Flavor anomalies and their high-p_T connections

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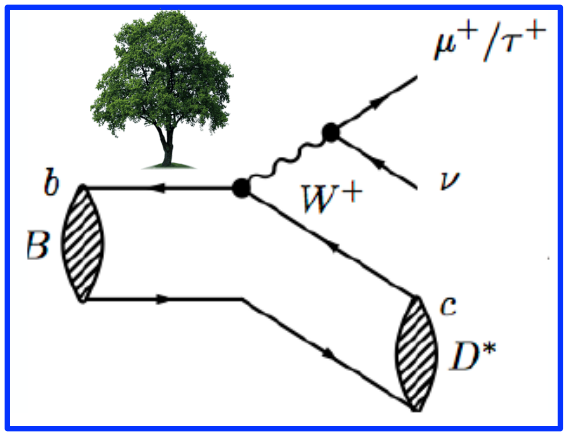
Prelude…

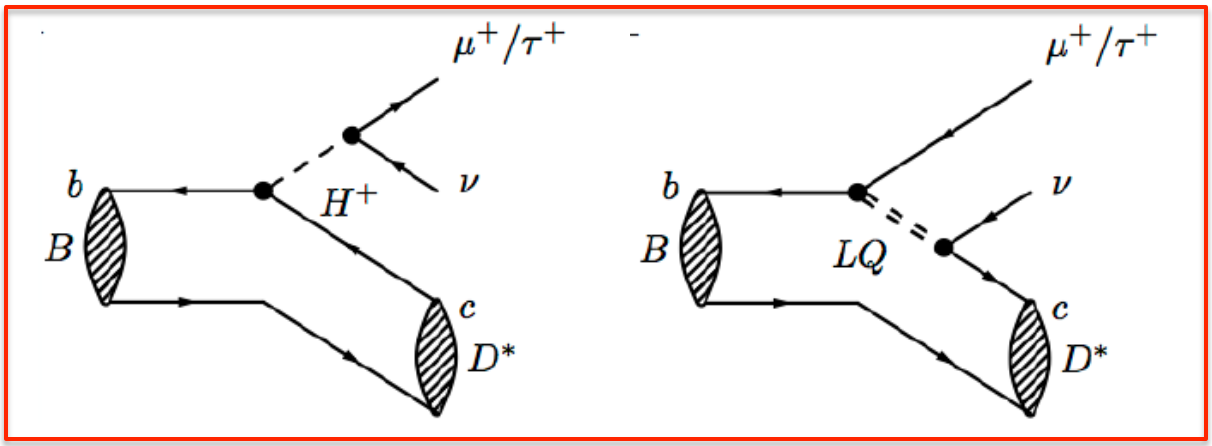
- We are caught of with a situation similar to what was encountered at the advent of 19th century

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + |D_\mu\phi|^2 - V(H) + Y_{ij}\psi_i\psi_j\phi + \text{h.c.}$$

- No signal of new physics in high p_T searches at LHC → ATLAS and CMS together have found no discrepancy after the (in)famous 750 GeV one
- On the other hand, a consistent set of hints seems to emerge from the flavor sector, going by the name "Flavor Anomalies"
- Whether the statistics is playing up or we are seeing something genuine, only time and more data will tell us...

Let's start with the tree...





$$R(D^{(*)}) = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\nu)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\nu)} \quad \ell = \mu, e$$

- Lepton universality in the B decay branching fraction to the τ vs. other two leptons is well predicted in the SM

Fajfer et al., PRD 85 (2012) 094025

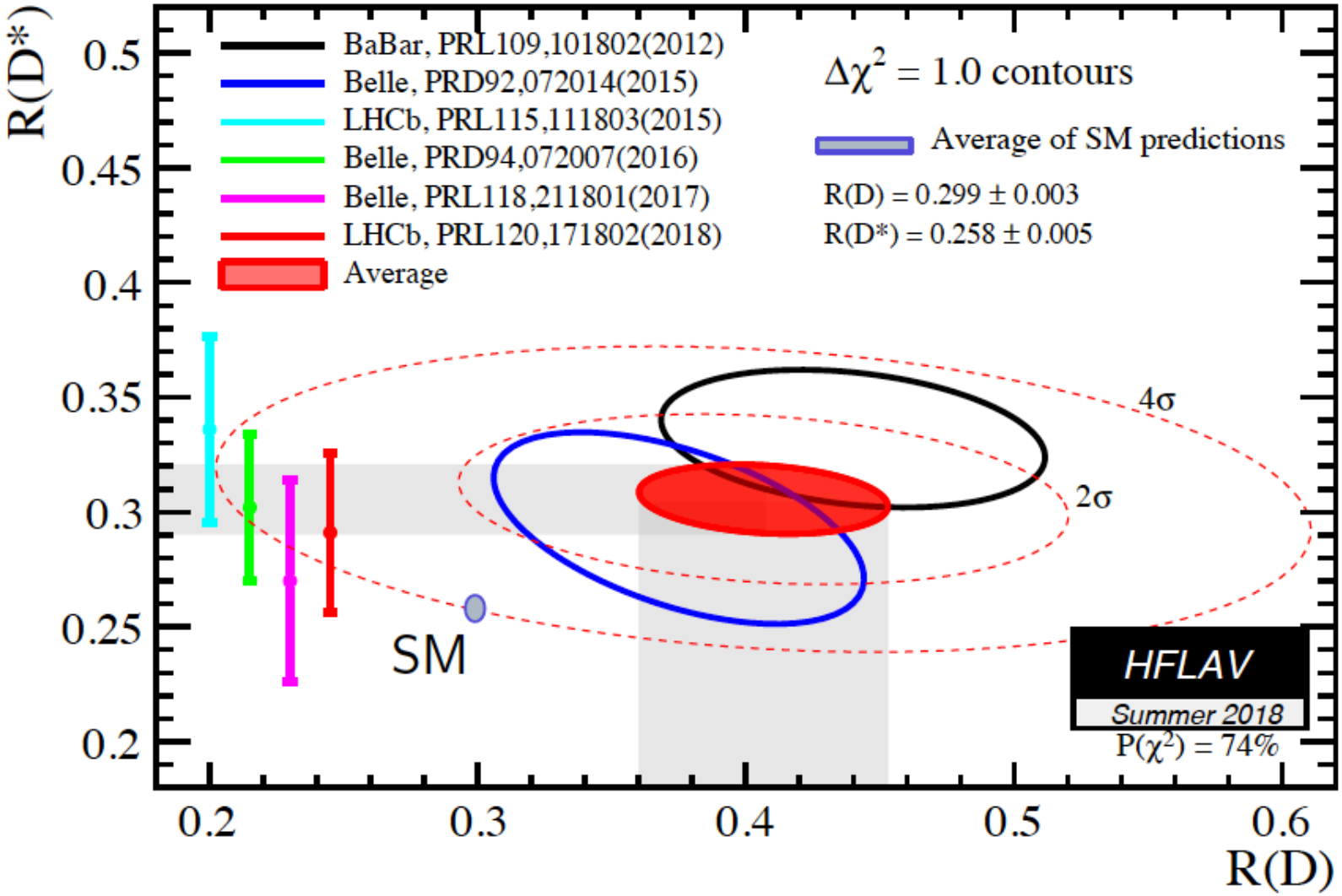
FLAG Working Group, EPJ C77 (2017) 112

$R(D^*) = 0.258 \pm 0.005$

$R(D) = 0.299 \pm 0.003$

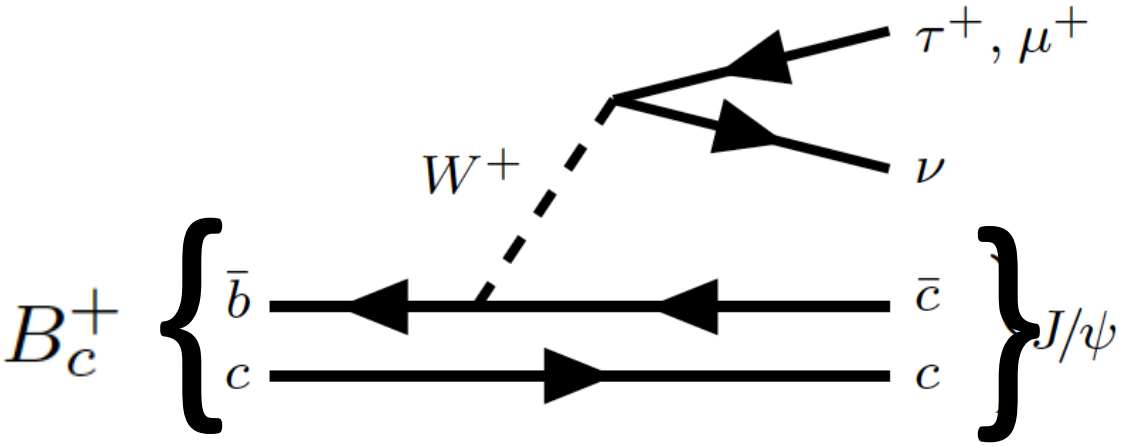
- Possible BSM contributions include charged Higgs boson and leptoquark (LQ)

Saga of R(D*) vs. R(D)...



