(Quark) Flavor Physics

Mike Williams
on behalf of the LHCb Collaboration

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

Lake Louise
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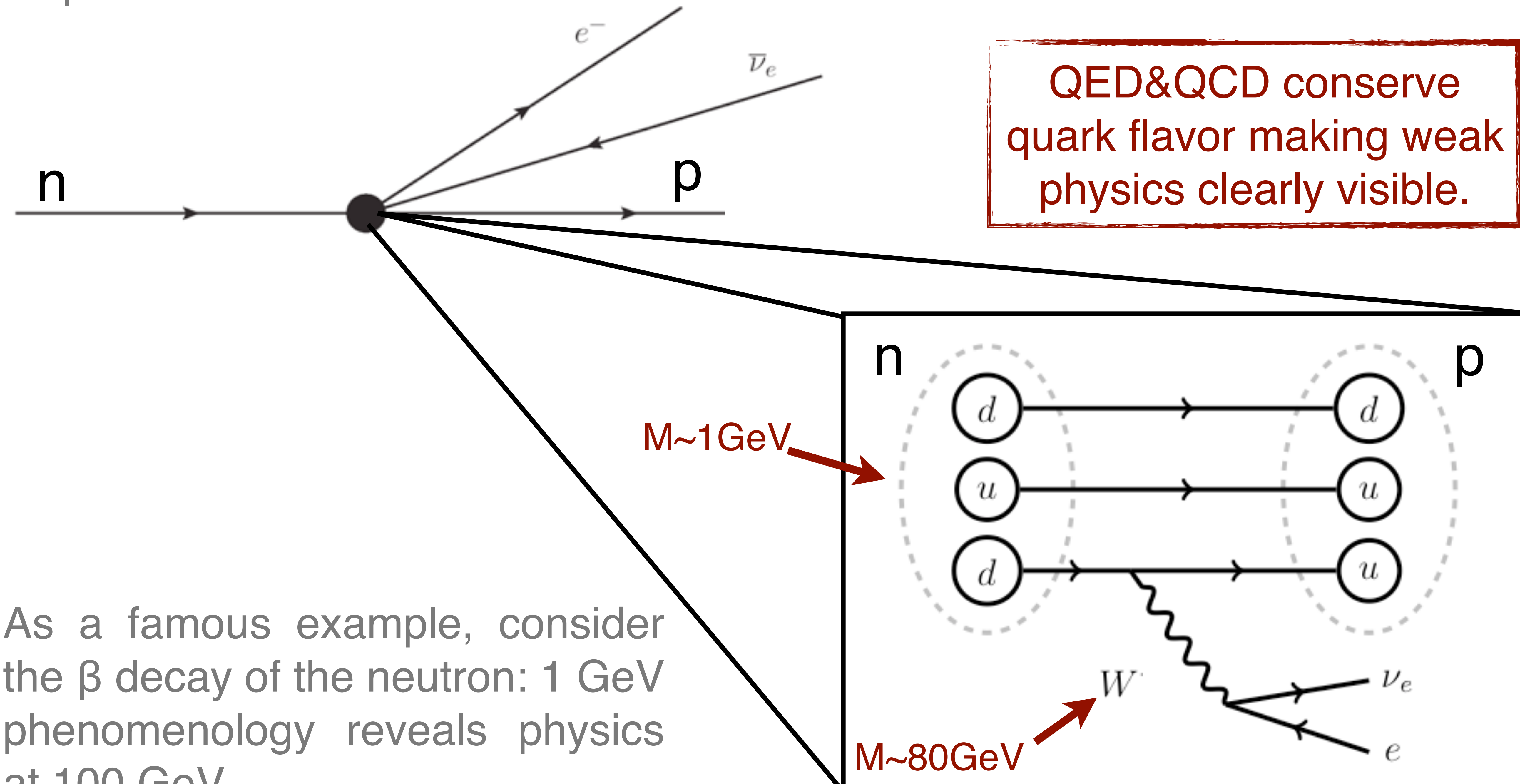
Indirect Observation

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.

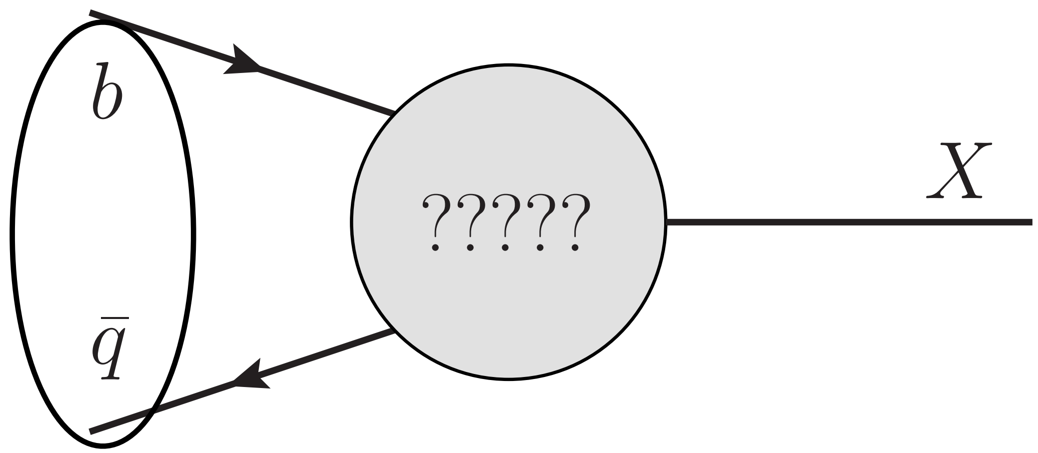
QED&QCD conserve quark flavor making weak physics clearly visible.



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

Indirect Observation

At its core, flavor physics involves searching for new physics by performing precise tests of the SM in reactions that do not preserve quark flavor.



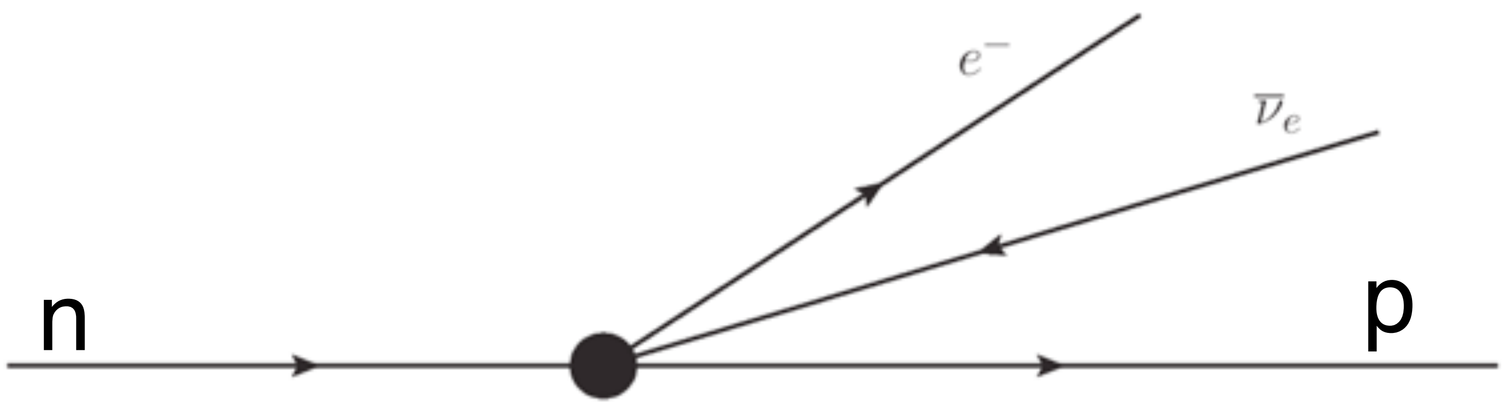
$$\mathcal{A} = \mathcal{A}_{\rm SM} + \mathcal{A}_{\rm BSM}$$

Focus on where O(100 TeV) particles can make significant contributions:

- ΔA : compare rates vs SM;
- Δϕ : compare ϕ vs SM or "same" ϕ in different reactions;
- δA : compare distributions vs SM.

