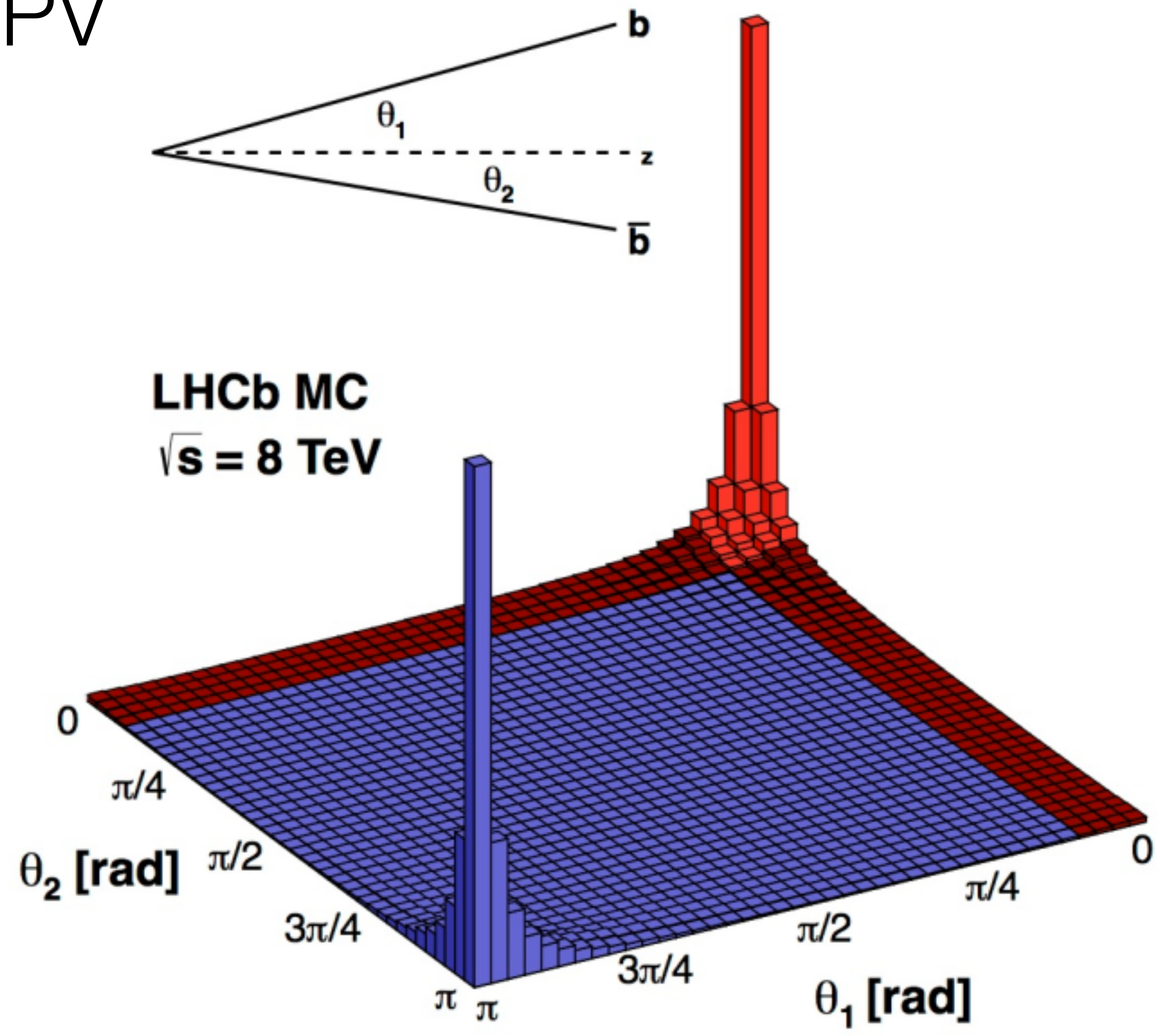
LHCb physics overview

Michal Kreps

Triggering discoveries in high energy physics, High Tatras, Dec. 2024

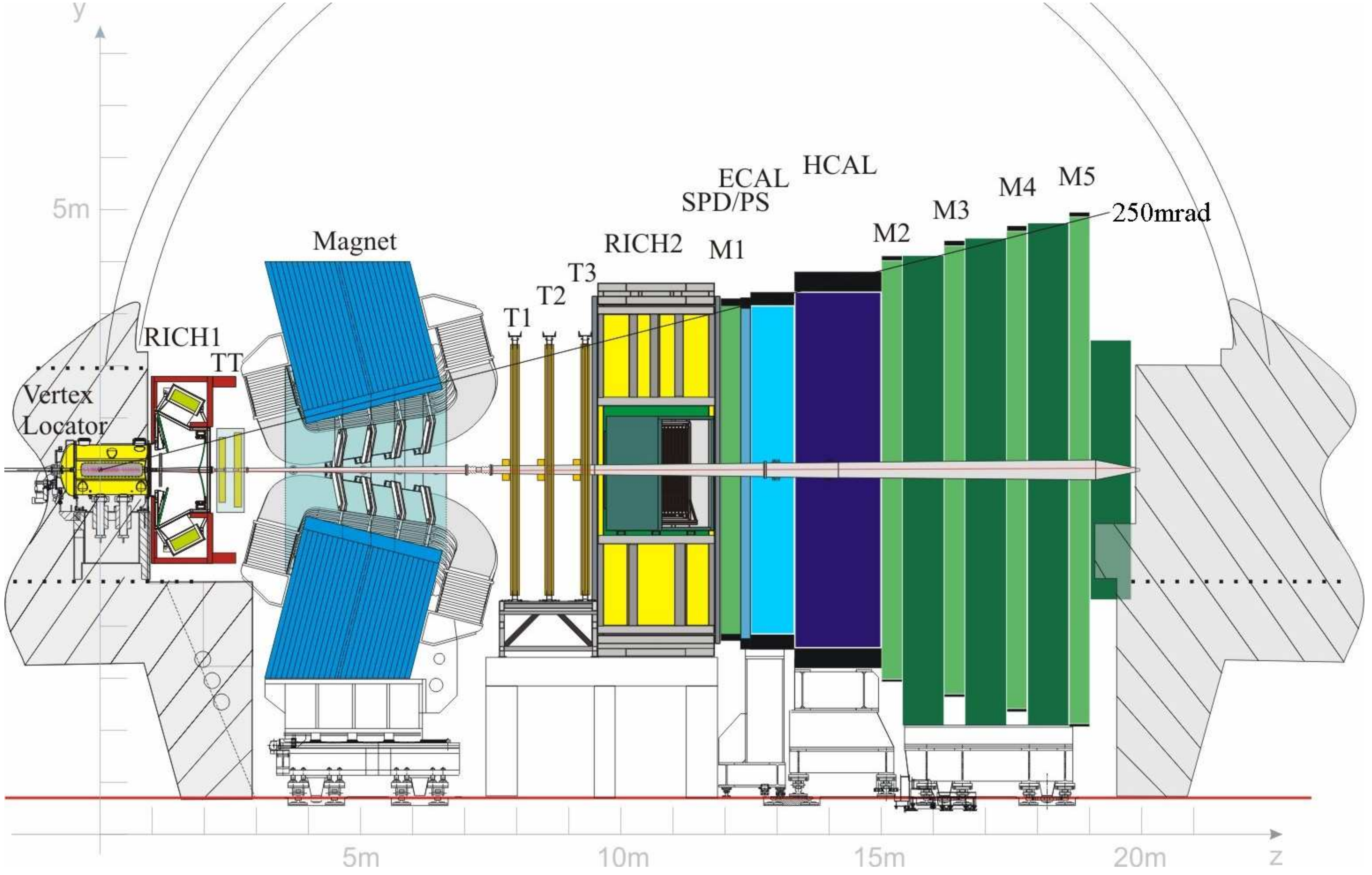
LHCb detector

- ➡ Primary focus of LHCb is to study decay of *B* hadrons
  - ❖ CKM angle γ, CPV in charmless 2-body B decays, CPV in $B_s \to J/\psi\phi$, $B_s \to \mu^+\mu^-$, angular analysis of $B^0 \to K^*\mu^+\mu^-$ and $B_s \to \phi\gamma$ (arXiv:0912.4179)
- ➡ Need
  - ❖ good time resolution
  - ❖ good momentum/mass resolution
  - ❖ particle identification
  - ❖ large production of *B* hadrons

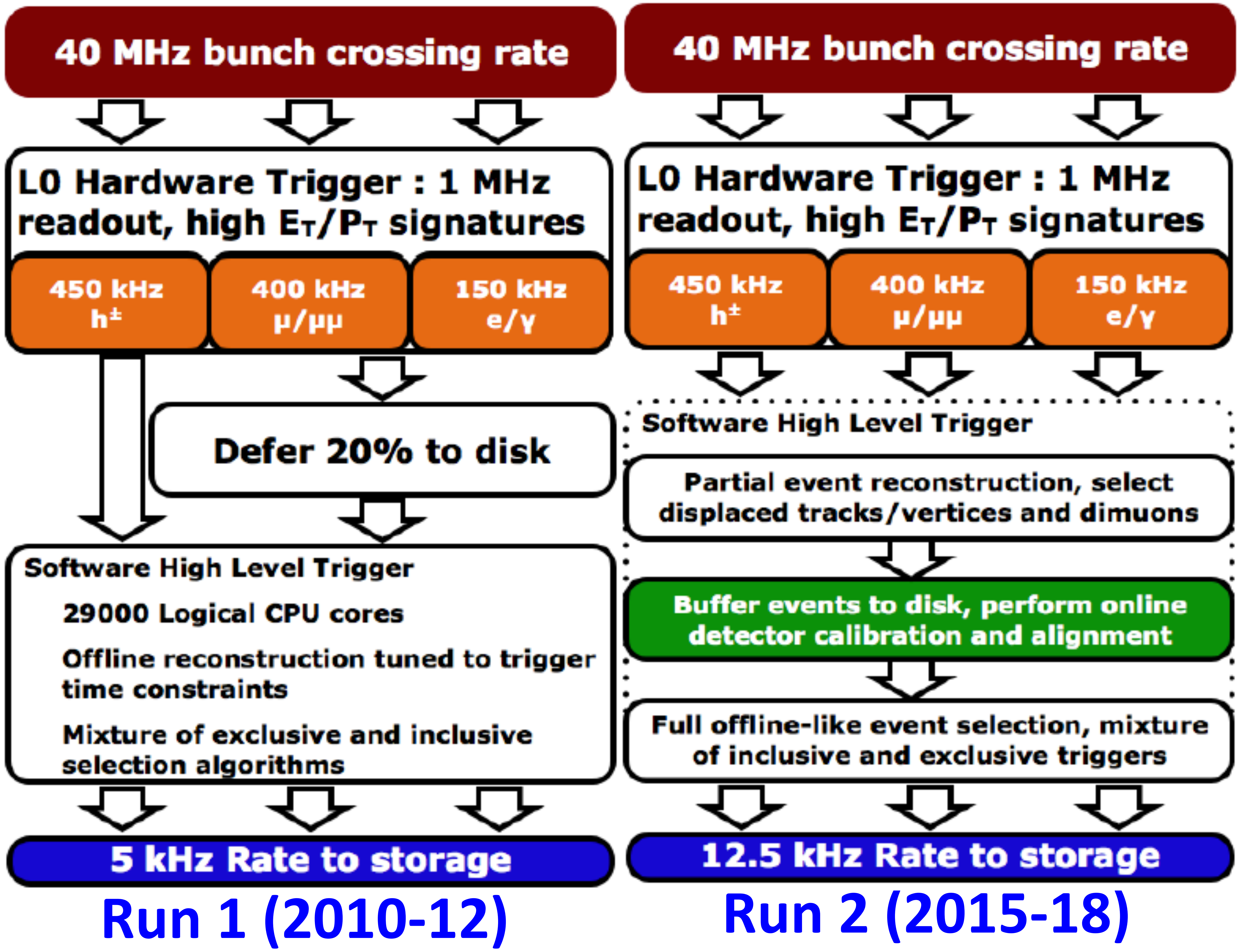


LHCb detector

- ➡ Exploit large b-hadron cross-section in forward region
- ➡ Excellent tracking, vertexing and particle identification
- ➡ Very flexible trigger



Trigger in a nutshell

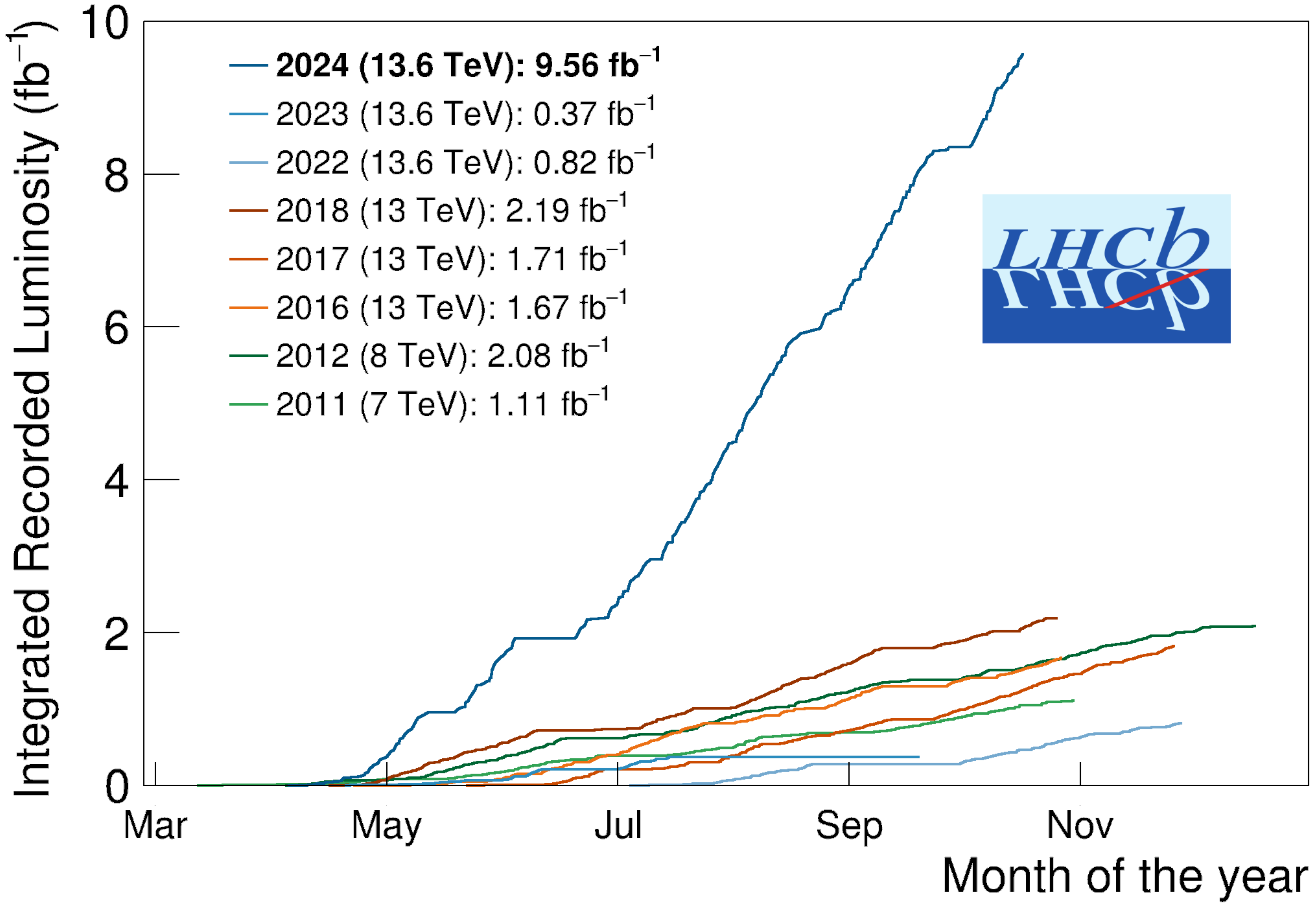


- ➡ Flexible trigger to accommodate new ideas
- ➡ Evolution over time to best utilise resources
- ➡ Detector calibration/alignment before running HTL2
- ➡ Offline quality reconstruction in HLT2
- ➡ Remove HW trigger in Run 3

See talk by Pawel Kopciewicz for details

LHCb dataset

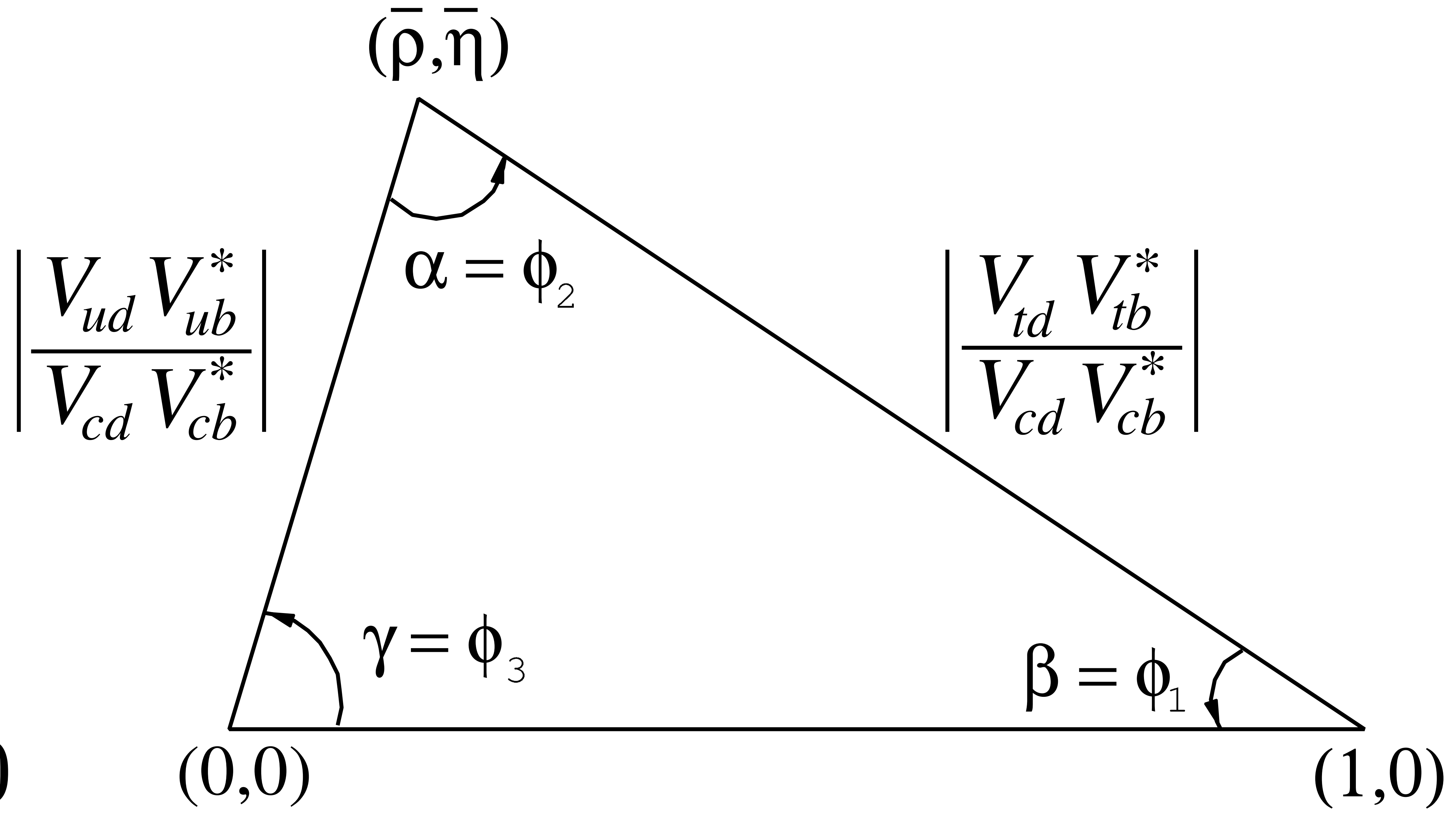
- ➡ About 9 fb^{-1} during Run 1 and Run 2
- ➡ In Runs 3–4 aim at 50 fb^{-1}
- ➡ Data from 2024 double out dataset
  - ❖ Effect is larger for some decays than pure luminosity scaling
- ➡ Typical data taking efficiency over 90%



The CKM unitarity triangle

- Flavour transitions in the SM described by CKM matrix
- 4 real parameters, three mixing angles and one complex phase
- Usually represented as a triangle in complex plane
- Only two parameters define triangle, can over-constrain

$$\begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

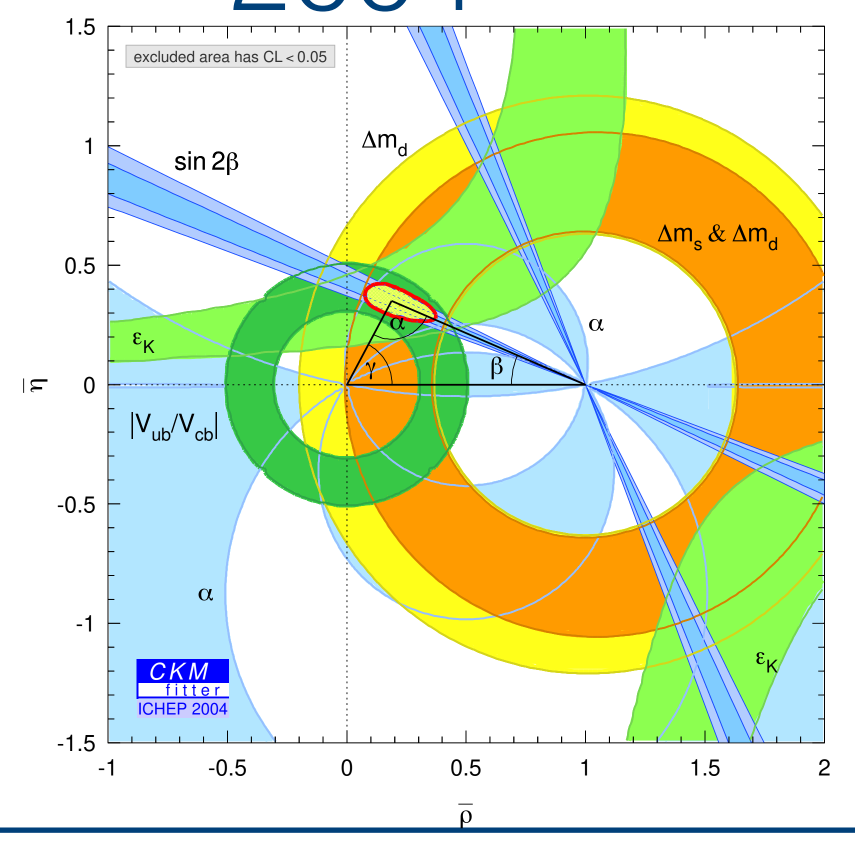


$$V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$$

The unitarity triangle

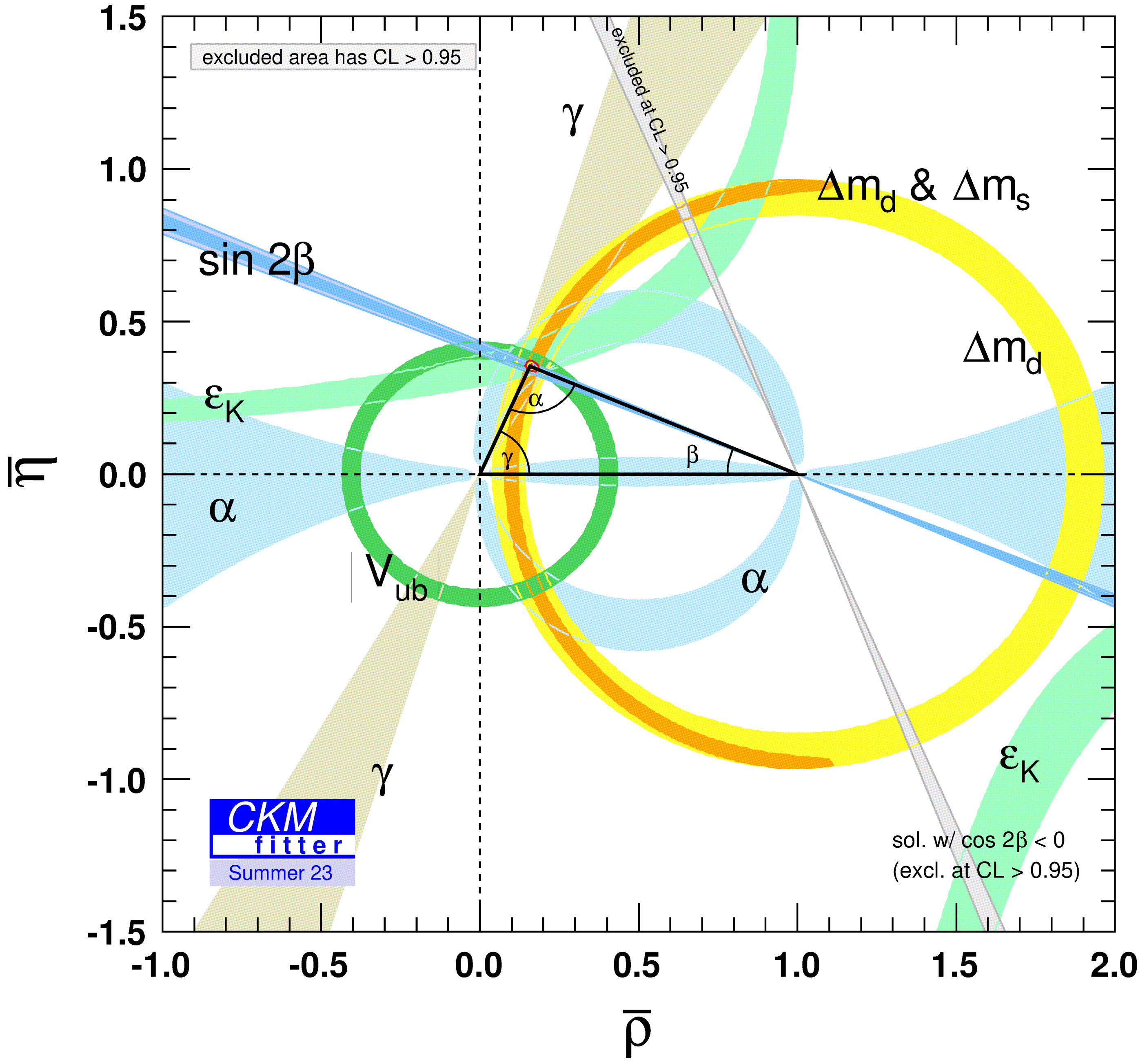
- ➡ Generally consistent picture, but there is still room for new physics
- ➡ We should not forget significant input from the whole community
- ➡ New physics can cause various counters not aligning to single point

2004

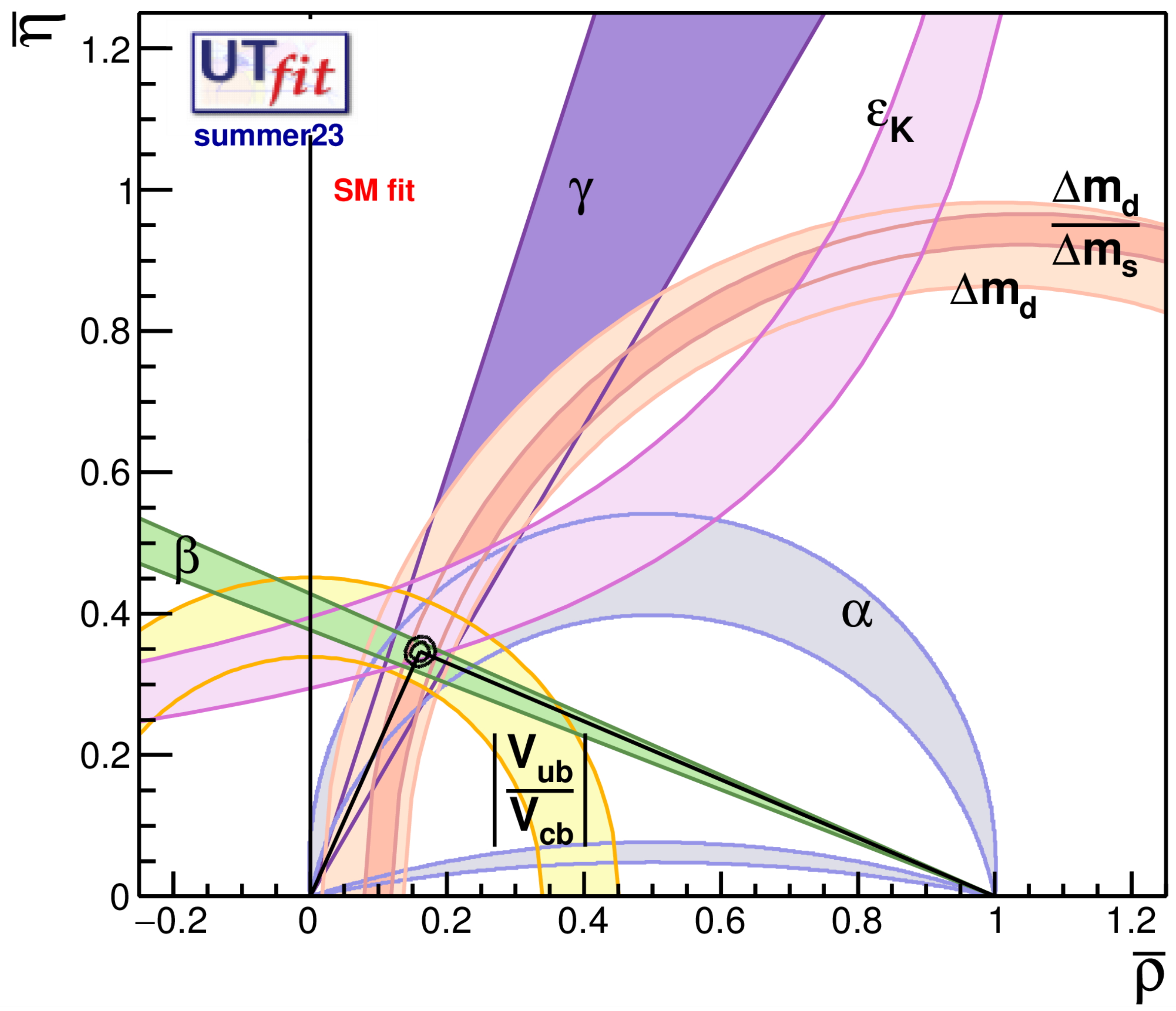


ckmfitter.in2p3.fr

2023



www.utfit.org



CP Violation

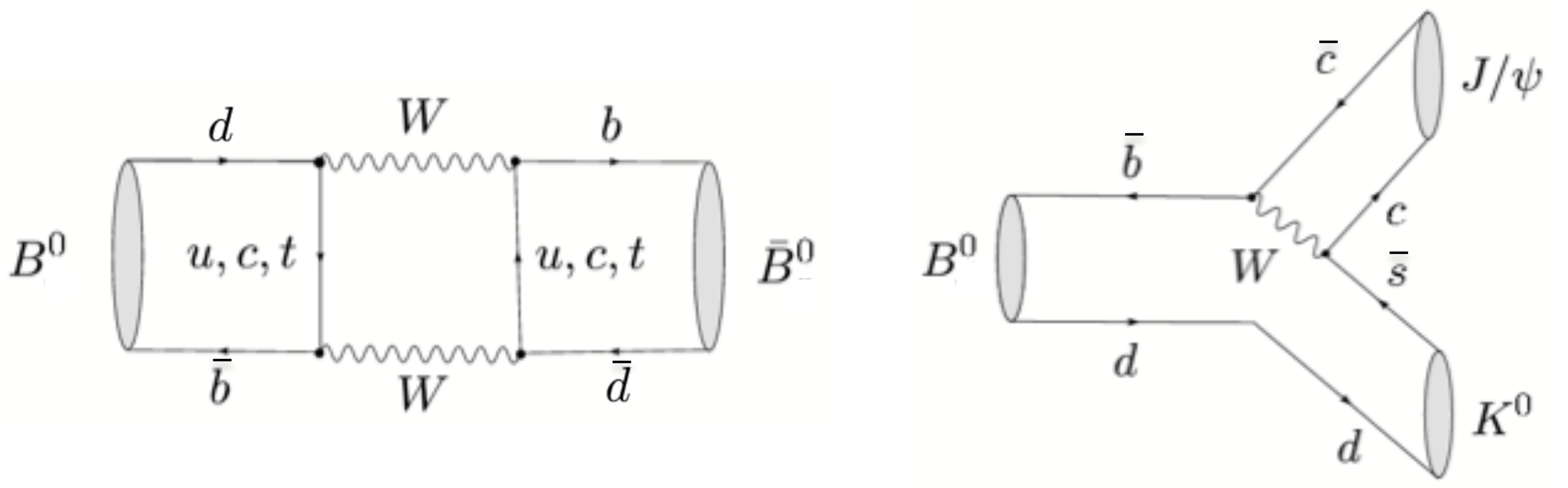
WARWICK
THE UNIVERSITY OF WARWICK

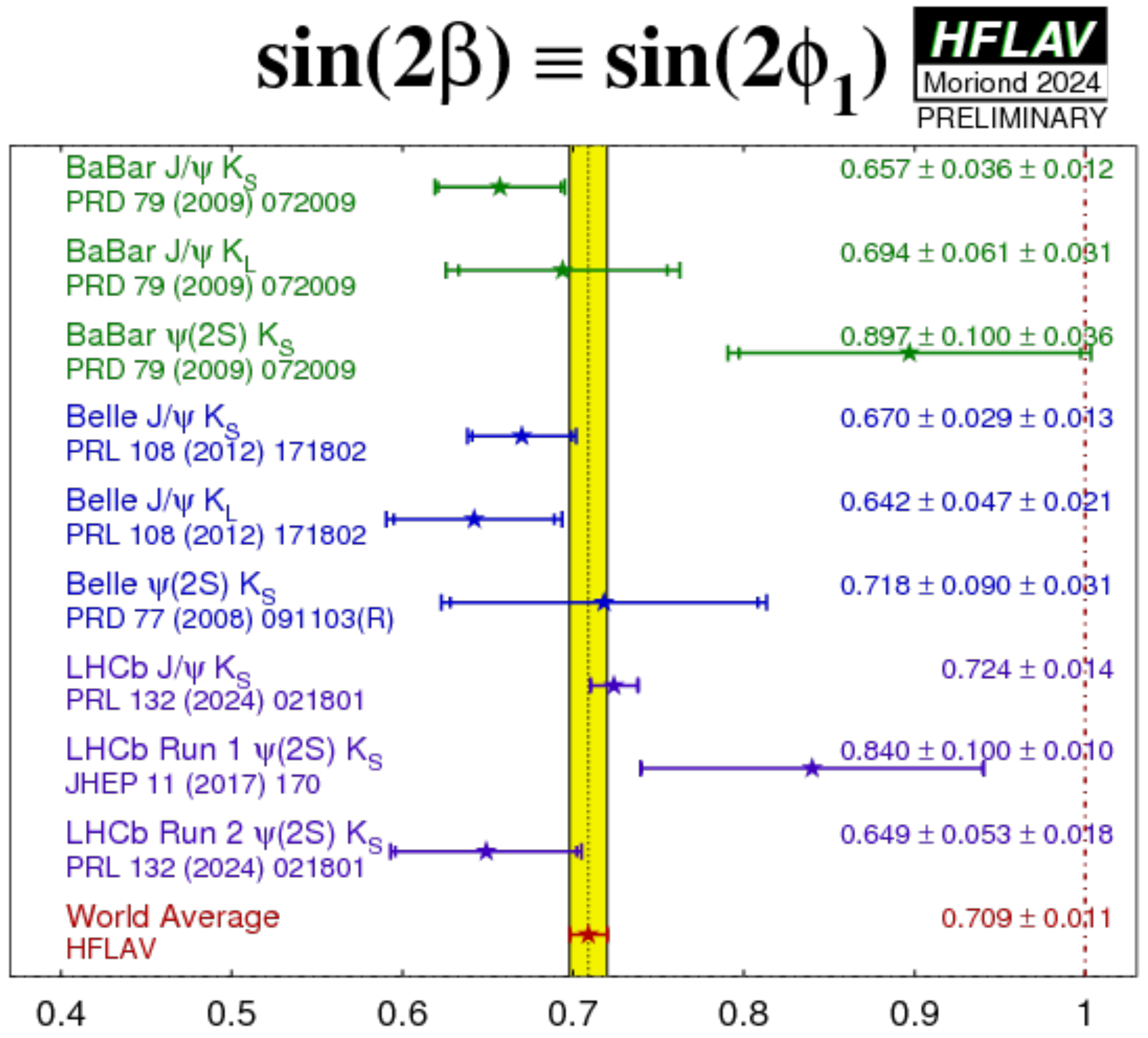
- CPV probes complex phase of CKM matrix → needs interference of amplitudes for measurable effect
- Three situations usually considered
  - CP violation in mixing — difference in oscillation rate of particle and antiparticle
  - CP violation in interference of decay with and without mixing — this is what B-factories observed in $B^0 \to J/\psi K_S$ decays
    - Effect in time-dependence
  - Direct CPV — decay rate for particle and antiparticle is different, only possibility for charged mesons and baryons
    - Typically interfering amplitudes need different not only weak phases but also strong phases

