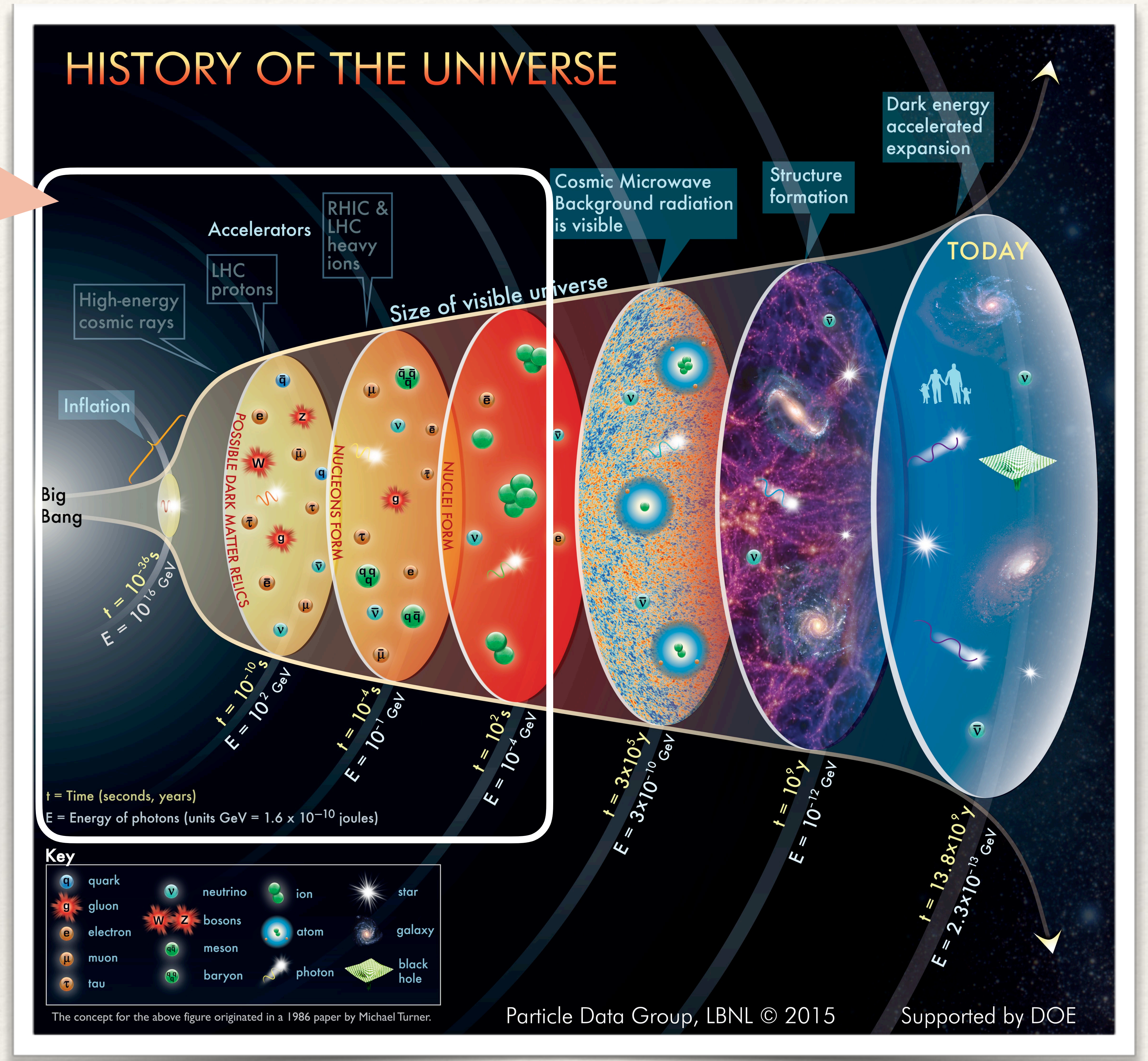
# Heavy ion and fixed target results at LHCb

Hengne Li
(South China Normal University)
on behalf of the LHCb collaboration

# Why study ultra-relativistic heavy ion collisions?

- It's about understanding our Universe.
- Ultra-relativistic heavy ion collisions can help us to understand what happened in the very beginning after the Big Bang.
  - Explore phase diagram of nuclear matter
  - Study QCD matter under extreme conditions
    - Formation of Quark Gluon Plasma at high T and/or energy density.
  - Many other things to explore in pA/AA: nucleon structure, intrinsic charm, QED at extreme field strengths, diffractive processes...



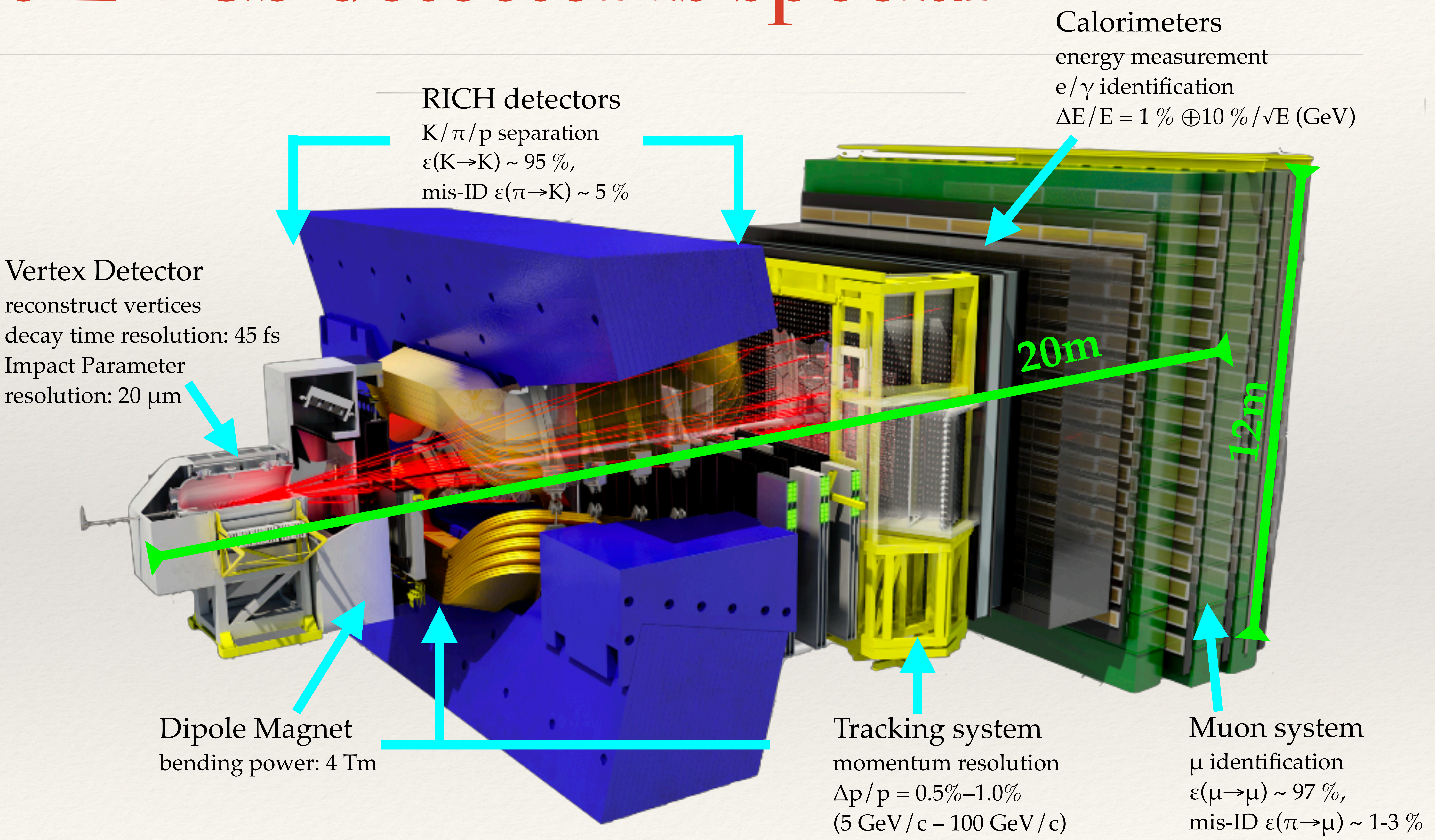
# The LHCb detector is special

[ JINST 3 (2008) S08005 ]
[ IJMPA 30 (2015) 1530022 ]

- LHCb is the only detector fully instrumented in forward region
- Unique kinematic coverage

  $2 < \text{Eta} < 5$

- A high precision device, down to very low-$p_T$, excellent particle ID, precision vertex reconstruction and tracking.

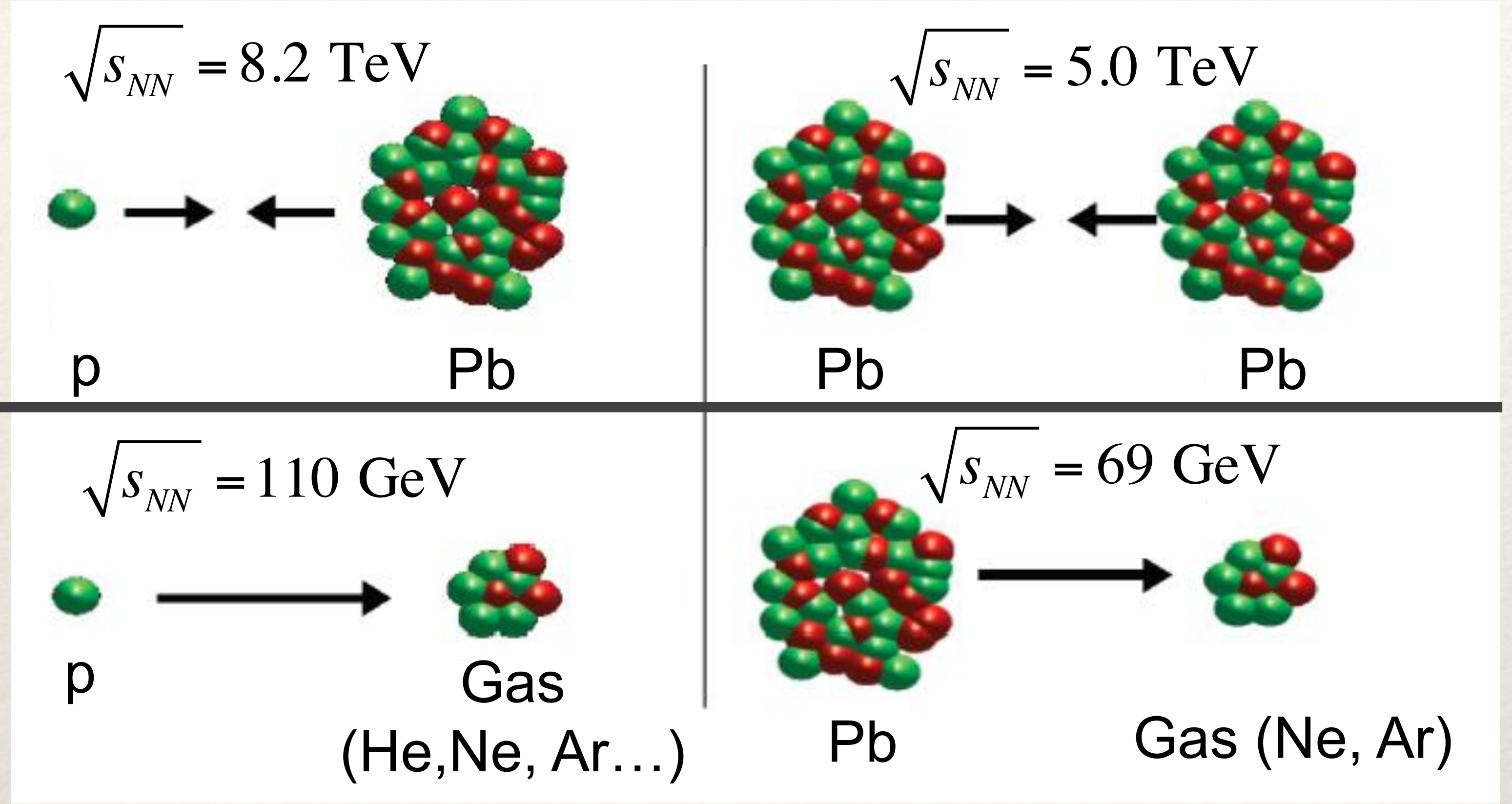


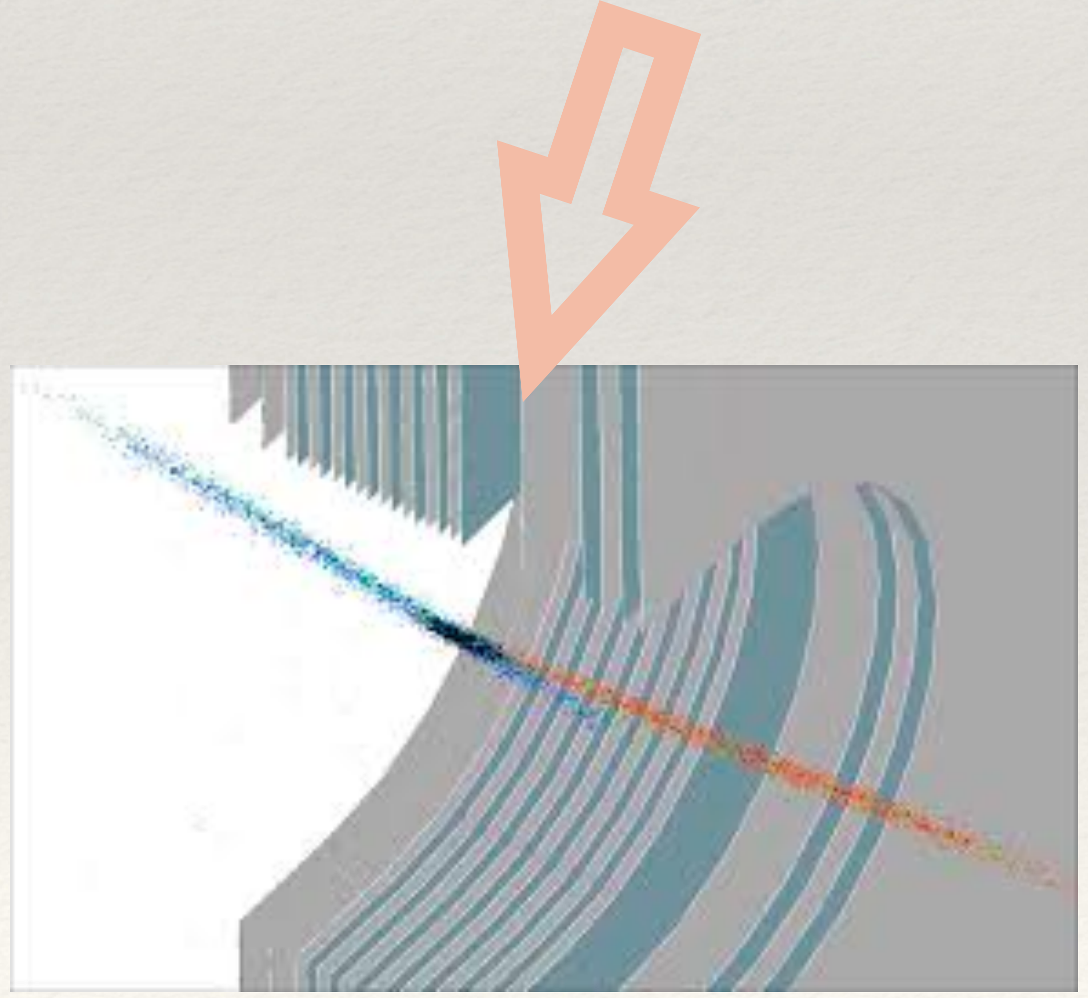
# LHCb running modes and kinematic coverage

**Both the collider mode and fixed target mode running at the same time:**

Collider Mode

Fixed-target Mode (SMOG)