Probing New Physics

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



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

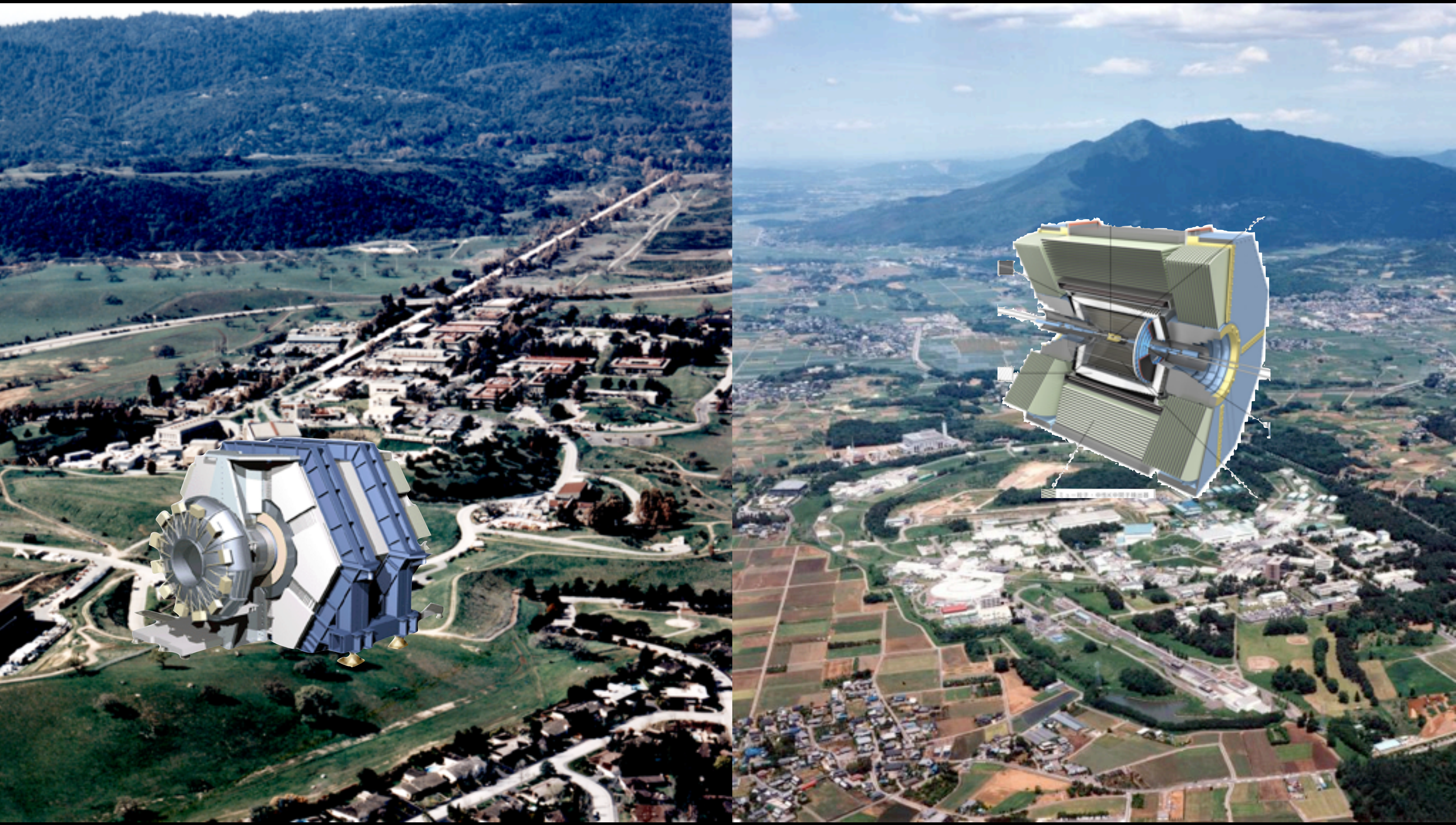
operator product expansion

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

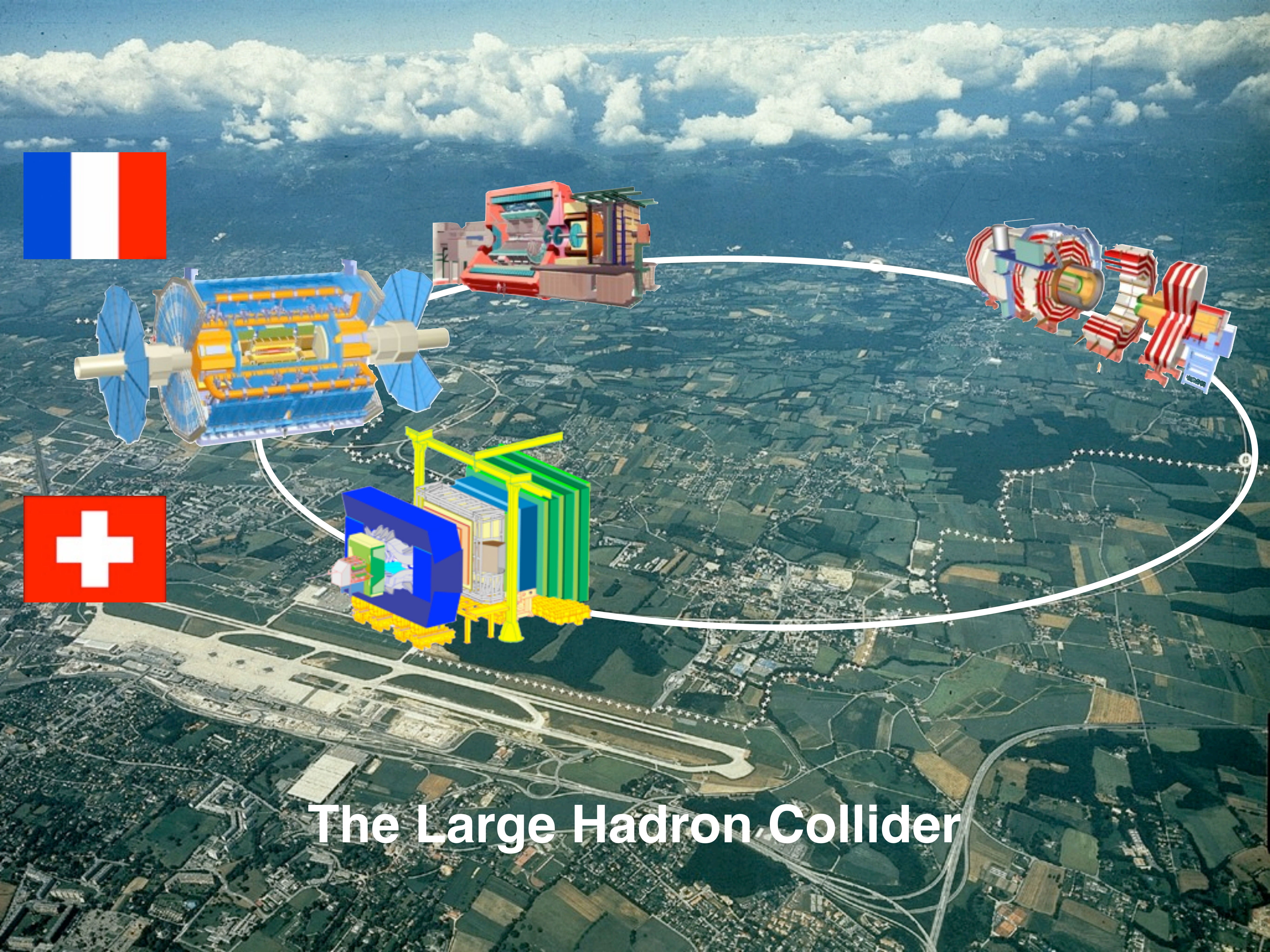
The "C" are the Wilson coefficients and "O" are local operators of all possible Lorentz structure, e.g., (V-A)[qq']*V(ll'), (V+A)[qq']*S(ll'),...

In principle sensitive to any mass scale (limited by experiment/theory precision).

Flavor Factories



e^+ ⟶ ⟵ e^-


The Large Hadron Collider

Where?

Flavor factory

pro:

- known initial state makes it possible to reconstruct “invisible” decays via missing E,p;
- low-background.

con:

- lower signal rates;
- access to specific hadron types.

Hadron Collider

pro:

- large signal rates;
- access to all hadron types;
- possibility for “parasitic” data taking.

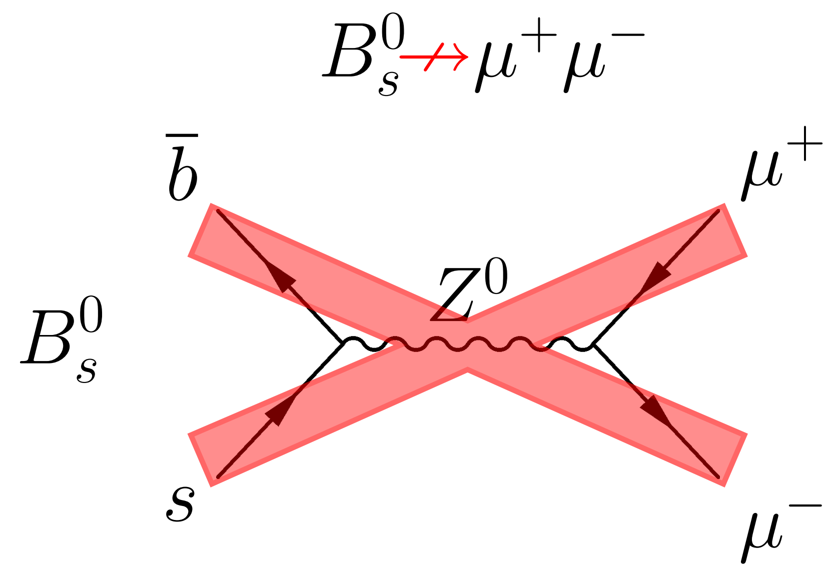
con:

- unknown initial state;
- background!

In summary: These are complimentary; it’s best to have both! For some things dedicated experiments are required, e.g., $\mu \rightarrow e$, rare K decays, etc.

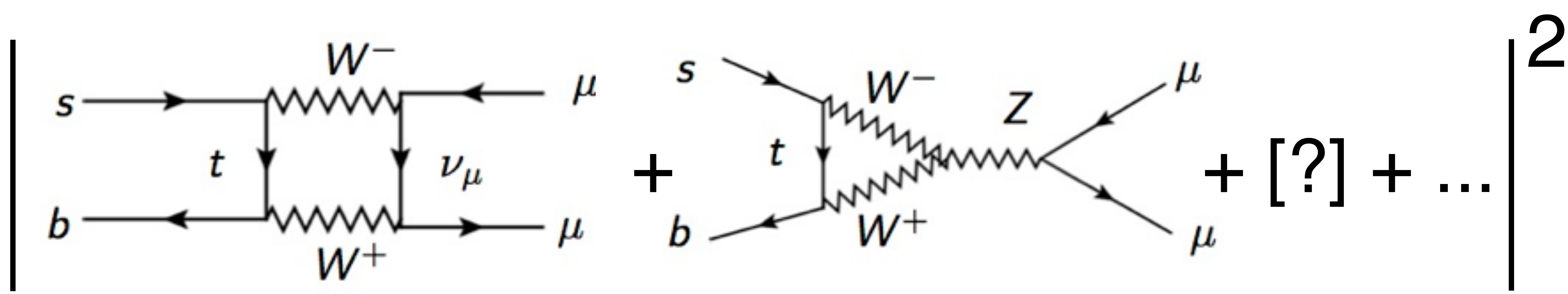
$B_{d,s} \rightarrow \mu^+\mu^-$

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).



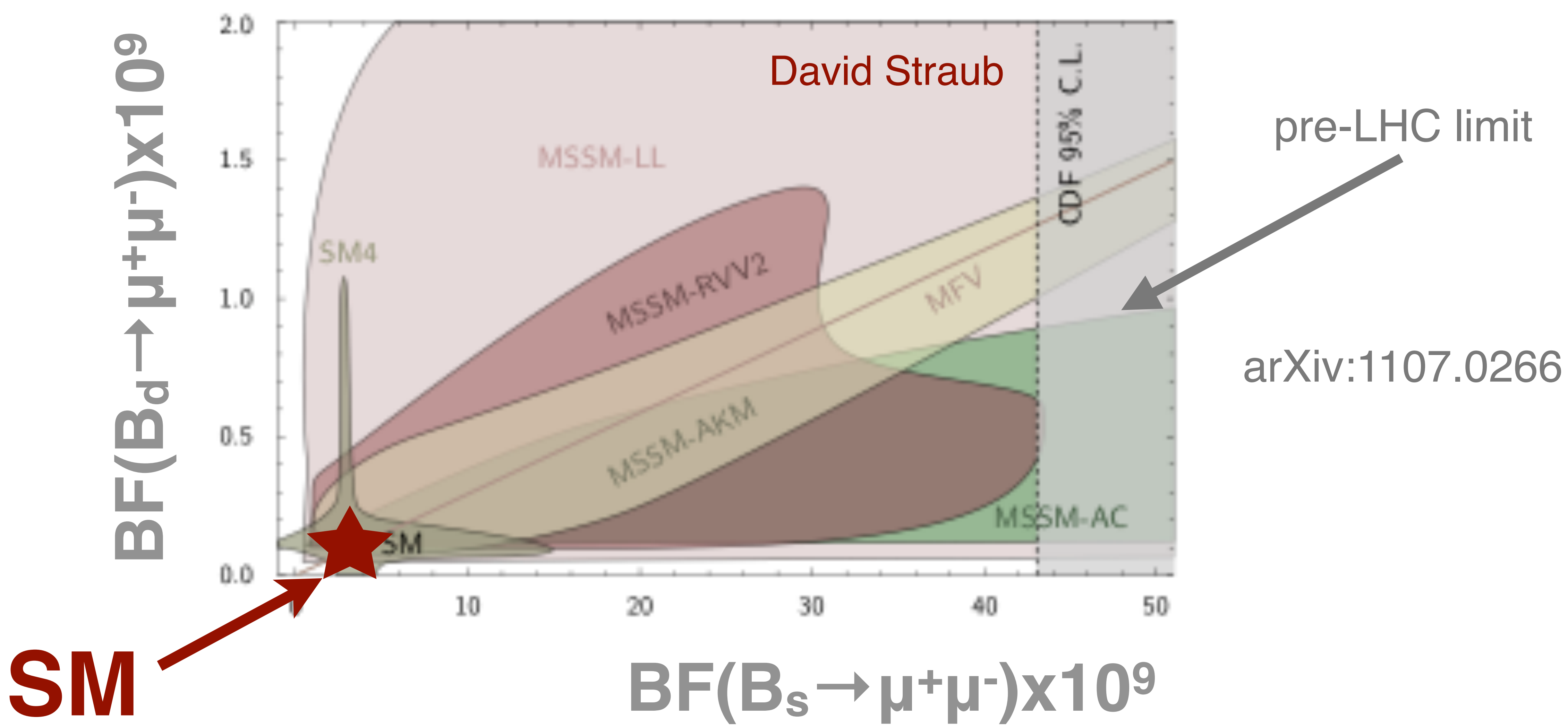
no tree-level amplitude in SM

rate ∝



The SM predicts the B_s (bound s-b) decays into two muons once every 3.4B decays (about 1/1.6 trillion pp collisions at LHCb).

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

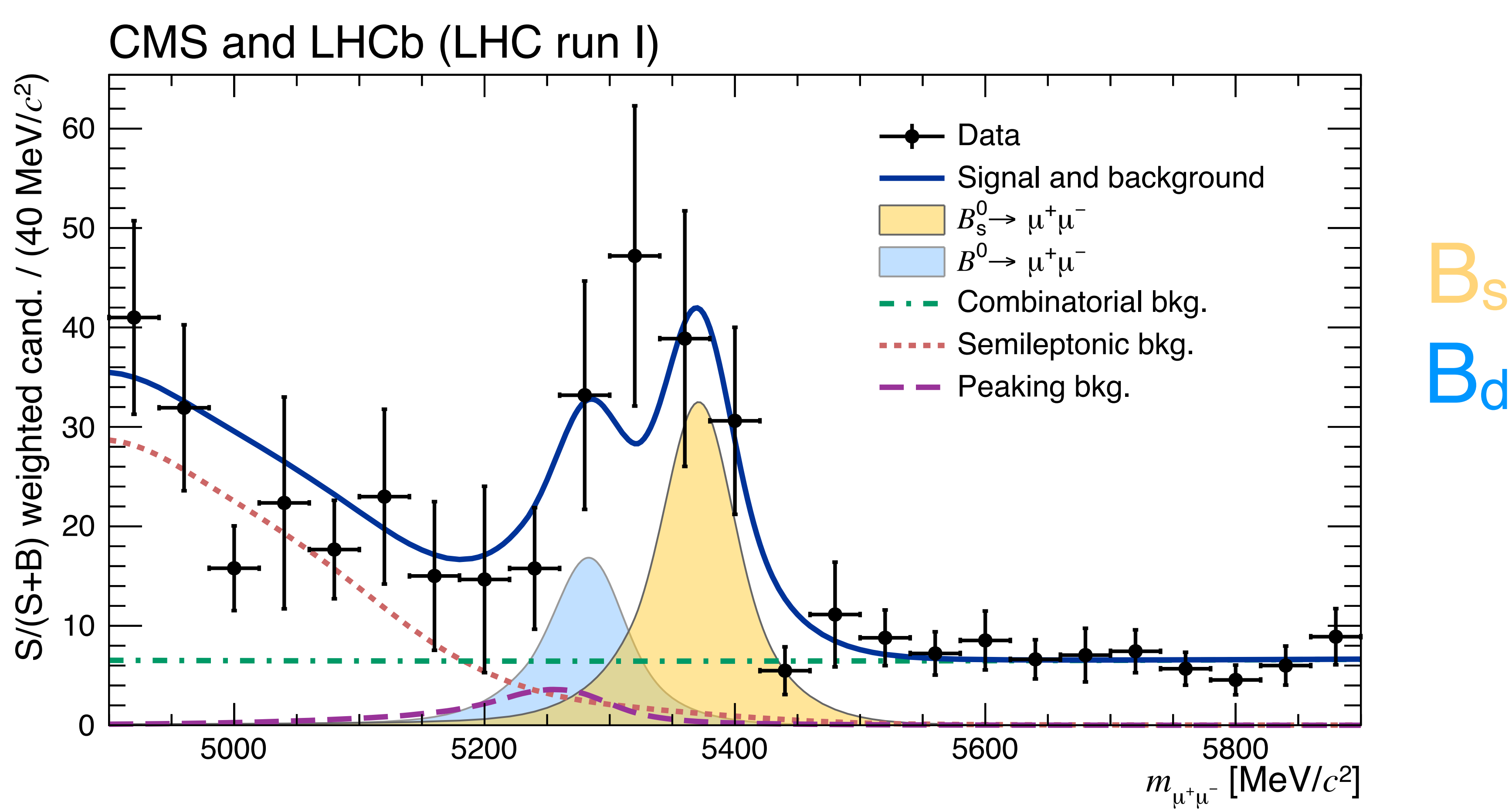


E.g., this plot shows various SUSY predictions prior to LHC running.

