Exotic spectroscopy at LHCb

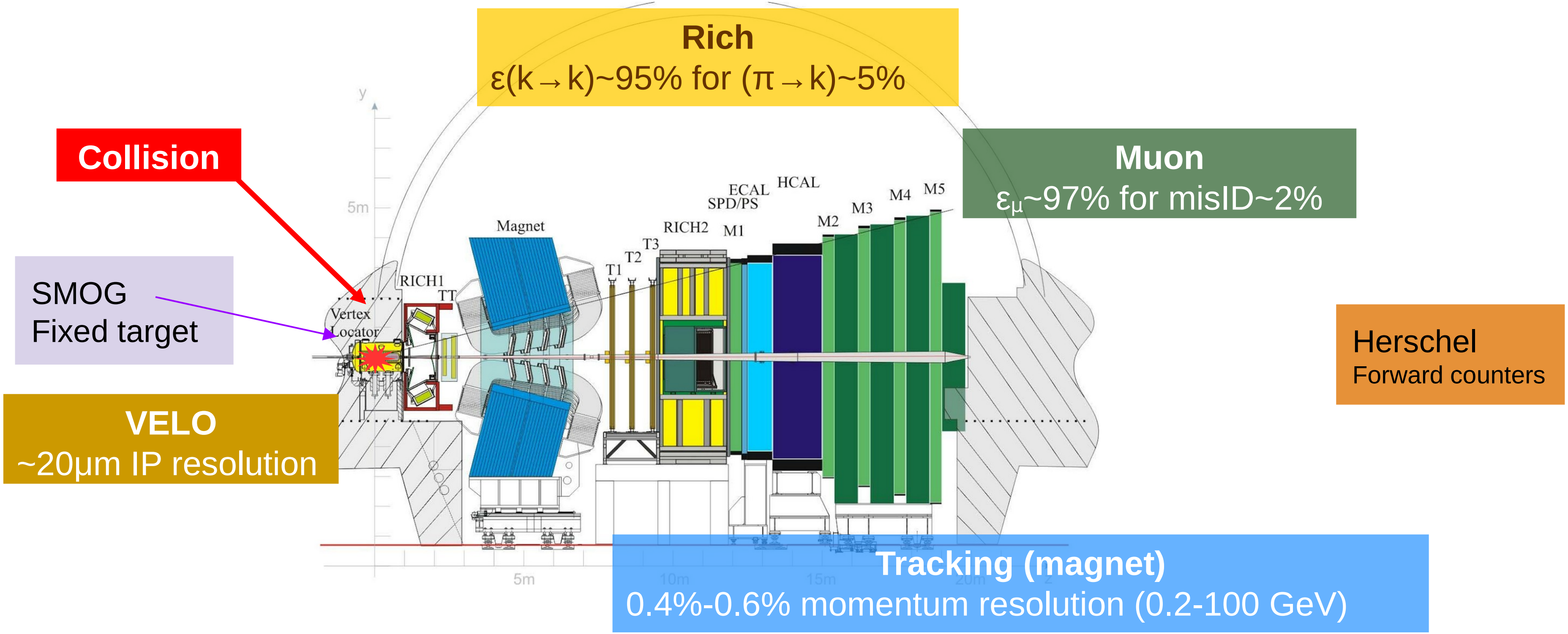
Murilo Rangel
on behalf of the LHCb Collaboration

LHCb experiment overview

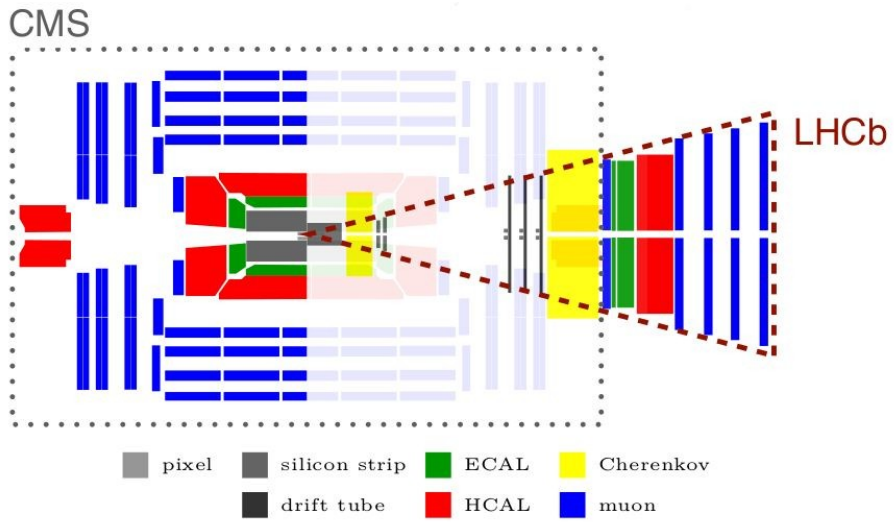
Single arm spectrometer fully instrumented in the forward region (2.0<η<5.0)

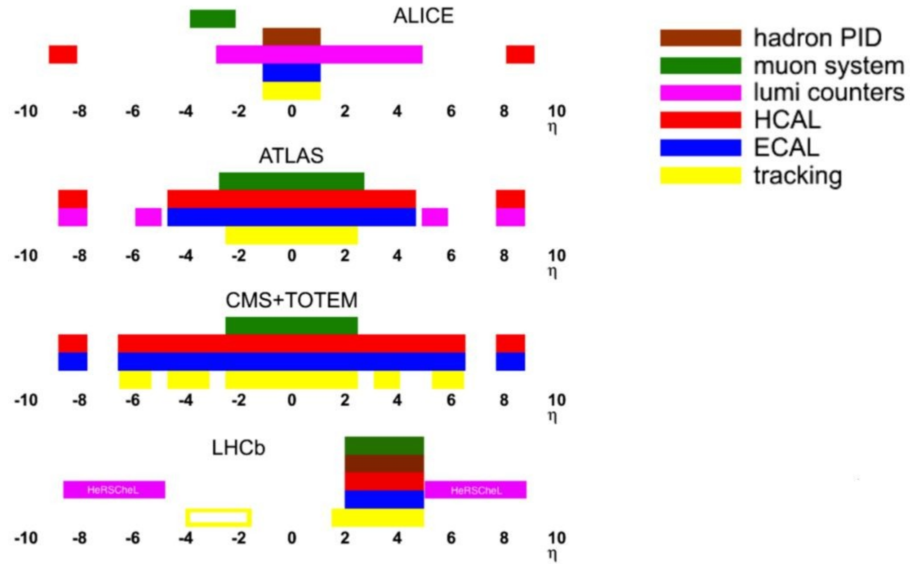
Designed for heavy flavour physics and also exploited for general purpose physics

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

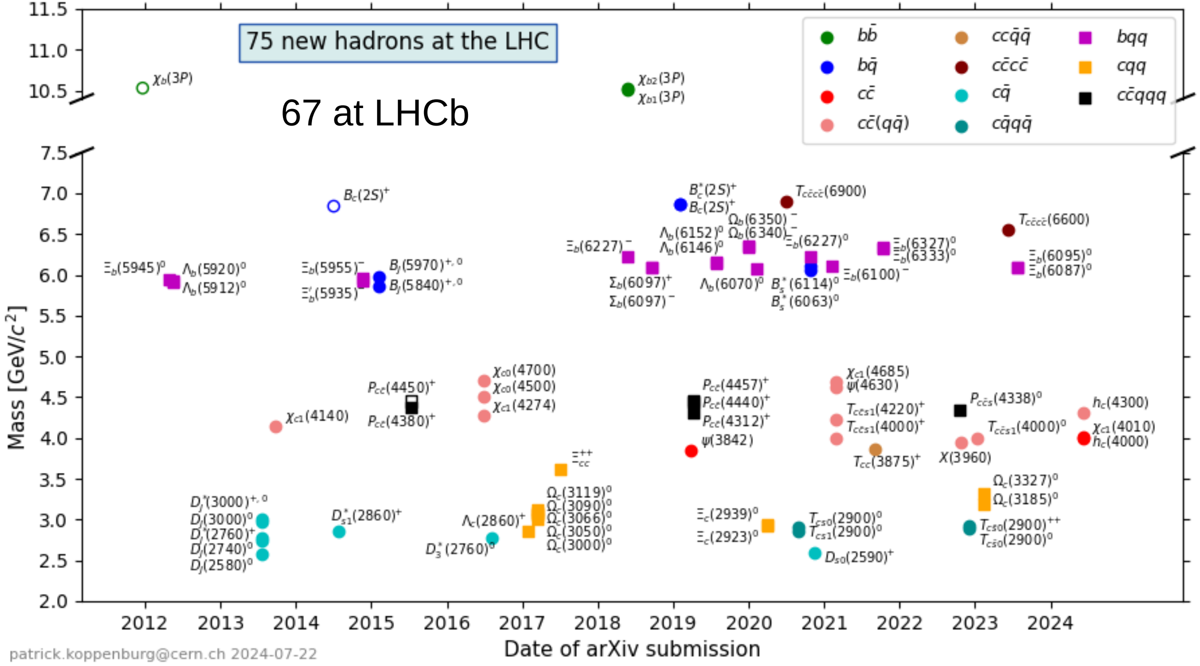


LHCb compared other experiments (outdated version)





Hadrons discovery at LHCb

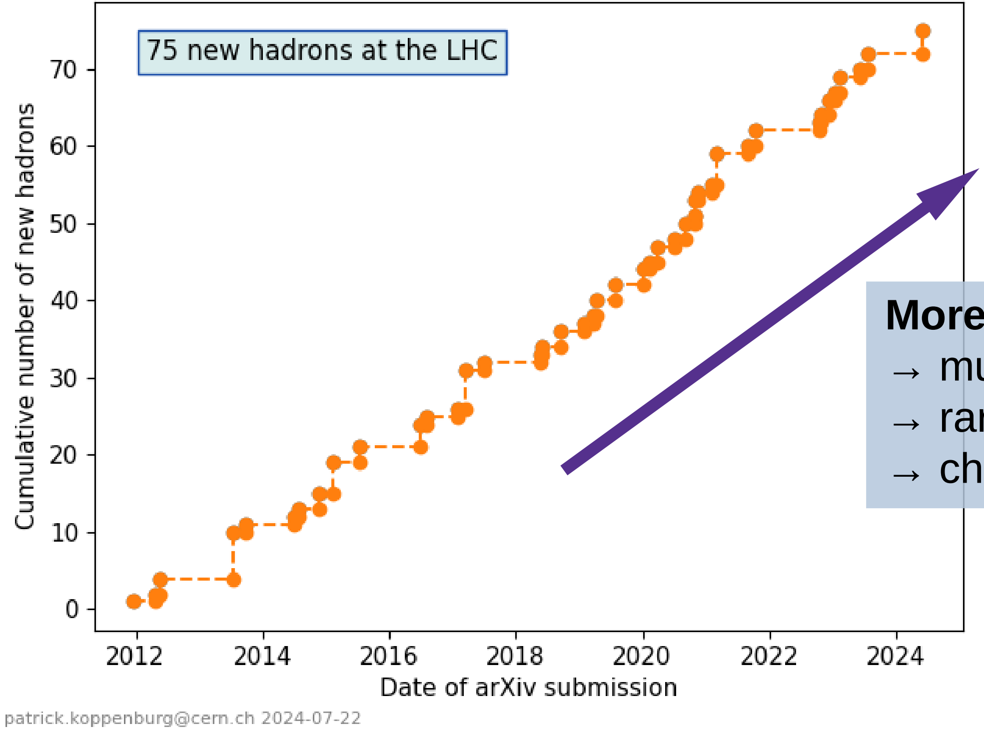


LHCb-FIGURE-2021-001 https://cds.cern.ch/record/2749030
https://www.nikhef.nl/~pkoppenb/particles.html

Many exotic hadrons observed that do not fit the conventional *qq* or *qqq* picture.

23 new exotic states:
- Charged, $c\bar{c}$, $cc\bar{c}\bar{c}$, open flavour
- Pentaquark candidates
- Search for unexpected contributions

Hadrons discovery at LHCb



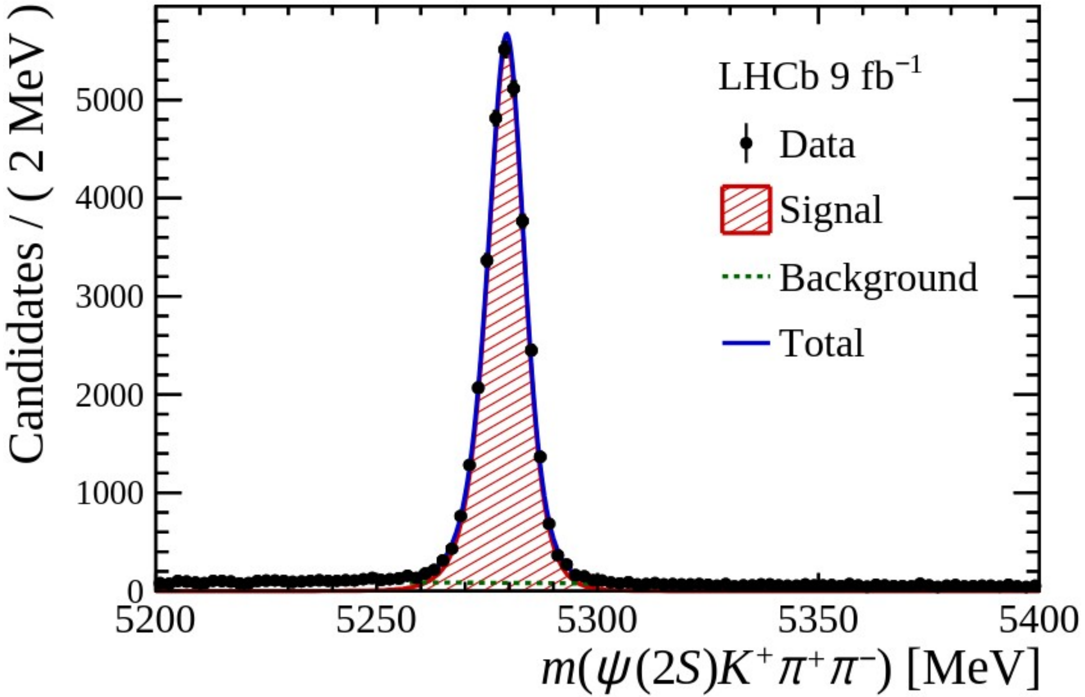
More data allows observation in different cases
→ multidimensional amplitude fits
→ rare decays
→ challenging S/B

