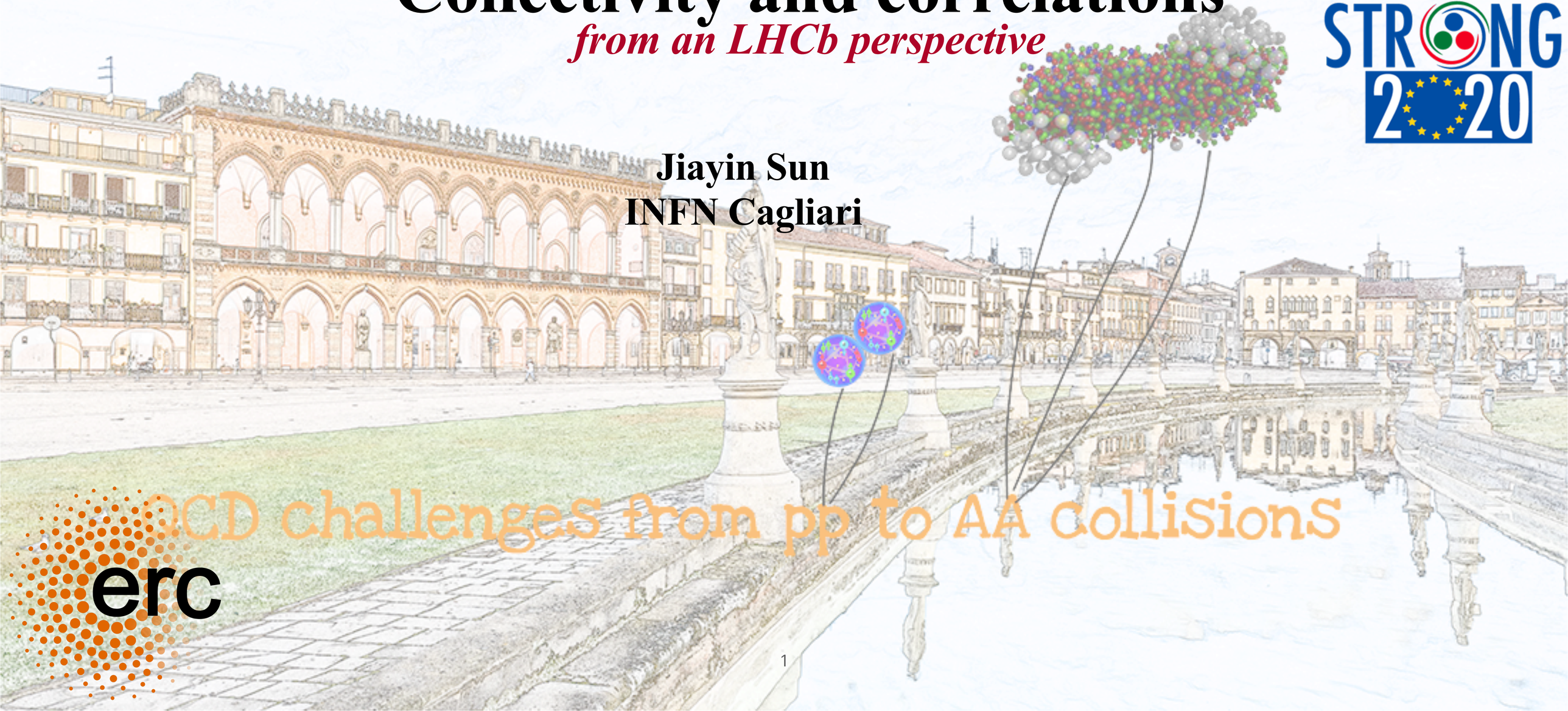
Collectivity and correlations

from an LHCb perspective

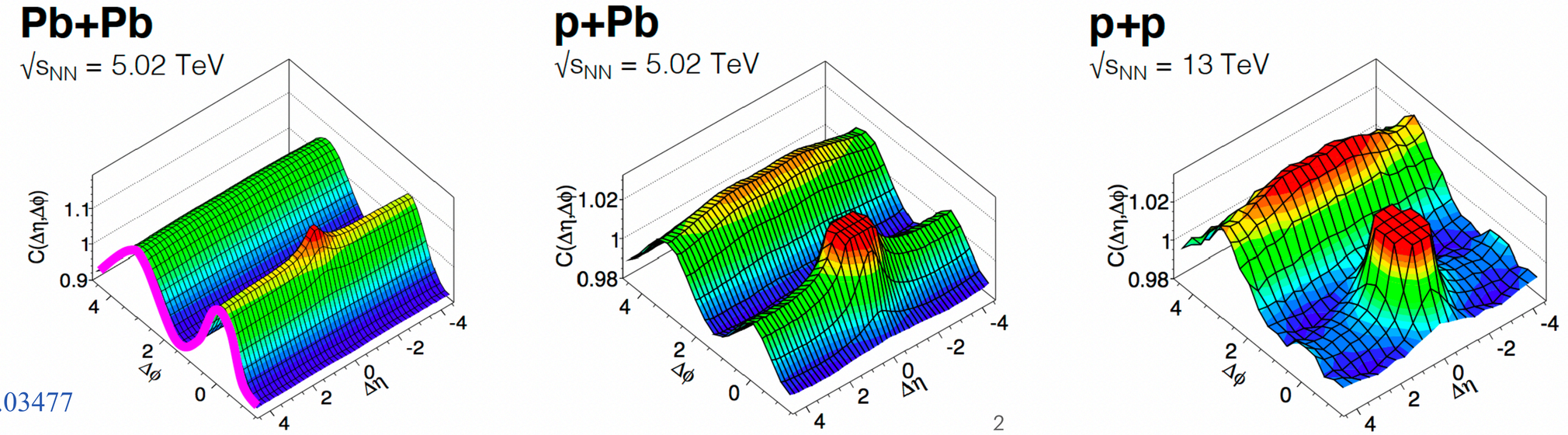


Jiayin Sun
INFN Cagliari

Introduction

Flow studies from an LHCb perspective

- Flow has been extensively studied at RHIC and LHC
  - A wealth of precise and sophisticated measurements from *pp* to AA collisions
  - LHCb trying to be a newcomer in the field
- The LHCb detector
  - Forward fully instrumented spectrometer (small Bjorken-*x*, lower energy density, direct photon…)
  - Designed to study heavy flavor (with low p_T coverage)
  - Excellent performance at small colliding systems (*pp* and *p*Pb)
  - Fixed-target program (gas target of different sizes)
- Recent flow results in small systems
- A few flow analyses ongoing at LHCb

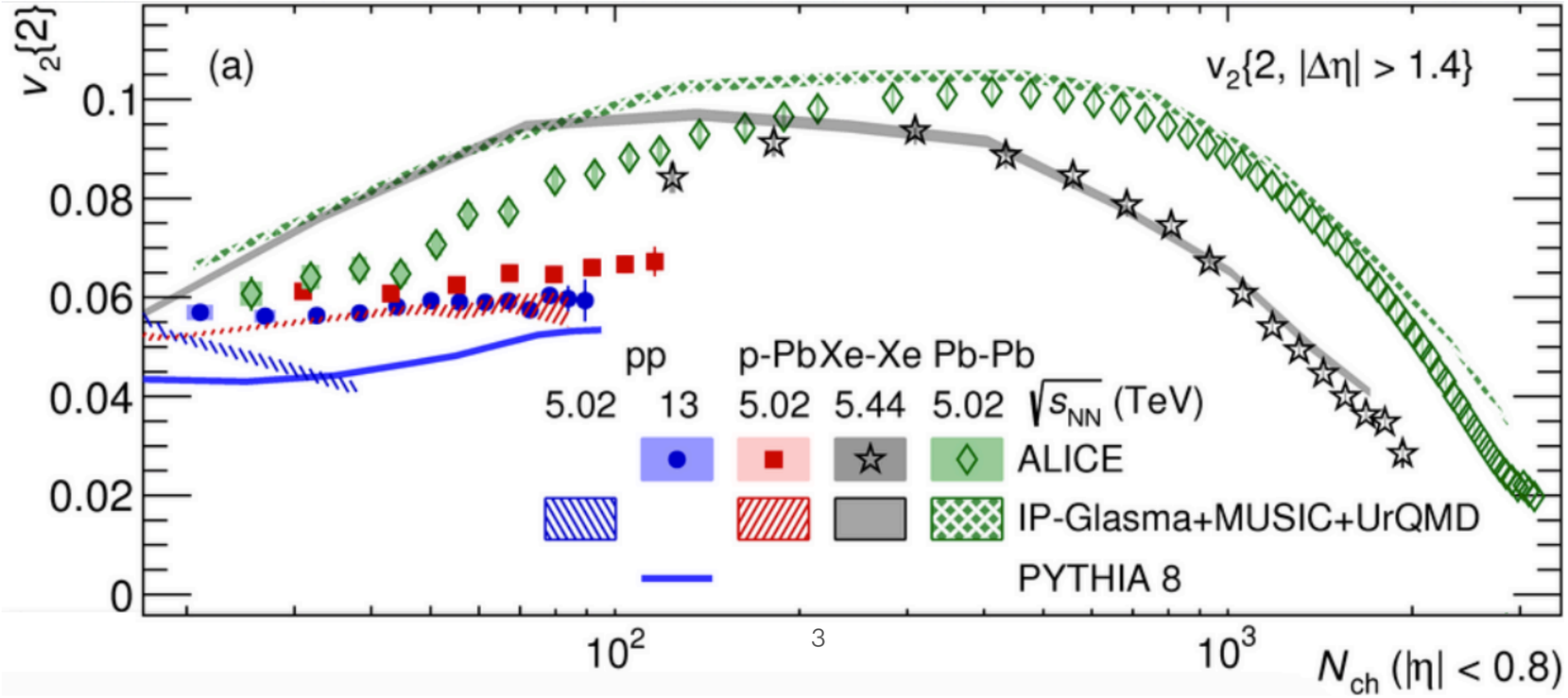


arXiv:1801.03477

Flow in small systems

- Most of the signatures of hydrodynamic flow in A+A collisions also existed in smaller systems.
  - Difference in small systems: exist only in high multiplicity events, jet quenching/energy loss not observed
- Origin of the flow in small systems under debate:
  - Hydrodynamic evolution of a high density partonic medium
  - Gluon saturation in the framework of a color-glass-condensate
  - Others…

ALICE, Phys. Rev. Lett. 123, 142301 (2019)

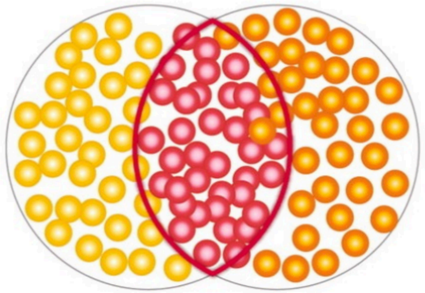


PHENIX small system scan

p+Au, *d*+Au *and* ^{3}He+Au **collisions**

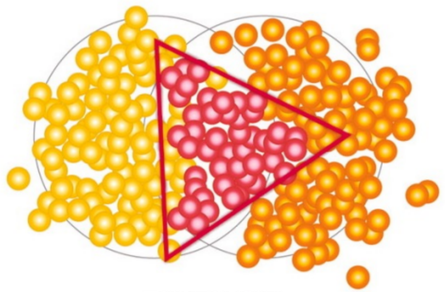
Nat. Phys. 15, 214–220 (2019)

- Flow in small system driven by initial geometry
- Hydrodynamics translate the initial geometry into dynamical v_n
- Cannot be reproduced from initial state effects only PRL 123, 039901



