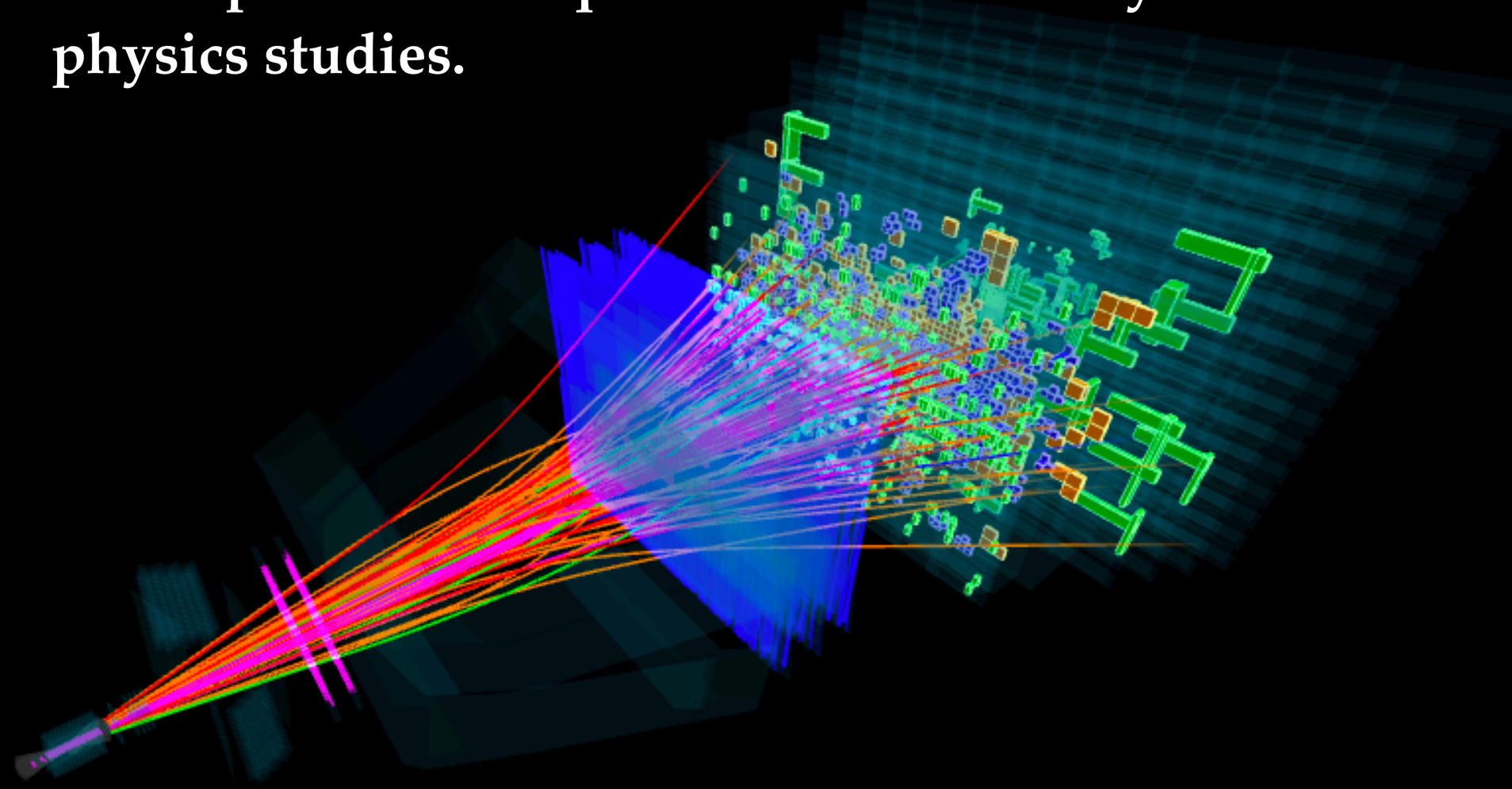
Z production in pPb collisions and charmonium production in Pb-Pb ultra-peripheral collisions (UPC) at LHCb

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

Outline

- **LHCb detector and datasets**
- **Z production in pPb collisions**
- **Charmonium production in PbPb UPC**

LHCb provides unique datasets for Heavy Ion physics studies.



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

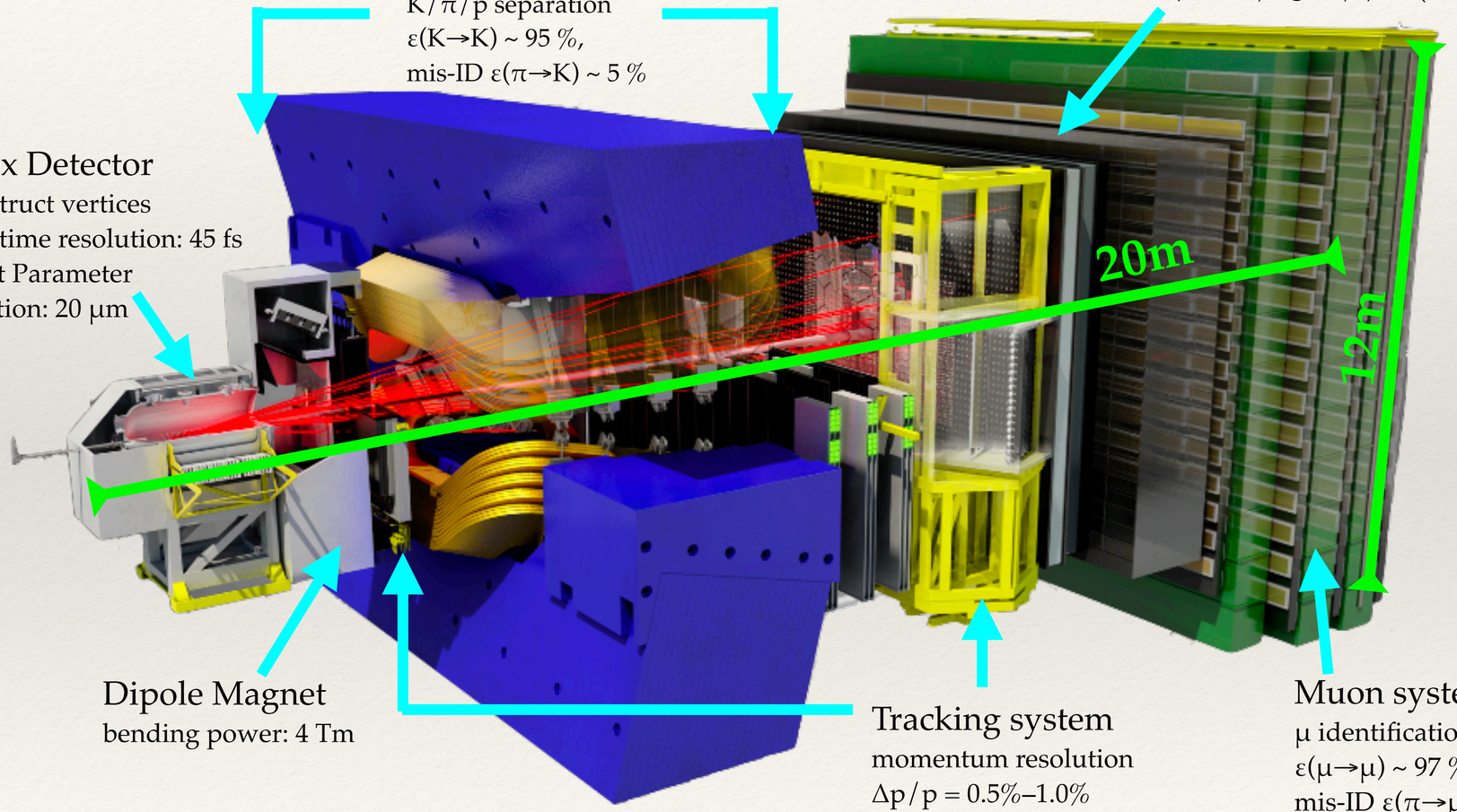
[JINST 3 (2008) S08005]
[IJMPA 30 (2015) 1530022]

The LHCb detector is special

- 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.



