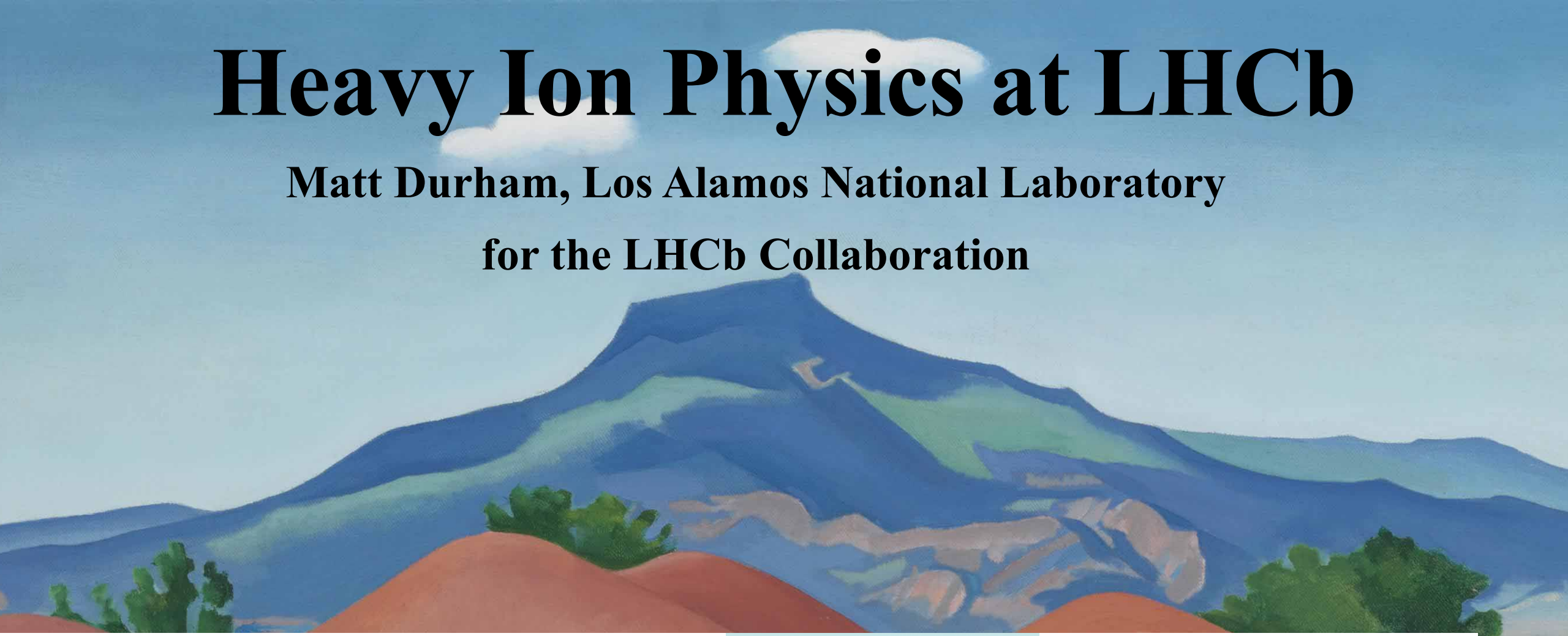
# Heavy Ion Physics at LHCb

**Matt Durham, Los Alamos National Laboratory**

**for the LHCb Collaboration**



XLIX International Symposium on Multiparticle Dynamics

International Symposium on Multiparticle Dynamics

**Santa Fe, NM 9-13 September 2019**

LHCb

Los Alamos NATIONAL LABORATORY EST. 1943

# Outline

- Brief overview of LHCb physics program
- The LHCb Detector
- Constraining the nuclear PDF with charm in pPb Collisions
- Understanding bottomonium suppression in pPb Collisions
- A unique capability: accessing unexplored phase space in fixed target mode
- Upgrade Plan
- Conclusions

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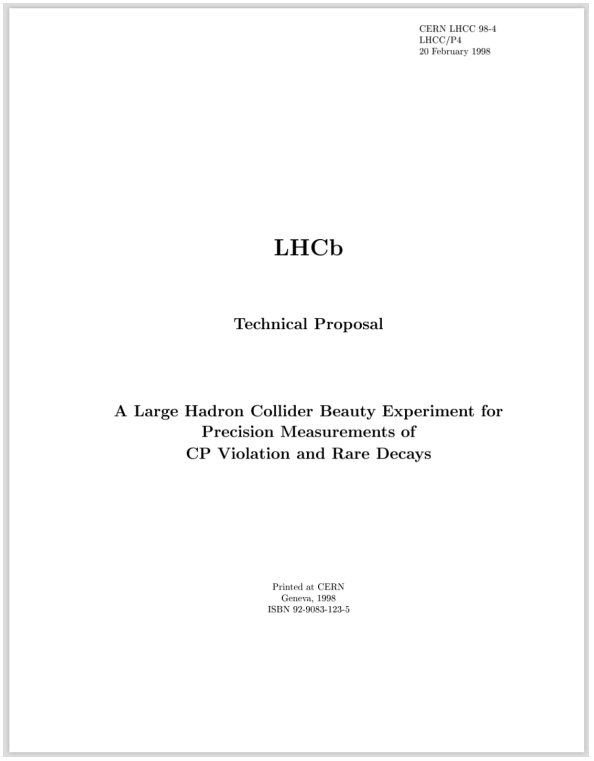
# LHCb Physics Program



CERN LHCC 98-4
LHCC/P4
20 February 1998

LHCb

Technical Proposal

A Large Hadron Collider Beauty Experiment for
Precision Measurements of
CP Violation and Rare Decays

Printed at CERN
Geneva, 1998
ISBN 92-9083-123-5

1998 Technical Proposal:
“CP Violation and Rare Decays”

# LHCb Physics Program

Phys. Rev. Lett. 122 211803 (2019)

PHYSICAL REVIEW LETTERS **122,** 211803 (2019)

Editors' Suggestion | Featured in Physics

## Observation of *CP* Violation in Charm Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 21 March 2019; revised manuscript received 2 May 2019; published 29 May 2019)

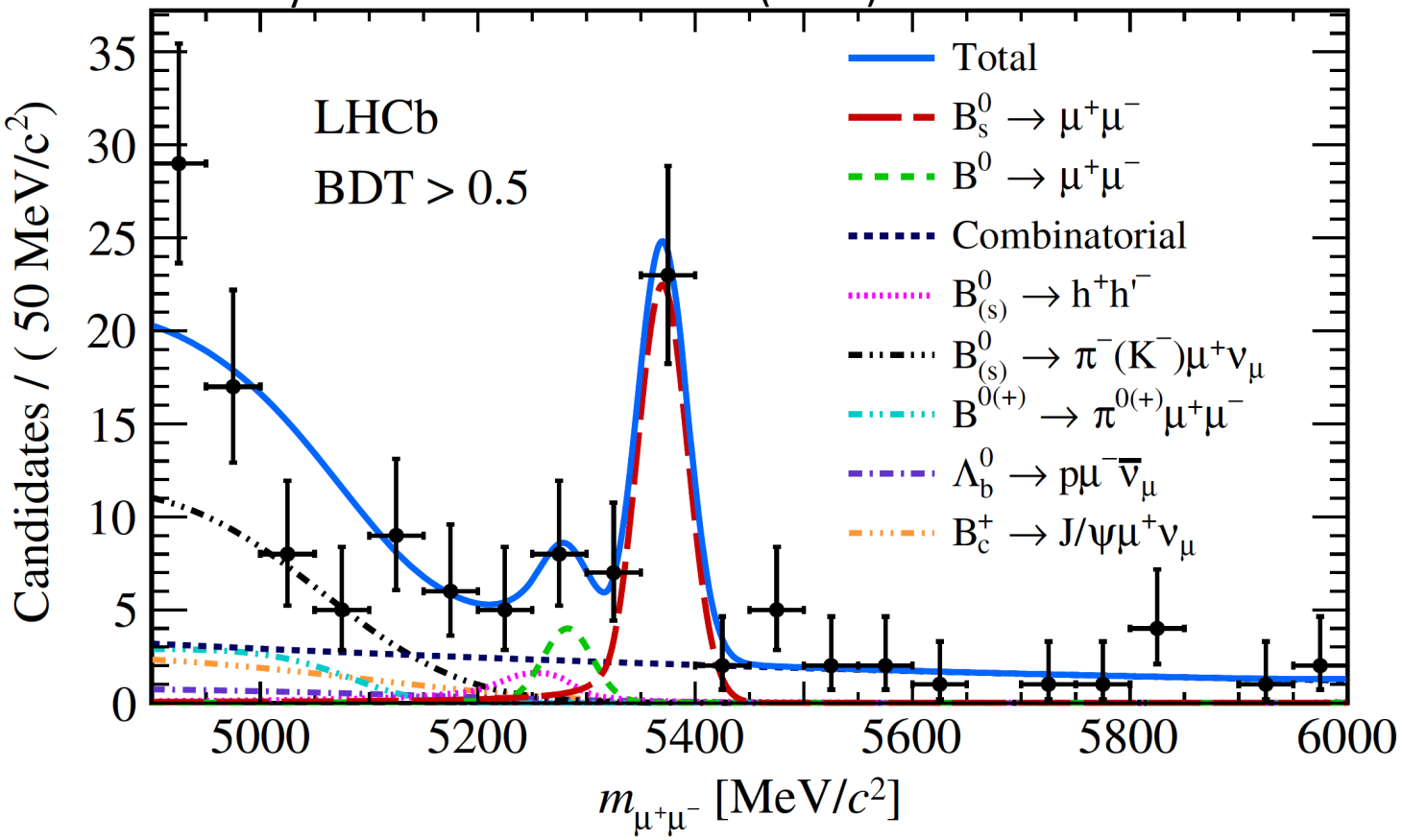
A search for charge-parity ($CP$) violation in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is reported, using $pp$ collision data corresponding to an integrated luminosity of 5.9 fb$^{-1}$ collected at a center-of-mass energy of 13 TeV with the LHCb detector. The flavor of the charm meson is inferred from the charge of the pion in $D^*(2010)^+ \to D^0\pi^+$ decays or from the charge of the muon in $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ decays. The difference between the $CP$ asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is measured to be $\Delta A_{CP} = [-18.2 \pm 3.2(\text{stat}) \pm 0.9(\text{syst})] \times 10^{-4}$ for $\pi$-tagged and $\Delta A_{CP} = [-9 \pm 8(\text{stat}) \pm 5(\text{syst})] \times 10^{-4}$ for $\mu$-tagged $D^0$ mesons. Combining these with previous LHCb results leads to $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$, where the uncertainty includes both statistical and systematic contributions. The measured value differs from zero by more than 5 standard deviations. This is the first observation of $CP$ violation in the decay of charm hadrons.

DOI: 10.1103/PhysRevLett.122.211803

- CKM Mechanism and CP violation
  - First observation of CP violation in the charm sector

# LHCb Physics Program

Phys. Rev. Lett. 118 191801 (2017)



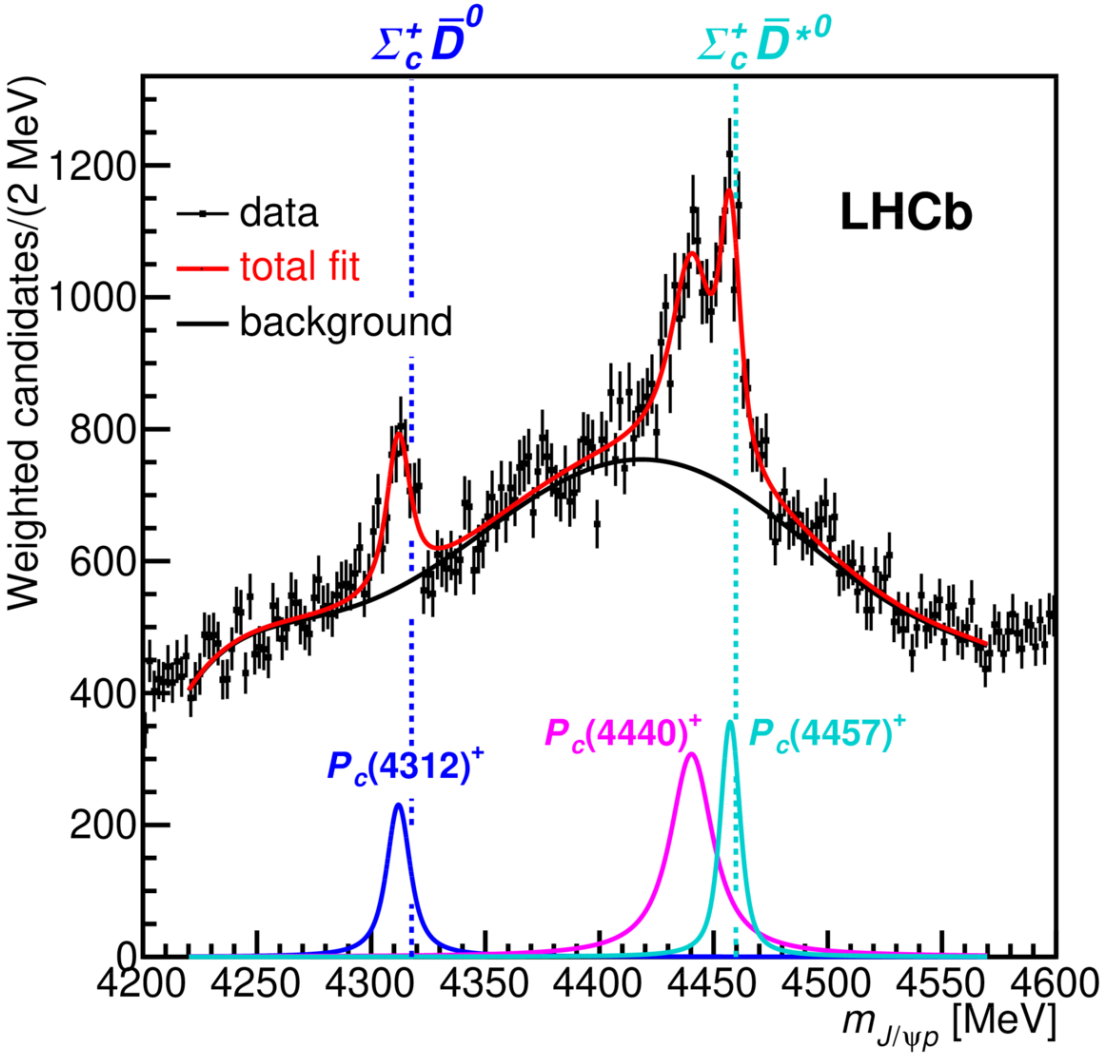

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

- CKM Mechanism and CP violation
  - First observation of CP violation in the charm sector

Rare decays
- $B_s \to \mu\mu$, $b \to s\,\ell^+\ell^-$

# LHCb Physics Program

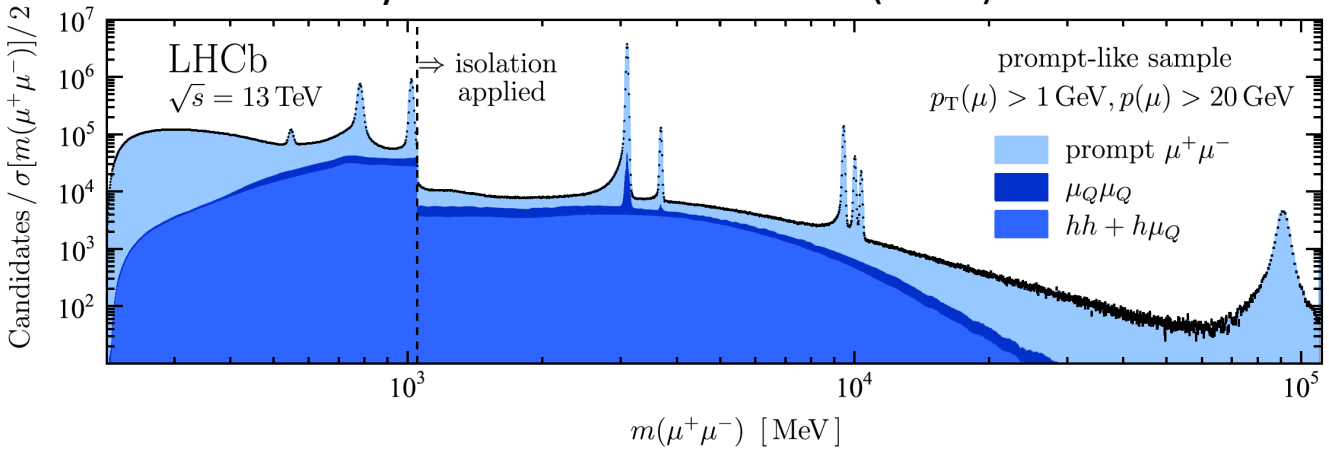
Phys. Rev. Lett. 122 222001 (2019)

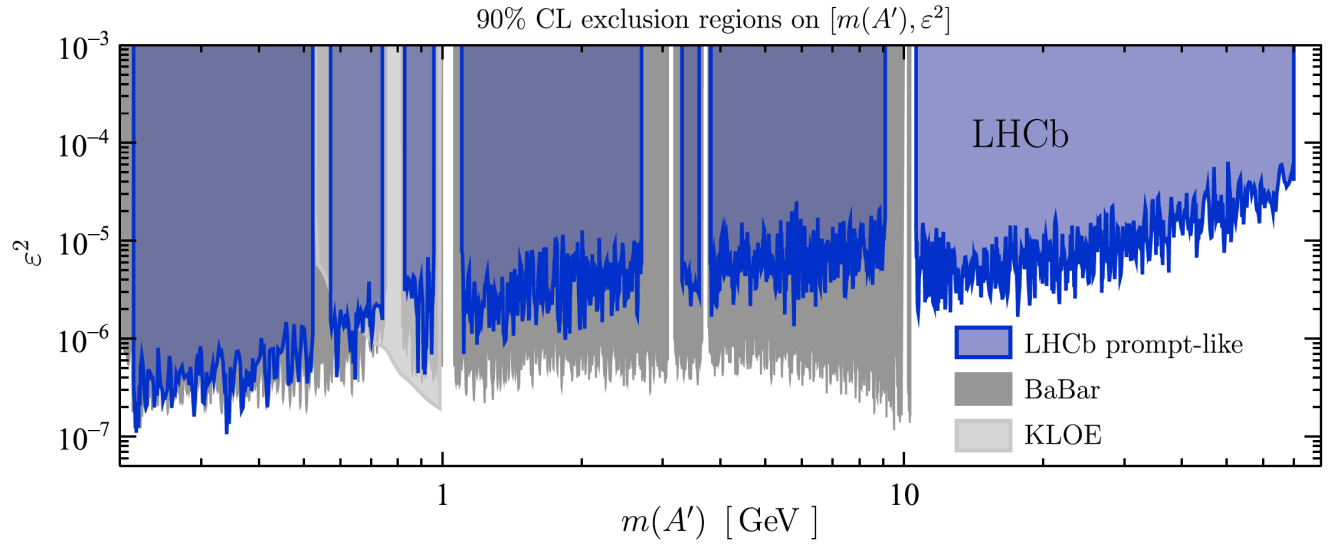



- CKM Mechanism and CP violation
  - First observation of CP violation in the charm sector
- Rare decays
  - $B_s \to \mu\mu$, $b \to s\,\ell^+\ell^-$
- Spectroscopy
  - Observation of multiple pentaquarks

# LHCb Physics Program

Phys. Rev. Lett. 120 061801 (2018)

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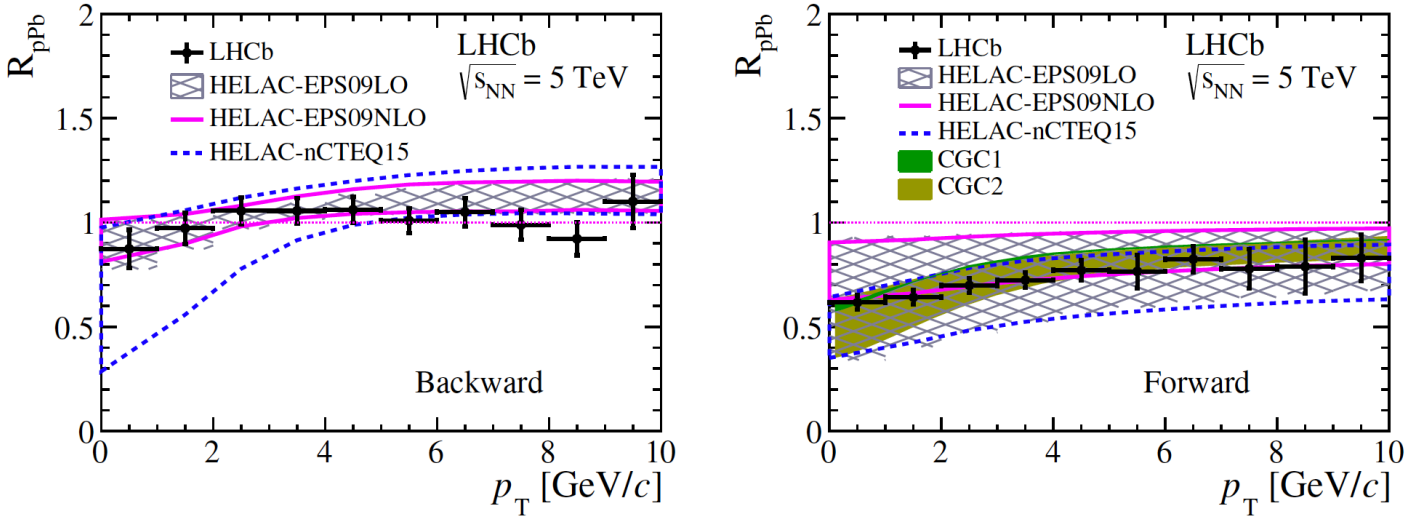
- EW, QCD, direct searches for BSM particles
  - Limits on $A' \to \mu\mu$ decays

