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South China Normal University



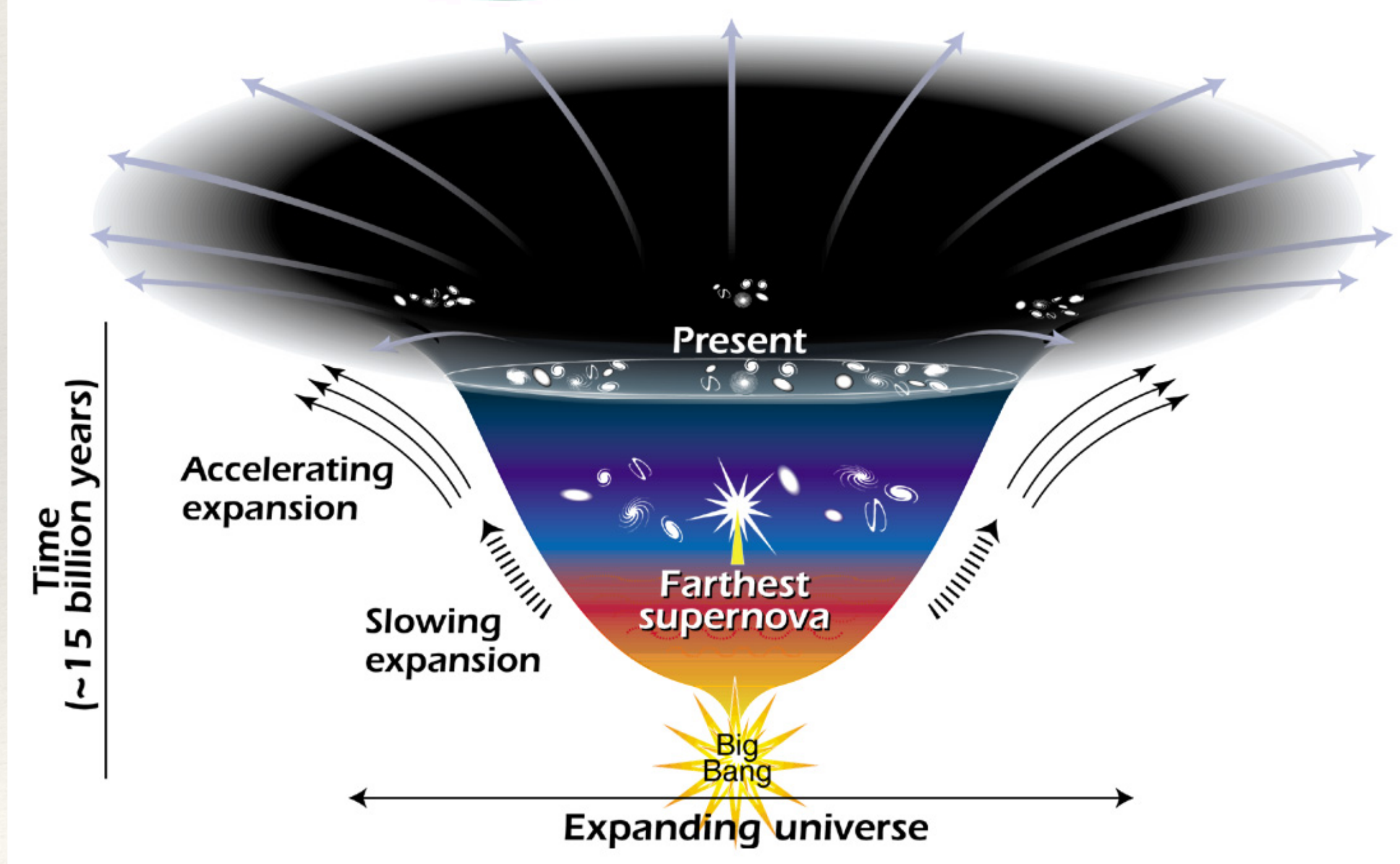
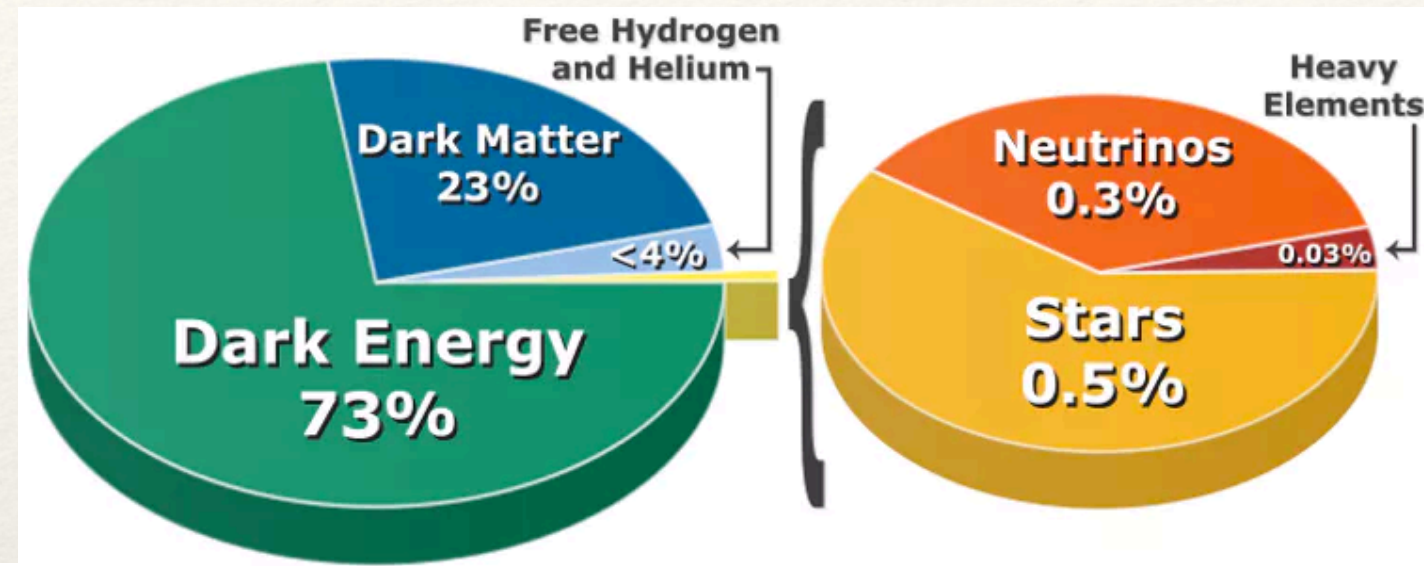
Strong physics at LHCb: probing nuclear matter effects in small systems

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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	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
QUARKS	u up	c charm	t top	g gluon	H higgs
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	d down	s strange	b bottom	γ photon	
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	e electron	μ muon	τ tau	Z Z boson	
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.39 \text{ GeV}/c^2$	
	0	0	0	± 1	
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS VECTOR BOSONS
					SCALAR BOSONS

Fundamental forces

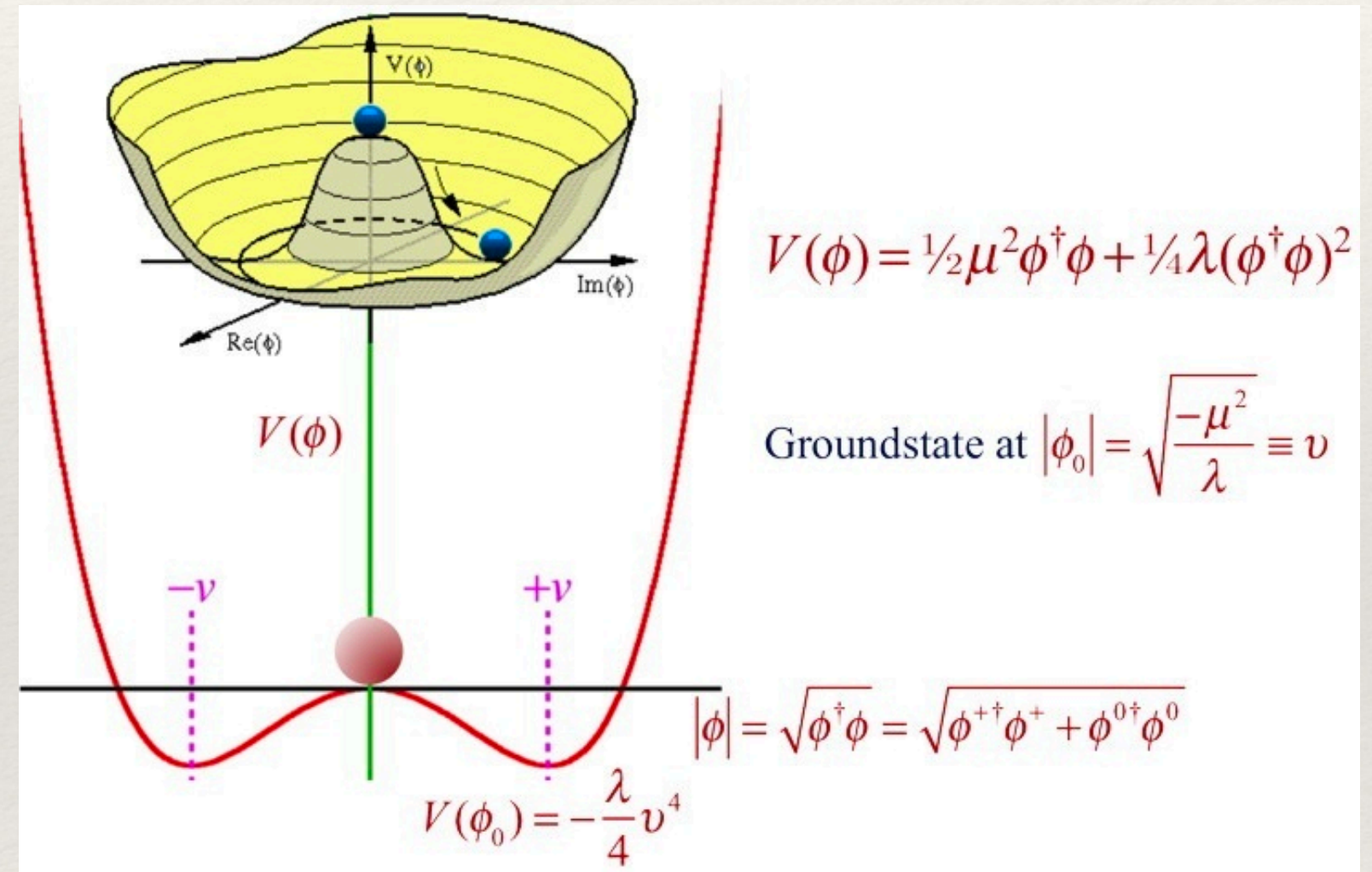
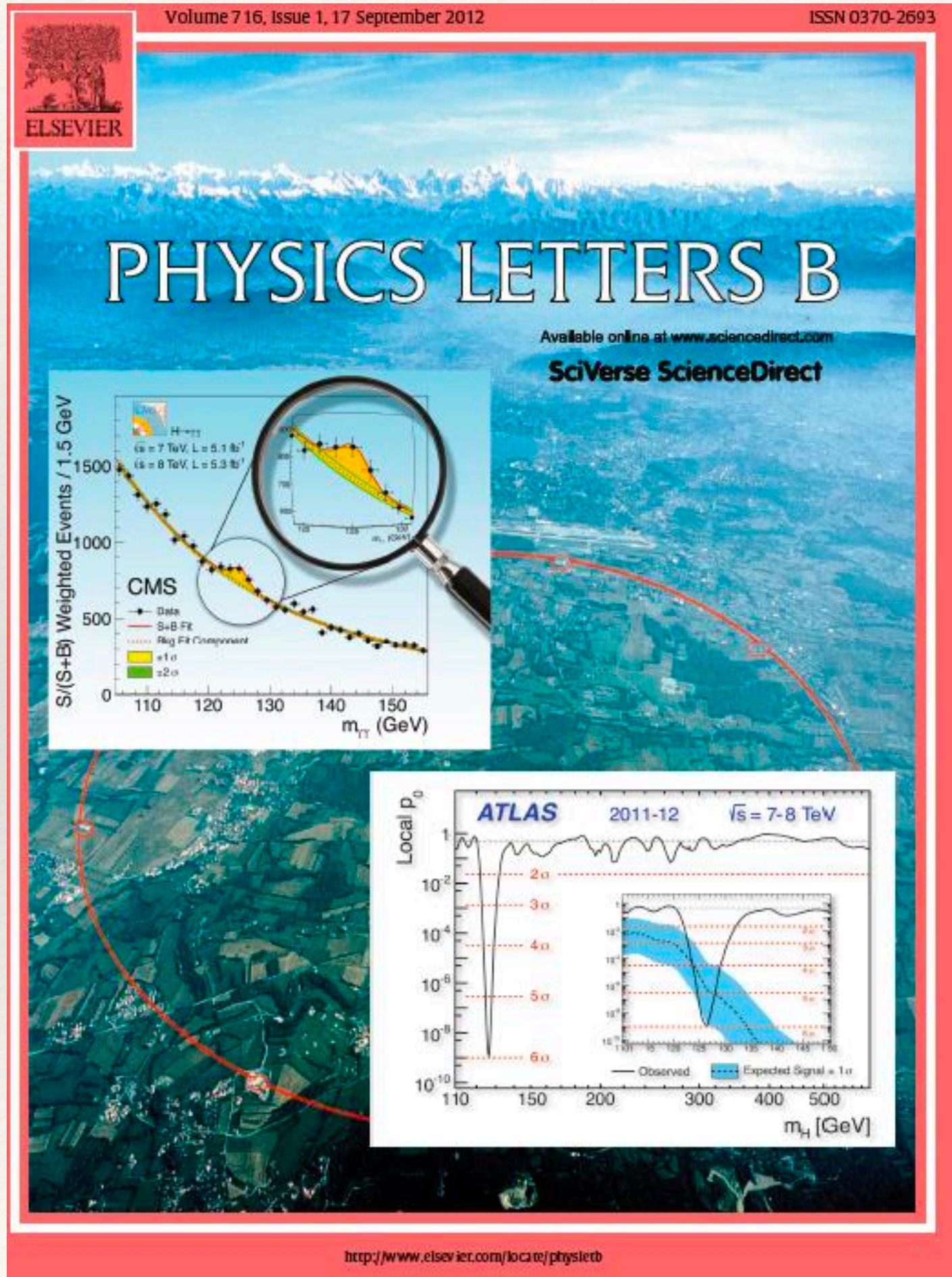
Interaction	Current theory	Mediators	Relative strength	Long-distance behavior	Range (m)
Strong	Quantum chromodynamics (QCD)	gluons	10^{38}	$\sim r$ (Color confinement)	10^{-15}
Weak	Electroweak Theory (EWT)	W and Z bosons	10^{25}	$1/r \cdot e^{-m_{W,Z} \cdot r}$	10^{-18}
Electro-magnetic	Quantum electrodynamics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

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

Example 1: prediction of the Higgs boson

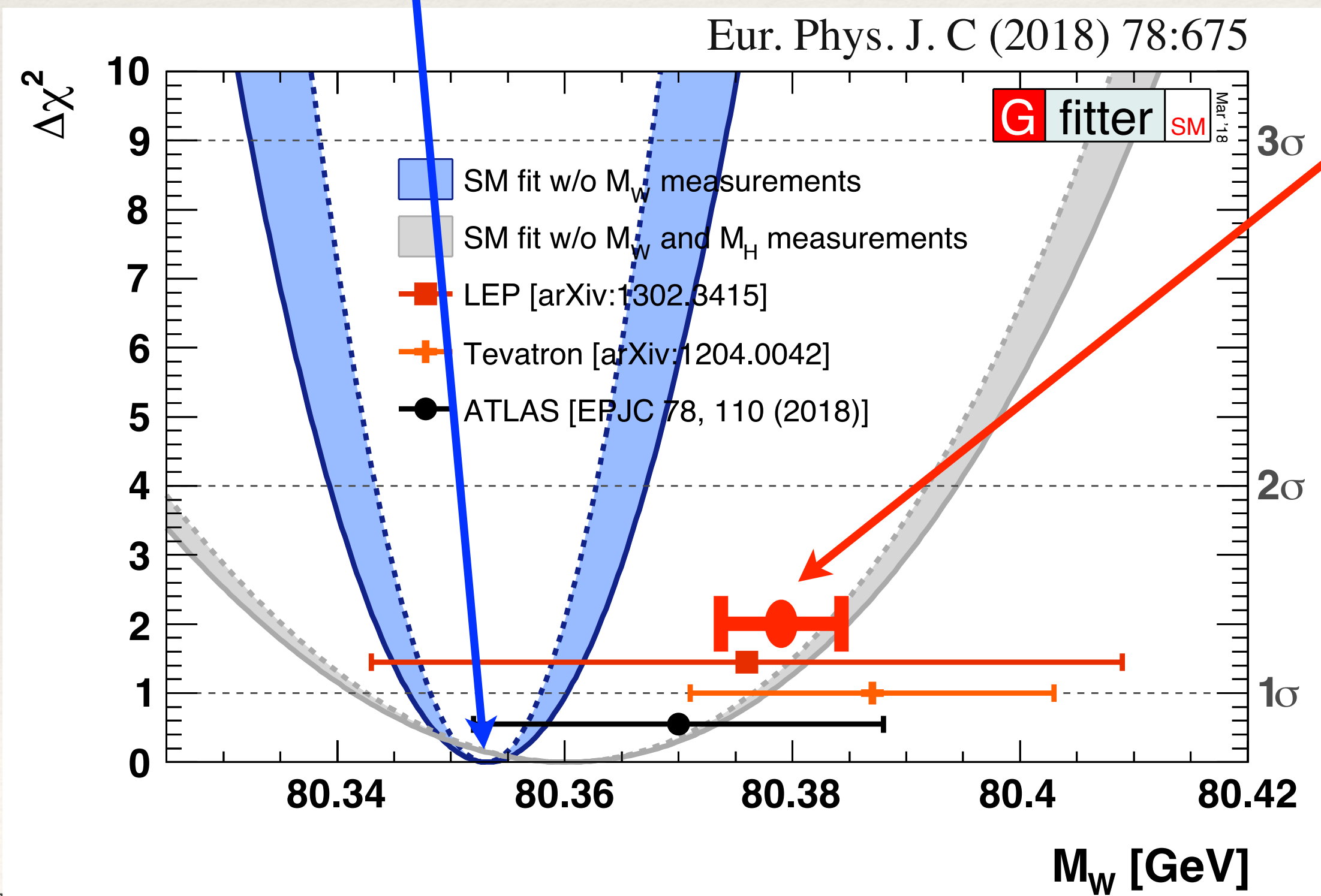


Example 2: Predictive power of the EW parameters

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

$$M_W = 80356 \text{ MeV} \pm 8 \text{ MeV}$$

Predicted



Comparing with the current world average directly measured value:

$$M_W = 80379 \text{ MeV} \pm 12 \text{ MeV}$$

[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!

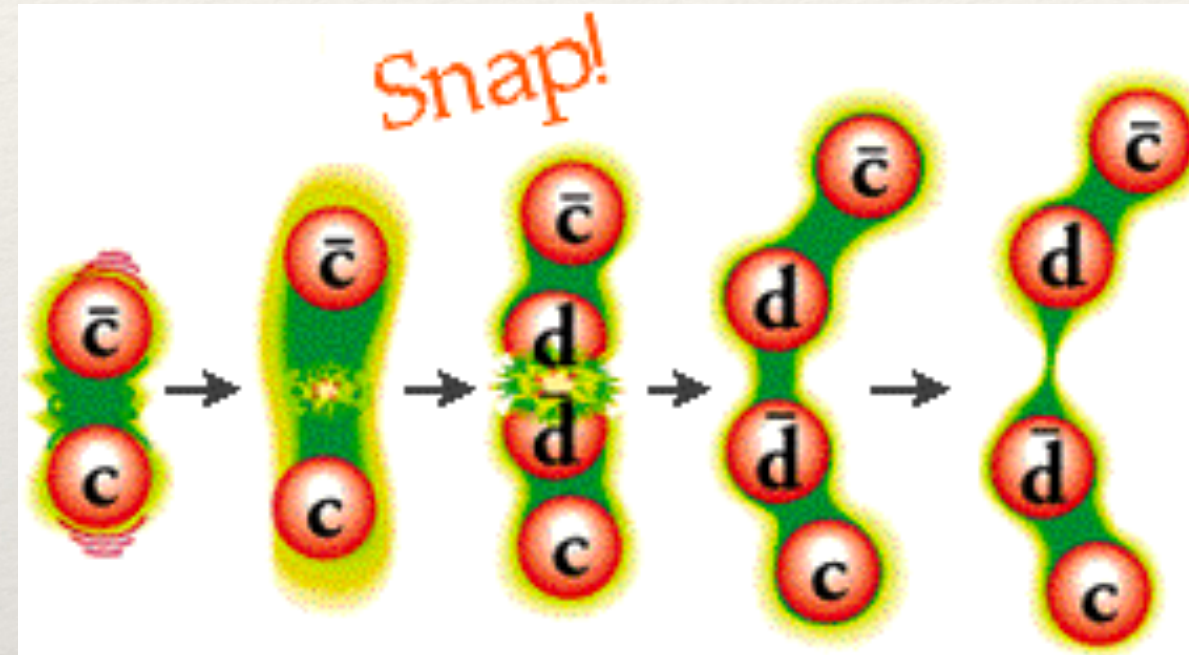
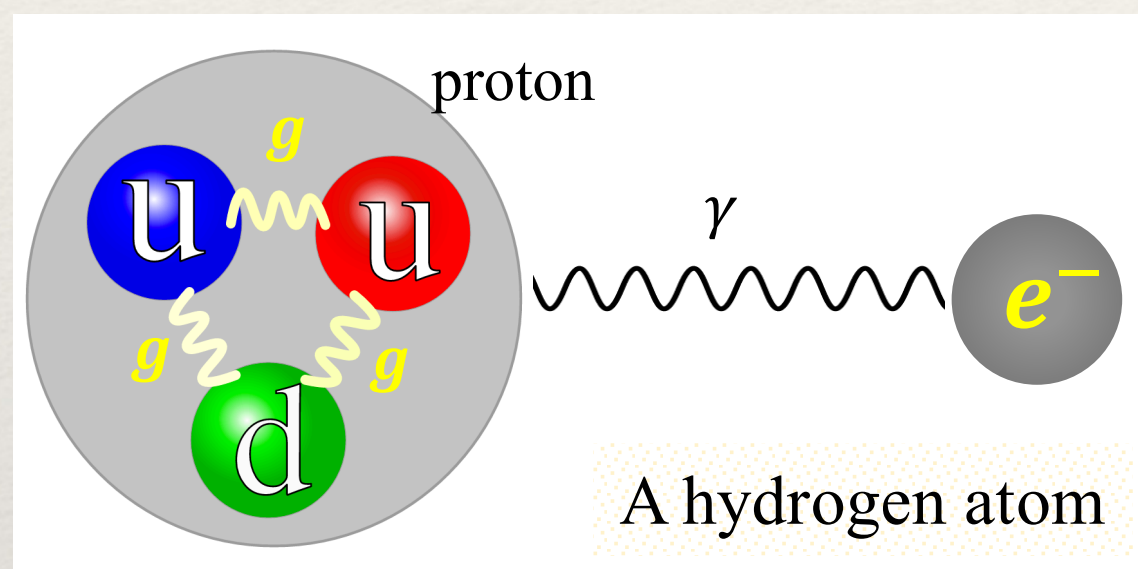
The strong interaction sector

Interaction	Current theory	Mediators	Relative strength	Long-distance behavior	Range (m)
Strong	Quantum chromodynamics (QCD)	gluons	10^{38}	$\sim r$ (Color confinement)	10^{-15}
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<i>Gravitation</i>	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)

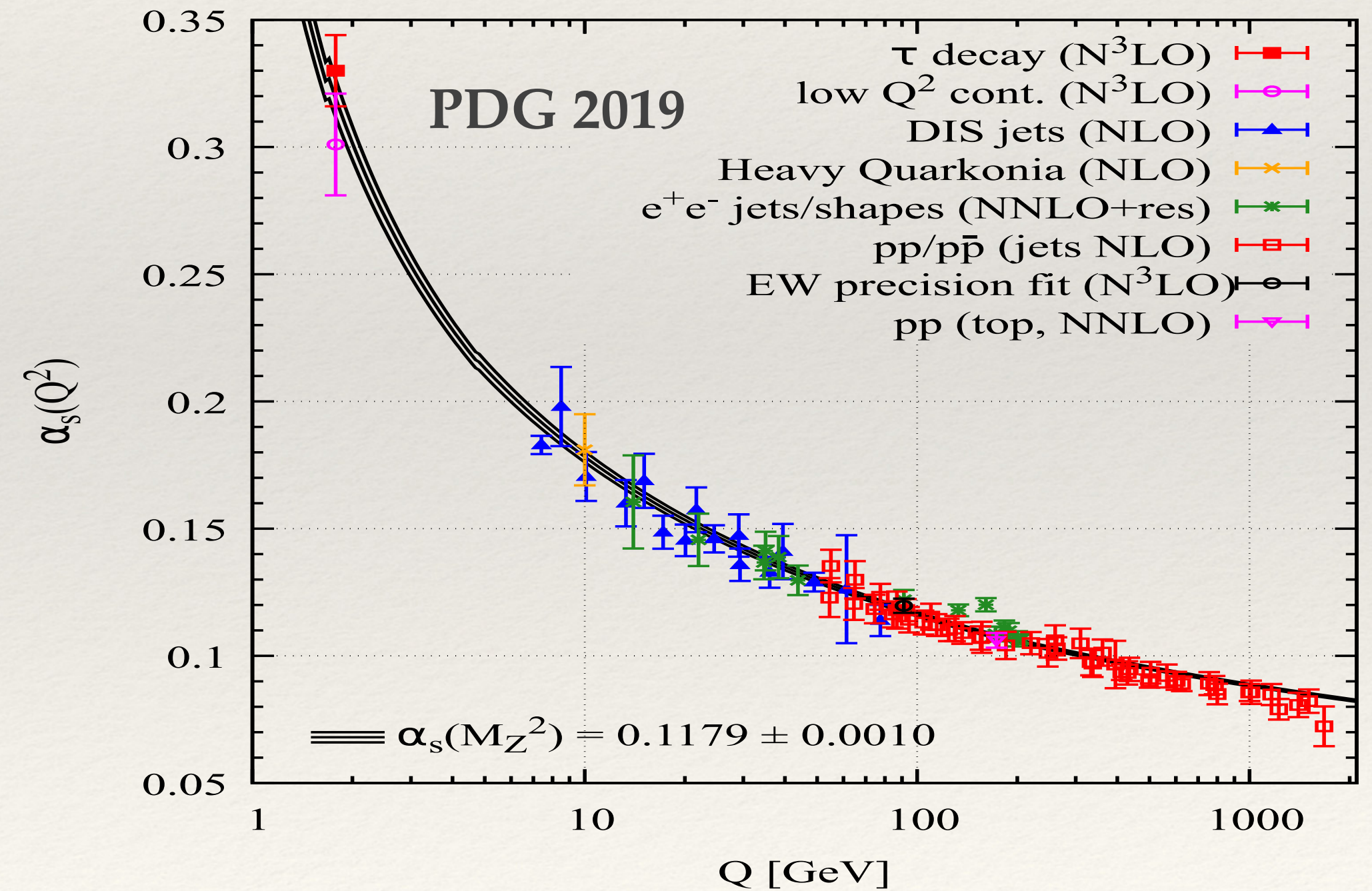
- ❖ Quarks bound together by strong force:
 - ❖ Gluons act as strong force mediators



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

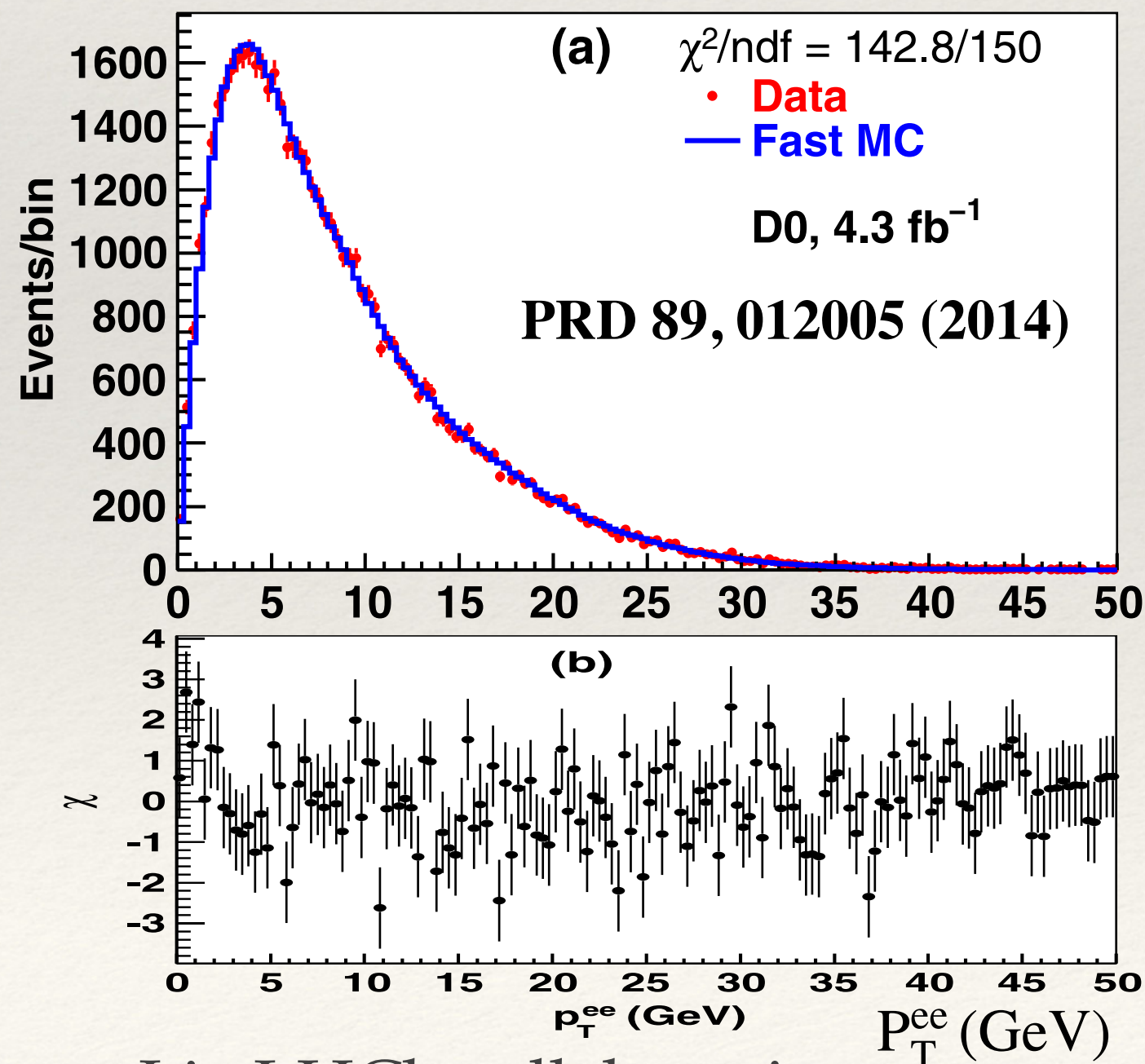
❖ Color-confinements:

