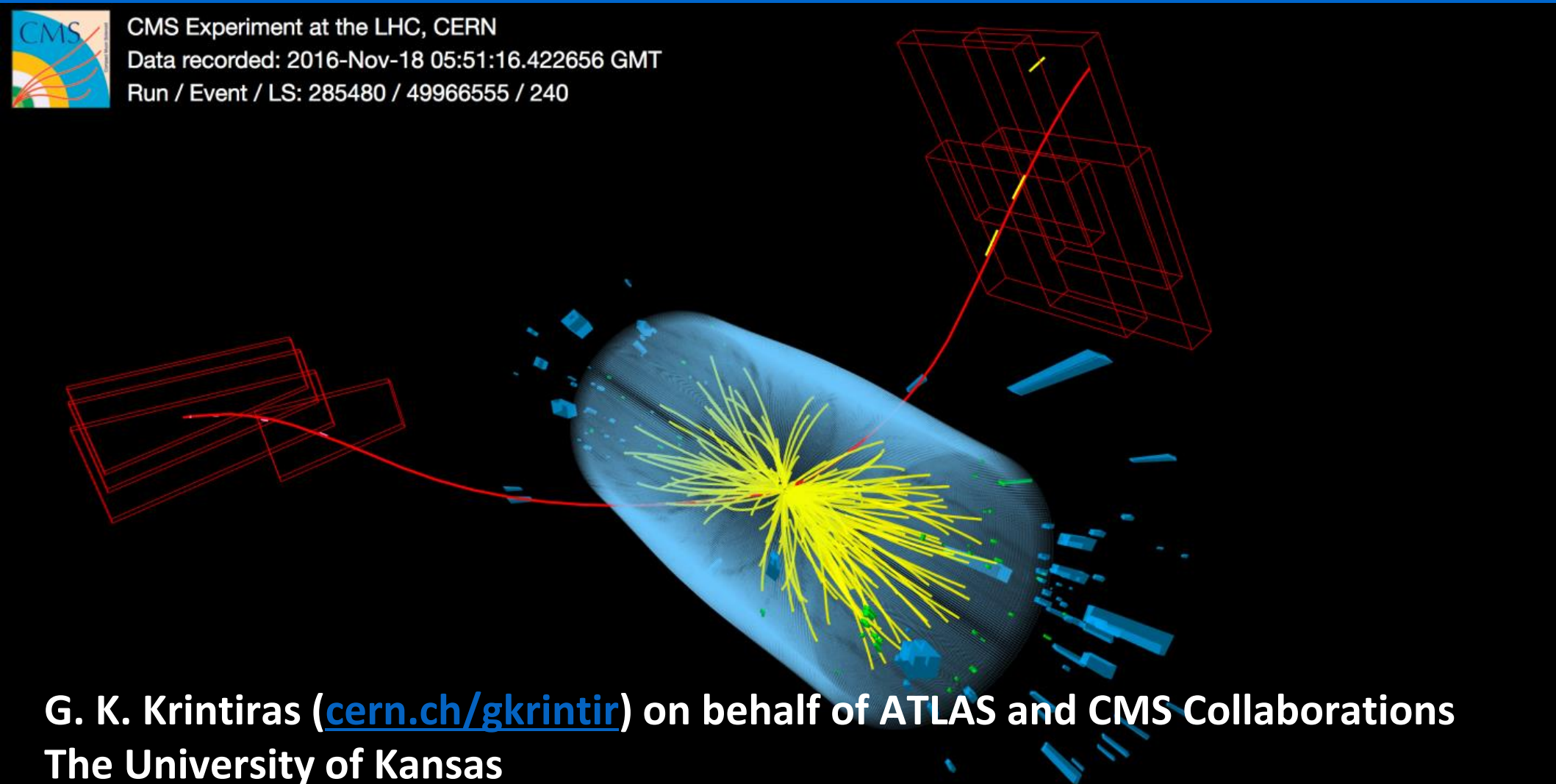
Recent heavy-flavor results in small systems with ATLAS and CMS

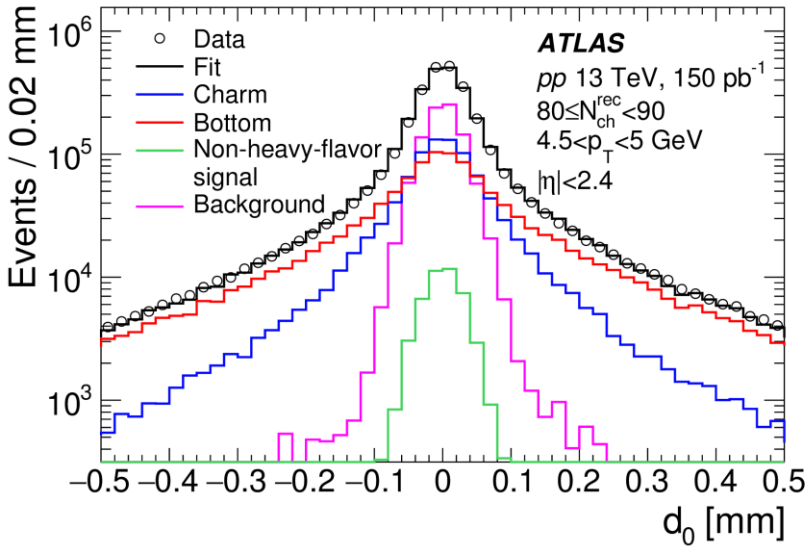


G. K. Krintiras (cern.ch/gkrintir) on behalf of ATLAS and CMS Collaborations
The University of Kansas

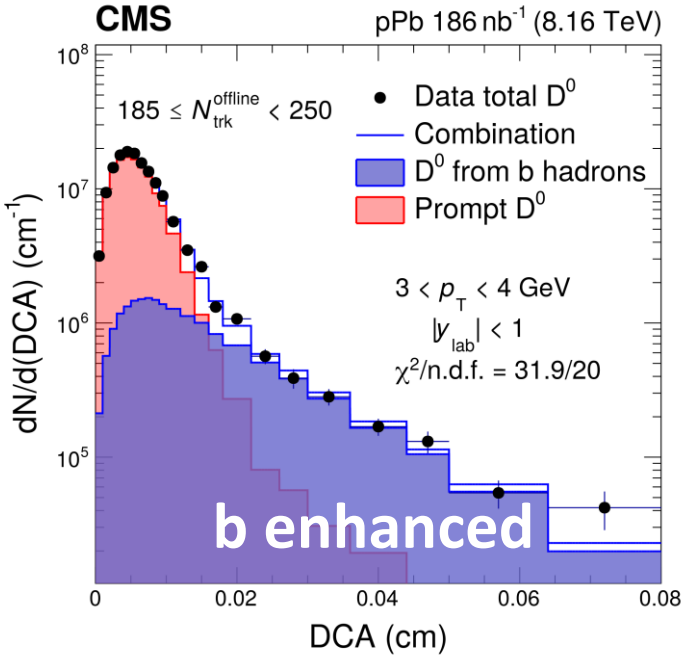
Key features of heavy flavor measurements

- **Variety** of meson/baryon states in a broad kinematic range
  - techniques to **separate** bottom from charm, also from light flavor decays
- We gain insights on
  - heavy quark **flow**
  - pQCD predictions, parton shower modeling, hadronization mechanisms
  - **parton interactions** in the QGP (energy loss,...) → cf. Mattia's talk

PRL **124** (2020) 082301

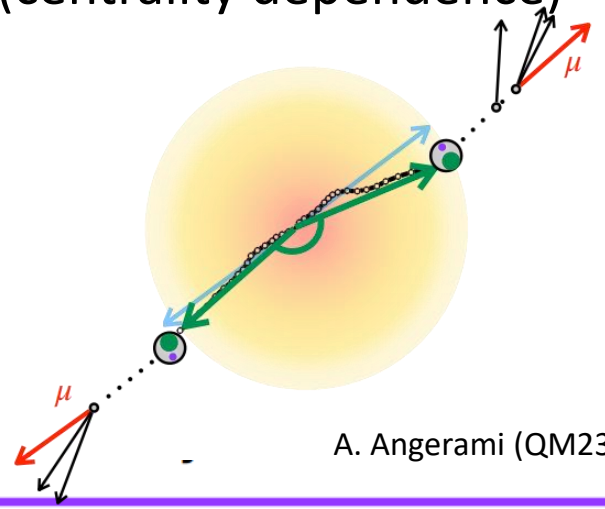


PLB **813** (2021) 136036



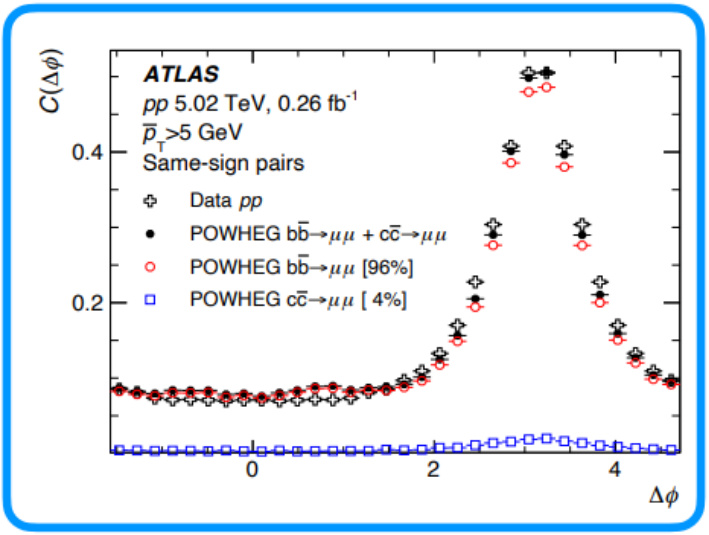
HF dimuon angural correlations

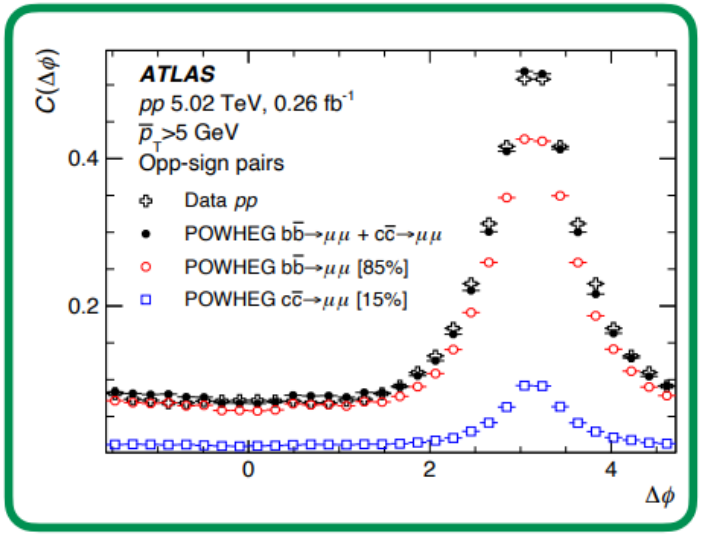
- Lepton pairs with large $|\Delta\eta|$ from HF hadron decays
- **Enhancement** on the "away-side" ($\Delta\phi = \pi$) → hard-scattering processes
- Same-, opposite-sign and combination have different b/c composition
- Compare the **widths** of the away-side peaks in pp vs PbPb (centrality dependence)

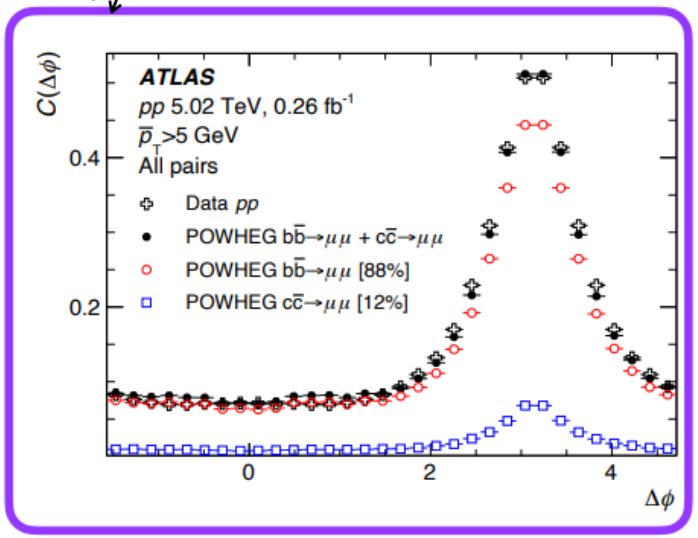


arXiv: 2308.16652 (submitted to PRL)

