Heavy Flavor Physics

Mike Williams
on behalf of the LHCb Collaboration

Department of Physics & Laboratory for Nuclear Science
Massachusetts Institute of Technology

APS DPF
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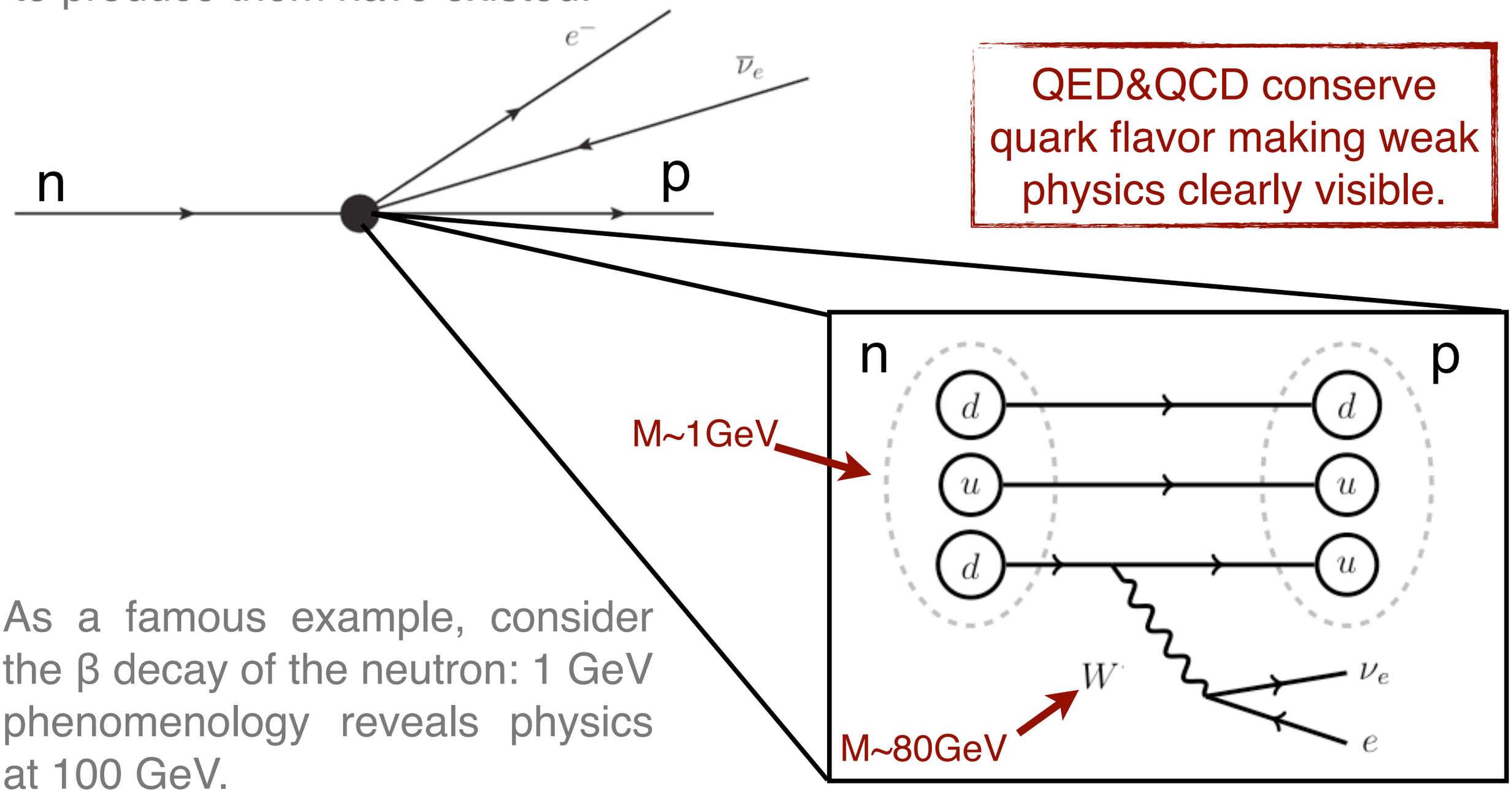
Indirect Observation

Indirect observations of “new physics” have historically been the portal used to predict the existence of particles before experiments with sufficient energy to produce them have existed.

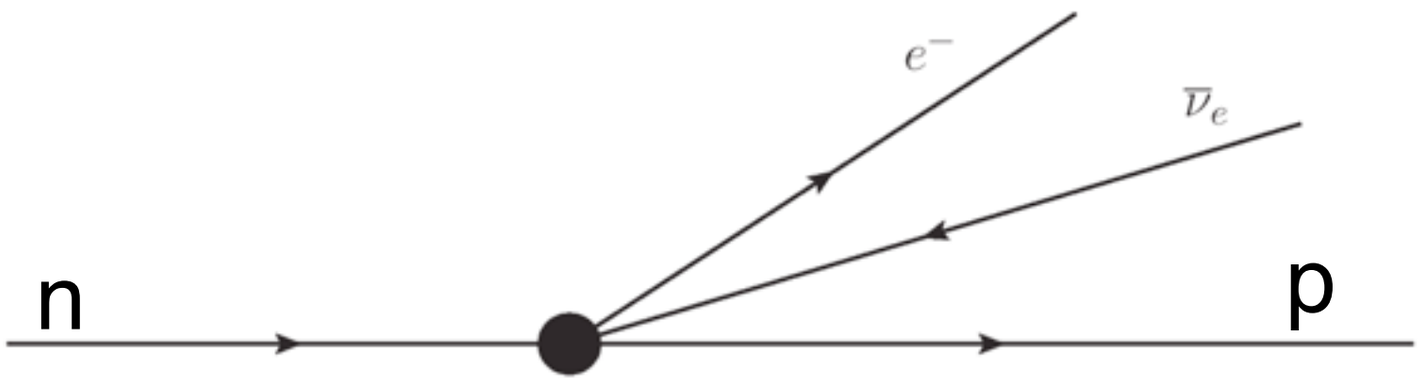


QED&QCD conserve quark flavor making weak physics clearly visible.

As a famous example, consider the β decay of the neutron: 1 GeV phenomenology reveals physics at 100 GeV.

Probing New Physics

Model-independent limits on new particles can be set using all quark-flavor-changing-current data.



$$\mathcal{A} \propto \frac{\text{const}}{M_W^2}$$

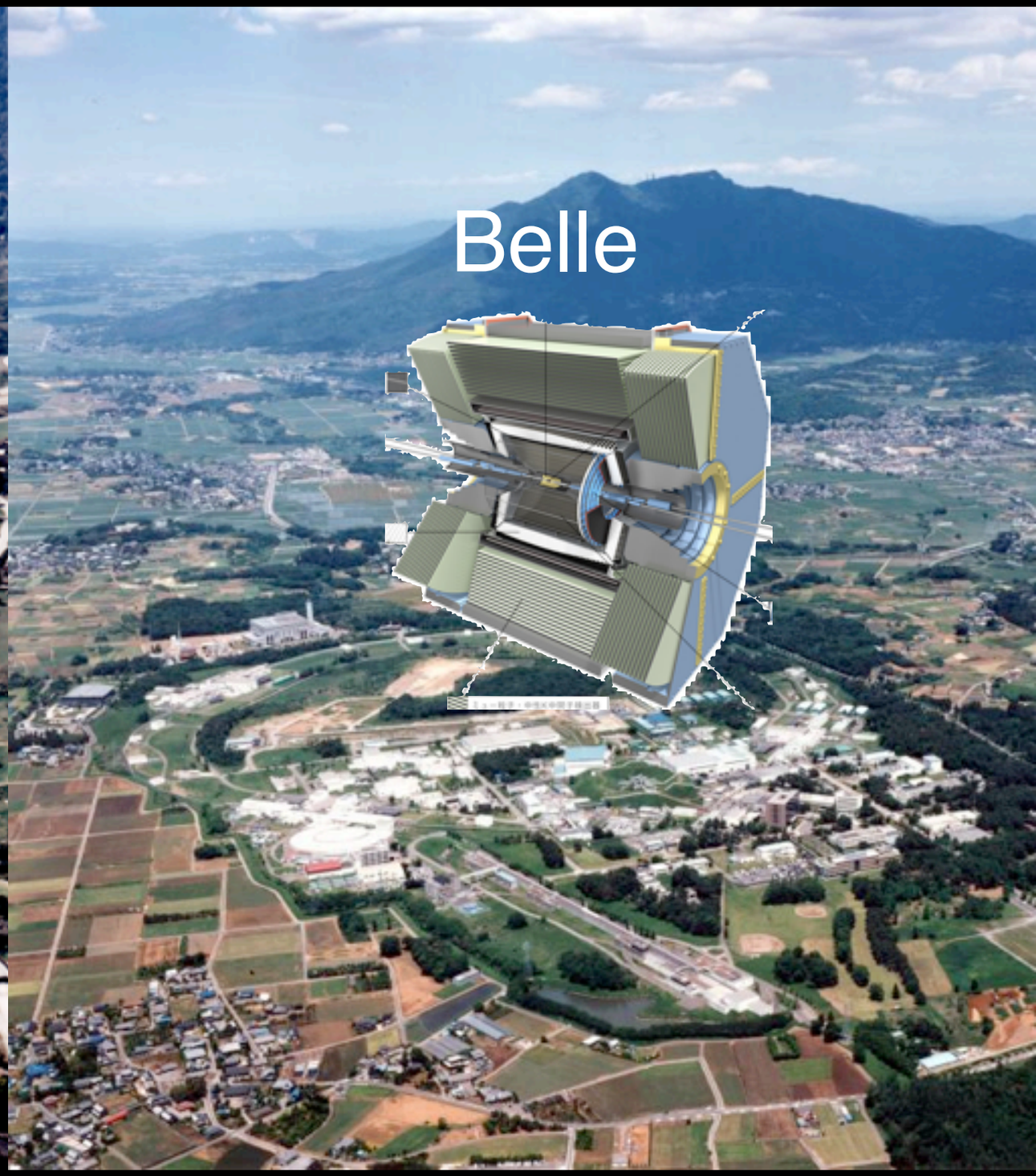
operator product expansion

$$\mathcal{H}_{eff} \propto \sum_i \left(\mathcal{C}^i_{SM} + \mathcal{C}^i_{BSM}\right) \mathcal{O}_i$$

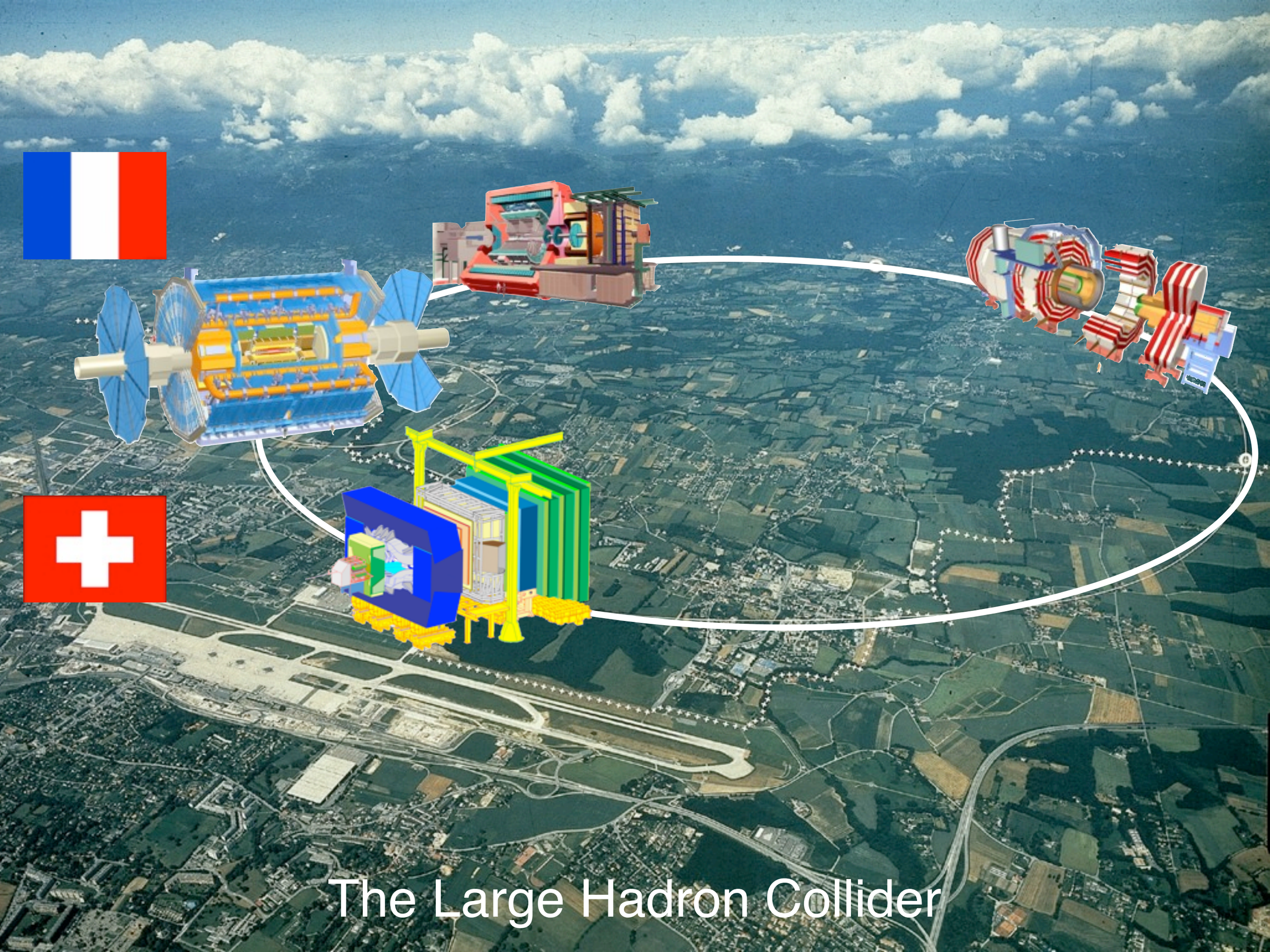
The “C” are the Wilson coefficients and “O” are local operators of all possible Lorentz structure, e.g., (V-A)[qq’]*V(ll’), (V+A)[qq’]*S(ll’),...

In principle sensitive to any mass scale (limited only by experimental and theoretical precision).

