



Overview of recent LHCb results

Rafael Silva Coutinho

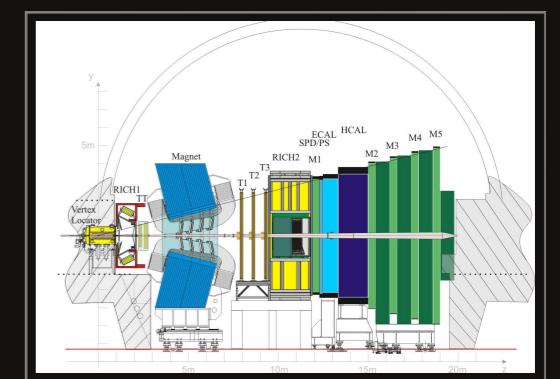
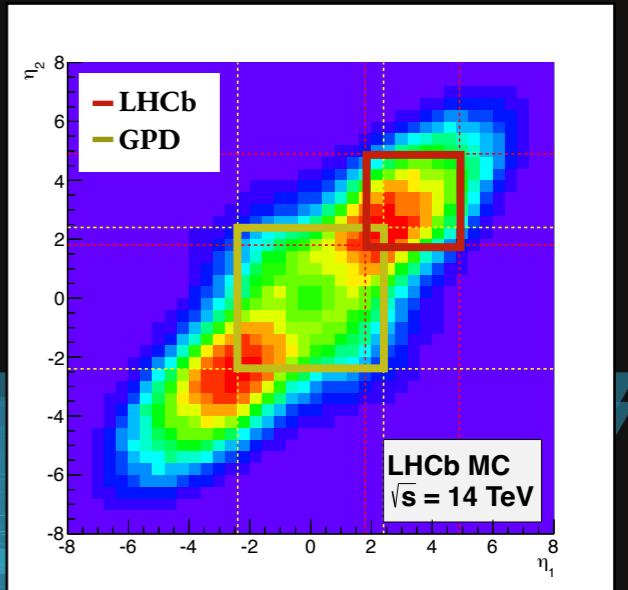
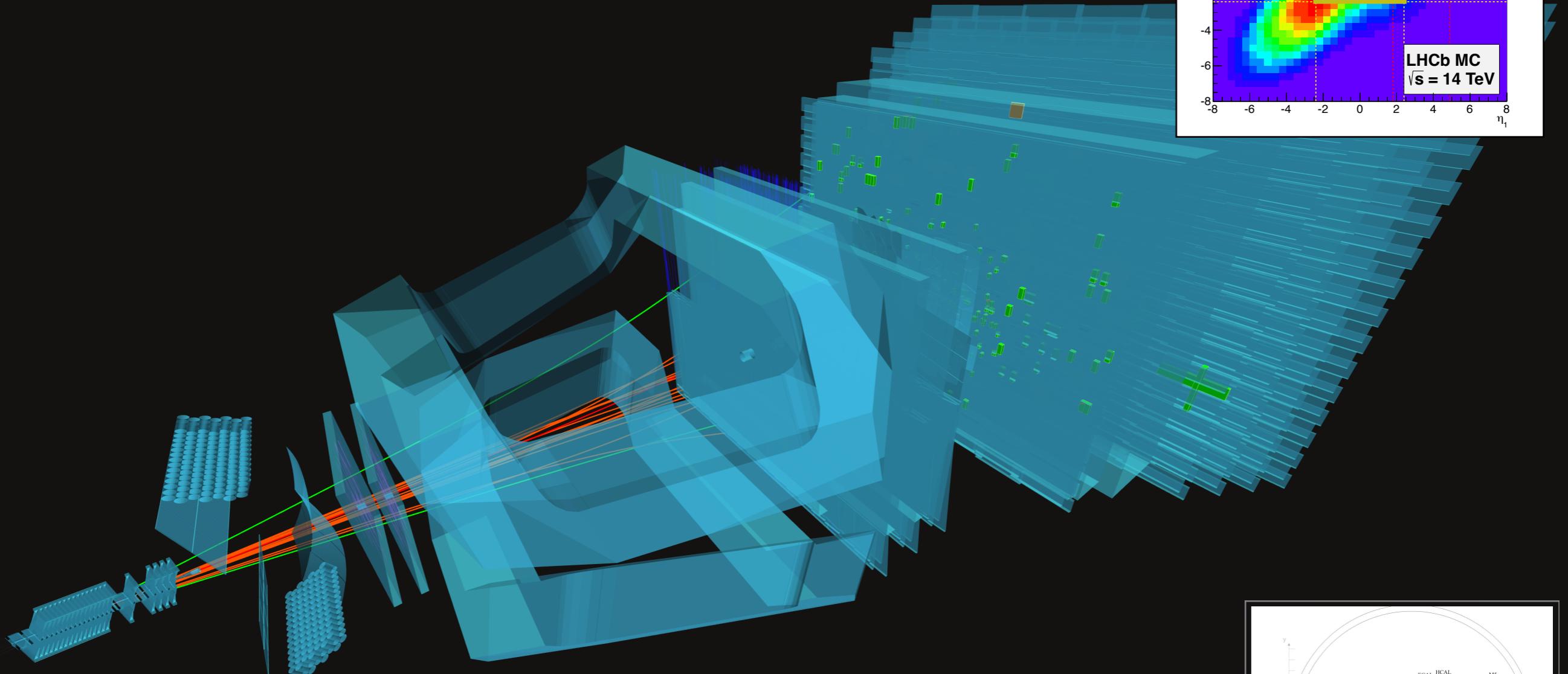
Syracuse University
On behalf of the LHCb Collaboration

**Prospecting for New Physics through Flavor, Dark Matter,
and Machine Learning**

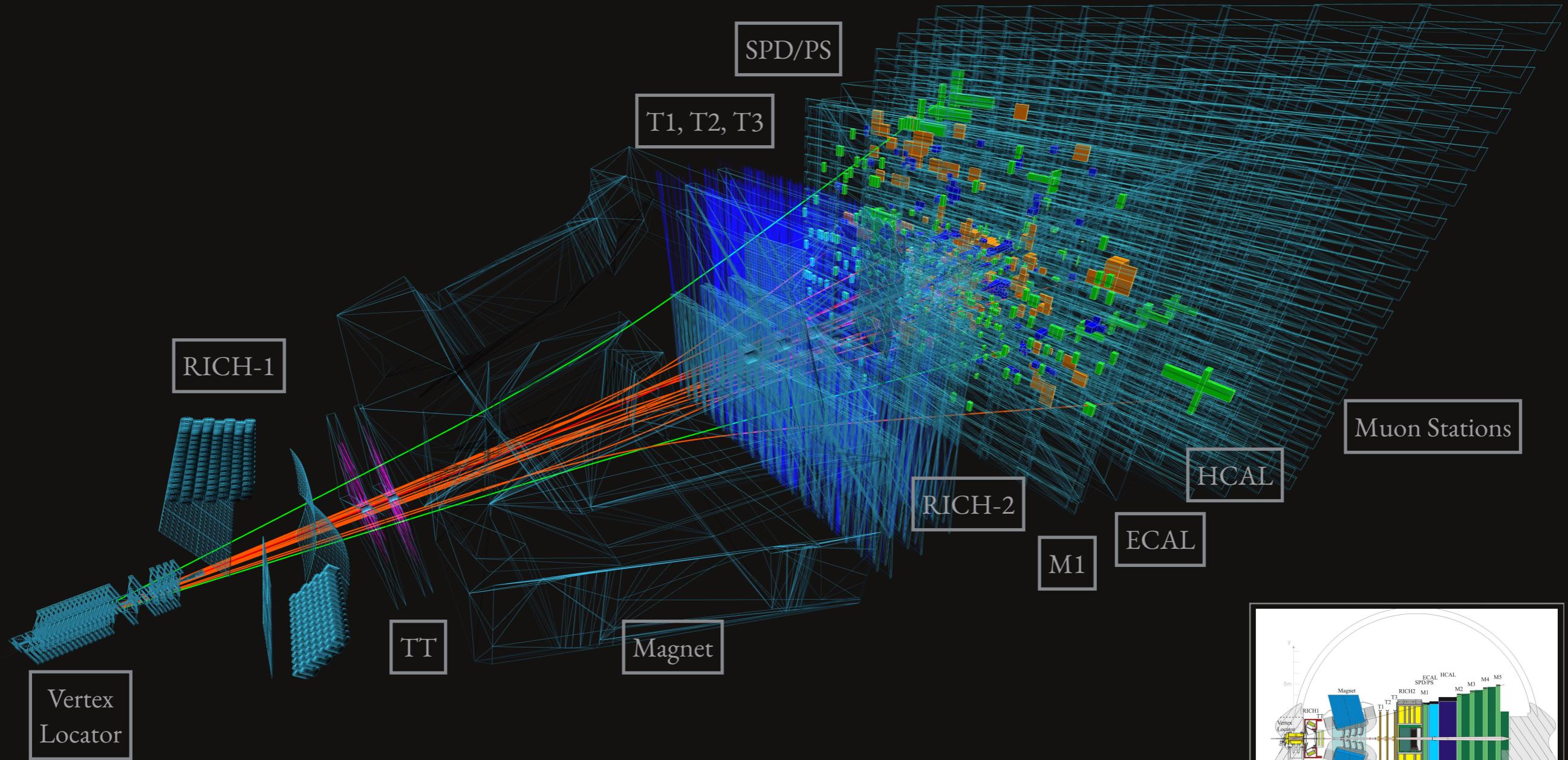
March 28th, 2023



The LHCb experiment

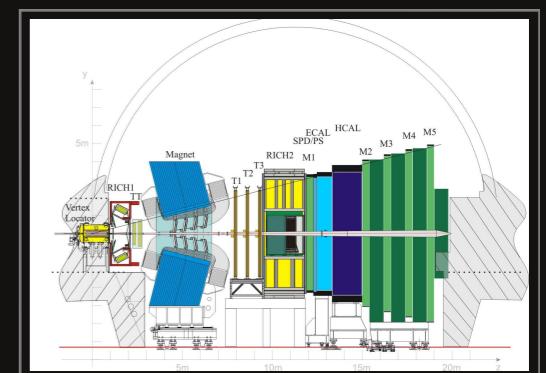


The LHCb experiment

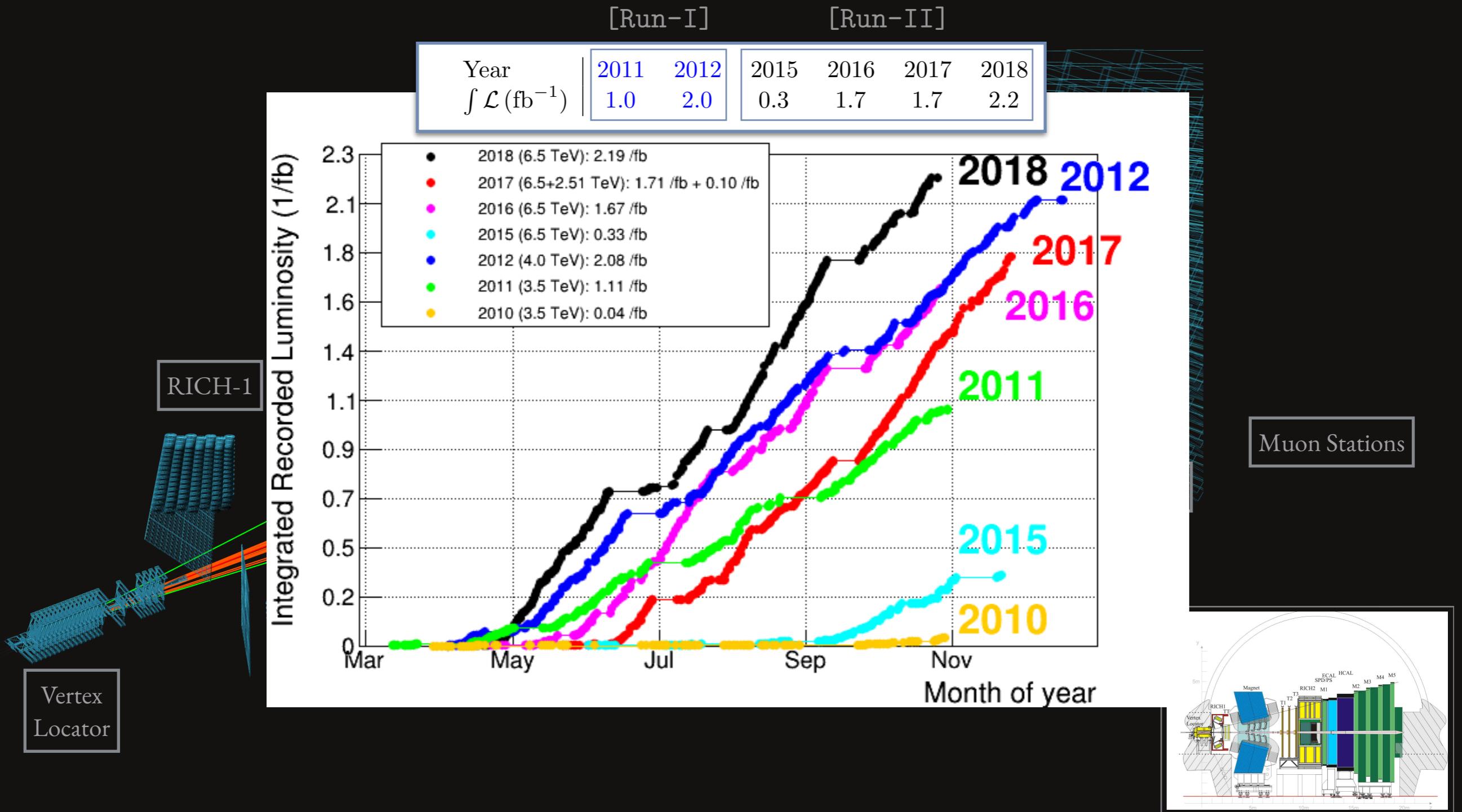


- ◆ Primary vertex, IP [$\approx 200\mu\text{m}$] and τ resolution [≈ 45 fs]
- ◆ Momentum resolution [$\approx 0.5\%$]
- ◆ Particle ID/misID, [e.g. $\epsilon(\text{K}) \approx 95\%$]

[Int. J. Mod. Phys. A30, (2015) 1530022]

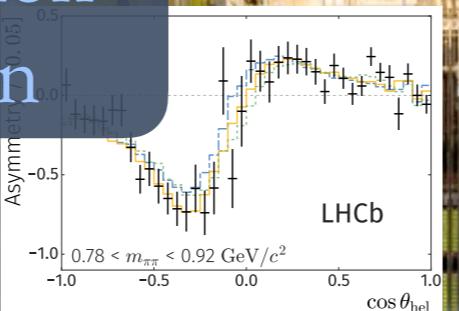


The LHCb experiment

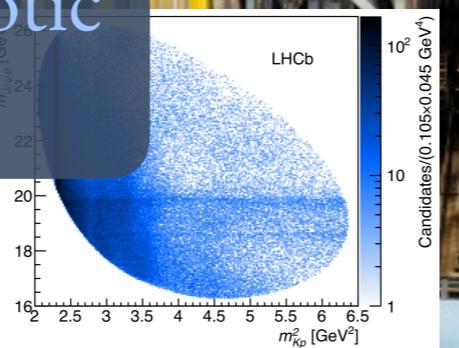


LHCb PHYSICS PROGRAMME

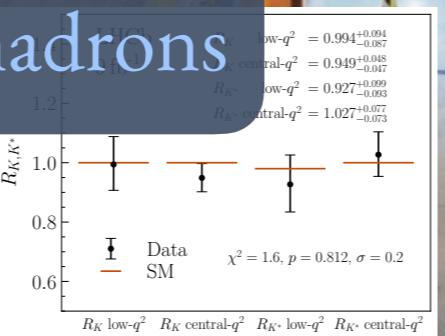
CKM and CP violation
with b and c hadron



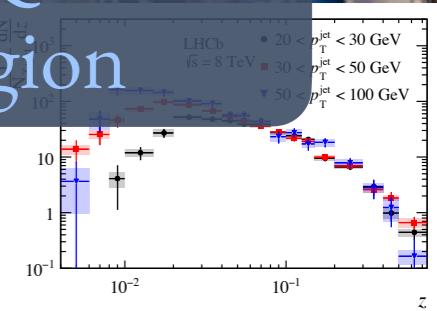
Conventional and exotic
spectroscopy



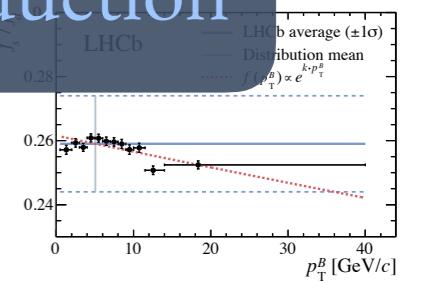
Rare decays of b and c hadrons



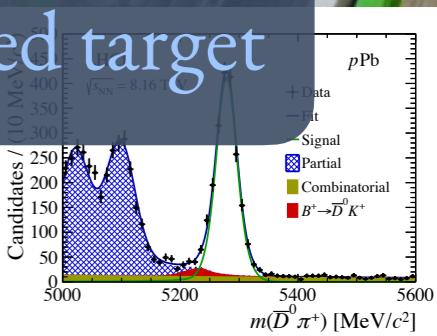
Electroweak and QCD in
the forward region



Heavy quark production

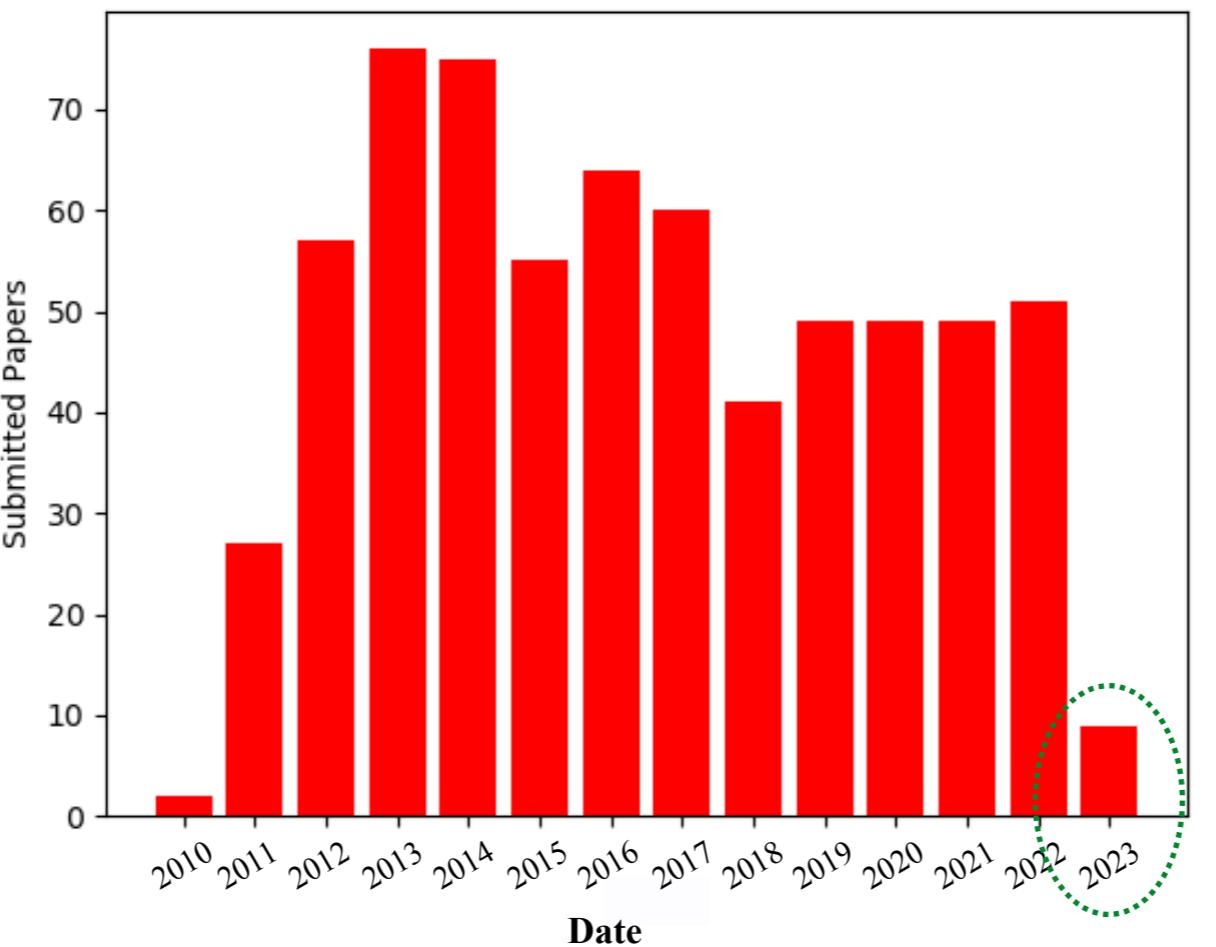


Ion physics and fixed target



LHCb PHYSICS PROGRAMME

How to choose a subset of results?



LHCb PHYSICS PROGRAMME

How to choose a subset of results?