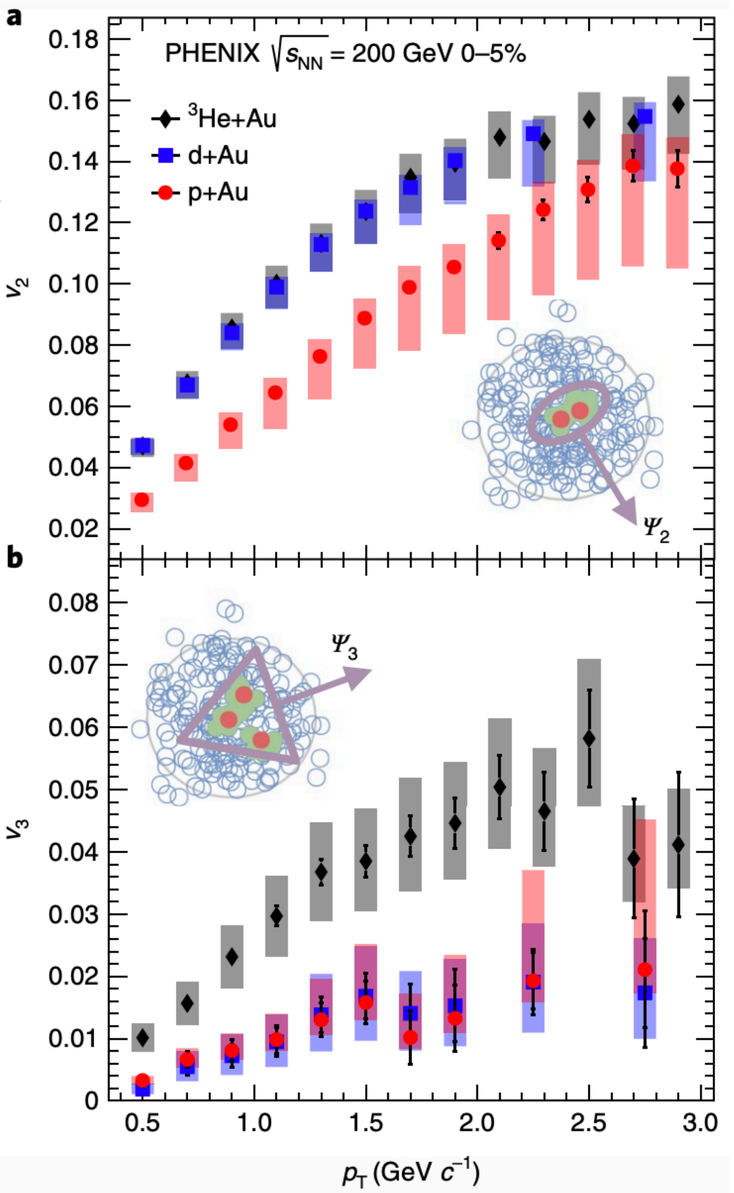
Elliptic flow

$$v_2^{\mathrm{p+Au}} < v_2^{\mathrm{d+Au}} \approx v_2^{\ {}^3\mathrm{He+Au}}$$



Triangular flow

$$v_3^{\mathrm{p+Au}} \approx v_3^{\mathrm{d+Au}} < v_3^{\ {}^3\mathrm{He+Au}}$$

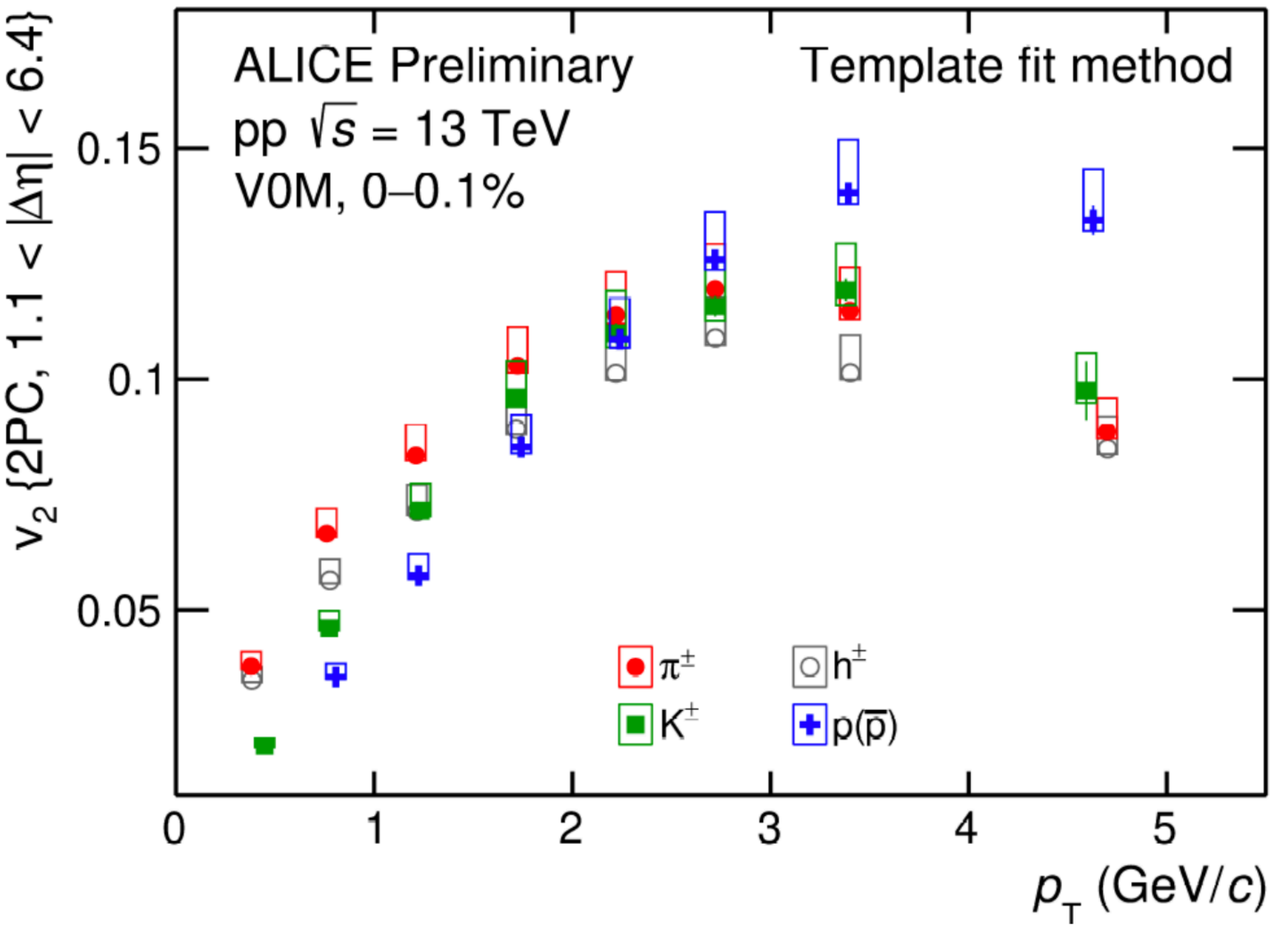


Flow in small systems

Light flavor in *pp* collisions

- Identified light hadron flow
- Mass ordering at low p_T
- Baryon-meson splitting at intermediate p_T
- Similar to *p*A and AA collisions

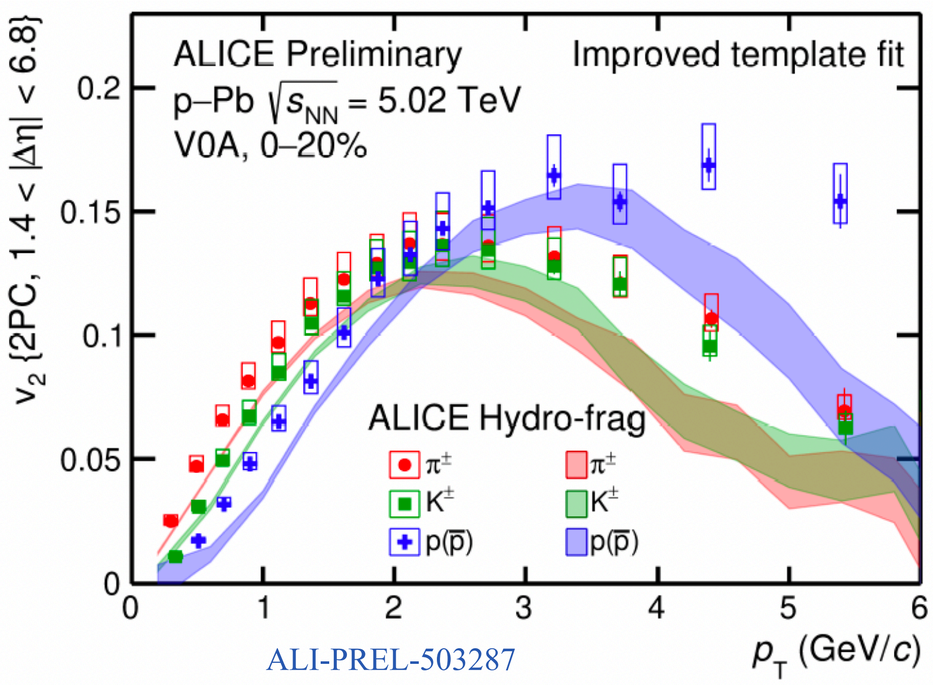
ALI-PREL-503287



Flow in small systems

Light flavor in *p*Pb collisions

- Identified light hadron flow
- Mass ordering at low p_T
- Baryon-meson splitting at intermediate p_T
- Models combine hydrodynamics, quark coalescence, and jet fragmentation
- Cannot describe data without quark coalescence —> partonic collectivity



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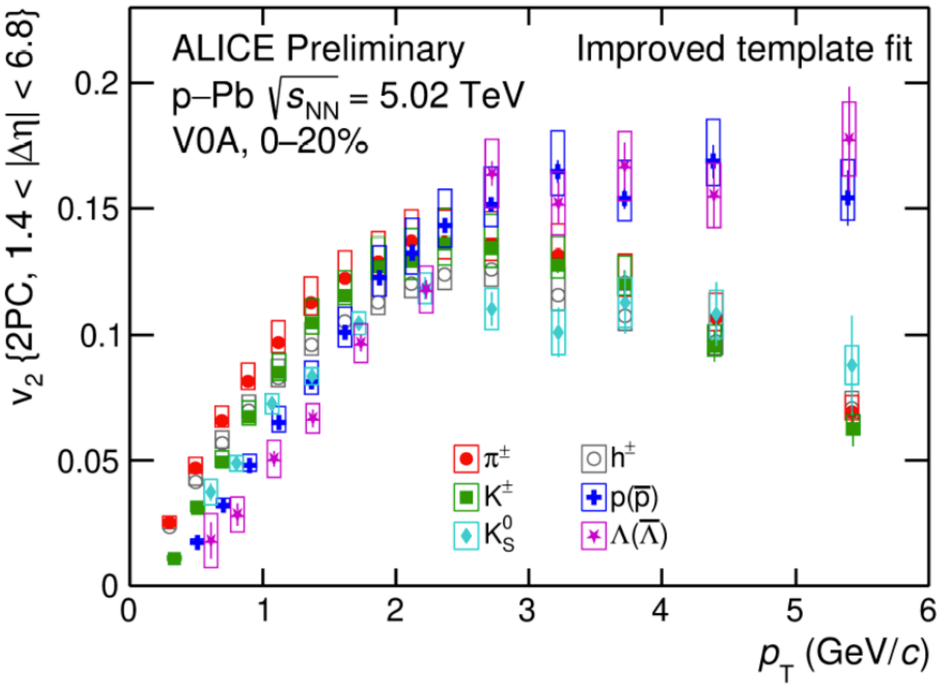

Flow in small systems

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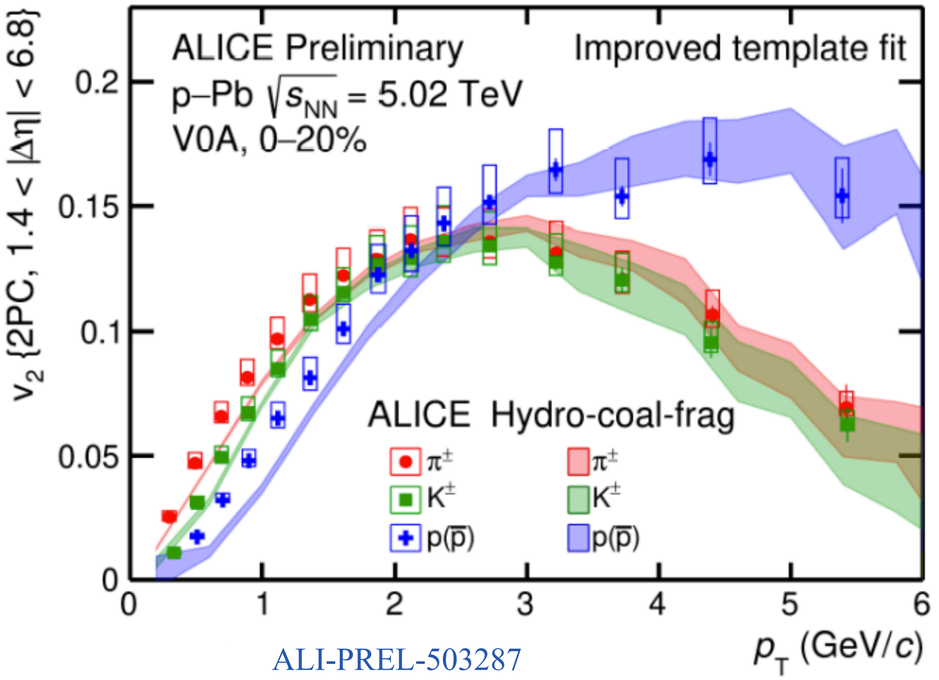

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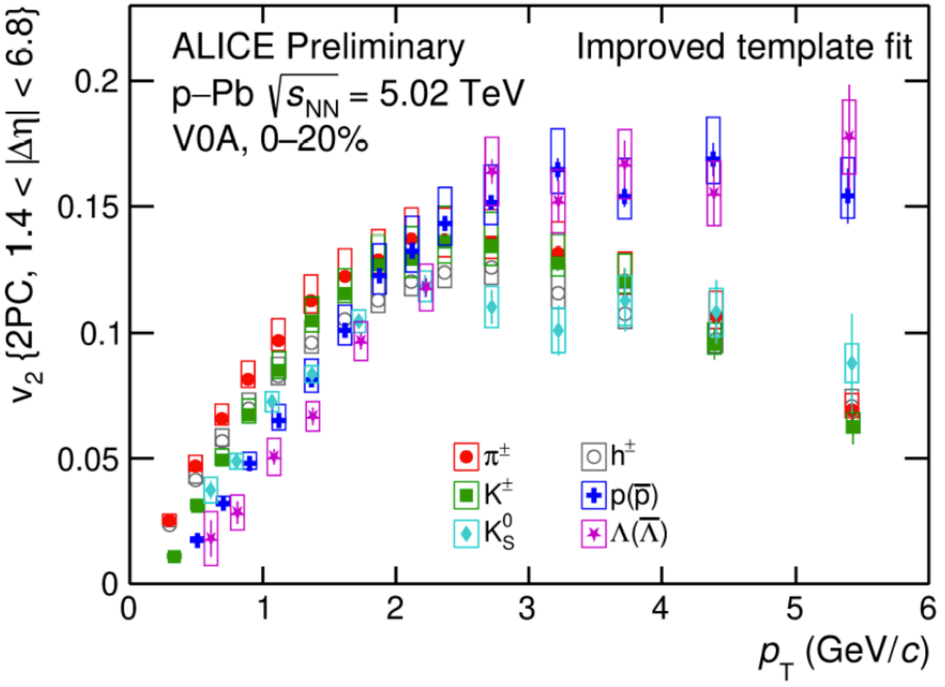
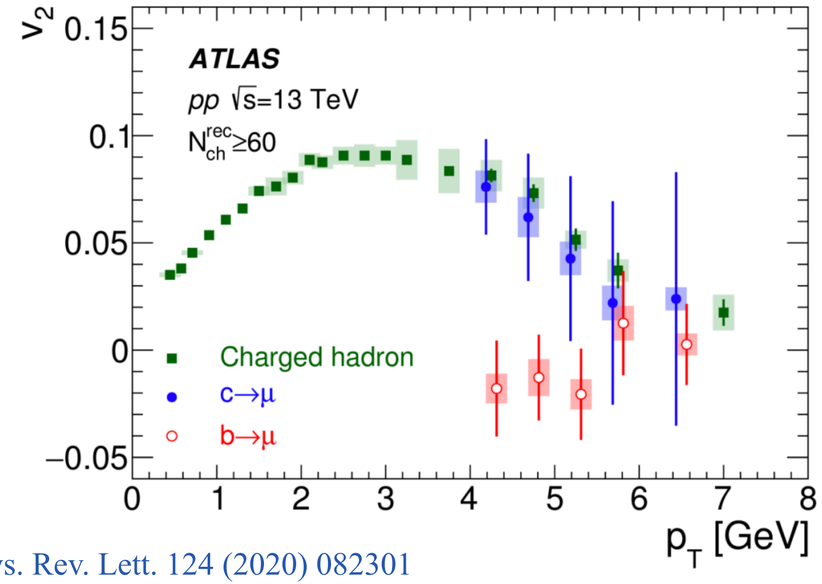