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

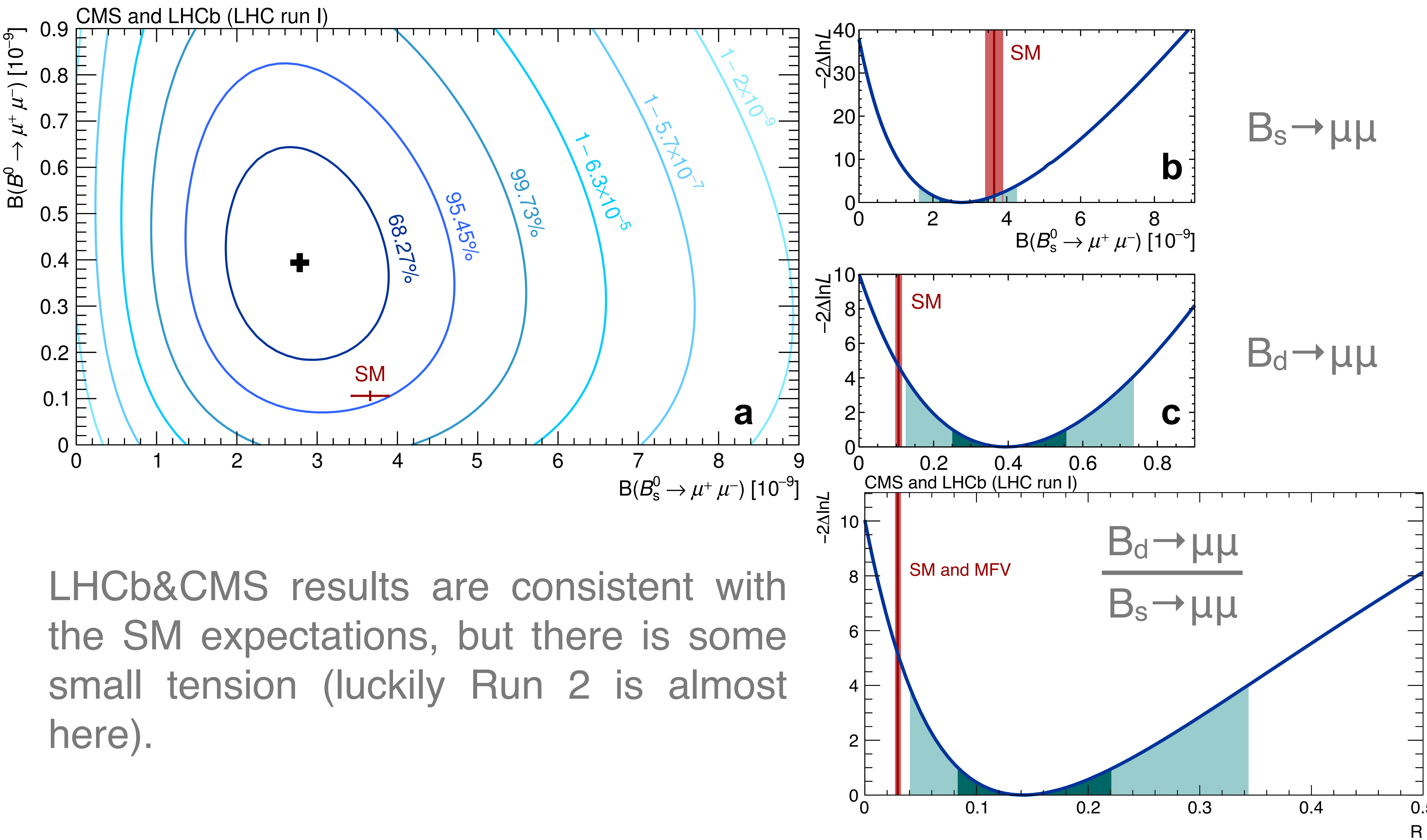
After 30 years of searching for these decays, both LHCb and CMS crossed the 4σ significance threshold in Run 1 for the B_s decay.

CMS&LHCb [CMS-BPH-13-007,LHCB-PAPER-2014-049]



CMS and LHCb combined our results to obtain >6σ for the B_s decay and >3σ for the B_d decay.

CMS&LHCb [CMS-BPH-13-007,LHCB-PAPER-2014-049]



$B_s \to \mu\mu$

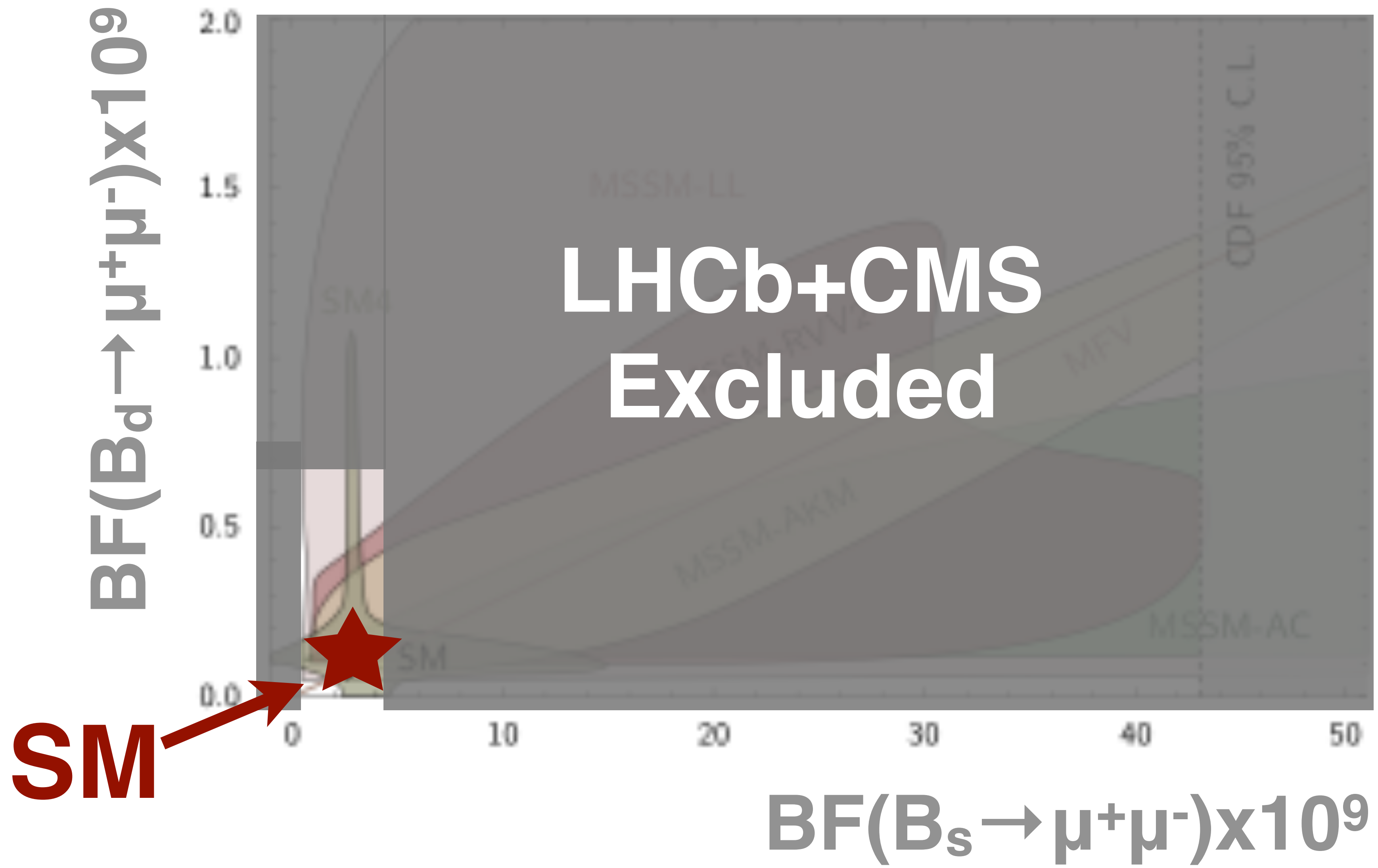
$B_d \to \mu\mu$

$\frac{B_d \to \mu\mu}{B_s \to \mu\mu}$

LHCb&CMS results are consistent with the SM expectations, but there is some small tension (luckily Run 2 is almost here).

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

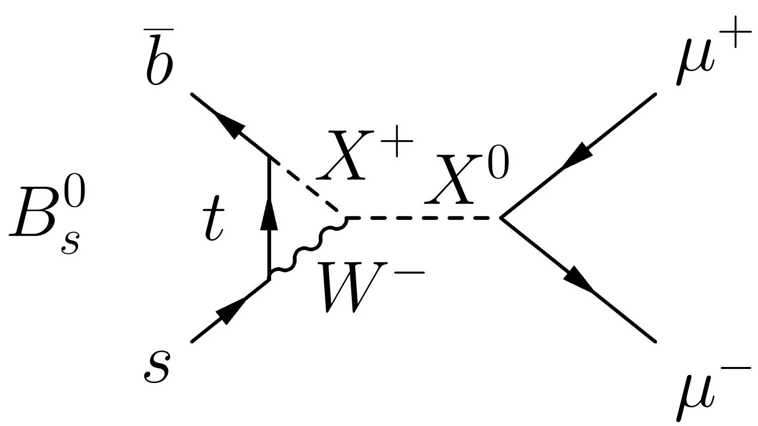
Rules out large regions of SUSY parameter space.

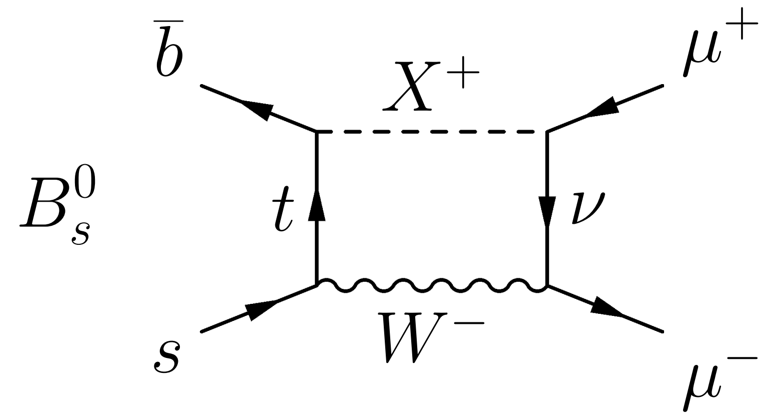


$B_{d,s} \to \mu^+\mu^-$

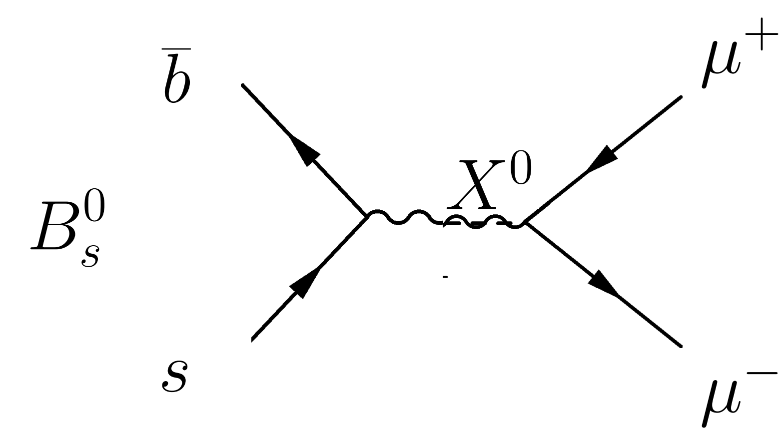
The mass scale probed depends on how BSM contributes. The highest mass scales are probed in diagrams that aren't otherwise suppressed.

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).

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.

$$R_K = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ \mu^+ \mu^-]}{dq^2} dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma[B^+ \to K^+ e^+ e^-]}{dq^2} dq^2}$$

SM prediction

$$R_K = 1.0003 \pm 0.0001$$

differs from 1 only due to H penguin diagrams and phase space

R_K @ LHCb (most systematic effects cancel in double ratio)

$$R_K = \left(\frac{\mathcal{N}_{K^+\mu^+\mu^-}}{\mathcal{N}_{K^+e^+e^-}}\right)\left(\frac{\mathcal{N}_{J/\psi(e^+e^-)K^+}}{\mathcal{N}_{J/\psi(\mu^+\mu^-)K^+}}\right)\left(\frac{\epsilon_{K^+e^+e^-}}{\epsilon_{K^+\mu^+\mu^-}}\right)\left(\frac{\epsilon_{J/\psi(\mu^+\mu^-)K^+}}{\epsilon_{J/\psi(e^+e^-)K^+}}\right)$$