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

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

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

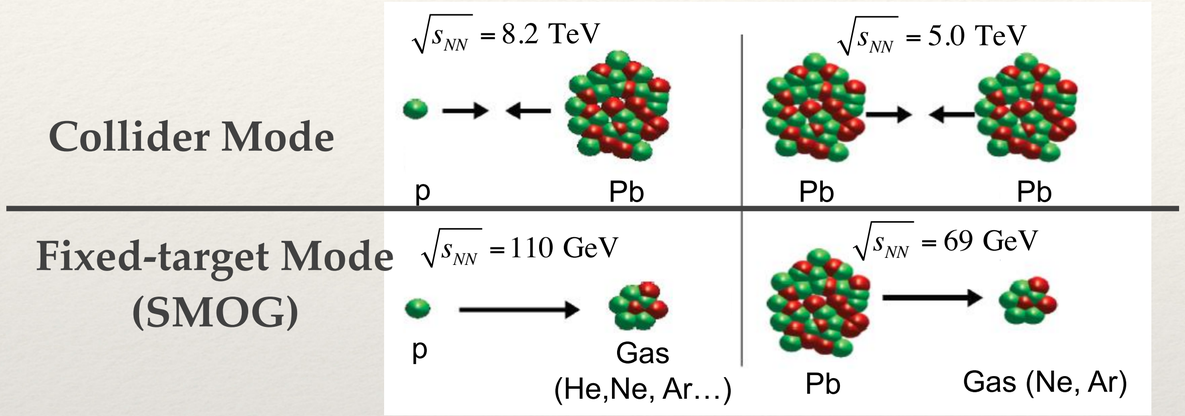
Dipole Magnet
bending power: 4 Tm

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

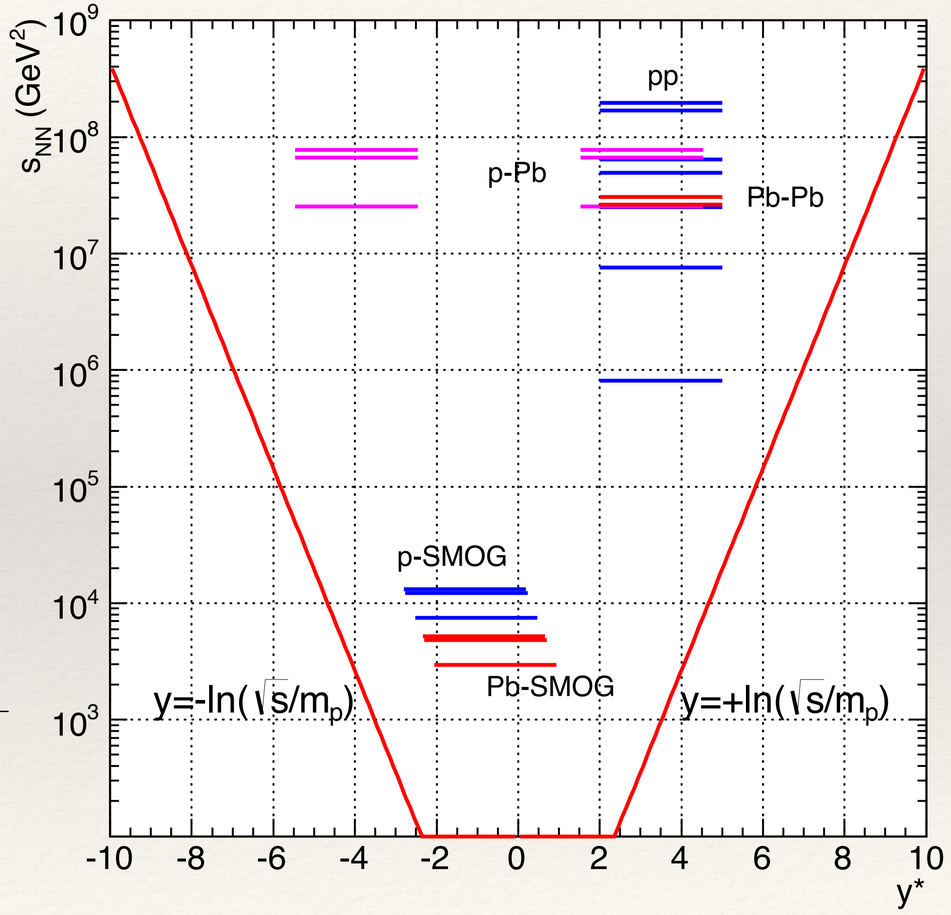
Muon system
μ identification
$\varepsilon(\mu\to\mu) \sim 97\,\%$,
mis-ID $\varepsilon(\pi\to\mu) \sim 1\text{-}3\,\%$

LHCb running modes and kinematic coverage

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



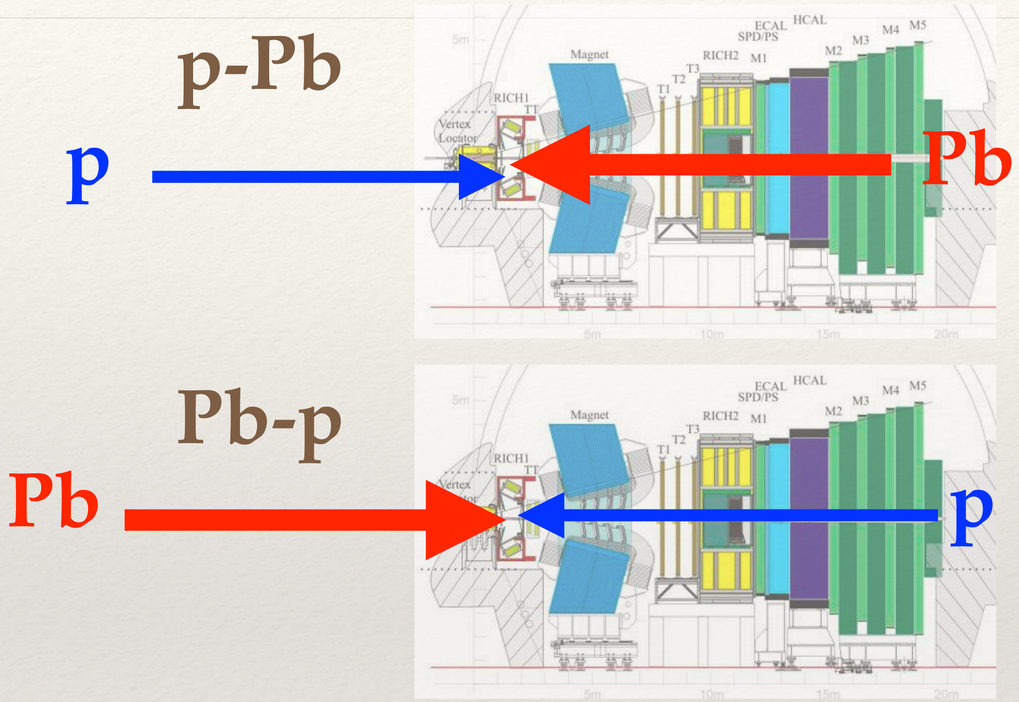
Kinematic Acceptance



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

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

Setups for proton-ion collisions



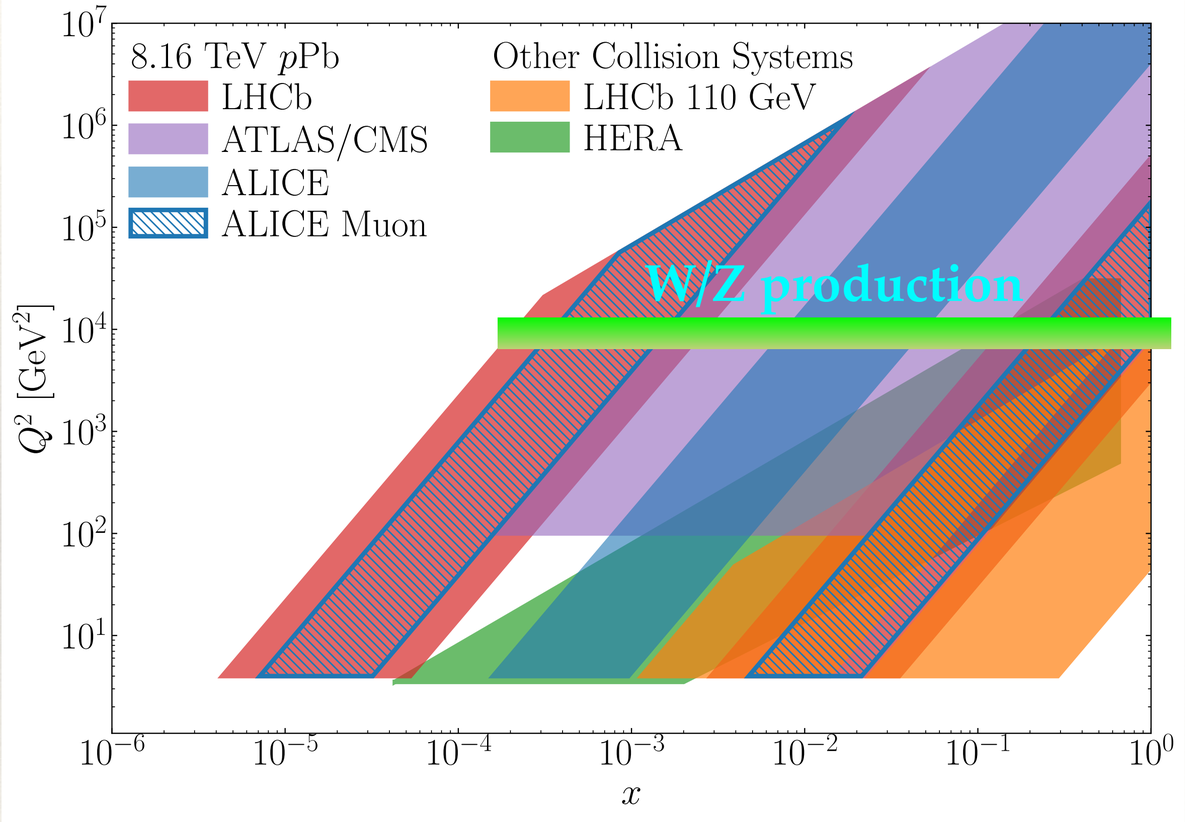
- **Forward production:**
  - Center of mass rapidity coverage: $1.5 < y^* < 4.0$
- **Backward production:**
  - Center of mass rapidity coverage: $-5.0 < y^* < -2.5$

