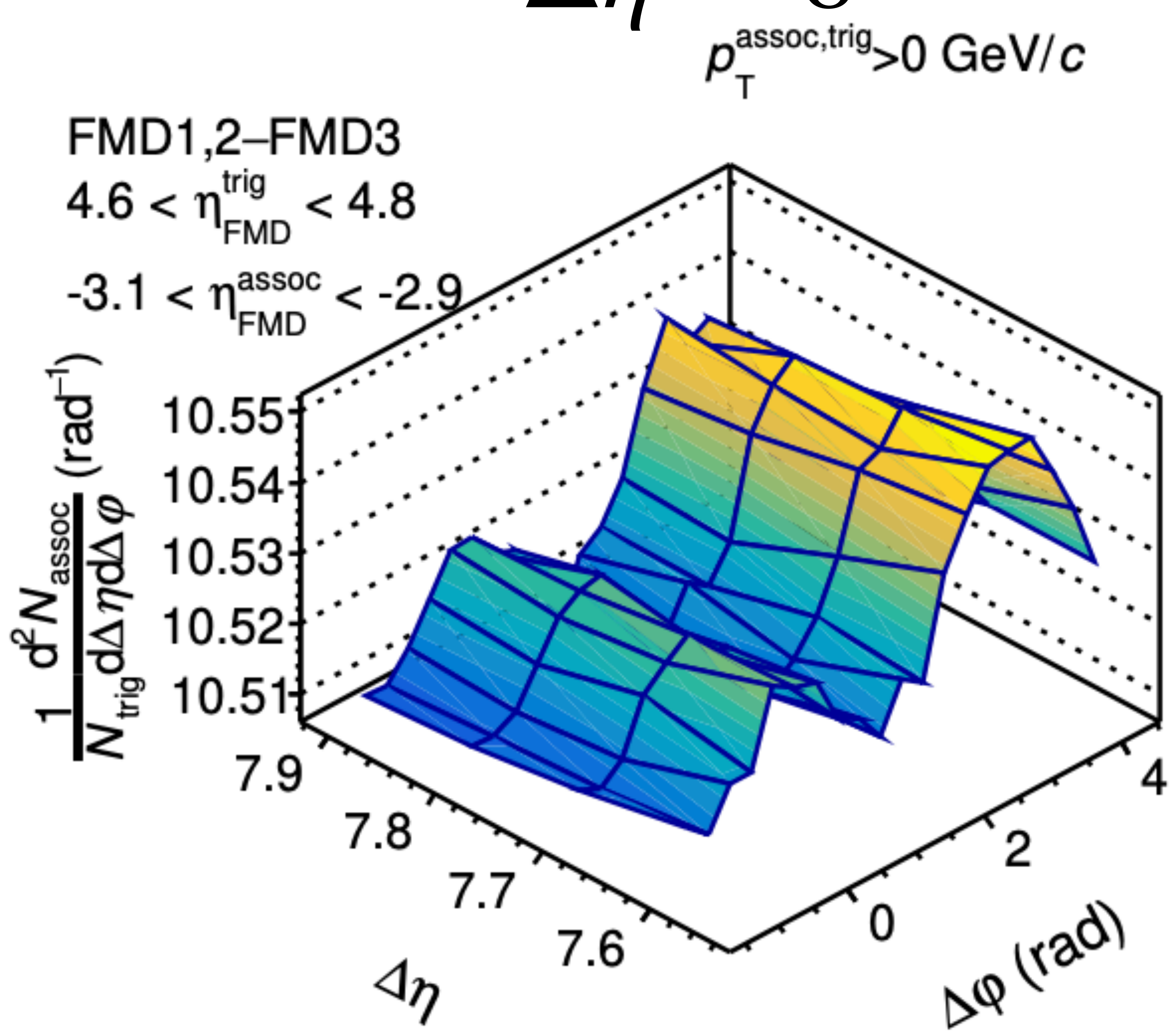
- **Run 4+ will enable correlations across very large acceptances**
  - **Ridge across 8 units of rapidity!**
  - **Will challenge MC models further**
- **EIC input with regards to potential explanations will add further challenges**





