Highlights from the CMS experiment

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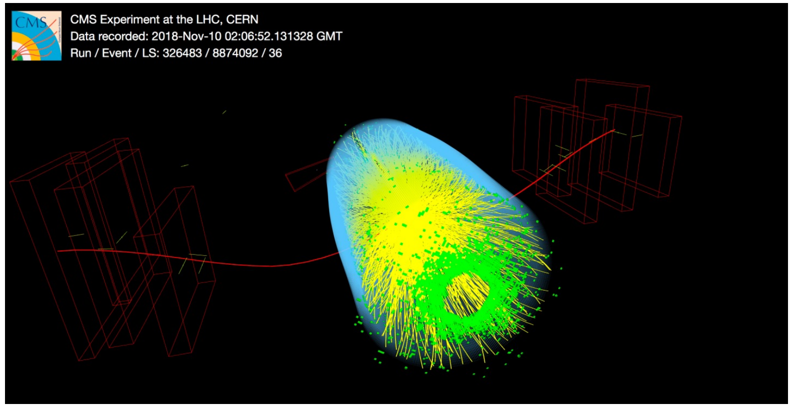
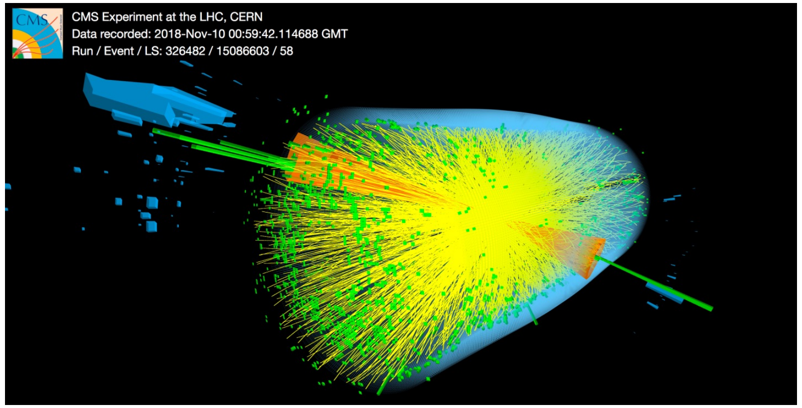
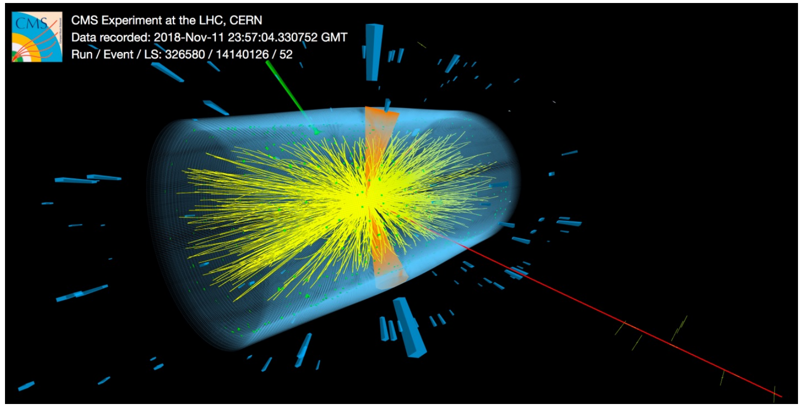
Experimental toolbox with CMS

- ✓ 4 colliding systems at LHC: p-p, p-Pb, Pb-Pb and Xe-Xe
- ✓ Wide range of center of mass energy available for different colliding species
- ✓ Large rapidity coverage in CMS



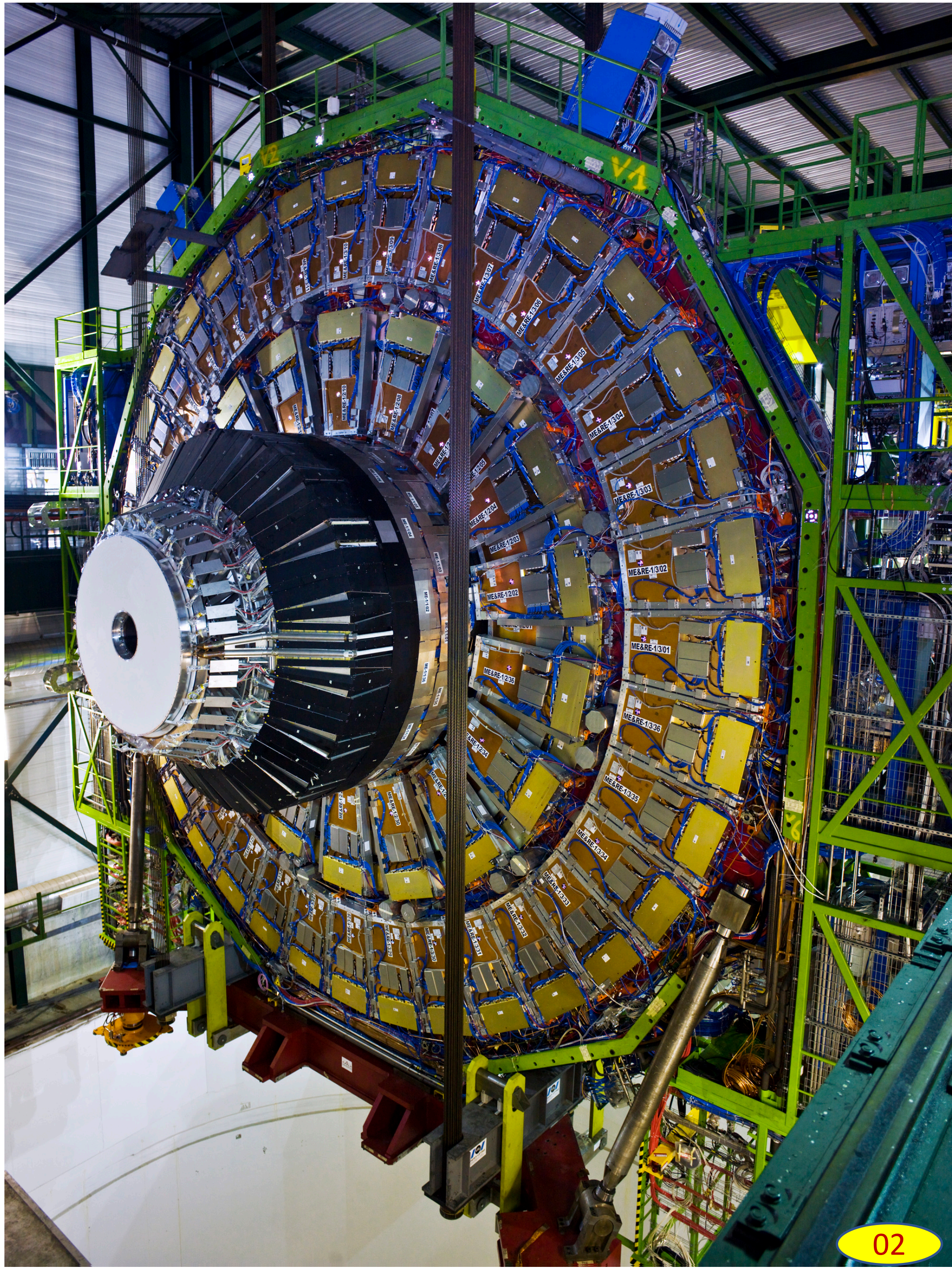




- ✓ Using the full experimental toolbox to probe heavy-ion collisions in CMS
  - colourless probes and photon processes for nuclear PDFs
  - heavy quark dynamics from small to large systems
  - medium modifications and medium response - cold vs. hot nuclear matter effects
  - charge particle correlations and fluctuations
  - new probes made accessible by high luminosity data samples

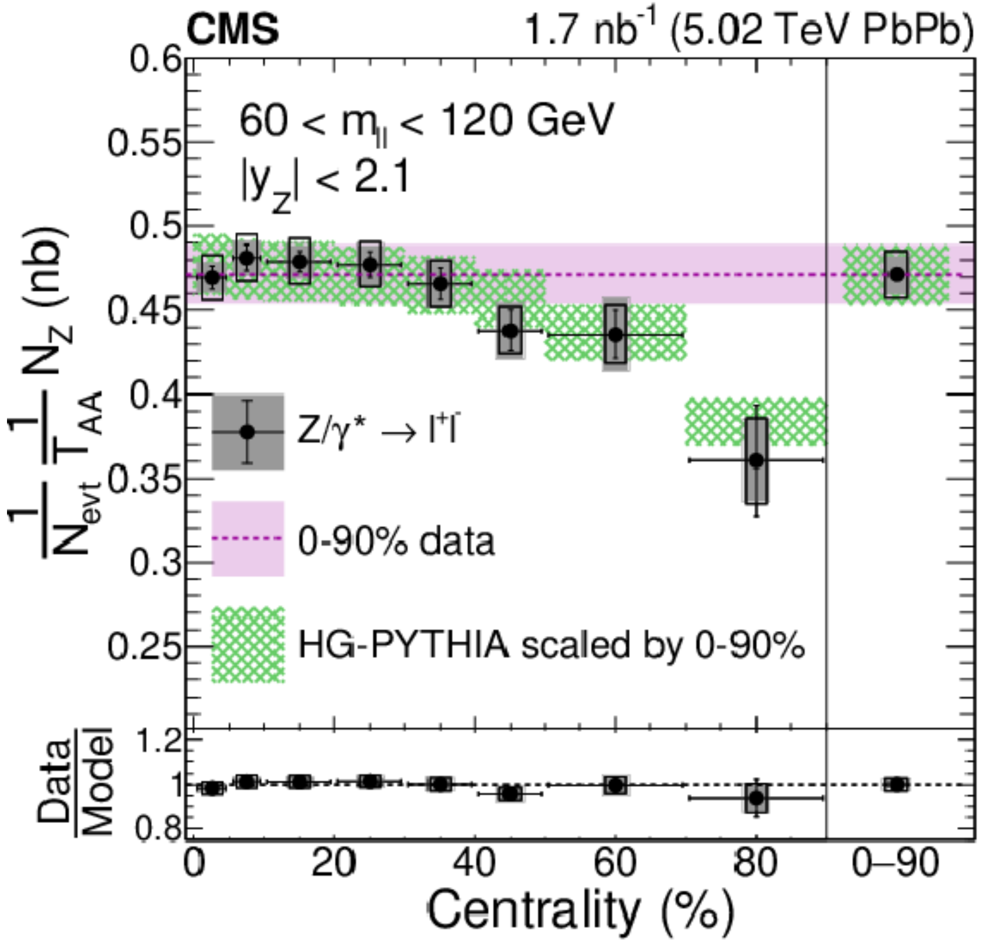
Outline – the probes

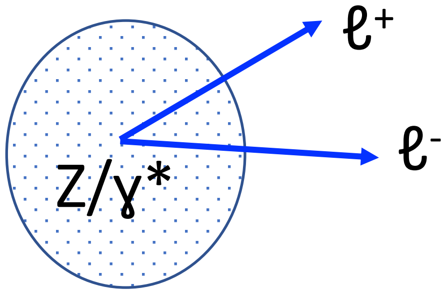
- Early dynamics and nPDFs
  - E/W bosons
  - J/ψ, dijets, Vn (UPC)
- Heavy quarks and quarkonia
  - J/ψ,Ψ(2S), D^0, Λ_c
  - B (→ D^0), $B_s{}^0$, $B_c{}^+$, Y(ns)
- Medium modifications
  - dijet and b jet shapes
  - dijet v_n
- Correlations & Fluctuations
  - intra jet correlation, $v_n - [p_T]$, $v_n\{2k\}$
  - net-charge fluctuations
- Run 3 and beyond



Early time dynamics and nPDFs

Z/ɣ* production in p-Pb and Pb-Pb

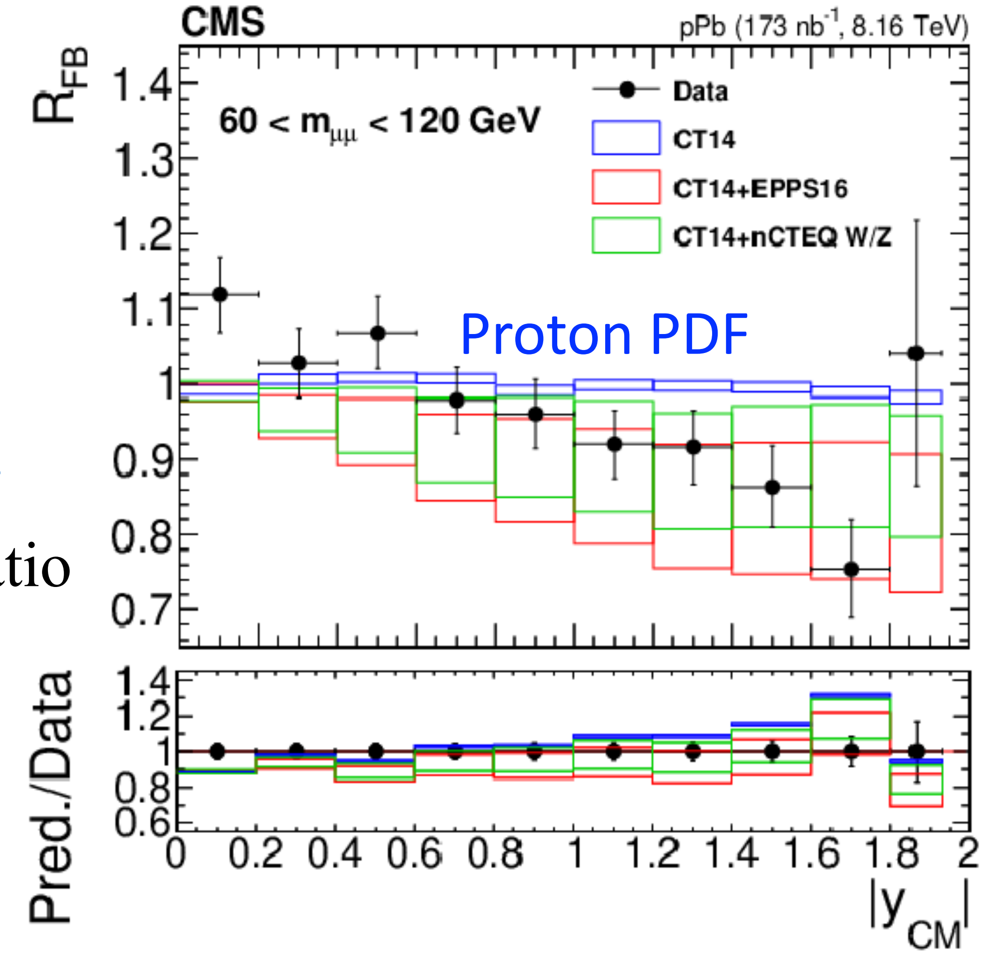




[JHEP05(2021)182](#)
[PRL 128 (2022) 122301](#)

Forward-backward ratio

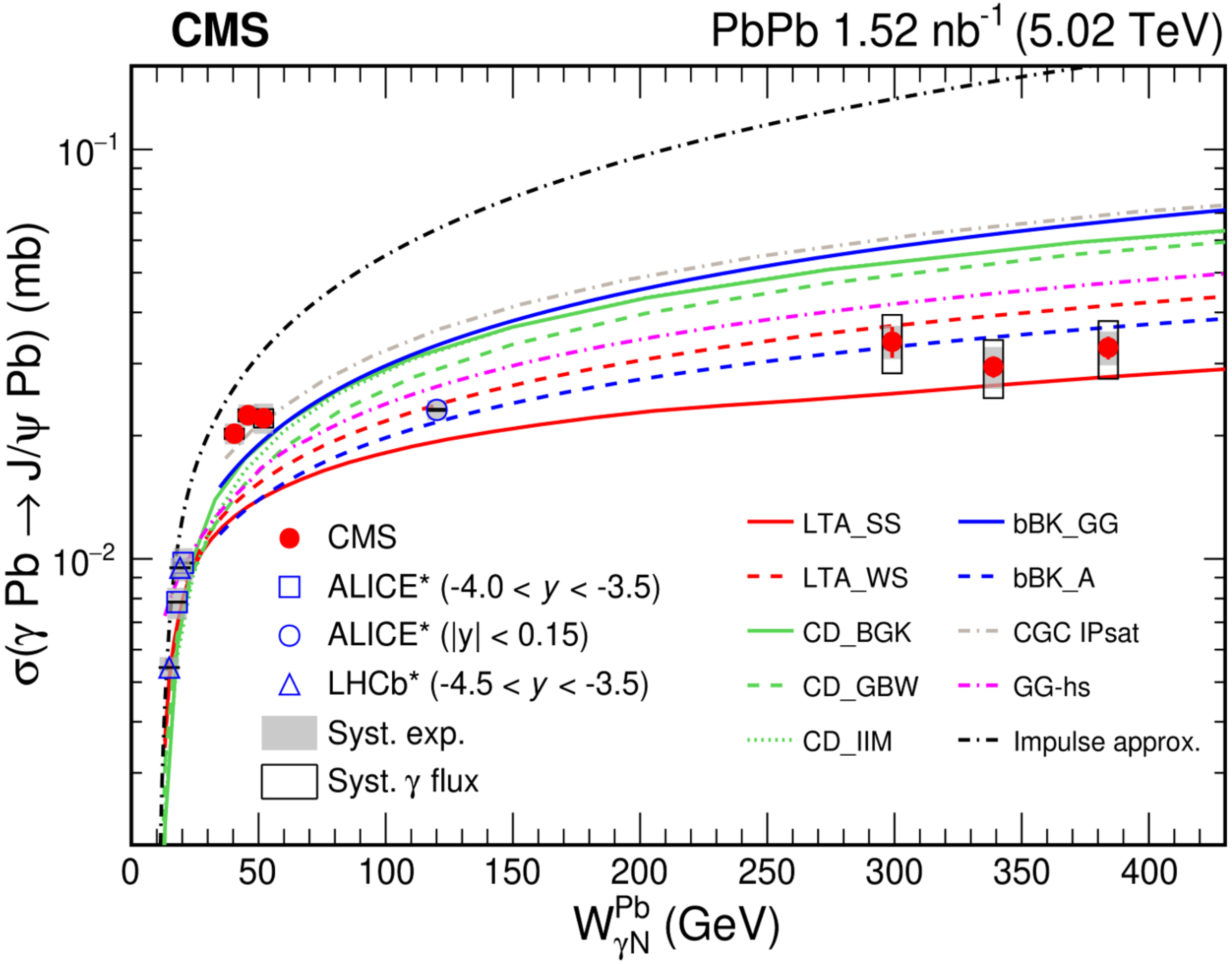
$$R_{FB} = \frac{d\sigma/dy\,|_{y>0}}{d\sigma/dy\,|_{y<0}}$$