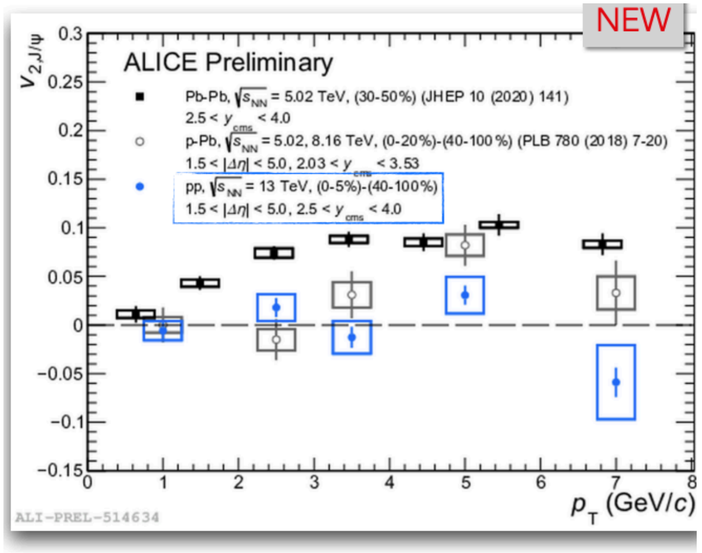
Flow in small systems

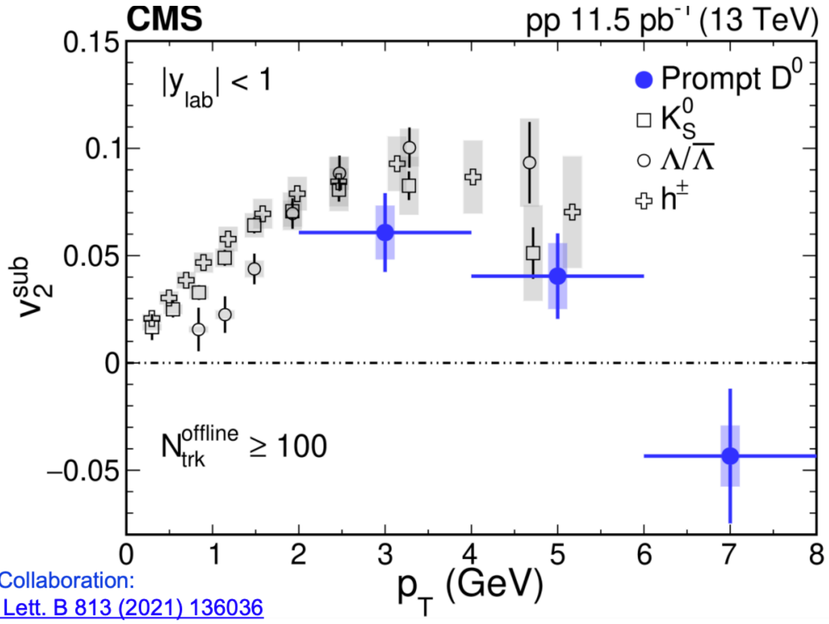
Strangeness and heavy flavor in *pp* collisions

- HF collectivity can potentially separate initial vs final-state effects
- Measured v_2 of muons produced in the semi-leptonic decays of *b* and *c* hadrons.
- Significant anisotropy observed for charm: comparable to inclusive hadrons.
- v_2 for muons from *b* decays consistent with zero.
- J/ψ v_2 consistent with 0.
- These HF anisotropy measurements can lead to further understanding of origin of the *pp* ridge



ATLAS: Phys. Rev. Lett. 124 (2020) 082301



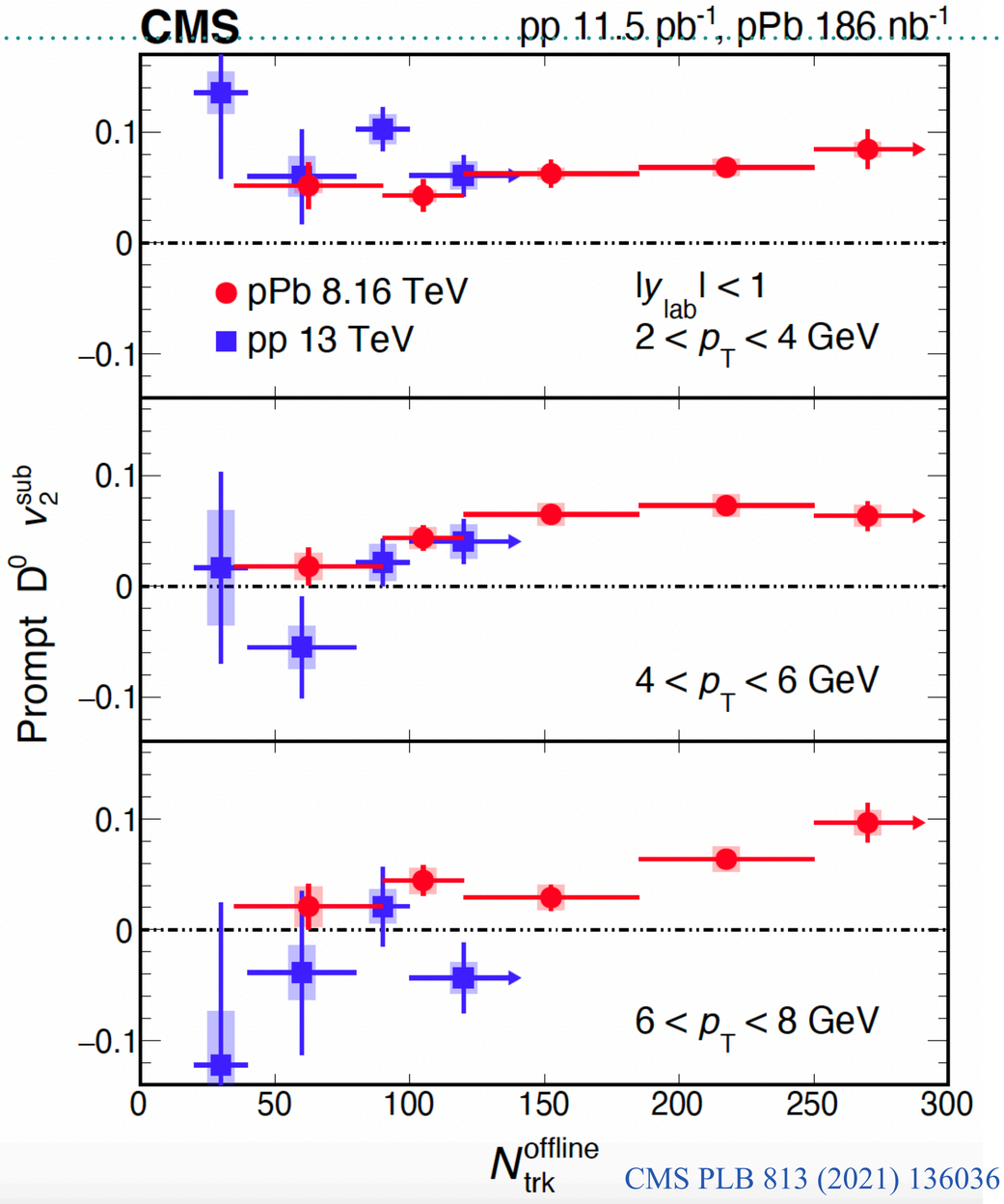


CMS Collaboration:
Phys. Lett. B 813 (2021) 136036

Flow in small systems

Strangeness and heavy flavor in *pp*/*p*Pb collisions

- Significant anisotropy observed for D^0:
  - *pp* comparable to *p*Pb at similar multiplicity



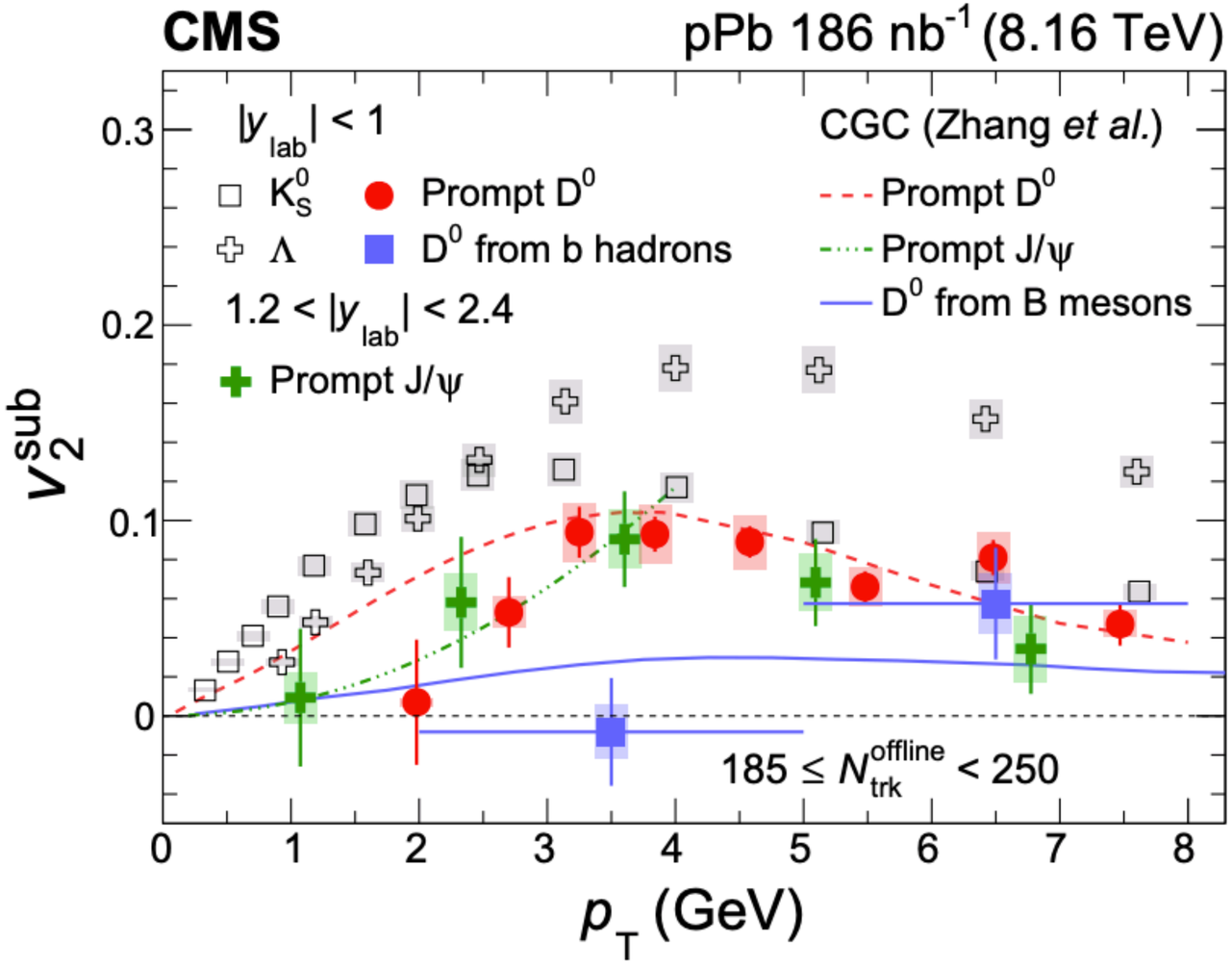
CMS PLB 813 (2021) 136036

Flow in small systems

Strangeness and heavy flavor in *p*Pb collisions

Phys. Lett. B 813 (2021) 136036

- Mass ordering:
  - lighter hadrons have larger v_2
- D^0 meson:
  - v_2(non-prompt) < v_2(prompt)
- Prompt D^0 v_2 ~ prompt J/ψ v_2
- Provide information on heavy flavor flow collectivity in small systems

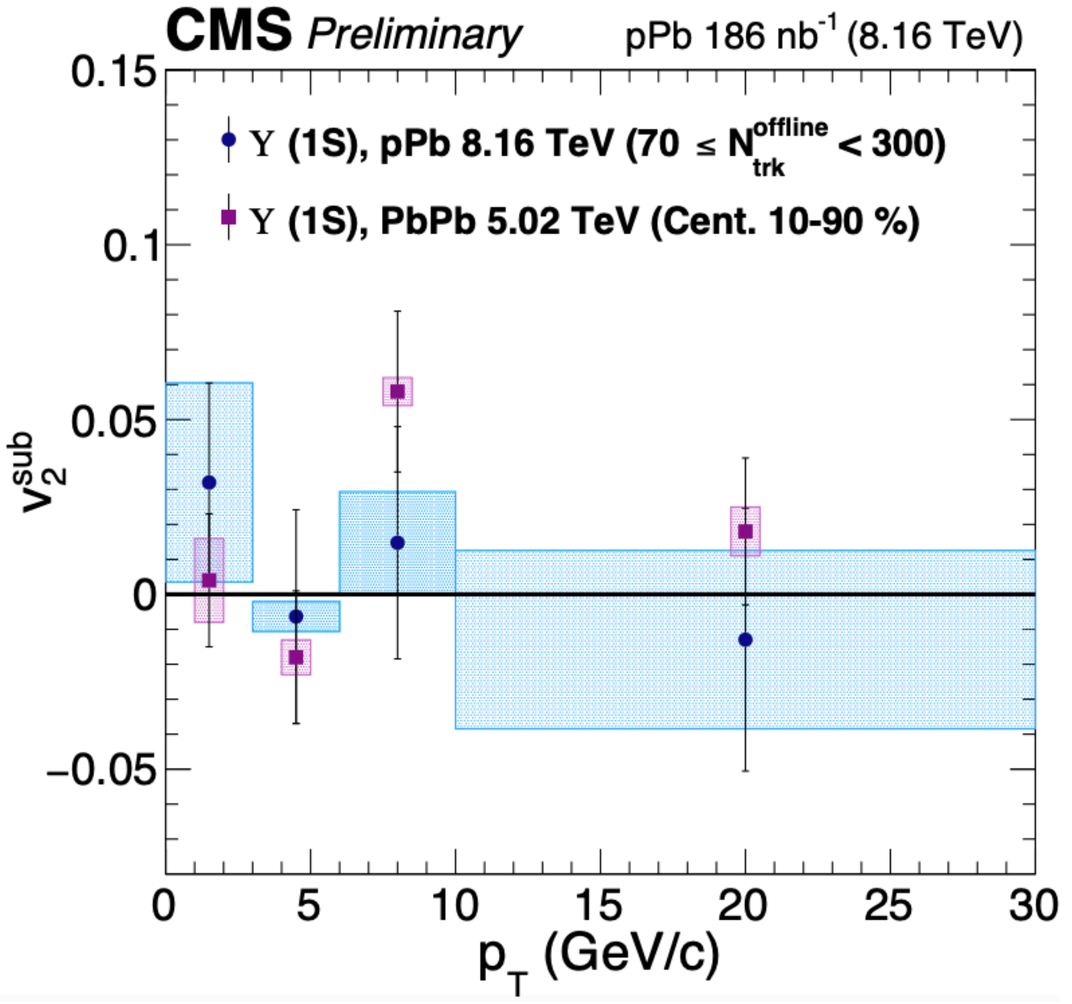


Flow in small systems

Upsilon in *p*Pb collisions

- Flow of quarkonia is a useful tool to study the path-length dependent modification effect and collectivity of heavy flavors
- PbPb:
  - $\Upsilon(1S)$ v_2 consistent with 0
- *p*Pb:
  - $\Upsilon(1S)$ v_2 consistent with 0

