Studies of low x physics and ultraperipheral collisions at LHCb

Murilo Rangel
on behalf of the LHCb Collaboration

Outline

--- LHCb experiment overview

--- Results discussed in this talk

Coherent charmonium in ultra-peripheral lead-lead collisions - JHEP 06 (2023) 146

Diffractive exotic J/ψϕ resonances in *pp* collisions - arXiv:2407.14301

Exclusive J/ψ and ψ(2S) production at 13 TeV - arXiv:2409.03496

Production of η and η′ mesons in pp and pPb collisions - Phys. Rev. C109 (2024) 024907

Prompt D^0 nuclear modification factor in pPb 8.16 TeV - Phys. Rev. Lett. 131 (2023) 102301

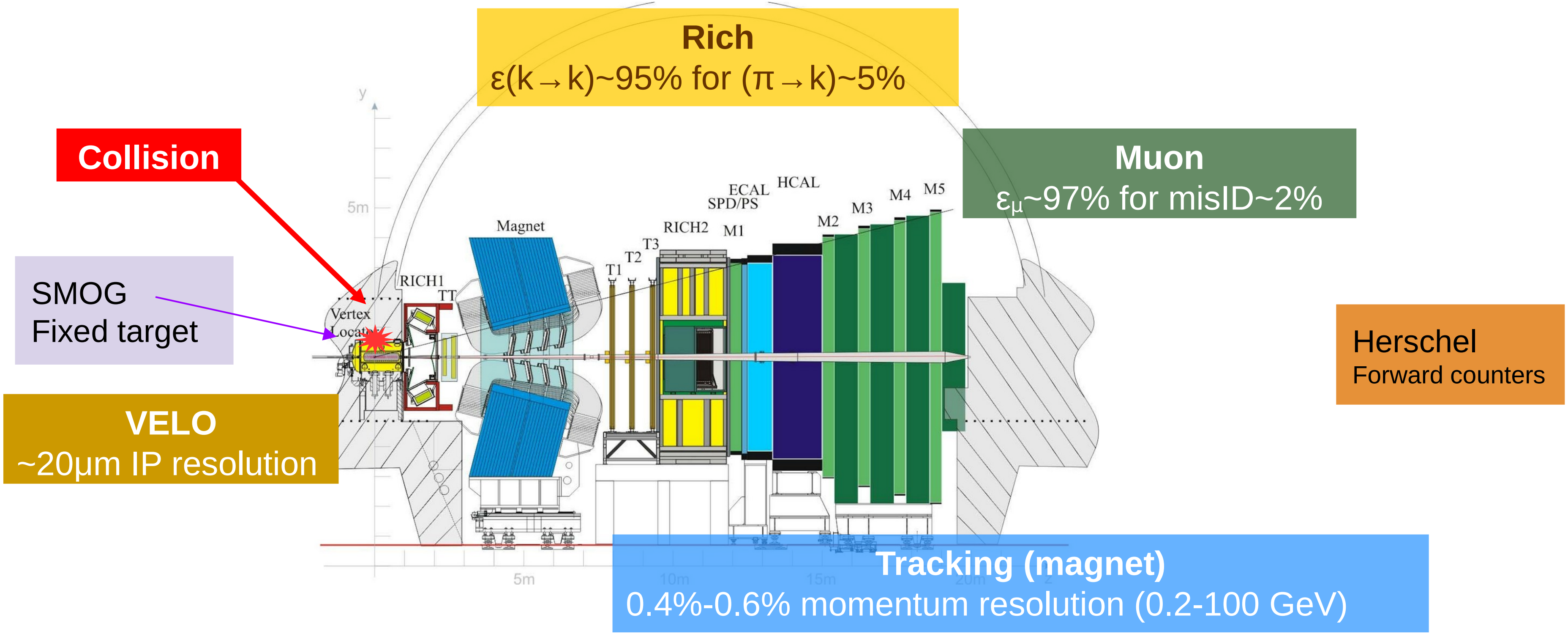
--- Summary

LHCb experiment overview

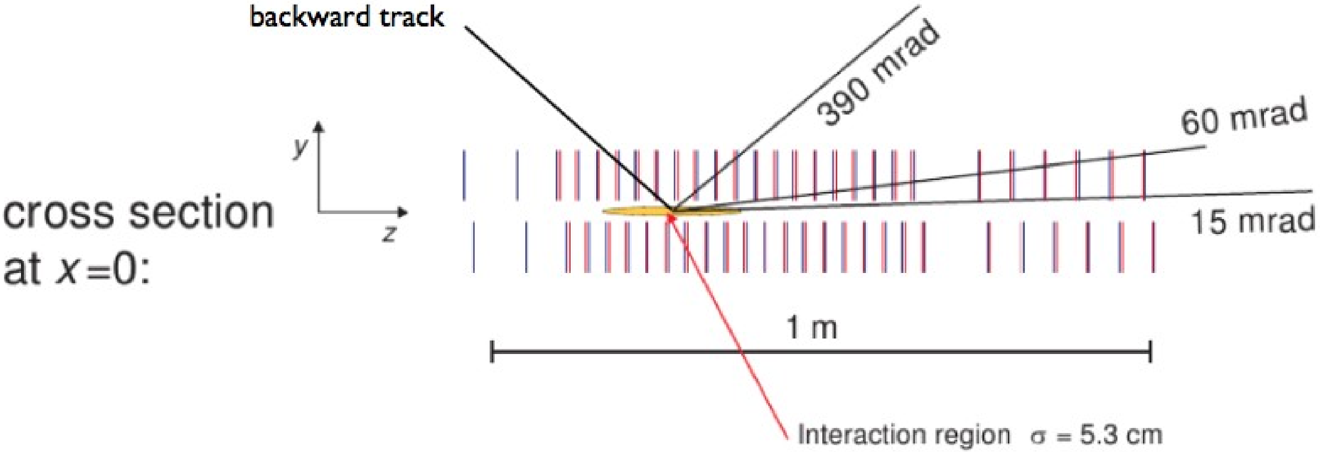
Single arm spectrometer fully instrumented in the forward region ($2.0<\eta<5.0$)

Designed for heavy flavour physics and also exploited for general purpose physics

[Int. J. Mod. Phys. A 30, 1530022 (2015)]



VELO acceptance



VELO (Vertex Locator)

→ surrounds the interaction point

→ no magnetic field

→ reconstructs backward tracks $(-3.5<\eta<-1.5)$

High **R**apidity **S**hower **C**ounters for **L**HCb – HERSCHEL

- installed at the end of 2014 → increase pseudorapidity coverage
- 5 stations with 4 scintillators with PMT
- able to detect forward particle showers and veto events with these
- removed at the end of Run 2

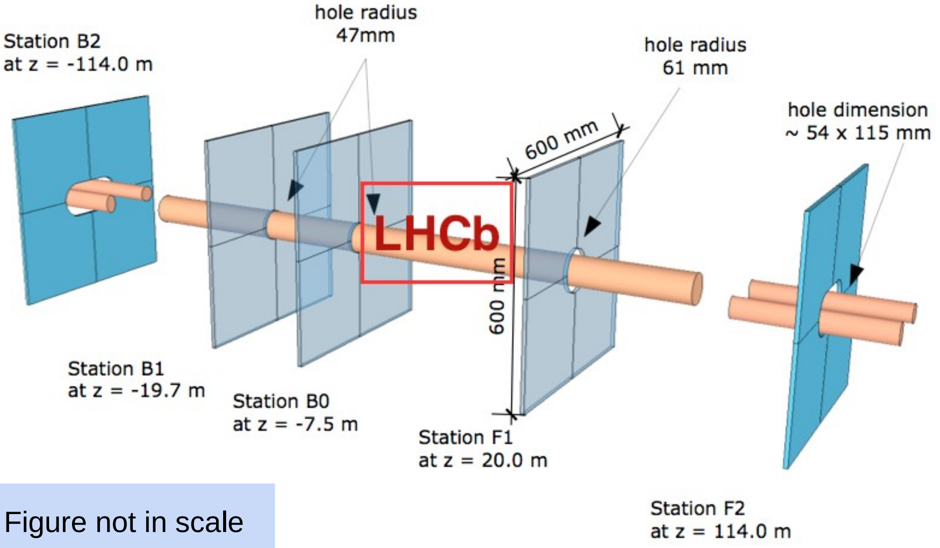
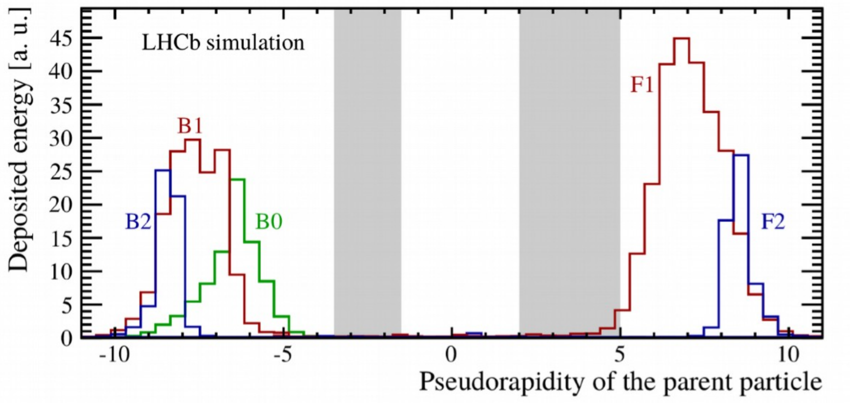
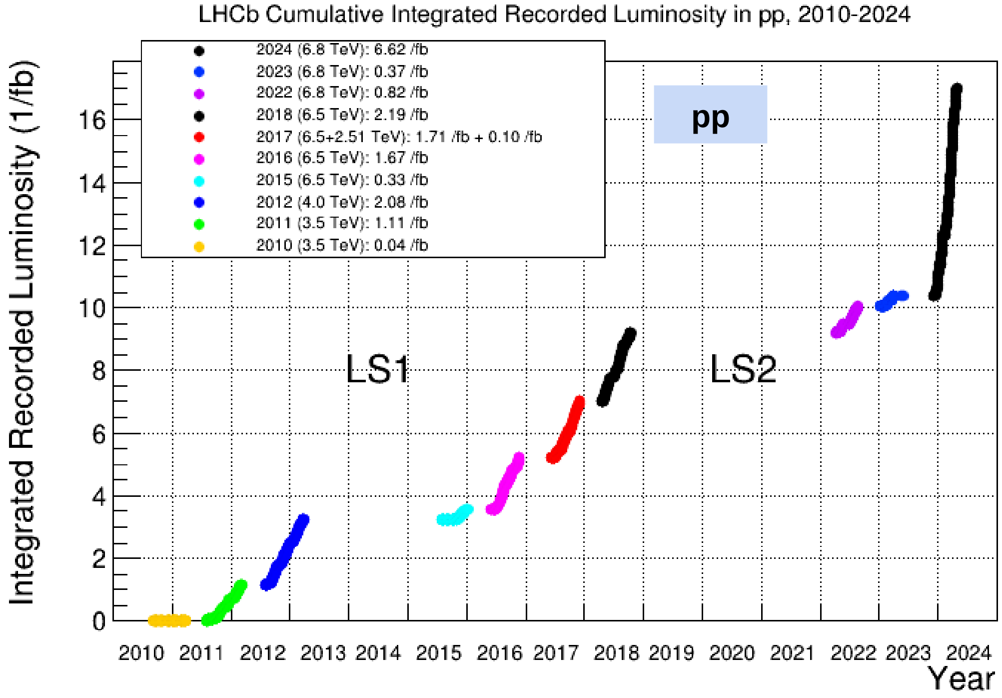


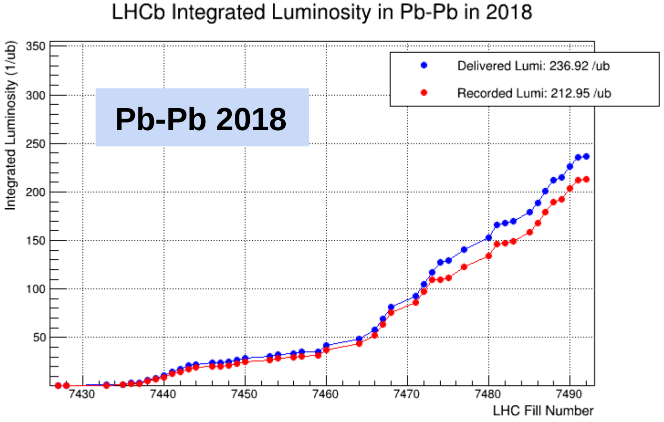
Figure not in scale

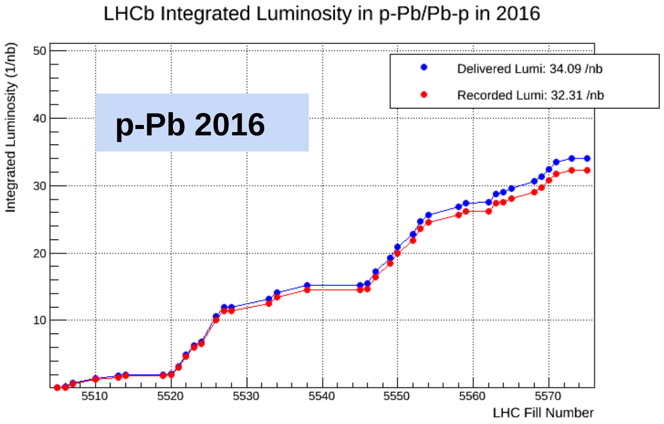
JINST 13 (2018) no.04, P04017

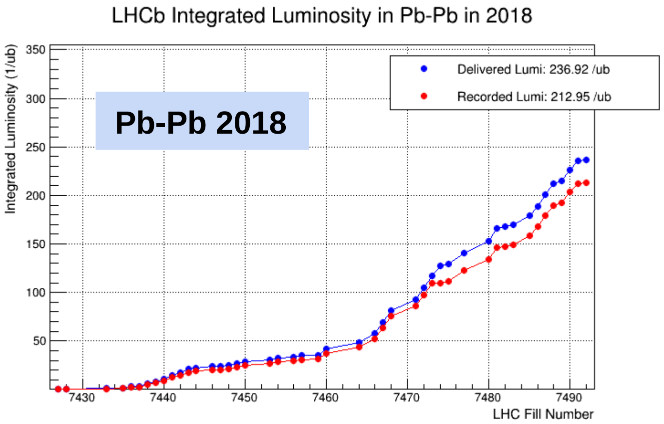


Data samples



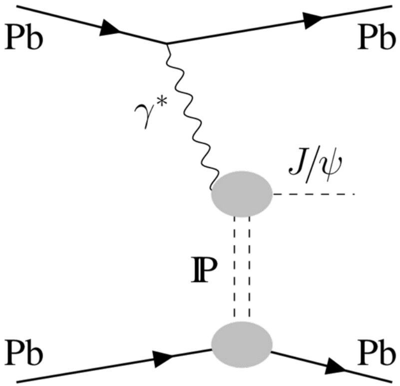




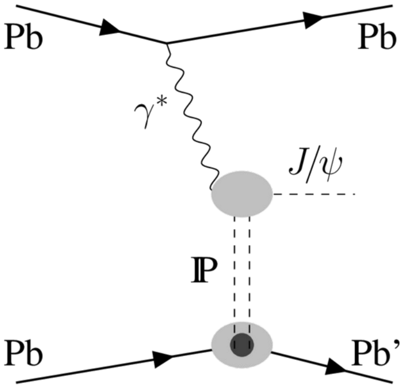

LHCb Integrated Luminosity in Pb-Pb in 2018
Pb-Pb 2018
Delivered Lumi: 236.92 /ub
Recorded Lumi: 212.95 /ub
Integrated Luminosity (1/ub)
LHC Fill Number
350
300
250
200
150
100
50
7430
7440
7450
7460
7470
7480
7490

