Strong physics at LHCb: probing nuclear matter effects in small systems

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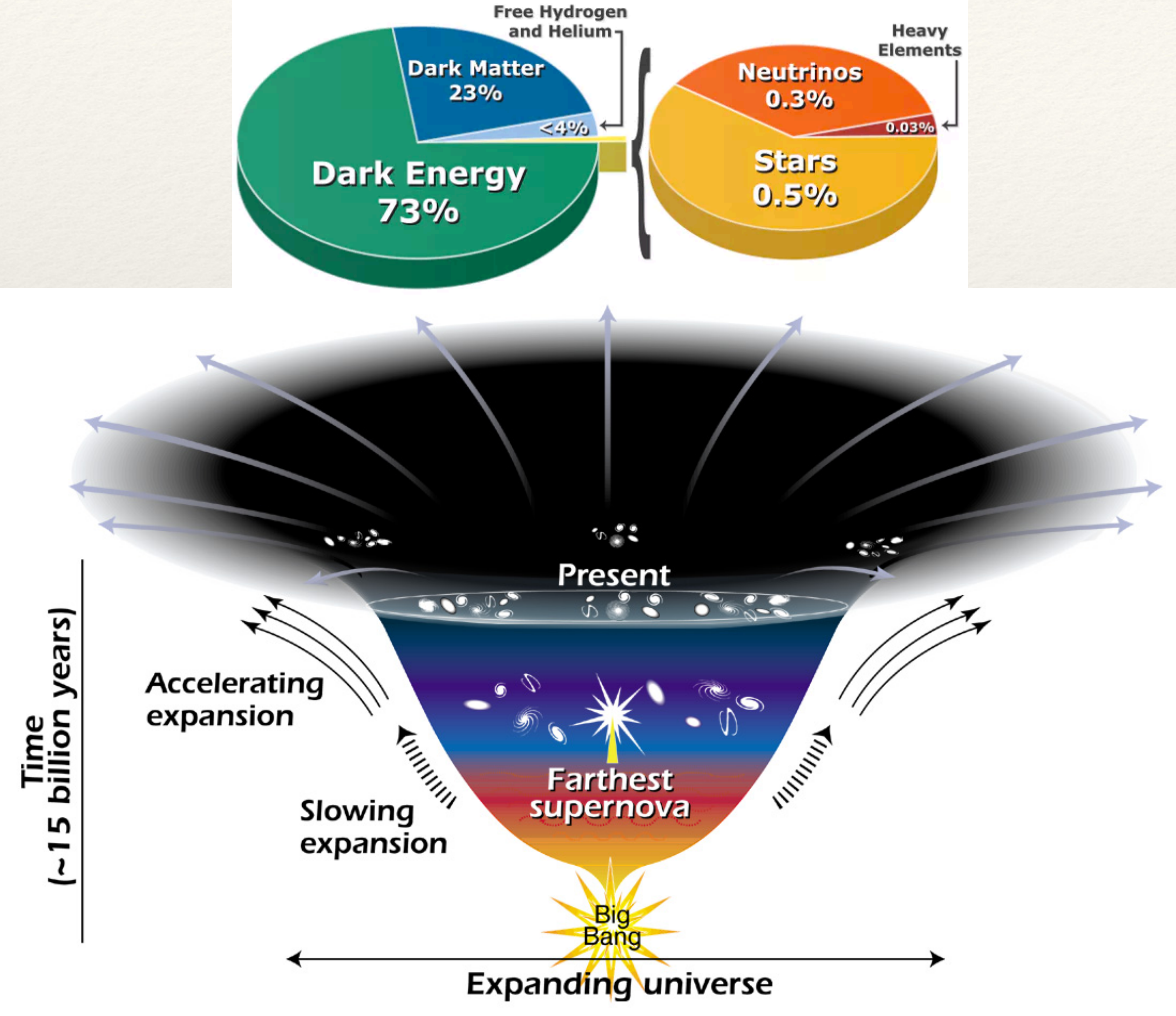
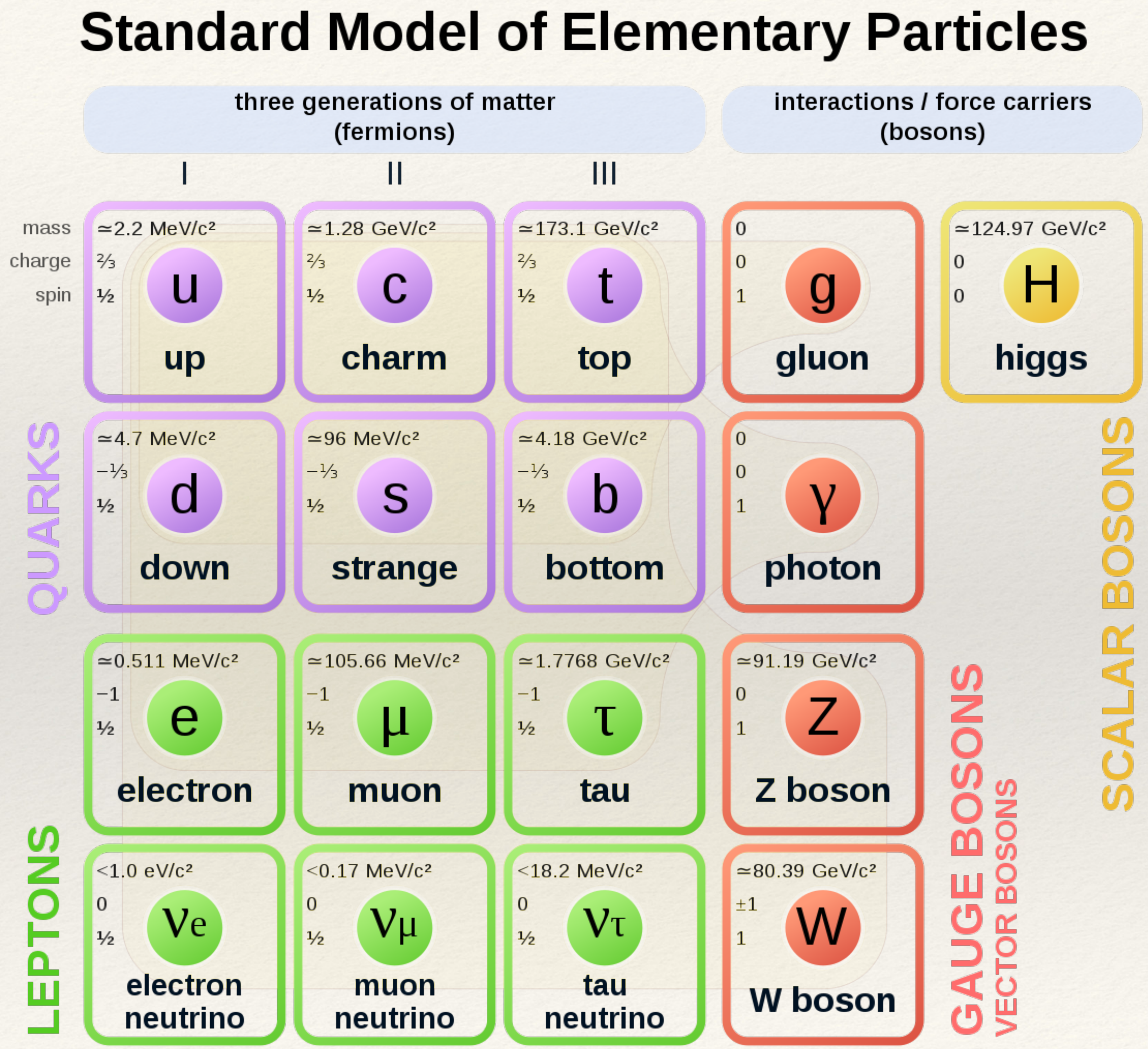
(South China Normal University)

on behalf of the LHCb collaboration

The big picture





Standard Model of Elementary Particles

	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass charge spin QUARKS	≃2.2 MeV/c² ⅔ ½ u up	≃1.28 GeV/c² ⅔ ½ c charm	≃173.1 GeV/c² ⅔ ½ t top	0 0 1 g gluon	≃124.97 GeV/c² 0 0 H higgs
QUARKS	≃4.7 MeV/c² −⅓ ½ d down	≃96 MeV/c² −⅓ ½ s strange	≃4.18 GeV/c² −⅓ ½ b bottom	0 0 1 γ photon	
LEPTONS	≃0.511 MeV/c² −1 ½ e electron	≃105.66 MeV/c² −1 ½ μ muon	≃1.7768 GeV/c² −1 ½ τ tau	≃91.19 GeV/c² 0 1 Z Z boson	
LEPTONS	<1.0 eV/c² 0 ½ ν_e electron neutrino	<0.17 MeV/c² 0 ½ ν_μ muon neutrino	<18.2 MeV/c² 0 ½ ν_τ tau neutrino	≃80.39 GeV/c² ±1 1 W W boson	

SCALAR BOSONS

GAUGE BOSONS
VECTOR BOSONS

Fundamental forces

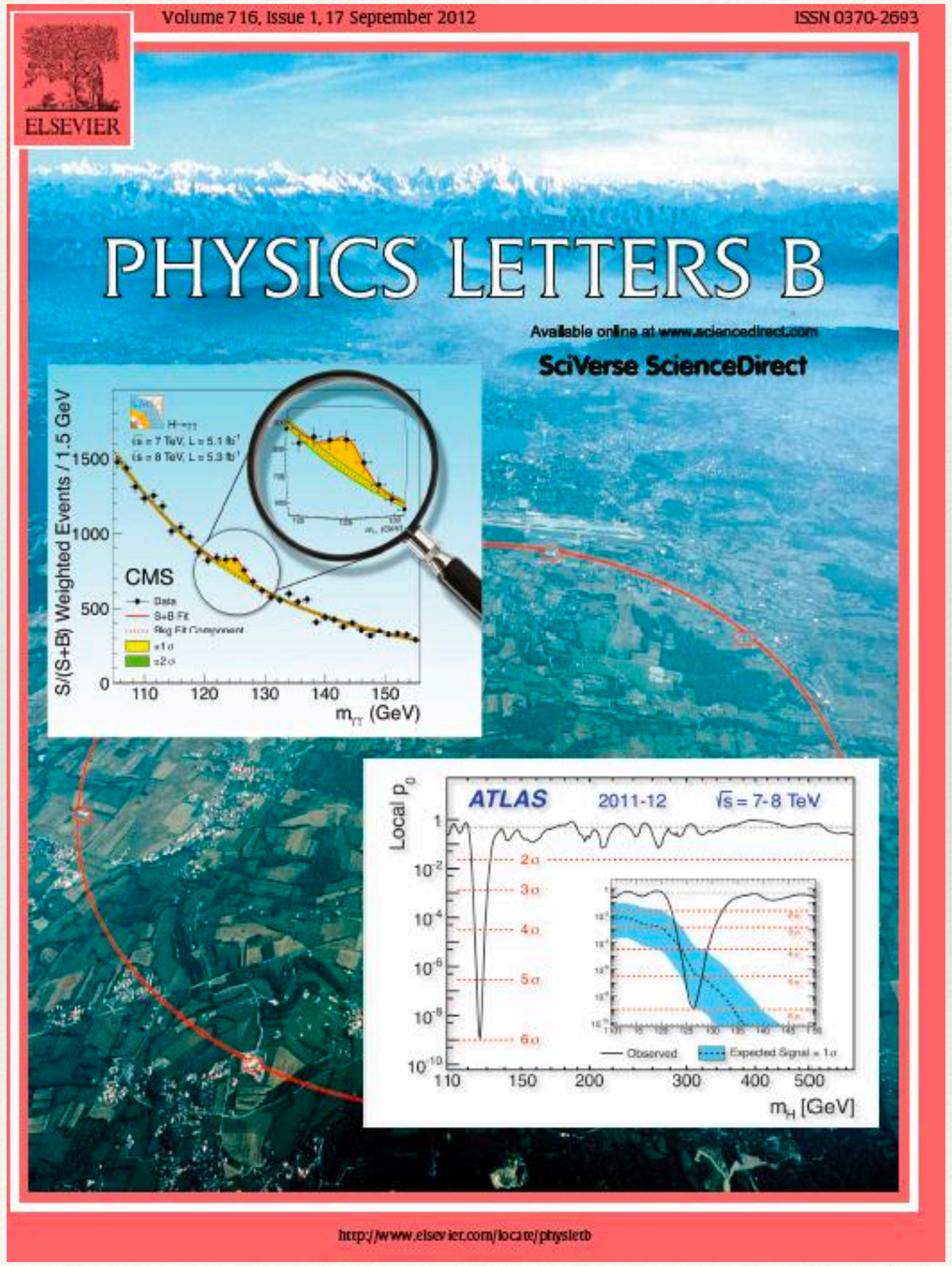
Interaction	Current theory	Mediators	Relative strength	Long-distance behavior	Range (m)
Strong	Quantum chromodynamics (QCD)	gluons	10^{38}	$\sim r$ (Color confinement)	10^{-15}
Weak	Electroweak Theory (EWT)	W and Z bosons	10^{25}	$1/r \cdot e^{-m_{W,Z} \cdot r}$	10^{-18}
Electro-magnetic	Quantum electrodynamics (QED)	photons	10^{36}	$1/r^2$	∞
Gravitation	General relativity (GR)	gravitons (hypothetical)	1	$1/r^2$	∞

The electroweak & Higgs sector

Interaction	Current theory	Mediators	Relative strength	Long-distance behavior	Range (m)
Strong	Quantum chromodynamics (QCD)	gluons	10^{38}	$\sim r$ (Color confinement)	10^{-15}
Weak	Electroweak Theory (EWT)	W and Z bosons	10^{25}	$1/r \cdot e^{-m_{W,Z} \cdot r}$	10^{-18}
Electro-magnetic	Quantum electrodynamics (QED)	photons	10^{36}	$1/r^2$	∞
Gravitation	General relativity (GR)	gravitons (hypothetical)	[illegible]	[illegible]	

In the Electro-weak sector, the SM shows great predictive power. Two examples: (next slide)

Example 1: prediction of the Higgs boson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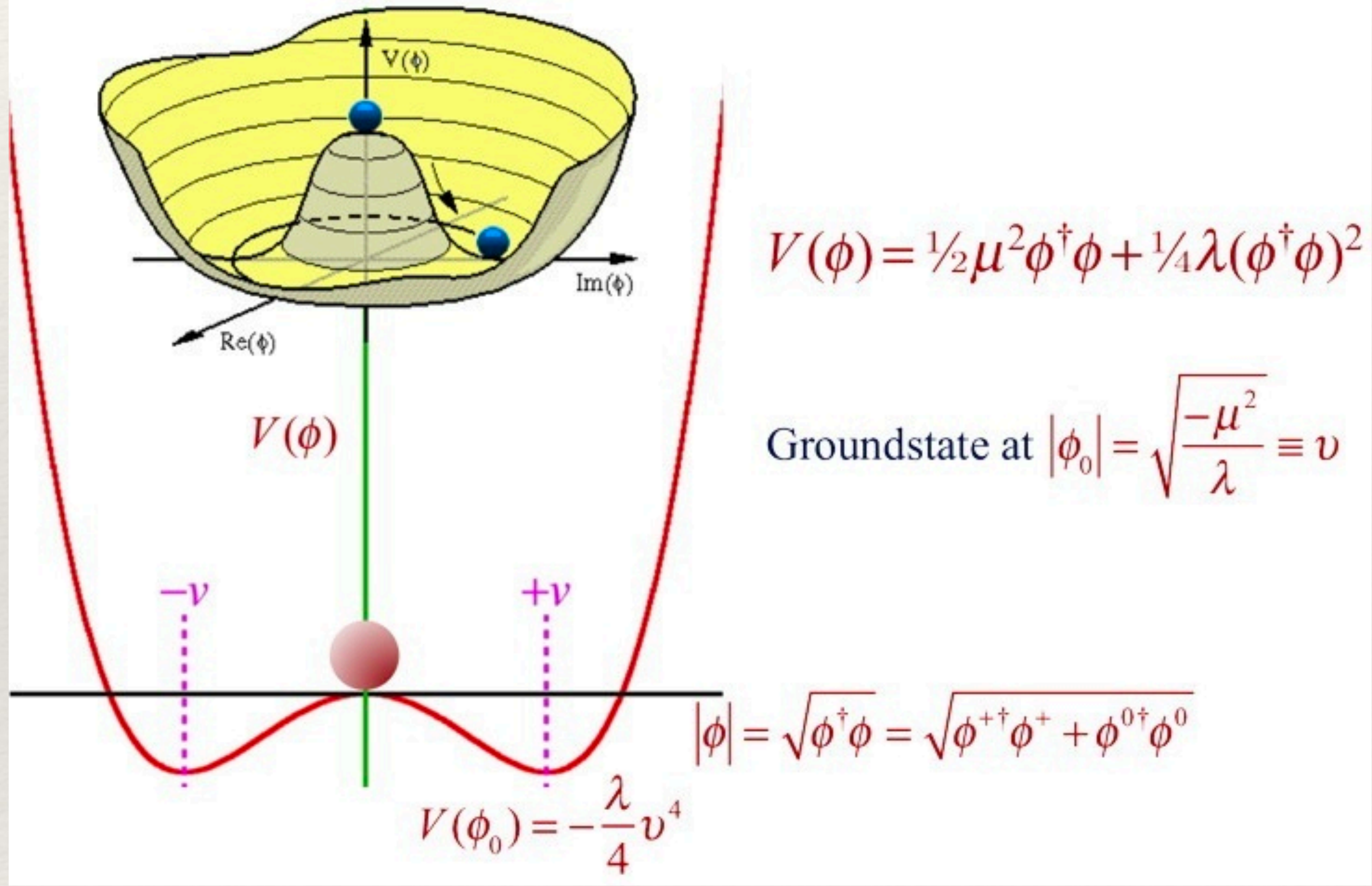


$$V(\phi)=\tfrac{1}{2}\mu^2\phi^\dagger\phi+\tfrac{1}{4}\lambda(\phi^\dagger\phi)^2$$

Groundstate at $|\phi_0|=\sqrt{\frac{-\mu^2}{\lambda}}\equiv v$

$$|\phi|=\sqrt{\phi^\dagger\phi}=\sqrt{\phi^{+\dagger}\phi^{+}+\phi^{0\dagger}\phi^{0}}$$

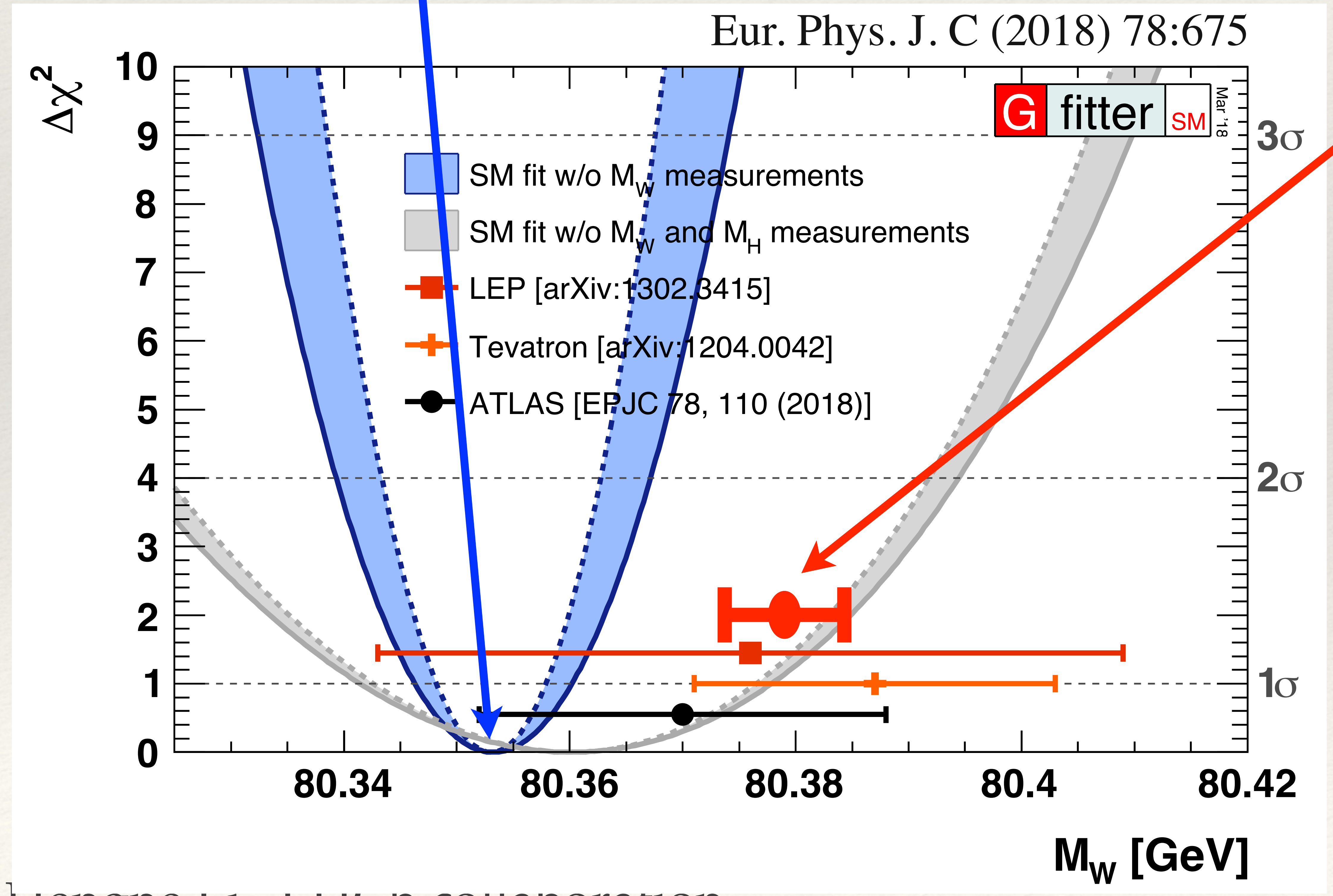
$$V(\phi_0)=-\frac{\lambda}{4}v^4$$

Example 2: Predictive power of the EW parameters

If we use the measured Higgs mass to constrain the W boson mass assuming SM, we get:

M_W = 80356 MeV ± 8 MeV

Predicted



Comparing with the current world average directly measured value:

M_W = 80379 MeV ± 12 MeV

[PDG 2019, Dec. 6, 2019]

Only ~1.5 sigma difference between the two M_W central values, given a precision of 0.12 per-mil!

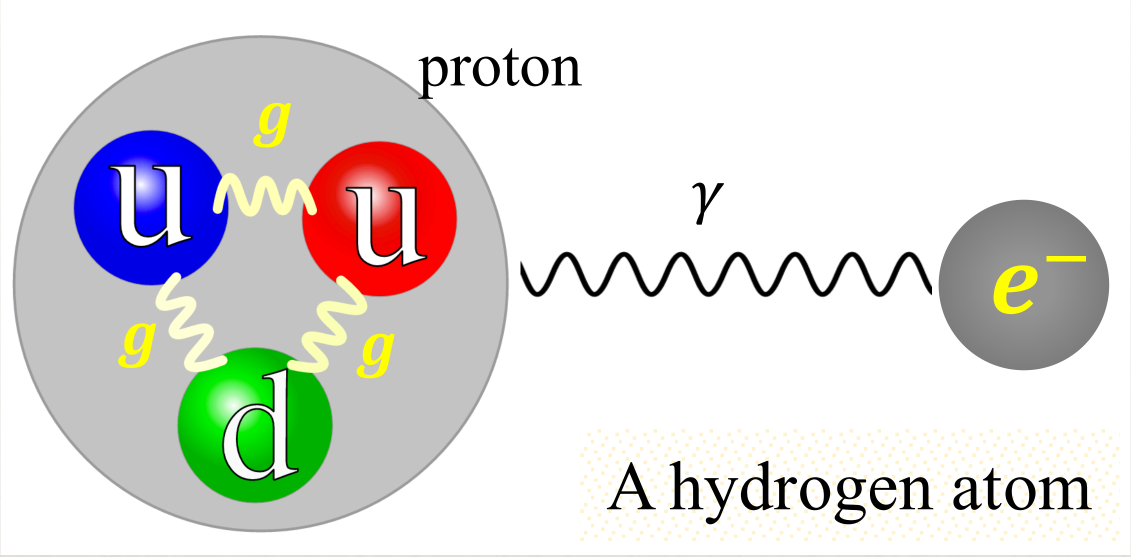
The strong interaction sector

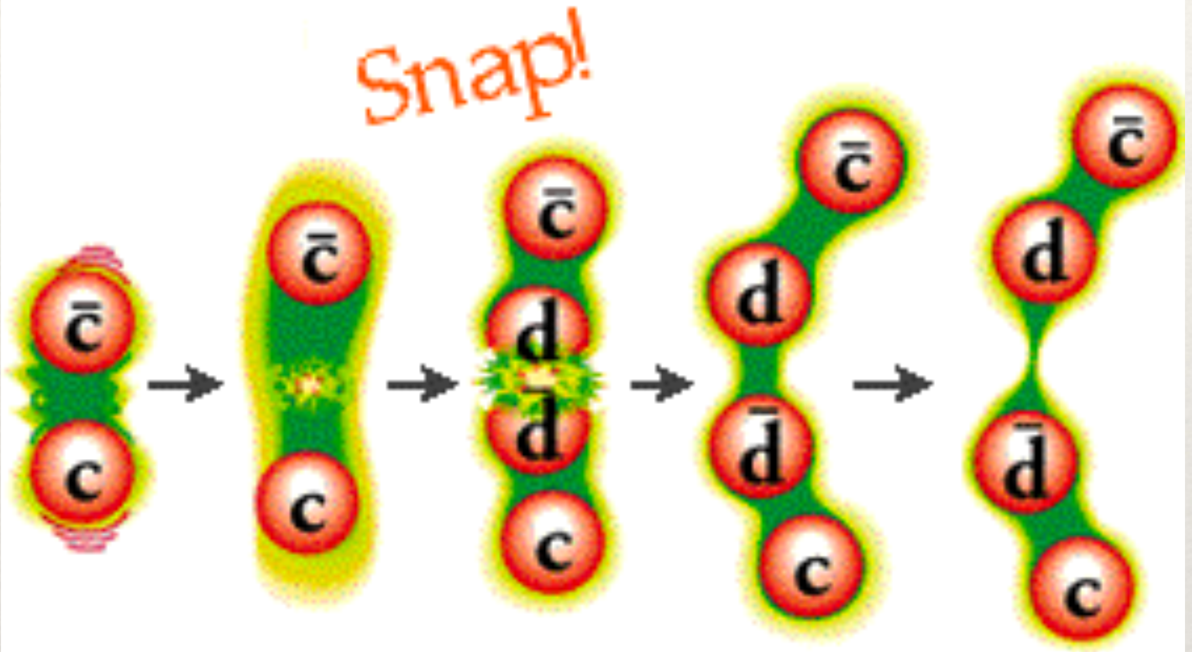
Interaction	Current theory	Mediators	Relative strength	Long-distance behavior	Range (m)
Strong	Quantum chromodynamics (QCD)	gluons	10^{38}	~ r (Color confinement)	10^{-15}
Weak	Electroweak Theory (EWT)	W and Z bosons	[illegible]	[illegible]	10^{-18}
Electro-magnetic	Quantum electrodynamics (QED)	photons	[illegible]	$1/r^2$	∞
Gravitation	General relativity (GR)	gravitons (hypothetical)	1	$1/r^2$	∞

In the Strong force sector, because of the color confinement (non-perturbative) nature, predictions are more difficult and complicated …

The Quantum Chromodynamics (QCD)

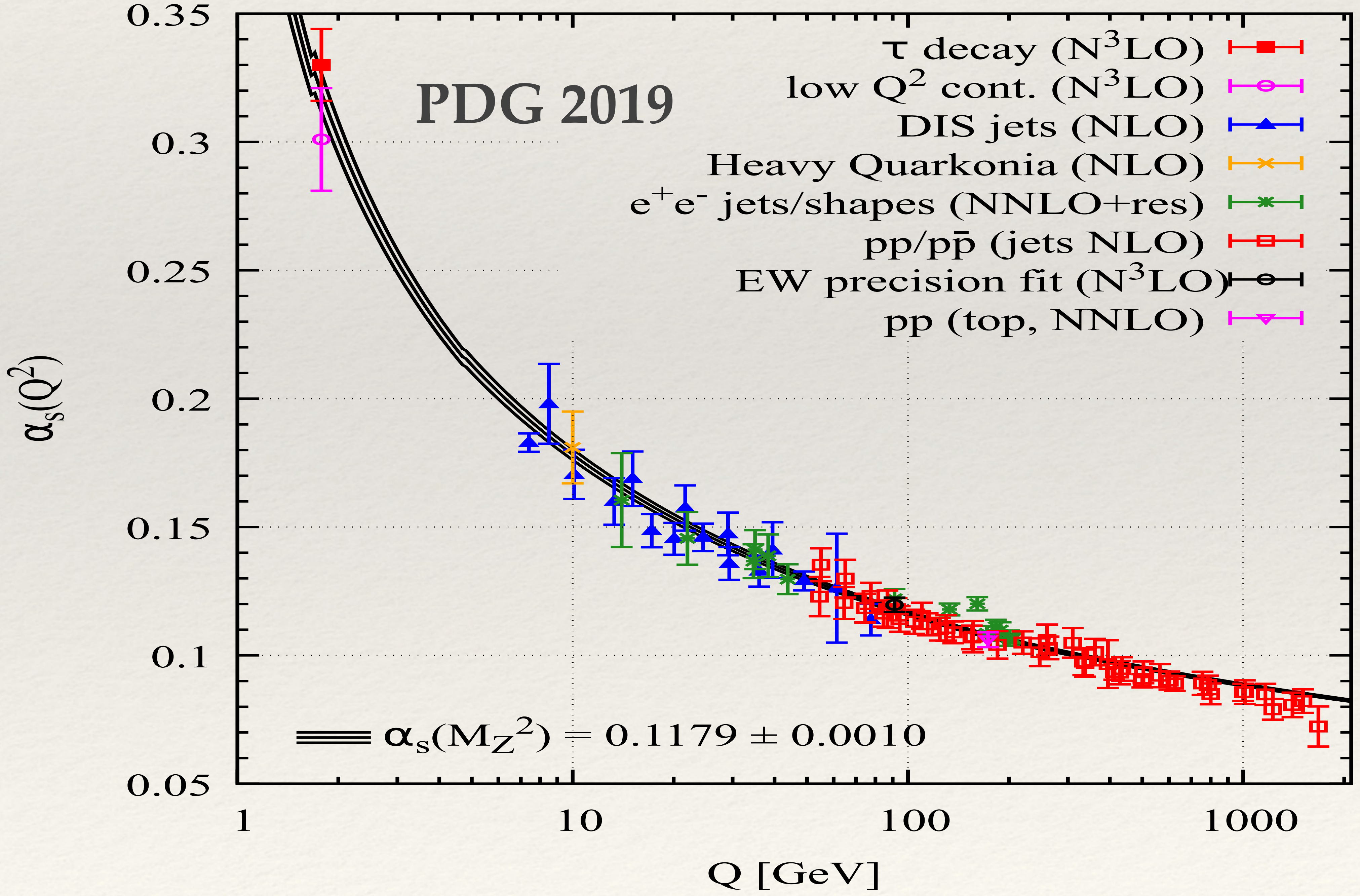
- Quarks bound together by strong force:
  - Gluons act as strong force mediators