- 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: $2.5 < |y^*| < 4.0$

pPb Z boson production

pPb Z boson production

- 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 factor of other processes



pPb Z boson production

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

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

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

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

【JHEP09(2014)030】【LHCb-CONF-2019-003】

- Using pPb datasets at 5.02 TeV and 8.16 TeV

	2013		2016	
$\sqrt{s_{NN}}$	5.02 TeV		8.16 TeV	
	pPb	Pbp	pPb	Pbp
$\mathcal{L}$	1.1 nb^{-1}	0.5 nb^{-1}	13.6 nb^{-1}	20.8 nb^{-1}

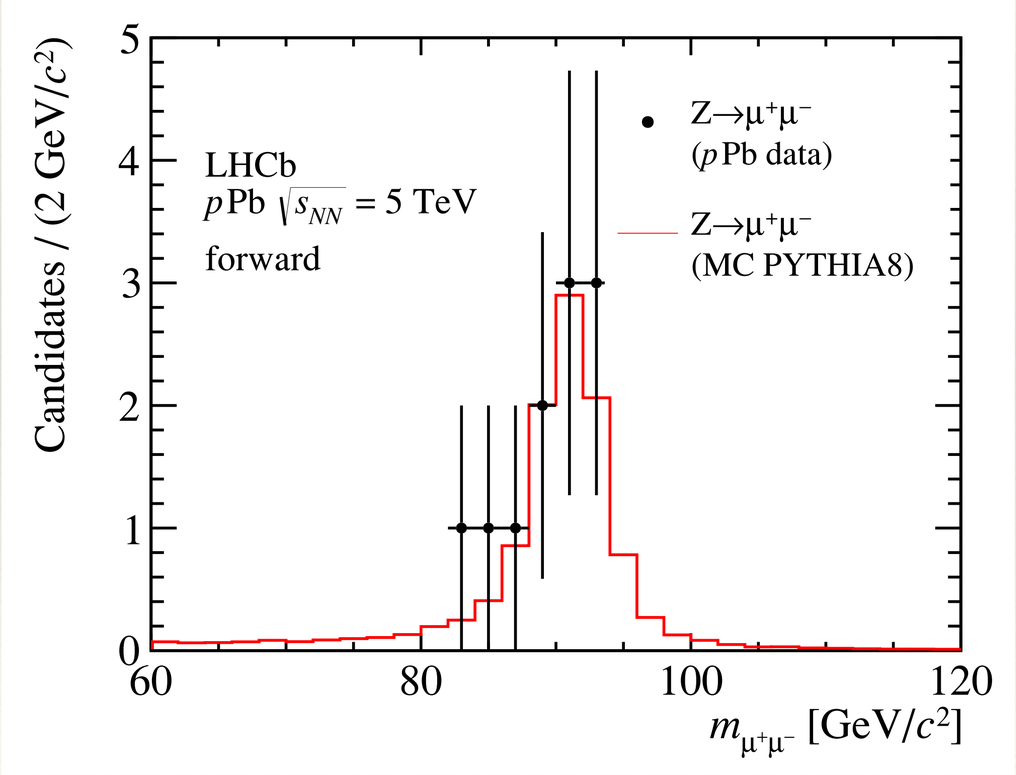
- Fiducial volume:
  $60 < m_{\mu\mu} < 120\,\text{GeV}$
  $2.0 < \eta^\mu < 4.5,\ p_T^\mu > 20\,\text{GeV}$

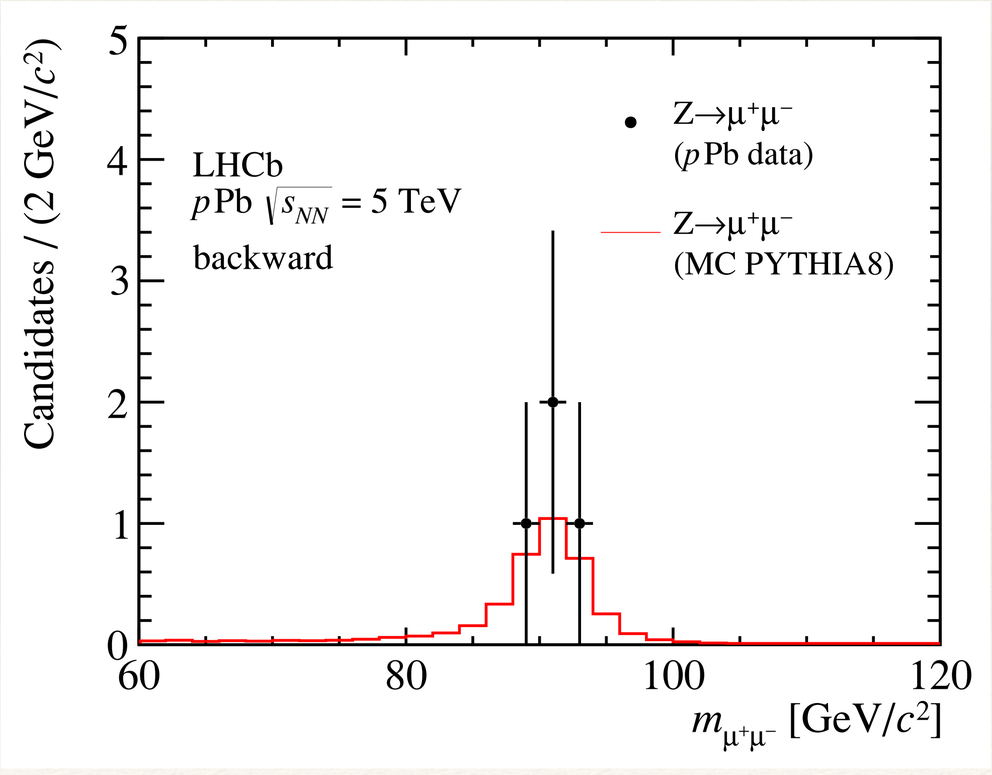
  - Purity ρ (signal fraction) is measured using same-sign muon pair and ABCD-method
  - Efficiencies are estimated using MC and tag-and-probe data-driven corrections

pPb Z boson production at 5 TeV

- 5 TeV in 2016,
- 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】





pPb Z boson production at 5 TeV

- Fiducial cross-section results:
  - Forward:

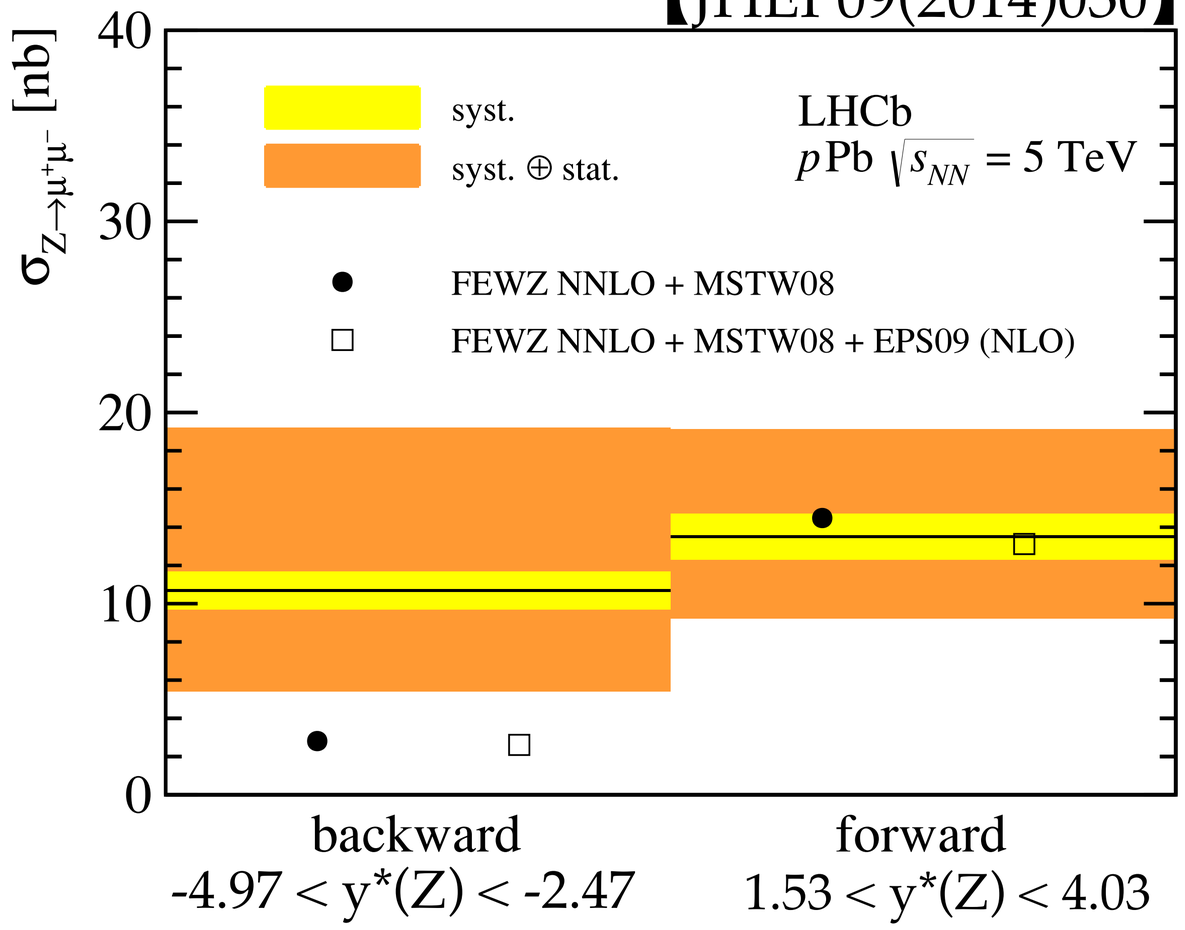
$$\sigma_{Z\to\mu^+\mu^-}(\text{fwd}) = 13.5^{+5.4}_{-4.0}(\text{stat.}) \pm 1.2(\text{syst.})\ \text{nb}$$