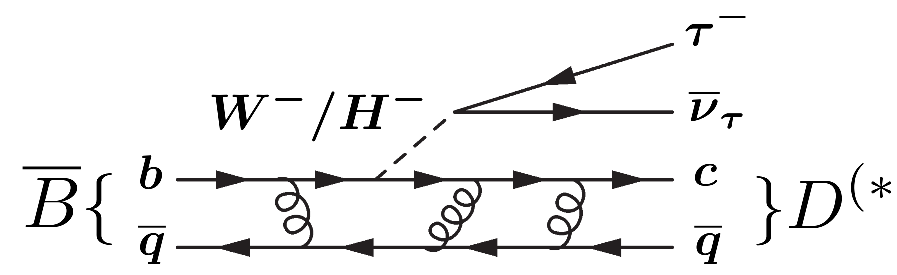
$1<q^2<6$ GeV

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

2.6σ from SM

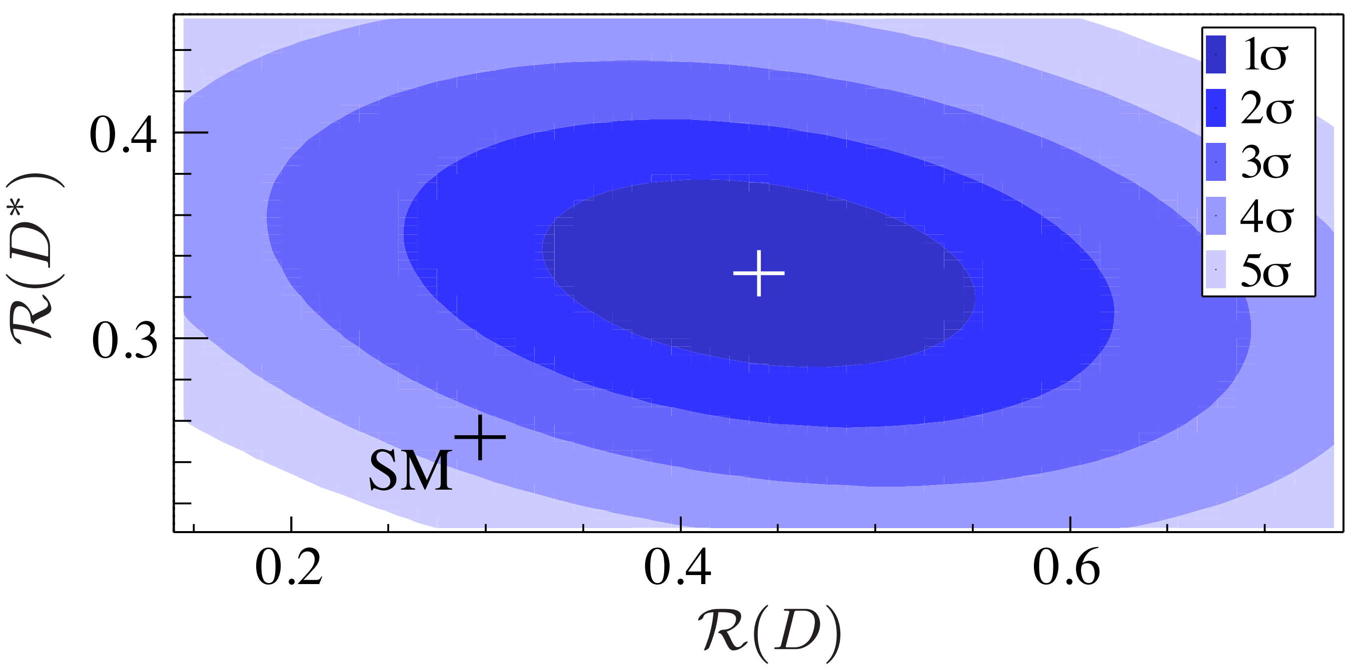
LHCb-PAPER-2014-024

If the LHCb result is due to BSM, then other similar ratios (e.g., involving tau leptons) should also show discrepancies.

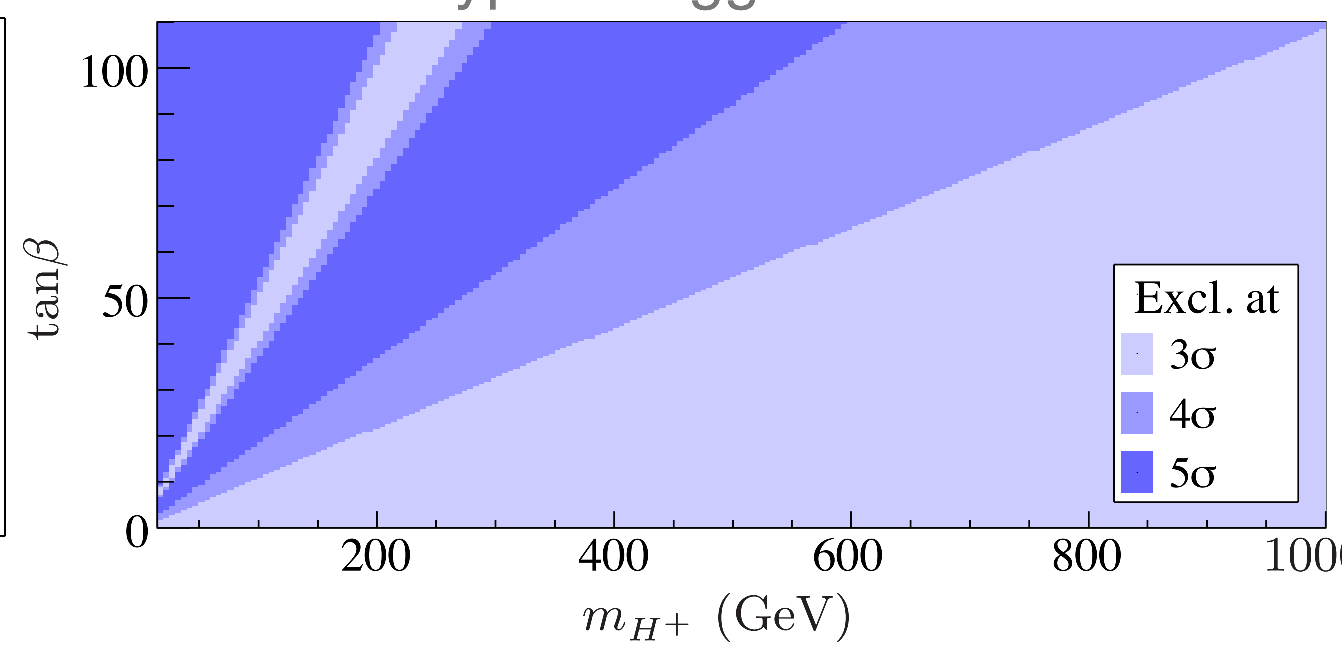


$$\mathcal{R}(D) = \frac{\mathcal{B}(\overline{B} \to D\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D\ell^-\overline{\nu}_\ell)}, \quad \mathcal{R}(D^*) = \frac{\mathcal{B}(\overline{B} \to D^*\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^*\ell^-\overline{\nu}_\ell)}$$

BaBar PUB-13/001



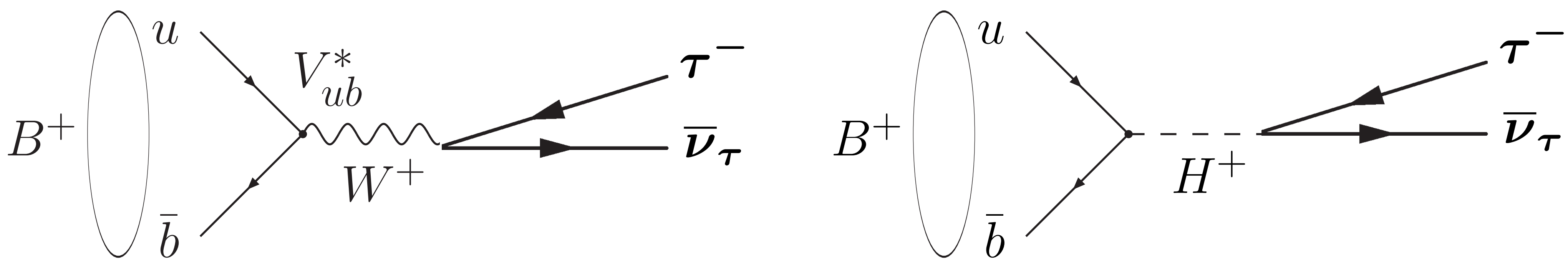
Type II Higgs Exclusion

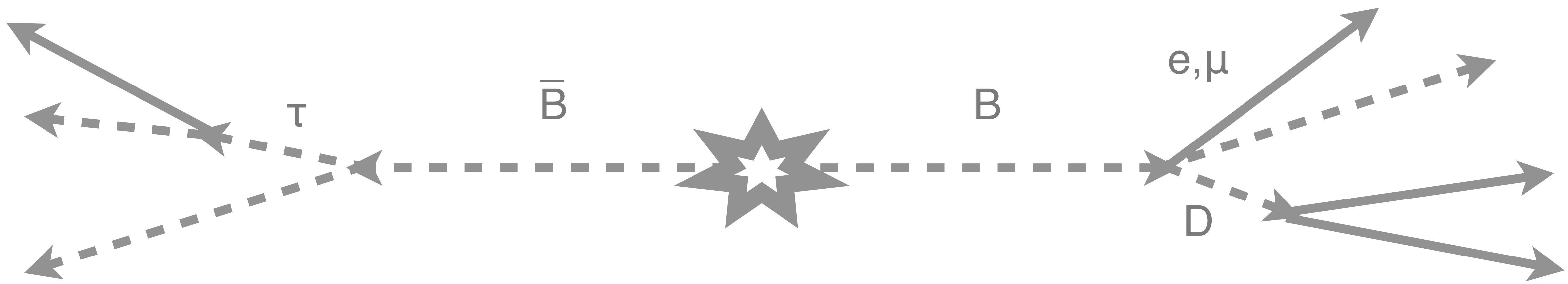


Belle results show similar excess but are less precise, hopefully they will be updated to the final Belle I data set soon.

More Leptons

Can also look for BSM effects in annihilation-type decays:





Belle-CONF-1401

$$\mathcal{B}(B^+ \to \tau^+ \nu_\tau) = [1.25 \pm 0.28(\text{stat.}) \pm 0.27(\text{syst.})] \times 10^{-4}$$

SM prediction

$$(0.753^{+0.102}_{-0.052}) \times 10^{-4}$$

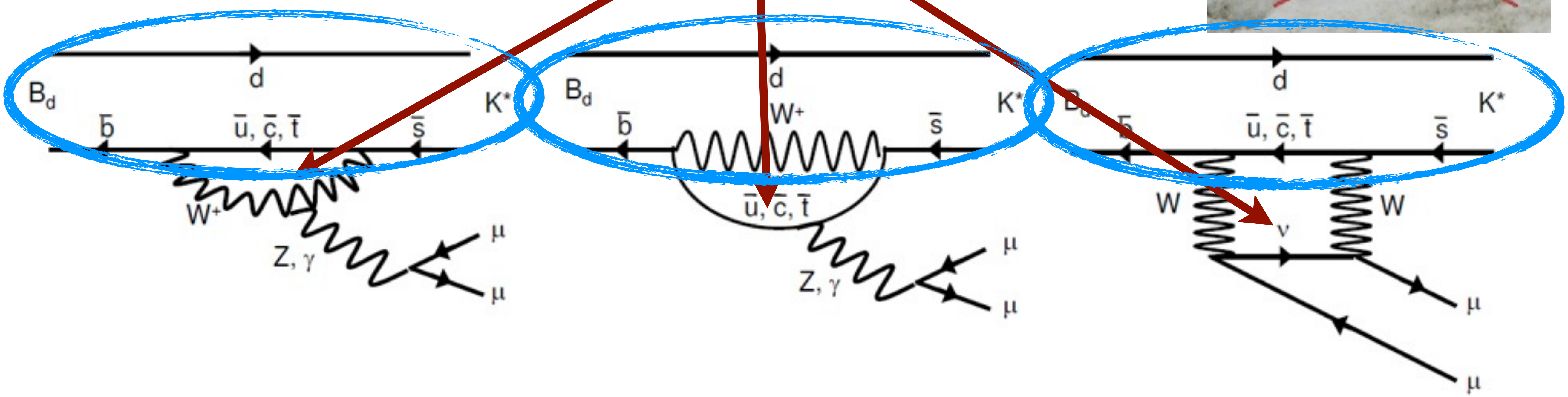
Consistent with the SM at about the 1σ level (and with enhanced coupling to tau leptons.)

$b \to s$ Penguins

The LHCb R_K result was from b→s "penguin" decays where loop suppression in the SM permits BSM contributions to be sizable. Unlike RK, however, most observables require control of the hadronic SM calculation.

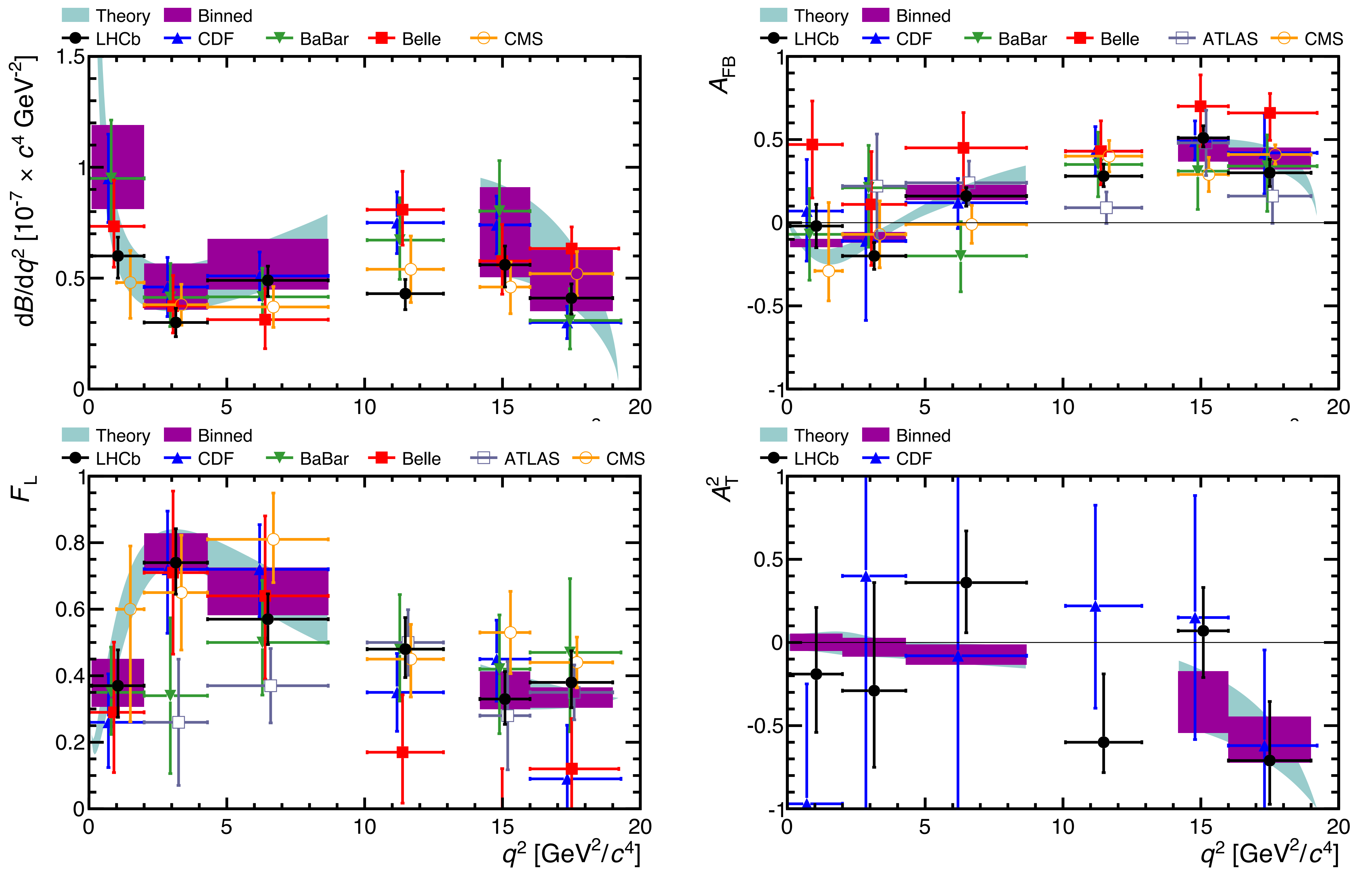
SM calculations need B→K form factors

BSM?