Flavor Factories

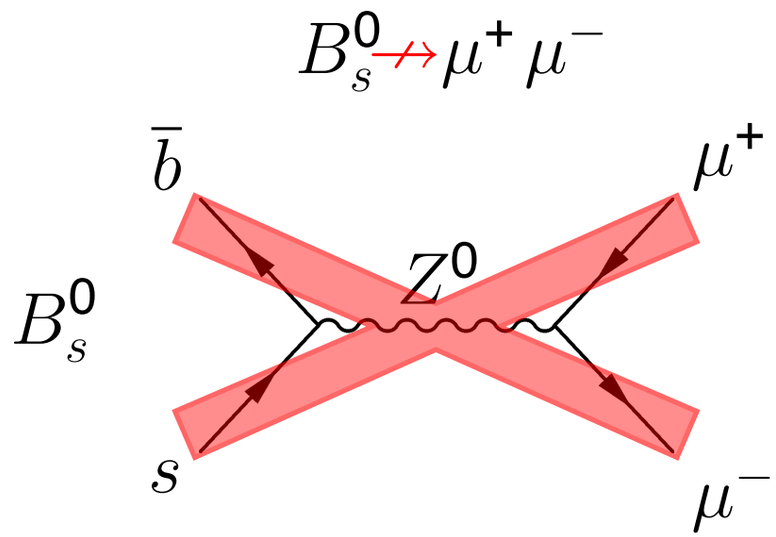


$e^+ \longrightarrow \quad \longleftarrow e^-$


The Large Hadron Collider

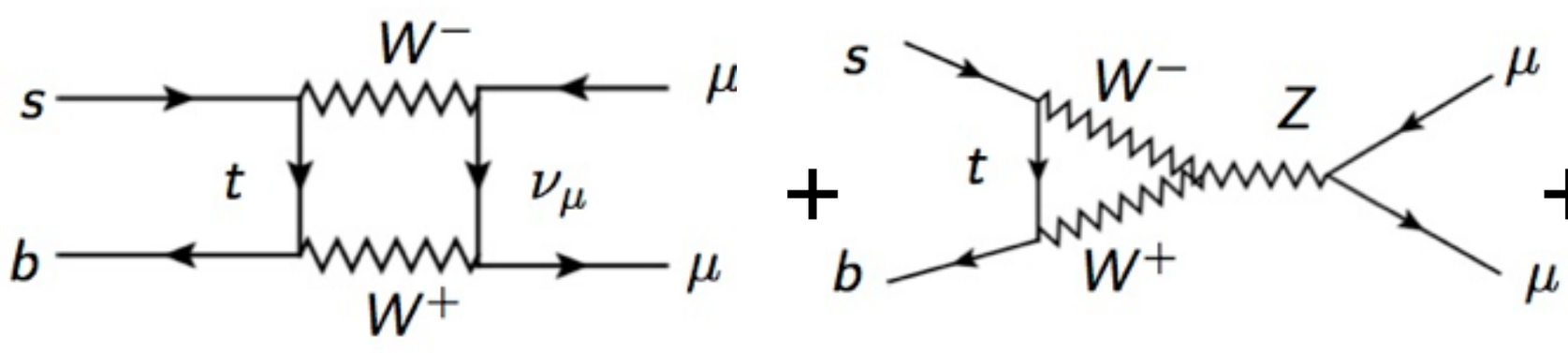
$B_{d,s} \to \mu^+\mu^-$

The size of a BSM amplitude is inversely proportional to the BSM mass scale, so we want to focus on measuring processes where a small amplitude can cause a measurable effect (and also where we know the SM prediction).



no tree-level amplitude in SM

rate $\propto$

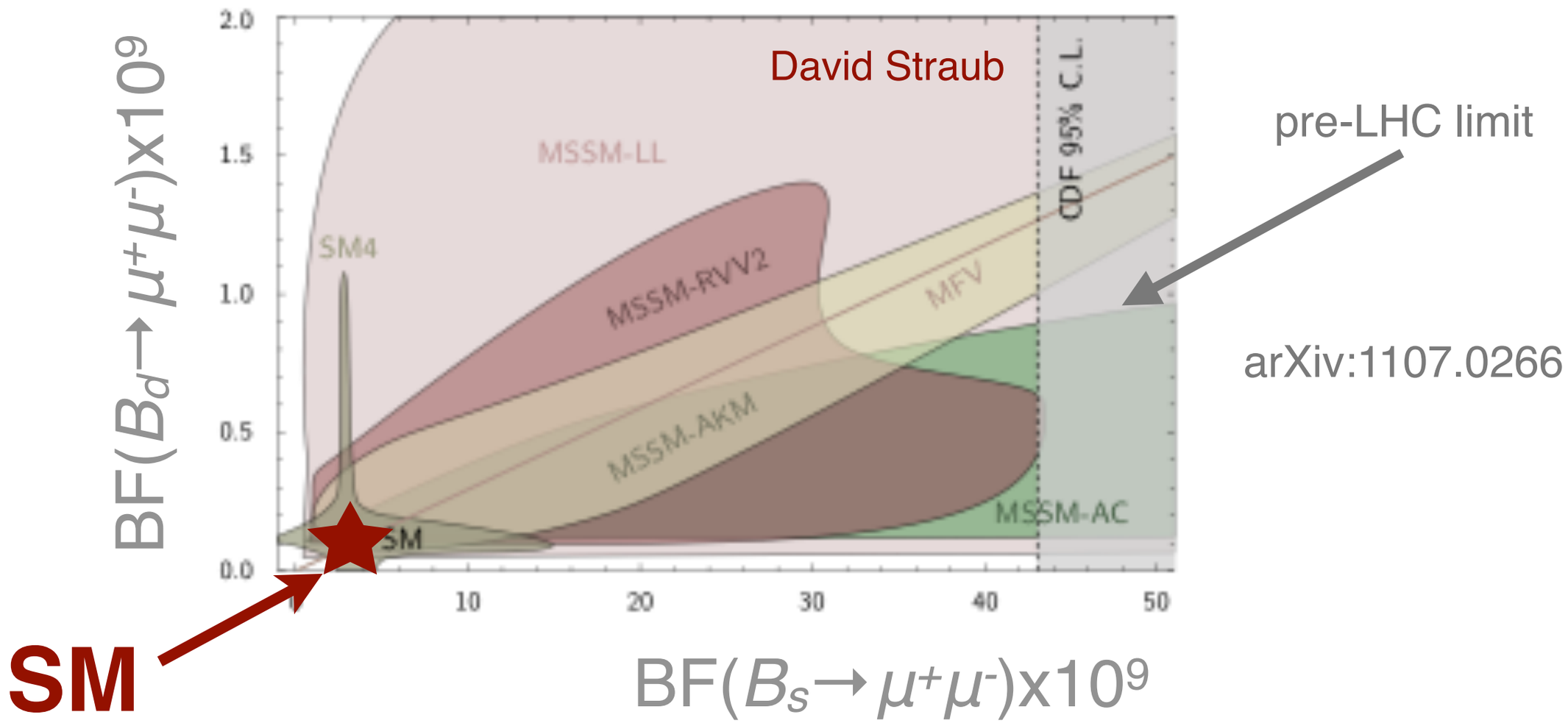


^{2} + [?] + ...

The SM predicts the B_s (bound s-b) decays into two muons once every 3.4B decays. BSM could significantly affect this decay rate.

$B_{d,s} \to \mu^+\mu^-$

How would BSM affect these decay rates? That depends on the BSM mass scale and what quark flavor-changing currents exist in the theory.

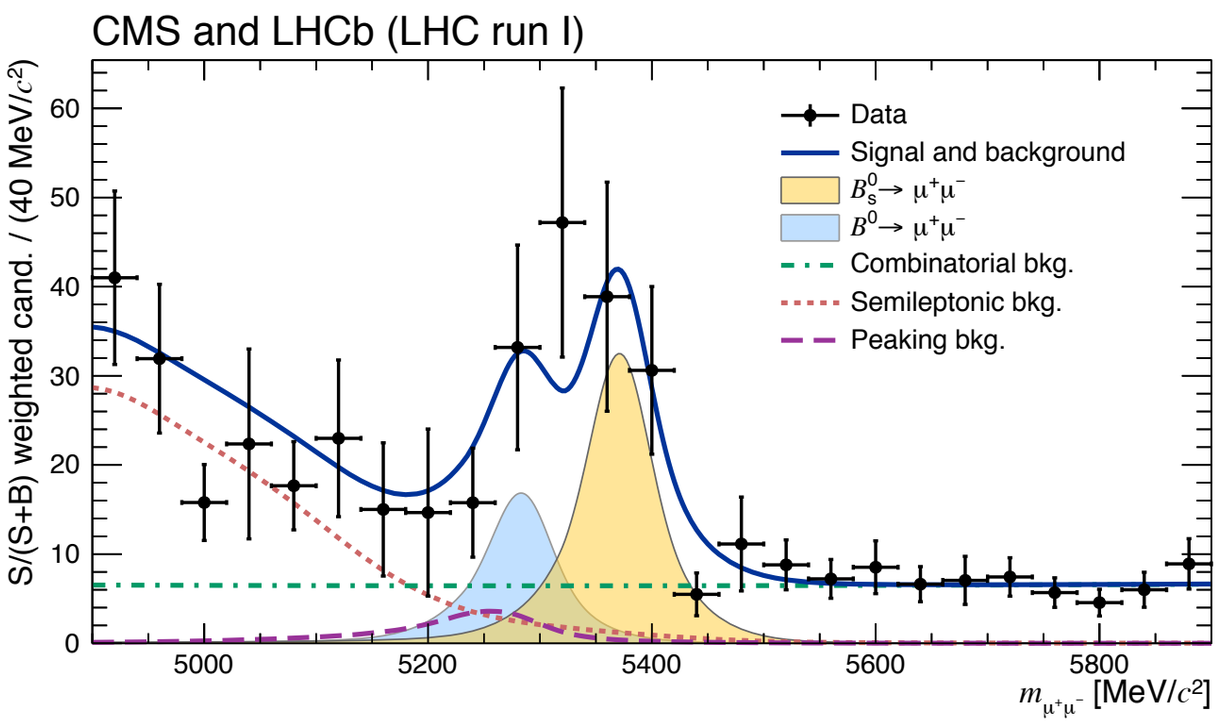


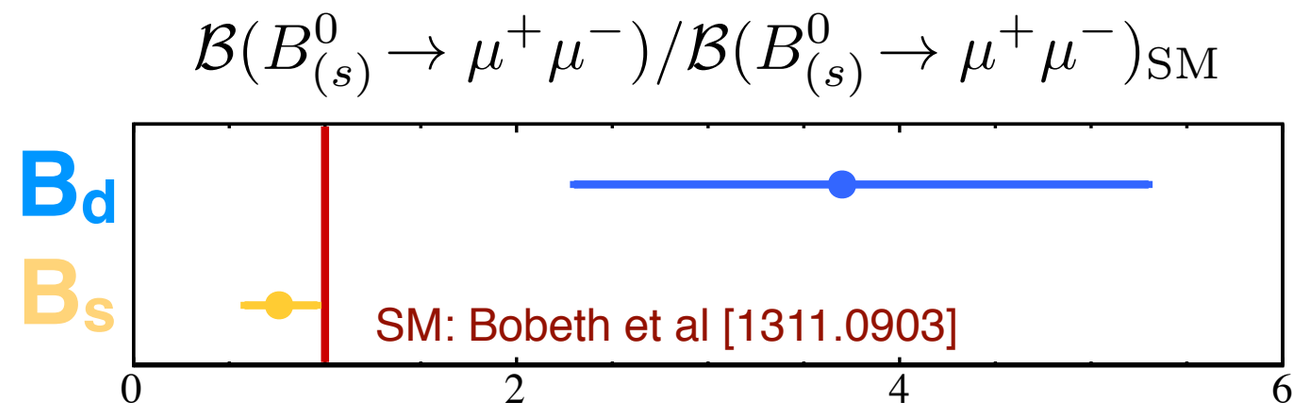
For example, this plot shows various SUSY predictions prior to LHC running.

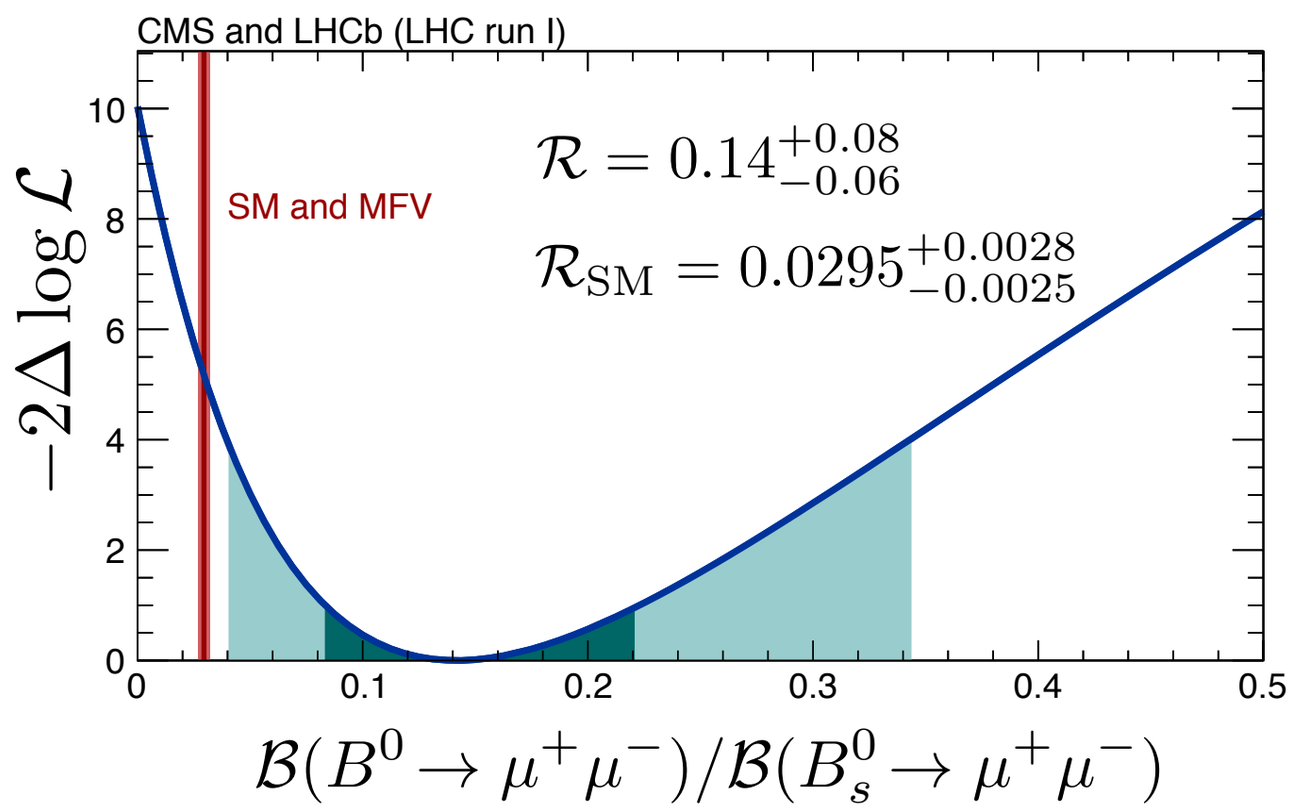
$B_{d,s} \to \mu^+\mu^-$

After 30 years of searching for these decays, both LHCb and CMS crossed the 4σ significance threshold in Run 1 for the B_s decay.

CMS&LHCb, Nature 522, 68 (2015).





