Los Alamos
NATIONAL LABORATORY

Forward heavy flavor at the LHC

Matt Durham
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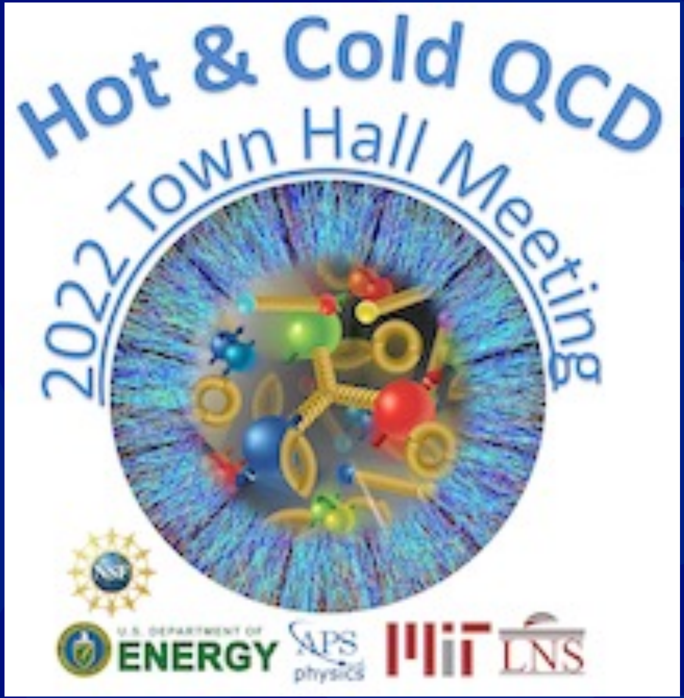


Heavy quarks in small systems

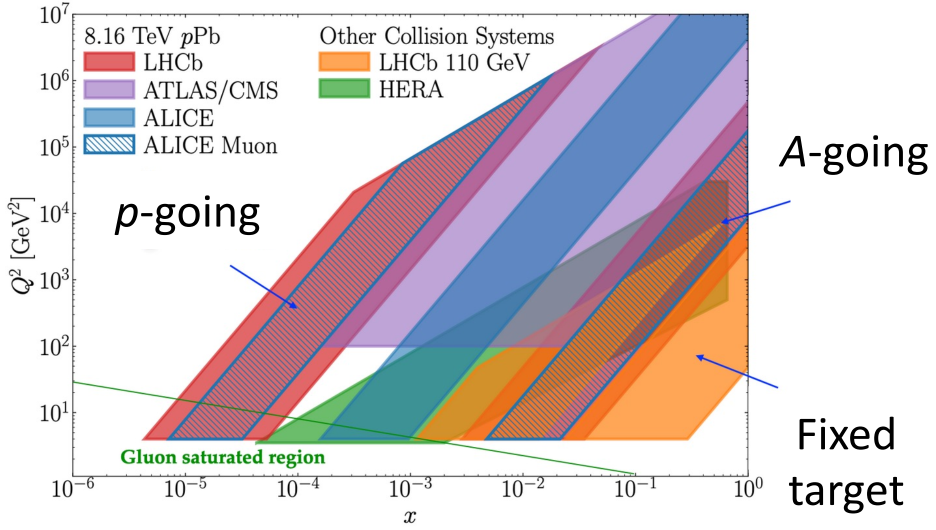
- Heavy quark pair production is **sensitive to structure of beam particles**
  - GOAL: quantitative understanding of parton distribution functions

- Nuclear modification **sensitive to range of initial/final state effects**
  - GOAL: understanding various contributions from
    - Energy loss in nucleus
    - Breakup outside the nucleus
    - Modification of hadronization mechanisms in medium
    - Hydrodynamic effects/short lived plasma phase
    - **Baseline for interpreting AA data**

- Well-known spectrum of conventional heavy quark states allows **unambiguous identification of exotic hadrons – pentaquark, tetraquarks**
  - GOAL: understand complete array of hadron structures allowed by QCD

Forward detectors

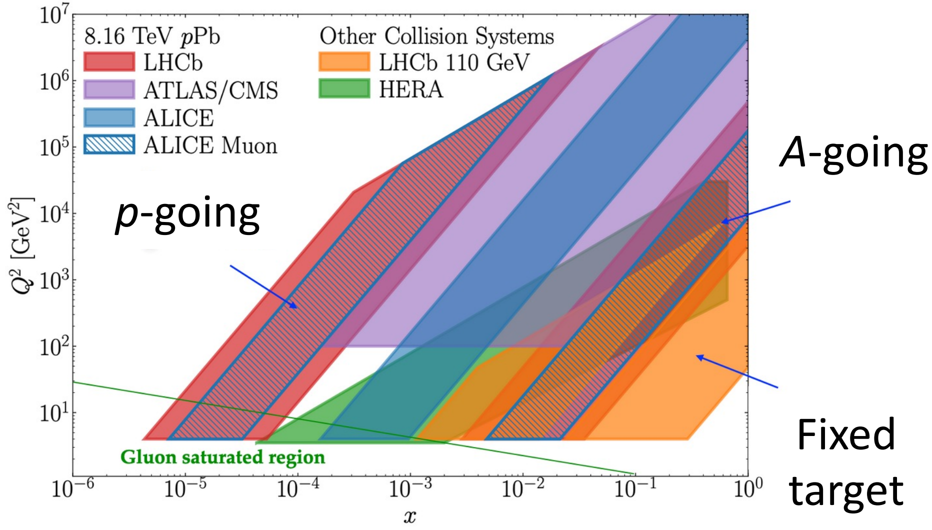
Access to extremes of *x* ranges



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

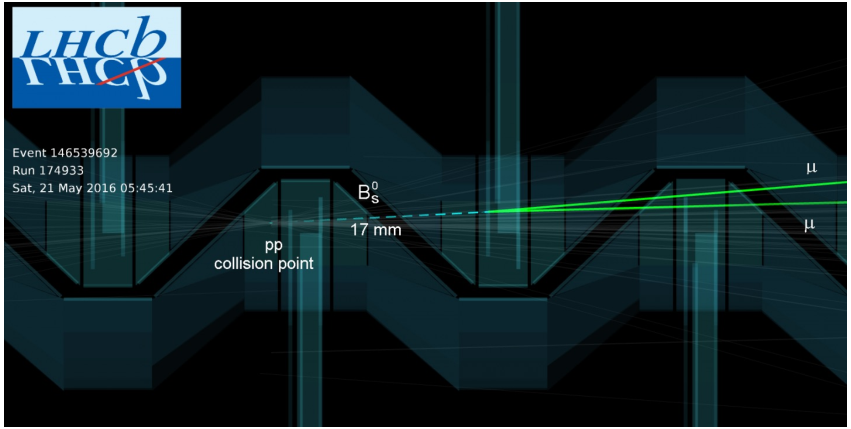
Forward detectors

Access to extremes of *x* ranges



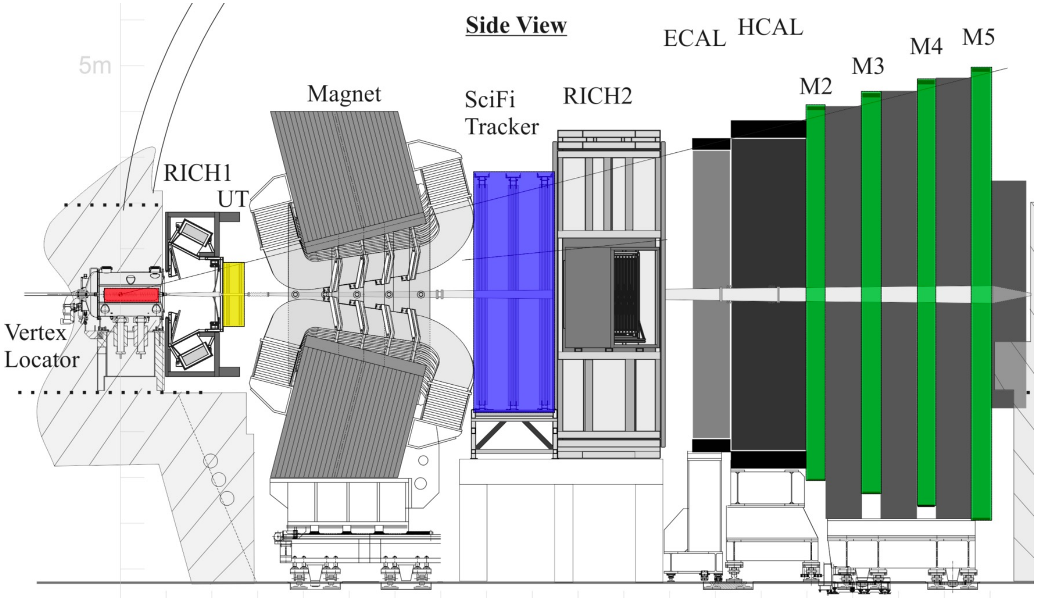
- Very low and very high x ranges can be probed by adjusting beam and target configurations

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



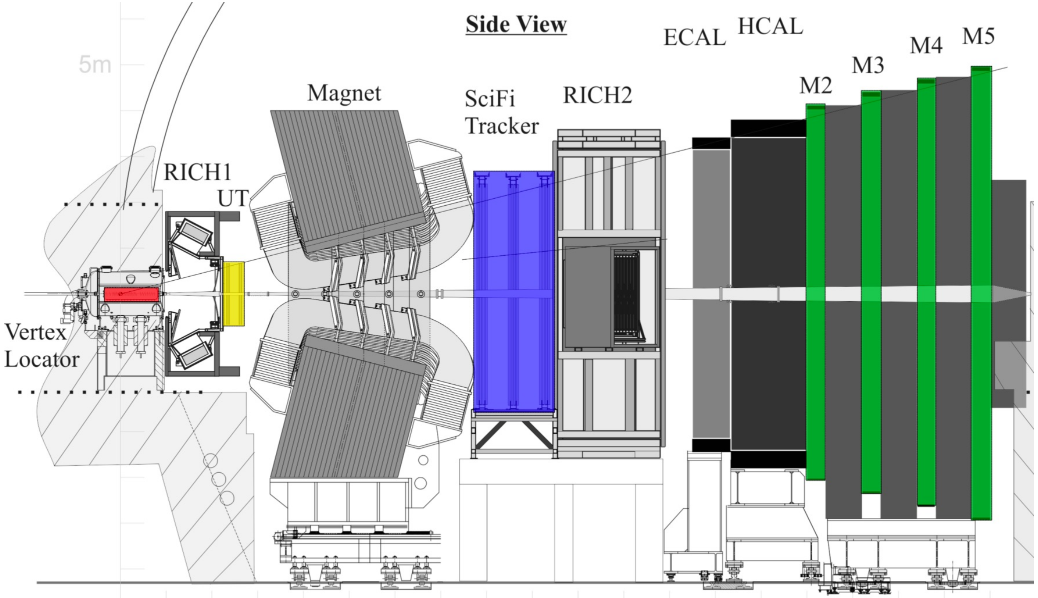
- Forward boost gives large distance between primary vertex and decay vertex – easier to reject prompt backgrounds
- High total momentum *p* aids access to relative low transverse momentum p_T

LHCb upgrade 1(a) - Run 3 (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)