- Combination of R(D) and R(D*) is 3.8σ away from the SM prediction

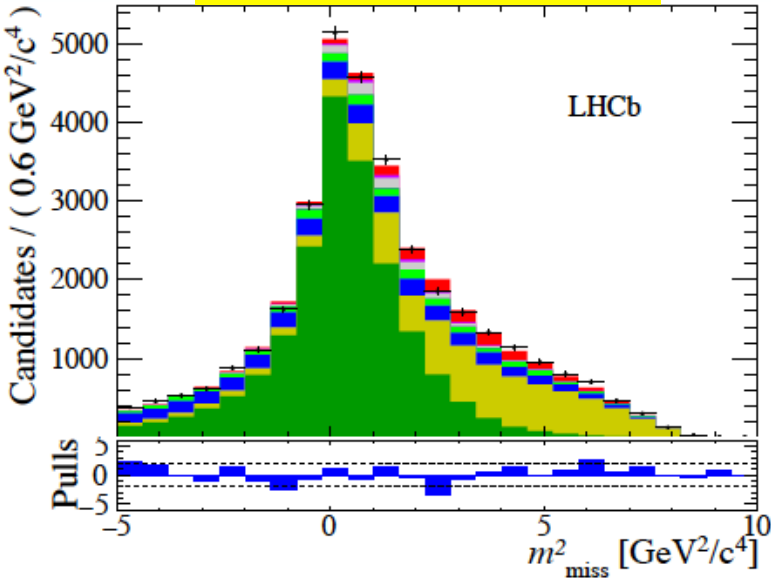
B_c also shows a similar trend...

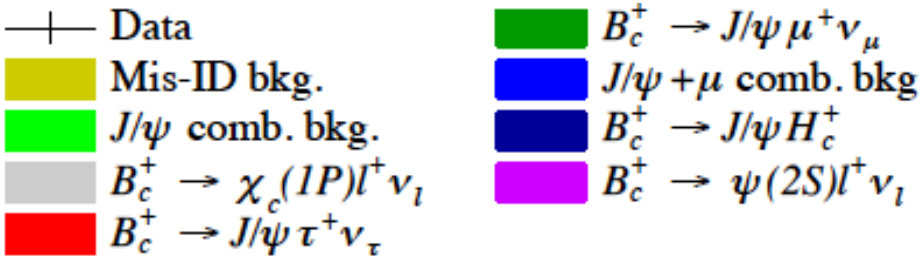


$$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$$

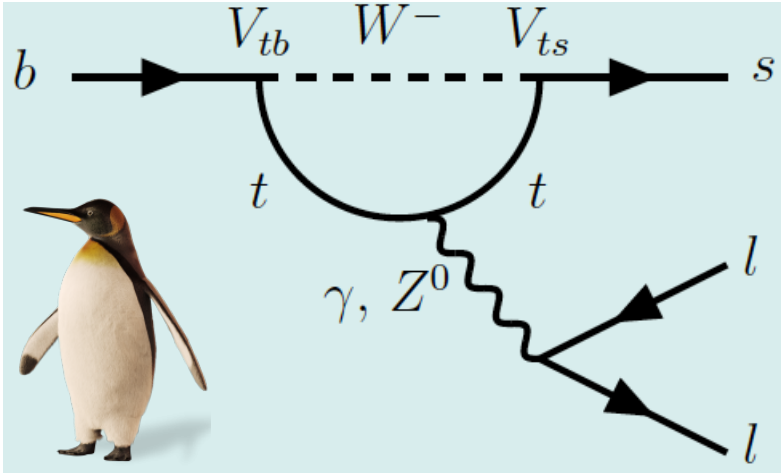
- Measured ratio 2σ above the SM value, which is in the range of 0.25-0.28

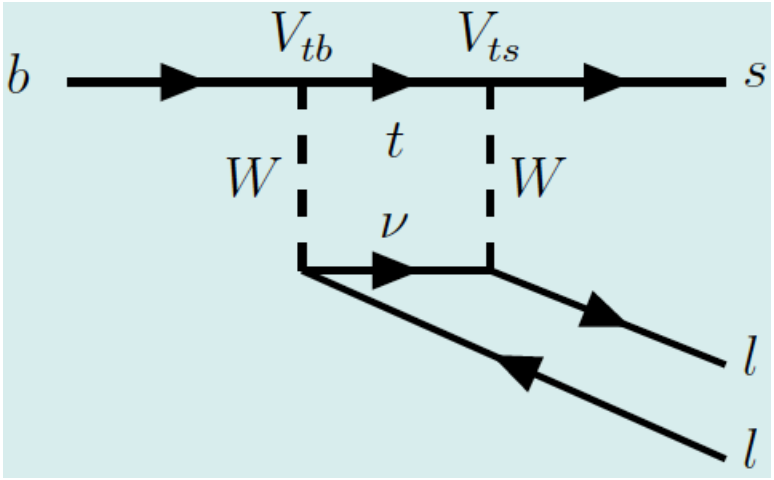
PRL 120 (2018) 121801



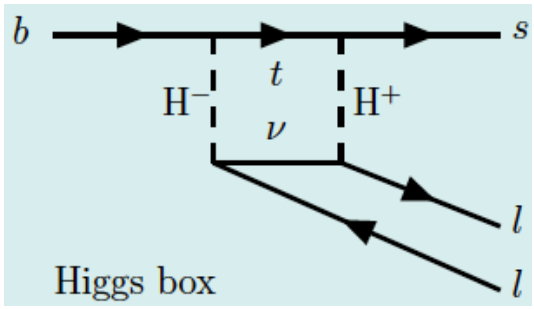


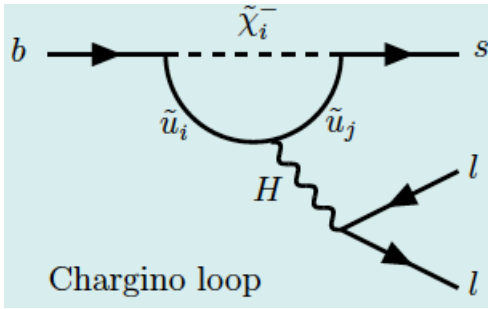
Now move on to penguins...

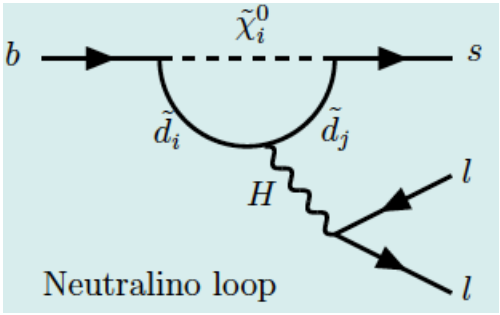




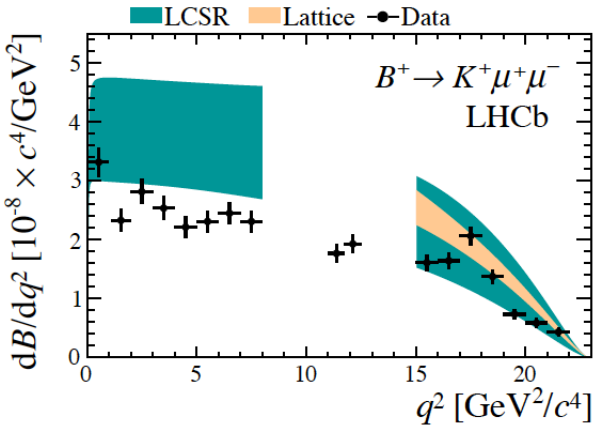
- Rare FCNC process: forbidden at tree level, need to go to the loop level
- Sensitive to new physics contributions (SUSY, 2HDM, fourth generation, LQ...)
- Few example diagrams are shown below





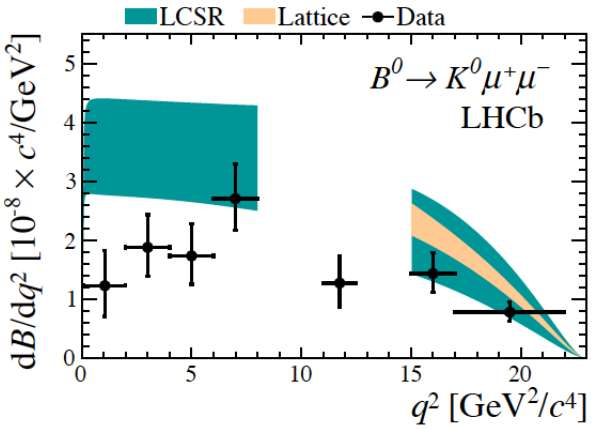


Differential branching fractions



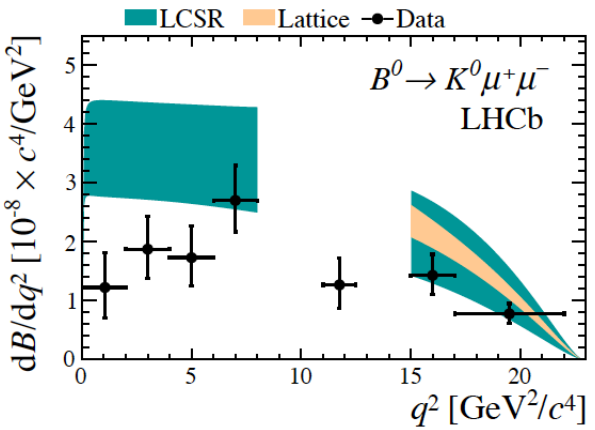
$B^+ \to K^+\mu^+\mu^-$

[JHEP 06 (2014) 133]