Observation of $J/\psi p$ Resonances Consistent with Pentaquark States in $\Lambda_b^0 \rightarrow J/\psi K^- p$ Decays #1

LHCb Collaboration • Roel Aaij (CERN) et al. (Jul 13, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 072001 • e-Print: [1507.03414 \[hep-ex\]](#)

[pdf](#)

[links](#)

[DOI](#)

[cite](#)

[claim](#)

[reference search](#)

1,533 citations

Spectroscopy (exotics)

Measurement of the ratio of branching fractions $\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \tau^- \bar{\nu}_\tau)/\mathcal{B}(\bar{B}^0 \rightarrow D^{*+} \mu^- \bar{\nu}_\mu)$ #4

LHCb Collaboration • Roel Aaij (CERN) et al. (Jun 29, 2015)

Published in: *Phys.Rev.Lett.* 115 (2015) 11, 111803, *Phys.Rev.Lett.* 115 (2015) 15, 159901 (erratum) • e-Print: [1506.08614 \[hep-ex\]](#)

[pdf](#)

[links](#)

[DOI](#)

[cite](#)

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[reference search](#)

1,137 citations

LFU

Evidence for CP violation in time-integrated $D^0 \rightarrow h^- h^+$ decay rates #23

LHCb Collaboration • R. Aaij (NIKHEF, Amsterdam) et al. (Dec, 2011)

Published in: *Phys.Rev.Lett.* 108 (2012) 111602 • e-Print: [1112.0938 \[hep-ex\]](#)

[pdf](#)

[DOI](#)

[cite](#)

[claim](#)

[reference search](#)

384 citations

CP violation

LHCb HIGHLIGHTS

CKM and CP violation
with b and c hadron

Search for \not{CP} in $D^+_{(s)} \rightarrow K^- K^+ K^+$

[arXiv:2303.04062, Submitted to JHEP]

Search for \not{CP} in $B_s^0 \rightarrow \phi\phi$

[LHCb-PAPER-2023-001, In preparation]

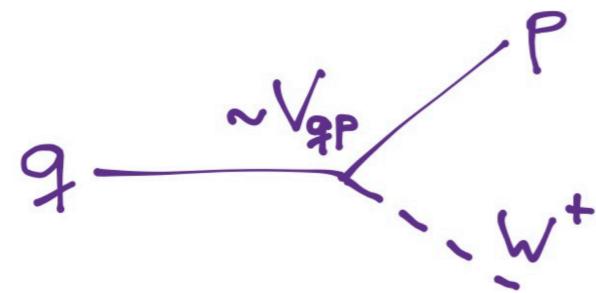


Lison Bernet
[@lisbouche - Rencontres de Moriond]

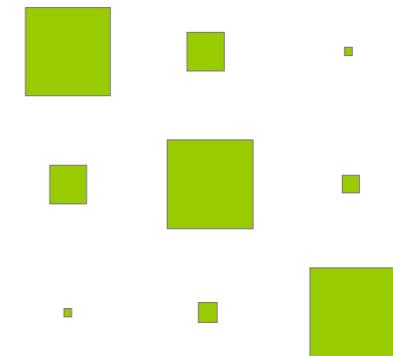


CP violation in the SM

QUARK-MIXING MATRIX [CKM]: $[dsb]_{\text{flavour}} = V_{\text{CKM}} [dsb]_{\text{mass}}$



$$V_{\text{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



DESCRIBED BY 4 INDEPENDENT PARAMETERS, IN PARTICULAR A **SINGLE** COMPLEX PHASE

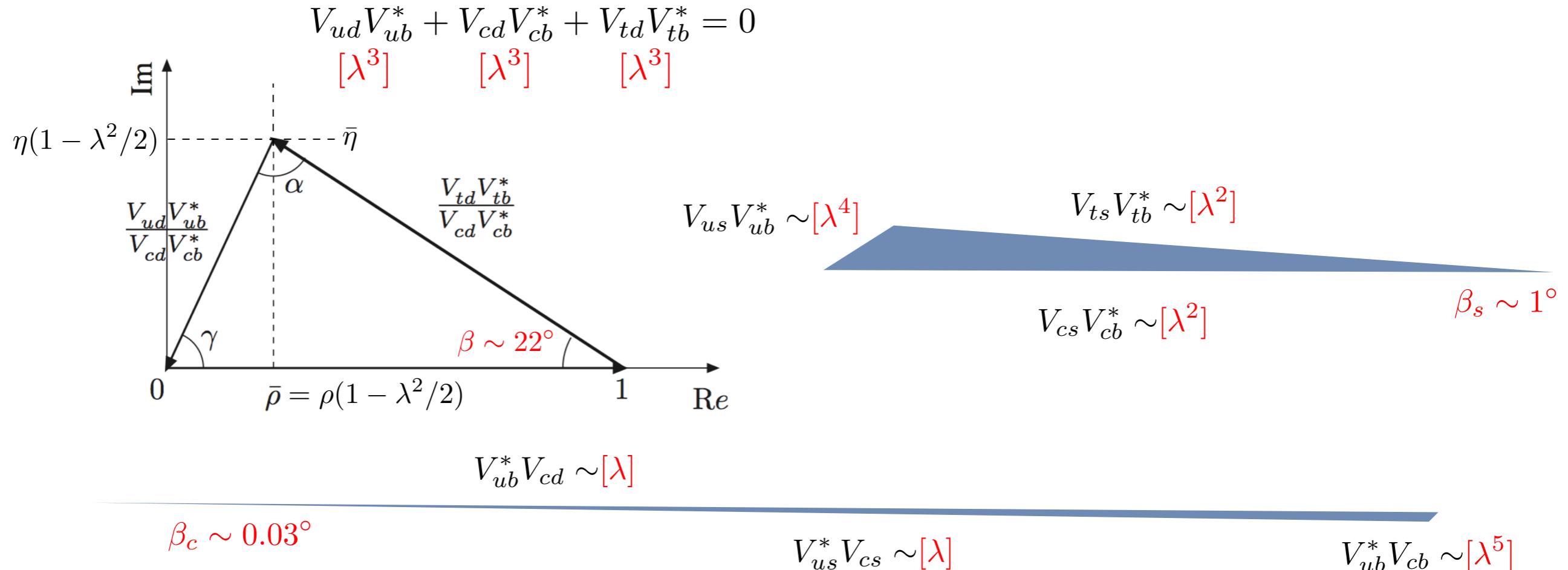
$$V_{\text{CKM}} \cong \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda \left[1 + A^2\lambda^4 \left(\rho + i\eta - \frac{1}{2} \right) \right] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 (1 + 4A^2) & A\lambda^2 \\ A\lambda^3 \left[1 - (\rho + i\eta) \left(1 - \frac{1}{2}\lambda^2 \right) \right] & -A\lambda^2 \left[1 + \lambda^2 \left(\rho + i\eta - \frac{1}{2} \right) \right] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$\begin{matrix} [\beta_c] \\ [\beta] \end{matrix} \qquad \qquad \qquad \begin{matrix} [\gamma] \\ A\lambda^3(\rho - i\eta) \end{matrix}$

Unitarity triangles

UNITARITY OF CKM MATRIX, I.E. $V_{CKM}^+ V_{CKM} = V_{CKM} V_{CKM}^+ = 1$

- ◆ Triangle openness indicates how large CP expected



ALL TRIANGLES HAVE SAME SURFACE AREA [representative plots only]



Search for CP violation at LHCb



IS AN IDEAL PLACE FOR CKM AND CP VIOLATION MEASUREMENTS IN BEAUTY AND CHARM DECAYS

MEASUREMENTS OF γ IS ONE OF THE KEY GOALS AT LHCb

$$B^\pm \rightarrow [K^\mp \pi^\pm \pi^\pm \pi^\mp]_D h^\pm \quad [\text{arXiv:2209.03692, Submitted to JHEP}]$$

$$\gamma = (54.8^{+6.0}_{-5.8}{}^{+0.6}_{-0.6}{}^{+6.7}_{-4.3})^\circ$$

$$B^\pm \rightarrow [h^+ h^- \pi^+ \pi^-]_D h'^\pm \quad [\text{arXiv:2301.10328, Submitted to Eur. Phys. J. C}]$$

$$\gamma = (116^{+12}_{-14})^\circ \quad \begin{array}{l} \text{[Precision/results might be affected by upcoming charm} \\ \text{model-independent measurements]} \end{array}$$

CP VIOLATION IN THE CHARM SECTOR IS PREDICTED TO BE SMALL (10^{-4} - 10^{-3})

FIRST CP VIOLATION IN DECAY OF $D^0 \rightarrow h^+ h^-$ OPENED DEBATE ON QCD CALCULATIONS
[PRL 122 (2019) 211803]

CP VIOLATION IN DECAY OF $D^0 \rightarrow \pi^- \pi^+$ AT 3.8σ LEVEL

[arXiv:2209.03179, Submitted to PRL]

FURTHER STUDIES ON THE CHARM SECTOR ARE CRUCIAL

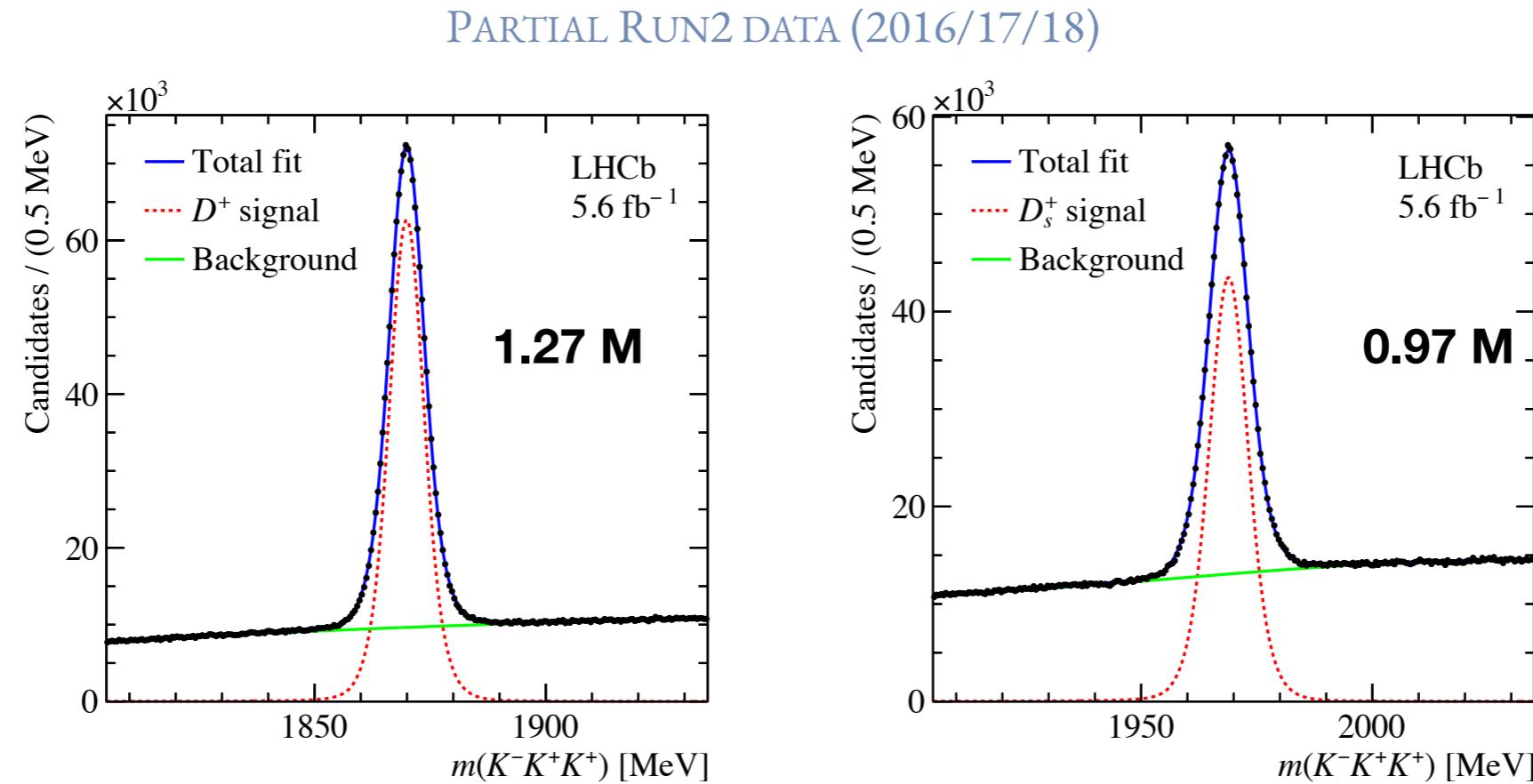
Search for CP violation charm three-body decays

[arXiv:2303.04062, Submitted to JHEP]

MULTIBODY DECAYS: LOCAL ANISOTROPIES CAN ENHANCE SENSITIVITY TO CP VIOLATION

$D_s^+ \rightarrow K^- K^+ K^+$: CABIBBO-SUPPRESSED → MIGHT MANIFEST CP VIOLATION EFFECTS

$D^+ \rightarrow K^- K^+ K^+$: DOUBLY-CABIBBO-SUPPRESSED → NO CP VIOLATION IN THE SM



Search for CP violation charm three-body decays

[arXiv:2303.04062, Submitted to JHEP]

DALITZ PLOT DIVIDED IN 21 BINS (INSPIRED IN THE UNDERLYING DYNAMICS)

VARIATION OF THE SIMPLE ANISOTROPY FORMULA [PRD 78 (2008) 051102, PRD 80 (2009) 096006]

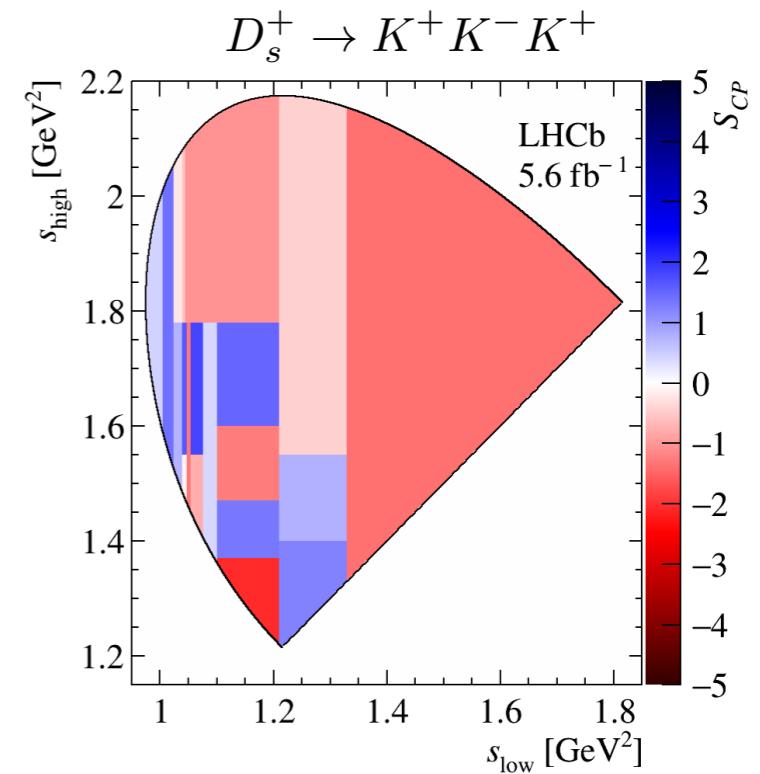
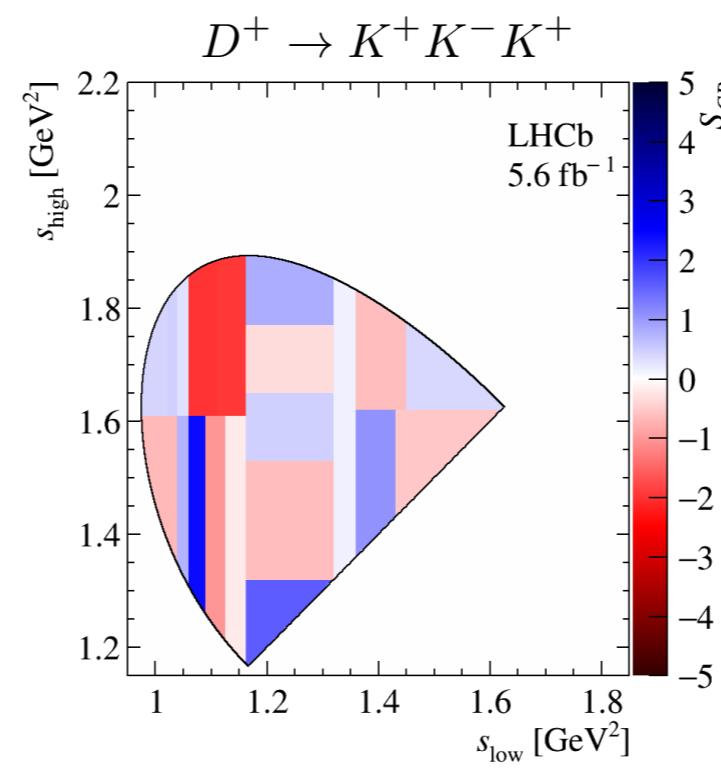
$$S_{CP}^i = \frac{N^i(D_{(s)}^+) - \alpha N^i(D_{(s)}^-)}{\sqrt{\alpha (\delta_{N^i(D_{(s)}^+)}^2 + \delta_{N^i(D_{(s)}^-)}^2)}} \quad \chi^2 = \sum_i (S_{CP}^i)^2$$

α takes into account global nuisance asymmetries

D_s^+ mode: p -value = 13.3%

D^+ mode: p -value = 31.6%

NO LOCAL CP
VIOLATION OBSERVED

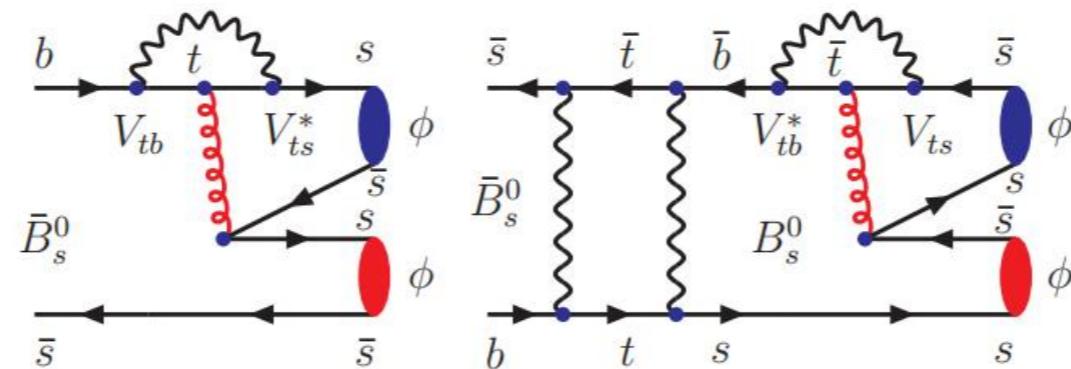


CP violation in $B_s^0 \rightarrow \phi\phi$ decays

[*LHCb-PAPER-2023-001*, In preparation]

FLAVOR-TAGGED TIME-DEPENDENT ANGULAR ANALYSIS OF THE DECAY $B_s^0 \rightarrow \phi\phi$

CP VIOLATION ARISES FROM THE INTERFERENCE BETWEEN DECAY AND MIXING,
CHARACTERIZED BY PHASE $\phi_s^{s\bar{s}s}$ AND $|\lambda|$ PARAMETER



SM PREDICTS NO DEPENDENCE ON THE POLARIZATION

- ▶ CP phase: $\phi_i = \phi_s^{s\bar{s}s} \approx 0$
 - ▶ Direct CP violation parameter: $|\lambda_i| = |\bar{A}_i/A_i| = |\lambda| \approx 1$
- ↑
No CPV in mixing

ANGULAR ANALYSIS REQUIRED TO DISENTANGLE THE THREE POLARIZATIONS OF $B \rightarrow VV$ DECAYS

- ▶ (0, CP even), (||, CP even), (⊥, CP odd)