**Collider mode:**

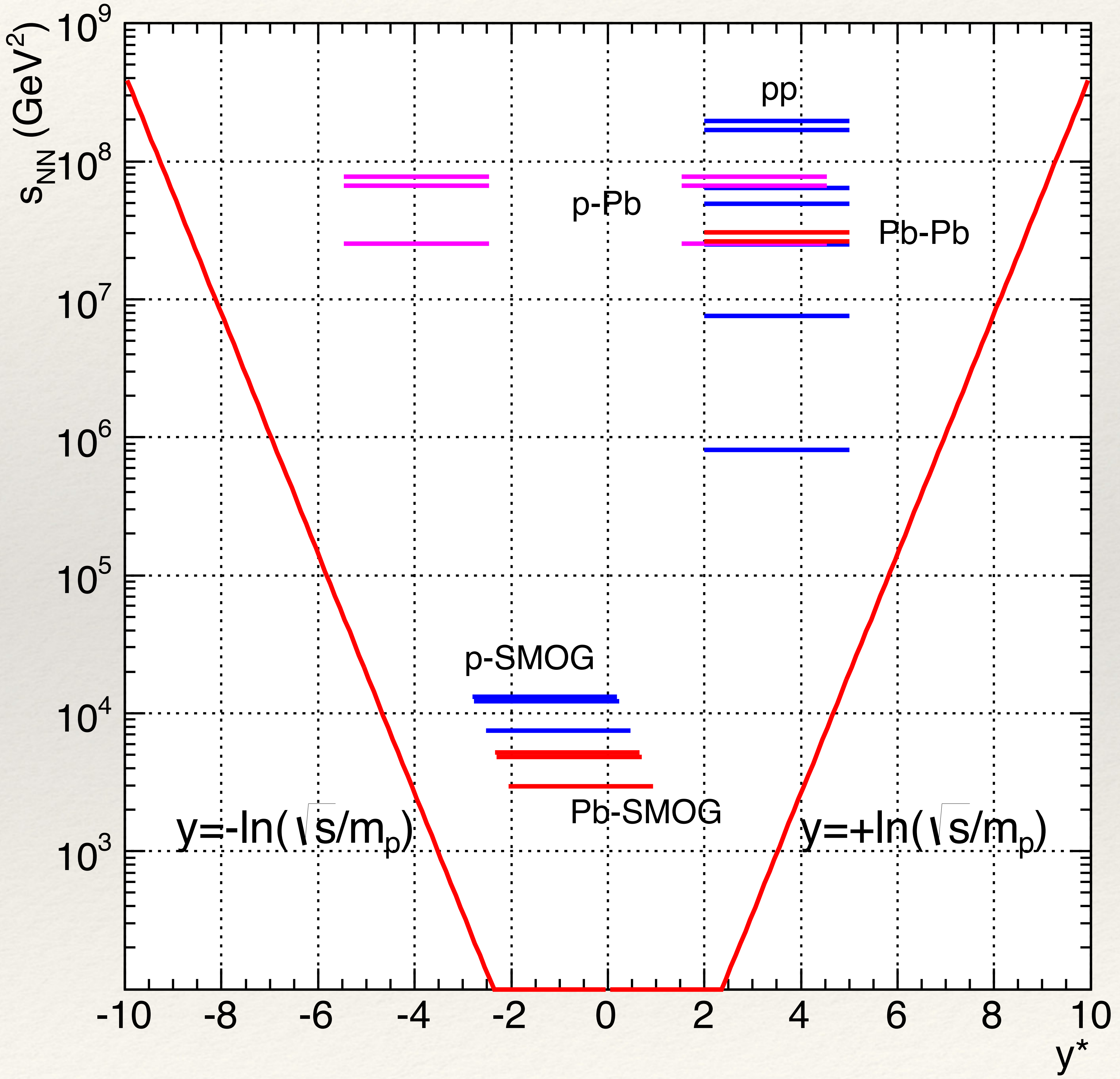
**Forward and backward coverage**

**Fixed target mode:**

**Central and backward coverage**

**$\sqrt{s_{NN}}$: 69 - 110 GeV, fills the gap between SPS (20 GeV) and RHIC (200 GeV) energy scales**

**Kinematic Acceptance**



# Data samples

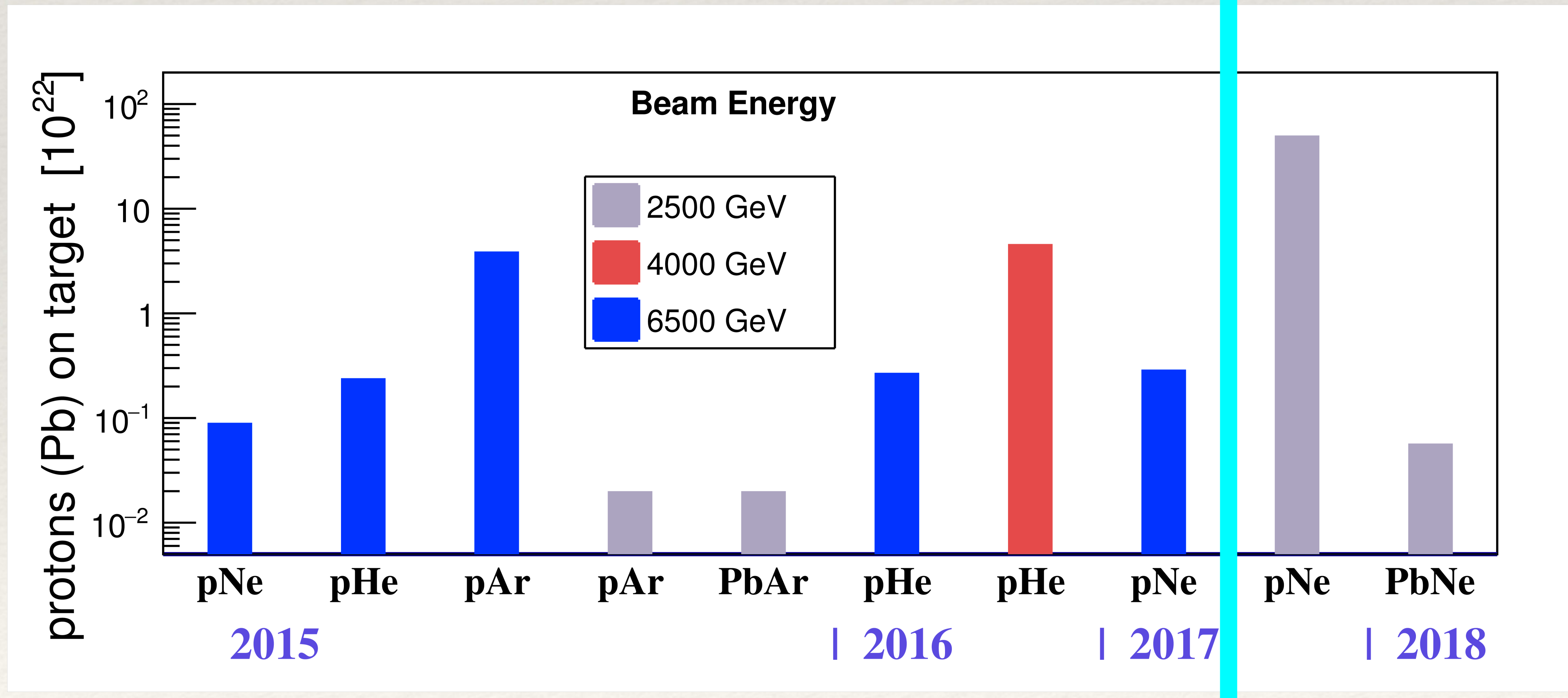
- **Colliding beam mode (pPb and PbPb):**

NEW!

| $\sqrt{s_{NN}}$ | 2013 5.02 TeV | | 2016 8.16 TeV | | 2015 5.02 TeV | 2017 5.02 TeV | 2018 5.02 TeV |
|---|---|---|---|---|---|---|---|
| | pPb | Pbp | pPb | Pbp | PbPb | XeXe | PbPb |
| $\mathcal{L}$ | $1.1\ \text{nb}^{-1}$ | $0.5\ \text{nb}^{-1}$ | $13.6\ \text{nb}^{-1}$ | $20.8\ \text{nb}^{-1}$ | $10\ \mu\text{b}^{-1}$ | $0.4\ \mu\text{b}^{-1}$ | $\sim 210\ \mu\text{b}^{-1}$ |

- **Fixed Target mode (SMOG):**
  - **$\sqrt{s_{NN}}$: 69-110GeV**

$$\int \mathcal{L}dt \sim 5\text{nb}^{-1} \times \frac{(protons\ on\ target)}{10^{22}} \times \frac{p_{gas}}{2\times 10^{-7}\text{mbar}} \times \text{Exp\_efficiency}$$

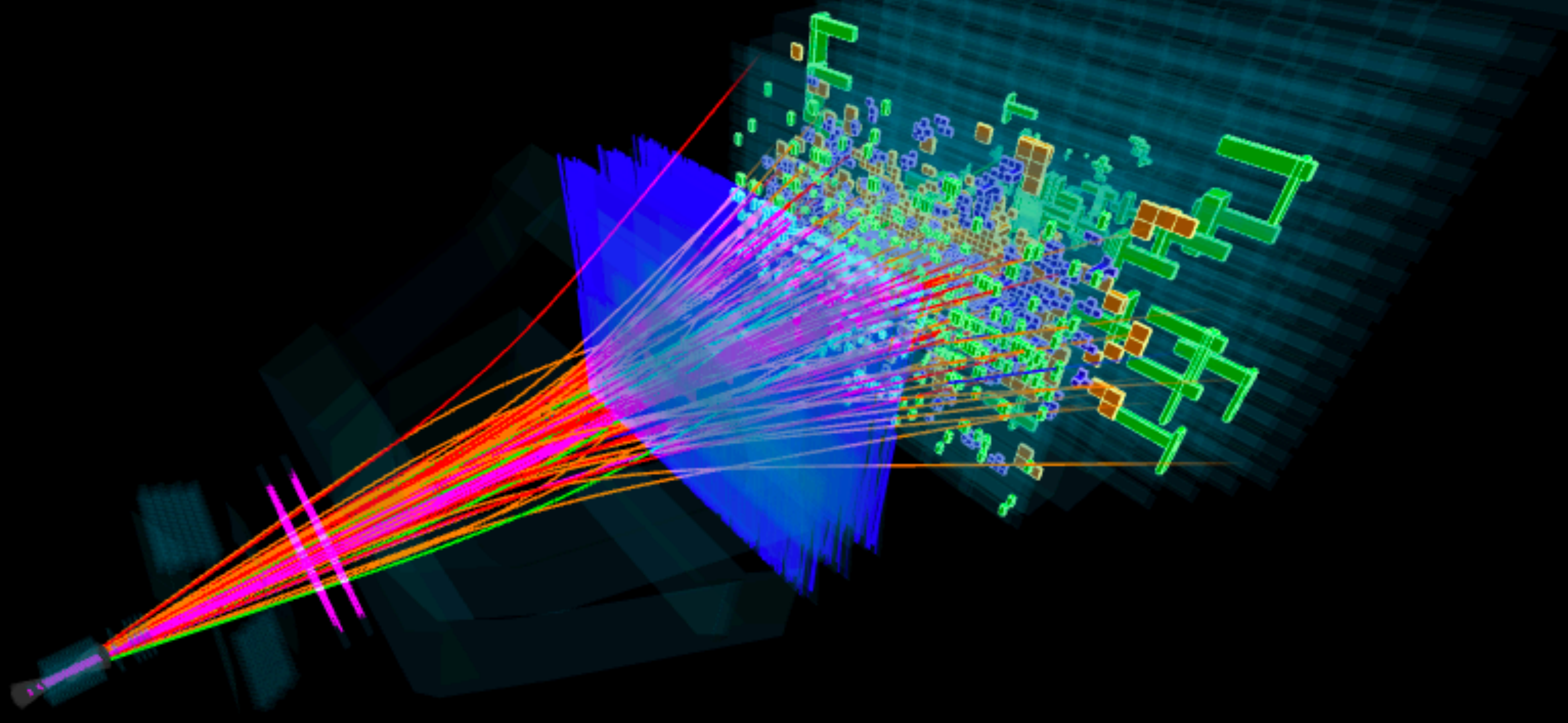


## LHCb provides unique datasets for Heavy Ion physics studies.

Event 21079095

Run 217709

Thu, 08 Nov 2018 22:56:35

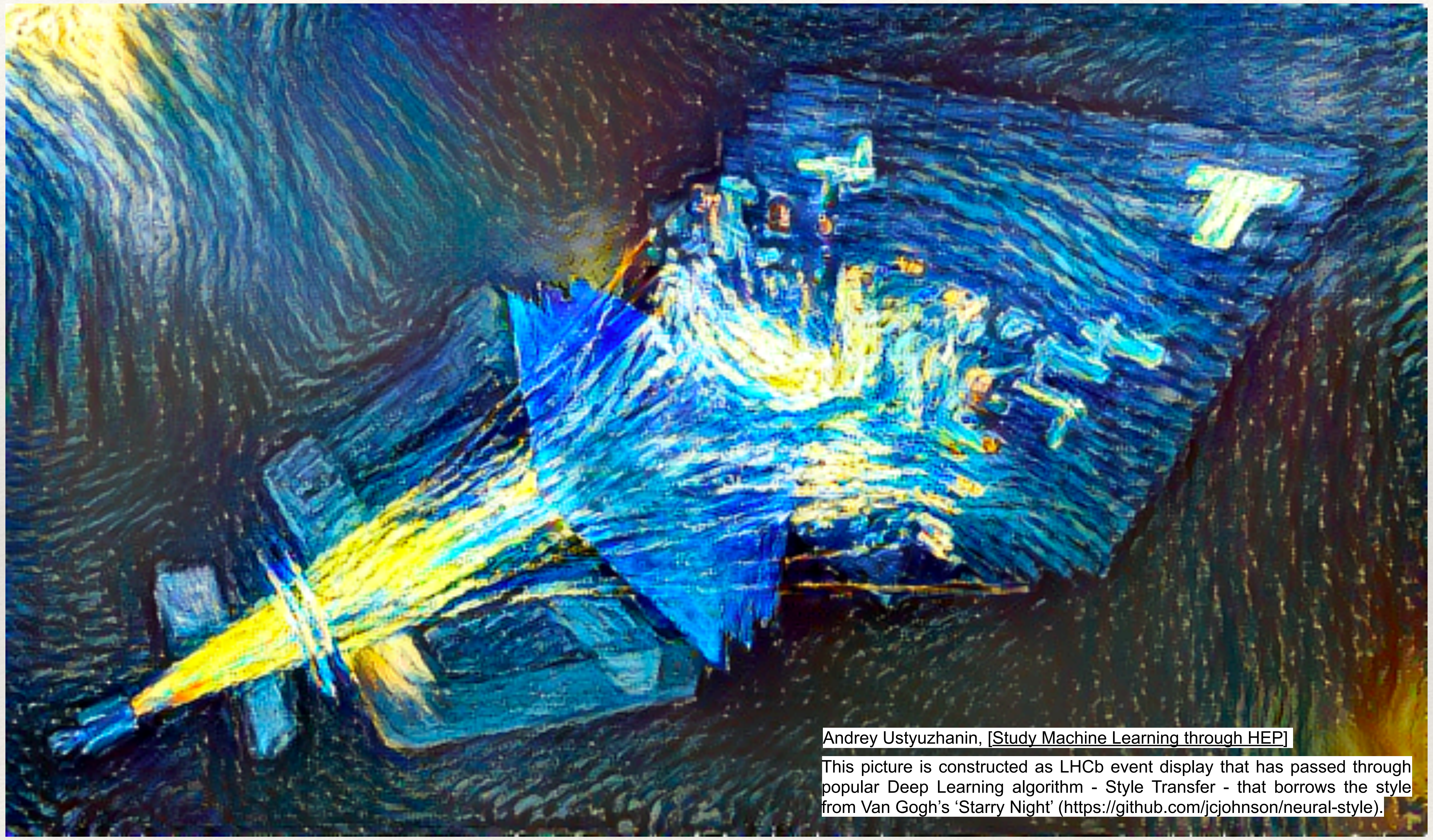


Event display from the first lead-lead LHC collisions in 2018

# Recent LHCb Heavy Ion Results

- **Charm production in fixed-target collisions:**
  - LHCb-PAPER-2018-023, arXiv:1810.07907
- **Anti-proton production in fixed-target collisions:**
  - PRL. 121, 222001 (2018)
- **Heavy flavor production in pPb collisions:**
  - $D^0$ at 5.02TeV: LHCb-PAPER-2017-015, JHEP (2017) 090 [backup slides]
  - $\Lambda_c^+$ at 5.02TeV: LHCb-PAPER-2018-021, arXiv:1809.01404
  - $J/\psi$ at 8.16TeV: LHCb-PAPER-2017-014, PLB774 (2017) 159 [backup slides]
  - $B^+$, $B^0$, $\Lambda_b^0$ at 8.16TeV: LHCb-CONF-2018-004
  - $\Upsilon$(nS) at 8.16TeV: JHEP 11 (2018) 194
- **Exclusive photonuclear J/Psi production in ultra-peripheral PbPb collisions:**
  - LHCb-CONF-2018-003

