Recent searches for new physics and rare decays at LHCb

俞洁晟（湖南大学）

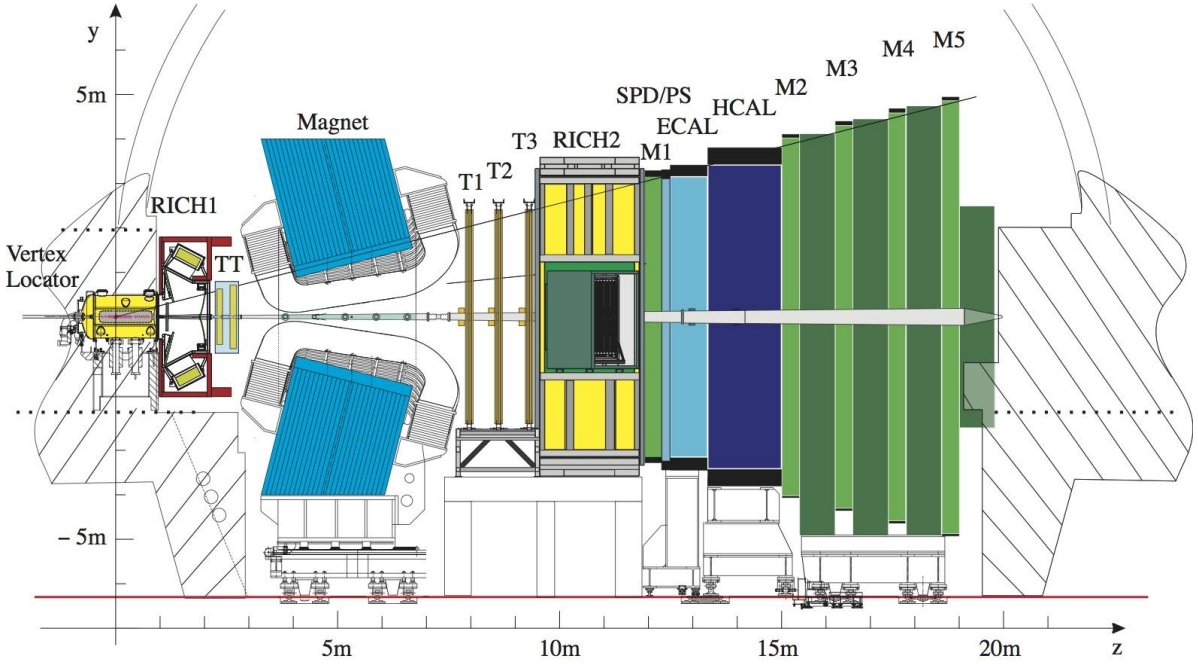
第5届LHCb前沿物理研讨会
武汉
2025年4月25-28日

Outline

- Introduction
- Rare decays
  - FCNC
  - Baryonic decays of B meson
- Prospects
- Summary

LHCb experiment

LHCb collaboration： 25 counties, 107 institutes, 1770 members

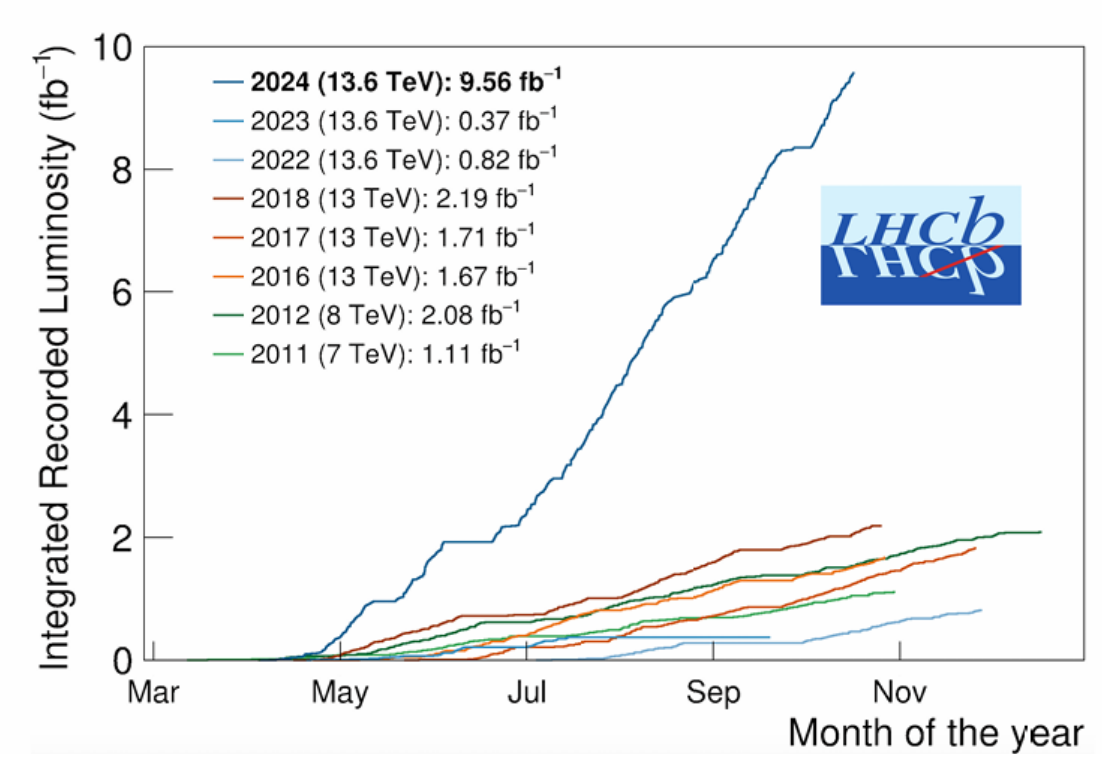


中国单位：
清华大学
华中师范大学
中国科学院大学
武汉大学
高能物理研究所
华南师范大学
北京大学
湖南大学
兰州大学
河南师范大学
西北工业大学
中国科学技术大学

- Understand matter-antimatter imbalance (CP violation)
- Search for new physics (Rare decays)
- Explore and understand QCD (Hadron properties, exotic hadrons)

LHCb data samples

Run 1: 3 fb^{-1}, Run 2: 6 fb^{-1}, Run 3: 9.6 fb^{-1},



Large $b\bar{b}$ and $c\bar{c}$ production cross sections:

$\sigma(b\bar{b}X) \sim 0.5\% \times \sigma_{pp}^{\text{inelas}}$, $\sigma(c\bar{c}X) \sim 10\% \times \sigma_{pp}^{\text{inelas}}$

FCNC $b \to s\gamma(l^+l^-)$ decays

- Angular analysis of $B^0 \to K^{*0}e^+e^-$ decays central q2 [arXiv:2502.10291v1] submit to JHEP
- Photon polarization in $B_s^0 \to \phi e^+e^-$, low q2 JHEP03(2025)047
- Angular analysis of the decay $B_s^0 \to \phi e^+e^-$ low q2 [arXiv:2504.06346v1] submit to JHEP

$b \to s l^+ l^-$ decays

➢ $b \to s l^+ l^-$ decays described by effective Hamiltonian

$$H = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i \, O_i + \frac{K}{\Lambda_{NP}^2} O_j^{(6)}$$

New physics can affect Wilson coefficients C_i or add new operators O_j

Wilson Coefficients: C_i

→ Perturbative, short distance physics

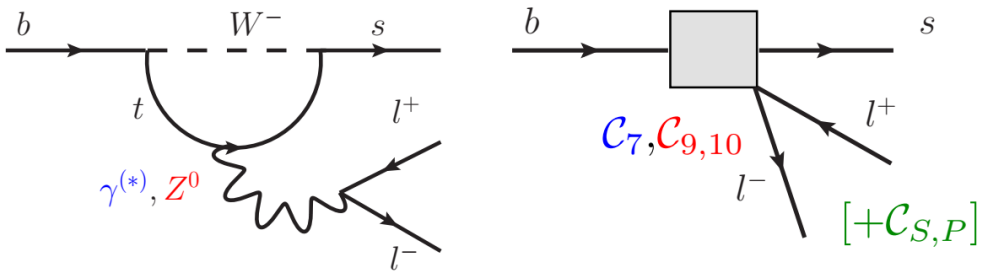
→ Describes heavy SM+NP effects

Operators: $\mathcal{O}_i$

→ Non-perturbative, long distance physics

→ Strong interactions, difficult to calculate

➢ Sensitivity to Wilson coefficients

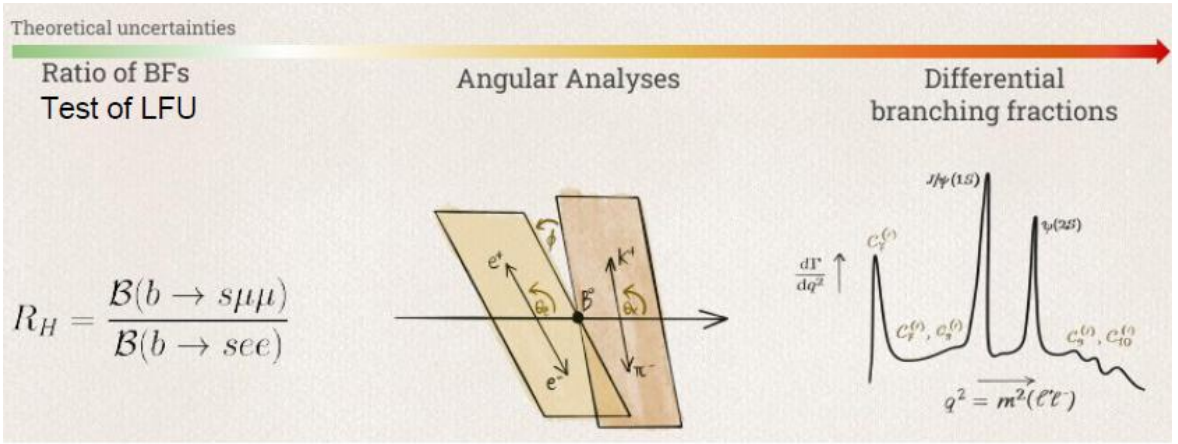


- $B^0_{(s)} \to l^+ l^-$ $[C_{10}, C_S, C_P]$
- $b \to s l^+ l^-$ $[C_7, C_9, C_{10}]$

