# Searching for Physics Beyond the Standard Model @ LHCb

Mike Williams

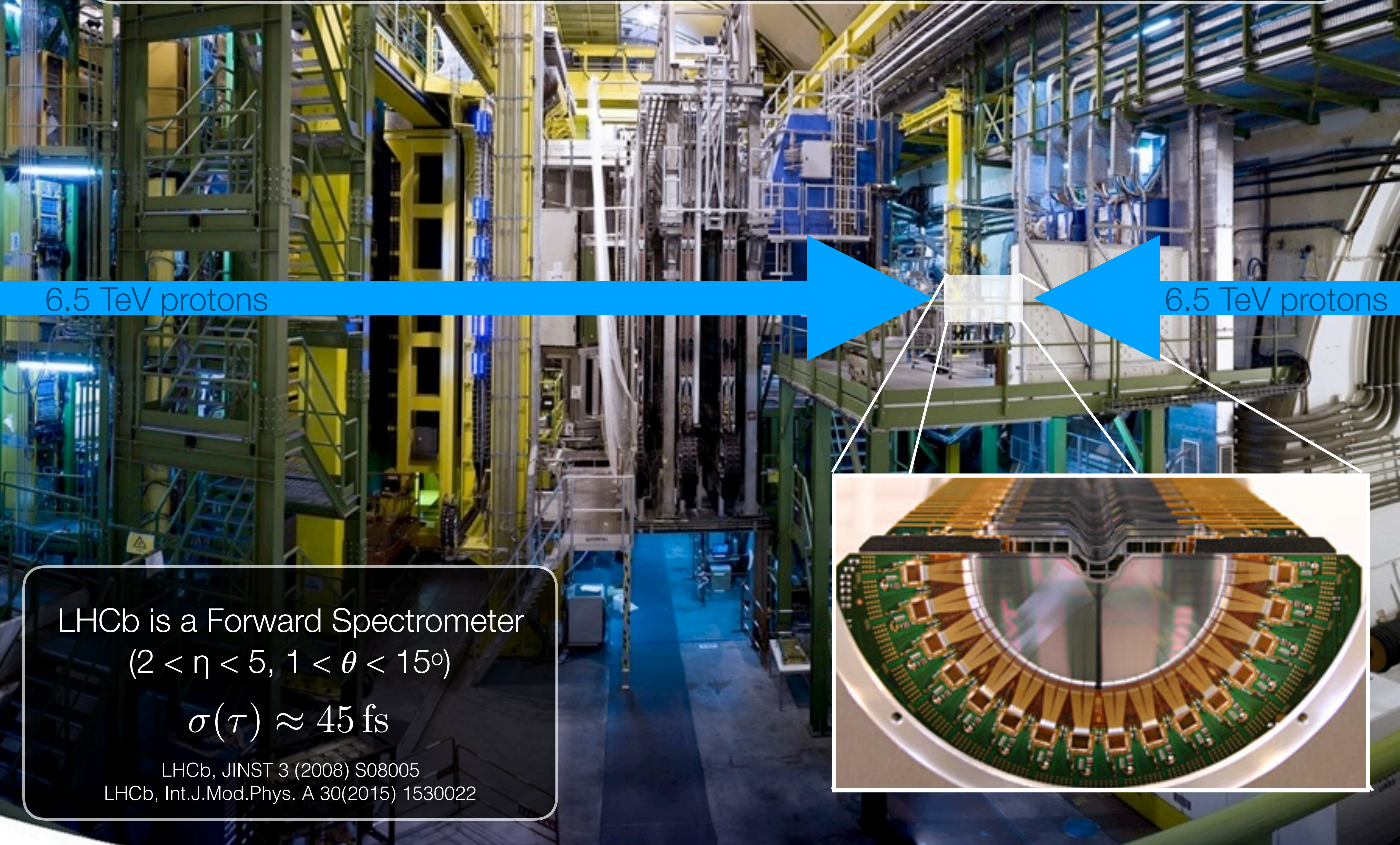
Department of Physics
NSF AI Institute for Artificial Intelligence and Fundamental Interactions
Laboratory for Nuclear Science
Statistics & Data Science Center
MIT

June 23, 2021

LHCb if painted by Van Gogh according to a Deep Neural Network.
https://github.com/jcjohnson/neural-style

# LHCb: The Large Hadron Collider beauty (quark) experiment

LHCb was built to study the decays of bound states containing b quarks, whose masses and lifetimes are ~5 GeV and ~1.5 ps, respectively. O(1%) of LHC pp collisions make b quarks.




LHCb is a Forward Spectrometer

($2 < \eta < 5$, $1 < \theta < 15^{o}$)

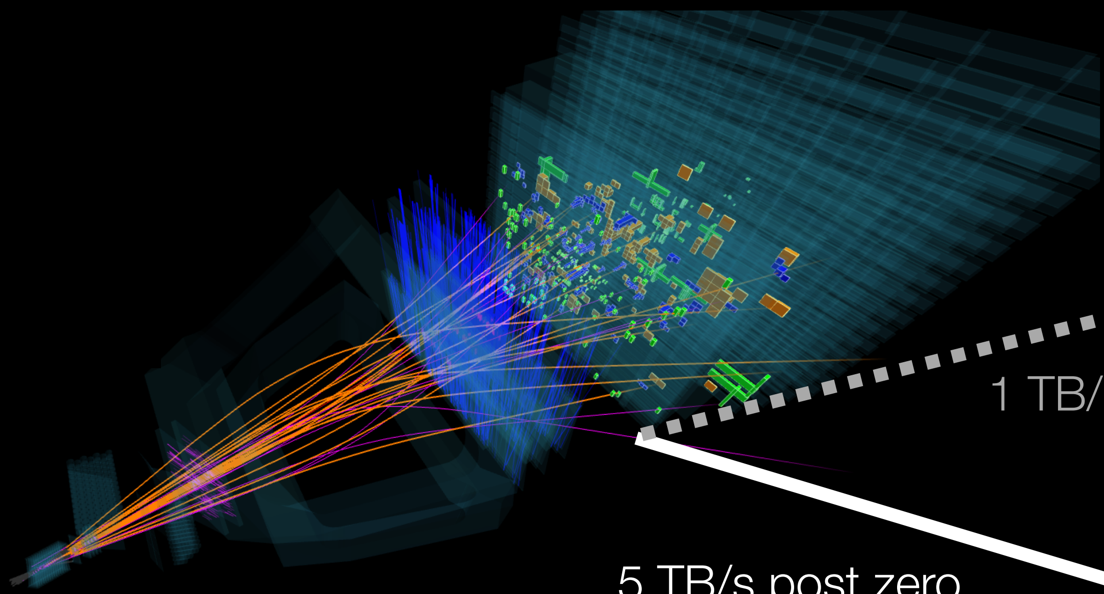
$$\sigma(\tau) \approx 45\,\mathrm{fs}$$

LHCb, JINST 3 (2008) S08005

LHCb, Int.J.Mod.Phys. A 30(2015) 1530022


The Large Hadron Collider
LHCb
90 institutes
18 countries
900 physicists
550 papers
40k citations

# Real-Time Calibration & Analysis



single-subsystem selection on FPGAs, O(microsecond) latency

1 TB/s

50 GB/s

5 TB/s post zero suppression (30 EB / year)

partial event inference

loose selection

IAIFI /ai fai/
https://iaifi.org

O(10) PB disk buffer

data buffered while all calibrations are run

O(100k) CPU cores

full event inference

classification, keep all info for some events, and only selected info for other events

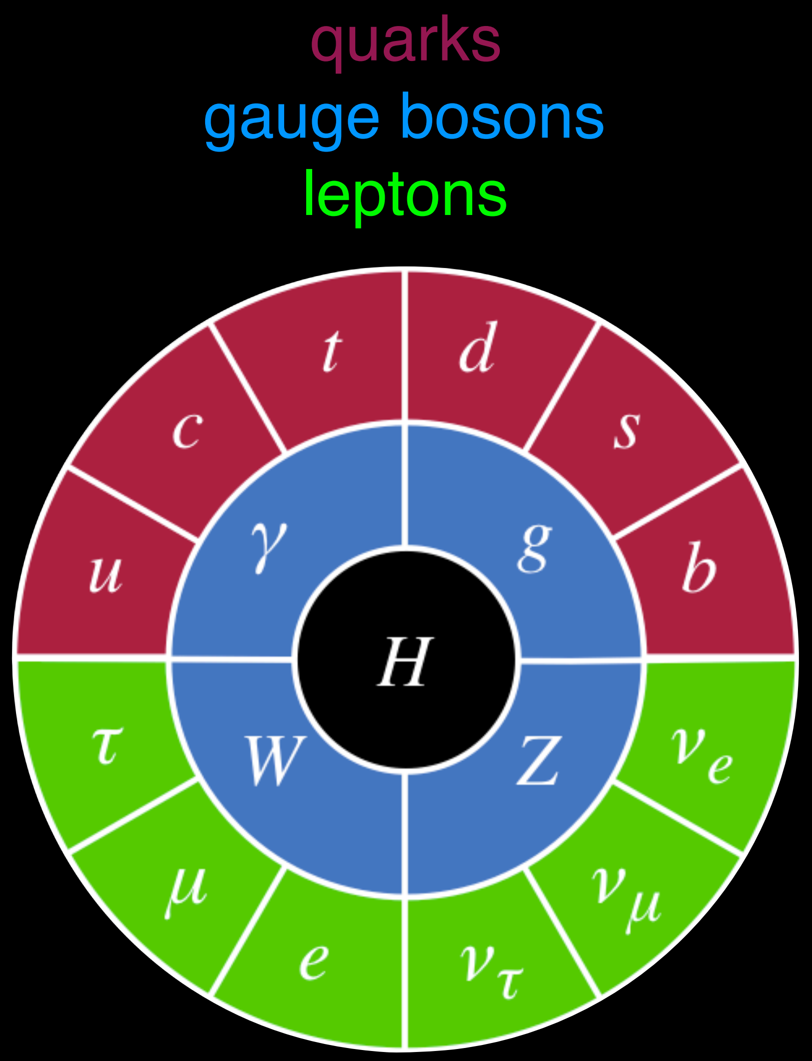
60 PB / year

offline storage

I am interested in robustness, quantification of uncertainties, building physics knowledge into AI, etc.

# The Standard Model of Particle Physics

The SM incorporates all known particles and interactions except gravity. It would be difficult to overstate the success of the SM at describing microscopic physics as observed in countless laboratory experiments — though within the SM many puzzles remain.




Why are there 3 generations (copies) of each particle type?

What is the origin of the fermion mass hierarchy?

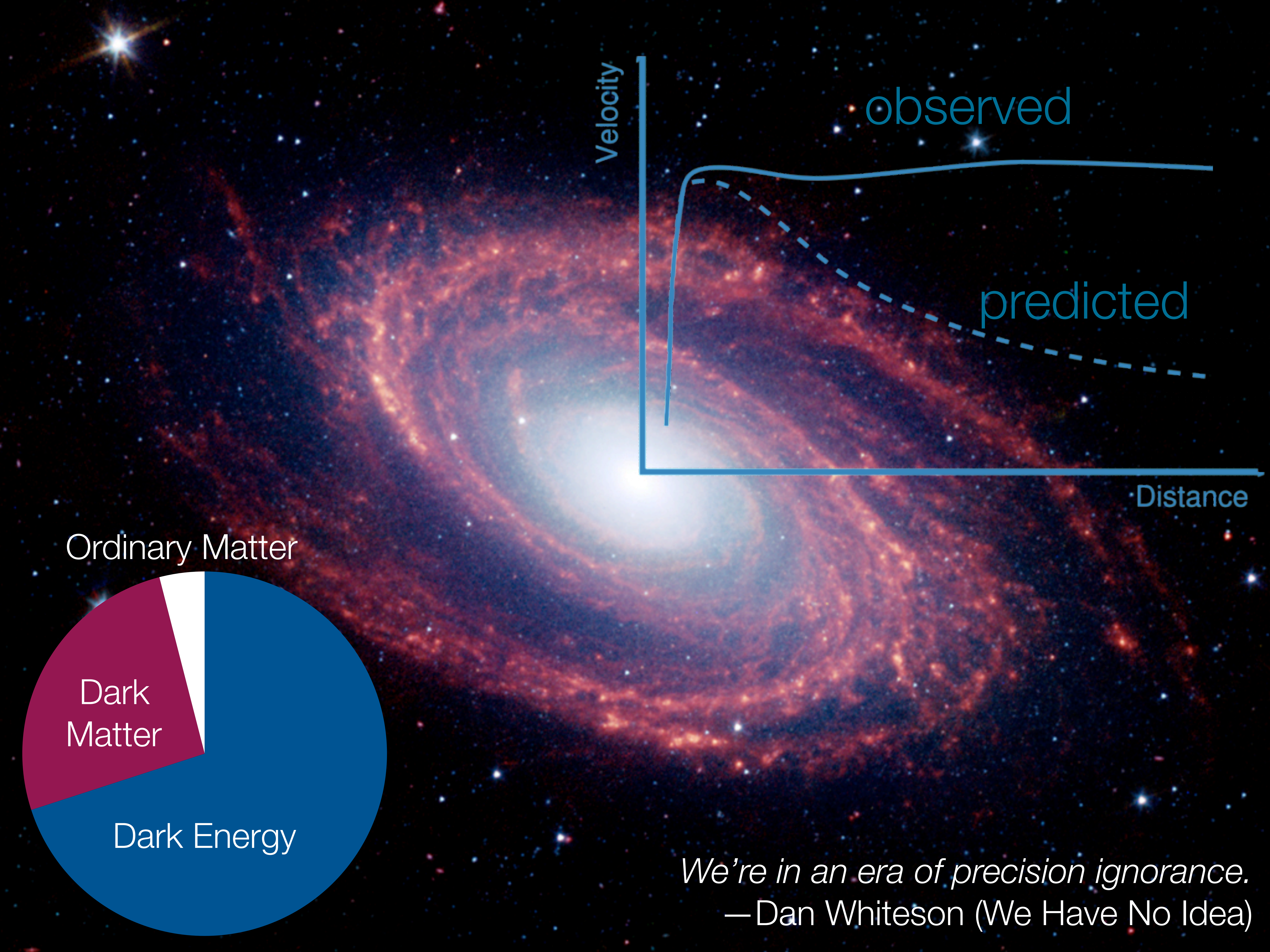
Why is the quark-mixing matrix almost diagonal?