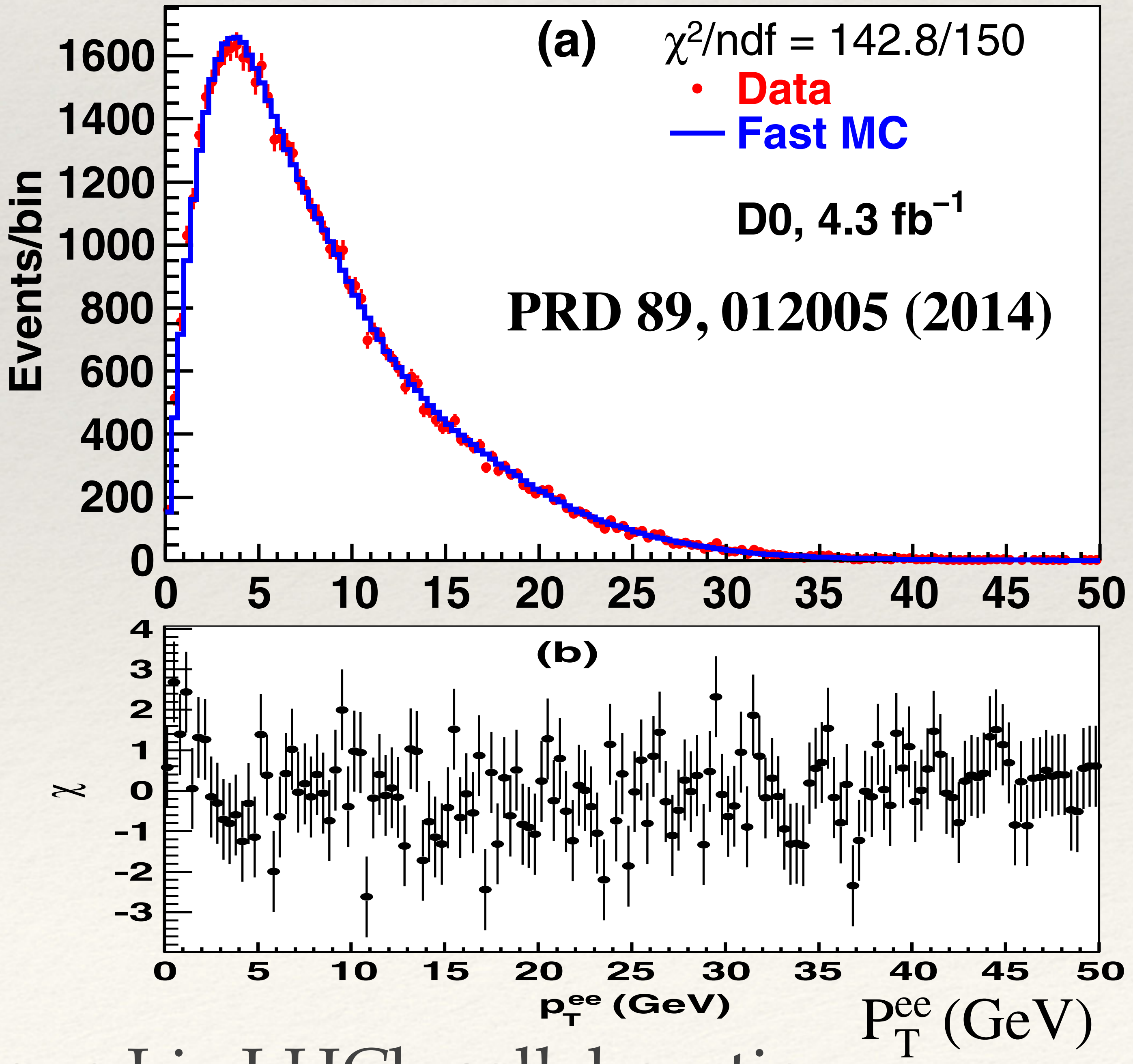
- No free quarks or gluons at low energy scale, but only colorless objects: hadrons
- Quarks loosely bound at small distance

- Color-confinements:
  - Strong force is described by QCD in SM
  - QCD coupling strength diverges at small energy scale, but small at large scale



The Quantum Chromodynamics (QCD)

- Perturbative QCD can solve part of the problems, not all.
- E.g. Z boson p_T modeling:
  - high p_T part: p-QCD
  - low p_T part: next-to-next-to-leading logarithm resummation of soft gluons e.g. PRD 56, 5558 (1997)



- Lattice-QCD has great predictive power, but need this:

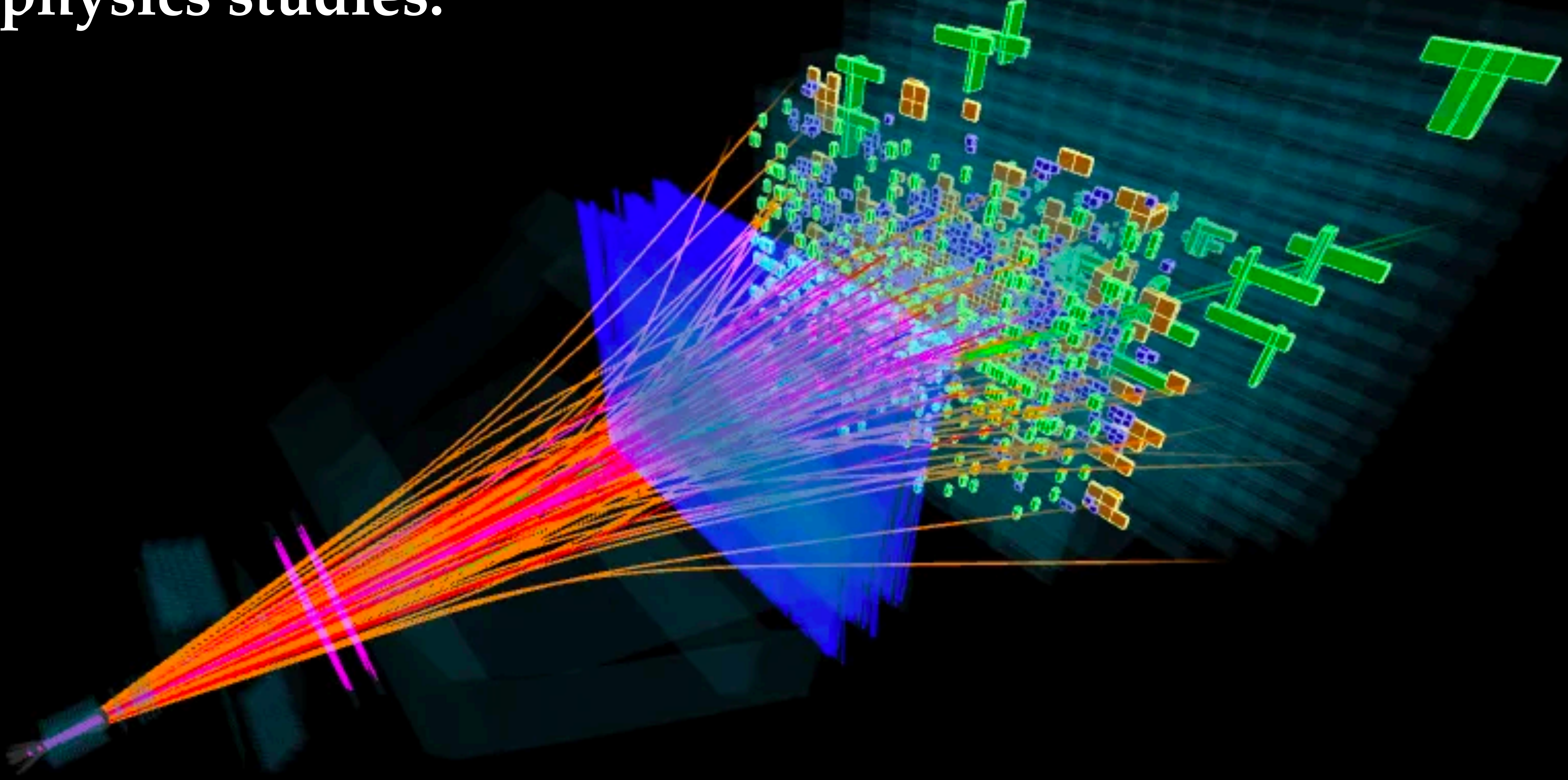
- A rich program in the strong force sector!

Today's main course

- **New results from LHCb at Quark Matter 2019:**
  - **Probing the nuclear matter effects:**
    - Study of the prompt D0 meson production in pPb at 8.16 TeV
      - [LHCb-CONF-2019-004]
    - Measurement of the Z production cross-section in proton-lead collisions at 8.16 TeV
      - [LHCb-CONF-2019-003]
  - **Understanding the nature of the X(3872) state:**
    - Multiplicity-dependent modification of $\chi_{c1}(3872)$ and $\psi(2S)$ production in pp collisions at 8 TeV
      - [LHCb-CONF-2019-005]

- **Let's first have a look at the LHCb detector**

LHCb provides unique datasets for Heavy Ion physics studies.



Event 351483885

Run 187340

Fri, 02 Dec 2016 20:56:29

Event display from the proton-lead collisions in 2016

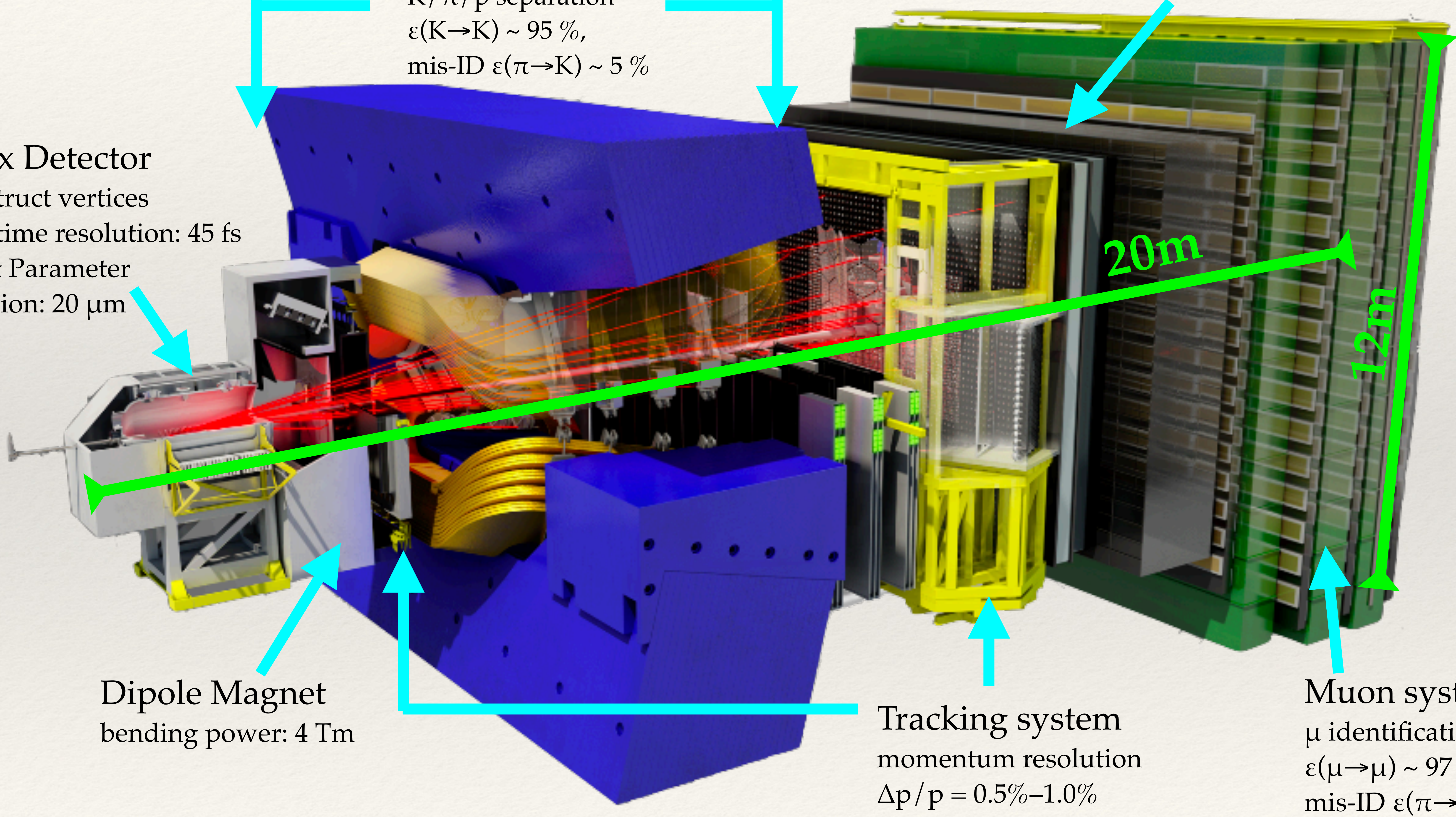
The LHCb detector is special

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

- LHCb is the only detector (at LHC) fully instrumented in forward region
- Unique kinematic coverage

  $2 < \eta < 5$

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



RICH detectors
K/π/p separation
$\varepsilon(K \to K) \sim 95\,\%$,
mis-ID $\varepsilon(\pi \to K) \sim 5\,\%$

Calorimeters
energy measurement
e/γ identification
$\Delta E/E = 1\,\% \oplus 10\,\%/\sqrt{E}$ (GeV)

Vertex Detector
reconstruct vertices
decay time resolution: 45 fs
Impact Parameter resolution: 20 μm

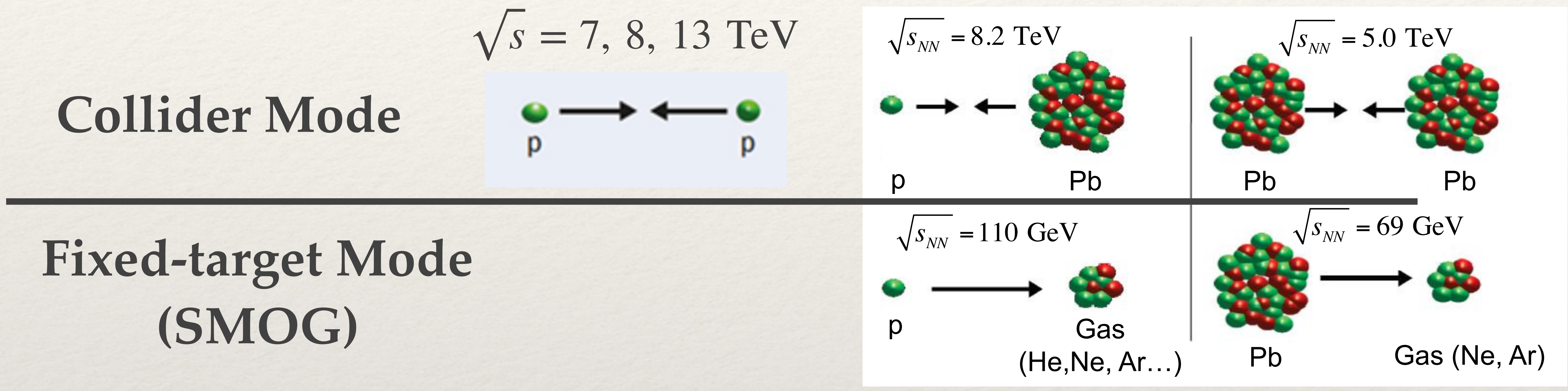
Dipole Magnet
bending power: 4 Tm

Tracking system
momentum resolution
$\Delta p/p = 0.5\%–1.0\%$
(5 GeV/c – 100 GeV/c)

Muon system
μ identification
$\varepsilon(\mu \to \mu) \sim 97\,\%$,
mis-ID $\varepsilon(\pi \to \mu) \sim 1\text{-}3\,\%$

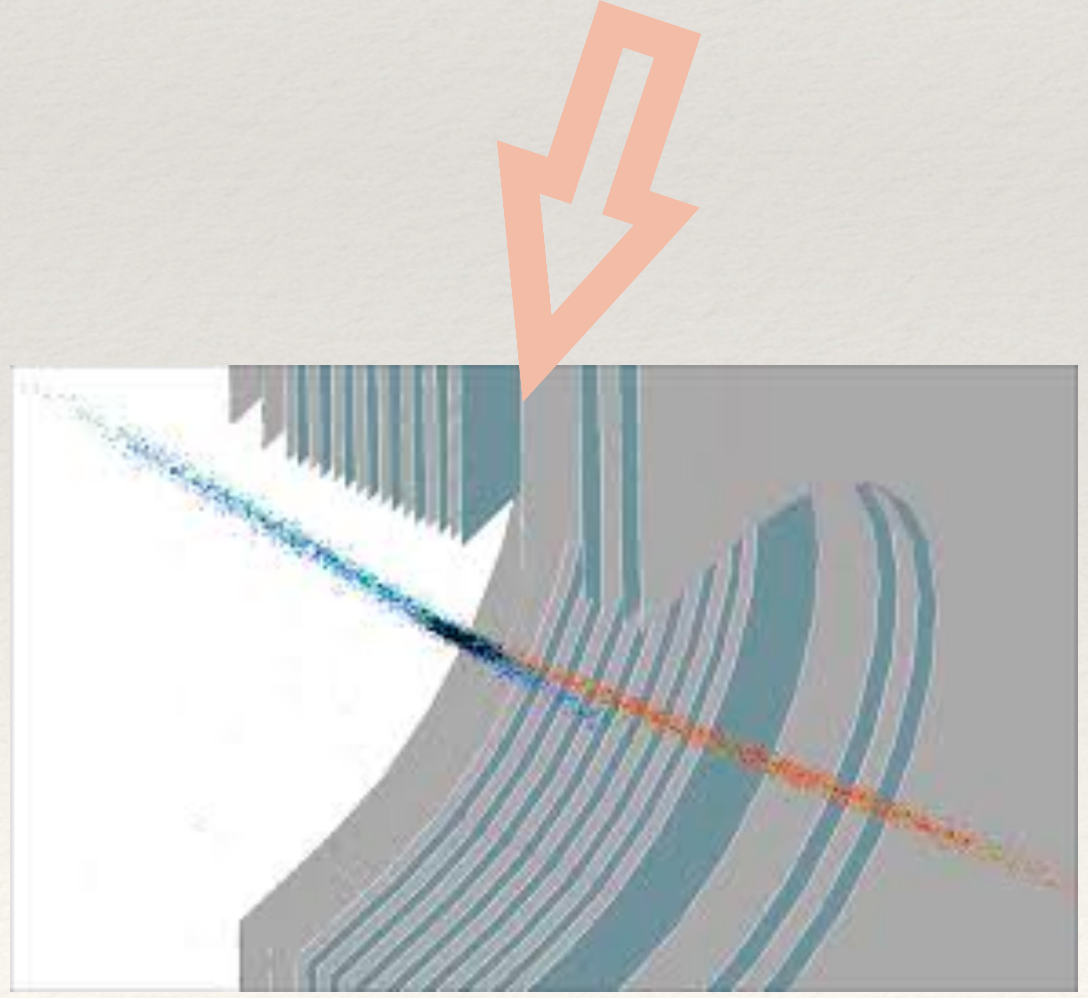
LHCb running modes and kinematic coverage

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



Collider Mode

Fixed-target Mode (SMOG)



Collider mode:

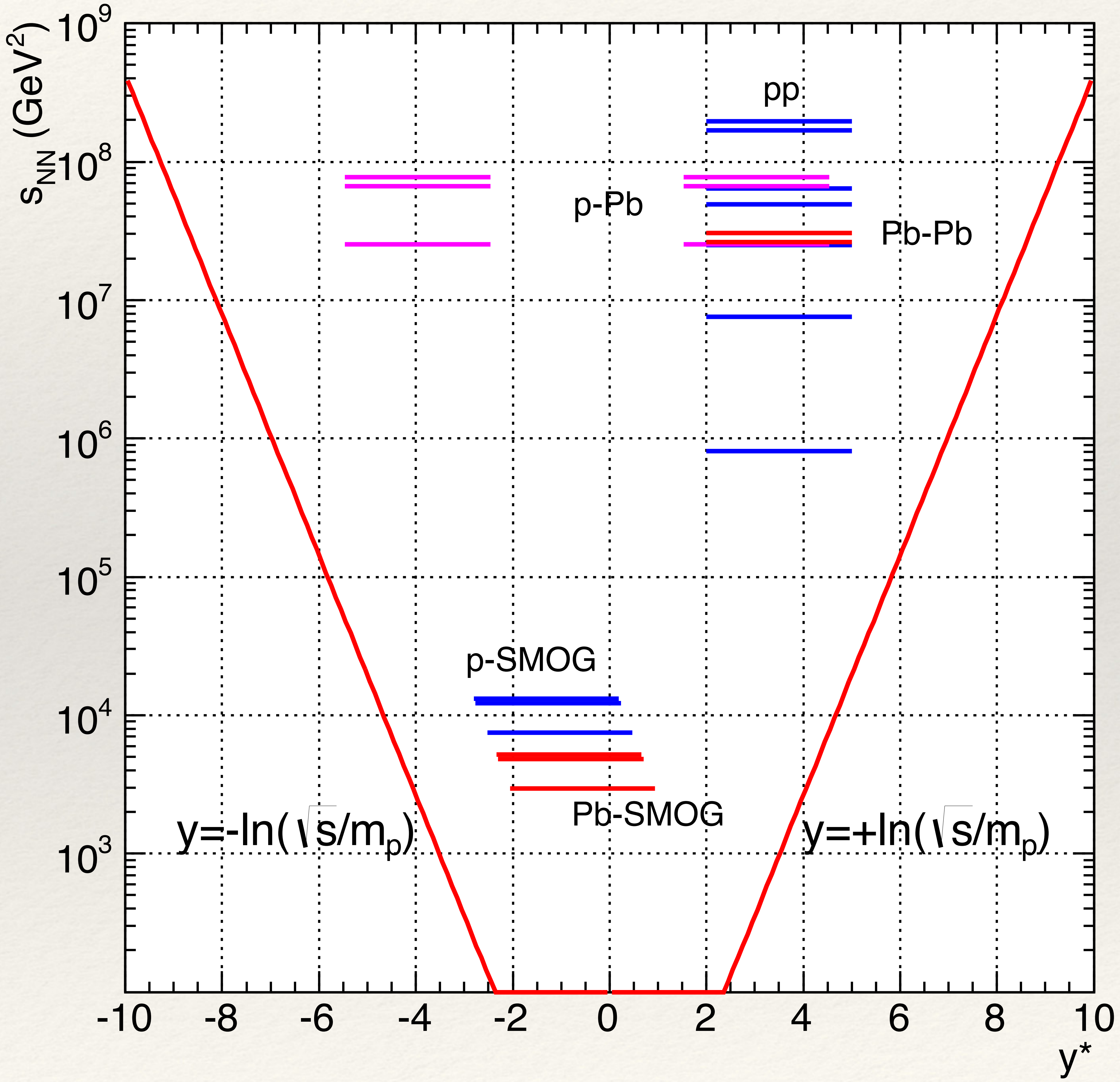
Forward and backward coverage

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

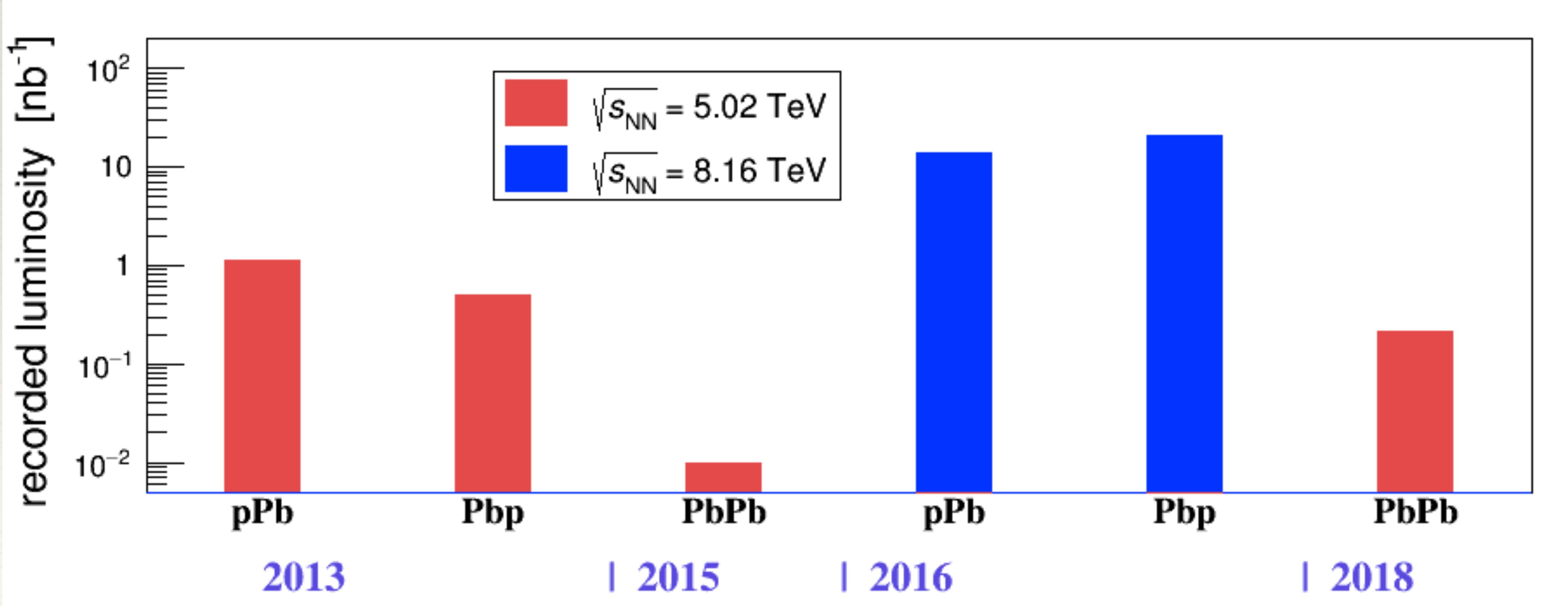
Kinematic Acceptance



Data samples

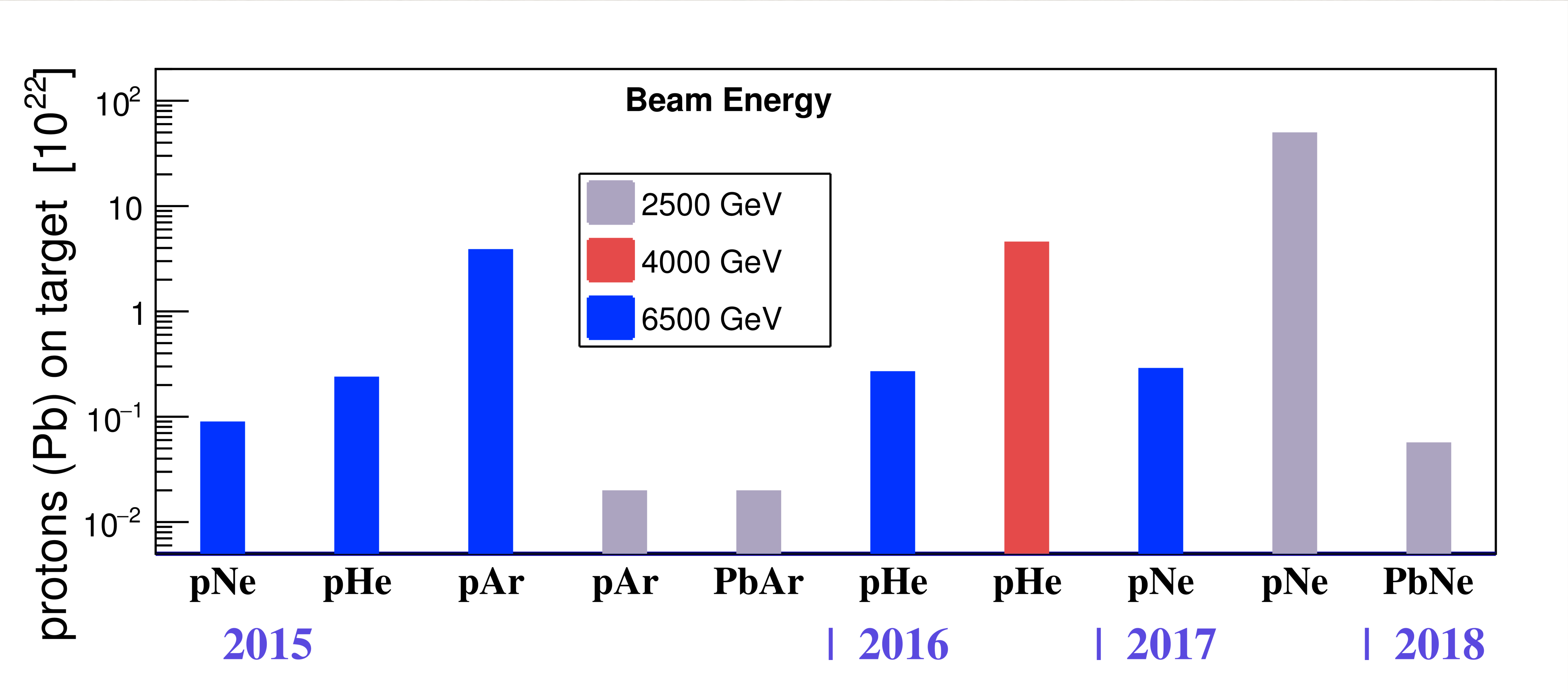
- **Colliding beam mode (pPb and PbPb):**