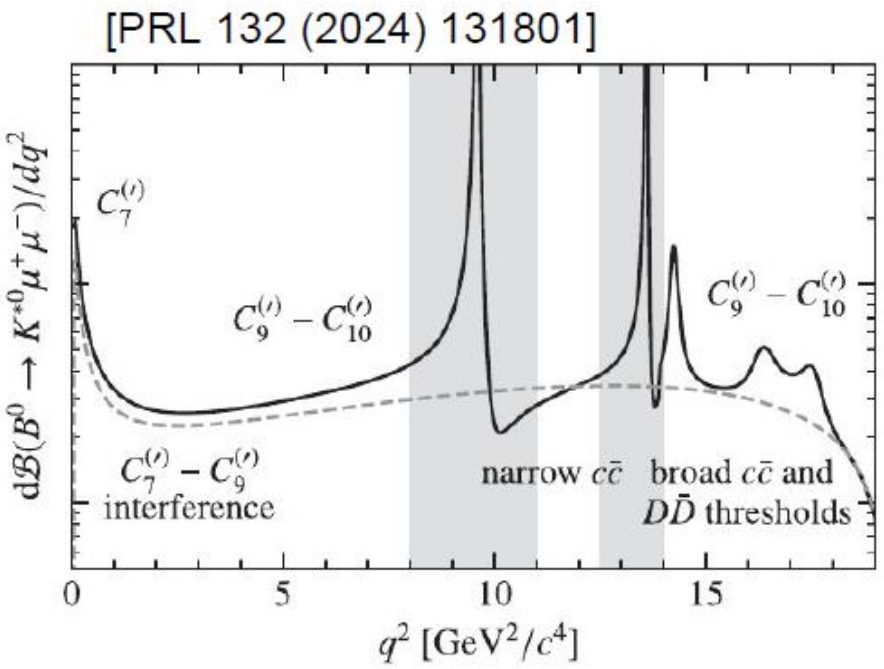
7: photon penguin; 9,10: EW penguin; S,P: (pseudo-) scalar penguin

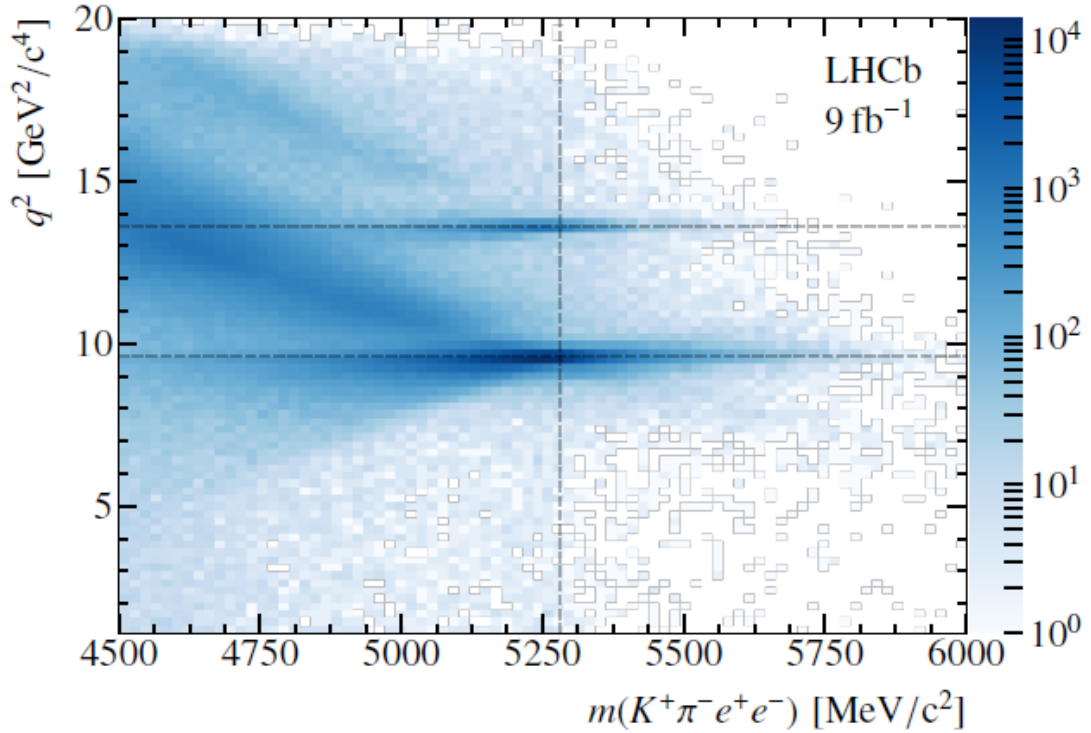
➢ Theoretically clean probes of NP

- Pure leptonic decays
- Ratio between $e/\mu/\tau$
- Special angular observables
- Differential BF



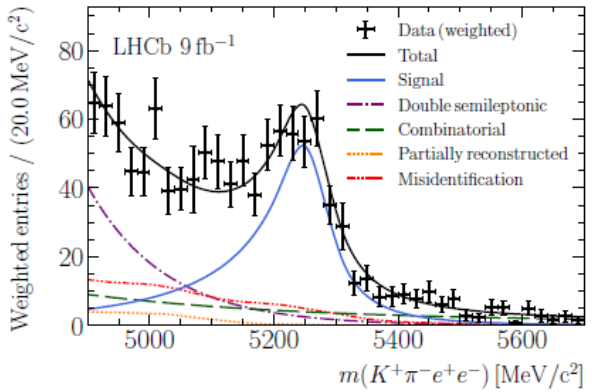
Angular analysis of $B^0 \to K^{*0} e^+ e^-$ with Run1&2 data

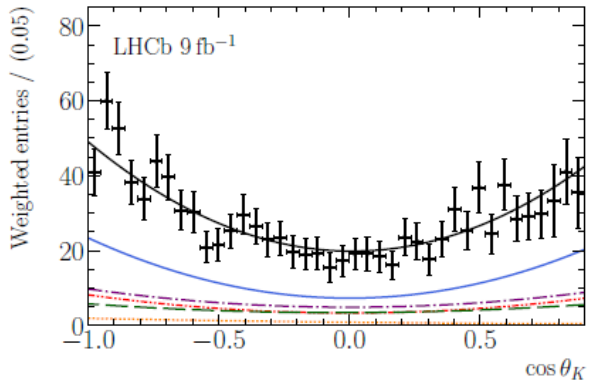


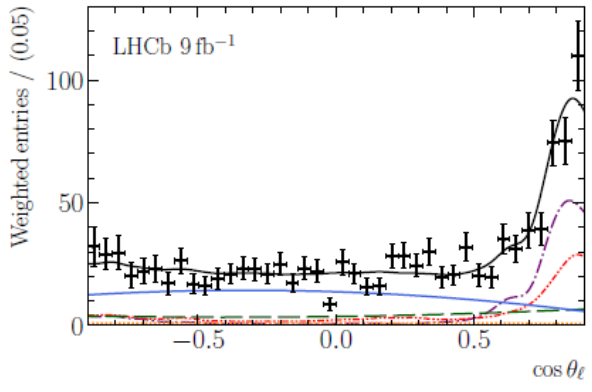


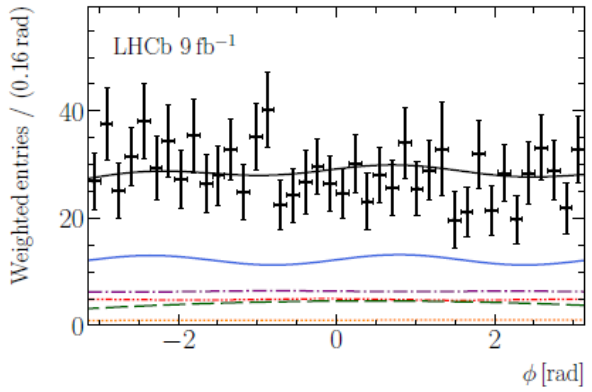
arXiv:2502.10291

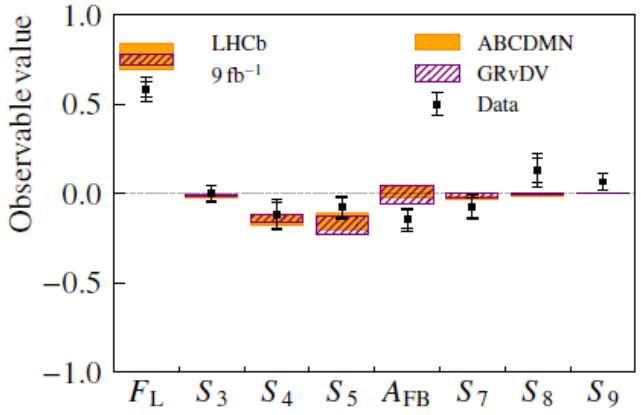
Angular analysis of $B^0 \to K^{*0} e^+ e^-$ with Run1&2 data

