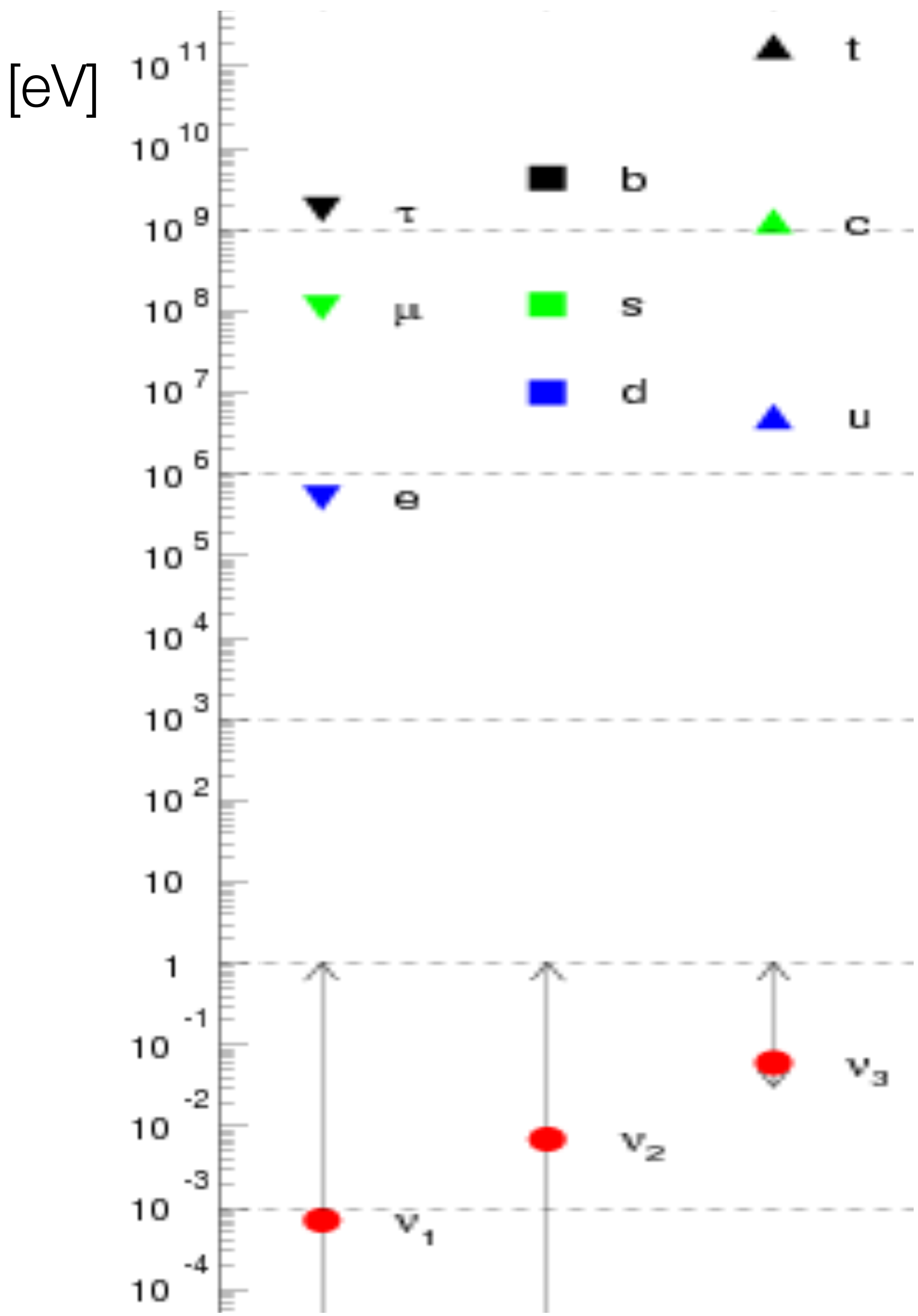
Flavour anomalies at LHCb

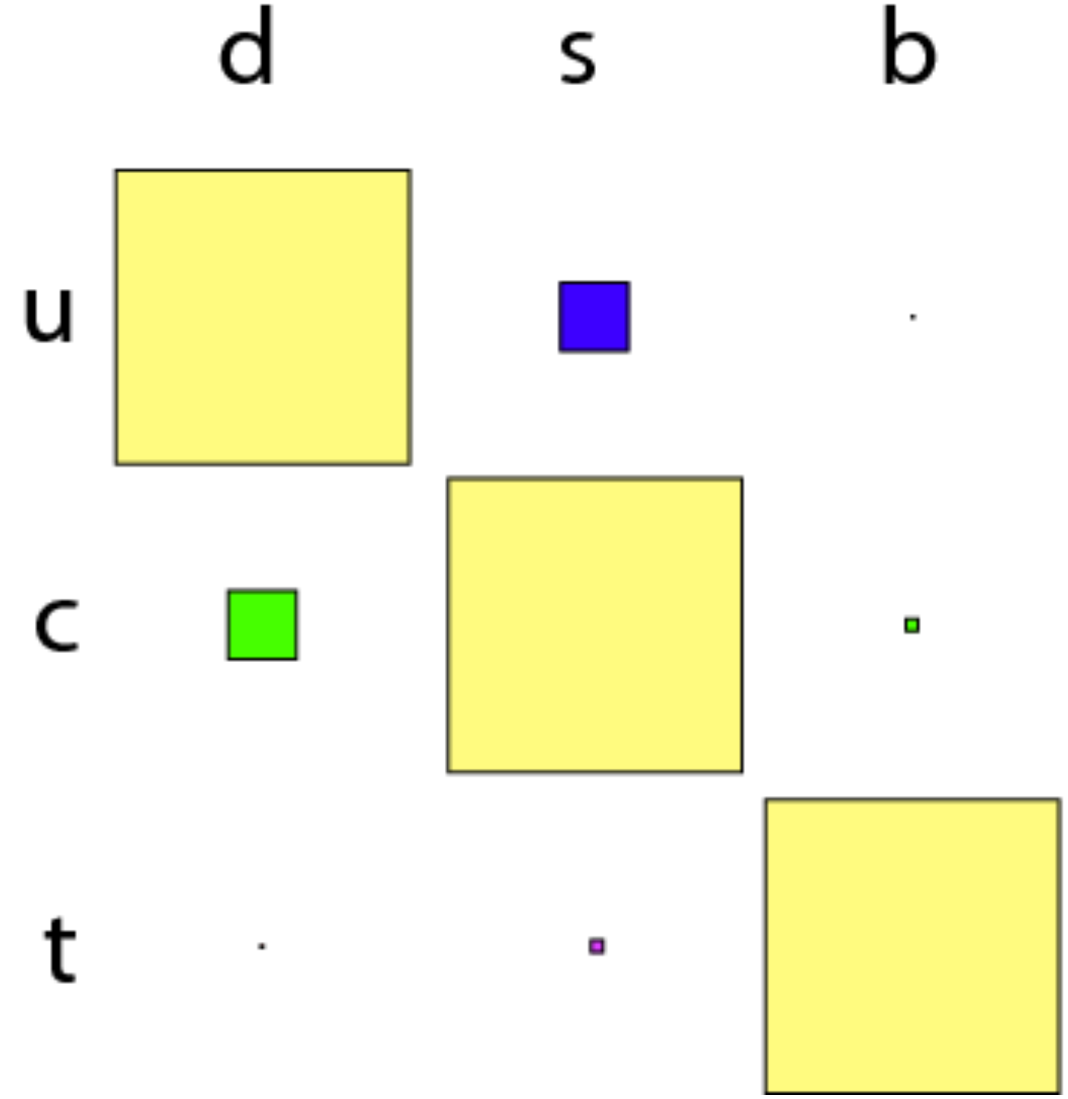
Mika Vesterinen
University of Warwick

UK HEP Forum: The Spice of flavour
27-28 November 2018

WARWICK

Why study flavour?





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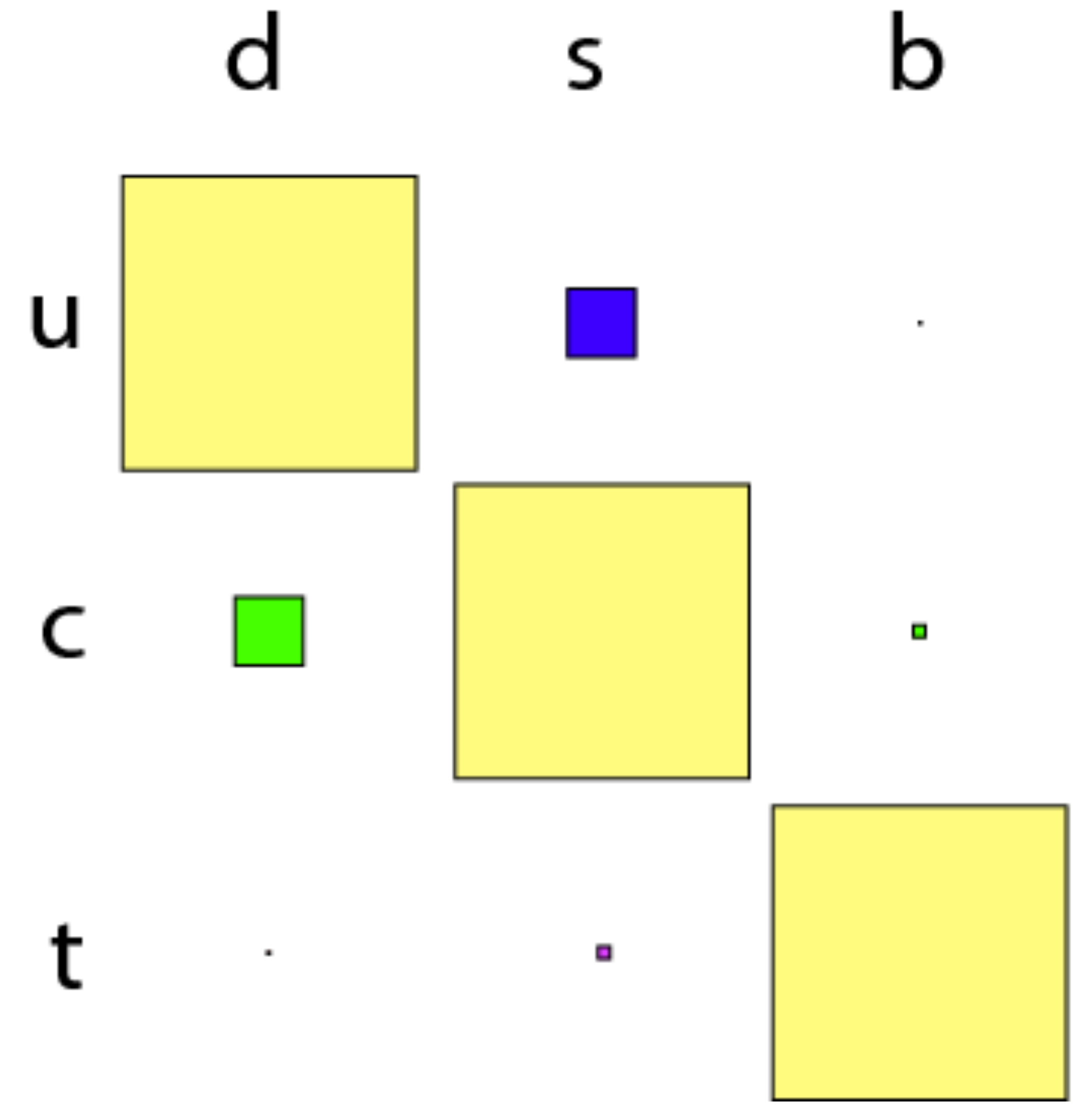

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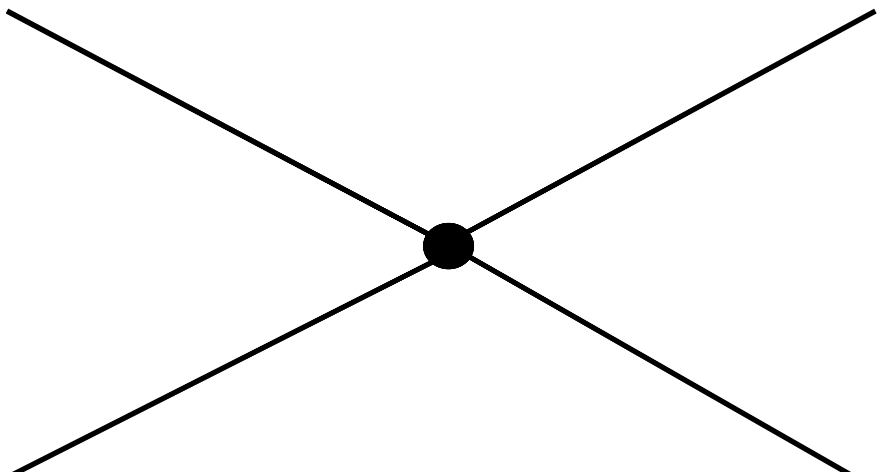
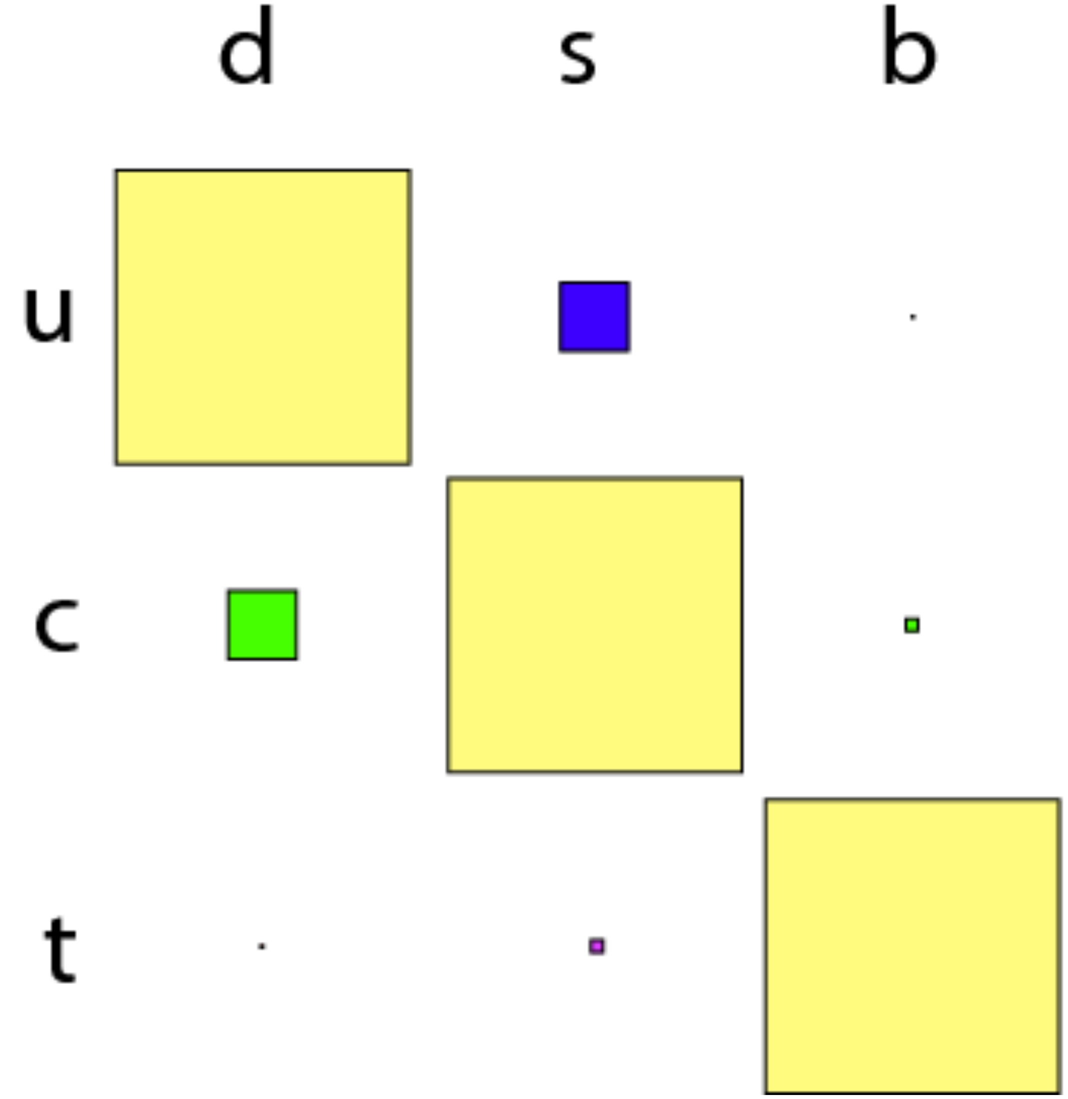


$$\mathcal{A}_0 \left(\frac{c_{\rm SM}}{v^2} + \frac{c_{\rm NP}}{\Lambda^2} \right)$$



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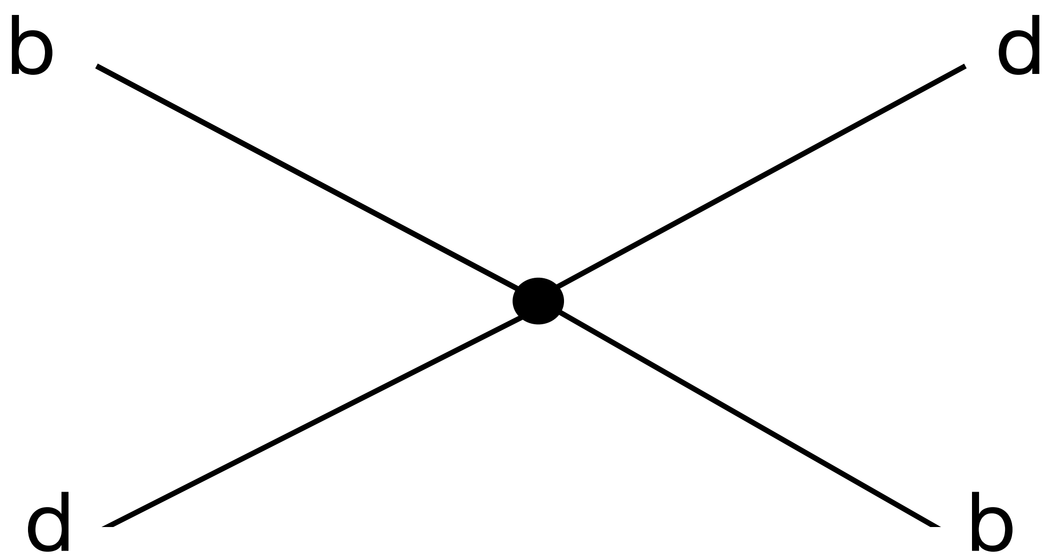

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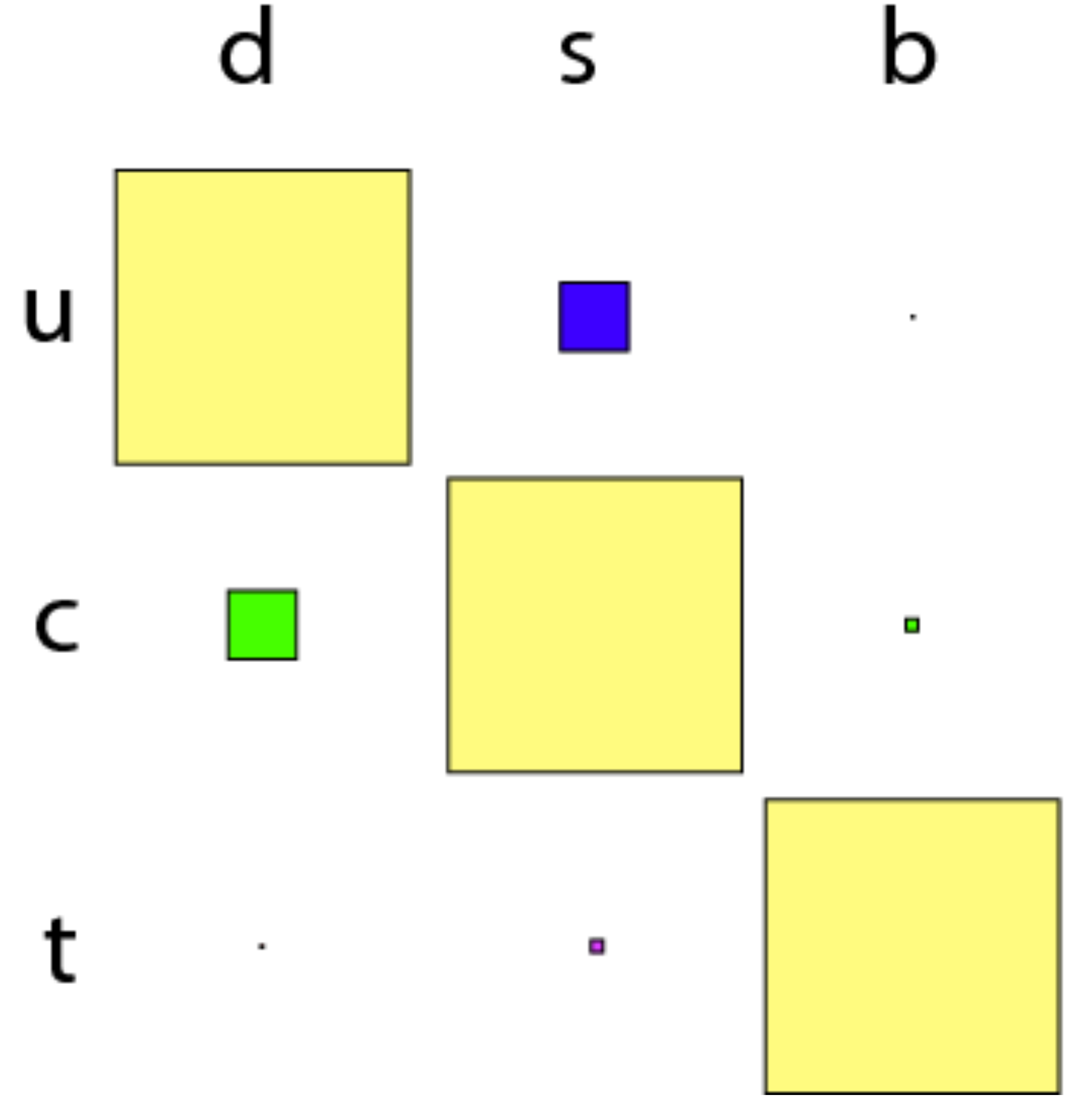

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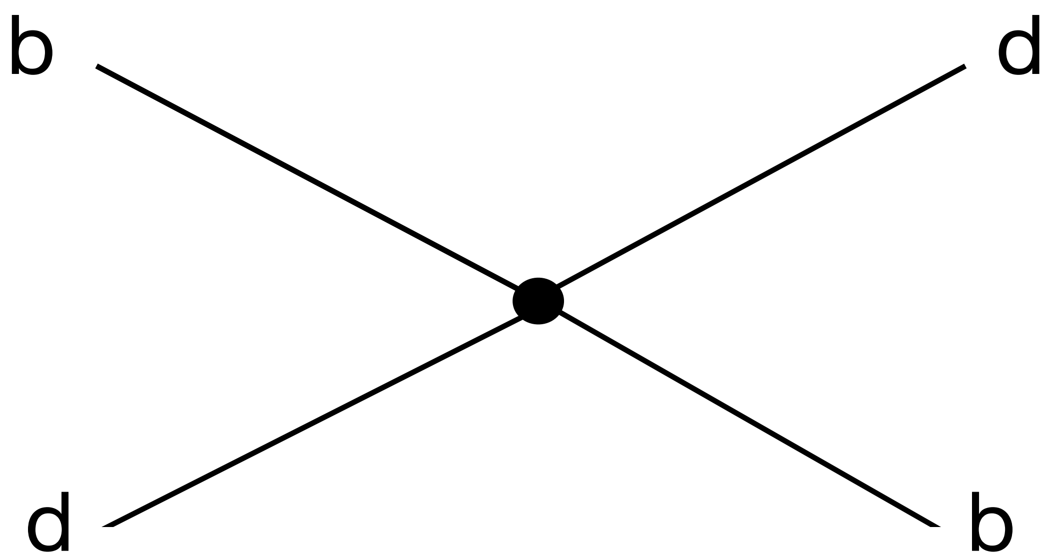

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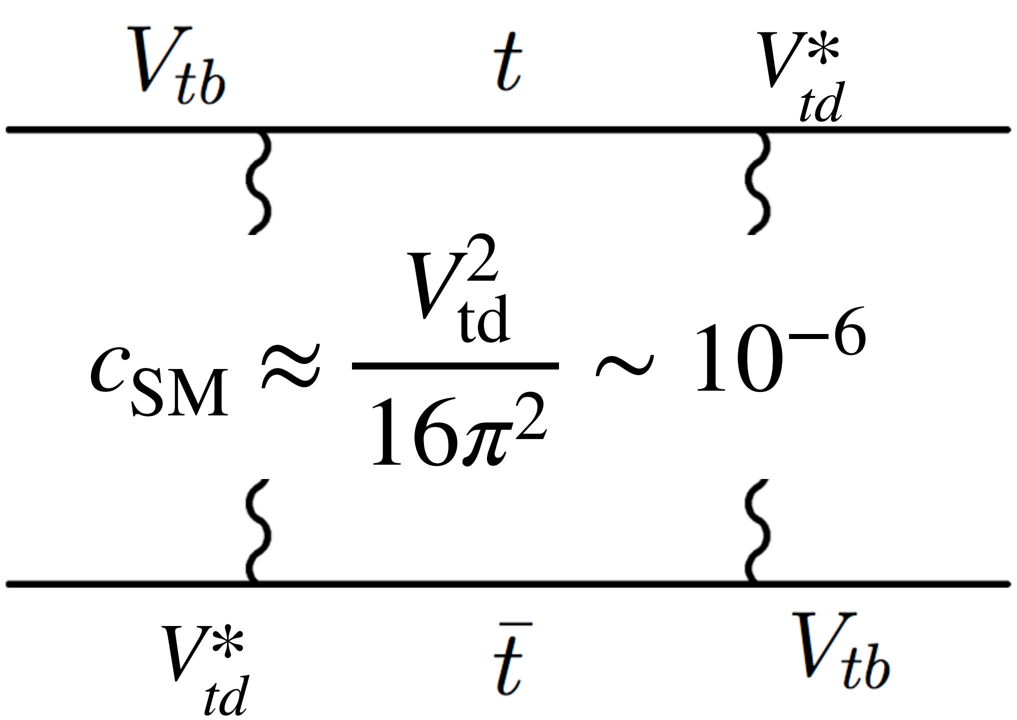
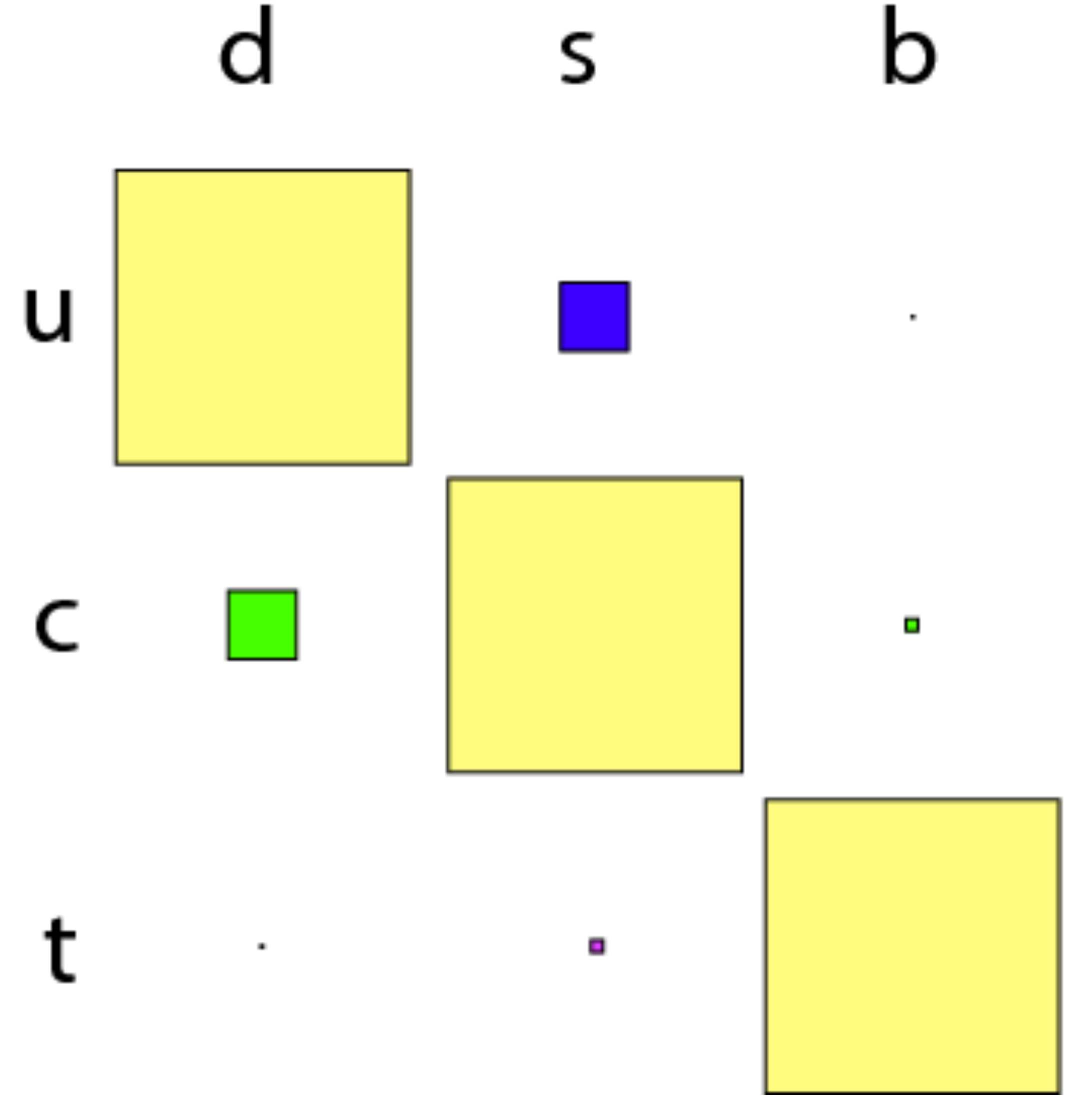


$$c_{\rm SM}\approx\frac{V_{\rm td}^2}{16\pi^2}\sim 10^{-6}$$

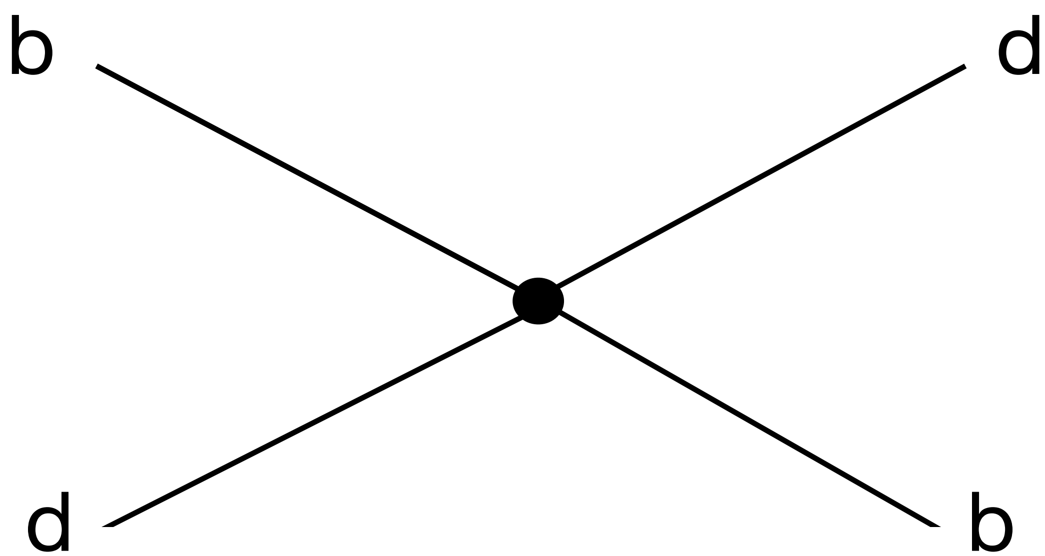


10% test probes

$$\frac{\Lambda^2}{c_{\rm NP}}\sim(10^3\ {\rm TeV})^2$$

The only limit is precision.

Why study flavour?