- HG-PYTHIA grasps evolution with centrality → initial geometry & centrality bias in 40-80%
- Forward-backward ratios $R_{FB} \equiv 1$in the absence of nuclear effects
- W bosons, dijets, top quarks sensitive to gluons at different x

Coherent J/ψ in Pb-Pb UPC

arXiv:2303.16984 Submitted to PRL



- First measurement of exclusive coherent J/ψ cross section in photon-nucleus frame
- CMS measurement up to W ~ 400 GeV
- No significant change in the range 40 < W < 400 GeV => evidence for strong gluon saturation or indication of other new physics?
- Probing small-x ∼ 10^{-4} – 10^{-5} gluons in nuclei

$W_{\gamma N}^{Pb}$ → photon–nucleus C.O.M. energy per nucleon

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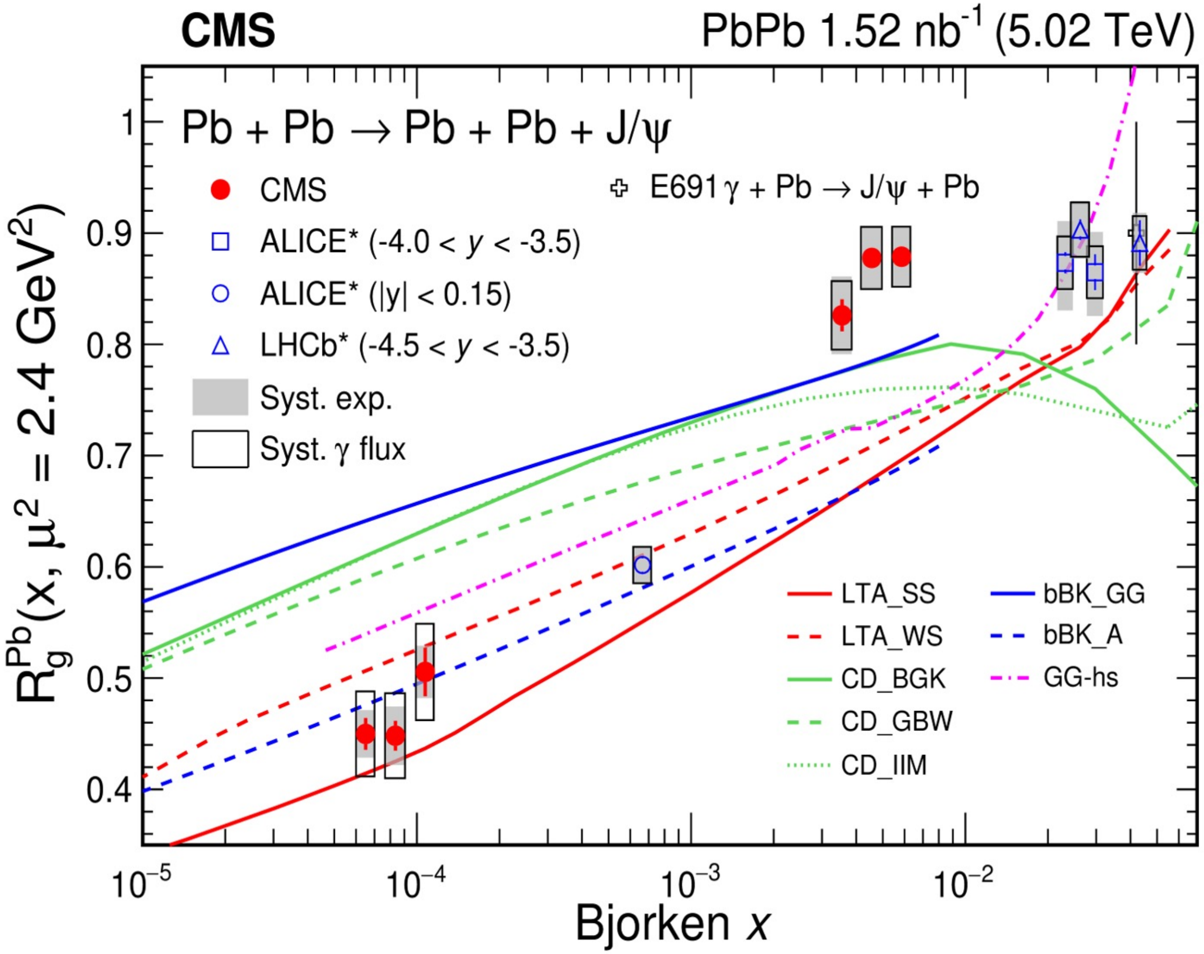
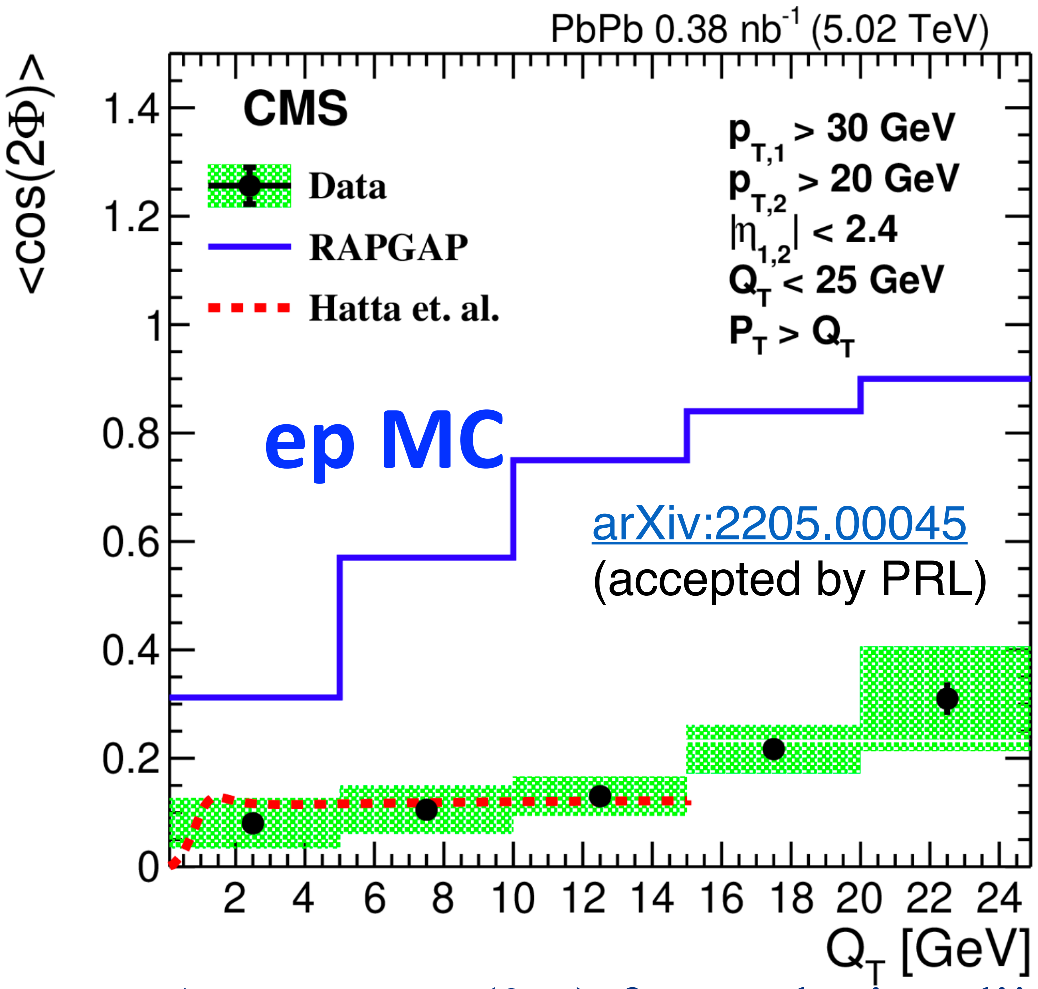


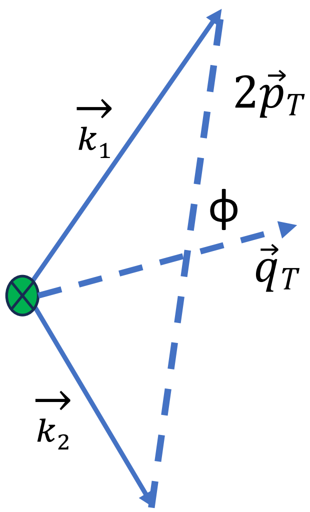
nuclear gluon suppression factor:

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

- Flattening of coherent J/ψ at Bjorken $x \sim 10^{-2}$ - 10^{-3}
- Rapid decrease towards small x region
  - Not described by the models
- LHC data seem to consistently point to a common x evolution

Angular correlations in excl. dijet and γp



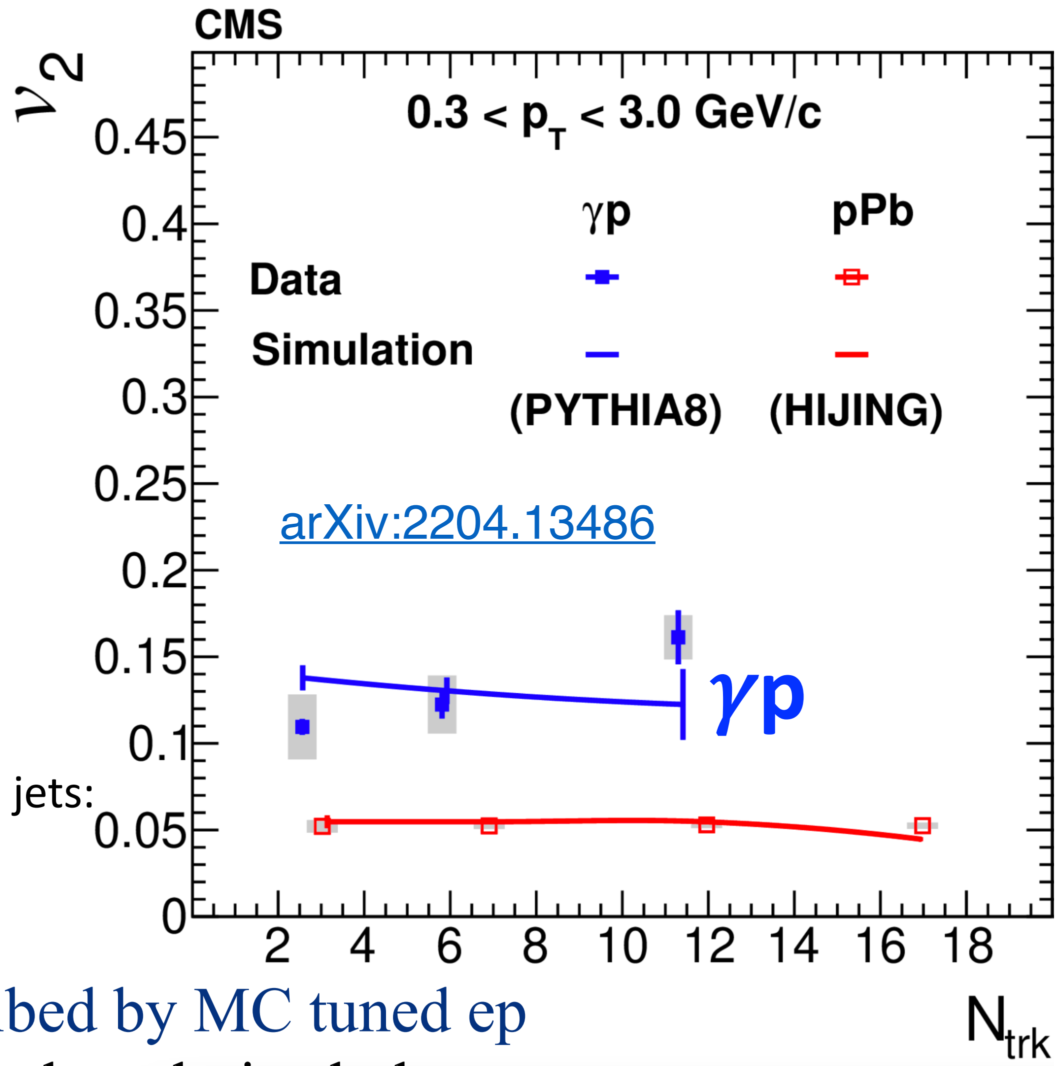


Vector sum of 2 jets:

$$\vec{Q}_T = \vec{k_1} + \vec{k_2}$$

Vector difference of 2 jets:

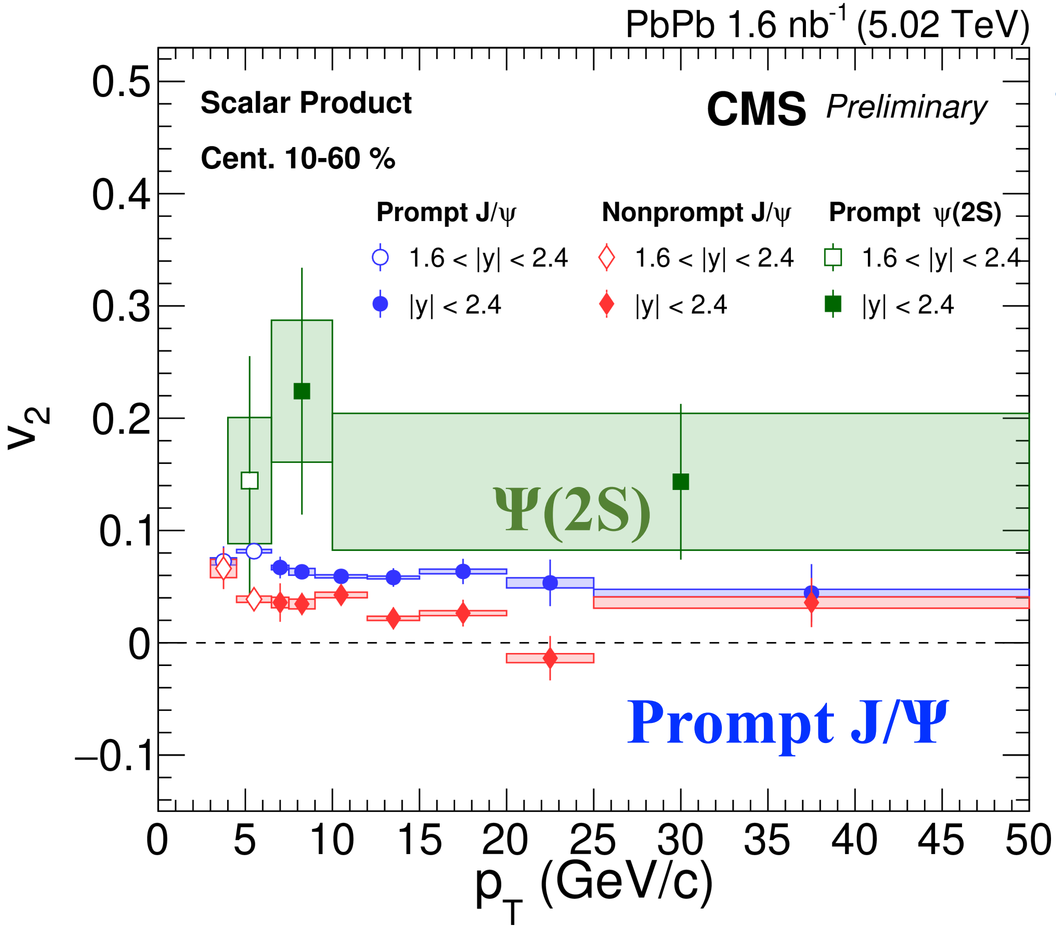
$$\vec{P}_T = \frac{1}{2}(\vec{k_1} - \vec{k_2})$$



- Average cos(2Φ) for exclusive dijets not well described by MC tuned ep
  - sensitive to primordial asymmetry due to the linearly polarized gluons
- Bridging large with exceedingly small systems