# LHCb Physics Program

JHEP10 (2017) 090

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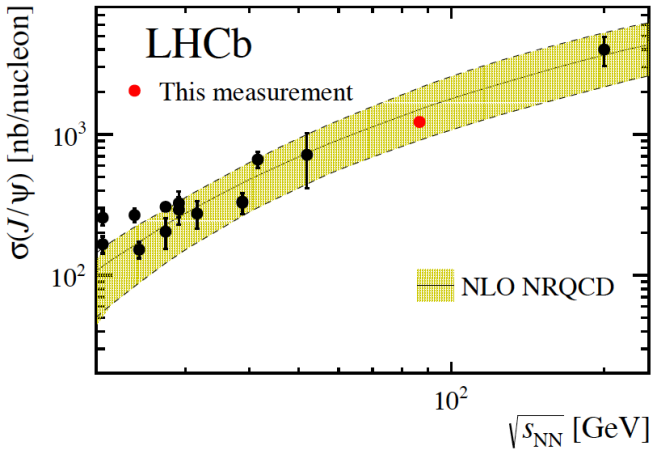
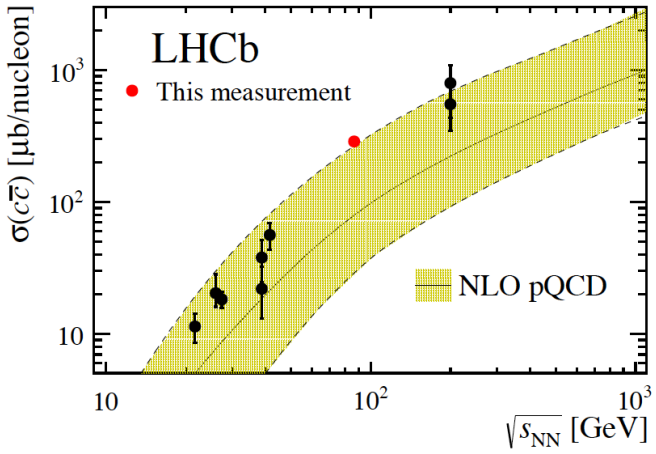
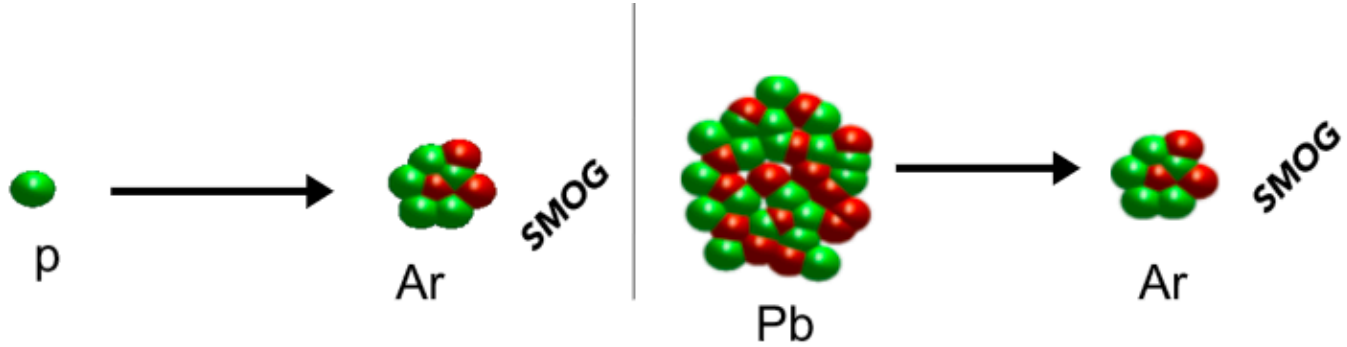
- Heavy ion collisions
  - Heavy flavor in pPb, PbPb collisions

# LHCb Physics Program

Phys. Rev. Lett. 122, 132002 (2019)

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  - pHe, pNe, pAr, PbNe, PbAr accessible by injecting gas into beampipe

# LHCb Physics Program

**LHCb is a *general purpose* detector covering forward rapidity**

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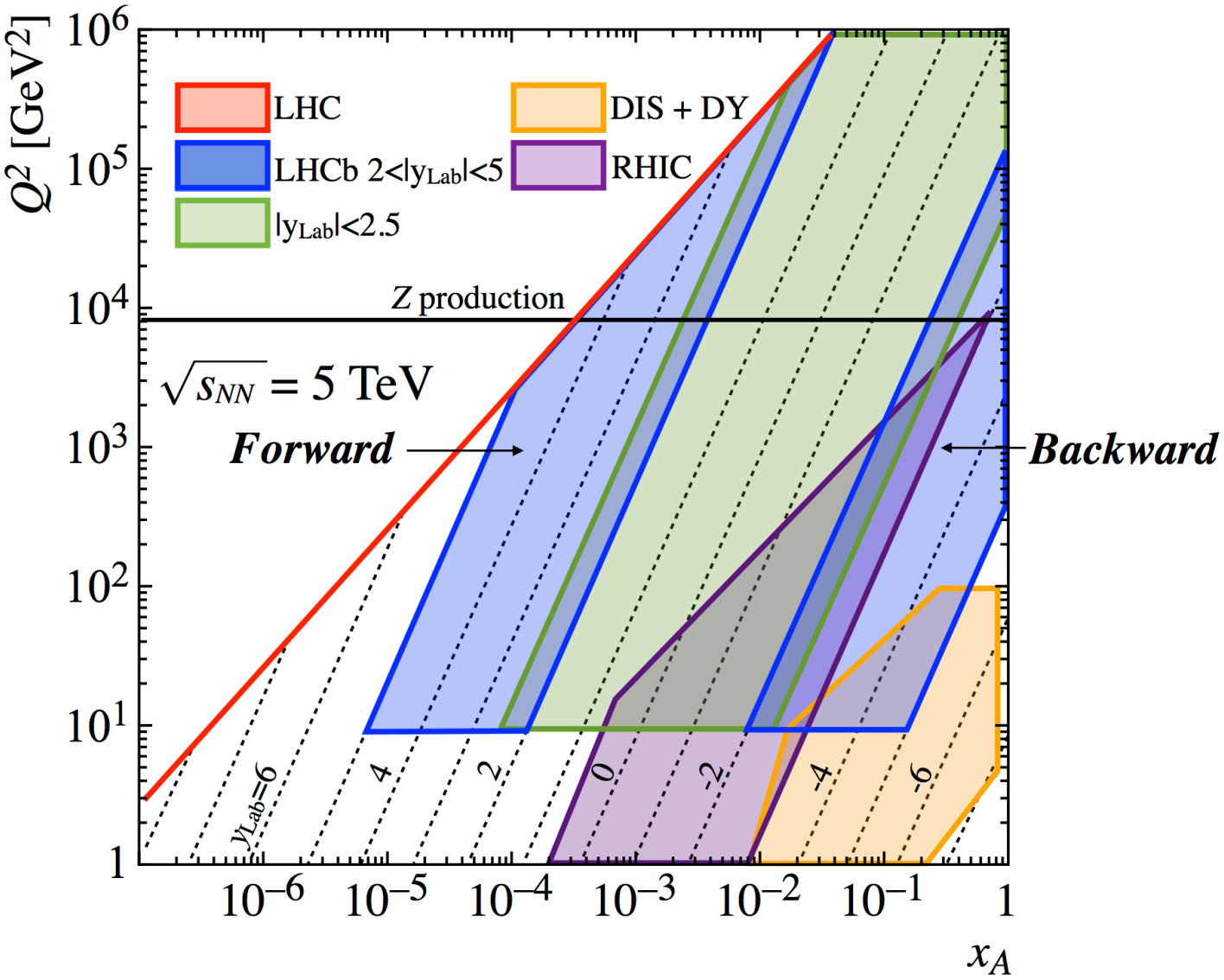


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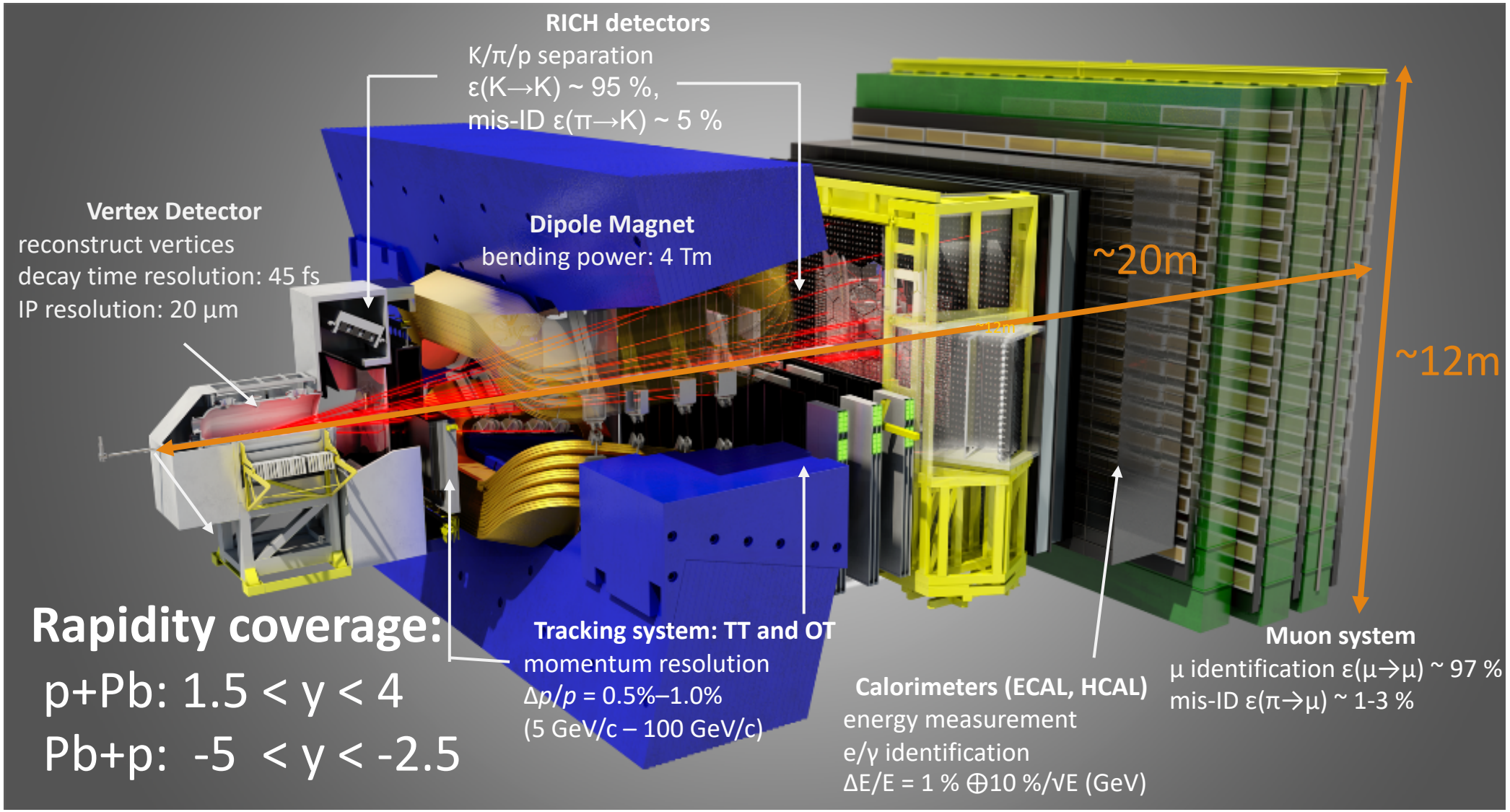
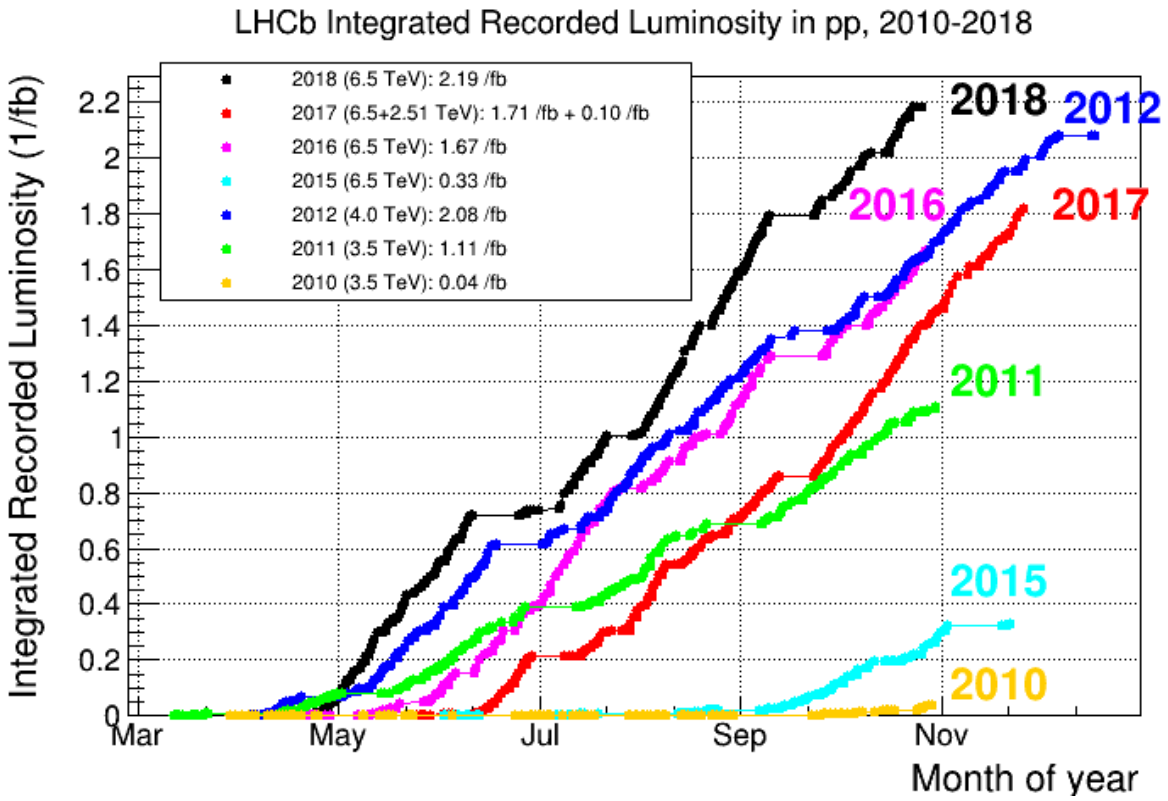
# The LHCb Detector

JINST 3 (2008) S08005
Int. J. Mod. Phys. A 30, 1530022 (2015)

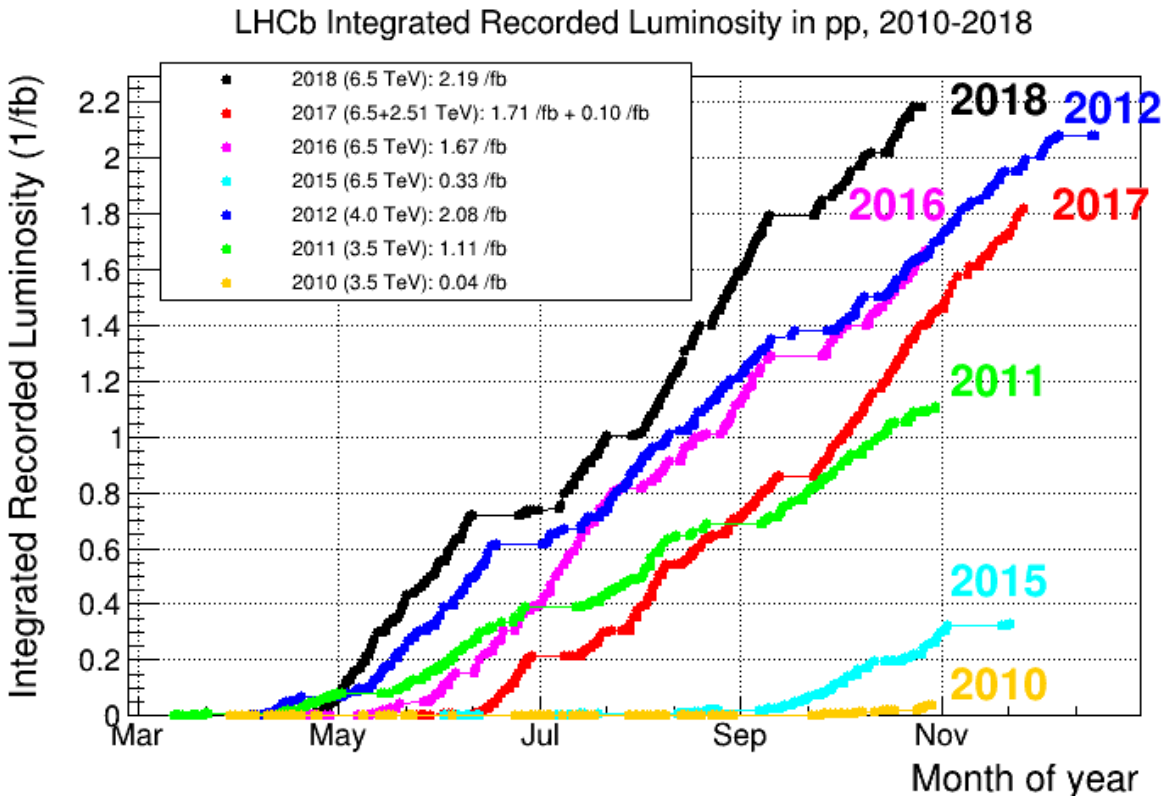



**Tracking detector granularity designed for *pp* collisions is not optimal for measurements in central PbPb collisions → upgrade ongoing!**

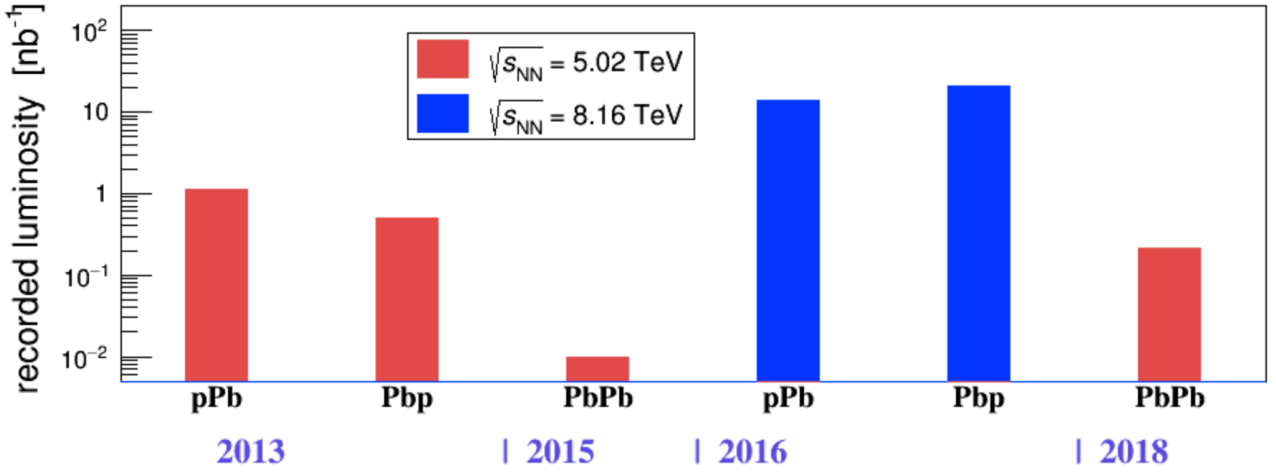
# Data Sets


LHCb Integrated Recorded Luminosity in pp, 2010-2018
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
2018
2012
2016
2017
2011
2015
2010
Integrated Recorded Luminosity (1/fb)
Mar
May
Jul
Sep
Nov
Month of year

