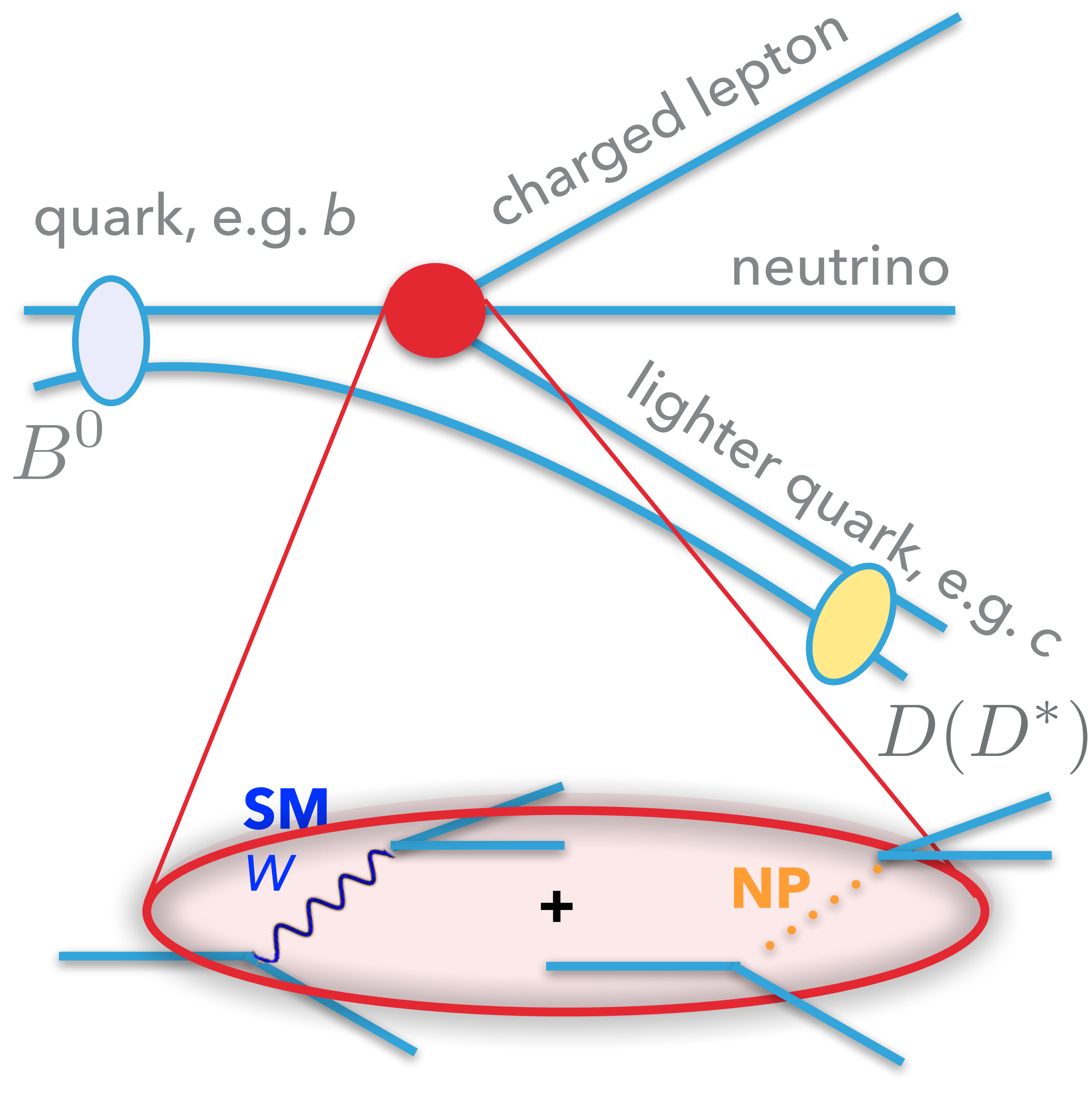
Flavour Physics at the LHC and elsewhere

Lucia Grillo

Joint APP, HEPP and NP Conference

8th April 2024

New Physics searches with flavour



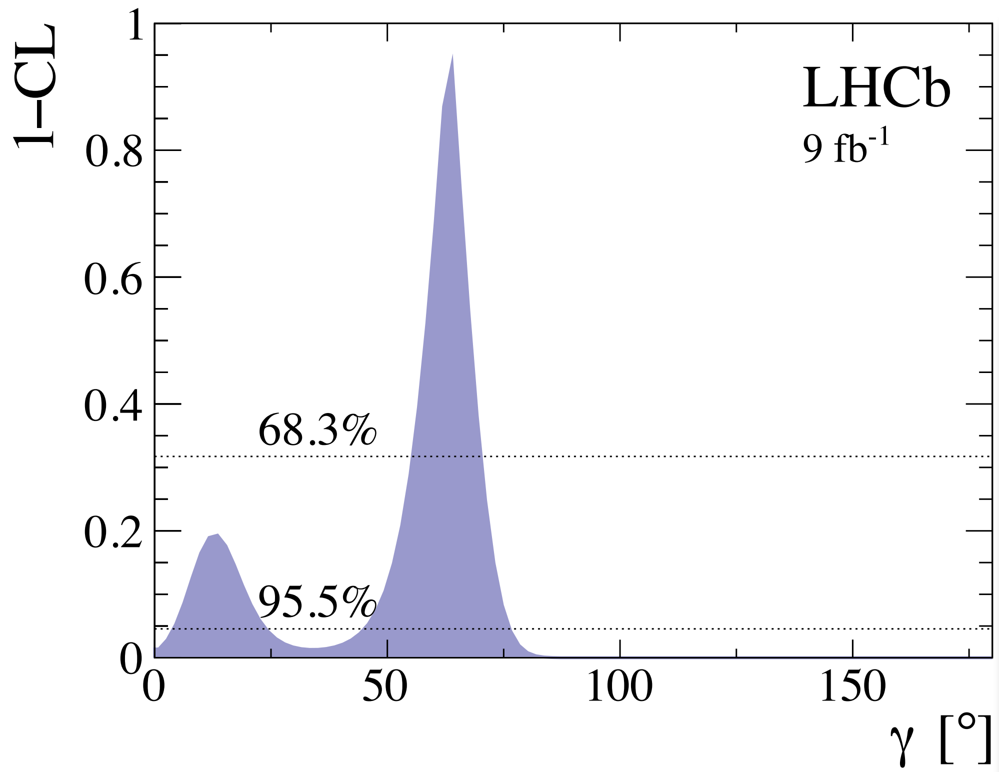
- Extensions of the Standard Model (SM) introduce additional processes, with new particles/interactions:
- Amplitudes are measured via flavour observables:
  - Magnitude: rate
  - Phase: CP violation
  - Lorentz structure: angular distributions
- Precision measurements test energy scales >100 TeV
- Complementary to direct New Physics (NP) searches

- Observables with very small theoretical uncertainty, e.g. CKM angle γ
- Rare processes (forbidden or suppressed in the SM)

Experiment ≠ SM predictions ⇒ New Physics

Selected highlights for today

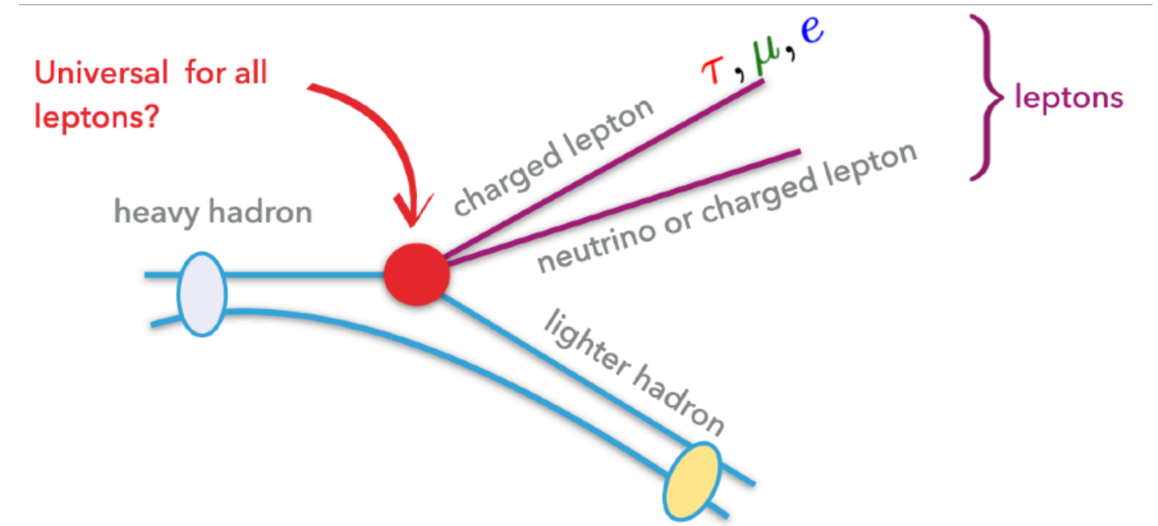
CP Violation and CKM metrology



Not included, but check out also:

- **Mo Ghani**'s poster *Measurement of the CKM matrix element $|V_{cb}|$ in ATLAS $t\bar{t}$ decays*

Lepton Flavour Universality and Rare Decays

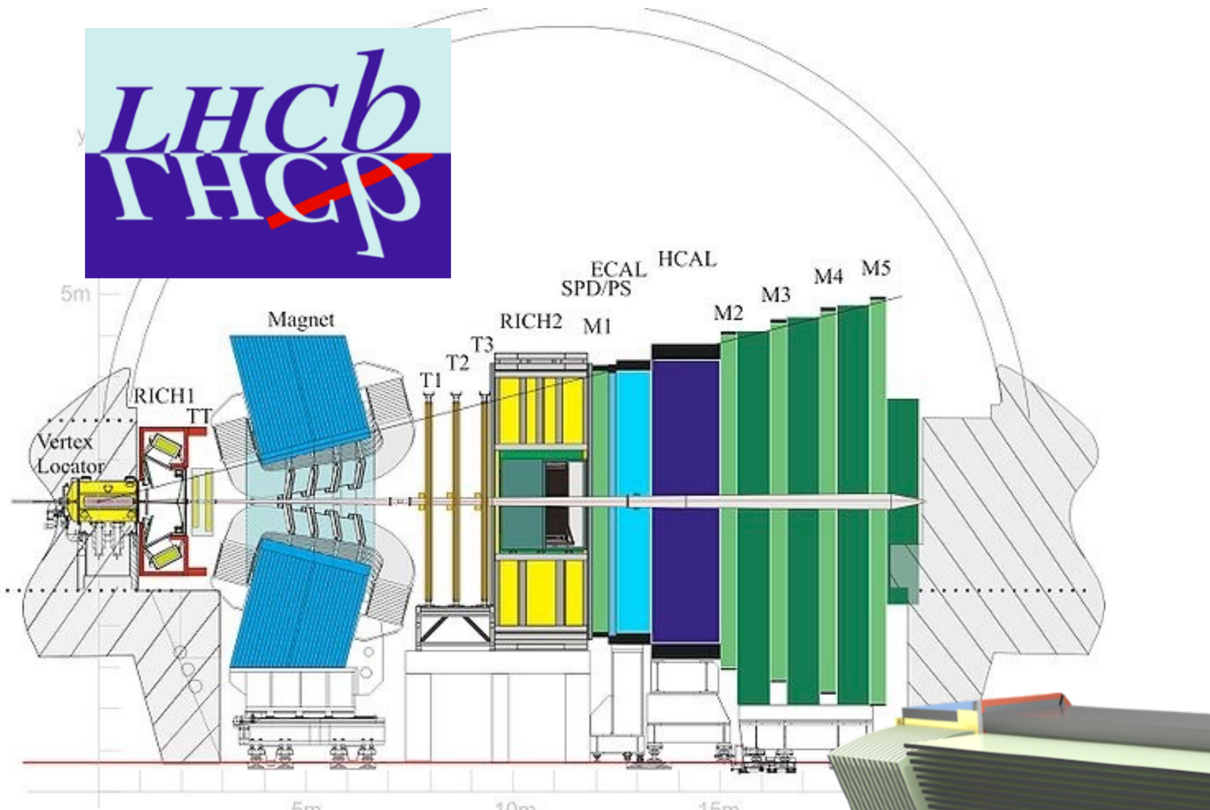


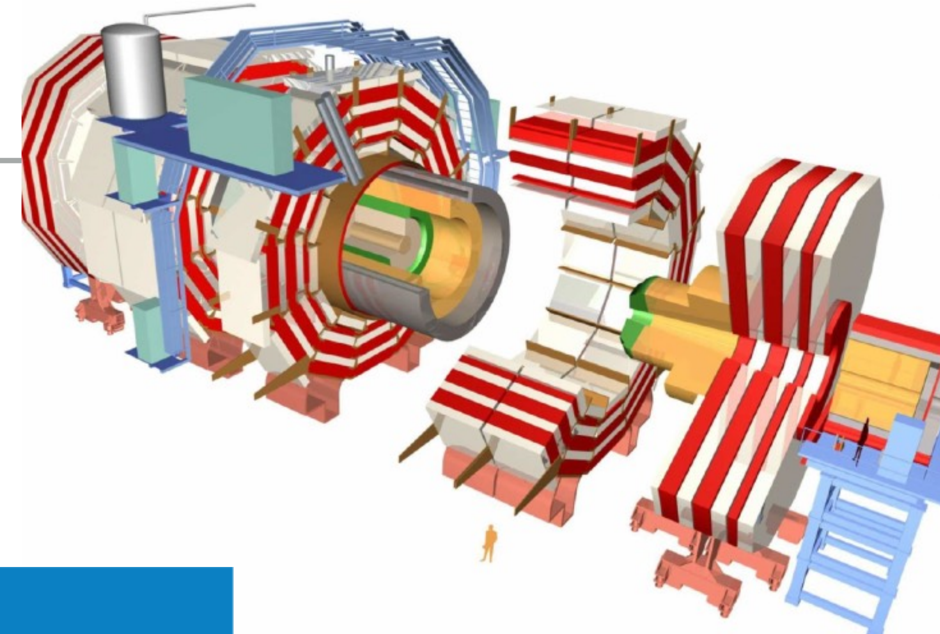
Not included, but check out also:

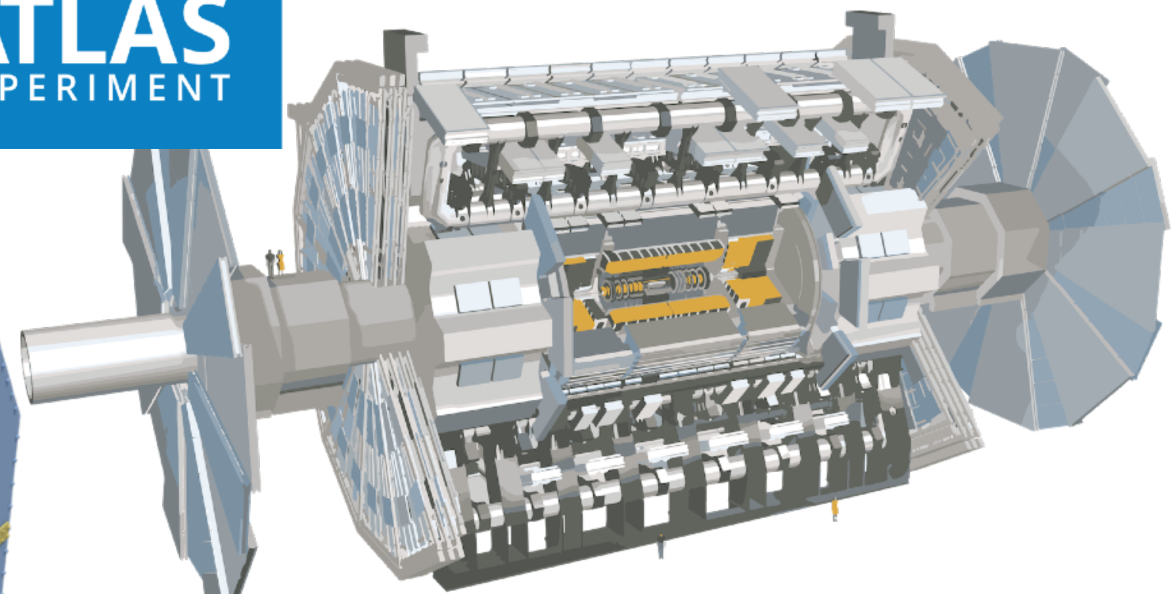
- **Conor McPartland**'s talk *A search for lepton flavour violating $\tau \to 3\mu$ decays at ATLAS* , Wed 9:00
- **Mary Richardson-Slipper**'s talk *Search for rare $B^0 \to \phi\phi$ decays in LHCb Run1+2* , Wed 11:30
- **James Brown**'s talk *Search for Right-Handed Weak Decays at LHCb* , Wed 12:15
- **Richard Williams**'s talk *Search for the very rare $B^+ \to \pi^+ e^+ e^-$ decay at LHCb* , Wed 13:30
- **Daniel Thompson**'s talk *Search for the Lepton Flavour Violating Decay $\Lambda_b^0 \to \Lambda(1520)\mu e$ at LHCb*, Wed 13:45

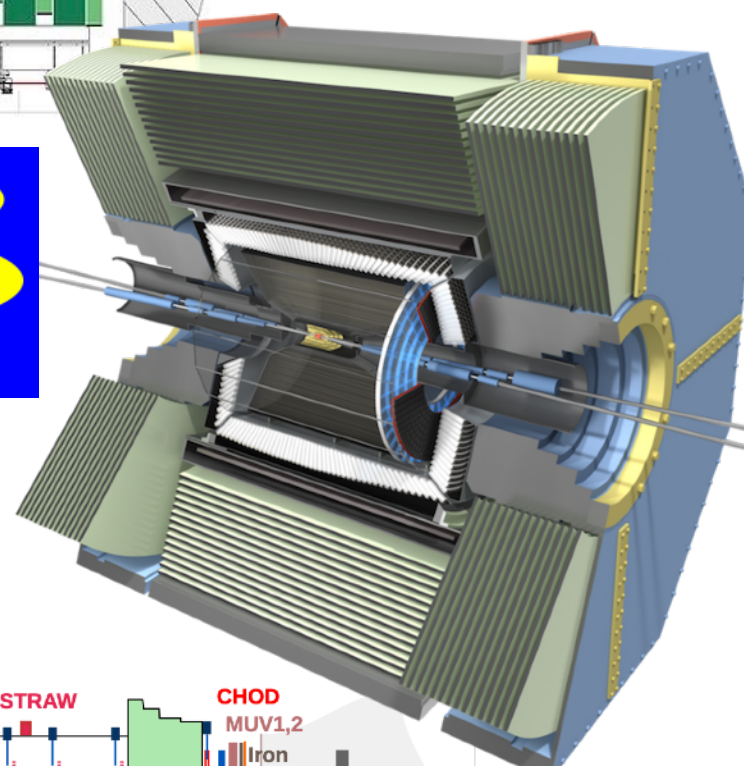
- **In this talk**: a selection of recent results, slightly biased towards UK contributions

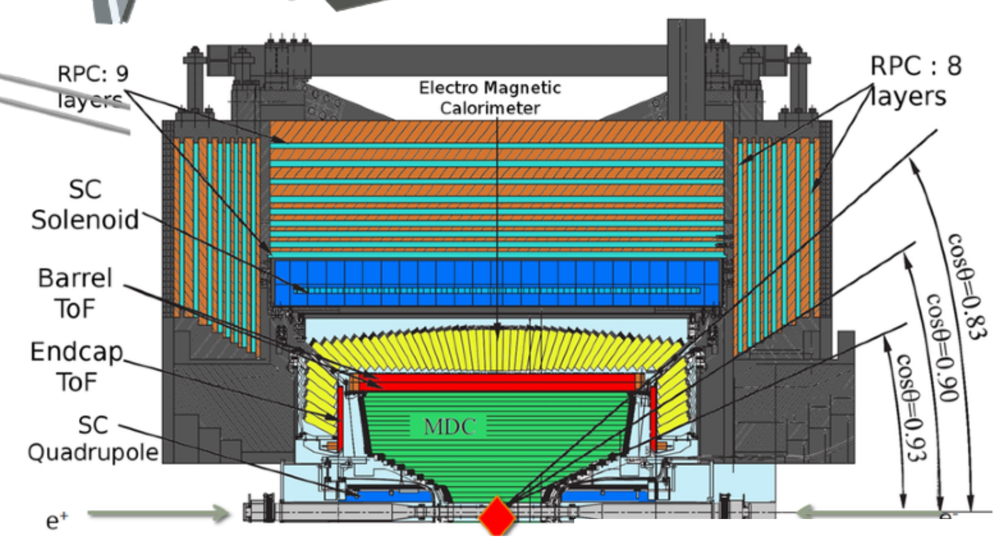
Many actors in the play

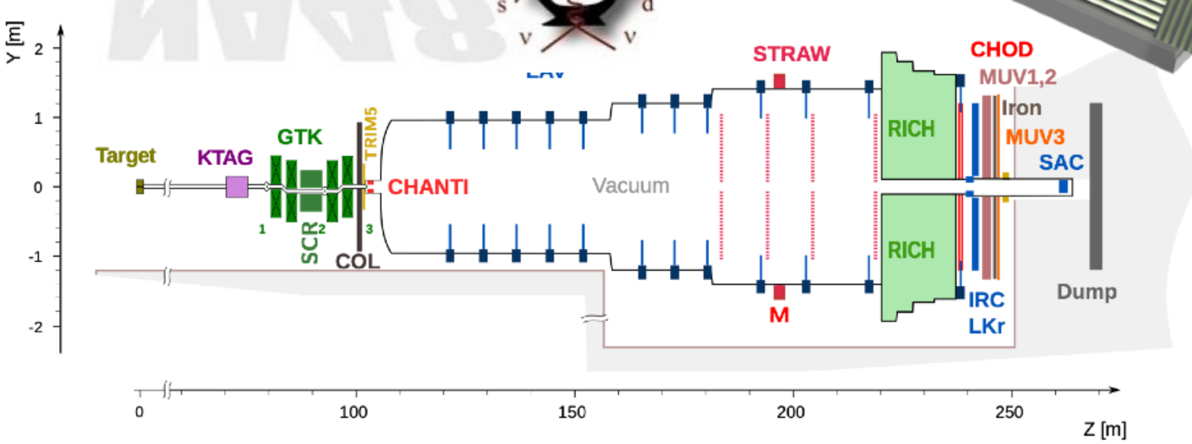








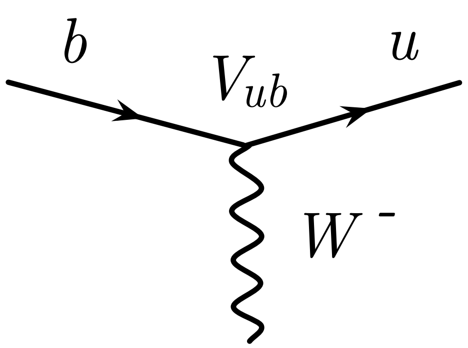




CP violation and CKM metrology

- The Standard Model predicted CP asymmetry is not sufficient to explain the baryon asymmetry of the Universe ⇒ New Physics CP violating effects are expected

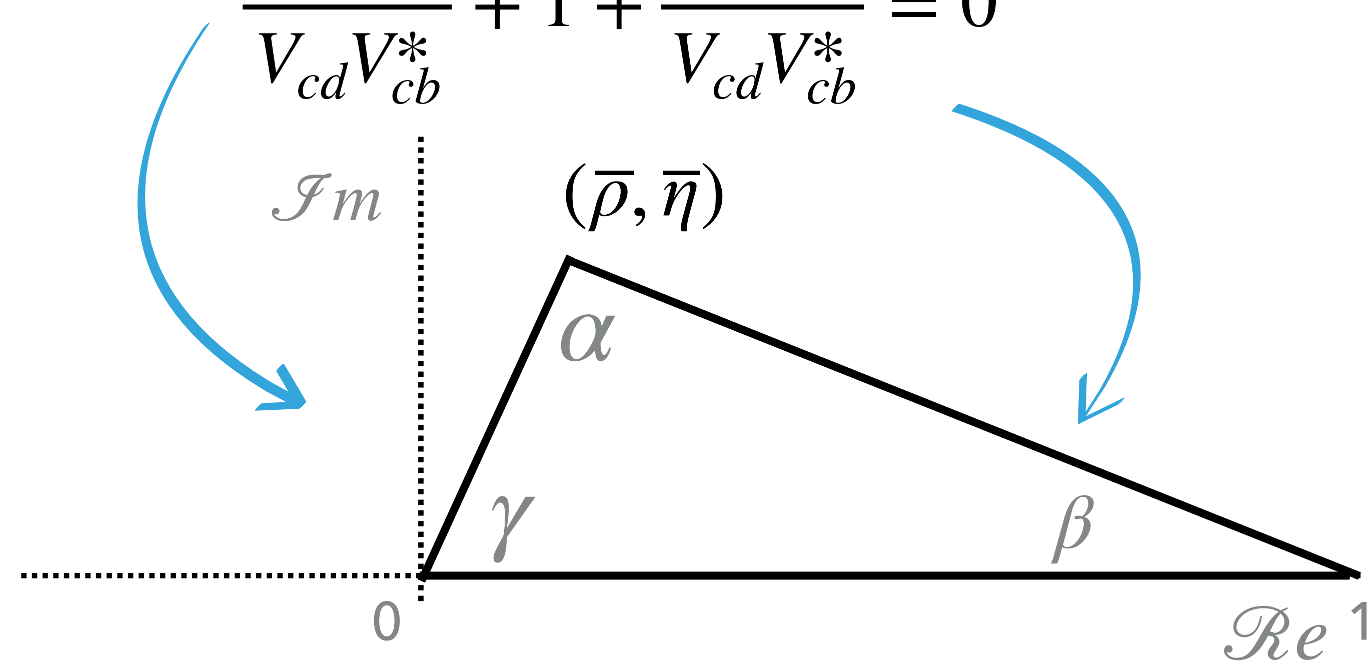
- The only established source of CP violation in the SM is contained in the imaginary part of the CKM matrix describing transitions between quarks



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & V_{\mathrm{ts}} & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

- Unitarity condition $V_{CKM}V_{CKM}^{\dagger} = 1$ leads to Unitarity triangles, e.g.

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + 1 + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0$$



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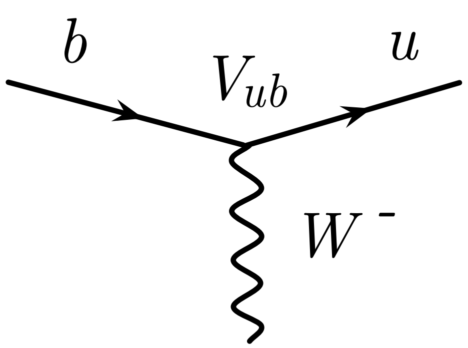

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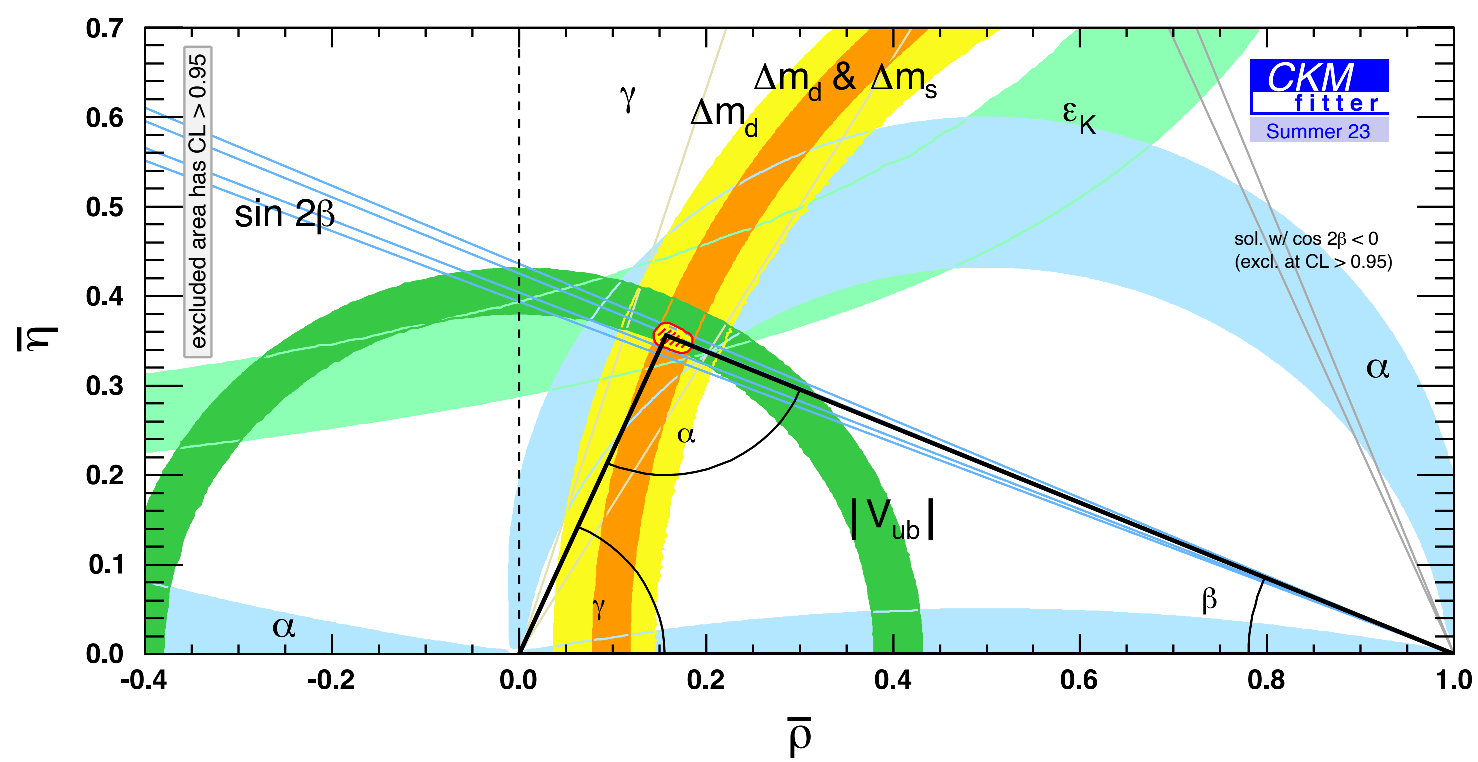
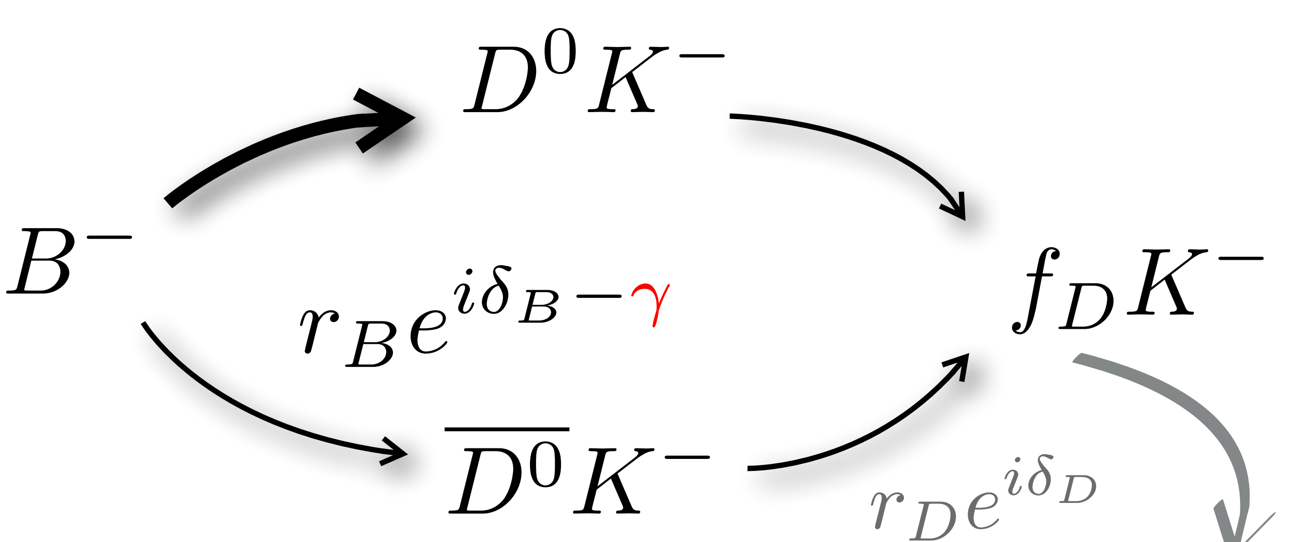
- Unitarity condition $V_{CKM}V^{\dagger}_{CKM} = 1$ leads to Unitarity triangles, e.g.