Why is our universe so thoroughly matter dominated?

What is the source of electroweak symmetry breaking?

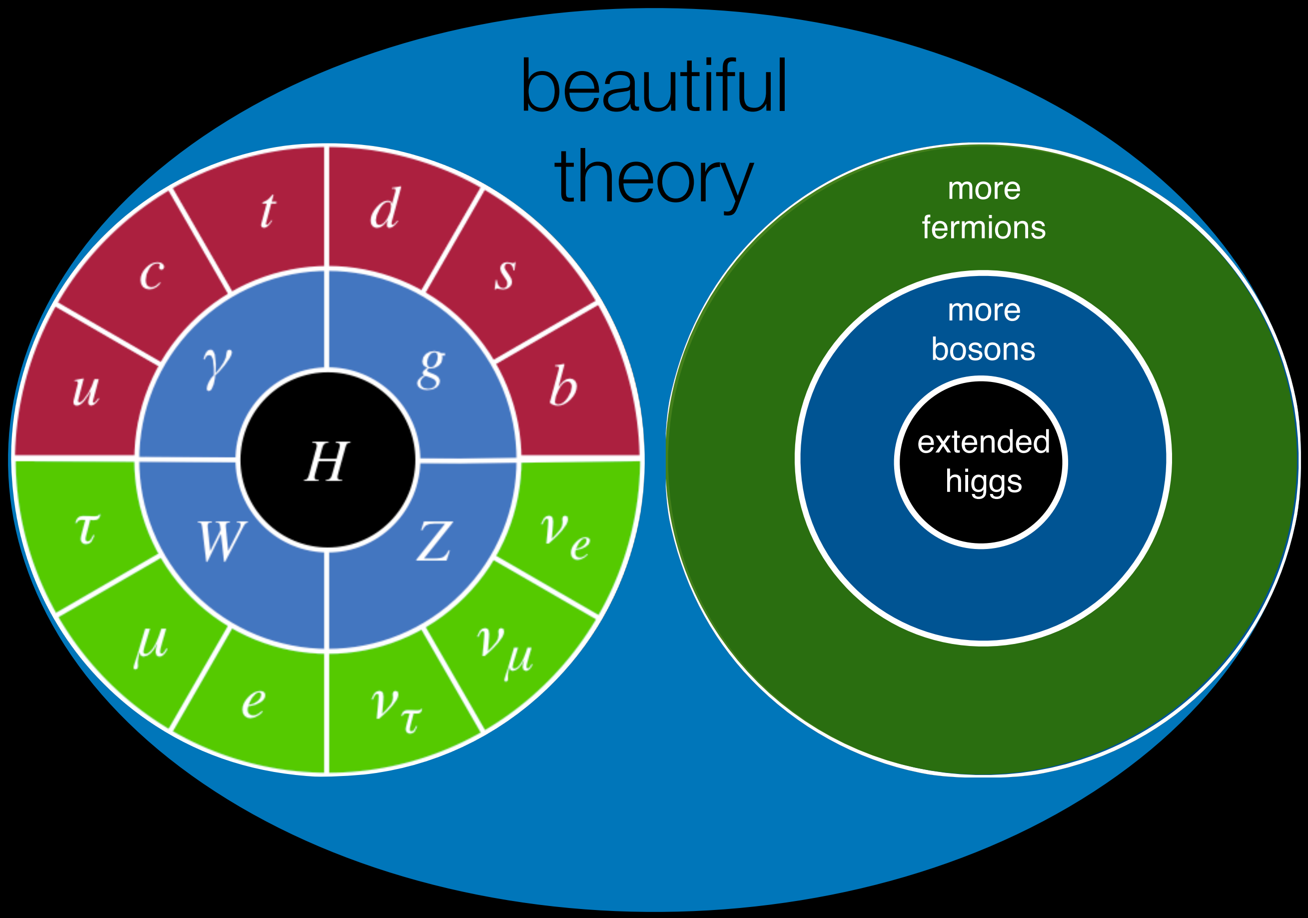
[…etc…]

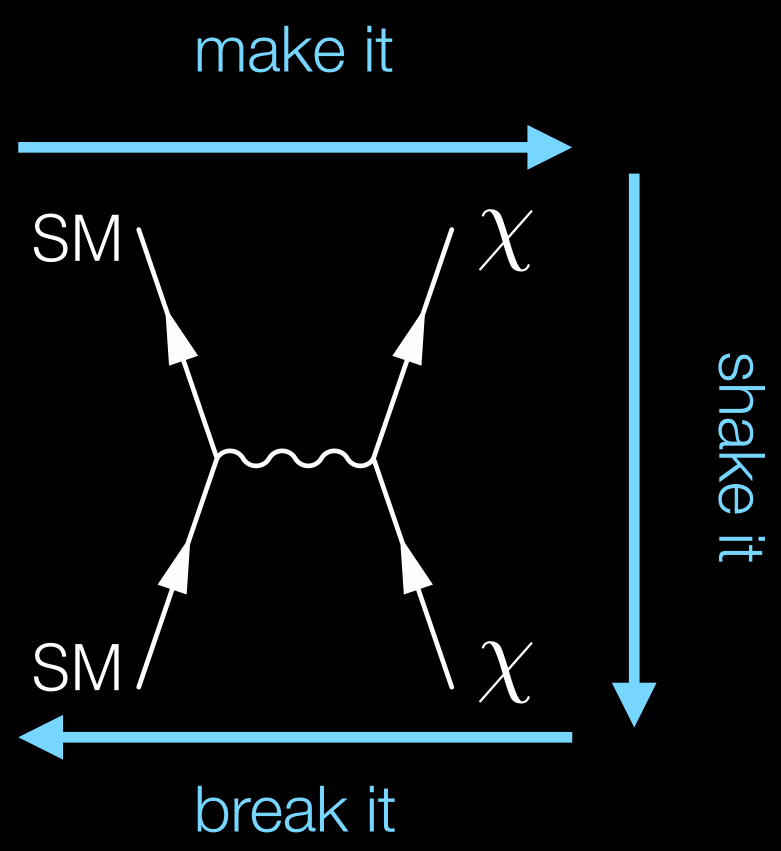
Puzzles aside, the SM provides an empirically valid description of ordinary matter up to the O(TeV) energy scale / down to the O($10^{-19}$ m) length scale — but it should break at the Planck scale ($10^{19}$ GeV) where quantum gravity becomes important.


Velocity
observed
predicted
Distance
Ordinary Matter
Dark Matter
Dark Energy
*We're in an era of precision ignorance.*
—Dan Whiteson (We Have No Idea)

# Weakly Interacting Massive Particles (WIMPs)

WIMP Miracle: If DM particles have EW-scale masses and interactions, and were in thermal equilibrium with SM particles in the early universe, the predicted relic DM density agrees with the observed value in the universe today.

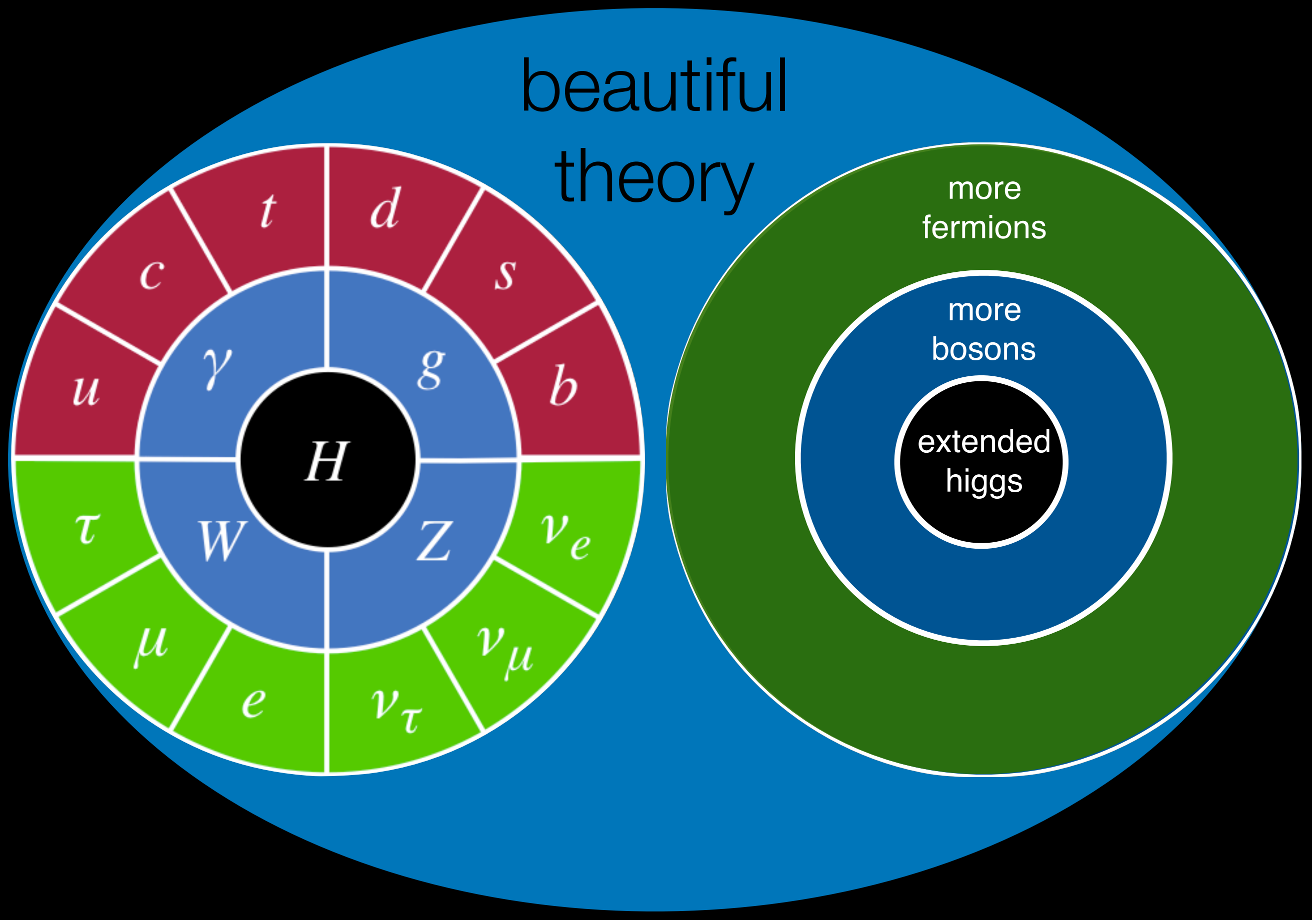



Strong constraints on WIMPs up to O(TeV) from production searches at the LHC, and from both direct and indirect dark matter searches. What if dark matter just happens to be 10—100 times heavier than our naive expectations?

# Weakly Interacting Massive Particles (WIMPs)

WIMP Miracle: If DM particles have EW-scale masses and interactions, and were in thermal equilibrium with SM particles in the early universe, the predicted relic DM density agrees with the observed value in the universe today.

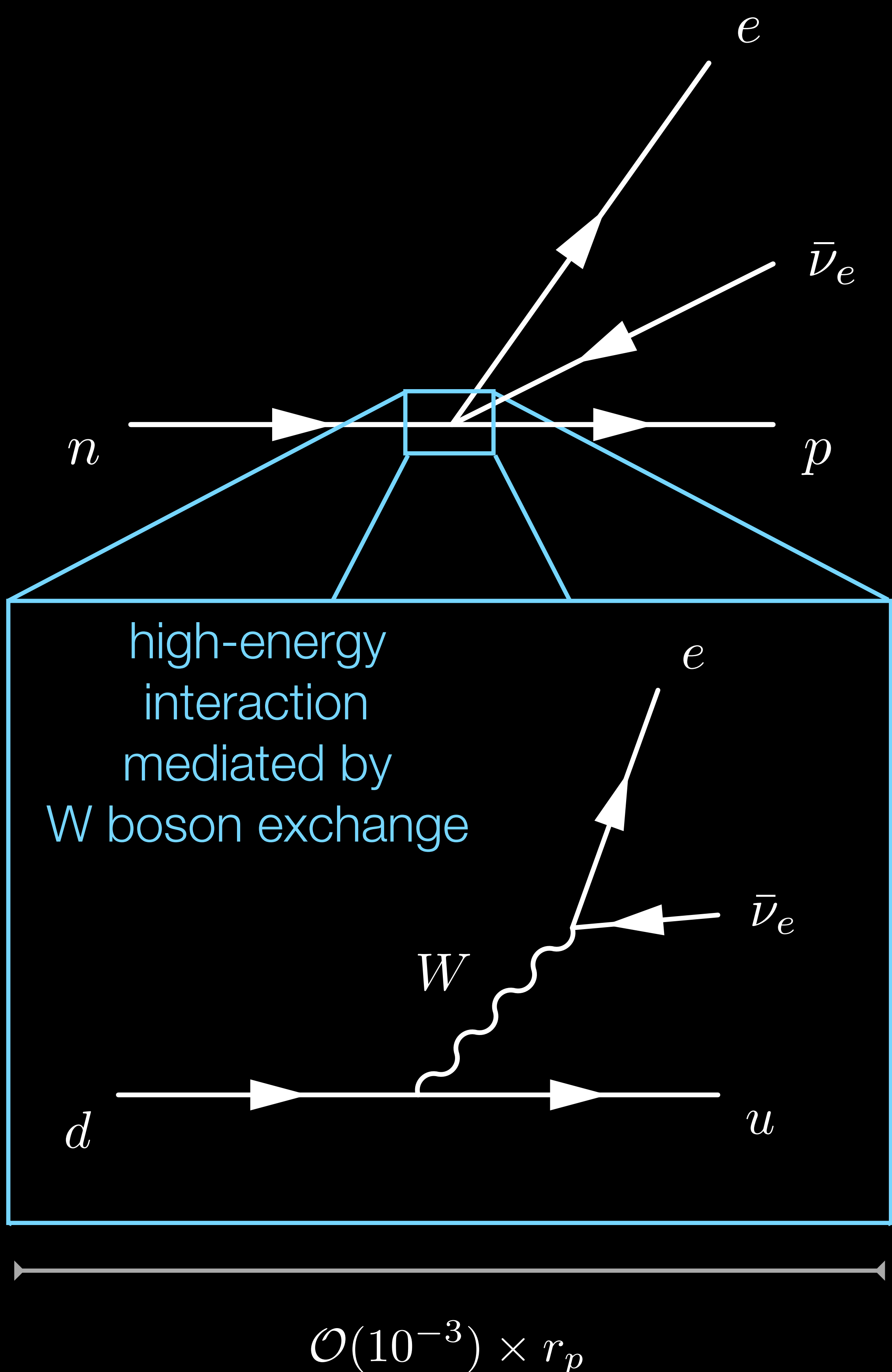



$$\frac{E(\mathrm{LHC})}{E(\mathrm{Planck})} \approx \frac{R(\text{solar system})}{R(\text{universe})} \approx 10^{-15}$$