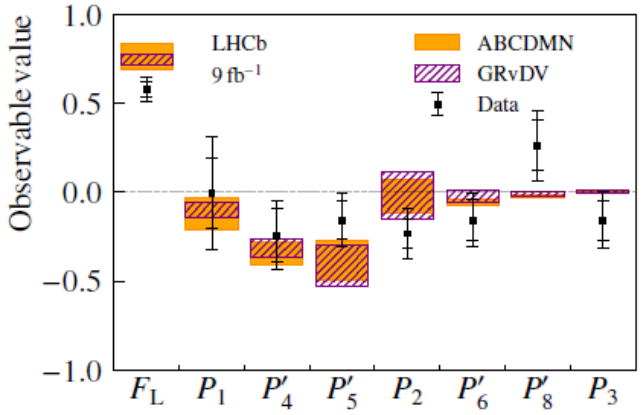












- Angular observables extracted from 4D fit
- General good agreement with SM predictions
- Most precise measurements up to date

arXiv:2502.10291

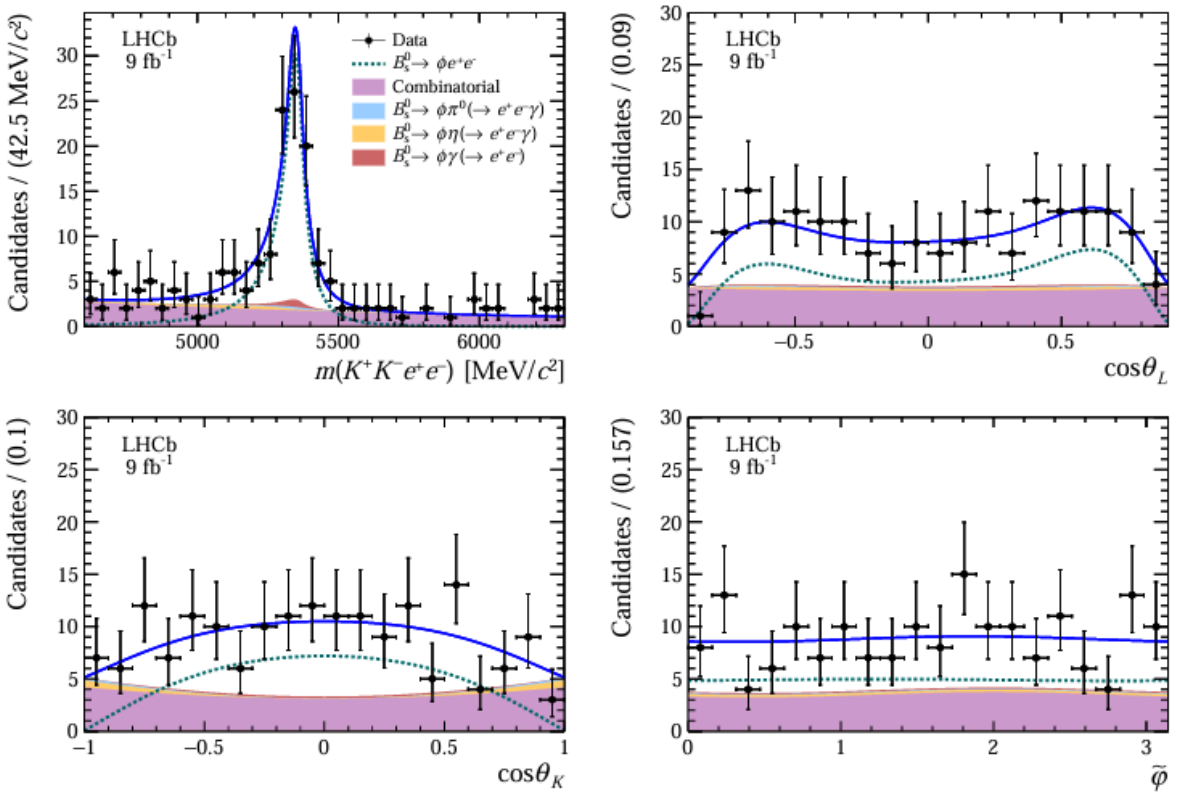
Angular observables			
F_L	$0.58 \pm 0.04 \pm 0.05$	F_L	$0.58 \pm 0.04 \pm 0.05$
S_3	$-0.00 \pm 0.04 \pm 0.02$	P_1	$-0.00 \pm 0.20 \pm 0.25$
S_4	$-0.12 \pm 0.07 \pm 0.04$	P_4'	$-0.24 \pm 0.15 \pm 0.13$
S_5	$-0.08 \pm 0.05 \pm 0.03$	P_5'	$-0.16 \pm 0.11 \pm 0.11$
A_{FB}	$-0.15 \pm 0.05 \pm 0.04$	P_2	$-0.23 \pm 0.08 \pm 0.12$
S_7	$-0.08 \pm 0.06 \pm 0.04$	P_6'	$-0.16 \pm 0.11 \pm 0.10$
S_8	$0.13 \pm 0.07 \pm 0.06$	P_8'	$0.26 \pm 0.14 \pm 0.14$
S_9	$0.07 \pm 0.05 \pm 0.02$	P_3	$-0.16 \pm 0.11 \pm 0.11$

Photon polarization in $B_s^0 \to \phi e^+ e^-$

- Perform angular analysis at very low $q2$ region , angular observables are sensitive to C_7 and C_7'

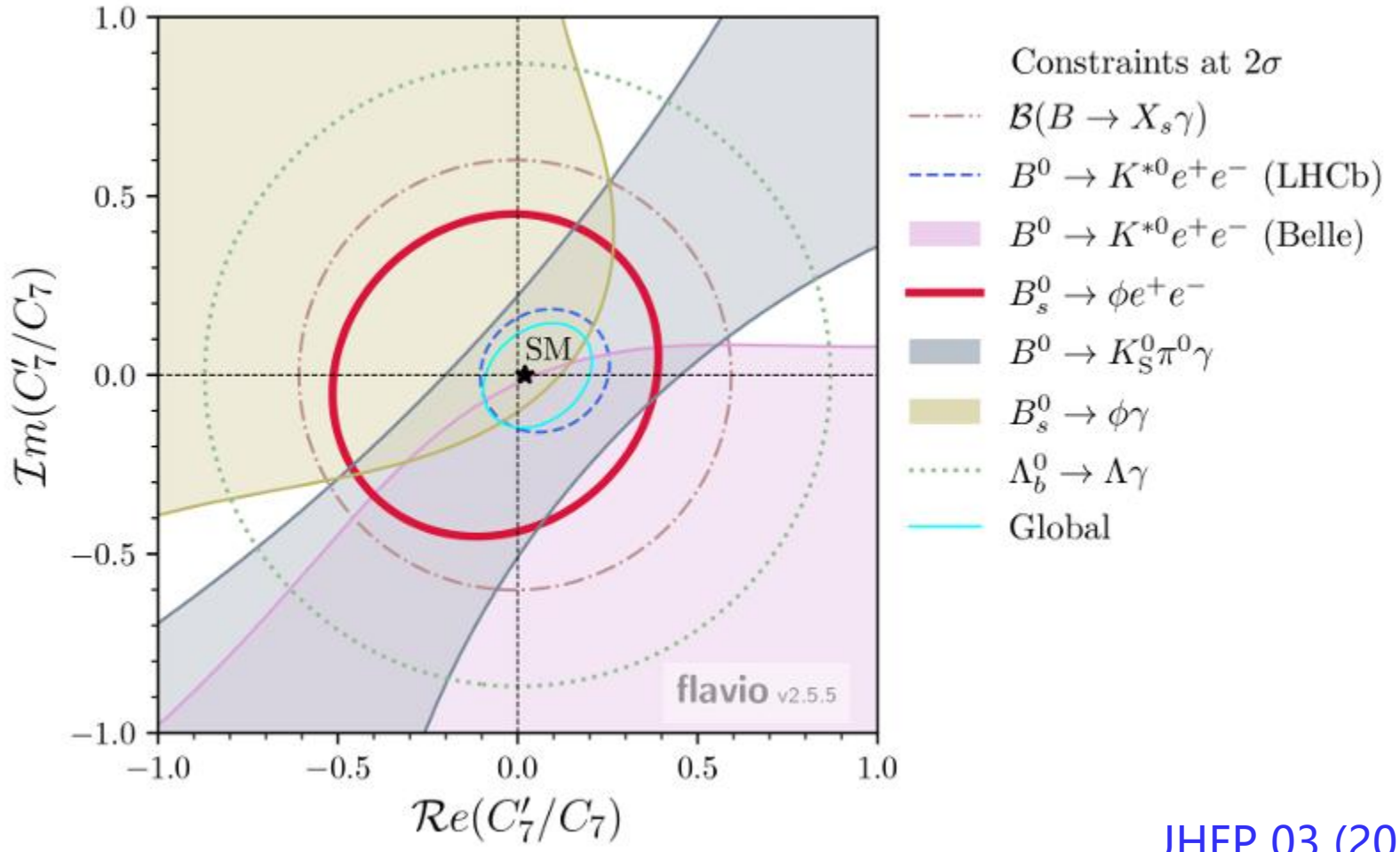
- First observation

$$
\begin{aligned}
A_{\mathrm{T}}^{(2)} &= -0.045 \pm 0.235 \pm 0.014\,, \\
A_{\mathrm{T}}^{\mathcal{I}mCP} &= 0.002 \pm 0.247 \pm 0.016\,, \\
A_{\mathrm{T}}^{\mathcal{R}eCP} &= 0.116 \pm 0.155 \pm 0.006\,, \\
F_{\mathrm{L}} &= (0.4 \pm 5.6 \pm 1.2)\%\,,
\end{aligned}
$$



