Heavy quarks at LHCb

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INT PROGRAM INT-22-3

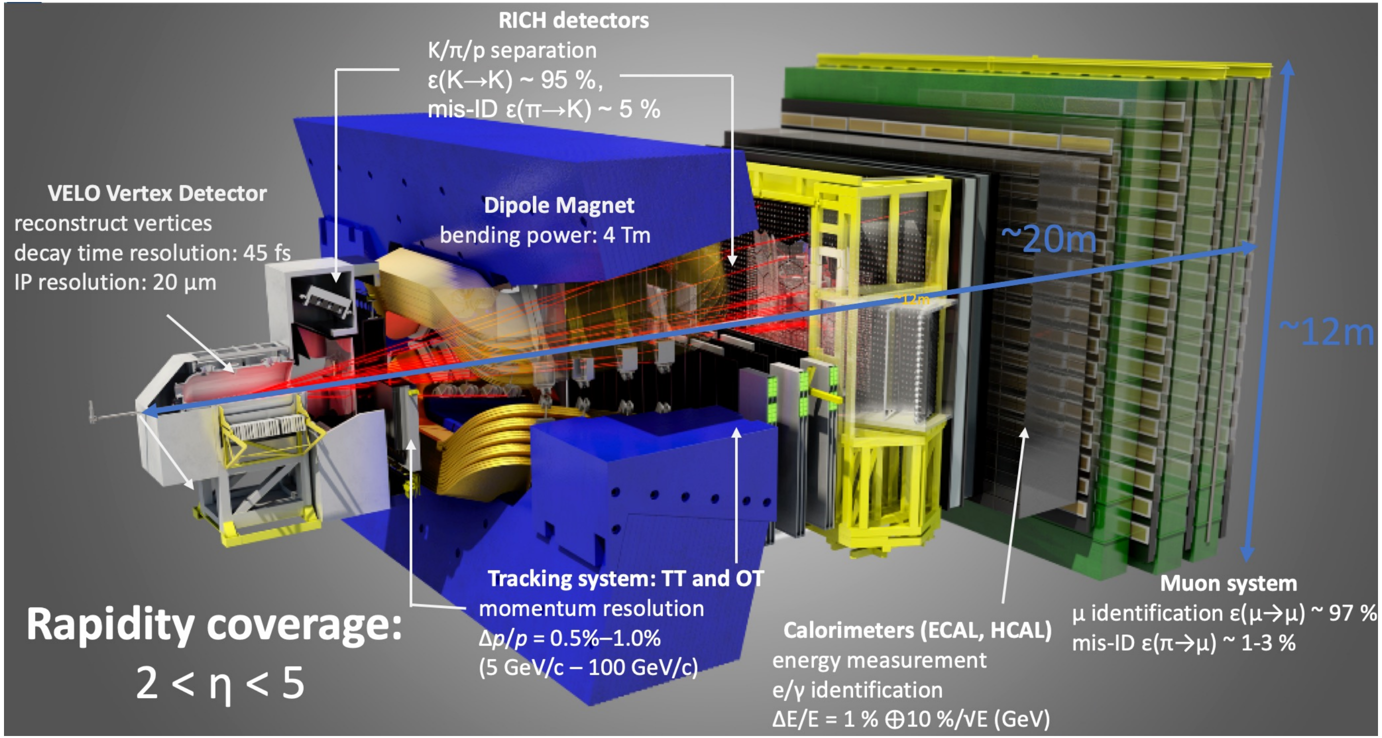
Heavy Flavor Production in Heavy-Ion and Elementary Collisions

October 3, 2022 - October 28, 2022

Outline

- LHCb apparatus
- Heavy quark measurements at high and low-x
  - *Strong new constraints on nucleon structure*
- Exotic hadrons in the nuclear medium
  - *Unique access to newly discovered particles*
- Fixed-target collisions
  - *A unique heavy-ion collision program with LHCb beams on gas target*
- Upgrades

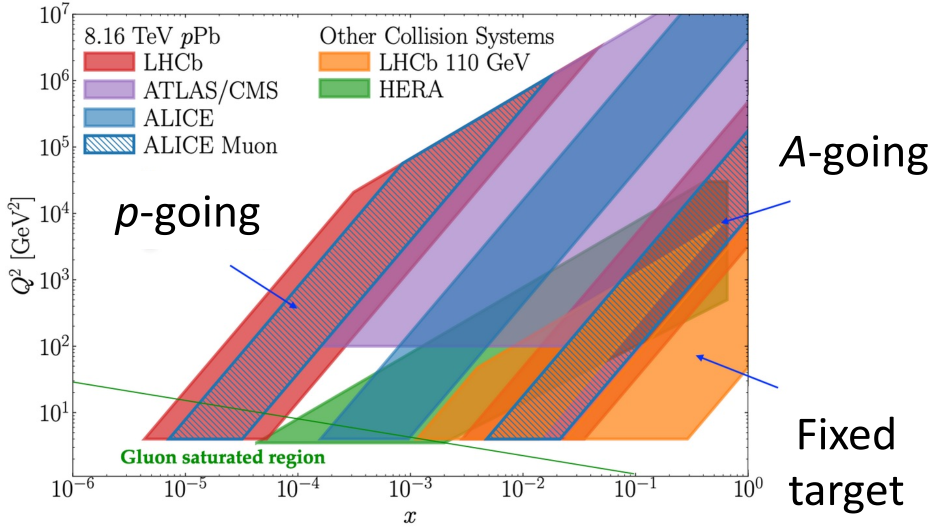
LHCb – Run 1 and 2



- Particle ID, precision vertexing, fast DAQ at forward rapidity
- Unique fixed target program with *p* and Pb beams
- Reconstruction limited to multiplicities <60% central PbPb

Forward detector advantages

Access to extremes of *x* ranges



- Very low and very high x ranges can be probed by adjusting beam and target configurations

Forward detector advantages

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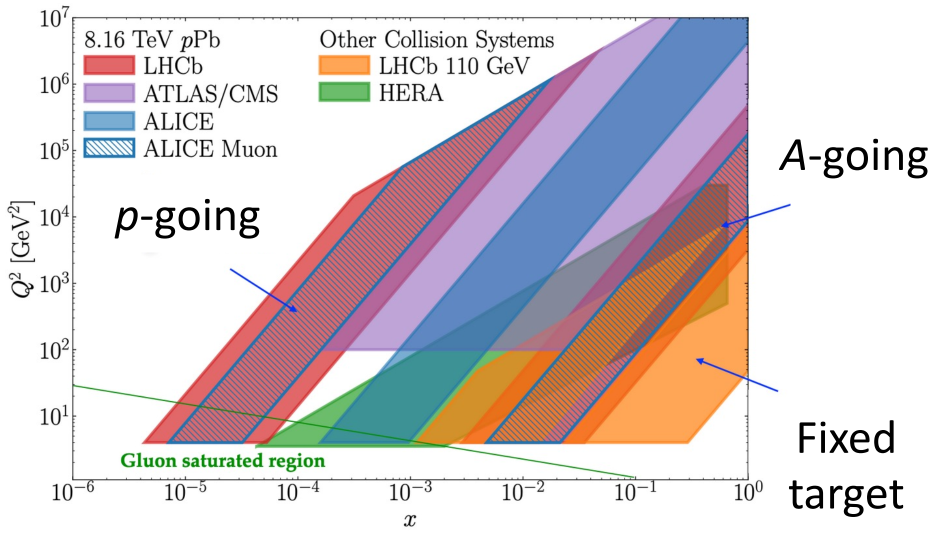
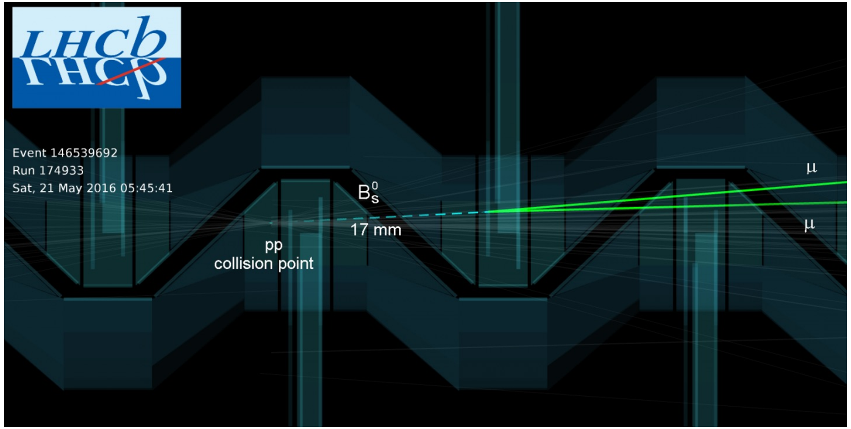


- Very low and very high x ranges can be probed by adjusting beam and target configurations

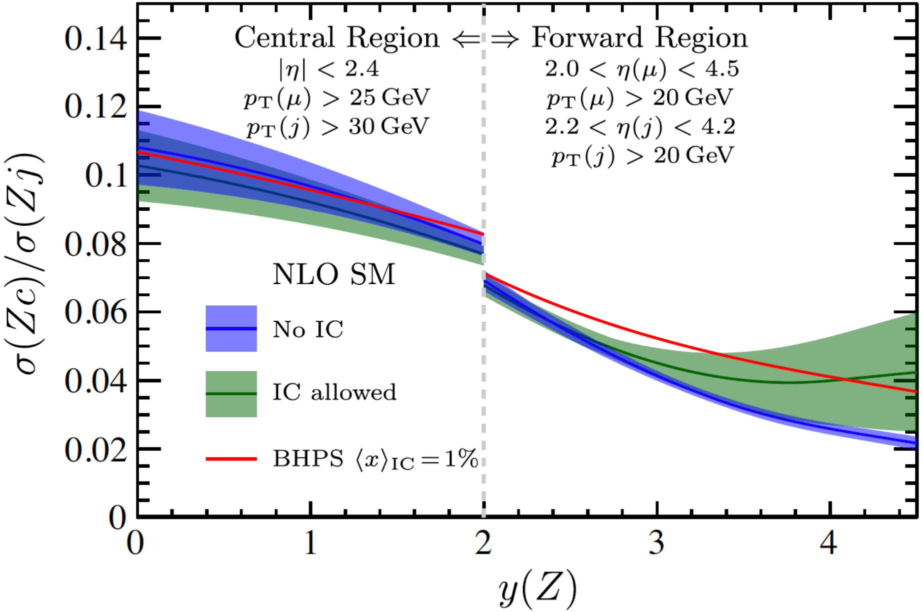
Event display of the rare decay $B_s^0 \to \mu^+\mu^-$



- Forward boost gives large distance between primary vertex and decay vertex – easier to reject prompt backgrounds
- High total momentum p aids access to relative low transverse momentum p_T

Proton structure – intrinsic charm

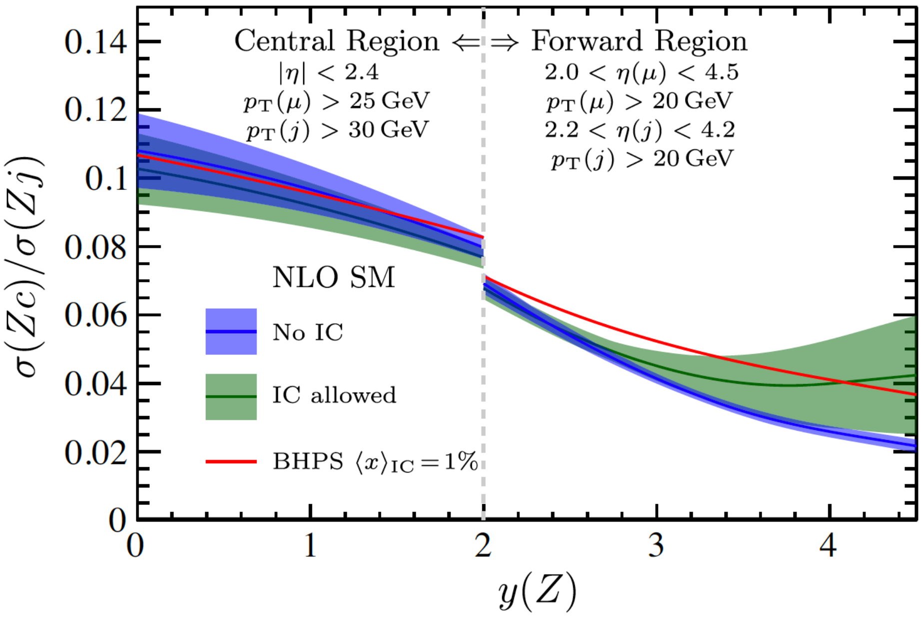
PRL 128 082001 (2022)