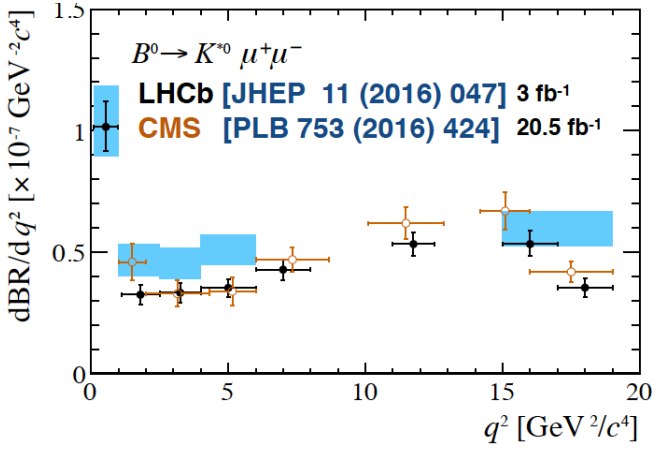
$B^0 \to K^0\mu^+\mu^-$

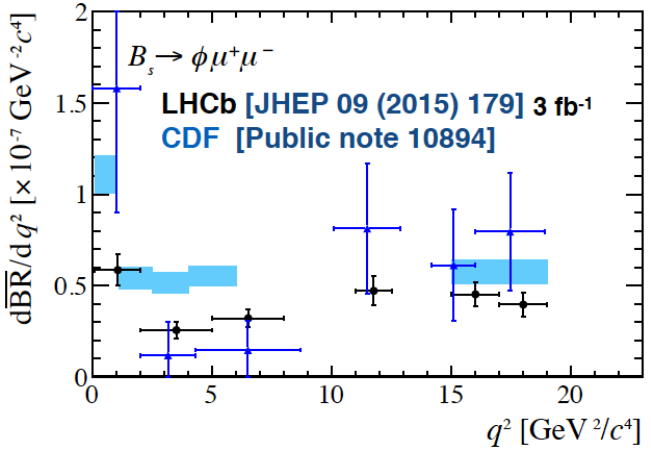
[JHEP 06 (2014) 133]

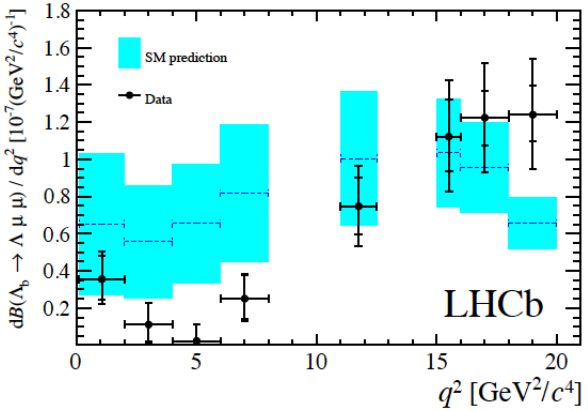


$B^+ \to K^{*+}\mu^+\mu^-$

[JHEP 06 (2014) 133]





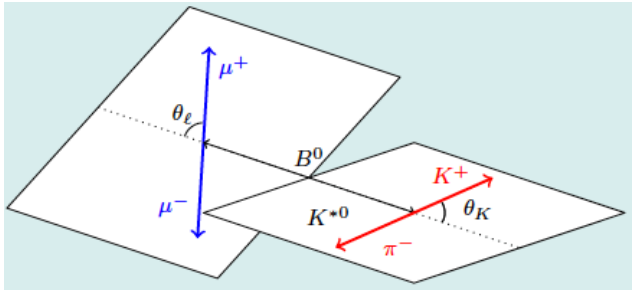


$\Lambda_b^0 \to \Lambda\mu^+\mu^-$

[JHEP 06 (2015) 115]

- Measured branching fractions are smaller than predicted by the SM

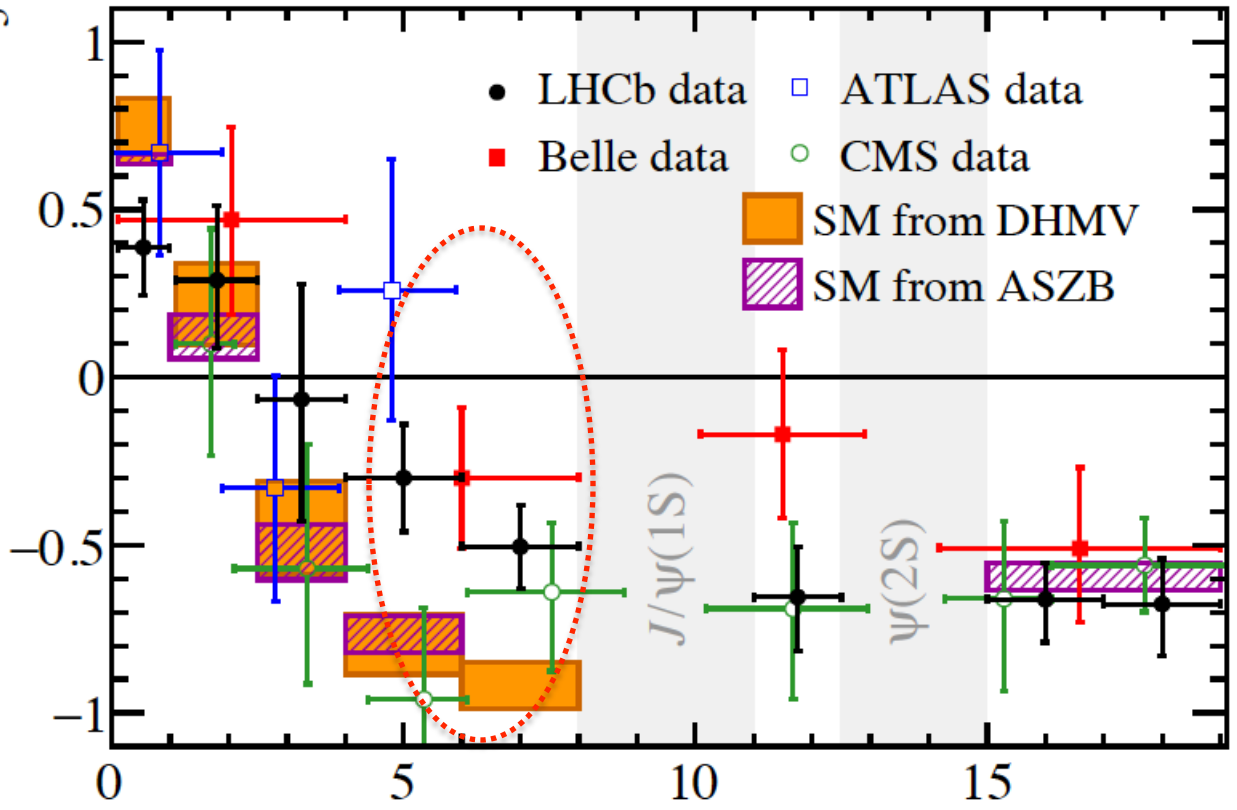
An angular observable



- Construct an angular asymmetry, which is expected to be independent of form factors

