Recent results and future prospects from LHCb

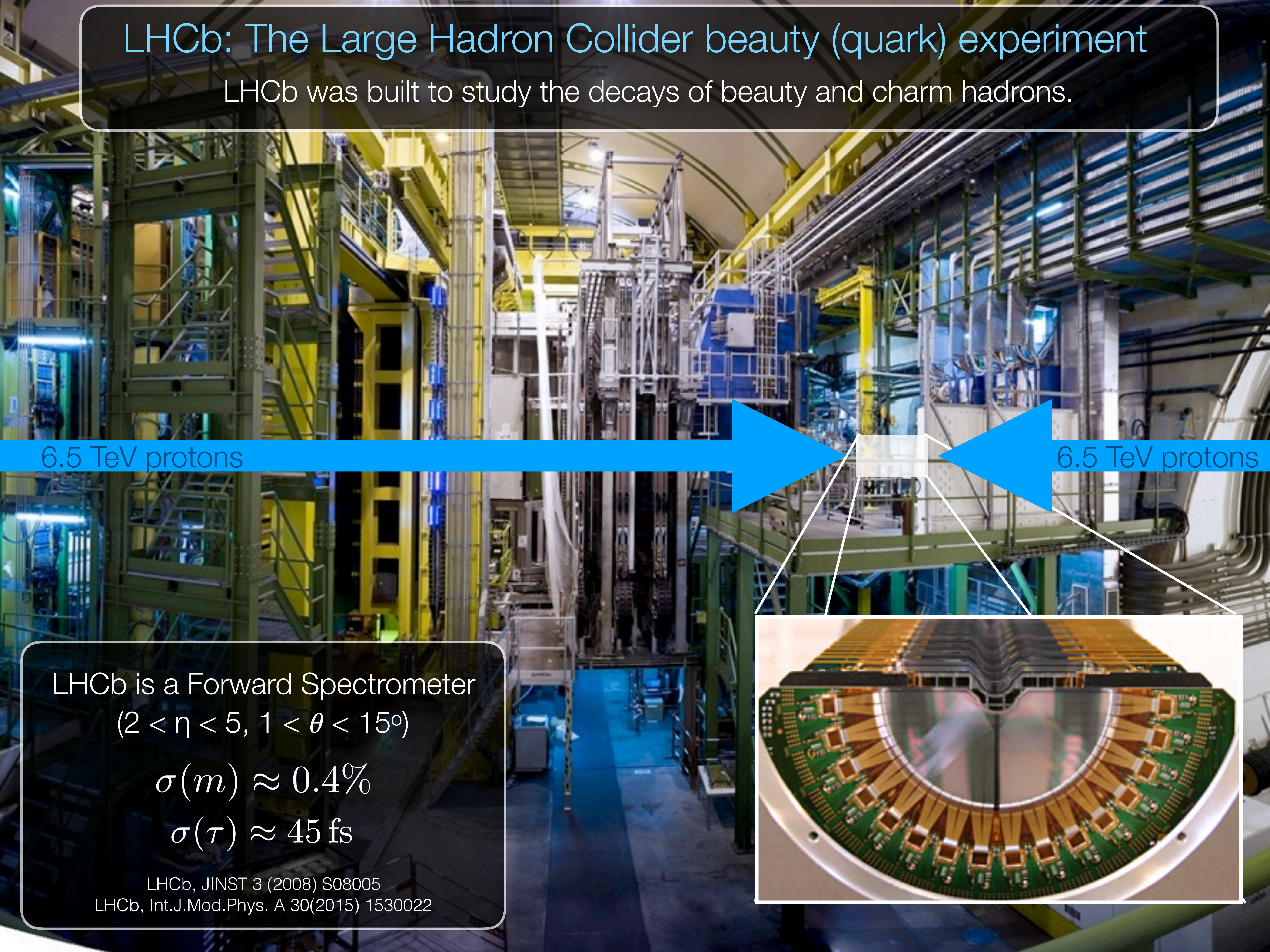
Mike Williams
on behalf of the LHCb collaboration

August 6, 2019

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 beauty and charm hadrons.



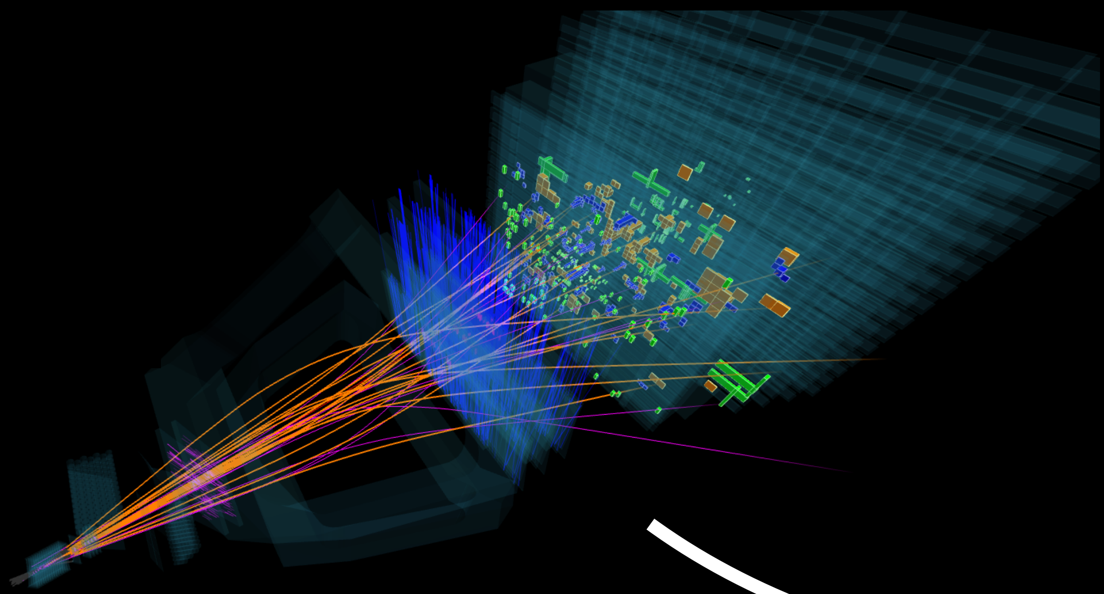
LHCb is a Forward Spectrometer
($2 < \eta < 5$, $1 < \theta < 15^{o}$)

$$\sigma(m) \approx 0.4\%$$

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

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

Real-Time Calibration & Analysis



LHCb, JINST 8 (2013) P04022

1 TB/s
post zero
suppression

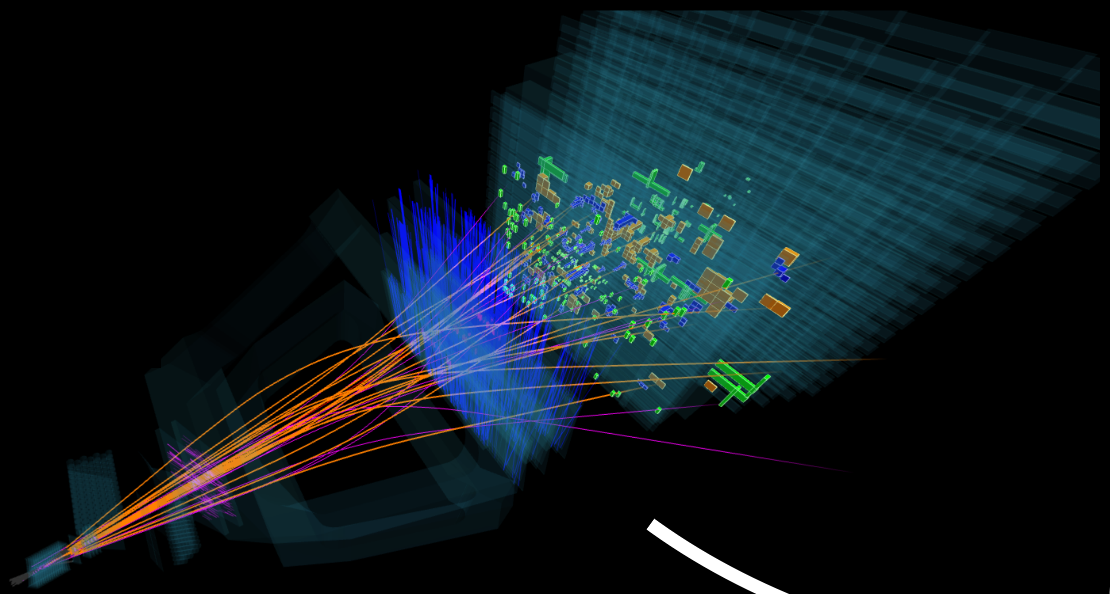
single-subsystem
selection
on FPGAs
O(μs) latency

50 GB/s

[1] T.Likhomanenko,…,MW [1510.00572]
[2] V.Gligorov, MW, JINST 8 (2012) P02013

Real-Time Calibration & Analysis

LHCb, JINST 8 (2013) P04022



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partial-event inference
on 50k CPUs,
mostly ML-based
selections[1]
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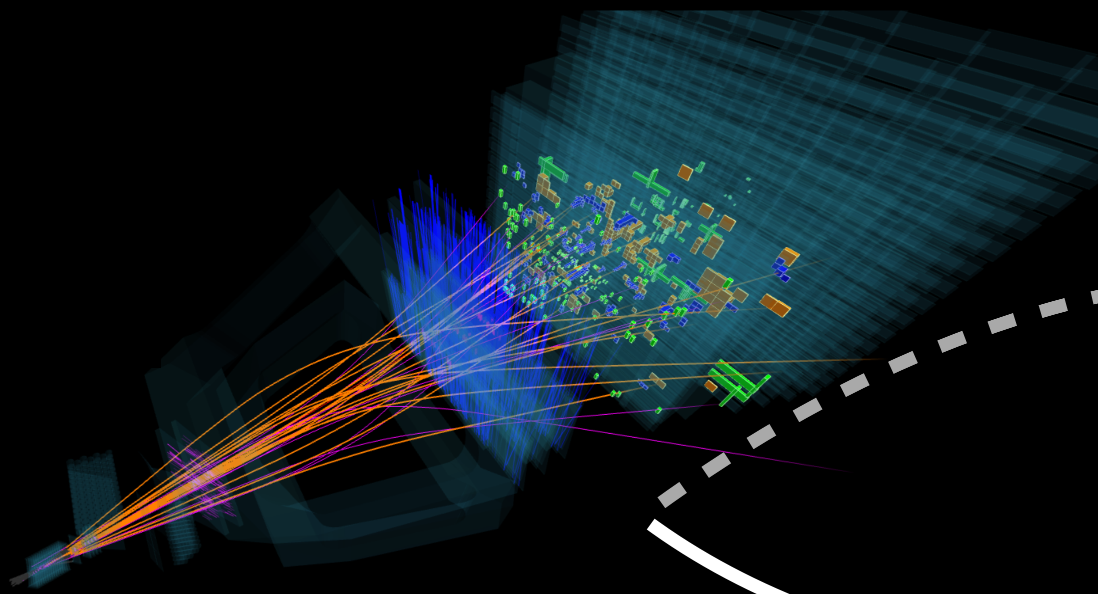

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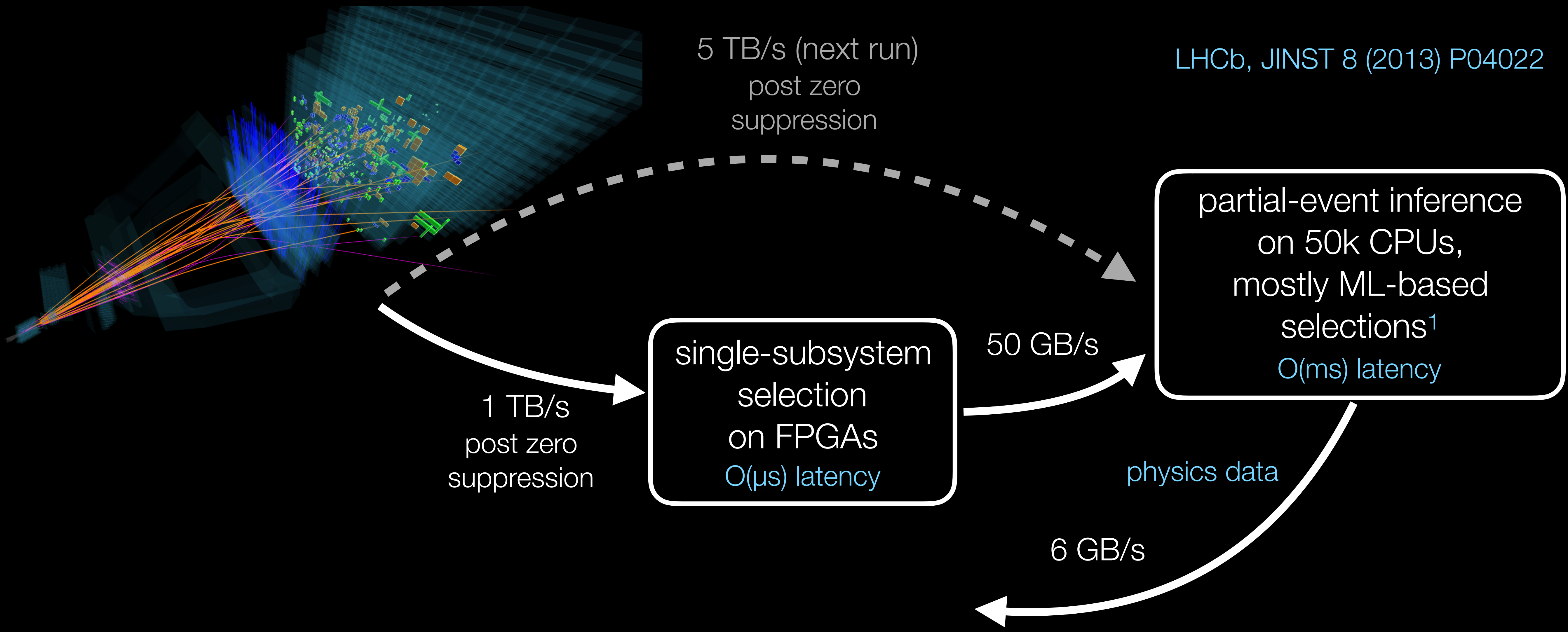