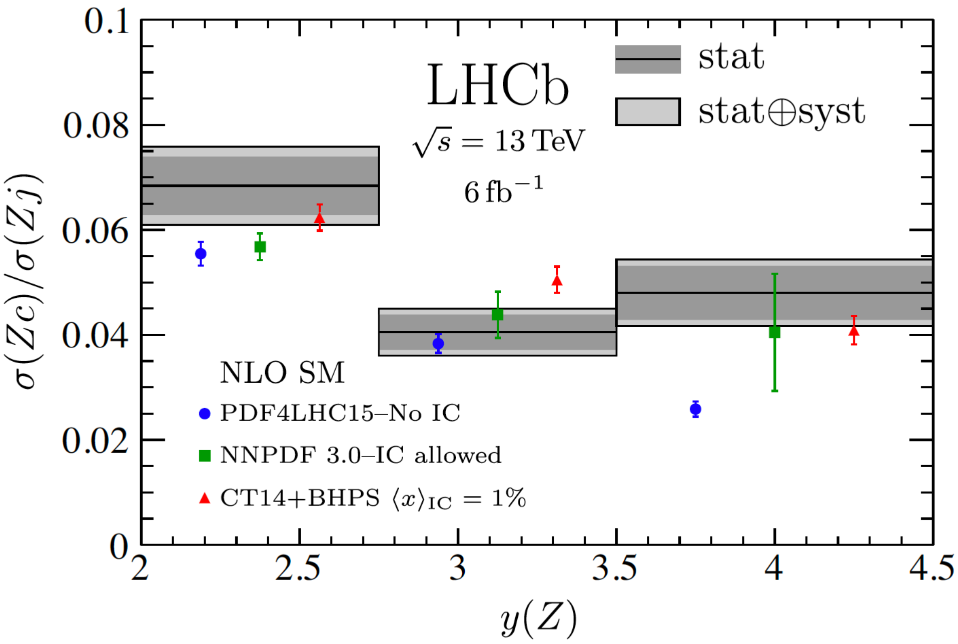


- *Z* + jet production at forward rapidity probes high x region – sensitive to intrinsic charm

Proton structure – intrinsic charm

PRL 128 082001 (2022)

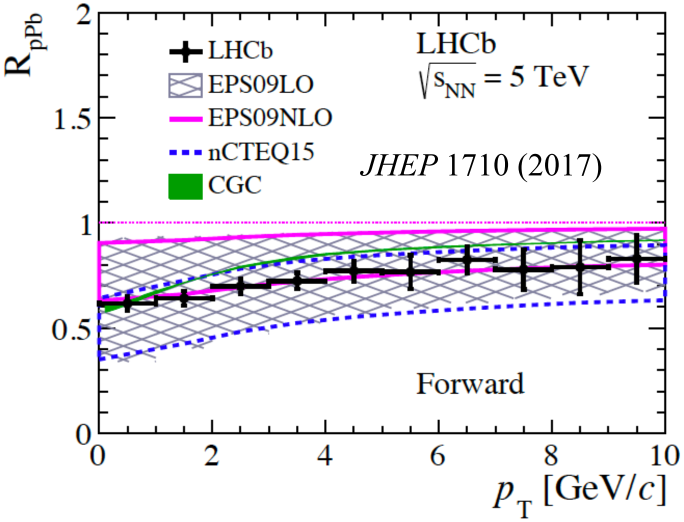




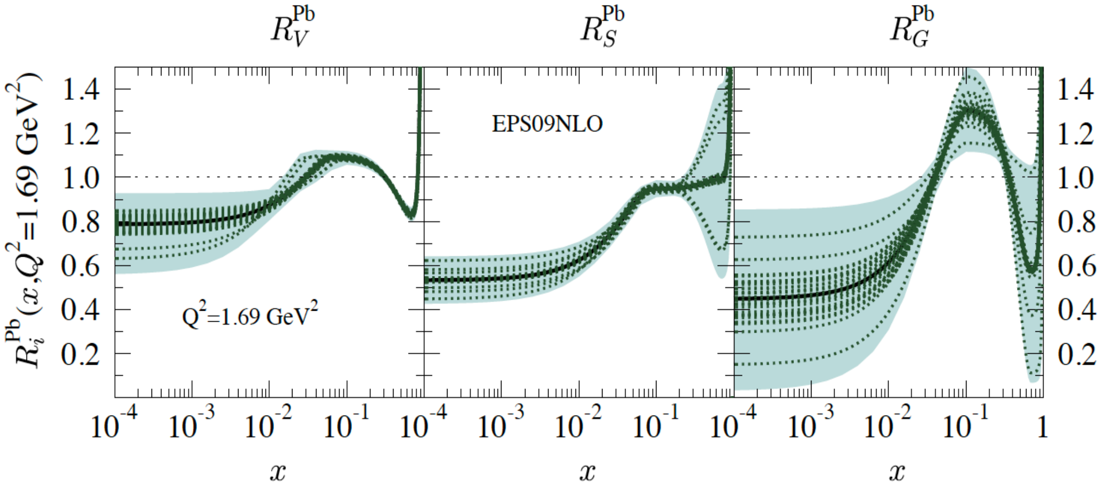
- *Z* + jet production at forward rapidity probes high x region – sensitive to intrinsic charm
- LHCb data favors calculations allowing IC at most forward rapidity

Recent global PDF analysis finds **3σ evidence** for IC in proton: NNPDF collab, *Nature* 608 (2022)

Constraining nPDFs – D mesons

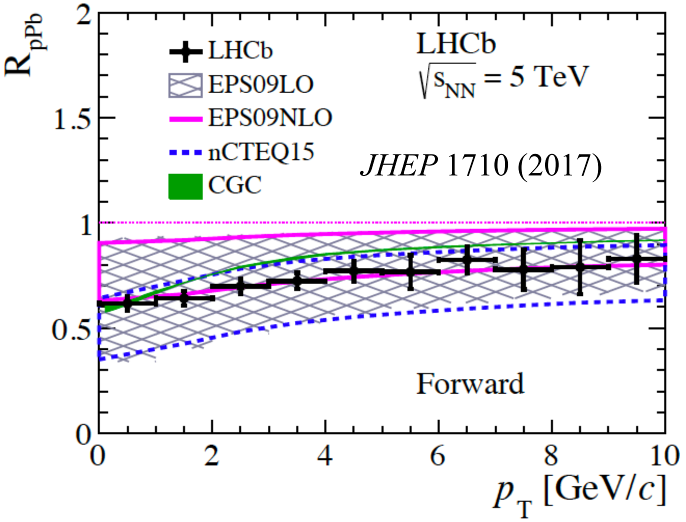


D meson nuclear modification
Data unc << nPDF unc



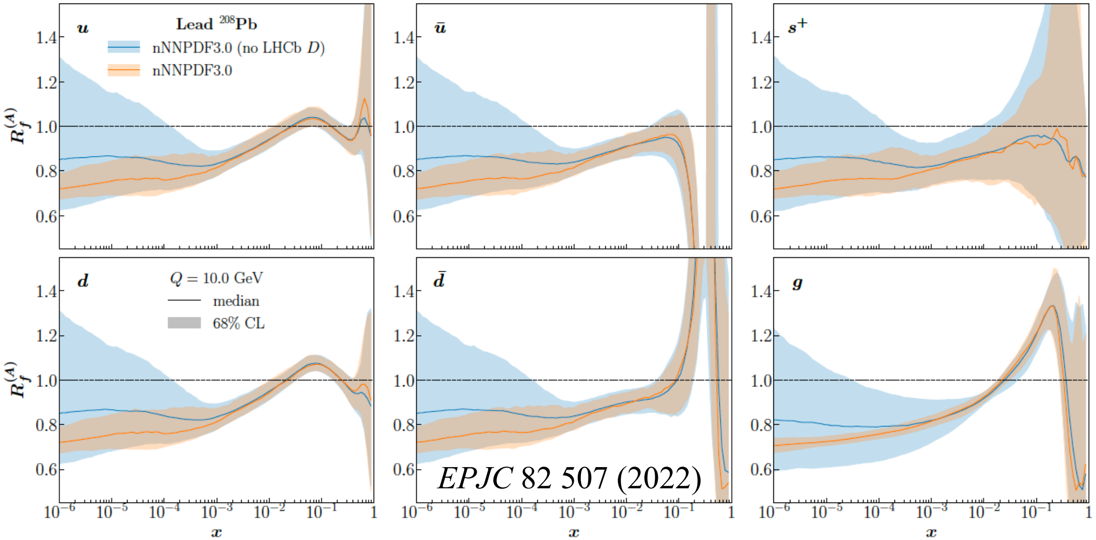
- EPS09: global nPDF analysis constrained by DIS, Drell Yan, and RHIC pion data
- Large uncertainties on low-x gluon distributions

Constraining nPDFs – D mesons



D meson nuclear modification
Data unc << nPDF unc

New state-of-the-art nPDFs

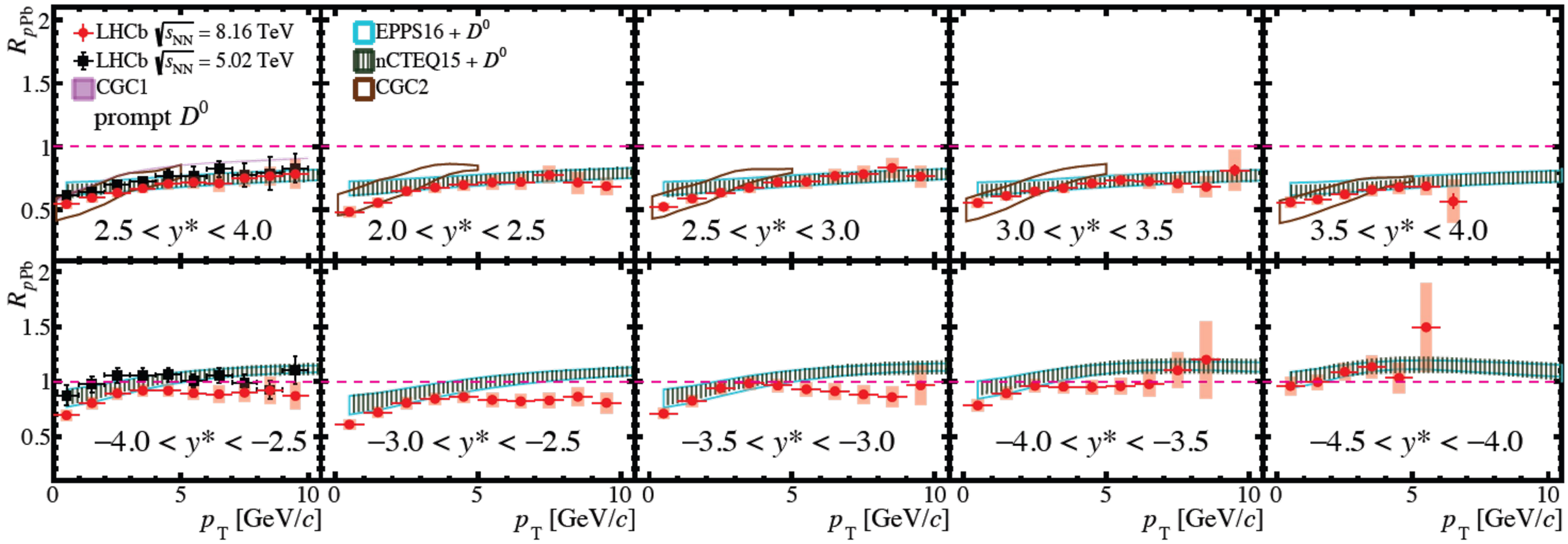


see also: *PRL* 121 052004 (2018), *JHEP* 05 (2020) 037

Inclusion of LHCb D meson data dramatically decreases nPDF uncertainties
Incredible progress made on nPDF constraints at low *x*