Heavy quarks and quarkonia

Charm and beauty flow in Pb-Pb



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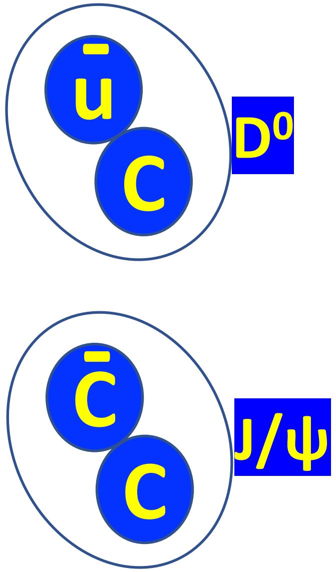
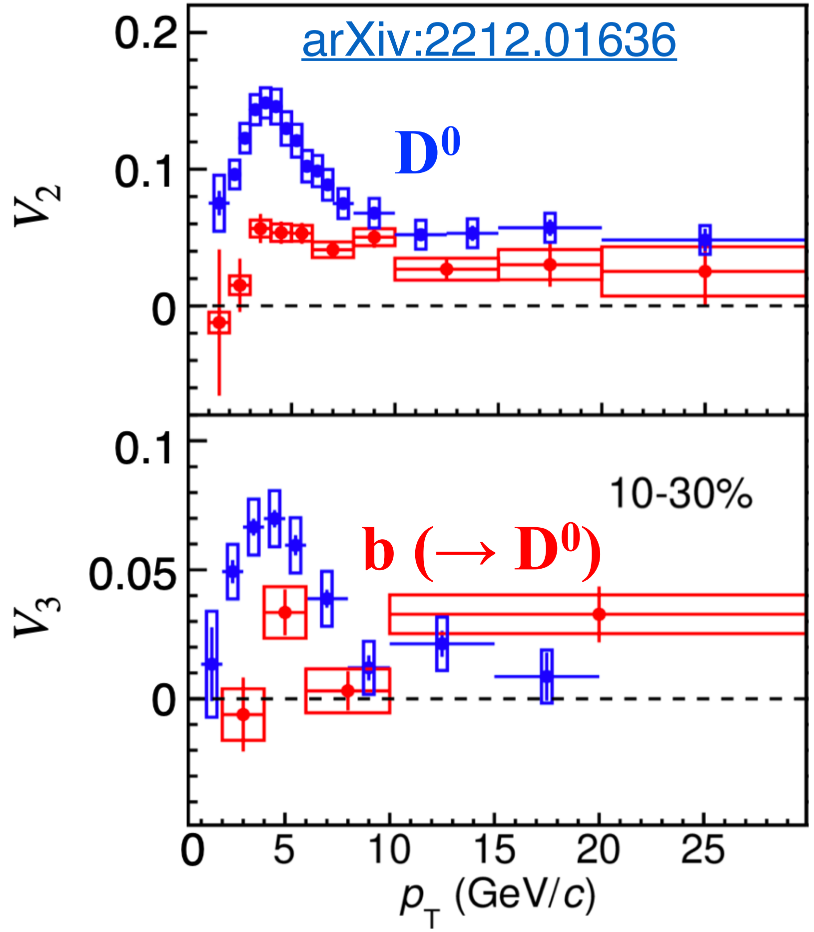
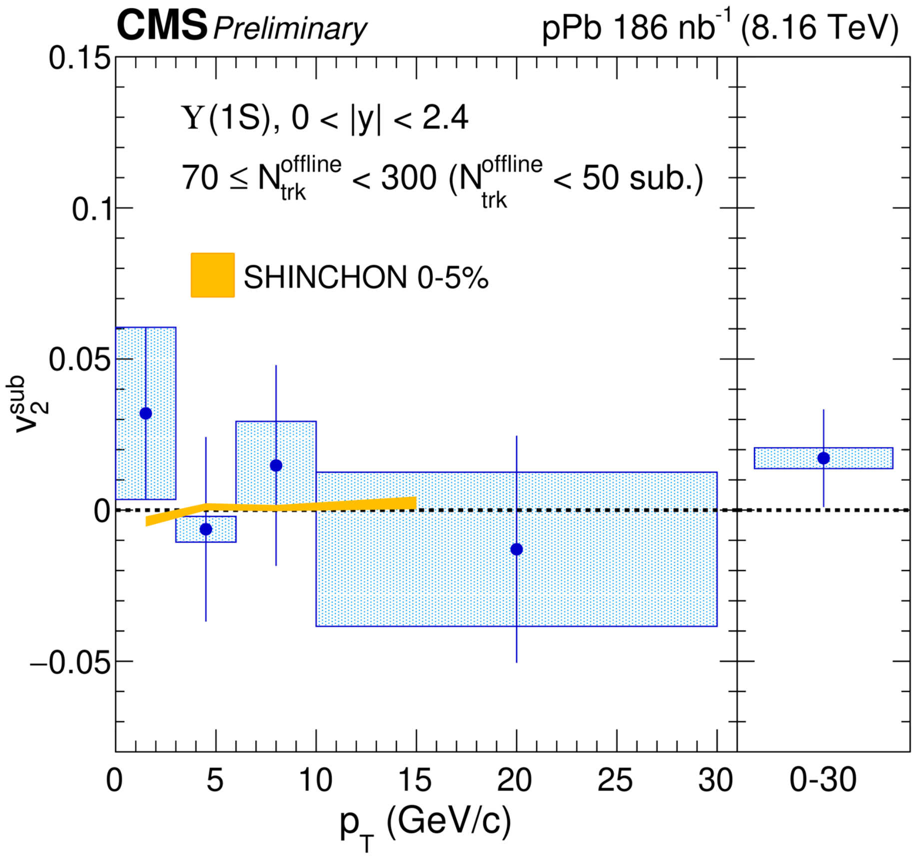


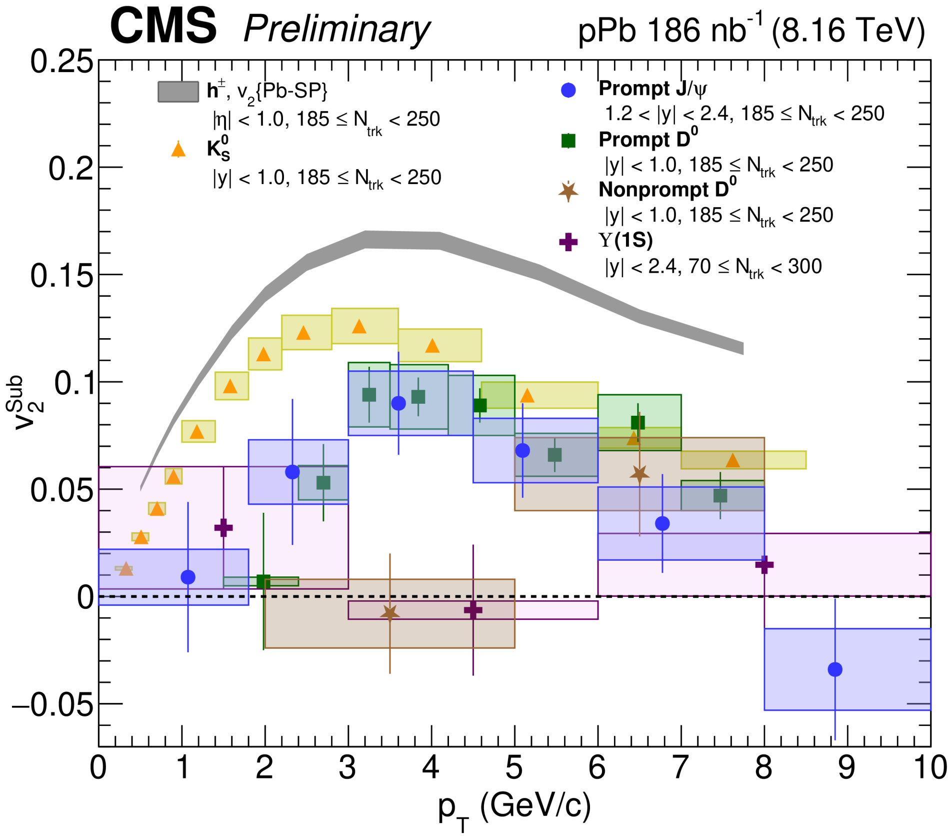


- First $v_{2,3}$ measurement for ψ(2S) → indicating recombination at later stage?
- First v_2 for b (→ D^0); b quark and D^0 meson p_T well correlated
  - v_2 of charm > b (→ D^0); whereas ϒ(1S), ϒ(2S) $v_2 \approx 0$
  - Evidence for b (→ D^0) $v_3 > 0$ at intermediate p_T

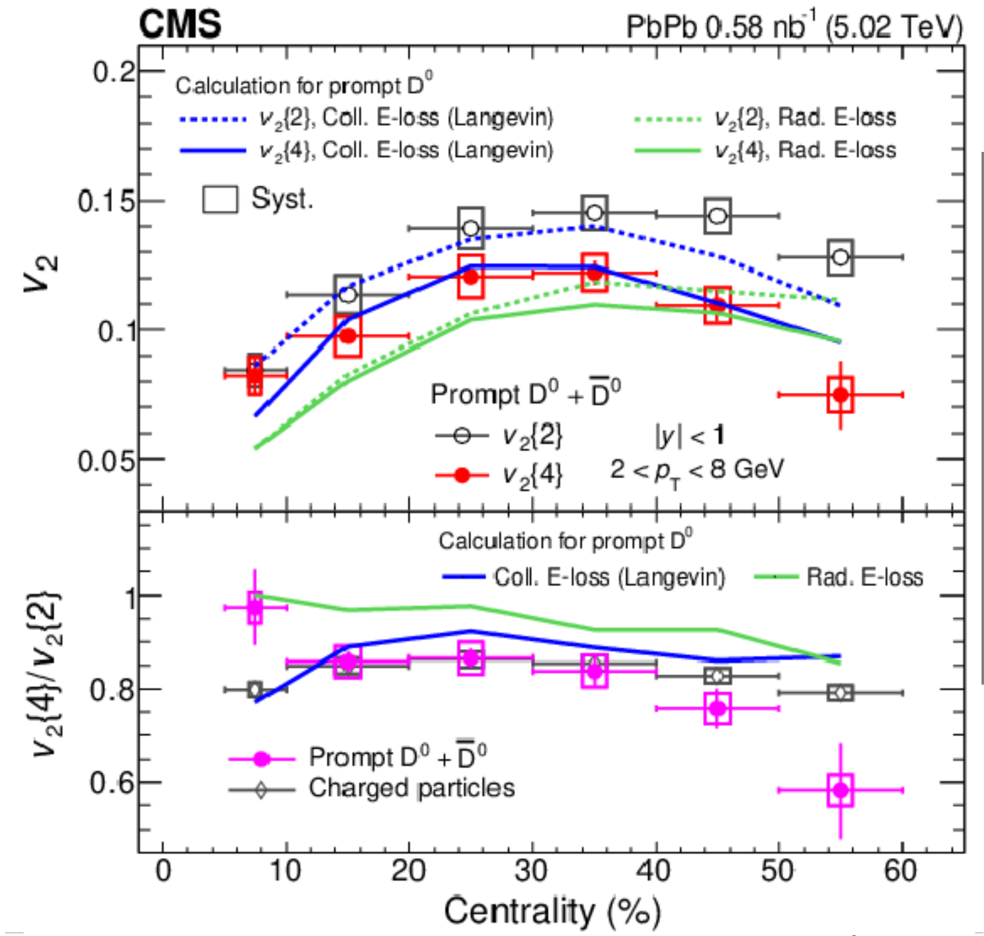
ϒ (1S) flow in high-multiplicity p-Pb



CMS-PAS-HIN-21-001

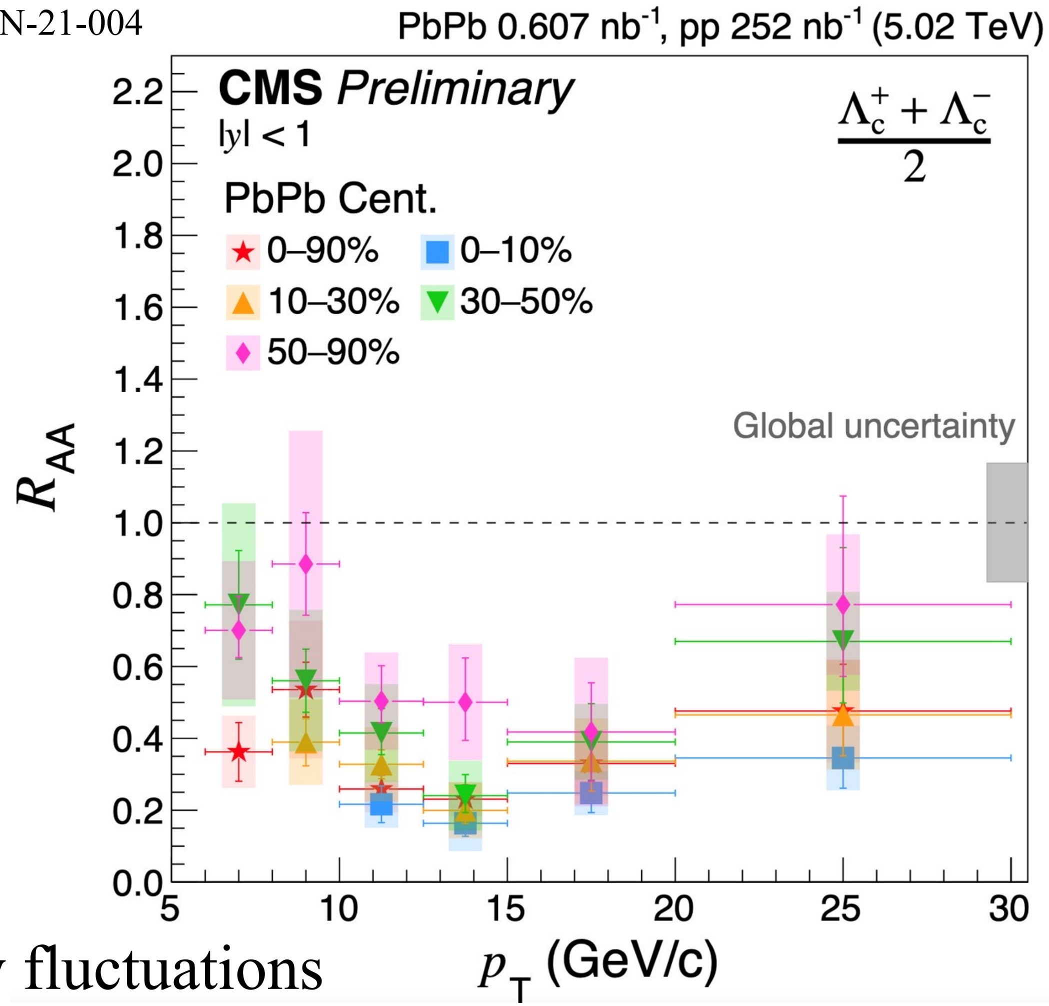


- First v_2 measurement of ϒ (1S) state in p-Pb
  - $v_2 \approx 0$ up to 30 GeV/c (!), similar to a model with final-state interactions only
- Bridging HF flow measurement in large and small systems
  - clear mass ordering → heavier particles flow less
  - do open/closed b hadrons flow in p-Pb?



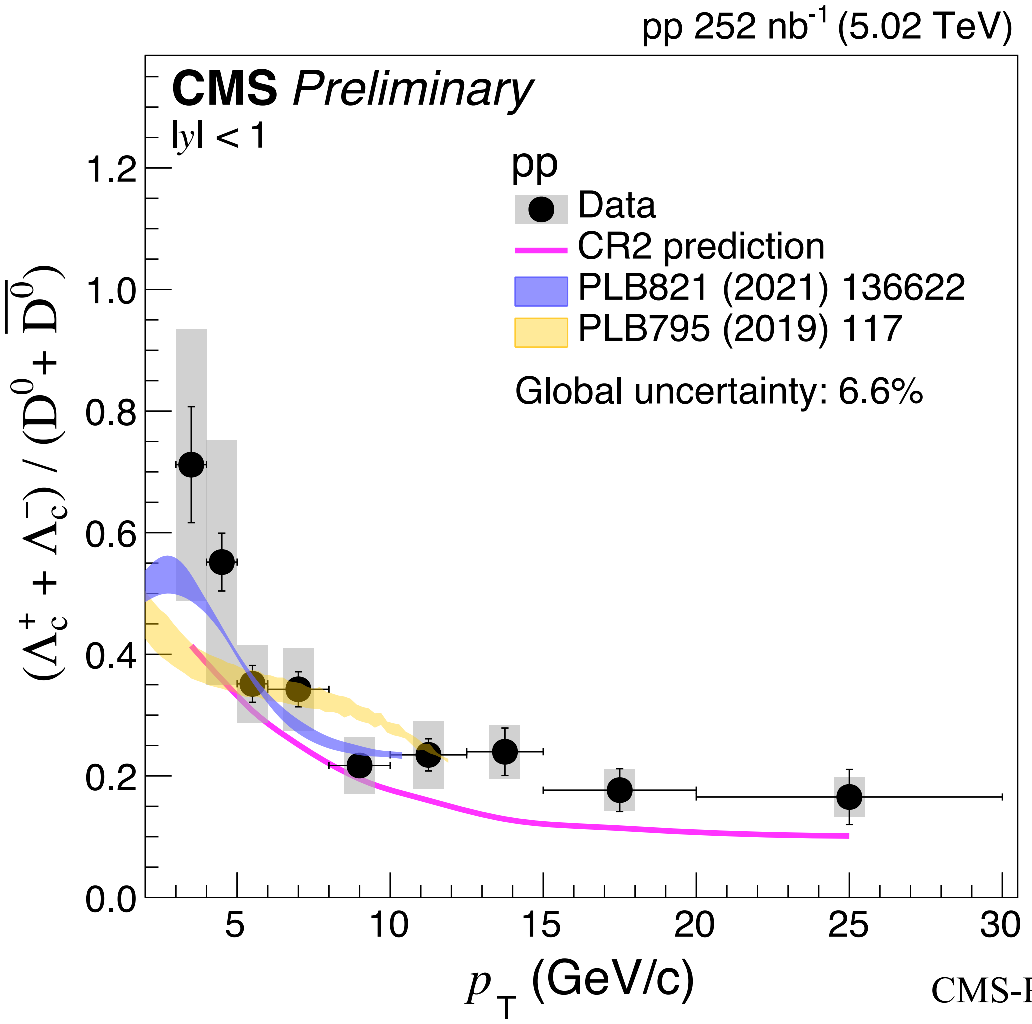
Phys. Rev. Lett. 129 (2022) 022001

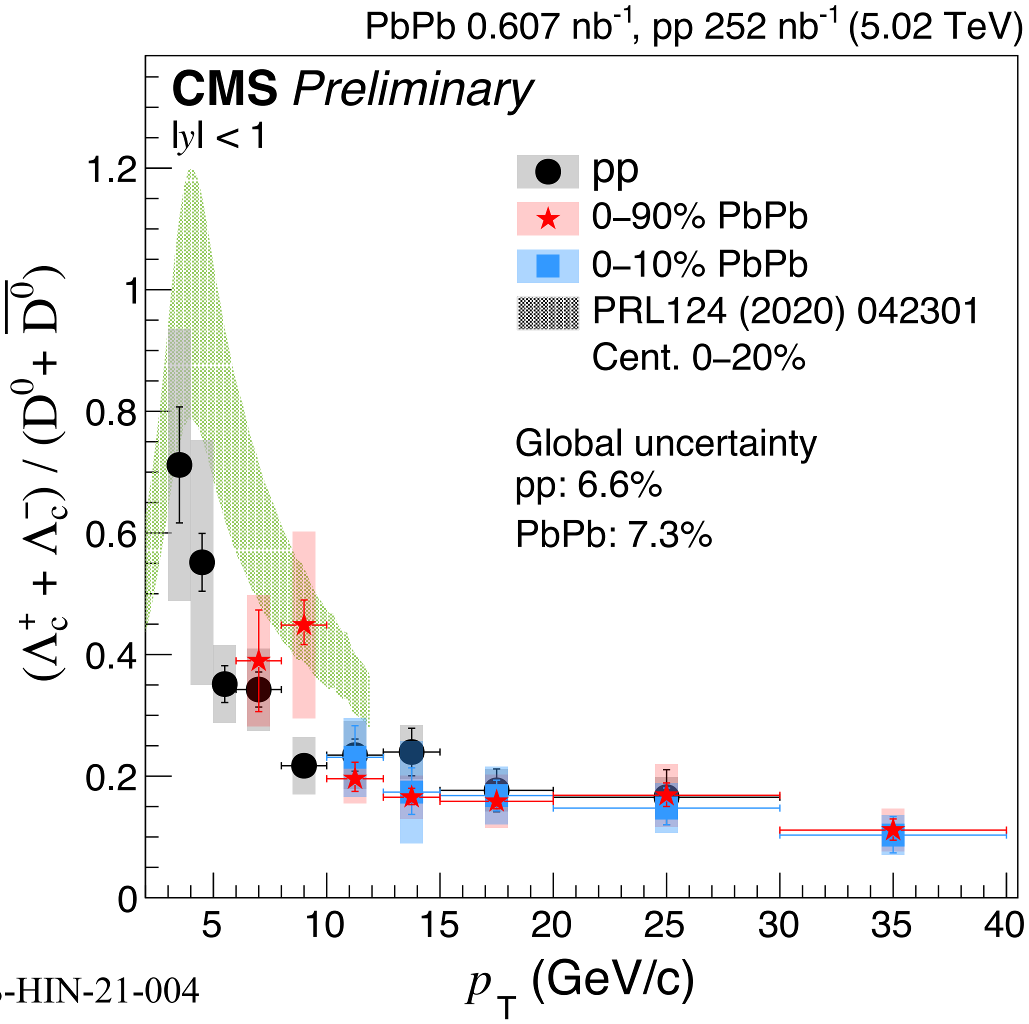
CMS-PAS-HIN-21-004



- $V_2\{4\} < V_2\{2\}$ for prompt D^0 → large flow fluctuations
- Fluctuations of initial geometry + parton energy loss
- Large suppression of Λ_c in most central (0-10%) Pb-Pb collisions
  - Trend consistent with other HF hadrons with min p_T R_{AA} different

