Title: LHCb: Results & Prospects

Date: Jan 19, 2016  01:00 PM

URL: http://pirsa.org/16010060

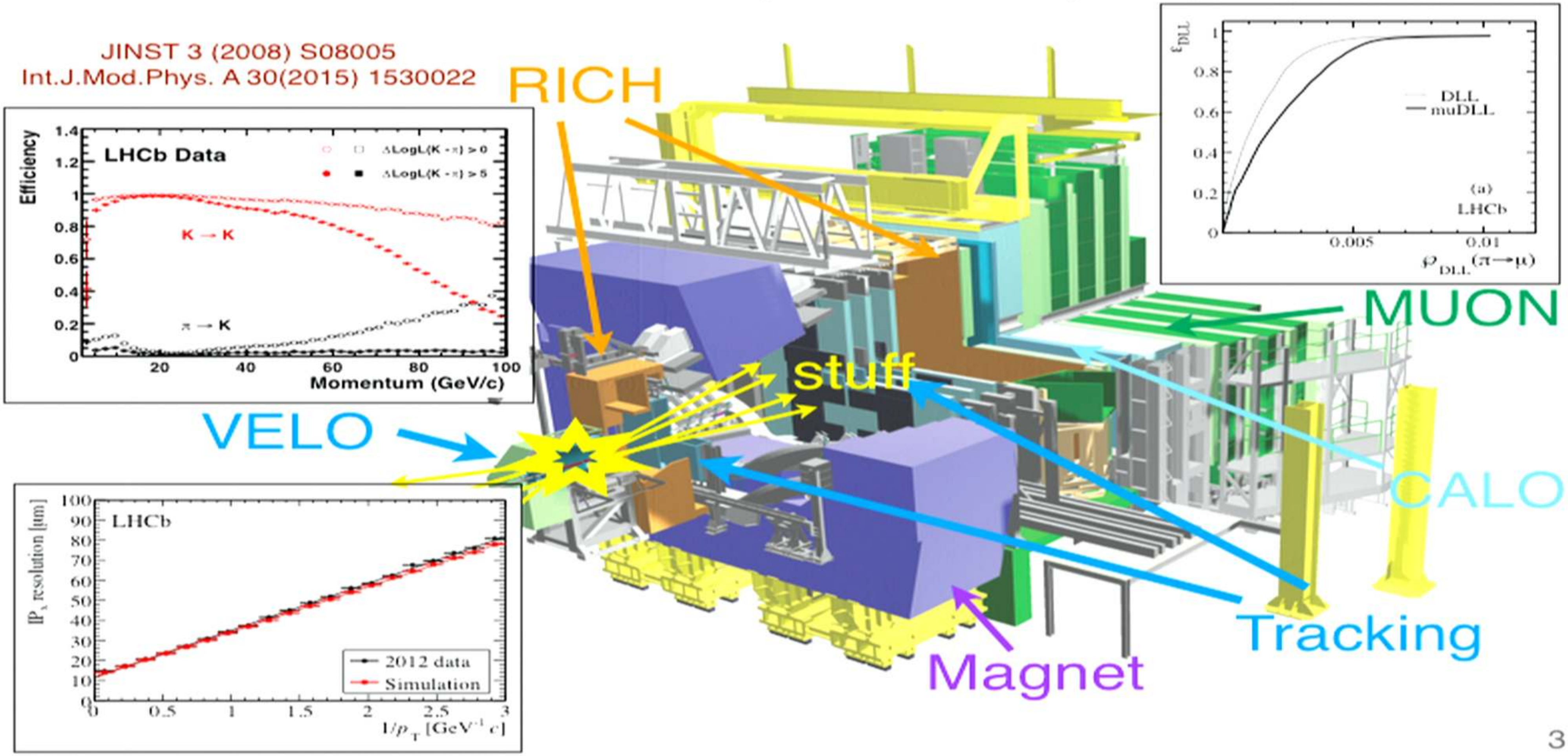
Abstract: <p>The LHCb detector was designed to be the dedicated heavy-flavor physics experiment at the LHC, and has been the world's premier lab for studying processes where the net quark content changes for several years. These studies permit observing virtual contributions from beyond the SM particles up to very high mass scales, potentially (greatly) exceeding the direct reach of the LHC.  I will summarize the constraints placed on high-mass BSM physics by such studies, and also highlight a few interesting anomalies.  I will also discuss direct searches for low-mass BSM physics, and a selection of novel SM studies.  Finally, future prospects will be presented. </p>


The Large Hadron Collider
Outline
LHCb detector
flavor physics
low-mass BSM
QCD

# LHCb Detector

LHCb is a forward Spectrometer ($2 < \eta < 5$)

JINST 3 (2008) S08005
Int.J.Mod.Phys. A 30(2015) 1530022

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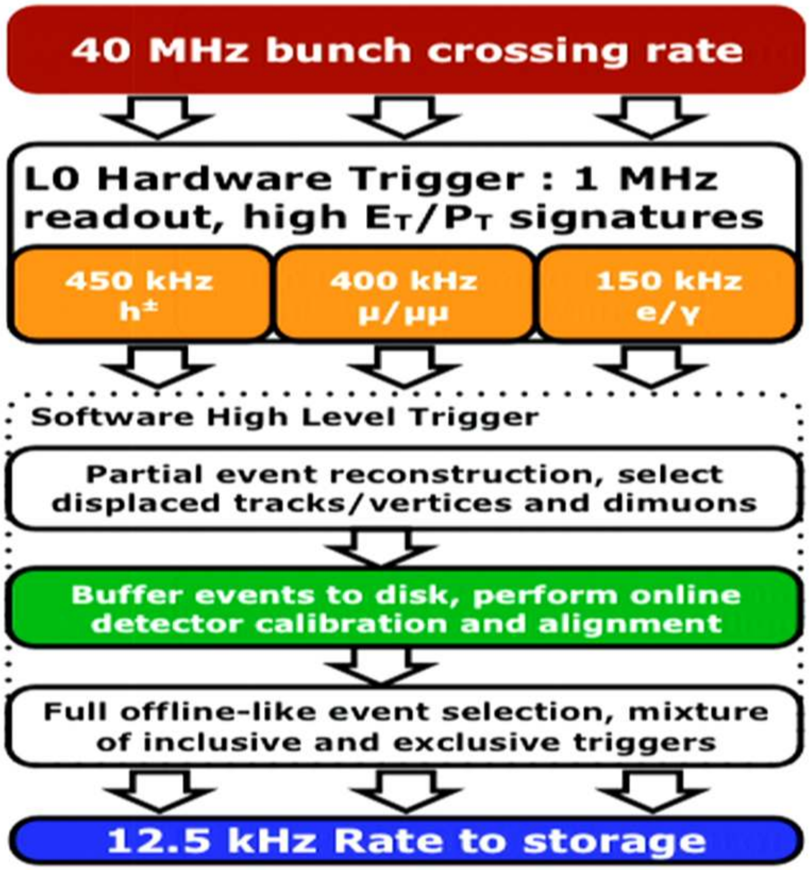
# LHCb Trigger




Precision measurements benefit greatly from using the final (best) reconstruction in the online event selection -- need real-time calibration!

JINST 8 (2013) P04022

all tracks $p_T > 0.5$ GeV (no IP requirements)

same calibration constants used online & offline

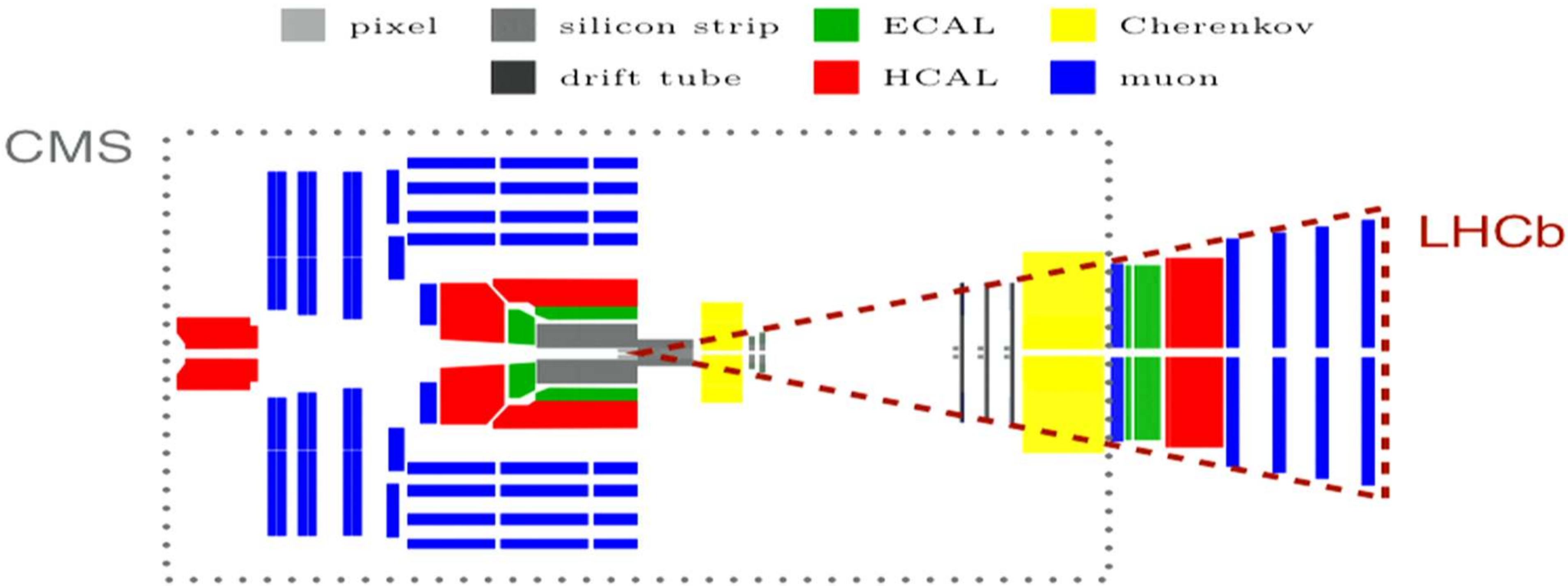
full reconstruction, offline-like particle ID, track quality, etc.