# Fixed target collisions

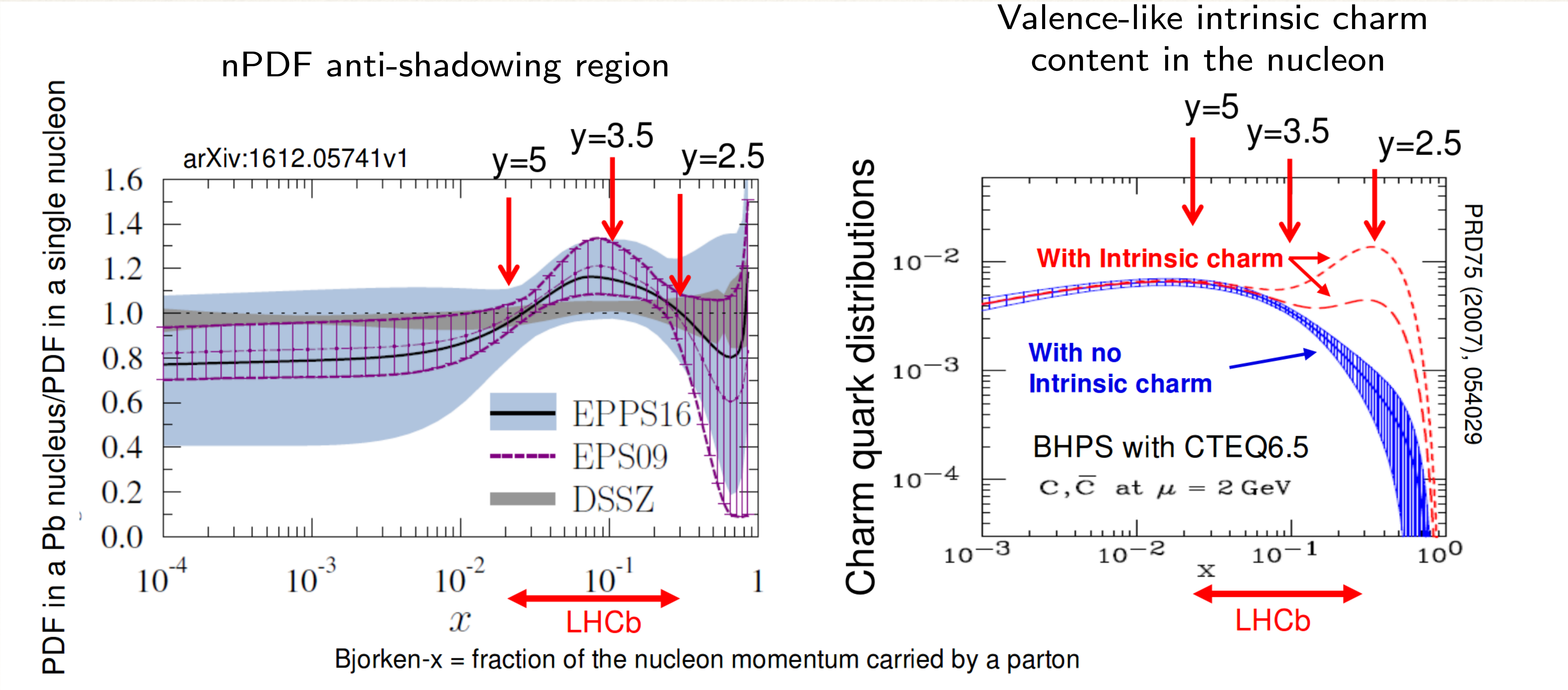


Andrey Ustyuzhanin, [Study Machine Learning through HEP]

This picture is constructed as LHCb event display that has passed through popular Deep Learning algorithm - Style Transfer - that borrows the style from Van Gogh's 'Starry Night' (https://github.com/jcjohnson/neural-style).

# Charm production in fixed-target

- Access to the anti-shadowing region of nPDF and probe the intrinsic charm content in the nucleons.



# Charm production in fixed-target collisions

LHCb-PAPER-2018-023
arXiv:1810.07907

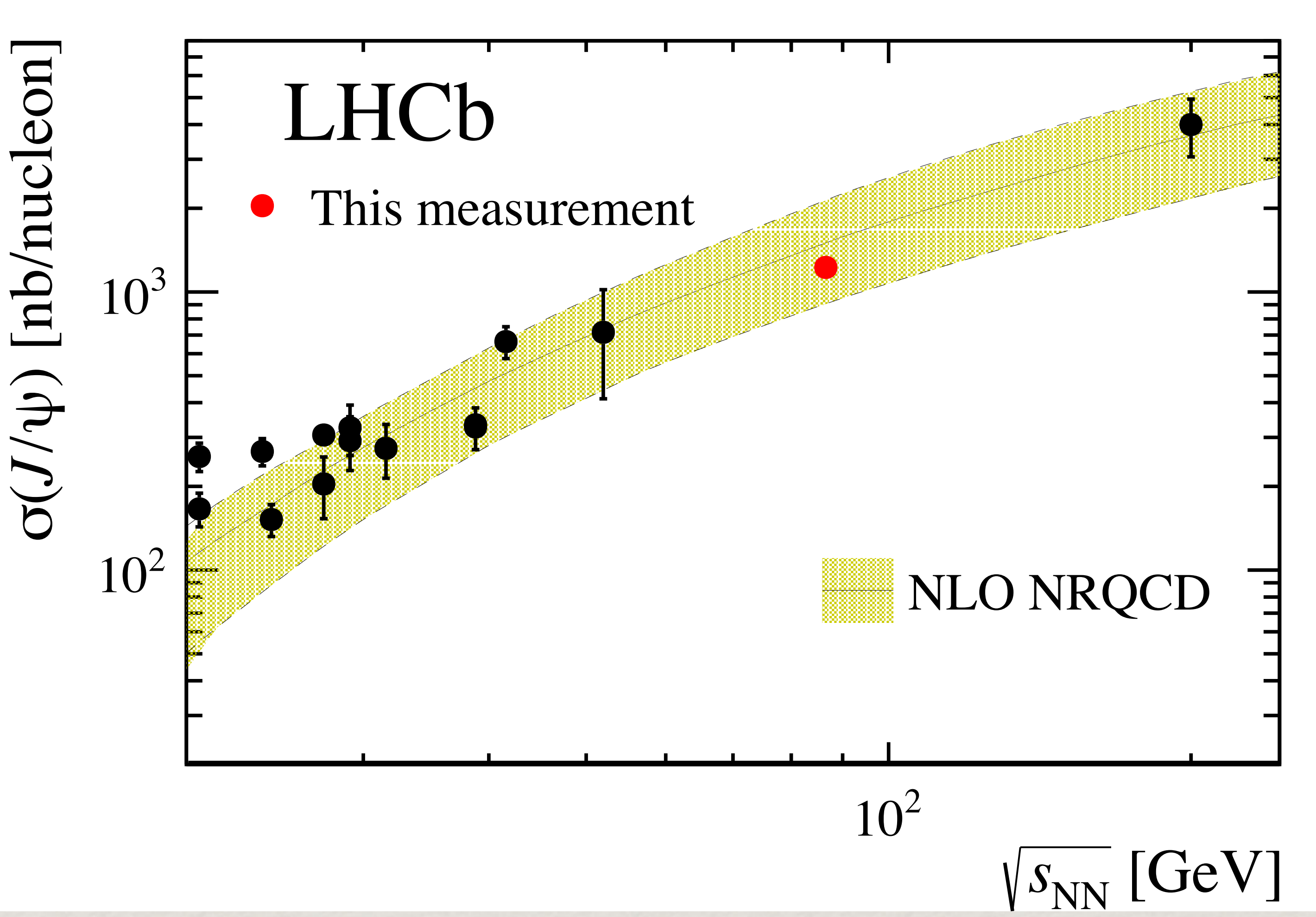
- J/ψ and $D^0$ inclusive cross section in pHe collisions $\sqrt{s_{NN}} = 86.6$ GeV:
  - Cross section measured in $J/\psi \to \mu^+\mu^-$ and $D^0 \to K^- \pi^+$ decays

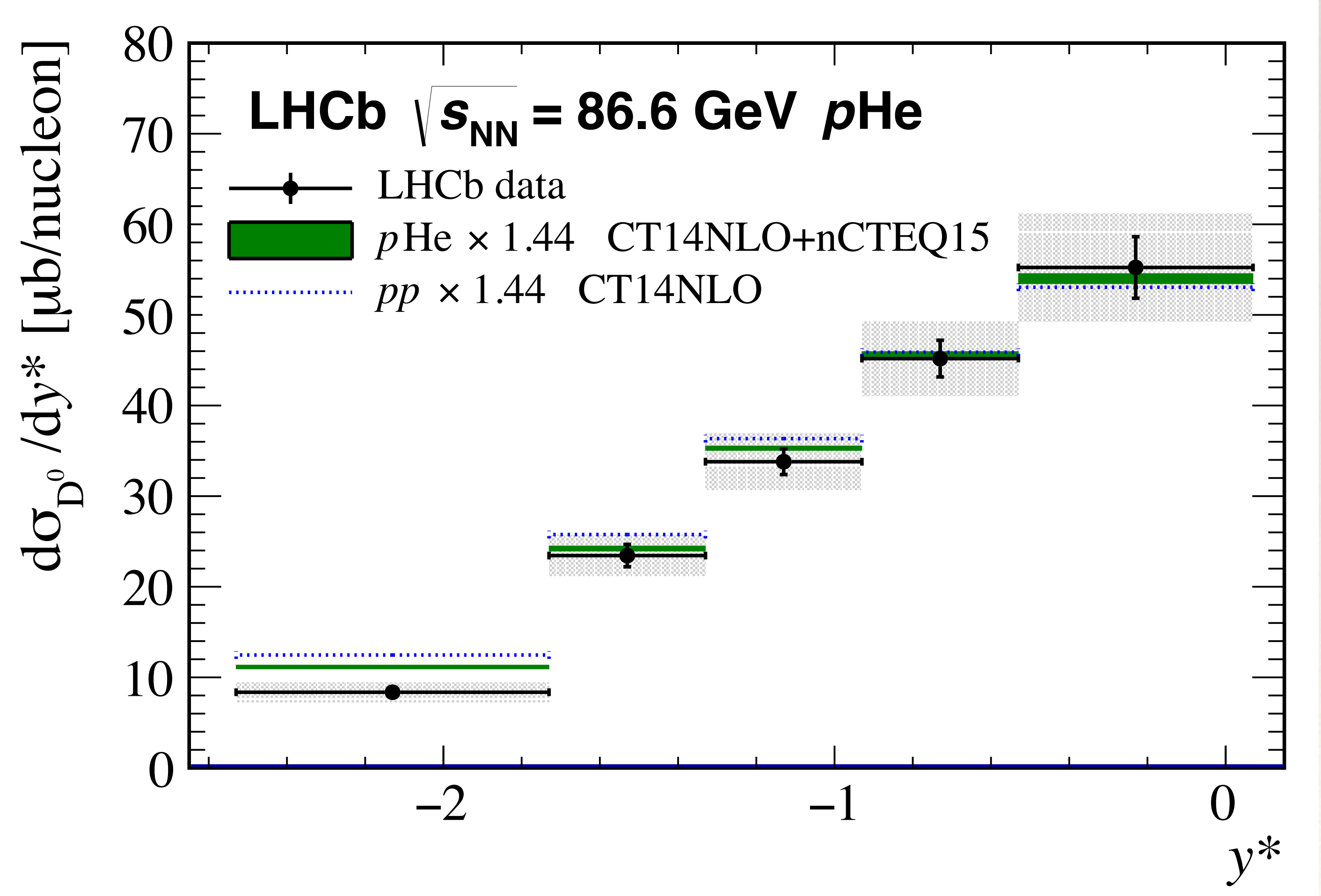
$$\sigma_{J/\psi} = 1225.6 \pm 100.7\,\text{nb/nucleon},$$
$$\sigma_{D^0} = 156.0 \pm 13.1\,\mu\text{b/nucleon},$$

- Scaling the $D^0$ cross-section with the global fragmentation ratio $f(c \to D^0) = 0.542 \pm 0.024$, the $c\bar{c}$ production cross section can be obtained: $\sigma_{c\bar{c}} = 288 \pm 24.2 \pm 6.9\,\mu\text{b/nucleon}$

- LHCb results in good agreement with NLO NRQCD fit (J/ψ) and NLO pQCD predictions ($c\bar{c}$) and other measurements

- No strong intrinsic charm content is observed.