- ❖ 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:



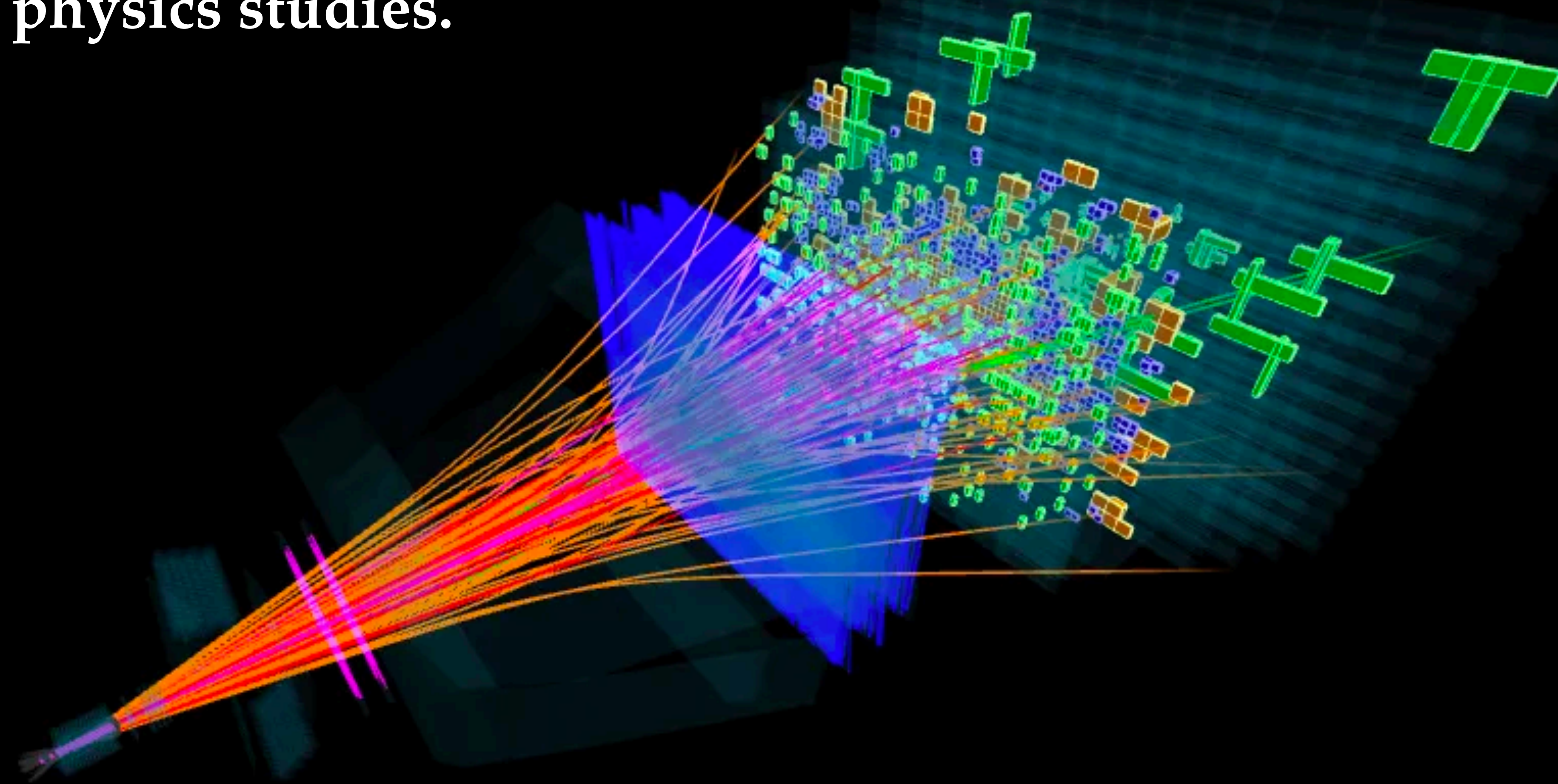
❖ A rich program in the strong force sector!

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.



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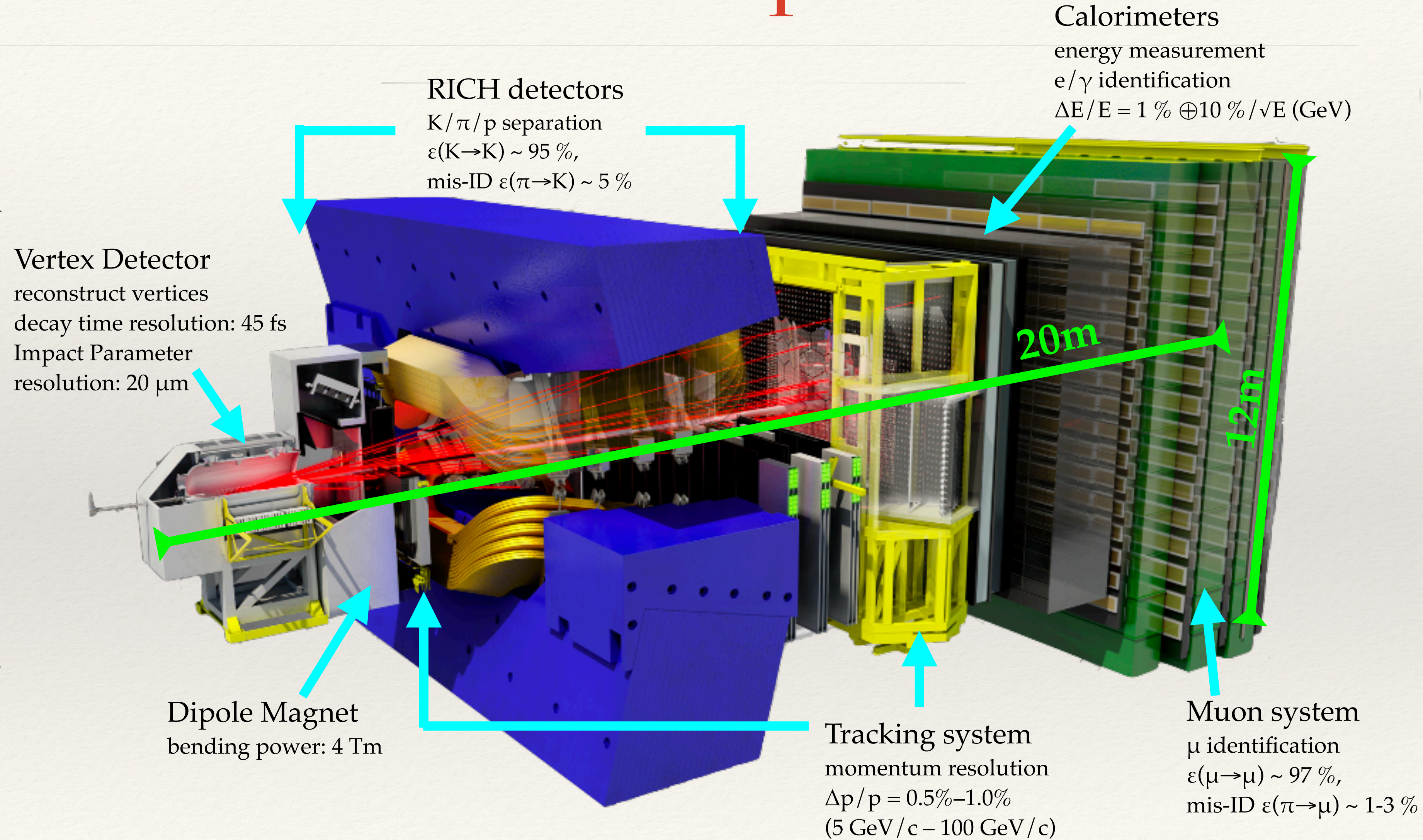
Run 187340

Fri, 02 Dec 2016 20:56:29

The LHCb detector is special

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

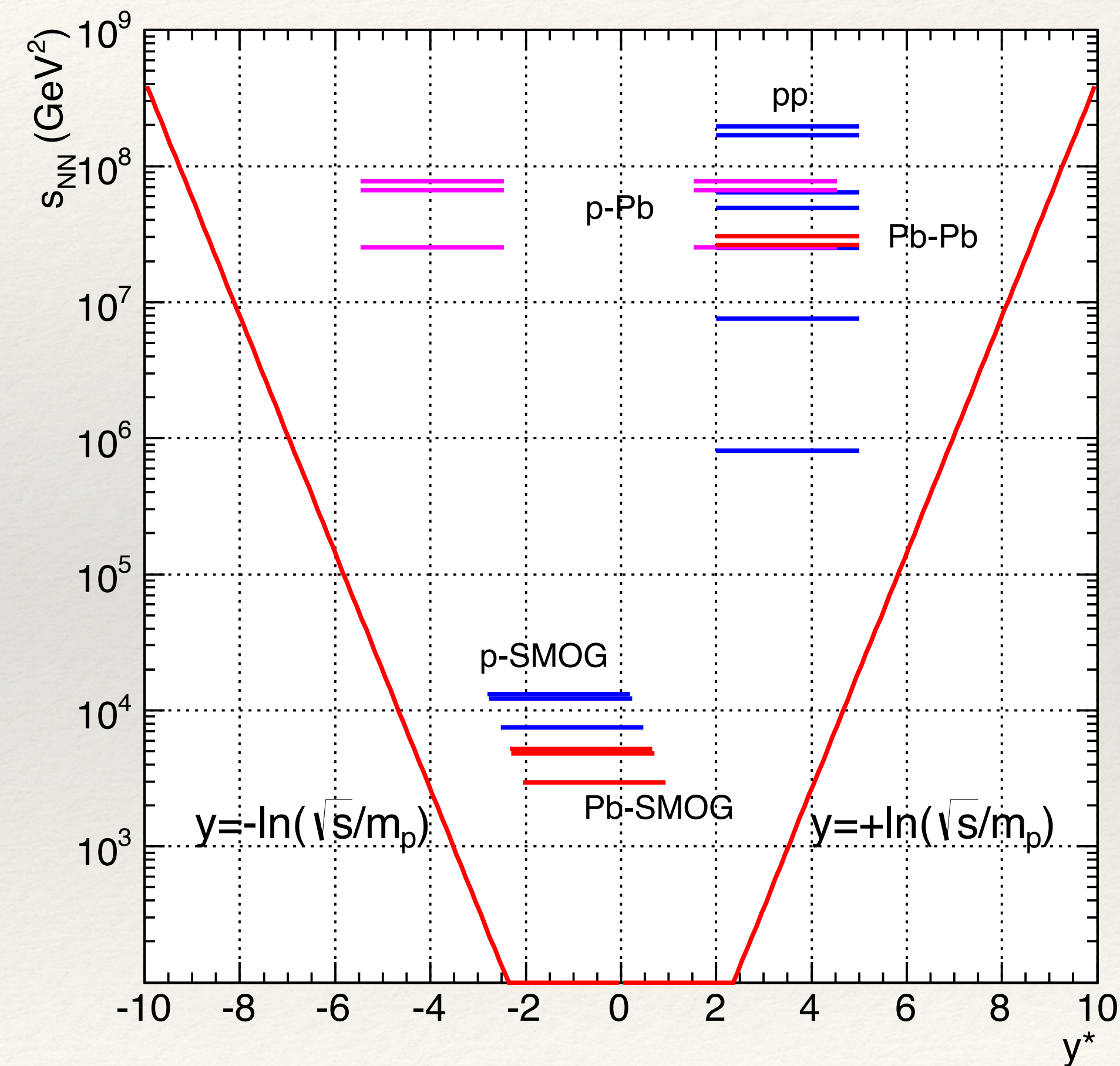
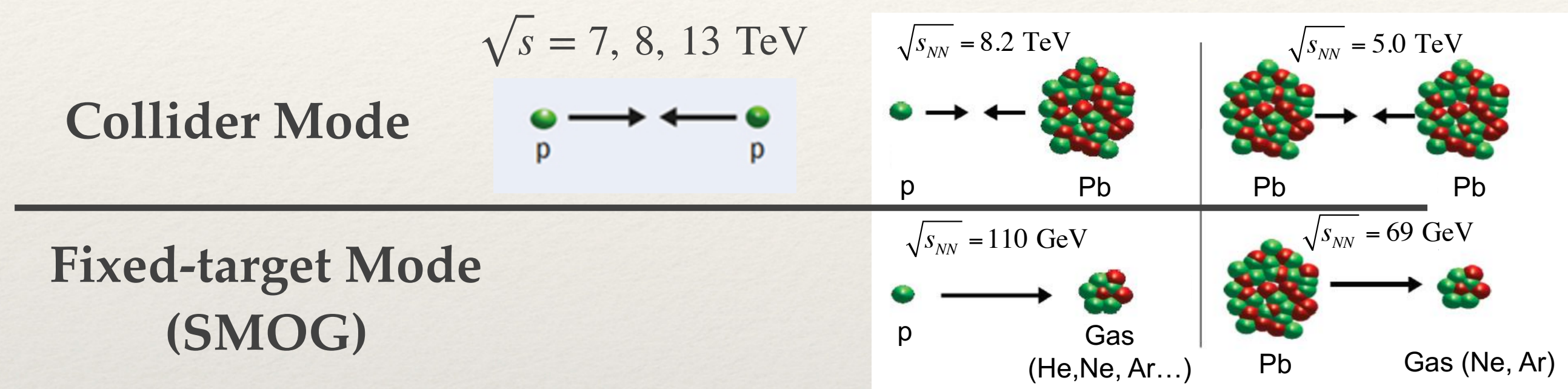
- ❖ LHCb is the only detector (at LHC) fully instrumented in forward region
- ❖ Unique kinematic coverage
 $2 < \eta < 5$
- ❖ A high precision device, down to very low- p_T , excellent particle ID, precision vertex reconstruction and tracking.



LHCb running modes and kinematic coverage

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

Kinematic Acceptance



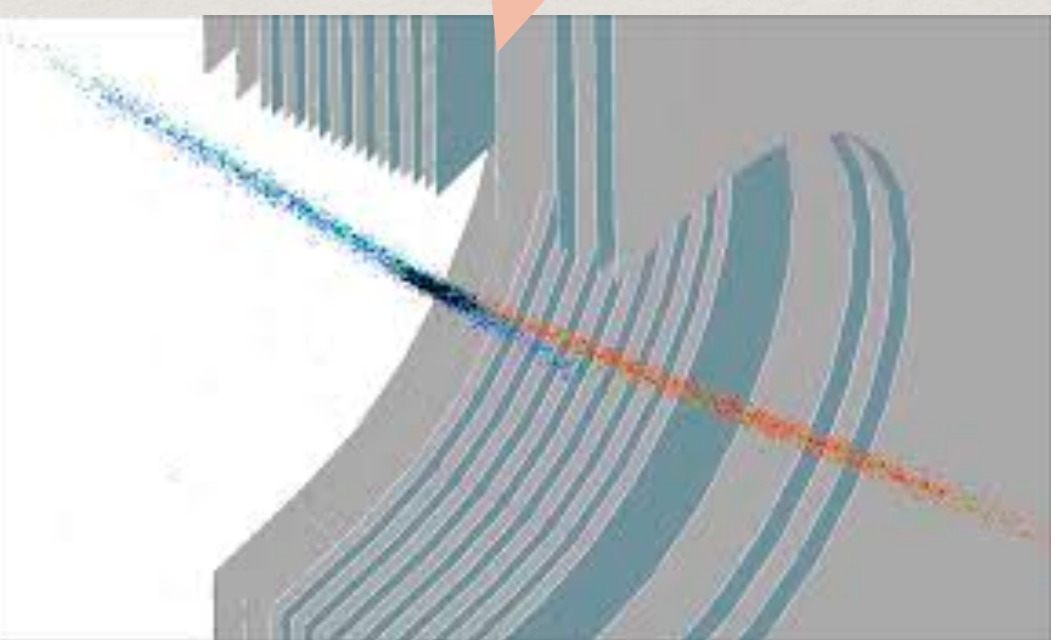
Collider mode:

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



Data samples

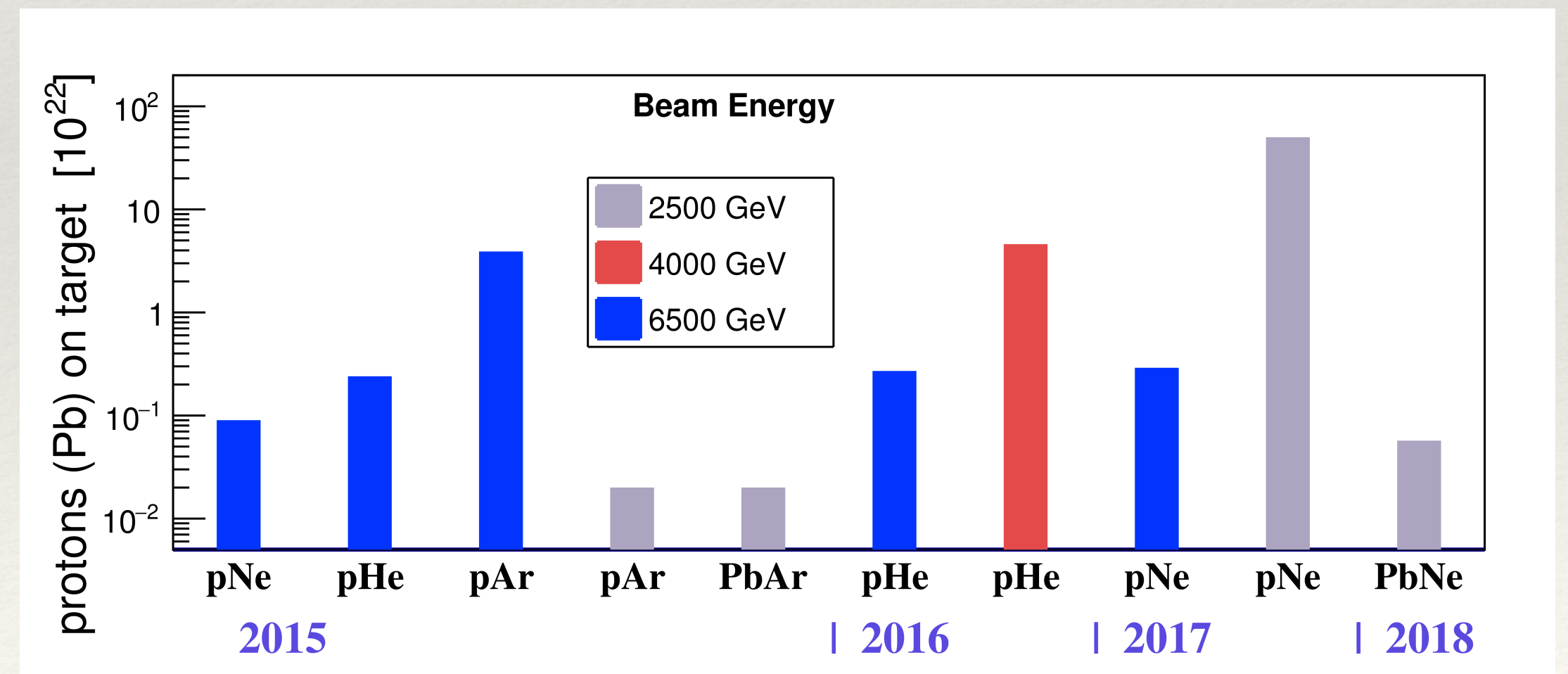
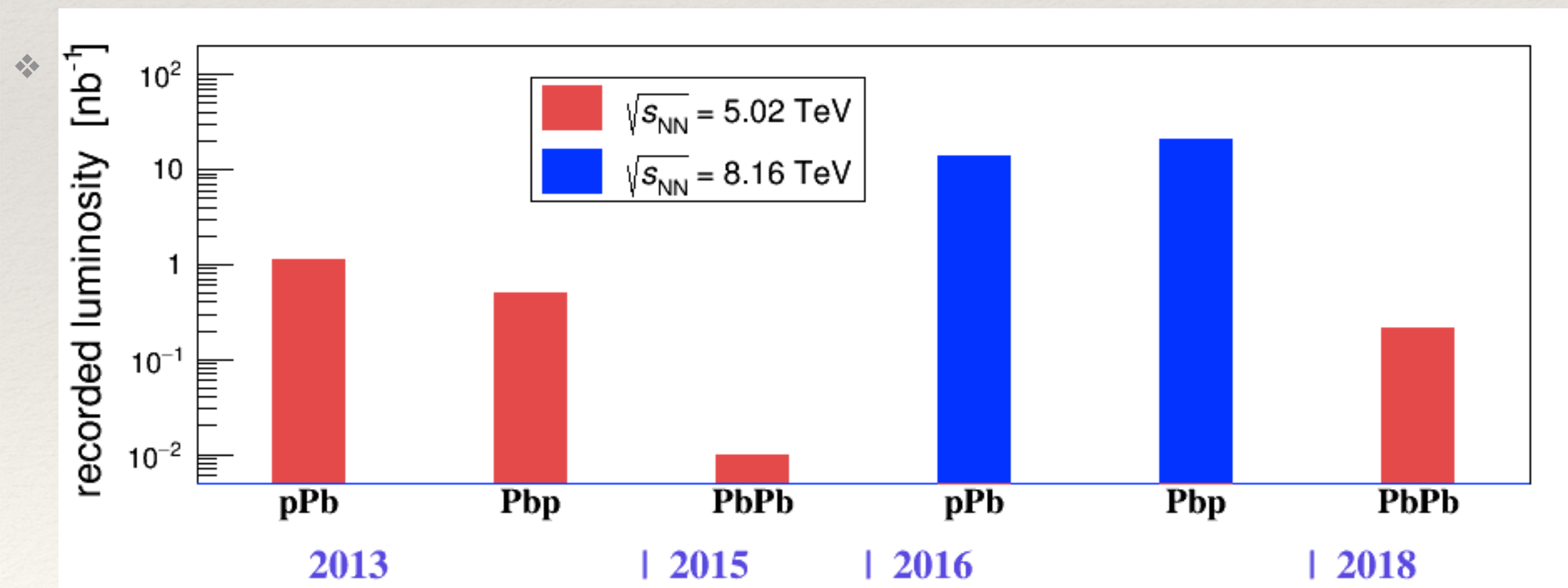
❖ Colliding beam mode (pPb and PbPb):

$\sqrt{s_{NN}}$	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 ~ 210 μb ⁻¹

❖ Fixed Target mode (SMOG):

❖ $\sqrt{s_{NN}}$: 69-110 GeV

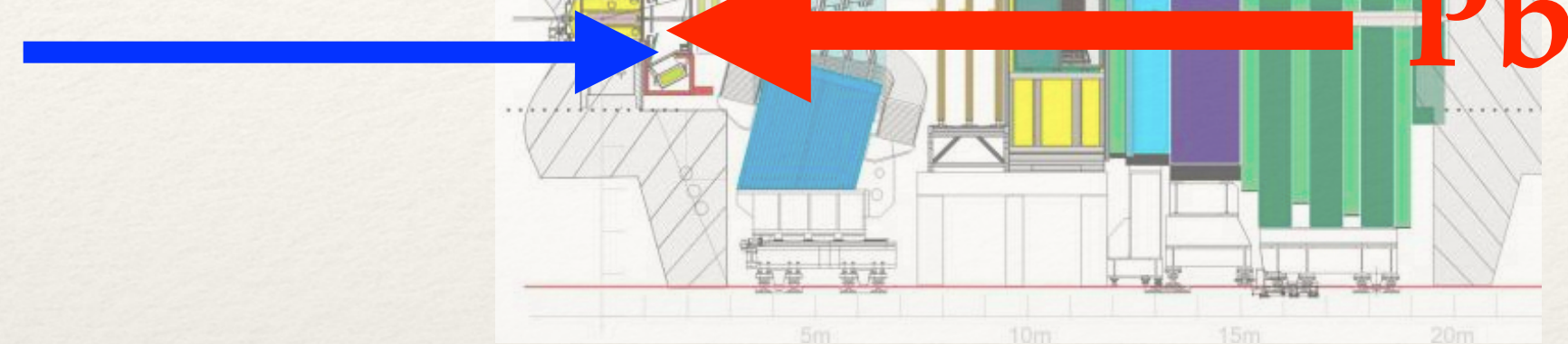
$$\int \mathcal{L} dt \sim 5 \text{nb}^{-1} \times \frac{(\text{protons on target})}{10^{22}} \times \frac{p_{\text{gas}}}{2 \times 10^{-7} \text{mbar}} \times \text{Exp_efficiency}$$



Setups for proton-ion collisions

p-Pb

p



❖ **Forward production:**

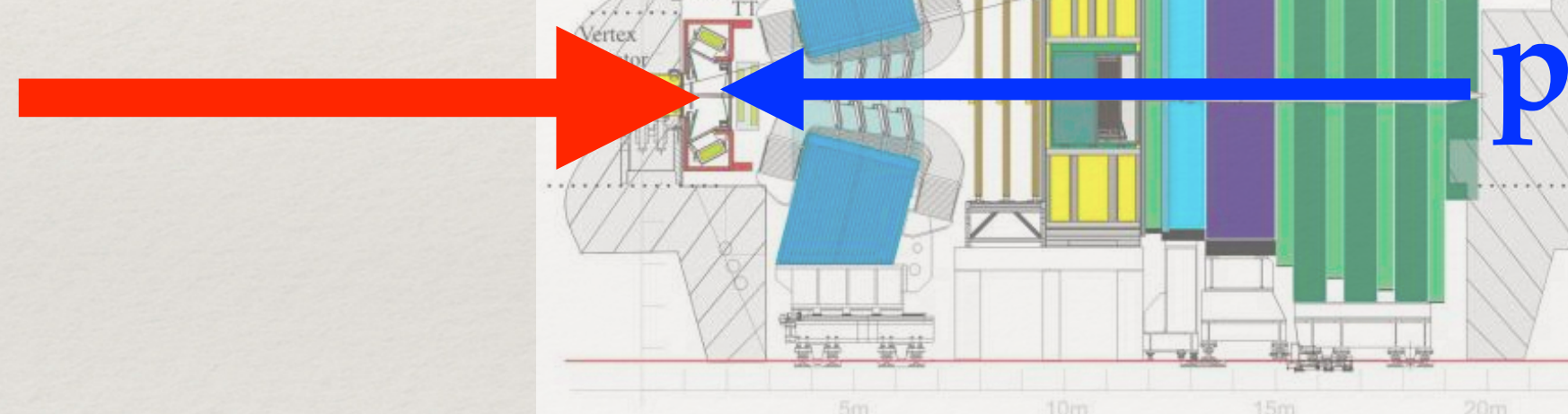
❖ Center of mass rapidity coverage:
 $1.5 < y^* < 4.0$