The B(s) → K(ϕ)μμ family of decays provide many sensitive observables (accessible via angular analysis) to measure.

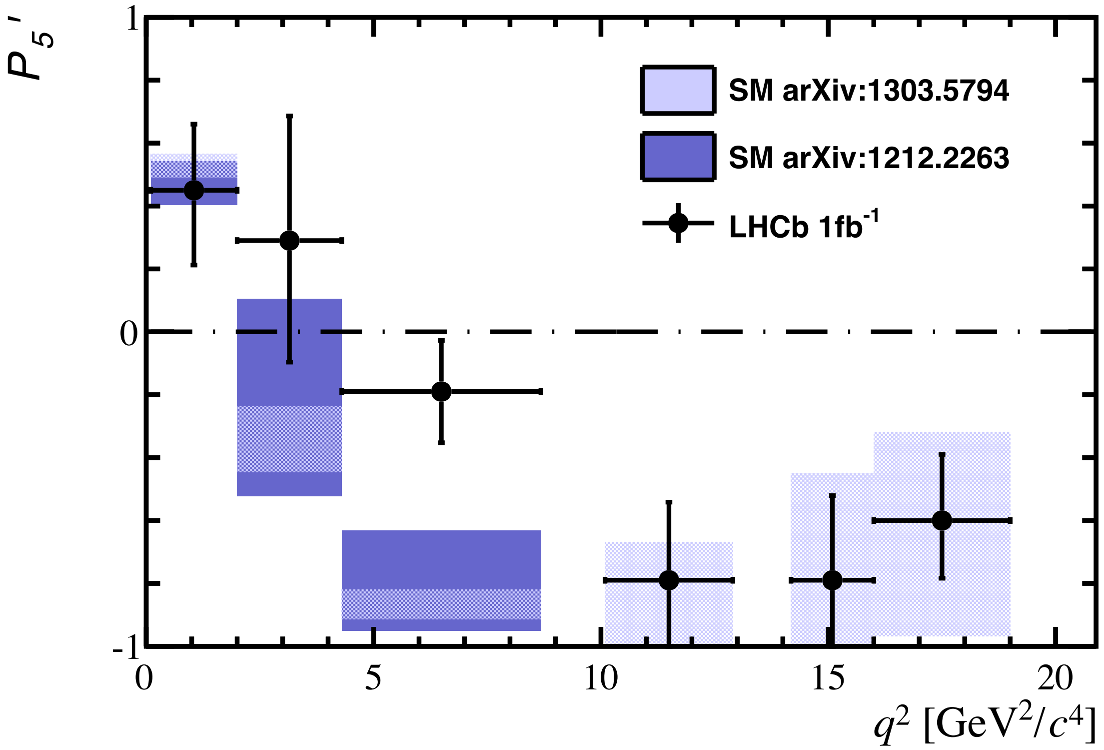
LHCb results are 2011 data only, 3x stats in hand.



LHCb-PAPER-2013-019 [1304.6325]

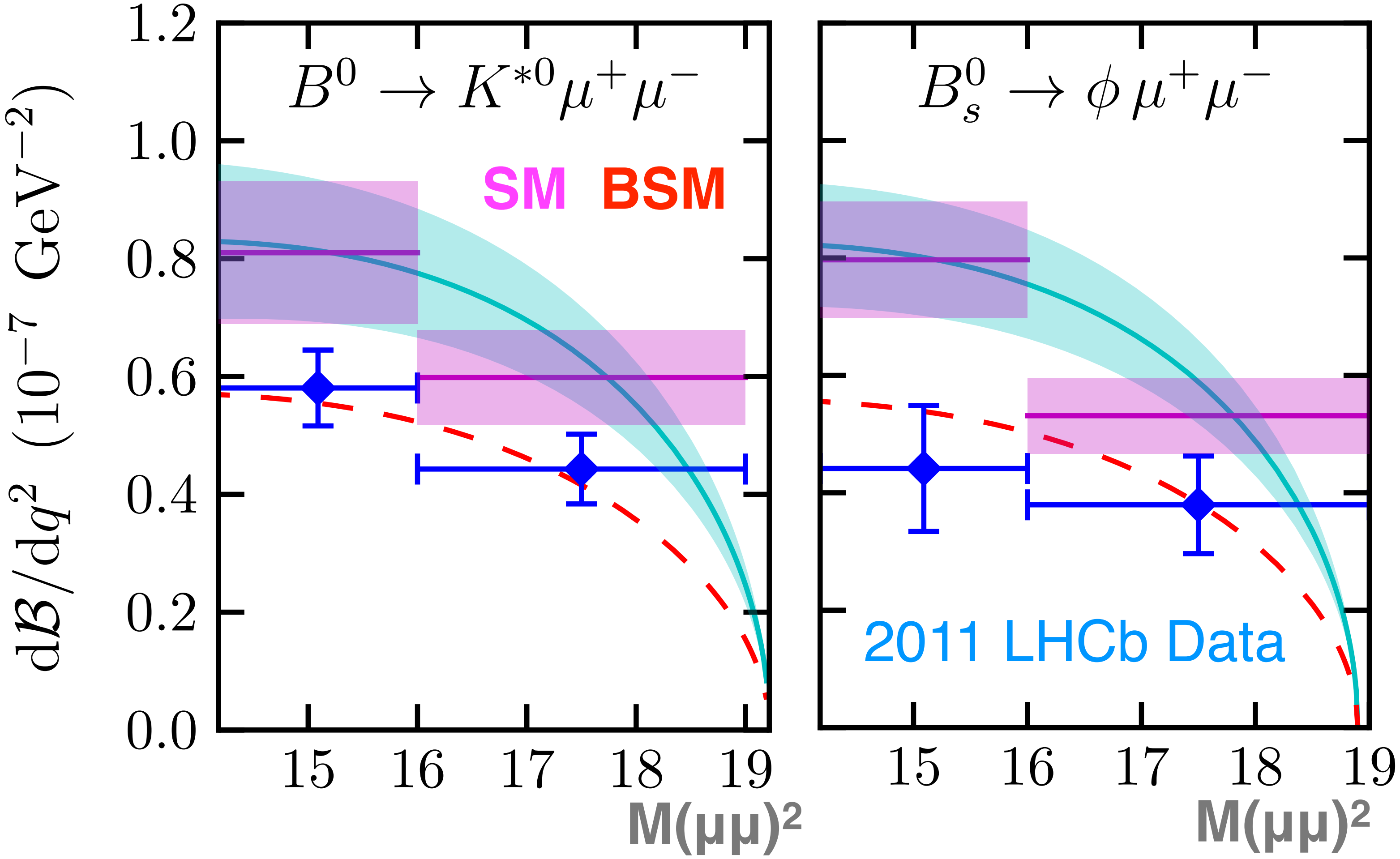
Many observables here show consistency with the SM while probing the O(10 TeV) scale.

LHCb-PAPER-2013-037



However, there are a few interesting exceptions, e.g., angular observables constructed to have minimal hadronic form factor dependence show some discrepancy in the same di-lepton mass range as R_K.

Horgan, Liu, Meinel, Wingate [1310.3887]

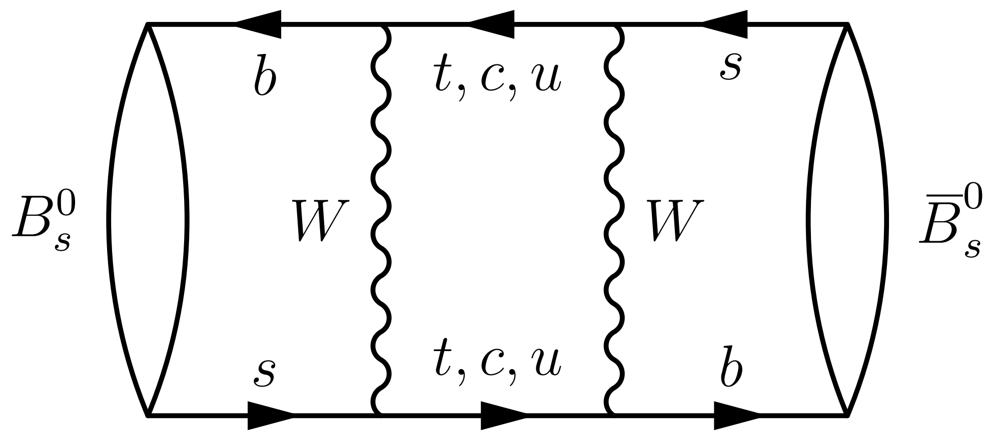


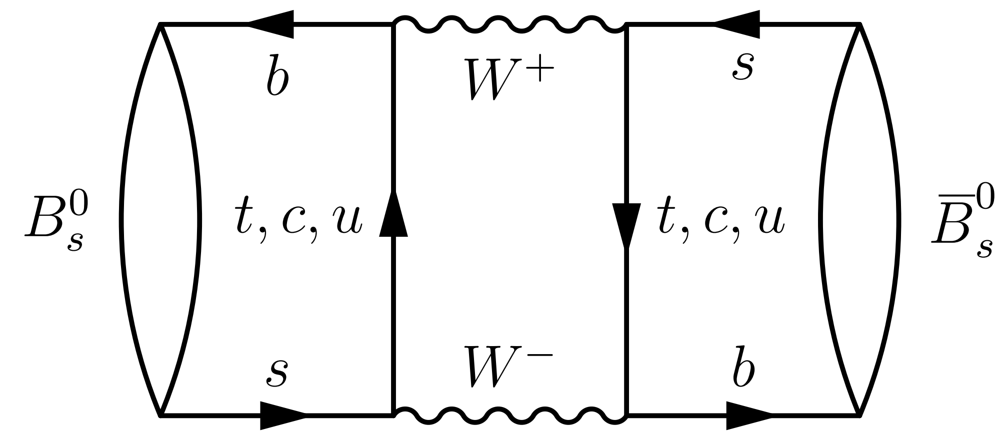
Also, general trend in decay rates is that they are lower than expected for all di-muon b→s penguin processes.

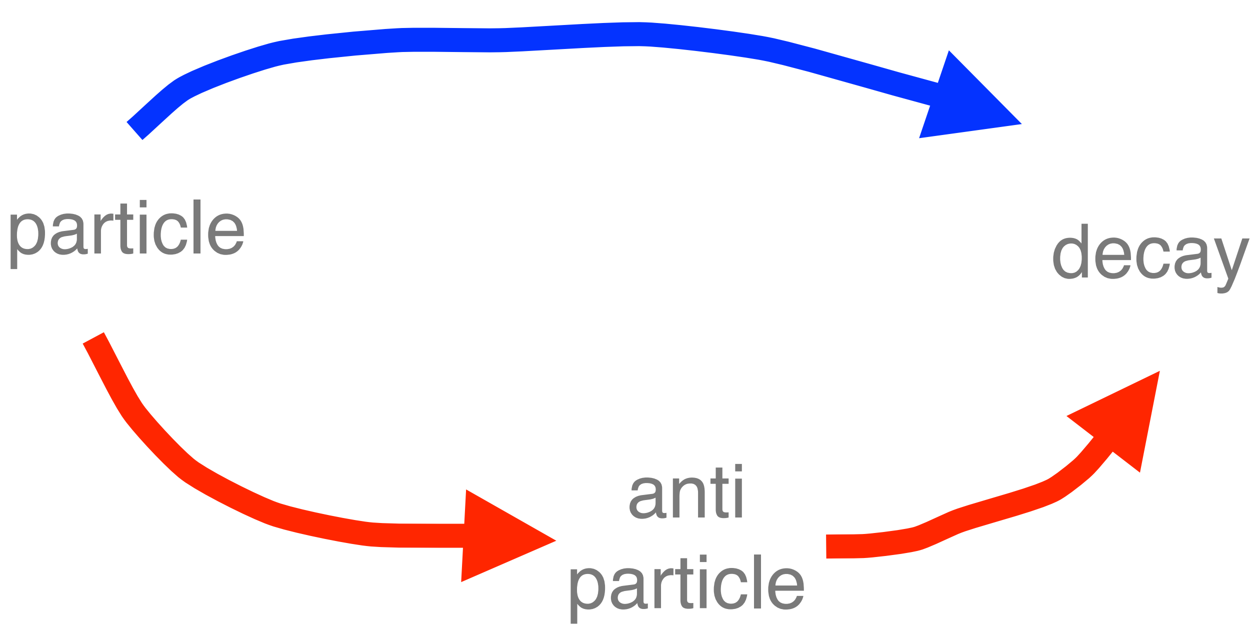
Is this BSM or QCD artifacts?

