

Rare *beauty* and *charm* decays



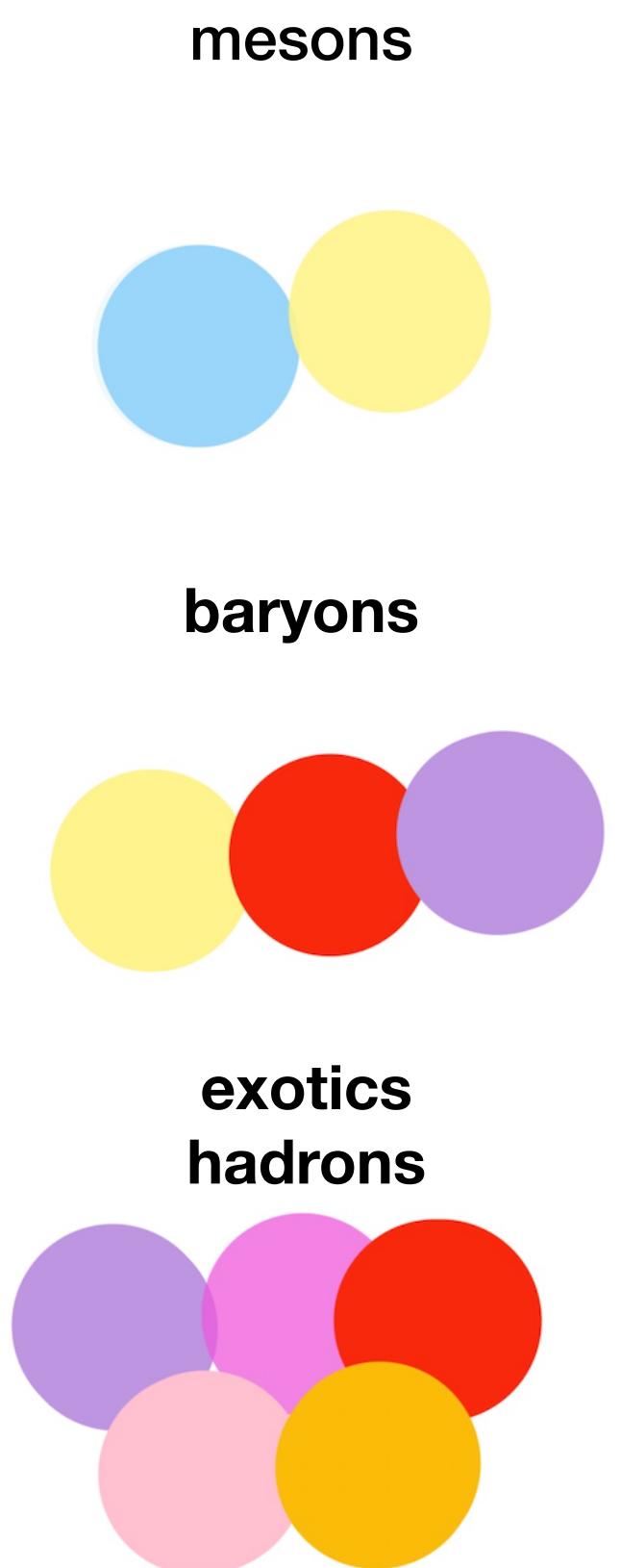
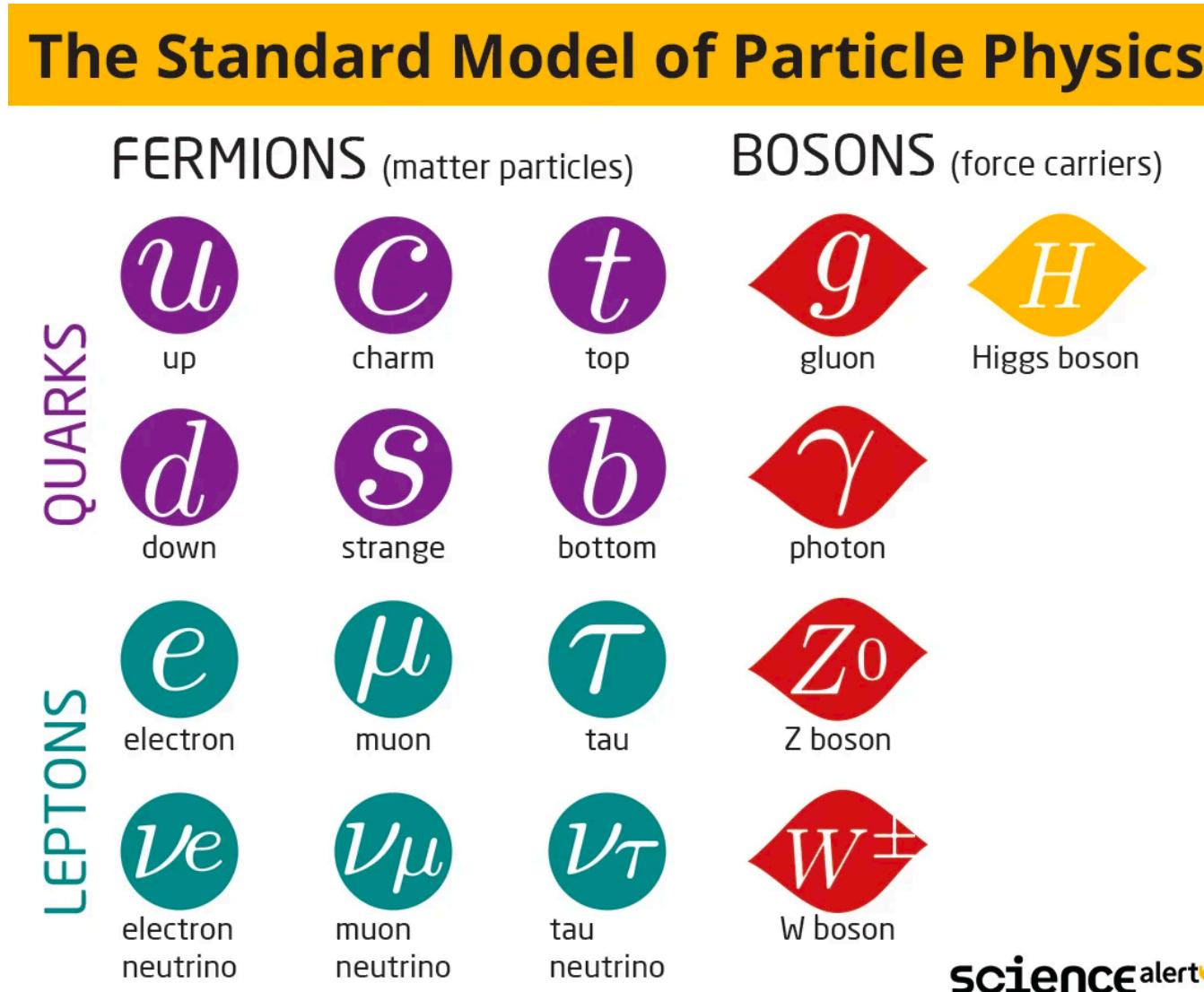
 @PrPetitesMains

Yasmine Amhis
on behalf of LHCb with material from
ATLAS, BaBar, Belle, Belle II, BES III, CMS and NA62.

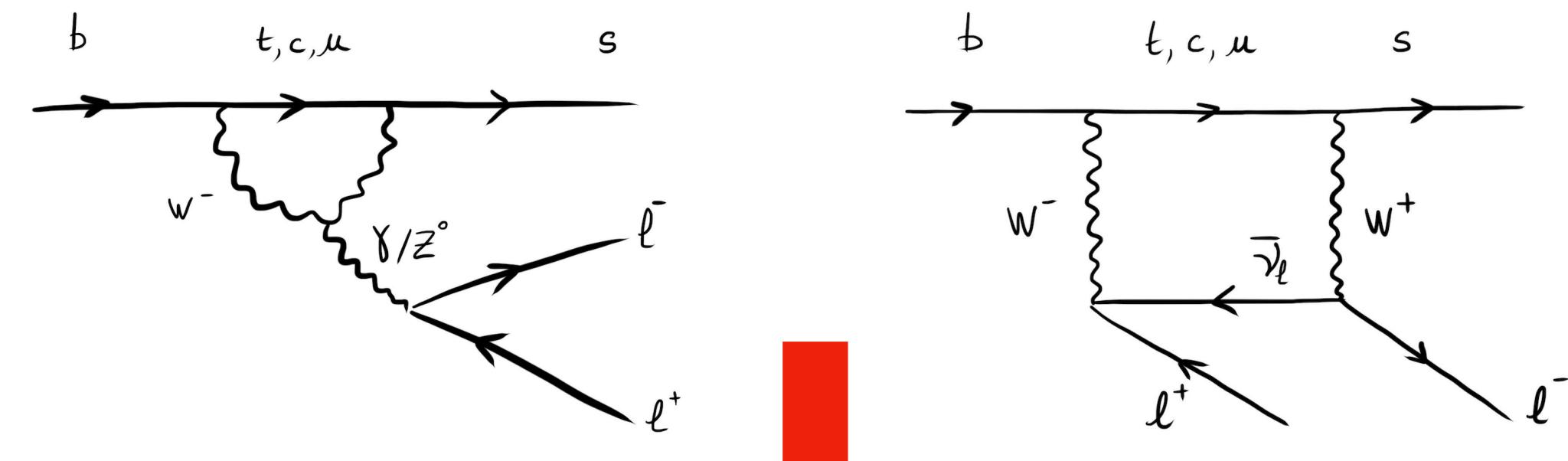
IJCLab

One the goals of flavour physics

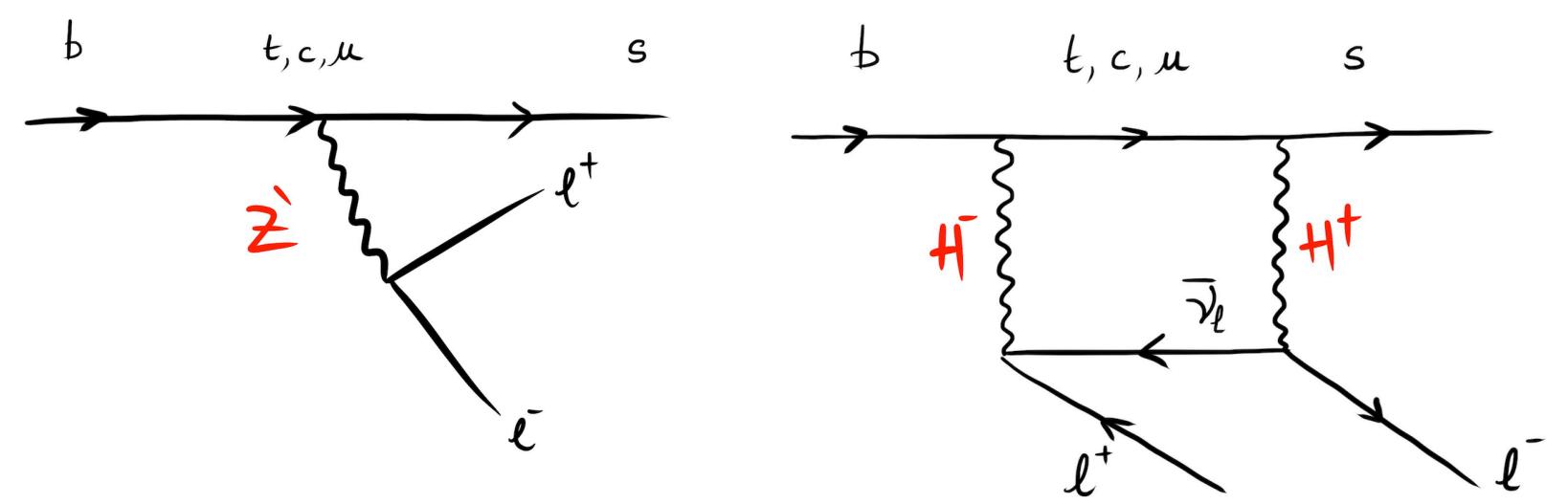
What we know



Standard Model

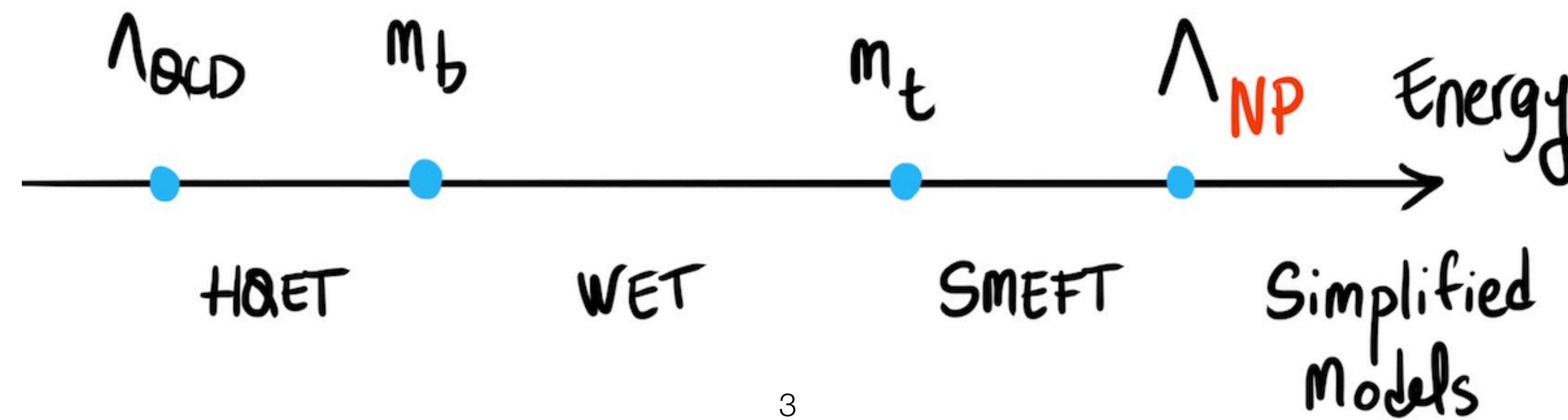
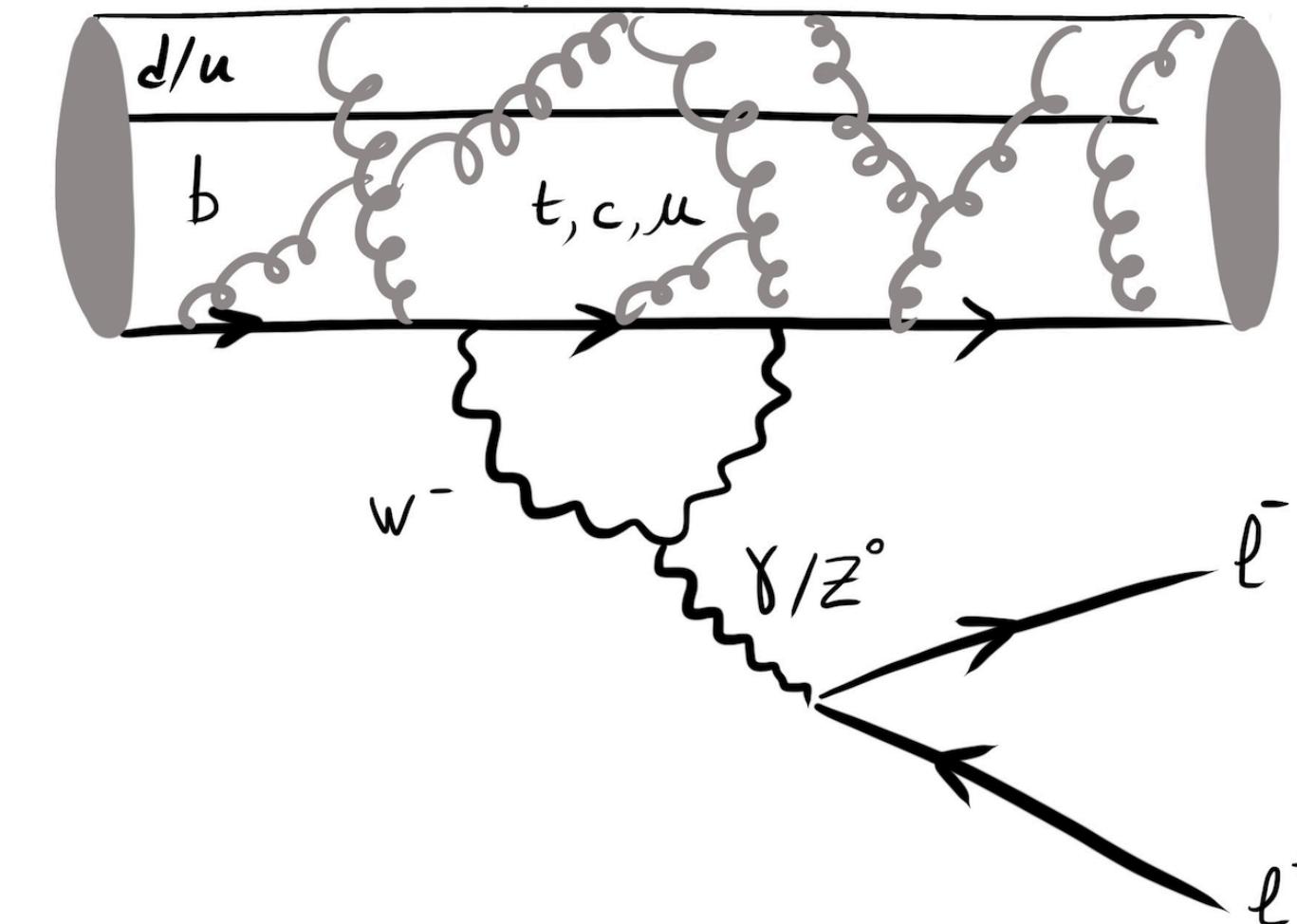
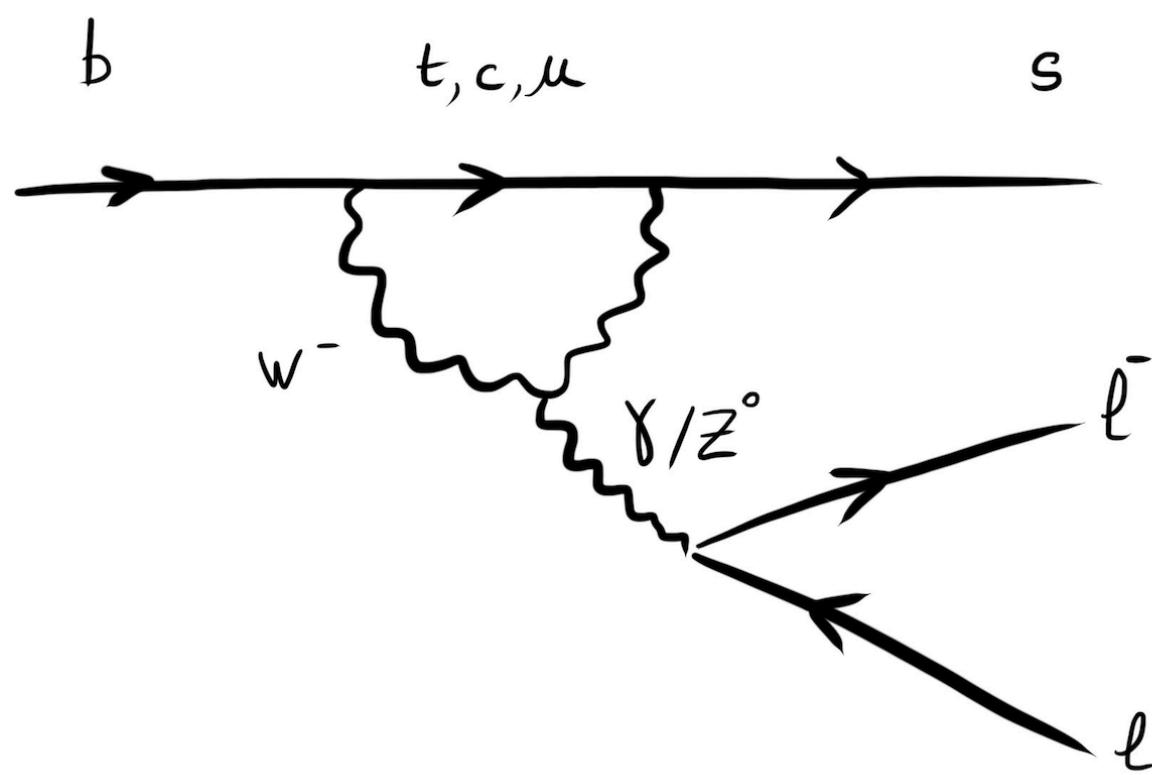


New Physics

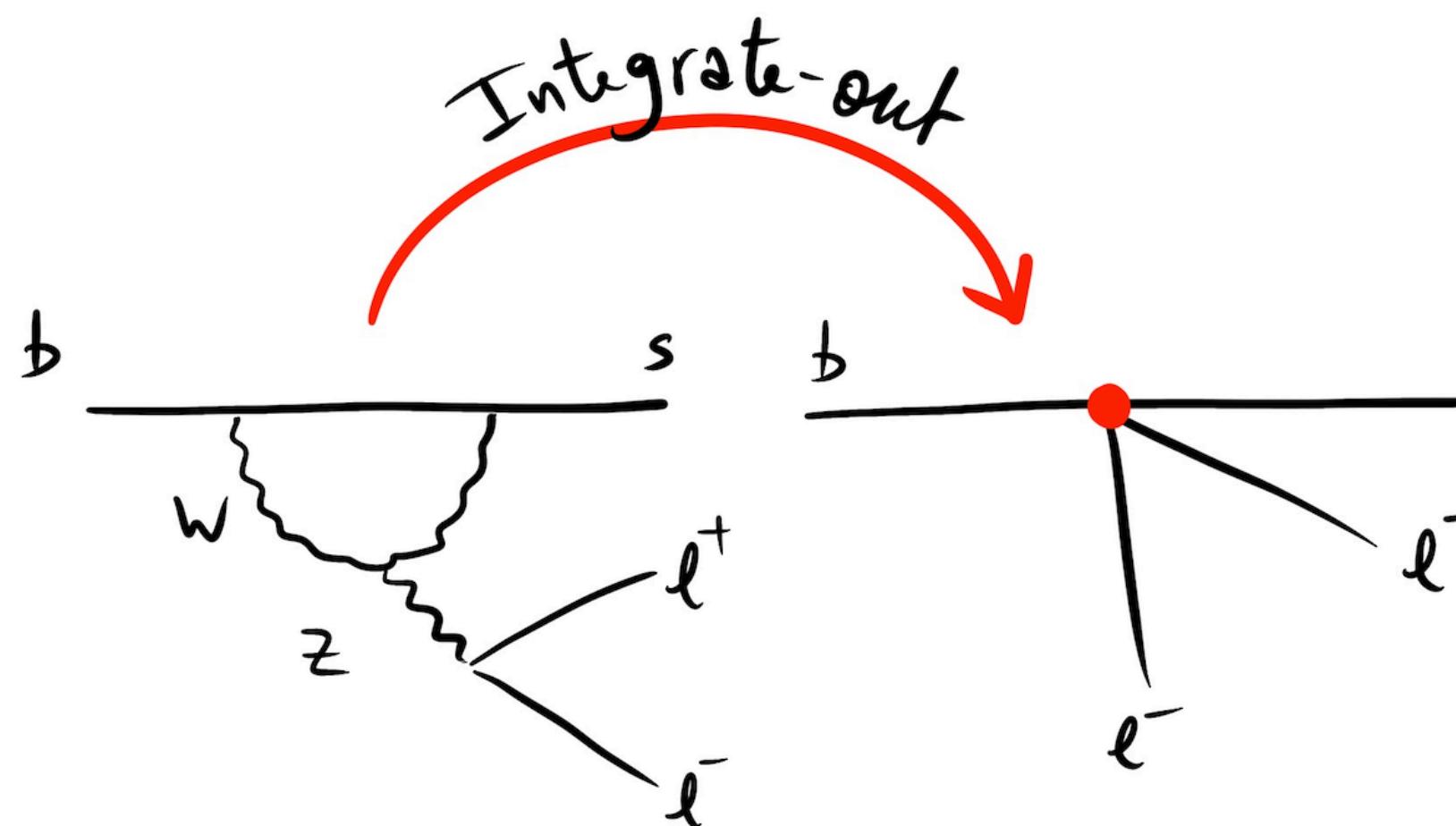


searches in an indirect way

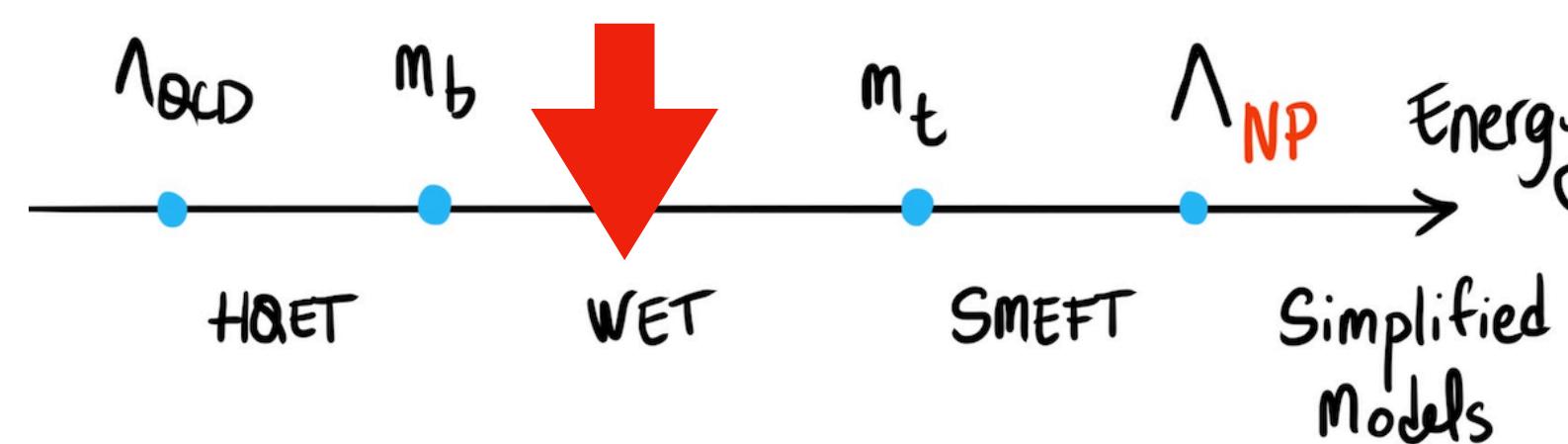
Effective Field Theory



Effective Field Theory

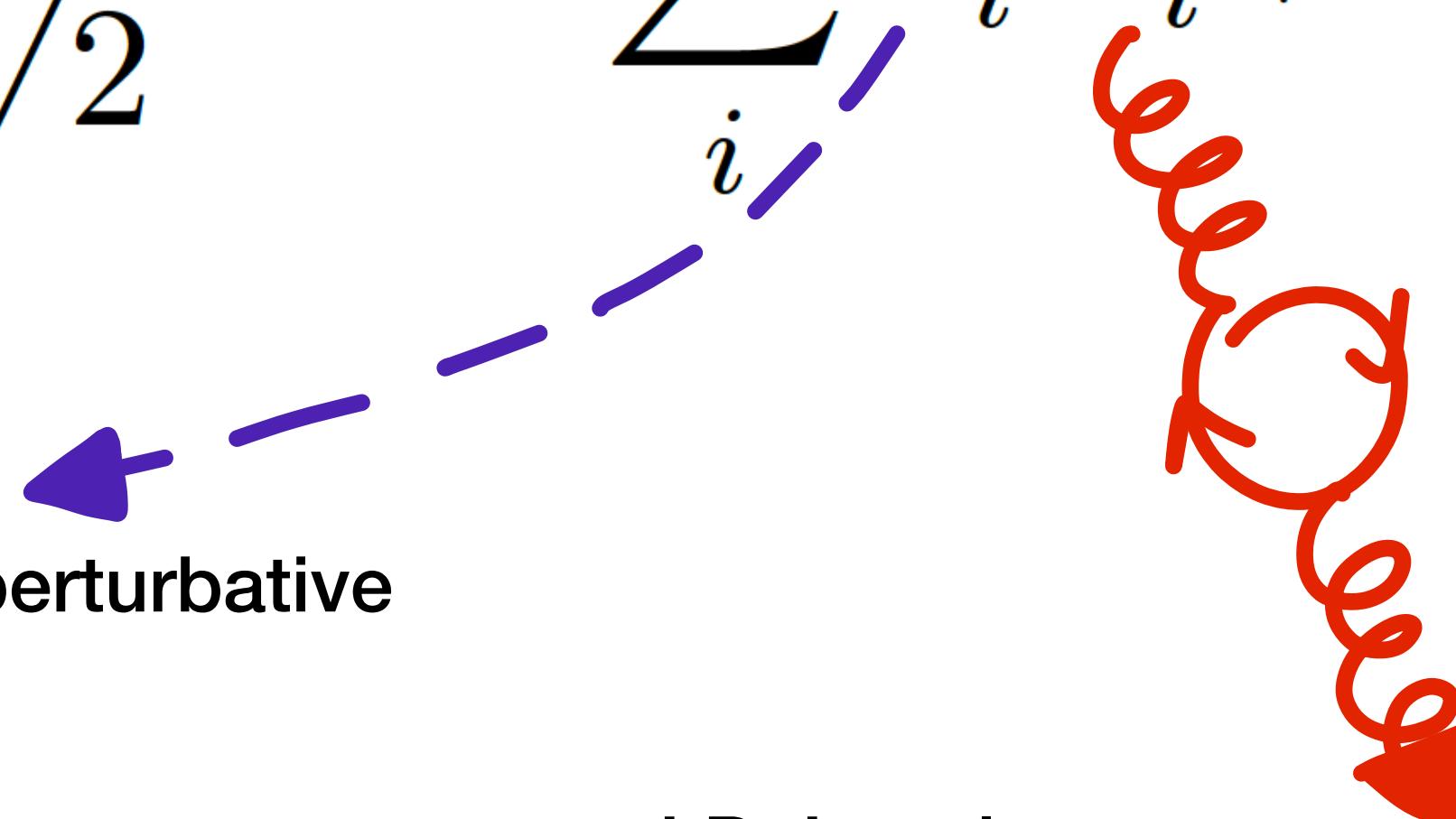


$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + h.c,$$



Effective Field Theory

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i O_i + h.c,$$

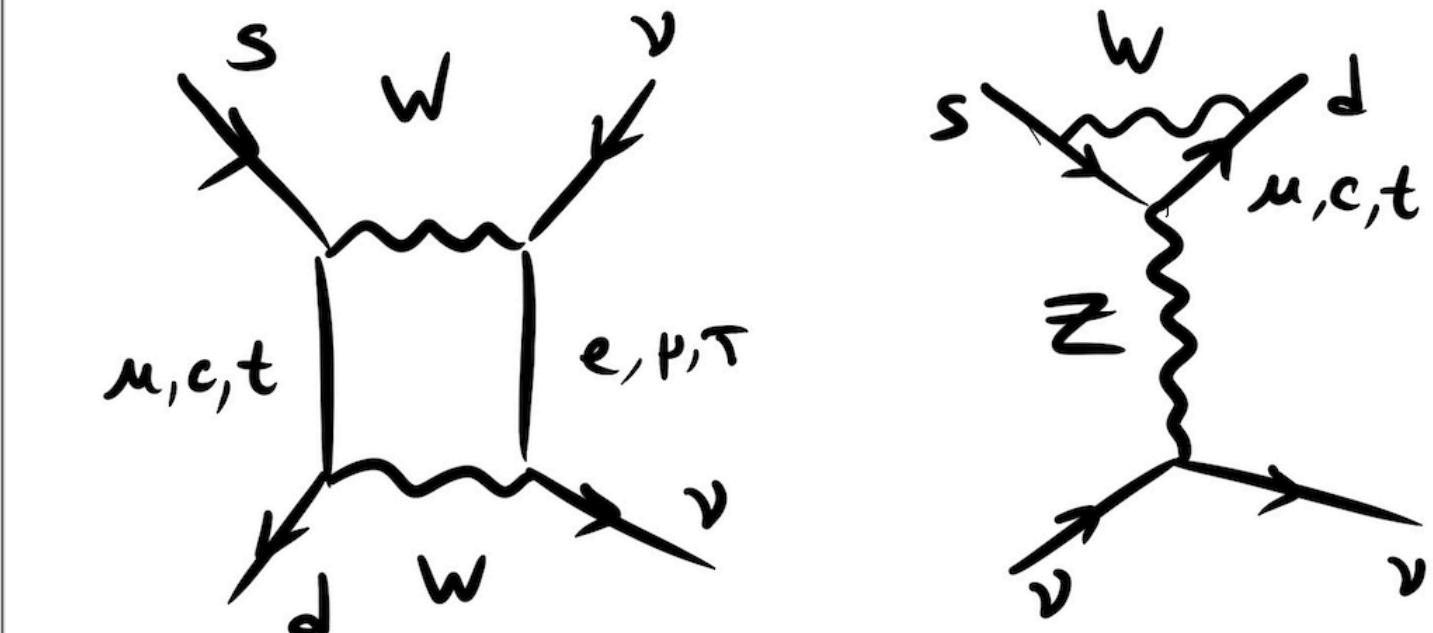
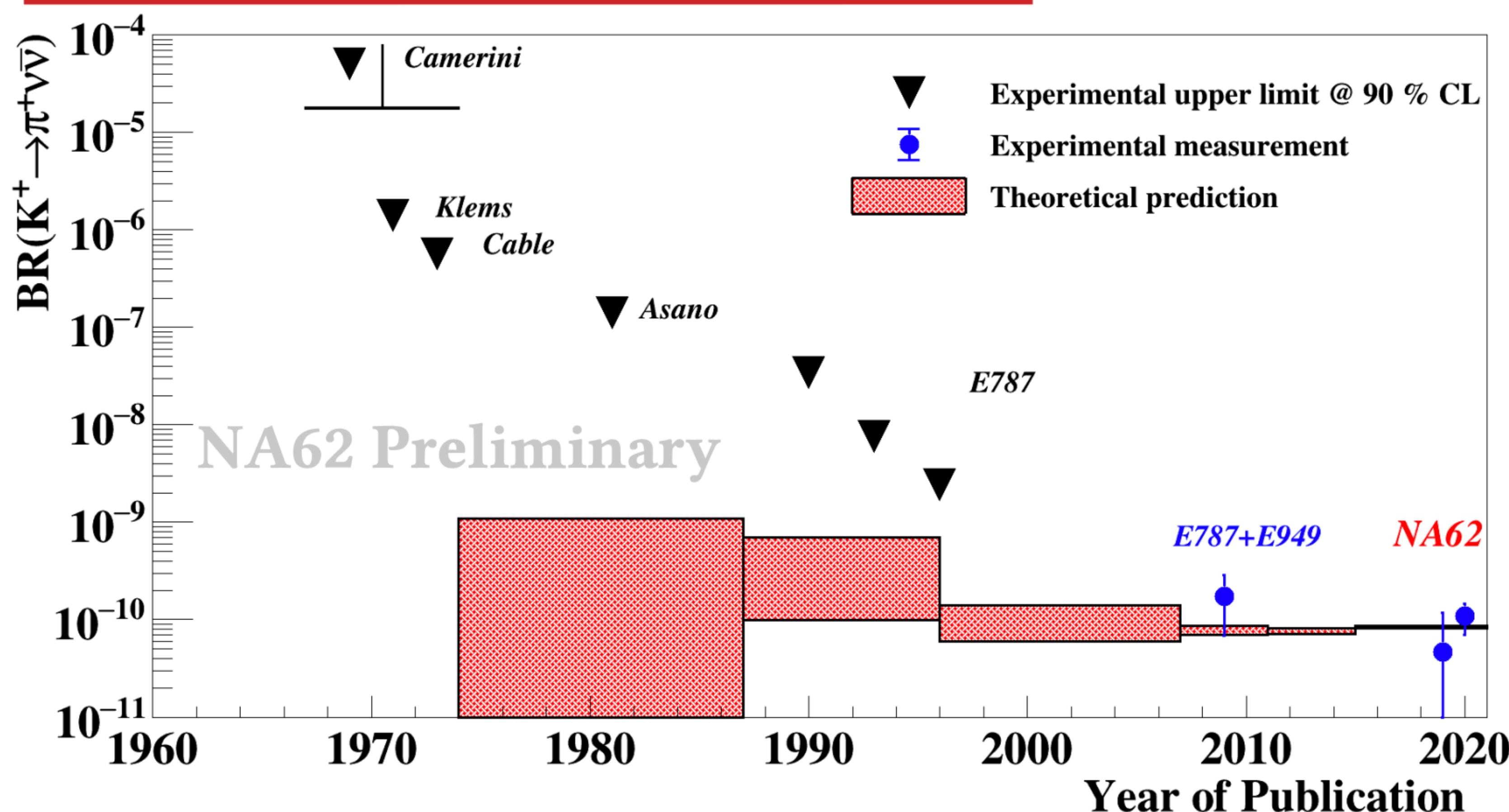


SD: Wilson coefficients + perturbative

LD: Local operators + non perturbative
(LCSR, Lattice, etc.)

Too good not to mention !

$K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay: Historical context



see slides !