A. Angerami (QM23)



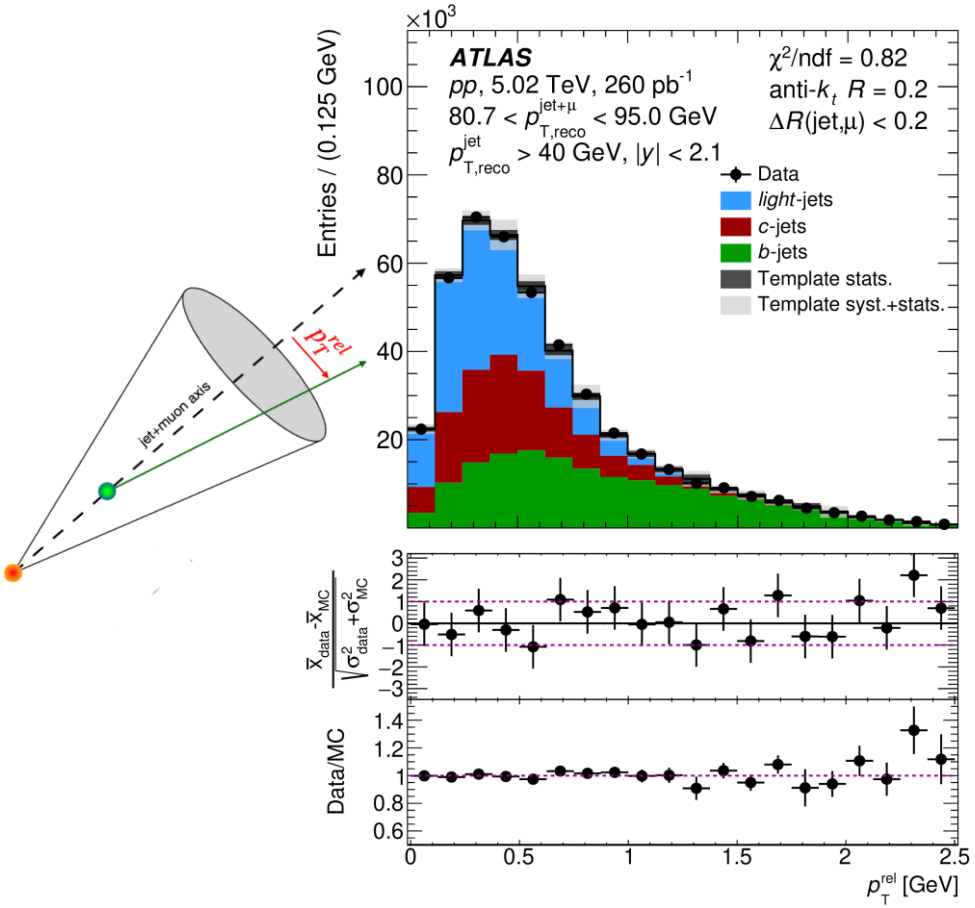




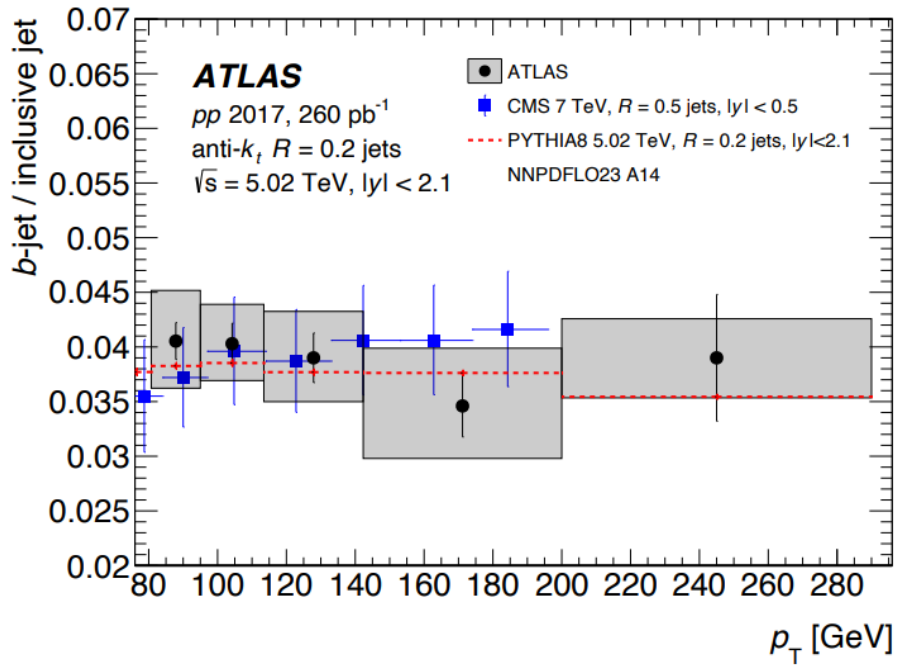
POWHEG (pp) for charge sign combinations

b jet production flow in pp

- Fraction of b jets estimated based on muon momentum relative to jet axis
- b jets **small fraction** (~4%) of the inclusive jet yield → we need more luminosity
- independent of √s (CMS @ 7 TeV) and consistent with PYTHIA8



EPJ. C **83** (2023) 438



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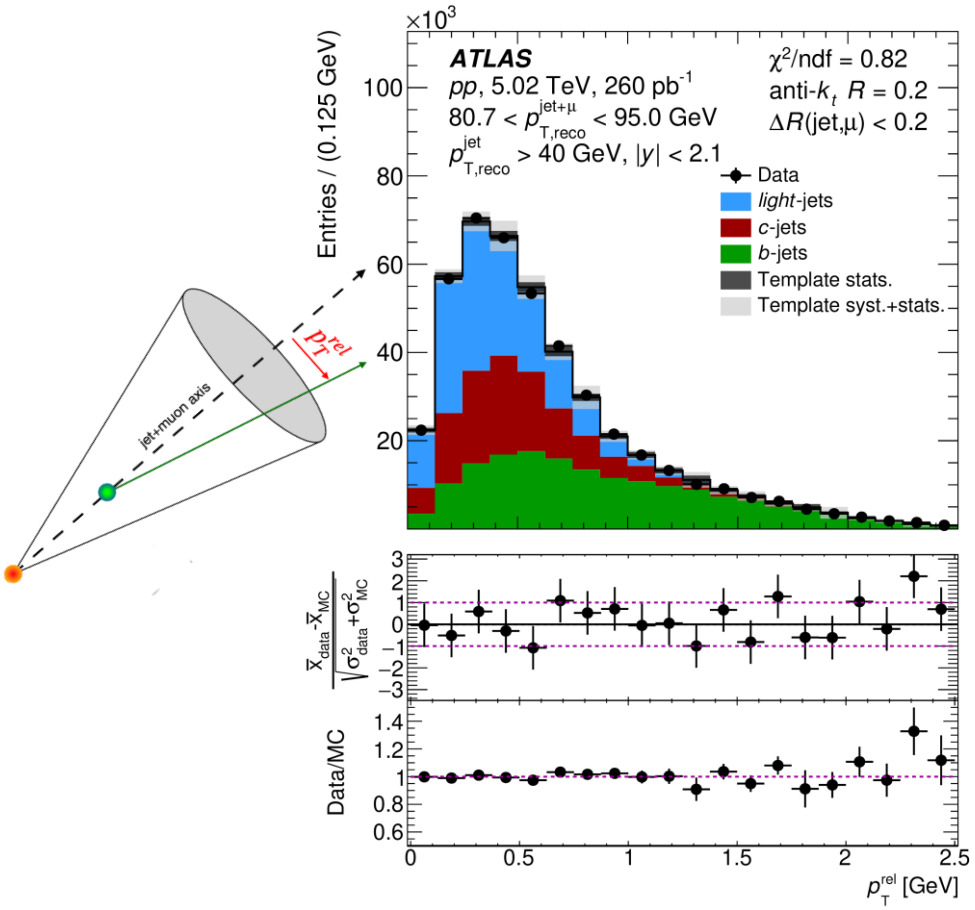
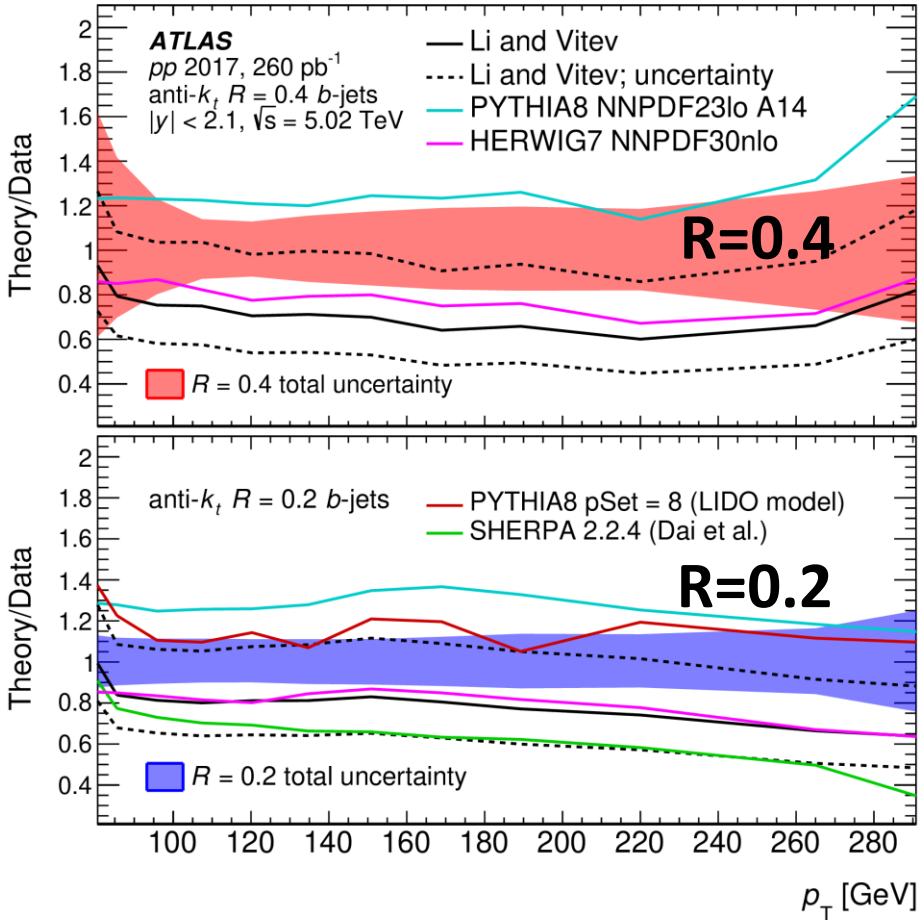
- Fraction of b jets estimated based on muon momentum relative to jet axis
- b jets **small fraction** (~4%) of the inclusive jet yield → we need more luminosity
- independent of √s (CMS @ 7 TeV) and consistent with PYTHIA8
- better agreement with **NLO+LL predictions** than HERWIG7, PYTHIA8, SHERPA 2.2.4



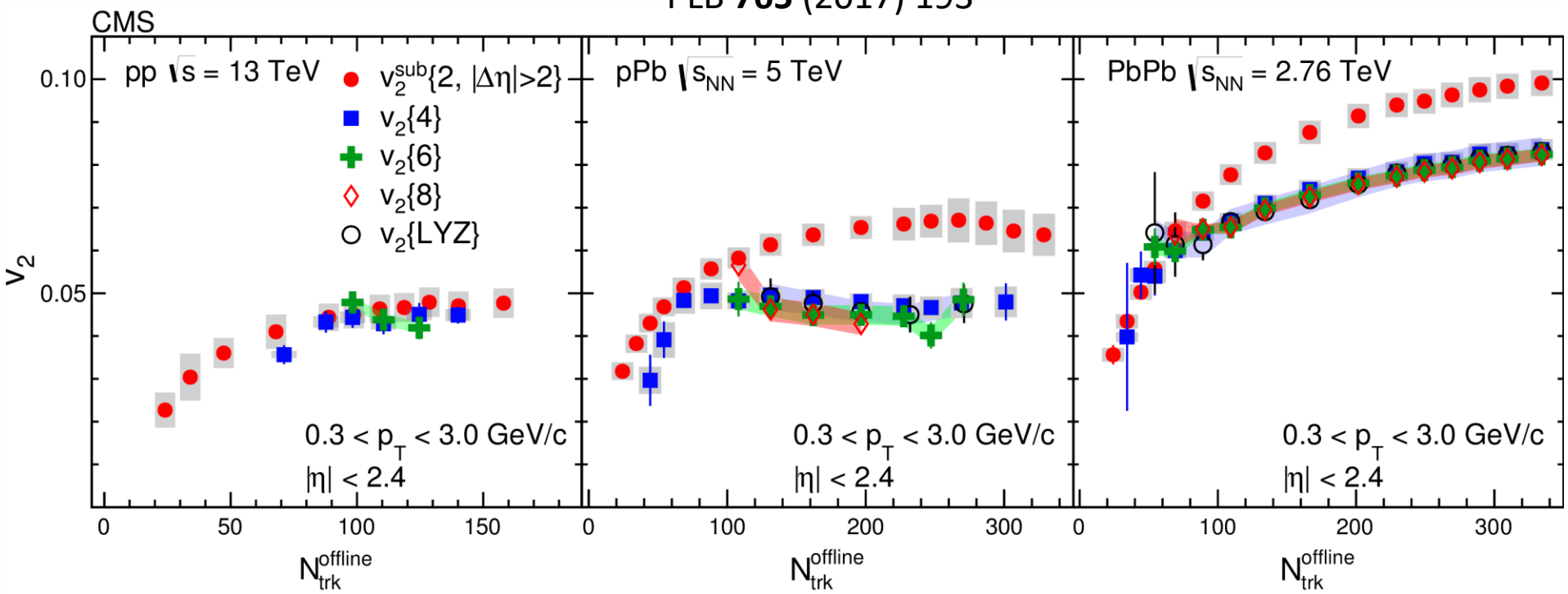
EPJ. C **83** (2023) 438



Collectivity in small systems?

- Detailed flow measurements in **pp/pPb** indicate that
- centrality/event activity and p_T dependence qualitatively **similar** to that in AA
- identified and multiparticle correlation techniques support **collective origin** of $\mathbf{v_n}$
- encompassed by hydrodynamical models, but not a unique description
- **What about HF?**