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

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

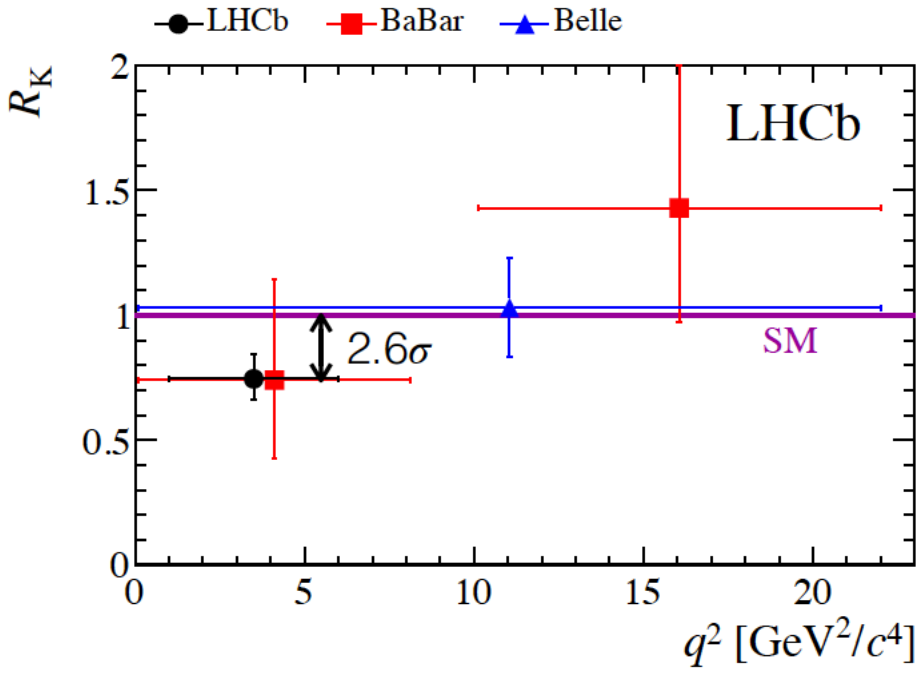


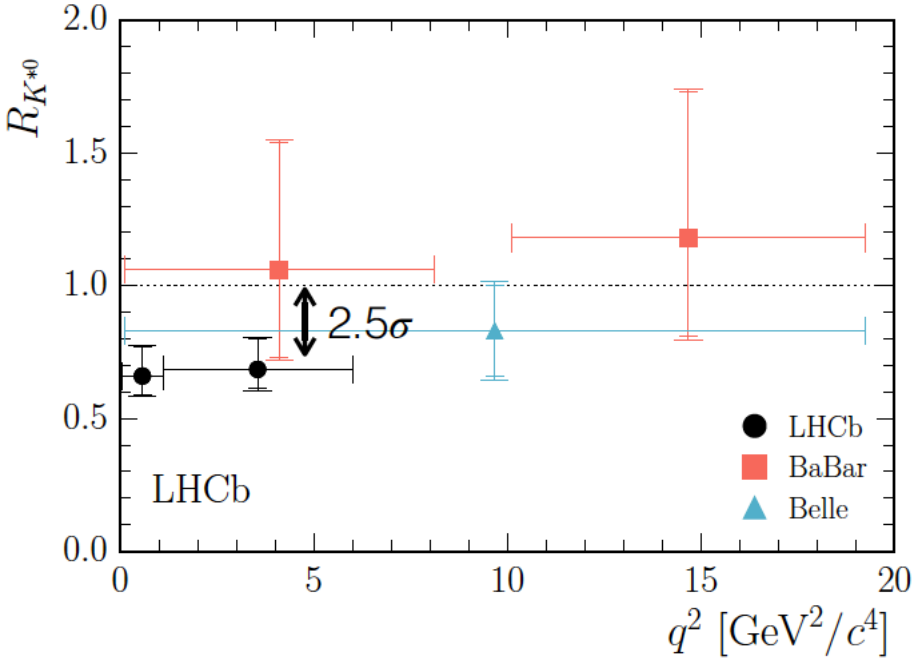
LHCb [JHEP 02 (2016) 104], Belle [PRL 118 (2017) 111801]
CMS [PLB 781 (2018) 517], ATLAS [arXiv:1805.04000]

Lepton universality tests

$$R_X = \frac{\int_{4m_\mu^2}^{q^2_{max}} ds \frac{d\Gamma\left(B \to X\mu^+\mu^-\right)}{ds}}{\int_{4m_\mu^2}^{q^2_{max}} ds \frac{d\Gamma\left(B \to Xe^+e^-\right)}{ds}} \overset{SM}{=} \begin{cases} 1.000 \pm 0.001 & X = K \\ 0.991 \pm 0.002 & X = K^* \end{cases}$$

Hiller & Krüger, PRD 69 (2004) 074020





➢ Interesting hints of non-universal lepton couplings

Is there an NP model?

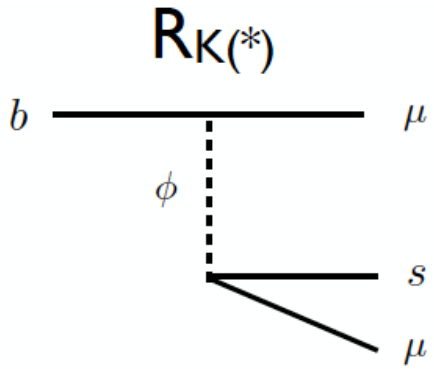
	Y	Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}}$ & $R_{D^{(*)}}$
scalar	1/3	S_1	✗*	✓	✗*
	7/6	R_2	✗*	✓	✗
	1/6	$\widetilde{R}_2$	✗	✗	✗
	1/3	S_3	✓	✗	✗
vector	2/3	U_1	✓	✓	✓
	2/3	U_3	✓	✗	✗

[Angelescu et al., arXiv:1808.08179]

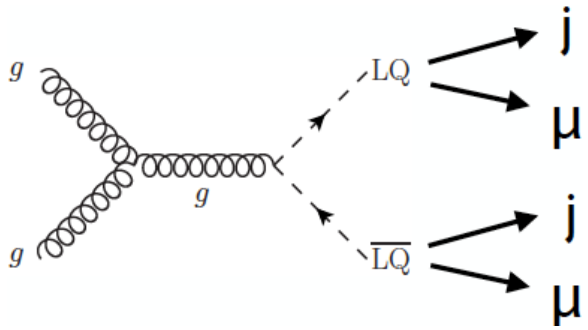
- It seems, a combination of scalar LQs e.g., S_1 and S_3 can explain both set of anomalies
- FCNC part alone can be explained by Z' boson