JHEP 03 (2025) 047

Photon polarization in $B_s^0 \to \phi e^+ e^-$



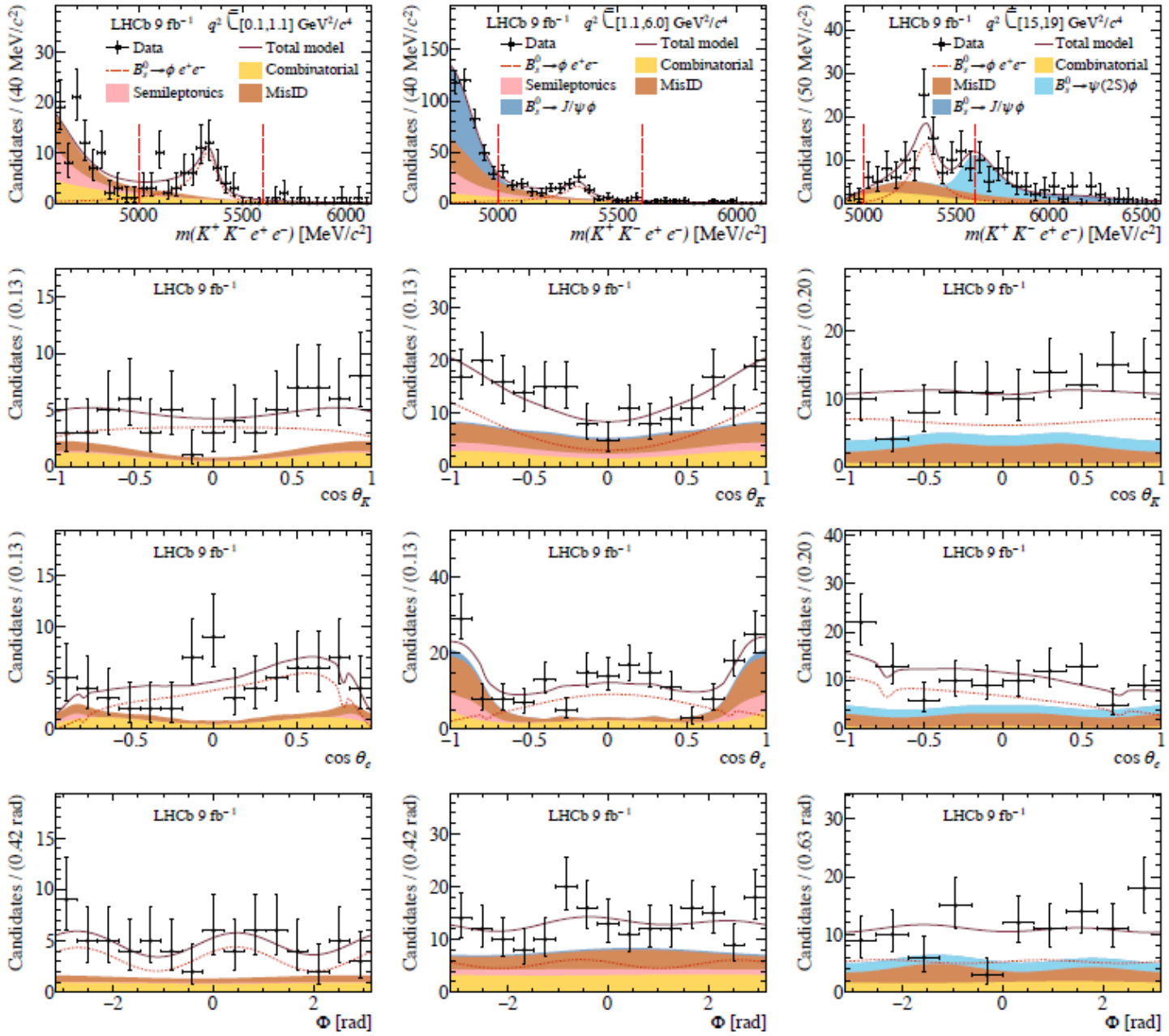
JHEP 03 (2025) 047

- Consistent with the SM predictions

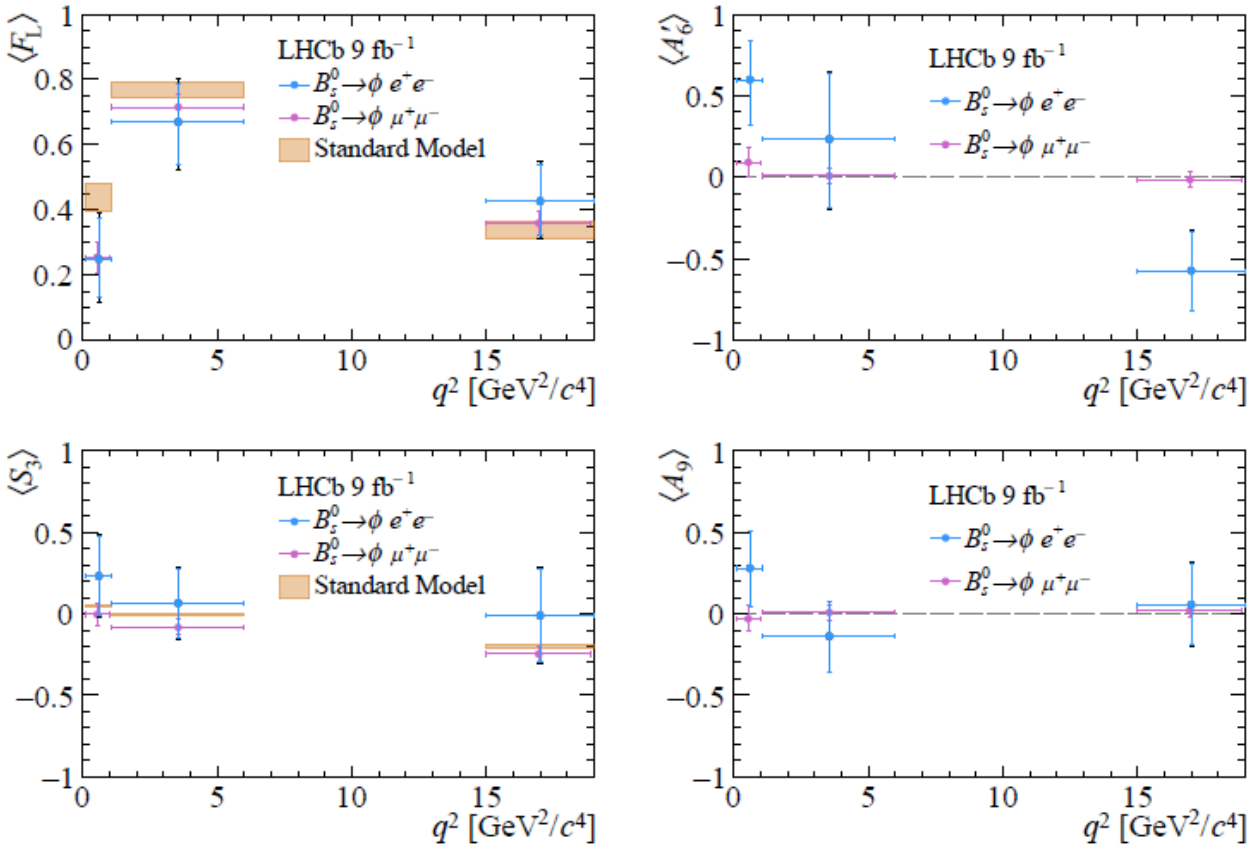
Angular analysis of the decay $B_s^0 \to \phi e^+ e^-$

- Angular analysis of similar decay mode in the low, central and high $q2$ regions

arxiv:2504.06346



Angular analysis of the decay $B_s^0 \to \phi e^+ e^-$



Observable	$0.1 < q^2 < 1.1\,\mathrm{GeV}^2/c^4$	$1.1 < q^2 < 6.0\,\mathrm{GeV}^2/c^4$	$15.0 < q^2 < 19.0\,\mathrm{GeV}^2/c^4$
$\langle F_L \rangle$	$0.25\,^{+0.12}_{-0.12} \pm 0.06$	$0.67\,^{+0.12}_{-0.13} \pm 0.06$	$0.43\,^{+0.11}_{-0.10} \pm 0.05$
$\langle A_6' \rangle$	$0.60\,^{+0.23}_{-0.28} \pm 0.05$	$0.24\,^{+0.40}_{-0.42} \pm 0.09$	$-0.57\,^{+0.24}_{-0.25} \pm 0.05$
$\langle S_3 \rangle$	$0.23\,^{+0.24}_{-0.24} \pm 0.07$	$0.07\,^{+0.21}_{-0.21} \pm 0.07$	$-0.01\,^{+0.29}_{-0.28} \pm 0.08$
$\langle A_9 \rangle$	$0.28\,^{+0.23}_{-0.24} \pm 0.04$	$-0.14\,^{+0.23}_{-0.24} \pm 0.04$	$0.06\,^{+0.25}_{-0.25} \pm 0.05$

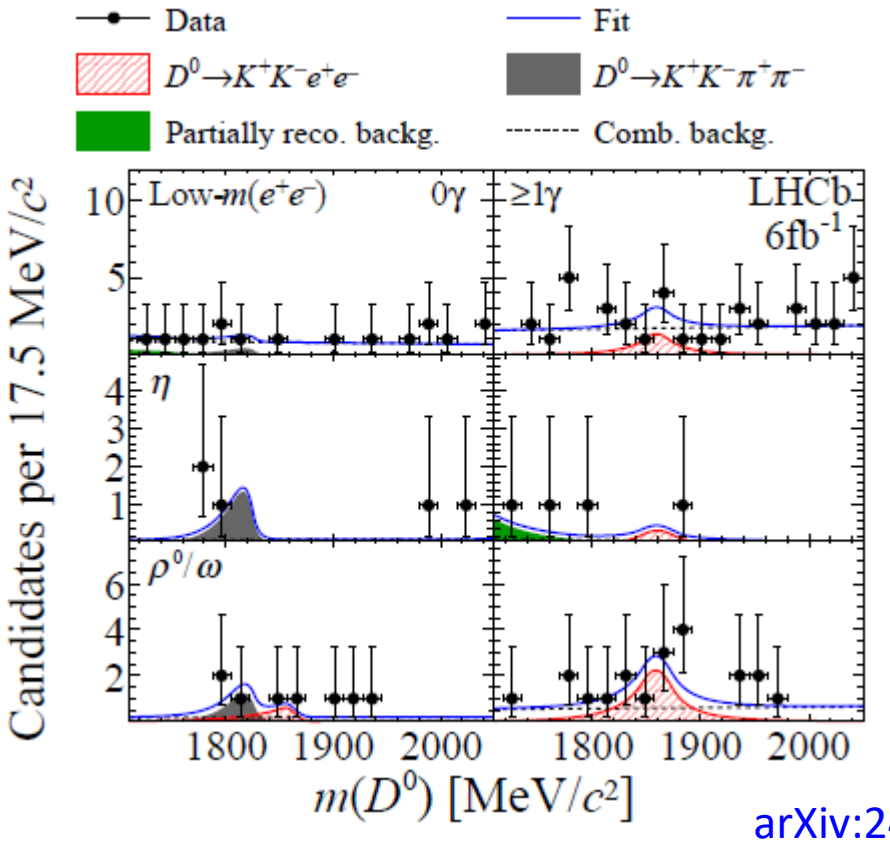
- Results compatible with SM predictions