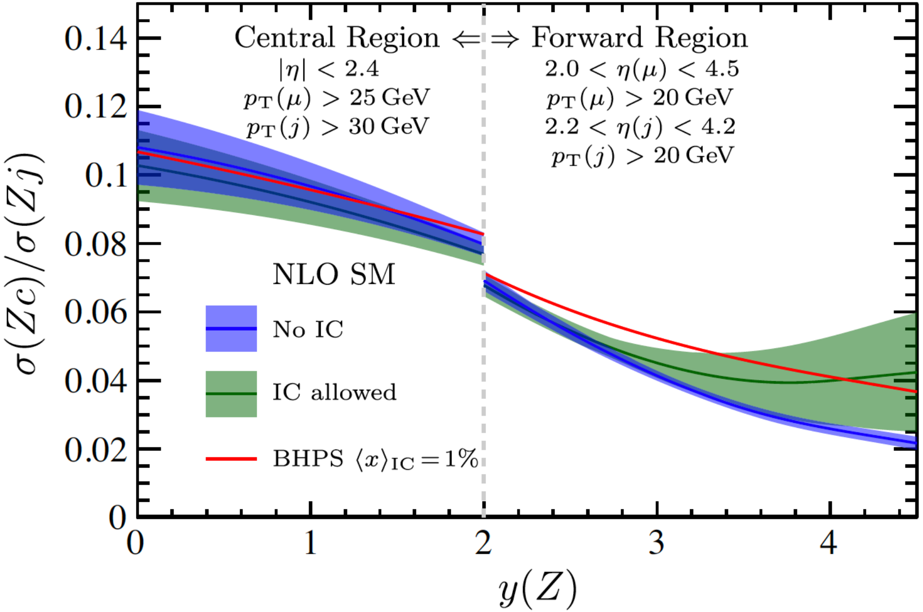
Example SMOG2 pAr at 115 GeV for one year

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**

Proton structure – intrinsic charm

PRL 128 082001 (2022)



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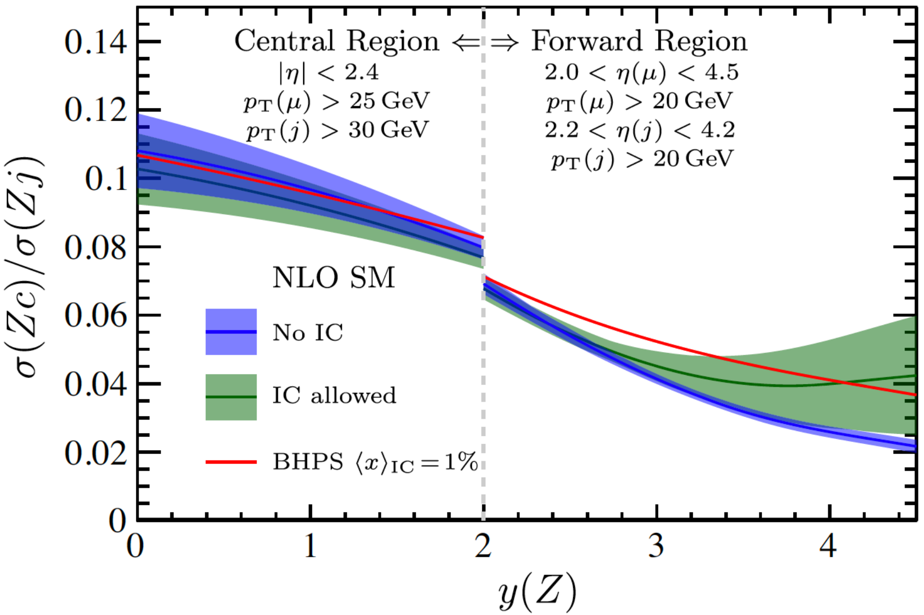
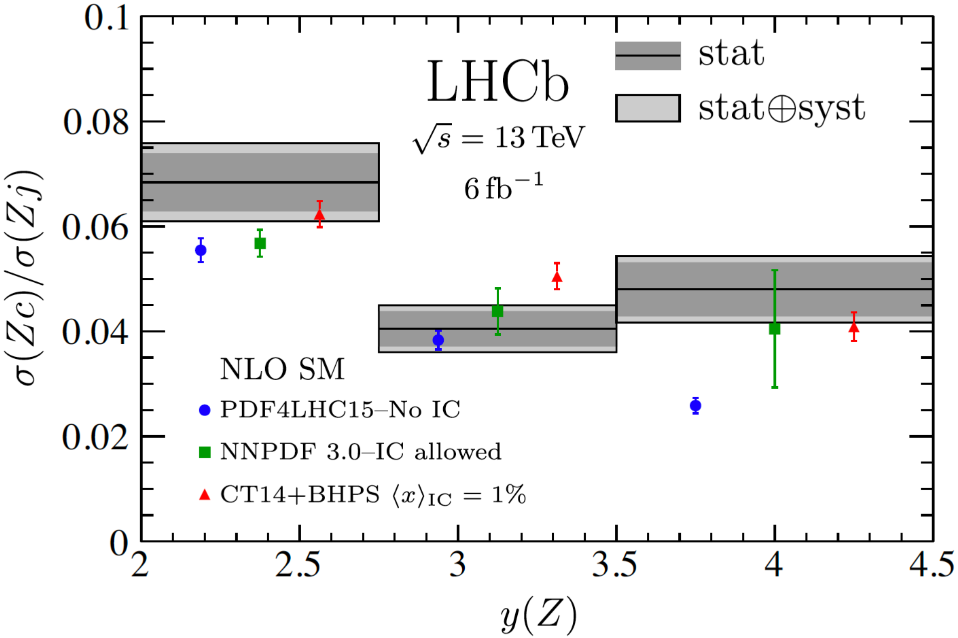




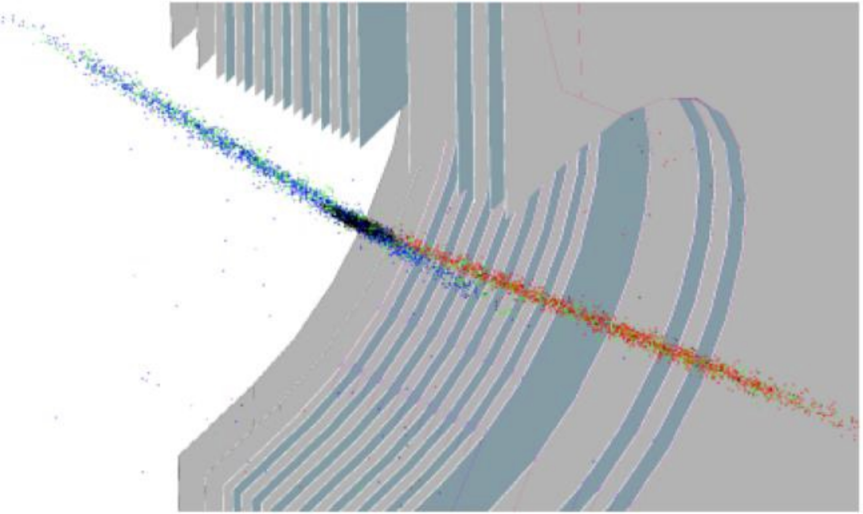
- *Z* + jet production at forward rapidity probes high x region – sensitive to intrinsic charm
- LHCb data favors calculations allowing IC at most forward rapidity

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

- Data currently statistics limited, Run 3+ fertile soil for future exploration

Fixed target collisions – intrinsic charm

Reconstructed beam+gas vertices inside LHCb VELO



- Unique LHCb SMOG system allows highest energy fixed target program
- Samples from anti-shadowing region in nPDF, relatively high x

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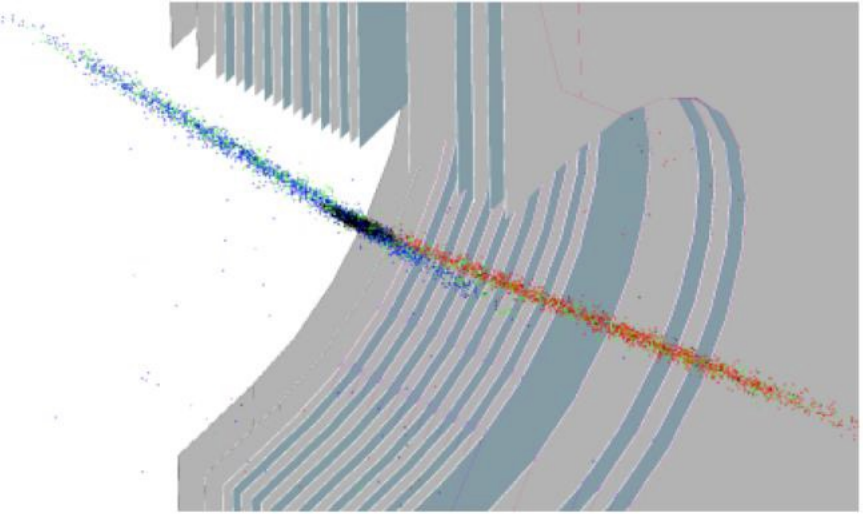

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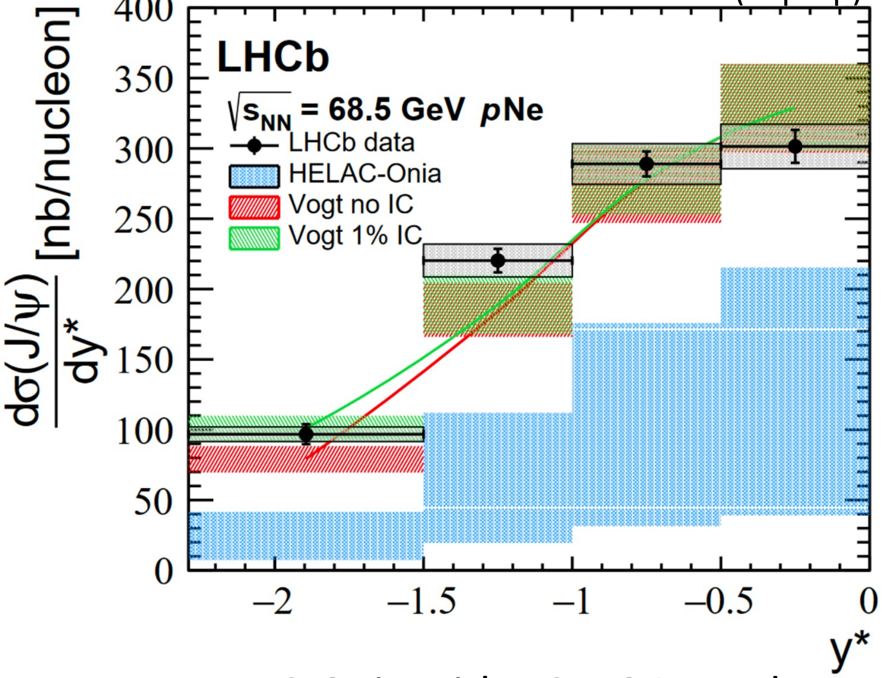
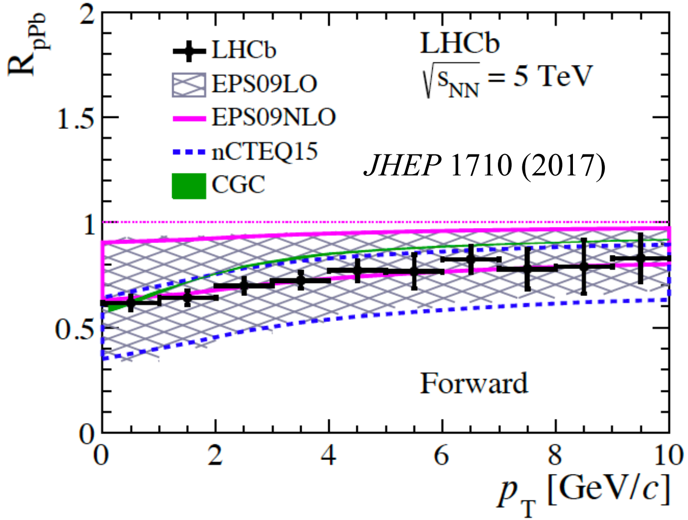
LHCb-PAPER-2022-014 (in prep)