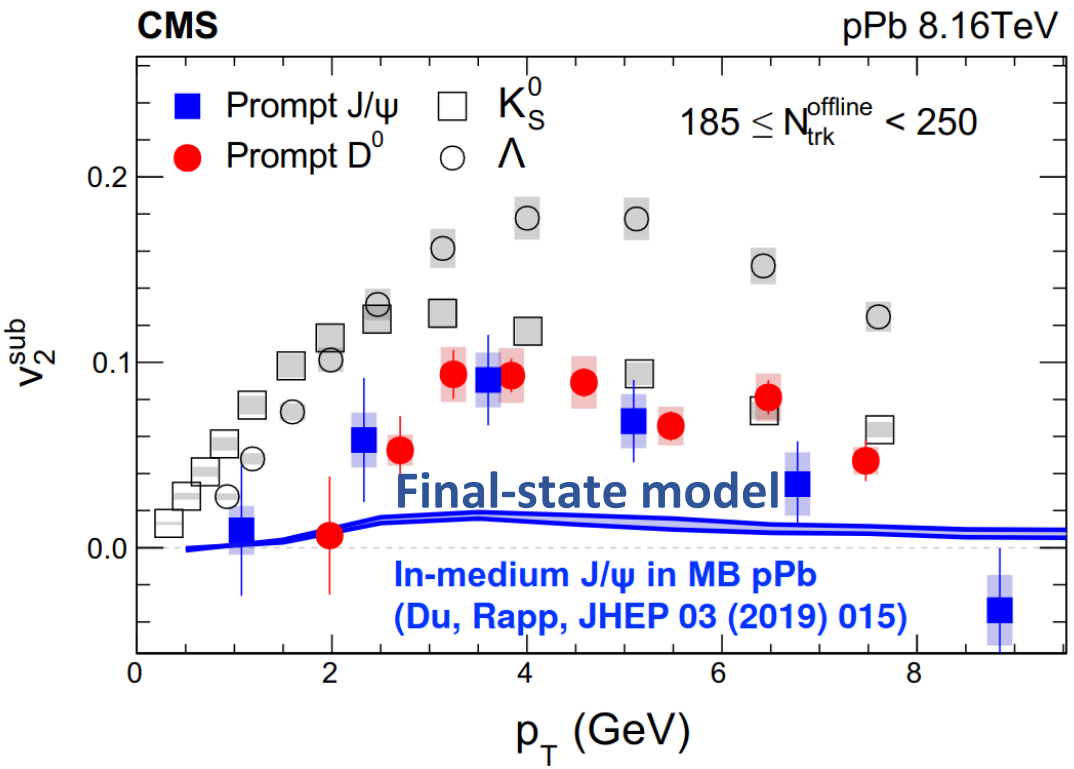
PLB **765** (2017) 193



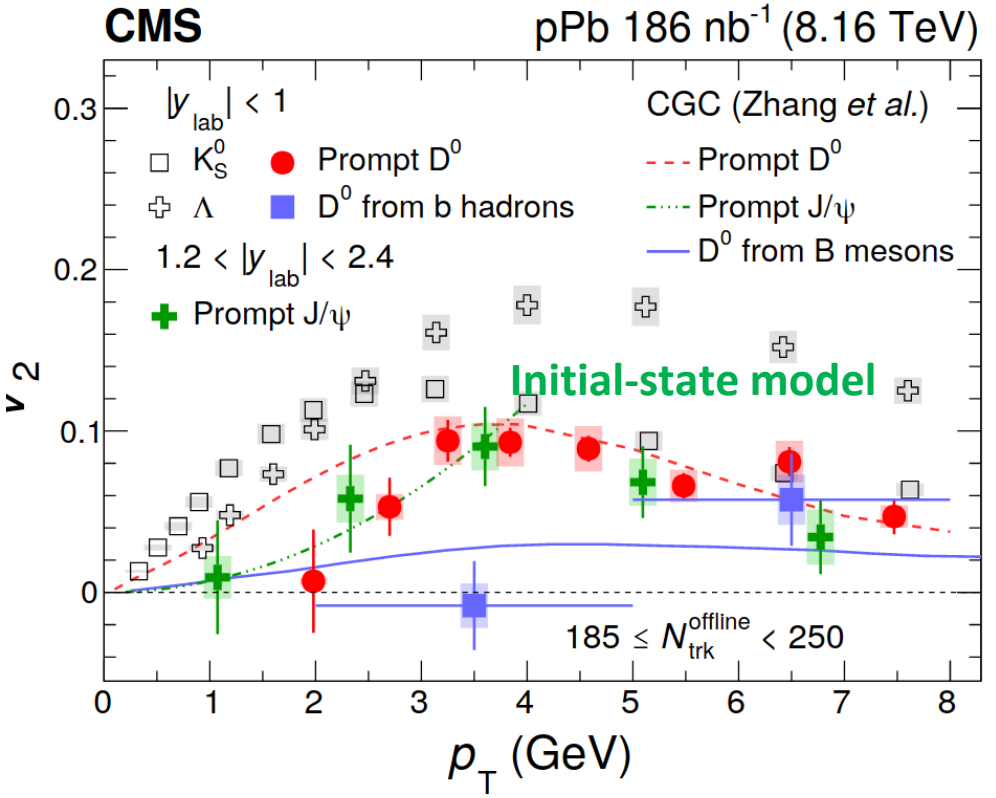
HF flow flow in pPb

- Observation of **c flow**
- the number-of-constituent-quark (n_q) scaling holds for $KE_T/n_q < 1$ GeV
- model with final-state interactions underestimates the v_2 signal

PLB **791** (2019) 172



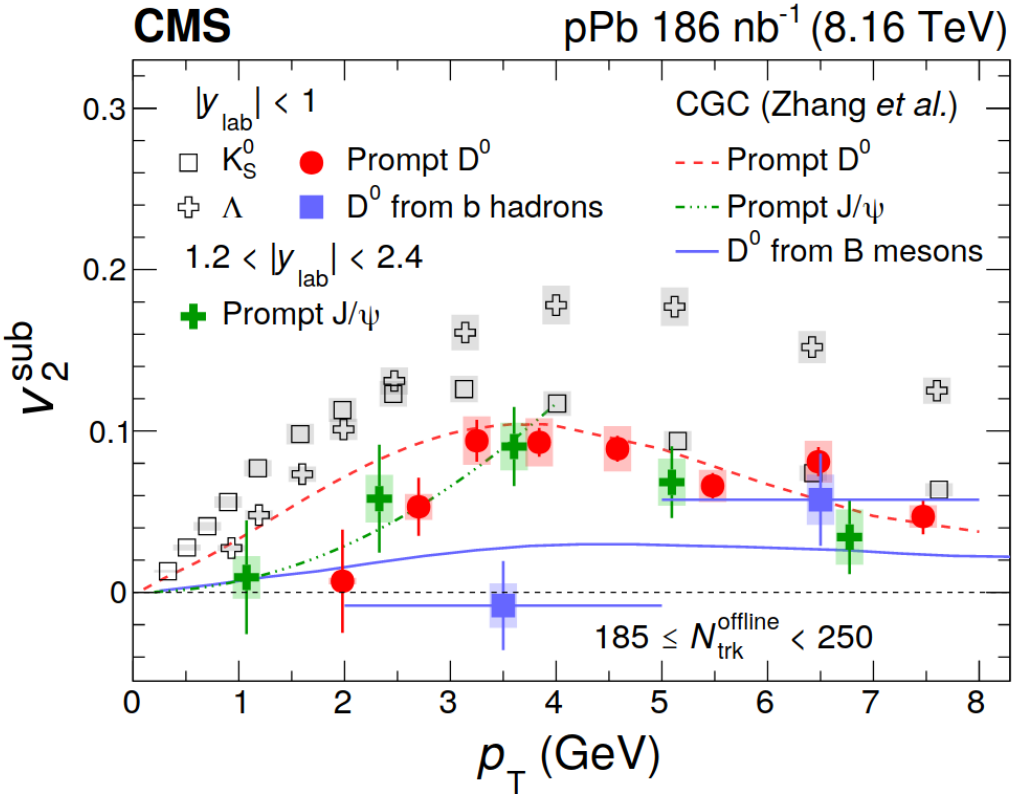
PLB **813** (2021) 136036



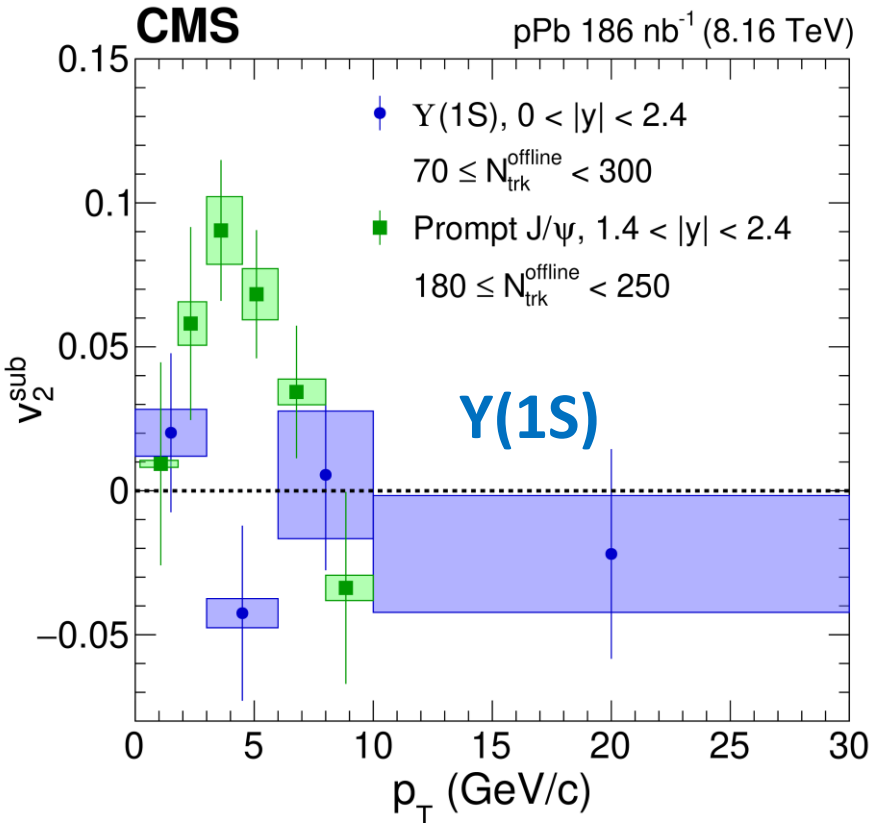
HF flow flow in pPb

- Observation of **c flow**
- the number-of-constituent-quark (n_q) scaling holds for $KE_T/n_q < 1$ GeV
- model with final-state interactions underestimates the v_2 signal
- First measurements of **b flow**, inducing **Y(1S)**
- flavor hierarchy for light, c, and b at low p_T
- **agreement with CGC** → important role for initial-state effects?

PLB **813** (2021) 136036

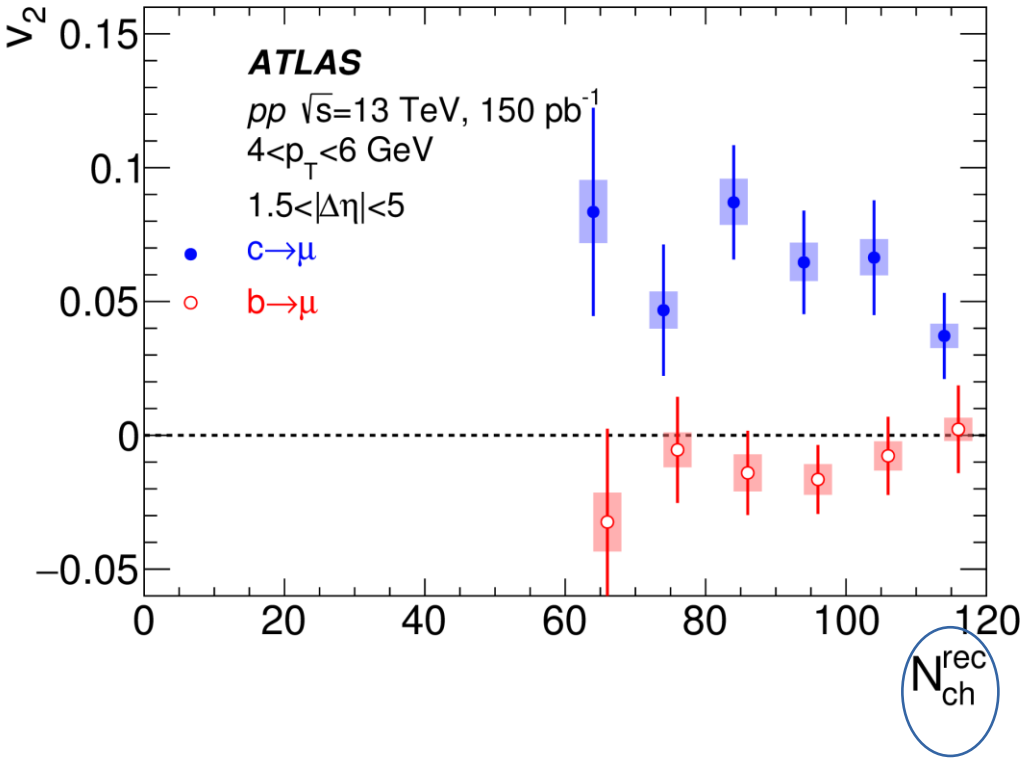


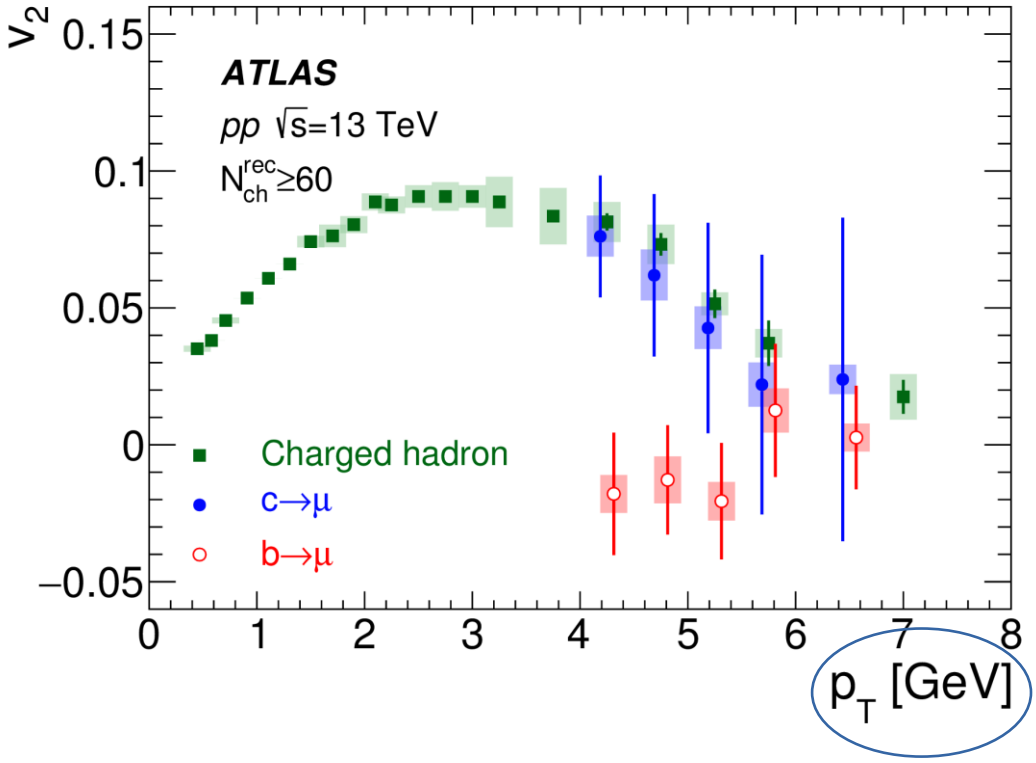
arXiv: 2310.03233 (submitted to PLB)



- First measurements of **c and b flow**
- no dependency on track multiplicity (CMS D^0 extends to $25< N_{ch} <150$)
- charm $v_2>0$ decreasing with p_T
- bottom $v_2 \sim 0$
- **No calculation** yet available in the smallest systems