CMS PAS-HIN-21-001



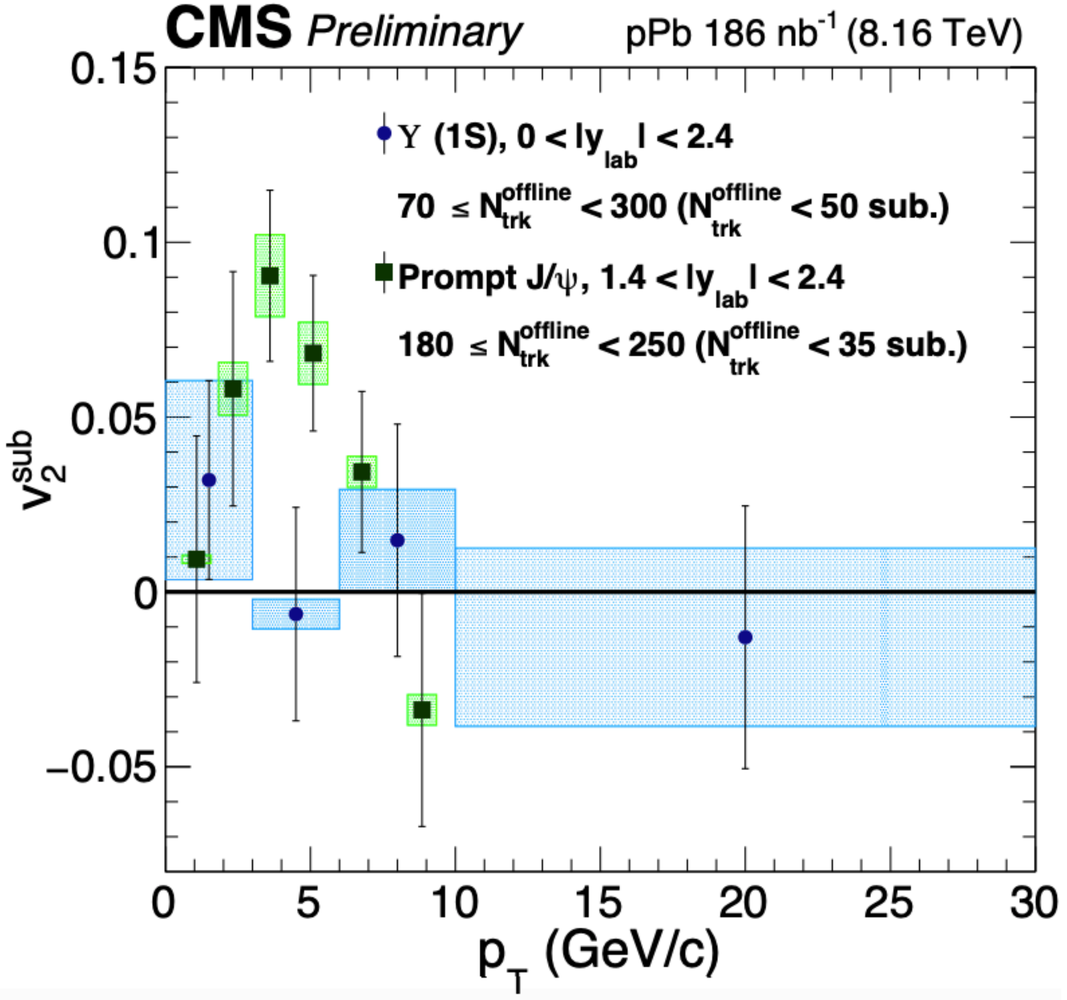
Flow in small systems

Upsilon

CMS PAS-HIN-21-001

- J/psi:
  - PbPb: large v_2 at low p_T from recombination effect
  - pPb: Non-zero v_2
- $\Upsilon(1S)$:
  - PbPb & pPb: v_2 consistent with 0

Different behavior between charmonia and bottomonia



Flow across colliding systems

- An incomplete summary of flow measurements
  - Measurements from UPC and ee, ep systems not included

flow signals?

	Light hadron	Strangeness	Prompt D	b —> D	Prompt J/psi	b —> J/psi	Upsilon	Dijet	Z boson	Photon
PbPb	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes
*p*Pb	Yes	Yes	Yes	No	Yes		No			
pp	Yes	Yes	Yes	No	No					

LHCb detector

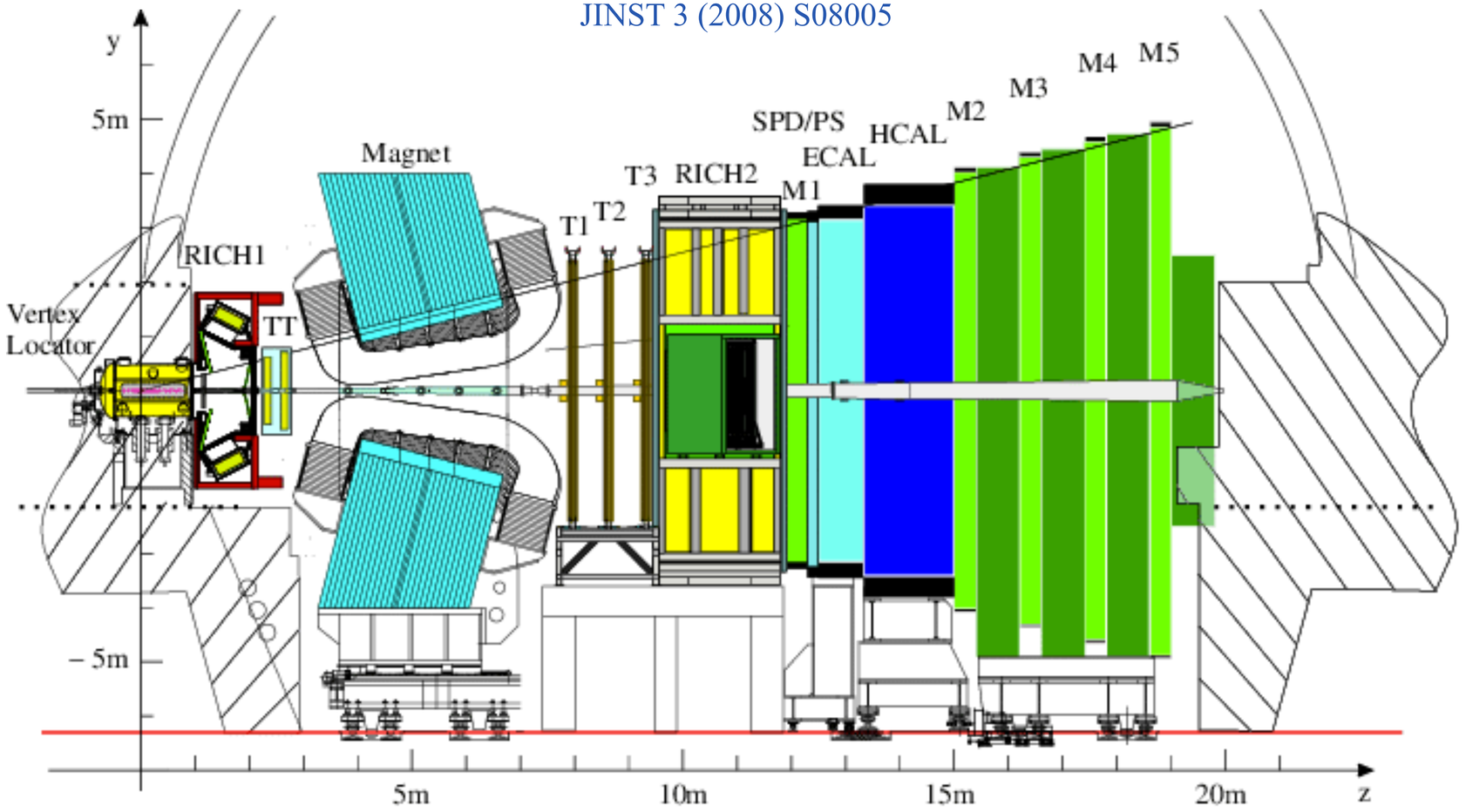
Run2 configuration

- Acceptance: $2 < \eta < 5$
- Vertex detector (VELO)
  - IP resolution ~ 20μm
- Tracking system
  - $\frac{\Delta p}{p} = 0.5 - 1\,\%$ (5-200 GeV/c)
- RICH
  - K/π/p seperation
- Electromagnetic + hadronic calorimeters
- Muon system
- Results presented in this talk are based on this configuration

Already upgraded for Run3! more later

- A single arm spectrometer in forward rapidity, optimized in measuring particles containing *s*, *c* or *b* quark.

JINST 3 (2008) S08005

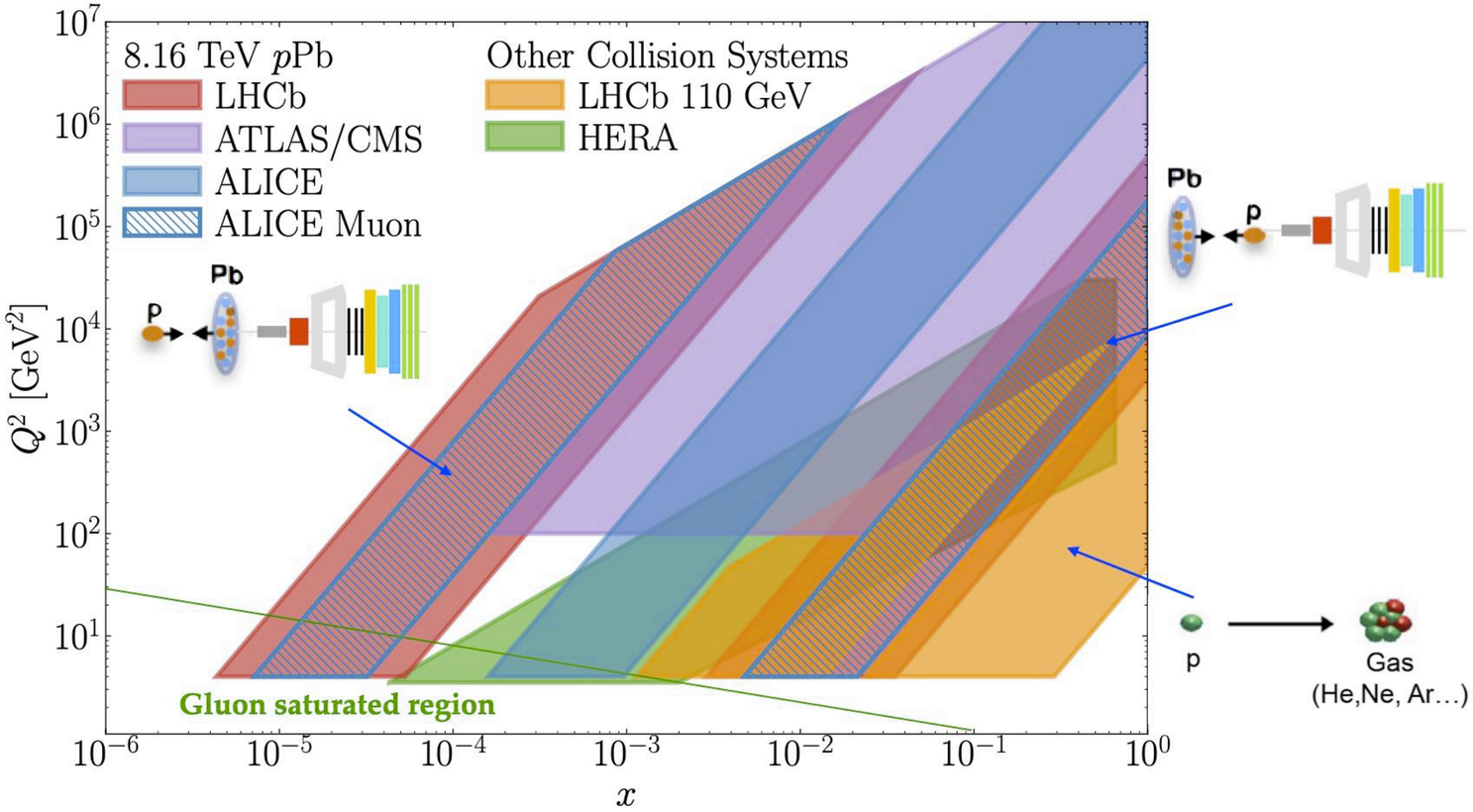


LHCb in heavy ion physics

Collider mode

- Designed to measure heavy flavor
- Excellent for studying *pp*/*p*Pb collisions
  - Constrain nPDF at small and large Bjorken-x
  - Probe gluon saturation in low x and low Q^2 region
  - Test hadronization mechanisms in medium
  - Study final state effects in medium
  - Search for possible QGP droplet formation in small systems
- How about flow/correlations in LHCb?
  - Forward rapidity
  - Reach into very low x region
  - Strong capabilities with small colliding systems and heavy flavor

$Q^2 \sim m^2 + p_{\mathrm{T}}^2$



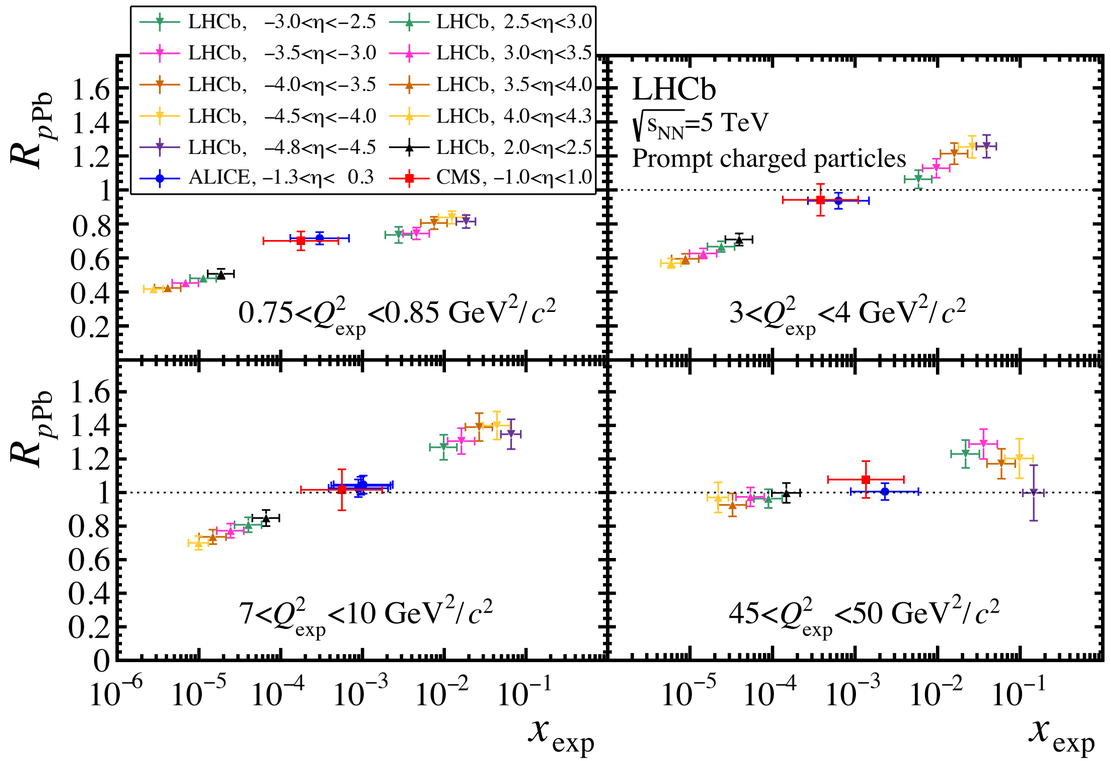
$x \sim \frac{Q}{\sqrt{s_{\mathrm{NN}}}} e^{-\eta}$