Study of exclusive photoproduction of charmonium in ultra-peripheral lead-lead collisions

JHEP 06 (2023) 146



coherent scatter with the Pb nucleus



incoherent interaction with a single nucleon

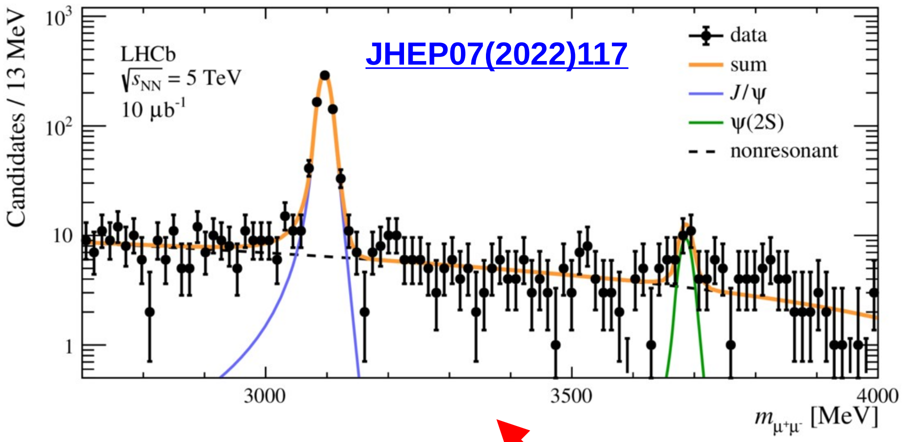
Ultraperipheral collisions: interaction of photons with gluons
single object with vacuum quantum numbers - pomeron

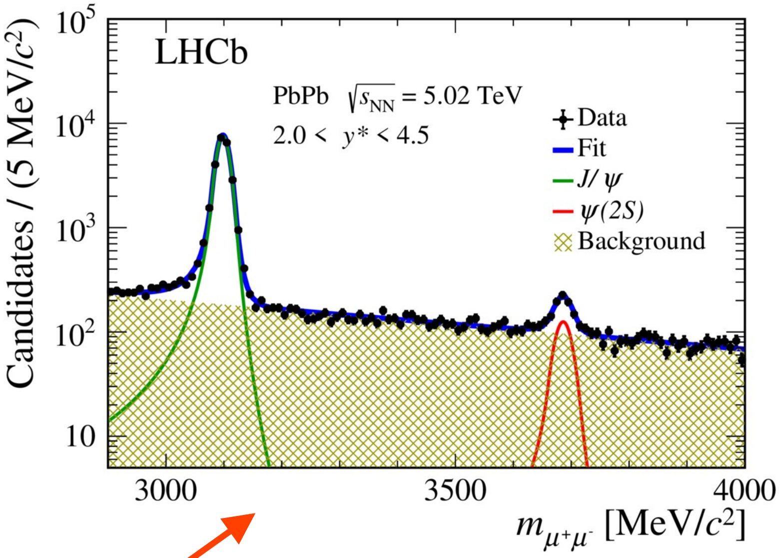
Values of the Bjorken variable can be studied down to 10^{-5} (large theoretical uncertainties)

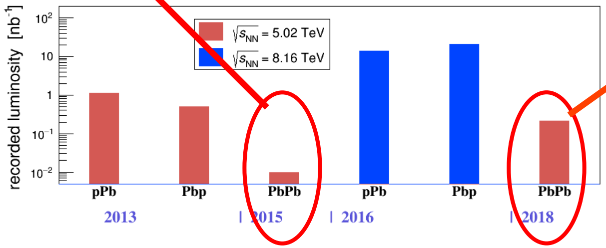
Experimental strategy: Two muons in very clean events - VELO and Herschel

Study of exclusive photoproduction of charmonium in ultra-peripheral lead-lead collisions

JHEP 06 (2023) 146

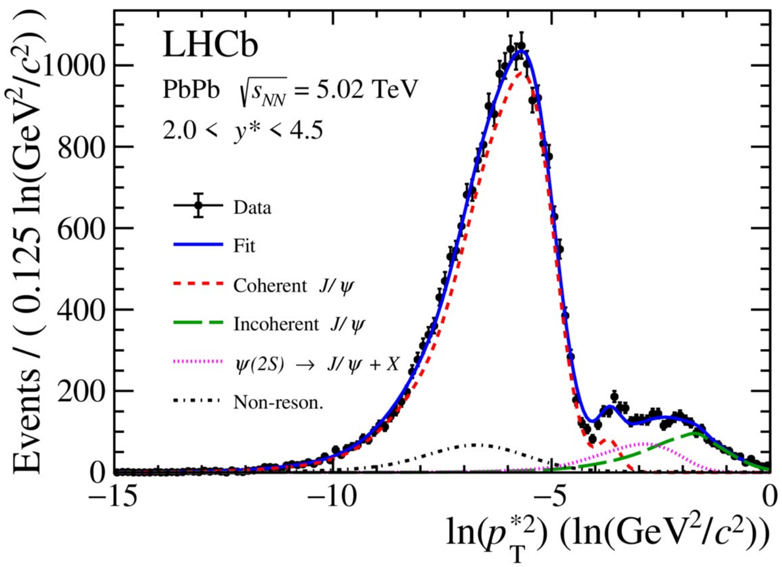


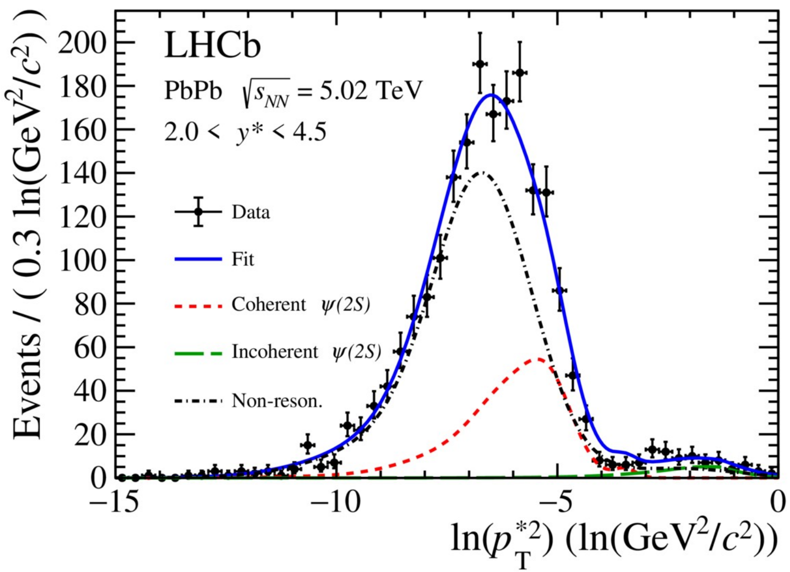




Study of exclusive photoproduction of charmonium in ultra-peripheral lead-lead collisions

JHEP 06 (2023) 146



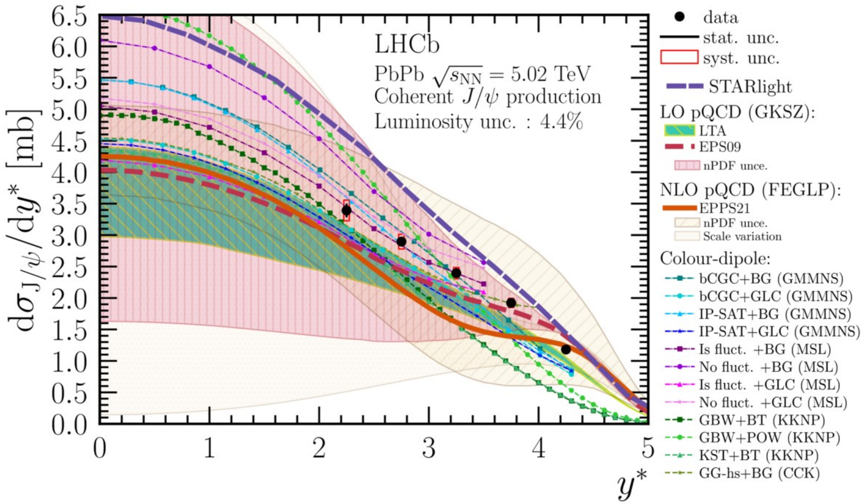


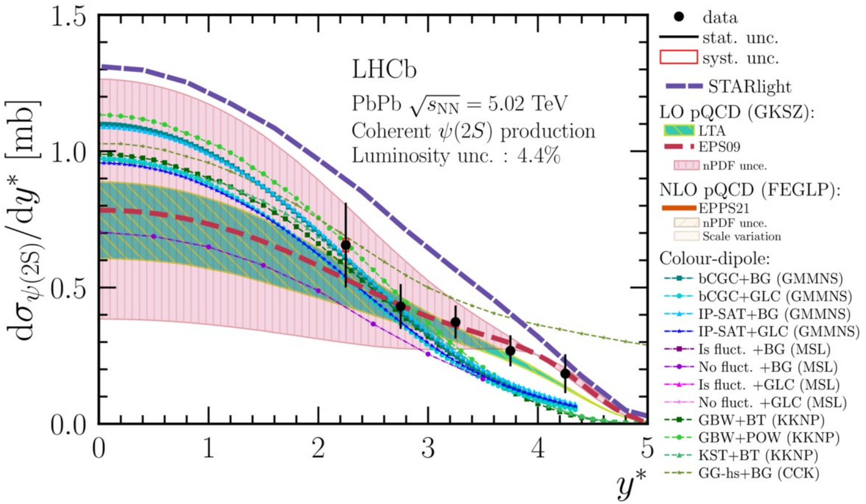
Charmonium PDFs are estimated using STARLight generator.

The shape of background taken from the side-band method, then the normalization is fixed from mass fit.

Study of exclusive photoproduction of charmonium in ultra-peripheral lead-lead collisions

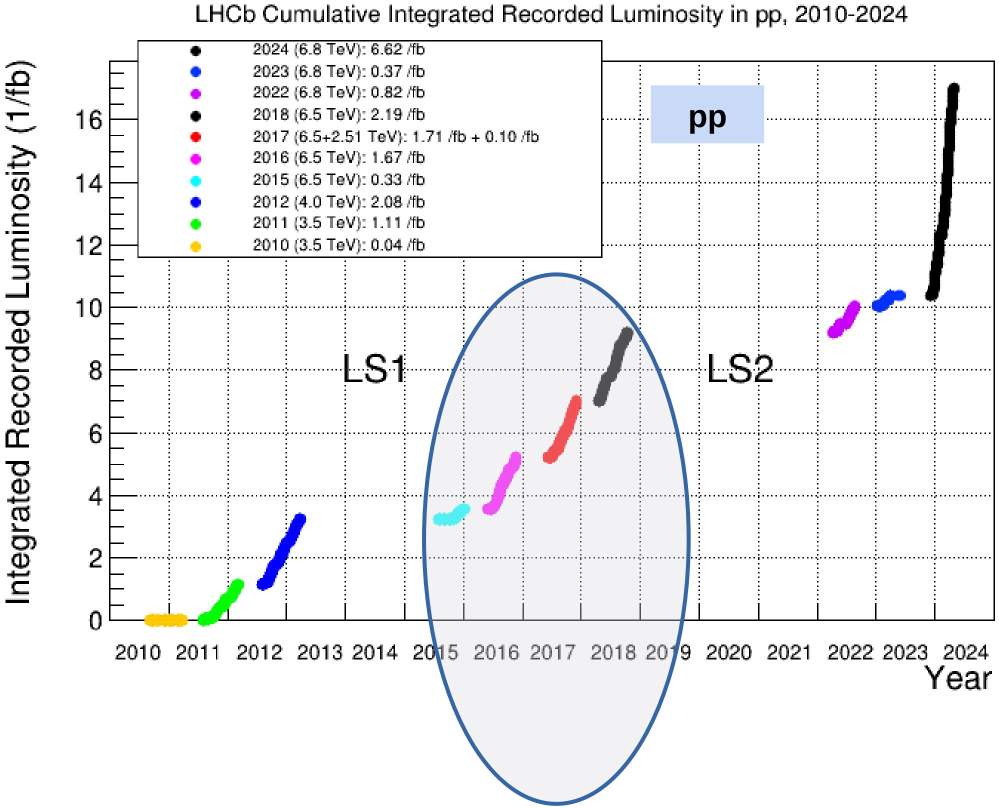
[JHEP 06 (2023) 146]





Differential cross-section as a function of rapidity results compared with
- color-dipole model (blue lines)
- pQCD model (red lines) theory predictions

The first coherent ψ(2S) measurement in forward rapidity region at the LHC

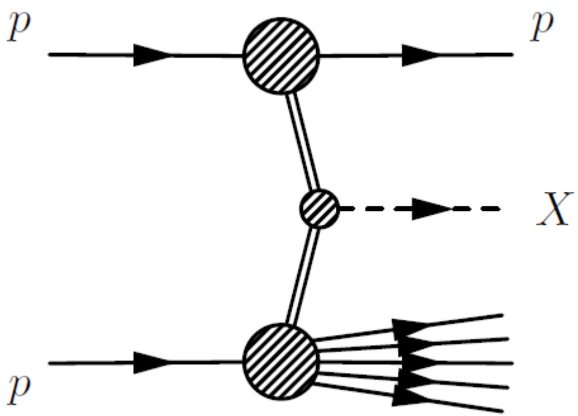

LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2024
2024 (6.8 TeV): 6.62 /fb
2023 (6.8 TeV): 0.37 /fb
2022 (6.8 TeV): 0.82 /fb
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
pp
LS1
LS2
Integrated Recorded Luminosity (1/fb)
Year
0
2
4
6
8
10
12
14
16
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024

Observation of diffractive exotic J/ψϕ resonances in *pp* collisions

arXiv:2407.14301

The first study of J/ψϕ production in diffractive processes in proton-proton collisions.