Charm quark hadronization in p-p and Pb-Pb

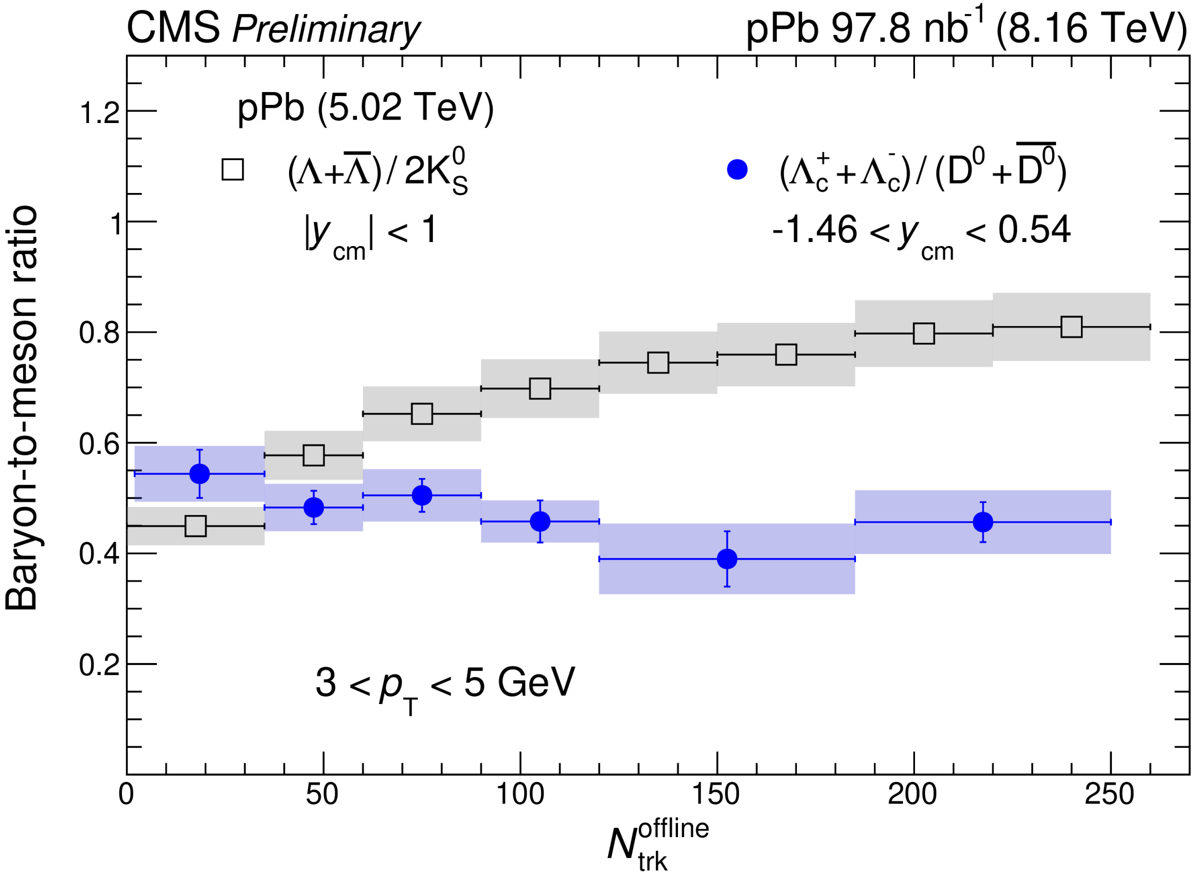


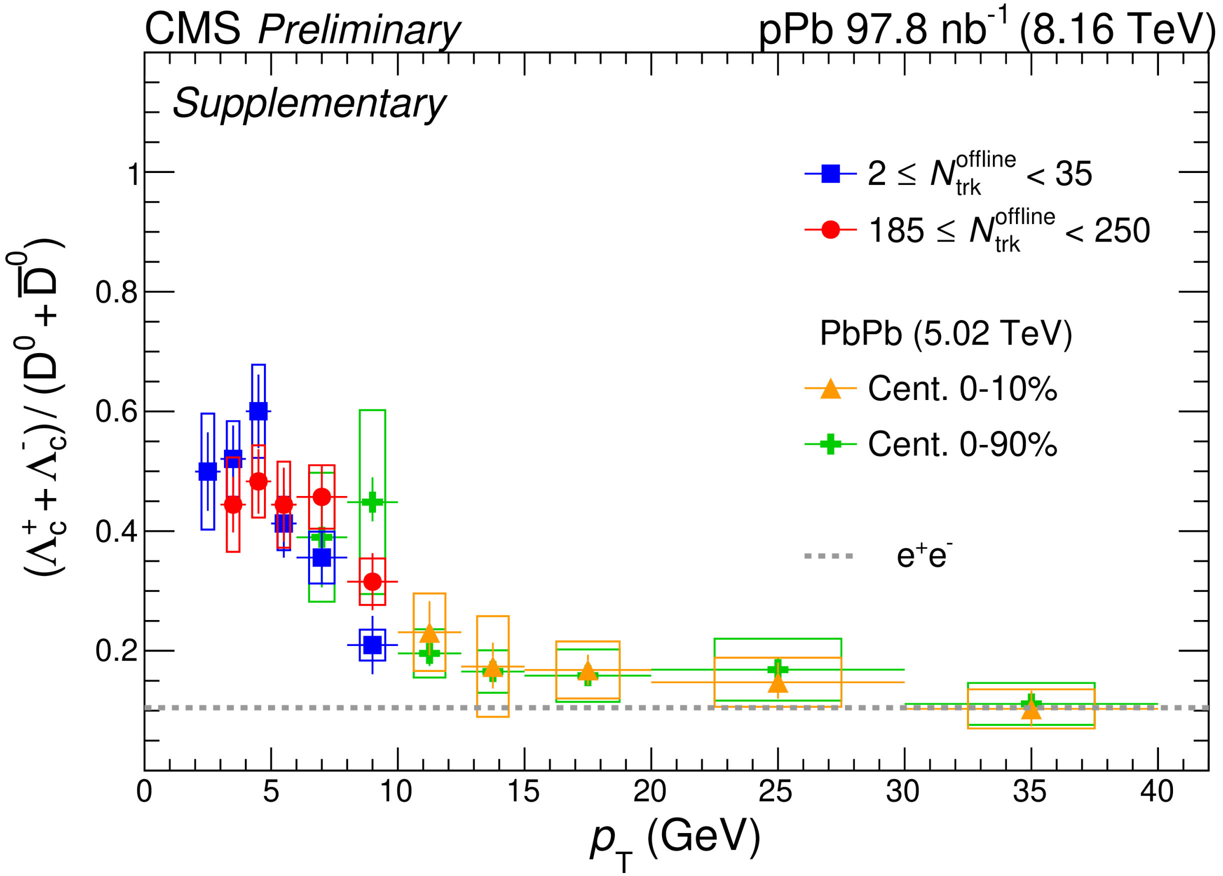


CMS-PAS-HIN-21-004

- PYTHIA8+CR2 describes Λ_c^+ to D^0 ratio in pp collisions
- Ratio consistent in pp and Pb-Pb → no significant contribution from coalescence

Charm quark hadronization in p-Pb and Pb-Pb

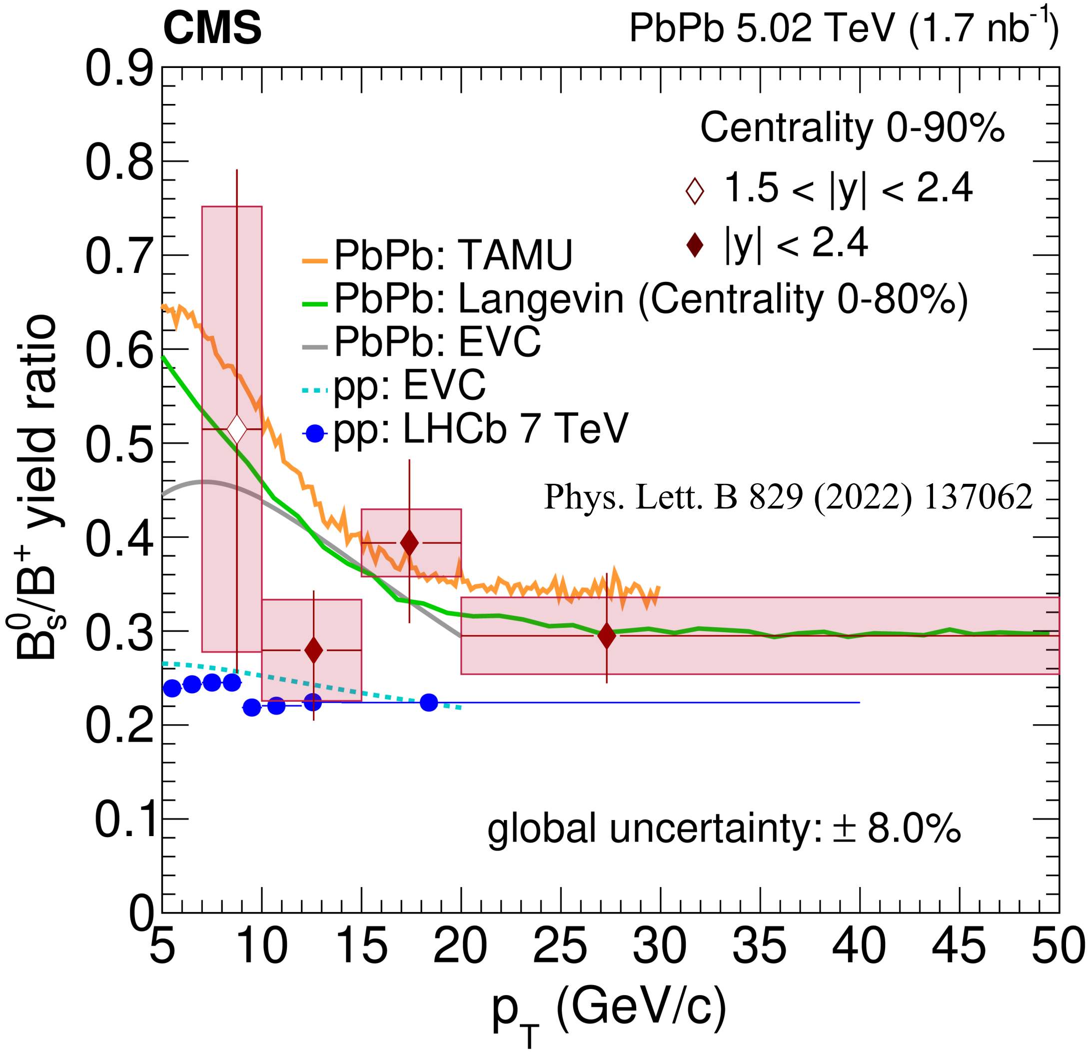


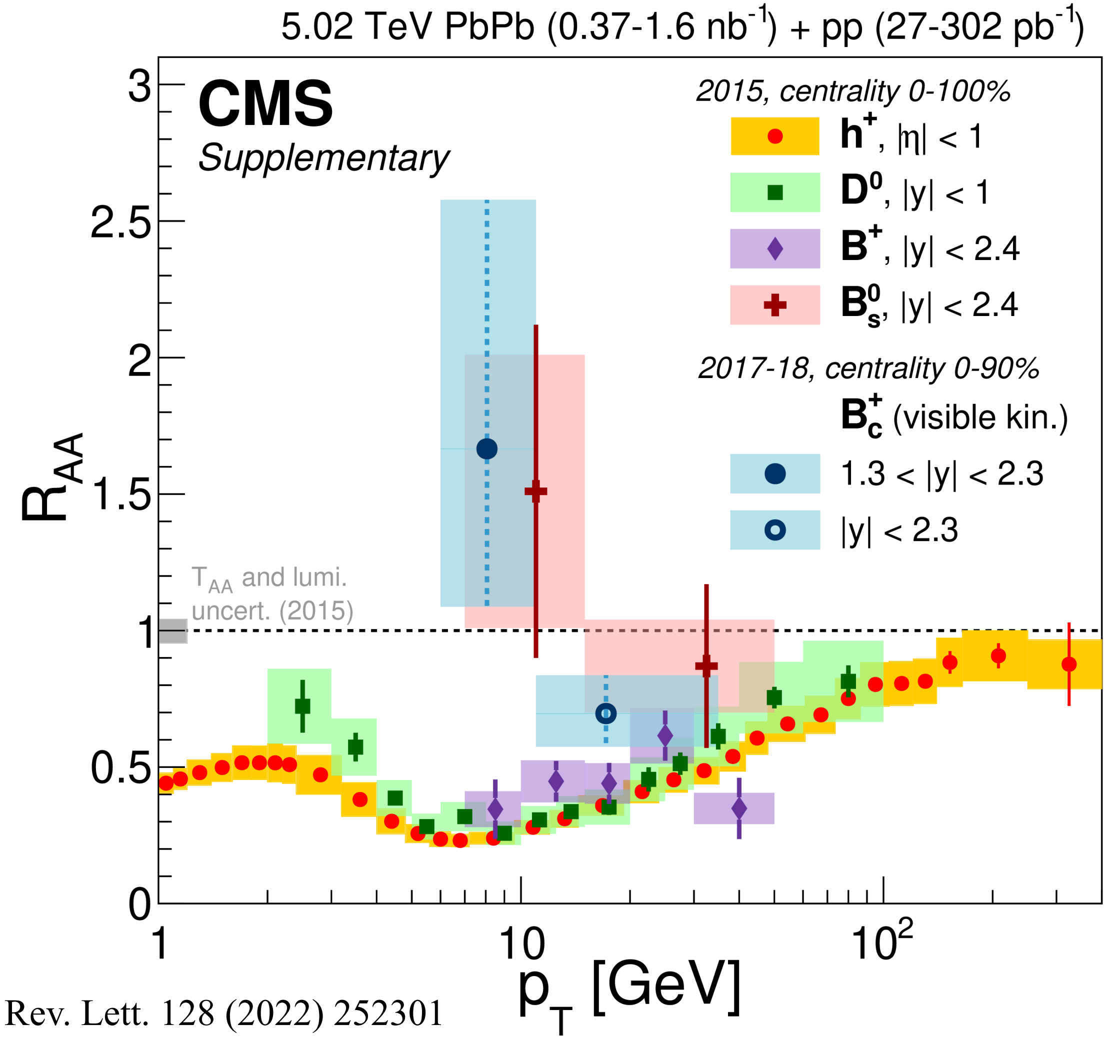


- First measurement of the Λ_c^+ / D^0 vs N_{trk} in p-Pb collisions
- p-Pb and MB Pb-Pb consistent at intermediate p_T