❖ **Backward production:**

❖ Center of mass rapidity coverage:
 $-5.0 < y^* < -2.5$

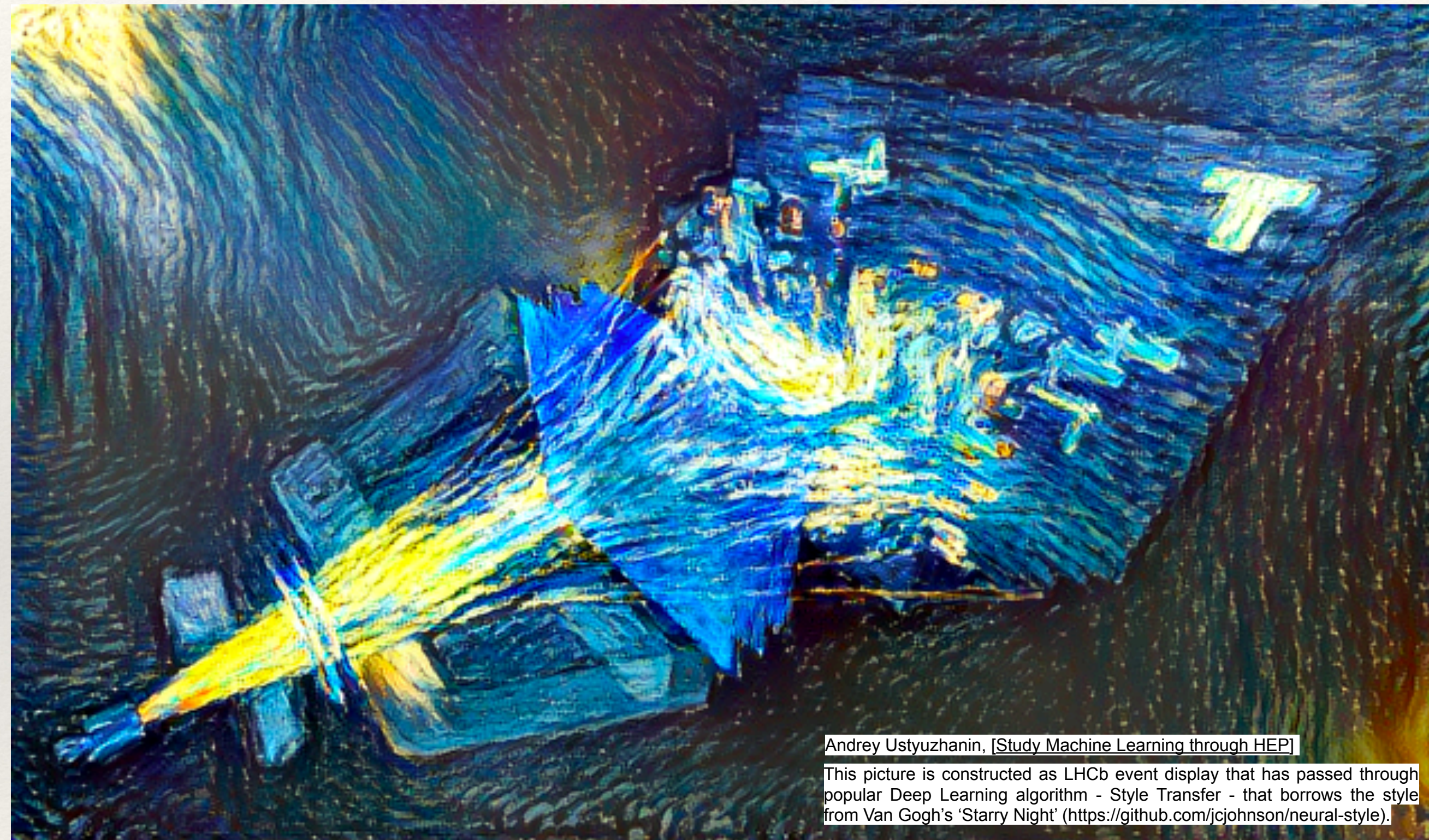
Pb-p

Pb



- ❖ 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



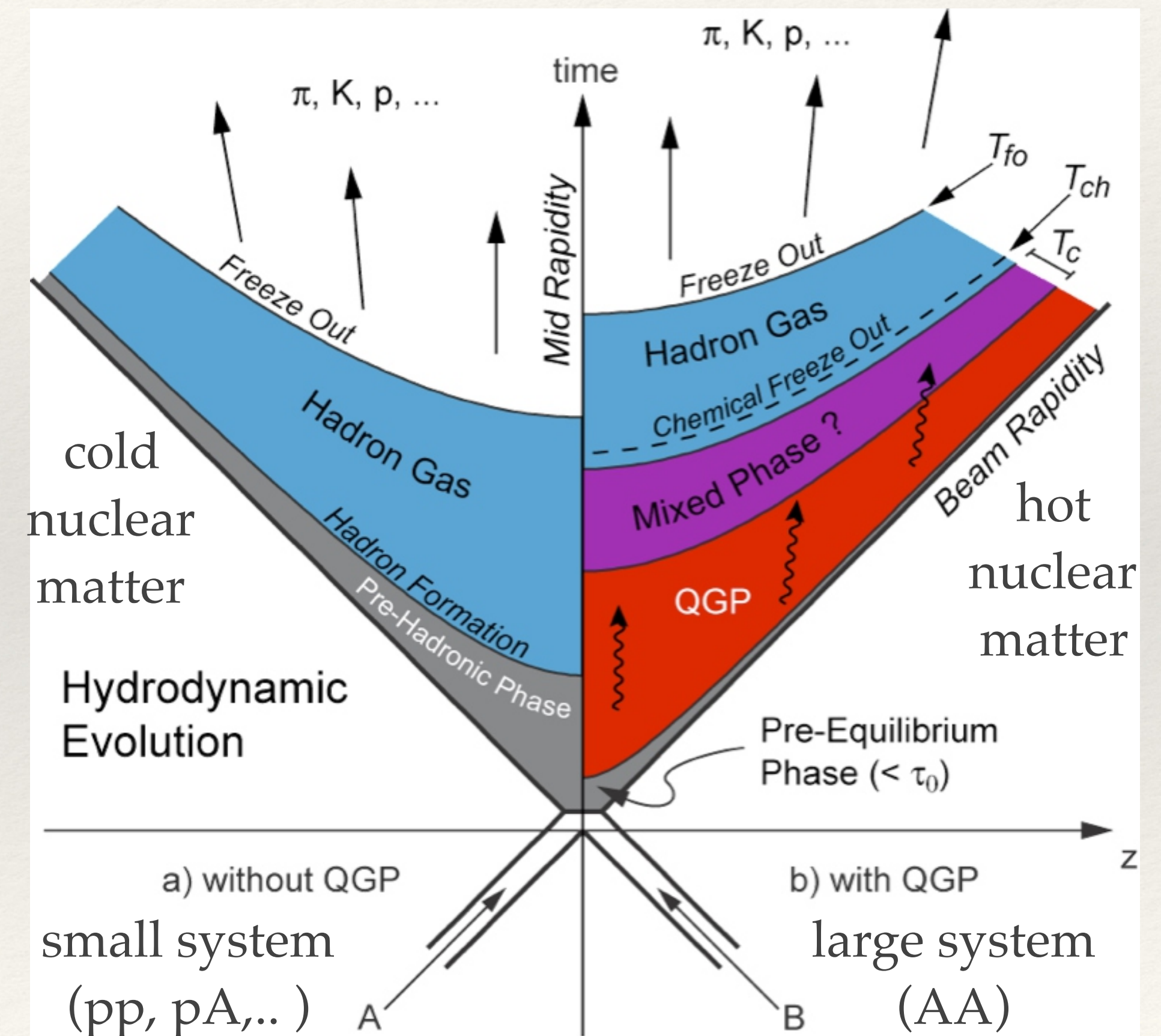
Andrey Ustyuzhanin, [Study Machine Learning through HEP]

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

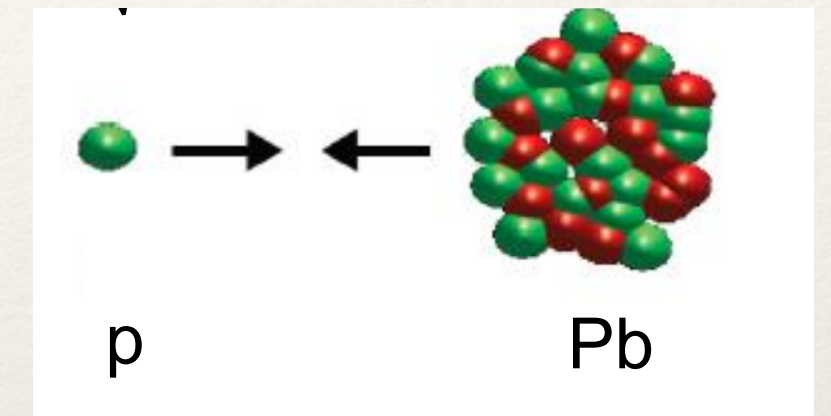
- ❖ Ultra-relativistic heavy ion collisions can help us to:
 - ❖ Explore phase diagram of nuclear matter
 - ❖ Large systems (AA):
 - ❖ Study QCD matter under extreme conditions (hot nuclear matter effects)
 - ❖ E.g. formation of Quark Gluon Plasma (QGP) at high temperature and/or energy density.
 - ❖ 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



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]

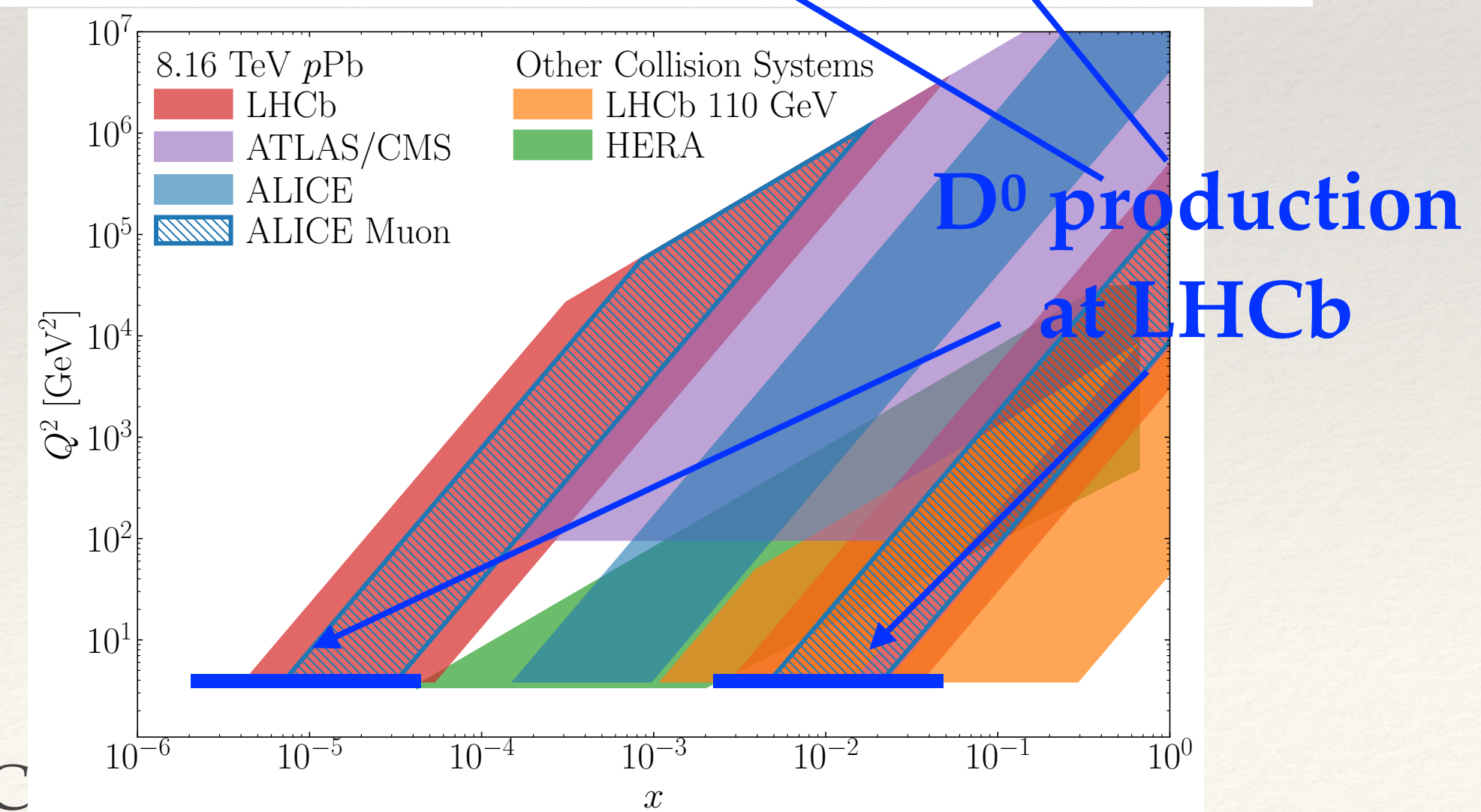
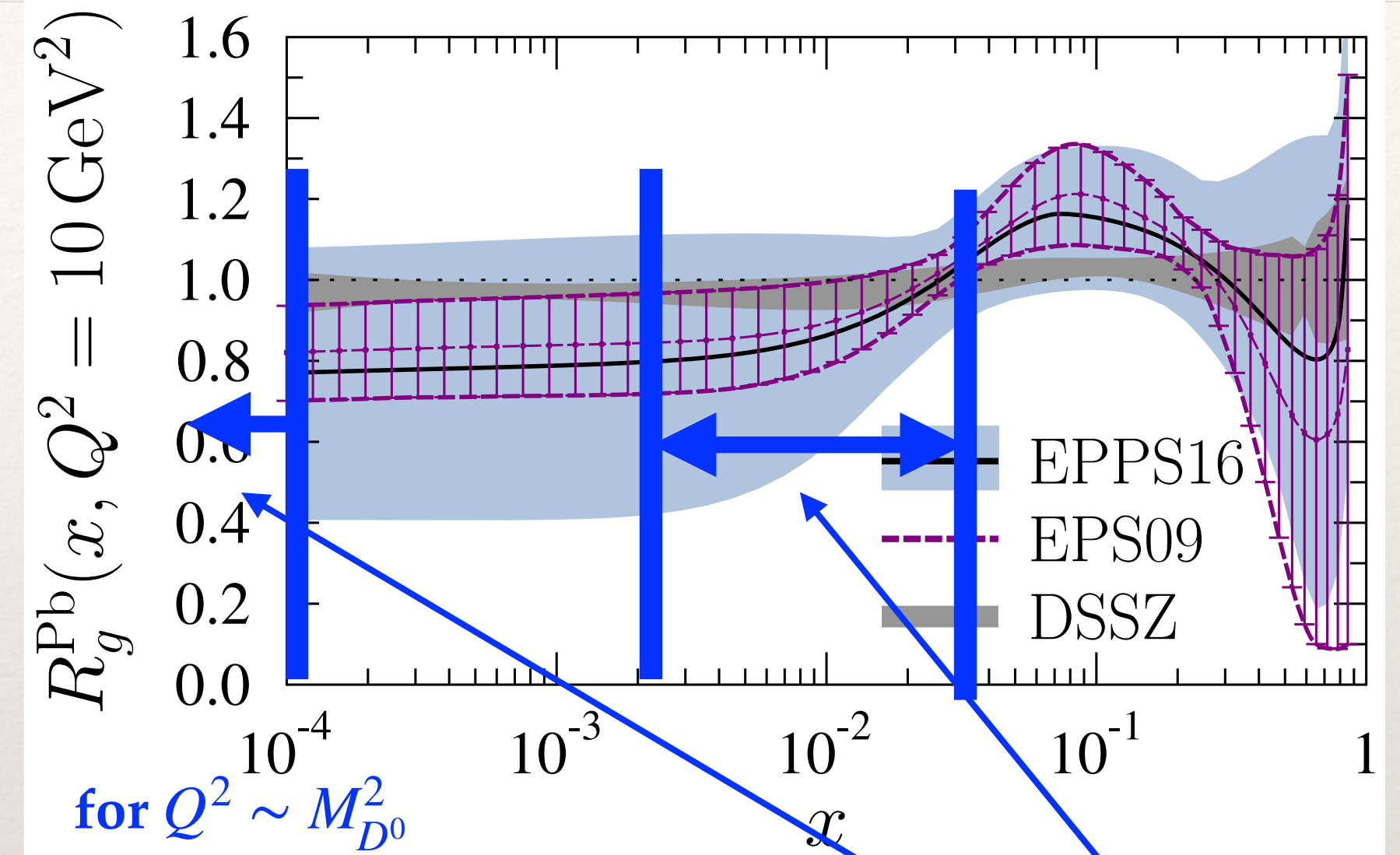
❖ Final state effects

- ❖ 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]

D⁰ production

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

- ❖ 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 Q^2 and very small Bjorken- x ($x < 10^{-4}$ and $5 \times 10^{-3} < x < 5 \times 10^{-2}$) in pPb collisions at $\sqrt{s} = 5.02$ TeV were published recently.
- ❖ High statistics data of pPb collisions at $\sqrt{s} = 8.16$ TeV are expected to provide high accuracy measurements of prompt open charm hadrons.



Definition of observables

❖ Double differential cross-section:

$$\frac{d^2\sigma}{dp_T dy^*} = \frac{N}{\mathcal{L} \times \epsilon_{\text{tot}} \times \mathcal{B} \times \Delta p_T \times \Delta y^*}$$

Prompt signal yields $\rightarrow N$

Integrated luminosity $\rightarrow \mathcal{L}$ Total efficiency $\rightarrow \epsilon_{\text{tot}}$ Branching ratio $\rightarrow \mathcal{B}$

❖ Nuclear modification factor :

$$R_{p\text{Pb}}(p_T, y^*) = \frac{1}{A} \frac{d^2\sigma_{p\text{Pb}}(p_T, y^*)/dp_T dy^*}{d^2\sigma_{pp}(p_T, y^*)/dp_T dy^*}$$

❖ Forward-backward production ratio:

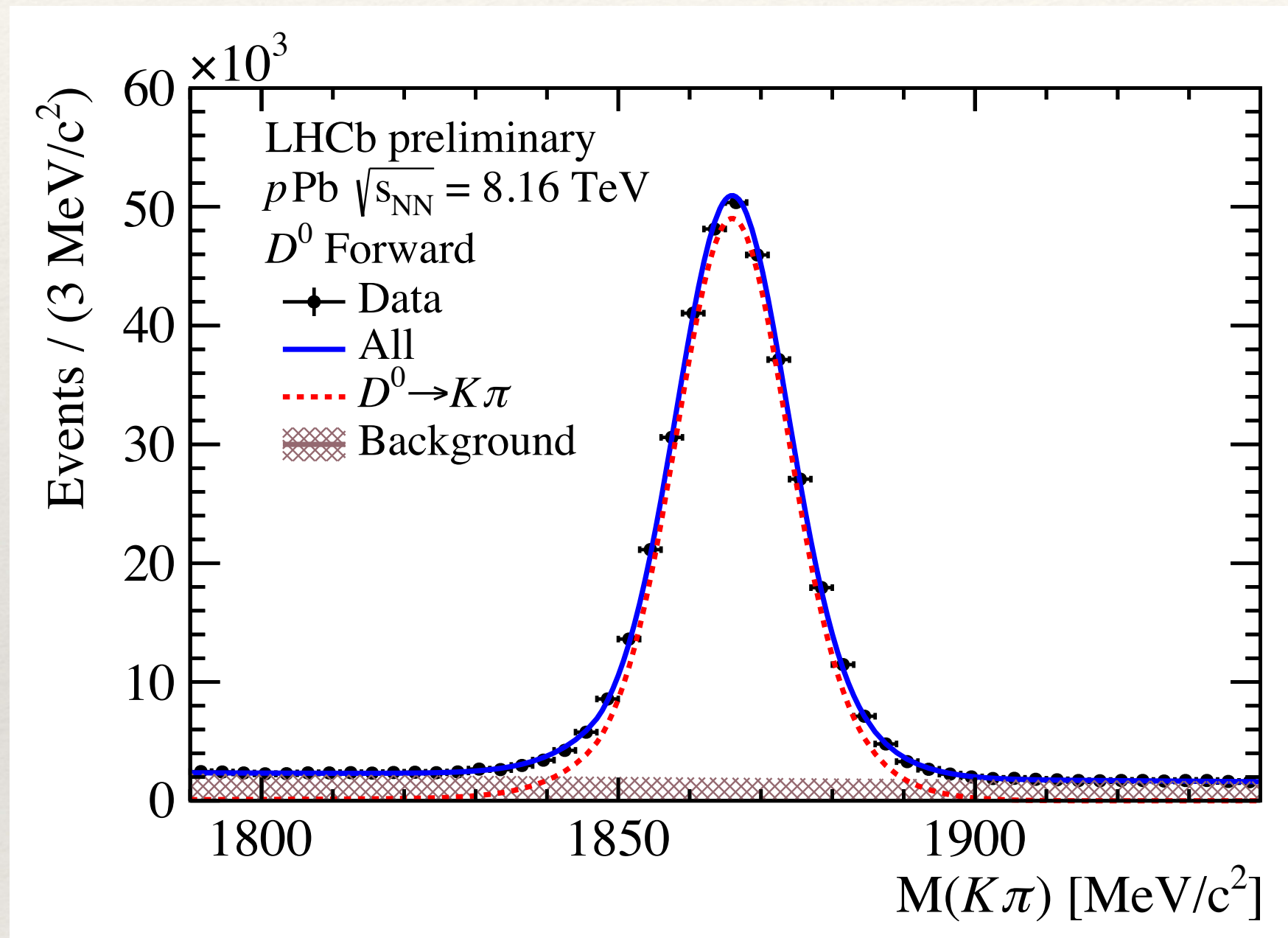
$$R_{\text{FB}}(p_T, y^*) = \frac{d^2\sigma_{p\text{Pb}}(p_T, +|y|^*)/dp_T dy^*}{d^2\sigma_{p\text{Pb}}(p_T, -|y|^*)/dp_T dy^*}$$

❖ Baryon to meson ratio:

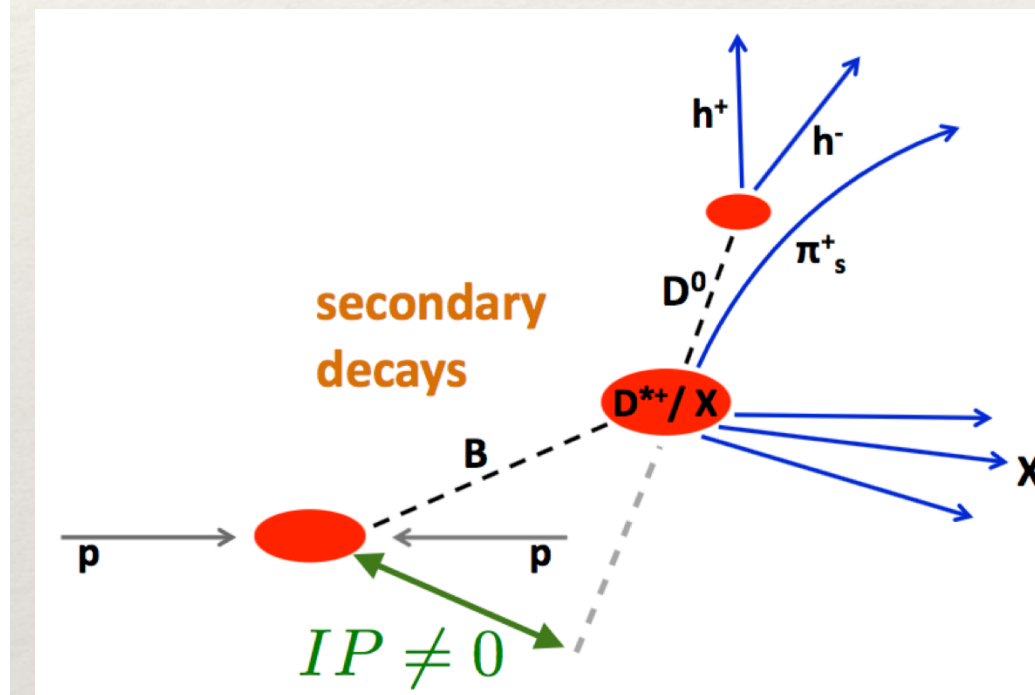
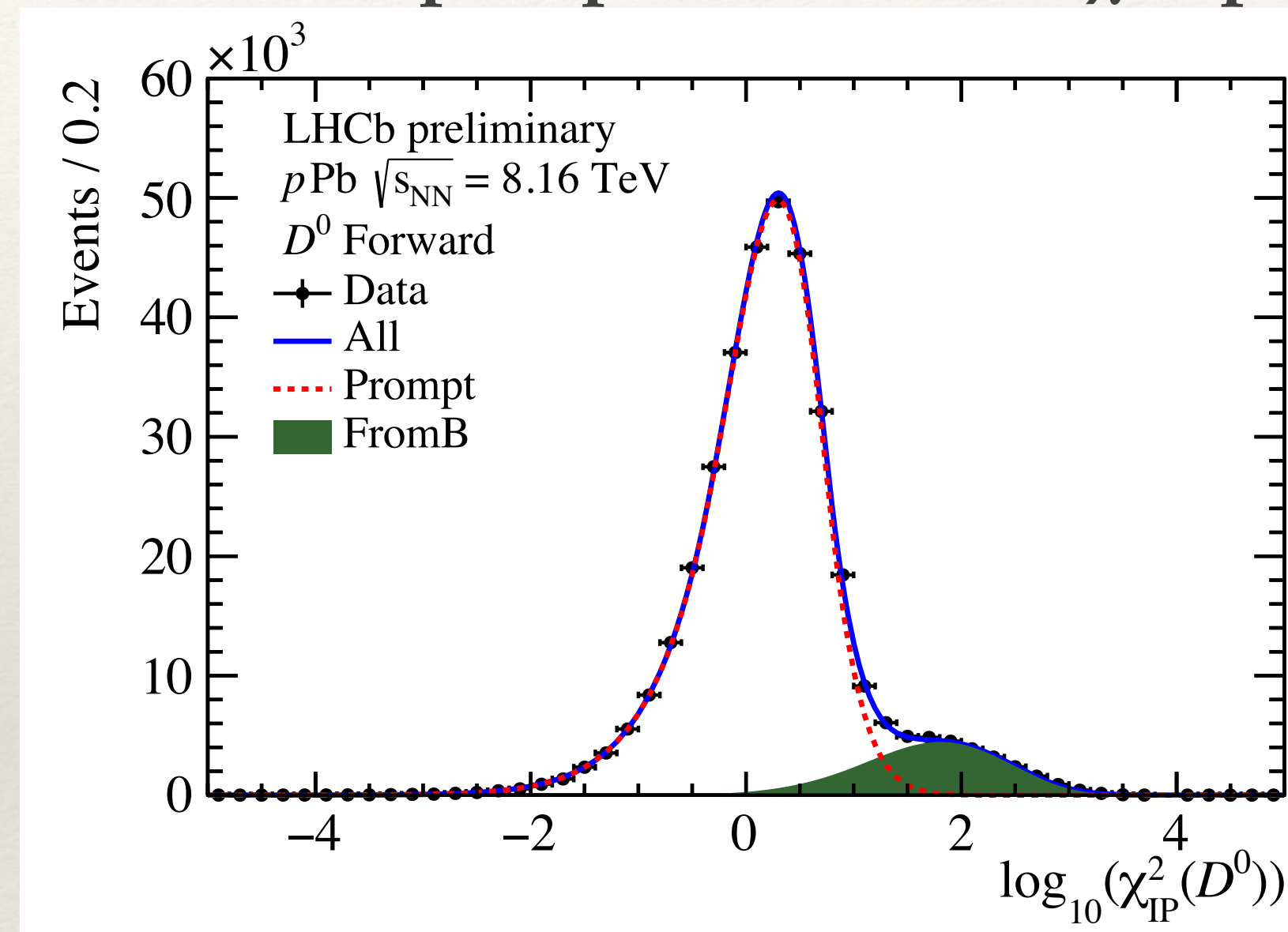
$$R_{\Lambda_c^+/D^0}(p_T, y^*) = \frac{d^2\sigma_{\Lambda_c^+}(p_T, y^*)/dp_T dy^*}{d^2\sigma_{D^0}(p_T, y^*)/dp_T dy^*}$$

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

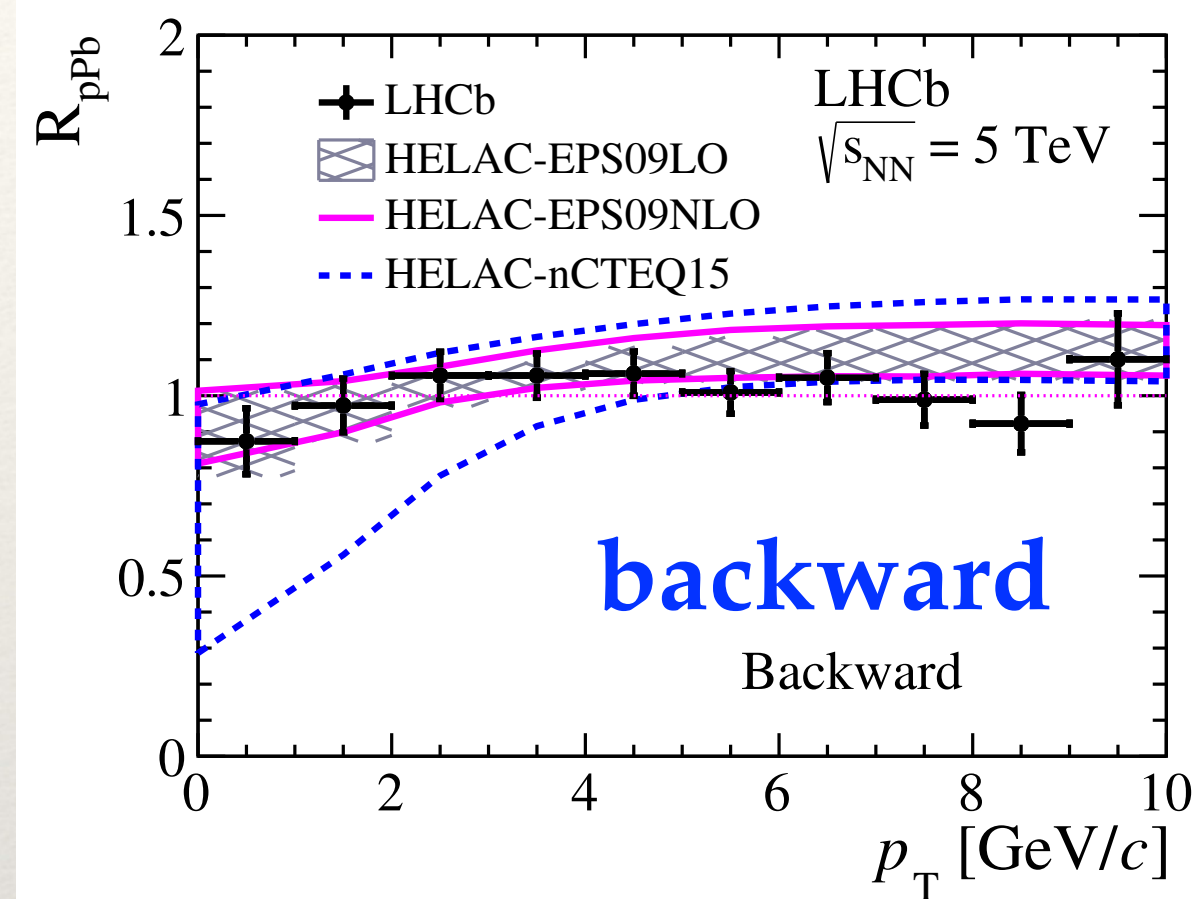
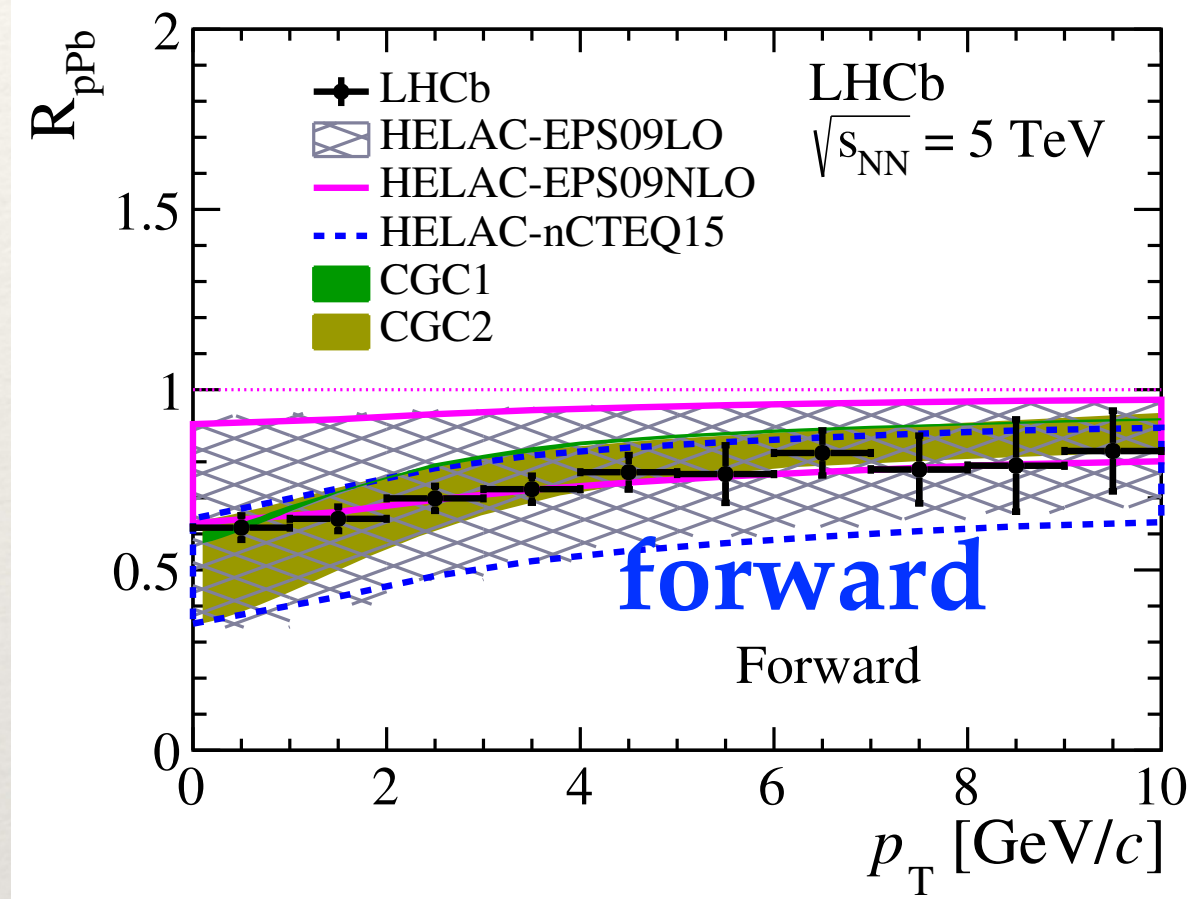