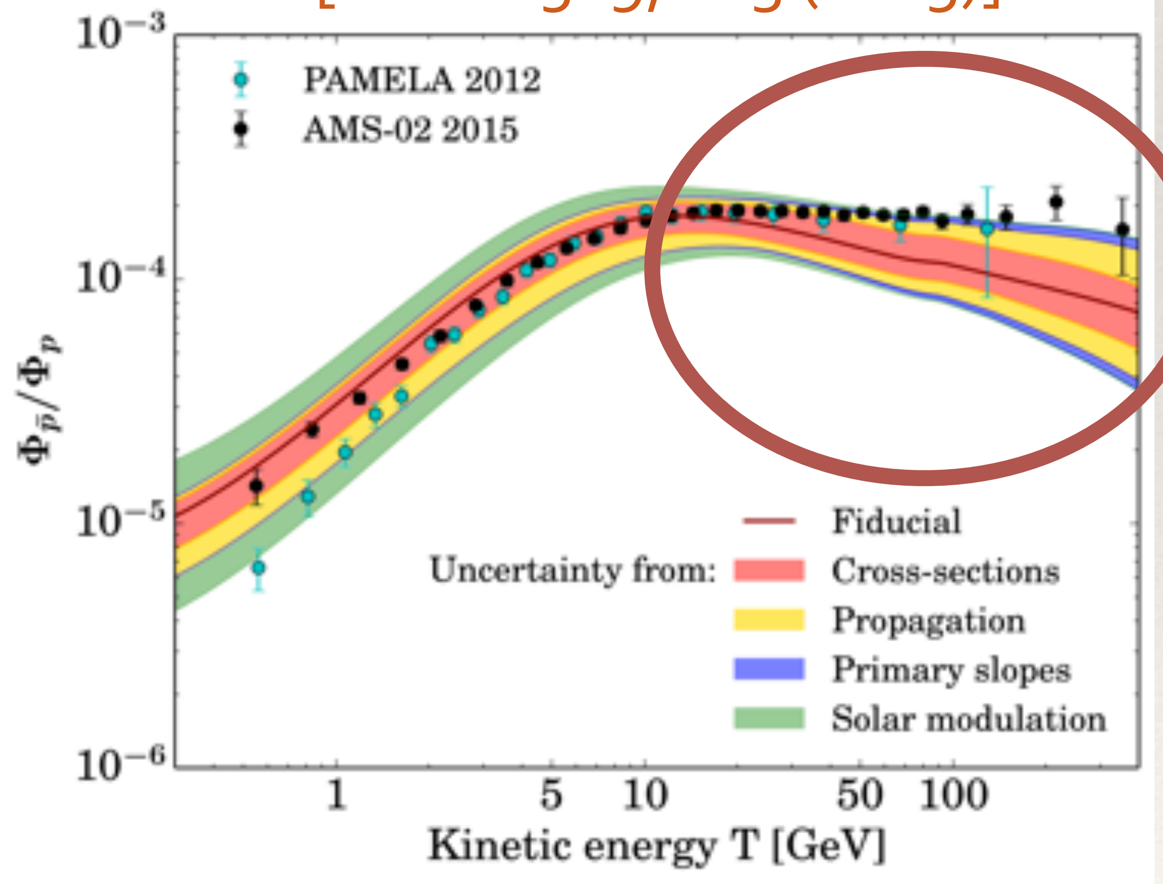


# Anti-proton production in fixed-target

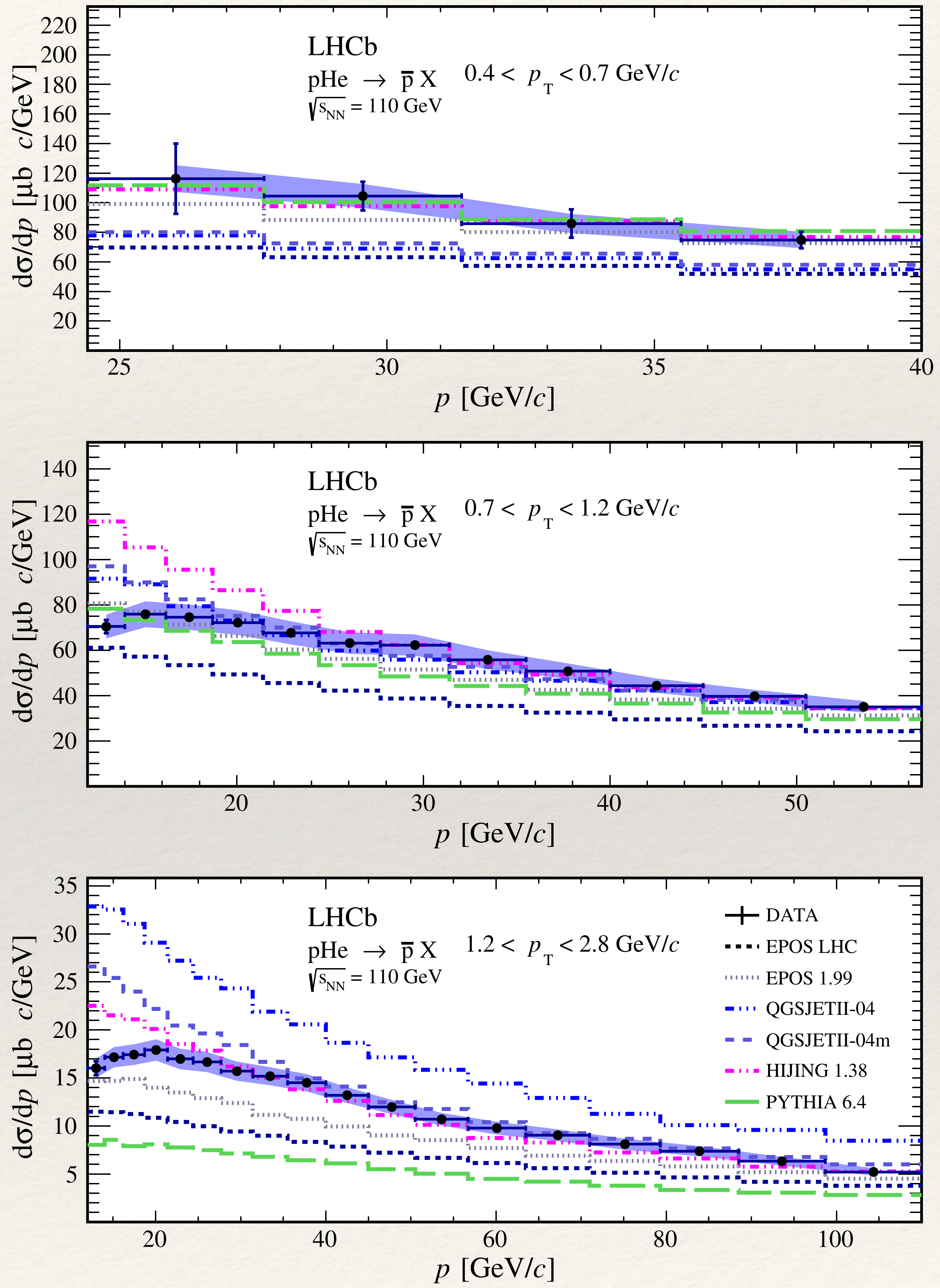
- $\bar{p}$-production measurement in fixed-target p-He collisions (2016, $\sqrt{s_{NN}} = 110$ GeV) at LHCb can help to constrain the theoretical uncertainties for Dark Matter searches.
  - AMS2 and PAMELA give precise measurement of anti-proton/proton ratio results.
  - But hard to draw a conclusion because imperfect knowledge of the $\bar{p}$-production cross-sections when comparing with theoretical predictions

[JCAP 1509, 023 (2015)]

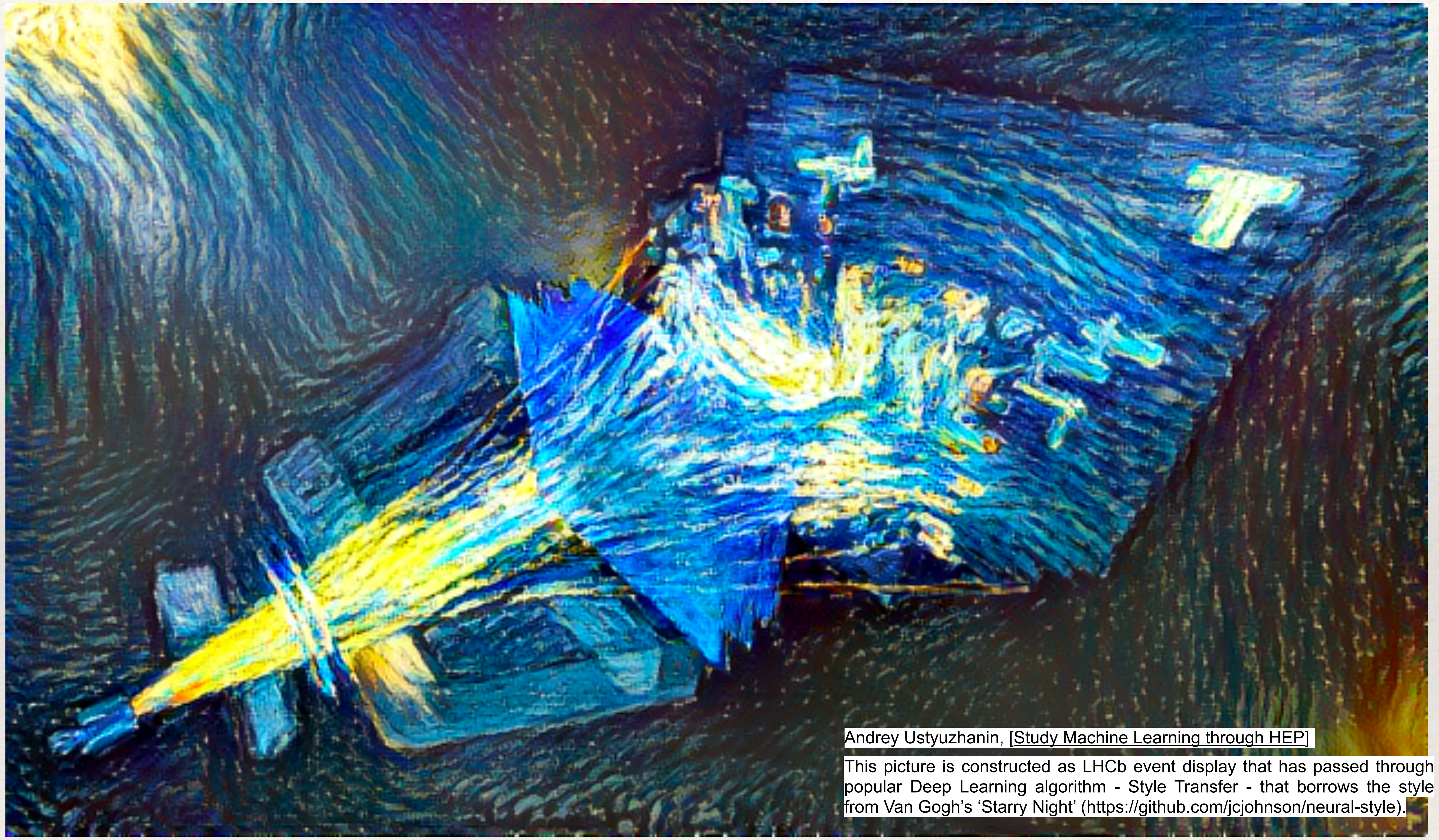



- The unique and precise LHCb $\bar{p}$-production results give a strong constraint to theoretical prediction.
- Gives a decisive contribution to shrink background uncertainties in dark matter searches in space

PRL. 121, 222001 (2018)



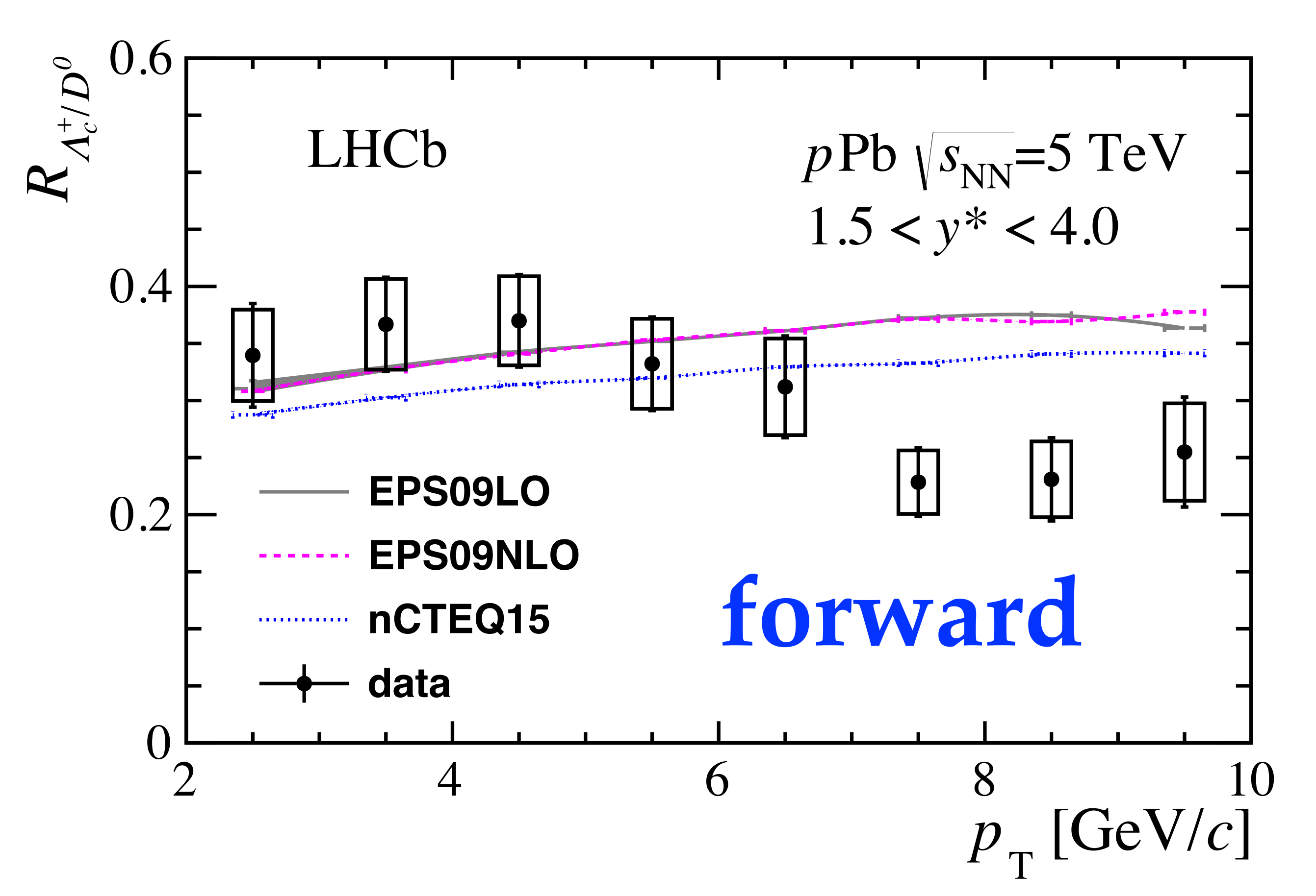
# Heavy flavor physics in p-lead collisions