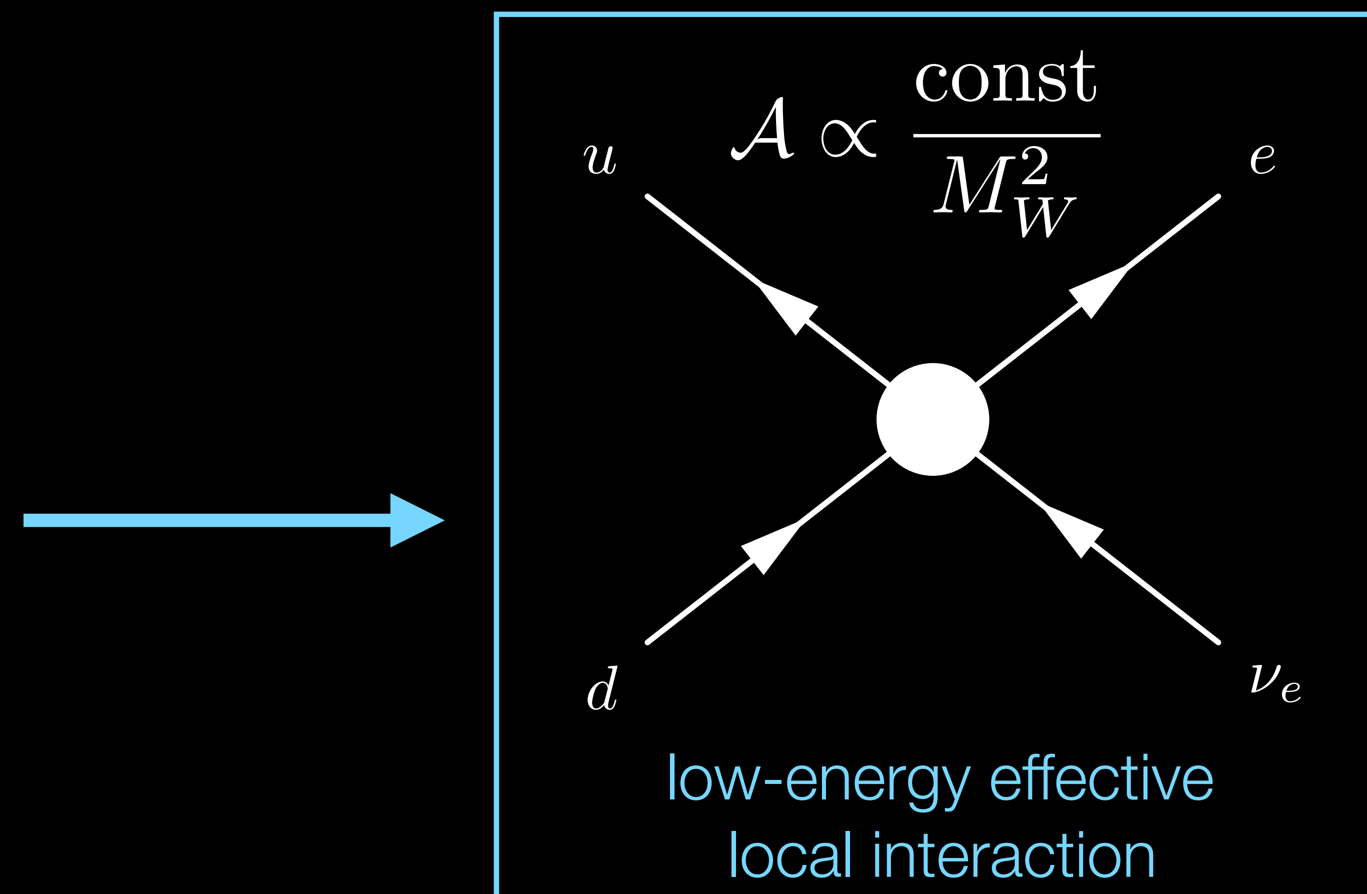
Of course, dark matter is not the only motivation for exploring new energy / length scales!

*I believe it is in our nature to explore, to reach out into the unknown. The only true failure would be to not explore at all.* —Ernest Shackleton

# Indirect Observation




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




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

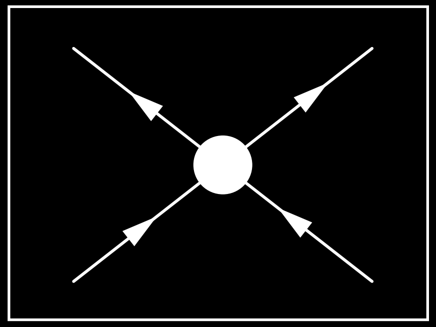
# Probing New Physics

Model-independent searches for physics beyond the SM can be performed via precise determination of the low-energy effective Hamiltonian of nature.

Complete description of nature at low energies in terms of local interactions.

Operator Product Expansion

$$\mathcal{H}_{\rm eff} = \sum_i \mathcal{C}_i \times \left[ \;\; \right]_i$$



$$\mathcal{C}_i \stackrel{?}{=} \mathcal{C}_i^{\rm SM}$$

A simple question: Is the effective low-energy Hamiltonian the one predicted by the SM?

In principal, sensitive to any mass scale—limited in practice by experimental precision and by our understanding of the SM.

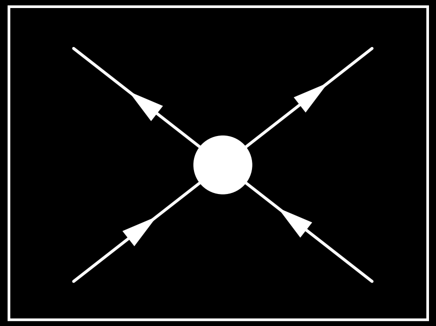
# Probing New Physics

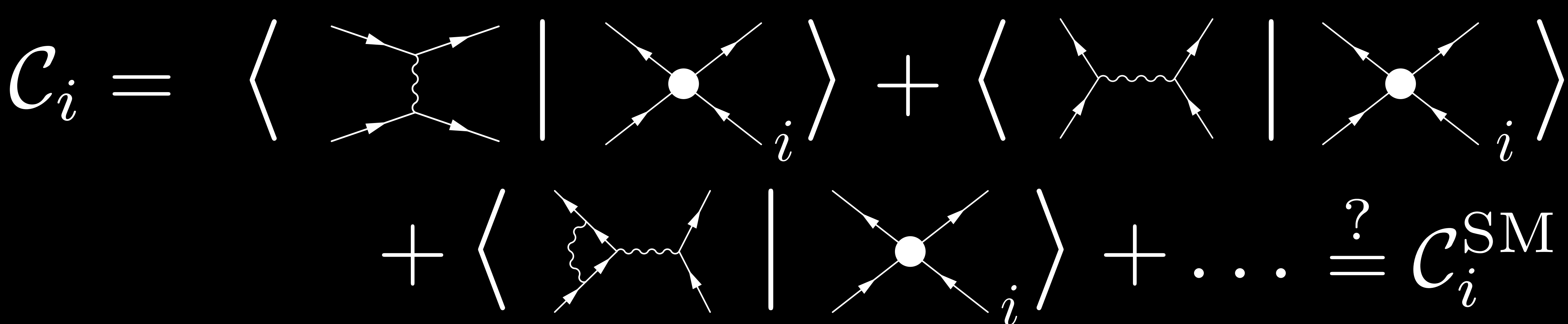
Model-independent searches for physics beyond the SM can be performed via precise determination of the low-energy effective Hamiltonian of nature.

Complete description of nature at low energies in terms of local interactions.

Operator Product Expansion

$$\mathcal{H}_{\mathrm{eff}} = \sum_i \mathcal{C}_i \times \left[\;\right]_i$$





High-energy paths project onto the local basis in a perturbative expansion.

We don't need to know this physics to measure *C*ᵢ.

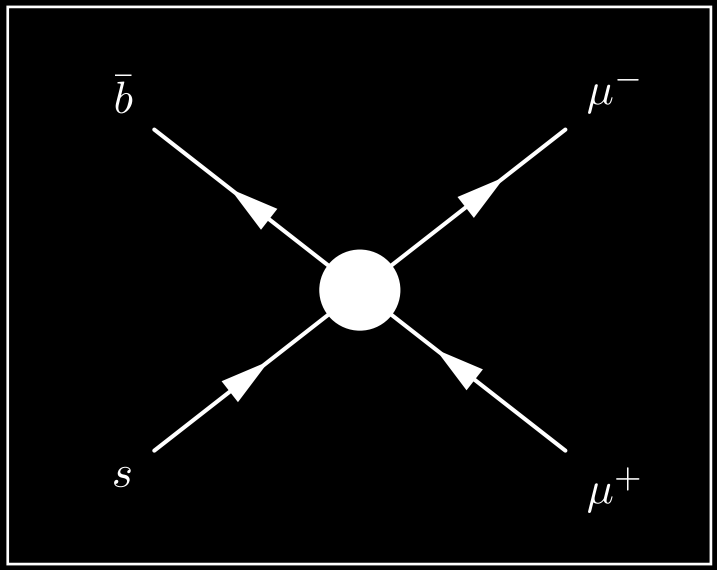
# $B_s(bs) \to \mu^+\mu^-$

The SM predicts the $B_s$ meson (spin-0 b-s state) decays into two muons 3 per billion decays, which results in less than one per trillion pp collisions producing this decay at LHCb.

measure this decay rate

determine if this is nonzero

$$\Gamma(B_s \to \mu^+\mu^-) \propto \left| \left(\mathcal{C}^{\rm SM}_{bs\mu\mu} + \mathcal{C}^{\rm BSM}_{bs\mu\mu}\right)_0 \right.$$




$$\left. \right|^2_0$$

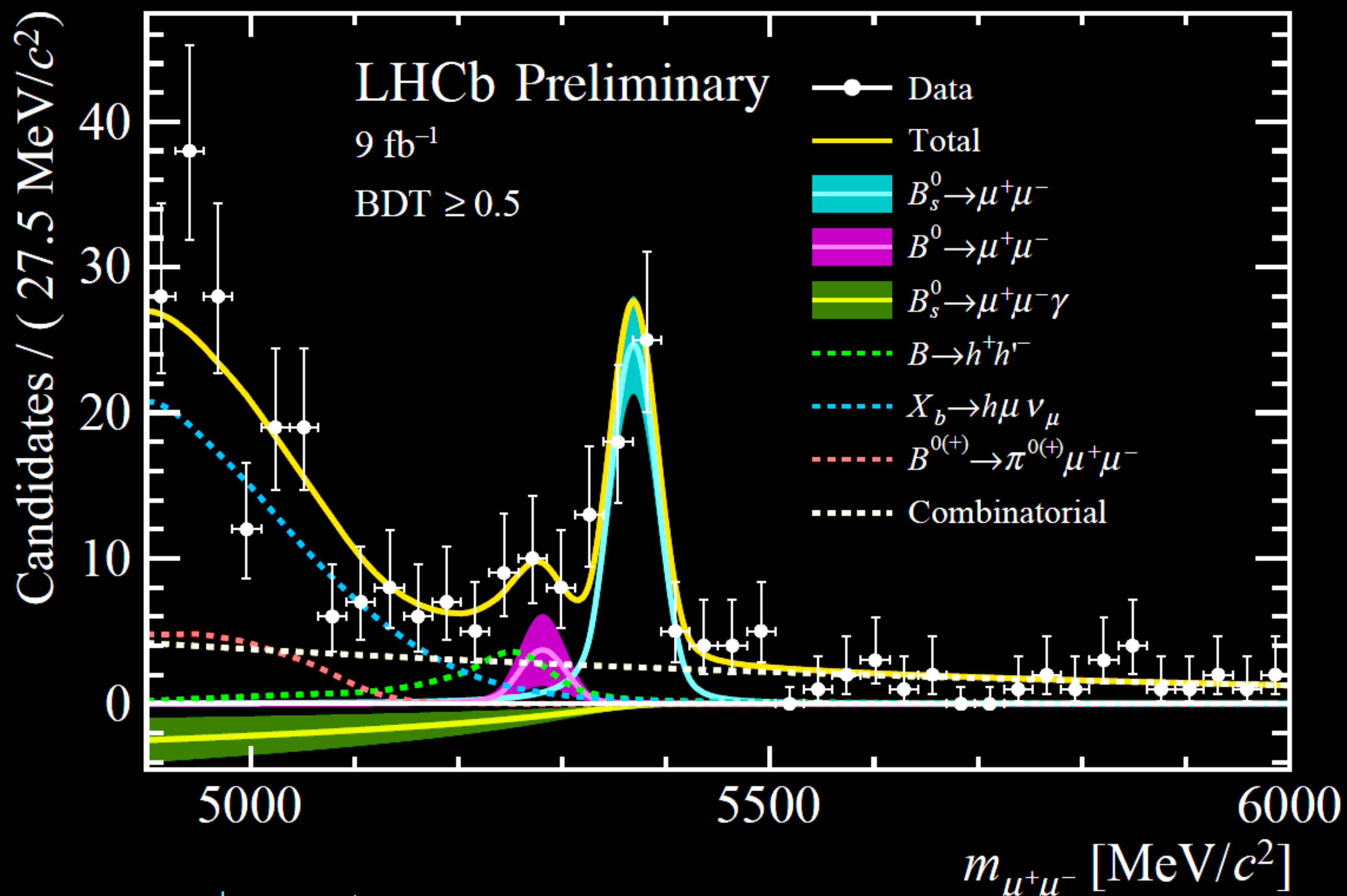
calculate these

The fact that the SM amplitude is so small—and that we know the SM prediction precisely—means that new physics could have an observable impact on this decay rate. Many supersymmetric theories (pre-LHC) predicted a factor of 10 enhancement in this rate.