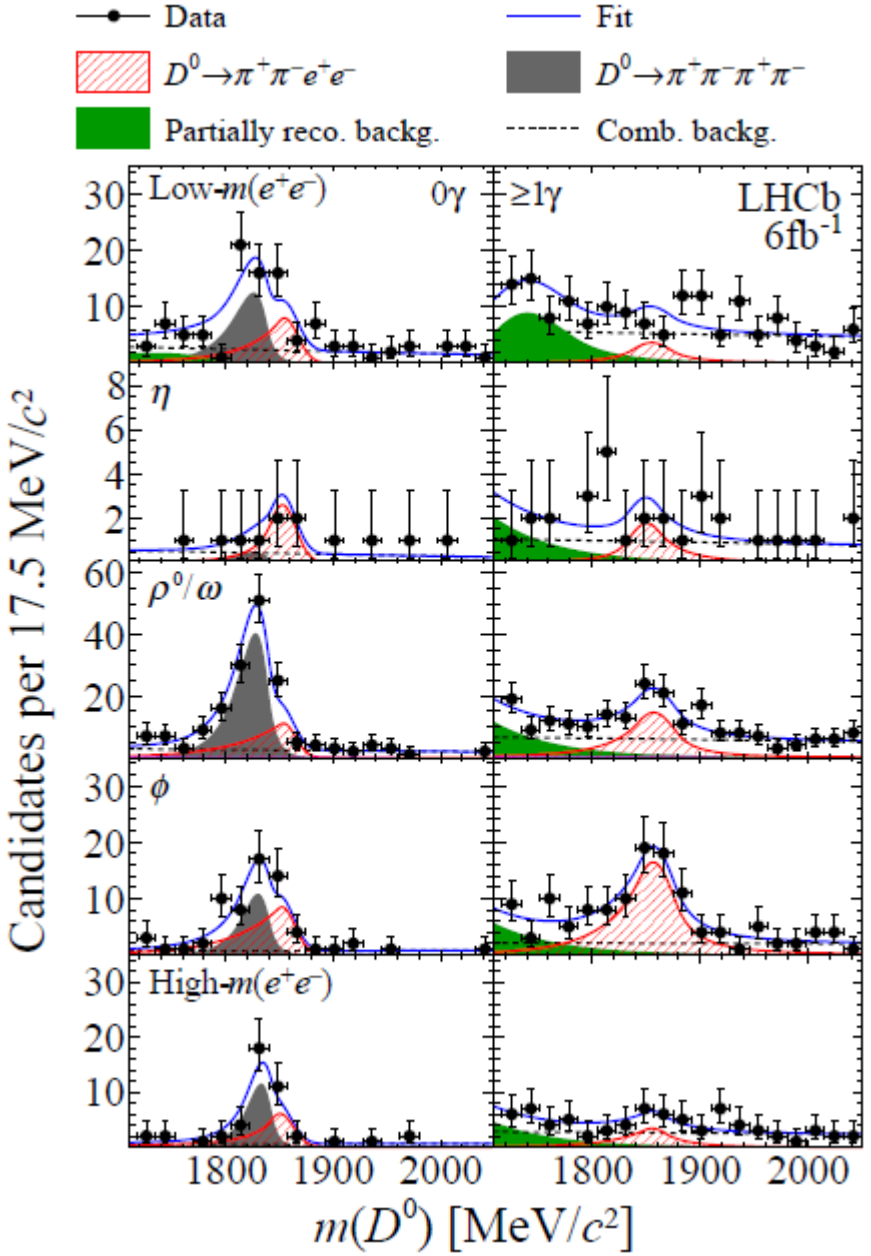
Other FCNC

- Search for $D^0 \rightarrow hhe^+e^-$ [arXiv:2412.09414v2] submit to PRL
- Observation of the very rare $\Sigma^+ \rightarrow p\mu^+\mu^-$ [arXiv:2504.06096v1] submit to PRL

Search for $D^0 \to \pi^+\pi^-(K^+K^-)e^+e^-$ with Run 2 data

- FCNC $c \to ul^+l^-$ in SM
  - BF~10^{-9} with short−distance contributions
  - BF~10^{-6} with long-distance processes
- $D^0 \to K^+\pi^-e^+e^-$ as normalization channel





arXiv:2412.09414

Search for $D^0 \to \pi^+\pi^-(K^+K^-)e^+e^-$ with Run 2 data

$m(e^+e^-)$ region	$[\mathrm{MeV}/c^2]$	Yield	$\mathcal{S}$
$D^0 \to \pi^+\pi^- e^+e^-$			
Low mass	$2m_\mu$–525	37 ± 13	2.8σ
η	525–565	10 ± 7	1.6σ
ρ^0/ω	565–950	97 ± 21	5.5σ
ϕ	950–1100	100 ± 18	8.1σ
High mass	> 1100	30 ± 11	2.9σ
$D^0 \to K^+K^- e^+e^-$			
Low mass	$2m_\mu$–525	4 ± 8	1.2σ
η	525–565	1 ± 2	1.1σ
ρ^0/ω	> 565	12 ± 7	2.2σ

$m(e^+e^-)$ region	$[\mathrm{MeV}/c^2]$	$\mathcal{B}$ $[10^{-7}]$
$D^0 \to \pi^+\pi^- e^+e^-$		
Low mass	$2m_\mu$–525	$< 4.8\,(5.4)$
η	525–565	$< 2.3\,(2.7)$
ρ^0/ω	565–950	$4.5 \pm 1.0 \pm 0.7 \pm 0.6$
ϕ	950–1100	$3.8 \pm 0.7 \pm 0.4 \pm 0.5$
High mass	> 1100	$< 2.0\,(2.2)$
$D^0 \to K^+K^- e^+e^-$		
Low mass	$2m_\mu$–525	$< 1.0\,(1.1)$
η	525–565	$< 0.4\,(0.5)$
ρ^0/ω	> 565	$< 2.2\,(2.5)$

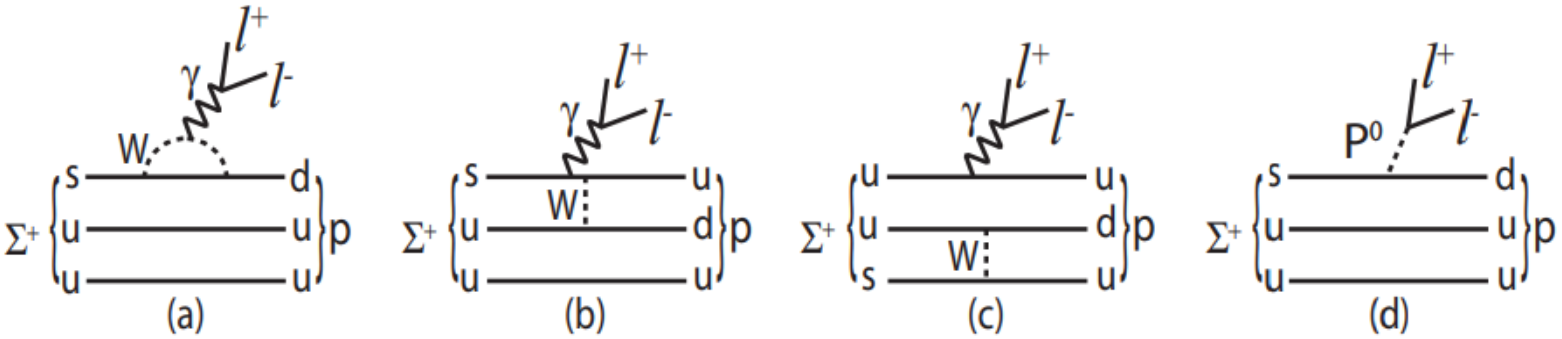
$$\mathcal{B}(D^0 \to \pi^+\pi^-[e^+e^-]_{m(e^+e^-)>2m_\mu}) = (13.3 \pm 1.1 \pm 1.7 \pm 1.8) \times 10^{-7},$$

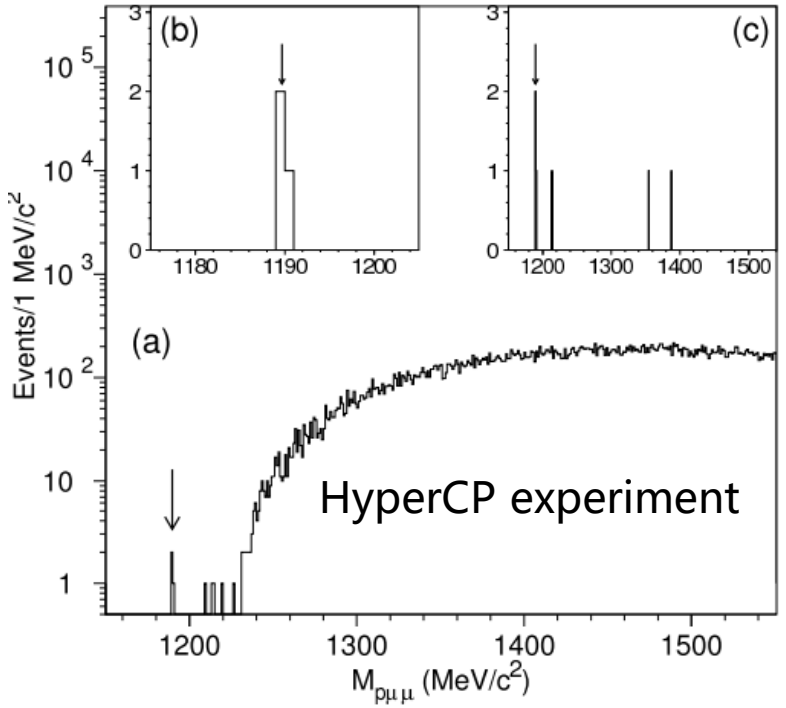
- First time observation of $\boldsymbol{D^0 \to \pi^+\pi^- e^+e^-}$
- No evidence of $\boldsymbol{D^0 \to K^+K^- e^+e^-}$

Observation of $\Sigma^+ \to p\mu^+\mu^-$ with Run 2 data

- $\Sigma^+ \to p\mu^+\mu^-$ is FCNC heavily suppressed in SM
  - BF~10^{-12} with short-distance contributions
  - BF~$[1.2,7.8] \times 10^{-8}$ with the long-distance SM contribution:
    $\Sigma^+ \to (\mathrm{N}\pi)^+ \to p\gamma^{(*)}$
  - Evidence in HyperCP experiment