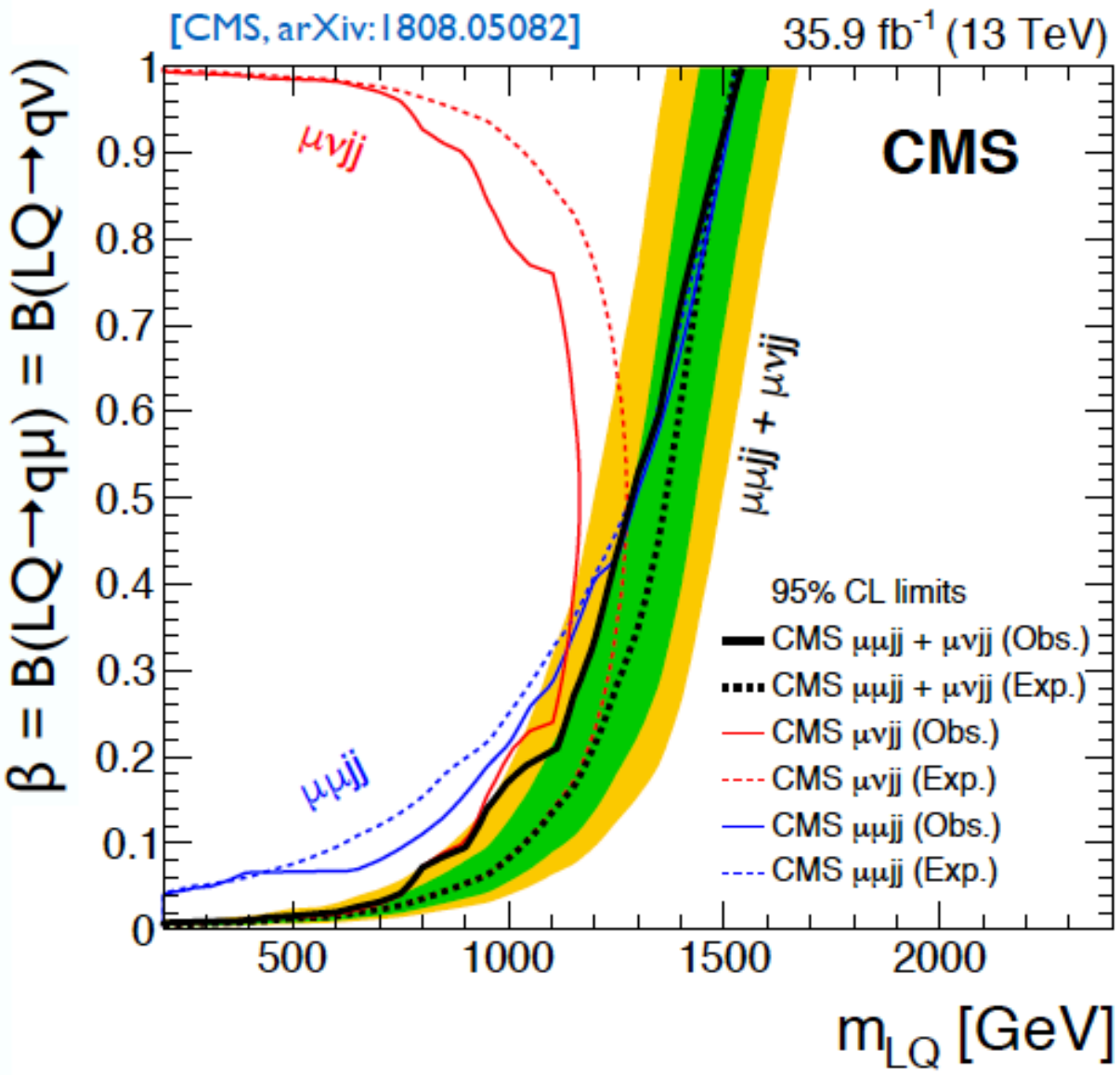
LQ results from CMS…

- Possible connection to $R_{K(*)}$ anomaly

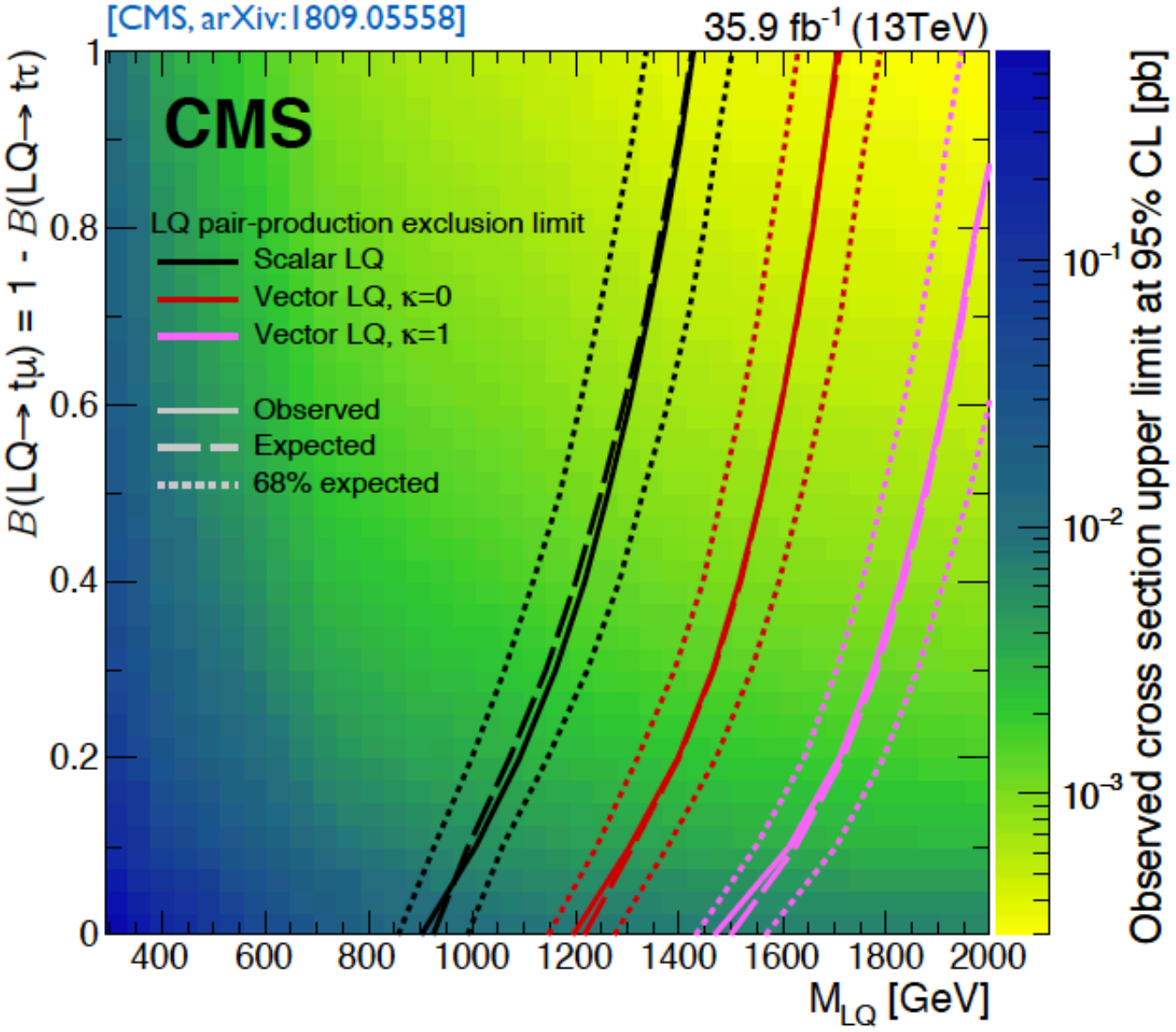


- Scalar 2nd generation LQ in μμjj final state





An interesting combination from CMS

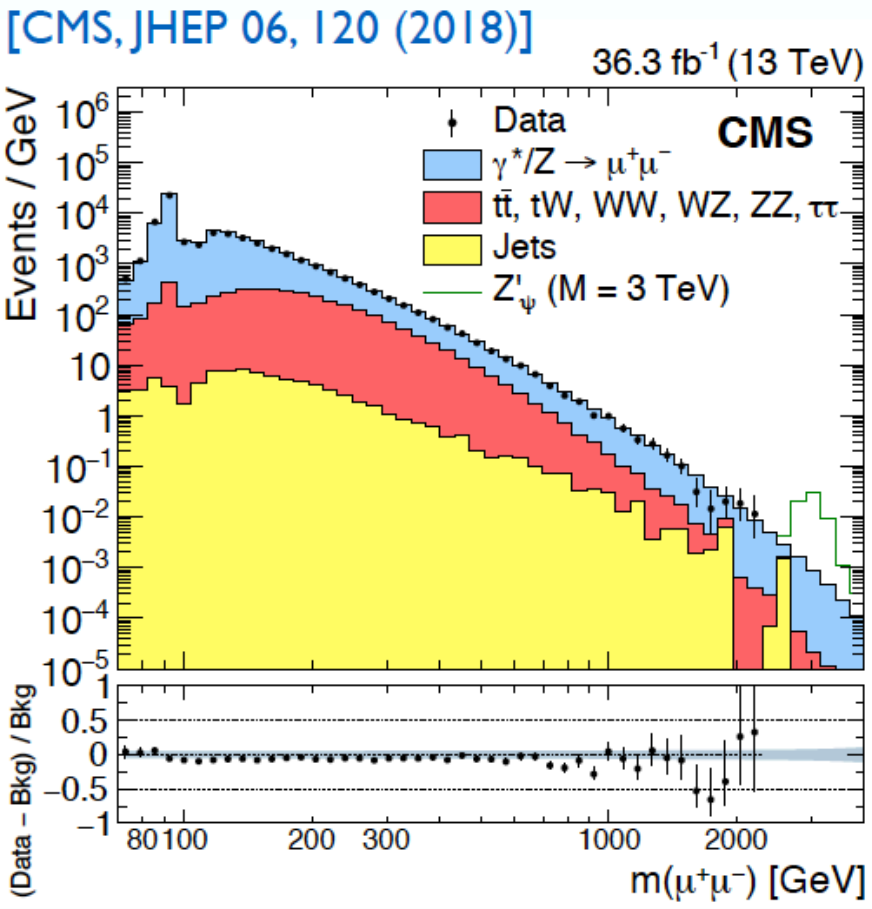


- Exclude scalar LQs between 0.9 and 1.4 TeV for tτ and tμ final states
- Expected reach at HL-LHC can be up to 2 TeV

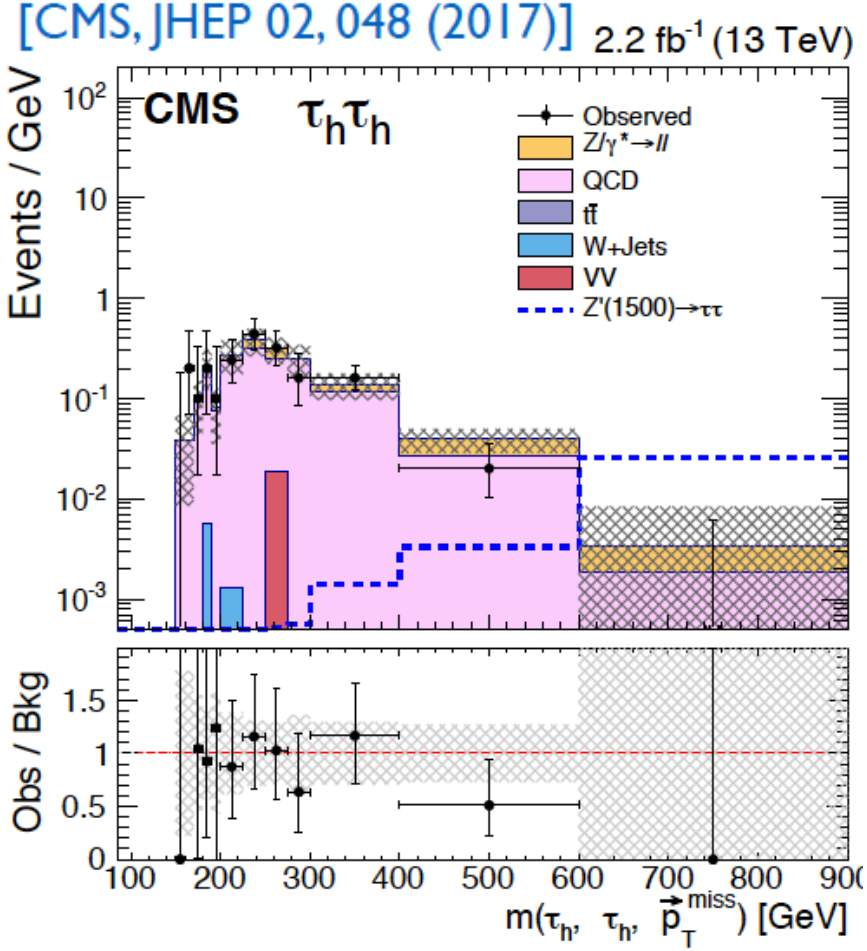
What about Z' at the LHC?