Possible production of exotic states

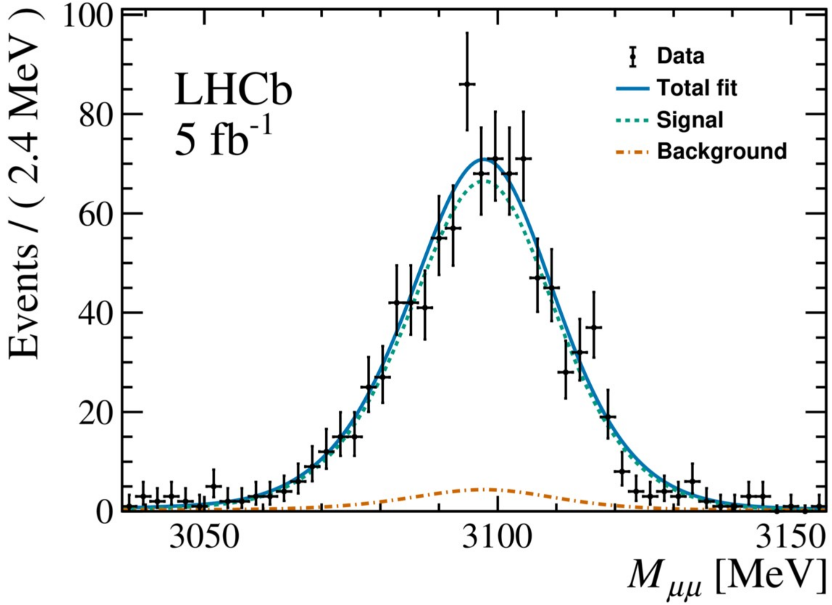


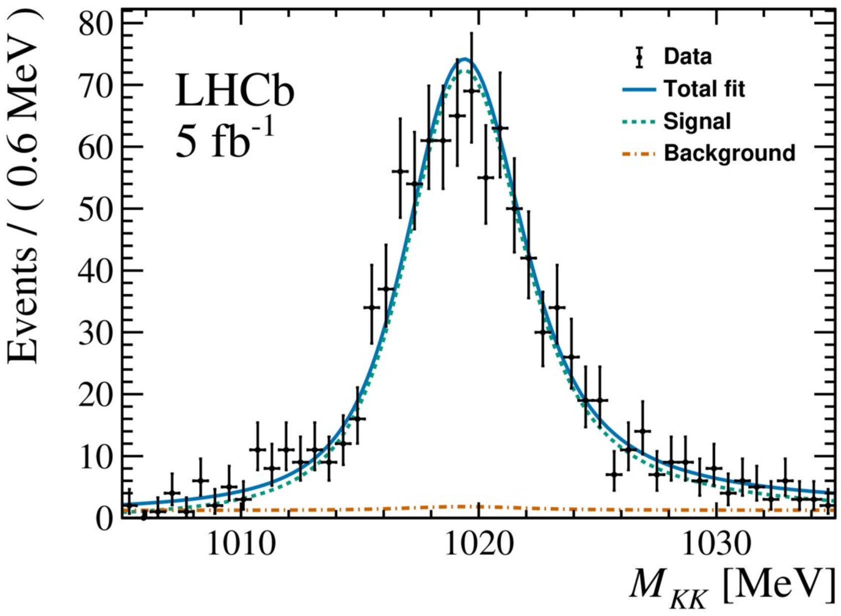
Experimental strategy: Selection of J/ψ(→μμ)ϕ(→KK) in low multiplicity events: Nb of VELO tracks must be 4

Observation of diffractive exotic J/ψϕ resonances in *pp* collisions

arXiv:2407.14301

Clear J/ψ and ϕ signals - two-dimensional unbinned fit is performed to extract yields





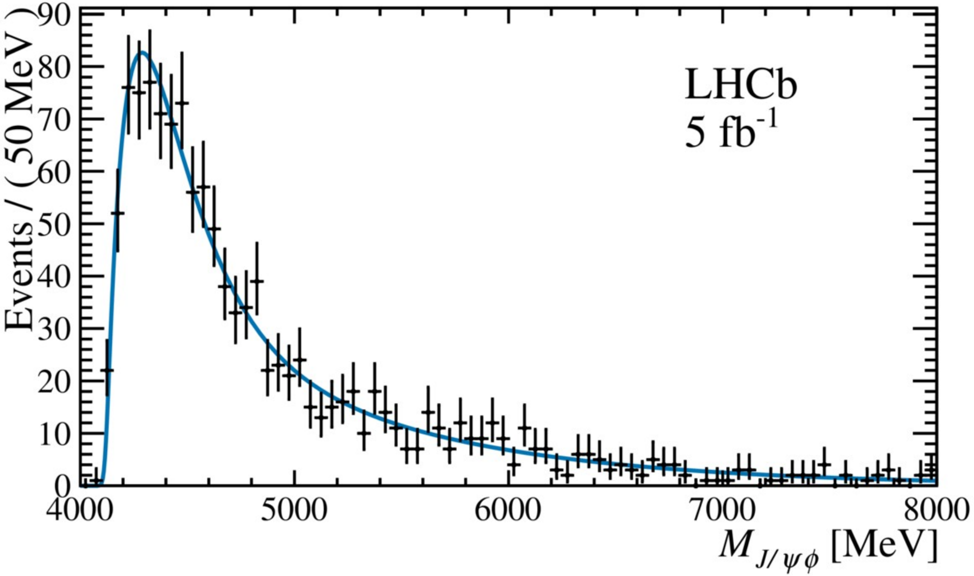
Observation of diffractive exotic J/ψϕ resonances in *pp* collisions

arXiv:2407.14301

Sideband sample

→ all selection requirements, except for an inverted offline requirement of more than four VELO tracks.

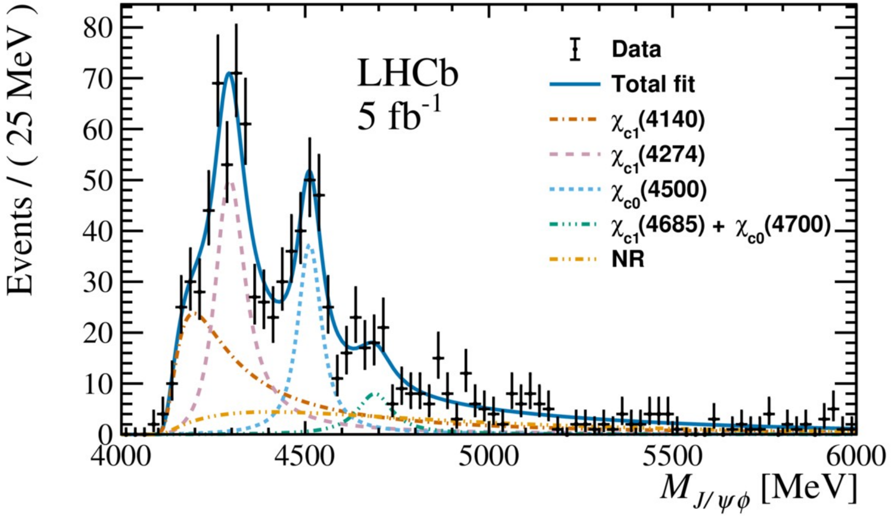
→ no clear mass structure



Observation of diffractive exotic J/ψϕ resonances in *pp* collisions

arXiv:2407.14301

After imposing the exclusivity requirement, a resonant structure appears



$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4140)} = (0.80 \pm 0.15 \pm 0.28)\,\text{pb},$$

$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} = (0.73 \pm 0.08 \pm 0.17)\,\text{pb},$$

$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)} = (0.42^{+0.09}_{-0.08} \pm 0.06)\,\text{pb},$$

$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06} \pm 0.06)\,\text{pb},$$

$$\sigma_{\rm NR} \times \mathcal{B}_{\rm eff}^{\rm NR} = (0.43^{+0.24}_{-0.18} \pm 0.20)\,\text{pb},$$

Fit performed with previously observed resonances in B decays.

- Turn-on derived from events with more than four VELO tracks
- Non-resonant is modeled by an exponential function
- No interference assumed

The significance for the resonances $\chi_{c1}(4140)$, $\chi_{c1}(4274)$ and $\chi_{c0}(4500)$ are 2.4 σ, 4.3 σ and 5.5 σ.

Several clear resonant structures are observed well-described by resonant model

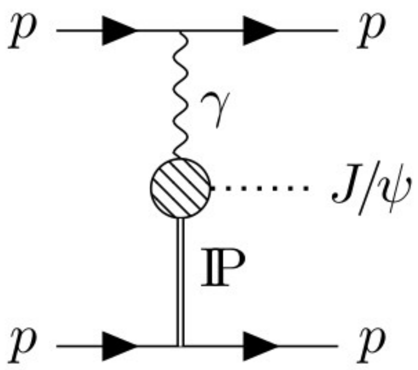
This is the first observation of X → J/ψϕ production in diffractive processes

Exclusive J/ψ and ψ(2S) production at 13 TeV

arXiv:2409.03496

Update measurement with full Run 2 data

For the first time, the dependence of the J/ψ and ψ(2S) cross-sections on the total transverse momentum transfer is determined in pp collisions

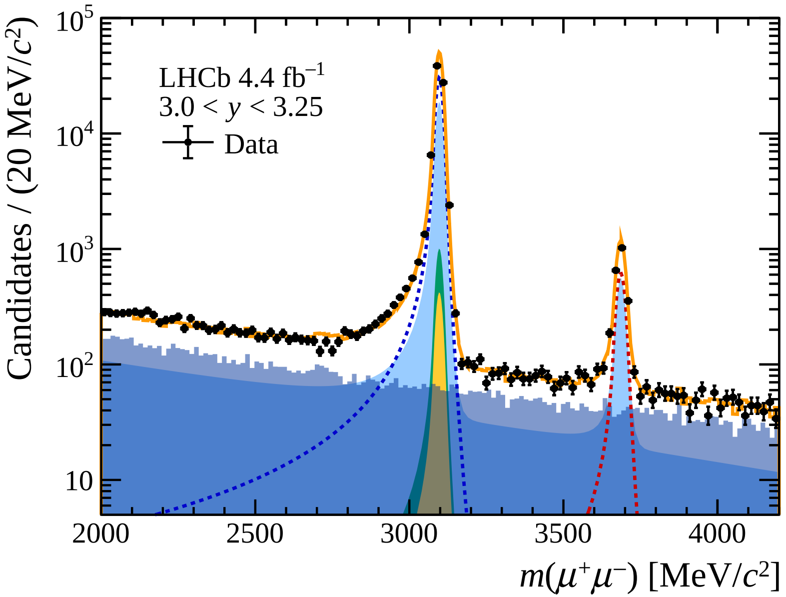


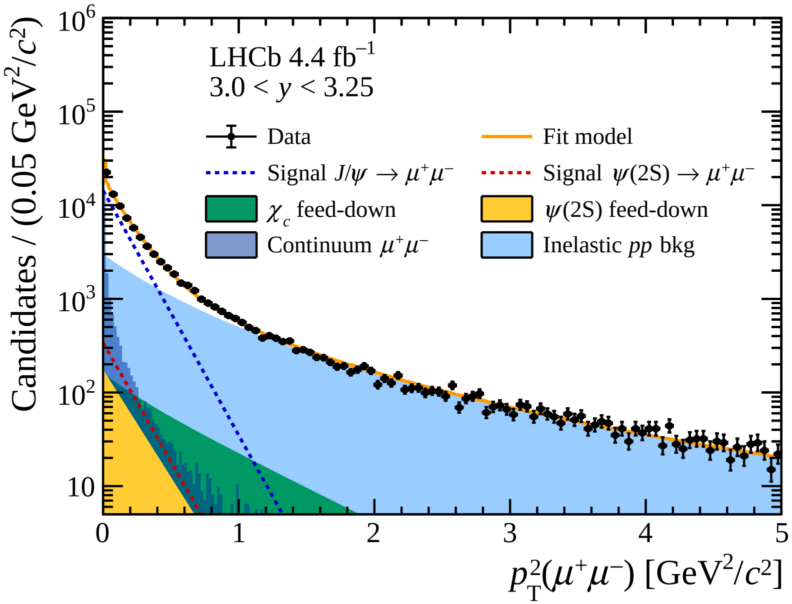
Experimental strategy: Two muons in very clean events

zero Photons, two VELO tracks and Herschel requirement

Exclusive J/ψ and ψ(2S) production at 13 TeV

arXiv:2409.03496

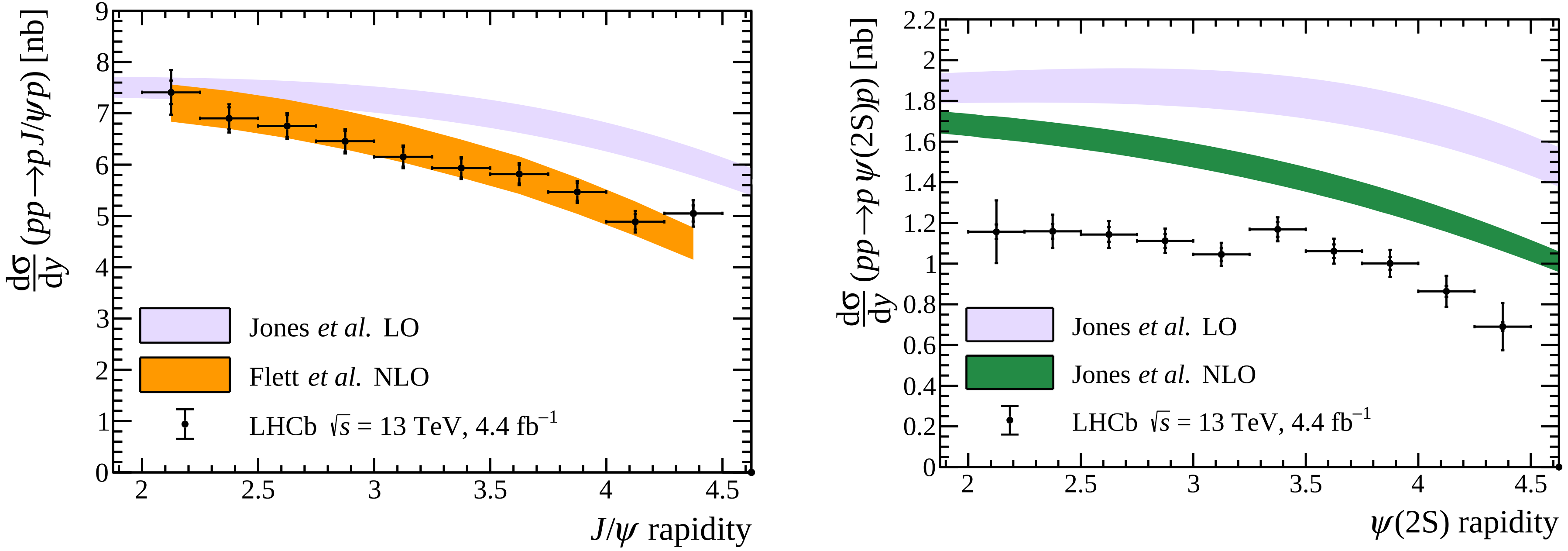




- Signal yields determined in each rapidity interval by a 2D unbinned extended maximum-likelihood fit
- Signal model by a Gaussian function, modified to have power-law tails on both sides
- ψ(2S) feed-down normalised by the ψ(2S) yield in each rapidity interval
- Normalisation of the feed-down from χ_c decays is determined by reconstructing J/ψγ candidates in data