Heavy use of machine learning algorithms throughout the Run 1 and Run 2 trigger.

V.Gligorov, MW, JINST 8 (2012) P02013.

Plan to move to a triggerless-readout system in Run 3!

# LHCb Detector

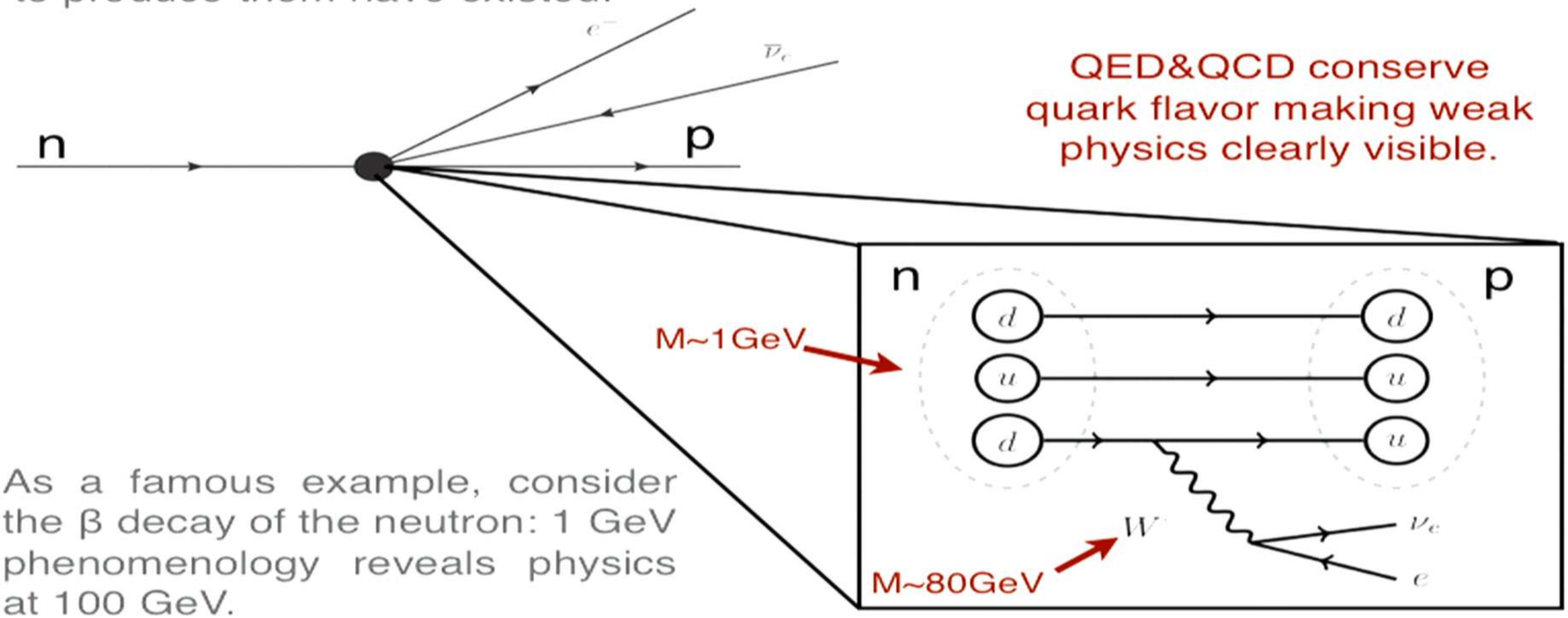



Complimentary kinematical coverage to CMS & ATLAS.

# Flavor Physics

# 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.

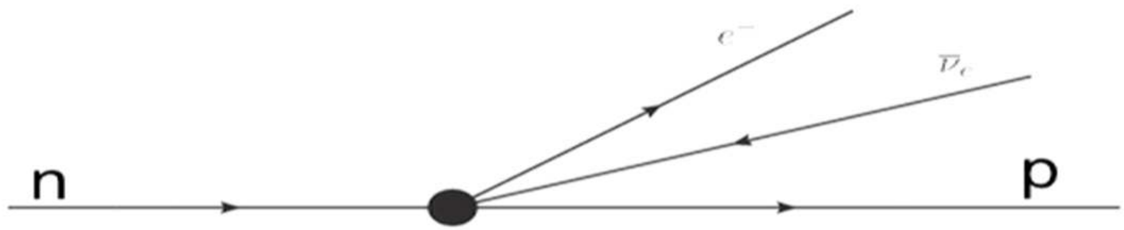



QED&QCD conserve quark flavor making weak physics clearly visible.

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.




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

operator product expansion

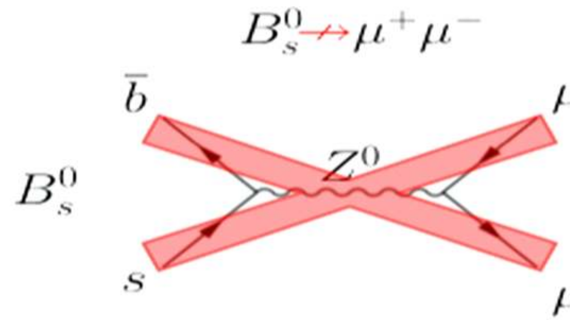
$$\mathcal{H}_{eff} \propto \sum_i \left(\mathcal{C}^i_{SM} + \mathcal{C}^i_{BSM}\right) \mathcal{O}_i$$

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 only by experimental and theoretical precision).

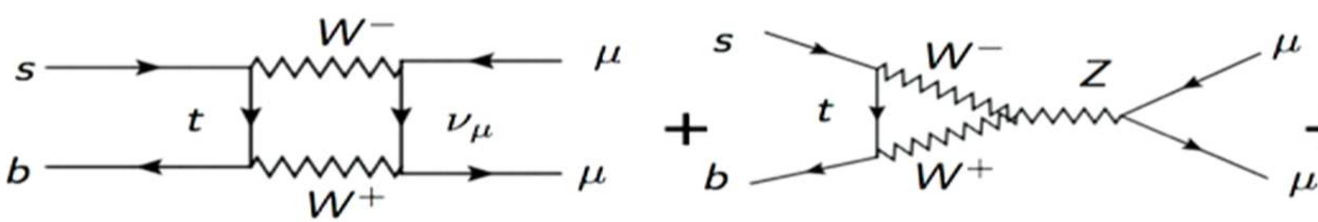
# $B_{d,s} \rightarrow \mu^+\mu^-$

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 ∝ |

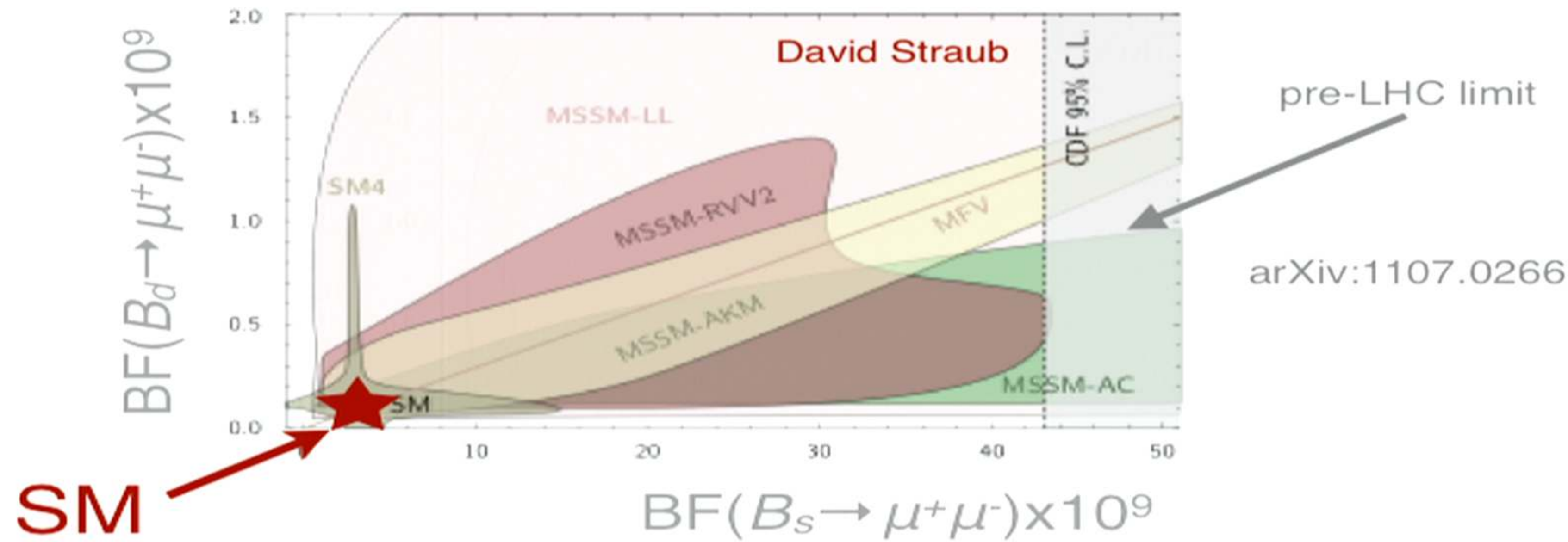



+ [?] + ... $|^2$

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.