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

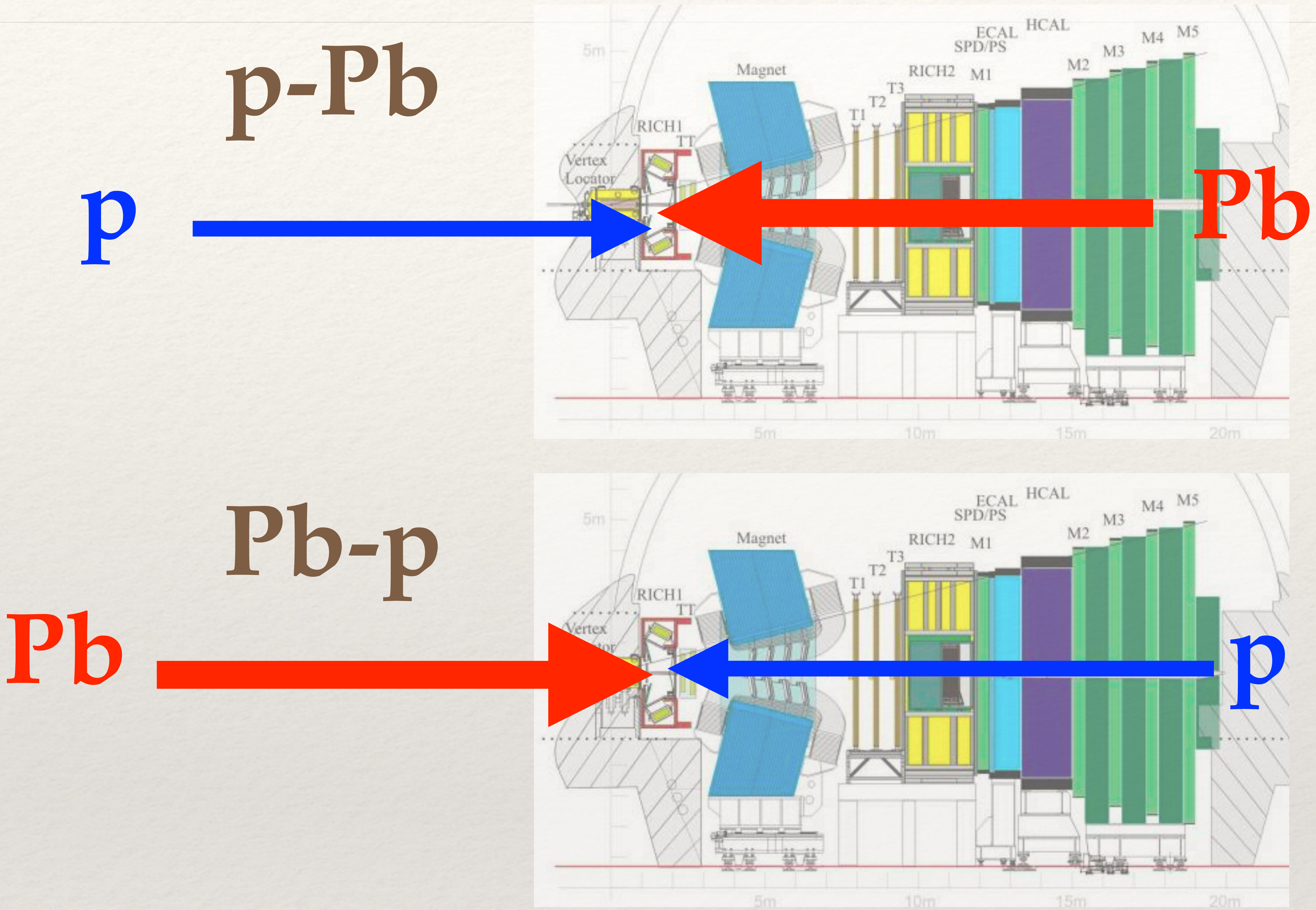


- **Fixed Target mode (SMOG):**
  - $\sqrt{s_{NN}}$: 69-110GeV

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



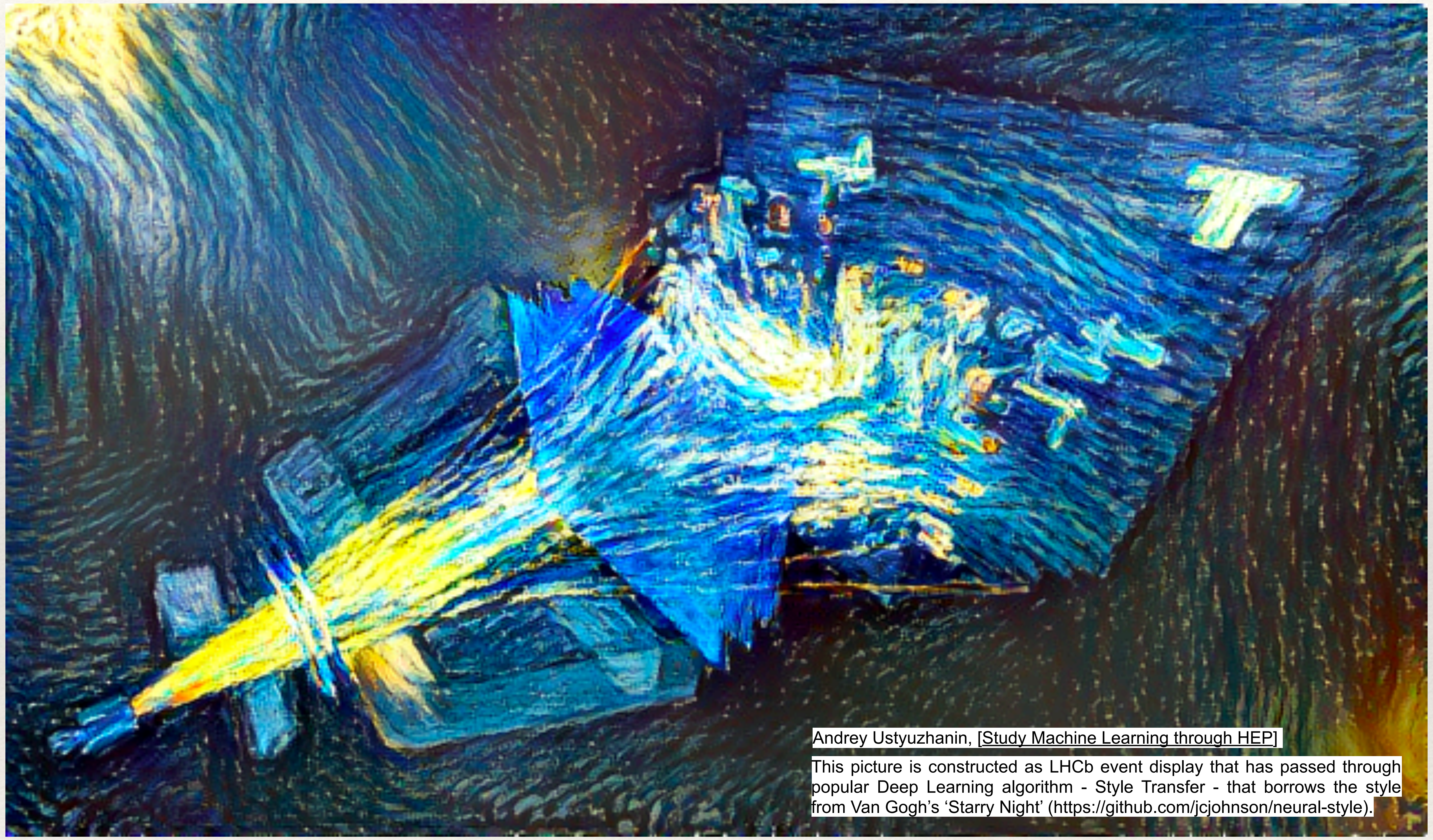
Setups for proton-ion collisions



- **Forward production:**
  - Center of mass rapidity coverage: $1.5 < y^* < 4.0$
- **Backward production:**
  - Center of mass rapidity coverage: $-5.0 < y^* < -2.5$

- Rapidity coverage in center of mass frame considers a rapidity shift of about 0.47 w.r.t. the lab frame coverage $2.0 < y < 4.5$
- Common range for the measurements: $2.5 < |y^*| < 4.0$

Probing the nuclear matter effects



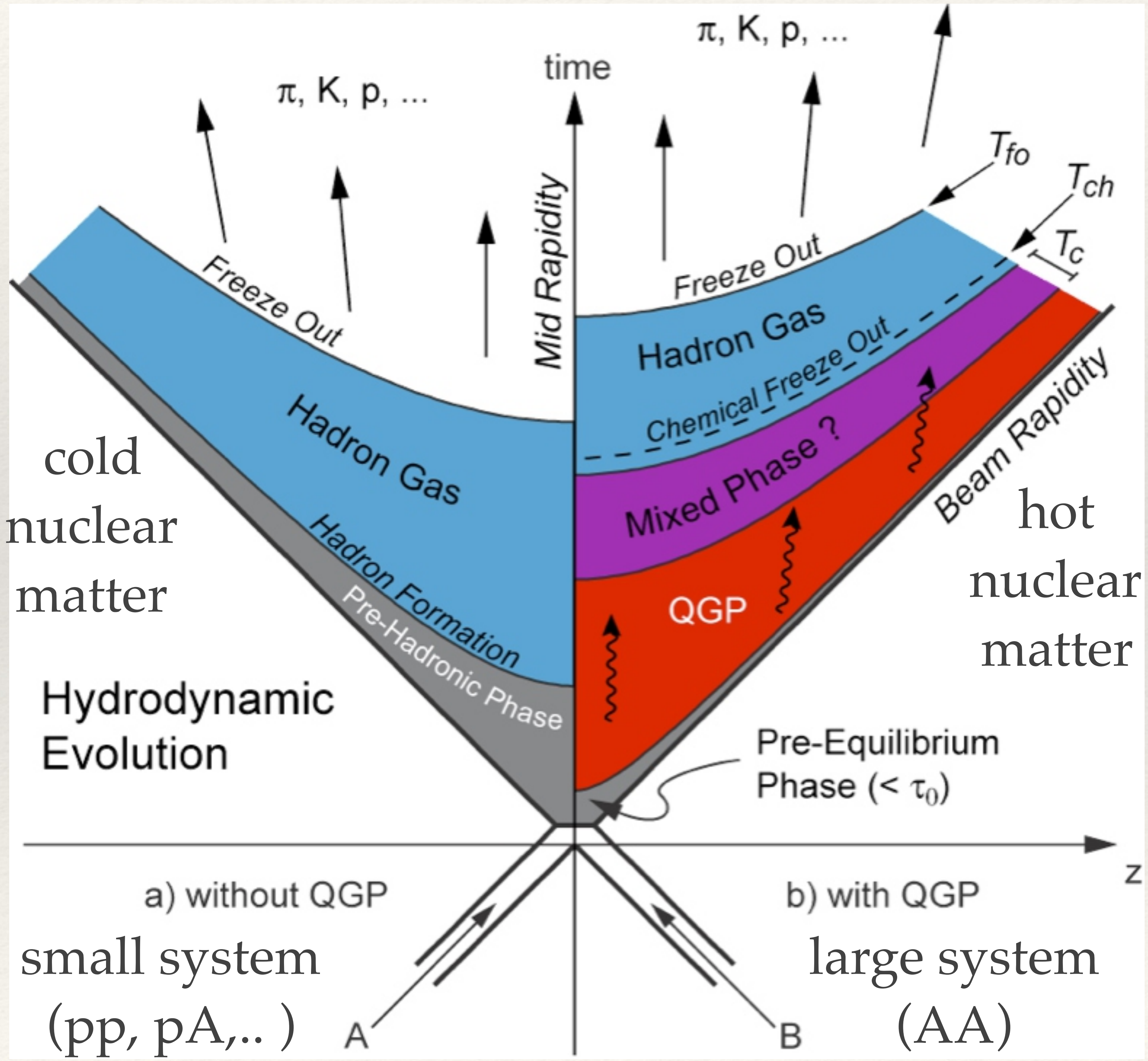
Andrey Ustyuzhanin, [Study Machine Learning through HEP]

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).

The nuclear matter effects

- Ultra-relativistic heavy ion collisions can help us to:
  - Explore phase diagram of nuclear matter
  - Large systems (AA):
    - Study QCD matter under extreme conditions (hot nuclear matter effects)
      - E.g. formation of Quark Gluon Plasma (QGP) at high temperature and/or energy density.
  - Small systems (pp, pA, ..):
    - Nucleon structure, intrinsic charm, reflected in the nuclear modifications (cold nuclear matter effects)
    - also QGP?
  - Many other things: QED at extreme field strengths, diffractive processes...

- Space-time evolution of the collision



cold nuclear matter

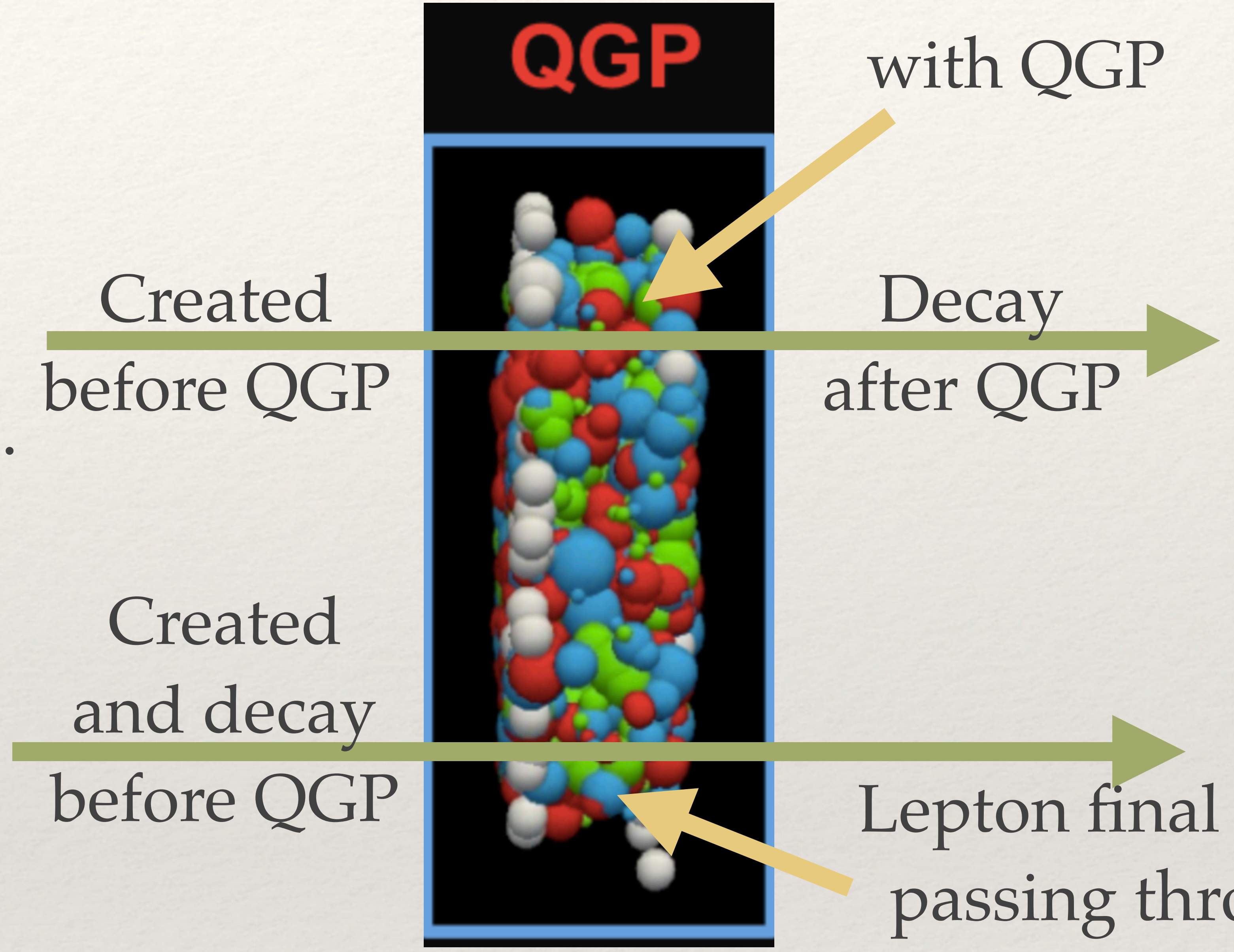
hot nuclear matter

small system (pp, pA,..)

large system (AA)

Soft probes, hard probes, EW probes

- Soft probes:
  - study the QGP medium itself: global characteristics such as multiplicities, correlations, azimuthal asymmetries, etc..
- Hard and electroweak probes:
  - using hard scatterings (pQCD controlled) created before the QGP medium formation, which propagated through the medium, to “probe” (study) the nuclear matter effects of the medium.
  - Heavy flavor hadrons, quarkonium, jets, etc., interact with QGP medium,
  - photon and W/Z bosons, decay before QGP formation, leptonic final states w/o impact by the medium
    ==> reference for hard probes.



Quarkonium,
Heavy flavor
hadrons, jets, etc.

Created
before QGP

interact
with QGP

Decay
after QGP

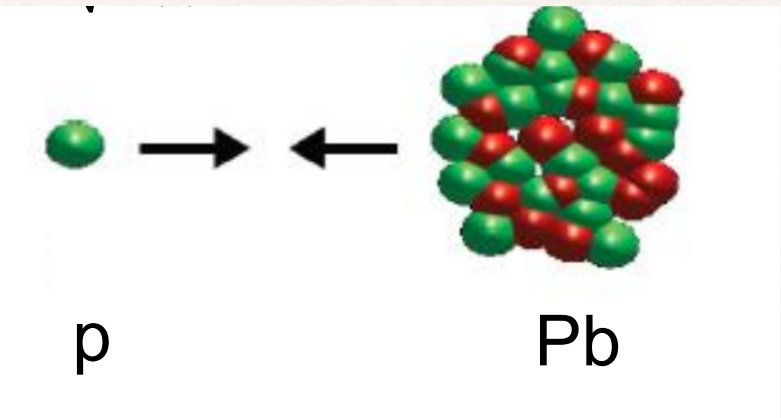
photon,
W, Z

Created
and decay
before QGP

Lepton final states
passing through
QGP with
negligible/no
modification

Proton-nucleus collisions

- Open Heavy flavors /Quarkonia / WZ boson productions as tools to study cold nuclear matter effect (CNM)
  - Necessary reference to disentangle QGP effects from CMT effects in AA collisions

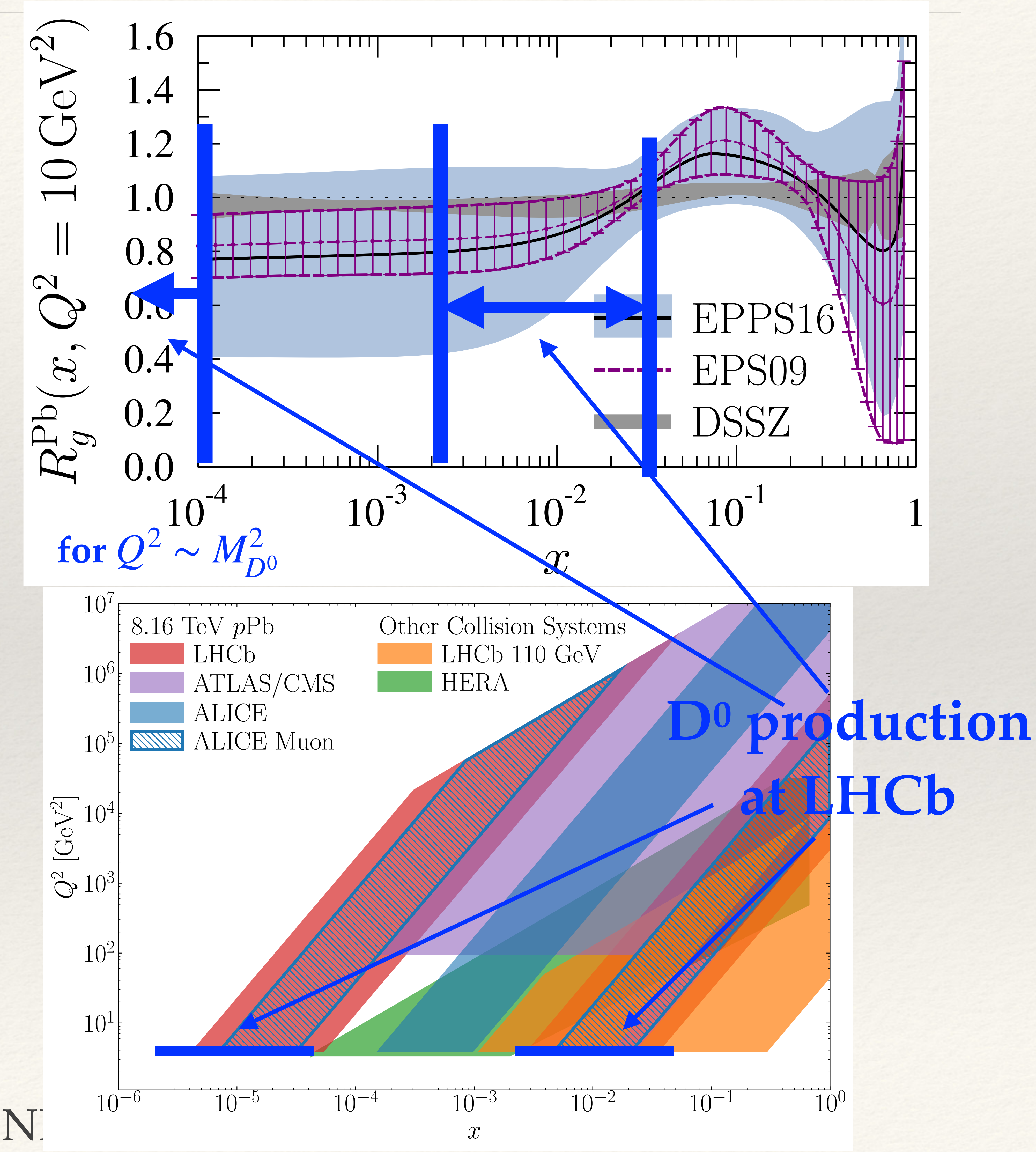


- **Initial state effects**
  - Nuclear shadowing, gluon shadowing at LHC [JHEP 0904 (2009) 065]
  - Parton saturation / CGC [Nucl. Phys. A770 (2006) 40]
  - Radiative energy loss [PRL 68 (1992) 1834]
  - Cronin effects [PRD 11:3105, 1975]
- **Final state effects**
  - Nuclear absorption [Nucl. Phys. A700 (2002) 539], expected to be small at LHC [JHEP 0902.014, 2009]
  - Radiative energy loss [PRC61 (2000) 035203]
  - Comovers [arXiv:1411.0549v2]
- **Neither initial nor final**
  - Coherent energy loss [PRL 109 (2012) 122301]

D^0 production

- Heavy quarks produced early in heavy-ion collisions are excellent probes of the cold and hot nuclear matter effects in pPb and PbPb collisions.
- Cold nuclear matter effects, including modification of PDFs in nuclei and other initial/final state effects, might be dominant in pPb collisions.
- The LHCb detector is excellent in pPb collisions for heavy quark production.
- Charm production can be used to probe nuclear modifications at very small Q² and very small Bjorken-x ($x < 10^{-4}$and $5 \times 10^{-3} < x < 5 \times 10^{-2}$) in pPb collisions at $\sqrt{s} = 5.02\,\mathrm{TeV}$ were published recently.
- High statistics data of pPb collisions at $\sqrt{s} = 8.16\,\mathrm{TeV}$ are expected to provide high accuracy measurements of prompt open charm hadrons.

J. Eskola, et al., EPJC 77 (2017) 163



D^0 production at LHCb

Definition of observables

- **Double differential cross-section:**

Prompt signal yields

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_\mathrm{T}\mathrm{d}y^*} = \frac{N}{\mathscr{L} \times \epsilon_\mathrm{tot} \times \mathscr{B} \times \Delta p_\mathrm{T} \times \Delta y^*}$$

Integrated luminosity

Total efficiency

Branching ratio

- **Nuclear modification factor :**

$$R_{p\mathrm{Pb}}\left(p_\mathrm{T}, y^*\right) = \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}\left(p_\mathrm{T}, y^*\right)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}\left(p_\mathrm{T}, y^*\right)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$

- **Forward-backward production ratio:**

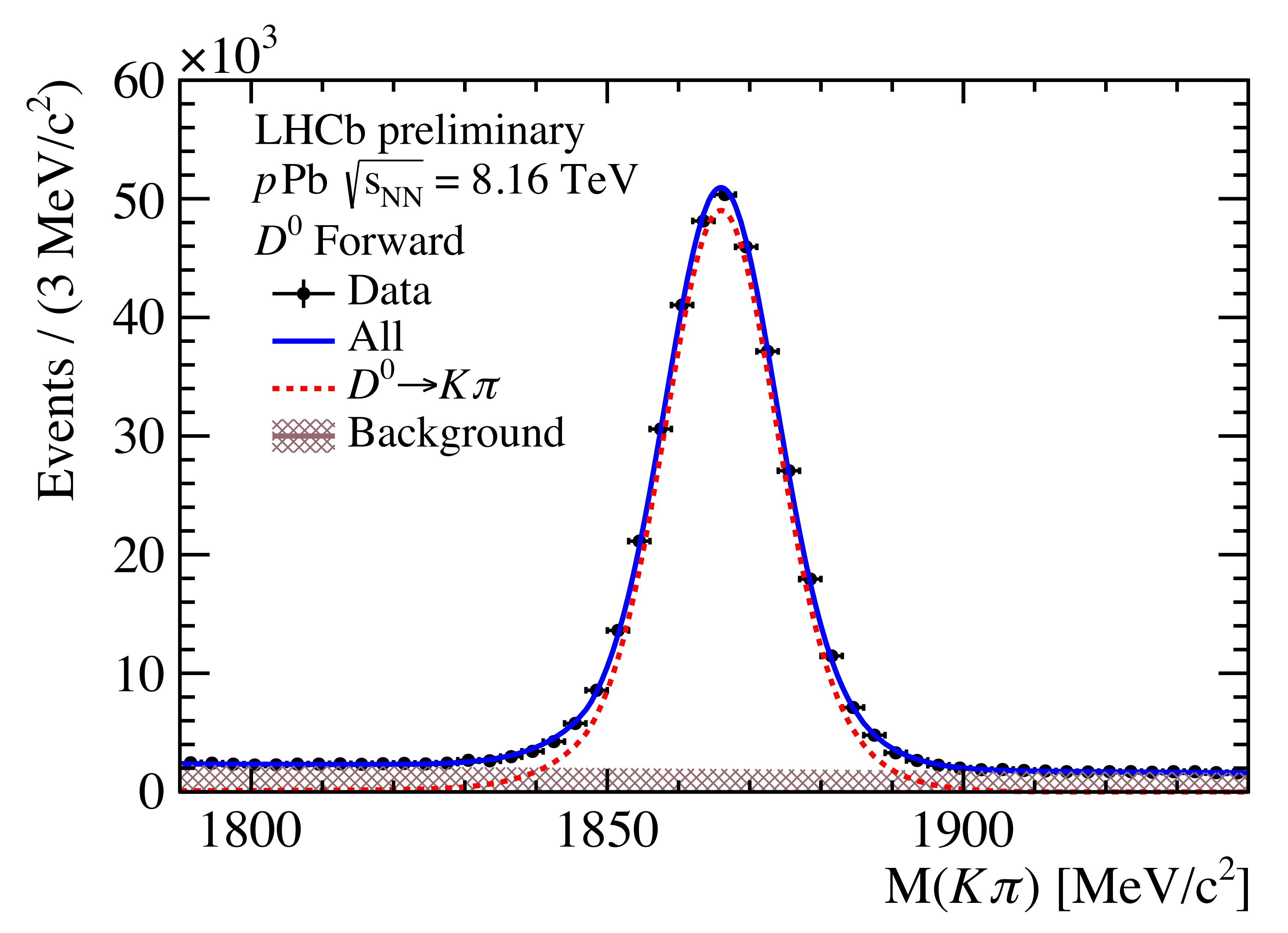
$$R_\mathrm{FB}\left(p_\mathrm{T}, y^*\right) = \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}\left(p_\mathrm{T}, +|y|^*\right)/dp_\mathrm{T}dy^*}{\mathrm{d}^2\sigma_{p\mathrm{Pb}}\left(p_\mathrm{T}, -|y|^*\right)/dp_\mathrm{T}dy^*}$$

- **Baryon to meson ratio:**

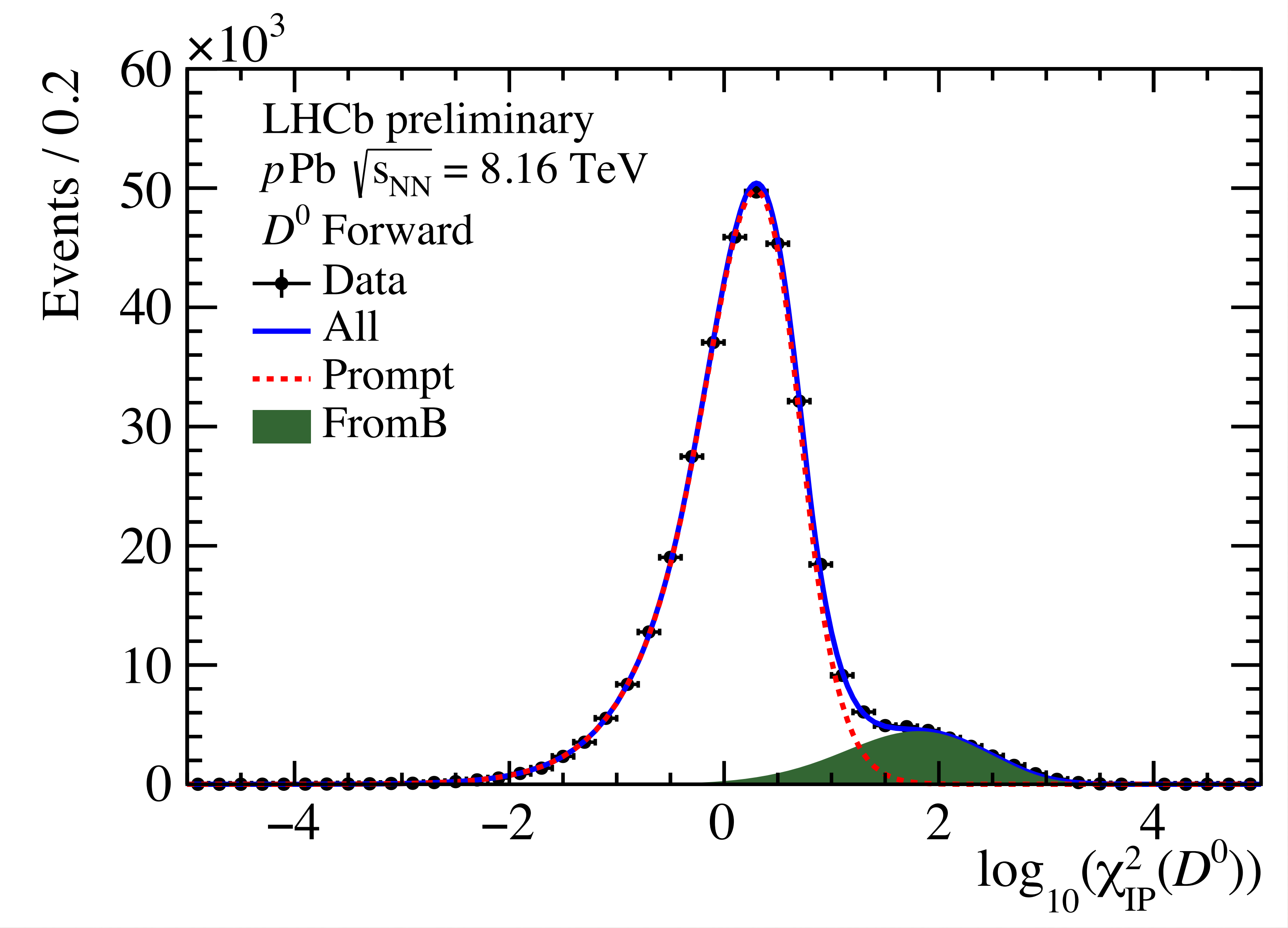
$$R_{\Lambda_c^+/D^0}\left(p_\mathrm{T}, y^*\right) = \frac{\mathrm{d}^2\sigma_{\Lambda_c^+}\left(p_\mathrm{T}, y^*\right)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{D^0}\left(p_\mathrm{T}, y^*\right)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$