Exclusive J/ψ and ψ(2S) production at 13 TeV

arXiv:2409.03496

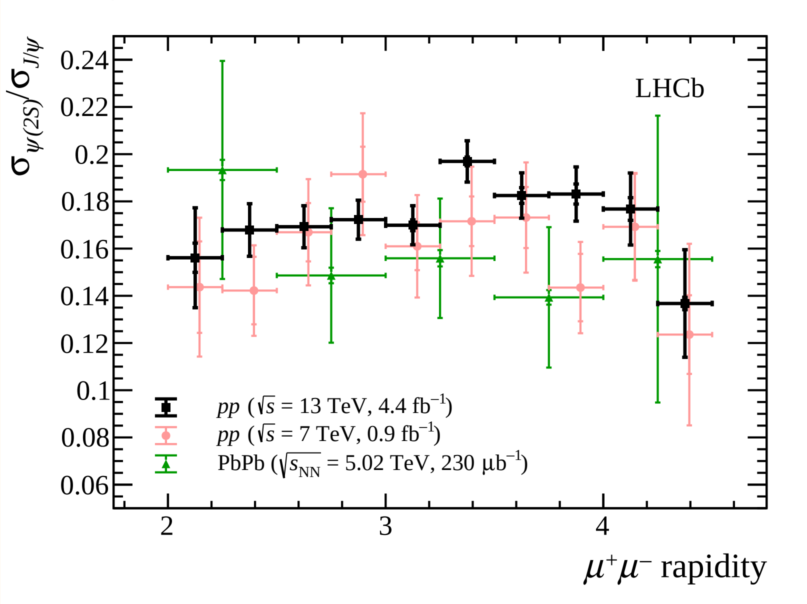


- J/ψ cross-section agrees with the NLO prediction
- ψ(2S) cross-section is significantly lower than both the LO and NLO predictions

Exclusive J/ψ and ψ(2S) production at 13 TeV

arXiv:2409.03496

$$\frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi}} = 0.1763 \pm 0.0029 \pm 0.0008 \pm 0.0039$$



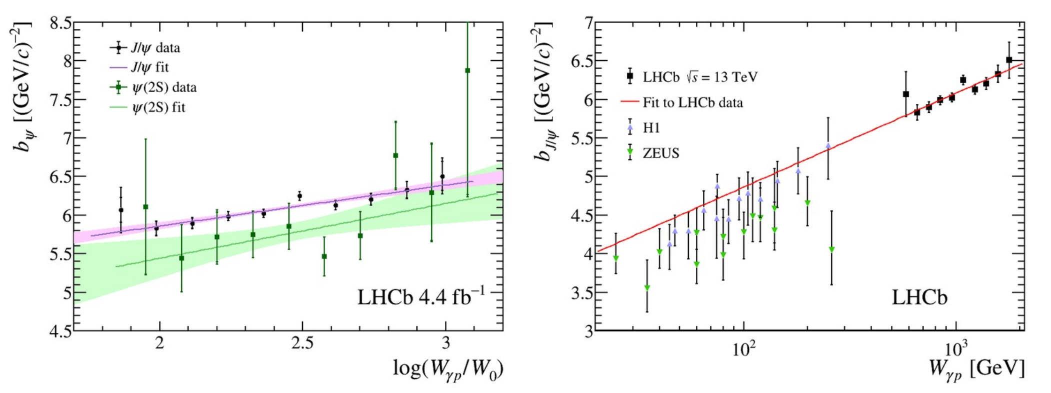
Ratio average is consistent with other LHCb measurements H1 and ZEUS results

Photoproduction cross-section can be calculated

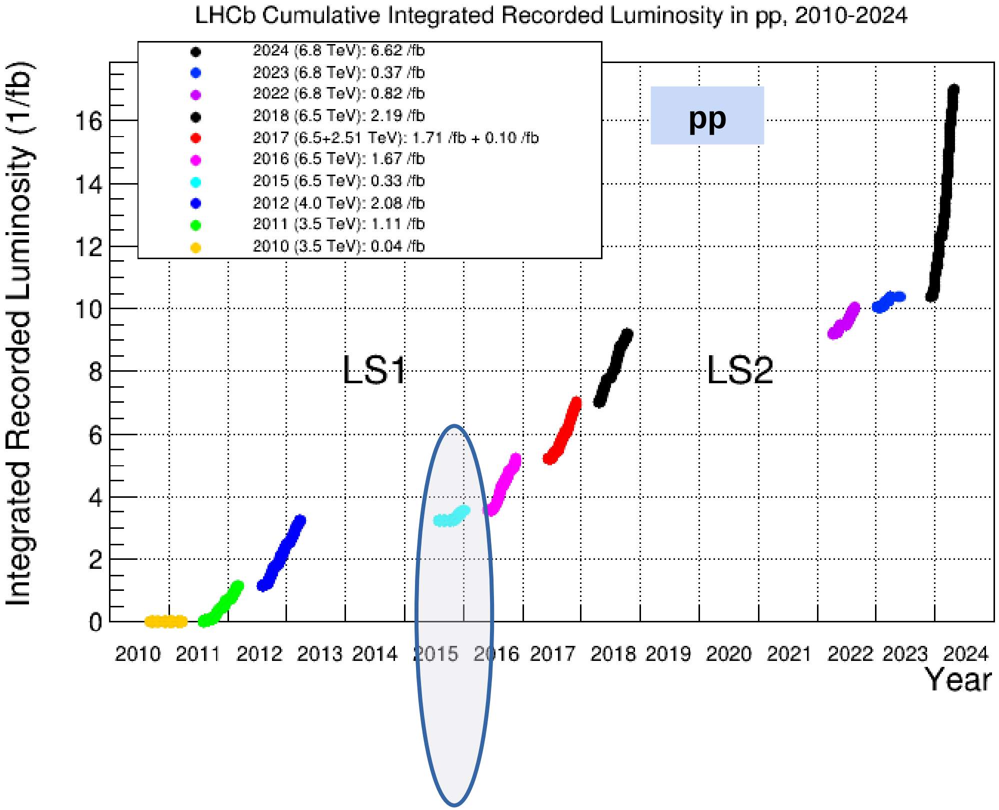
$$\frac{d\sigma}{dy}(pp \to p\psi p) = S^2(W_{\gamma p,+})\left(k_+\frac{dn}{dk_+}\right)\sigma^{W_{\gamma p,+}}_{\gamma p\to\psi p} + S^2(W_{\gamma p,-})\left(k_-\frac{dn}{dk_-}\right)\sigma^{W_{\gamma p,-}}_{\gamma p\to\psi p}$$

And exponential behavior can be measured

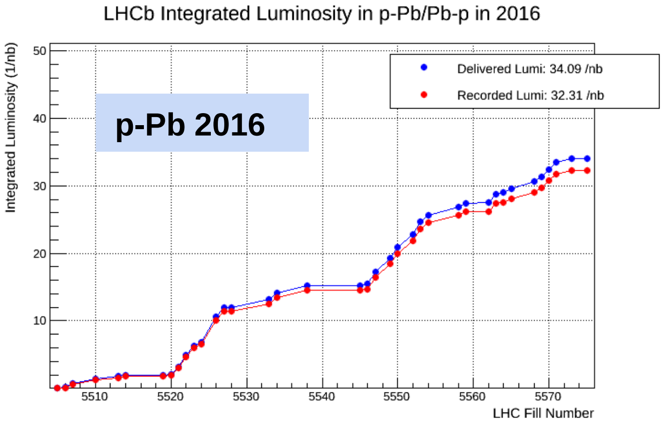
$$d\sigma/dp_T^2 \sim e^{-bp_T^2} \qquad b = b_0 + 4\alpha' \log\left(\frac{W_{\gamma p}}{W_0}\right)$$



J/ψ behavior agrees with data from ep collisions



LHCb Cumulative Integrated Recorded Luminosity in pp, 2010-2024
2024 (6.8 TeV): 6.62 /fb
2023 (6.8 TeV): 0.37 /fb
2022 (6.8 TeV): 0.82 /fb
2018 (6.5 TeV): 2.19 /fb
2017 (6.5+2.51 TeV): 1.71 /fb + 0.10 /fb
2016 (6.5 TeV): 1.67 /fb
2015 (6.5 TeV): 0.33 /fb
2012 (4.0 TeV): 2.08 /fb
2011 (3.5 TeV): 1.11 /fb
2010 (3.5 TeV): 0.04 /fb
pp
LS1
LS2
Integrated Recorded Luminosity (1/fb)
Year



LHCb Integrated Luminosity in p-Pb/Pb-p in 2016
Delivered Lumi: 34.09 /nb
Recorded Lumi: 32.31 /nb
p-Pb 2016
Integrated Luminosity (1/nb)
LHC Fill Number

η and η′ production in pp and pPb collisions

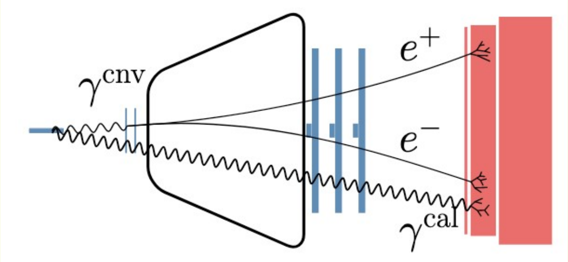
Phys. Rev. C109 (2024) 024907

→pPb data at 8.16 TeV

→pp samples at 5 TeV and 13 TeV (8 TeV is constructed by interpolating both samples)

→η(→γγ) and η'(→ηππ)candidates reconstructed with two ECAL cluster photons

→Reconstruction efficiencies are calibrated using candidates with one converted photon



→η/η' yield is obtained using binned maximum likelihood fits in each p_T region.

Background:

combinatorial background (using mixing events)

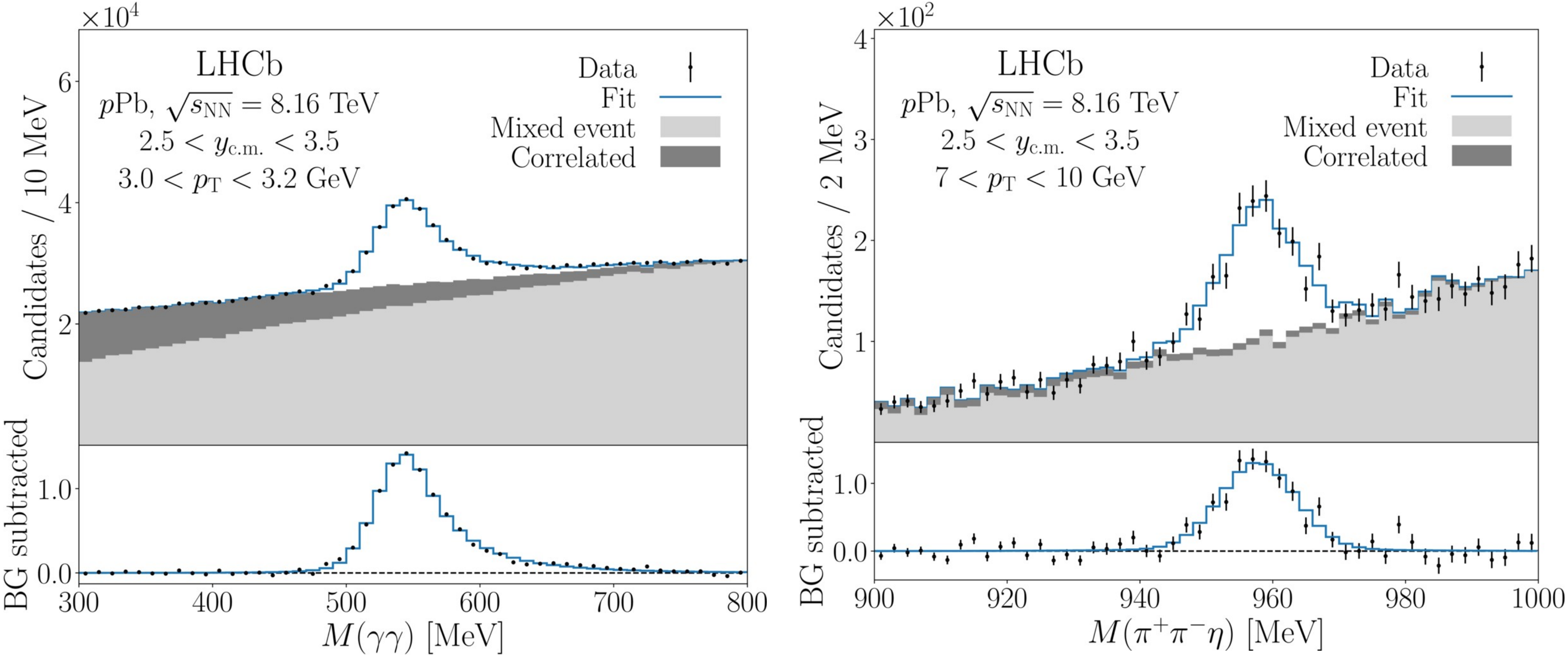
correlated production: photons nearby in the detector (function to model)

Signal: two-sided Crystal Ball function (tails fixed from simulation)