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

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

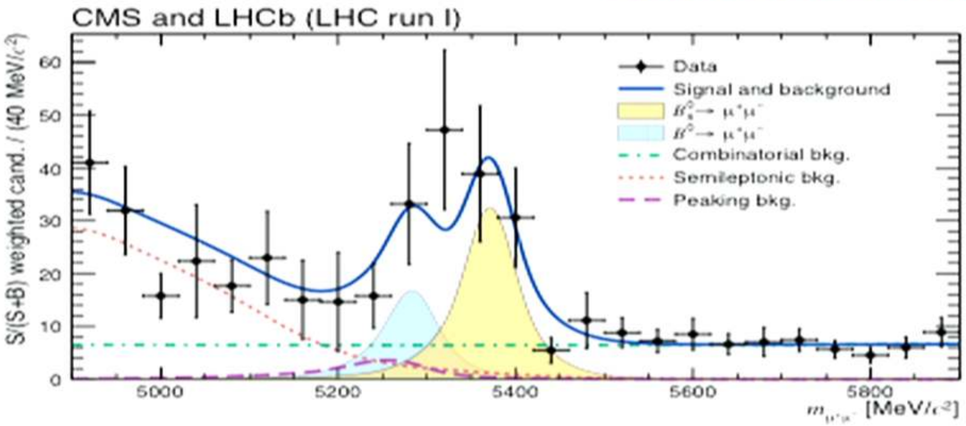



For example, this plot shows various SUSY predictions prior to LHC running.

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

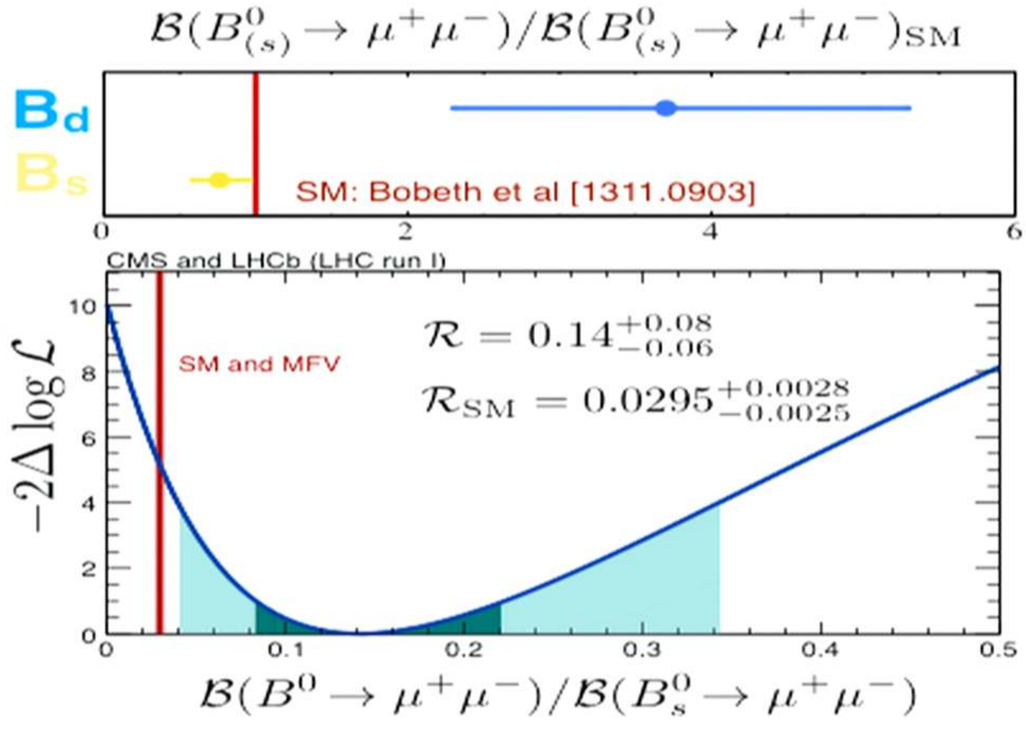
After 30 years of searching for these decays, both LHCb and CMS crossed the 4σ significance threshold in Run 1 for the $B_s$ decay.

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



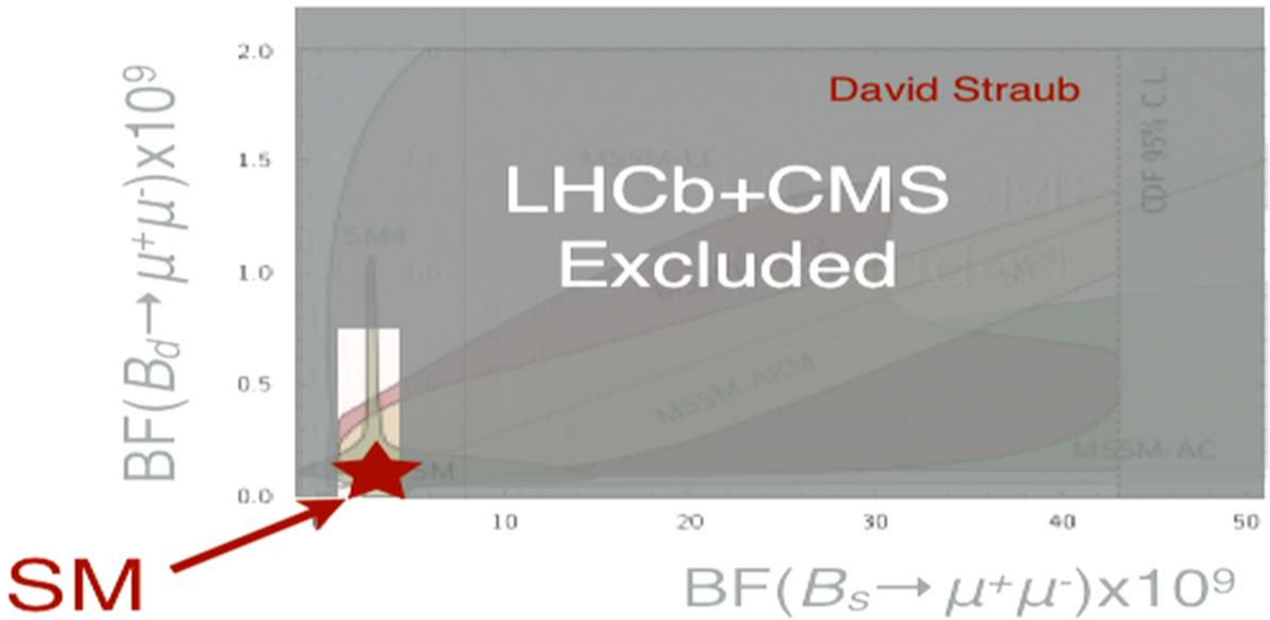

Results from combined CMS & LHCb data obtain 6.2σ for the $B_s$ decay and 3.0σ for the $B_d$ decay.

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



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

Results rule out large regions of SUSY parameter space.

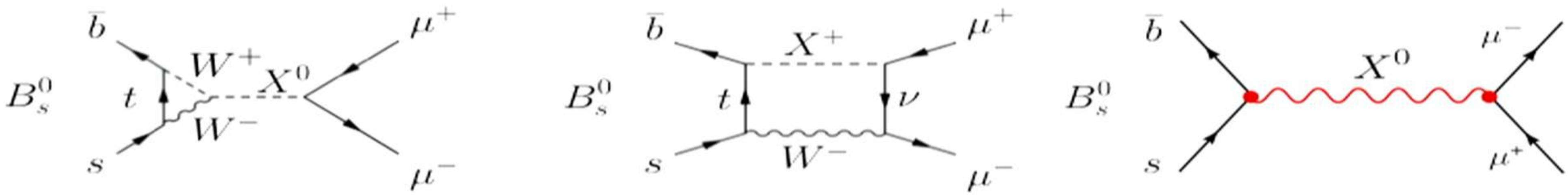



arXiv:1107.0266

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

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

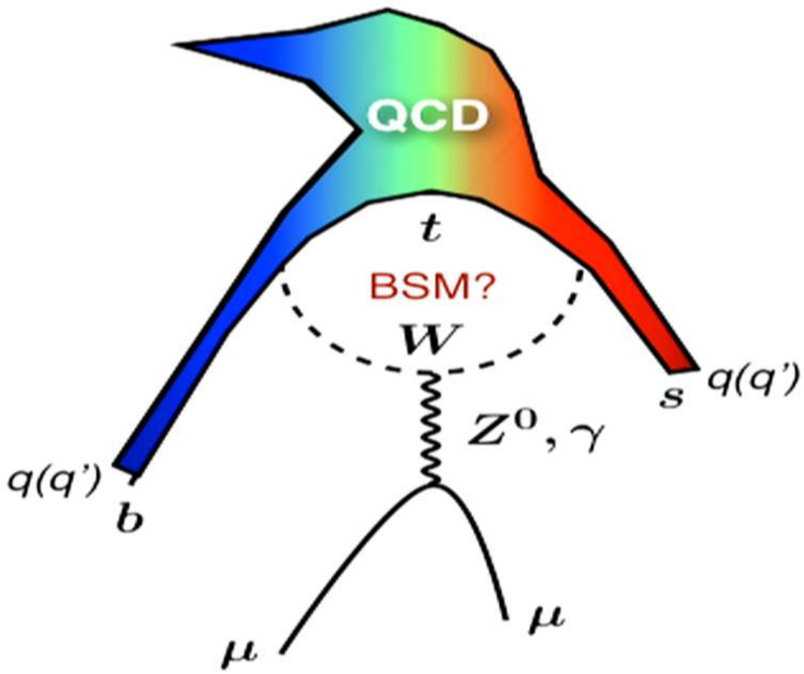
loops (could be MFV or not) tree (requires FV)




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).