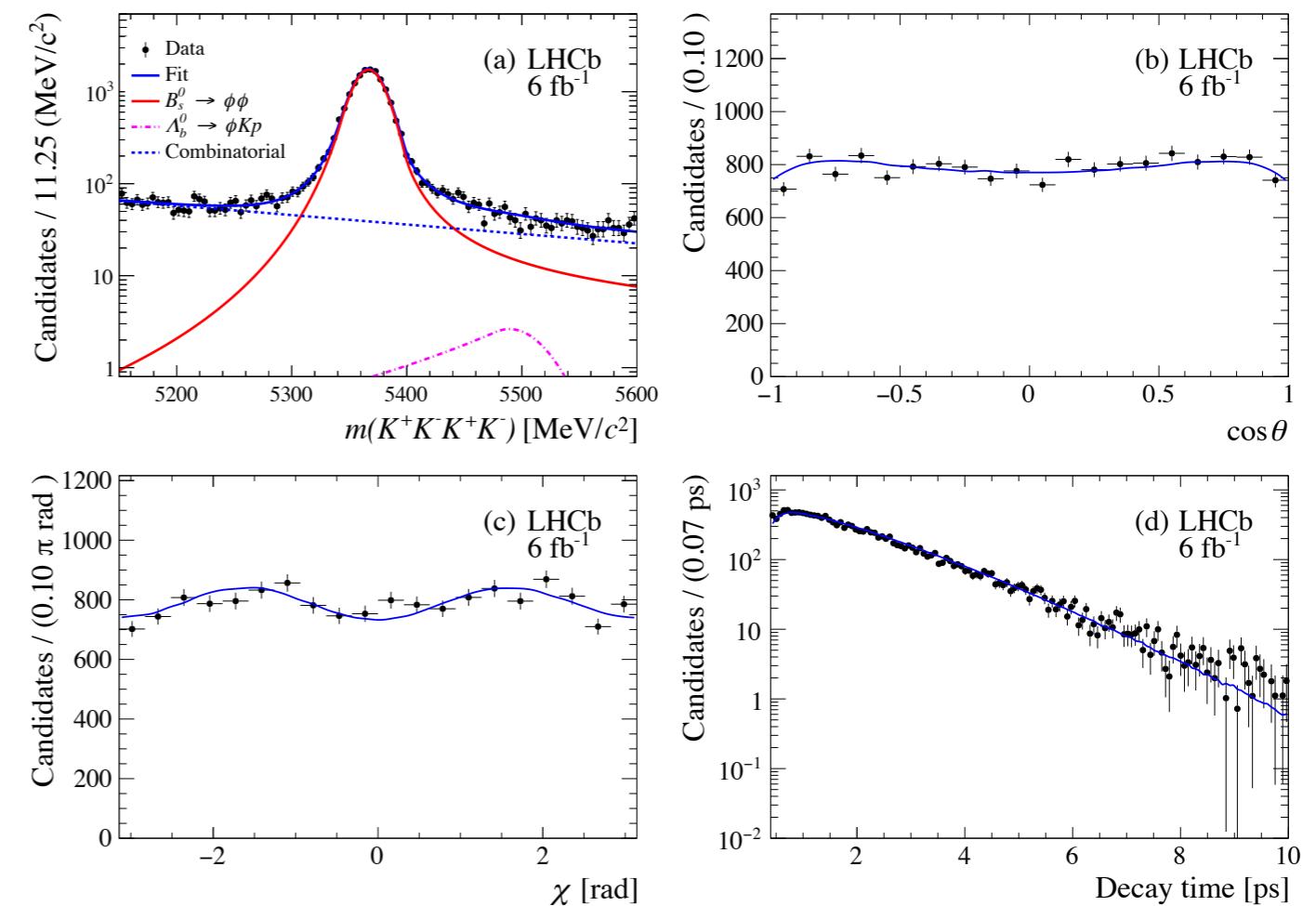
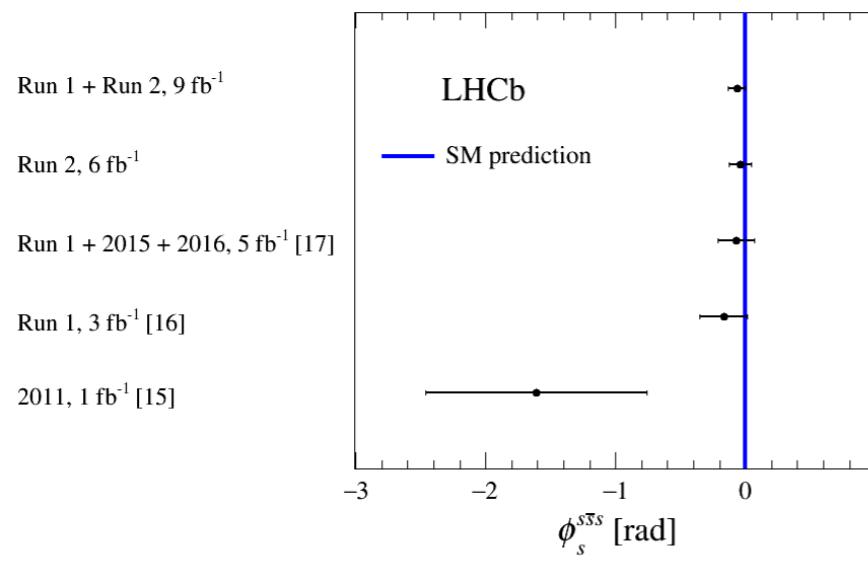
CP violation in $B_s^0 \rightarrow \phi\phi$ decays

[LHCb-PAPER-2023-001, In preparation]

RUN 2 DATA, WHICH LATER IS COMBINED WITH RUN 1 RESULTS

NO DIFFERENCE OBSERVED BETWEEN POLARIZATIONS

$$\begin{array}{ll}
 \phi_{s,0} = -0.18 \pm 0.09 \text{ rad} & |\lambda_0| = 1.02 \pm 0.17 \\
 \phi_{s,\parallel} - \phi_{s,0} = 0.12 \pm 0.09 \text{ rad} & |\lambda_\perp/\lambda_0| = 0.97 \pm 0.22 \\
 \phi_{s,\perp} - \phi_{s,0} = 0.17 \pm 0.09 \text{ rad} & |\lambda_\parallel/\lambda_0| = 0.78 \pm 0.21
 \end{array}$$

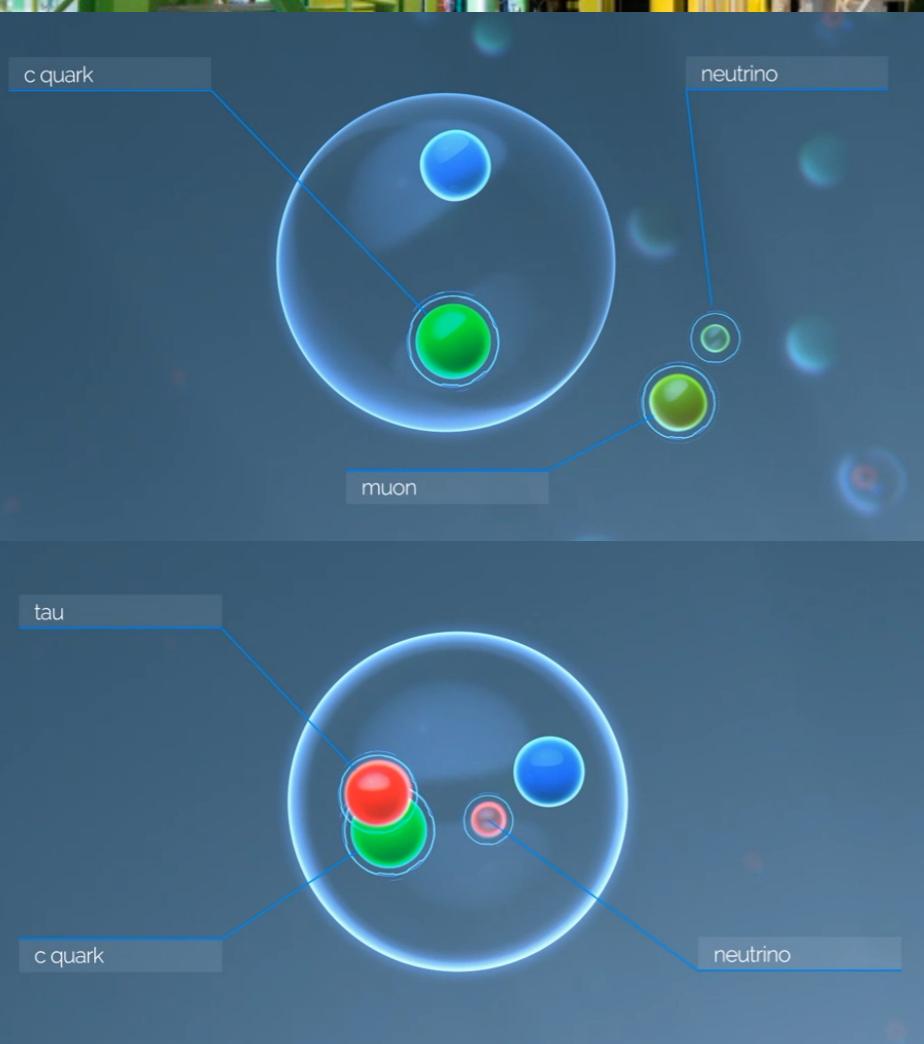


MOST PRECISE MEASUREMENT TO DATE, IN AGREEMENT WITH THE SM

LHCb HIGHLIGHTS

Lepton Flavor Universality?

A long stand anomaly



arXiv:2303.02886
[Submitted to PRL]

LHCb-PAPER-2022-052
[In preparation]

[Results in neutral currents in the backup]

Lepton Flavor Universality as a probe for *New Physics*

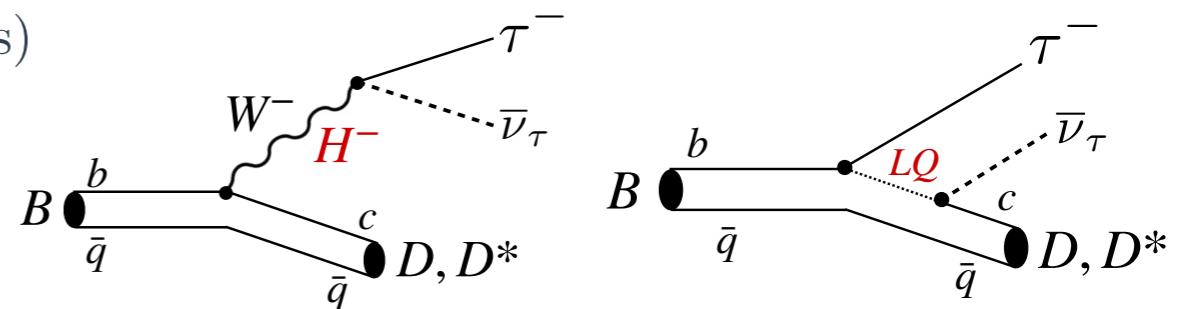
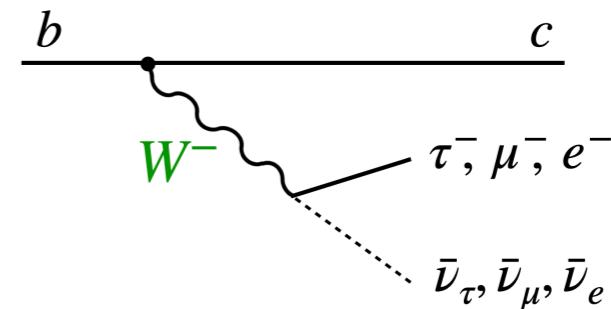
IN THE **STANDARD MODEL**, ELECTROWEAK COUPLINGS TO EACH LEPTON GENERATION ARE IDENTICAL (EXCEPT YUKAWA)

COUPLINGS AFFECTED BY **NEW PHYSICS** (NP) CONTRIBUTIONS

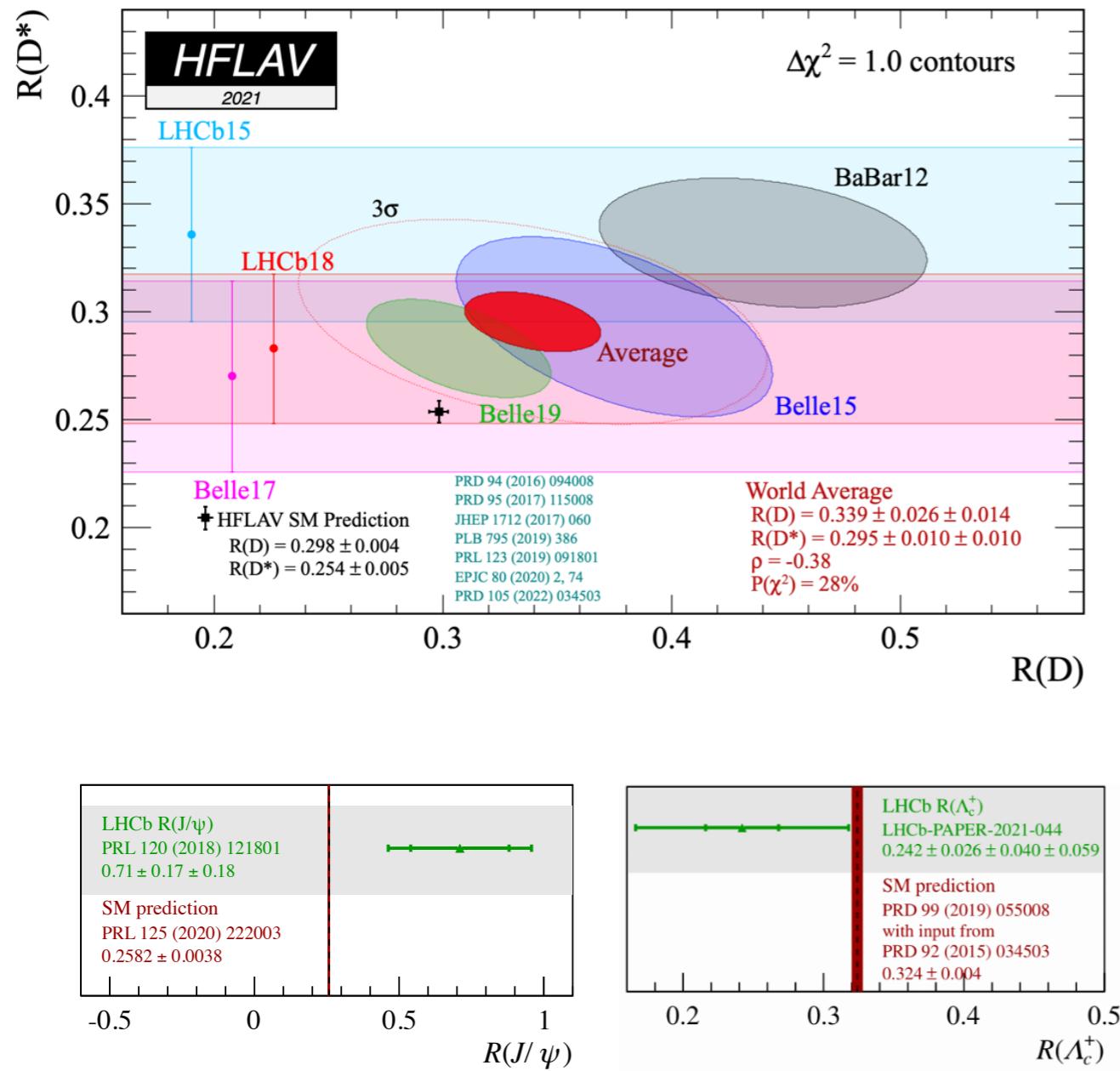
RATIO OF BRANCHING RATIO IDEAL LFU PROBES

$$R(\mathcal{H}_c) = \frac{\mathcal{B}(\mathcal{H}_b \rightarrow \mathcal{H}_c \tau \nu_\tau)}{\mathcal{B}(\mathcal{H}_b \rightarrow \mathcal{H}_c \ell' \nu_{\ell'})}$$

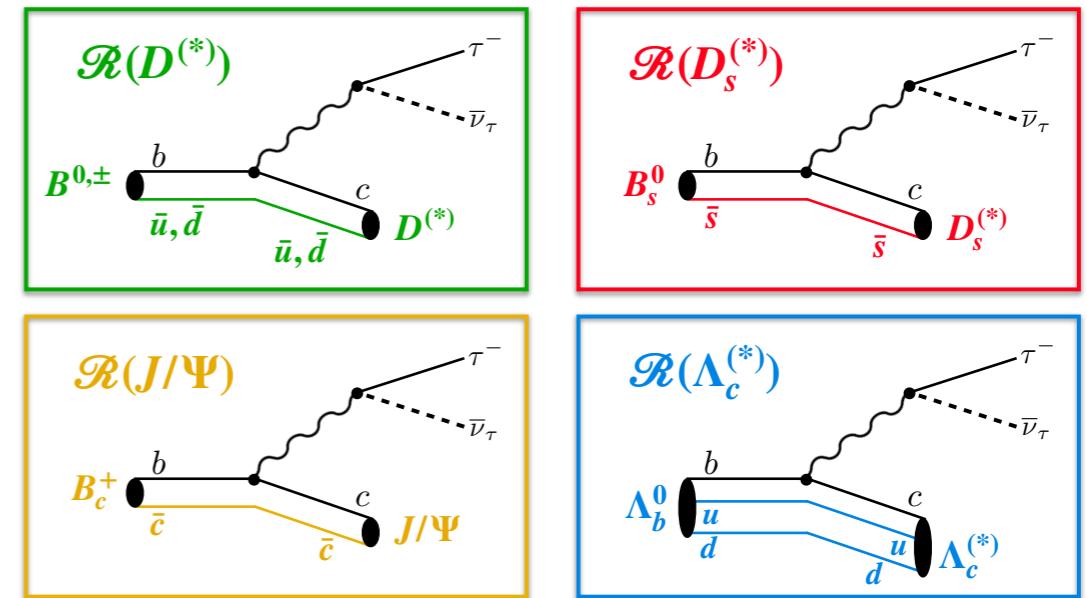
$$\begin{aligned} \mathcal{H}_b &= B^0, B_{(c)}^+, \Lambda_b^0, B_s^0 \dots & \ell' &= e/\mu \text{ (B-factories)} \\ \mathcal{H}_c &= D^*, D^0, D^+, D_s, \Lambda_c^{(*)}, J/\psi \dots & \ell' &= \mu \text{ (LHCb)} \end{aligned}$$



Lepton Flavor Universality as a probe for *New Physics*

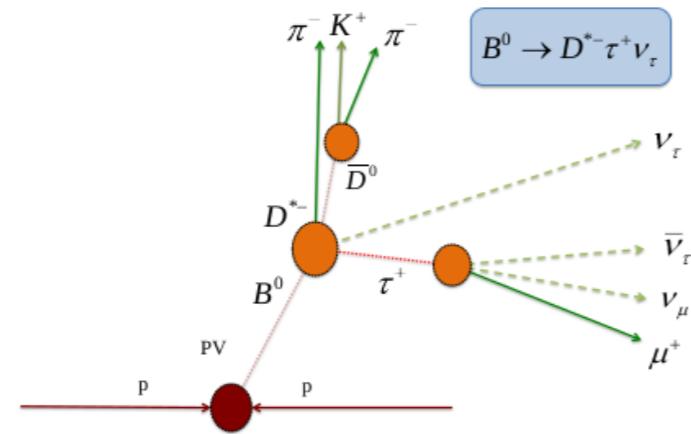


LHCb HAS A UNIQUE ABILITY TO PROBE THIS SECTOR SINCE ALL DIFFERENT B-HADRON SPECIES ARE AVAILABLE

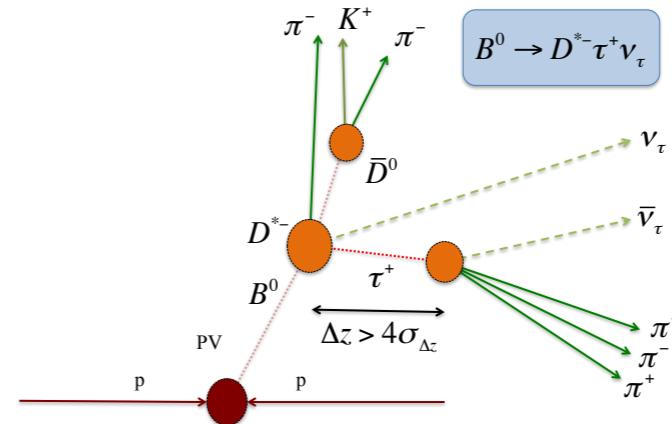


MEASUREMENTS FROM THE B-FACTORIES AND LHCb AT THE $> 3\sigma$ WRT THE SM

LFU measurements at LHCb



$$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$$



$$\tau^+ \rightarrow \pi^+ \pi^- \pi^+ (\pi^0) \bar{\nu}_\tau$$

USE MUONIC DECAY OF THE TAU

$$\mathcal{B}(\tau \rightarrow \mu \nu \bar{\nu}) = (17.39 \pm 0.04)\%$$

- EXTRACT DIRECTLY $\mathcal{R}(\mathcal{H}_c)$
- THREE MISSING NEUTRINOS;
APPROXIMATE KINEMATICS
- TEMPLATE FITS TO KINEMATIC VARIABLES
IN SIGNAL & CONTROL REGIONS

USE HADRONIC (3-PRONG) DECAY OF THE TAU

$$\mathcal{B}(\tau \rightarrow 3\pi\nu) = (9.31 \pm 0.05)\%$$

$$\mathcal{B}(\tau \rightarrow 3\pi\pi^0\nu) = (4.62 \pm 0.05)\%$$

- RECONSTRUCT TAU VERTEX; BETTER CONstrained KINEMATICS
- NORMALIZE WITH HADRONIC FINAL STATES - EXTERNAL INPUTS FOR $\mathcal{R}(\mathcal{H}_c)$

$R_{D^{(*)}}$ (muonic) measurements at LHCb

[arXiv:2303.02886, Submitted to PRL]

SIMULTANEOUS ANALYSIS OF R_D AND R_{D^*} WITH RUN1 DATA USING MUONIC DECAY

3D TEMPLATE FIT TO:

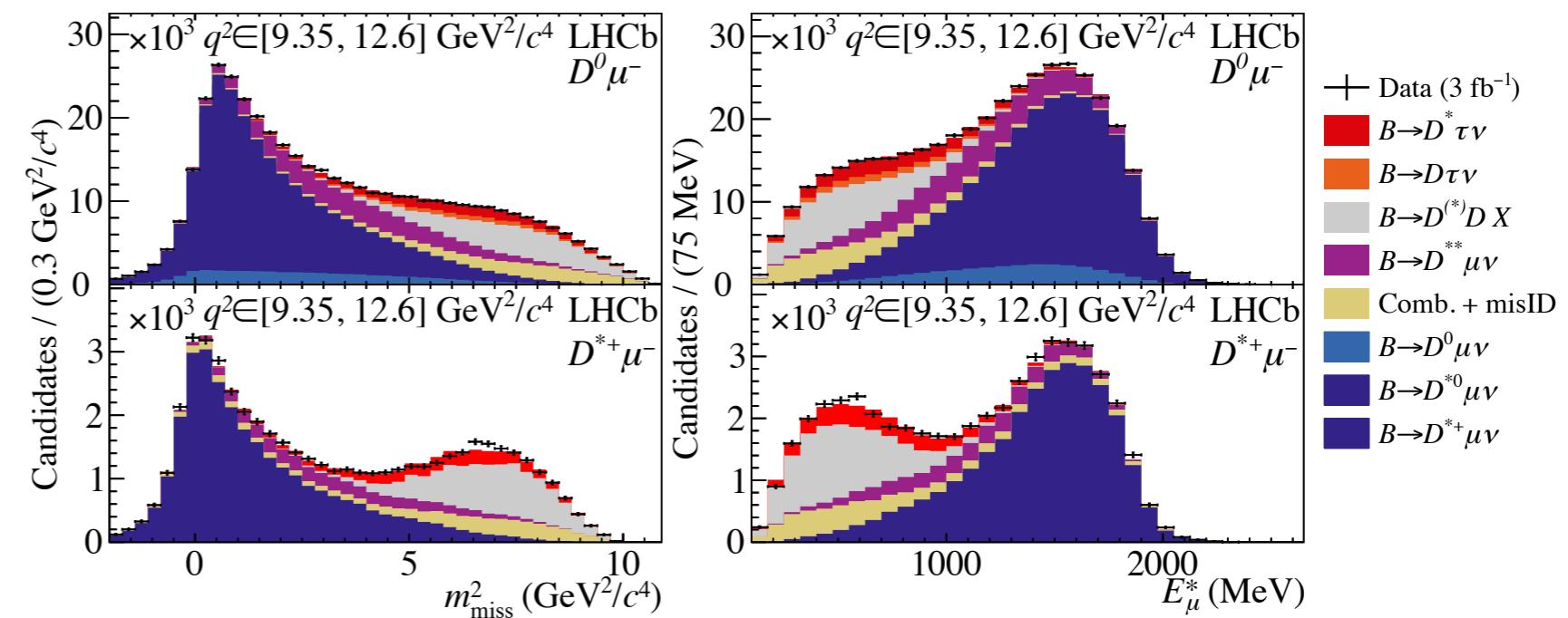
$$q^2 \equiv (p_B - p_{D^{(*)}})^2$$

$$m_{\text{miss}}^2 \equiv (p_B - p_{D^{(*)}} - p_\mu)^2$$

E_μ^* energy of μ

FOR EACH $[D^{*+} \mu^-]$ AND $[D^0 \mu^-]$

- 1 SIGNAL REGION
- 3 CONTROL REGIONS ENRICHED IN BACKGROUND (USING REVERSED ISOLATION CRITERIA)



$$R(D) = 0.441 \pm 0.060(\text{stat}) \pm 0.066(\text{syst})$$

$$R(D^*) = 0.281 \pm 0.018(\text{stat}) \pm 0.023(\text{syst})$$

Agreement with SM at 1.9σ

R_{D^*} (hadronic) measurement at LHCb

[LHCb-PAPER-2022-052, In preparation]

MEASUREMENT OF R_{D^*} WITH PARTIAL RUN2 DATA (2015+16) USING HADRONIC DECAY

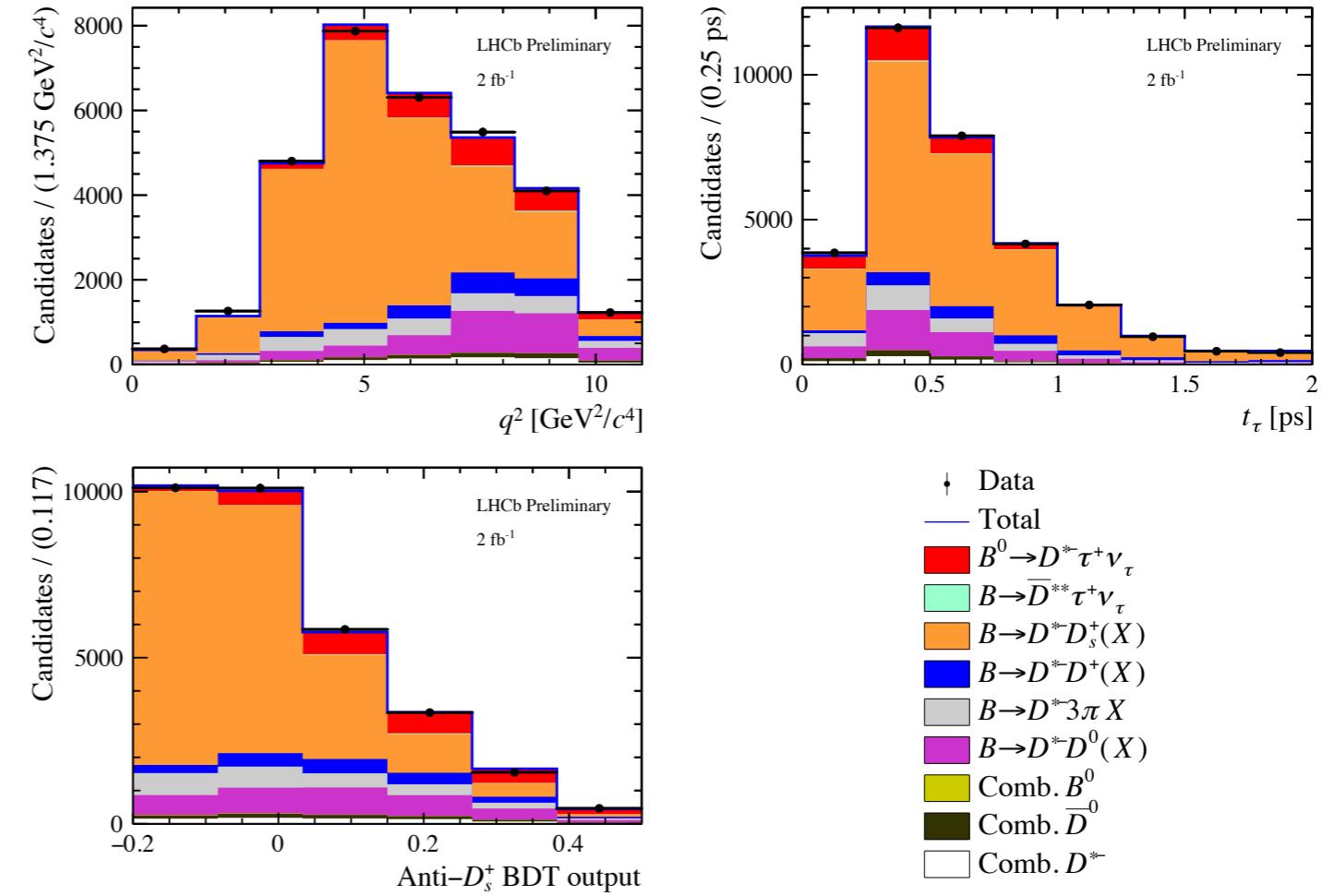
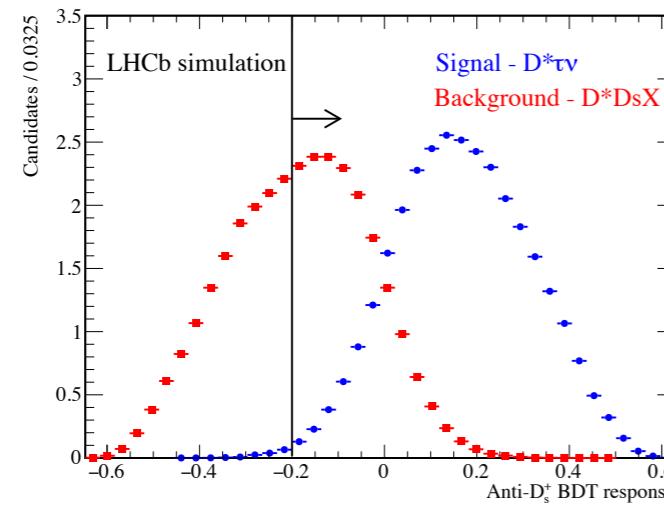
$$R(D^*) = 0.247 \pm 0.015(\text{stat}) \pm 0.015(\text{syst}) \pm 0.012(\text{ext})$$

3D TEMPLATE FIT TO:

$$q^2 \equiv (p_{B^0} - p_{D^*})^2$$

τ^+ decay time

Anti- D_s^+ BDT output



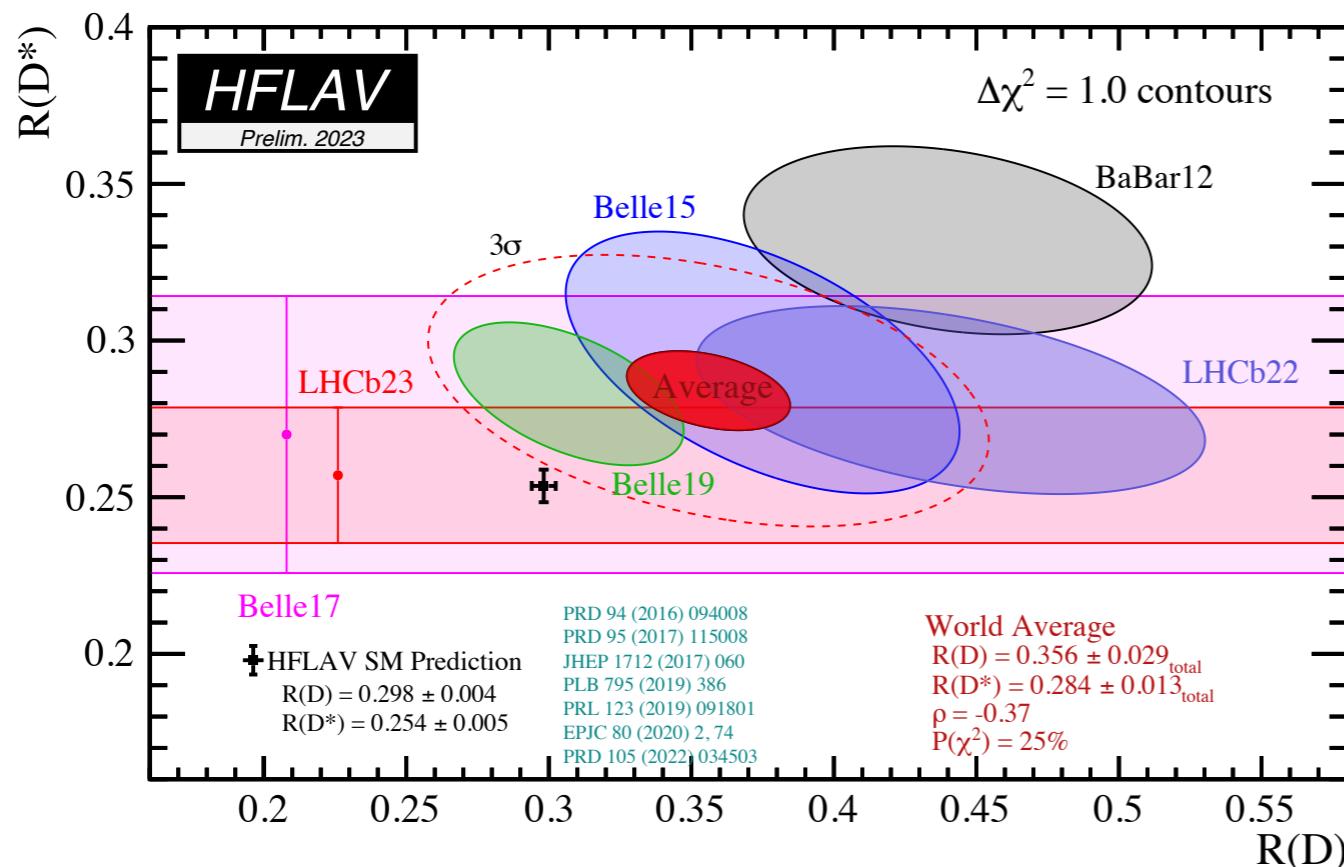
COMBINING WITH RUN 1 RESULTS:

$$R(D^*)_{2011-2016} = 0.257 \pm 0.012(\text{stat}) \pm 0.014(\text{syst}) \pm 0.012(\text{ext})$$

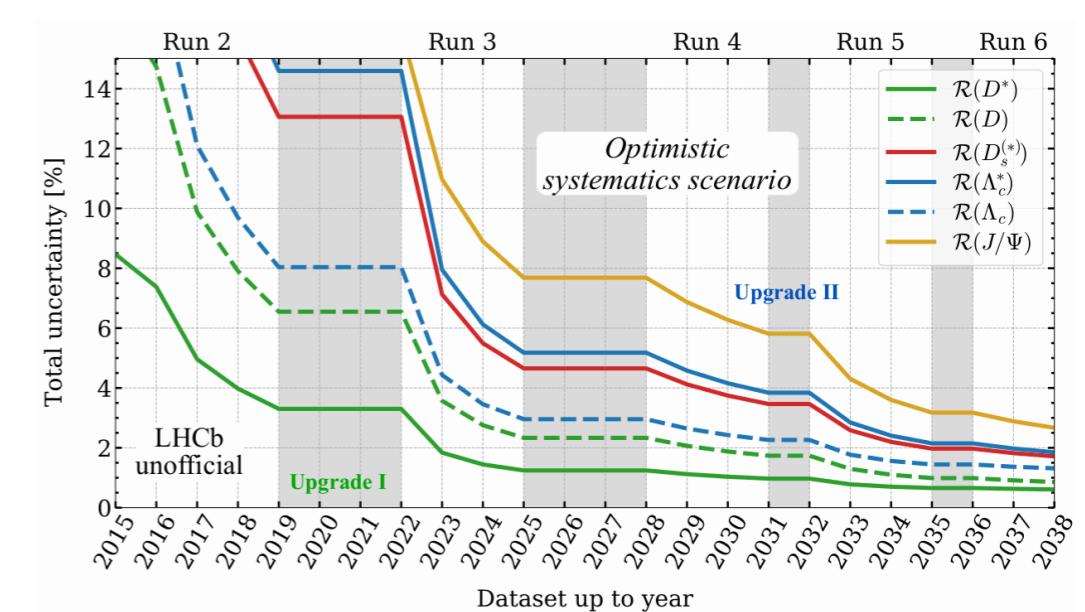
LFU measurement at LHCb

[arXiv:2303.02886, LHCb-PAPER-2022-052]

GLOBAL PICTURE UNCHANGED FOR R_{D^*} AND R_D
COMBINATION WITH THE SM AT 3 SIGMA



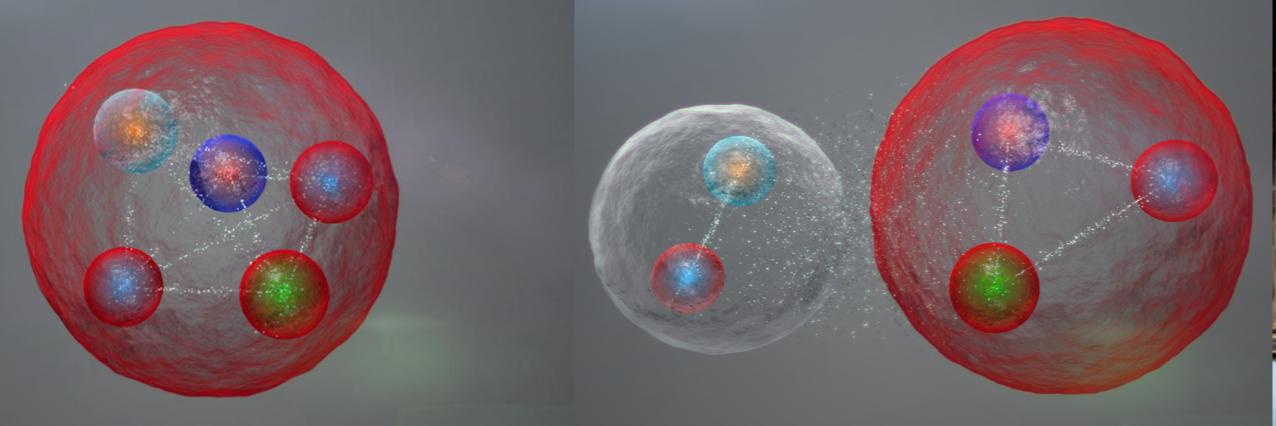
SEMILEPTONIC DECAYS EXTREMELY CHALLENGING
AT HADRONIC MACHINES, BUT PRECISION AT
LHCb SIMILAR TO BELLE!



OUTLOOK FOR THIS SECTOR EXTREMELY FRUITFUL! MORE DATA, NOVEL OBSERVABLES (E.G. ANGULAR ANALYSIS)

LHCb HIGHLIGHTS

Spectroscopy at LHCb



Conventional & Exotics

[arXiv:2302.04733](https://arxiv.org/abs/2302.04733)

[Submitted to PRL]

[arXiv:2301.04899](https://arxiv.org/abs/2301.04899)

[Submitted to PRL]

[arXiv:2212.02717](https://arxiv.org/abs/2212.02717)

[Submitted to PRD]

[arXiv:2210.10346](https://arxiv.org/abs/2210.10346)

[Submitted to PRL]

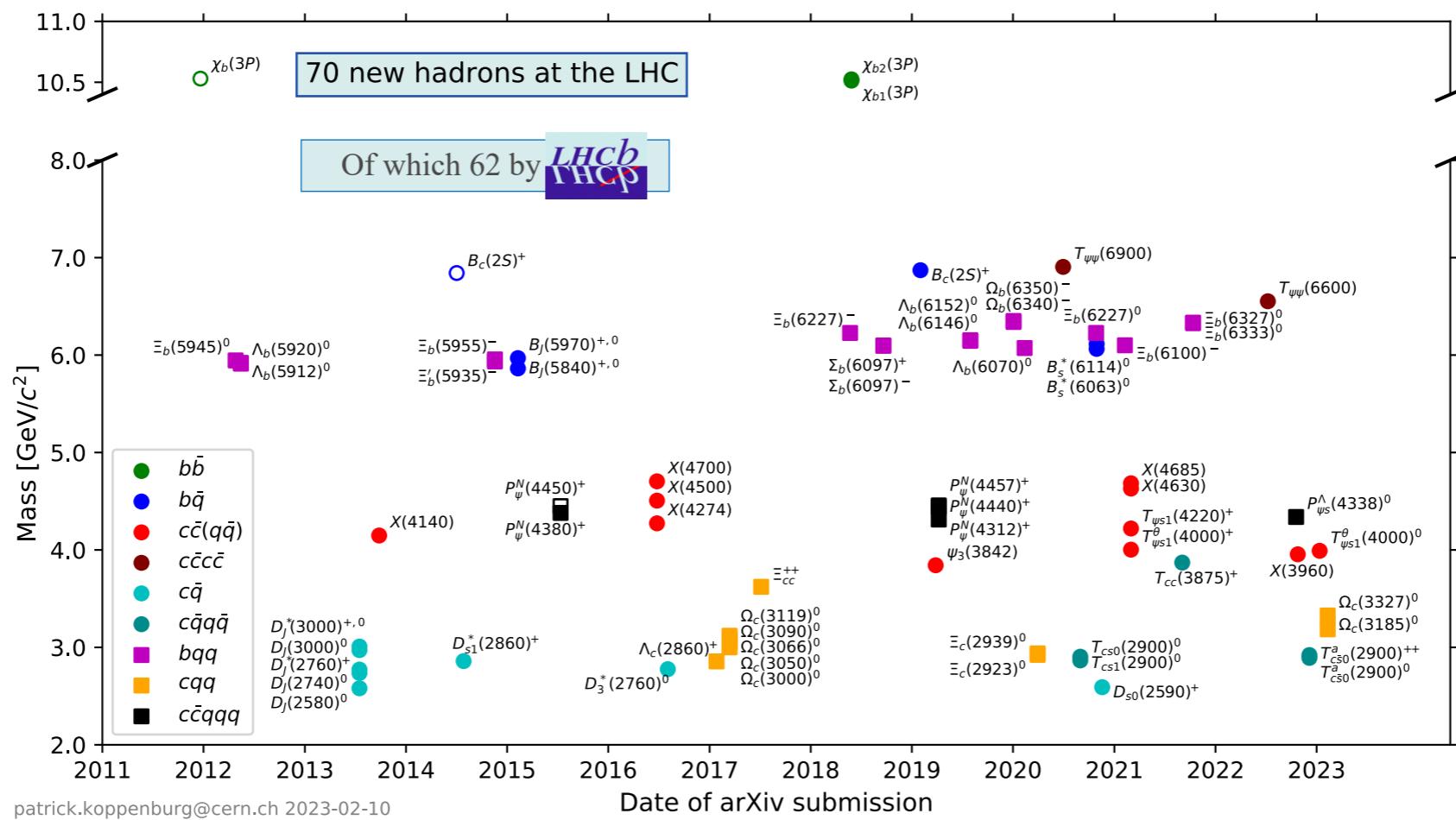
Conventional and exotic spectroscopy

CLASSICAL HADRONS: MESONS [QUARK + ANTIQUARK] OR BARYONS [3 QUARKS]

EXOTIC HADRONS: IN PRINCIPLE ANYTHING ELSE, TETRAQUARK, PENTAQUARK, HEXAQUARK, ...

STUDIED BY DIFFERENT EXPERIMENTS:

LHCb, BESIII, ATLAS, CMS, Belle, Belle II, BaBar, CDF, D0, ALICE ...