- Precise measurements of heavy hadron decays ⇒ Redundant determination of the CKM parameters



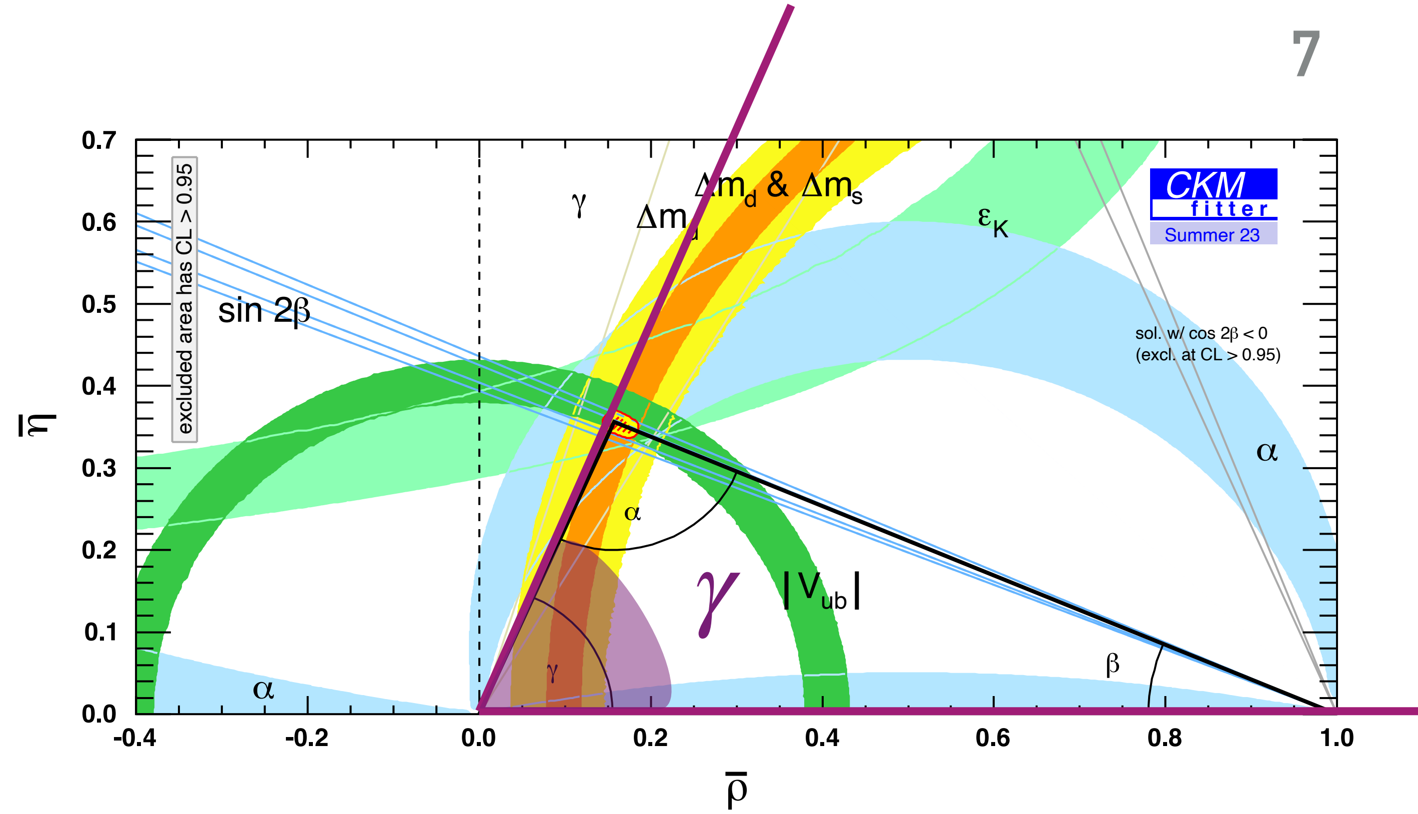
CKM angle γ

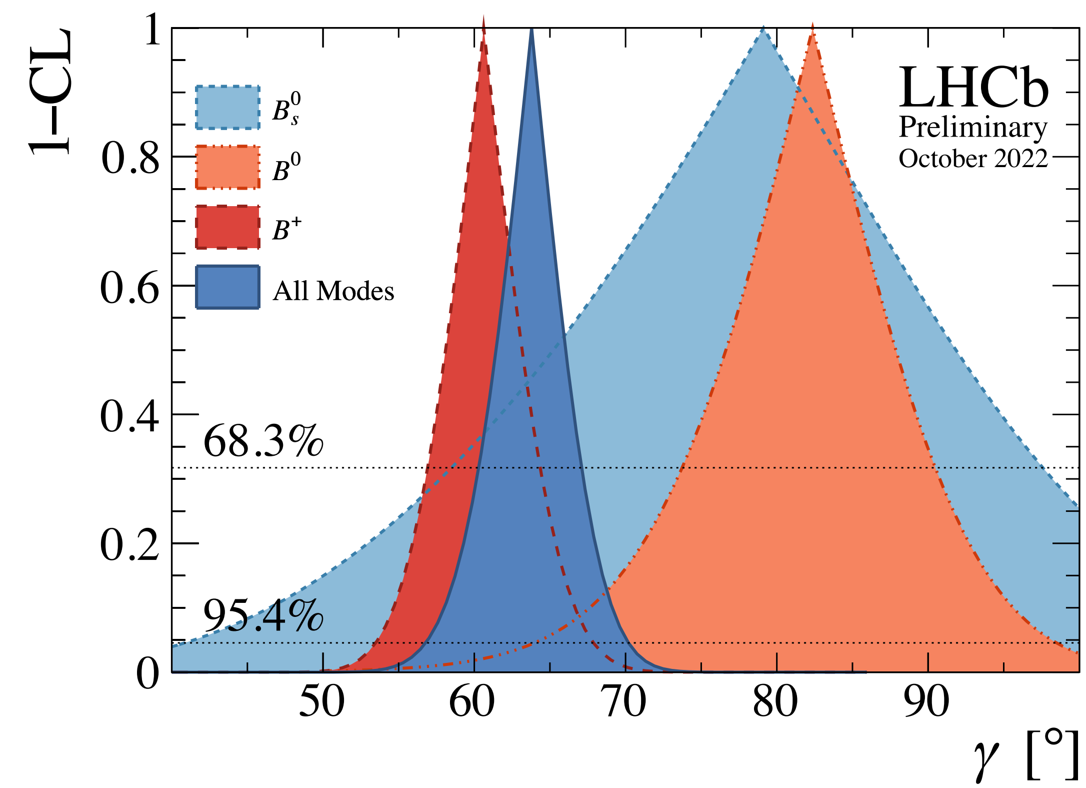
- CKM angle $\gamma \equiv \arg(-V_{ud}V_{ub}^{*}/V_{cd}V_{cb}^{*})$
- SM theory uncertainty is very small $\delta\gamma/\gamma \sim \mathcal{O}(10^{-7})$
- New Physics models can lead to sizeable effects
- CP-violating parameter that can be measured using tree-level transitions
- Exploit interference between amplitudes, conventionally $B^{\pm} \to Dh^{\pm}$



$A_{CP} \propto r_B \sin\delta_B \sin\gamma$

f_D accessible from both D^0 and $\overline{D}^0$





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LHCB-CONF-2022-003

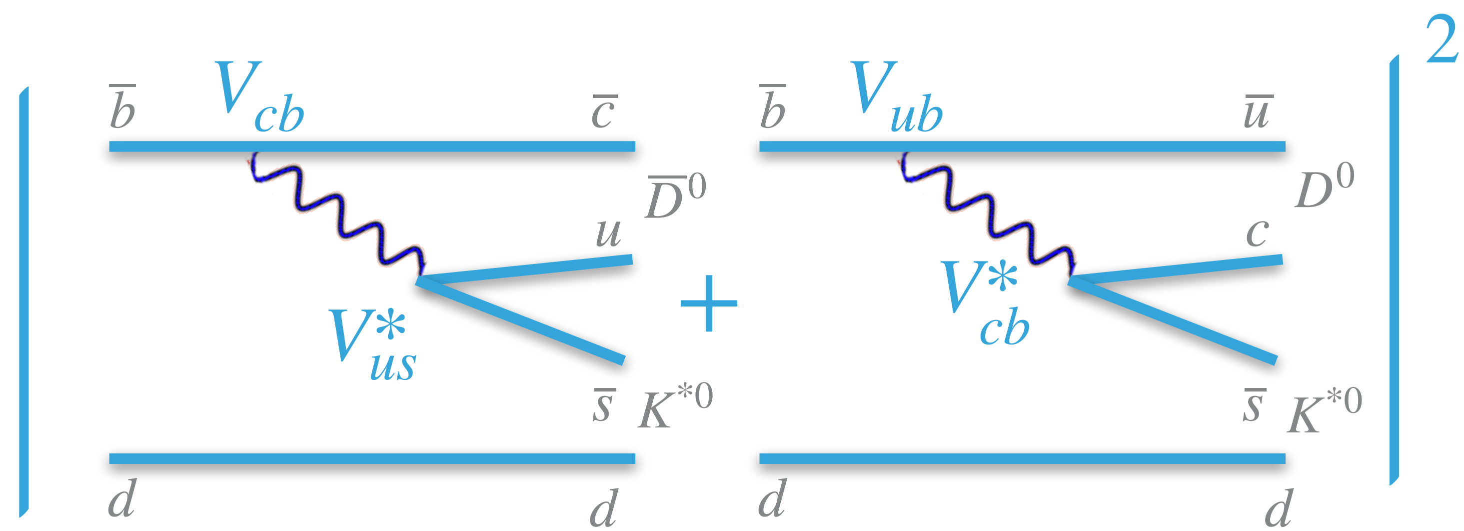
$\gamma = (63.8^{+3.5}_{-3.7})^{\circ}$

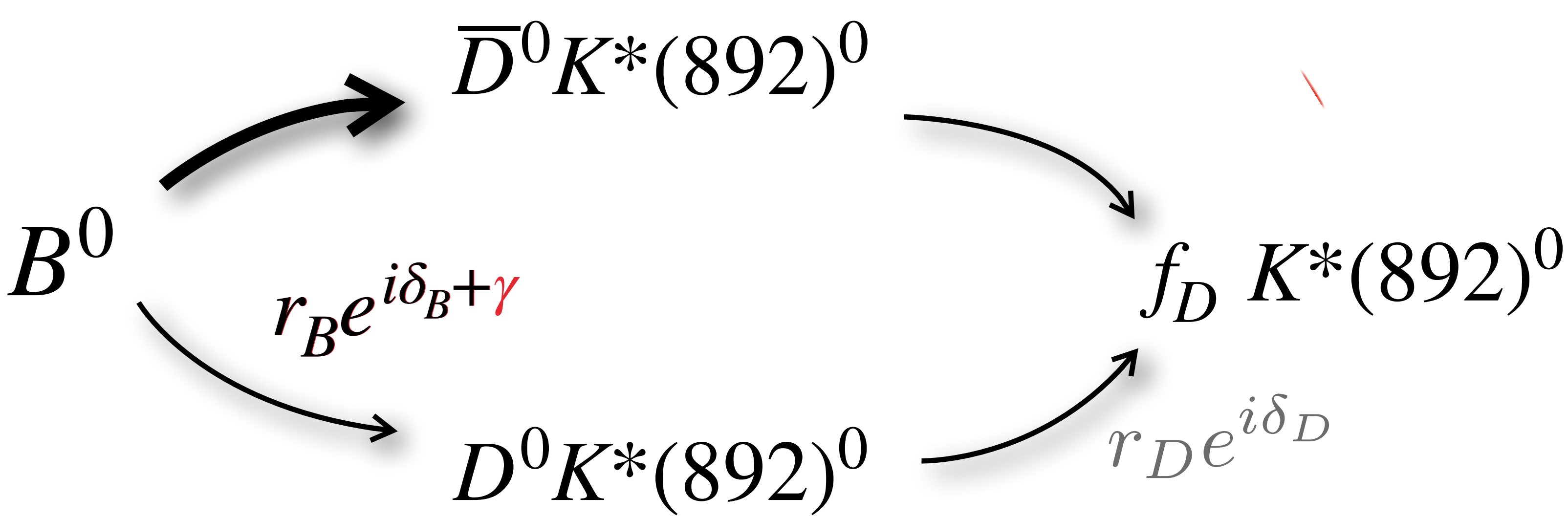
HFLAV

$\gamma = (66.2^{+3.4}_{-3.6})^{\circ}$

CKM angle γ

- CKM angle $\gamma \equiv \arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$
- CP-violating parameter that can be measured using tree-level transitions
- Exploit interference between amplitudes, e.g.





$K^*(892)^0 \to K^+\pi^-$

$$A_{CP} \propto r_B \sin\delta_B \sin\gamma$$

Need non-zero strong and weak phases to observe A_{CP}

$f_D : K^-\pi^+(\pi^-\pi^+)$

Mixture of $D^0 \to K^+\pi^-$ and $\overline{D}^0 \to K^+\pi^-$:

$f_D : K^+K^-$ and $\pi^-\pi^+$

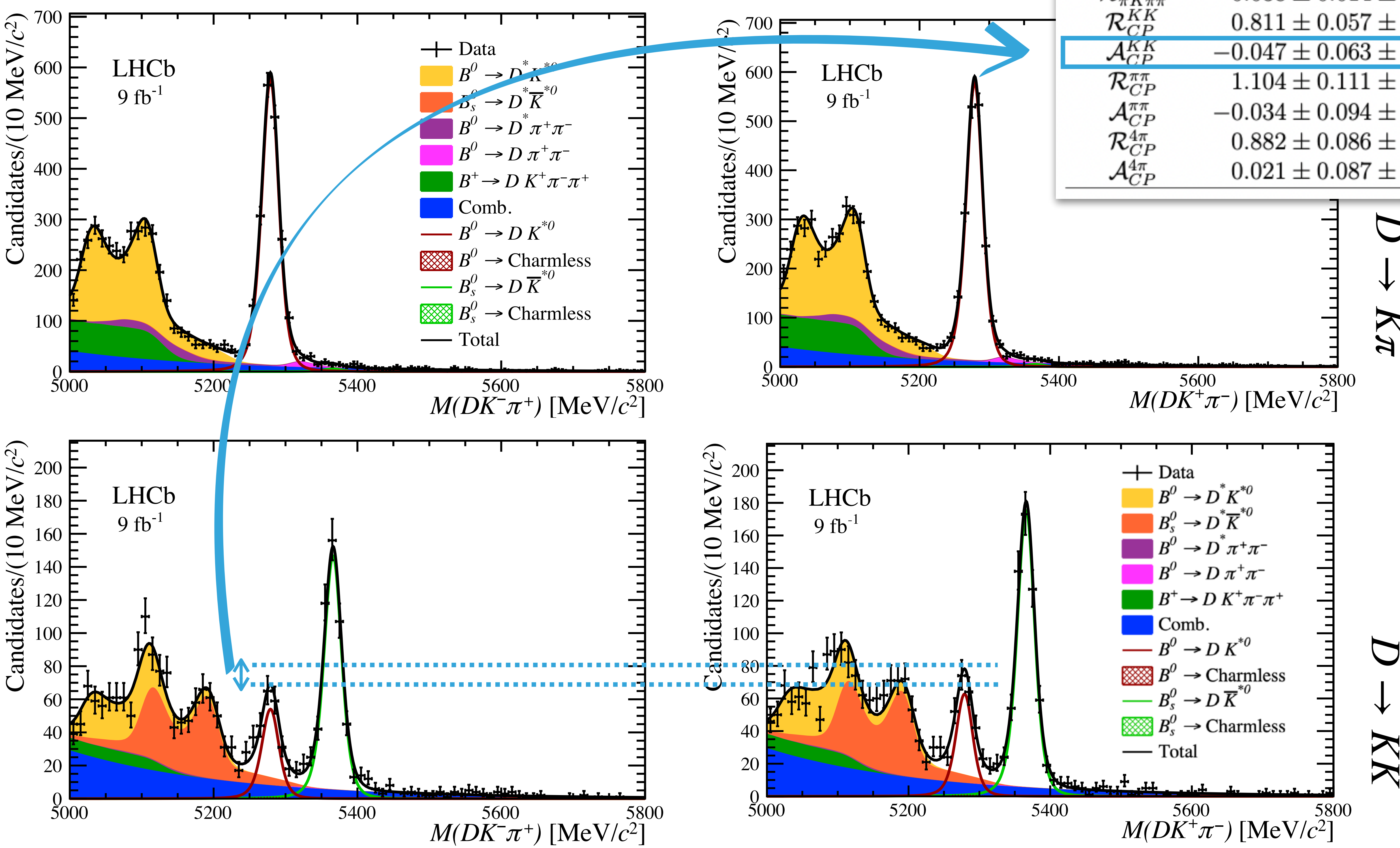
CP-eigenstates final states

CKM angle γ

LHCB-PAPER-2023-040

- Run1 + Run2 dataset, ADS and (extended) GLW final states
- Measure CP observables and relate them to γ, $r_{B^0}^{DK^*}$, $\delta_{B^0}^{DK^*}$

Parameter	Value
$\mathcal{A}_{K\pi}$	$0.031 \pm 0.017 \pm 0.015$
$\mathcal{R}_{\pi K}^{+}$	$0.069 \pm 0.013 \pm 0.005$
$\mathcal{R}_{\pi K}^{-}$	$0.093 \pm 0.013 \pm 0.005$
$\mathcal{A}_{K\pi\pi\pi}$	$-0.012 \pm 0.018 \pm 0.016$
$\mathcal{R}_{\pi K\pi\pi}^{+}$	$0.060 \pm 0.014 \pm 0.006$
$\mathcal{R}_{\pi K\pi\pi}^{-}$	$0.038 \pm 0.014 \pm 0.006$
$\mathcal{R}_{CP}^{KK}$	$0.811 \pm 0.057 \pm 0.017$
$\mathcal{A}_{CP}^{KK}$	$-0.047 \pm 0.063 \pm 0.015$
$\mathcal{R}_{CP}^{\pi\pi}$	$1.104 \pm 0.111 \pm 0.026$
$\mathcal{A}_{CP}^{\pi\pi}$	$-0.034 \pm 0.094 \pm 0.016$
$\mathcal{R}_{CP}^{4\pi}$	$0.882 \pm 0.086 \pm 0.033$
$\mathcal{A}_{CP}^{4\pi}$	$0.021 \pm 0.087 \pm 0.016$



CKM angle γ

LHCB-PAPER-2023-040

- Measure CP observables and relate them to γ, $r_{B^0}^{DK^*}$, $\delta_{B^0}^{DK^*}$
- Four solutions are found → a combined analysis with $B^0 \to DK^{*0}$, $D \to K_S^0 h^+ h^-$ breaks the 90° degeneracy

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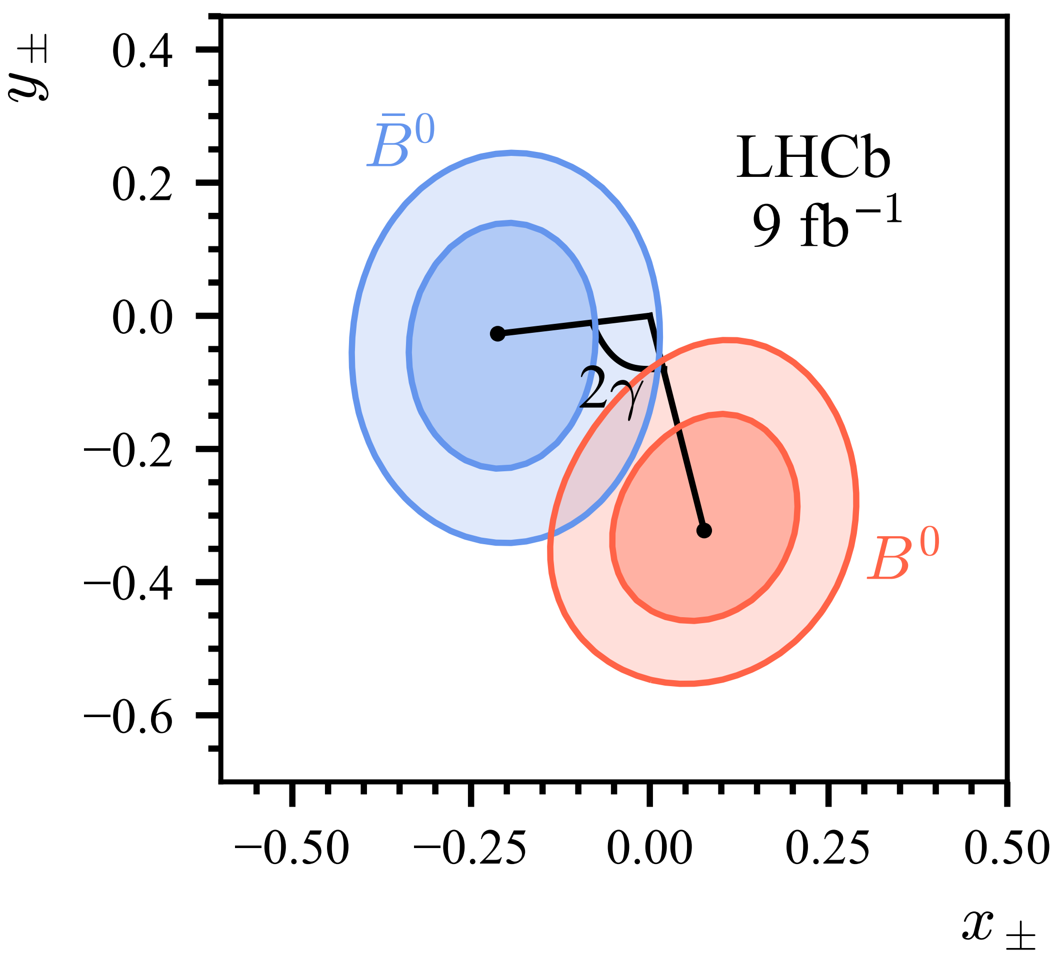
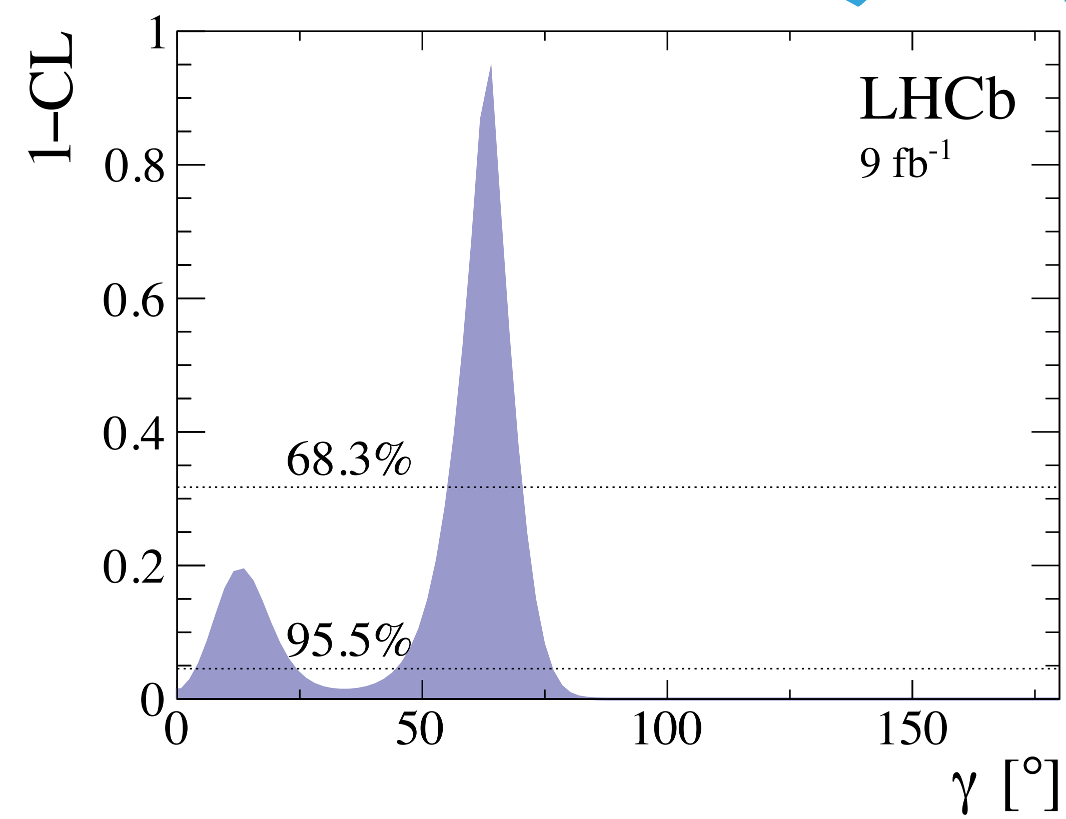


- Measure CP observables in bins of the 3-body charm decay phase space

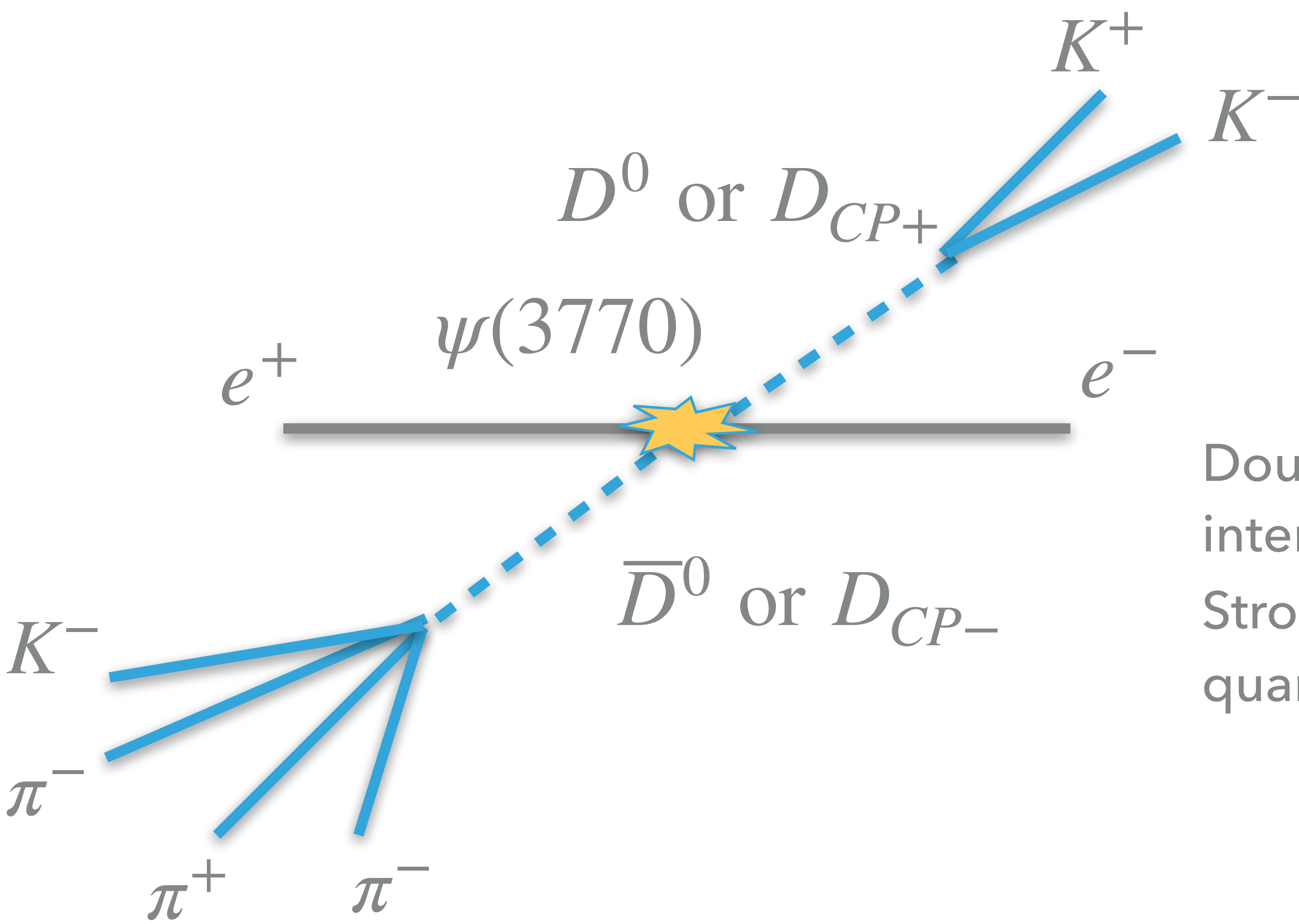
$$x_\pm \equiv r_{B^0} \cos(\delta_{B^0} \pm \gamma)$$
$$y_\pm \equiv r_{B^0} \sin(\delta_{B^0} \pm \gamma)$$



$$\gamma = (63.3 \pm 7.2)^\circ$$
$$r_{B^0}^{DK^*} = 0.233 \pm 0.016$$
$$\delta_{B^0}^{DK^*} = (191.9 \pm 6.0)^\circ$$

Strong phases: charm at threshold at BESIII

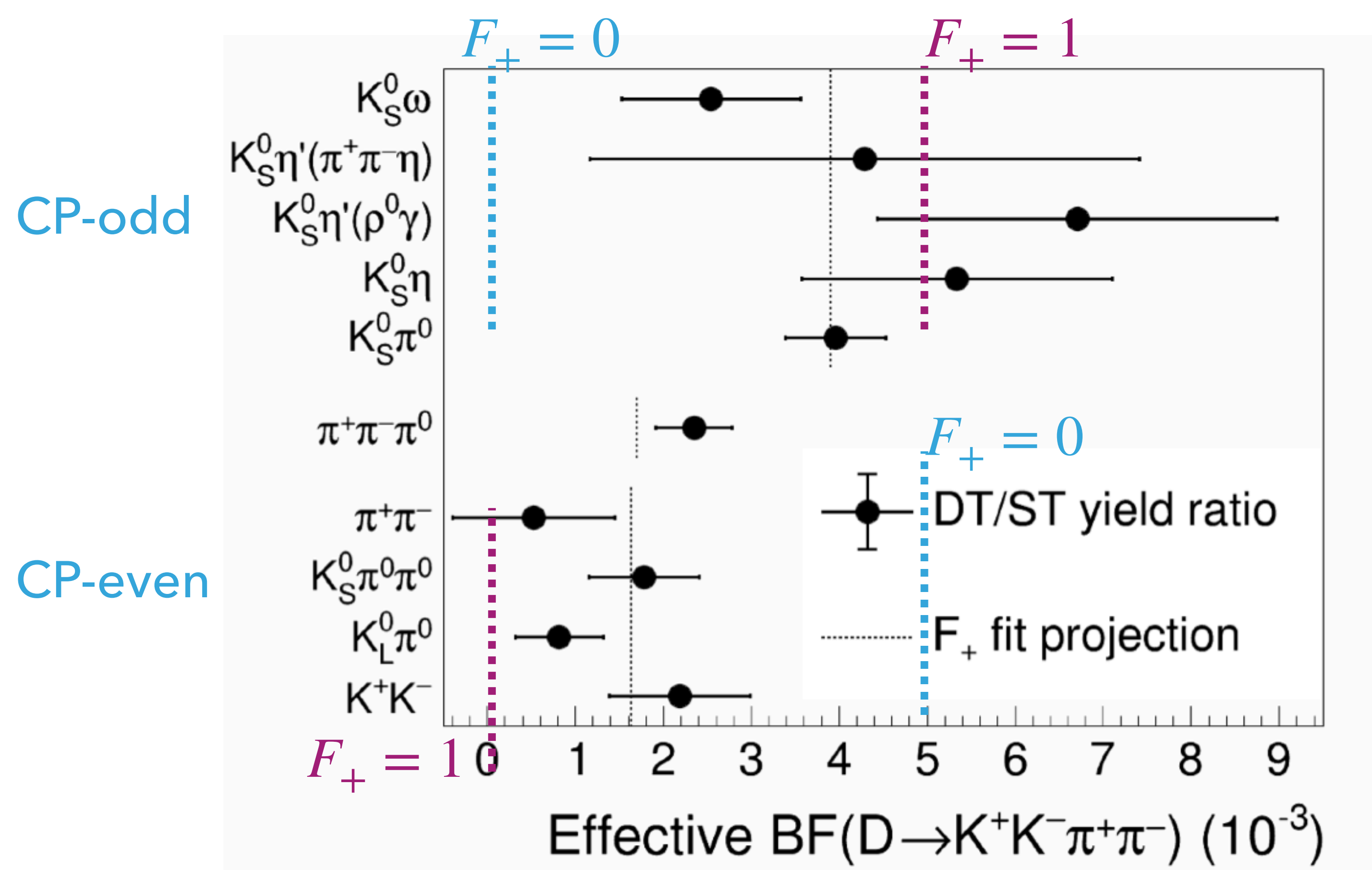
- BEPCII is a symmetric e^+e^- collider, with variable centre of mass energy
    - Dataset at $\psi(3770) \to D\overline{D}$: no energy for a single additional pion
    - The D and $\overline{D}$ mesons are produced in a quantum correlated state
    - Unique access to relative strong phases, CP composition