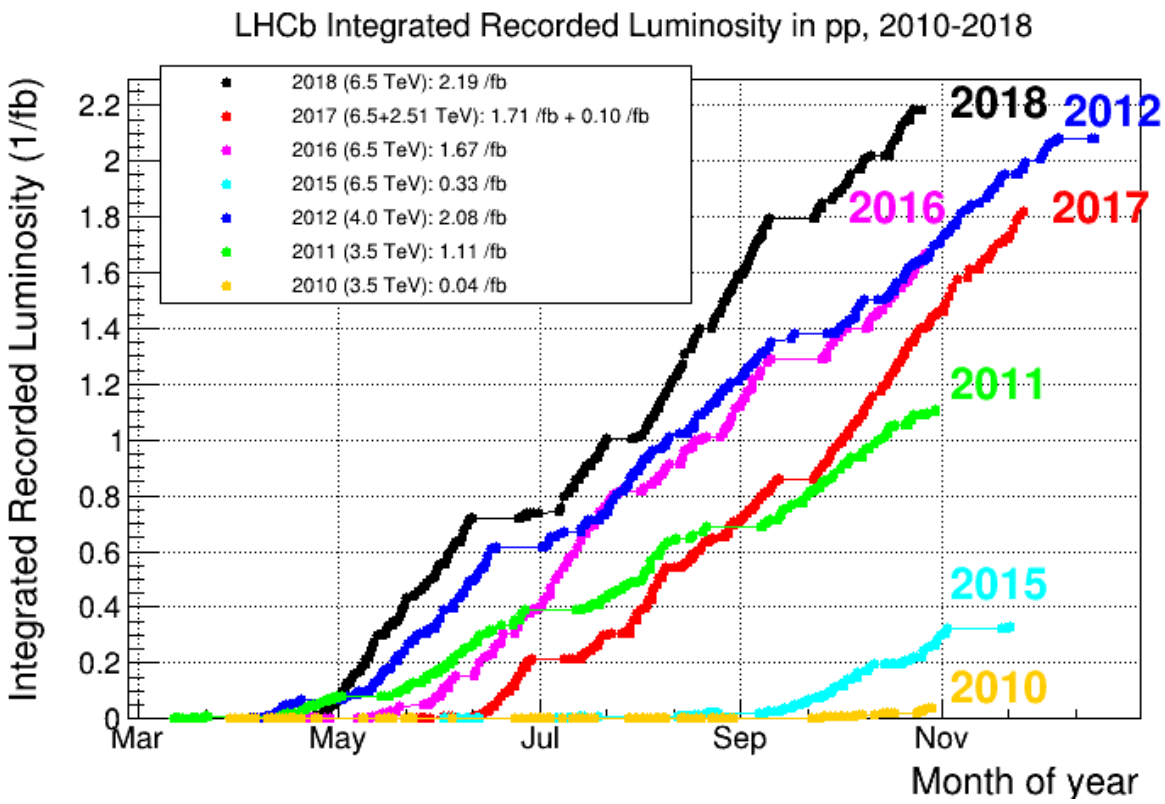
# Data Sets




Collider Mode – Heavy Ions



# Data Sets

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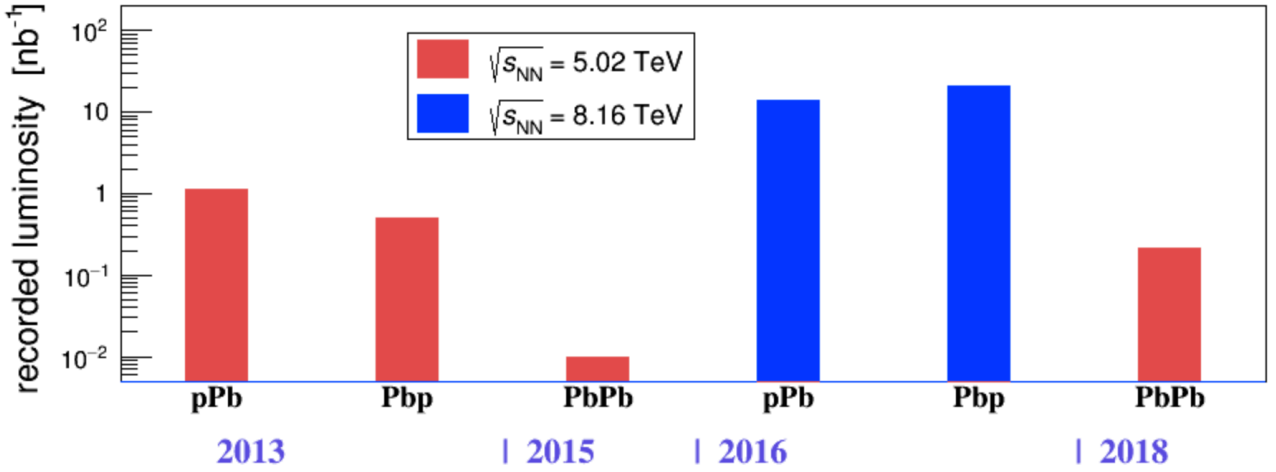
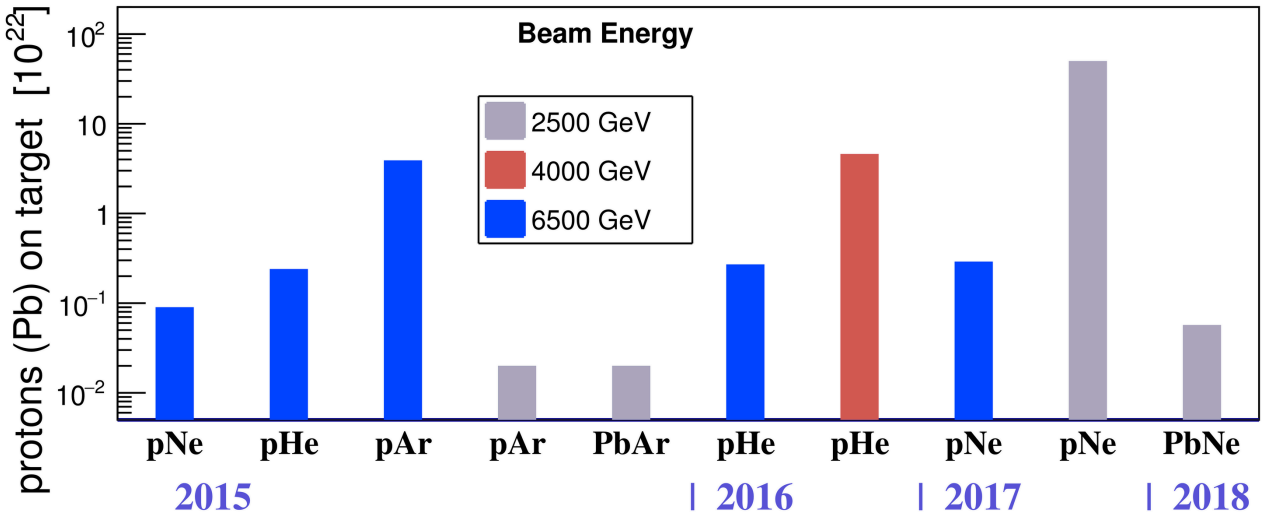
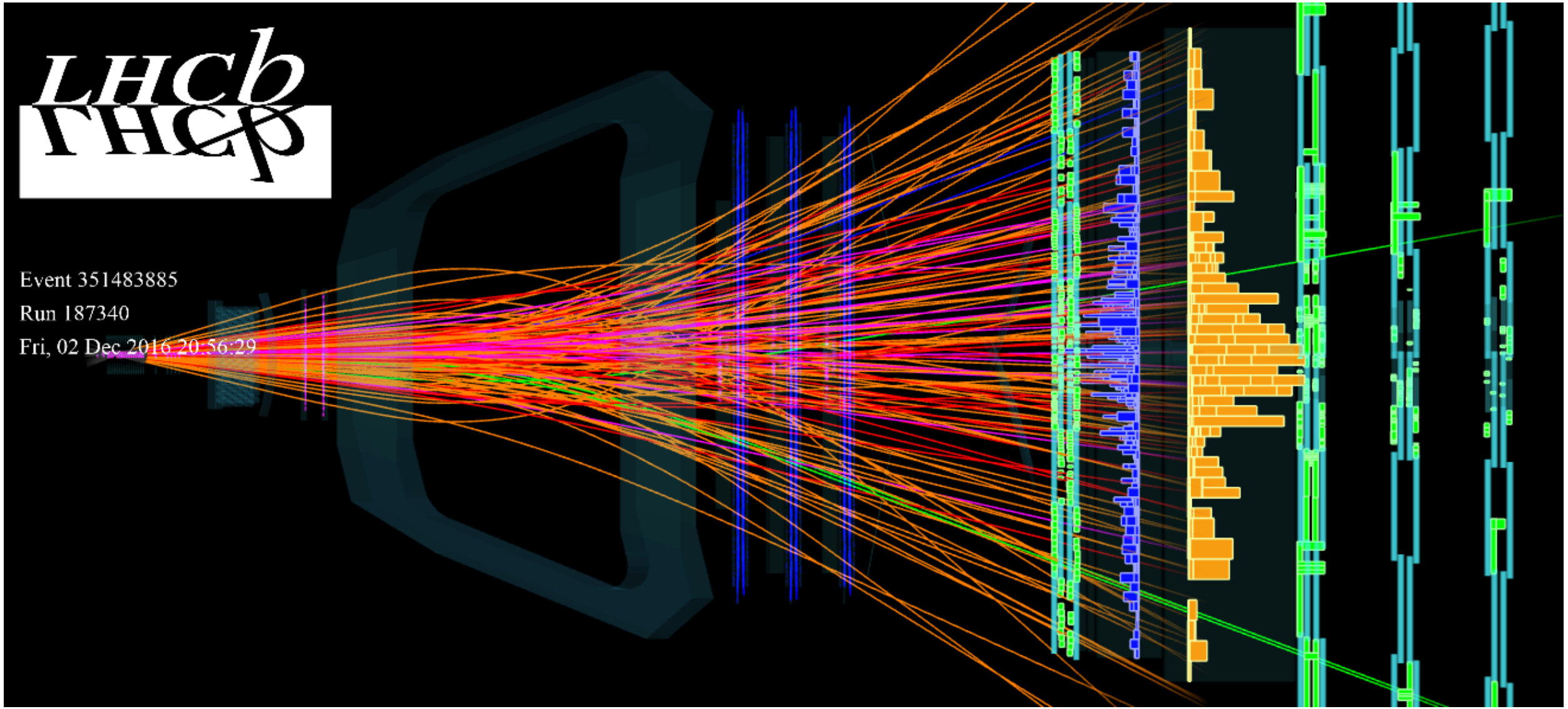



Fixed Target Mode (SMOG)




LHCb
Event 351483885
Run 187340
Fri, 02 Dec 2016 20:56:29

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# Heavy Quarks in Nuclear Collisions

$$d\sigma(Q^2, \sqrt{s})_{pA\to a+X} = \sum_{i,j=q,\bar{q},g} f_i^p(x_1, Q^2) \otimes A f_i^A(x_2, Q^2) \otimes d\hat{\sigma}(Q^2, x_1, x_2)_{i,j\to a+X}$$

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**Measurable at experiments**

**Calculable by pQCD**

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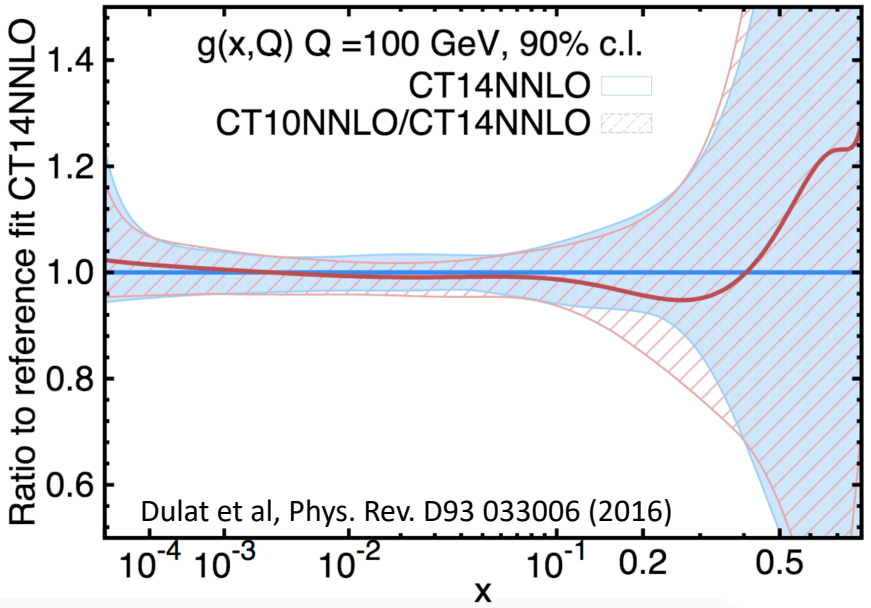
**Measurable at experiments**

**Proton PDF: Fairly well constrained HERA and other data**

**Calculable by pQCD**



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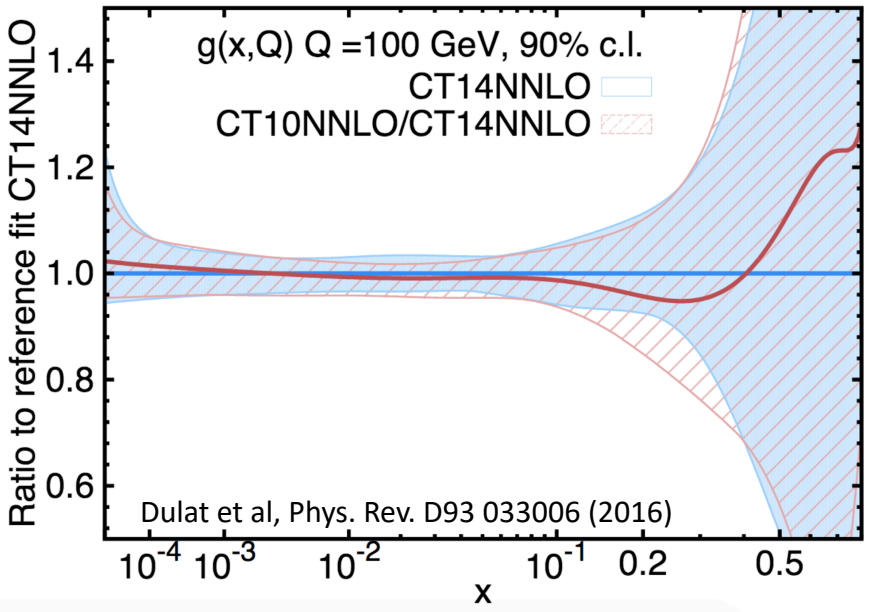
**Measurable at experiments**

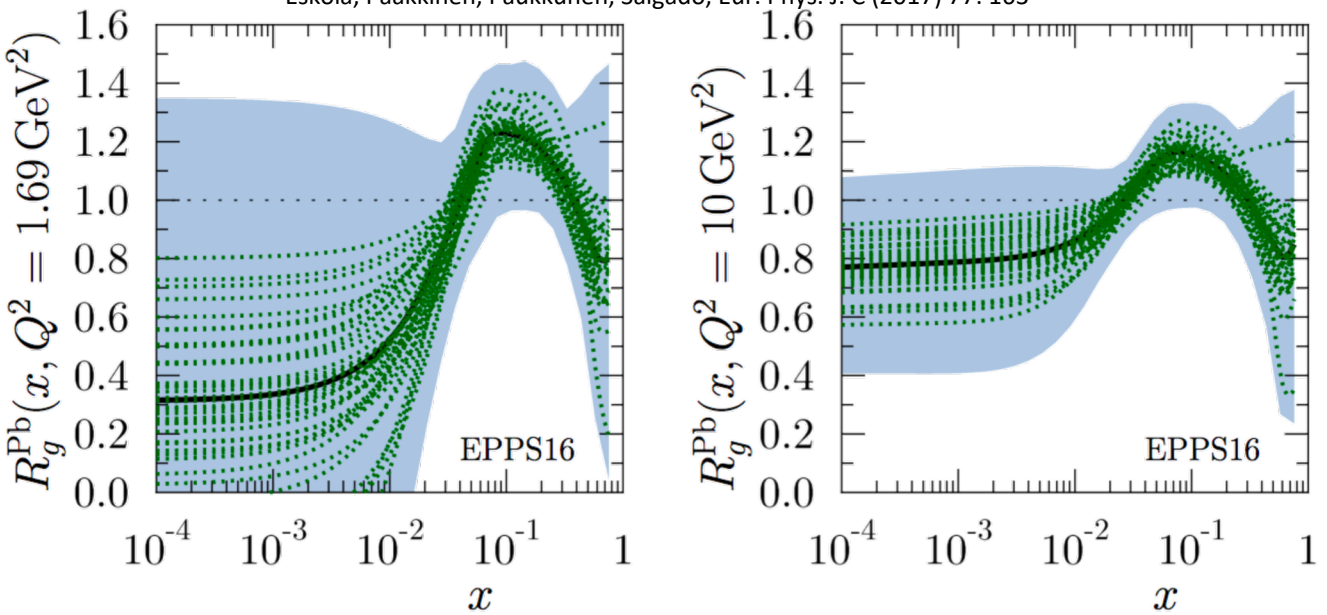
**Proton PDF: Fairly well constrained HERA and other data**

**Calculable by pQCD**

**Nuclear PDF is not well constrained**



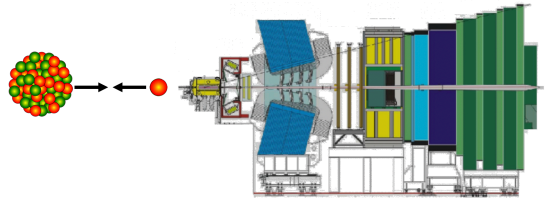

Eskola, Paakkinen, Paukkunen, Salgado, Eur. Phys. J. C (2017) 77: 163

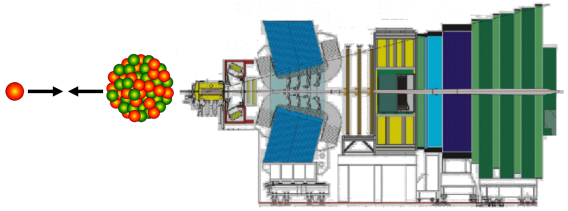


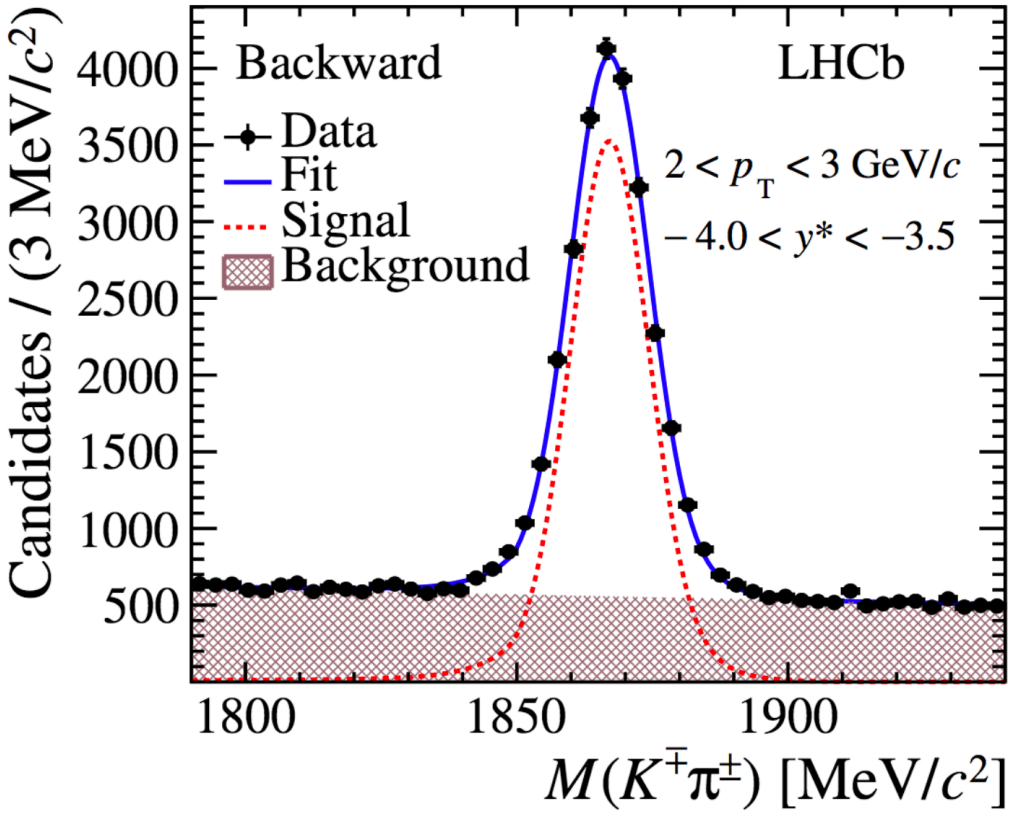
# Open Charm Mesons in *p*Pb collisions: $D^0$

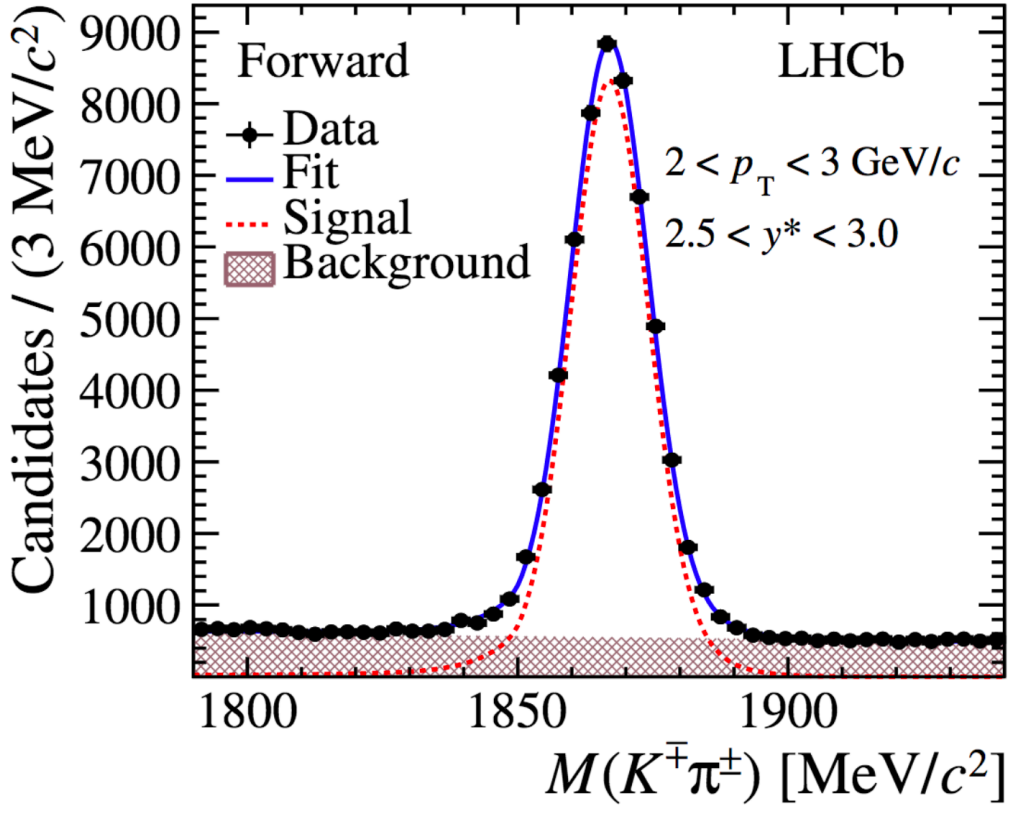
**Fully reconstructed through decay channel $D^0 \to K^{\mp}\pi^{\pm}$**