LHCb-CONF-2019-004

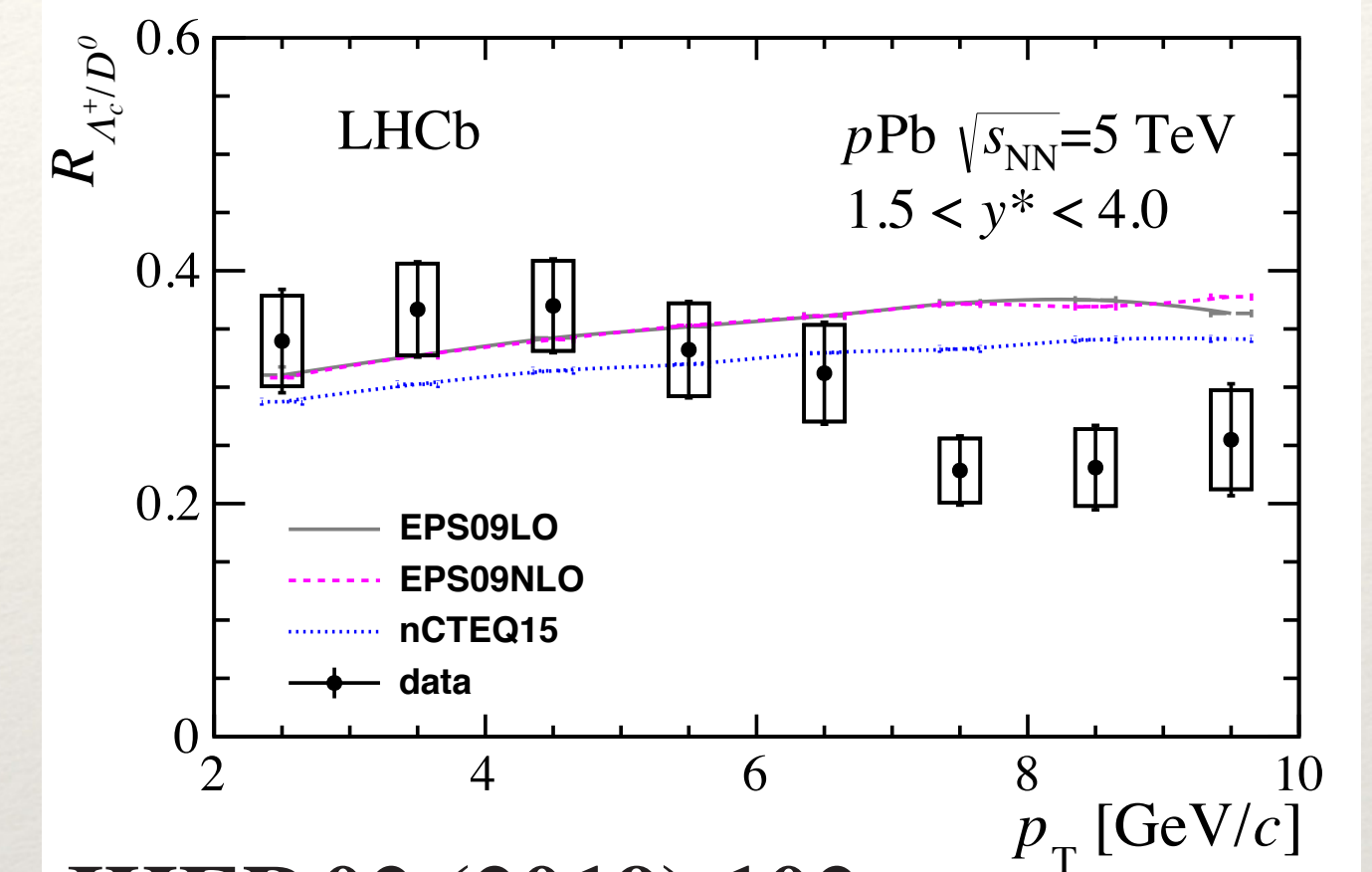
- ❖ Total efficiency calculated using simulation and calibration data samples:
 - ❖ Forward: from 0.8% to 14%
 - ❖ Backward: from 0.7% to 13%

Results from 5.02 TeV pPb collisions

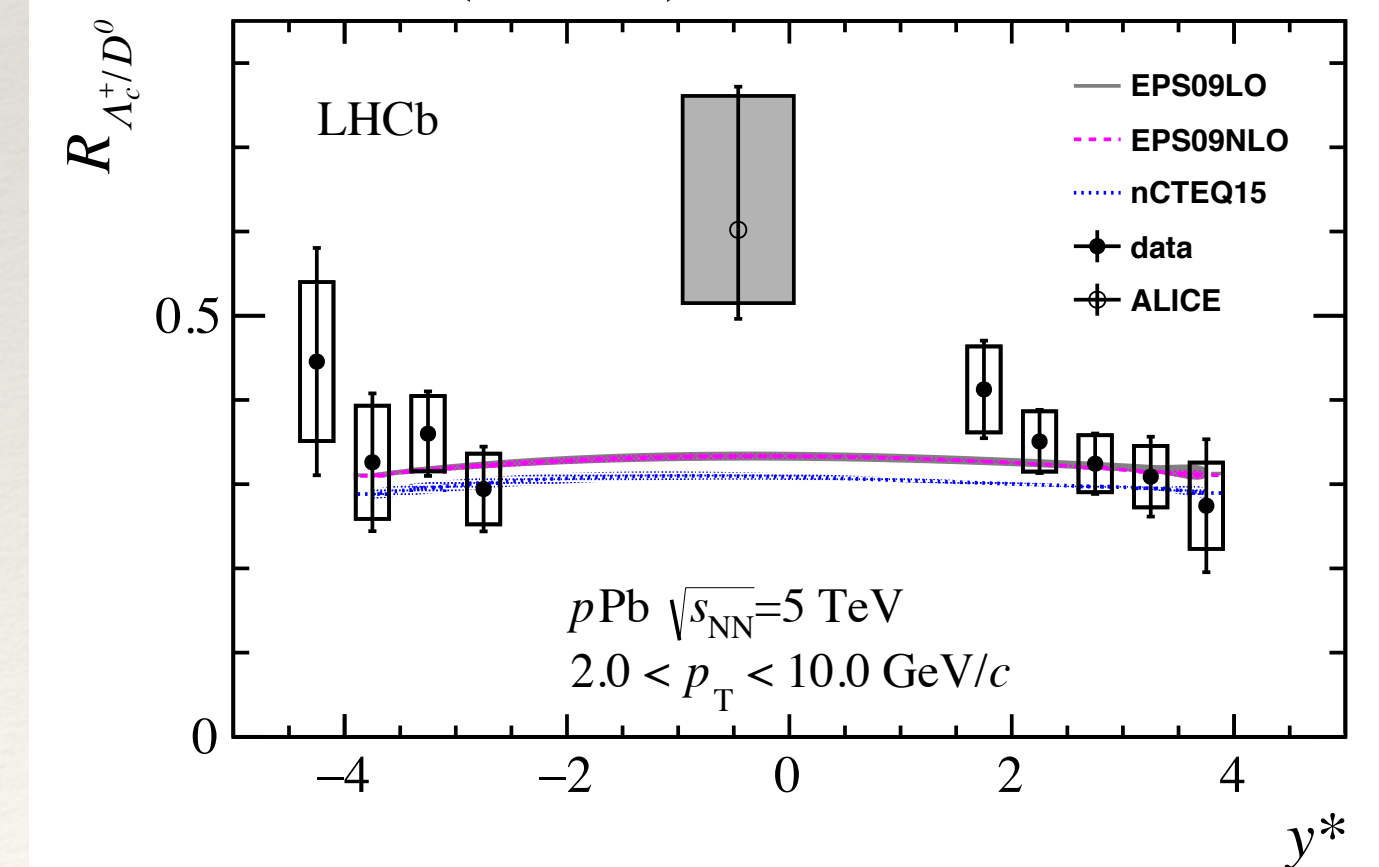
Nuclear modification factor vs. D^0 p_T



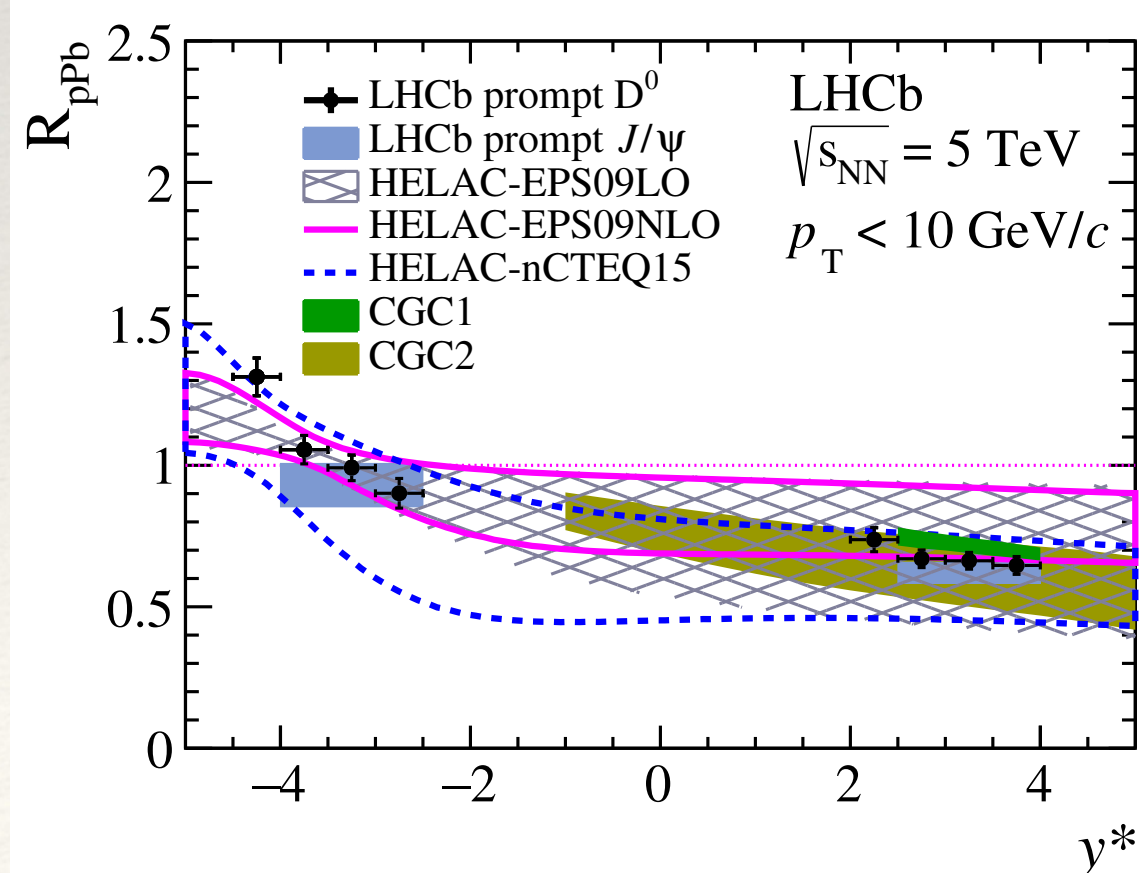
Ratio between D^0 and Λ_c^+



JHEP 02 (2019) 102



JHEP 10 (2017) 090



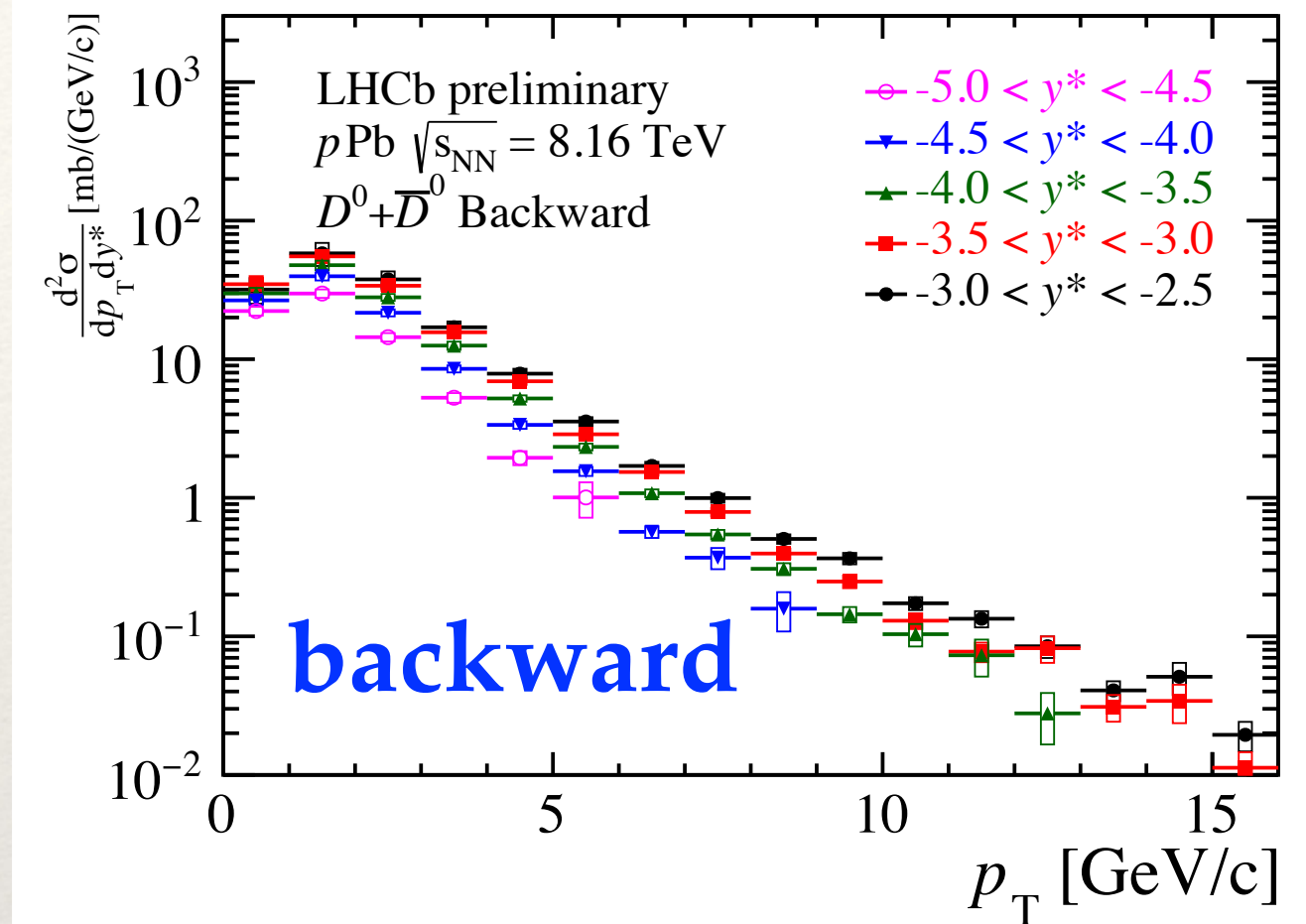
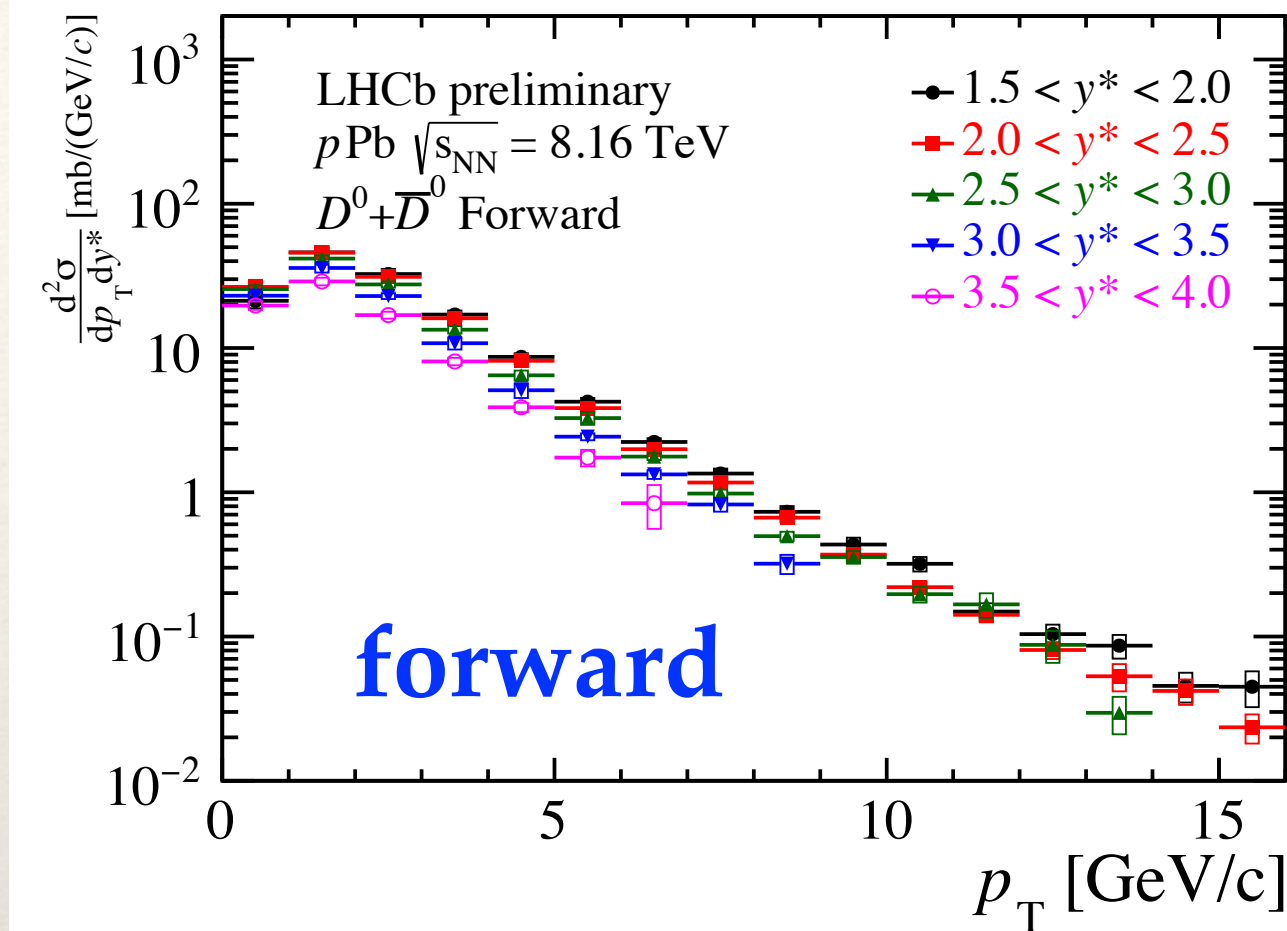
Nuclear modification factor vs. D^0 rapidity

- ❖ R_{pPb} suppressed in forward region ($\sim 30\%$), 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

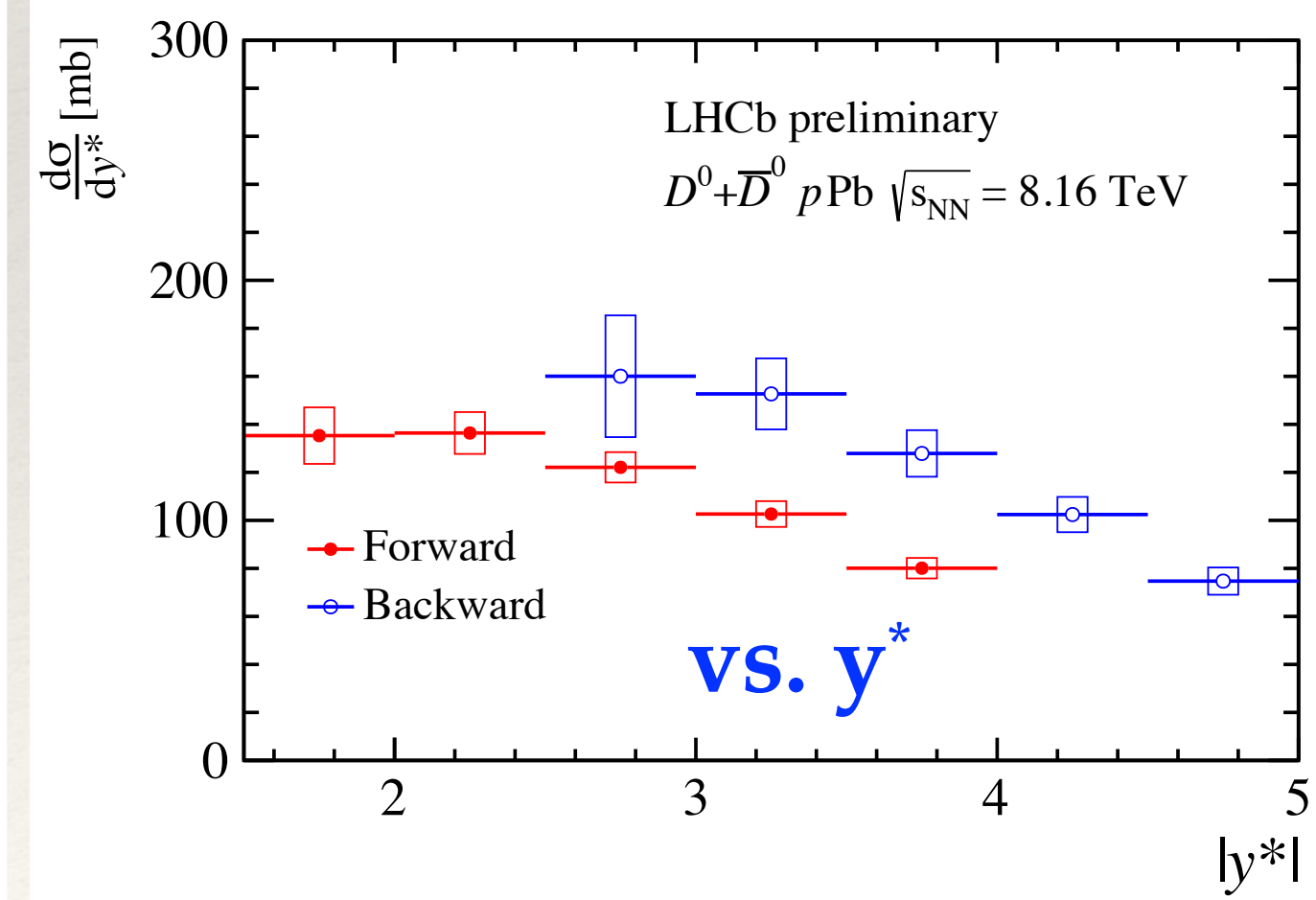
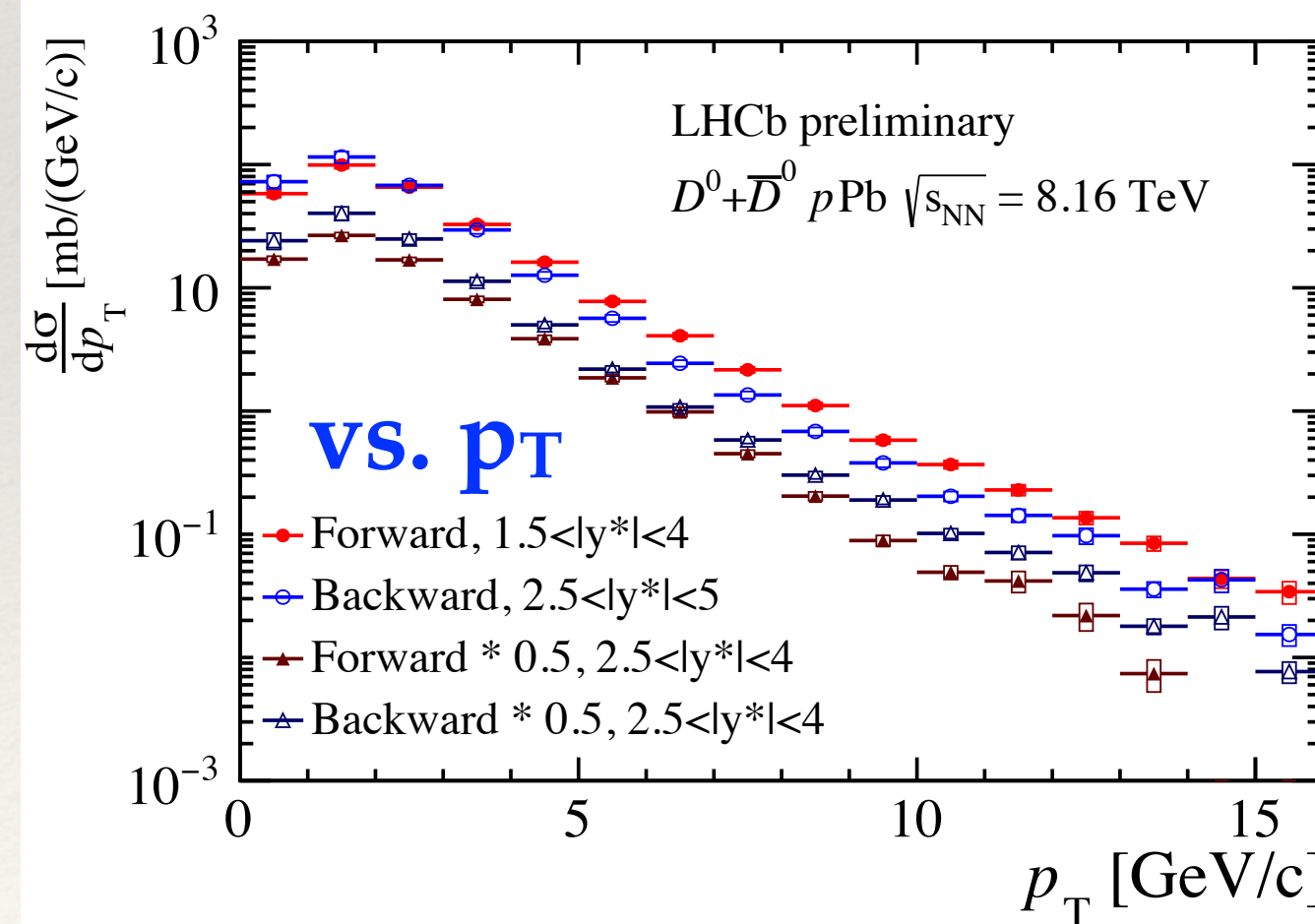
Differential cross-section at 8.16 TeV

LHCb-CONF-2019-004

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



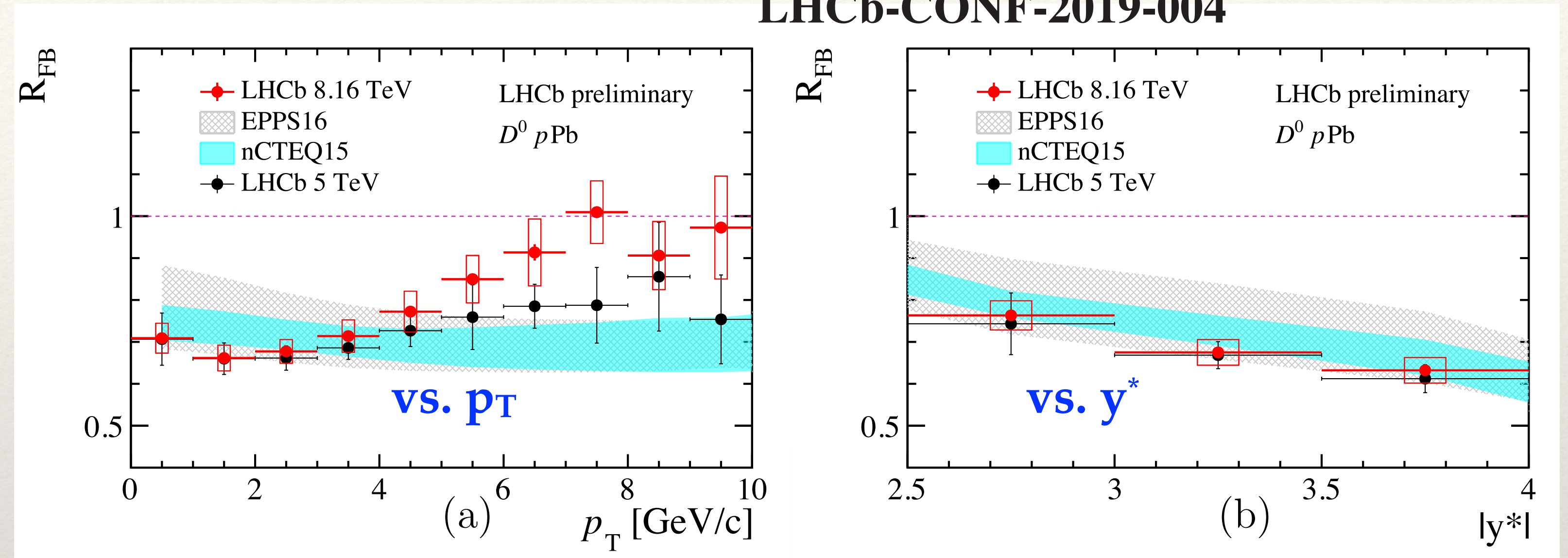
❖ Differential cross-sections (vs. p_T) and (vs. y^*) for forward and backward separately