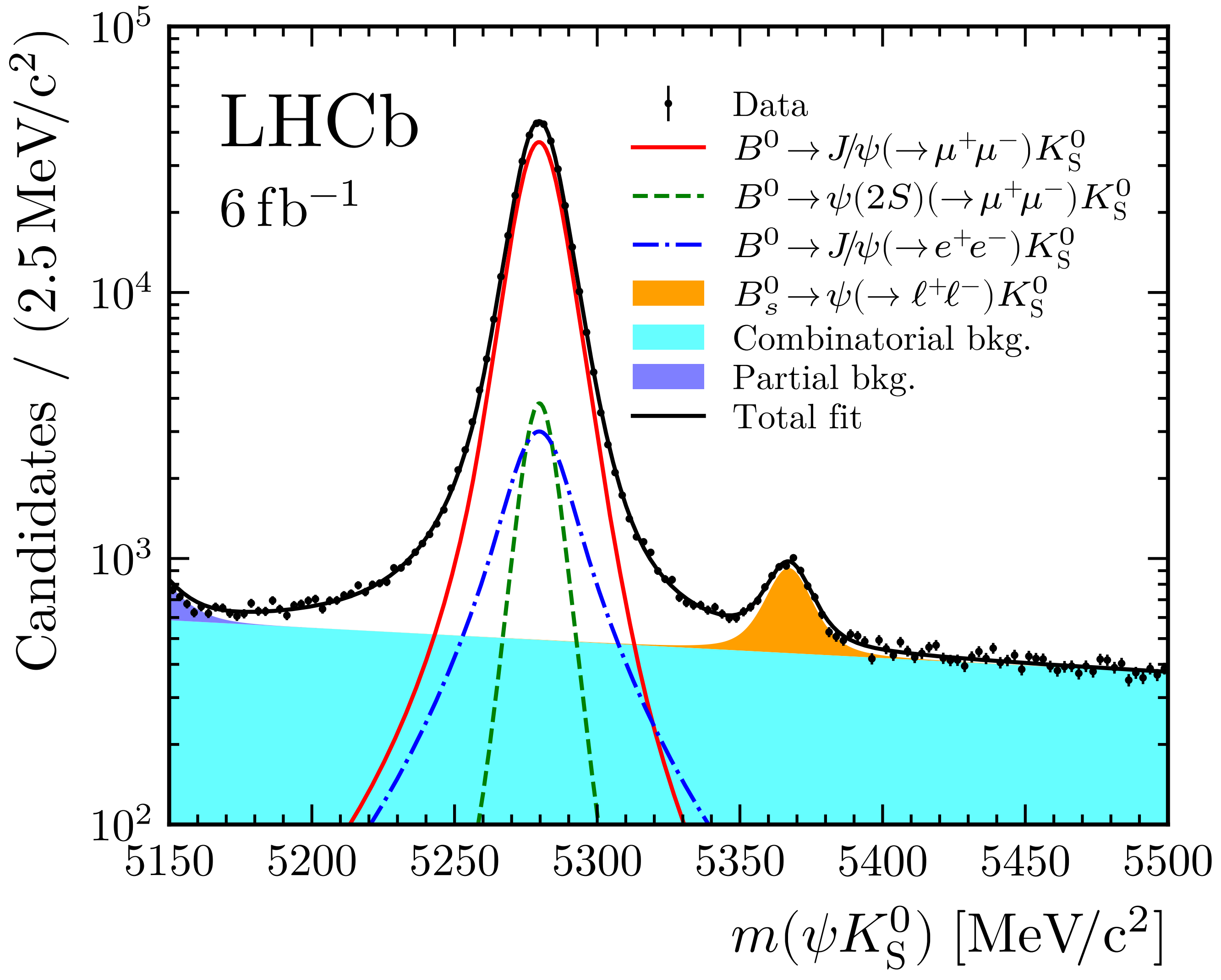
Phys. Rev. Lett. 132 (2024) 021801

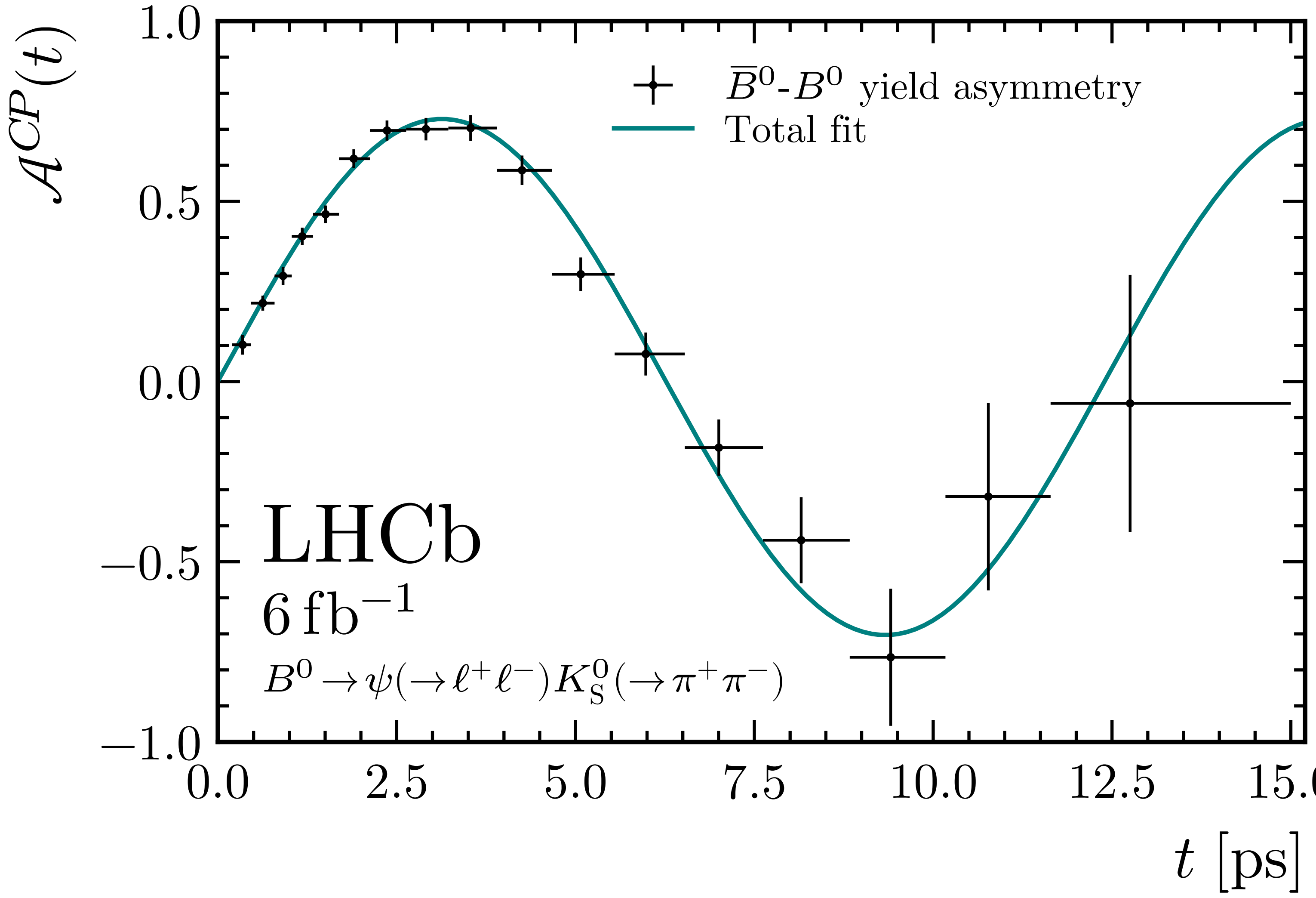
CKM angle β

- ➡ Interference of decays with and without mixing
- ➡ Golden measurement confirming CKM paradigm
- ➡ Flavour tagged time-dependent analysis
- ➡ World's best measurement







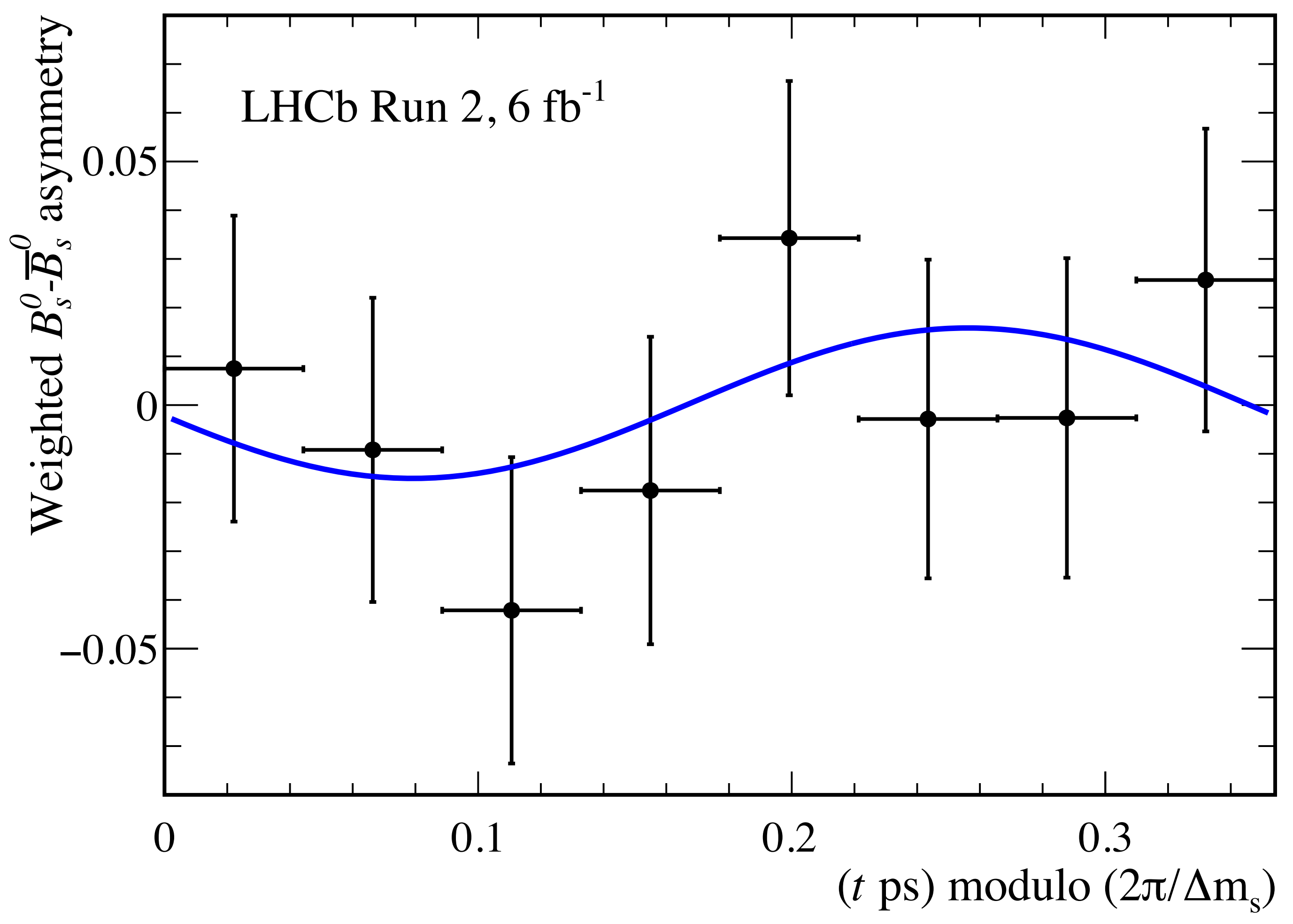


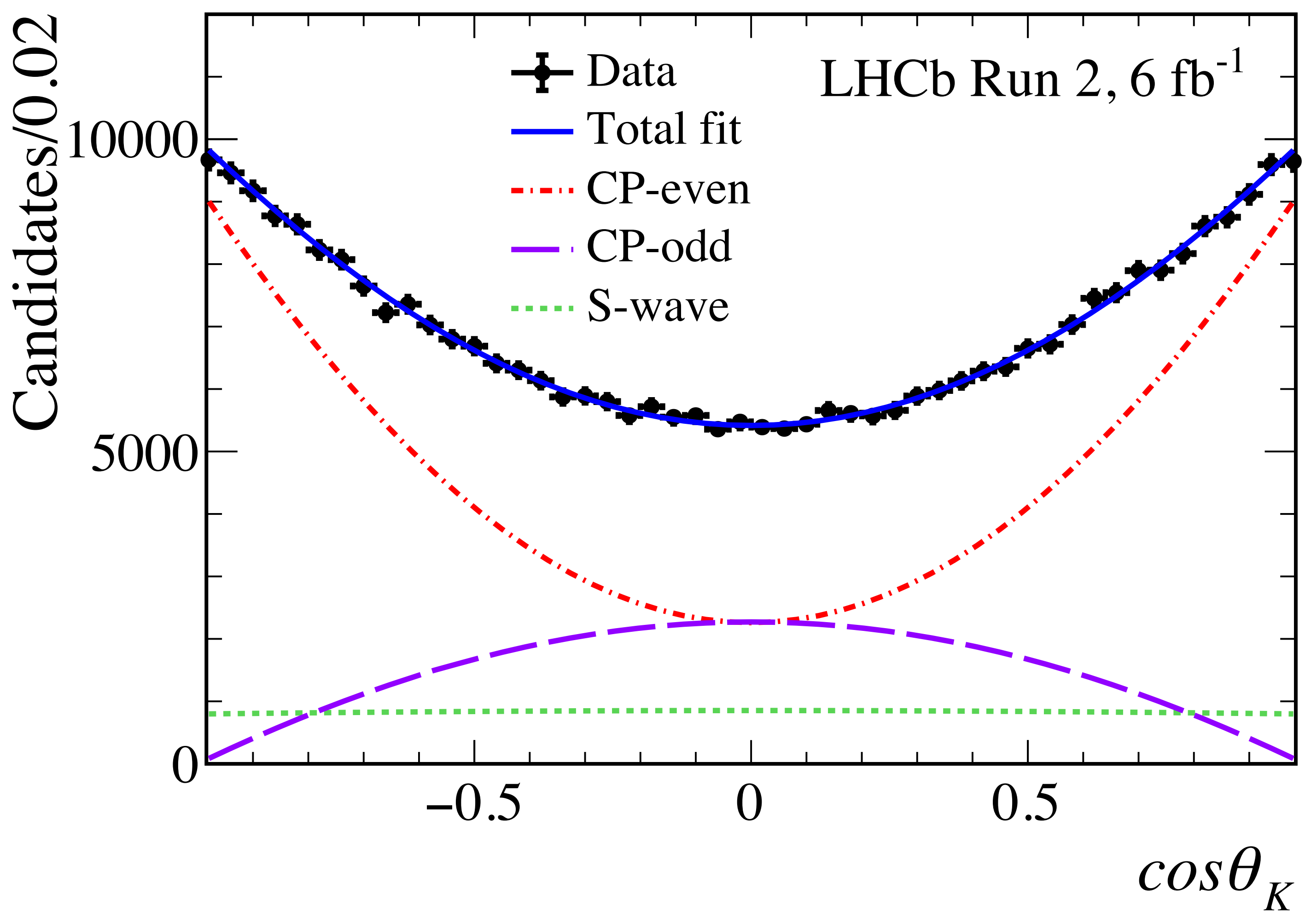
Phys. Rev. Lett. 132 (2024) 051802

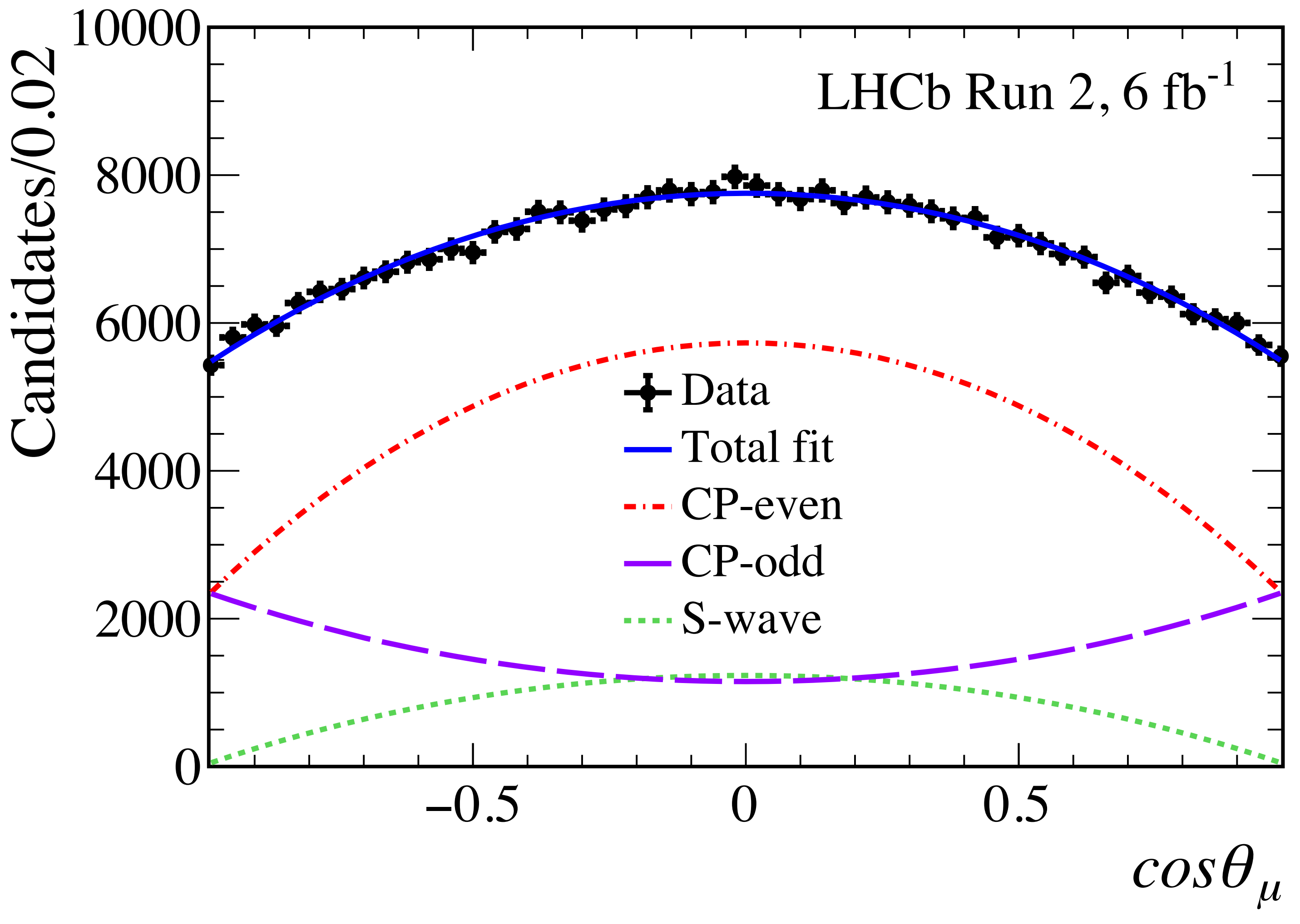
ϕ_s in $B_s \to J/\psi K^+ K^-$

WARWICK
THE UNIVERSITY OF WARWICK

- Equivalent to CKM angle β in the B_s sector
- Additional challenges as final state is not *CP* eigenstate — Need angular analysis to separate *CP* eigenstates
- Large B_s mixing frequency — Need very good time resolution





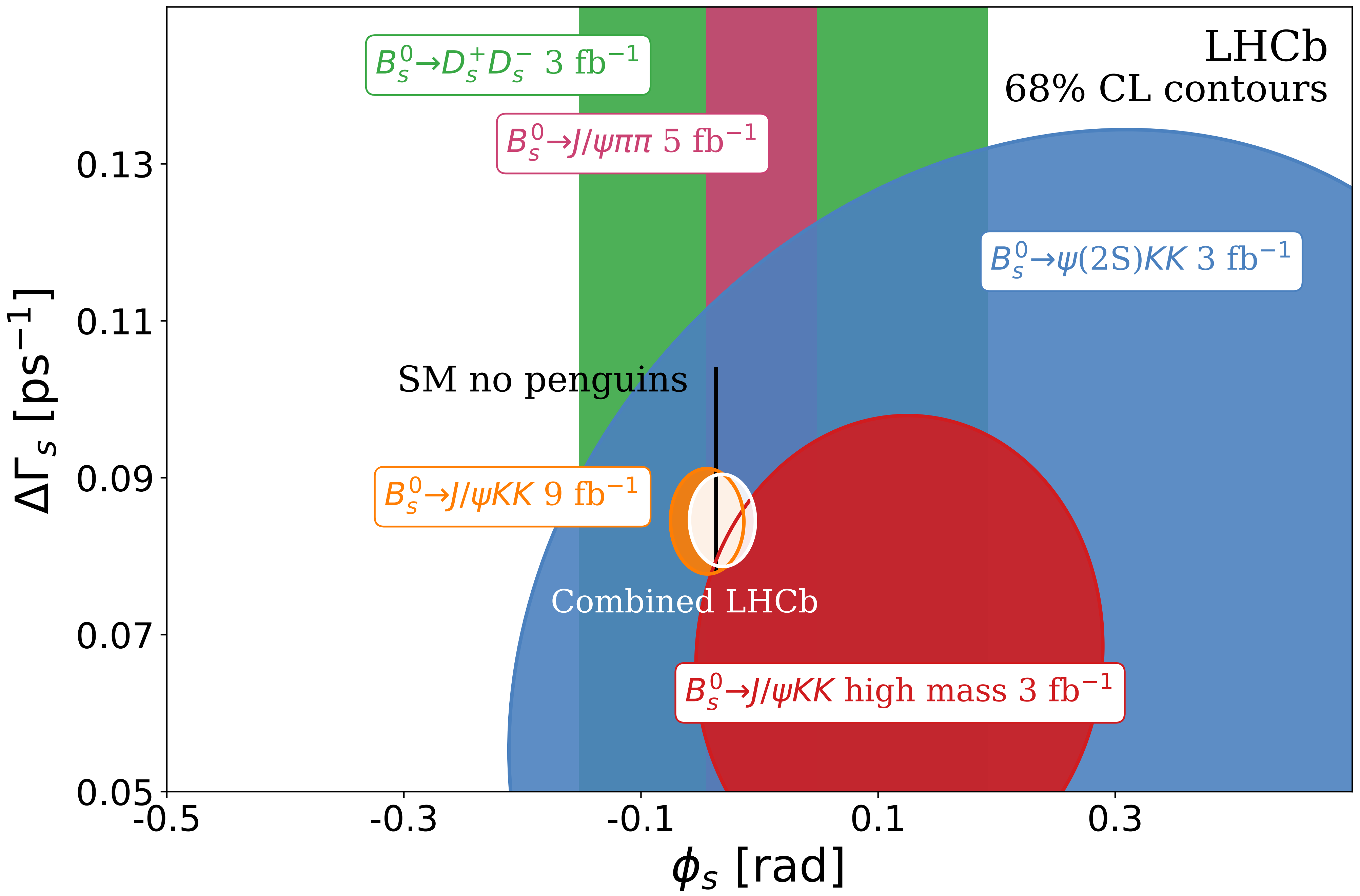


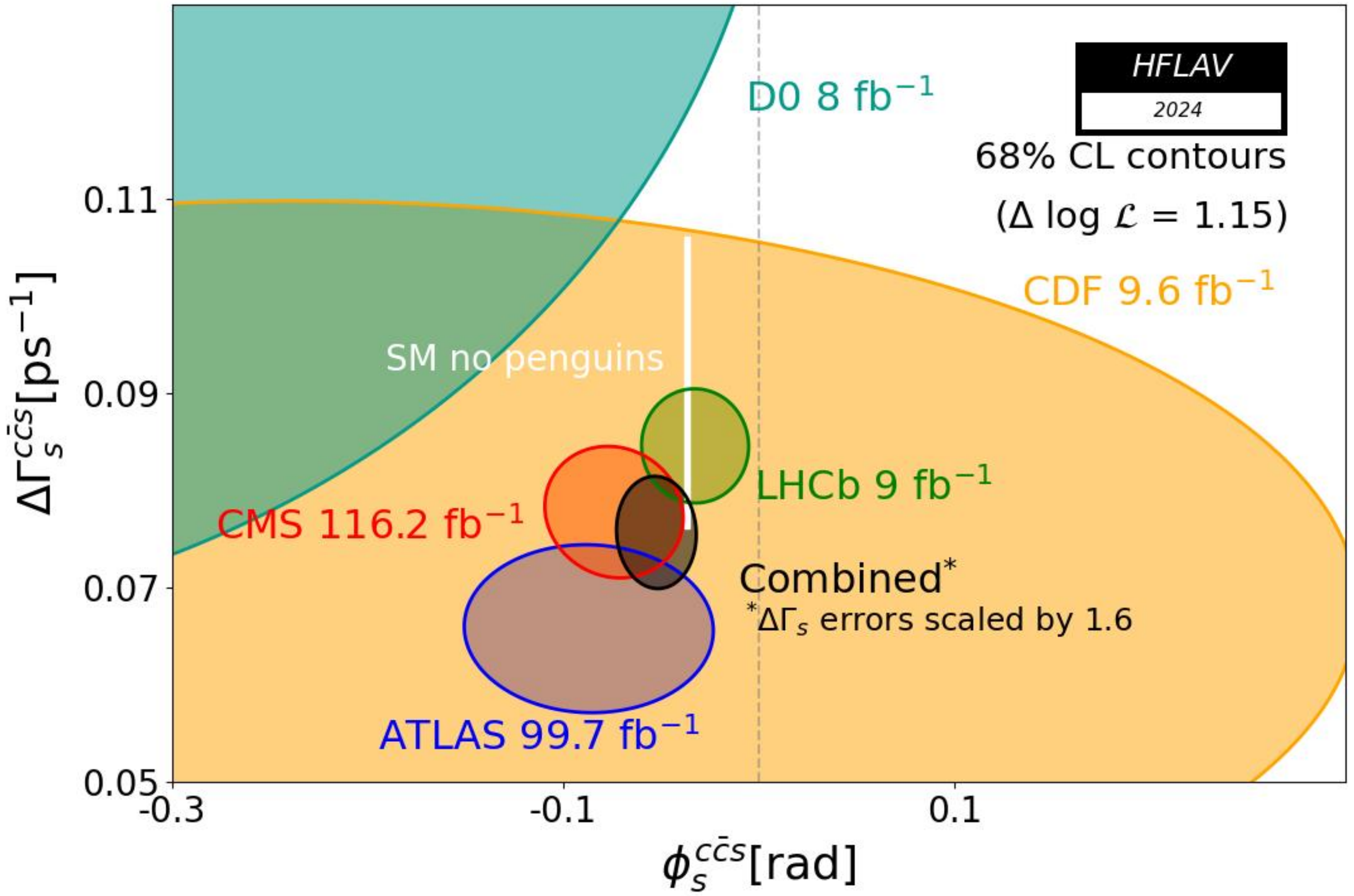
Phys. Rev. Lett. 132 (2024) 051802

ϕ_s in $B_s \to J/\psi K^+K^-$

WARWICK
THE UNIVERSITY OF WARWICK

- ➡ Significant constraints on possible deviations from the SM
- ➡ Still room for new physics
- ➡ Measured also with $B_s \to D_s^+D_s^-$ and $B_s \to J/\psi\pi^+\pi^-$ decays

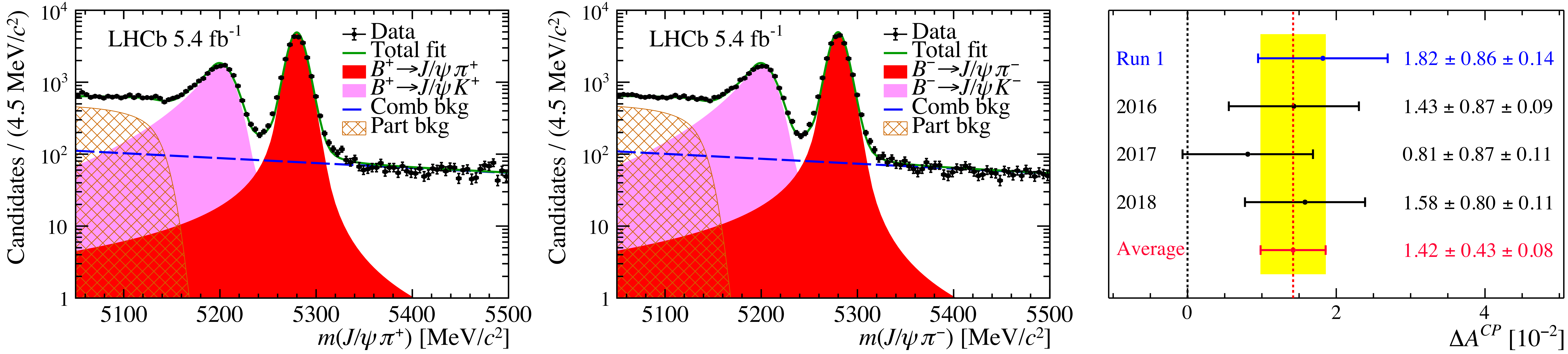




arXiv:2411.12178

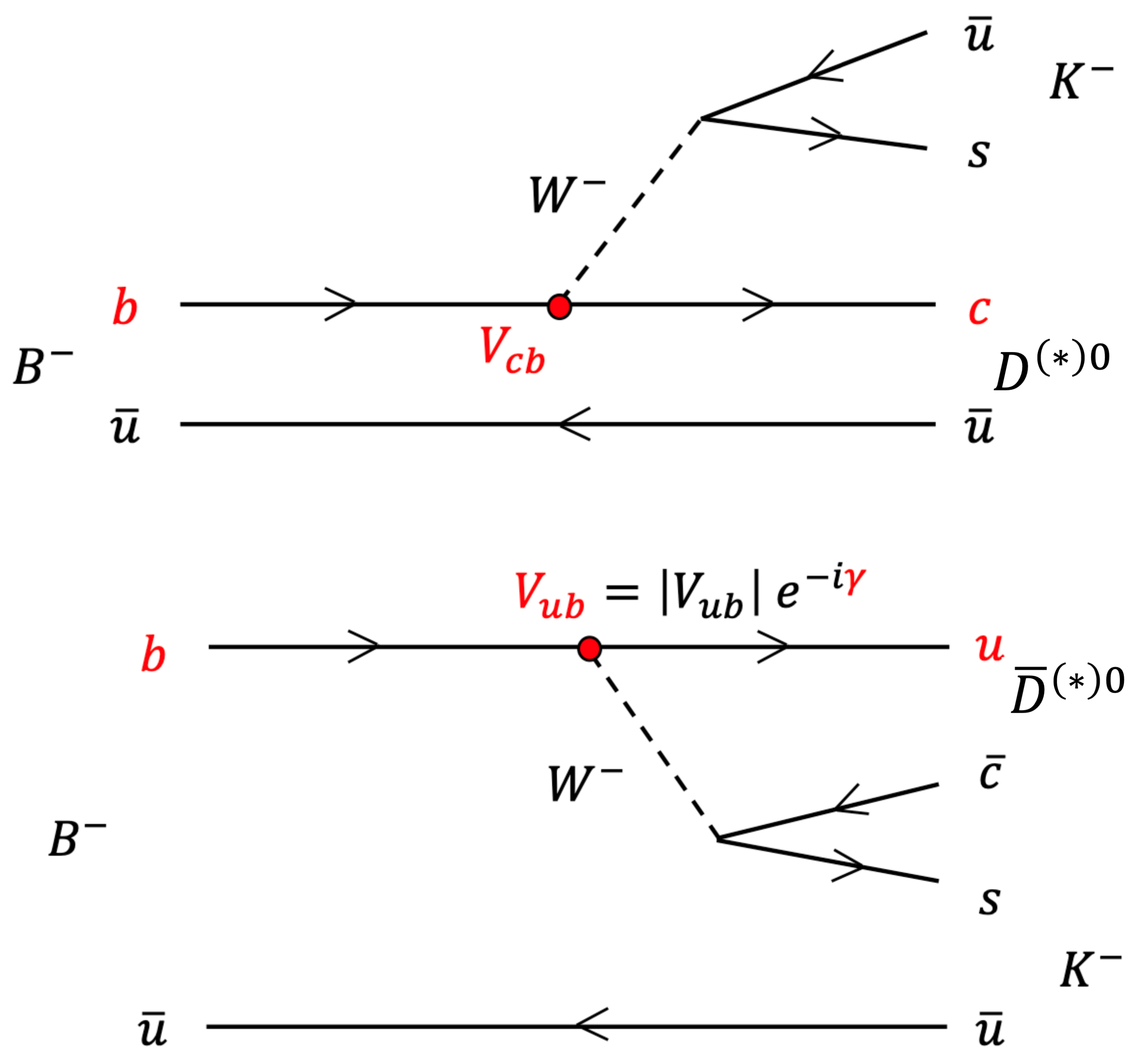
Direct CPV in $B^+ \to J/\psi\pi^+$

- Cabbibo suppressed tree level decay — do not expect significant CPV
- Measured relative to $B^+ \to J/\psi K^+$ decays
- First evidence (significance 3.2σ) in these kind of decays
- At least one of the two decays have to exhibit CPV