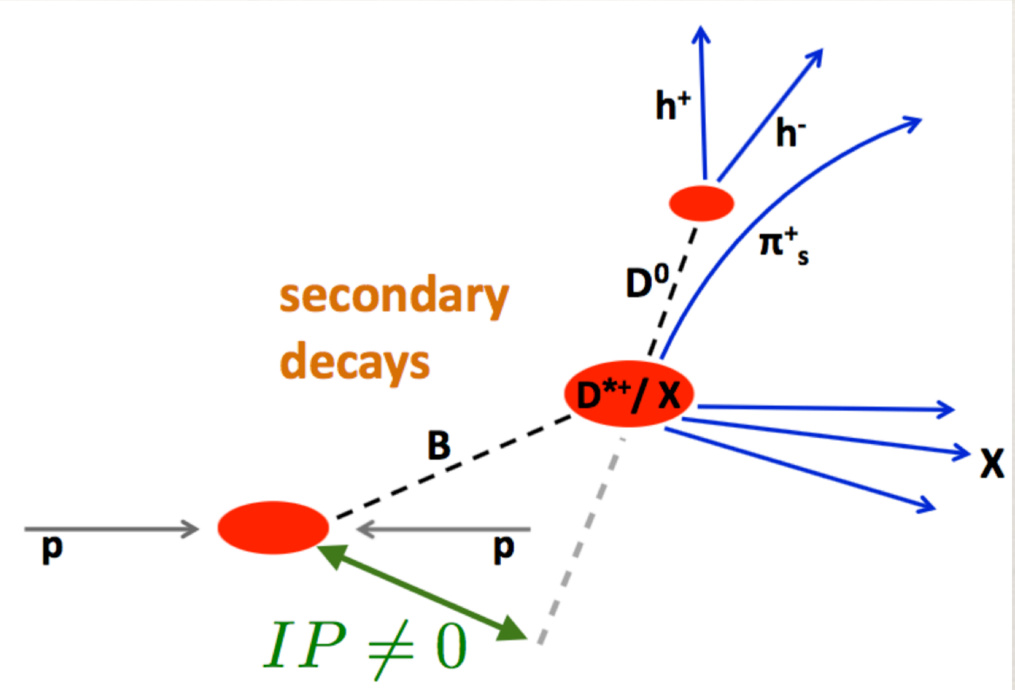
Cross-section measurement

- D^0 yields extracted from $K^{\mp}\pi^{\pm}$ mass fits



- Prompt and non-prompt (from b-decay) are separated using fit to the impact parameter (IP) χ^2 spectrum



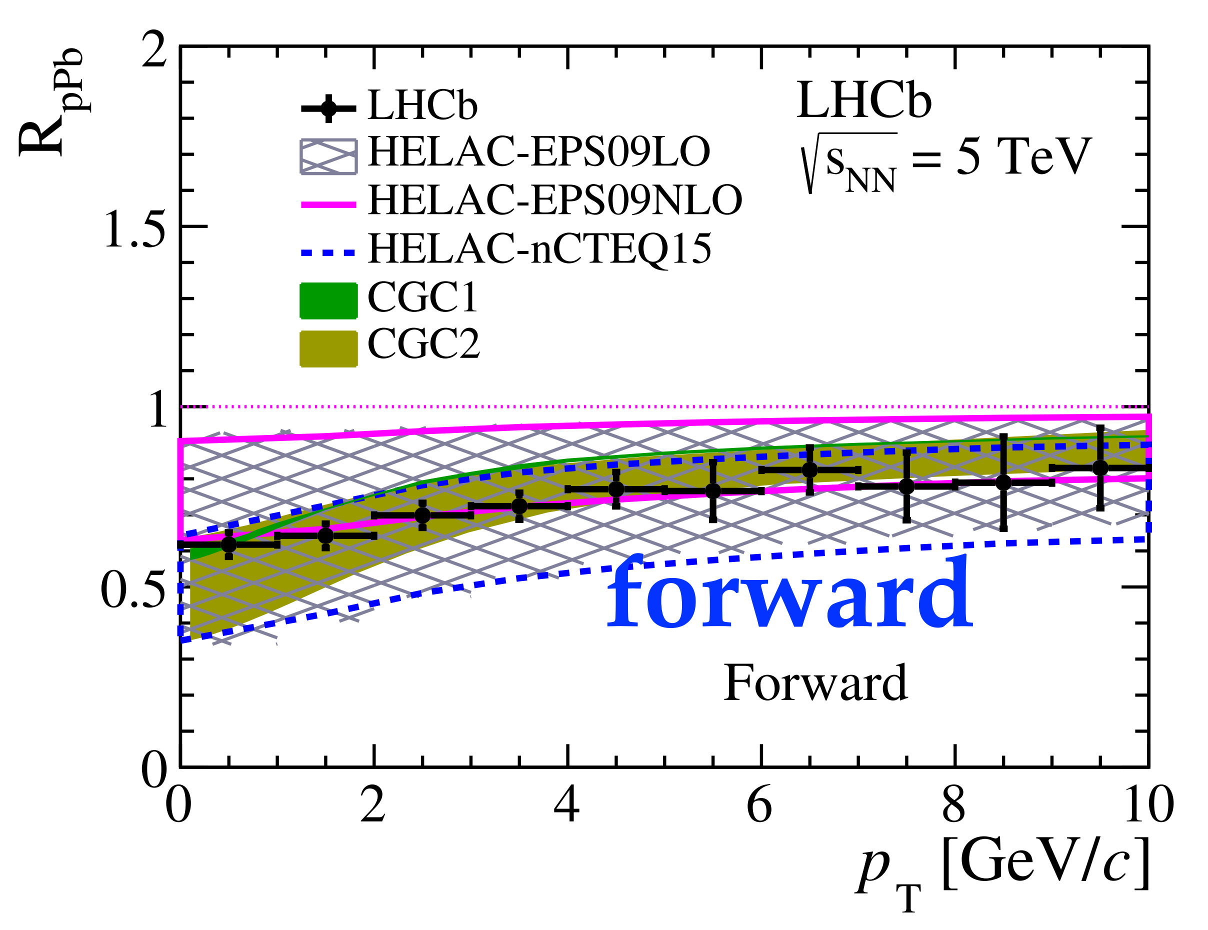


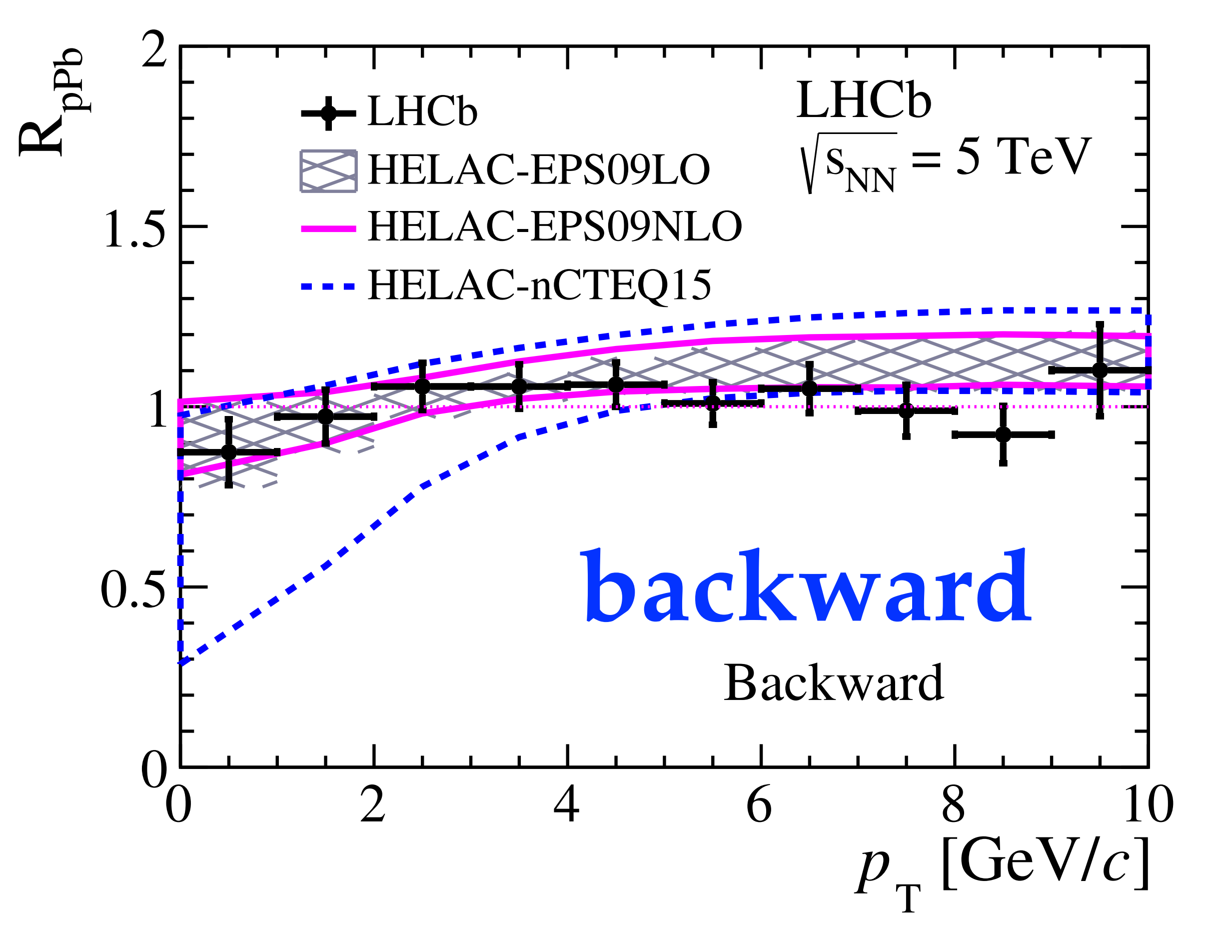
LHCb-CONF-2019-004

- Total efficiency calculated using simulation and calibration data samples:
  - Forward: from 0.8% to 14%
  - Backward: from 0.7% to 13%

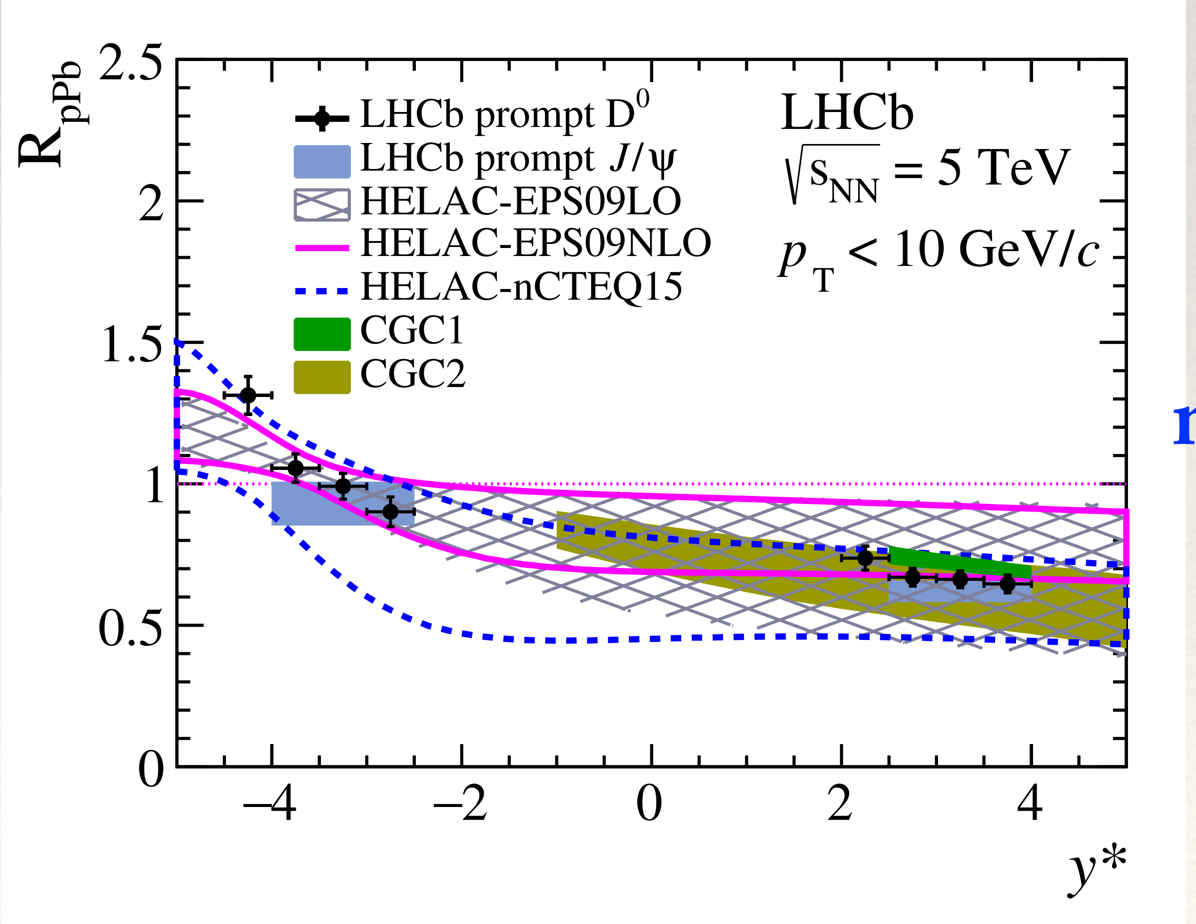
Results from 5.02 TeV pPb collisions

Nuclear modification factor vs. D^0 pT





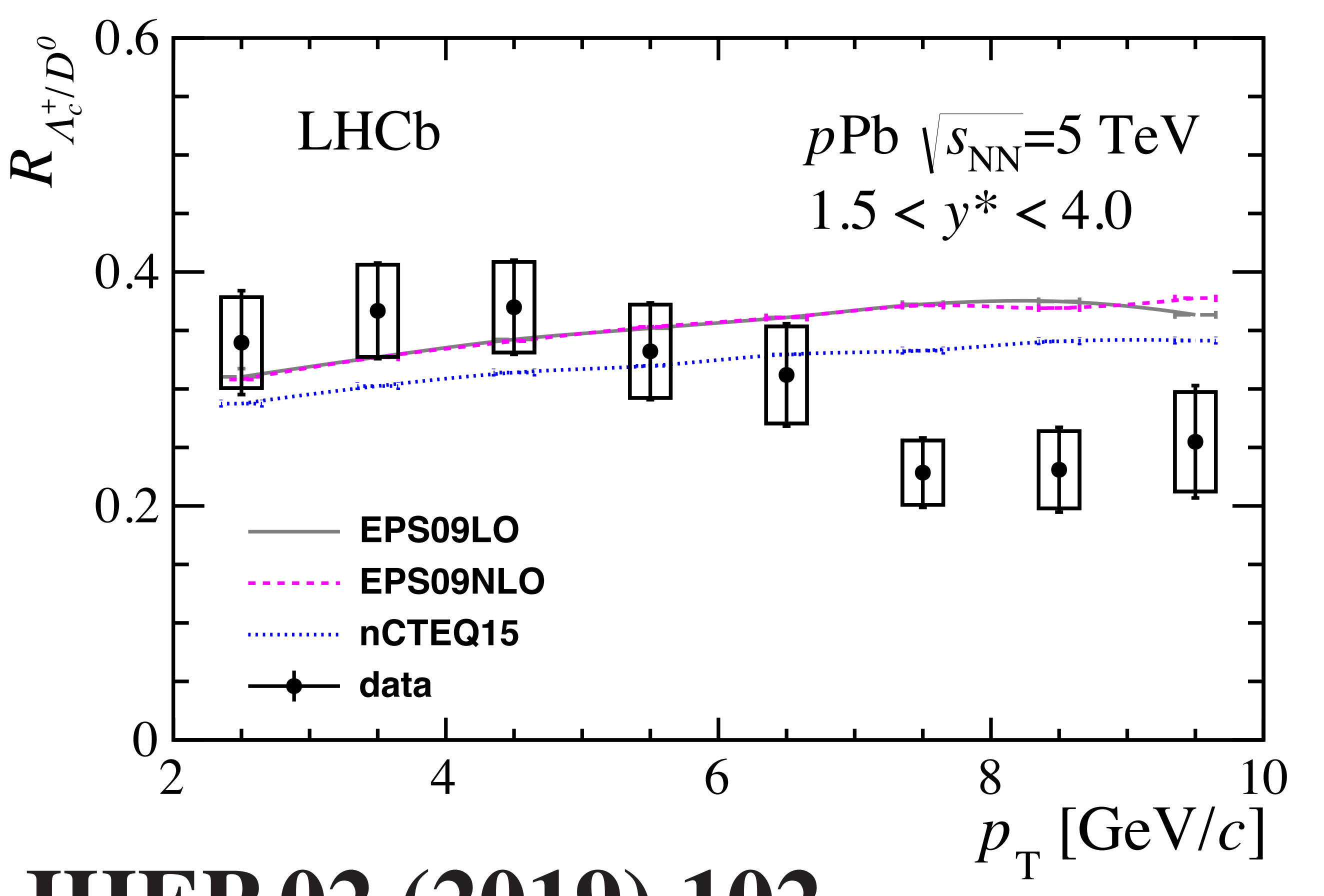
JHEP 10 (2017) 090



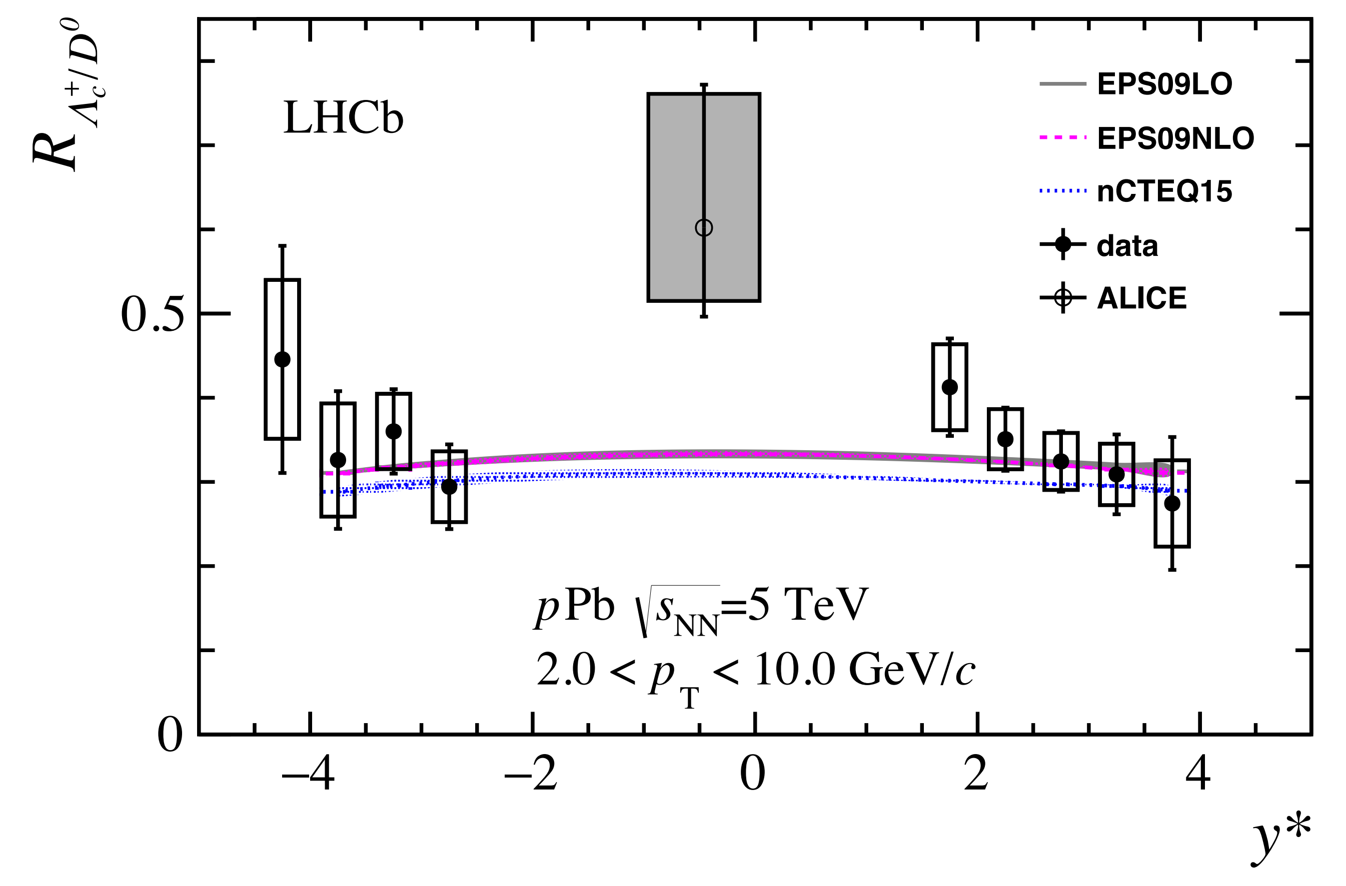
Nuclear modification factor vs. D^0 rapidity

- R_{pPb} suppressed in forward region (~30%), no suppression in backward region, hint of small excess at large backward rapidity ($y^*<-4$)
- Baryon-to-meson, forward rapidity: discrepancies at high-p_T between data and models tuned to pp

Ratio between D^0 and Λ_c^+



JHEP 02 (2019) 102

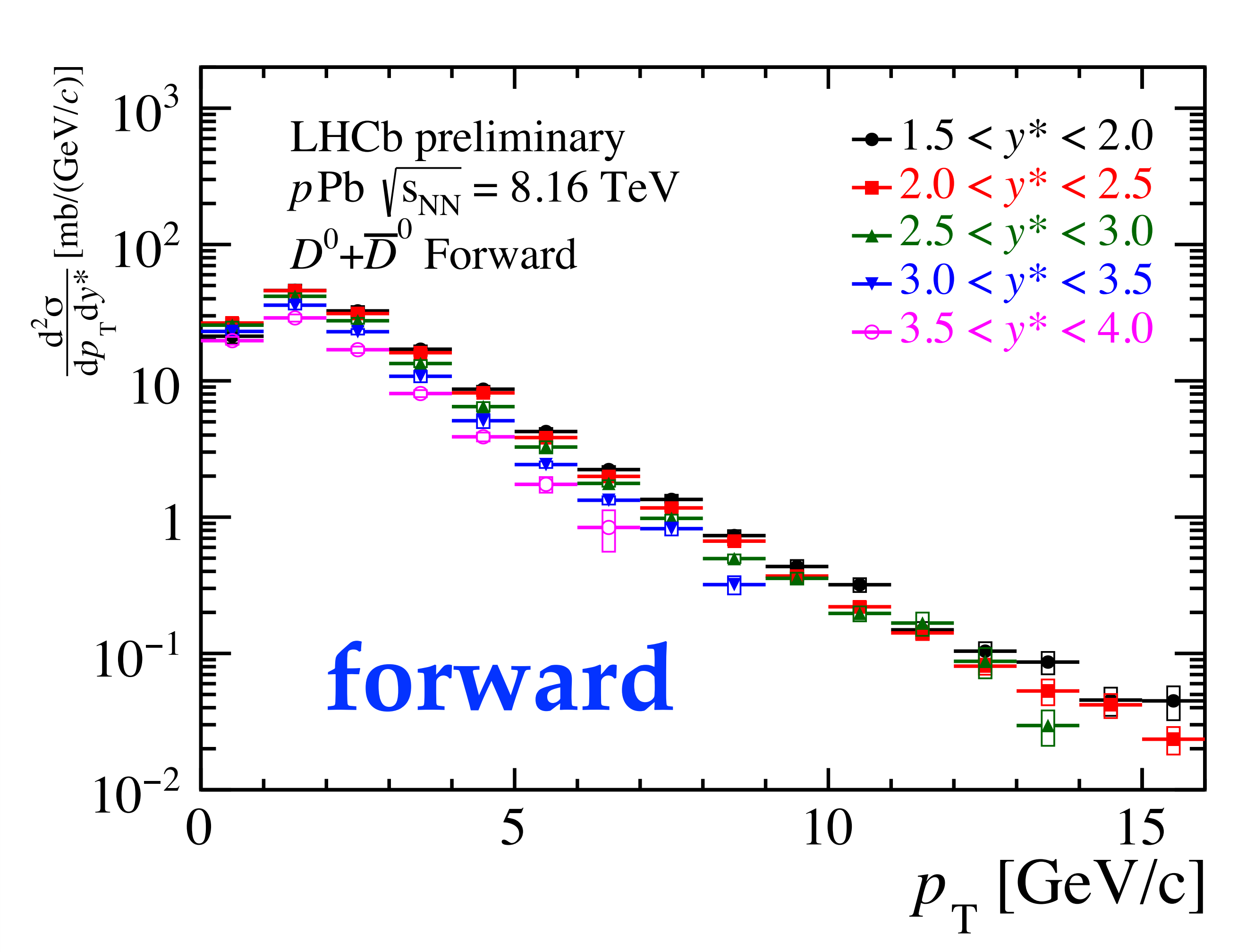


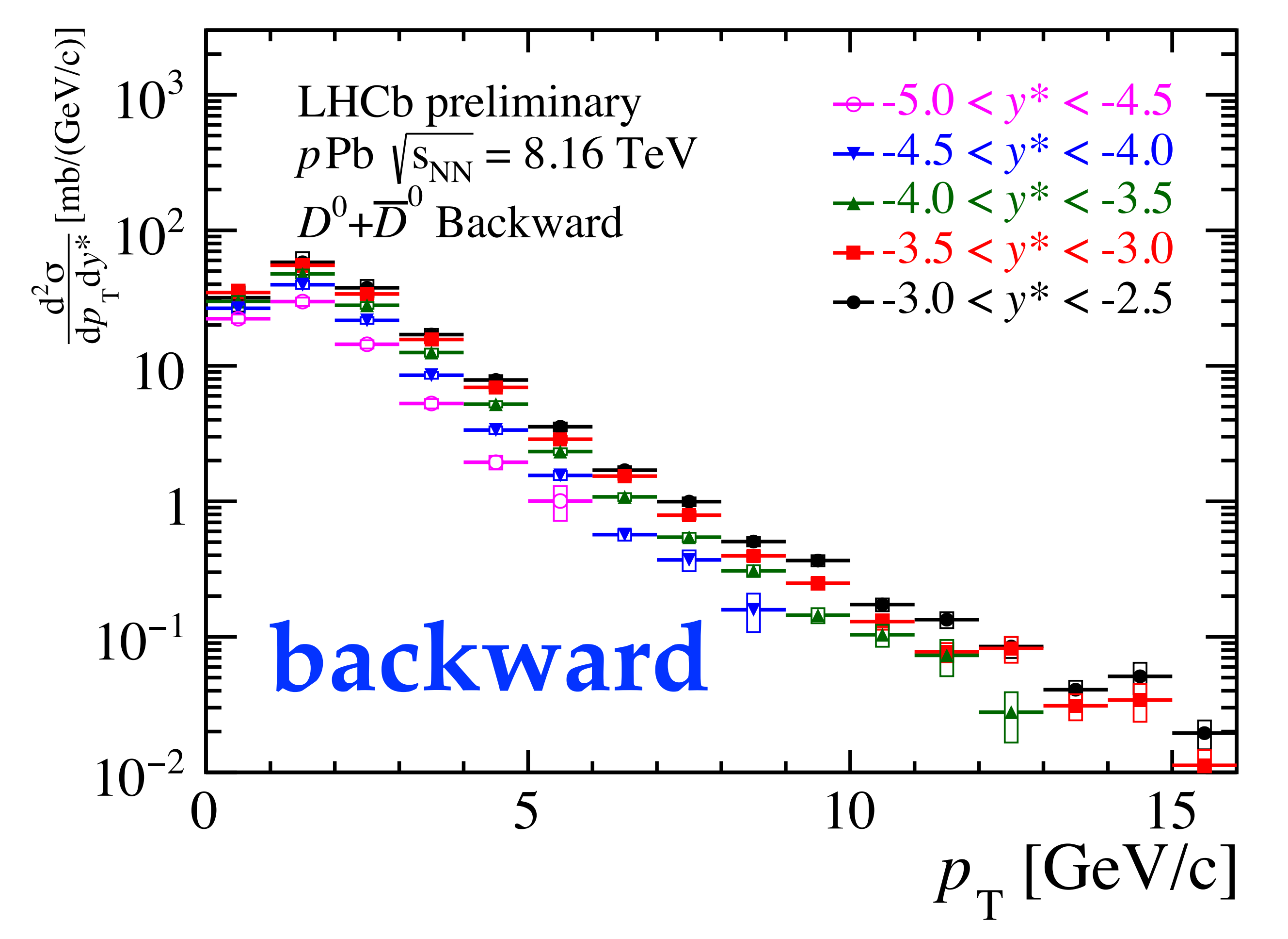
Differential cross-section at 8.16 TeV

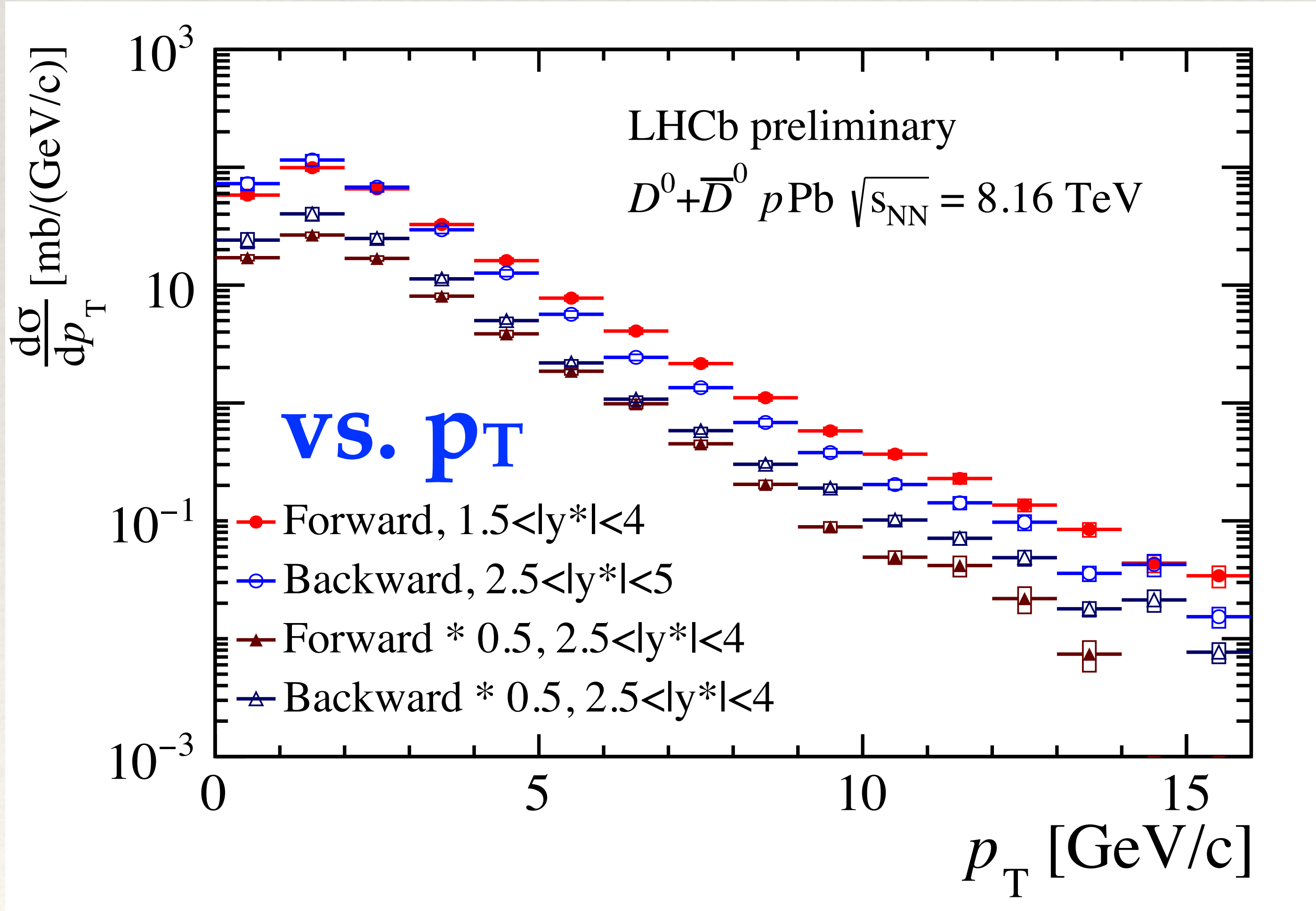
LHCb-CONF-2019-004

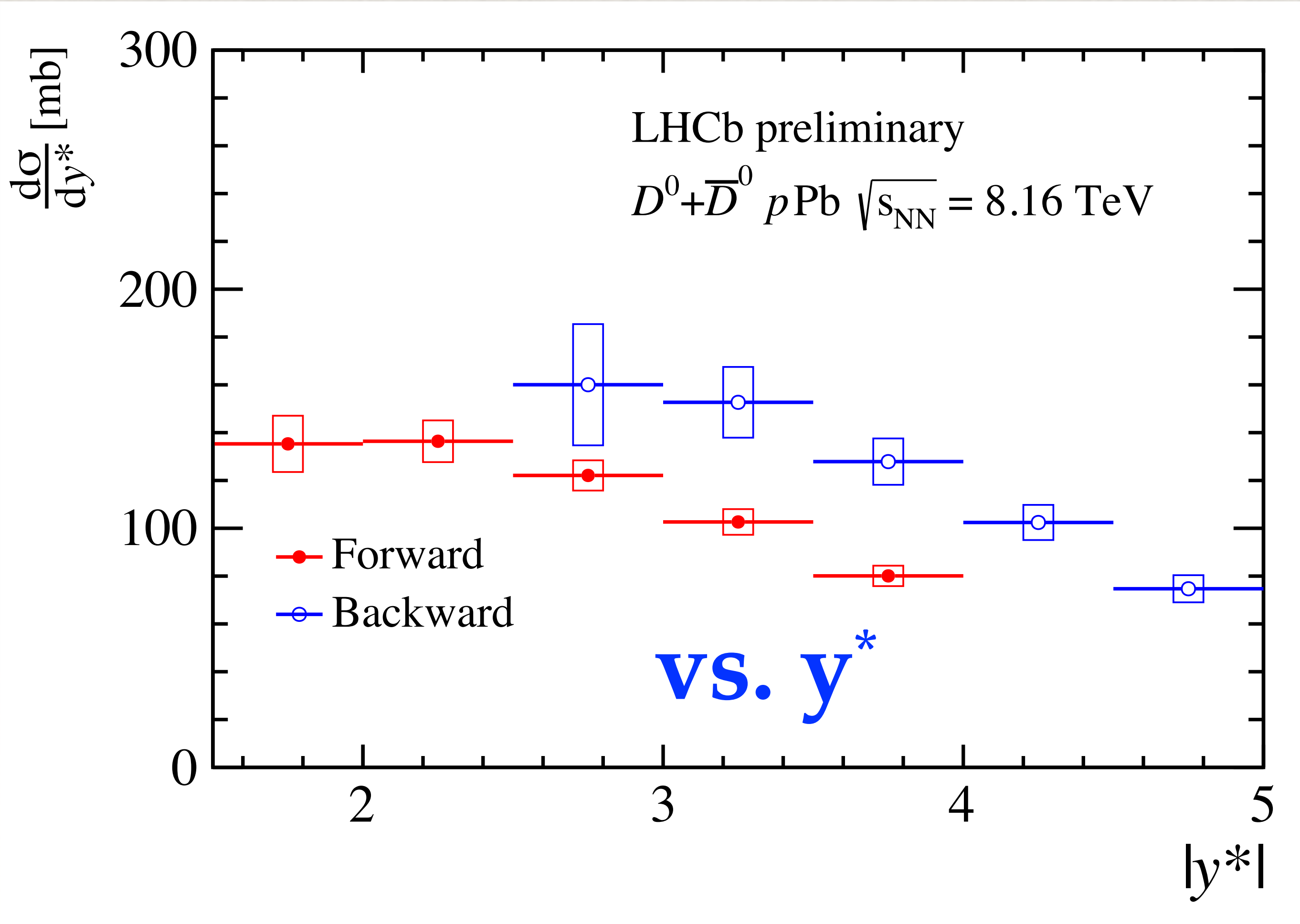
- **Double-differential cross-section** $d^2\sigma/dp_T dy^*$