CMS-PAS-HIN-21-004
CMS-PAS-HIN-21-016

Beauty hadronization in Pb-Pb

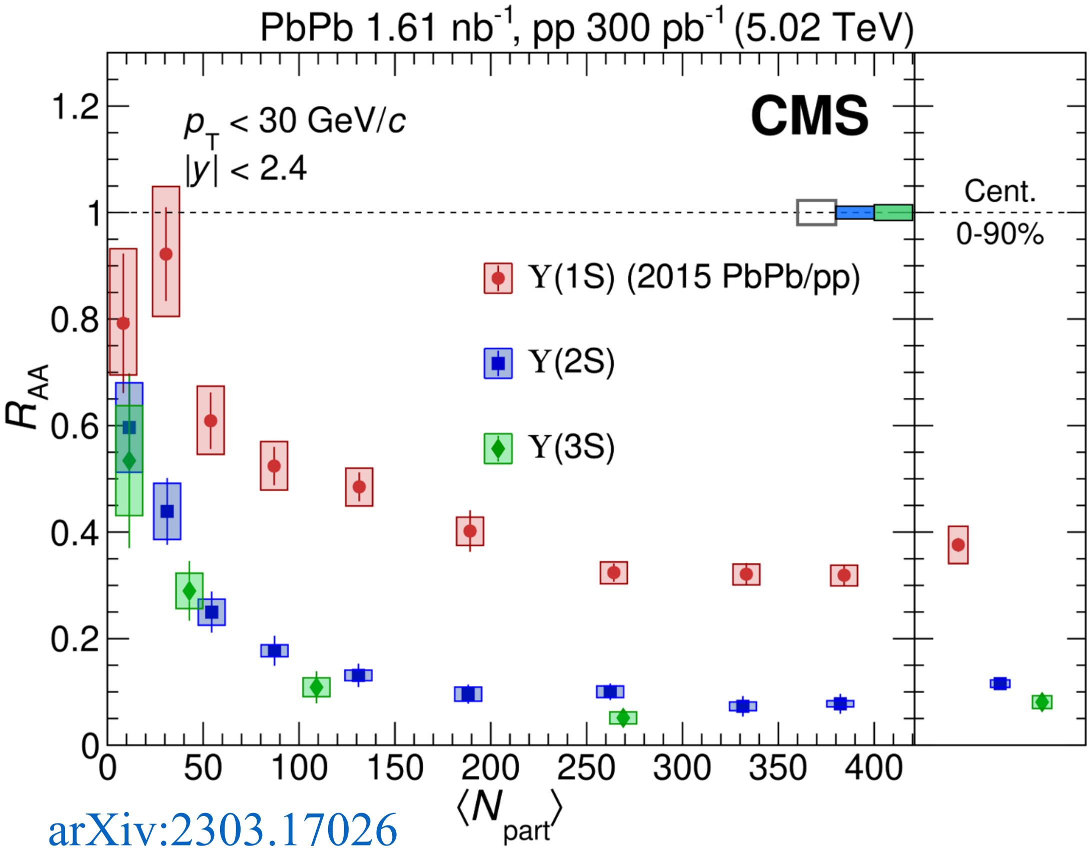




Phys. Rev. Lett. 128 (2022) 252301

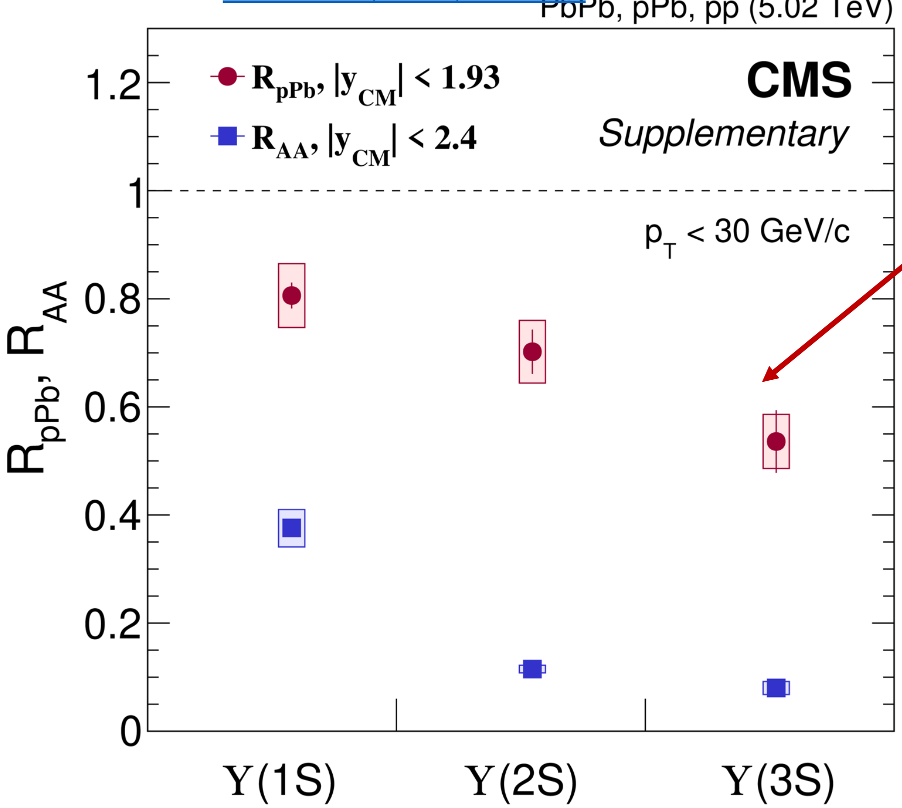
- Indication of enhanced B_s^0/B^+ (with large uncertainty) in Pb-Pb compared to pp at low p_T
- Flavor dependent R_{AA} → recombination of c and b

ϒ (nS) suppression in p-Pb and Pb-Pb



arXiv:2303.17026

PLB 835 (2022) 137397



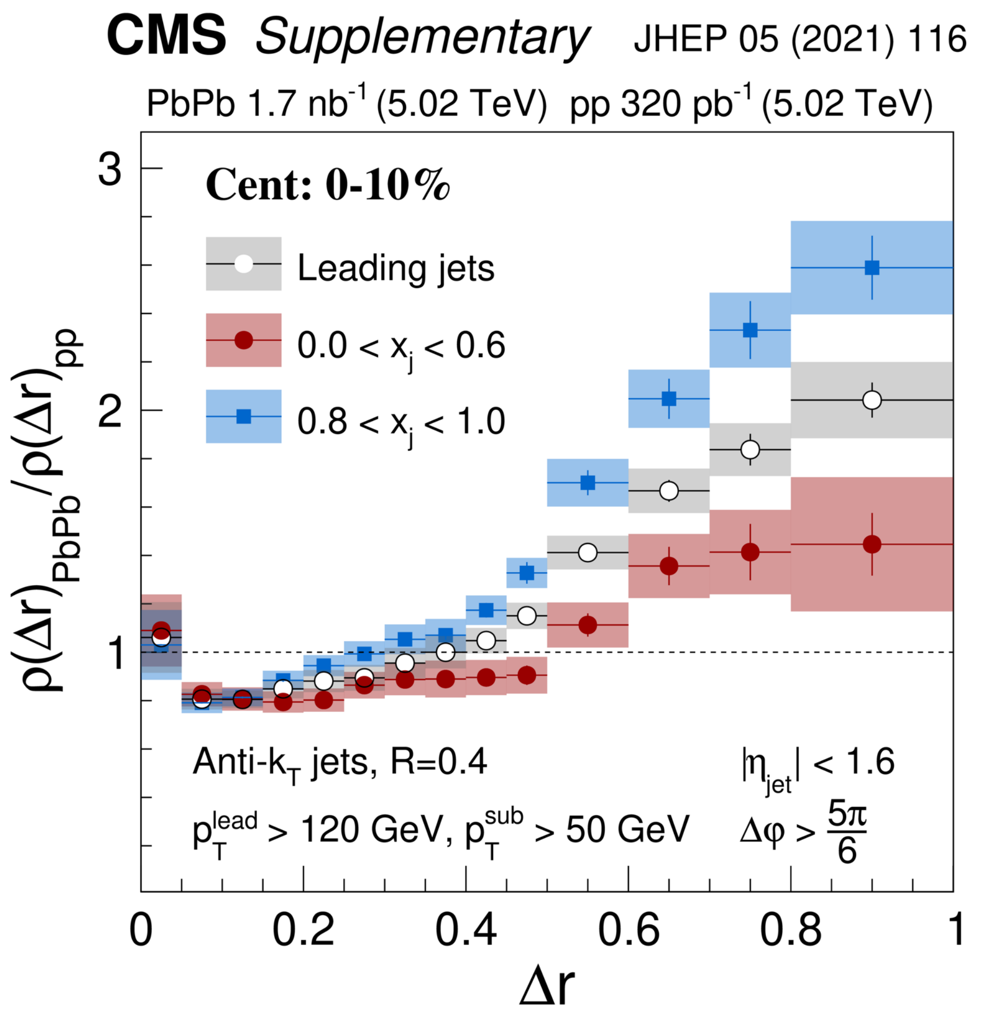
Ordering in p-Pb: suggests some final state effects

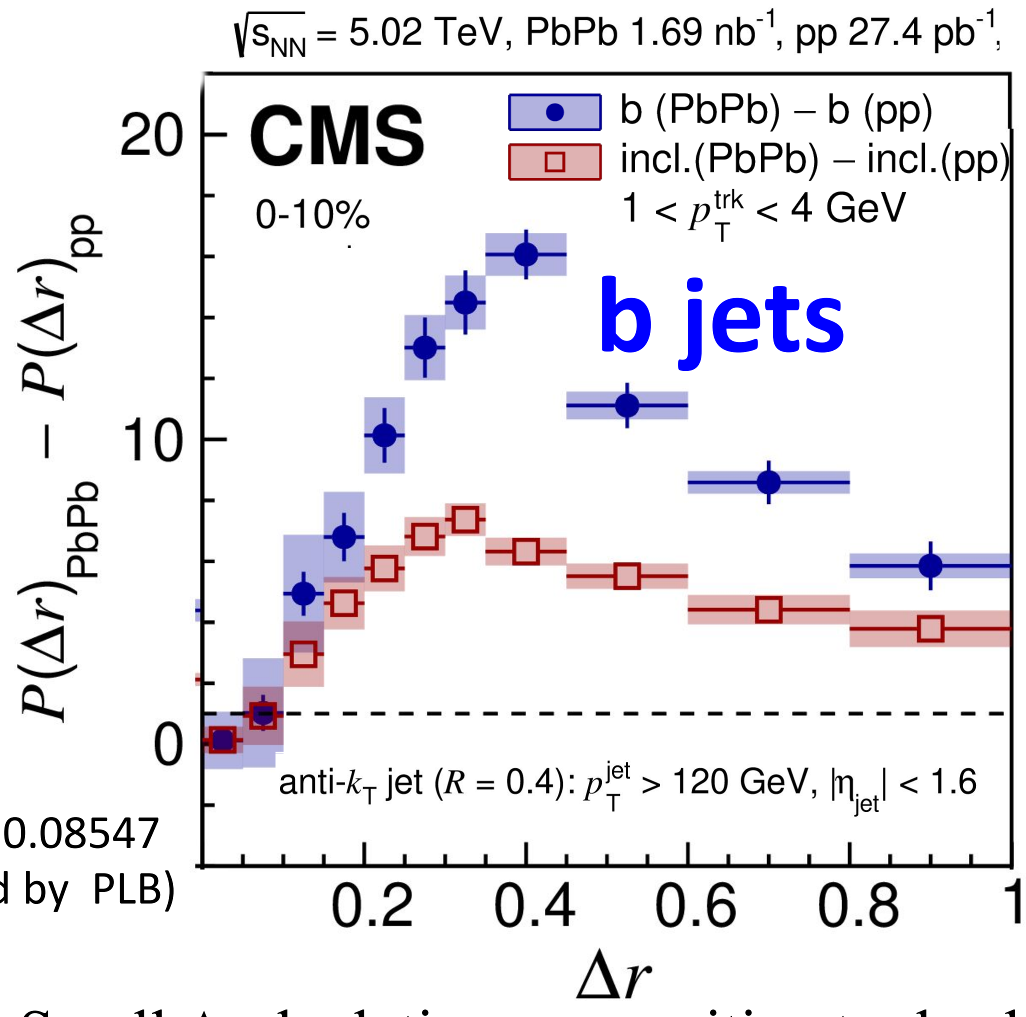
Large effect from hot nuclear effect

- ϒ states are suppressed sequentially: ϒ(3S) → ϒ(2S) → ϒ(1S)
- Suppression observed for both Pb-Pb and p-Pb collisions
  - Suppression magnitude in p-Pb is much smaller compared to Pb-Pb
- p-Pb vs Pb-Pb: helps disentangle cold nuclear effects and hot nuclear effects

Medium modifications

How does energy loss distributed ?

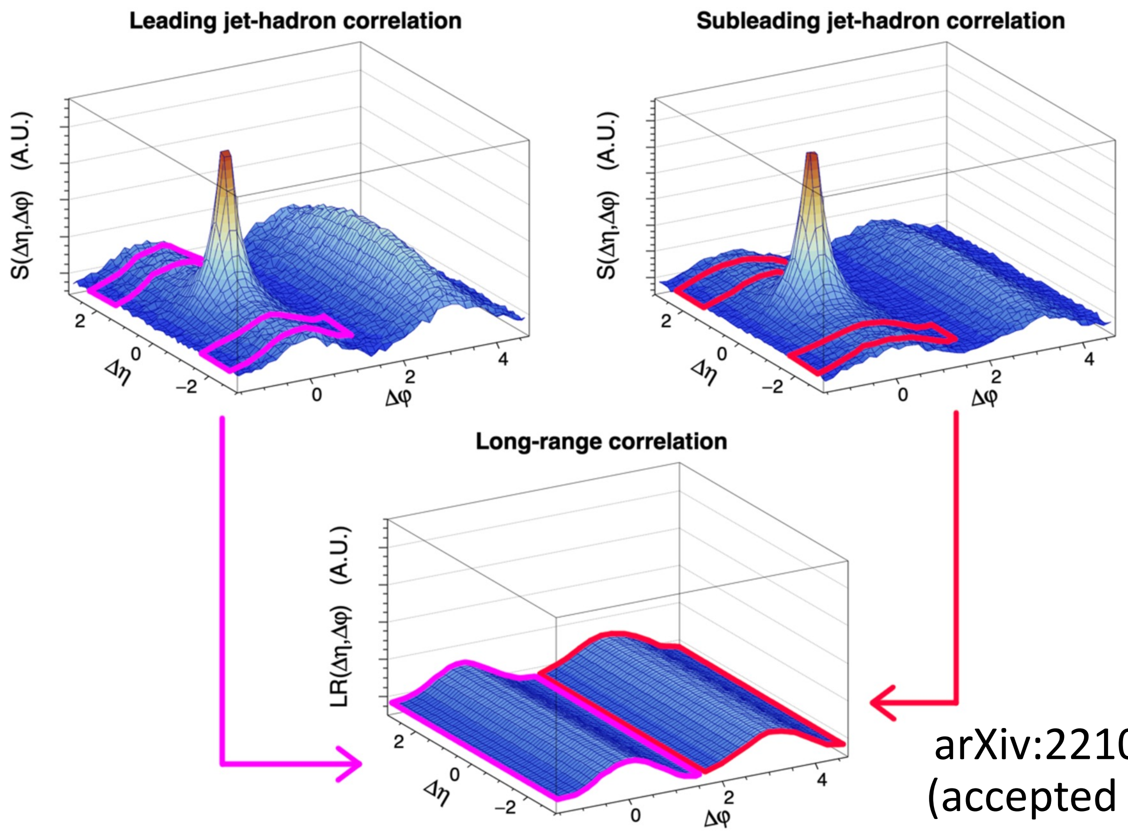




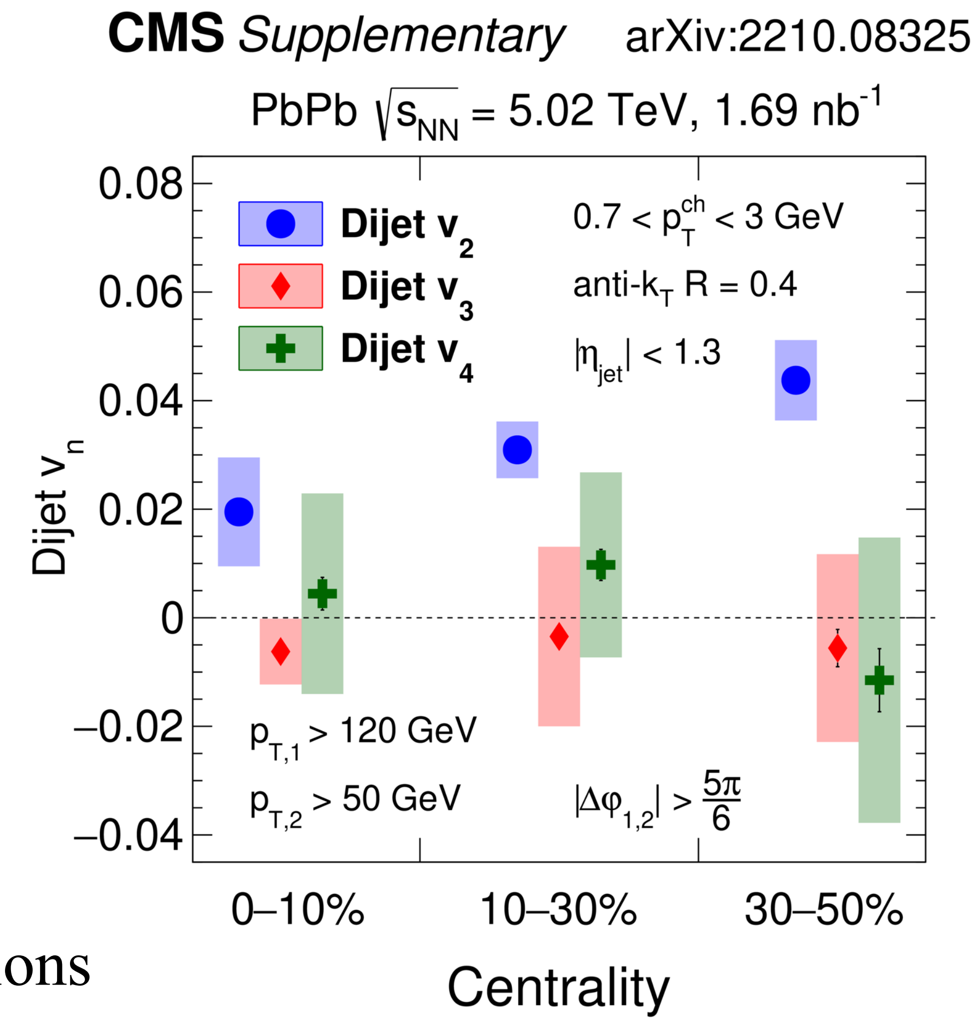
arXiv:2210.08547
(accepted by PLB)