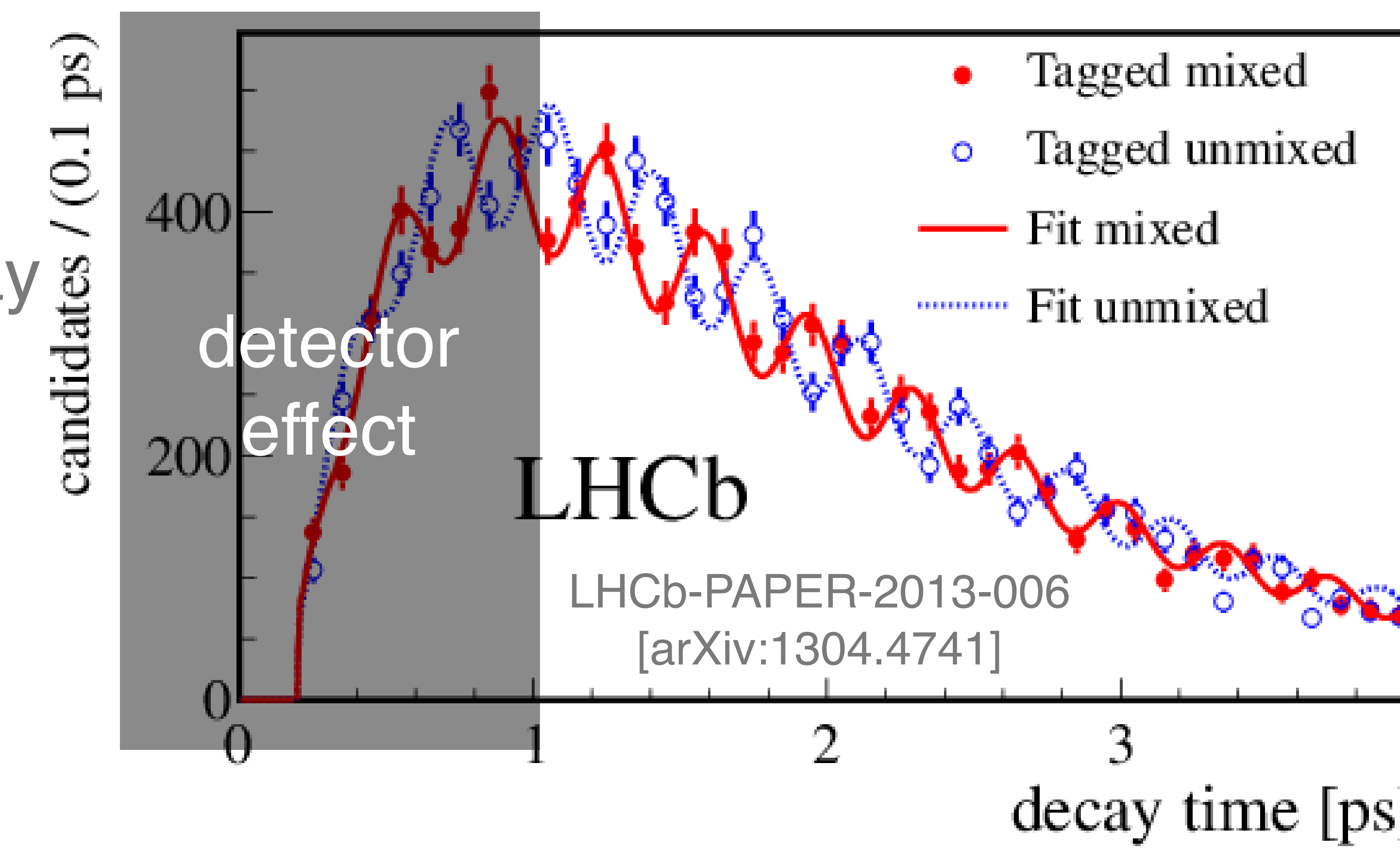
Oscillations

Neutral mesons can oscillate between particle/anti-particle. In the SM this is loop and CKM suppressed so could be affected greatly by BSM particles.



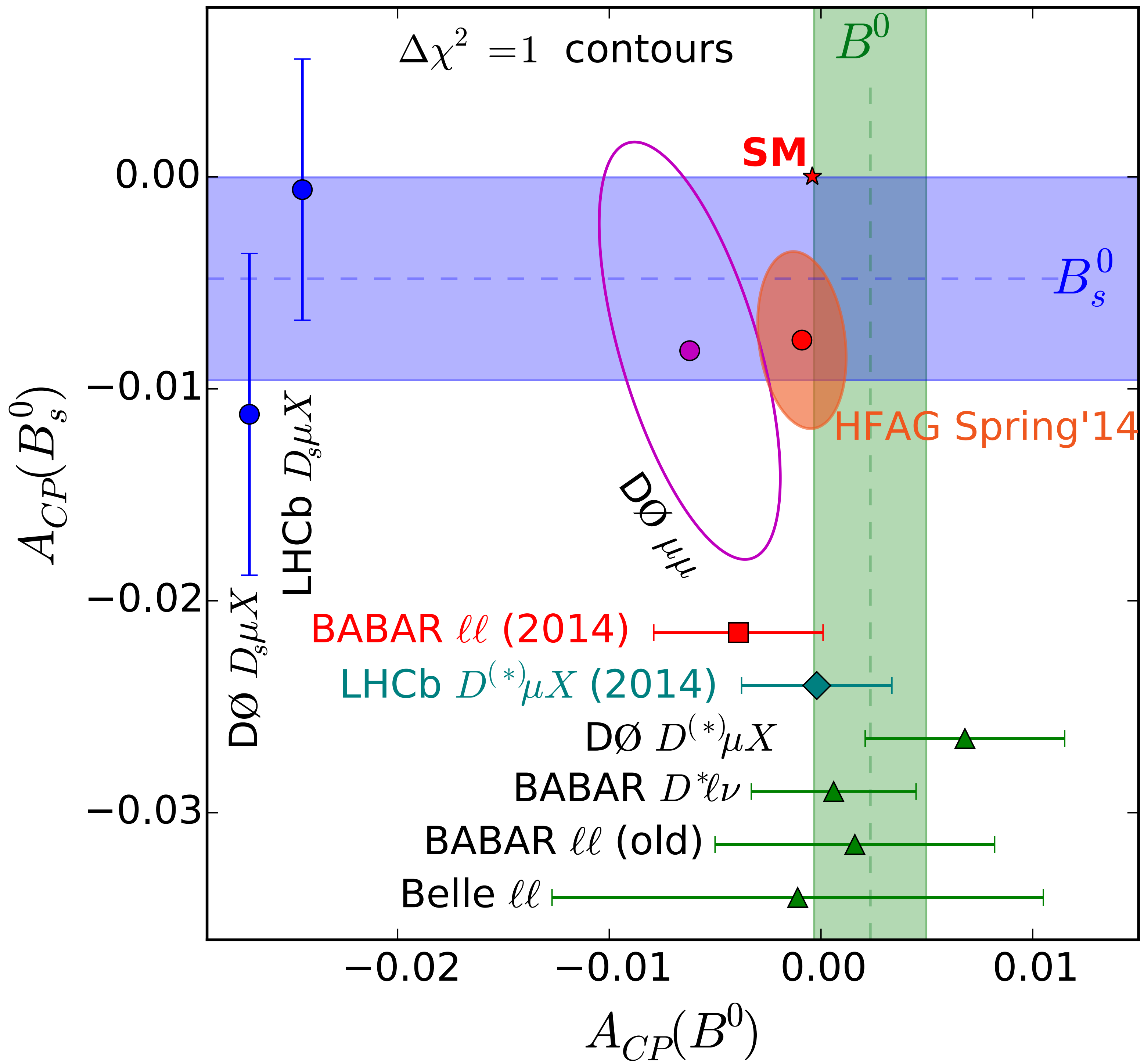






CPV in $B_{d,s}$

$B_s \longrightarrow \overline{B}_s = \overline{B}_s \longrightarrow B_s$?

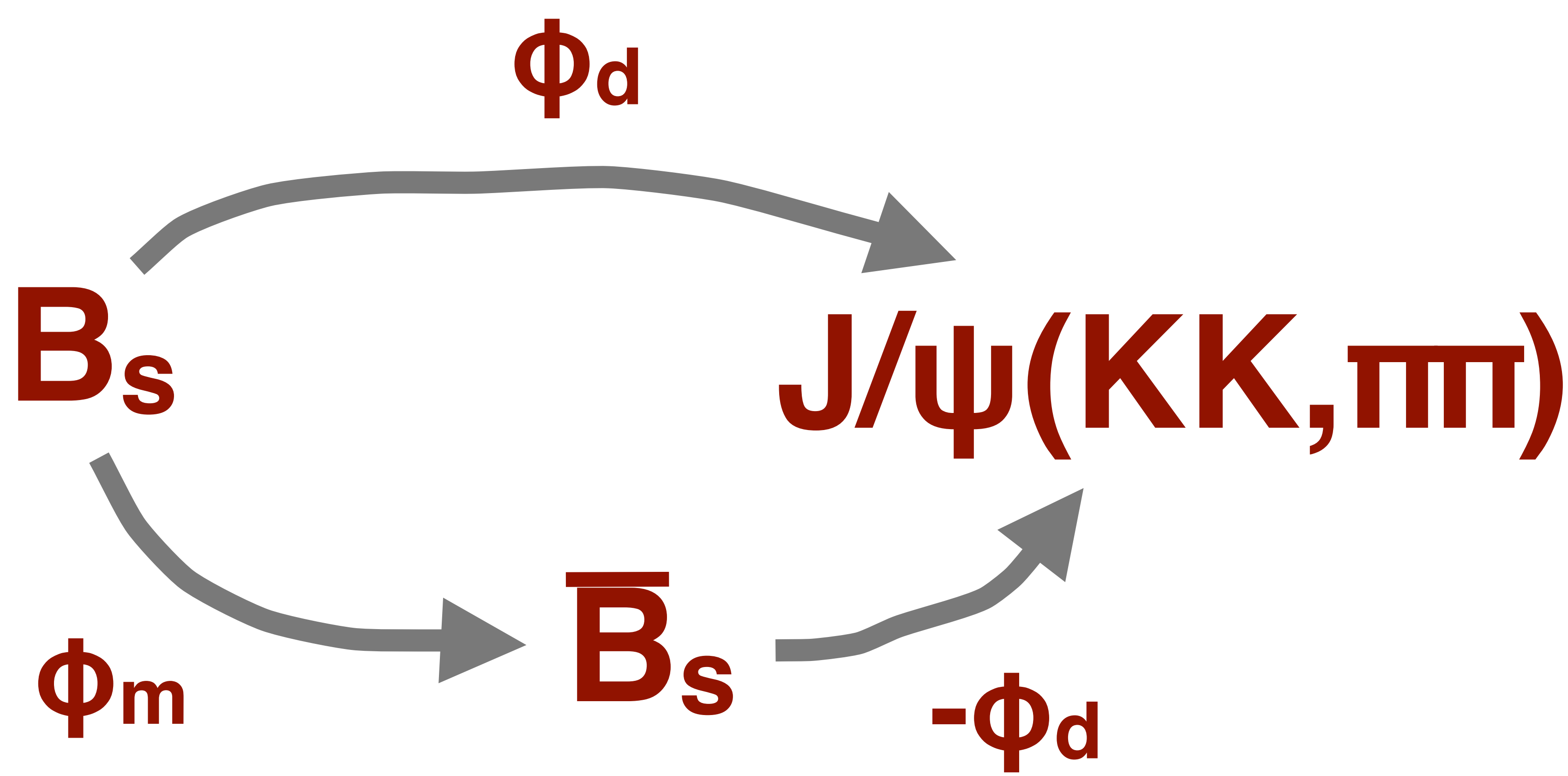


LHCb, Belle & BaBar agree with the SM.

$B_d \longrightarrow \overline{B}_d = \overline{B}_d \longrightarrow B_d$?

$B_s \to J/\psi hh$

Interference between mixing and decay amplitudes gives rise to a CPV phase $\phi_s = \phi_m - 2\phi_d$. BSM could give a non-SM measurement.



LHCb-PAPER-2014-059

LHCb: $\phi_s = -0.010 \pm 0.039$; SM: $\phi_s = -0.036 \pm 0.002$

This phase is accessible experimentally via a time-dependent angular analysis to measure the time-dependent CP asymmetry.

Probing New Physics

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

operator product expansion

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

Fitting all available data simultaneously gives the following picture:

- Constraints on |C| for (V-A)[qq']*(V,A)(ll') roughly < 4/3 C(SM).
- Constraints on |C| for (V+A)[qq']*(V,A)(ll') roughly same.
- Strong constraints on scalar, tensor, etc., operators.

See Blake, Gershon, Hiller for an excellent summary. [1501.03309]

Overall the data is largely consistent with the SM and global fits place constraints on BSM particles of about 0.5-50 TeV (depending on model).

BSM?

We shouldn't get too excited about a few 2-3σ discrepancies given how many "sensitive" flavor physics results have been published in the past few years (we do expect a few 3σ's).

> ***The optimist regards the future as uncertain.***
>
> **Eugene Wigner**

But let's follow Wigner's advice and be optimists and see what this means if we are, in fact, seeing the first hints of BSM physics.

Probing New Physics

Assuming the observed discrepancies are really BSM, this means that:

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

One viable option is a O(1-10 TeV) Z' which in a simple model suggests the following triple correlation which is consistent with data.