# $B_s(bs) \rightarrow \mu^+\mu^-$

LHCb made the first single-experiment observation in 2017 and recently improved the precision using the full Runs 1 and 2 data samples.

LHCb-PAPER-2021-00(7,8)

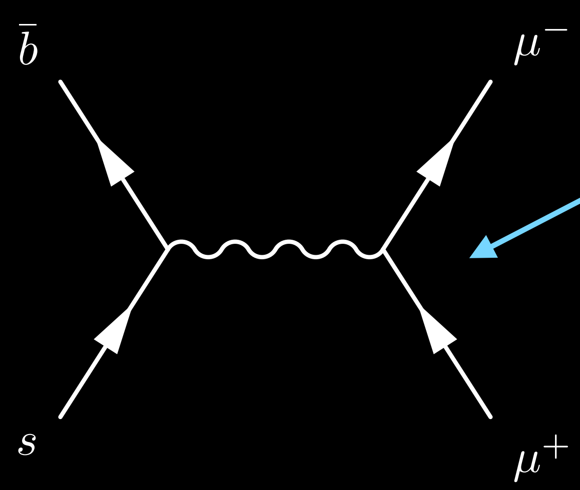



$$\frac{\Gamma(B_s \rightarrow \mu^+\mu^-)_{\mathrm{LHCb}}}{\Gamma(B_s \rightarrow \mu^+\mu^-)_{\mathrm{SM}}} = 0.84 \pm 0.12 \pm 0.04 \pm 0.04$$

# Strong Constraints on O(1 — 100) TeV Physics

The $B_s \to \mu^+\mu^-$ rate places strong constraints on local (pseudo)scalar (spin-0) interactions. The mass scale probed depends on what type of path(s) a BSM theory provides for this reaction.

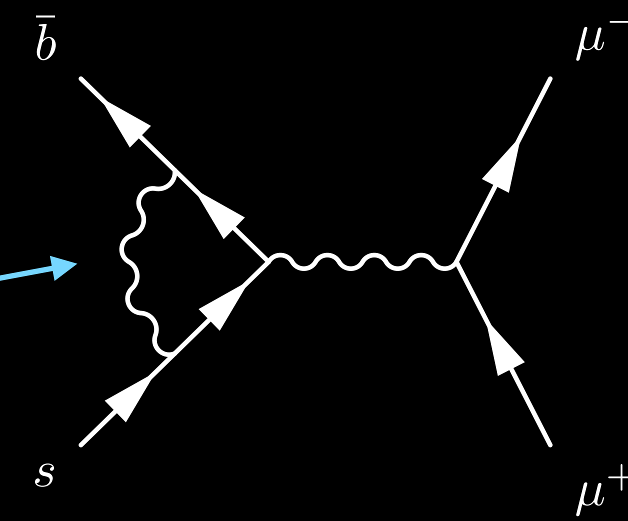
$M_X \gtrsim \mathcal{O}(50\,\mathrm{TeV})$




simple path
strongest constraints

complicated path
weaker constraints

$M_X \gtrsim \mathcal{O}(1\,\mathrm{TeV})$




Impact proxy: LHCb $B_s \to \mu^+\mu^-$ papers ~2000 unique citations.

LHCb has made the most precise measurements of hundreds of observables involving b and c quarks that are consistent with the SM predictions.

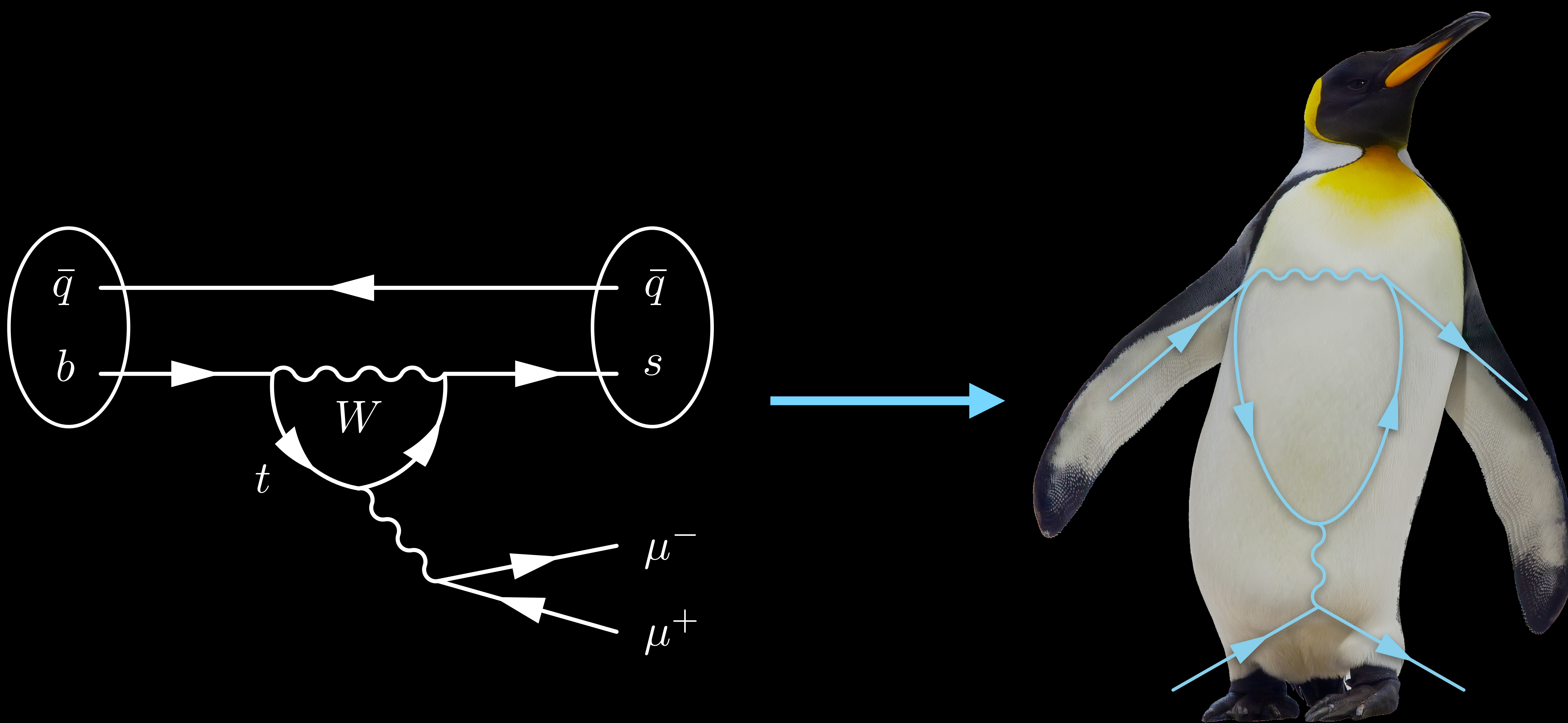
We have also made the most precise measurements of CP violation (i.e matter/anti-matter asymmetries)—and even though we do observe many reactions with sizable CP violation, these asymmetries (or lack thereof) are all consistent with the SM expectations.

Main message: Strong constraints on TeV-scale physics beyond the SM!

See T.Blake, T. Gershon, G. Hiller [1501.03309] for an accessible review.

# Penguin Decays

b→s “penguin” decays are highly sensitive to many possible extensions to the SM (in many cases, these decays are by far the best way to make new types of particles).



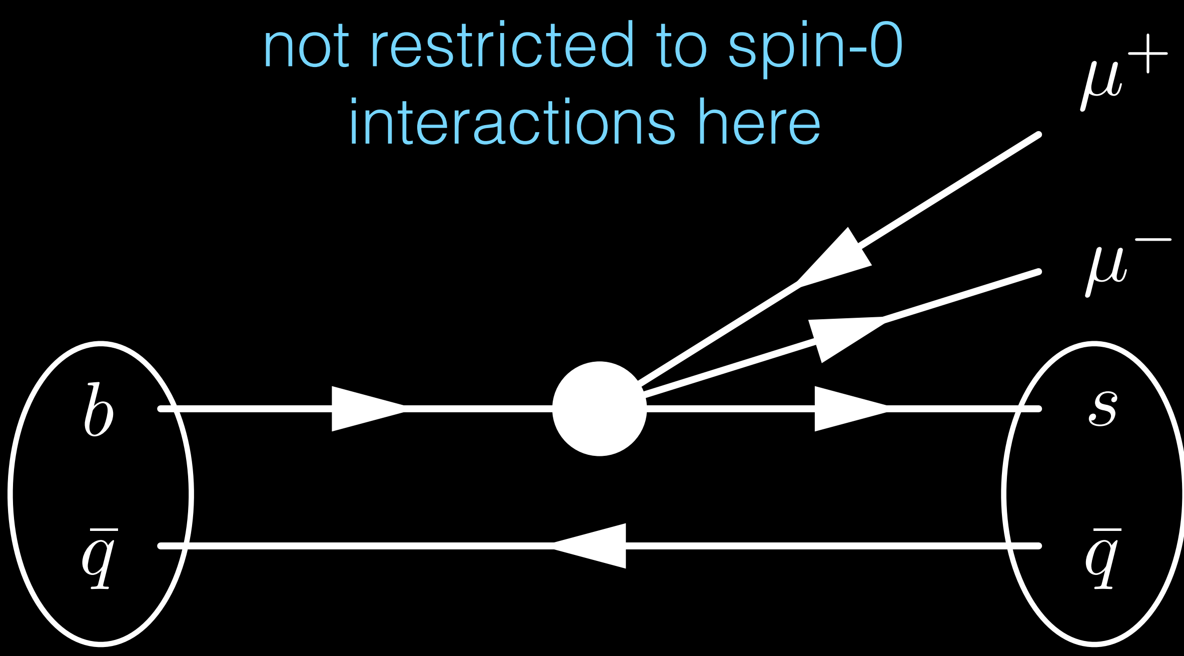

If you’re in the right state of mind, the Feynman diagram may (sort of) look like a penguin.

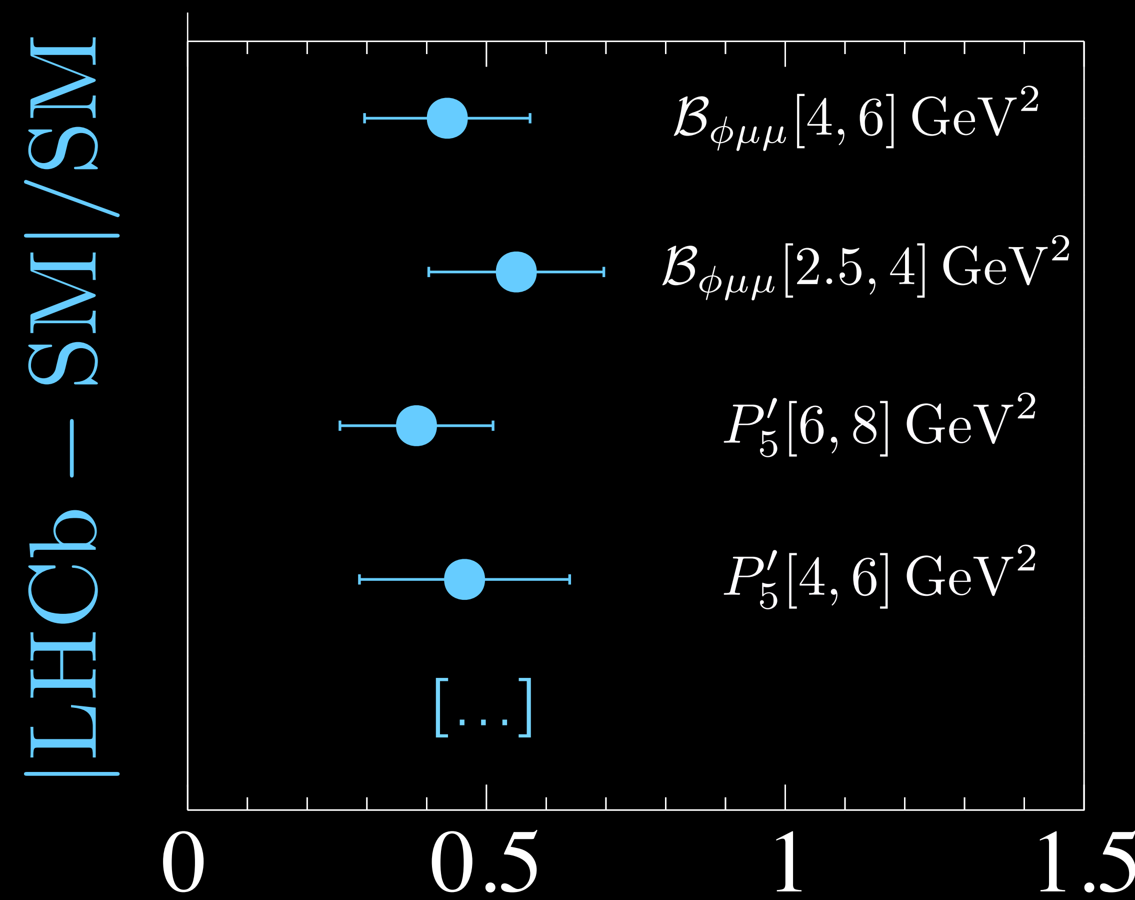
(see https://en.wikipedia.org/wiki/Penguin_diagram)

# $b \to s\mu^+\mu^-$

We can play the same game with b→s *penguin* decays as we did with $B_s \to \mu^+\mu^-$. The b→sμμ family of decays provide many sensitive observables (decay rates, angular distributions, etc) to test the Lorentz structure of the SM.