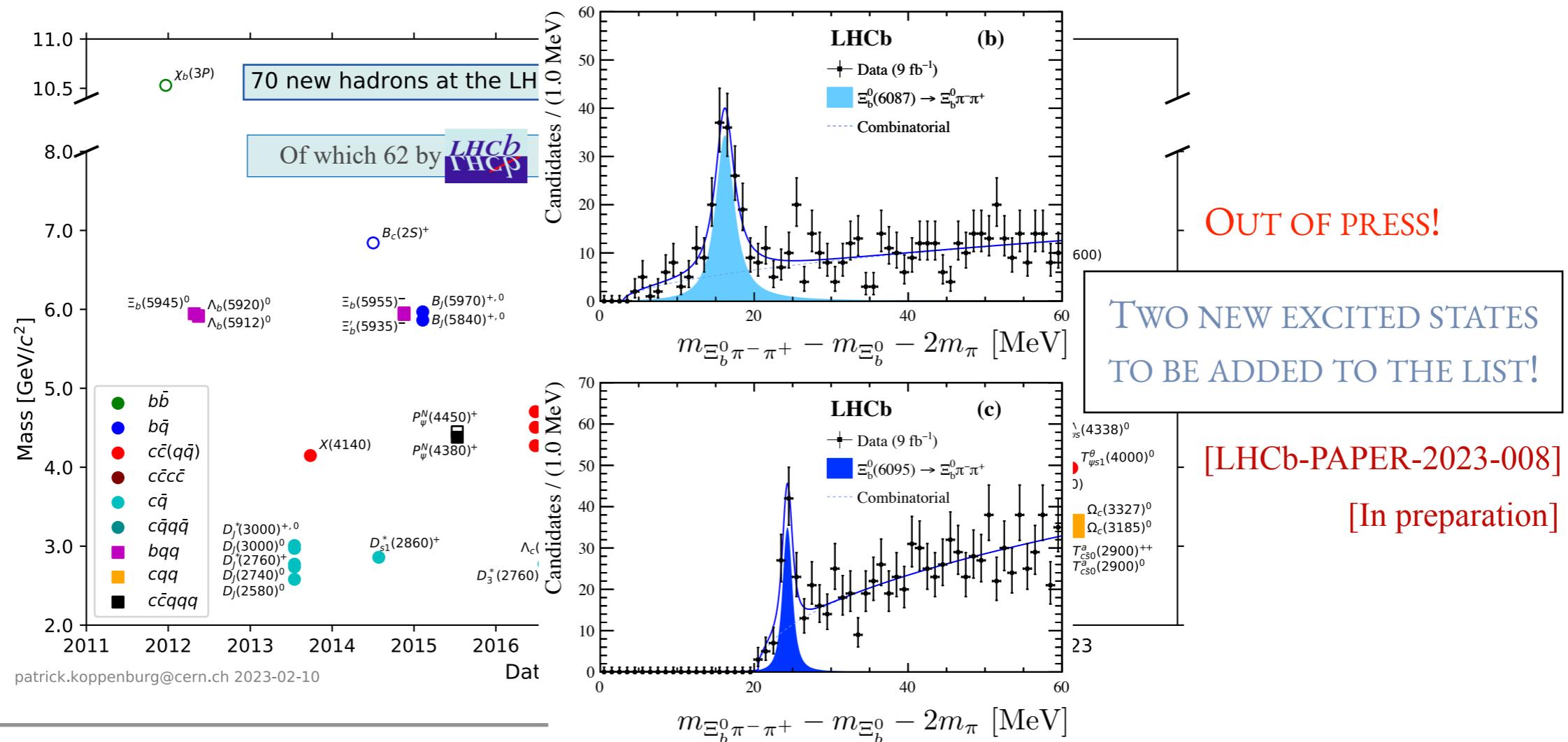
Conventional and exotic spectroscopy

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STUDIED BY DIFFERENT EXPERIMENTS:

LHCb, BESIII, ATLAS, CMS, Belle, Belle II, BaBar, CDF, D0, ALICE ...



Observation of new Ω_c^0 states

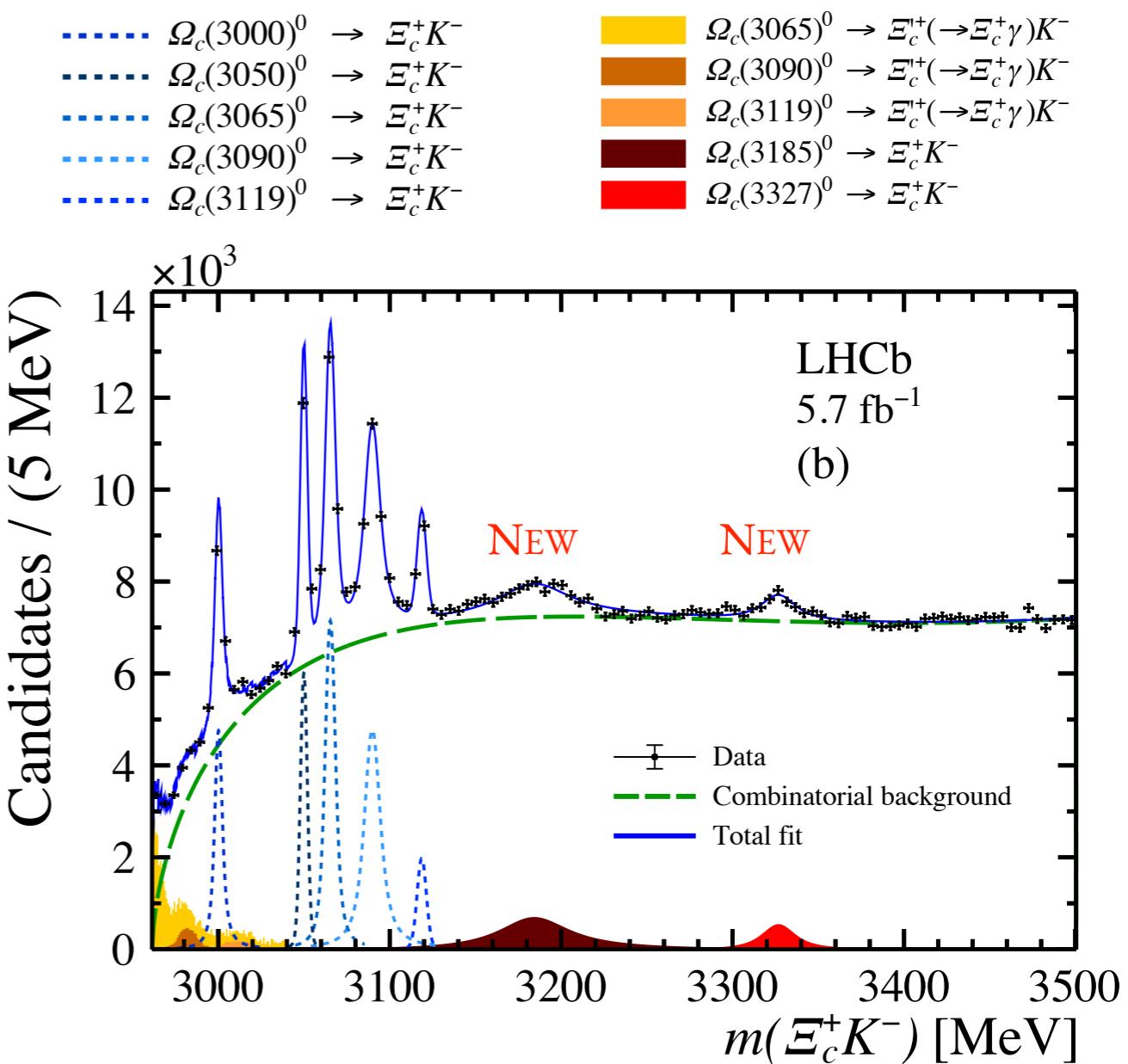
[arXiv:2302.04733, Submitted to PRL]

ANALYSIS OF THE FULL LHCb DATASET OF $\Omega_c^0 \rightarrow \Xi_c^+ K^-$ DECAYS

FIVE STATES FROM PREVIOUS ANALYSIS
CONFIRMED (MOST PRECISE)

Resonance	m (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.44 \pm 0.07^{+0.07}_{-0.13} \pm 0.23$	$3.83 \pm 0.23^{+1.59}_{-0.29}$
$\Omega_c(3050)^0$	$3050.18 \pm 0.04^{+0.06}_{-0.07} \pm 0.23$	$0.67 \pm 0.17^{+0.64}_{-0.72}$
$\Omega_c(3065)^0$	$3065.63 \pm 0.06^{+0.06}_{-0.06} \pm 0.23$	$< 1.8 \text{ MeV}, 95\% \text{ C.L.}$
$\Omega_c(3090)^0$	$3090.16 \pm 0.11^{+0.06}_{-0.10} \pm 0.23$	$8.48 \pm 0.44^{+0.61}_{-1.62}$
$\Omega_c(3119)^0$	$3118.98 \pm 0.12^{+0.09}_{-0.23} \pm 0.23$	$0.60 \pm 0.63^{+0.90}_{-1.05}$
$\Omega_c(3185)^0$	$3185.1 \pm 1.7^{+7.4}_{-0.9} \pm 0.2$	$50 \pm 7^{+10}_{-20}$
$\Omega_c(3327)^0$	$3327.1 \pm 1.2^{+0.1}_{-1.3} \pm 0.2$	$20 \pm 5^{+13}_{-1}$

TWO NEW EXCITED STATES OBSERVED:
 $\Omega_c(3185)^0$ AND $\Omega_c(3327)^0$





Exotic spectroscopy

[arXiv:2206.15233]



NAME SCHEME: NEW EXOTIC HADRON NAMING CONVENTION

- **T** for tetraquark
- **P** for pentaquark
- **superscript:** based on existing symbols, to indicate isospin, parity and G-parity
- **subscript:** heavy quark content

Minimal quark content	Current name	$I^{(G)}, J^{P(C)}$	Proposed name	Reference
$c\bar{c}$	$\chi_{c1}(3872)$	$I^G = 0^+, J^{PC} = 1^{++}$	$\chi_{c1}(3872)$	[24, 25]
$c\bar{c}u\bar{d}$	$Z_c(3900)^+$	$I^G = 1^+, J^P = 1^+$	$T_{\psi 1}^b(3900)^+$	[26–28]
$c\bar{c}u\bar{d}$	$X(4100)^+$	$I^G = 1^-$	$T_\psi(4100)^+$	[29]
$c\bar{c}u\bar{d}$	$Z_c(4430)^+$	$I^G = 1^+, J^P = 1^+$	$T_{\psi 1}^b(4430)^+$	[30, 31]
$c\bar{c}(s\bar{s})$	$\chi_{c1}(4140)$	$I^G = 0^+, J^{PC} = 1^{++}$	$\chi_{c1}(4140)$	[32–35]
$c\bar{c}u\bar{s}$	$Z_{cs}(4000)^+$	$I = \frac{1}{2}, J^P = 1^+$	$T_{\psi s1}^\theta(4000)^+$	[7]
$c\bar{c}u\bar{s}$	$Z_{cs}(4220)^+$	$I = \frac{1}{2}, J^P = 1^?$	$T_{\psi s1}(4220)^+$	[7]
$c\bar{c}c\bar{c}$	$X(6900)$	$I^G = 0^+, J^{PC} = ?^?+$	$T_{\psi\psi}(6900)$	[4]
$cs\bar{u}\bar{d}$	$X_0(2900)$	$J^P = 0^+$	$T_{cs0}(2900)^0$	[5, 6]
$cs\bar{u}\bar{d}$	$X_1(2900)$	$J^P = 1^-$	$T_{cs1}(2900)^0$	[5, 6]
$cc\bar{u}\bar{d}$	$T_{cc}(3875)^+$		$T_{cc}(3875)^+$	[8, 9]
$b\bar{b}u\bar{d}$	$Z_b(10610)^+$	$I^G = 1^+, J^P = 1^+$	$T_{\gamma 1}^b(10610)^+$	[36]
$c\bar{c}uud$	$P_c(4312)^+$	$I = \frac{1}{2}$	$P_\psi^N(4312)^+$	[3]
$c\bar{c}uds$	$P_{cs}(4459)^0$	$I = 0$	$P_{\psi s}^\Lambda(4459)^0$	[20]

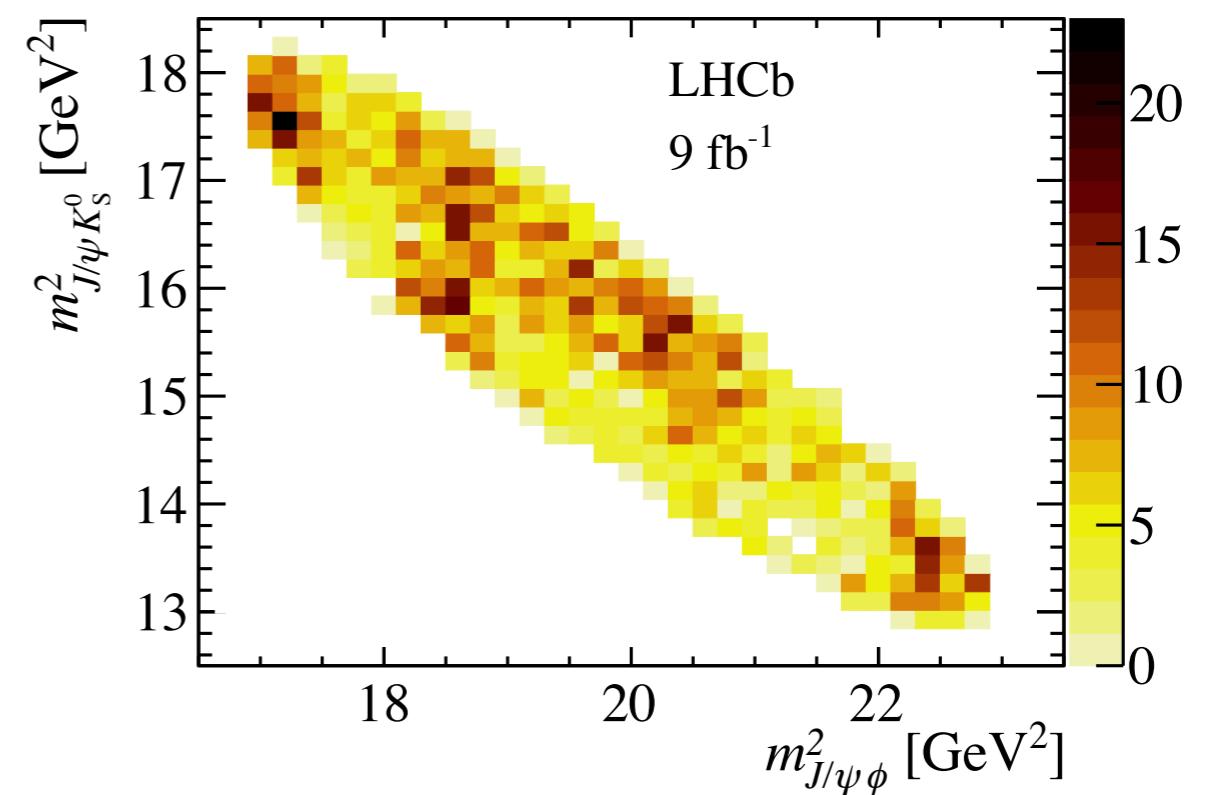
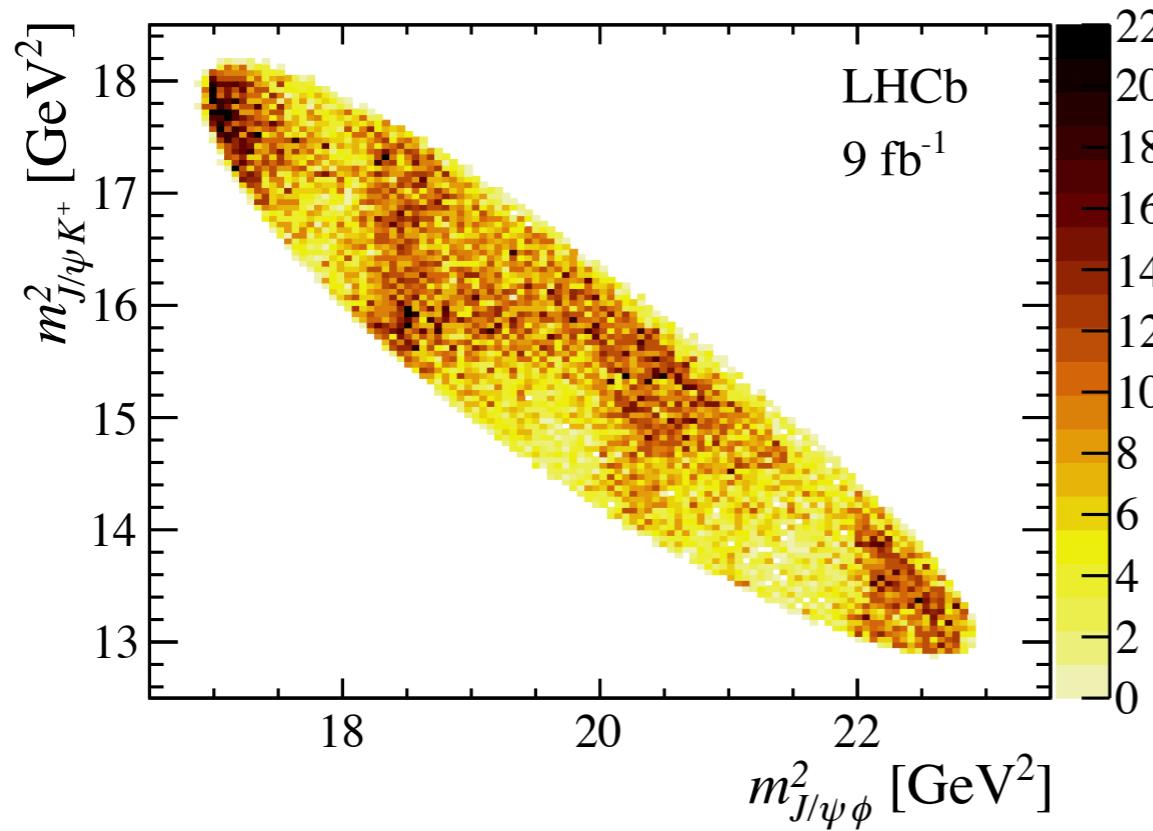
Evidence of the $T_{\psi s1}^\theta(4000)^0$ state

[arXiv:2301.04899, Submitted to PRL]

ANALYSIS OF THE $B^+ \rightarrow J/\psi \phi K^+$ DECAY OBSERVED TWO STATES: $T_{\psi s1}^\theta(4000)^+$ AND $T_{\psi s1}^\theta(4220)^+$
 [PRL 127 (2021) 082001]

IS THERE A ISOSPIN PARTNER IN $B^0 \rightarrow J/\psi \phi K_s^0$ DECAYS?

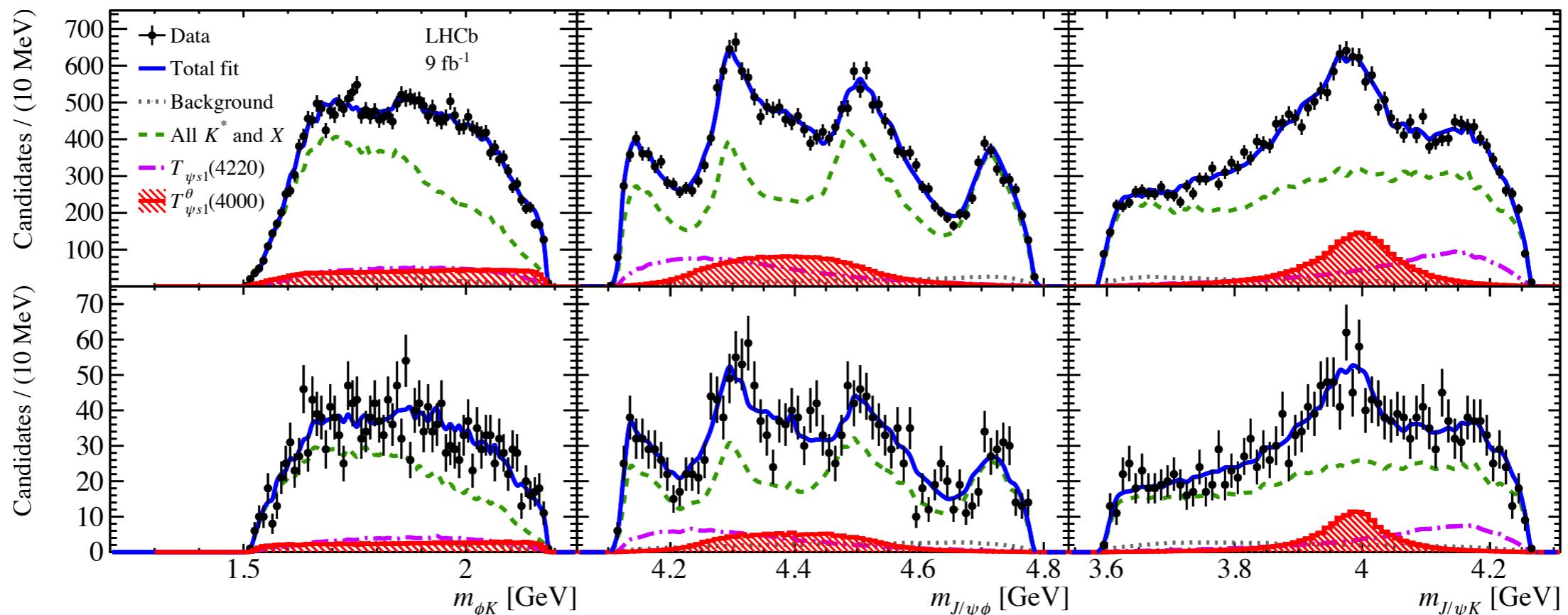
A SIMULTANEOUS AMPLITUDE FIT IS PERFORMED IN BOTH CHANNELS WITH FULL STATISTICS



Evidence of the $T_{\psi s1}^\theta(4000)^0$ state

[arXiv:2301.04899, Submitted to PRL]