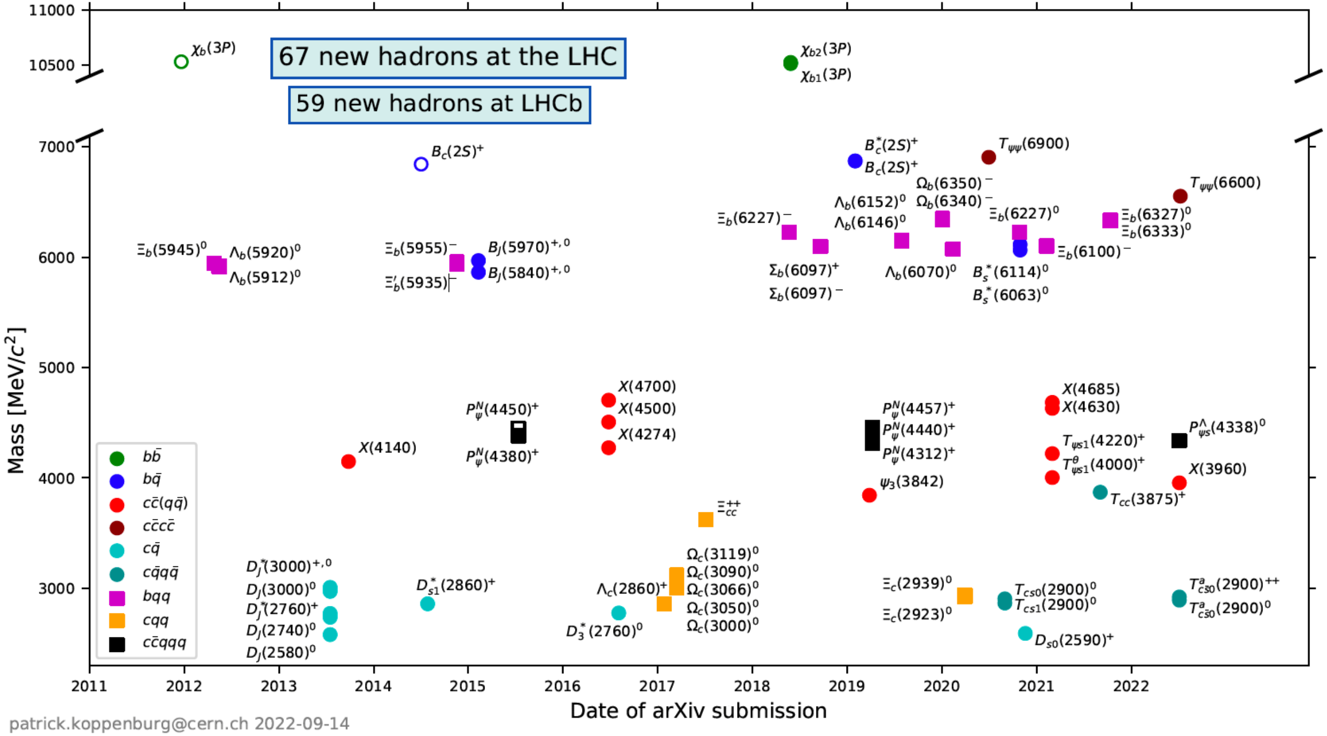
Challenging nPDFs – D mesons

LHCb 2205.03936



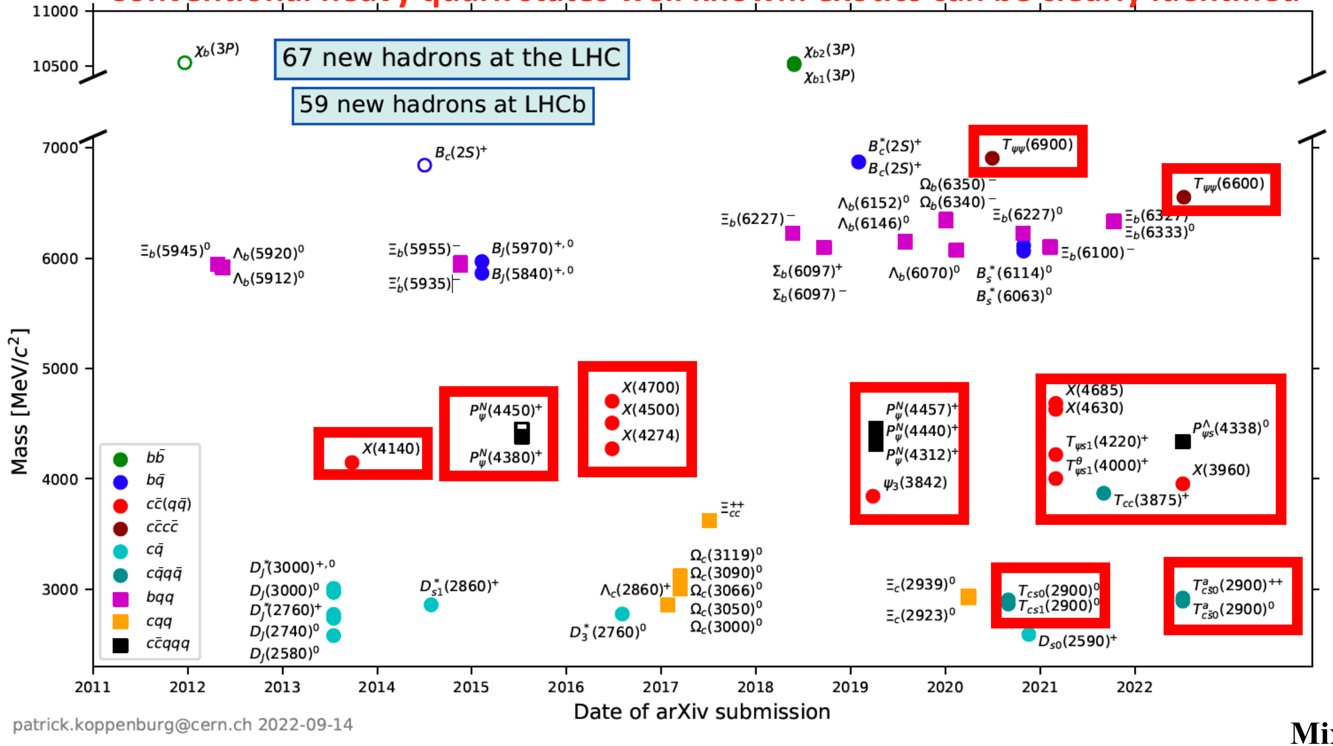
- Forward rapidity well described by updated nPDF calculations
- **Discrepancy** between 8.16 TeV data and nPDF occurs at **backwards** rapidity
    - Additional final-state effects coming into play? Energy loss? Hadronization modified?

New hadrons discovered at LHC



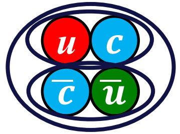
Exotic hadrons discovered at LHC

Conventional heavy quark states well known: exotics can be clearly identified

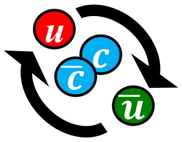


The quark model is rapidly expanding:
study of exotics states largely driven by experiment

Compact tetraquark/pentaquark

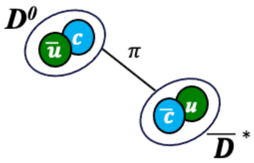


Diquark-diantiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



Hadrocharmonium/ adjoint charmonium
PLB 666 344 (2008)
PLB 671 82 (2009)

Hadronic Molecules



PLB 590 209 (2004)
PRD 77 014029 (2008)
PRD 100 0115029(R) (2019)

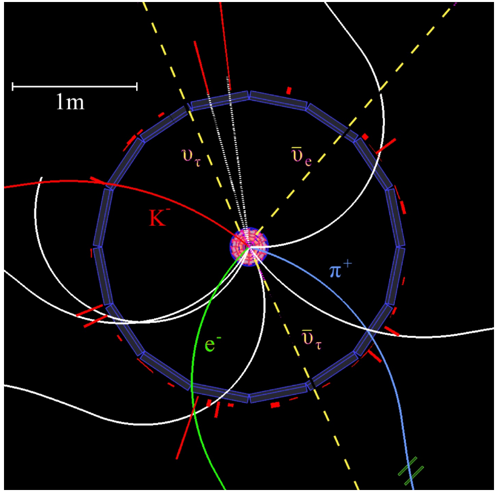
Mixtures

$$X = a\,|c\bar{c}\rangle + b\,|c\bar{c}q\bar{q}\rangle$$

PLB 578 365 (2004)
PRD 96 074014 (2017)

Exotics in the QCD medium

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$ event from Belle



B decays are a great way to discover exotics and measure some properties:

- Well constrained initial state
- Low backgrounds
- Not all states accessible
- After 20 years, fundamental questions about exotics remain unanswered

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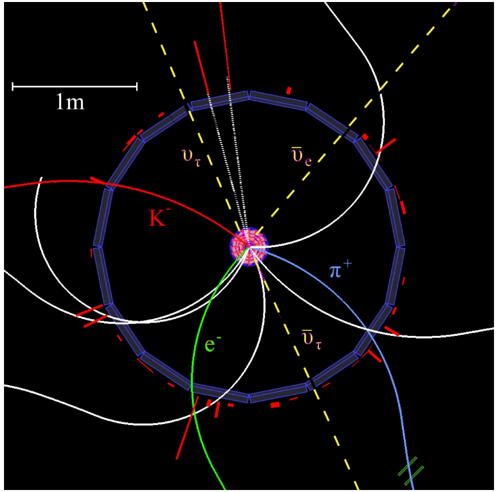

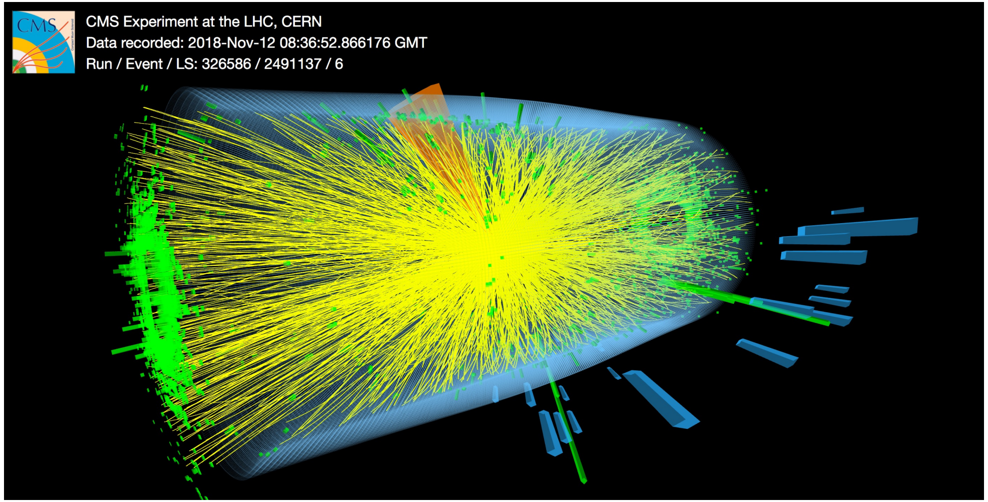

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- Well constrained initial state
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Prompt production exposes exotics to the QCD medium and unique effects:

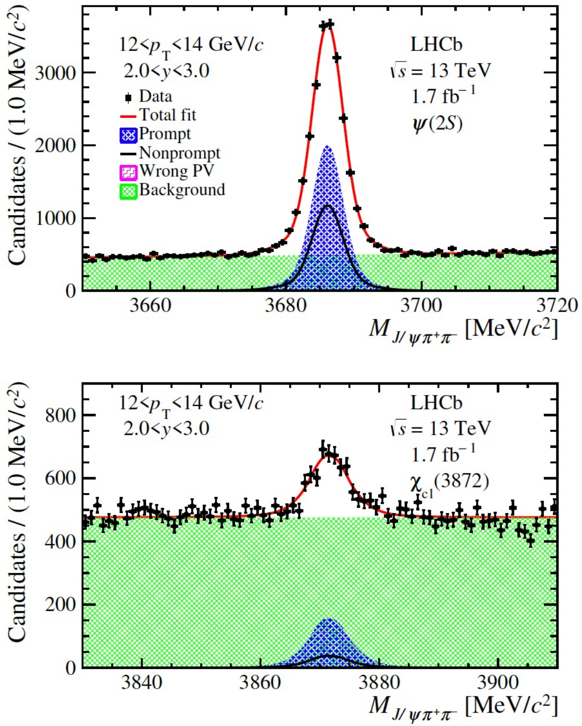
- Breakup with comoving particles
- Collectivity
- Production via coalescence/recombination
- Signal extraction can be COMPLICATED

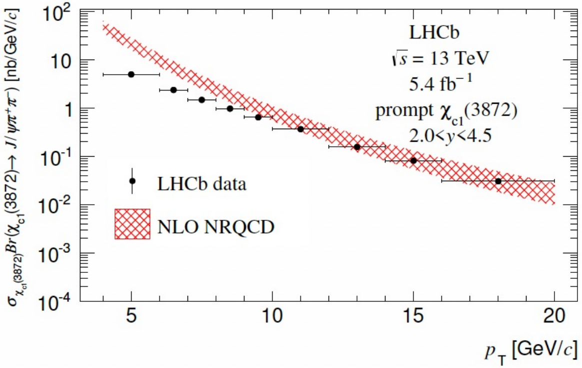
Effects are sensitive to ***size/binding energy of bound state*** and ***density of medium***

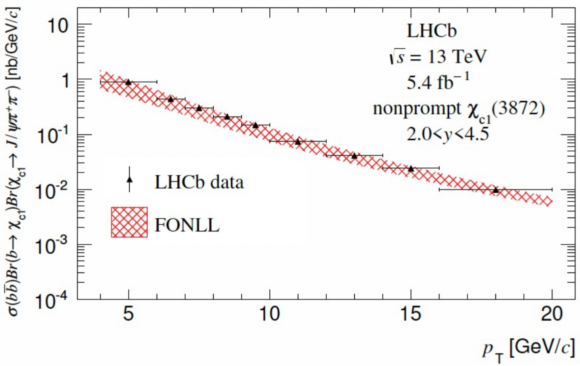
Exotic states provide ***new tests of models*** in an ***expanded range of*** n_{cq}

X(3872) production in *pp*

JHEP01 (2022) 131







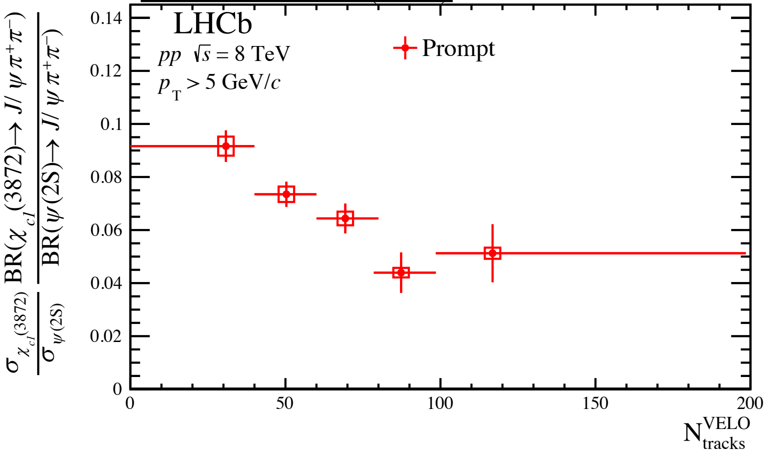
- NRQCD calculation matches high-p_T data well
- Overpredicts yield at lower p_T
- Room for additional effects?

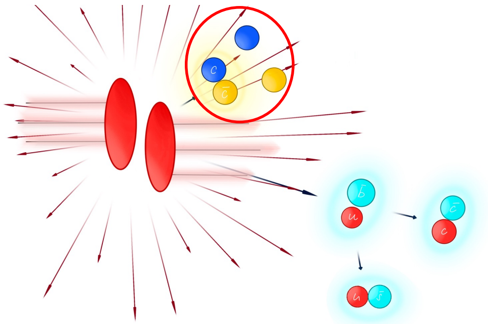
- FONLL describes non-prompt X(3872) production well (also at ATLAS and CMS)

Examine X(3872)/ψ(2S) ratio for direct comparison between exotic hadron and well-known conventional charmonium

X(3872)/ψ(2S) vs multiplicity

PRL 126 092001 (2021)





Prompt component:

Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases

X(3872)/ψ(2S) vs multiplicity

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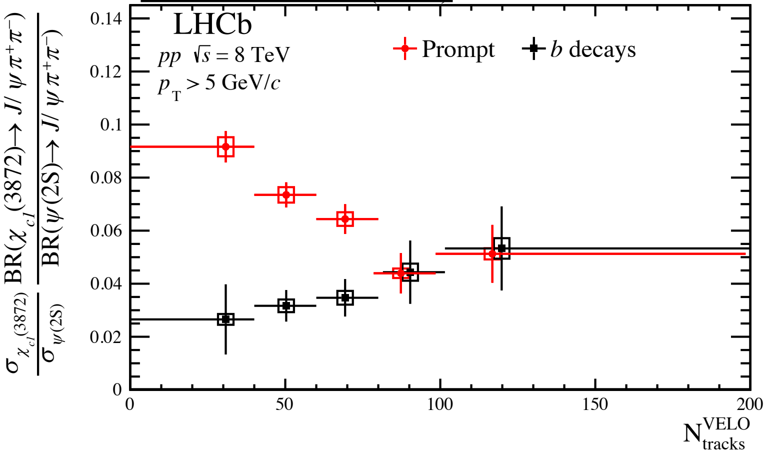
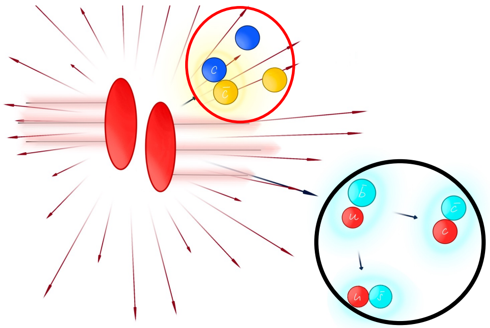




Prompt component:

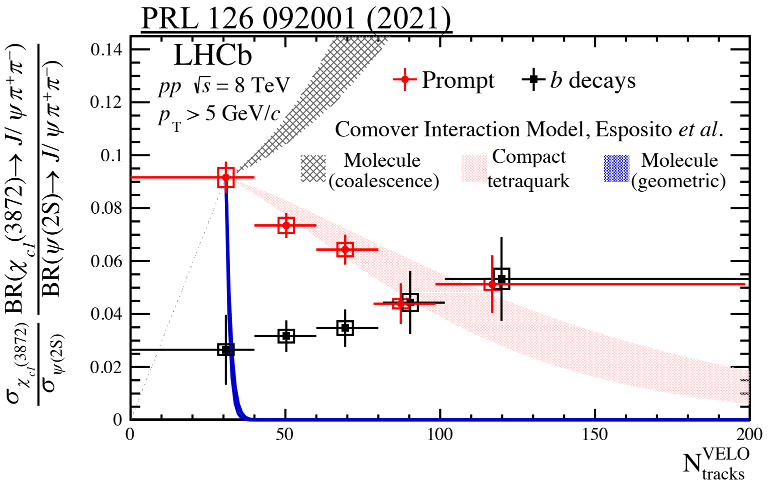
Increasing suppression of $\mathbf{X(3872)}$ production relative to $\boldsymbol{\psi(2S)}$ as multiplicity increases

***b*-decay component:**

Totally different behavior: no significant change in relative production, as expected for decays in vacuum. Ratio is set by ***b*** decay branching ratios.

X(3872)/ψ(2S) vs multiplicity

PRL 126 092001 (2021)



Geometric comover model:

$$\langle v\sigma\rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\rm geo}\left\langle\left(1-\frac{E_{\mathcal{Q}}^{\rm thr}}{E_c}\right)^n\right\rangle$$

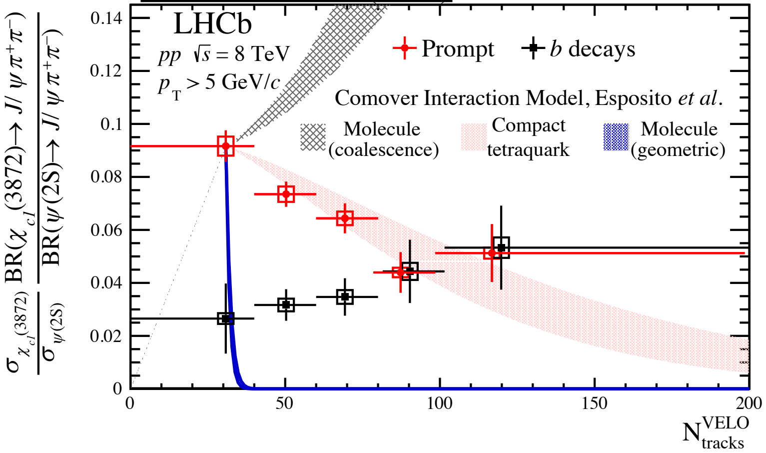
Molecular X(3872) immediately broken up

Compact X(3872) gradually dissociated

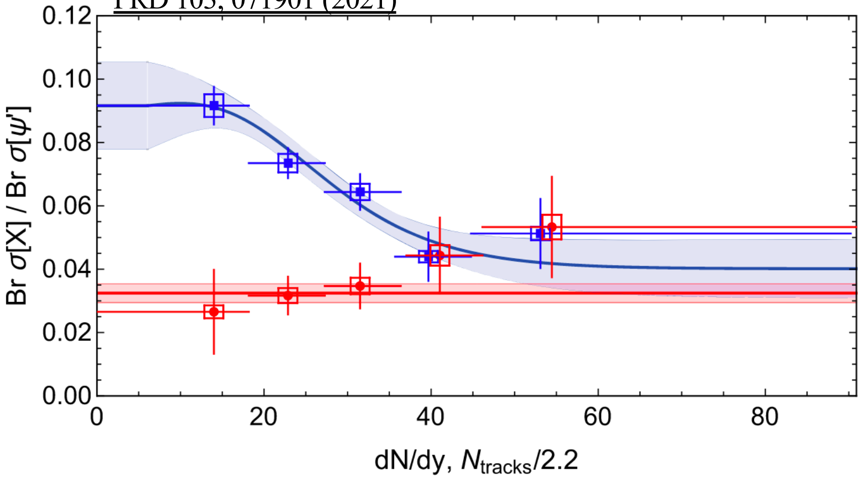
Data is consistent with **compact tetraquark** model.