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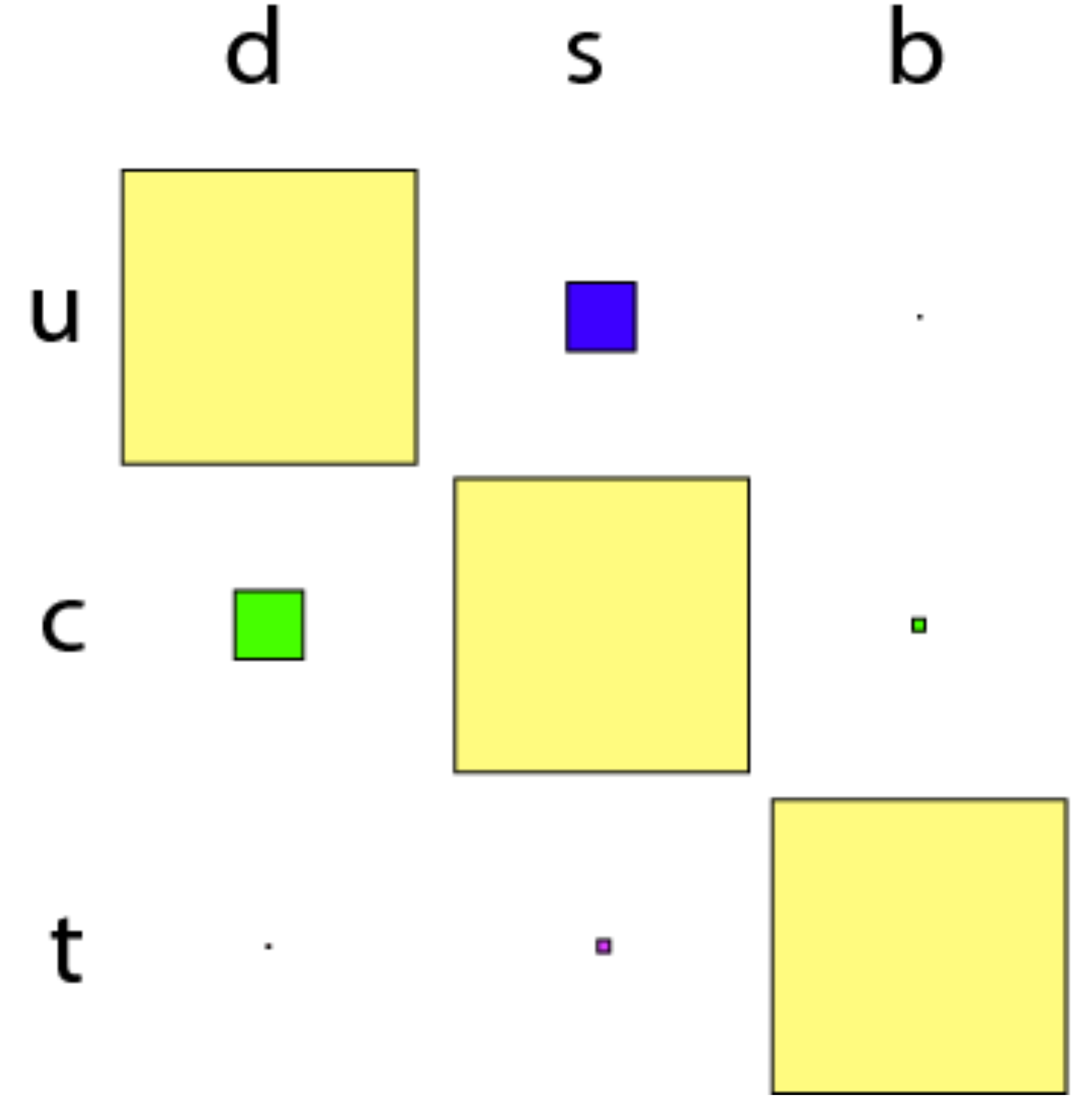
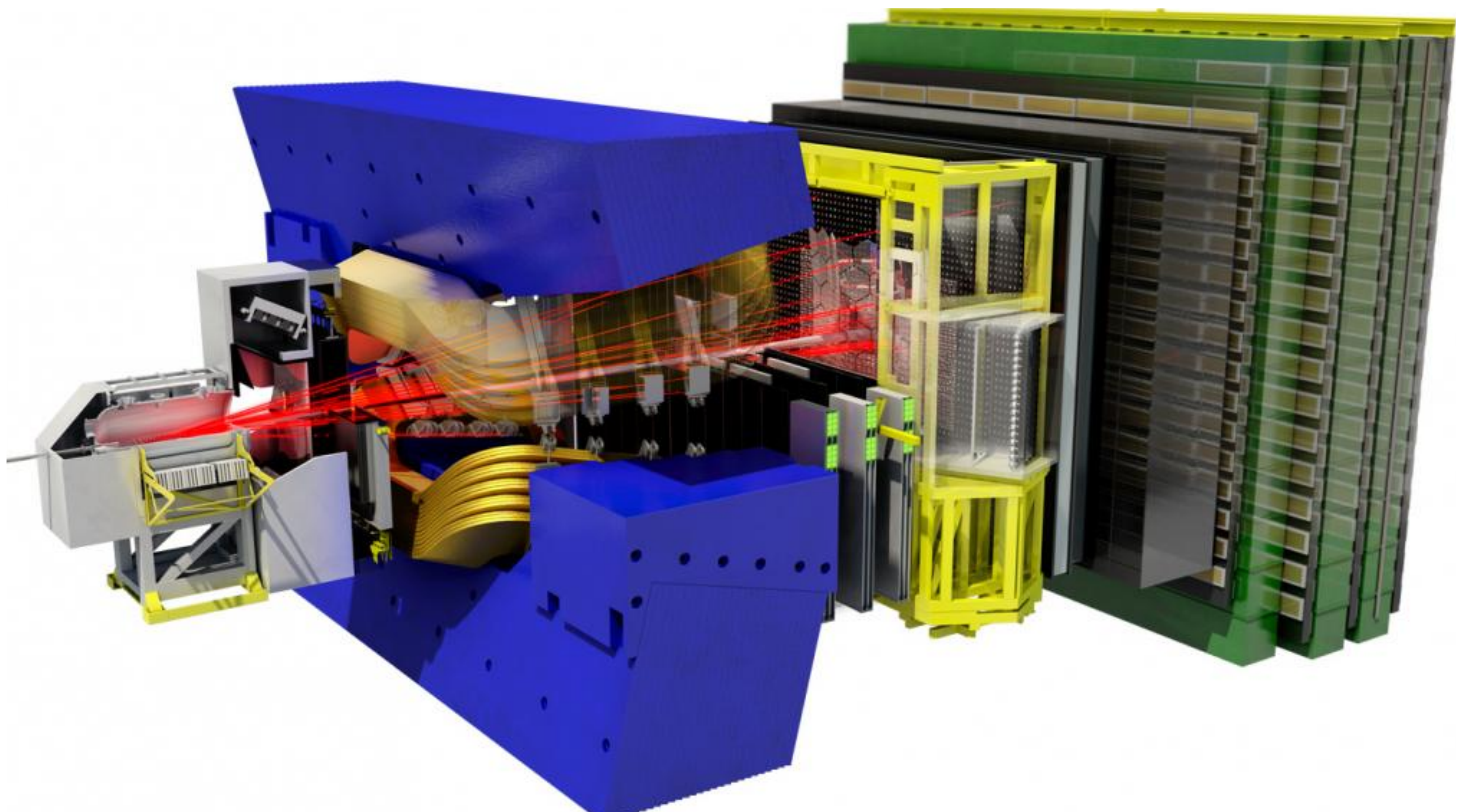


The role of QCD is important.

Talks of Matt Wingate and Roman Zwicky.

The LHCb experiment today



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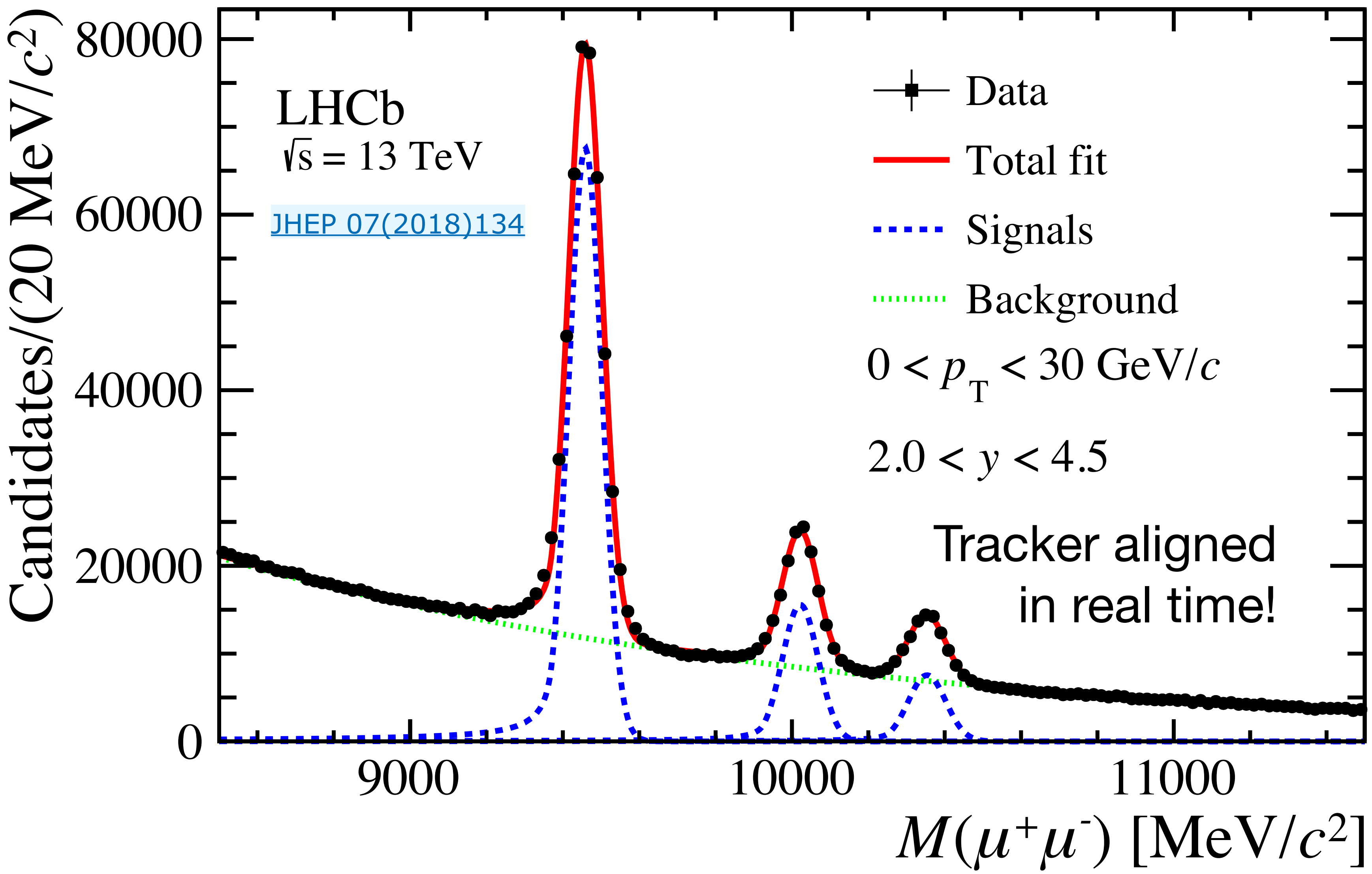

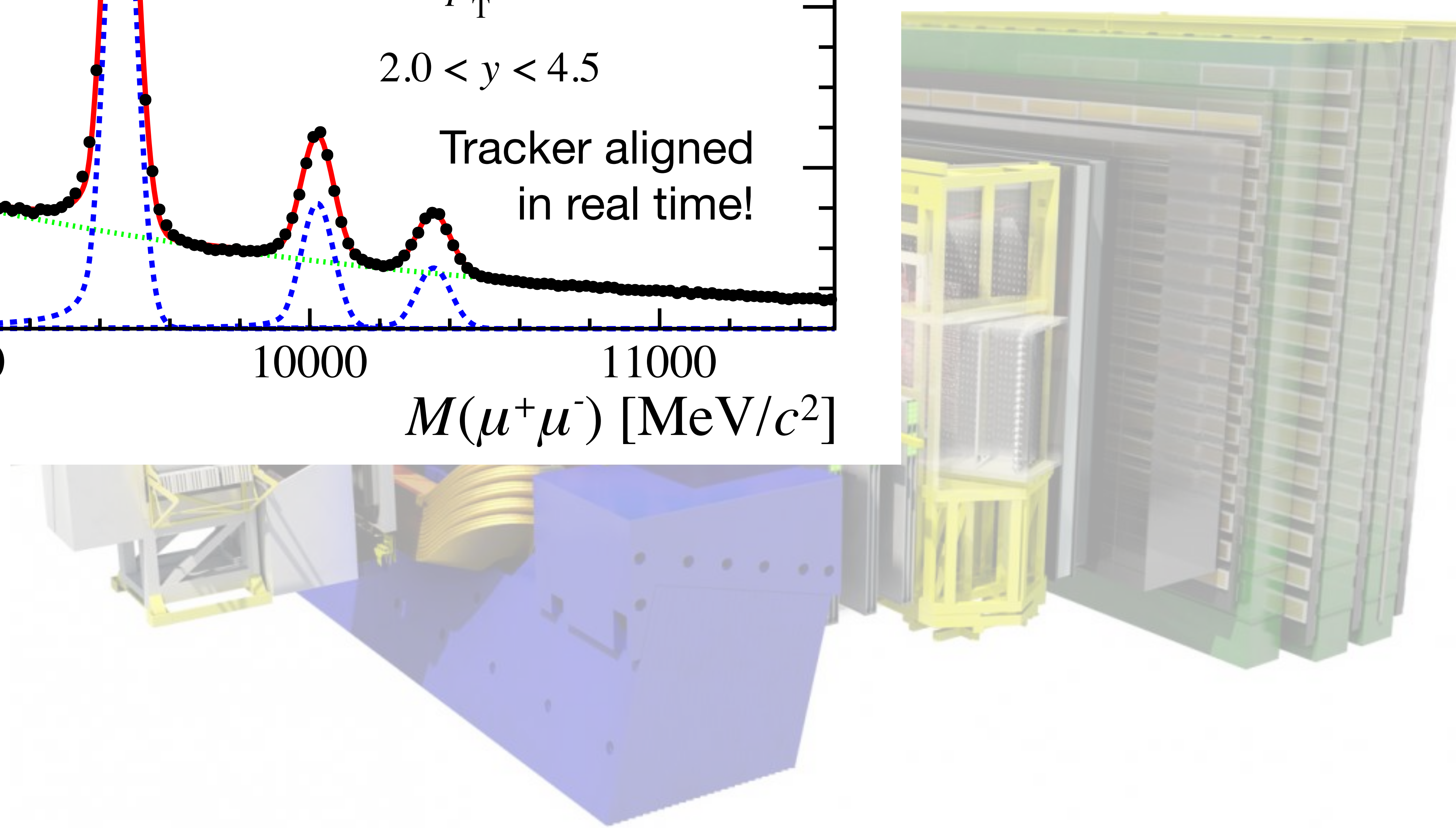

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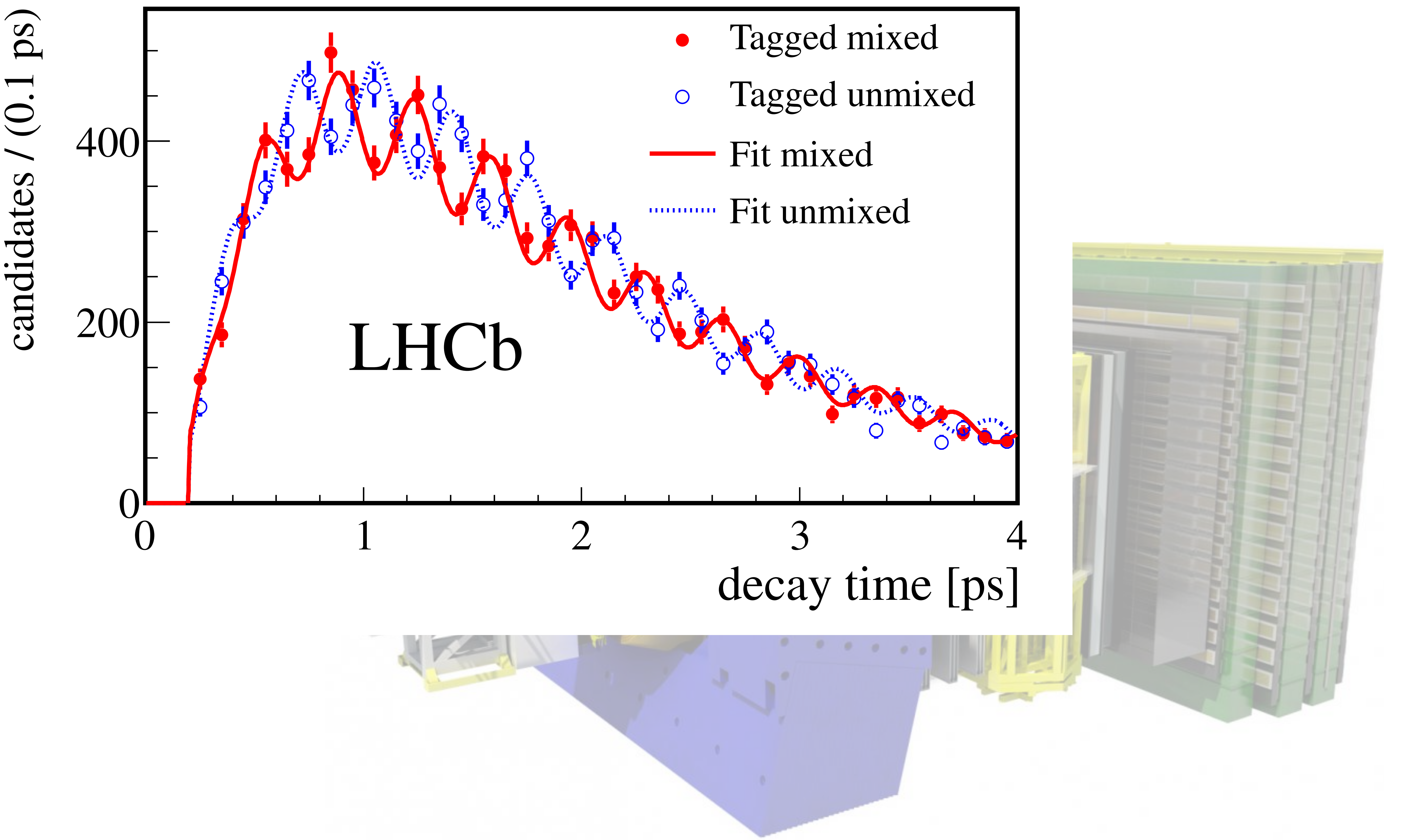

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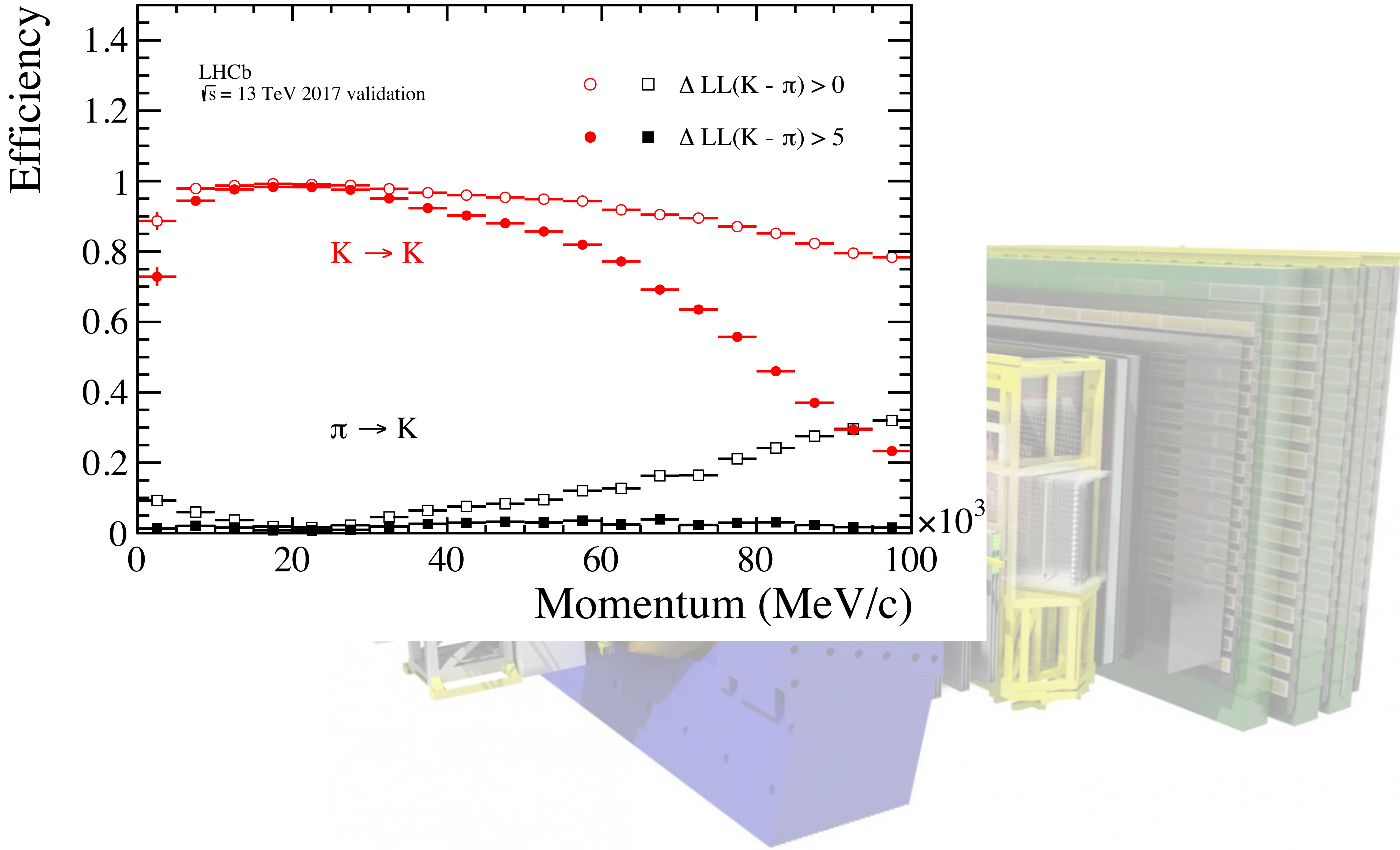
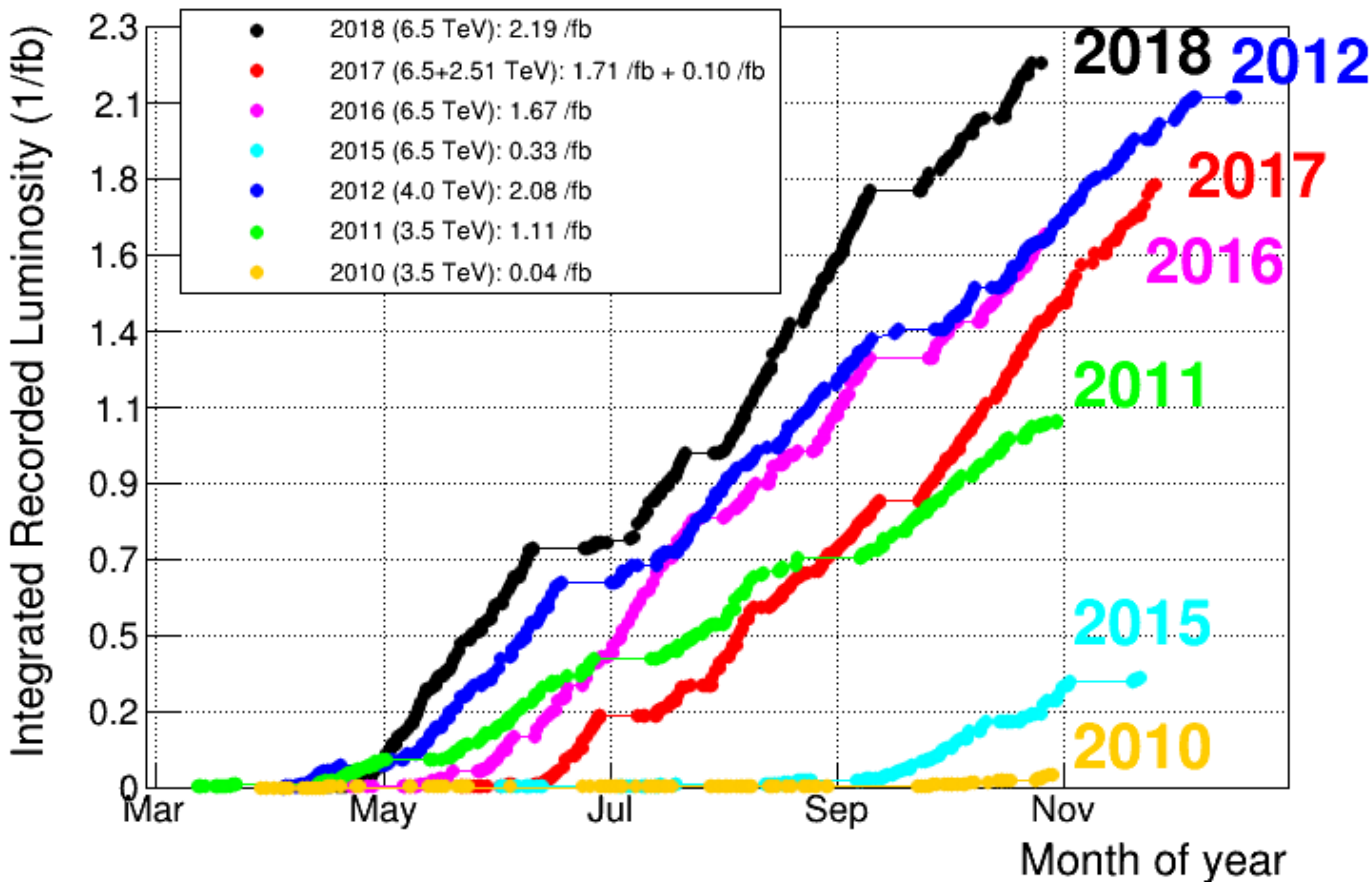


2018: the best year yet

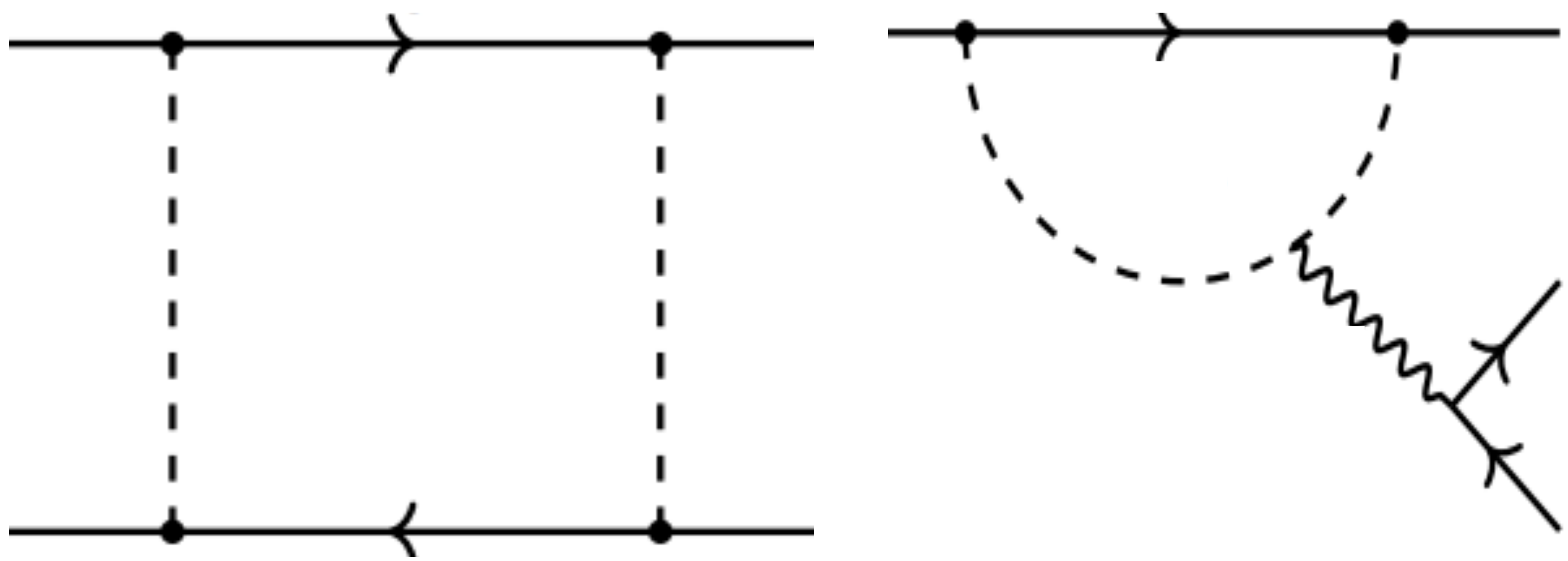


A few exceptions, but most results based on 3 fb^{-1} from Run-I.

Full dataset is now equivalent to 5x more b hadrons than Run-I.

The need for loops and trees

NP would be more visible in FCNCs.

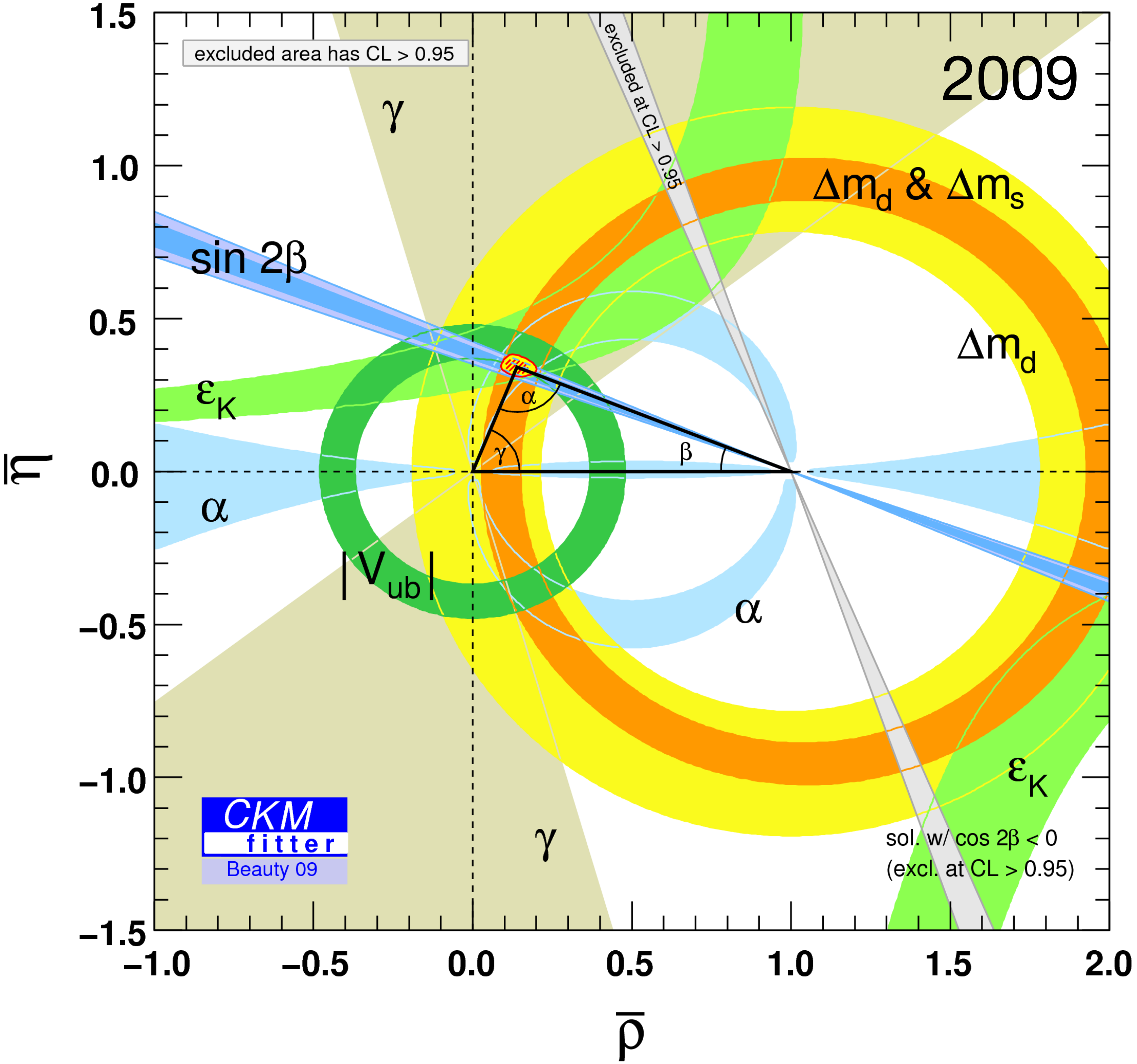


$$\mathcal{A}_0\left(\frac{c_{\rm SM}}{v^2}+\frac{c_{\rm NP}}{\Lambda^2}\right)$$

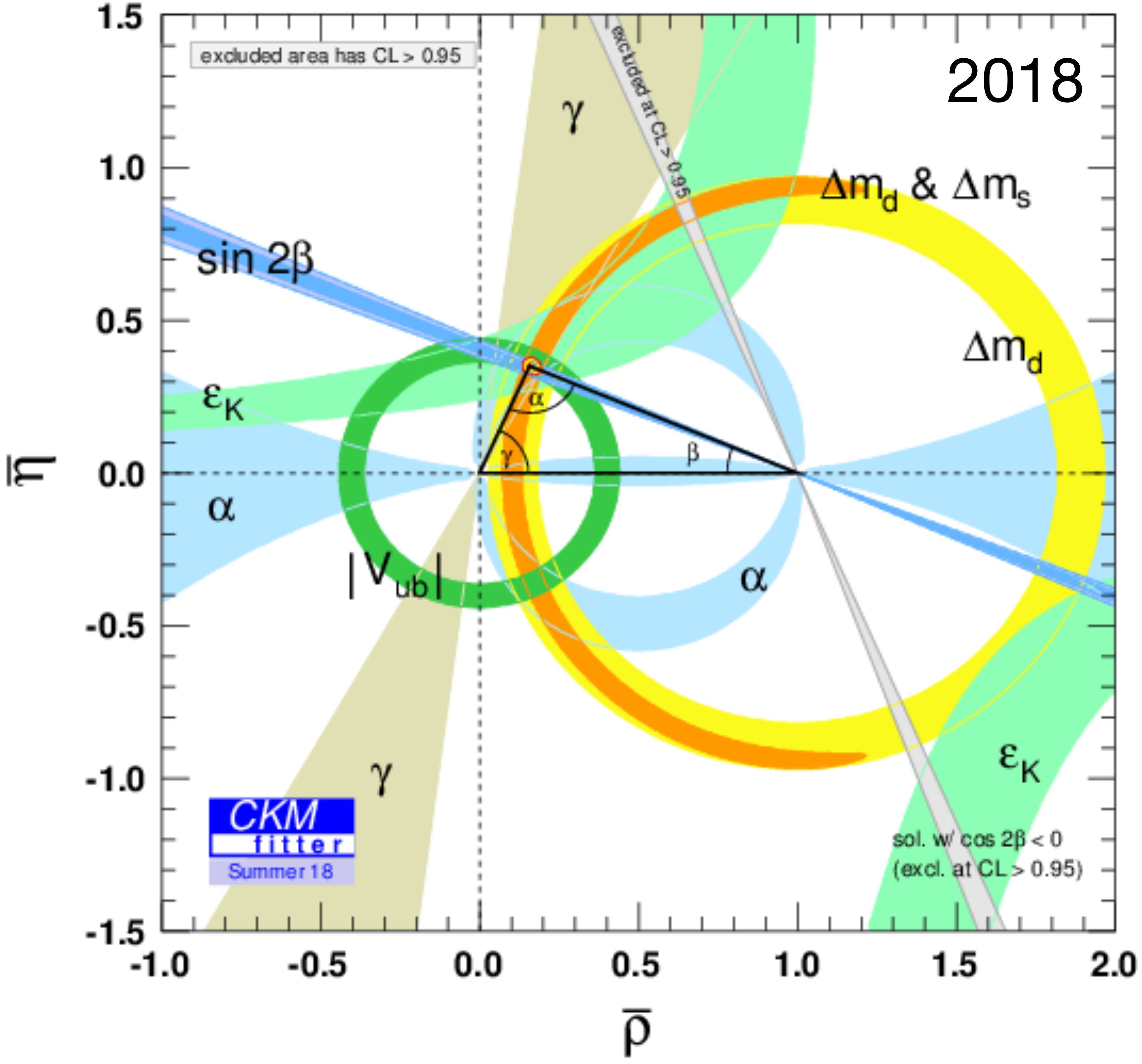
However, nature may choose NP in charged current process.

Most FCNC observables can't be predicted until we determine the 4 CKM parameters.