A SIMULTANEOUS AMPLITUDE FIT IS PERFORMED IN BOTH CHANNELS WITH FULL STATISTICS



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

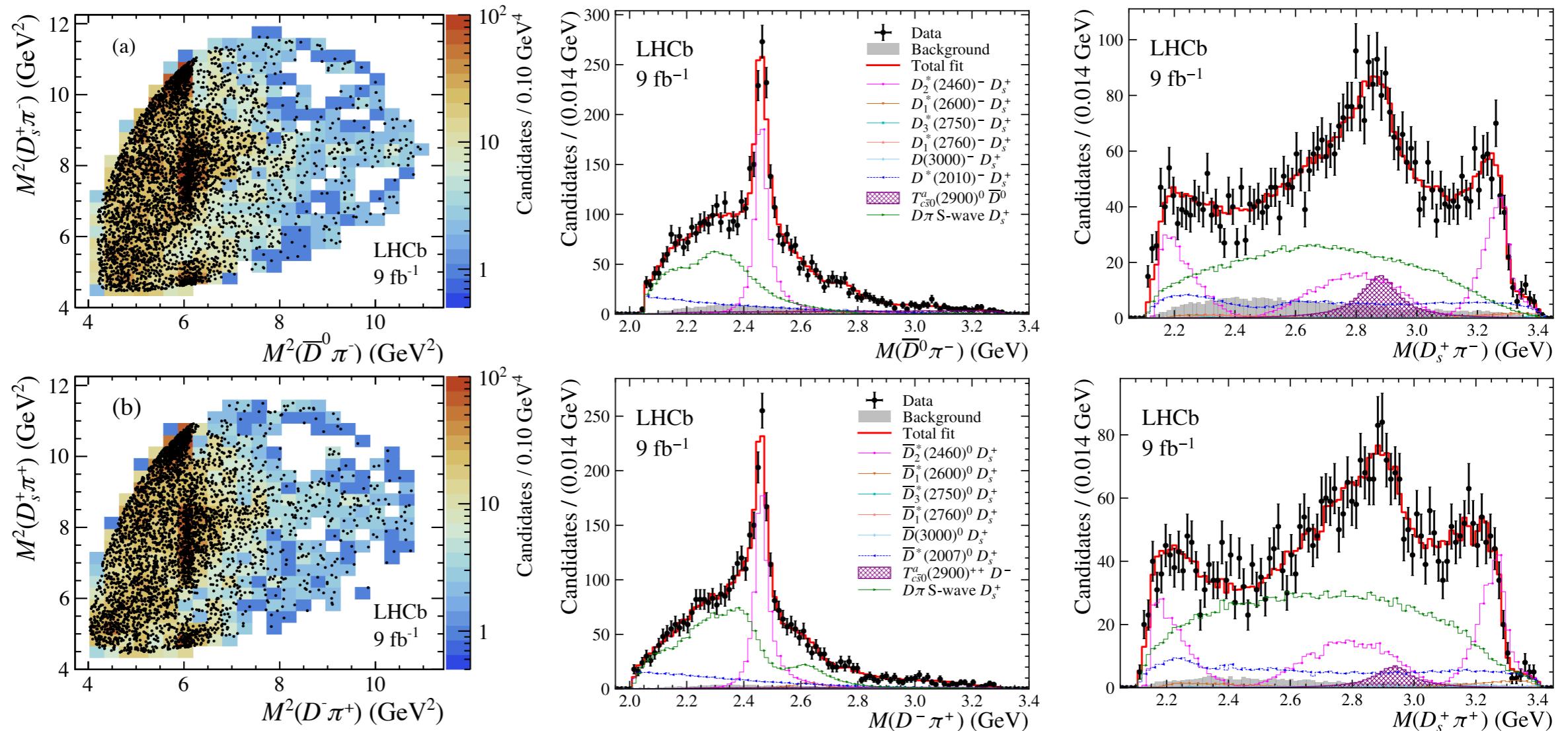
$$\Gamma(T_{\psi s1}^\theta(4000)^0) = 105^{+29 + 17}_{-25 - 23} \text{ MeV}$$

NEUTRAL PARTNER $T_{\psi s1}^\theta(4000)^0$: SIGNIFICANCE OF 4σ (5.4σ ASSUMING ISOSPIN SYMMETRY)

Doubly charged and neutral open charmed tetraquarks

[arXiv:2212.02717, Submitted to PRD]

SIMULTANEOUS ANALYSIS OF $B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$ (TOP) AND $B^+ \rightarrow D^- D_s^+ \pi^+$ (BOTTOM) DECAYS

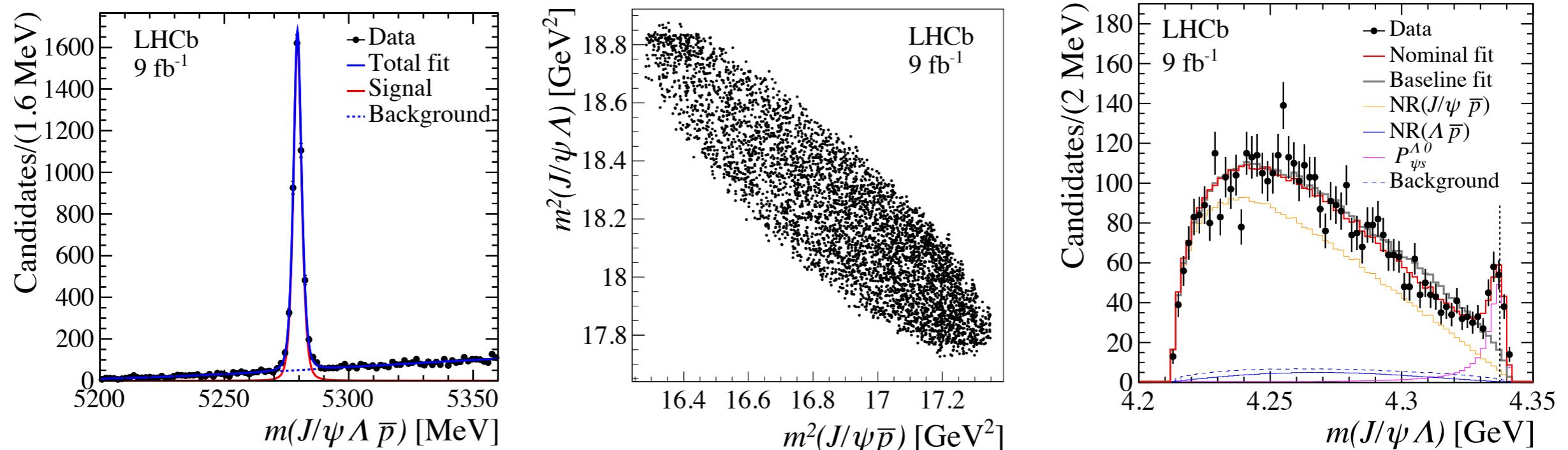


SCALAR RESONANCE-LIKE STRUCTURE IN $D_s^+ \pi^-$ CHANNEL: $T_{c\bar{s}0}(2900)^0$ AND $T_{c\bar{s}0}(2900)^{++}$

Strange pentaquark candidate

[arXiv:2210.10346, Submitted to PRL]

AMPLITUDE ANALYSIS OF THE $B^- \rightarrow J/\psi \Lambda \bar{p}$ DECAY



KNOWN $J/\psi p$ PENTAQUARK AND $P_{\psi s}^\Lambda(4459)^0$ DO NOT CONTRIBUTE TO THE PHASE SPACE

NEW PENTAQUARK CANDIDATE (WITH STRANGE QUARK CONTENT) $P_{\psi s}^\Lambda(4338)^0$ WITH MASS FOUND AT THE THRESHOLD FOR $\Xi_c^+ D^-$ BARYON-MESON PRODUCTION

PROMISING MODE FOR PENTAQUARK CONFIRMATION AT B FACTORY!



SUMMARY

- VERY FRUITFUL FLAVOR PHYSICS PROGRAM,
GOING WAY BEYOND INITIAL DESIGN
- VERY SMALL SUBSET OF RESULTS SHOWN HERE

i.e. CKM MEASUREMENTS, LFU, SPECTROSCOPY

WHAT COMES NEXT?

- EXISTING DATA NOT YET FULLY EXPLORED!



- A PRECISION FLAVOUR PHYSICS ERA AHEAD OF US!

[A “COMPASS” TO THE LHC SEARCHES?]



R_{D*}(hadronic) measurement at LHCb

[LHCb-PAPER-2022-052, In preparation]

MEASUREMENT OF R_{D*} WITH PARTIAL RUN2 DATA (2015+16) USING HADRONIC DECAY

ANALYSIS STRATEGY

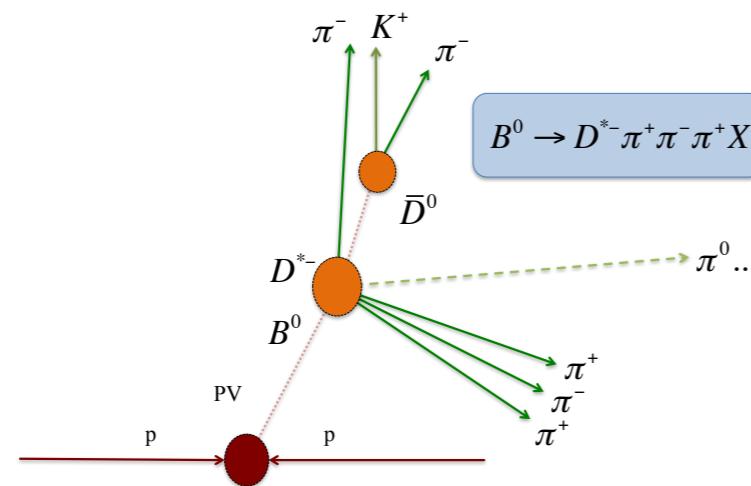
$$\mathcal{K}(D^*) = \frac{\mathcal{B}(B^0 \rightarrow D^{*-} \tau^+ \nu_\tau)}{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)} = \frac{N_{\text{sig}}}{N_{\text{norm}}} \frac{\varepsilon_{\text{norm}}}{\varepsilon_{\text{sig}}} \frac{1}{\mathcal{B}(\tau^+ \rightarrow 3\pi^\pm (\pi^0) \bar{\nu}_\tau)}$$

CONVERT INTO THE RATIO

$$R(D^*) = \mathcal{K}(D^*) \left\{ \frac{\mathcal{B}(B^0 \rightarrow D^{*-} 3\pi^\pm)}{\mathcal{B}(B^0 \rightarrow D^{*-} \mu^+ \nu_\mu)} \right\}_{\text{ext. input}}$$

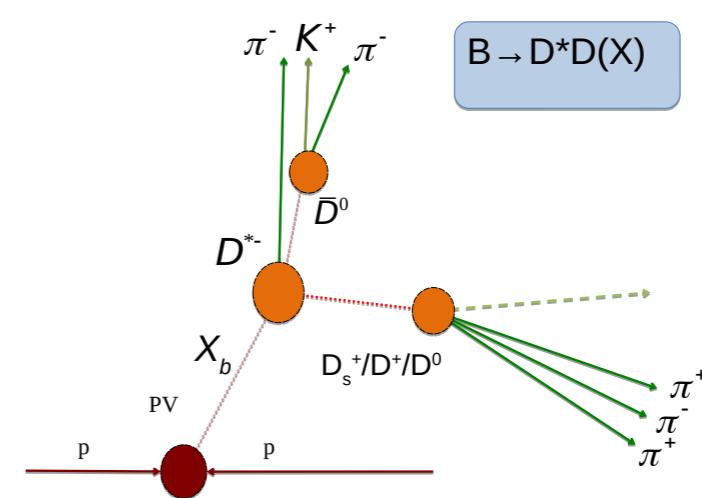
DOMINANT BACKGROUND

- AROUND ~ 100X SIGNAL DECAY



SECOND LARGEST CONTRIBUTION

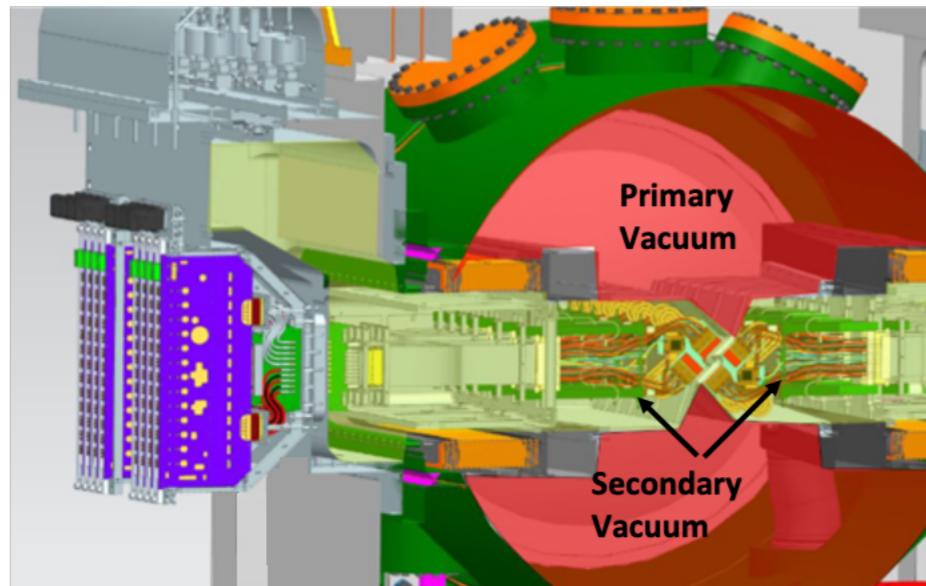
- D_s CONTRIBUTION ~ 10X SIGNAL DECAY



VELO incident

The VELO detector is installed in a **secondary vacuum** inside the LHC **primary vacuum**.

The **primary** and **secondary** volumes are separated by two thin walled Aluminium boxes, the RF foils



On 10th January 2023, during a VELO warm up in neon, there was a loss of control of the protection system

A pressure differential of 200 mbar built up between the two volumes, whereas the foils are designed to withstand 10 mbar only

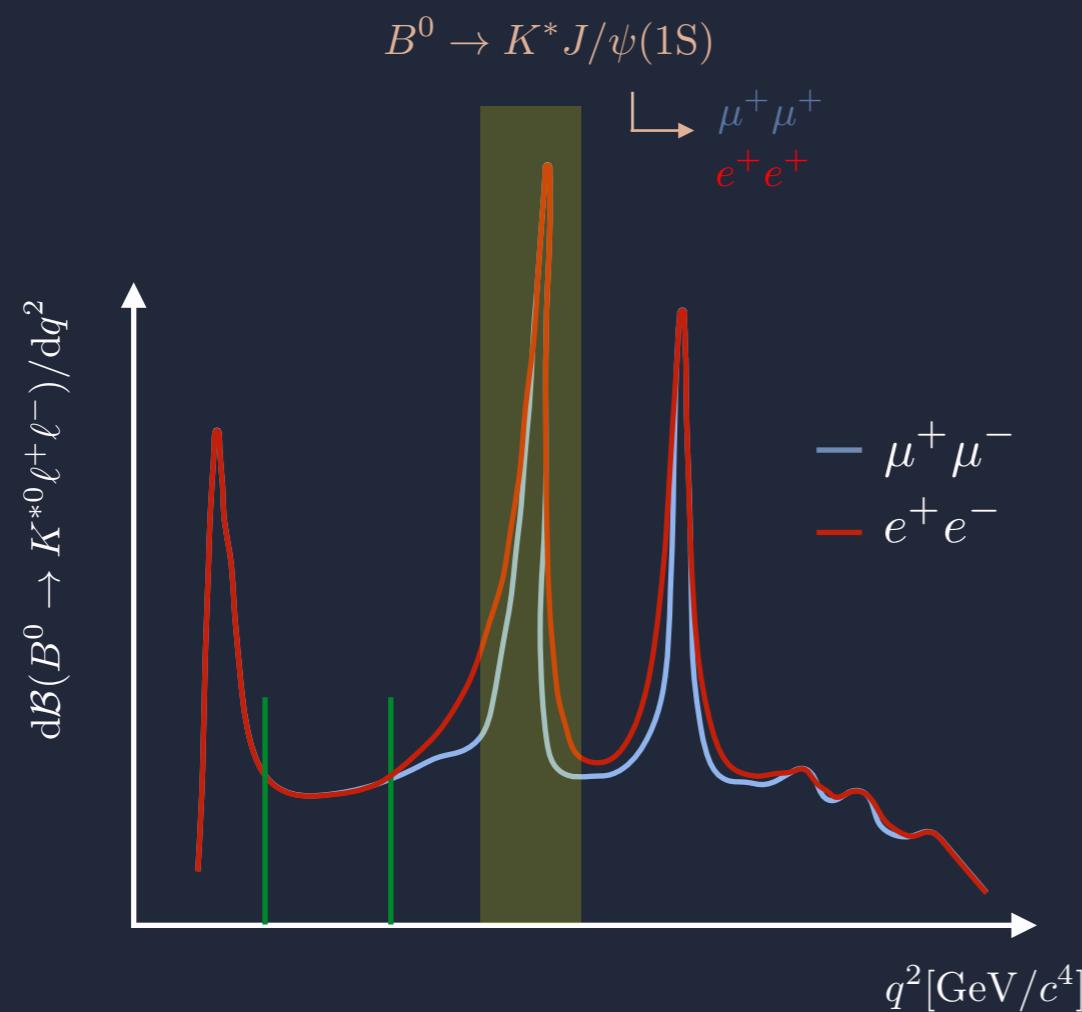
Initial investigations show no damage to the VELO modules; sensors show **correct leakage currents**, microchannels show **no leaks**

RF foils have suffered plastic deformation up to 14 mm and have to be replaced. Major intervention, planning under study

- Replace now (delay), or replace at the end of the year (run in 2023 with VELO partially open)
- Physics programme of 2023 is significantly affected, commissioning of Upgrade I systems can proceed as planned

LFU analysis strategy: *legacy measurement*

DOUBLE RATIO WITH RESPECT TO EQUIVALENT CHARMONIUM MODE TO REDUCE SYSTEMATIC UNCERTAINTIES



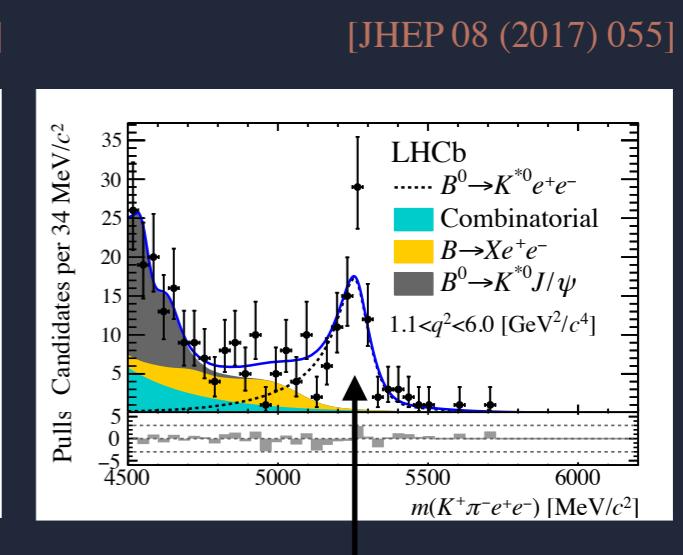
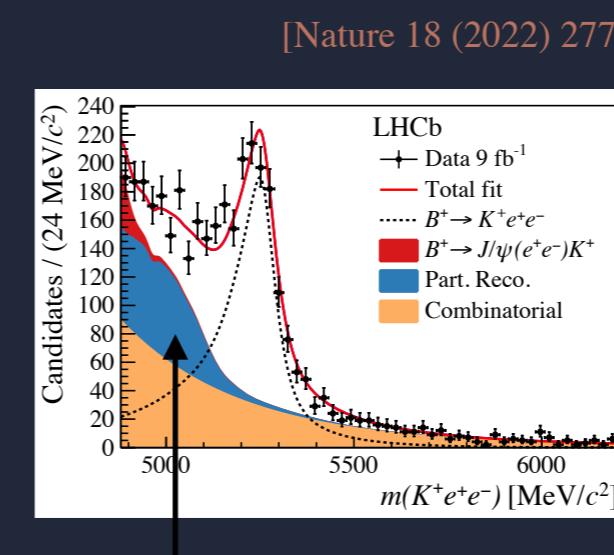
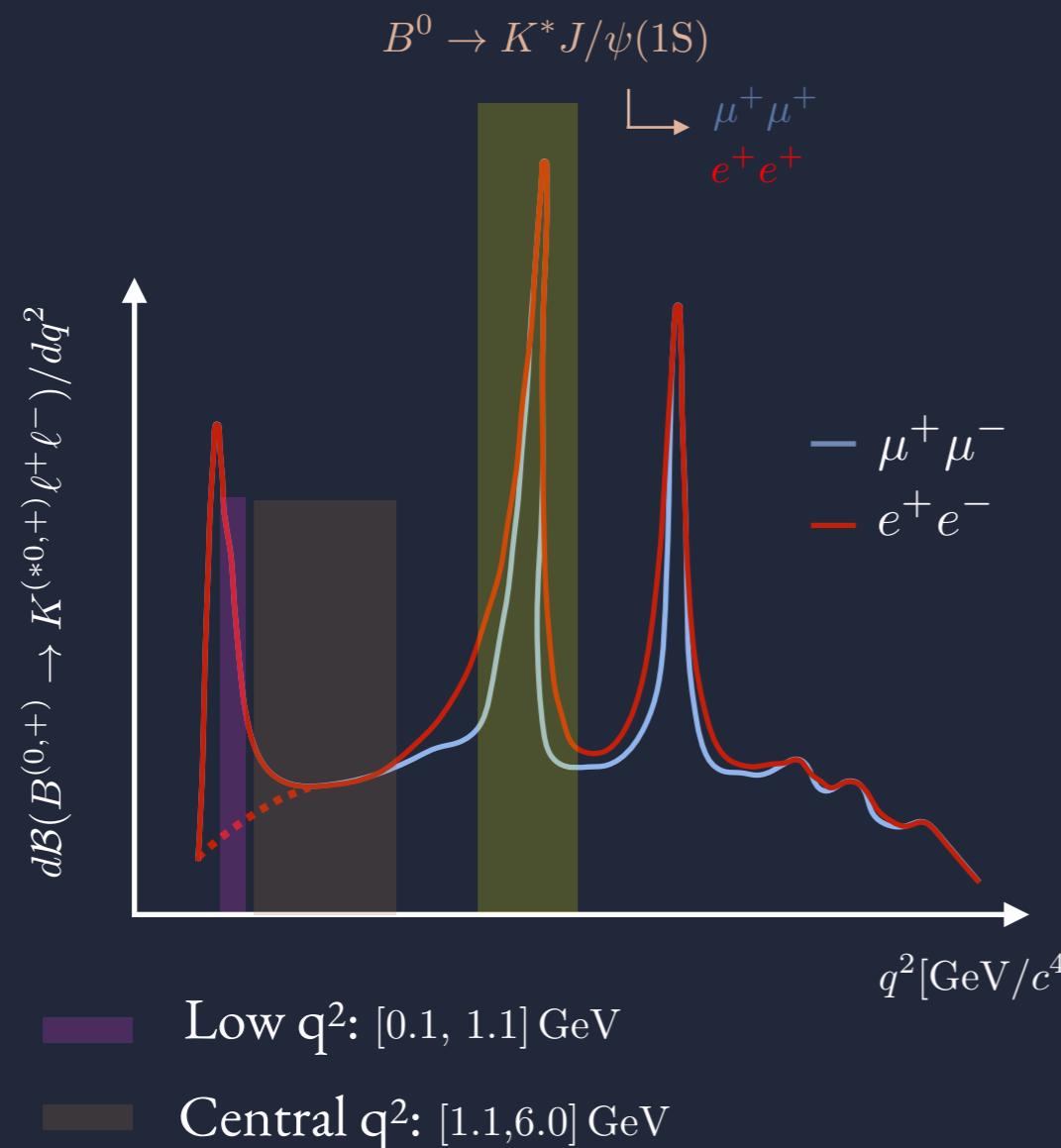
$$R_{K^*} = \frac{\mathcal{B}(B \rightarrow K^* \mu^+ \mu^-)}{\mathcal{B}(B \rightarrow K^* J/\psi(\rightarrow \mu^+ \mu^-))} \Bigg/ \frac{\mathcal{B}(B \rightarrow K^* e^+ e^-)}{\mathcal{B}(B \rightarrow K^* J/\psi(\rightarrow e^+ e^-))}$$

$$R_{K^*} = \frac{N_{\mu^+ \mu^-}^{\text{rare}} \epsilon_{\mu^+ \mu^-}^{J/\psi}}{N_{\mu^+ \mu^+}^{J/\psi} \epsilon_{\mu^+ \mu^-}^{\text{rare}}} \times \frac{N_{e^+ e^-}^{\text{rare}} \epsilon_{e^+ e^-}^{J/\psi}}{N_{e^+ e^+}^{J/\psi} \epsilon_{e^+ e^-}^{\text{rare}}}$$