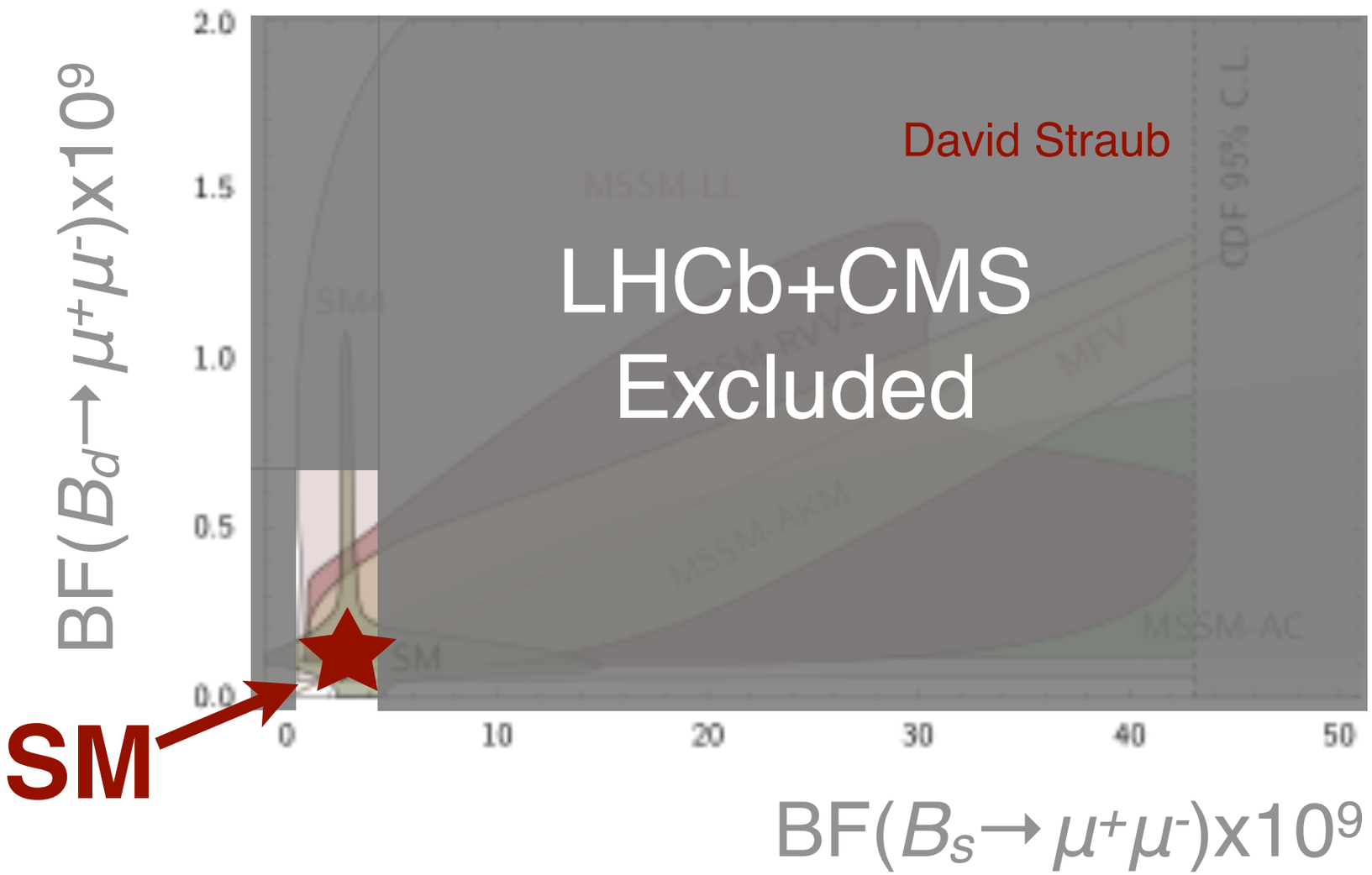


Results from combined CMS & LHCb data obtain 6.2σ for the B_s decay and 3.0σ for the B_d decay.

There is some minor tension in the branching-fraction ratio, looking forward to Run 2 data.

$B_{d,s} \to \mu^+\mu^-$

Rules out large regions of SUSY parameter space.

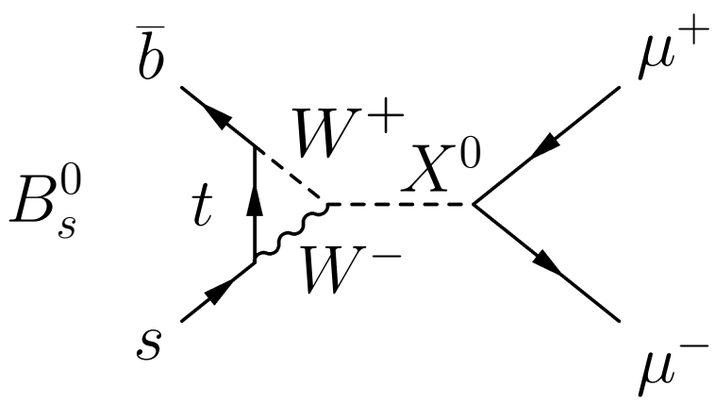


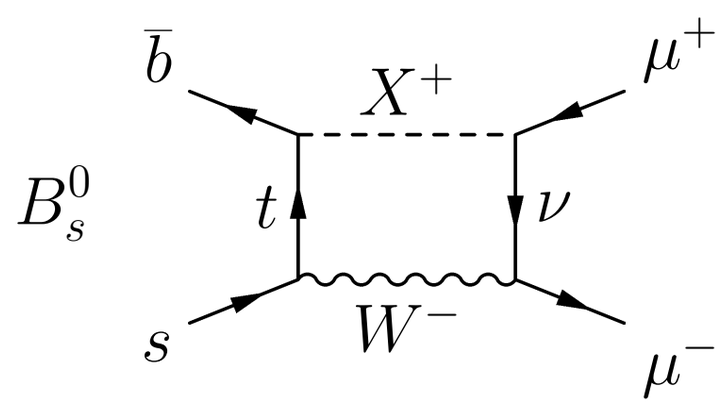
arXiv:1107.0266

$B_{d,s} \to \mu^+\mu^-$

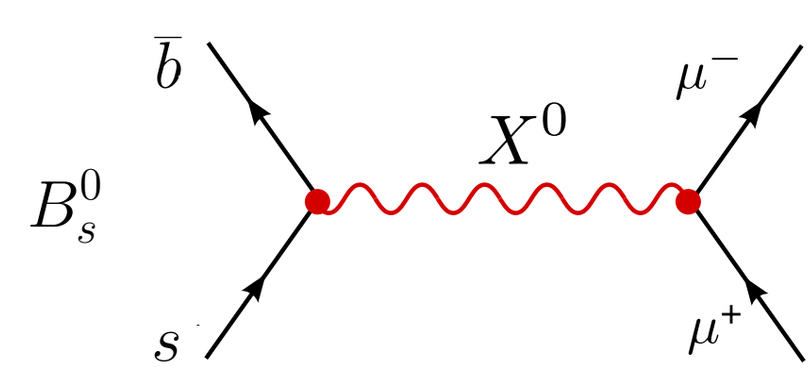
The mass scale probed depends on how BSM contributes. The highest mass scales are probed in diagrams that aren't otherwise suppressed.

loops (could be MFV or not)





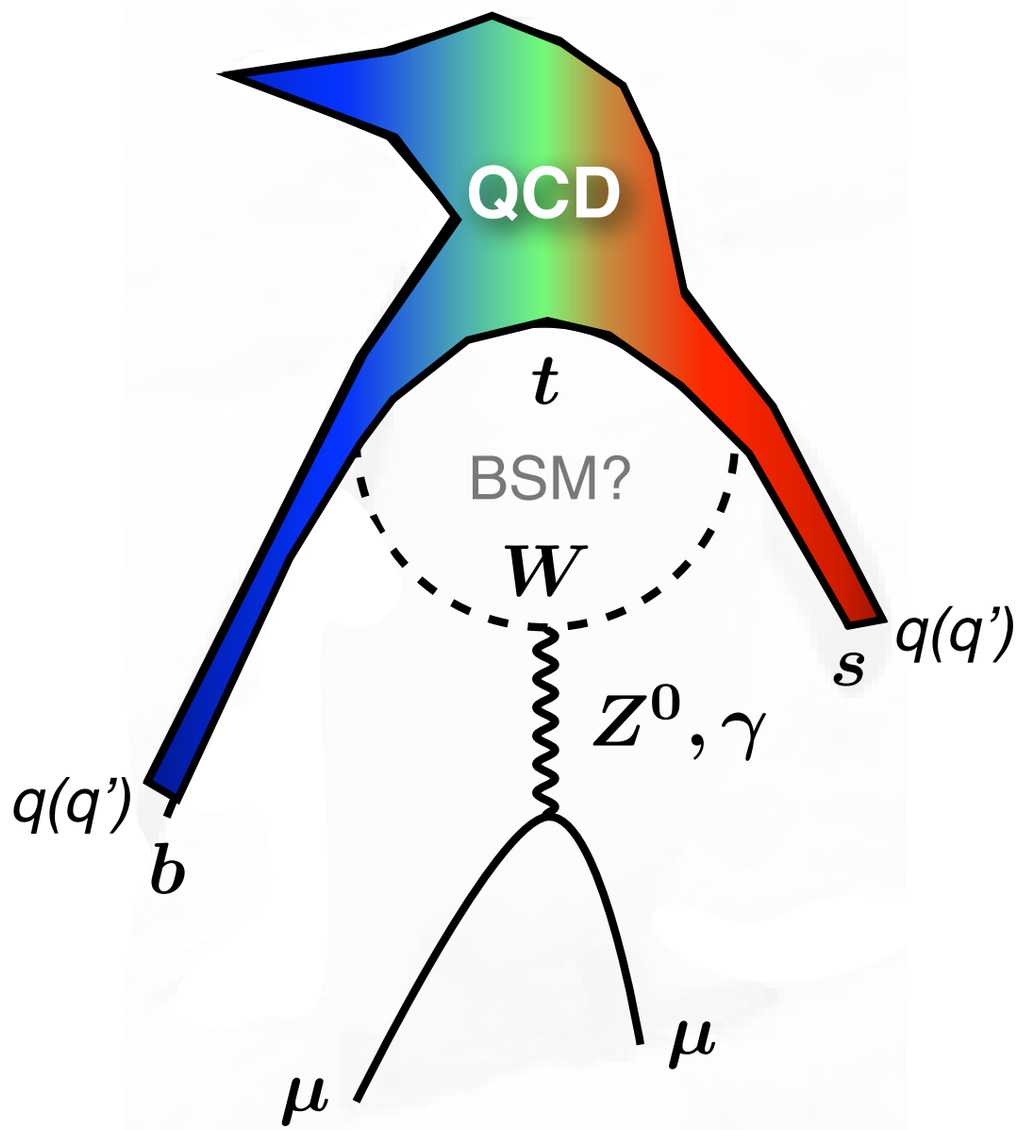
tree (requires FV)



If BSM affects this process, it must also affect other processes. The game is to find all discrepancies (and agreement) with the SM, then solve the puzzle (i.e., figure out how to explain all the results in a single (new SM) model).

$b \to s$ Penguins

b→s "penguin" decays are loop/CKM suppressed in the SM, which permits sizable BSM contributions; however, calculations require control of the hadronic effects.



SM calculations need B→K form factors

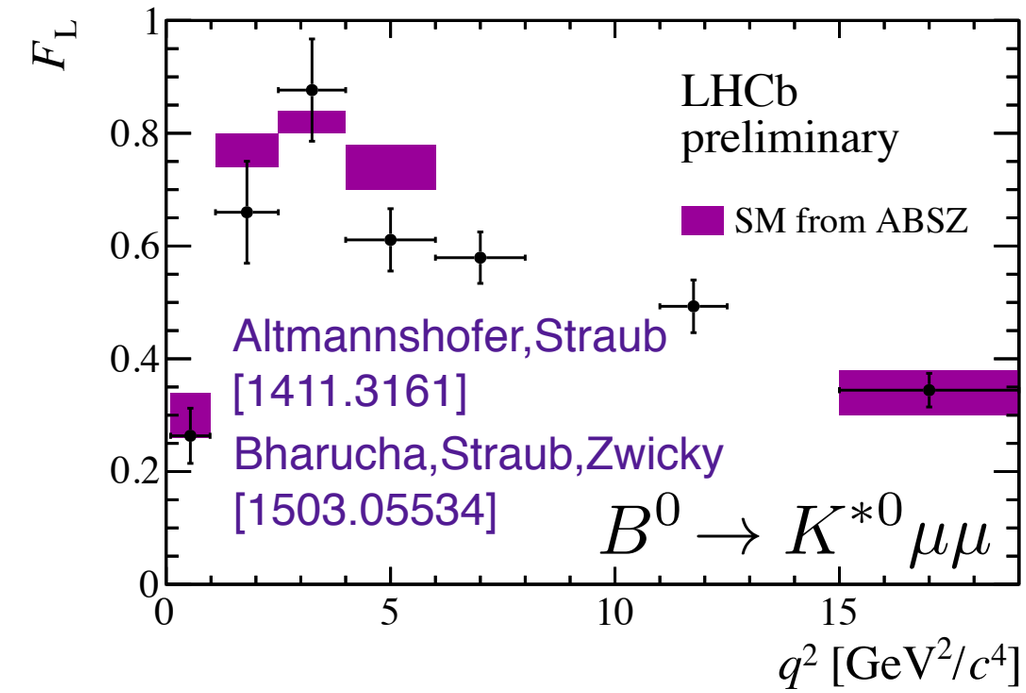
The b→sμμ family of decays provide many sensitive observables (accessible via angular analysis) with which to test the Lorentz structure of the SM.

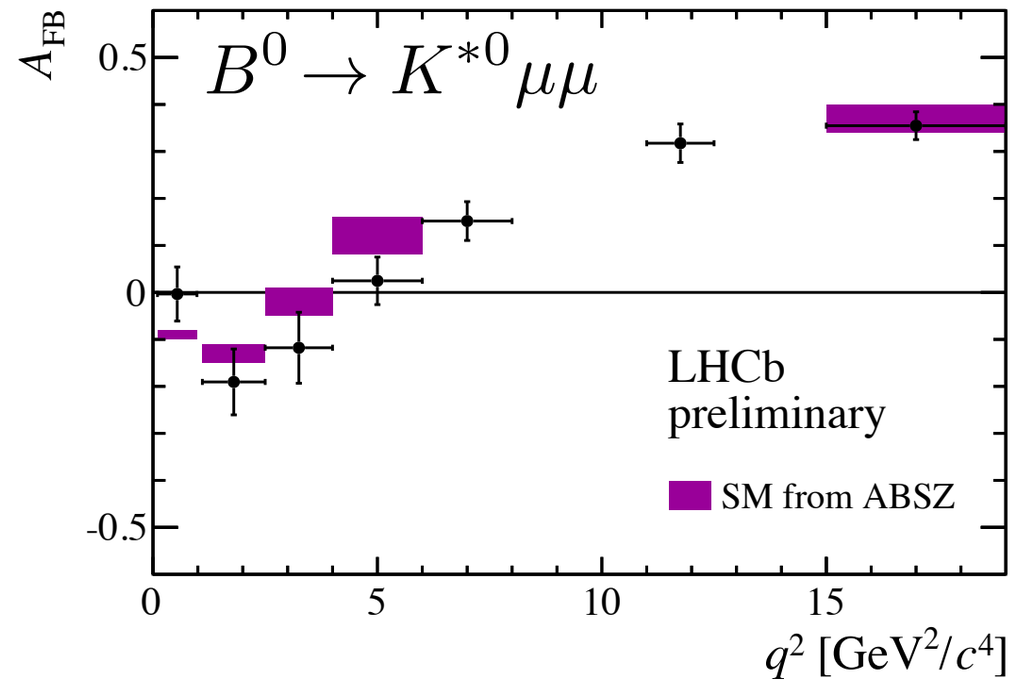
$b \to s$ Penguins

Many observables show consistency with the SM while probing O(10 TeV).