- These searches are sensitive to potential FCNC interactions in B sector
- No sign of a signal and Z' is excluded up to 2-3 TeV

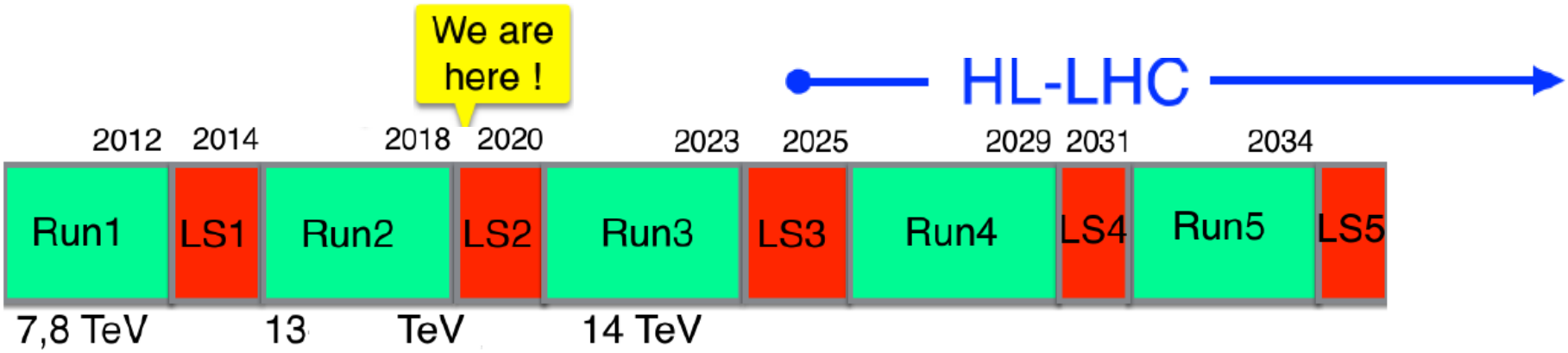
[CMS, JHEP 06, 120 (2018)]



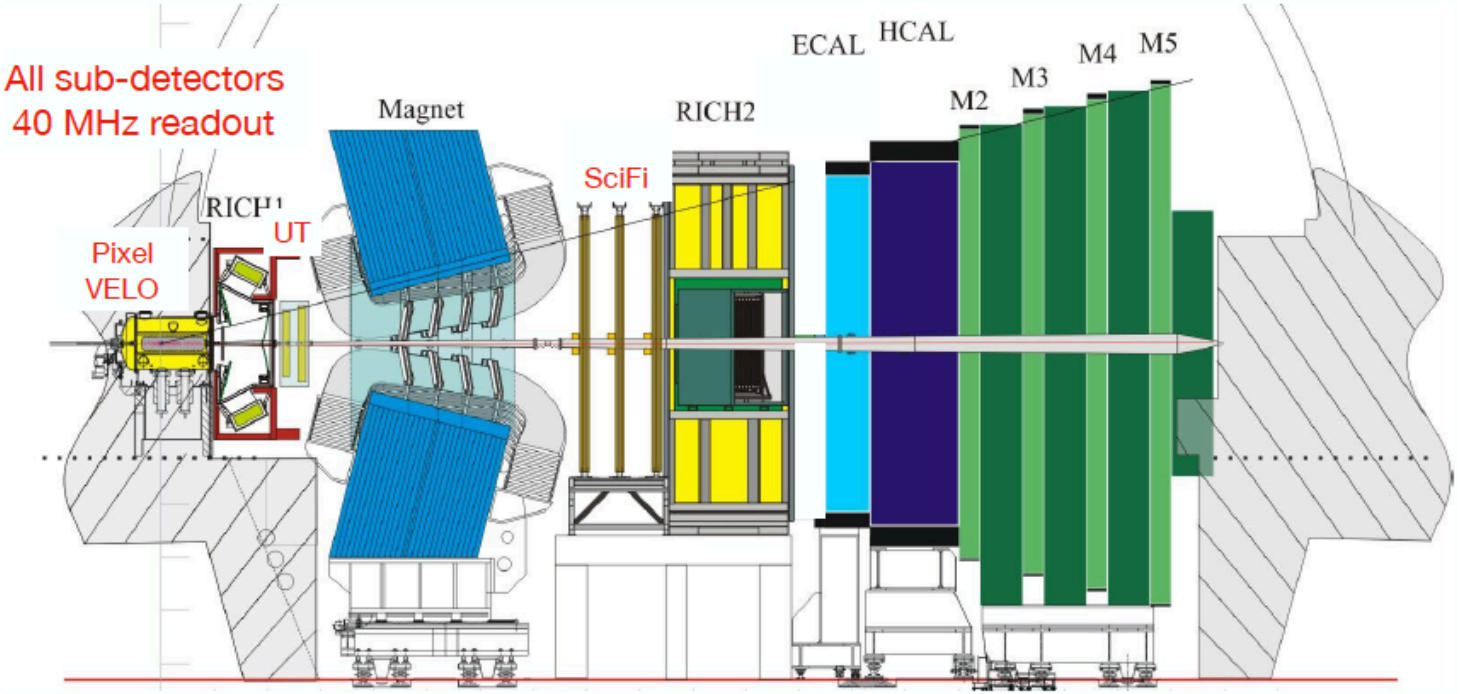
[CMS, JHEP 02, 048 (2017)]



Looking to future…



- LHCb will install an upgrade detector and integrate about 25 fb^{-1} data between 2021-2030

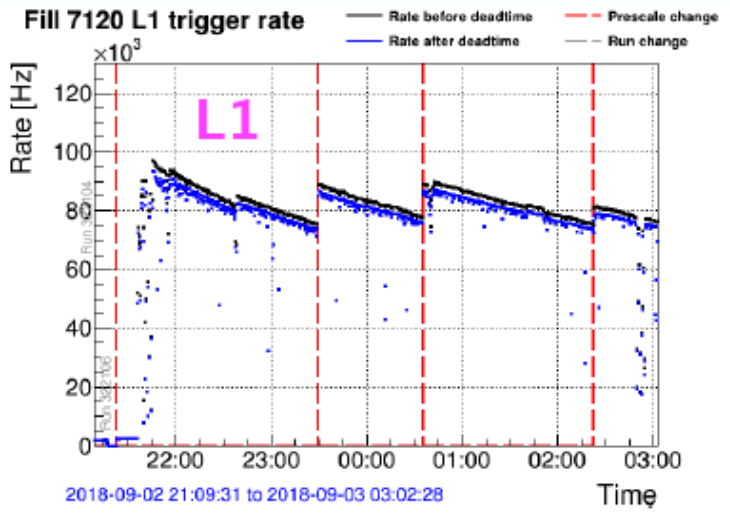


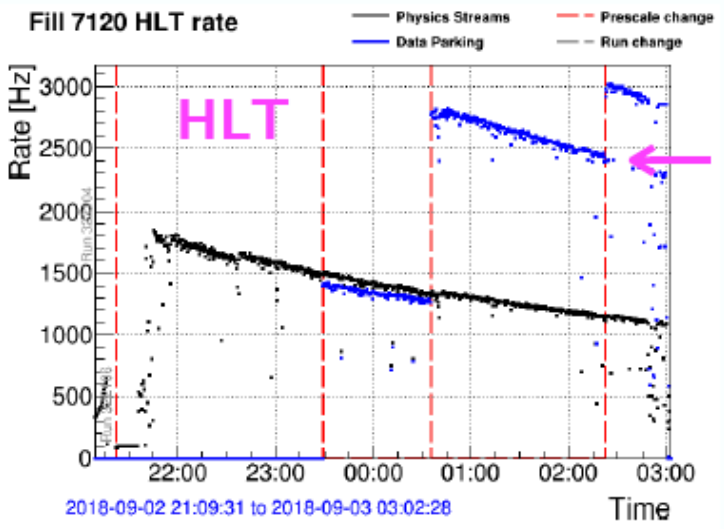
BTW, can CMS do more on this?