CKM angle γ

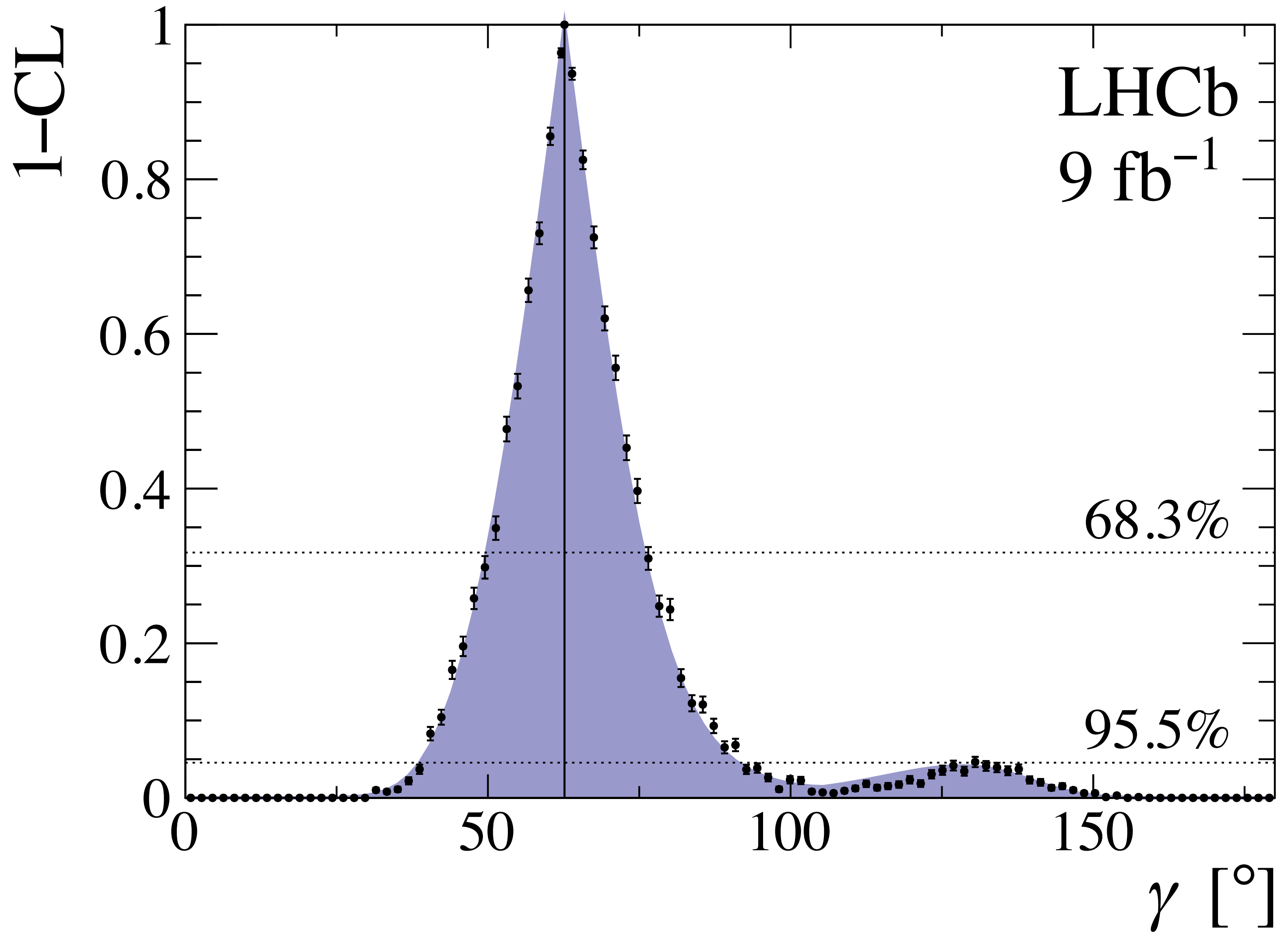
- ➡ Only place to access CKM matrix complex phase in tree level decays
- ➡ Interference when D^0 and $\bar{D}^0$ decay to common final state
  - ❖ Doubly Cabibbo suppressed $D^0 \to K^+\pi^-$
  - ❖ Single Cabibbo suppressed $D^0 \to K^+K^-(\pi^+\pi^-)$
  - ❖ Multibody decays like $D^0 \to K_S\pi^+\pi^-$ with non-trivial dependence over phase space
- ➡ In practice, combine all possible measurements together

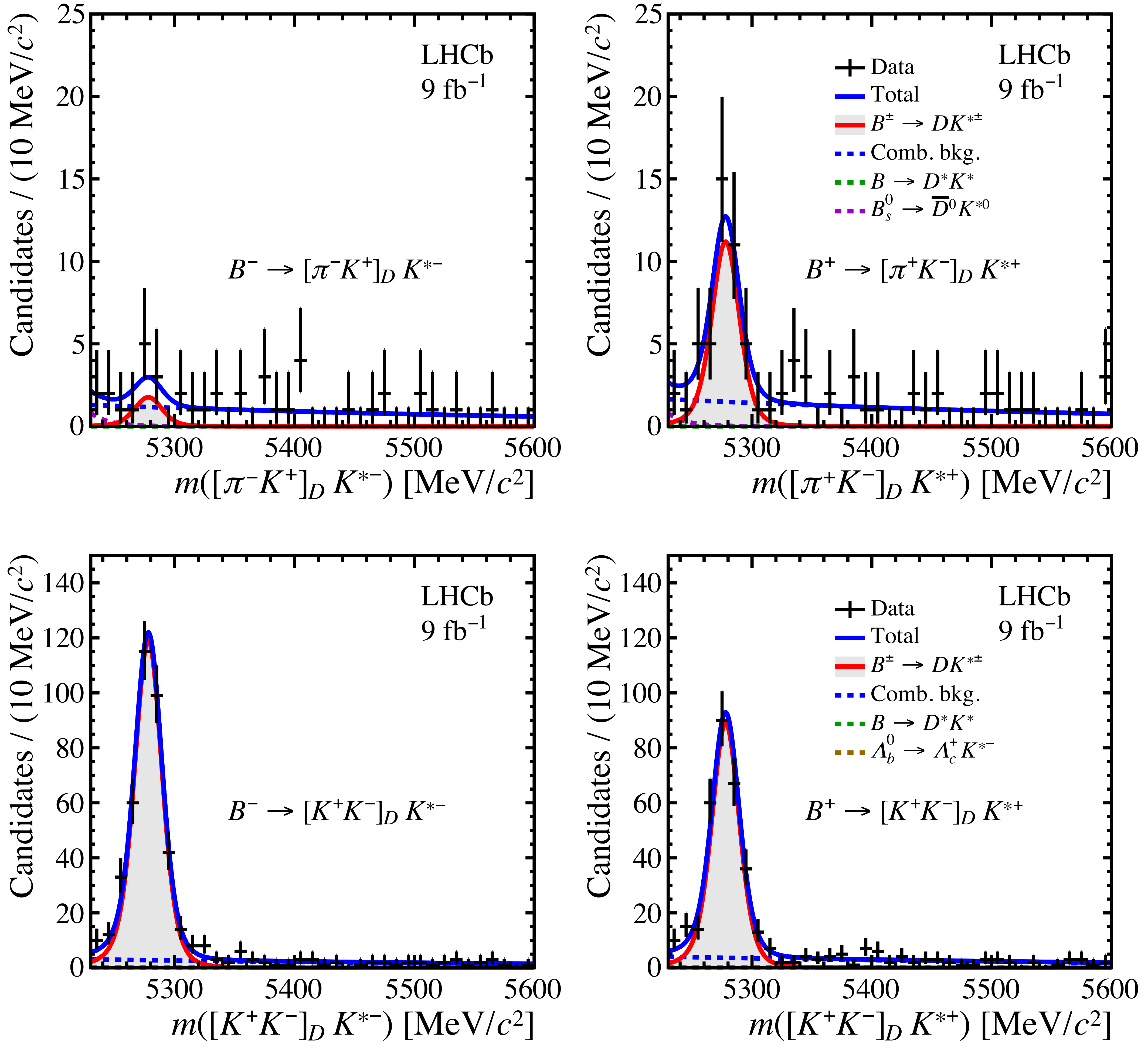


CKM angle γ

- ➡ Latest measurement using DK^* decays with multiple D decays
- ➡ Suppressed decays observed for the first time
- ➡ Clear CPV seen

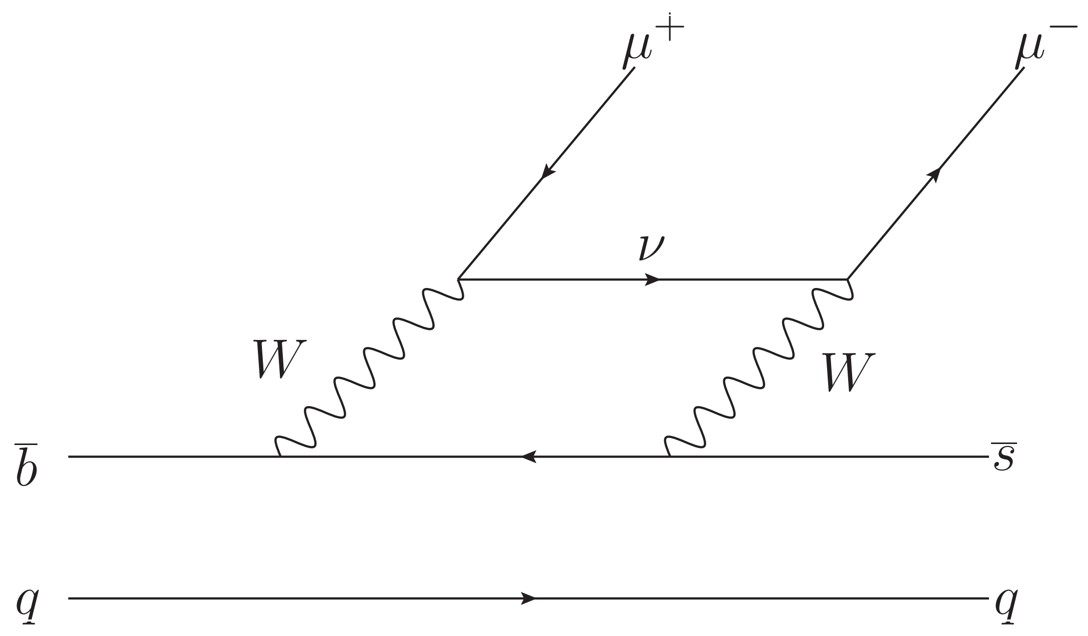
$$\gamma = (63 \pm 13)^\circ$$

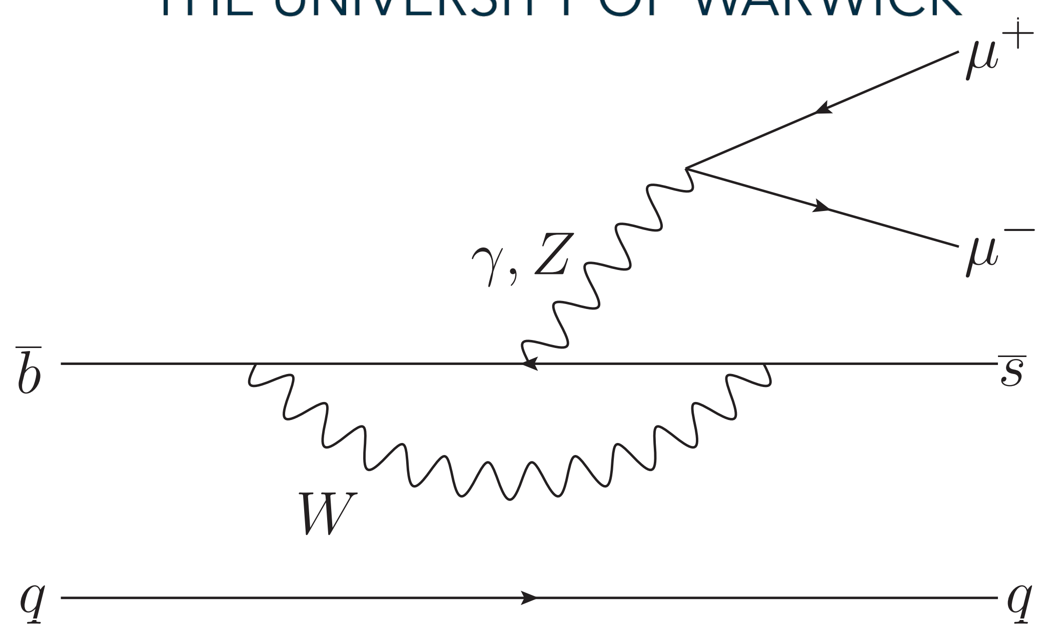


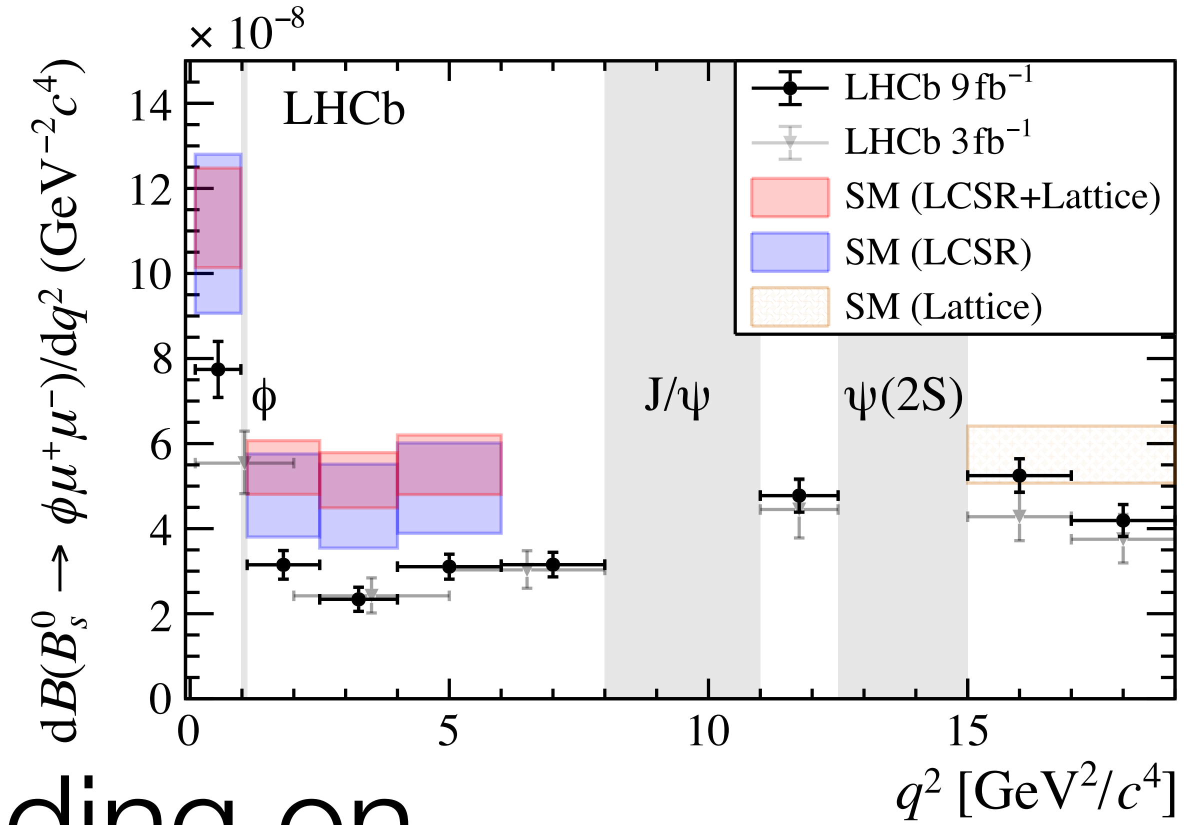


Rare FCNC decays

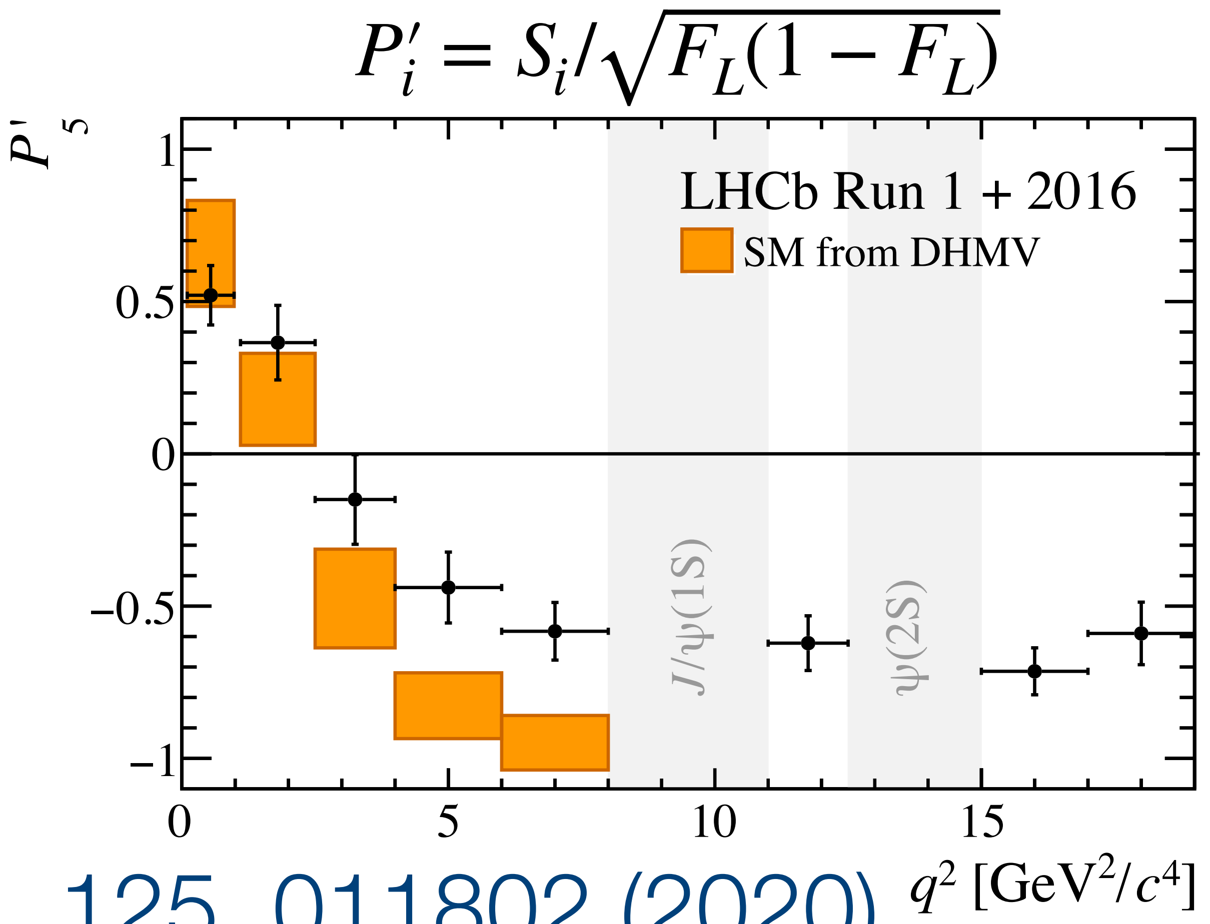
- ➡ In the SM, $b \to sll$ cannot happen at tree level
- ➡ FCNC decays through loop diagrams
- ➡ SM predicts BF of the order 10^{-6}
- ➡ Typically such decays have complex angular structure offering variety of observables
  - ❖ Precision of SM prediction varies depending on sensitivity to form factors
- ➡ Sensitive probe of NP contribution
- ➡ Many intriguing measurements in the past







PRL 127, 151801 (2021)



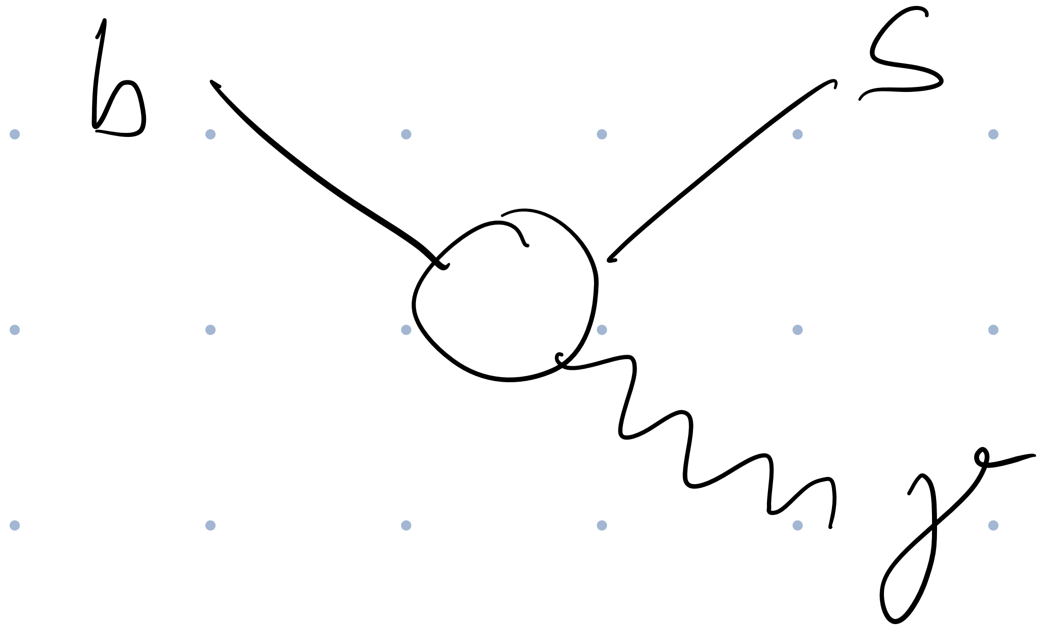
PRL 125, 011802 (2020)

Rare FCNC decays

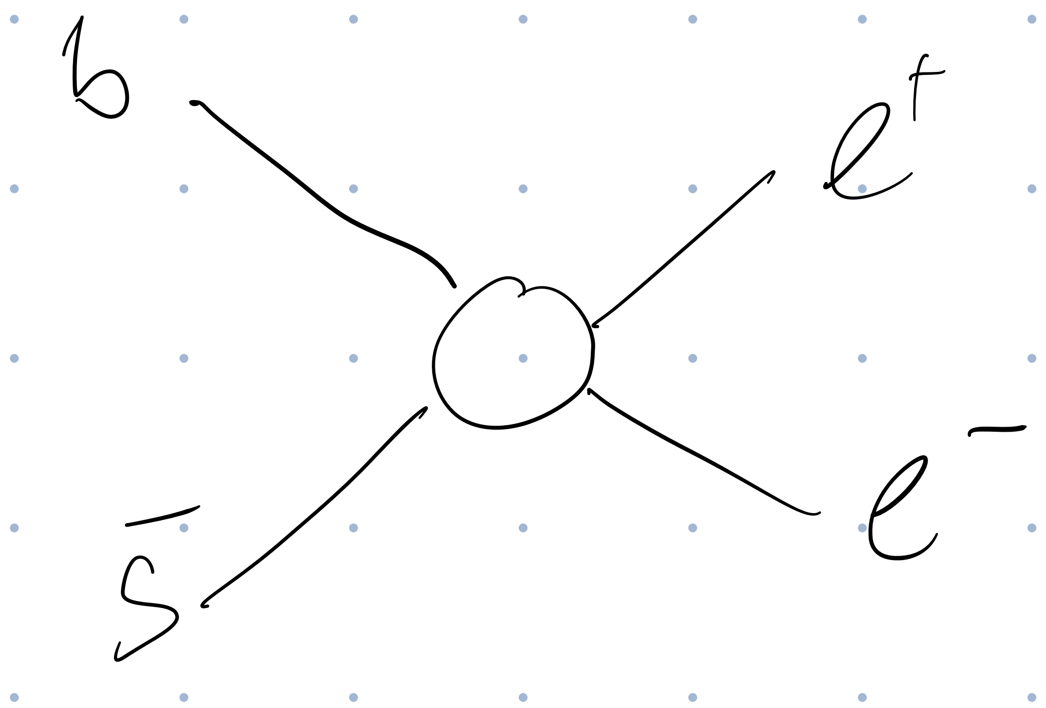
- Decays can be described by effective Hamiltonian

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu)\mathcal{O}_i(\mu)$$

- $C_i(\mu)$ are Wilson coefficients (strength of given interaction), describe short distance effects
- $\mathcal{O}_i(\mu)$ are operators, describing long-distance effects



$\mathcal{O}_7 \propto (\bar{s}_L \sigma_{\mu\nu} b_R) F^{\mu\nu}$



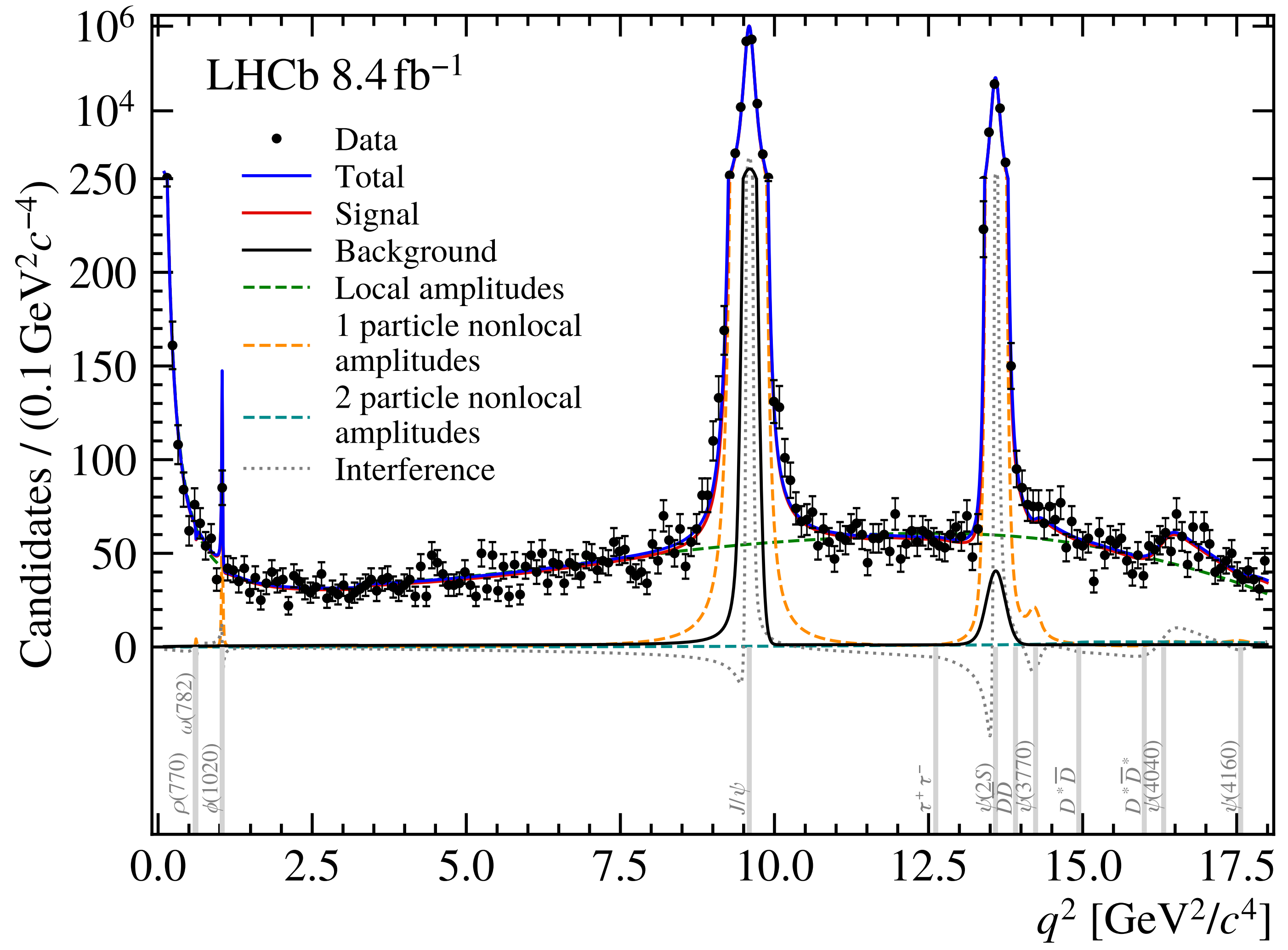
$\mathcal{O}_9 \propto (\bar{s}_L \gamma_\mu b_L)(\bar{l}\gamma^\mu l)$

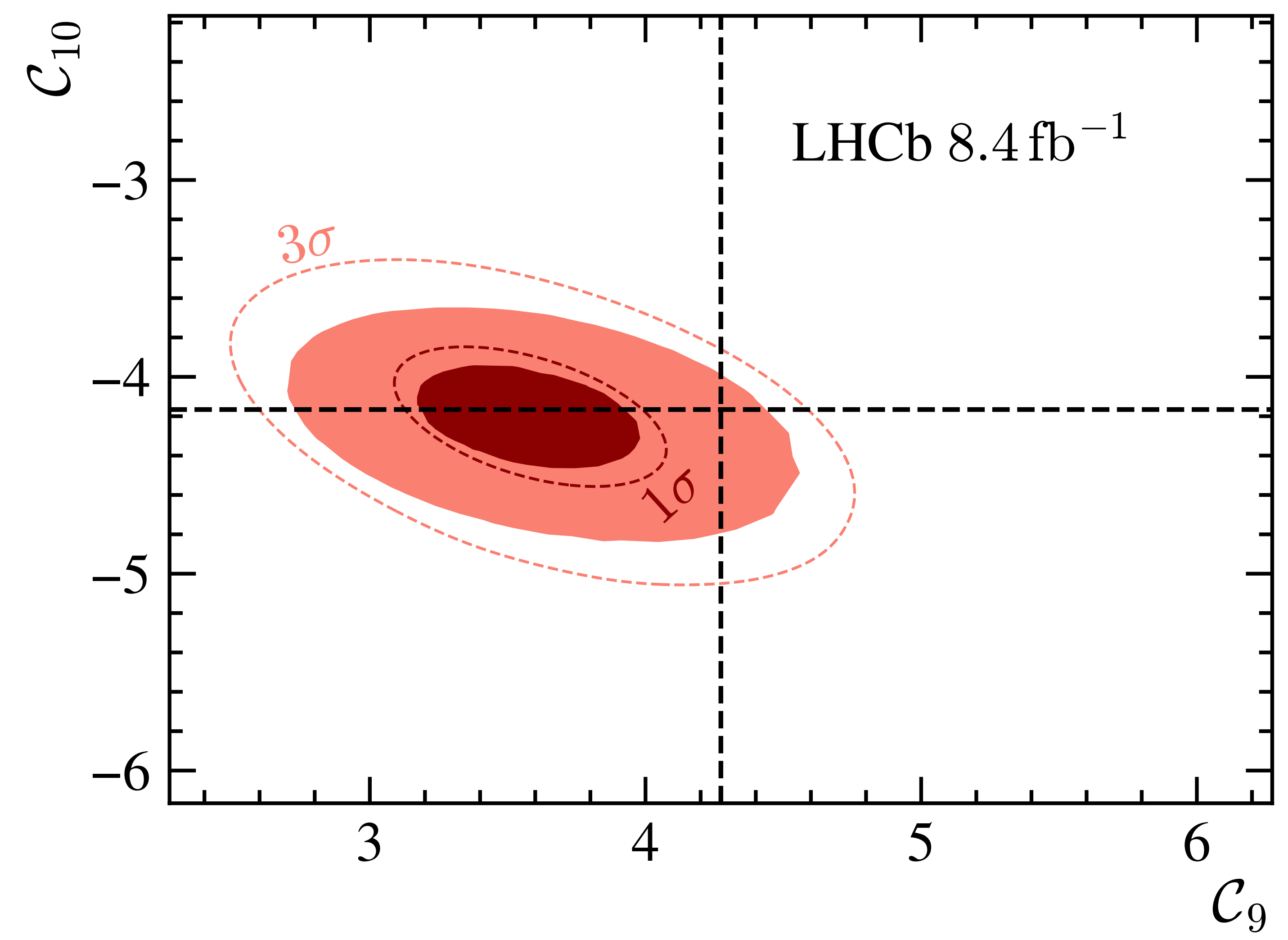
$\mathcal{O}_{10} \propto (\bar{s}_L \gamma_\mu b_L)(\bar{l}\gamma^\mu \gamma^5 l)$

JHEP 2409 (2024) 026

$B^0 \to K^{*0}\mu^+\mu^-$ angular ana

- Rich phenomenology in angular distributions
- Past measurements show some discrepancies, but there is long-standing debate what they exactly mean
- Precision is now so high that tiny details in predictions matter
  - Local contributions are well understood
  - But there are contributions from charm or τ lepton loops and interference effects
- Perform unbanned analysis in which non-local contributions are part of the fit