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

Constraining nPDFs – D mesons



D meson nuclear modification
Data unc << nPDF unc

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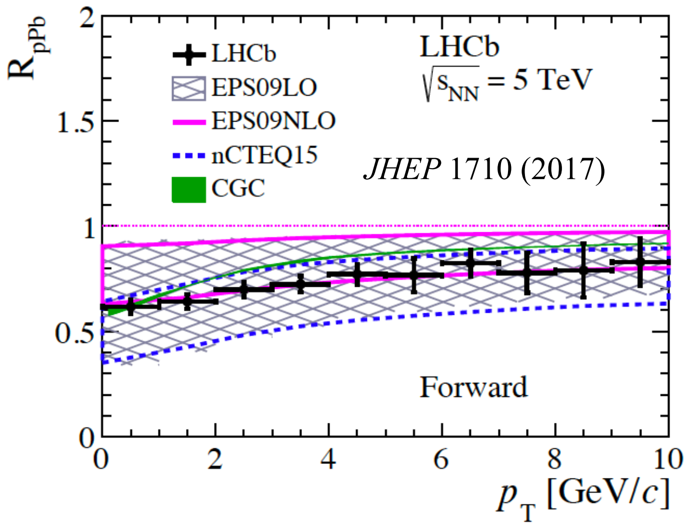

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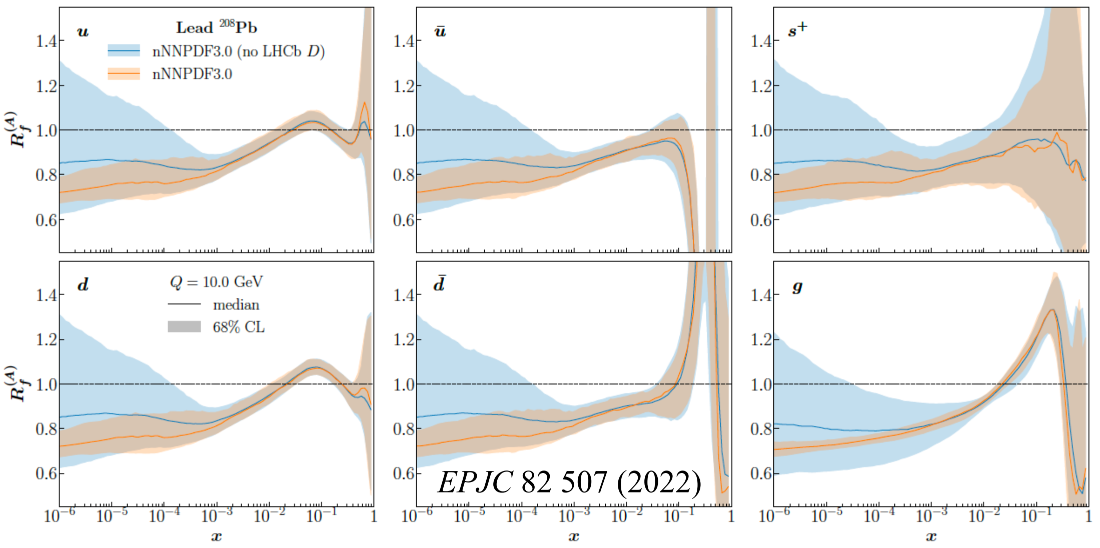


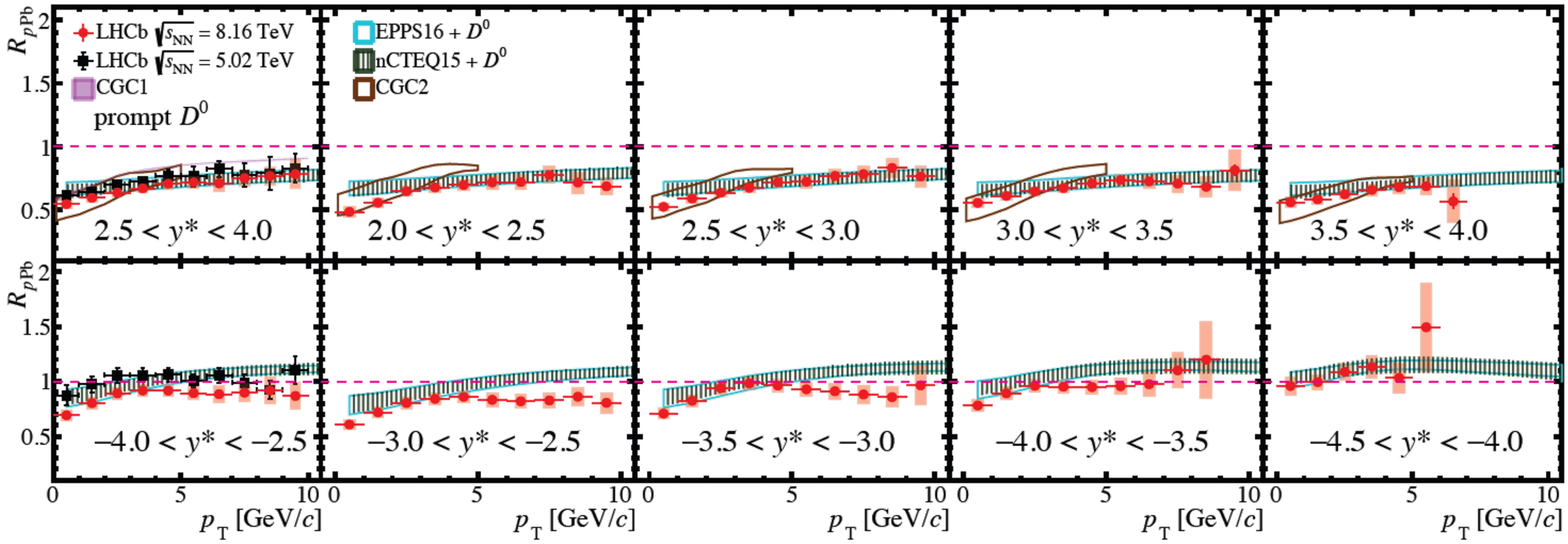
see also: *PRL* 121 052004 (2018), *JHEP* 05 (2020) 037

Incredible progress made on nPDF constraints at low *x*

Hadron collisions complementary to DIS for exploring nucleon structure

Challenging nPDFs – D mesons

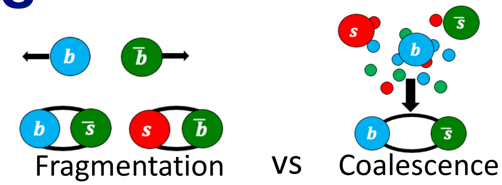
LHCb 2205.03936



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

Hadronization mechanisms

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



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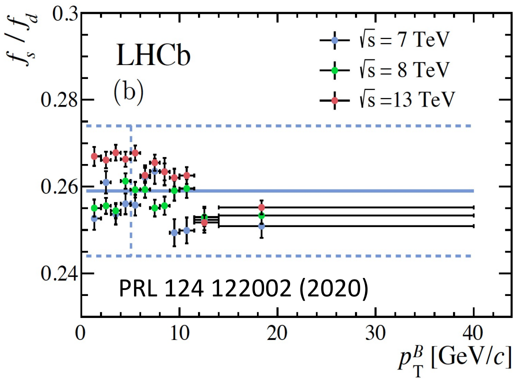

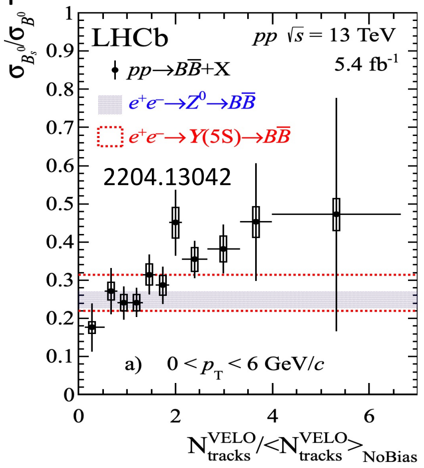

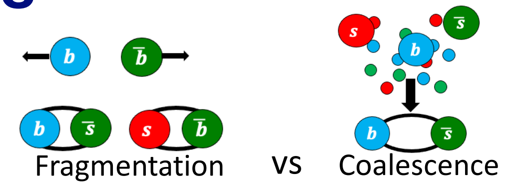

- B_s fraction depends on $\sqrt{s}$, multiplicity

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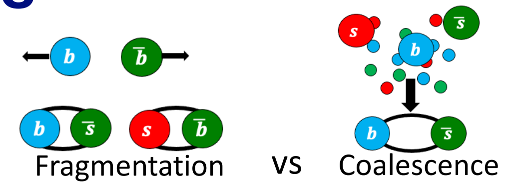

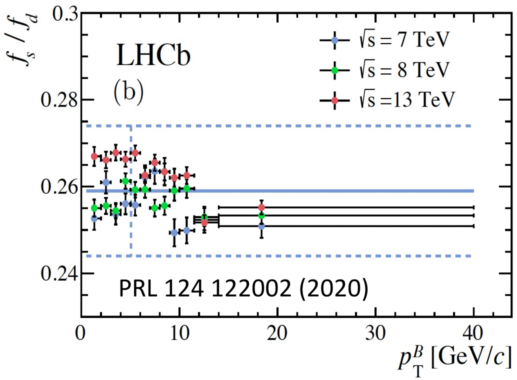

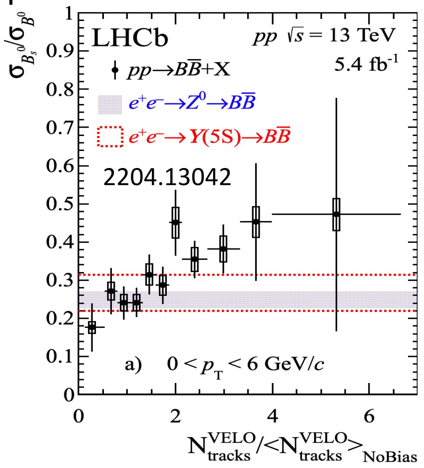

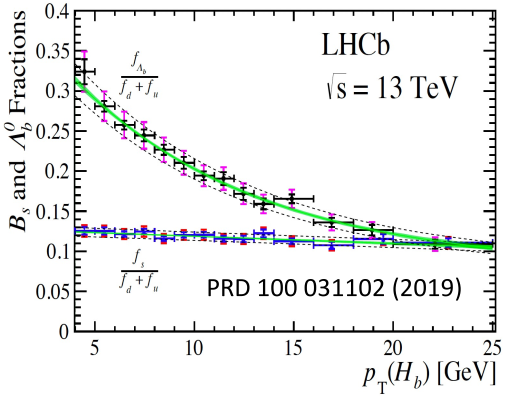

- B_s fraction depends on $\sqrt{s}$, multiplicity
- Baryon fraction has strong p_T dependence
- **Points to other hadronization mechanisms beyond fragmentation**