# $b \rightarrow s$ 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.



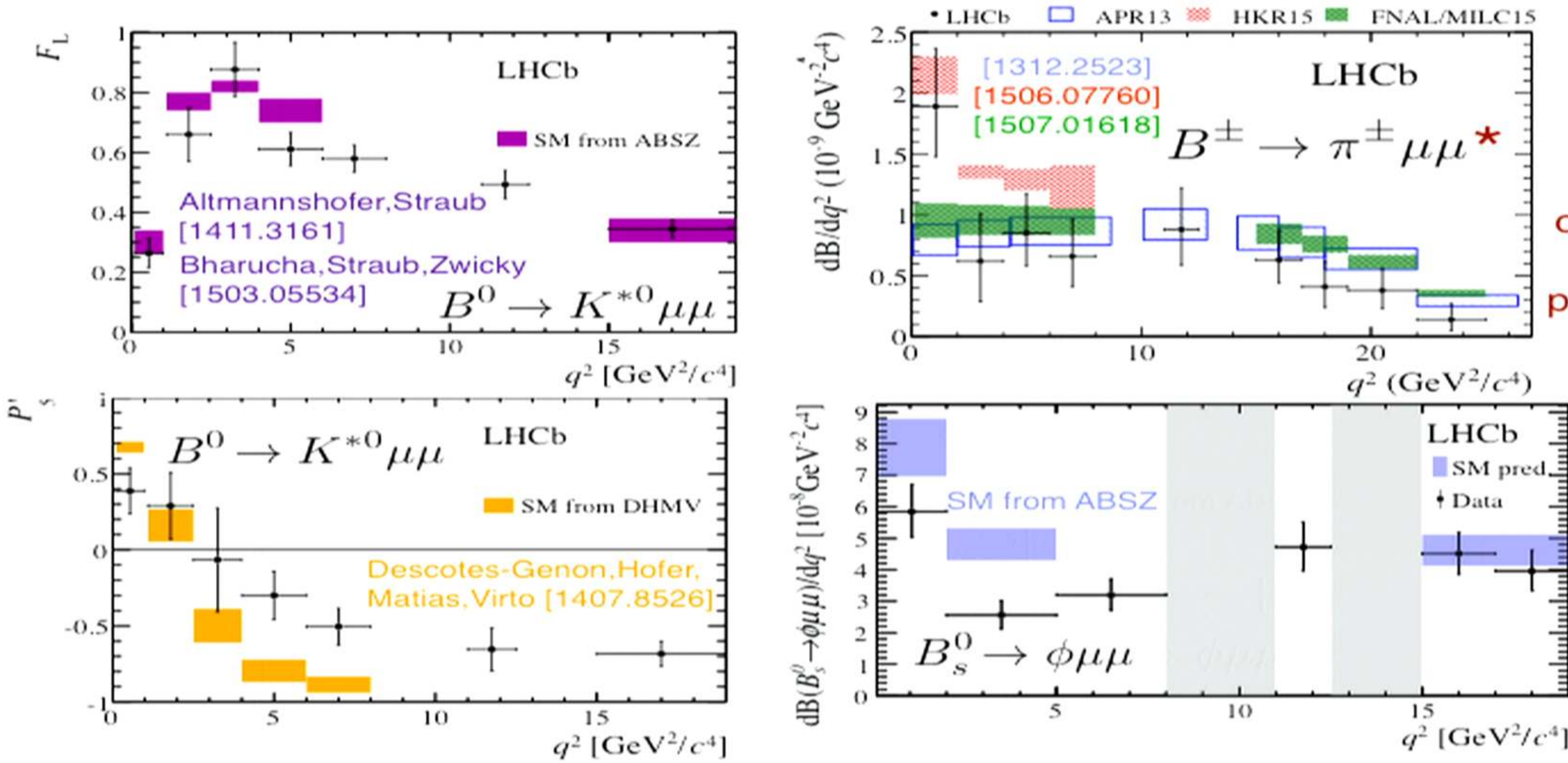

SM calculations need
B→K form factors

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-2015-051, LHCb-PAPER-2015-023, LHCb-PAPER-2015-035



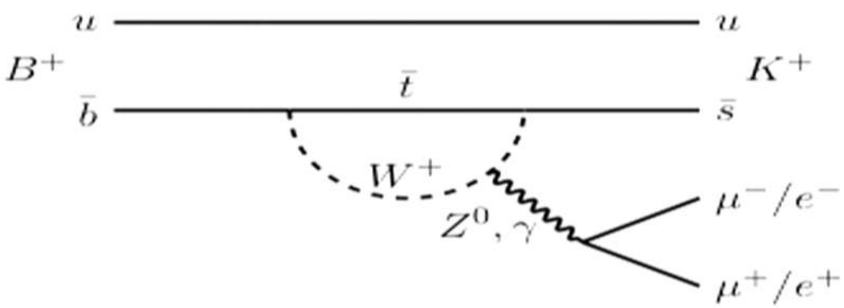

*this one's a $b \to d$ penguin

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.

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

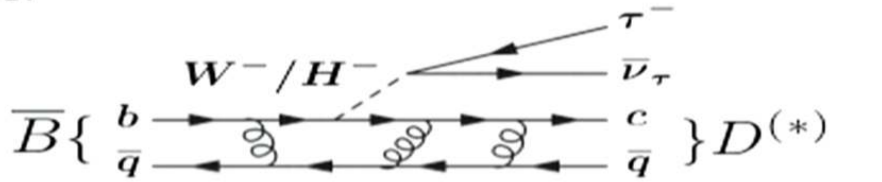


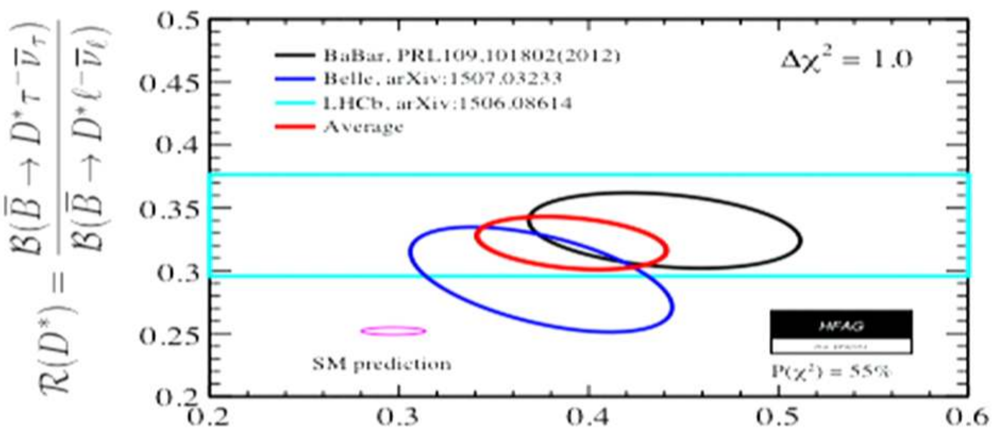

LHCb-PAPER-2014-024
PRL 113 (2014) 151601

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

2.6σ from SM

$1<q^2<6$ GeV



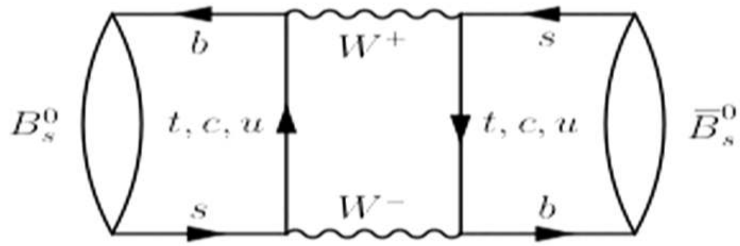

$$\mathcal{R}(D^*) = \frac{\mathcal{B}(\overline{B} \to D^*\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D^*\ell^-\overline{\nu}_\ell)}$$

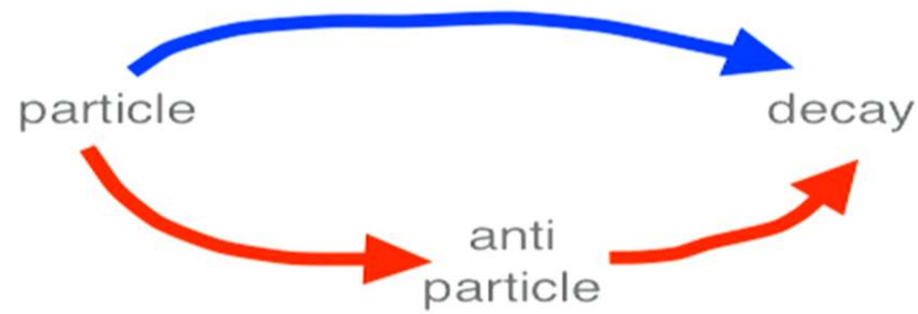
$$\mathcal{R}(D) = \frac{\mathcal{B}(\overline{B} \to D\tau^-\overline{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D\ell^-\overline{\nu}_\ell)}$$

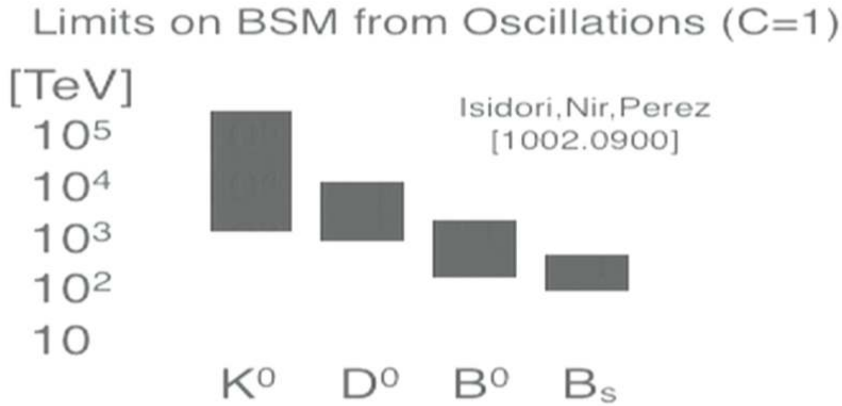
Measurement of $R_{D^{(*)}}$ by BaBar, Belle, and LHCb show a 3.9σ discrepancy with the SM prediction.