- Dijets: In-medium path length for leading jets is larger when $x_j \approx 1$
- Small Δr depletion → sensitive to dead cone effects
- Large Δr enhancement → medium response to b quark

Dijet v_n in Pb-Pb



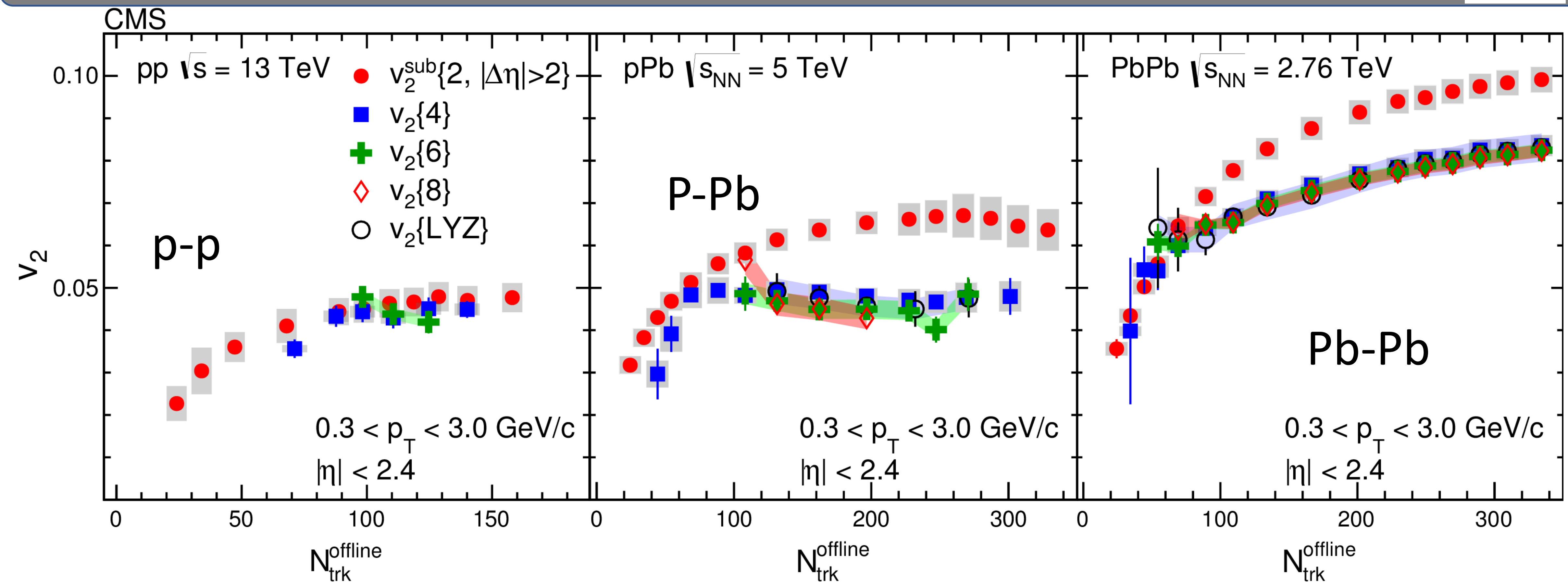
arXiv:2210.08325
(accepted by JHEP)



- Path-length dependent energy loss and it's fluctuations
  - dijet $v_2 > 0$ with expected centrality dependence → consistent with high-p_T hadron v_2
  - dijet v_3, $v_4 \approx 0$ → need to reduce uncertainty to be sensitive to initial state or energy loss fluctuations

Correlation & Fluctuations

Onset of collectivity from large to small systems



- Collectivity: $V_2\{2\} \approx V_2\{4\} \approx V_2\{6\}$
  - Similar trend with different magnitude in all 3 systems
  - Initial state fluctuations play important role

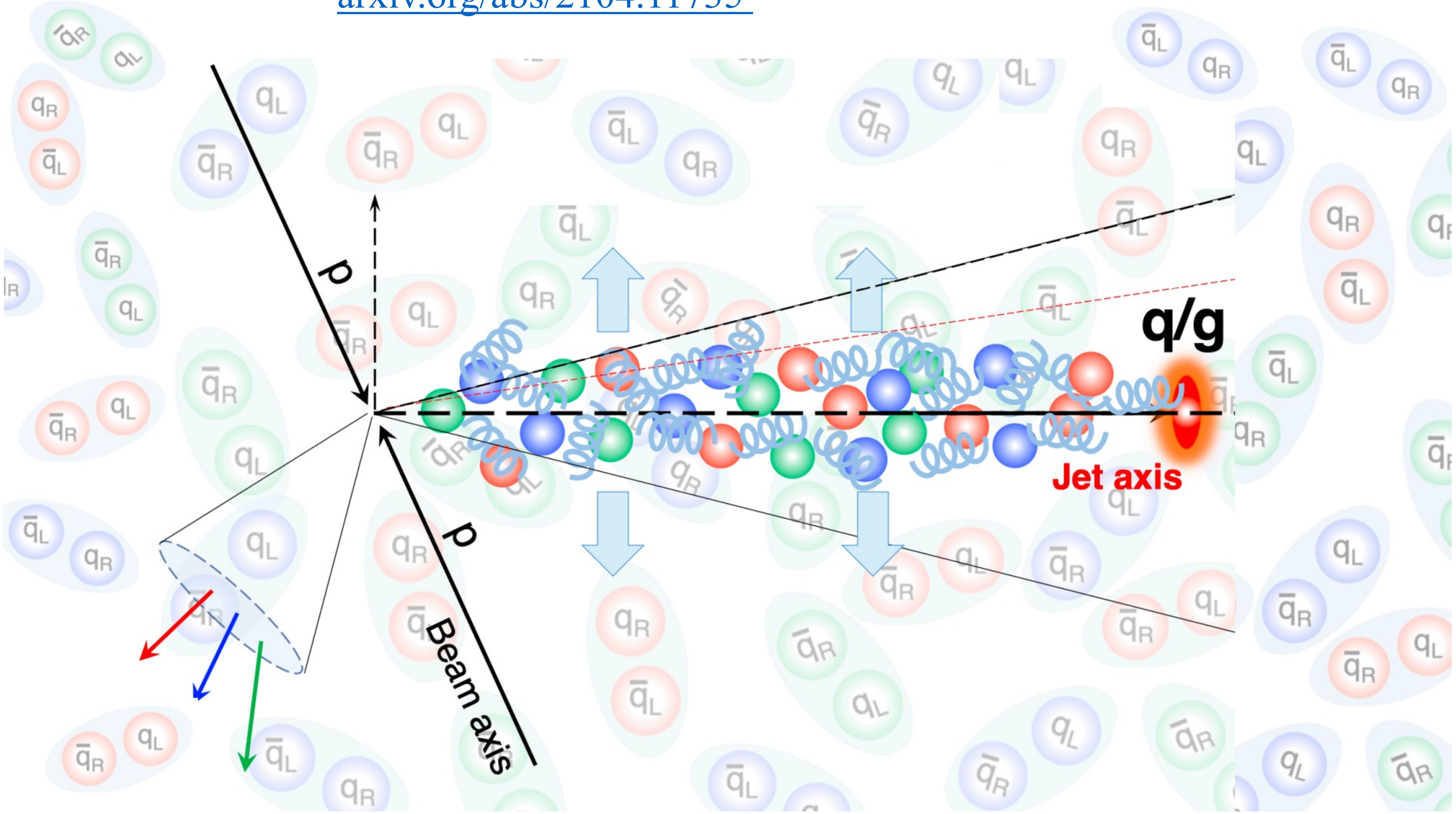
Phys. Lett. B 765 (2017) 193

What is the underlying mechanism driving collectivity?

How small of a system can partonic collectivity emerge?

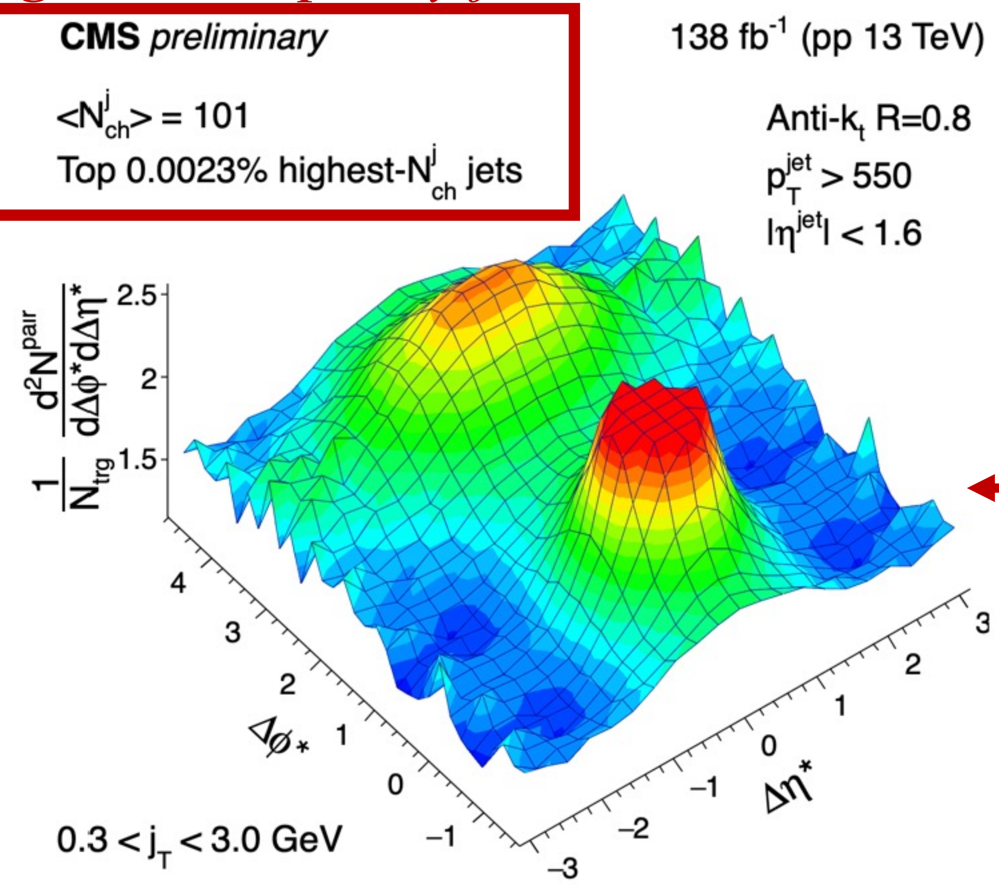
Strongly interacting QGP-like state can be formed by system initiated by single quark or gluon propagating through QCD vacuum.

arxiv.org/abs/2104.11735



Intra-jet correlation in p-p collisions

Highest multiplicity jets



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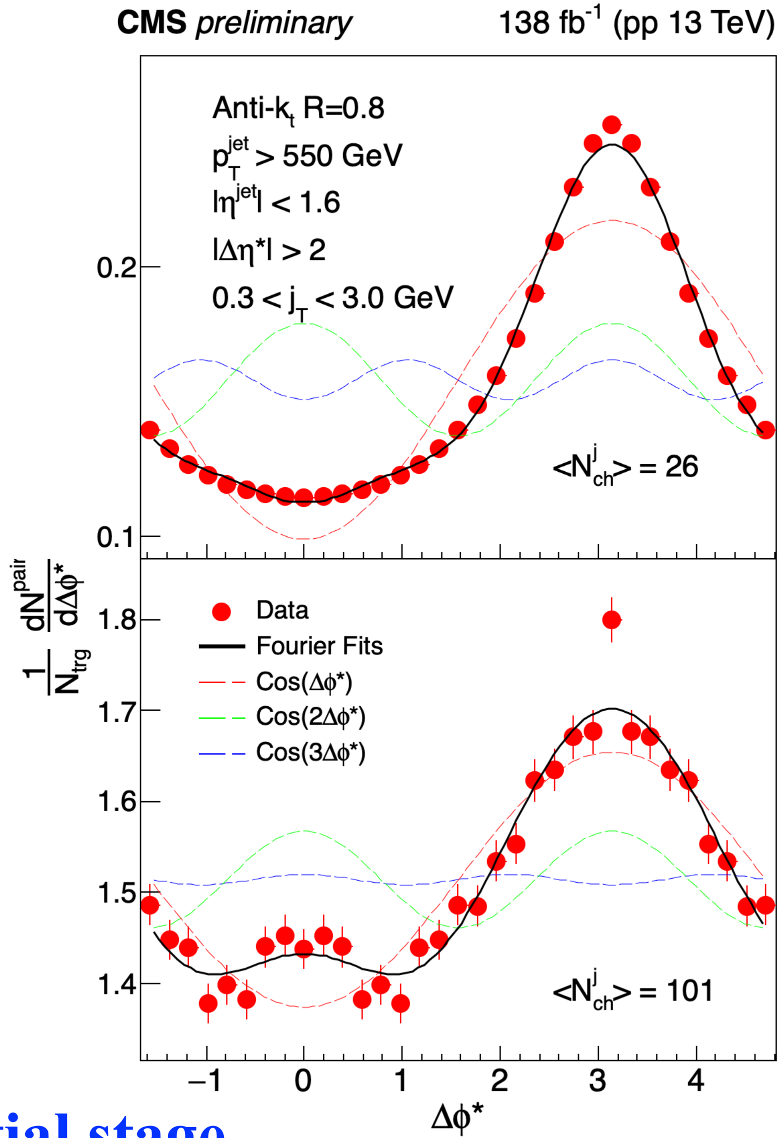
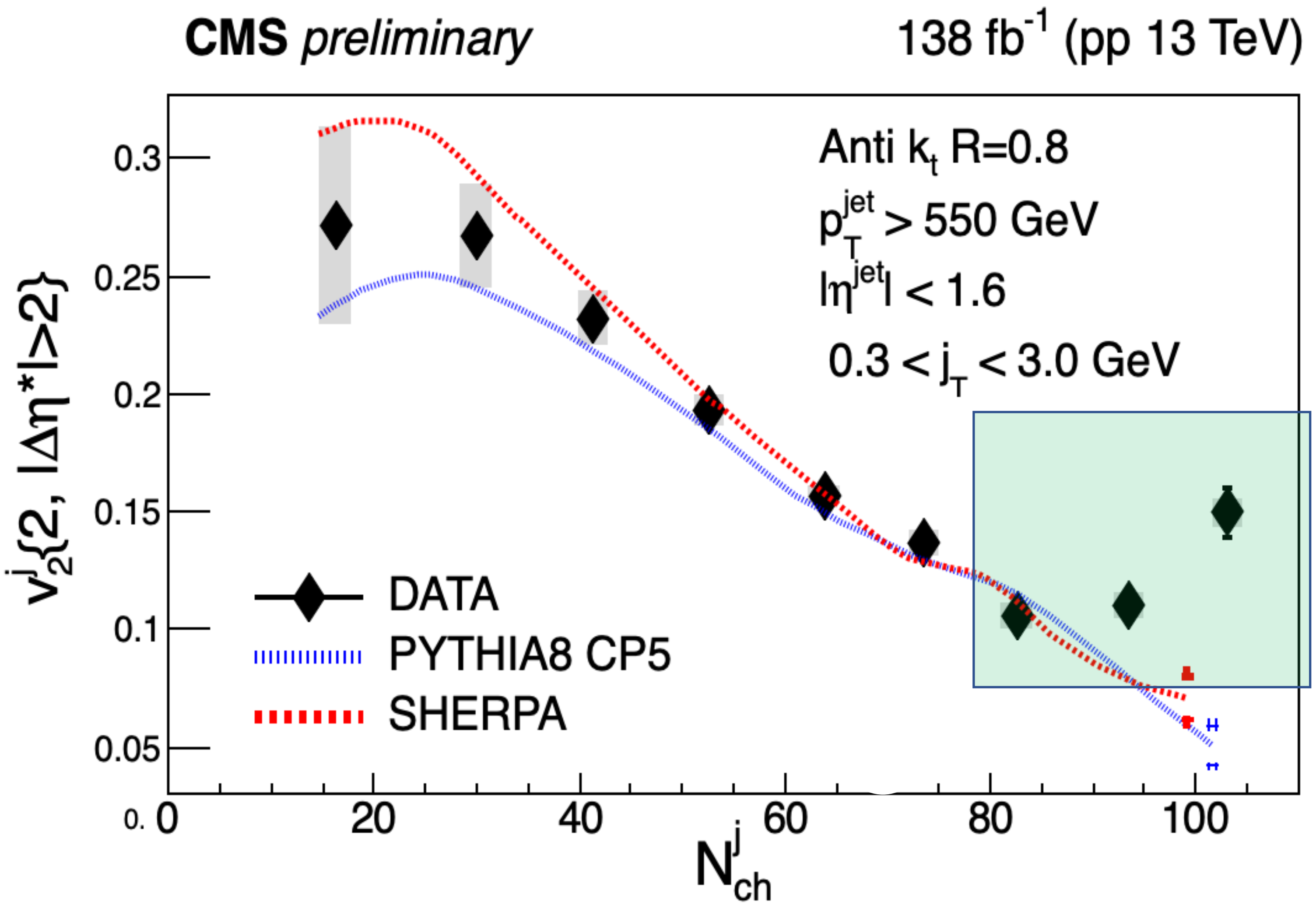