X(3872)/ψ(2S) vs multiplicity

PRL 126 092001 (2021)



PRD 103, 071901 (2021)



Geometric comover model:

$$\langle v\sigma\rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{geo} \left\langle \left(1 - \frac{E_{\mathcal{Q}}^{thr}}{E_c}\right)^n \right\rangle$$

Constituent comover model:

$$\sigma^{incl}[\pi X] \approx \frac{1}{2}(\sigma[\pi D^0] + \sigma[\pi \bar{D}^0] + \sigma[\pi D^{*0}] + \sigma[\pi \bar{D}^{*0}])$$

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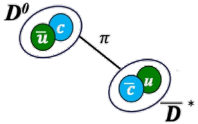
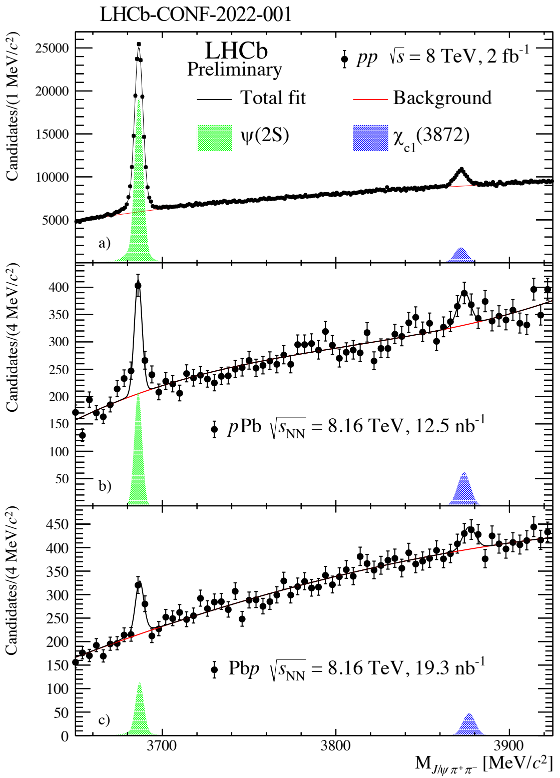
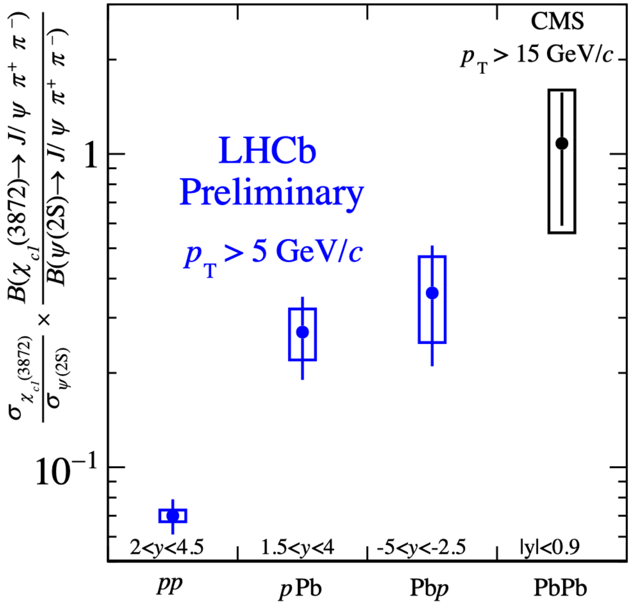


Data is consistent with **hadronic molecule** model.

Exotic X(3872) in pPb, PbPb

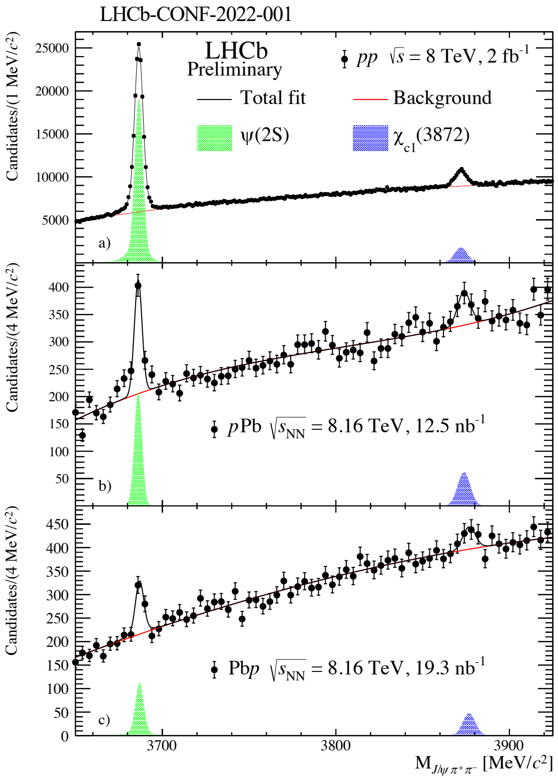


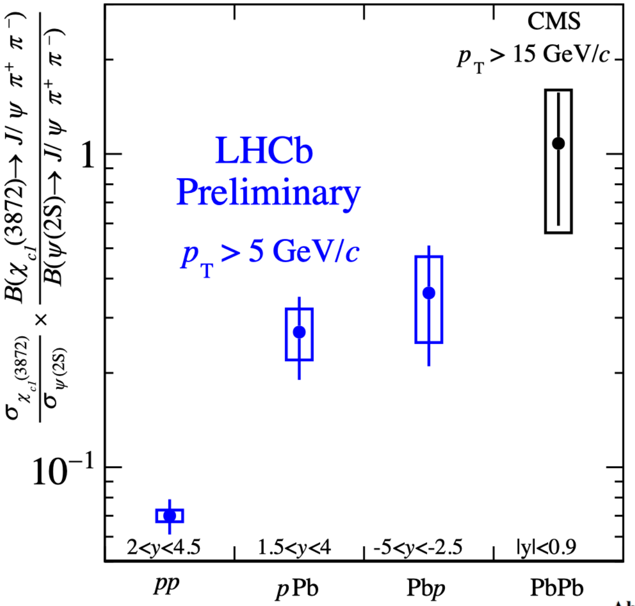


- Comparison between X(3872) and ψ(2S) suggests ***something different*** may be happening to exotic vs conventional hadrons in medium
- Enhancing effects start to out compete breakup?

Higher statistics datasets in future should allow study of multiplicity dependence in pA/AA

Exotic X(3872) in pPb, PbPb





- Comparison between X(3872) and ψ(2S) suggests ***something different*** may be happening to exotic vs conventional hadrons in medium

- Enhancing effects start to out compete breakup?

2017 PREDICTION: X(3872) enhanced in pA

Nuclear effects on tetraquark production by double parton scattering

F. Carvalho (Diadema, Sao Paulo Fed. U.), F.S. Navarra (Sao Paulo U.)
2017

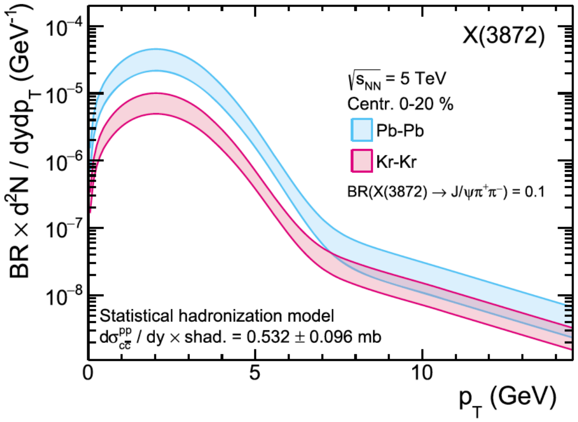
8 pages
Part of Proceedings, 12th Conference on Quark Confinement and the Hadron Spectrum (Confinement XII) : Thessaloniki, Greece
Published in: *EPJ Web Conf.* 137 (2017) 06004
Contribution to: Confinement XII
Published: 2017
DOI: 10.1051/epjconf/201713706004

Abstract. In this work we study the nuclear effects in exotic meson production. We estimate the total cross section as a function of the energy for *pPb* scattering using a version of the color evaporation model (CEM) adapted to Double Parton Scattering (DPS). We fond that the cross section grows significantly with the atomic number, indicating that the hypothesis of tetraquark states can be tested in pA collisions at LHC.

Higher statistics datasets in future should allow study of multiplicity dependence in pA/AA

Models of X(3872) in PbPb

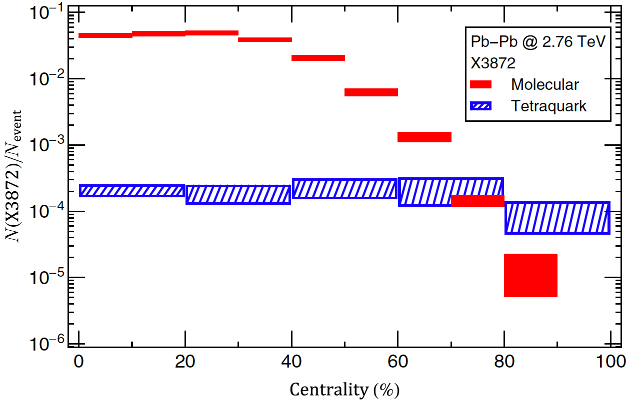
PLB 797 (2019) 134836



SHMC model:
Significant increase in X(3872) predicted for central AA collisions

Yield reaches up to ~1% of J/ψ yield

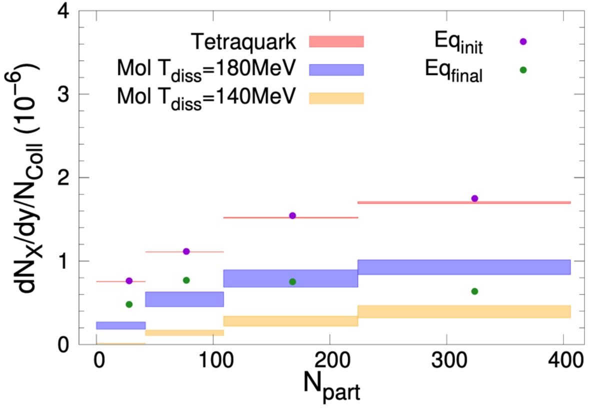
PRL 126 012301 (2021)



AMPT model:
difference in molecule vs diquark-diquark coalescence gives dramatically different yields and centrality dependence:

$N_{molecule} > N_{tetraquark}$

EPJA 57 122 (2021)



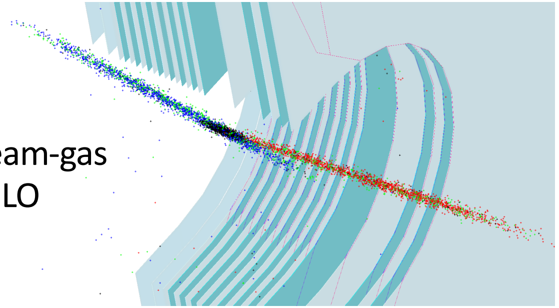
Transport calculation:
molecules have larger reaction rate, formed later in fireball evolution