Roadmap for today's talk

$B^0 \rightarrow K^* \mu^+ \mu^-$ angular



$B^+ \rightarrow K^+ \mu^+ \mu^-$ angular

$B^0 \rightarrow K^* \gamma$ preview

$B^0 \rightarrow K^* e^+ e^-$ angular

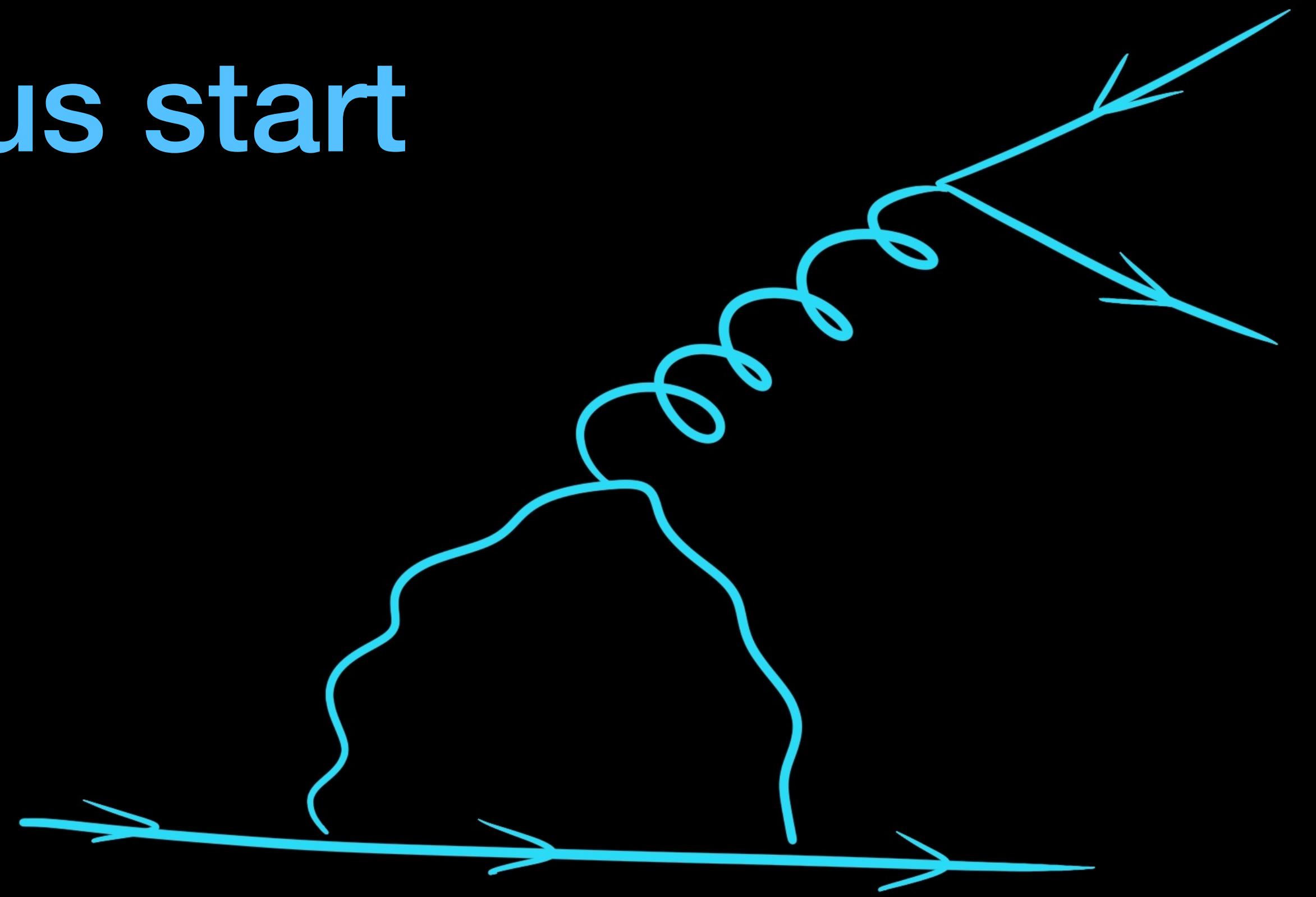
$B_{(s)} \rightarrow l^+ l^-$



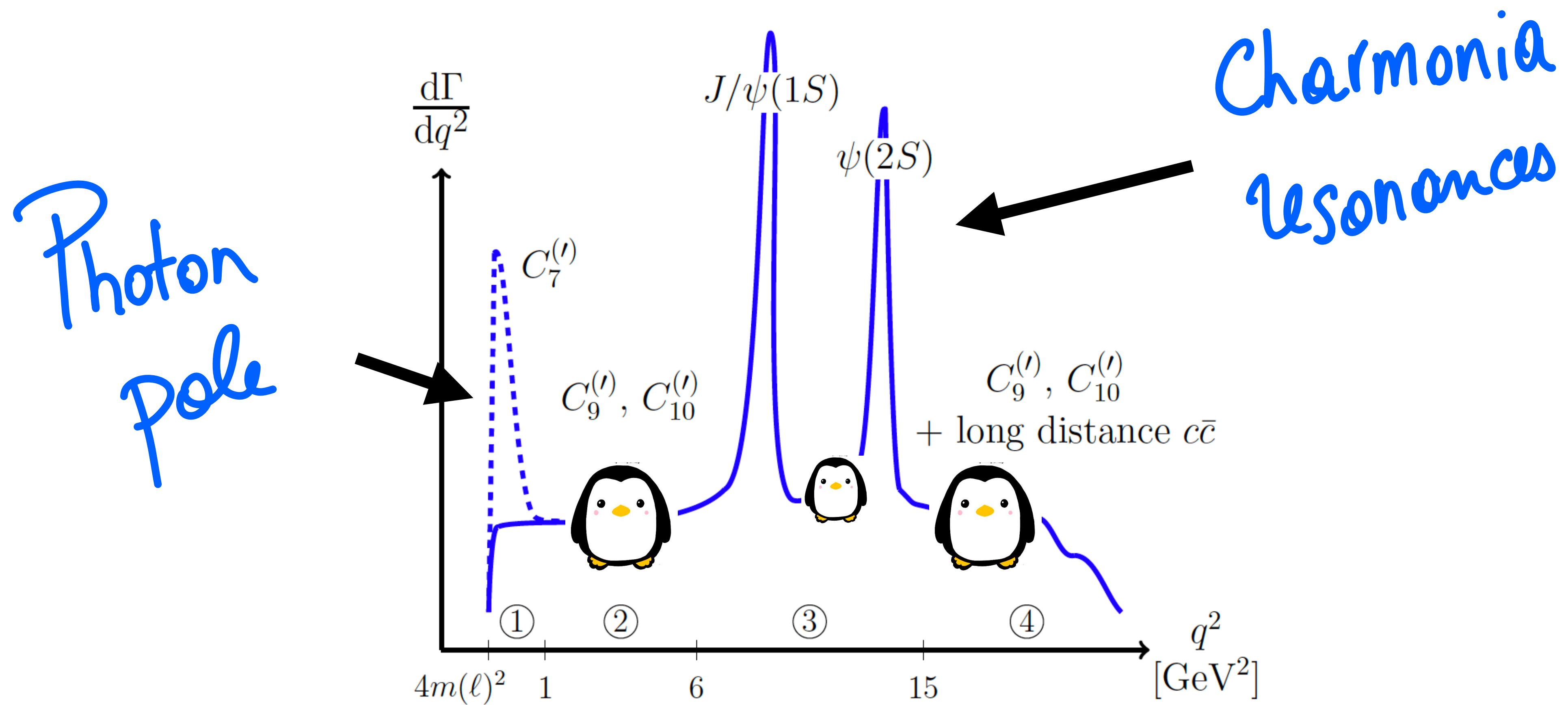
LFV decays

Rare and forbidden charm

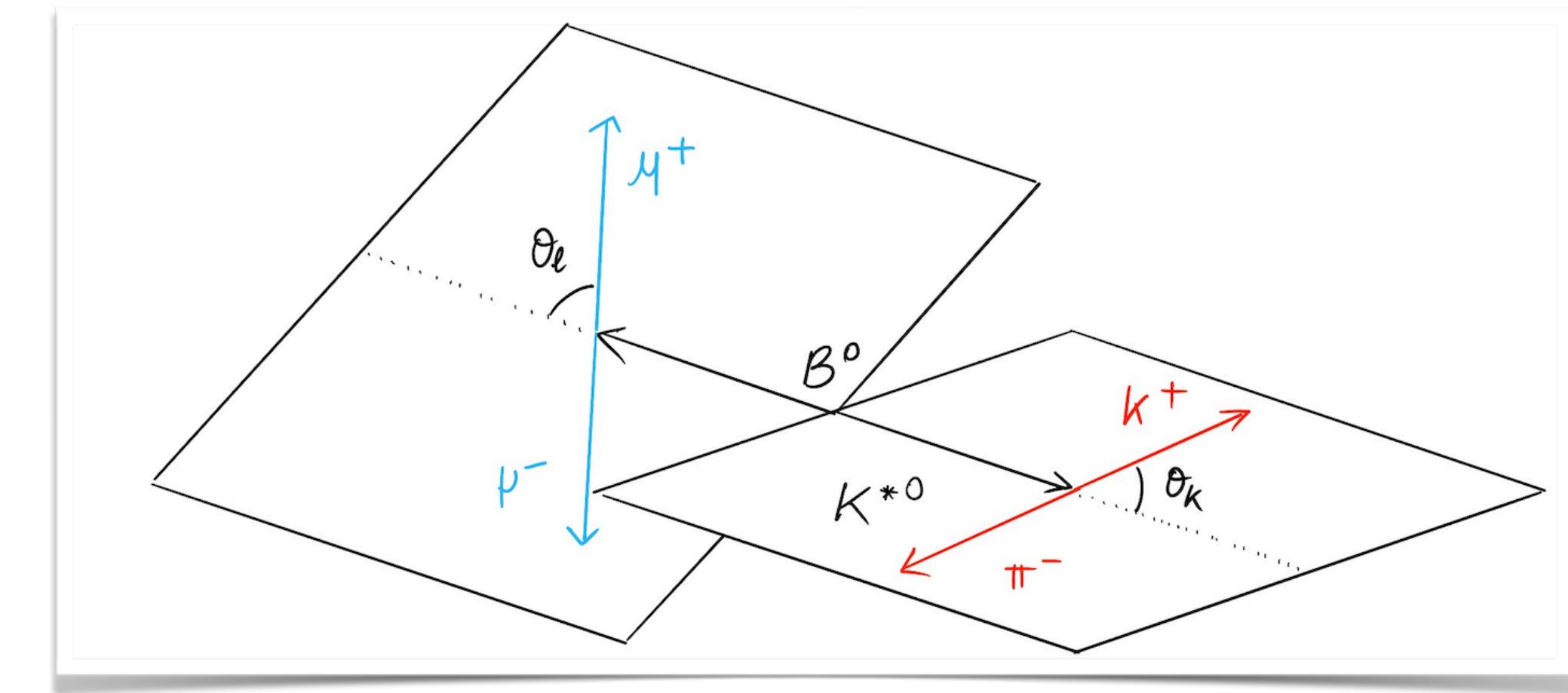
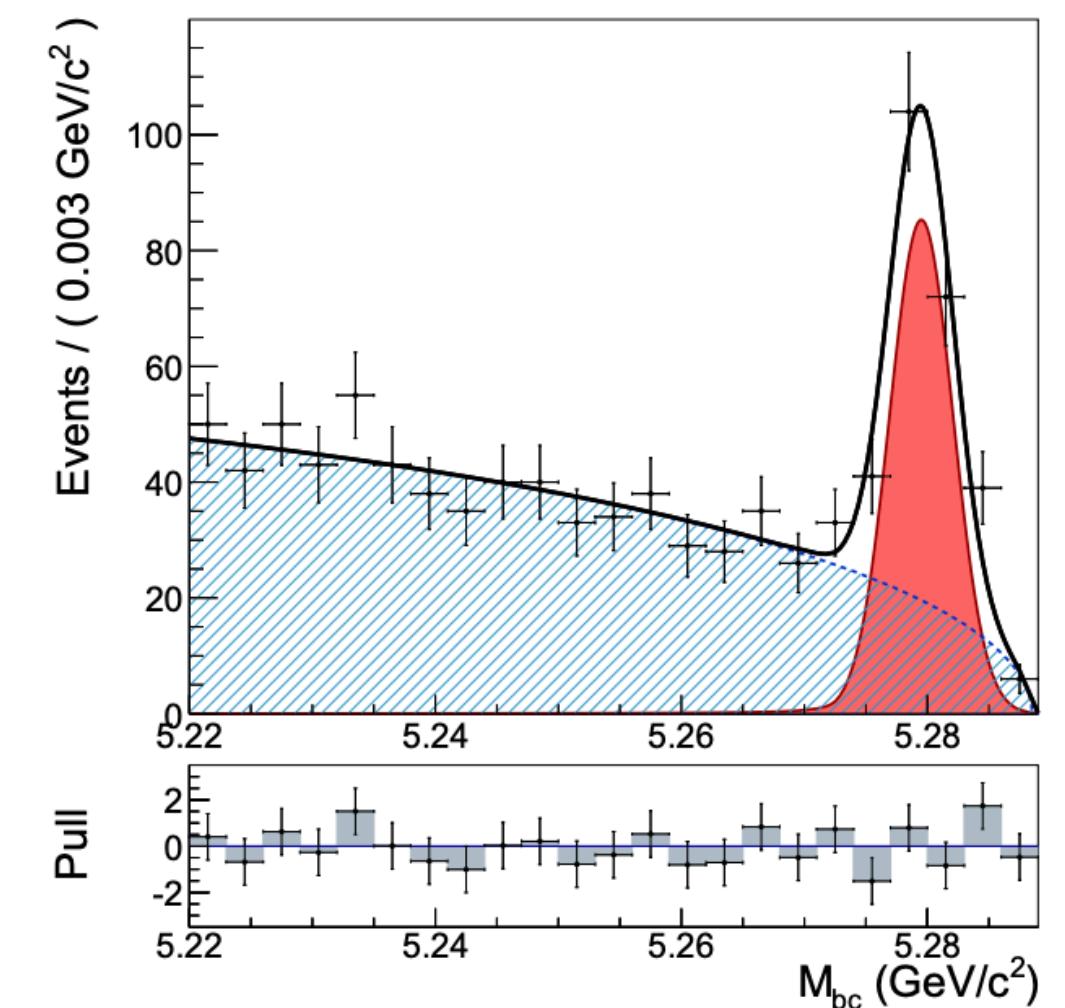
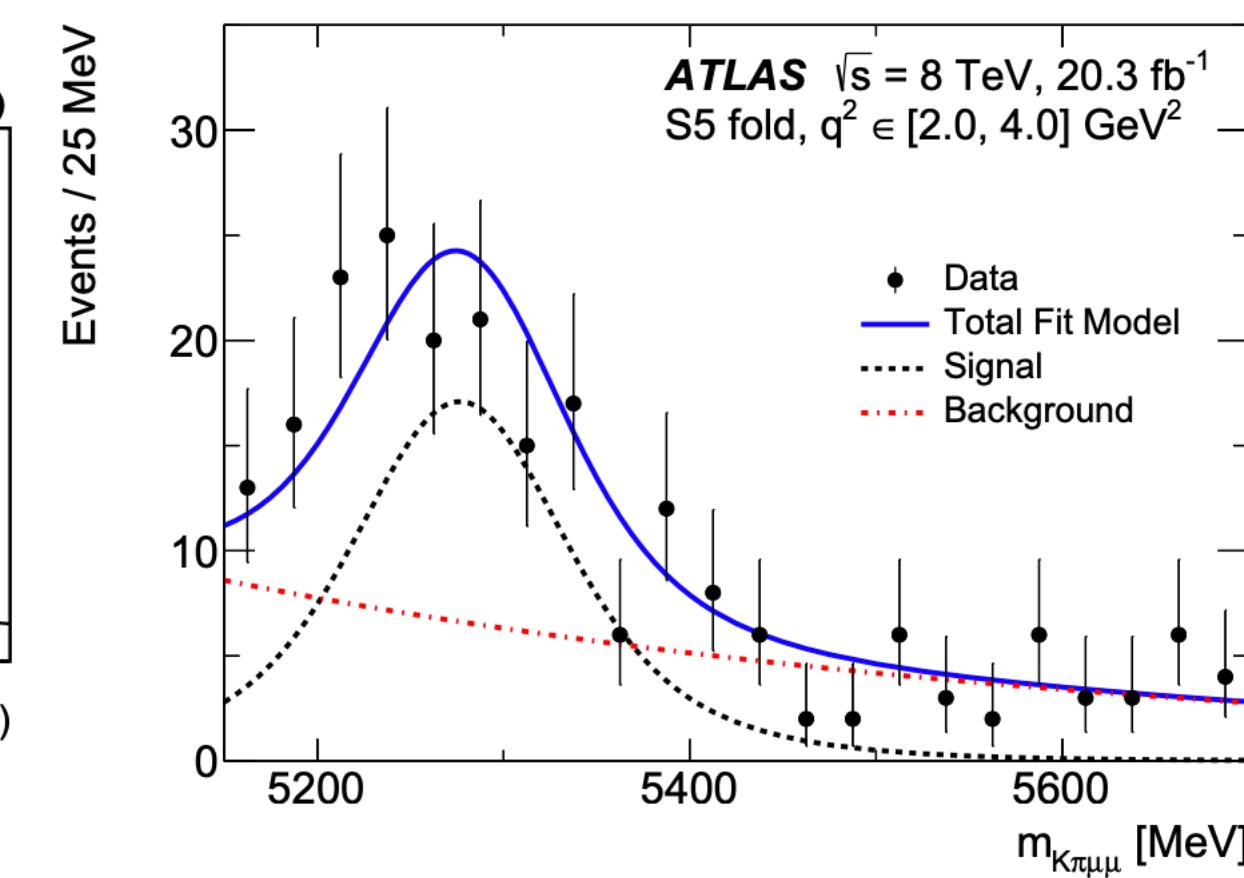
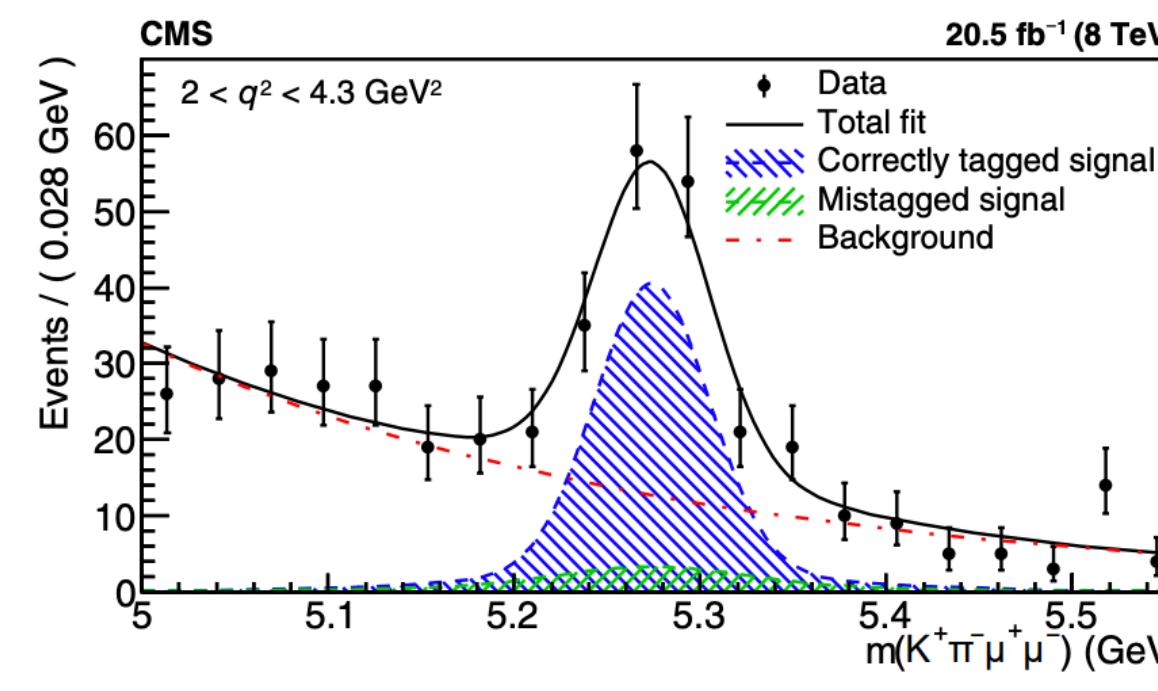
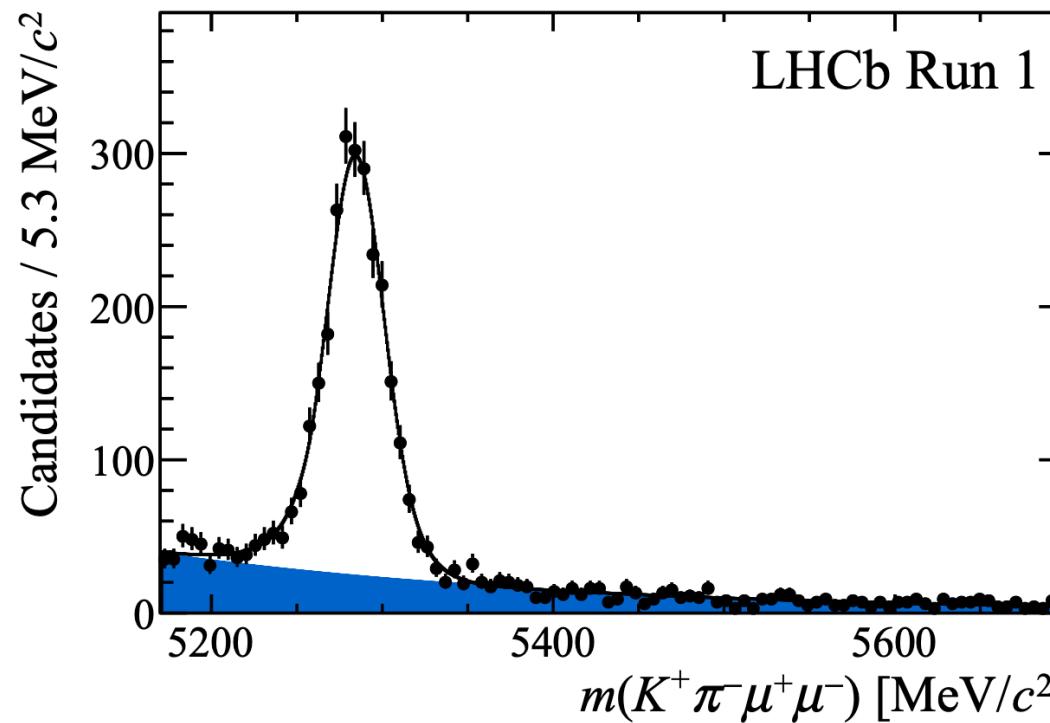
Let us start



$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \lambda^{\text{CKM}} \sum_i C_i \mathcal{O}_i + h.c,$$



$b \rightarrow s\ell^+\ell^-$ angular analyses



LHCb PRL 125 (2020) 011802
 CMS PRL B781 (2018) 517
 ATLAS JHEP 10 (2018) 048
 Belle PRL 118 (2017) 111801

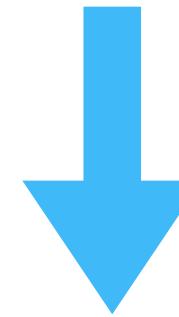
Many observables:

- * Decay rates or ratio of lepton flavours.
- * Angular asymmetries.
- * decay rates as a function of angles of decay products give access to large range of obs. (with small theory uncertainties).
- * Helps to deduce nature of New Physics models.

$B^0 \rightarrow K^* \mu^+ \mu^-$ Angular expressions

$$\left. \frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\vec{\Omega}} \right|_P = \frac{9}{32\pi} \left[\begin{aligned} & \frac{3}{4}(1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K \\ & + \frac{1}{4}(1 - F_L) \sin^2 \theta_K \cos 2\theta_l \\ & - F_L \cos^2 \theta_K \cos 2\theta_l + S_3 \sin^2 \theta_K \sin^2 \theta_l \cos 2\phi \\ & + S_4 \sin 2\theta_K \sin 2\theta_l \cos \phi + S_5 \sin 2\theta_K \sin \theta_l \cos \phi \\ & + \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_l + S_7 \sin 2\theta_K \sin \theta_l \sin \phi \\ & + S_8 \sin 2\theta_K \sin 2\theta_l \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_l \sin 2\phi \end{aligned} \right]$$

S_i 8 CP-averaged observables are extracted from the fit



Optimise the observables which are expressed in an different basis P_i

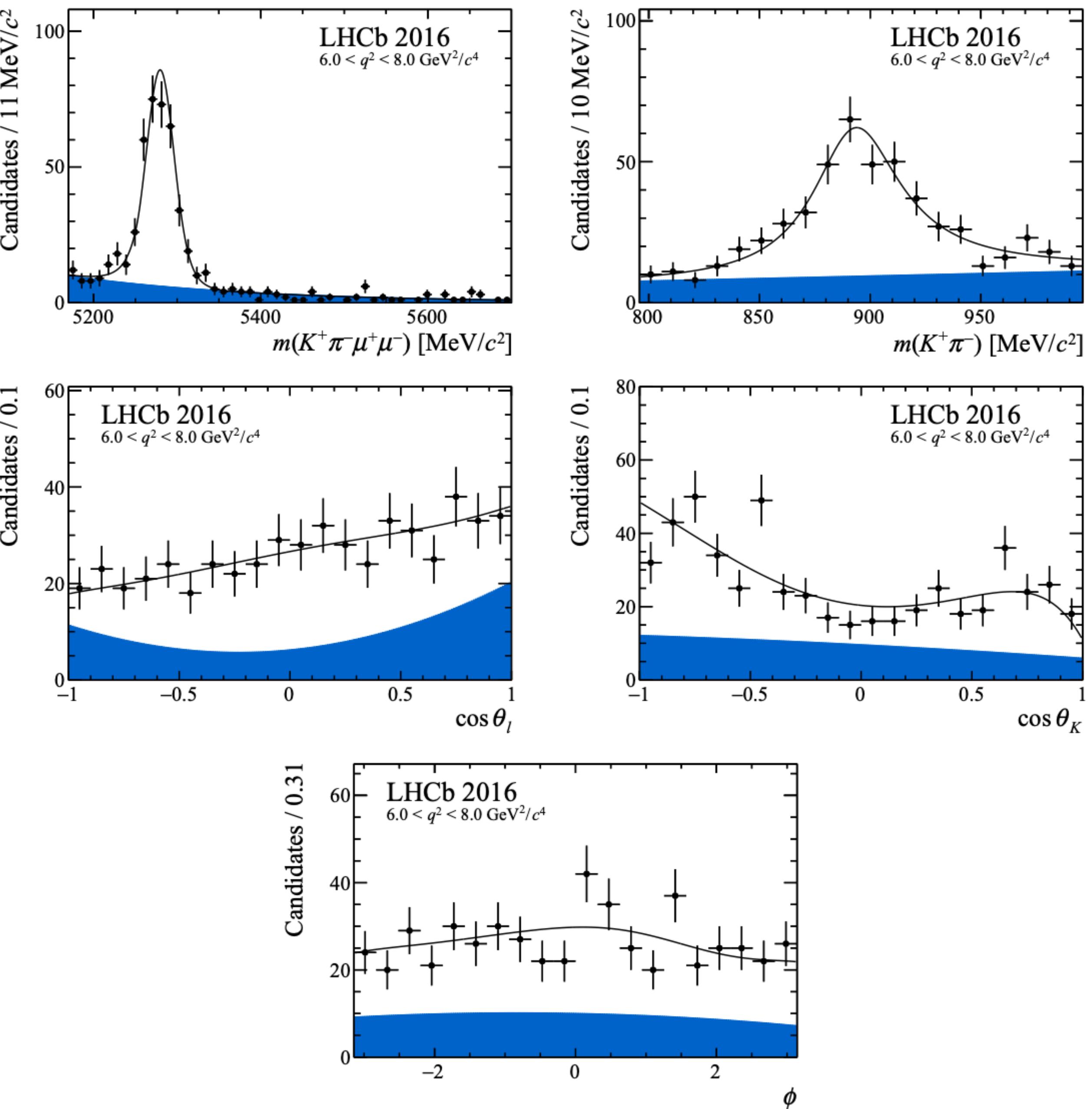
$$P'_{4,5,8} = \frac{S_{4,5,8}}{\sqrt{F_L(1 - F_L)}}$$

$$P'_6 = \frac{S_7}{\sqrt{F_L(1 - F_L)}}$$

The fit is performed in both basis S_i and P_i !

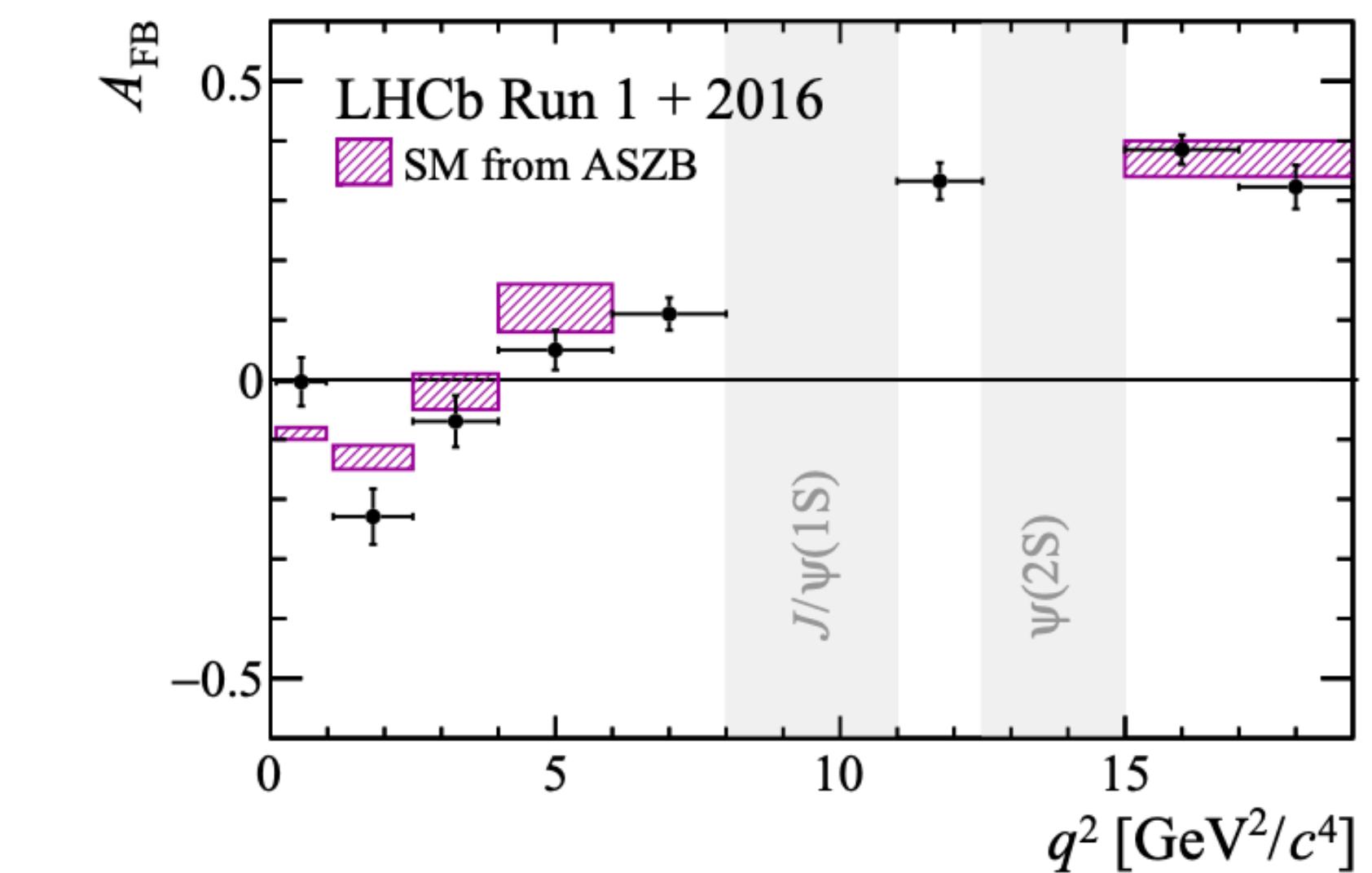
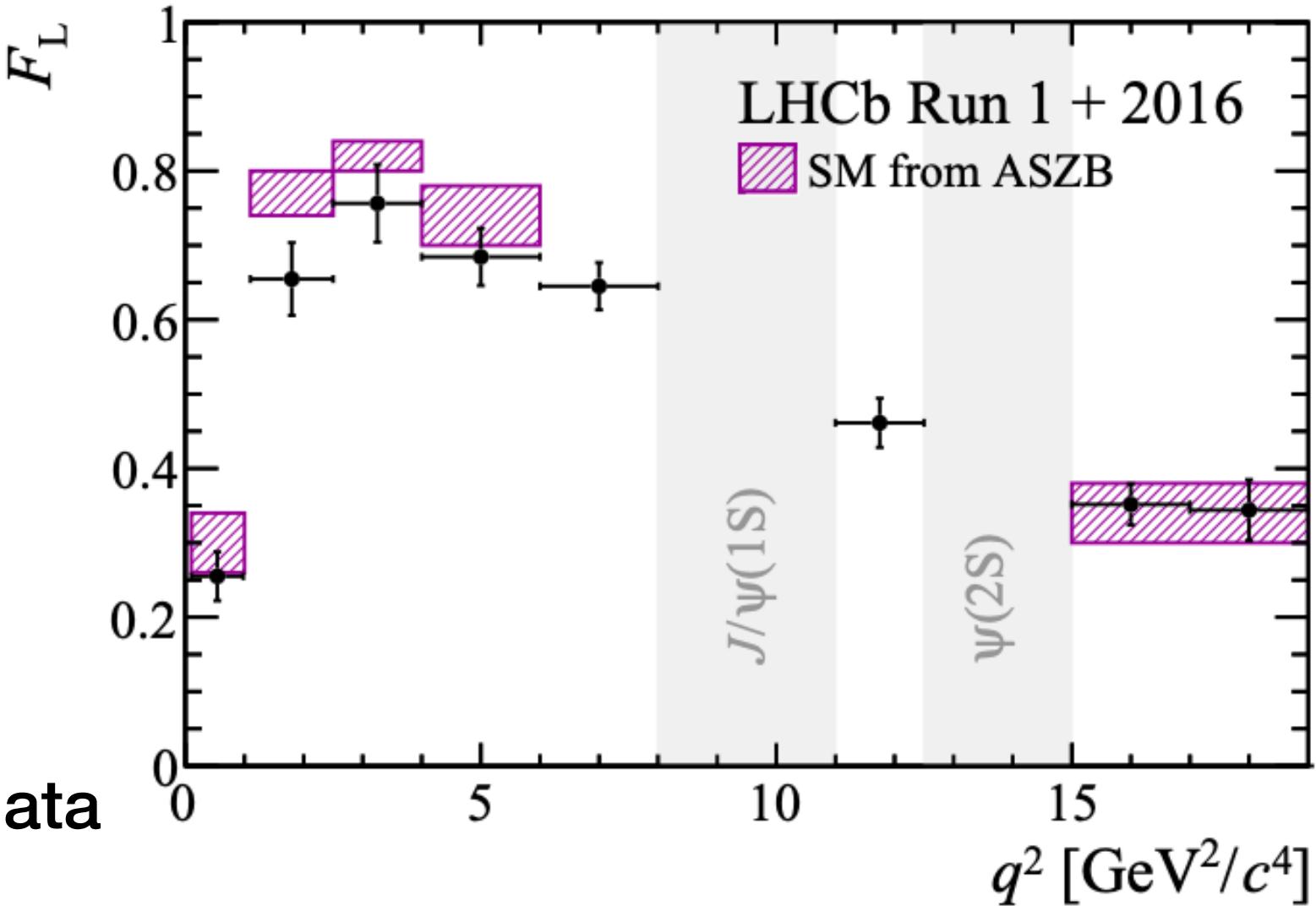
$$B^0 \rightarrow K^* \mu^+ \mu^-$$

- 5D fit B and K^* mass + angles.
- Use 8 q^2 bins.
- 4D (q^2 and angles) acceptance correction is convoluted into the fit PDF
- simultaneous fit of Run 1 & 2016 data samples.



$B^0 \rightarrow K^* \mu^+ \mu^-$

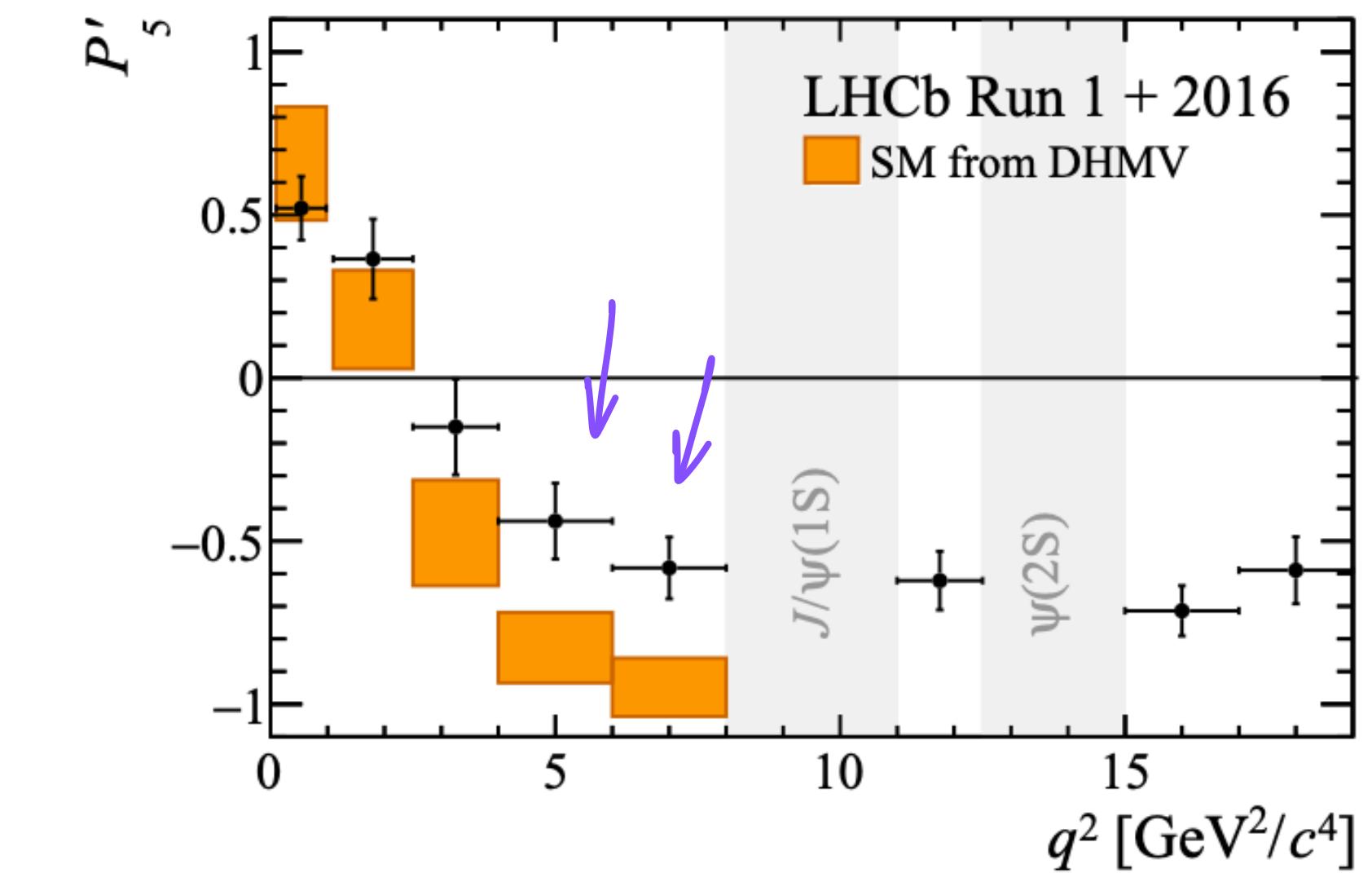
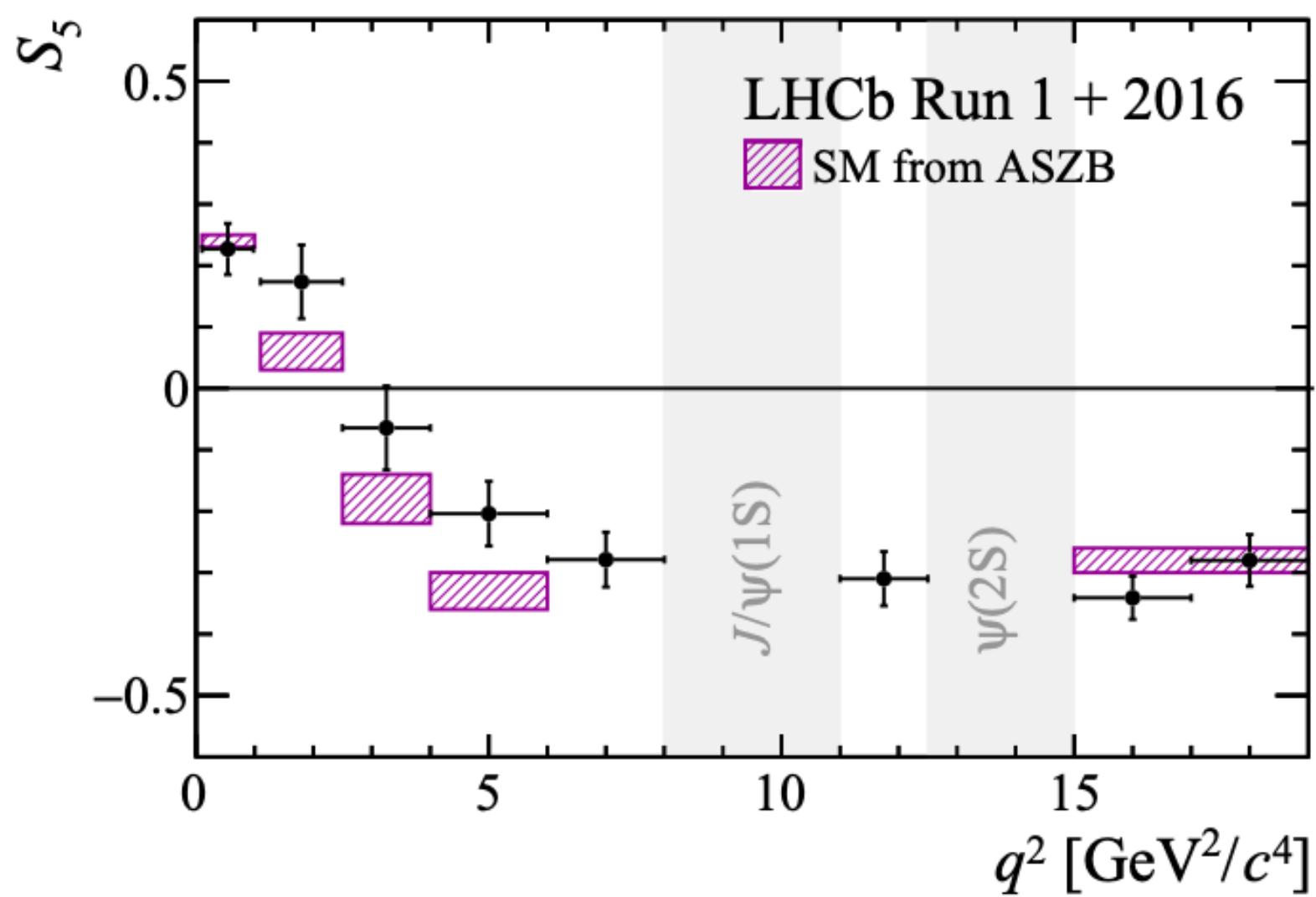
Phys. Rev. Lett. 125 (2020) 011802



Very good agreement between Run1 & 2016 data

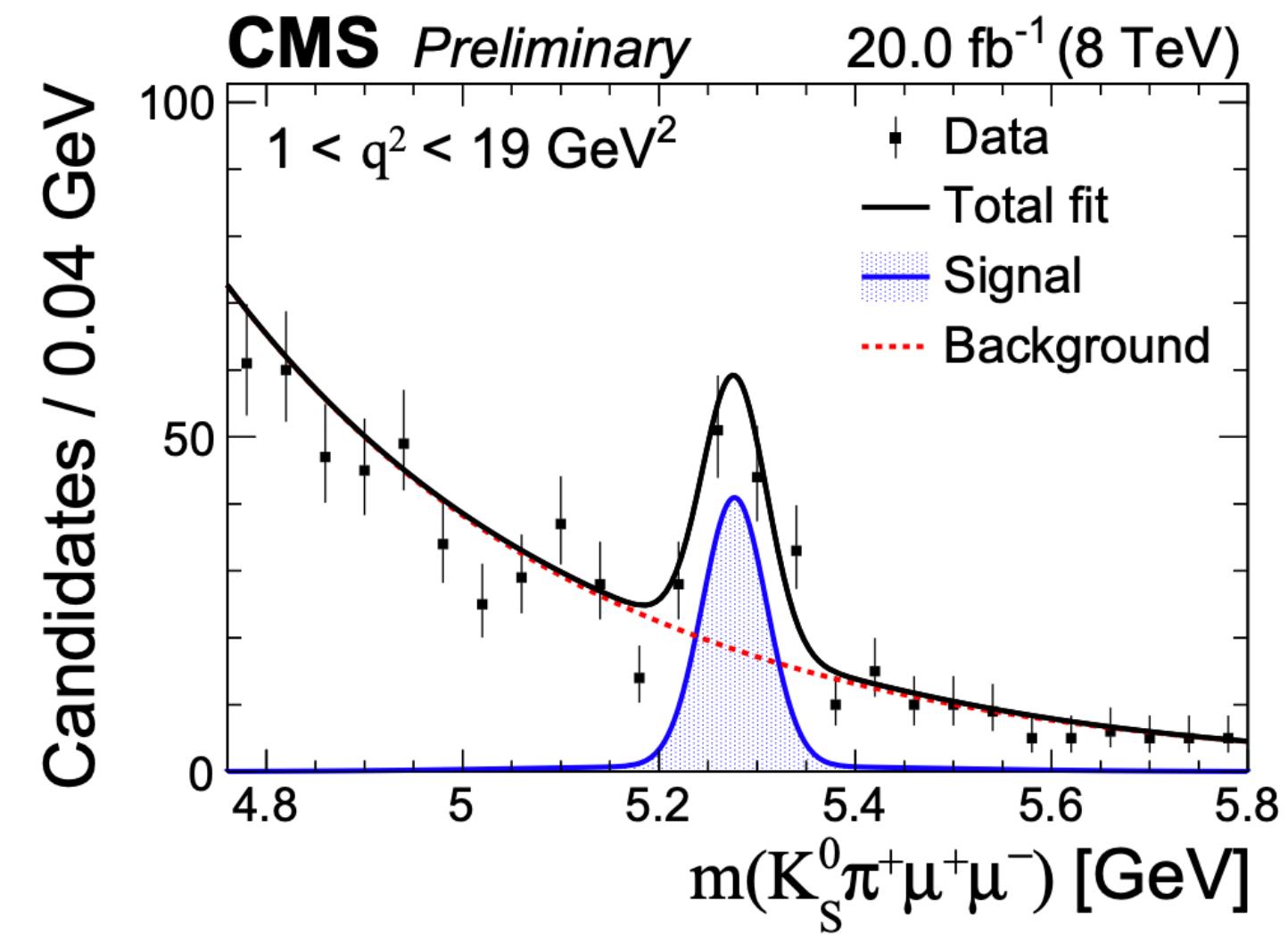
Local discrepancies between 2.5 and 2.9
for P'_5 in middle q^2 bins.