The unitarity triangle and LHCb impact



The unitarity triangle and LHCb impact



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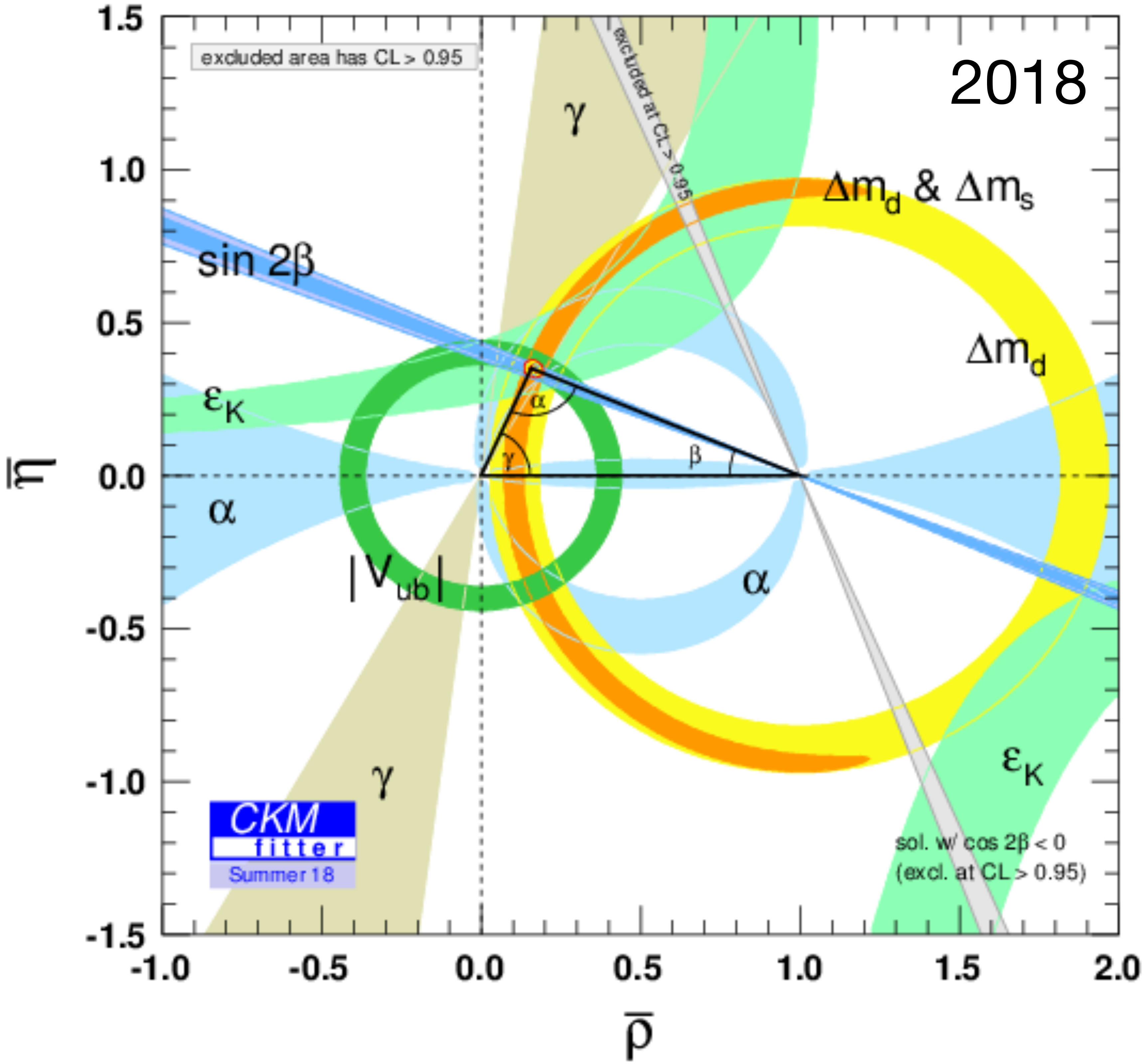
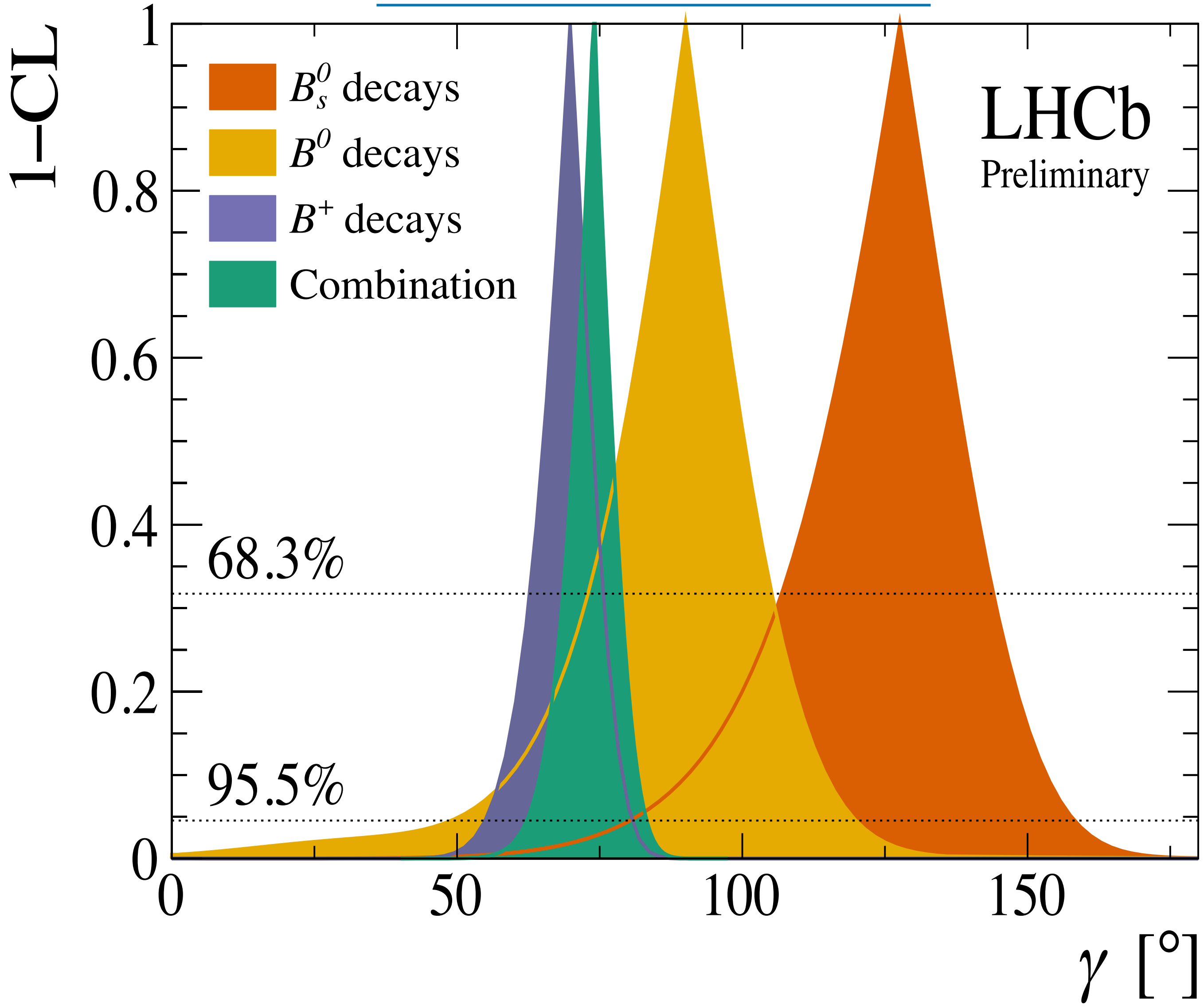


Of course some of this improvement must be attributed to new results from BaBar, Belle, and lattice QCD.

The tree constraints highlight some unique capabilities of LHCb…

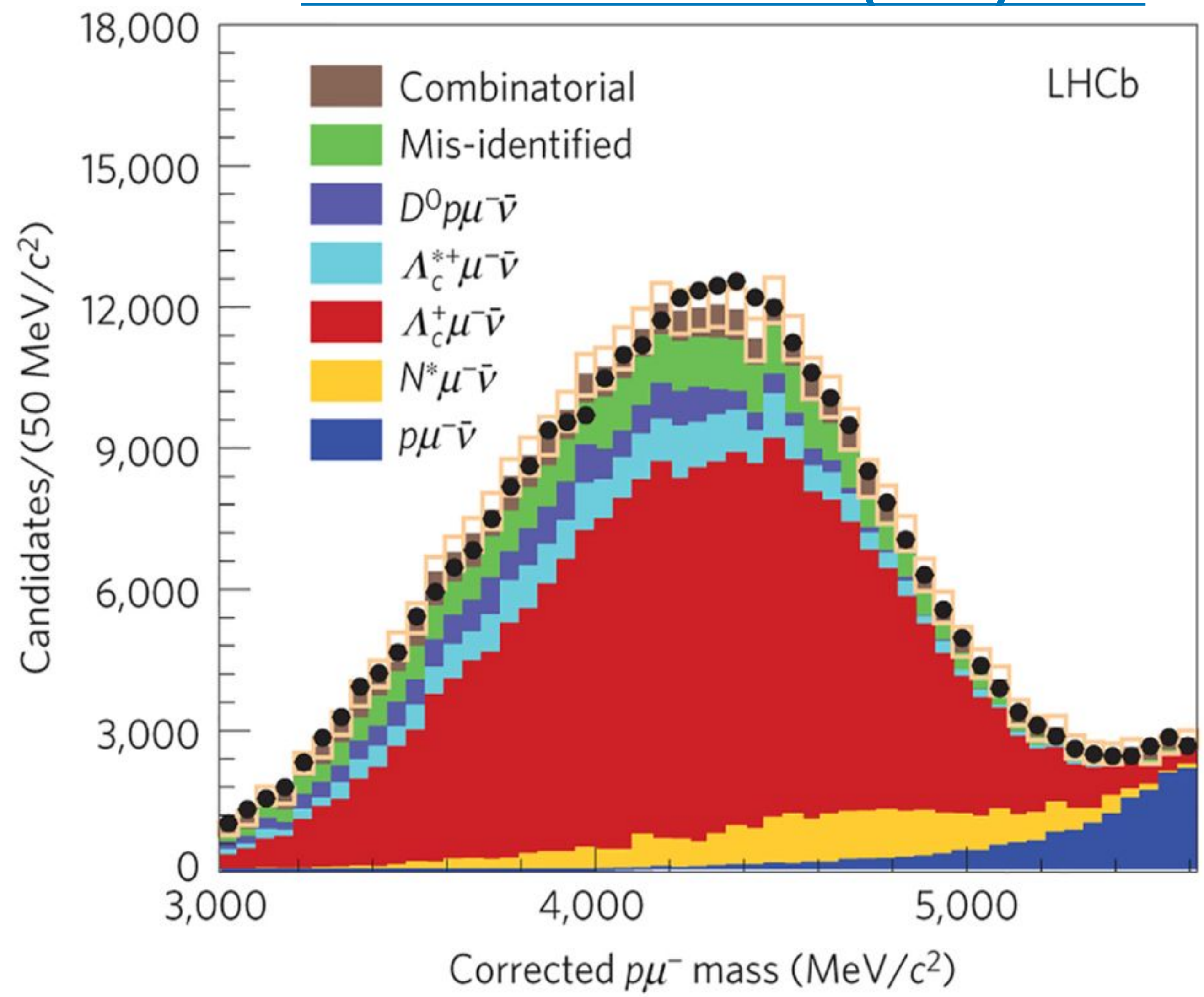
LHCb tree-level CKM constraints

[LHCb-CONF-2018-002](#)



$$\gamma = (74.0\,^{+5.0}_{-5.8})^\circ$$

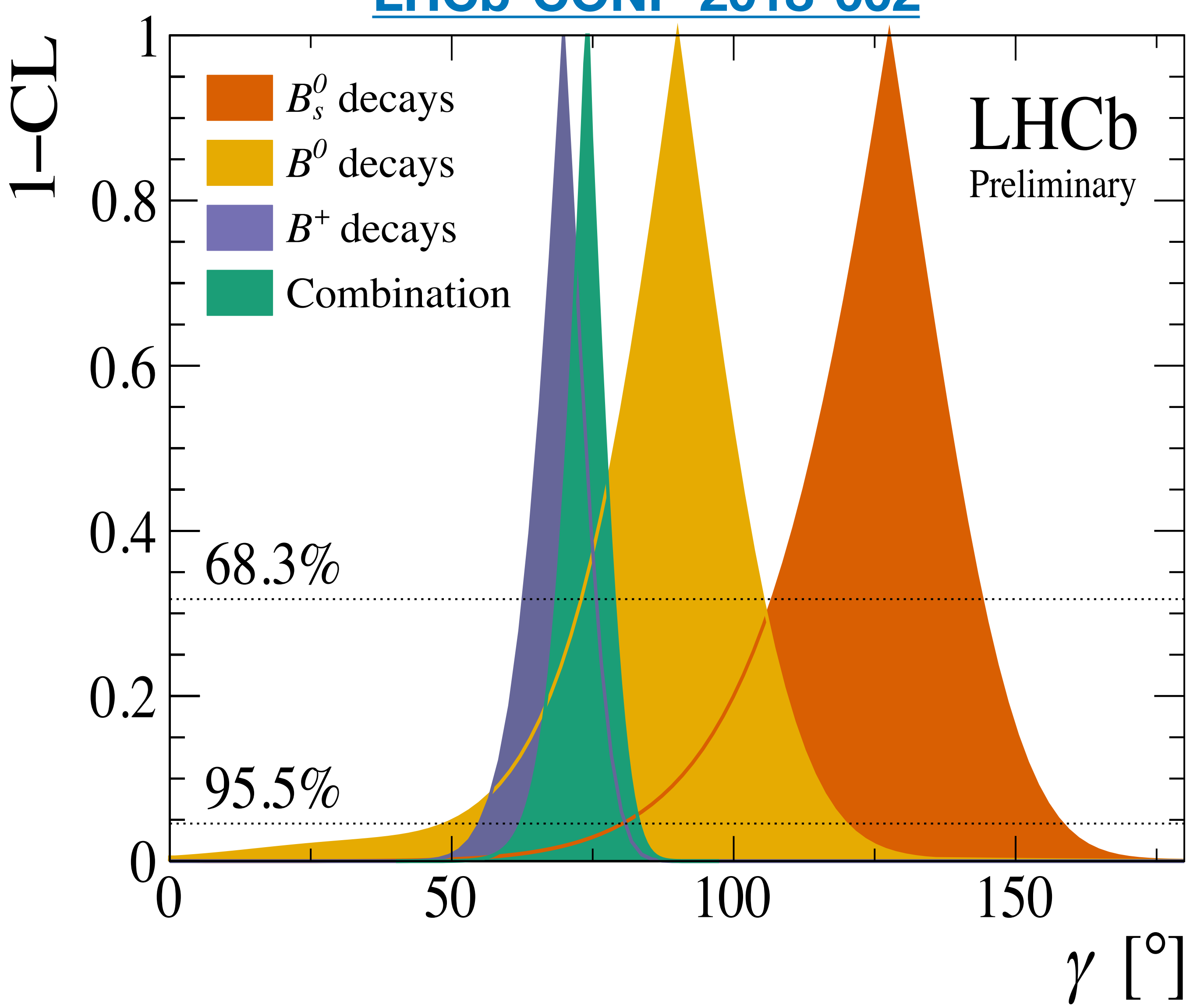
[NATURE PHYSICS 10 (2015) 1038](#)



$$\frac{\mathcal{B}(\Lambda_b^0 \to p\mu^-\overline{\nu}_\mu)_{q^2>15\,\mathrm{GeV}/c^2}}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+\mu^-\overline{\nu}_\mu)_{q^2>7\,\mathrm{GeV}/c^2}} = (1.00 \pm 0.04 \pm 0.08) \times 10^{-2}\,,$$

LHCb tree-level CKM constraints

LHCb-CONF-2018-002



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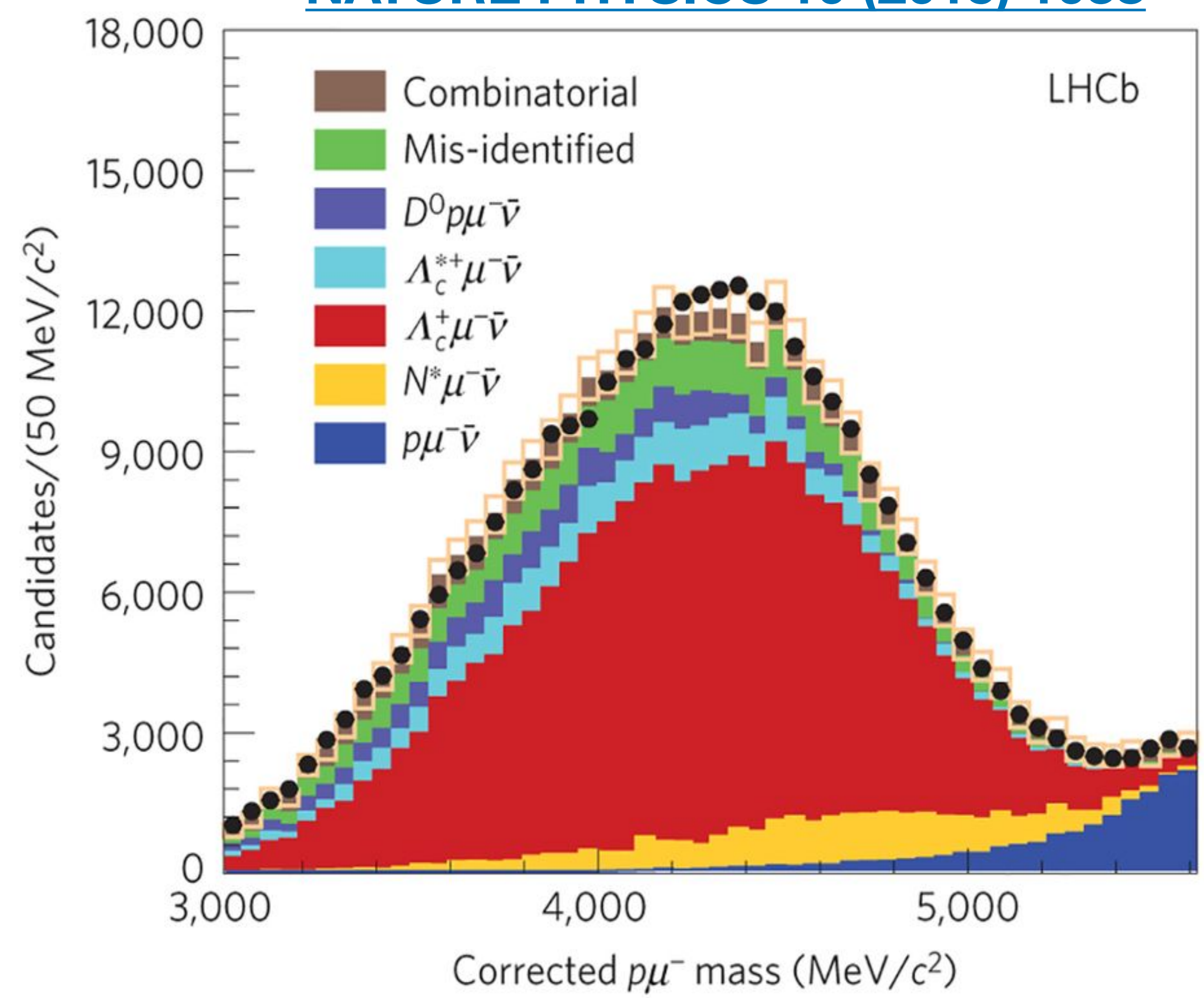
NATURE PHYSICS 10 (2015) 1038

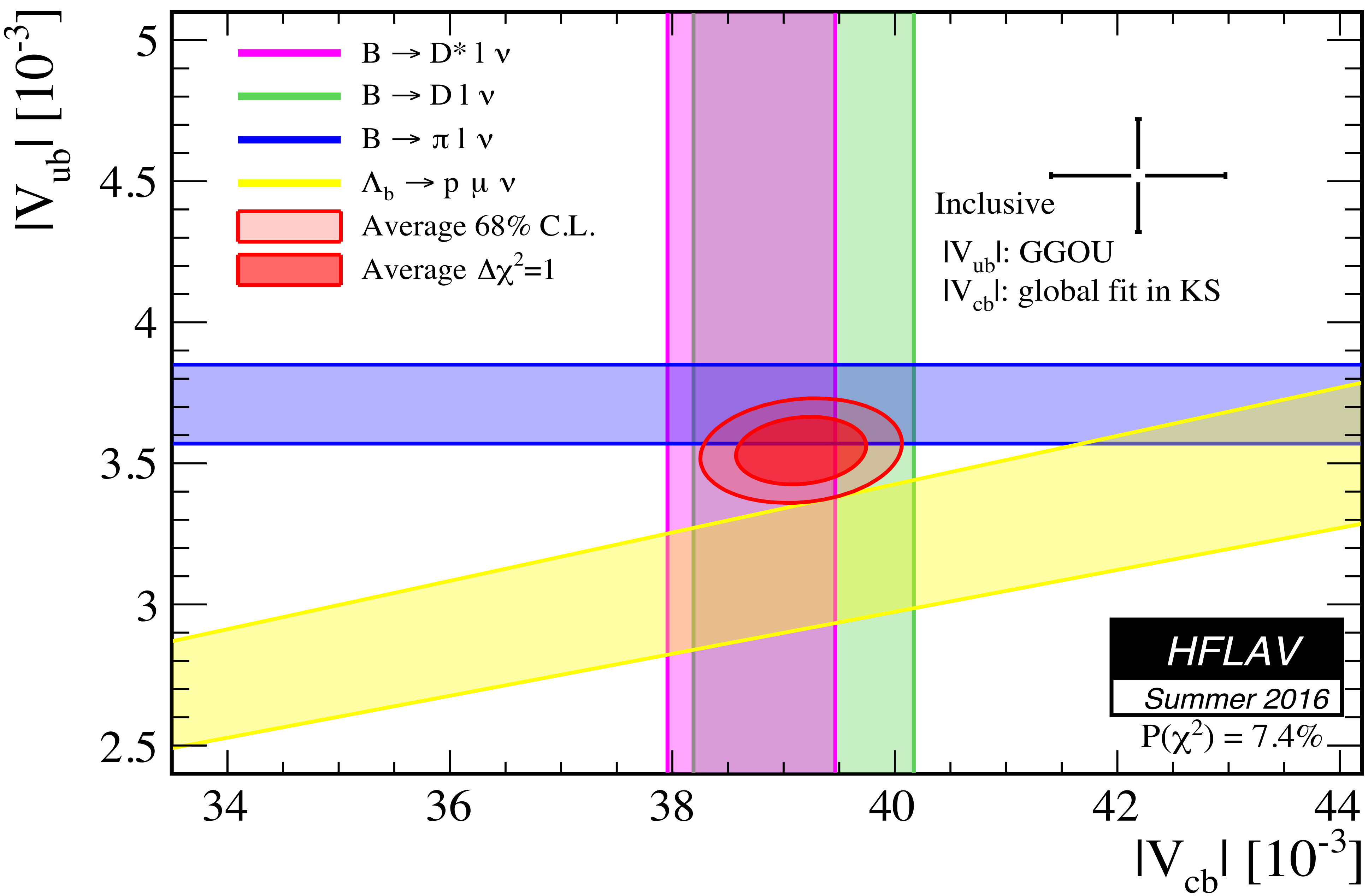


LQCD form factors from
Detmold et al., PRD 92, 034503 (2015)

$$\frac{|V_{ub}|}{|V_{cb}|} = 0.083 \pm 0.004 \pm 0.004\,,$$

LHCb tree-level CKM constraints

NATURE PHYSICS 10 (2015) 1038



Inclusive-exclusive puzzle: new b→c data from Belle provoked a revisit of some assumptions in the form factors, but a possible resolution of the puzzle is far from conclusive.

BELLE-CONF-1612

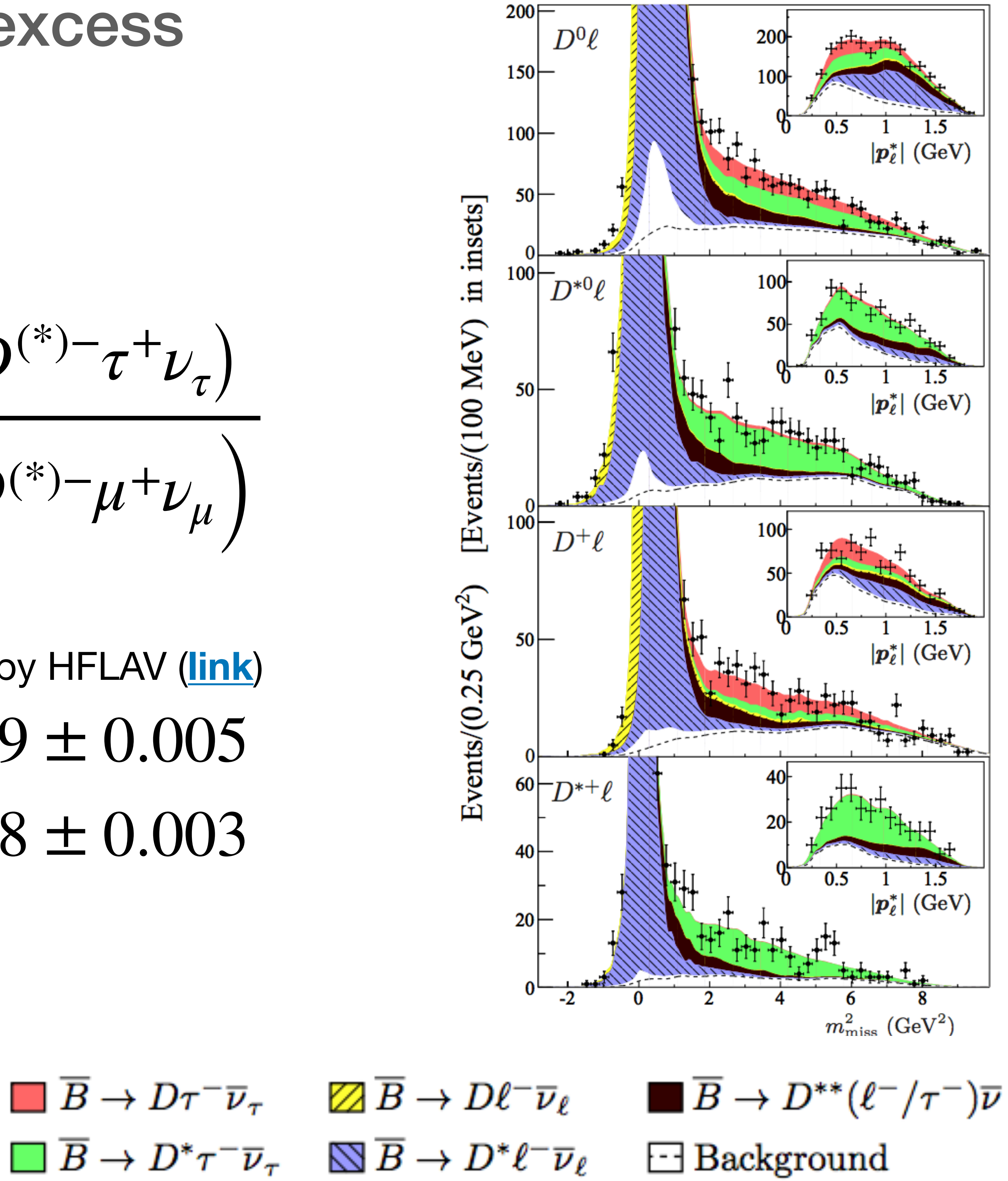
Evidence for a $D^{(*)}\tau\nu$ excess

PRL 109, 101802 (2012)

$$R(D^{(*)}) = \frac{B\left(B^0 \to D^{(*)-}\tau^+\nu_\tau\right)}{B\left(B^0 \to D^{(*)-}\mu^+\nu_\mu\right)}$$

Current SM predictions as seen by HFLAV (link)

$$R_{\rm SM}(D) = 0.299 \pm 0.005$$
$$R_{\rm SM}(D^*) = 0.258 \pm 0.003$$



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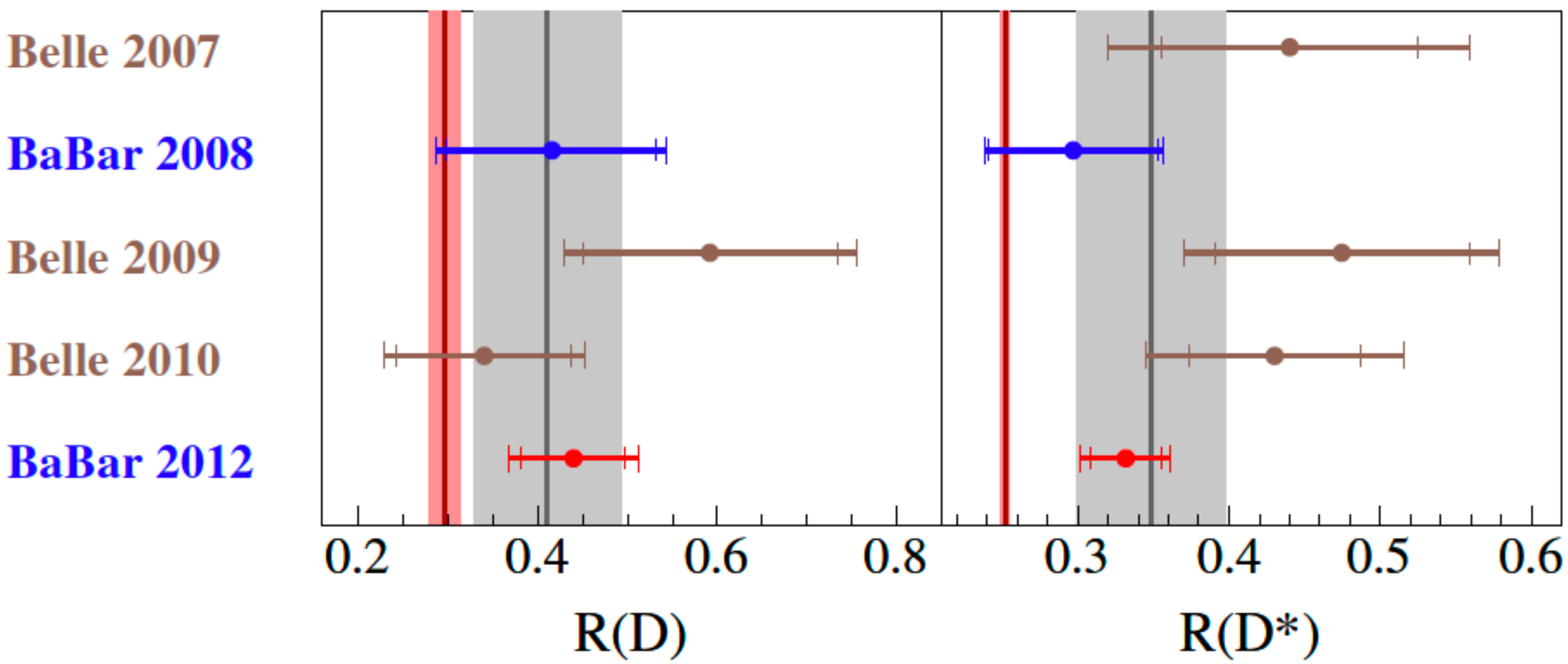
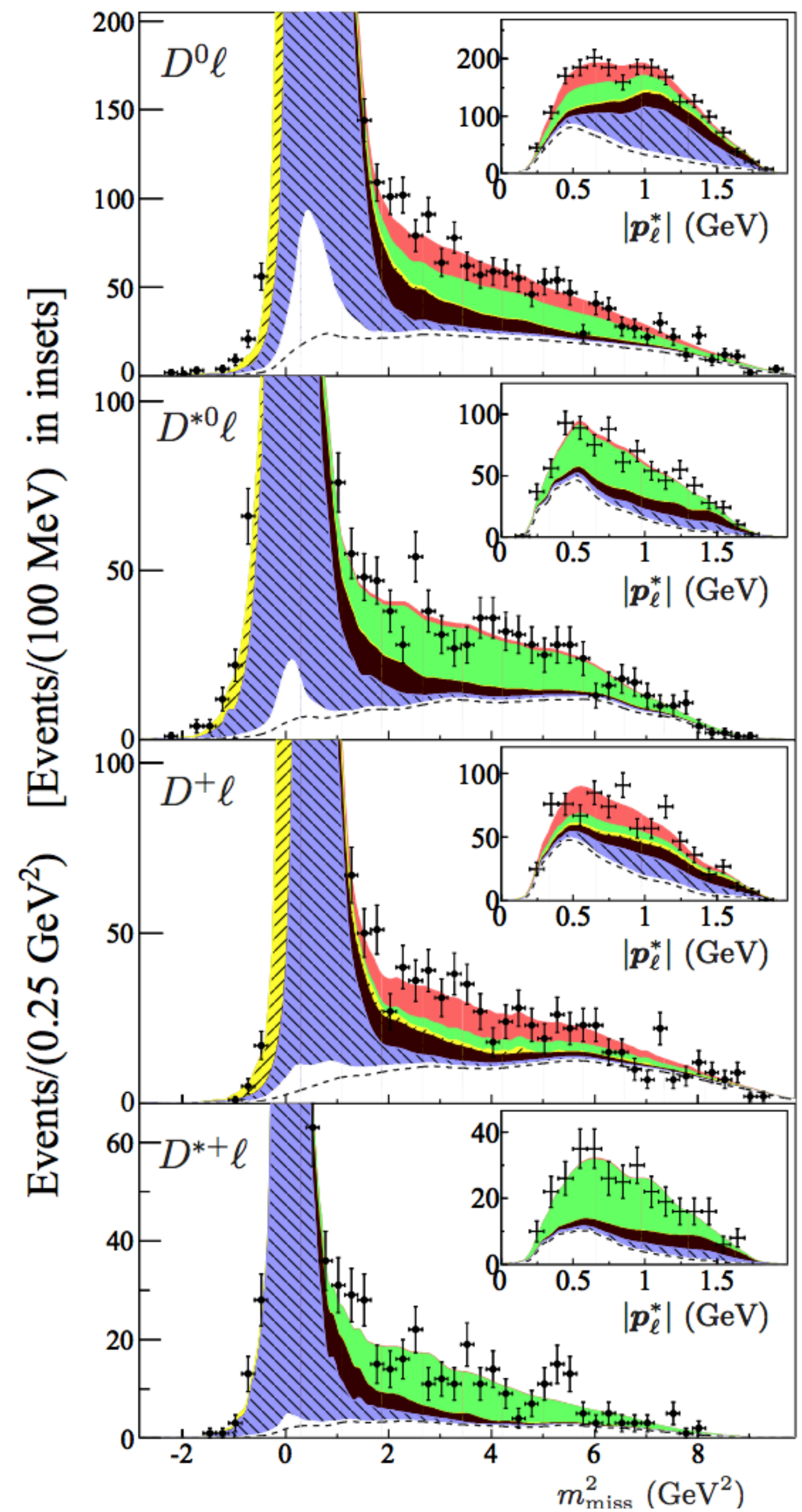
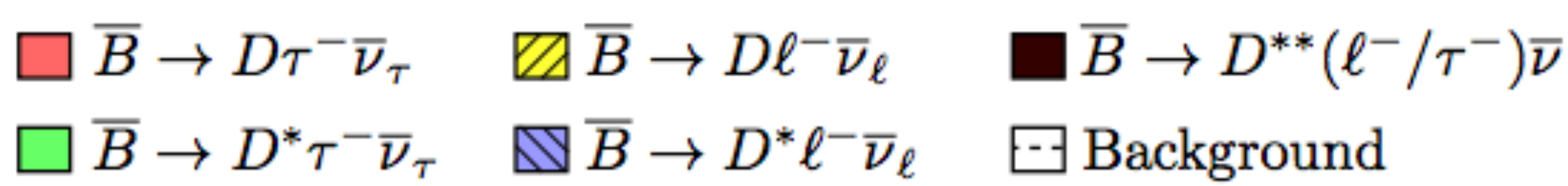
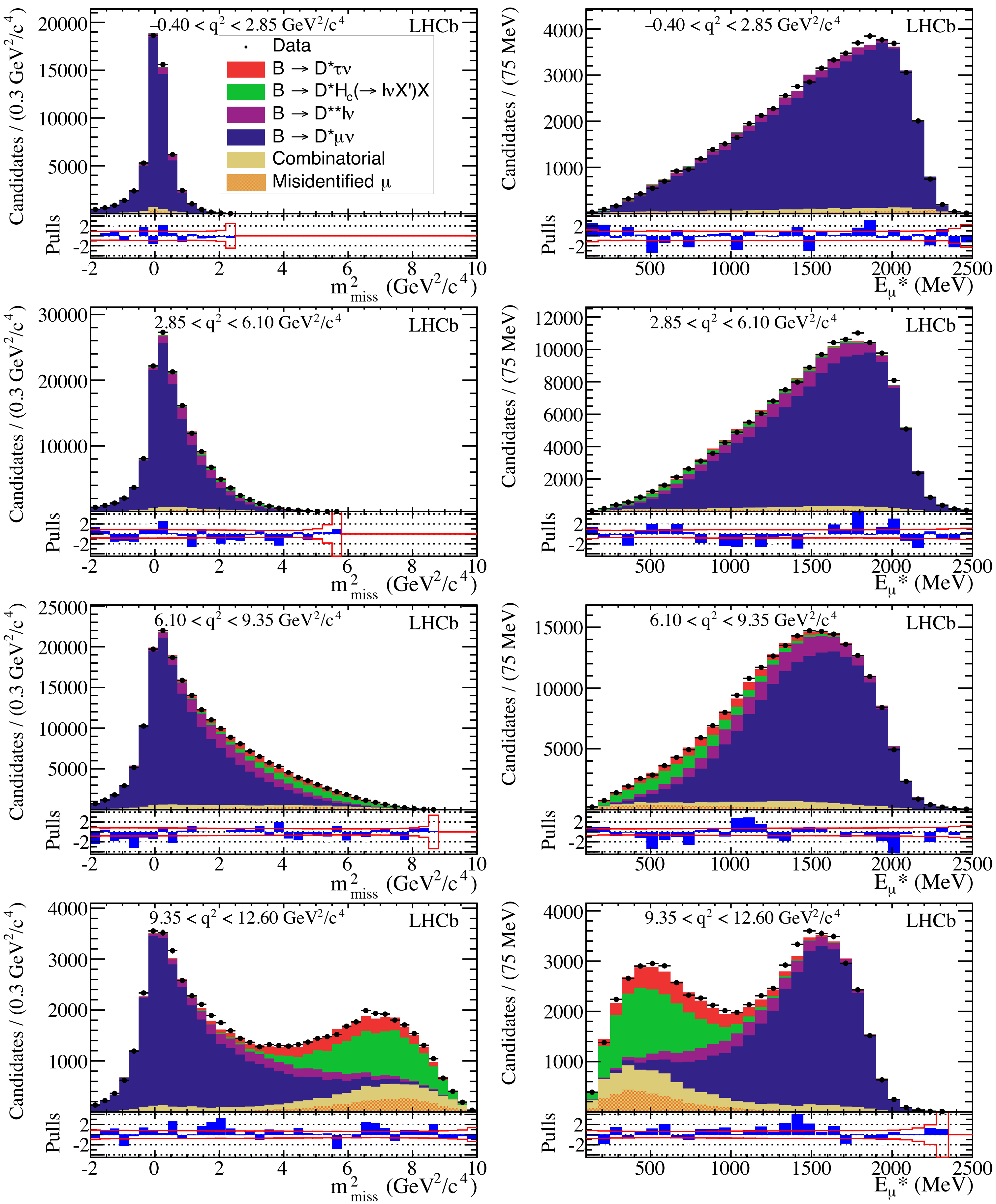