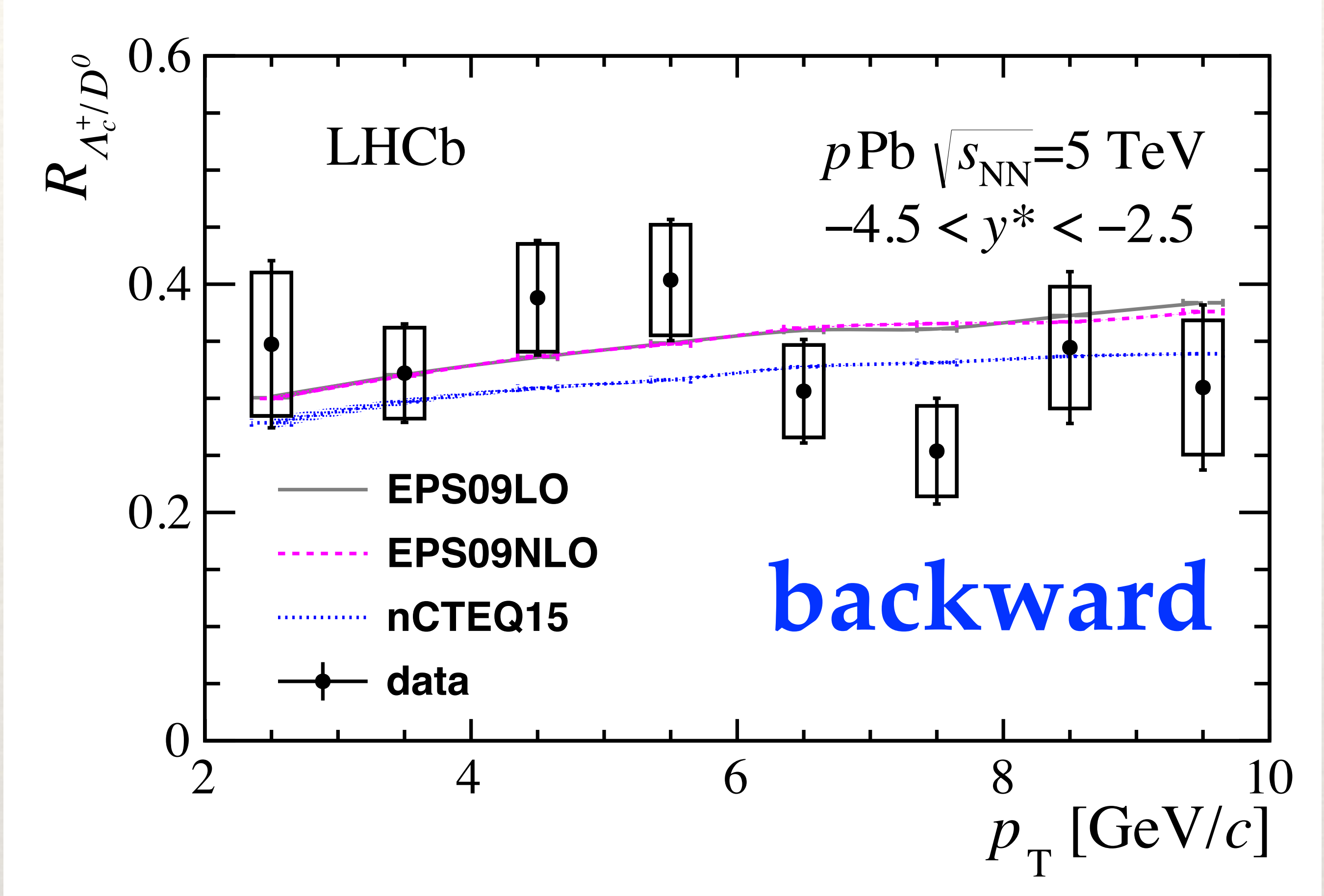


# Prompt $\Lambda^+_c$ production

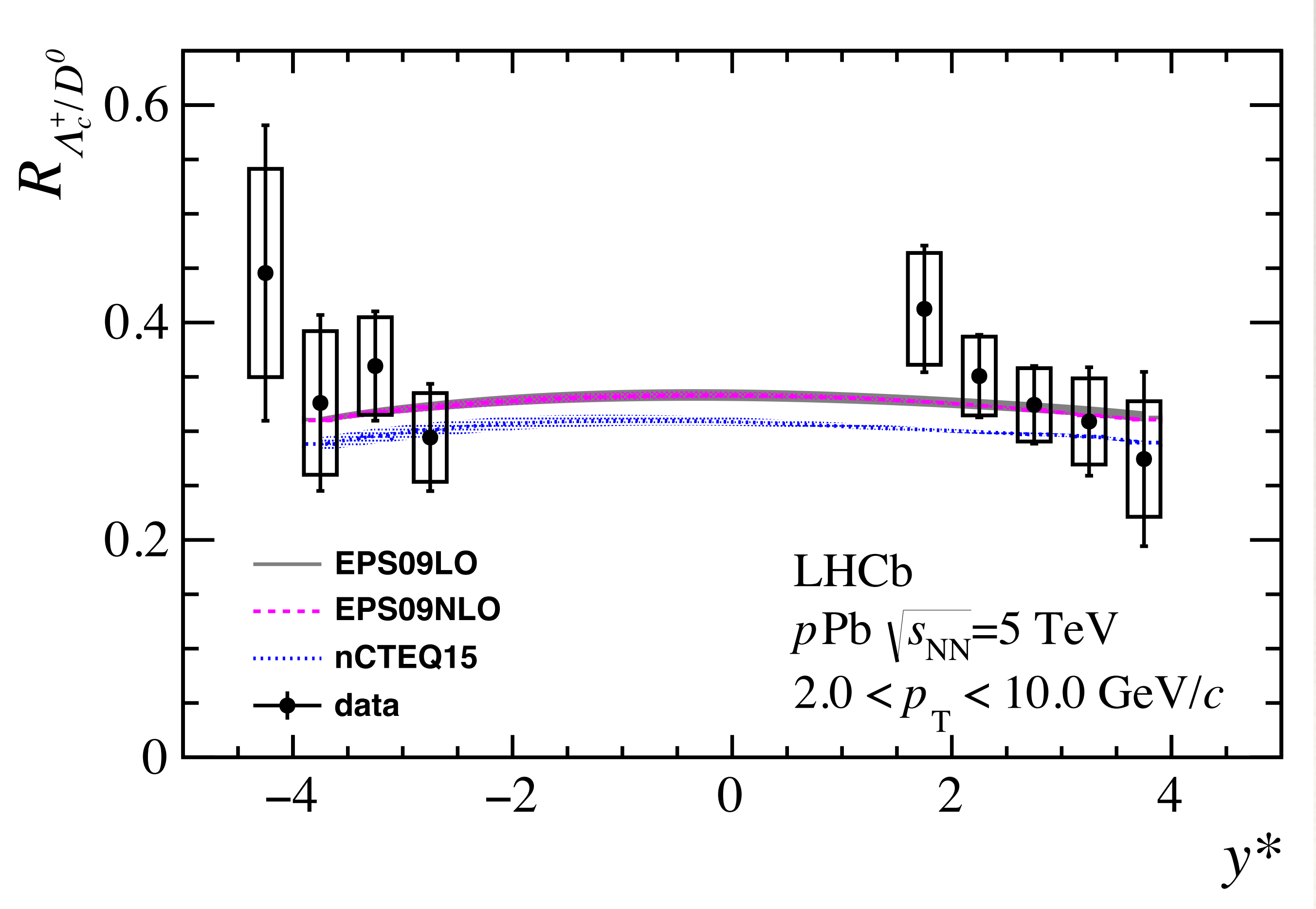
- Baryon-to-meson cross-section ratio $\Lambda^+_c / D^0$ is sensitive to charm hadronisation mechanism
  - Forward rapidity: discrepancies at high-$p_T$ between data and models tuned to pp
  - Backward rapidity: good agreement between data and model predictions
- Compared with nPDFs:
  EPS09LO: [Comput. Phys. Commun. 184 (2013) 2562]
  EPS09NLO: [Comput. Phys. Commun. 198 (2016) 238]
  nCTEQ15: [EPJC 77 (2017) 1]

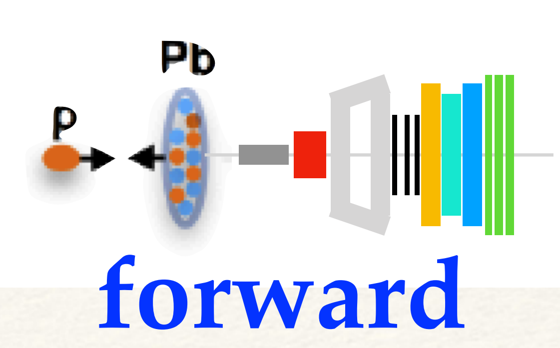
**$\Lambda^+_c / D^0$ Ratio vs. pT**

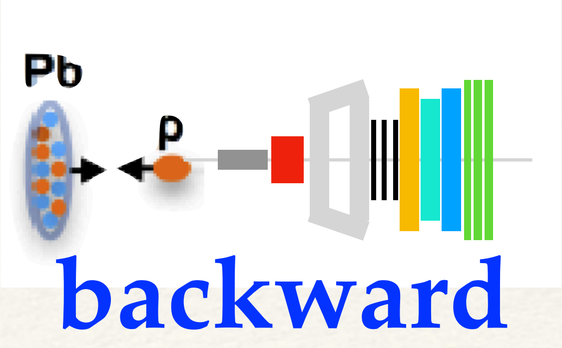



**$\Lambda^+_c / D^0$ Ratio vs. Rapidity**



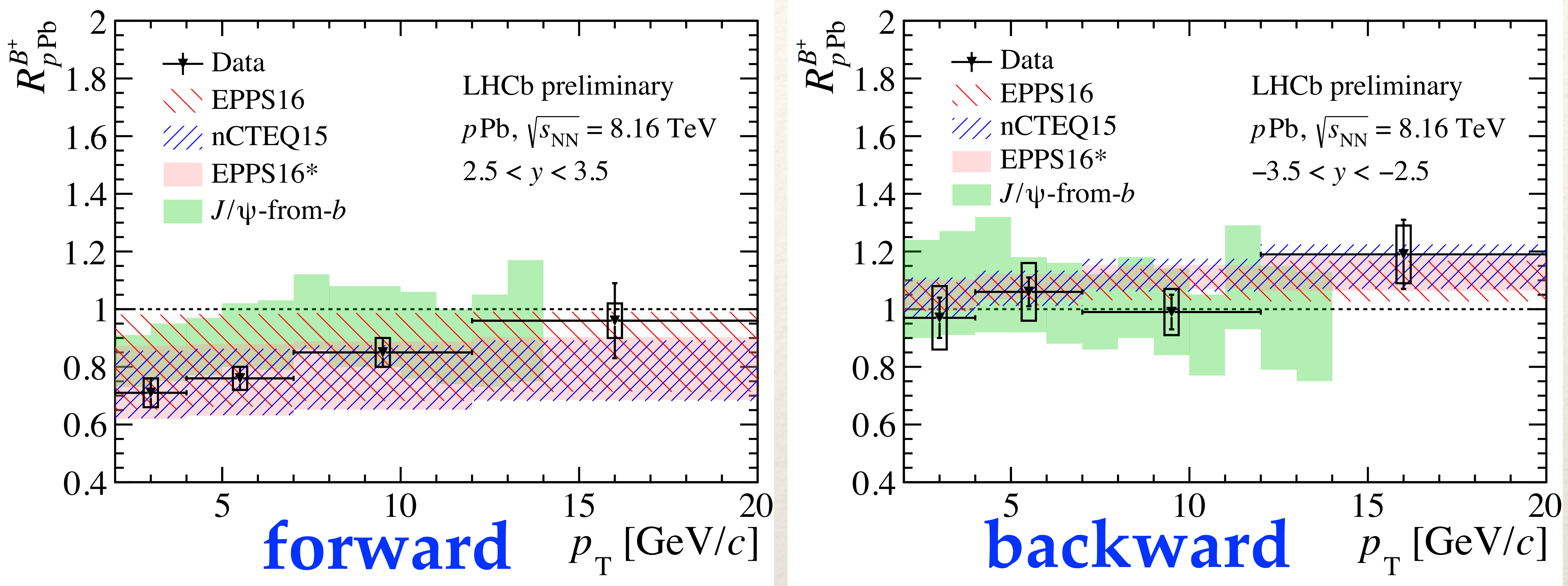




**LHCb-PAPER-2018-021**
**arXiv:1809.01404**

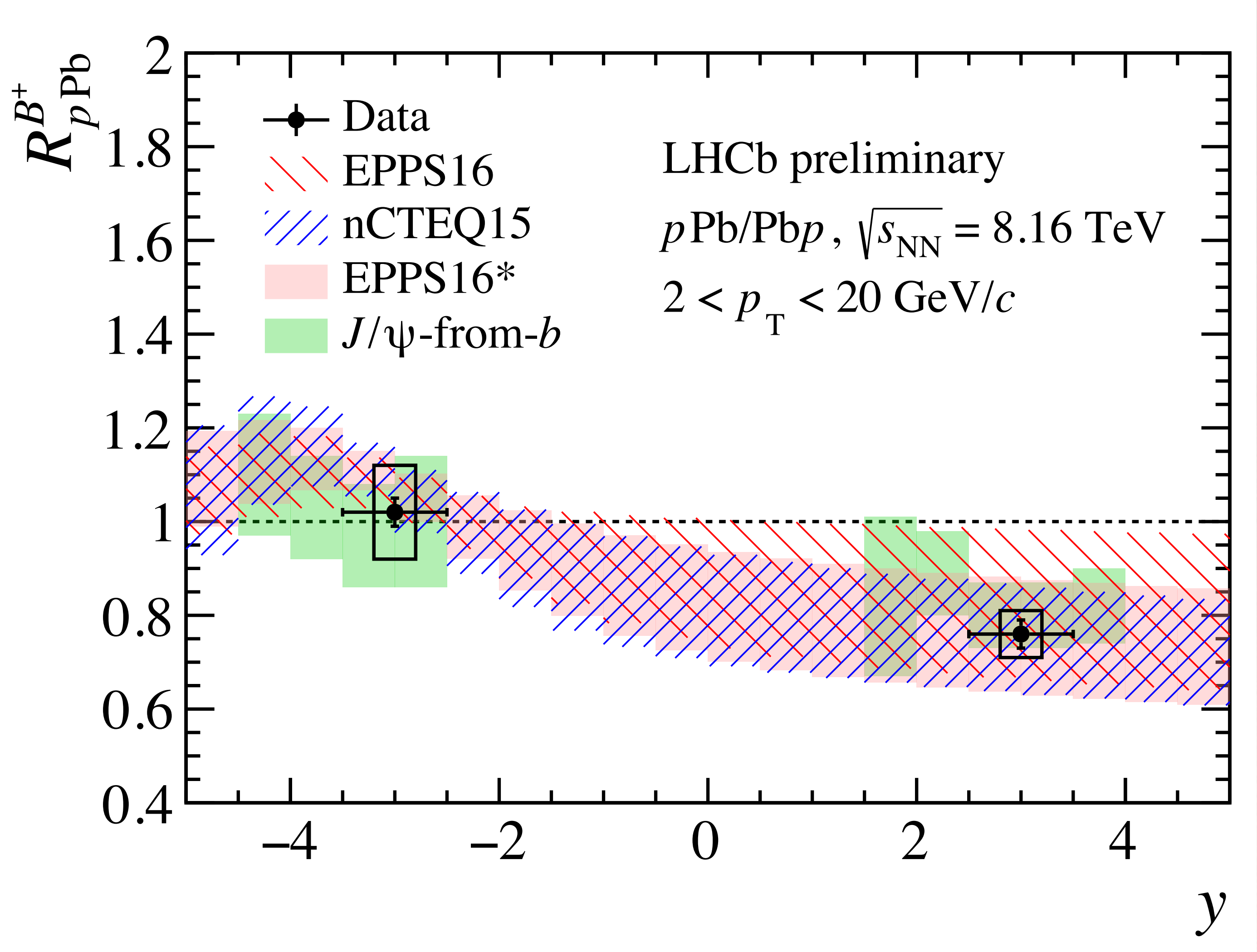
# b - hadron production in pPb

- Exclusive decay modes:
  $B^+ \to J/\psi K^+$, $B^+ \to D^0 \pi^+$, $B^0 \to D^- \pi^+$, $\Lambda_b^0 \to \Lambda_c^+ \pi^-$
- Pattern consistent with $R_{pA}$ of $D^0$ mesons
- Significant suppression (≈ 25%) in fwd rapidity, suppression decreases at large $p_T$
- Consistent with unity at backward rapidity
- Measurements in good agreement with J/ψ-from-b decay data and calculations using nPDF sets [JHEP 04 (2009) 065, EPJ C77 (2017) 1, CPC. 198 (2016) 238]