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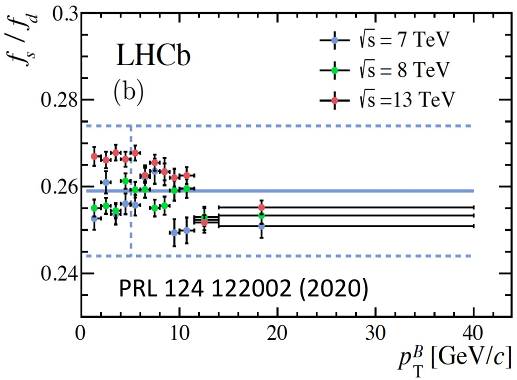

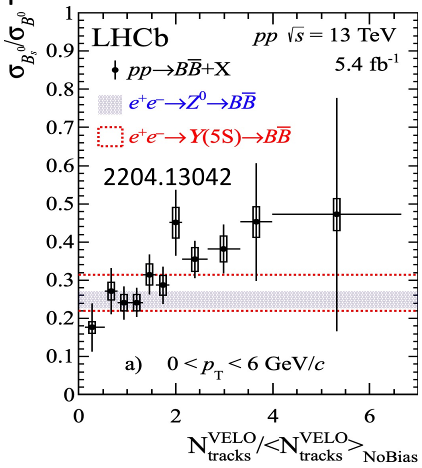

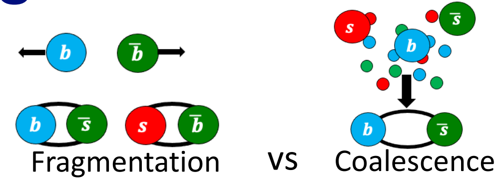

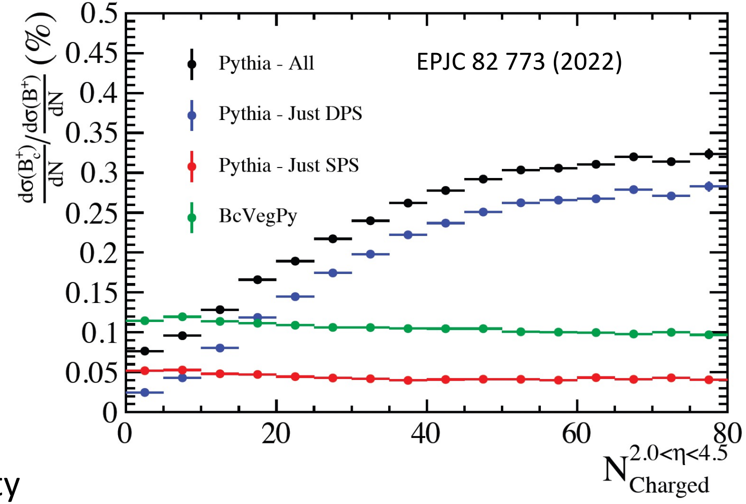

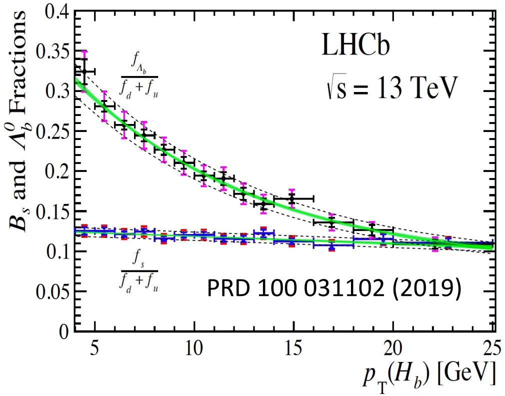

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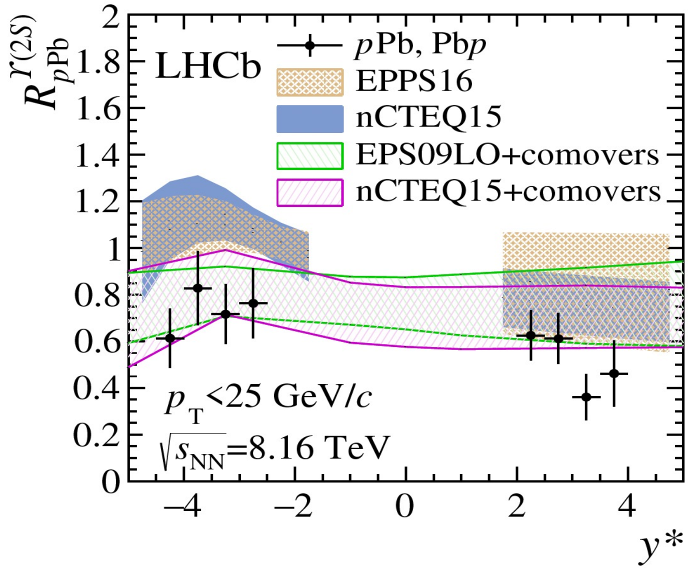
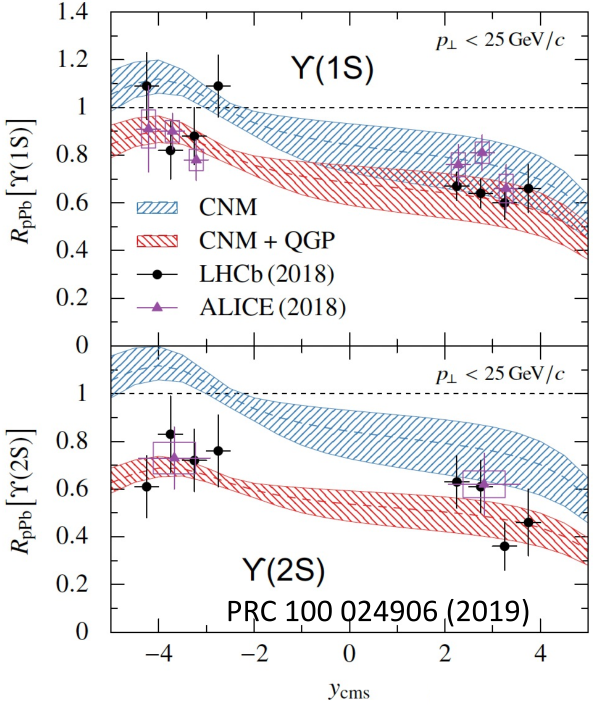
- **Points to other hadronization mechanisms beyond fragmentation**

- 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

Quarkonia in small systems

JHEP 11 (2018) 194

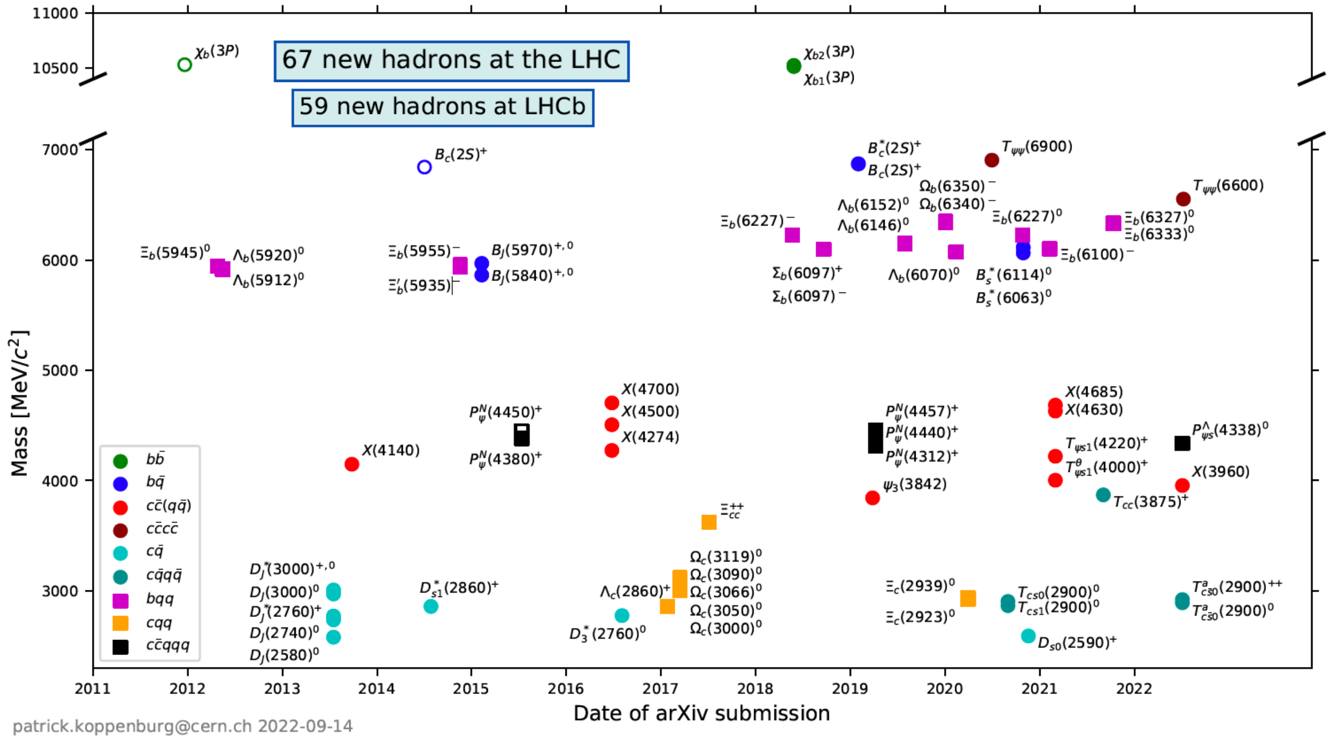




PRC 100 024906 (2019)

- **Control of CNM effects crucial for understanding color screening in QGP**
- Competing models with very different physical motivations both describe data
- Solution require further tests of models: fixed target data vs collider; flow measurements

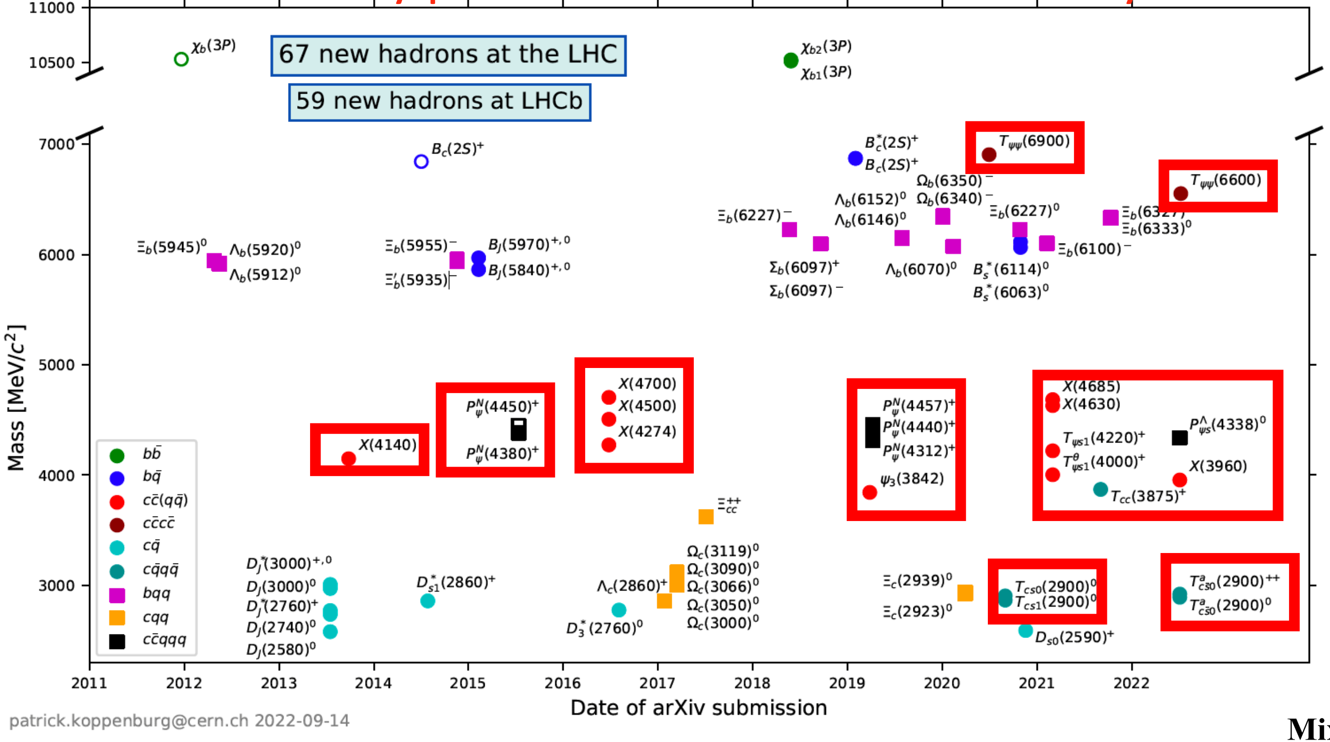
New hadrons discovered at LHC



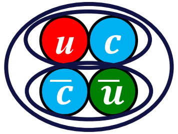
Exotic hadrons discovered at LHC

See also: Justin Stevens Sat 8:30

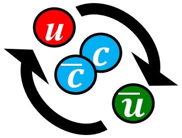
Conventional heavy quark states well known: exotics can be clearly identified