LHCb, PRL 125 (2020); LHCb-PAPER-2021-014; etc…



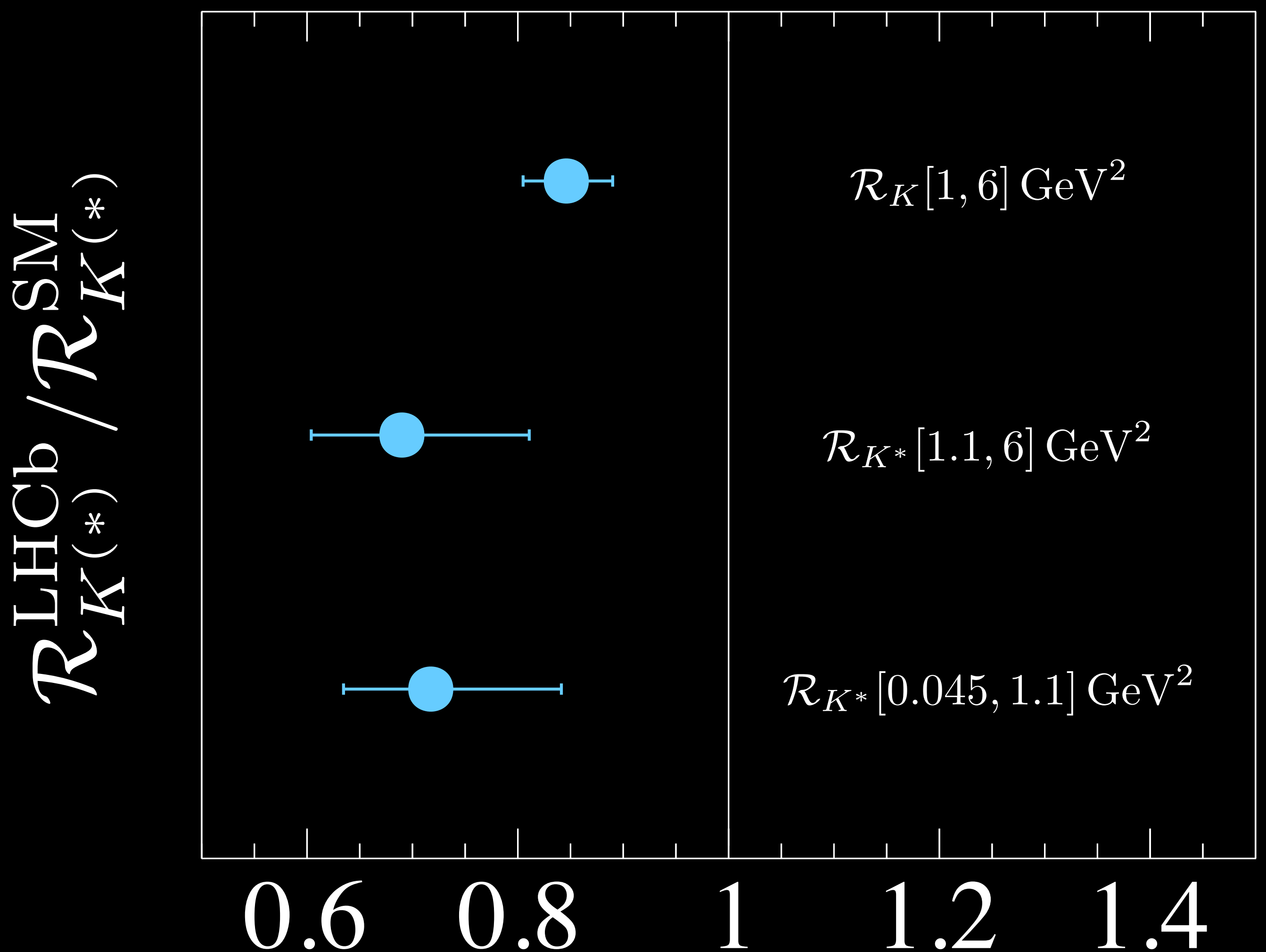




Global analyses quote 4-5σ deviations with the SM; however, these calculations require understanding the QCD effects that bind the quarks—and QCD is hard!

# Lepton Universality

Since leptons are neutral under QCD, ratios of decay rates where only the lepton flavors differ largely avoid QCD theory uncertainties. Of course, the experimental systematic effects are also reduced — always measure ratios.

$$\mathcal{R}_{K^{(*)}} \equiv \frac{\Gamma(B \to K^{(*)}\mu\mu)}{\Gamma(B \to K^{(*)}ee)} \overset{\text{SM}}{\approx} 1$$

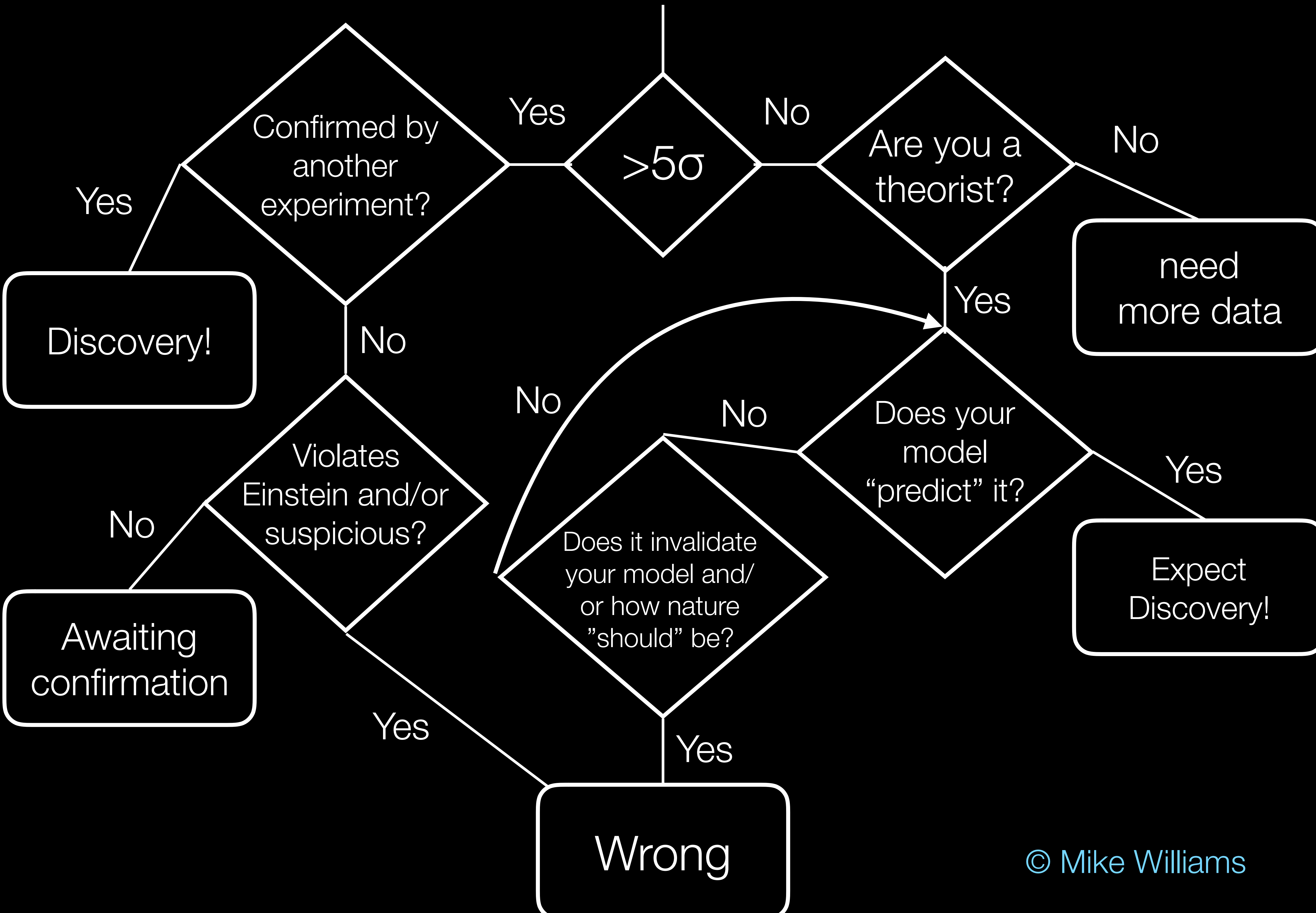



LHCb-PAPER-2021-004
(Run 1 and Run 2 data)

LHCb-PAPER-2017-013
JHEP 08 (2017) 055
(Run 1 data)

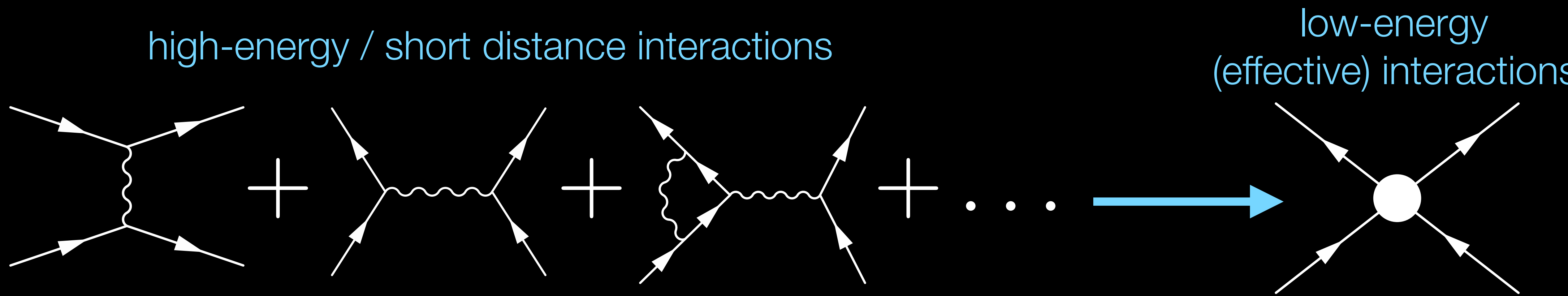
*Who ordered that?* —I.I. Rabi

# Interpreting Results — a Flow Chart



# Summary of Low-Energy/High-Mass Searches

Precise determination of the low-energy effective Hamiltonian of nature provides sensitivity to new physics at higher mass scales (shorter distances) than can be accessed directly.




LHCb has made many of the most precise measurements ever of reaction rates and CP asymmetries involving b and c quarks — and explored a lot of what was *terra incognita*. For the most part, the O(1—100 TeV) scale looks very SM-like.

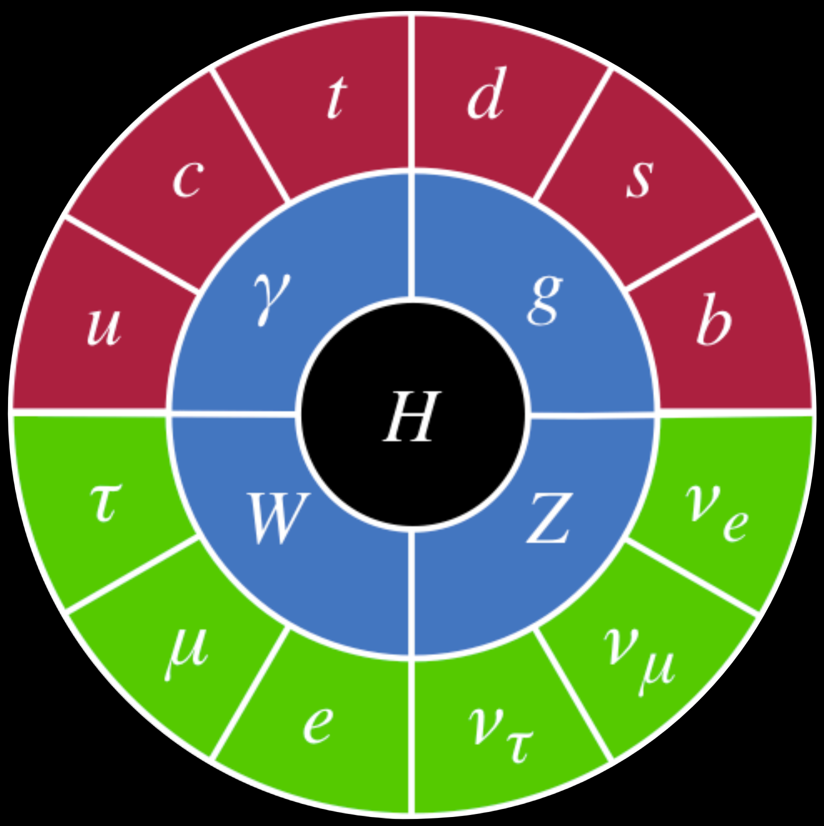
## Main message: Strong constraints on TeV-scale physics beyond the SM!