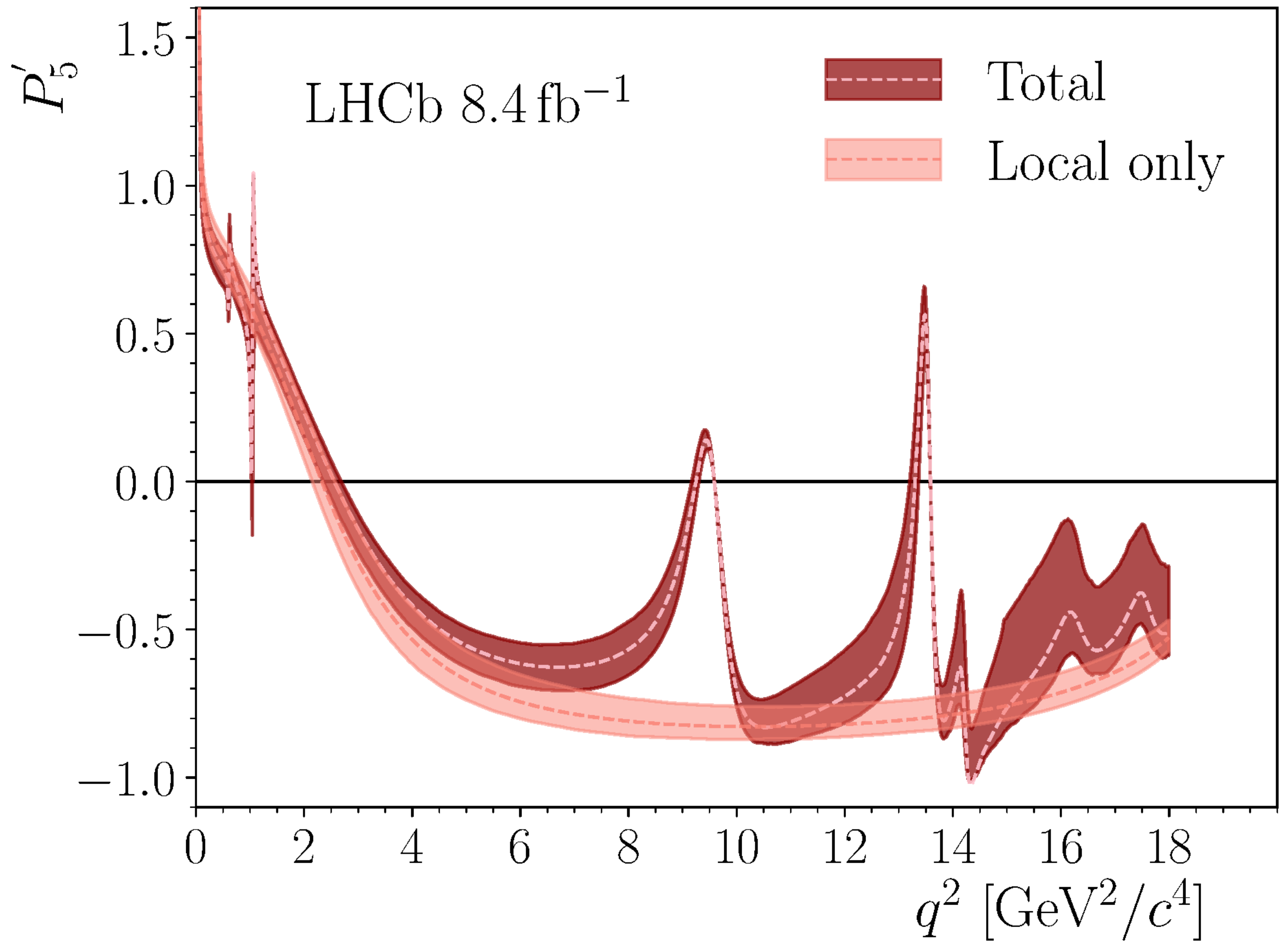


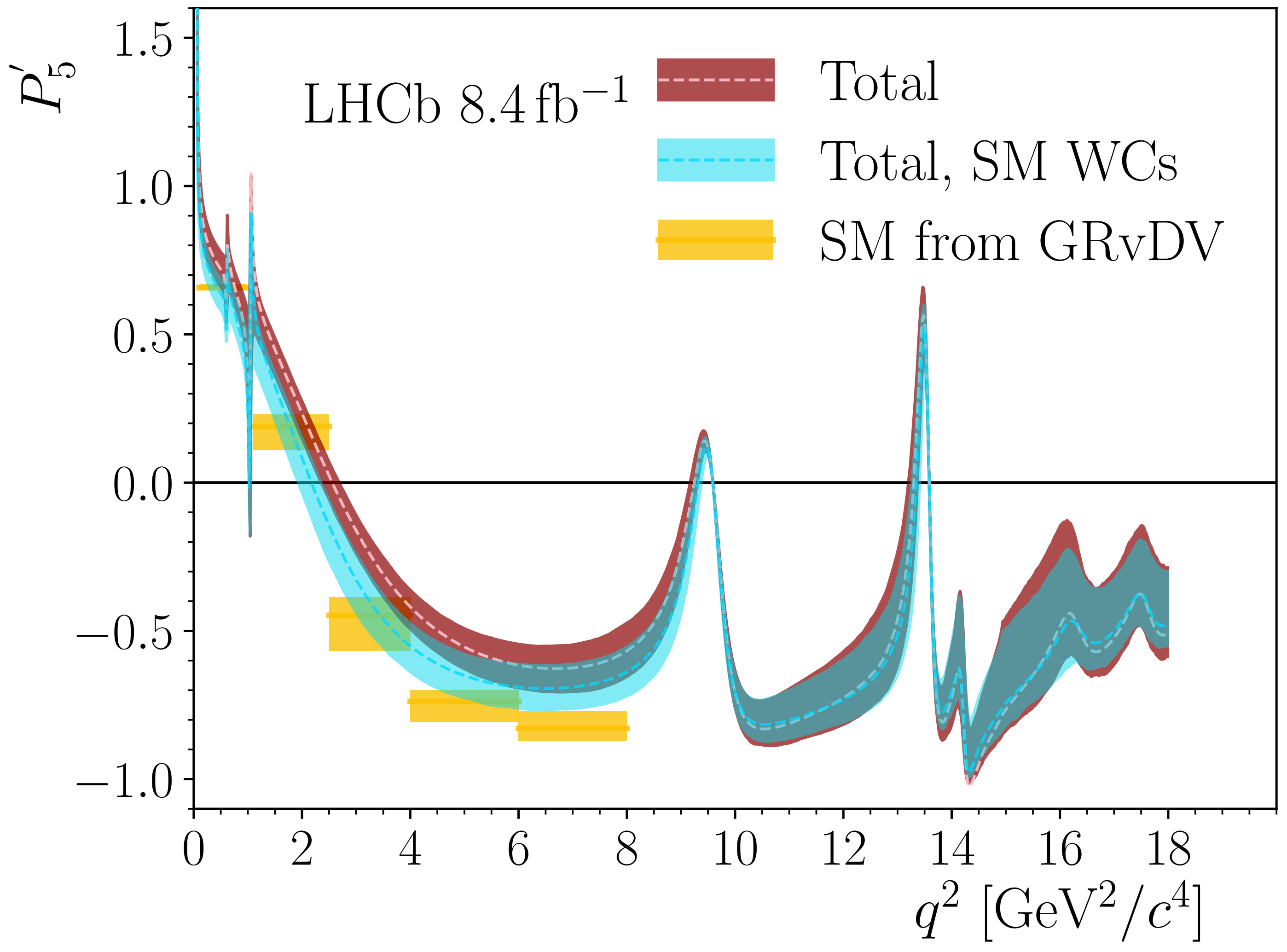
JHEP 2409 (2024) 026

$B^0 \to K^{*0}\mu^+\mu^-$ angular ana

- ➡ Shift from the SM not as large as in other analyses
  - ❖ There is more freedom to accommodate differences
- ➡ Provides information about various amplitudes
  - ❖ Hopefully, theory can use it to understand non-local contributions better

Wilson Coefficient results	
$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$
$\mathcal{C}'_9$	$0.28 \pm 0.41 \pm 0.12$
$\mathcal{C}'_{10}$	$-0.09 \pm 0.21 \pm 0.06$
$\mathcal{C}_{9\tau}$	$(-1.0 \pm 2.6 \pm 1.0) \times 10^2$





arXiv:2410.13748

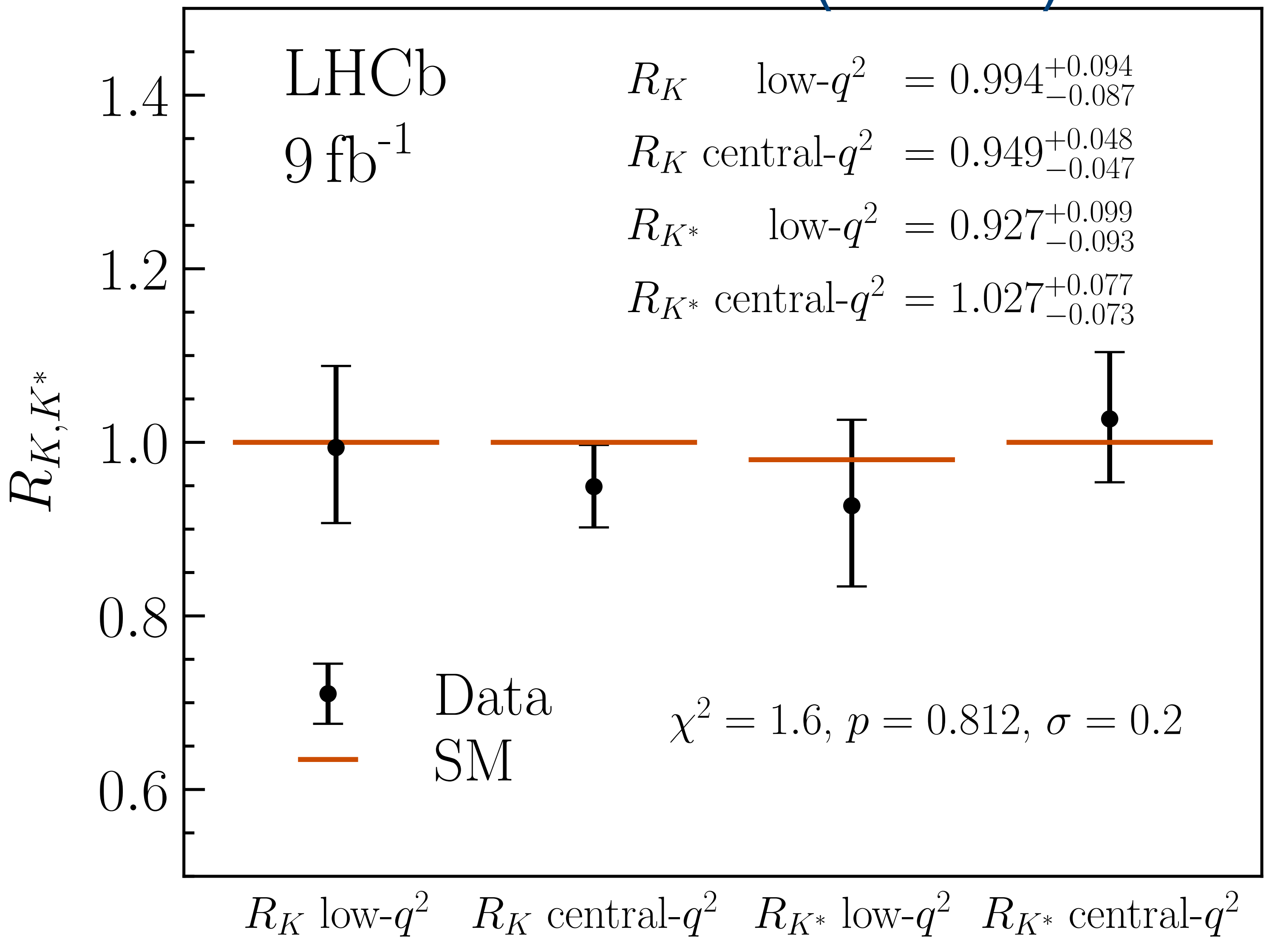
LFU tests

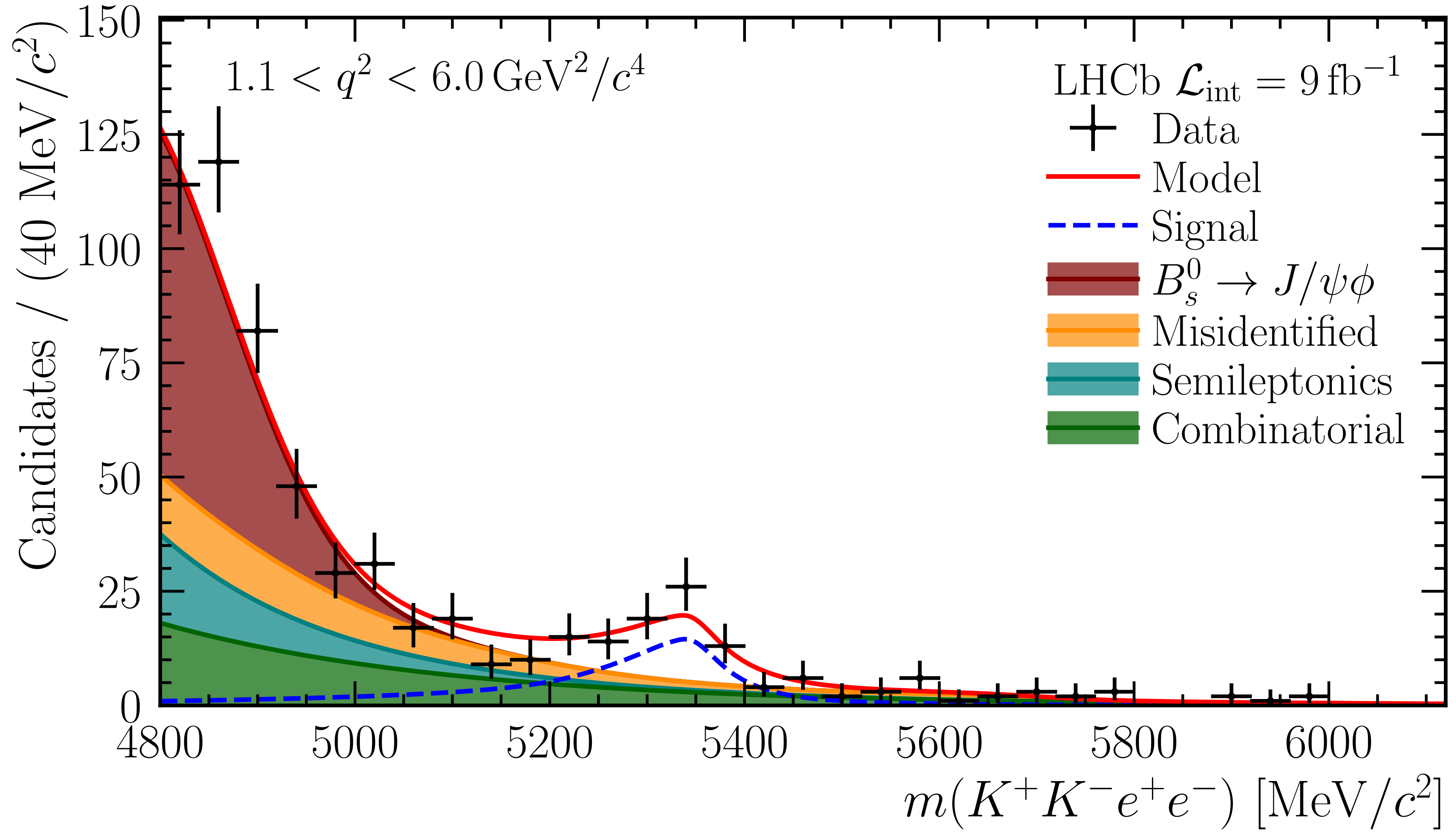
WARWICK
THE UNIVERSITY OF WARWICK

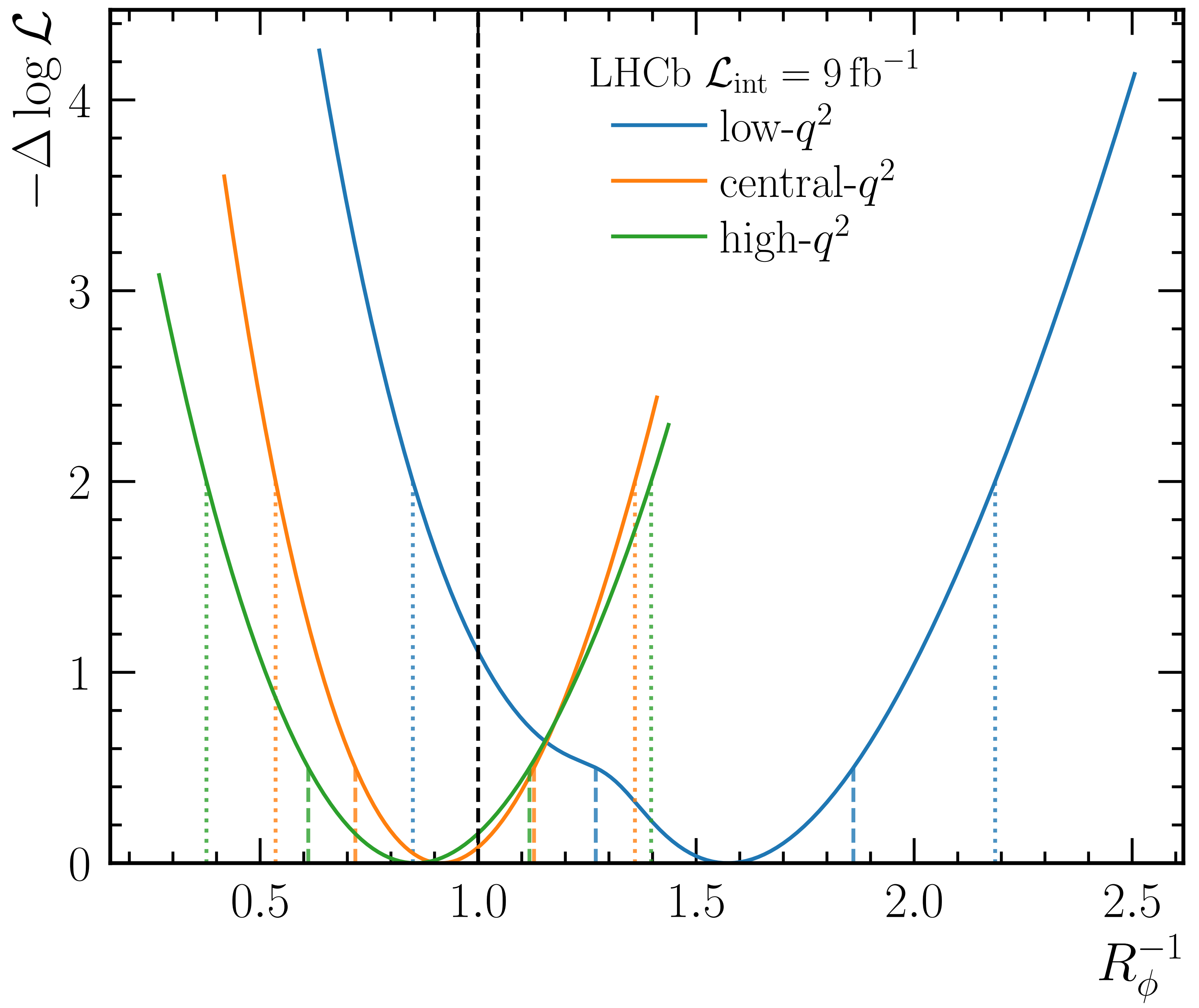
- ➡ In the SM, leptons coupling is universal, so decays with different leptons should be same
- ➡ Latest test using $B_s \to \phi l^+l^-$ decays
- ➡ Consistent with SM

q^2 [GeV$^2/c^4$]	R_ϕ^{-1}
$0.1 < q^2 < 1.1$	$1.57\,^{+0.28}_{-0.25} \pm 0.05$
$1.1 < q^2 < 6.0$	$0.91\,^{+0.20}_{-0.19} \pm 0.05$
$15.0 < q^2 < 19.0$	$0.85\,^{+0.24}_{-0.23} \pm 0.10$

PHYS. REV. D 108 (2023) 032002







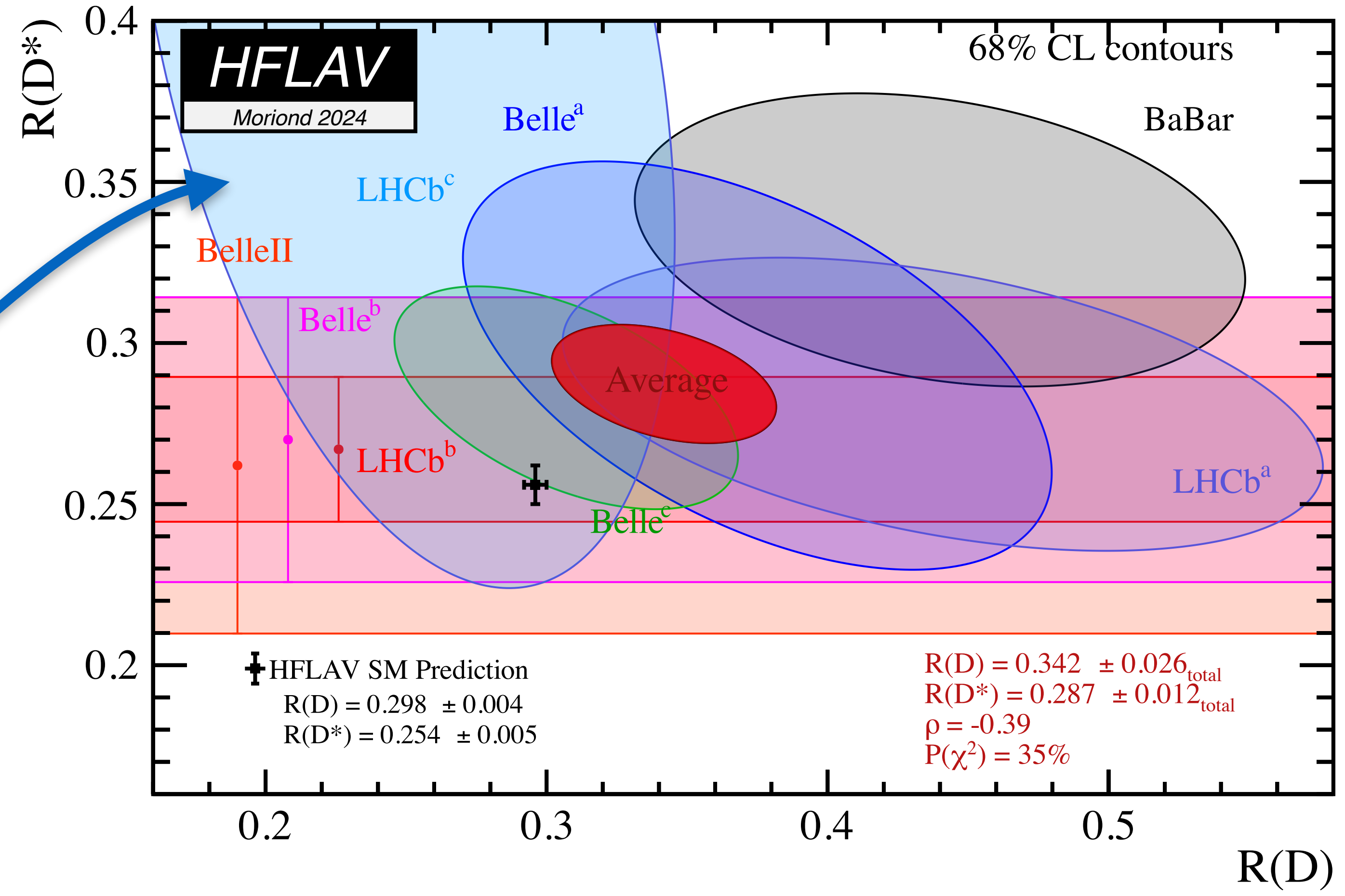
arXiv:2406.03387

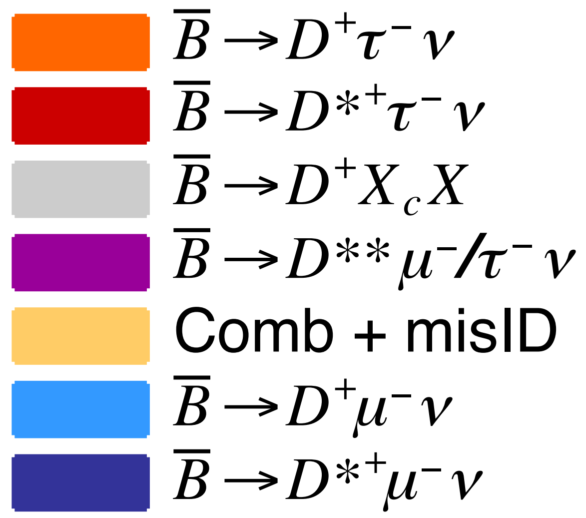
LFU tests

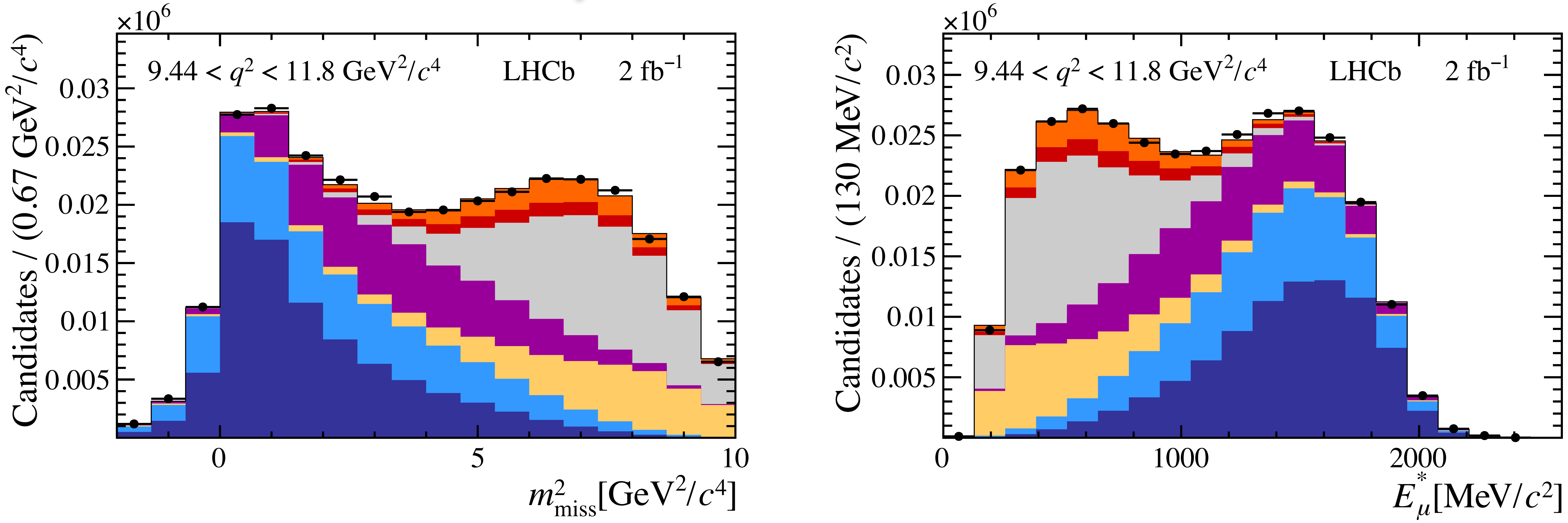
- ➡ Semileptonic tree level $B \to D^{(*)+} l^- \nu$ can be also used to test LFU
  - ❖ Usually testing τ vs. μ
  - ❖ Mass effects are significantly larger ⇒ expectation differs from 1
- ➡ Agrees with SM

$D^+ \to K^-\pi^+\pi^+$

$\tau^- \to \mu^- \nu_\mu \nu_\tau$





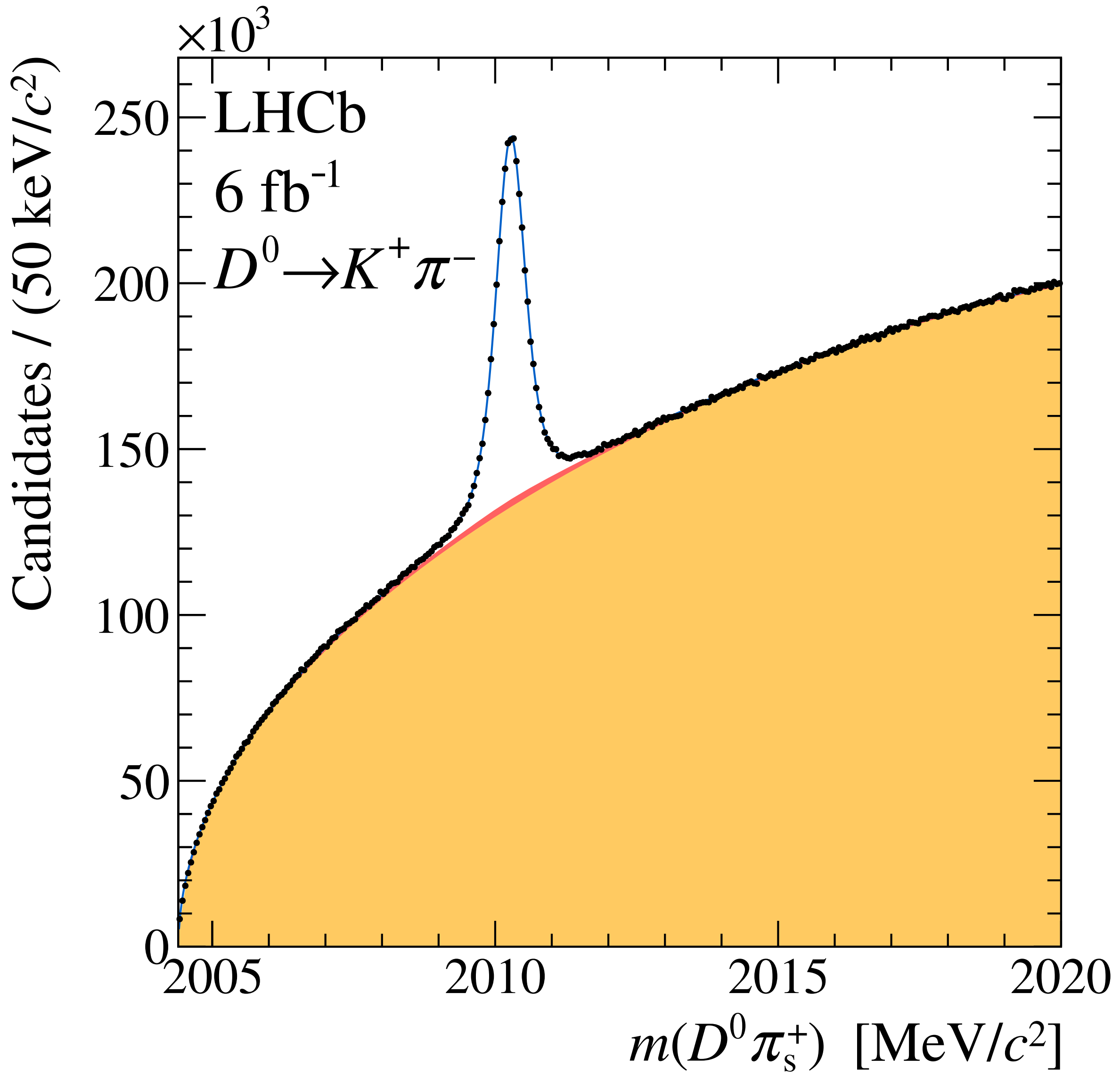


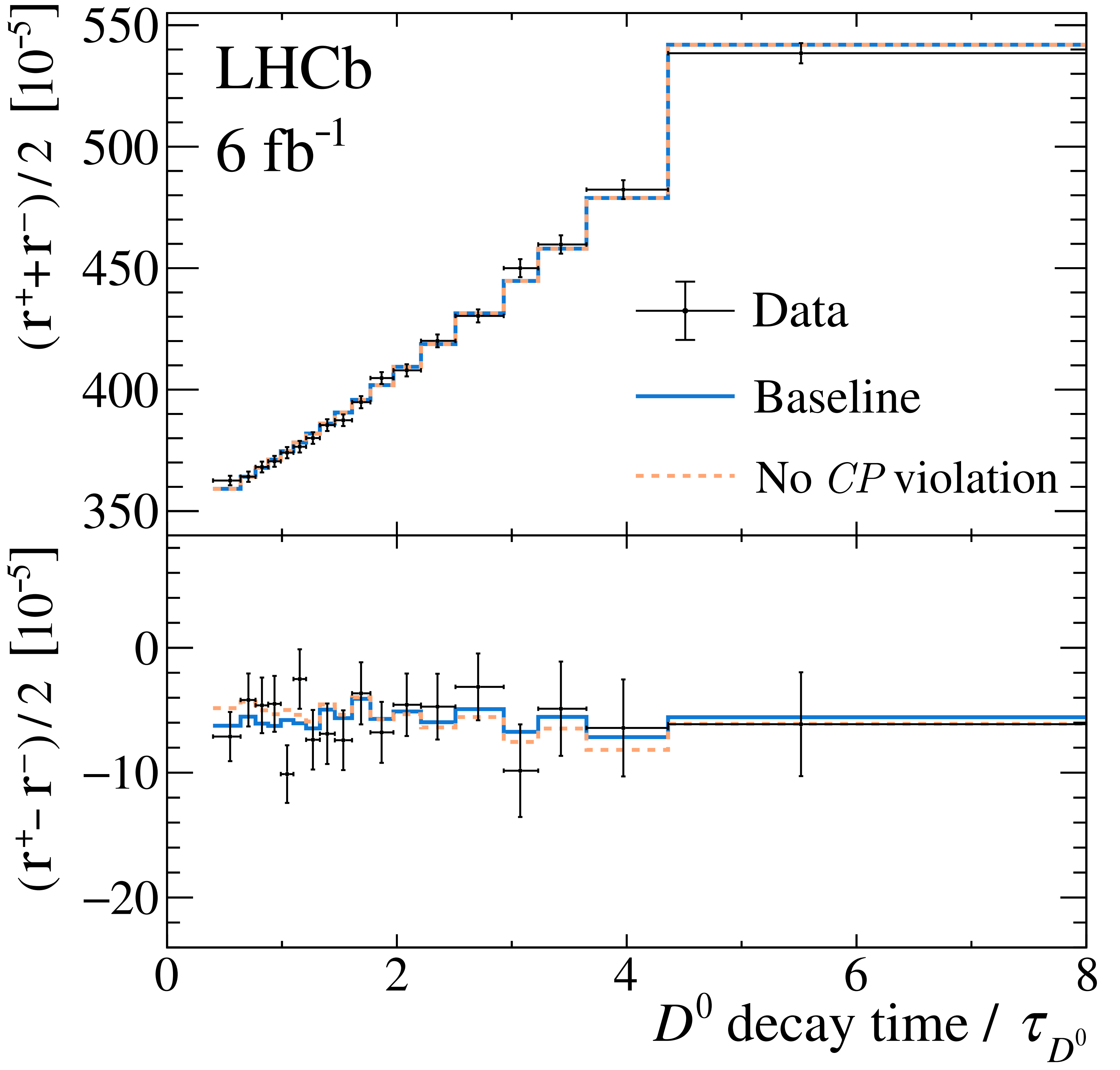
$$R(D^+) = 0.249 \pm 0.043 \pm 0.047$$
$$R(D^{*+}) = 0.402 \pm 0.081 \pm 0.085$$