Forward-backward ratio at 8.16 TeV

LHCb-CONF-2019-004

❖ Forward-backward ratio R_{FB}

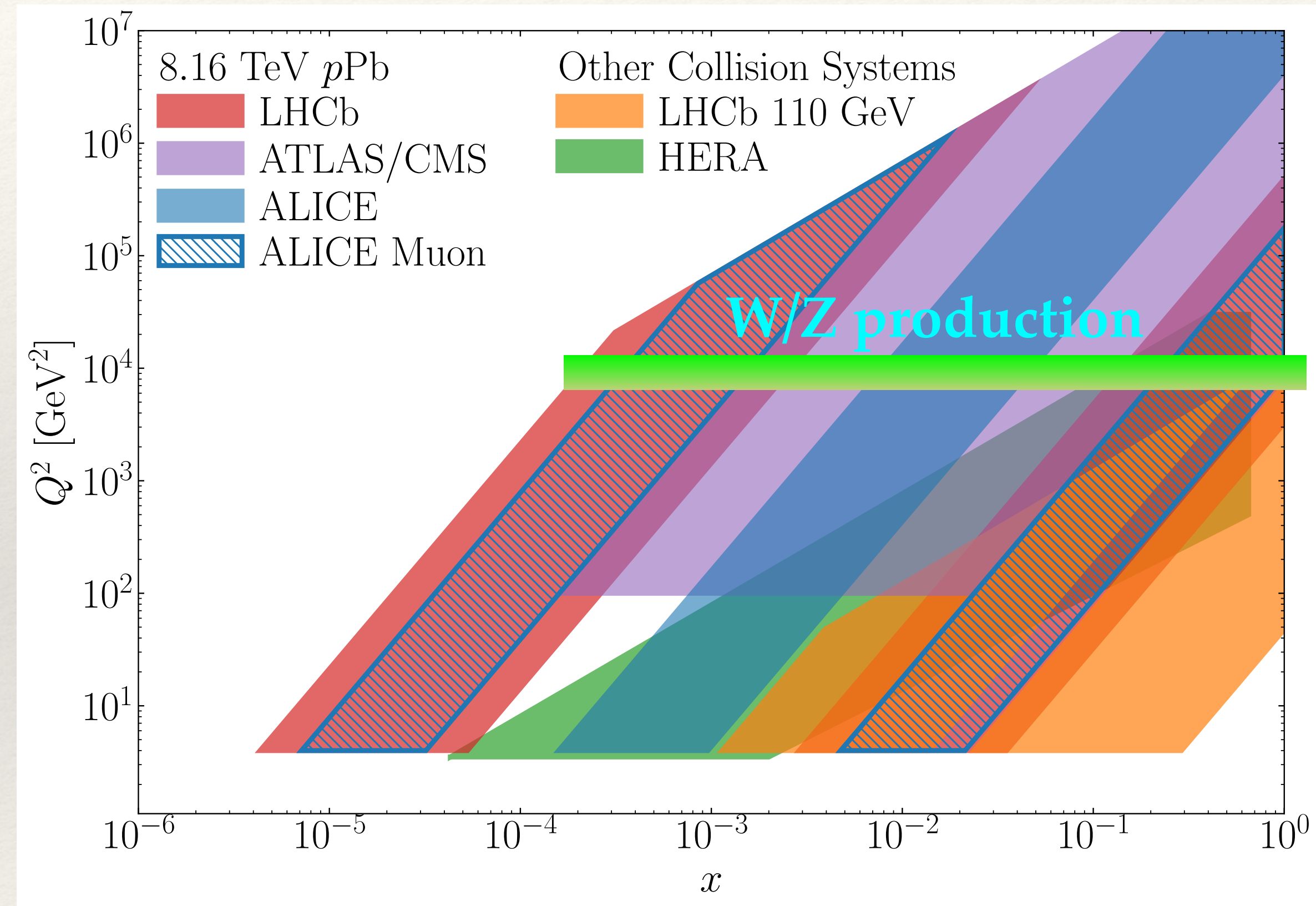


- ❖ Improved statistics by factor 20 compared to previous LHCb results.
- ❖ Tension between data and nPDFs predictions. Additional effects required.

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 $\sim 10^{-4}$ to 1 at $Q^2 \sim 10^4 \text{ GeV}^2$
- ❖ 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:

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

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

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

- ❖ Fiducial volume:

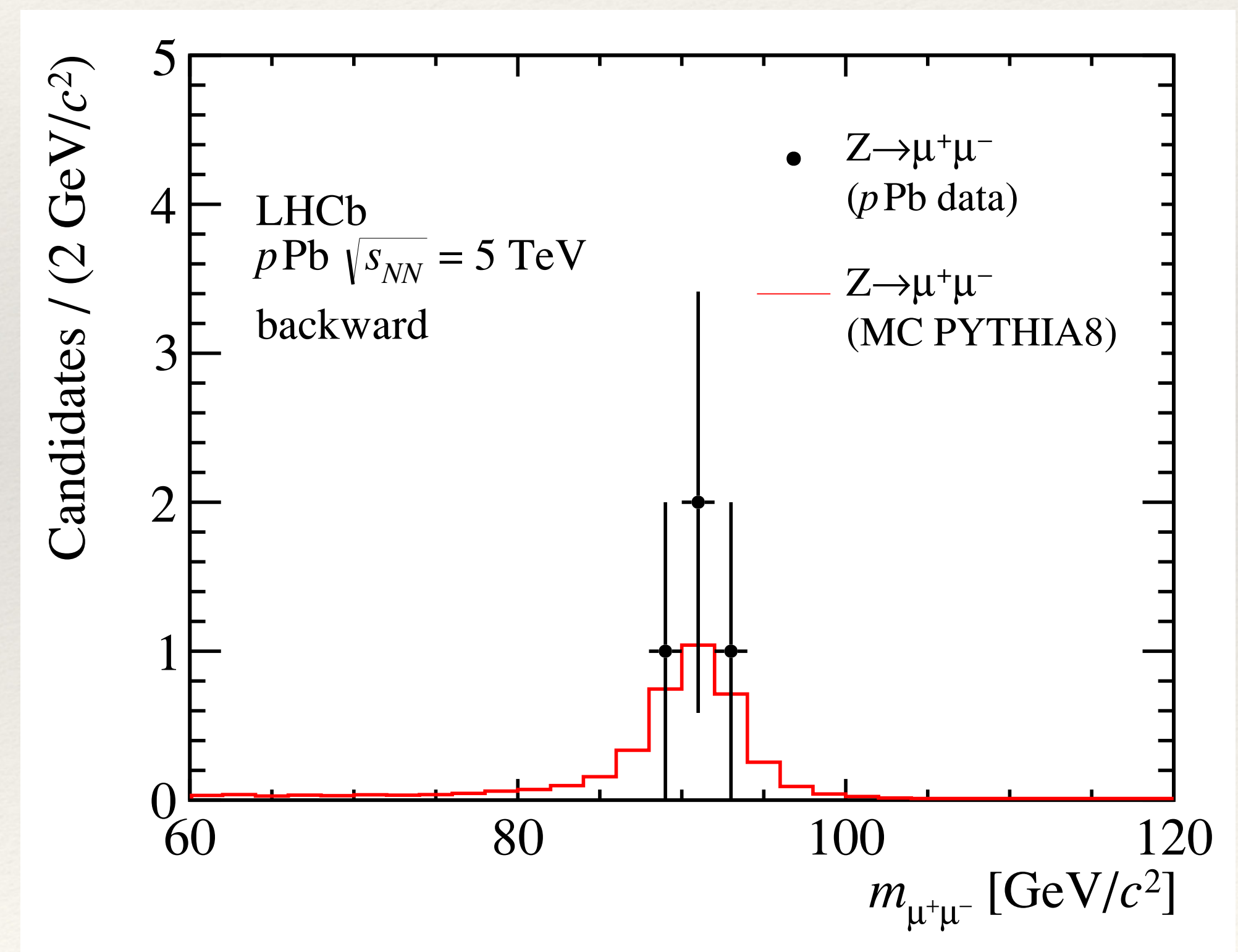
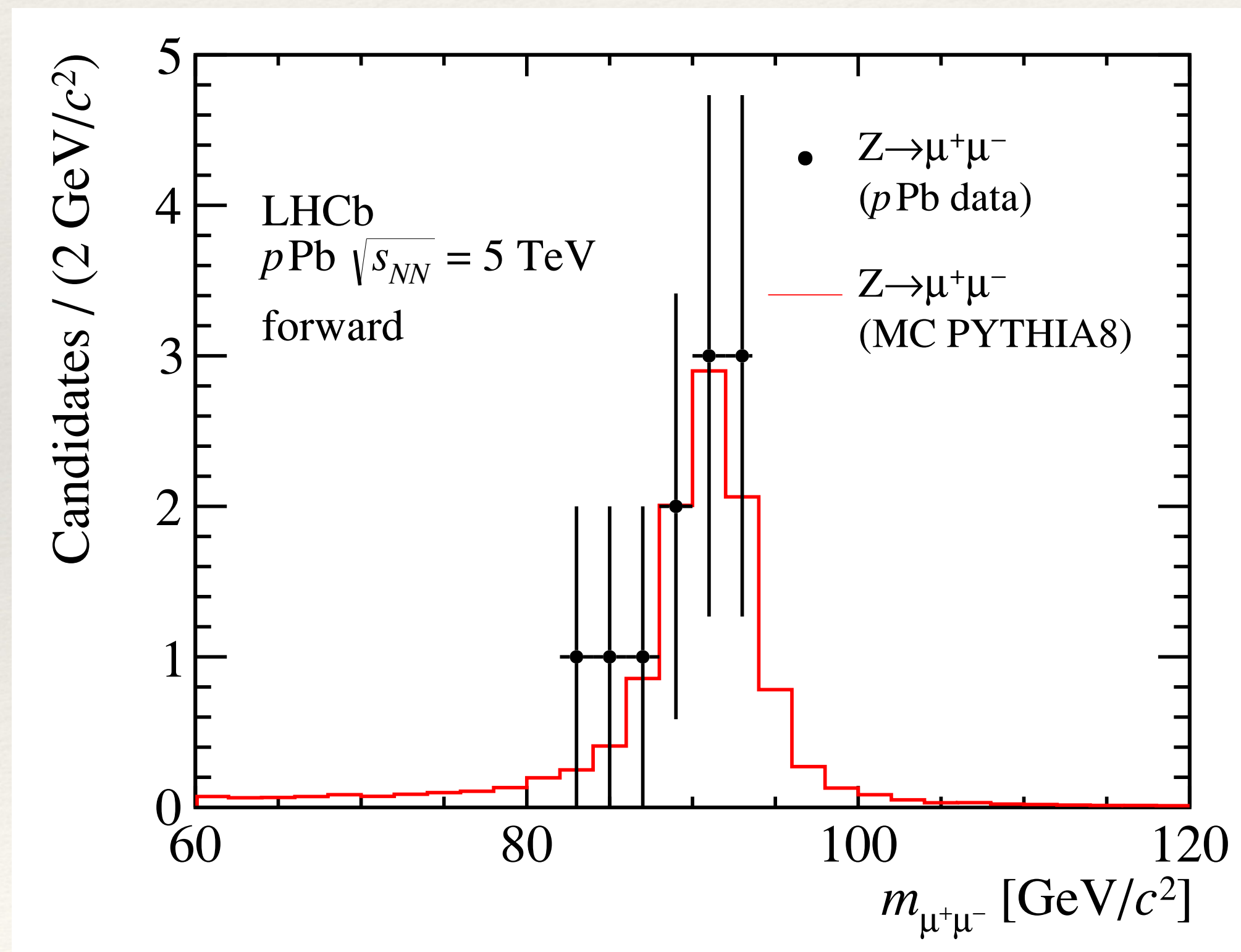
$$60 < m_{\mu\mu} < 120 \text{ GeV}$$

$$2.0 < \eta^\mu < 4.5, p_T^\mu > 20 \text{ GeV}$$

Z boson production in pPb at 5 TeV

- ❖ Integrated luminosity: forward ($1.099 \pm 0.021 \text{ nb}^{-1}$) / backward ($0.521 \pm 0.011 \text{ nb}^{-1}$)
- ❖ Yields: forward (11 events) / backward (4 events)

【JHEP09(2014)030】



Z boson production in pPb at 5 TeV

❖ Fiducial cross-section results:

❖ Forward:

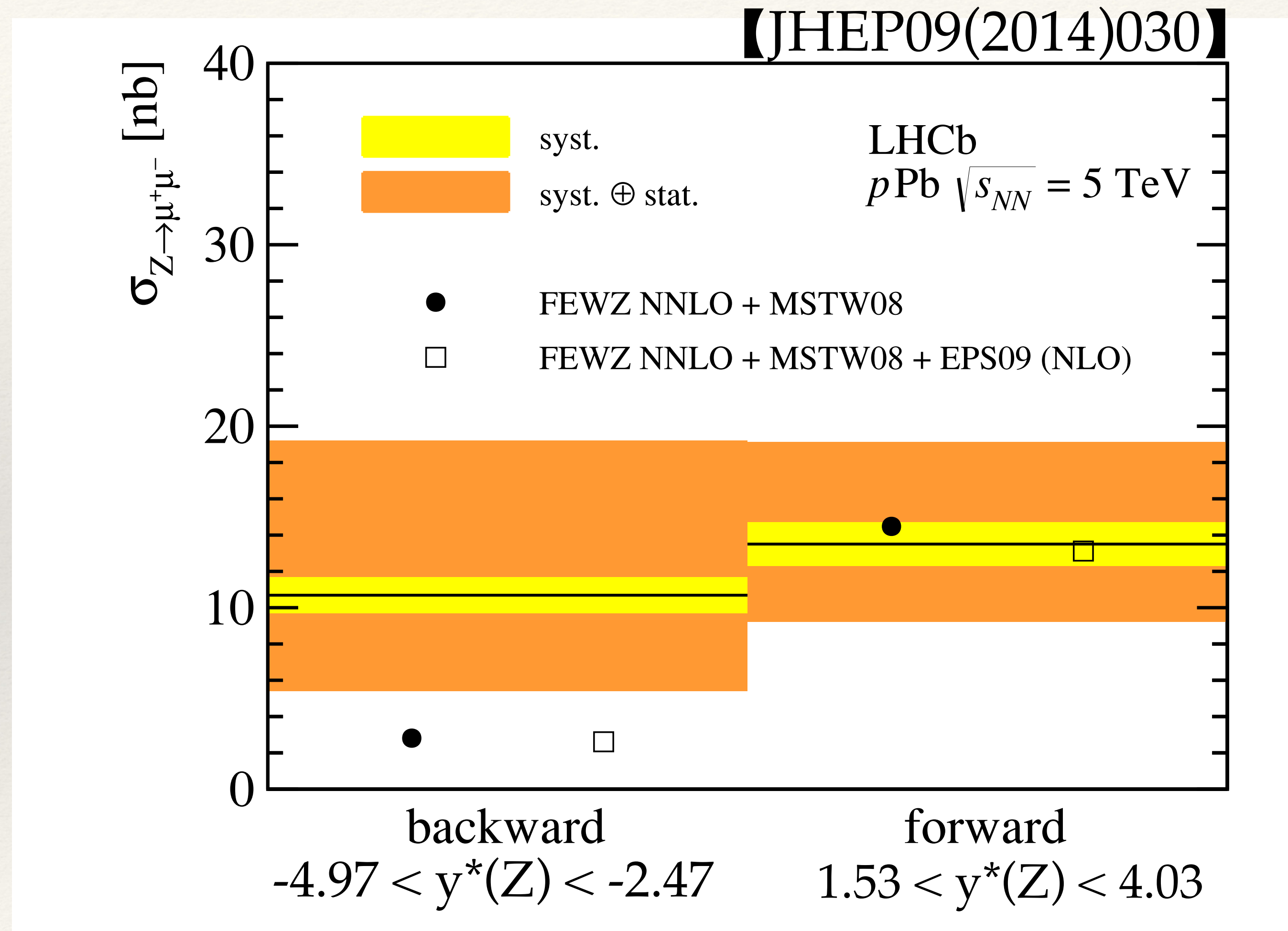
$$\sigma_{Z \rightarrow \mu^+ \mu^-}(\text{fwd}) = 13.5_{-4.0}^{+5.4}(\text{stat.}) \pm 1.2(\text{syst.}) \text{ nb}$$

❖ Backward:

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

❖ Compatible with theoretical predictions using FEWZ(NNLO pQCD+NLO pEW) with:

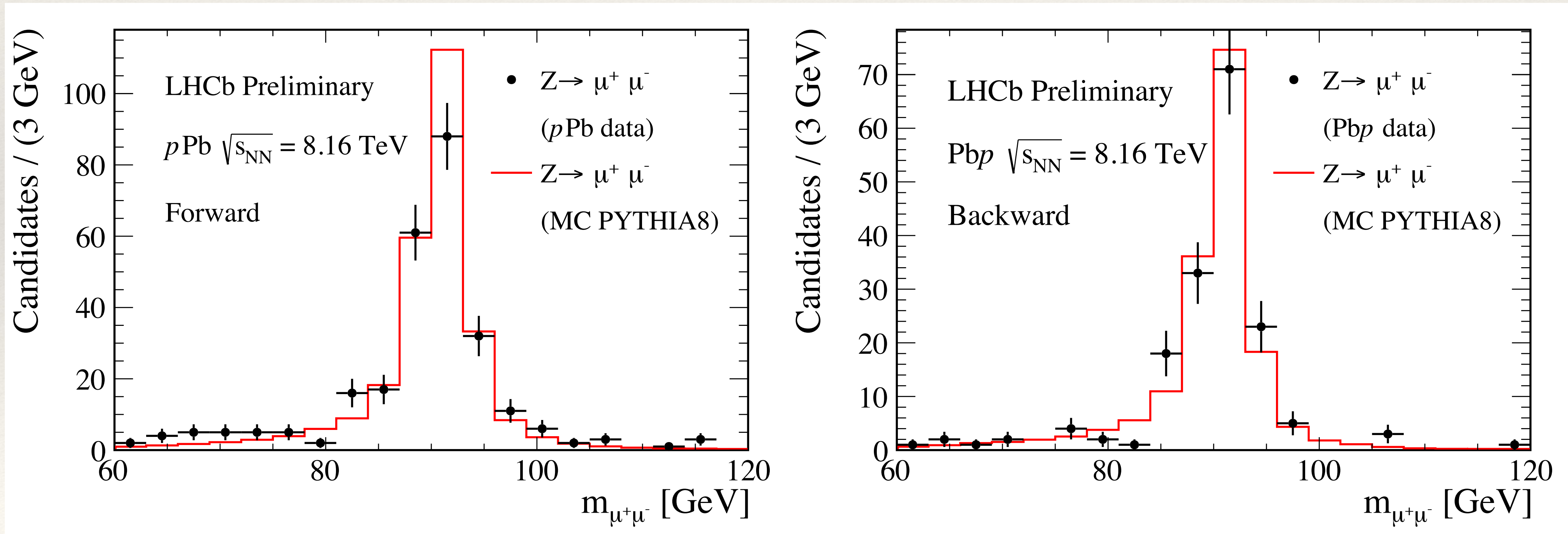
- ❖ MSTW08(PDF) for both p and Pb
- ❖ MSTW08(PDF) for p and EPS09(nPDF) for Pb



Z boson production in pPb at 8 TeV

- ❖ Integrated luminosity: forward ($12.2 \pm 0.3 \text{ nb}^{-1}$) / backward ($18.6 \pm 0.5 \text{ nb}^{-1}$)
- ❖ Yields: forward (268 events) / backward (167 events)

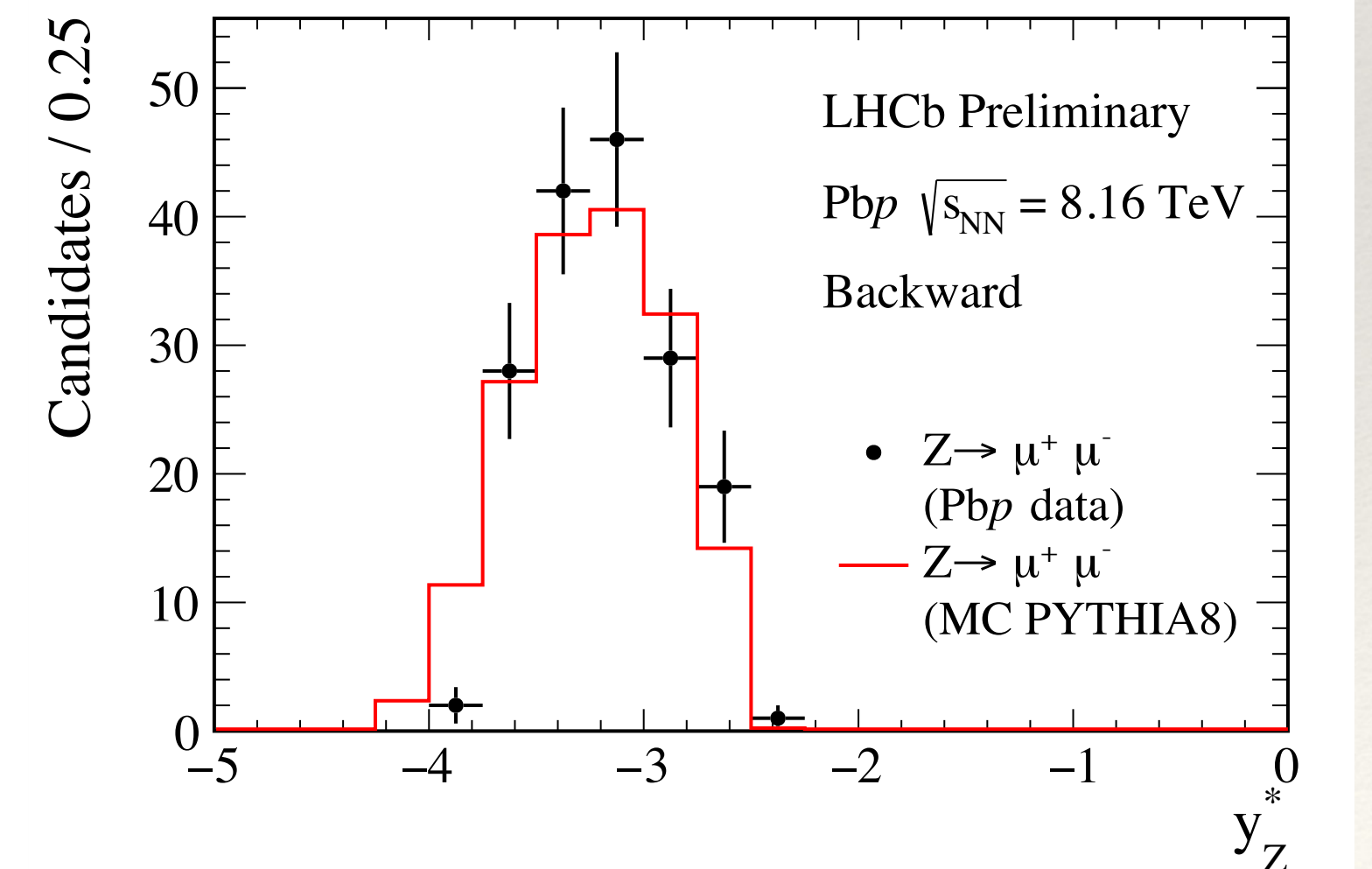
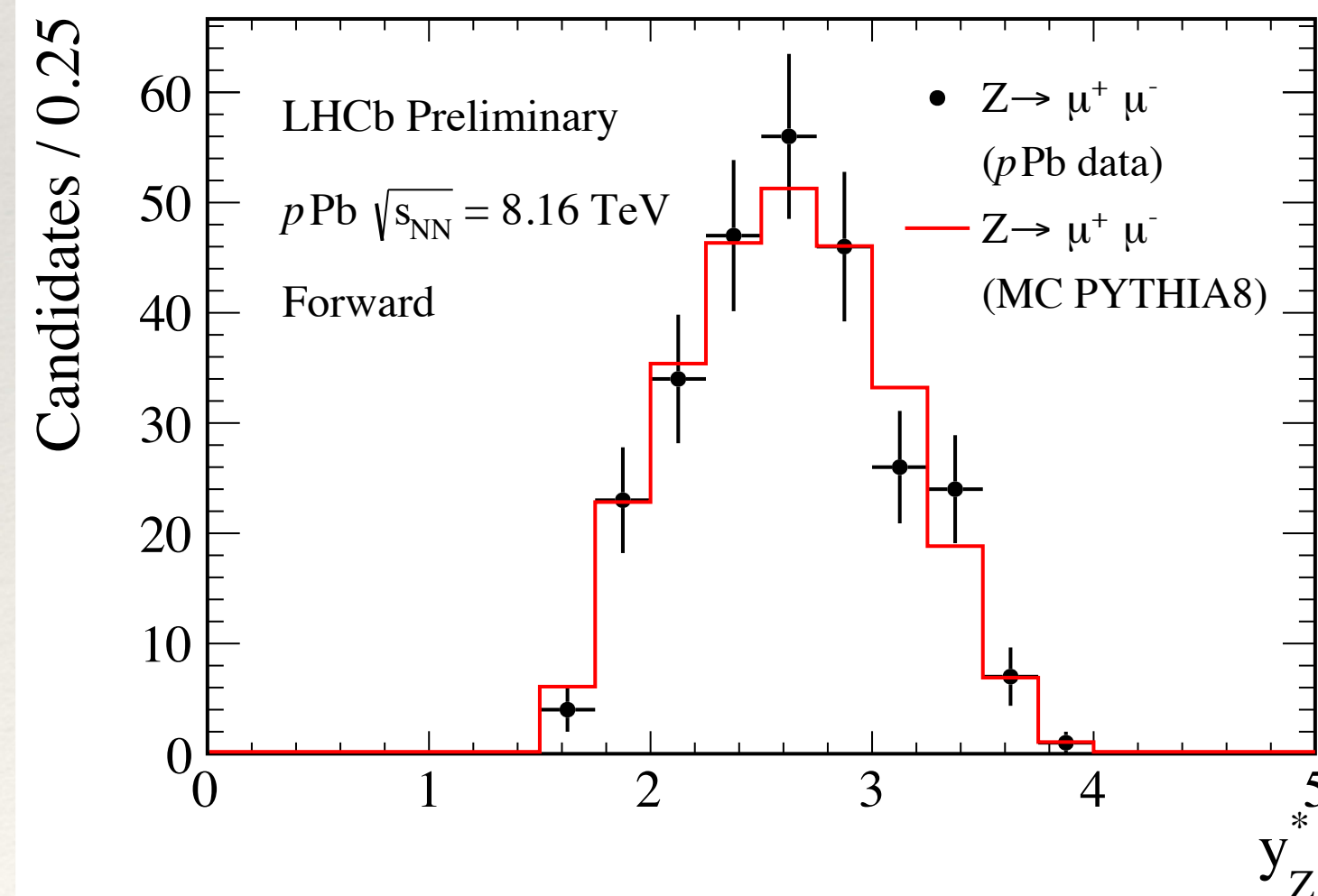
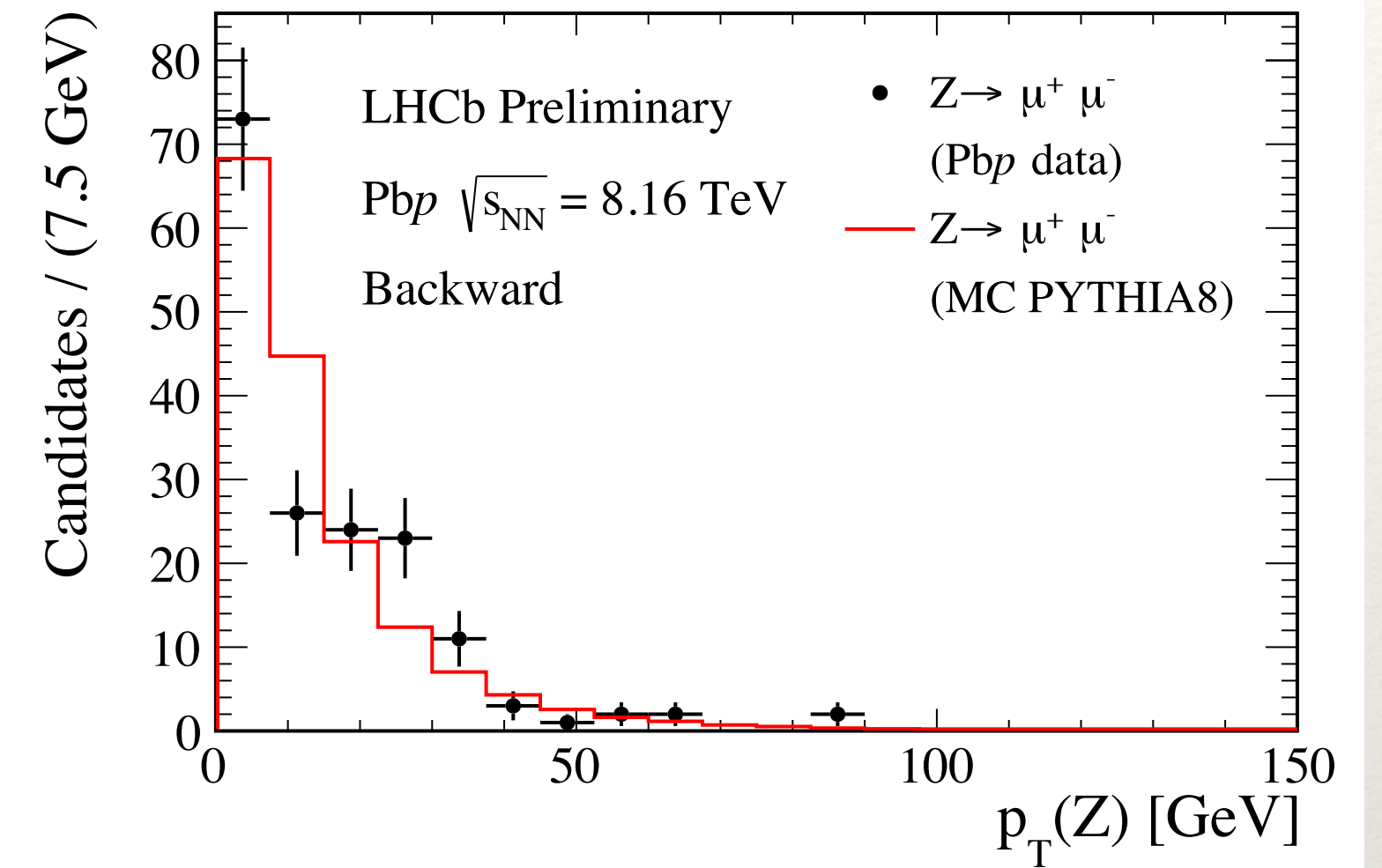
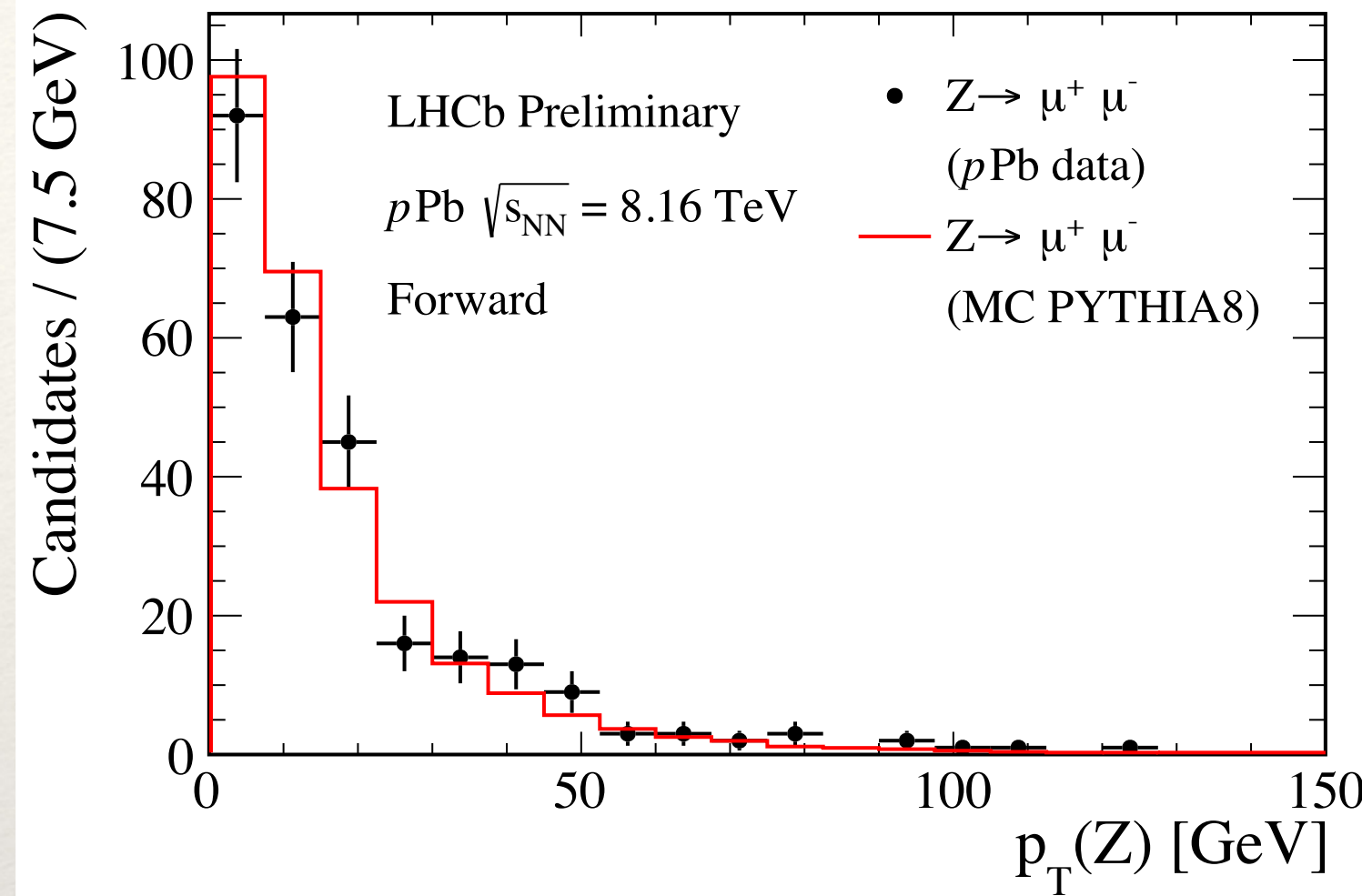
【LHCb-CONF-2019-003】