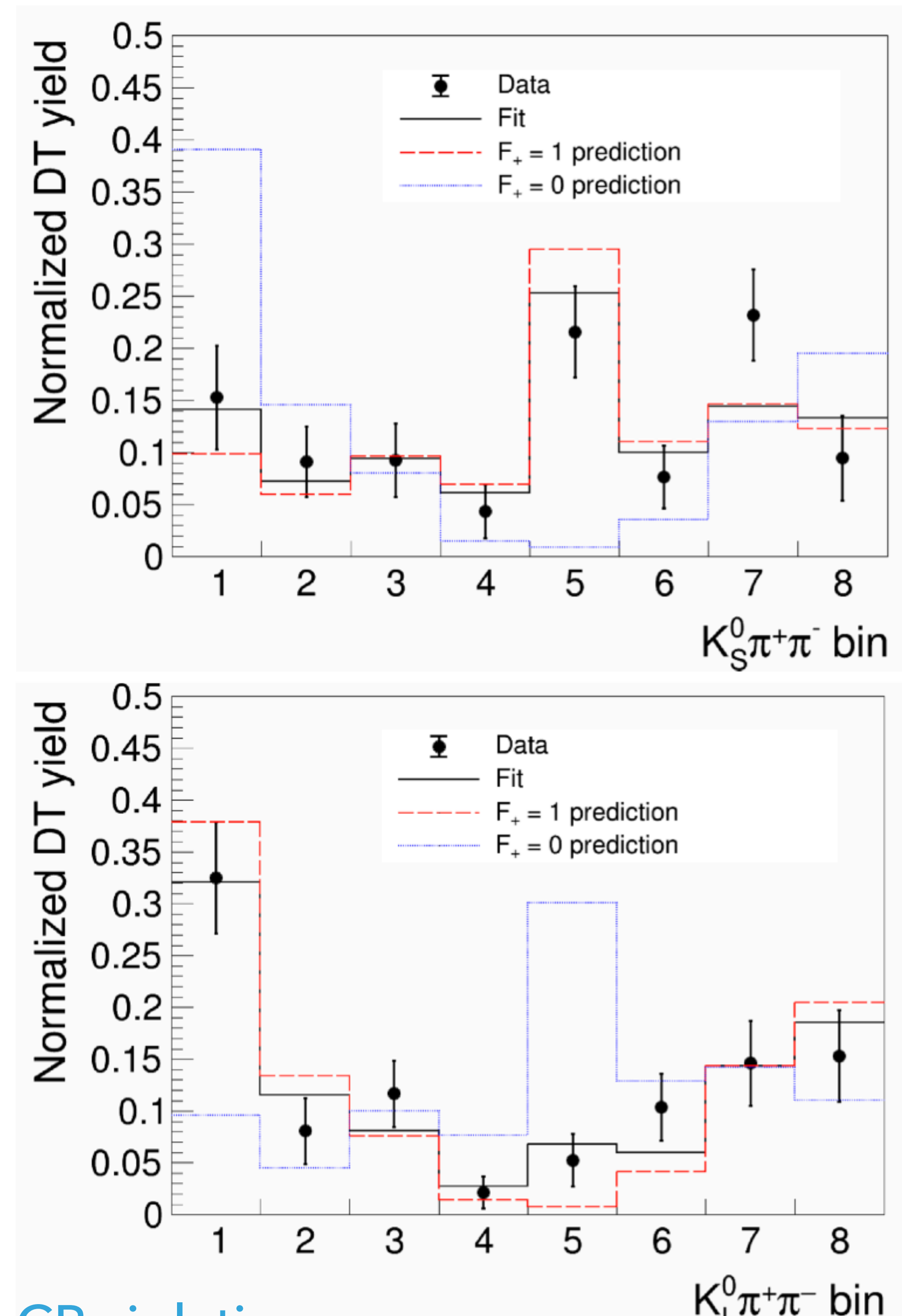


Double-tag method possible: decay mode of interest tagged with a set of known tag modes. Strong phase of D decay of interest inferred from quantum correlation

CP-even fraction

- Measurement of the CP-even fraction of $D^0 \to K^+K^-\pi^+\pi^-$
- Effective BF of $D \to K^+K^-\pi^+\pi^-$ using 10 different CP tag modes: BF from CP-even (odd) tags are suppressed (enhanced)
- Complementary determination using the self-conjugate $K_{S,L}\pi^+\pi^-$ tags





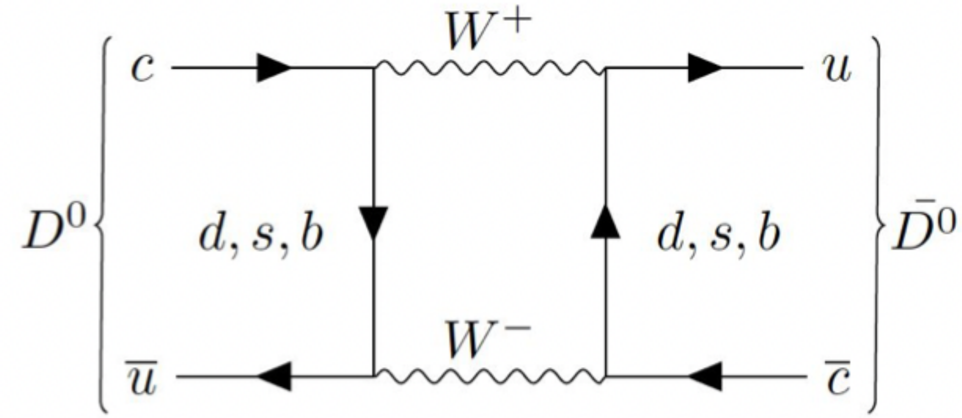
Phys. Rev. D 107, 032009

$$F_+ = 0.730 \pm 0.037 \pm 0.021$$

- Valuable input for CKM angle γ and charm mixing and CP violation
- Measurement of the CP-even fraction of $D^0 \to \pi^+\pi^-\pi^+\pi^-$ Phys. Rev. D 106, 092004

Charm – flavour oscillations and CP violation

- $D^0 - \overline{D}^0$ flavour oscillations:
  - Challenging theory calculations
  - Mixing diagrams suppressed: slow oscillation and very small CP violation
  - CPV in mixing? i.e. $\mathscr{P}(D^0 \to \overline{D}^0) = \mathscr{P}(\overline{D}^0 \to D^0)$?



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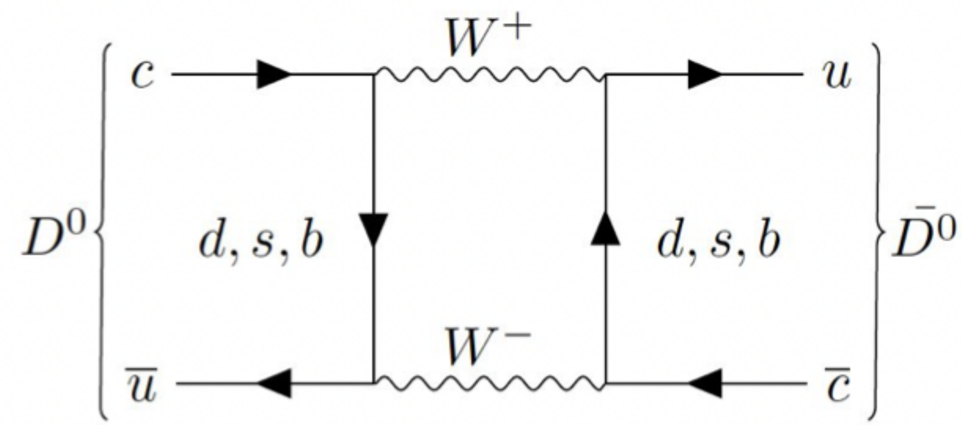
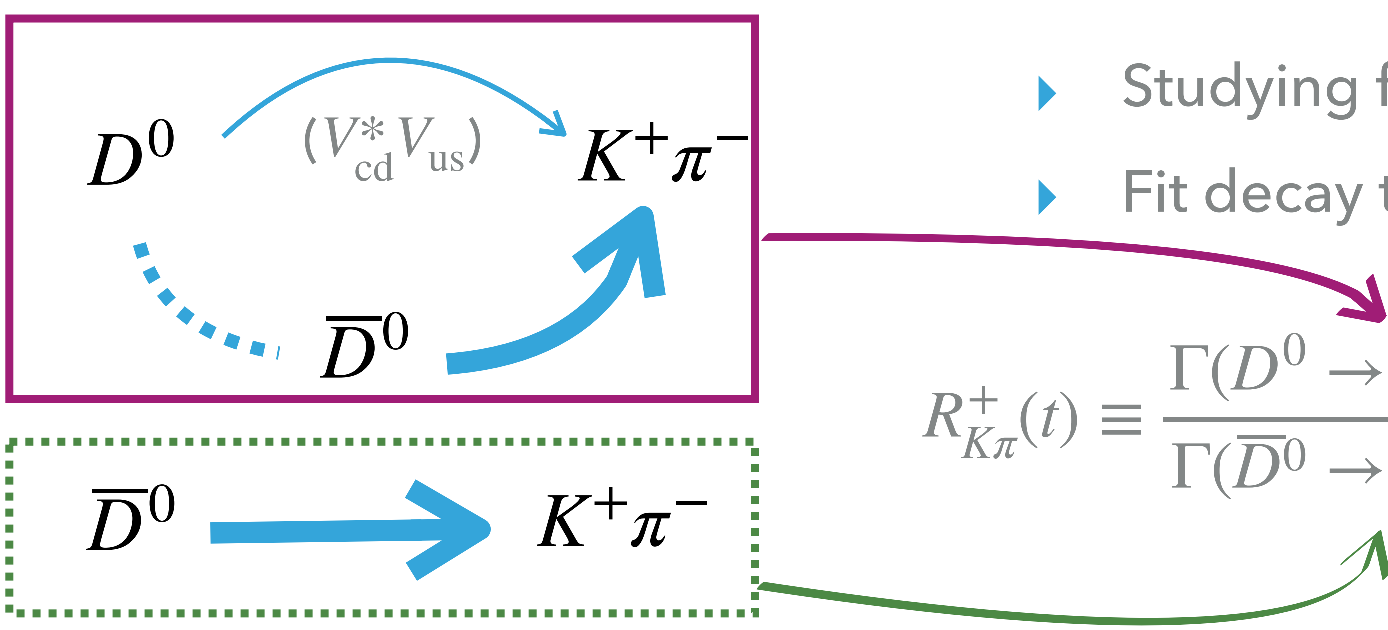


- Measurement of $D^0 - \overline{D}^0$ mixing and search for CPV with $D^0 \to K^+\pi^-$ decays



- Studying full Run 2 $D^{*+} \to D^0(\to K^+\pi^-)\pi^+_{tag}$ decays
- Fit decay time dependent ratios:

$$R^+_{K\pi}(t) \equiv \frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(\overline{D}^0 \to K^+\pi^-)} \qquad R^-_{K\pi}(t) \equiv \frac{\Gamma(\overline{D}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+)}$$

CPV in decay — CPV in mixing

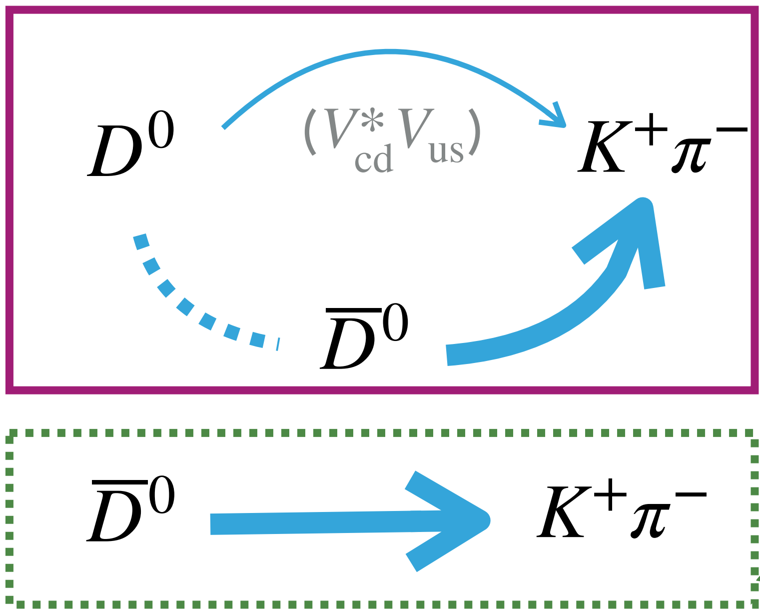
$$R^\pm_{K\pi} \approx R_{K\pi}(1 \pm A_{K\pi}) + \sqrt{R_{K\pi}(1 \pm A_{K\pi})}(c_{K\pi} \pm \Delta c_{K\pi})\frac{t}{\tau_{D^0}} + (c'_{K\pi} \pm \Delta c'_{K\pi})\left(\frac{t}{\tau_{D^0}}\right)^2$$

Suppressed decay — Interference — Mixing

LHCb-PAPER-2024-008 in preparation

Charm – flavour oscillations and CP violation

- Measurement of $D^0 - \overline{D}^0$ mixing and search for CPV with $D^0 \to K^+\pi^-$ decays



- Studying full Run 2 $D^{*+} \to D^0(\to K^+\pi^-)\pi^+_{tag}$ decays
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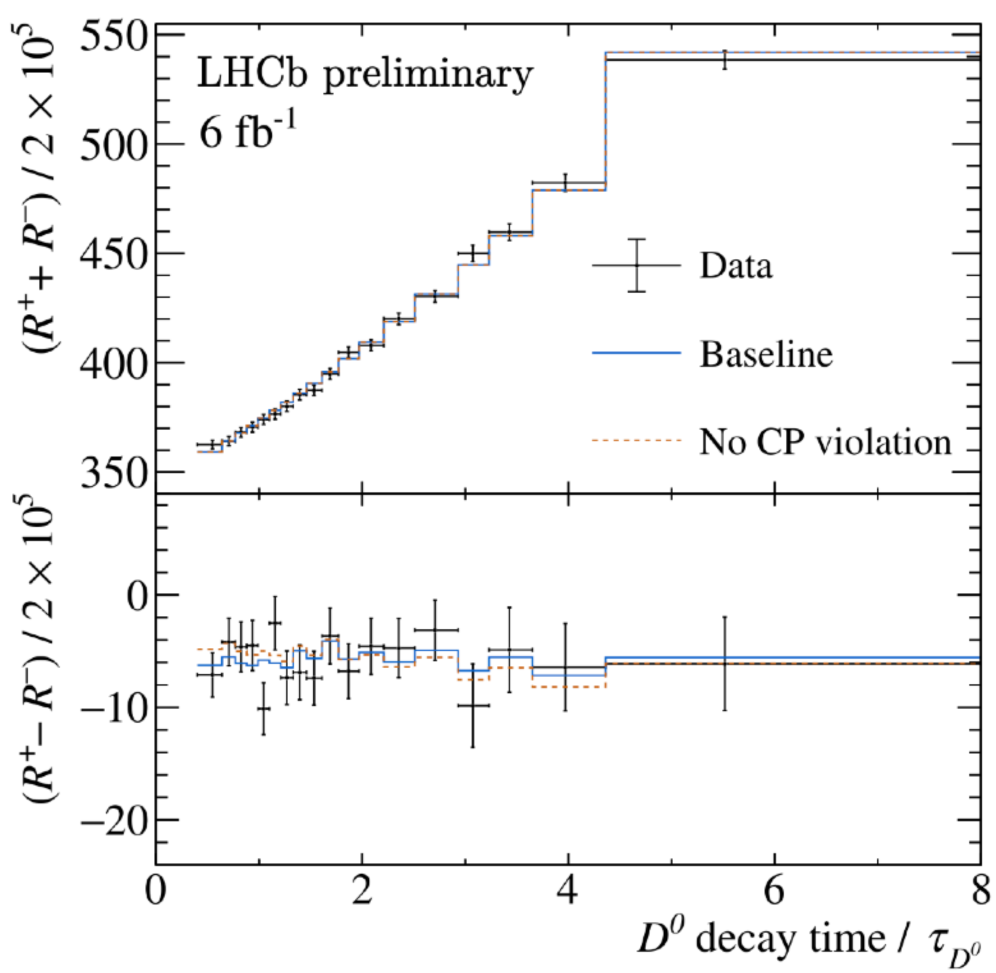


Parameters	
$R_{K\pi}$	$(342.7 \pm 1.9) \times 10^{-5}$
$c_{K\pi}$	$(52.8 \pm 3.3) \times 10^{-4}$
$c'_{K\pi}$	$(12.0 \pm 3.5) \times 10^{-6}$
$A_{K\pi}$	$(-6.6 \pm 5.7) \times 10^{-3}$
$\Delta c_{K\pi}$	$(2.0 \pm 3.4) \times 10^{-4}$
$\Delta c'_{K\pi}$	$(-0.7 \pm 3.6) \times 10^{-6}$

First evidence of quadratic behaviour ($c'_{K\pi}$)

No evidence of CPV ($A_{K\pi}$, $\Delta c_{K\pi}$, $\Delta c'_{K\pi}$)

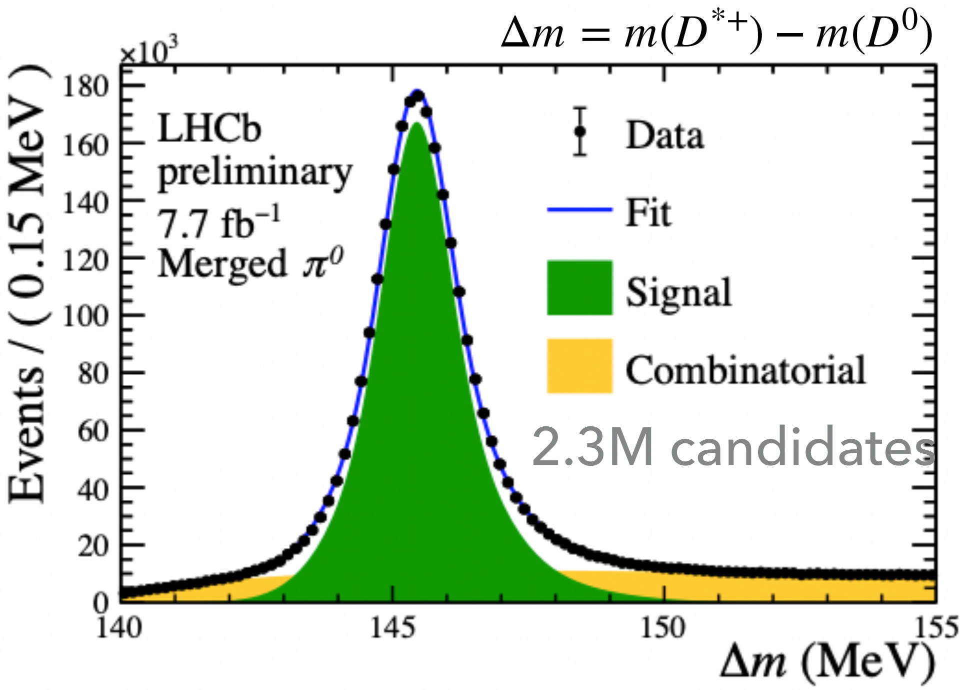
60% improvement in precision compared to previous best. Still statistically limited.

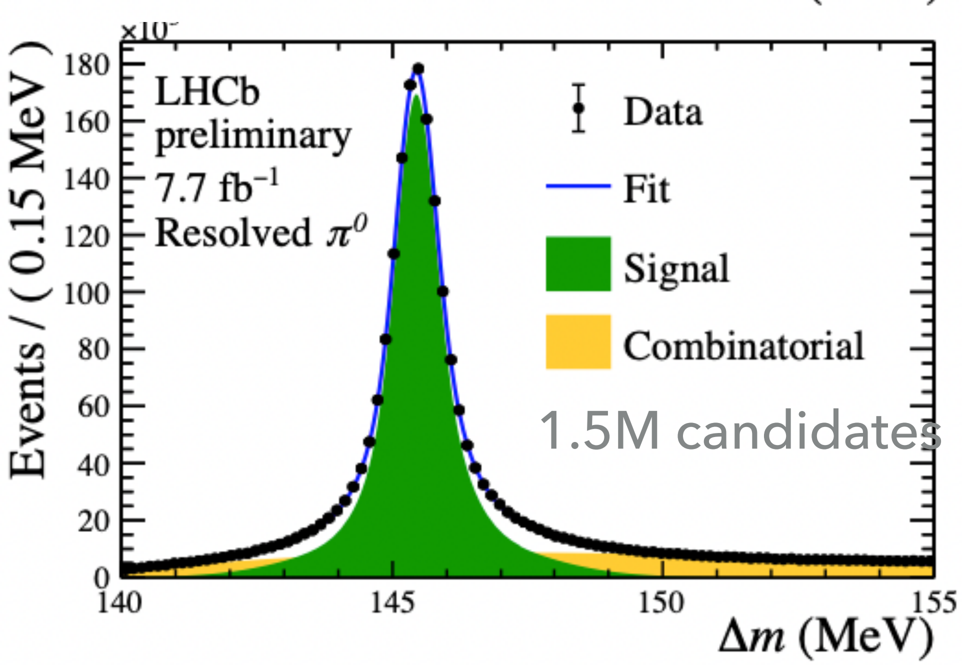
LHCb-PAPER-2024-008 in preparation

Charm – multi-body decays

- Search for time dependent CP violation in $D^0 \to \pi^+\pi^-\pi^0$ decays

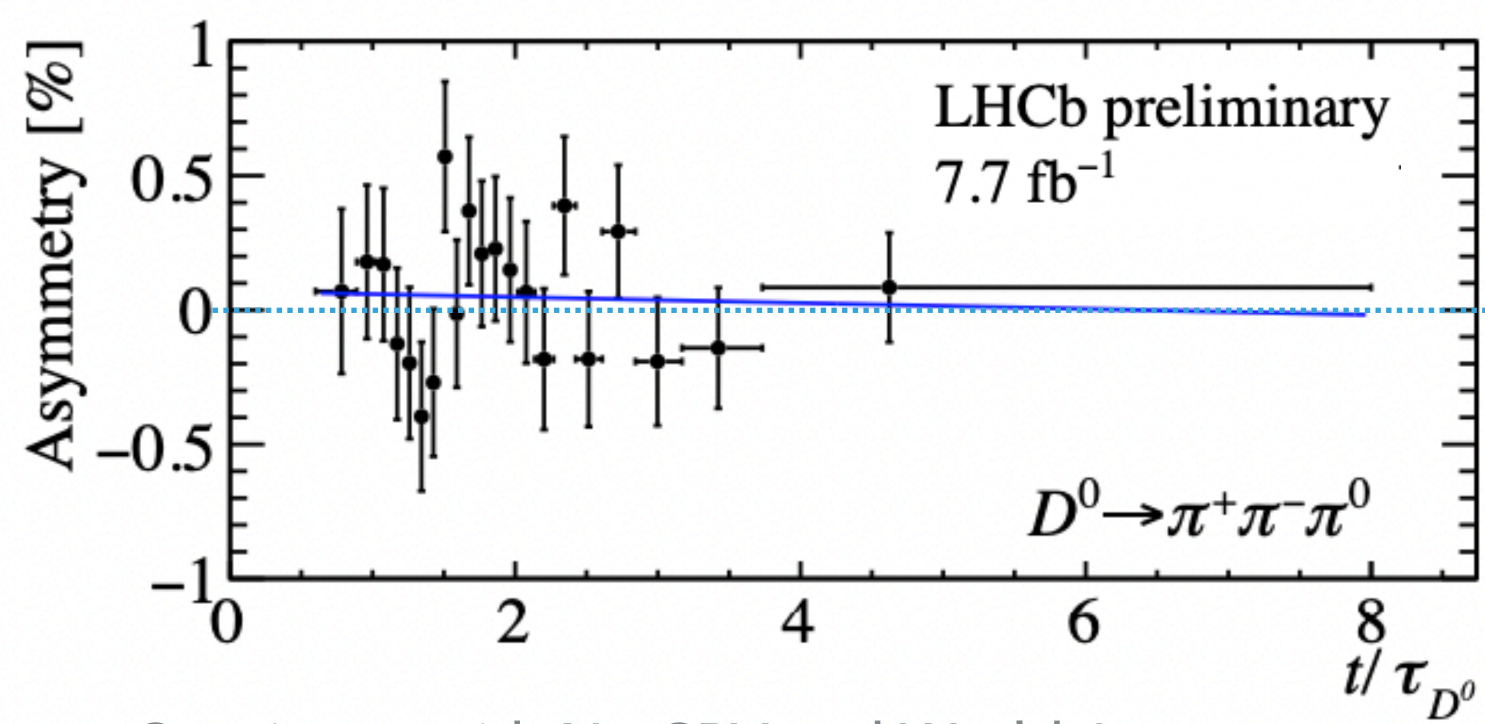
LHCb-PAPER-2024-003
in preparation





- Studying prompt decays $D^{*+} \to D^0(\to \pi^+\pi^-\pi^0)\pi^+_{tag}$
- Data driven weighting procedure to correct for detection asymmetries
- Extract ΔY^{eff} (slope) from mass fits in bins of t/τ_{D^0}

$$A^f_{CP}(t) = \frac{\Gamma_{D^0\to f}(t) - \Gamma_{\overline{D}^0\to f}(t)}{\Gamma_{D^0\to f}(t) + \Gamma_{\overline{D}^0\to f}(t)} \approx a^{\rm dir}_f + \Delta Y^{eff} \frac{1}{\tau_{D^0}}$$



- Consistent with No CPV and World Average

- Search for CP violation in the phase space of $D^0 \to \pi^+\pi^-\pi^0$ decays with the energy test
  - unbinned model-independent approach provides sensitivity to local CP violation
  - Results consistent with CP symmetry

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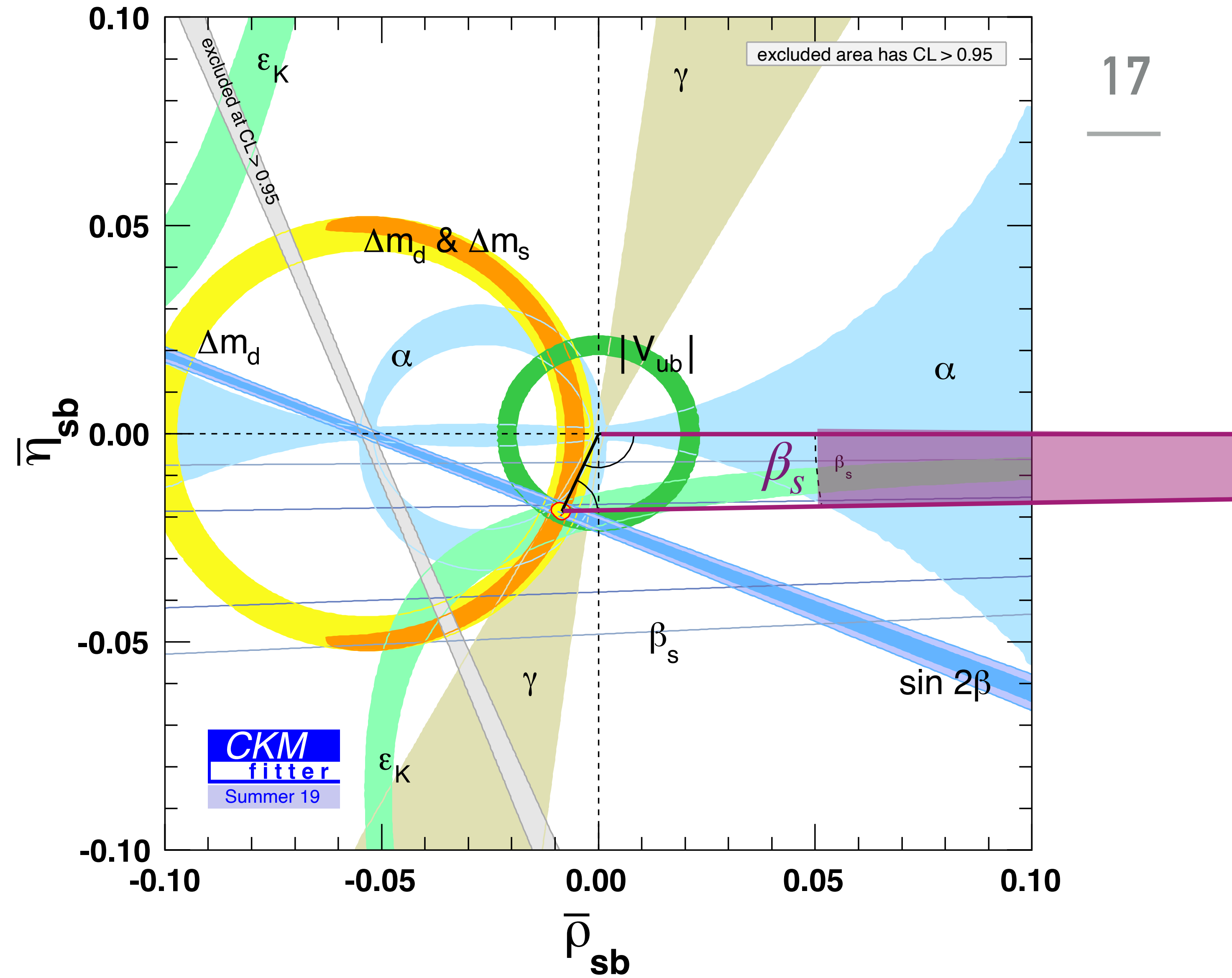
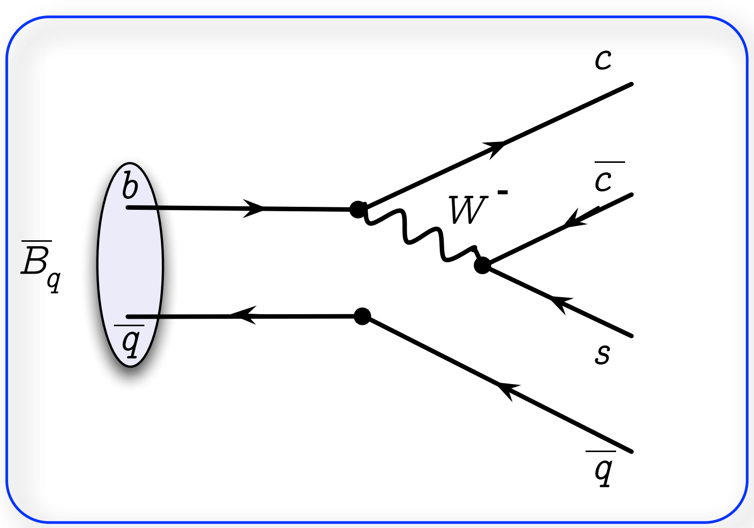
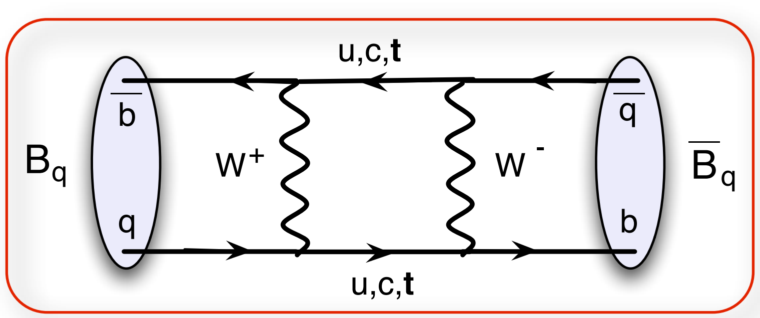
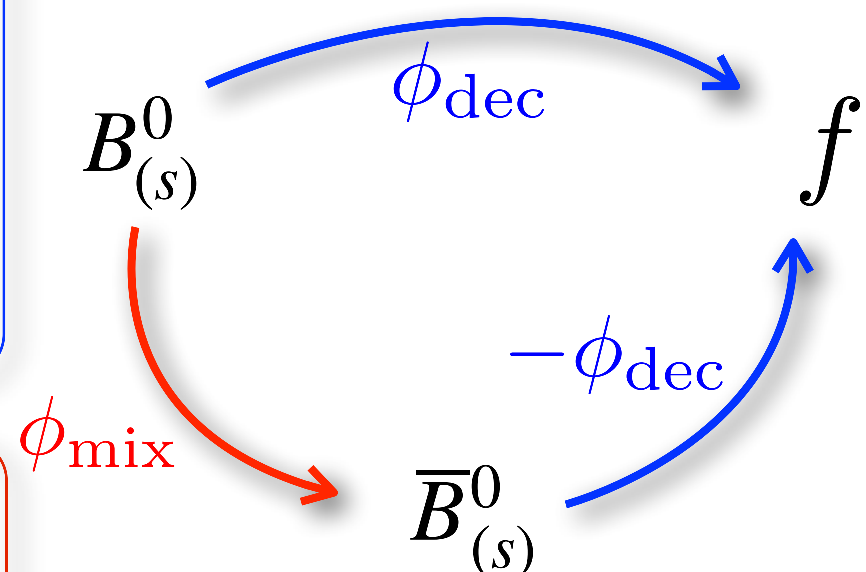
CP violation in B_s^0 mesons