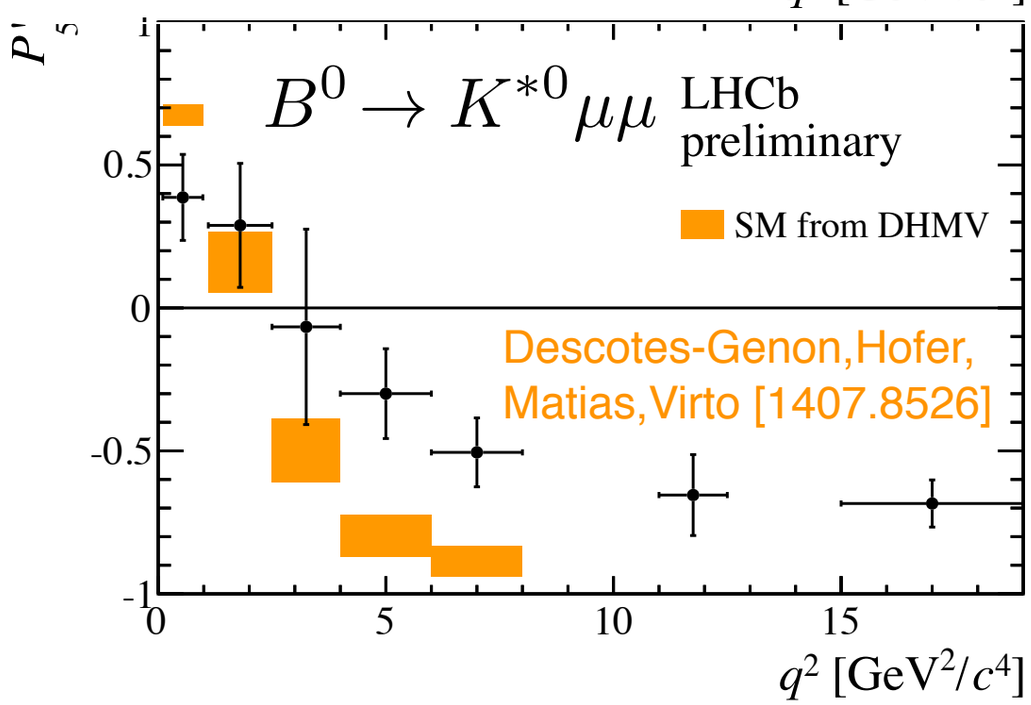
LHCb-PAPER-2015-023

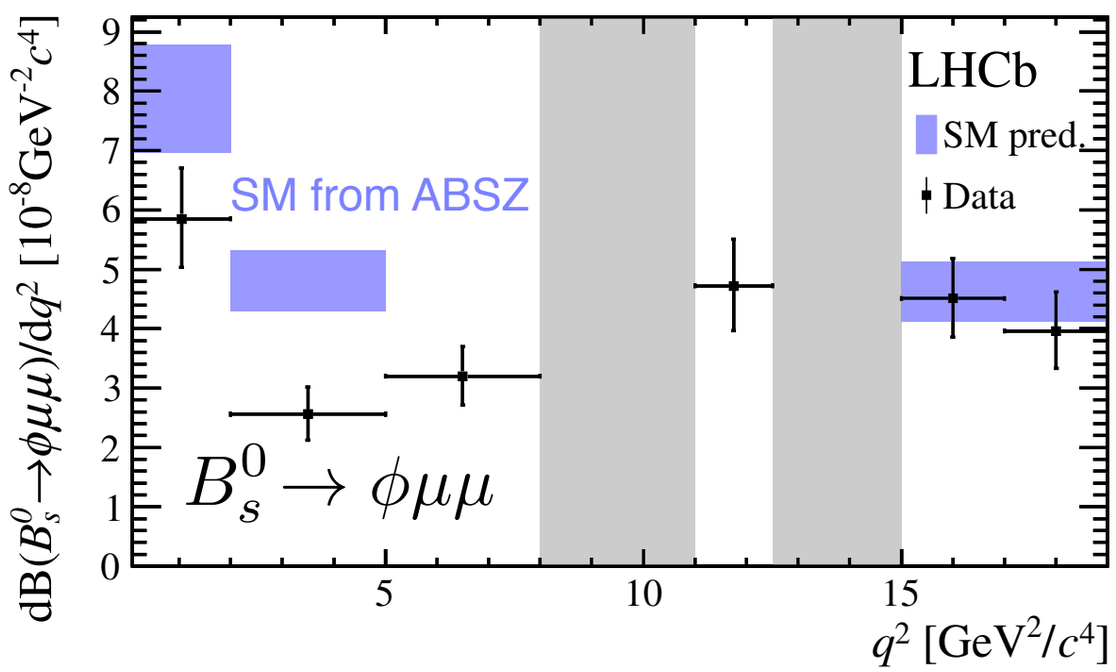
LHCb-CONF-2015-002, LHCb-PAPER-2015-023





See talks by Bowen, Kolpin, De & Tekampe in QLF

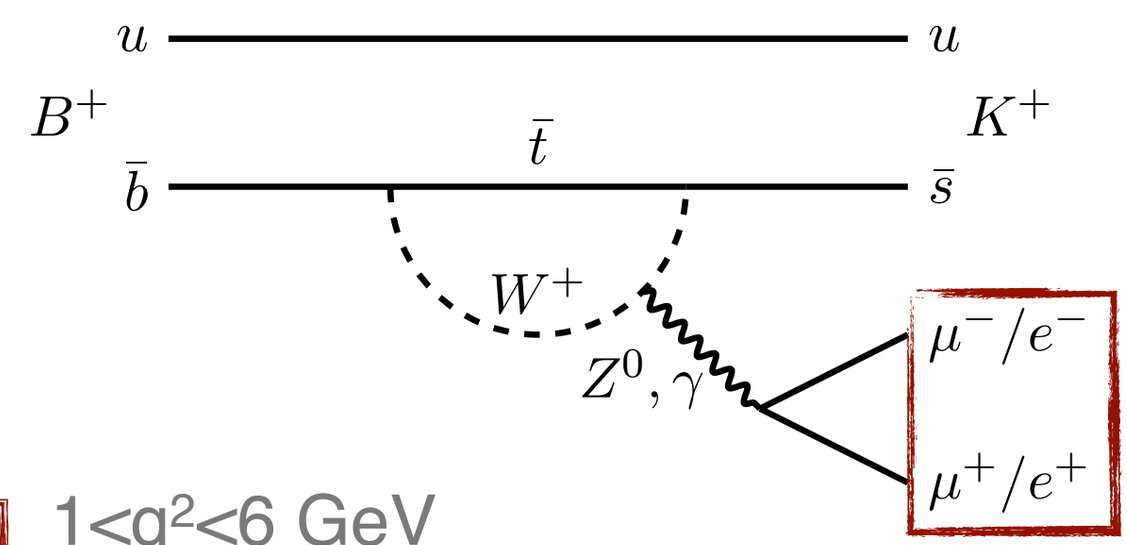




A few do not, e.g. a 3.7σ discrepancy in a "less QCD dependent" observable.

Lepton Universality

In the SM only the Higgs boson has non-universal lepton couplings. This results in SM predictions of nearly unity for various decay-rate ratios.



$$R_K = \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to K^+e^+e^-)} \overset{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-3})$$

LHCb-PAPER-2014-024

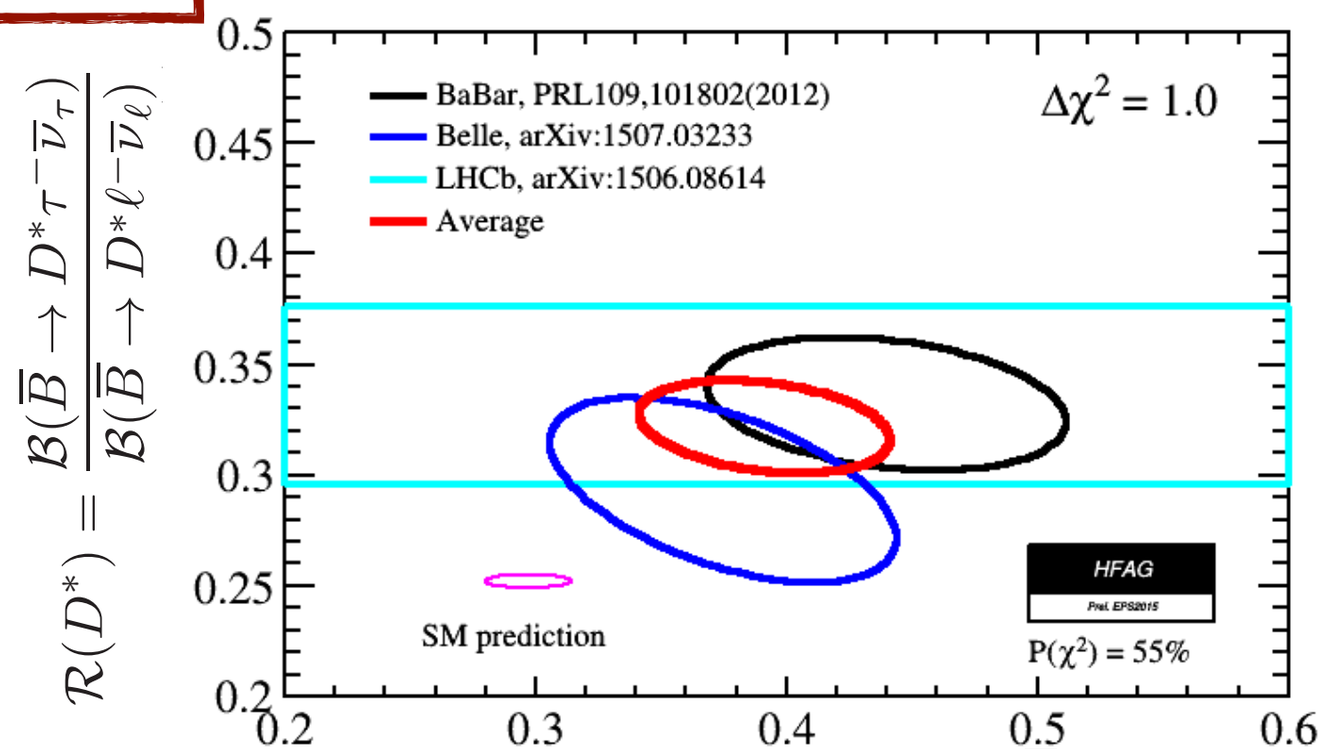
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

$1<q^2<6$ GeV

2.6σ from SM

If R_K discrepancy is due to BSM, then other similar ratios (e.g., involving τ) should also show discrepancies.

Measurement of $R_{D^{(*)}}$ by BaBar, Belle, and LHCb show a 3.7σ discrepancy with the SM prediction.

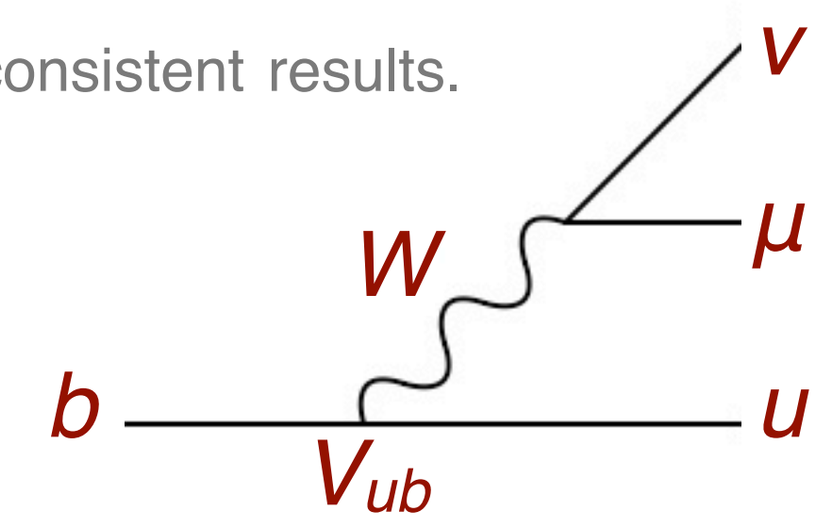


See talk by Hamilton in QLF

V_{ub}

Different methods of measuring the b→u coupling give inconsistent results.
This "Vub puzzle" has persisted for a long time.

Possible solution: contribution from a RH current.



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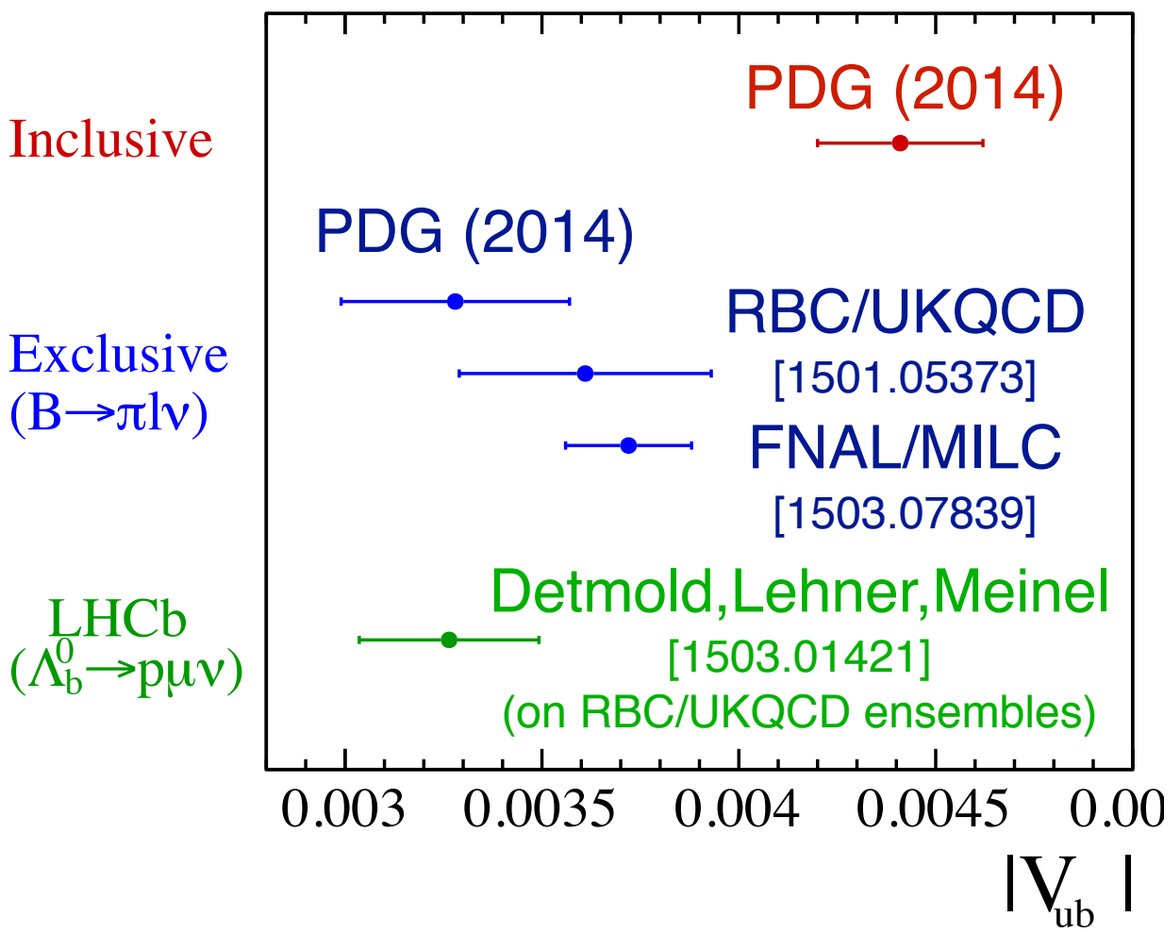