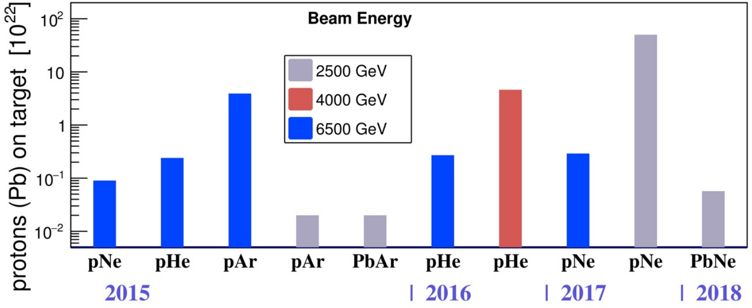
$N_{tetraquark} > N_{molecule}$

Fixed target collisions

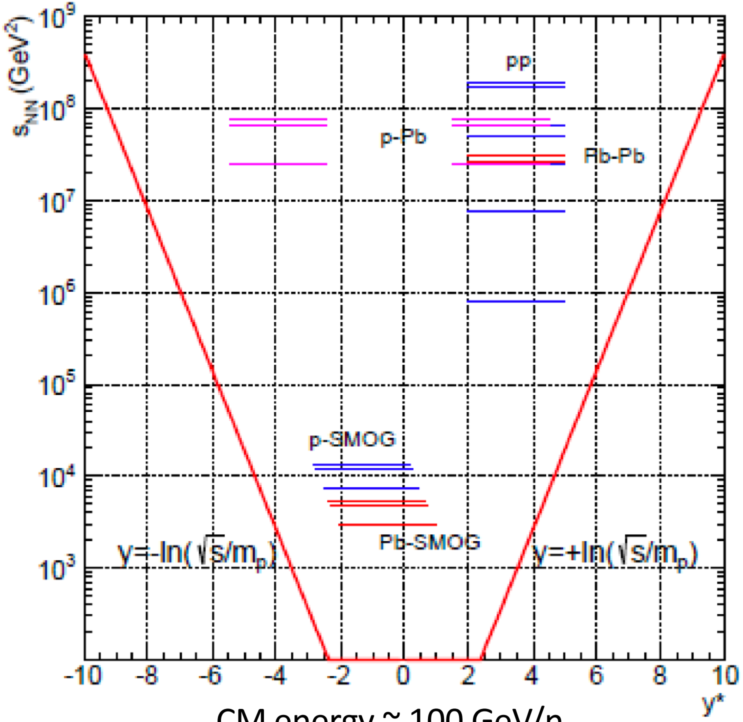
A unique capability at LHCb: inject noble gas into beampipe
Originally intended for precise luminosity measurements:
Precision on 2012 pp data is ±1.16%, best ever at bunched beam collider
JINST **9** P12005 (2014)

Reconstructed beam-gas vertices inside VELO



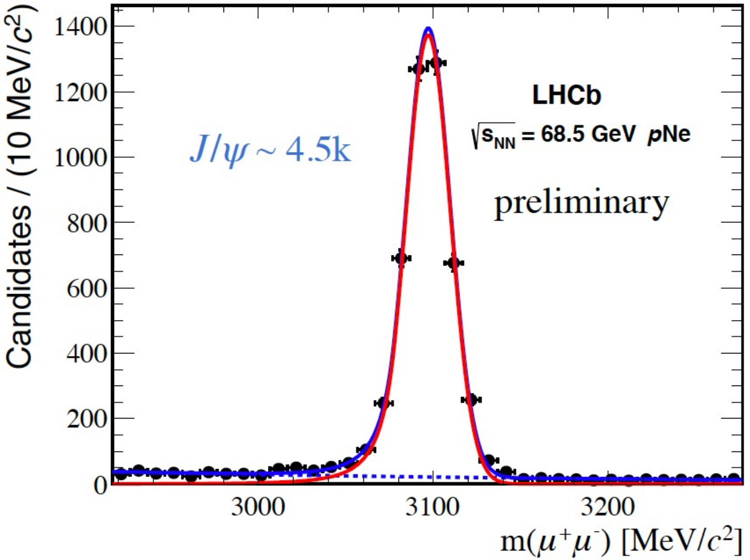


"System for Measurement of Overlap with Gas"

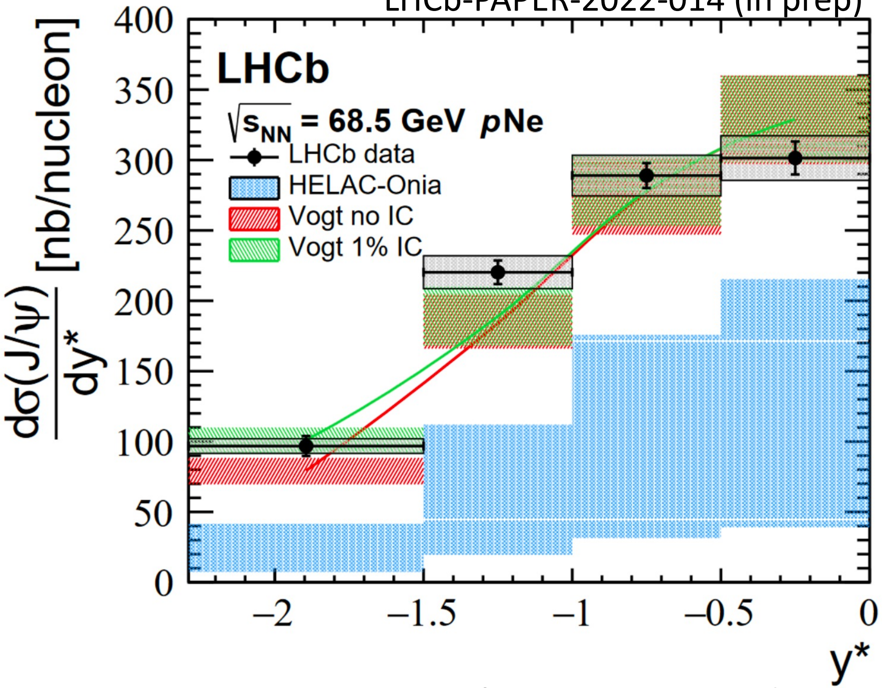


CM energy ~ 100 GeV/n
No limits on centrality

Fixed target *p*Ne collisions – intrinsic charm

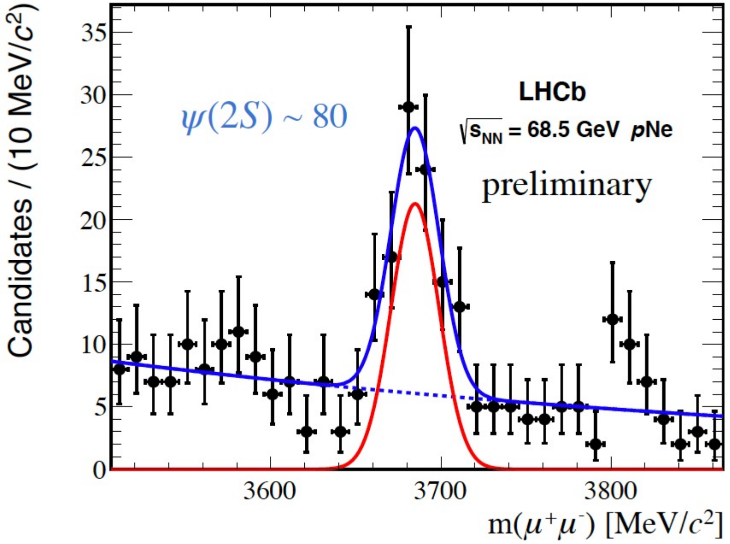


LHCb-PAPER-2022-014 (in prep)



- HELAC-Onia with nCTEQ15 underpredicts J/ψ yield in *p*Ne collisions at 68.5 GeV
- Data consistent with (and without) IC

Fixed target pNe collisions – $\psi(2S)$



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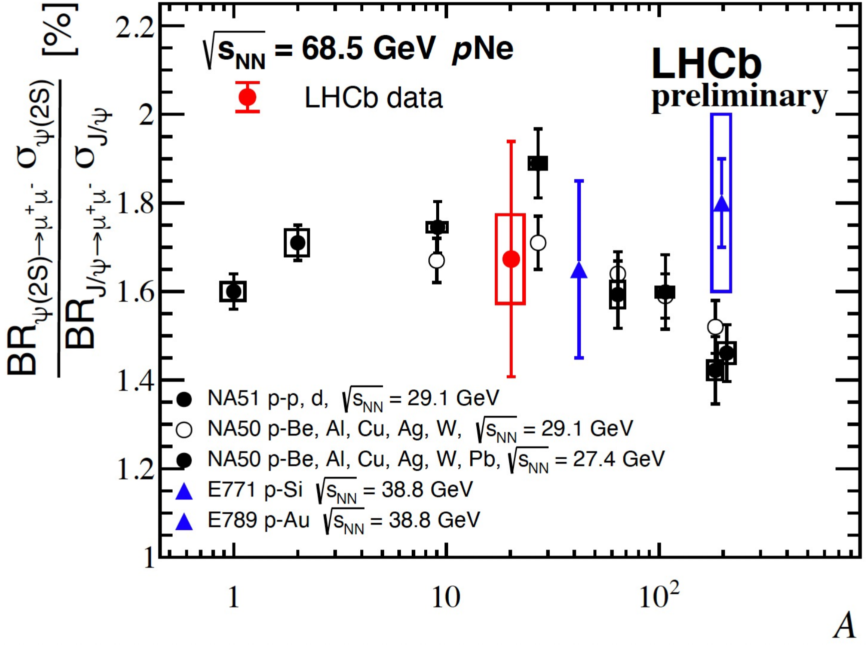
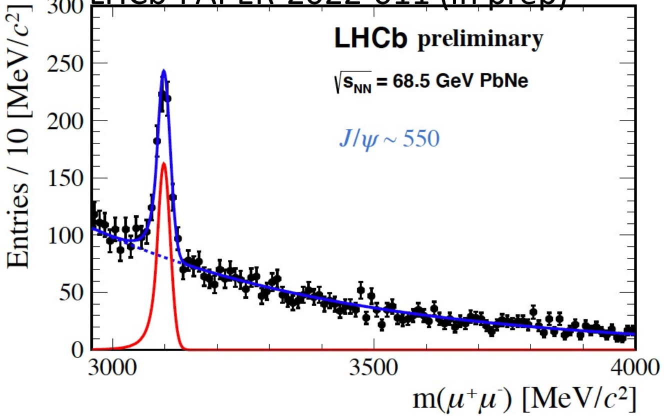
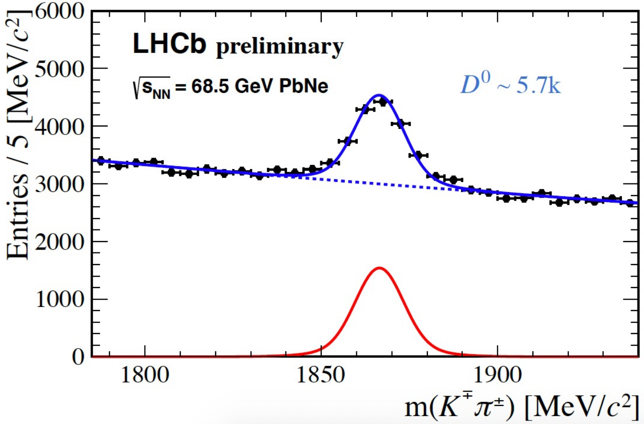


- Ratio consistent with other measurements in small systems (within significant uncertainties)

Fixed target PbNe collisions

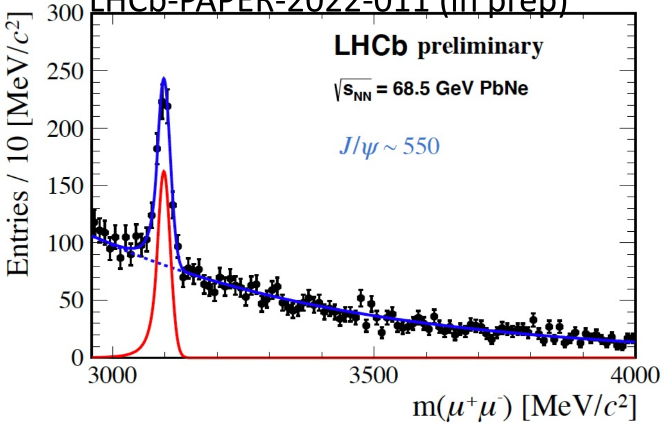
LHCb-PAPER-2022-011 (in prep)