○ Long range Δη correlation → collectivity → initial stage

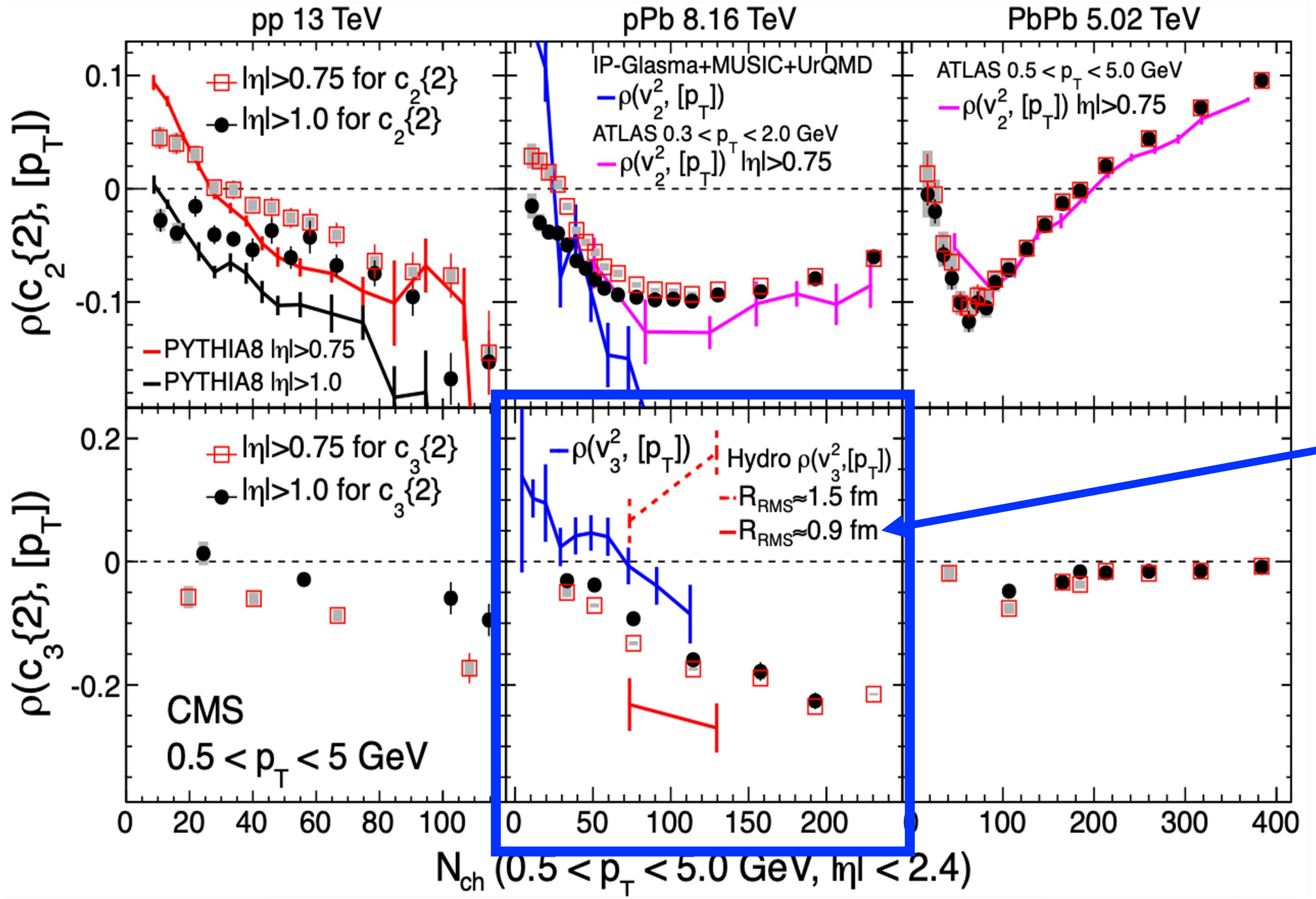
Intra-jet correlation in highest multiplicity p-p collisions

CMS-PAS-HIN-21-013



- In-jet v_2 w.r.t. the jet axis increases in data
- Models show different trend compared to data at higher N_{ch}
- Data indicates collectivity in single parton jets during fragmentation
- Is collectivity an intrinsic nature of nonperturbative QCD?

Cumulant - $[p_T]$ correlations



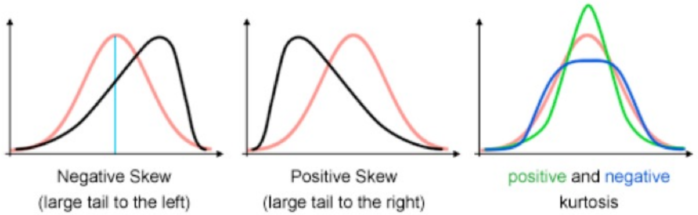
- No sign change with wider η gap in smaller (pp, pA) collisions
  - v_2 sensitive to non-flow
  - v_3 confirms initial geometry fluctuation

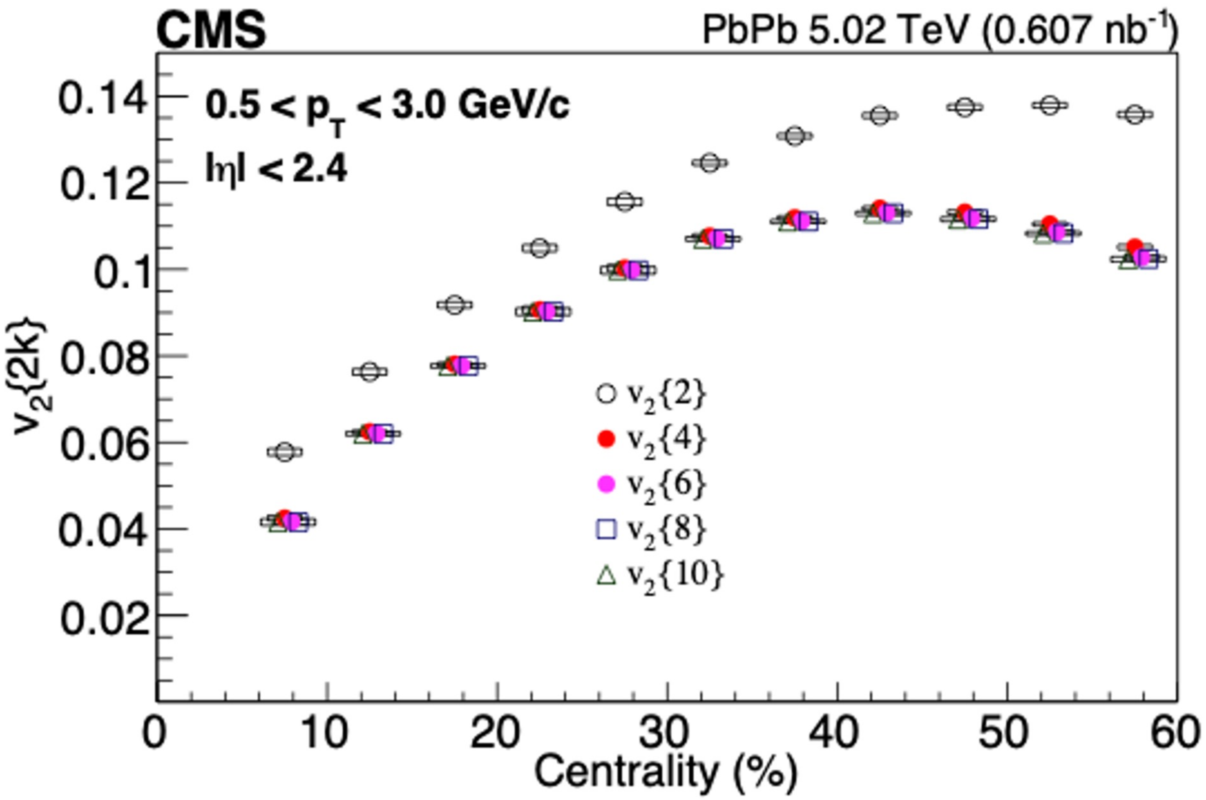
v_3 correlation qualitatively better described by the smaller initial fireball in p-Pb

CMS-PAS-HIN-21-012

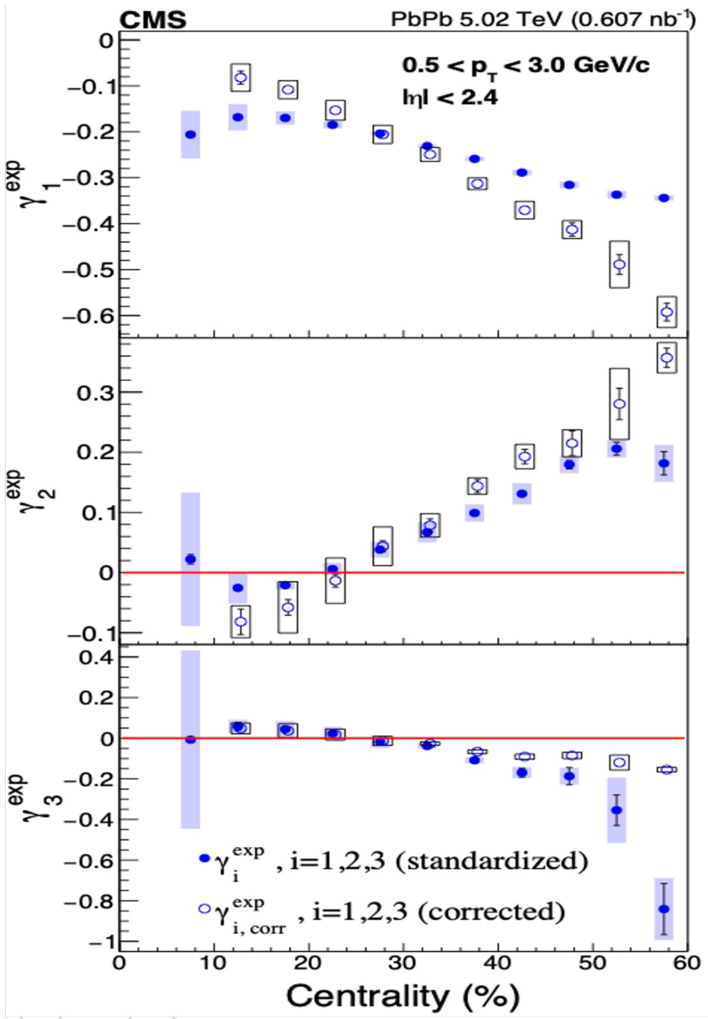
Higher-order cumulants $v_2\{2k\}$ in Pb-Pb collisions

- E-by-E fluctuations in anisotropic flow → early state dynamics of the collisions





CMS-PAS-HIN-21-010



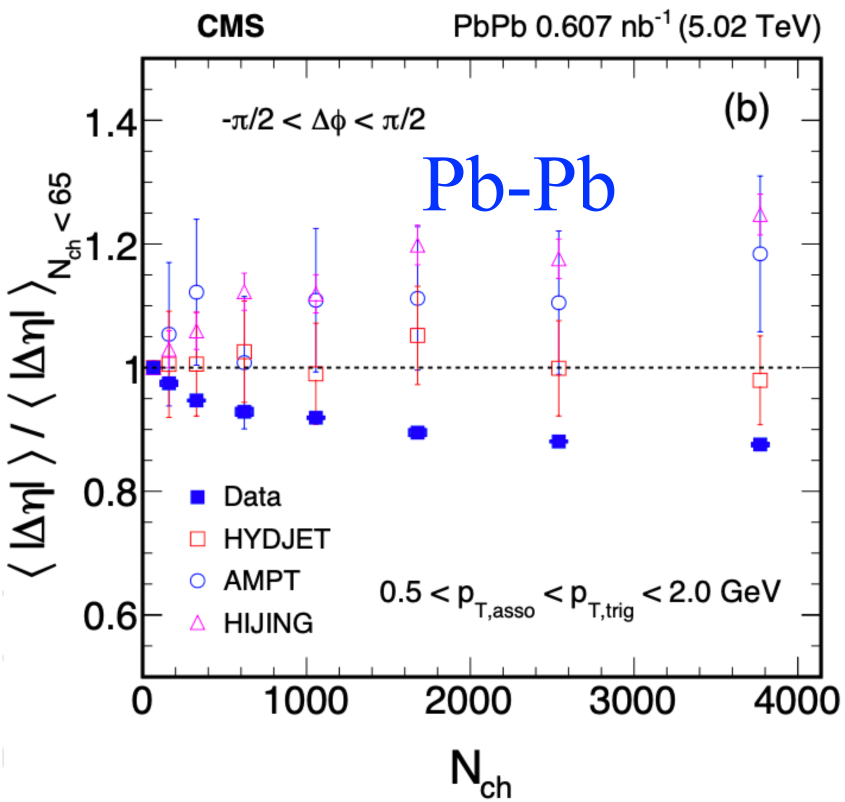
- Fine splitting observed with higher-order cumulants
  - Indication of non-Gaussian behavior of the fluctuations
  - Non-zero values for skewness, kurtosis, and superskewness

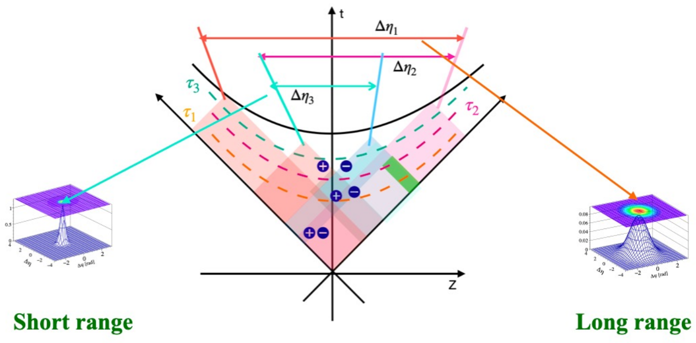
Charge balance function in p-Pb and Pb-Pb collisions

$$\text{Balance function} = \frac{1}{2}\left[C_2(+,-) + C_2(-,+) - C_2(+,+) - C_2(-,-)\right]$$

sensitive to hadronization time & system evolution

} LCC & radial flow effect





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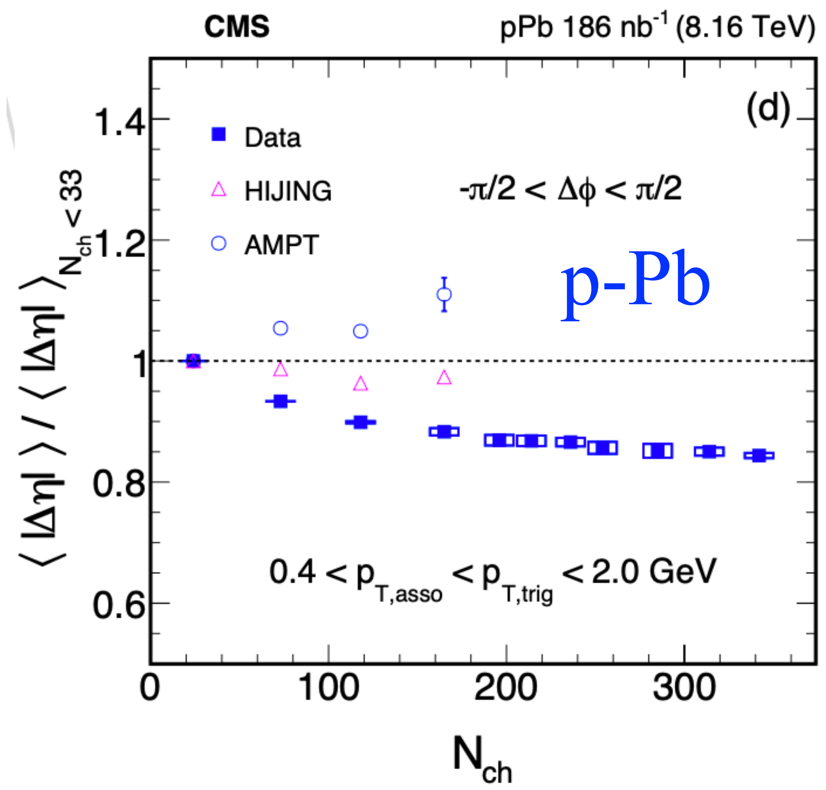
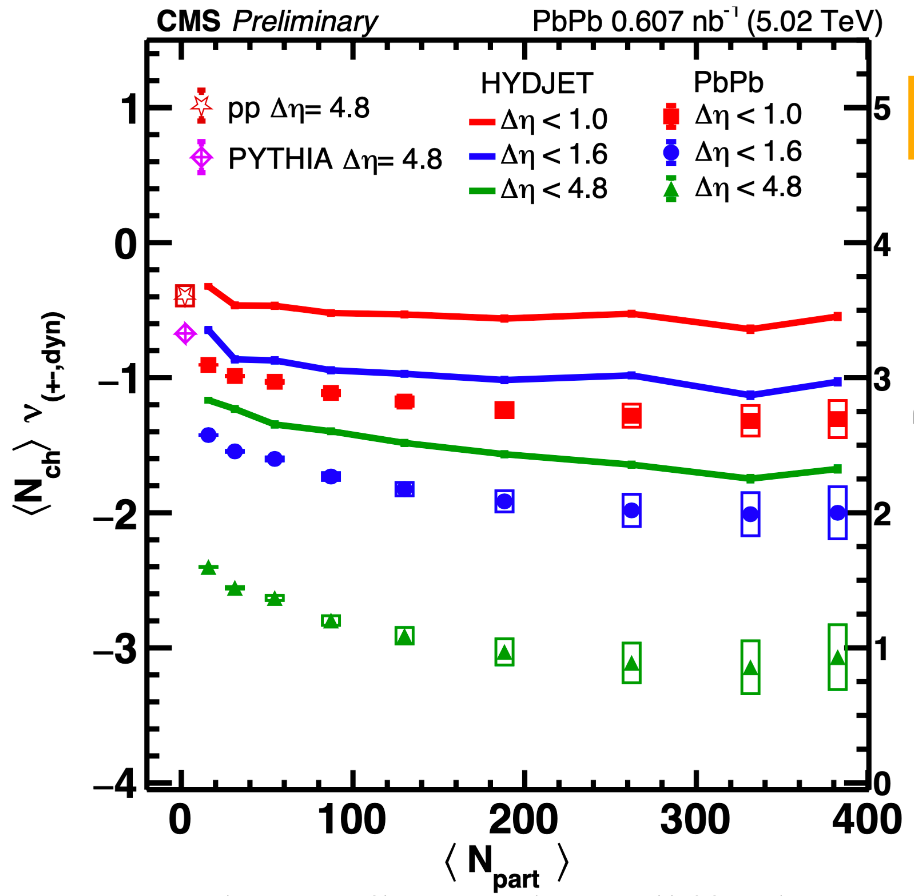


- Narrowing of balance function with increasing multiplicity both in p-Pb and Pb-Pb
  - Consistent with the delayed hadronization mechanism and radial flow effect in high multiplicity than low multiplicity events