WARWICK
THE UNIVERSITY OF WARWICK

Charm CPV

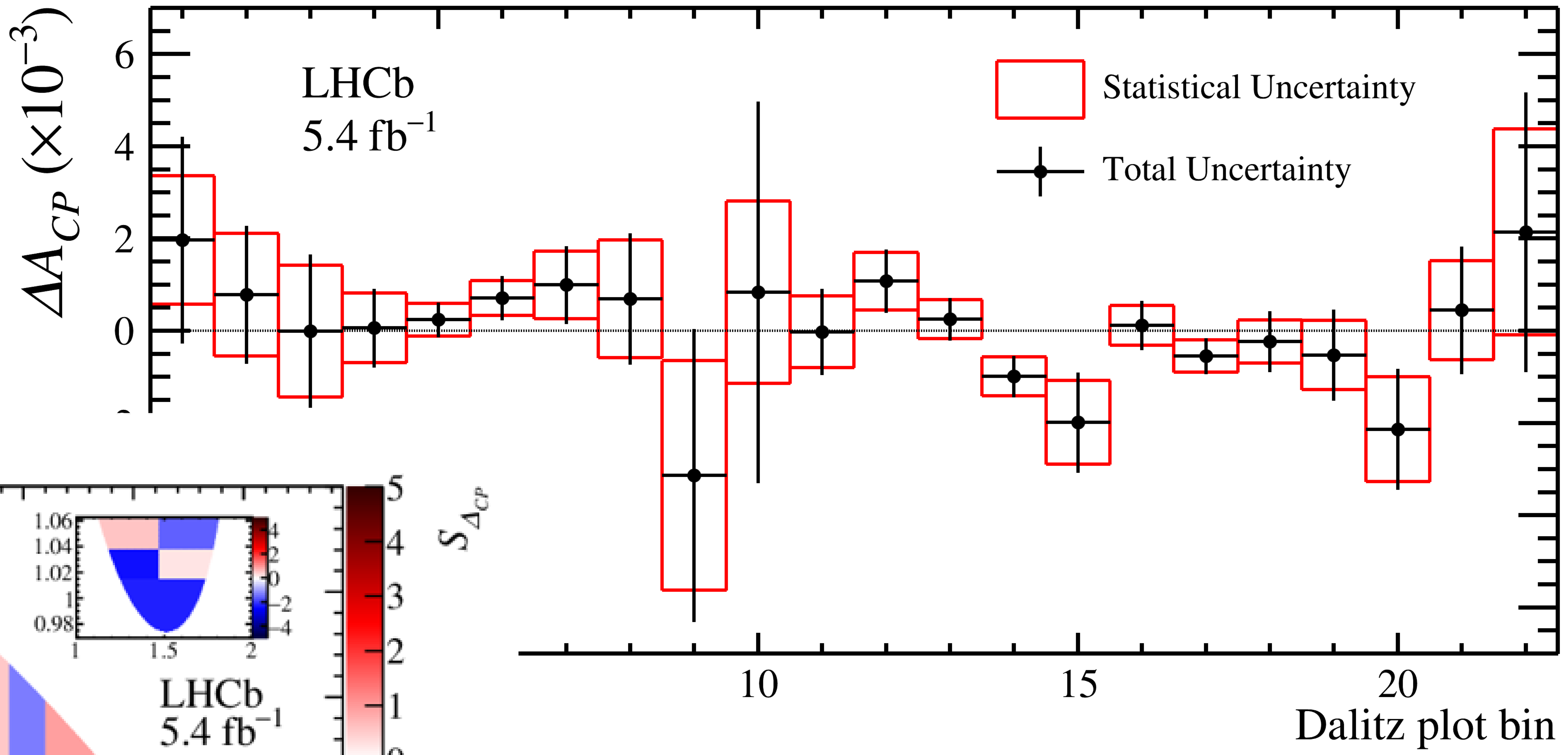
- ➡ Only place where we can study CPV with up-type quarks
- ➡ Measurements involving mixing require huge statistics as oscillation is very slow
- ➡ Measurement with doubly Cabibbo suppressed $D^0 \rightarrow K^+\pi^-$ decays from D^{*+}
- ➡ Consistent with no CPV within uncertainty of 5.7×10-3
- ➡ Large benefit from trigger innovation in Run 2

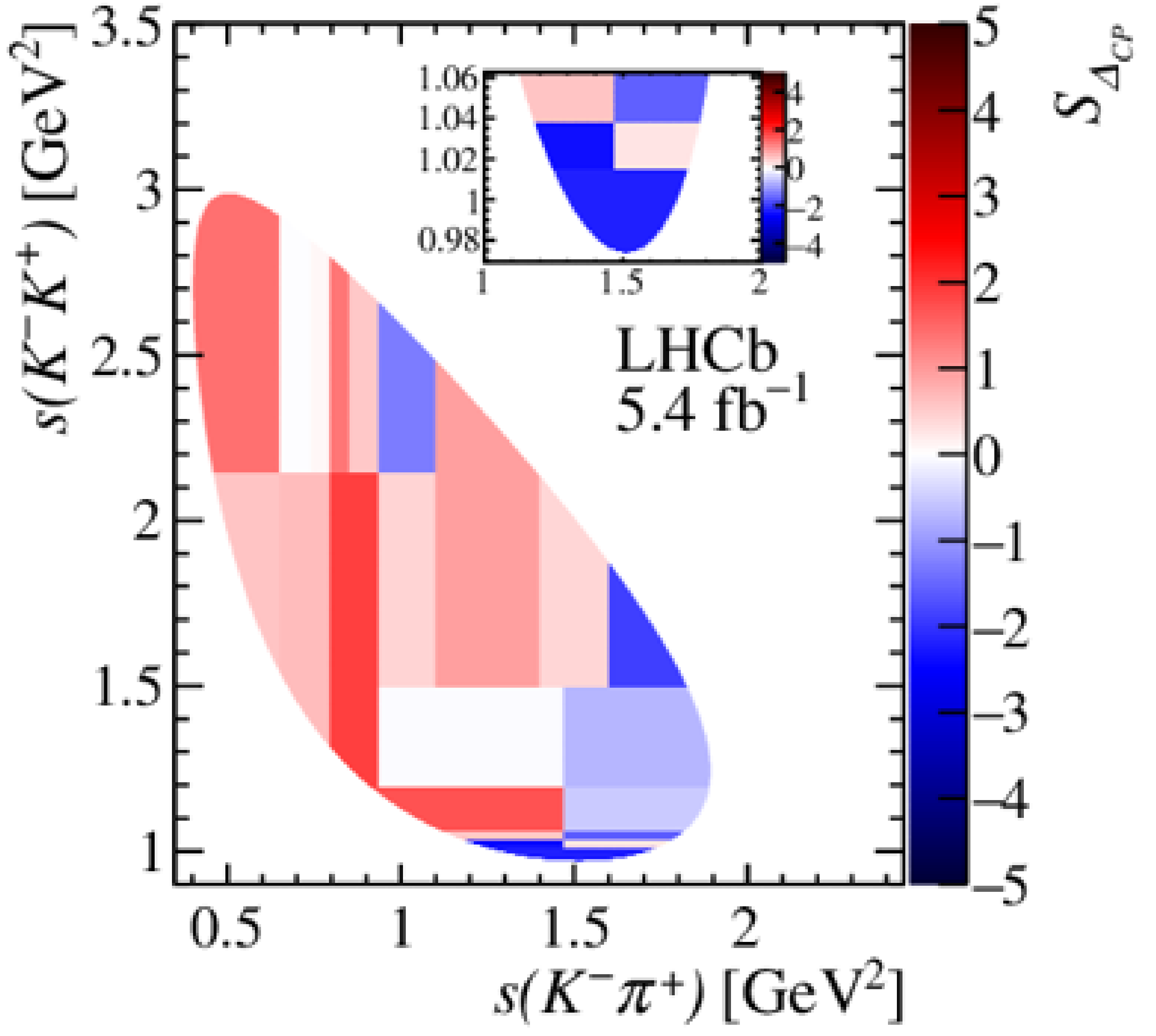




Direct CPV in $D^+ \to K^-K^+\pi^+$

- Cabibbo suppressed D^+ decays
- Uses $D_s^+ \to K^-K^+\pi^+$ to subtract detector effects
- Reached uncertainty of the order 10^{-3}
- Consistent with no CPV with p-value of 8.1%



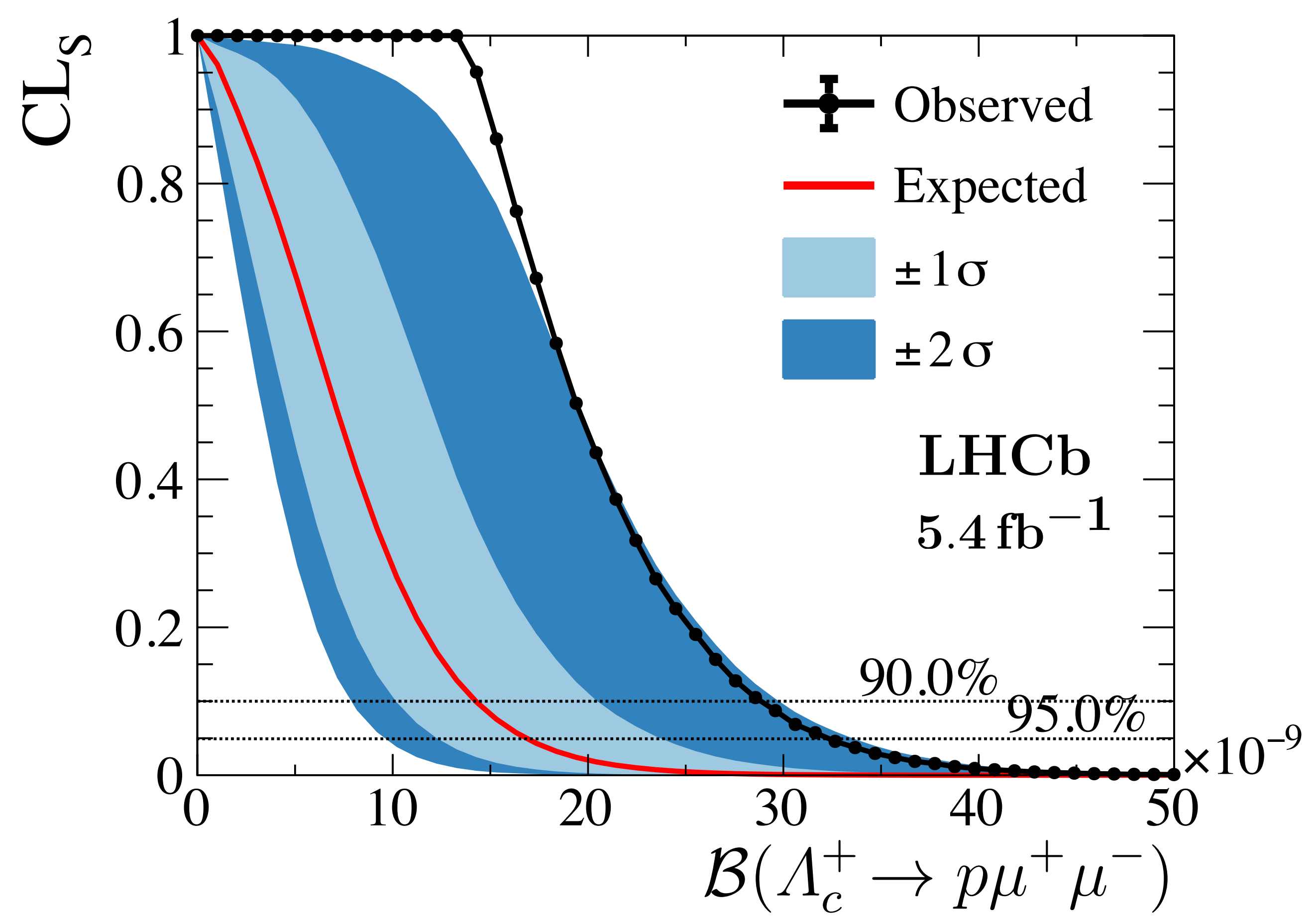


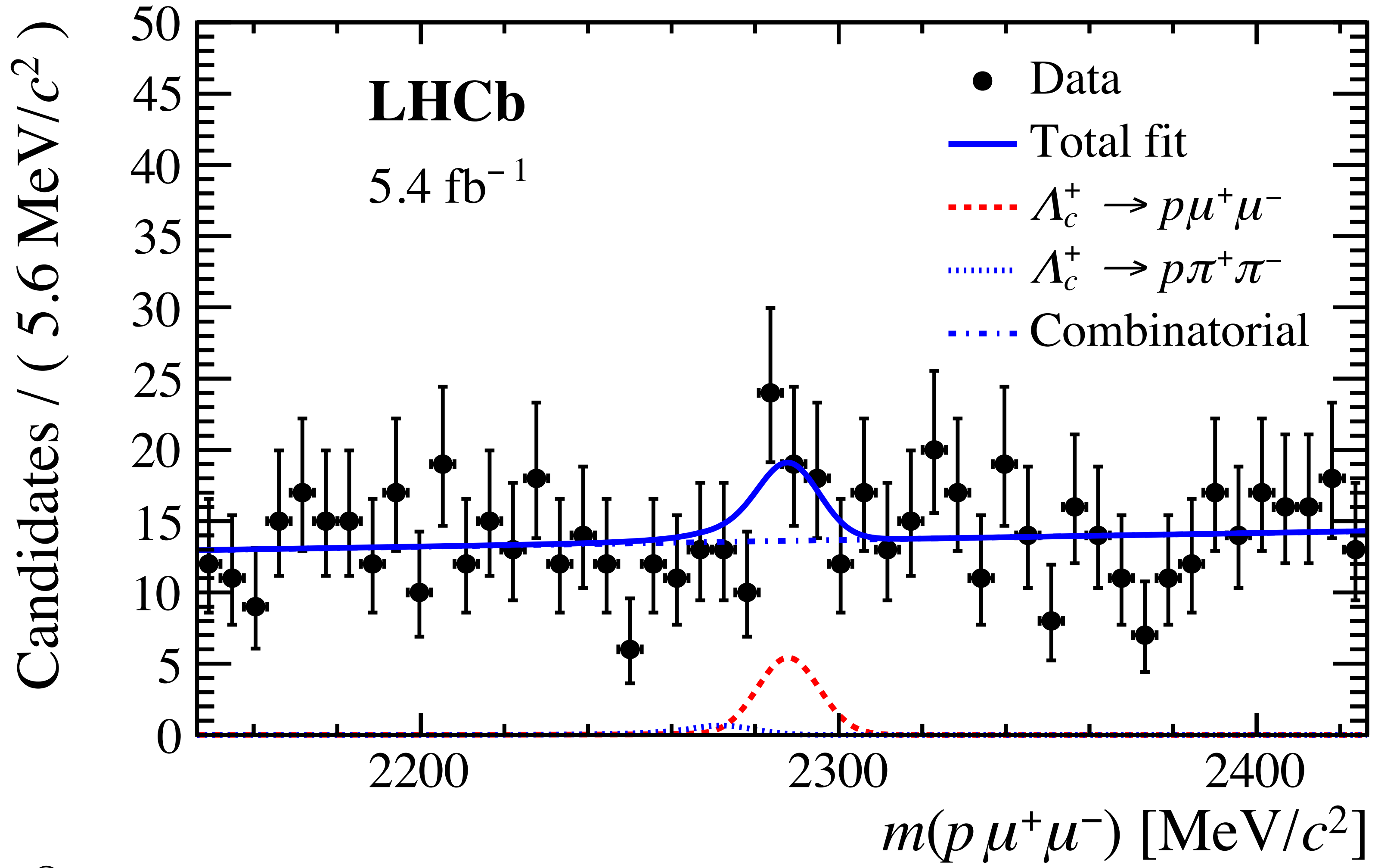
$$A_{CP|S}^{\phi\pi^+} = (0.95 \pm 0.43 \pm 0.26) \times 10^{-3},$$
$$A_{CP|S}^{\overline{K}^{*0}K^+} = (-0.26 \pm 0.56 \pm 0.18) \times 10^{-3}$$

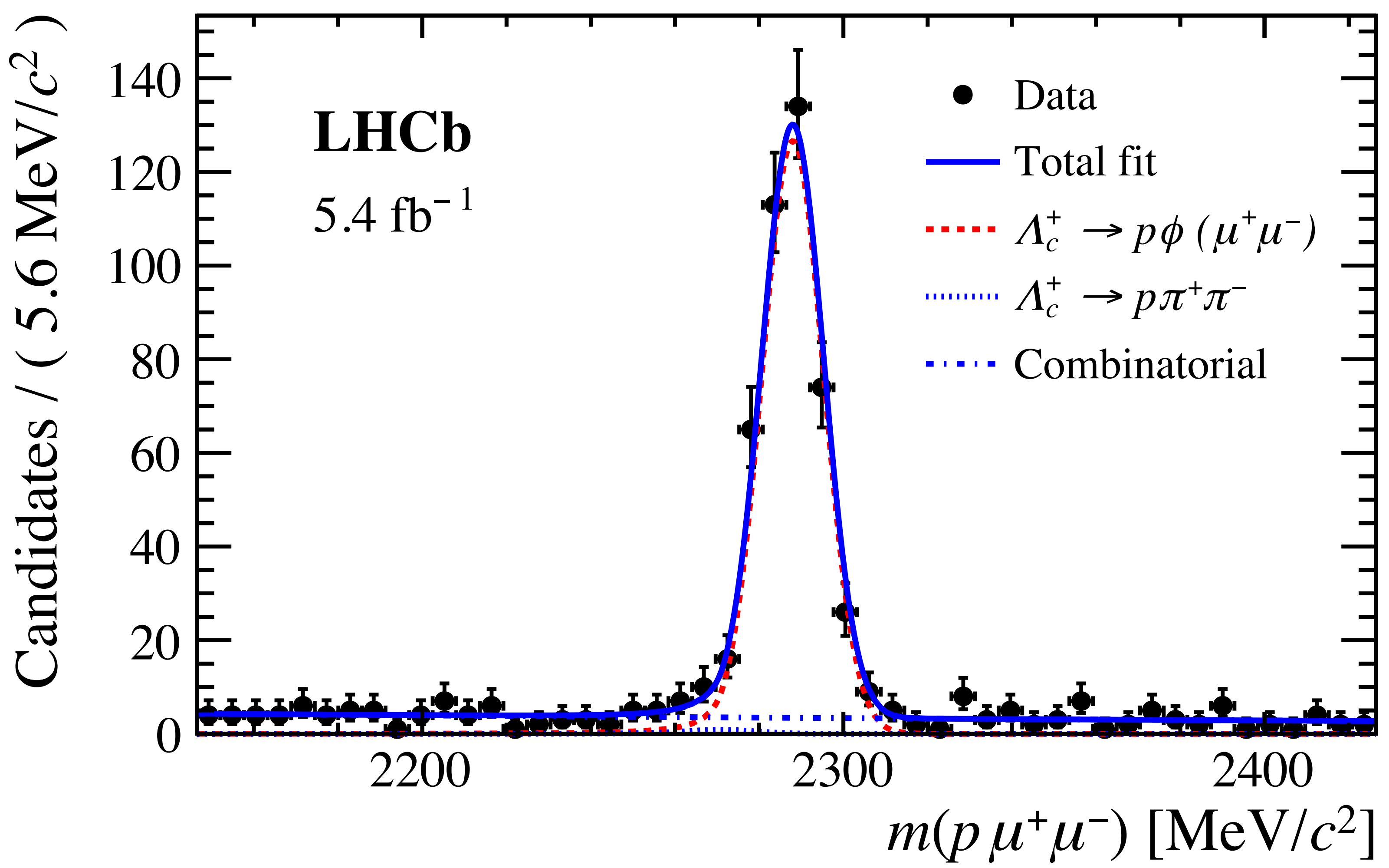
arXiv:2407.11474

Search for $\Lambda_c^+ \rightarrow p\mu^+\mu^-$

- ➡ Rare FCNC decay, expected BF of order 10^{-8}
- ➡ New physics can significantly enhance it
- ➡ Excess at high dimuon mass with 2.8σ significance
- ➡ Overall rate to $p\mu^+\mu^-$ dominated by decays through light resonances
- ➡ Run 3 data should give evidence if excess is real





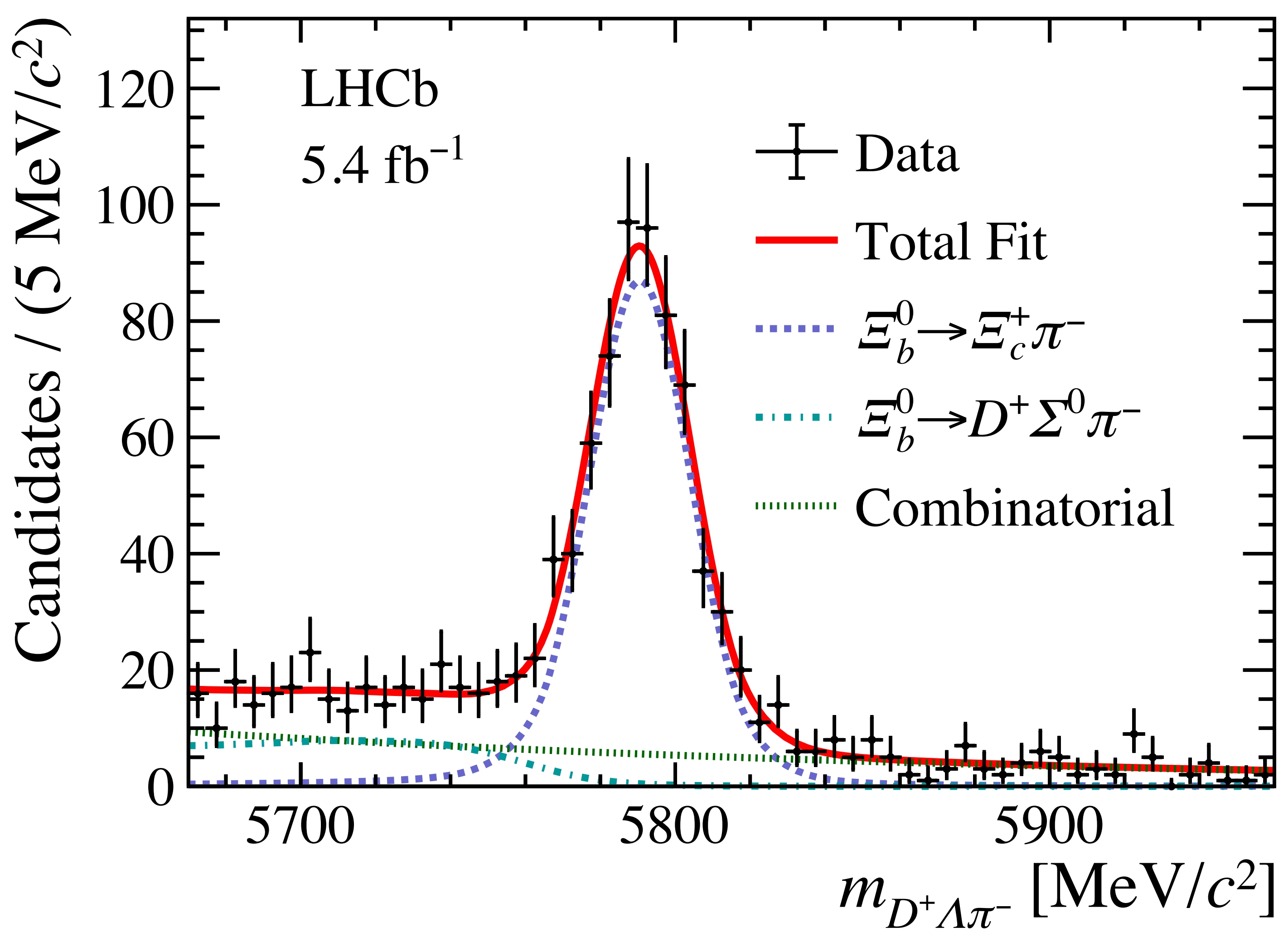


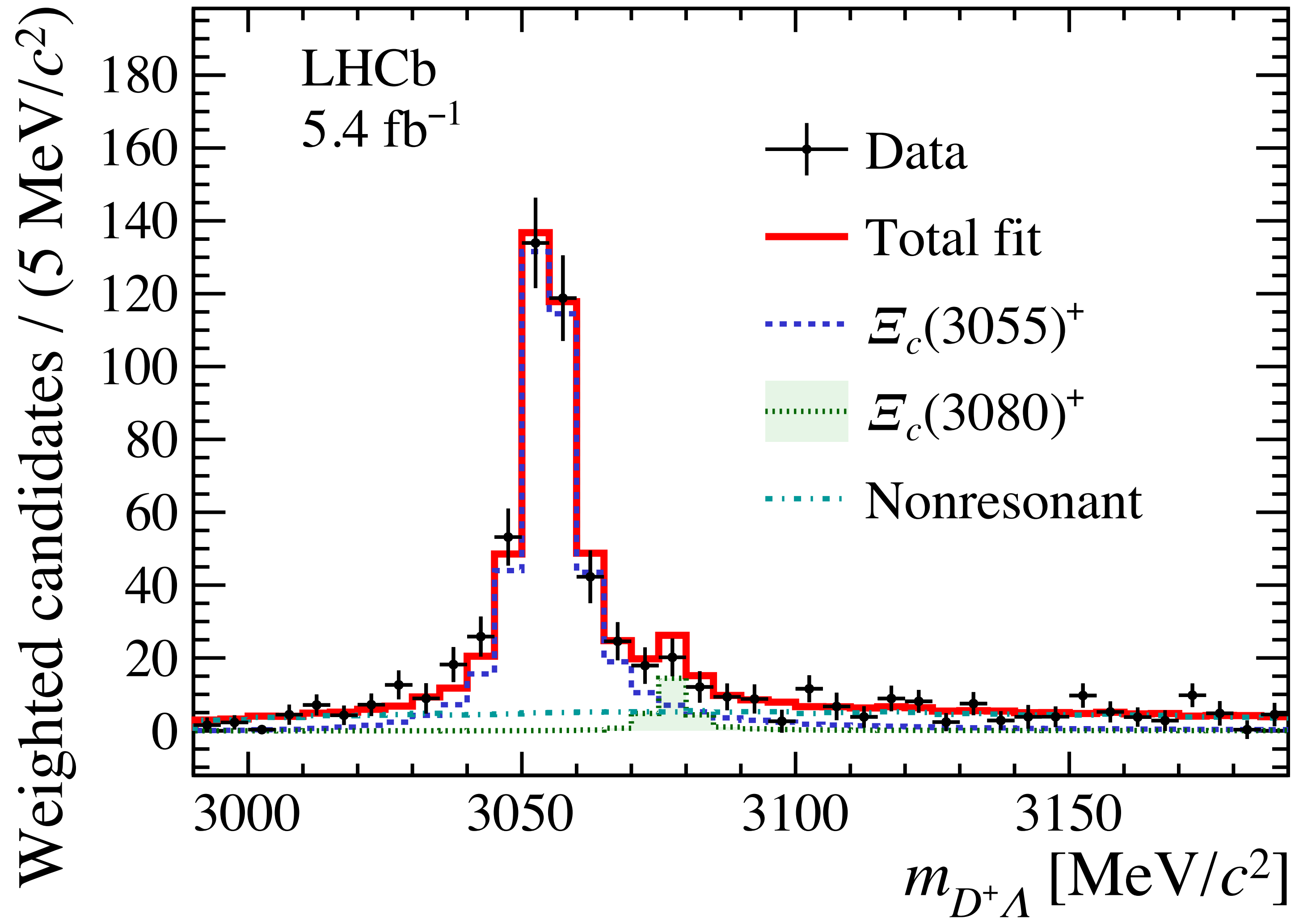
$$\mathcal{B}(\Lambda_c^+ \rightarrow p\mu^+\mu^-) < 2.9\ (3.2) \times 10^{-8} \quad \text{at} \ \ 90\%\ (95\%)\ \text{CL}$$

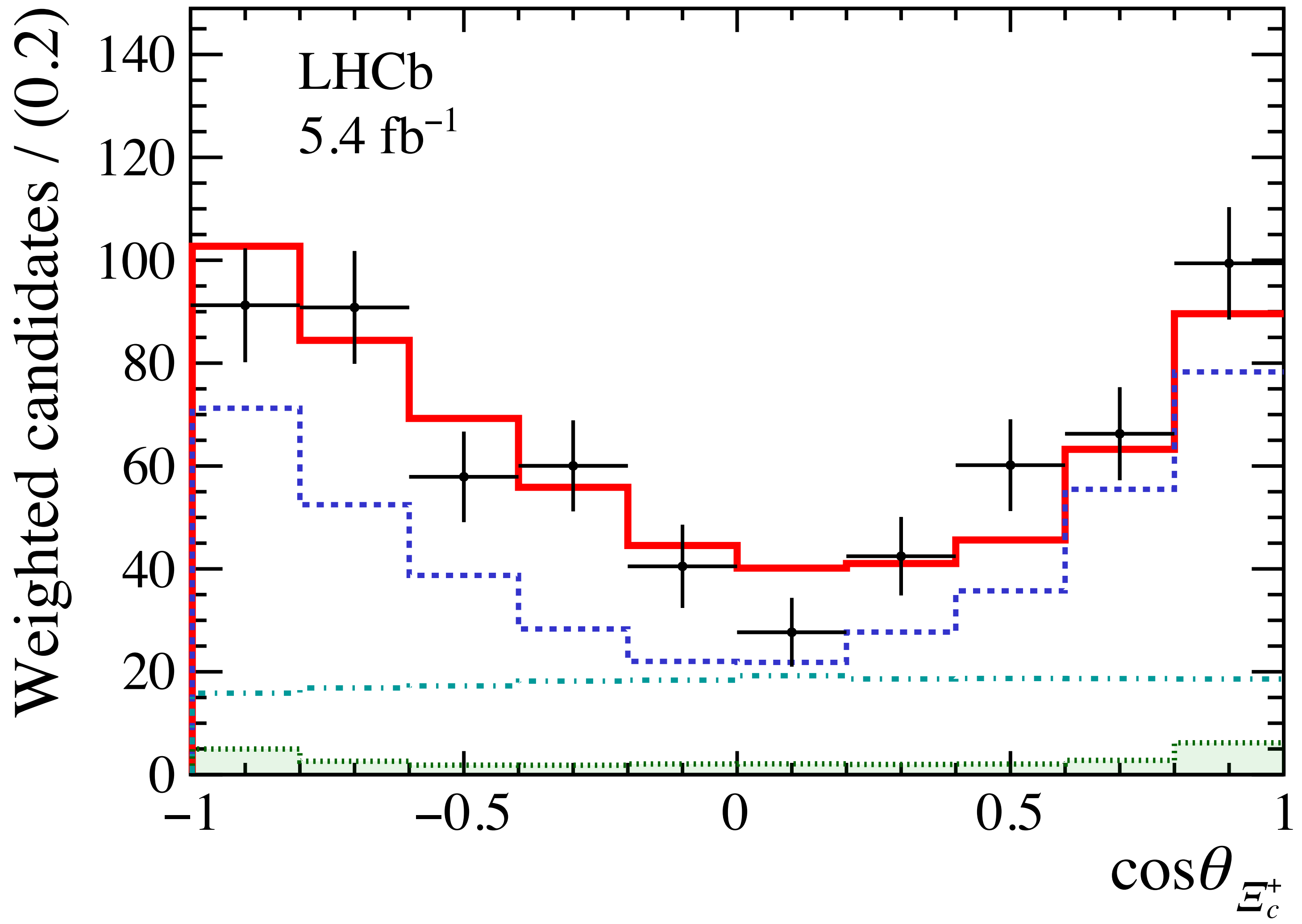
arXiv:2409.05440

Spin-parity of $\Xi_c(3055)$

- ➡ Amplitude analysis of b-hadrons is powerful tool to study c-hadrons
- ➡ Analysis of $\Xi_b \to \Xi_c \pi^{\pm}$ with $\Xi_c \to D\Lambda$
- ➡ Clear contributions from $\Xi_c(3055)$ with hint of $\Xi_c(3080)$ and non-resonant
- ➡ Significance of 4.4σ for $\Xi_c^+(3080)$ and 3.6σ for $\Xi_c^0(3080)$