ATLAS: PRL **124** (2020) 082301
CMS: PLB **813** (2021) 136036

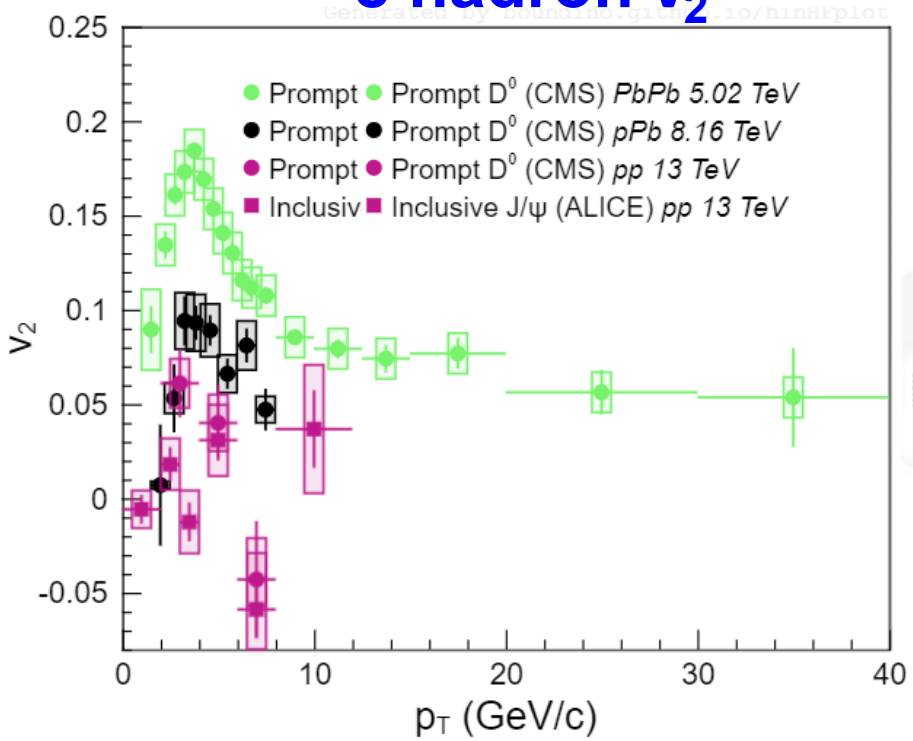




Comparing HF particle flow in all systems

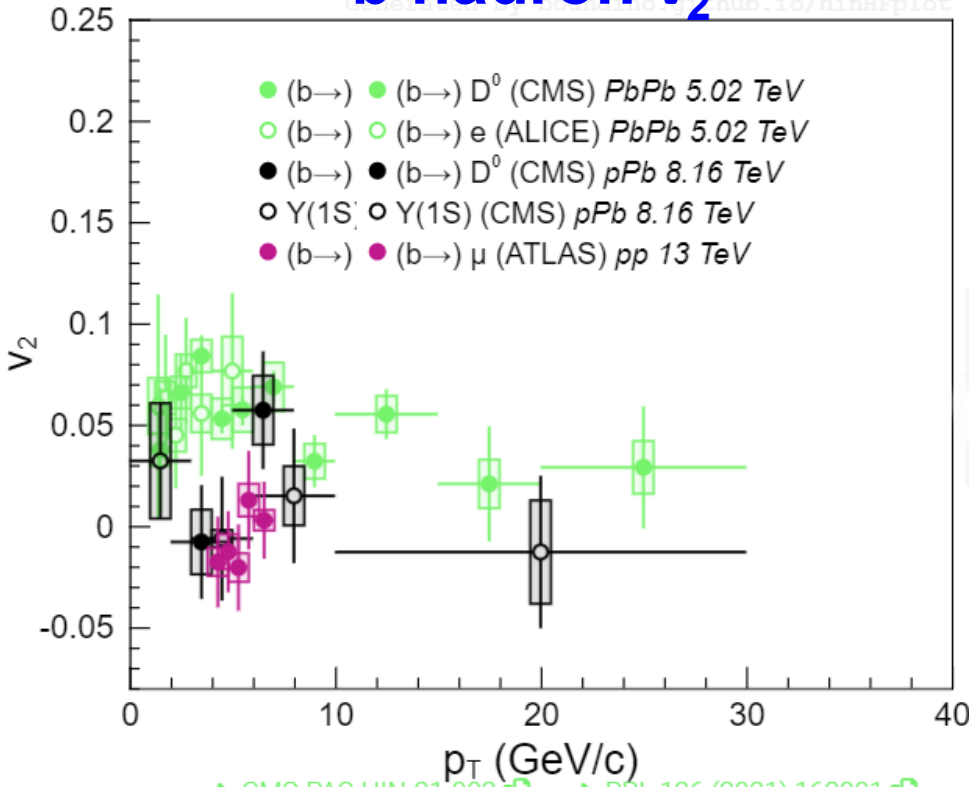
- There is charm anisotropy... everywhere
- apparent ordering: v_2 (PbPb) > v_2 (pPb) > v_2 (pp)
- so **system size** should play a role?
- For open bottom hadrons: v_2 (PbPb) > 0 but v_2 (pPb) ~ v_2 (pp) ~ 0
- do we hit some **threshold** between charm and beauty processes?

c hadron v_2



PLB 816 (2021) 136253 PRL 121 (2018) 082301
PLB 813 (2021) 136036 ALICE Preliminary

b hadron v_2

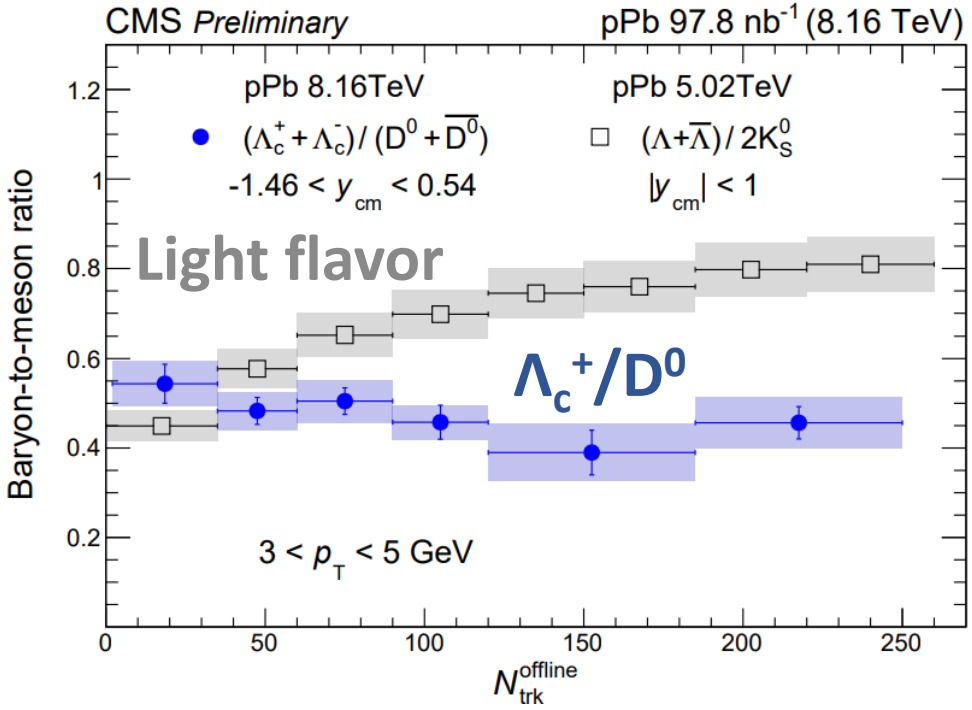


CMS-PAS-HIN-21-003 PRL 126 (2021) 162001
PLB 813 (2021) 136036 CMS-PAS-HIN-21-001
PRL 124 (2020) 082301

Charm quark hadronization in pPb

- First measurement of Λ_c^+/D^0 **vs** $\mathbf{N_{trk}}$
- small dependence on $\mathbf{N_{trk}}$ contrary to the strange sector

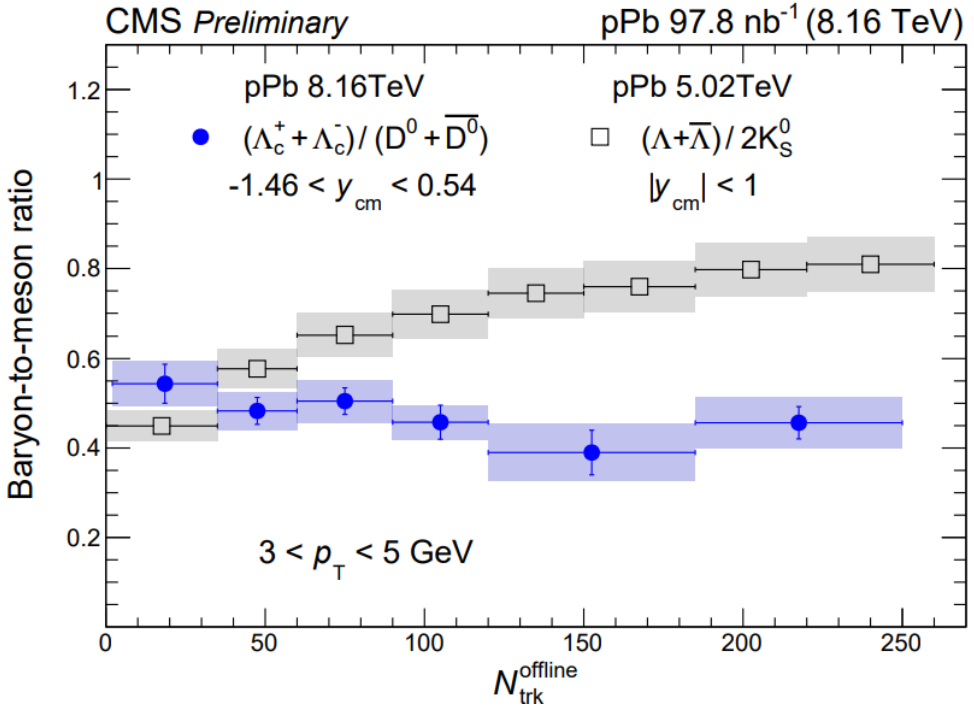
pPb: CMS-PAS-HIN-21-016
PbPb: arXiv: 2307.11186 (submitted to JHEP)

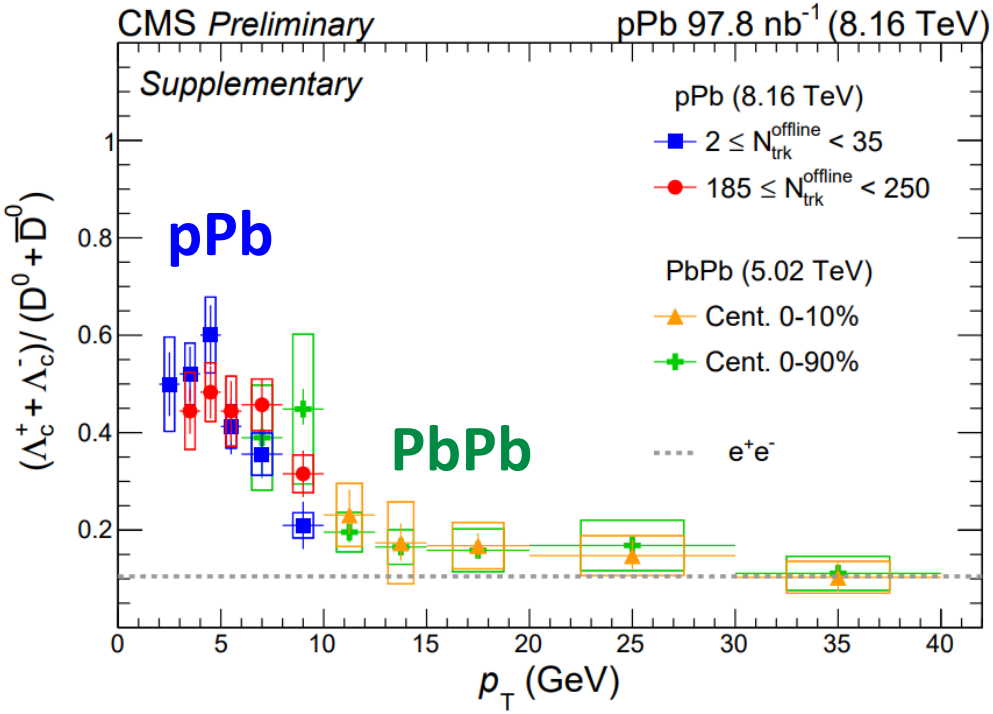


Charm quark hadronization in pPb (and PbPb)

- First measurement of Λ_c^+/D^0 **vs** $\mathbf{N_{trk}}$
- small dependence on $\mathbf{N_{trk}}$ contrary to the strange sector
- Extending system (pPb 8 TeV), p_T (<40 GeV), centrality (0–90%) reach of Λ_c^+/D^0
- in pPb and MB PbPb consistent at intermediate p_T → **coalescence**?
- Λ_c^+/D^0 approaches the ratio from e^+e^- at high p_T

pPb: CMS-PAS-HIN-21-016
PbPb: arXiv: 2307.11186 (submitted to JHEP)