Global fits to the Wilson coefficients
Indicate tension of 2.9 standard deviations !



Theory predictions from
S. Descotes Genon et al. JHEP 12 (2014) 125,
A. Khojamirian et al. JHEP 09 (2010) 089

$B^+ \rightarrow K^{*+}(\rightarrow K_S\pi)\mu^+\mu^-$ Angular analysis

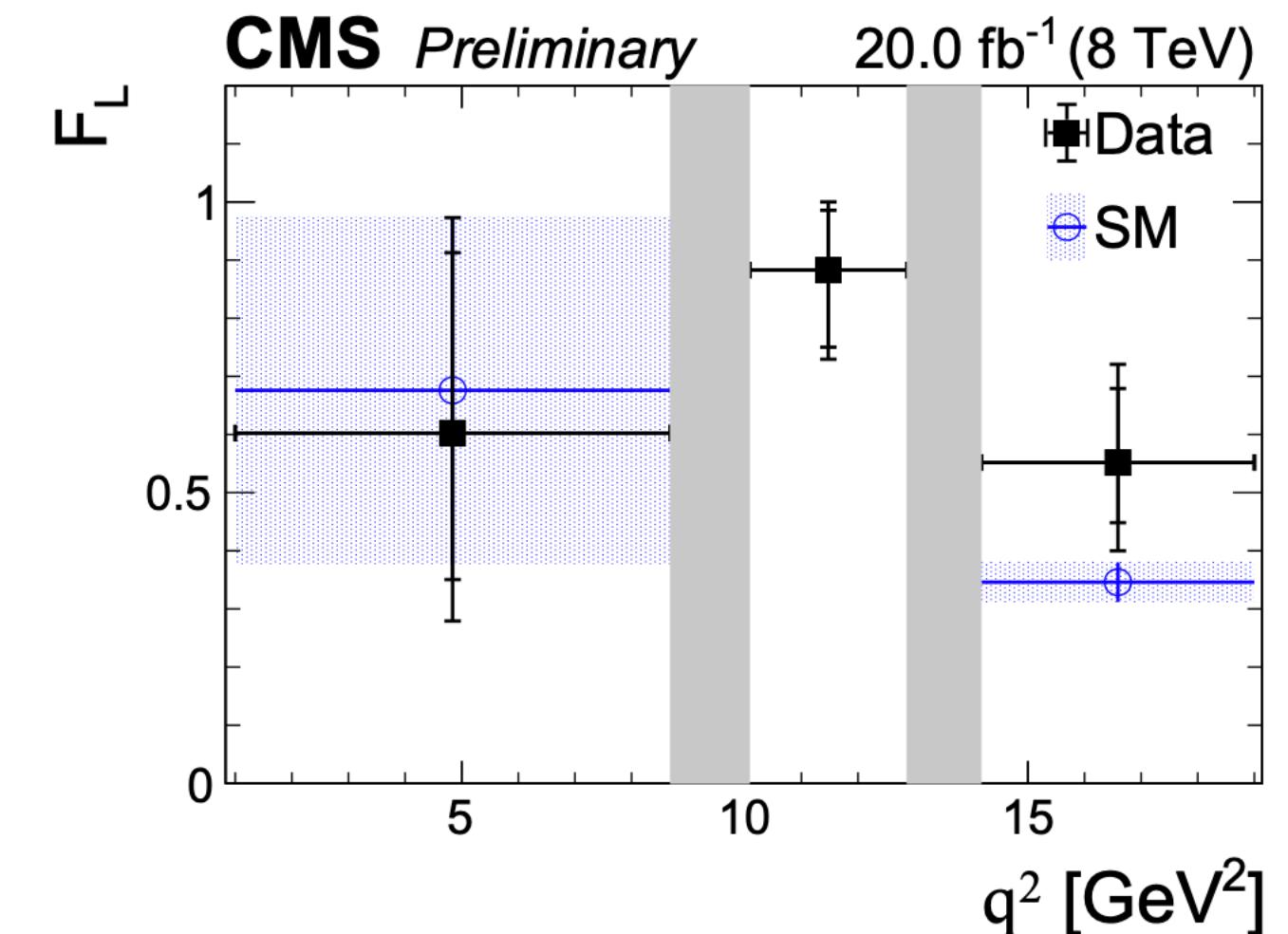
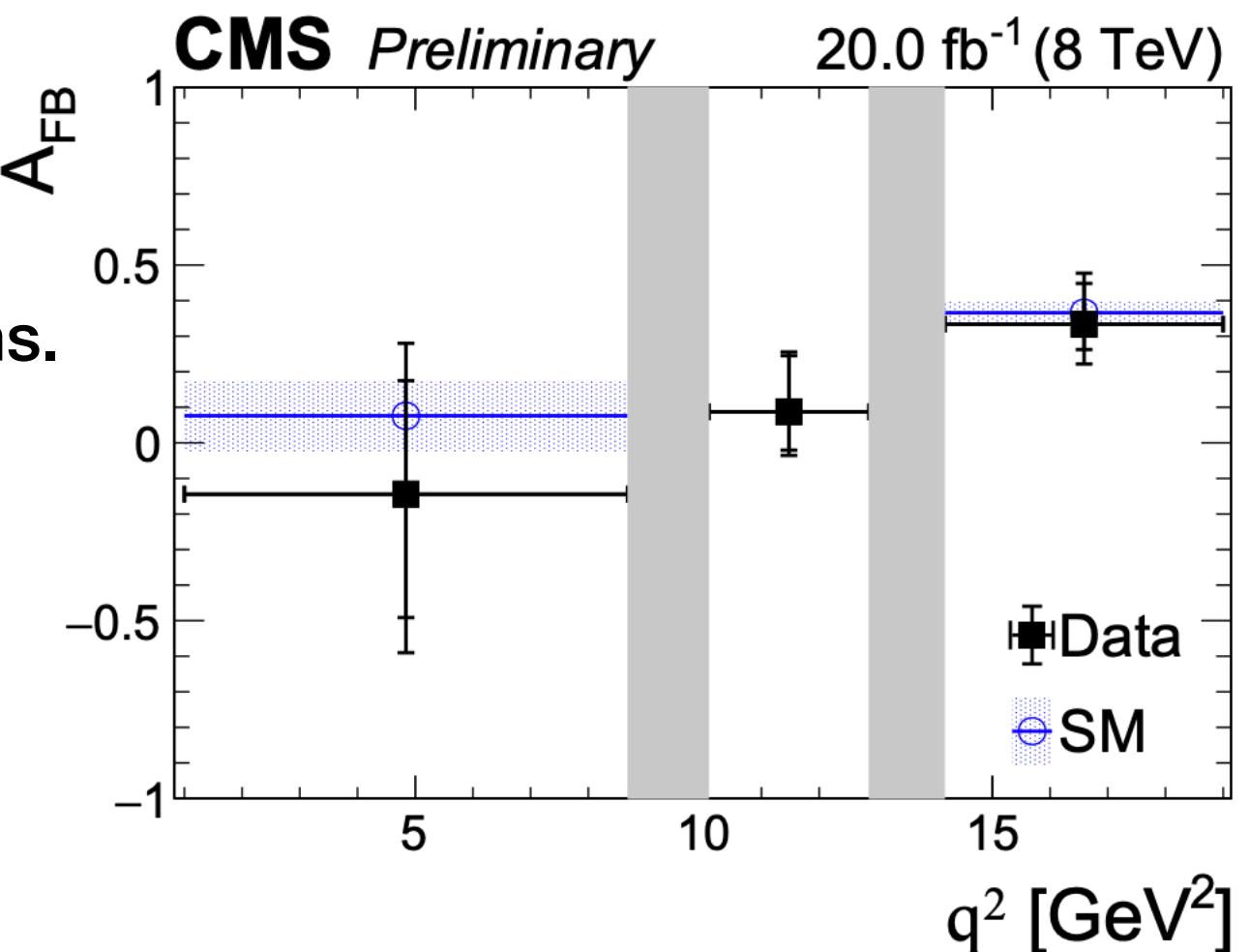


3D fit done in three q^2 signal bins and to the combination of bins.

Statistical uncertainties extracted using profiled Feldman-Cousins techniques.

Dominant systematic uncertainty from background angular description.

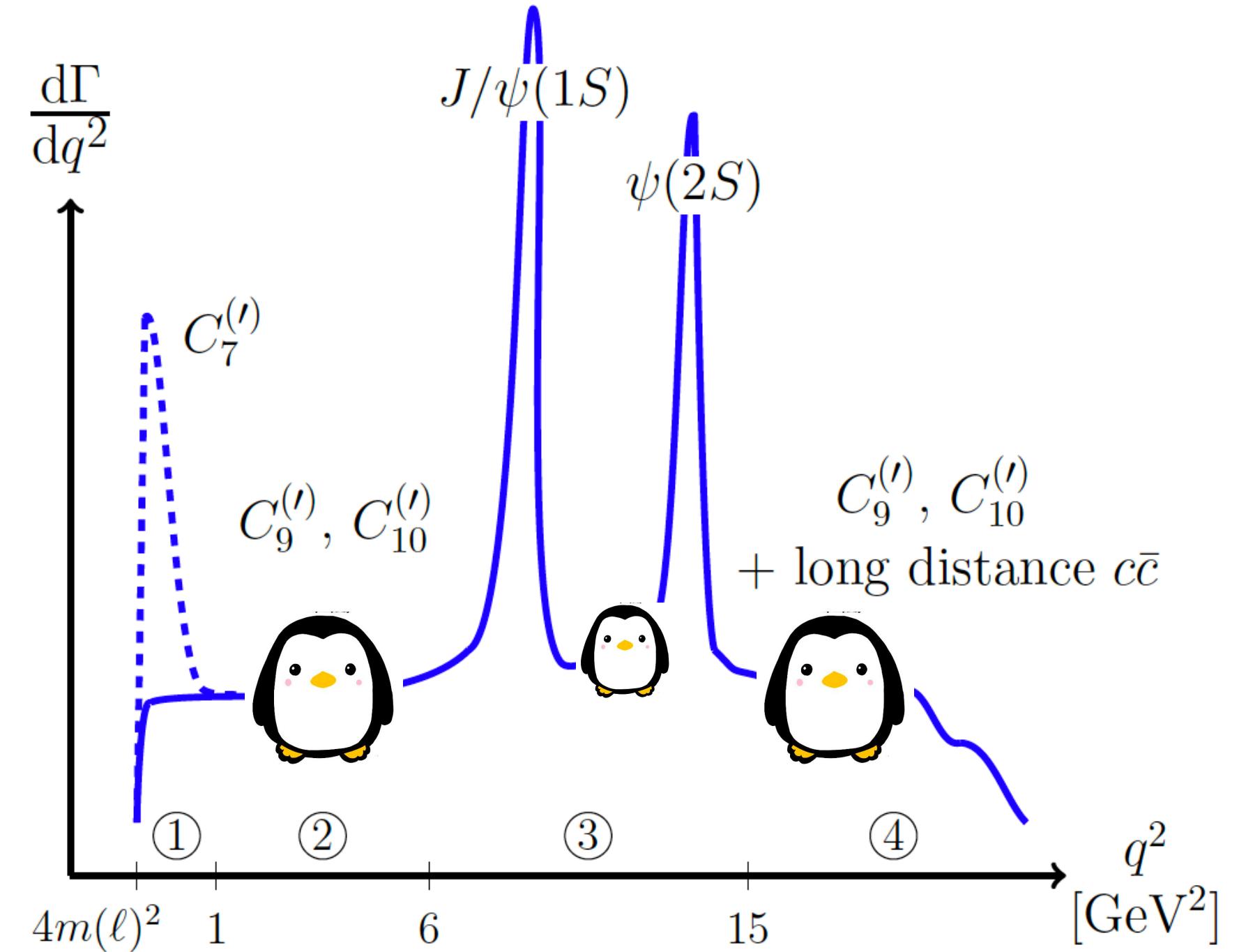
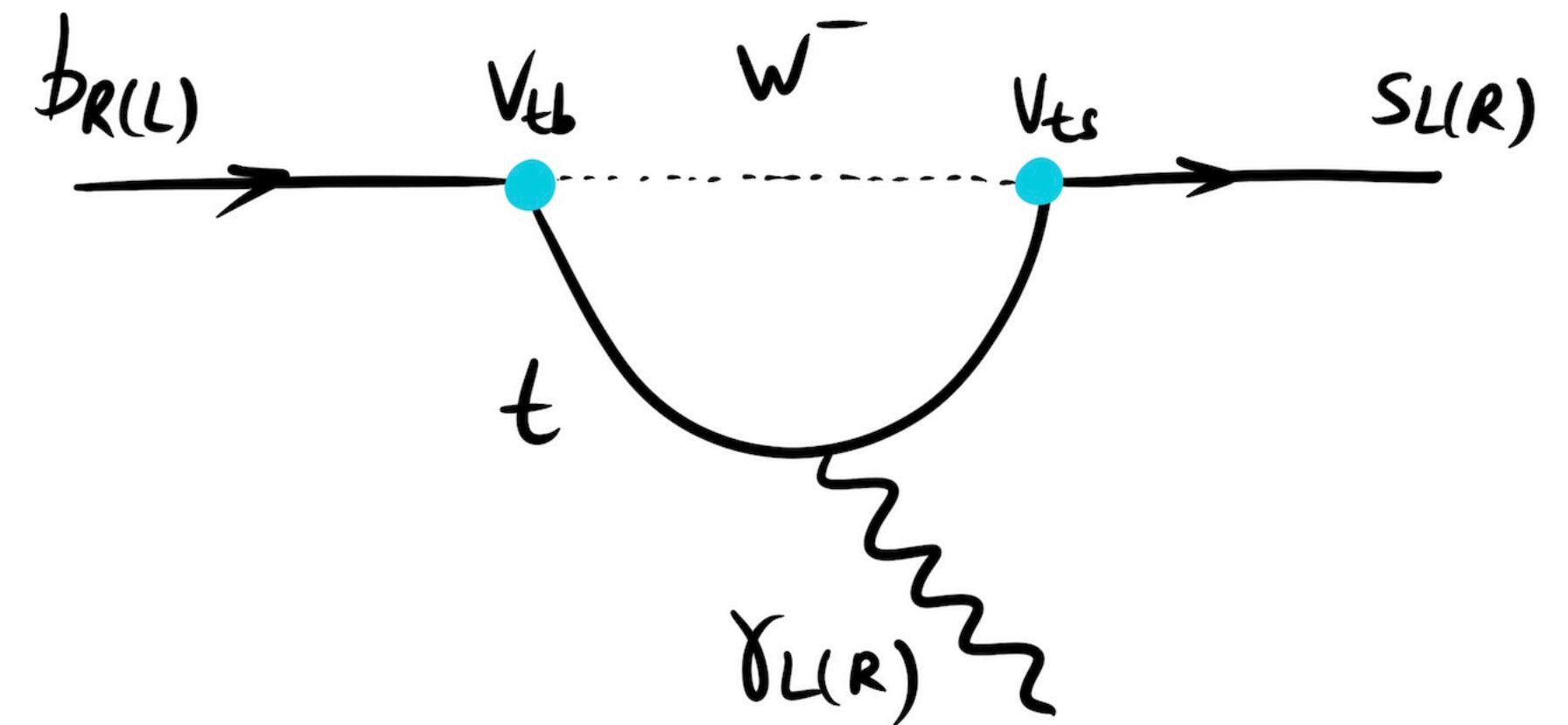
$$\begin{aligned} \frac{1}{\Gamma} \frac{d^3\Gamma}{d\cos\theta_K d\cos\theta_\ell dq^2} = & \frac{9}{16} \left\{ \frac{2}{3} \left[F_S + 2A_S \cos\theta_K \right] (1 - \cos^2\theta_\ell) \right. \\ & + (1 - F_S) \left[2F_L \cos^2\theta_K (1 - \cos^2\theta_\ell) \right. \\ & + \frac{1}{2} (1 - F_L) \left(1 - \cos^2\theta_K \right) (1 + \cos^2\theta_\ell) \\ & \left. \left. + \frac{4}{3} A_{FB} \left(1 - \cos^2\theta_K \right) \cos\theta_\ell \right] \right\}. \end{aligned}$$



Results in agreement with the SM predictions !

Where muons can't go

Measurement of the left and right handed components of $C_7^{(\prime)}$



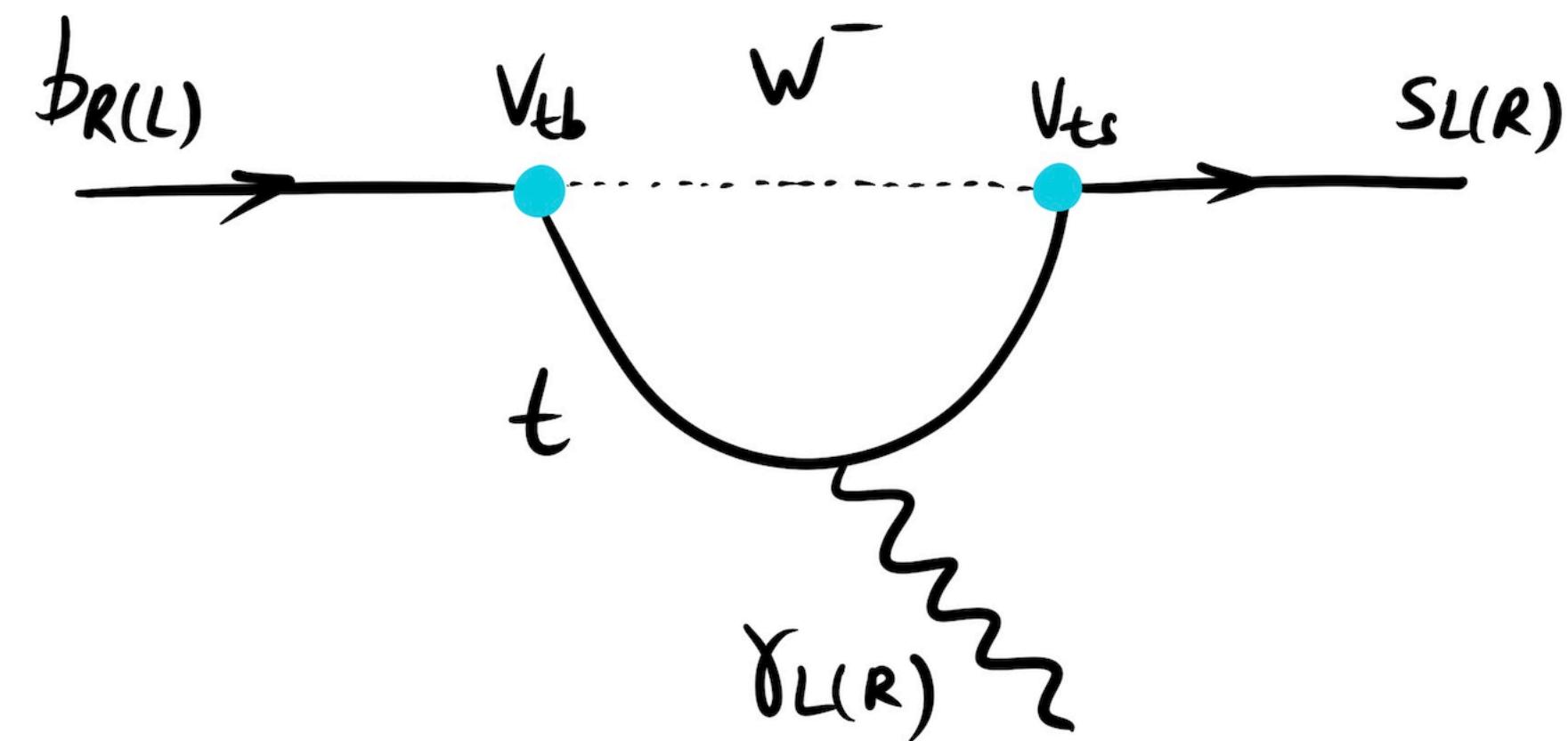
Prediction from the SM

$$\frac{C_7'}{C_7} \simeq \frac{A_R}{A_L} \simeq \frac{m_s}{m_b} \simeq 0.02$$

Radiative decays

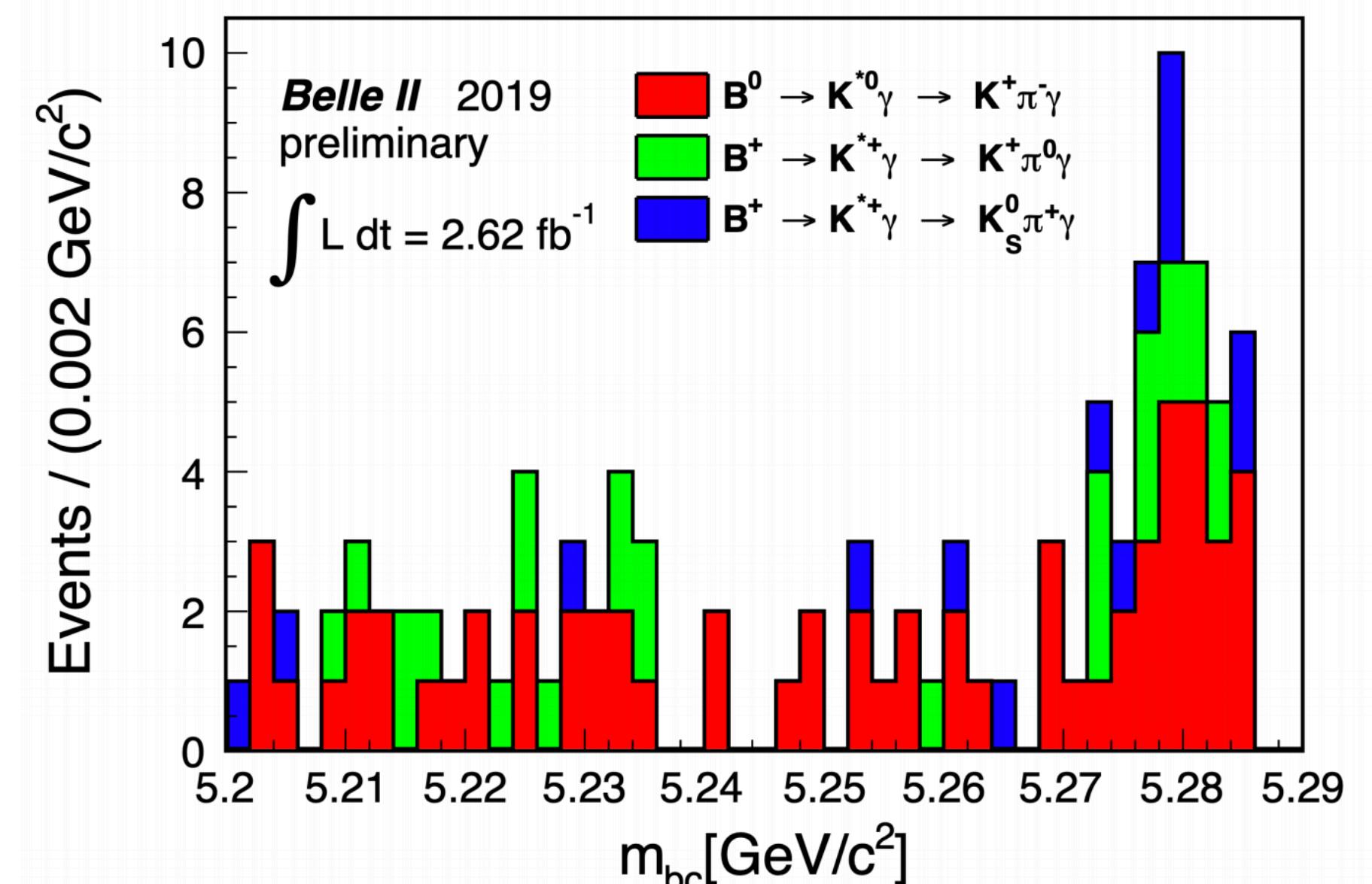
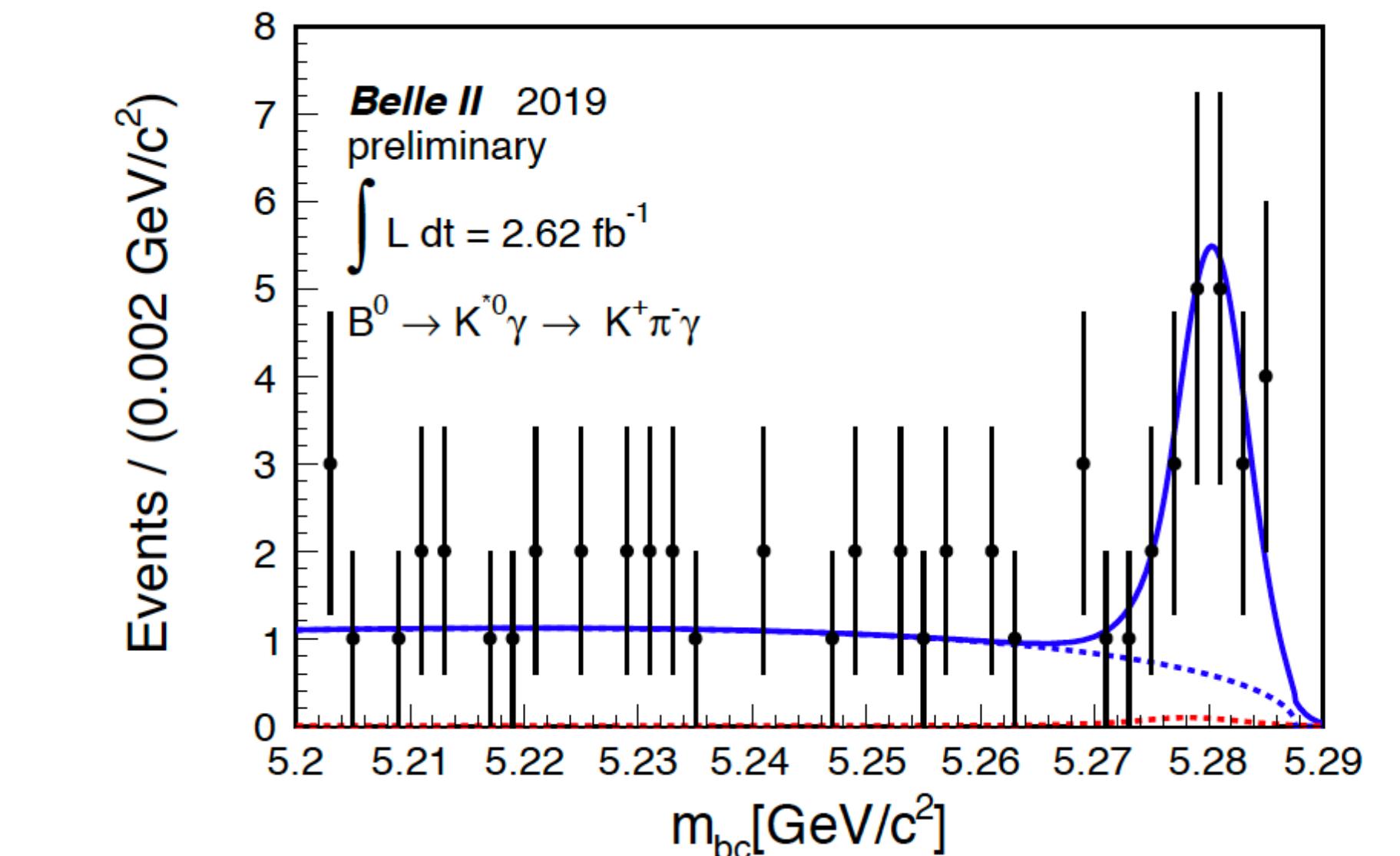
Sneak peek of what to expect from Belle II !

Measurement of the left and right handed components of $C_7^{(')}$



Prediction from the SM

$$\frac{C_7'}{C_7} \simeq \frac{A_R}{A_L} \simeq \frac{m_s}{m_b} \simeq 0.02$$



$B^0 \rightarrow K^* e^+ e^-$ Angular analysis @ very low q^2



$$\begin{aligned}
\frac{1}{d(\Gamma + \bar{\Gamma})/dq^2} \frac{d^4(\Gamma + \bar{\Gamma})}{dq^2 d\cos\theta_\ell d\cos\theta_K d\tilde{\phi}} = & \frac{9}{16\pi} \left[\frac{3}{4}(1 - F_L) \sin^2\theta_K + F_L \cos^2\theta_K \right. \\
& + \frac{1}{4}(1 - F_L) \sin^2\theta_K \cos 2\theta_\ell - F_L \cos^2\theta_K \cos 2\theta_\ell \\
& + (1 - F_L) A_T^{\text{Re}} \sin^2\theta_K \cos\theta_\ell \\
& + \frac{1}{2}(1 - F_L) A_T^{(2)} \sin^2\theta_K \sin^2\theta_\ell \cos 2\tilde{\phi} \\
& \left. + \frac{1}{2}(1 - F_L) A_T^{\text{Im}} \sin^2\theta_K \sin^2\theta_\ell \sin 2\tilde{\phi} \right]. \tag{1}
\end{aligned}$$

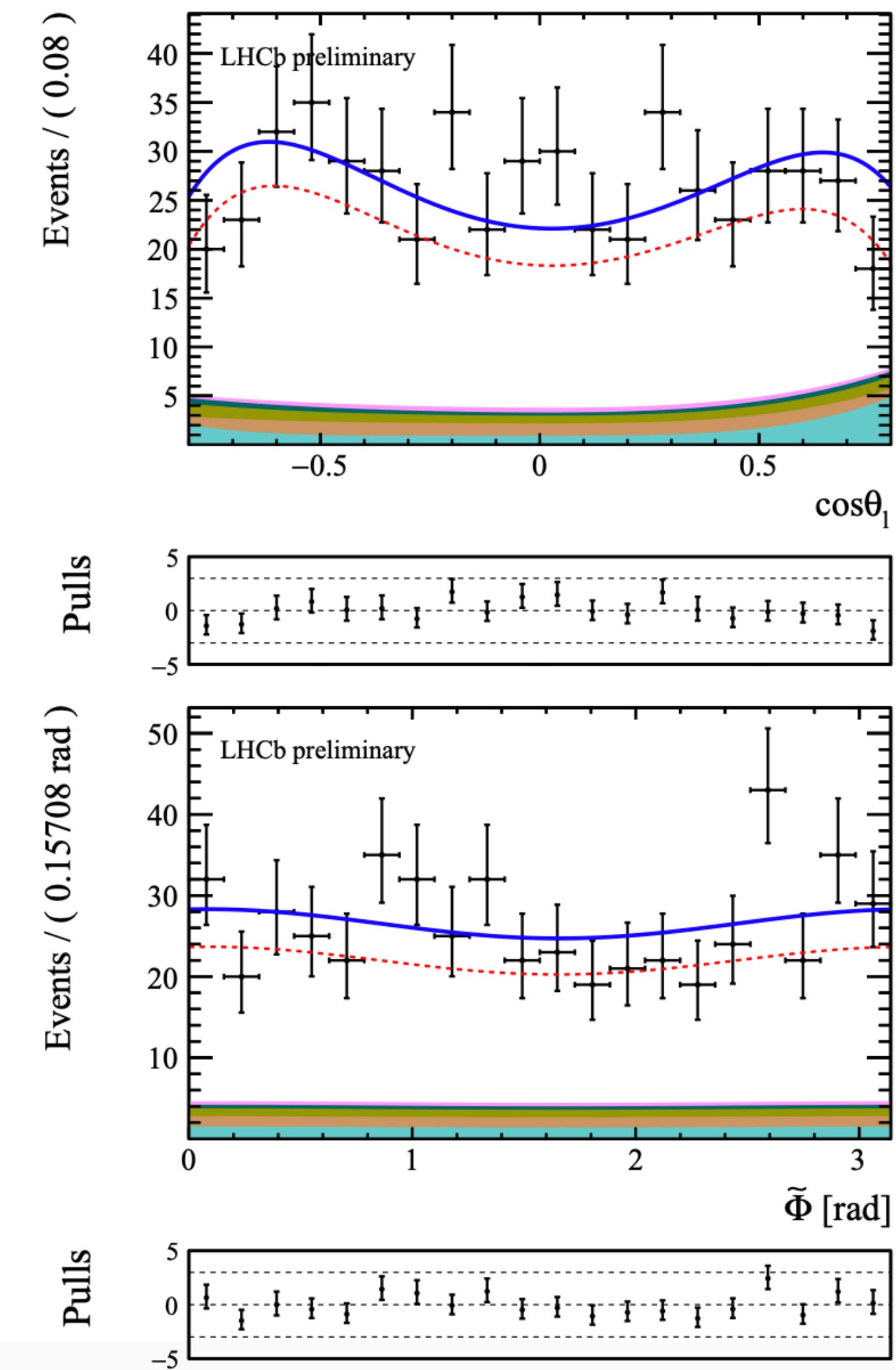
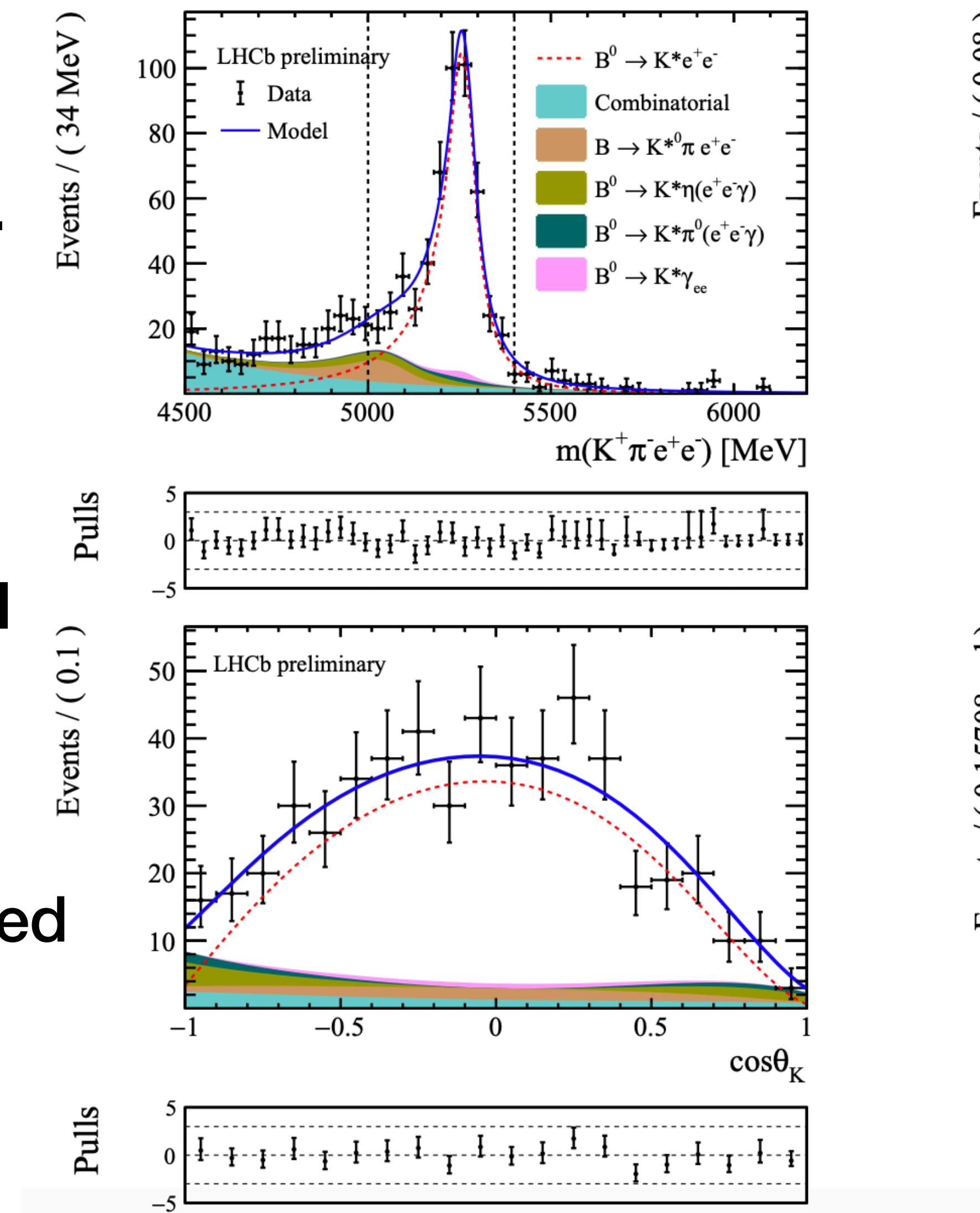
Access to photon polarisation !

$$\begin{aligned}
A_T^{(2)}(q^2 \rightarrow 0) &= \frac{2\mathcal{R}\epsilon(C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2} \\
A_T^{\text{Im}}(q^2 \rightarrow 0) &= \frac{2\mathcal{I}m(C_7 C_7'^*)}{|C_7|^2 + |C_7'|^2}
\end{aligned}$$