LHCb-FIGURE-2021-001 https://cds.cern.ch/record/2749030
https://www.nikhef.nl/~pkoppenb/particles.html

Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$

[arXiv:2407.12475]

Deepen understanding of exotic states in independent decay modes.
Clean signal with ~3% background fraction

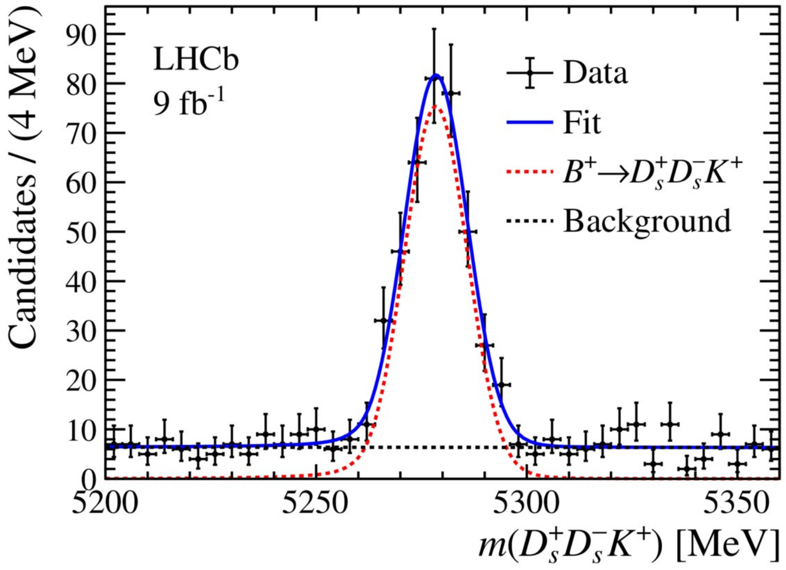


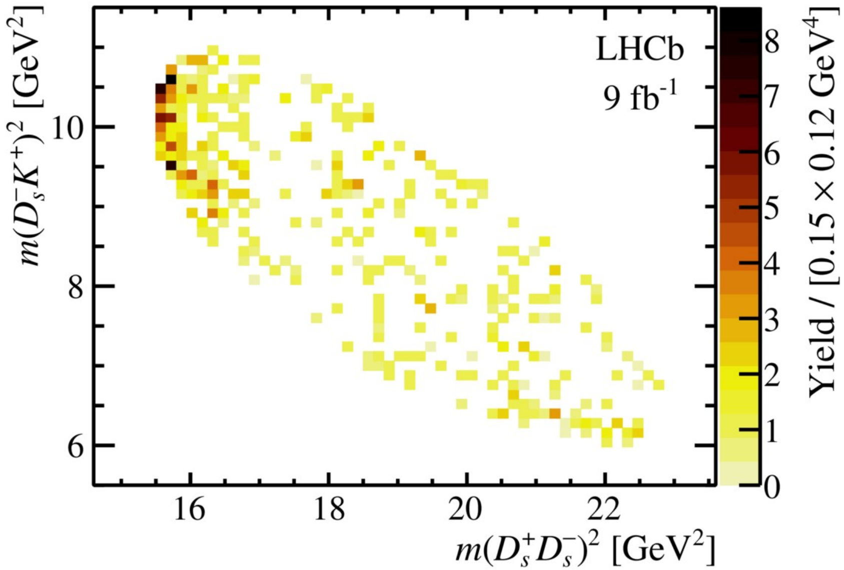
Observation of X(3960)

[PRL131,071901(2023)]

Amplitude analysis using $B^+ \to D_s^+ D_s^- K^+$ with $D_s^+ \to K^+ K^- \pi^+$

PRD 108, 034012 (2023)





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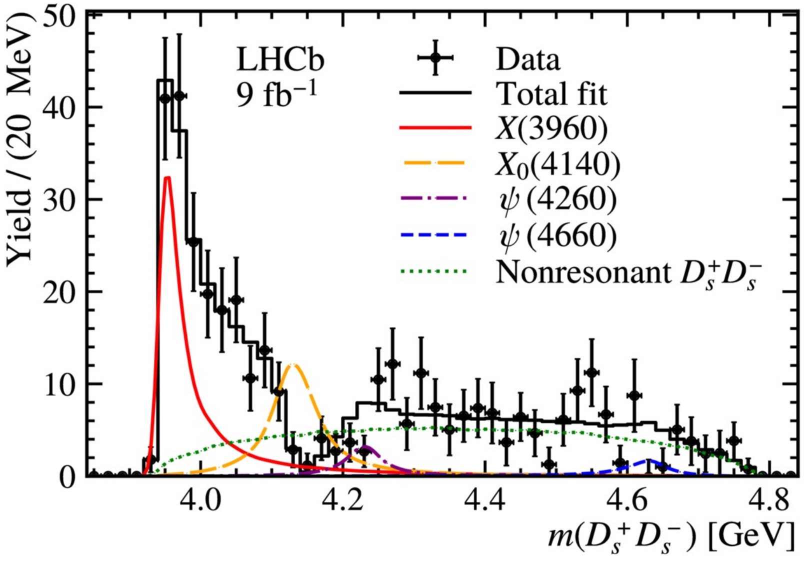
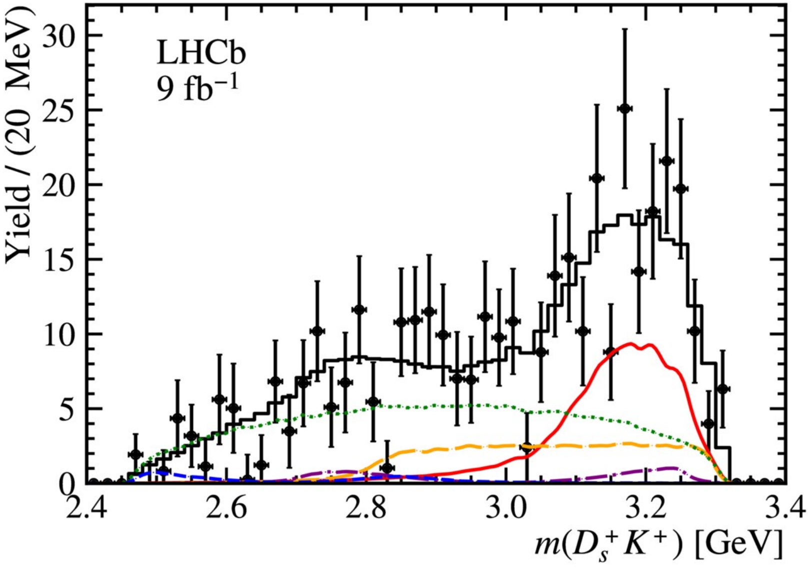


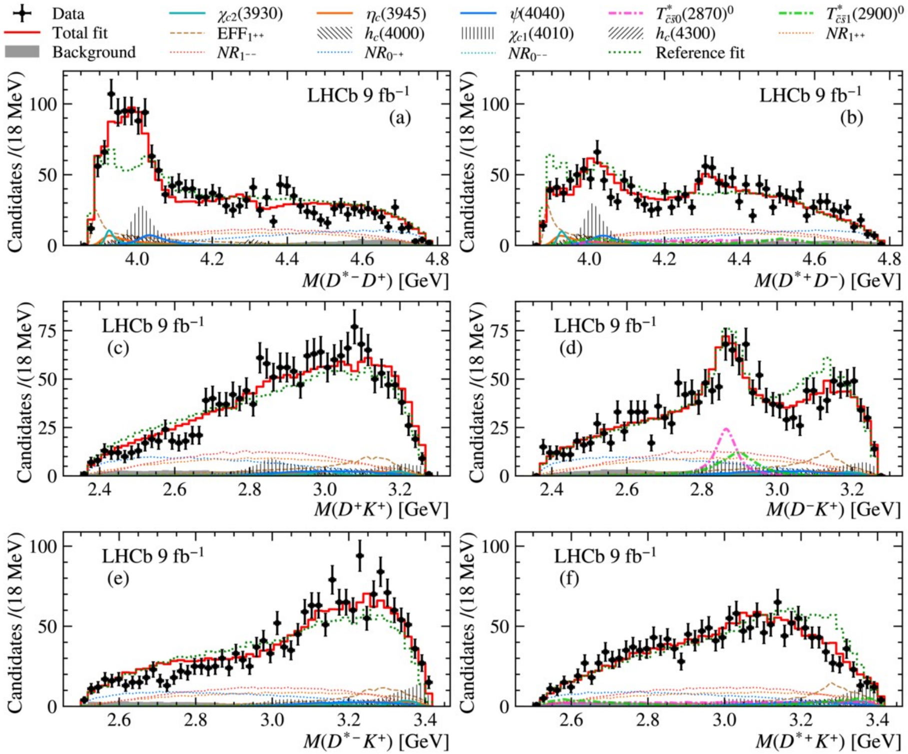


+ Threshold enhancement in the $D_s^+ D_s^-$ mass spectrum
+ X(3960) (14σ) and X_0(4140) (3.9σ) both with preferred $J^{PC} = 0^{++}$
+ X(3960) state is the same as χ_c^0(3930) observed in $B^+ \to D^+ D^- K^+$?
+ More precise measurement are needed and on-going

Amplitude analysis of $B^+ \to D^{*\pm} D^{\mp} K^+$ decays

[arXiv:2406.03156]

Confirmation of the states previously observed in the $B^+ \to D^+ D^- K^+$ [PRD102(2020)112003]



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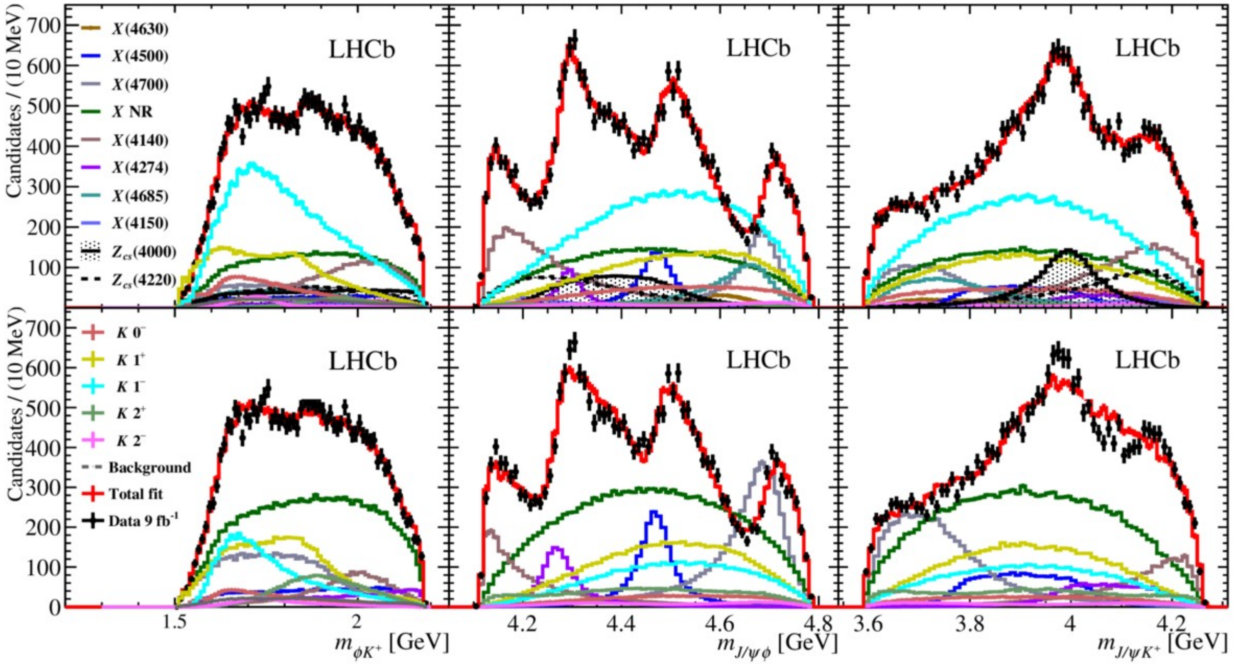
Property	This work	Previous work
$T^*_{\bar{c}\bar{s}0}(2870)^0$ mass [MeV]	$2914 \pm 11 \pm 15$	2866 ± 7
$T^*_{\bar{c}\bar{s}0}(2870)^0$ width [MeV]	$128 \pm 22 \pm 23$	57 ± 13
$T^*_{\bar{c}\bar{s}1}(2900)^0$ mass [MeV]	$2887 \pm 8 \pm 6$	2904 ± 5
$T^*_{\bar{c}\bar{s}1}(2900)^0$ width [MeV]	$92 \pm 16 \pm 16$	110 ± 12
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})$	$(4.5\,^{+0.6}_{-0.8}\,^{+0.9}_{-1.0} \pm 0.4) \times 10^{-5}$	$(1.2 \pm 0.5) \times 10^{-5}$
$\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})$	$(3.8\,^{+0.7}_{-1.0}\,^{+1.6}_{-1.1} \pm 0.3) \times 10^{-5}$	$(6.7 \pm 2.3) \times 10^{-5}$
$\frac{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}0}(2870)^0 D^{(*)+})}{\mathcal{B}(B^+ \to T^*_{\bar{c}\bar{s}1}(2900)^0 D^{(*)+})}$	$1.17 \pm 0.31 \pm 0.48$	0.18 ± 0.05

Exotics in $B^+ \to J/\psi\phi K^+$

[PRL 127 (2021) 082001]

+ In Run1, analysis four $X \to J/\psi\phi$ states were observed with $S>5\sigma$
+ In Run2, ~6 times larger sample: Add more states to the Run1 model to get good description