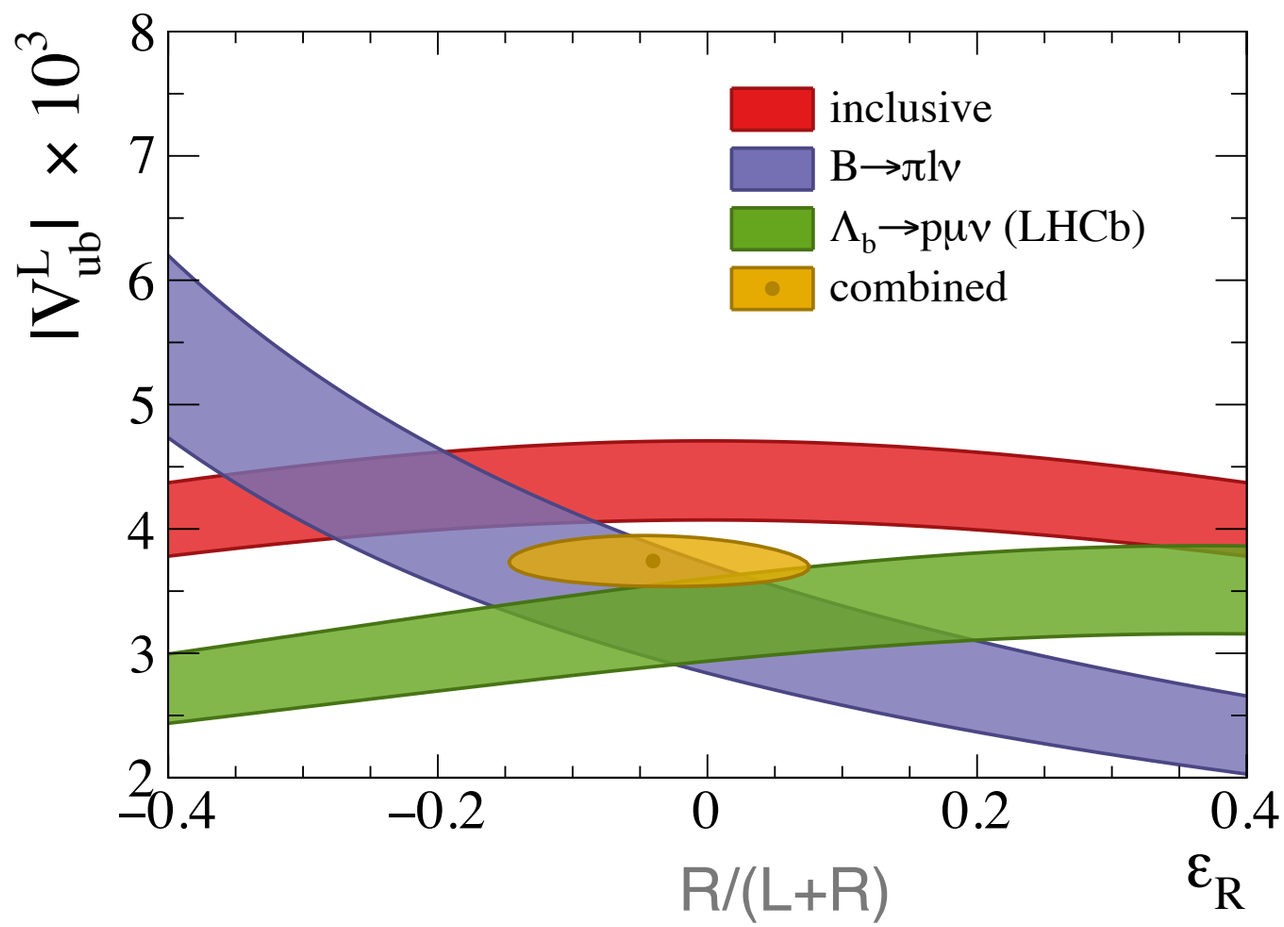

LHCb (first ever) baryonic result removes the need for RH current.

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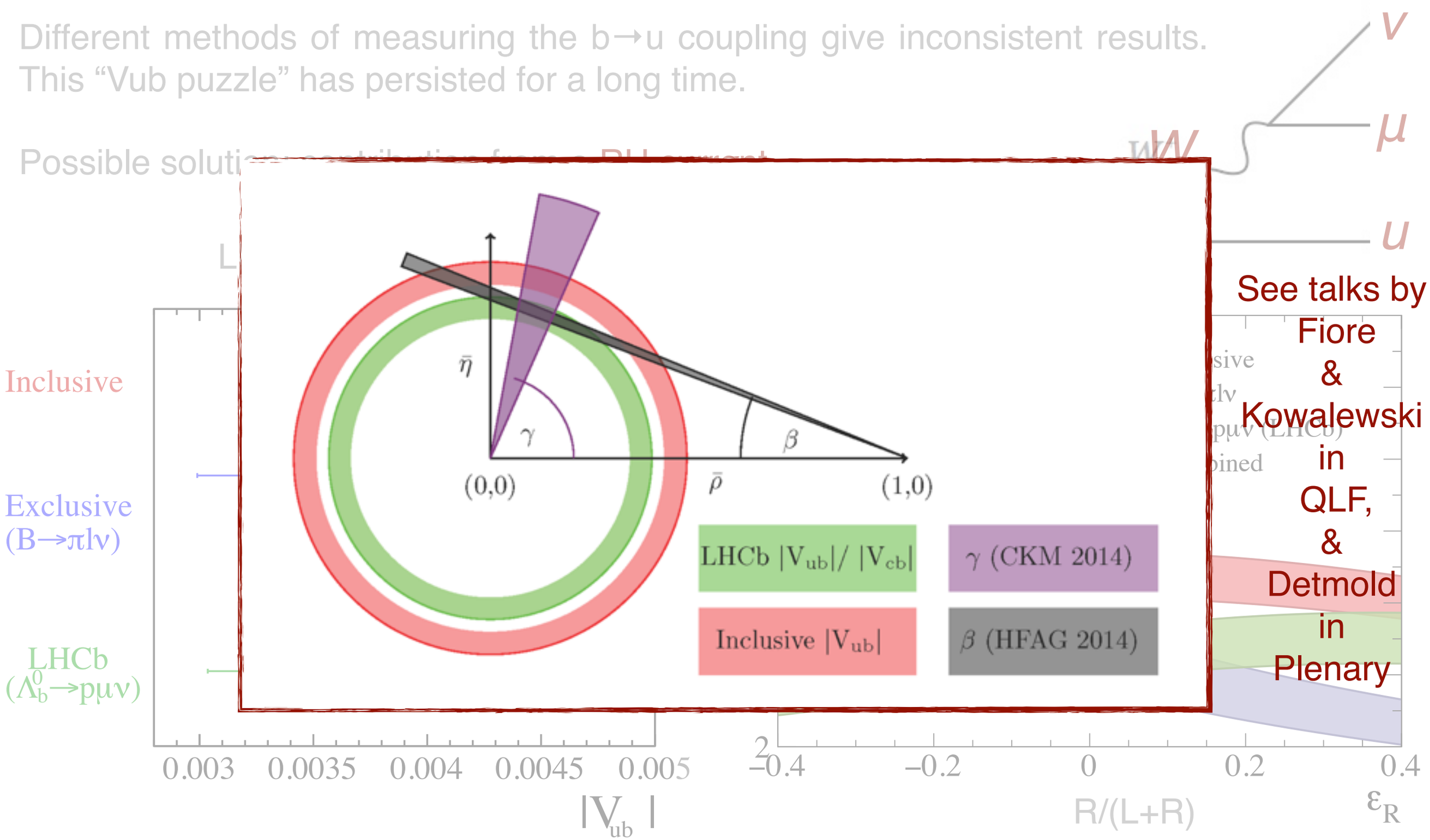
Possible soluti

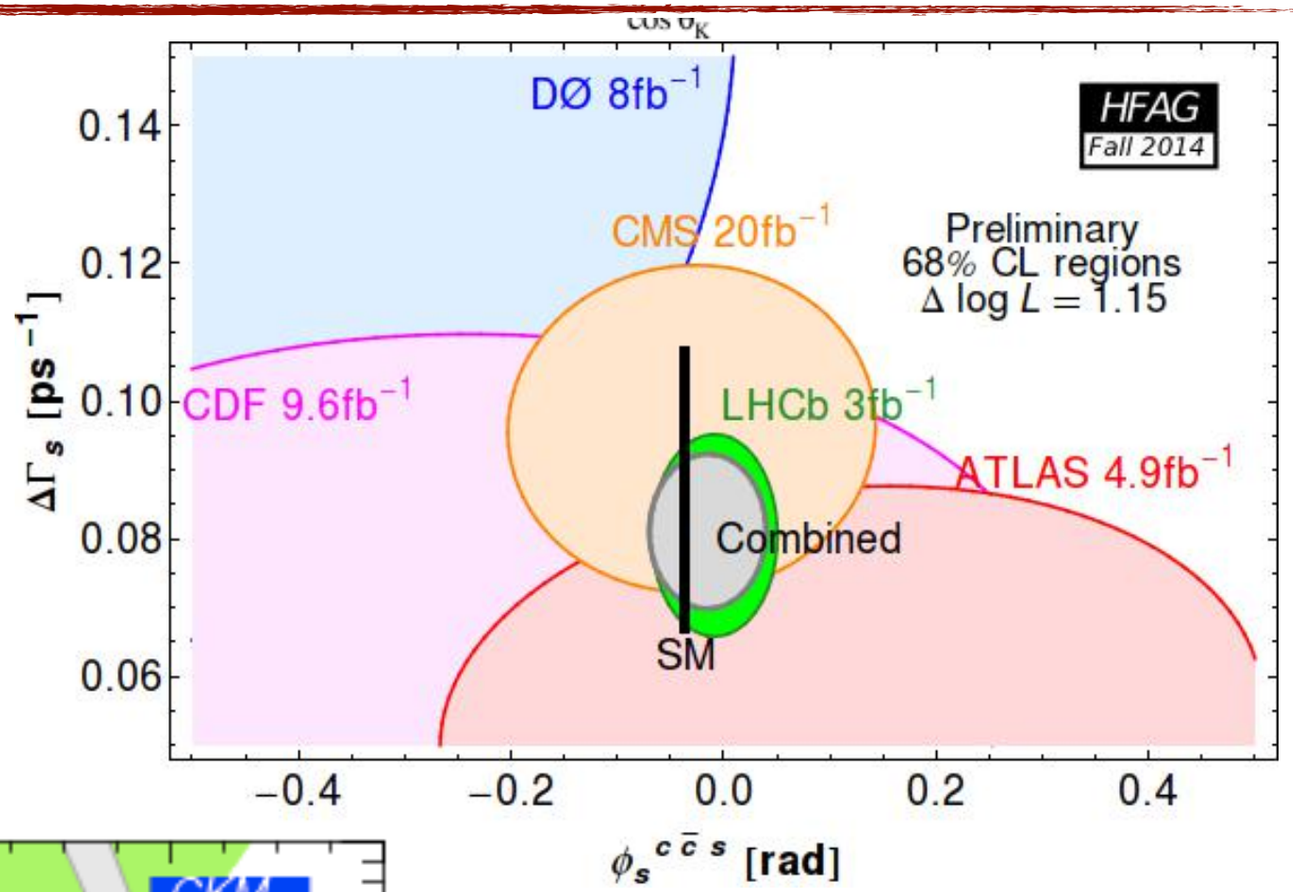


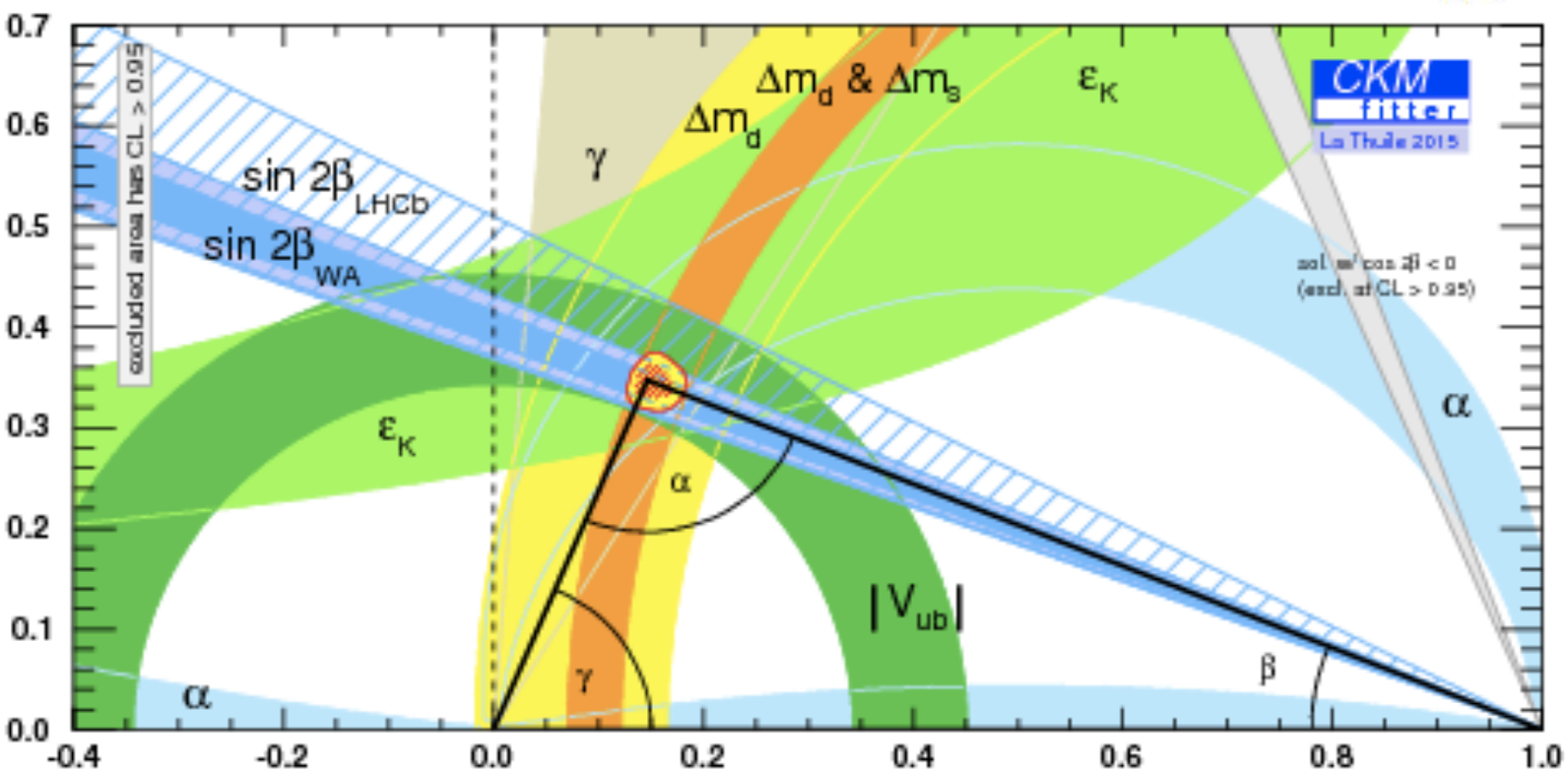
See talks by Fiore & Kowalewski in QLF, & Detmold in Plenary

LHCb (first ever) baryonic result removes the need for RH current but the puzzle remains.