From a recent talk of M. Pierini at CERN

CMS data taking in 2018

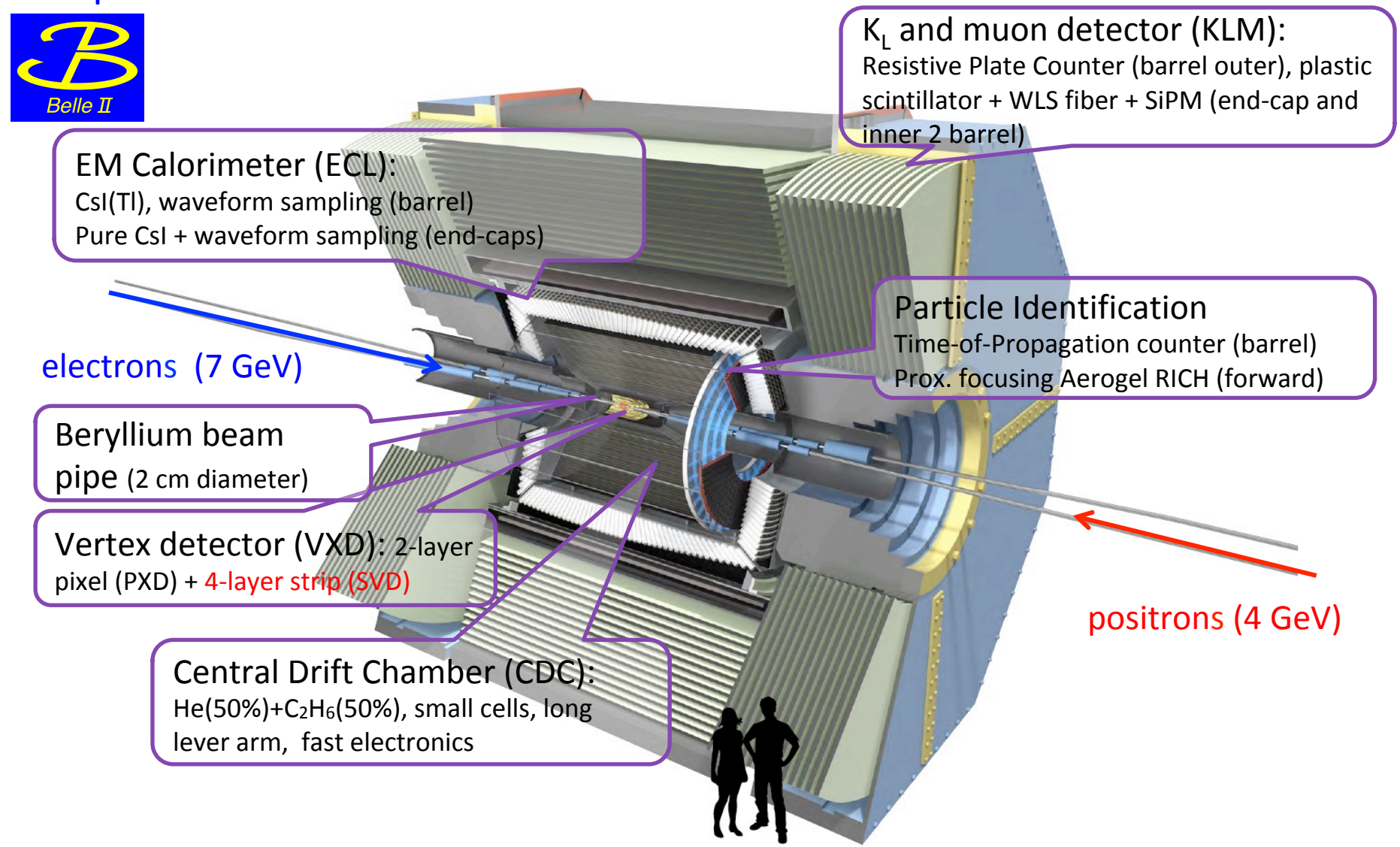
- Smooth running – only minor updates to trigger have been implemented.
- **L1 trigger** rate reaching **95 kHz** at 2×10^{34} cm^{-2} s^{-1}
  - We been able to lower L1 thresholds for single Egamma, MET, di-tau to improve HLT turn-on curves.
- **HLT** rate reaching **1.8 kHz** at 2×10^{34} cm^{-2} s^{-1} – averaging 1.1 kHz over 12h fill
- We are **"parking" an unbiased sample of B mesons** for future analysis
  - rates reach 5 kHz, so far we have recorded over 9B events.





There is another player in town…

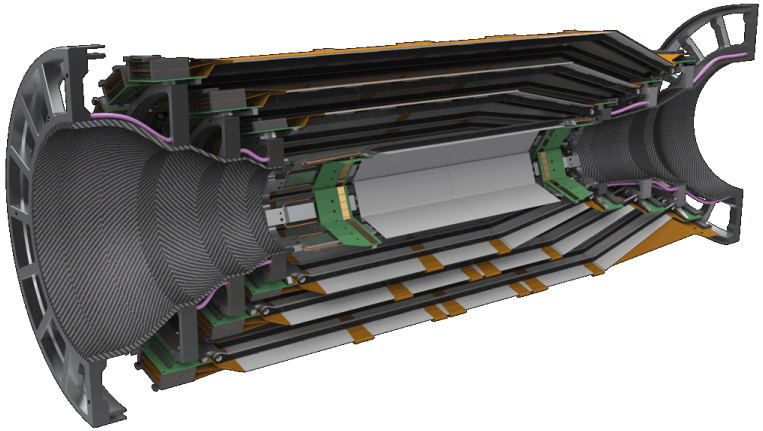
- With 50 times more data than its predecessor, Belle II will be in a good position to address these flavor anomalies

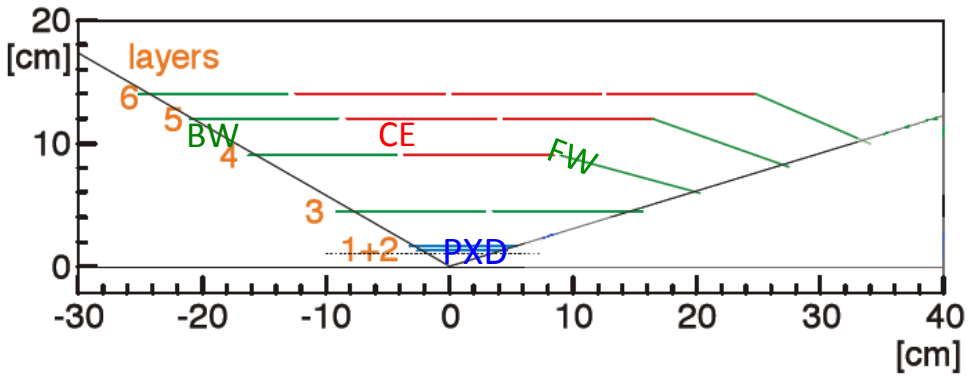


India in Belle-II

- SVD will play a key role in physics harvesting
  1) Precise decay vertex determination
  2) Low-momentum tracking & particle ID
  3) K_S reconstruction

Layer	Ladder	Institute
3	7(+1)	Melbourne
4	10(+2)	TIFR Mumbai
5	12(+3)	HEPHY Vienna
6	16(+4)	Kavli IPMU



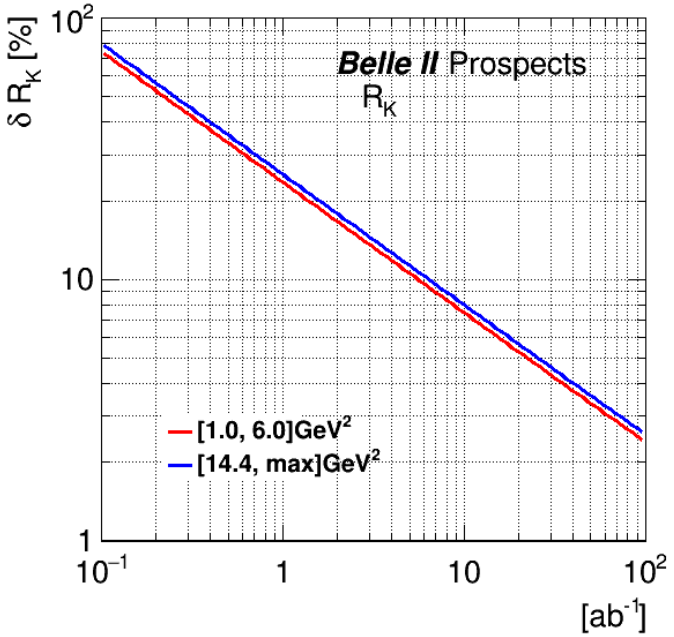


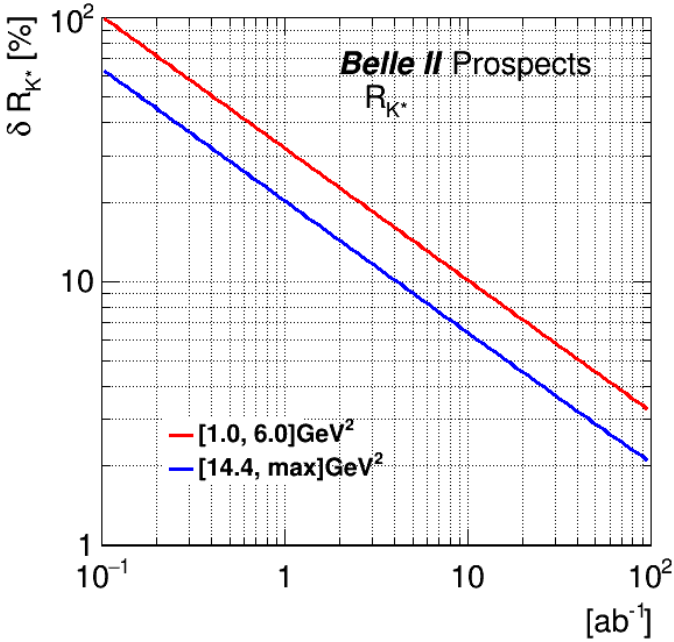
Layer#	Sensor/ladder	Origami	Length	Radius	Slant angle	Occupancy
3	2	0	262 mm	38 mm	0°	6.7%
4	3	1	390 mm	80 mm	11.9°	2.7%
5	4	2	515 mm	104 mm	17.2°	1.3%
6	5	3	645 mm	135 mm	21.1°	0.9%