Compact tetraquark/pentaquark

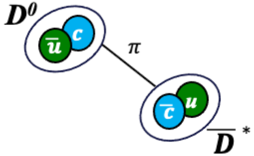


Diquark-diantiquark
PRD 71, 014028 (2005)
PLB 662 424 (2008)



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)

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

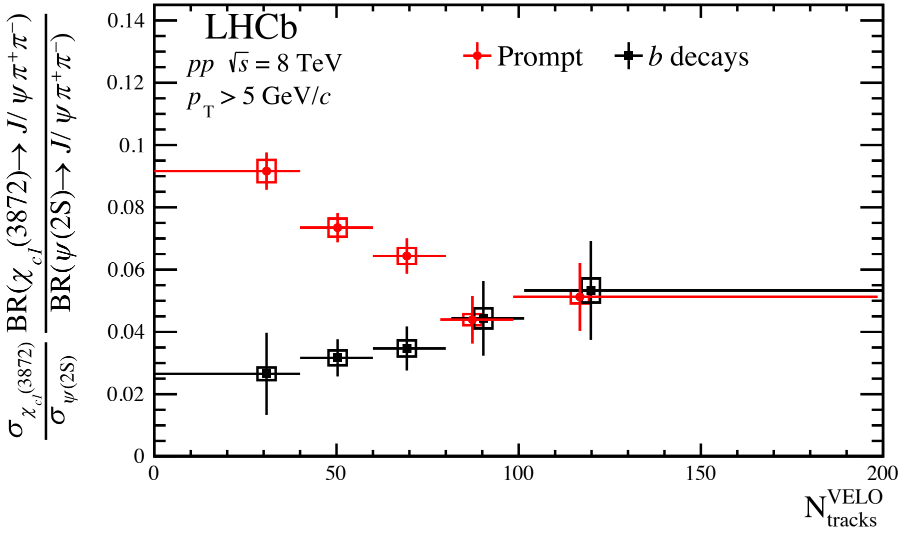
Mixtures

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

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

Exotic X(3872) - first studies in medium

- Most exotics have only been studied as products on B decays
- Medium effects on PROMPT exotics can potentially give information on their structure



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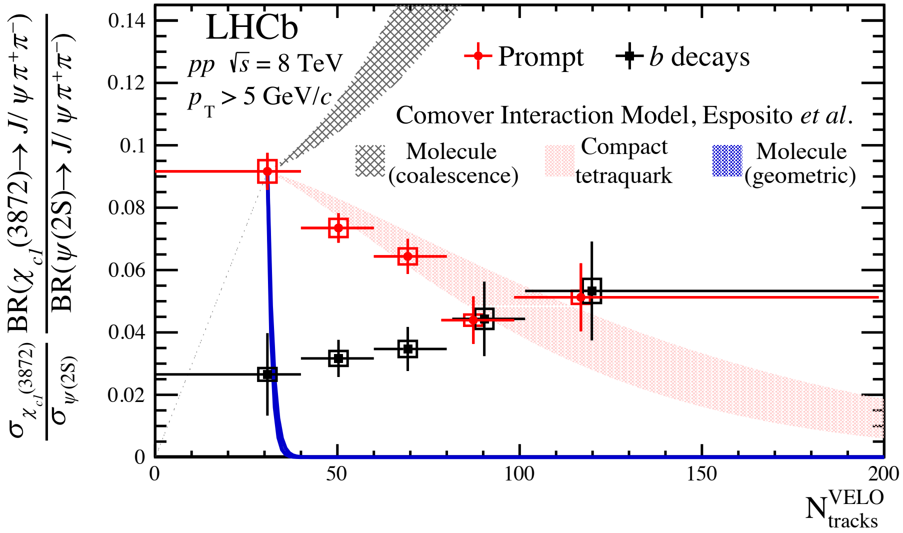

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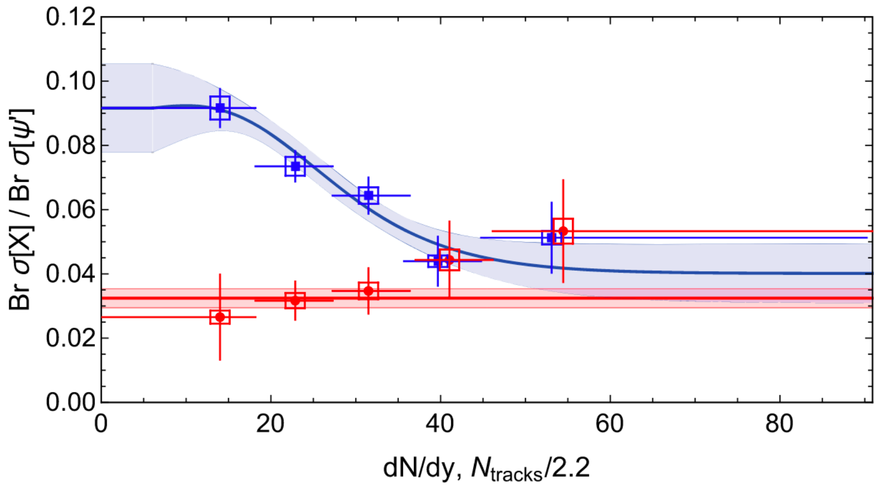

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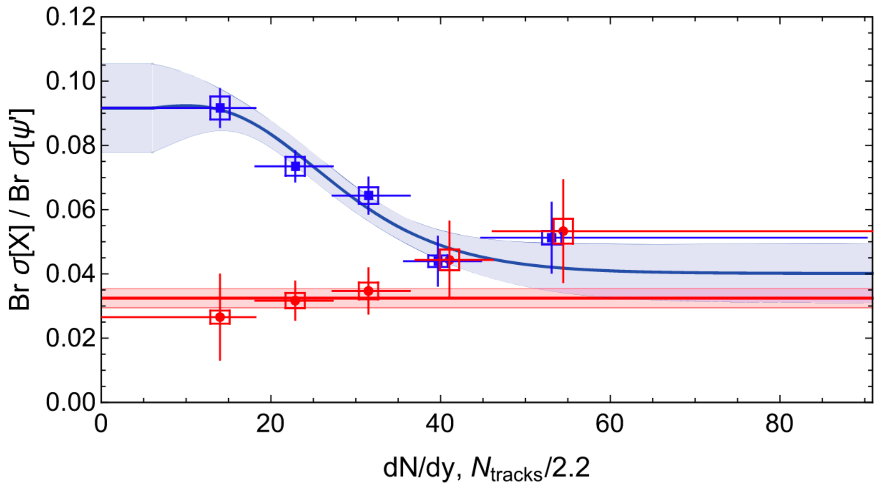

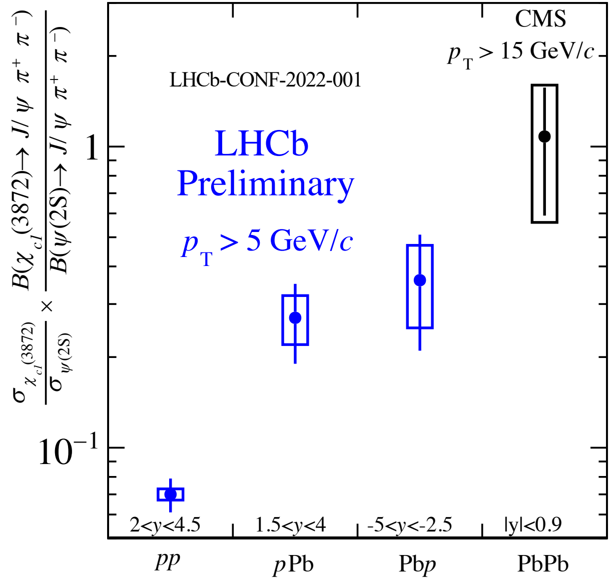

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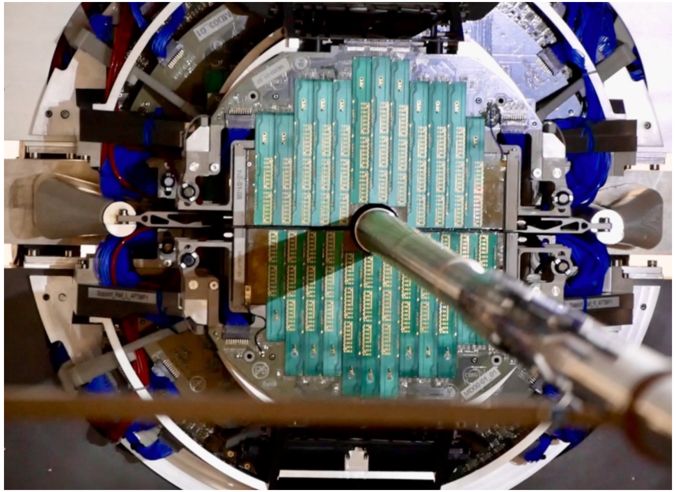
-Ratio could be enhanced in pPb, PbPb
-Significant disagreement between various models on tetraquark vs molecule enhancement

Significant effort from theory and experiment needed for progress

Forward upgrades at the LHC

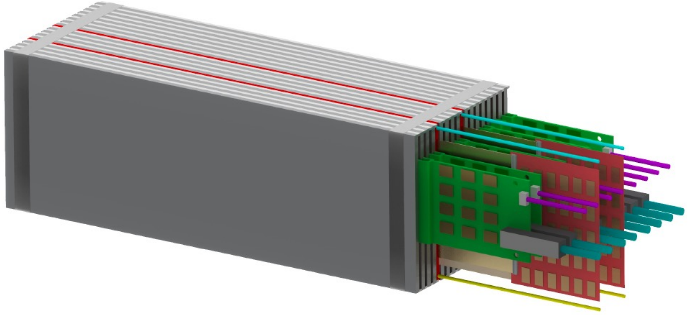
ALICE MFT, Run 3



- Precision vertexing in front of absorber
- Separate HF muons from charm vs bottom, prompt vs non-prompt J/ψ