- **Differential cross-sections (vs. p_T) and (vs. y^*) for forward and backward separately**









Forward-backward ratio at 8.16 TeV

- Forward-backward ratio R_{FB}

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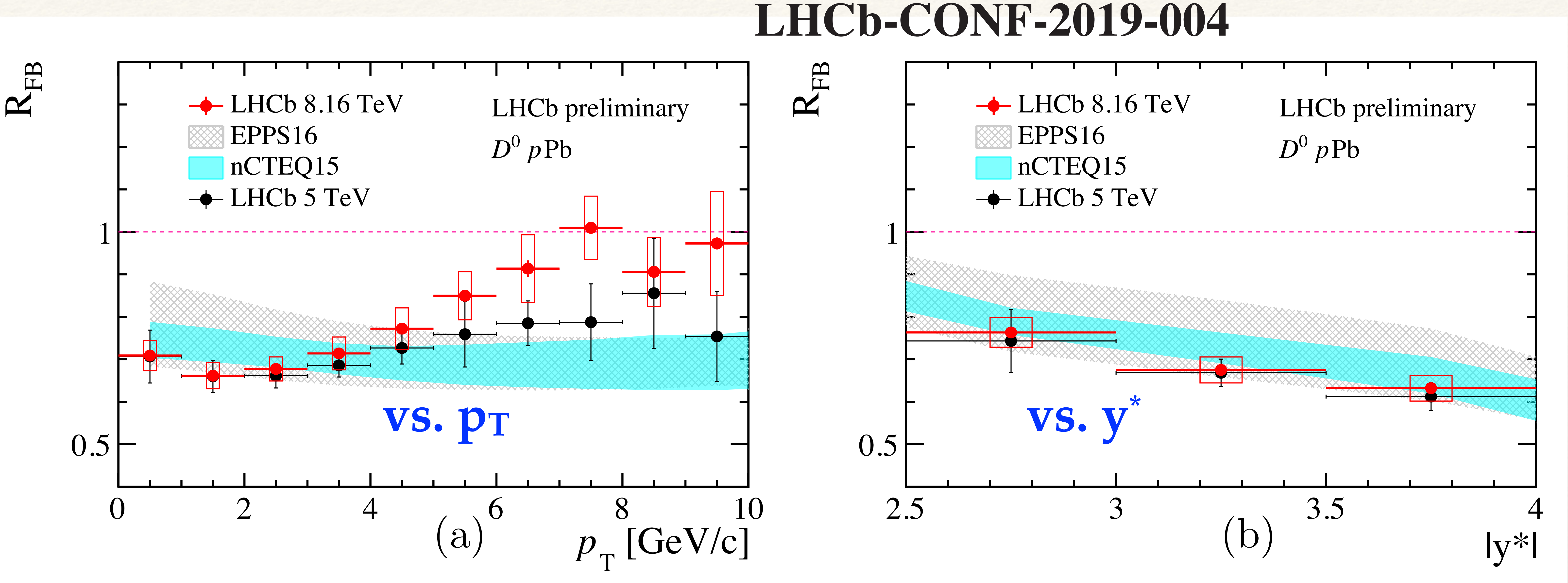
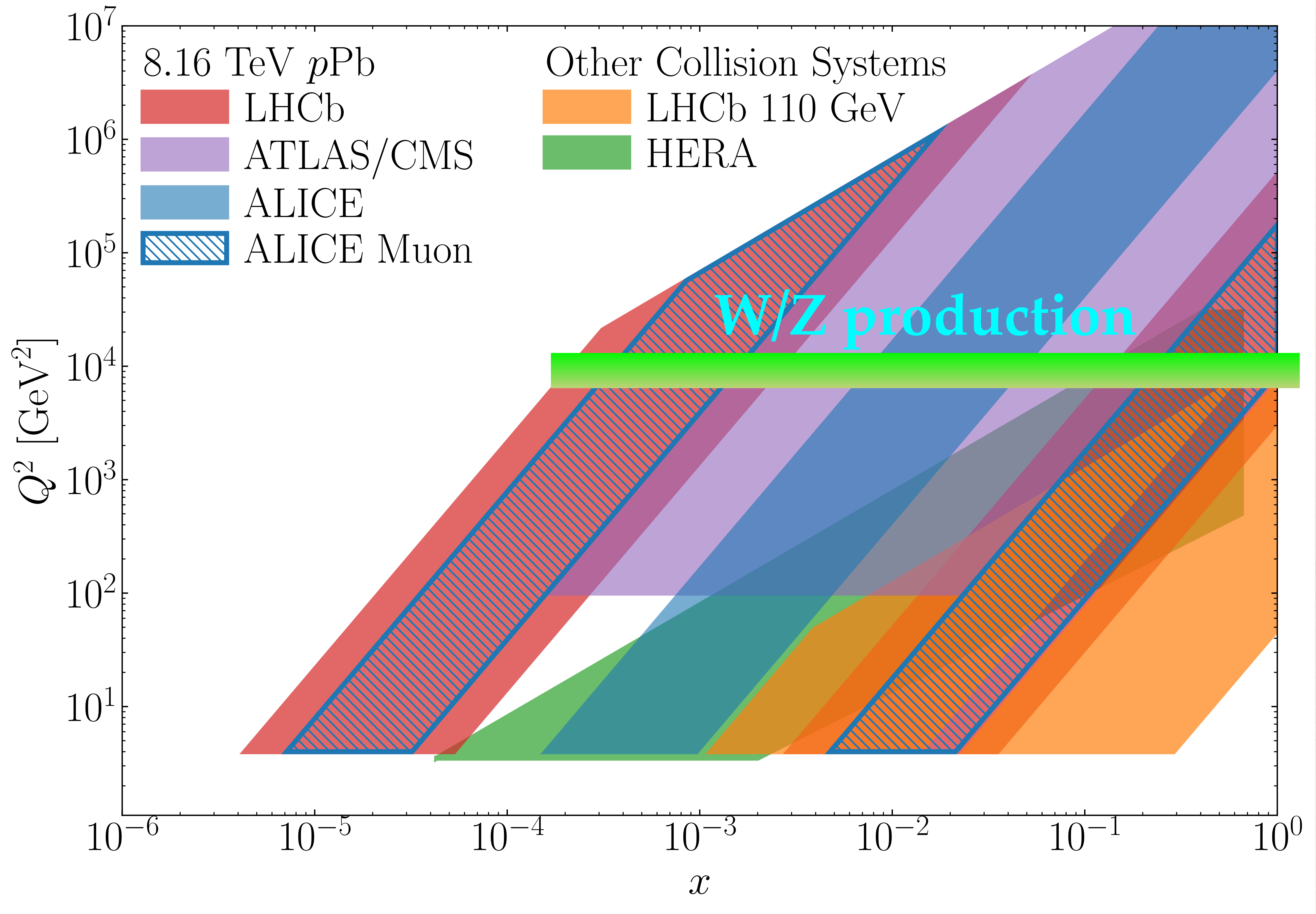


- **Improved statistics by factor 20 compared to previous LHCb results.**
- **Tension between data and nPDFs predictions. Additional effects required.**

J.-P. Lansberg and H.-S.Shao, EPJC 77 (2017) S10052.
A. Kusina, et al., PRL 121 (2018) 052004.
H.-S. Shao, CPC 184 (2013) 2562-2570.
H.-S. Shao, CPC 198 (2016) 238-259.

Z boson production in pPb

- Electroweak bosons are unmodified by the hot and dense medium created in heavy ion collisions,
- Their leptonic decays pass through the medium without being affected by the strong interaction.
- Therefore, electroweak boson productions well "conserved" the initial conditions of the collisions, can be:
  - used to probe (cold) nuclear effects and constraint nPDFs for Bjorken-x from ~10^{-4} to 1 at $Q^2 \sim 10^4$ GeV^2
  - and can be used as a calibration of the nuclear modification of other processes such as heavy quark production



Z boson production in pPb

- Cross-sections measured in fiducial volume for both pPb and Pbp:

$$\sigma_{Z\to\mu^+\mu^-} = \frac{N_{\text{sig.}}}{\mathscr{L}\cdot\epsilon_{\text{tot}}}$$

- Forward-backward ratio measured in fiducial volume + common rapidity coverage:

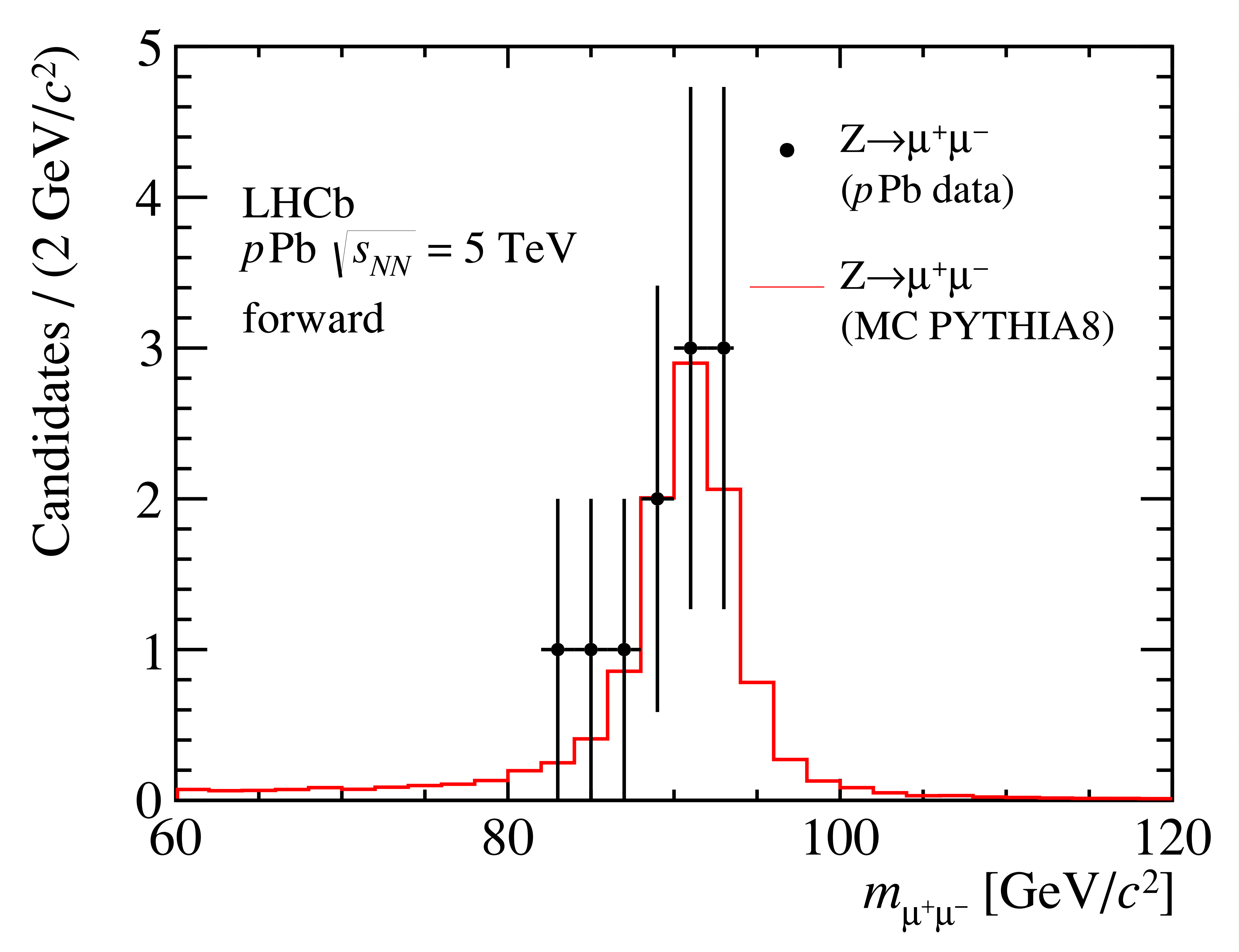
$$R_{\text{FB}}^{2.5<|y^*|<4.0} = \left.\frac{\sigma_{Z\to\mu^+\mu^-,p\,\text{Pb}}}{\sigma_{Z\to\mu^+\mu^-,\text{Pb}\,p}}\right|_{2.5<|y^*|<4.0}$$

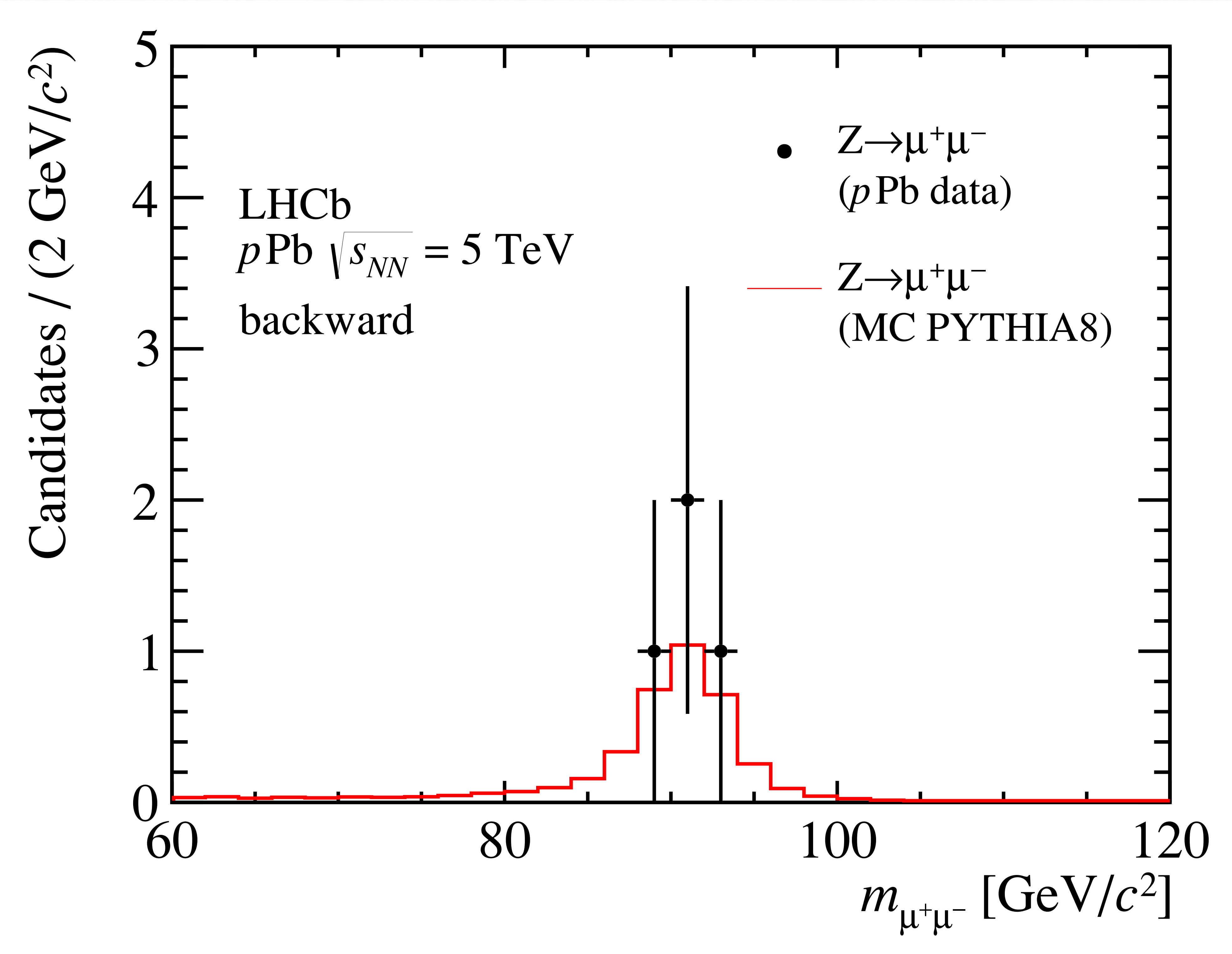
- Fiducial volume:
  $60 < m_{\mu\mu} < 120\,\text{GeV}$
  $2.0 < \eta^\mu < 4.5,\ p_T^\mu > 20\,\text{GeV}$

Z boson production in pPb at 5 TeV

- Integrated luminosity: forward (1.099 ± 0.021 nb^{-1}) / backward(0.521 ± 0.011 nb^{-1})
- Yields: forward (11 events) / backward (4 events)

【JHEP09(2014)030】





Z boson production in pPb at 5 TeV

- Fiduсial cross-section results:
  - Forward:

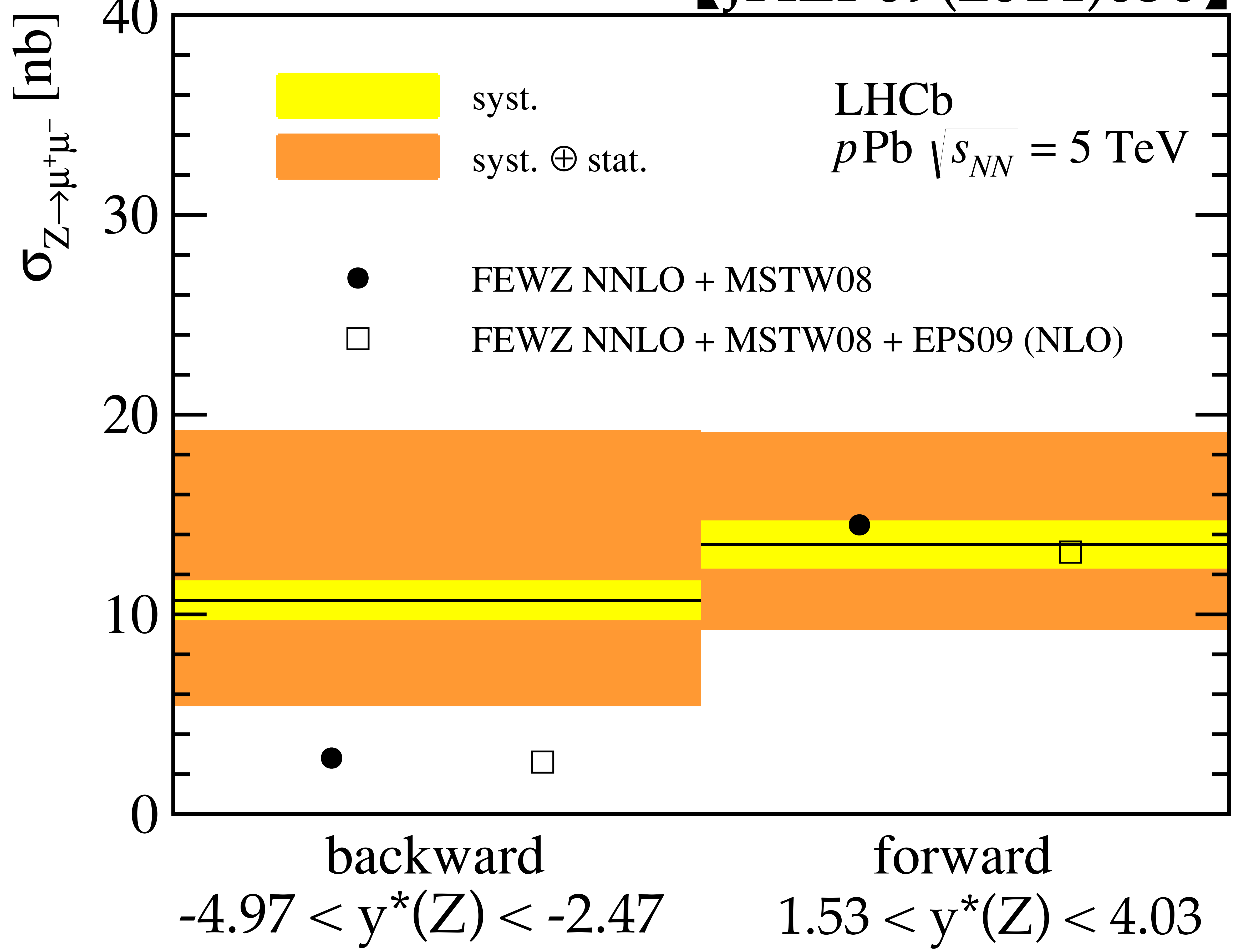
$$\sigma_{Z\to\mu^+\mu^-}(\mathrm{fwd}) = 13.5^{+5.4}_{-4.0}(\mathrm{stat.}) \pm 1.2(\mathrm{syst.})\ \mathrm{nb}$$

  - Backward:

$$\sigma_{Z\to\mu^+\mu^-}(\mathrm{bwd}) = 10.7^{+8.4}_{-5.1}(\mathrm{stat.}) \pm 1.0(\mathrm{syst.})\ \mathrm{nb}$$

- Compatible with theoretical predictions using FEWZ(NNLO pQCD+NLO pEW) with:
  - MSTW08(PDF) for both p and Pb
  - MSTW08(PDF) for p and EPS09(nPDF) for Pb

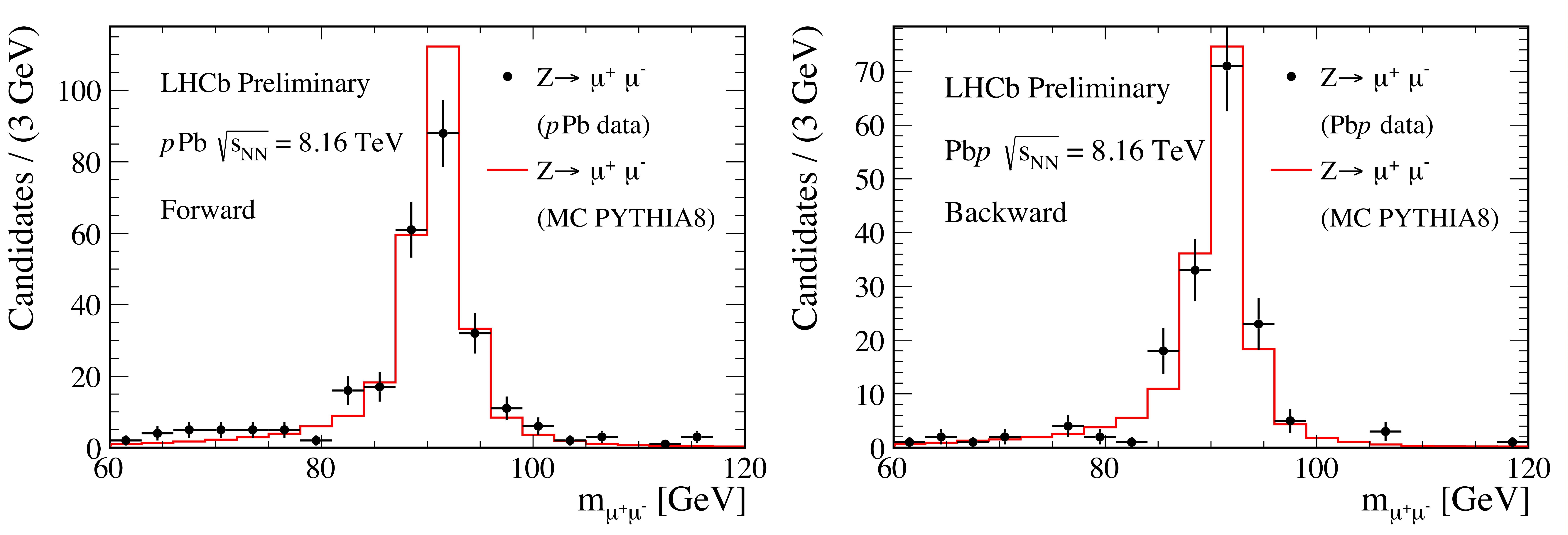
【JHEP09(2014)030】



Z boson production in pPb at 8 TeV

- Integrated luminosity: forward (12.2 ± 0.3 nb^{-1}) / backward(18.6 ± 0.5 nb^{-1})
- Yields: forward (268 events) / backward (167 events)

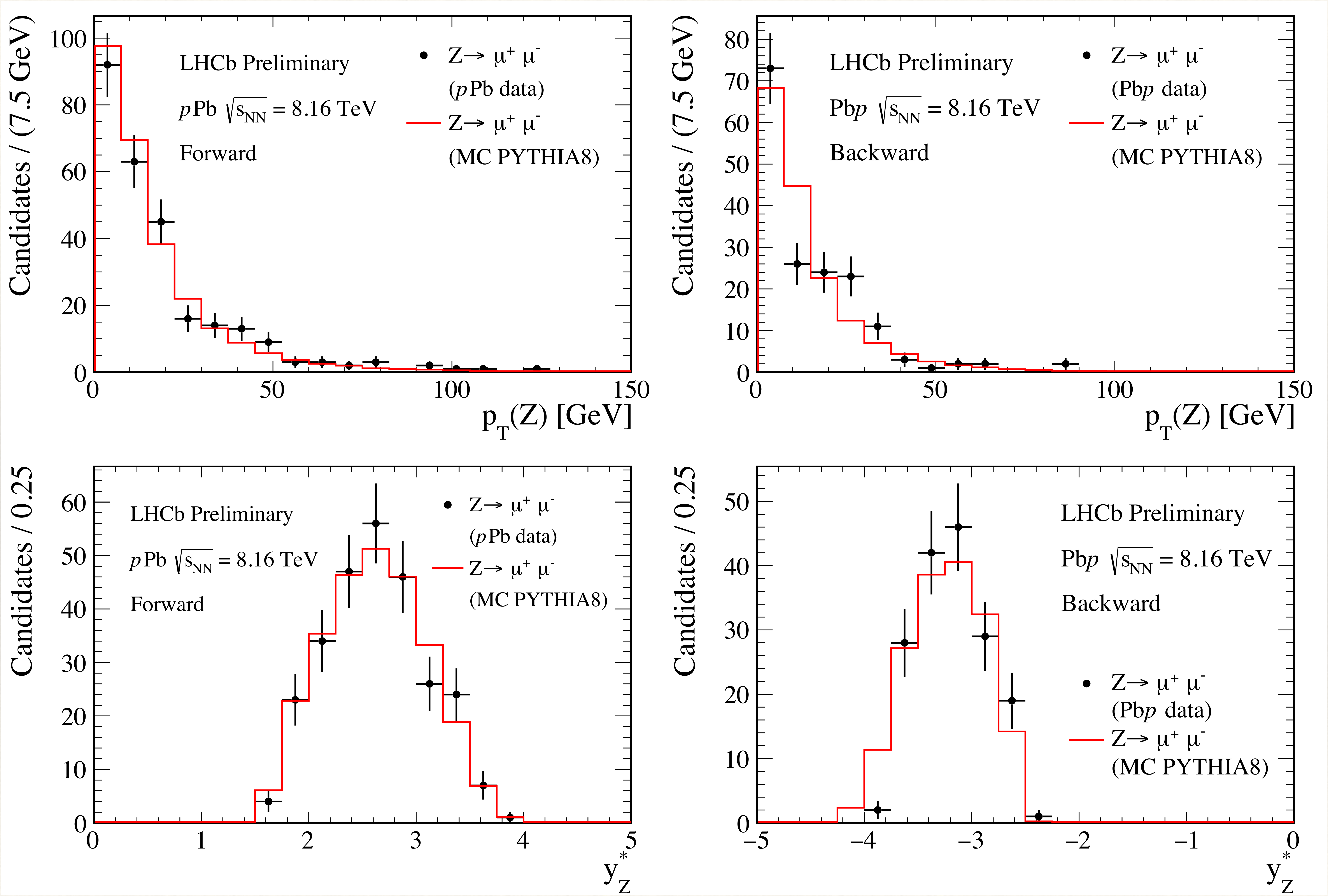
【LHCb-CONF-2019-003】



pPb Z boson production at 8 TeV

- Integrated luminosity:
  forward (12.2 ± 0.3 nb^{-1})
  backward(18.6 ± 0.5 nb^{-1})
- Yields:
  forward (268 events)
  backward (167 events)
- MC normalized to data yields