Etc

Too many amazing results to cover in this (or any) talk. We have definitely now reached the precision era in our knowledge of quark-flavor-changing couplings.





Overall, the agreement with the SM is … frustrating.

Probing New Physics

Summary of the constraints on Wilson Coefficients from global fits of all flavor-changing data:

See Blake, Gershon, Hiller [1501.03309]

- (V-A)[qq']*(V,A)(ll') < ~SM;
- (V+A)[qq']*(V,A)(ll') roughly same as V-A;
- strong constraints on scalar, tensor, etc.

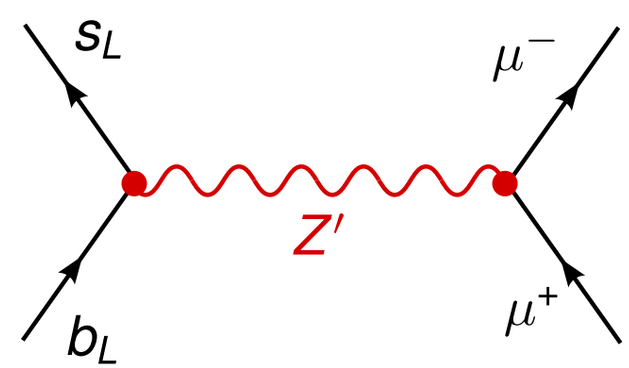
Overall the data are largely consistent with the SM and global fits place constraints on BSM particles of about 0.5-50 TeV (depending on model) ... however, global fits also show ~4σ discrepancy.

Main message: Strong constraints placed on BSM, but some intriguing anomalies remain. We need more data!

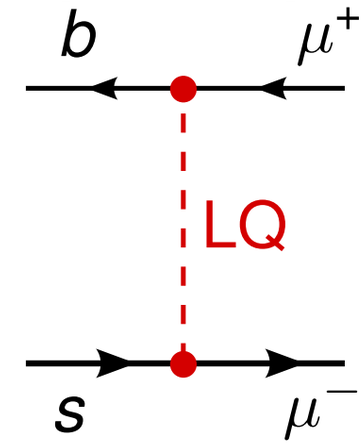
If these discrepancies are BSM and not QCD artifacts and fluctuations:

- it couples to leptonic V and/or A currents;
- it has non-universal leptonic couplings;
- it may couple to RH quark currents.

Glashow, Guadagnoli, Lane [1411.0565]



Hiller, Schmaltz [1408.1627]

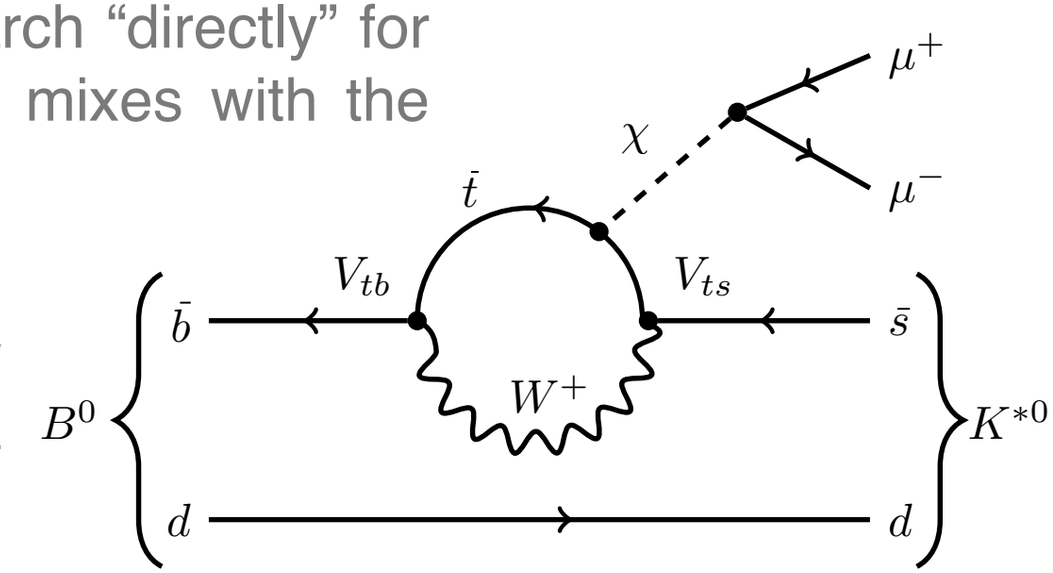


Potential candidates include O(1-10 TeV) Z' or leptoquarks.

See talk by Altmannshofer in QLF

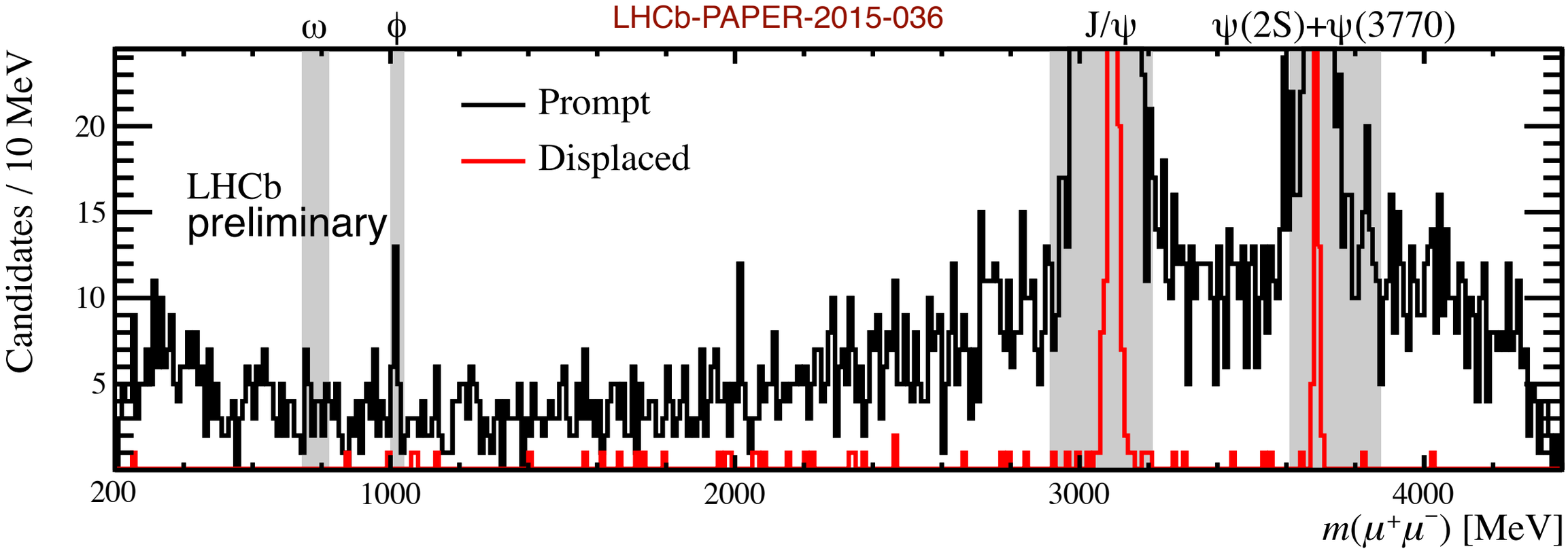
Hidden Sectors

b→*s* penguin decays are also an excellent lab to search "directly" for low-mass hidden-sector particles (e.g., anything that mixes with the Higgs sector).



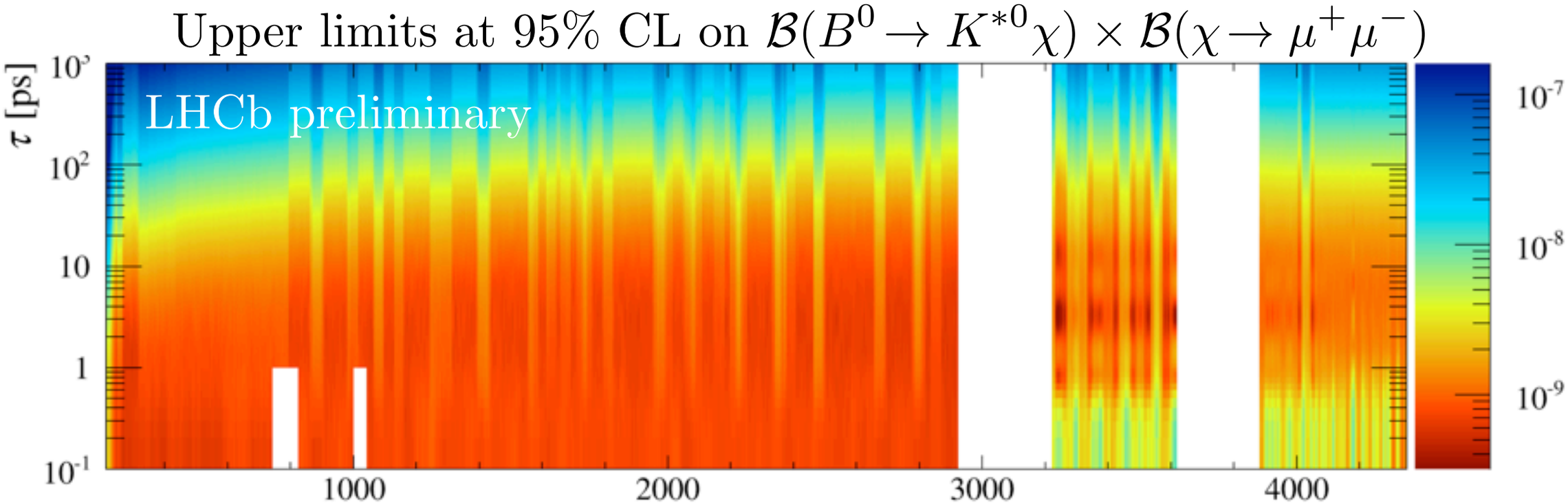
Search for *B*→*K*X*, *X*→*μμ* by scanning m(μμ) and allowing (not requiring) non-zero τ(μμ). Strategy handles possible qq resonance contributions in a simple manner (MW [1503.04767]). Use of novel "uniform BDT" (J.Stevens, MW [1305.7248]).

LHCb-PAPER-2015-036



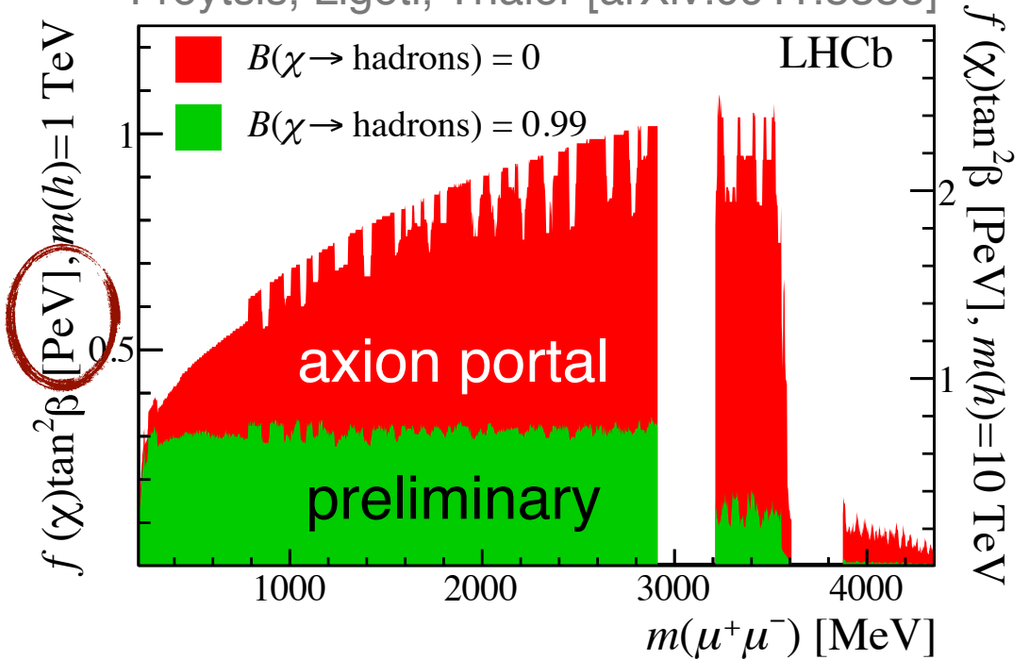
No evidence for a hidden-sector boson so model-independent limits are set.

Hidden Sectors



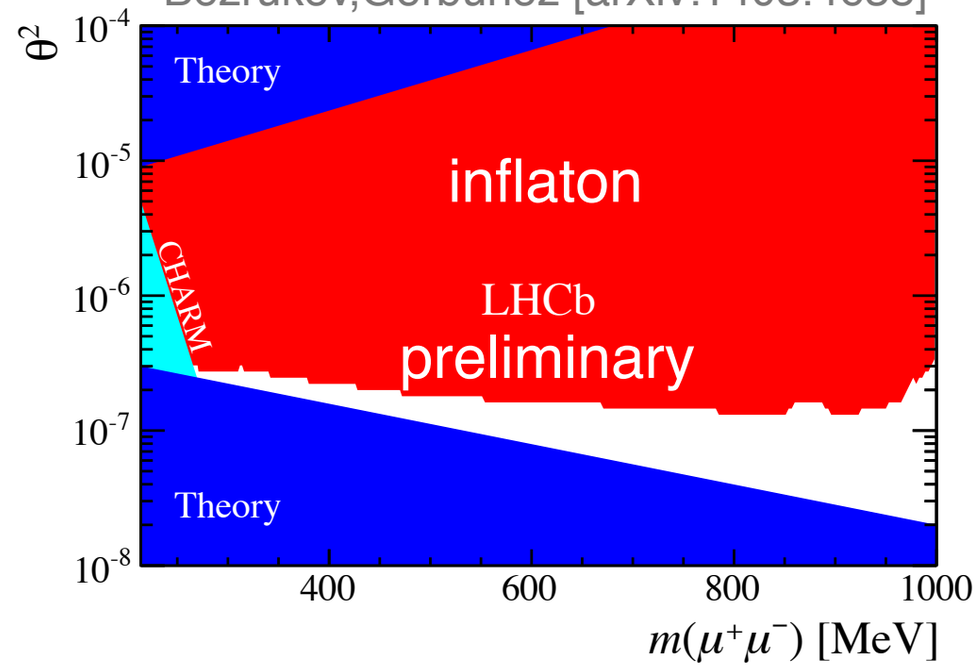
LHCb-PAPER-2015-036

Freytsis, Ligeti, Thaler [arXiv:0911.5355]



PeV scale!