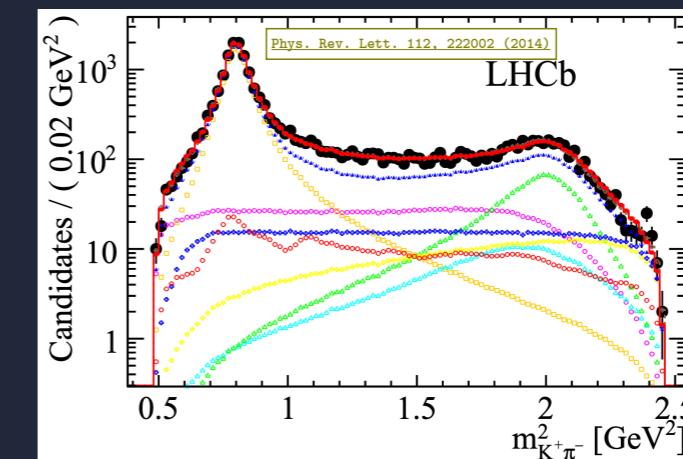
R_X COMPUTATION REDUCES TO MASS FITS AND
EFFICIENCY CALCULATIONS (SIMULATION)

LFU analysis strategy: *legacy measurement*

SIMULTANEOUS ANALYSIS OF R_K AND R_{K^*} RATIOS AND TWO DILEPTON BINS



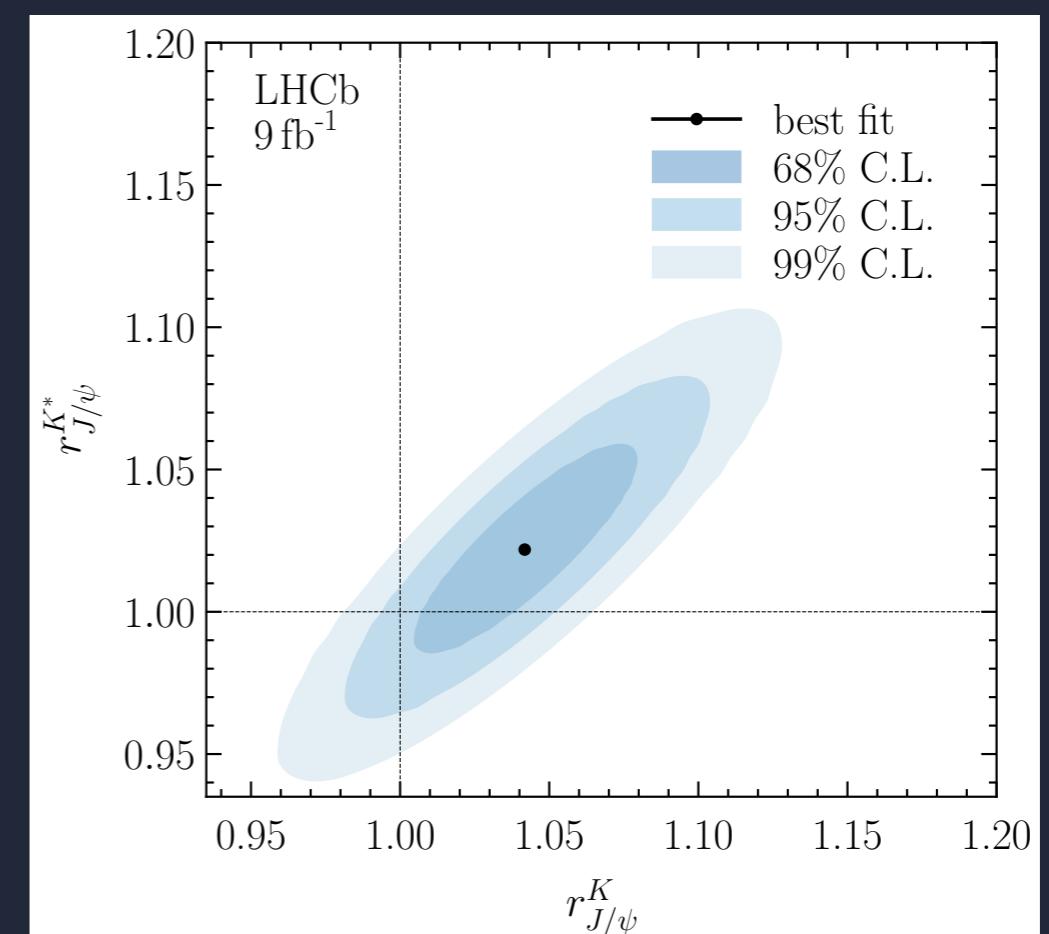
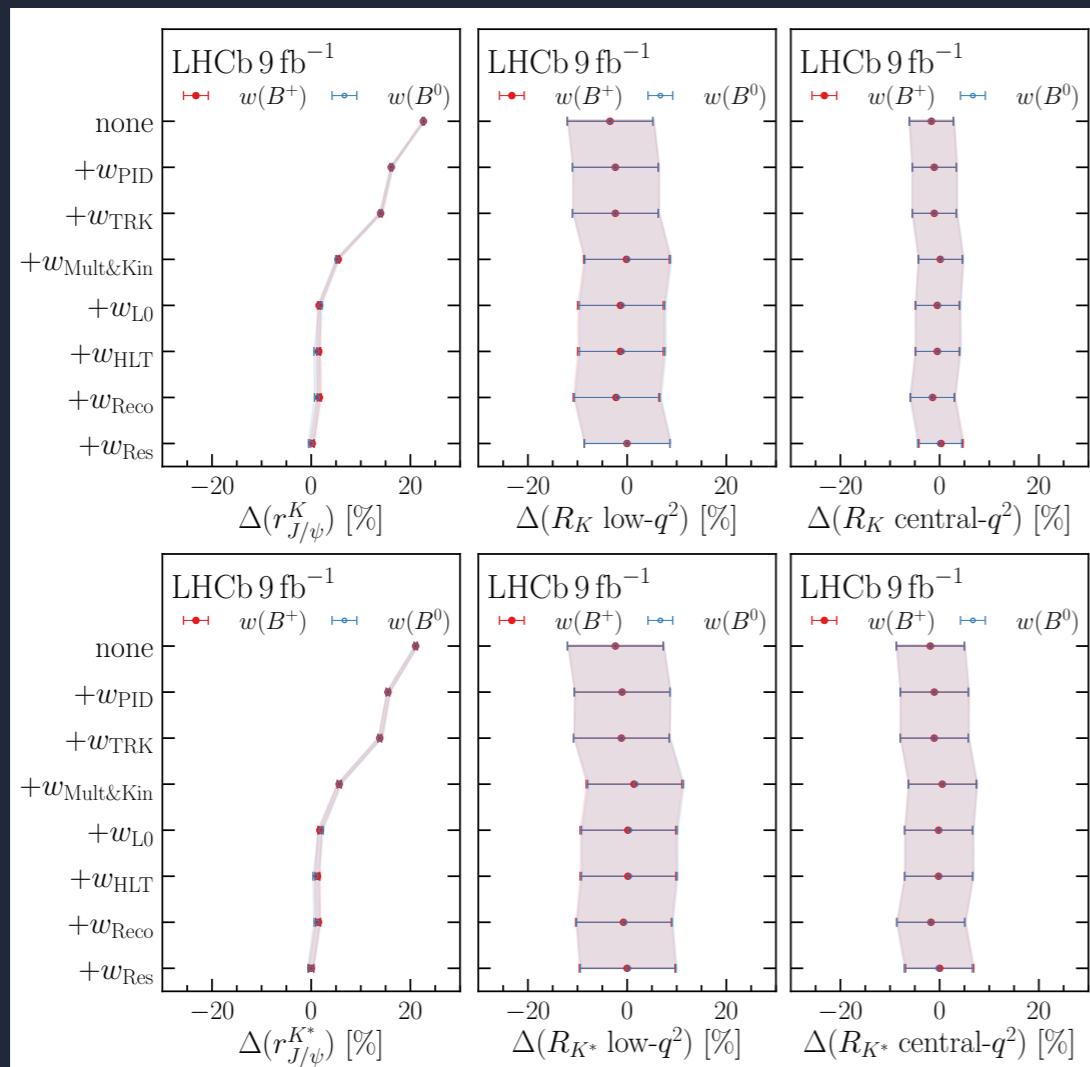
CROSSFEED IN MASS FITS (IMPROVED SENSITIVITY)



+ MORE ROBUST CONTROL (EXTRAPOLATIONS)

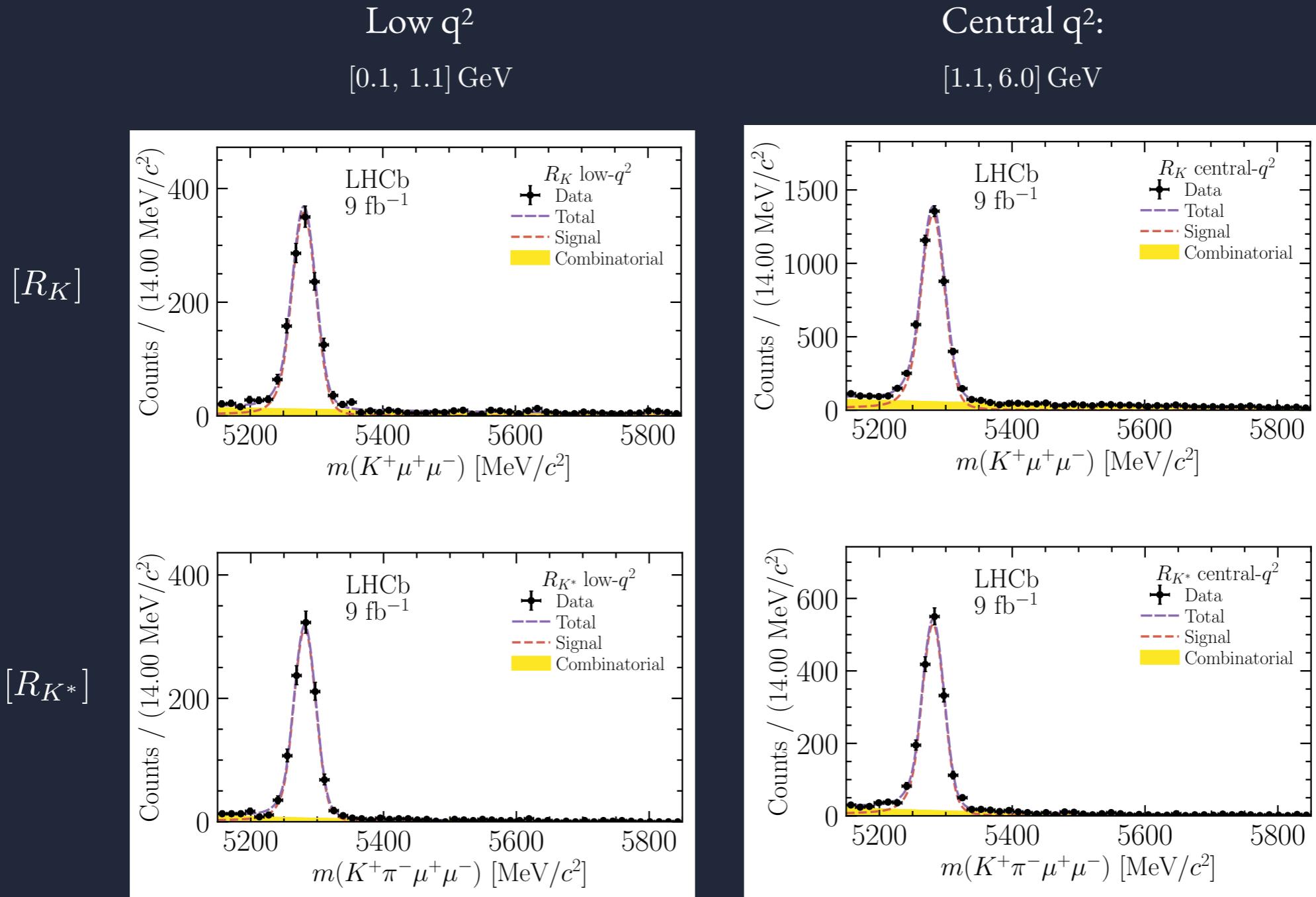
Legacy Measurement: efficiency and double ratios

IMPROVED SIMULATION CORRECTIONS AND STRINGENT CROSSCHECK WITH RESONANT MODES

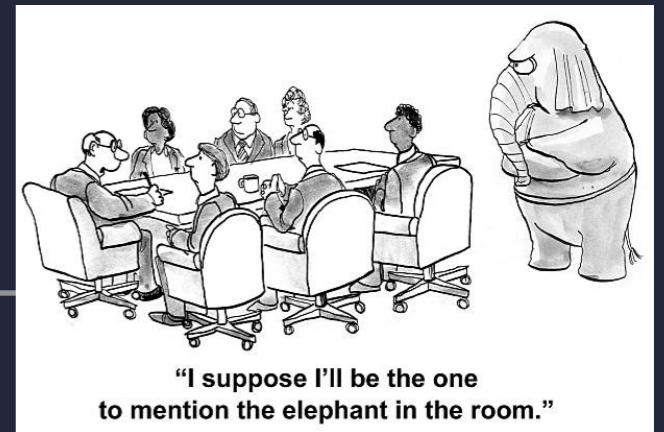


SIMILAR RESULT FOR OTHER CHARMONIUM (2S)

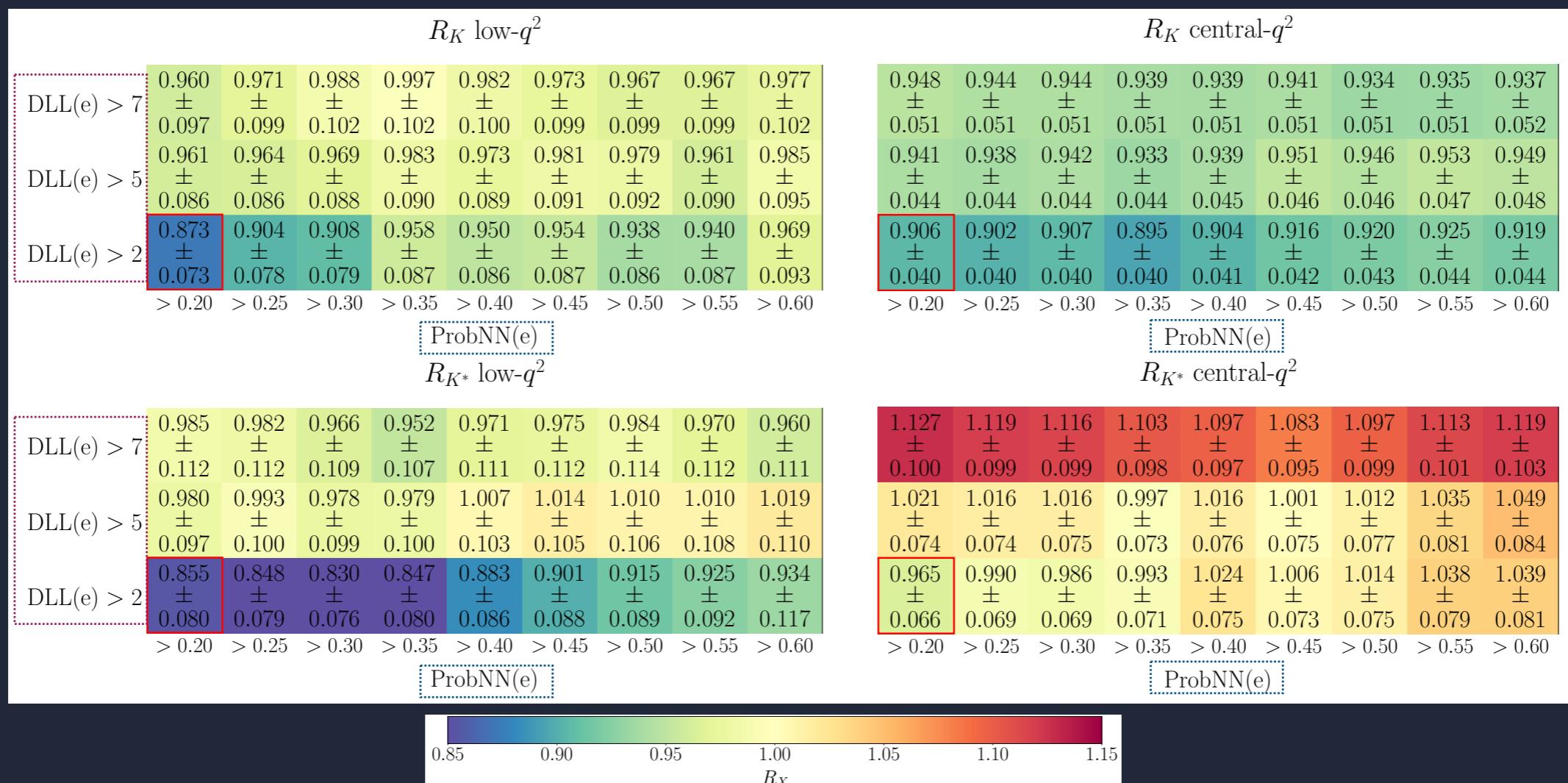
Legacy Measurement: *muon data fits*



Legacy Measurement: *the elephant in the room*

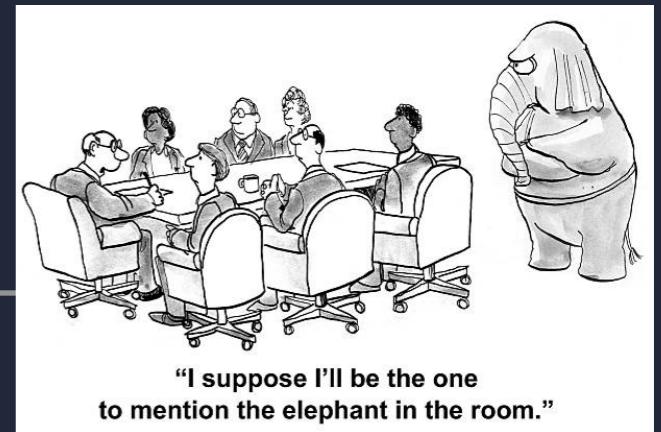


TIGHTENING ELECTRON PID EXHIBITS A COHERENT PATTERN



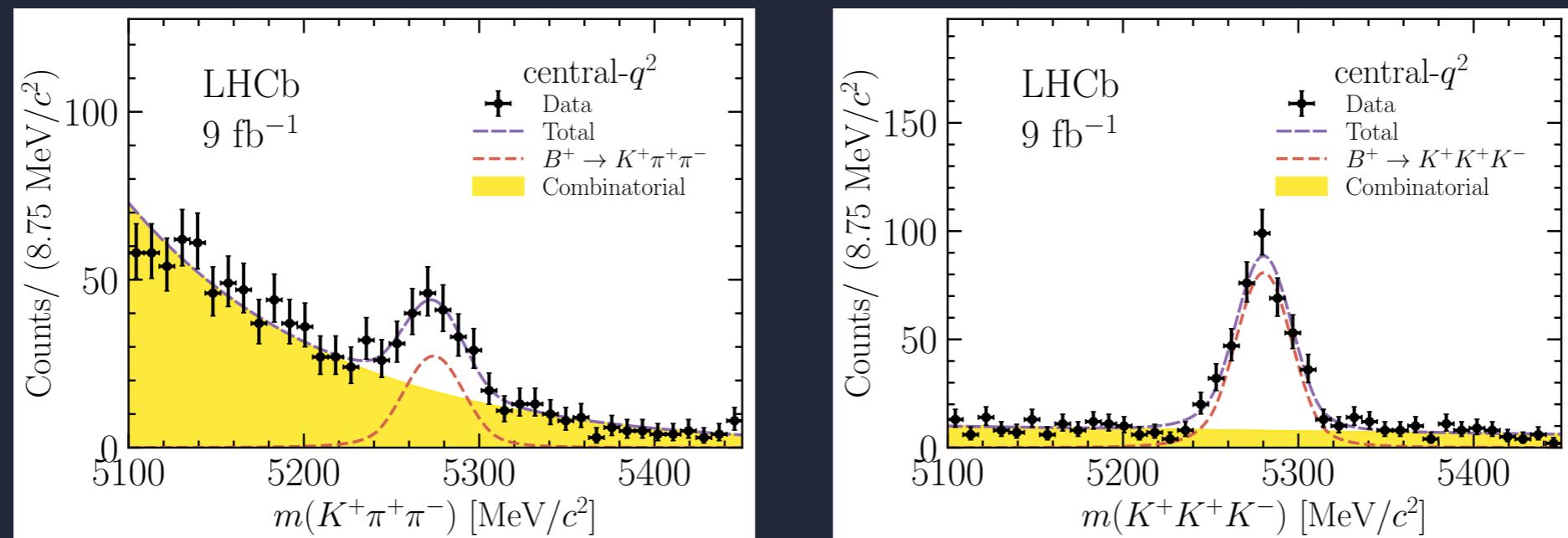
DLL(e): combination of sub-detectors delta log-likelihood for π/e
ProbNN(e): neural-net based e-ID score

Legacy Measurement: *the elephant in the room*



DID WE MISS SOMETHING? WHAT ABOUT DOUBLE MISIDENTIFICATION?