3.4σ discrepancy with the SM





First LHCb R(D*) measurement, 2015



$\tau \to \mu\nu\bar{\nu}$

Fit in q^2, m^2_{miss}, E_μ

$R(D^*) = 0.336 \pm 0.027 \pm 0.030$

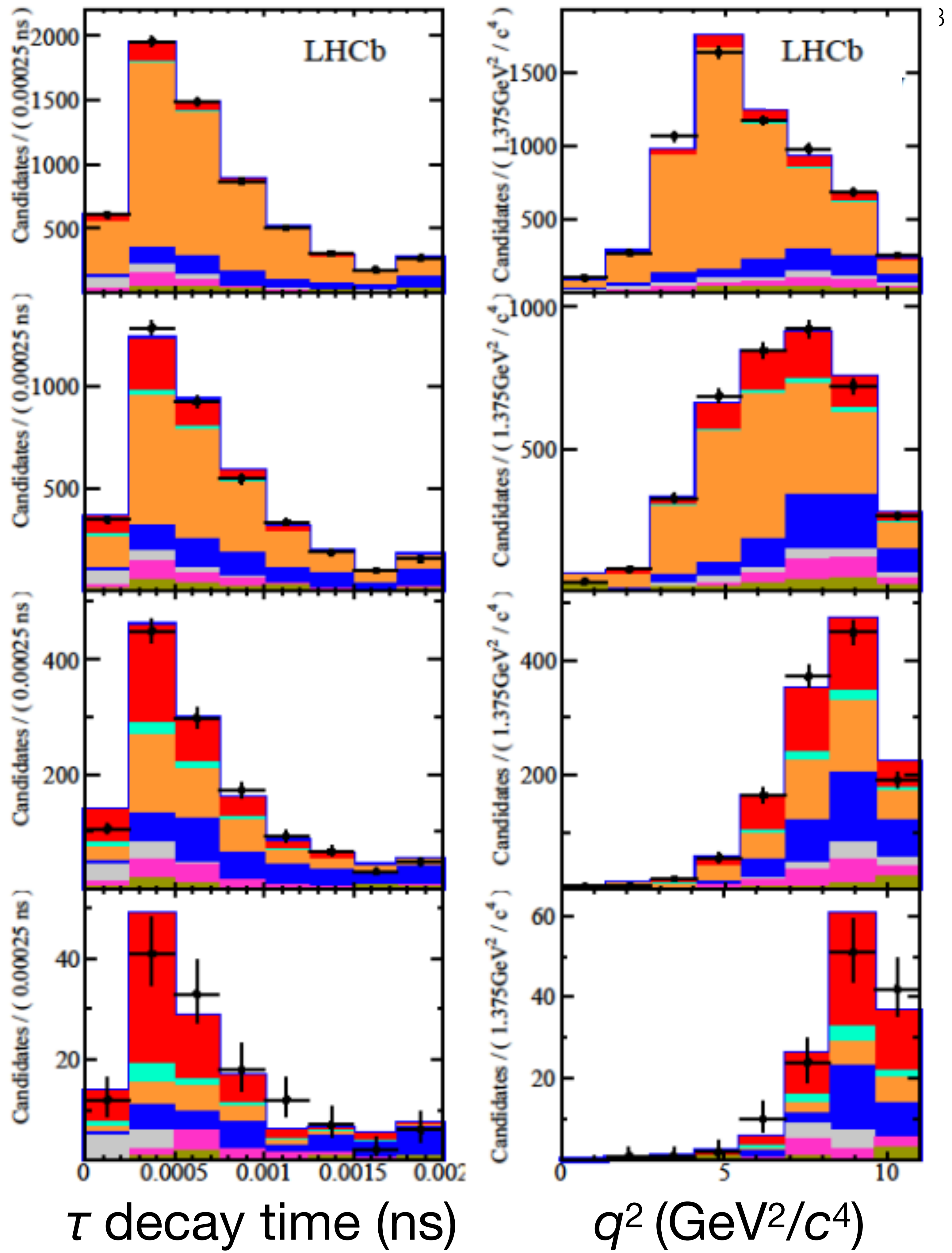
2.1σ above SM

- B → D*τν
- B → D*H_c(→ lνX')
- B → D**lν
- B → D*μν
- Combinatorial
- Misidentified μ

LHCb hadronic R(D*)

[Phys. Rev. D 97, 072013 (2018)]

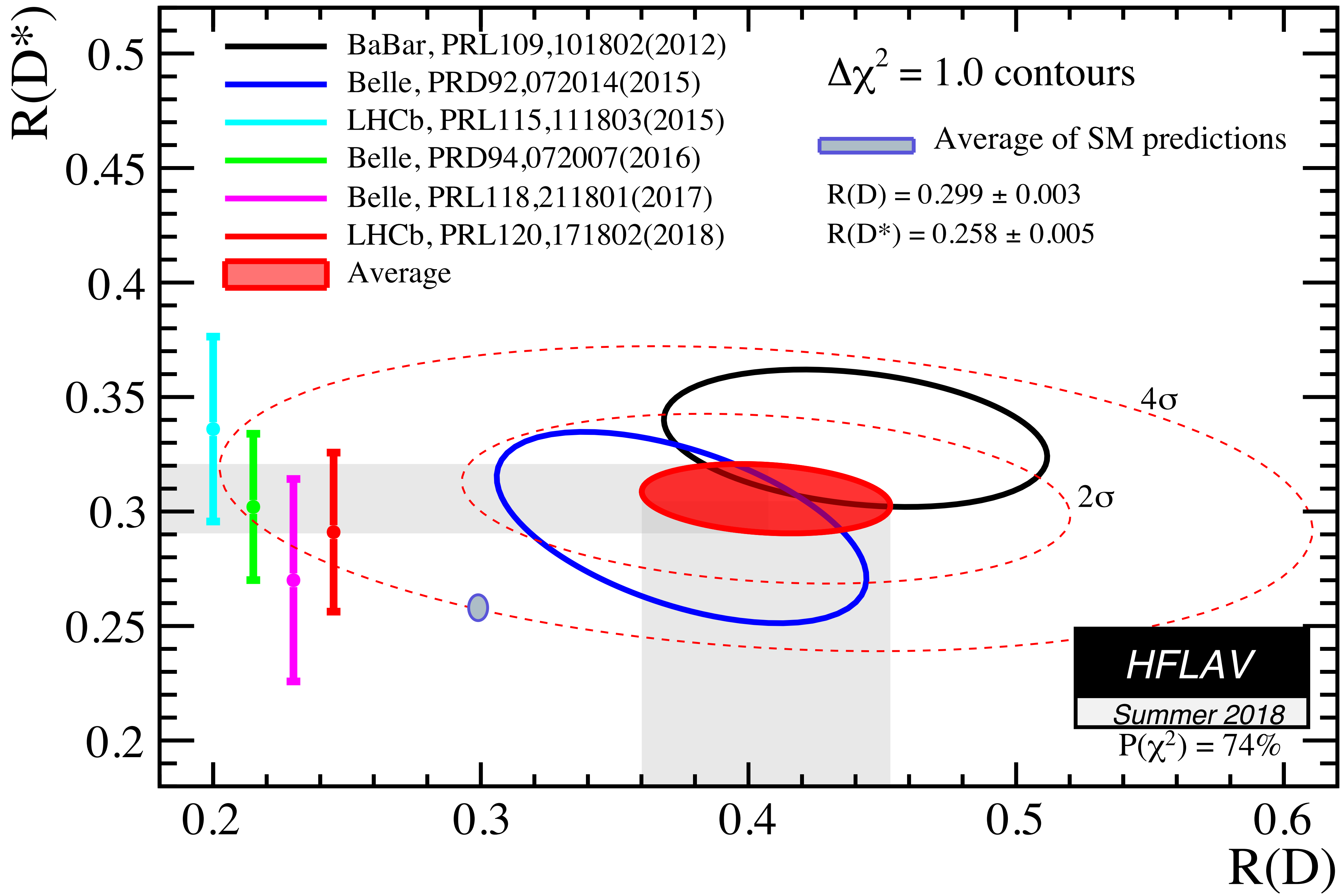
[Phys. Rev. Lett. 120, 171802 (2018)]



$$R(D^*) = 0.286 \pm 0.019 \pm 0.025 \pm 0.021$$

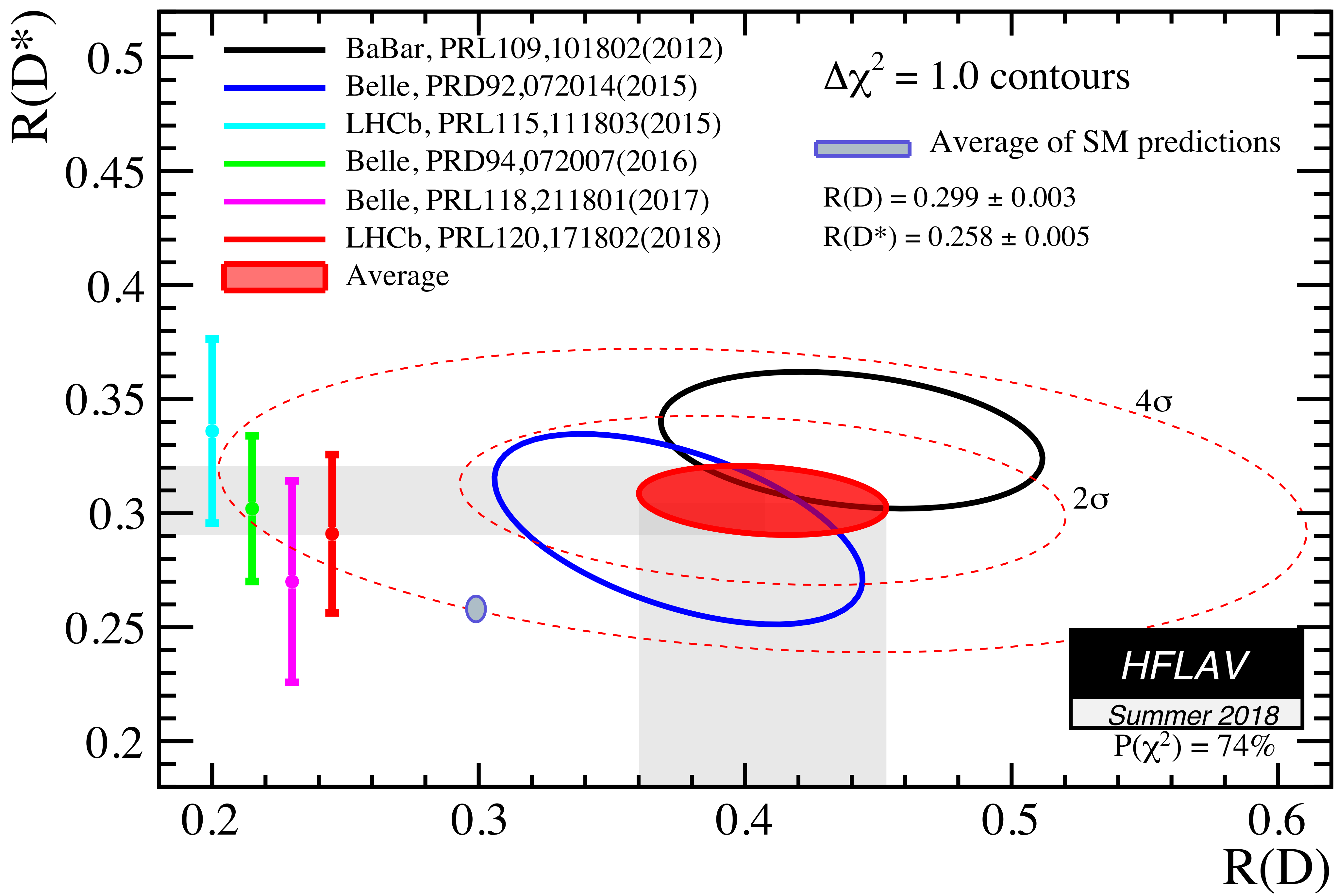
1σ above SM

Summer 2018 R(D) and R(D*) averages



HFLAV claim a discrepancy with the SM of 3.8σ.

Summer 2018 R(D) and R(D*) averages



$$\mathcal{A}_0\left(\frac{c_{\rm SM}}{v^2}+\frac{c_{\rm NP}}{\Lambda^2}\right) \qquad C_{\rm SM}\approx V_{cb} \qquad \frac{\Lambda^2}{C_{\rm NP}}\sim(3\ \text{TeV})^2$$

What next for R(D*)?

LHCb still to analyse Run-II data, and new observables $R(D^0)$, $R(D^+)$, $R(D_s)$, $R(\Lambda_c^{(*)})$, $R(J/\Psi)$.

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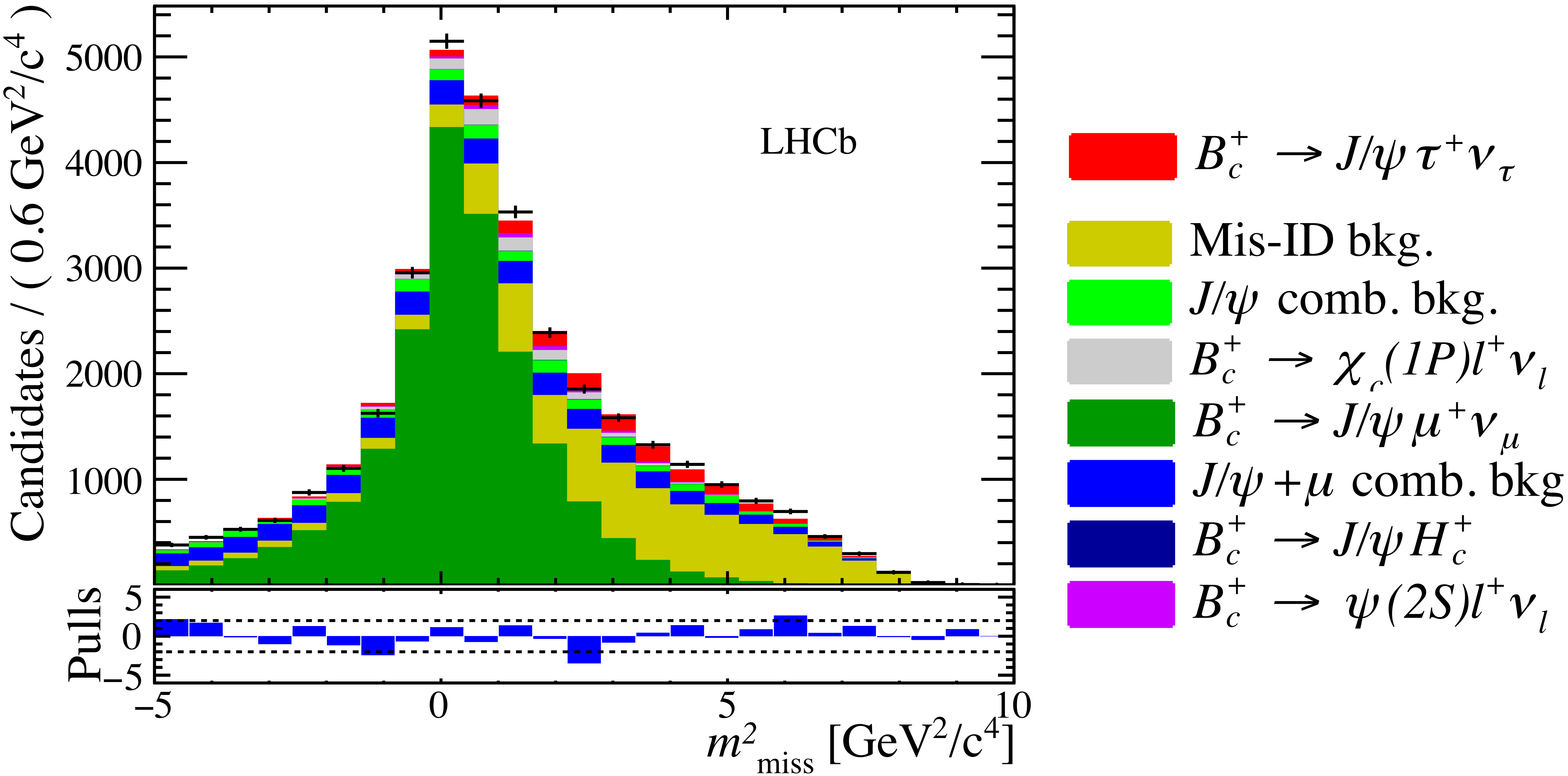
PHYS. REV. LETT. 120, 121801 (2018)

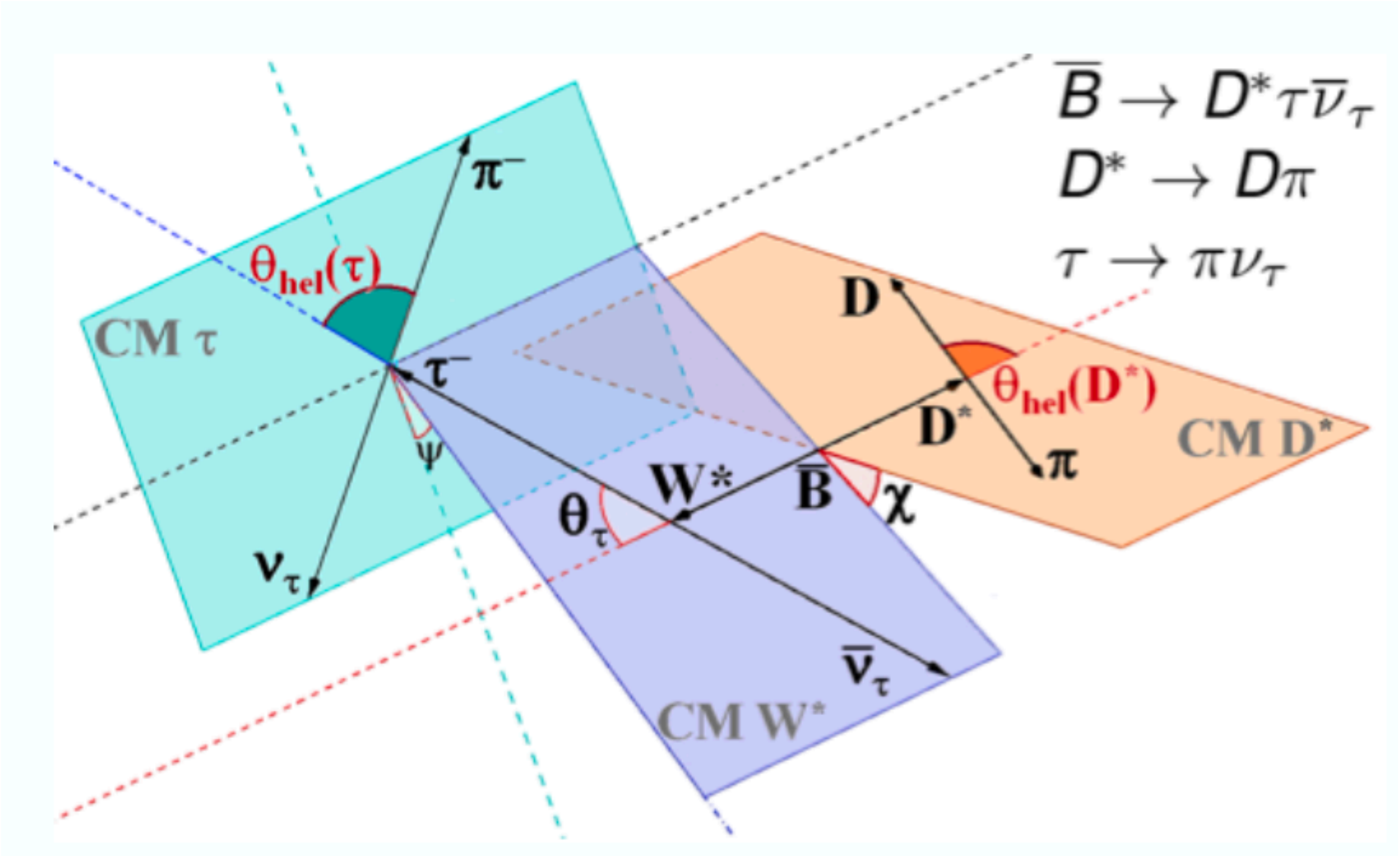


$$\mathcal{R}(J/\psi) = 0.71 \pm 0.17\,(\text{stat}) \pm 0.18\,(\text{syst})$$

What next for R(D*)?

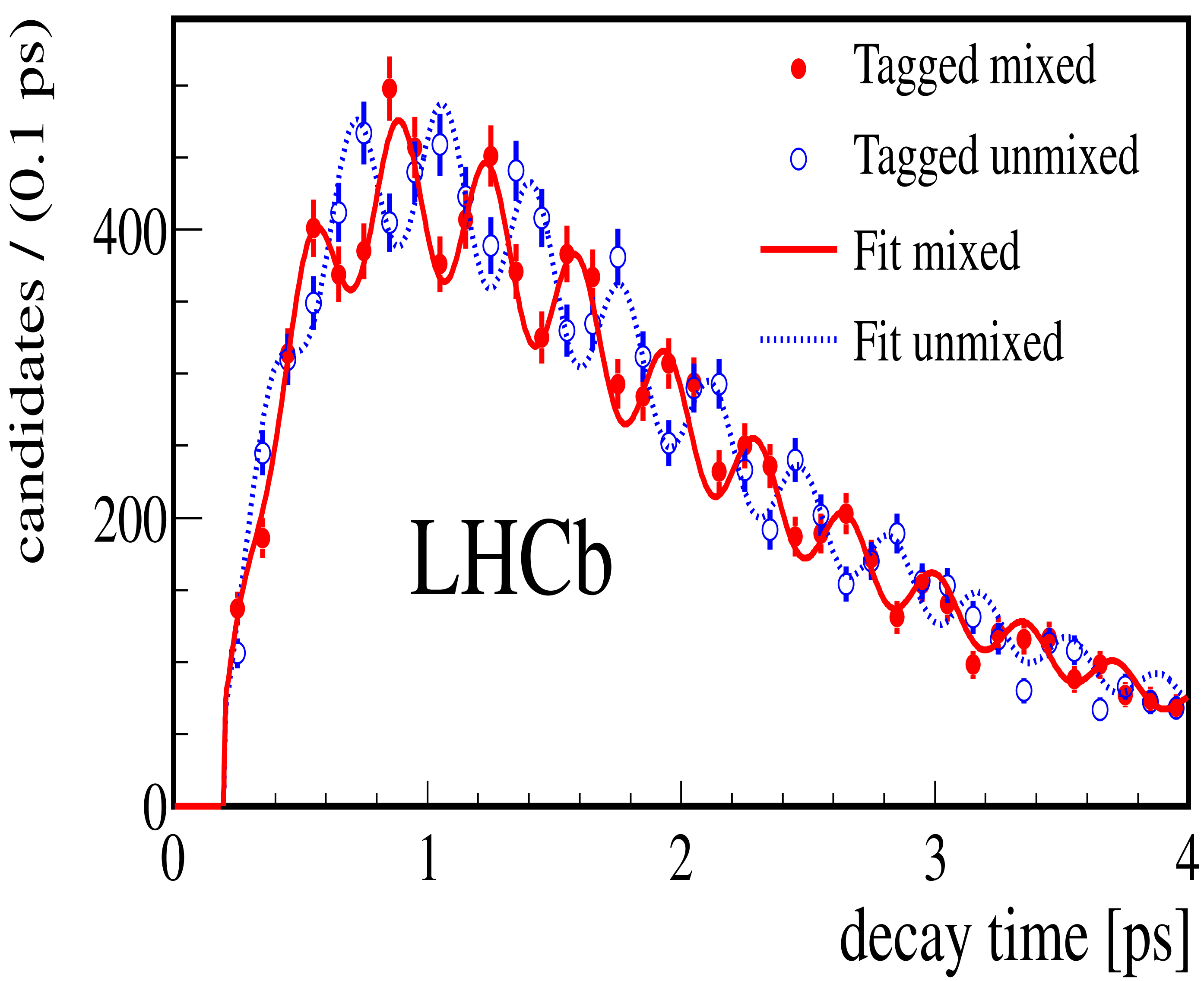
LHCb still to analyse Run-II data, and new observables $R(D^0)$, $R(D^+)$, $R(D_s)$, $R(\Lambda_c^{(*)})$, $R(J/\Psi)$.

Angular analysis will require substantially larger luminosities.

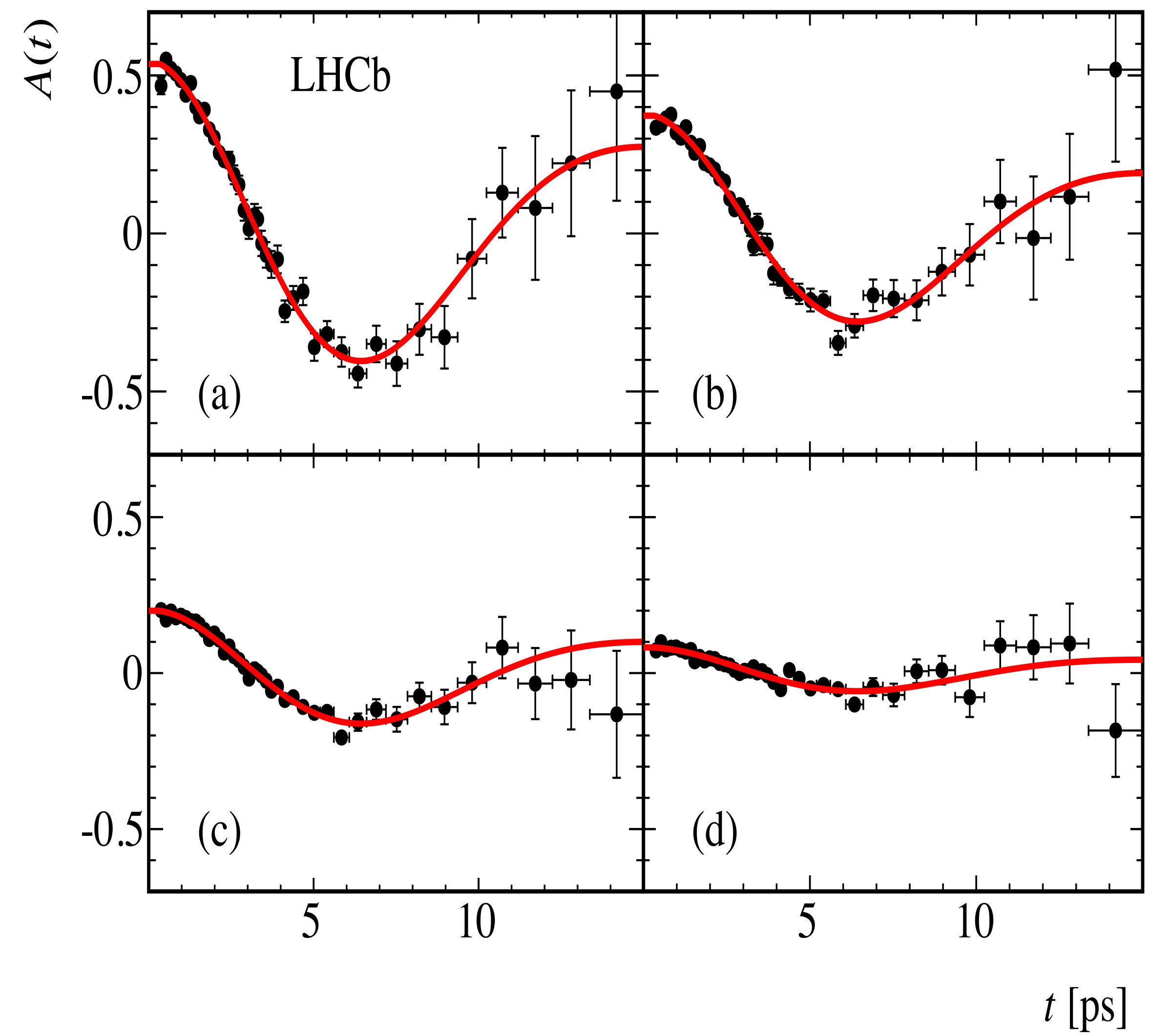


B-$\overline{\text{B}}$ mixing

NEW J. PHYS. 15 (2013) 053021



EUR. PHYS. J. C (2016) 76:412



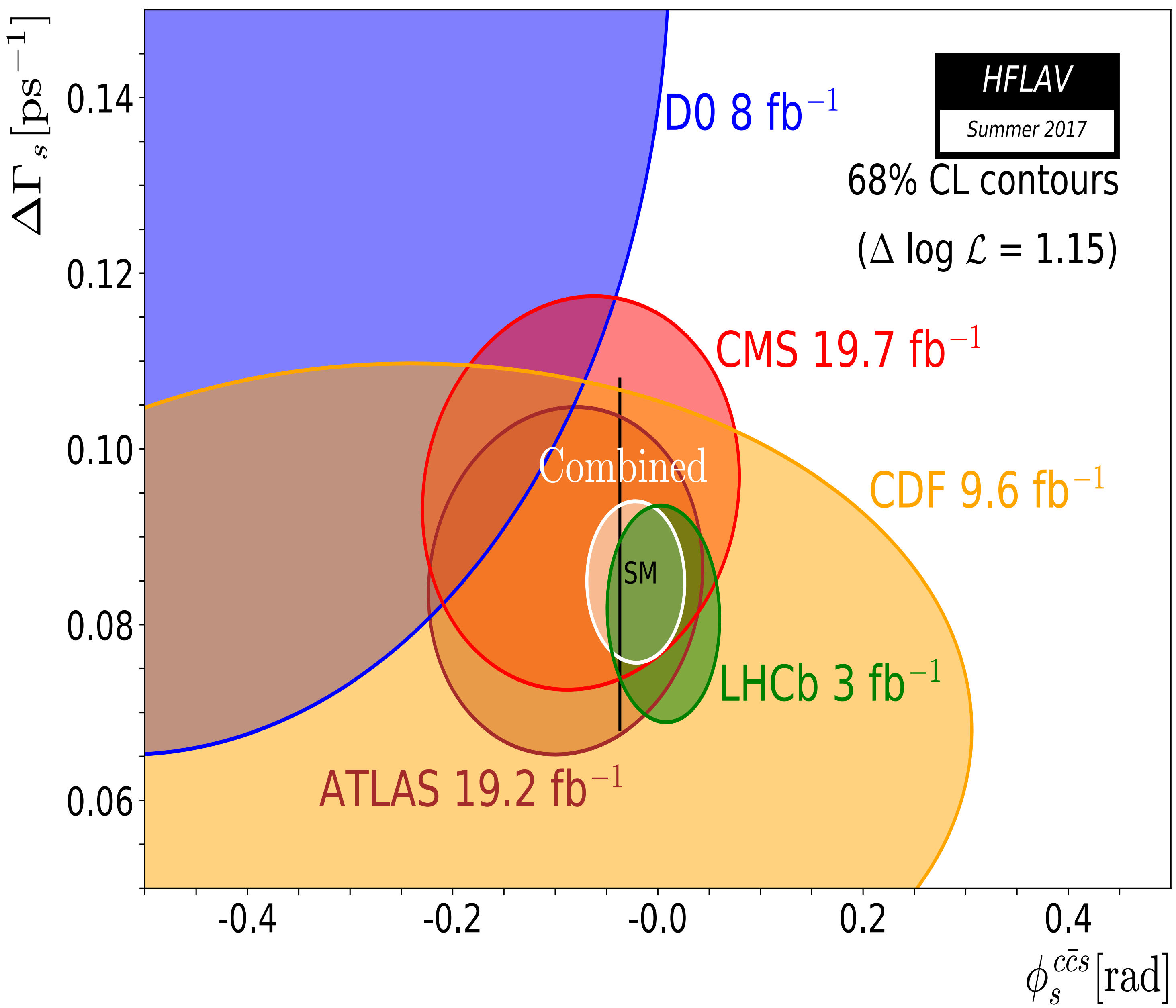
$$\Delta M_s = 17.768 \pm 0.023 \pm 0.006 \text{ ps}^{-1}$$

$$\Delta M_d = 505.0 \pm 2.1 \pm 1.0 \text{ ns}^{-1}$$

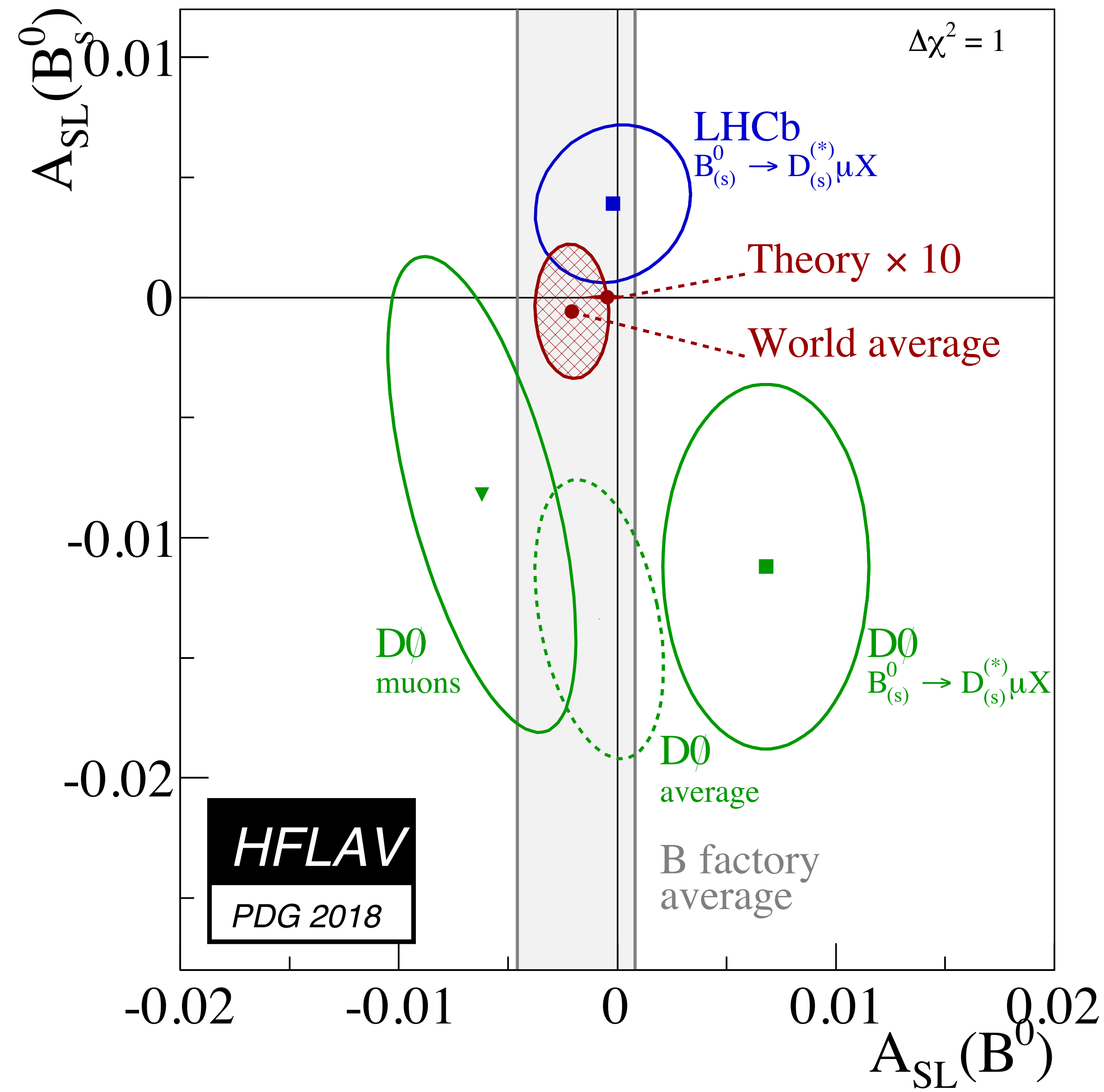
Interpretation now limited by lattice QCD, but there is an obvious class of theoretically clean, NP sensitive, observables…