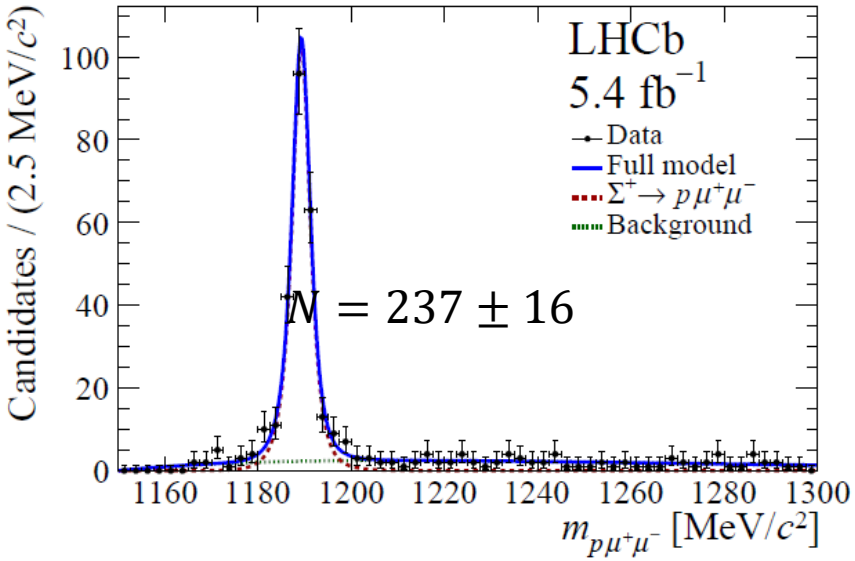
$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$$

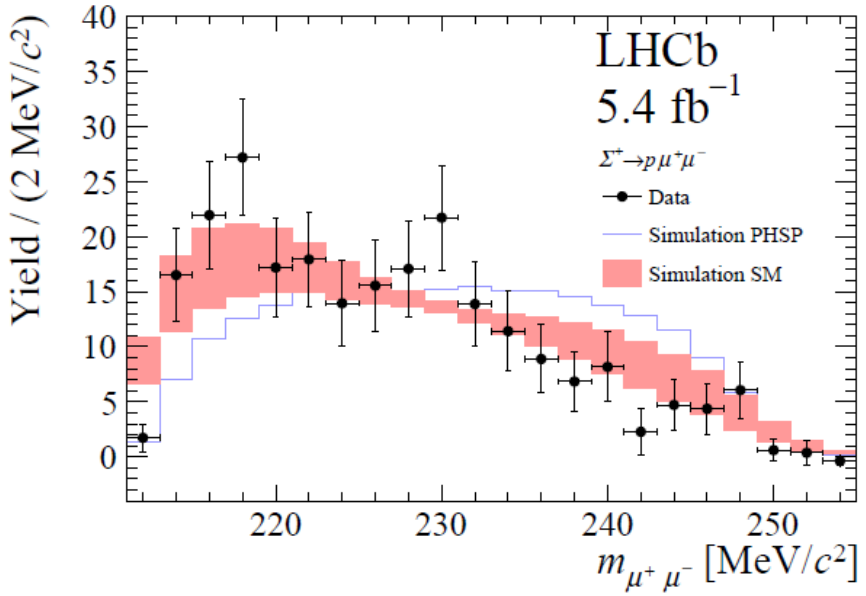




Phys. Rev. Lett. 94 (2005) 021801

Observation of $\Sigma^+ \to p\mu^+\mu^-$ with Run 2 data





- $\Sigma^+ \to p\pi^0$ as normalization channel

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = \frac{\varepsilon_{\text{Norm}}}{\varepsilon_{\text{Sig}}} \frac{N_{\text{Sig}}}{N_{\text{Norm}}} \mathcal{B}(\Sigma^+ \to p\pi^0) = \alpha N_{\text{Sig}}$$

- No structure is seen in $m_{\mu\mu}$,
- Combined with the Run 1 result:

$$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (1.09 \pm 0.17) \times 10^{-8}.$$

- Agreement with the SM predictions

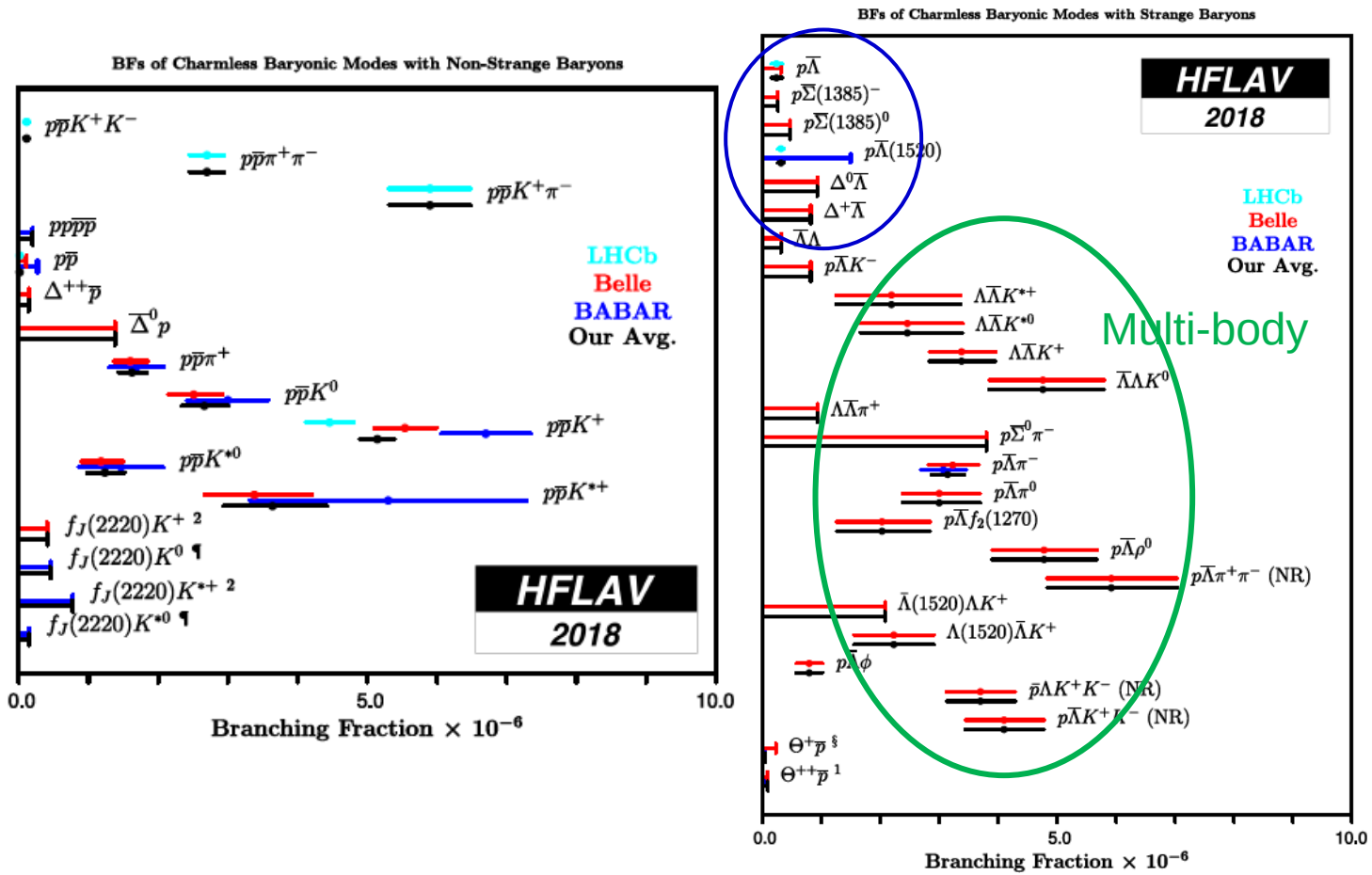
Phys. Rev. D 110 (2024) 052007

Baryonic decays of B meson

The feature of B baryonic decays

- Two-body baryonic decays suppressed with respect to multibody decays
- Decays of B mesons into multiple baryons still far from being fully understood

Two-body

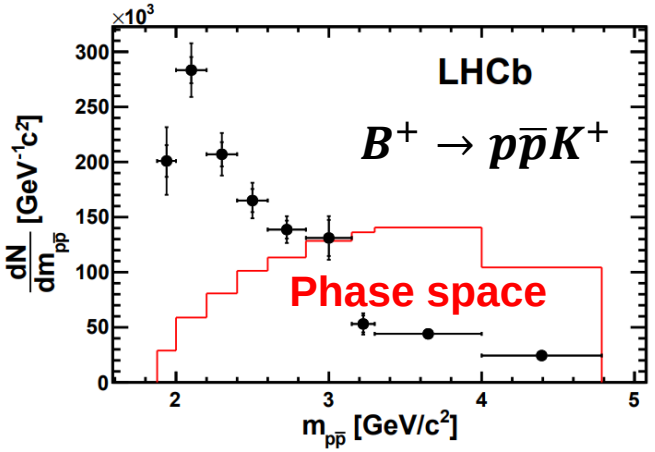


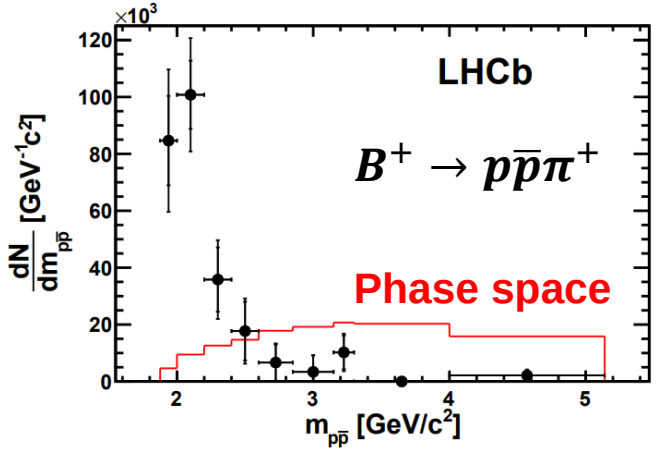
Charmless baryonic $B^+$and B^0 modes branching fractions reported by HFLAV

Charmless baryons threshold enhancement

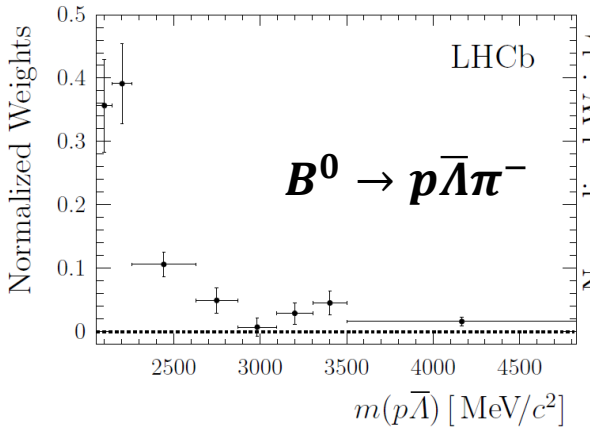
- Many channels have the special feature: baryon-antibaryon pair peaks near threshold