**Nuclear modification factor vs. $B^+$ $p_T$**




**Nuclear modification factor vs. $B^+$ rapidity**



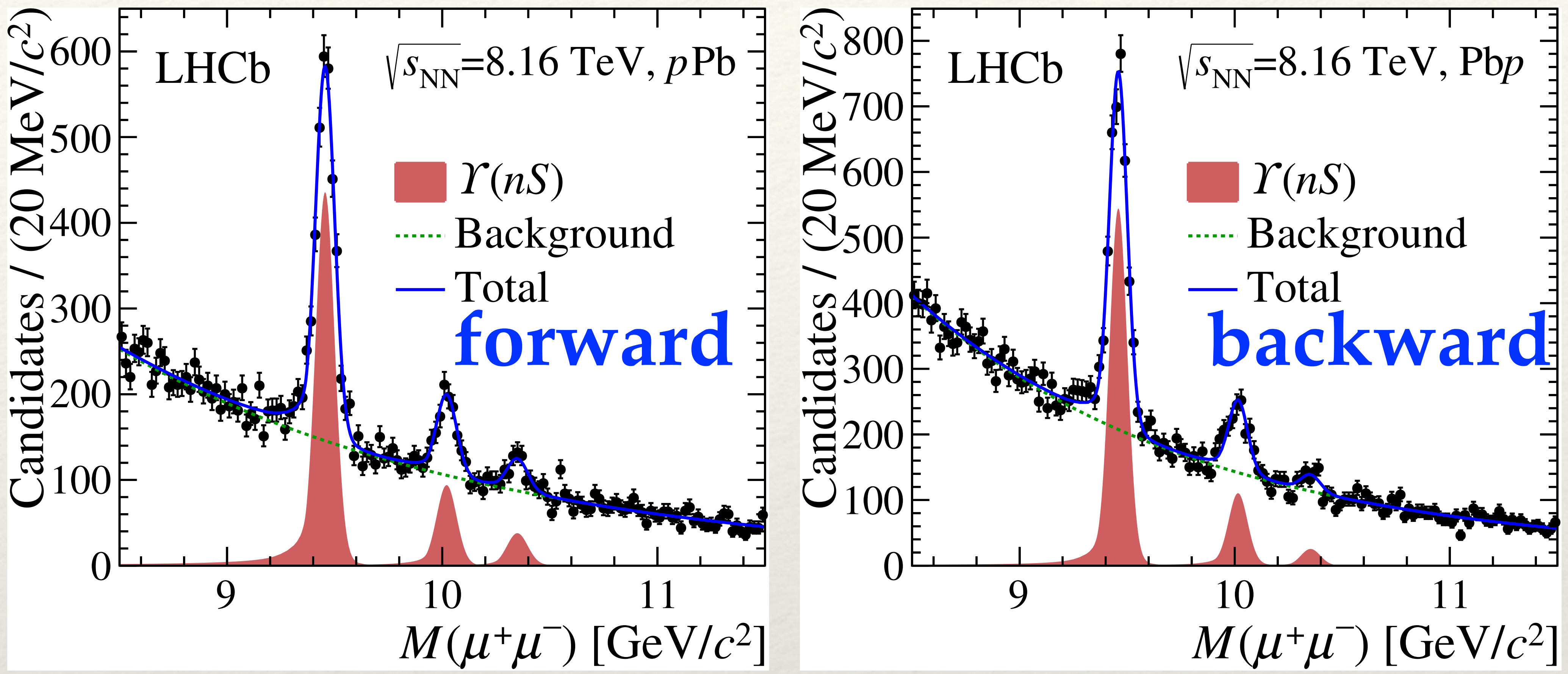

**LHCb-CONF-2018-004**

# ϒ(nS) production in pPb

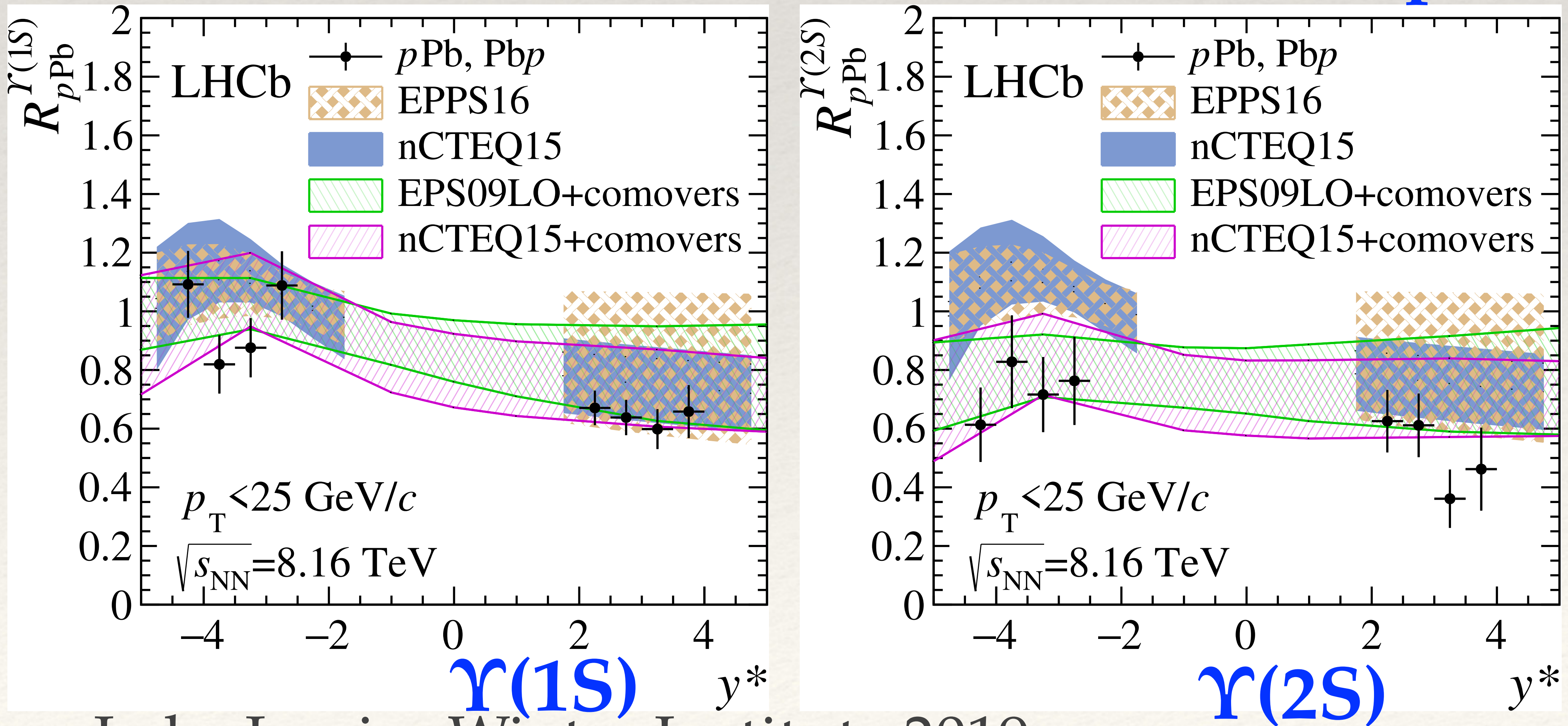
**JHEP 11 (2018) 194**

- ϒ(nS) suppression observed in PbPb and pPb/Pbp by CMS and ALICE at low-pT
- LHCb results at 8.16 TeV:
  - Clear ϒ(3S) signal in both forward and backward rapidity
  - ϒ(1S) forward suppressed by ~30%
  - ϒ(1S) backward compatible with 1 within nPDF uncertainties
  - ϒ(2S) additional suppression confirmed
- Comparing with models:
  - EPPS16: Eur. Phys. J. C (2017) 77 163
  - EPS09: JHEP 04 (2009) 065
  - nCTEQ15: Phys.Rev.D93 (2016) 085037
  - Comovers: Phys. Lett. B749 (2015) 98

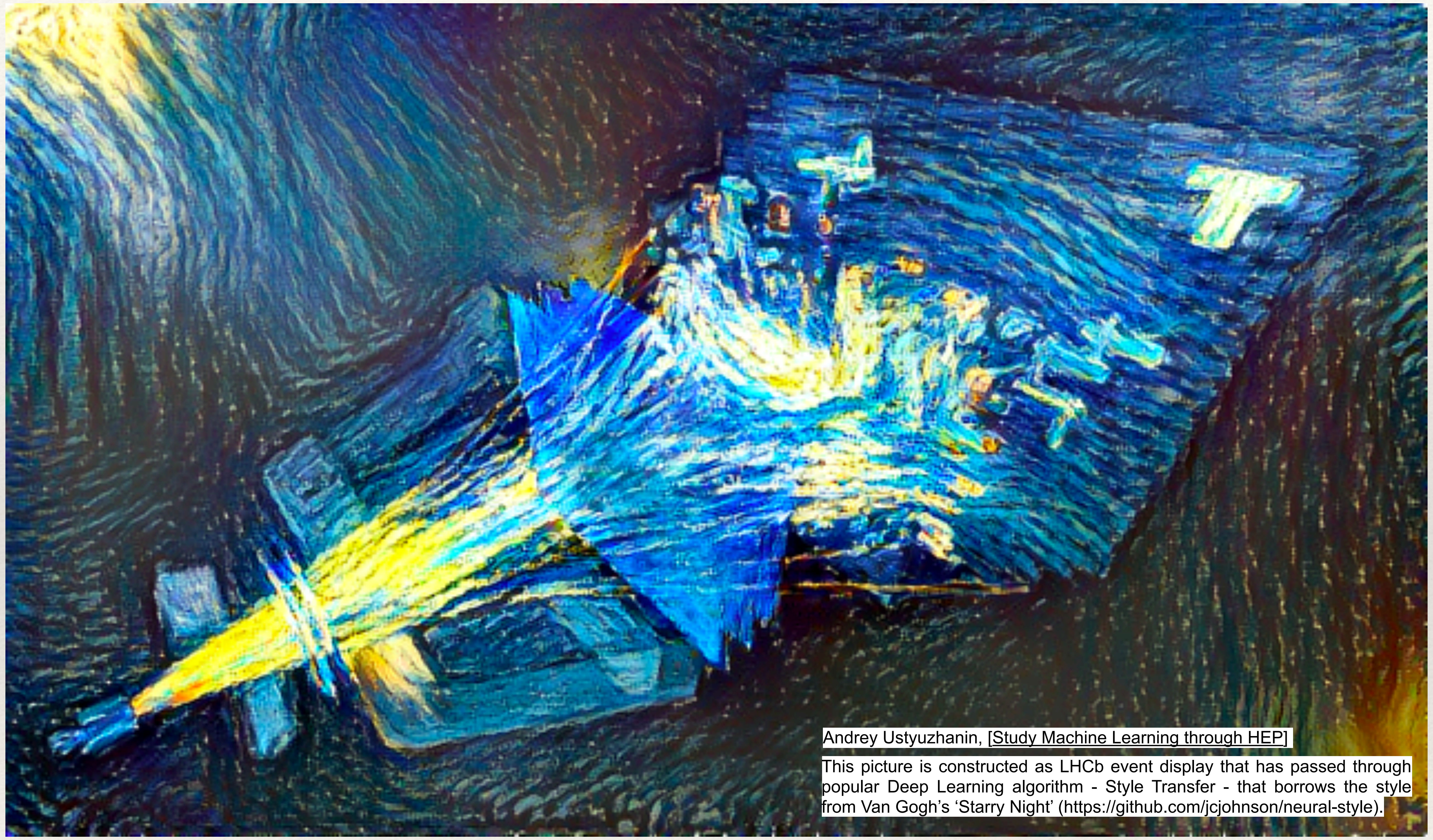
**Di-muon invariant mass**




**Nuclear modification factor vs. ϒ(nS) rapidity**



# Lead-lead collisions



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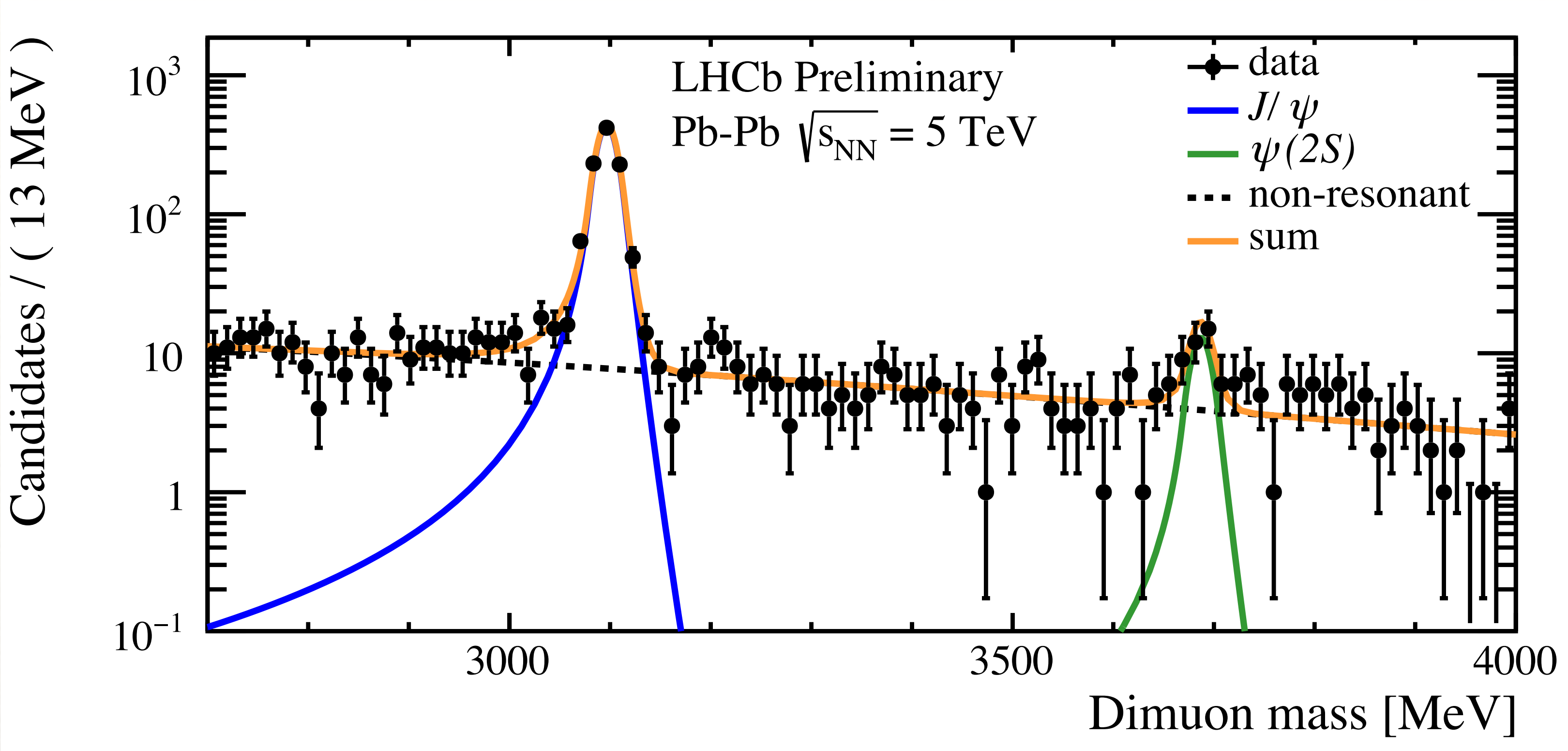
# J/ψ production in ultra-peripheral PbPb collisions

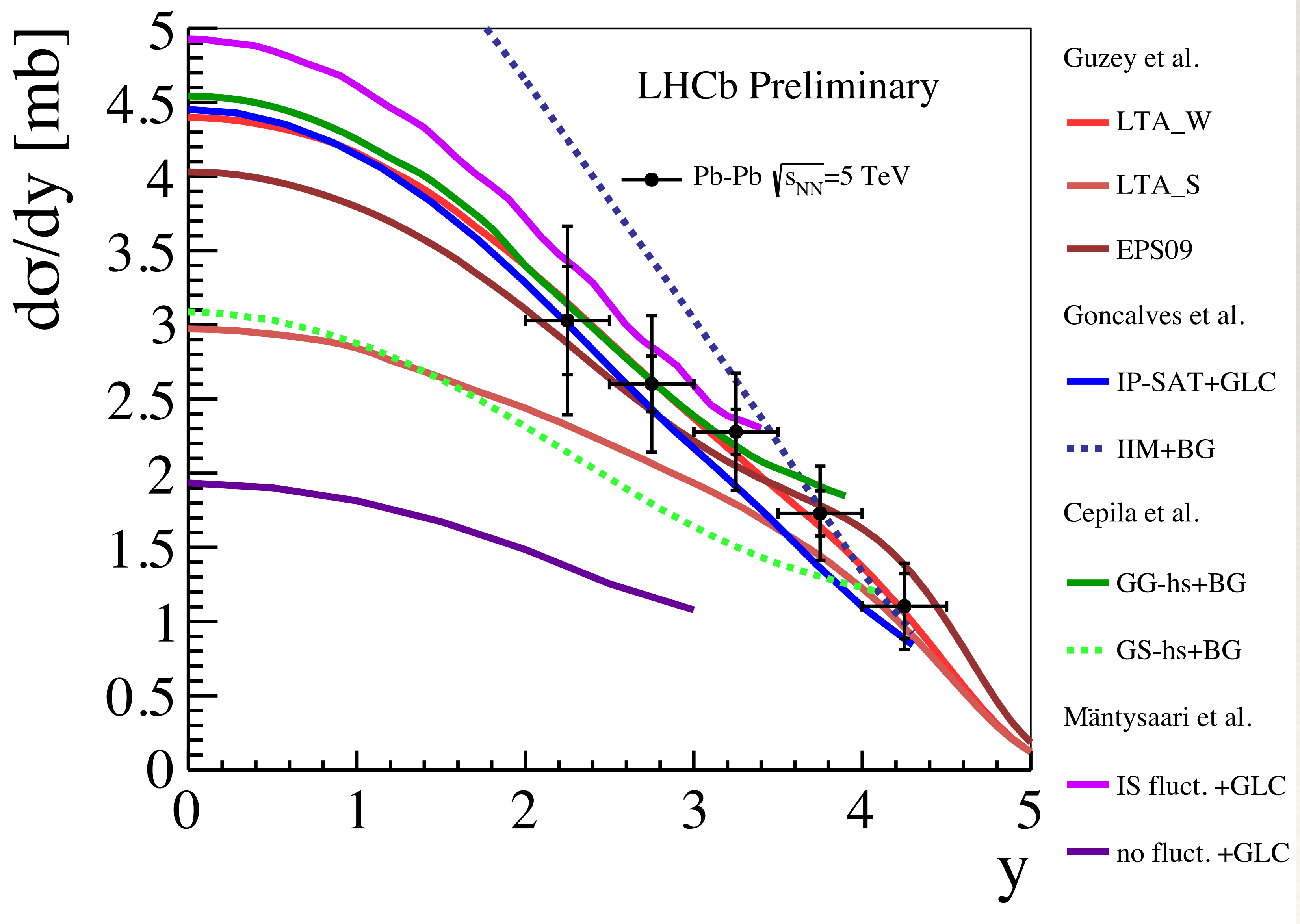
- Ultra-peripheral collisions: Two nuclei bypass each other with an impact parameter larger than the sum of their radii.
- Photon-induced J/ψ production cross-section is enhanced by the strong electromagnetic field of the nucleus
- Coherent (photon couples to all nucleons) J/ψ production gives constraints to nPDF
- Cross section for coherent J/ψ production at 5 TeV:

$$\sigma = 5.3 \pm 0.2\ (\mathrm{stat}) \pm 0.5\ (\mathrm{syst}) \pm 0.7\ (\mathrm{lumi})\ \mathrm{mb}$$