CP violation

Interference between mixing and decay

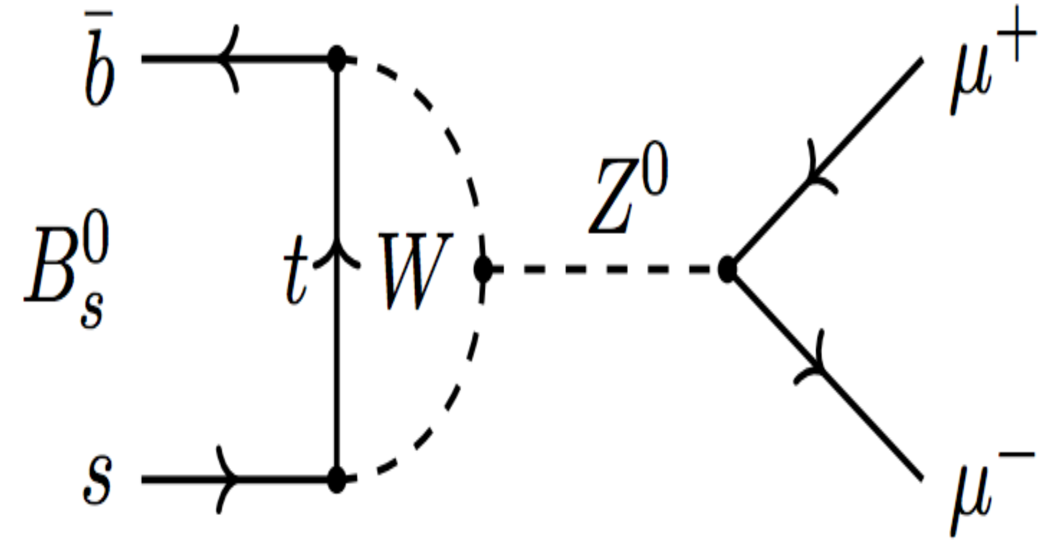


CP violation in mixing



These are very constraining NULL results.
Far from any theory uncertainty floor.

The golden rare B decay

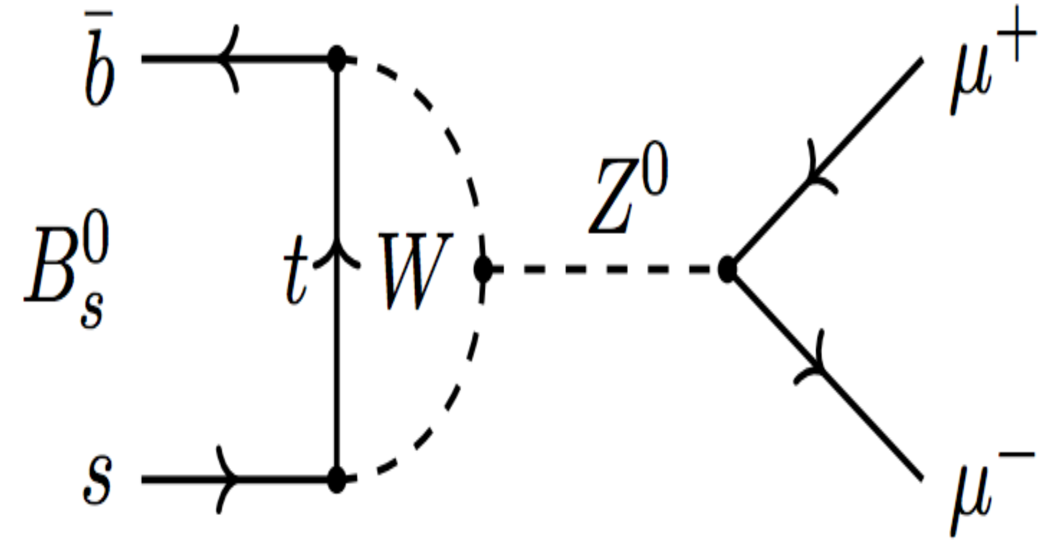


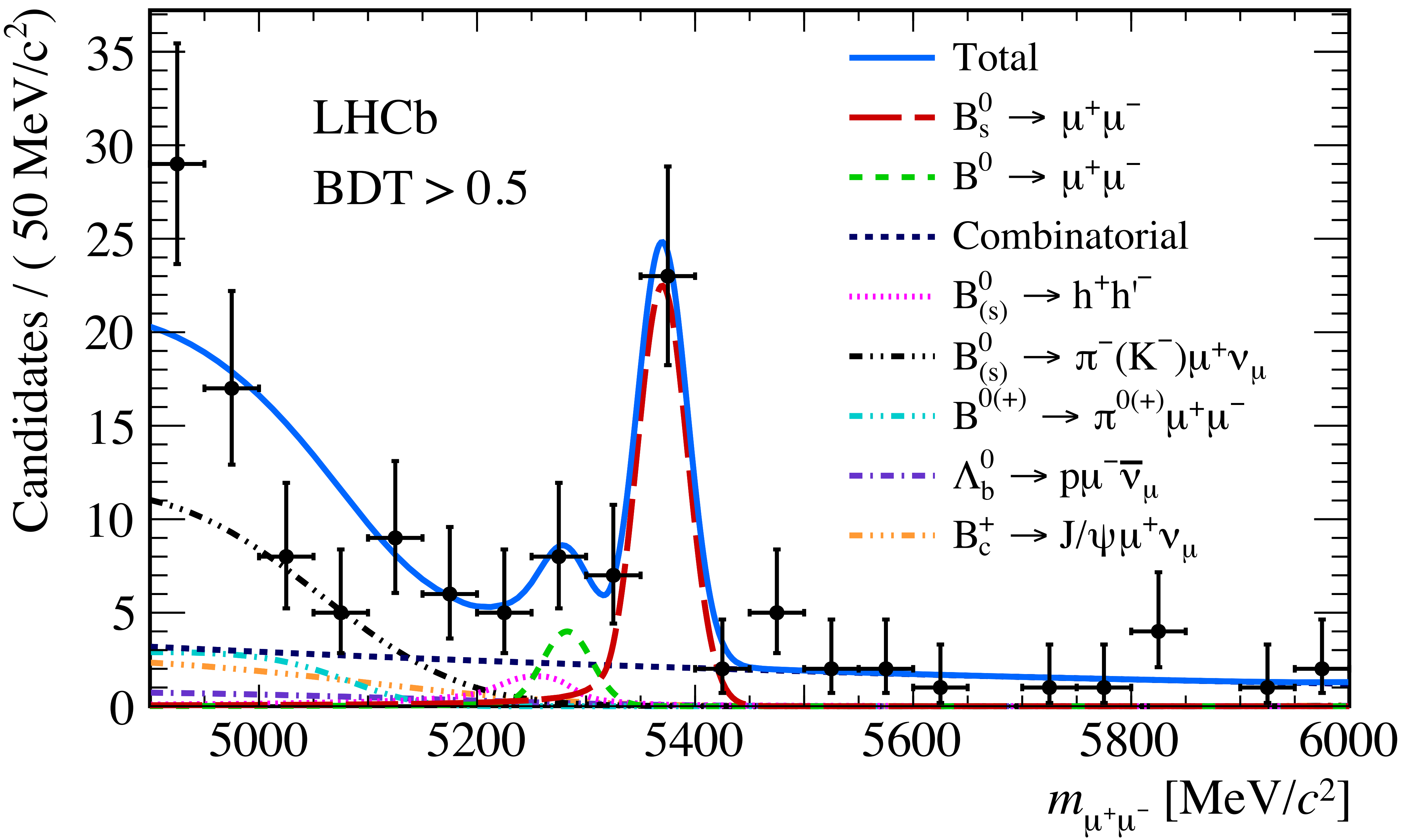
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

Bobeth et al.
[PRL 112 (2014) 101801]

The golden rare B decay

[PHYS. REV. LETT. 118, 191801 (2017)]





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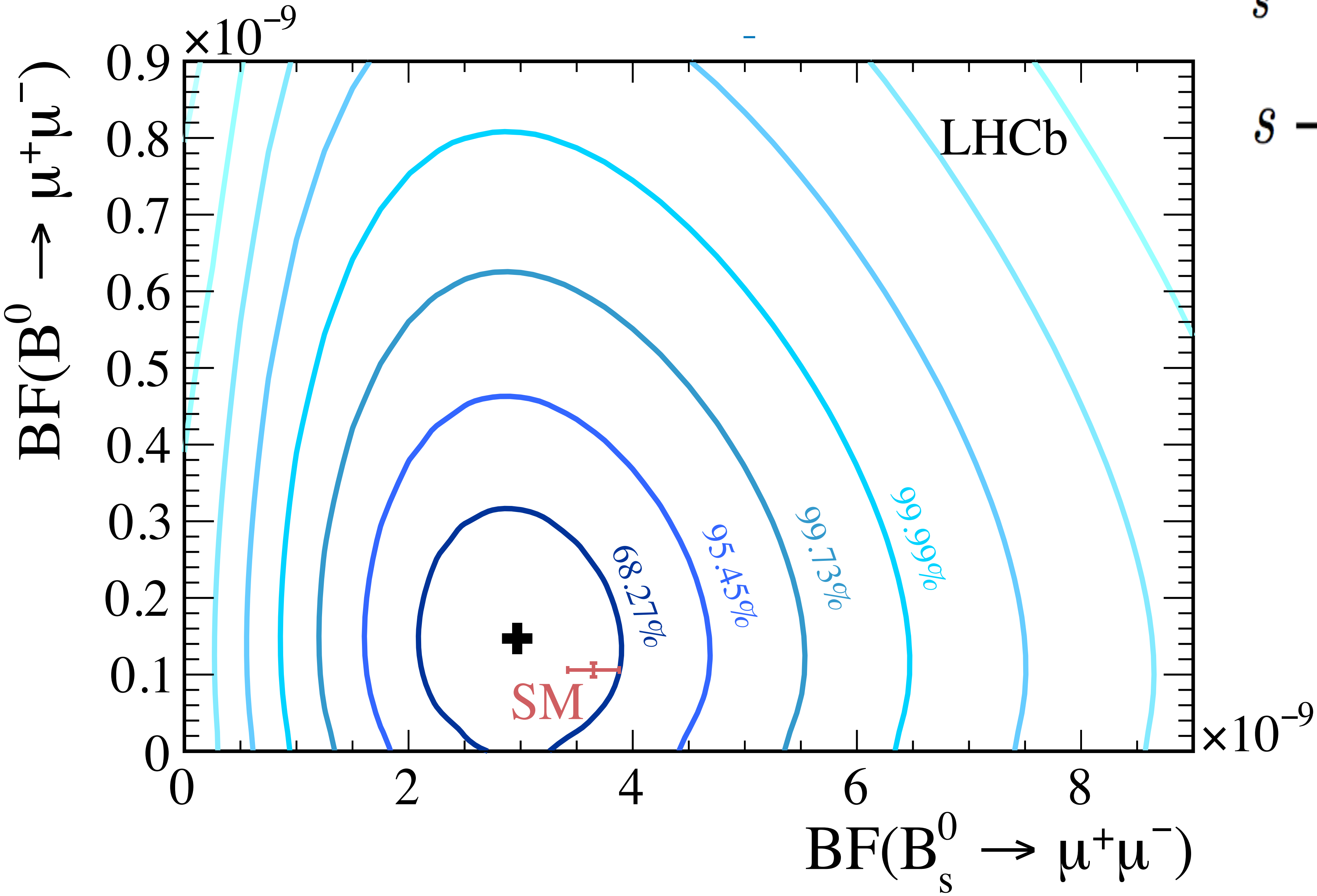
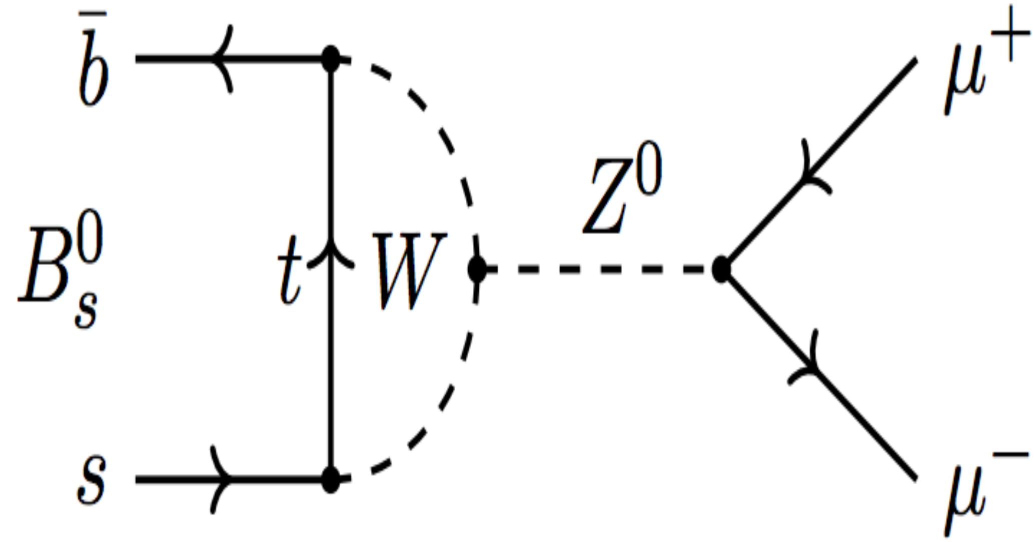


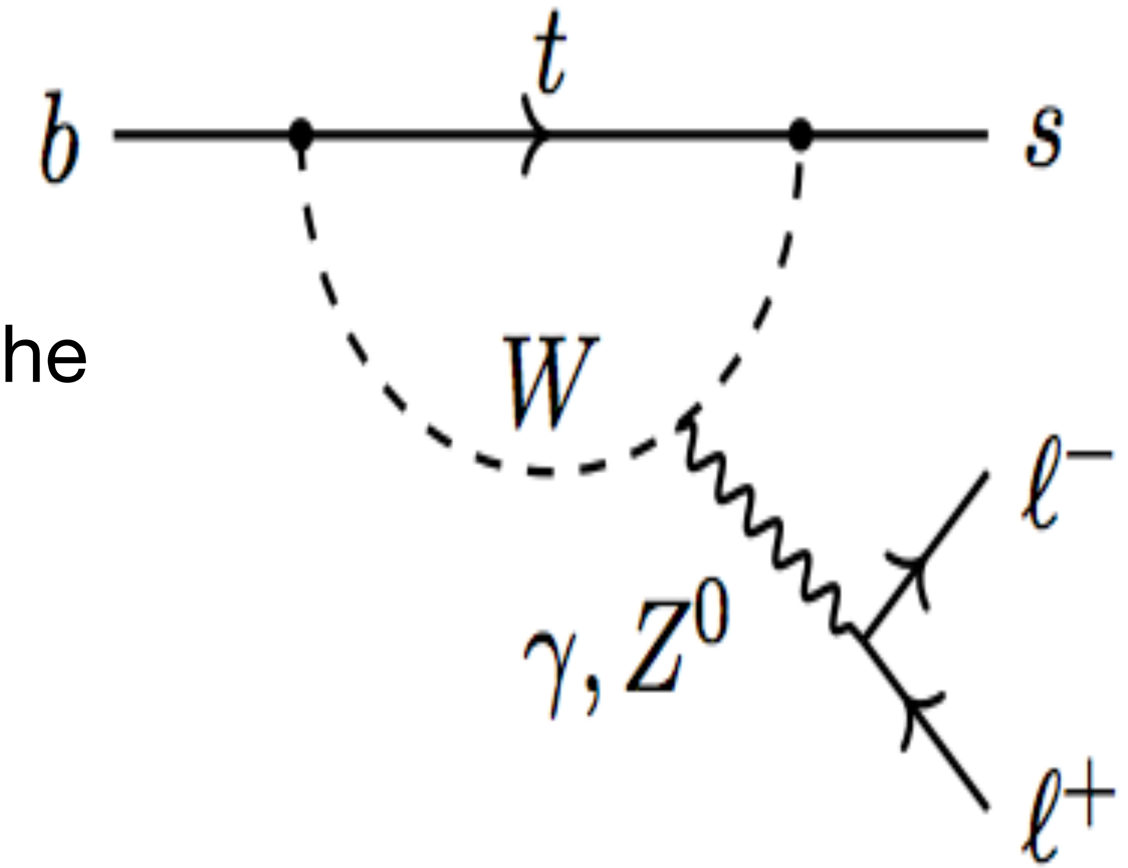


The SM-like result in $B_s \to \mu\mu$ is crucial to consider alongside anomalies that might show up in related observable.

A precision test of $B_d \to \mu\mu$, and other observables, will require far more luminosity.

Semileptonic b→sμμ

Theoretically far more challenging due to the hadronic form factors.



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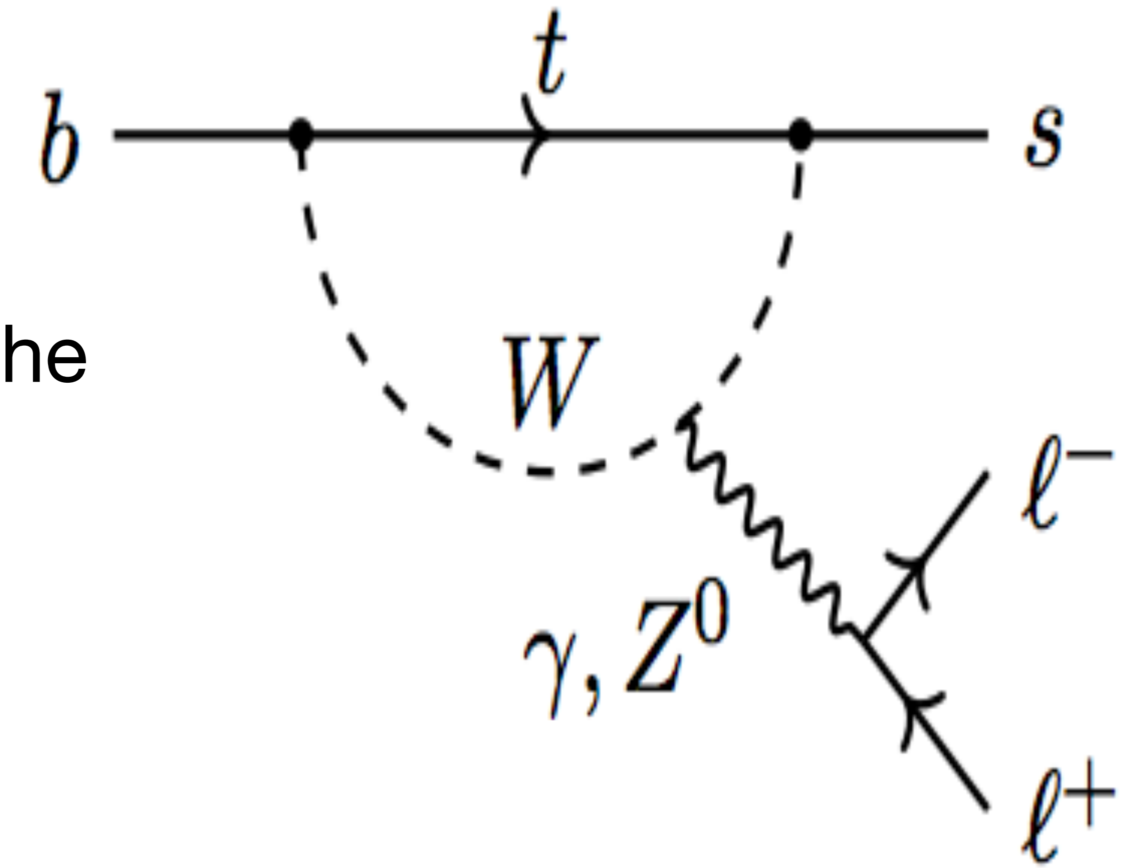

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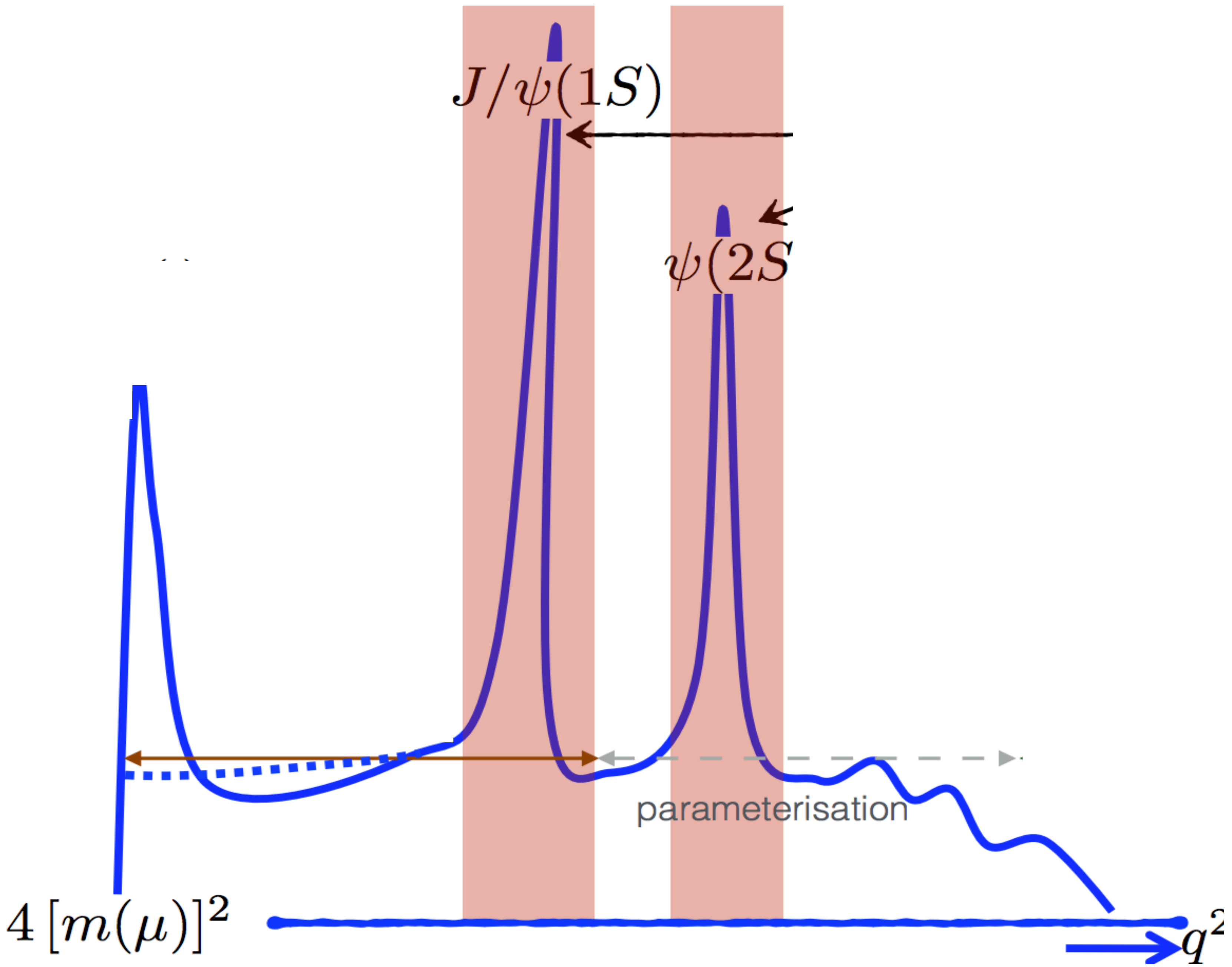

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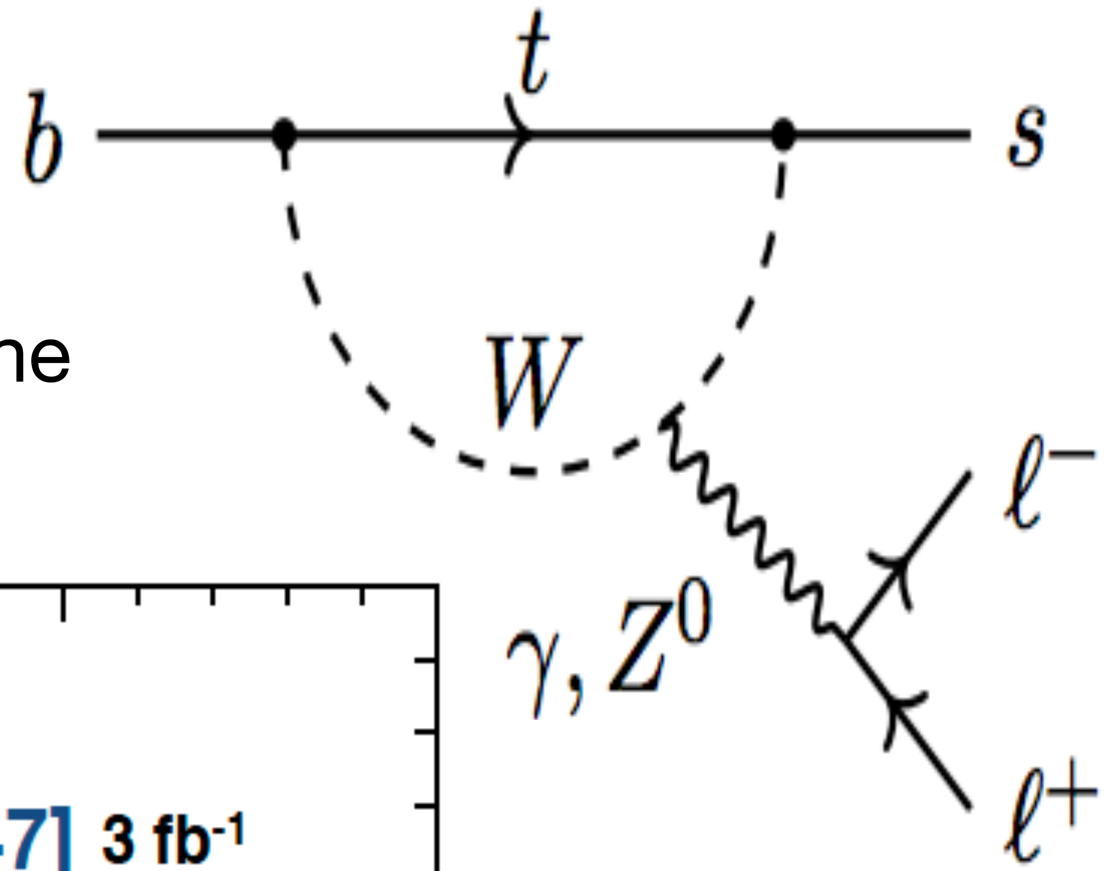

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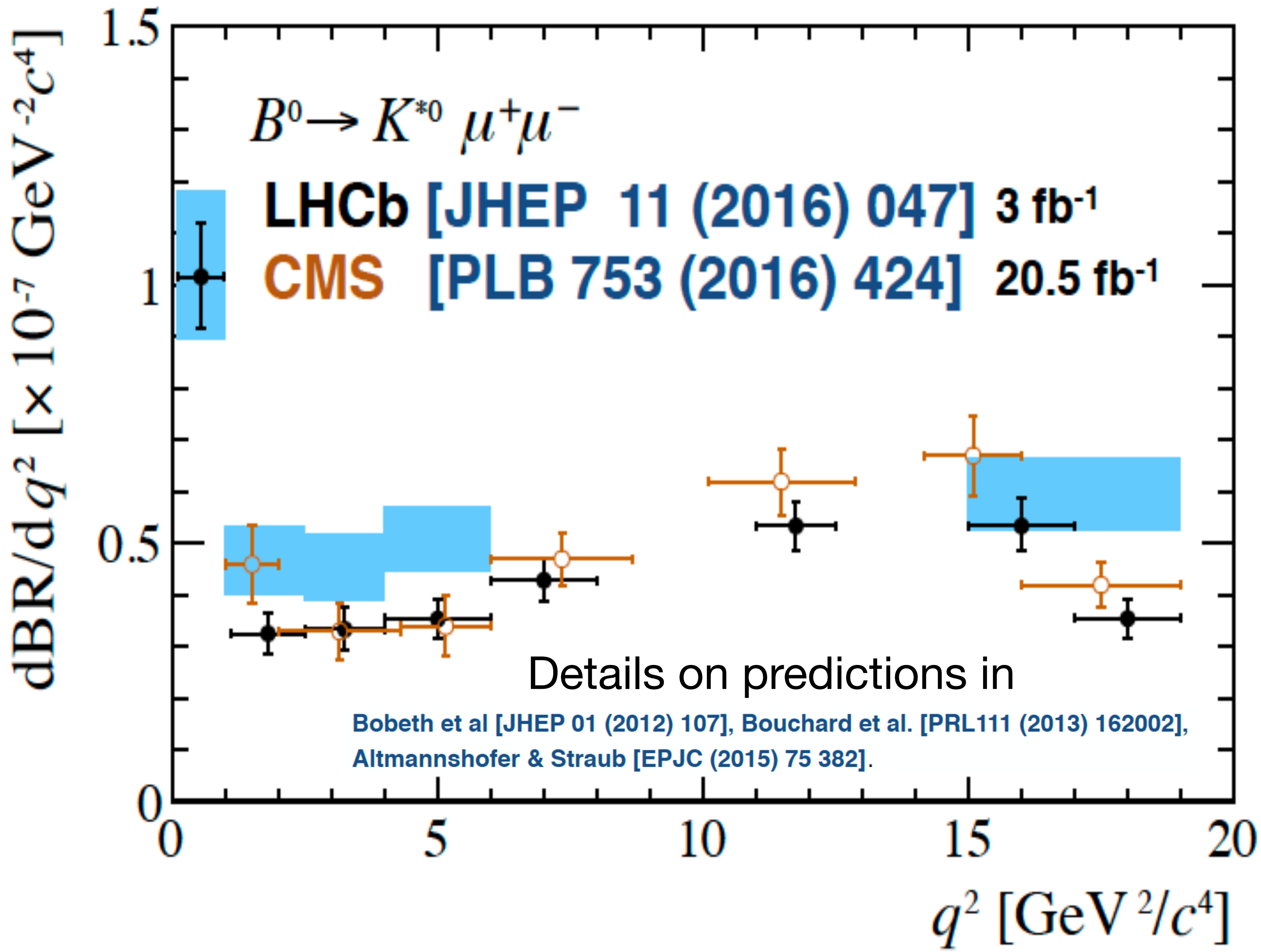

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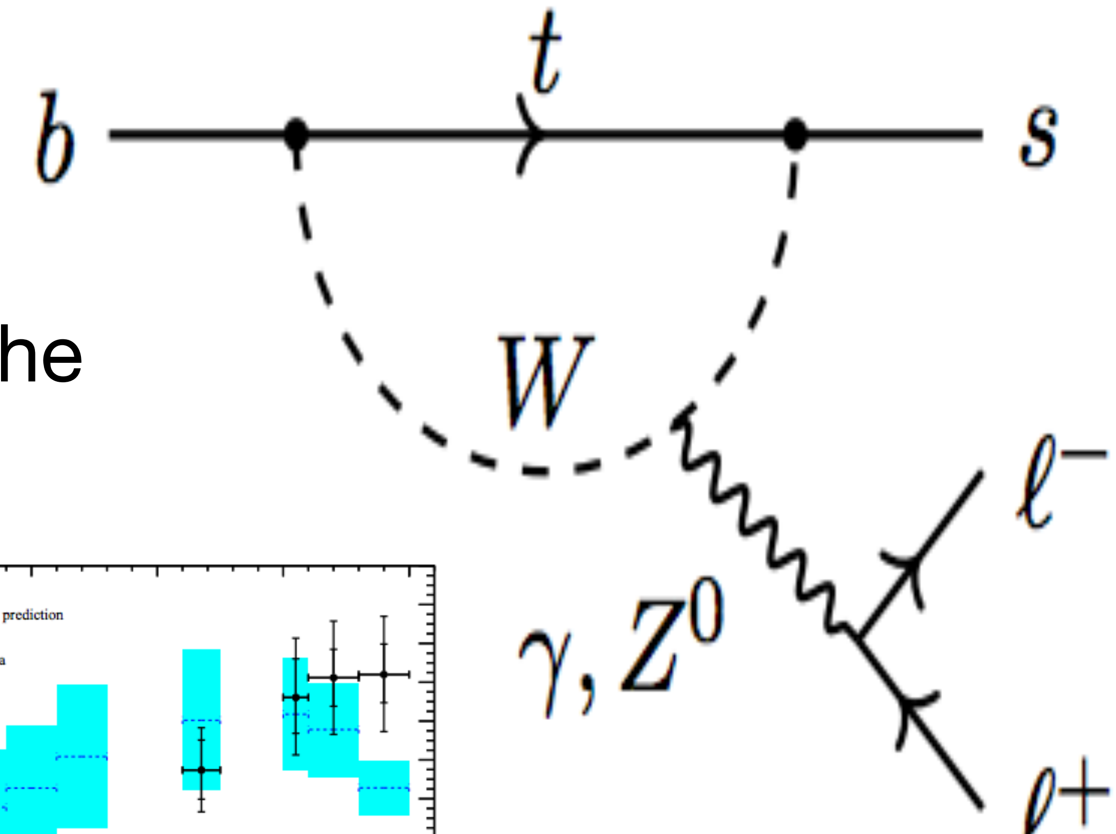