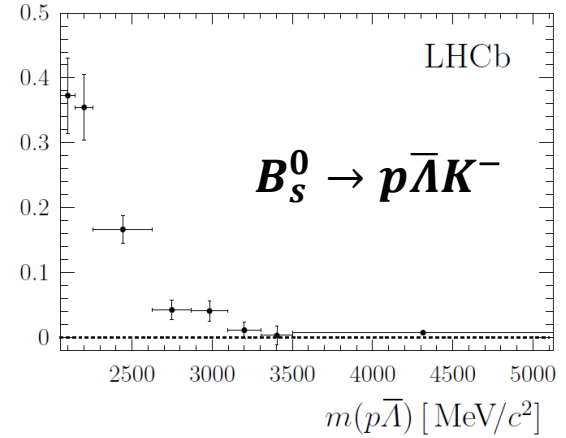
PRD 88, 052015 (2013)

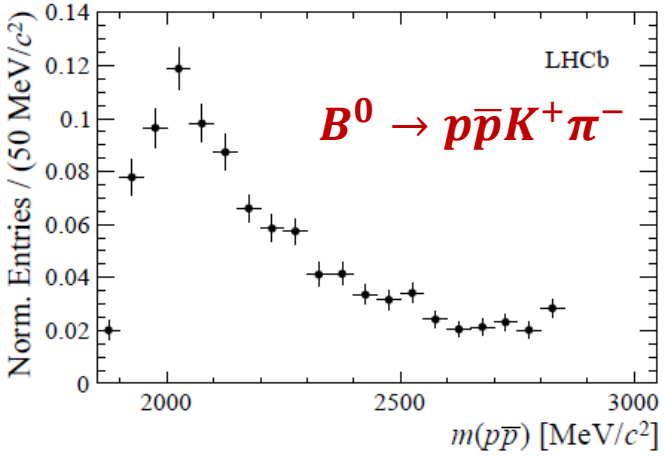


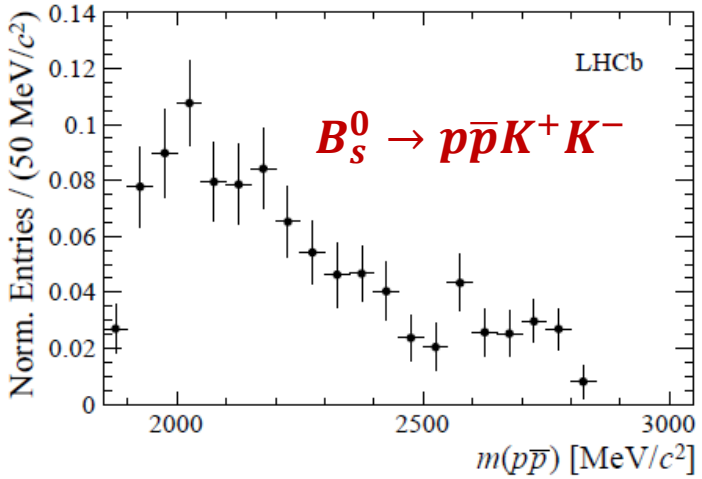


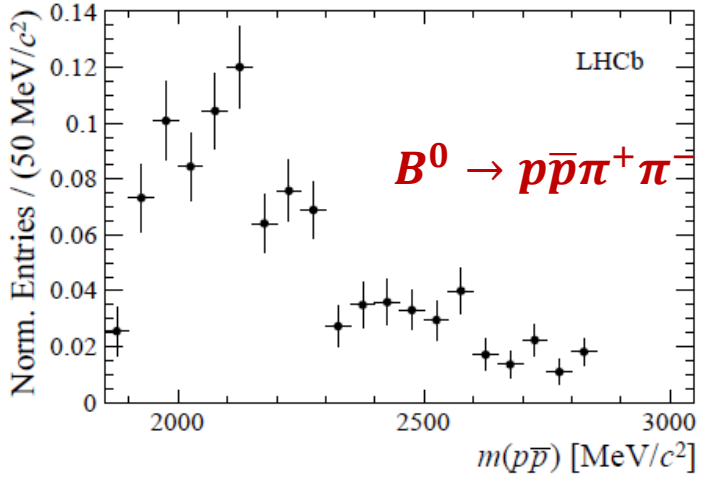
Phys. Rev. Lett. 119 (2017) 041802





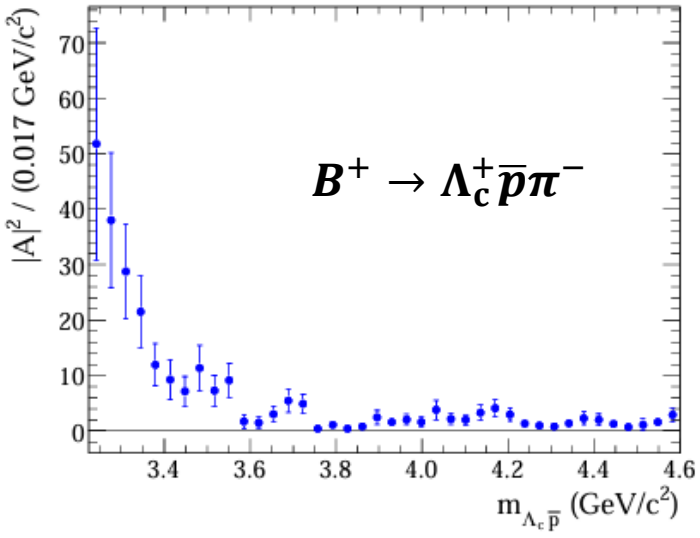




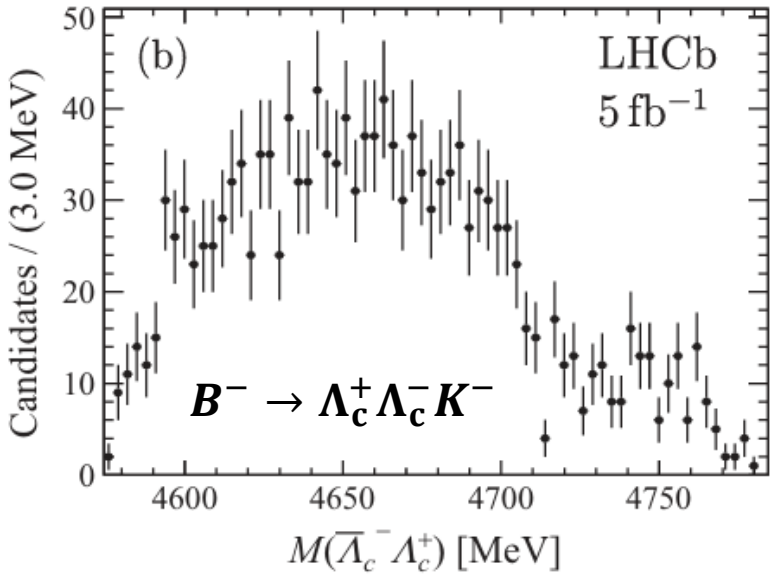


Phys. Rev. D 96 (2017) 051103

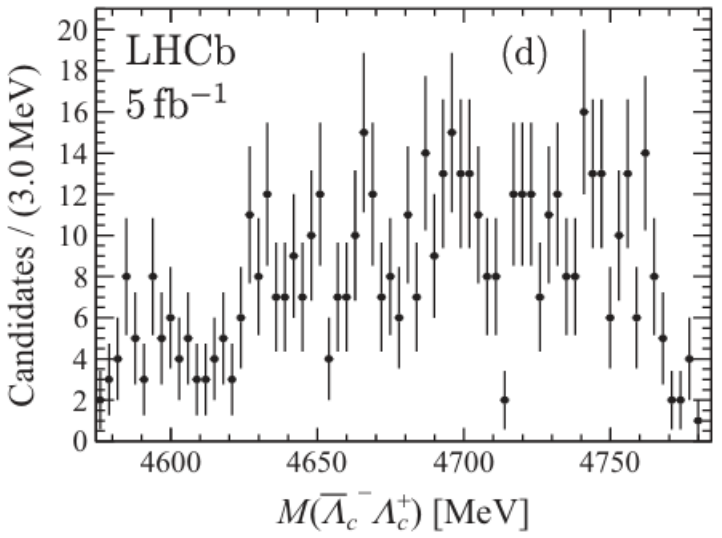
Charm baryon threshold enhancement



PhysRevD.78.112003



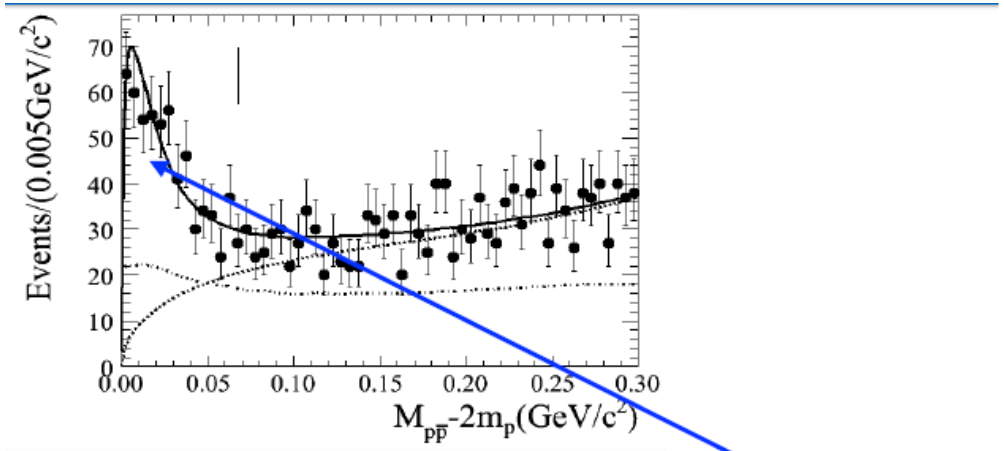
PhysRevD. 108, 012020 (2023)