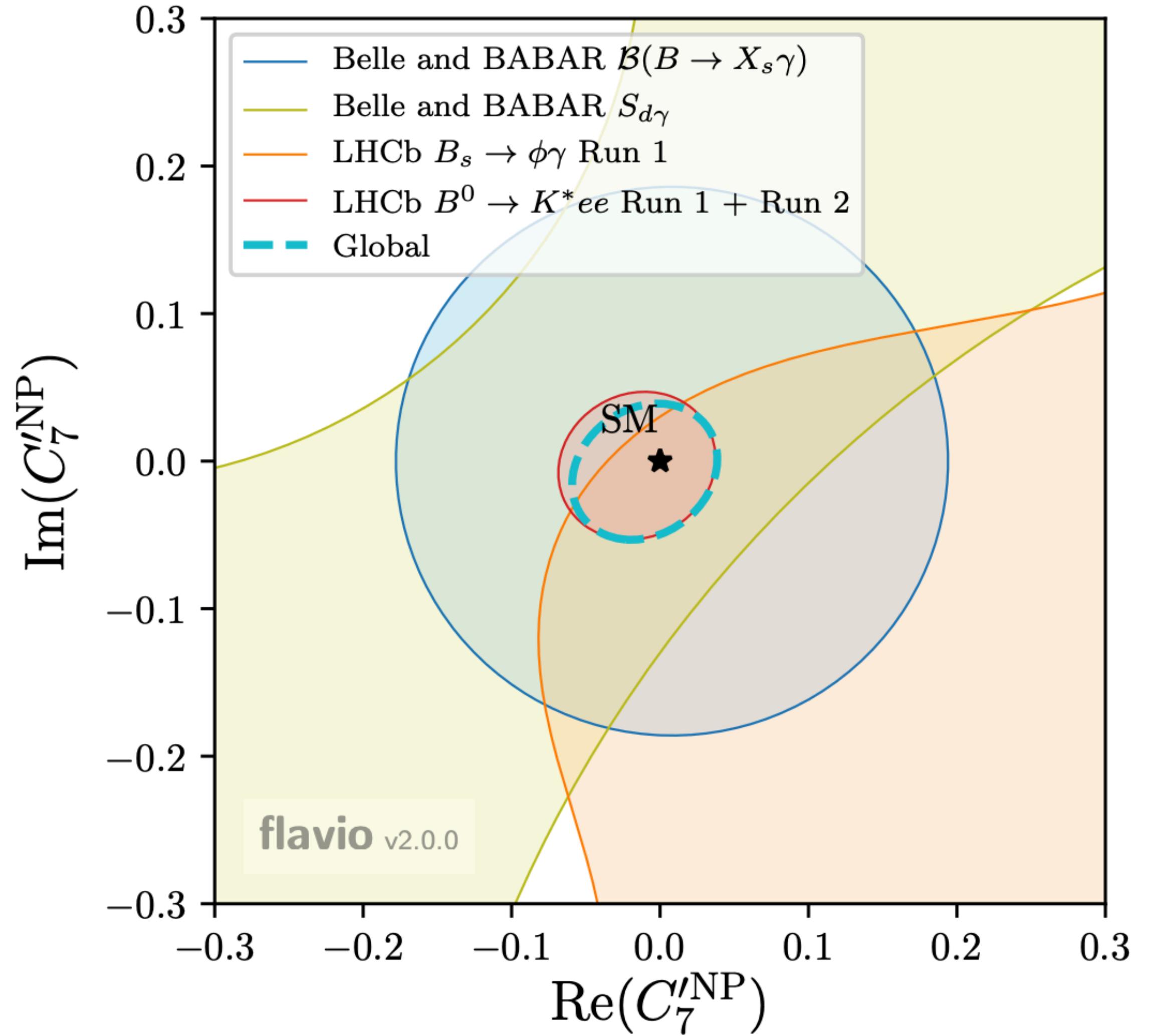
$q^2 \in [0.0008, 0.257] \text{ GeV}/c^2$

$$B^0 \rightarrow K^* e^+ e^-$$

- 4D-fit to B mass and angles.
- When possible backgrounds modelled using data.
- Main systematics from signal acceptance and angular background modelling.
- Fit procedure thoroughly tested with pseudo-experiments



$$B^0 \rightarrow K^* e^+ e^-$$

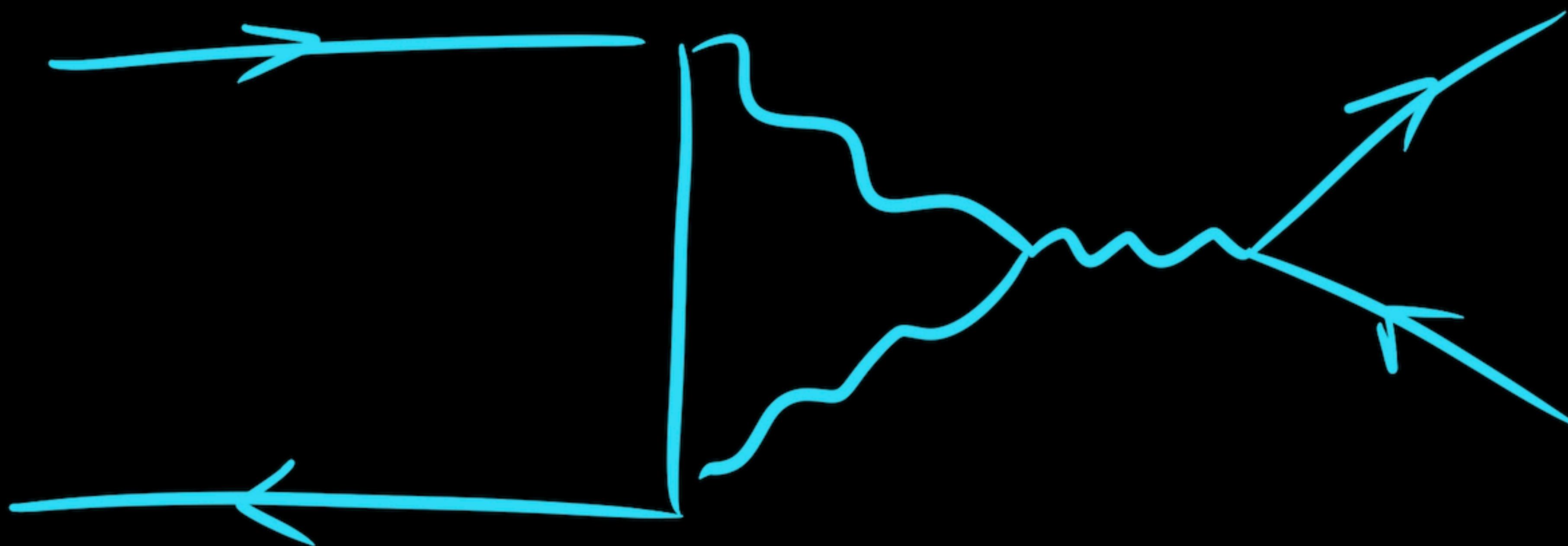


Results

F_L	$= 0.044 \pm 0.026 \pm 0.014$
A_T^{Re}	$= -0.064 \pm 0.077 \pm 0.015$
$A_T^{(2)}$	$= +0.106 \pm 0.103^{+0.016}_{-0.017}$
A_T^{Im}	$= +0.015 \pm 0.102 \pm 0.012,$

**Even if still statistically limited
best sensitivity to right-handed
quark coupling C_7'**

Now we go down by a few
order of magnitudes



$$B_q^0 \rightarrow \ell^+ \ell^-$$

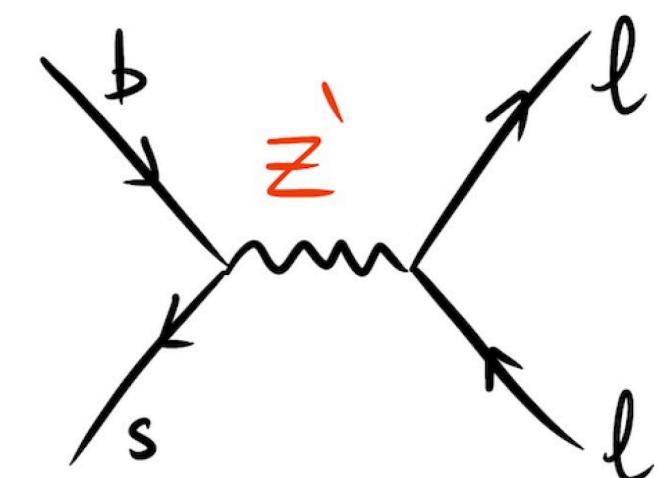
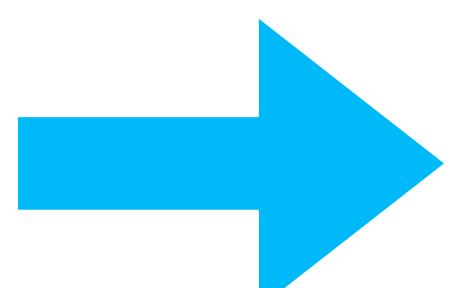
Branching fraction prediction in the SM:

$$\bar{B}_{q\ell} = \frac{|N|^2 M_{Bq}^3 f_{Bq}^2}{8\pi \Gamma_H^2} \beta_{q\ell} r_{q\ell}^2 |c_A(\mu_\nu)|^2 + \mathcal{O}(\alpha_{em})$$

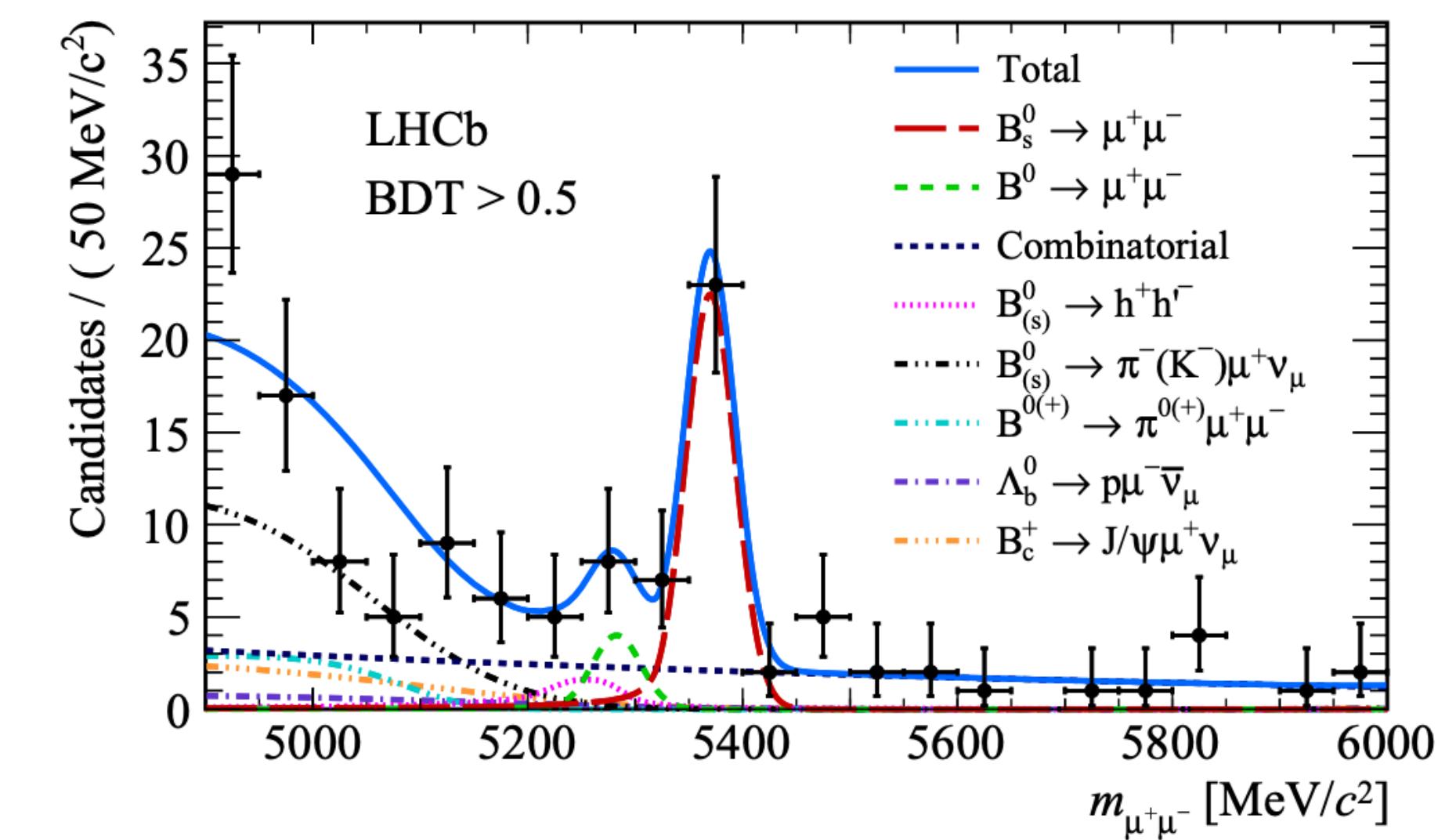
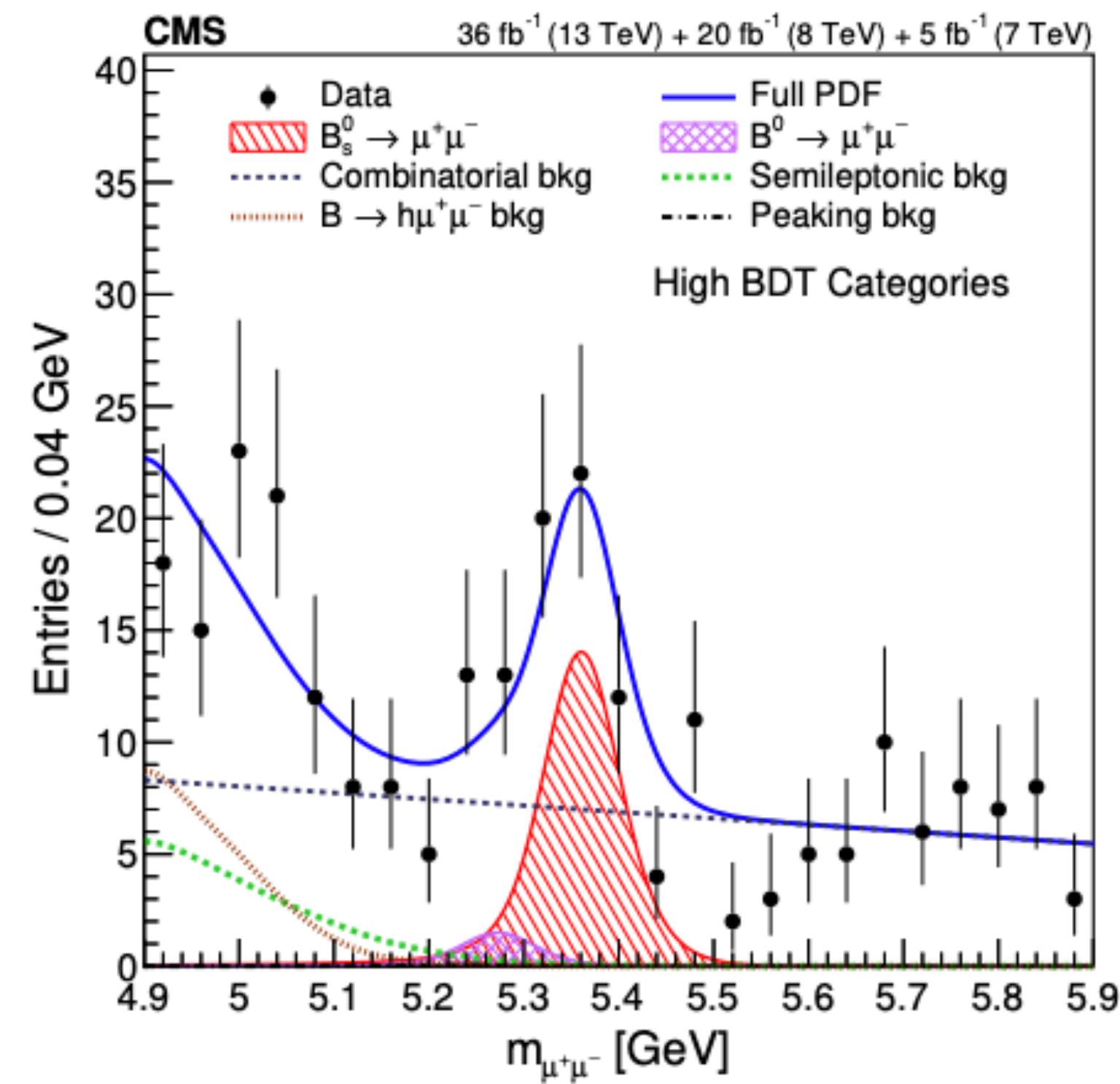
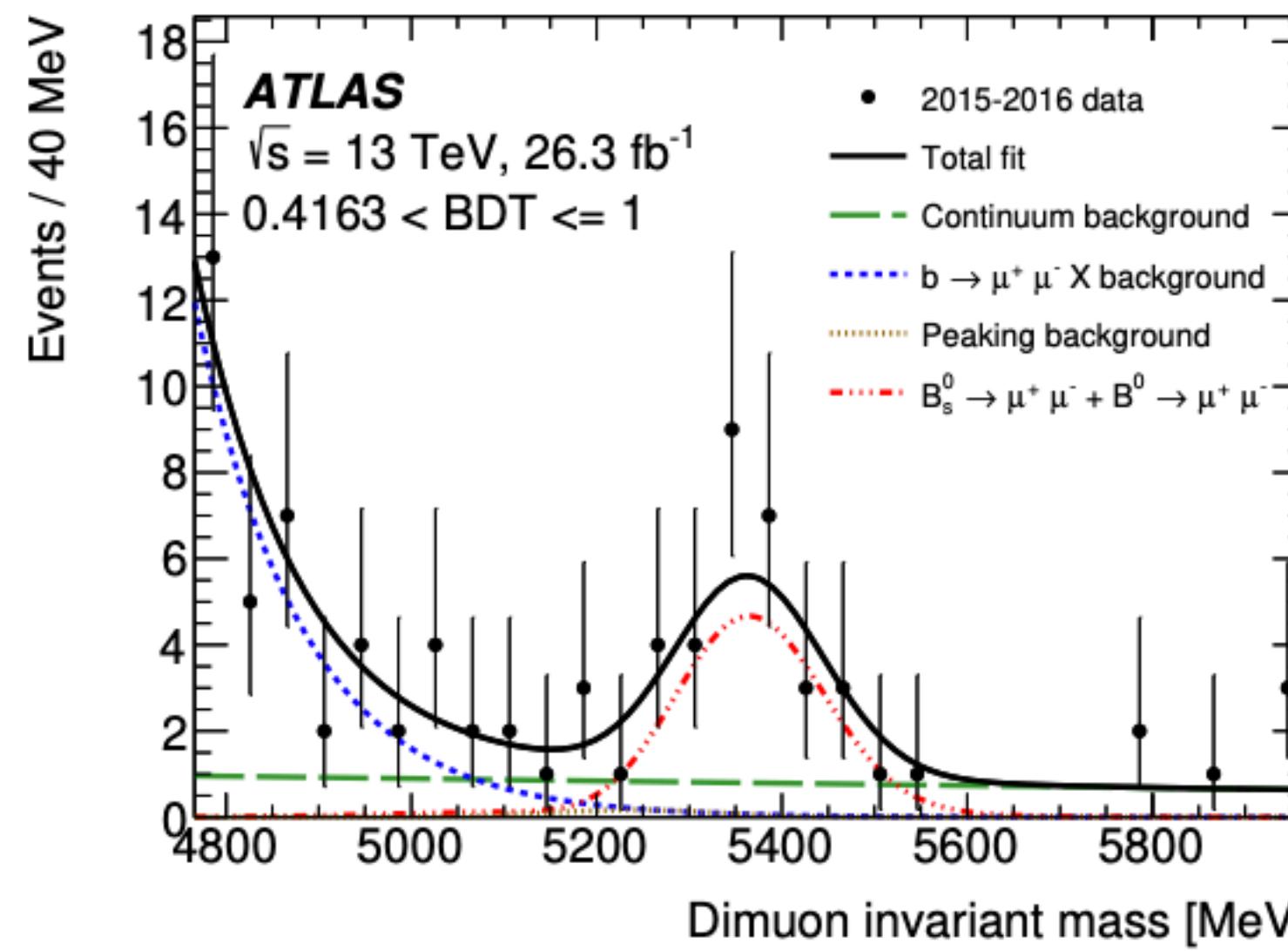
$$\frac{g_{me}}{M_{Bq}}$$

$$\sqrt{1 - r_{q\ell}^2}$$

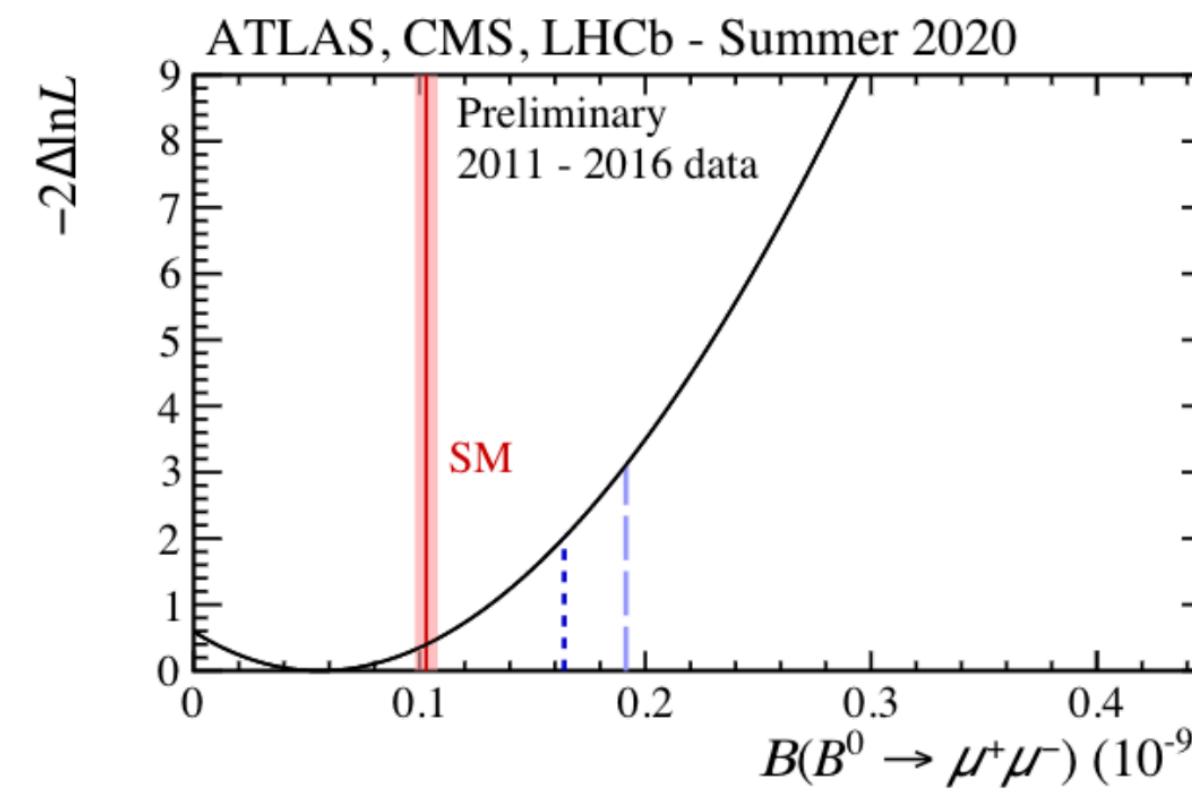
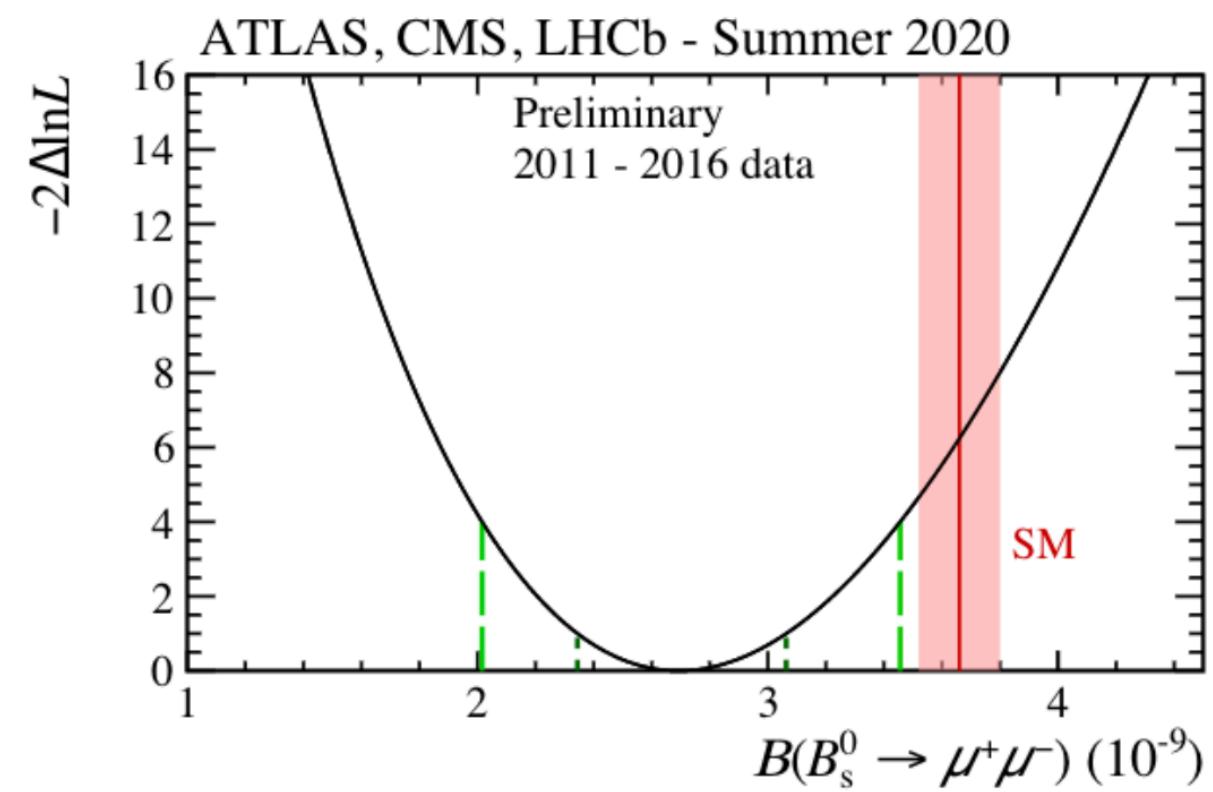
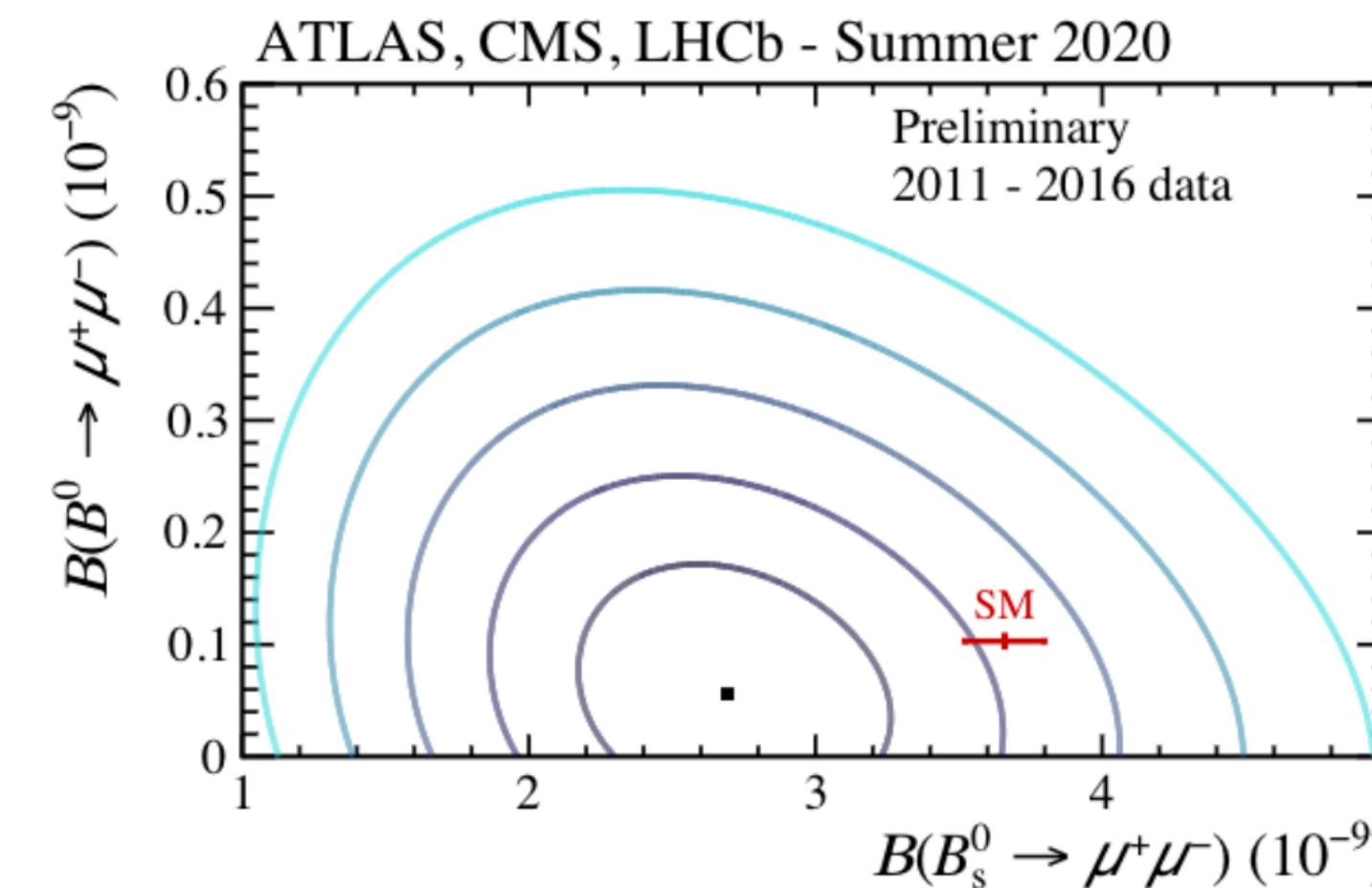
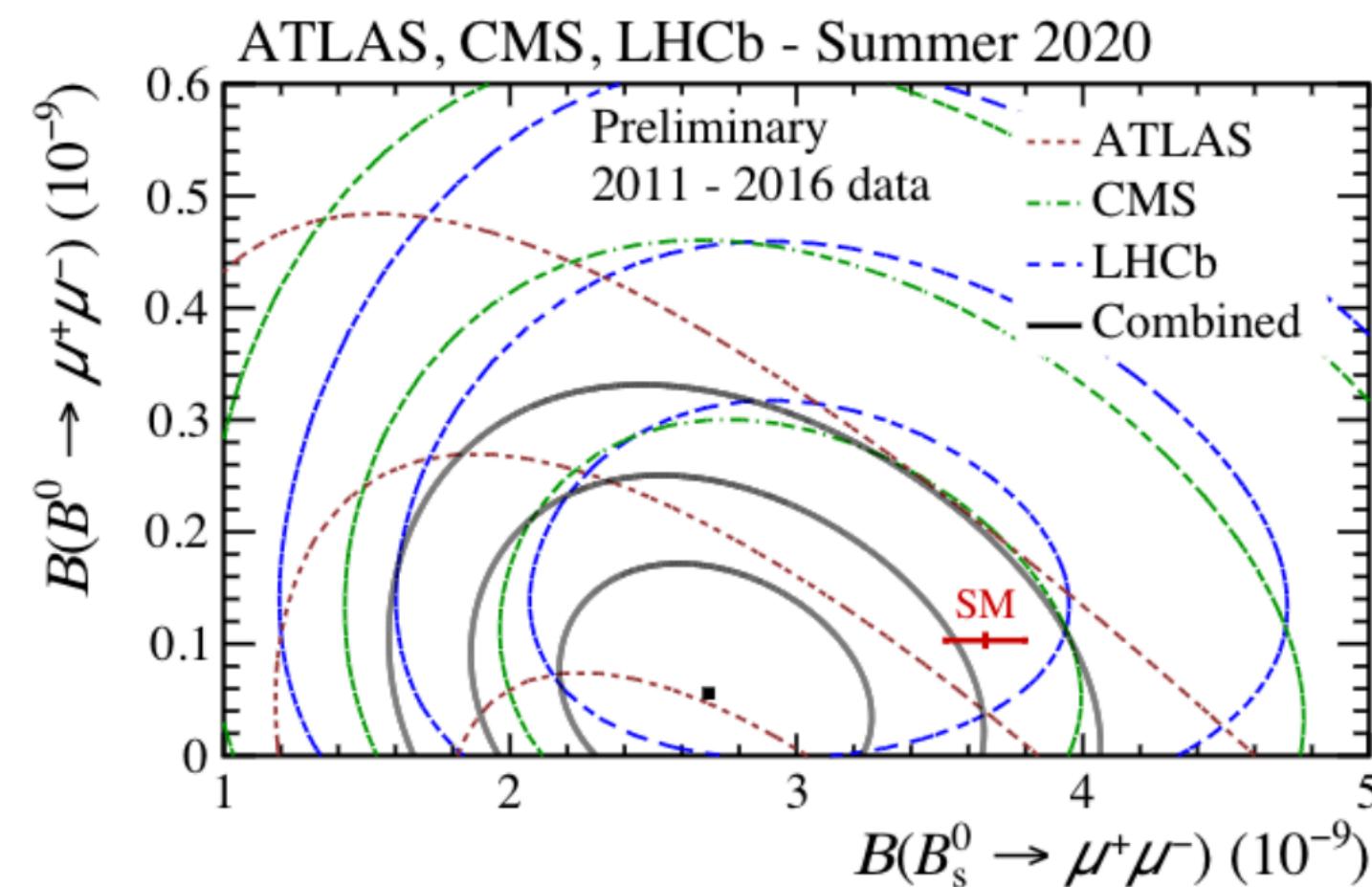
Theoretically clean observable



$B_s^0 \rightarrow \mu^+ \mu^-$ "seen" across the ring !



ATLAS, CMS & LHCb combination

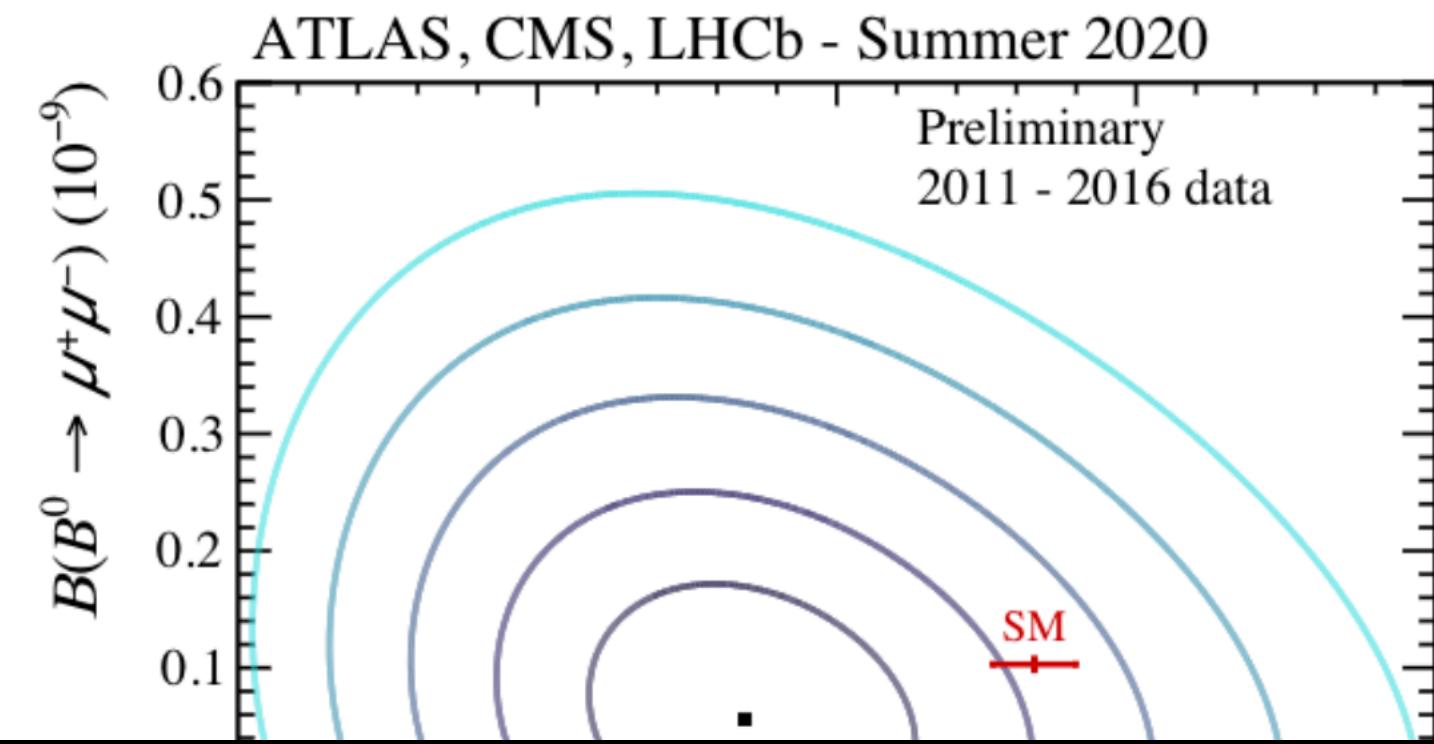
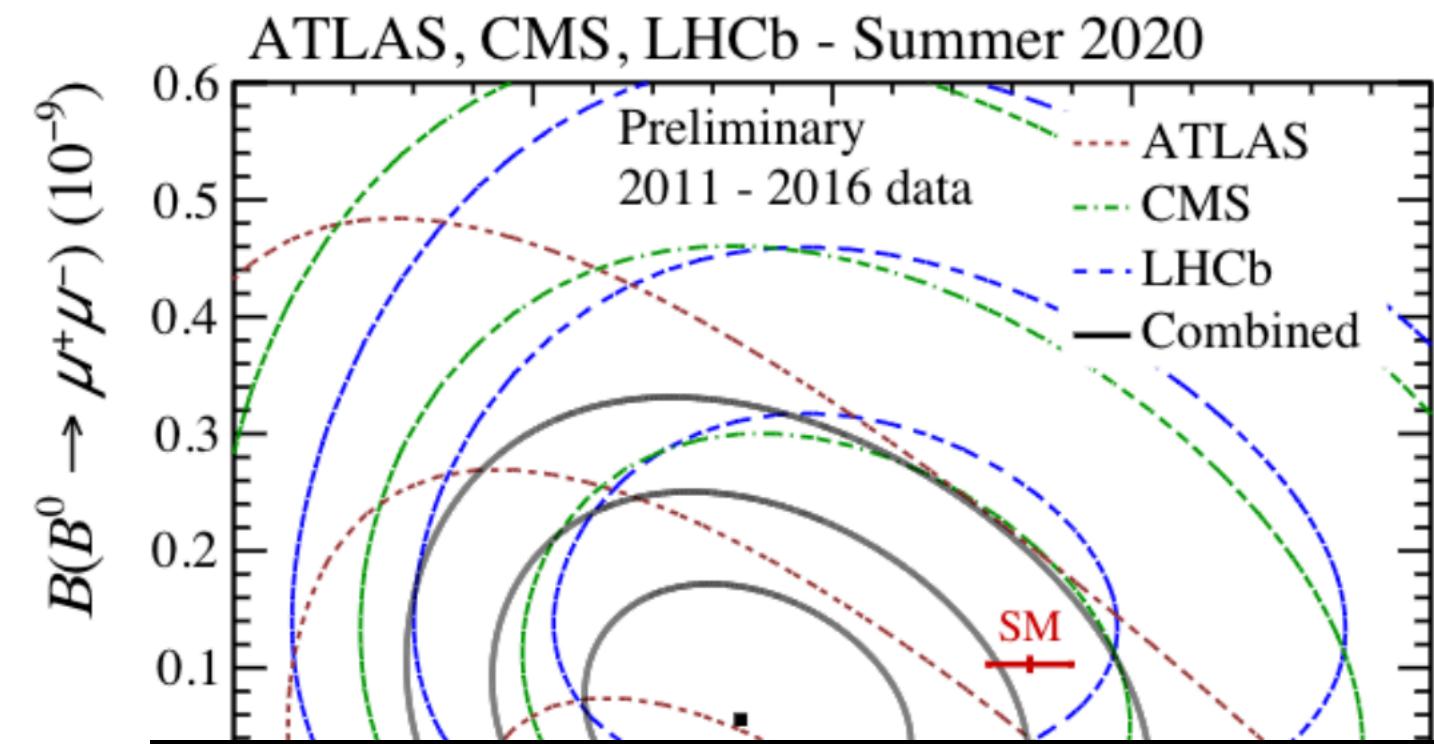


$$\mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) < 1.6(1.9) \times 10^{-10} @ 90\% (95\%) \text{ CL}$$

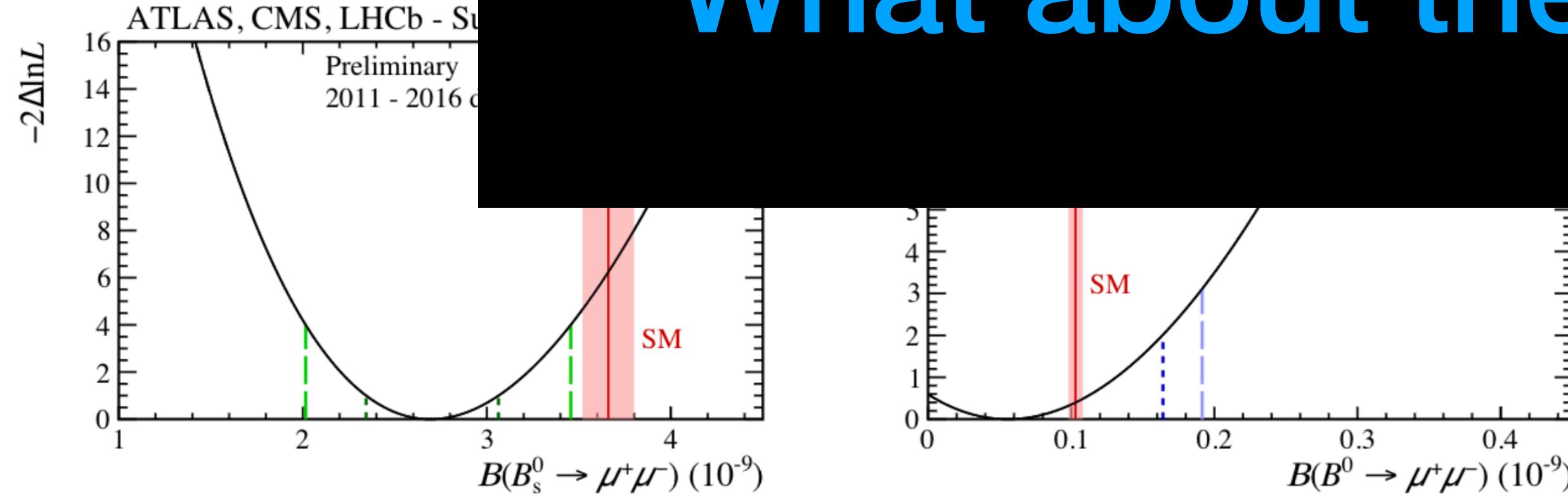
$$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$

Results compatible with the SM within 2.1 standard deviations in 2D plane.

ATLAS, CMS & LHCb combination



What about the electrons ?