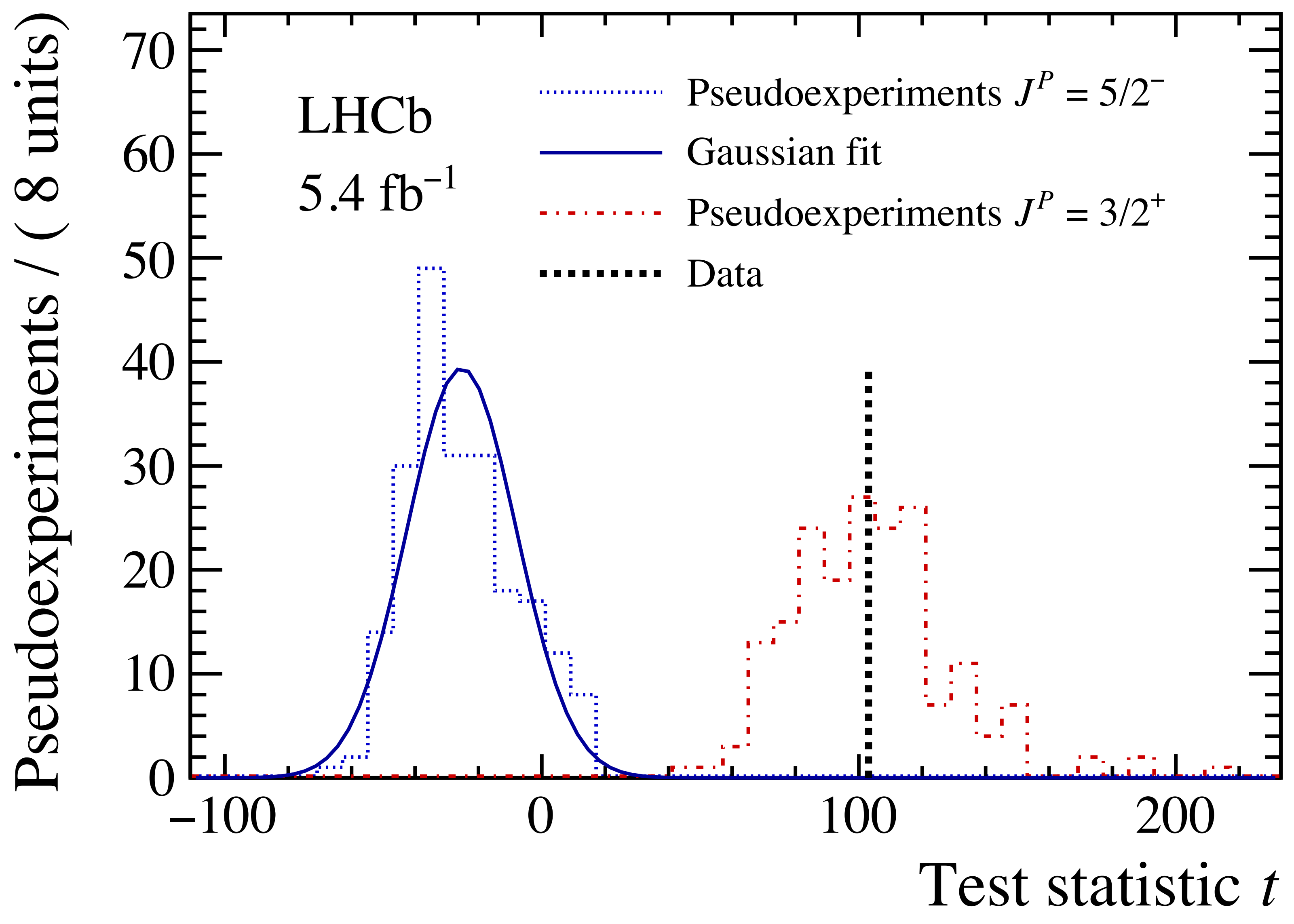


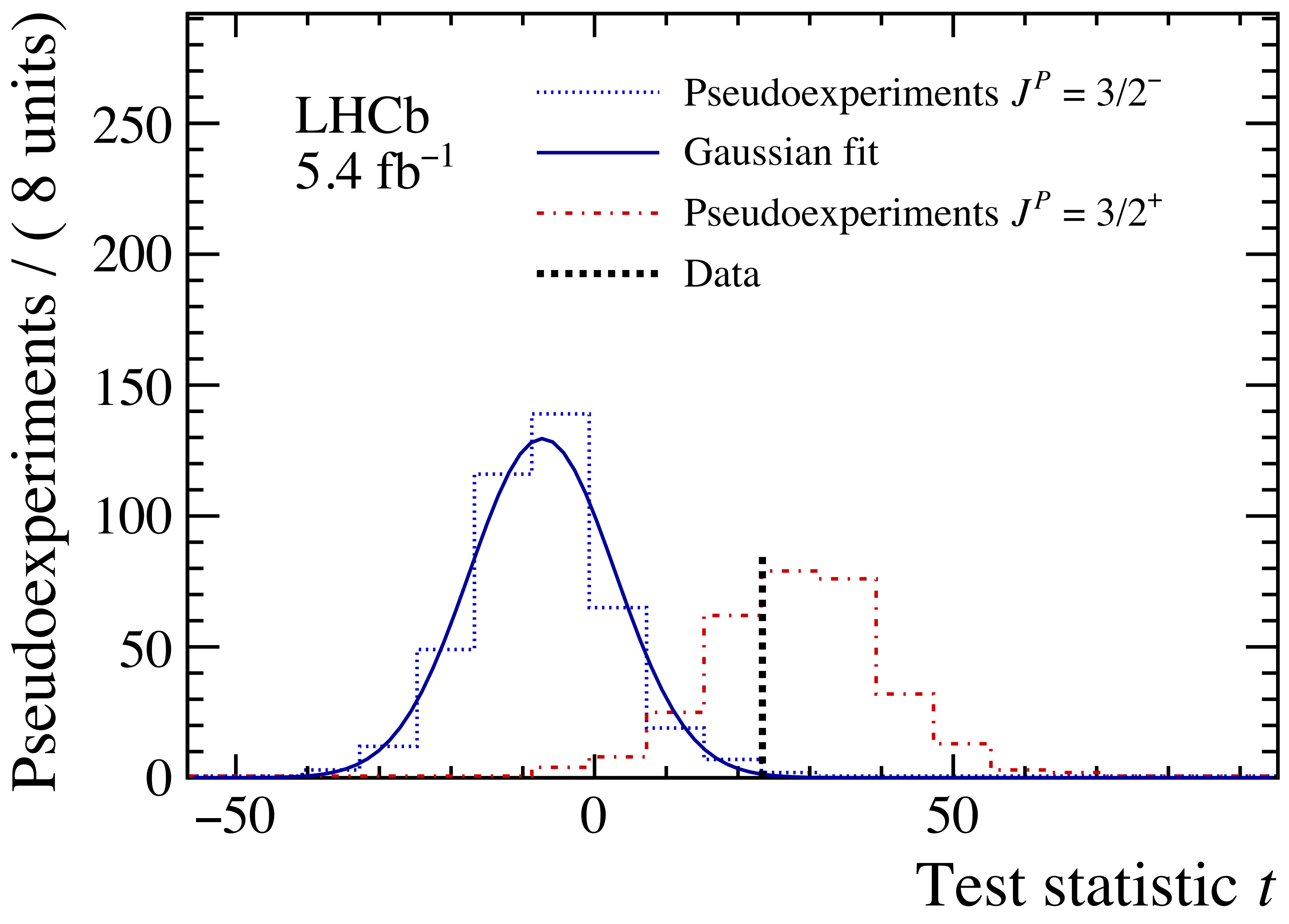




Spin-parity of $\Xi_c(3055)$

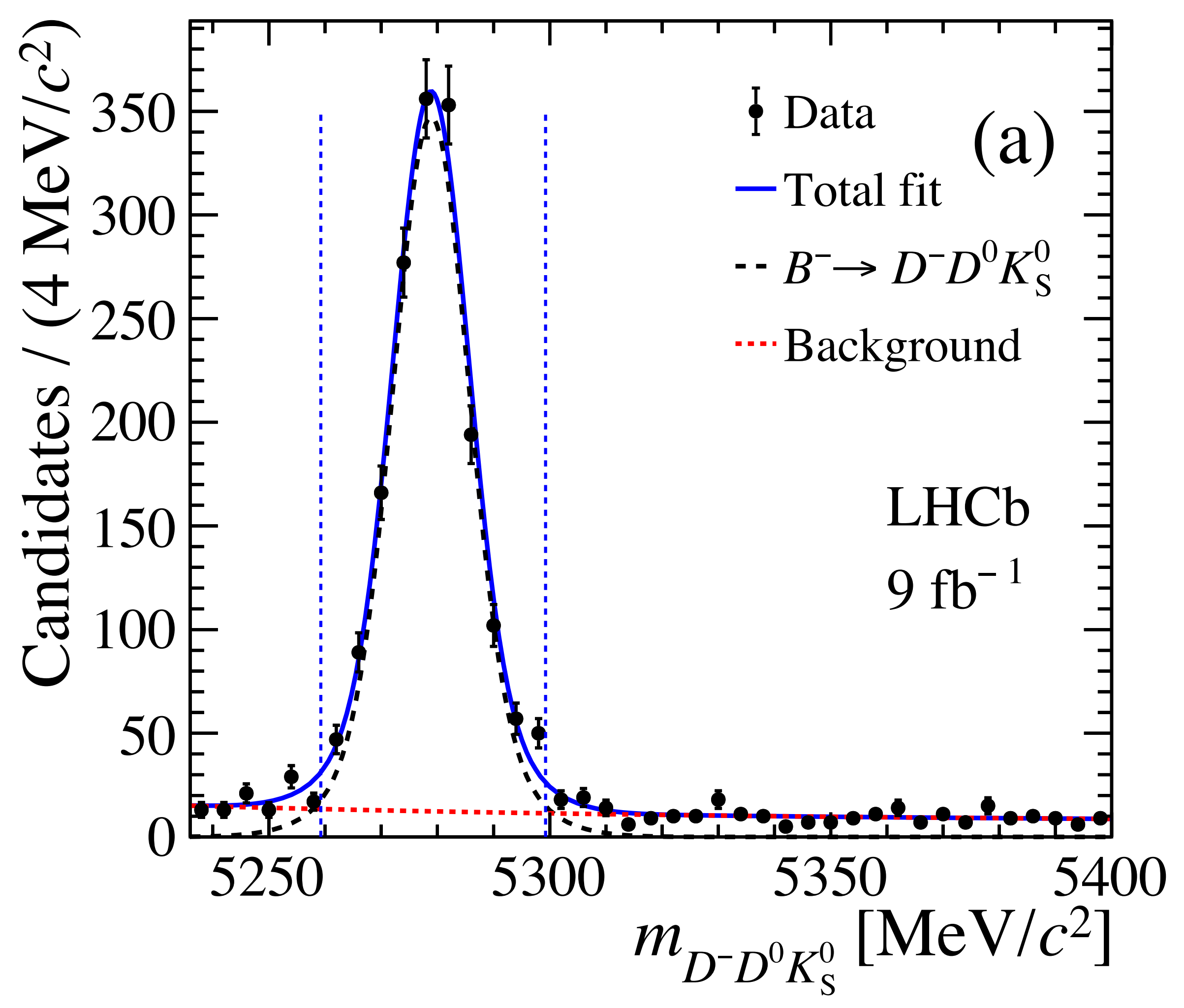
- Use likelihood ratio test to determine spin and parity
- Best hypothesis is $3/2^+$
  - 6.5σ for $\Xi_c^+(3055)$, second best is $5/2^-$
  - 3.5σ for $\Xi_c^0(3055)$ with second best hypothesis $3/2^-$

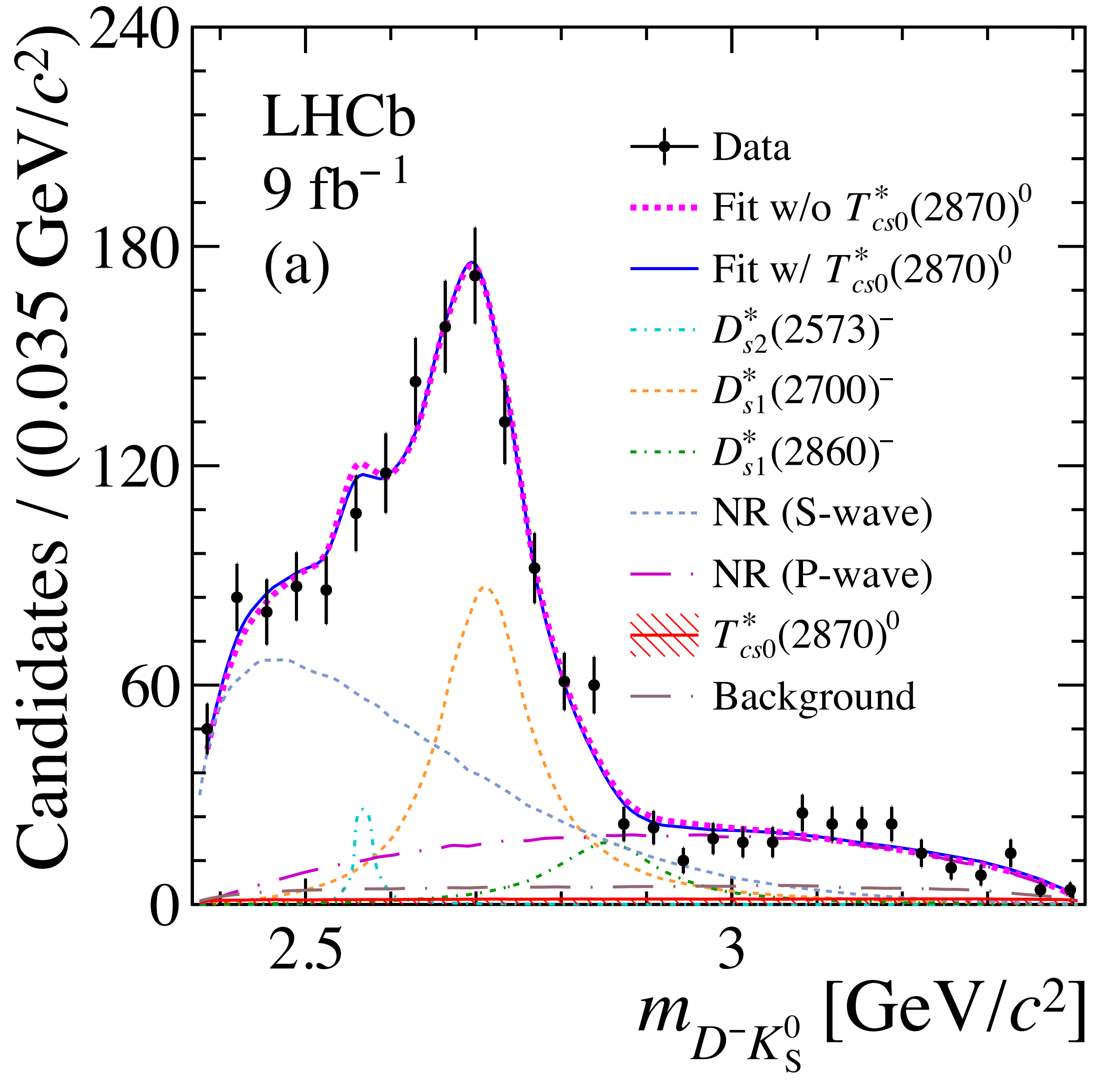


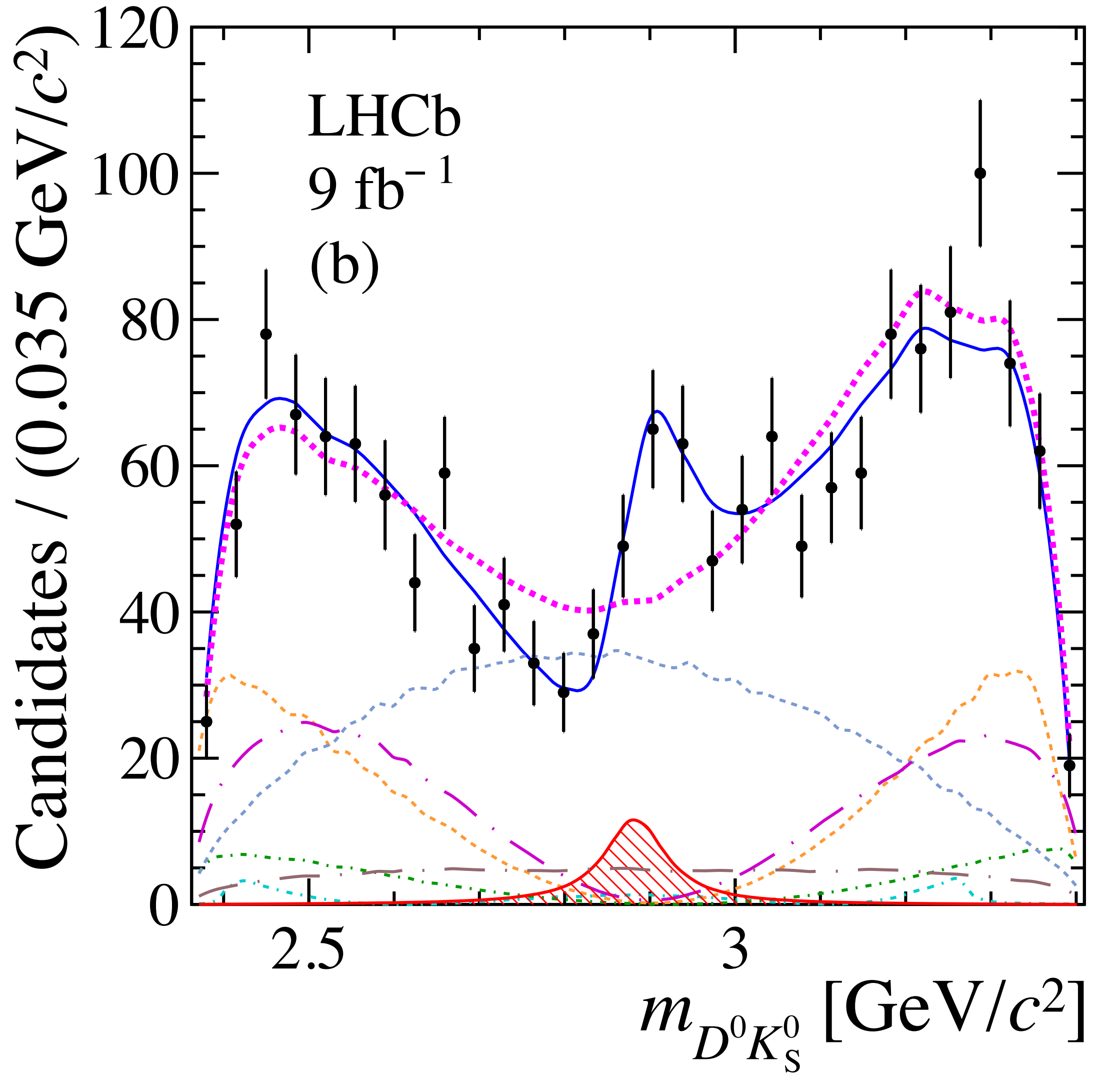


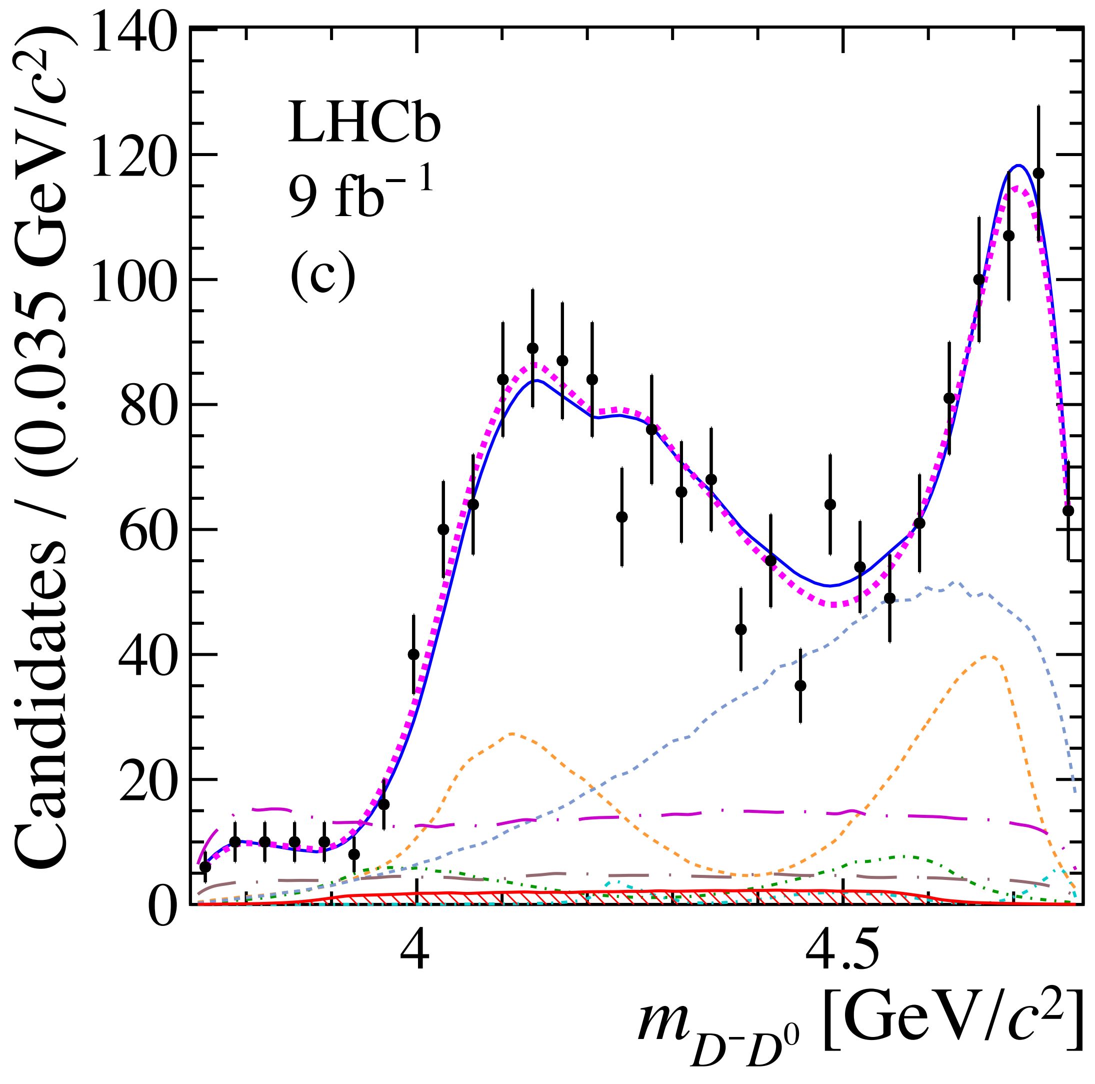
Open charm $T_{cs0}^*(2870)^0$

- ➡ Charm tetra-quark states seen previously in $B^- \to D^- D^+ K^-$ decays
- ➡ Search for same states in $B^- \to D^- D^0 K_S$ decays
- ➡ Observation of $T_{cs0}^*(2870)^0$ with 5.3σ significance







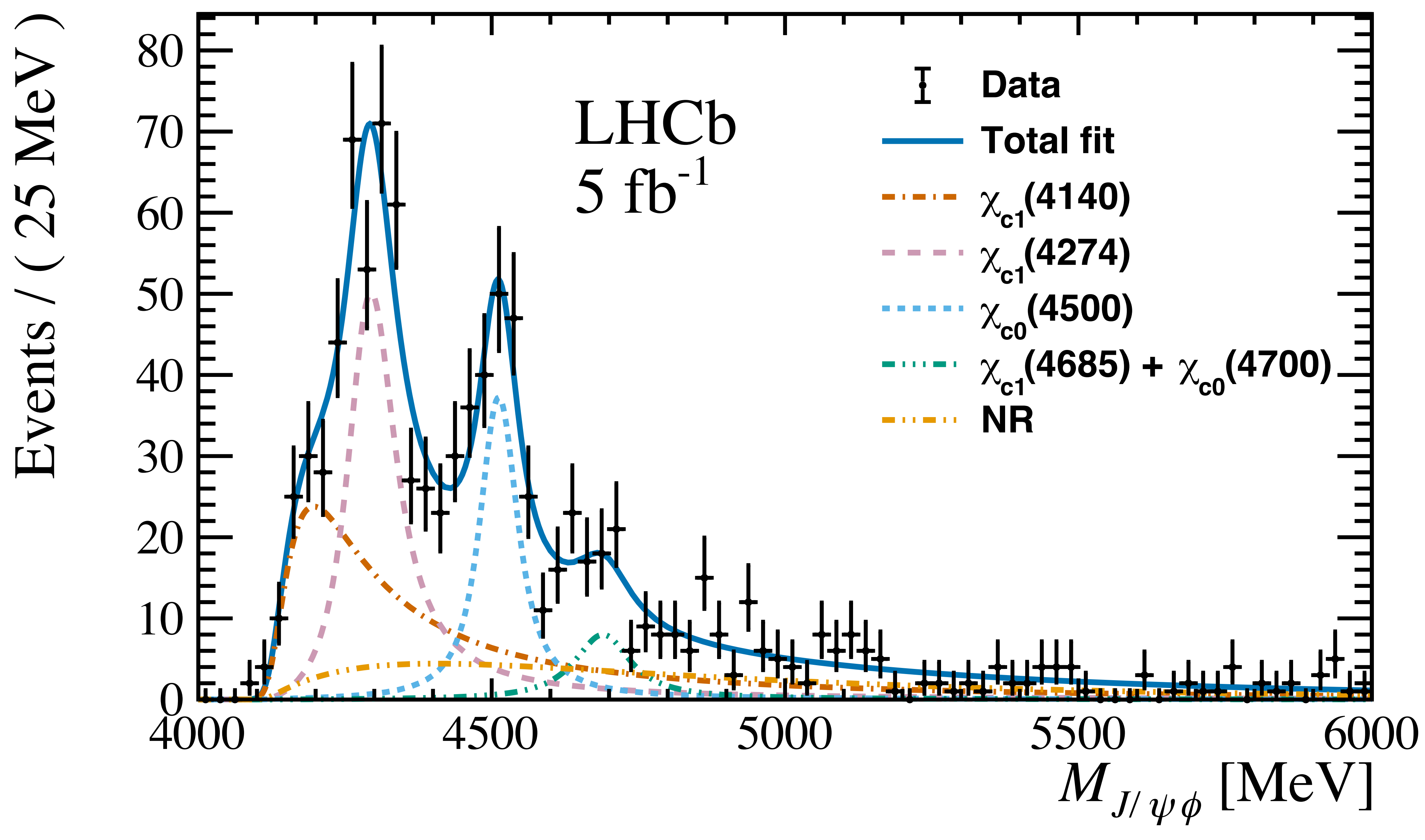


$$M(T^{*0}_{cs0}) = 2883 \pm 11 \pm 7\,\text{MeV}/c^2,$$
$$\Gamma(T^{*0}_{cs0}) = 87^{+22}_{-47} \pm 6\,\text{MeV},$$
$$\text{FF}(T^{*0}_{cs0} \to D^0 K^0_S) = (2.6 \pm 1.2 \pm 0.2)\%,$$

arXiv:2407.14301

$J/\psi\phi$ in diffractive processes

- ➡ Study of exclusive production of exotic hadrons can help to understand their nature
- ➡ Events with very low activity (<20 SPD hits and <8 tracks)
- ➡ Study $J/\psi\phi$ invariant mass spectrum
- ➡ Dominated by resonances, some previously seen only in *B* decays
- ➡ Cross-section for several of them measured



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

arXiv:2410.18018

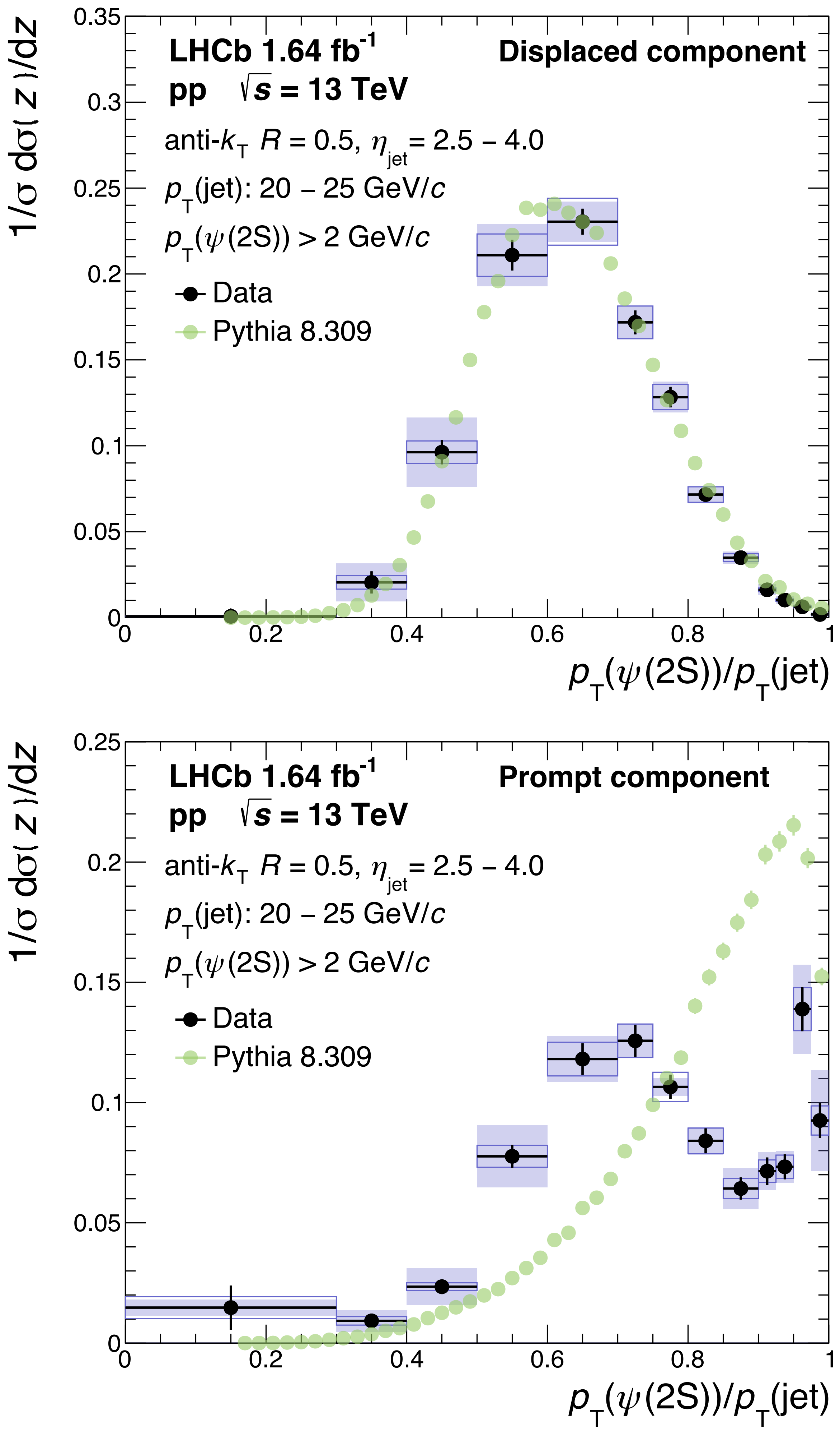
$\psi(2S)$ produced in jets

➡ Quarkonia production not well understood with some discrepancies between theory and experiment
- ❖ NRQCD predicts large polarisation at high p_T which is not observed
- ❖ Prediction is mostly isolated production, but measurement with J/ψ produced in jets

➡ Measure also $\psi(2S)$, which is less affected by feed down from higher resonances

➡ Reasonable agreement for those from B decays

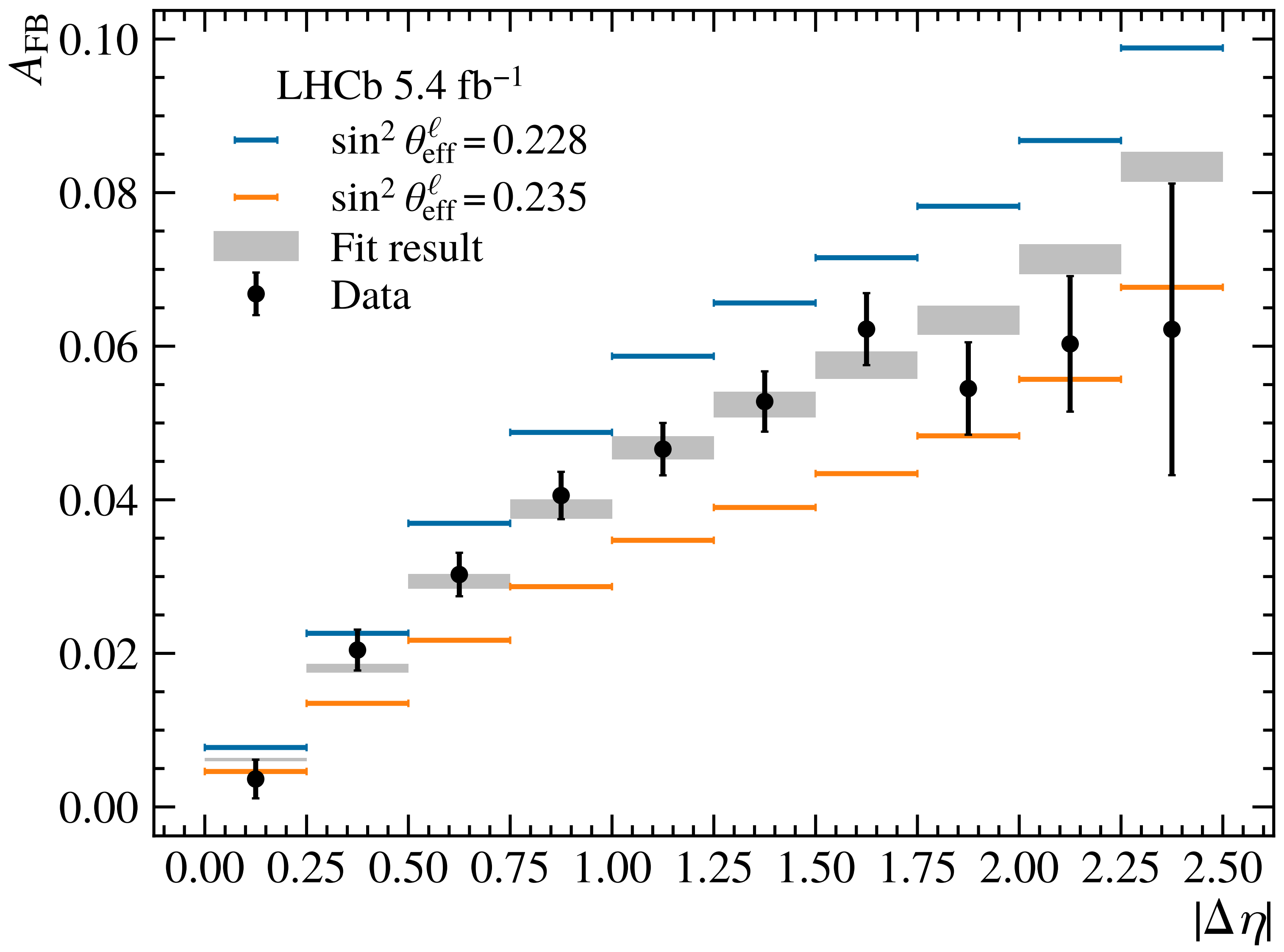
➡ Significant differences for prompt component



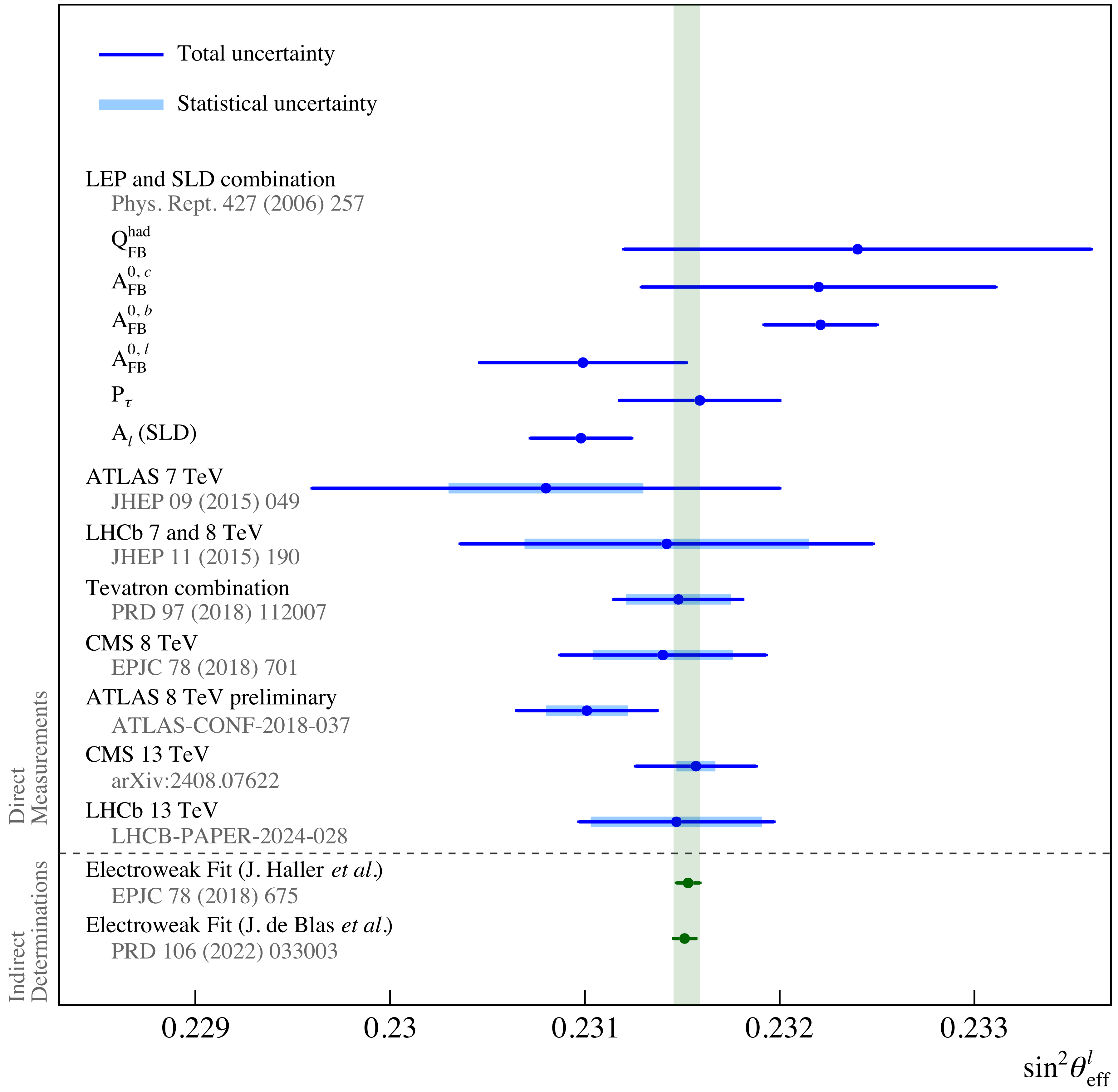
arXiv:2410.02502

Measurement of $\sin^2\theta^l_{eff}$

- ➡ Related to $\sin^2\theta_W$, fundamental parameter of the SM
- ➡ Measured from forward-backward asymmetry in $Z \to \mu^+\mu^-$ decays
- ➡ Use Powheg-box to extract $\sin^2\theta^l_{eff}$ from A_{FB}