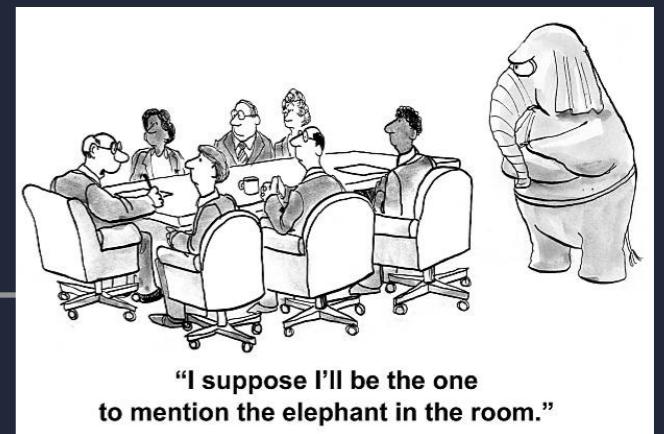
INVERTING THE PID SELECTION



- ▶ SIMILAR STRUCTURE SEEN IN R_{K^*} ; HOWEVER UNKNOWN DYNAMICS
- ▶ SINGLE MISIDENTIFICATION AS WELL; OFTEN UNKNOWN

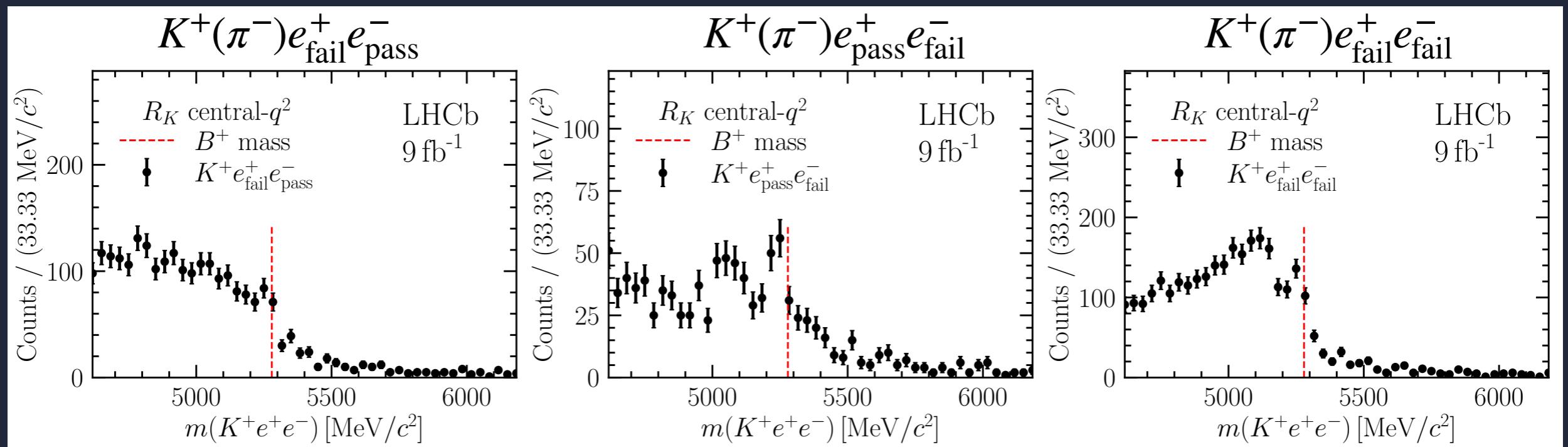
NEW DATA-DRIVEN METHODOLOGY TO ESTIMATE MISIDENTIFIED BACKGROUNDS

Legacy Measurement: *the elephant in the room*



INVERT PID REQUIREMENTS ON ONE OR BOTH ELECTRONS (CONTROL CHANNEL)

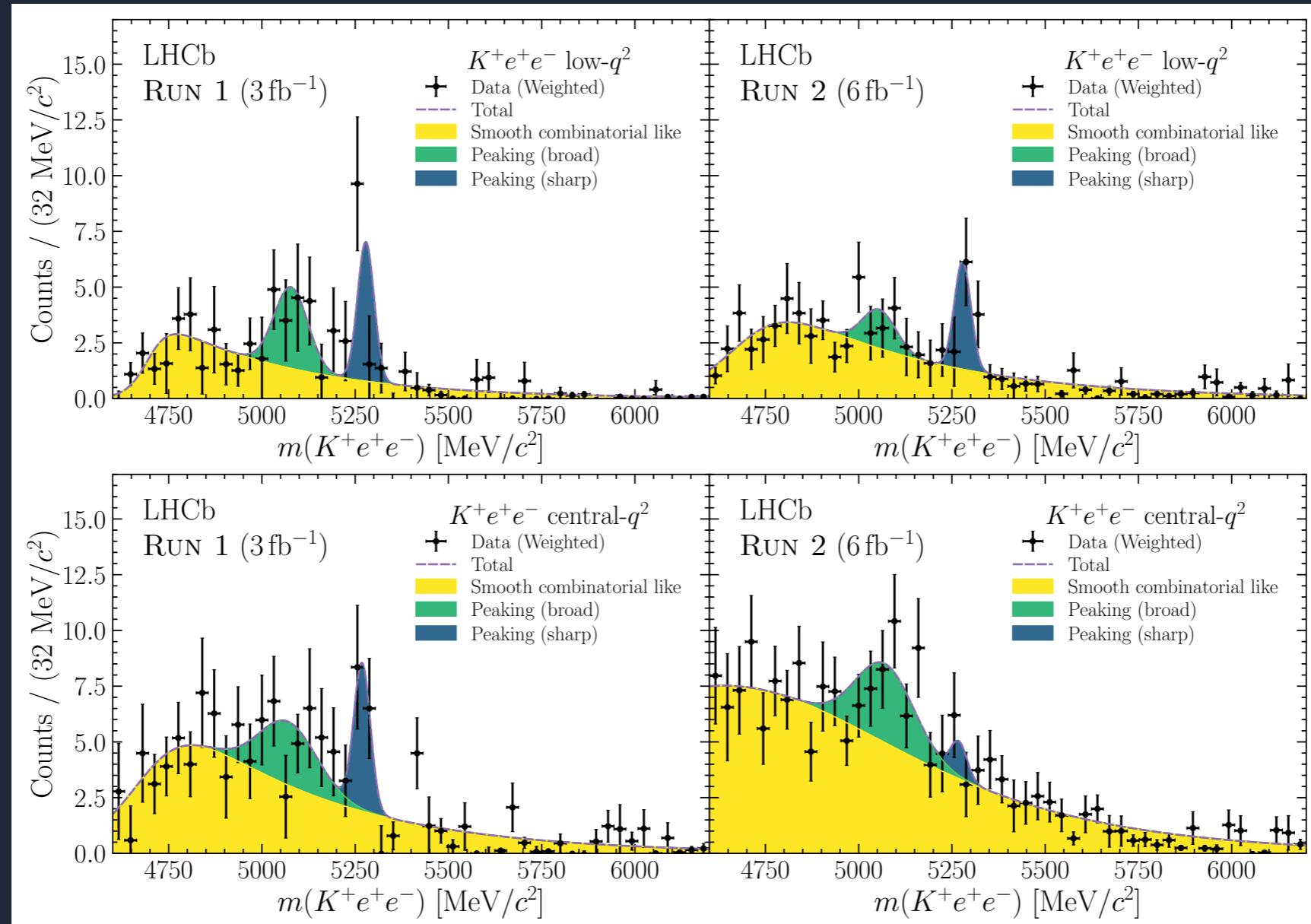
CONTROL REGIONS



- ▶ CATEGORISE PION- AND KAON-LIKE ELECTRONS IN CONTROL REGION WITH NEURAL-NET ID
- ▶ PARAMETRIZE SHAPE AND PREDICT NORMALISATION OF SUCH CONTRIBUTION

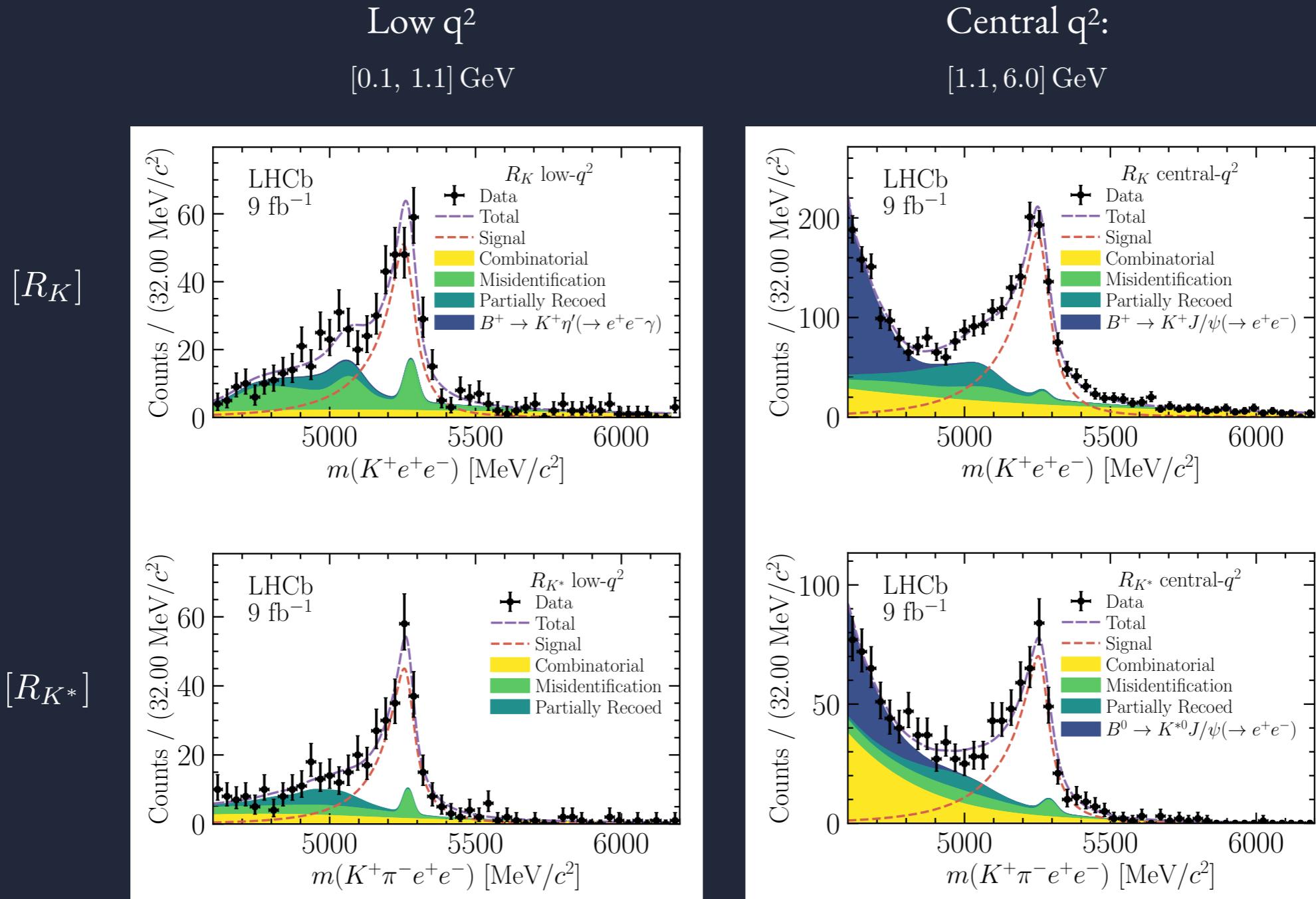
Legacy Measurement: misidentified background (electrons)

$[R_K]$



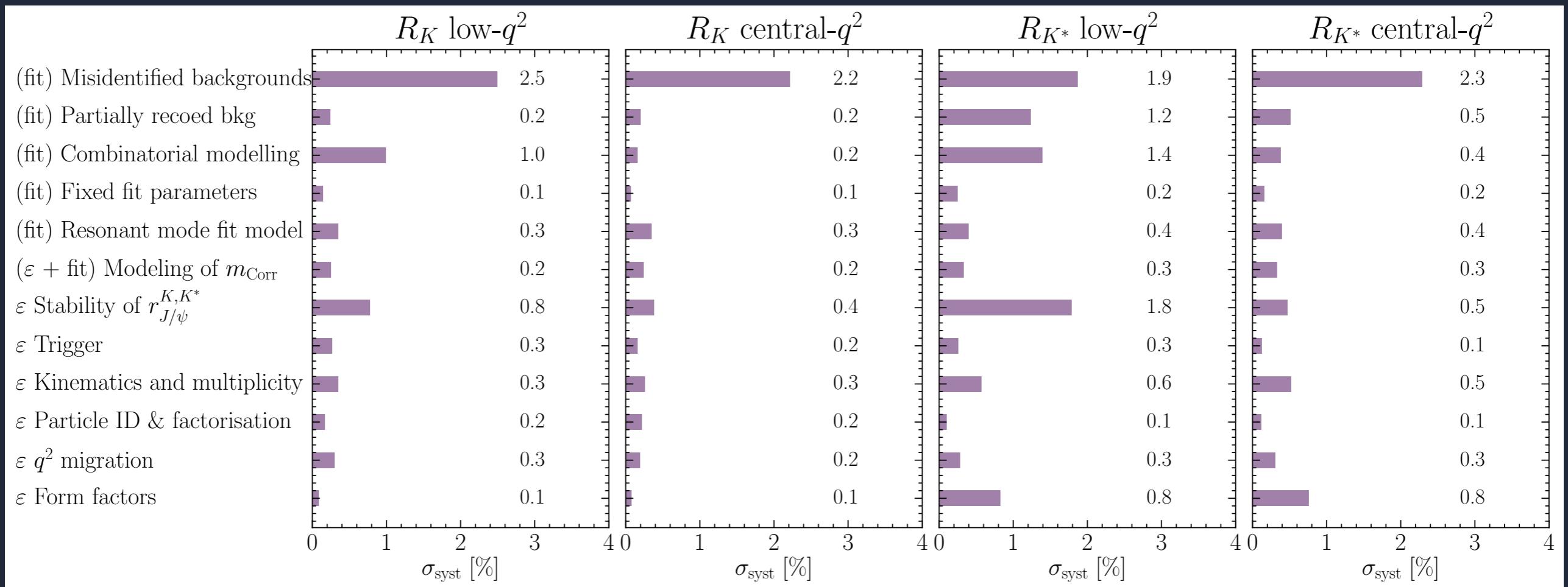
SIMILAR MISIDENTIFIED BACKGROUND MODELLING FOR R_{K^*}

Legacy Measurement: *data mass fits*



Legacy Measurement: *systematics breakdown*

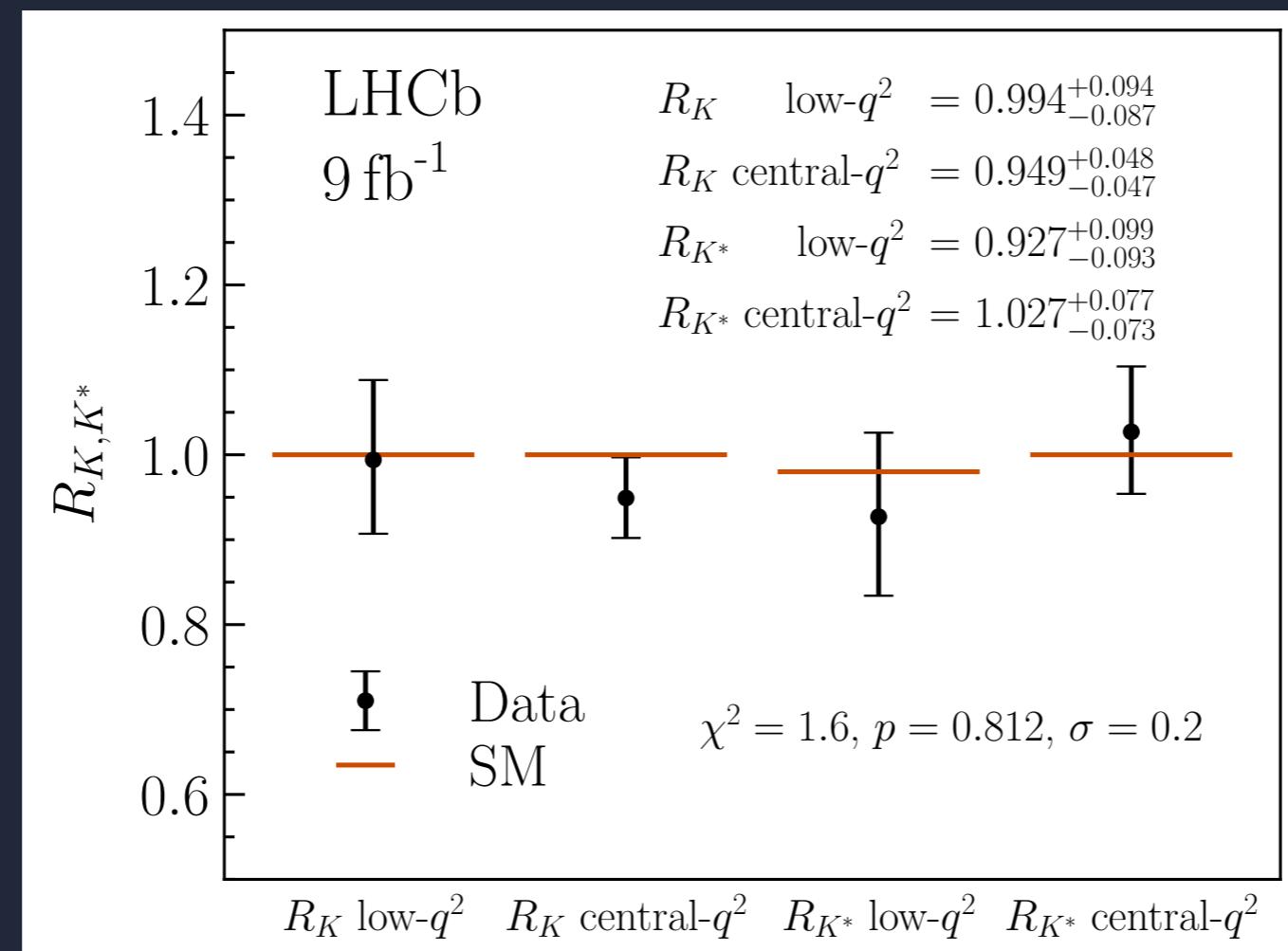
DOMINANT SYSTEMATIC FROM MISIDENTIFIED BACKGROUNDS ESTIMATION



MEASUREMENT STILL STATISTICALLY DOMINATED

Legacy Measurement: *results*

MOST STRINGENT LFU MEASUREMENT IN THESE TRANSITIONS



COMPATIBILITY WITH THE SM (SIMPLE CHI-TEST) ON 4 MEASUREMENTS OF 0.2 SIGMA