η and η′ production in pp and pPb collisions

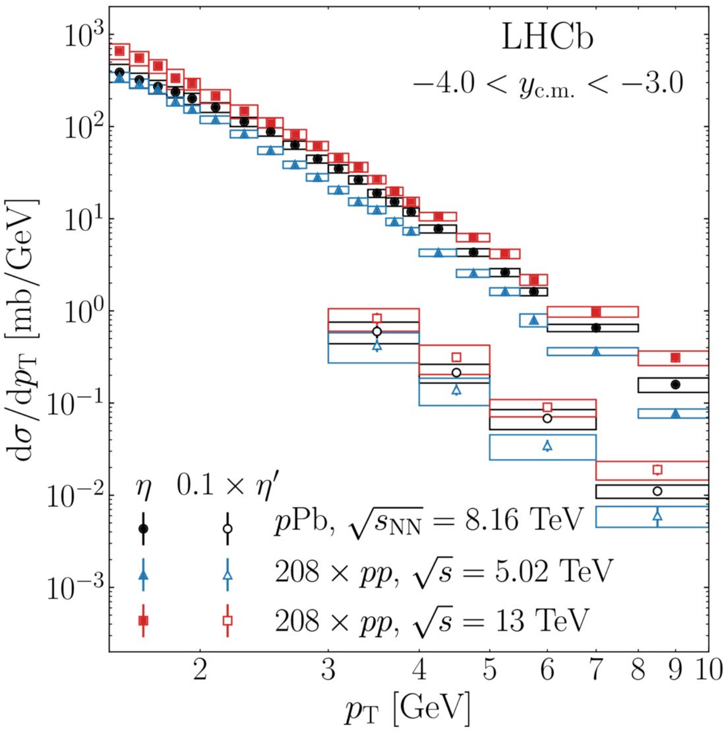
Phys. Rev. C109 (2024) 024907

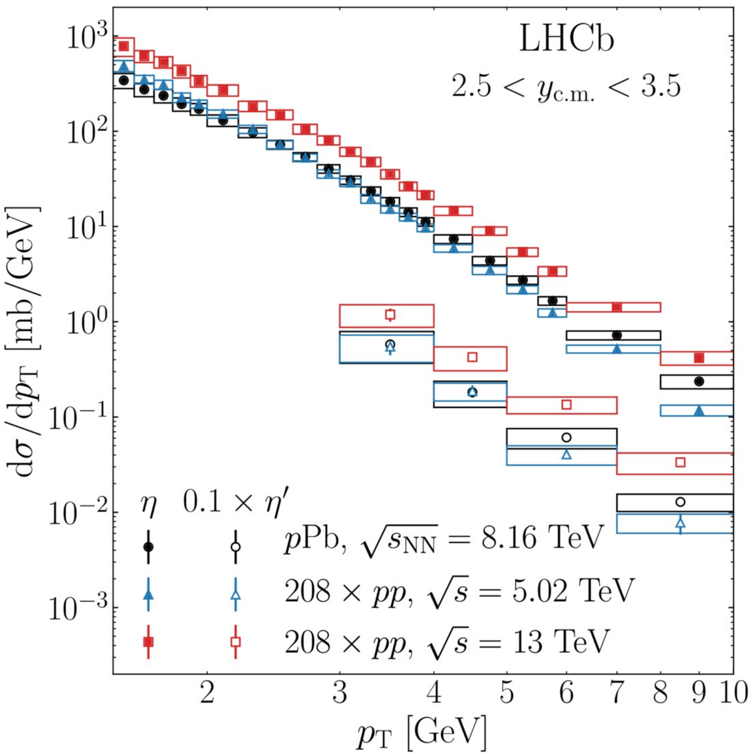
$y_{CM} = y_{lab} - 0.465$



η and η′ production in pp and pPb collisions

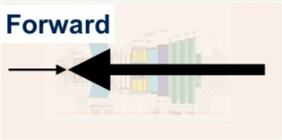
Phys. Rev. C109 (2024) 024907

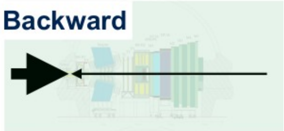


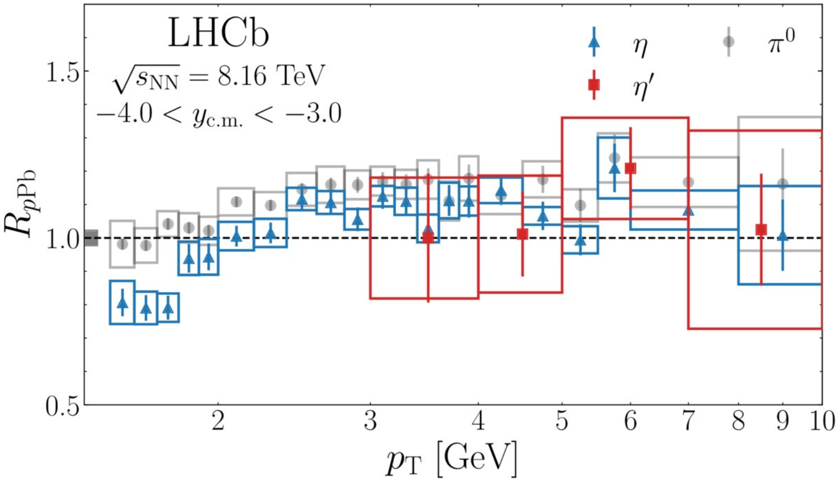


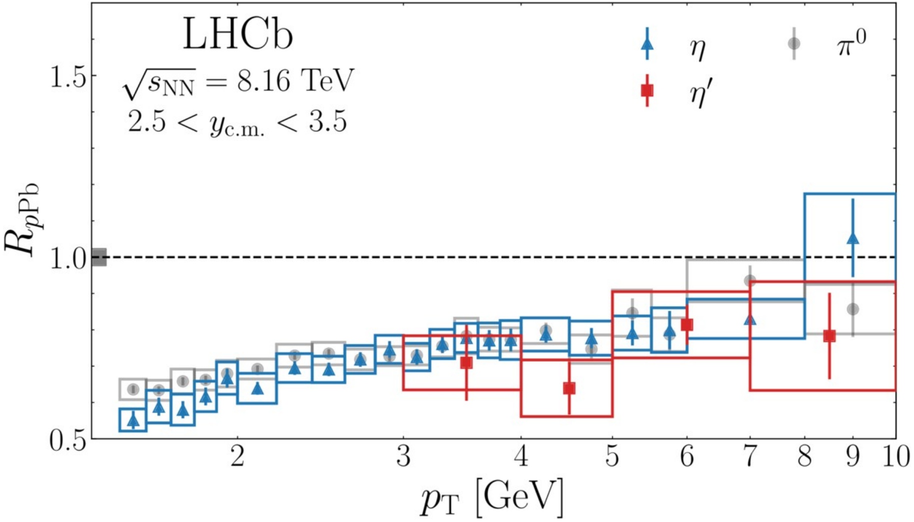
η and η′ production in pp and pPb collisions

Phys. Rev. C109 (2024) 024907





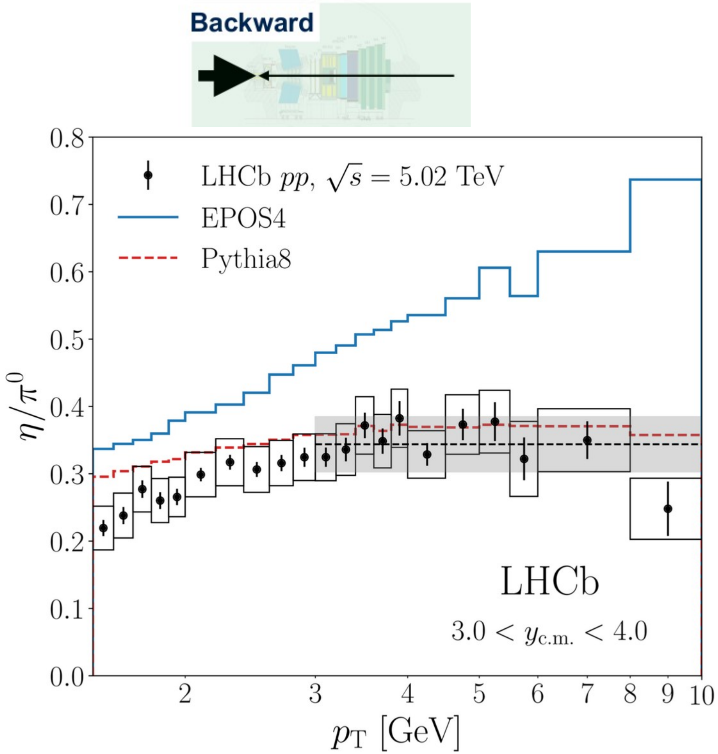


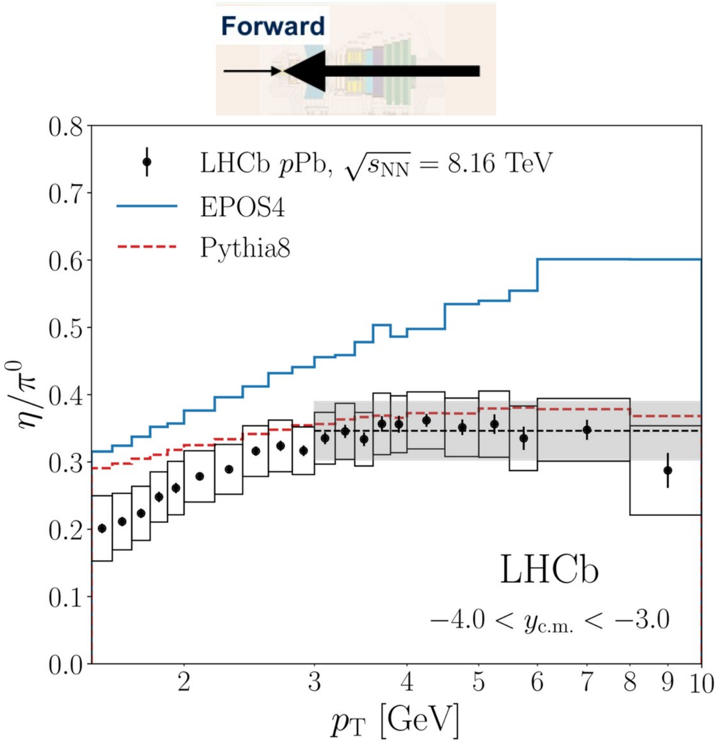


-- Observed suppression consistent with the effects of nuclear shadowing
-- Small deviations at low $p_T < 3$ GeV.
-- No significant evidence for mass dependence of the nuclear modification factor of light neutral mesons.

η and η′ production in pp and pPb collisions

Phys. Rev. C109 (2024) 024907



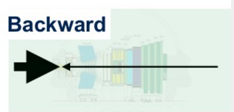


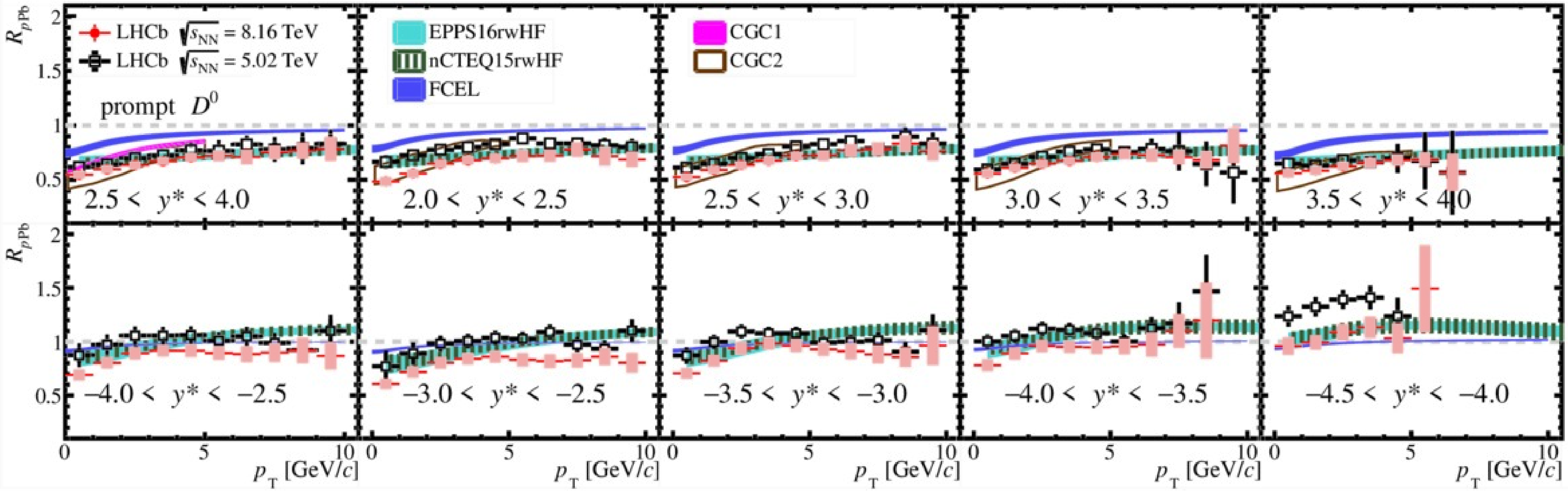
Pythia8 generally describes the data well
EPOS4 generally overestimates the η/π^0 ratio, especially at high p_T .