- CKM angle $\beta_s \equiv \arg(-V_{cb}V_{cs}^*/V_{tb}V_{ts}^*)$
- NP can significantly enhance β_s
- Accessible using B_s^0 decays, measuring CP violation generated by the interference between direct decays and mixing
- Golden mode: $B_s^0 \to J/\psi\phi$









$$\phi_q = \phi_{\rm mix} - 2\phi_{\rm dec}$$

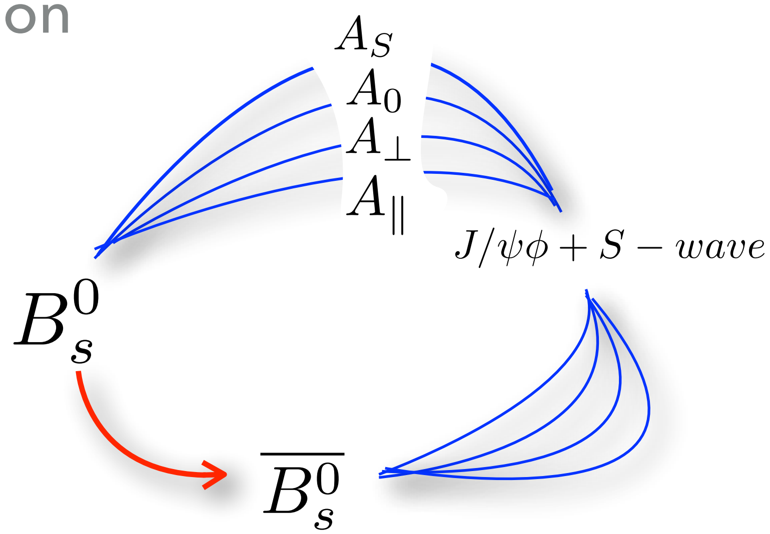
$$\phi_q = -2\left(-\frac{V_{cb}V_{cq}^*}{V_{tb}V_{tq}^*}\right) = 2\beta_{(s)}$$

neglecting penguin contributions

CP violation in B_s^0 mesons

A. Bragnolo, Moriond '24

- A time- flavour- angular- dependent analysis of 491k $B_s^0 \to J/\psi\phi$ candidates (2017-2018)
  - Angular analysis to separate CP-eigenstates
  - Flavour tagging to identify B_s^0 flavour at the production



Results

Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-73	± 23	± 7
$\Delta\Gamma_s$ [ps^{-1}]	0.0761	$\pm$ 0.0043	$\pm$ 0.0019
Γ_s [ps^{-1}]	0.6613	$\pm$ 0.0015	$\pm$ 0.0028
Δm_s [$\hbar$ps^{-1}]	17.757	$\pm$ 0.035	$\pm$ 0.017
$\lvert\lambda\rvert$	1.011	$\pm$ 0.014	$\pm$ 0.012
$\lvert A_0\rvert^2$	0.5300	$\pm$ 0.0016	$\pm$ 0.0044
$\lvert A_\perp\rvert^2$	0.2409	$\pm$ 0.0021	$\pm$ 0.0030
$\lvert A_S\rvert^2$	0.0067	$\pm$ 0.0033	$\pm$ 0.0009
$\delta_\parallel$	3.145	$\pm$ 0.074	$\pm$ 0.025
$\delta_\perp$	2.931	$\pm$ 0.089	$\pm$ 0.050
$\delta_{S\perp}$	0.48	$\pm$ 0.15	$\pm$ 0.05

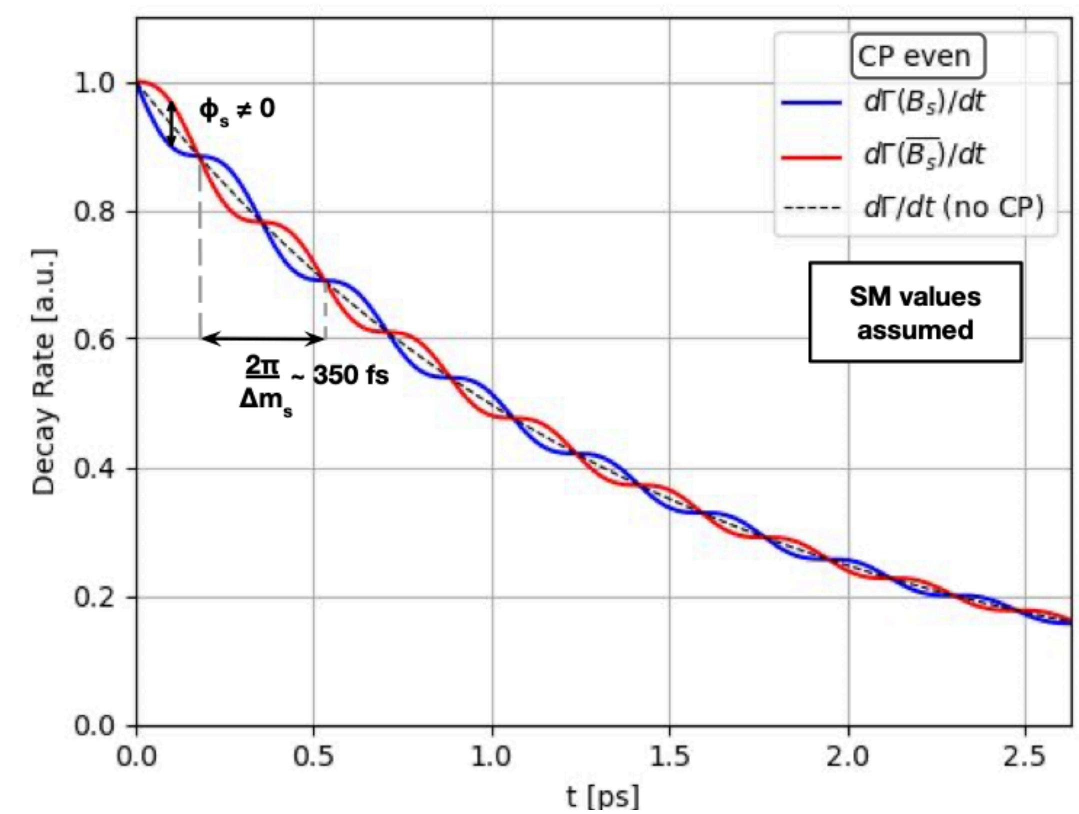
CMS combined

$\phi_s = -74 \pm 23$ [mrad]
$\Delta\Gamma_s = 0.0780 \pm 0.0045$ [ps^{-1}]

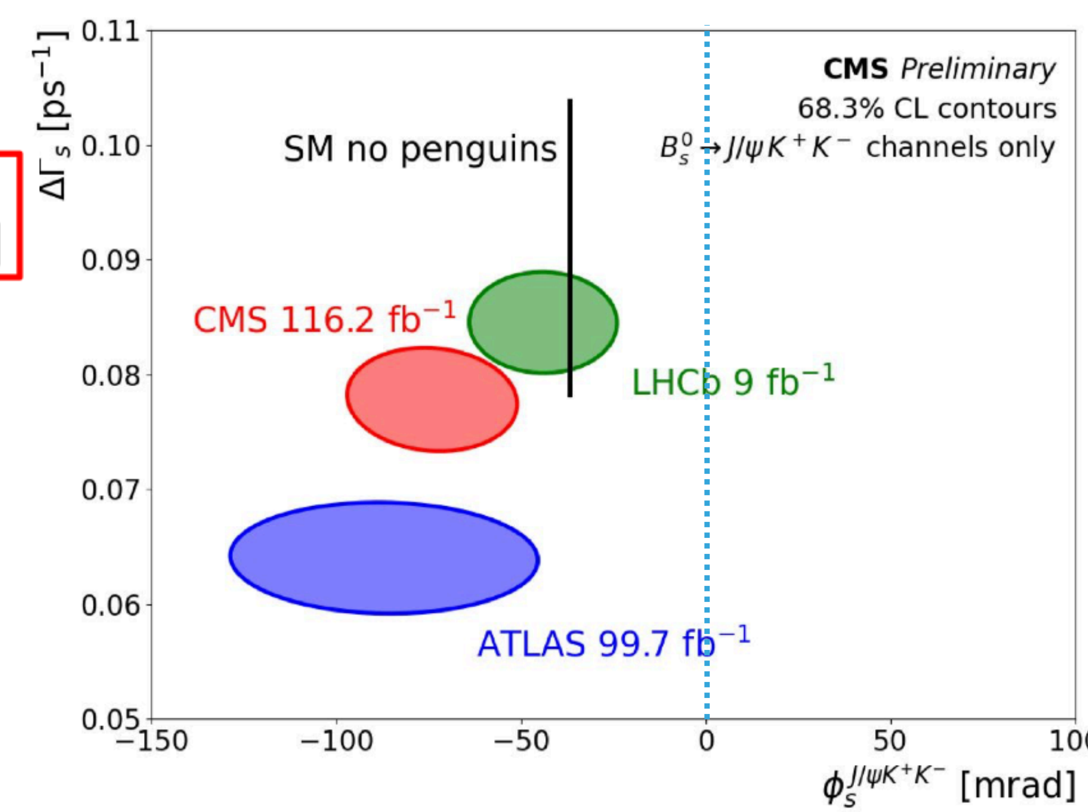
Precision comparable to single most precise measurement!

Compatible with SM, first evidence of CPV (3.2σ) in $B_s^0 \to J/\psi\phi$

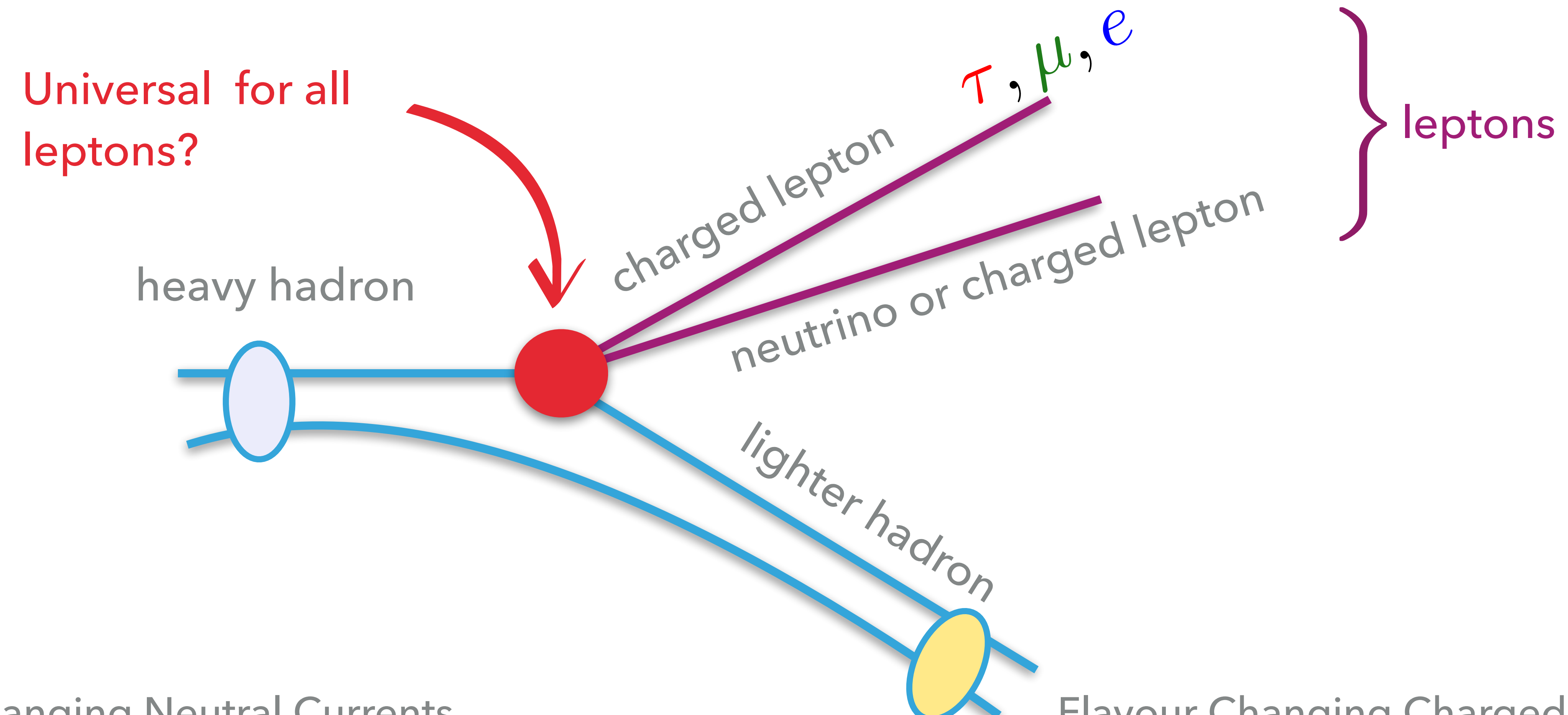
Decay rate for a CP-even final state



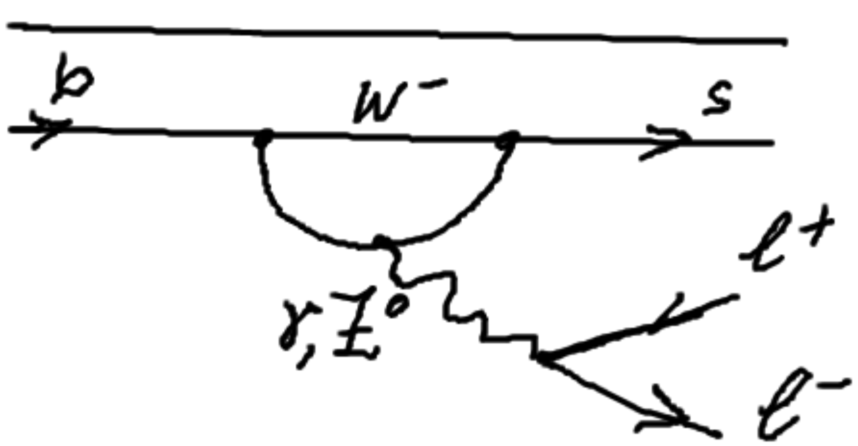
Comparison with other LHC experiments



Lepton Flavour Universality



Flavour Changing Neutral Currents

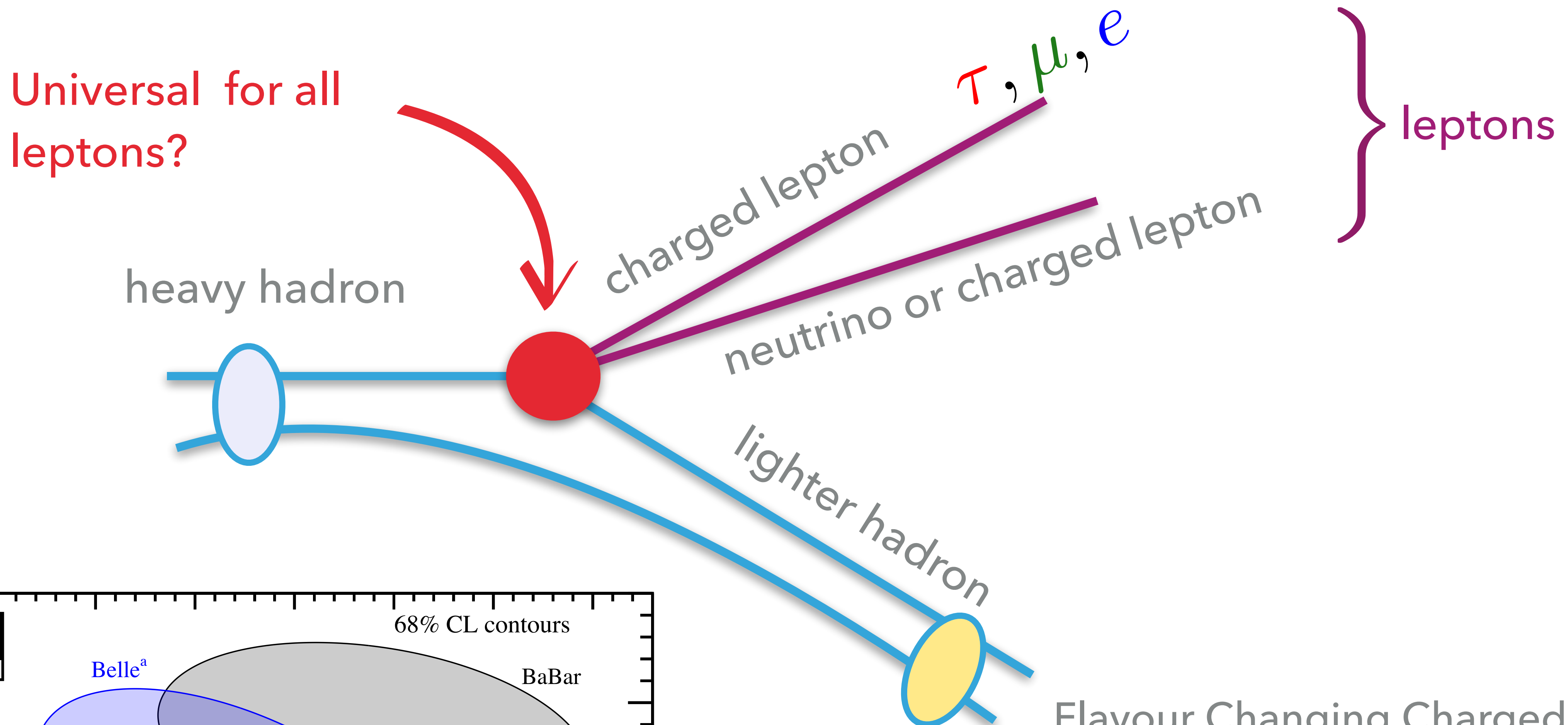


"Rare" decays, forbidden at tree level, decay rate $< 10^{-6}$, fully reconstructed, theoretically clean, depending on observables, very precise Lepton Universality rations predictions

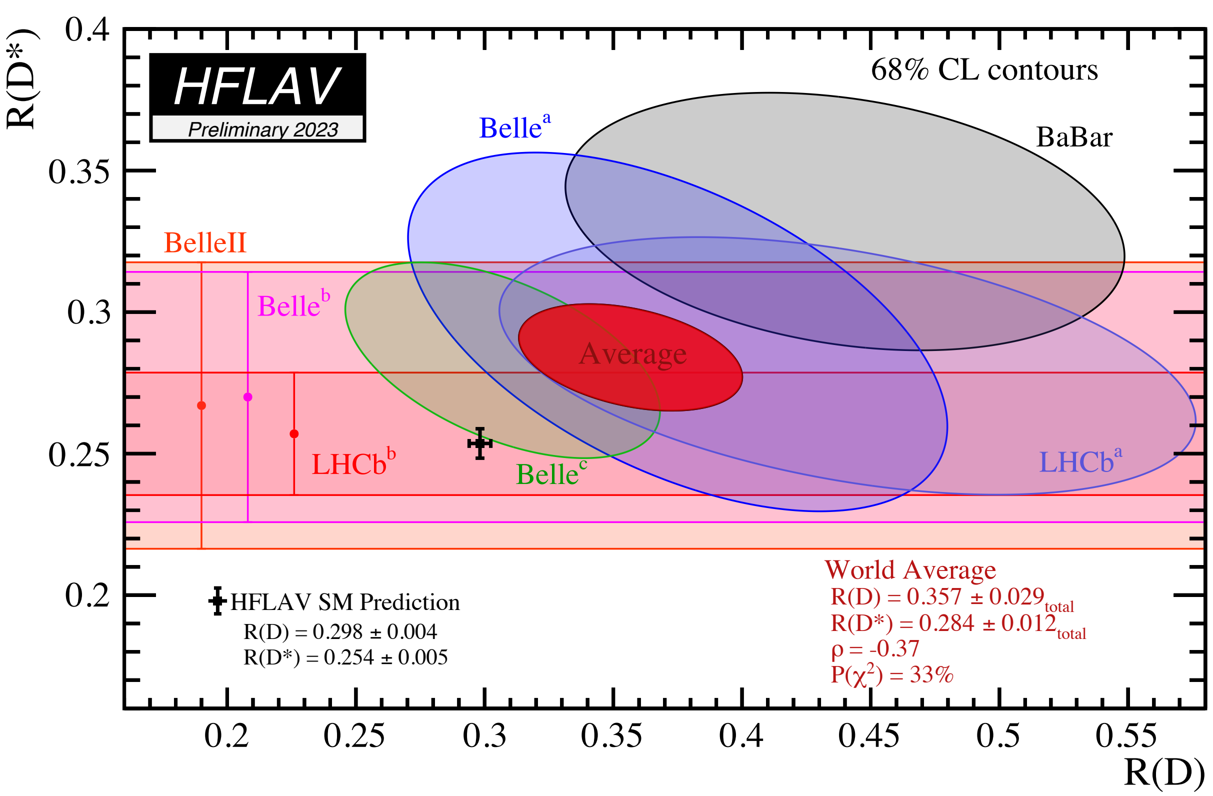
Flavour Changing Charged Currents

Tree-level, semileptonic b-hadron decays, decay rate ~ 10%, unprecedented samples, experimental challenging (neutrinos in the final state), controllable theory uncertainties

Lepton Flavour Universality



Flavour Changing Charged Currents



$$R(D^{(*)}) = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu)}{\mathscr{B}(B \to D^{(*)}\ell\nu)}$$

World average about 3.34σ from SM

Tree-level, semileptonic b-hadron decays, decay rate ~ 10%, unprecedented samples, experimental challenging (neutrinos in the final state), controllable theory uncertainties

Tree-level transitions: measurement of $R(D^{(*)+})$

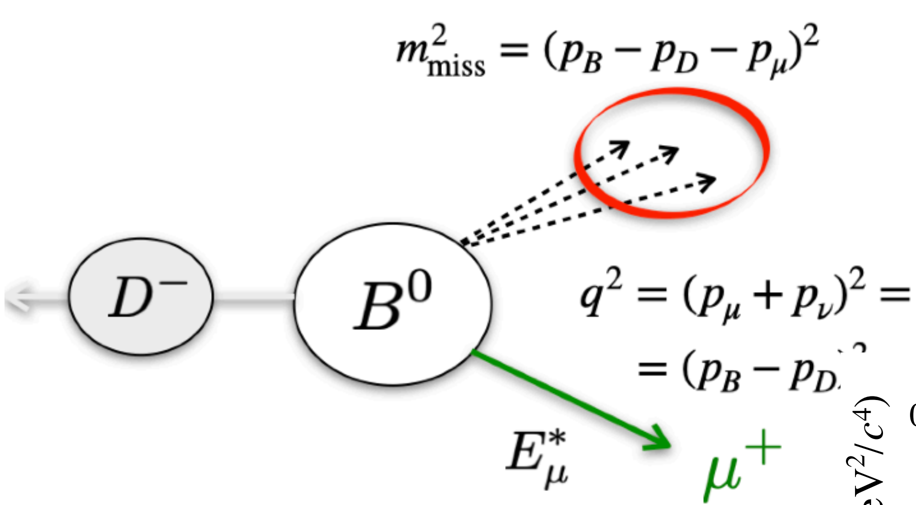
LHCb-PAPER-2024-007
in preparation

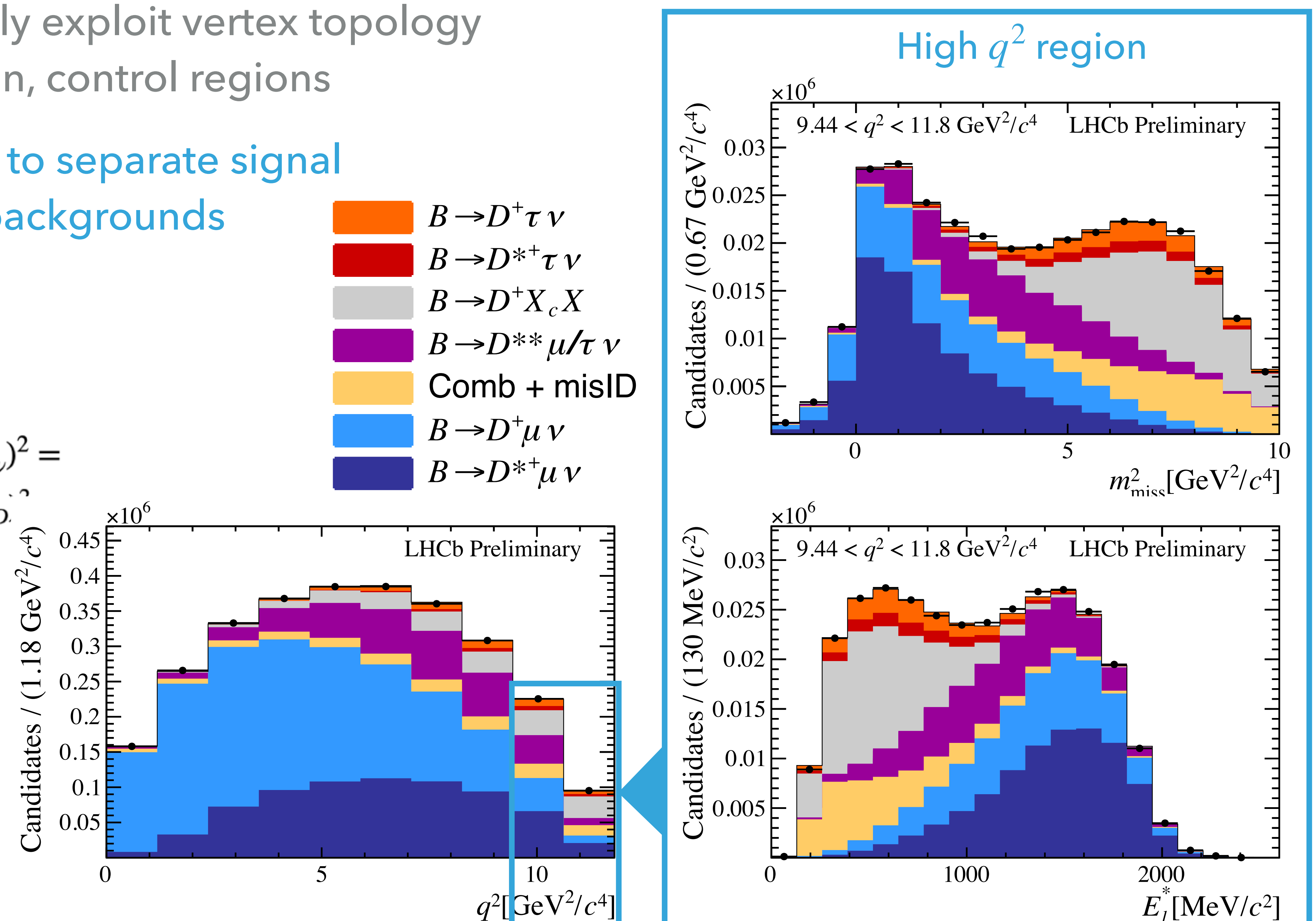
- First LHCb measurement (2015+2016 dataset) using the D^+ ground state, with $D^+ \to K^-\pi^+\pi^+$, muonic-tau decay
  - Feed-down from $D^{*+} \to D^+\pi^0/\gamma$, w/o reconstructing π^0/γ gives access to $R(D^{*+})$ with the same final state

$$R(D^{(*)+}) = \frac{\mathcal{B}(B \to D^{(*)+}\tau\nu)}{\mathcal{B}(B \to D^{(*)+}\mu\nu)}$$

- Partial reconstruction → unconstrained kinematics , large backgrounds: need to fully exploit vertex topology information, track isolation, control regions

- Fit to kinematic variables to separate signal from normalisation and backgrounds



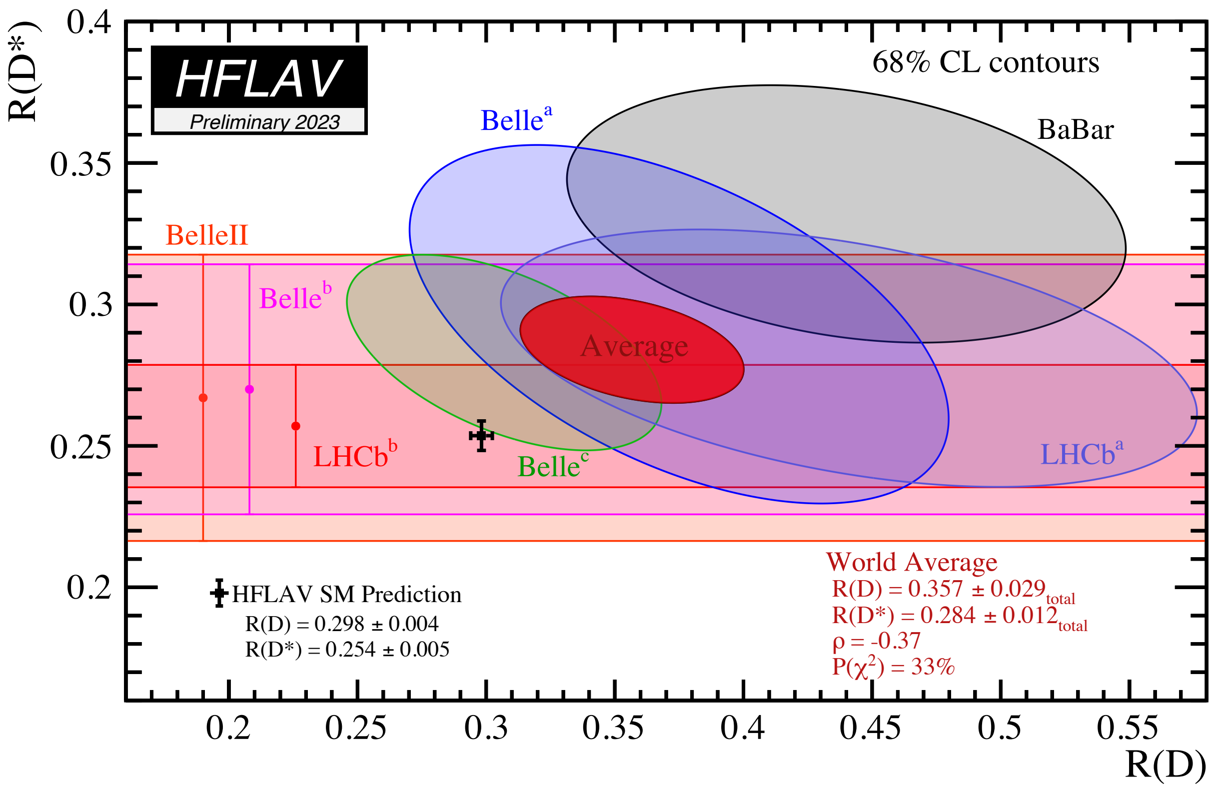


Tree-level transitions

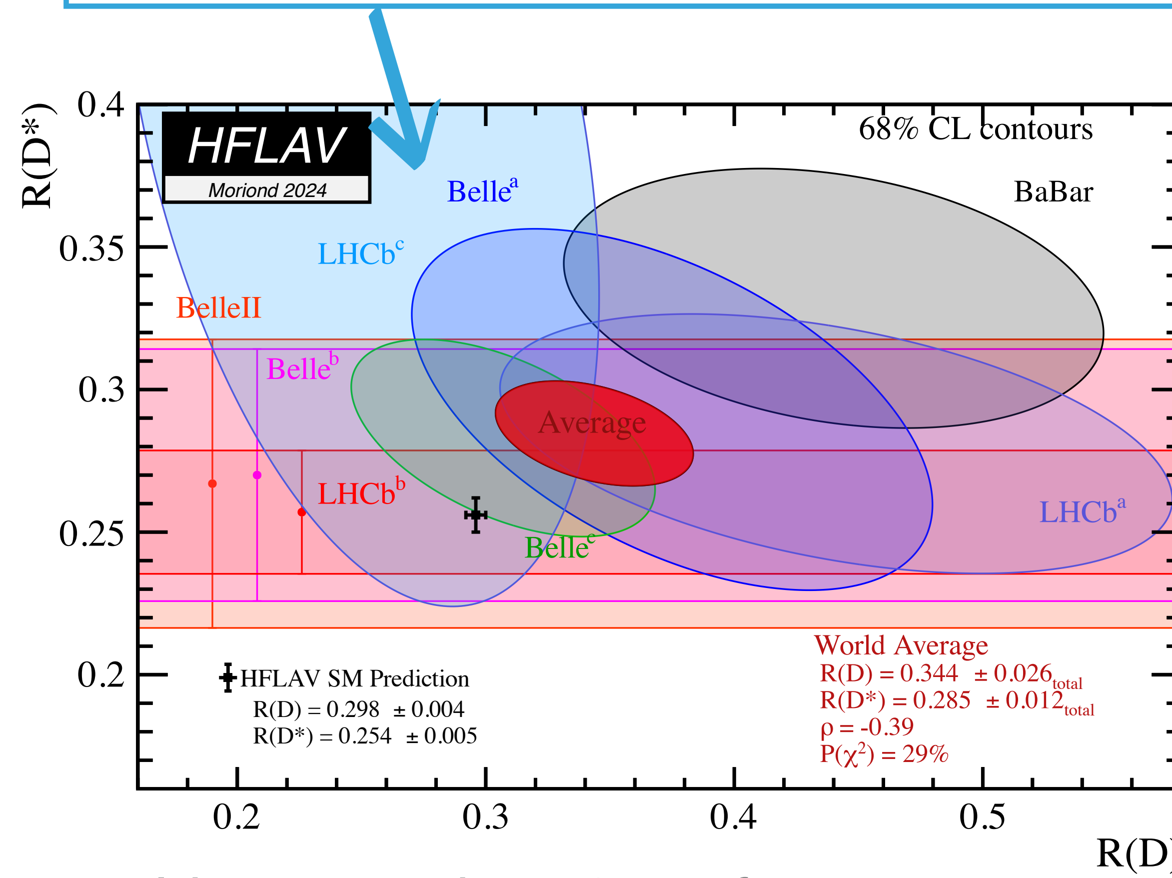
LHCb-PAPER-2024-007
in preparation

- Result compatible with SM (0.78σ) and (previous) World Average (1.09σ)
- Leading systematics hadronic form factors parametrisation and background modelling

$$R(D^{+}) = 0.240 \pm 0.043(\text{stat}) \pm 0.047(\text{syst})$$
$$R(D^{*+}) = 0.402 \pm 0.081(\text{stat}) \pm 0.085(\text{syst})$$
$$\rho = -0.39$$