  - Backward:

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

- 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

【JHEP09(2014)030】

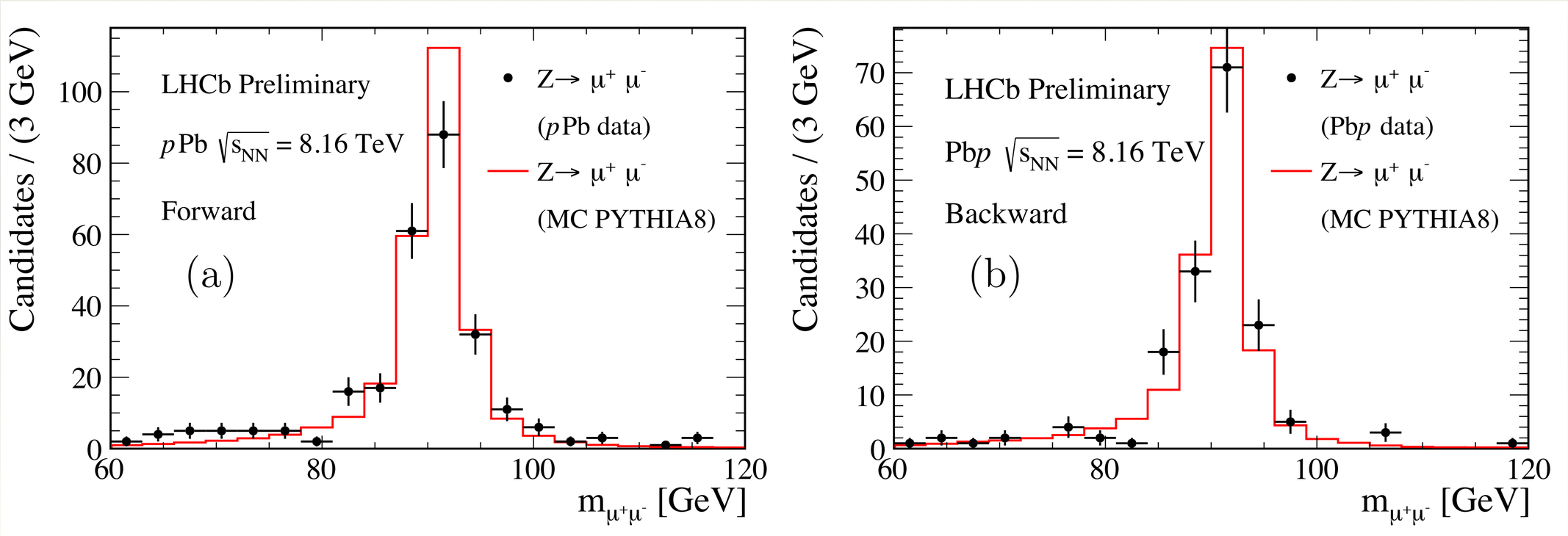


pPb Z boson production at 8 TeV

New!

- 8 TeV in 2016,
- 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】

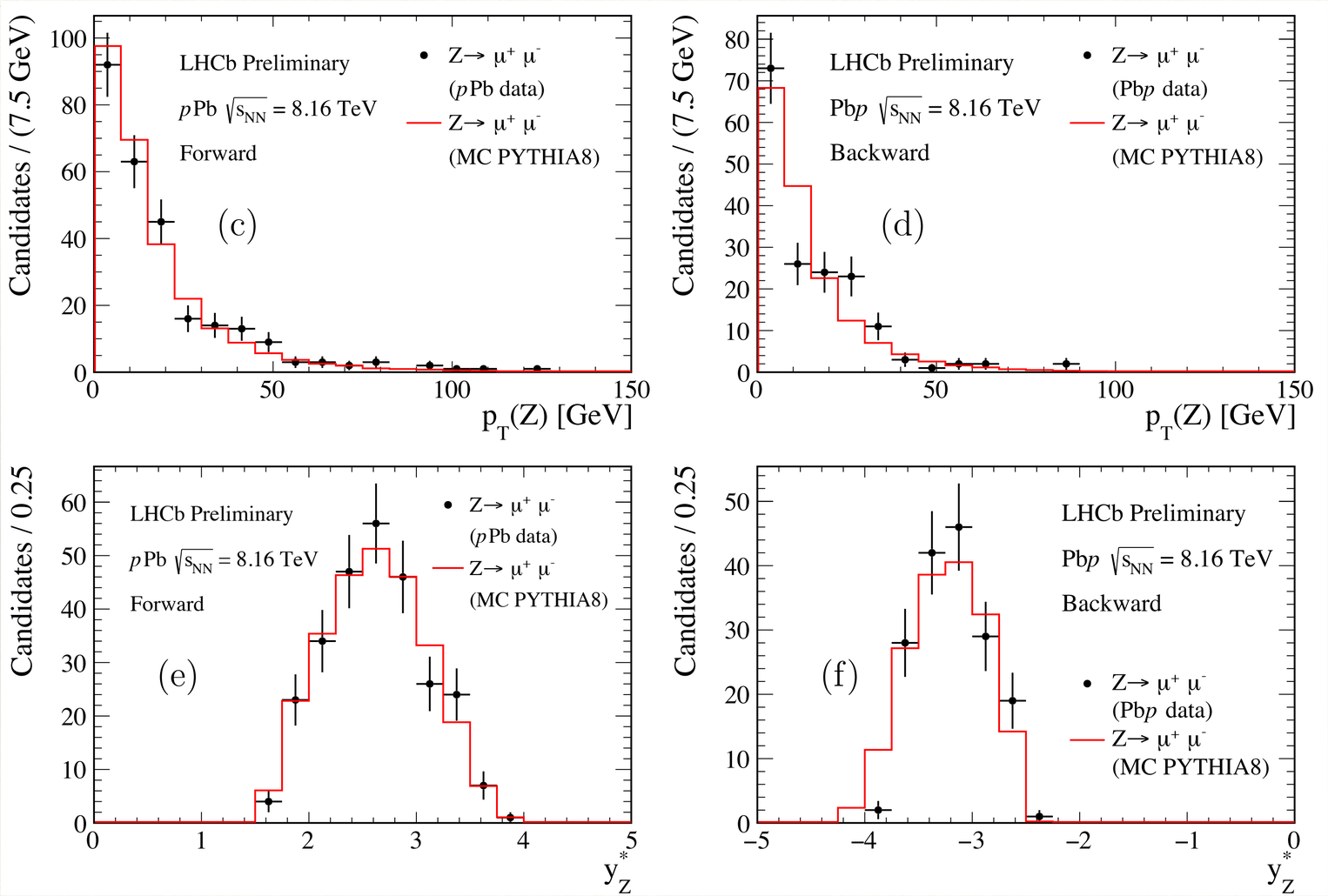


pPb Z boson production at 8 TeV

New!