  5 K* states + 4 X states + $J/\psi\phi$ non-res.



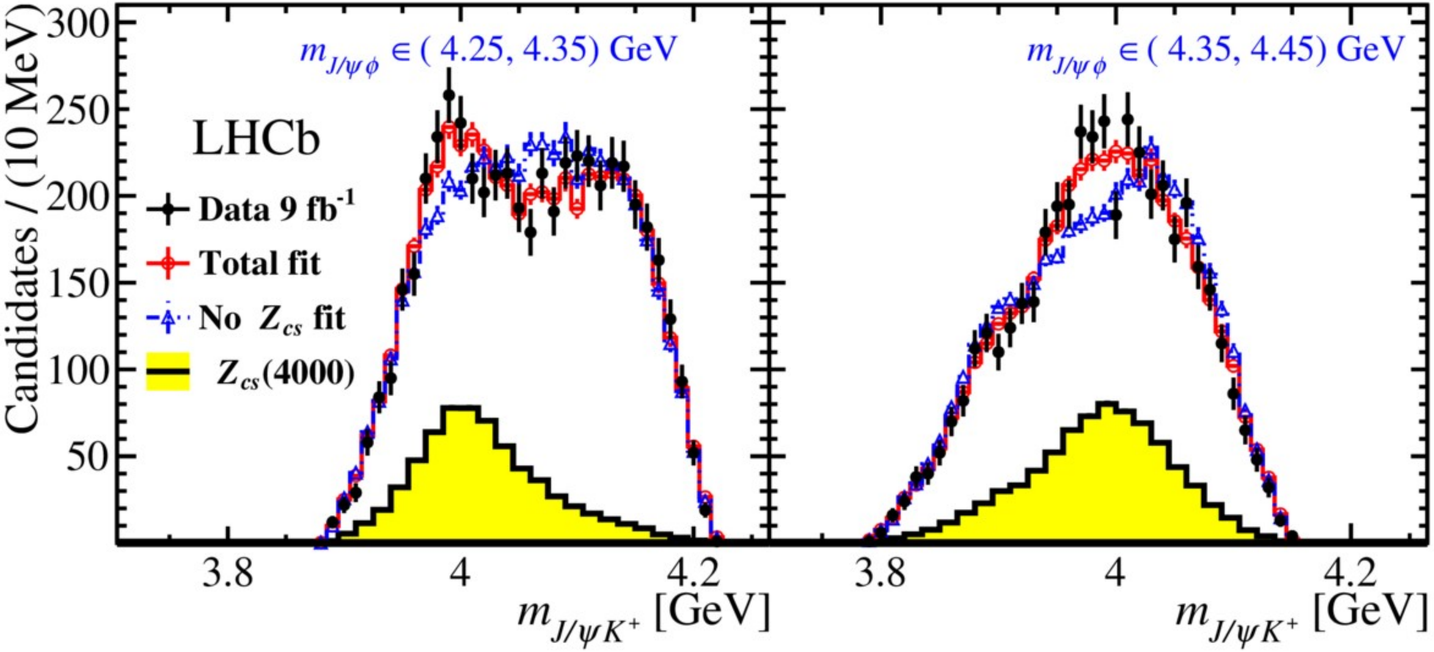
New model

Run 1 model

Exotics in $B^+ \to J/\psi\phi K^+$

[PRL 127 (2021) 082001]

Projections of the fits with in two slices of $J/\psi\phi$ mass shows evidence of Z_{cs} at 4 GeV



Exotics in $B^+ \to J/\psi\phi K^+$

[PRL 127 (2021) 082001]

J^P	Contribution	Significance (σ)	M_0 (MeV)	Γ_0 (MeV)	FF (%)
2^-	$X(4150)$	4.8 (8.7)	$4146 \pm 18 \pm 33$	$135 \pm 28^{+59}_{-30}$	$2.0 \pm 0.5^{+0.8}_{-1.0}$
1^-	$X(4630)$	5.5 (5.7)	$4626 \pm 16^{+18}_{-110}$	$174 \pm 27^{+134}_{-73}$	$2.6 \pm 0.5^{+2.9}_{-1.5}$
0^+	$X(4500)$	20 (20)	$4474 \pm 3 \pm 3$	$77 \pm 6^{+10}_{-8}$	$5.6 \pm 0.7^{+2.4}_{-0.6}$
	$X(4700)$	17 (18)	$4694 \pm 4^{+16}_{-3}$	$87 \pm 8^{+16}_{-6}$	$8.9 \pm 1.2^{+4.9}_{-1.4}$
	$NR_{J/\psi\phi}$	4.8 (5.7)			$28 \pm 8^{+19}_{-11}$
1^+	$X(4140)$	13 (16)	$4118 \pm 11^{+19}_{-36}$	$162 \pm 21^{+24}_{-49}$	$17 \pm 3^{+19}_{-6}$
	$X(4274)$	18 (18)	$4294 \pm 4^{+3}_{-6}$	$53 \pm 5 \pm 5$	$2.8 \pm 0.5^{+0.8}_{-0.4}$
	$X(4685)$	15 (15)	$4684 \pm 7^{+13}_{-16}$	$126 \pm 15^{+37}_{-41}$	$7.2 \pm 1.0^{+4.0}_{-2.0}$
1^+	$Z_{cs}(4000)$	15 (16)	$4003 \pm 6^{+4}_{-14}$	$131 \pm 15 \pm 26$	$9.4 \pm 2.1 \pm 3.4$
	$Z_{cs}(4220)$	5.9 (8.4)	$4216 \pm 24^{+43}_{-30}$	$233 \pm 52^{+97}_{-73}$	$10 \pm 4^{+10}_{-7}$

New states found w.r.t. Run 1 result

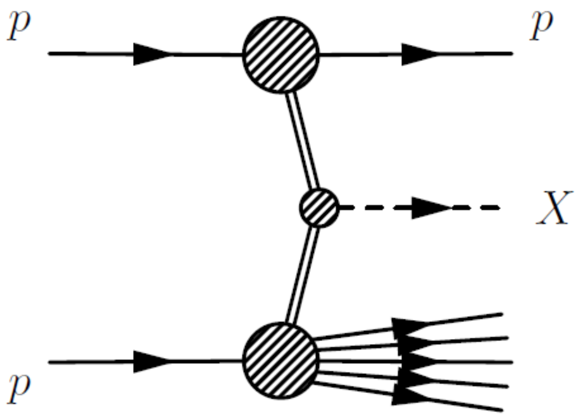
Some states can be produced in photon or pomeron induced processes.

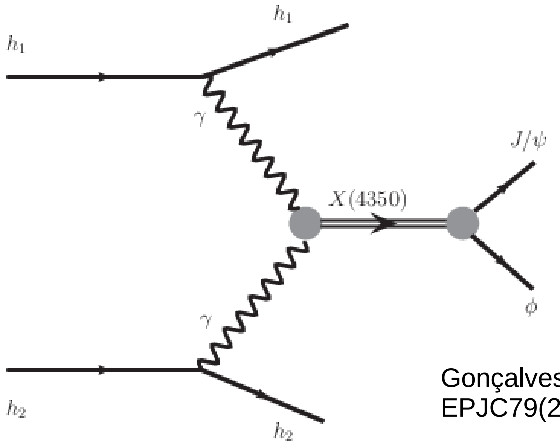
Observation of diffractive exotic J/ψϕ resonances in *pp* collisions

[arXiv:2407.14301]

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

Possible production of exotic states

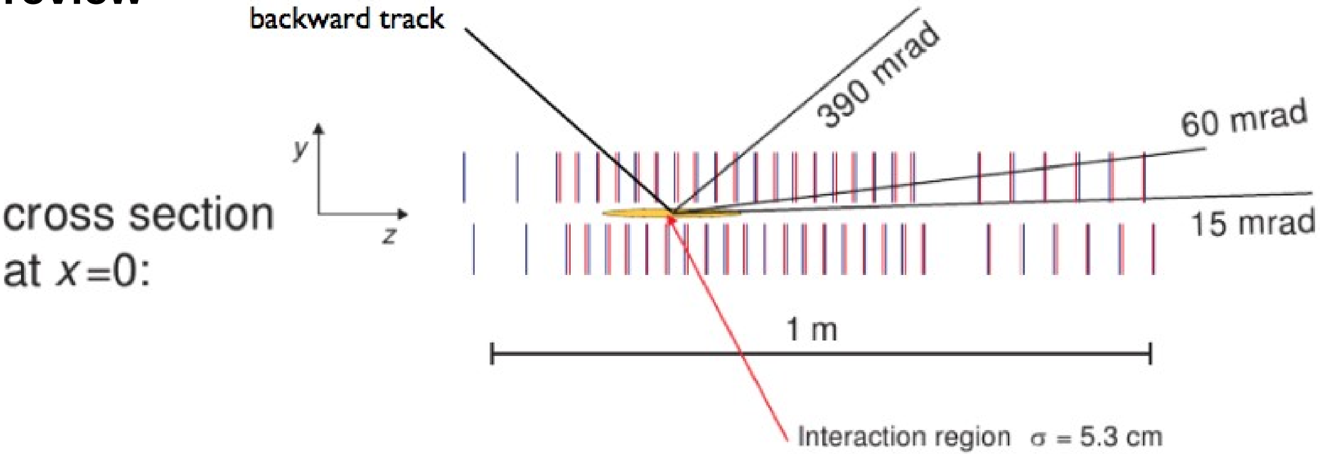




Gonçalves, Moreira
EPJC79(2019)1,7

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

VELO acceptance review



VELO (Vertex Locator)

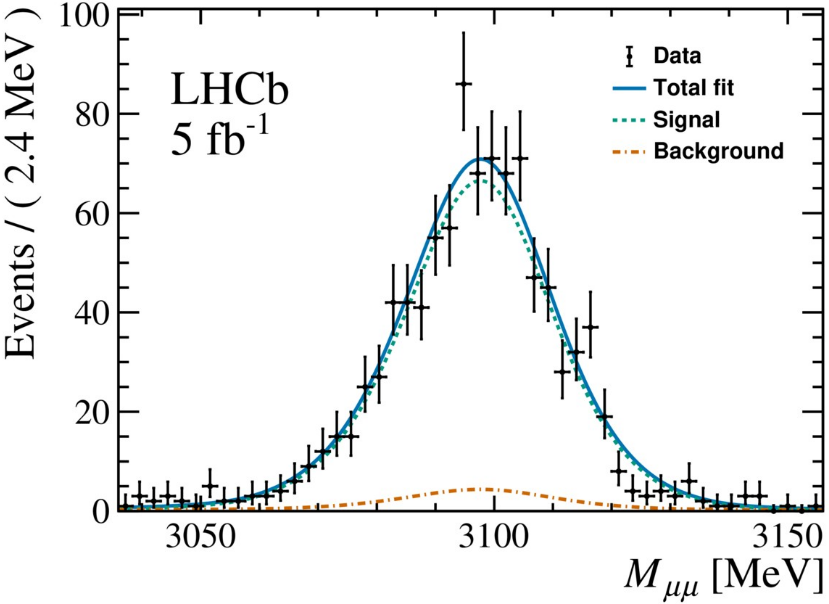
→ surrounds the interaction point

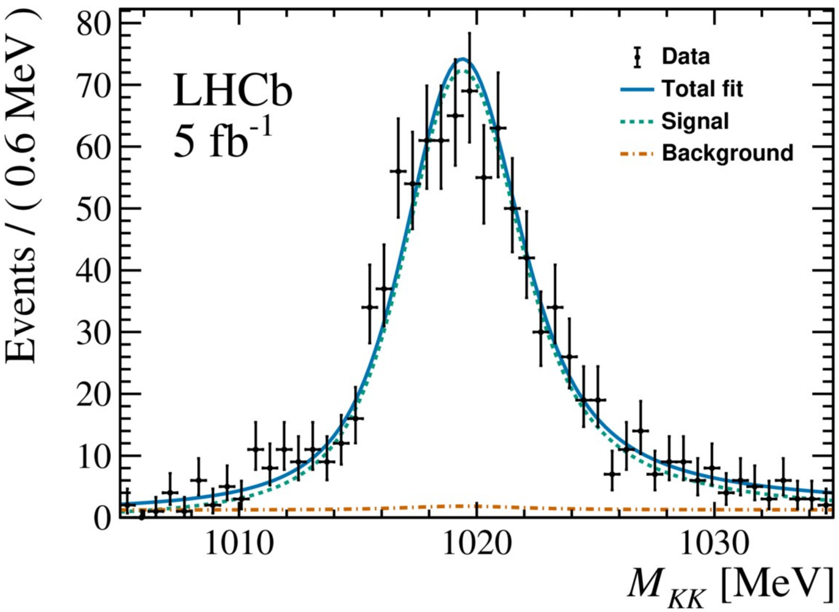
→ no magnetic field

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

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





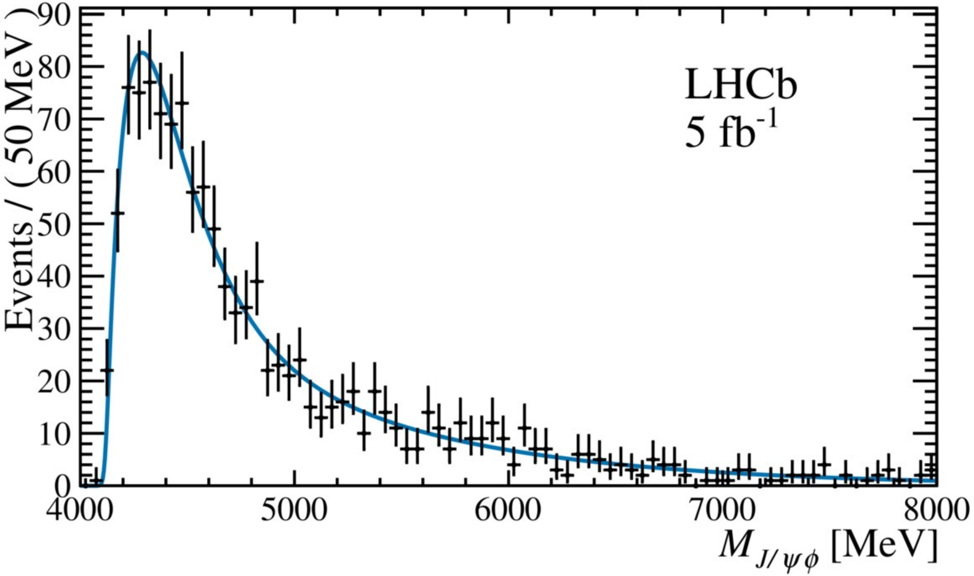
Observation of diffractive exotic J/ψϕ resonances in *pp* collisions