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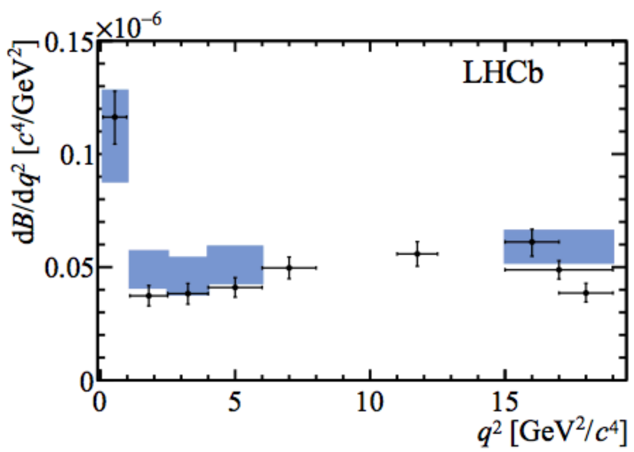
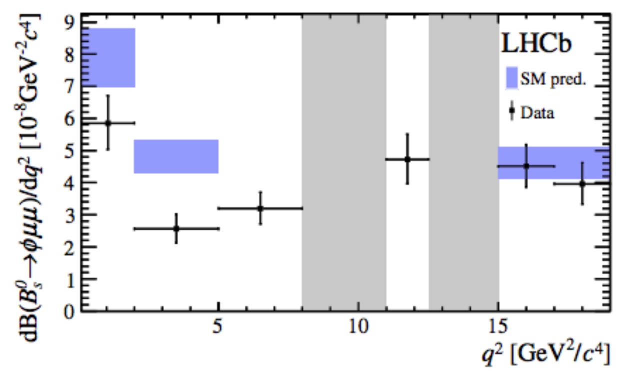


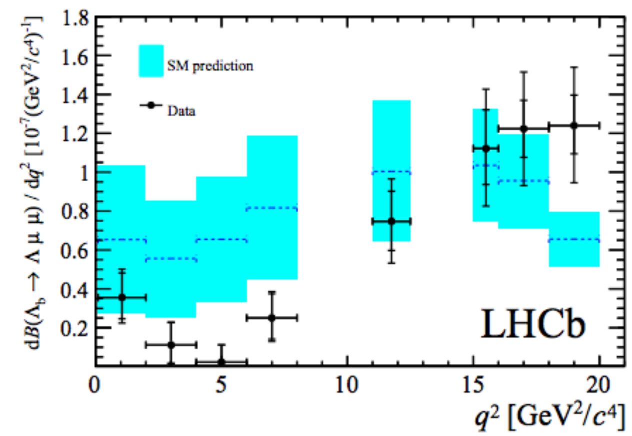
$B^0 \to K^{*0}\mu^+\mu^-$

[JHEP 11 (2016) 047]



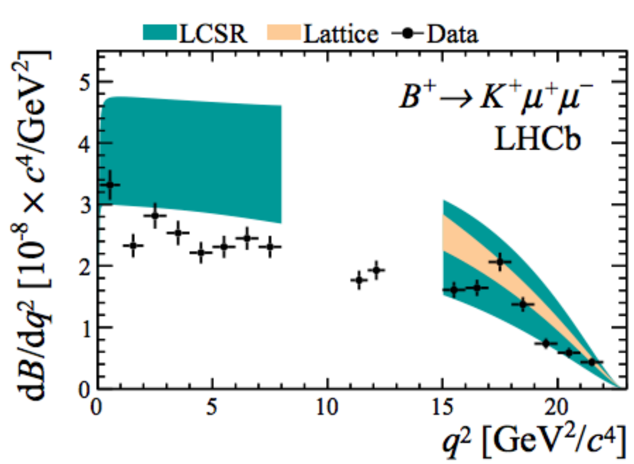
$B^0_s \to \phi\mu^+\mu^-$

[JHEP 09 (2015) 179]



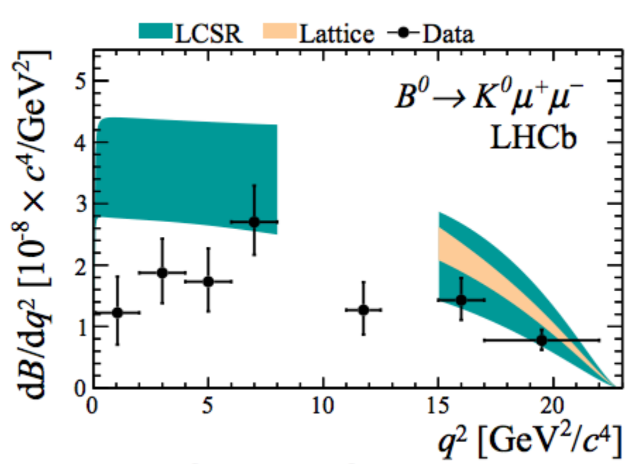
$\Lambda^0_b \to \Lambda\mu^+\mu^-$

[JHEP 06 (2015) 115]



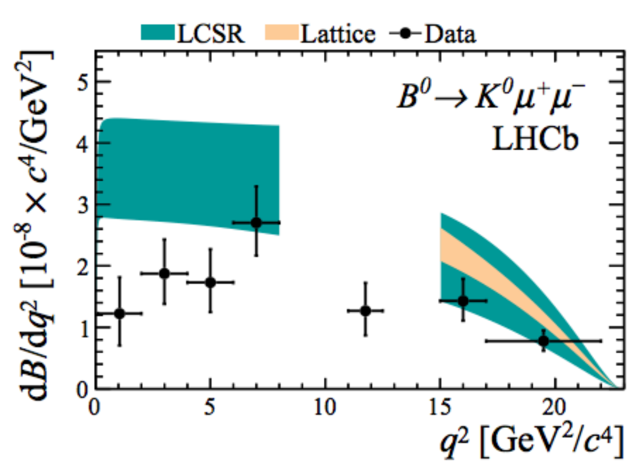
$B^+ \to K^+\mu^+\mu^-$

[JHEP 06 (2014) 133]



$B^0 \to K^0\mu^+\mu^-$

[JHEP 06 (2014) 133]



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

[JHEP 06 (2014) 133]

Are the data too low? This is a question for theory.

Semileptonic b→sμμ — angular distribution

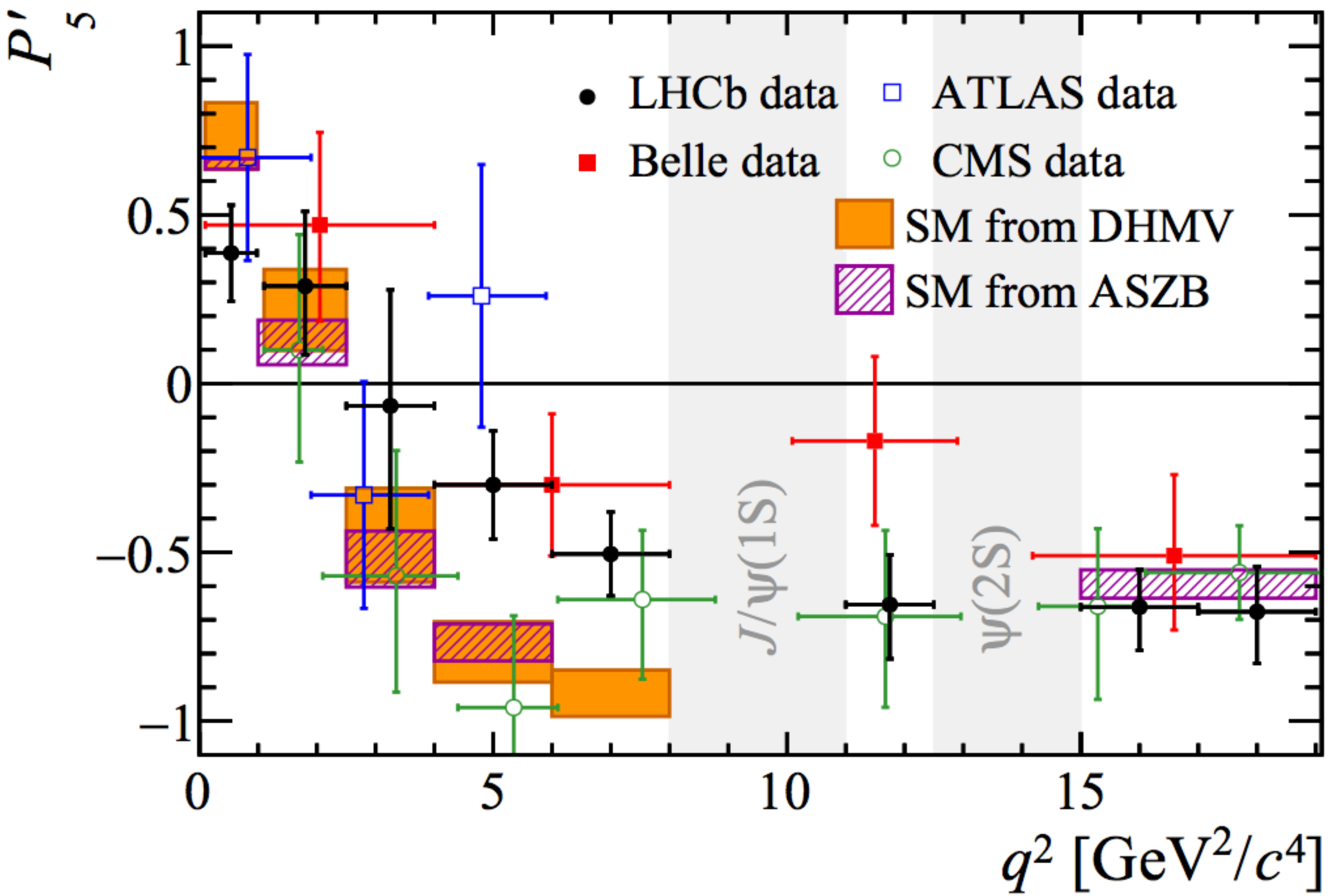
The angular distribution in B→(K*→Kπ)μμ

$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}}\Big|_{\mathrm{P}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \\ +\tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_l \\ -F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_l + S_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi \\ +S_4\sin 2\theta_K\sin 2\theta_l\cos\phi + S_5\sin 2\theta_K\sin\theta_l\cos\phi \\ +\tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_l + S_7\sin 2\theta_K\sin\theta_l\sin\phi \\ +S_8\sin 2\theta_K\sin 2\theta_l\sin\phi + S_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$

Form-factor free observables, e.g. $P_5' = S_5/\sqrt{F_L(1-F_L)}$

Descotes-Genon *et al*. [JHEP 04 (2012) 104]

Semileptonic b→sμμ — P′$_5$



Interesting ~3-4σ effect, but quickly caused the theorists to reconsider the uncertainties, in particular the role of “charm loops”.

Lepton universality tests with b→sll decays

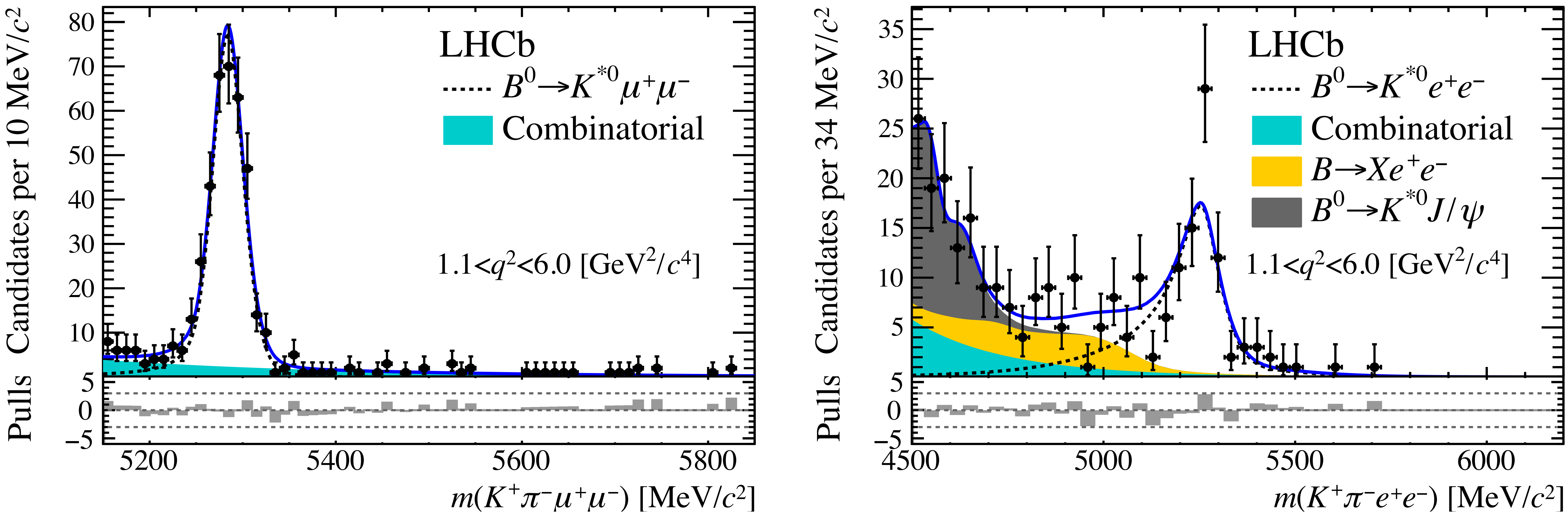
$$R_X = \int \frac{\mathrm{d}\Gamma(B\to X\mu^+\mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2 \Big/ \int \frac{\mathrm{d}\Gamma(B\to Xe^+e^-)}{\mathrm{d}q^2}\mathrm{d}q^2 \stackrel{\mathrm{SM}}{=} 1 \pm \mathcal{O}(1\%)$$

EPJC 76 (2016) 8,440

Lepton universality tests with b→sll decays

$$R_X = \int \frac{\mathrm{d}\Gamma(B \to X \mu^+ \mu^-)}{\mathrm{d}q^2}\mathrm{d}q^2 \Big/ \int \frac{\mathrm{d}\Gamma(B \to X e^+ e^-)}{\mathrm{d}q^2}\mathrm{d}q^2 \stackrel{\mathrm{SM}}{=} 1 \pm \mathcal{O}(1\%)$$

EPJC 76 (2016) 8,440

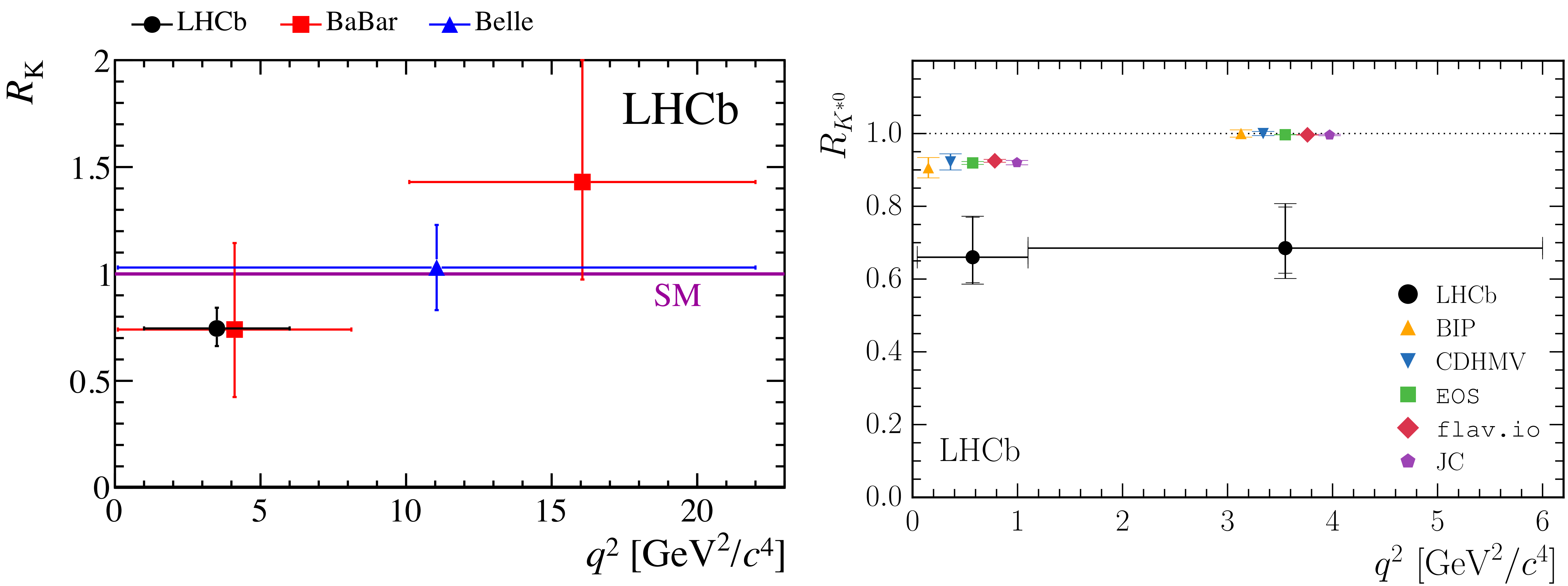


The detector is clearly far from universal in its response to leptons, but the systematic uncertainties are controlled by a clever double-ratio including the J/Ψ region.

Lepton universality tests with b→sll decays

$$R_X = \int \frac{d\Gamma(B \to X\mu^+\mu^-)}{dq^2} dq^2 \Big/ \int \frac{d\Gamma(B \to X e^+ e^-)}{dq^2} dq^2 \overset{\text{SM}}{=} 1 \pm \mathcal{O}(1\%)$$

EPJC 76 (2016) 8,440

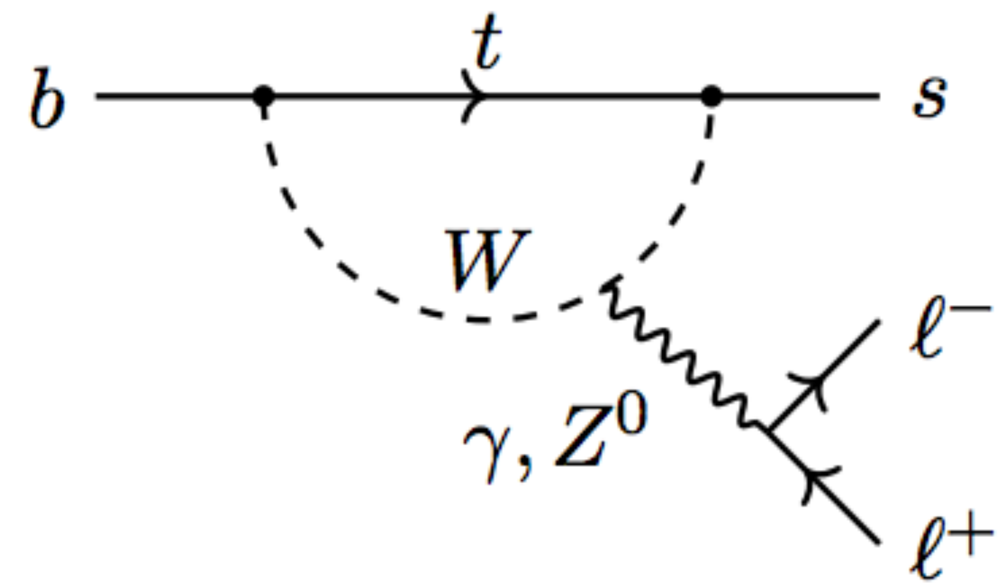


$R_{K^*}(0.045 < q^2 < 1.1\,\text{GeV}^2) = 0.66^{+0.11}_{-0.07} \pm 0.03$ at low q^2: $2.1\text{-}2.3\,\sigma$

$R_{K^*}(1.1 < q^2 < 6.0\,\text{GeV}^2) = 0.69^{+0.11}_{-0.07} \pm 0.05$ at central q^2: $2.4\text{-}2.5\,\sigma$

$R_K(1 < q^2 < 6.0\,\text{GeV}^2) = 0.745^{+0.090}_{-0.074} \pm 0.036$ at central q^2: $2.6\,\sigma$

What *could* this mean?



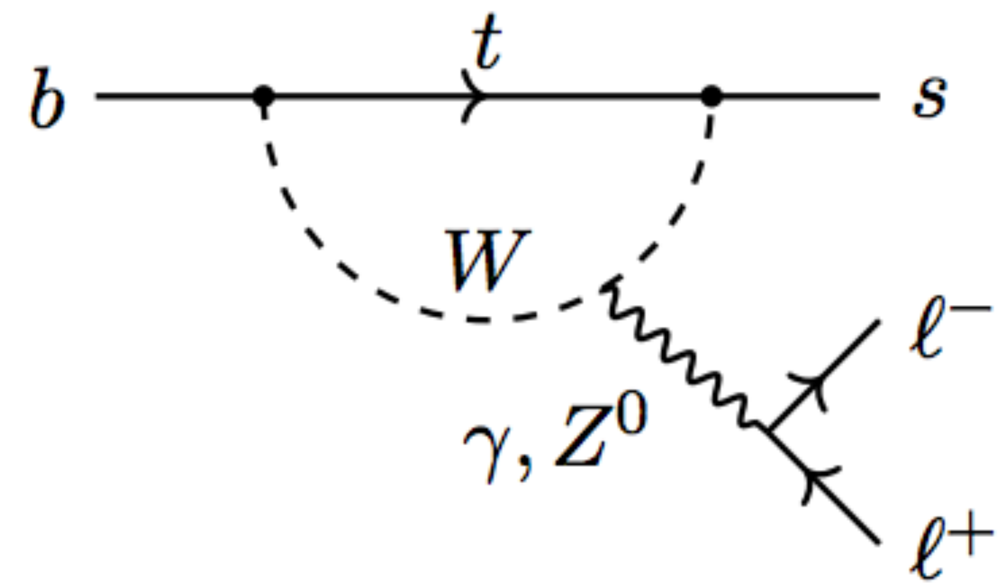
$$\mathcal{A}_0 \left(\frac{c_{\rm SM}}{v^2} + \frac{c_{\rm NP}}{\Lambda^2} \right)$$

20-30% effect in $bs\mu\mu$

$$C_{\rm SM} = V_{ts}/16\pi^2$$

$$\frac{\Lambda^2}{C_{\rm NP}} \sim (30\ \mathrm{TeV})^2$$

What *could* this mean?



$$\mathcal{A}_0\left(\frac{c_{\rm SM}}{v^2}+\frac{c_{\rm NP}}{\Lambda^2}\right)$$

20-30% effect in $bs\mu\mu$

$$C_{\rm SM} = V_{ts}/16\pi^2$$

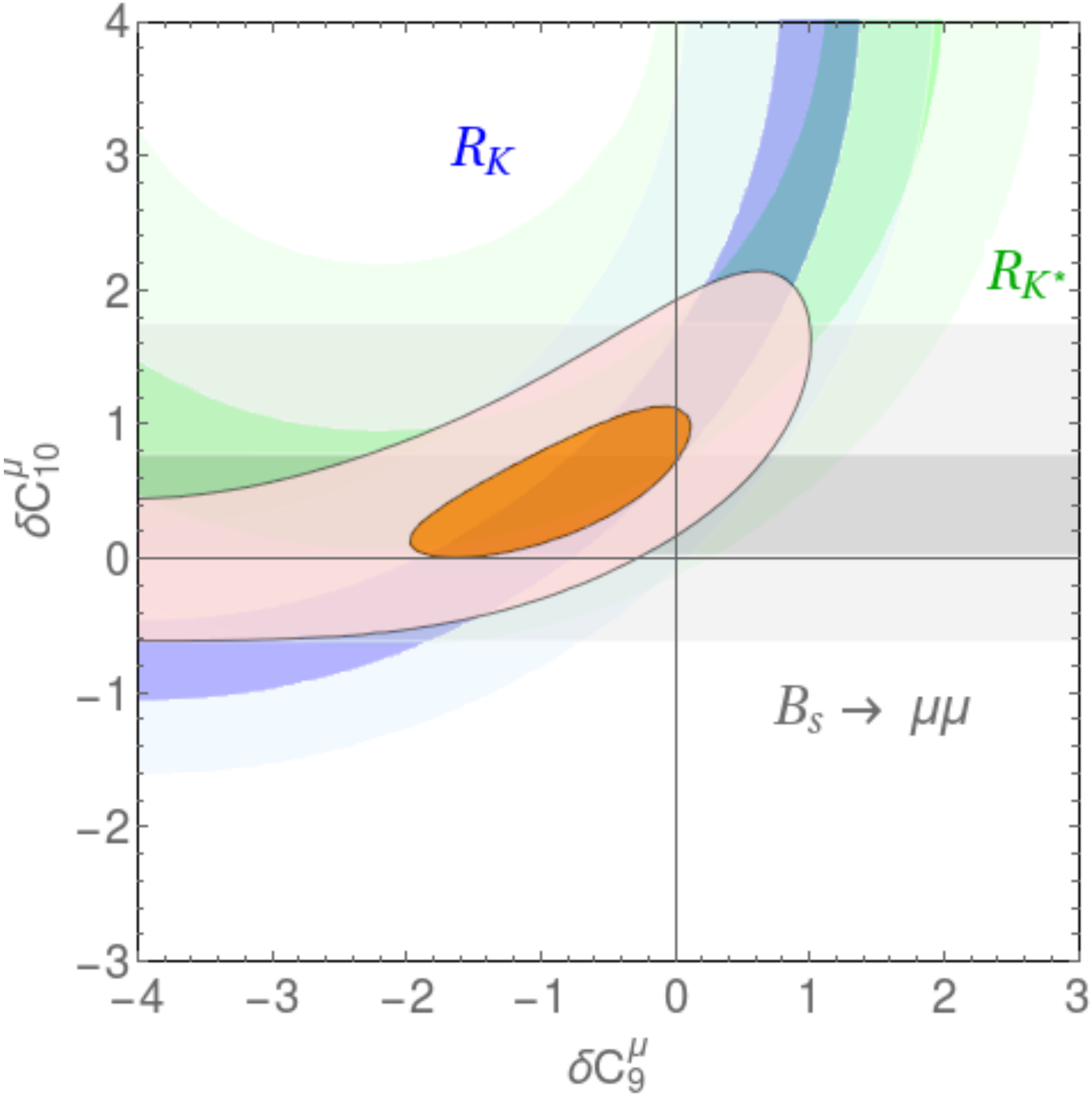
$$\frac{\Lambda^2}{C_{\rm NP}} \sim (30\ \text{TeV})^2$$

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^*\frac{\alpha}{4\pi}\sum_i C_i(\mu)\mathcal{O}_i(\mu)$$

$$C_9\ \ (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\mu)$$

$$C_{10}\ (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu\gamma^5\mu)$$

What *could* this mean?



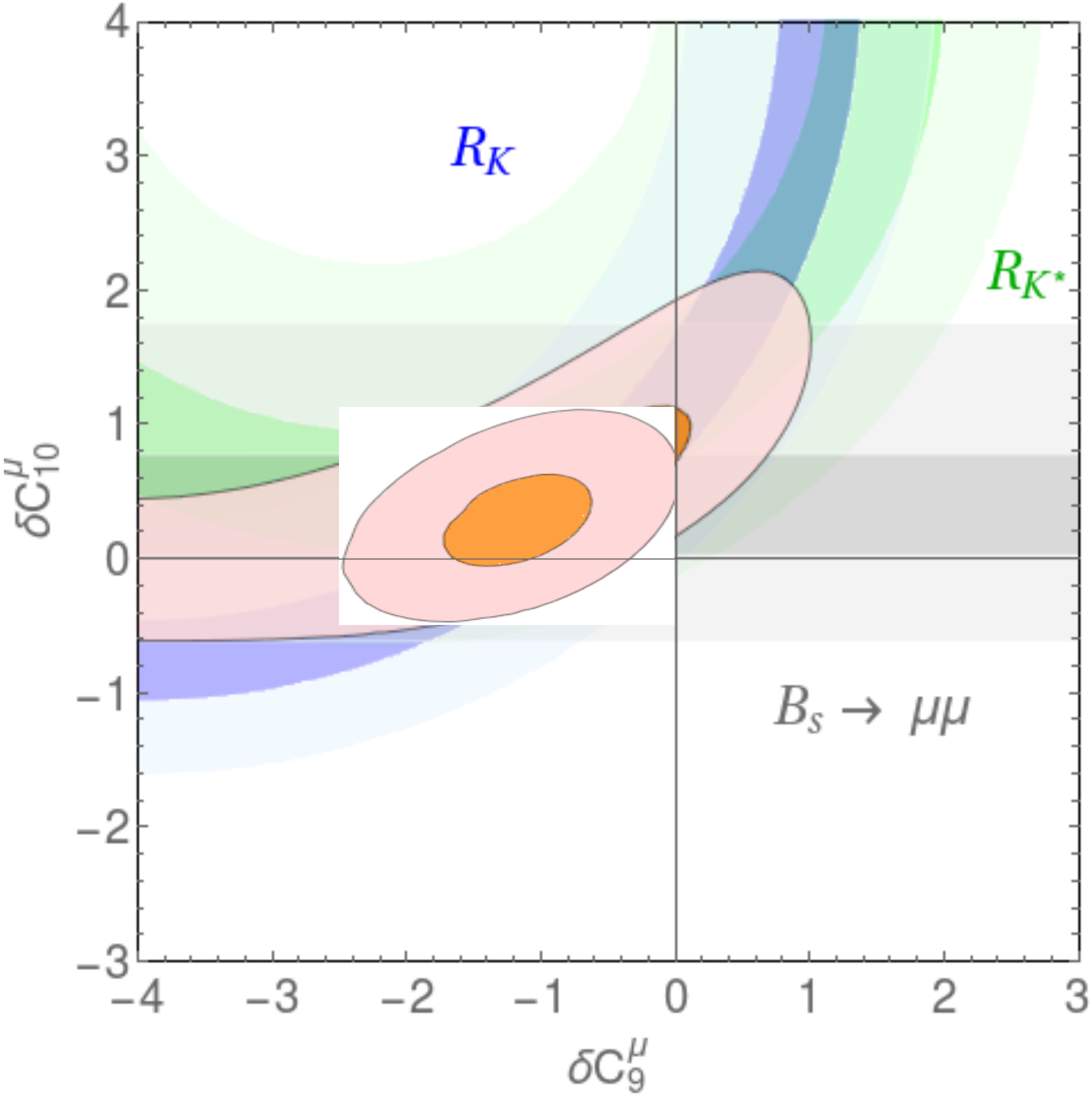
Only “clean” observables

$$C_9 \;\; (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

$$C_{10} \, (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma^5 \mu)$$

[Geng, Grinstein, Jaeger, Camalich, Ren, Shi PRD 96, 093006 (2017)]

What *could* this mean?