Bezrukov,Gorbunoz [arXiv:1403.4638]



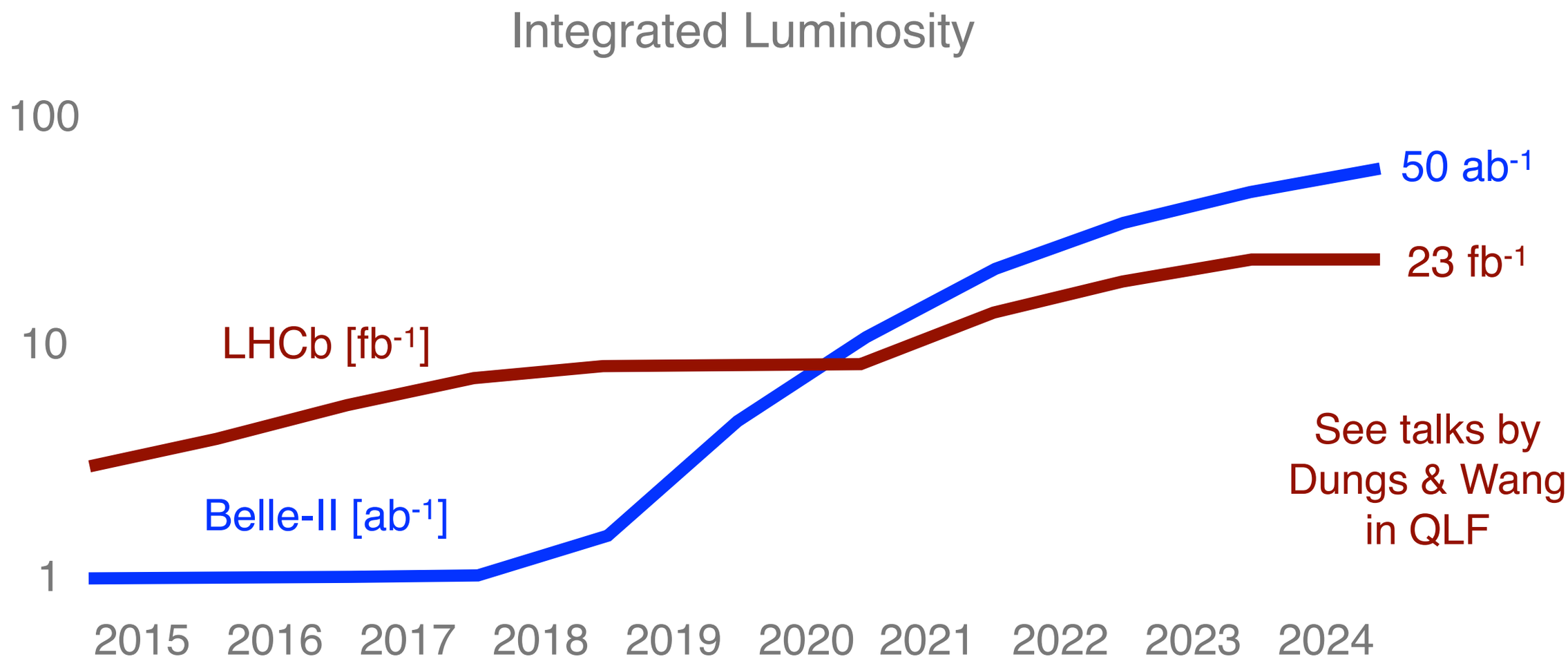
Very strong constraints placed on theories that invoke mixing with the Higgs sector.

A look to the future...

...Belle-II and the LHC runs 2 and 3.

Belle II & LHCb

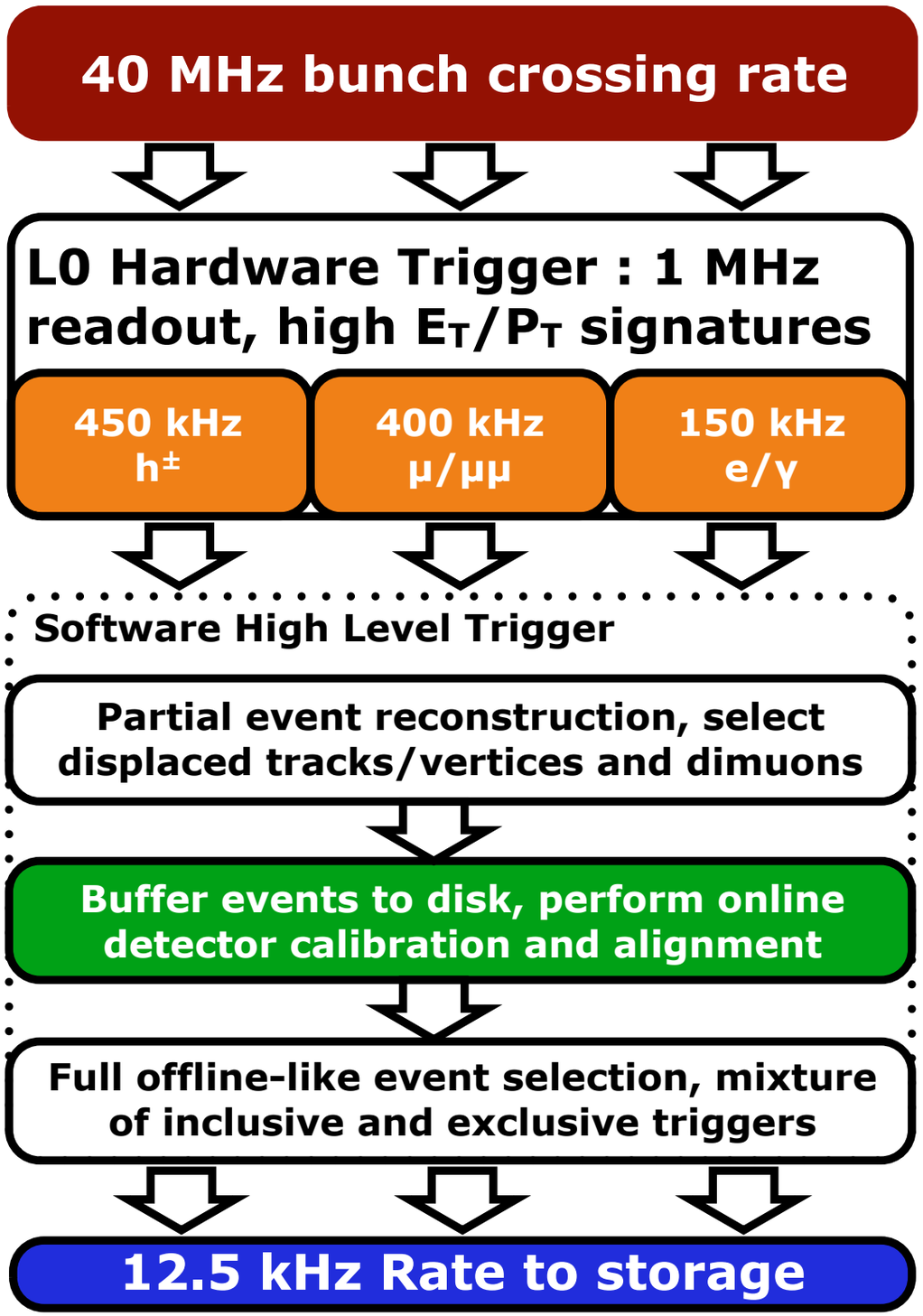
LHCb has resumed taking data and expects to collect 5/fb in Run 2, followed by about 15/fb in Run 3. The upgraded Belle-II experiment plans to collect 50/ab by 2025.



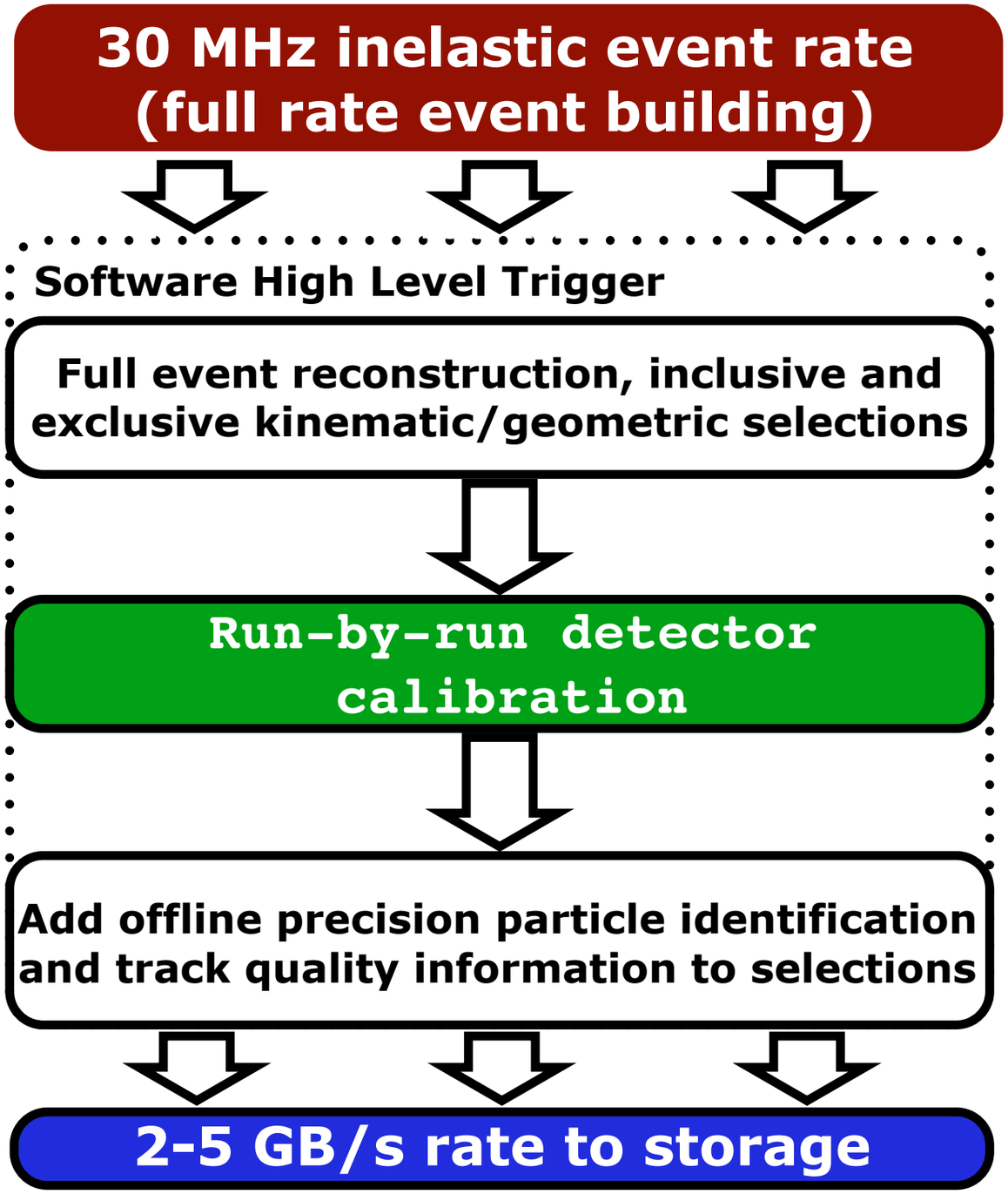
Both experiments have gained vital experience with existing data so expect to improve beyond just statistical power.