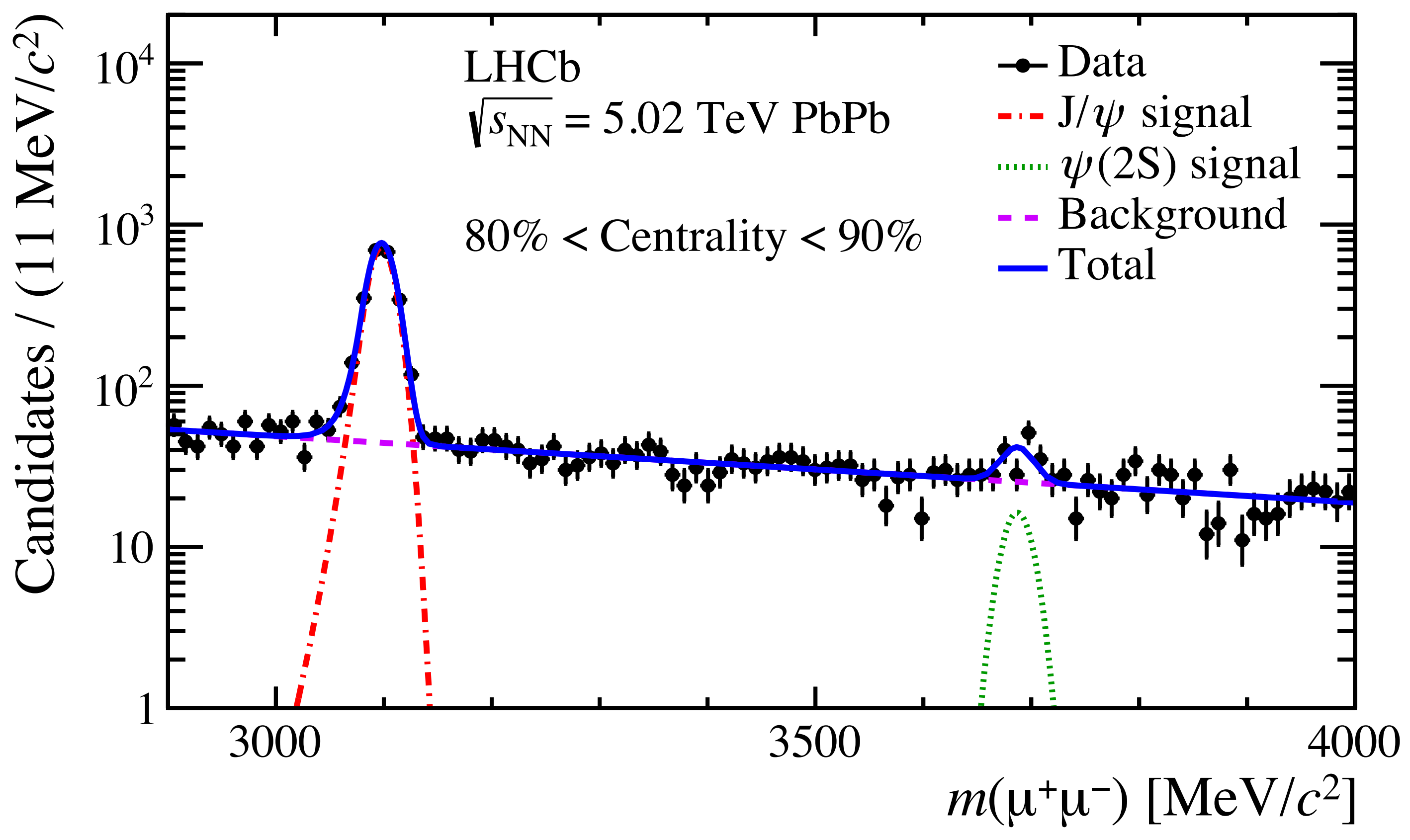


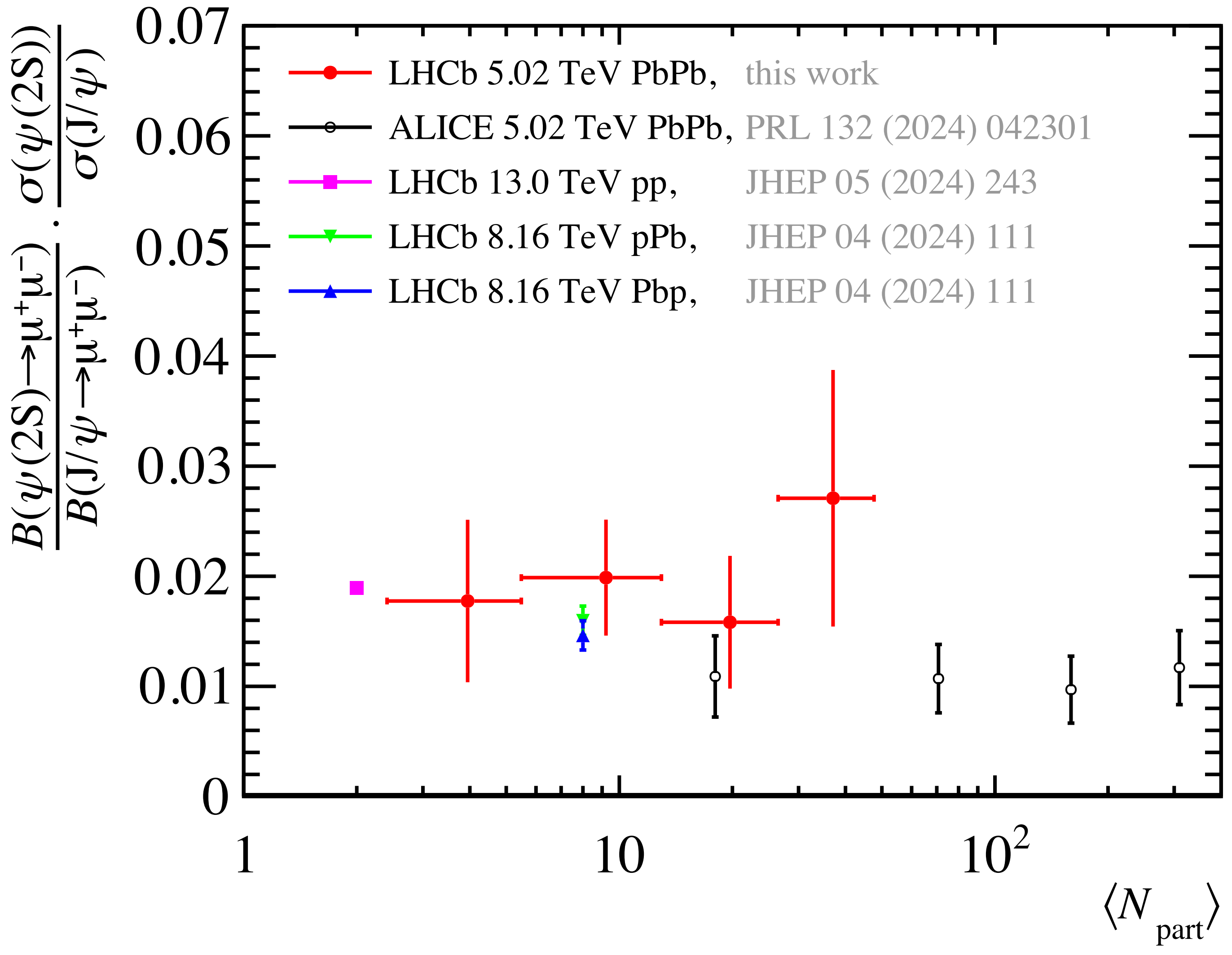
$$\sin^2\theta^\ell_{eff} = 0.23148 \pm 0.00044 \pm 0.00005$$

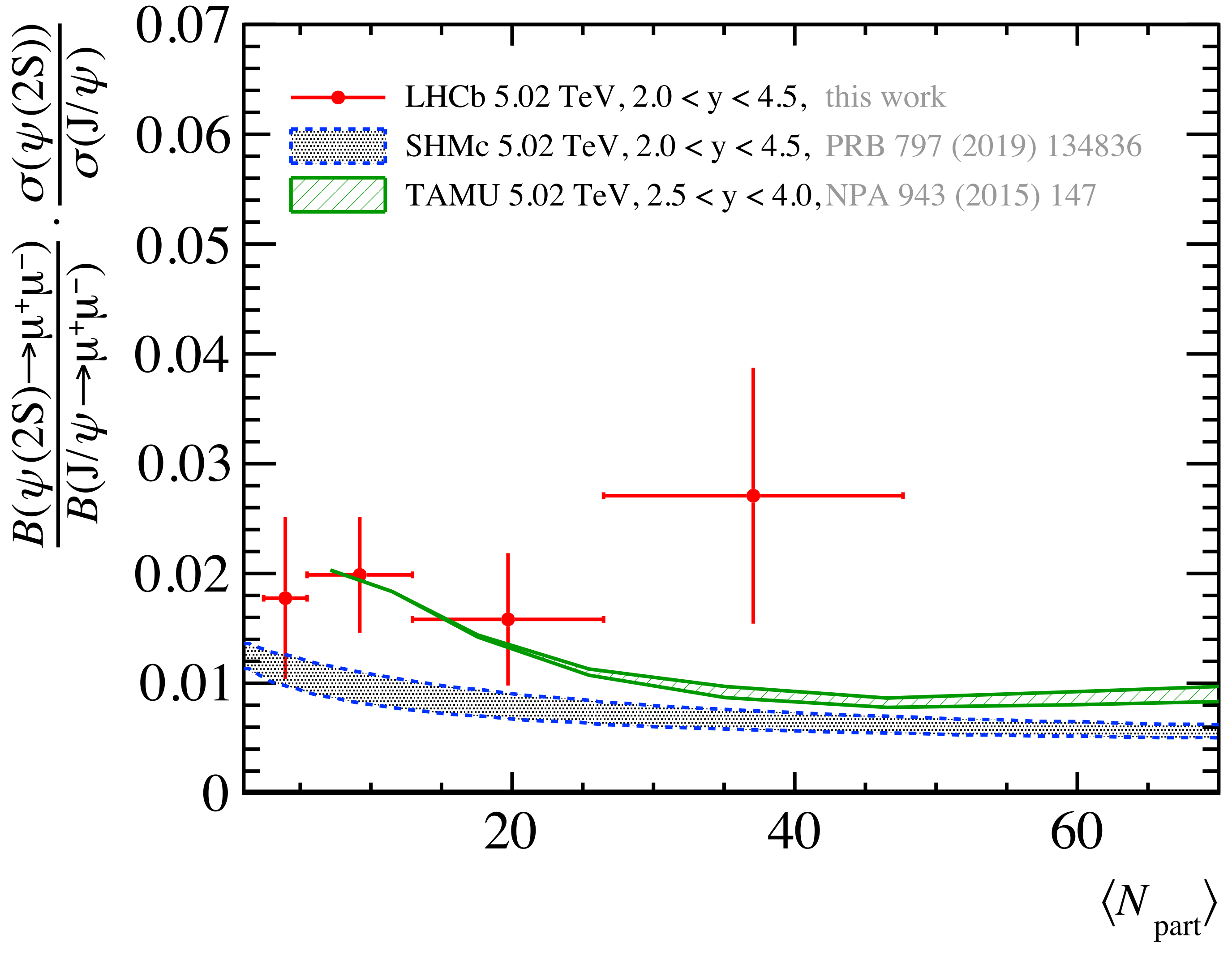


$\psi(2S)$ to J/ψ ratio in PbPb

- In QGP charmonia can become unbound under the effect of colour screening
- Effect depends on the binding energy → ratio of states with different binding energy should change with centrality
- Data consistent with no dependence
- In Run 3, expect to push to higher centrality and better statistics



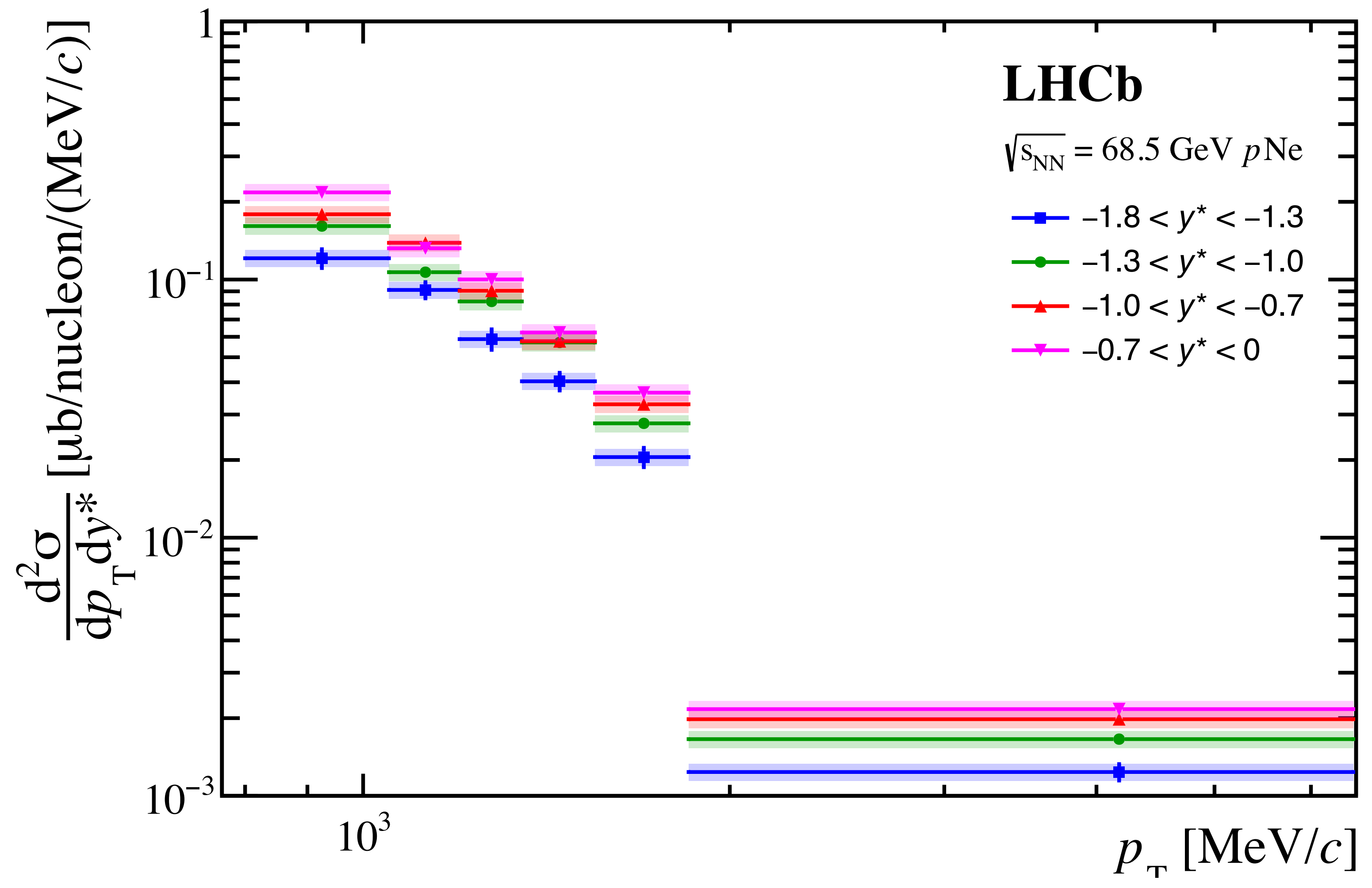


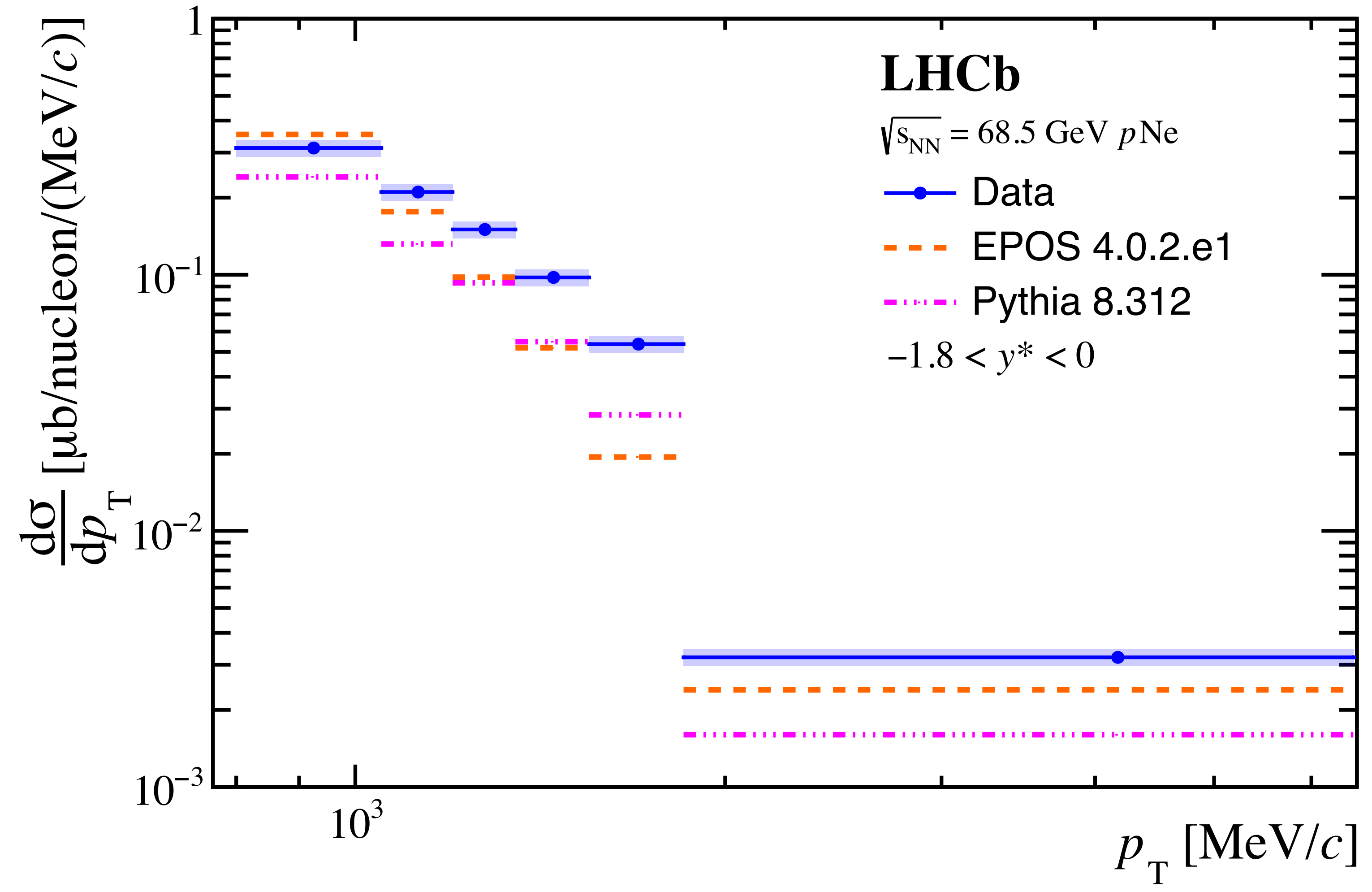


arXiv:2411.09343

ϕ production in *p*Ne

- ➡ ϕ meson is good probe of QGP
  - ❖ In ordinary matter production OZI suppressed
  - ❖ In QGP can be produced by coalescence of strange quarks and bypass OZI suppression
- ➡ Study in systems of different sizes in attempt to disentangle QGP from cold nuclear matter effects
- ➡ Unique opportunity thanks to detector geometry which allows also fixed target mode
- ➡ Do not expect QGP
- ➡ Models underestimate production





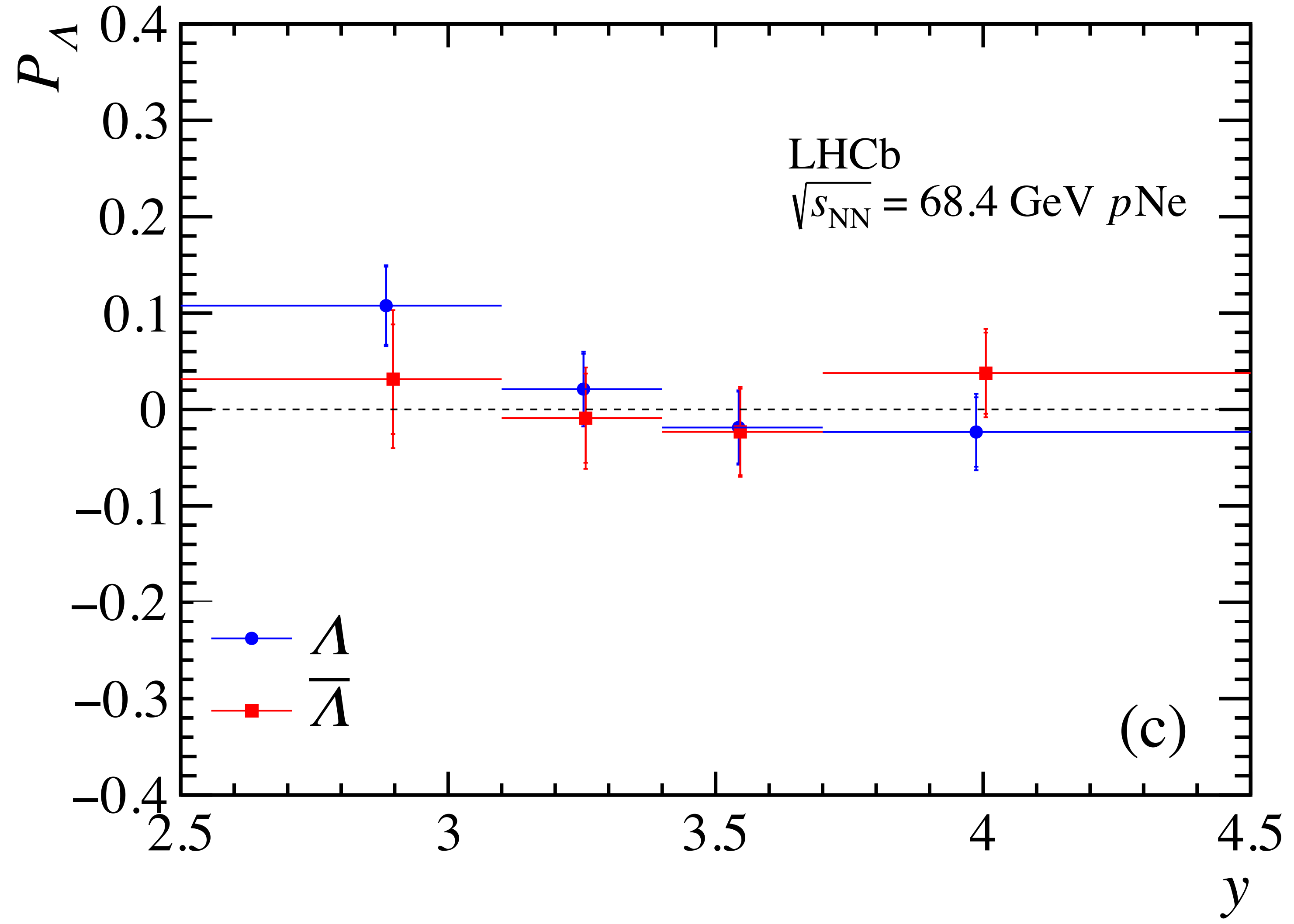
WARWICK
THE UNIVERSITY OF WARWICK

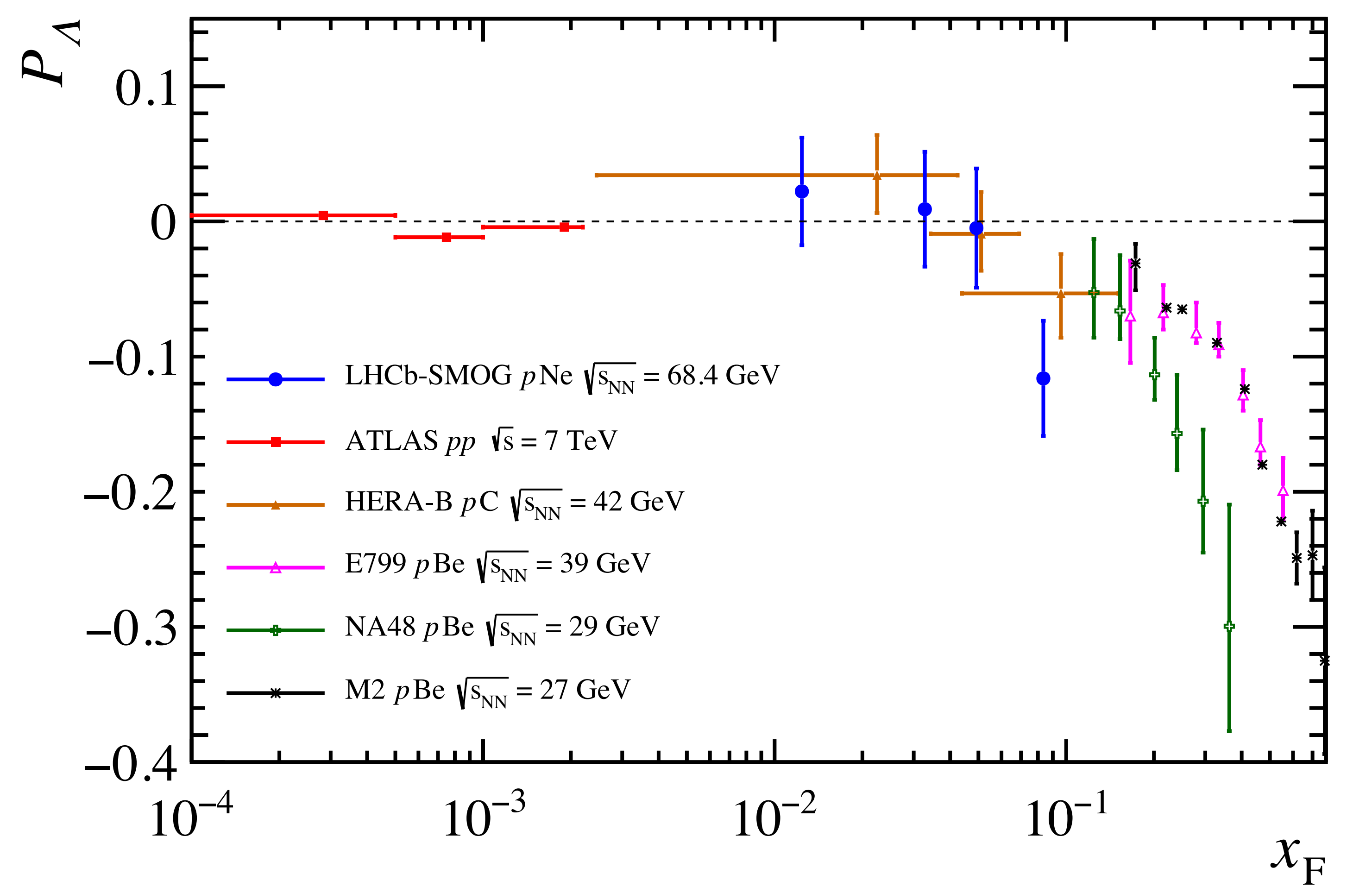
Λ polarisation in pNe

- ➡ First observed in pBe fixed target in 1976
- ➡ Purely understood with no fully satisfactory description
  - ❖ Based on polarising fragmentation function
- ➡ Fixed target capability can add information in purely covered region
- ➡ Measurement agrees with previous results
- ➡ Integrated result

$$P_{\Lambda} = 0.029 \pm 0.019\,(\mathrm{stat}) \pm 0.012\,(\mathrm{syst})$$

$$P_{\bar{\Lambda}} = 0.003 \pm 0.023\,(\mathrm{stat}) \pm 0.014\,(\mathrm{syst})$$

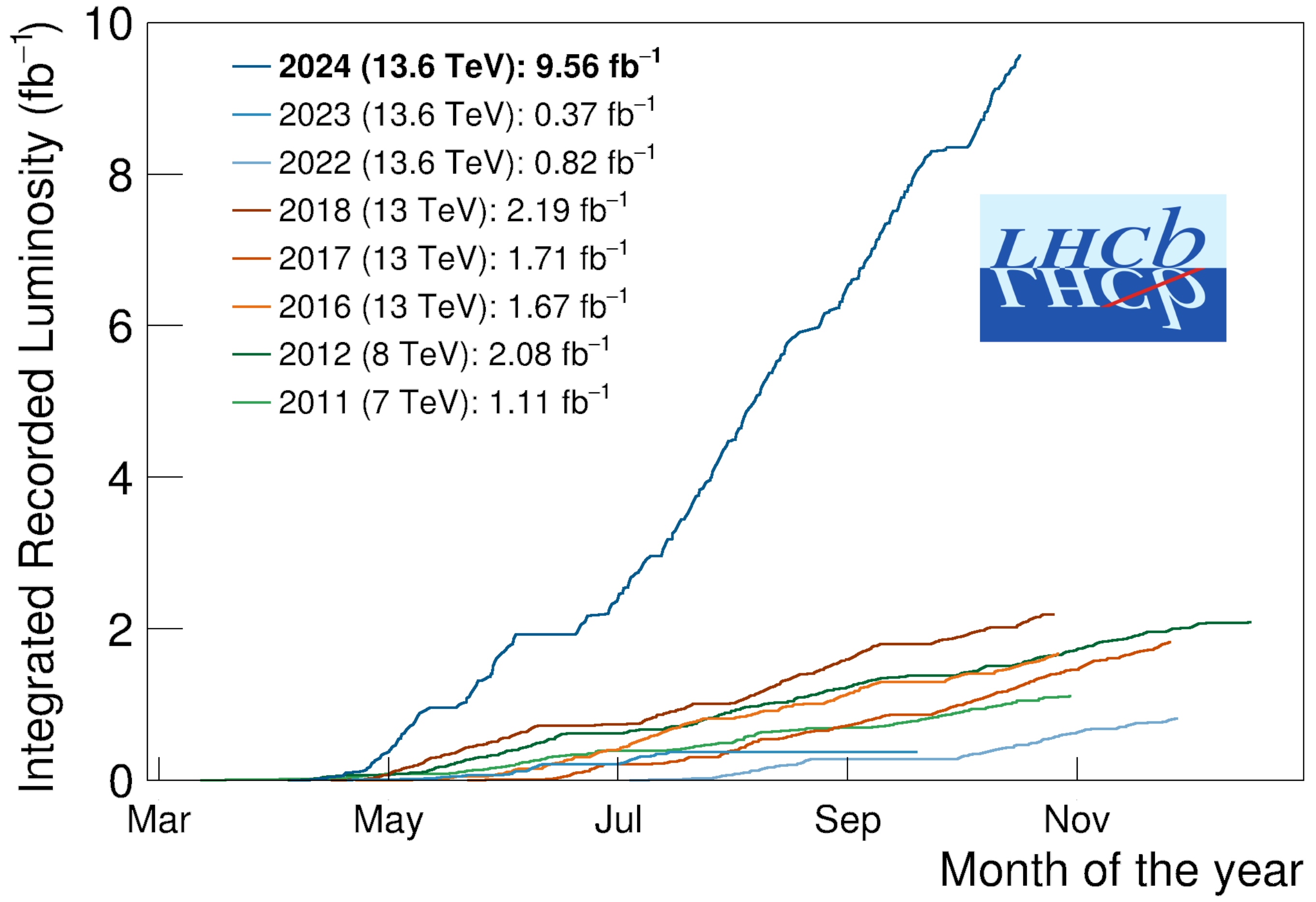


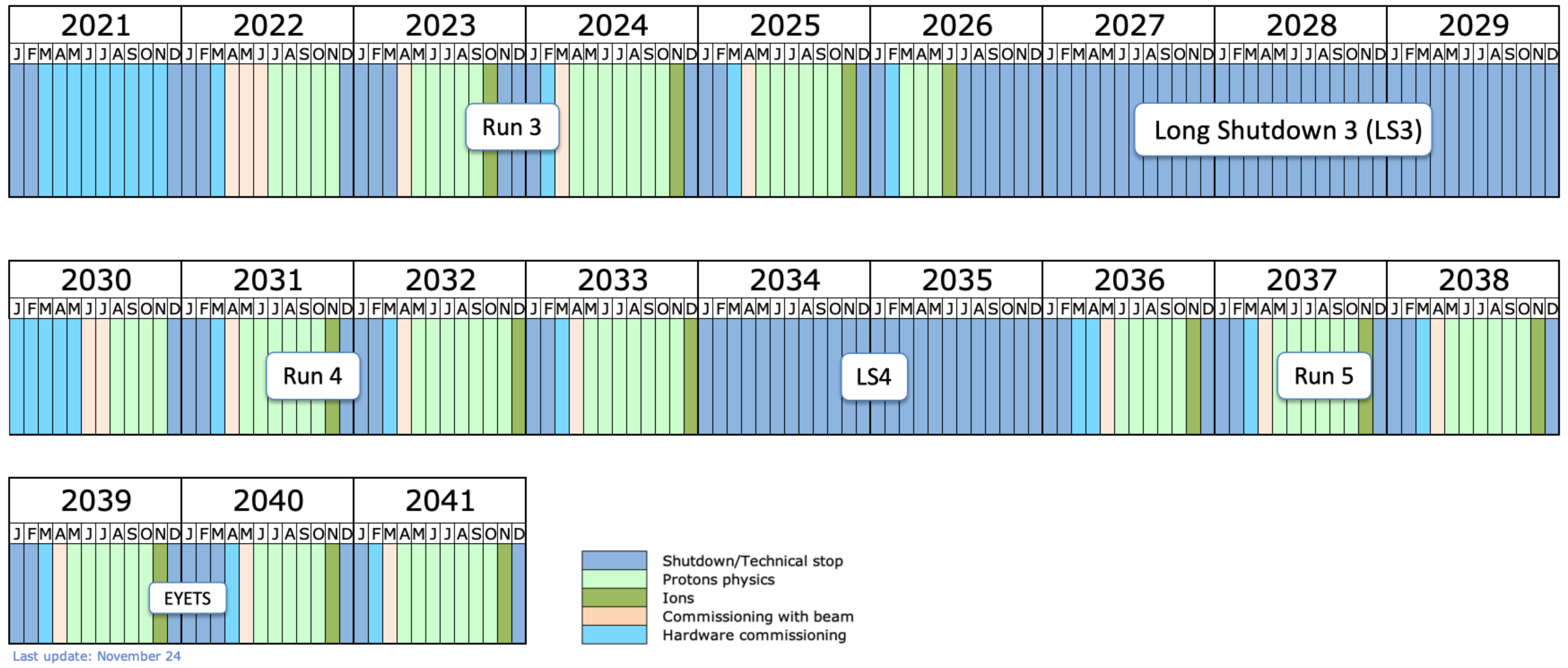


Run 3 prospects

WARWICK
THE UNIVERSITY OF WARWICK

- ➡ Collected almost 10 fb^{-1} this year
- ➡ Well on track for over 20 fb^{-1} of data in Run 3 and at least 50 fb^{-1} by the end of Run 4
- ➡ Removed HW trigger, which increases efficiency for many channels
- ➡ Benefit from lessons learned from charm in Run 2 and use reconstruction from HLT2 for analysis
  - ❖ Get around bandwidth to some level