Net-charge fluctuation in Pb-Pb collisions

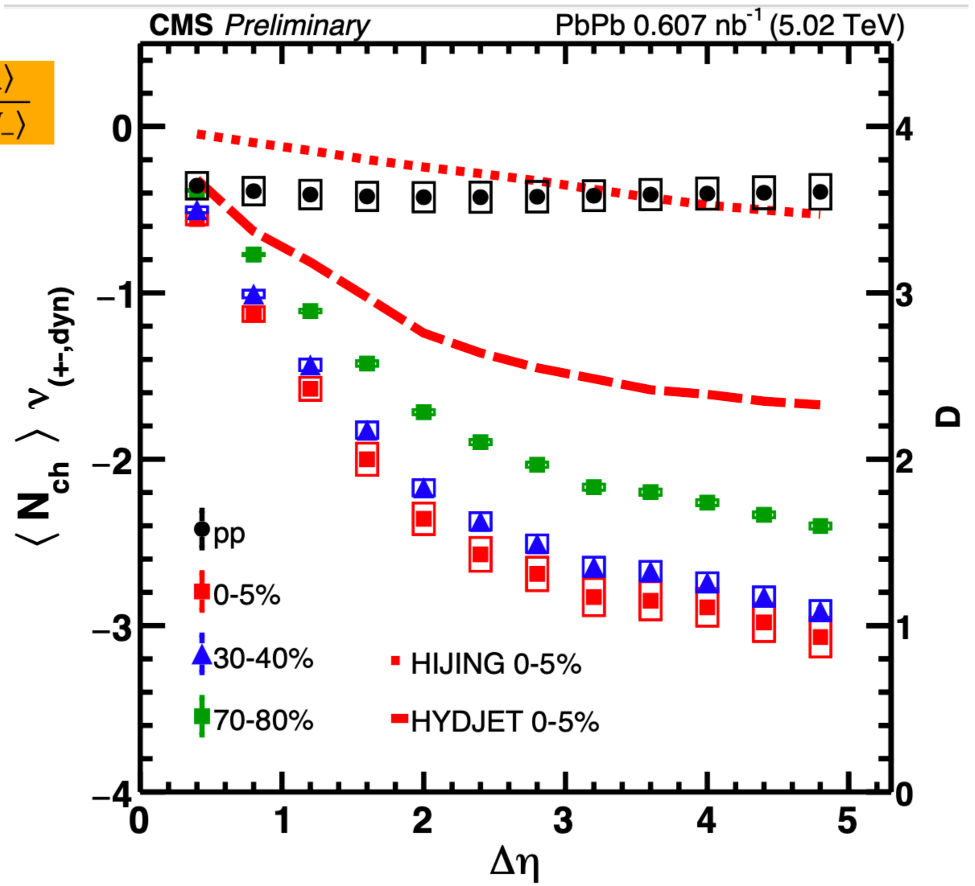


$$\nu_{(+-,dyn)} = \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_--1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_+N_-\rangle}{\langle N_+\rangle\langle N_-\rangle}$$

CMS-PAS-HIN-22-005

Hadron Gas: $q = \pm 1,\ q^2 = 1$

QGP: $q = \pm\frac{1}{3};\frac{2}{3},\ \ q^2 = \frac{1}{9};\frac{4}{9}$



- Net-charge fluctuations differ between QGP and hadron gas phase
  - The less $|\nu_{dyn}|$ is, the more + and – charges are equilibrated → signature of QGP
- Dilution in rapidity during system evolution (hadronization to kinetic freeze-out) → diluting fluctuation
- Both data and MC approach to Poissonian limit for smaller acceptance
- Charge conservation and resonance contribution coupled with radial flow and/or any other effects?

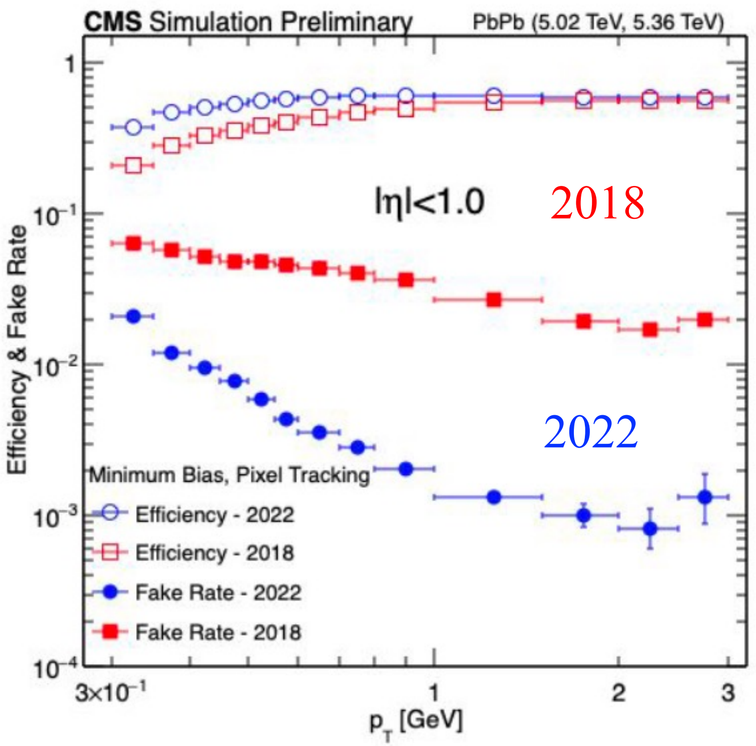
Run 3 and beyond in CMS

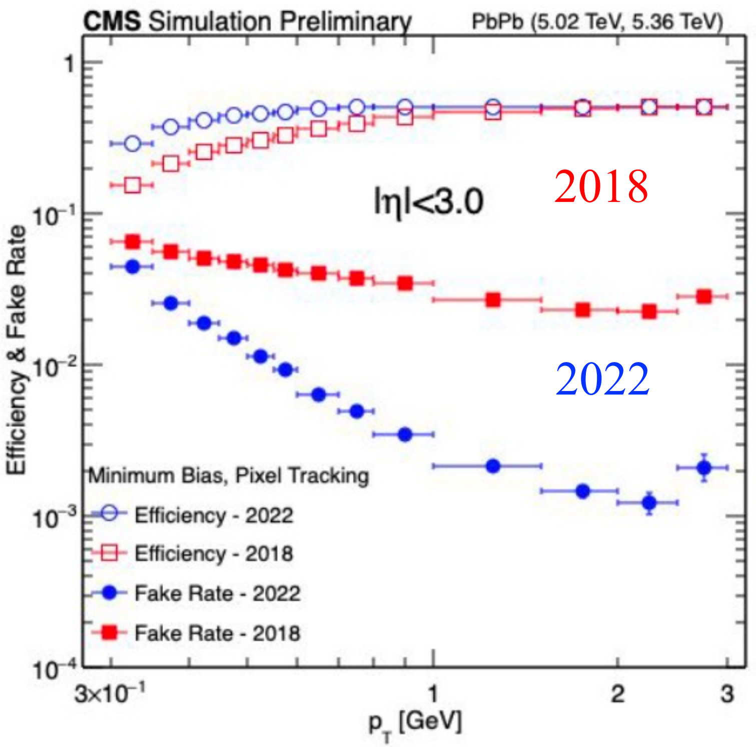
CMS Run 3 improvement

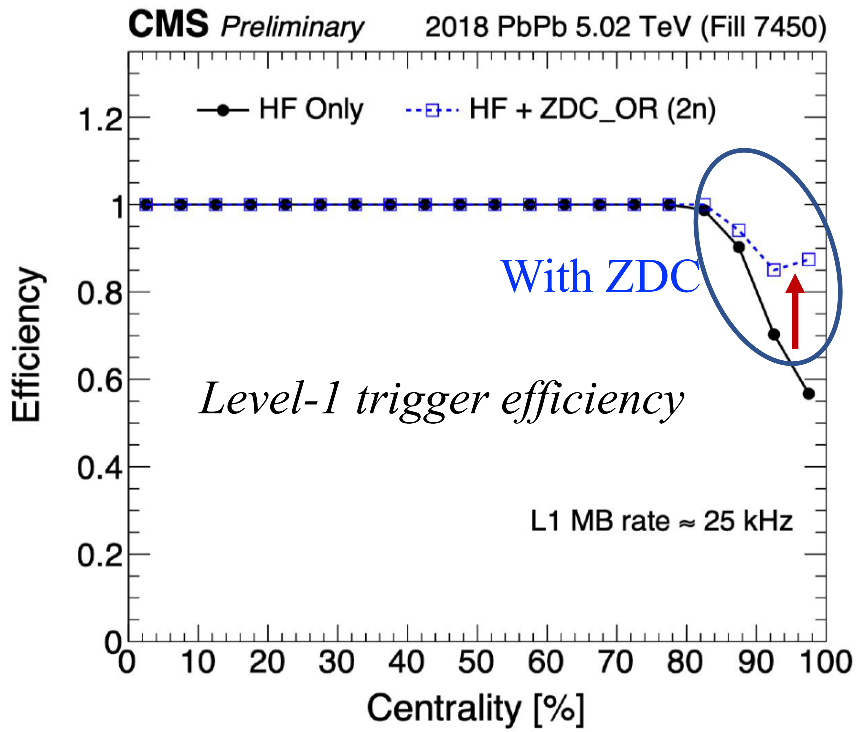
Improvement in tracking efficiency for Run3

Chosen examples

CMS-DP-2023-011







- Expected better tracking performance & lower fake rate for Run 3!
  - Online: increased MB trigger efficiency in peripheral events with ZDC
  - Offline: improved low-p_T tracking with the innermost pixel layer
- Expected CMS to record 25kHz of MB Pb-Pb events in Run3
  - An increase of ~3 times that of 2018

CMS phase-II upgrades (HIN related)

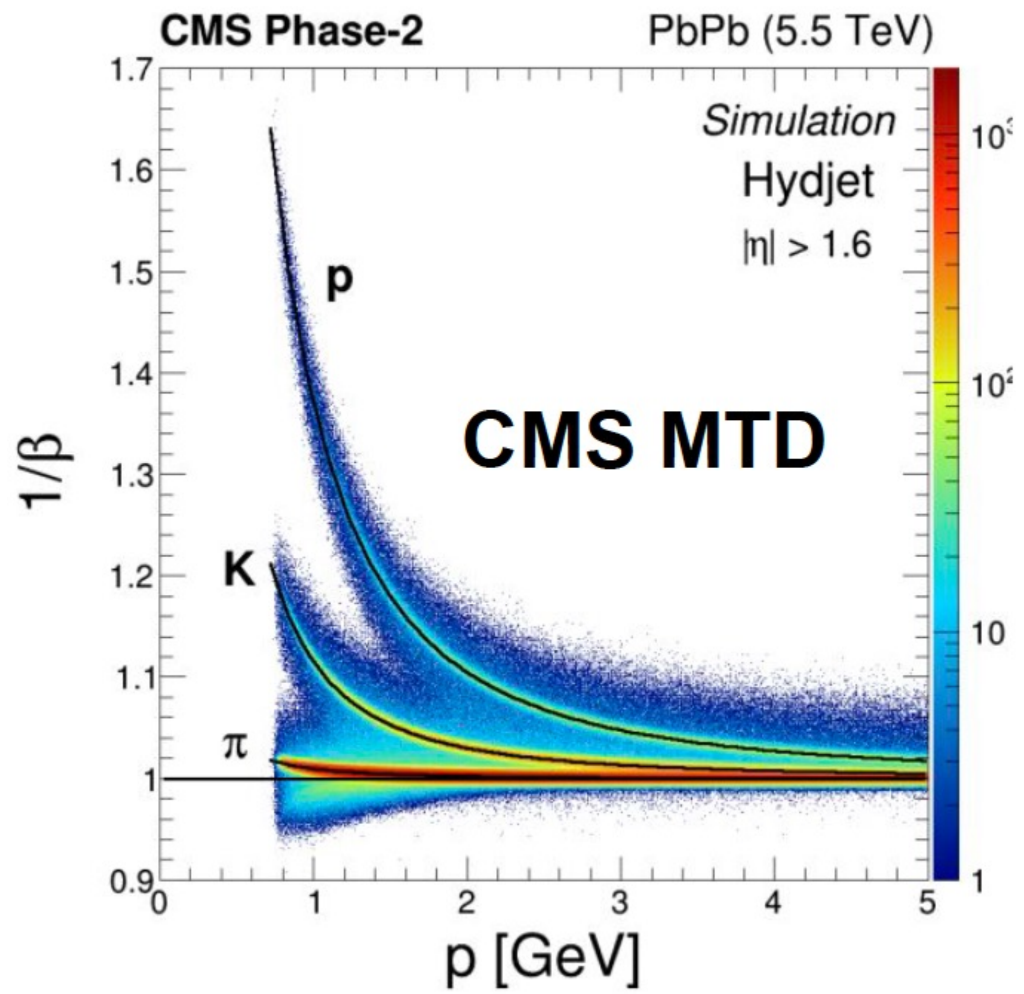
CMS-DP-2021-037 ; CERN-CMS-DP-2021-037

Phase 2 Upgrade

CMS Phase 2 for Run 4

- Tracker |η|<4
- Muon ID up to |η|<2.8
- High Granularity Calorimeter
- MIP timing detector
    - 4D vertexing
    - **p/K/π PID** (CMS MTD)
- L1 trigger update: 750 kHz for CMS
- DAQ: 51 GB/s for CMS
- L1 track triggers
- ZDC

PID: **π**, K, p

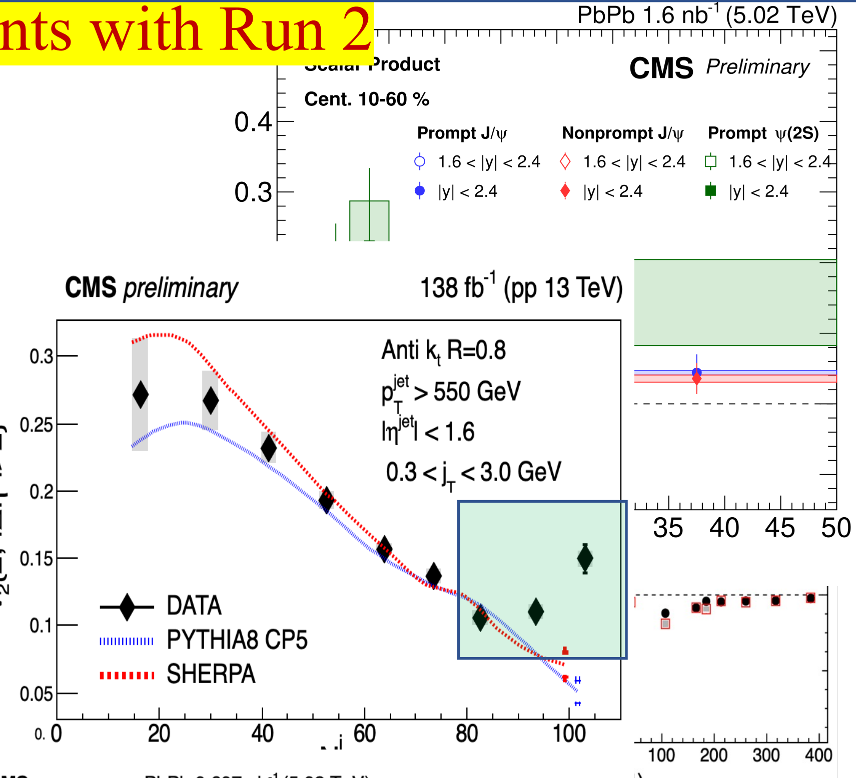


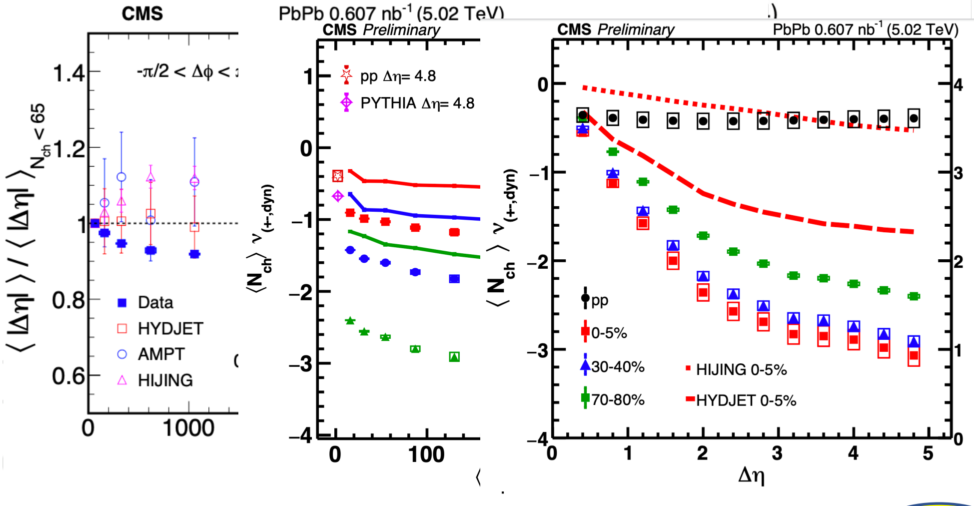
- ➢ CMS major upgrades for Run 4
    - o A unique hermetic particle identification detector – MTD
    - o Unprecedent time resolution (30-40 ps)

Summary

CMS has provided a wealth of very interesting measurements with Run 2

- E/W bosons, dijets, top quarks sensitive to nPDFs at different (x, Q^2)
- Very low-x gluon regime probed by J/ψ in UPC Pb-Pb
- Charm and beauty quarks collectivity in small to large systems
- Bottomonium collectivity in p-Pb and Pb-Pb
- Jet shapes with dijets and b jets input for more precise energy loss
- Path-length dependent energy loss and it's fluctuations with dijet vn
- Nature of collectivity in highest multiplicity p-p collisions
- Probes fluctuations of initial density profile
- Hadronization mechanism with balance function
- QCD phase transition with net-charge fluctuations
- Improved Run 3 and excellent prospects for Run 4





STAY TUNE FOR MORE COMING NEXT!!!

Thank you 🙏