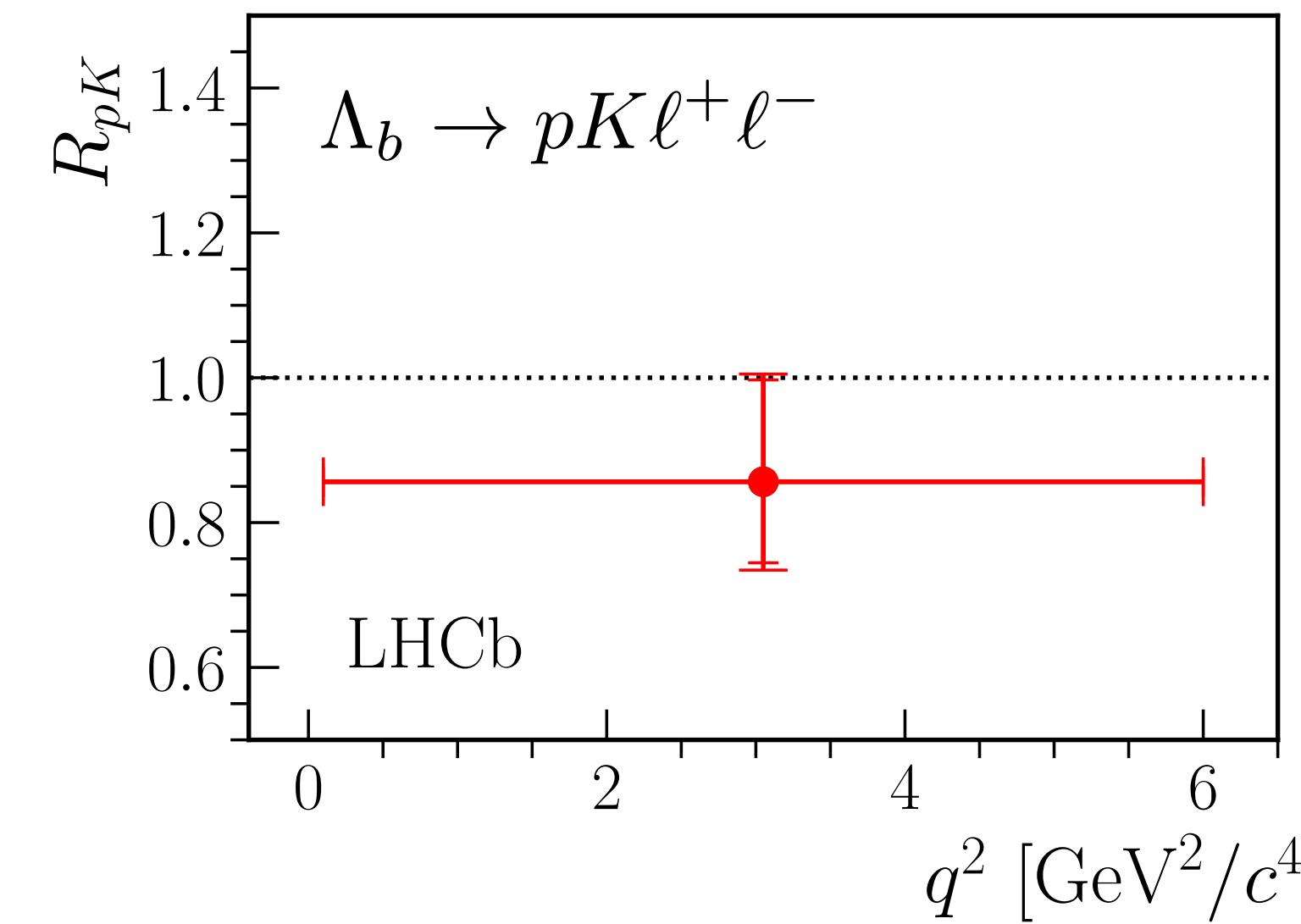


$\times 10^{-10} @ 90\% (95\%) \text{ CL}$

$$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-) = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$

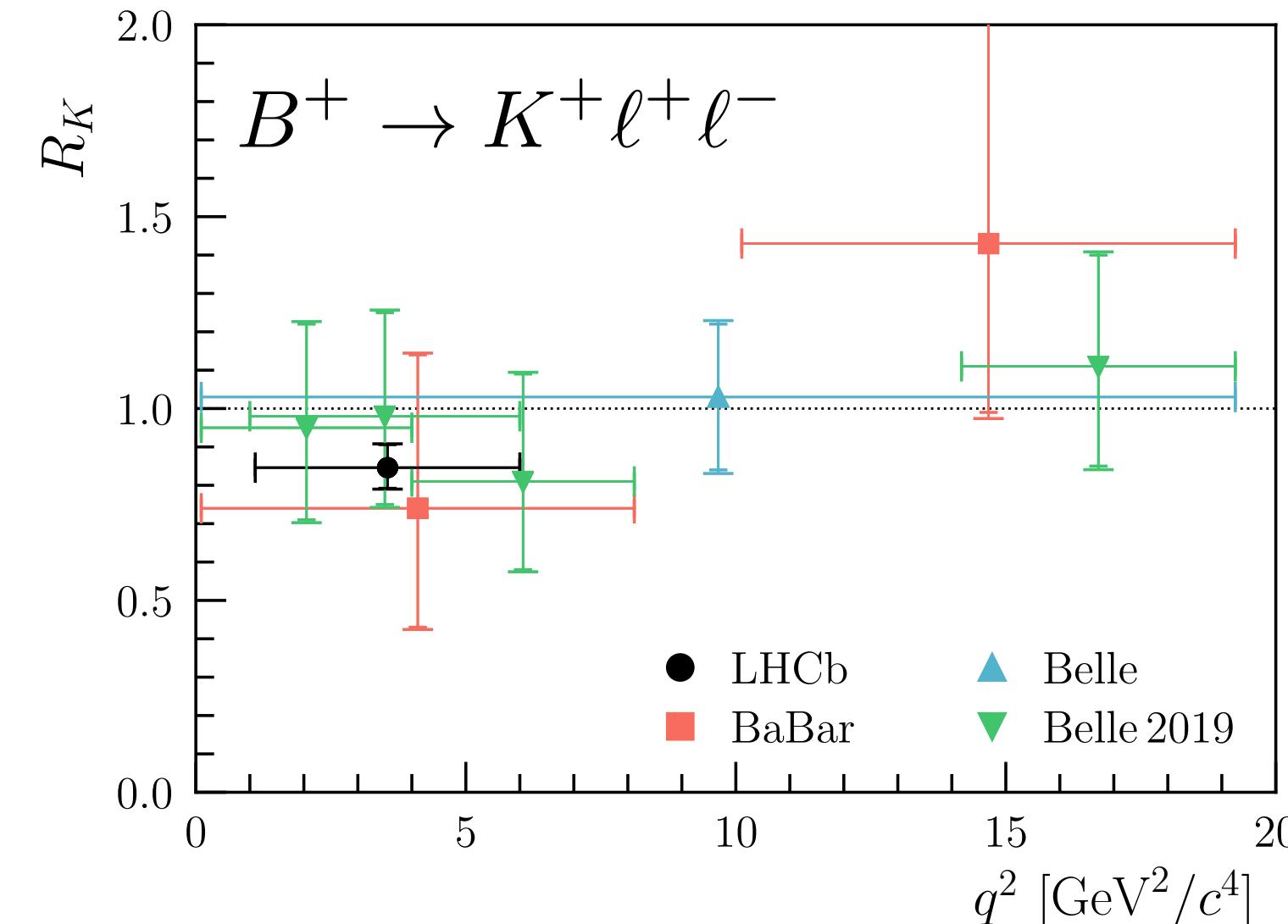
Results compatible with the SM within 2.1 standard deviations in 2D plane.

Lepton Universality



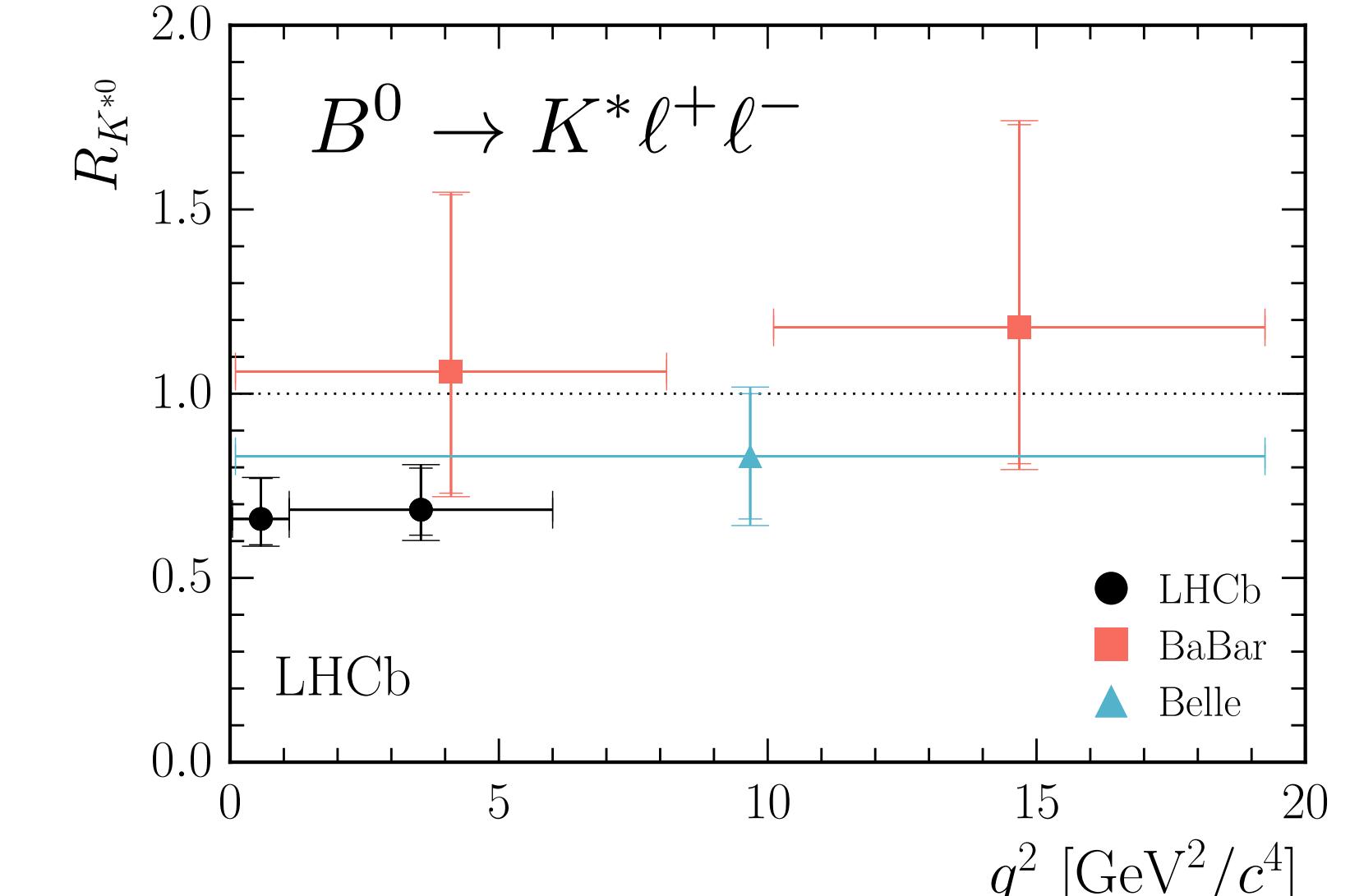
$$R_{pK} = 0.86^{+0.14}_{-0.11} \pm 0.05$$

$0.1 < q^2 < 6$ GeV 2



$$R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$$

$1.1 < q^2 < 6$ GeV 2

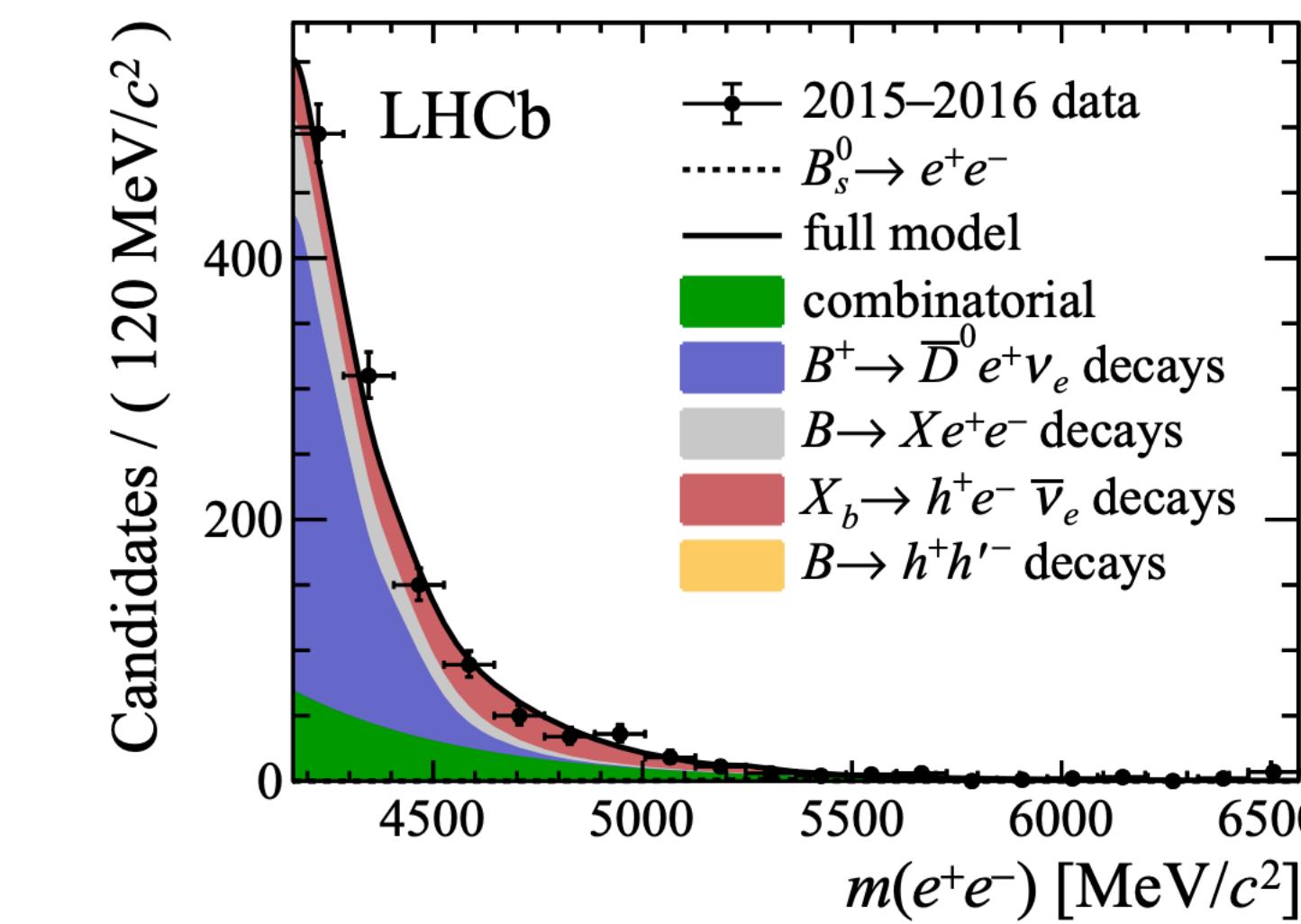
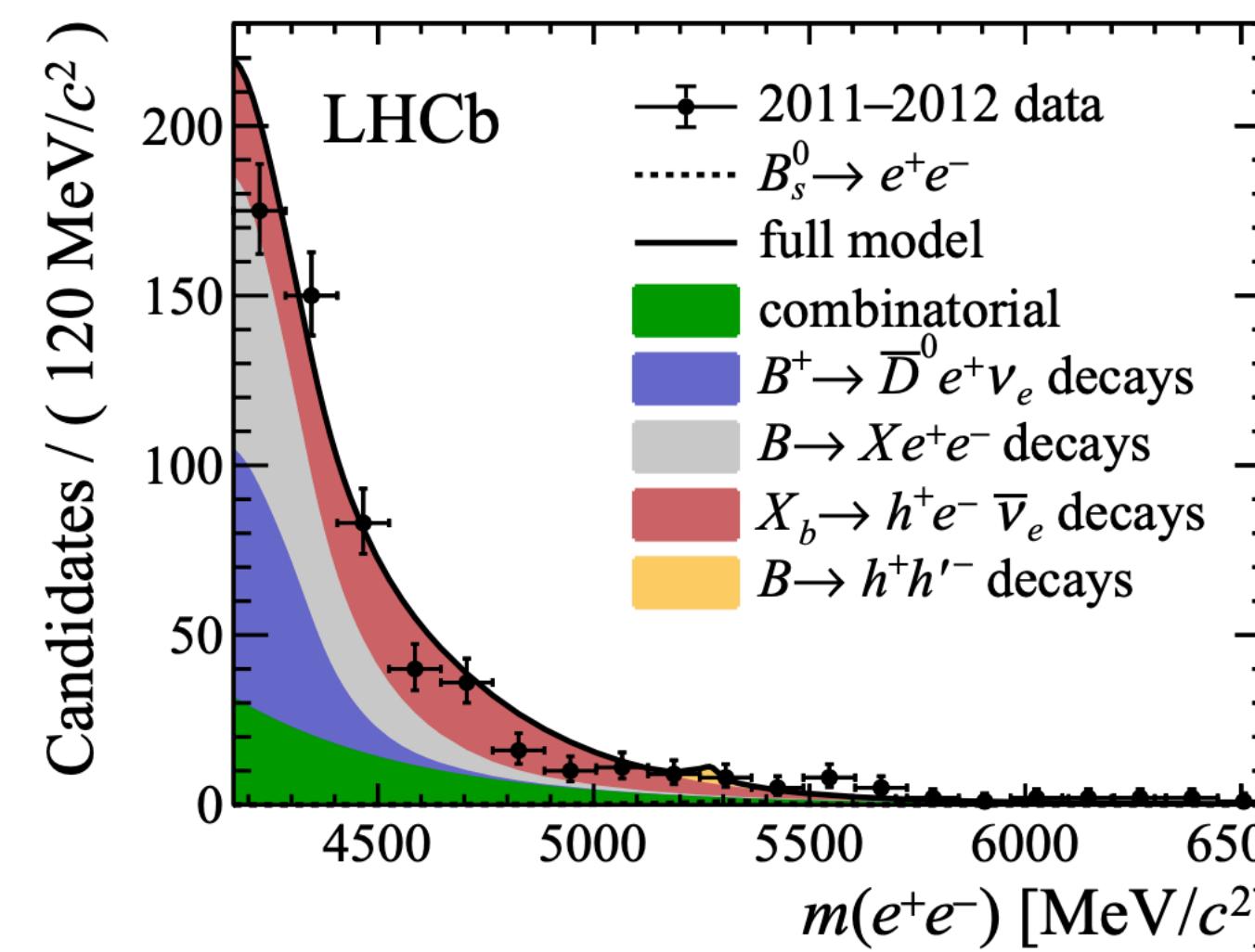


$$R_{K^{*0}} = 0.69^{+0.11}_{-0.07} \pm 0.05$$

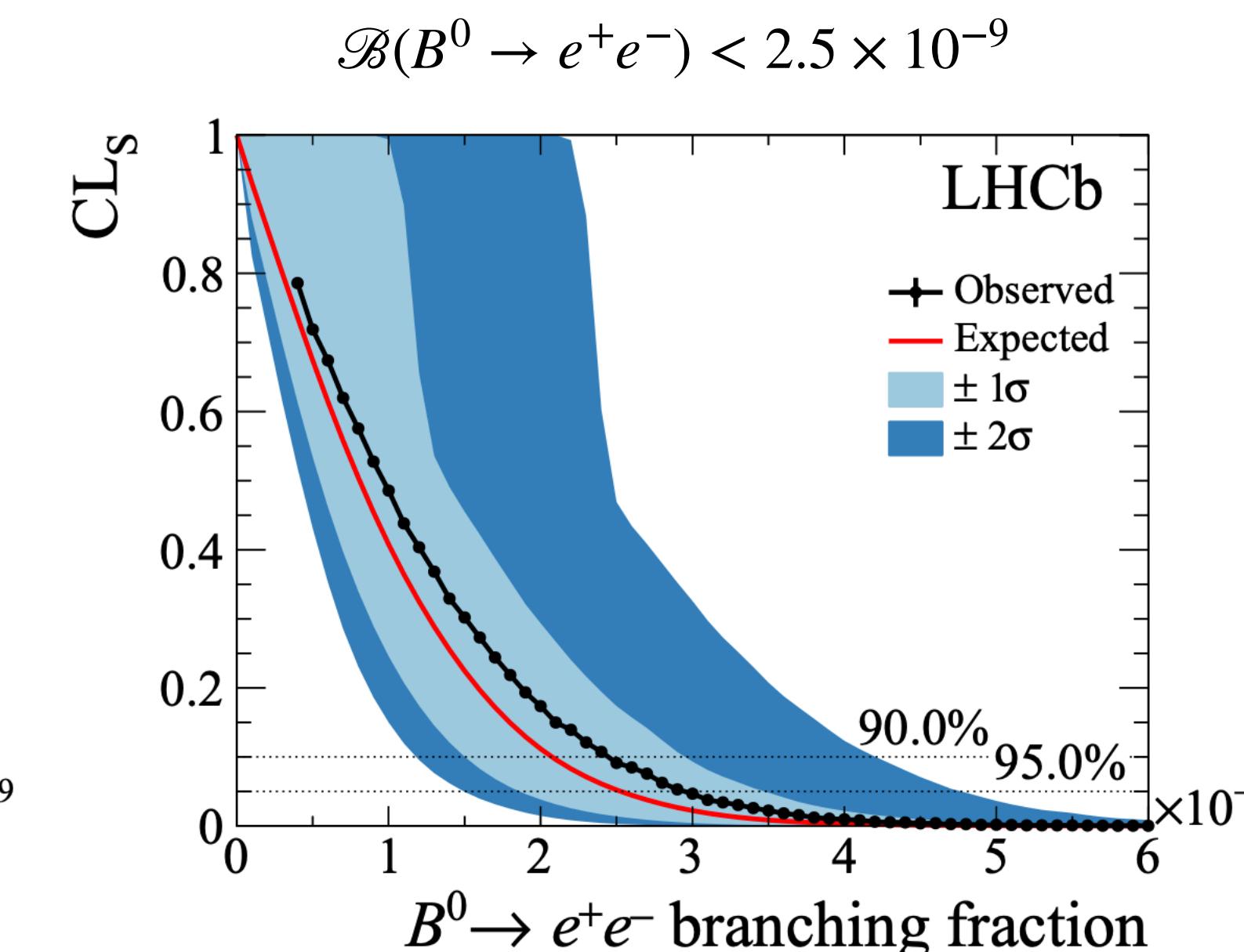
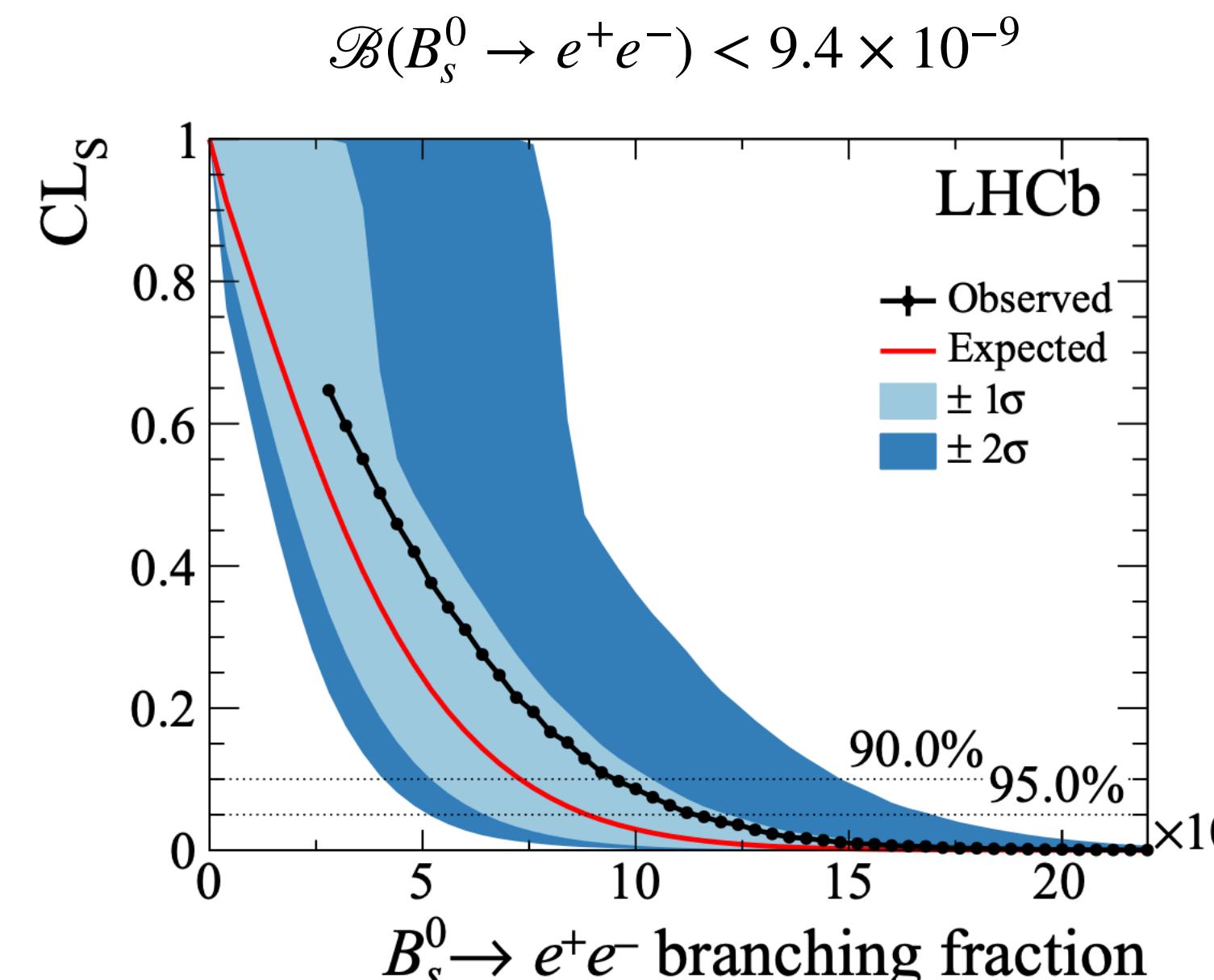
$1.1 < q^2 < 6$ GeV 2

Are we seeing a coherent pattern in the data ?

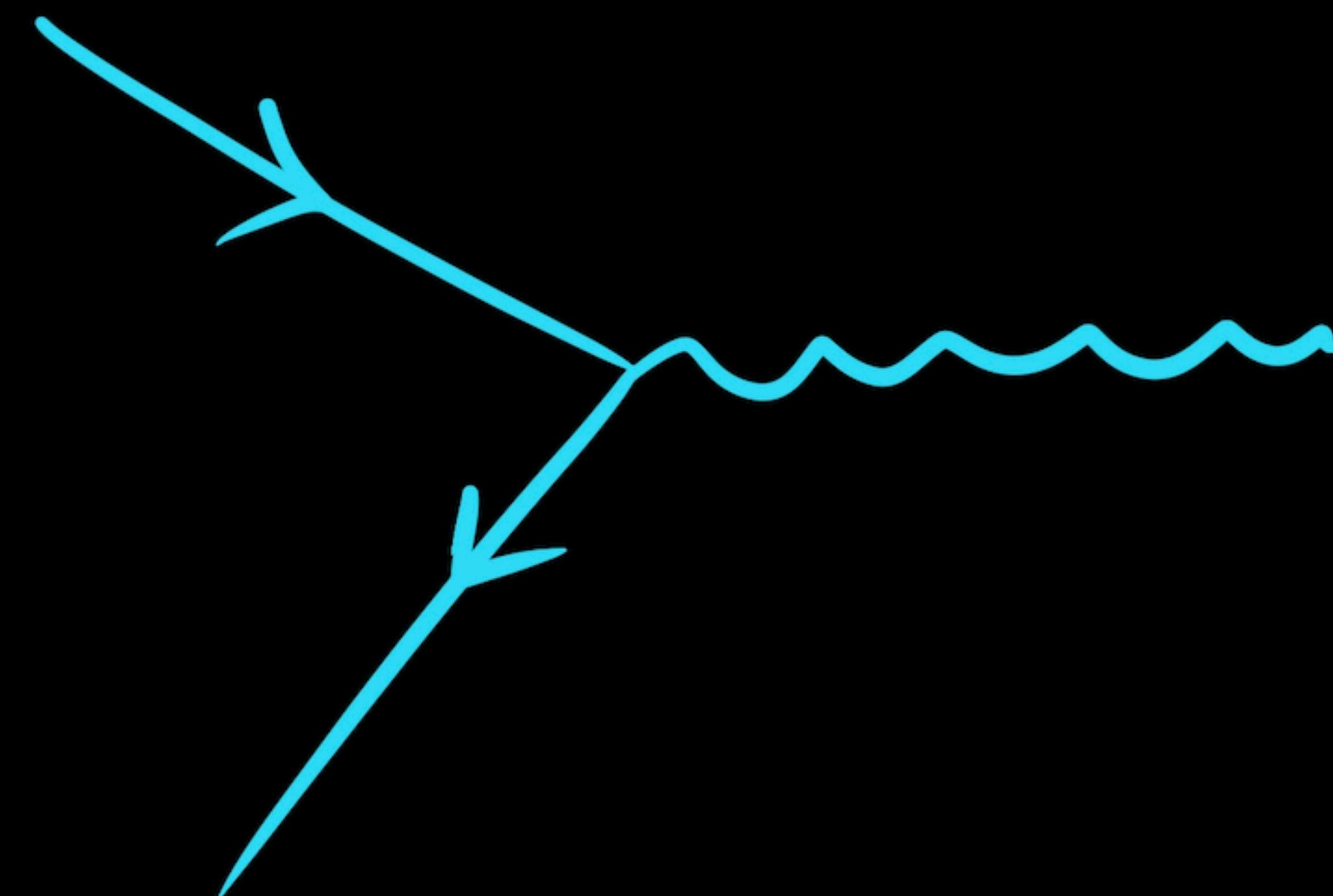
$$B_s^0 \rightarrow e^+ e^-$$



No significant signal; limits set @ 90%CL



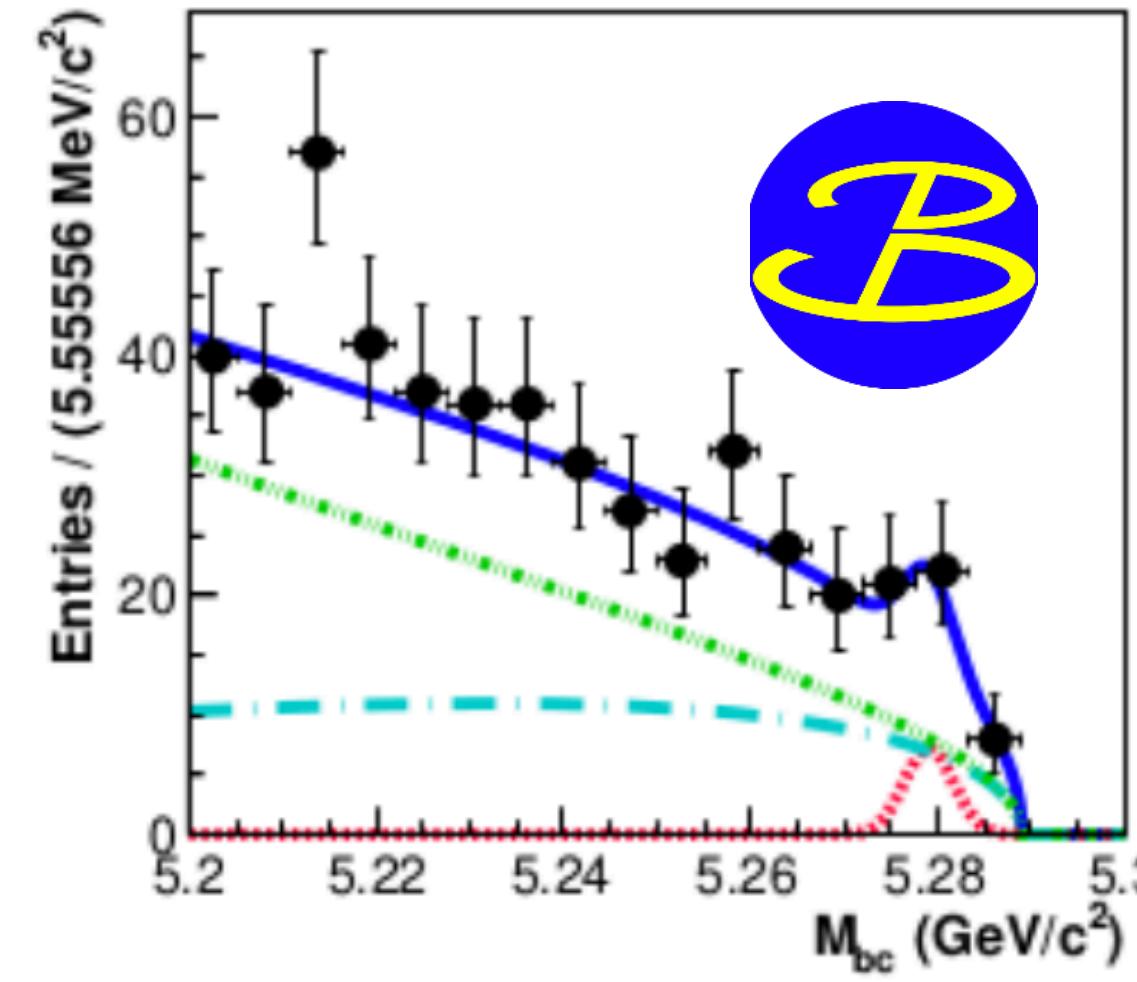
Now let's test the forbidden



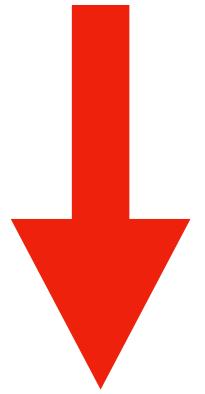
$B^+ \rightarrow K^+ \mu^+ e^-$, $B^+ \rightarrow K^+ \mu^- e^+$, $B^0 \rightarrow K_s^0 \mu^\pm e^\mp$ searches



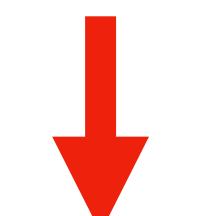
Many BSM models predict LFV [L. Glashow et al. PRL 114, 091801]



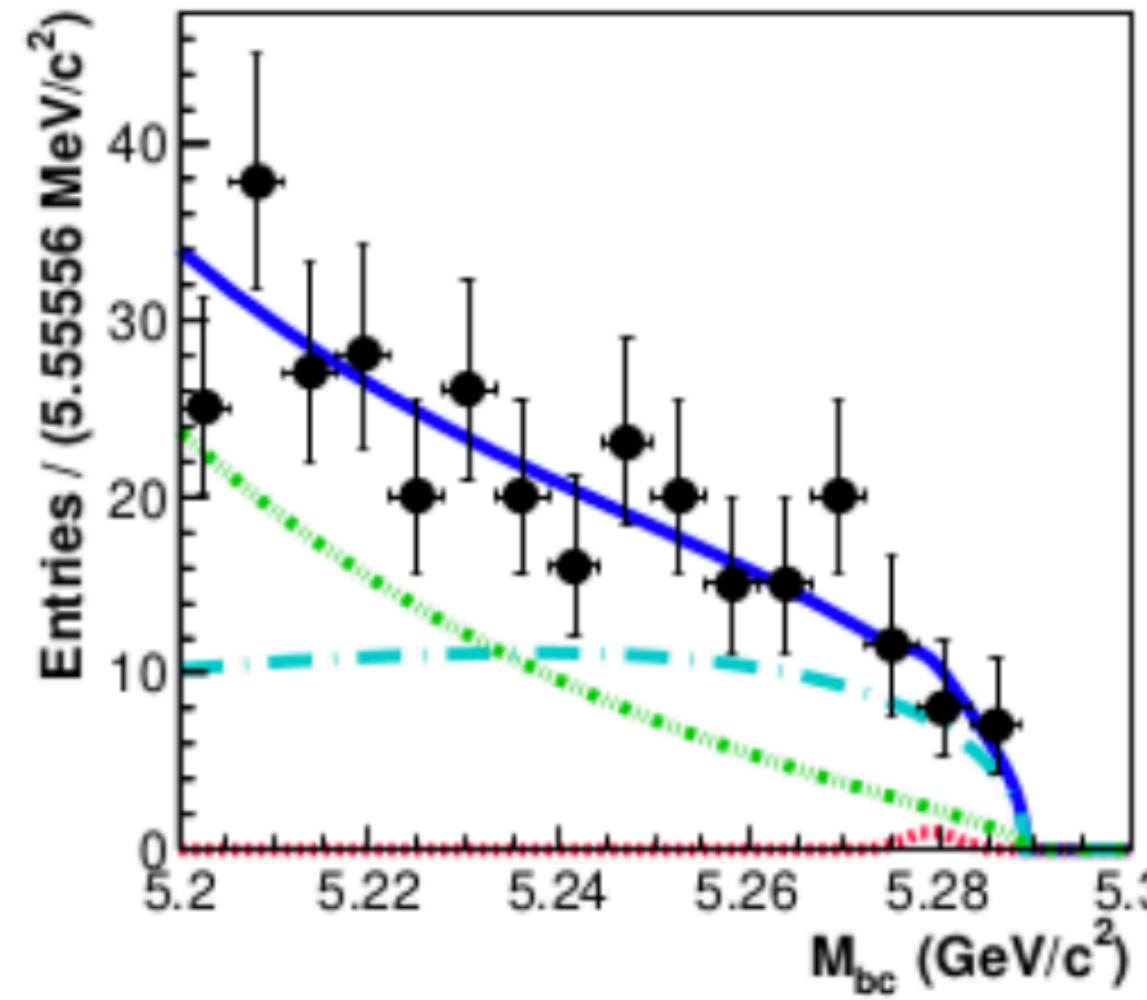
$$\mathcal{B}(B^+ \rightarrow K^+ \mu^+ e^-) < 8.5 \times 10^{-8}$$



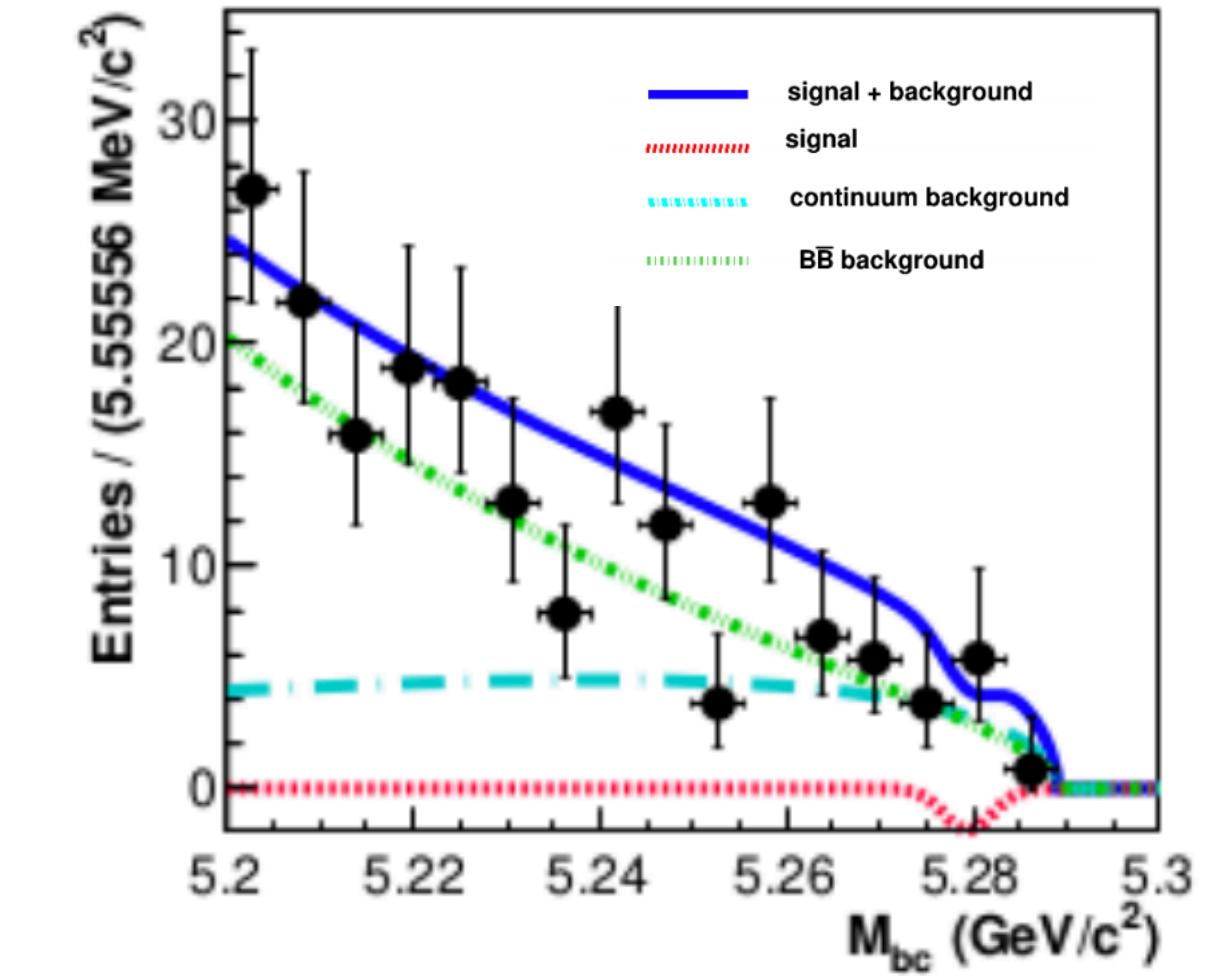
3.2 standard deviations above
BR is also quoted.