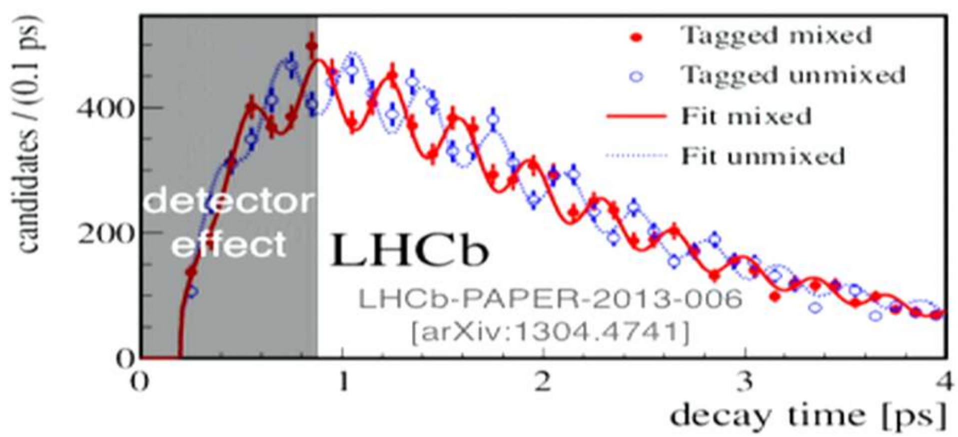
# Oscillations

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.




Oscillation rates and (lack of) CP violation (rates consistent in both directions) consistent with SM expectations (strong constraints on BSM).

# 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.

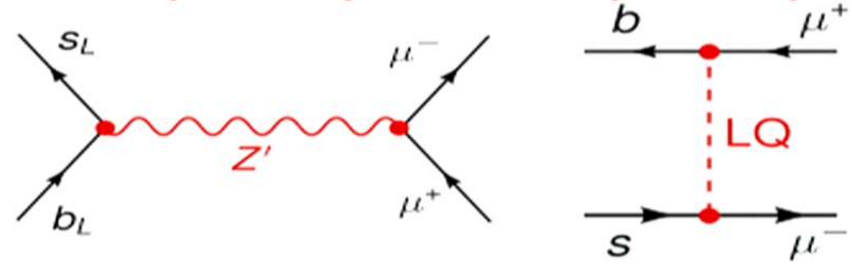
**Main message:** Strong constraints placed on BSM, but some intriguing anomalies remain. We need more data!

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]

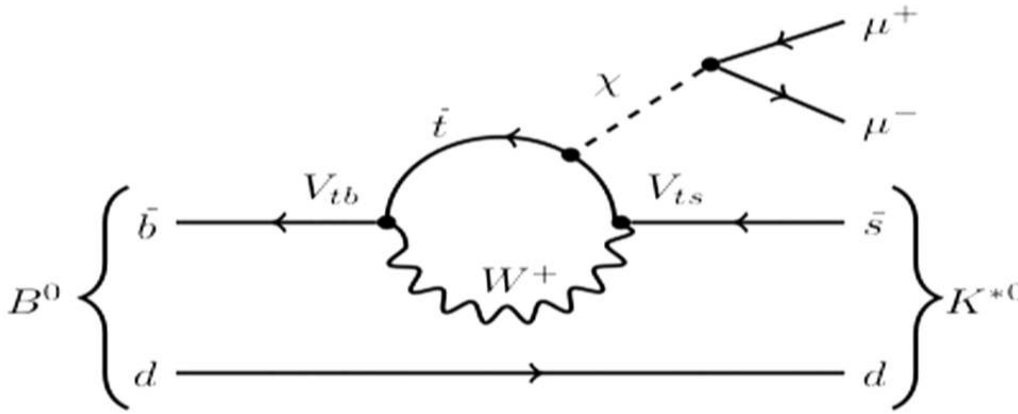



Potential candidates include O(1-10 TeV) Z' or leptoquarks.

# Low-Mass BSM

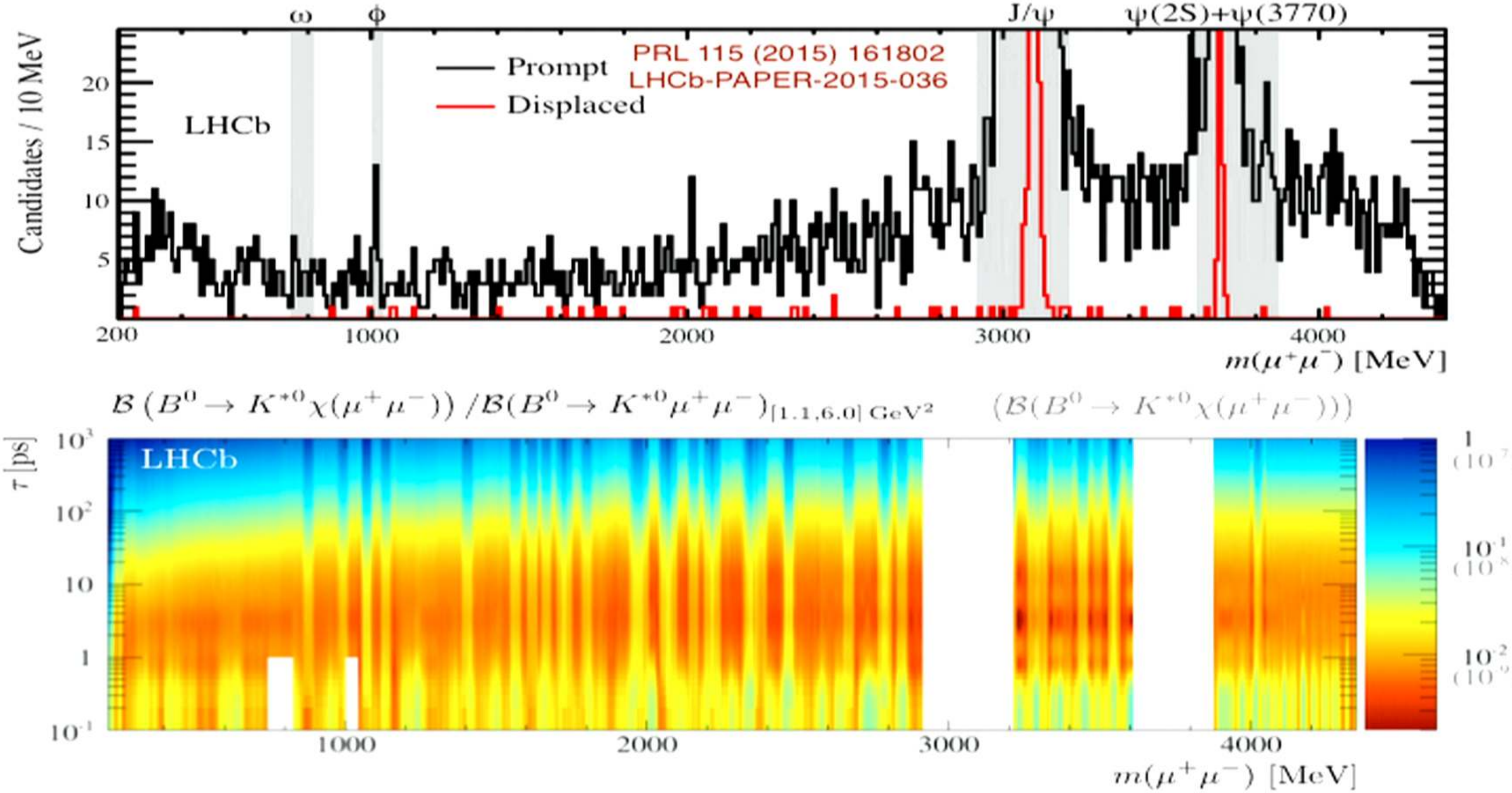
# Hidden Sectors

$b \to s$ penguin decays are also an excellent place to search for low-mass hidden-sector particles (e.g., anything that mixes with the Higgs sector).




Search for $B \to K^*X$, $X \to \mu\mu$ by scanning m(μμ) and allowing (not requiring) non-zero τ(μμ). Strategy handles possible qq resonance contributions (MW [1503.04767]), and uses a novel "uniform BDT" (J.Stevens, MW [1305.7248]).