pPb Z boson production at 8 TeV

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

【LHCb-CONF-2019-003】



pPb Z boson production at 8 TeV

much higher precision

【LHCb-CONF-2019-003】

❖ Fiducial cross-section results:

$\sigma_{Z \rightarrow \mu^+ \mu^-, pPb}$ (forward)

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

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

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

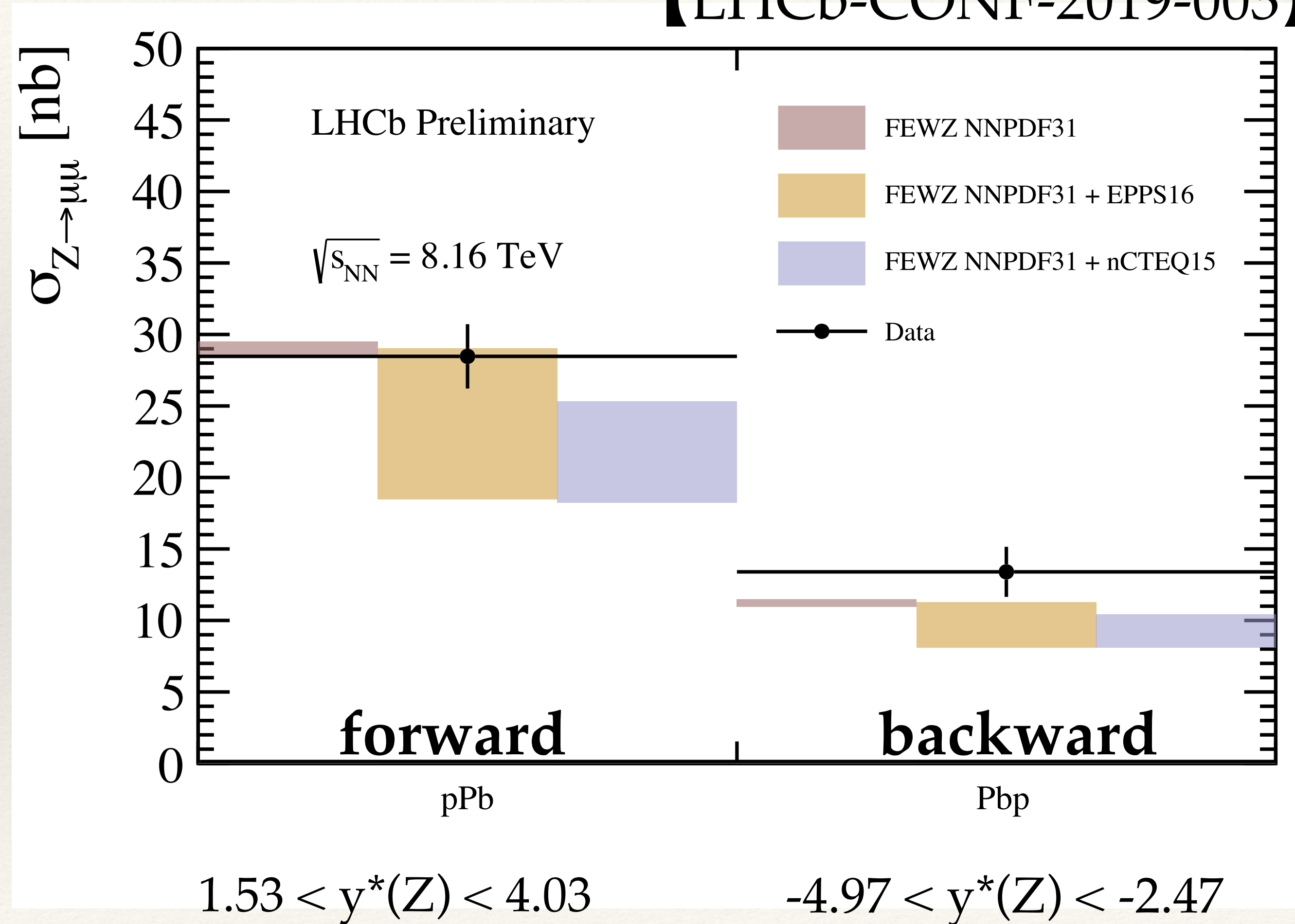
❖ Compatible with theoretical predictions using FEWZ(NNLO pQCD+NLO pEW) with NNPDF3.1(PDF) for p and

❖ NNPDF3.1(PDF)

❖ EPPS16 (nPDF)

❖ nCTEQ15 (nPDF)

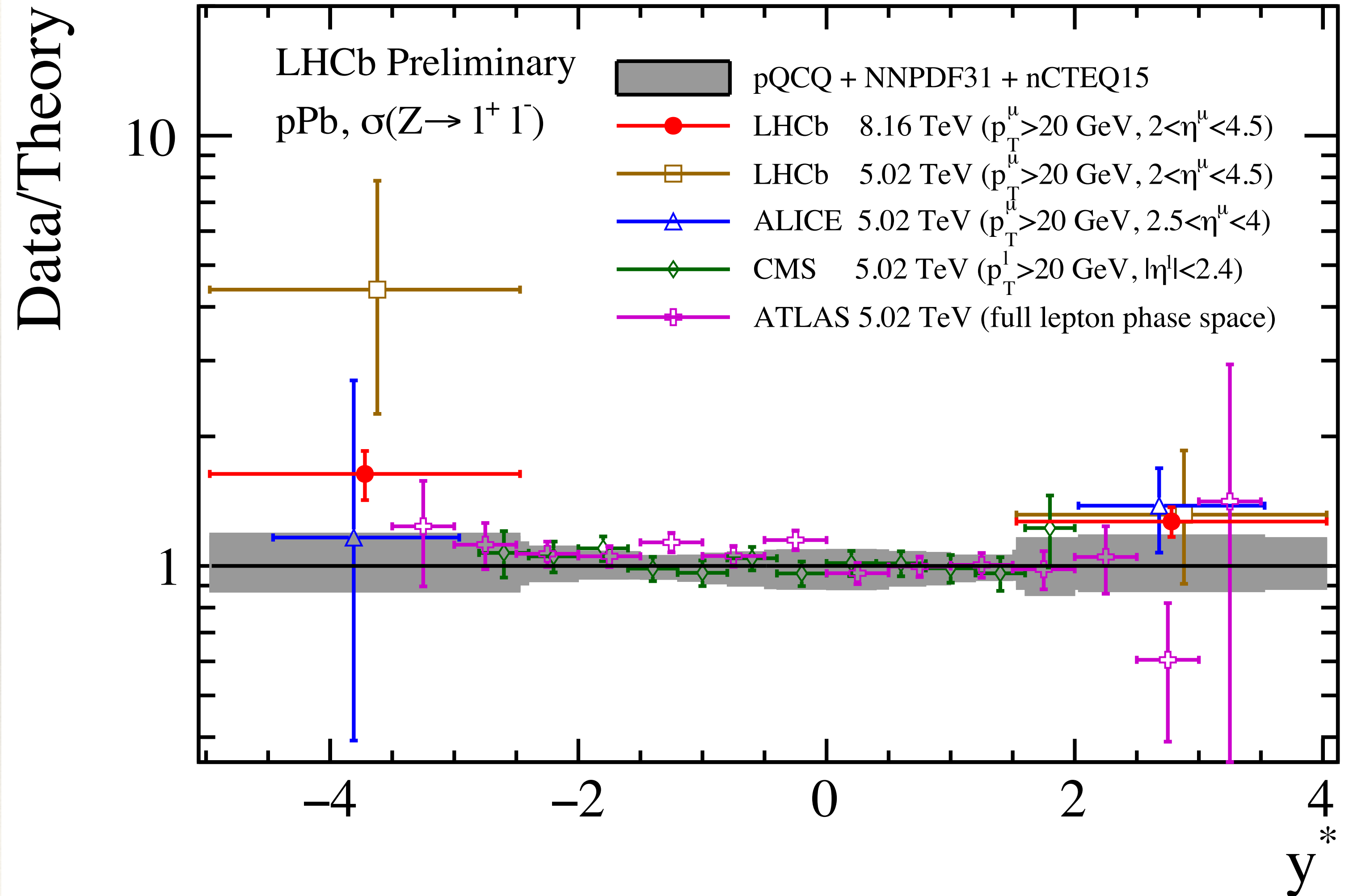
} for Pb



Compare with results at 5 TeV

【LHCb-CONF-2019-003】

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



* 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:

$$\sigma_{Z \rightarrow \mu^+ \mu^-, p \text{ Pb}}^{2.5 < |y^*| < 4.0} = 17.1 \pm 1.4(\text{stat.}) \pm 0.7(\text{syst.}) \pm 0.4(\text{lumi.}) \text{ nb},$$

$$\sigma_{Z \rightarrow \mu^+ \mu^-, \text{ Pb } p}^{2.5 < |y^*| < 4.0} = 13.3 \pm 1.0(\text{stat.}) \pm 1.4(\text{syst.}) \pm 0.3(\text{lumi.}) \text{ nb},$$

- ❖ Measured forward-backward ratio

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

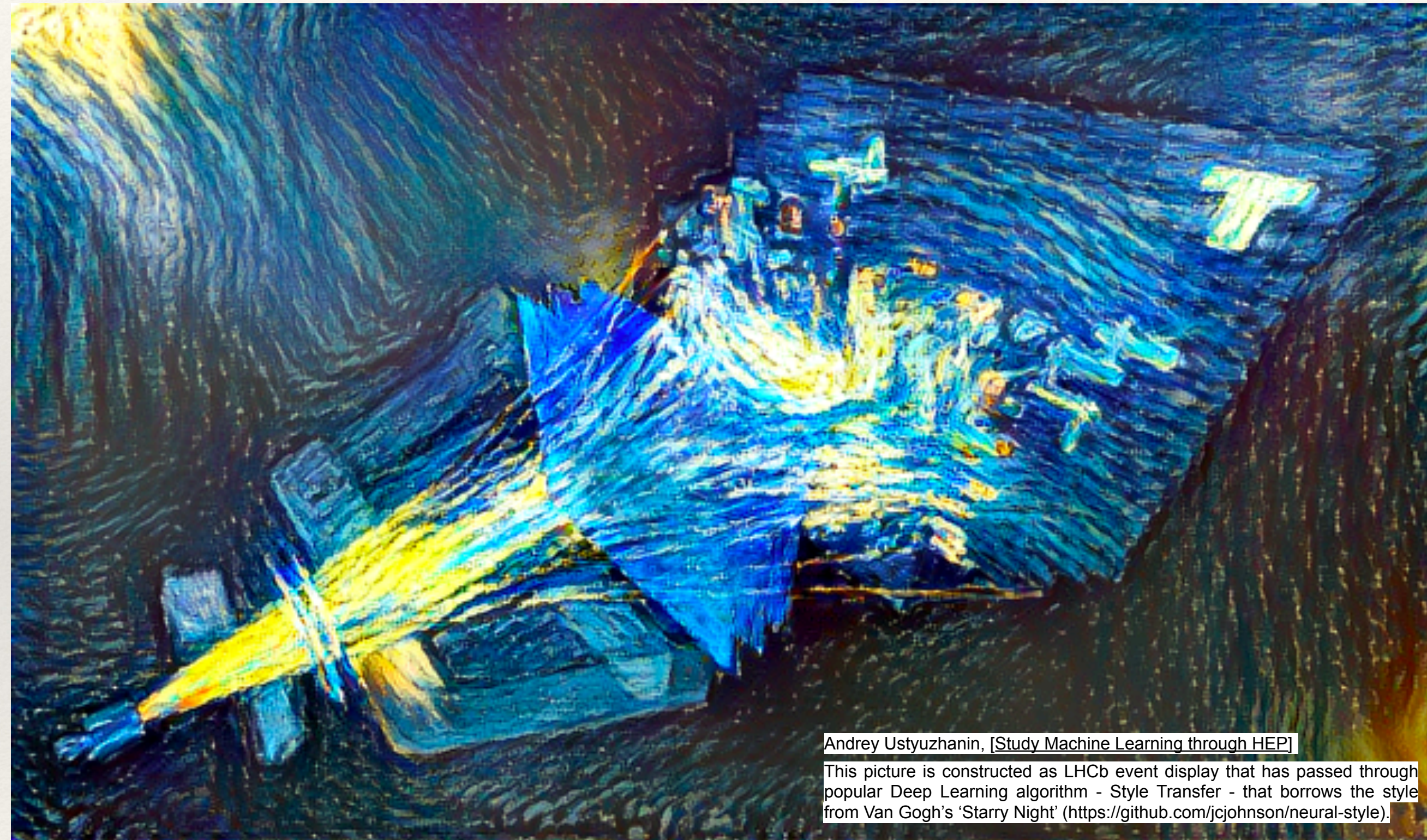
- ❖ Compatible with theoretical predictions:

$$R_{\text{FB,NNPDF3.1}}^{2.5 < |y^*| < 4.0} = 1.59 \pm 0.10(\text{theo.}) \pm 0.01(\text{num.}) \pm 0.05(\text{PDF}),$$

$$R_{\text{FB,NNPDF3.1+EPS16}}^{2.5 < |y^*| < 4.0} = 1.45 \pm 0.10(\text{theo.}) \pm 0.01(\text{num.}) \pm 0.27(\text{PDF}),$$

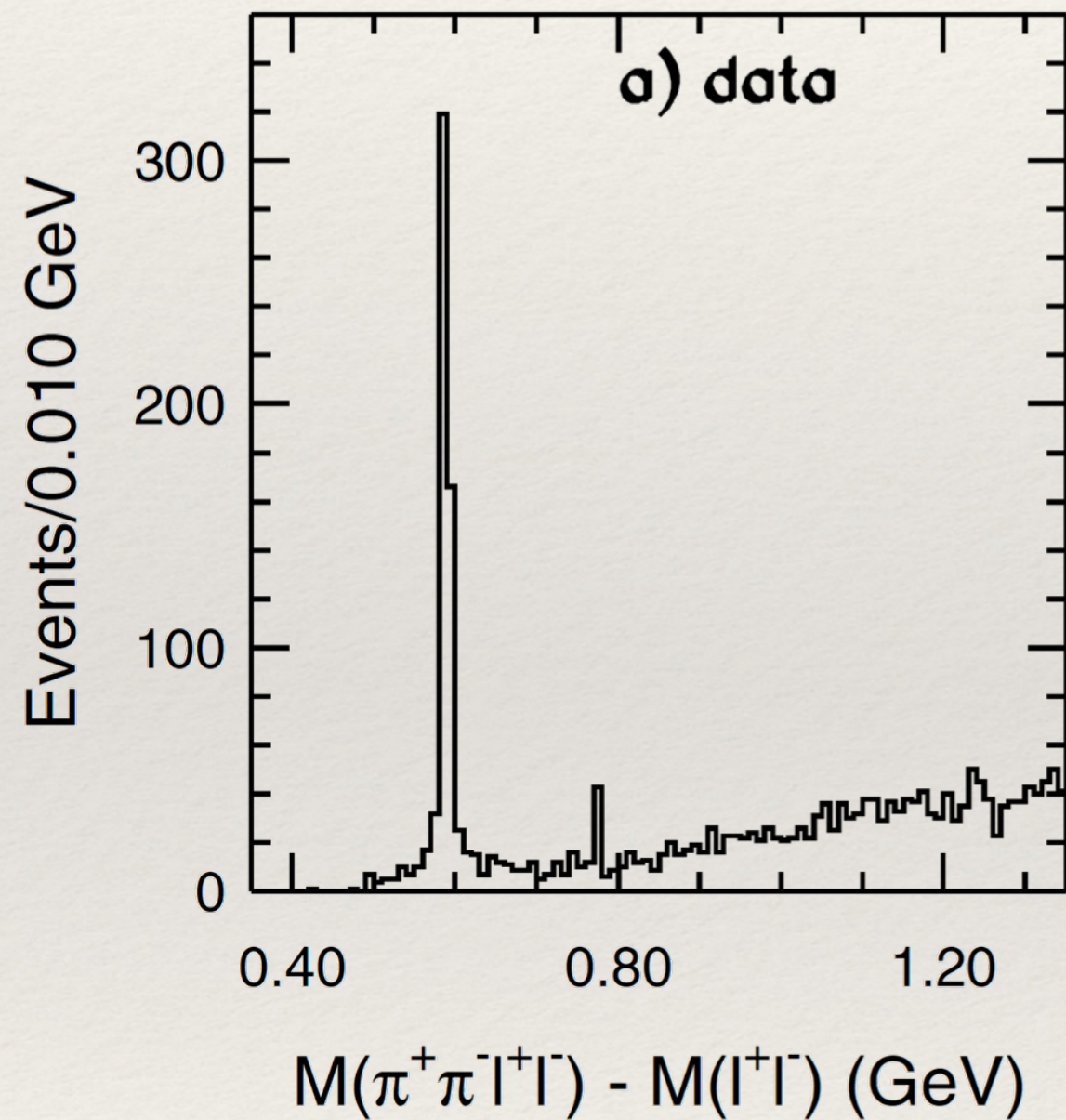
$$R_{\text{FB,NNPDF3.1+nCTEQ15}}^{2.5 < |y^*| < 4.0} = 1.44 \pm 0.10(\text{theo.}) \pm 0.01(\text{num.}) \pm 0.20(\text{PDF}).$$

Understanding the nature of the $X(3872)$

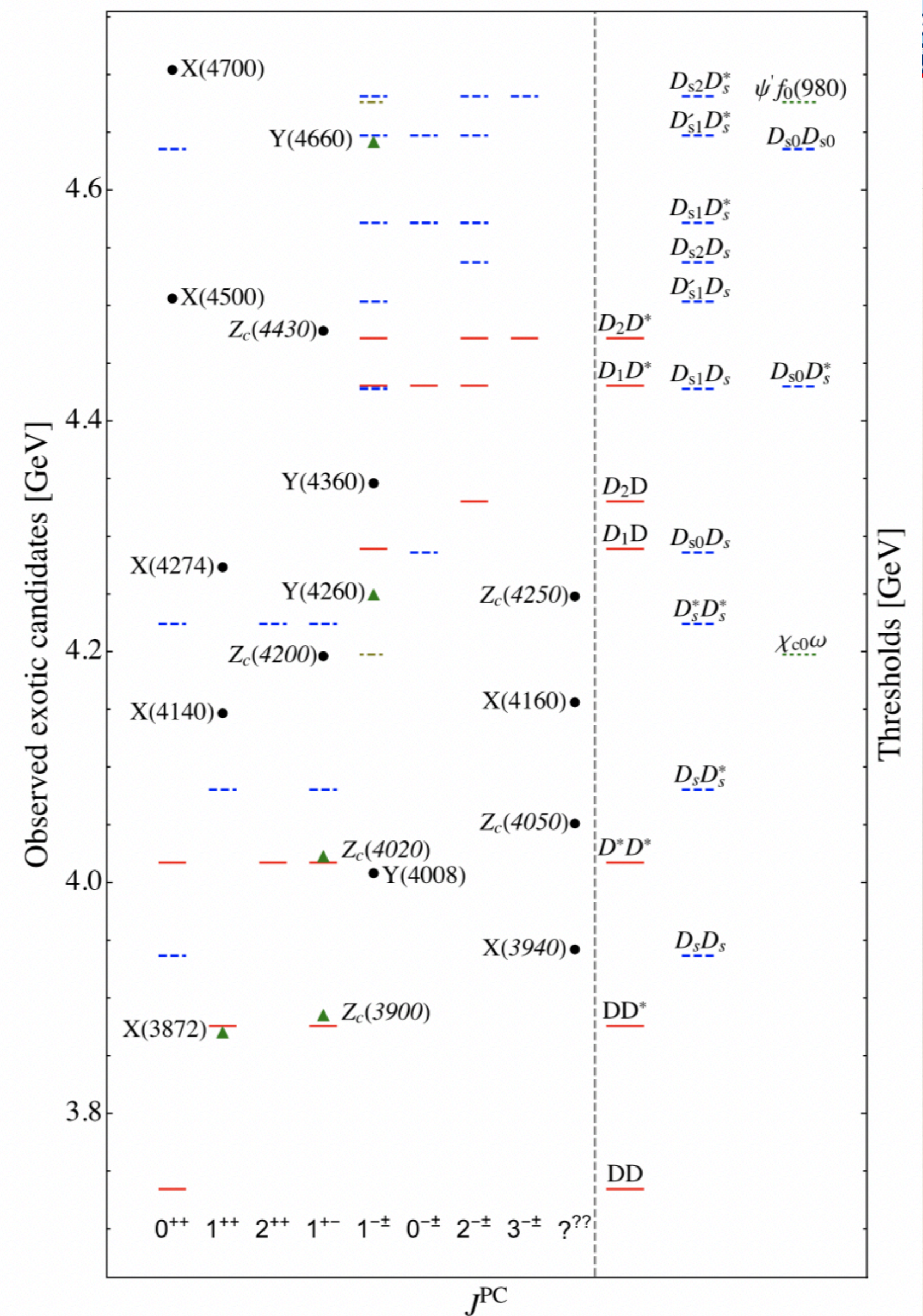


The story started in 2003

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]

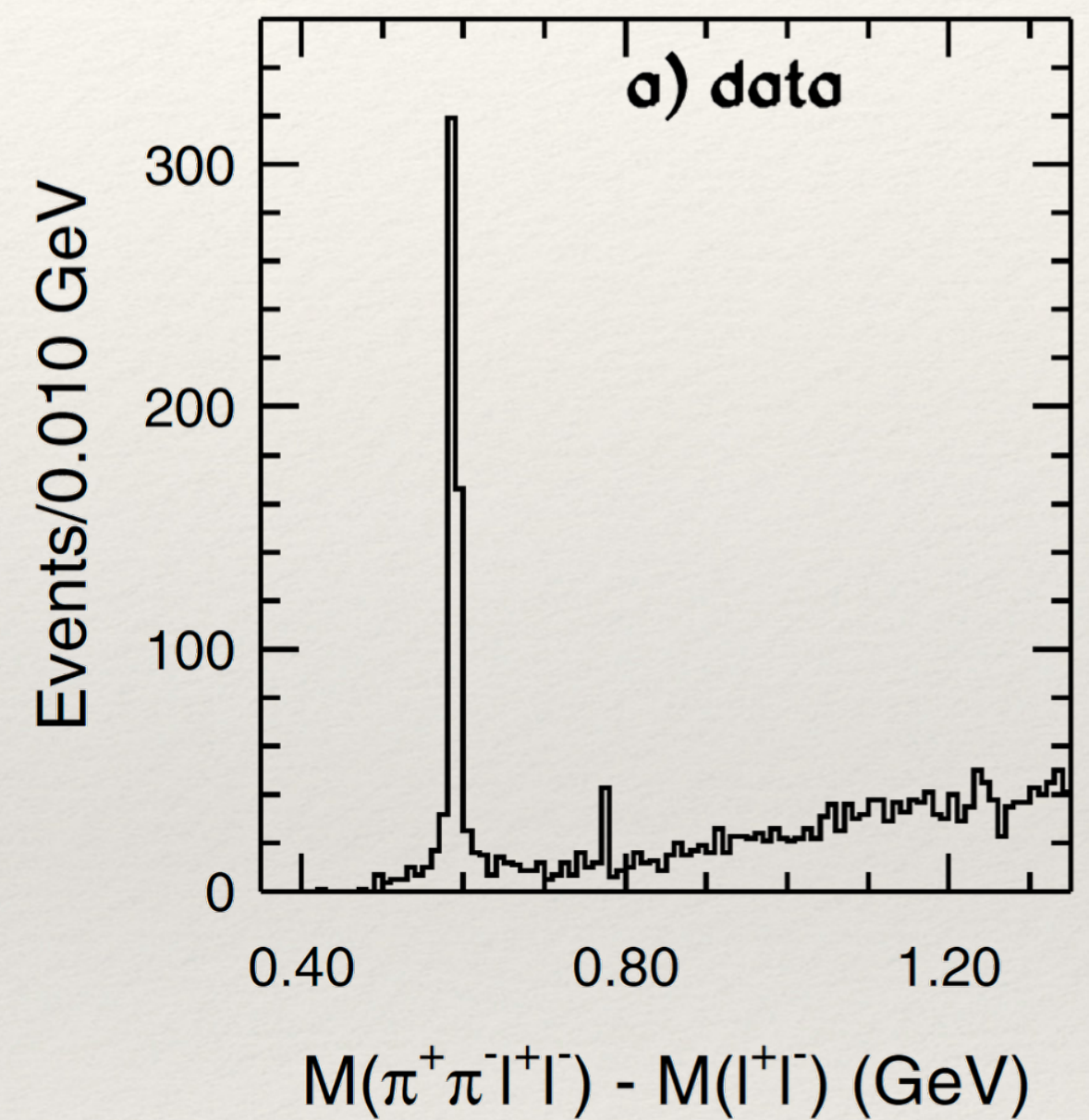
- ❖ $J^{PC} = 1^{++}$

- ❖ Mass is consistent with sum of D^0 and \bar{D}^{*0} masses:

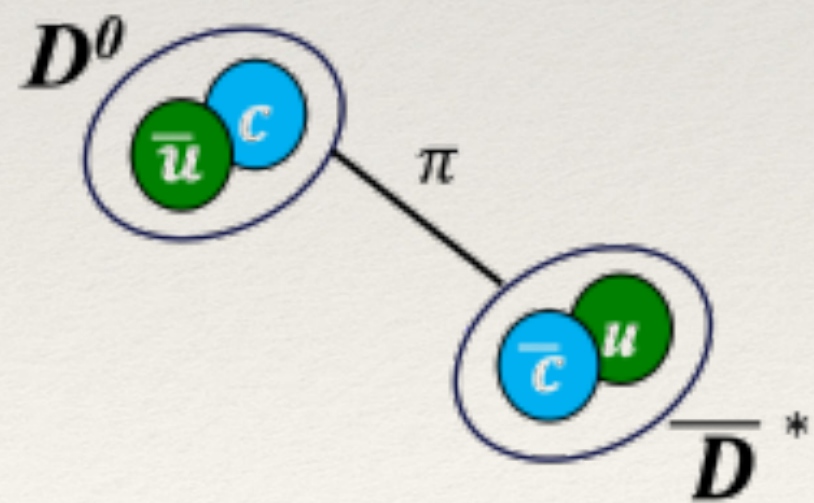
$$M_{\chi_{c1}(3872)} - (M_{D^0} + M_{\bar{D}^{*0}}) = 0.01 \pm 0.27 \text{ MeV}$$

PDG 2019 has changed the naming X(3872) to $\chi_{c1}(3872)$

Belle Collaboration
PRL 91 262001 (2003)

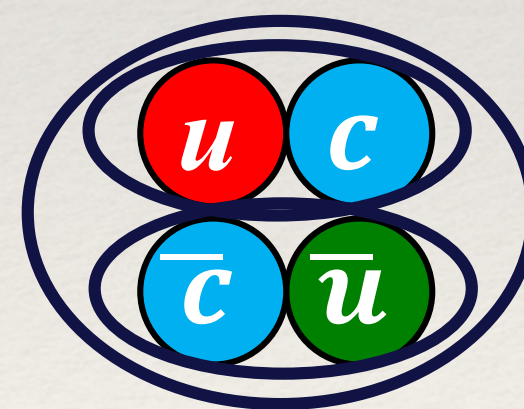


$D^0 \bar{D}^{*0}$ Molecule



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

Compact tetraquark



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

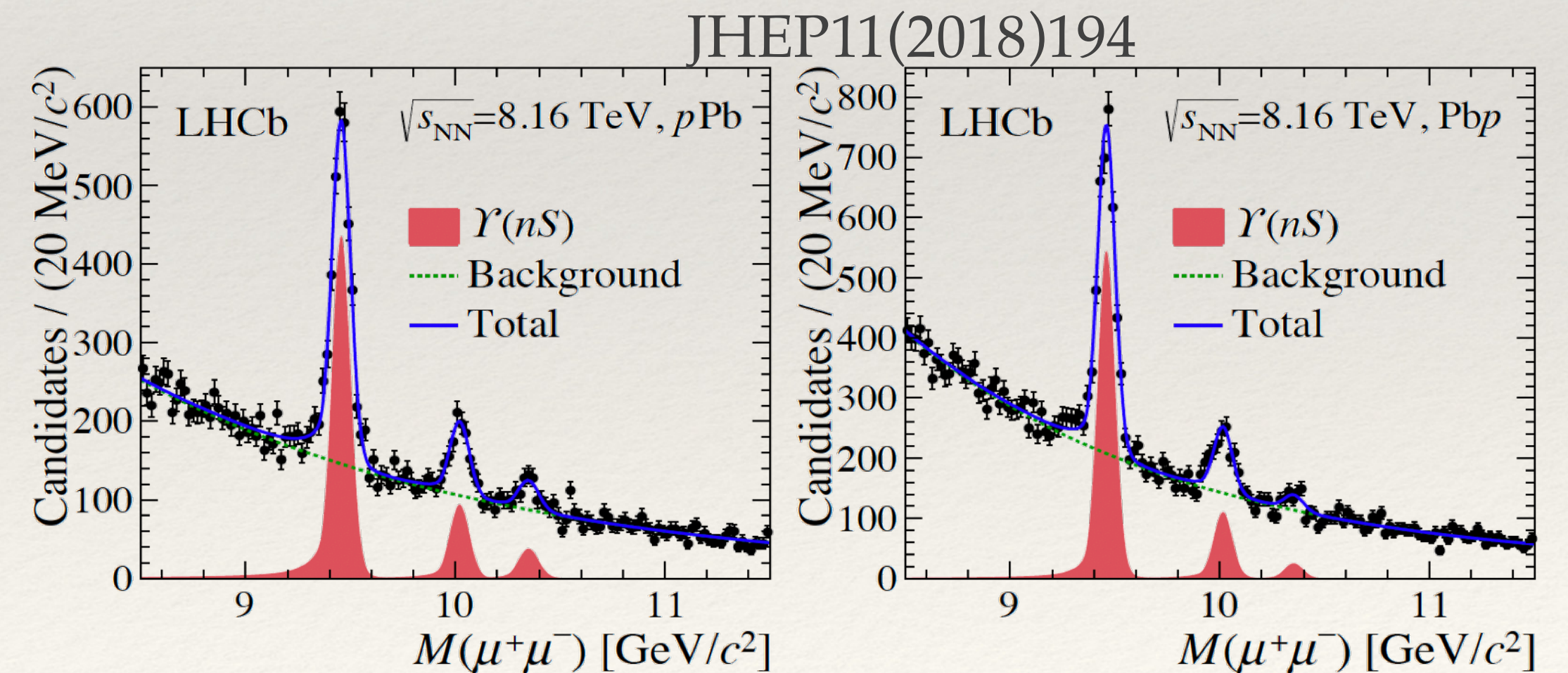
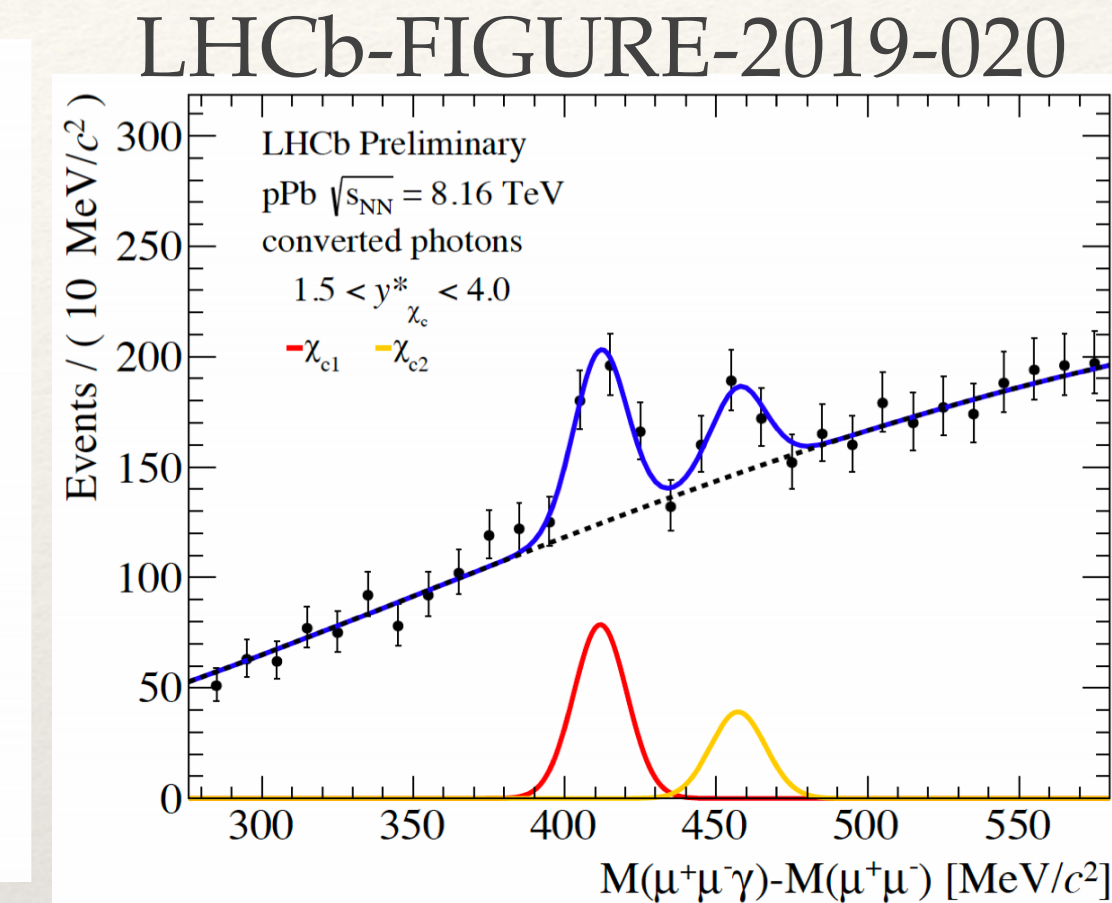
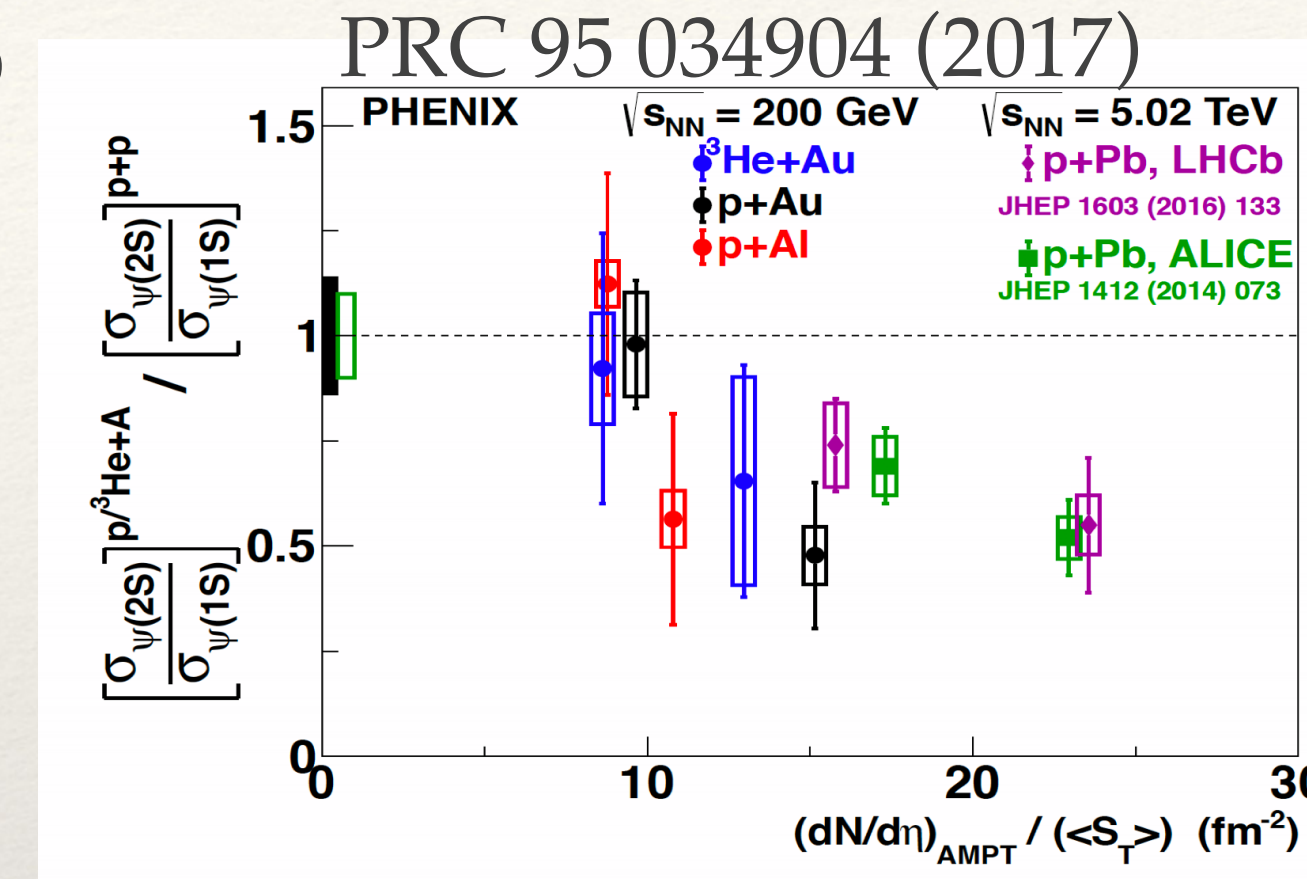
Effects of binding energy learned from pA collisions

- 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

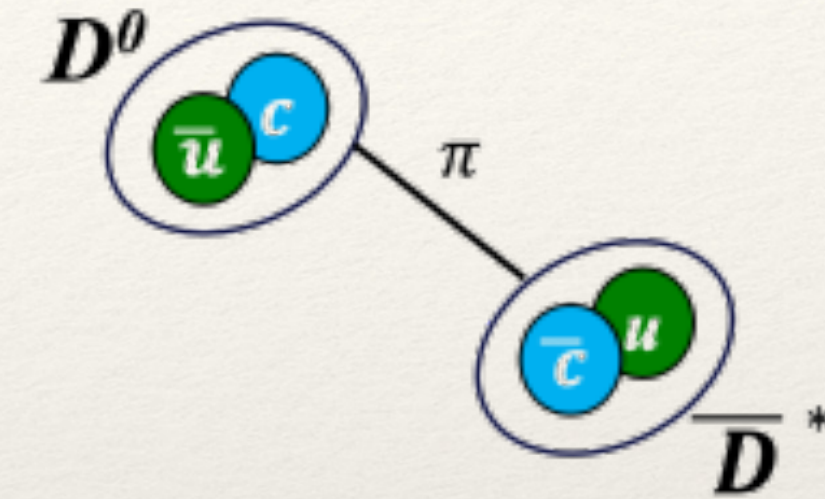
- Suppression of weakly-bound quarkonia states has been studied for decades in pA collisions
- Ratios of $[\psi(2S)]/[J/\psi]$ and $[\Upsilon(2S,3S)]/[\Upsilon(1S)]$
- Suppression is generally explained with final state effects: regions with high particle multiplicities



Apply the binding energy understanding to pp

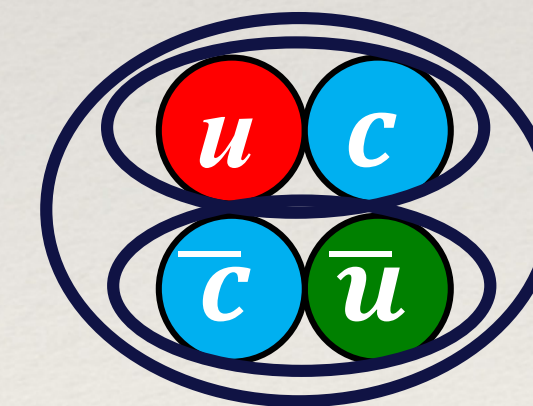
- ❖ Strength of the binding energy could be a key point to understand the nature of the exotic state
- ❖ Suppression of weakly-bound quarkonia states has been studied for decades in pA collisions
- ❖ Suppression is generally explained with final state effects: regions with high particle multiplicities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

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



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

Compact tetraquark



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

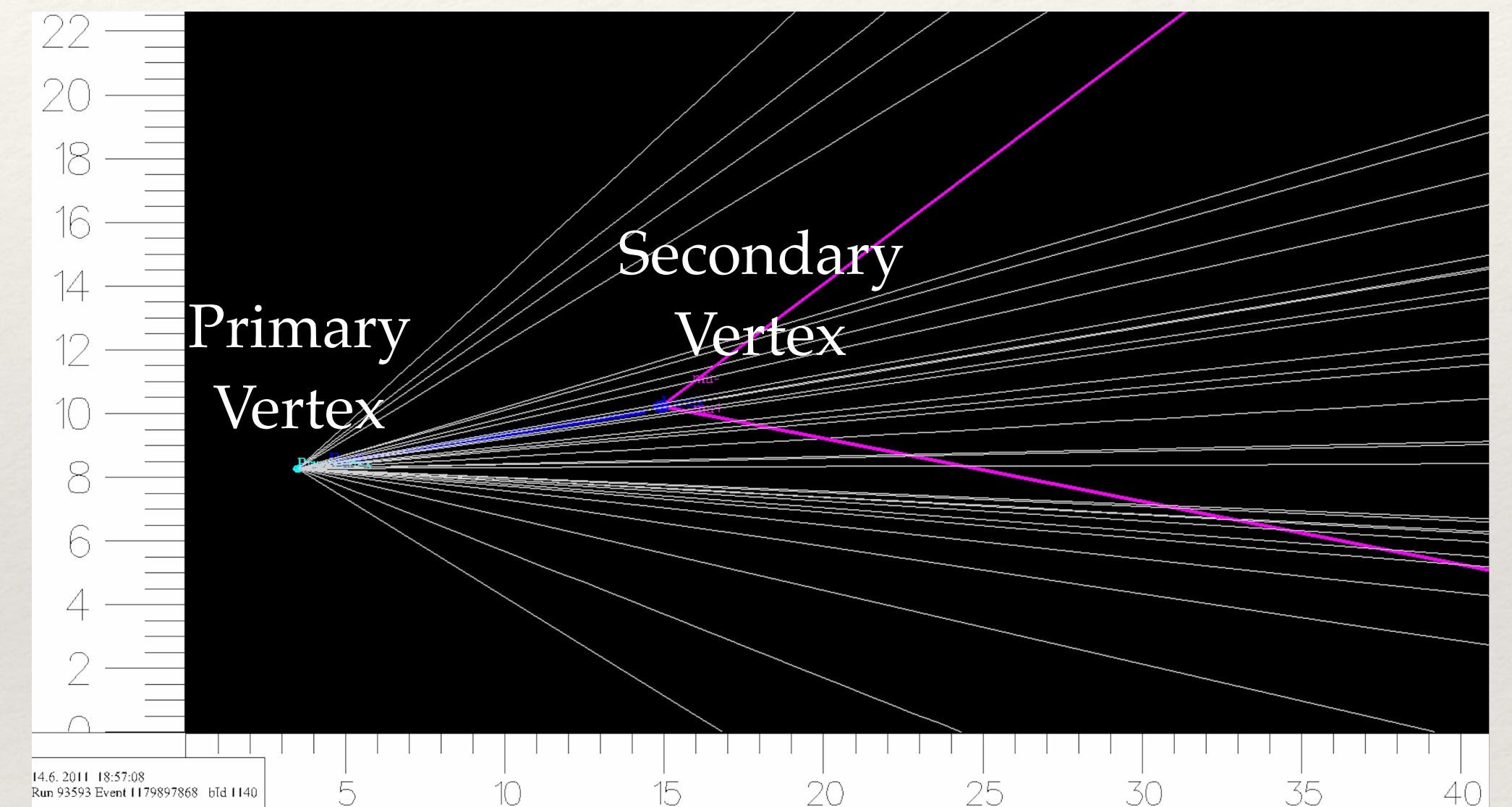
$D \bar{D}^*$ Molecule

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

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



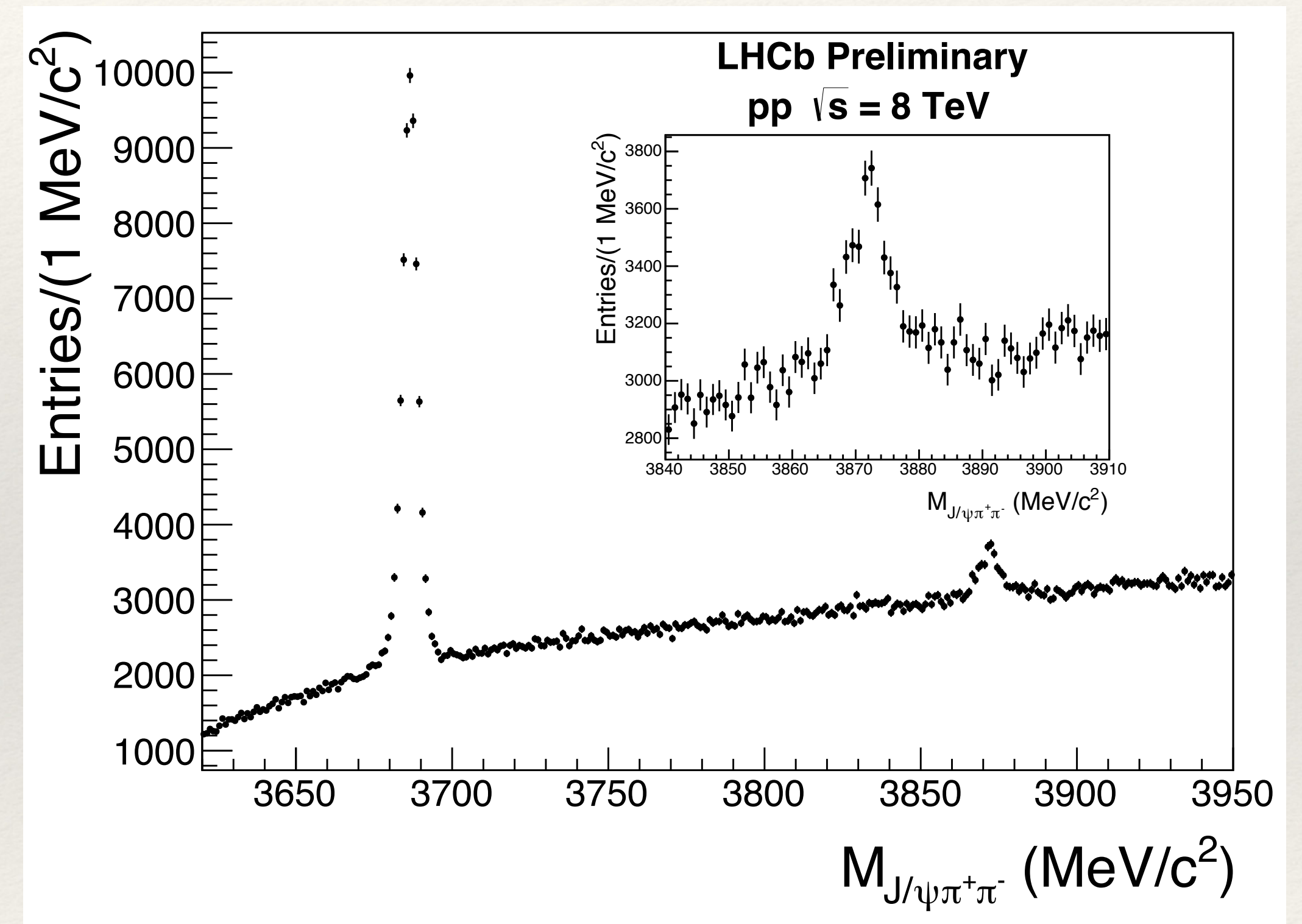
Event display of $B_s^0 \rightarrow \mu^+ \mu^-$ candidate,
PRL 118 191801 (2017)

Selection of $X(3872)$

LHCb-CONF-2019-005

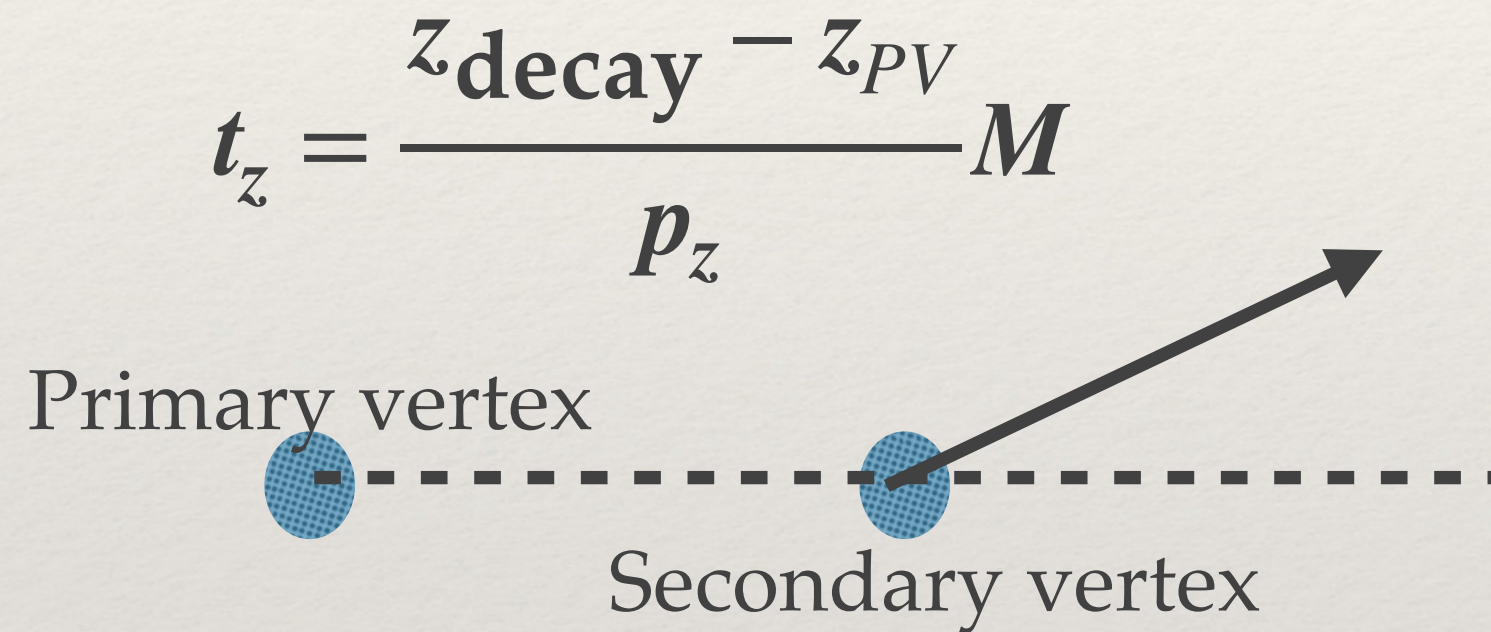
- ❖ LHCb pp collisions at 8 TeV
- ❖ Reconstruct the $X(3872)$ and $\psi(2S)$ from $\mu^+\mu^-\pi^+\pi^-$ final states:
 $X(3872) \rightarrow J/\psi (\rightarrow \mu^+\mu^-) \rho (\rightarrow \pi^+\pi^-)$
 $\psi(2S) \rightarrow J/\psi (\rightarrow \mu^+\mu^-) \pi^+\pi^-$
- ❖ Select J/ψ from dimuons, combine 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 $\psi(2S)$ and exotic $X(3872)$ via ratio of cross sections:

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



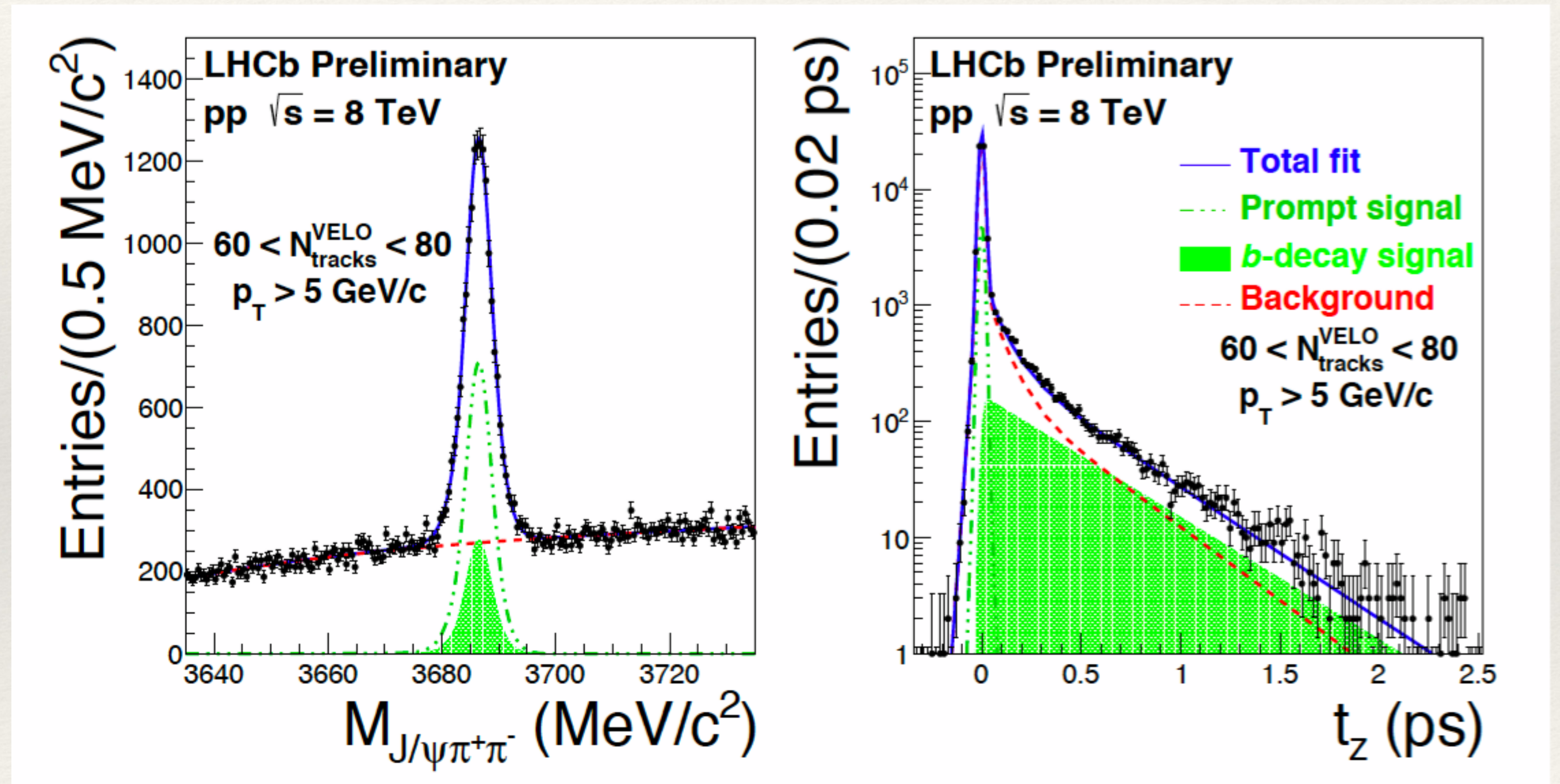
Prompt / b-decay separation

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



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

LHCb-CONF-2019-005



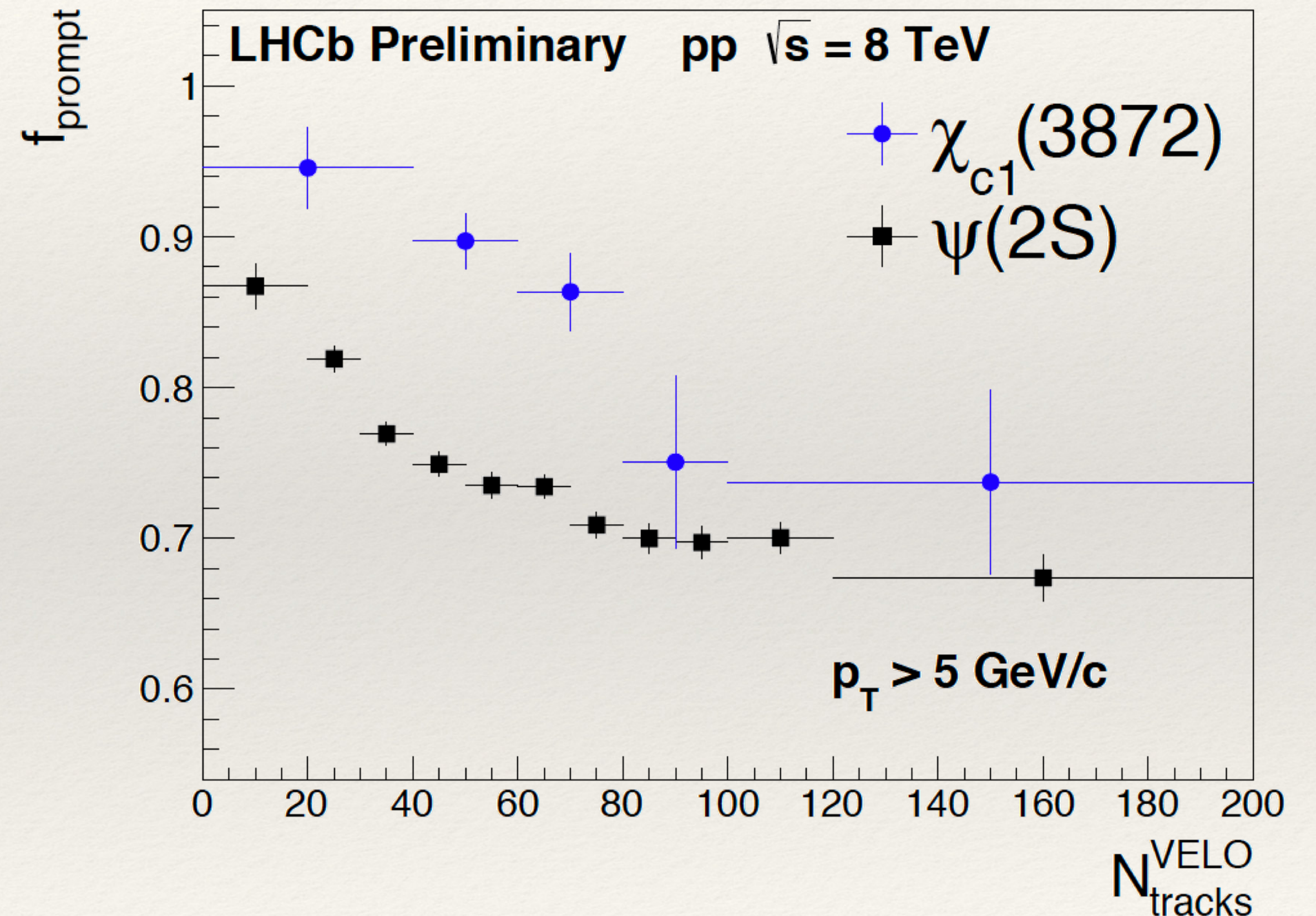
Prompt fraction

- ❖ Prompt fraction

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

- ❖ 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.