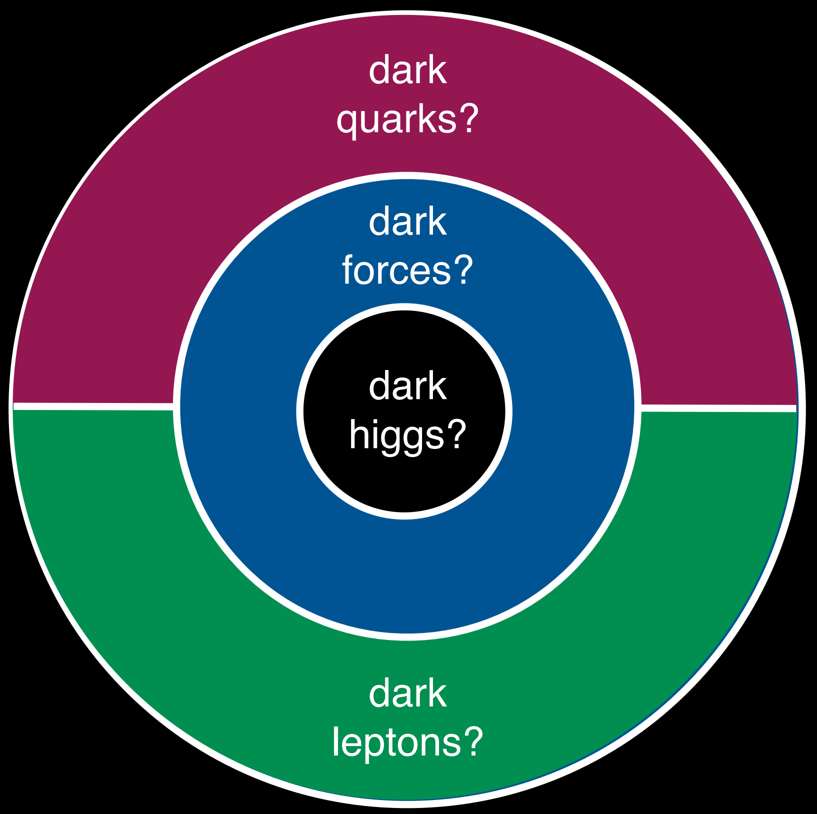
An intriguing exception is $b \to s\mu\mu$ penguin decays, which suggest nature may posses new (possibly lepton-flavor non-universal) interactions — though we need more data to be sure.

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

# Hidden (Dark) Sectors

What if there is no connection between the SM and dark sector up to the Planck scale?
(Hidden sectors can result from a Grand Unified Theory (GUT) of nature, and are generic in string theory constructions.)



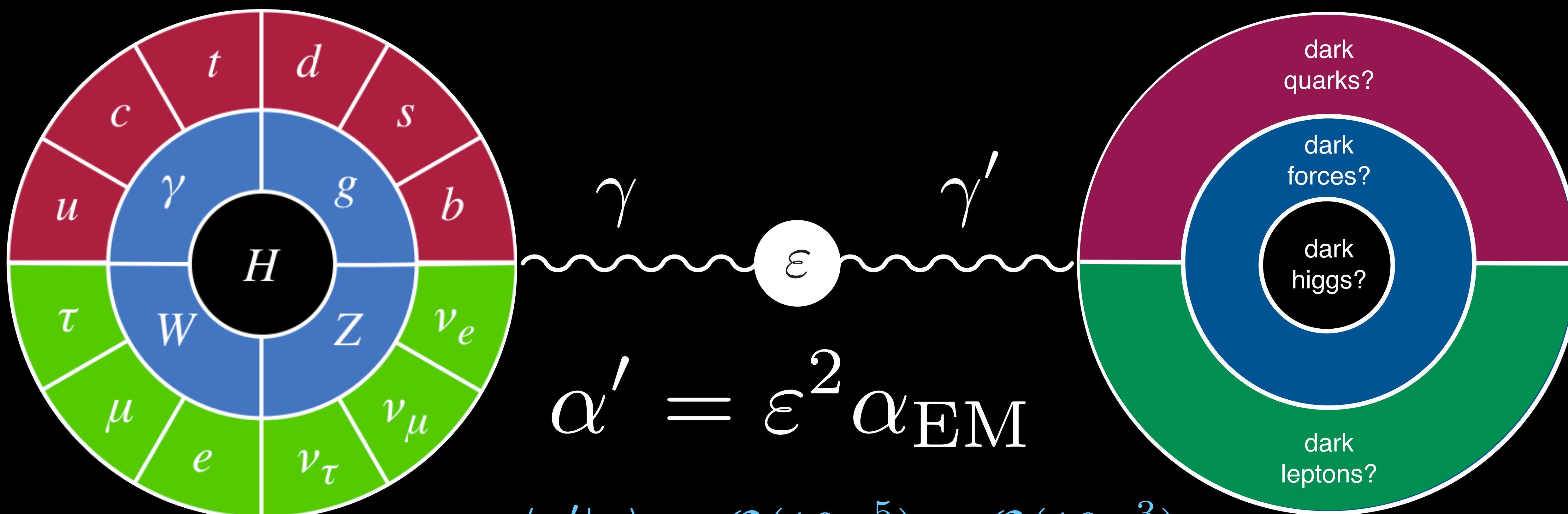




lightest DM particle could be stable because it's (dark) charged

*When things are at their blackest, I say to myself "Cheer up, things could get worse." And sure enough, they get worse.* —Robert Asprin

# Hidden (Dark) Sectors

What if there is no connection between the SM and dark sector up to the Planck scale?
(Hidden sectors can result from a Grand Unified Theory (GUT) of nature, and are generic in string theory constructions.)




$$\alpha' = \varepsilon^2 \alpha_{\mathrm{EM}}$$

$$\varepsilon \equiv \langle \gamma' | \gamma \rangle \approx \mathcal{O}(10^{-5}) - \mathcal{O}(10^{-3})$$

lightest DM particle could be stable because it's (dark) charged

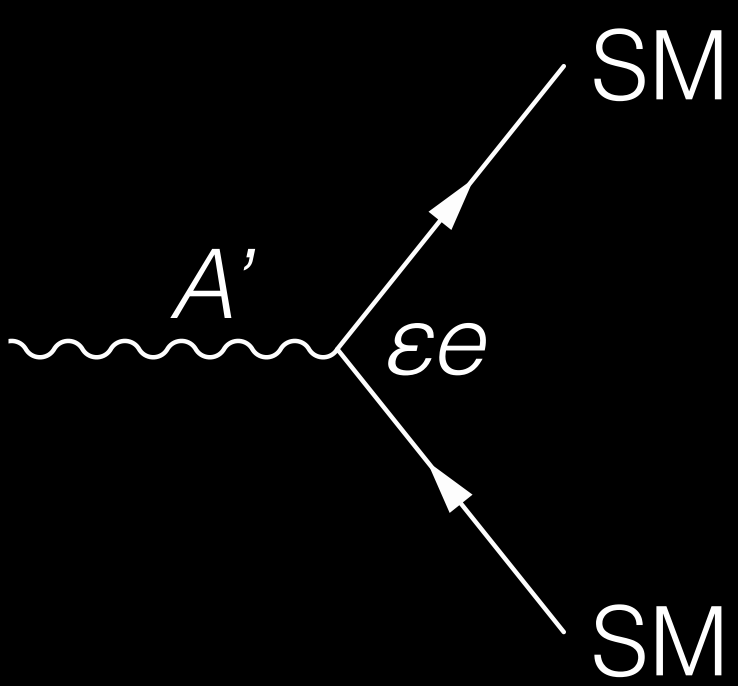
As long as the sectors are connected at some scale (e.g. if they are both part of a GUT), then quantum mechanical mixing between the photon and dark photon is unavoidable. We can make it in the lab, and it can decay into SM particles that we can detect.

# A’ Paradigms

There are two possible paradigms that greatly affect the A’ phenomenology. LHCb can only search for visible A’ decays, so I will focus on the paradigm on the left.

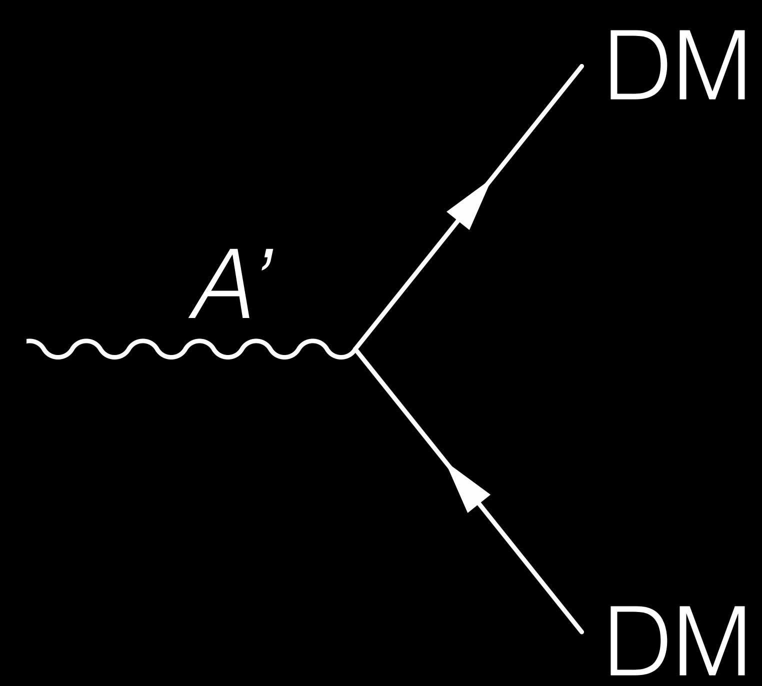
$$m_{A'} < 2m_{\mathrm{DM}}$$

Decays visibly into SM final states.
(Coupling strength affects lifetime.)




$$m_{A'} > 2m_{\mathrm{DM}}$$

Decays invisibly into DM final states.

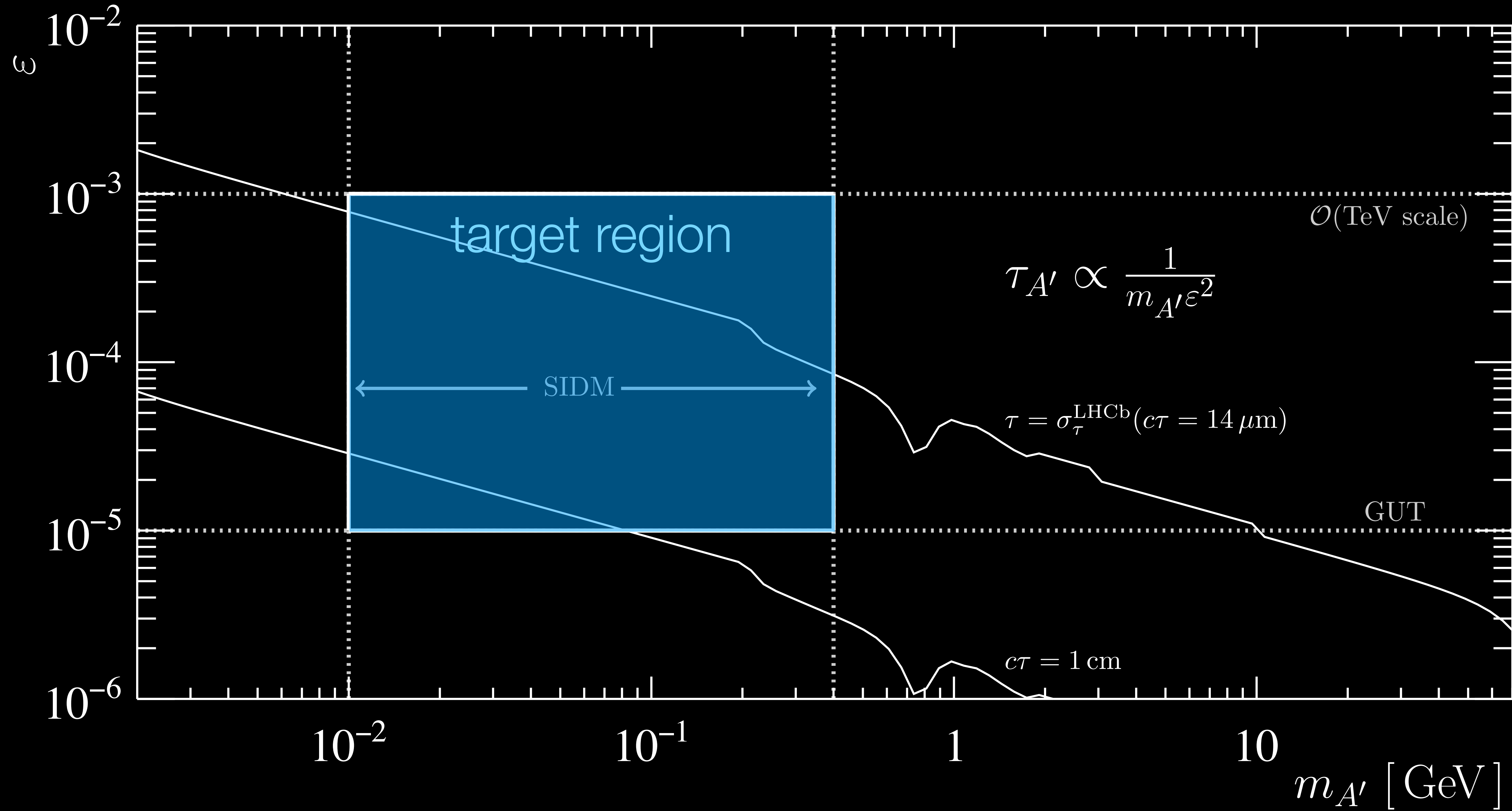



DM self-interactions mediated by an A’ with a mass in the 10—400 MeV range can explain several anomalies in small-scale structure, e.g. the core-cusp problem — let’s focus there.