# Hidden Sectors




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

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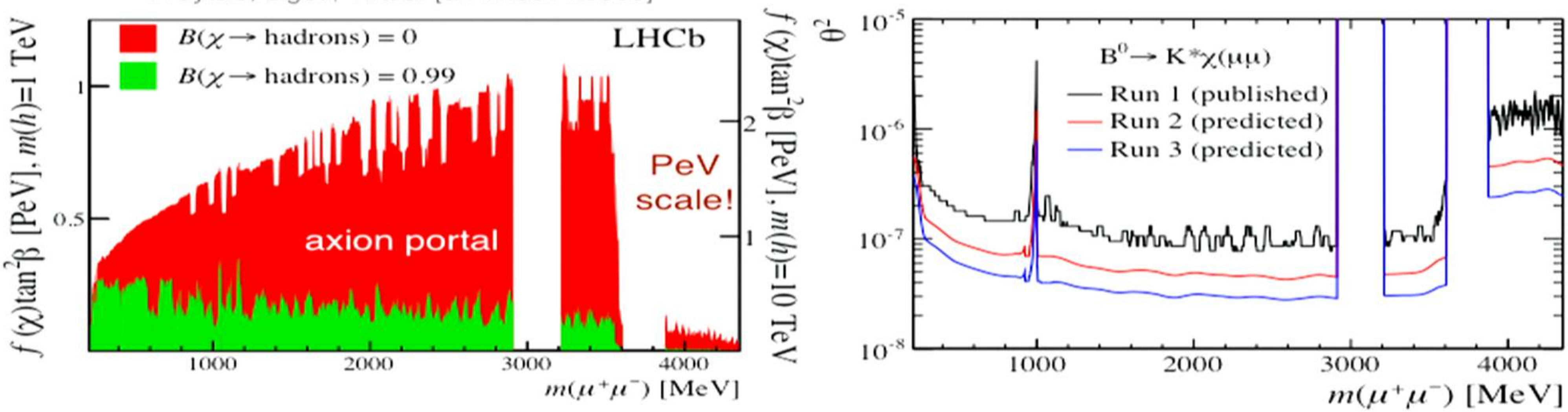
# Hidden Sectors

Can also look at constraints on specific models:

Freytsis, Ligeti, Thaler [arXiv:0911.5355]

PRL 115 (2015) 161802
LHCb-PAPER-2015-036



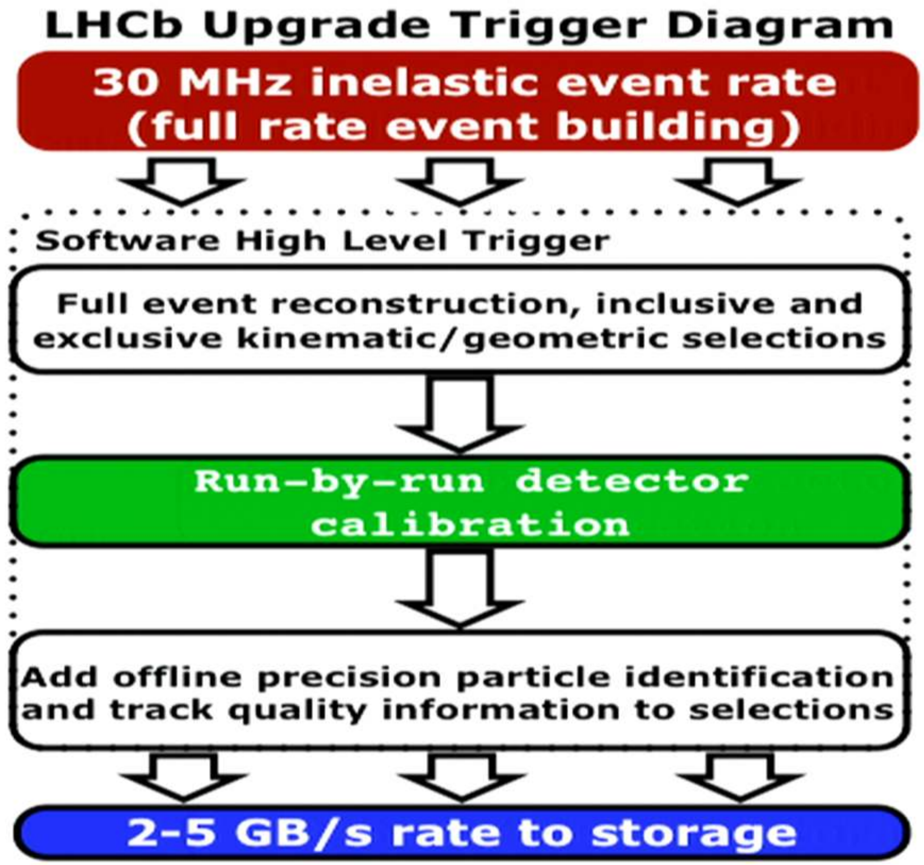

Predicted reach after Run 3 will overlap the smallest Higgs mixing angles probed by SHIP.

# Triggerless Readout

Plan to remove the 1MHz readout bottleneck and process all events by the HLT in Run 3.

Will enable further improving our flavor-physics program.

Will also have a huge impact on low-mass BSM searches, and other areas where a striking signature is only present after full reconstruction.



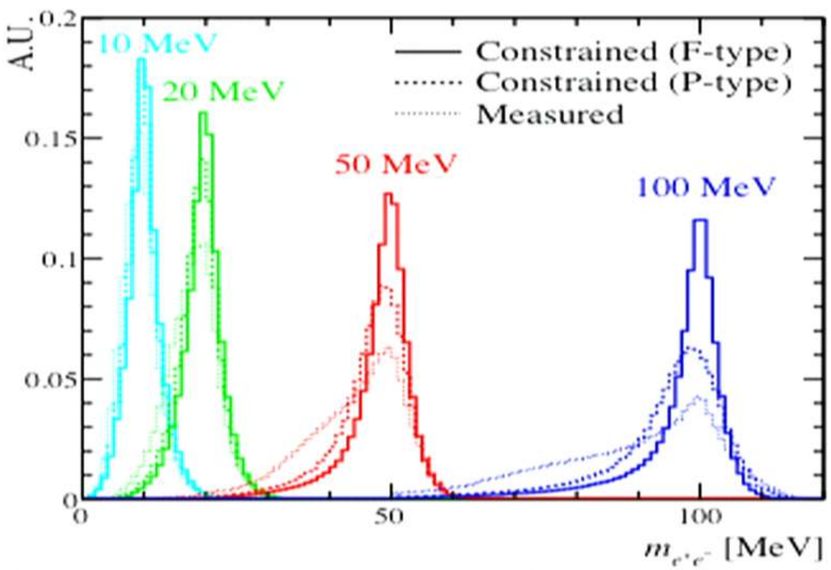
# Dark Photons

We* first considered the low-mass region using the decay $D^{*0} \rightarrow D^0 A'(ee)$, which can potentially probe the region 2m(e) to ~142 MeV. The SM decay $D^{*0} \rightarrow D^0 \gamma$ will occur within LHCb acceptance at almost 1 MHz in Run 3.

*Ilten, Thaler, MW, Xue [1509.06765]


$$\frac{\Gamma(D^{*0} \to D^0 A')}{\Gamma(D^{*0} \to D^0 \gamma)} = \epsilon^2 \left(1 - \frac{m_{A'}^2}{\Delta m_D^2}\right)^{3/2},$$

Soft electrons are easily identified by the RICH.

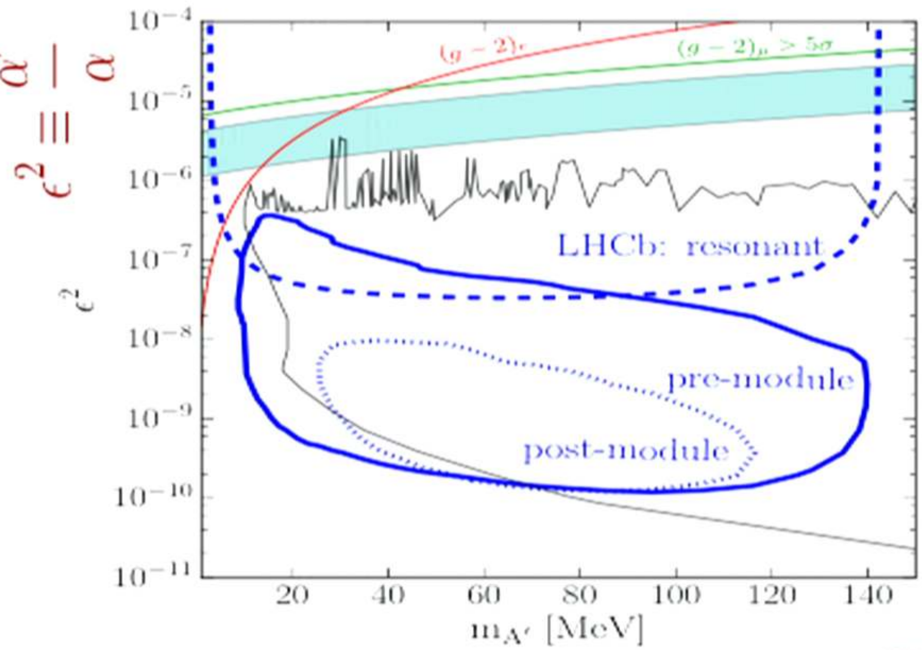


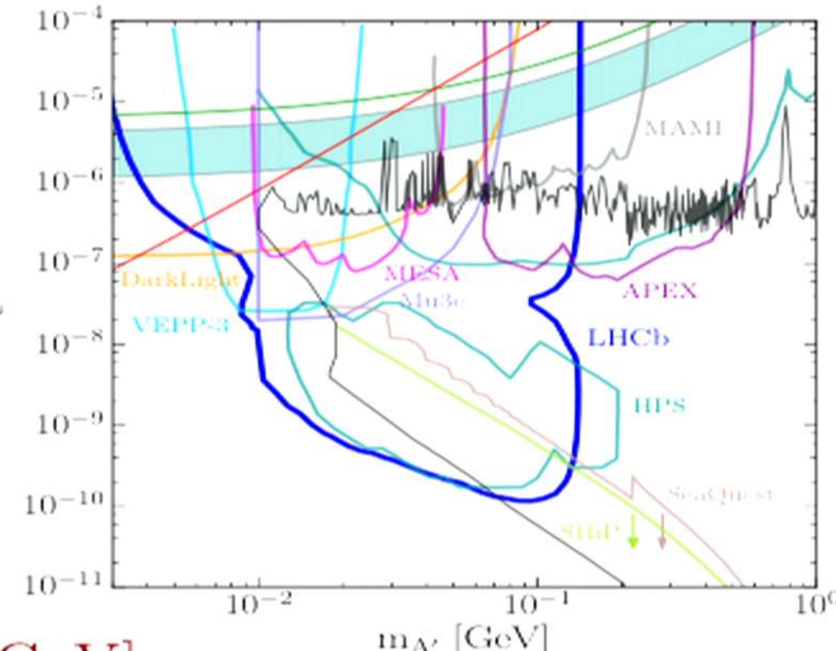

Poor m(ee) resolution due to BREM is greatly improved by performing a mass-constrained fit using known $m(D^{*0})$ and well-measured $D^0$. Cutting on $m(D^0ee)$ makes combinatorial BKGD negligible.