World average about 3.34σ from SM



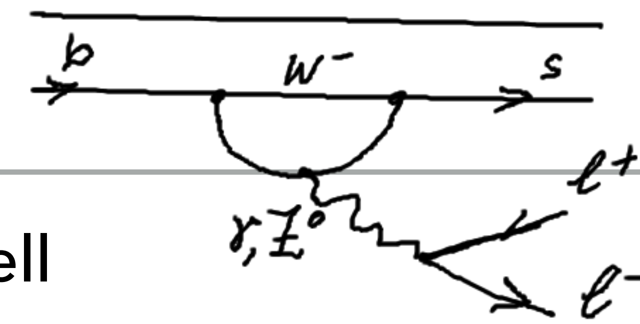
World average about 3.17σ from SM

- New: $R(J/\psi)$ measurement by CMS, with 2018 data: CMS PAS BPH-22-012

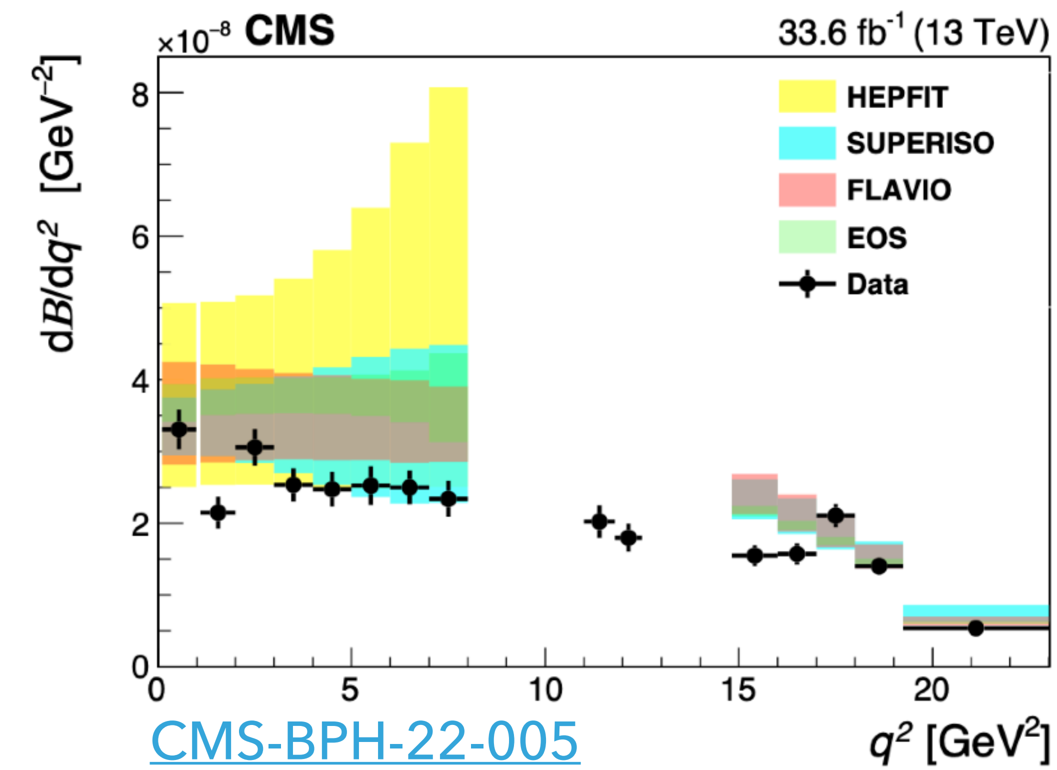
$$R(J/\psi) = 0.17^{+0.18}_{-17}(\text{stat})^{+0.21}_{-0.22}(\text{syst})^{+0.19}_{-0.18}(\text{theo})$$

Compatible with the SM within 0.3σ

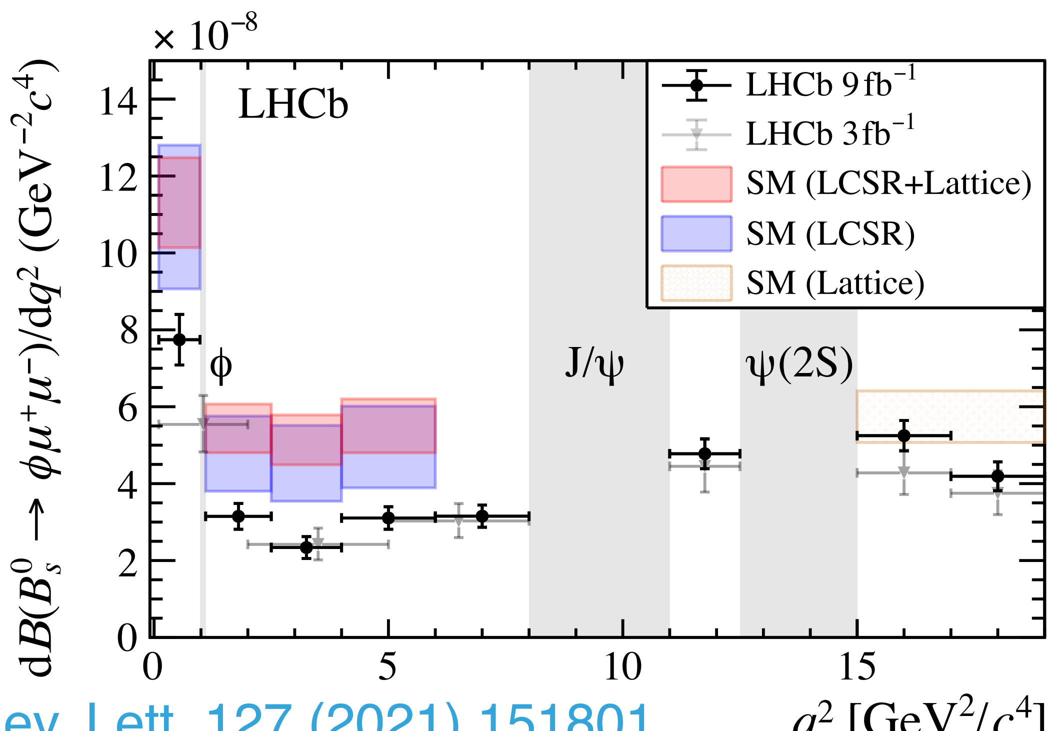
Analyses of $b \to s\ell^+\ell^-$ decays



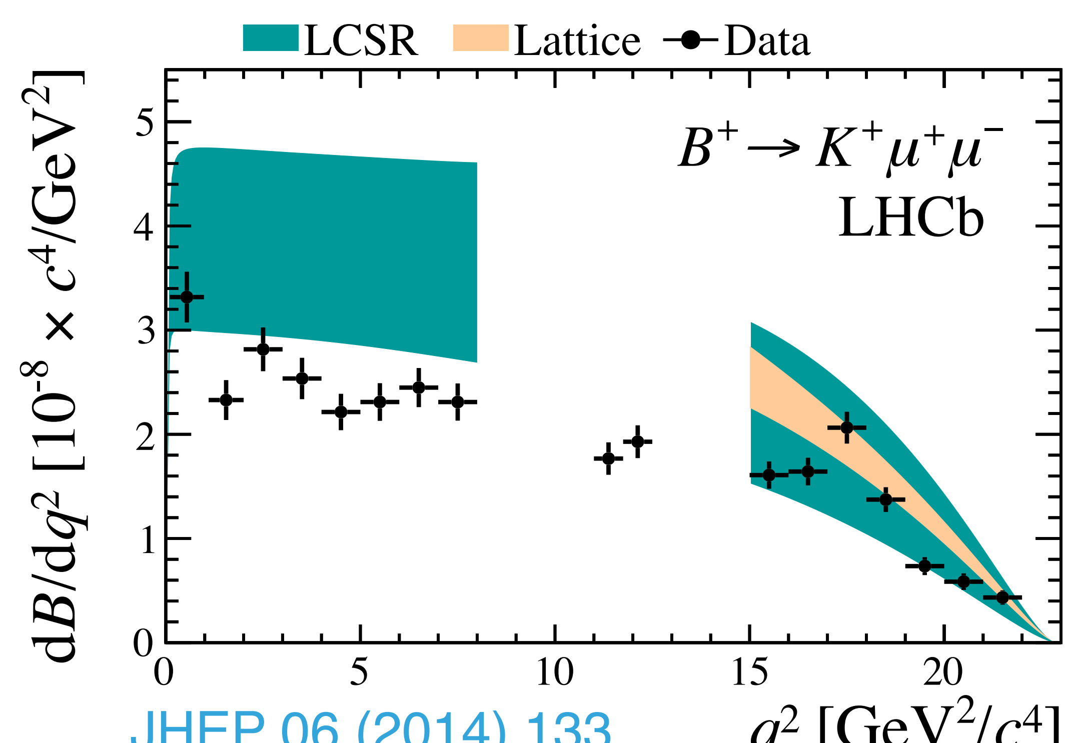
- First test of lepton universality R_K @CMS, as well as differential and integrated BF, with 2018 parked data CMS-EXO-23-007
- See also **Jay Odedra**'s talk *CMS Run 3 RK measurement and di-electron triggers*, Wed 2:30pm
- $d\mathcal{B}/dq^2$ seems to undershoot SM
- Differential branching fractions and angular observables are not as theoretically clean as lepton universality tests
- Is it all NP? Can we measure long-distance (hadronic) contributions ?



CMS-BPH-22-005



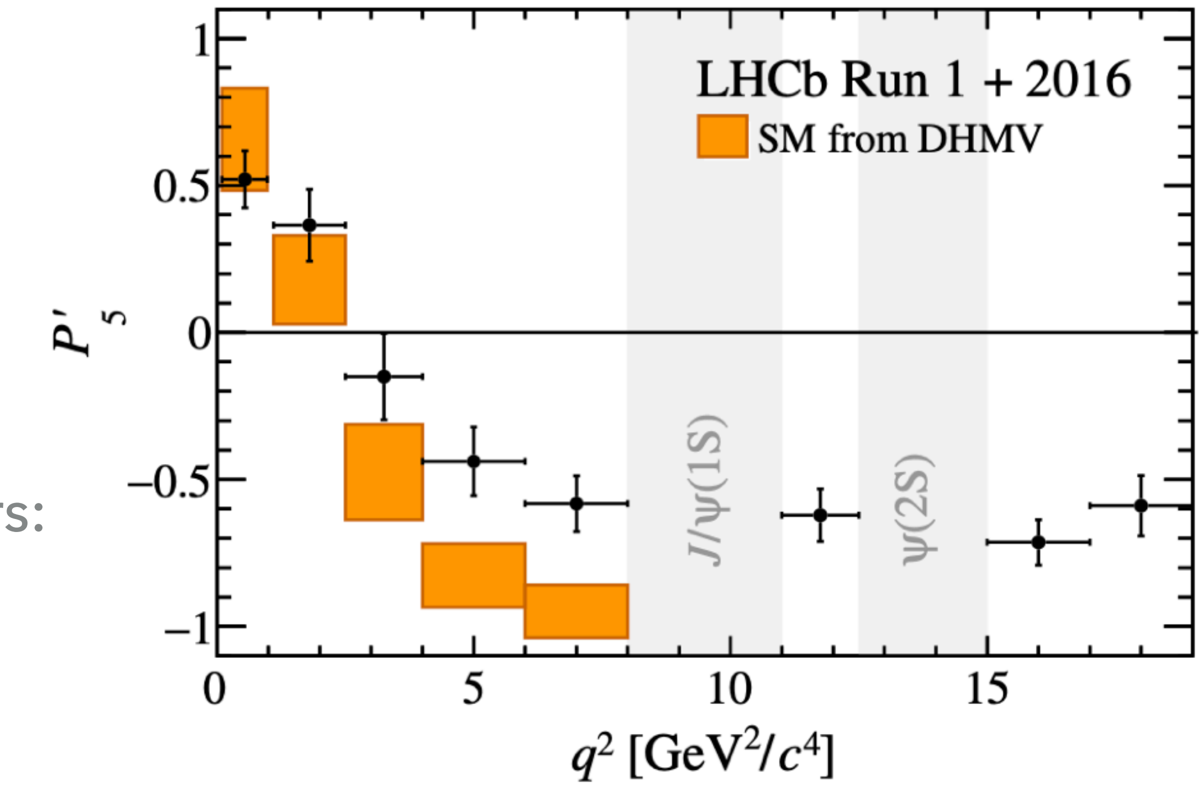
Phys. Rev. Lett. 127 (2021) 151801



JHEP 06 (2014) 133

Analyses of $b \to s\ell^+\ell^-$ decays

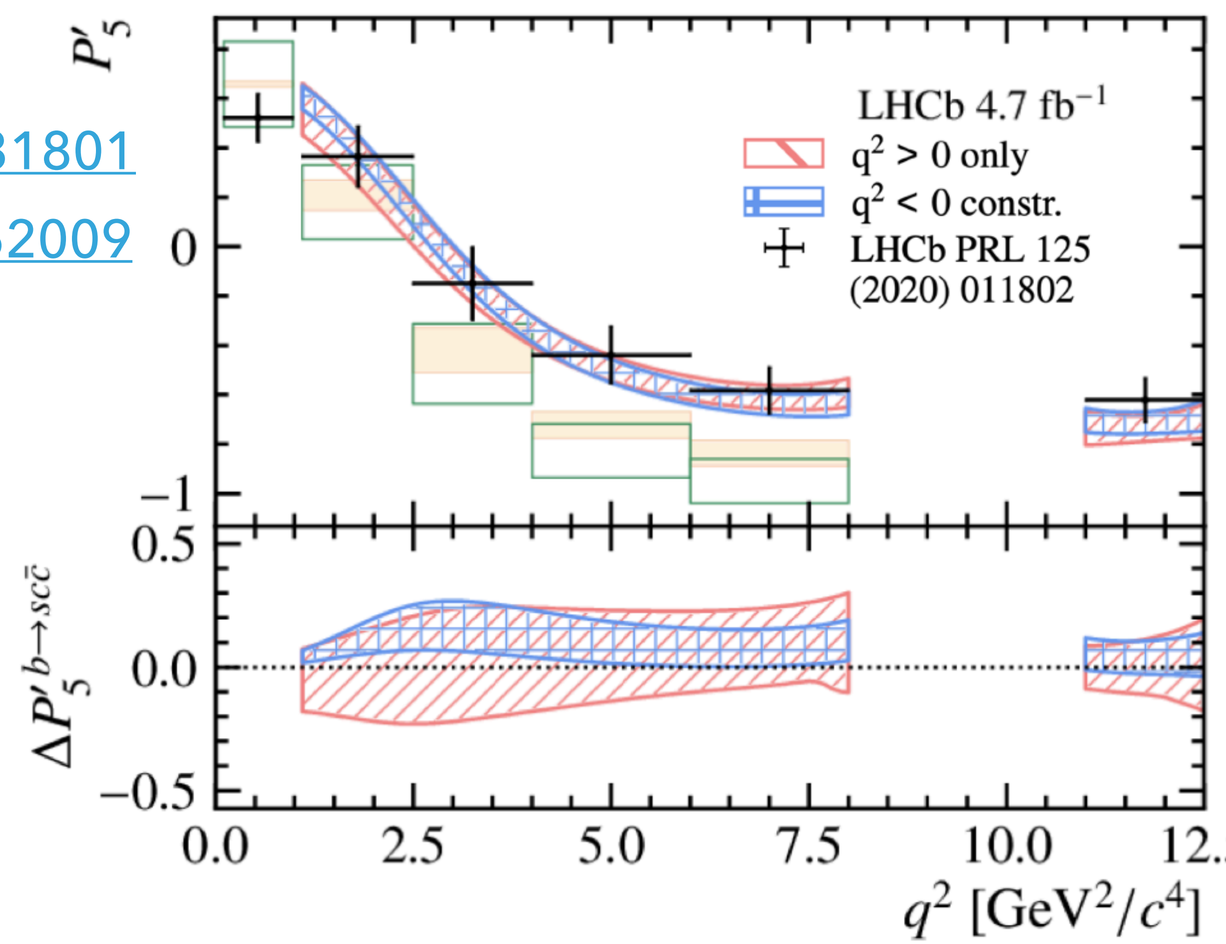
Phys.Rev.Lett. 125 (2020) 1, 011802



- Differential branching fractions and angular observables are not as theoretically clean as lepton universality tests
- Is it all NP? Can we measure long-distance (hadronic) contributions?
- Unbinned fit in q^2 for the amplitude parameters: hadronic form factors, Wilson Coefficients
    - Good agreement with binned results

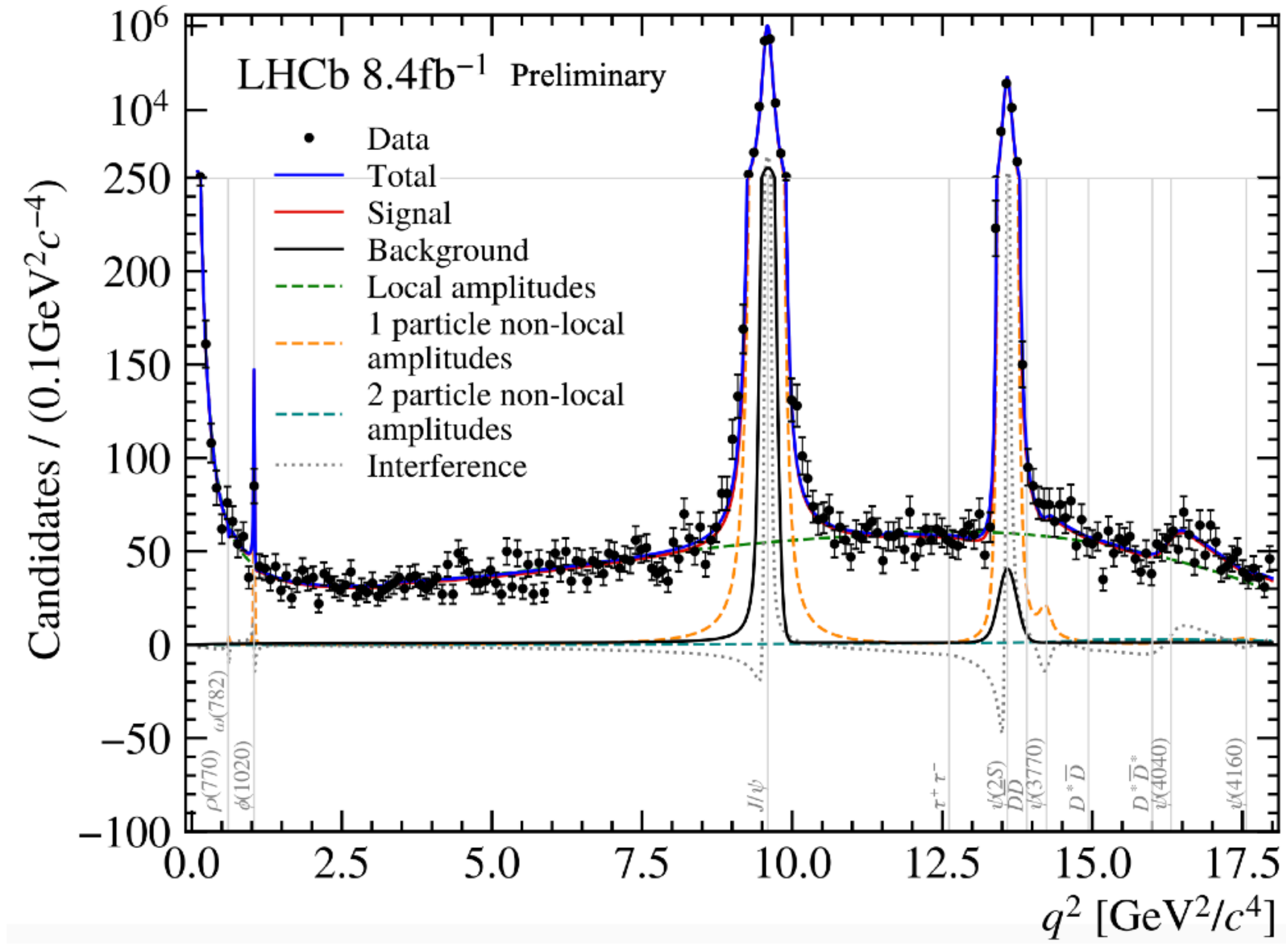
Phys. Rev. Lett. 132 (2024) 131801

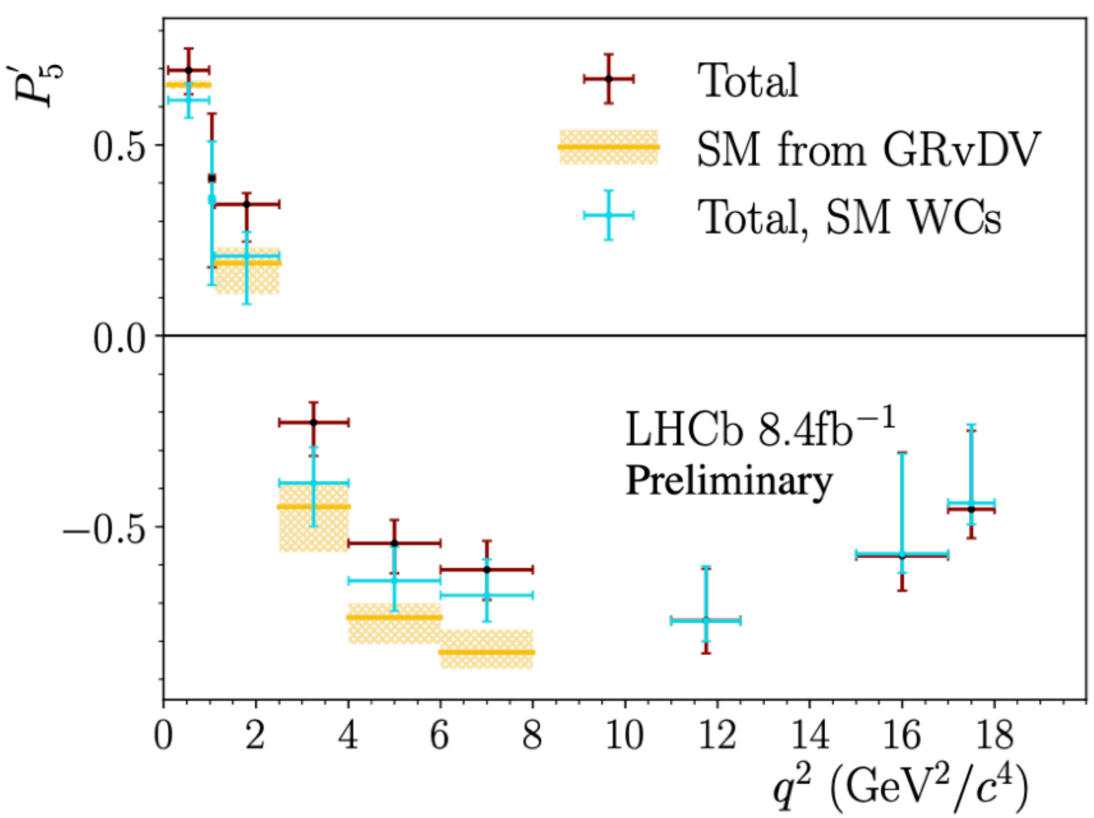
Phys. Rev. D 109 (2024) 052009



Analyses of $b \to s\ell^+\ell^-$ decays

- Unbinned amplitude analysis to the whole $q^2 = m(\mu^+\mu^-)$ region, in the three decay angles and q^2
- Run1 (2011-2012) + Run2 (2016-2018)
- Measurement of local and non-local amplitudes in $B^0 \to K^{*0}\mu^+\mu^-$ decays (150 fit parameters including Wilson Coefficients, hadronic form factors, resonances, interference)





Red vs Cyan: *impact of allowing NP*

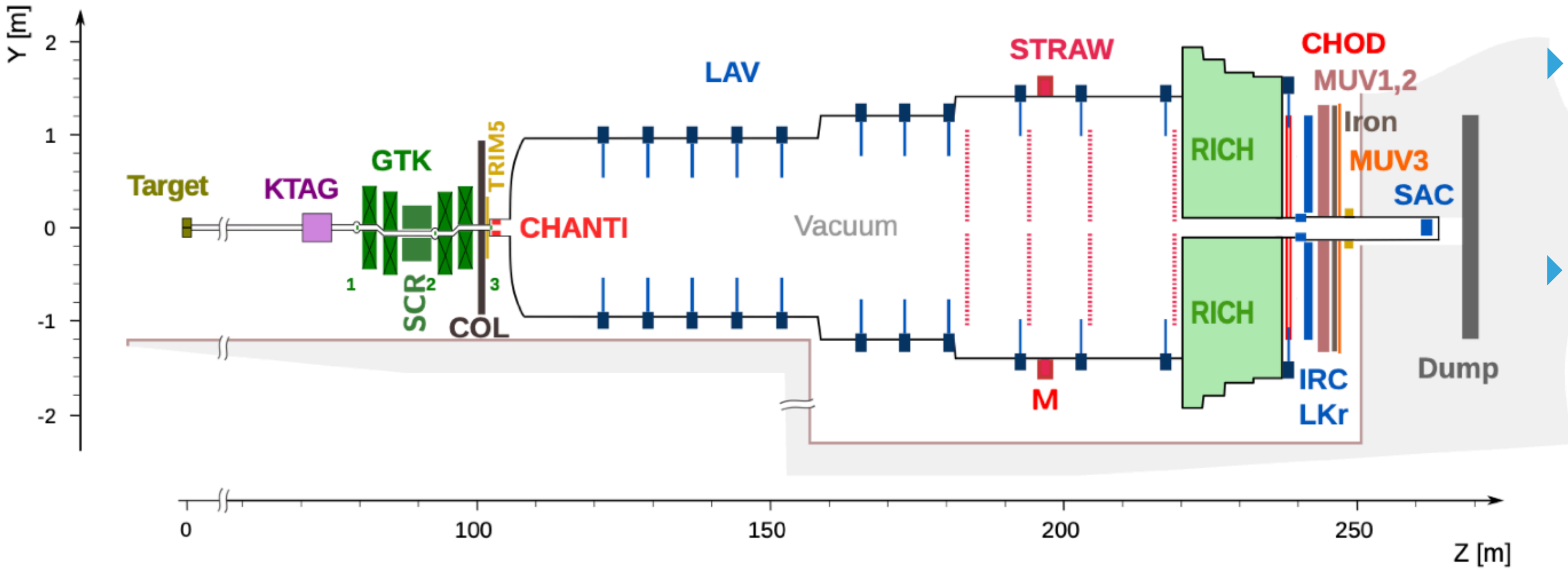
Cyan vs Yellow: *impact of allowing non-local modelling*

$\mathcal{C}_9$	$3.56 \pm 0.28 \pm 0.18$	2.1σ
$\mathcal{C}_{10}$	$-4.02 \pm 0.18 \pm 0.16$	0.6σ
$\mathcal{C}_9'$	$0.28 \pm 0.41 \pm 0.12$	0.7σ
$\mathcal{C}_{10}'$	$-0.09 \pm 0.21 \pm 0.06$	0.4σ
$\mathcal{C}_9^\tau$	$-116 \pm 264 \pm 98$	0.4σ

- See also **Jake Amey**'s talk *Amplitude Analysis of $B^0 \to D^0\overline{D}^0K^+\pi^-$decays* , Wed 11:15am
- See also **Lorenzo Paolucci**'s talk *Angular analysis of rare Bs decays involving electrons at LHCb* , Wed 11:45am
- See also **James Herd**'s talk *Test of lepton flavour universality using $B^+ \to K^+\ell^+\ell^-$*, Wed noon

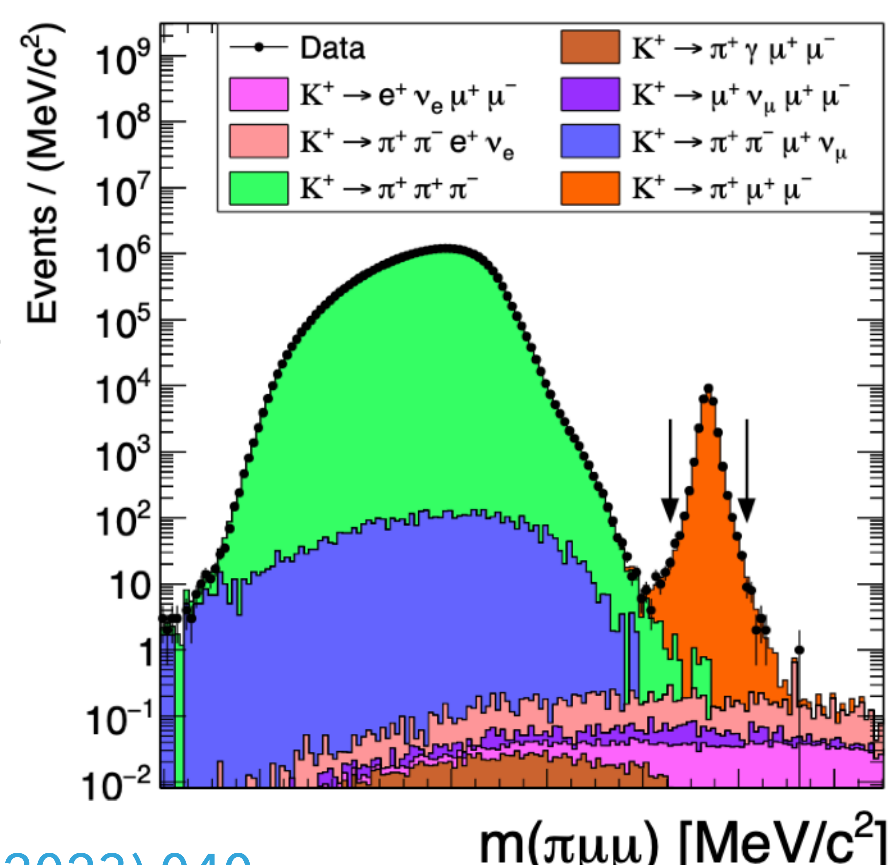
A measurement of $K^+ \to \pi^+\mu^+\mu^-$

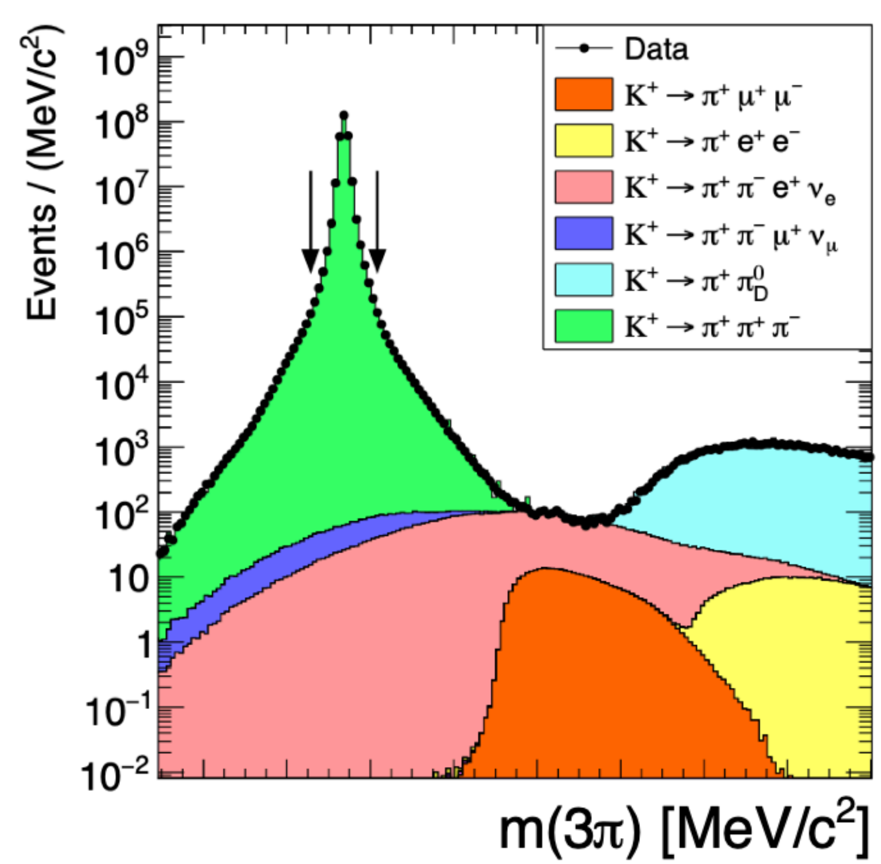
- 27679 $K^+ \to \pi^+\mu^+\mu^-$ candidates with negligible background contamination was collected by the NA62 experiment in 2017-2018