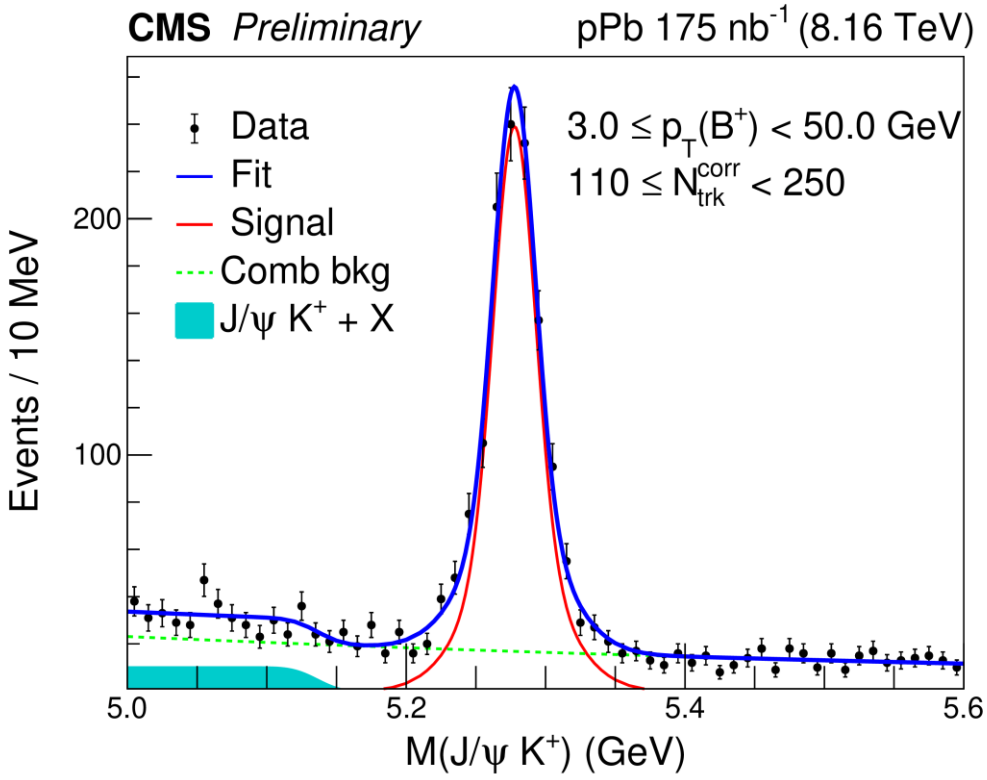


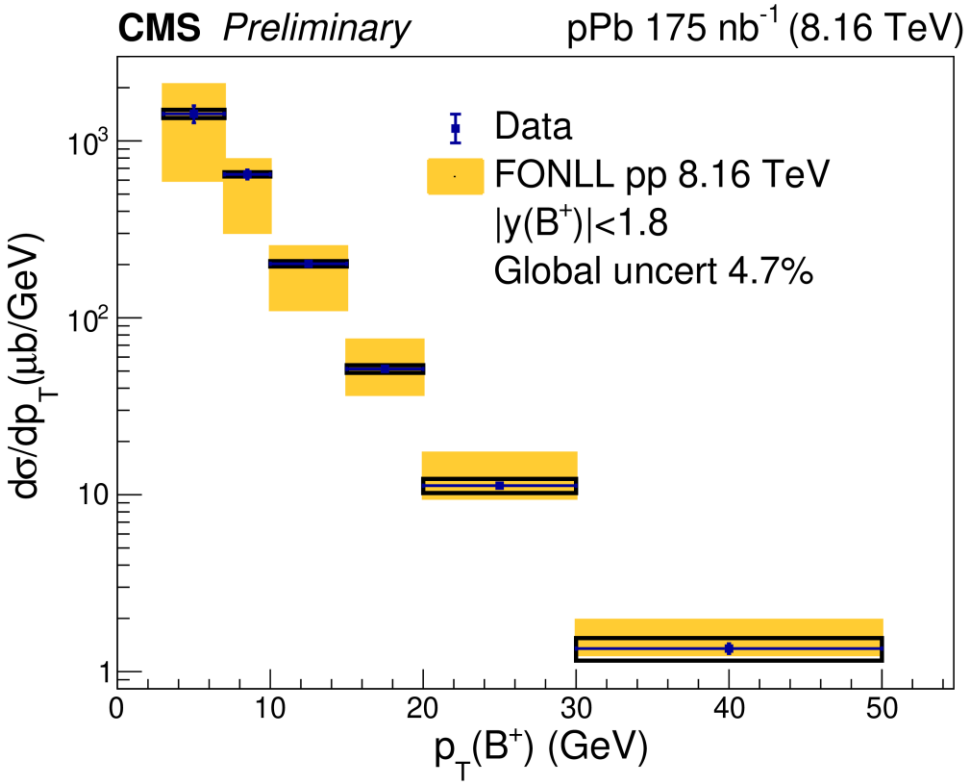


B^+ production in pPb

- Using $B^+ \rightarrow J/\psi K^+$ in an extended $3 < p_T < 50$ GeV
- differential p_T cross section **consistent with FONLL** (scaled pp)

CMS-PAS-HIN-22-001

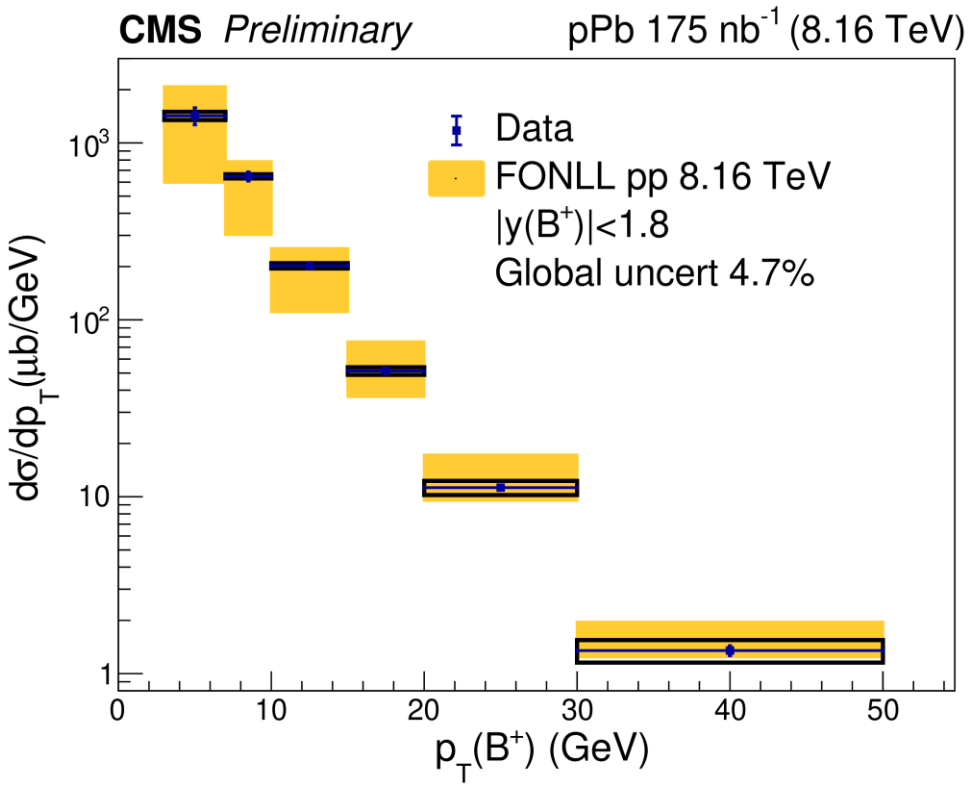


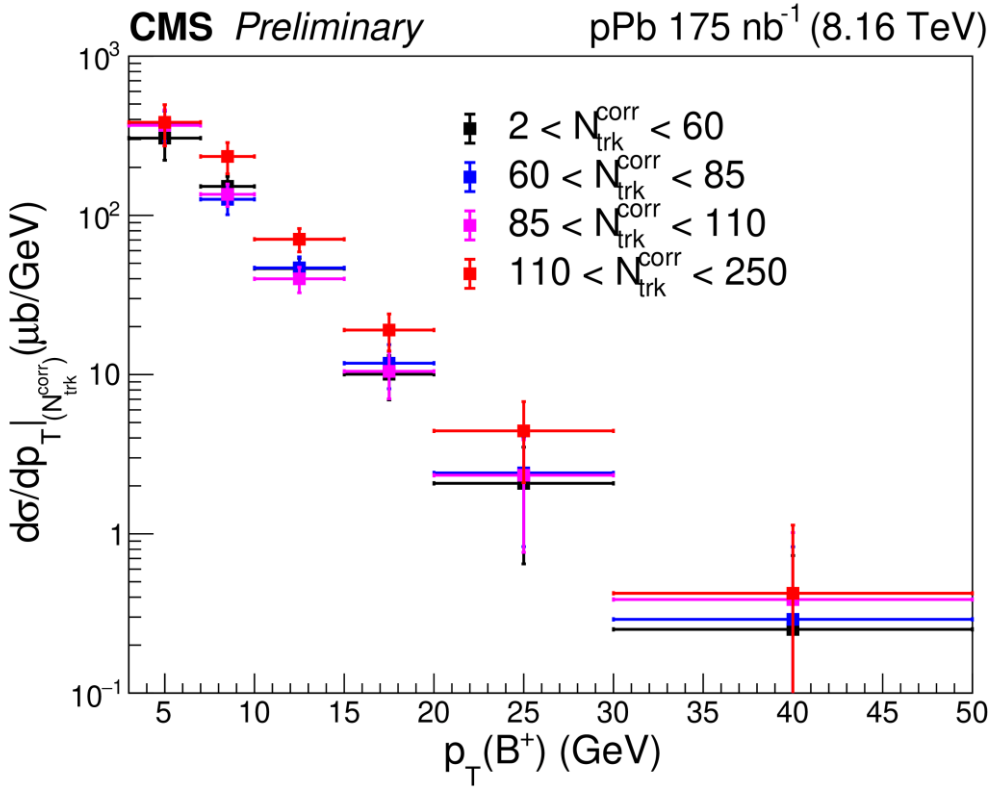


B^+ production in pPb vs N_{trk}

- Using $B^+ \rightarrow J/\psi K^+$ in an extended $3 < p_T < 50$ GeV
- differential p_T cross section **consistent with FONLL** (scaled pp)
- Extending measurement vs $\mathbf{N_{trk}}$ for the first time
- **density** of the hadronic environment impacts B^+ production?

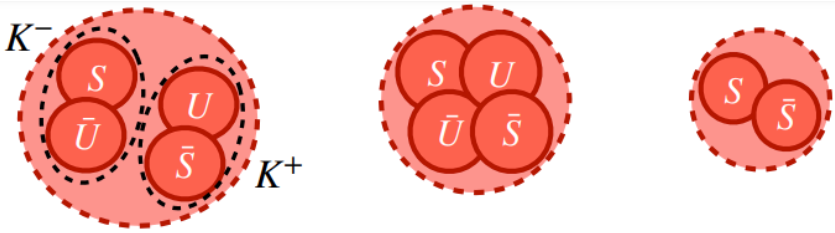
CMS-PAS-HIN-22-001





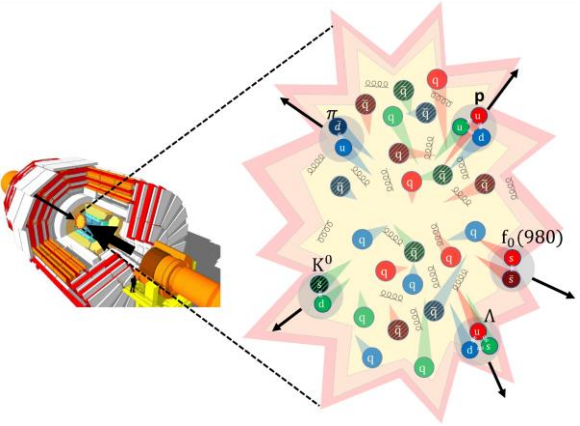
Constraining $f_0(980)$ quark content

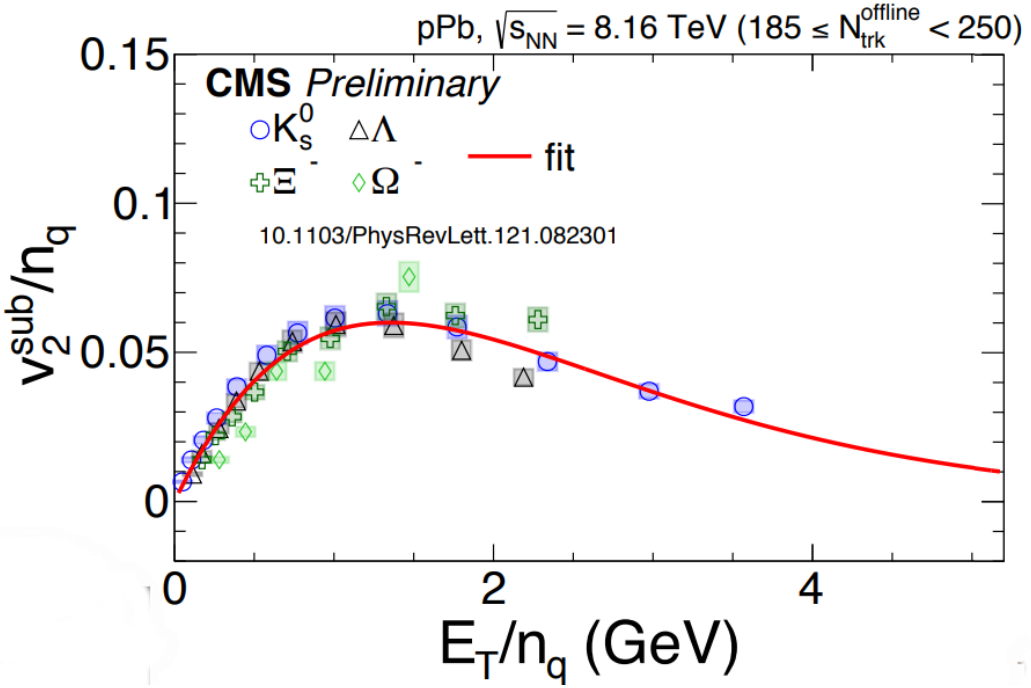
- $f_0(980)$ structure not well established
- KK molecule, tetraquark, diquark?
- Use n_q scaling of v_2 to infer number of quarks