This issue is very much unresolved, see Tulin & Yu [ 1705.02358] for a recent review.

# (Visible) Dark Photon Searches

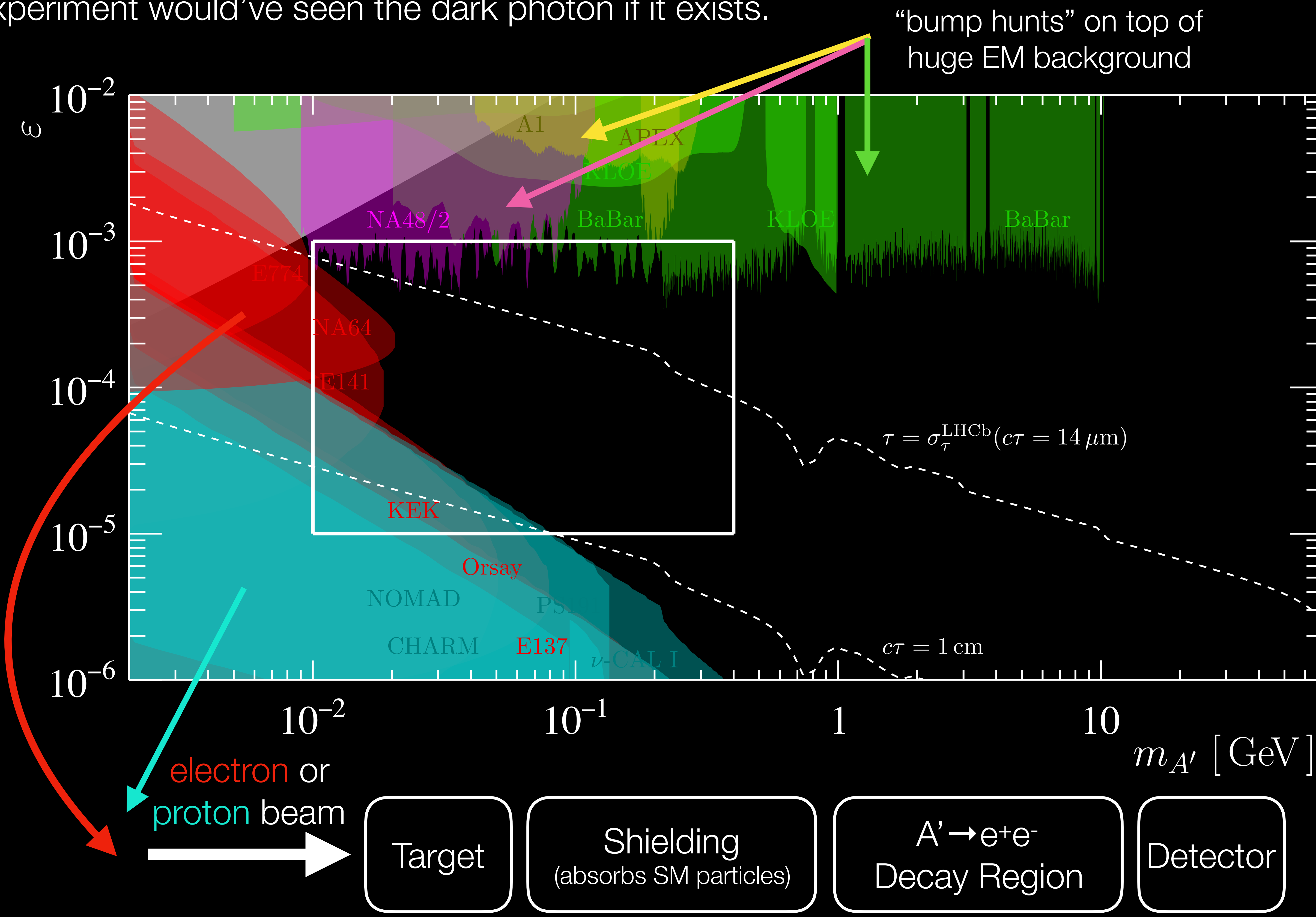
Well defined target region of mass-coupling space to search assuming a SIDM-sized cross section and a particle-physics-type connection between sectors up to the Planck scale.




Additional constraints: BBN requires ε > $10^{-10}$ and, if SM-DM were in thermal equilibrium in the early universe, we need ε > $10^{-8}$ ; tests of Coulomb's Law $m_{A'}$ > $10^{-4}$ GeV, etc.

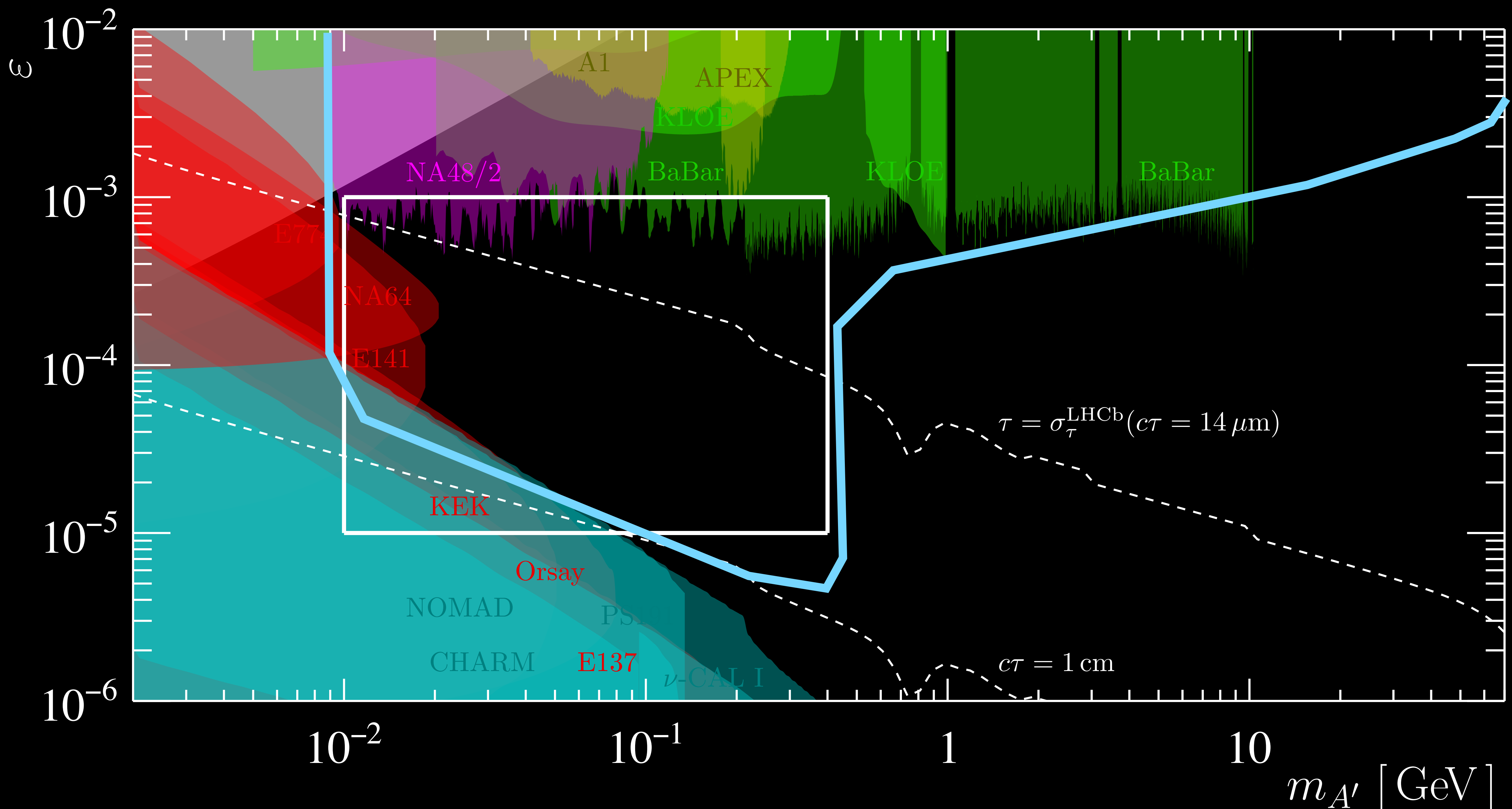
# Dark Photon Constraints

Existing constraints (circa 2016) left the target region largely unexplored, i.e. no laboratory experiment would've seen the dark photon if it exists.



# Dark Photons @ LHCb

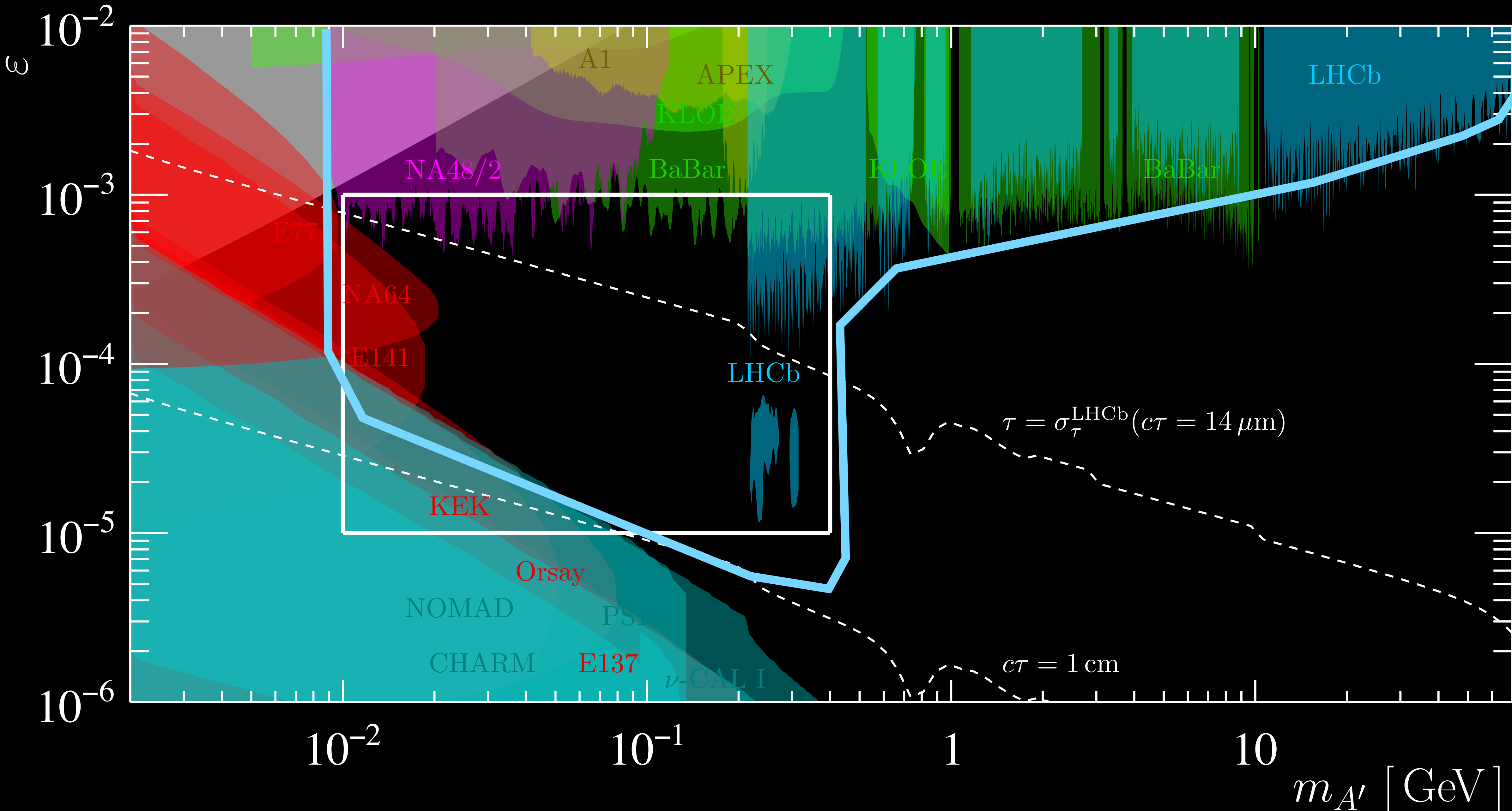
We proposed leveraging LHCb's excellent lifetime and mass resolution—and the planned move to triggerless readout in Run 3 — to probe all of the unexplored dark photon space.[1,2]




[1] Ilten, Soreq, Thaler, MW, Xue, PRL 116 (2016) 251803—proposed inclusive search for $A' \to \mu^+\mu^-$.
[2] Ilten, Thaler, MW, Xue, PRD 92 (2015) 115017—proposed search using radiative charm decays and $A' \to e^+e^-$.

# Dark Photons @ LHCb

Using a Run 2 data sample ~30 times smaller than expected in Run 3, we showed[1,2] that our predictions are accurate—and achieved the first ever sensitivity using a displaced vertex. LHCb will be able to fully explore the A' space in the next 5 years.