- NA62: secondary beam of π, p, K from SPS beam
- Excellent timing, momentum resolution and PID

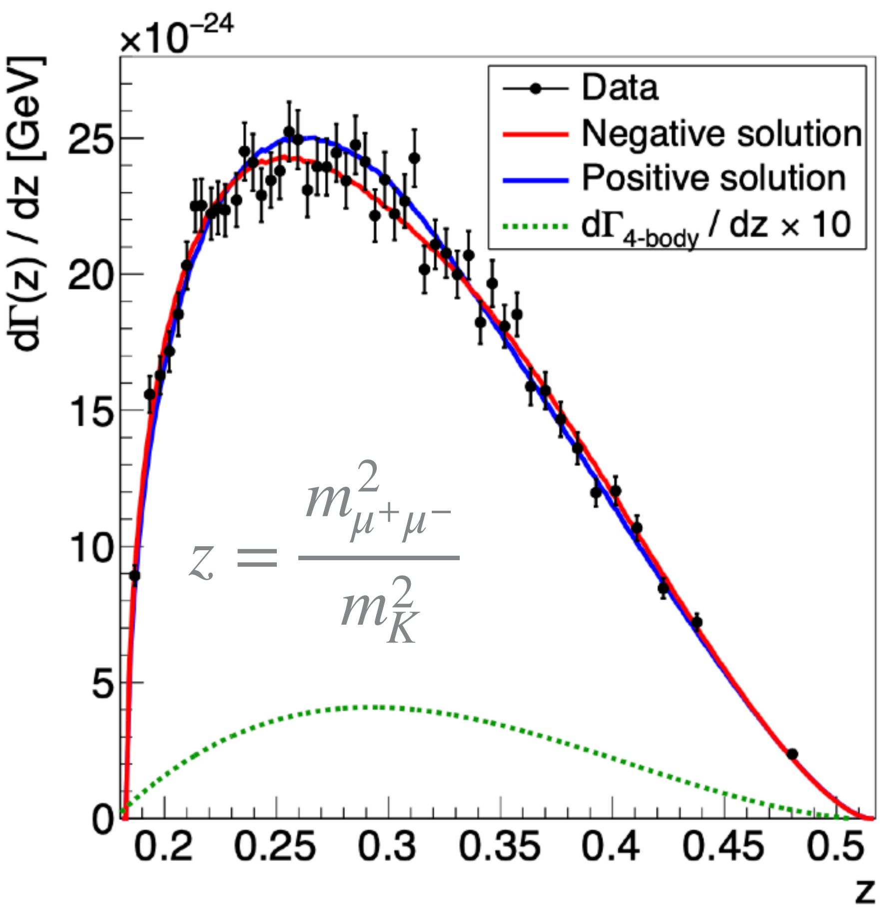
- Studies of $K^+ \to \pi^+\mu^+\mu^-$ and $K^+ \to \pi^+e^+e^-$ decay form factors contribute to LFU picture

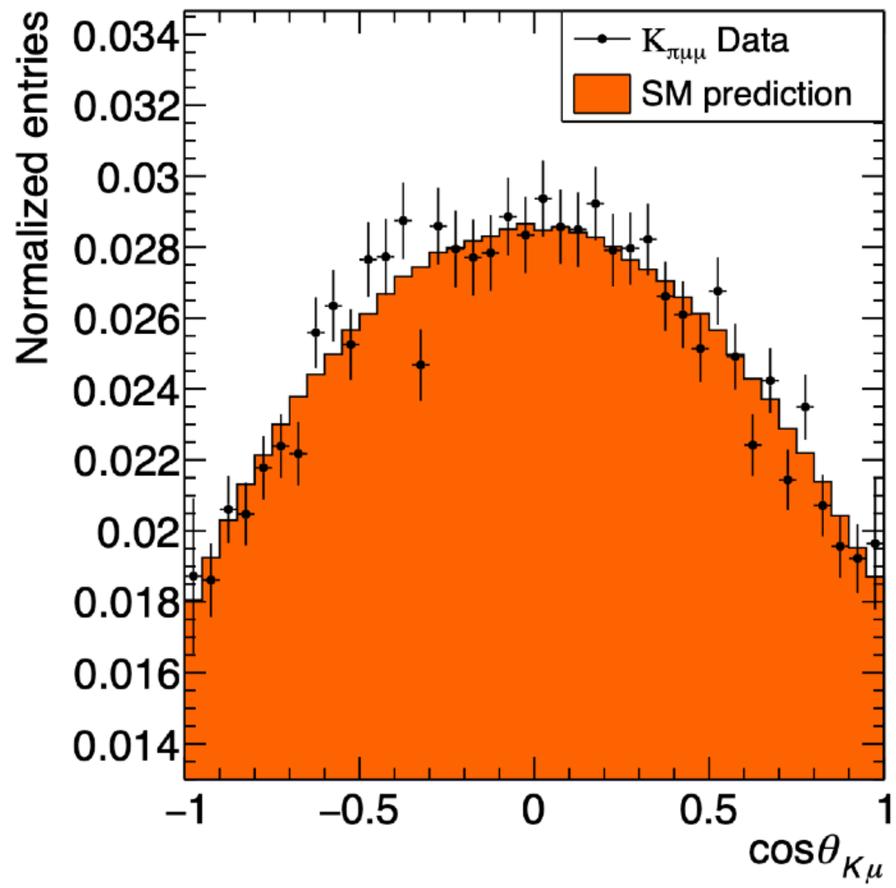


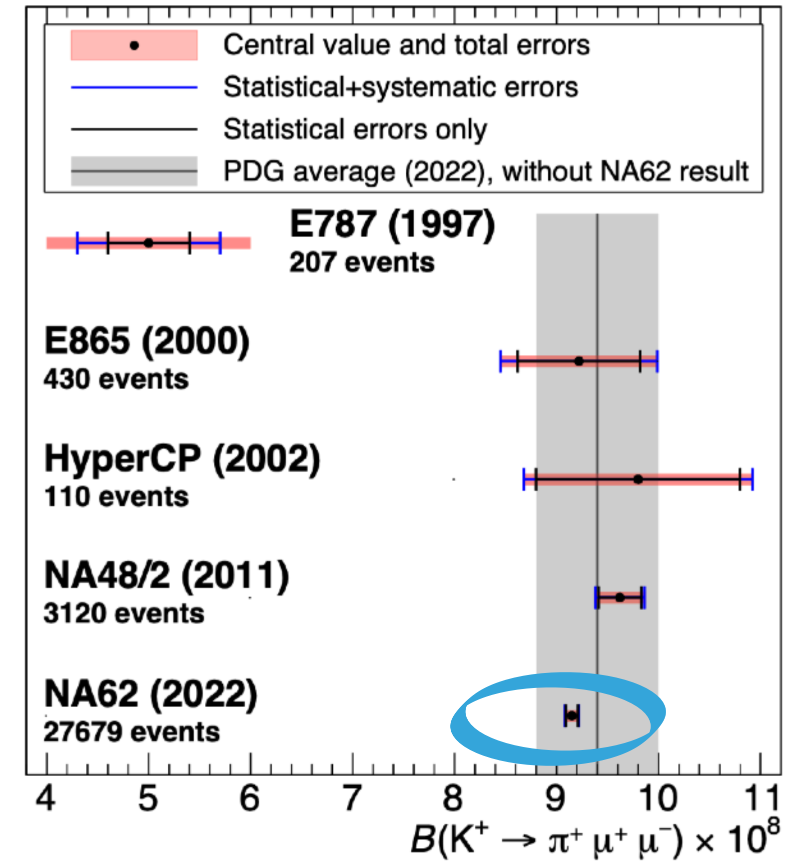


JHEP 11 (2022) 011, JHEP 06 (2023) 040

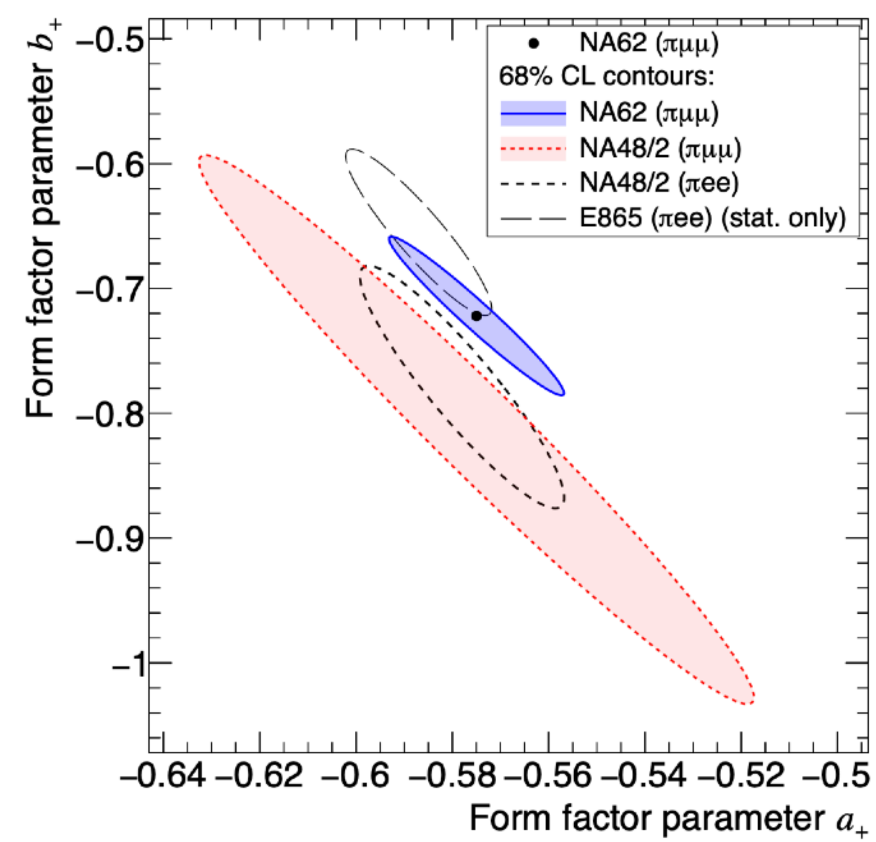
A measurement of $K^+ \to \pi^+\mu^+\mu^-$







- Measurement of:
  - Model independent $\mathscr{B}(K^+ \to \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \times 10^{-8}$
  - form factor parameters in the framework of the Chiral Perturbation Theory at $\mathcal{O}(p^6)$
  - $A_{\rm FB} = (0.0 \pm 0.7) \times 10^{-2}$, x 2.6 improvement in precision
- The size of the $K^+ \to \pi^+\mu^+\mu^-$ data sample is the main limiting factor



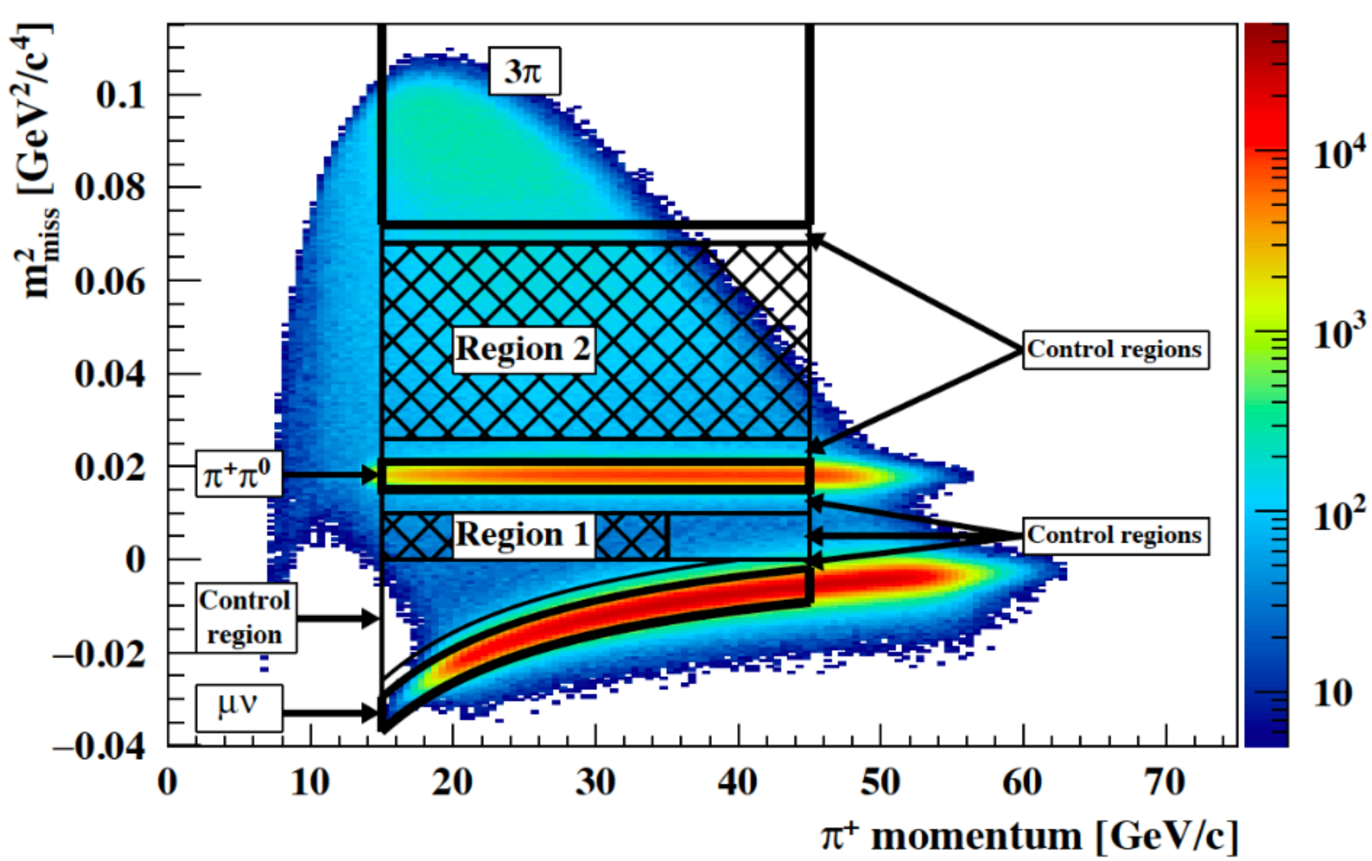
JHEP 11 (2022) 011, JHEP 06 (2023) 040

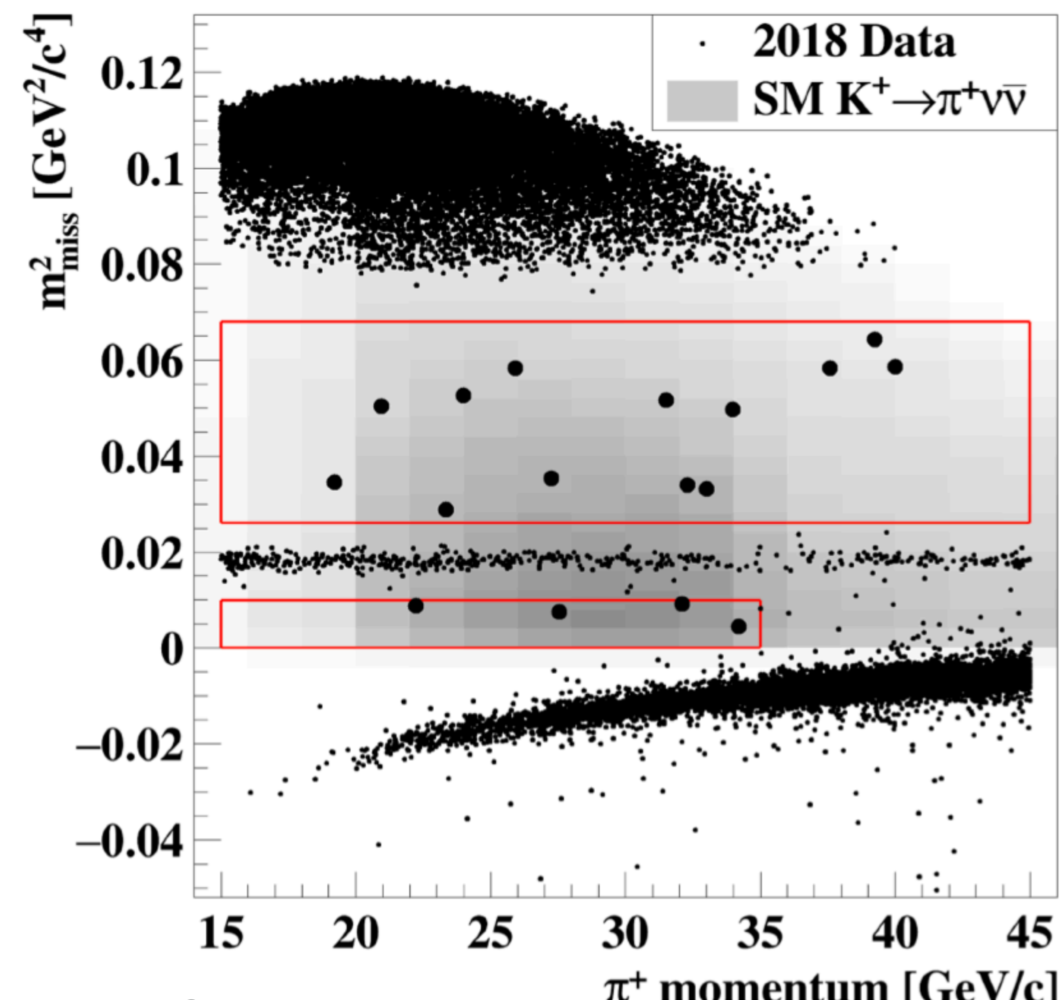
The very rare $K^+ \to \pi^+ \nu \bar{\nu}$

JHEP 06 (2021) 093

- SM expectation $\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (8.4 \pm 1.0) \times 10^{-11}$
- find one Kaon, one pion; make sure there is nothing else
- Look at the mass of the two neutrino system (m^2_{miss})
- Exclude the regions with the most dominant backgrounds: $K^+ \to \pi^+ \pi^0$ with a missed π^0 and $K^+ \to \mu^+ \nu$ with a muon mis-identified as pion

The mass of the two ν system





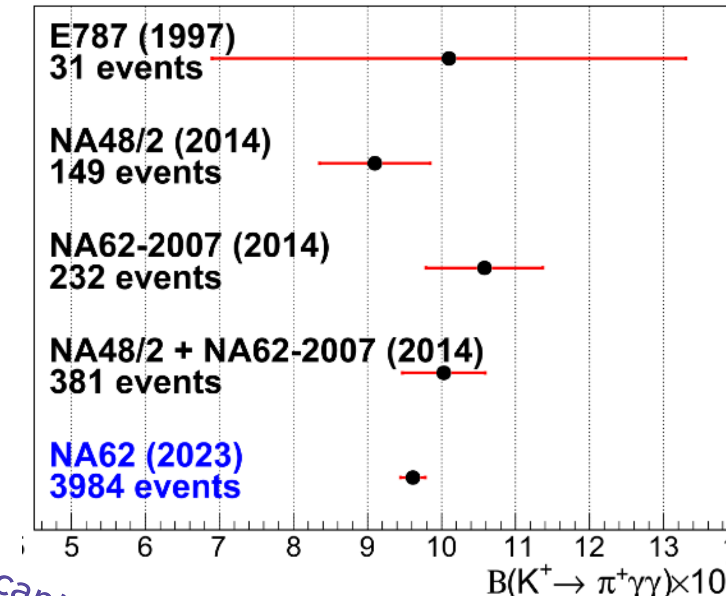
- 20 events in 2016 + 2017 + 2018; expected background of 7

$$\mathscr{B}(K^+ \to \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4}(\text{stat}) \pm 0.9(\text{syst})) \times 10^{-11}$$

3.4σ evidence of this decay

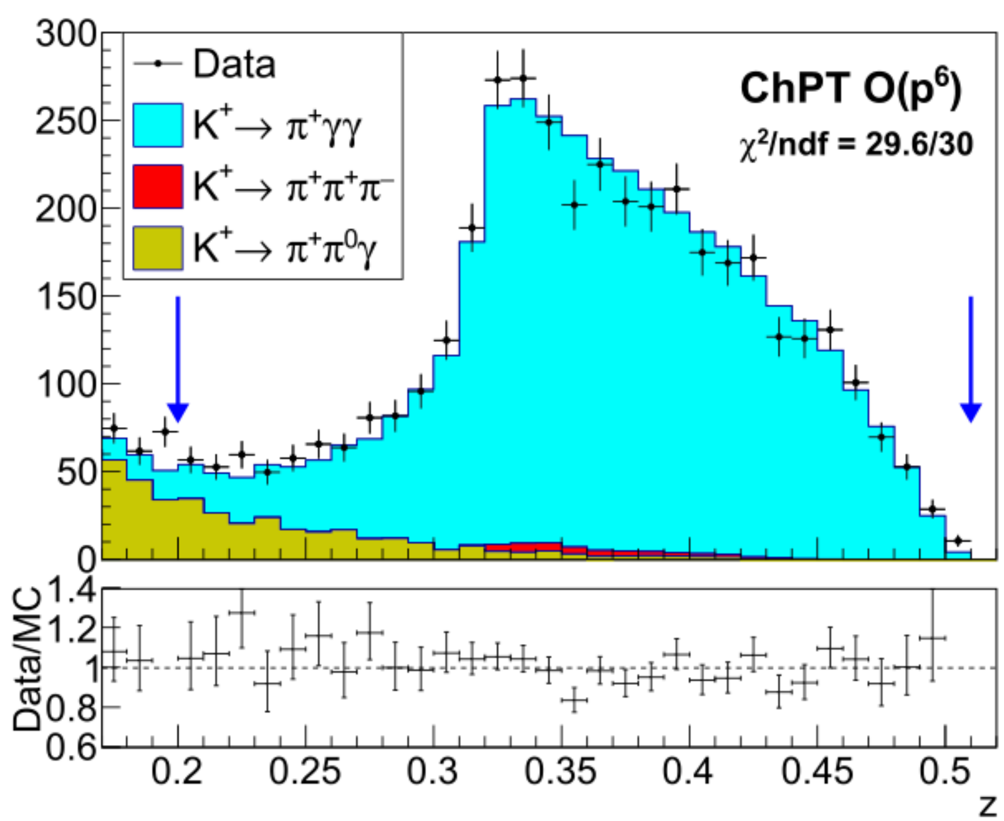
Measurement of $K^+ \to \pi^+\gamma\gamma$

- Analysis of the di-photon mass spectrum is performed in the chiral perturbation theory framework to **measure the decay branching ratio and the parameter characterising the spectrum.**
- First **search for production and prompt decay of an axion-like particle with gluon coupling in the process** $K^+ \to \pi^+ a,\ a \to \gamma\gamma$ (search for peaks in $\sqrt{(P_K - P_\pi)^2}$)
- 3984 candidates in 2017+2018 dataset, estimated background 291 ± 14

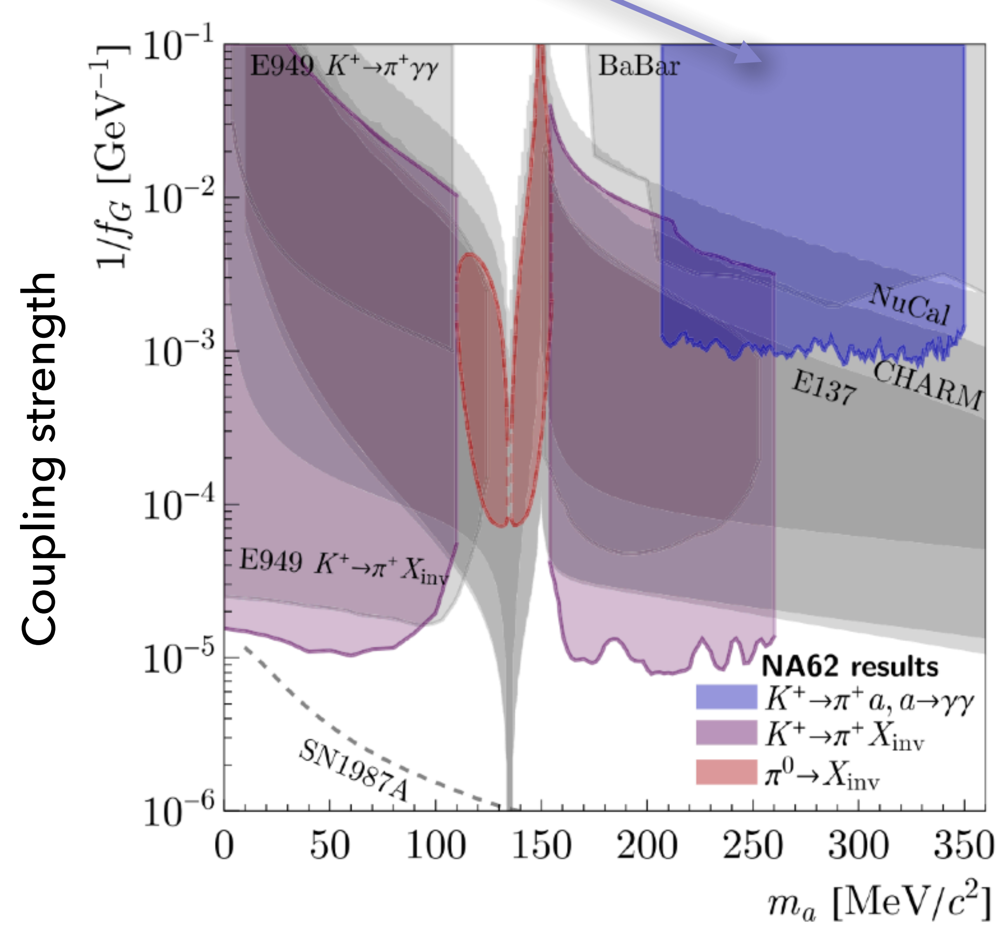


Phys. Lett. B 850 (2024) 138513

No significant evidence for $K^+ \to \pi^+ a,\ a \to \gamma\gamma$



$z = \frac{m_{\gamma\gamma}^2}{m_k^2}$



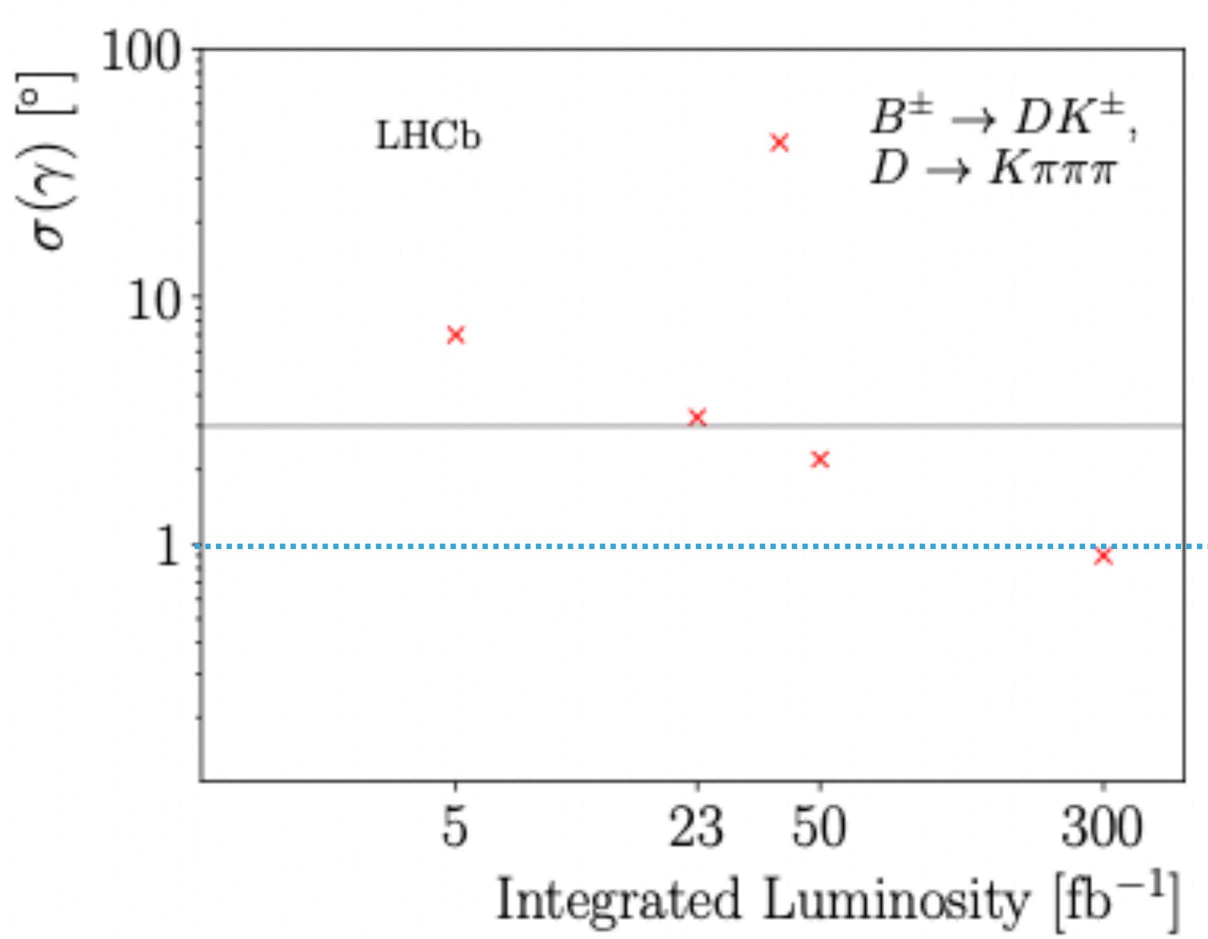
BC11 hidden sector scenario

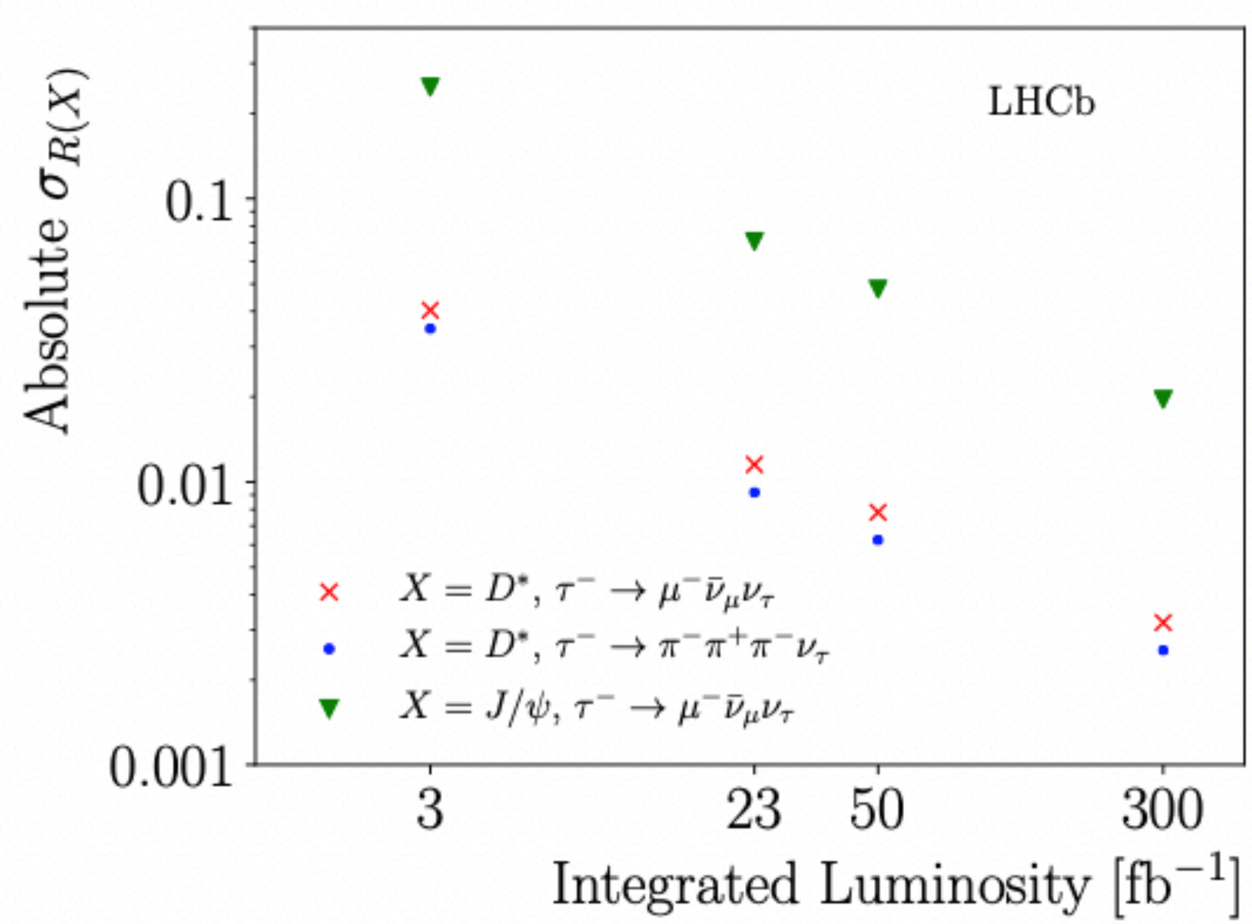
Exclusion regions at 90% CL

Future datasets: LHCb Upgrade II

- Additional datasets being collected by the experiments (e.g Run 3 for the LHC)
- Flavour physics in the high luminosity era: LHCb Upgrade II
- ~300/fb integrated luminosity foreseen, with instantaneous luminosity $\mathcal{O}(10^{34})\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Strong physics case for flavour physics, also covering EW physics, dark sector, spectroscopy