*J. High Energ. Phys. 10 (2017) 90*







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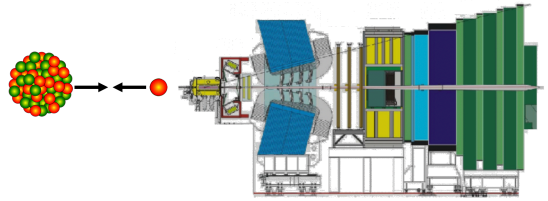

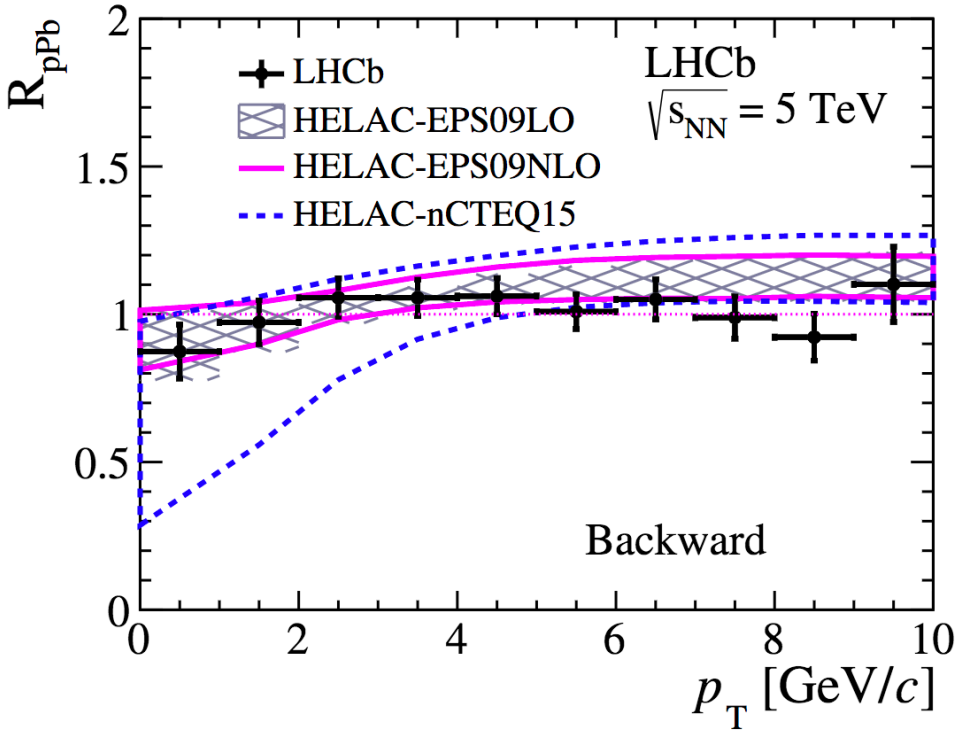


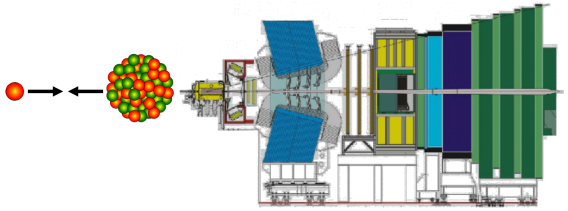

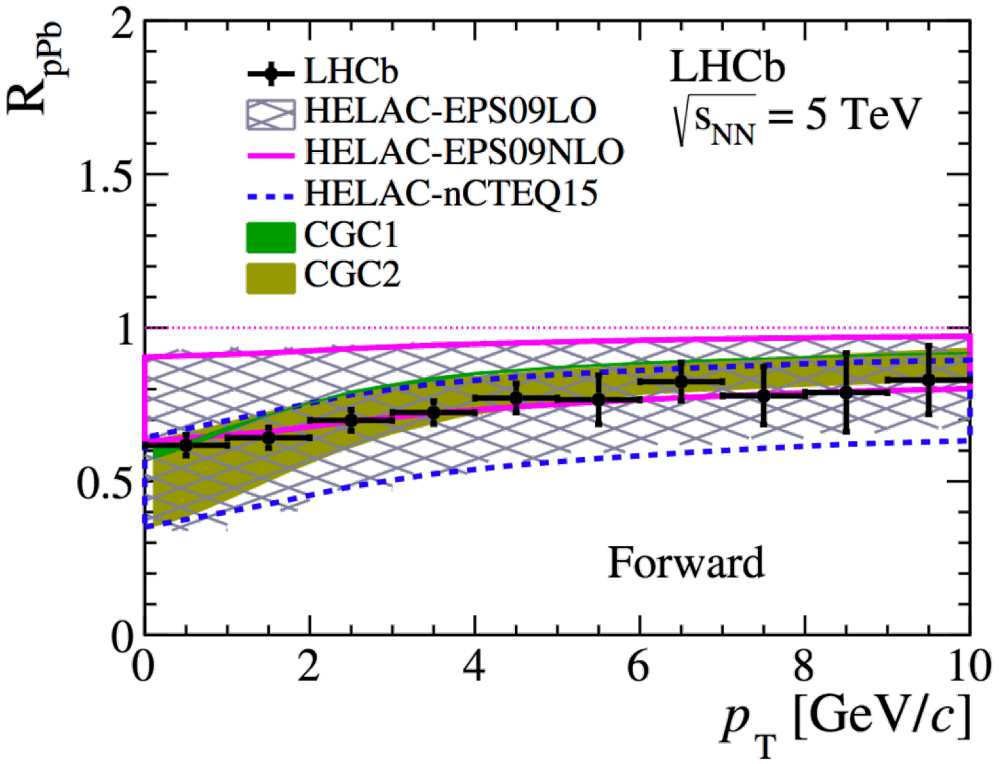


Error bars < calculation uncertainties

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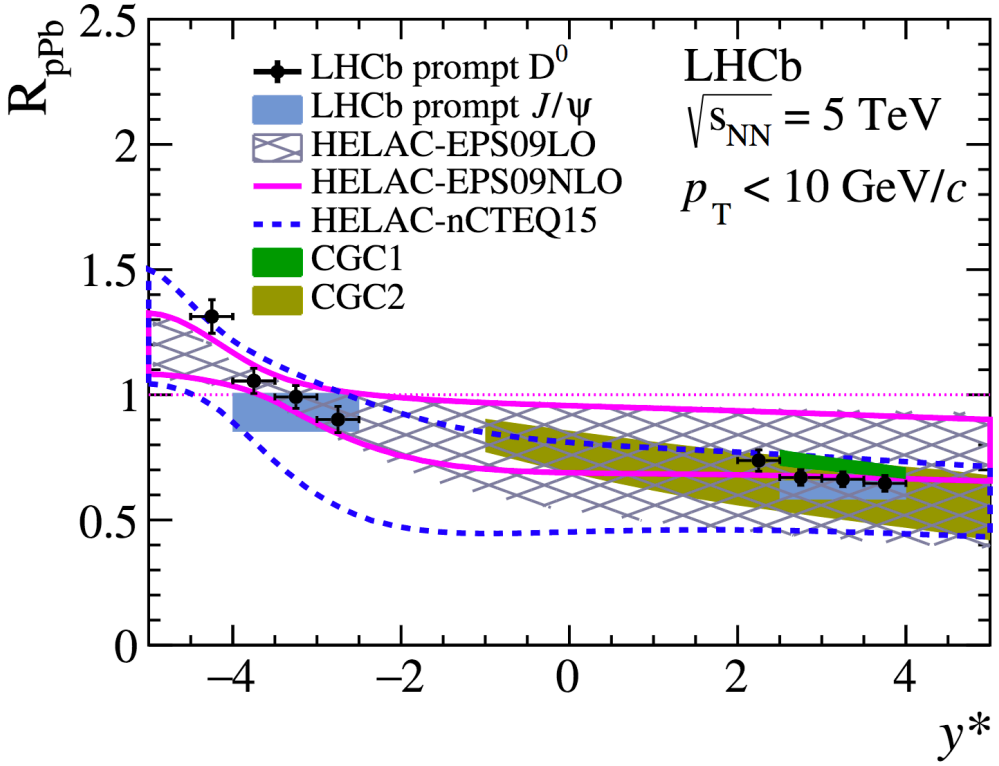
***J. High Energ. Phys. 10 (2017) 90***



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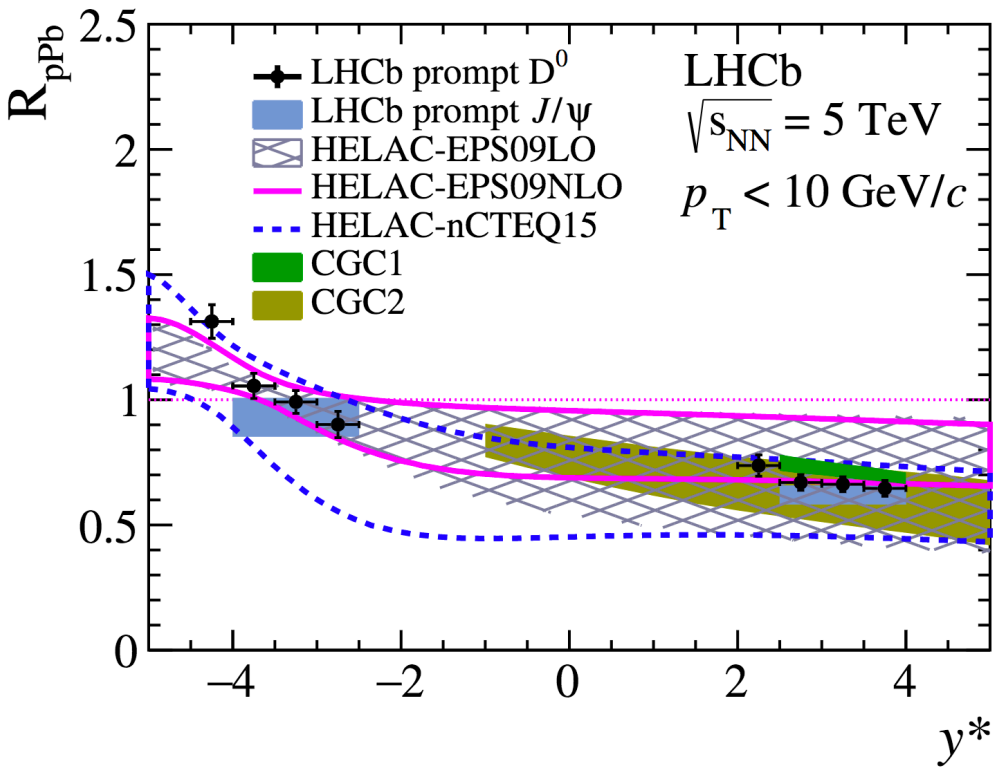
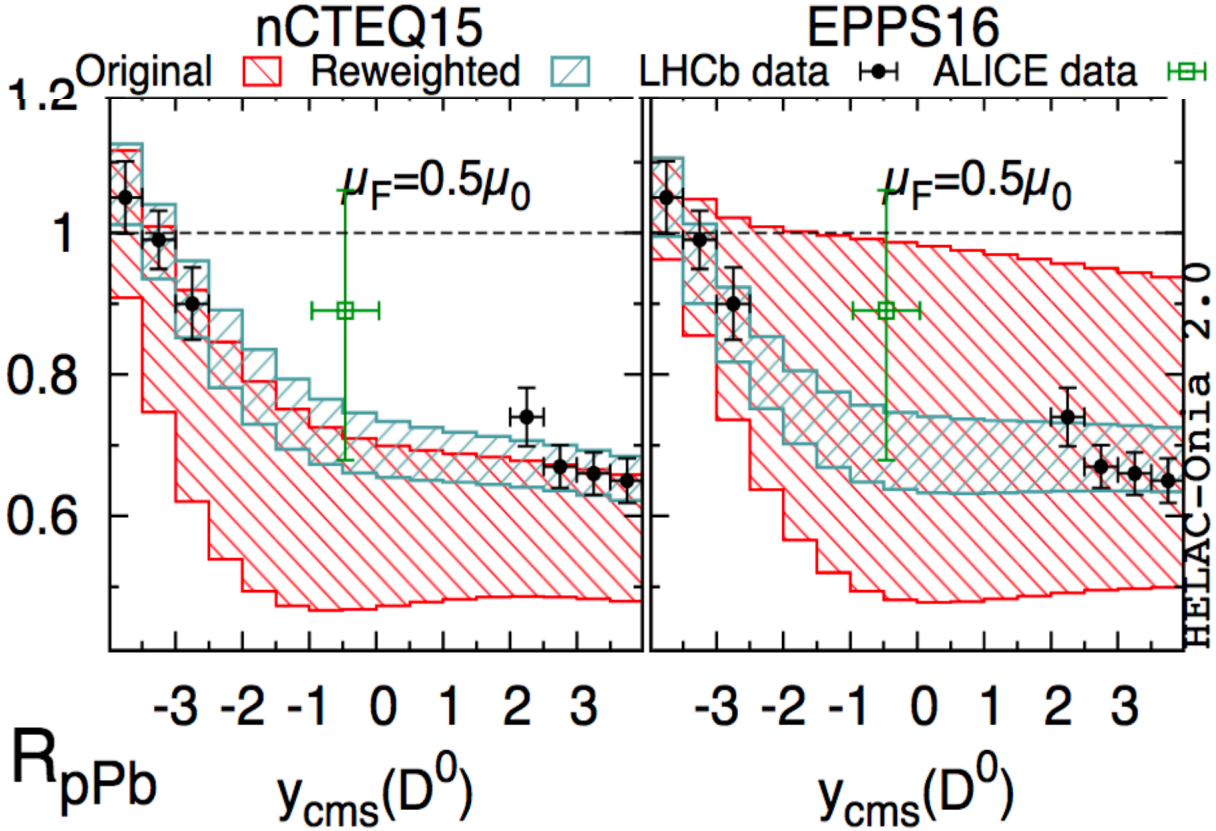
*J. High Energ. Phys. 10 (2017) 90*




**This data is already being used to constrain the gluon nPDF down to x~5x10$^{-6}$**

**Kusina, Lansberg, Schienbein, Shao,**
***Gluon shadowing and antishadowing in heavy-flavor production at the LHC***

Phys. Rev. Lett. 121, 052004 (2018)

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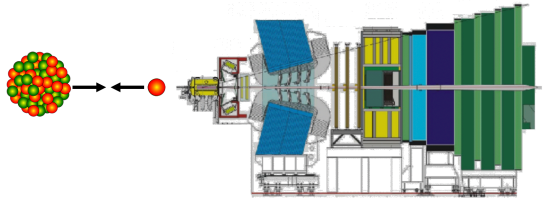
# Bottomonium Production in *p*Pb

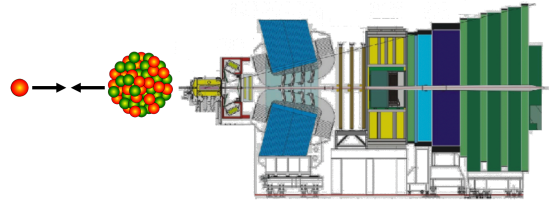
Sensitive to a range of effects that cannot be probed in *pp* collisions:

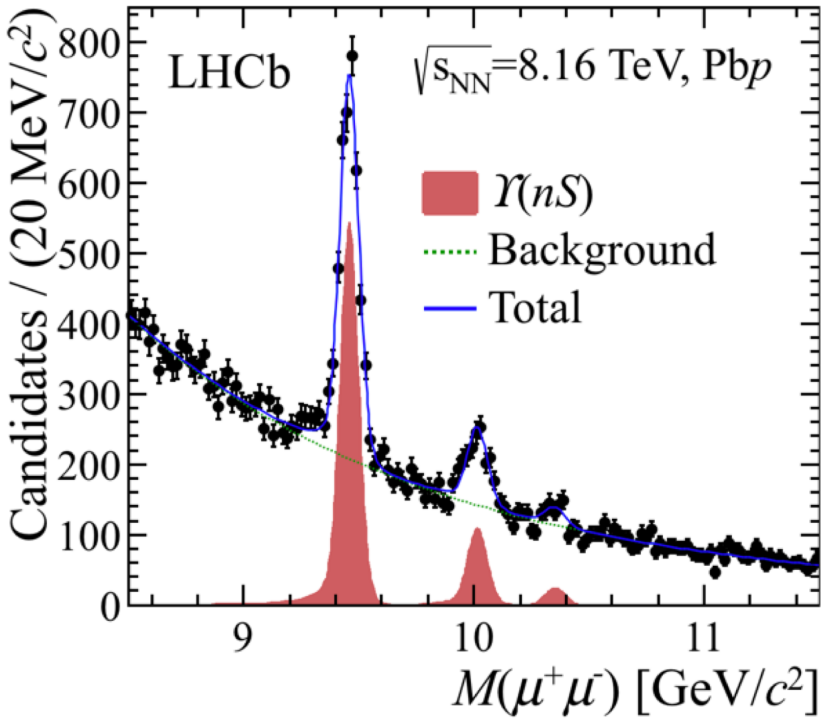
- nPDF modification
- QCD energy loss in the nucleus
- Final state suppression
- Crucial for interpreting PbPb

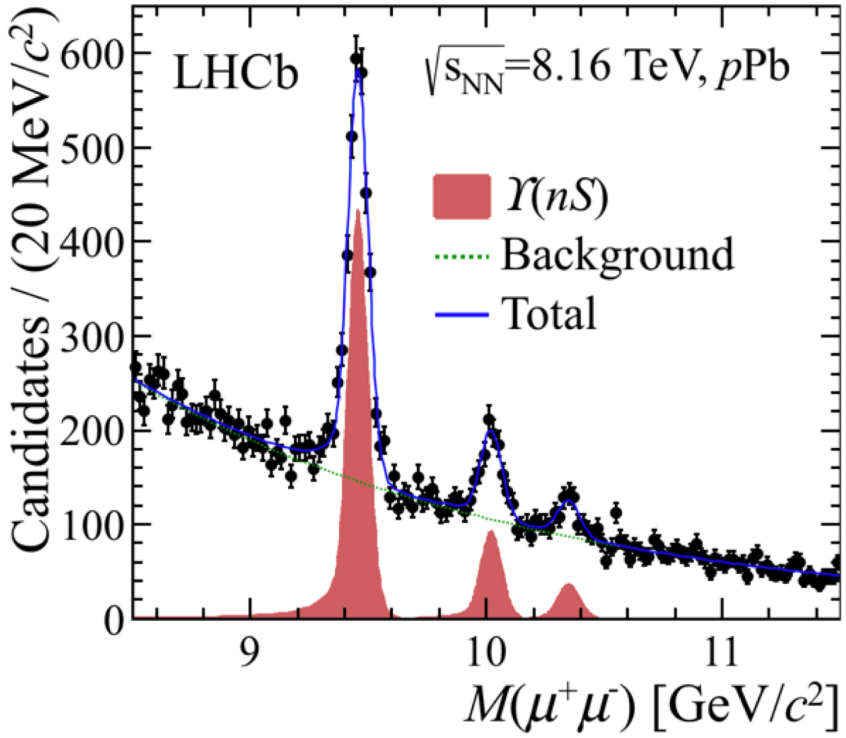
JHEP 11 (2018) 194

| Yields | $\Upsilon(1S)$ | $\Upsilon(2S)$ | $\Upsilon(3S)$ | $\mathcal{L}$ |
|---|---|---|---|---|
| *p*Pb | $2705 \pm 87$ | $584 \pm 49$ | $262 \pm 44$ | 12.5 $\text{nb}^{-1}$ |
| Pb*p* | $3072 \pm 82$ | $679 \pm 54$ | $159 \pm 39$ | 19.3 $\text{nb}^{-1}$ |