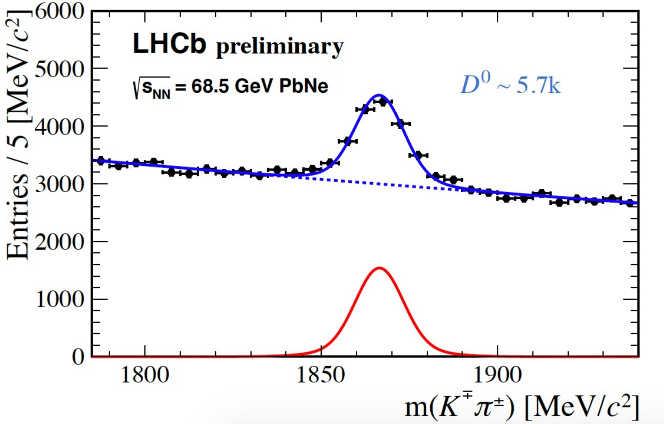




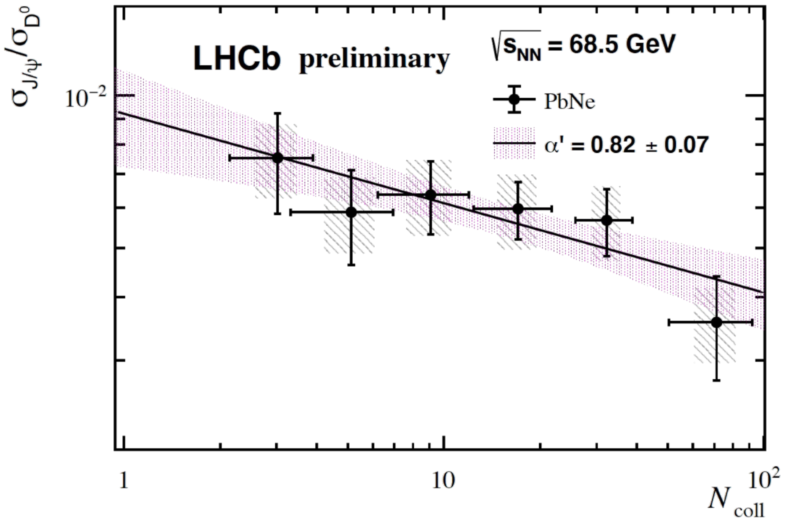
Fixed target PbNe collisions

LHCb-PAPER-2022-011 (in prep)



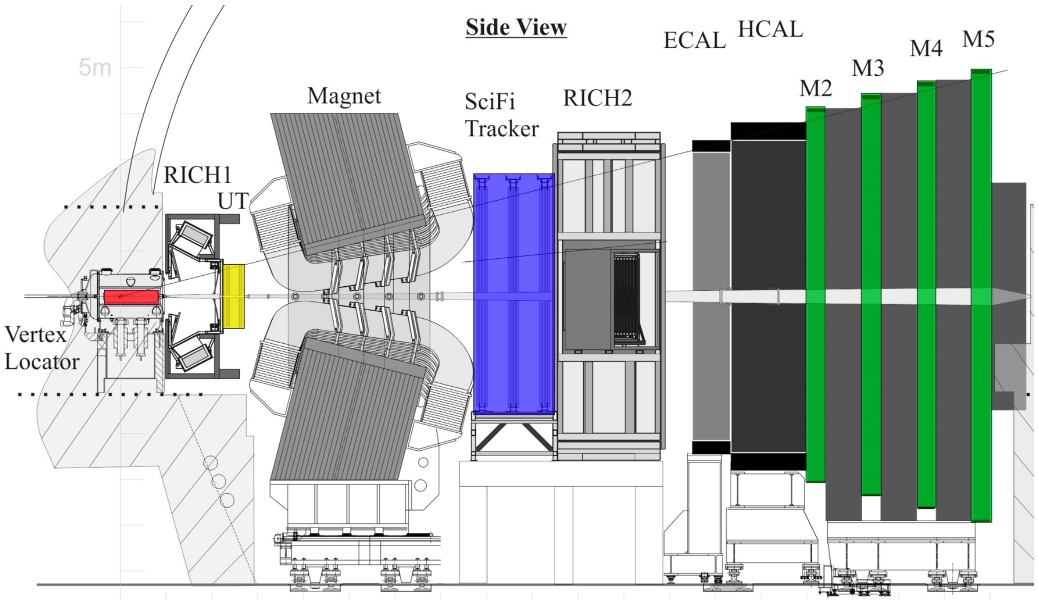


- First fixed-target results using Pb beams



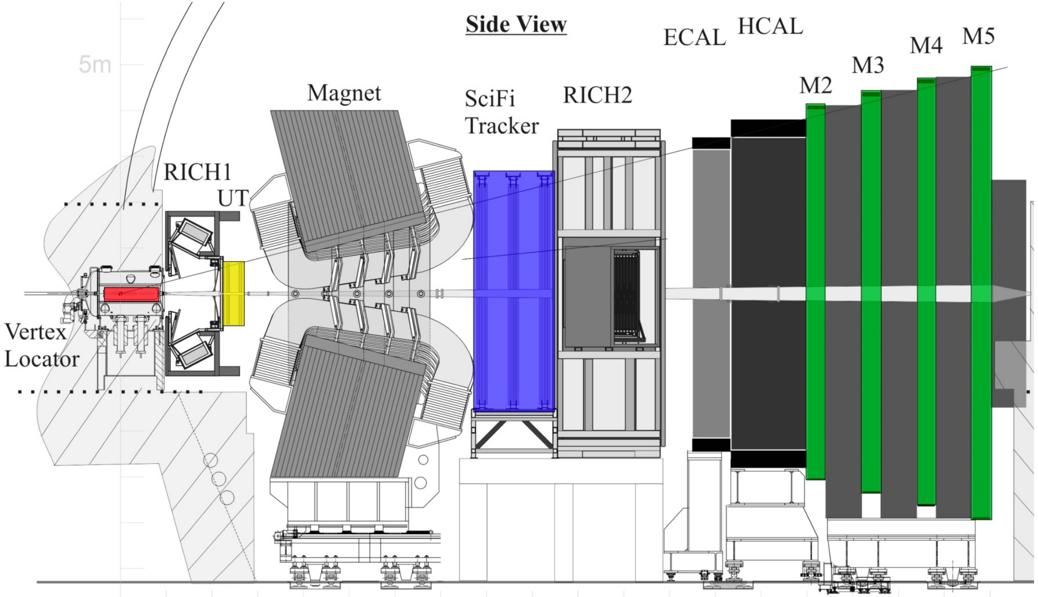
- Use D meson production as baseline for charm:
- Assume $\sigma_{J/\psi} \propto N_{coll}^{\alpha'}$ and $\sigma_D \propto N_{coll}$
- Consistent with NA50 measurements in pA: no “anomalous” suppression

LHCb upgrade 1(a) - Run 3 (commissioning now)



- LHCb has **advanced the state of the art** with full streaming readout in pp at 40MHz
- *All new tracking system reconstructs up to 30% most central PbPb collisions*

LHCb upgrade 1(a) - Run 3 (commissioning now)



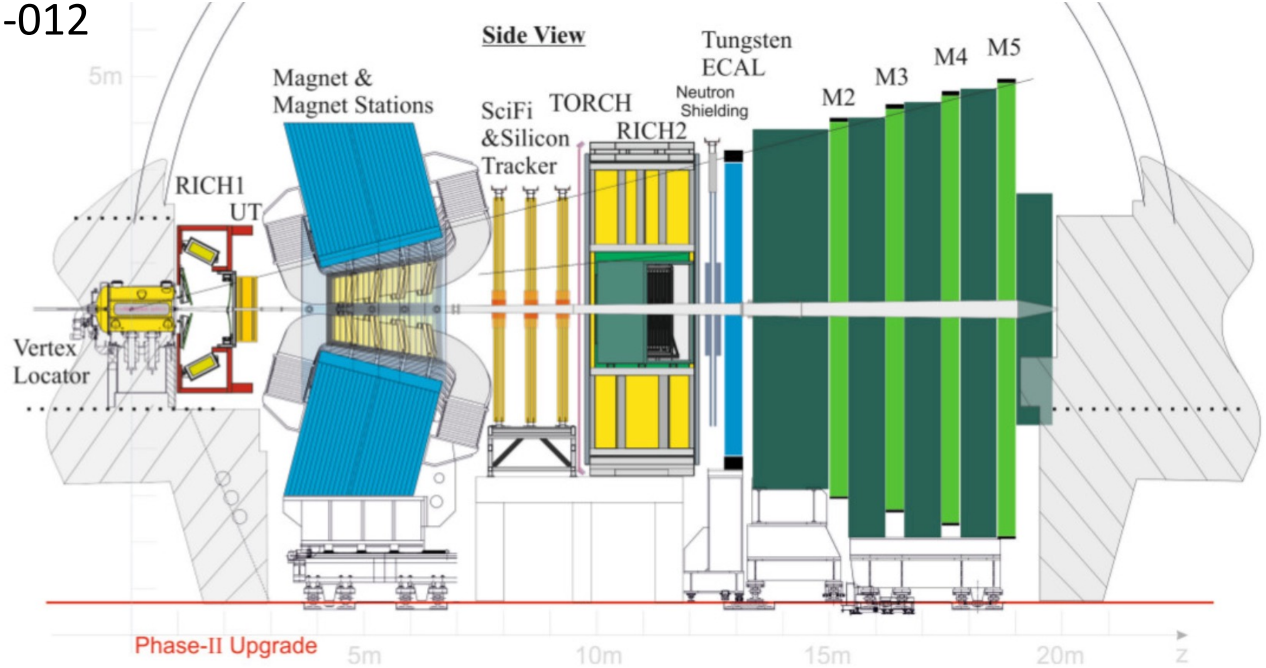
Example SMOG2 pAr at 115 GeV for one year

Int. Lumi.		80 pb^{-1}
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

- LHCb has **advanced the state of the art** with full streaming readout in pp at 40MHz
- *All new tracking system reconstructs up to 30% most central PbPb collisions*
- Upgraded ***SMOG2*** storage cell in front of Vertex Locator greatly increases fixed target rates
  - Simultaneous running with *pp* collisions gives high statistics p+He, p+Ar, p+Xe, etc
  - **Can record O+O, Ar+Ar, etc data at two energies simultaneously**

LHCb upgrade 2 - Run 5+

CERN-LHCC-2021-012



Further upgraded tracking to deal with high *pp* pileup and heavy ion collisions

- *Full PbPb centrality range accessible*
- ***B hadrons, exotic states, and more at low p_T in central collisions***
- ***Solid target? Polarized target?***

Summary

- **LHCb has a unique dense QCD/heavy ion physics program:**

- Forward data places strong constraints on partonic structure of protons and nuclei
  - New information on intrinsic charm currently statistics limited
  - Open questions remain on role of medium effects on PDF extractions

- An explosion of new info on allowed configurations of quarks inside hadrons
  - Fundamental questions remain about the nature of many new particles
  - Guidance from experiment and theory needed to make progress

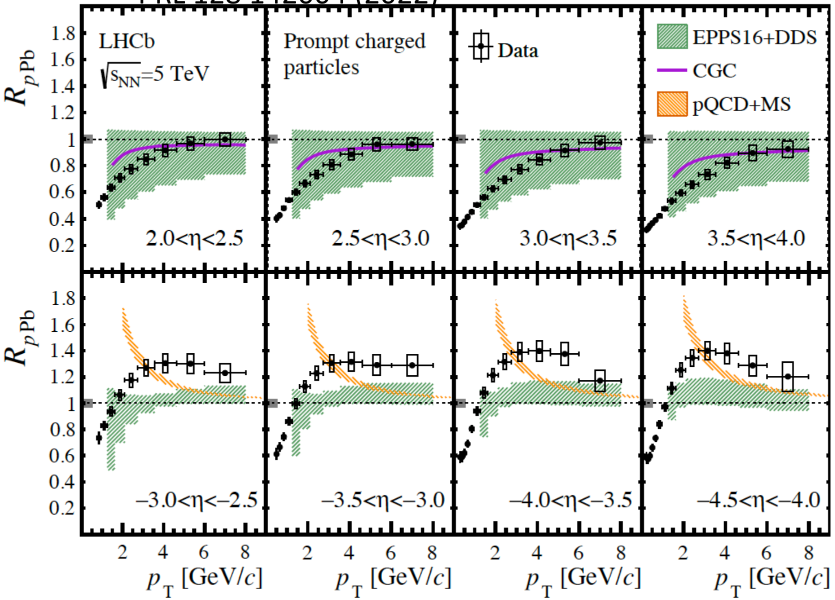
- Unique fixed target program just getting underway
  - Major upgrade installed