ALICE pPb Data

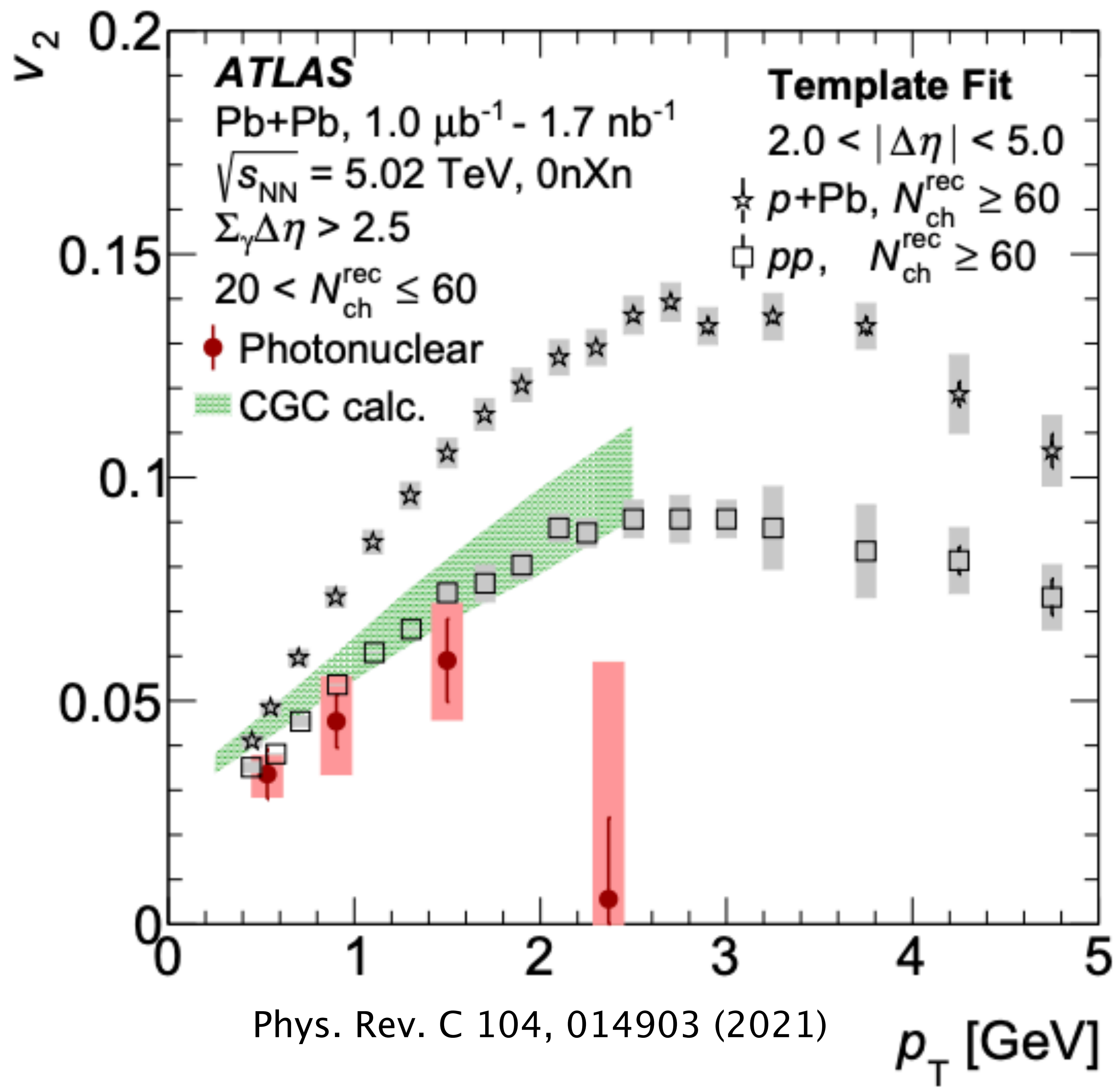
$\Delta\eta \sim 8$



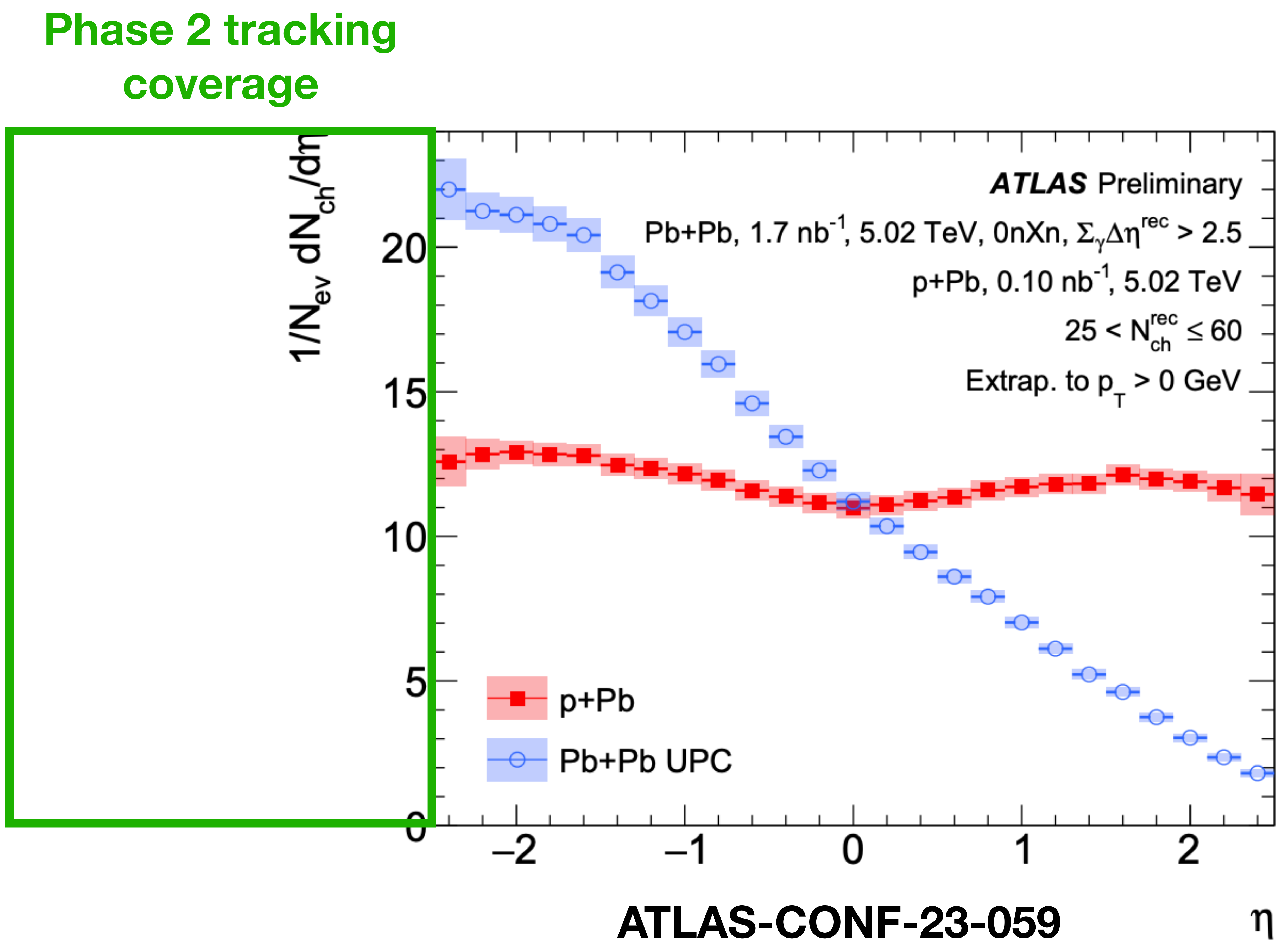
JHEP 01 (2024) 199

Exploring v_2 in UPC

- **Possibility of flow-like effects in resolved γA should be considered for EIC**
- **Extended tracker + trigger in Run 4 will enable higher statistics studies**
  - **Larger $\Delta\eta$ range can be probed, larger rapidity gaps, etc.**



Phys. Rev. C 104, 014903 (2021)



ATLAS-CONF-23-059

Summary

- CMS will be greatly upgraded in Run 4+
- Clear synergies with EIC physics program
- Many potential avenues to study final-state effects
  - Studies of hadrons, jets, correlations, etc…
- Run 4 and 5 pA datasets will be key to make connection to EIC