Prompt D^0 production in pPb at 8.16 TeV

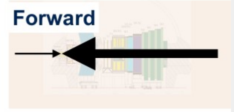
Phys. Rev. Lett. 131 (2023) 102301

→ pPb data at 5 TeV → Prompt D^0 decaying into $K^{\pm}\pi^{\mp}$
→ Nuclear modification factor in different rapidity bins





++ R_{pPb} in forward regions in general agreement with CGC and nPDF models
++ Stronger suppression for R_{pPb} at lowest p_T in forward rapidity than nPDF prediction
++ More suppressed R_{pPb} at high p_T in backward region than nPDF models

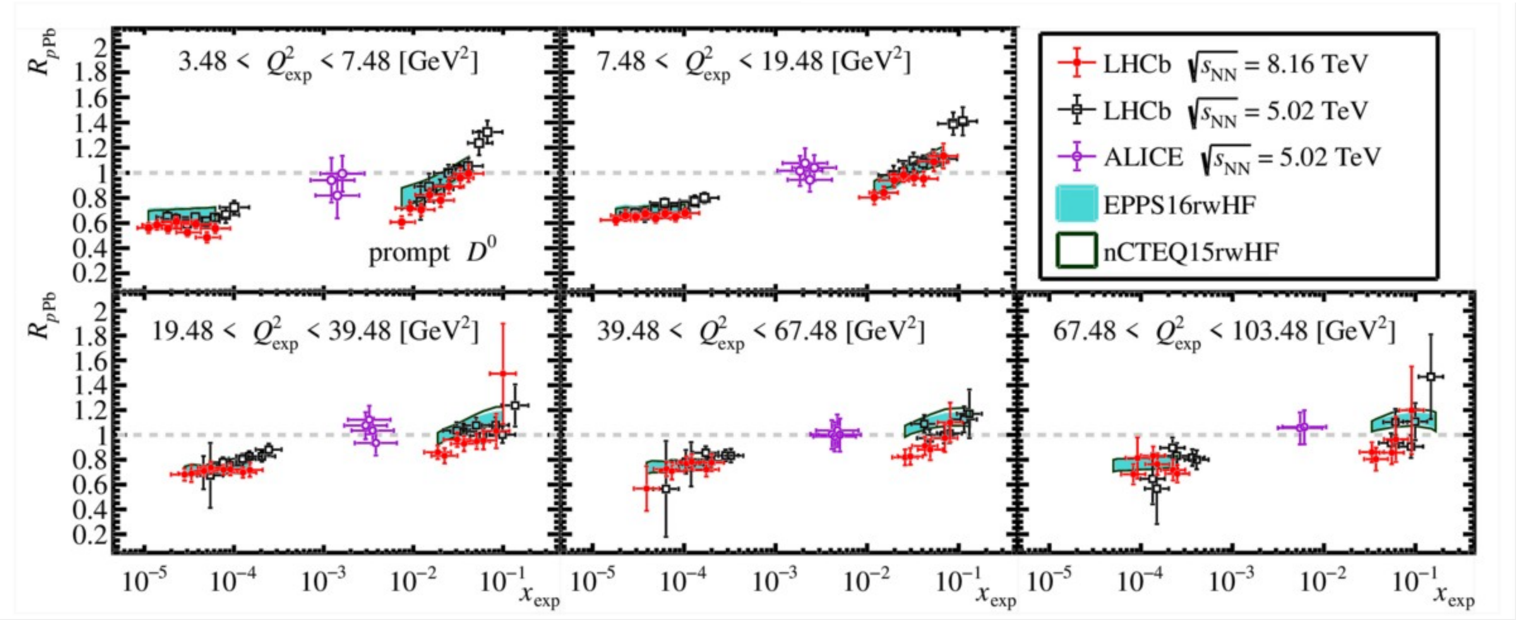


Prompt D^0 production in pPb at 8.16 TeV

Phys. Rev. Lett. 131 (2023) 102301

→ Experimental proxies for comparing results in different energy and kinematic regions

$$x_{\text{exp}} \equiv 2\frac{\sqrt{p_{\mathrm{T}}^2(D^0)+M^2(D^0)}}{\sqrt{s_{\mathrm{NN}}}}e^{-y^*} \text{ and } Q^2_{\text{exp}} \equiv p_{\mathrm{T}}^2(D^0)+M^2(D^0)$$



Consistency between LHCb results at 5.02 TeV and 8.16 TeV

Stronger suppression than nPDF calculations in x ~0.01 at larger Q^2

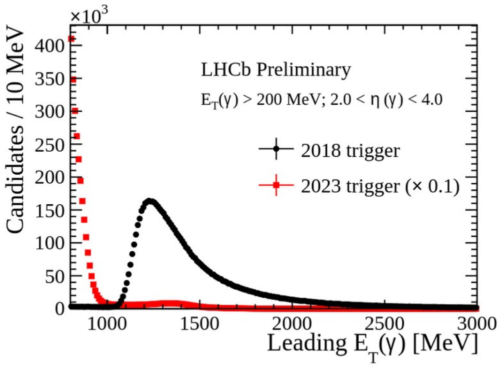
Summary

--- LHCb experiment collected data in pp/pA/PbA collisions with unique coverage

--- Measurements already can constrain models in low-x regions and nuclear effects

--- New results in the pipeline with Run 2 data

--- Run 3 data collection on-going → interesting results ahead with better trigger lines

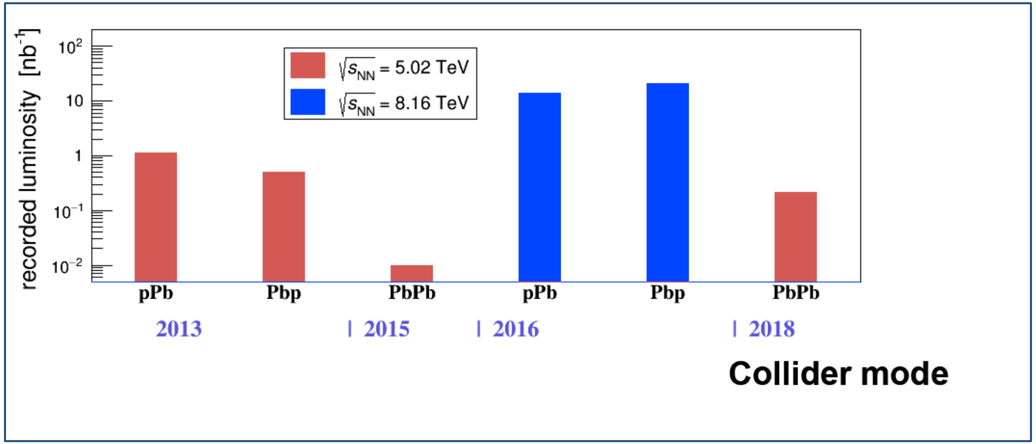


2023 UPC photon trigger line is able to select lower E_T photons than 2018

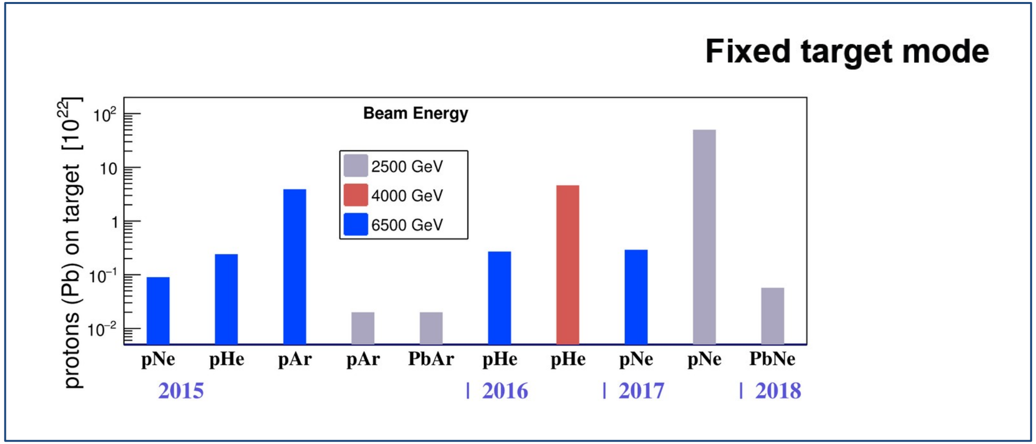
https://cds.cern.ch/record/2898822/files/LHCb-FIGURE-2024-012.pdf

--- Other measurements not shown can be found https://lbfence.cern.ch/alcm/public/analysis

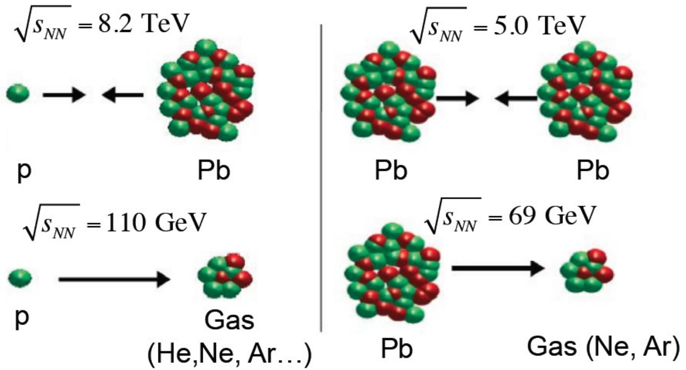
THANK YOU



recorded luminosity [nb^{-1}]
$\sqrt{s_{NN}}$ = 5.02 TeV
$\sqrt{s_{NN}}$ = 8.16 TeV
pPb
Pbp
PbPb
pPb
Pbp
PbPb
2013
2015
2016
2018
Collider mode



Fixed target mode
protons (Pb) on target [10^{22}]
Beam Energy
2500 GeV
4000 GeV
6500 GeV
pNe
pHe
pAr
pAr
PbAr
pHe
pHe
pNe
pNe
PbNe
2015
2016
2017
2018

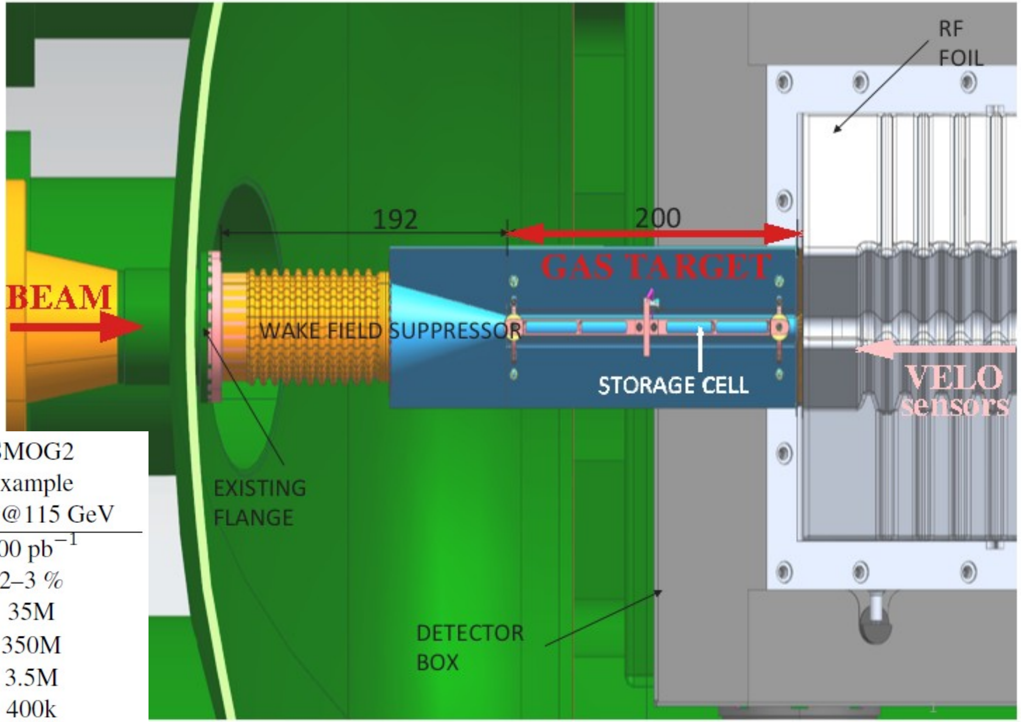


$\sqrt{s_{NN}} = 8.2$ TeV
p
Pb
$\sqrt{s_{NN}} = 5.0$ TeV
Pb
Pb
$\sqrt{s_{NN}} = 110$ GeV
p
Gas
(He,Ne, Ar…)
$\sqrt{s_{NN}} = 69$ GeV
Pb
Gas (Ne, Ar)

The gas target upgrade - SMOG2

LHCC-2019-0051/LHCb TDR 20

- 20cm long storage cell, 5mm radius around the beam, just upstream the VELO
- possibly inject other gases
- Up to x100 higher gas density with same gas flow of current SMOG
- Faster switch between gas species



	SMOG largest sample p–Ne@68 GeV	SMOG2 example p–Ar@115 GeV
Integrated luminosity	$\sim 100\ \mathrm{nb}^{-1}$	$100\ \mathrm{pb}^{-1}$
syst. error on J/ψ x-sec.	6–7%	2–3 %
J/ψ yield	15k	35M
D^0 yield	100k	350M
Λ_c yield	1k	3.5M
$\psi(2S)$ yield	150	400k
$\Upsilon(1S)$ yield	4	15k
Low-mass ($5 < M_{\mu\mu} < 9\ \mathrm{GeV}/c^2$) Drell-Yan yield	5	20k

LHCb Upgrade I

CERN-LHCC-2012-007

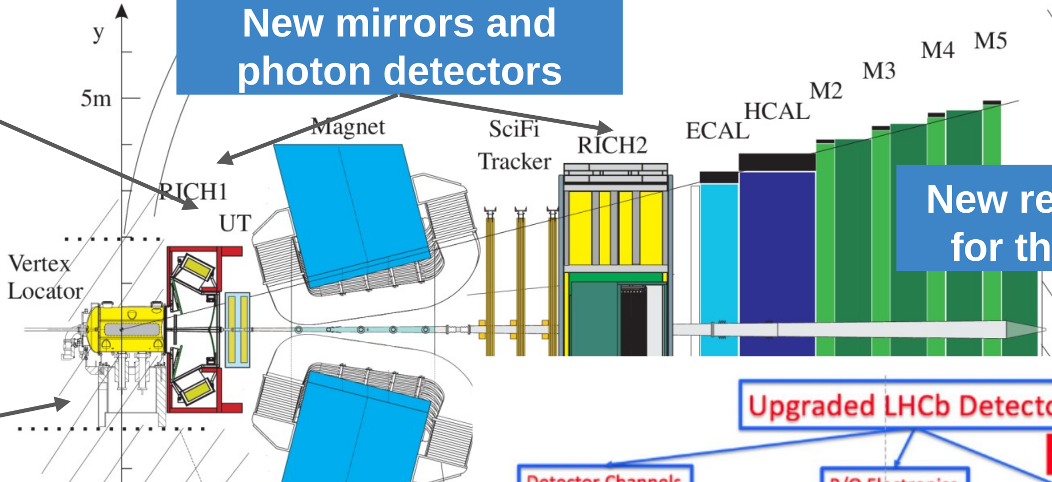
UT
(new silicon tracker)

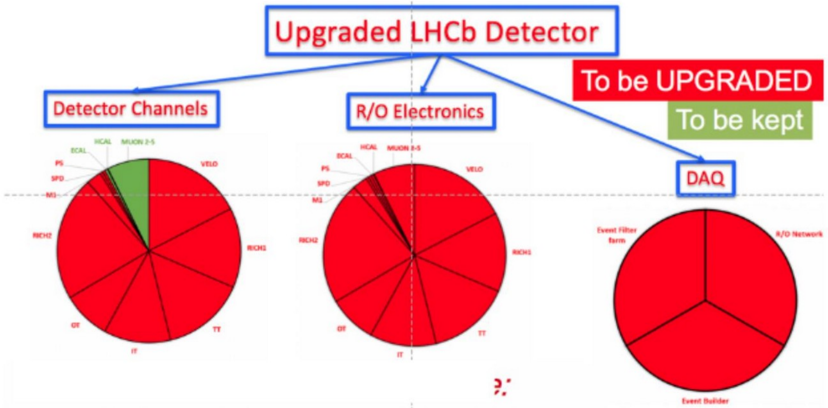
New mirrors and photon detectors

New readout electronics for the entire detector

New VELO
(Pixel Detector)