# Dark Photons

Ilten, Thaler, MW, Xue [1509.06765]

Several search strategies considered with the reach conservatively estimated for Run 3 (in reality, likely follow MW [1503.04767] to combine searches).




We are currently working on a more general strategy to look for direct production of A' followed by (prompt or displaced) A'→μμ.

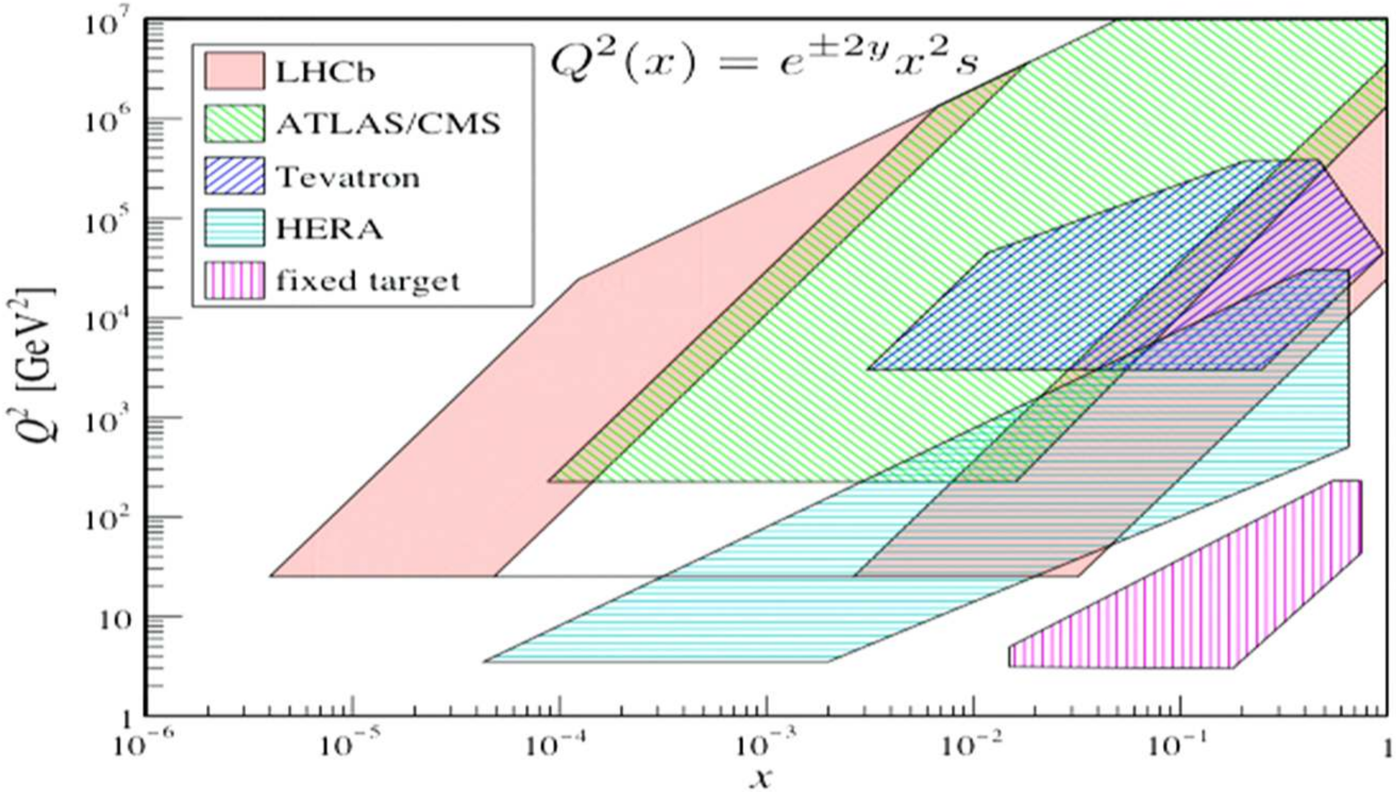
# Advantages of LHCb

- Parasitic running: LHCb has many unique but generically useful capabilities and so can be used for A' searches during nominal running -- which is ~continuous for ~decades.
- Large production rates: basically everything is produced at a large rate in 250 MHz pp collisions @ 14 TeV.
- LHCb itself: VELO, RICHes, triggerless-readout system.
- Access to small opening angles: A' produced into the VELO, opening angle limited only by hit resolution (~few mrad).
- Large Lorentz boosts: larger FD for same A' lifetime.
- Access to ~all masses.


QCD

# PDFs

LHCb probes unique regions of (x,Q) so there are many measurements we can (potentially) make that are sensitive to (largely unknown) PDFs.

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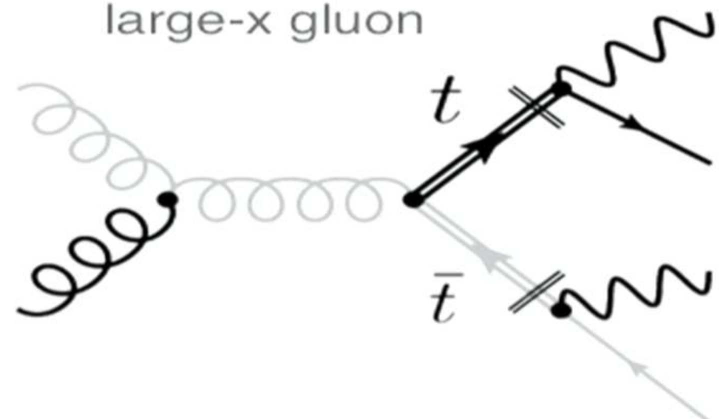
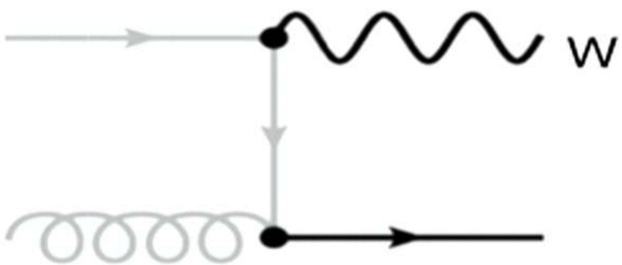
# Potential PDF Probes

small-x gluon

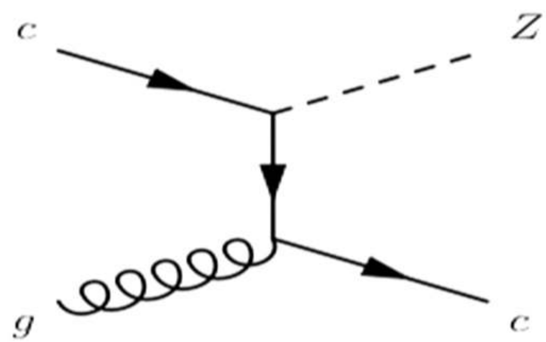

large-x gluon



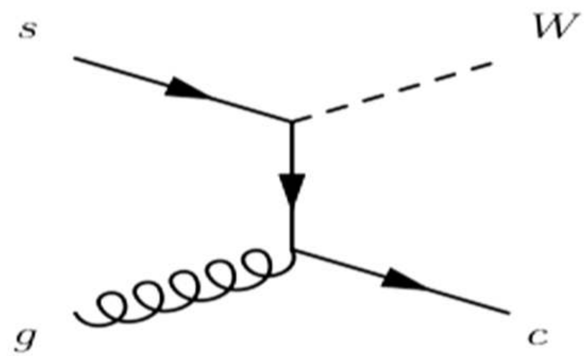

large-x d/u




intrinsic charm




s vs s-bar

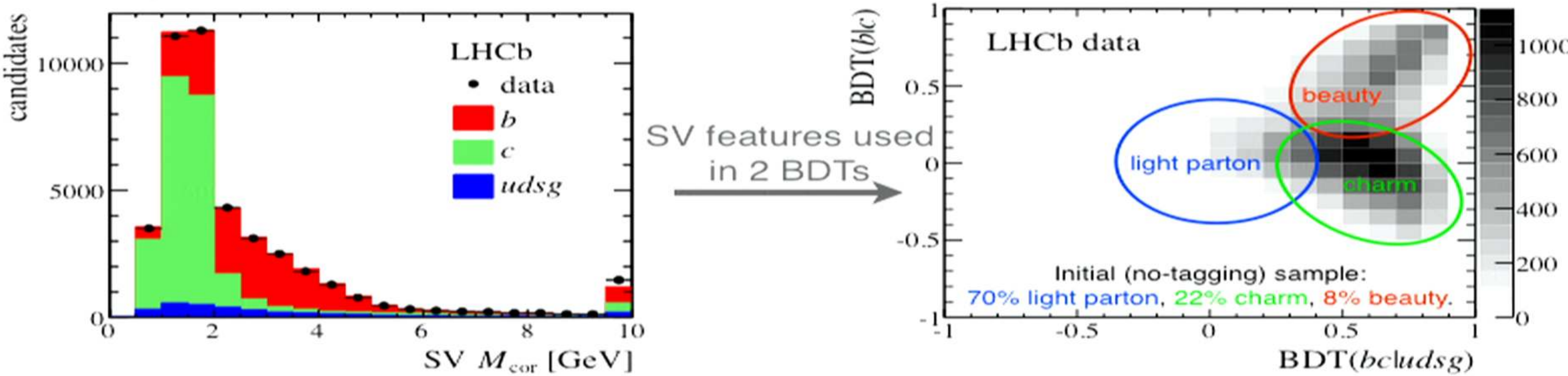


# Jet Tagging

Use a SV-based algorithm to identify b and c jets (leveraging LHCb VELO):

JINST 10 (2015) P06013
LHCb-PAPER-2015-016

example SV feature: "corrected mass"




Performance validated & calibrated using large heavy-flavor-enriched jet data samples. Two-D BDT distributions fitted to extract SV-tagged jet flavor content; c-jet and b-jet yields each precisely determined simultaneously.