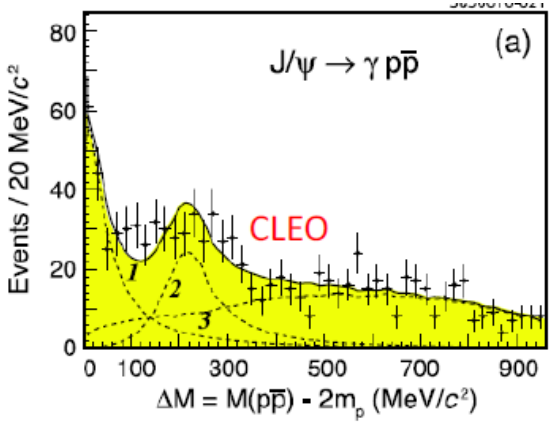


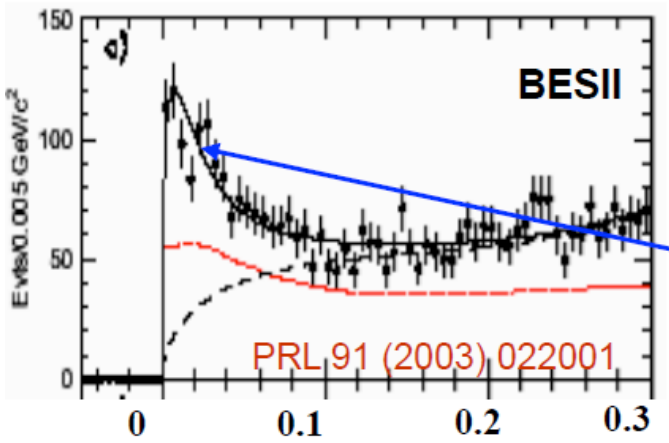
$B^- \to \Lambda_c^+ \Lambda_c^- K^-(2900$
$< \mathrm{M}(\Lambda_c^+ K^-) < 2970\ \mathrm{MeV})$

- How to understand the kinetic mechanism of the threshold effect
- How to fit the data

Observation of threshold enhancement at BESIII







$M=1859\ ^{+3}_{-10}\ ^{+5}_{-25}\ MeV/c^2$

$\Gamma < 30\ MeV/c^2\ (90\%\ CL)$

$M=1861\ ^{+6}_{-13}\ ^{+7}_{-26}\ MeV/c^2$

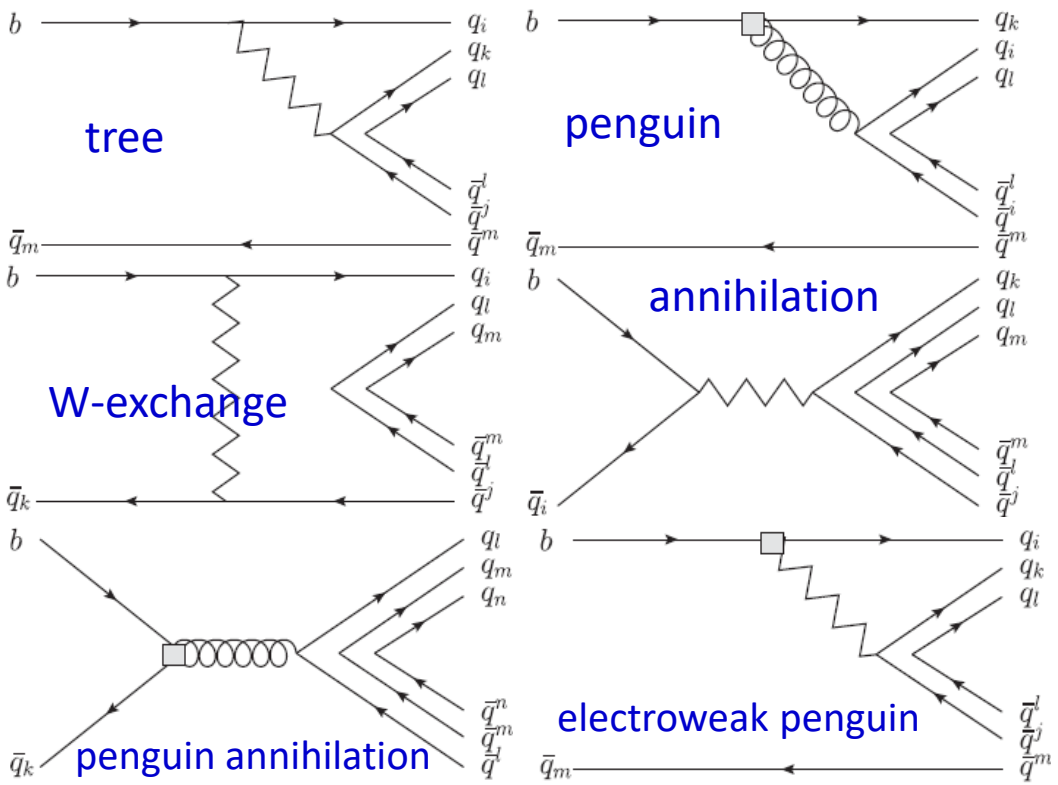
$\Gamma < 38\ MeV/c^2\ (90\%\ CL)$

- It can not be pure FSI effect

Two-body baryonic decays of B

- Provides information on the dynamics of B decays and tests QCD based models of the hadronization process
- BF of two-body as input to multi-body decays

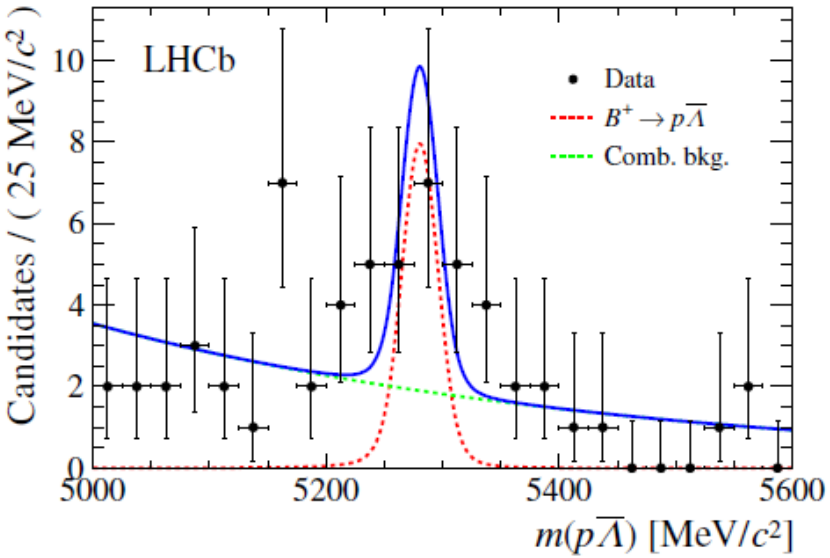
Phys. Rev. D 95, 096004 (2017)



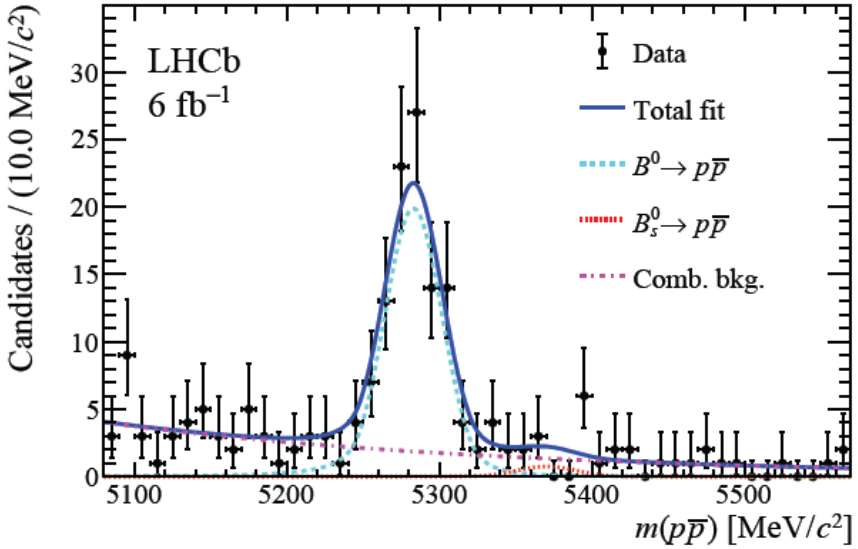
- $B^0 \to p\bar{p}$ and $B^+ \to p\bar{\Lambda}$ as inputs to predict other $B \to \mathfrak{B}_1\mathfrak{B}_2$
- Baryonic B decays are also interesting in the study of CP violation
- Pure penguin modes are expected to be sensitive to new physics contributions

Two−body baryonic decays of B at LHCb

JHEP 04(2017)162



Phys. Rev. D 108, 012007



- $\mathcal{B}(B^+ \to p\overline{\Lambda}) = (2.4^{+1.0}_{-0.8} \pm 0.3) \times 10^{-7}$
- $\mathcal{B}(B^0 \to p\bar{p}) = (1.27 \pm 0.15 \pm 0.05 \pm 0.04) \times 10^{-8}$
- $\mathcal{B}(B_s^0 \to p\bar{p}) < 4.5(5.1) \times 10^{-9}$@90%(95%) CL

Prospects

- **Upgrade (2025: 14 fb^{-1} and Upgrade-II: 300 fb^{-1})**

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [606]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [607]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [608]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [609]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [610]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

CERN-LHCC-2018-027, 2021-012

Summary

- **There is no sign of beyond the SM source yet**
  - Many first searches, angular analyses

- **Opportunities in future**
  - Higher precision in rare decay measurements: $B^0_{s/d} \to \mu^+\mu^-$, angular distributions and LFU tests in $b \to s l^+ l^-$ decays, …
  - Wider scope for exploitation: more $s \to d l^+ l^-$ decays, $c \to u l^+ l^-$ decays,…
  - More B meson baryonic decays are on the way: $B^- \to \Lambda \bar{p}$, $B^0_{(s)} \to \Lambda_c^+ \bar{\Lambda}_c^-$, $B^0_{(s)} \to \Lambda_c^+ \bar{\Xi}_c^-$, $B^0_{(s)} \to \Xi_c \bar{\Xi}_c$,…

Thank you