- India has built a full layer (~30%) of the SVD

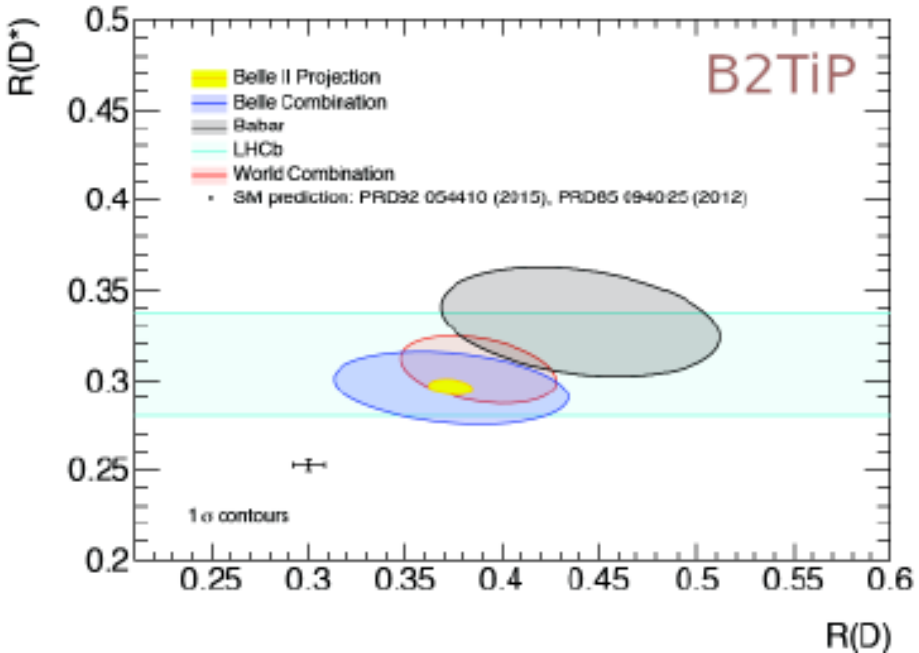
What can Belle II do here?

- Belle II should be able to confirm $R_{K(*)}$ anomaly with 5σ significance

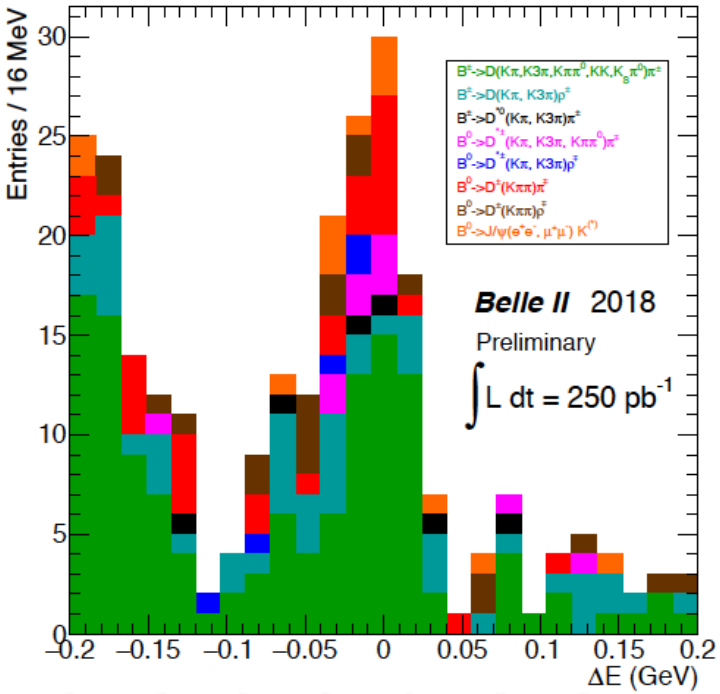


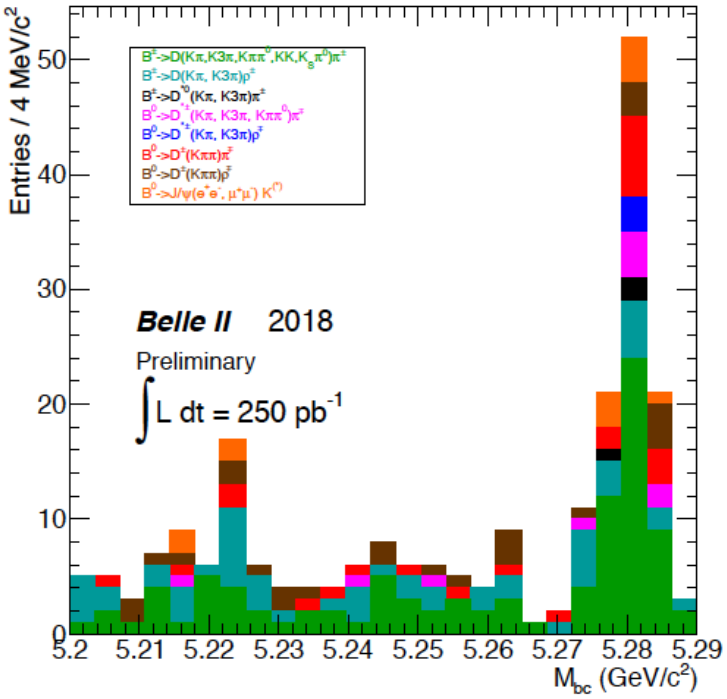


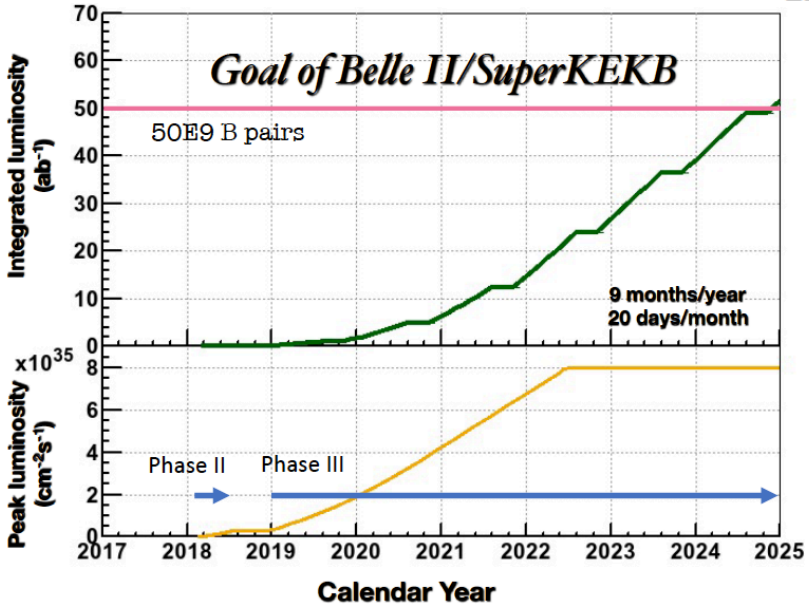
- Similar or better situation with the $R_{D(*)}$ part



First events from Belle II







- Above we show some B candidates detected in phase-II commissioning run
  - Beam commissioning and physics run with partial VXD
- Phase III, physics run with full VXD, will start this March

Postlude...

- Around 3σ anomalies both in tree-level and FCNC transitions of quark flavor sector
- We need to make more precise measurements before drawing firm conclusion: whether a play of statistics or signature of new physics
- If it turns out to be former, flavor physics would still have its own role in deciphering the DNA of new physics, complementary to high p_T
- On the other hand, we may be lucky as history can and does repeat

- **Beta decay => Gf => W....**
- **Huge suppression of KL => mu mu; miniscule ΔmK=> charm**
- **KL =>2 pi but very rarely; mostly to 3pi =>CP violation => 3 families**
- **Largish Bd –mixing => large top mass**
- **etc.....**

From a recent talk of A. Soni