Study of small-x at LHCb

Prompt charged particle and π^0 in pPb collisions

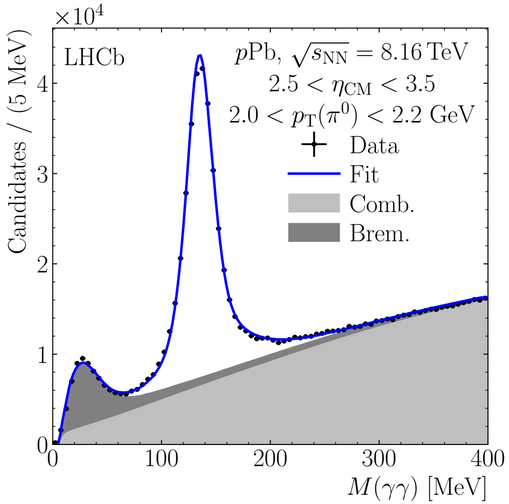
PhysRevLett. 128 (2022)142004
arXiv:2204.10608
Accepted by PRL

- Prompt charged particle production in 5 TeV pPb collisions
- High precision at very small Bjorken-x
- Forward flow with identified hadrons possible

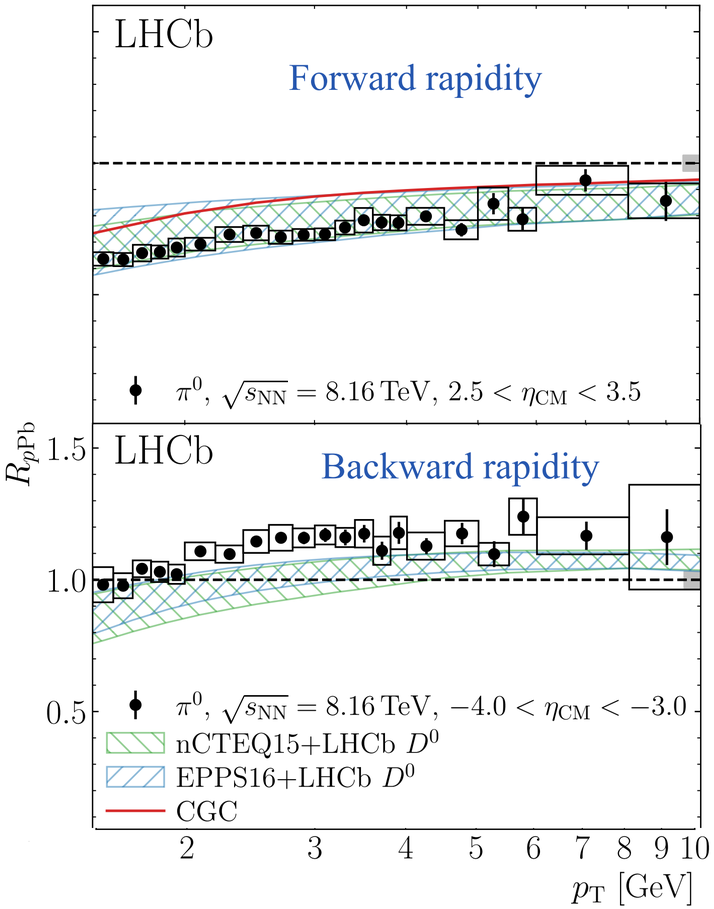


$$Q^2_{exp} \equiv m^2 + p_{\mathrm{T}}^2 \qquad x_{exp} \equiv \frac{Q_{exp}}{\sqrt{s_{nn}}} e^{-\eta}$$

- First π^0 result in forward rapidity at LHC.
- Gateway to direct photon measurement at small x



Direct photon-hadron correlation analysis near completion
Direct photon v_2 in pPb in near future?



Flow analyses at LHCb

- Published result:
  - Charged hadron long-range correlations in 5 TeV *p*Pb collisions

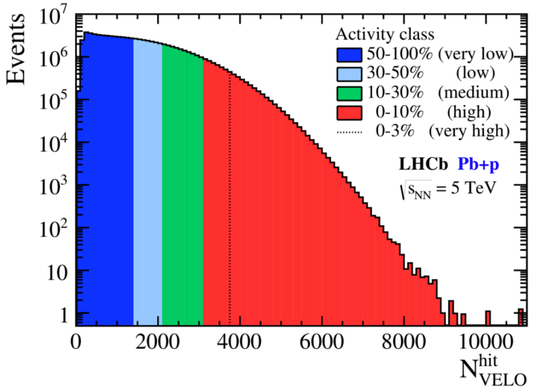
- Current flow analyses:
  - Charged hadron v_n in PbPb collisions at 5 TeV
  - Charged hadron v_n in *p*Pb collisions at 8.16 TeV
  - Prompt D^0 meson v_n in *p*Pb collisions at 8.16 TeV
- Planning:
  - Upsilon v_2 in 13TeV *pp* collisions
  - Charged hadron v_n in SMOG (*p*-Gas and Pb-Gas)

Charged hadron long-range correlations in *p*Pb collisions

PHYS. LETT. B762 (2016) 473

- LHCb di-hadron correlations in 5 TeV *p*Pb collisions
  - 2-particle angular correlation method
  - First time in the forward region
- Correlation function constructed from

$$\frac{1}{N_{trig}}\frac{d^2N_{pairs}}{d\Delta\phi d\Delta\eta} = B(0,0)\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$



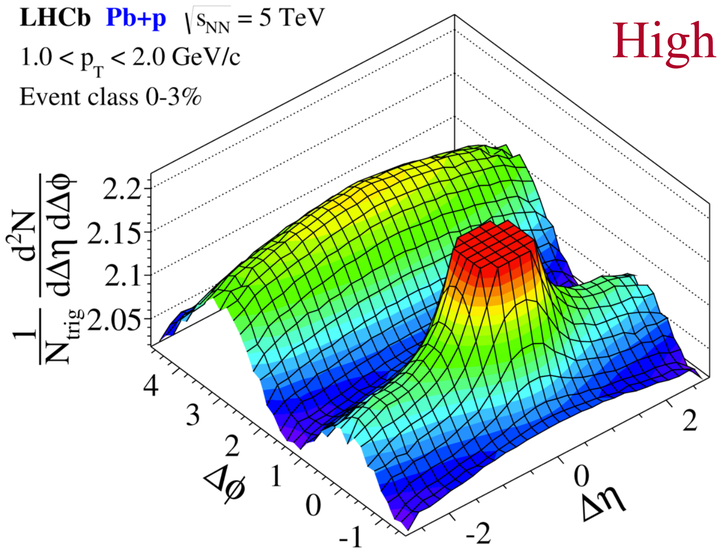
$$S(\Delta\eta,\Delta\phi) = \frac{1}{N_{trig}}\frac{dN^{same}_{pairs}}{d\Delta\phi}$$

Pairs from the same events

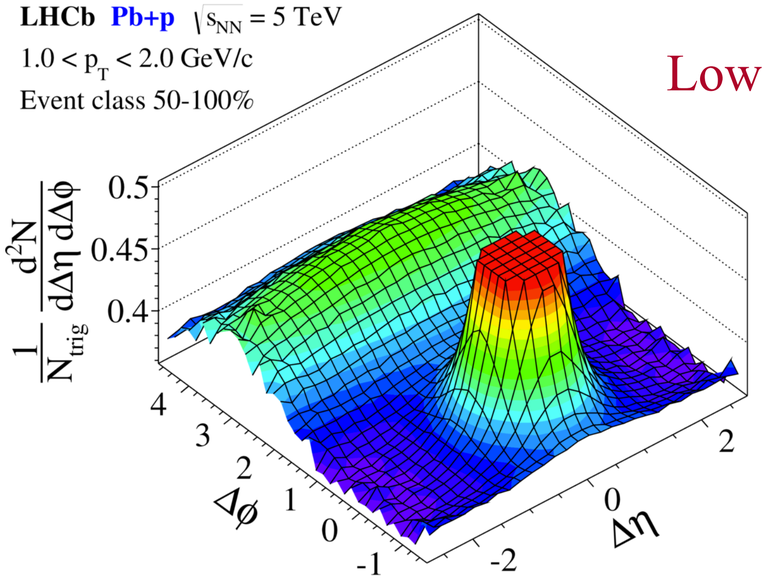
$$B(\Delta\eta,\Delta\phi) = \frac{1}{N_{pairs}(\Delta\phi=0)}\frac{dN^{mixed}_{pairs}}{d\Delta\phi}$$

Pairs from mixed events

- Observation of near side ridge in high activity events



High activity



Low activity

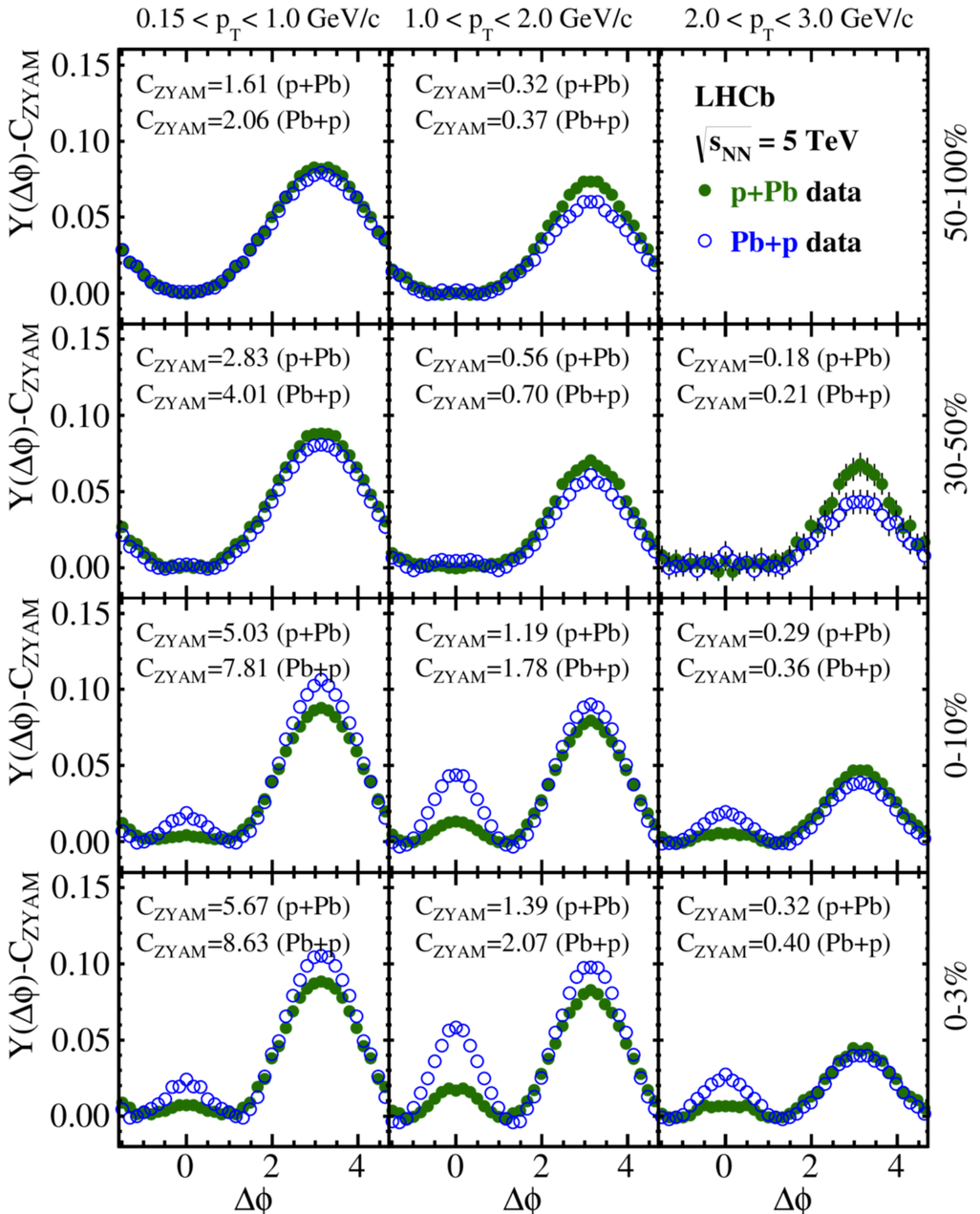
Charged hadron long-range correlations in *p*Pb collisions

Low activity

- Integrate over $2 < |\Delta\eta| < 2.8$
- Near-side ridge is most pronounced in $1 < p_{\mathrm{T}} < 2$ GeV/c
- Near-side ridge in Pbp is larger in pPb
- Near-side correlation shows a consistent increase with increasing event activity

- Ongoing analyses with dihadron correlations:
  - Charged hadron v_n in PbPb collisions at 5 TeV
  - Charged hadron v_n in pPb collisions at 8.16 TeV