[arXiv:2407.14301]

Sideband sample

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

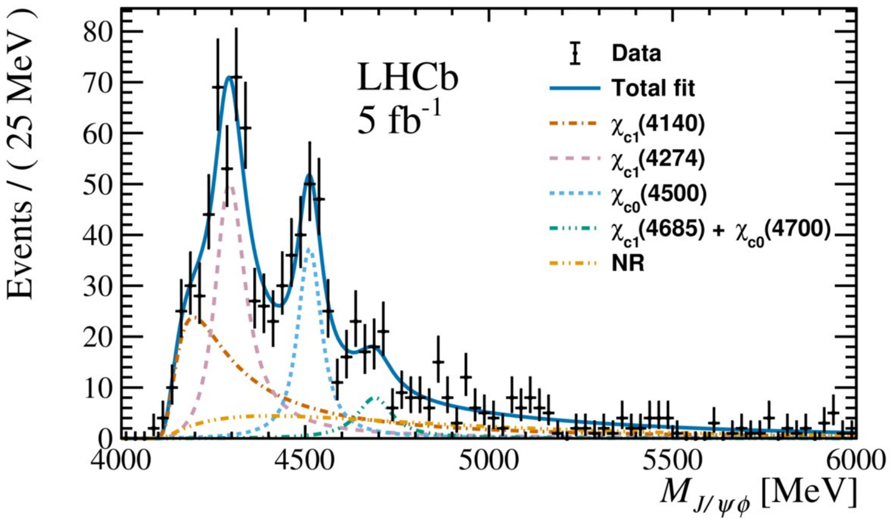
→ no mass structure



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

[arXiv:2407.14301]

After imposing the exclusivity requirement, a resonant structure appears



$$\sigma_{\chi_{c1}(4140)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4140)} = (0.80\pm0.15\pm0.28)\,{\rm pb},$$
$$\sigma_{\chi_{c1}(4274)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4274)} = (0.73\pm0.08\pm0.17)\,{\rm pb},$$
$$\sigma_{\chi_{c0}(4500)} \times \mathcal{B}_{\rm eff}^{\chi_{c0}(4500)} = (0.42^{+0.09}_{-0.08}\pm0.06)\,{\rm pb},$$
$$\sigma_{\chi_{c1}(4685)+\chi_{c0}(4700)} \times \mathcal{B}_{\rm eff}^{\chi_{c1}(4685)+\chi_{c0}(4700)} = (0.14^{+0.07}_{-0.06}\pm0.06)\,{\rm pb},$$
$$\sigma_{\rm NR} \times \mathcal{B}_{\rm eff}^{\rm NR} = (0.43^{+0.24}_{-0.18}\pm0.20)\,{\rm pb},$$

PRL127(2021)082001

Parameter [MeV]	Current analysis	Ref. [13]
$M_{\chi_{c1}(4274)}$	$4298\pm6\pm9$	$4294\pm4^{+3}_{-6}$
$\Gamma_{\chi_{c1}(4274)}$	$92^{+22}_{-18}\pm57$	$53\pm5\pm5$
$M_{\chi_{c0}(4500)}$	$4512.5^{+6.0}_{-6.2}\pm3.0$	$4474\pm3\pm3$
$\Gamma_{\chi_{c0}(4500)}$	$65^{+20}_{-16}\pm32$	$77\pm6^{+10}_{-8}$

Fit performed with previously observed resonances in B decays.

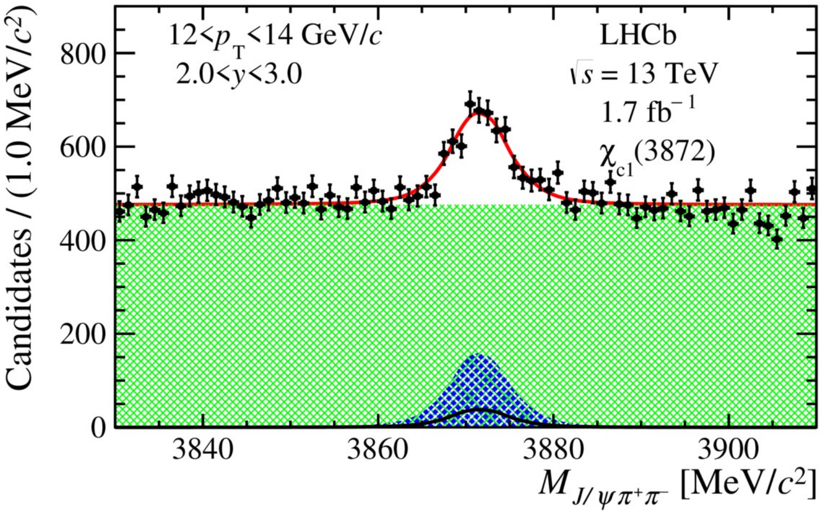
- Turn-on derived from events with more than four VELO tracks
- Non-resonant is modeled by an exponential function
- No interference assumed

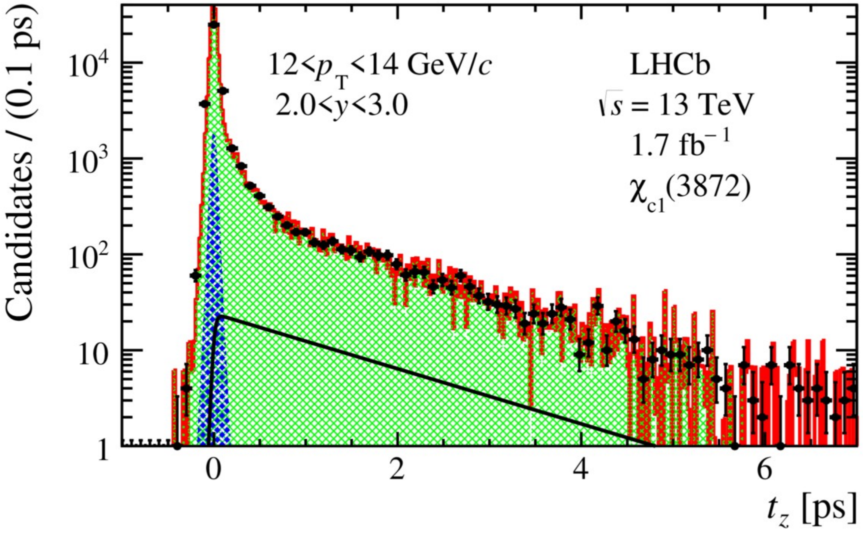
The significance for the resonances $\chi_{c1}(4140)$, $\chi_{c1}(4274)$ and $\chi_{c0}(4500)$ are 2.4 σ, 4.3 σ and 5.5 σ.

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

Measurements of the $\chi_{c1}(3872)$

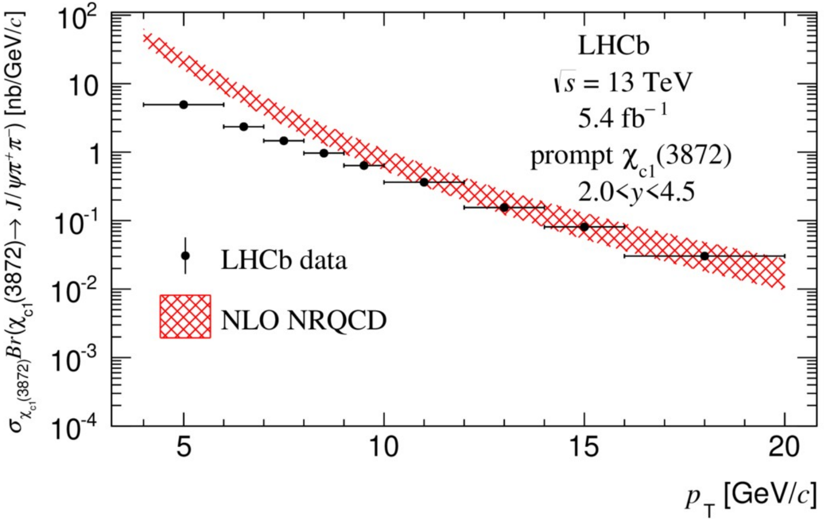
JHEP 01 (2022) 131

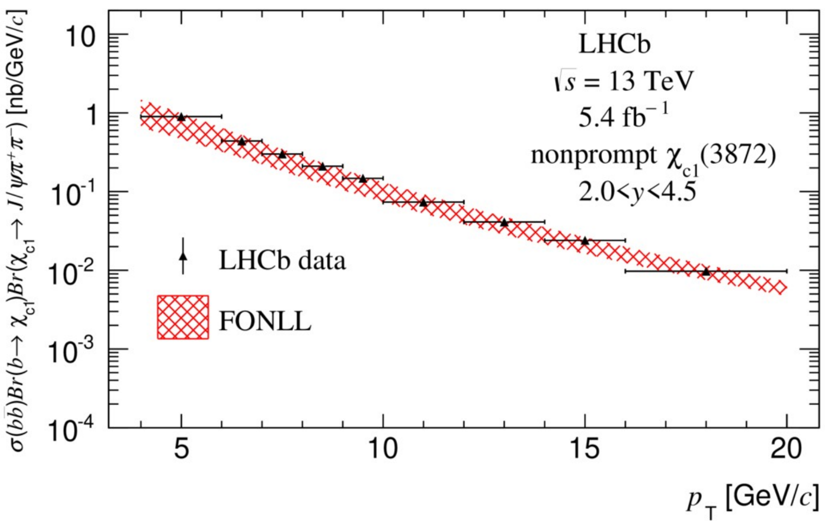




Measurements of the χ_{c1}(3872)