Could be a statistical fluctuation ?



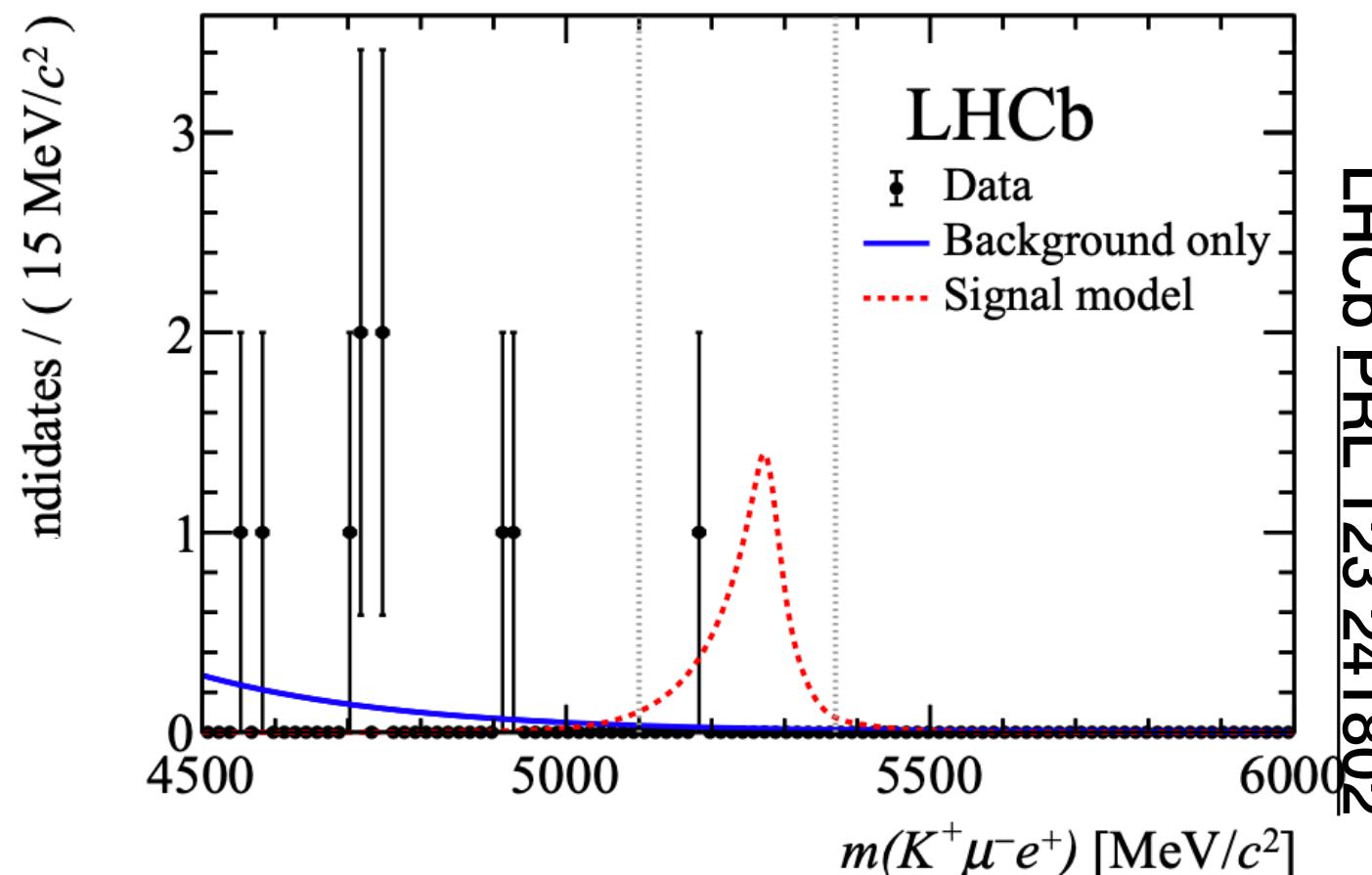
$$\mathcal{B}(B^+ \rightarrow K^+ \mu^- e^+) < 3.0 \times 10^{-8}$$



$$\mathcal{B}(B^0 \rightarrow K_s^0 \mu^\pm e^\mp) < 1.9 \times 10^{-8}$$

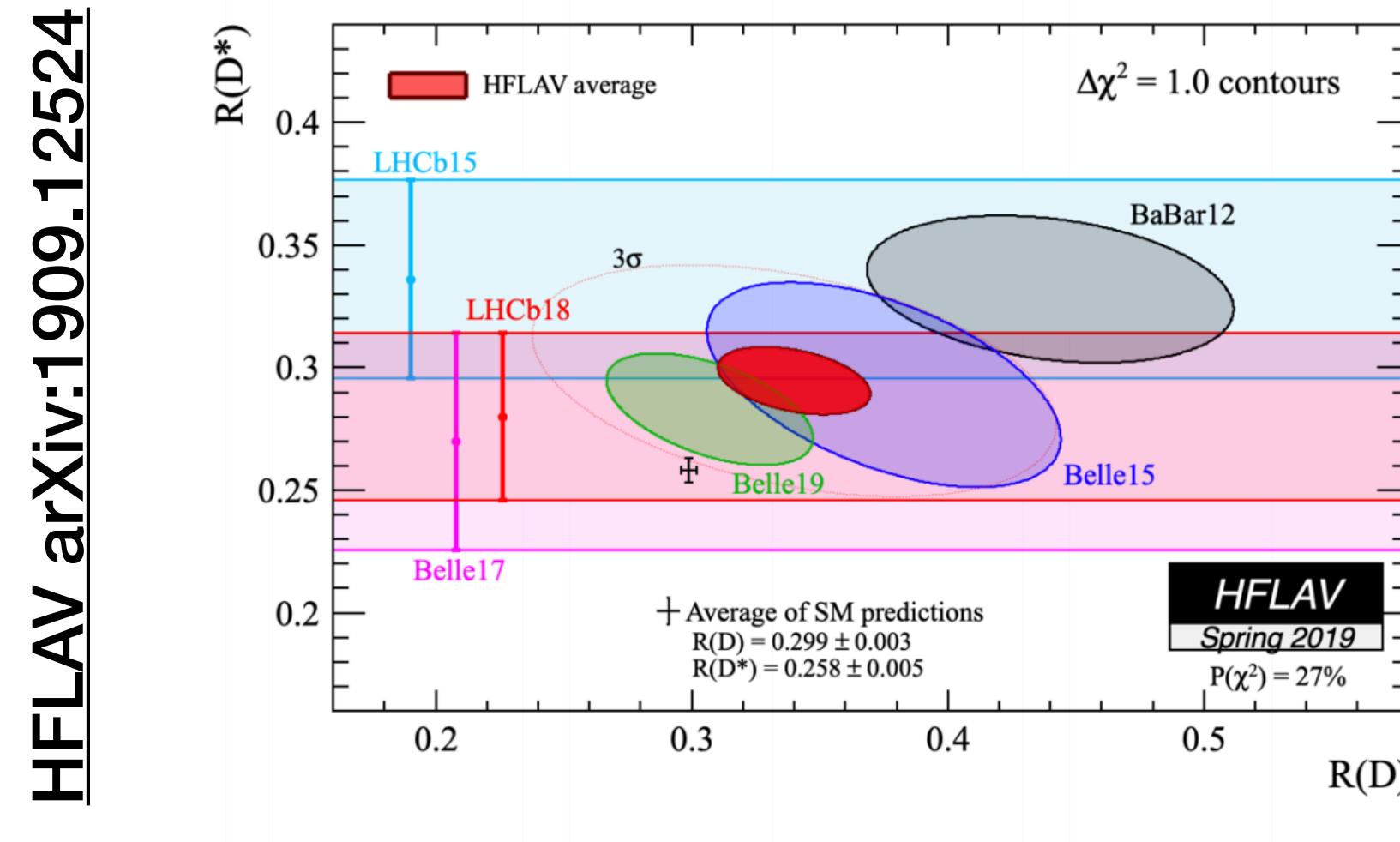
However the limit from LHCb

	90% C. L.	95% C. L.
$\mathcal{B}(B^+ \rightarrow K^+ \mu^- e^+)/10^{-9}$	7.0	9.5
$\mathcal{B}(B^+ \rightarrow K^+ \mu^+ e^-)/10^{-9}$	6.4	8.8

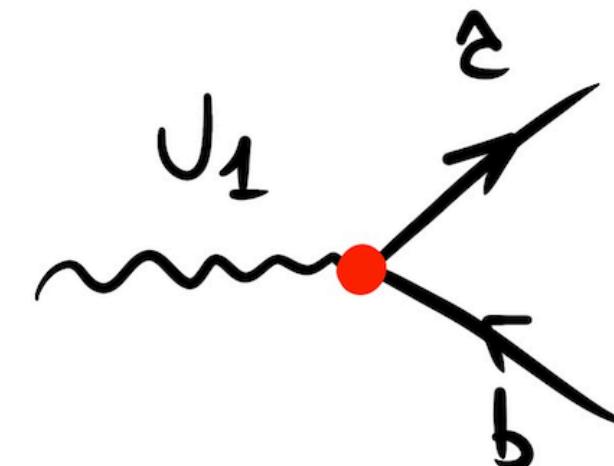


$$B^+ \rightarrow K^+ \tau^+ \mu^-$$

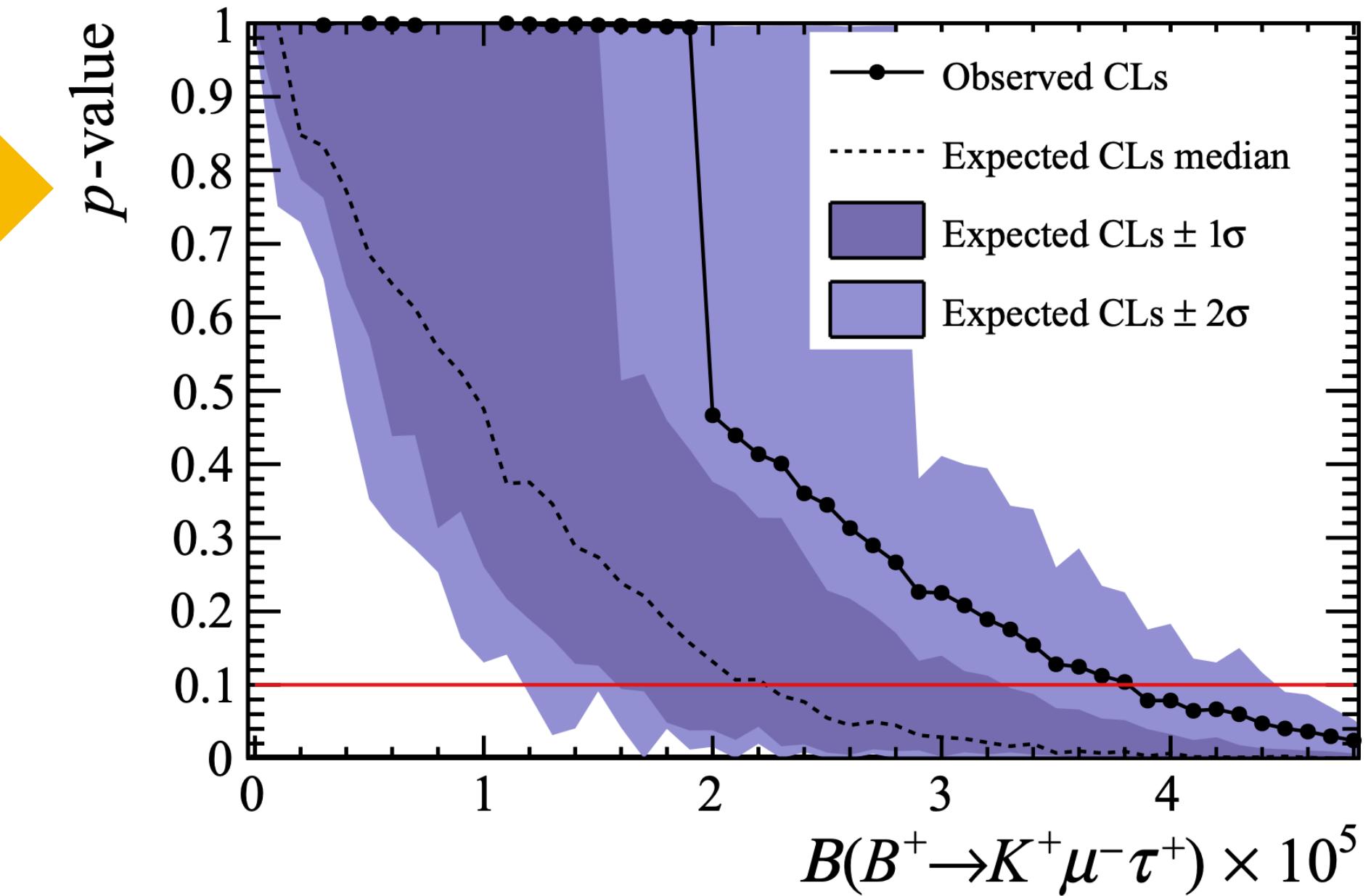
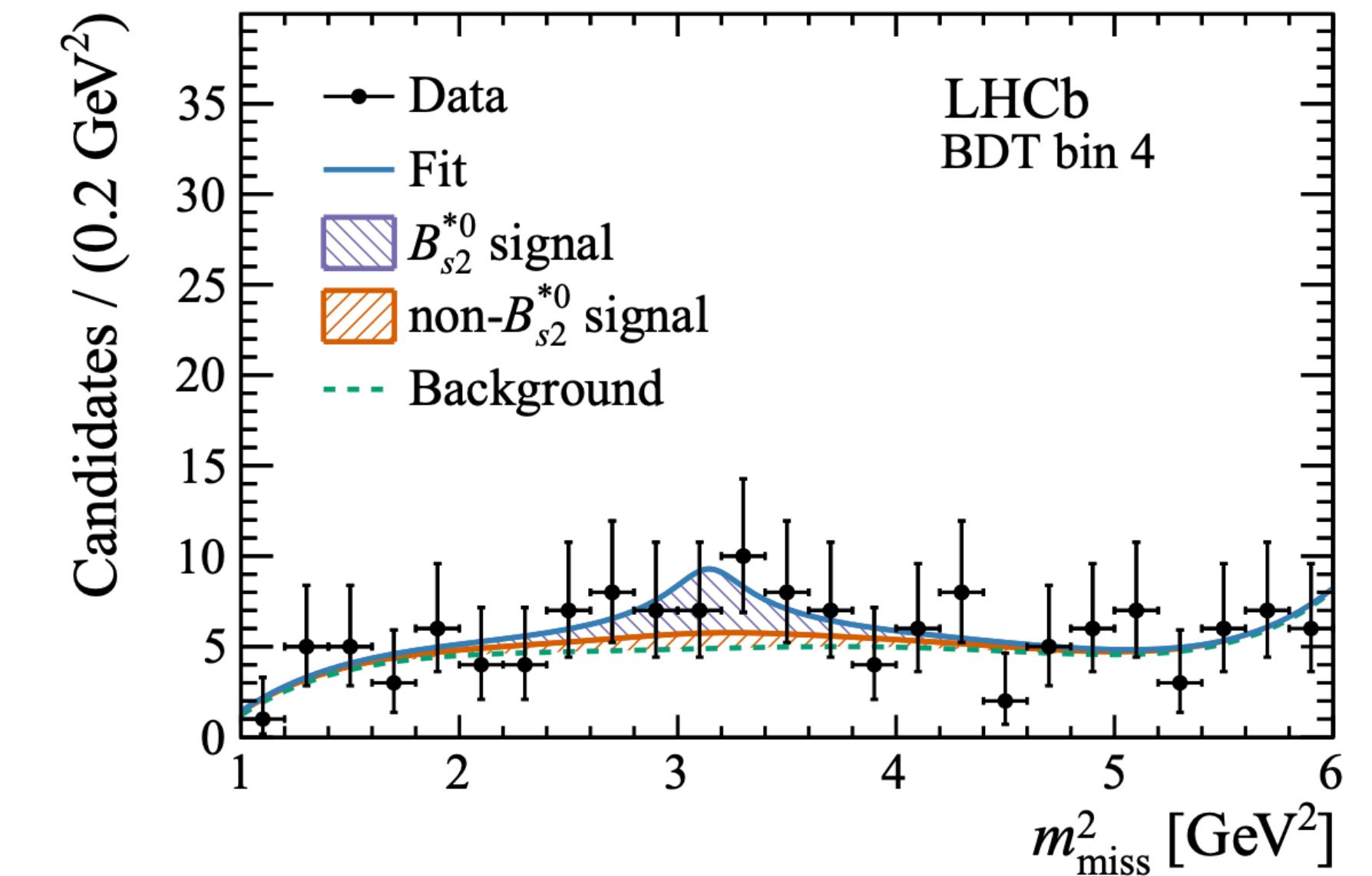
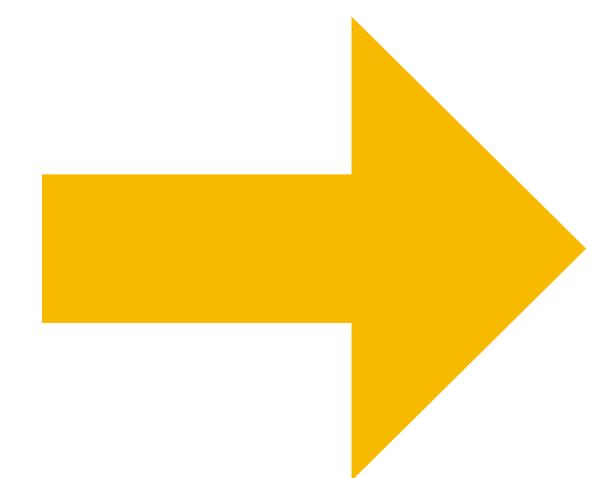
Let us not forget about the third family of Leptons !



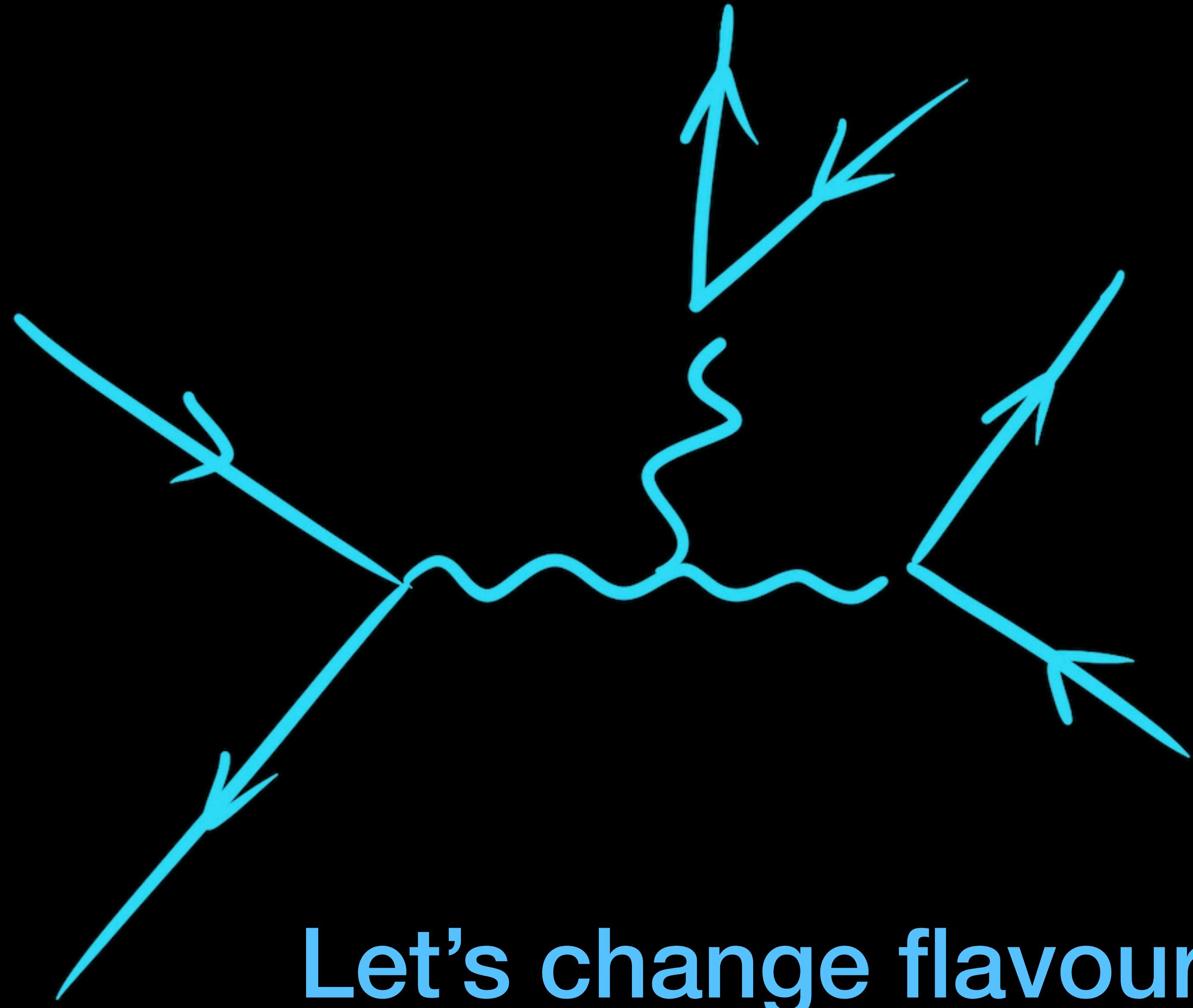
Example of a theoretical model that predicts the existence of LQ



for ex: Cornella et al. arXiv:1903.11517

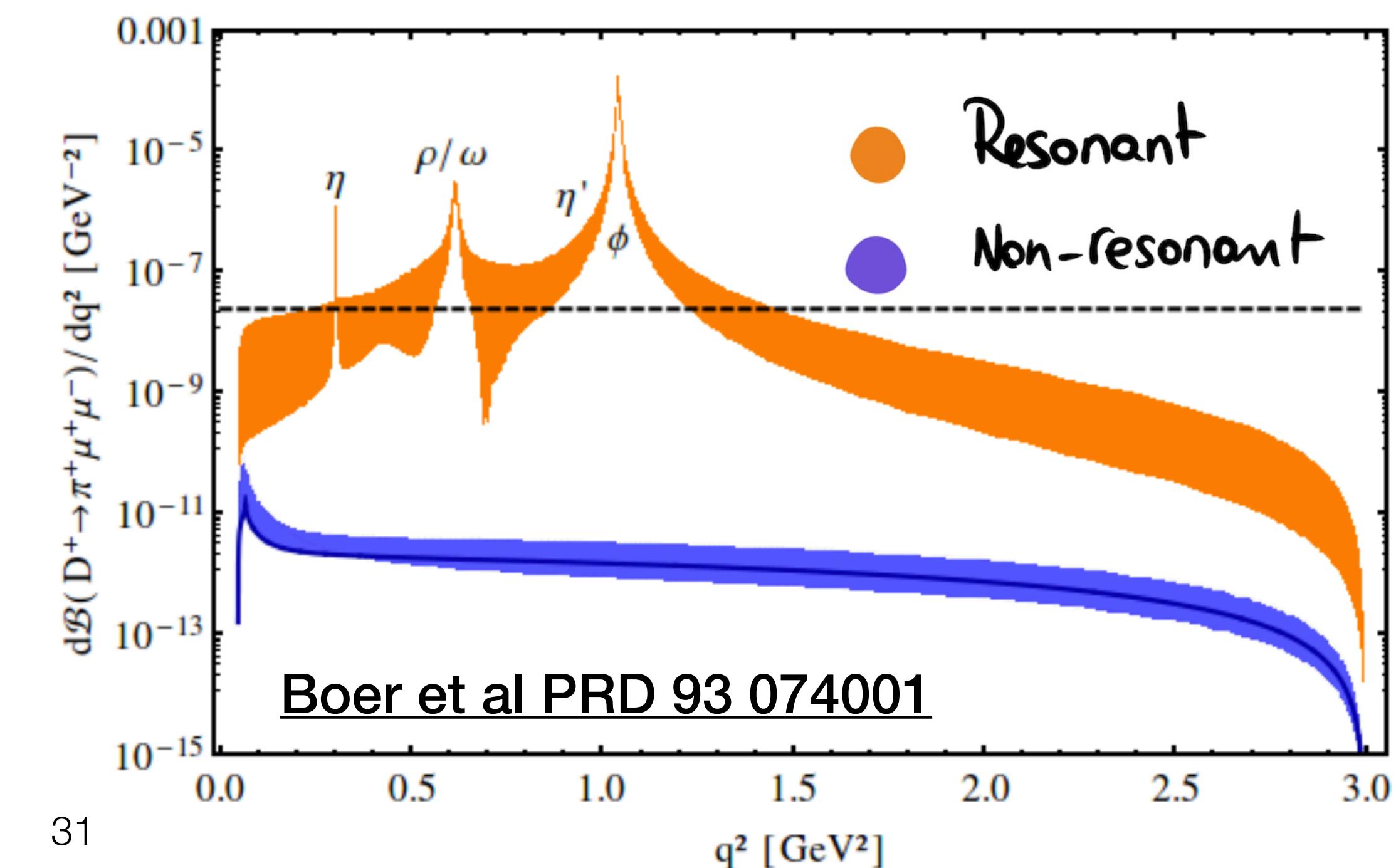
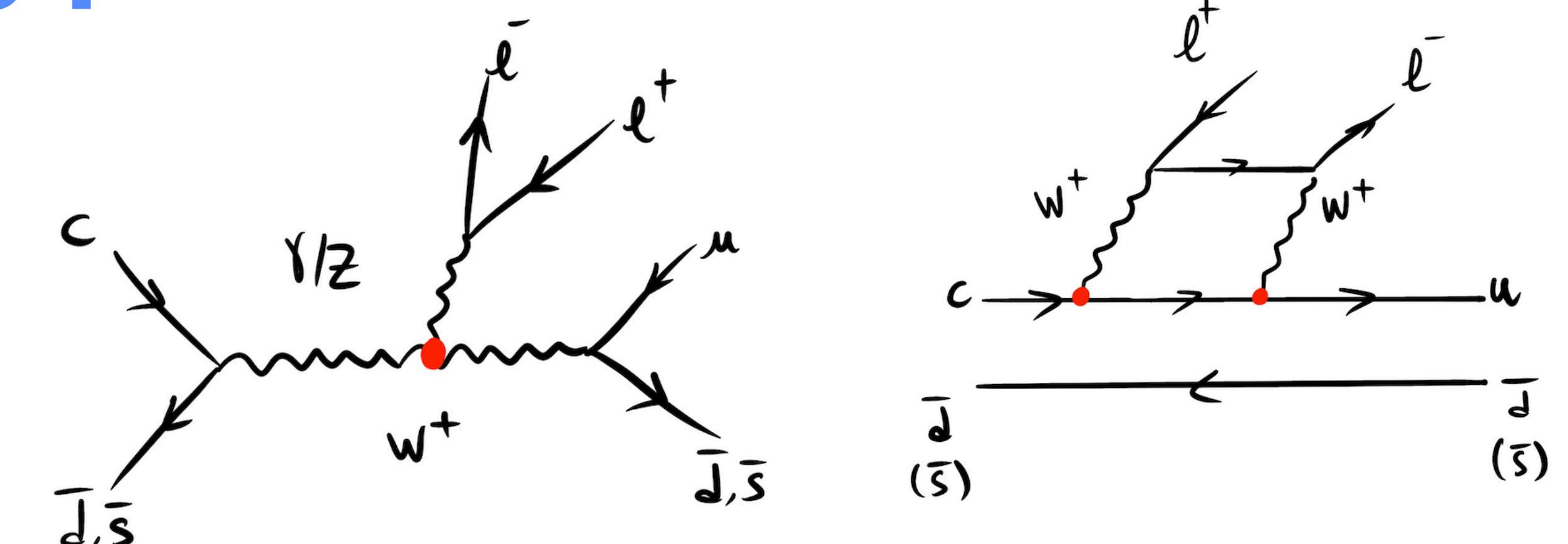
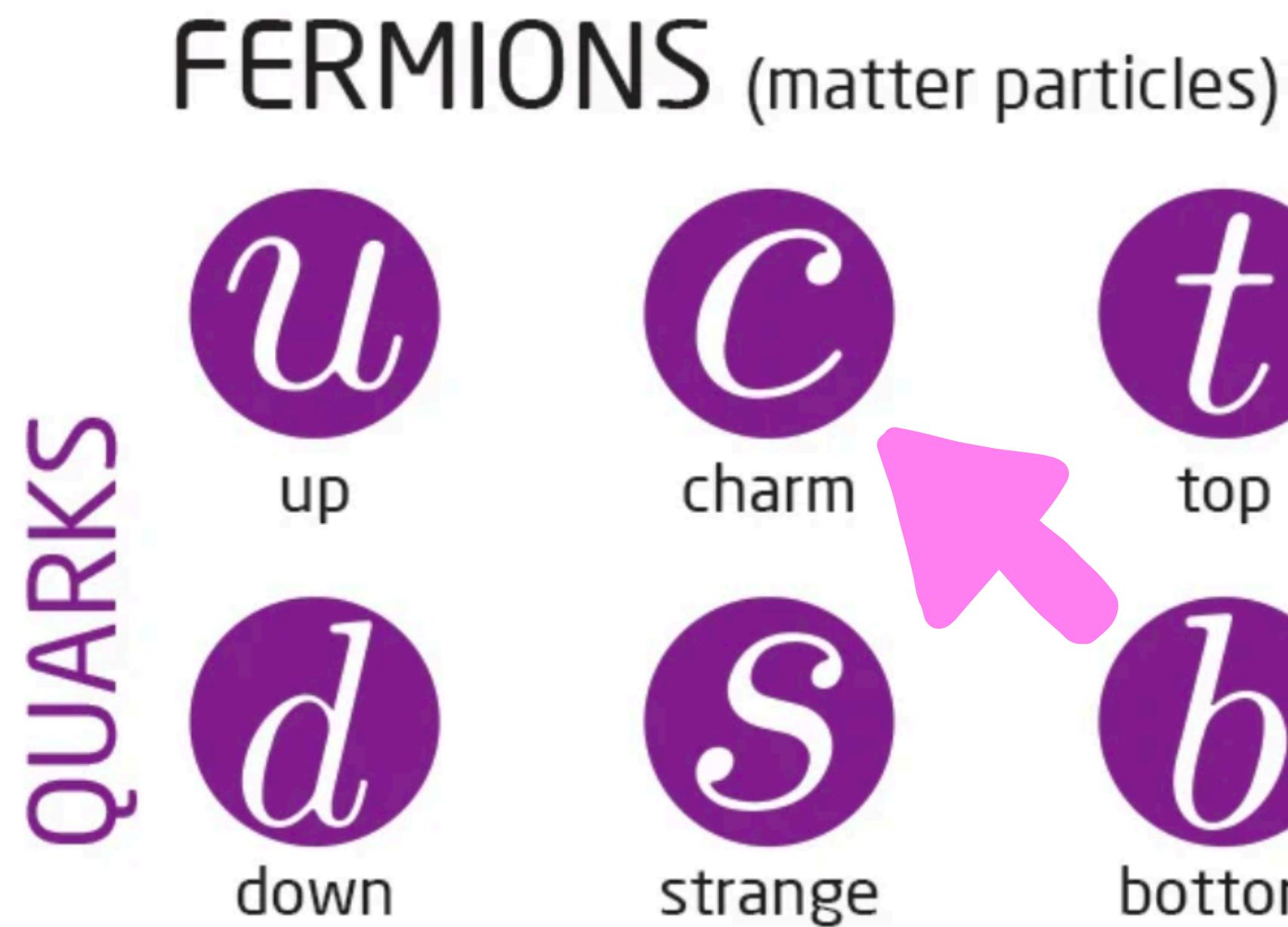


$\mathcal{B}(B^+ \rightarrow K^+ \mu^- \tau^+) < 3.9 \times 10^{-5}$ at 90% CL,

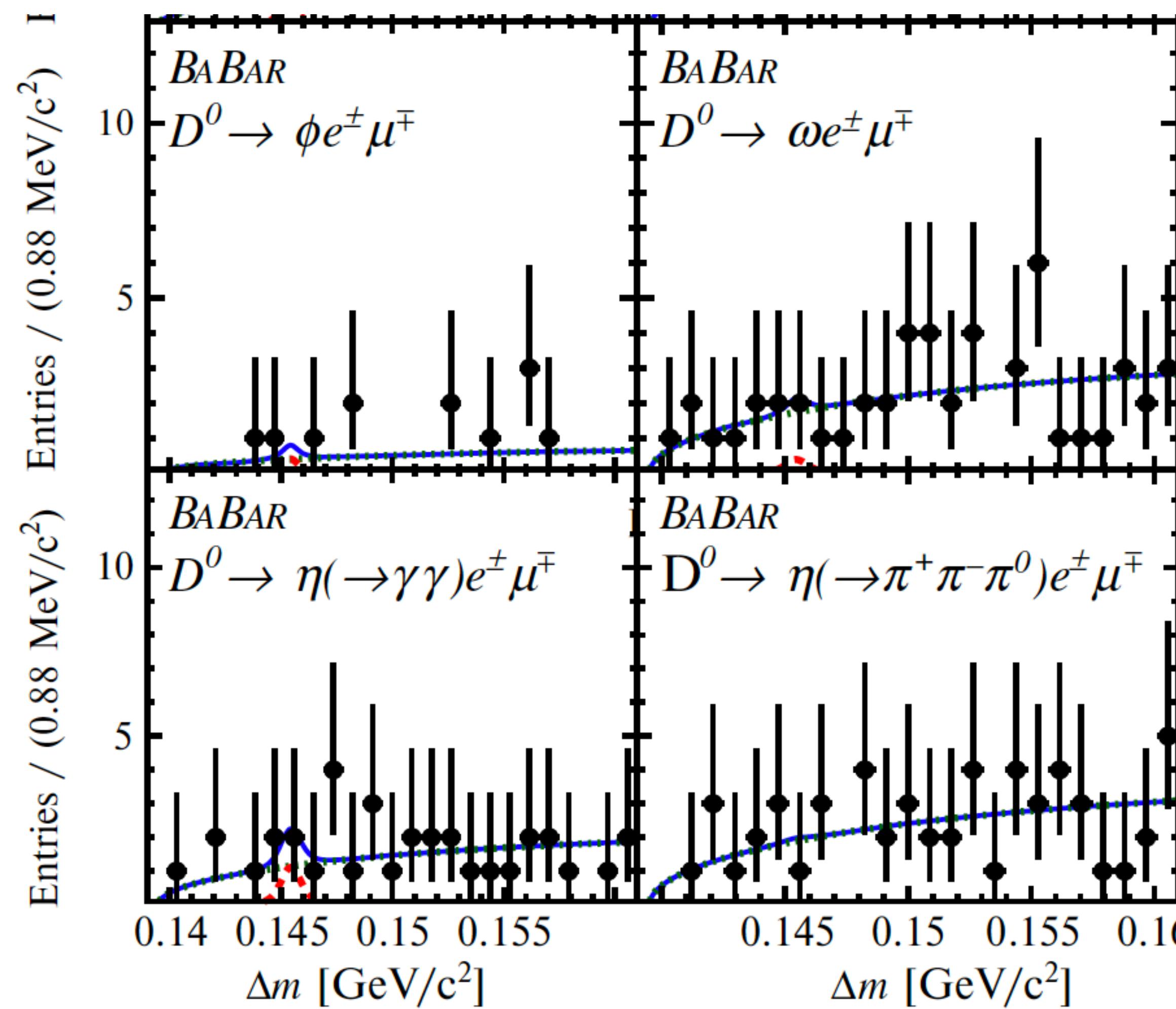


Let's change flavours

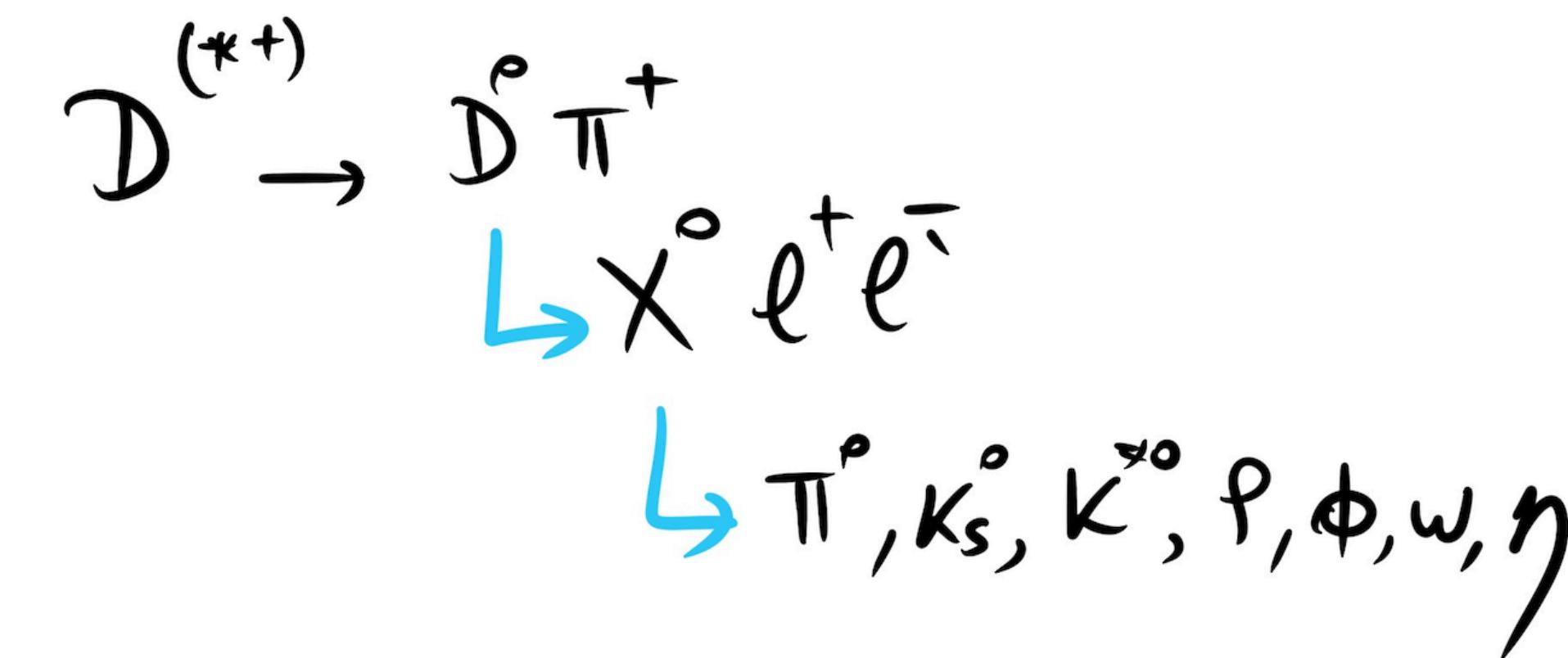
Let's change families !