High activity

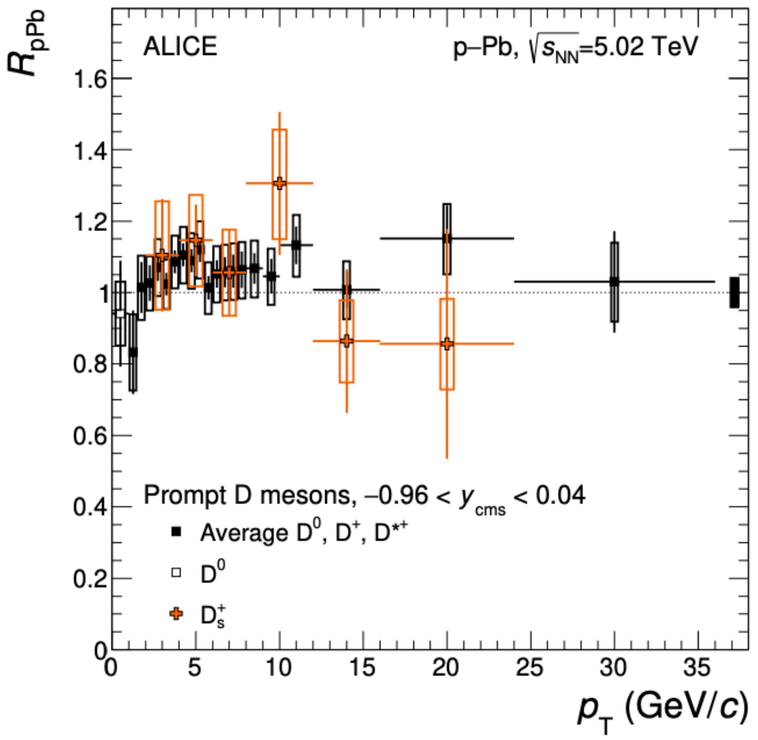


PHYS. LETT. B762 (2016) 473

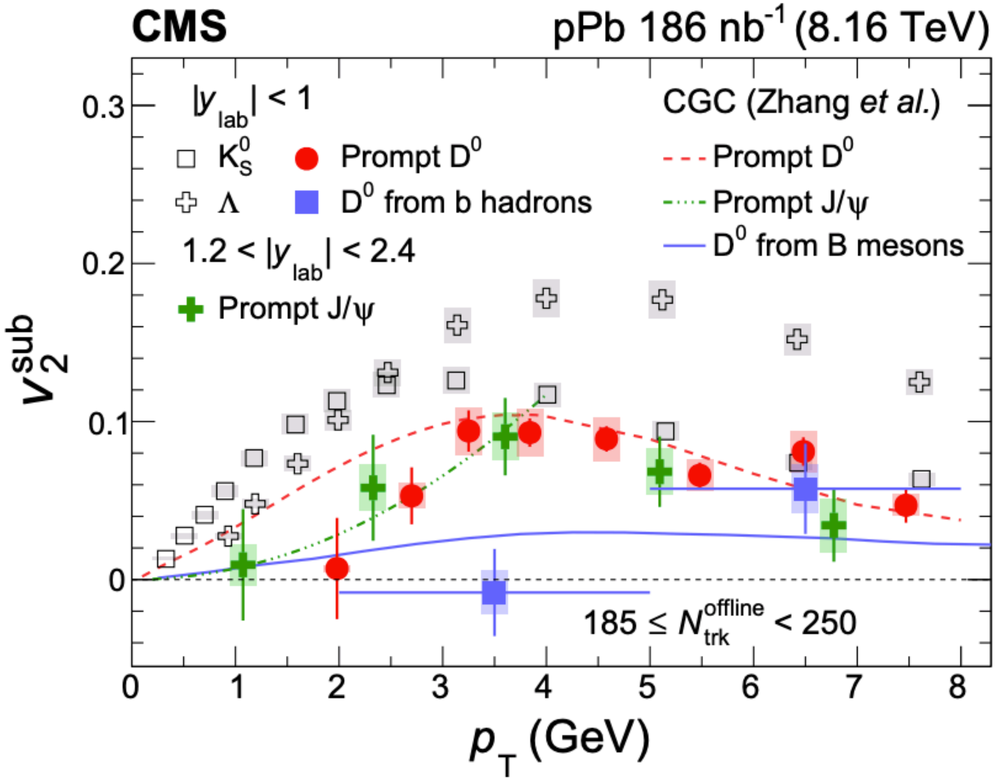
Open heavy flavor in *p*Pb collisions

An open question

JHEP12(2019)092



Phys. Lett. B 813 (2021) 136036



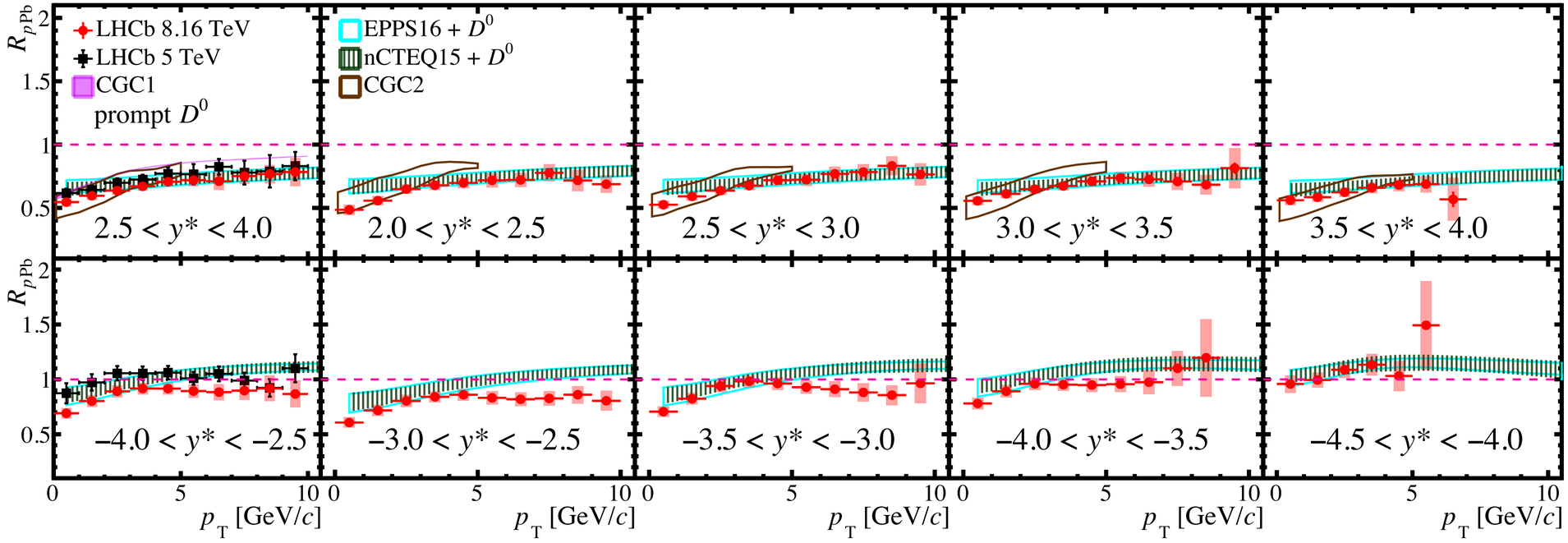
- $R_{p\mathrm{Pb}}$ measured in midrapidity consistent with 1
- Significant v_2

Prompt D^0 production in pPb collisions at 8.16TeV

arXiv:2205.03936, submitted to PRL

Forward →

Backward →

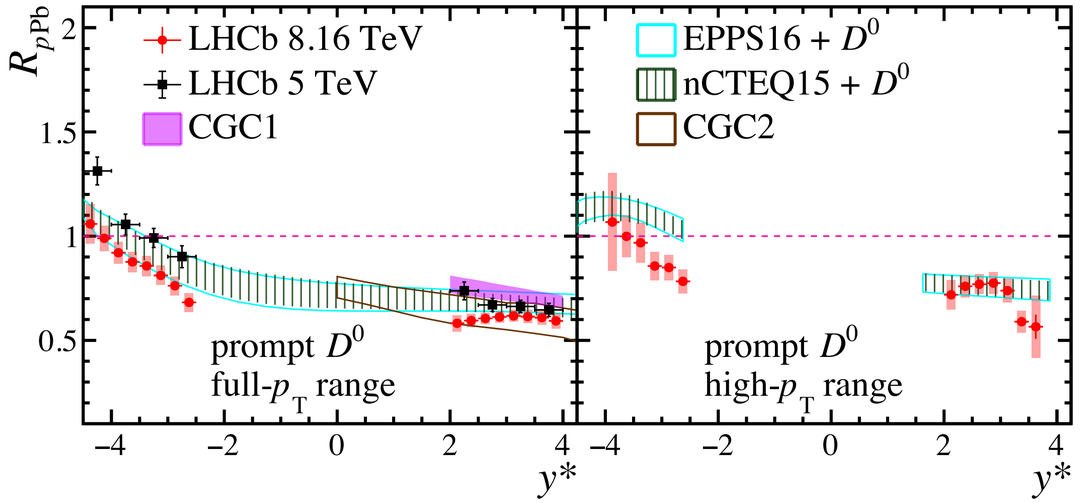


$$R_{p\mathrm{Pb}} = \frac{\sigma_{p\mathrm{Pb}}}{208 \times \sigma_{pp}}$$

pp reference from interpolation between 5&13 TeV data

JHEP 06 (2017) 147
JHEP 05 (2017) 074

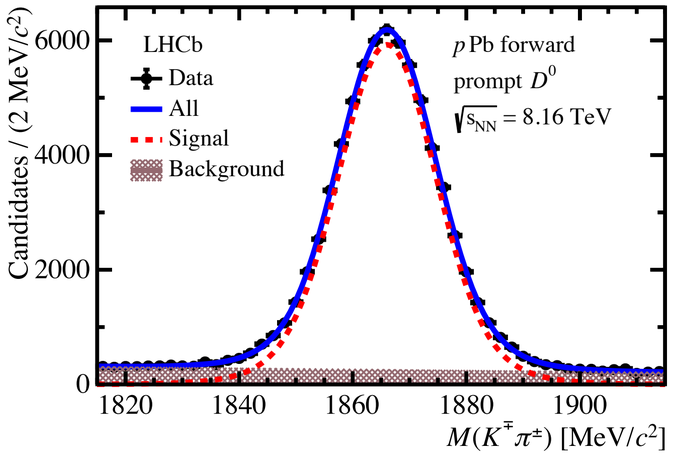
- Room for additional suppression effects in
  - Very low p_{T} at forward rapidity
  - High p_{T} in the backward rapidity

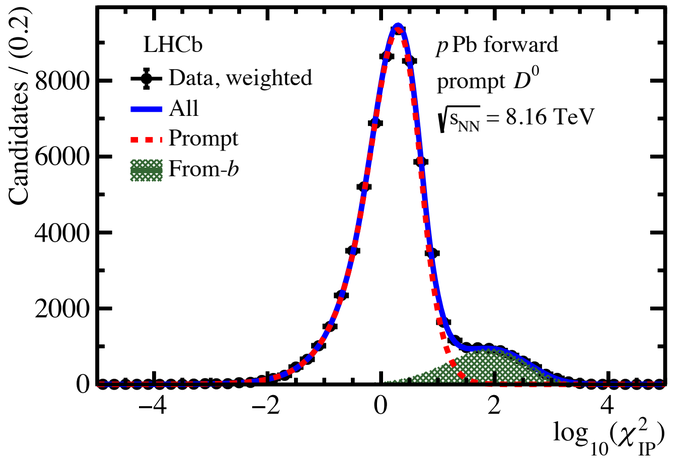


Open heavy flavor flow in *p*Pb

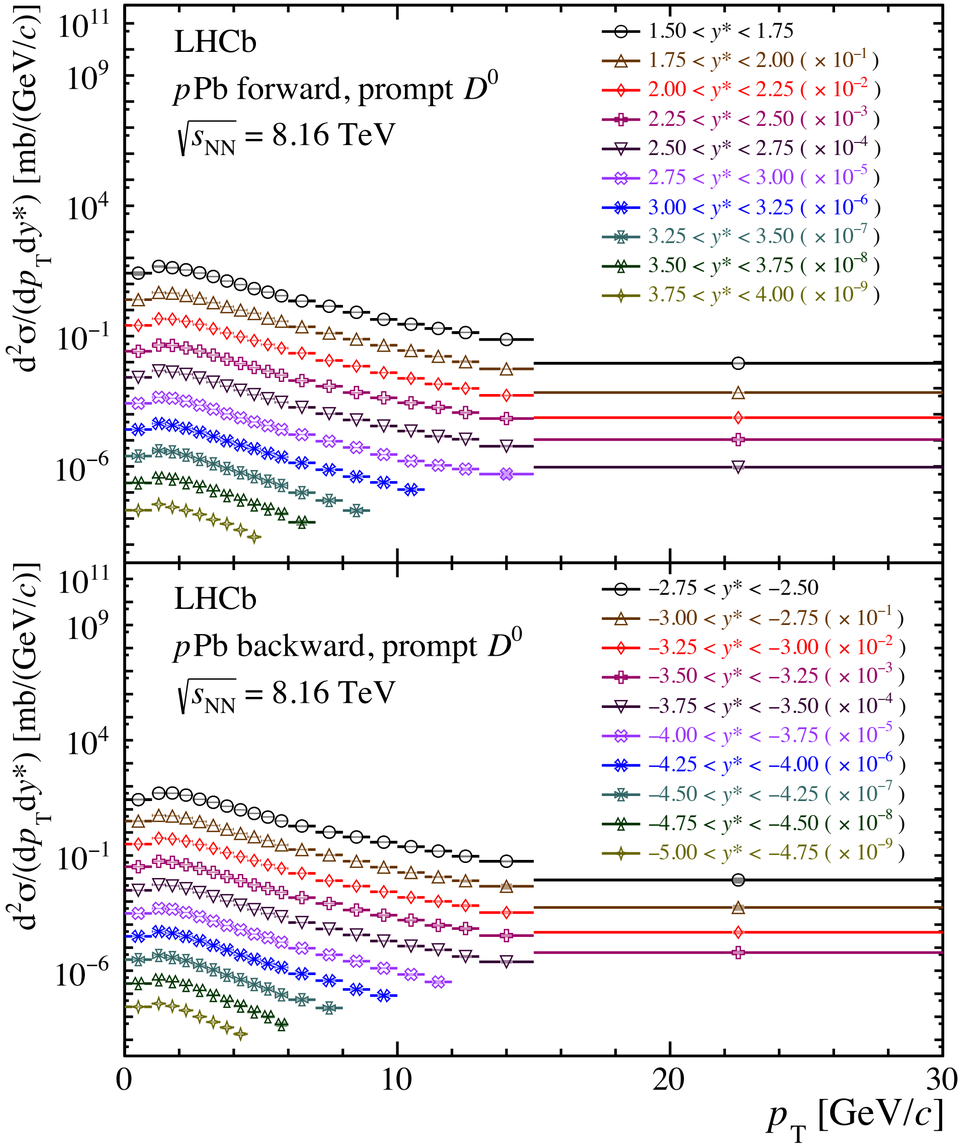
Prompt D^0 mesons in *p*Pb collisions at 8.16TeV

arXiv:2205.03936, submitted to PRL





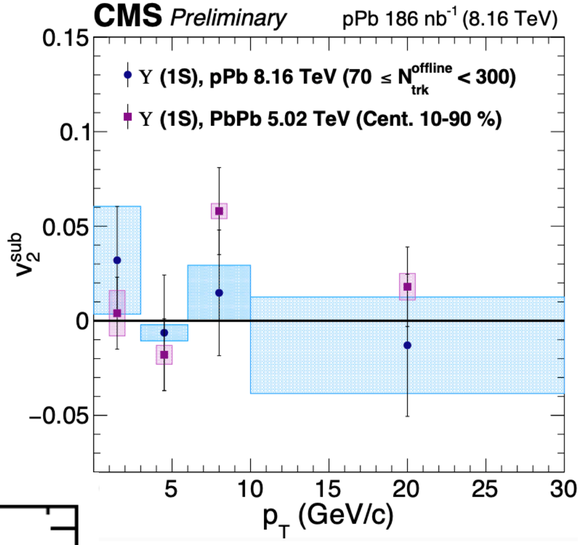
- $D^0 \to K^-\pi^+$
- Use impact parameter to separate the prompt and *b*-decay components
- Clean prompt D^0 signals
- High statistics
- $0 < p_T < 30$ GeV/c
- *p*Pb: $1.5 < y < 4.0$; Pb*p*: $-5.0 < y < -2.5$