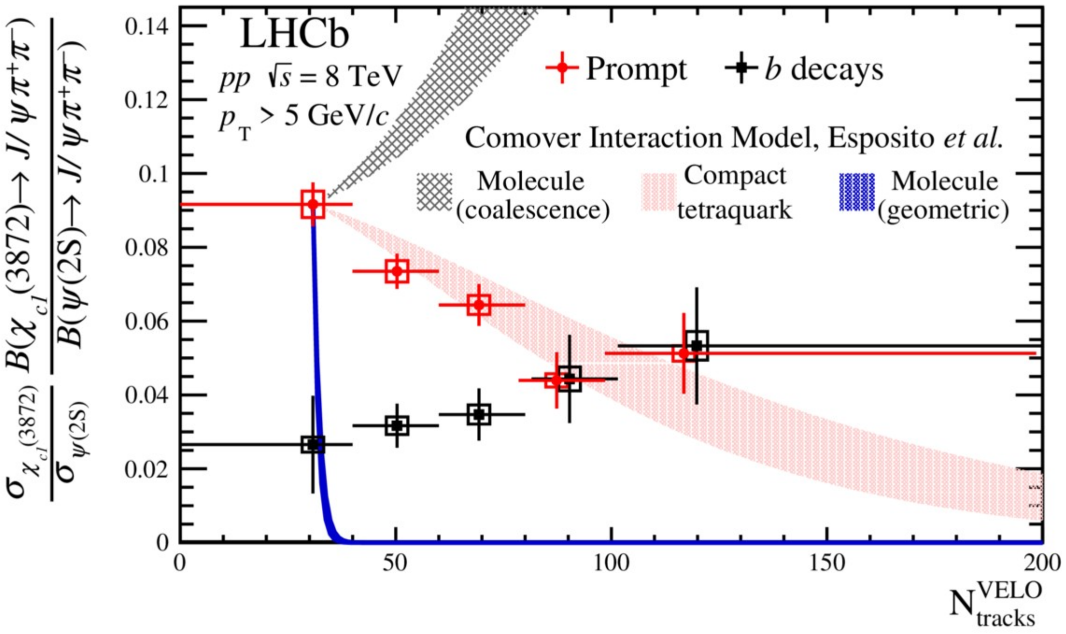
JHEP 01 (2022) 131





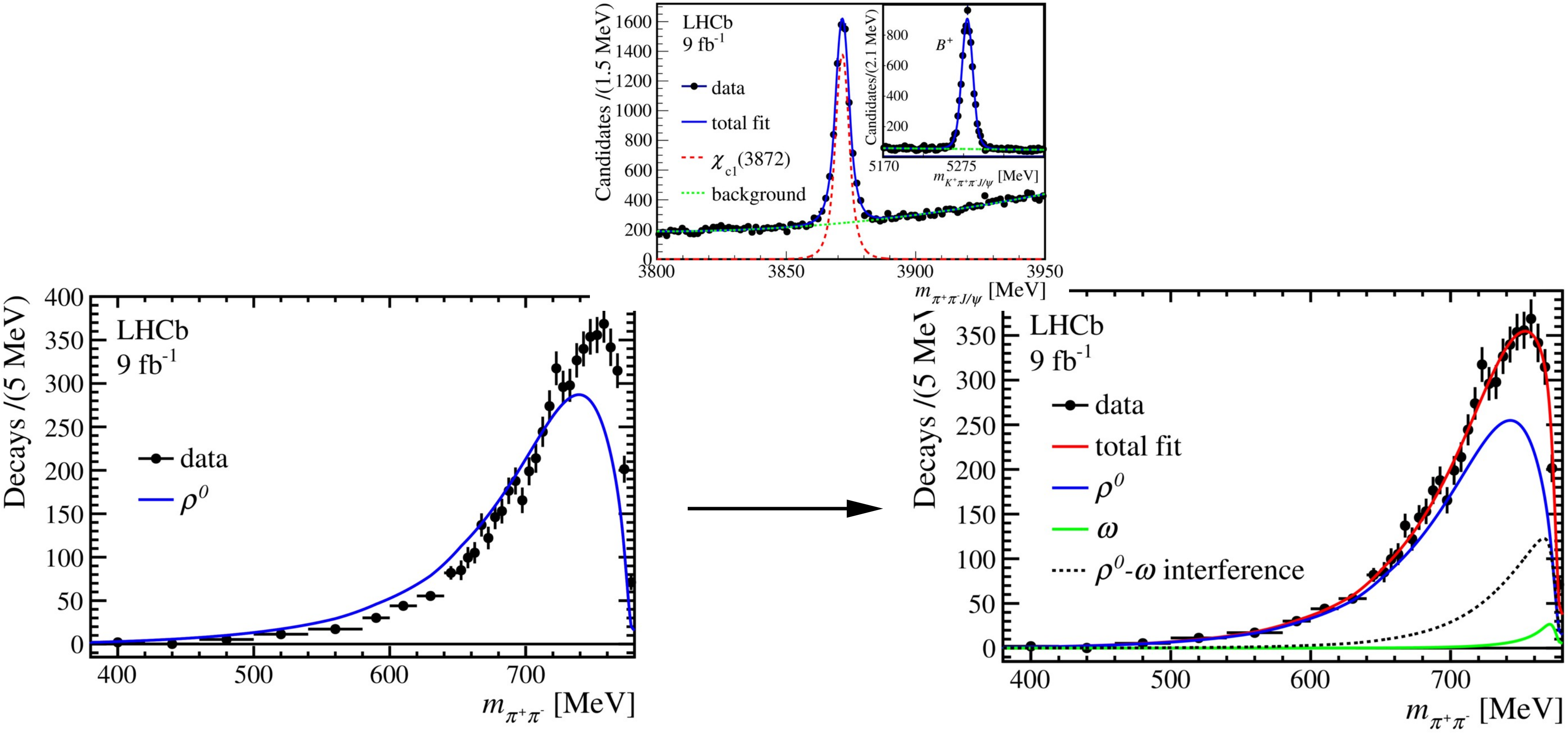
Measurements of the $\chi_{c1}(3872)$

PRL126 (2021) 092001



Observation of sizeable ω Contribution to $\chi_{c1}(3872)$

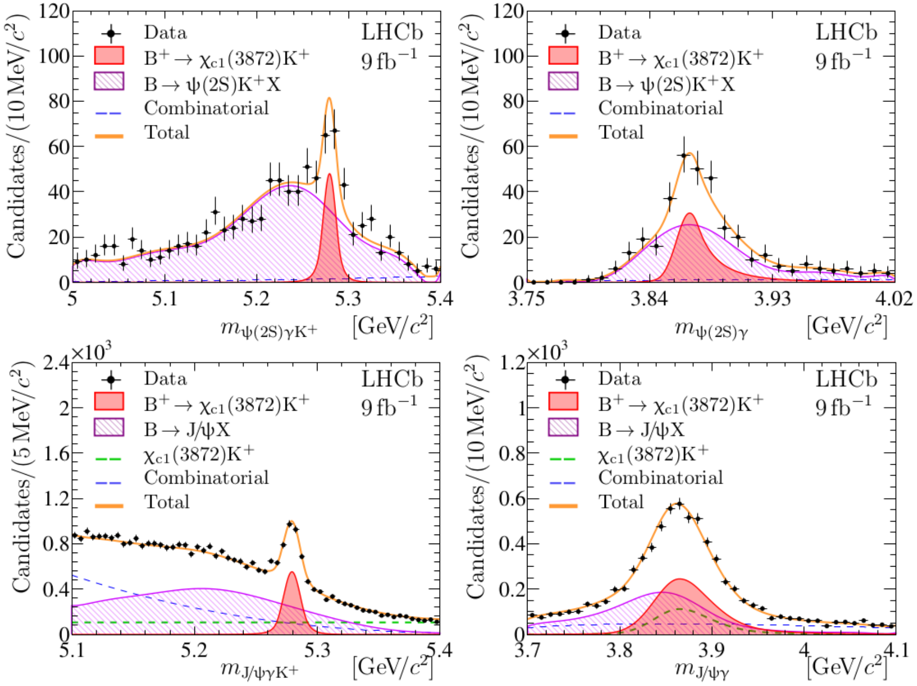
PRD 131 (2023) L011103



Radiative decays of the $\chi_{c1}(3872)$

[arXiv:2406.17006]

First observation of the $\chi_{c1}(3872) \rightarrow \psi(2S)\gamma$ decay(6σ)

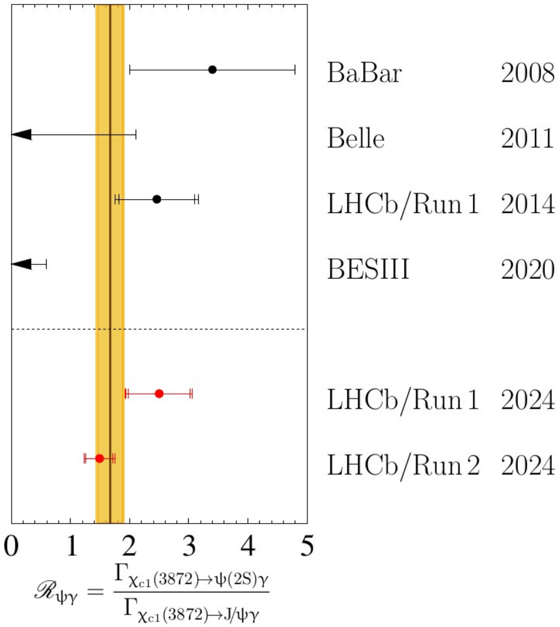


Radiative decays of the $\chi_{c1}(3872)$

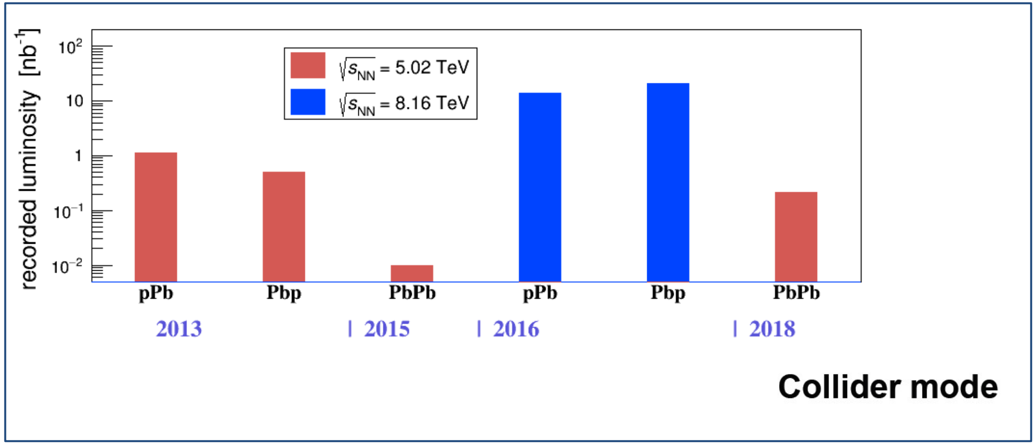
[arXiv:2406.17006]

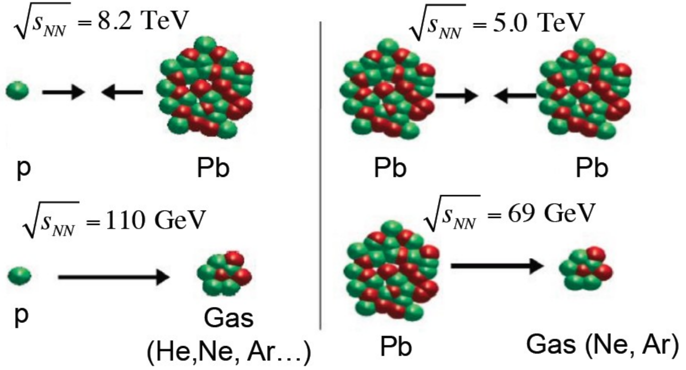
Measurement of the ratio

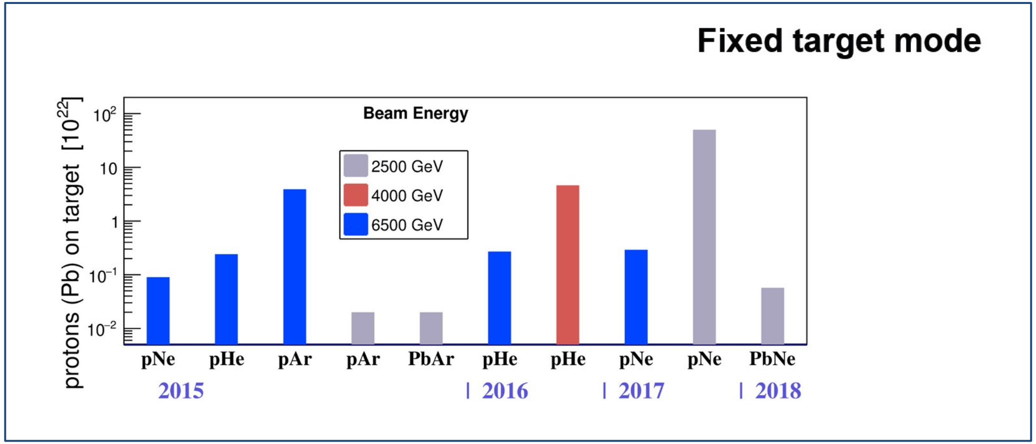
$$\mathscr{R}_{\psi\gamma} \equiv \frac{\Gamma_{\chi_{c1}(3872)\to\psi(2S)\gamma}}{\Gamma_{\chi_{c1}(3872)\to J/\psi\gamma}} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$



LHCb also studies heavy-ion collider and fixed target mode



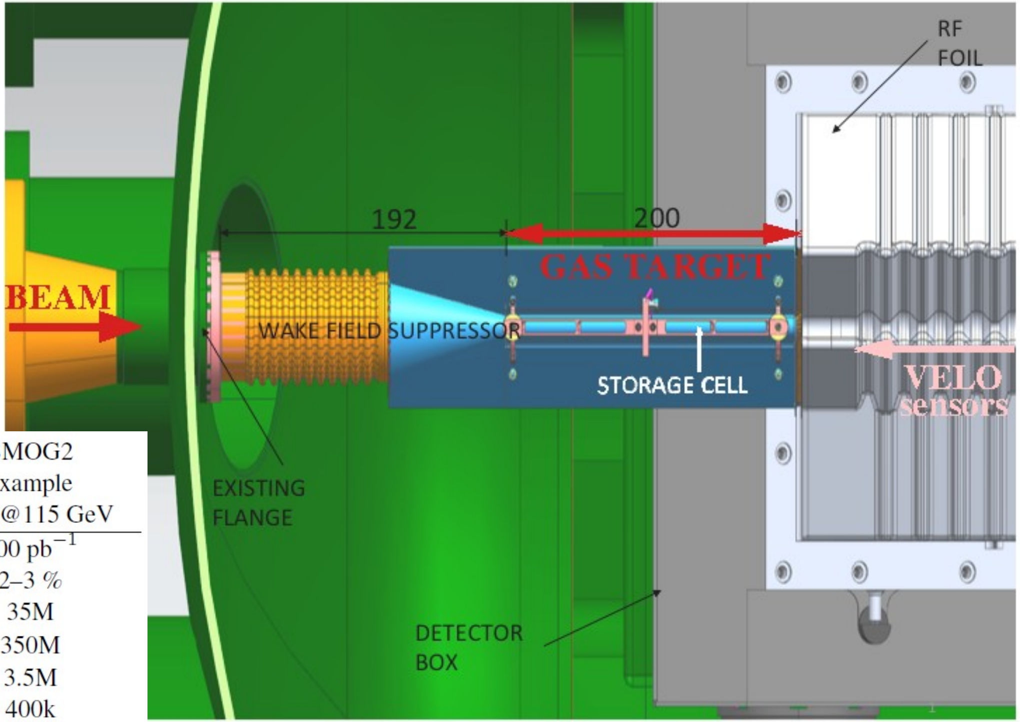




Run3 SMOG2

[LHCC-2019-0051/LHCb TDR 20]

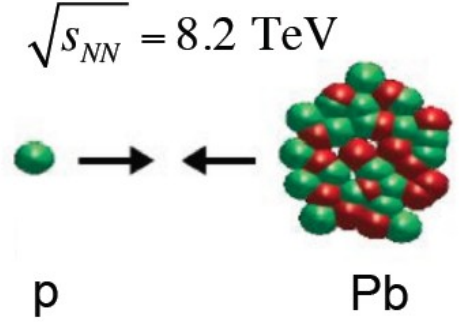
- **o** 20cm long storage cell, 5mm radius around the beam, just upstream the VELO
- **o** possibly inject other gases
- **o** Up to x100 higher gas density with same gas flow of current SMOG
- **o** Faster switch between gas species

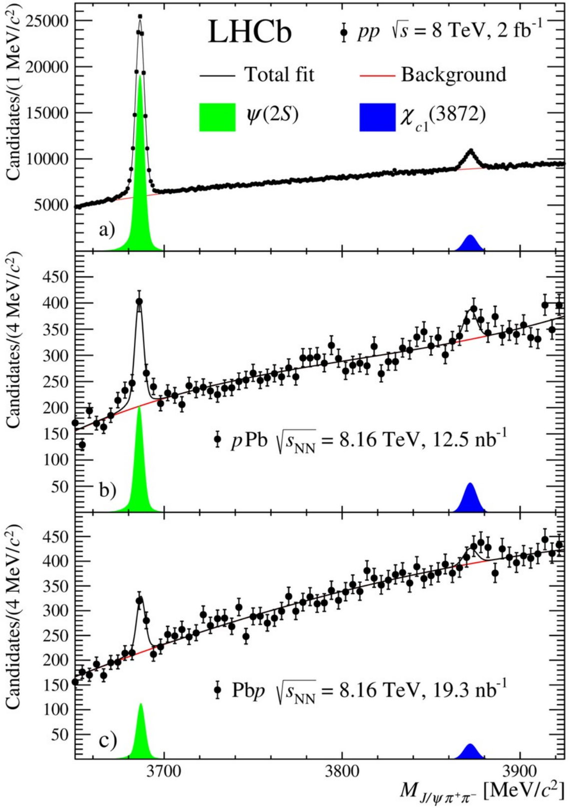


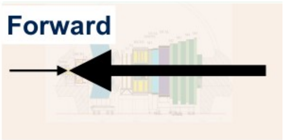
	SMOG largest sample p–Ne@68 GeV	SMOG2 example p–Ar@115 GeV
Integrated luminosity	$\sim 100\ \mathrm{nb}^{-1}$	$100\ \mathrm{pb}^{-1}$
syst. error on J/ψ x-sec.	6–7%	2–3 %
J/ψ yield	15k	35M
D^0 yield	100k	350M
Λ_c yield	1k	3.5M
$\psi(2S)$ yield	150	400k
$\Upsilon(1S)$ yield	4	15k
Low-mass ($5 < M_{\mu\mu}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