SciFi
(new scintillating fibre tracker)





Murilo Santana Rangel (UFRJ)
33

LHCb Upgrade I

CERN-LHCC-2012-007

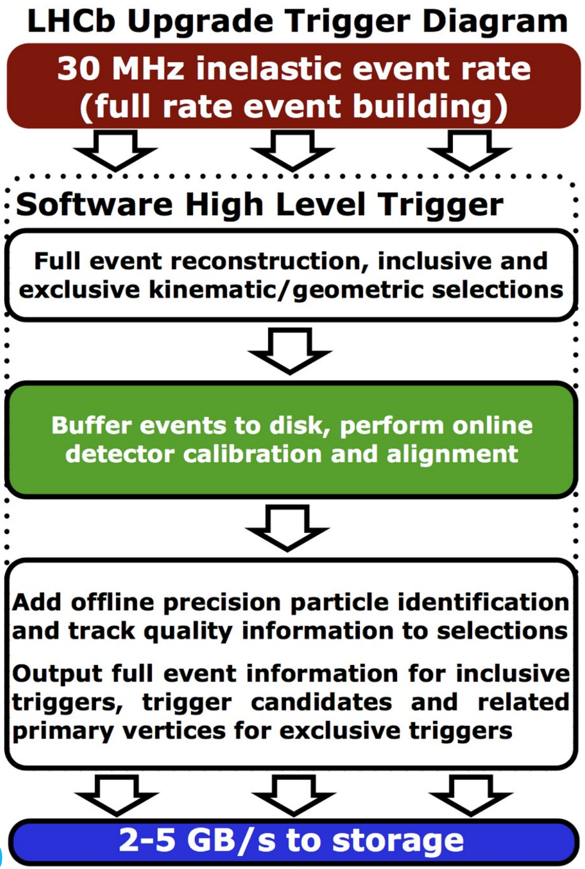
❈ Increase instantaneous luminosity:
$4 \times 10^{32} \rightarrow 2 \times 10^{33}\ cm^{-2}\ s^{-1}$

❈ Replacement of tracking detectors
♯ finer granularity to cope with higher particle density
♯ new front-end electronics compatible with 30 MHz readout

❈ Remove hardware trigger stage and operate software trigger at 30 MHz input rate with 5 x more pileup than Run 2.

❈ Prospects for integrated luminosity for heavy-ion

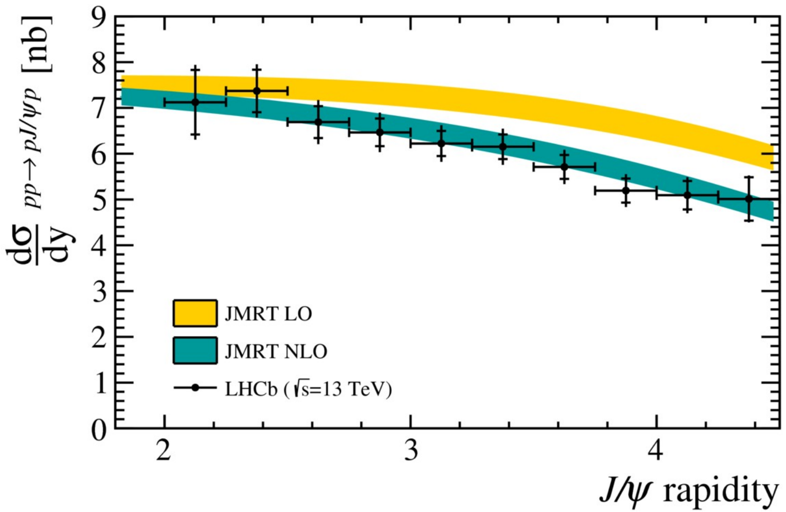
PbPb	**0.5/nb**
pPb	**150/nb**

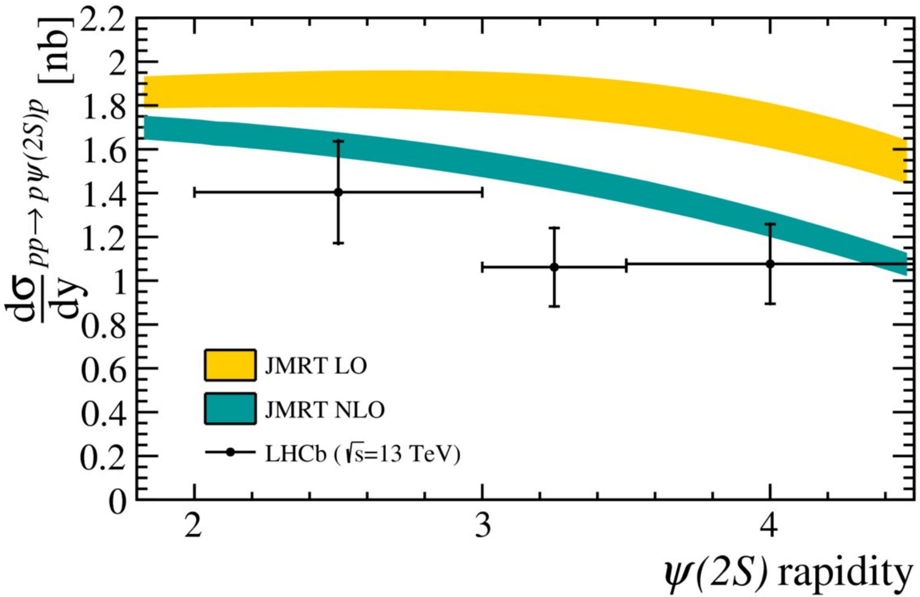


LHCB-PUB-2014-0

J/ψ and $\psi(2S)$ - 13 TeV

JHEP 10 (2018) 167





N → candidate events
P → signal purity
ϵ → efficiencies
Δy → rapidity bin width
L → luminosity

$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy}(2.0 < \eta_\mu < 4.5) = \frac{\mathcal{P}N}{\epsilon_{rec}\epsilon_{sel}\Delta y \epsilon_{single}\mathcal{L}_{tot}}$$

J/ψ and $\psi(2S)$ - 13 TeV

JHEP 10 (2018) 167

Selection

→ 2 reconstructed muons $(2<\eta<4.5)$

→ No additional tracks or photons

→ Herschel requirement (next slide)

→ Mass window requirements

→ $p_T^2<0.8\,GeV^2$

$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy}(2.0<\eta_\mu<4.5)=\frac{\mathcal{P}N}{\epsilon_{rec}\epsilon_{sel}\Delta y\epsilon_{single}\mathcal{L}_{tot}}$$

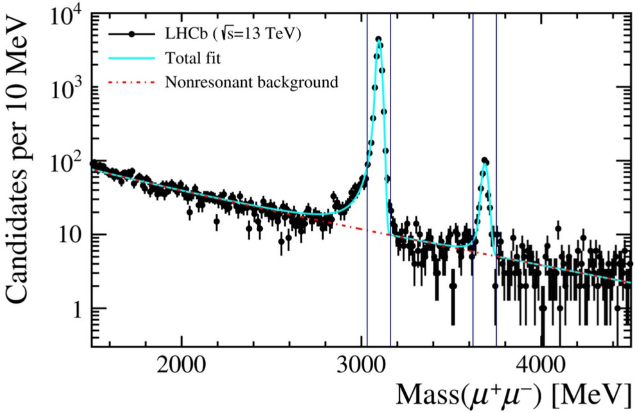
N → candidate events

P → signal purity

ϵ → efficiencies

Δy → rapidity bin width

L → luminosity



$L=204\,pb^{-1}(2015)$

14753 J/ψ candidates

440 $\psi(2S)$ candidates

J/ψ and $\psi(2S)$ - 13 TeV

JHEP 10 (2018) 167

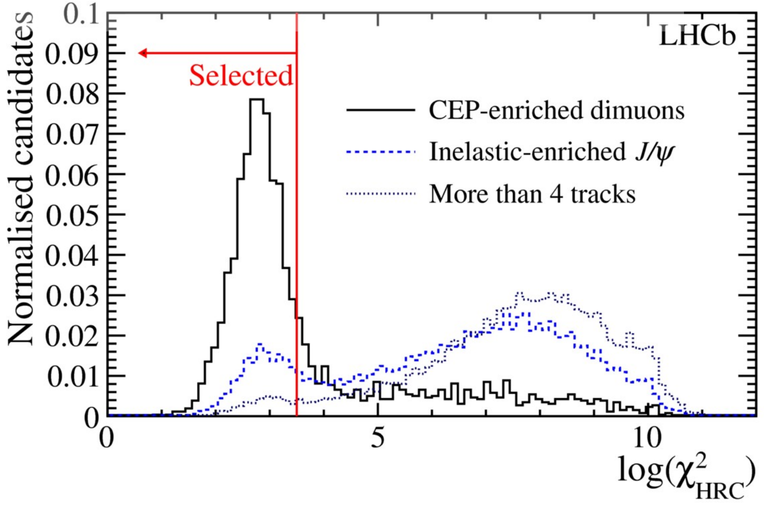
The HeRSCheL response is described using a variable χ^2_{HRC} that quantifies the activity above noise, taking account of correlations between thecounters.

Clear discrimination observed when comparing:

+CEP-enriched dimuons: $p_T^2 < 0.01\, GeV^2$

+More than four tracks

+Inelastic-enriched J/ψ: $p_T^2 > 1\, GeV^2$



J/ψ and $\psi(2S)$ - 13 TeV

$$\frac{d\sigma_{\psi\to\mu^+\mu^-}}{dy}(2.0 < \eta_\mu < 4.5) = \frac{\mathcal{P}N}{\epsilon_{rec}\epsilon_{sel}\Delta y \epsilon_{single}\mathcal{L}_{tot}}$$

Background fractions for J/ψ ($\psi(2S)$)

➔Non-resonant estimated from DiMuon mass: 0.009 (0.161)

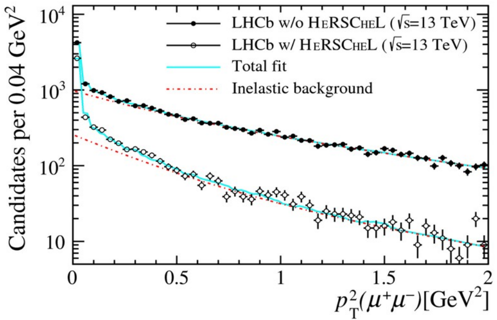
➔Feed-down estimated using data: 0.06 (neglected)

➔Proton dissociation with a new techinique (see next slide): 0.175 (0.11)

Efficiencies

≫ reconstruction and selection➔data driven methods

≫ fraction of single interaction beam crossings➔0.3662 ± 0.0003



Fits to the p_T^2 distributions give the non-resonant CEP events with and without the HeRSCheL veto

The ratio of these gives the efficiency of the veto 0.723 ± 0.008

New Technique:

$N_{HRC} = \varepsilon N_{sig} + \beta(p_T)N_{bkg}$

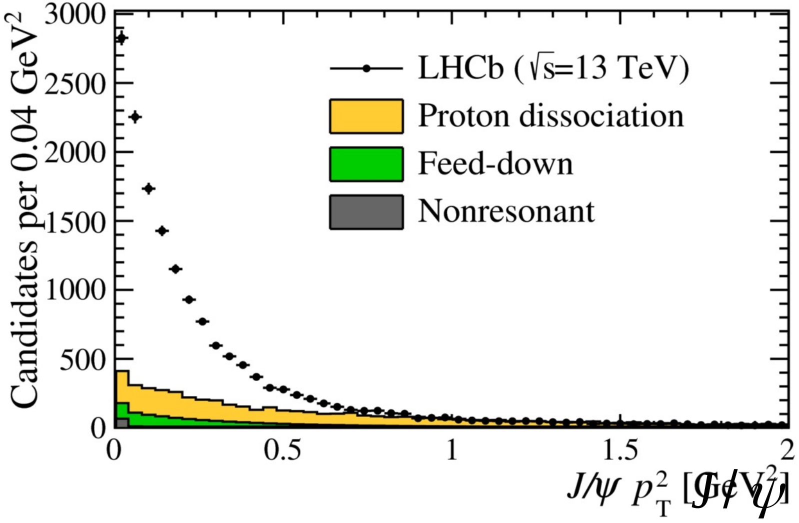
$N_{anti\text{-}HRC} = [1-\varepsilon]N_{sig} + [1-\beta(p_T)]\, N_{bkg}$

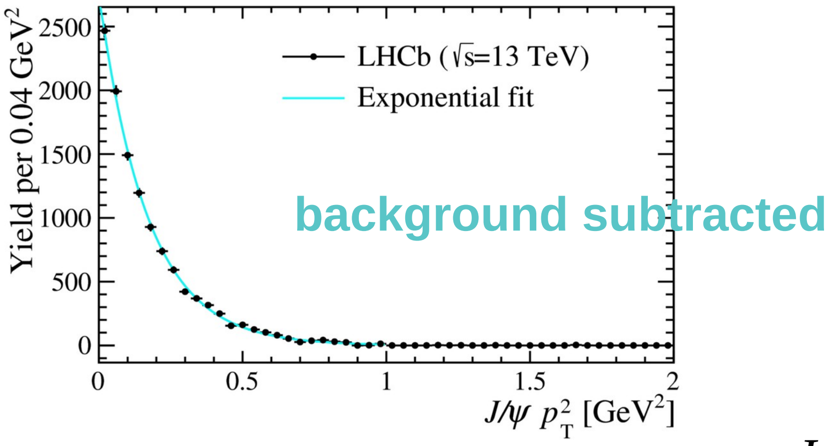
ε known from QED sample

Pure bkg sample obtained

Subtract bkg from total => Signal derived

$$\beta = S_{\bar{\mathrm{H}}} - ((1-\epsilon_{\mathrm{H}})/\epsilon_{\mathrm{H}})S_{\mathrm{H}}$$