- Phenomenological models:
PRC 97 024901 (2018), PRD 96 094027 (2017), PRC 93 055206 (2016), PLB 772 (2017) 832

**LHCb-CONF-2018-003**



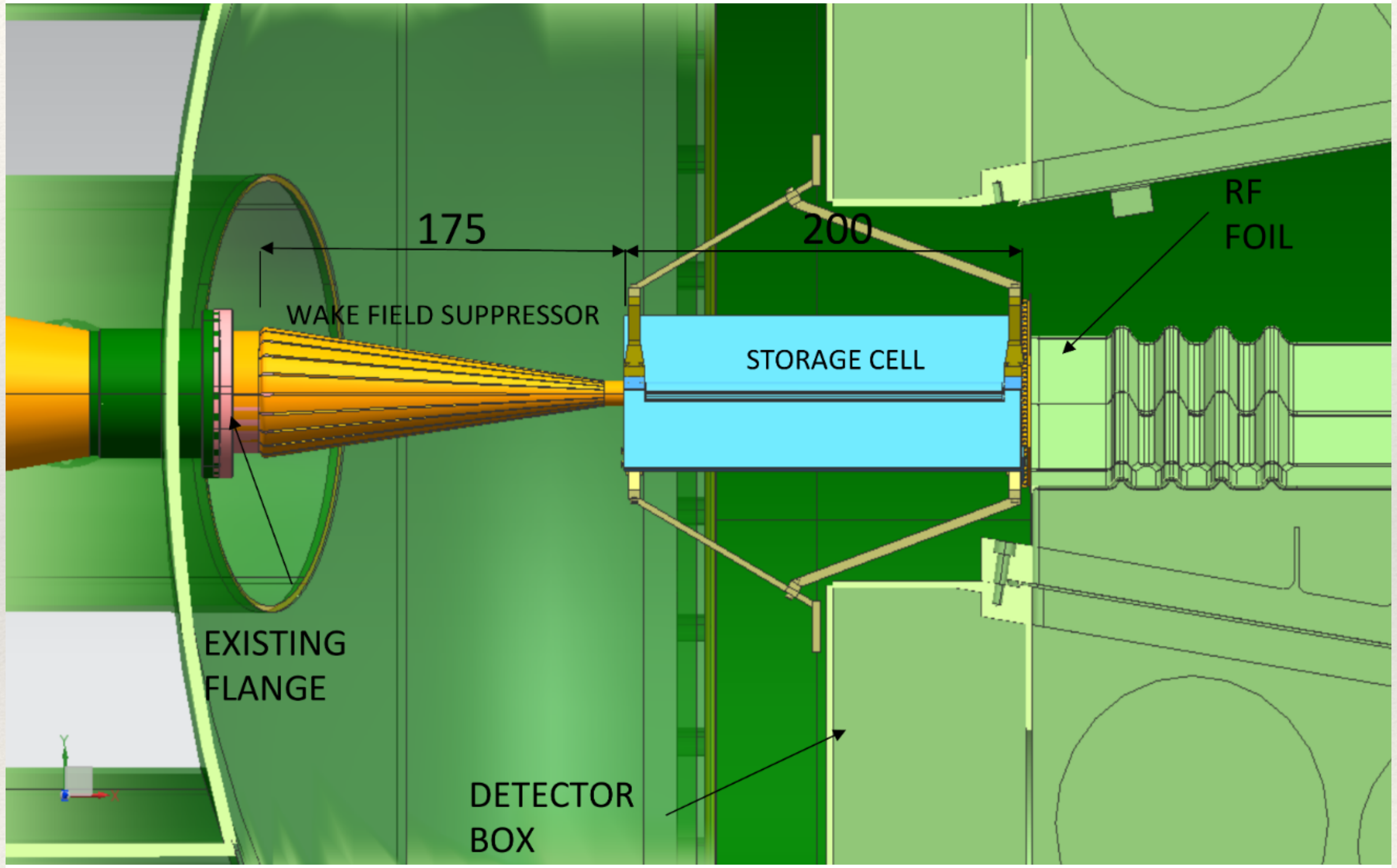
# Conclusions

- LHCb provides unique datasets for Heavy Ion physics studies.
  - The collider mode gives unique constraints on nuclear modifications in proton-nucleus collisions at low-x and high-x
  - The fixed-target mode covers the center-of-mass energy gap between SPS and RHIC, sensitive to nuclear modification of PDFs & intrinsic charm contents
- Some recent results have been presented, and more results to come
  2016 pPb analyses ongoing
  2018 PbPb collisions have got 20 times more statistics than 2015
  2017 large pNe data sample to analyze and 2018 PbNe collisions
- Rich heavy ion program with LHCb upgrade and the fixed-target upgrade !

# Fixed-target system (SMOG) upgrade!

- Current LHCb fixed-target setup will be upgraded for Run 3
- Plan for a storage cell, placed upstream
  - Injection of noble gases but also $H_2$ and $D_2$ gas as references
  - 10–100 times larger instantaneous luminosity per unit length
- Other upgrades (crystal target, polarised target, wire target) under discussion

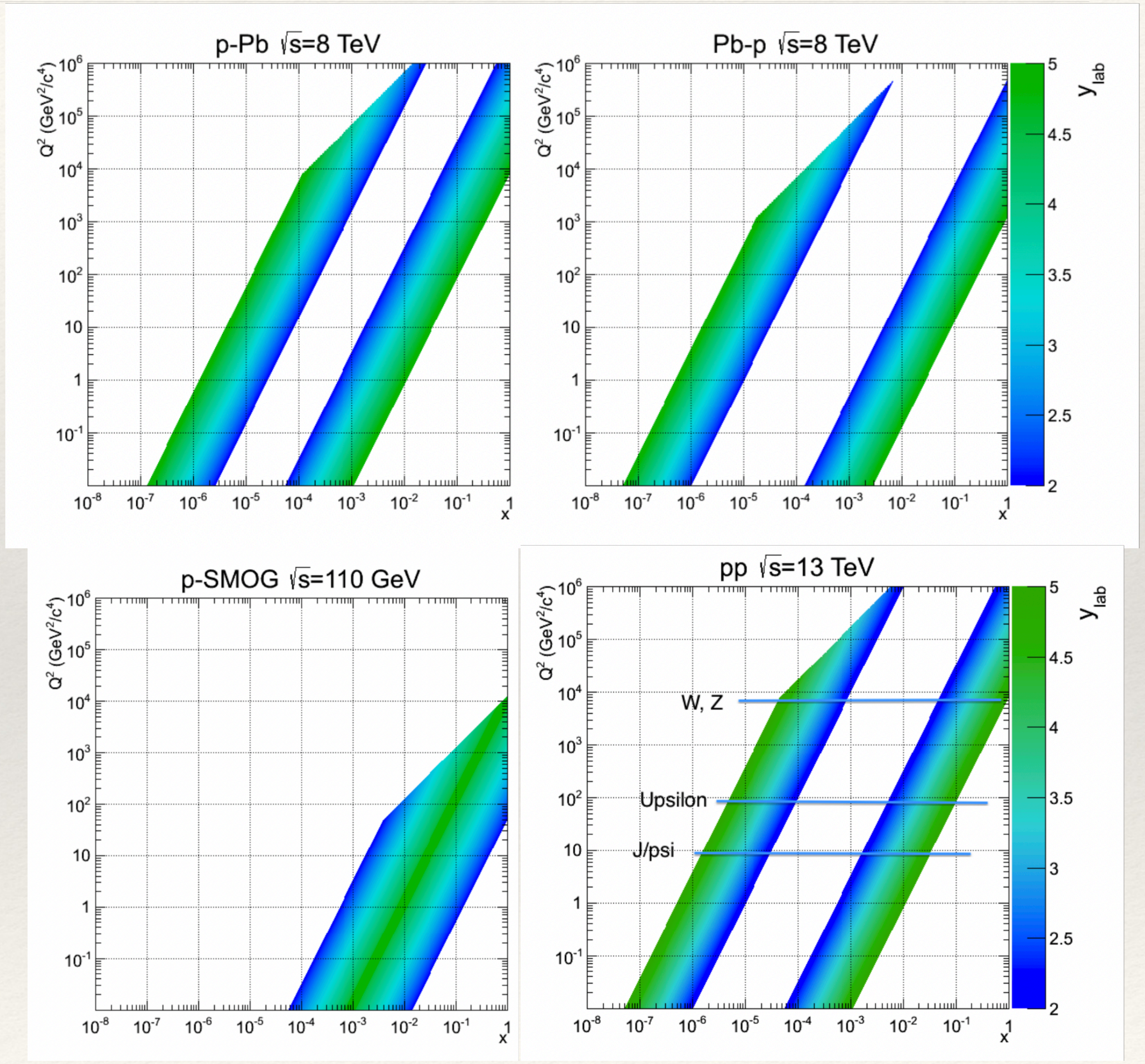
**Stay tuned!**



# Backup slides

# Motivation for Heavy Ion Studies at LHCb

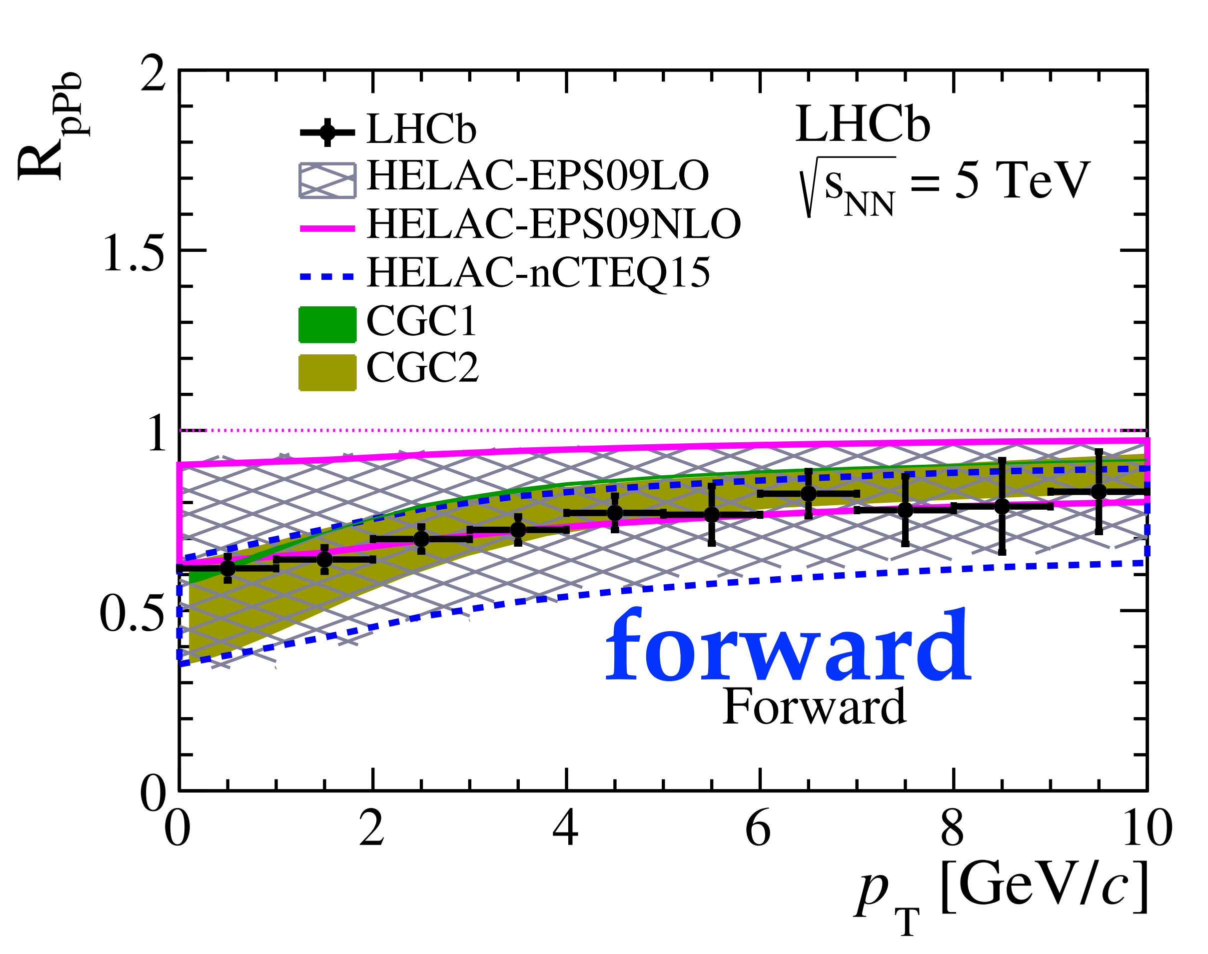
- Investigate the nucleon structure by comparing free p-p interactions versus bound nucleons (pA) inside the nucleus
  - nPDFs can be probed via quarkonia, electroweak bosons, Drell-Yan measurements, etc..
  - Access to very small x (colliding beam mode) and large x (fixed target mode)
- Dynamics of hadronization process [nuclear matter effects]
  - Measurement of total cross sections, energy flow, particle multiplicities, etc…
- Complementary probes of QCD
  - Ultra-peripheral collisions: exclusive $\rho^0$ production, exclusive photo-production of $J/\psi$...