- 8 TeV in 2016
- 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

New!

much higher precision

【LHCb-CONF-2019-003】

- Fiducial cross-section results:

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

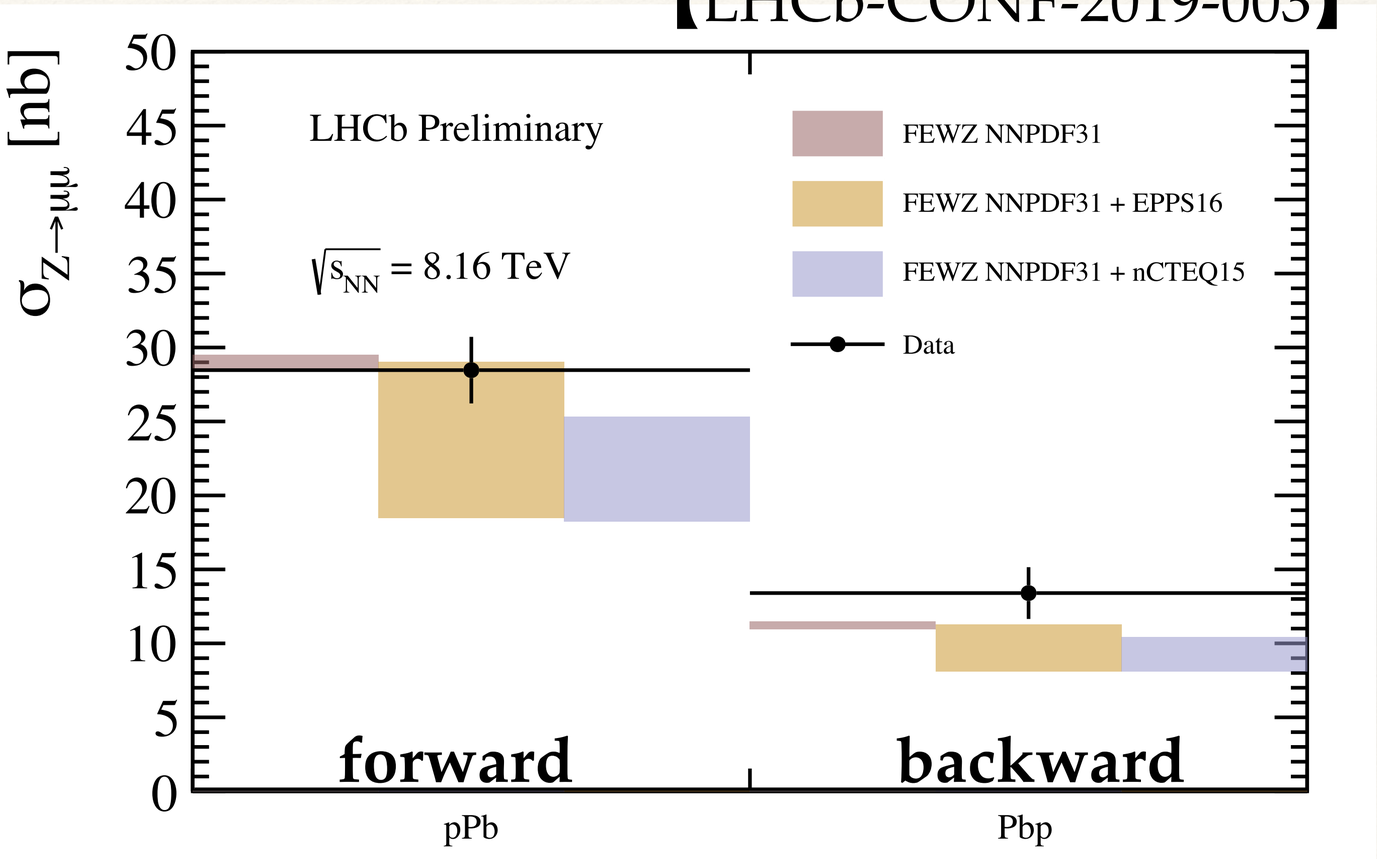
  $= 28.5 \pm 1.7(\mathrm{stat.}) \pm 1.2(\mathrm{syst.}) \pm 0.7(\mathrm{lumi.})$ nb

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

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



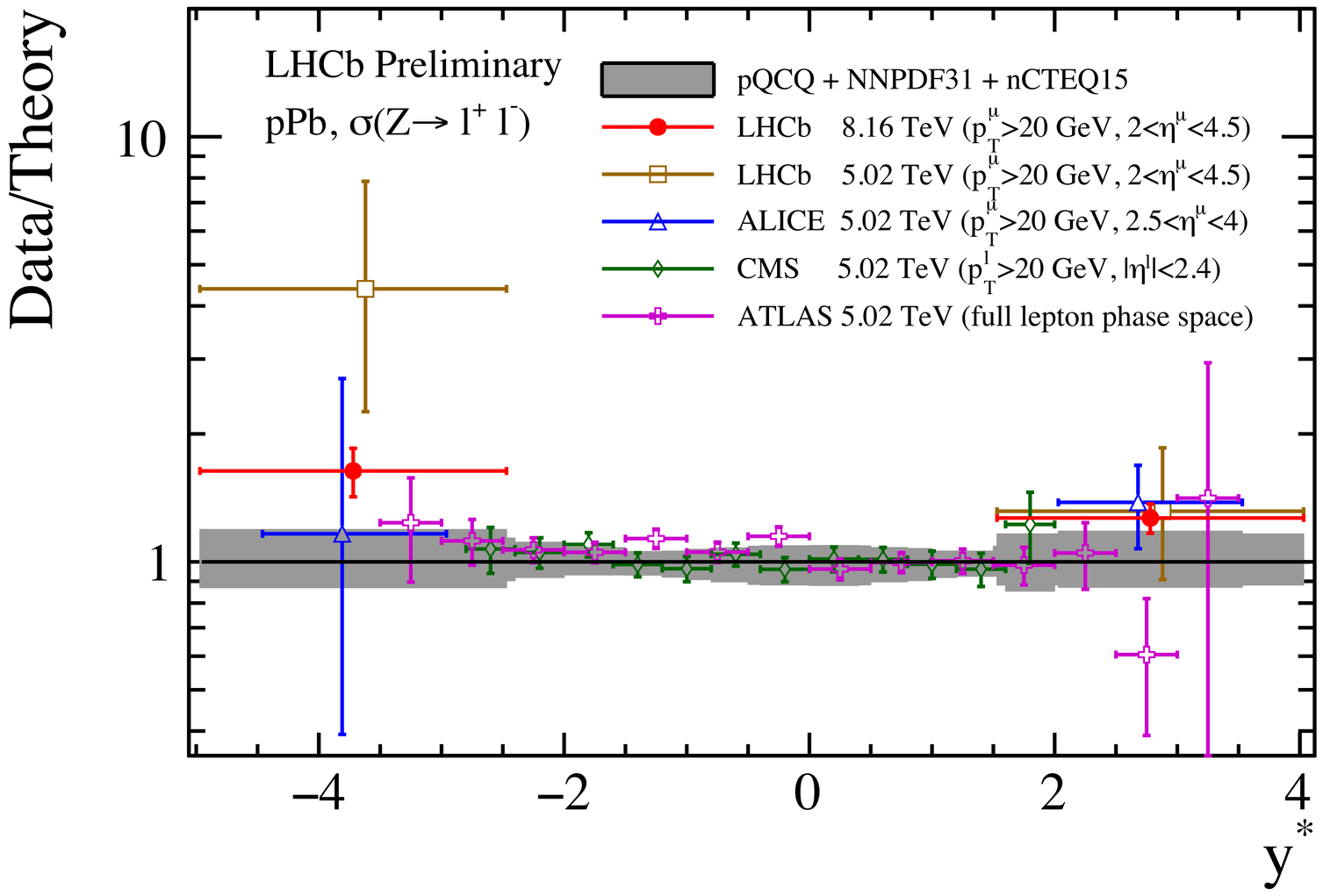
$1.53 < y^*(Z) < 4.03$ $\quad$ $-4.97 < y^*(Z) < -2.47$

Compare with results at 5 TeV

New!

【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

New!

【LHCb-CONF-2019-003】

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

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

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

- 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:

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

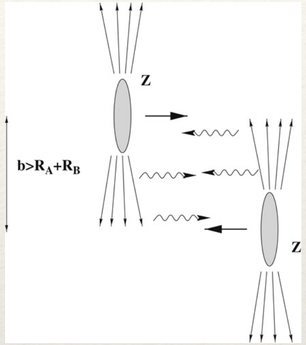
$$R^{2.5<|y^*|<4.0}_{\mathrm{FB,NNPDF3.1+EPPS16}} = 1.45 \pm 0.10(\mathrm{theo.}) \pm 0.01(\mathrm{num.}) \pm 0.27(\mathrm{PDF}),$$

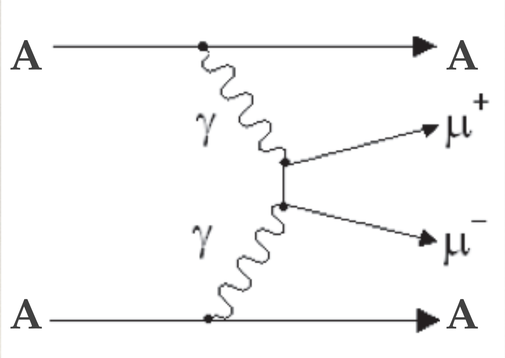
$$R^{2.5<|y^*|<4.0}_{\mathrm{FB,NNPDF3.1+nCTEQ15}} = 1.44 \pm 0.10(\mathrm{theo.}) \pm 0.01(\mathrm{num.}) \pm 0.20(\mathrm{PDF}).$$