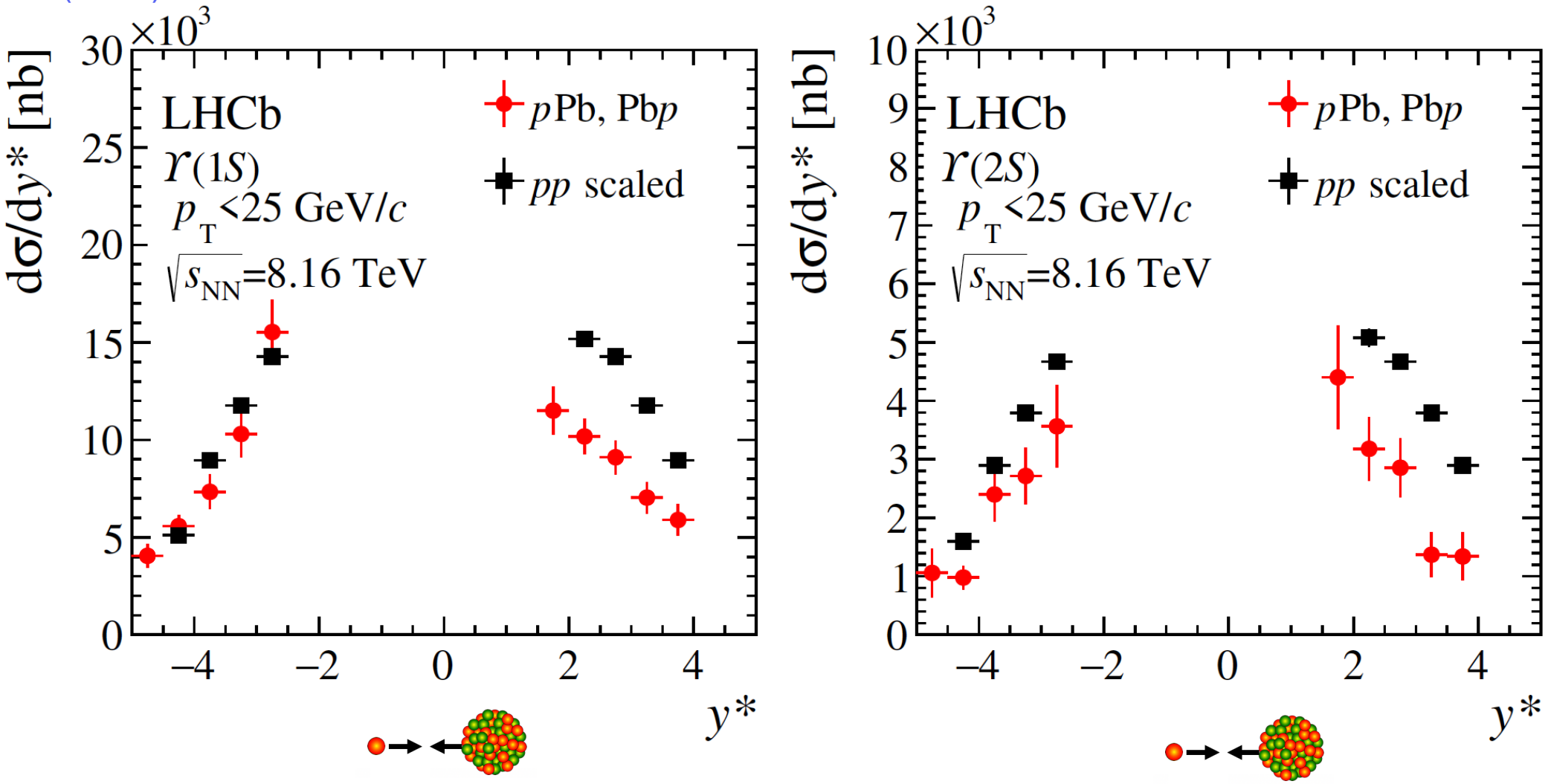




# Bottomonium Production in *p*Pb

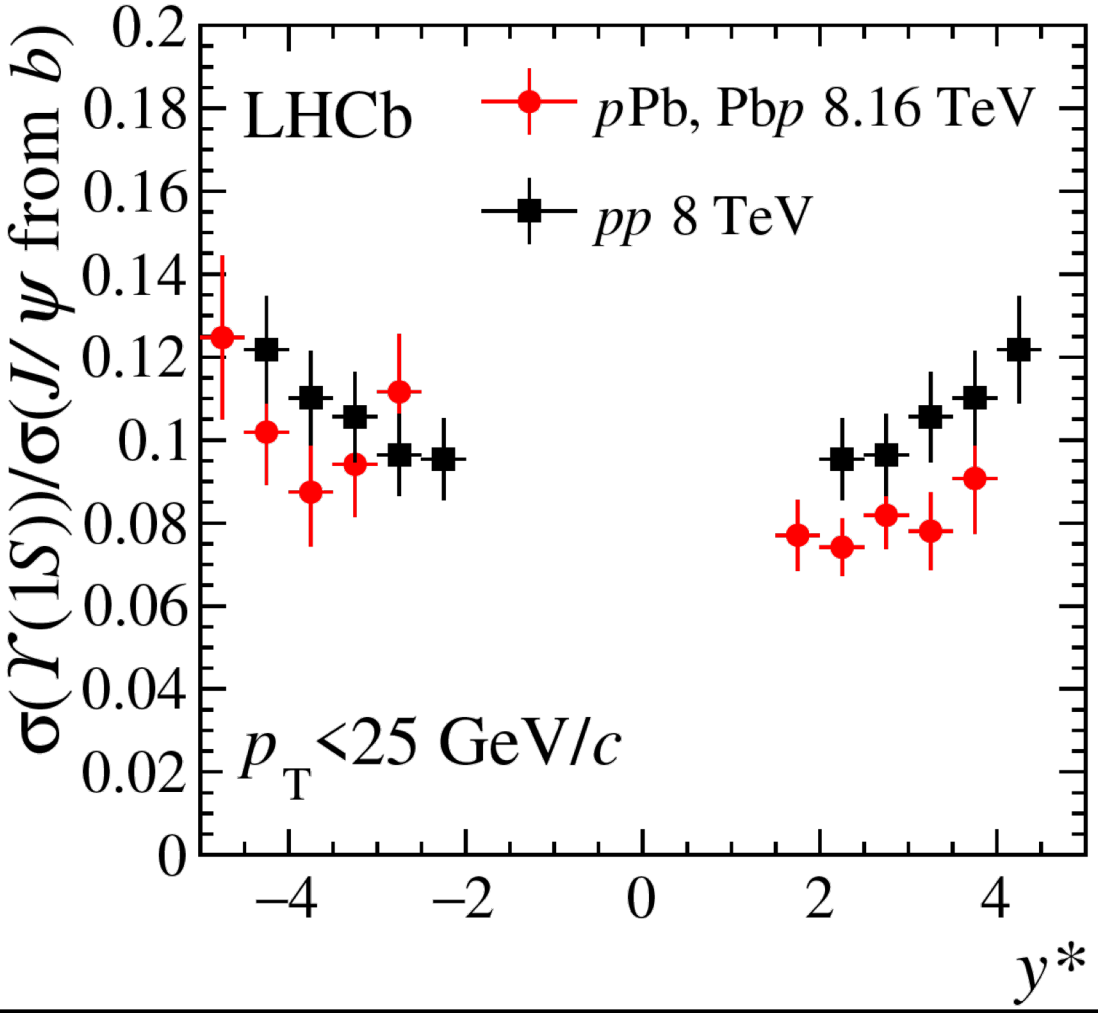
JHEP 11 (2018) 194



# Model-independent comparisons

JHEP 11 (2018) 194

As stand in for open bottom, use $J/\psi$ from $b$ decays:
Sensitive to same initial state effects, immune to breakup



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JHEP 11 (2018) 194

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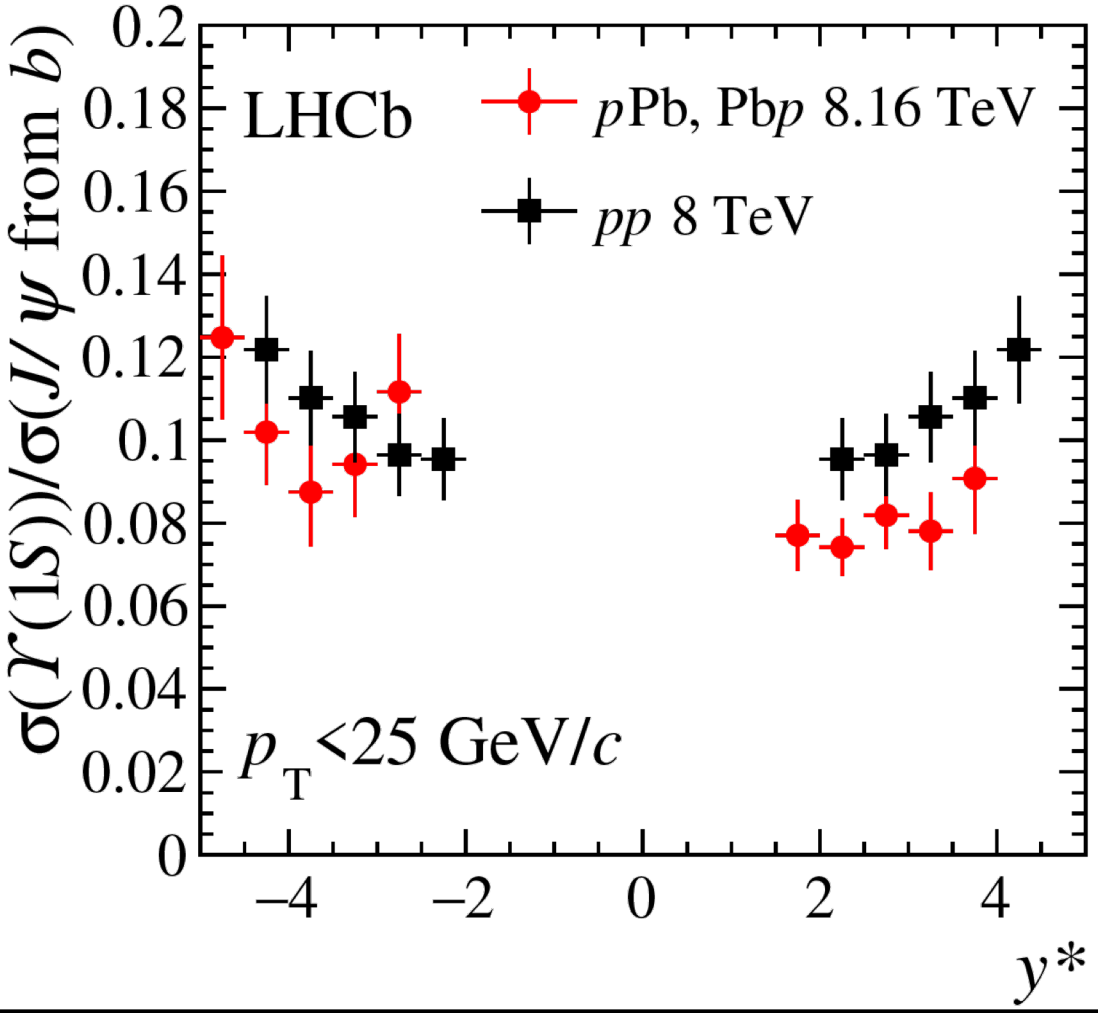


Double ratio of states in pPb or Pbp with pp:
Sensitive to effects on different states

$$\Re^{\Upsilon(2S)/\Upsilon(1S)}_{p\mathrm{Pb}/pp} = 0.86 \pm 0.15$$

$$\Re^{\Upsilon(3S)/\Upsilon(1S)}_{p\mathrm{Pb}/pp} = 0.81 \pm 0.15$$

$$\Re^{\Upsilon(2S)/\Upsilon(1S)}_{\mathrm{Pb}p/pp} = 0.91 \pm 0.21$$

$$\Re^{\Upsilon(3S)/\Upsilon(1S)}_{\mathrm{Pb}p/pp} = 0.44 \pm 0.15$$

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JHEP 11 (2018) 194

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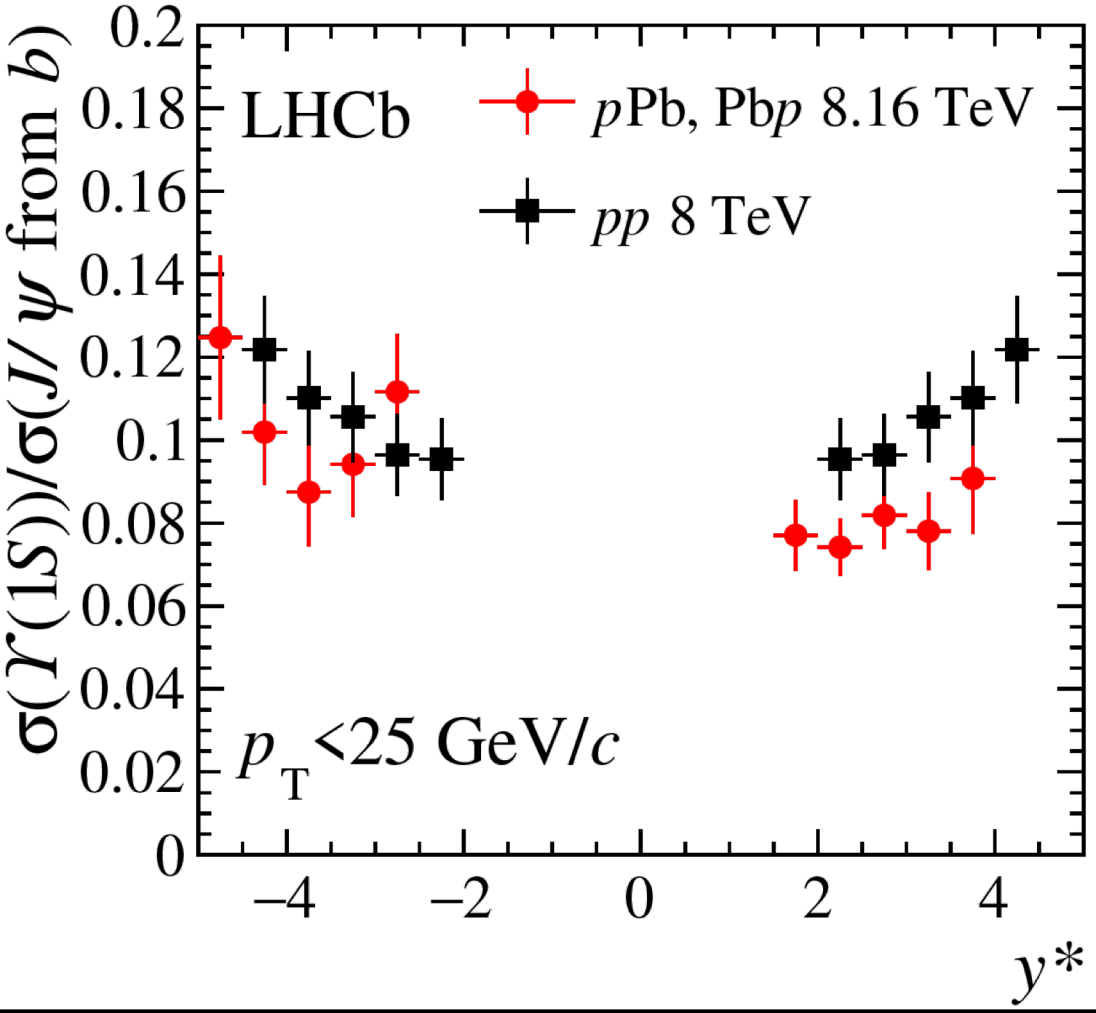


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JHEP 11 (2018) 194

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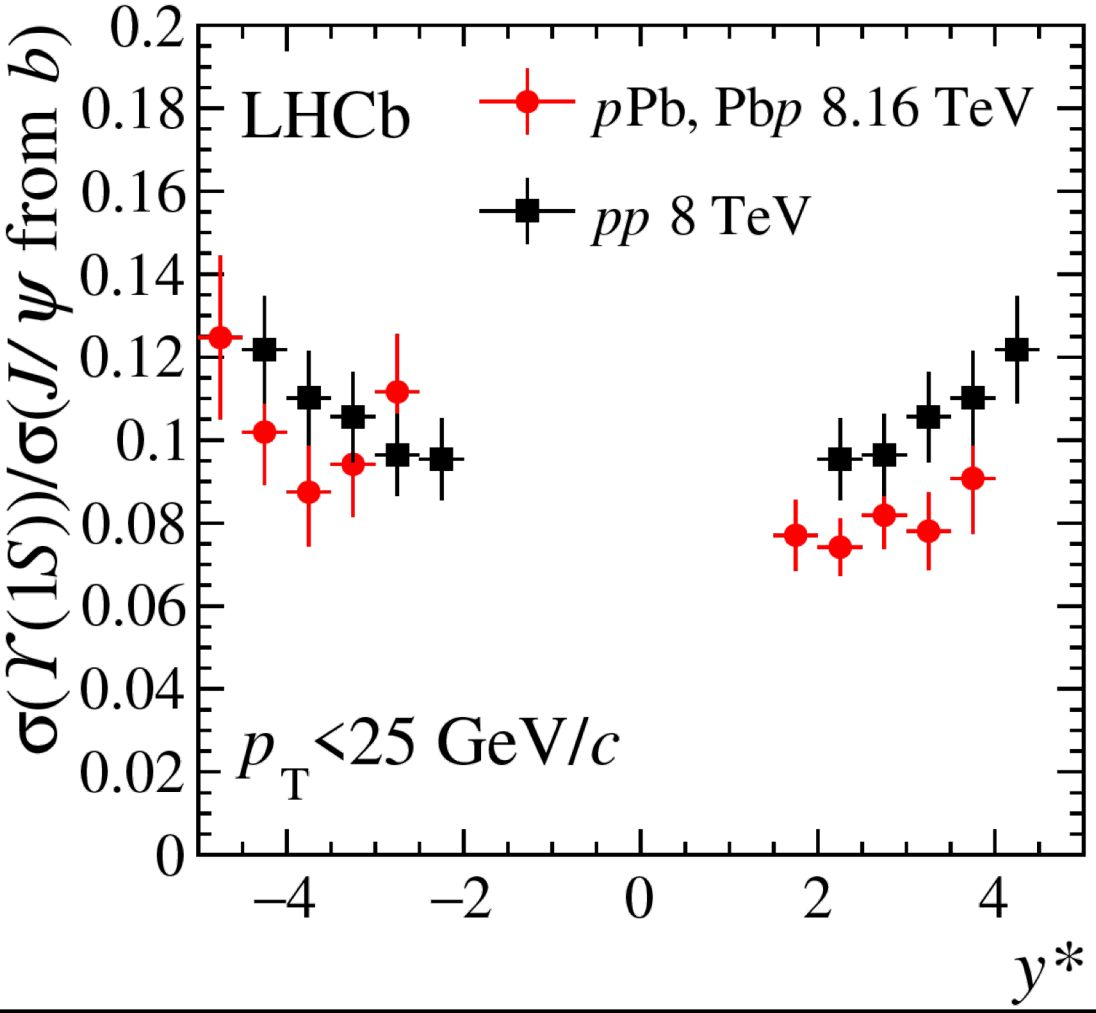


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**Significant difference between forward/backward**

# Model Comparisons

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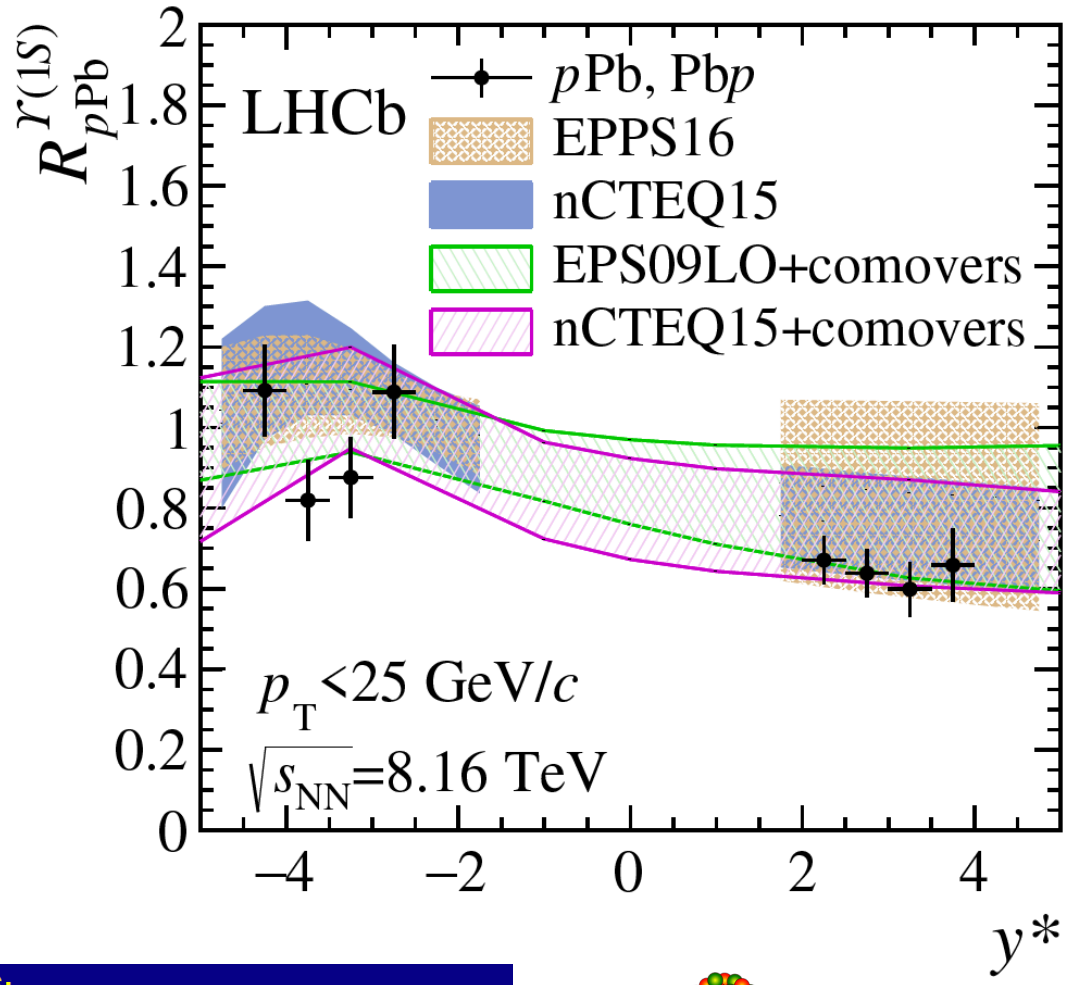
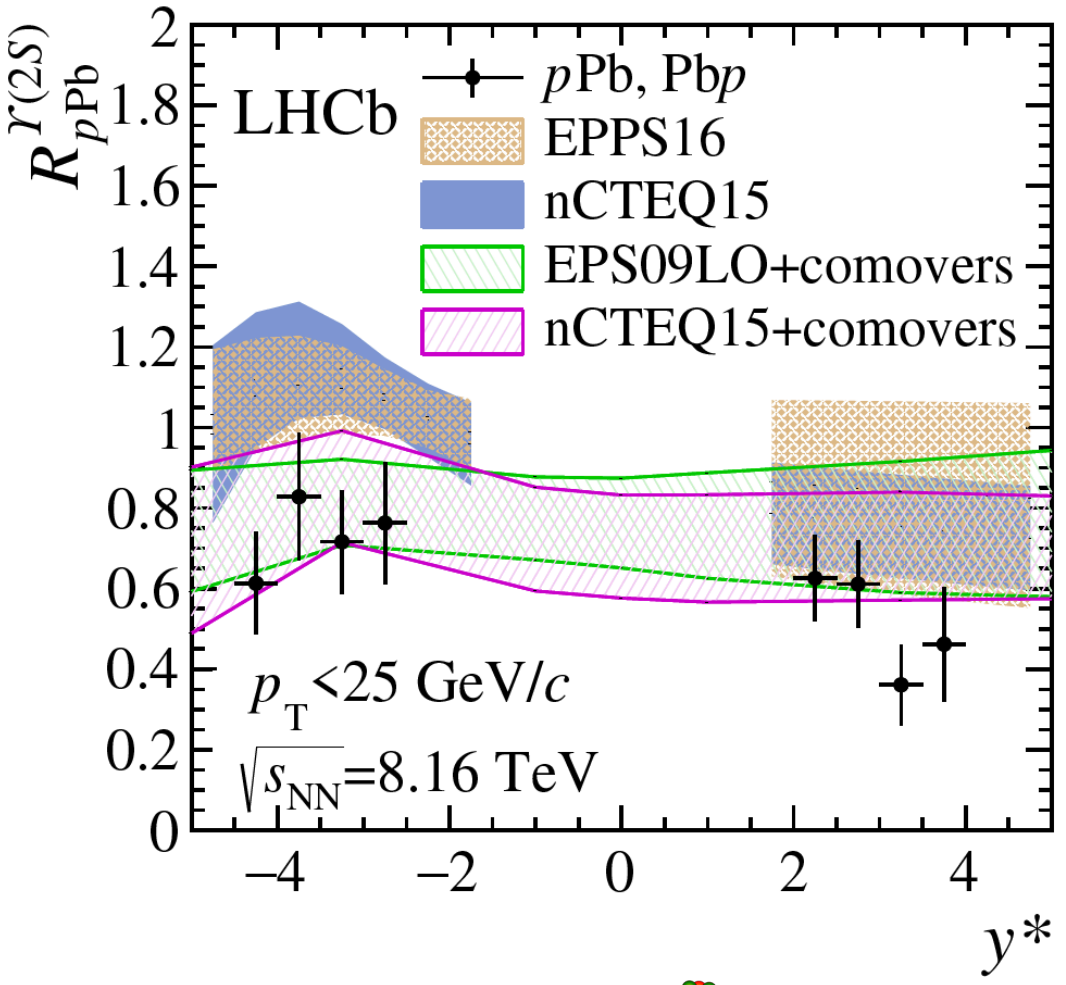
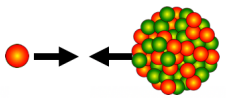
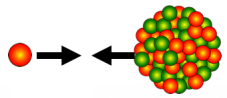