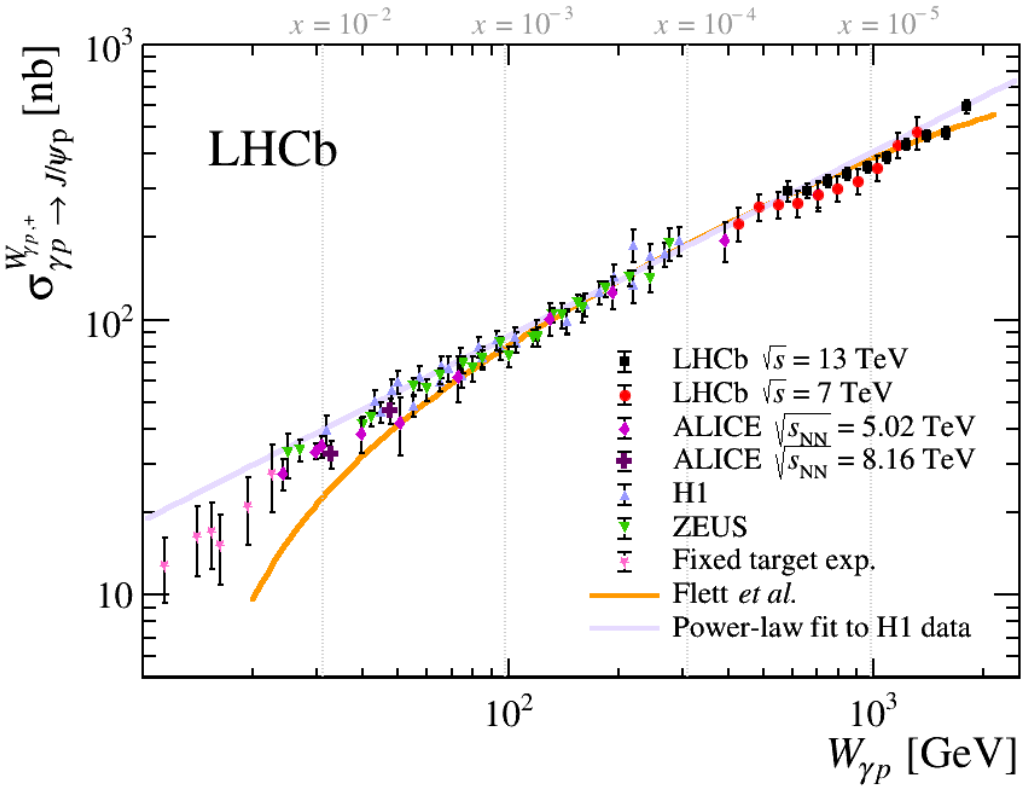


J/ψ

Exclusive J/ψ and ψ(2S) production at 13 TeV

arXiv:2409.03496

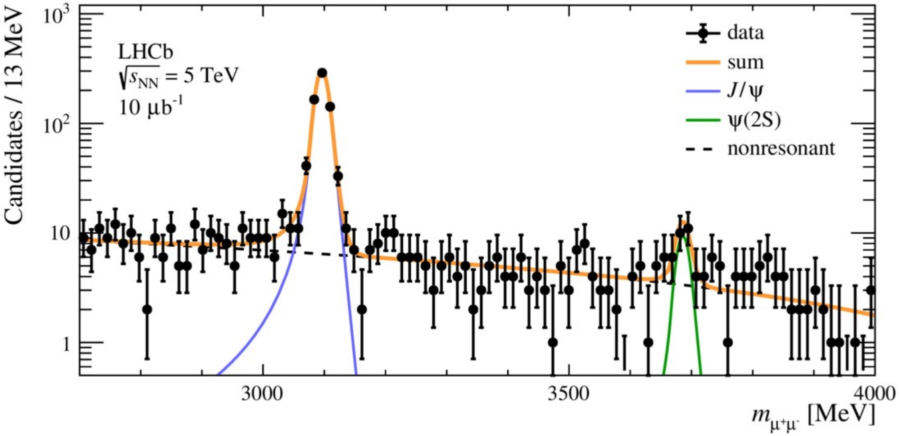
Marker	Experiment	collision	Energy	Refs.
● (red)	LHCb	pp	$\sqrt{s} = 7$ TeV	[33]
◆ (purple)	ALICE	pPb	$\sqrt{s_{\rm NN}} = 5.02$ TeV	[102, 103]
+ (purple)	ALICE	pPb	$\sqrt{s_{\rm NN}} = 8.16$ TeV	[39]
▲ (blue)	H1	ep	$40 < W_{\gamma p} < 305$ GeV	[95]
▲ (blue)	H1	ep	$25 < W_{\gamma p} < 110$ GeV	[89]
▼ (green)	ZEUS	ep	$20 < W_{\gamma p} < 290$ GeV	[96]
✶ (pink)	E87	γBe	$0 < E_\gamma < 250$ GeV	[104]
✶ (pink)	E401	γH and γ^2H	$60 < E_\gamma < 300$ GeV	[105]
✶ (pink)	E516	γH	$60 < E_\gamma < 160$ GeV	[106]

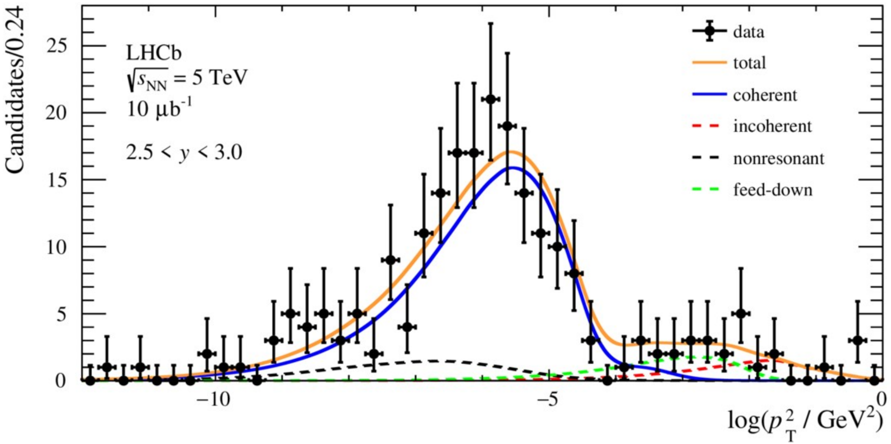


Study of coherent J/ψ production in ultraperipheral PbPb collisions

JHEP07(2022)117

J/ψ Coherent yields are obtained from a fit to the mass and $\log(p_T^2)$ distribution

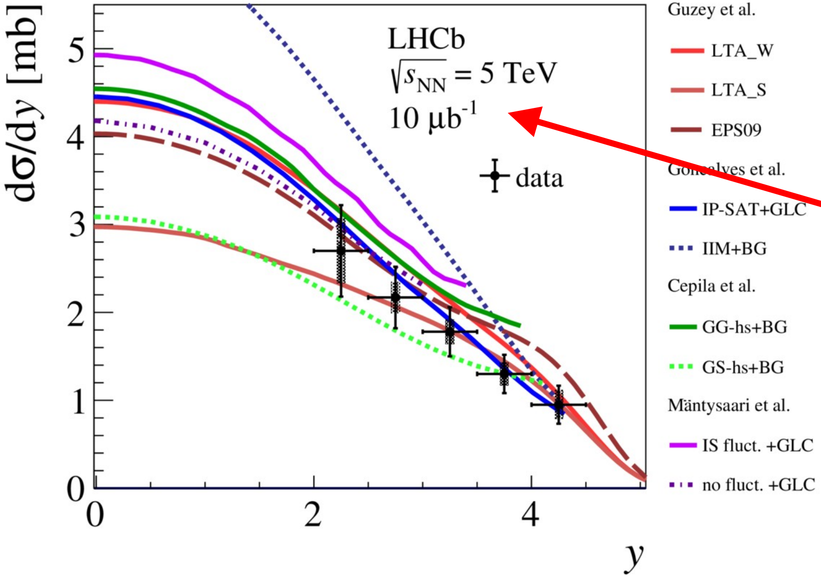


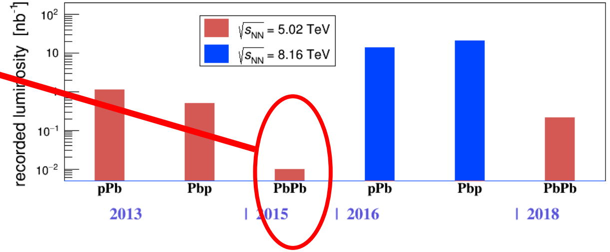


Good signal to background ratio assuming only coherent includes only intact Pb interactions.

Study of coherent J/ψ production in ultraperipheral PbPb collisions

JHEP07(2022)117





Differential cross-sections are compared to predictions from different phenomenological models

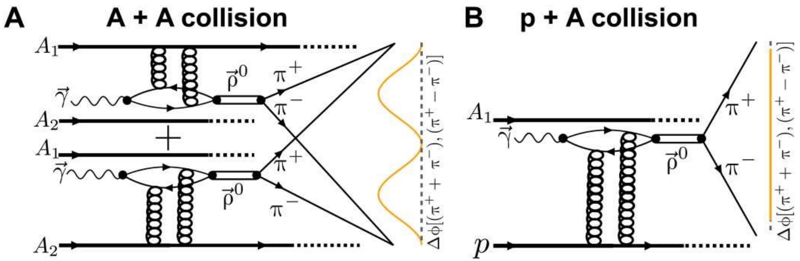
Some prescriptions are disfavored by data

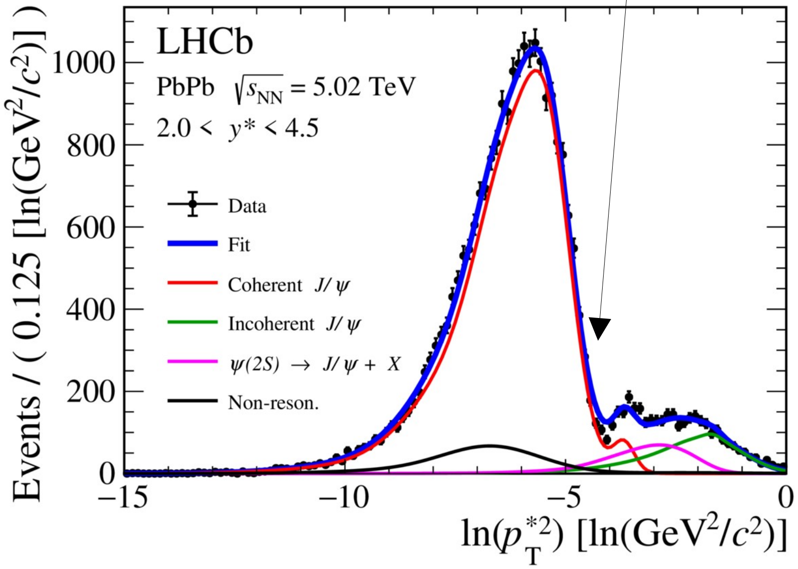
Discussion - Tomography studies

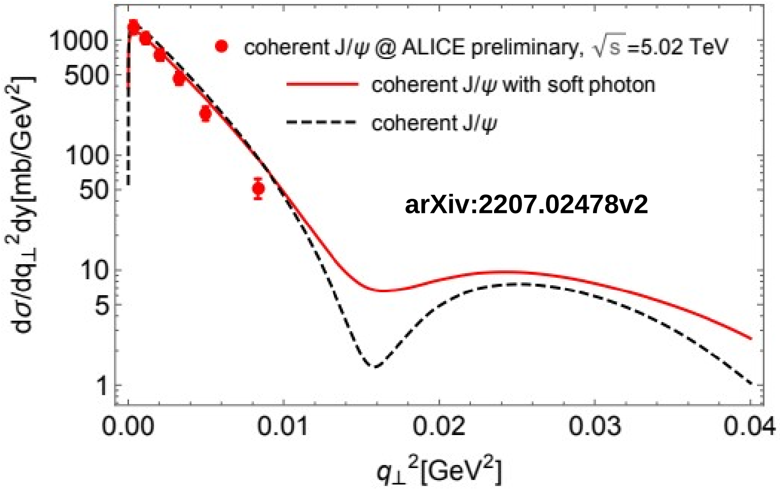
- explore interference for PbPb collisions

- “Double-slit” interference for J/Psi already observed?

STAR Collaboration, Sci. Adv. 9, eabq3903 (2023)







arXiv:2207.02478v2

Observation of diffractive exotic J/ψϕ resonances in *pp* collisions

arXiv:2407.14301

Source	$\chi_{c1}(4140)$	$\chi_{c0}(4700)$	ΔM	δ_1	δ_2	δ_3	Total
$M_{\chi c1}(4274)$ [MeV]	1.7	0.2	1.5	8.0	0.2	2.9	8.9
$\Gamma_{\chi c1}(4274)$ [MeV]	10	0.3	0.7	56	0.8	6.2	57
$M_{\chi c0}(4500)$ [MeV]	0.4	0.4	1.4	0.6	1.6	2.0	3.0
$\Gamma_{\chi c0}(4500)$ [MeV]	1.7	0.2	2.0	3.4	4.4	31	32
$\sigma_{\chi c1}(4140)$	31%	1.5%	0.9%	11%	1.5%	8.3%	35%
$\sigma_{\chi c1}(4274)$	19%	1.6%	0.8%	11%	1.6%	5.8%	24%
$\sigma_{\chi c0}(4500)$	3.2%	0.7%	0.2%	6.5%	11%	5.1%	15%
$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)}$	5.3%	18%	7.3%	3.1%	13%	31%	41%

Observation of diffractive exotic J/ψϕ resonances in *pp* collisions
arXiv:2407.14301

Parameter [MeV]	Current analysis	Ref. [13]
$M_{\chi c1}(4274)$	$4298 \pm 6 \pm 9$	$4294 \pm 4^{+3}_{-6}$
$\Gamma_{\chi c1}(4274)$	$92^{+22}_{-18} \pm 57$	$53 \pm 5 \pm 5$
$M_{\chi c0}(4500)$	$4512.5^{+6.0}_{-6.2} \pm 3.0$	$4474 \pm 3 \pm 3$
$\Gamma_{\chi c0}(4500)$	$65^{+20}_{-16} \pm 32$	$77 \pm 6^{+10}_{-8}$

η and η′ production in pp and pPb collisions

Phys. Rev. C109 (2024) 024907

Systematic uncertainties are dominated by photon efficiency, fit model and interpolation.

Source (%)	$d\sigma^{\eta}/dp_{\mathrm{T}}$	$R^{\eta}_{p\mathrm{Pb}}$	$d\sigma^{\eta'}/dp_{\mathrm{T}}$	$R^{\eta'}_{p\mathrm{Pb}}$
Fit model	0.7–22.9	0.5–12.3	6.0–33.8	2.5–26.4
Unfolding	0.1–2.9	0.1–2.5	0.1–0.3	0.1–0.4
Interpolation	...	0.5–7.5	...	0.1–9.1
Material budget	8.0	...	10.8	...
Photon efficiency	2.5–4.5	1.9–4.7	5.8–10.5	10.1–11.5
Tracking efficiency	...	...	0.2–0.5	0.2–0.4
Luminosity	2.0–2.6	2.2–2.3	2.0–2.6	2.2–2.3
Total systematic	9.1–24.6	3.4–14.8	16.4–36.6	10.8–29.1
Statistical	1.6–13.1	2.7–10.6	4.8–26.1	6.8–16.4