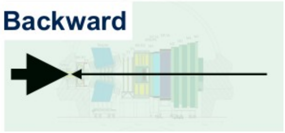
Exotic hadron nuclear modification factor
[PRL132(2024)242301]

Prompt production of X(3872) and ψ(2S) in pp, pPb and Pbp



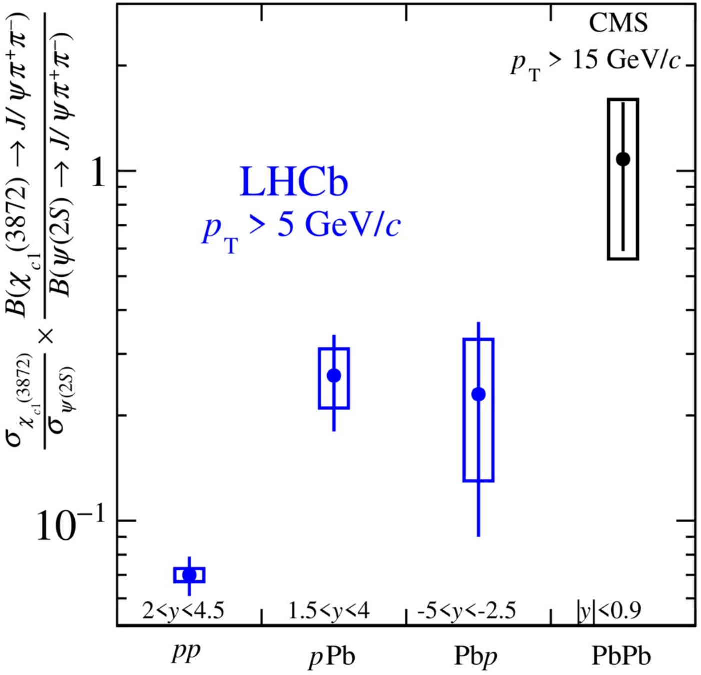






Exotic hadron nuclear modification factor

[PRL132(2024)242301]



Comparison between X(3872) and ψ(2S) suggests differences between exotic and conventional hadrons in medium

N.B. Initial state effects (eg shadowing) should largely cancel in ratio

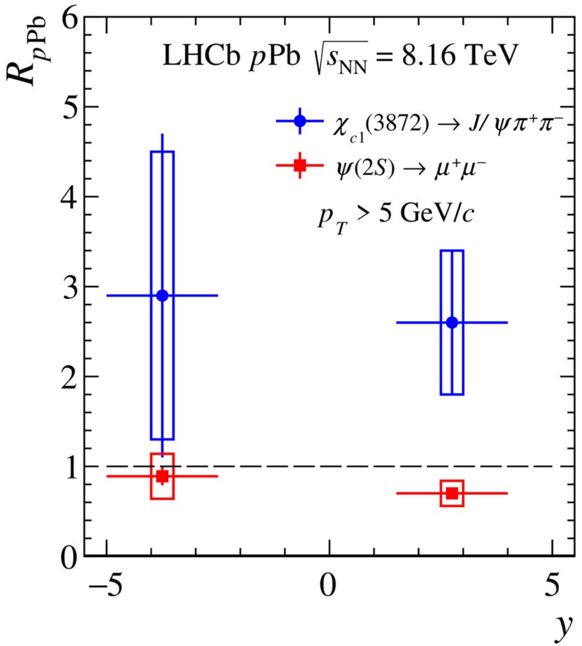
For PbPb predictions see for example:
Abreu, Navarra, Vieira – PRD110(2024)1,014011
https://indico.cern.ch/event/1356329/timetable/#66-the-x3872-to-psi2s-yield-ra

Exotic hadron nuclear modification factor

[PRL132(2024)242301]

First measurement of nuclear modification factor for an exotic hadron

$$R_{pA}^{\chi_{c1}(3872)} = \frac{\sigma_{pA}^{\chi_{c1}(3872)}}{208 \times \sigma_{pp}^{\chi_{c1}(3872)}}$$



Production of χ_{c1}(3872) hadrons in pPb collisions may be enhanced relative to pp collisions.

Run3 SMOG2

LHCC-2019-0051/LHCb TDR 20

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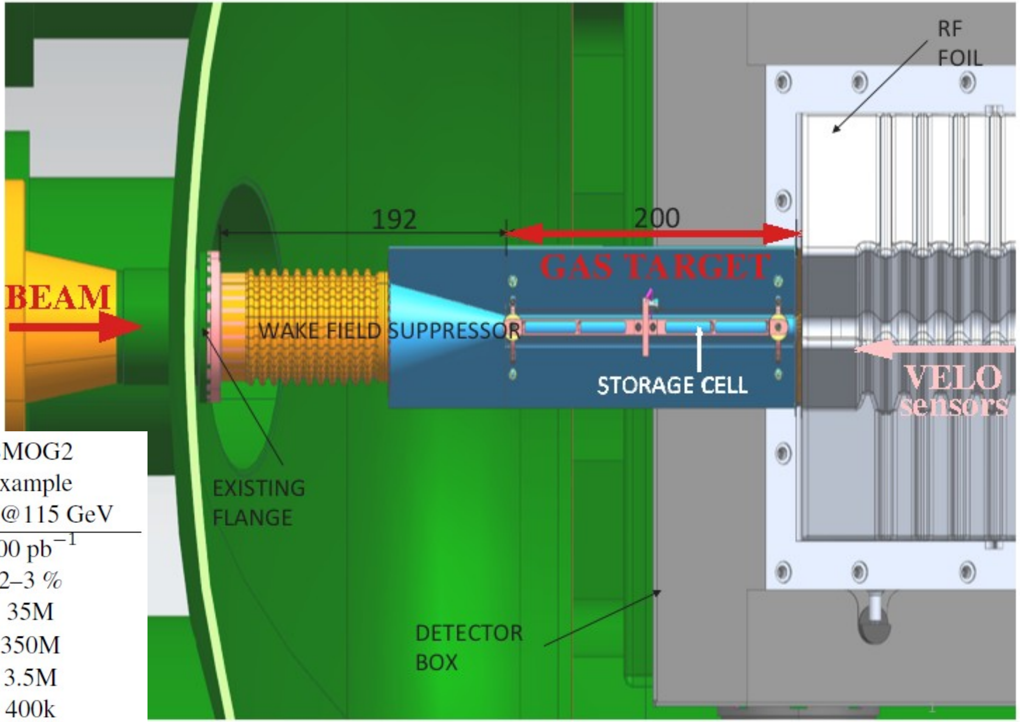

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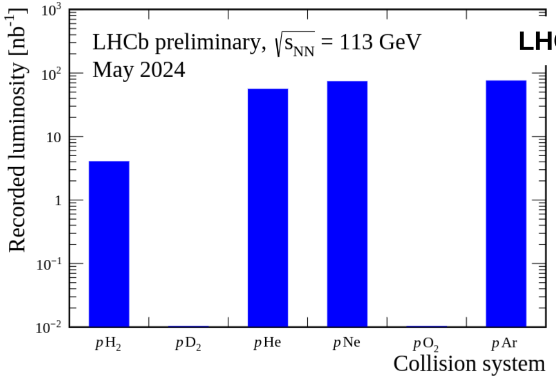
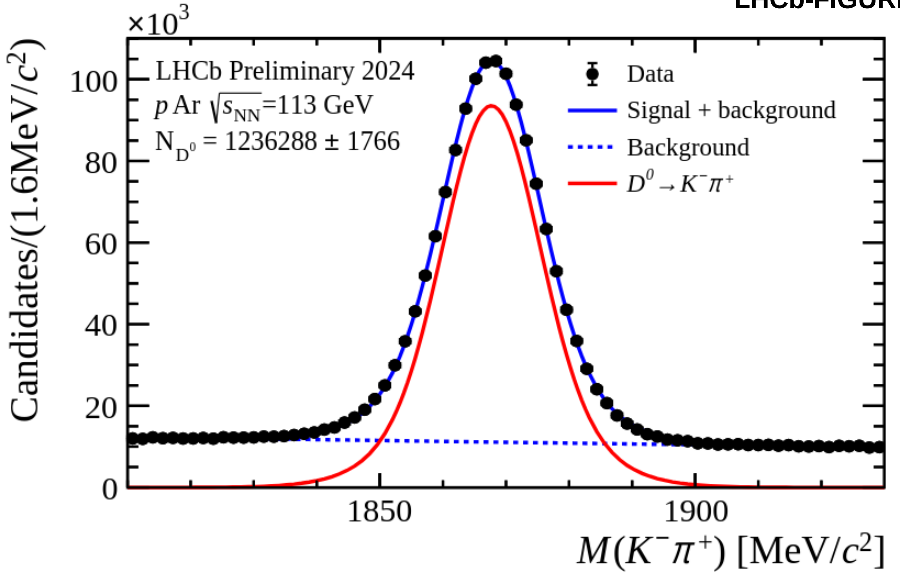
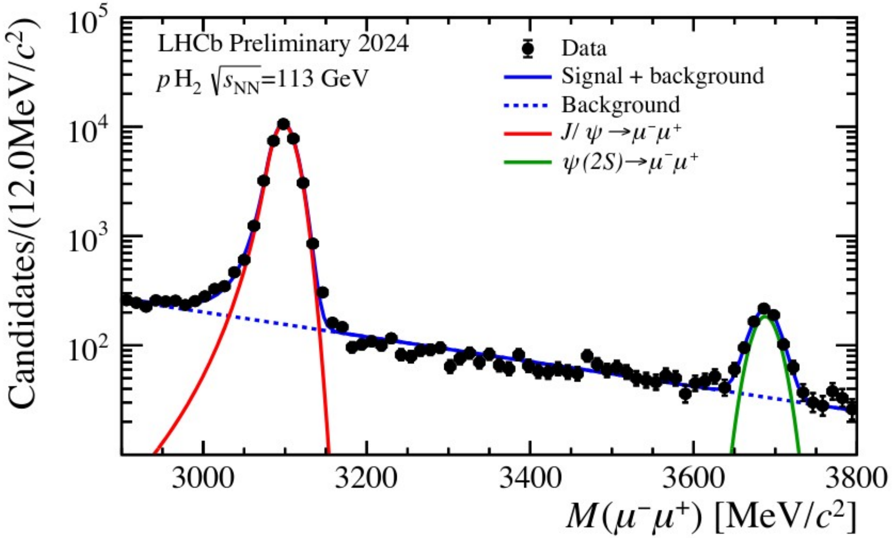


LHCb-FIGURE-2024-005

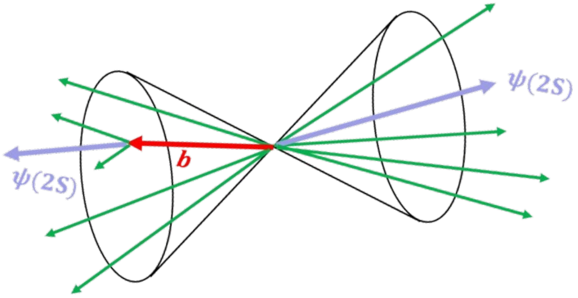
LHCb-FIGURE-2024-023



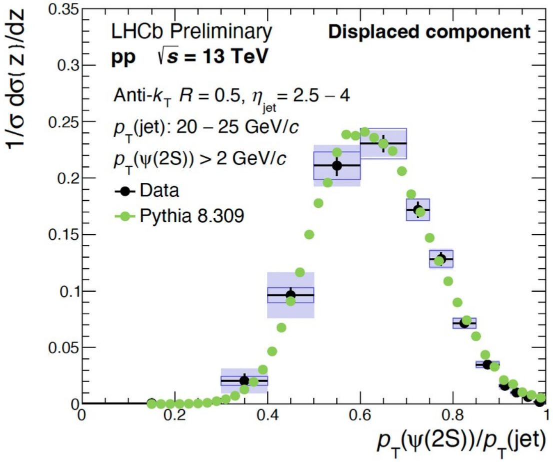


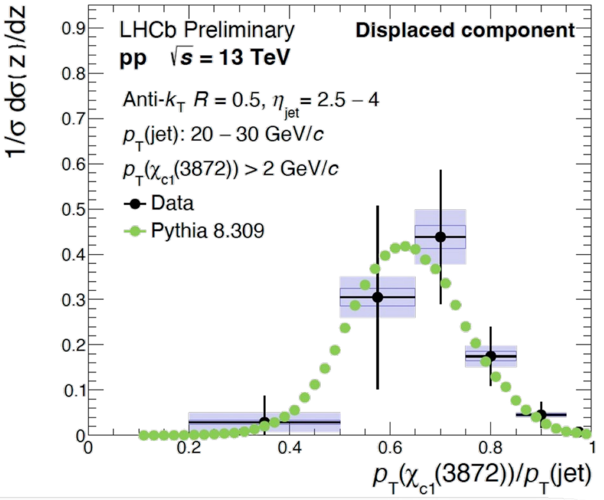
$X(3872)$ in jets
[LHCb-PAPER-2024-021]

+ Challenge with description of production and polarization
+ Exotic in jets provides new way to examine production mechanisms

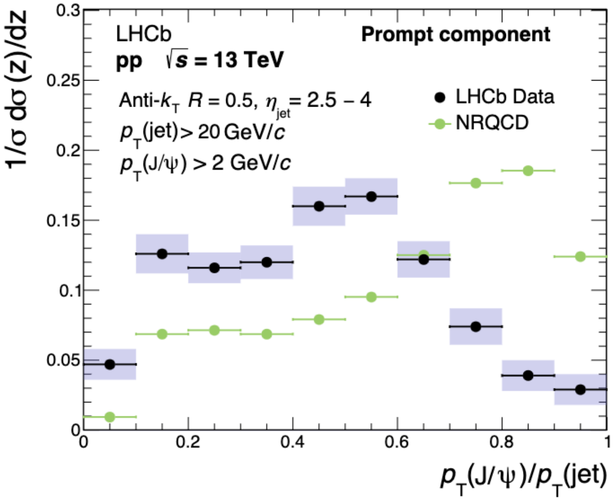


$b \to \psi(2S)$ and $b \to X(3872)$
+ well described by PYTHIA
+ very similar to $b \to J/\psi$, $\psi(2S)$