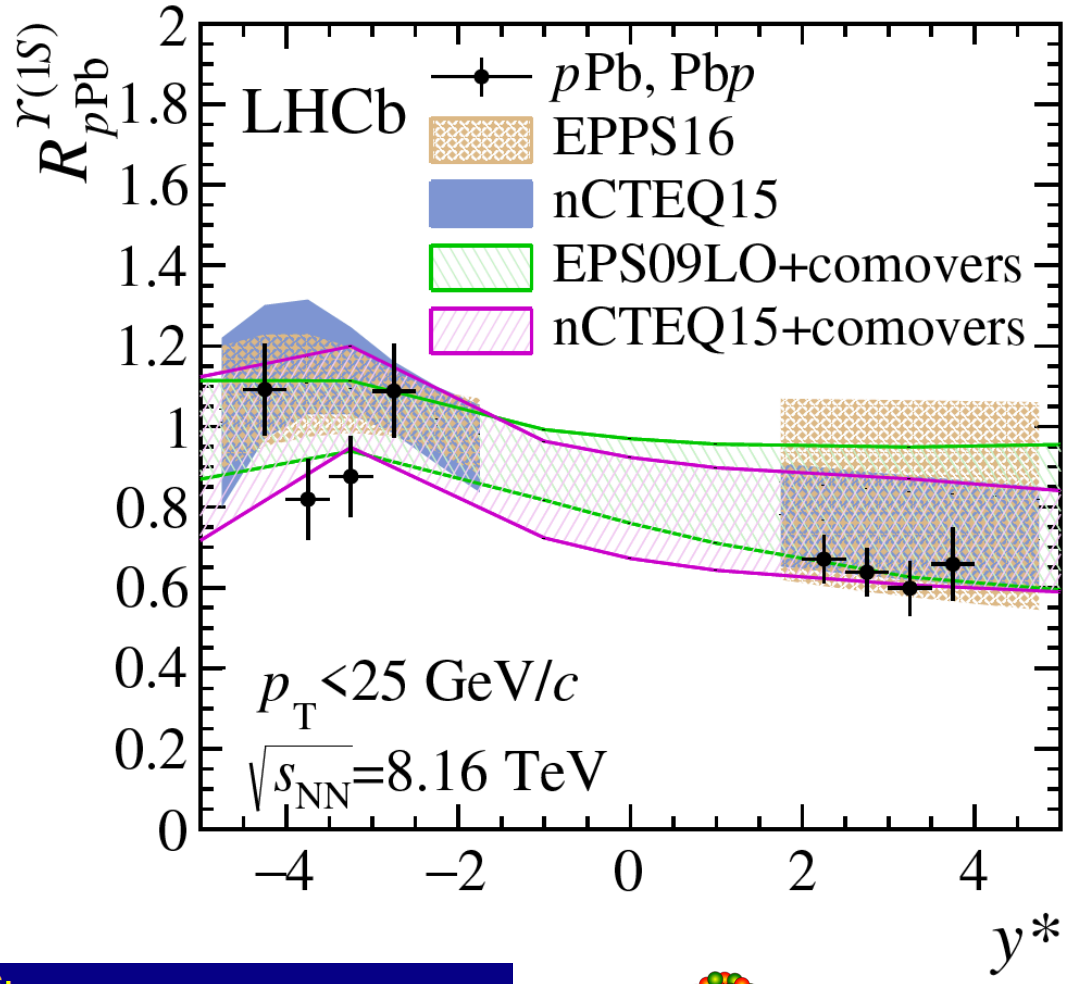



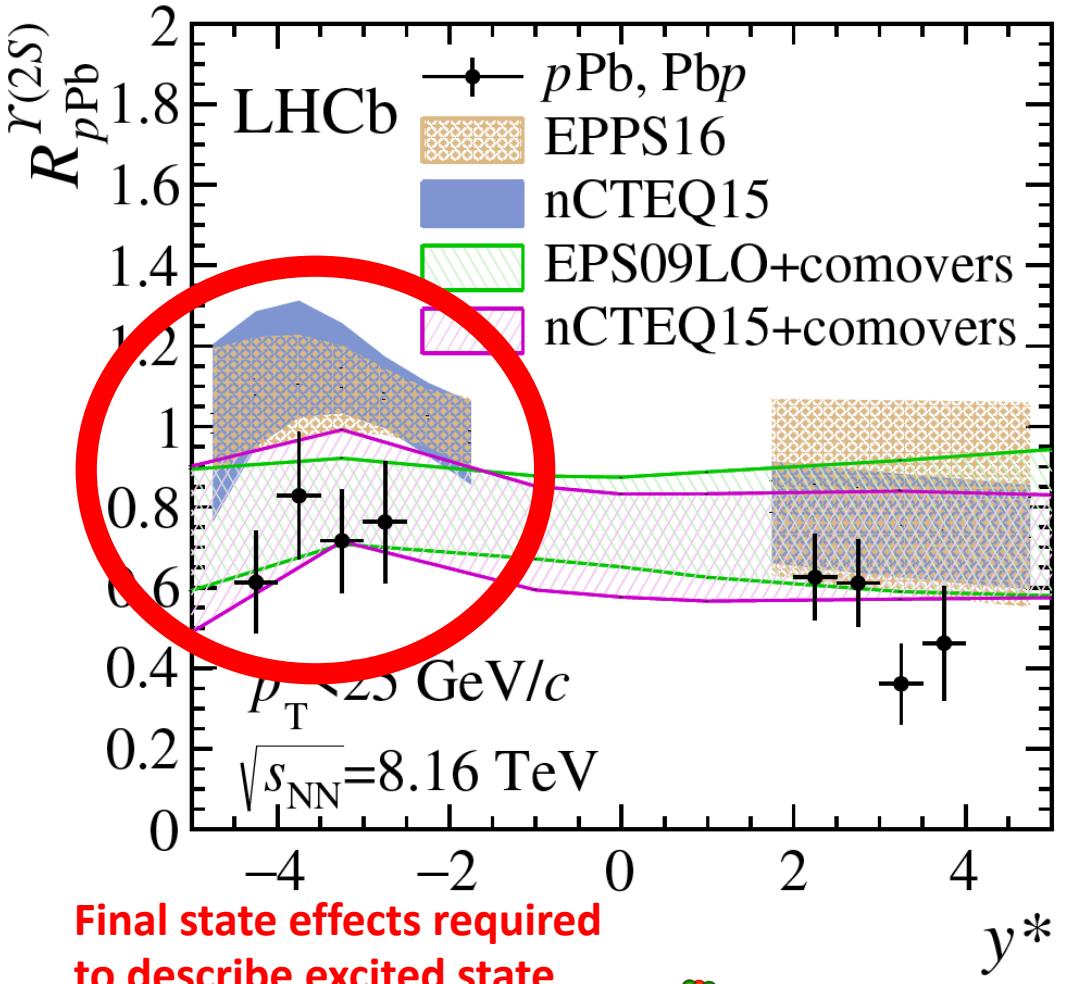


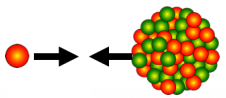
**MODELS:**
**EPPS16**: Eur. Phys. J. C (2017) 77: 163
**EPS09**: JHEP 04 (2009) 065, arXiv:0902.4154.
**nCTEQ15**: Phys. Rev. D93 (2016) 085037.
**Comovers**: arXiv:1804.04474; Phys. Lett. B749 (2015) 98, arXiv:1411.0549

# Model Comparisons

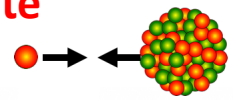
JHEP 11 (2018) 194



**Final state effects required to describe excited state suppression**



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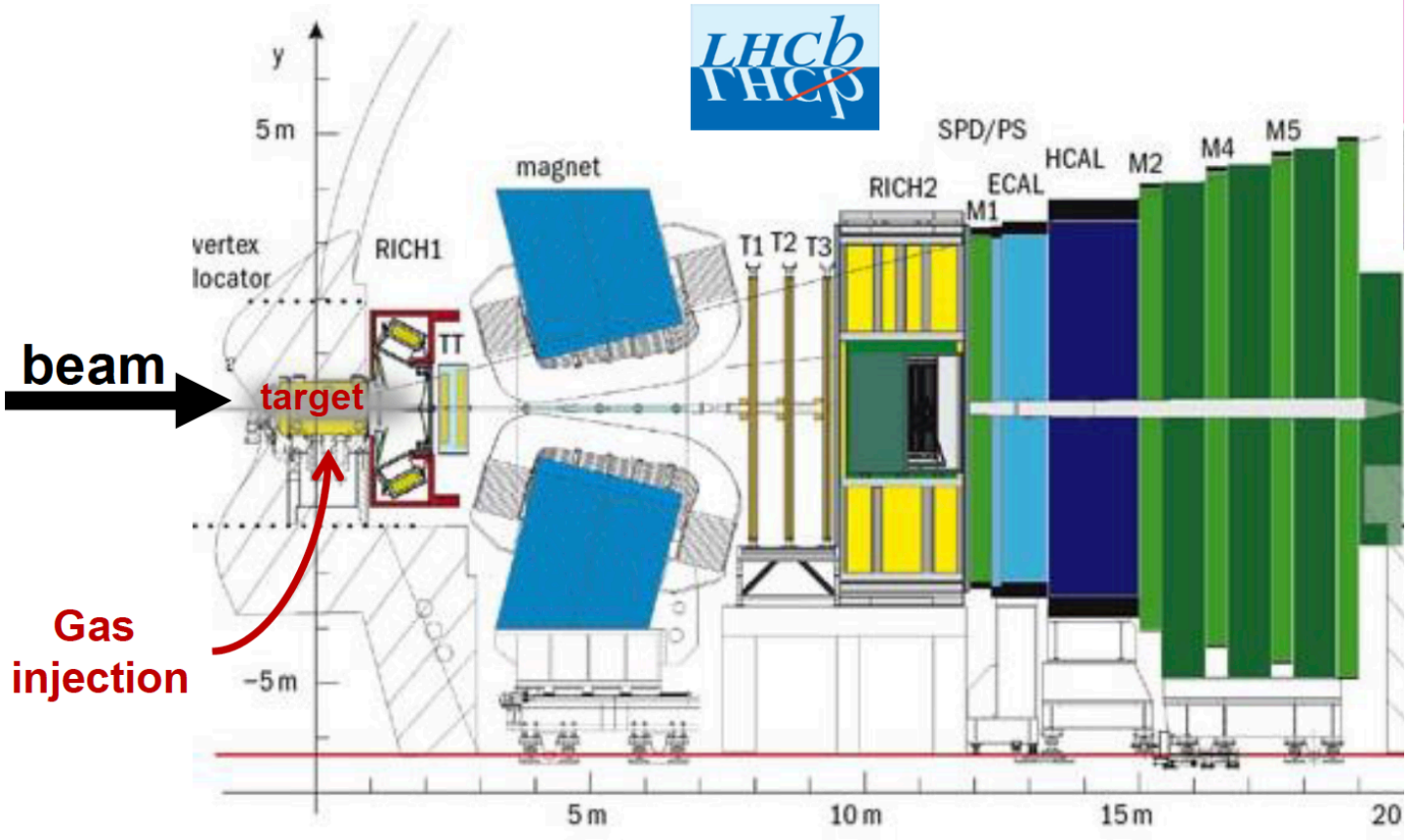
- Understanding bottomonium suppression in pPb Collisions
- A unique capability: accessing unexplored phase space in fixed target mode
- Upgrade Plan
- Conclusions

# Fixed target configuration - SMOG



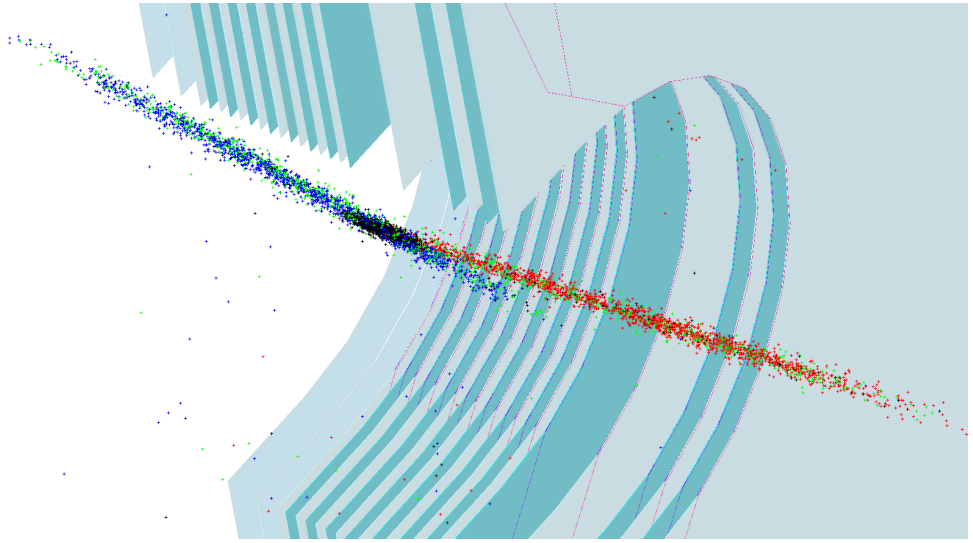

A unique capability at the LHC: fixed target collisions with noble gas injected into beampipe

**Noble gas only :**
(very low chemical reactivity)

He, Ne, Ar, …
A = 4, 20, 40

Gas pressure:
$10^{-7}$ to $10^{-6}$ mbar

# Fixed target configuration - SMOG



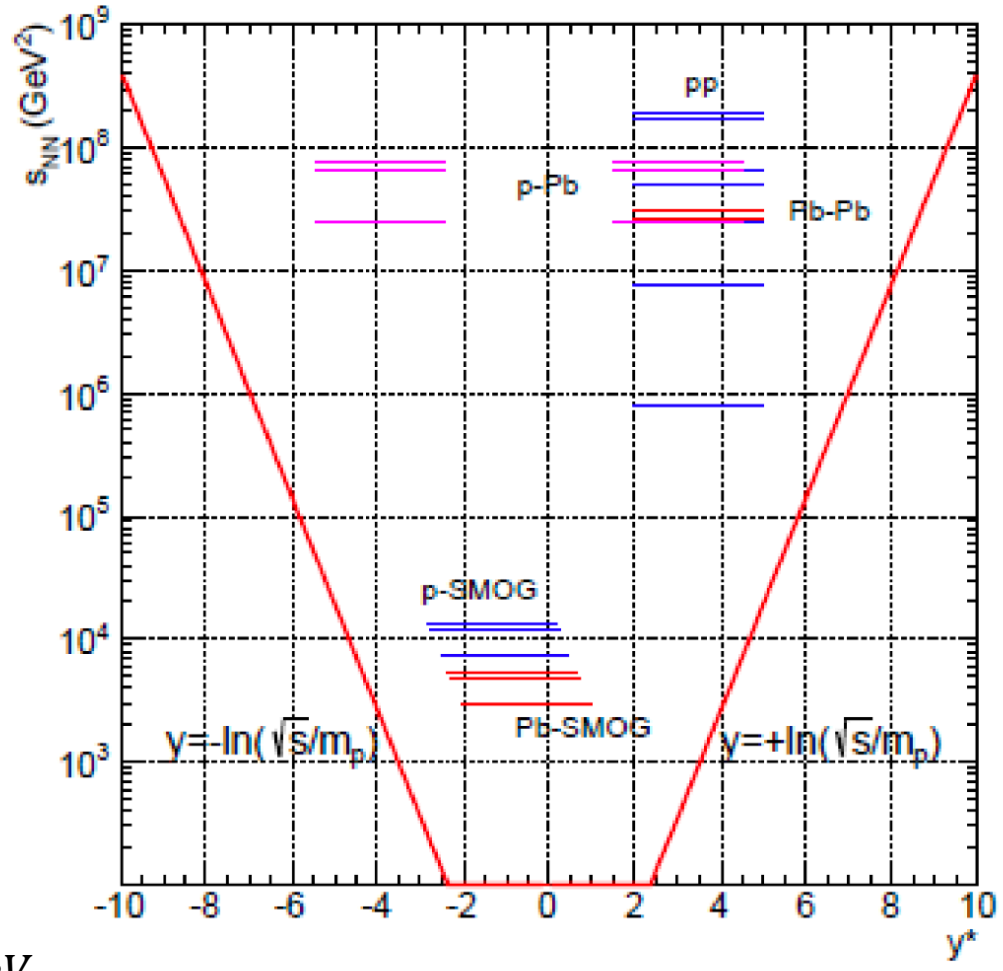
Reconstructed beam-gas vertices inside VELO

$\sqrt{s_{NN}}^{SPS} \approx 20\ GeV$

$\sqrt{s_{NN}}^{SMOG} \approx \mathbf{70 - 110\ GeV}$

$\sqrt{s_{NN}}^{RHIC} = 200\ GeV$

$\sqrt{s_{NN}}^{LHC} = 5\ TeV$



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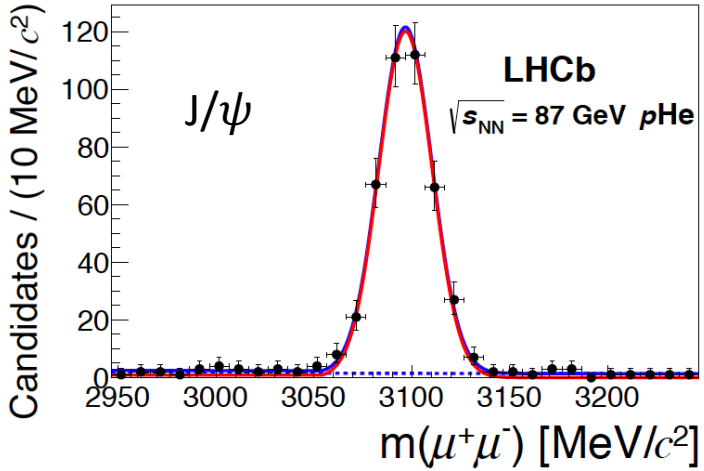
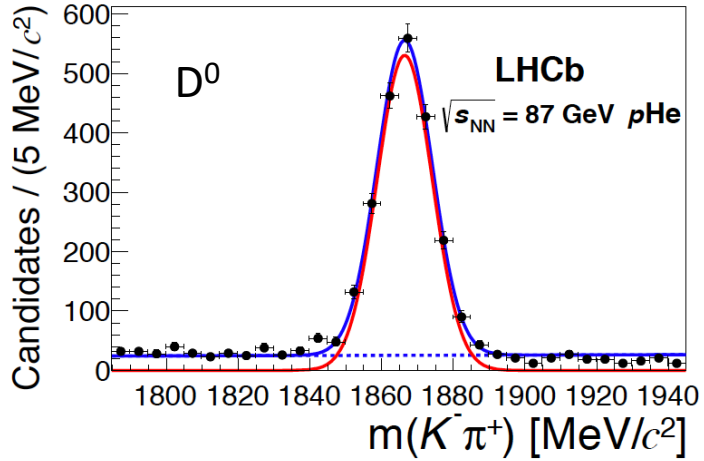
Phys. Rev. Lett. 122 132002 (2019)