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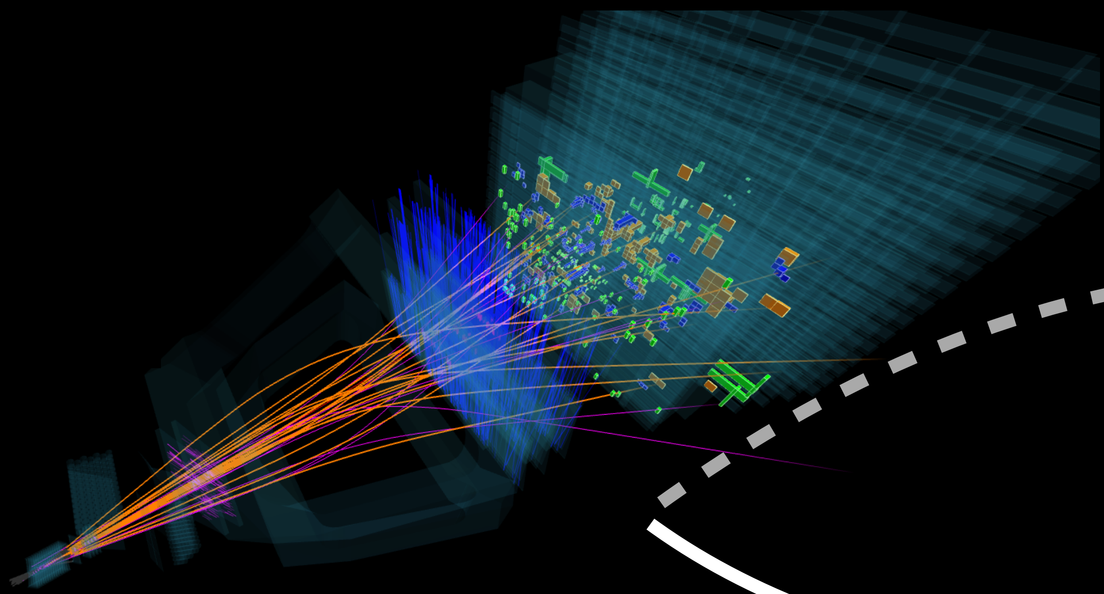

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physics data

6 GB/s

data buffered on
10 PB disk

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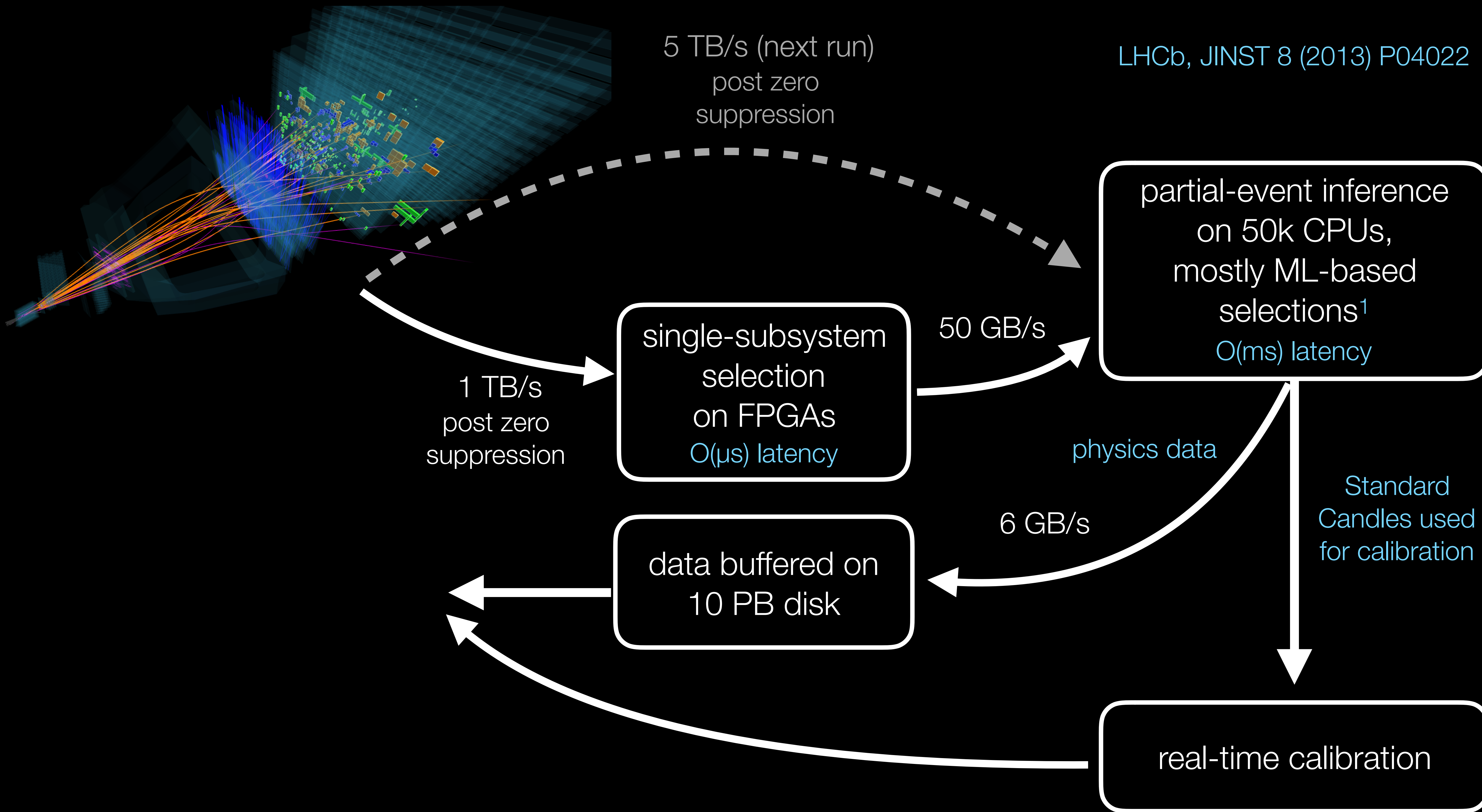

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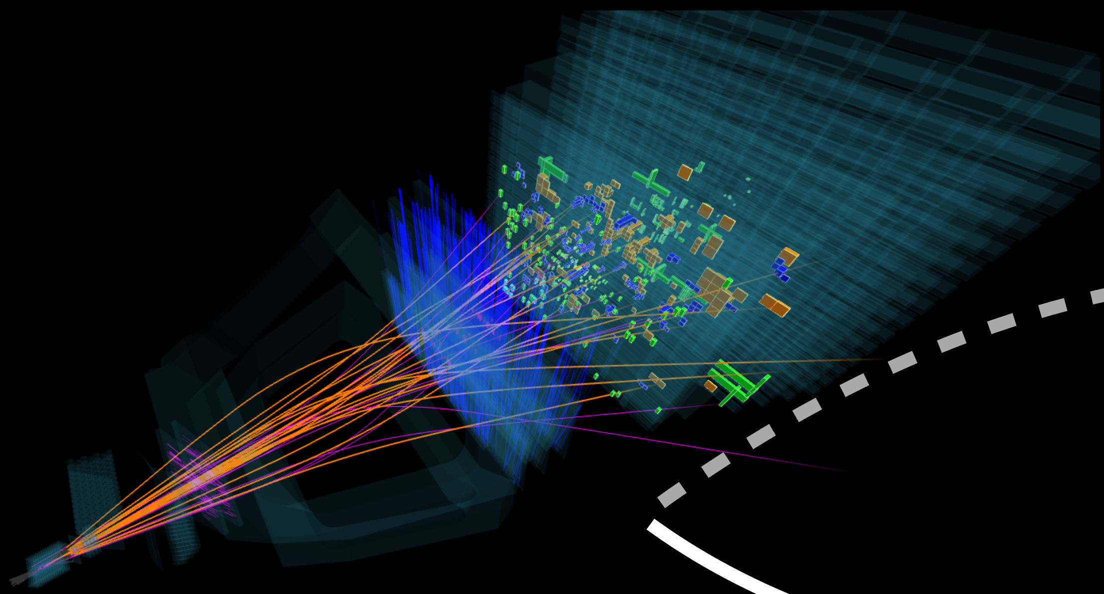

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LHCb, JINST 8 (2013) P04022

partial-event inference
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selections[1]
O(ms) latency

single-subsystem
selection
on FPGAs
O(μs) latency

50 GB/s

1 TB/s
post zero
suppression

fully calibrated data permits
usage of ML algorithms for
most tasks here

physics data

Standard
Candles used
for calibration

6 GB/s

inference using full
event information,
primary selection
ML-based[2]

data buffered on
10 PB disk

real-time calibration

[1] T.Likhomanenko,…,MW [1510.00572]
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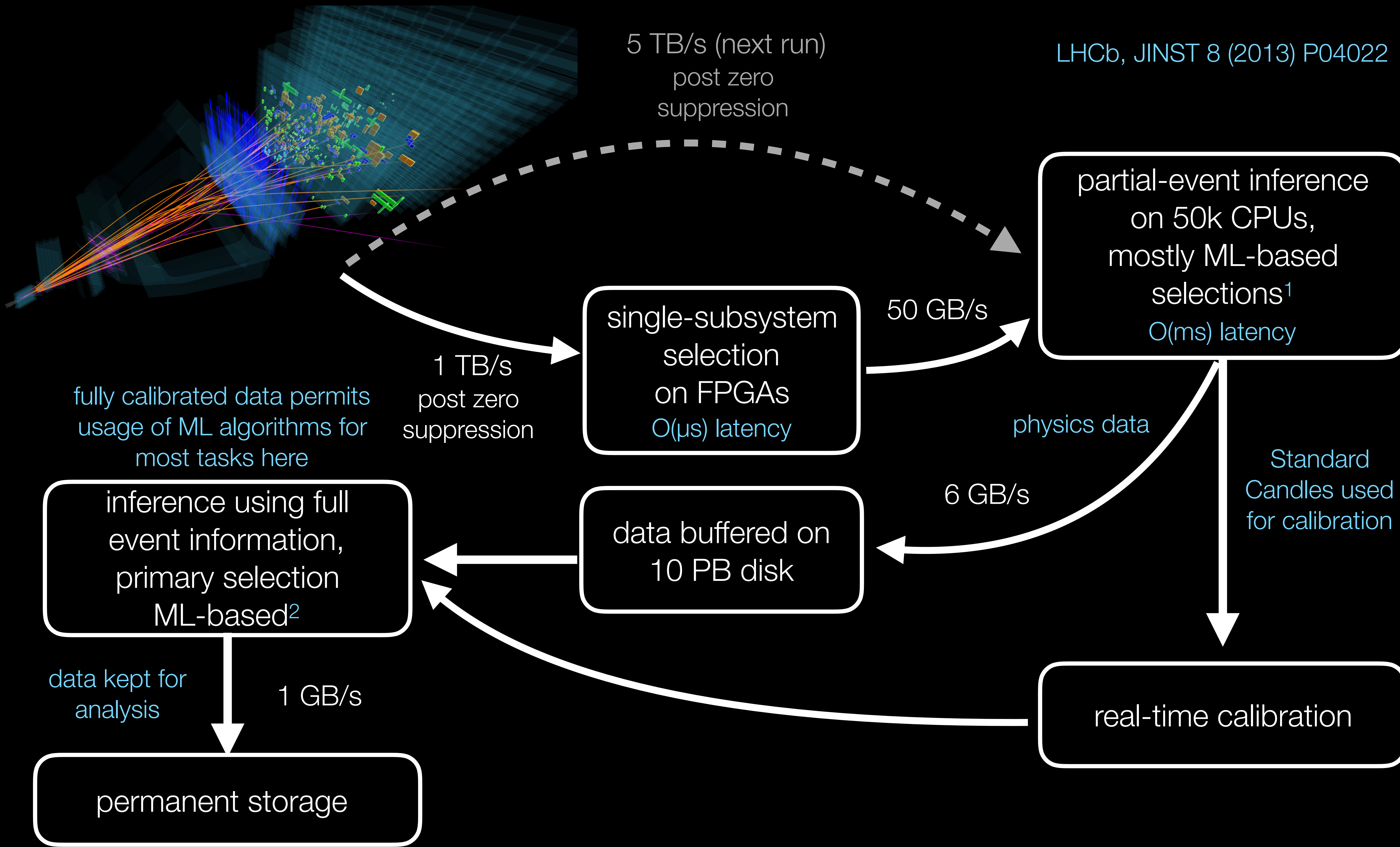
Real-Time Calibration & Analysis