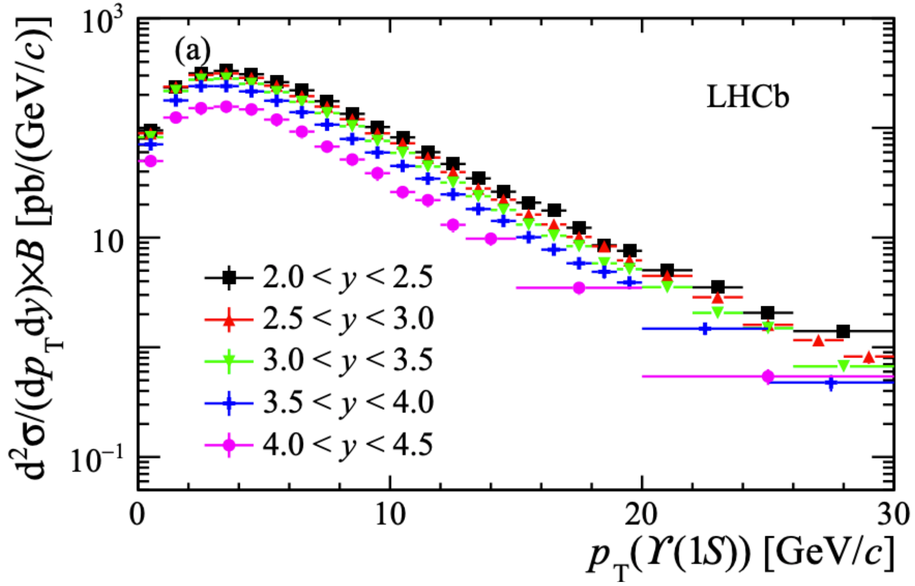


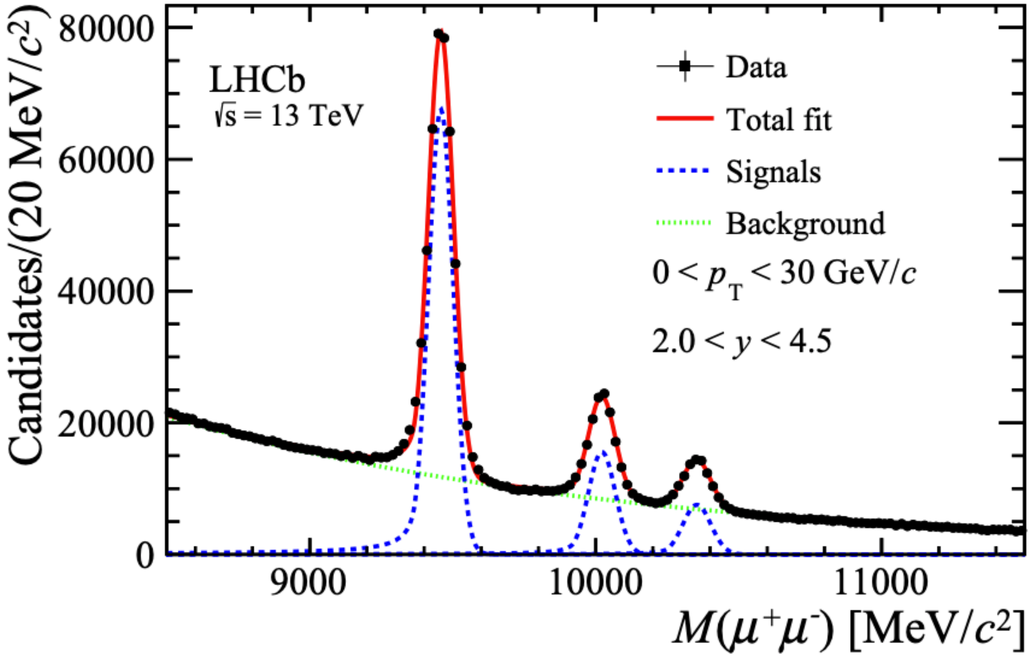
$\Upsilon(nS)$ in 13 TeV *pp* collisions

JHEP 07 (2018) 134

- $\Upsilon(nS)$ flow in *pp* collisions not yet measured
- Separate measurements of $\Upsilon(1S)$ and $\Upsilon(2S)$ v_2?
- Possible measurement under investigation

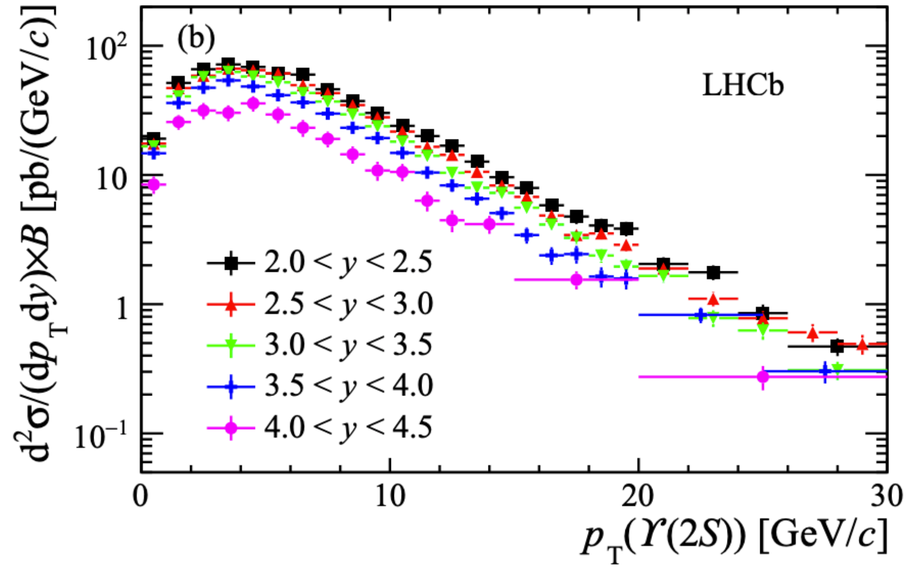






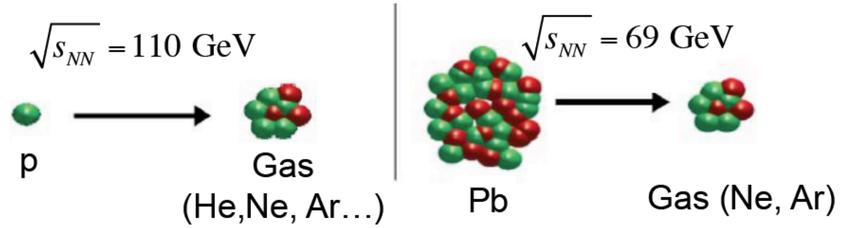
2015 *pp* @13TeV ~ $277 pb^{-1}$

400k Upsilon(1S)
100k Upsilon(2S)
51k Upsilon(3S)



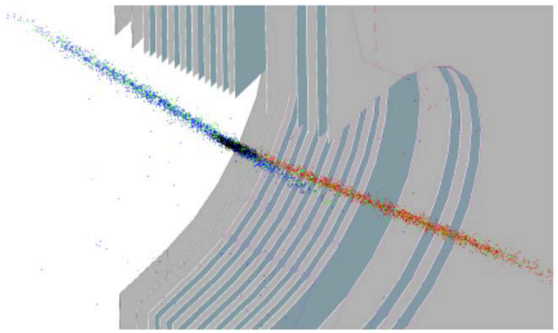
Fixed-target at LHCb: SMOG

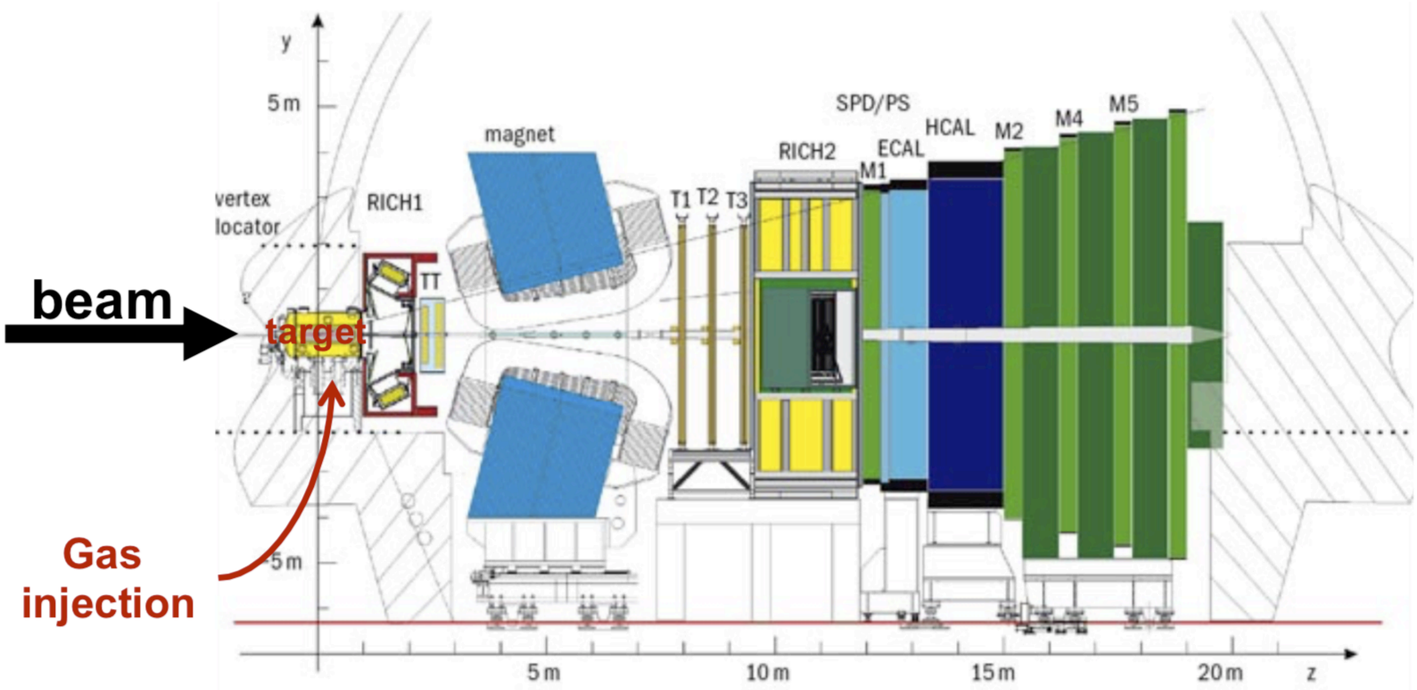
Fixed target mode



- SMOG: System for Measuring Overlap with Gas
- A noble gas (**He, Ne, Ar**) at ~2×10^{-7} mbar pressure injected into the LHC vacuum around the LHCb interaction region
- Originally used to determine luminosity, since 2015 started to collect fixed-target collision data

- $\sqrt{s_{NN}}$ = 69-110 GeV between SPS & RHIC
- $-3.0 < y^* < 0$
- Access nPDF anti-shadowing region

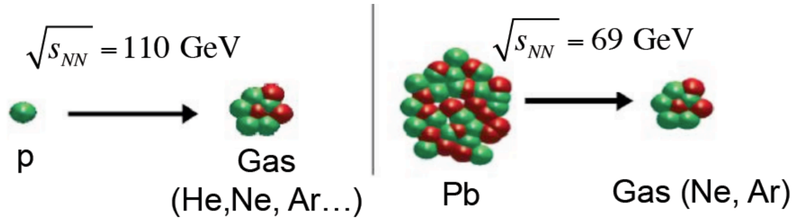




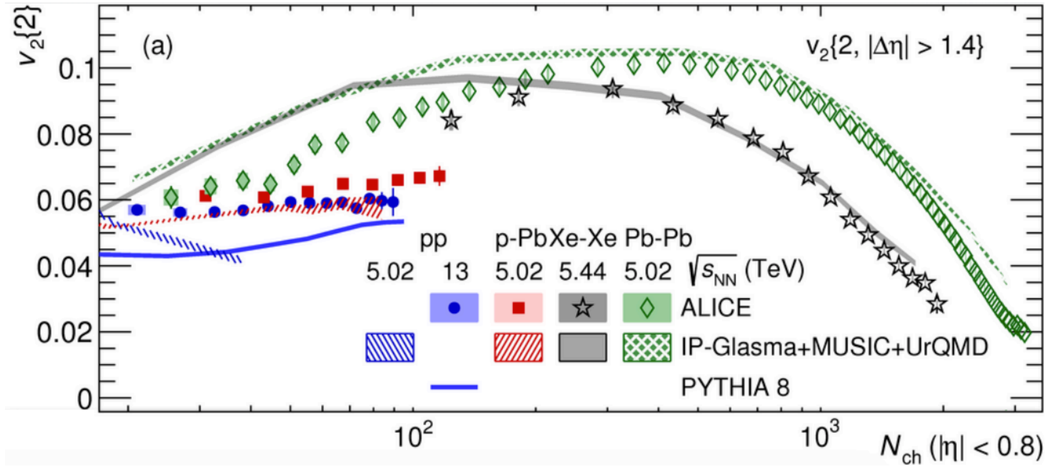
SMOG datasets

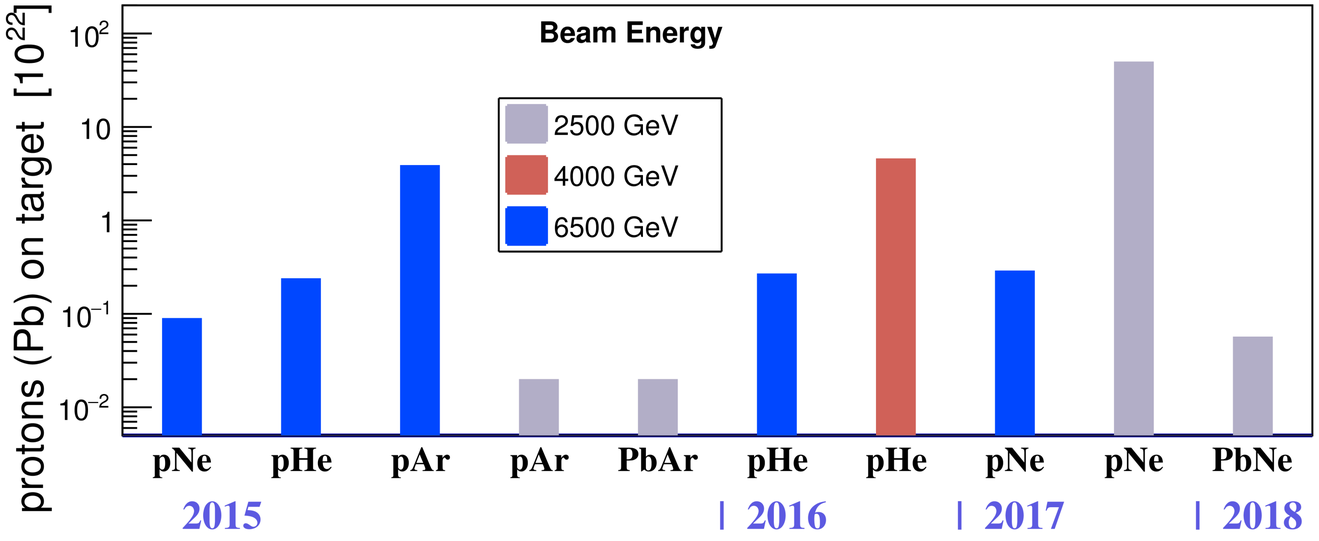
Study flow with different system sizes:
what happens between *pp* and *p*Pb, *p*Pb and PbPb?