LHCC-2013-014

ALICE FoCal, Run 4

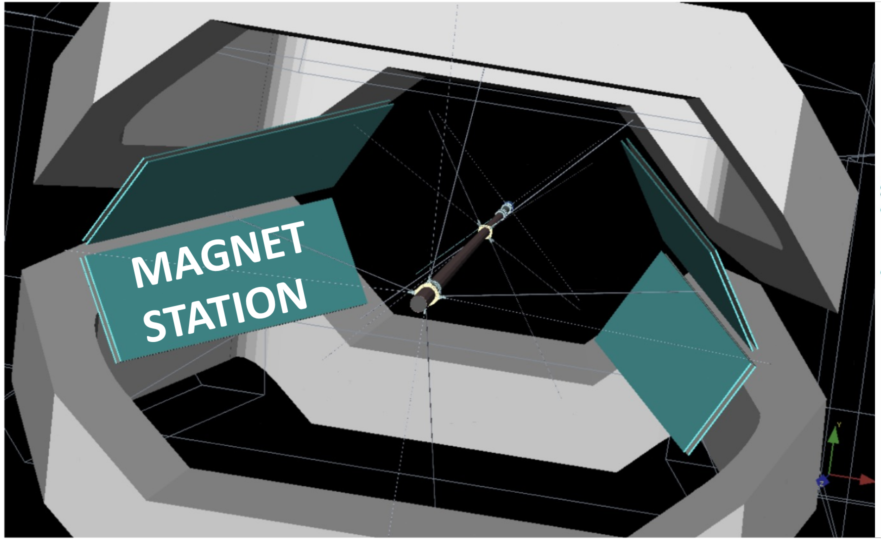


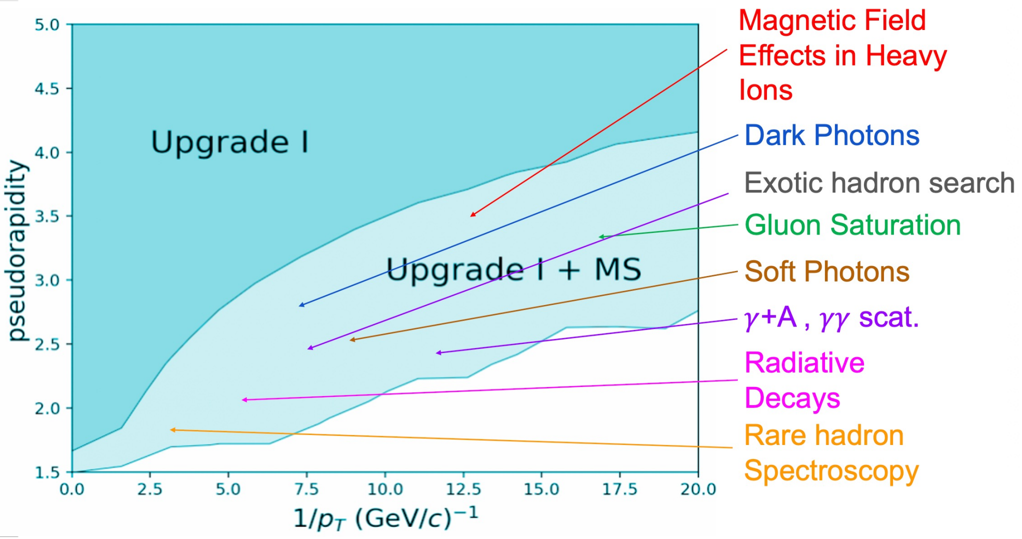
- Combination EM/hadron calorimeter at forward range $3.4 < \eta < 5.8$
- Access direct photons to probe gluon distribution without final state effects

LHCC-2020-009

See also: Anthony Timmins Fri 17:20

LHCb upgrade 1(b) – Magnet Station

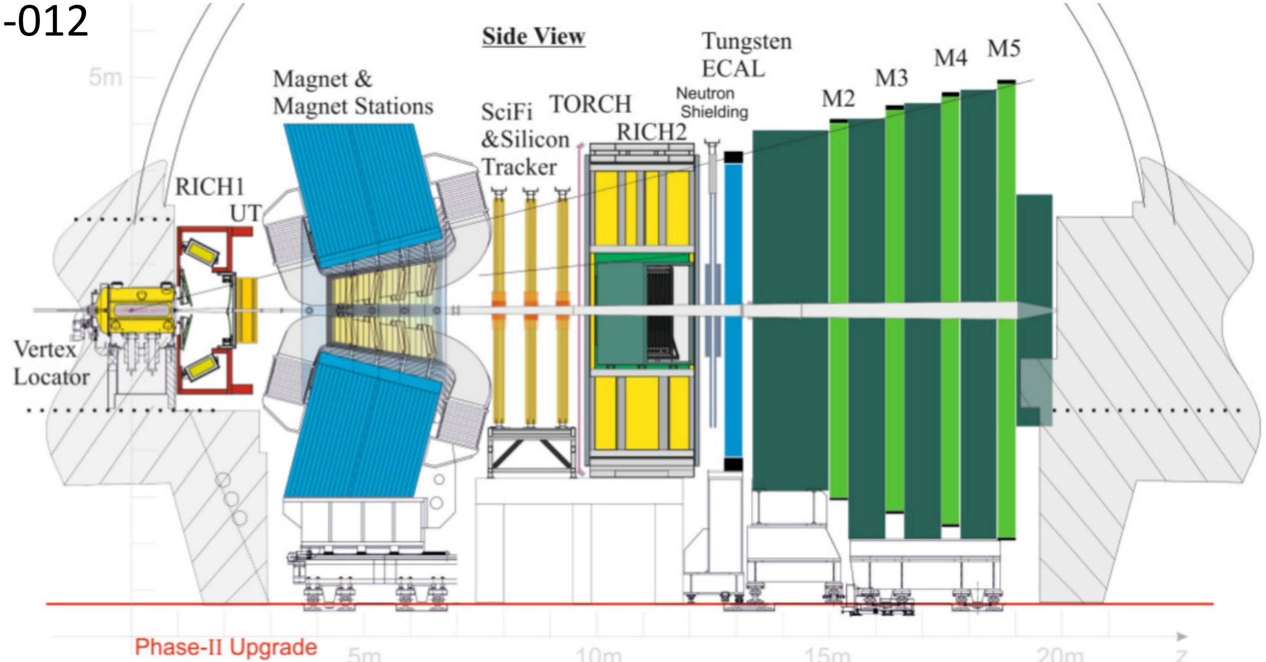




- Scintillating bar tracker for very soft particles at LHCb, to be installed for Run 4 , with US leadership
- Expands soft physics channels previously unreachable at the LHC.
- Allows access to very low x, Q^2 region where gluon saturation may exist in nuclei and isolated protons.

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

- **Heavy quarks are extremely versatile for probing non-perturbative QCD:**

- Production is sensitive to the 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

- Heavy hadron chemistry sensitive to final state effects in hadron collisions
  - Can be disentangled from PDF using multiple probes (HQ vs gamma vs PID hadrons)

- 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

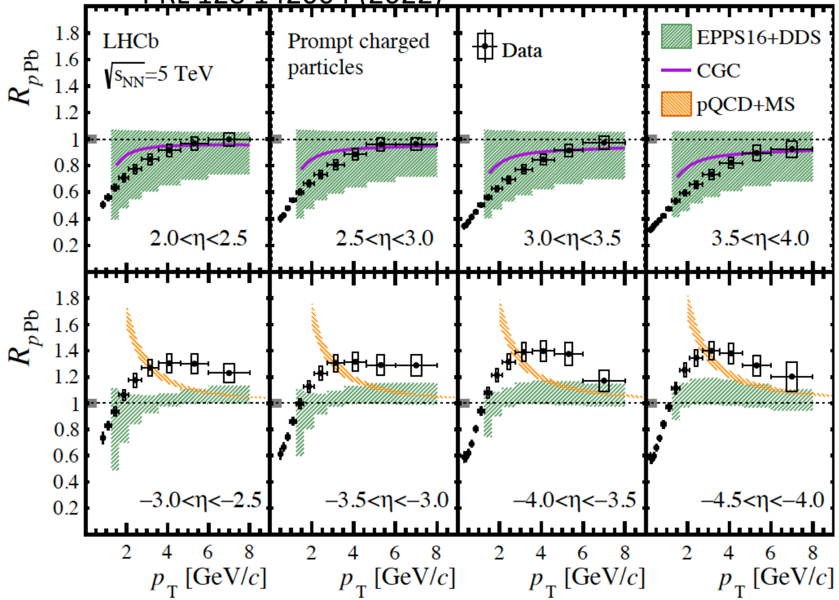
Los Alamos is supported by the DOE/Office of Science/Nuclear Physics,

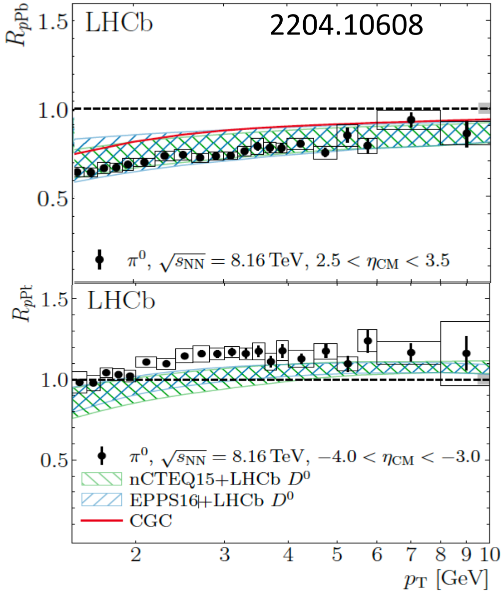
and DOE Early Career Awards program


CONSTRAINING PDFS
HEAVY QUARKS
FORWARD RAPIDITY

Challenging nPDFs – light flavor

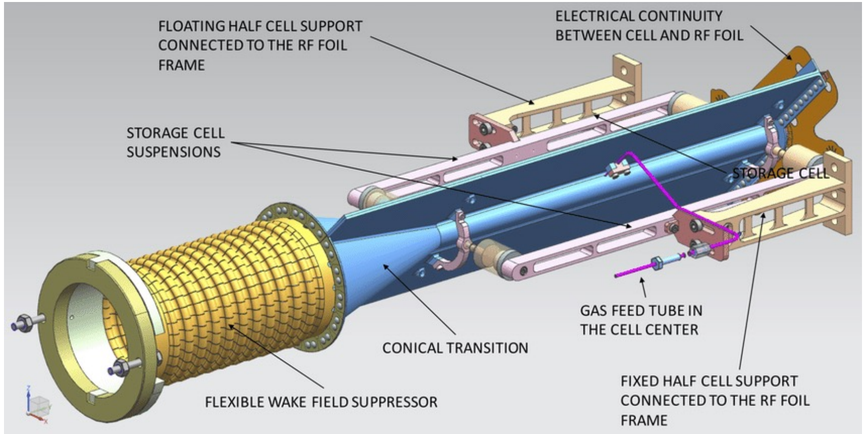
PRL 128 142004 (2022)