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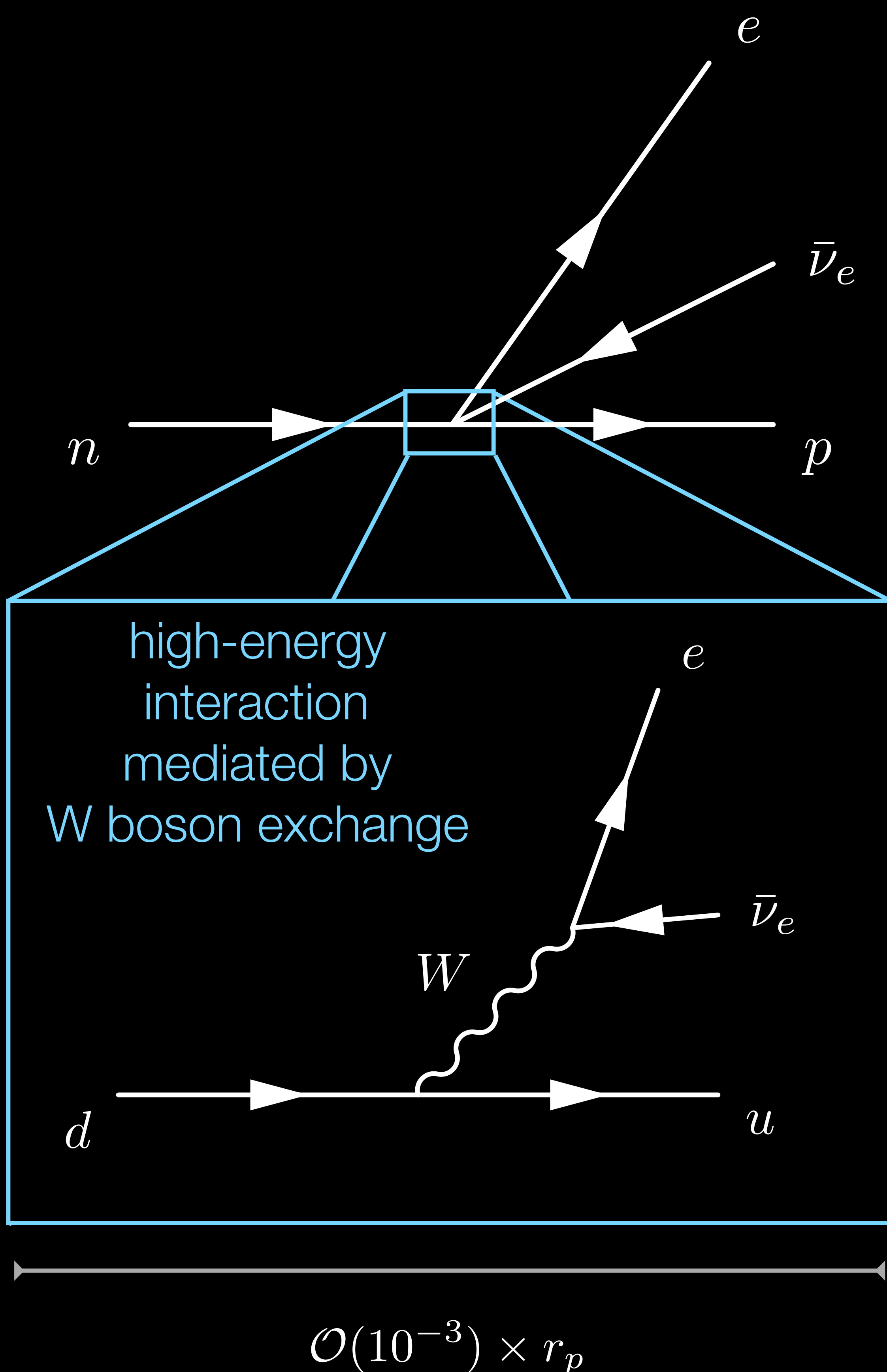
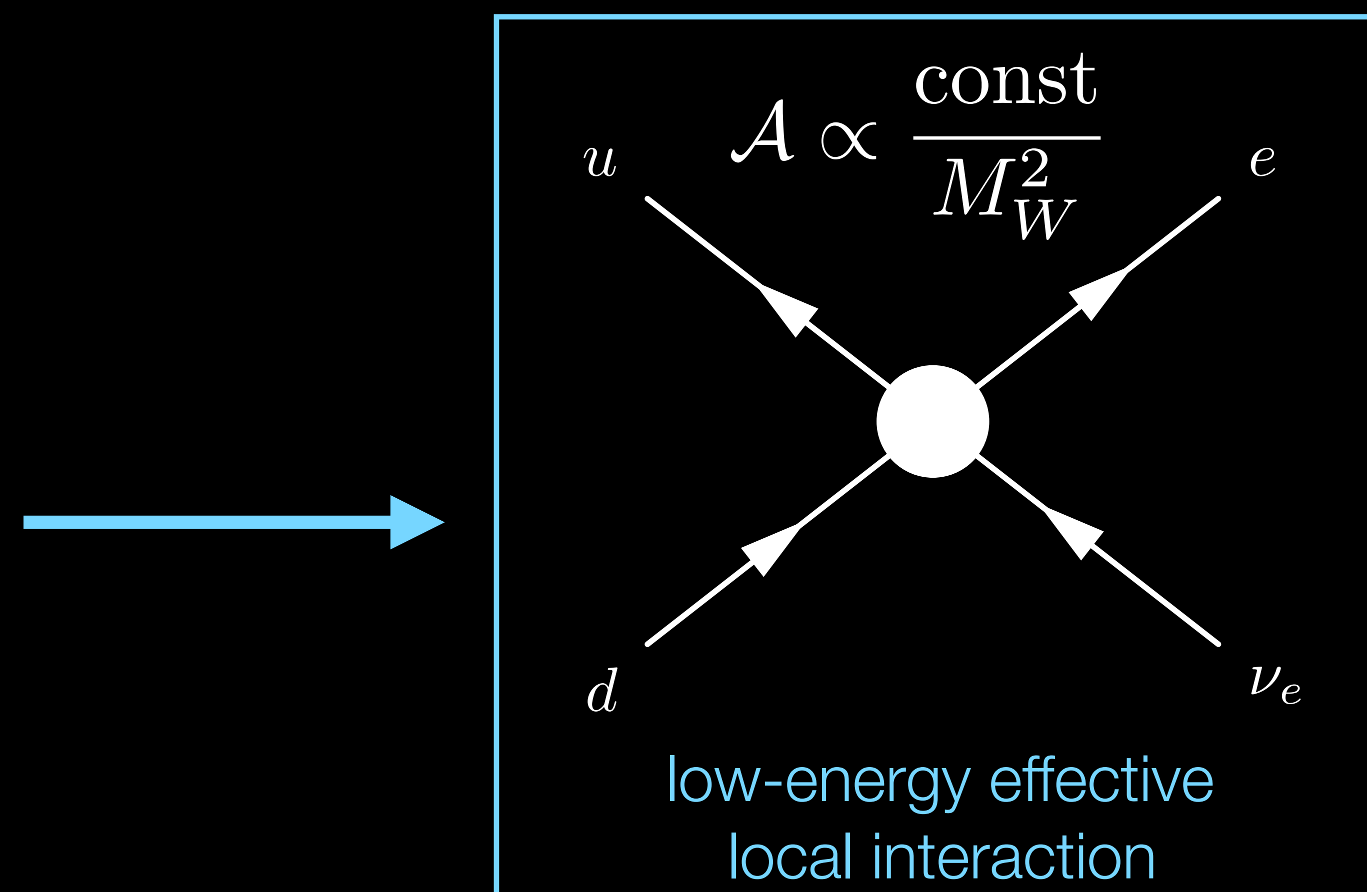
Indirect Observation



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.

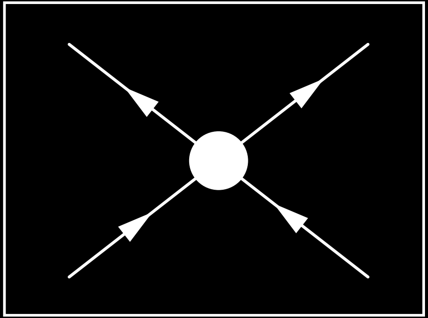
Probing New Physics

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

$$\mathcal{H}_{\text{eff}} = \sum_i \mathcal{C}_i \times$$



$$_i$$

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

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.

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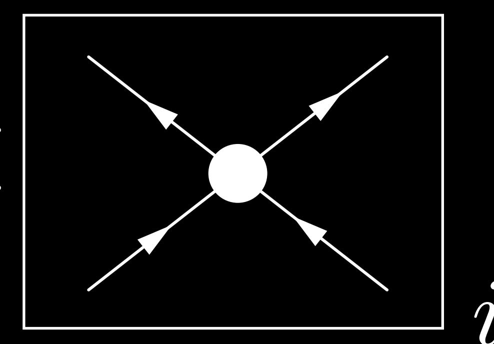
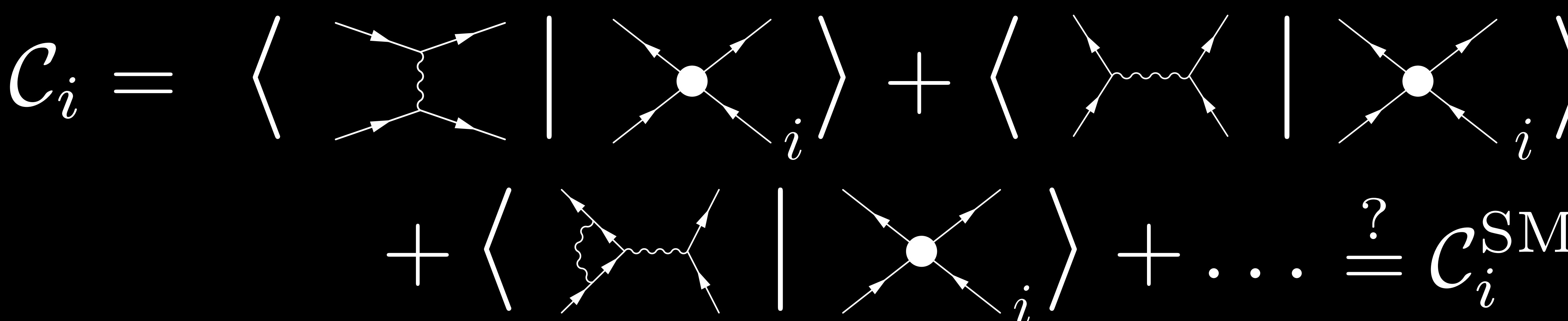




High-energy paths project onto the local basis in a perturbative expansion.