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Ratio of the cross-sections

❖ **Ratio of cross-sections:**

$$\frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}[\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-]}{\mathcal{B}[\psi(2S) \rightarrow J/\psi \pi^+ \pi^-]} = \frac{N_{\chi_{c1}(3872)} f_{\text{prompt}}^{\chi_{c1}(3872)}}{N_{\psi(2S)} f_{\text{prompt}}^{\psi(2S)}} \times \frac{\epsilon_{\psi(2S)}}{\epsilon_{\chi_{c1}(3872)}}$$

❖ **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):**

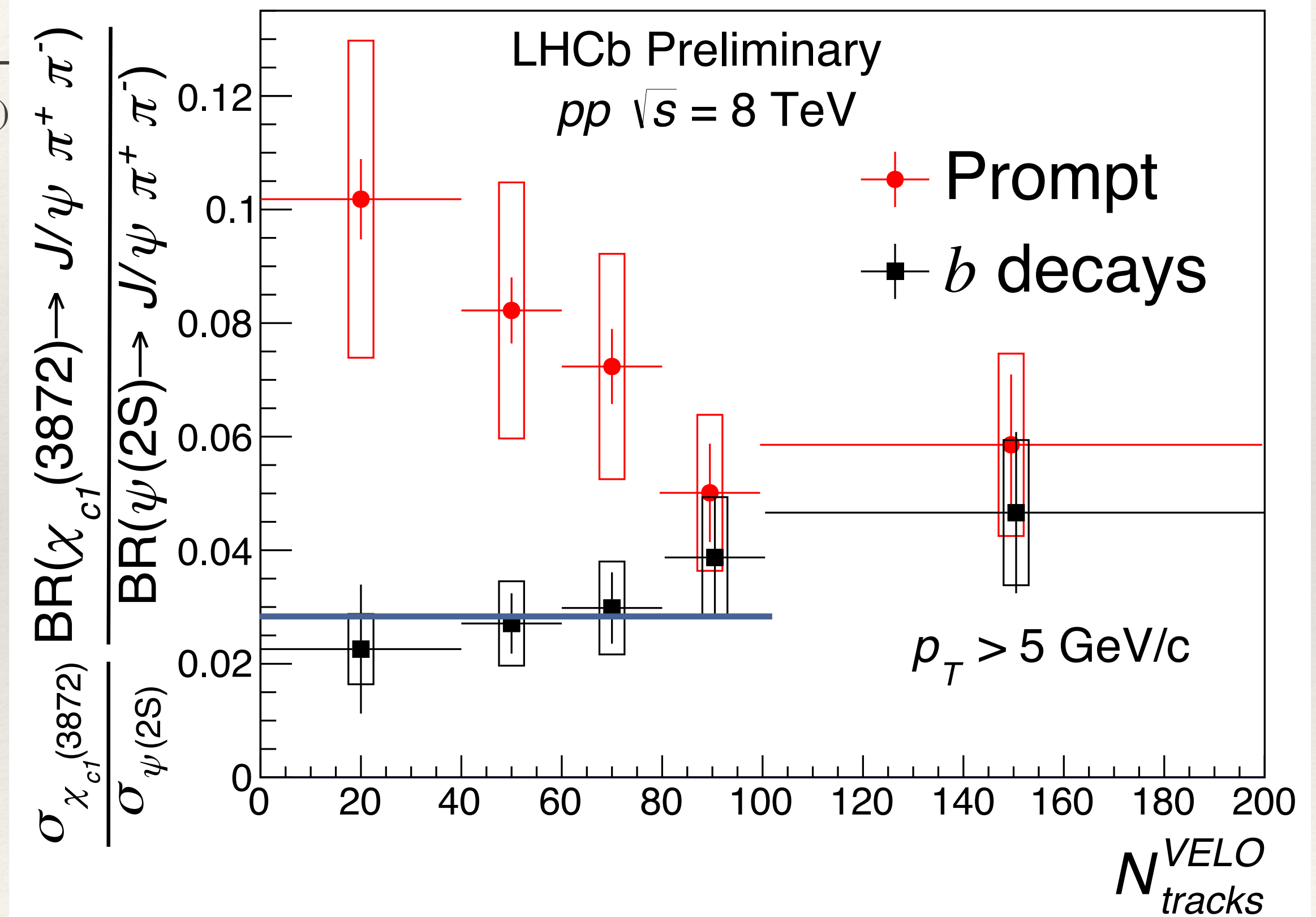
❖ No significant change in relative production, as expected for decays in vacuum (compatible with a straight line).

❖ Ratio is set by decay branching fractions of b and X(3872).

❖ The average ratio agrees with ATLAS measurement

❖ $R = 0.0395 \pm 0.0032 \pm 0.0008$ ($p_T > 10 \text{ GeV}$) [JHEP 2017:117 (2017)]

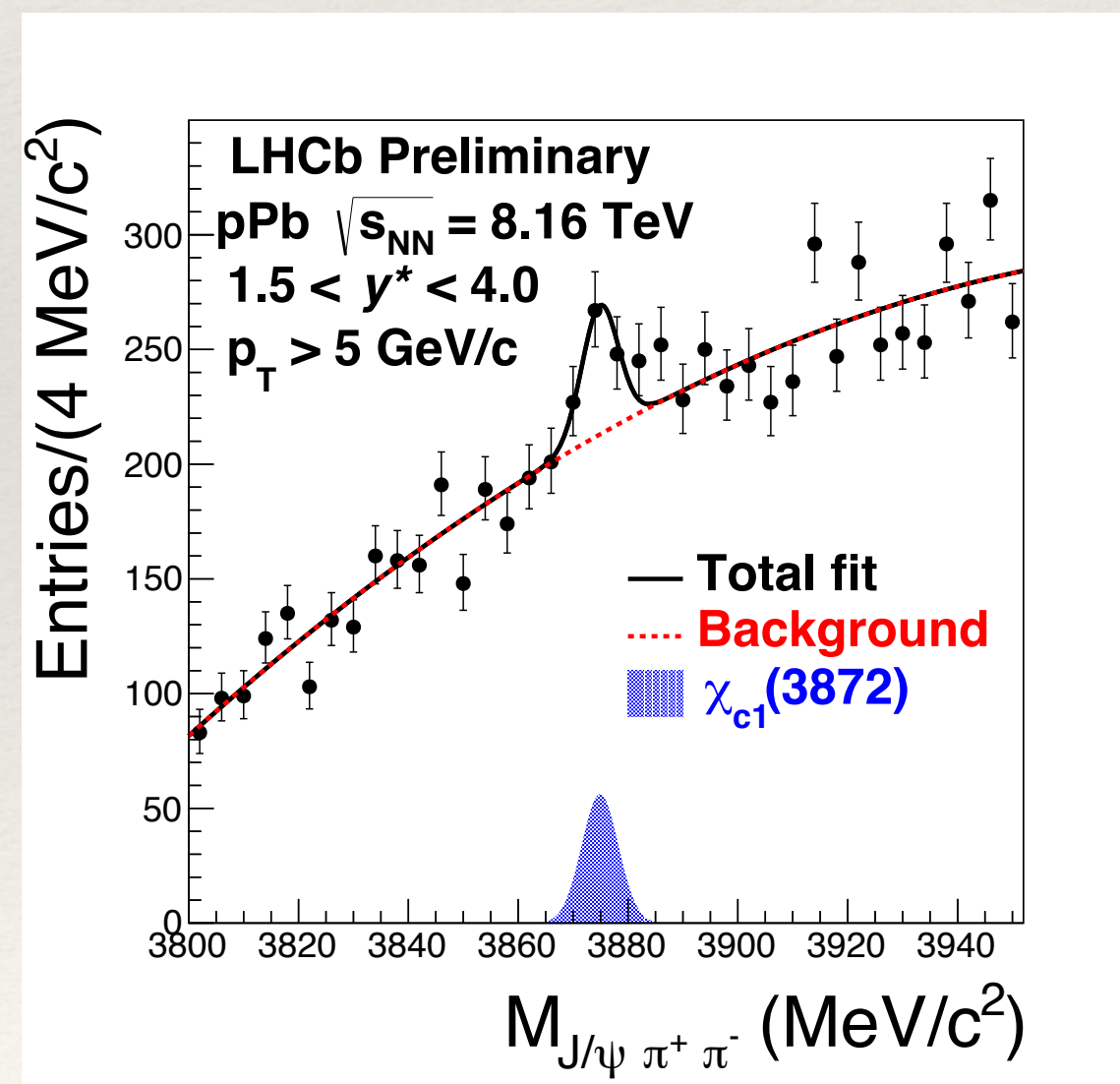
LHCb-CONF-2019-005



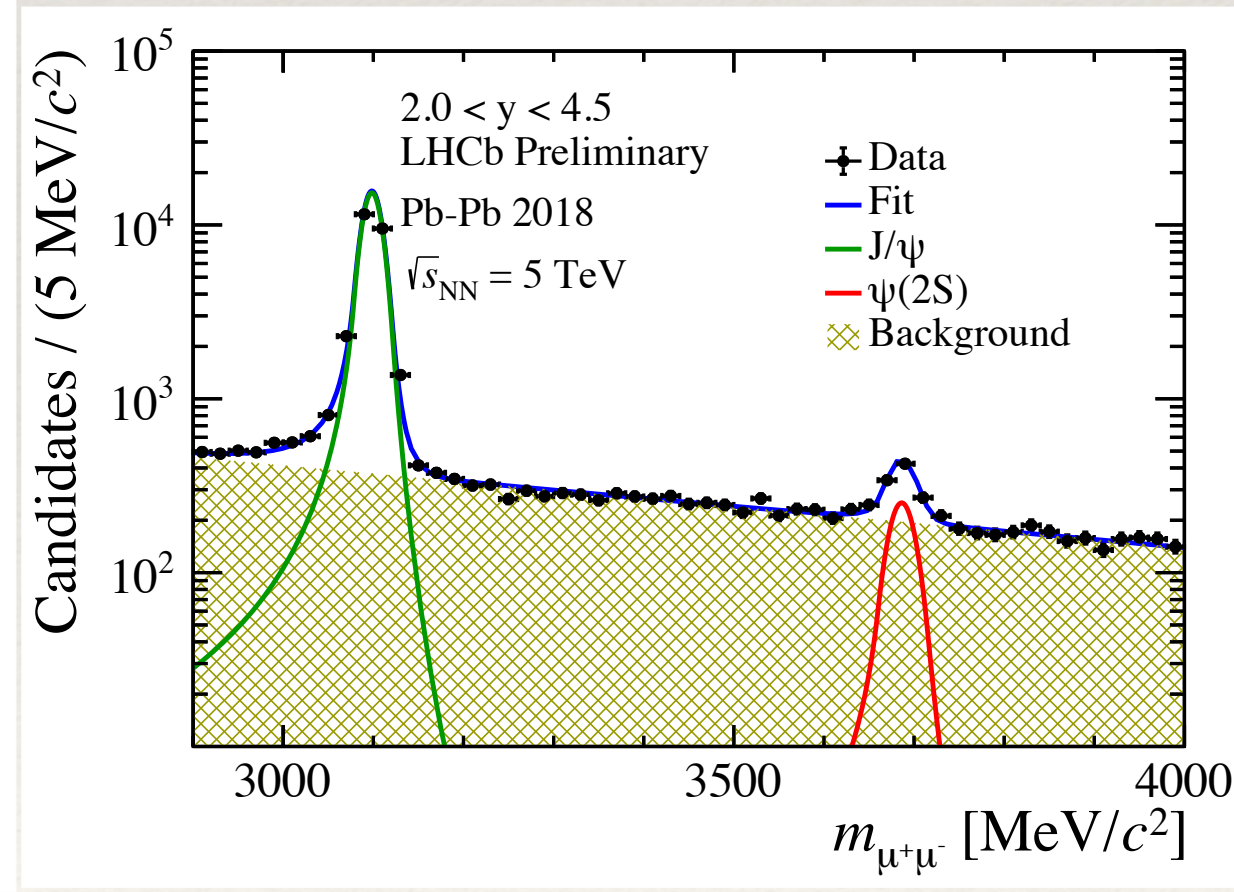
Outlook

- ❖ 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>

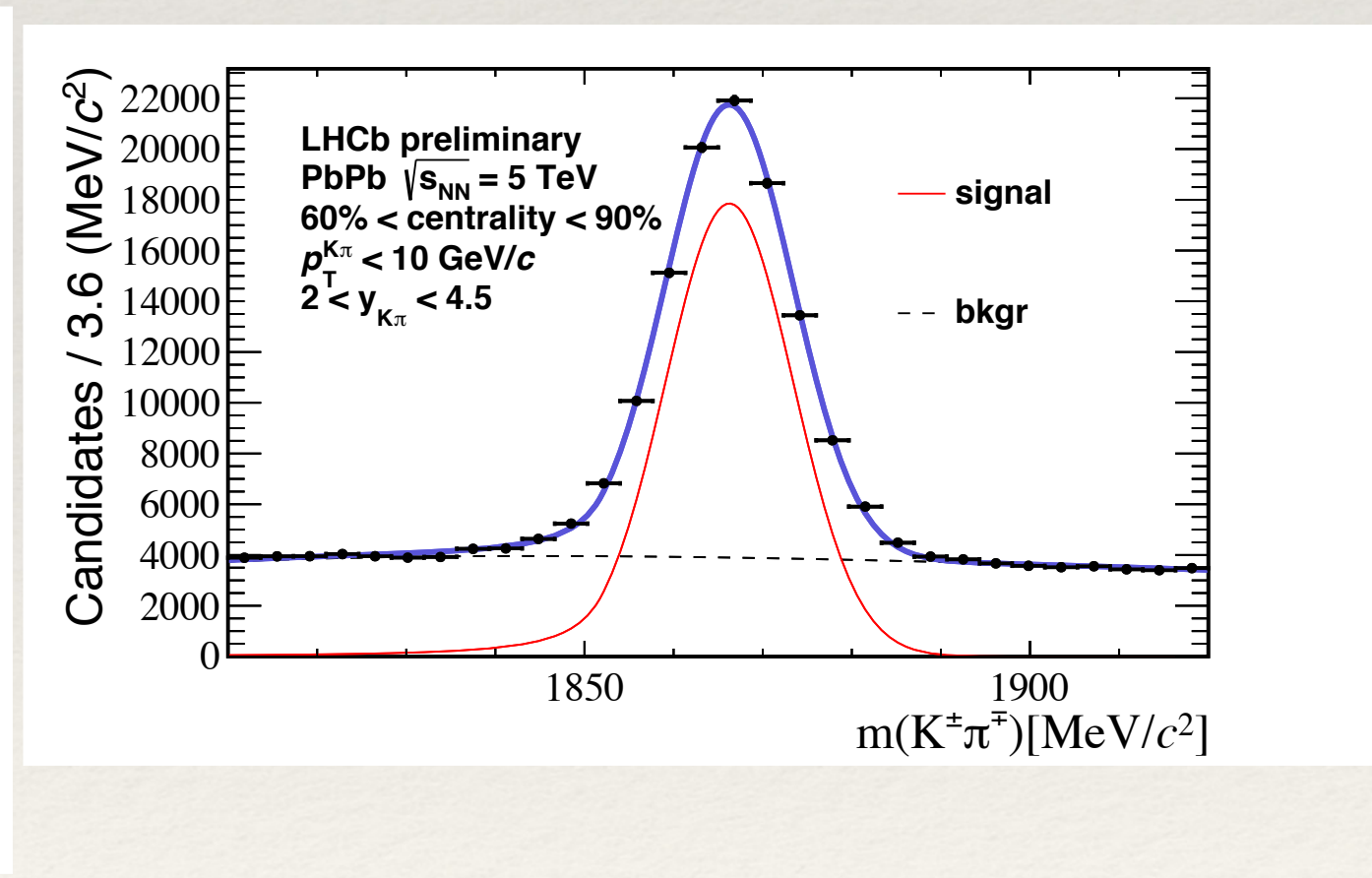
X(3872) in pPb



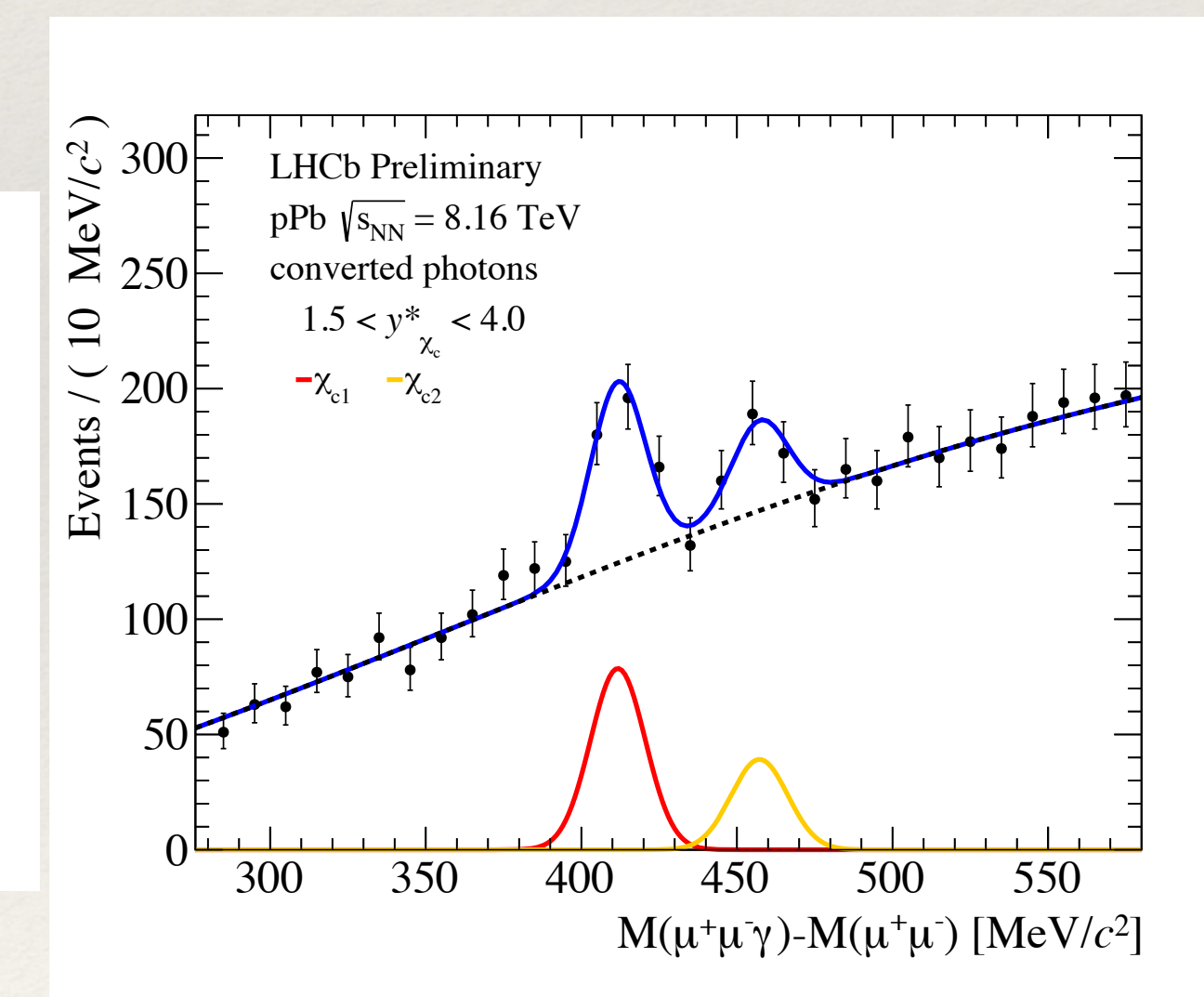
J/ ψ and $\psi(2S)$ in 2018
PbPb UPC



Open charm in 2018 PbPb



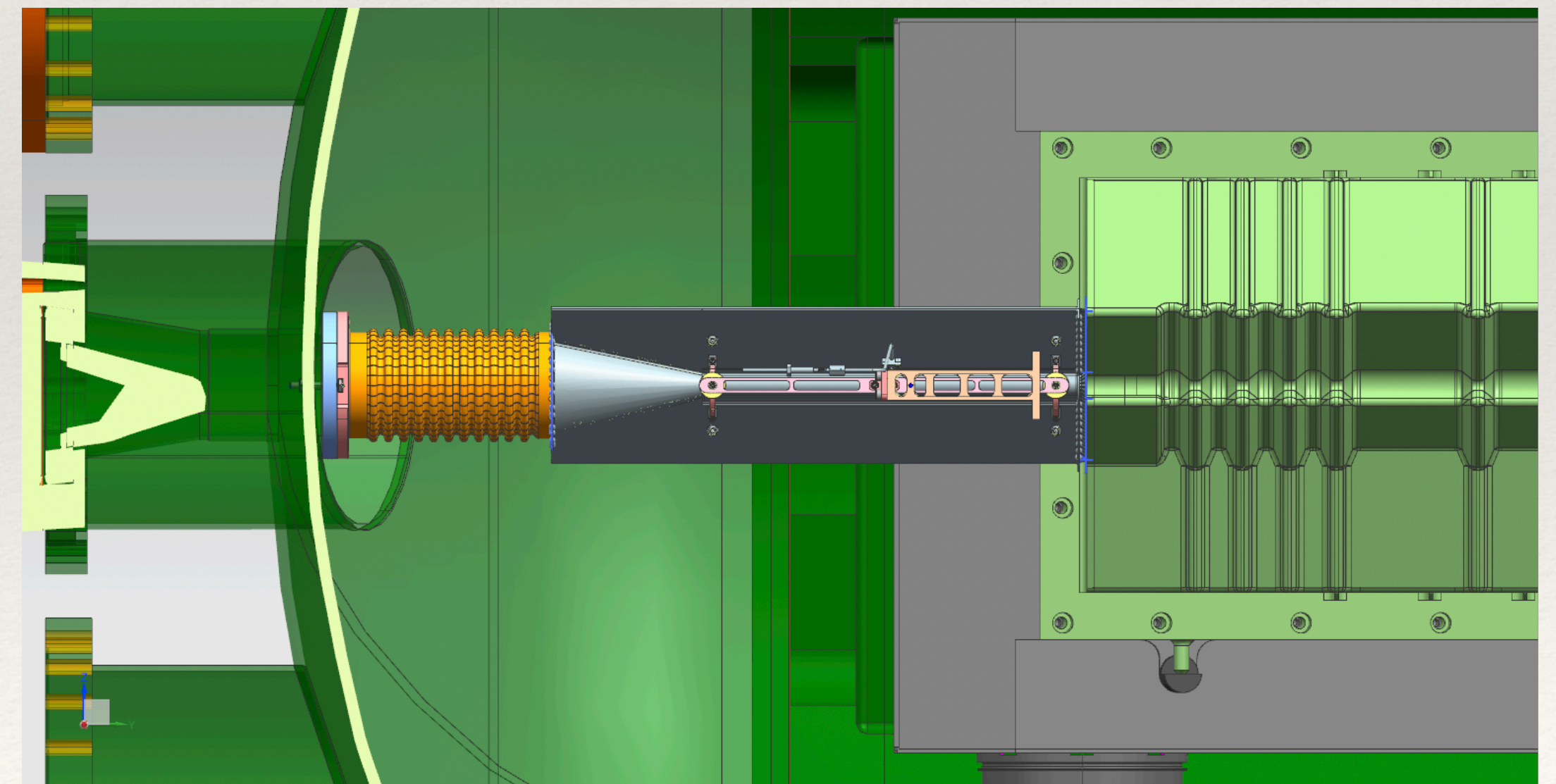
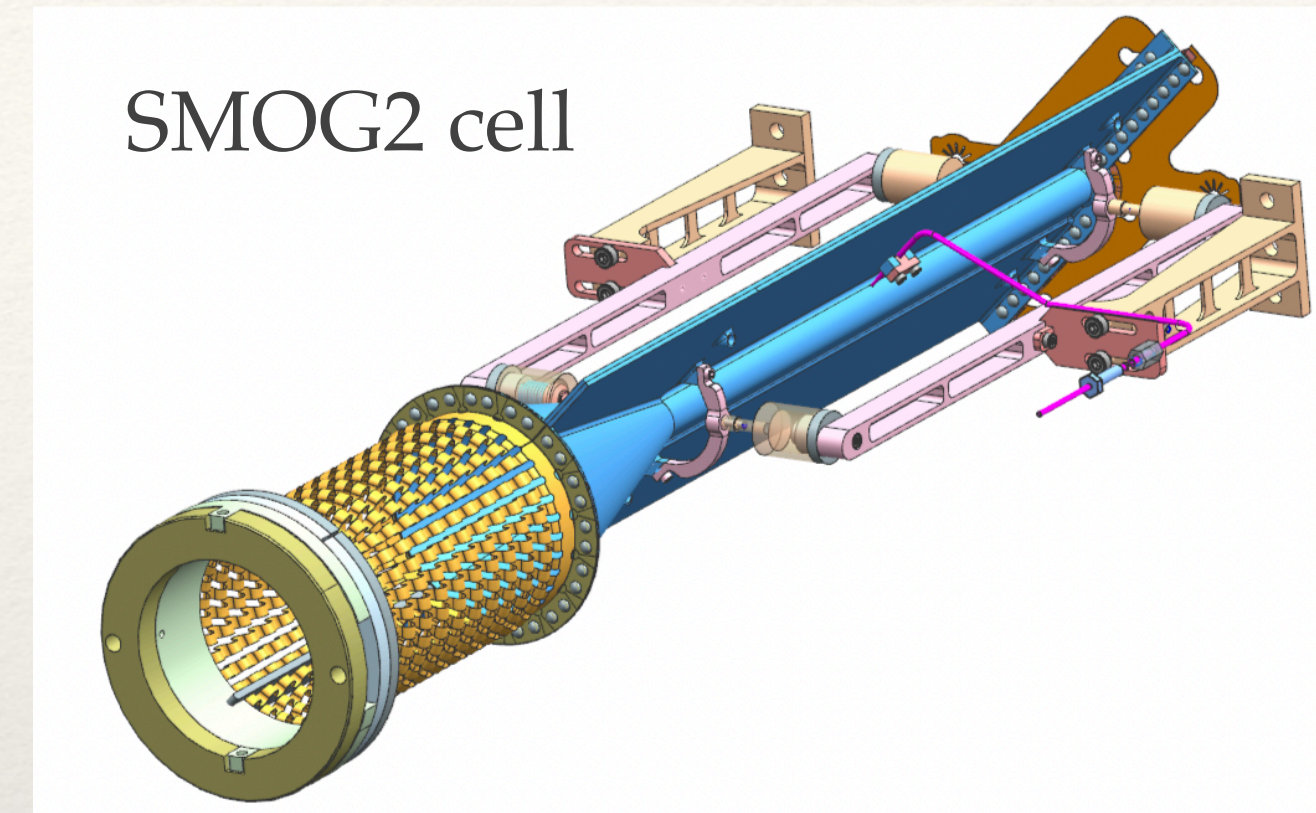
Open charm in 2016 pPb



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.