Only “clean” observables

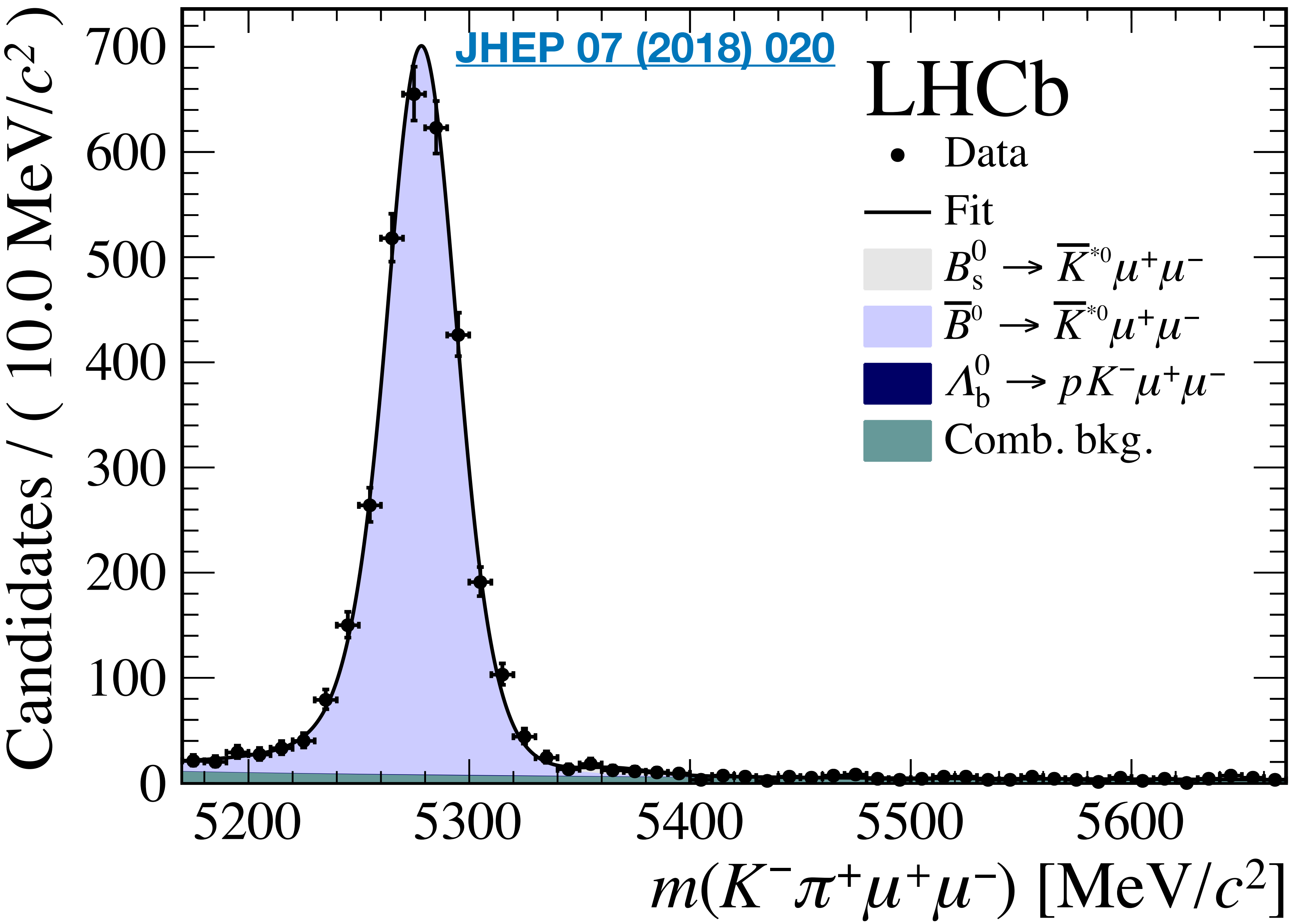
Including b→sμμ angular

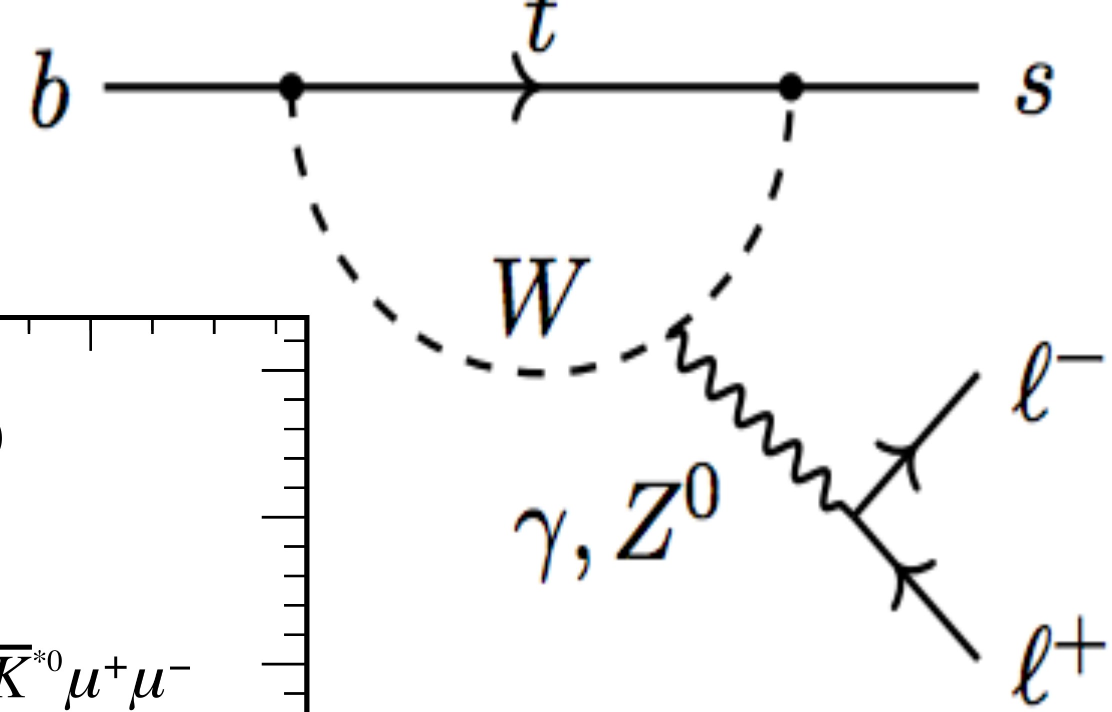
$$C_9 \;\; (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

$$C_{10} \, (\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma^5 \mu)$$

[Geng, Grinstein, Jaeger, Camalich, Ren, Shi PRD 96, 093006 (2017)]

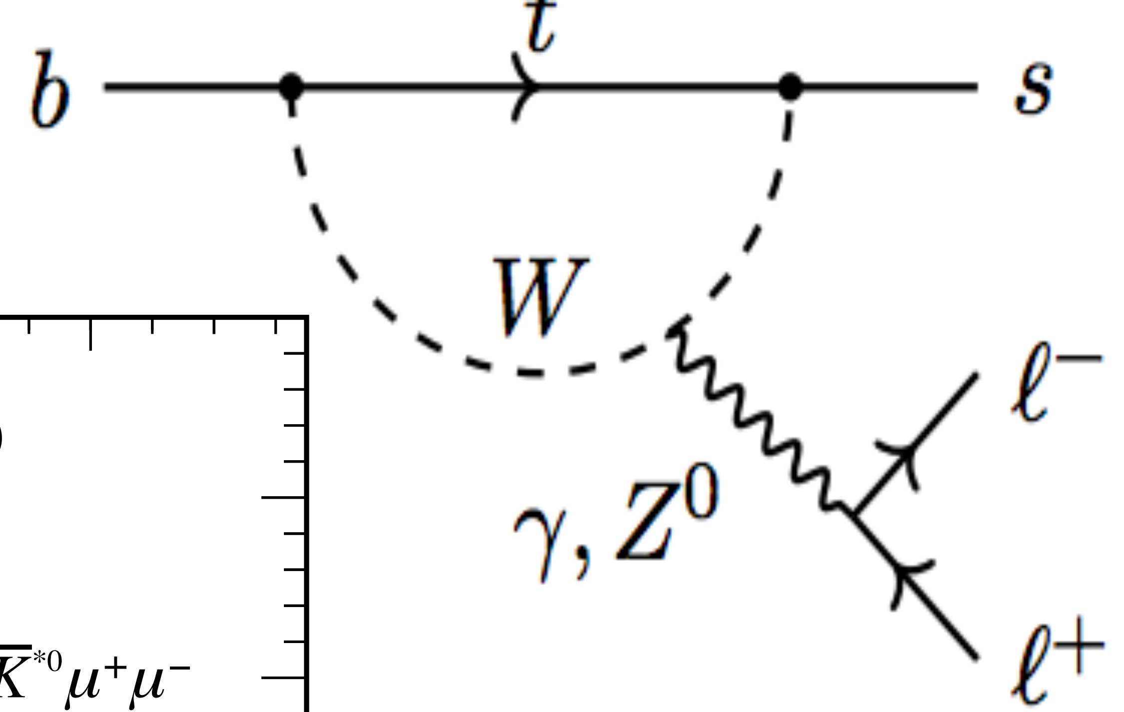
A glimpse to the future

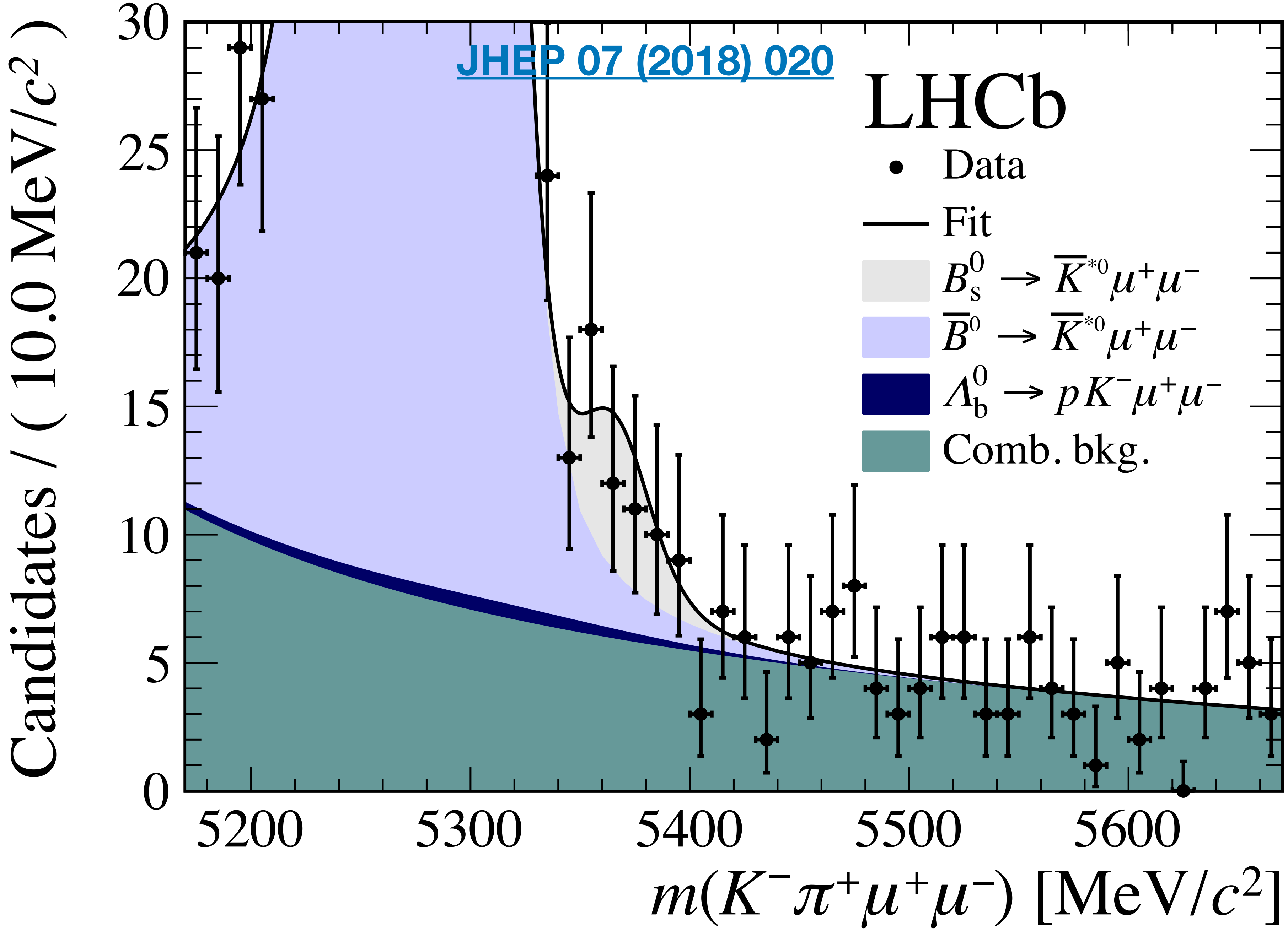




$$(V_{td}/V_{ts})^2 \sim 4 \times 10^{-2}$$

A glimpse to the future



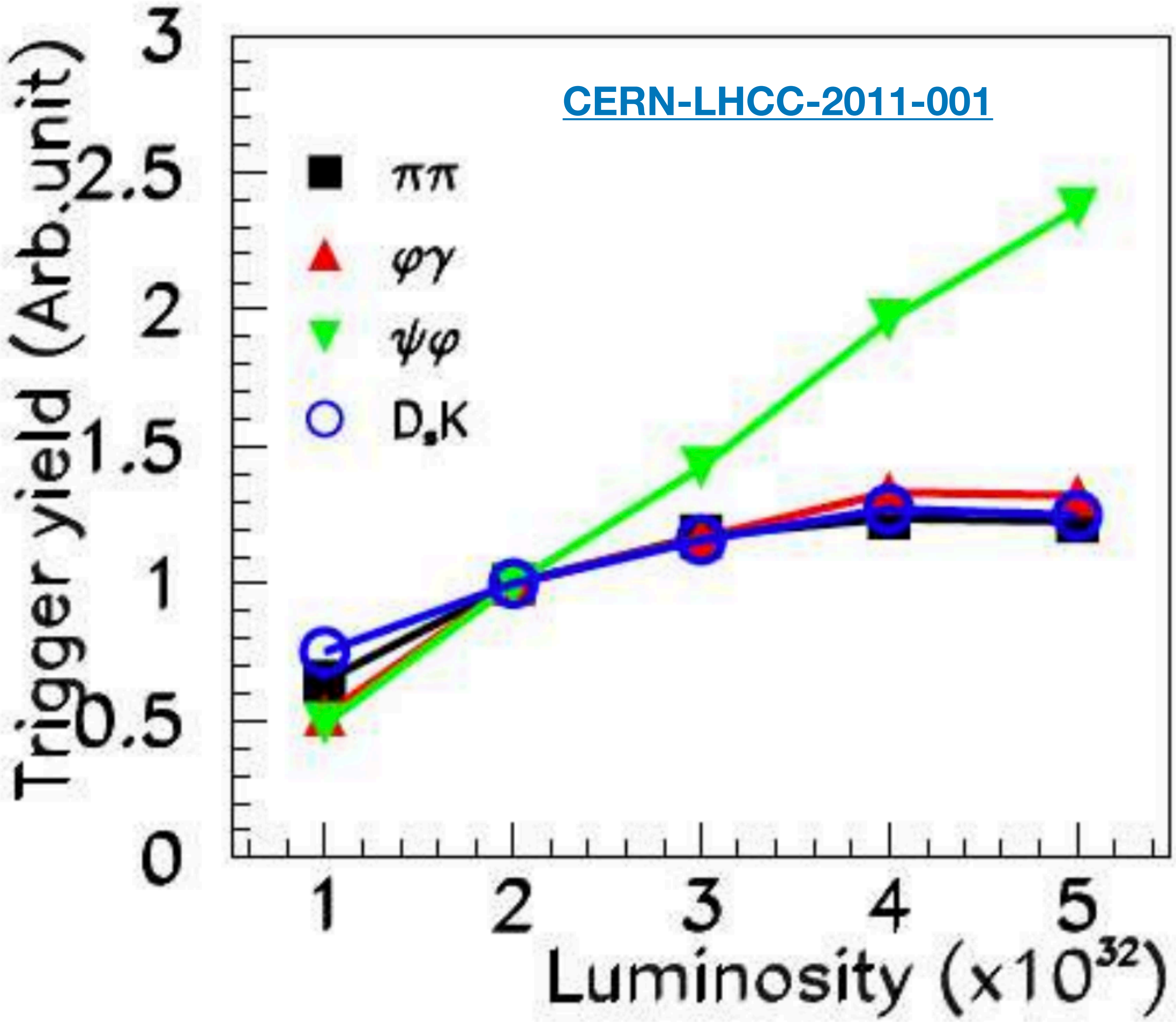


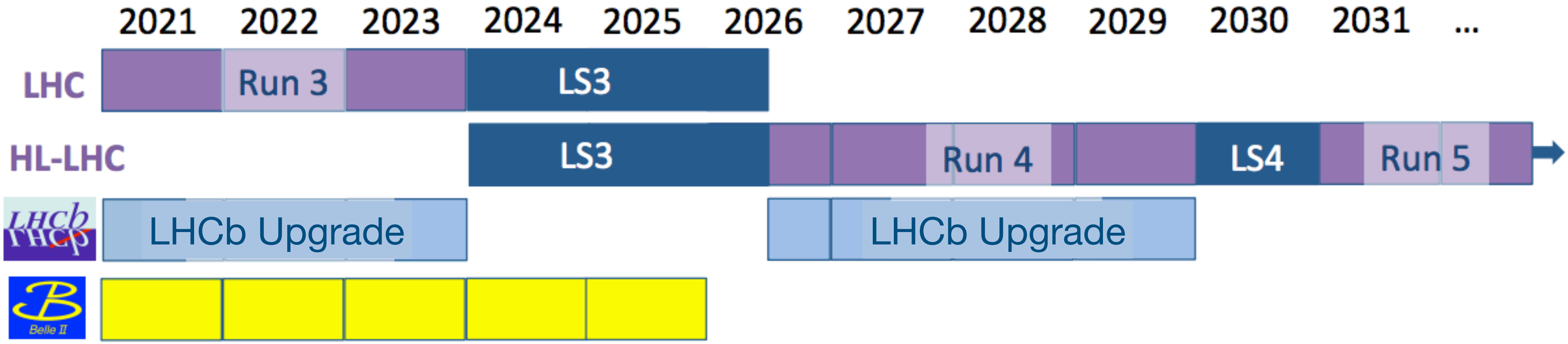
$$(V_{td}/V_{ts})^2 \sim 4 \times 10^{-2}$$

$$\mathscr{B}(B_s^0 \to \overline{K}^{*0}\mu^+\mu^-) = [2.9 \pm 1.0(\text{stat}) \pm 0.2(\text{syst}) \pm 0.3(\text{norm})] \times 10^{-8}$$

Far larger luminosities will be required for precision tests with V_{td} decays. Many similar examples, e.g. angular analysis of electron modes.

Why don't we run at higher luminosity?

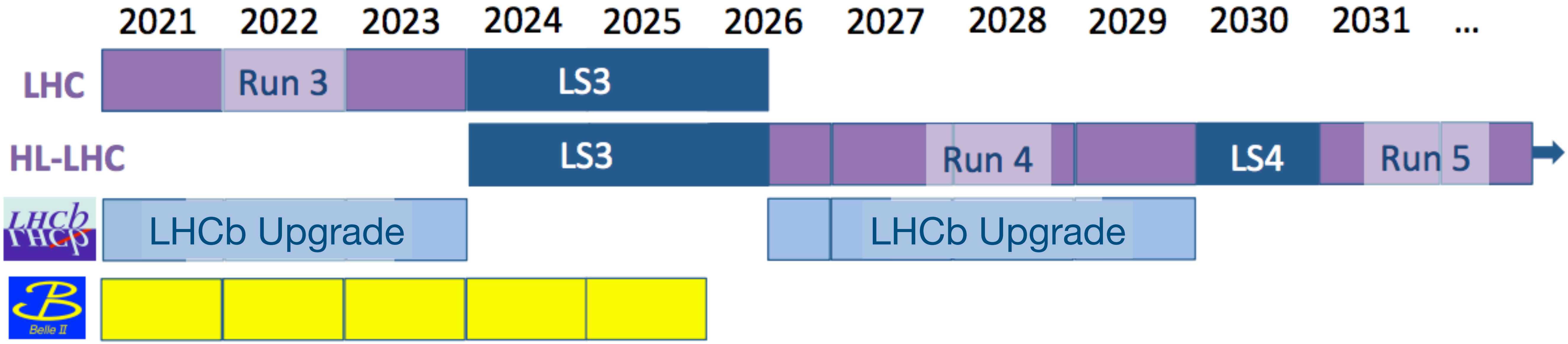




LHCb Upgrade

1. **Full software trigger** to allow effective operation at higher luminosities with higher efficiency for hadronic decays.

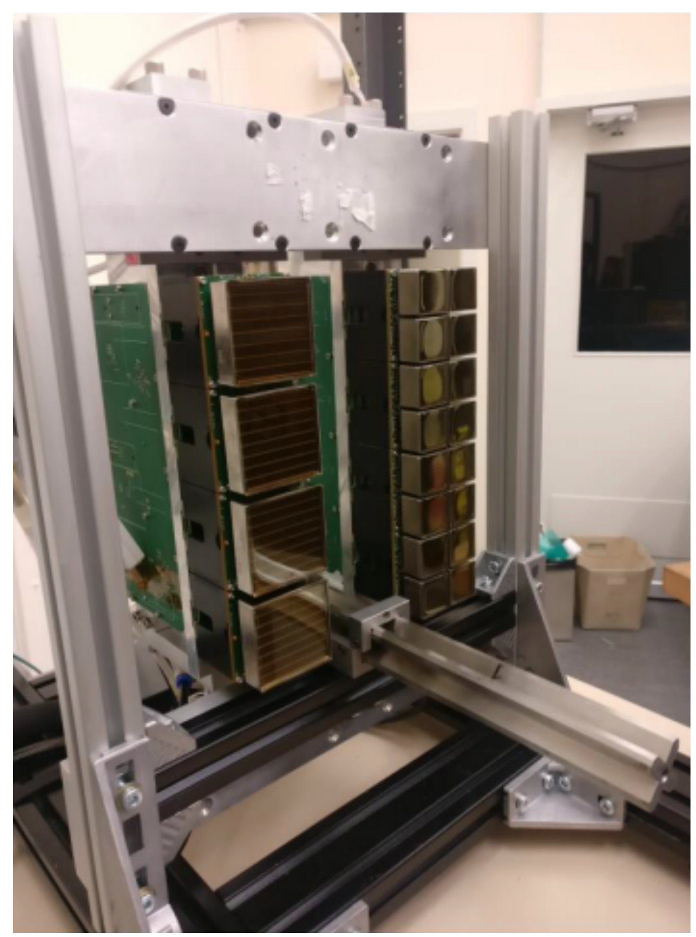
2. **Luminosity** to be raised (x5) to $2\text{x}10^{33}$ $cm^{-2}s^{-1}$.



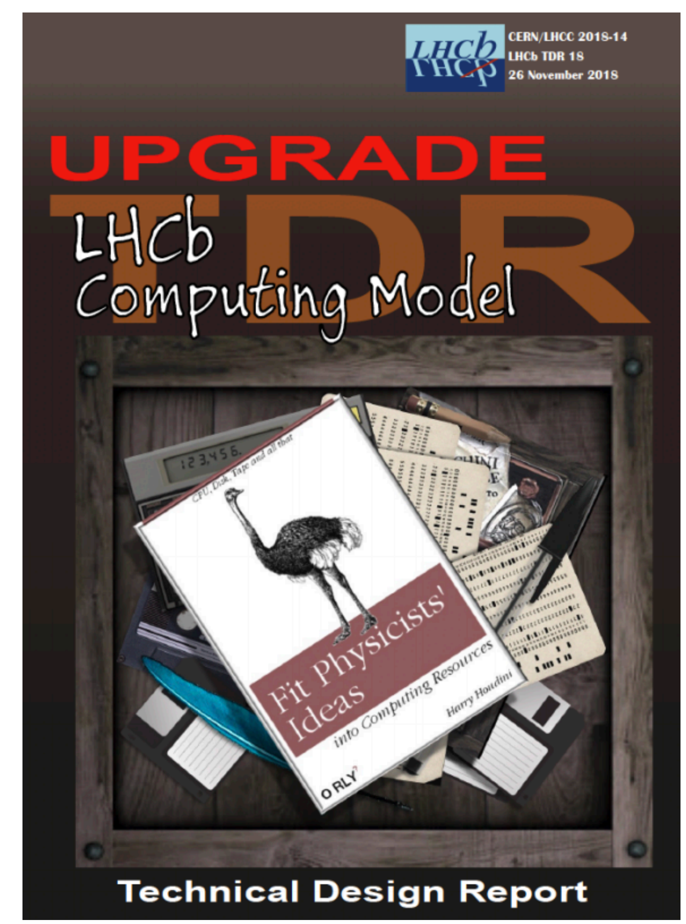
LHCb upgrade progressing well, e.g. the three main UK projects:

Pixel VELO

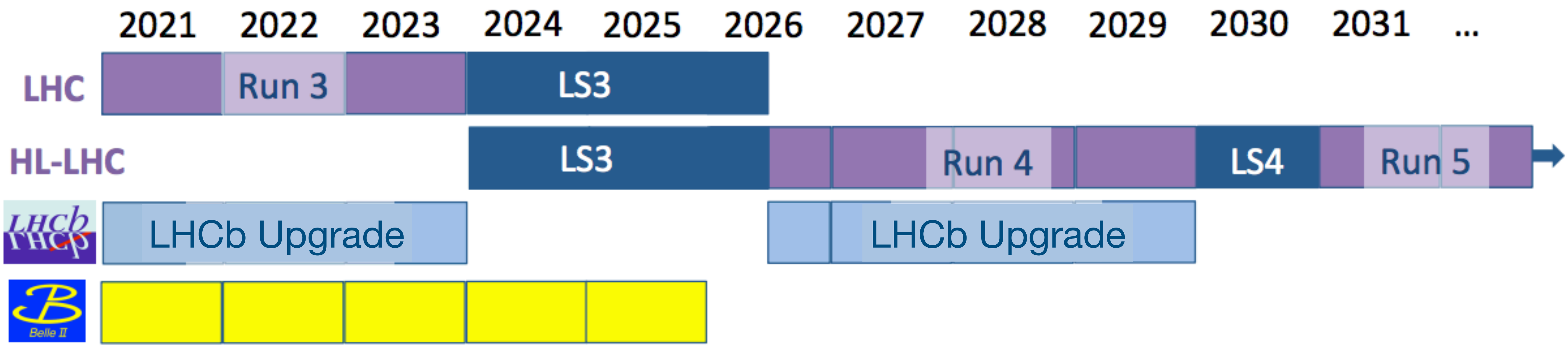
RICH



Computing

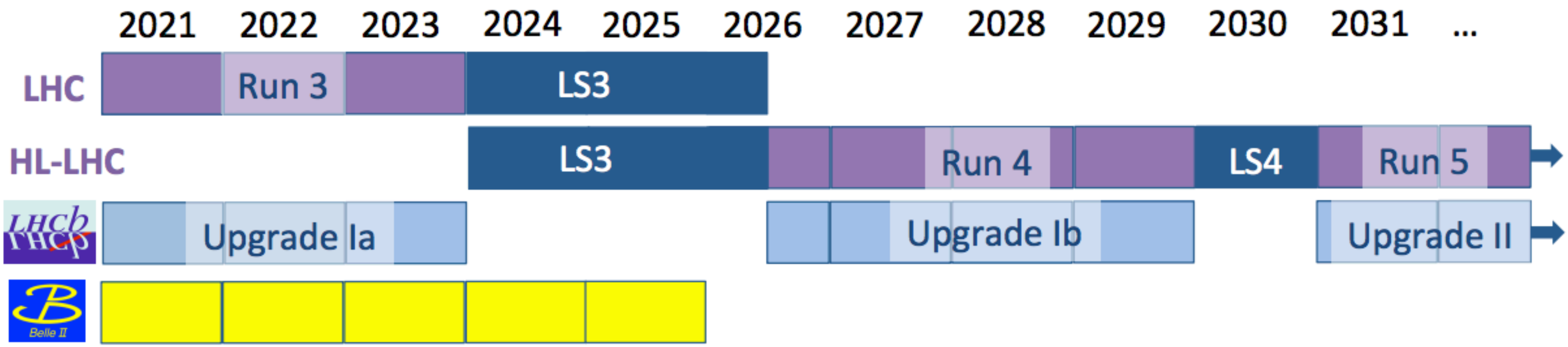


LHCB-TDR-018

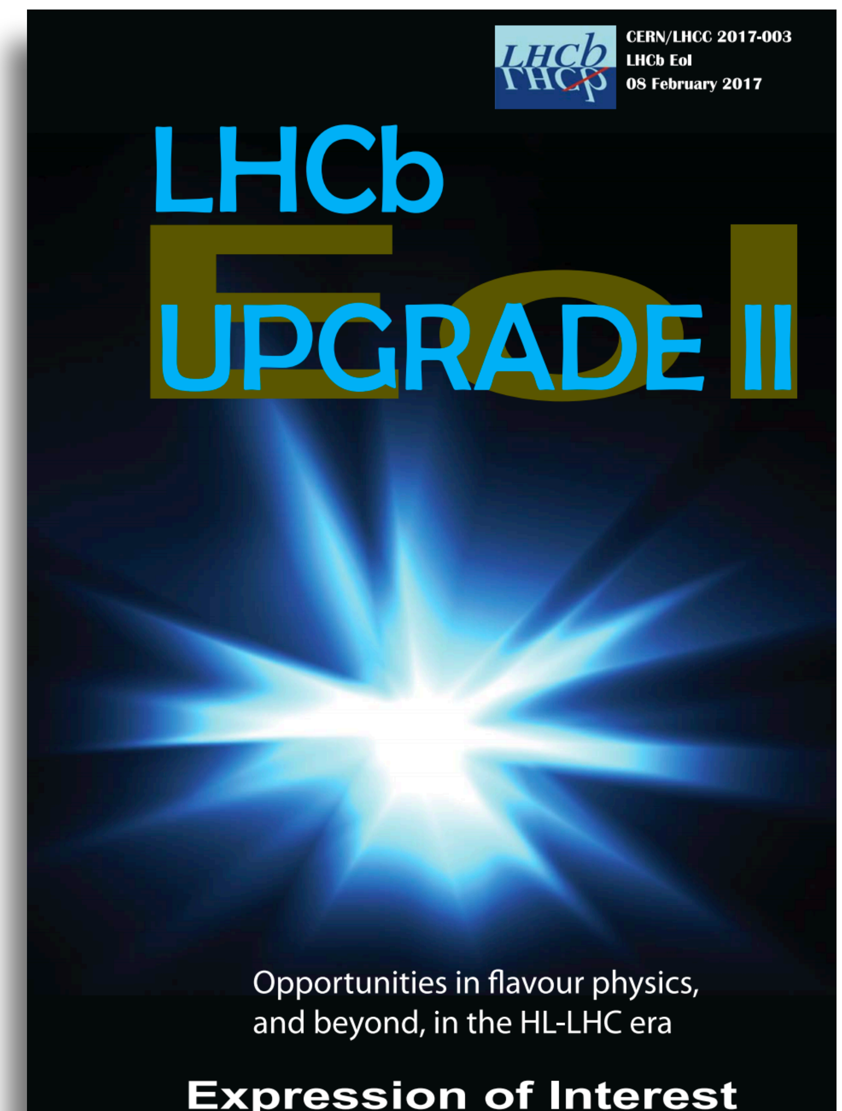


Belle II and LHCb upgrade will improve the flavour precision by an order of magnitude.

However, many NP sensitive observables are far from any systematic floor, and others will remain out of reach.

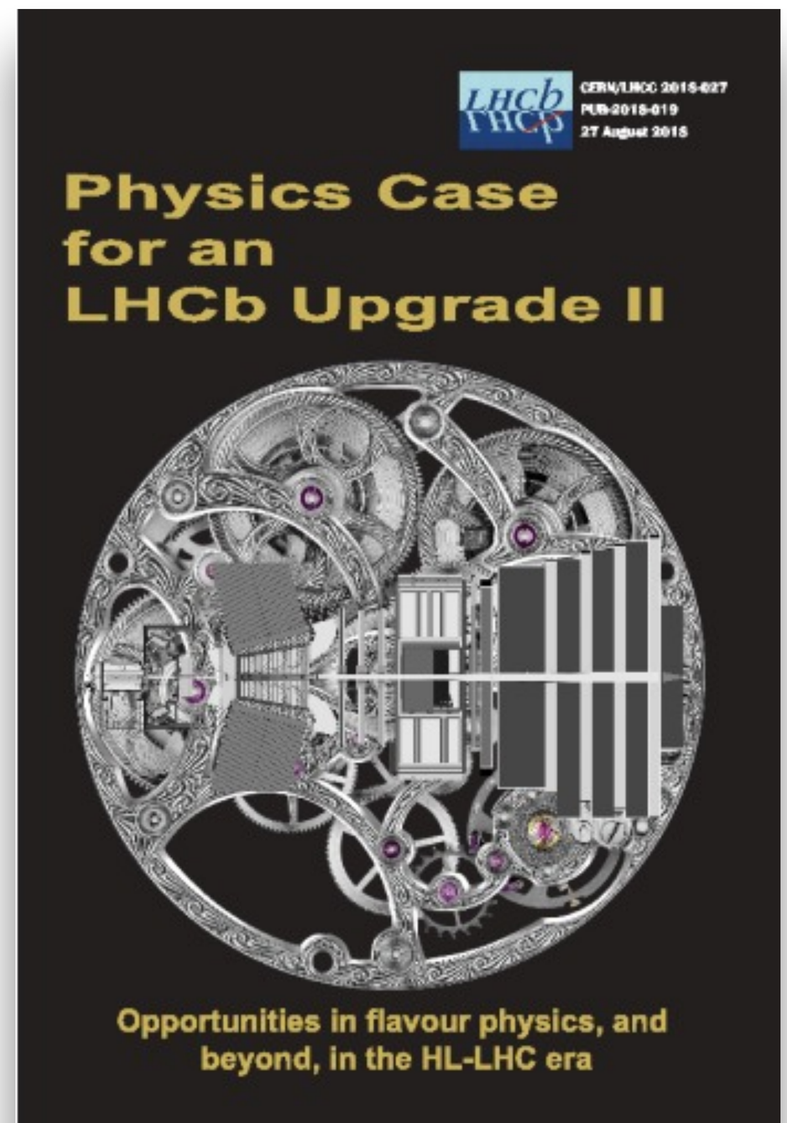


Feb 2017

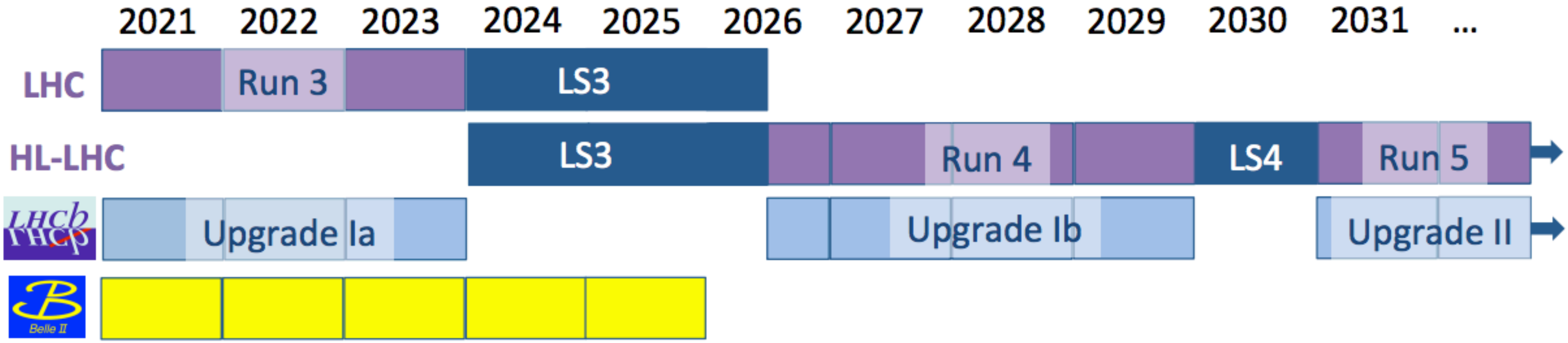


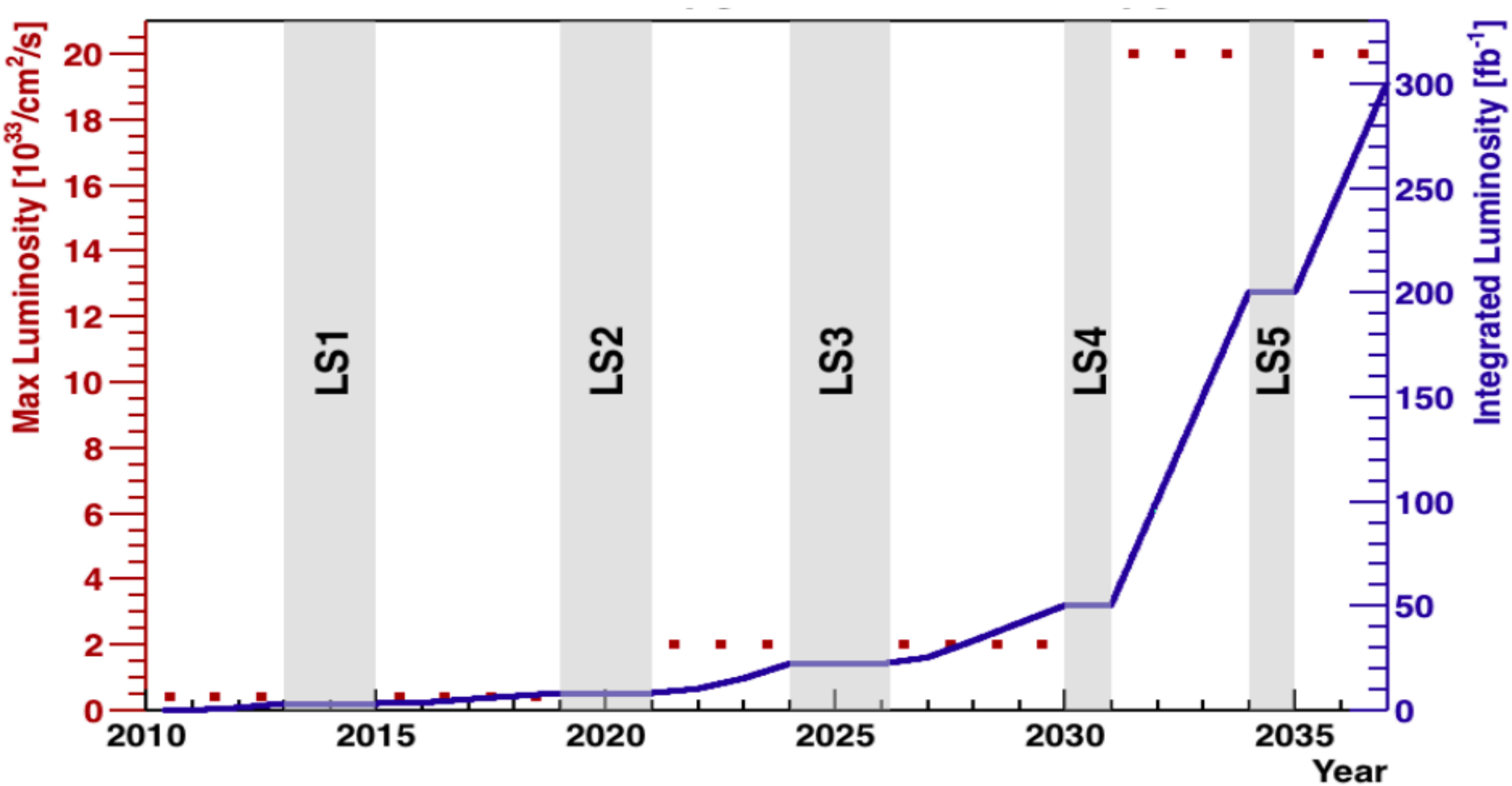
CERN-LHCC-2017-003

Aug 2018

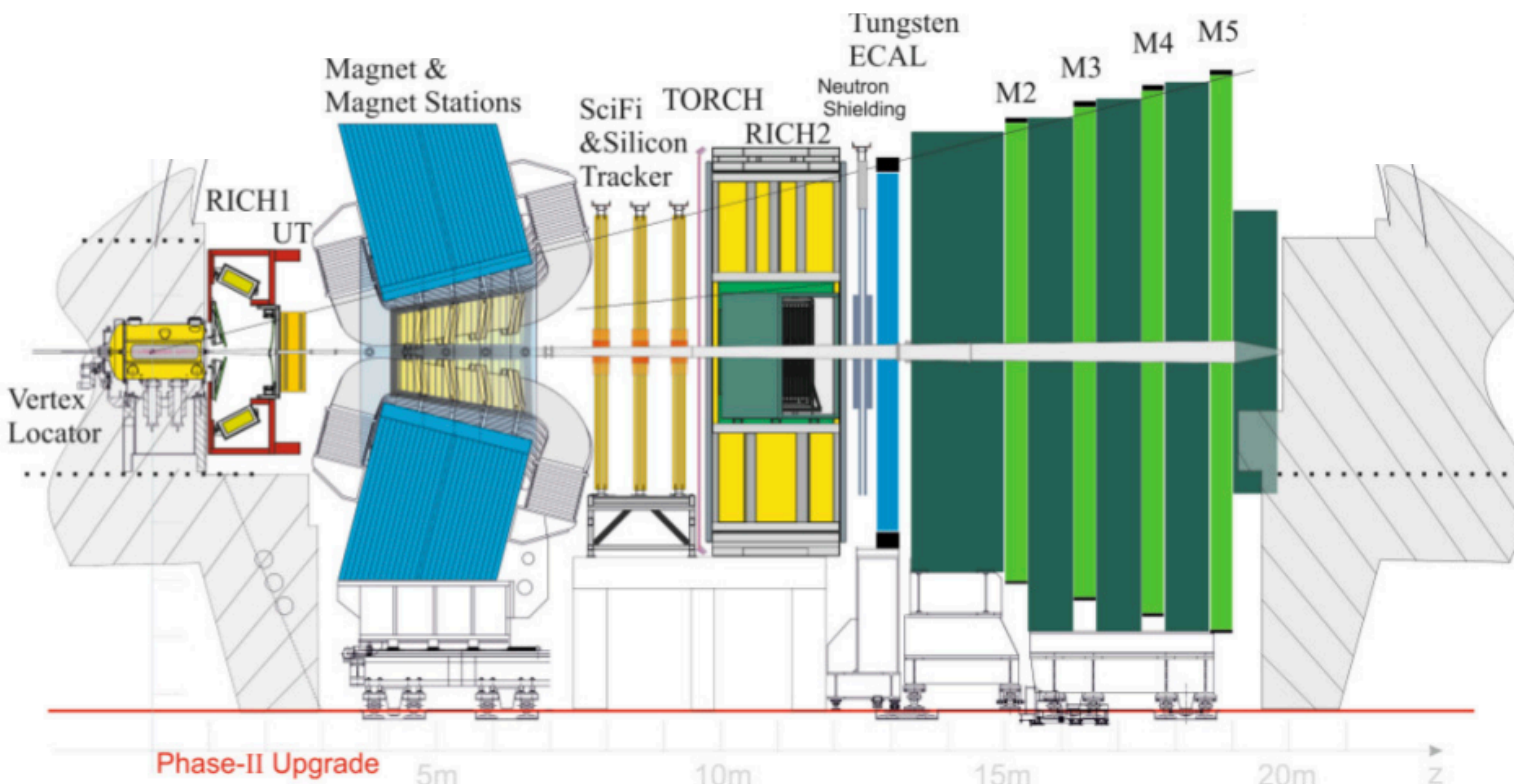


1808.08865


2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
...
LHC
Run 3
LS3
HL-LHC
LS3
Run 4
LS4
Run 5
LHCb
Upgrade Ia
Upgrade Ib
Upgrade II
Belle II