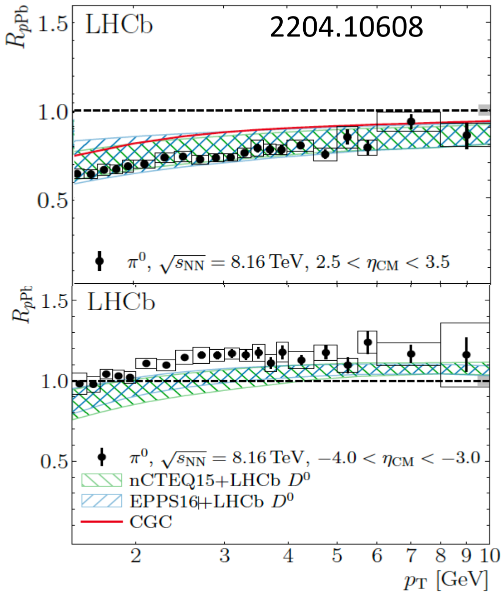
Los Alamos is supported by the DOE/Office of Science/Nuclear Physics,

and DOE Early Career Awards program

Challenging nPDFs – light flavor

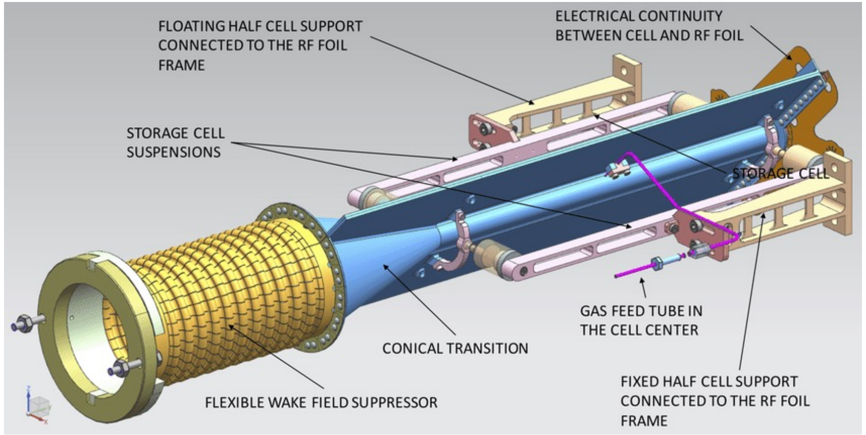
PRL 128 142004 (2022)





- Prompt charged particle and π^0 modification agrees with nPDF at forward rapidity
- **Discrepancy** between data and nPDF occurs at **backwards** rapidity
- High x effect? Final state effects? *Does this data challenge assumptions of PDF fits?*
- To separate effects: non-interacting probes like Z, direct photons, gamma-h correlations

SMOG2



https://cds.cern.ch/record/2673690/files/LHCB-TDR-020.pdf

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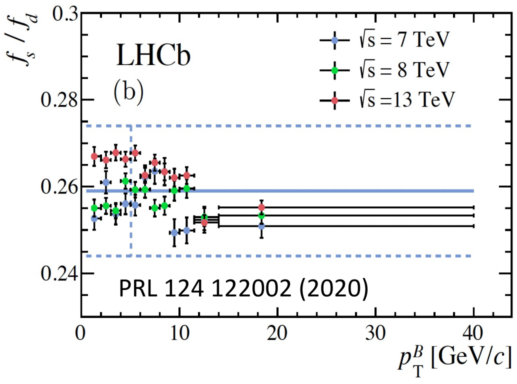
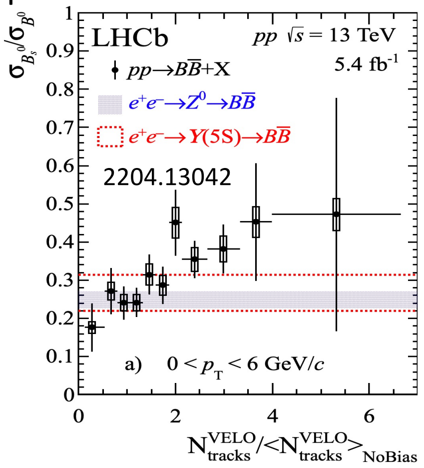
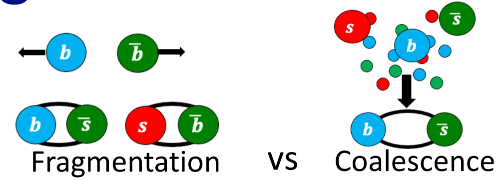
- Upgraded SMOG 2 system at LHCb allows greatly increased rates of beam+gas collisions at LHCb
- Variable target gases – allows hadronic environment to be adjusted (H, He, …, Xe)
- Access to exotic states near RHIC energies
- Can potentially run concurrent with proton+proton collisions – large data sets

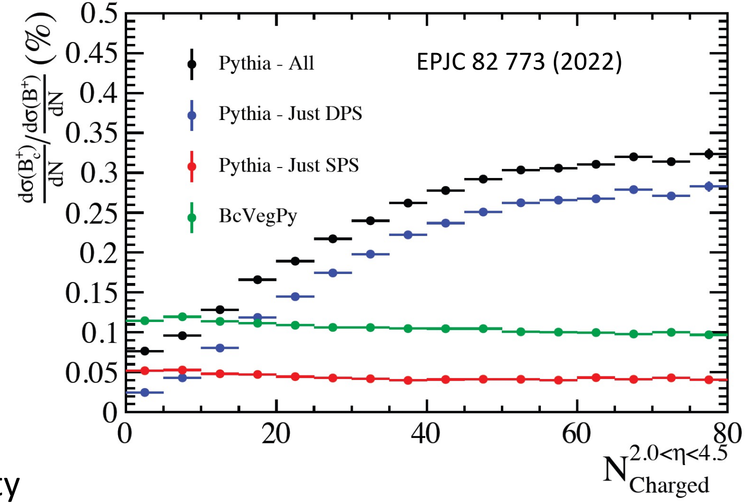
Hadronization mechanisms

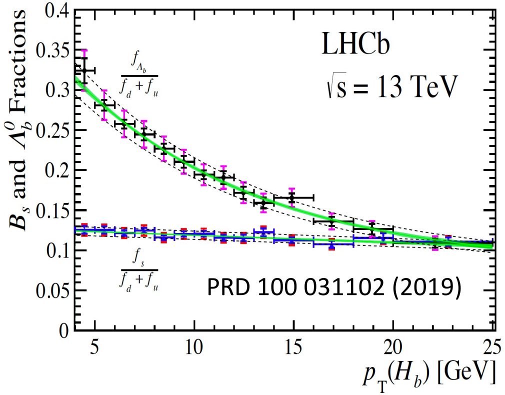
Measuring how *b* quarks arrange into various hadrons gives information on the non-perturbative hadronization process





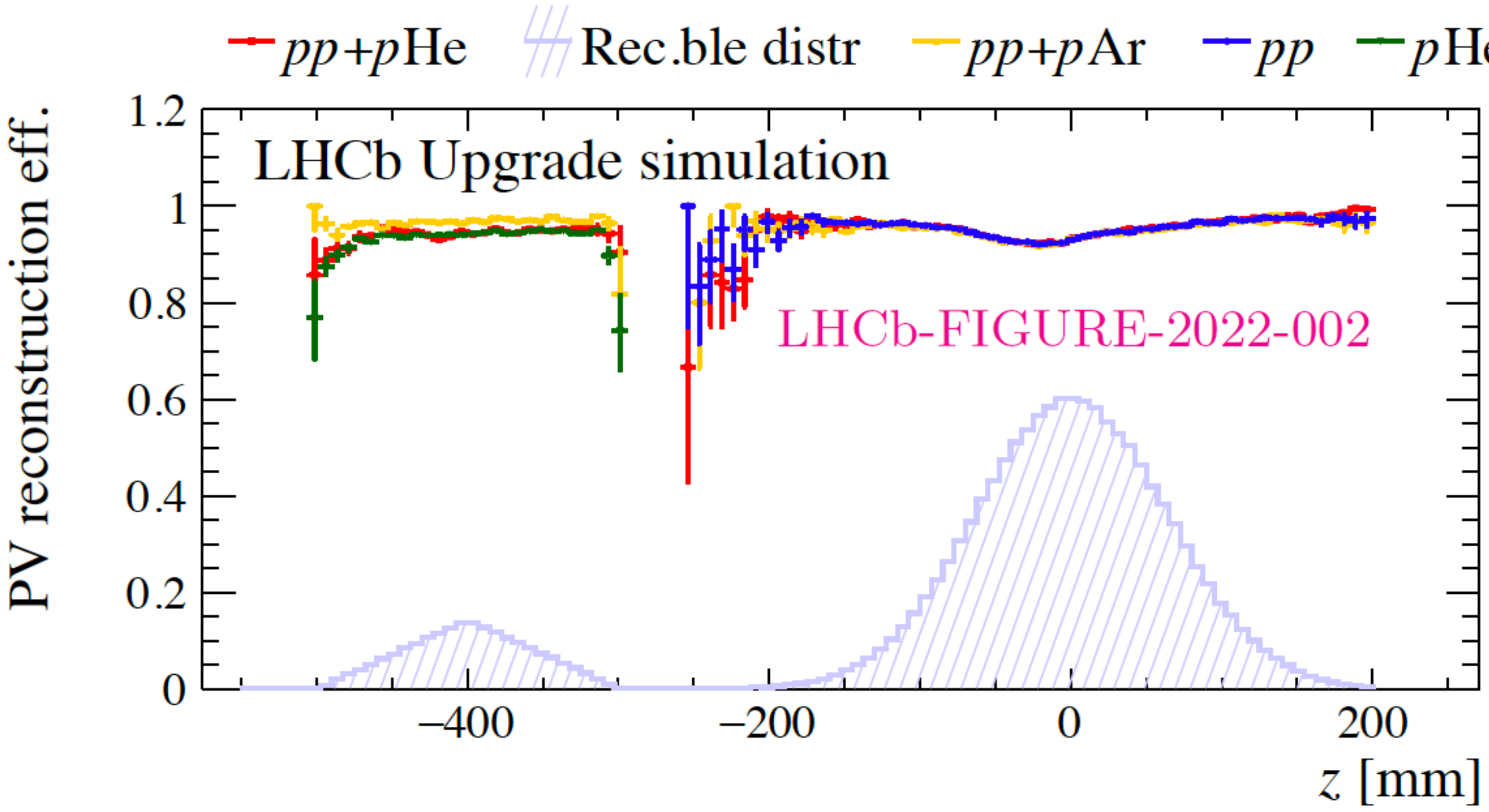






- B_s fraction depends on $\sqrt{s}$, multiplicity
- Baryon fraction has strong p_T dependence
- **Points to other hadronization mechanisms beyond fragmentation**

- Dramatic difference predicted in B_c multiplicity dependence for DPS vs SPS
- Can be used in future to pin down double-heavy production mechanism and understand role of MPIs



pp+pHe
Rec.ble distr
pp+pAr
pp
pHe
PV reconstruction eff.
1.2
1
0.8
0.6
0.4
0.2
0
LHCb Upgrade simulation
LHCb-FIGURE-2022-002
−400
−200
0
200
z [mm]