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

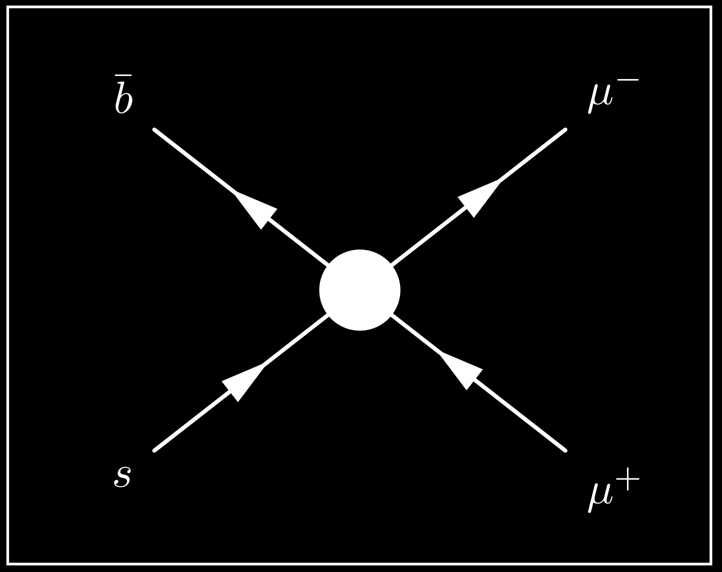
$B_s(bs) \to \mu^+\mu^-$

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

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



$$\Big|^2_0$$

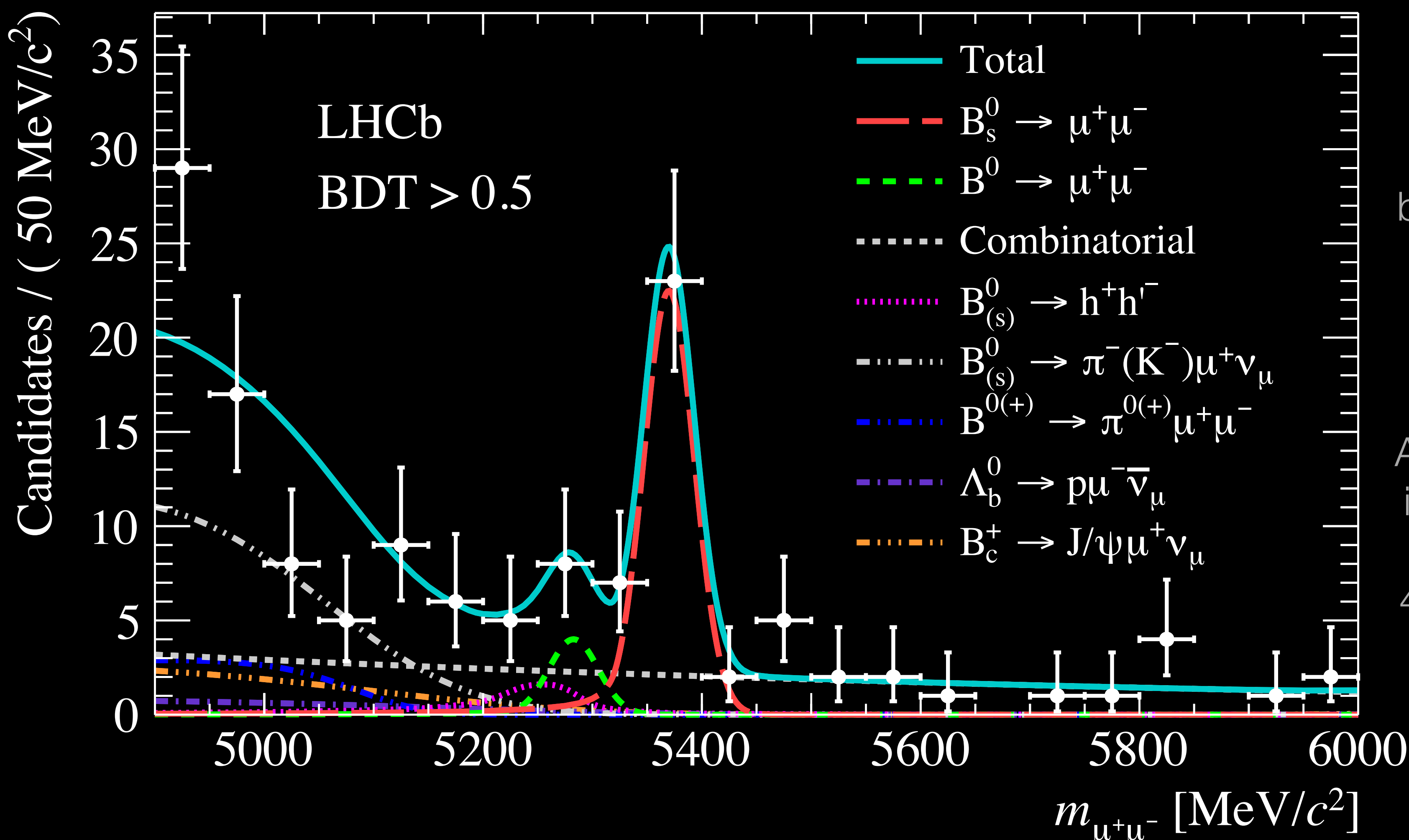
calculate these

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.

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

Both LHCb and CMS crossed the 4σ significance threshold in Run 1. We combined our Run 1 data samples which reaches over 6σ. CMS & LHCb, Nature 522 (2015) 68

LHCb, PRL 118 (2017) 191801



CMS presented yesterday their first CMS-only observation by also adding 2015-16 data, achieving 5.6σ (about 20% worse precision c.f. LHCb).

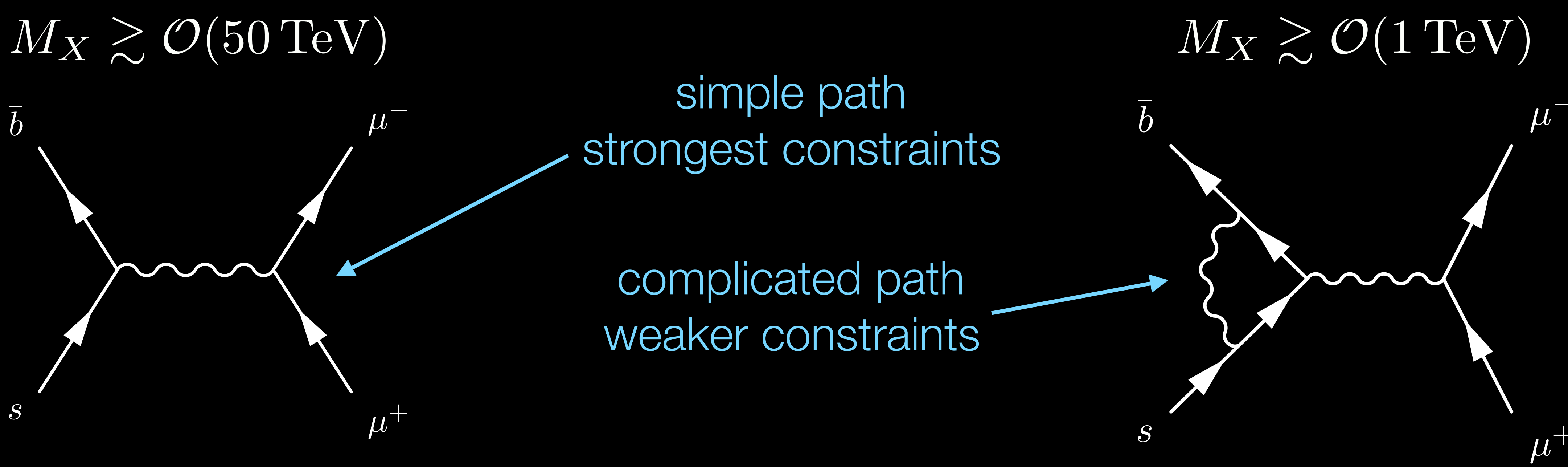
ATLAS published results including 2015-16 data last winter, achieving 4.6σ (about 30% worse precision c.f. LHCb).

$$\frac{\Gamma(B_s \rightarrow \mu^+\mu^-)_{\rm LHCb}}{\Gamma(B_s \rightarrow \mu^+\mu^-)_{\rm SM}} = 0.82 \pm 0.16 \pm 0.08 \pm 0.06$$

LHCb combined Run 1 + 2015-16 data sample provides the first single-experiment observation at almost 8σ. All results are consistent with the SM predictions.

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.



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

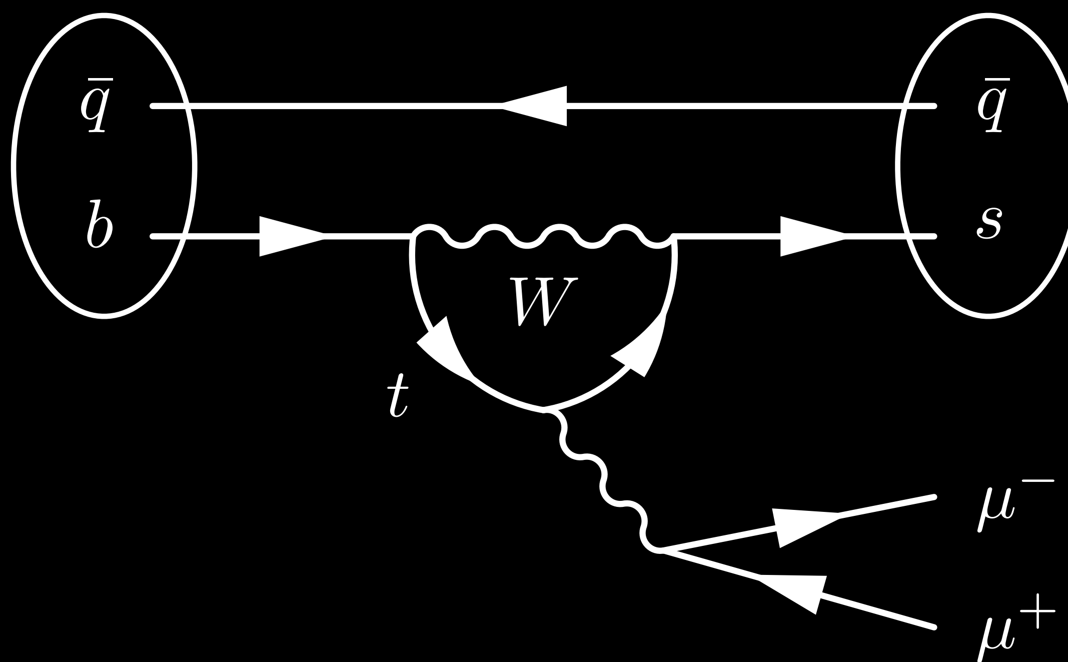
We have also made the most precise measurements of CP violation (i.e matter/anti-matter asymmetries)—and even though we do observe many reactions with sizable CP violation, these asymmetries (or lack thereof) are all consistent with the SM expectations.

See, e.g., first observation of CP violation in charm decays LHCb-PAPER-2019-006!

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

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).