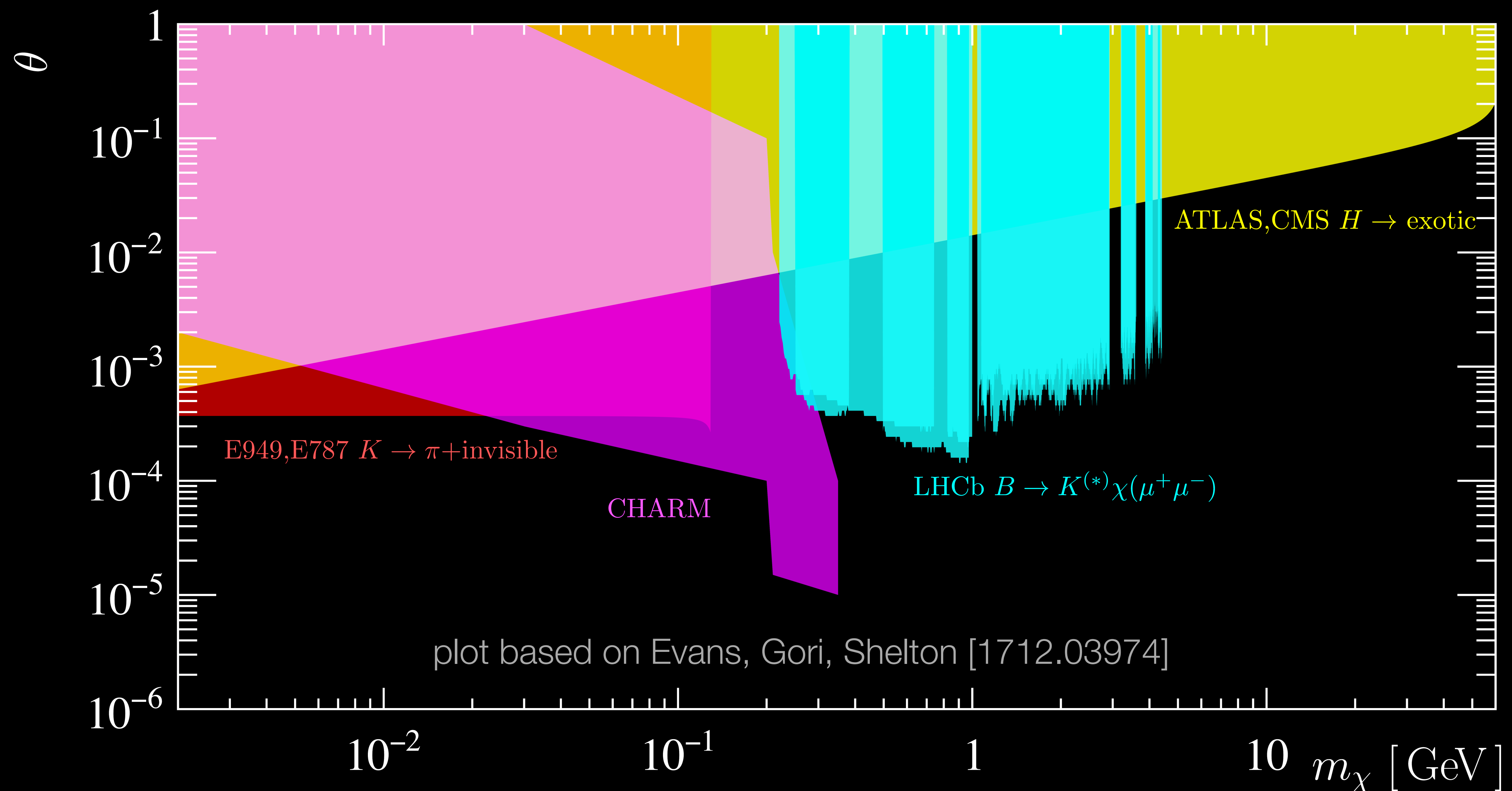

[1] LHCb, PRL 120 (2018) 061801
Technical support papers: LHCb, JINST 13 (2018) P06008; MW, JINST 12 (2017) P09034.
[2] LHCb, PRL 124 (2020) 041801.
See also model-independent searches in LHCb, JHEP 10 (2020) 156.

# Higgs Portal

Strongest constraints are from beam dumps, kaon decays, b→s penguin decays @ LHCb, the upper limit on exotic Higgs decays from ATLAS/CMS, and heavy Higgs searches at ATLAS/CMS (these are O(0.1), not shown on the plot).

LHCb-PAPER-2015-036, PRL 115 (2015) 161802 [1508.04094]
LHCb-PAPER-2016-052, PRD (2017) 071101 [1612.07818]

both LHCb searches only use Run 1 data

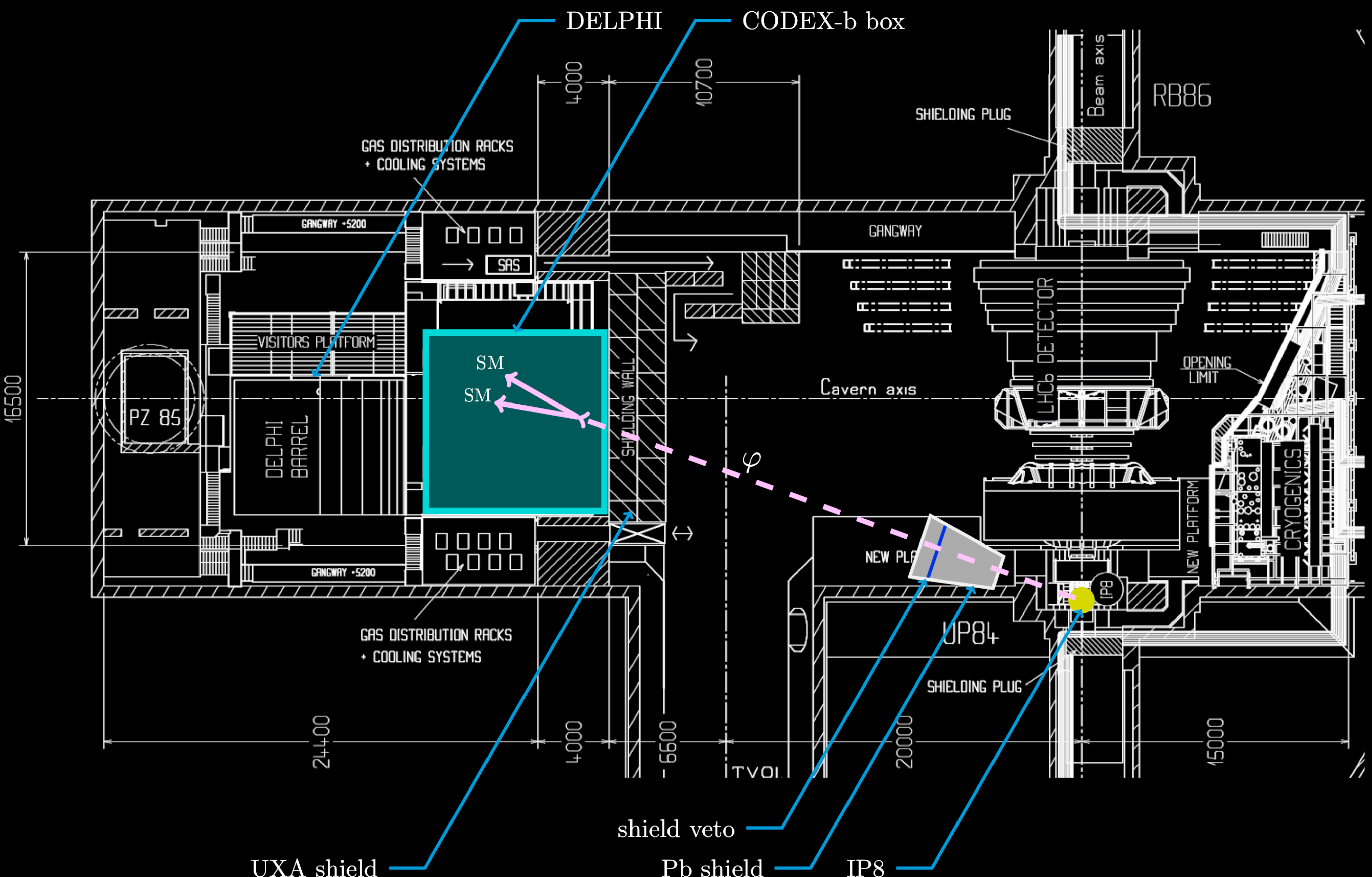



See Batell, Pospelov, Ritz [0911.4938], Izaguirre, Lin, Shuve [1611.09355], Aloni, Soreq, MW [1811.03474] for ALP production in penguin decays. LHCb is working on these searches now.

# CODEX-b

Large space (will be) available to add a well-shielded detector for LLPs, potentially integrated into the LHCb DAQ. Proximity to pp collisions would allow probing large regions of LLP parameter space at a rather modest cost.

Gligorov, Knapen, Papucci, Robinson [1708.09395]




Background measurements look as expected. Looking at installing a *demonstrator* for Run 3, then the full detector for Run 4 — assuming we can get funding.

# Long Term Plans

LHCb is dead. Long live LHCb!

implemented real-time alignment & calibration

major detector upgrades
removal of FPGA trigger stage
will need to process 5 TB / s in real time

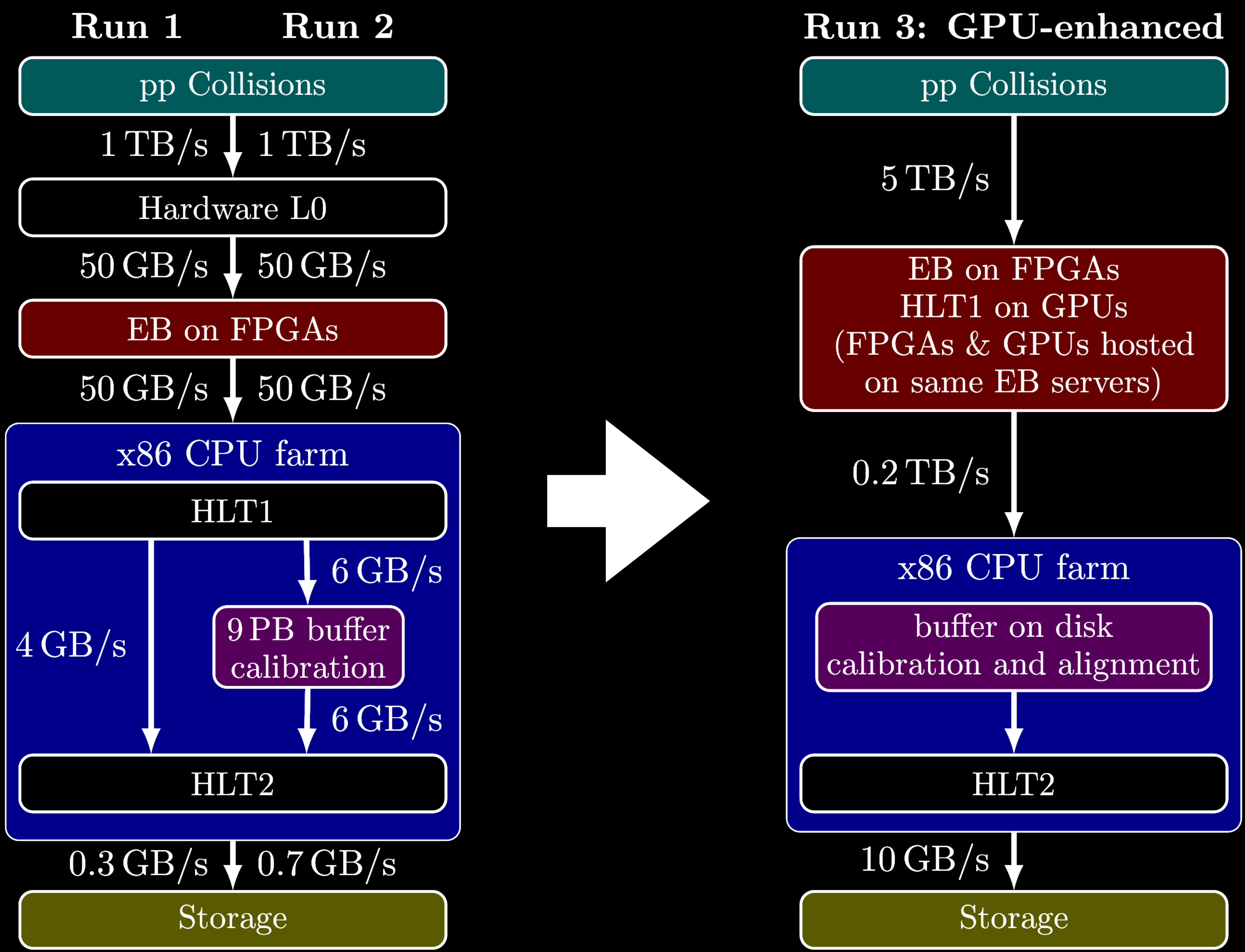
| | | |
|---|---|---|
| Run 1 | 2010-2012 | 3/fb @ 7-8 TeV |
| Run 2 | 2015-2018 | +6/fb @ 13 TeV |
| Run 3 | 2022-2024 | +15/fb @ 14 TeV |
| Run 4 | 2027-2030 | +25/fb @ 14 TeV |
| Run 5 | 2032-2034 | +100/fb @ 14 TeV |
| Run(s) ??? | 2036-20?? | Total: 300/fb |

additional detector upgrades (not as major as for Run 3)

a miracle occurs?

In the next 5 years, we will have a 20 x larger sample of b-quark decays, access to all target visible dark photon space, etc…

# Real-Time Analysis in Run 3




GPU-enhanced option greatly increases our discovery potential in Run 3!

# Summary

- Precise determination of the low-energy effective Hamiltonian of nature provides sensitivity to new physics at higher mass scales (shorter distances) than can be accessed directly.

- LHCb has made many of the most precise measurements ever of reaction rates and CP asymmetries involving b and c quarks — and explored a lot of what was *terra incognita*. For the most part, the O(1-100 TeV) scale looks very SM-like.

- An intriguing exception is $b \rightarrow s\mu\mu$ penguin decays, which suggest nature may posses new (possibly lepton-flavor non-universal) interactions — though we need more data to be sure.

- Dark matter may have velocity-dependent self interactions. If so, there is a well defined target region of mass-coupling space to search for a dark photon. We showed that LHCb can fully explore this space in the next ~5 years (much of it next year).

- LHCb is undergoing a major upgrade for the next LHC run. We will increase the proton-proton collision rate (x5), while also moving to processing every event at the software level (5 TB / s of data in real time). This will greatly increase our physics discovery potential.

# Thanks!
# Questions?

LHCb if painted by Van Gogh according to a Deep Neural Network.
https://github.com/jcjohnson/neural-style