Ultra-peripheral PbPb Collisions

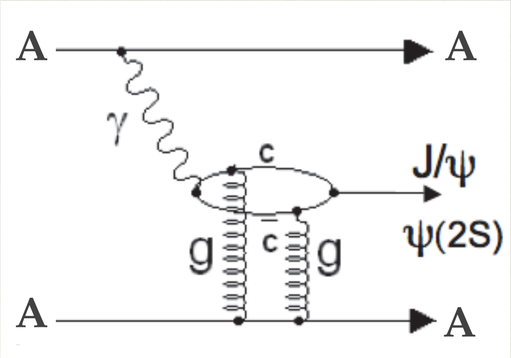
Ultra-peripheral PbPb Collisions

- Ultra-peripheral collisions: Two nuclei bypass each other with an impact parameter larger than the sum of their radii.
- Photon-induced interactions are enhanced by the strong electromagnetic field of the nucleus
- Coherent J/ψ production gives constraints on the gluon Probability Density Functions
- The (J/ψ) / ψ(2S) ratio measurement is helpful to constrain the choice of the vector meson wave function in dipole scattering models [e.g. PLB 772 (2017) 832, PRC (2011) 011902]





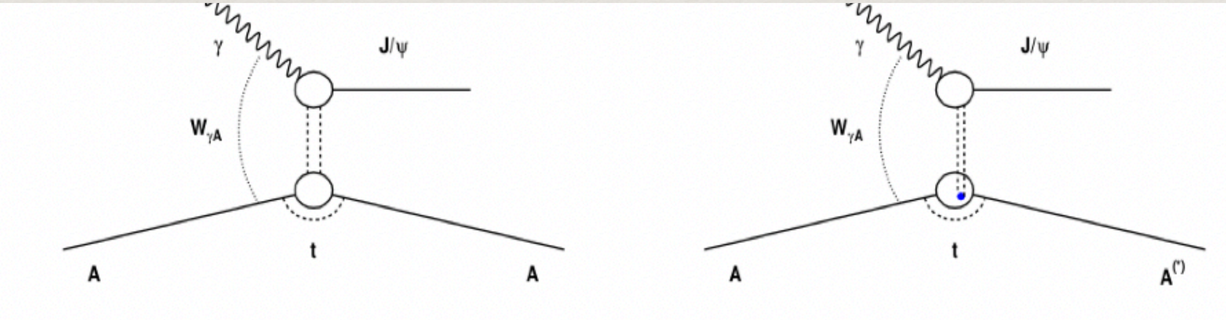
Photon-Photon interactions
Precisely know at p-QED



Photon-induced quarkonium production: A $q\bar{q}$ loop created by the photon interactions with a pair of gluon exchange (pomeron) to produce a quarkonium ($c\bar{c}$, $b\bar{b}$, etc.)

Coherent J/ψ production: photon interact with the whole nucleus coherently

Incoherent J/ψ production: photon interact with particular nucleons in the nucleus



The charmonium measurement in PbPb UPC

- Cross-sections

$$\frac{d\sigma_{\text{coh.},\,J/\psi}}{dy} = \frac{N_{\text{coh.},\,J/\psi}}{\varepsilon_{\text{total}} \cdot \mathcal{B}(J/\psi \to \mu^+\mu^-) \cdot \mathcal{L} \cdot \Delta y}$$

$$\frac{d\sigma_{\text{coh.},\,\psi(2S)}}{dy} = \frac{N_{\text{coh.},\,\psi(2S)}}{\varepsilon_{\text{total}} \cdot \mathcal{B}(\psi(2S) \to \mu^+\mu^-) \cdot \mathcal{L} \cdot \Delta y}$$

- The signal yields are extracted from the dimuon mass fits

- Acceptance is defined as :
  $2.0 < \eta^{\mu} < 4.5,\ p_T^{\mu} > 700\,\text{MeV},$
  $p_T^{\mu\mu} < 1\,\text{GeV},\ |\Delta\phi_{\mu\mu}| > 0.9\,\pi$

- Using PbPb datasets in 2015 and 2018

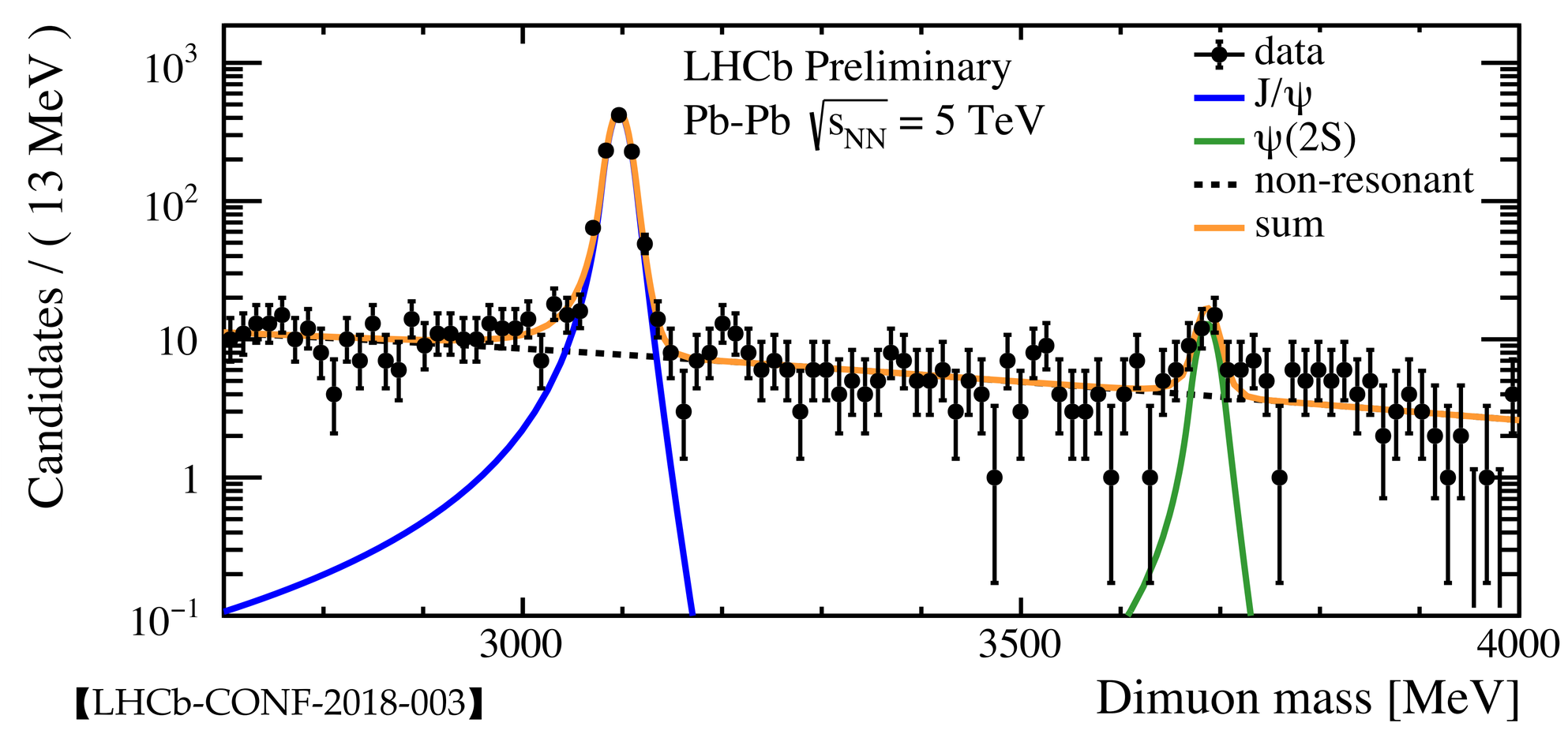
	2015	2018
$\sqrt{s_{NN}}$	5.02 TeV	5.02 TeV
	PbPb	PbPb
$\mathcal{L}$	10 μb^{-1}	$\sim$ 210 μb^{-1}

- Event selection require a near empty detector with only two long tracks reconstructed.

- Herschel detector is used to further reduce the multiplicities [JINST 13 (2018) 04 P04017]