【LHCb-CONF-2019-003】



pPb Z boson production at 8 TeV

- Fiducial cross-section results:

  $\sigma_{Z\to\mu^+\mu^-,\ p\mathrm{Pb}}$ (forward)

  $= 28.5 \pm 1.7(\mathrm{stat.}) \pm 1.2(\mathrm{syst.}) \pm 0.7(\mathrm{lumi.})\ \mathrm{nb}$

  $\sigma_{Z\to\mu^+\mu^-,\ \mathrm{Pb}p}$ (backward)

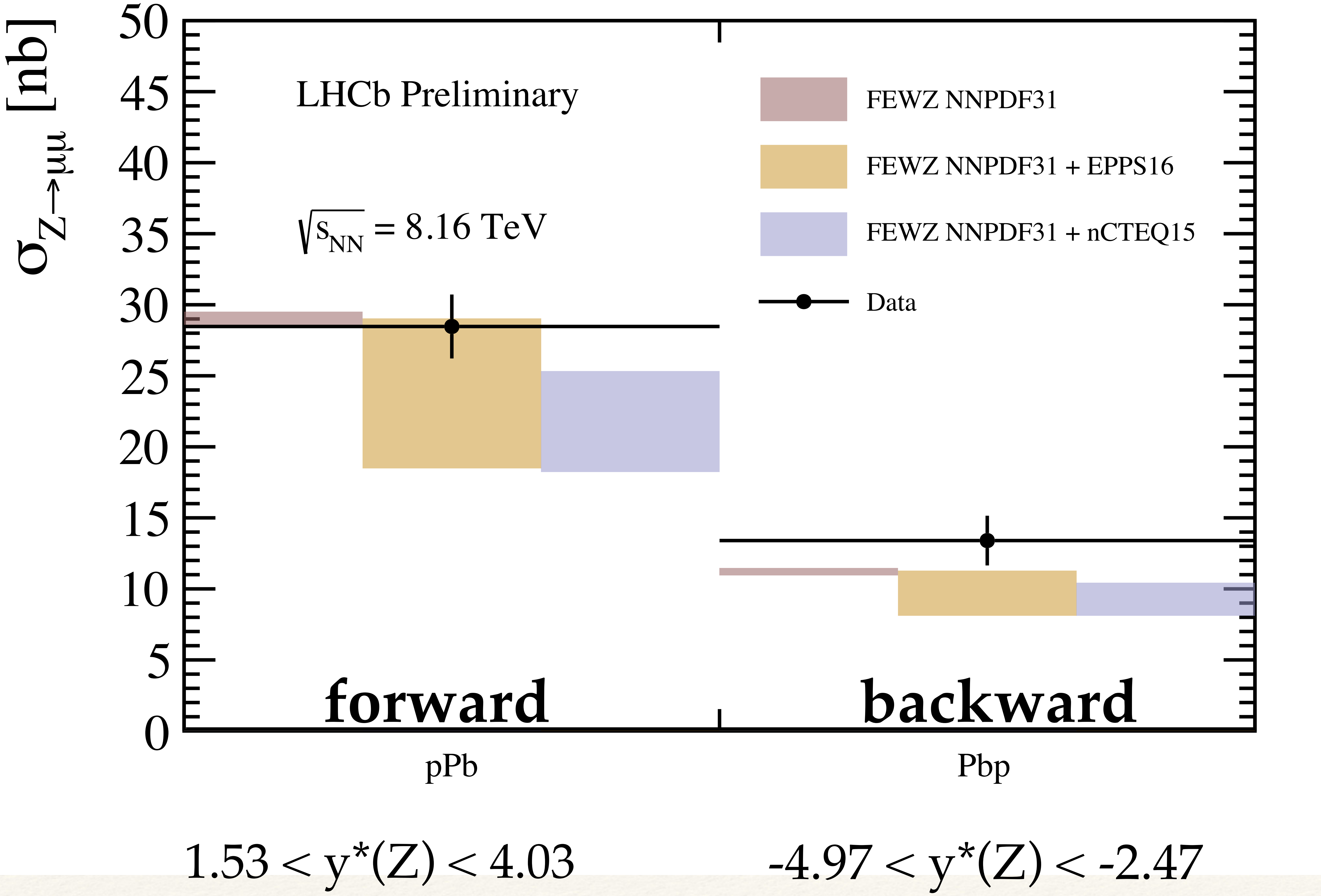
  $= 13.4 \pm 1.0(\mathrm{stat.}) \pm 1.4(\mathrm{syst.}) \pm 0.3(\mathrm{lumi.})\ \mathrm{nb}$

- Compatible with theoretical predictions using FEWZ(NNLO pQCD+NLO pEW) with NNPDF3.1(PDF) for p and
  - NNPDF3.1(PDF)
  - EPPS16 (nPDF)
  - nCTEQ15 (nPDF)

  } for Pb

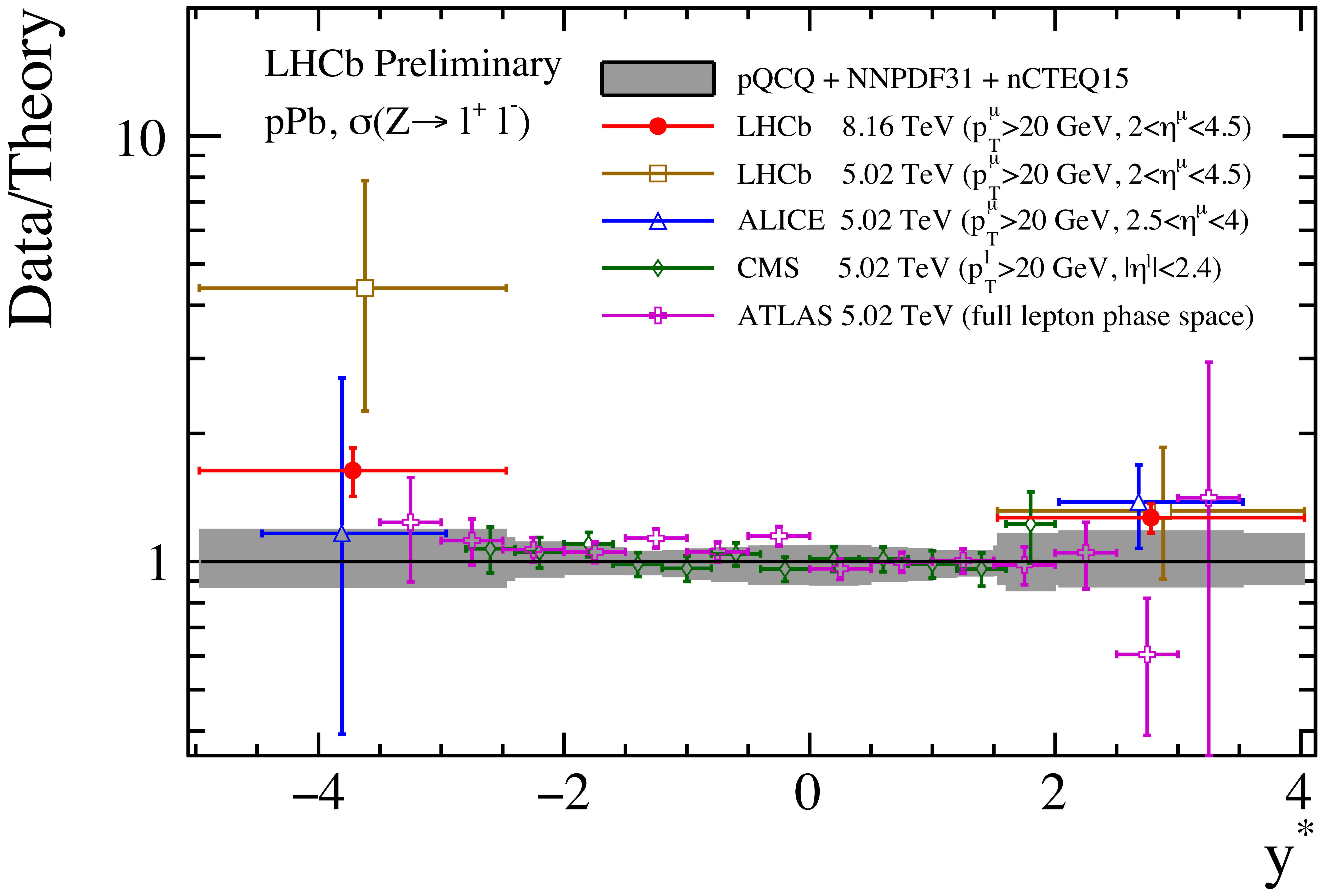
much higher precision

【LHCb-CONF-2019-003】



Compare with results at 5 TeV

- Results are compatible with previous 5 TeV results from various experiments
- The 20 times higher statistics bring higher precision in the measurements



【LHCb-CONF-2019-003】

* only exp. uncert. shown on data/theory ratio, theo. PDF uncert. shown separately on the line at one.

Forward-backward ratio

【LHCb-CONF-2019-003】

- Forward-backward ratio is derived based on cross-sections measured in the common rapidity range:

$$\begin{aligned}\sigma^{2.5<|y^*|<4.0}_{Z\to\mu^+\mu^-,\ p\mathrm{Pb}} &= 17.1 \pm 1.4(\mathrm{stat.}) \pm 0.7(\mathrm{syst.}) \pm 0.4(\mathrm{lumi.})\,\mathrm{nb},\\ \sigma^{2.5<|y^*|<4.0}_{Z\to\mu^+\mu^-,\ \mathrm{Pb}p} &= 13.3 \pm 1.0(\mathrm{stat.}) \pm 1.4(\mathrm{syst.}) \pm 0.3(\mathrm{lumi.})\,\mathrm{nb},\end{aligned}$$

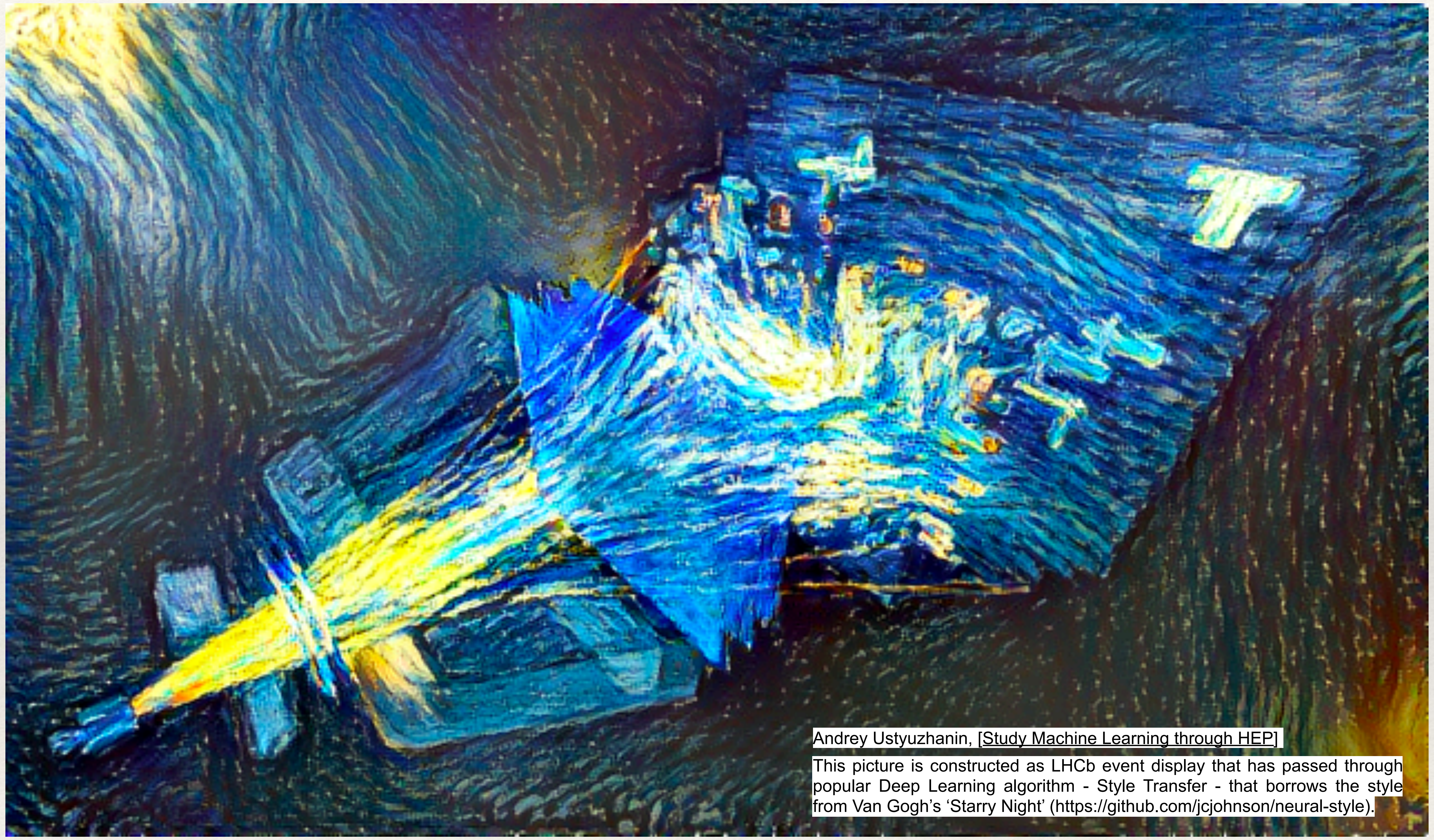
- Measured forward-backward ratio

$$R^{2.5<|y^*|<4.0}_{\mathrm{FB}} = 1.28 \pm 0.14(\mathrm{stat.}) \pm 0.14(\mathrm{syst.}) \pm 0.05(\mathrm{lumi.}).$$

- Compatible with theoretical predictions:

$$\begin{aligned}R^{2.5<|y^*|<4.0}_{\mathrm{FB,NNPDF3.1}} &= 1.59 \pm 0.10(\mathrm{theo.}) \pm 0.01(\mathrm{num.}) \pm 0.05(\mathrm{PDF}),\\ R^{2.5<|y^*|<4.0}_{\mathrm{FB,NNPDF3.1+EPPS16}} &= 1.45 \pm 0.10(\mathrm{theo.}) \pm 0.01(\mathrm{num.}) \pm 0.27(\mathrm{PDF}),\\ R^{2.5<|y^*|<4.0}_{\mathrm{FB,NNPDF3.1+nCTEQ15}} &= 1.44 \pm 0.10(\mathrm{theo.}) \pm 0.01(\mathrm{num.}) \pm 0.20(\mathrm{PDF}).\end{aligned}$$

Understanding the nature of the X(3872)

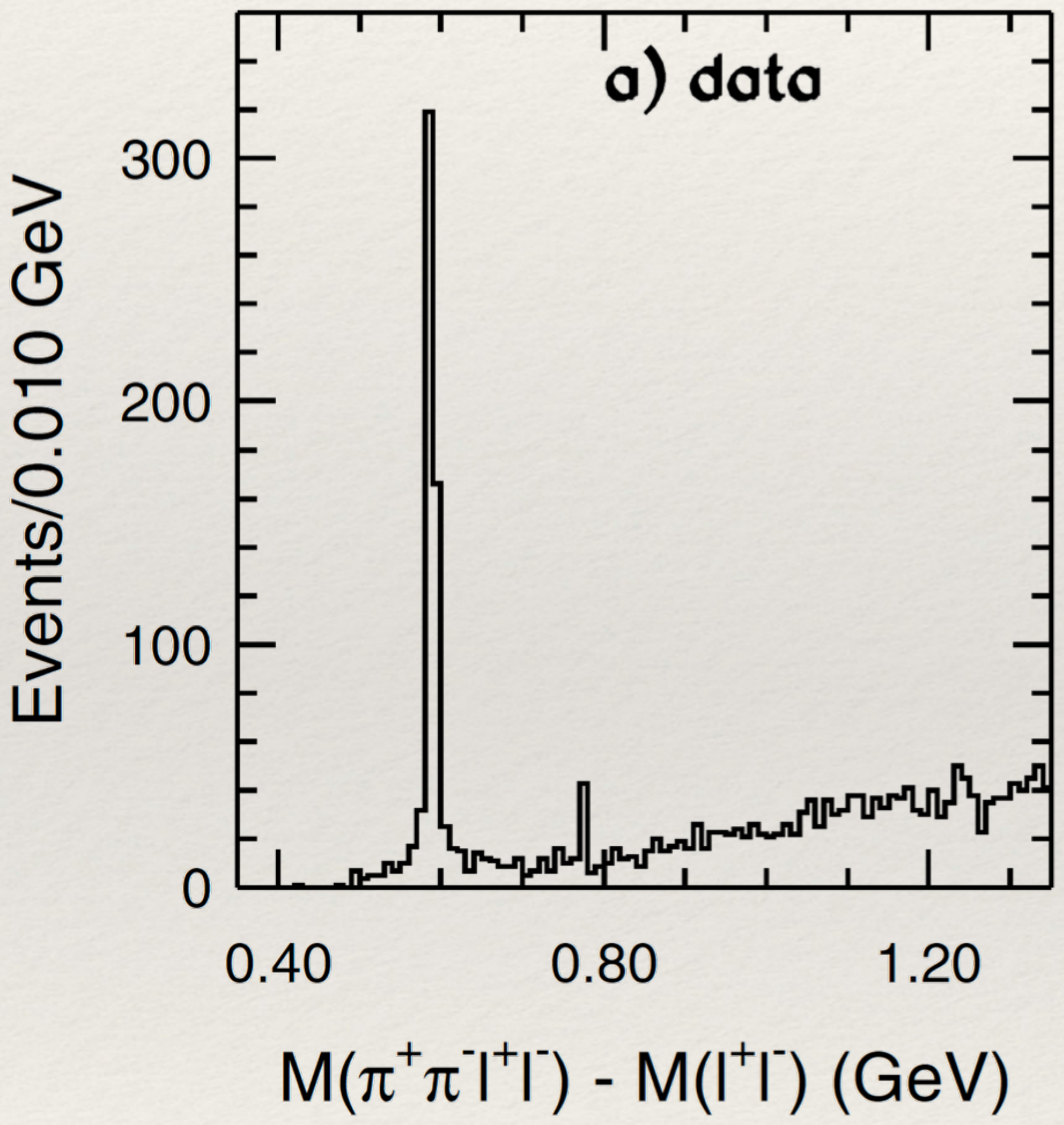


Andrey Ustyuzhanin, [Study Machine Learning through HEP]

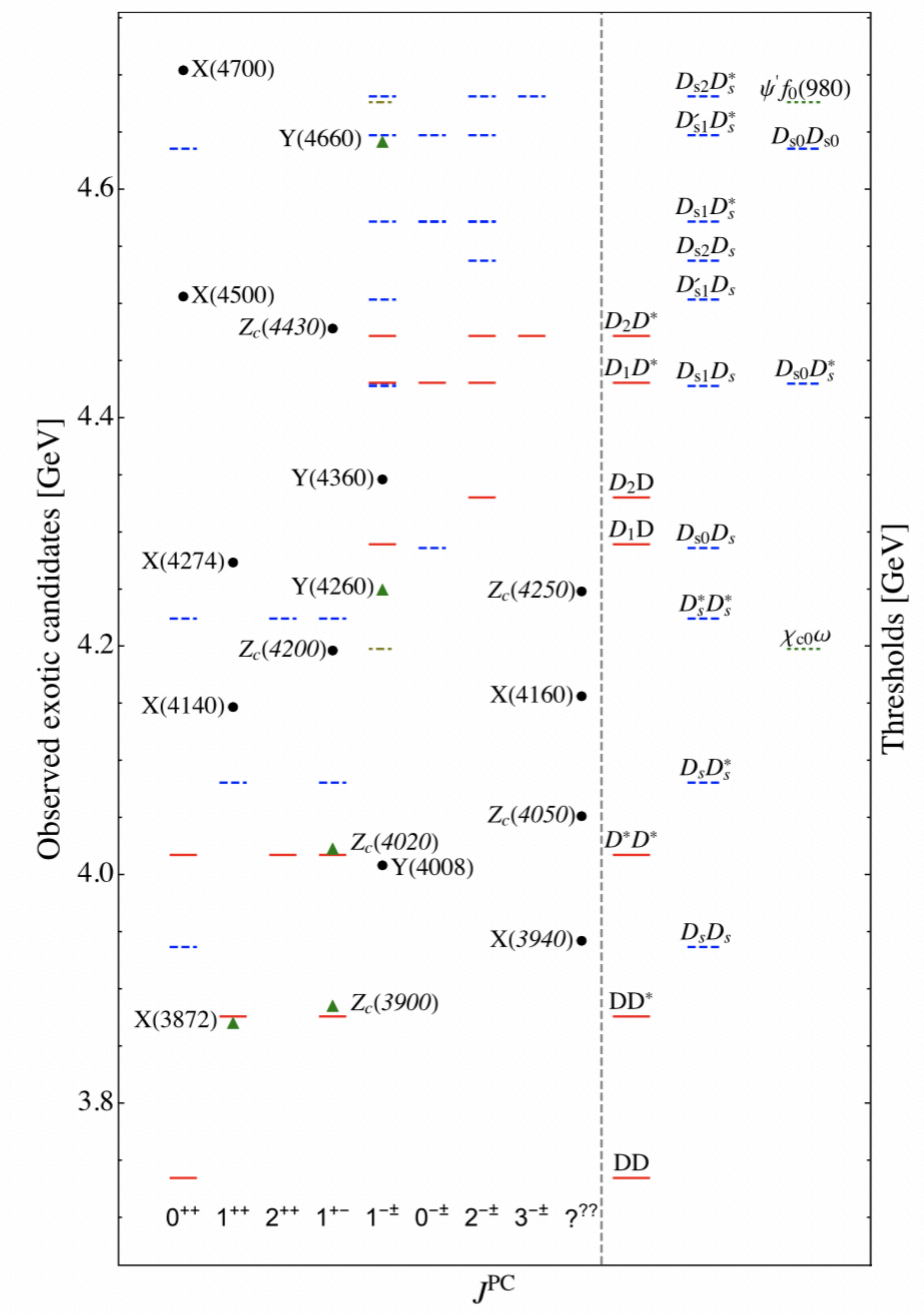
This picture is constructed as LHCb event display that has passed through popular Deep Learning algorithm - Style Transfer - that borrows the style from Van Gogh's 'Starry Night' (https://github.com/jcjohnson/neural-style).

The story started in 2003

Belle Collaboration
PRL 91 262001 (2003)



- **The first exotic hadron – discovered in $J/\psi\pi^+\pi^-$ mass spectrum from B decays by Belle in 2003**
- **Properties do not appear to fit the standard picture of charmonium state**
- **More than 20 previously unpredicted charmonium- and bottomonium-like states have been discovered, and the understanding of heavy quarkonium physics is undetermined.**



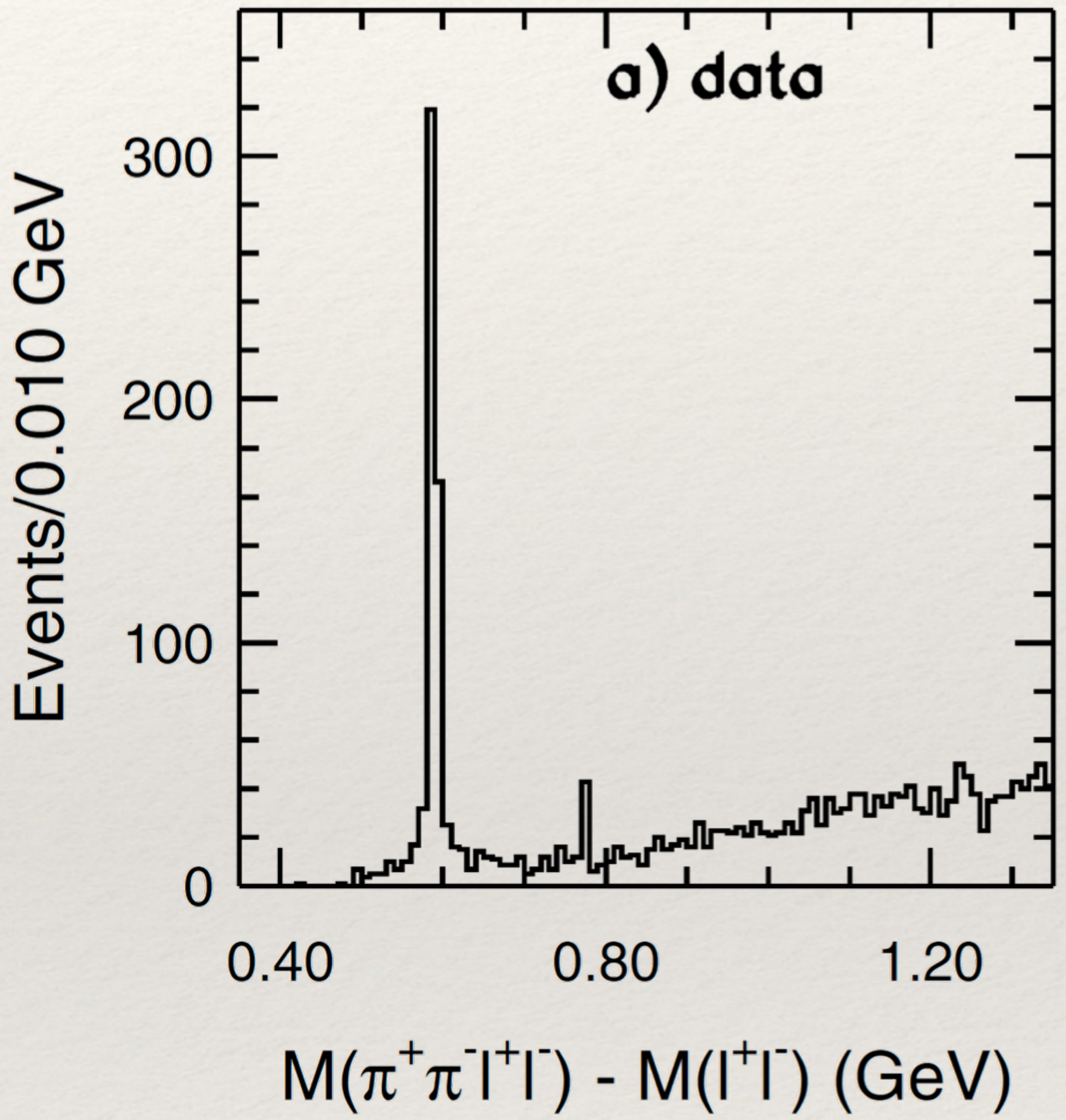
X(3872): a puzzle

- The first exotic hadron – discovered in $J/\psi\pi^+\pi^-$ mass spectrum from B decays by Belle in 2003
- LHCb measured quantum numbers [PRL 110 (2013) 222001]
  - $J^{PC} = 1^{++}$
- Mass is consistent with sum of D^0 and $\overline{D}^{*0}$ masses:

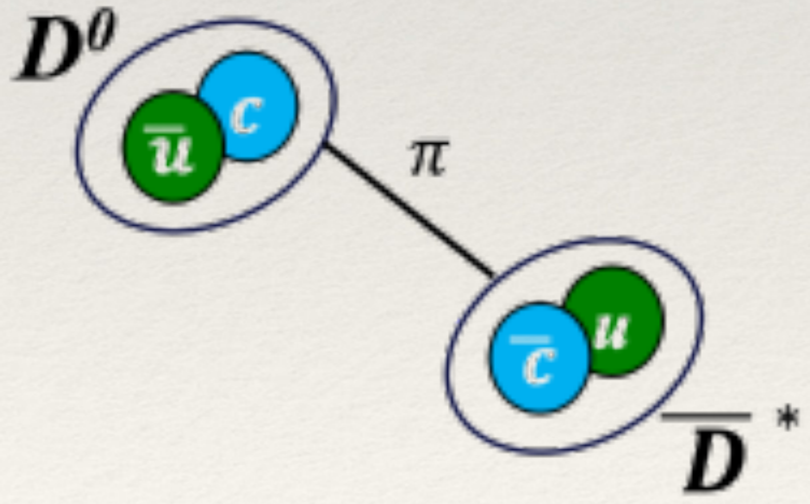
$$M_{\chi_{c1}(3872)} - \left(M_{D^0} + M_{\overline{D}^{*0}}\right) = 0.01 \pm 0.27\text{MeV}$$

PDG 2019 has changed the naming X(3872) to χ_{c1}(3872)

Belle Collaboration
PRL 91 262001 (2003)

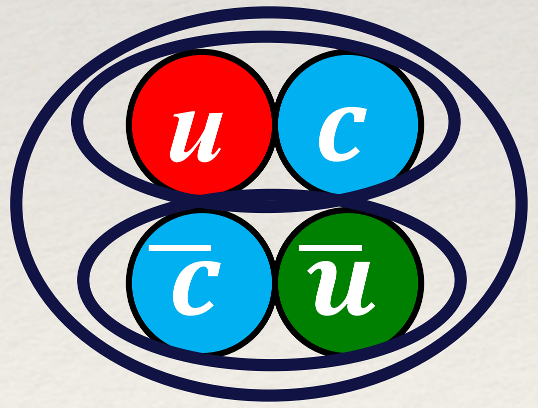


$D^0\overline{D}^{*0}$ Molecule



Very small binding energy and very large radius, ~ 7 fm

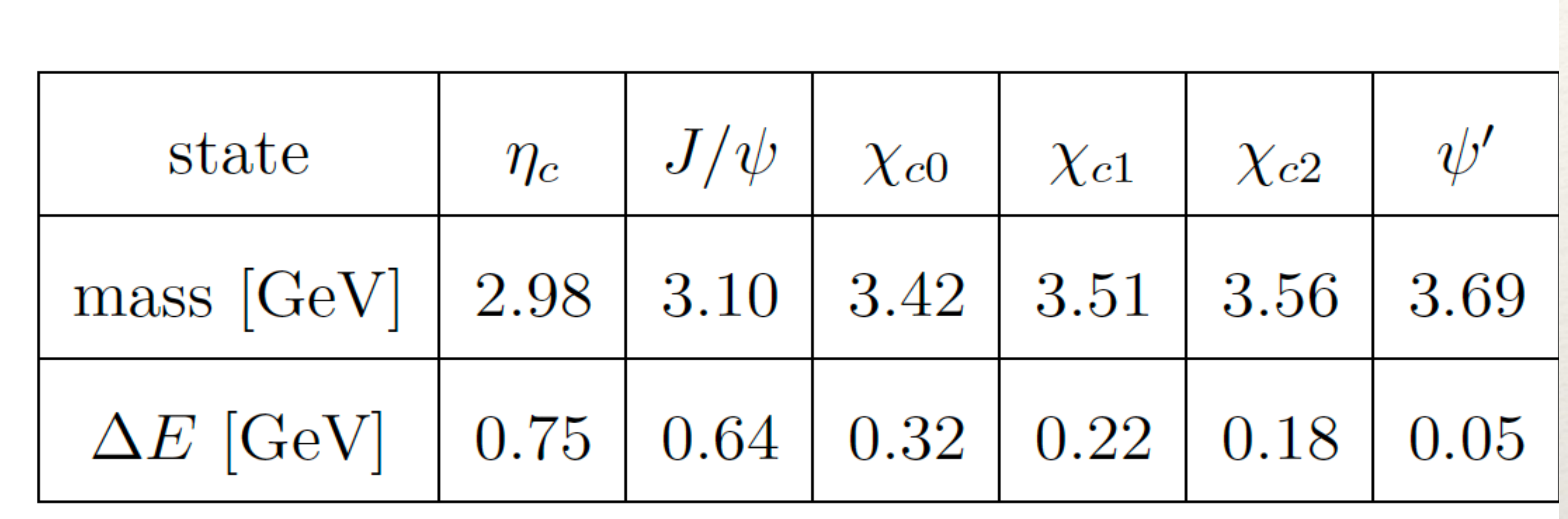
Compact tetraquark



Tightly bound via color exchange between diquark
Small radius, ~ 1 fm

Effects of binding energy learned from pA collisions

- Strength of the binding energy could be a key point to understand the nature of the exotic state