A. Baty (QM23)

CMS-PAS-HIN-20-002





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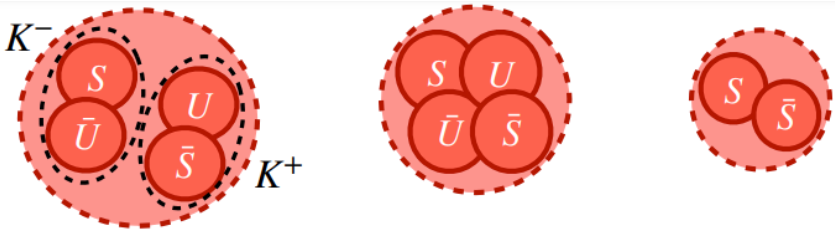
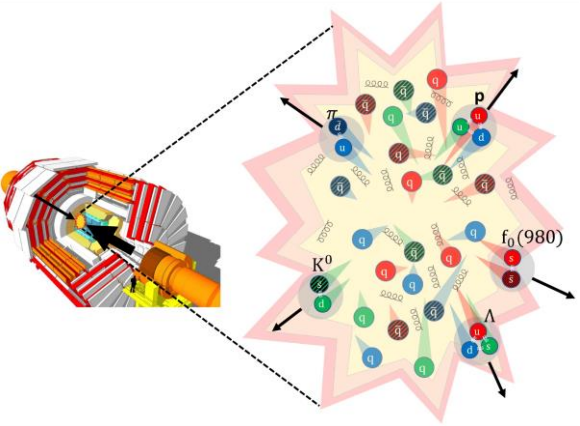
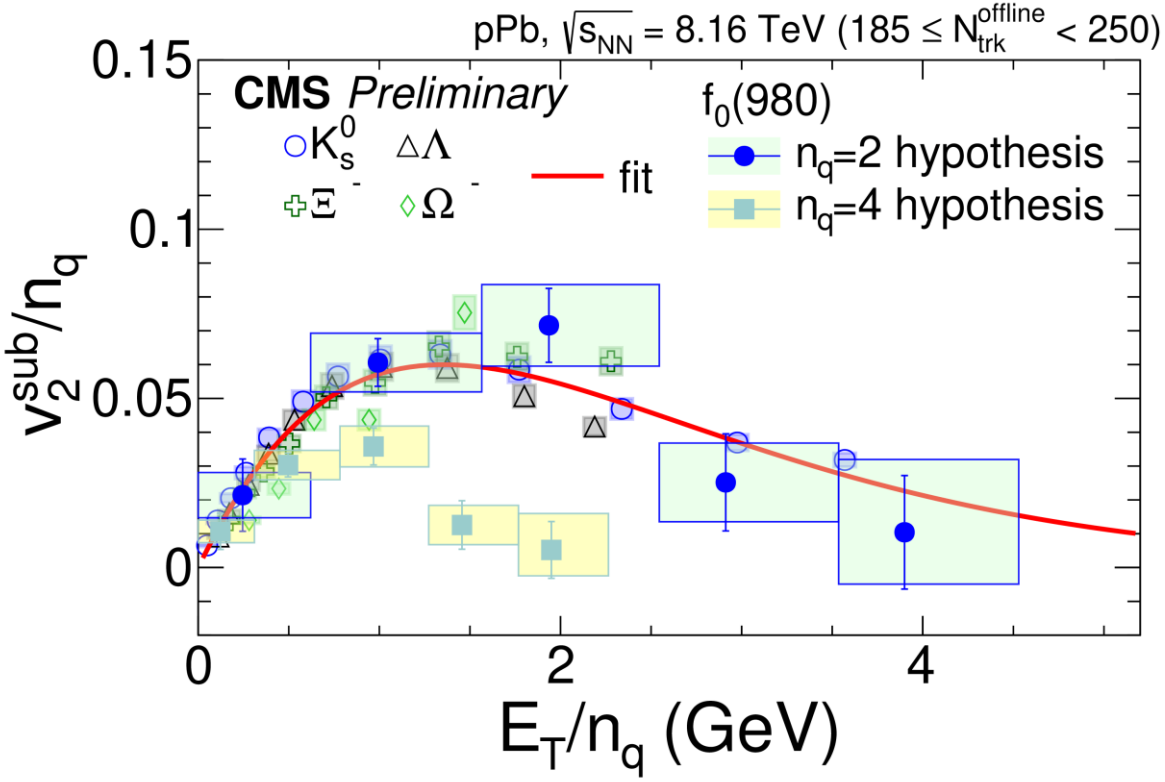
- $f_0(980)$ structure not well established
- KK molecule, tetraquark, diquark?
- Use n_q scaling of v_2 to infer number of quarks
- $n_q = 4$ excluded at 3.1σ
- **$n_q = 2$ favored**



A. Baty (QM23)

CMS-PAS-HIN-20-002

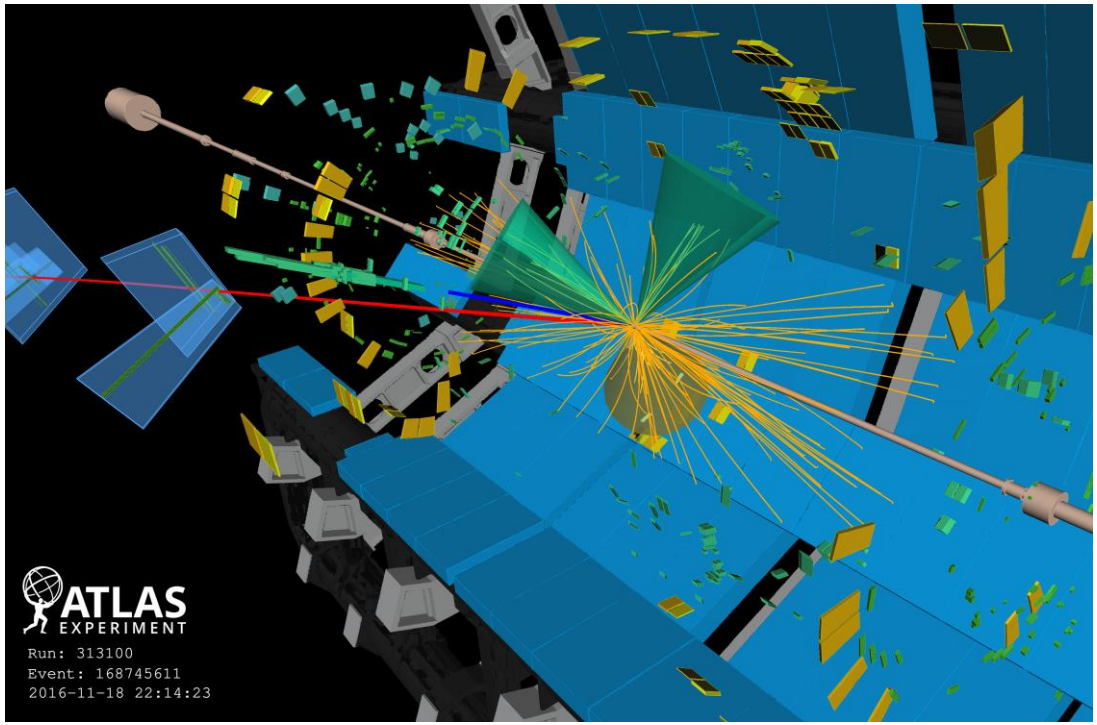




Top quark production in pPb

- Probes high-*x* gluons in a **poorly constrained** kinematic region
- dilepton channel cleaner but with lower yield than semileptonic

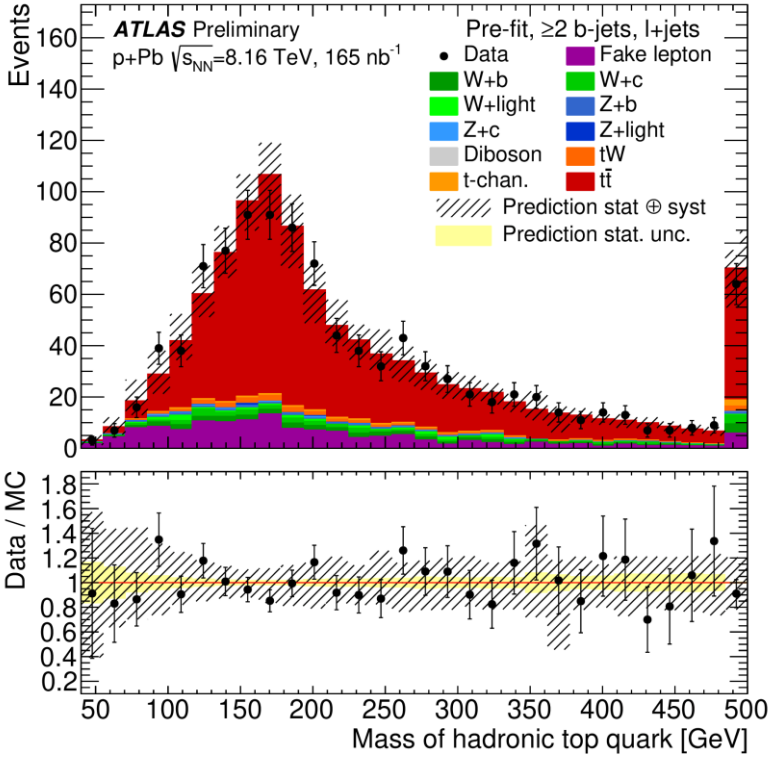
ATLAS: ATLAS-CONF-2023-063
CMS: PRL **119** (2017) 242001 (editor's suggestion)

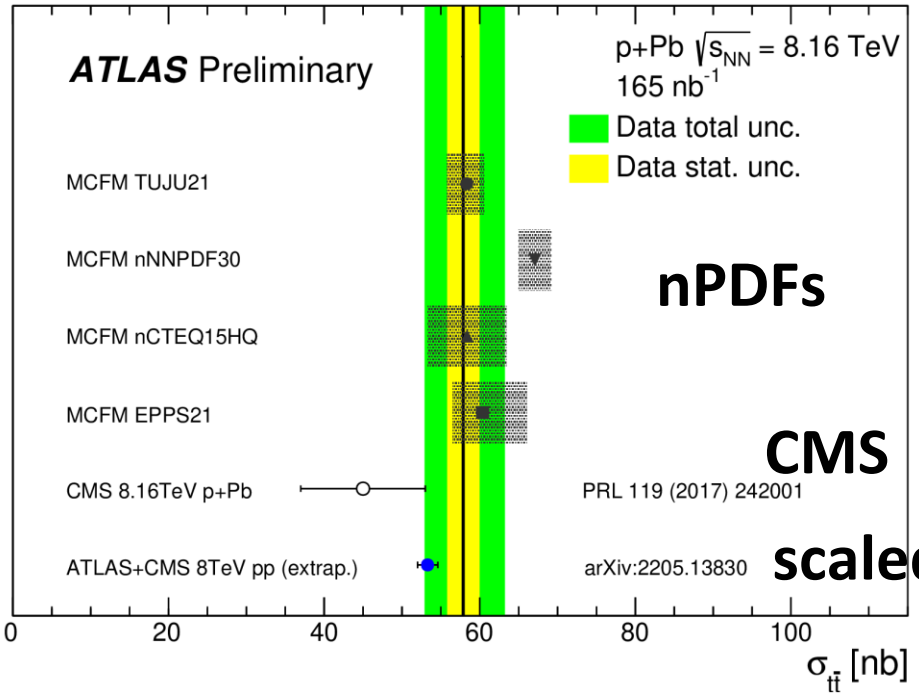


Top quark production in pPb

- Probes high-*x* gluons in a **poorly constrained** kinematic region
- dilepton channel cleaner but with lower yield than semileptonic
- ATLAS achieved a 9% precision → **most precise** tt measurement in HI collisions
- results consistent with the combined ATLAS+CMS pp cross section
- good agreement with NNLO using several nPDFs (tension with nNNPDF30?)

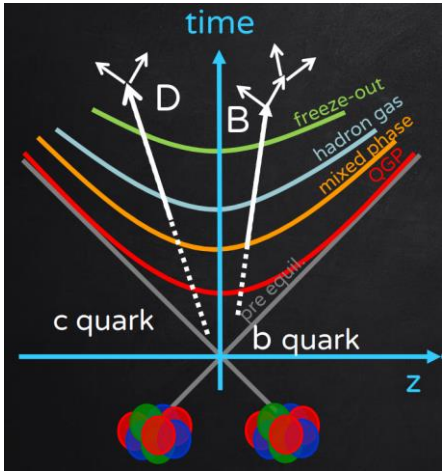
ATLAS: ATLAS-CONF-2023-063
CMS: PRL **119** (2017) 242001 (editor's suggestion)





Summary

- HF important tool to study **production and bulk properties**
  - provides a reference to understand "beyond pQCD", e.g., dimuon correlations, b jets
- Comprehensive studies of HF collectivity in **all** systems
  - charm v_2 in pPb&pp is significant, but lower than in PbPb
  - b flows in PbPb, but seems not(?) in pPb or pp → more lumi
- First **Λ_c^+/D^0 and B^+ vs N_{ch} in pPb** for dedicated high-density studies
- Small systems can be used in **novel ways**, e.g., hadron spectroscopy and "very HF"
  - extracted n_q=2 for $f_0(980)$ using NCQ scaling of v_2, ever-increasing top quark precision
- pp ref in Run 3~Run 2, no pPb before Run 4 (but **upgraded detectors**)



Plot here

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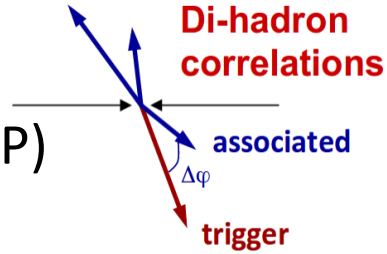
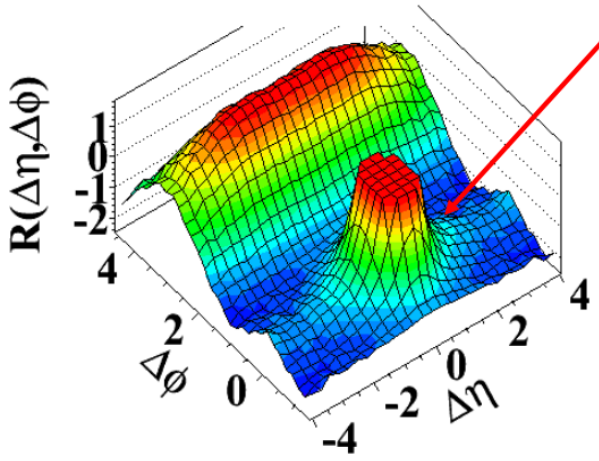
slides

"Everything...flows"(?)