Dimuon mass fits

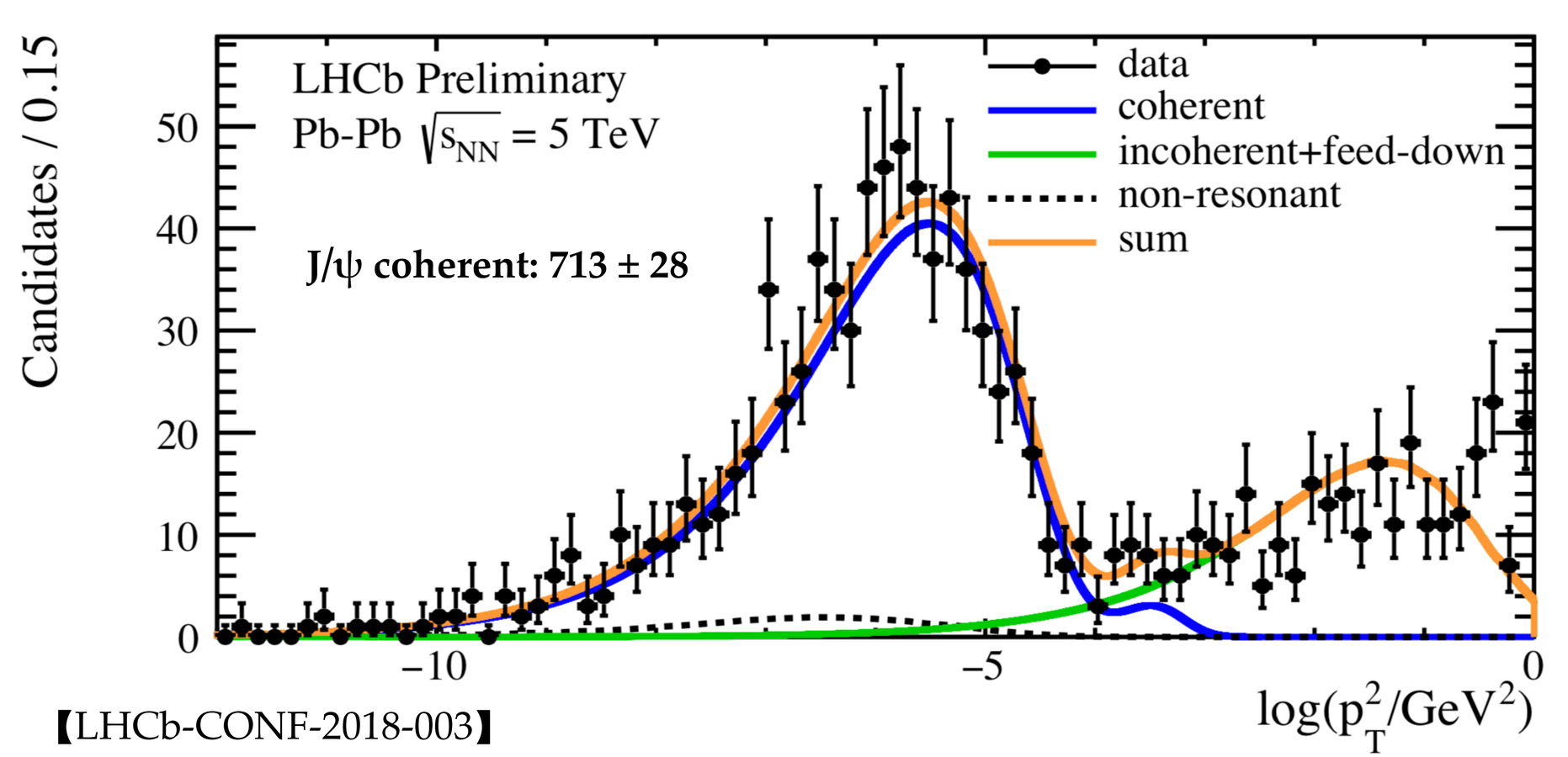
- **2015 dataset: 1003 ± 30 J/ψ and about 30 ψ(2S)**



【LHCb-CONF-2018-003】

Ln(p_T^2) fits to extract the coherent component

- **2015 dataset**

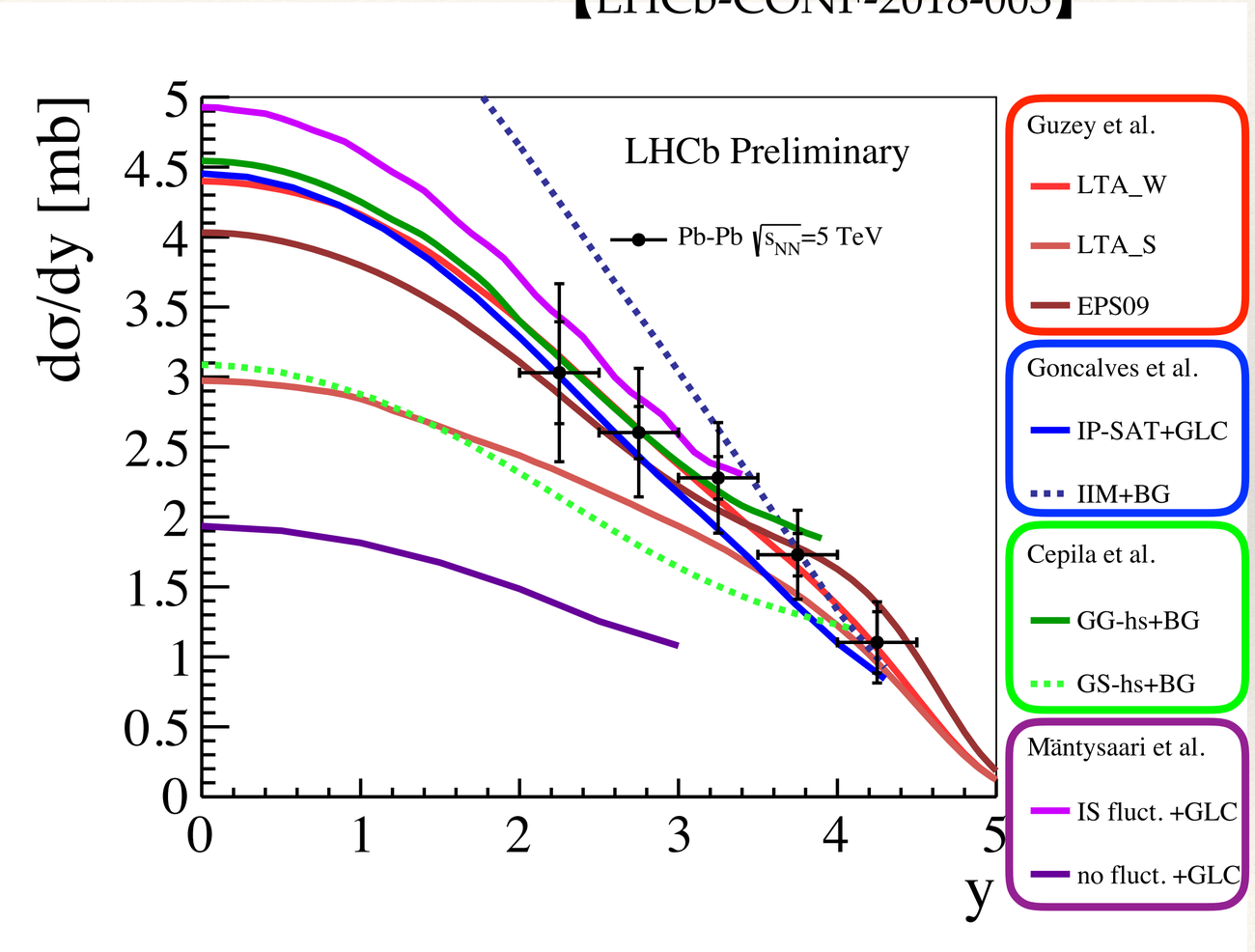


【LHCb-CONF-2018-003】

The 2015 dataset results

- Coherent J/ψ cross-section:
  $\sigma = 5.27 \pm 0.21\,(\text{stat}) \pm 0.49\,(\text{syst.}) \pm 0.68\,(\text{lumi.})$ mb
- The analysis is repeated in bins of half unit rapidity y(J/ψ)
- Uncertainties for statistics, systematic and luminosity are of comparable magnitude
- The LHCb acceptance is interesting to discriminate between the models
  - pQCD calculations: [PRC 93 (2016) 055206]
  - Color dipole models:
    [PRD 96 (2017) 094027]
    [PRC 97 (2018) 024901]
    [PLB 772 (2017) 832]

【LHCb-CONF-2018-003】

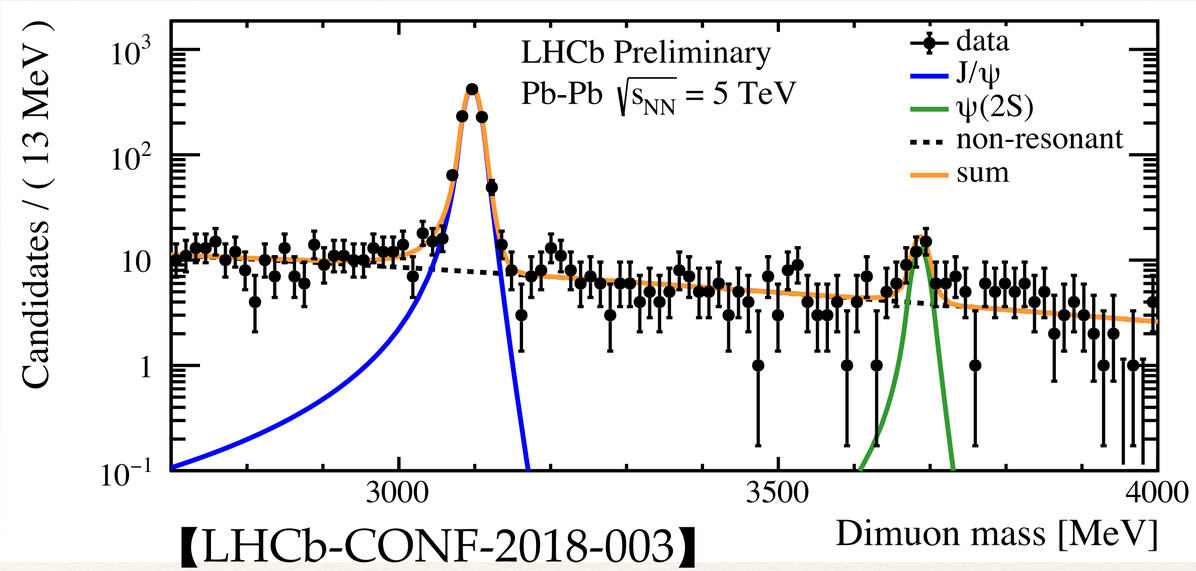


The 2018 dataset

	2015	2018
$\sqrt{s_{NN}}$	5.02 TeV	5.02 TeV
	PbPb	PbPb
$\mathcal{L}$	10 μb^{-1}	$\sim$ 210 μb^{-1}