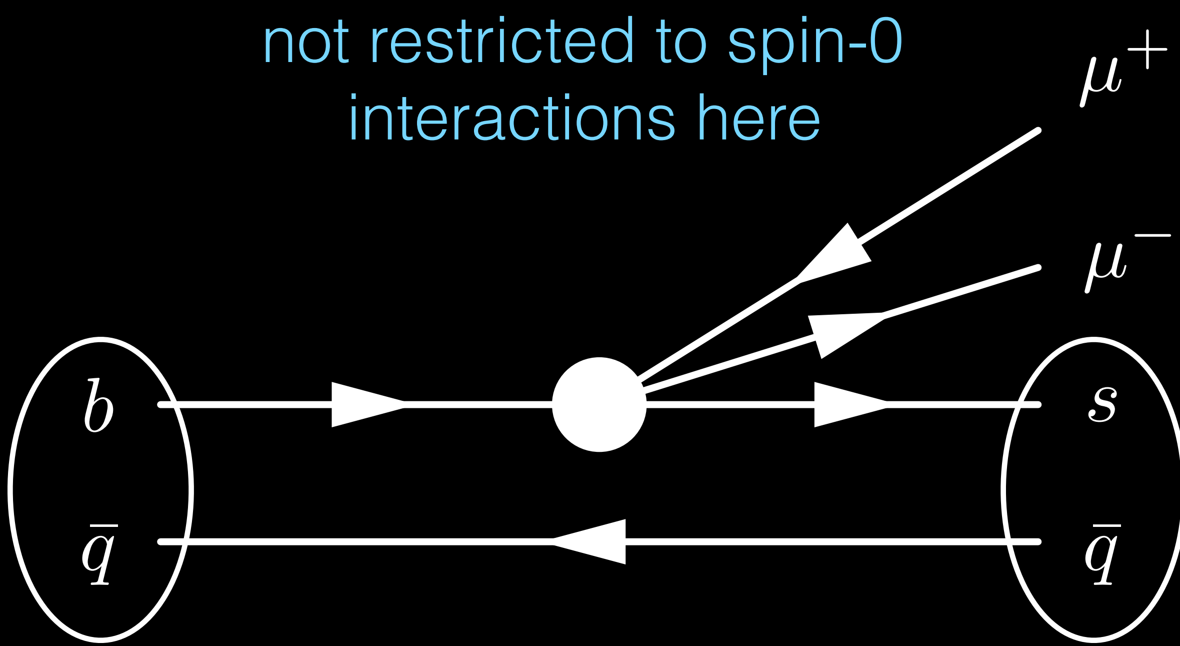


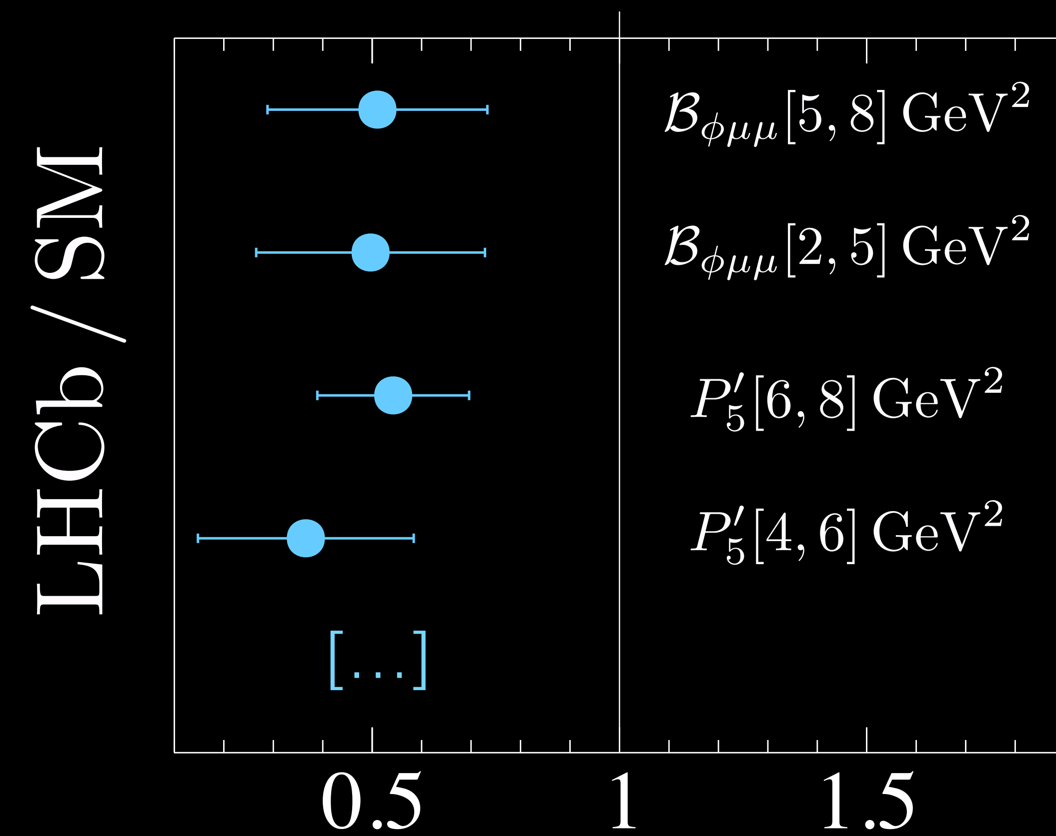
If you're in the right state of mind, the Feynman diagram may (sort of) look like a penguin.
(see https://en.wikipedia.org/wiki/Penguin_diagram)

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

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 111 (2013); JHEP 02 (2016); JHEP 04 (2014); etc.





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

Incomplete data from other experiments, though largely consistent where available and even competitive or slightly better than LHCb for some points (though not the observables shown above).

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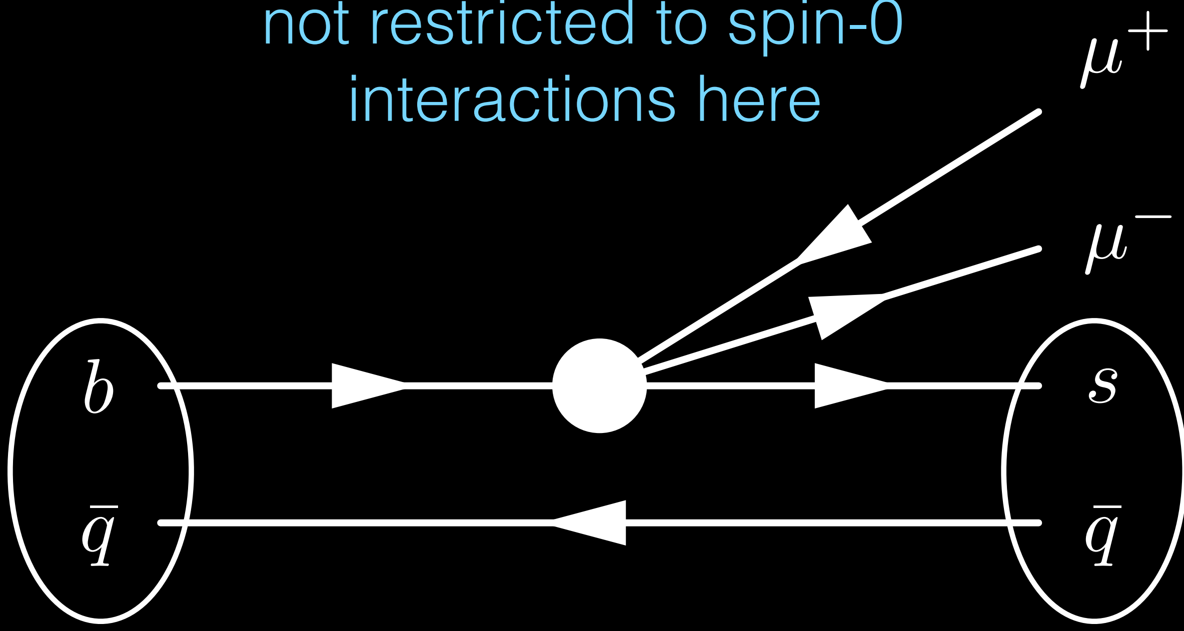
not restricted to spin-0 interactions here



very much NOT easy

"easy"

$$\mathcal{A}_{\rm SM} = \mathcal{A}_{\rm QCD} \times \mathcal{A}_{\rm EW}$$

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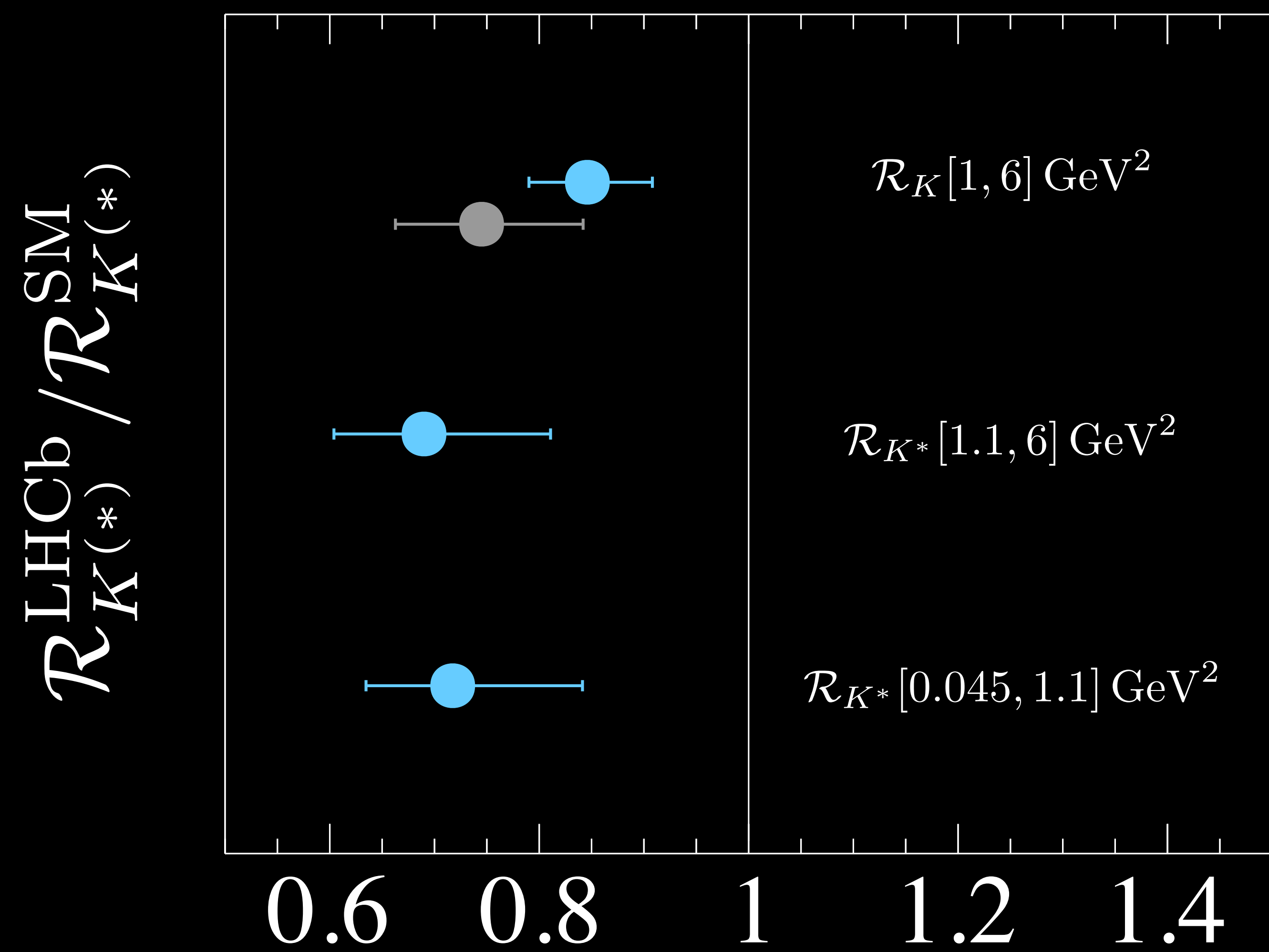
Incomplete data from other experiments, though largely consistent where available and even competitive or slightly better than LHCb for some points (though not the observables shown above).

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.

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



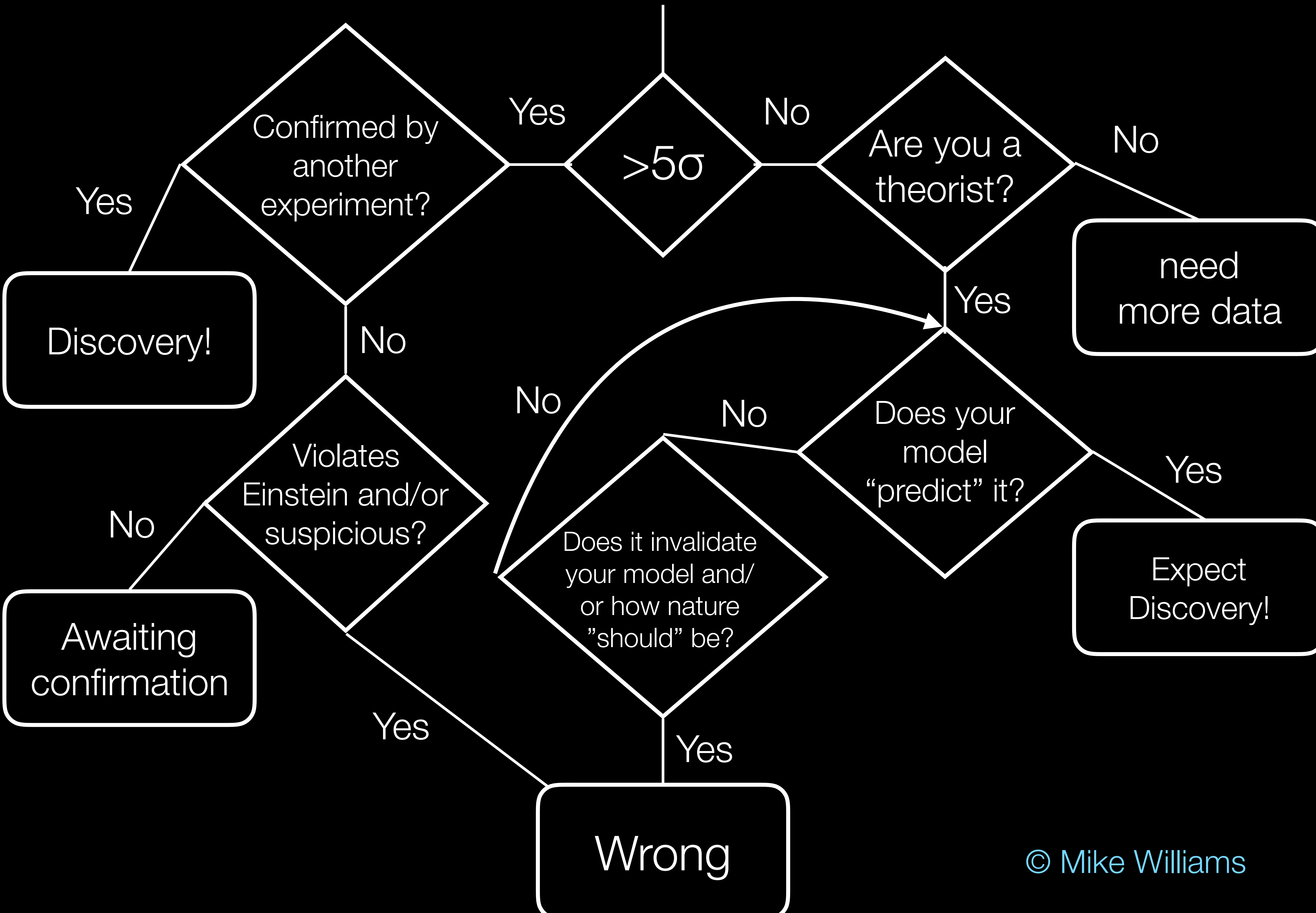
LHCb-PAPER-2019-009
PRL 122 (2019) 191801
(Run 1 data + 2015-16)