Glashow, Guadagnoli, Lane [1411.0565]

$$R_K \cong \frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)_{exp}}{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)_{SM}} \cong \frac{\mathcal{B}(B_s \to \mu^+\mu^-)_{exp}}{\mathcal{B}(B_s \to \mu^+\mu^-)_{SM}}$$

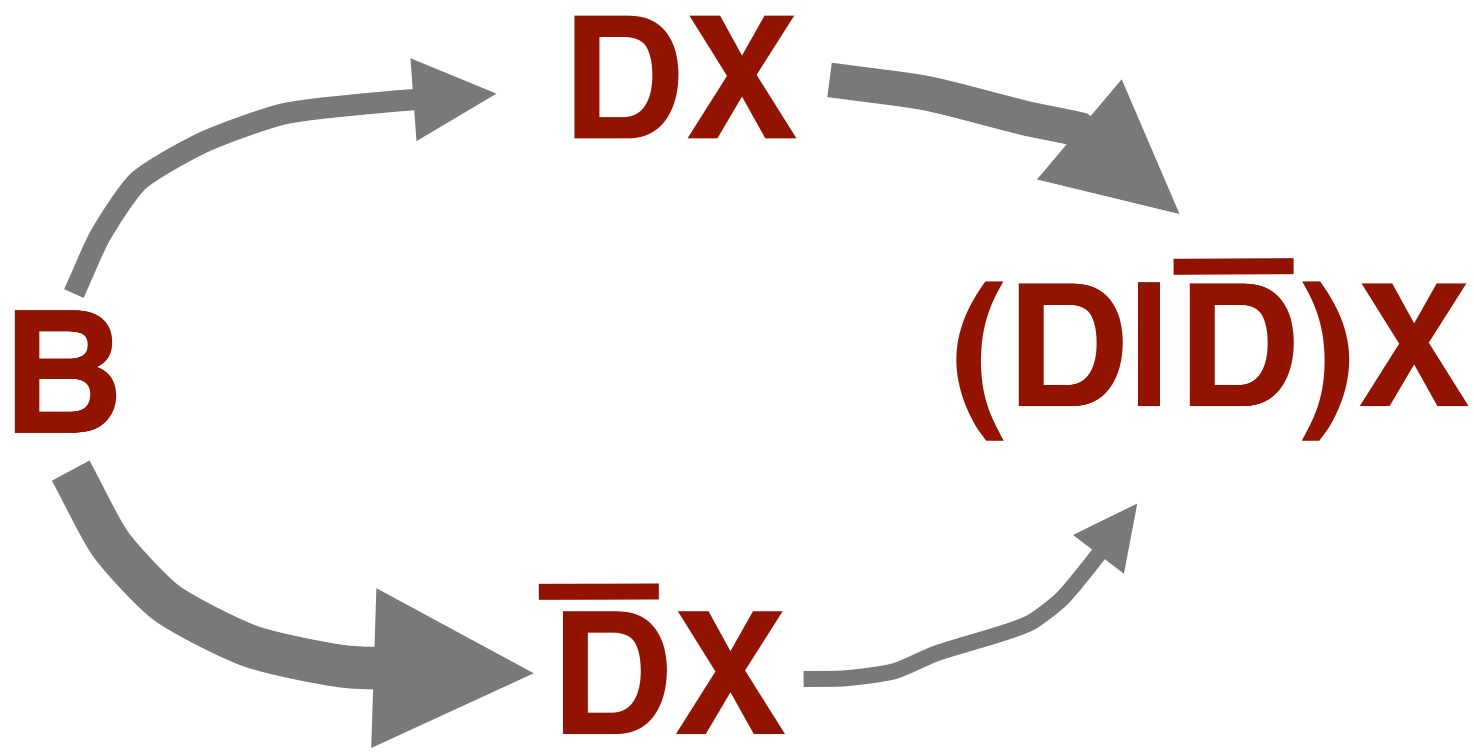
Another option is leptoquarks which "naturally" explain non-universality in the lepton sector. Both leptoquarks and Z' may be visible directly at CMS and ATLAS, but only if they're light enough. Hiller, Schmaltz [1408.1627]

Why are these all made of matter?

How did we end up with such a huge matter/anti-matter imbalance?
This is a mystery!

CP Violation

Use interference b/t $\mathcal{A}_{b\to u}^{\bar{b}\to\bar{u}} = \mathcal{A}_{bu}e^{\pm i\gamma}$ and $\mathcal{A}_{b\to c}^{\bar{b}\to\bar{c}} = \mathcal{A}_{bc}$ to extract γ.

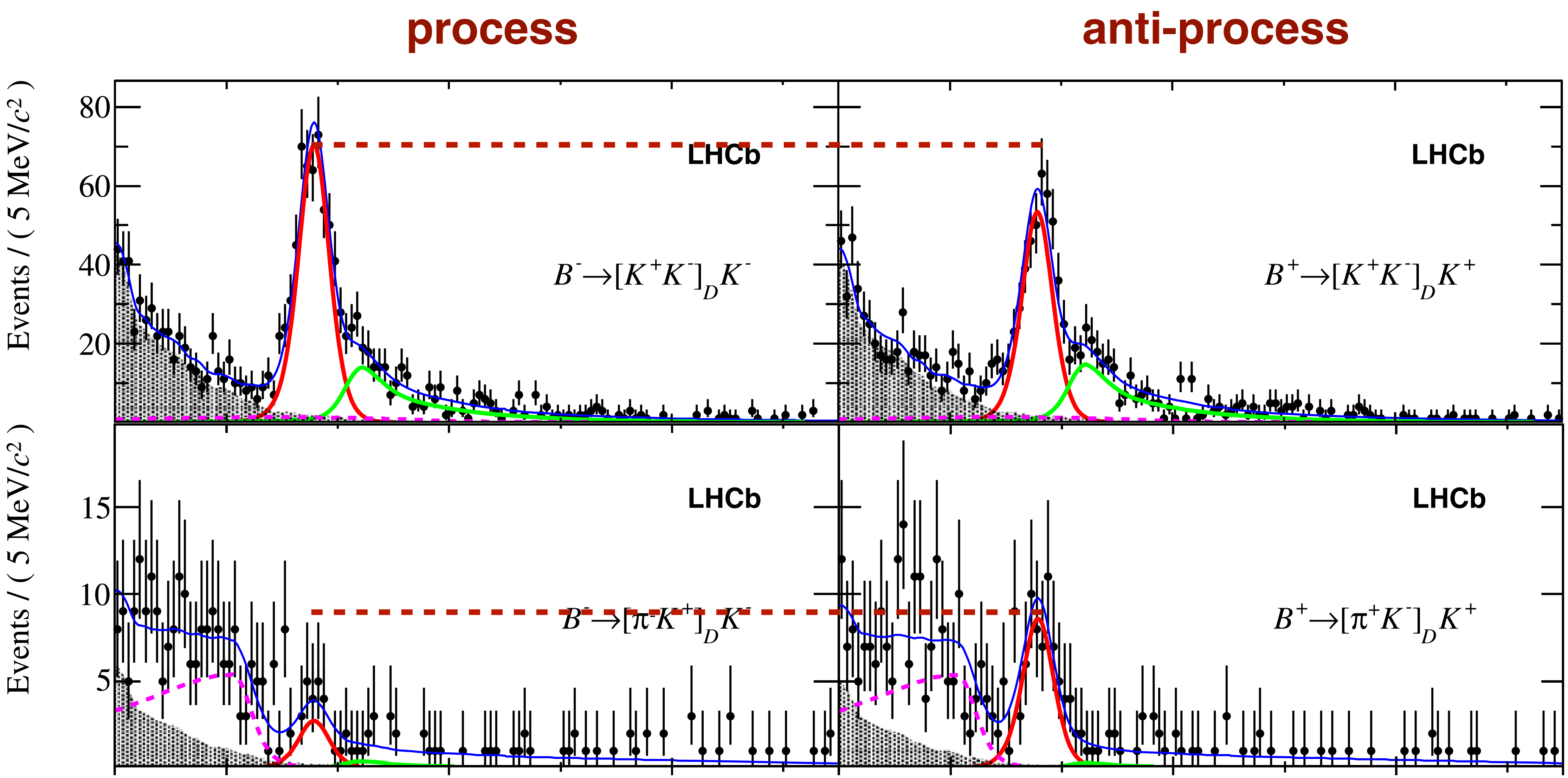


$$\mathcal{N}_{\pm} = |\mathcal{A}_{B\to DX} + \mathcal{A}_{B\to \bar{D}X}|^2$$
$$= |\mathcal{A}_D|^2 + |\mathcal{A}_{\bar{D}}|^2 + 2|\mathcal{A}_D||\mathcal{A}_{\bar{D}}|\cos\left(\Delta\theta_{\rm strong} \pm \gamma\right)$$

Can look for BSM by comparing to “ɣ” from “trees” and “loops” and also this measurement is vital in the global CKM constraints.

CP Violation

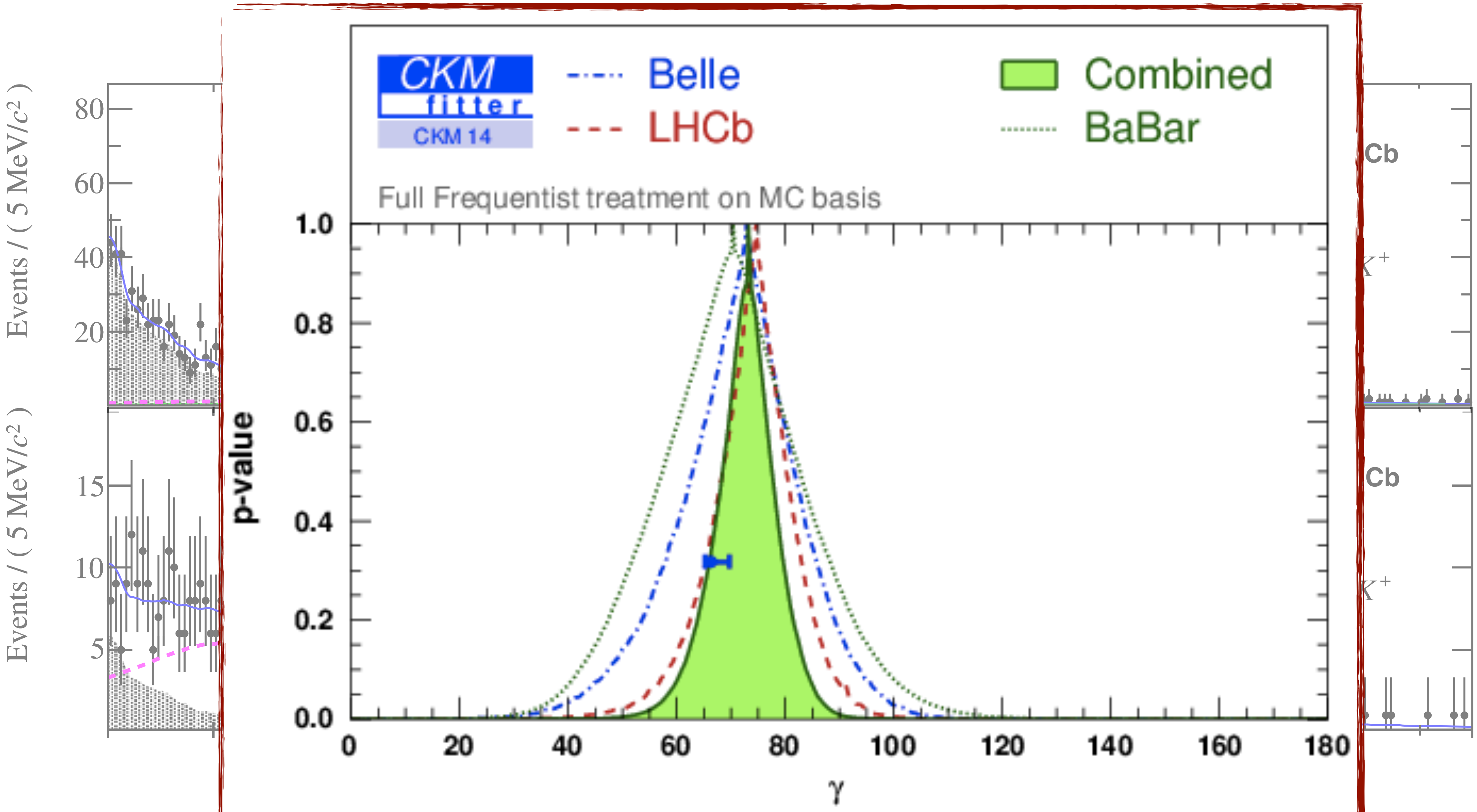
CPV can be large in some processes.