LHCC-2021-012





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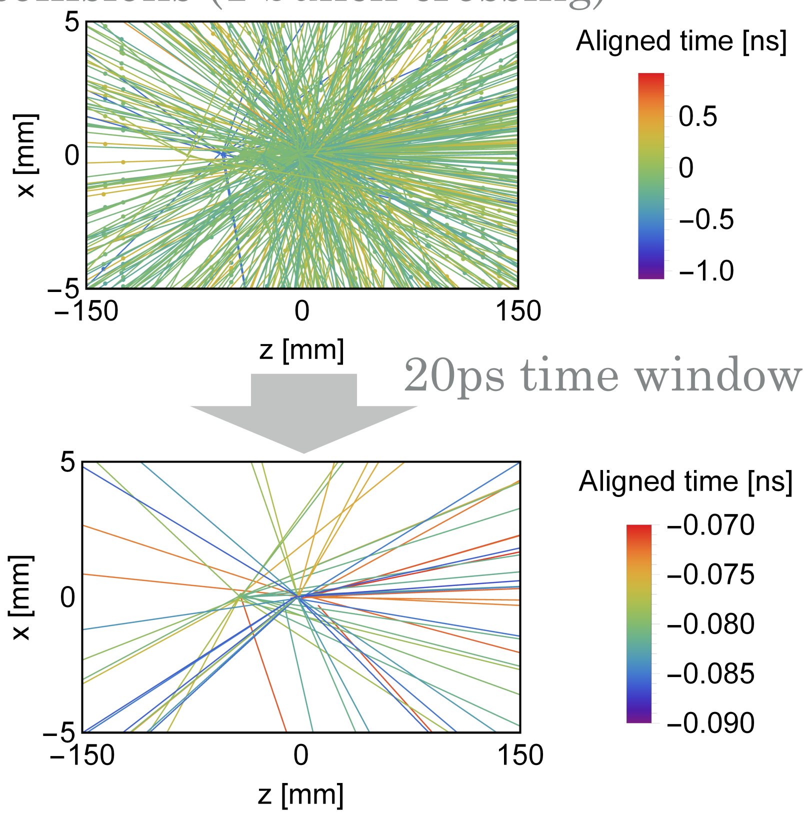
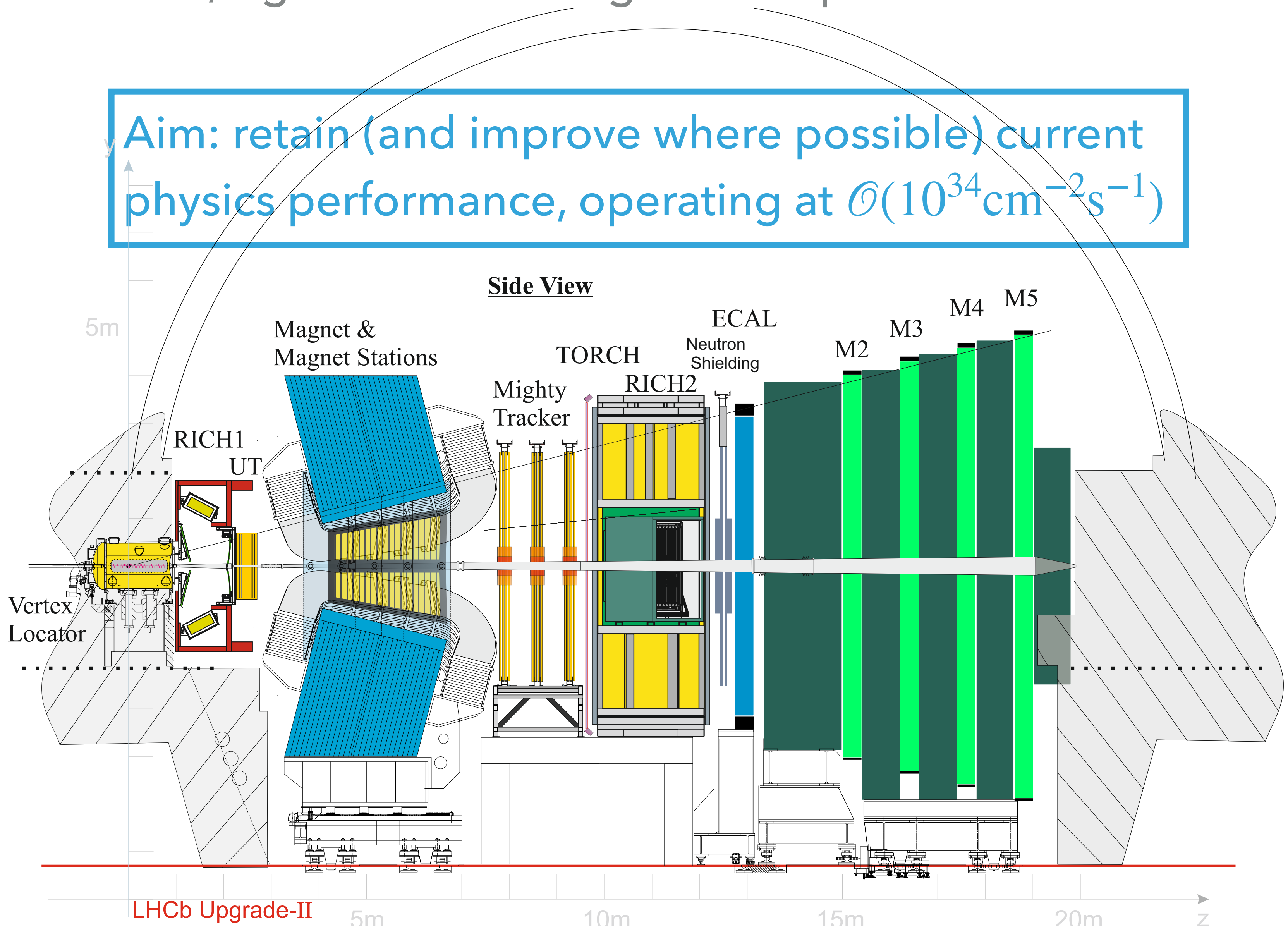
- Flavour physics in the high luminosity era: LHCb Upgrade II
- ~300/fb integrated luminosity foreseen, with instantaneous luminosity $\mathcal{O}(10^{34})\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
- **Essentials**: efficient charged particles reconstruction, vertices reconstruction and association, mass (momentum) resolution, signal versus background separation
- Extensive R&D under way

Track density generated by 42 collisions (1 bunch crossing)



Aim: retain (and improve where possible) current physics performance, operating at $\mathcal{O}(10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1})$



- See also **Constantinos Vrahas**'s talk *Characterisation of irradiated SiPMs* , Wed 11:00am

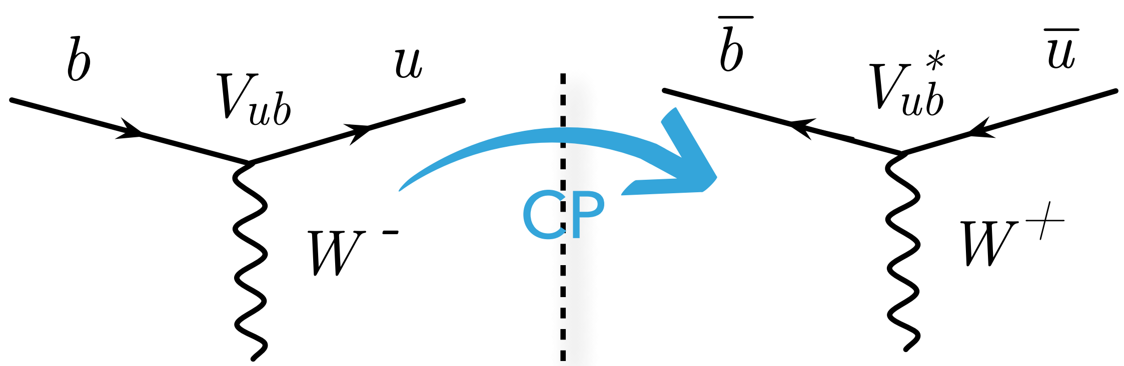
Summary

- The flavour physics programme is thriving at LHCb and in other experiments
  - A selection of LHC Run 2 new results shown
- Wonderful to see how complementarity of different experiments and methods helps to perform higher precision measurements
  - A selection of recent BESIII and NA62 shown
- Exciting to see first results from CMS (including parked data) - more independent measurements to come!
- Run 3 on-going: new high statistics data samples being collected
- Studies and R&D for LHCb Upgrade II on going

Backup

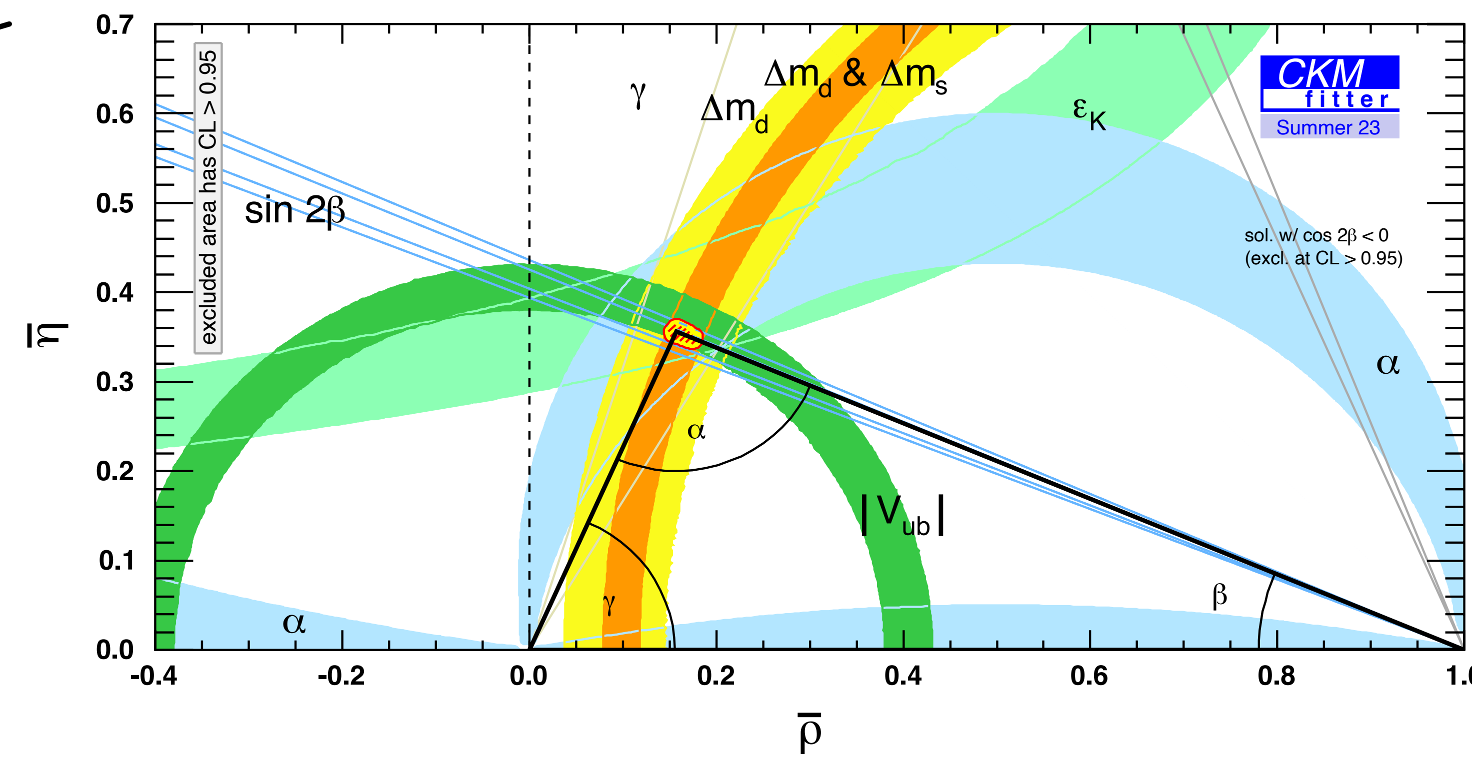
CP violation and CKM metrology

- The Standard Model predicted CP asymmetry is not sufficient to explain the baryon asymmetry of the Universe ⇒ New Physics CP violating effects are expected
- The only established source of CP violation in the SM is contained in the imaginary part of the CKM matrix describing transitions between quarks
- Unitarity condition $V_{CKM}V^{\dagger}_{CKM} = 1$ leads to Unitarity triangles



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

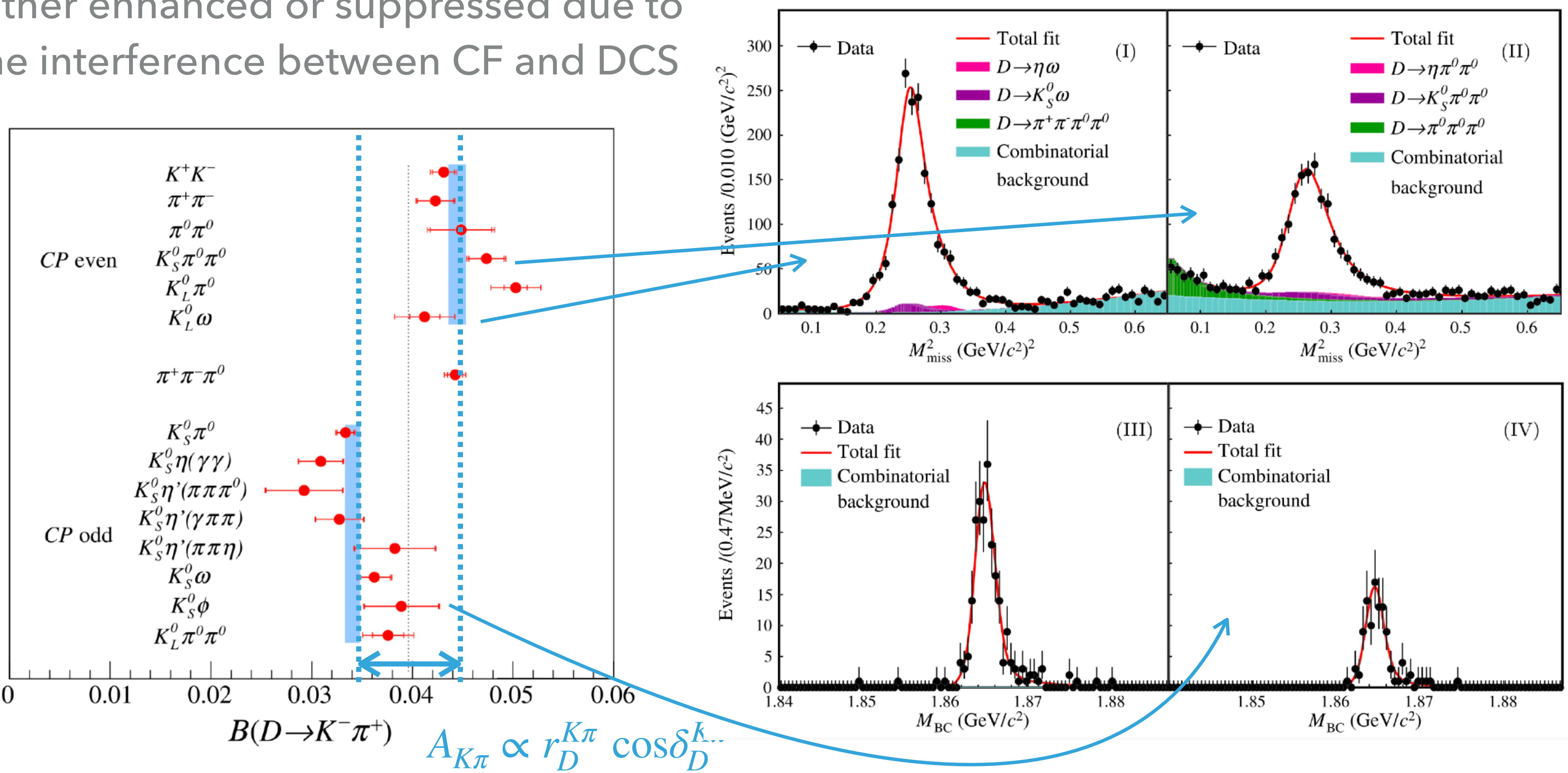
$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$



- Precise measurements of heavy hadron decays ⇒ Redundant determination of the CKM parameters

Strong phases: charm at threshold at BESIII

- Measurement of $\delta_D^{K\pi}$, strong phase difference between the Cabibbo-favoured (CF) $D^0 \to K^+\pi^-$ and doubly Cabibbo-suppressed (DCS) $\overline{D}^0 \to K^+\pi^-$
- Effective BF of $D \to K^+\pi^-$ for each tag is either enhanced or suppressed due to the interference between CF and DCS



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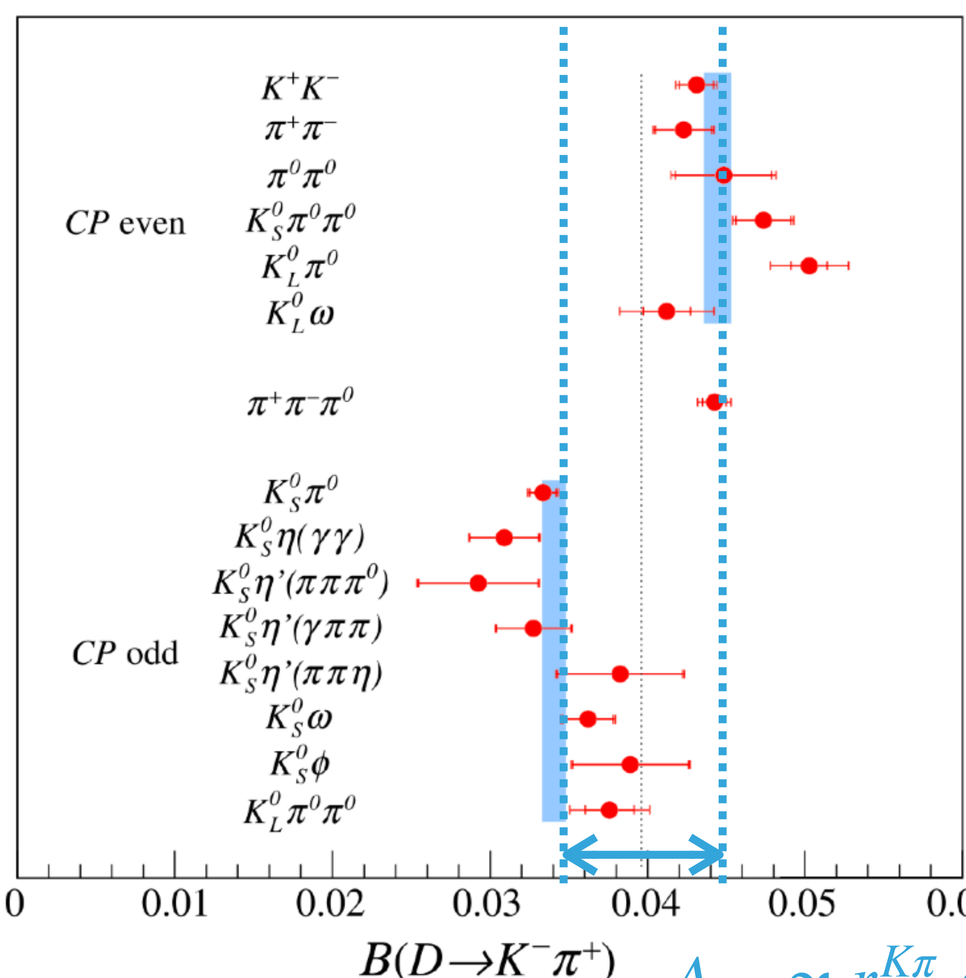
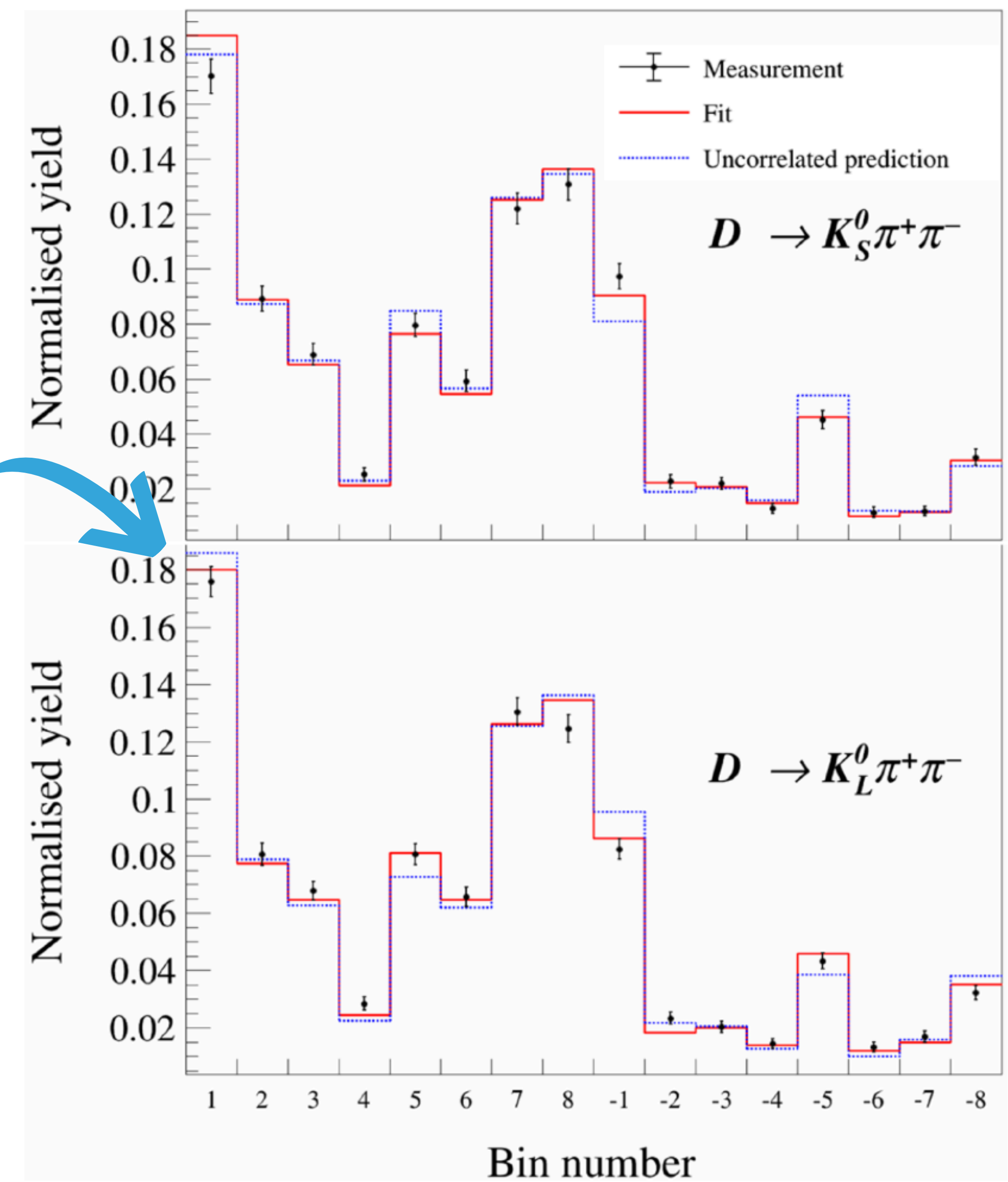


$A_{K\pi} \propto r_D^{K\pi}\ \cos\delta_D^{K\pi}$



Bin Yield relate to both $r_D^{K\pi}\ \cos\delta_D^{K\pi}$ and $r_D^{K\pi}\ \sin\delta_D^{K\pi}$

- Using both determinations: $\delta_D^{K\pi} = 187.6^{+8.9+5.4}_{-9.7-6.4}$

Charm – time-dependent CP violation

- Search for time dependent CP violation in $D^0 \to \pi^+\pi^-\pi^0$ decays
- Probe CPV in up-type quarks
- Time-dependent CP- asymmetry:

$$A^f_{CP}(t) = \frac{\Gamma_{D^0\to f}(t) - \Gamma_{\overline{D}^0\to f}(t)}{\Gamma_{D^0\to f}(t) + \Gamma_{\overline{D}^0\to f}(t)} \approx a_f^{\mathrm{dir}} + \Delta Y^{eff}\frac{1}{\tau_{D^0}}$$

$$\Delta Y^{eff} \approx (2F_f^+ - 1)\left[x\sin\phi - \left(\left|\frac{q}{p}\right| - 1\right)y\right]$$

Parameter measured, related to charm mixing parameters (and CP-even fraction, ~0.97)

- World average of previous measurements:

$$-\Delta Y \approx A_\Gamma = (0.9 \pm 1.1) \times 10^{-4}$$

$$\frac{\Delta Y}{|2F_f^+ - 1|} = \Delta Y \approx -A_\Gamma$$

Neutral mesons flavour oscillations

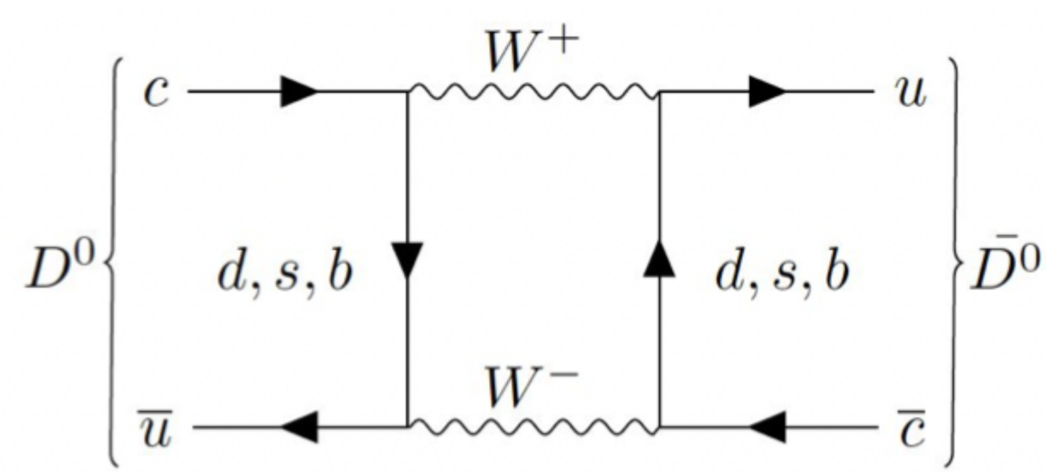
With $|D_1\rangle \approx$ CP-even

$|D_{1,2}\rangle = p|D^0\rangle \mp q|\overline{D}^0\rangle$

$x = (m_1 - m_2)/\Gamma$

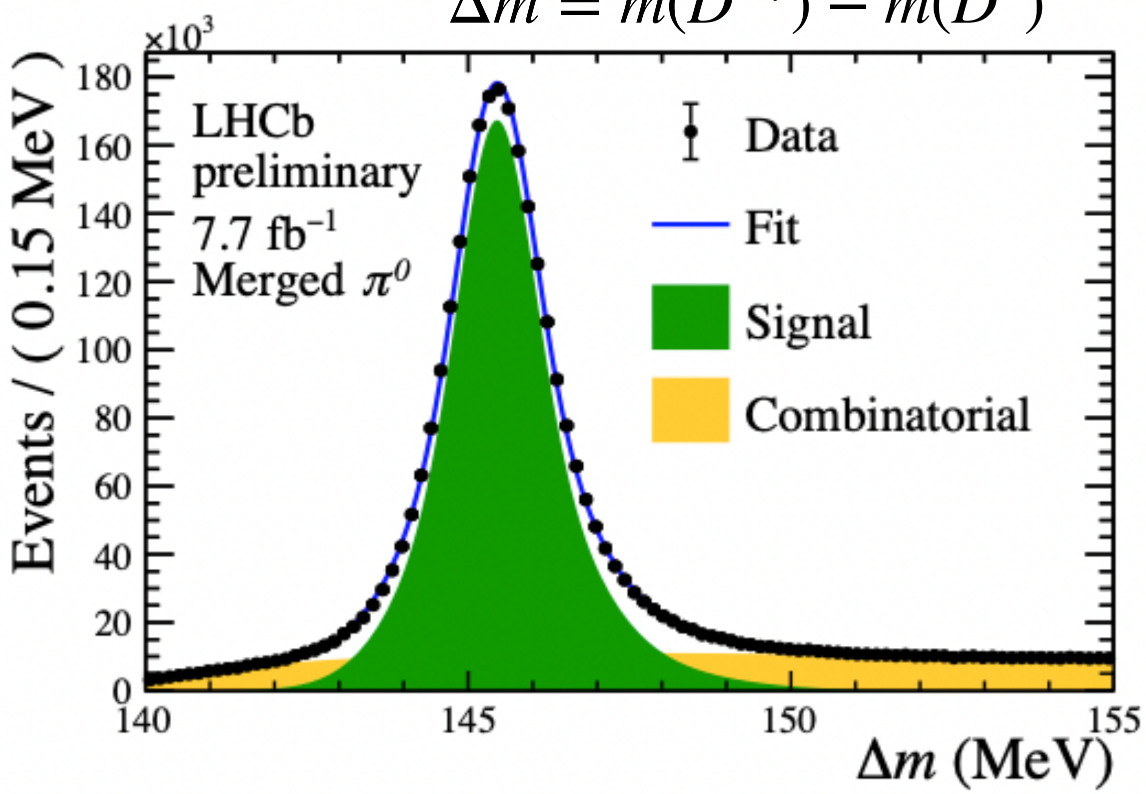
$y = (\Gamma_1 - \Gamma_2)/2\Gamma$

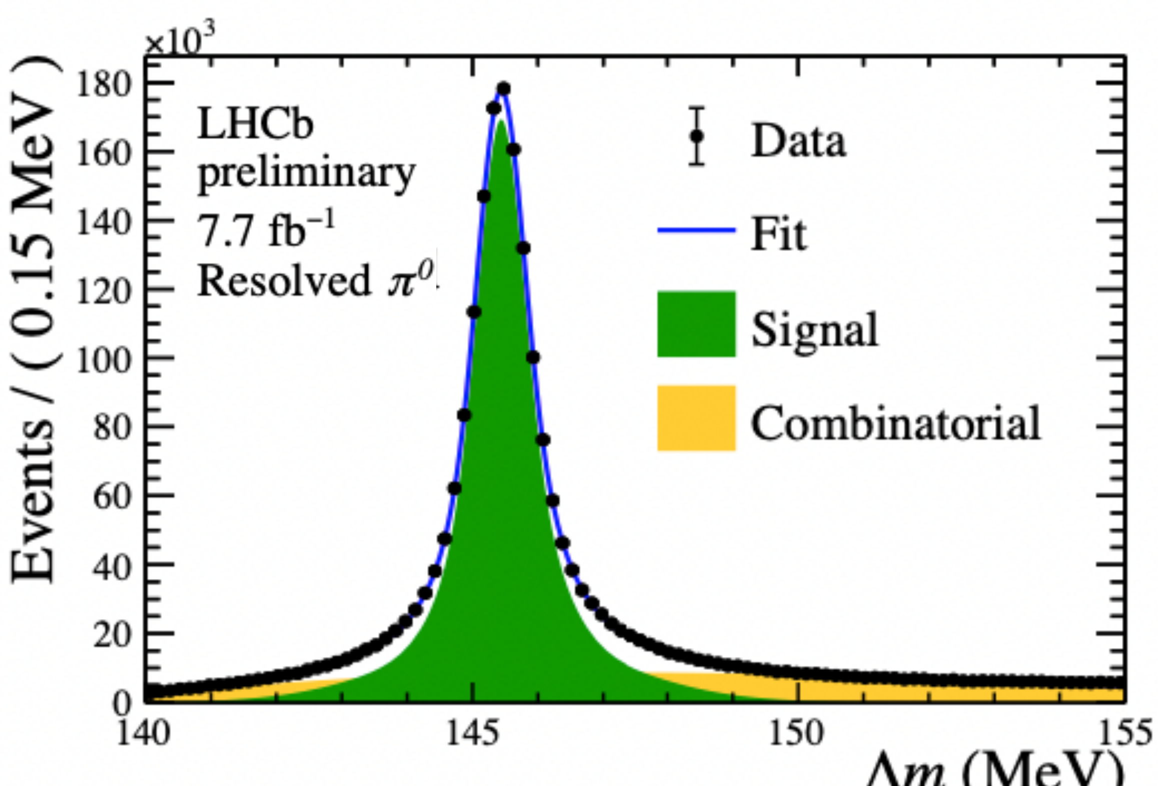
$\phi = \arg(q/p)$



Charm – time-dependent CP violation

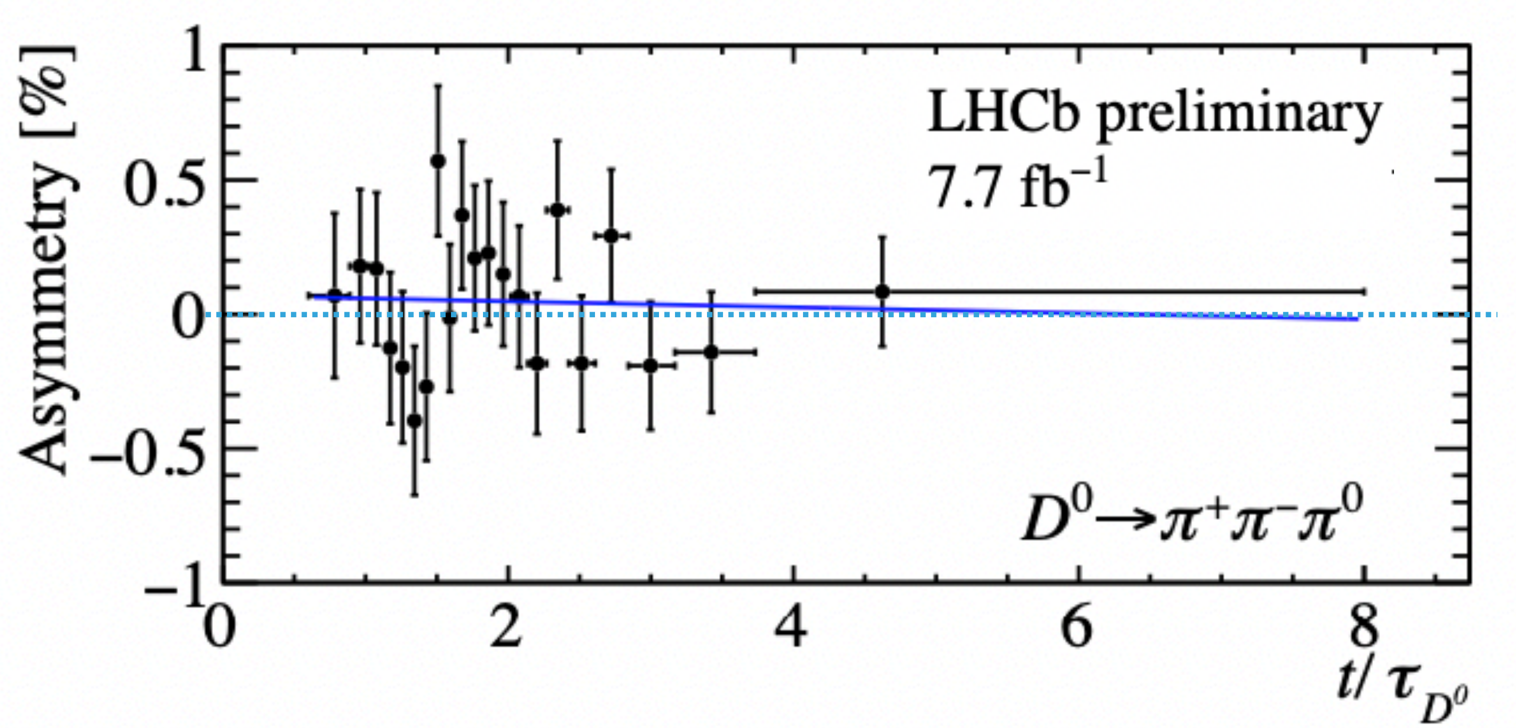
$\Delta m = m(D^{*+}) - m(D^0)$





- Studying prompt decays
  $D^{*+} \to D^0(\to \pi^+\pi^-\pi^0)\pi^+_{tag}$
- 2.3M (1.5M) merged (resolved) π^0 candidates in 2012-2018 dataset
- Data driven weighting procedure to correct for detection asymmetries
- Extract ΔY^{eff} (slope) from mass fits in bins of t/τ_{D^0}

$$A^f_{CP}(t) = \frac{\Gamma_{D^0\to f}(t) - \Gamma_{\overline{D}^0\to f}(t)}{\Gamma_{D^0\to f}(t) + \Gamma_{\overline{D}^0\to f}(t)} \approx a_f^{\rm dir} + \Delta Y^{eff}\frac{1}{\tau_{D^0}}$$