First measurement of beauty forward-central asymmetry.

LHCb-PAPER-2014-023: PRL 113 (2014) 082003.

# PDF Results & Prospects

•Precise differential measurements of open charm production used to reduce the uncertainty on the gluon PDF at x = 1e-5 by a factor of 3.

LHCb-PAPER-2015-041  LHCb-PAPER-2012-041: Nucl. Phys. B871 (2013) 1  Gauld, Rojo, Rittoli, Talbert [1506.0825]

•Precise Wj and Zj agree with NLO SM predictions. Differential Wj measurements with large $p_T(j)$ will probe d/u at $x \sim 0.7$ in Run 3.

LHCb-PAPER-2013-058: JHEP 01 (2014) 33  LHCb-PAPER-2015-021: PRD 92 (2015) 052001  Farry, Gauld [1505.01399]

•Statistically limited Wb and Wc measurements agree with NLO SM predictions. Run 2 Wc charge asymmetry will probe s-sbar asymmetry.

LHCb-PAPER-2015-021: PRD 92 (2015) 052001

•Statistically limited top measurements agree with NLO SM predictions. Run 2 results expected to greatly reduce large-x gluon uncertainty.

LHCb-PAPER-2015-022 : PRL 115 (2015) 112001  Gauld [1311.1810]

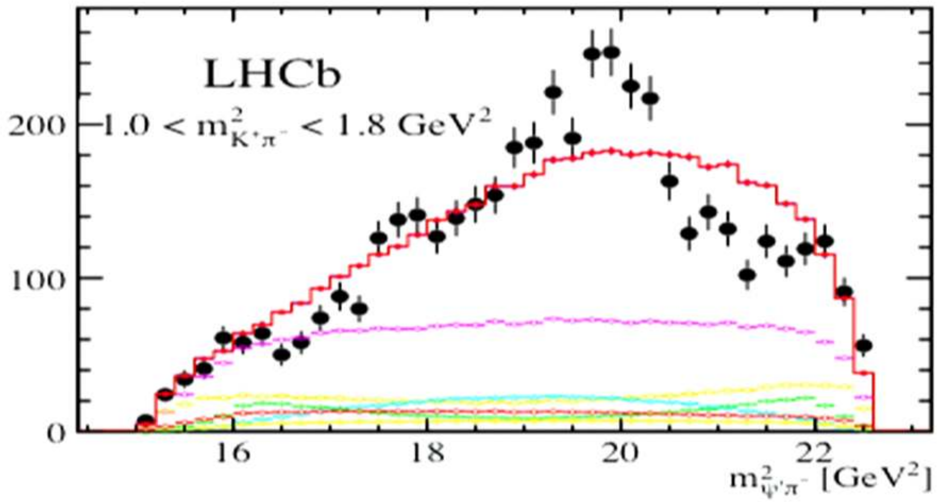
•Run 2(3) Zc measurements will probe intrinsic charm at the 0.3%(1%) level. Impacts central Higgs production, IceCube backgrounds, etc.

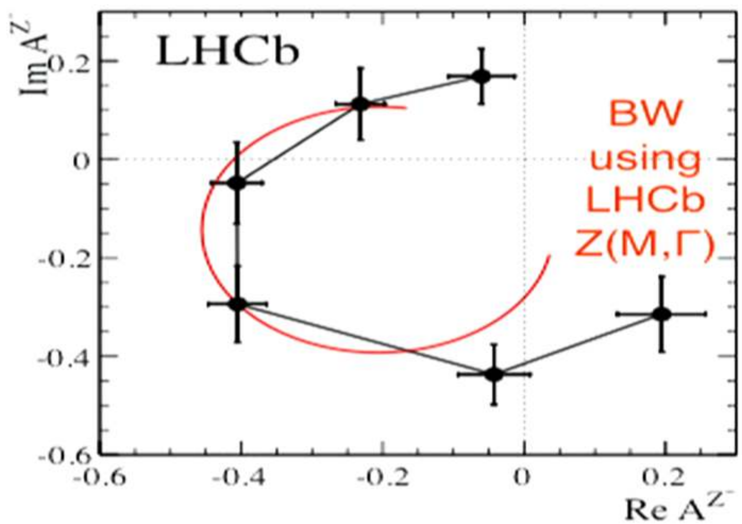
Boettcher, Ilten, MW [arxiv:1512.06666]

# Z(4430)±

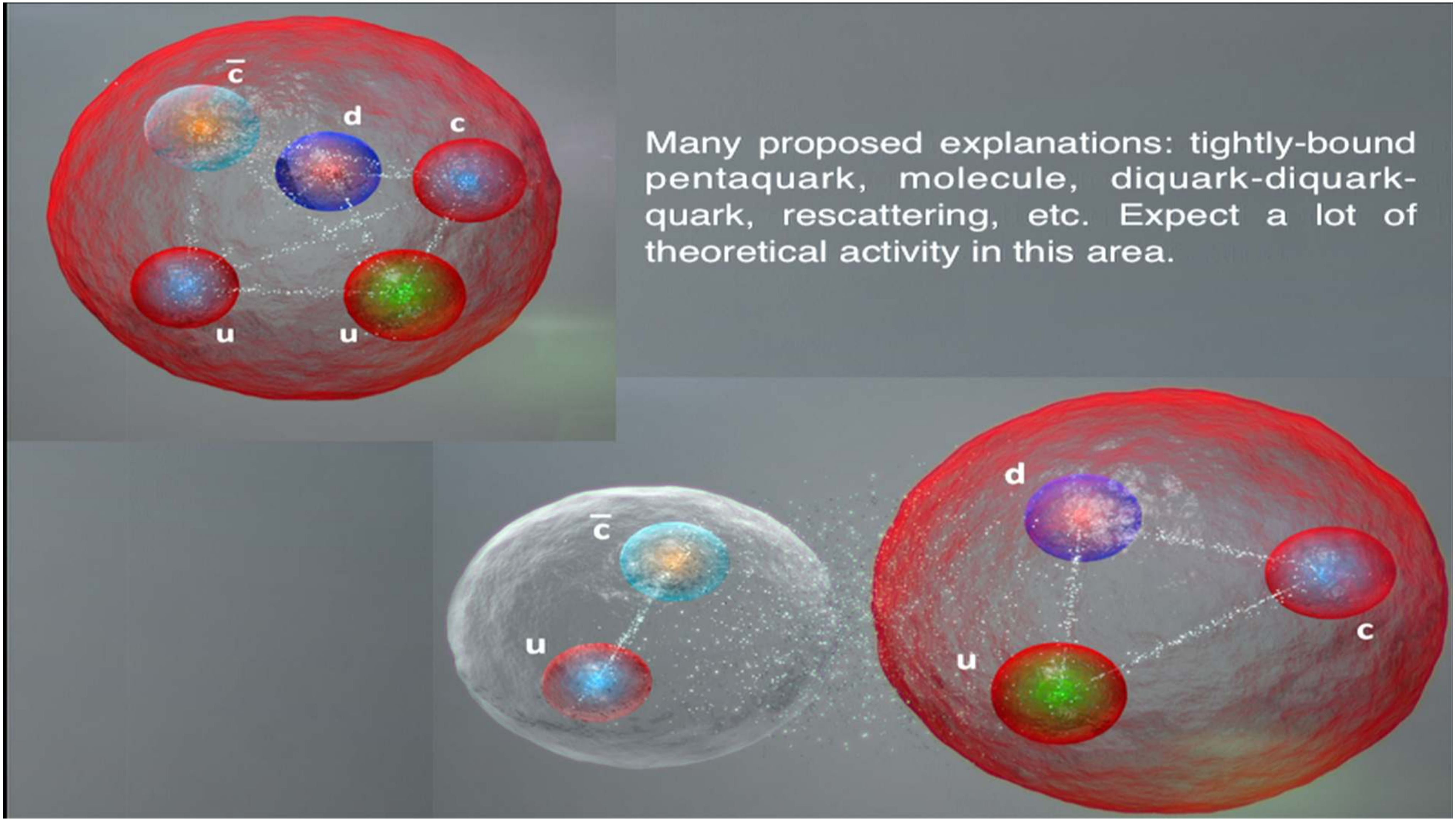
Peaking structure observed in the ψ(2S)π (c-cbar-u-dbar) system in the decay B→ψ(2S)[μμ]Kπ (first seen by Belle; not seen by BaBar). LHCb has ~12x stats of the B factories so could perform a 4-D amplitude analysis.

LHCb-PAPER-2014-014




Argand diagram obtained from (Z) model-independent amplitude fits shows clear resonant-like behavior.


Many proposed explanations: tightly-bound pentaquark, molecule, diquark-diquark-quark, rescattering, etc. Expect a lot of theoretical activity in this area.
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# Summary

LHCb is a general-purpose detector in the forward region.