LHCb-PAPER-2014-024
PRL 113 (2014) 151601
(Run 1 data)

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

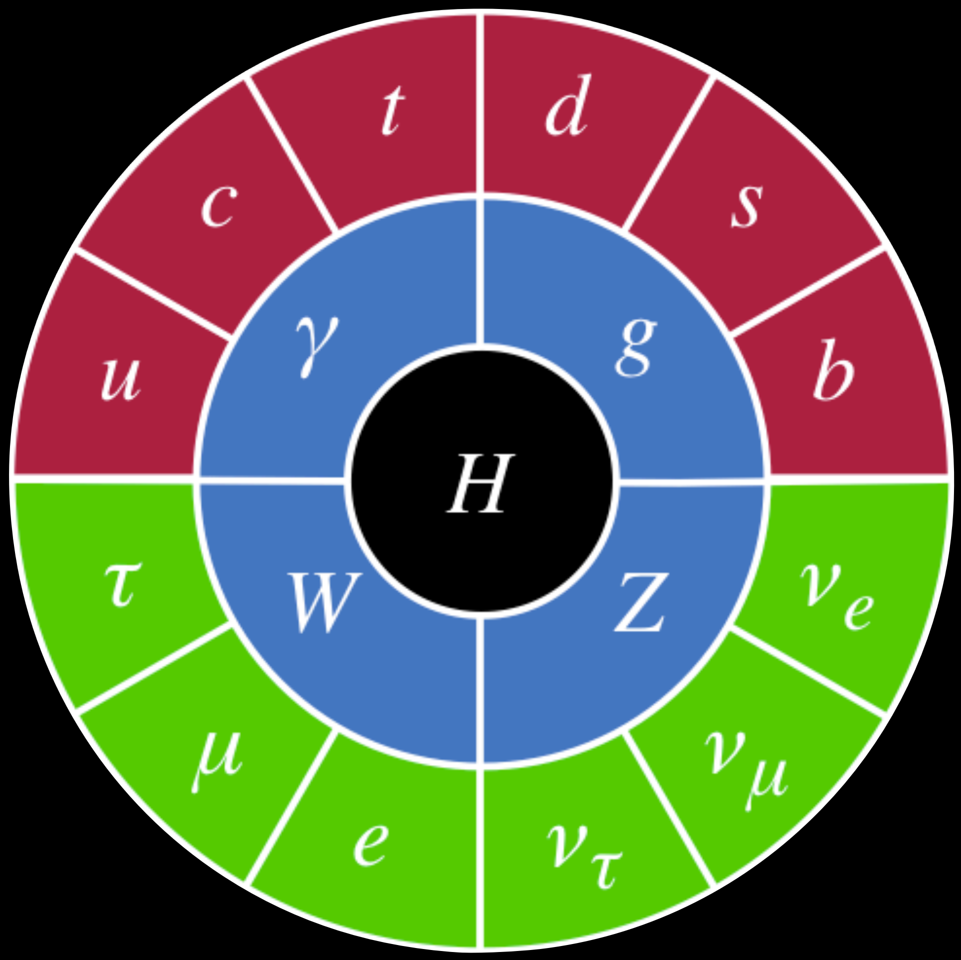
Who ordered that? —I.I. Rabi

Interpreting Results — a Flow Chart



Hidden (Dark) Sectors

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

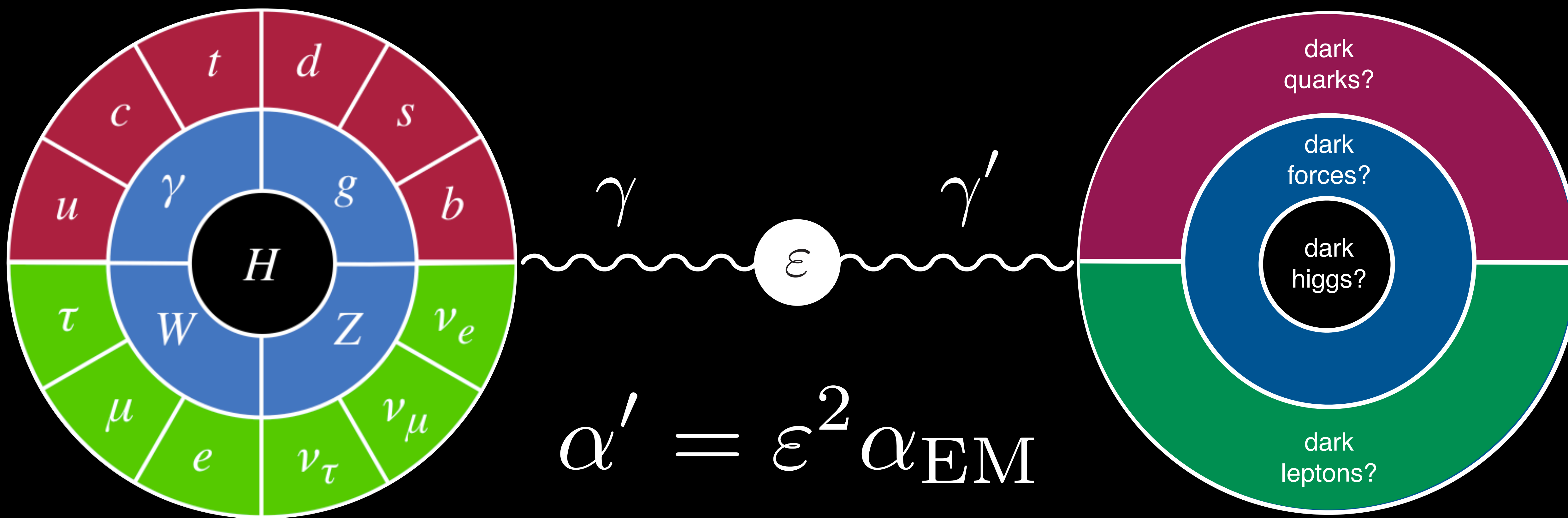


lightest DM particle could be
stable because it's (dark) charged

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

Dark Photons

As long as our sector and the dark sector are connected at some scale (e.g. if they are both part of a GUT), then there is some path to get from a photon to a dark photon.



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

e.g, particle carrying both EM and dark-EM charge

e.g, GUT near the Planck scale

$\varepsilon \sim \mathcal{O}(10^{-3})$

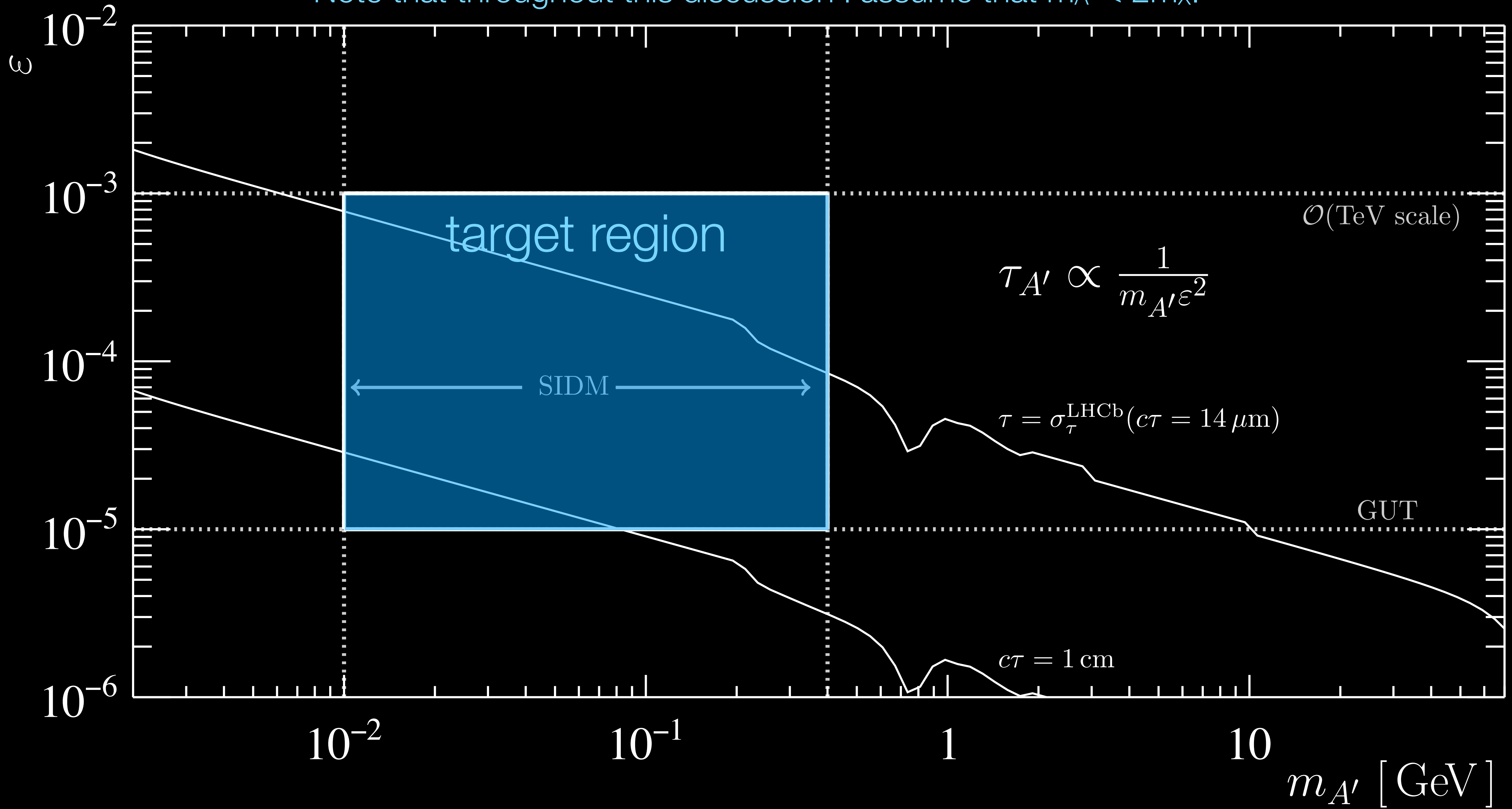
$\varepsilon \sim \mathcal{O}(10^{-5})$

At low energy, we don't need to know the details. The bottom line is that the A' picks up a suppressed coupling to charged SM particles. We can make it in the lab, and it can decay into SM particles that we can detect.

Dark Photon Searches

Well defined target region to search, e.g., assuming a SIDM-sized cross section and connection between sectors at the few-loop level (*cum grano salis*).