$D^0 \rightarrow X^0 e^\pm \mu^\mp$ searches



Decay chains :



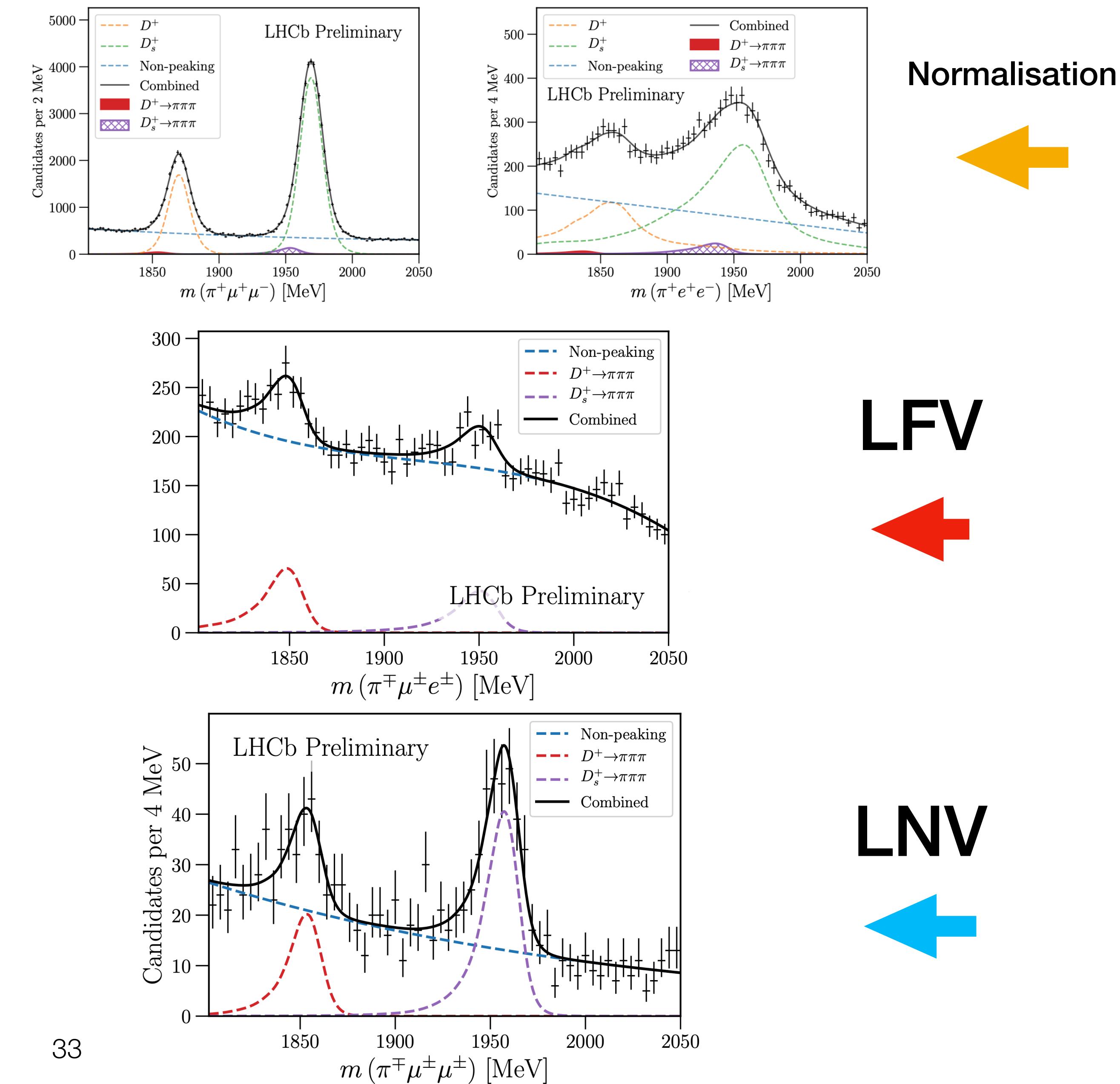
Extended unbinned maximum likelihood
fit to Δm to extract the signal yield

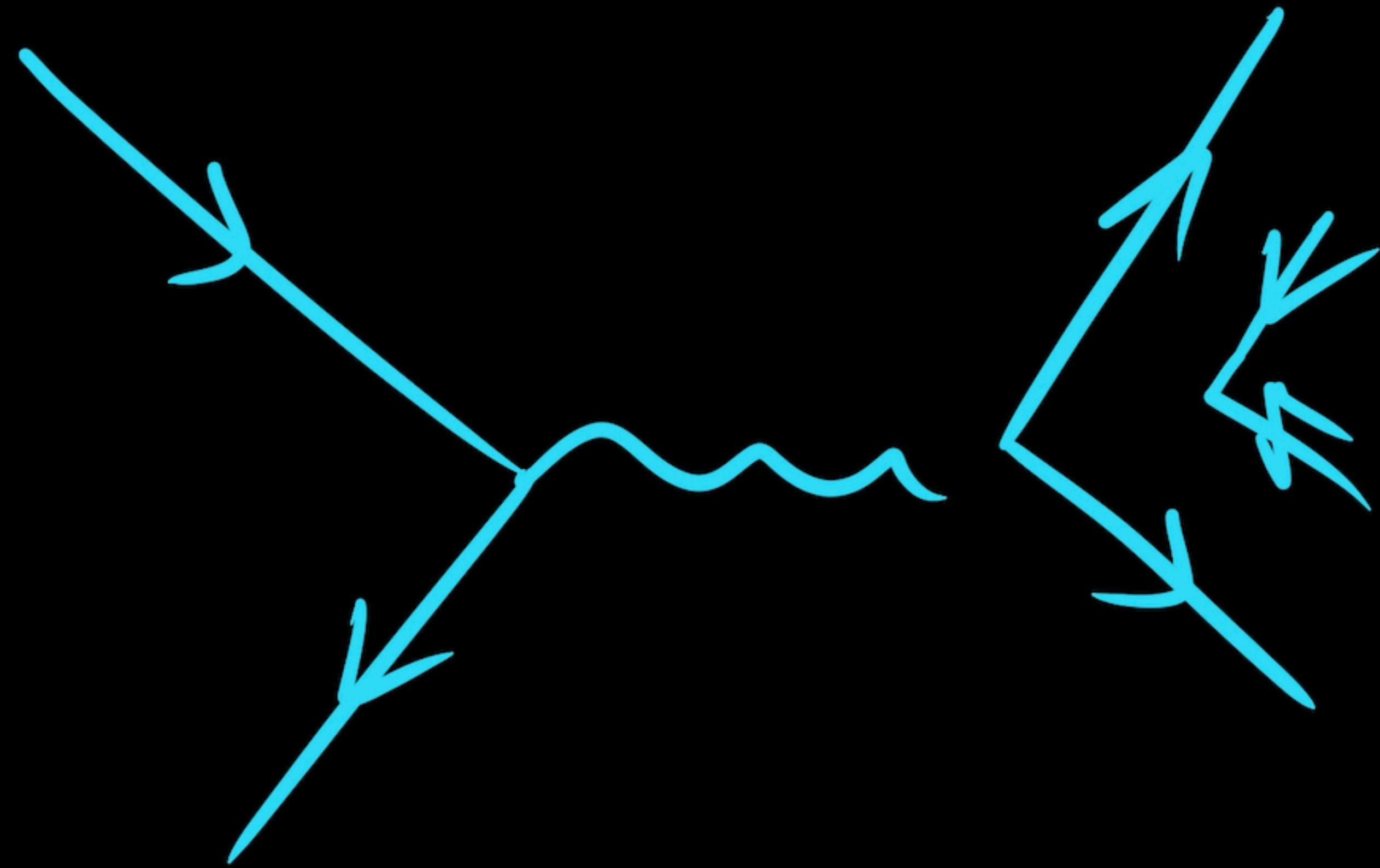
Searches for 25 rare and forbidden decays

- Four rare charm decays $D^+ \rightarrow \pi^+ \ell^+ \ell^-$ and $D_s^+ \rightarrow K^+ \ell^+ \ell^-$:
 - $c \rightarrow u\ell^+\ell^-$ and weak annihilation diagrams
 - dominated by light resonances ($\eta, \rho, \omega, \phi \rightarrow \ell^+ \ell^-$)
 - excluded the region $525 < m(\ell^+ \ell^-) < 1250$ MeV
- Four weak-annihilation decays $D^+ \rightarrow K^+ \ell^+ \ell^-$ and $D_s^+ \rightarrow \pi^+ \ell^+ \ell^-$
- Eight $D_{(s)}^+ \rightarrow h^+ \ell^+ \ell^-$ LFV modes ($h = \pi, K$)
- Nine $D_{(s)}^+ \rightarrow h^- \ell^+ \ell^+$ and $D_{(s)}^+ \rightarrow h^- \ell^+ \ell'^+$ LNV modes
- Normalised and calibrated with $D_{(s)}^+ \rightarrow \pi^+ \phi(\ell^+ \ell^-)$

Even if mis-identified components are significant, all the data is described well by background only models.

23 world's best limits !

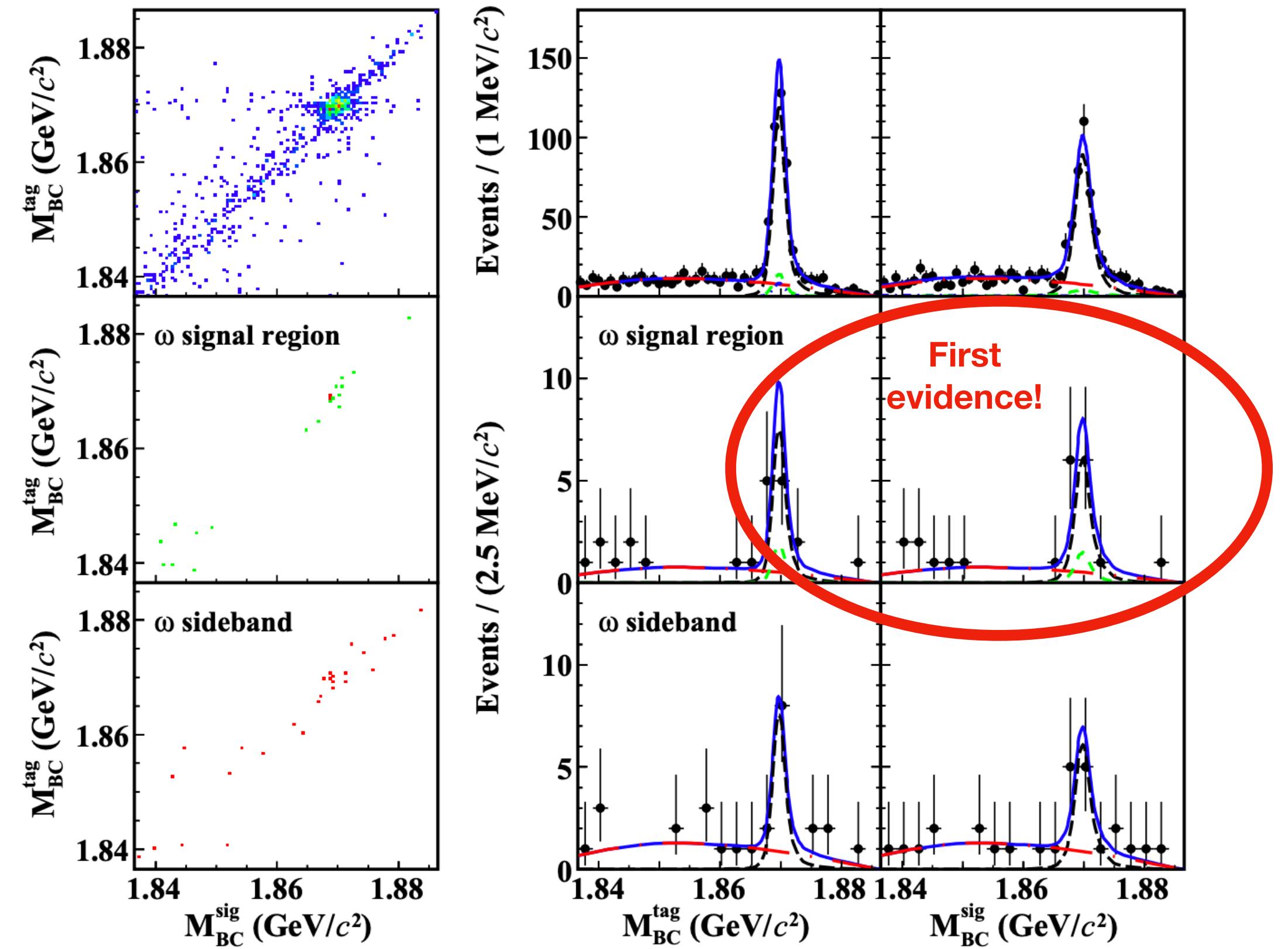
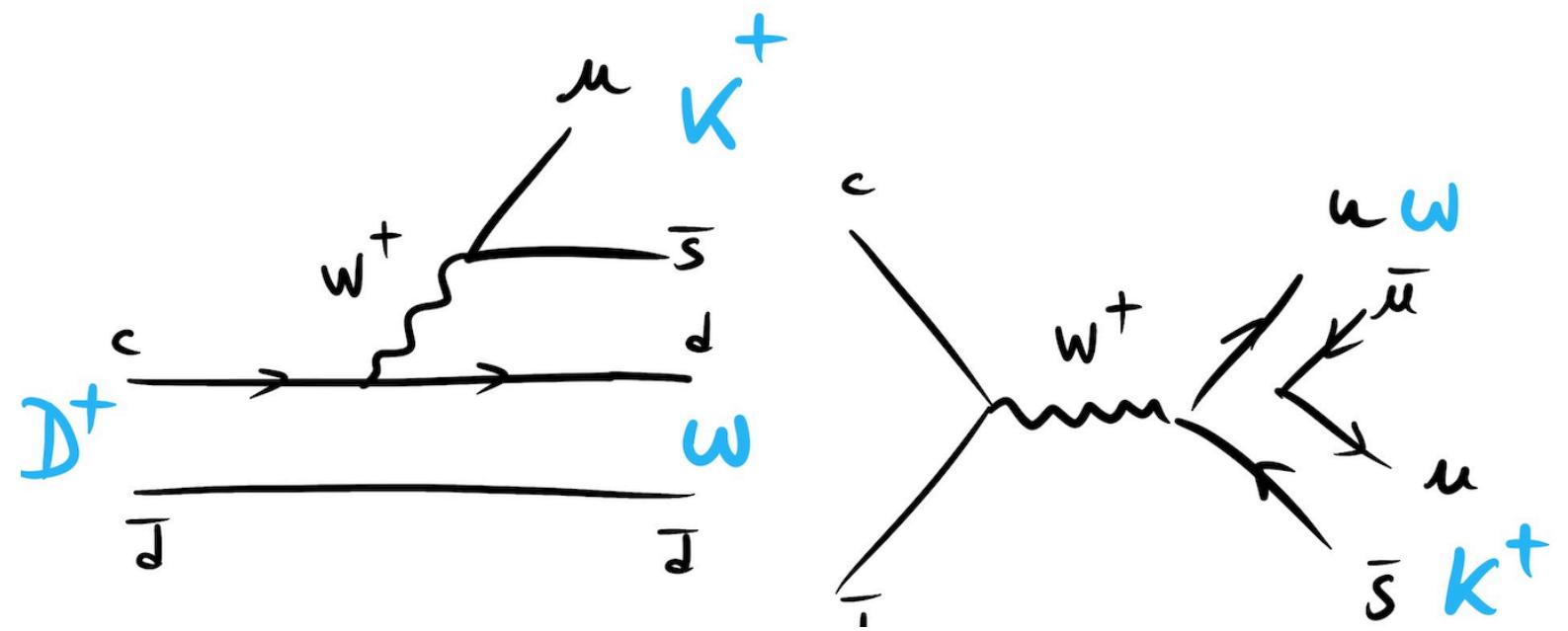




How about testing symmetries

DCS of D decays

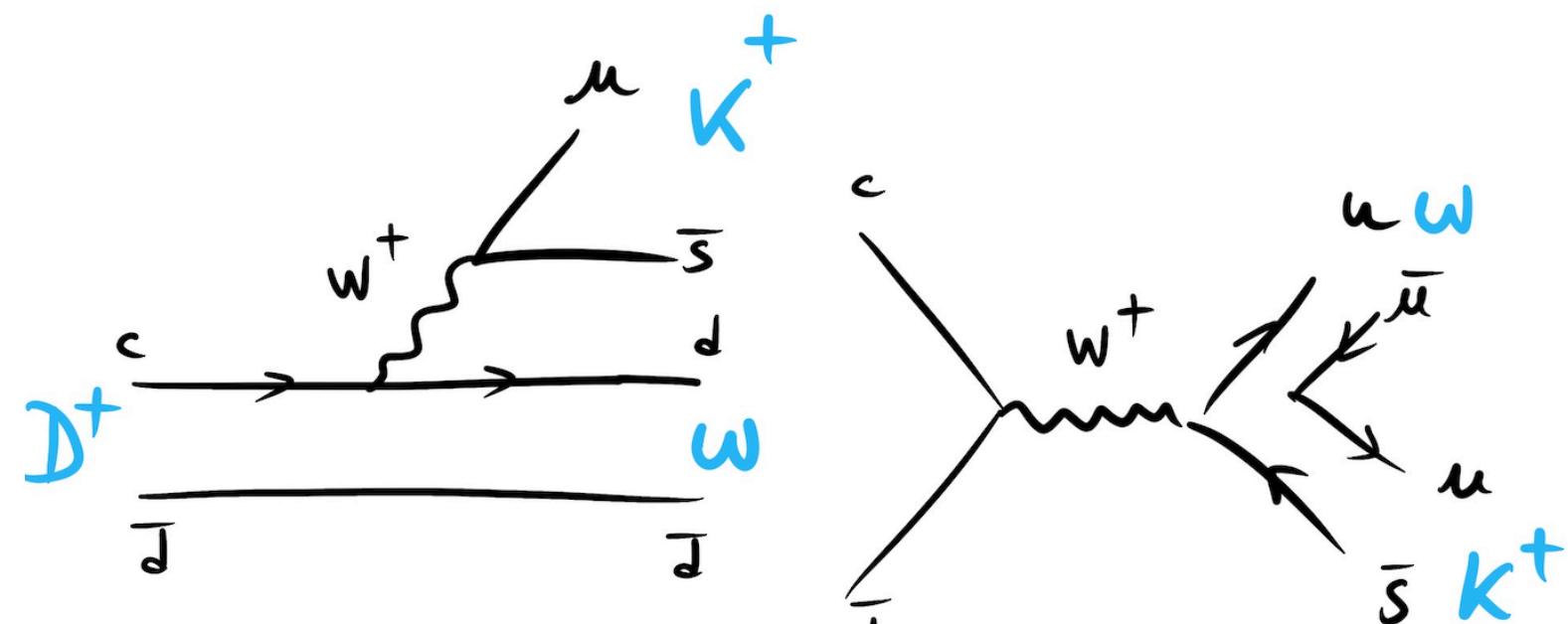
Will give more constraint to understand SU(3) flavor symmetry and its break effects.



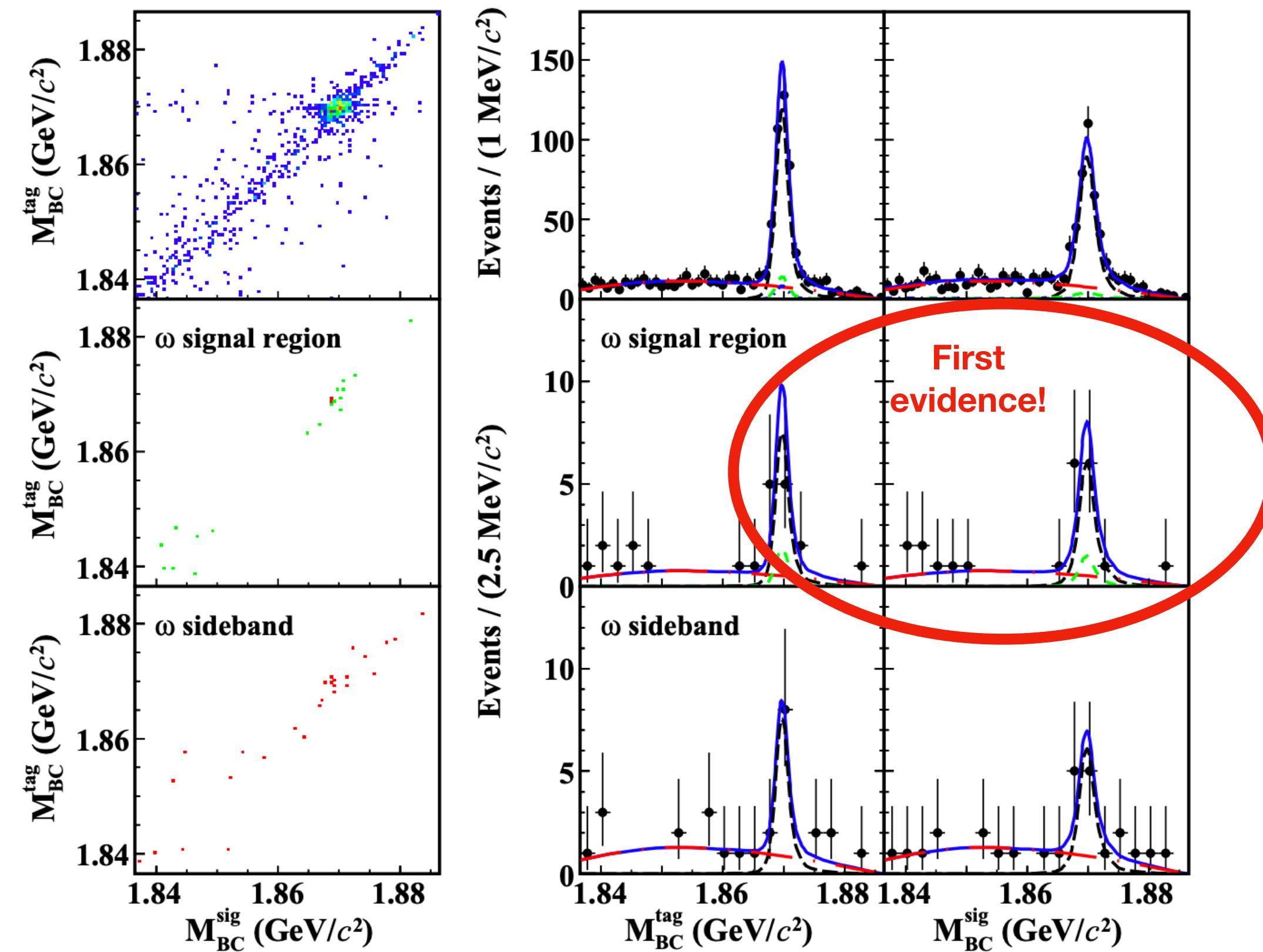
DCS of D decays



Will give more constraint to understand SU(3) flavor symmetry and its break effects.



Expectation: $\frac{\text{doubly Cabibbo-suppressed}}{\text{Cabibbo-favored}} \propto \tan^4 \theta_C \sim 0.29\%$.



First observation & measurement of branching fraction !

$$\frac{\mathcal{B}_{D^+ \rightarrow K^+ \pi^+ \pi^- \pi^0}}{\mathcal{B}_{D^+ \rightarrow K^- \pi^+ \pi^+ \pi^0}} = (6.28 \pm 0.52) \tan^4 \theta_C$$

Large isospin violation in these decays probably due to final state interactions.

Conclusion

The field of flavour physics and rare decays in particular is very exciting.

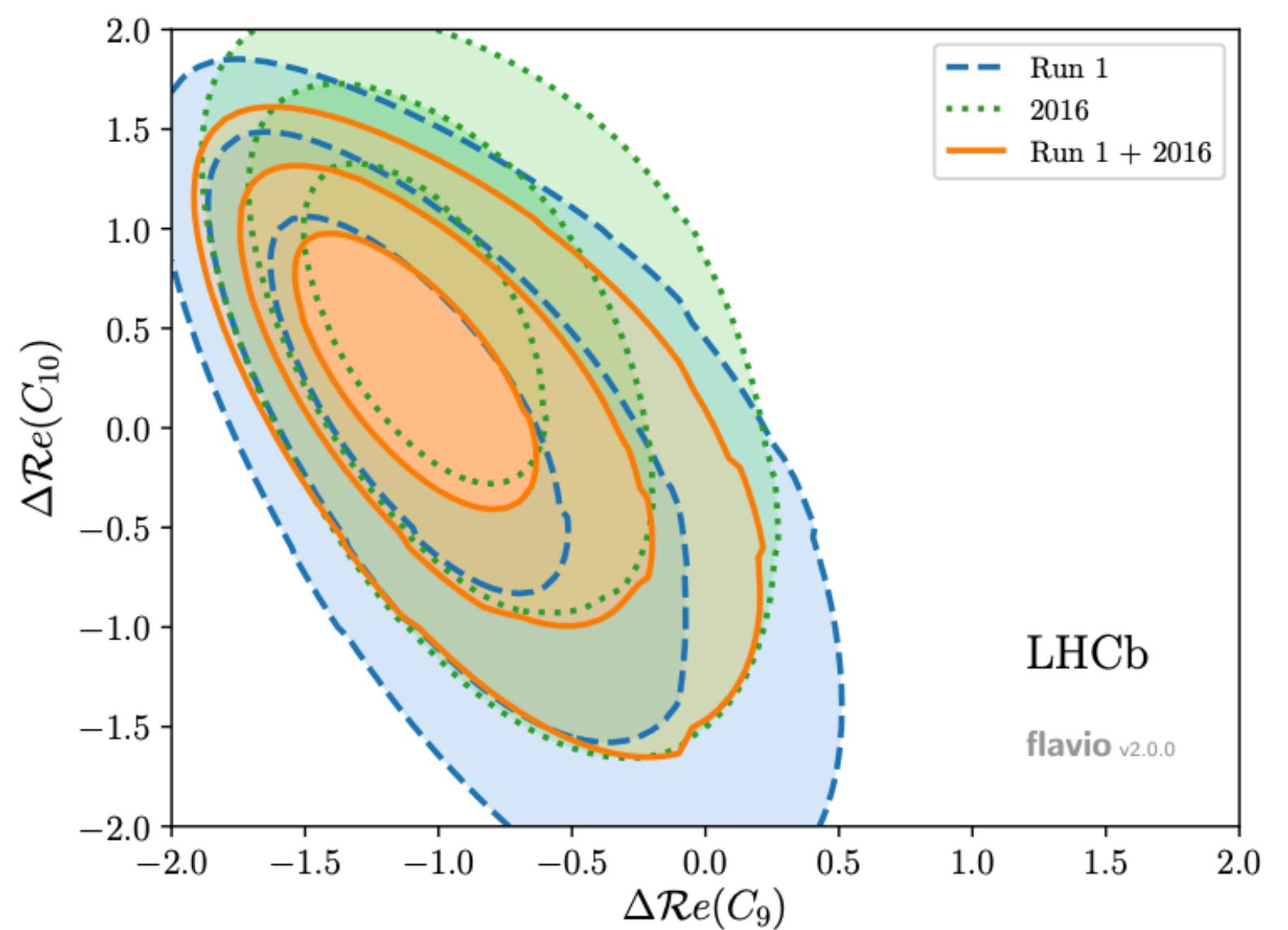
We are “seeing” a coherent pattern of tensions in b -decays
which opens the route to many interesting studies and questions to be addressed.

We are pursuing the exploration of rare and forbidden charm decays.

These are exciting times...really.

We are looking forward to see if these patterns hold and lead to even more
curious results.

Thank you !



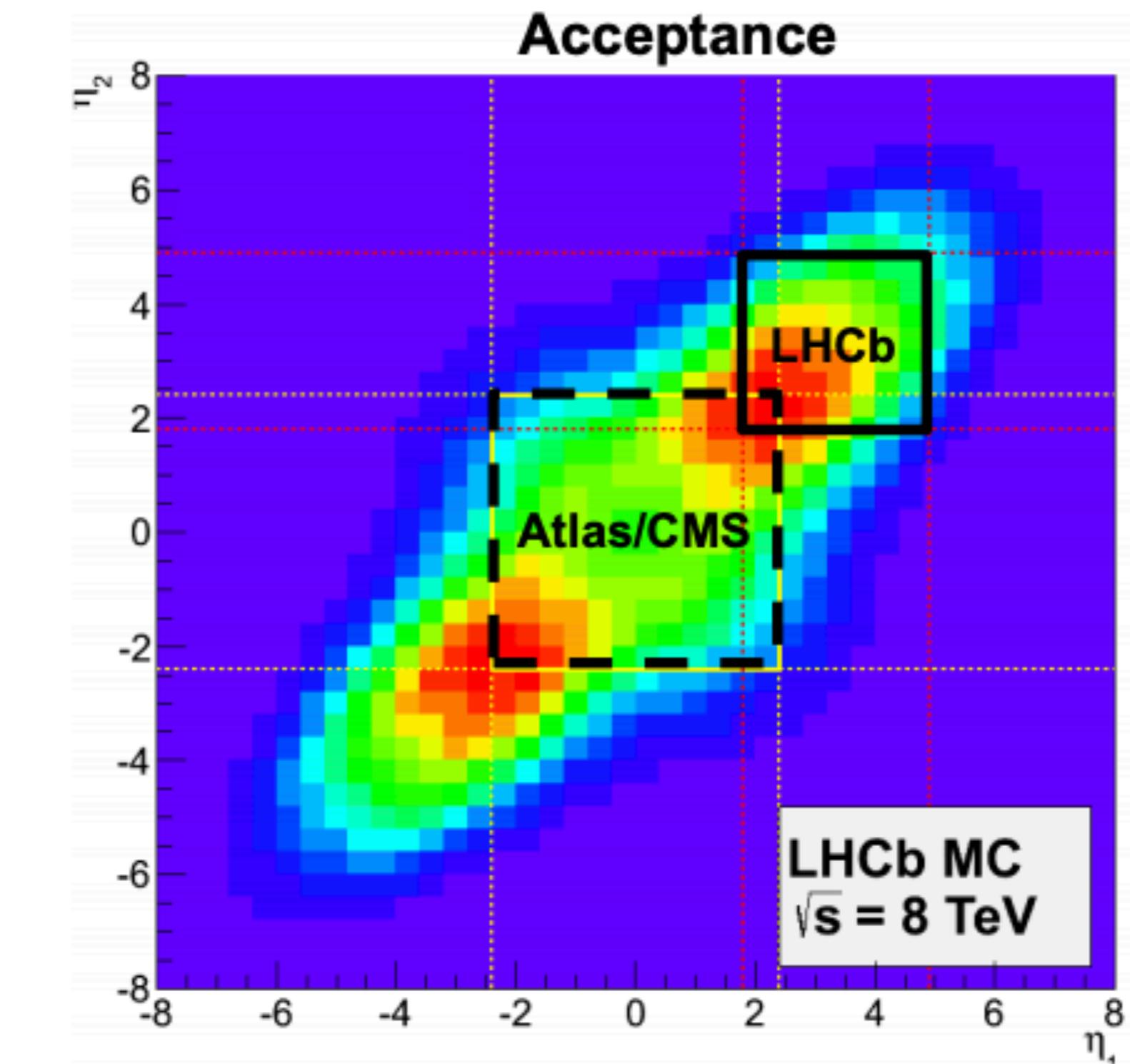
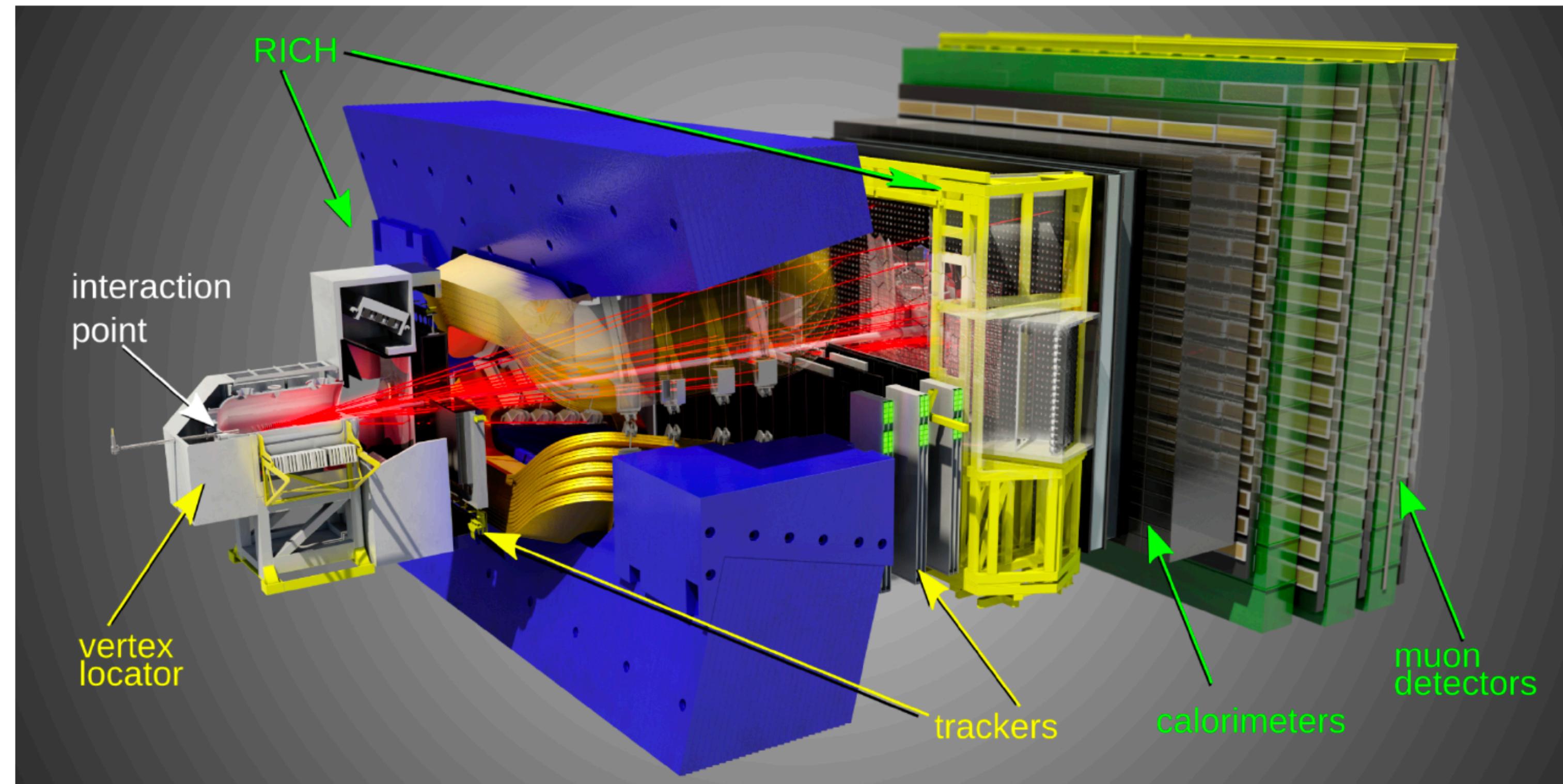


Be safe keep & looking for cool things.

The LHCb detector

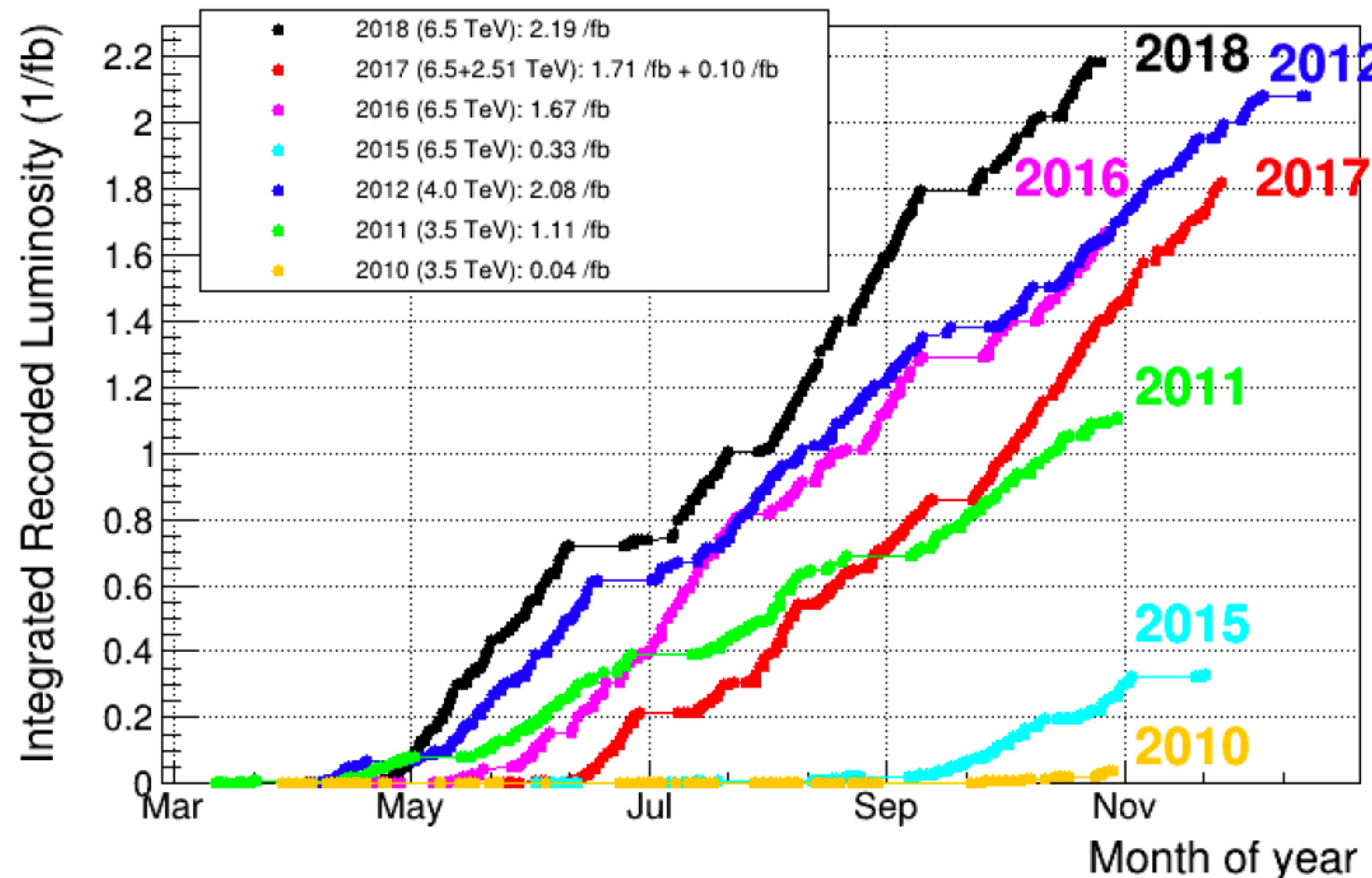


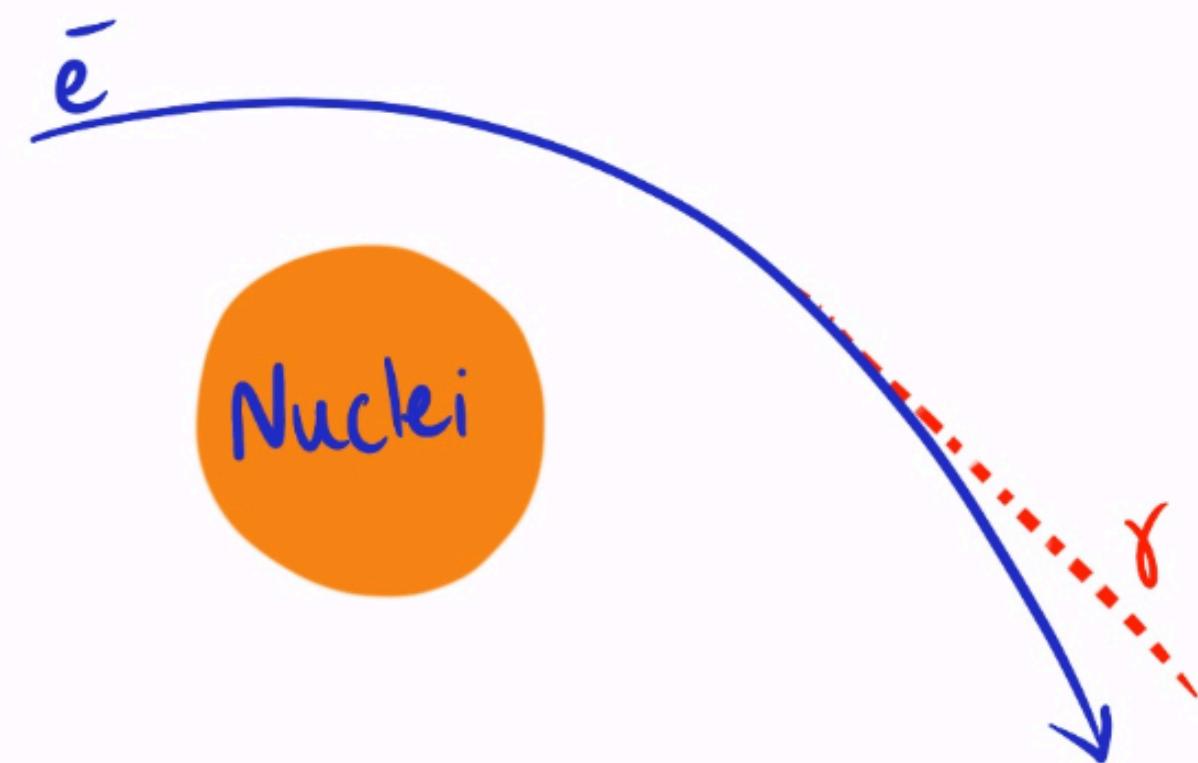
The LHCb detector



- Good vertex and impact parameter resolution $\sigma(\text{IP}) = 15 + 29/p_T$ mm.
- Excellent momentum resolution ~ 25 MeV/c² two-body decays.
- Excellent particle ID (μ -ID 97% for $(\pi \rightarrow \mu)$ misID of 1-3%).
- Versatile & efficient trigger.