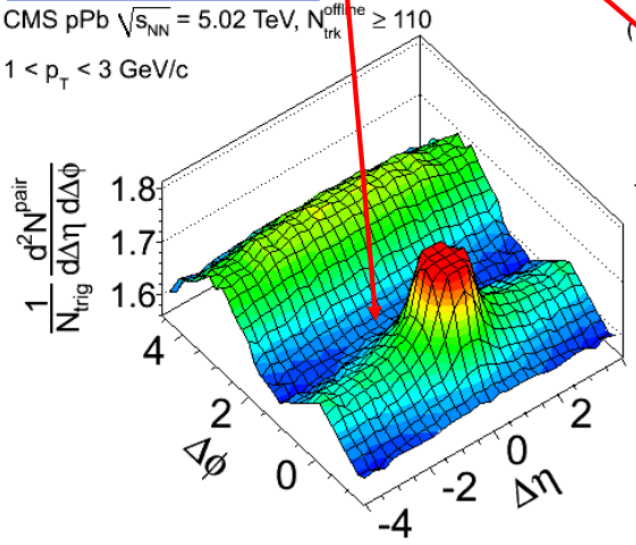
- Long-range ($2 < |\Delta\eta| < 4$), near-side ($\Delta\phi \approx 0$) angular correlations in
- heavy ion (XeXe and PbPb), **and**
- "small systems", i.e., high-multiplicity pPb and pp collisions
- Signs reminiscent of **collective behavior** of a quark-gluon plasma (QGP)



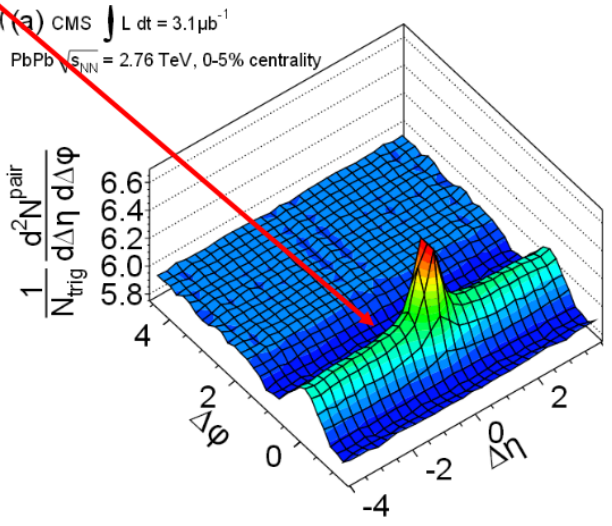
pp 7 TeV



pPb 5.02 TeV



PbPb 2.76 TeV, 0-5%



JHEP **09** (2010) 091

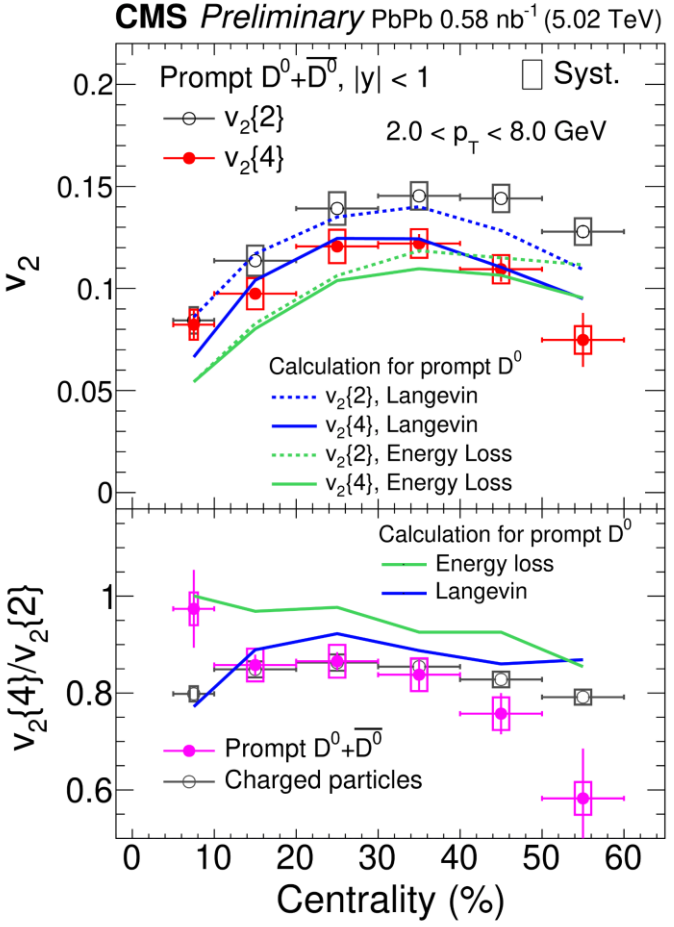
PLB **718** (2013) 795

JHEP **07** (2011) 076

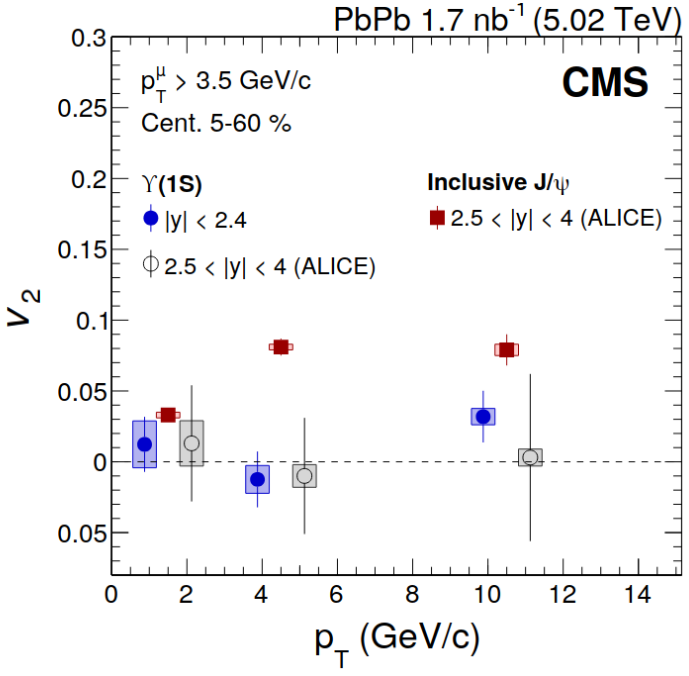
Measuring HF particle flow in PbPb

- HF hadrons and their decay products are effective probes of QGP
  - a series of measurements with, e.g., D^0, J/ψ, Υ(nS), and heavy-flavor decay leptons
  - extension to studies of **EM fields effects**, e.g., no rapidity dependence of Δv_2 (D^0–$\overline{D^0}$)
  - The harmonics for **c** mesons are **comparable to** the light-flavor hadrons
  - **Closer to zero** anisotropy observed for nonprompt D^0, Υ(nS) or beauty decay e's/μ's

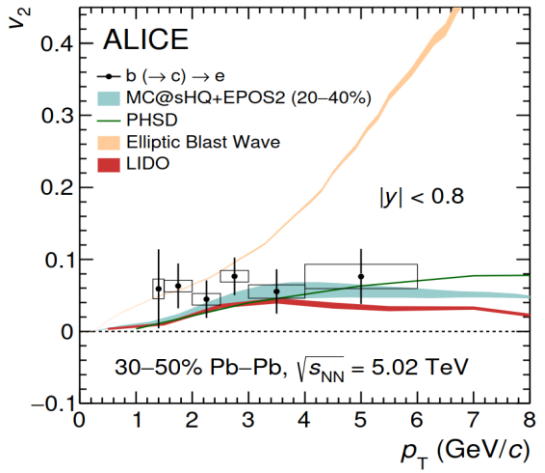
CMS-PAS-HIN-**20-001**



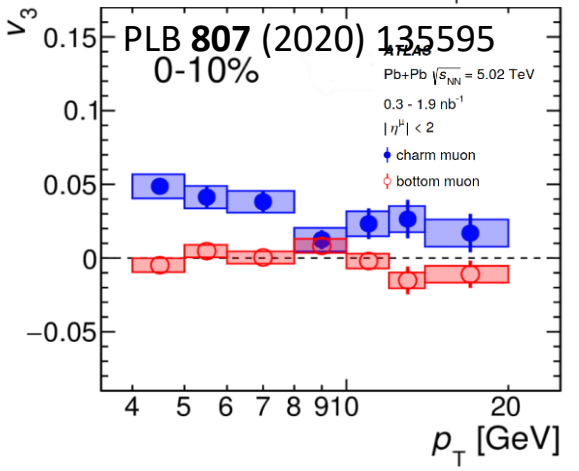
PLB **819** (2021) 136385



PRL **126** (2021) 162001



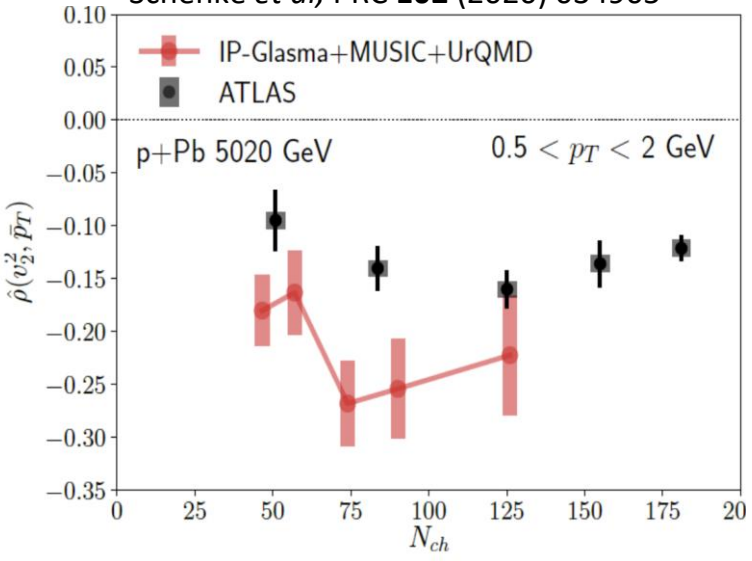
PLB **807** (2020) 135595



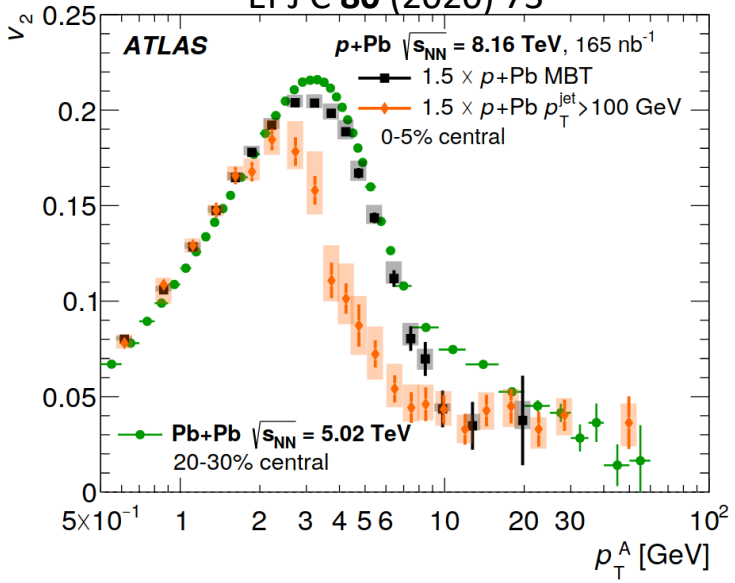
Understanding collectivity in small systems

- Correlation between $\mathbf{v_n}$ and $[p_T]$ (radial flow) sensitive to initial conditions
- $\mathbf{v_2}$–$[p_T]$ in pPb favors **a more compact** initial state → stronger flow and prominent ridge
- **Process-dependent $\mathbf{v_n}$** can distinguish complementary production mechanisms
- $\mathbf{v_{2,3}}$ similarity (ordering) in MB vs jet-triggered events indicates flow (soft+hard mix)
- $\mathbf{v_{2\text{-}4}}$ largely independent of whether measured in jet enriched/depleted pp events
- Photonuclear **collisions in UPC** offer an alternative dynamics of small systems
- competing explanations tested in cases one of the "beams" has a **simpler** initial state
- ATLAS see **significant $\mathbf{v_2}$** in UPC PbPb contrary to γp collisions (CMS)

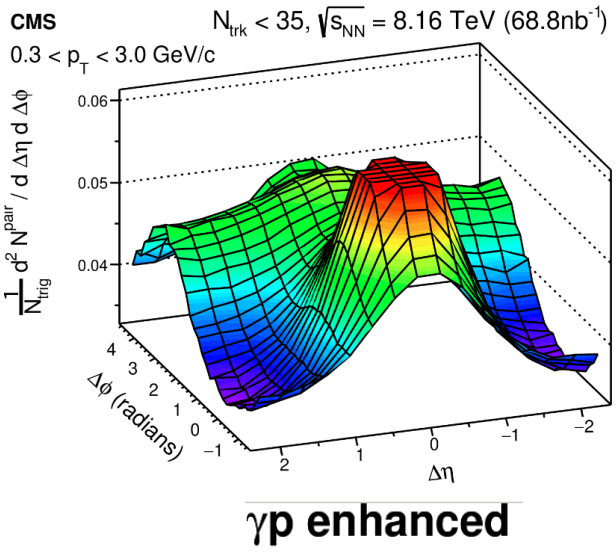
Schenke *et al,* PRC **102** (2020) 034905