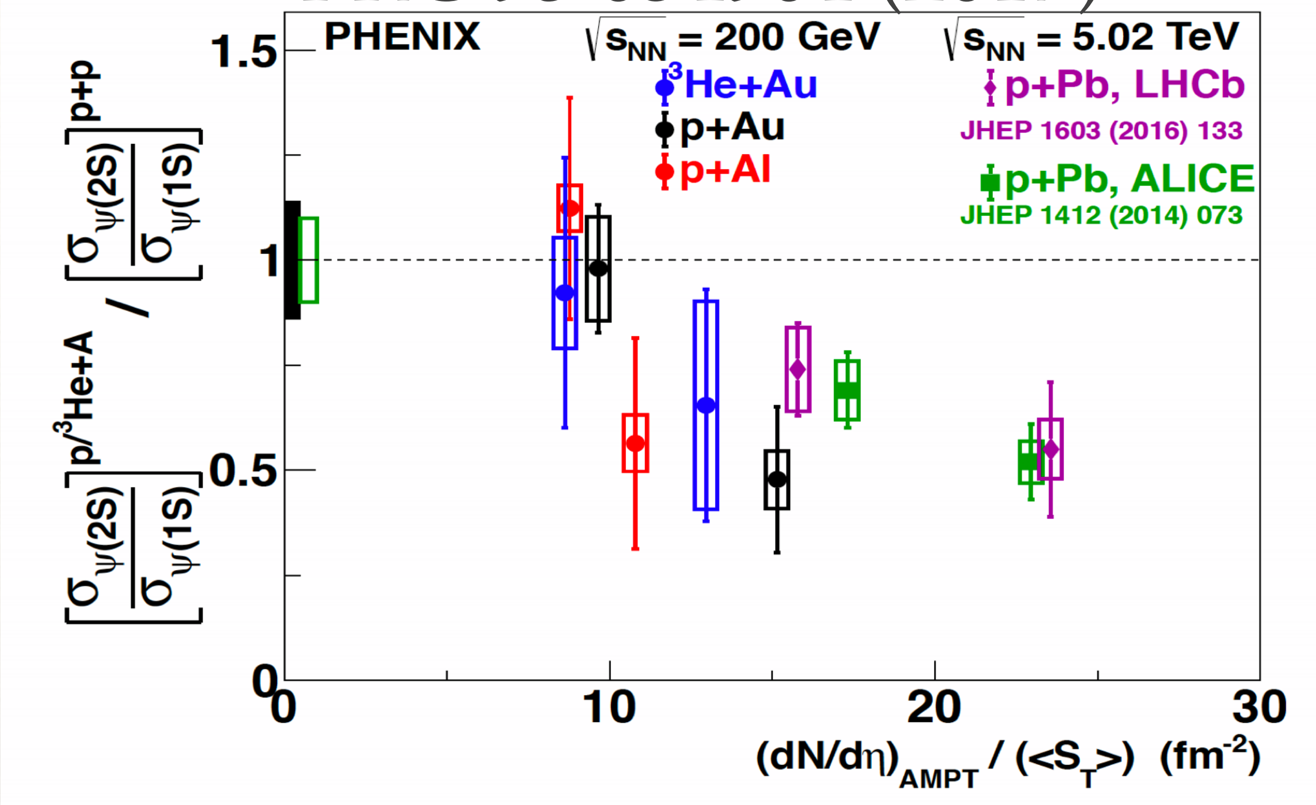


state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

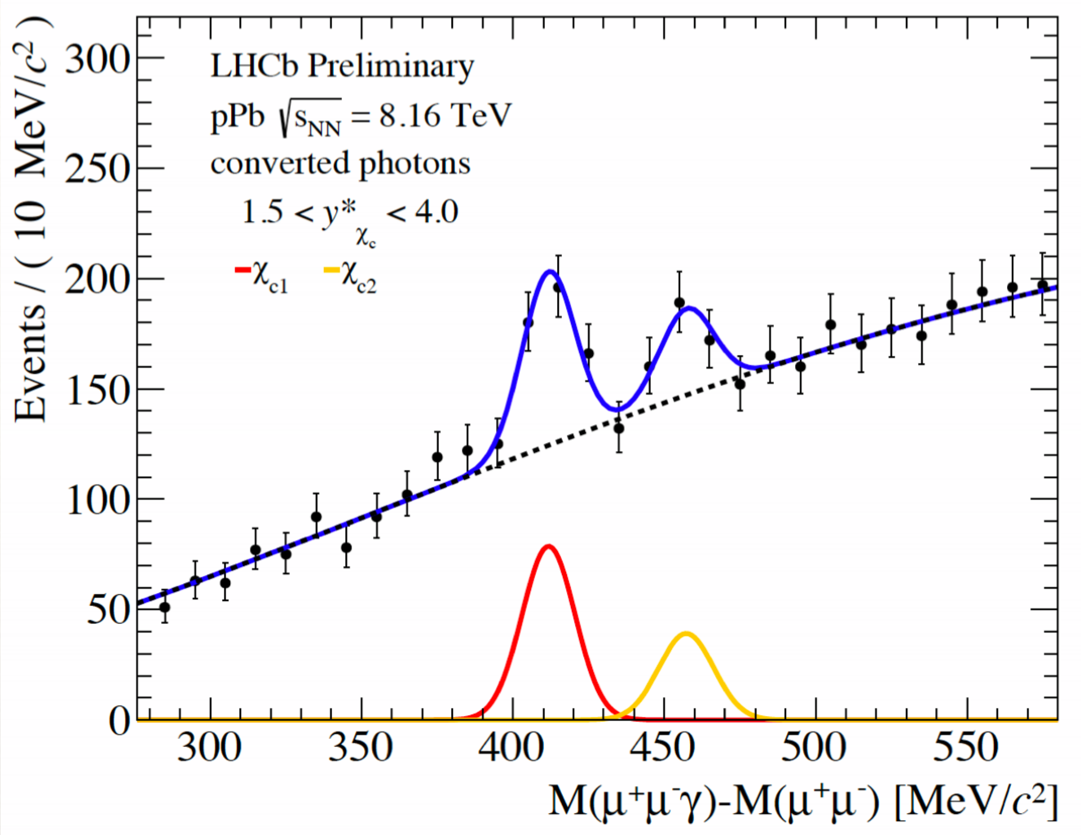
Satz, J. Phys. G 32 (3) 2006

- Suppression of weakly-bound quarkonia states has been studied for decades in pA collisions
  - Ratios of $[\psi(2S)]/[J/\psi]$ and $[\Upsilon(2S,3S)]/[\Upsilon(1S)]$
- Suppression is generally explained with final state effects: regions with high particle multiplicities

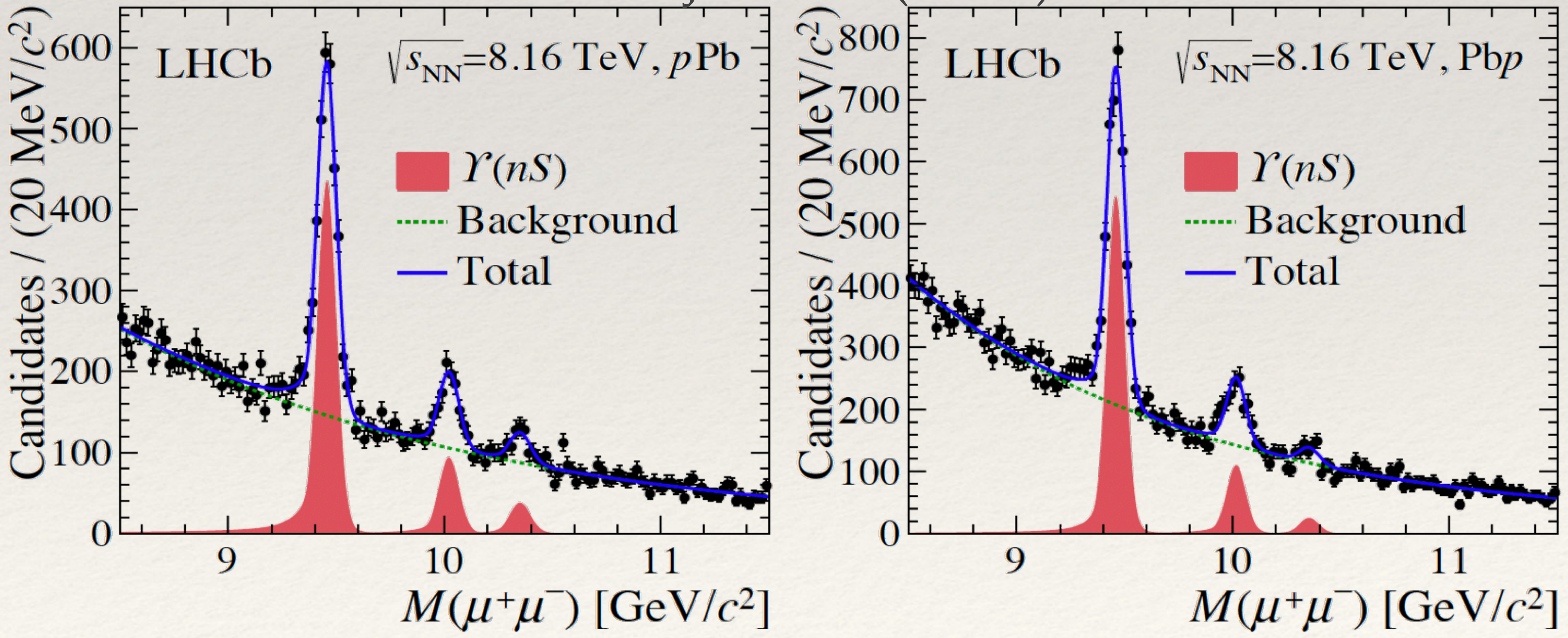
PRC 95 034904 (2017)



LHCb-FIGURE-2019-020

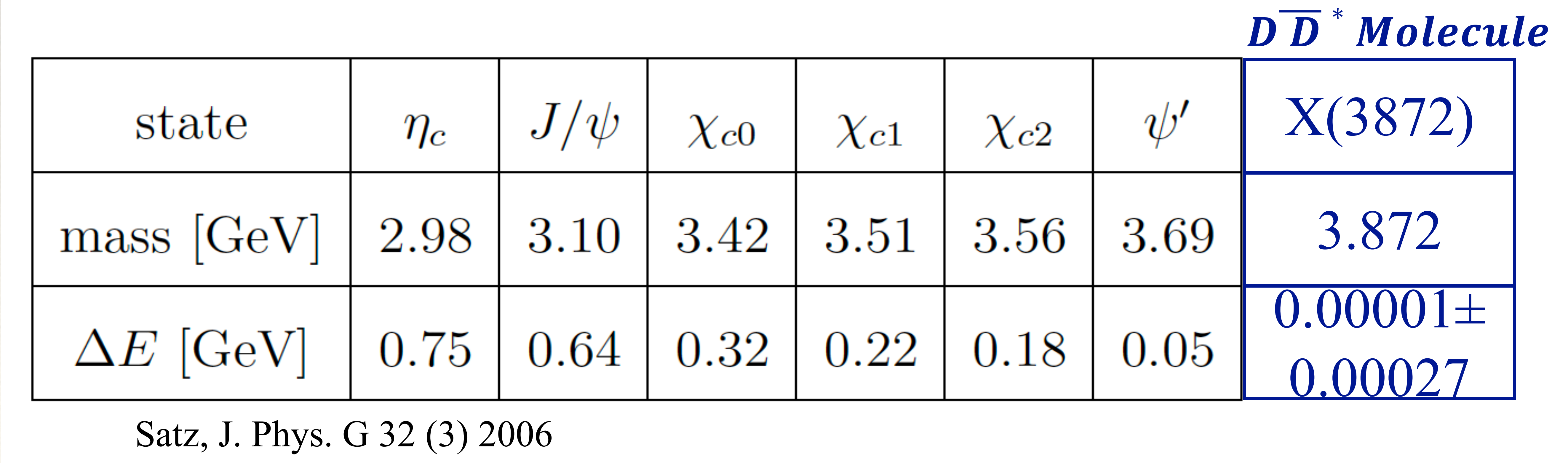


JHEP11(2018)194



Apply the binding energy understanding to pp

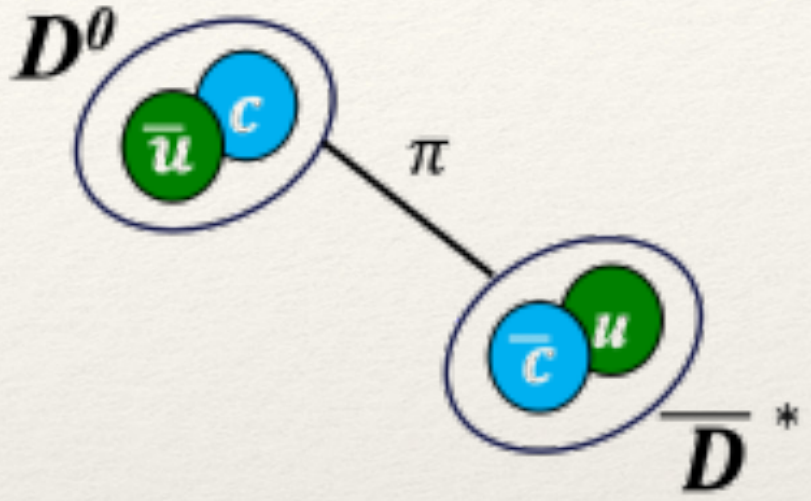
- Strength of the binding energy could be a key point to understand the nature of the exotic state
- Suppression of weakly-bound quarkonia states has been studied for decades in pA collisions
- Suppression is generally explained with final state effects: regions with high particle multiplicities
- **If X(3872) is a weakly bound hadronic molecule, it may show similar effects:**



							$D\overline{D}^*$ ***Molecule***
state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'	X(3872)
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69	3.872
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05	0.00001± 0.00027

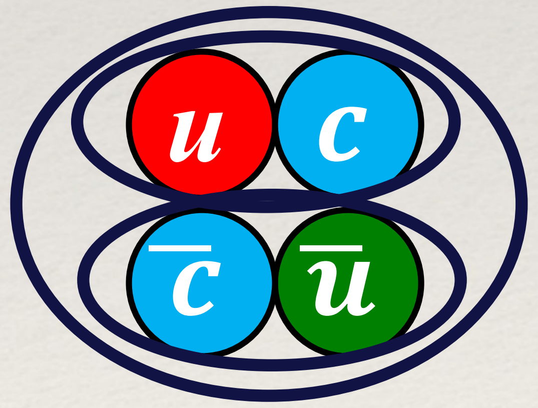
Satz, J. Phys. G 32 (3) 2006

$D^0\overline{D}^{*0}$ Molecule



Very small binding energy and very large radius, ~ 7 fm

Compact tetraquark

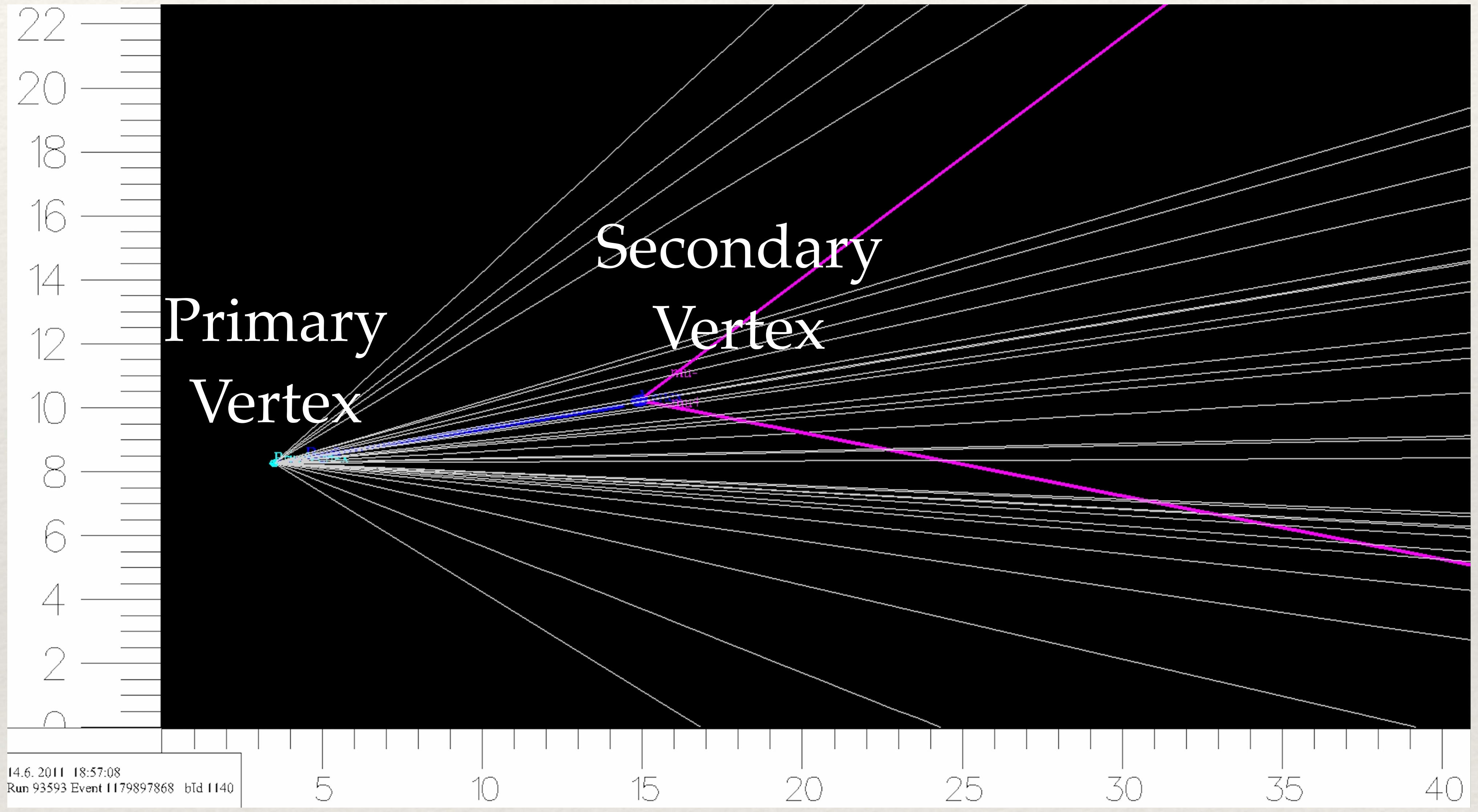


Tightly bound via color exchange between diquark

Small radius, ~ 1 fm

Probing X(3872) structure in high-multiplicity conditions

- **Prompt production (study object):**
  - X(3872) produced at collision vertex can be subject to further interactions with e.g. co-moving particles produced in the event, potentially subject to breakup effects ==> suppression!
- **Production in b-decays (control sample):**
  - X(3872) is produced outside of the primary collision volume
  - Hadrons containing b travel down the beampipe and decay away from the primary vertex and decay in vacuum
  - X(3872) is not subject to interactions with co-moving particles



Event display of $B^0_s \to \mu^+\mu^-$ candidate,

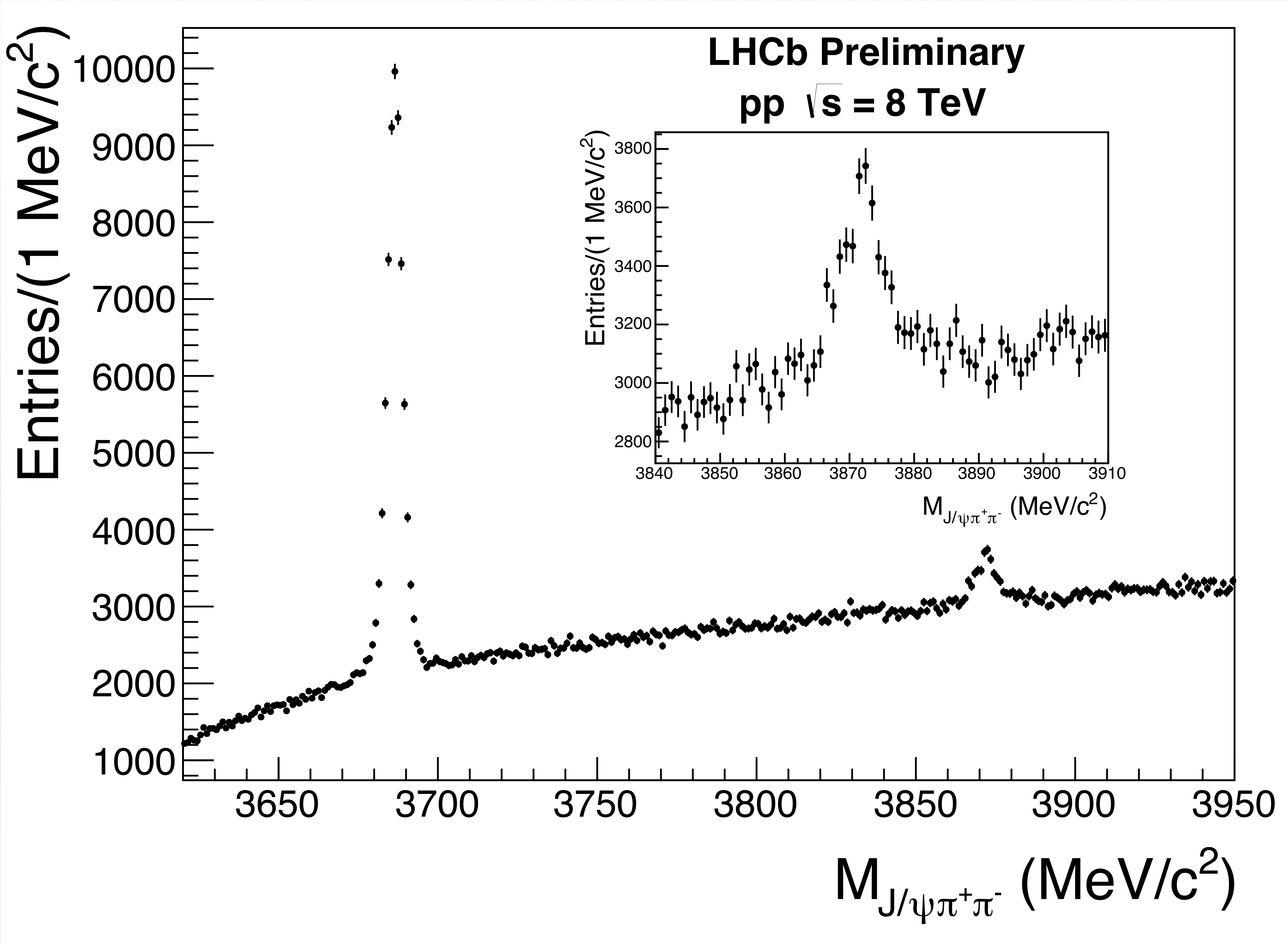
PRL 118 191801 (2017)

Selection of X(3872)

- **LHCb pp collisions at 8 TeV**
- **Reconstruct the X(3872) and ψ(2S) from $\mu^+\mu^-\pi^+\pi^-$ final states:**
  $X(3872) \to J/\psi\left(\to \mu^+\mu^-\right)\rho\left(\to \pi^+\pi^-\right)$
  $\psi(2S) \to J/\psi\left(\to \mu^+\mu^-\right)\pi^+\pi^-$
- **Select J/ψ from dimuons, combine with two identified pions. Kinematic fit constraining J/ψ mass to known value and all four tracks to identical vertex.**
- **Direct comparison between conventional charmonium ψ(2S) and exotic X(3872) via ratio of cross sections:**

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathscr{B}\left[\chi_{c1}(3872) \to J/\psi\pi^+\pi^-\right]}{\mathscr{B}\left[\psi(2S) \to J/\psi\pi^+\pi^-\right]}$$

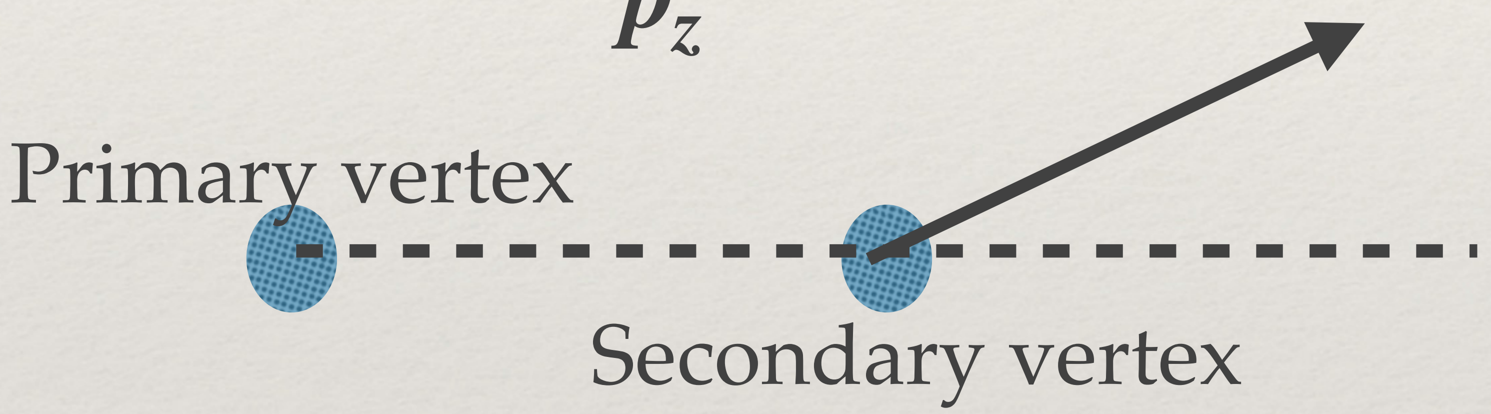
LHCb-CONF-2019-005



Prompt / b-decay separation

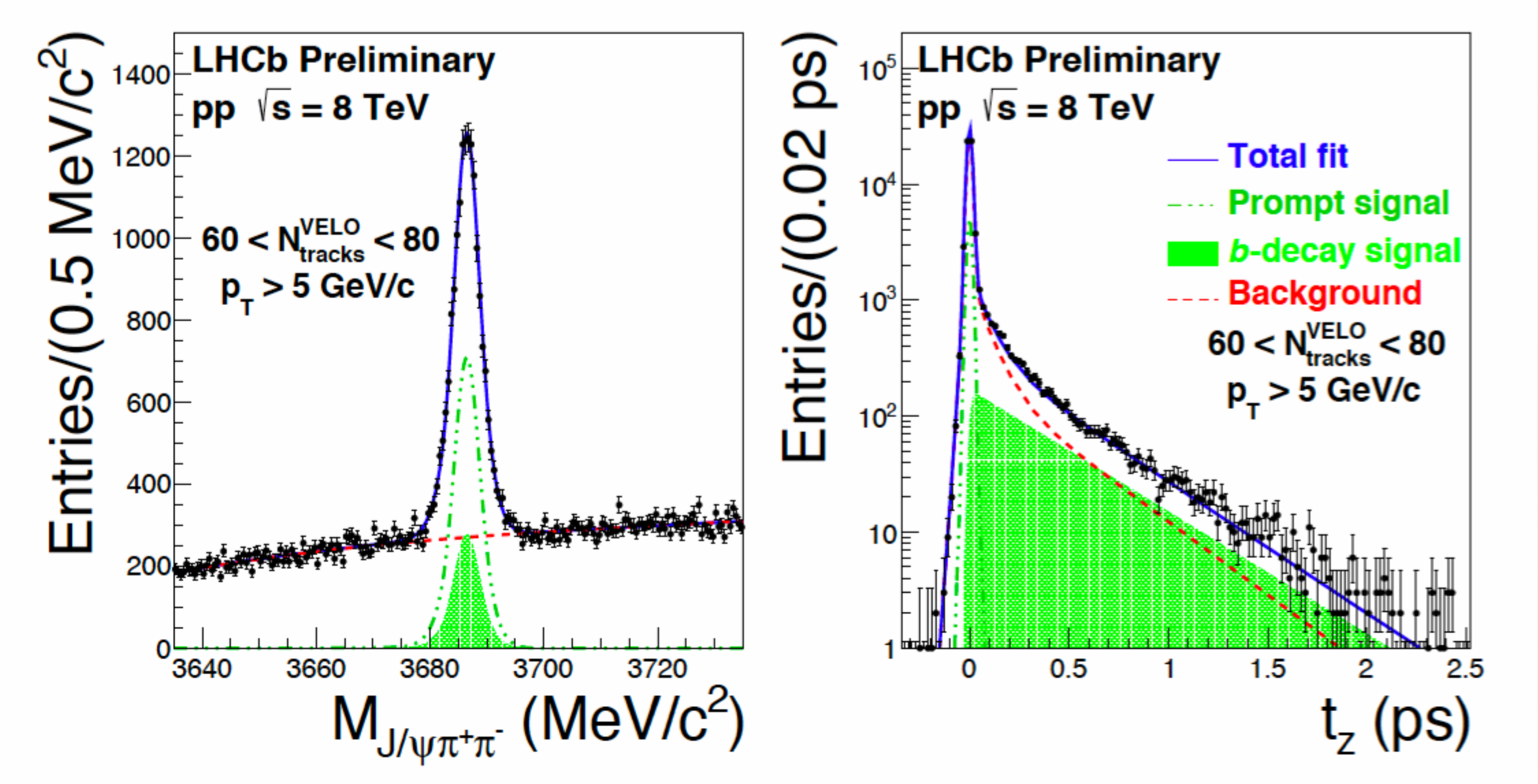
- **Simultaneous fit to invariant mass and pseudo proper time spectrum:**

$$t_z = \frac{z_{\mathrm{decay}} - z_{PV}}{p_z} M$$



- **Invariant mass to separate resonance vs. background**
- **Pseudo proper time to separate prompt and b-decay components**

LHCb-CONF-2019-005



Prompt fraction

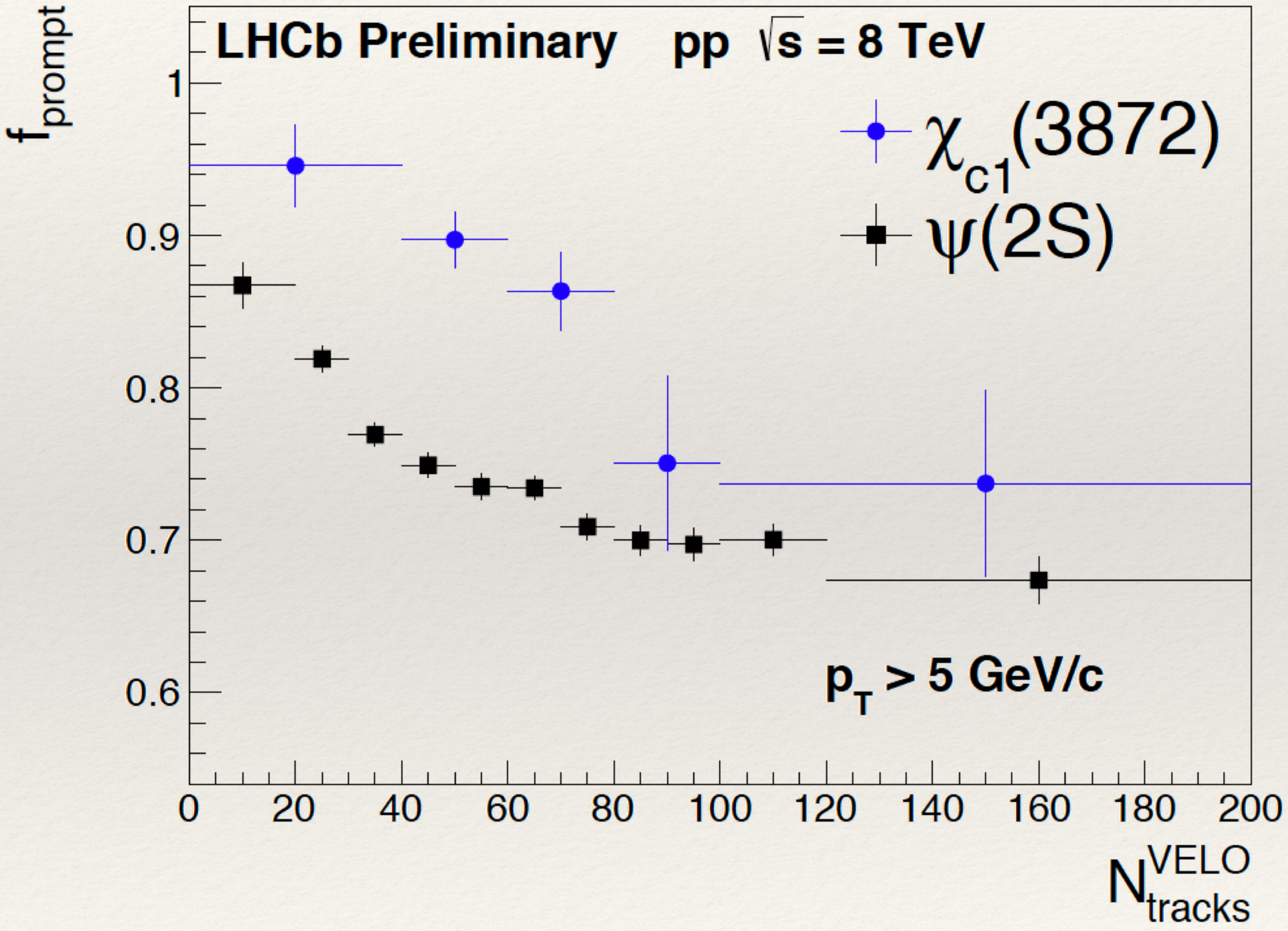
- Prompt fraction

$$f_{\mathbf{prompt}} = \frac{N_{\mathbf{prompt}}}{N_{\mathbf{prompt}} + N_{b-\mathbf{decay}}}$$

- Significant decrease in prompt fraction of both $X(3872)$ and $\psi(2S)$ as event activity increases

- Formation of prompt $X(3872)$ and $\psi(2S)$ may be disrupted at the primary vertex, which cannot affect production via b decays in vacuum.