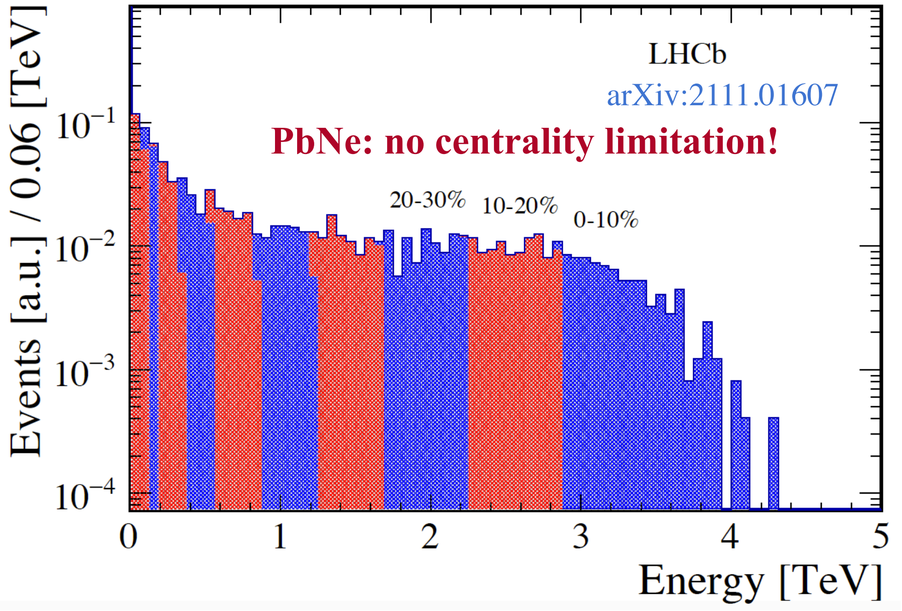
Fixed target mode



ALICE, Phys. Rev. Lett. 123, 142301 (2019)

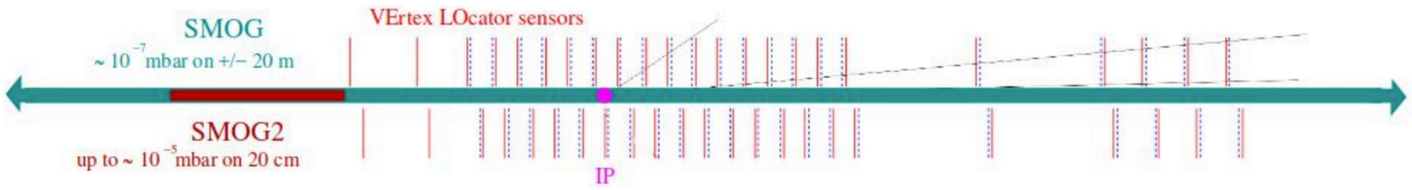


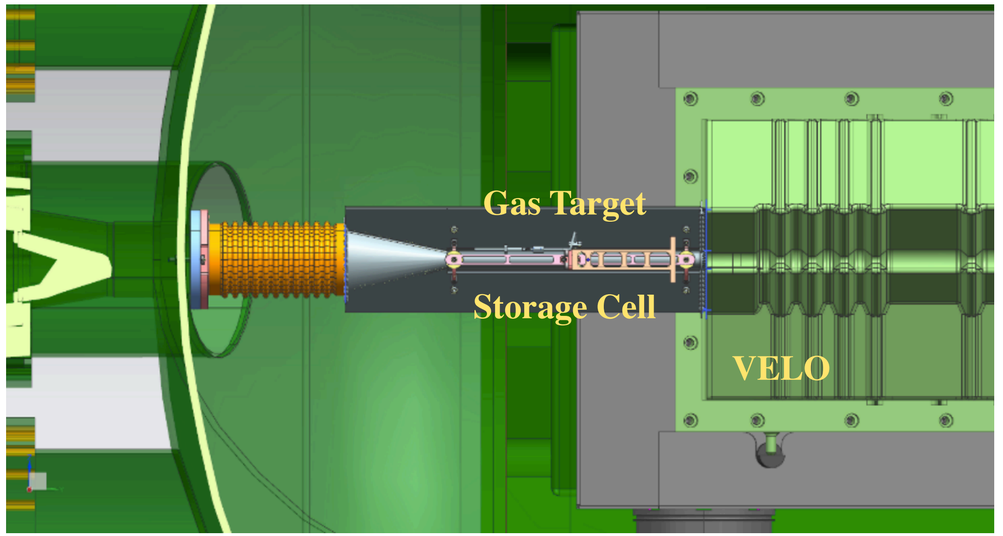




Centrality determined by energy in ECal

SMOG2





LHCb-TDR-020

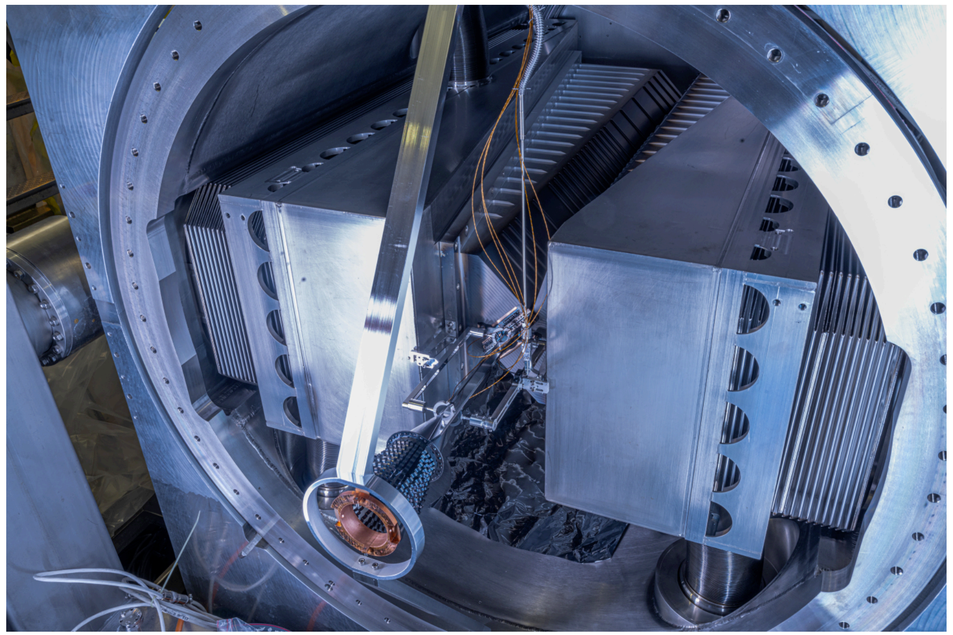
- SMOG2: Storage Cell for the gas upstream of the nominal IP (z in [-500, -300] mm) and precisely calibrated Gas Feed System.
  - Gas density increased by up to two orders of magnitude ==> much higher luminosity
  - More gas targets: H_2, D_2, He, N_2 , O_2, Ne, Ar, Kr, Xe

- beam-beam and beam-gas separate luminous regions:

  ==> simultaneous *pp*-SMOG2 data-taking

  ==> large statistics

No centrality limitation!



SMOG2

Statistics in 1 year data-taking

simultaneous *pp*-SMOG2 data-taking

No centrality limitation!

SMOG2 *p*Ar @ 115 GeV

Int. Lumi.		80/pb
Sys.error of J/Ψ	xsection	~3%
J/Ψ	yield	28 M
D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
$DY\ \mu^+\mu^-$	yield	24 k

- Measure flow system size dependence with precision
- Measurements of heavy flavor possible

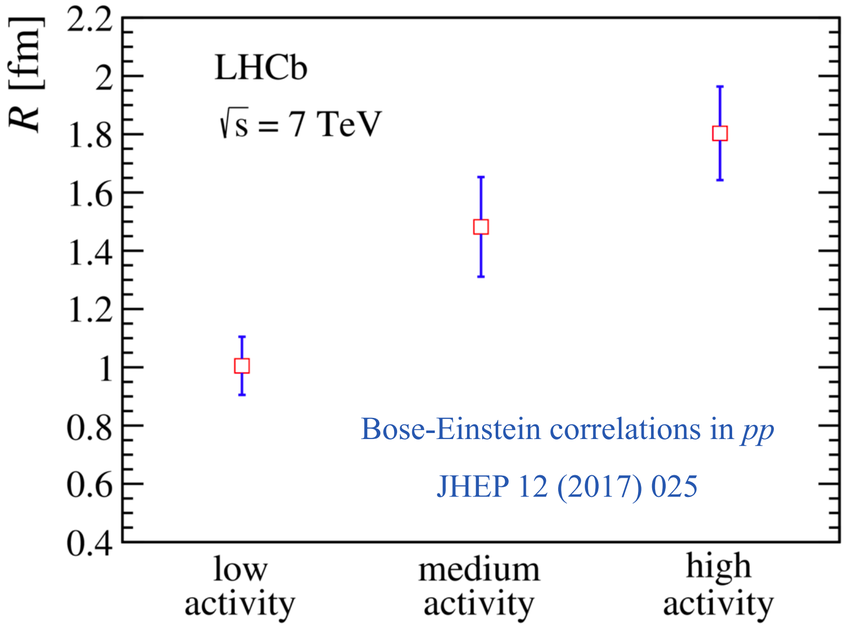
Conclusion

Thanks for your attention

- **Ongoing/upcoming flow analyses with LHC Run2 data:**
- Charged hadron in 5 TeV PbPb collisions:
  - In the forward rapidity region
  - In 60-90% centrality
- Charged hadron in 8.16 TeV *p*Pb collisions:
  - High statistics
- Heavy flavor in *pp* and *p*Pb collisions:
  - *D* mesons in 8.16 TeV *p*Pb collisions
  - Quarkonia in *pp* collisions
- SMOG

- **Other upcoming correlation analyses with LHC Run2 data:**
  - Bose-Einstein correlations in 5 TeV *p*Pb collisions
  - Direct photon-hadron correlations in 8.16 TeV *p*Pb collisions
  - …

- **After upgrade in Run3:**
- Up to 30% in PbPb collisions
- System size study with SMOG2 data
  - High statistics
  - With heavy flavor

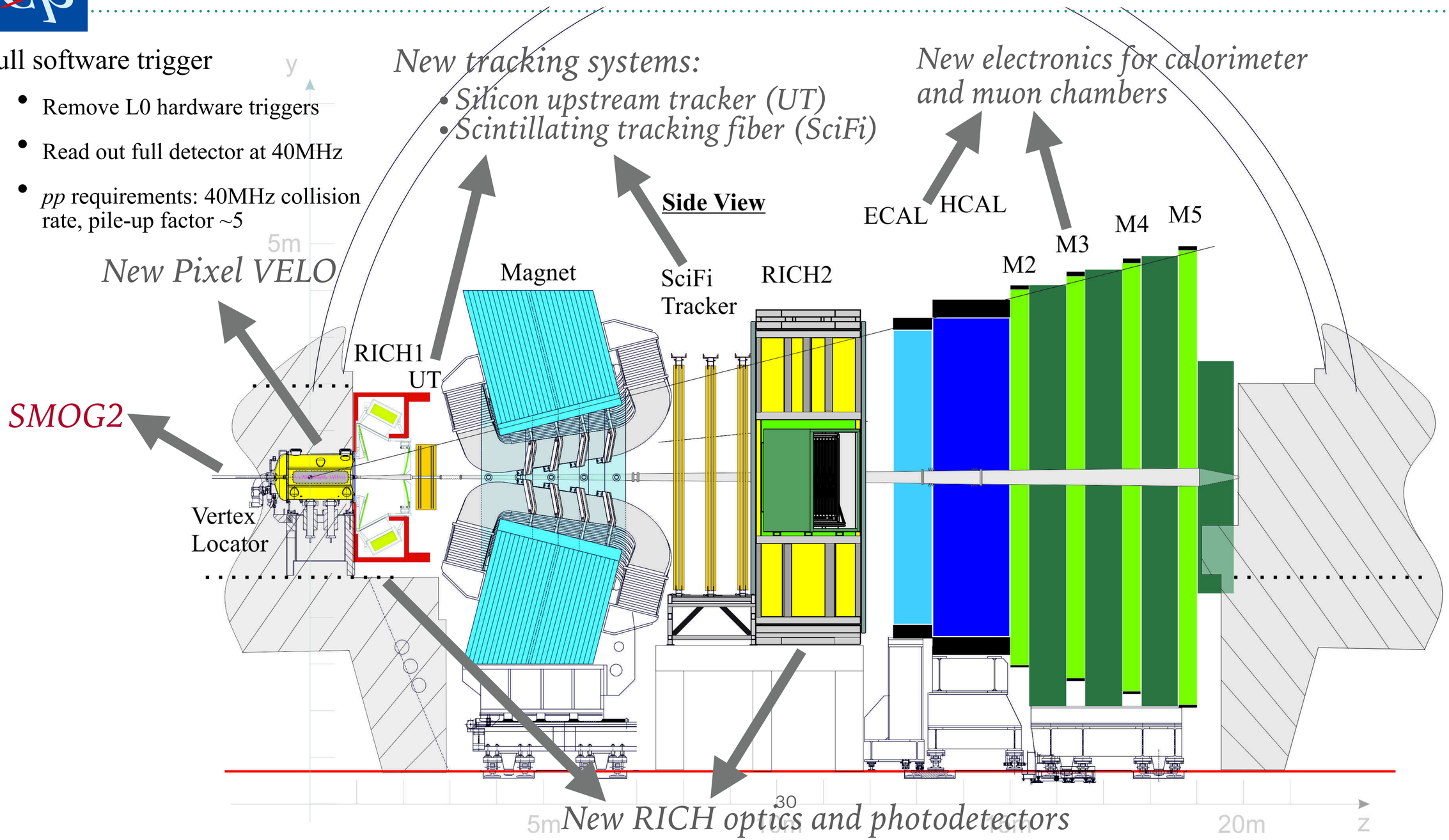


backup

LHCb phase-I upgrade

Full software trigger

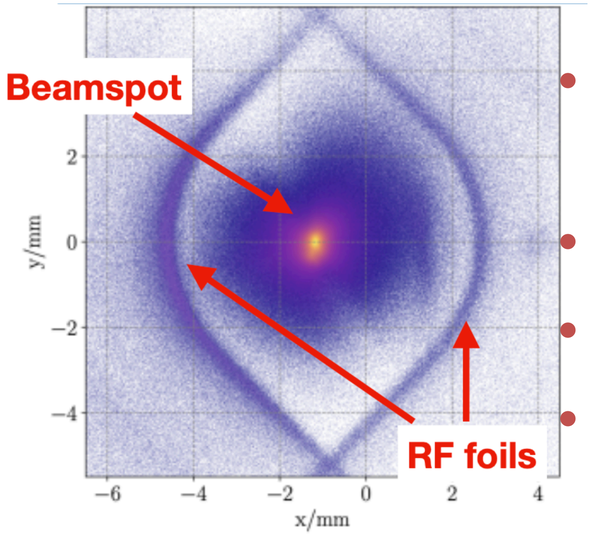
- Remove L0 hardware triggers
- Read out full detector at 40MHz
- *pp* requirements: 40MHz collision rate, pile-up factor ~5



Upgrade I - VELO incident

- Damage of the RF box between VELO and Primary Vacuum 10/1/23

RF foils imaged in 2022



- multiple equipment failures resulted in a build up of pressure beyond specification between VELO and beam volumes
- RF foils have been deformed. VELO modules do not show damage
- Foil to be replaced in shutdown, current or year end
- Physics programme significantly affected in 2023

ATLAS PhysRevC.104.014903