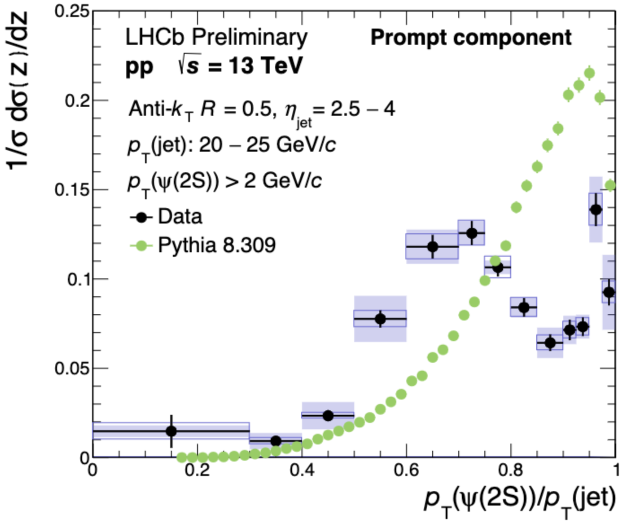




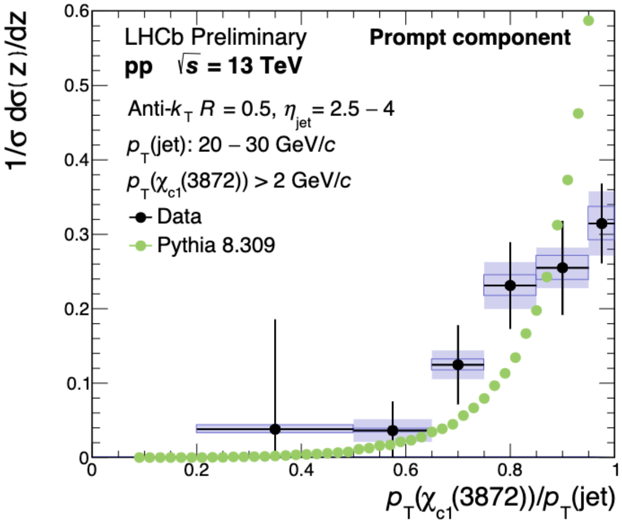
$X(3872)$ in jets
[LHCb-PAPER-2024-021]



Prompt: Less isolated than expected



Prompt: Two component structure: Different mechanisms?



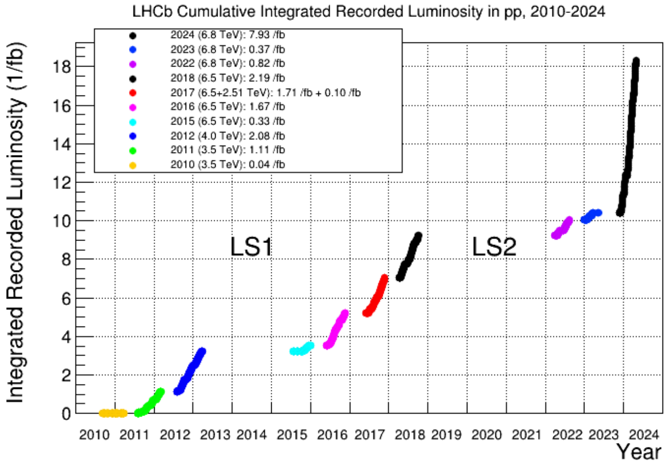
Prompt: Rises towards isolation, very different from conventional state $\psi(2S)$

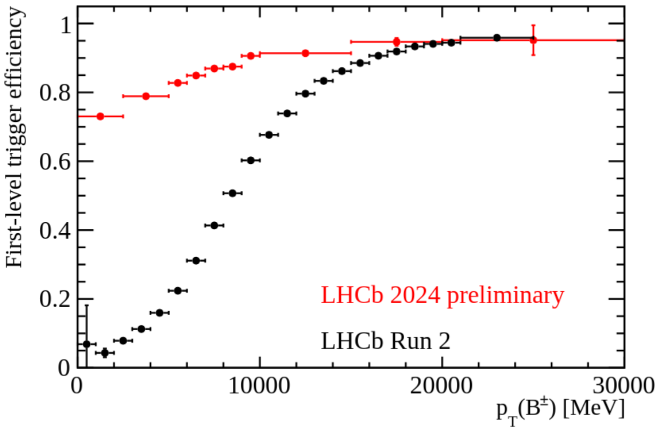
Summary

--- Recent results demonstrate exotic spectroscopy is still an unexplored territory.

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

--- Run 3 data collection on-going → interesting results ahead with higher statistics and better selection





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

http://lape.if.ufrj.br
facebook/instagram/youtube: @lapeufrj
rangel@if.ufrj.br rangel@cern.ch

THANK YOU

Run 3 detector

CERN-LHCC-2012-007

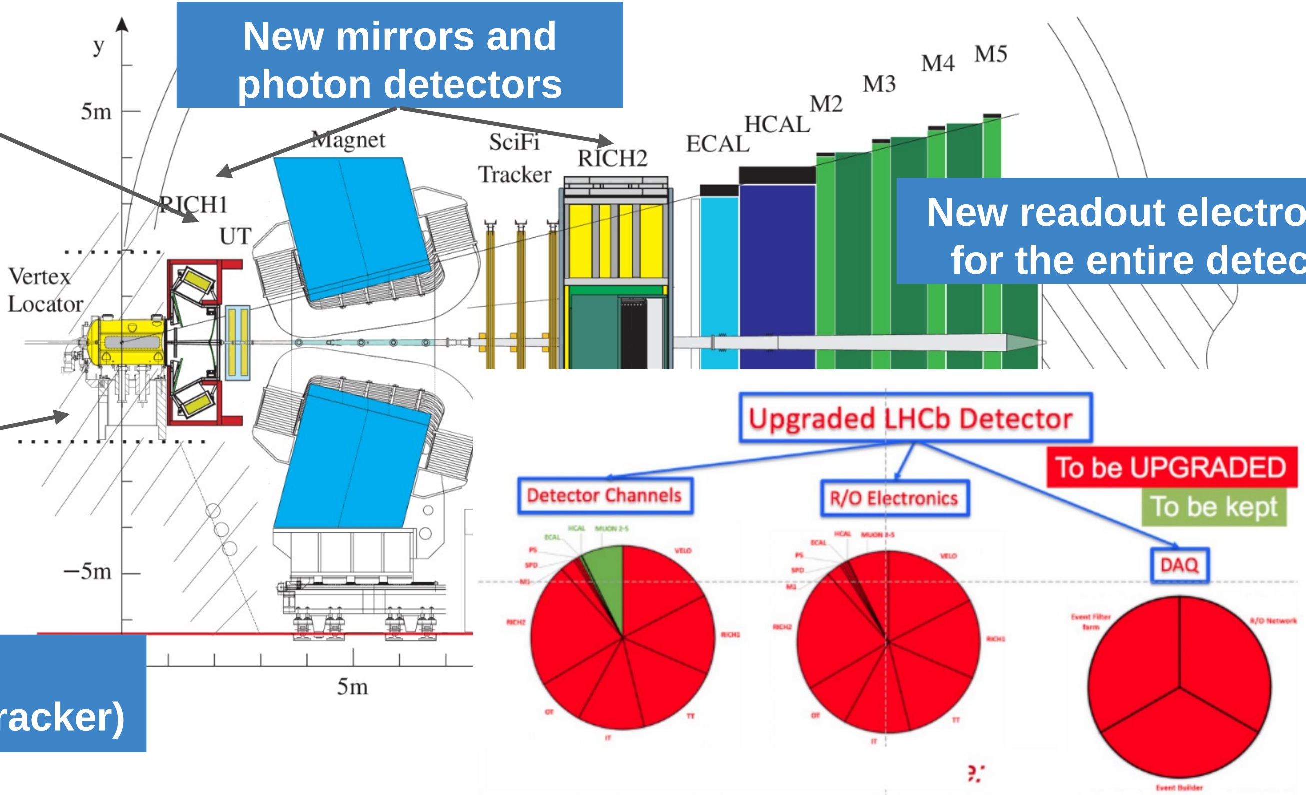
UT
(new silicon tracker)

New mirrors and
photon detectors

New readout electronics
for the entire detector

New VELO
(Pixel Detector)

SciFi
(new scintillating fibre tracker)



Run 3 Real time analysis

CERN-LHCC-2012-007

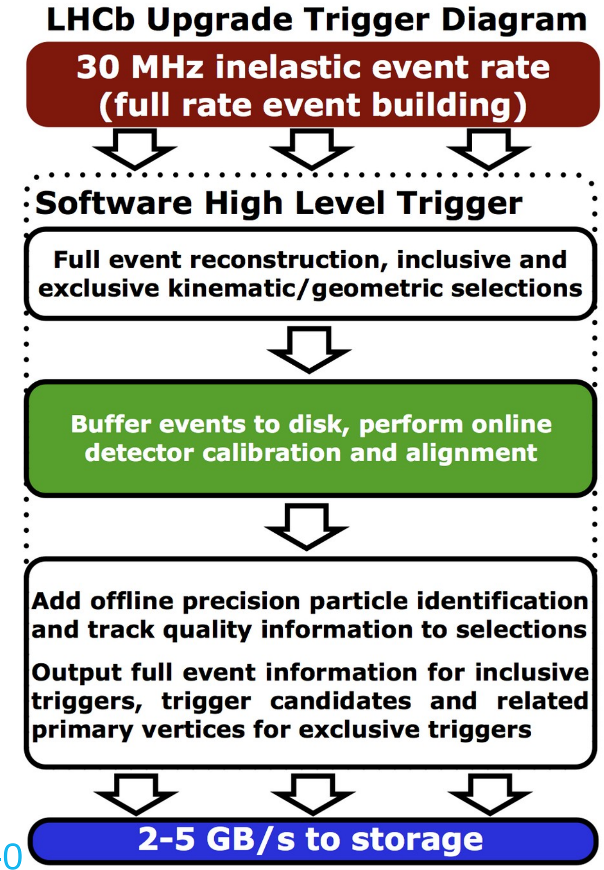
❈ Increase instantaneous luminosity:
$4 \times 10^{32} \rightarrow 2 \times 10^{33}$ cm^{-2} s^{-1}

❈ 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

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

Observation of X(3960)

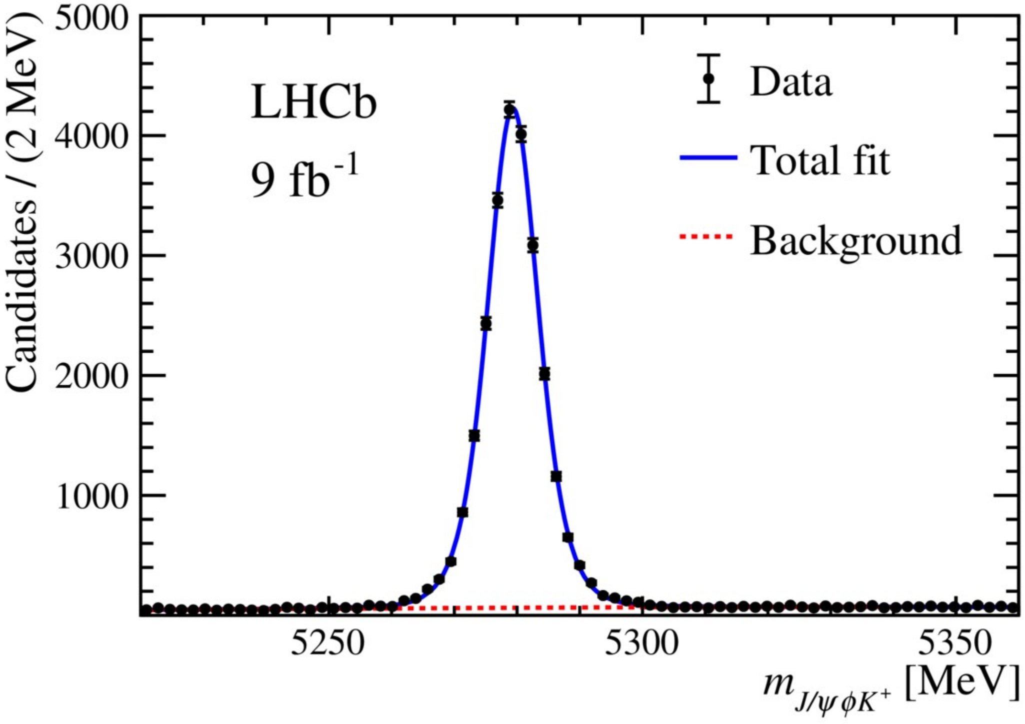
arXiv:2407.14301

Component	J^{PC}	M_0 (MeV)	Γ_0 (MeV)	$\mathcal{F}$ (%)	$\mathcal{S}$ (σ)
$X(3960)$	0^{++}	$3956 \pm 5 \pm 10$	$43 \pm 13 \pm 8$	$25.4 \pm 7.7 \pm 5.0$	12.6 (14.6)
$X_0(4140)$	0^{++}	$4133 \pm 6 \pm 6$	$67 \pm 17 \pm 7$	$16.7 \pm 4.7 \pm 3.9$	3.8 (4.1)
$\psi(4260)$	1^{--}	4230 [62]	55 [62]	$3.6 \pm 0.4 \pm 3.2$	3.2 (3.6)
$\psi(4660)$	1^{--}	4633 [32]	64 [32]	$2.2 \pm 0.2 \pm 0.8$	3.0 (3.2)
NR	0^{++}	-	-	$46.1 \pm 13.2 \pm 11.3$	3.1 (3.4)