- About 20 times more statistics in 2018

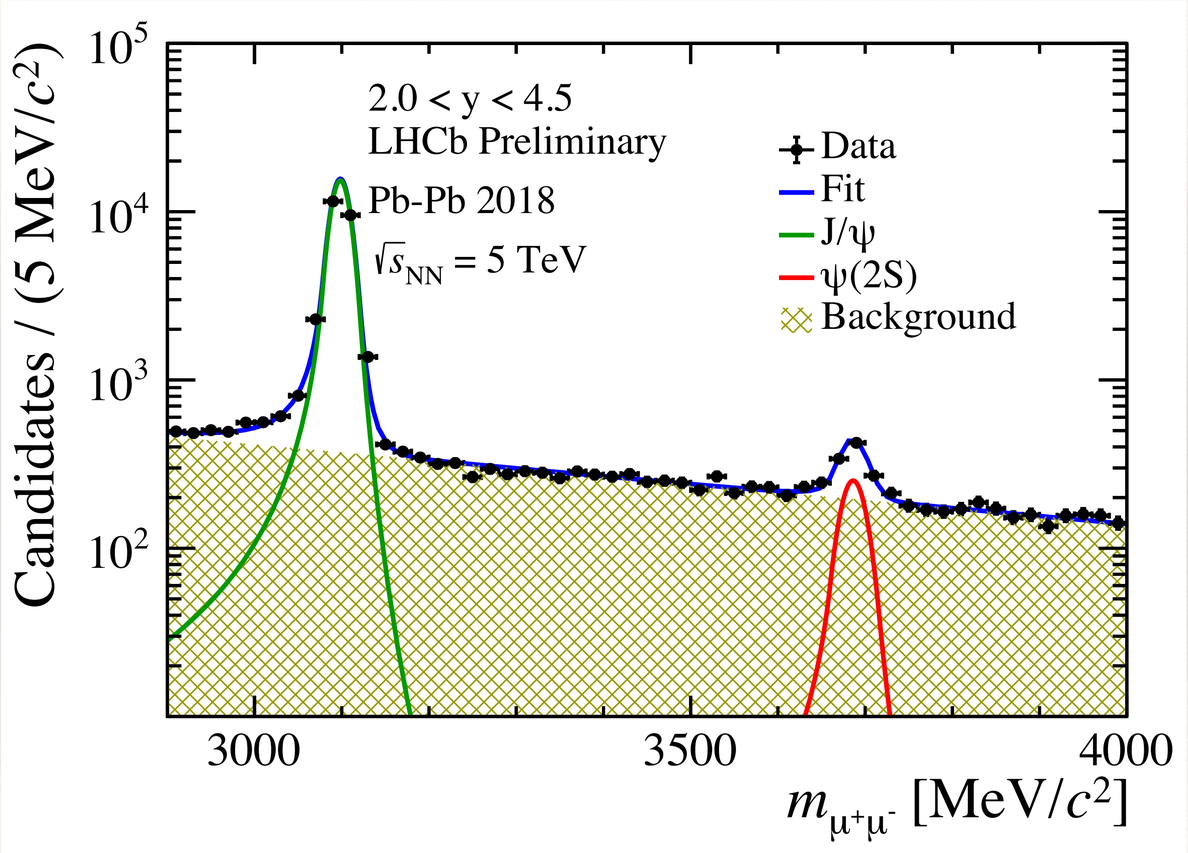
- 2015 dataset: 1003 ± 30 J/ψ and about 30 ψ(2S)



【LHCb-CONF-2018-003】

New!

- 2018 dataset



【https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlotsQM2019】

Dimuon mass fits

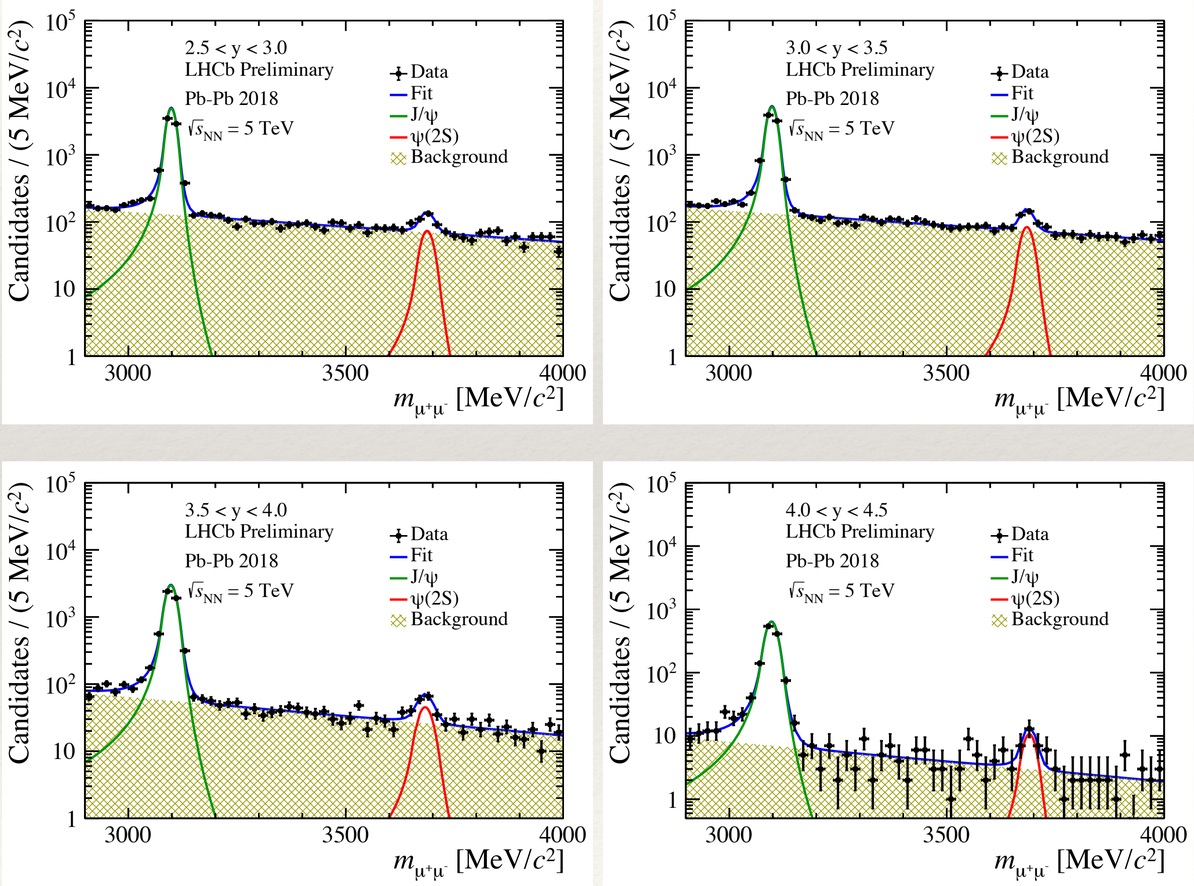
	2015	2018
$\sqrt{s_{NN}}$	5.02 TeV	5.02 TeV
	PbPb	PbPb
$\mathcal{L}$	10 μb^{-1}	$\sim$ 210 μb^{-1}

- The 20 times high statistics make it possible to determine the cross-sections of both both J/ψ and ψ(2S) simultaneously in 5 rapidity bins

- Can also measure the cross-section ratio (J/ψ) / ψ(2S)

$$\frac{\sigma_{\text{coh.},\,J/\psi}}{\sigma_{\text{coh.},\,\psi(2S)}} = \frac{N_{J/\psi}\cdot\varepsilon_{\psi(2S)}\cdot\mathcal{B}(\psi(2S)\to\mu^+\mu^-)}{N_{\psi(2S)}\cdot\varepsilon_{J/\psi}\cdot\mathcal{B}(J/\psi\to\mu^+\mu^-)}$$

- **2018 dataset**



New!

【https://twiki.cern.ch/twiki/bin/view/LHCb/LHCbPlotsQM2019】

Conclusion

- LHCb provides a unique opportunity to probe the cold nuclear matter effects using Z boson production
  - pPb->Z boson production at 5 TeV and 8 TeV results are presented
  - Results are compatible with theoretical predictions
  - 8 TeV results give much higher precision
- Charmonium production in Ultra-peripheral Pb-Pb collisions are of particular interests to probe gluon Parton Density Functions
  - Results based on 2015 PbPb dataset at 5 TeV are presented
  - Higher precision results using 2018 data set with 20 times higher statistics for both the J/ψ and ψ(2S) cross-sections are coming soon.