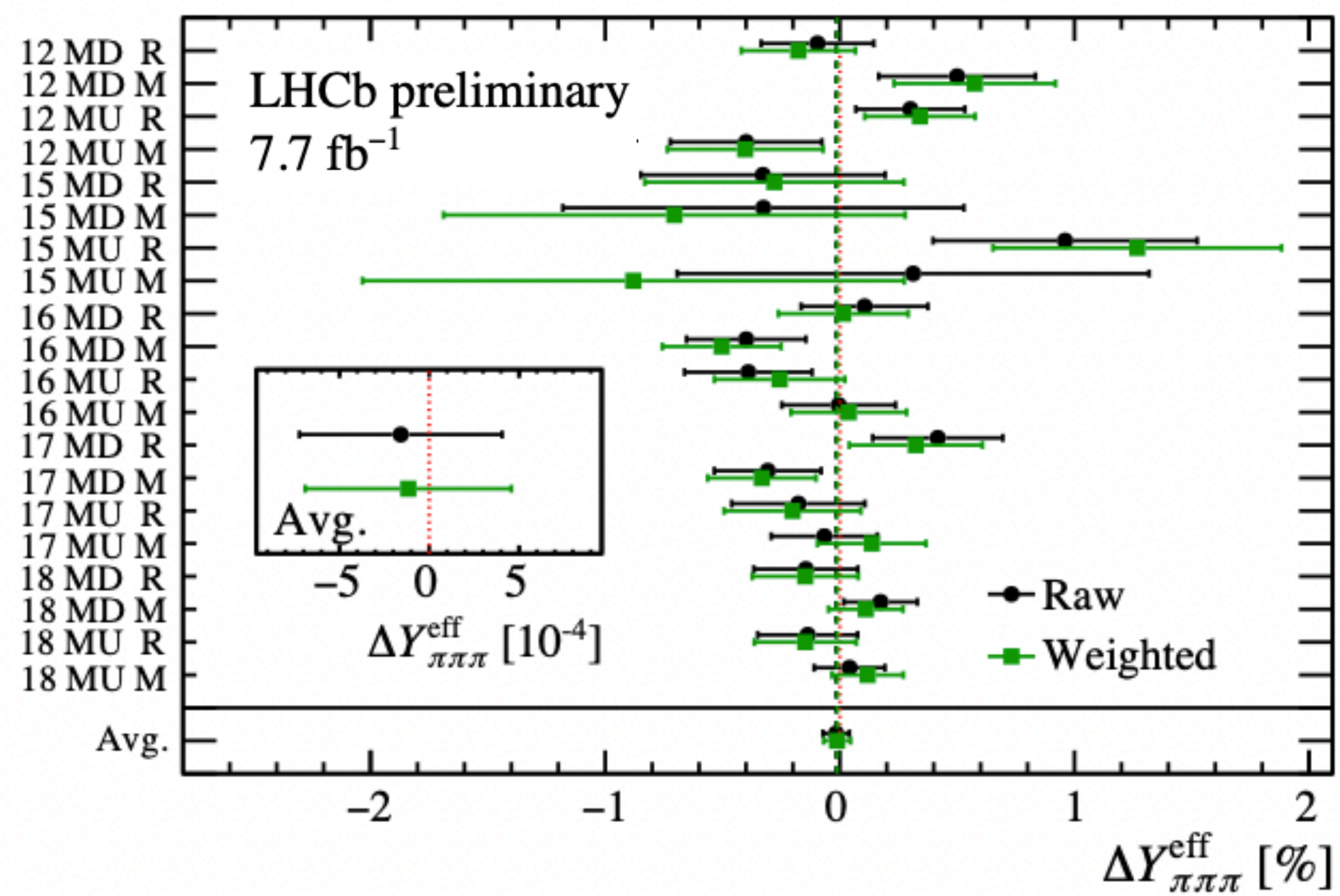
Charm – time-dependent CP violation

- Result consistent with no CP violation and compatible with world average

$$\Delta Y^{\text{eff}}_{\pi\pi\pi} = (-1.2 \pm 6.0\,(\text{stat.}) \pm 2.3\,(\text{syst.})) \times 10^{-4}$$

$$\Rightarrow \Delta Y = (-1.3 \pm 6.3\,(\text{stat.}) \pm 2.4\,(\text{syst.})) \times 10^{-4}$$

- First measurement of time-dependent CPV in a D^0 decay with a neutral pion at a hadron collider



- Search for CP violation in the phase space of $D^0 \to \pi^+\pi^-\pi^0$ decays with the energy test
  - unbinned model-independent approach provides sensitivity to local CP violation
  - Results consistent with CP symmetry

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Tree-level transitions: measurement of $R(D^{(*)+})$

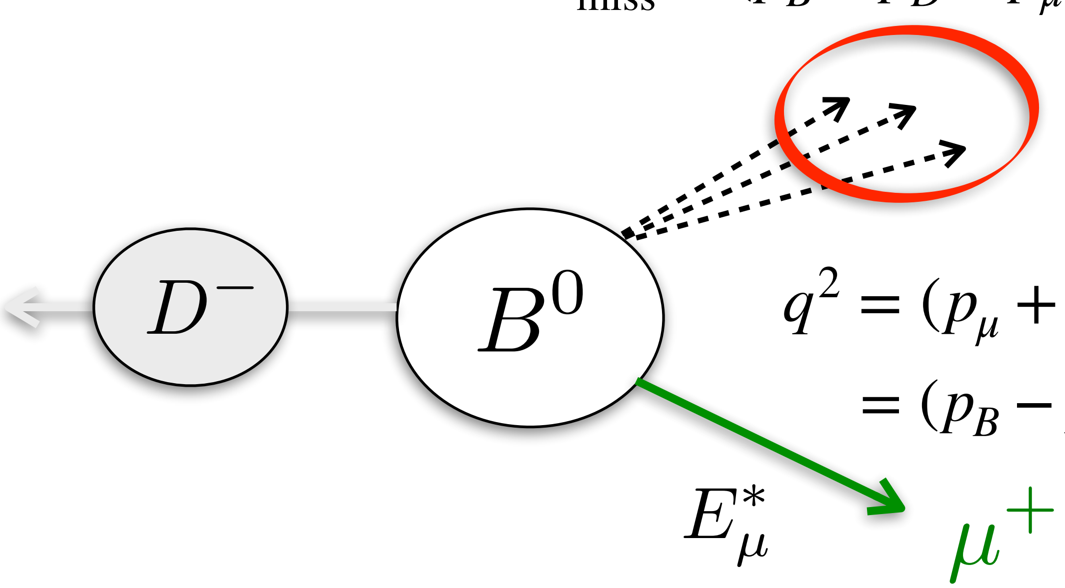
LHCb-PAPER-2024-007
in preparation

- First LHCb measurement using the D^+ ground state, with $D^+ \to K^-\pi^+\pi^+$, muonic-tau decay
  - Feed-down from $D^{*+} \to D^+\pi^0/\gamma$, w/o reconstructing π^0/γ gives access to $R(D^{*+})$ with the same final state

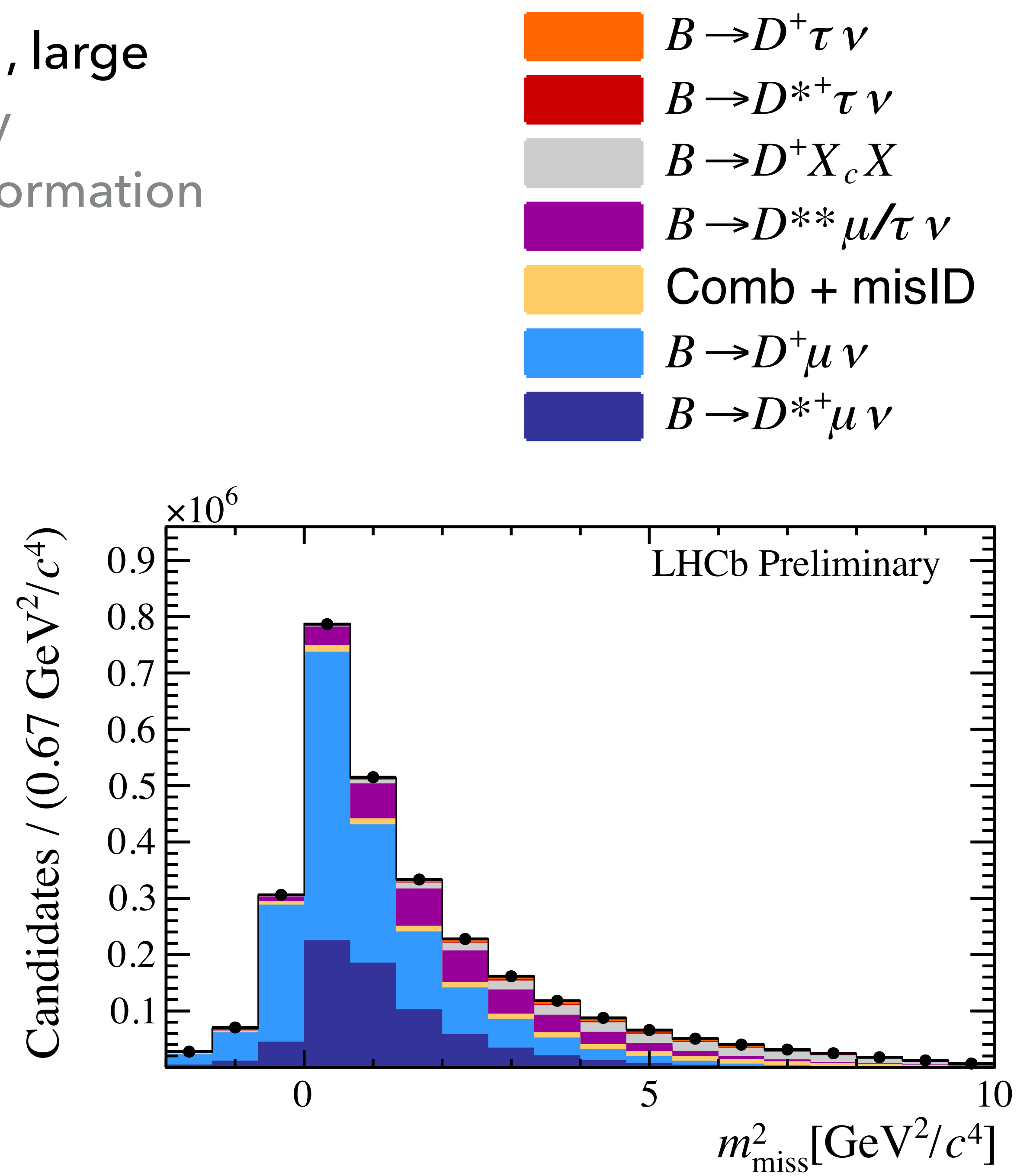
$$R(D^{(*)}) = \frac{\mathcal{B}(B^0 \to D^{(*)}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)}l\nu)}$$

- **Partial reconstruction → unconstrained kinematics , large backgrounds:** need to fully exploit vertex topology information, track isolation, available kinematic information
- Fit to kinematic variables to separate signal from normalisation, from backgrounds

$$m^2_{\text{miss}} = (p_B - p_D - p_\mu)^2$$

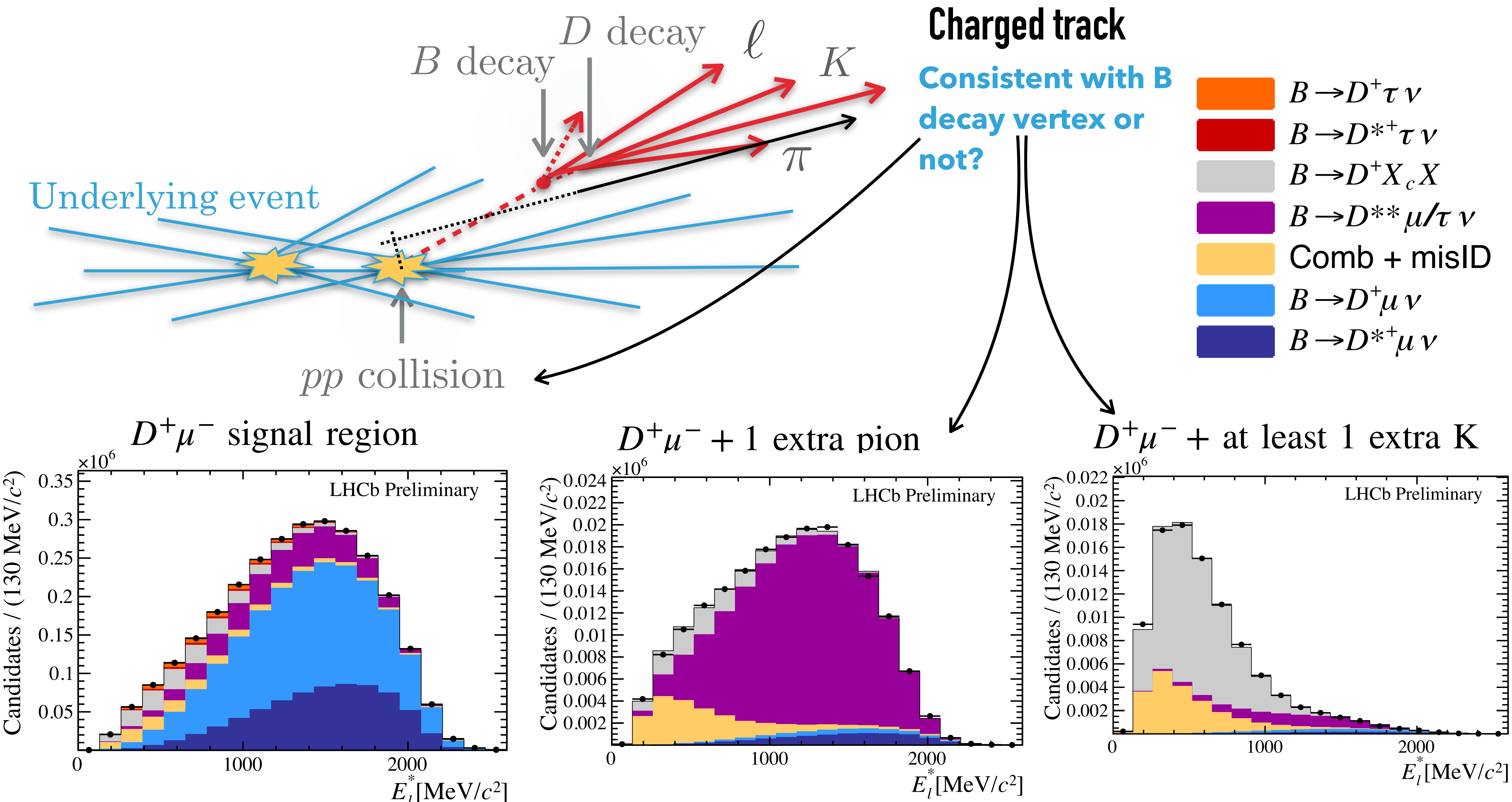


$$q^2 = (p_\mu + p_\nu)^2 = (p_B - p_D)^2$$



Tree-level transitions: measurement of $R(D^{(*)+})$

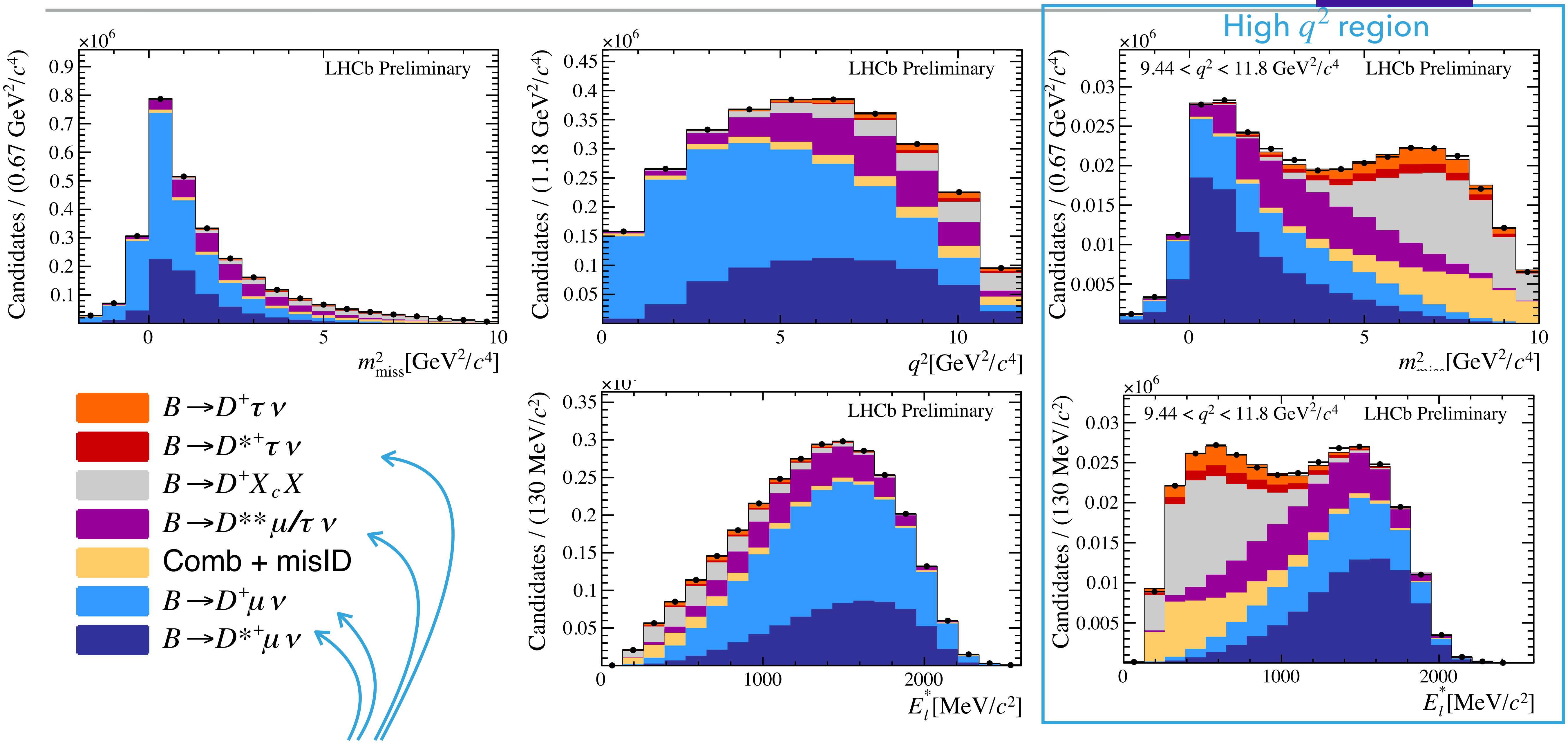
- Partial reconstruction → unconstrained kinematics , large backgrounds: need to fully exploit vertex topology information, track isolation, available kinematic information



LHCb-PAPER-2024-007

Tree-level transitions

LHCb-PAPER-2024-007



- Hadronic form factors: $B \to D$ BGL [PRD 94 (2016) 094008], $B \to D^*$BGL [Eur. Phys. J. C 82, 1141 (2022)],$B \to D^{**}$ BLR [PRD 95 (2017) 014022]
- First analysis that uses HAMMER [Eur. Phys. J. C. 80 (2020) 883] and RooHammerModel [JINST 17 (2022) T04006] to vary the form factor parameters in the fit (with external constraints applied)
- First analysis using Tracker-Only fast simulation

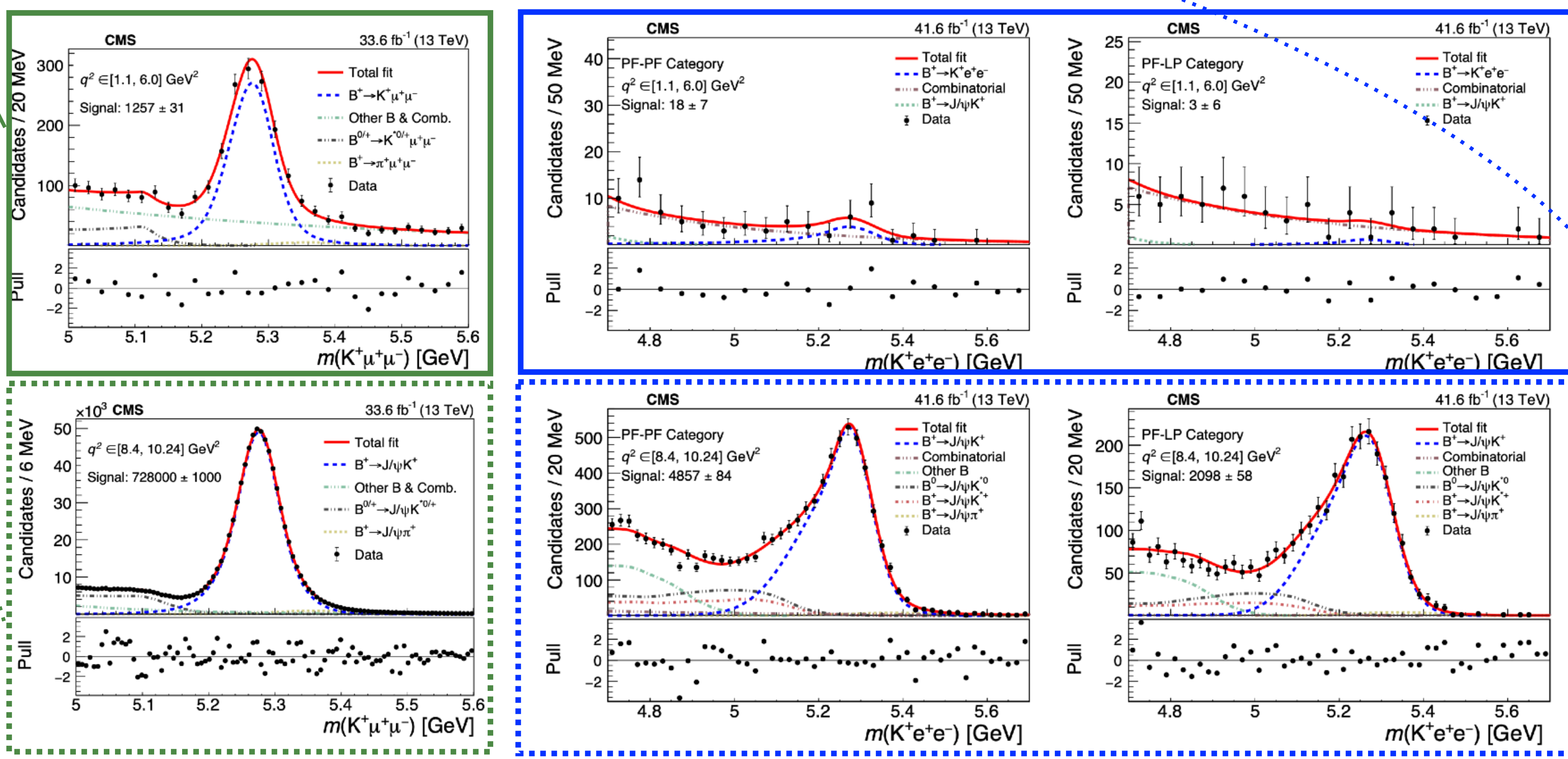
Analyses of $b \to s\ell^+\ell^-$ decays

- First test of lepton universality R_K @CMS, as well as differential and integrated BF, with 2018 parked data CMS-EXO-23-007

$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+(J/\psi \to \mu^+\mu^-))} \Big/ \frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to K^+(J/\psi \to e^+e^-))}$$

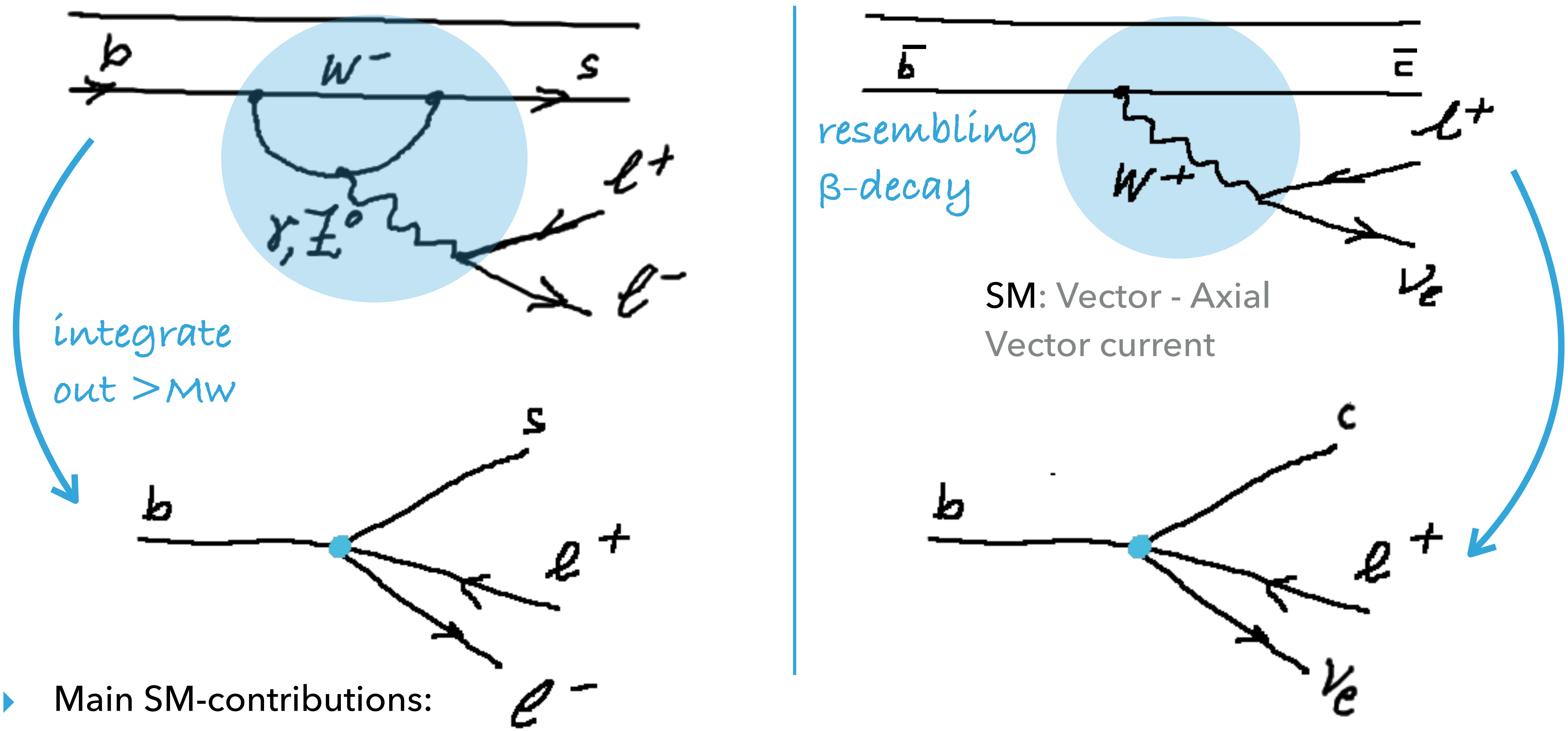
$$= \frac{N_{K^+\mu^+\mu^-}/\epsilon_{K^+\mu^+\mu^-}}{N_{K^+(J/\psi\to\mu^+\mu^-)}/\epsilon_{K^+(J/\psi\to\mu^+\mu^-)}} \Big/ \frac{N_{K^+e^+e^-}/\epsilon_{K^+e^+e^-}}{N_{K^+(J/\psi\to e^+e^-)}/\epsilon_{K^+(J/\psi\to e^+e^-)}}$$

CMS-BPH-22-005



$$R(\mathrm{K}) = 0.78^{+0.46}_{-0.23}\,(\mathrm{stat})^{+0.09}_{-0.05}\,(\mathrm{syst}) = 0.78^{+0.47}_{-0.23}$$

A word about weak effective theory



- Main SM-contributions:
  - Vector (C9) and Axial Vector (C10) leptonic currents
  - Dipole b → sγ* contribution in C7

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{tb} V_{tx}^* \sum_i C_i O_i$$

$$C_i = C_i^{SM} + C_i^{NP}$$