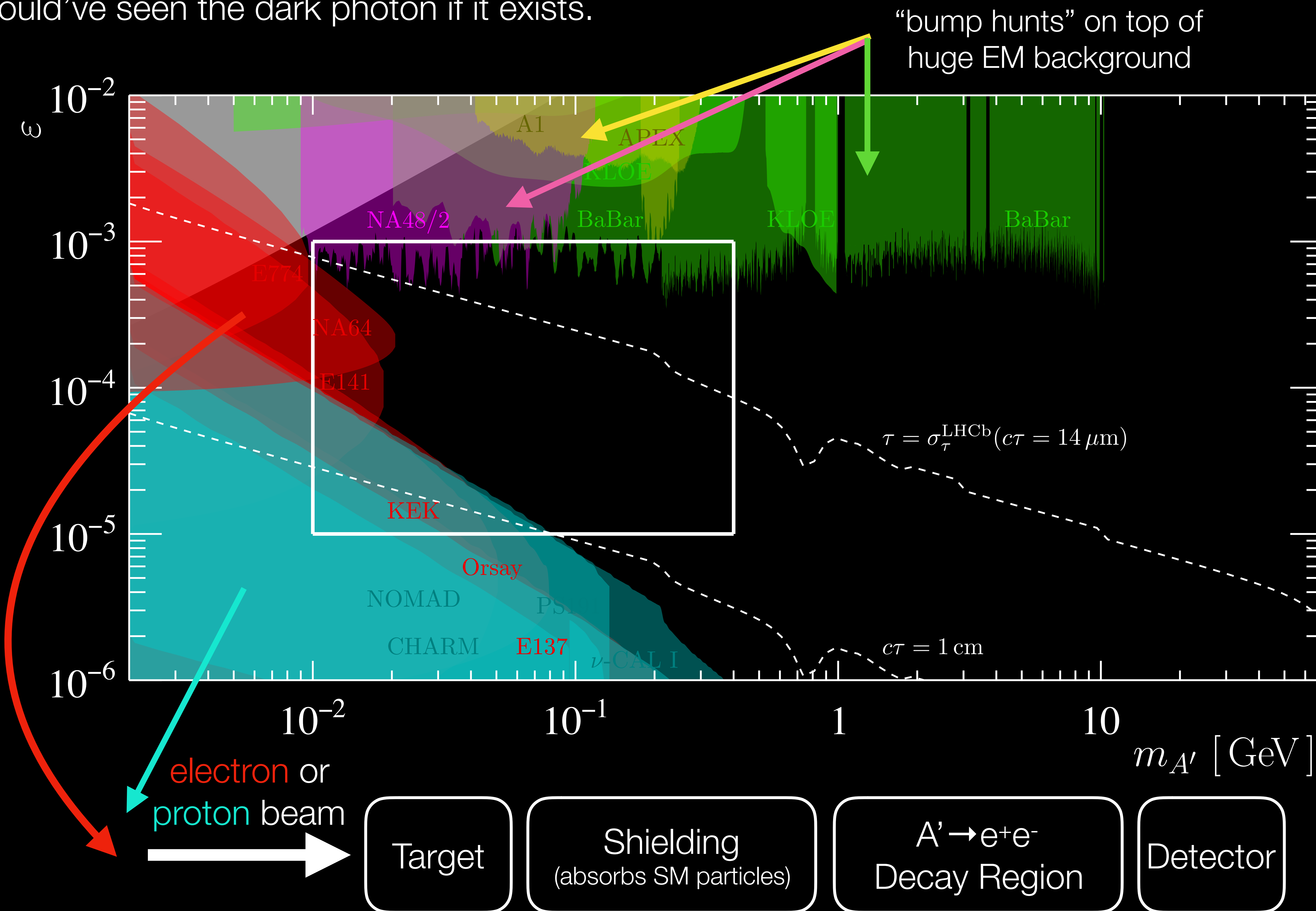
Note that throughout this discussion I assume that $m_{A'} < 2m_X$.



Additional constraints from BBN, tests of Coulomb's Law, etc. also motivate focusing (very roughly) on this target region (within a few orders of magnitude of it).

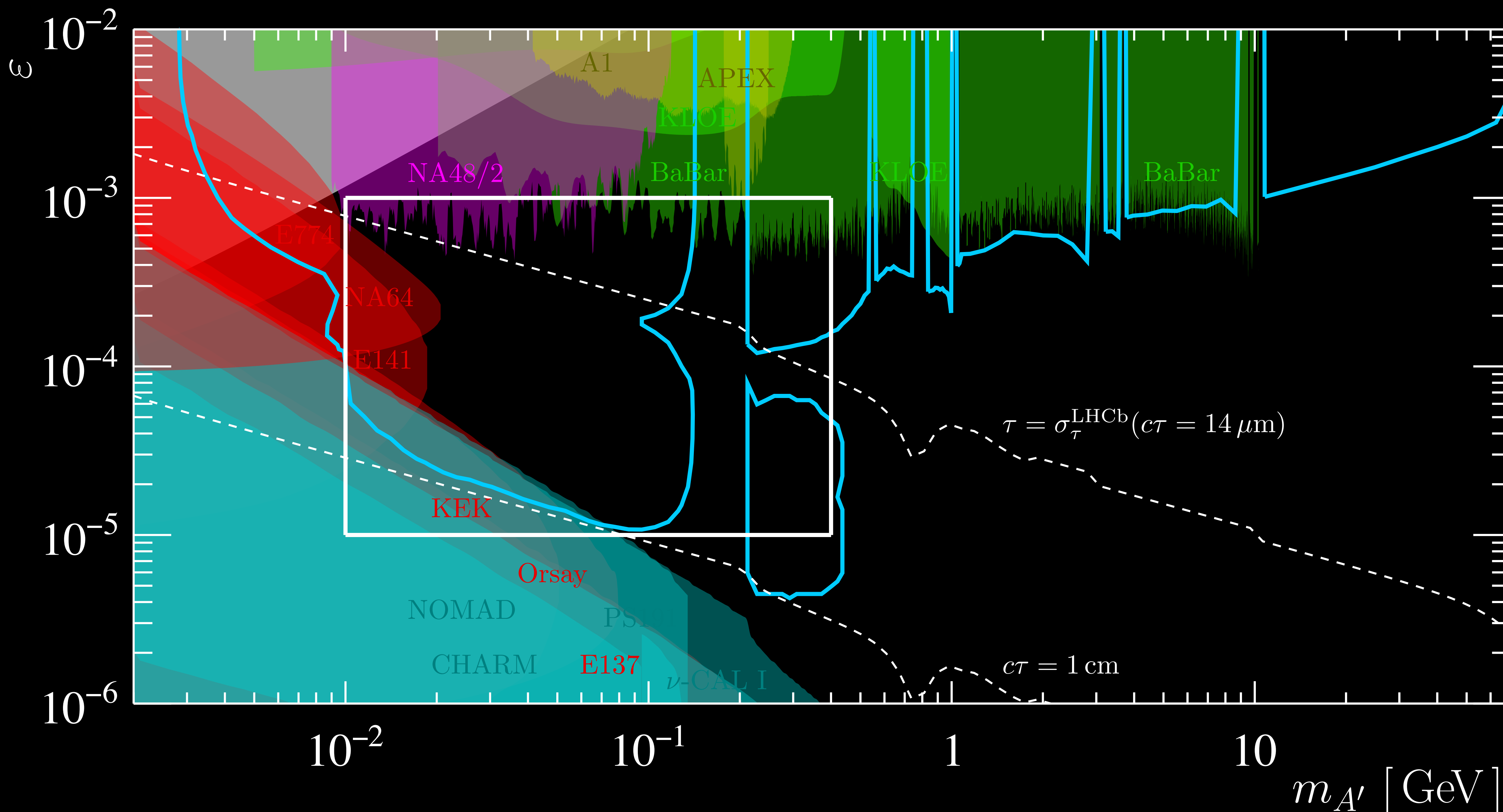
Dark Photon Constraints

Existing constraints leave the target region largely unexplored, i.e. no laboratory experiment would've seen the dark photon if it exists.



Dark Photons @ LHCb

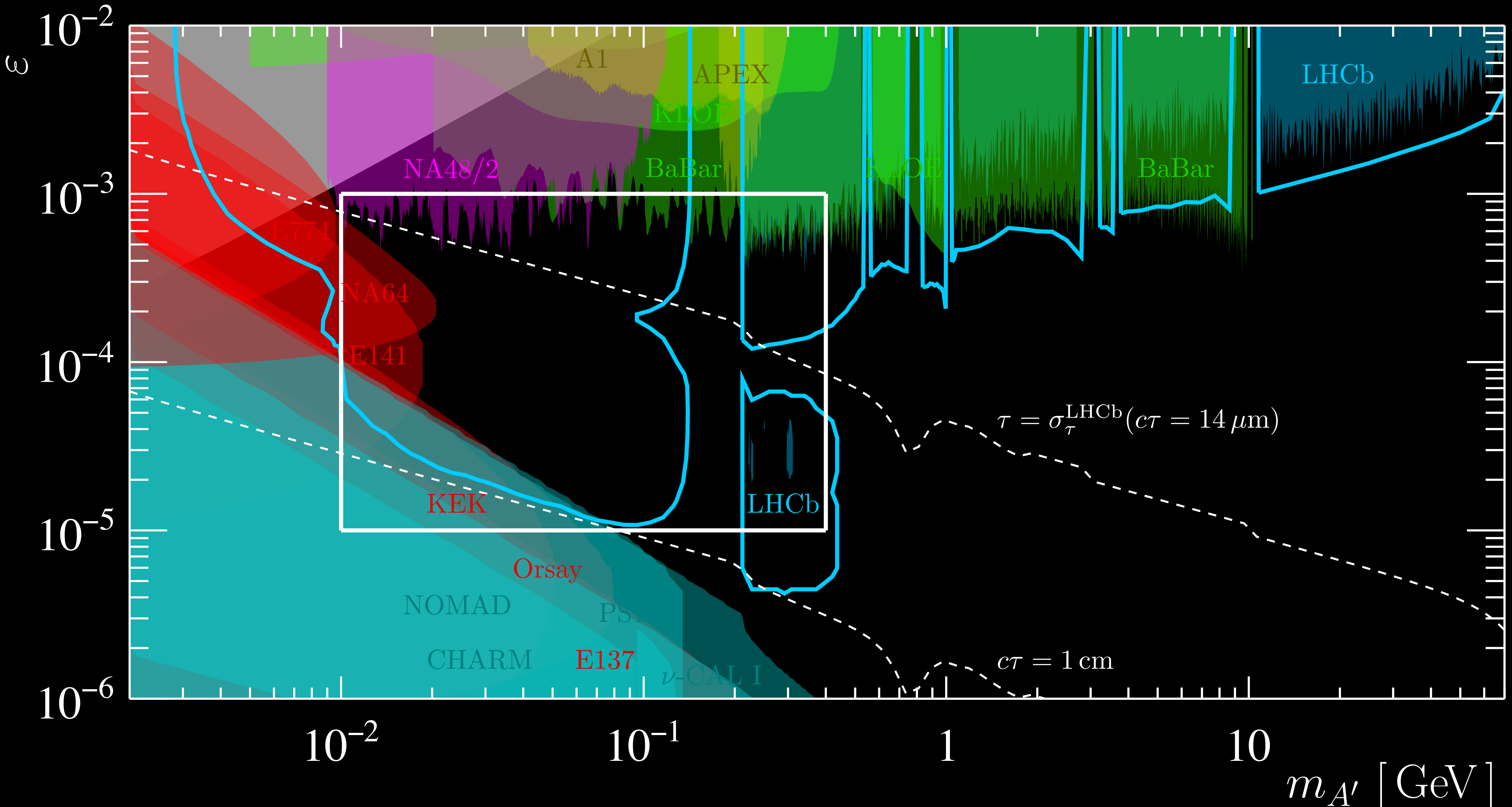
We proposed leveraging LHCb's excellent lifetime and mass resolution—and the planned move to triggerless readout in Run 3 — to probe all of the unexplored dark photon space.[1,2,3]



[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 $A' \to e^+e^-$.
[3] The gap between [1] and [2] is accessible in $\eta \to \gamma A'$ decays; entire low-mass region accessible using inclusive $A' \to e^+e^-$.

Dark Photons @ LHCb

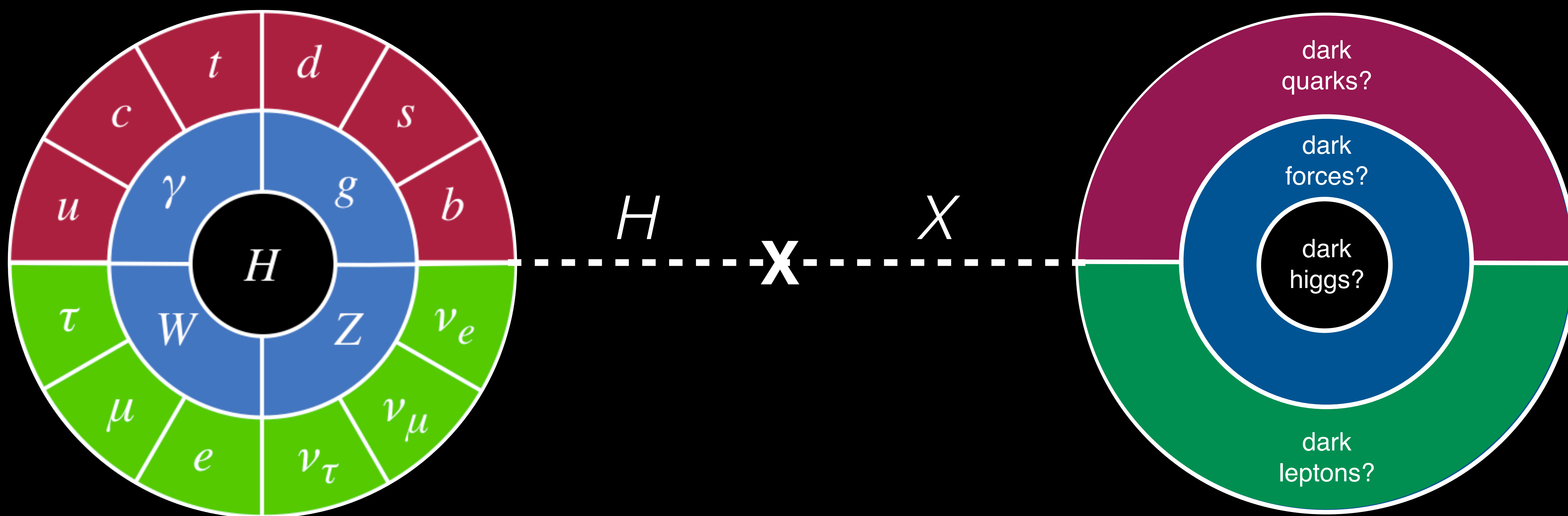
Using a 2016 data sample O(100) times smaller than expected in Run 3, LHCb showed[1] that our predictions are accurate[2]—and achieved the first ever sensitivity using a displaced vertex. LHCb will be able to fully explore the A' space in the next 5 years (much of it by 2019).