LHCb Integrated Recorded Luminosity in pp, 2010-2018





Bremsstrahlung @ LHCb

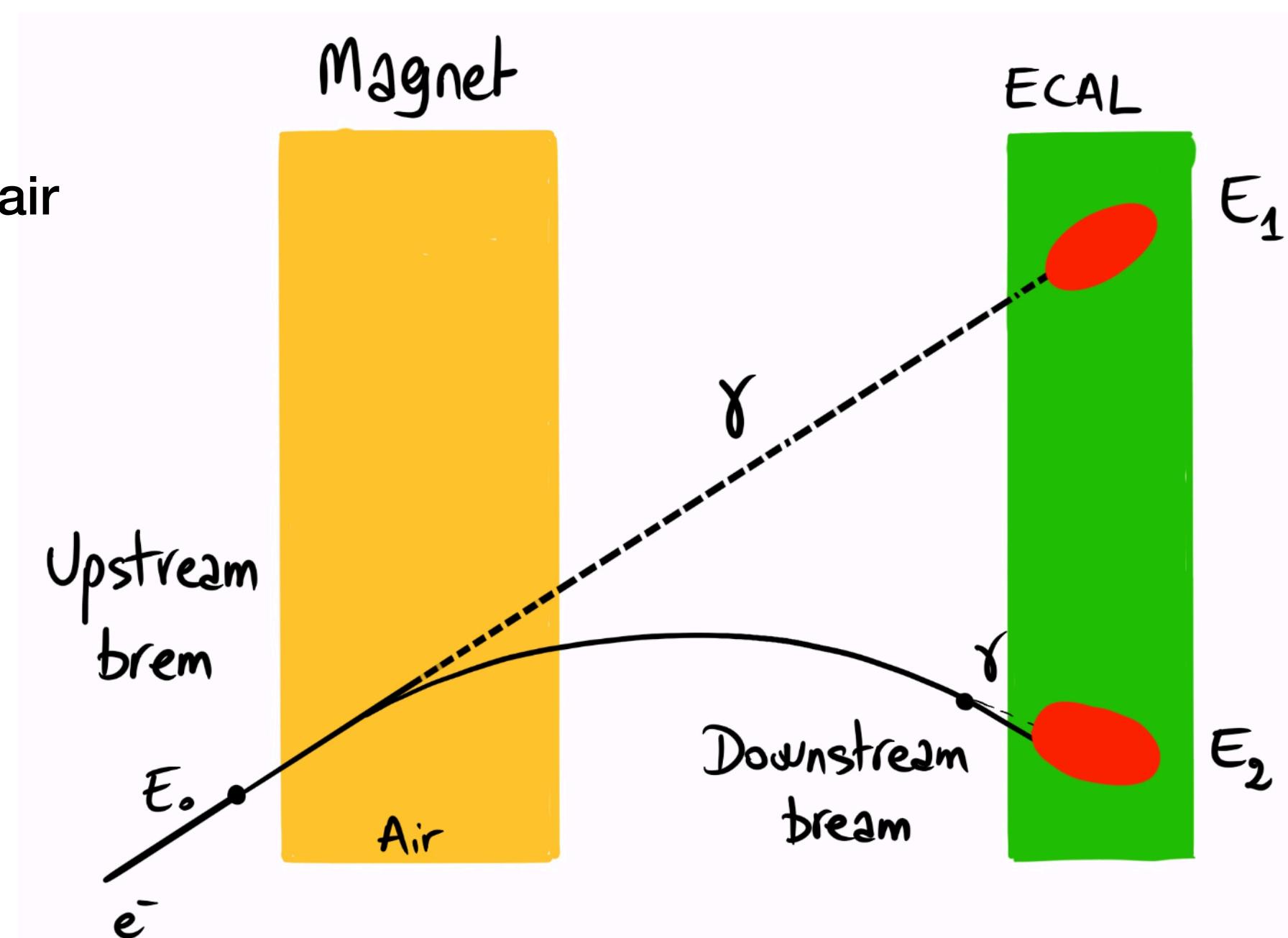
Electrons emit bremsstrahlung photons when cross the material
 Match electron tracks to photon clusters in the ECAL
 Correct electron momenta by “attaching” photons.

$$\sigma \propto 1/m_l^2$$

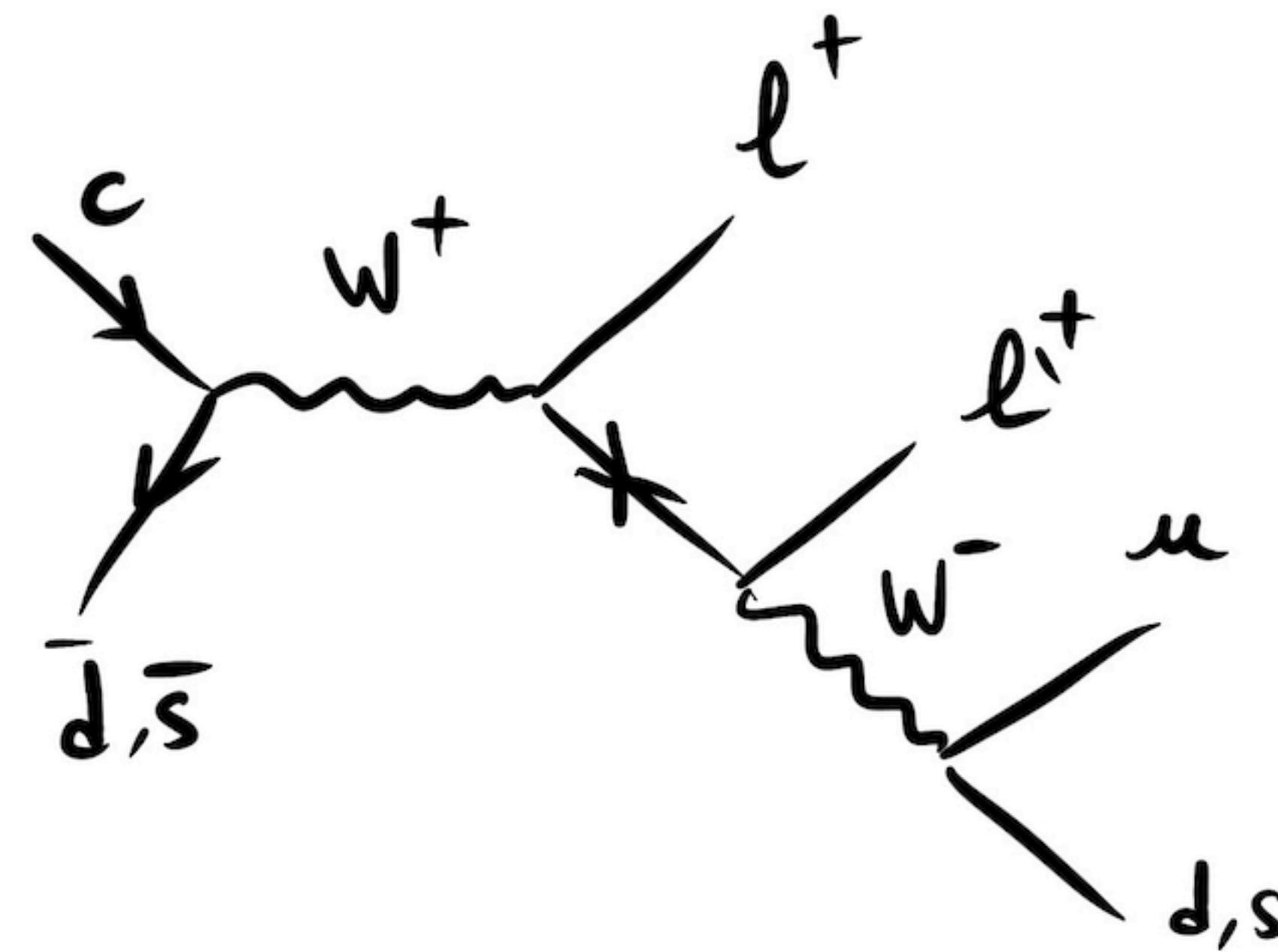
Energy loss $\propto E_e$

Energy loss \propto material

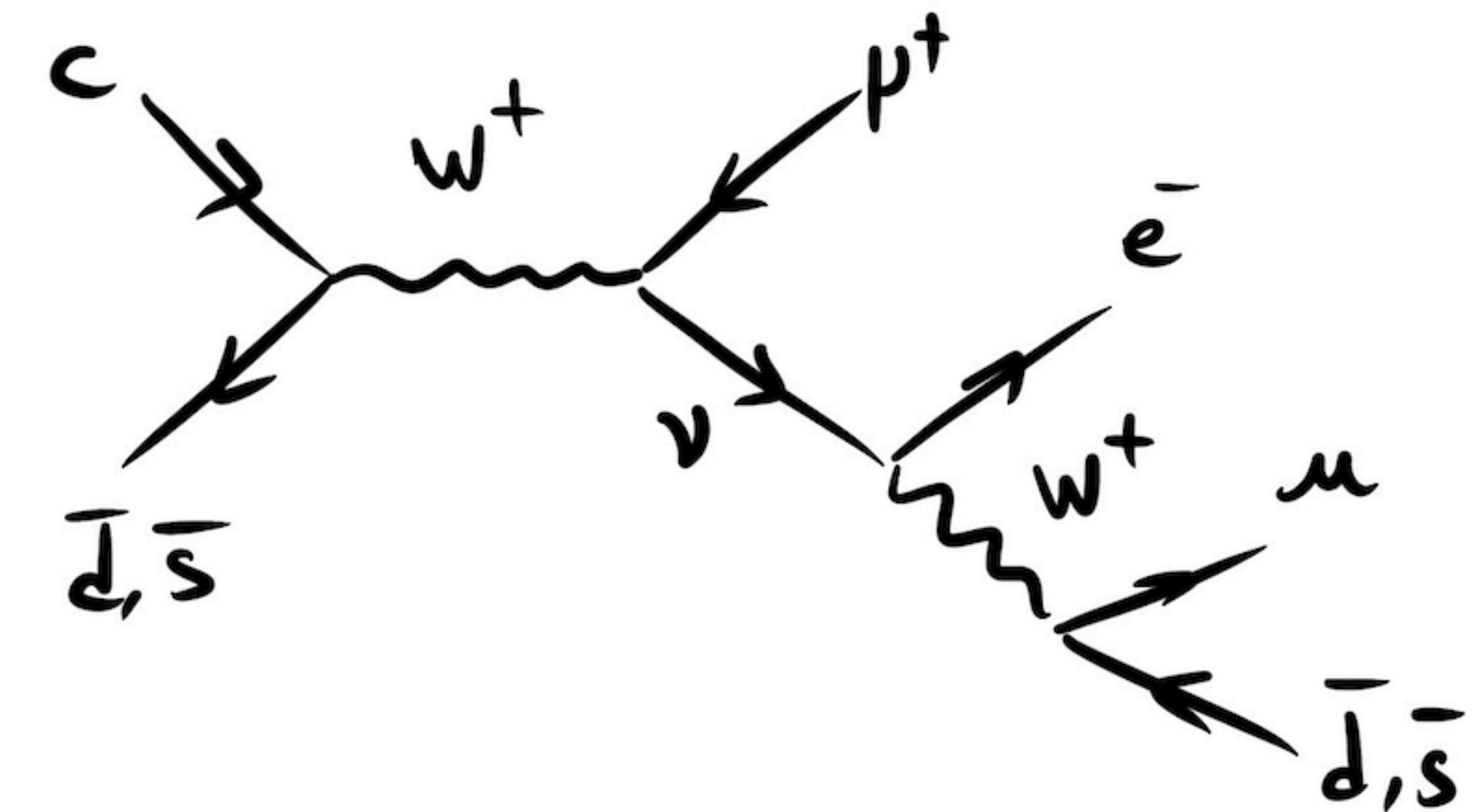
Three categories of events: 0, 1, > 1 photons attached to dielectron pair
 Different invariant mass shapes due to under- or over-correcting
 ECAL resolution is worse than tracker.



How can these decays be enhanced ?

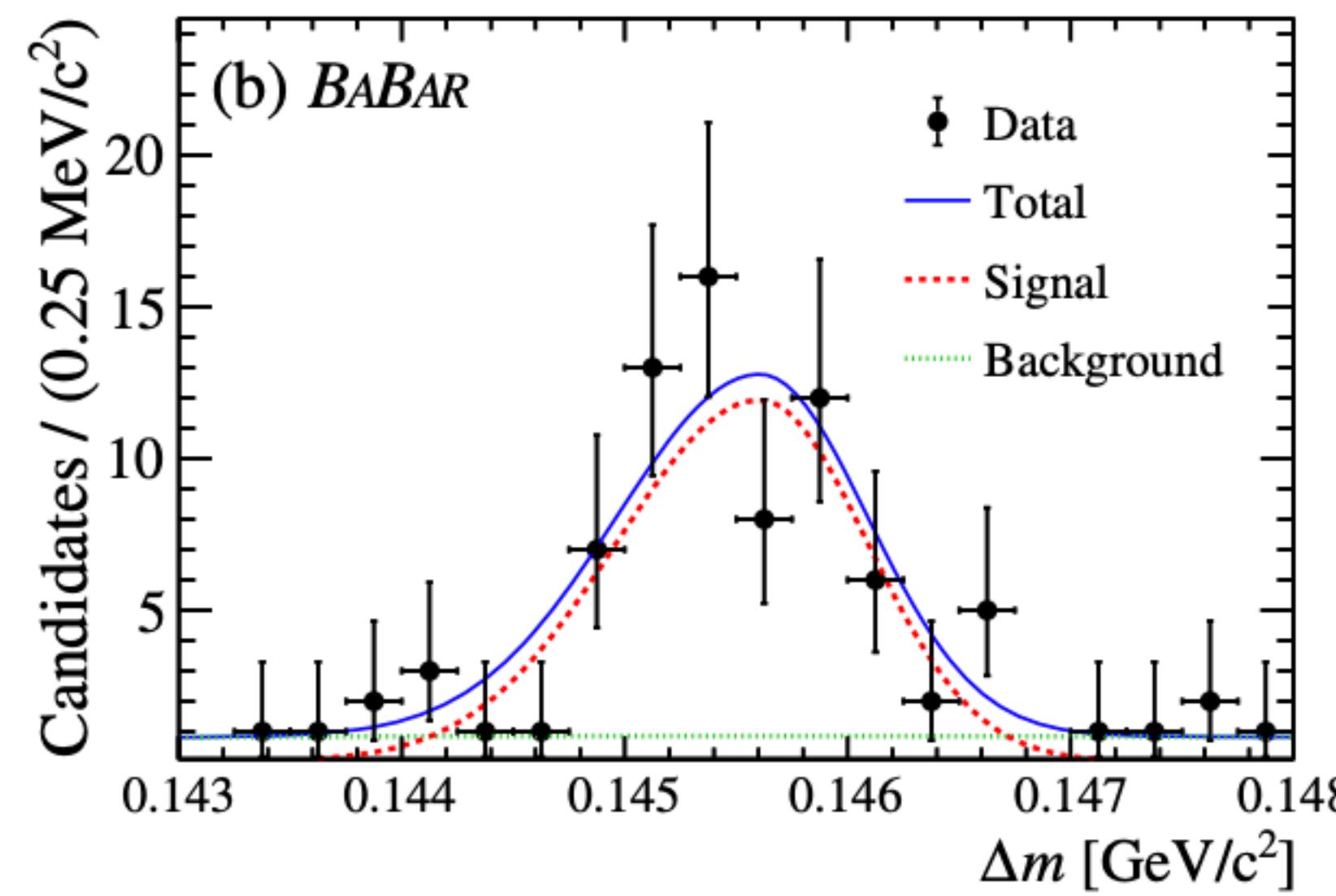
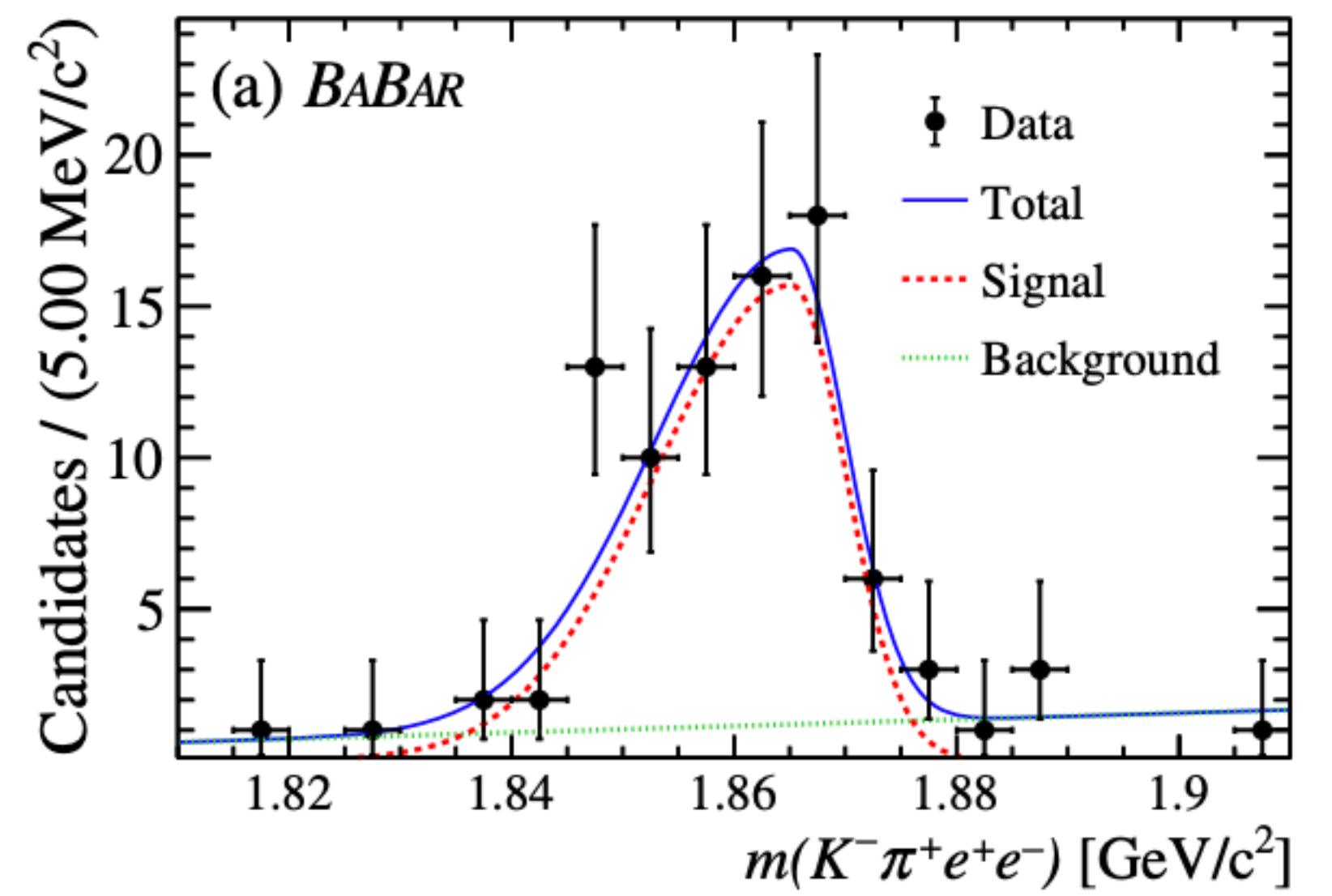


Majorana neutrino

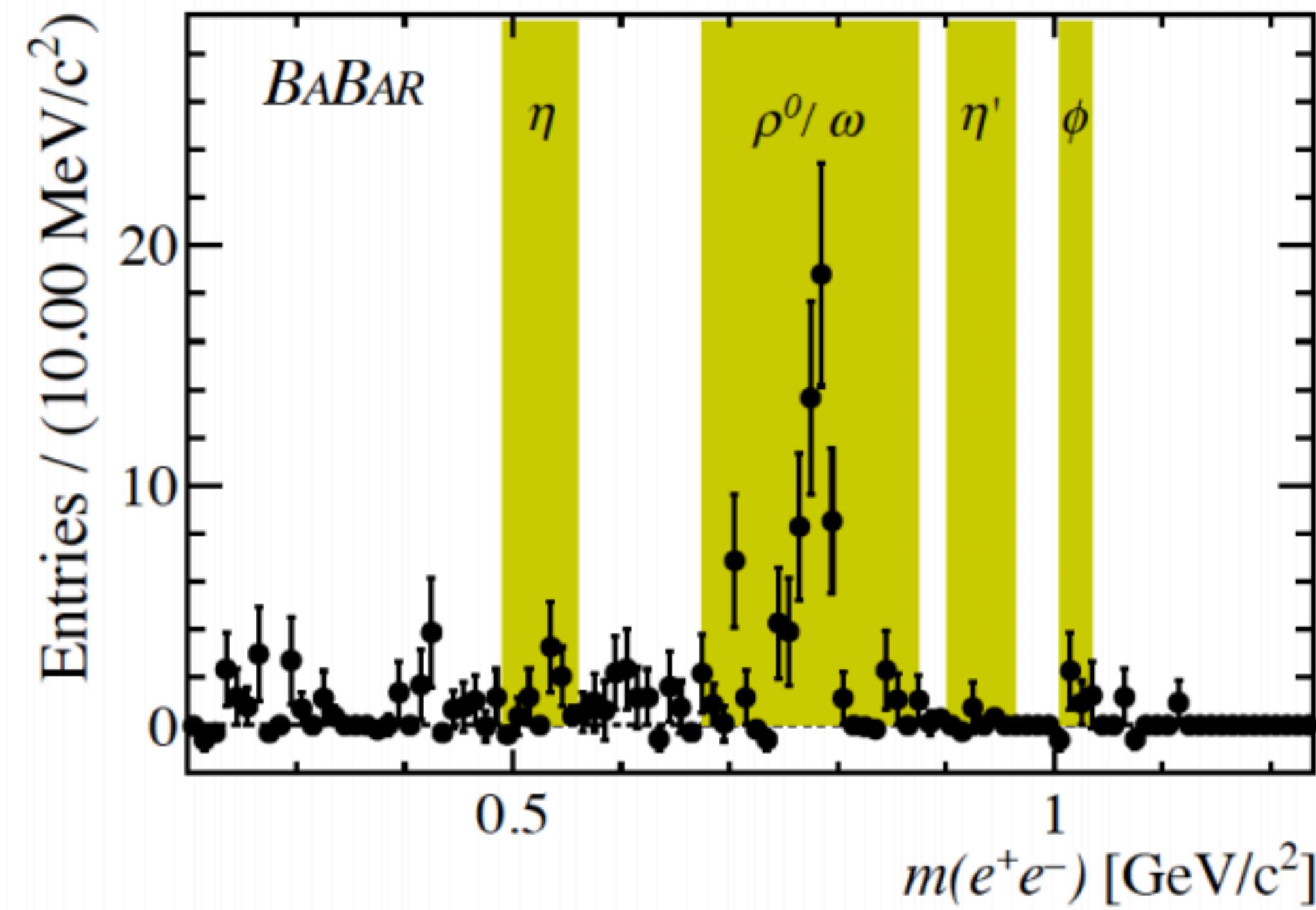
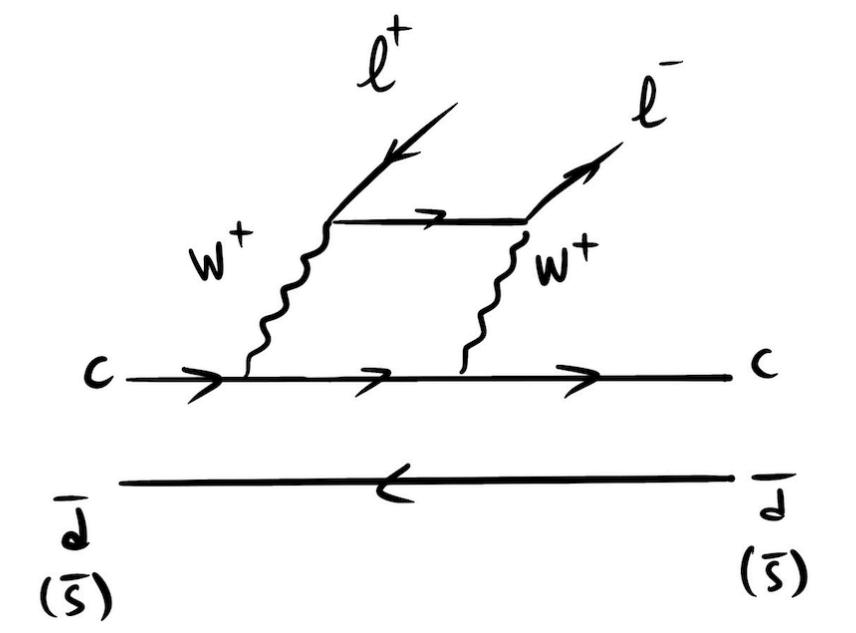


Oscillating SM neutrino

$$D^0 \rightarrow K^- \pi^+ e^+ e^-$$



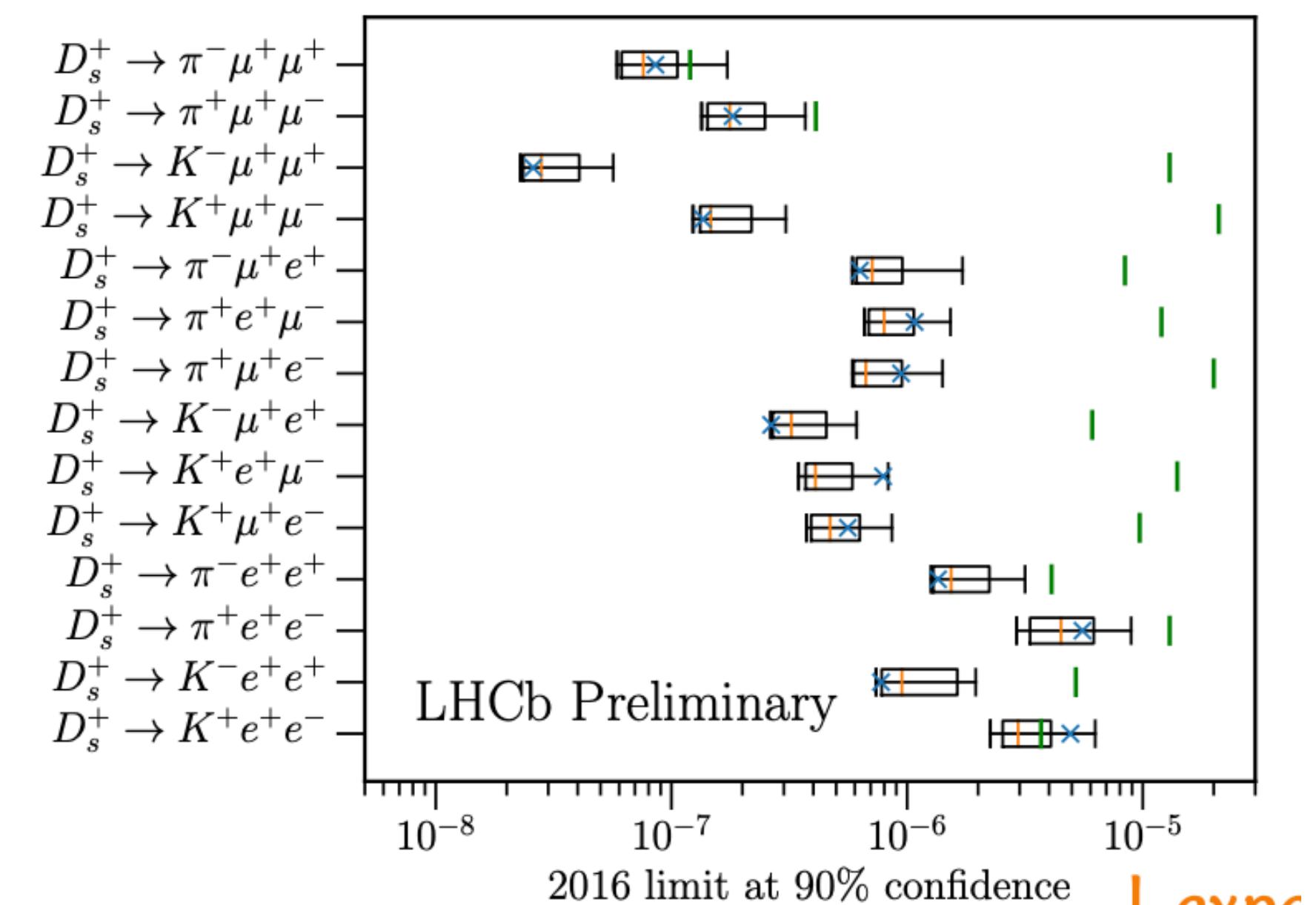
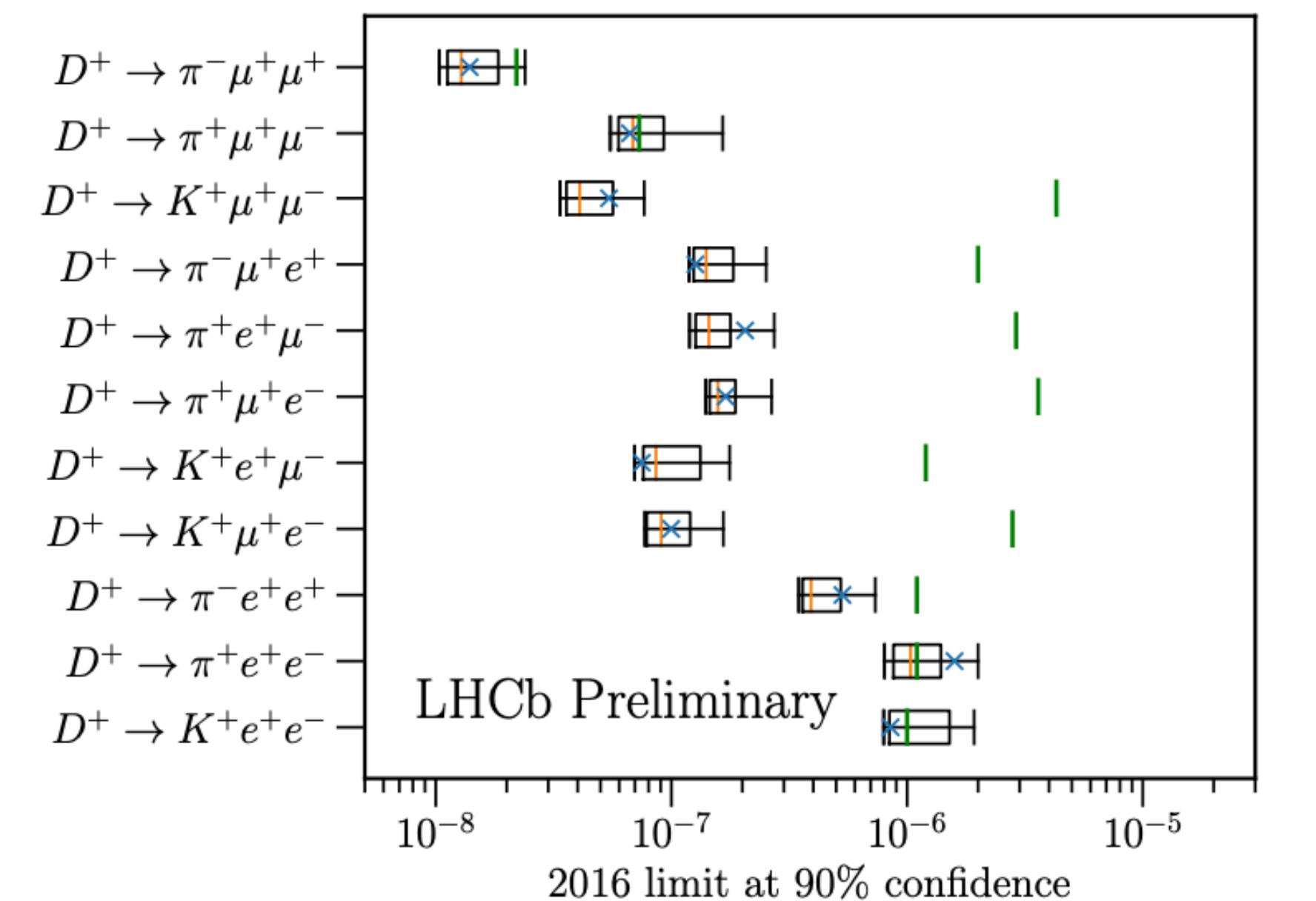
$$\mathcal{B}(D^0 \rightarrow K^- \pi^+ e^+ e^-) = (4.0 \pm +0.5 \pm 9.2 \pm 0.1) \times 10^{-6}$$



23 world's best limits !

Decay	Branching fraction upper limit [10^{-9}]				Improvement factor	
	D^+		D_s^+		D^+	D_s^+
	90 % CL	95 % CL	90 % CL	95 % CL		
$D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^-$	67	74	180	210	1.1	2.3
$D_{(s)}^+ \rightarrow \pi^- \mu^+ \mu^+$	14	16	86	96	1.6	1.4
$D_{(s)}^+ \rightarrow K^+ \mu^+ \mu^-$	54	61	140	160	79.0	150.0
$D_{(s)}^+ \rightarrow K^- \mu^+ \mu^+$	-	-	26	30	-	500.0
$D_{(s)}^+ \rightarrow \pi^+ e^+ \mu^-$	210	230	1100	1200	14.0	11.0
$D_{(s)}^+ \rightarrow \pi^+ \mu^+ e^-$	220	220	940	1100	16.0	21.0
$D_{(s)}^+ \rightarrow \pi^- \mu^+ e^+$	130	150	630	710	16.0	13.0
$D_{(s)}^+ \rightarrow K^+ e^+ \mu^-$	75	83	790	880	16.0	18.0
$D_{(s)}^+ \rightarrow K^+ \mu^+ e^-$	100	110	560	640	28.0	17.0
$D_{(s)}^+ \rightarrow K^- \mu^+ e^+$	-	-	260	320	-	23.0
$D_{(s)}^+ \rightarrow \pi^+ e^+ e^-$	1600	1800	5500	6400	0.7	2.3
$D_{(s)}^+ \rightarrow \pi^- e^+ e^+$	530	600	1400	1600	2.1	3.0
$D_{(s)}^+ \rightarrow K^+ e^+ e^-$	850	1000	4900	5500	1.2	0.8
$D_{(s)}^+ \rightarrow K^- e^+ e^+$	-	-	770	840	-	6.7

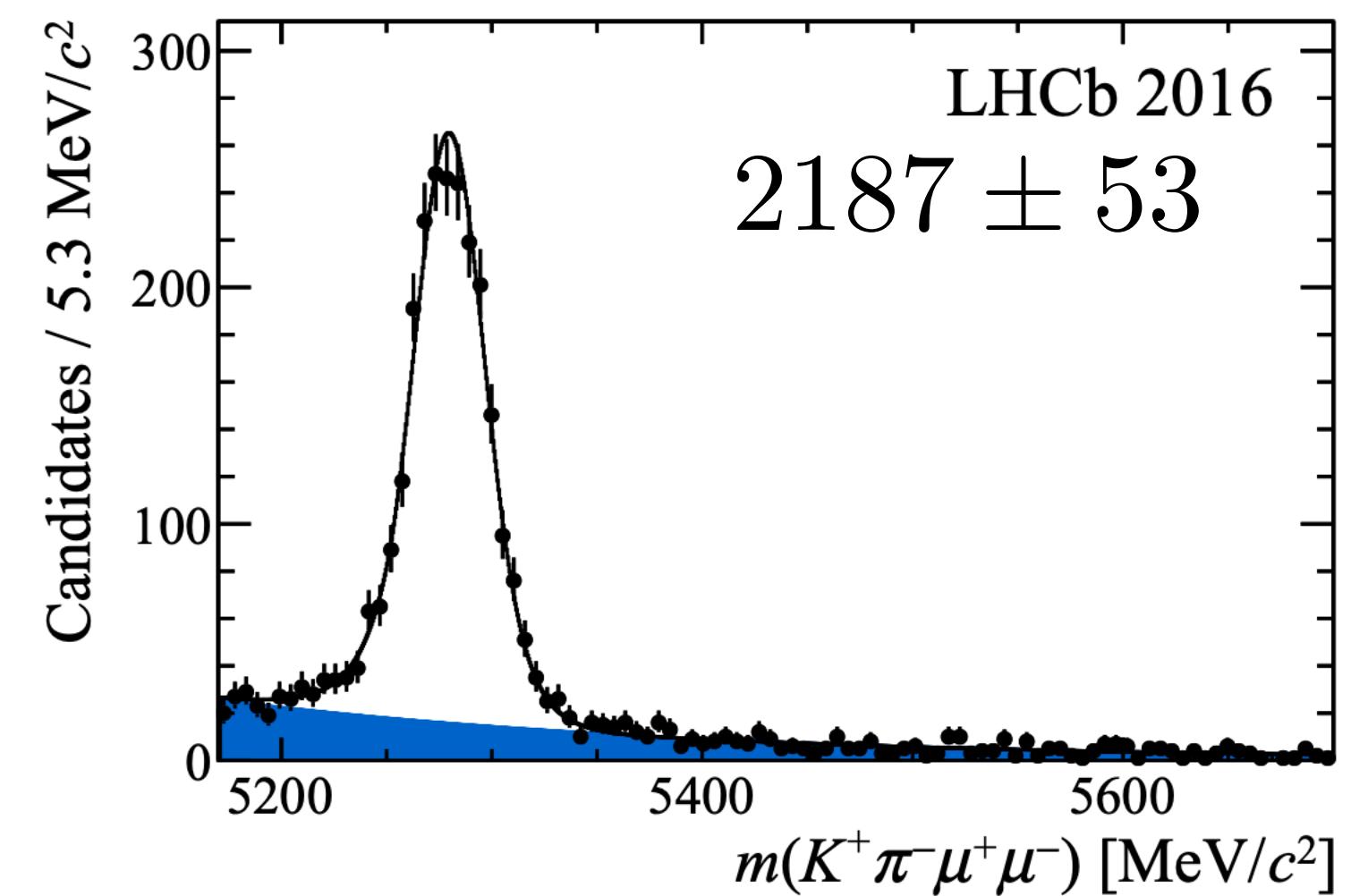
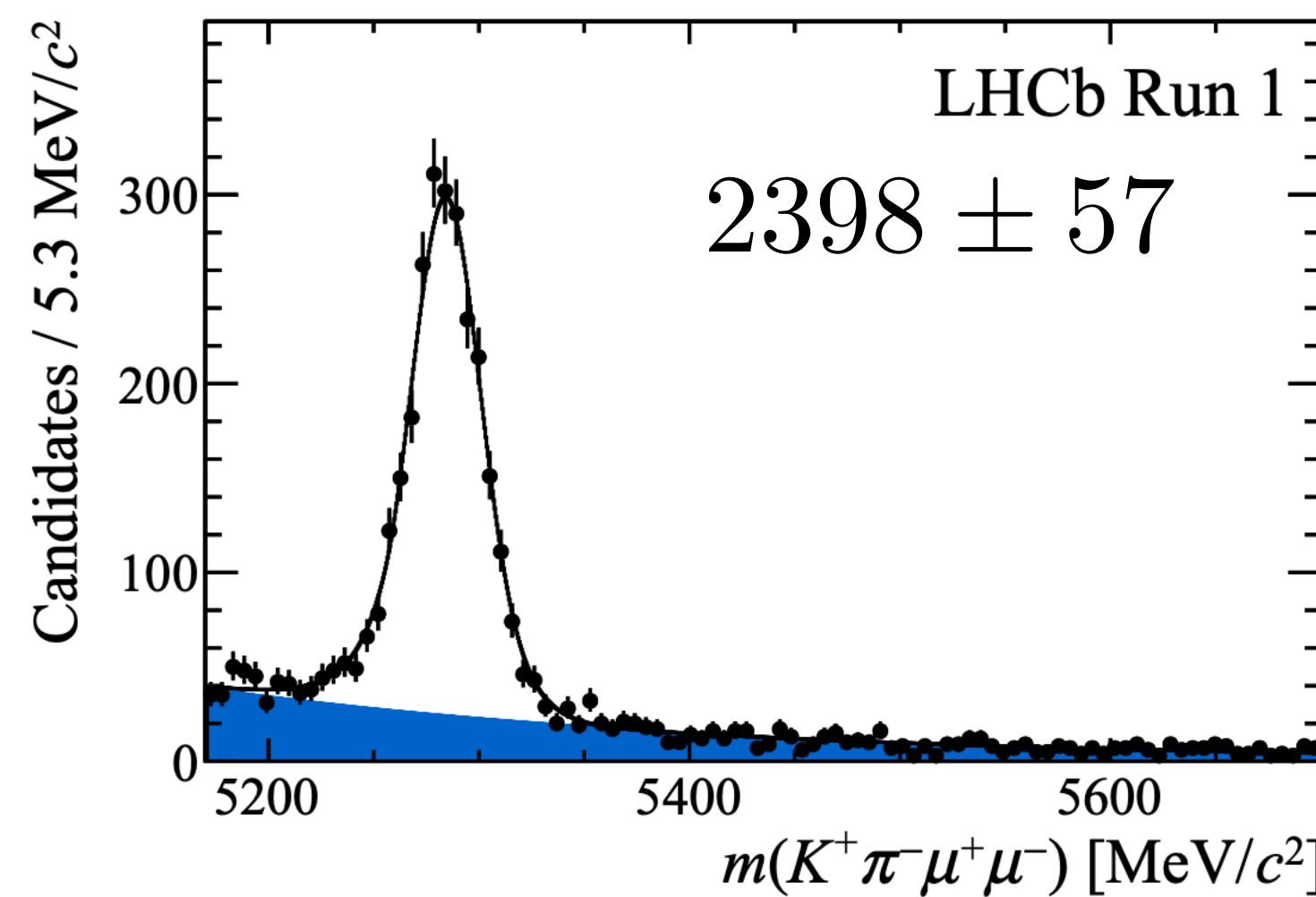
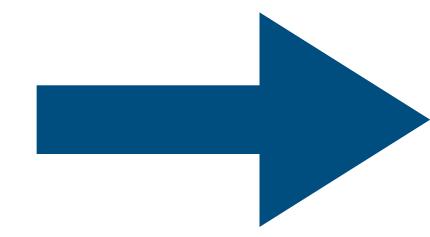
2017-18 dataset yet to be analysed.



$$B^0 \rightarrow K^* \mu^+ \mu^-$$

Very “clean” Invariant mass distribution necessitates a simple fit

Signal extraction



$$\vec{\Omega} = (\cos\theta_\ell, \cos\theta_\ell, \phi)$$

$$q^2 = m^2(\mu^+\mu^-)$$

$$\frac{\int d^4\Gamma [\bar{B}^0 \rightarrow \bar{K}^* \mu^+ \mu^-]}{dq^2 d\vec{\Omega}} = \frac{g}{32\pi} \sum_i I_i(q^2) f_i(\vec{\Omega})$$

Angular
coefficients

Angular
functions

LHCb contributors to parallel session