Exotics in $B^+ \to J/\psi\phi K^+$

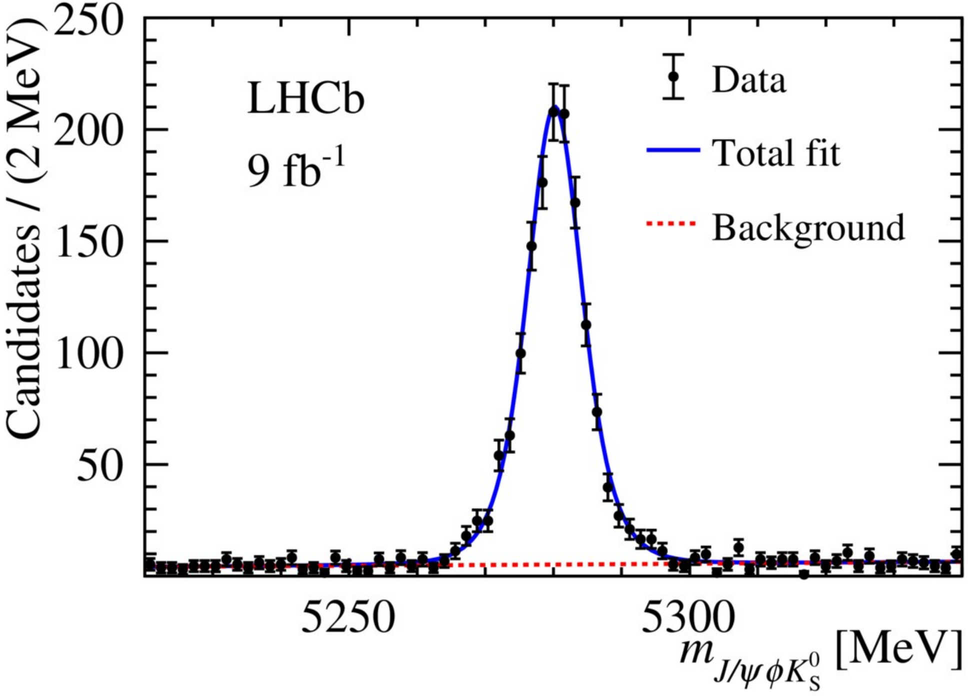
[PRL 127 (2021) 082001]

~ 4% background fraction



Evidence for a $J/\psi K_s^0$ structure
[PRL 131 (2023) 131901]

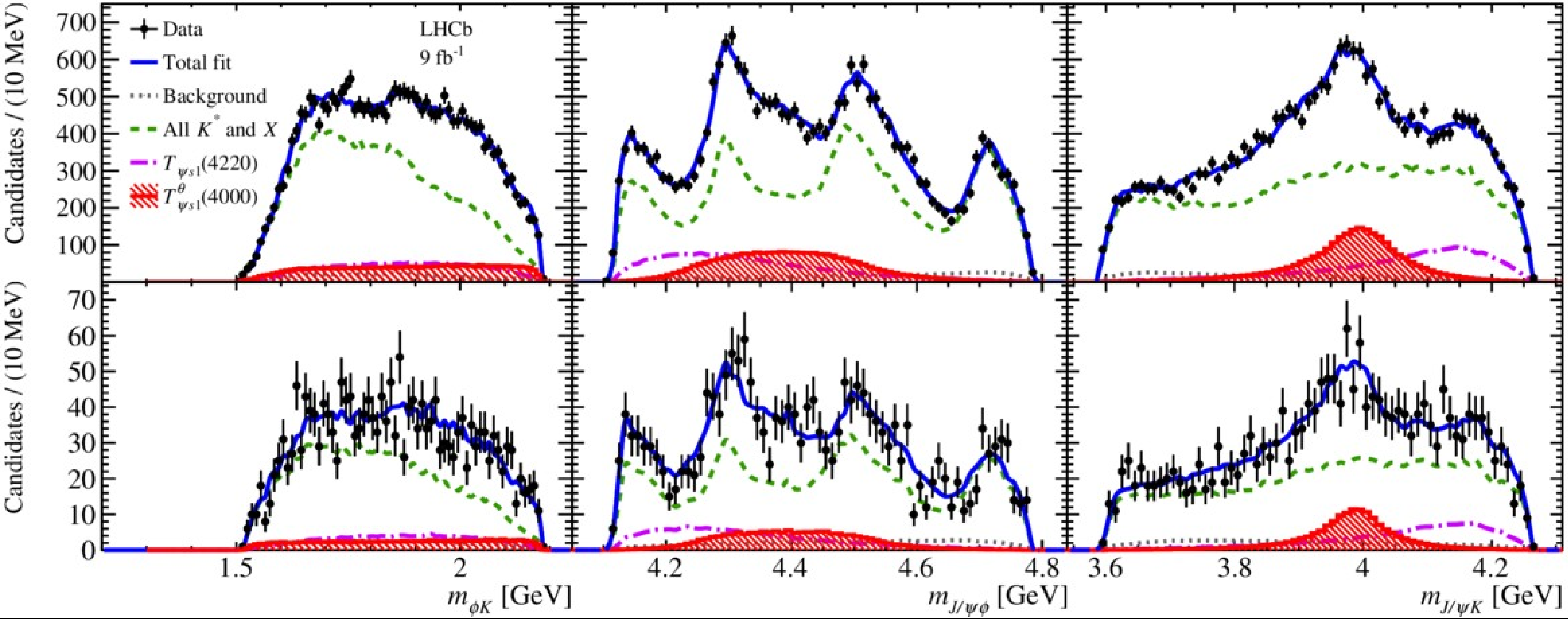
Amplitude analysis of $B^0 \rightarrow J/\psi\phi K_s^0$



Evidence for a $J/\psi K_s^0$ structure

[PRL 127 (2021) 082001], [PRL 131 (2023) 131901]

+ Simultaneous fit is performed to the $B^0 \to J/\psi\phi K_S^0$ sample and the $B^+ \to J/\psi\phi K^+$ sample
+ Amplitudes in the two decay modes are related through isospin symmetry
+ Amplitude model includes 9 excited *K* states and the 9 observed *J/ψφ* exotic resonances



$B^+ \to J/\psi\varphi K^+$

$B^0 \to J/\psi\varphi K_s^0$

Evidence for a $J/\psi K_s^0$ structure

[PRL 127 (2021) 082001], [PRL 131 (2023) 131901]

The mass and width of this state are measured to be

$$M(T^{\theta}_{\psi s1}(4000)^0) = 3991\,^{+12}_{-10}\,^{+\ 9}_{-17}\,\mathrm{MeV}$$

$$\Gamma(T^{\theta}_{\psi s1}(4000)^0) = 105\,^{+29}_{-25}\,^{+17}_{-23}\,\mathrm{MeV}$$

The mass difference between the possible isospin partner $T^{\theta}_{\psi s1}(4000)^+$

$$\Delta M = -12\,^{+11}_{-10}\,^{+6}_{-4}\,\mathrm{MeV}$$

Consistent with the two states being isospin partners.

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

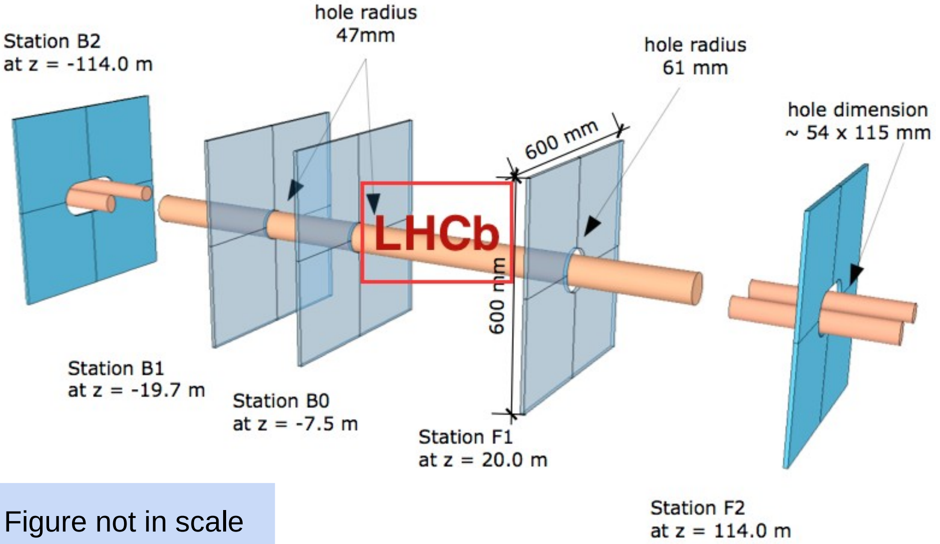
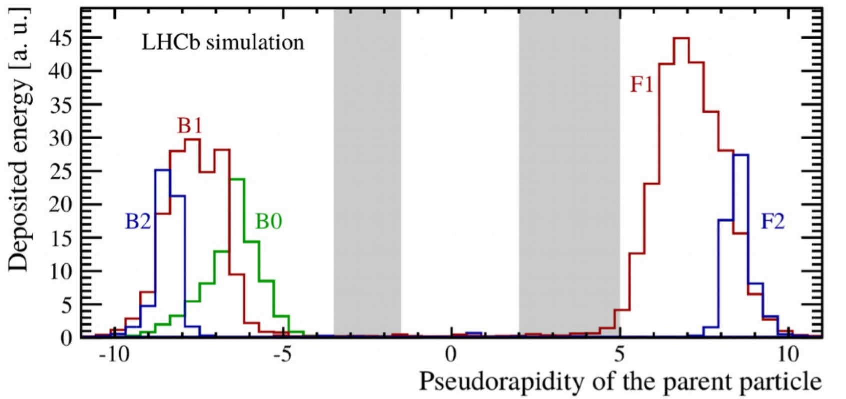


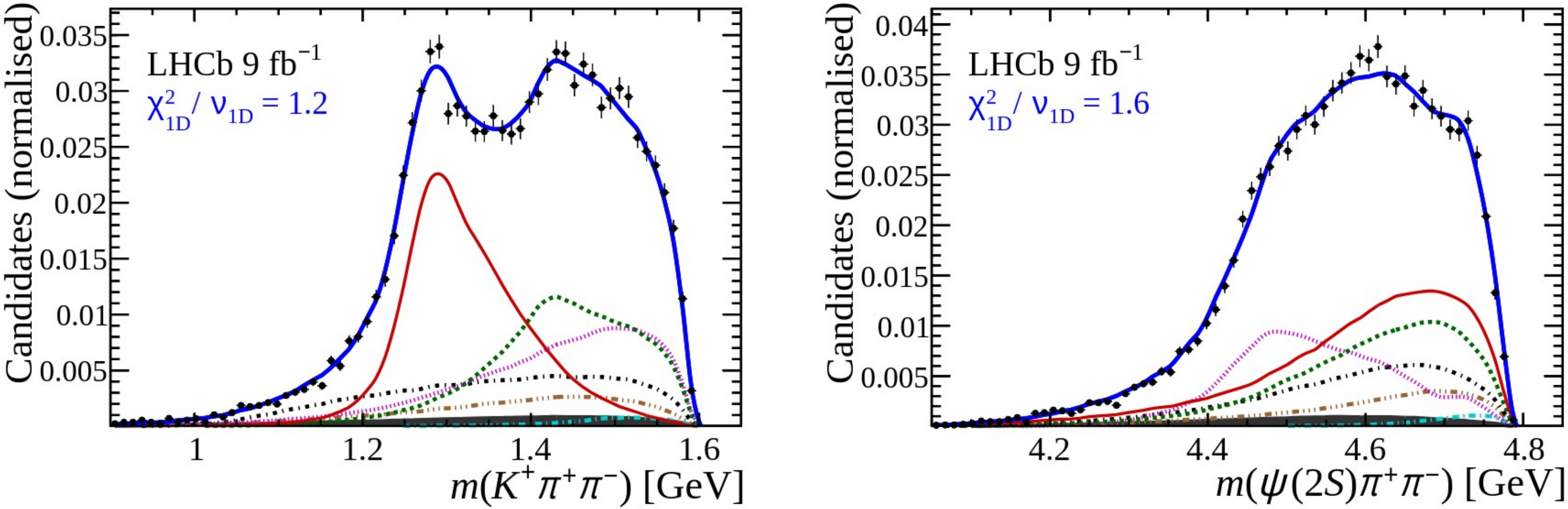
Figure not in scale

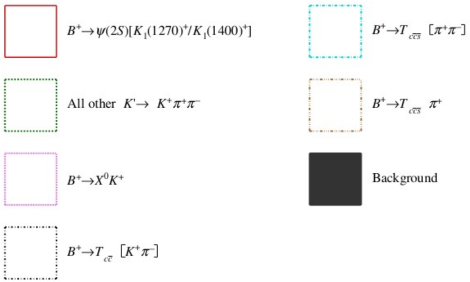
JINST 13 (2018) no.04, P04017



Amplitude analysis of $B^+ \to \psi(2S) K^+ \pi^+ \pi^-$

[arXiv:2407.12475]





Algorithmic model-building procedure used in the amplitude analysis

Amplitude analysis of $B^+ \to \psi(2S)K^+\pi^+\pi^-$

[arXiv:2407.12475]

Resonance	J^P	m_0 [MeV]	Γ_0 [MeV]
$\chi_{c0}(4475)$	0^+	$4475 \pm 7 \pm 12$	$231 \pm 19 \pm 32$
$\chi_{c1}(4650)$	1^+	$4653 \pm 14 \pm 27$	$227 \pm 26 \pm 22$
$\chi_{c0}(4710)$	0^+	$4710 \pm 4 \pm 5$	$64 \pm 9 \pm 10$
$\eta_{c1}(4800)$	1^-	$4785 \pm 37 \pm 119$	$457 \pm 93 \pm 157$
$T^*_{c\bar{c}1}(4055)^+$	1^-	4054 (fixed)	45 (fixed)
$T_{c\bar{c}1}(4200)^+$	1^+	$4257 \pm 11 \pm 17$	$308 \pm 20 \pm 32$
$T_{c\bar{c}1}(4430)^+$	1^+	$4468 \pm 21 \pm 80$	$251 \pm 42 \pm 82$
$T_{c\bar{c}\bar{s}1}(4600)^0$	1^+	$4578 \pm 10 \pm 18$	$133 \pm 28 \pm 69$
$T_{c\bar{c}\bar{s}1}(4900)^0$	1^+	$4925 \pm 22 \pm 47$	$255 \pm 55 \pm 127$
$T^*_{c\bar{c}\bar{s}1}(5200)^0$	1^-	$5225 \pm 86 \pm 181$	$226 \pm 76 \pm 374$
$T_{c\bar{c}\bar{s}1}(4000)^+$	1^+	4003 (fixed)	131 (fixed)

Exotic $\psi(2S)K^+\pi^-$ resonances are observed for the first time