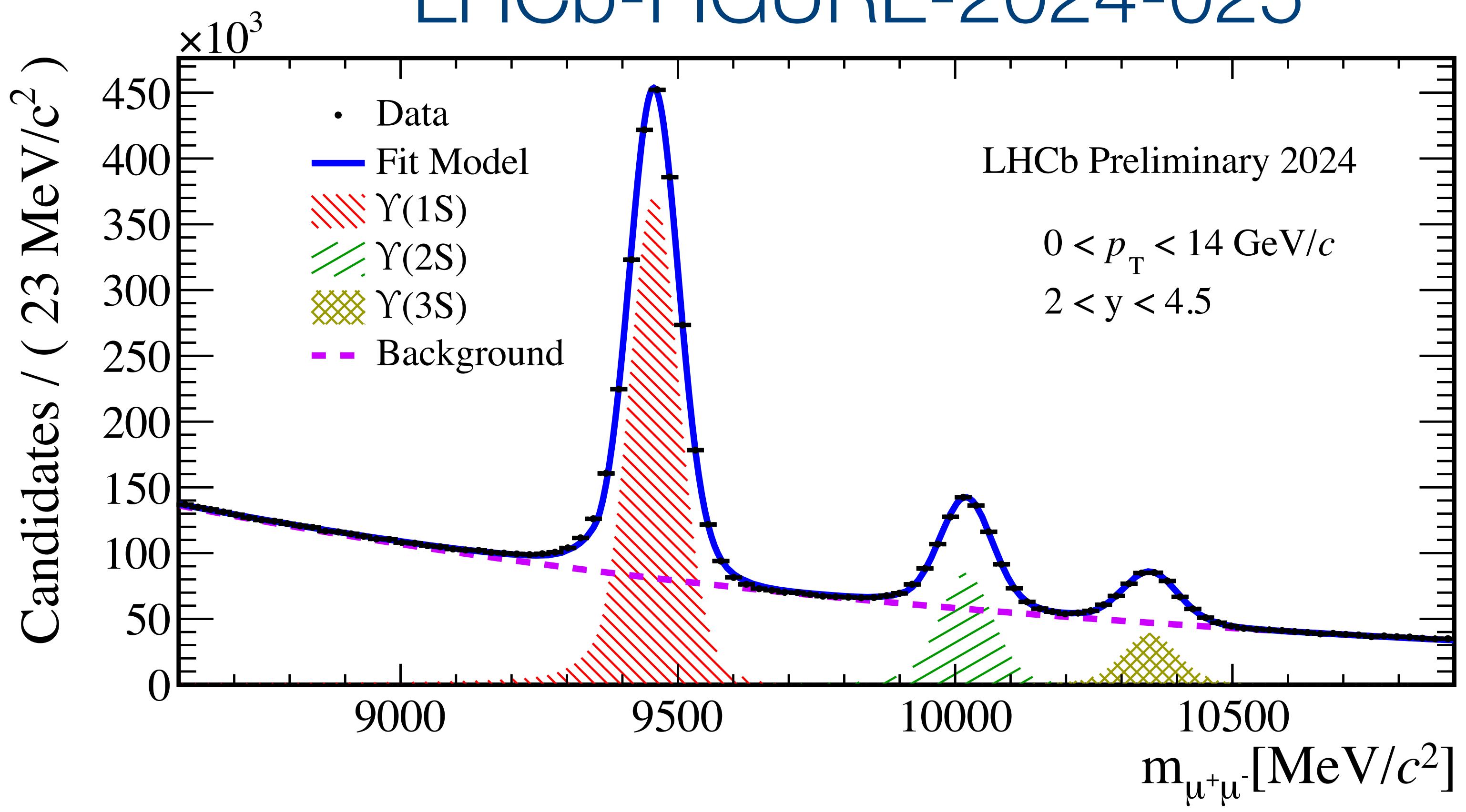




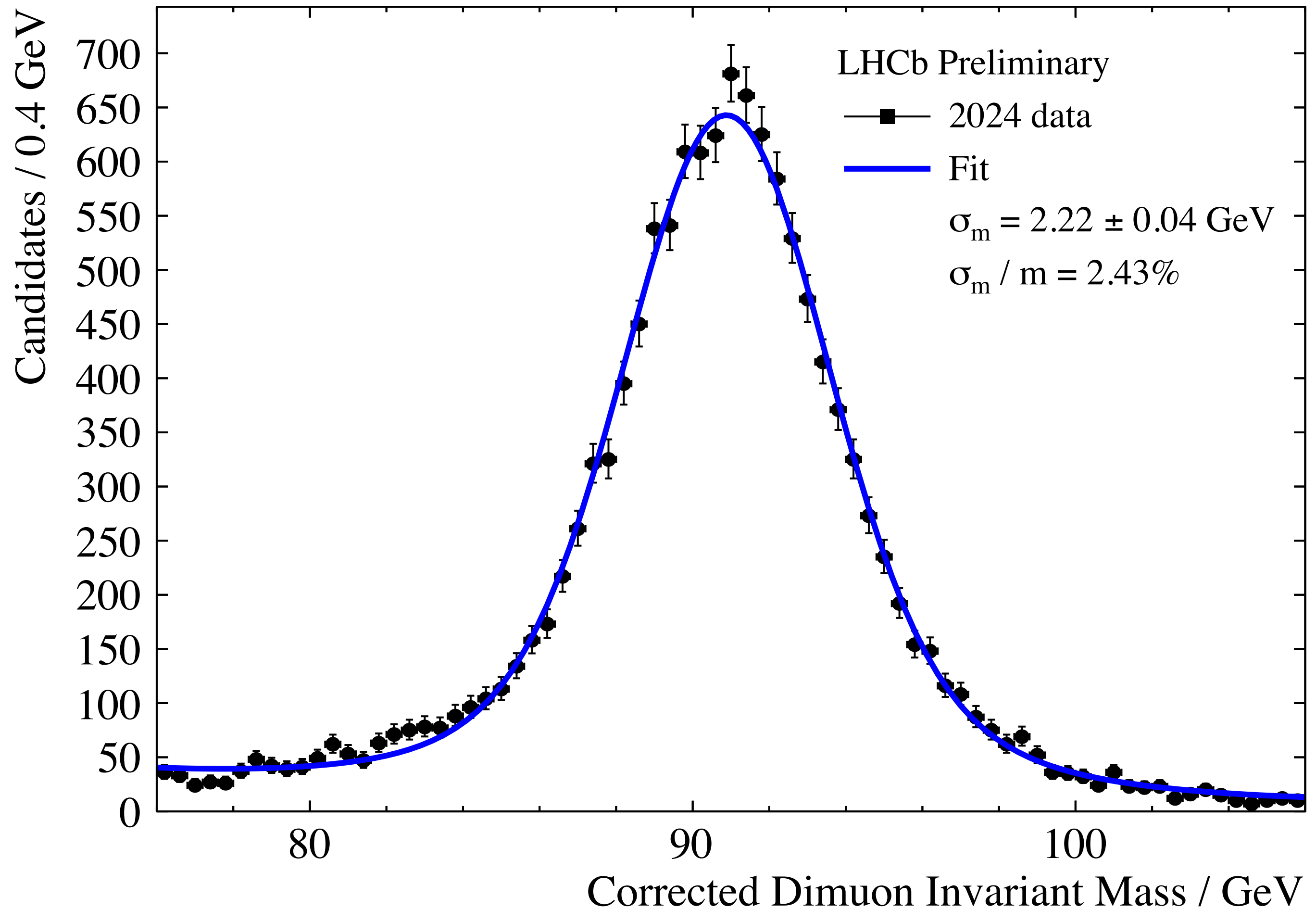
Run 3 prospects

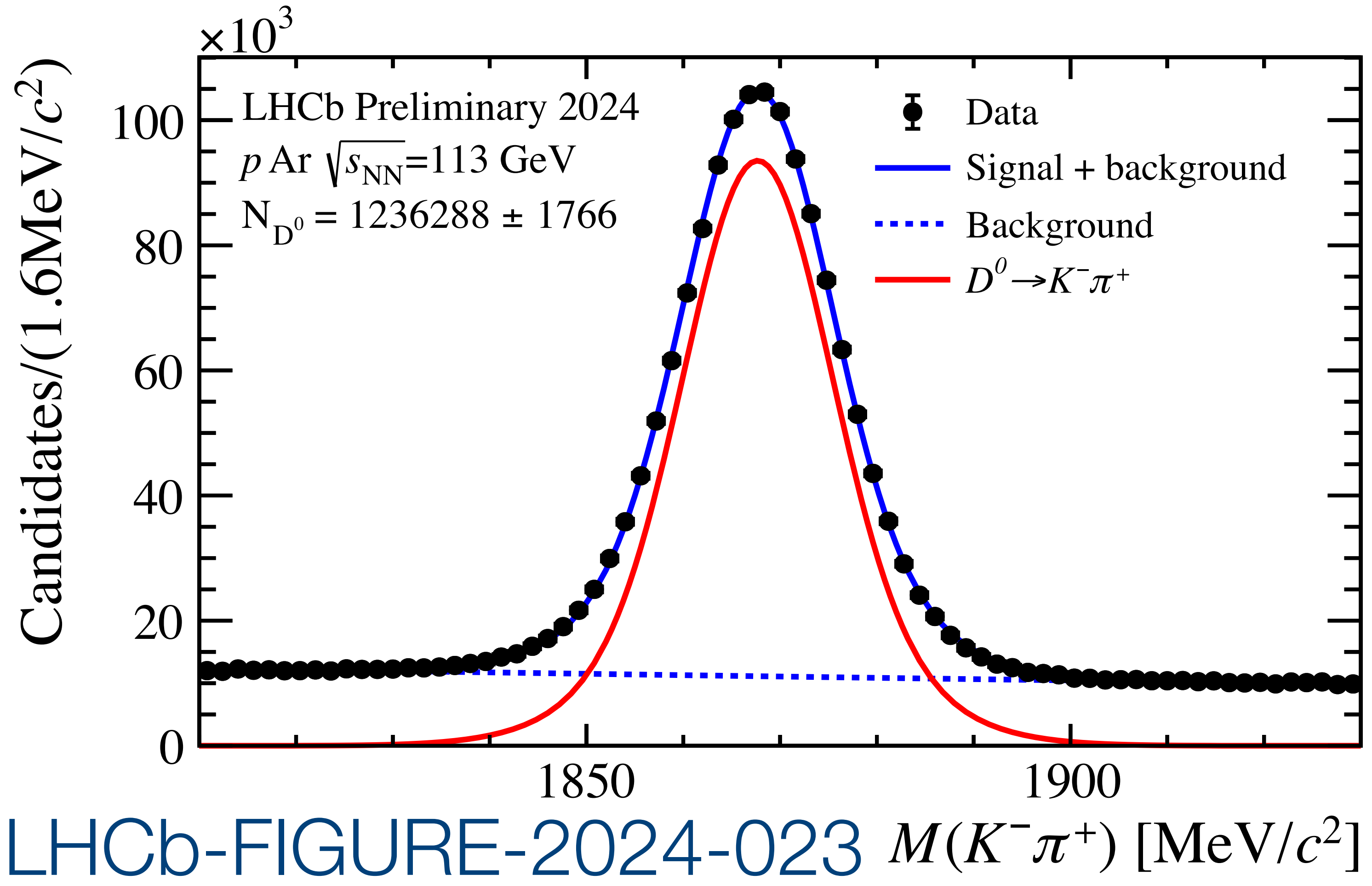
WARWICK
THE UNIVERSITY OF WARWICK

LHCb-FIGURE-2024-025



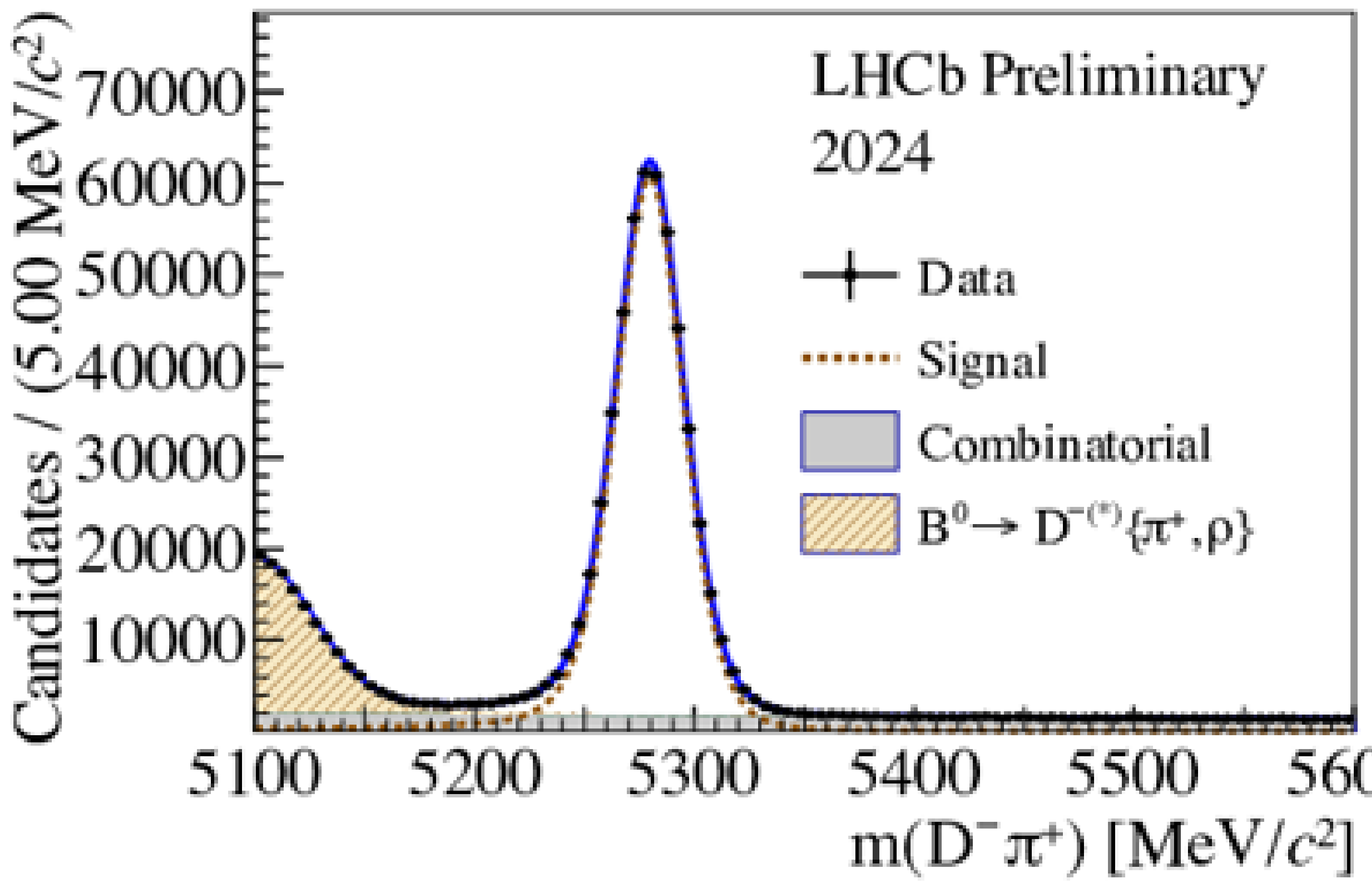
LHCb-FIGURE-2024-020

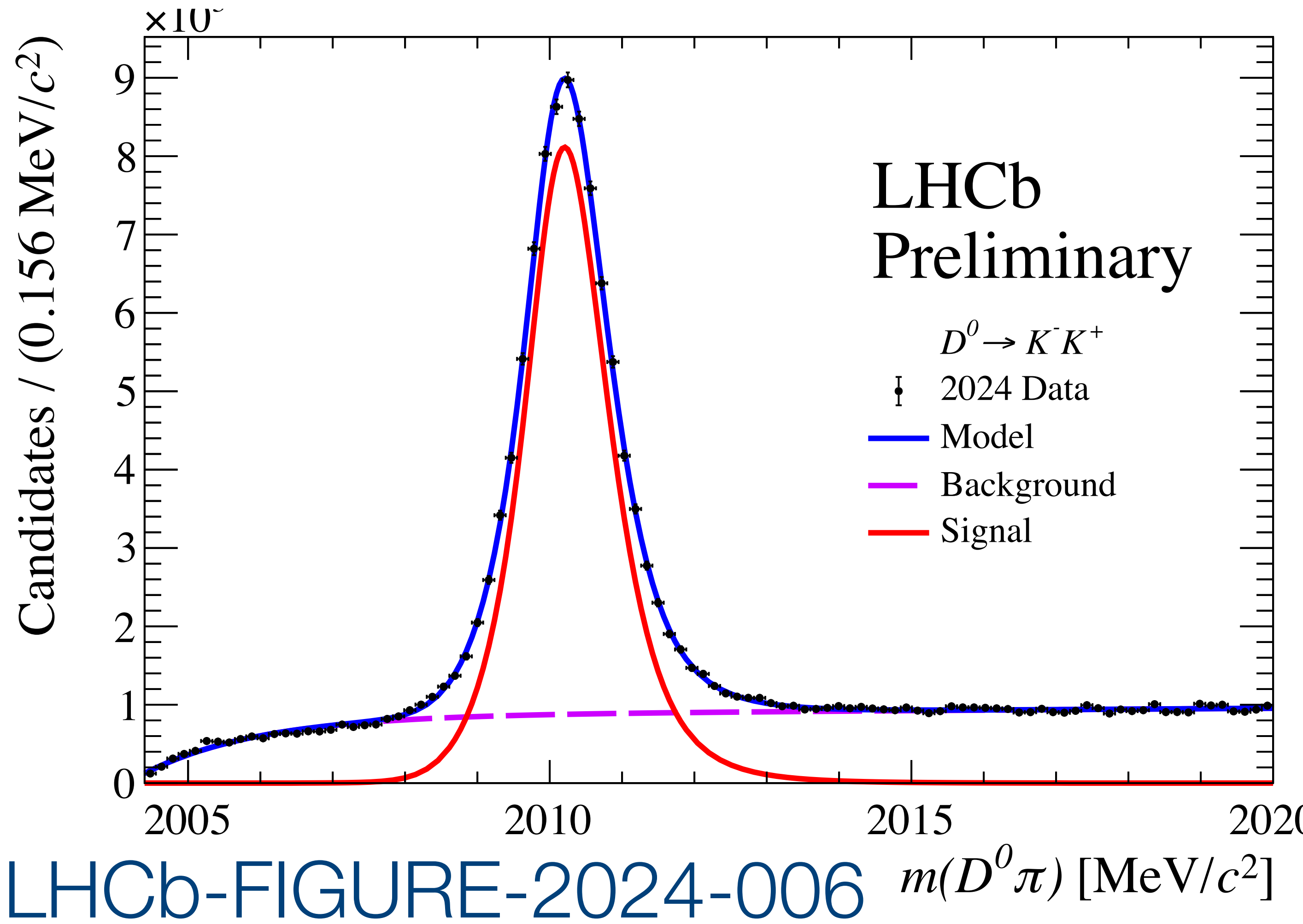




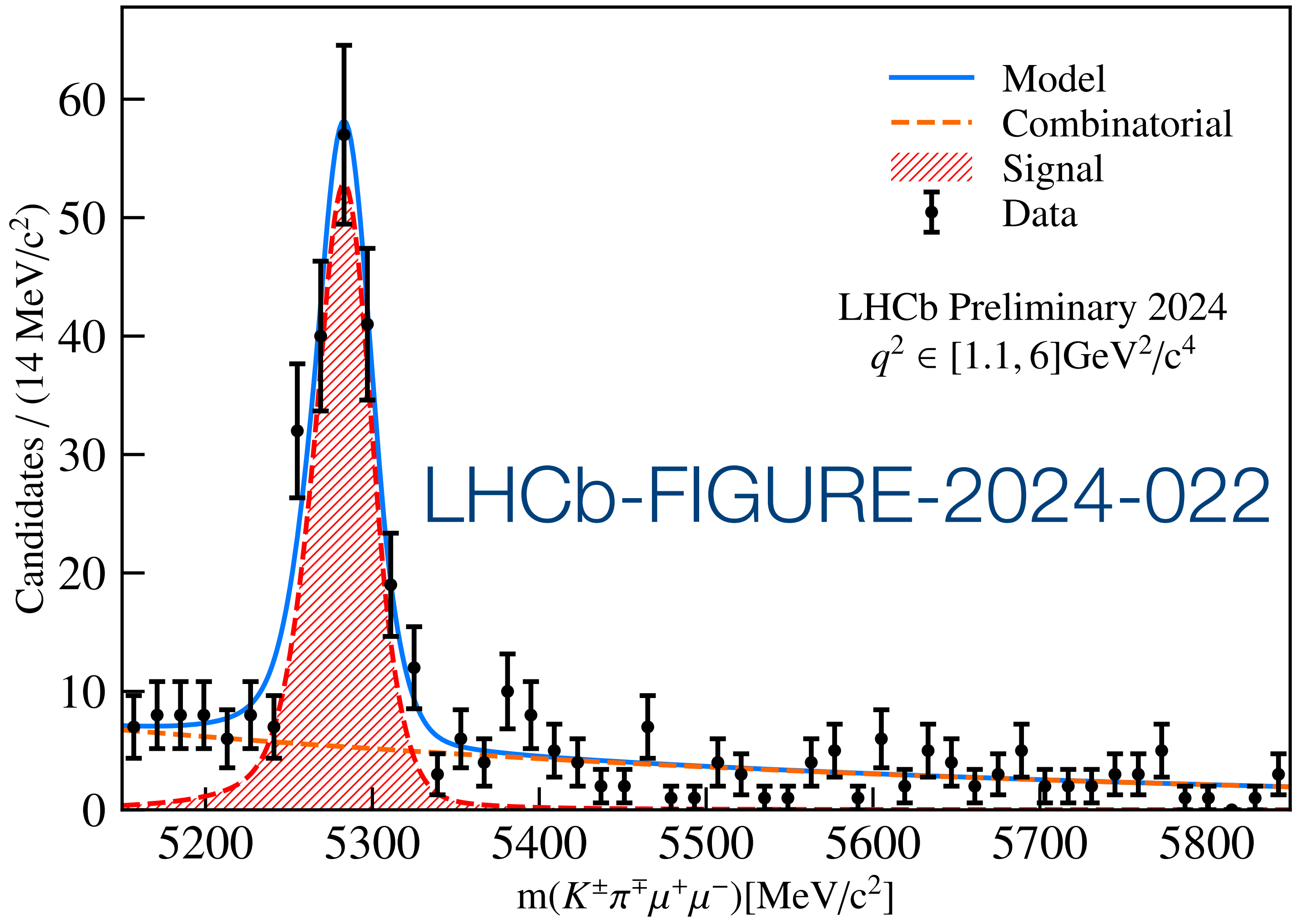
LHCb-FIGURE-2024-023

LHCb-FIGURE-2024-021





LHCb-FIGURE-2024-006

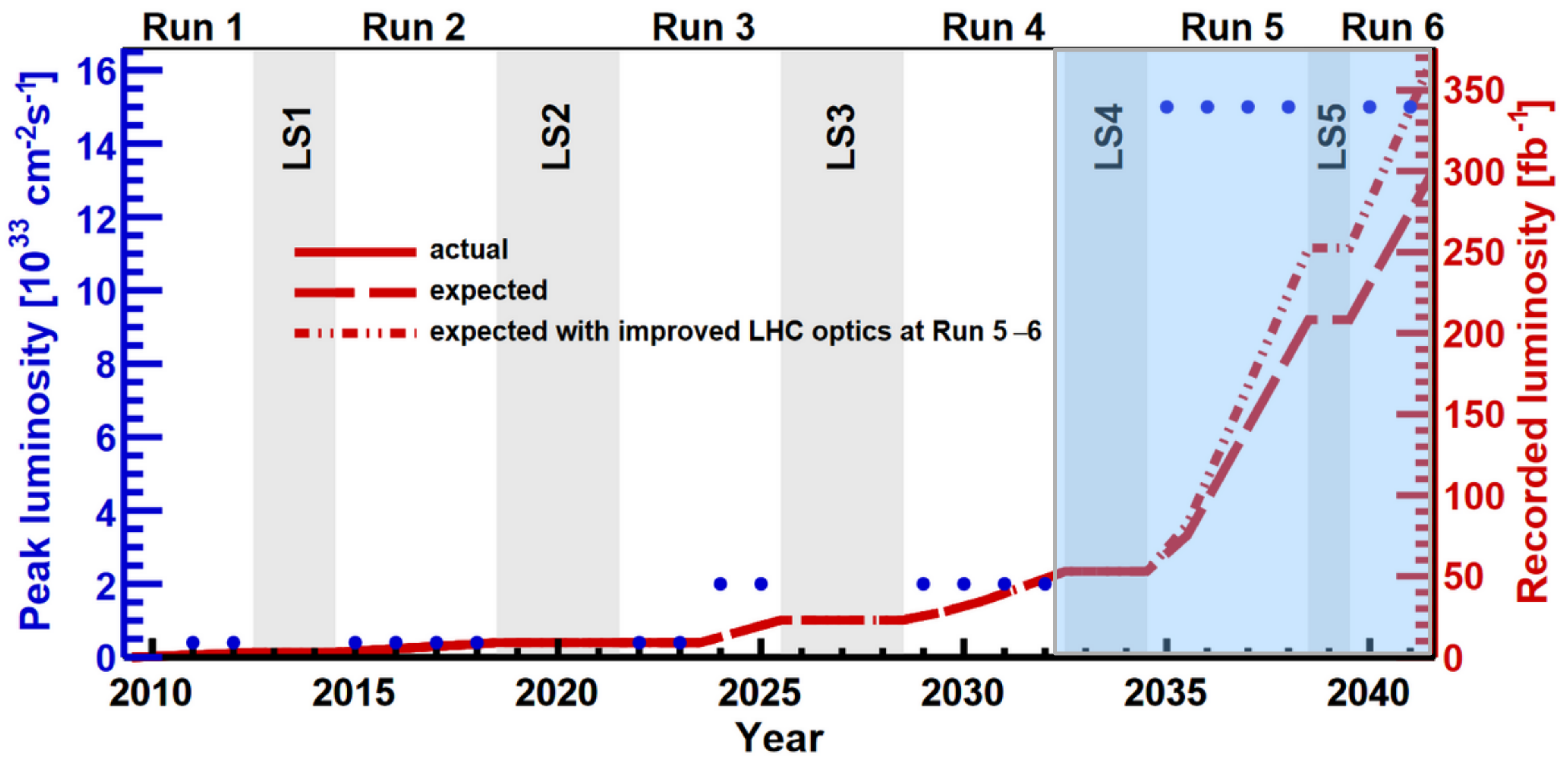


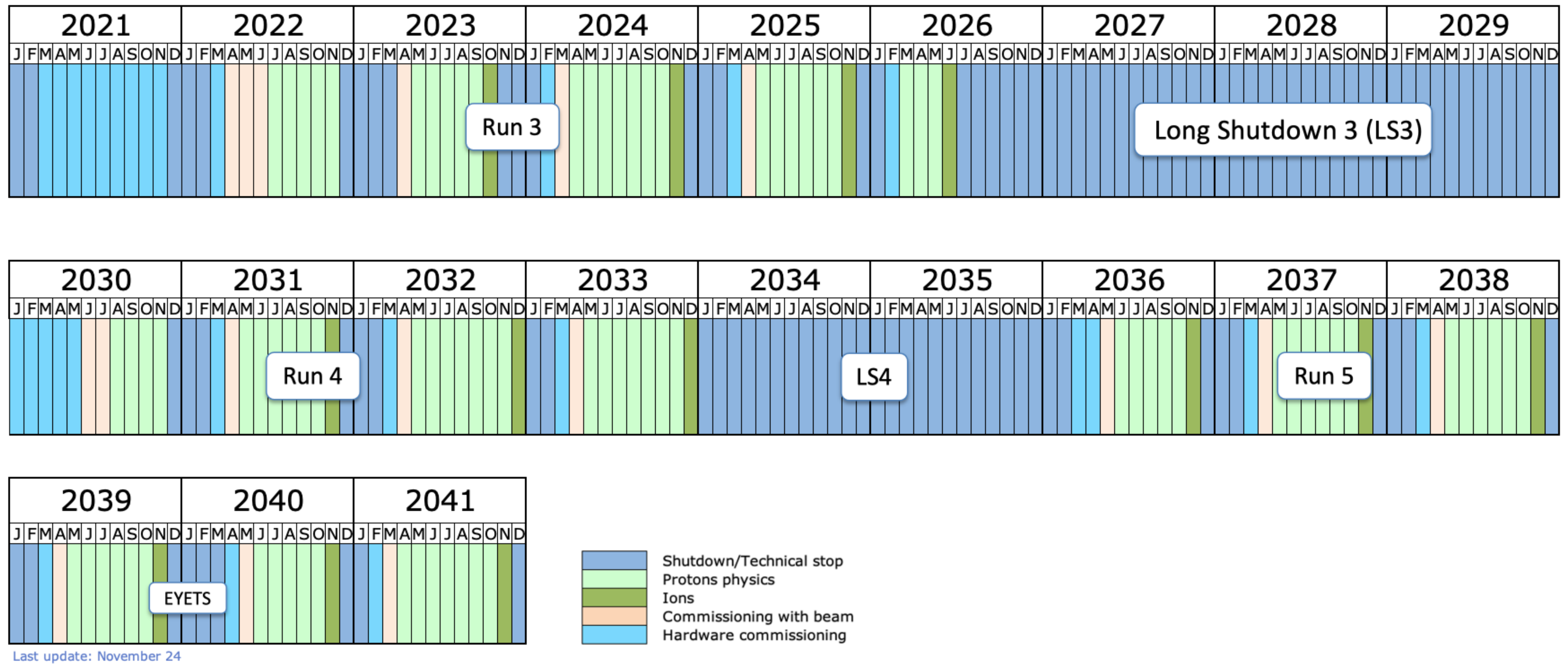
LHCb-FIGURE-2024-022

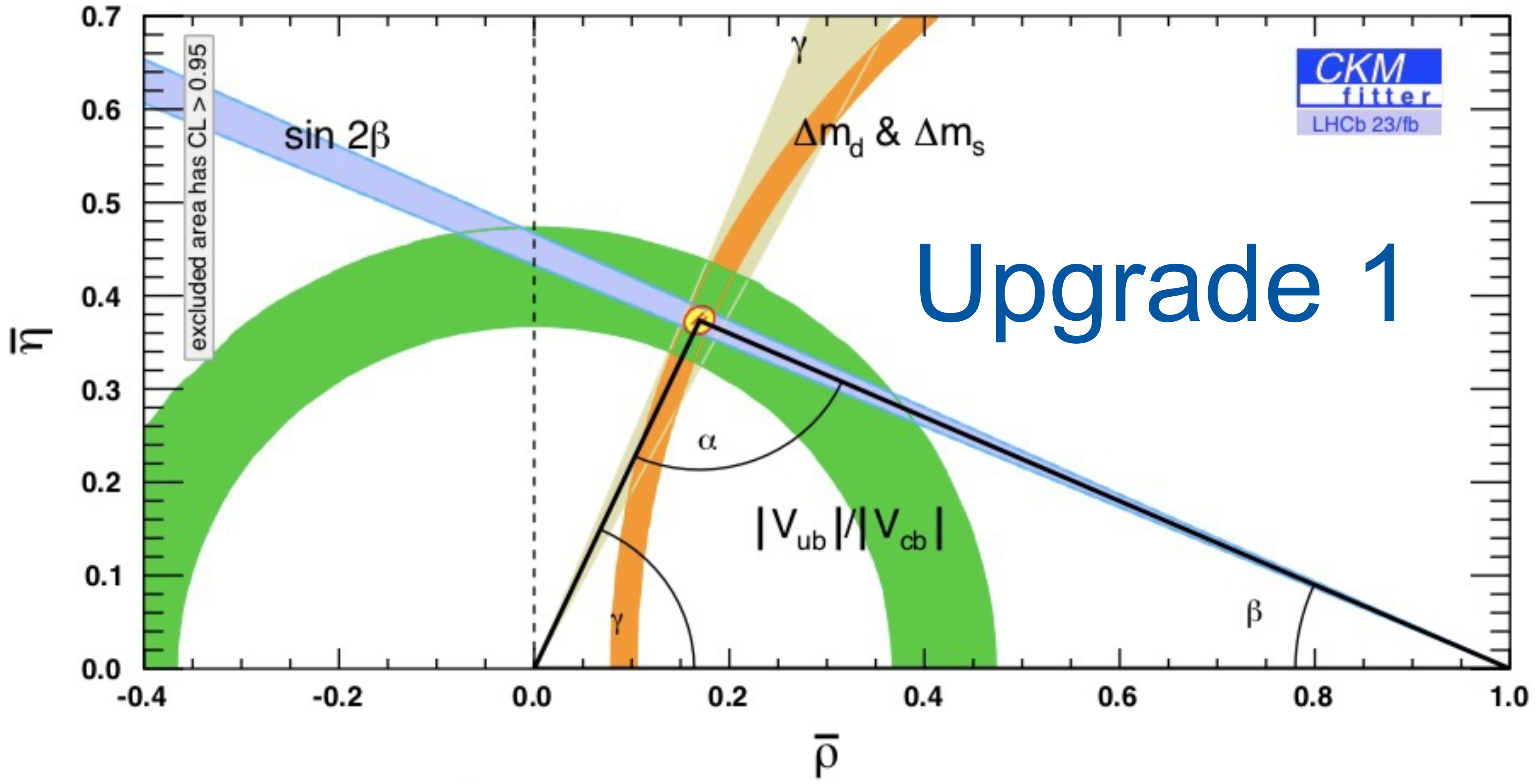
Future upgrades

WARWICK
THE UNIVERSITY OF WARWICK

- ➡ Work ongoing on next upgrade during LS4
- ➡ Aim to increase statistics by another factor of 5-6 with target luminosity of 300 fb^{-1}
- ➡ Ultimate quark flavour physics experiment
- ➡ See presentation by Lennart Uecker







Summary

THE UNIVERSITY OF WARWICK

- ➡ LHCb is specialised experiment with wide physics program
- ➡ With data taken between 2011—2018 we made tremendous progress on quark flavour physics
- ➡ Over the years we enlarged our physics programs finding unique possibilities thanks to forward geometry and flexible trigger
- ➡ So far in Run 3 we doubled our dataset — working hard on analysing new data and expect new results soon
- ➡ Expect at least 5 times larger dataset by the end of Run 4