- 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

Example SMOG2 pAr at 115 GeV for one year

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D^0	yield	280 M
Λ_c	yield	2.8 M
Ψ'	yield	280 k
$\Upsilon(1S)$	yield	24 k
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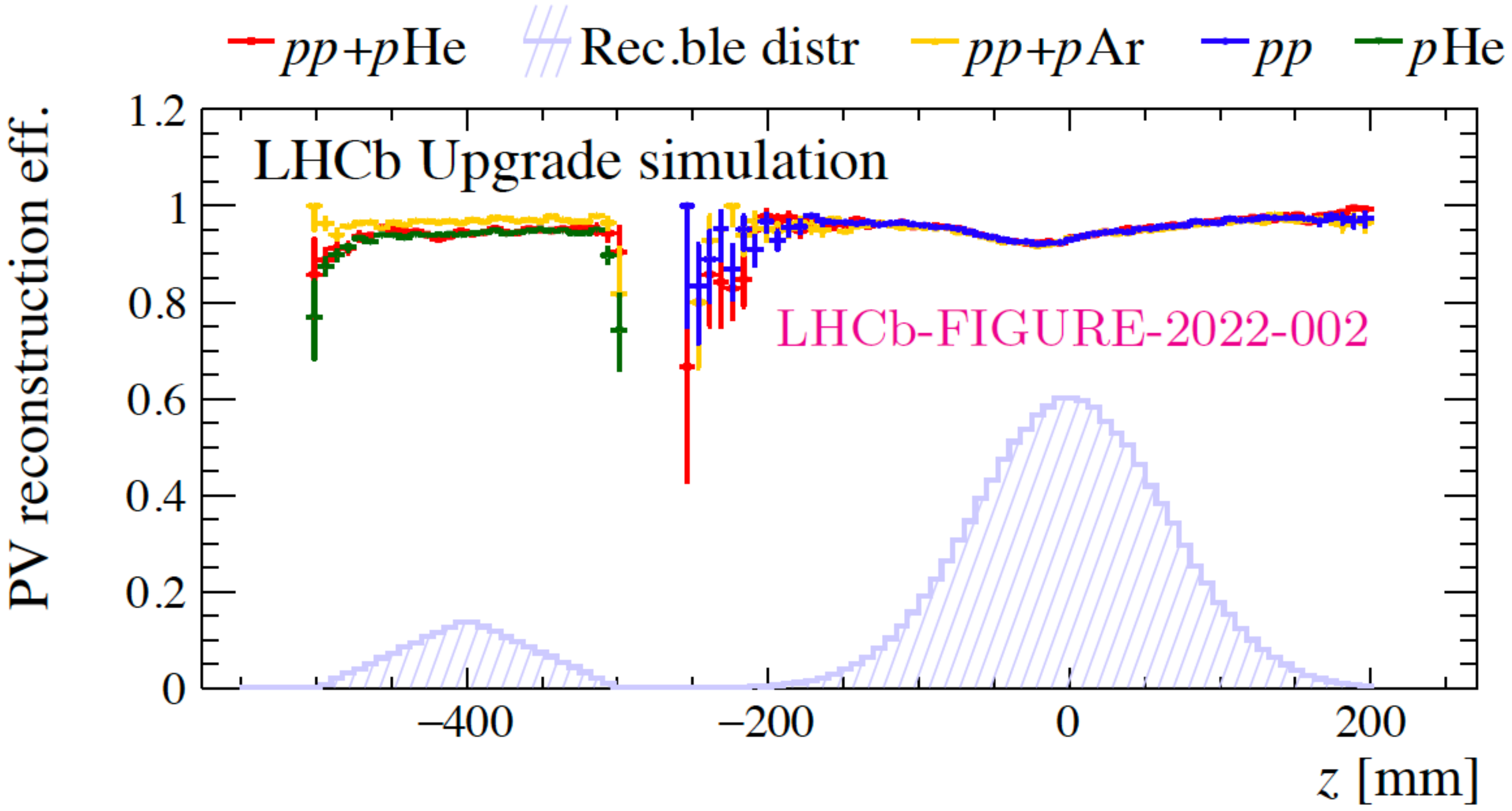
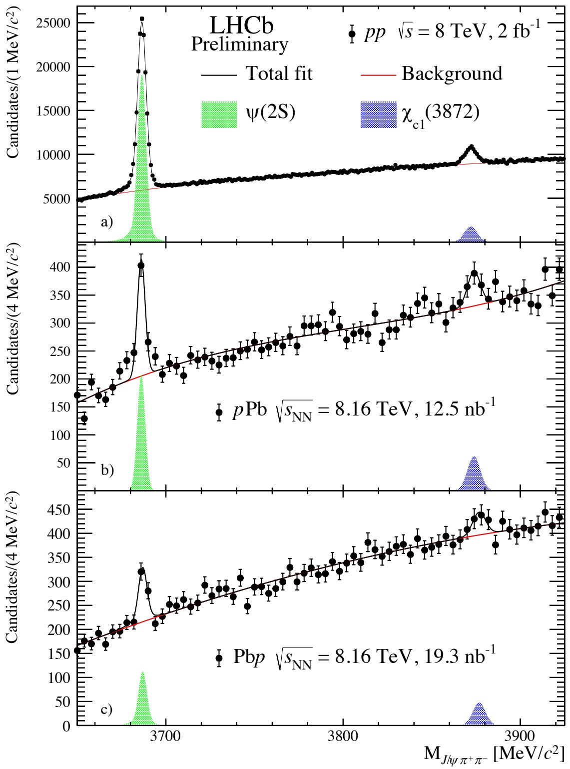
- Upgraded SMOG 2 system at LHCb allows greatly increased rates of beam+gas collisions at LHCb
- Variable target gases – allows hadronic environment to be adjusted (H, He, …, Xe)
- Access to exotic states near RHIC energies
- Can potentially run concurrent with proton+proton collisions – large data sets

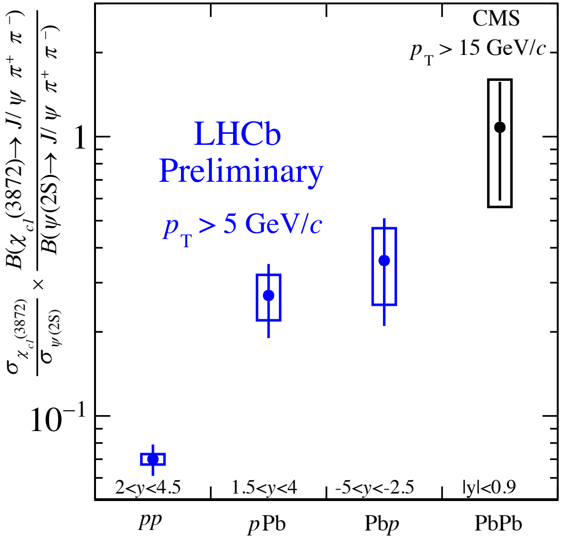


pp+pHe
Rec.ble distr
pp+pAr
pp
pHe
PV reconstruction eff.
LHCb Upgrade simulation
LHCb-FIGURE-2022-002
1.2
1
0.8
0.6
0.4
0.2
0
−400
−200
0
200
z [mm]

Exotic X(3872)

LHCb-CONF-2022-001



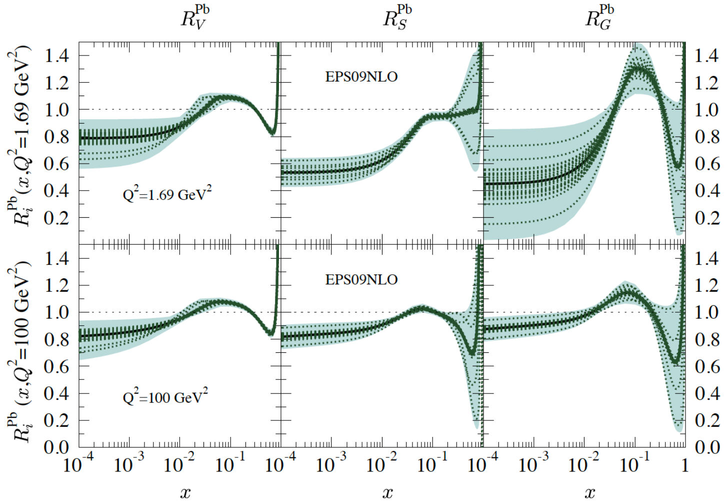


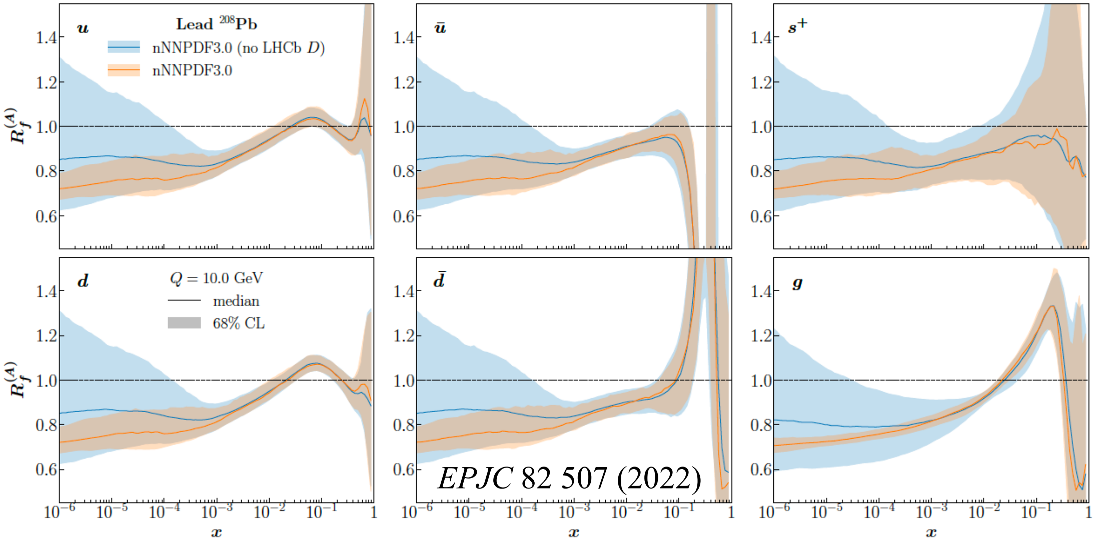
- Comparison between X(3872) and ψ(2S) suggests ***something different*** may be happening to exotic vs conventional hadrons in medium
- Initial state effects (eg shadowing) should largely cancel in ratio
- Enhancing effects start to out compete breakup?