EPJ C **80** (2020) 73



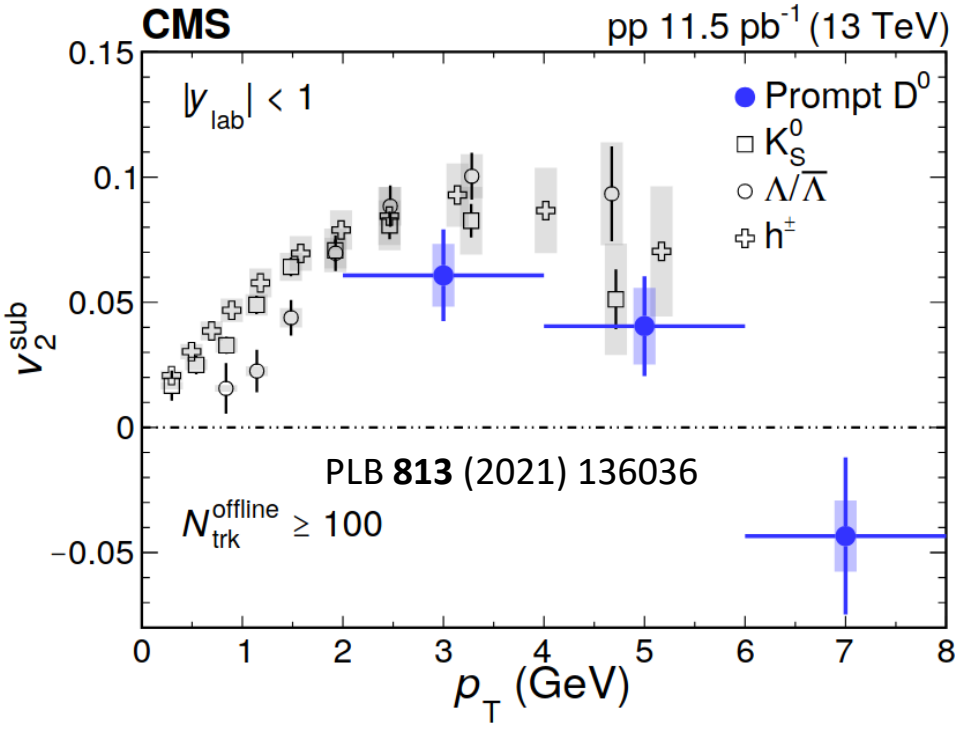
PLB **844** (2023) 137905

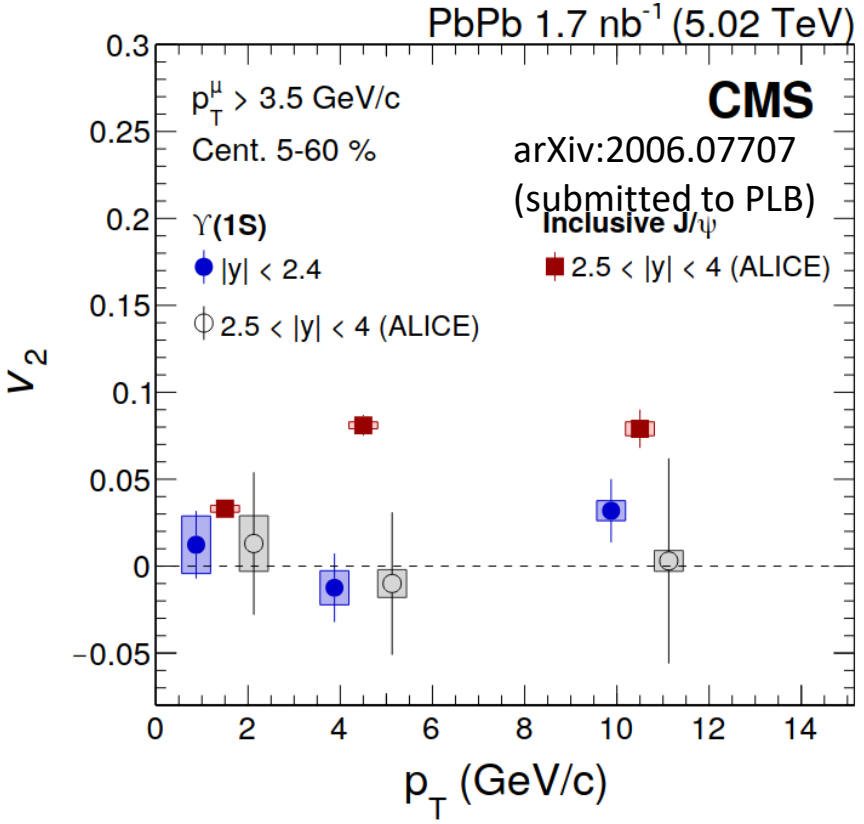


γp enhanced

Prompt D^0 v_2 in pp and Y(nS) v_2 in PbPb

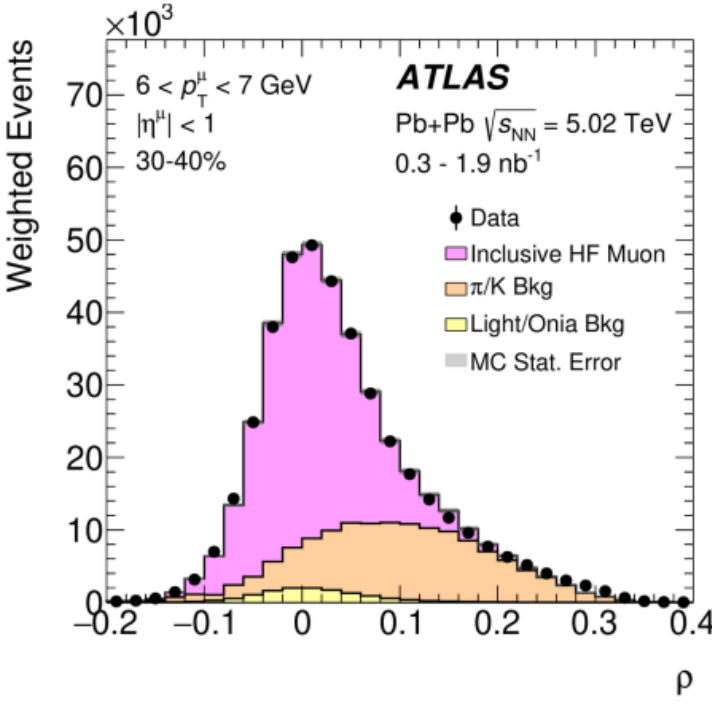
- **First** measurement with high-multiplicity events in pp
  - $v_2 \neq 0$; close to the v_2 of light flavors
- Flow of bottomonia in PbPb
  - Precise Y(1S) v_2 consistent with 0
  - **First** Y(2S) v_2 measurement consistent with 0 too
  - in contrast to larger J/ψ v_2

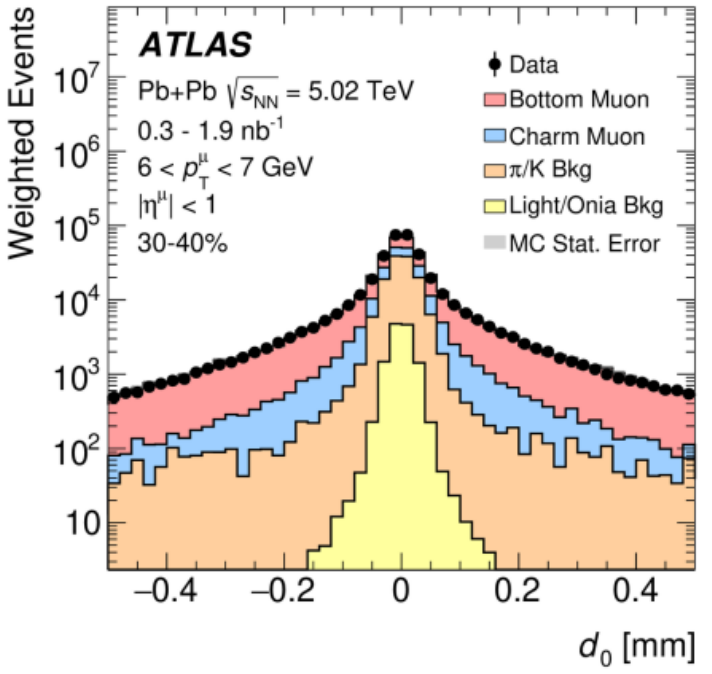




Flow of heavy flavor decay leptons

- Reconstruction of μ's from c and b hadron decays separated from π/K bkg using
- the momentum imbalance $\rho = (p^{ID} - p^{MS})/p^{ID}$
- between the inner detector and muon spectrometer
- real muons have a ρ distribution peaked around zero
- π/K bkg a broader ρ shifted towards higher values
- the transverse impact parameter d_0
- different d_0 due to c and b hadrons' decay lengths



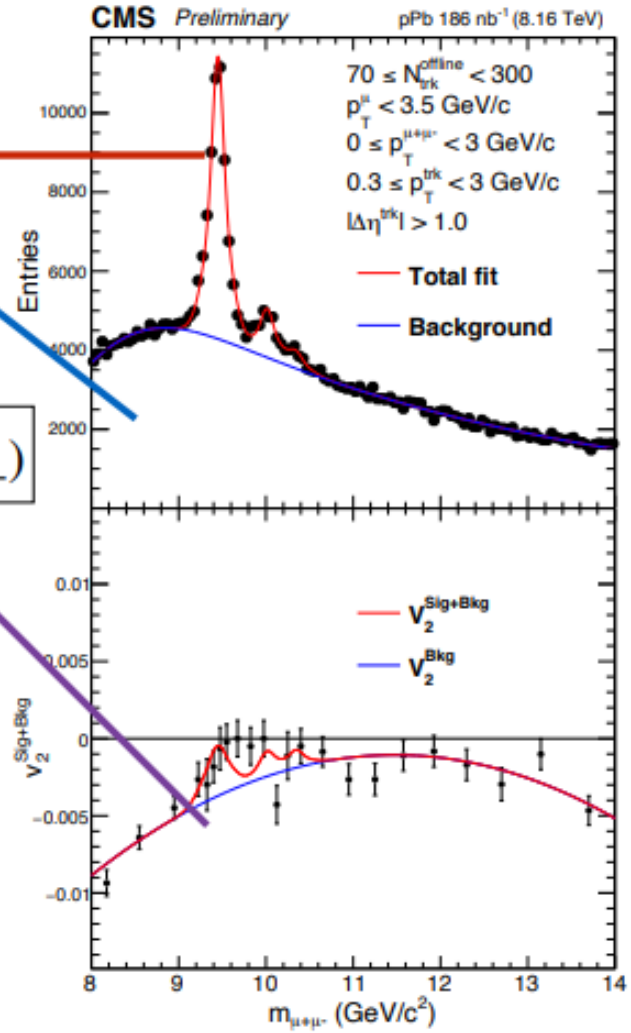


Simultaneous fitting

PAS-HIN-21-001

$$f_{\text{sig}} = \frac{\text{signal}}{\text{signal+background}}$$

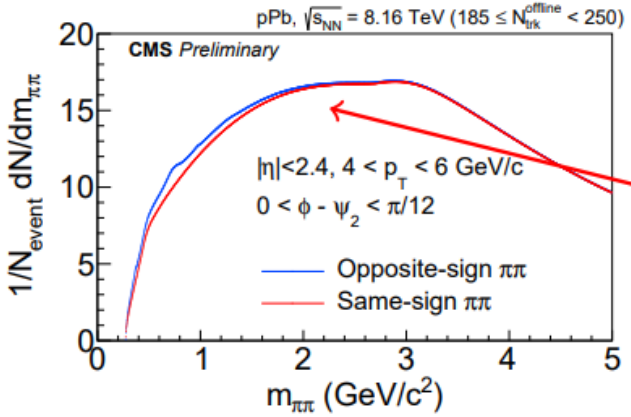
$$V_2^{S+B}(m_{\mu+\mu-}) = f_{\text{sig}} V_2^{\text{sig}} + (1 - f_{\text{sig}}) V_2^{\text{bkg}}(m_{\mu+\mu-})$$



- Observed V_2 is composed of signal-track correlation and background-track correlation
- To extract signal V_2, simultaneous fitting with mass is applied

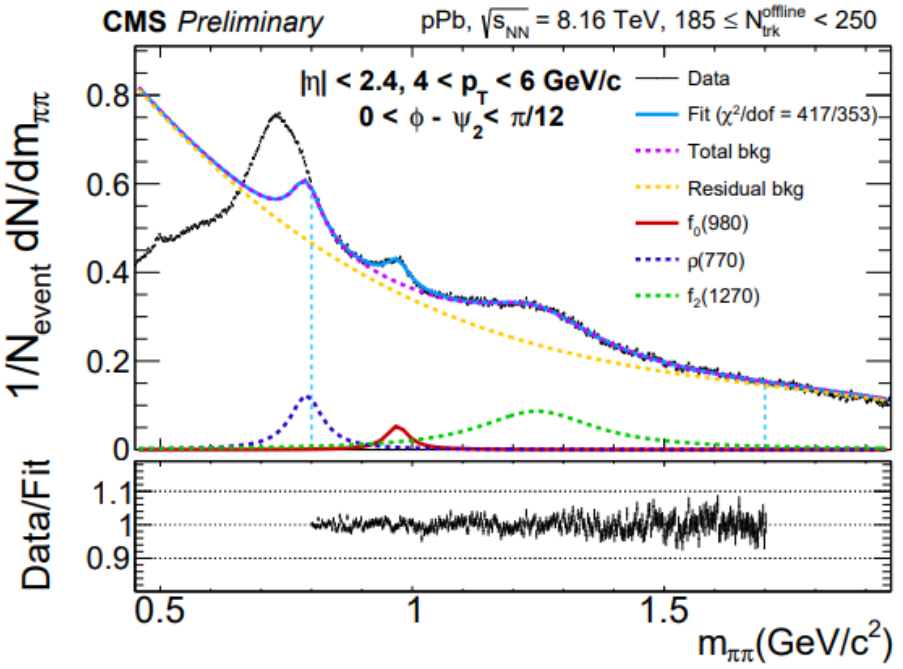
Data Analysis: Reconstruction of $f_0(980)$

- Dataset: pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV in high multiplicity events collected in 2016.
- Dominant decay channel: $f_0(980) \rightarrow \pi^+\pi^-$.
- No PID in this analysis; All charged tracks assumed to be pions
- Mass Spectrum: opposite sign pair $\pi^+\pi^-$ subtracted by same sign pair $\pi^+\pi^+$, $\pi^-\pi^-$



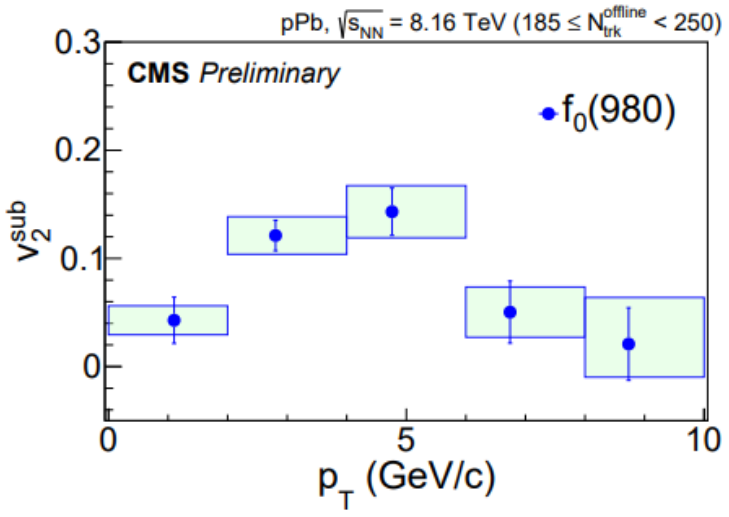
Large Combinatorial Background

- Peak is modeled with Breit-Wigner function
- Residual background: 3rd order polynomial
- Fitting range: $0.8 < m_{\pi\pi} < 1.7\ GeV/c^2$



QM23: f0(980)

v_2^{sub} results and systematic uncertainties



- Systematic uncertainties of $\mathrm{f}_0(980)$ v_2
  - Mix-Event Correction
  - Track Selection
  - Event-plane Resolution
  - Signal Form
  - Residual Background Form
  - Fit Range
  - Nonflow Subtraction
- Systematic uncertainties of $\mathrm{f}_0(980)$ n_{q}

Source	n_{q} uncertainty
Statistical	0.16
$\mathrm{f}_0(980)$ v_2 systematics	0.12
Non-flow effects on v_2^{sub}	0.10
NCQ-scaling fit parameters	0.05
NCQ-scaling functional form	0.04
NCQ-scaling using $p_{\mathrm{T}}/n_{\mathrm{q}}$	0.04