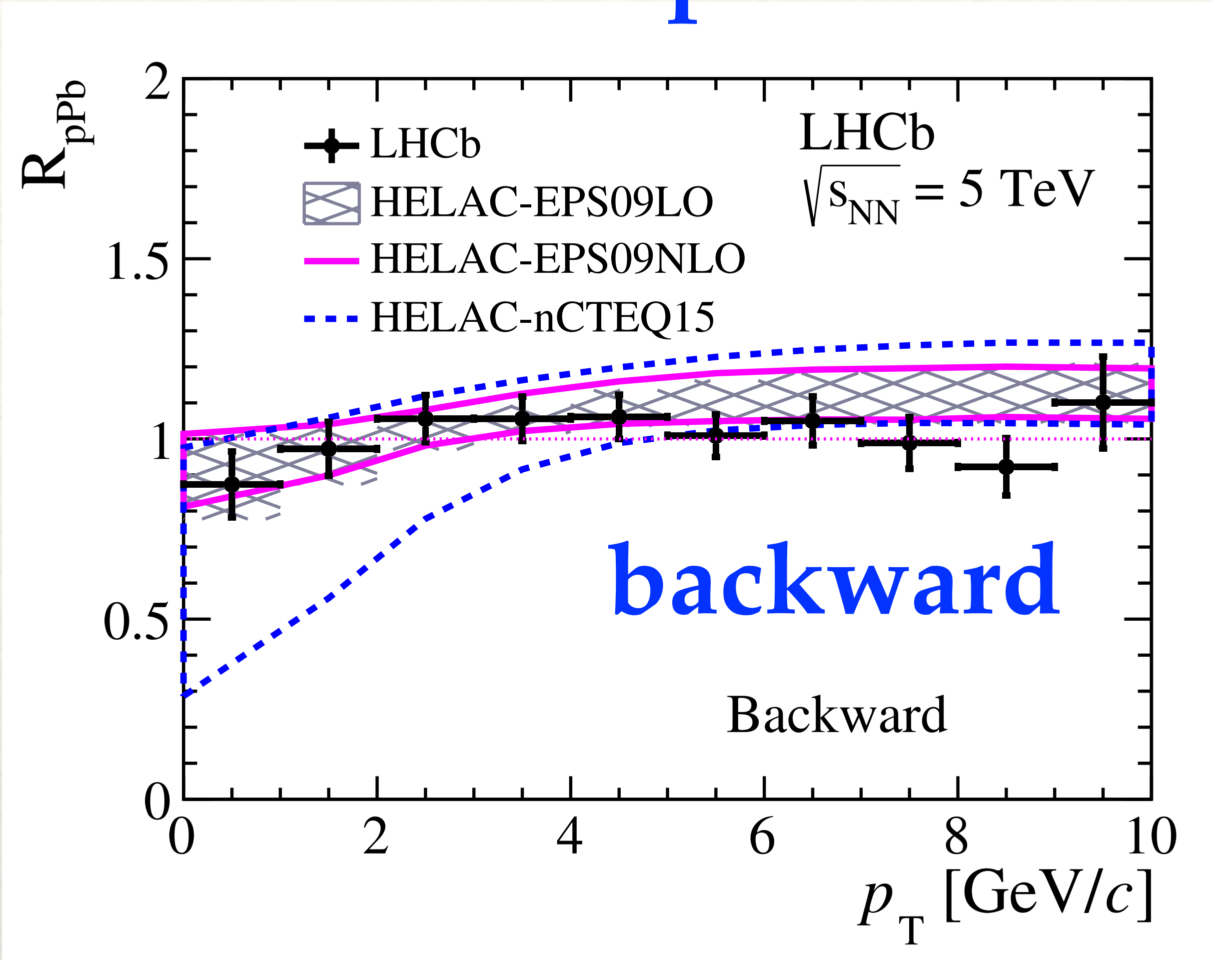


# Prompt $D^0$ modification factor

- $D^0$ cross-section and modification factor in pPb at $\sqrt{s}$ = 5.02 TeV
- $D^0$ fully reconstructed through $D^0 \to K^- \pi^+$ decays
- $R_{pPb}$ suppressed in forward region (~30%), no suppression in backward region, hint of small excess at large backward rapidity (y*<-4)
- Measurements consistent with predictions using nPDFs or CGC framework: [ EPJC 77 (2017) 1, Comp. Phys. Com. 198 (2016) 238, Comp. Phys. Com. 184 (2013) 2562 ]
- At forward rapidity measurement also consistent with CGC models: [Phys. Rev. D91 (2015) 114005, arXiv:1706.06728]

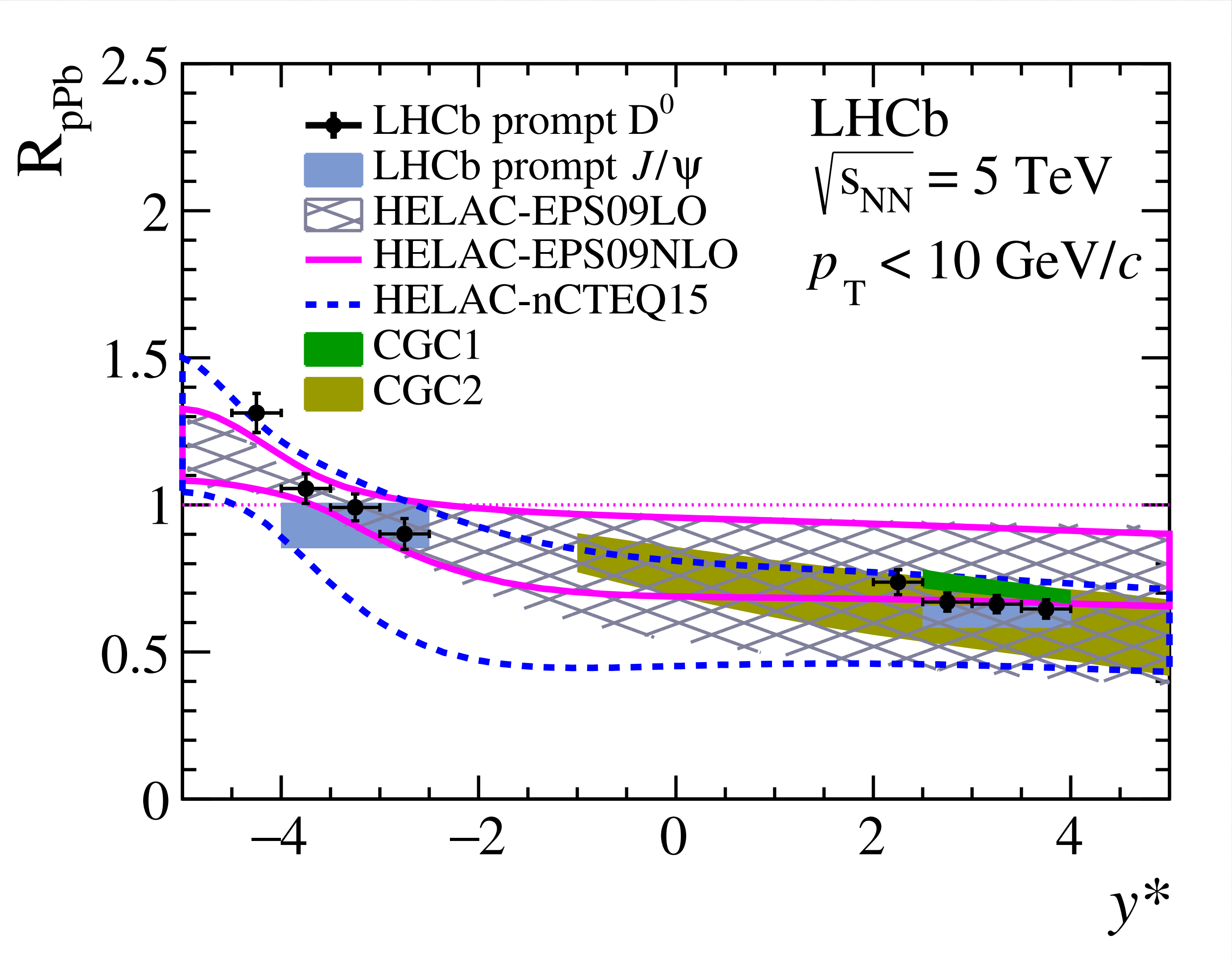
**Nuclear modification factor vs. $D^0$ pT**




**JHEP 2017 090**

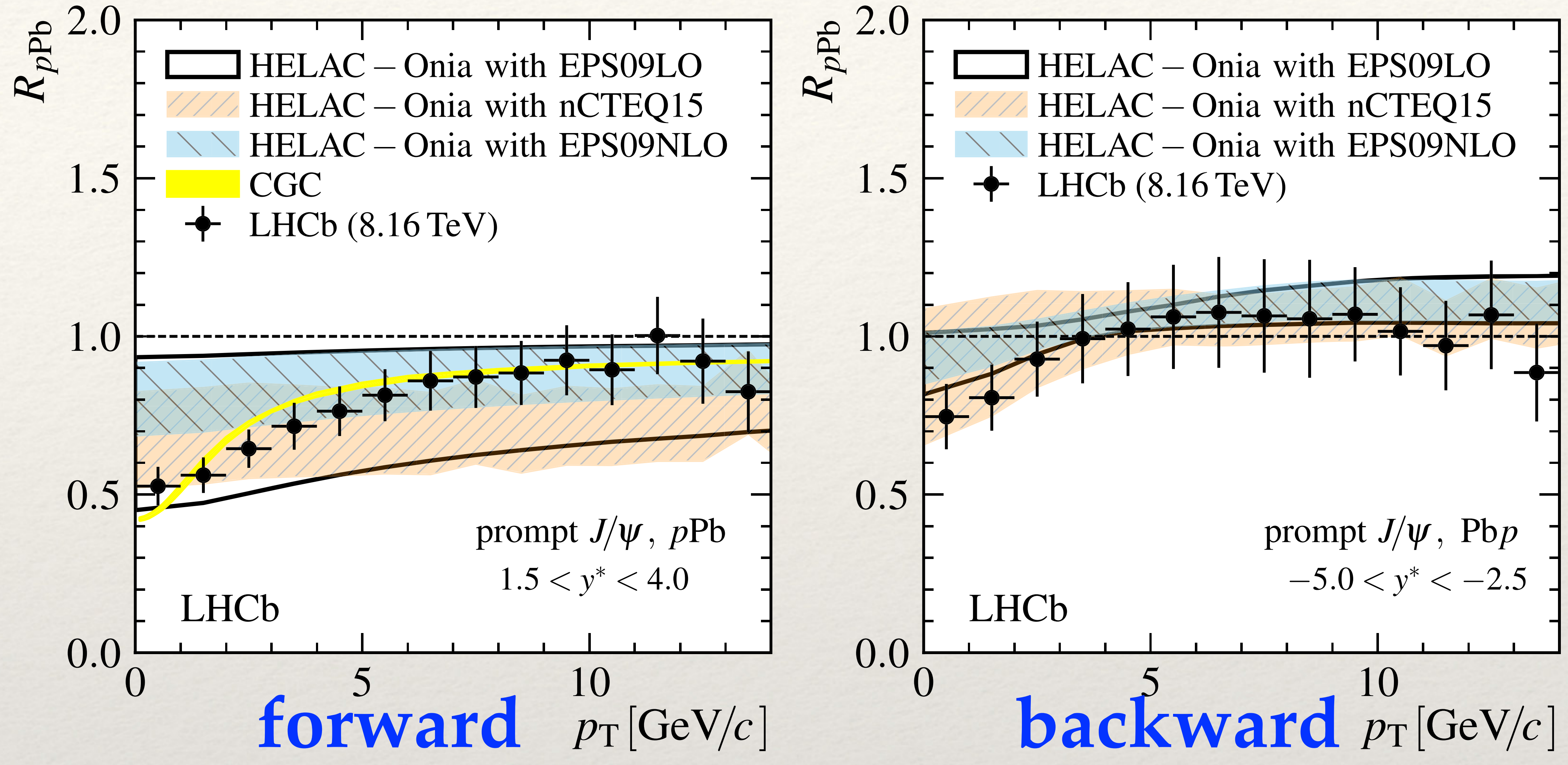
**Nuclear modification factor vs. $D^0$ rapidity**



# Prompt J/ψ modification factor

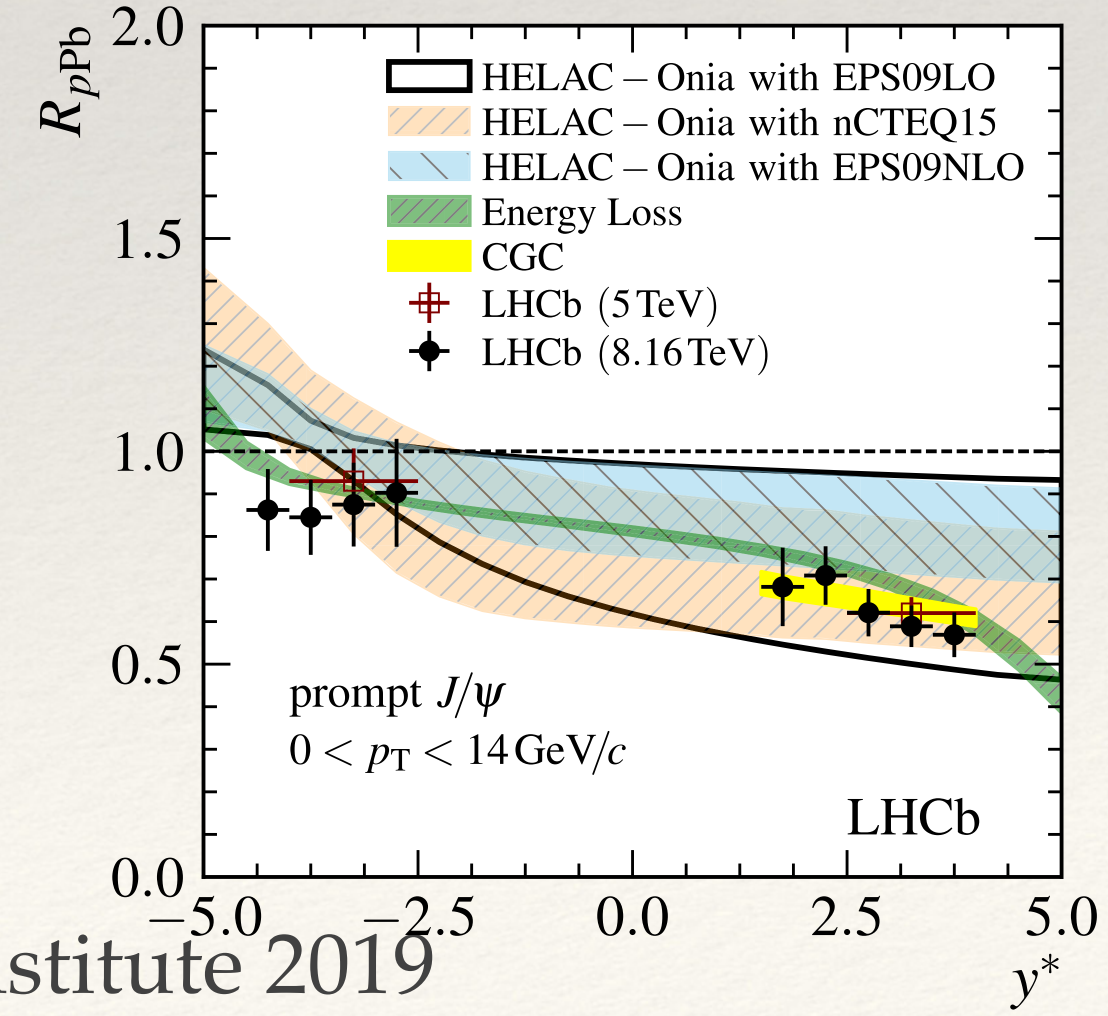
- In forward region: up to 50% suppression at low $p_T$ , converging to unity at high $p_T$
- In backward region: $R_{pPb}$ closer to unity, intriguing low values at low $p_T$
- Overall good agreement with models, but some have large uncertainties
- Results are compatible with LHCb results at 5 TeV [JHEP 02 (2014) 072]
- Result on Ψ(2S) modification factor is coming soon

**Nuclear modification factor vs. J/ψ pT**




**PLB774 (2017) 159**

**Nuclear modification factor vs. J/ψ rapidity**



# Centrality of the PbPb collisions

- **Detector limitation: Saturation in the Vertex Locator and the Tracking System for the most central PbPb collisions**
  - Current LHCb tracking algorithm, efficient for centrality above 50%
- **Centrality measured using the total energy deposited in the calorimeters:**
  - A good centrality estimator.
  - No saturation of calorimeter signals even for most central collisions