LHCb-CONF-2019-005



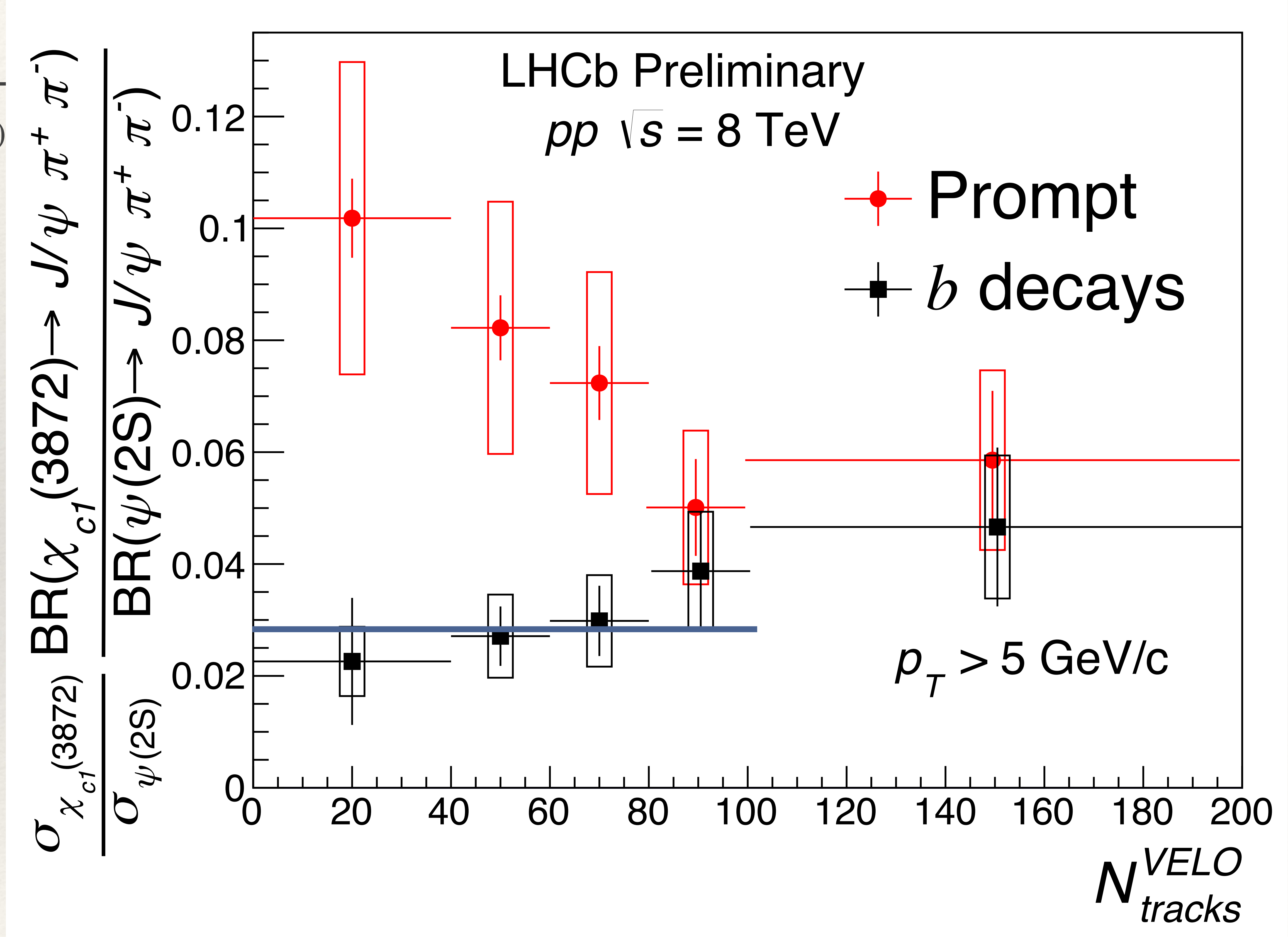
Ratio of the cross-sections

- Ratio of cross-sections:

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathscr{B}\left[\chi_{c1}(3872) \to J/\psi\pi^+\pi^-\right]}{\mathscr{B}\left[\psi(2S) \to J/\psi\pi^+\pi^-\right]} = \frac{N_{\chi_{c1}(3872)} f^{\chi_{c1}(3872)}_{\text{prompt}}}{N_{\psi(2S)} f^{\psi(2S)}_{\text{prompt}}} \times \frac{\varepsilon_{\psi(2S)}}{\varepsilon_{\chi_{c1}(3872)}}$$

- **Prompt Component (study object):**
  - **Increasing suppression of $X(3872)$ production relative to $\psi(2S)$ as event activity increases**
  - Syst. uncert. due to eff. is fully correlated bin-by-bin
- **b-decay component (control sample):**
  - **No significant change in relative production, as expected for decays in vacuum (compatible with a straight line).**
  - **Ratio is set by decay branching fractions of b and X(3872).**
- **The average ratio agrees with ATLAS measurement**
  - **R = 0.0395 ± 0.0032 ± 0.0008 (p_T>10GeV) [JHEP 2017:117 (2017)]**

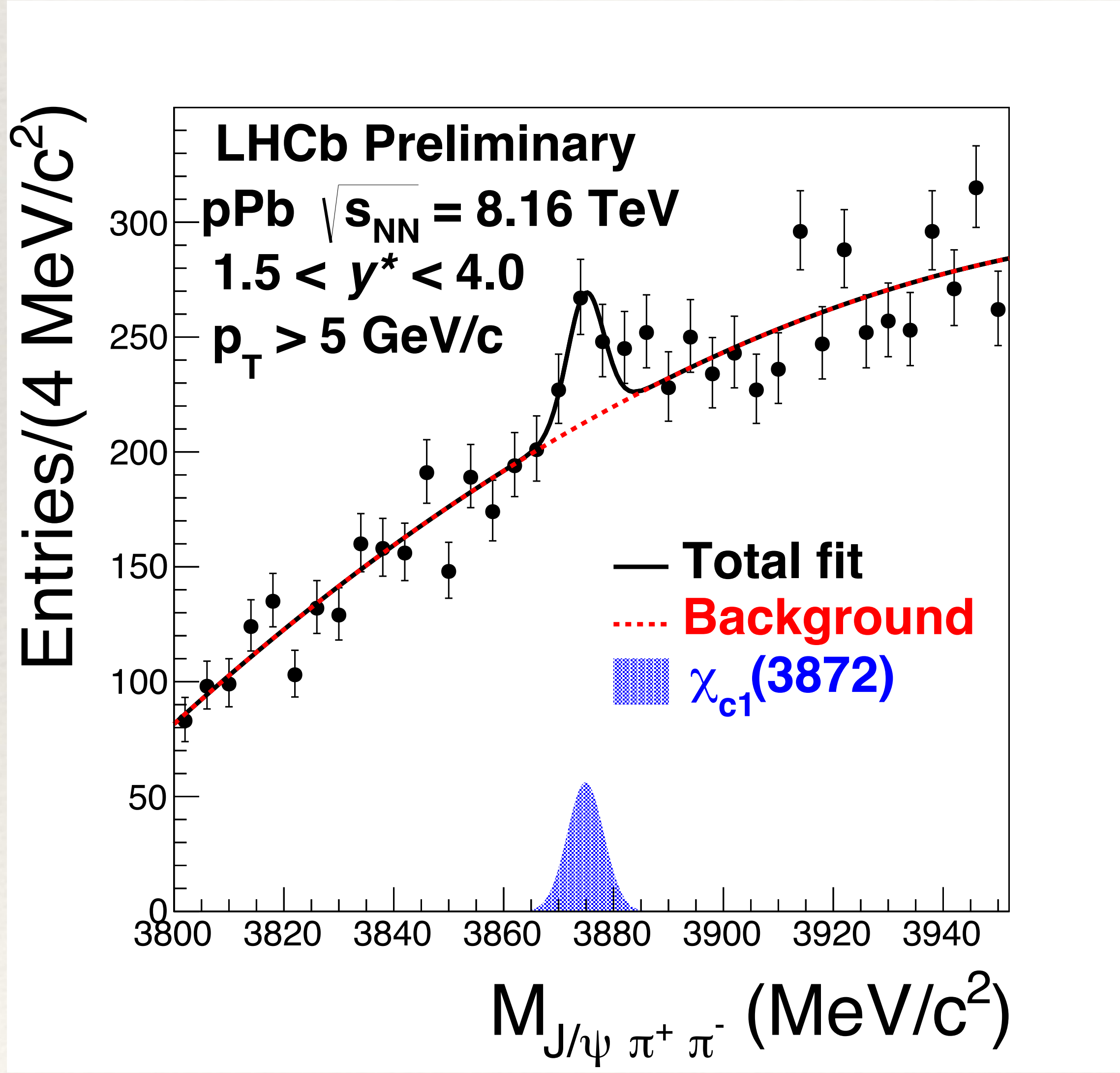
LHCb-CONF-2019-005



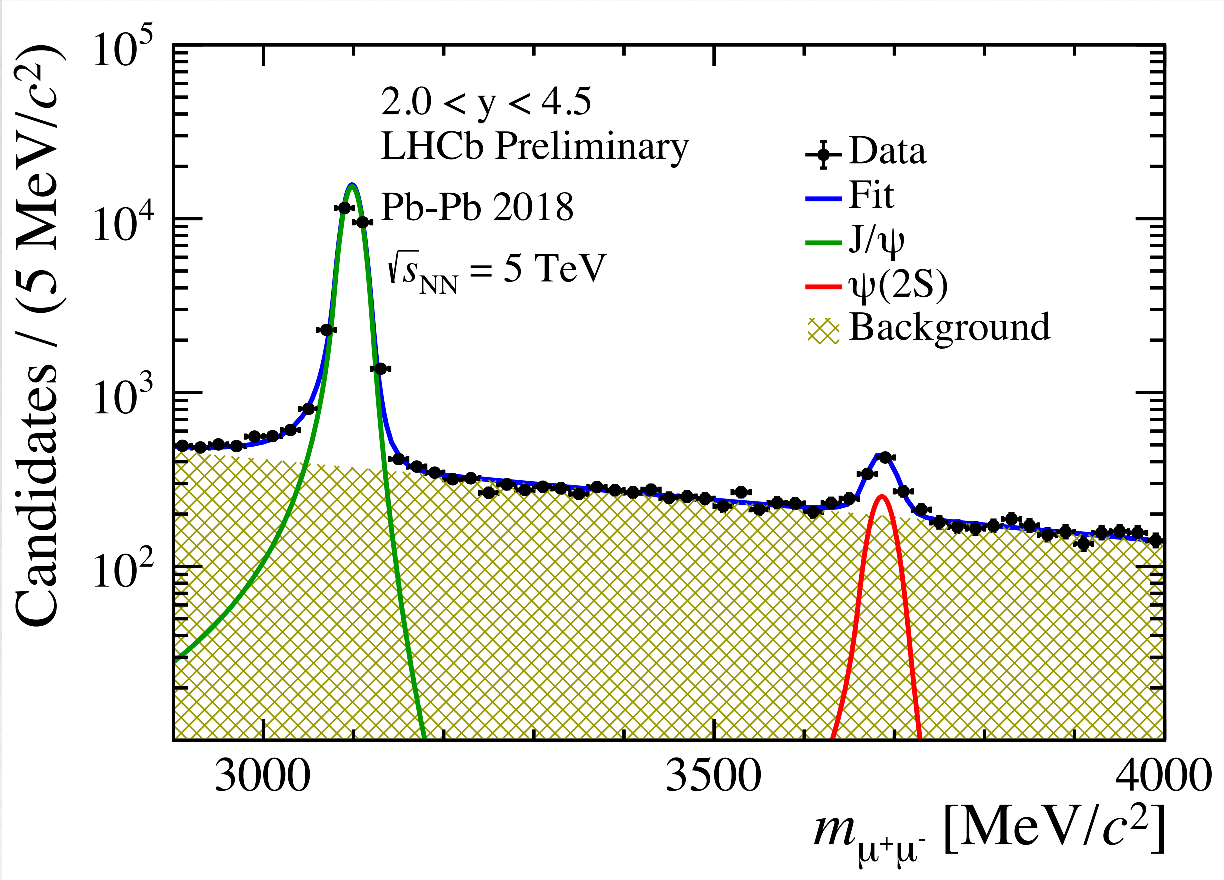
Outlook

- Rich heavy ion program in understanding strong interactions are on going at LHCb.
- Results of the following analyses are coming soon!
  - more plots see: https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlotsQM2019

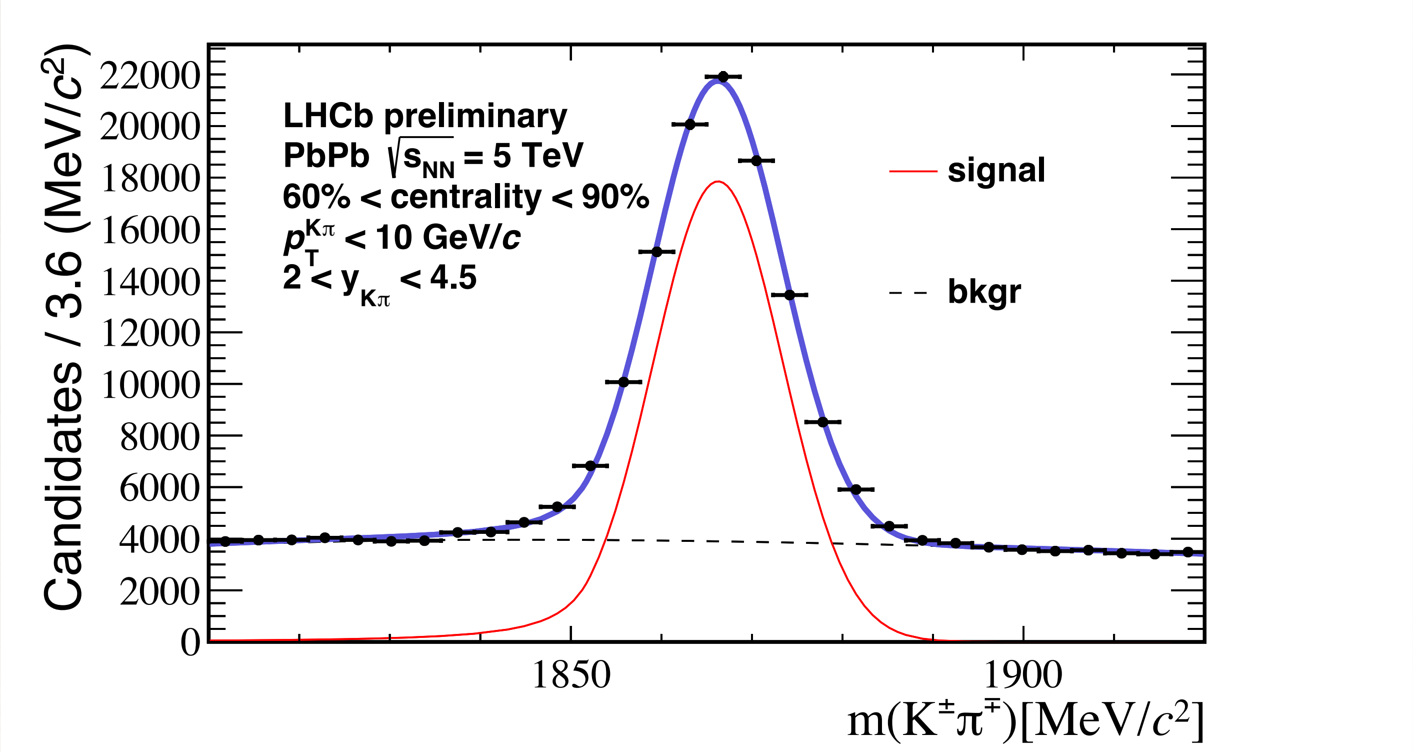
X(3872) in pPb



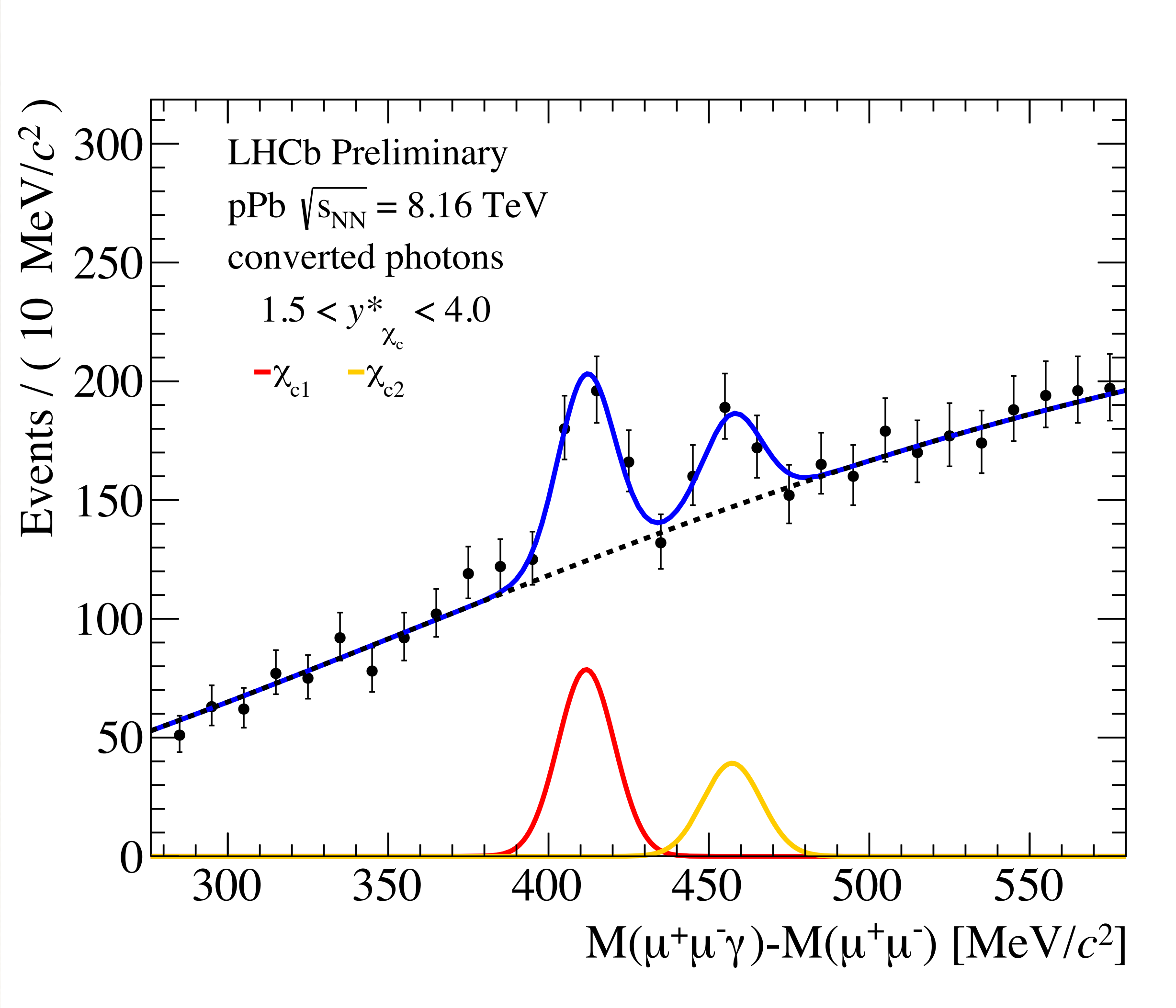
J/ψ and ψ(2S) in 2018 PbPb UPC



Open charm in 2018 PbPb



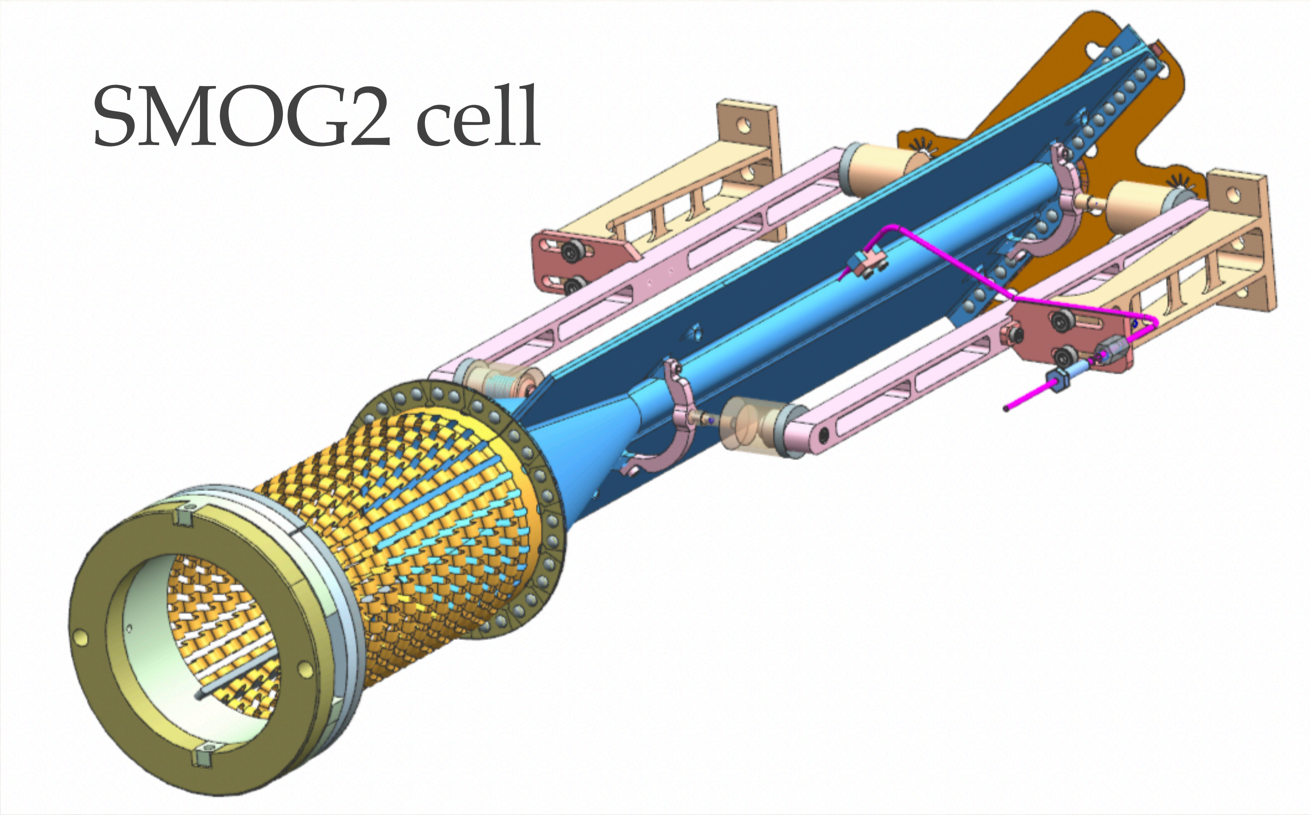
Open charm in 2016 pPb

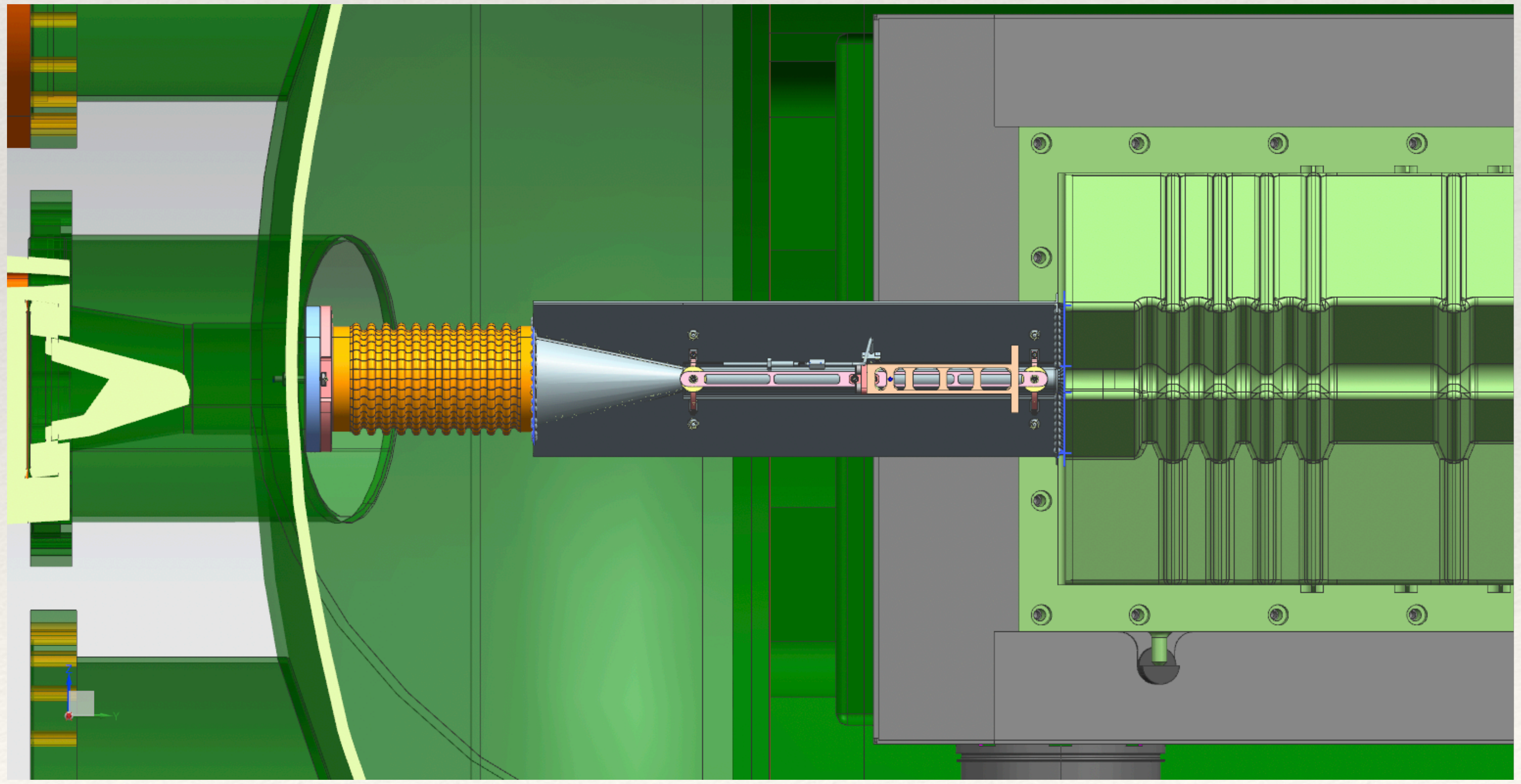


LHCb-FIGURE-2019-020

LHCb fixed-target program evolution

- SMOG 2 (TDR) : Standalone gas storage cell covering z position -500 to -300 mm :
  - Up to x100 higher gas density with same gas flow of current SMOG.
  - Gas feed system measures the gas density with few % accuracy.
- Installation due in December 2019, to be operational from the start of LHC Run 3.





Conclusion

- The Standard Model of particle physics has demonstrated its predictive power in the electroweak and Higgs sectors
- Due to the nonperturbative nature of QCD at low energy scales, the predictive power of the SM in the strong sector is more limited. ==> rich program in the strong force sector is still in front of us!
- The LHCb detector has unique capabilities at the LHC, being the only dedicated forward detector.
  - Capabilities can also be applied to strong interaction physics.
- Recent results from LHCb:
  - Probing cold nuclear matter effects using D^0 and Z boson production have been discussed
  - The efforts to understand the nature of the X(3872) resonance has been presented.
- Rich heavy ion program in understanding strong interactions are on going at LHCb.