Prompt X(3872)/ ψ(2S) = 0.27 ± 0.08 ± 0.05 in forward pPb

Prompt X(3872)/ ψ(2S) = 0.36 ± 0.15 ± 0.11 in backward pPb

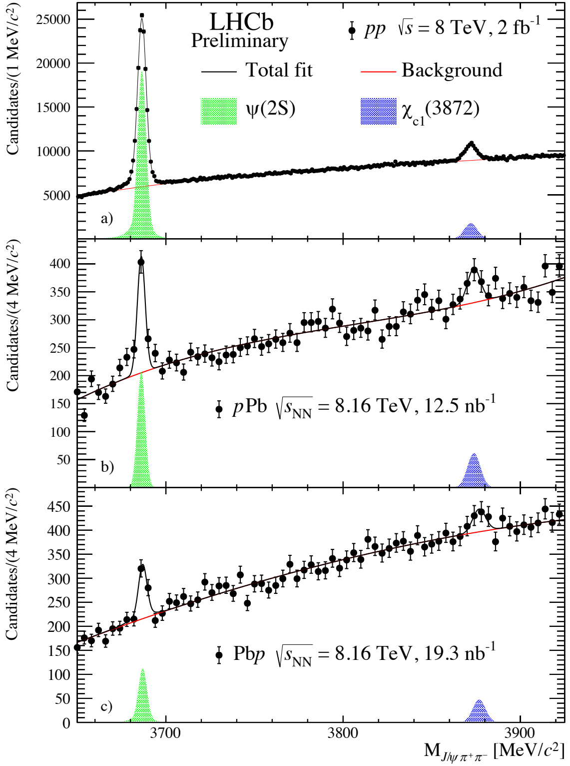
Falls between pp (~0.1) and PbPb (~1.0)

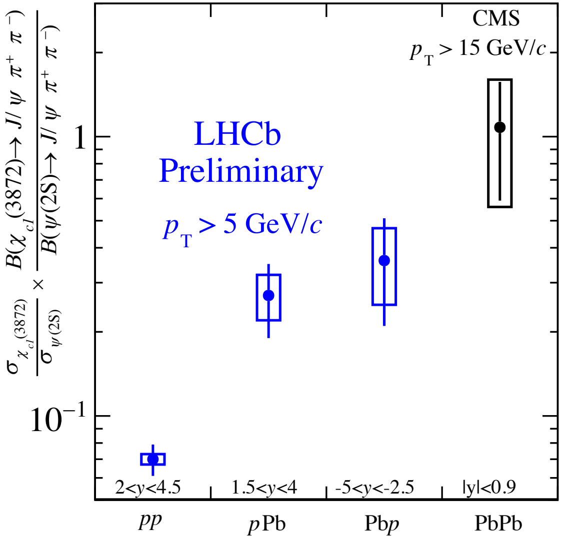

R_V^{Pb}
R_S^{Pb}
R_G^{Pb}
EPS09NLO
Q^2=1.69 GeV^2
Q^2=100 GeV^2
$R_i^{Pb}(x,Q^2=1.69\ GeV^2)$
$R_i^{Pb}(x,Q^2=100\ GeV^2)$
x


Lead ^{208}Pb
nNNPDF3.0 (no LHCb D)
nNNPDF3.0
Q = 10.0 GeV
median
68% CL
u
$\bar{u}$
s^+
d
$\bar{d}$
g
$R_f^{(A)}$
x
EPJC 82 507 (2022)

Exotic X(3872)

LHCb-CONF-2022-001





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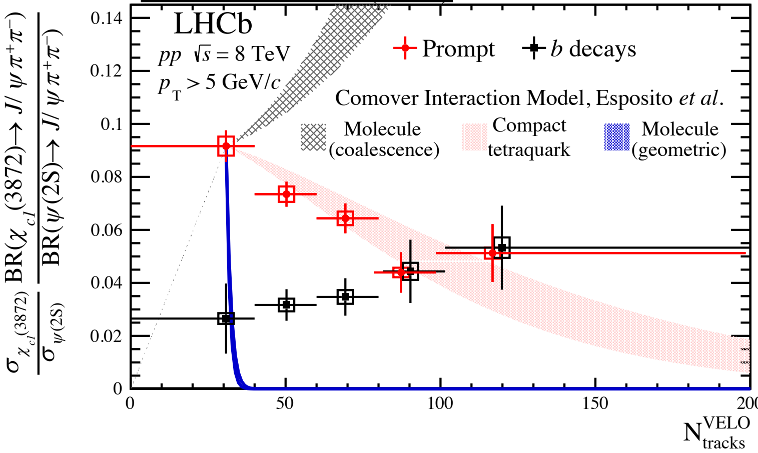
X(3872)/ψ(2S) vs multiplicity

PRL 126 092001 (2021)



Geometric comover model:

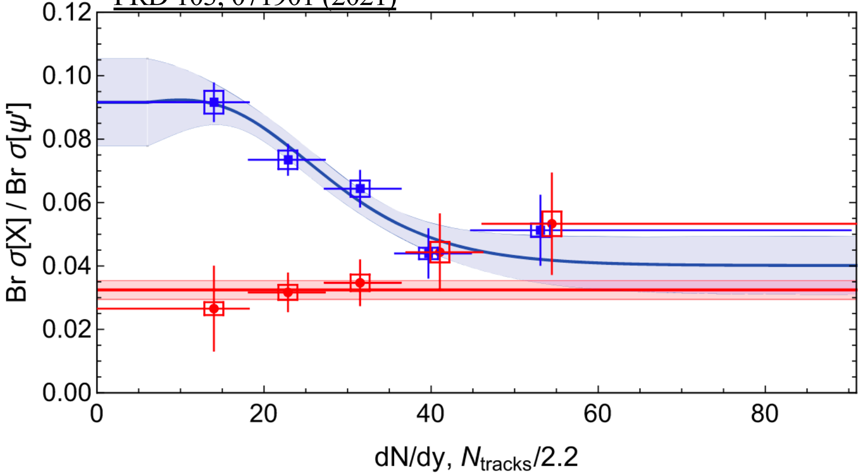
$$\langle v\sigma\rangle_{\mathcal{Q}} = \sigma_{\mathcal{Q}}^{\mathrm{geo}} \left\langle \left(1 - \frac{E_{\mathcal{Q}}^{\mathrm{thr}}}{E_c}\right)^n \right\rangle$$

Molecular X(3872) immediately broken up

Compact X(3872) gradually dissociated

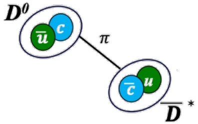
Data is consistent with **compact tetraquark** model.

PRD 103, 071901 (2021)



Constituent comover model:

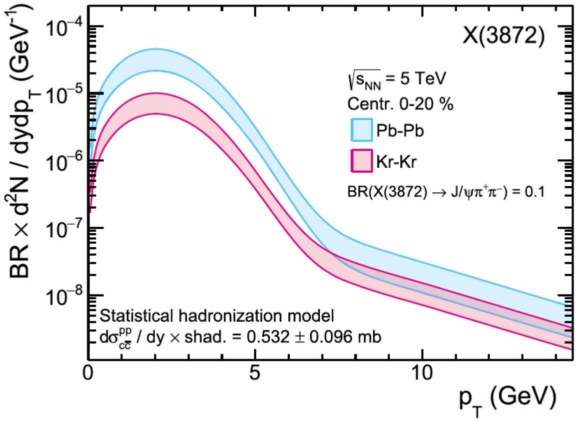
$$\sigma^{\mathrm{incl}}[\pi X] \approx \frac{1}{2}(\sigma[\pi D^0] + \sigma[\pi \bar{D}^0] + \sigma[\pi D^{*0}] + \sigma[\pi \bar{D}^{*0}])$$



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

X(3872) in PbPb

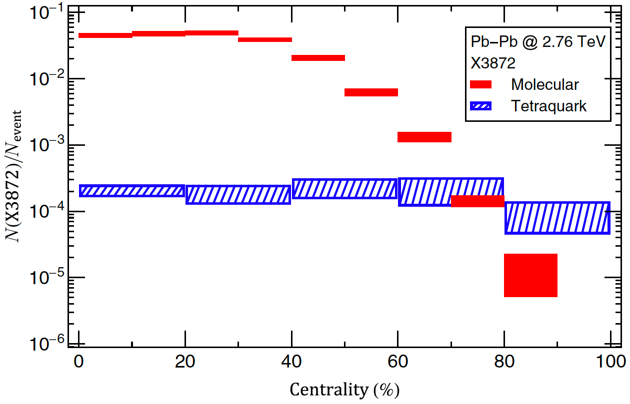
PLB 797 (2019) 134836



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

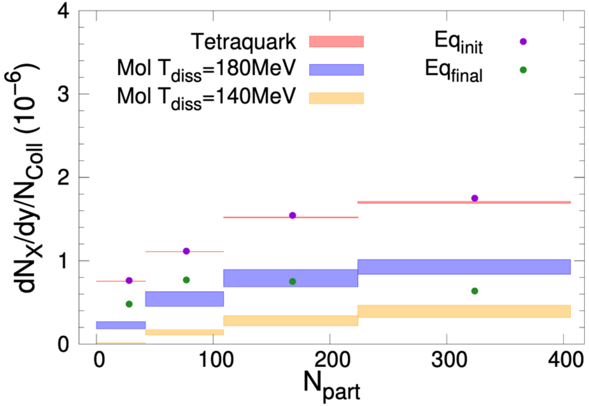
Yield reaches up to ~1% of J/ψ yield

PRL 126 012301 (2021)

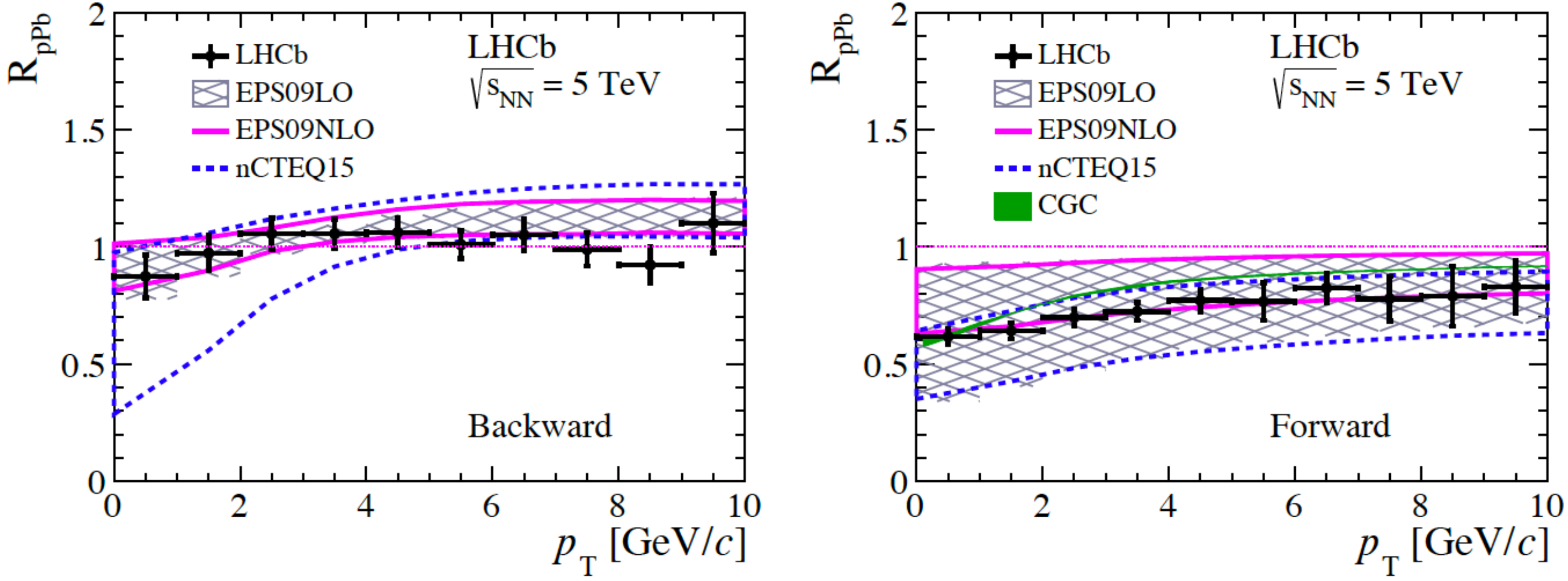


AMPT model:
difference in molecule vs diquark-diquark coalescence gives dramatically different yields and centrality dependence:
$N_{molecule} > N_{tetraquark}$

EPJA 57 122 (2021)



Transport calculation:
molecules have larger reaction rate, formed later in fireball evolution
$N_{tetraquark} > N_{molecule}$



R_pPb
LHCb
EPS09LO
EPS09NLO
nCTEQ15
LHCb
√s_NN = 5 TeV
Backward
p_T [GeV/c]
R_pPb
LHCb
EPS09LO
EPS09NLO
nCTEQ15
CGC
LHCb
√s_NN = 5 TeV
Forward
p_T [GeV/c]