Max Luminosity [10^{33}/cm^2/s]
Integrated Luminosity [fb^{-1}]
LS1
LS2
LS3
LS4
LS5
0
2
4
6
8
10
12
14
16
18
20
0
50
100
150
200
250
300
2010
2015
2020
2025
2030
2035
Year

For upgrade II we have a qualitatively new challenge, namely pileup. However, this can be mitigated with fast-timing technology, benefiting from clear synergies with ATLAS and CMS.

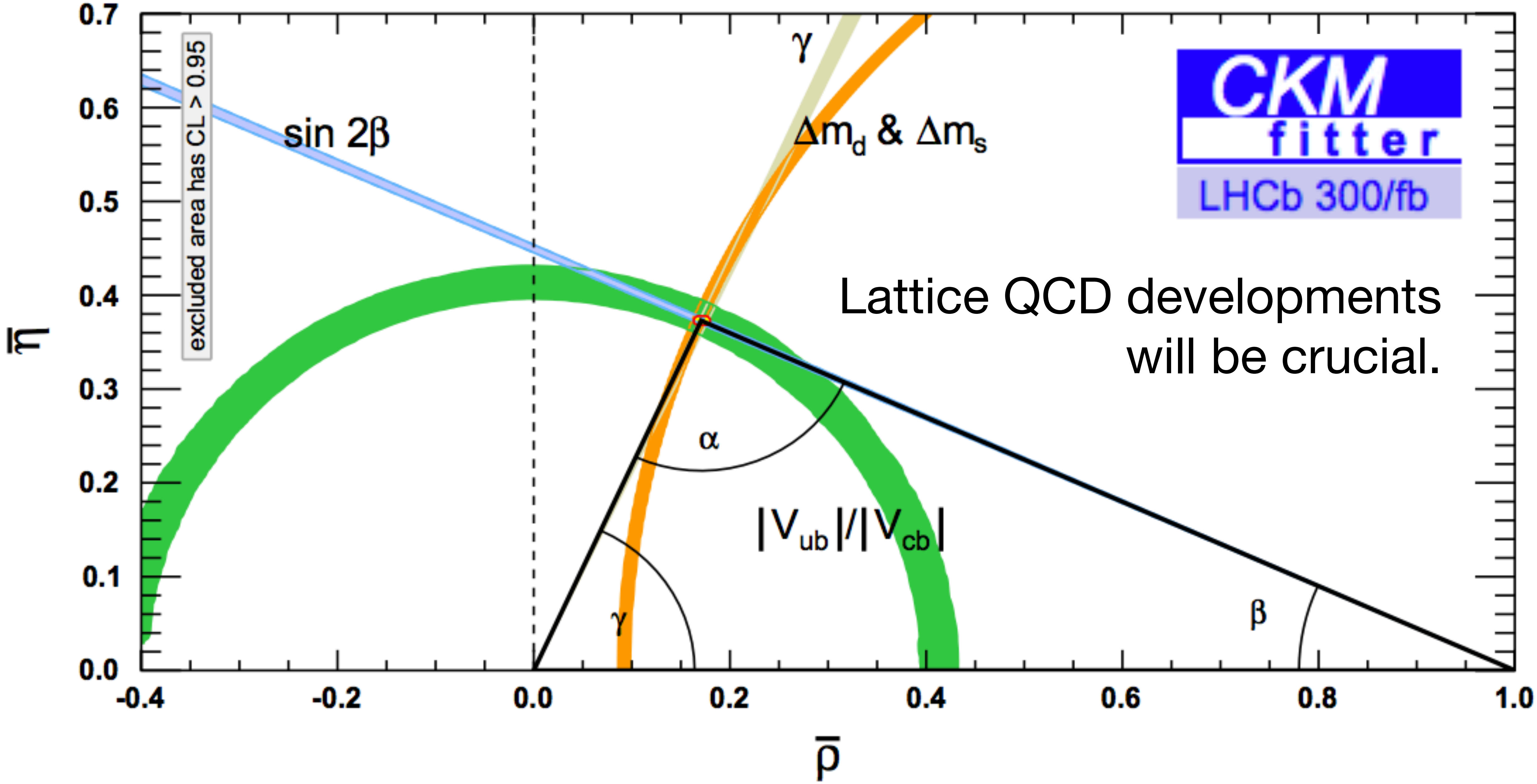


Physics highlights

Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

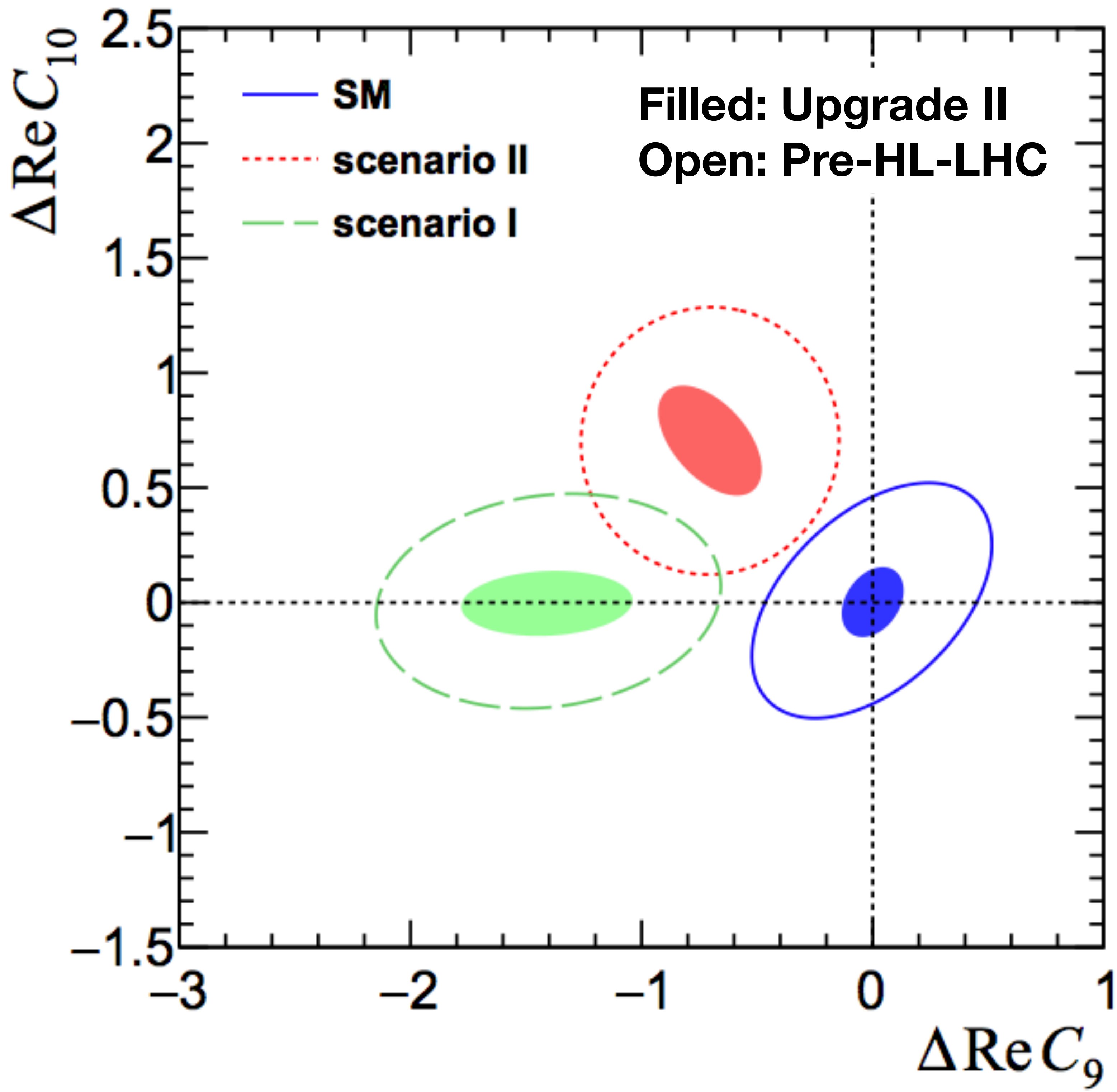
Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1<q^2<6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1<q^2<6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0\to\mu^+\mu^-)/\mathcal{B}(B_s^0\to\mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0\to\mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b\to c\ell^-\bar{\nu}_l$ **LUV studies**					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK-\pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x\sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x\sin\phi$ from $D^0\to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x\sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

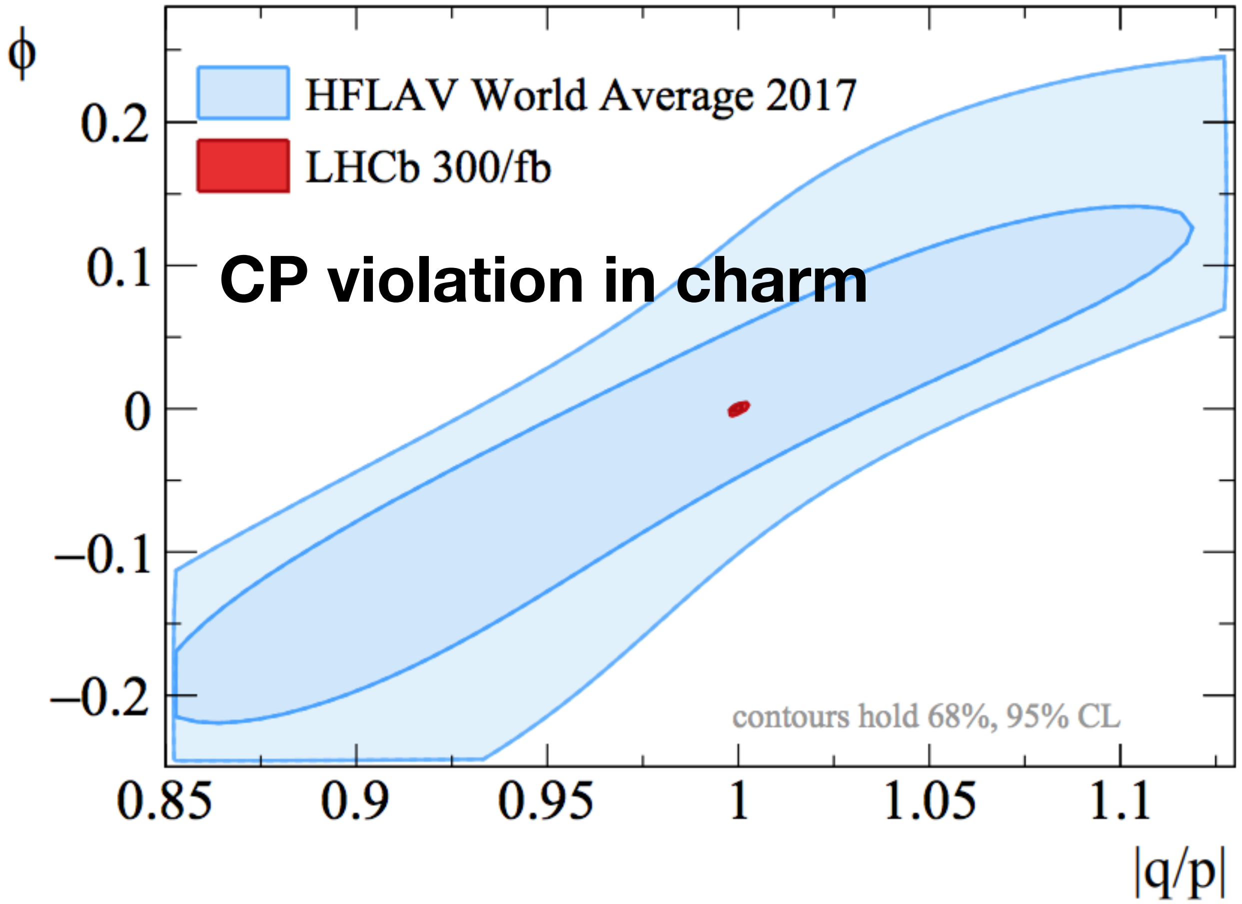
LHCb Upgrade II, example 1

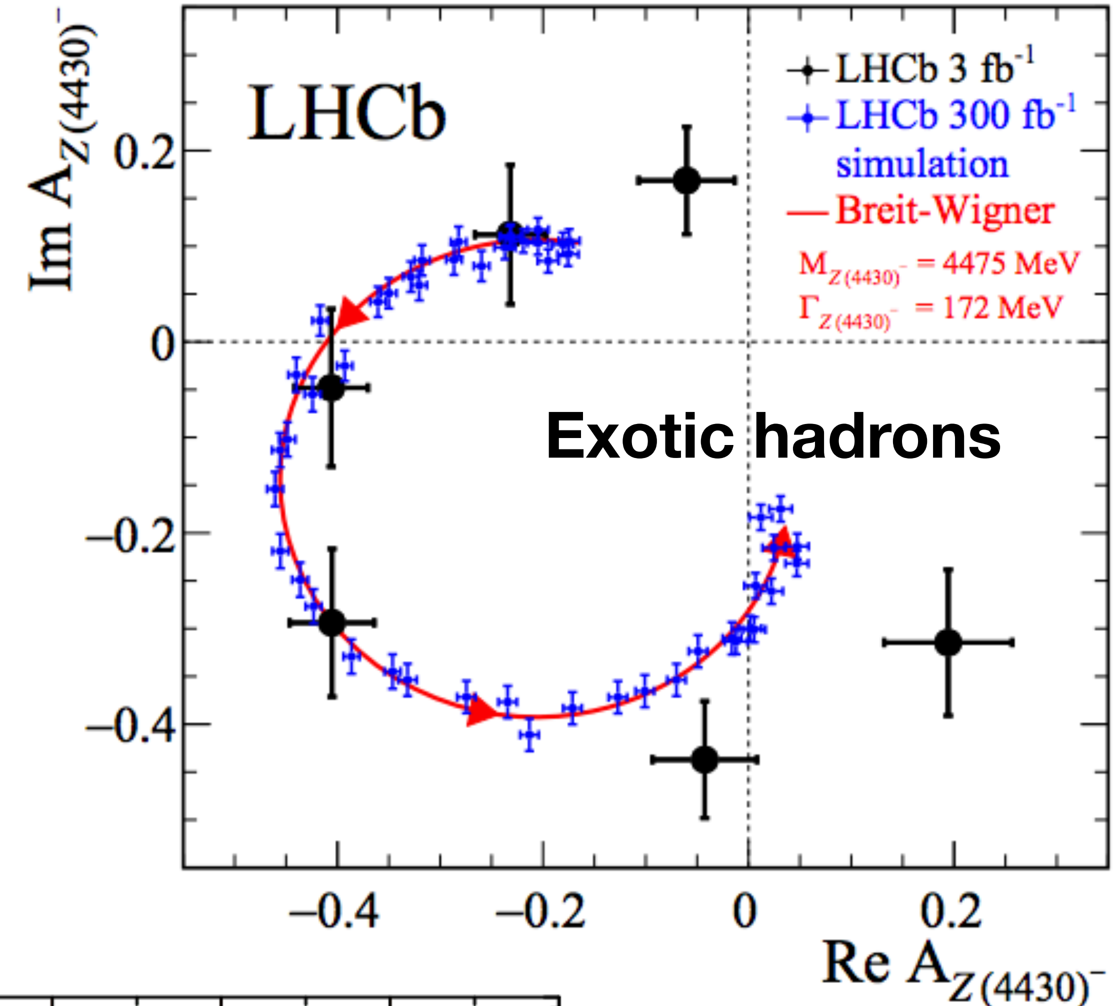


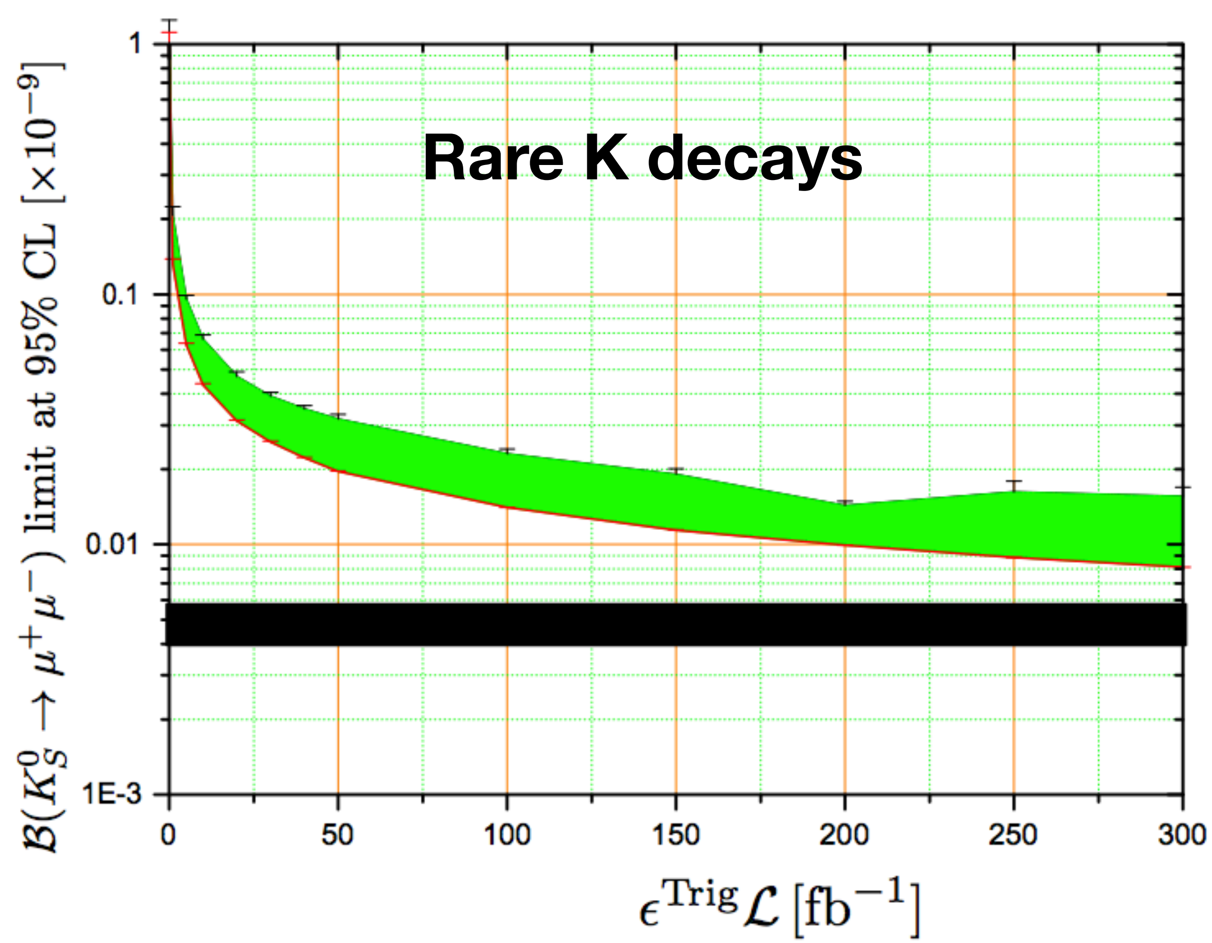
Lattice QCD developments will be crucial.

LHCb Upgrade II, example 2

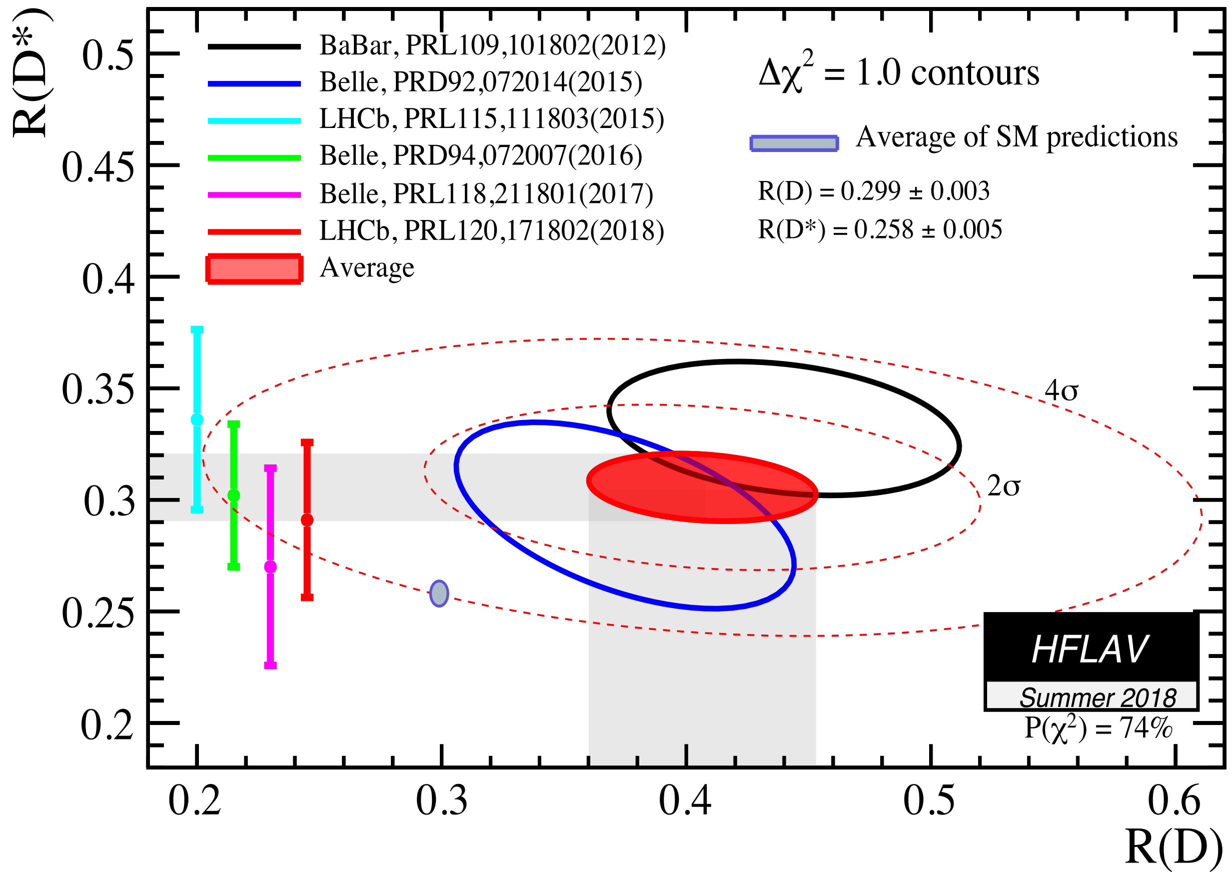


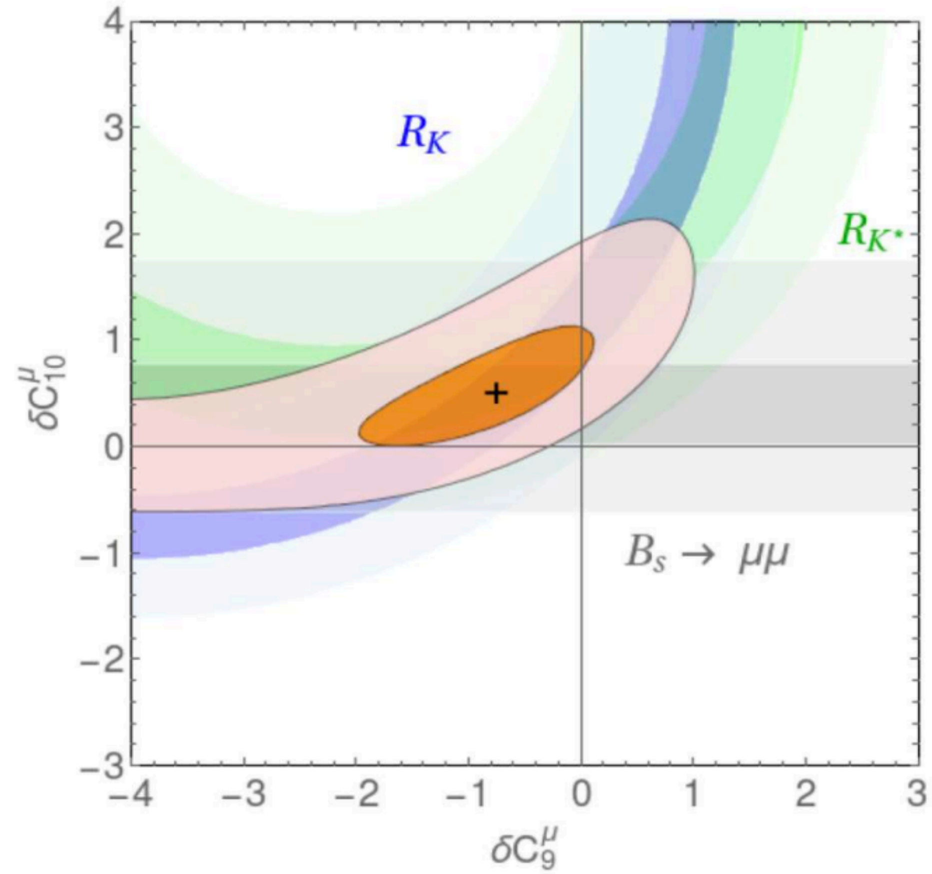

CP violation in charm
HFLAV World Average 2017
LHCb 300/fb
contours hold 68%, 95% CL
ϕ
|q/p|
0.2
0.1
0
−0.1
−0.2
0.85
0.9
0.95
1
1.05
1.1


LHCb
Exotic hadrons
LHCb 3 fb-1
LHCb 300 fb-1 simulation
Breit-Wigner
M_Z(4430)- = 4475 MeV
Γ_Z(4430)- = 172 MeV
Im A_Z(4430)-
Re A_Z(4430)-
0.2
0
−0.2
−0.4
0.2


Rare K decays
B(K0S → μ+μ−) limit at 95% CL [×10−9]
εTrig L [fb−1]
1
0.1
0.01
1E-3
0
50
100
150
200
250
300

Conclusions





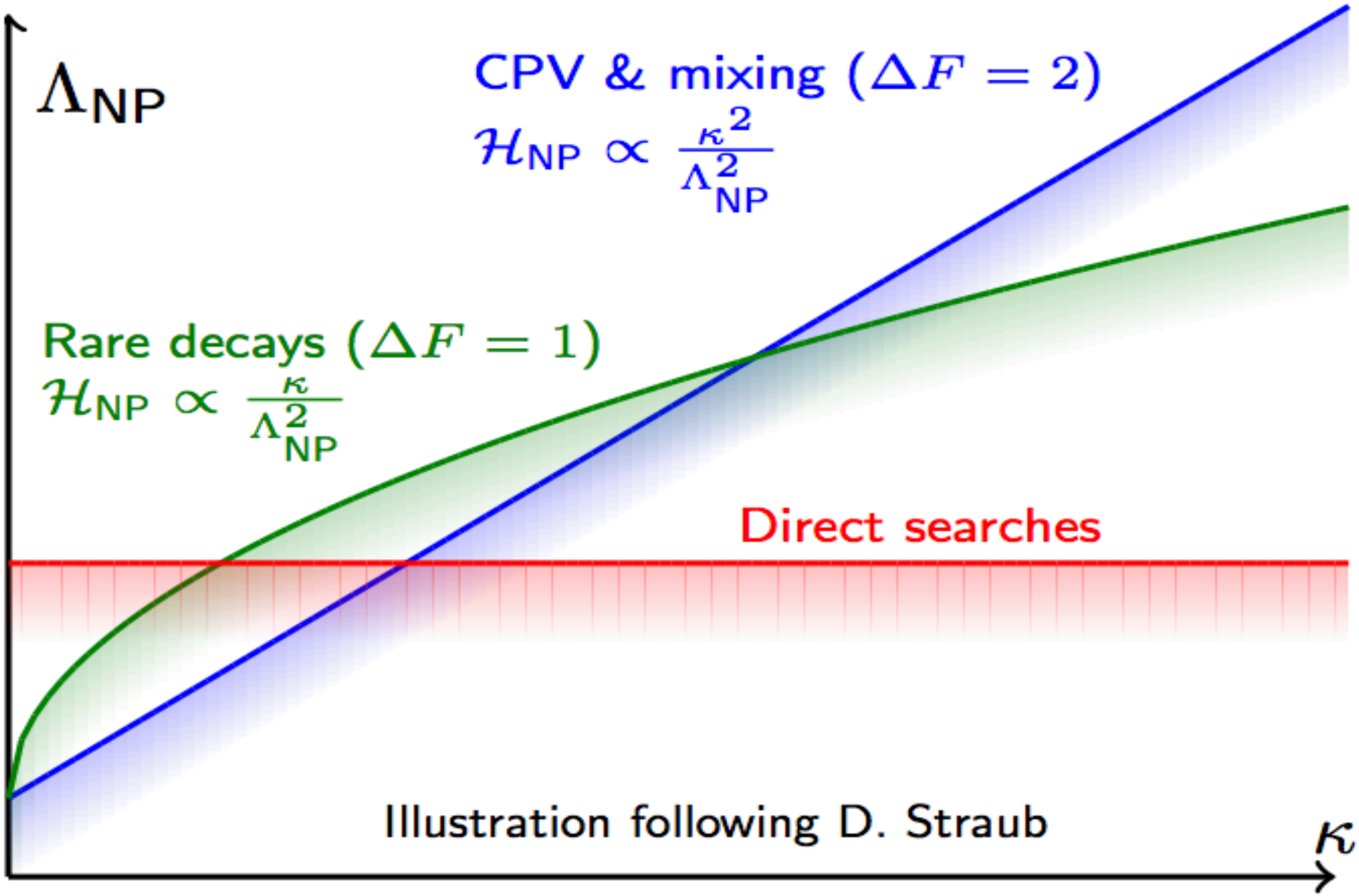
These anomalies are exciting, but inconclusive with current data.

They sit aside powerful null results in B→μμ and B mixing.

LHCb Run-II data *could* be sufficient to claim a discovery.

The LHCb upgrades are required to fully exploit the HL-LHC capabilities in characterisation of the anomalies.

Backup slides follow from here…


Λ_{NP}
CPV & mixing ($\Delta F = 2$)
$\mathcal{H}_{NP} \propto \frac{\kappa^2}{\Lambda_{NP}^2}$
Rare decays ($\Delta F = 1$)
$\mathcal{H}_{NP} \propto \frac{\kappa}{\Lambda_{NP}^2}$
Direct searches
Illustration following D. Straub
κ

K*μμ angles