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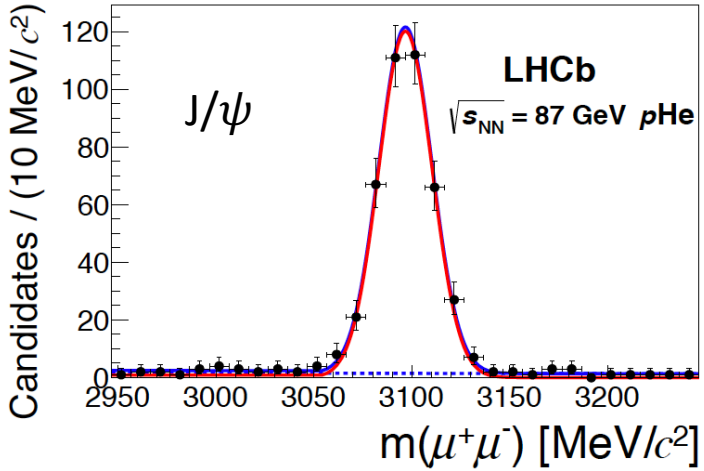


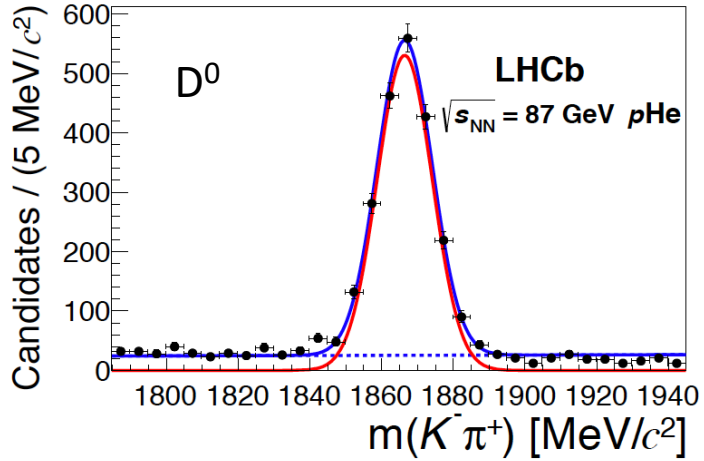


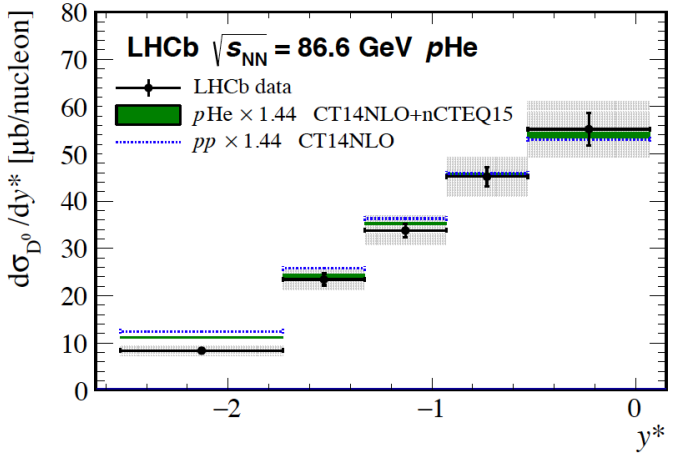


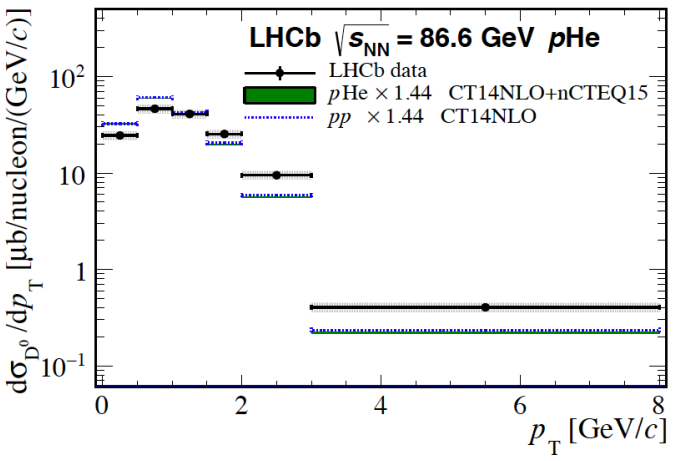


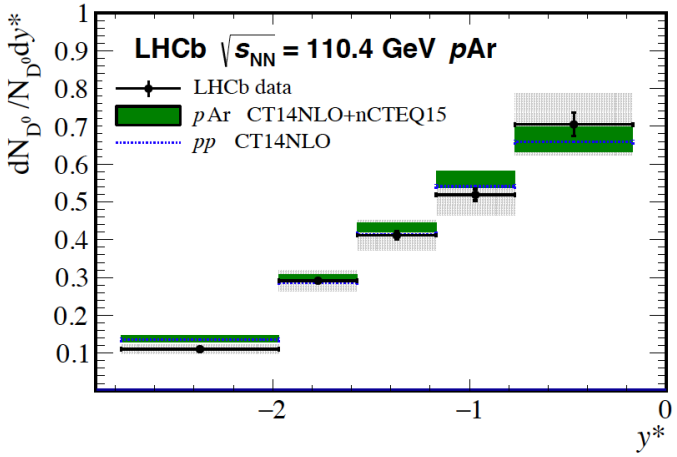


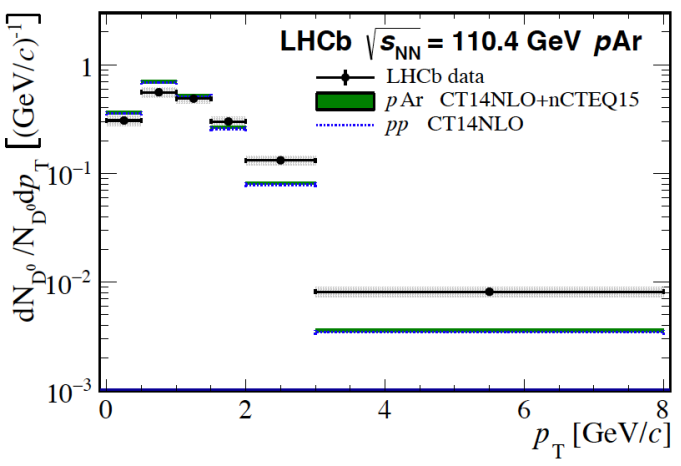

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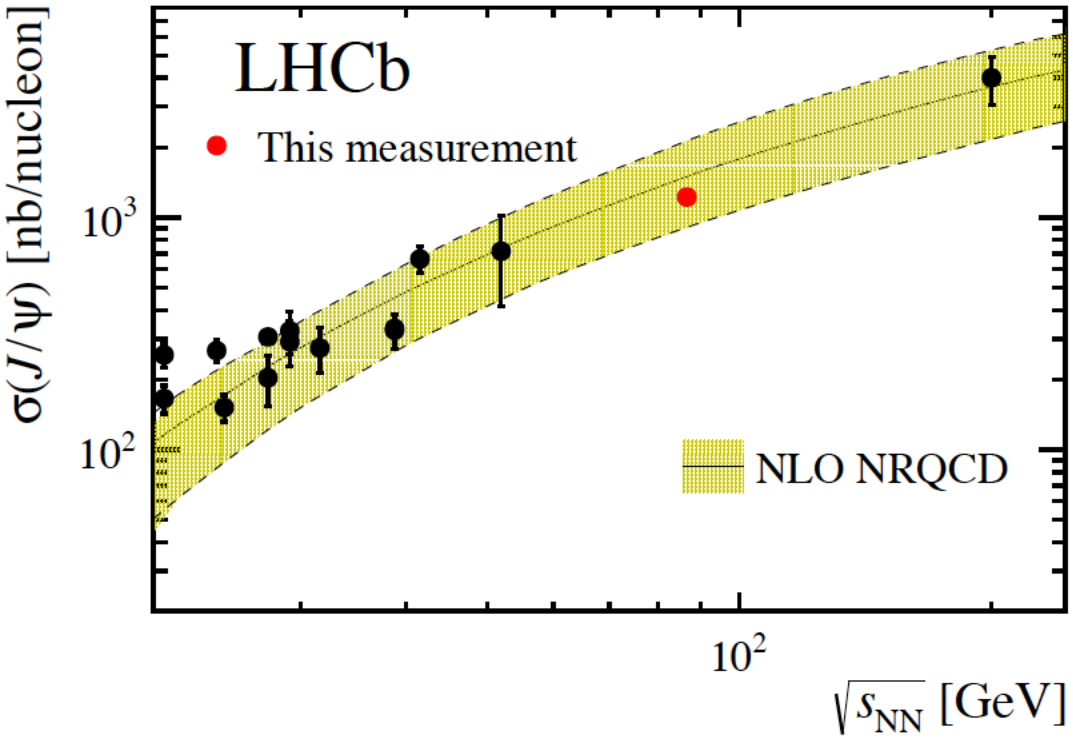
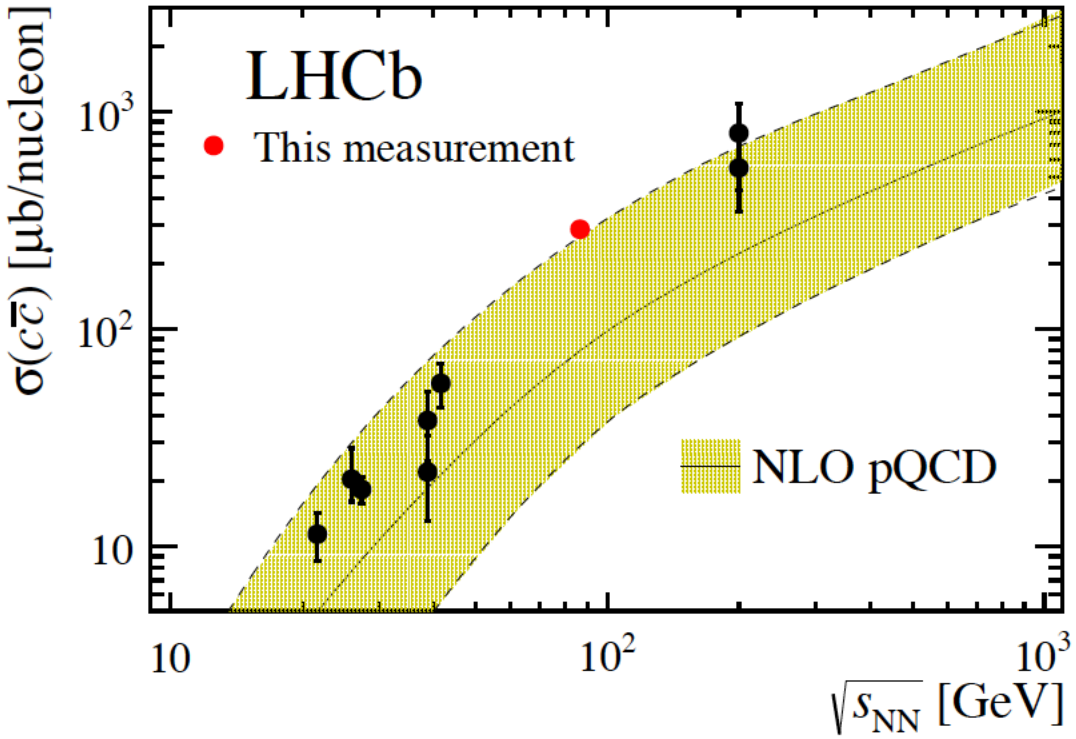
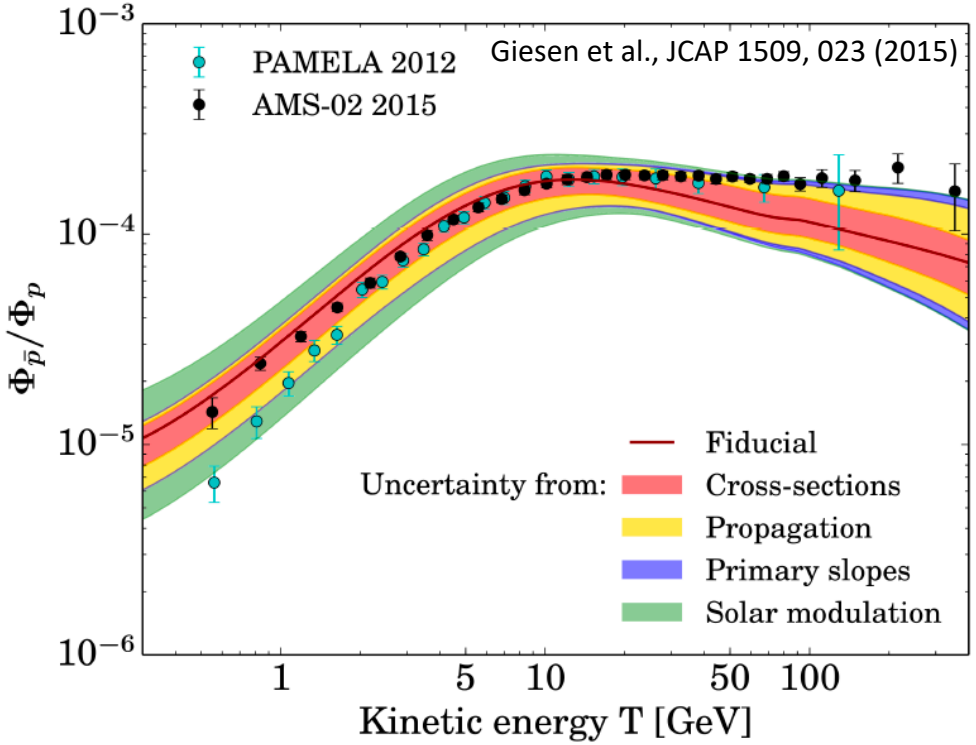



Precise cross sections in largely unexplored region of CM energies
Exploration of this unique capability has only just begun.

# SMOG Antiprotons

Hints of excess in cosmic $\bar{p}/p$ ratio – possibly sensitive to new physics




Large fraction of uncertainties from production cross sections

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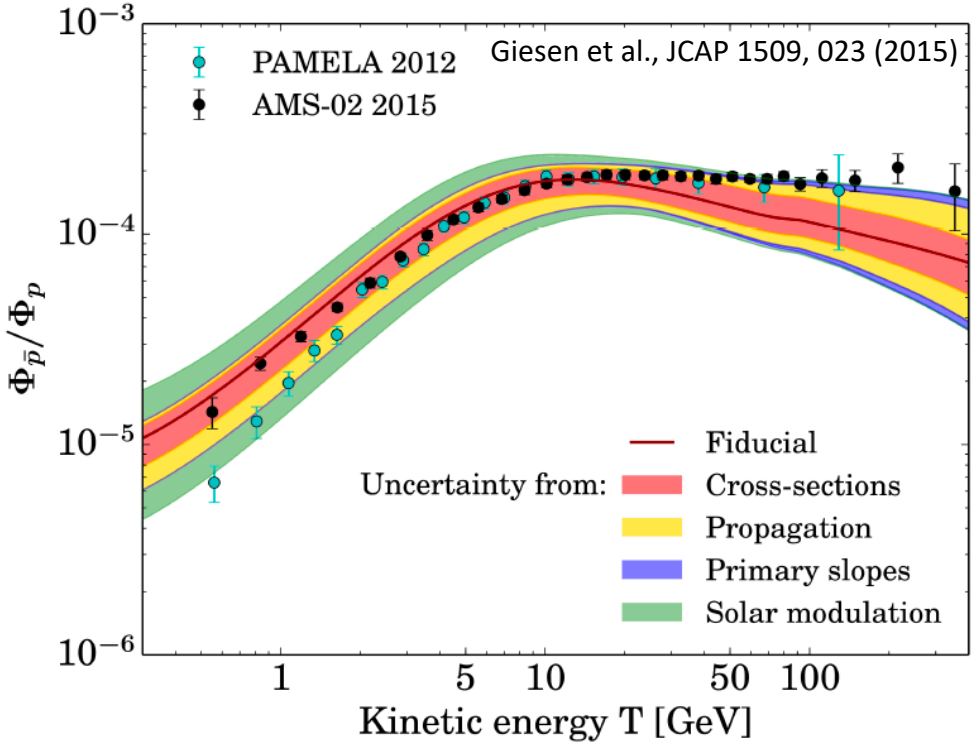
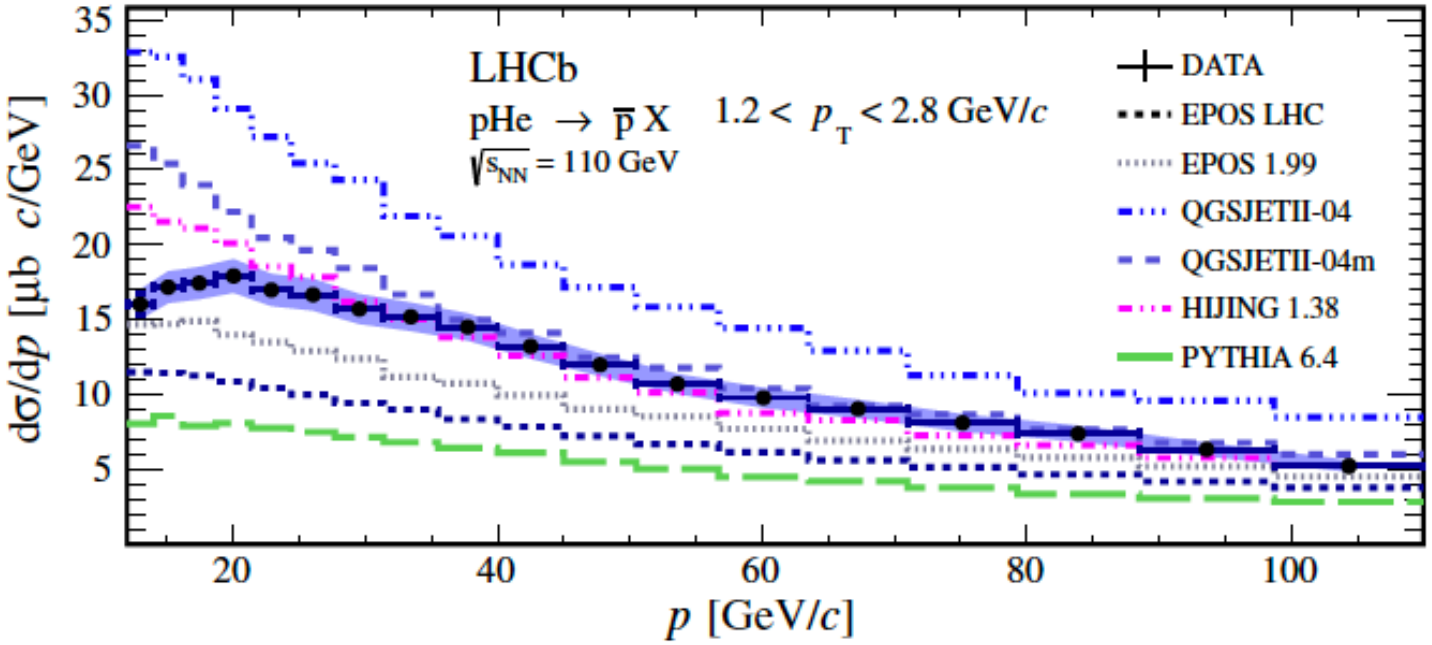



Large fraction of uncertainties from production cross sections

Phys. Rev. Lett. 122 211803 (2019)