LHCb Trigger

Run 2



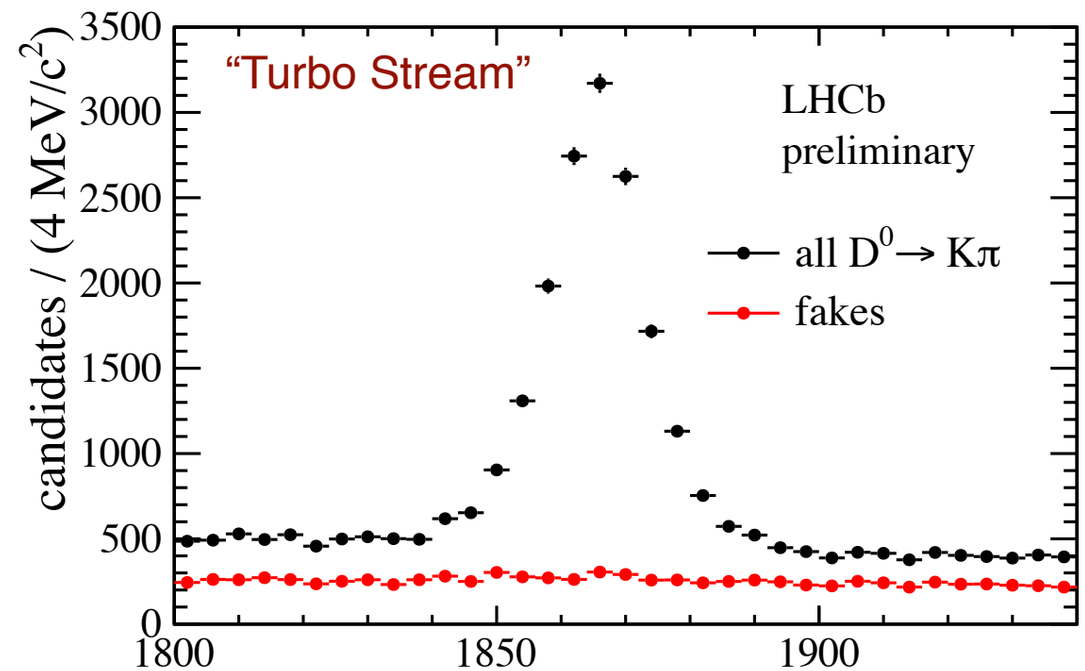
LHCb Upgrade Trigger Diagram

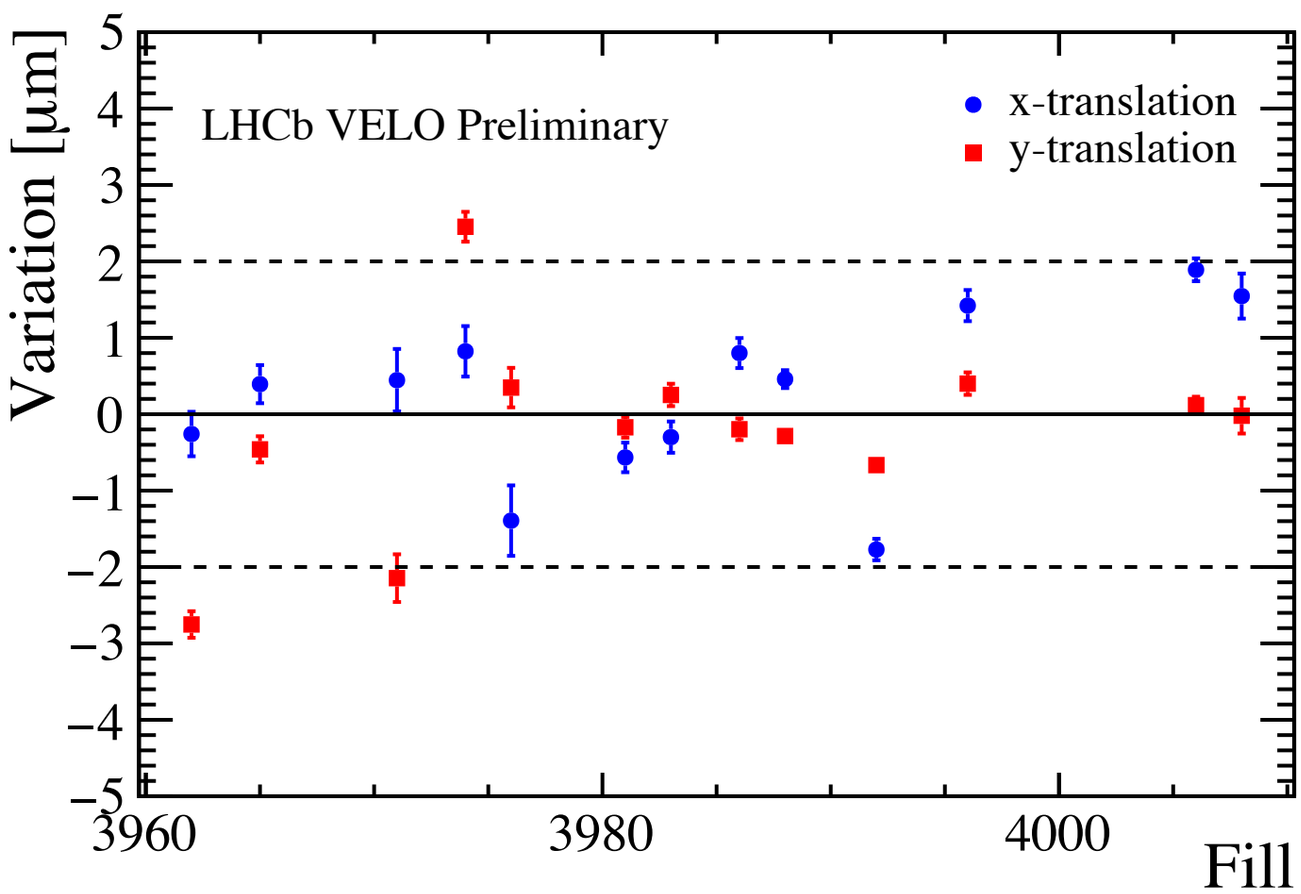


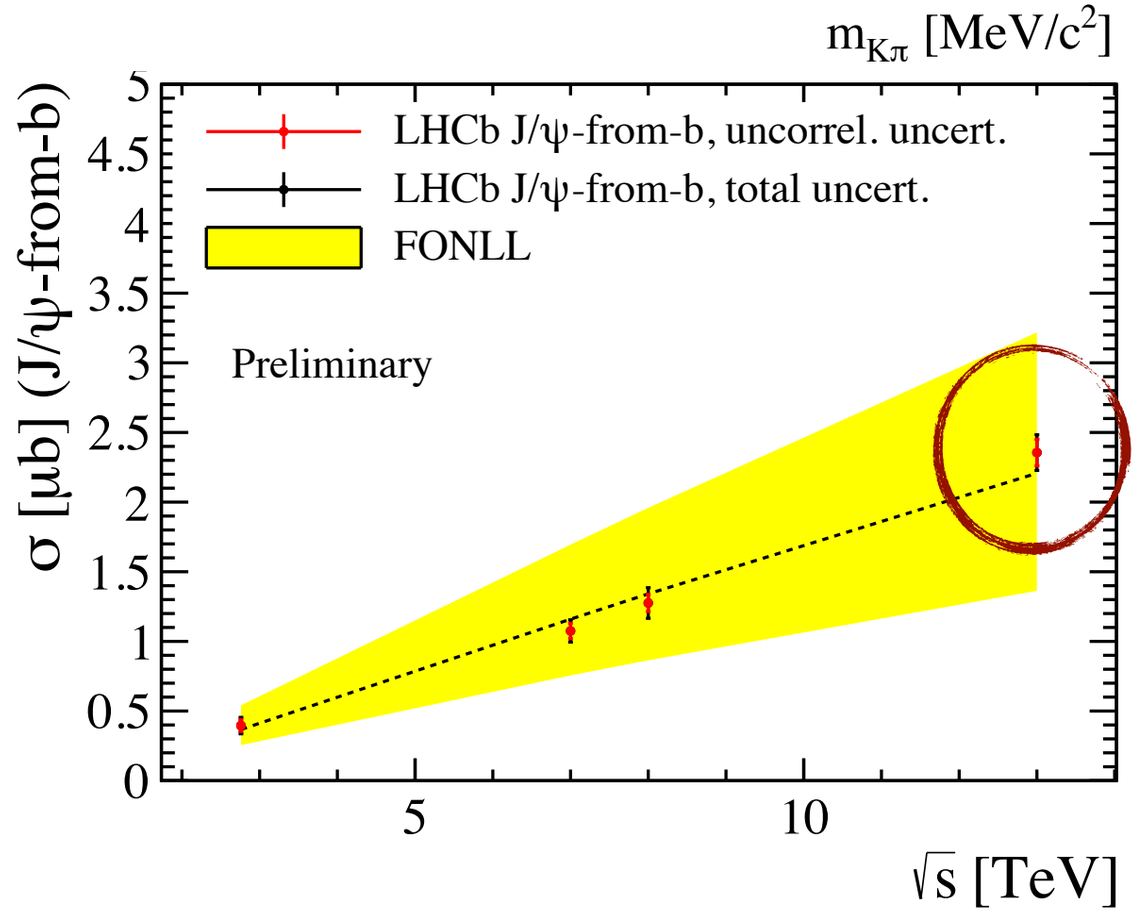
LHCb Run 2

Real-time alignment & calibration commissioned. Fake-track killing neural-network algorithm commissioned for online use. Etc.

Already analyzing online-reconstructed data: σ(bb) @ 13 TeV!

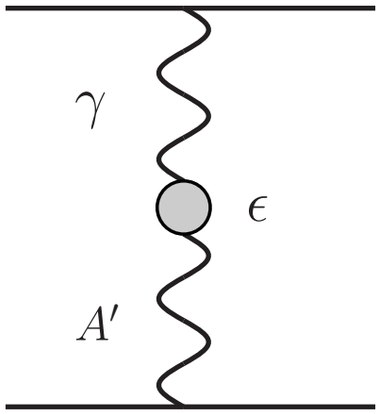




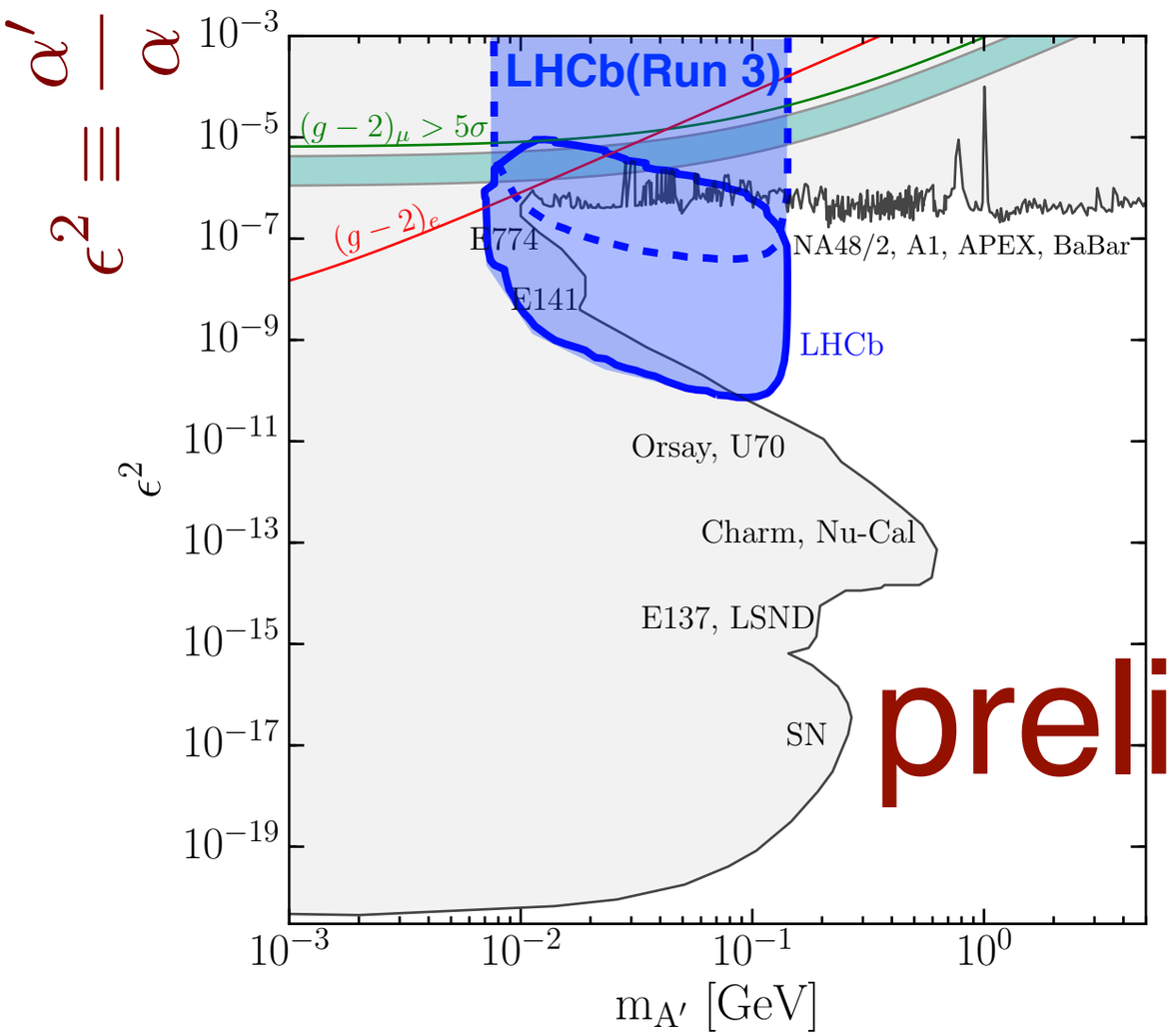


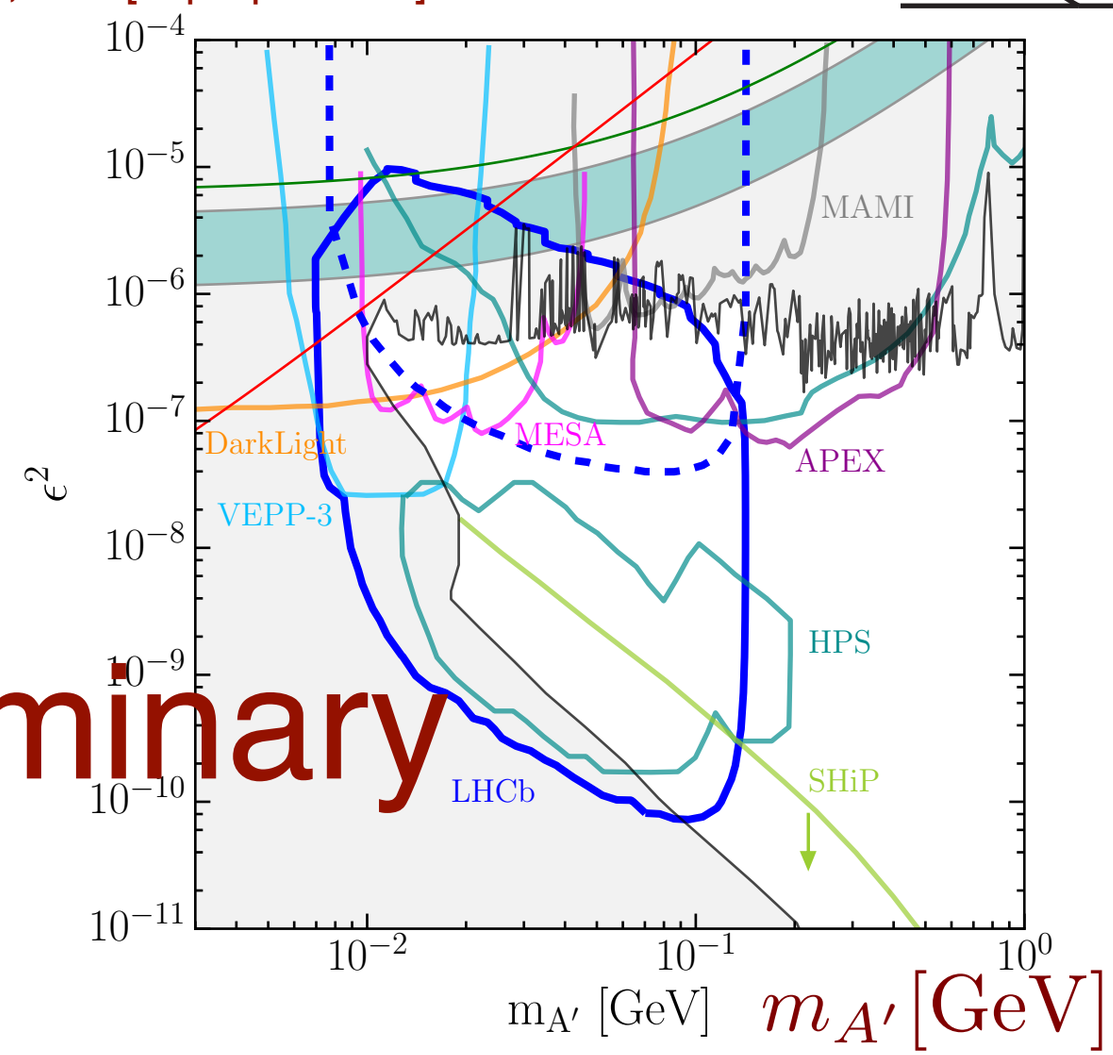
Dark Photons

Additional U(1)' gauge field may couple to SM particles via kinetic mixing with the photon. Huge effort world-wide to search for dark photons, with many planned near-future experiments. LHCb could "close the door" for 2m(e) < m(A') < 100 MeV in Run 3 using D*→DA'(ee).



Ilten, Thaler, MW, Xue [in preparation].





preliminary

Large production rates combined with triggerless readout & real-time calibration permits high-efficiency searches for light BSM particles with feeble interactions with SM particles!

Summary