LHCb-PAPER-2012-001
[arXiv:1203.3662]

CP Violation

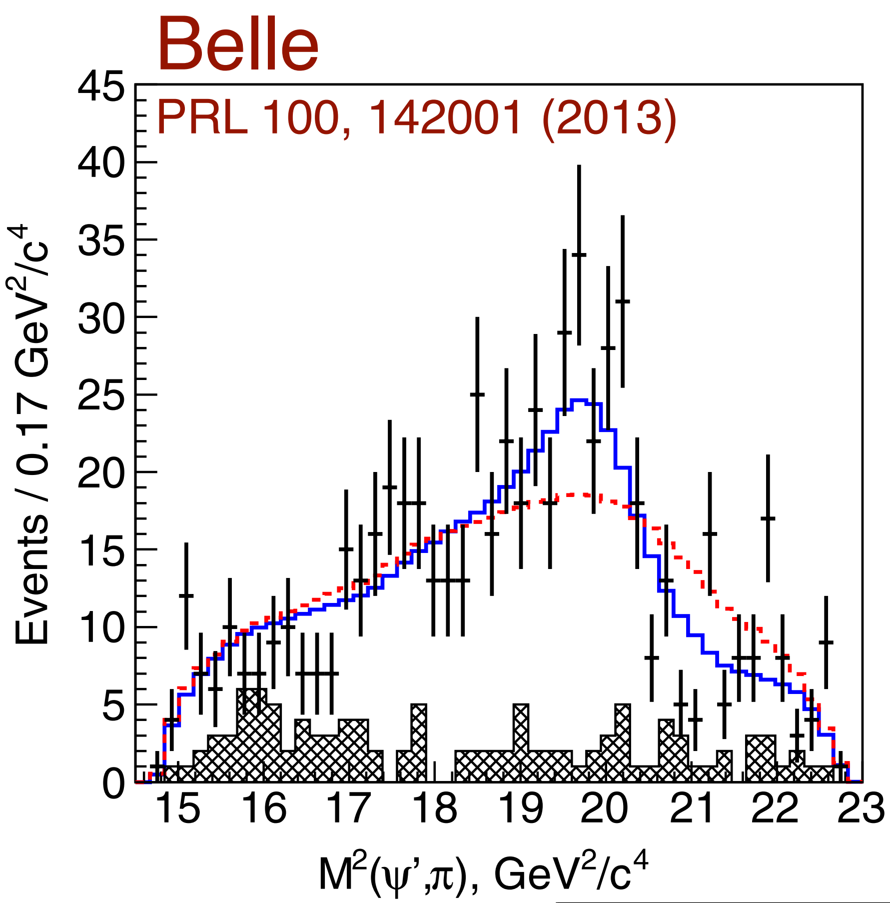
CPV can be large in some processes.



[arXiv:1203.3662]

Still much work to do here to increase the precision ... need more data!

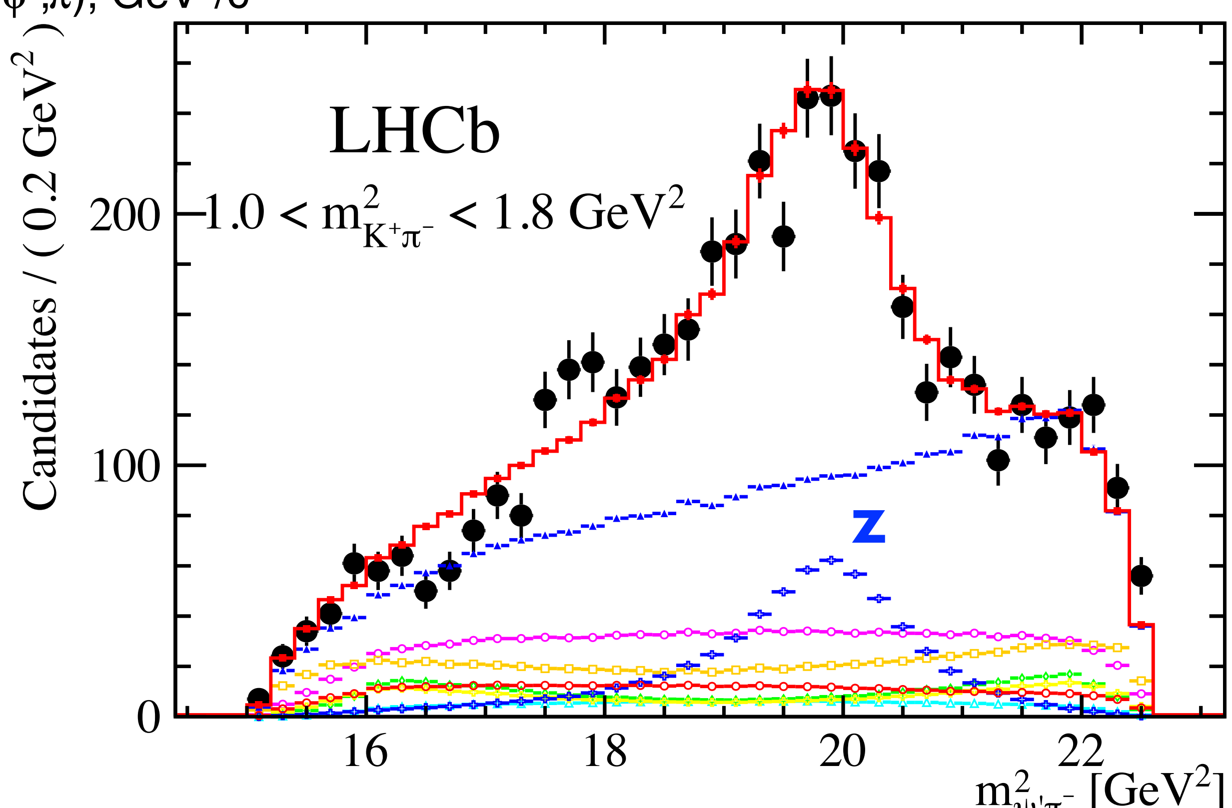
Spectroscopy

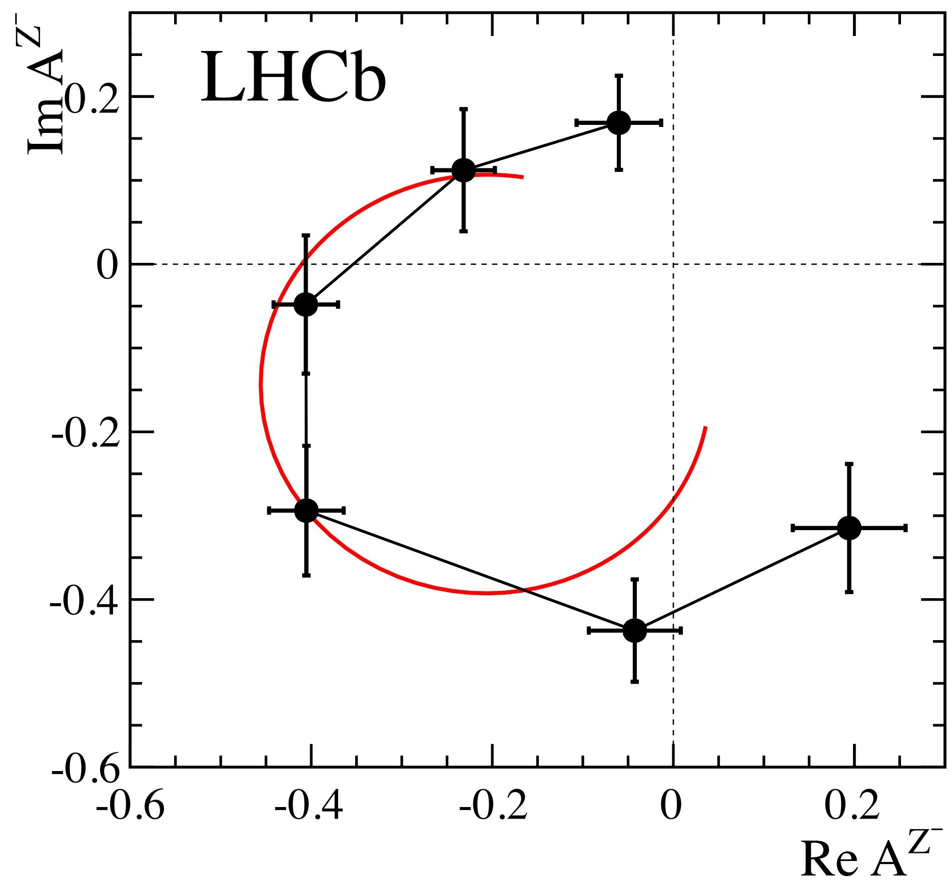


Many exciting results in exotic spectroscopy in recent years have come from “flavor” experiments, e.g., first (unambiguous) 4-quark state observed!

Bound states containing heavy quarks are an excellent lab for studying QCD.

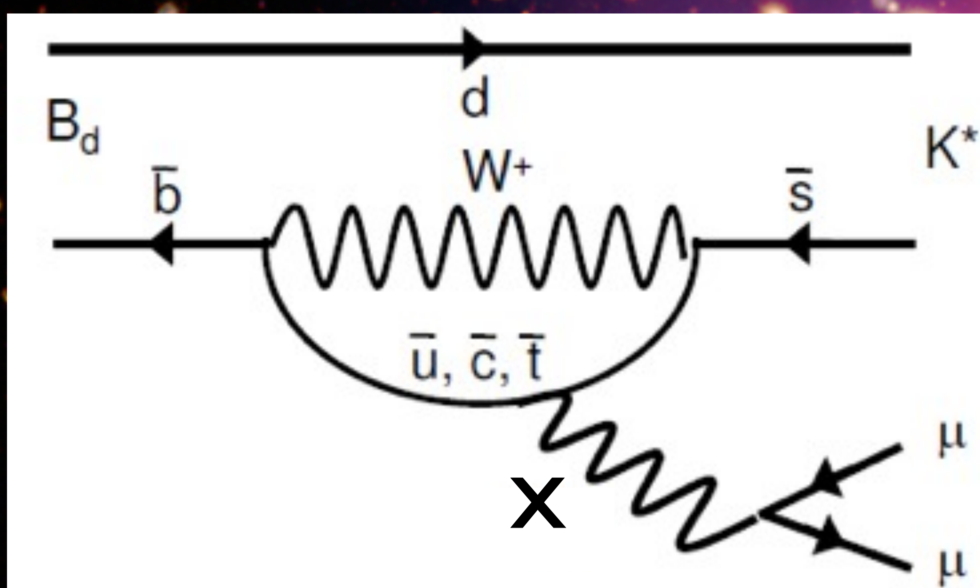
[LHCb-PAPER-2014-014]





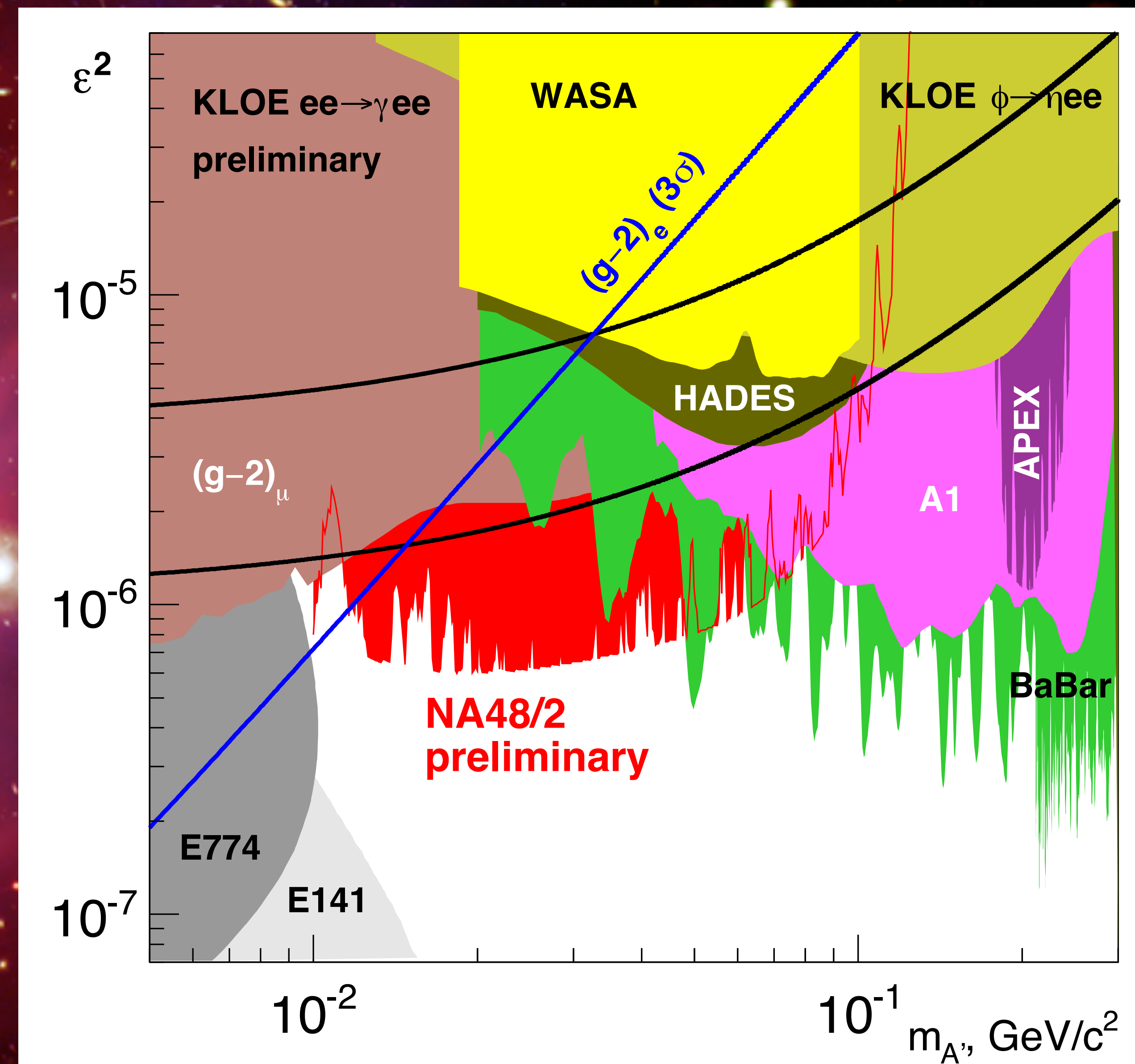
Dark Matter

dark bosons that couple to mass



searches underway @ LHCb

dark photon limits



Flavor experiments often are the best places to look for light BSM.

Summary

Historically in particle physics, new physics has first shown up at the precision frontier (beta decay, GIM, CPV,...). Will that again be the case?

flavor physics (now)

flavor physics (2018)?

We are really now just reaching a level of sensitivity where one might expect “realistic” BSM effects to become significant.

The optimist regards the future as uncertain.

Eugene Wigner