SMOG provides unique data on antiproton production to constrain models

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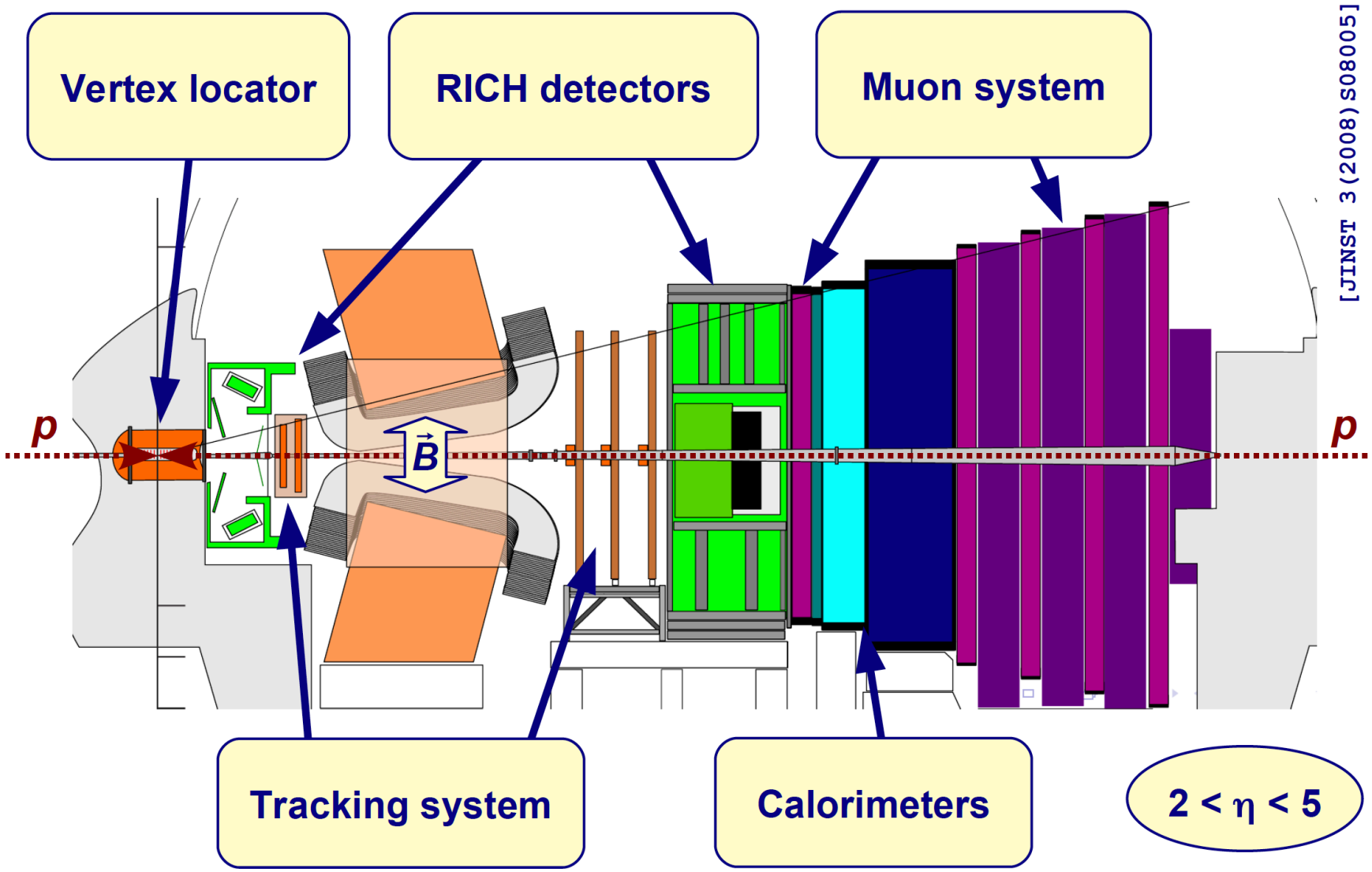
# Major Upgrades Underway



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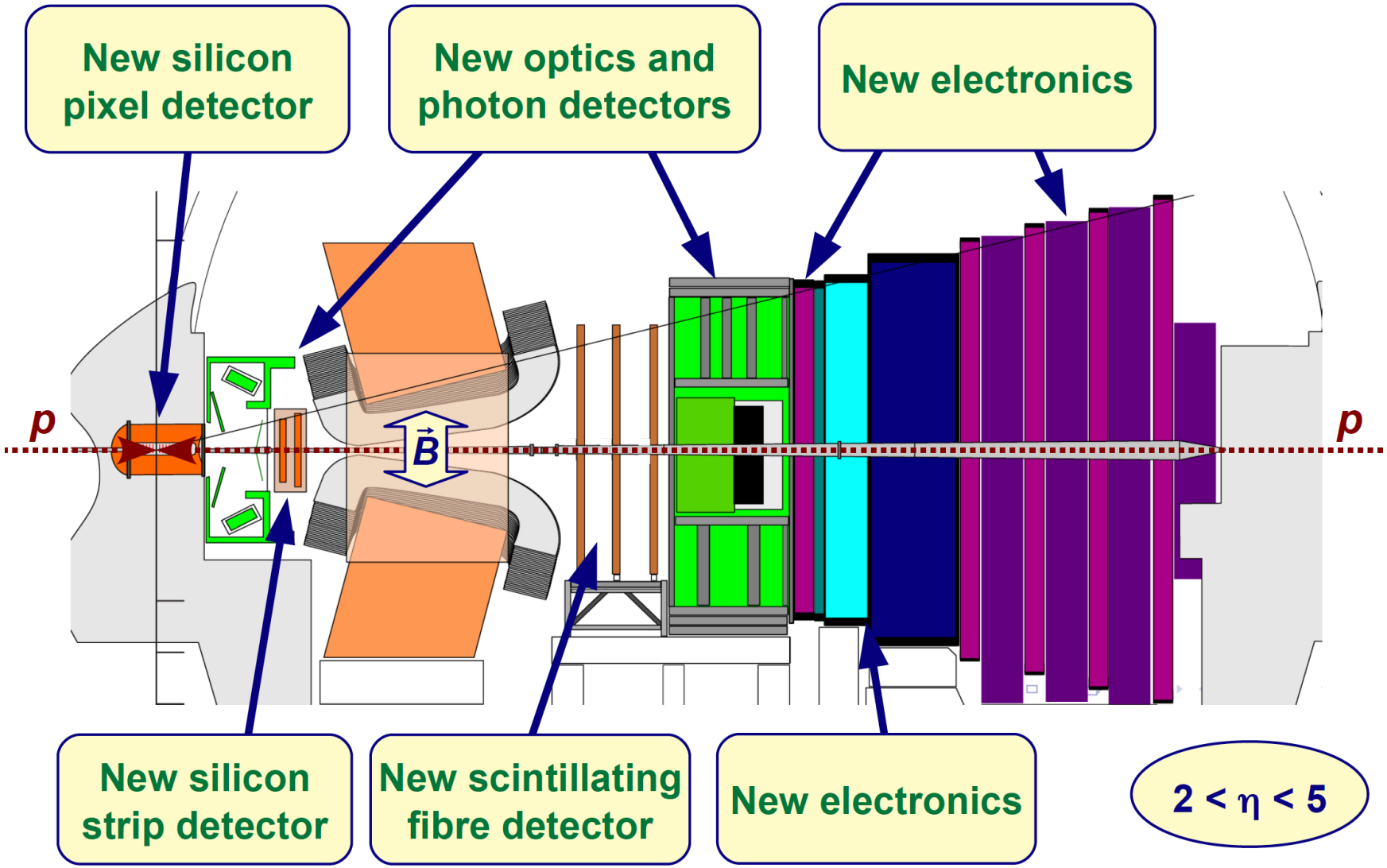
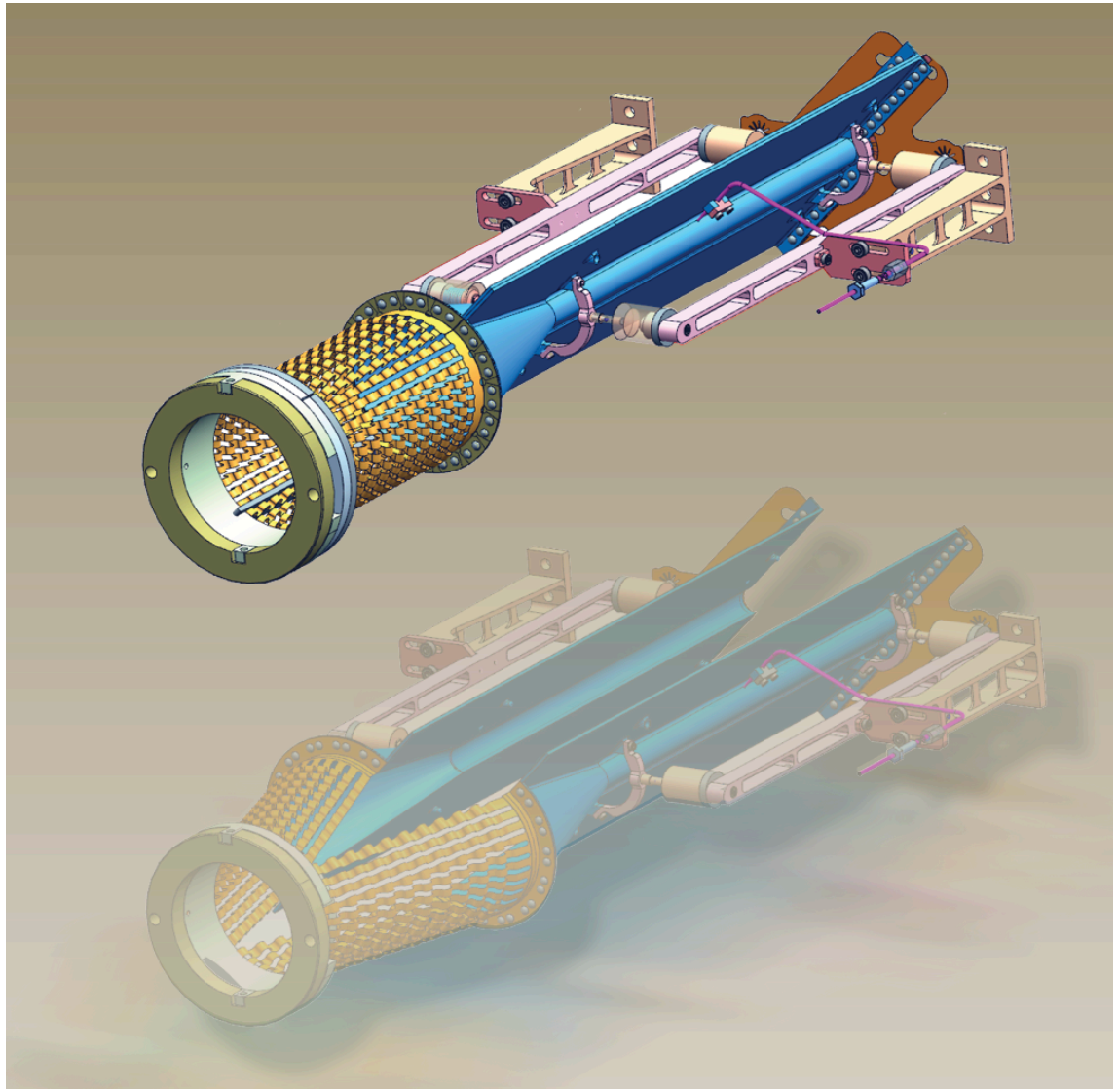



**Trigger-less readout of full 40MHz LHC collision rate**

**Granularity of tracking system greatly increased: improved performance in heavy ion collisions**

# SMOG II Upgrades Underway



**Upgraded SMOG system increases fixed target rates by factor of 10-100**

**Storage cell upstream of Vertex Locator**

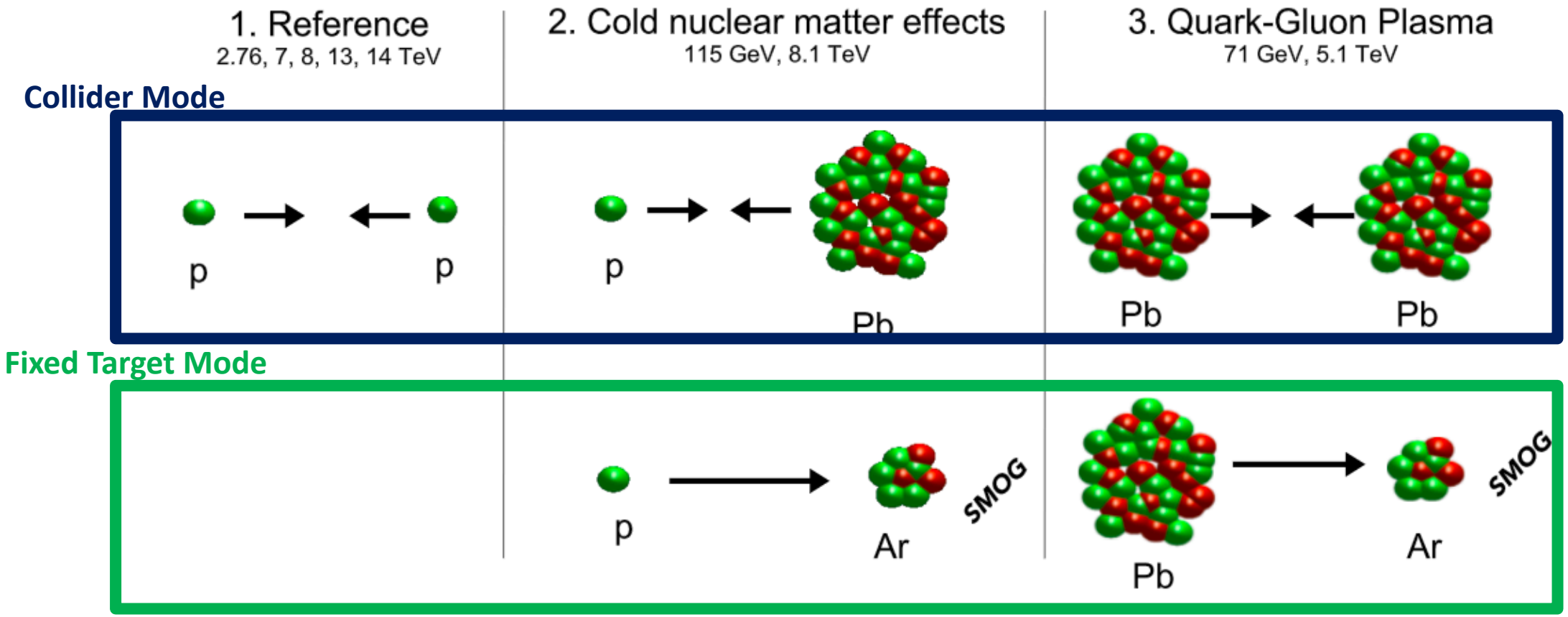
**For full details see TDR:**
**http://cds.cern.ch/record/2673690?ln=en**

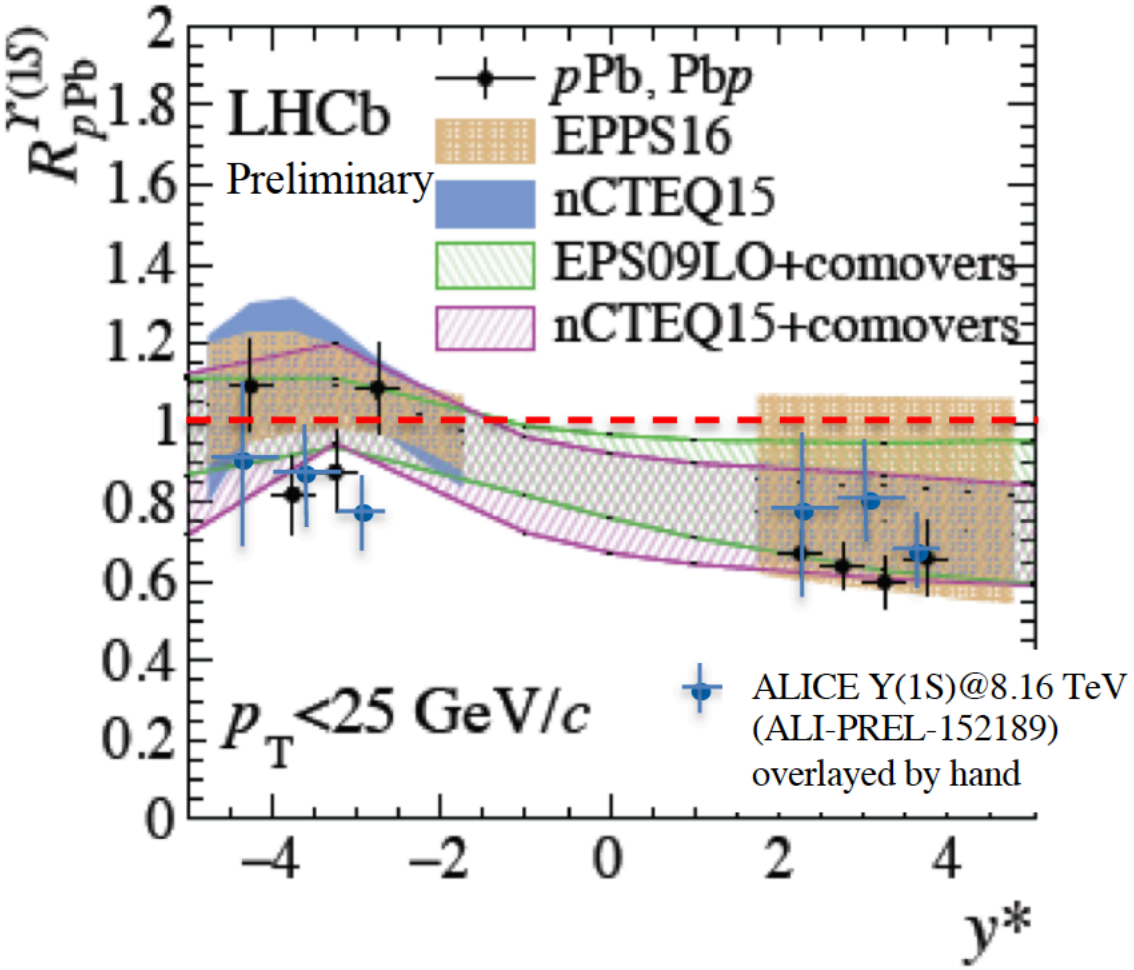
# Conclusions

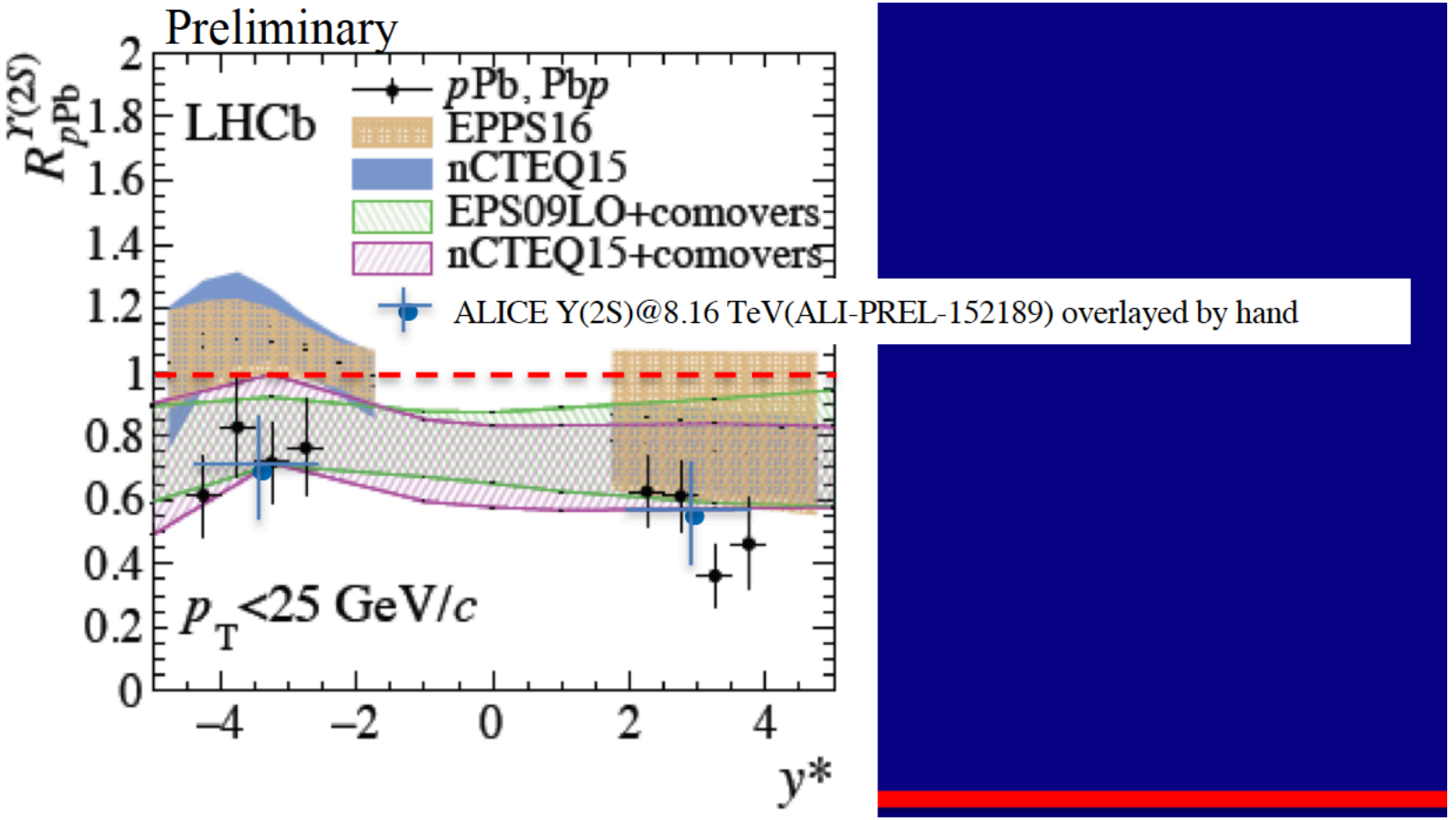
- **The LHCb Detector – a unique facility for forward physics in heavy ion collisions**
- **Unique access to fully reconstructed heavy flavor hadrons at forward rapidity provides powerful constraints on nuclear PDFs and models**
- **Late stage effects on quarkonia (especially excited states) likely important in pPb/PbPb collisions**
  - **Studies with other quarkonia states in pPb at LHCb are underway**
- **SMOG provides precision access to an interesting region of $x,Q^2$**
- **We have only scratched the surface of LHCb capability in heavy ion physics**

# BACKUPS

# Fixed target configuration - SMOG




$R_{pPb}^{\Upsilon(1S)}$
LHCb
Preliminary
$p$Pb, Pb$p$
EPPS16
nCTEQ15
EPS09LO+comovers
nCTEQ15+comovers
$p_T$<25 GeV/$c$
ALICE Y(1S)@8.16 TeV
(ALI-PREL-152189)
overlayed by hand
$y^*$


Preliminary
LHCb
pPb, Pbp
EPPS16
nCTEQ15
EPS09LO+comovers
nCTEQ15+comovers
ALICE Y(2S)@8.16 TeV(ALI-PREL-152189) overlayed by hand
$R_{pPb}^{\Upsilon(2S)}$
$p_T$<25 GeV/$c$
y*
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
−4
−2
0
2
4

# 5 Tev vs 8 TeV comparison