[1] LHCb-PAPER-2017-038, PRL 120 (2018) 061801 [1710.02867]
Technical support papers: LHCb, JINST 13 (2018) P06008; MW, JINST 12 (2017) P09034.
[2] LHCb achieves slightly better sensitivity than expected by rescaling our predictions for Run 3 to this data sample.
See Ilten, Soreq, MW, Xue JHEP 6 (2018) for recasting to any other vector force model.

Higgs Portal

We can play a similar game with the Higgs this time, where now couplings to SM particles will be proportional to mass (not electric charge).



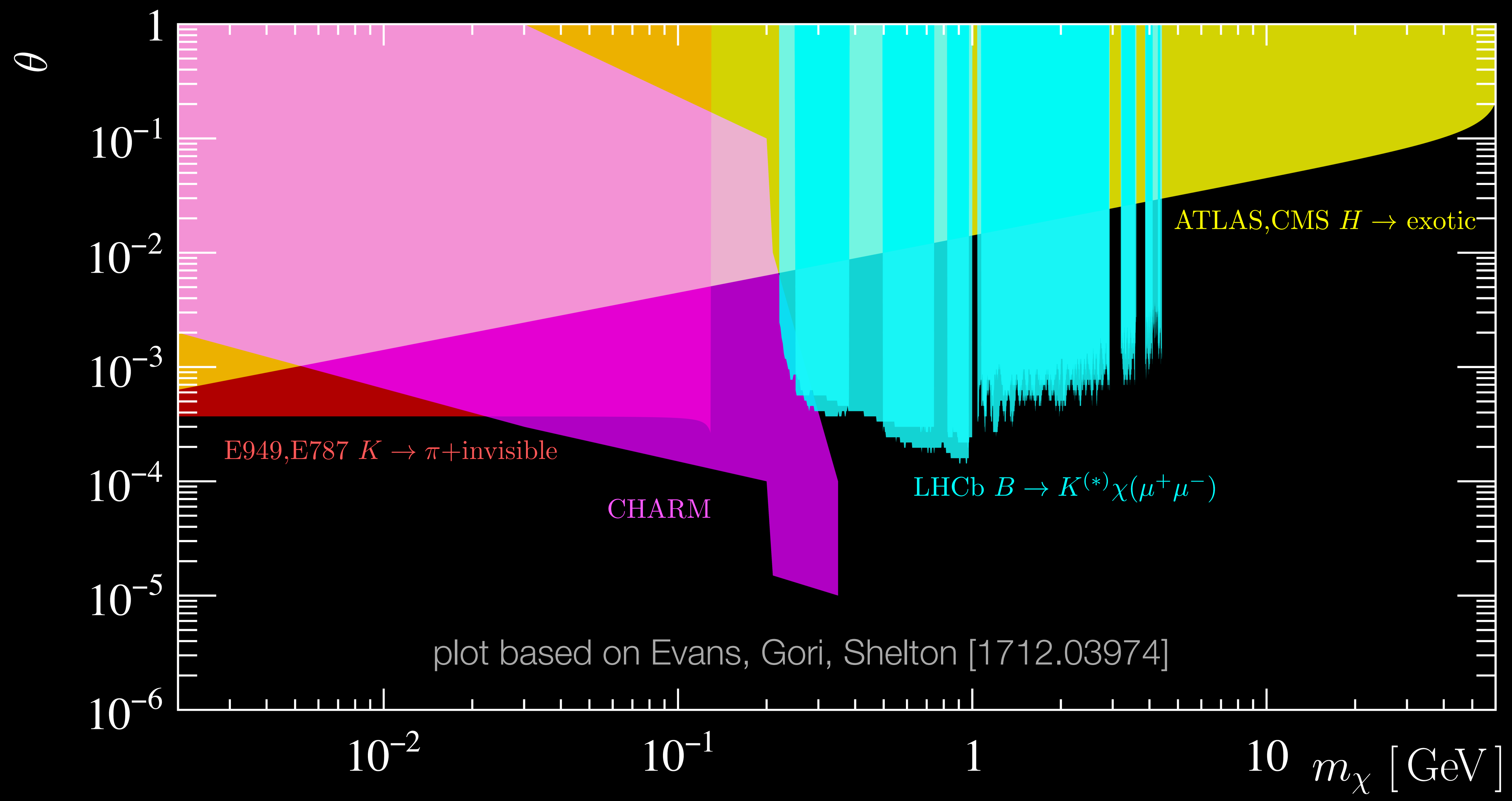
$$\begin{pmatrix} H \\ \chi \end{pmatrix}_{\text{physical}} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} H \\ \chi \end{pmatrix}_{\text{ideal}}$$

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]

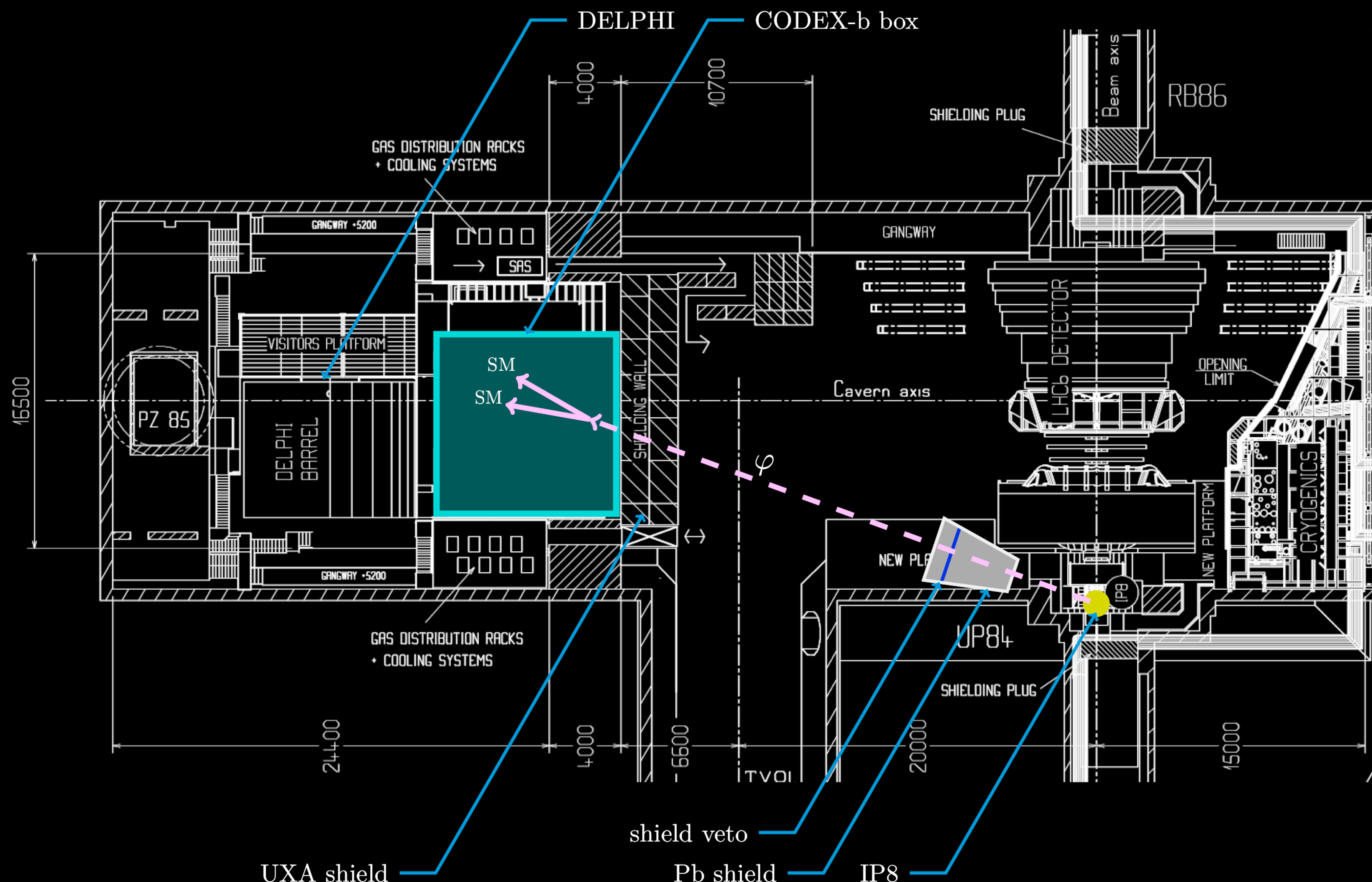
both LHCb searches only use Run 1 data



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.



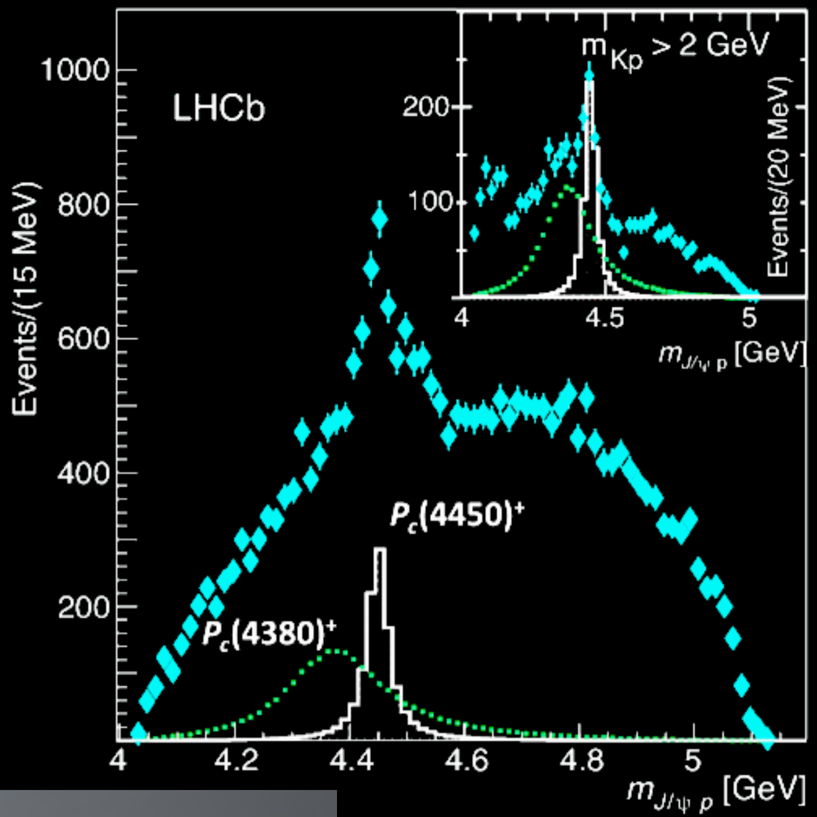
Background measurements look as expected. Looking at possibly installing a *demonstrator* for Run 3, then the full detector for Run 4 — assuming we can get funding.

Serendipity

If we knew what we were doing, it wouldn't be called research, would it? —(possibly) Albert Einstein

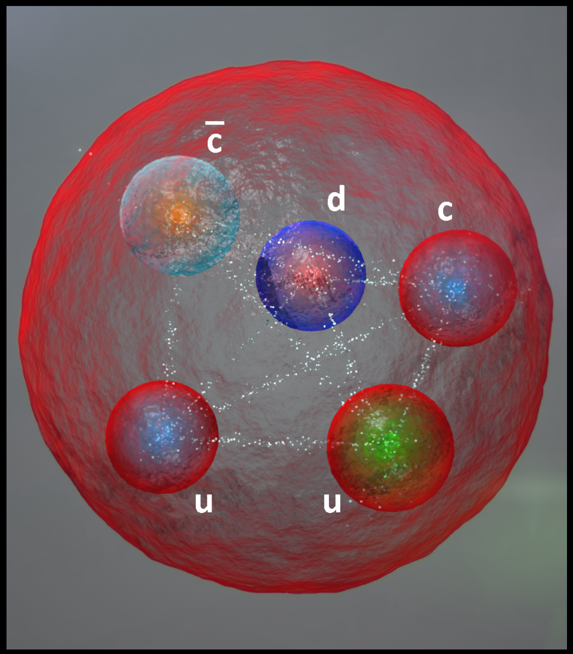
Using $\Lambda_b \to J/\psi pK$ decays, LHCb solved the so-called Λ_b lifetime puzzle: unsurprisingly, previous experiments were inaccurate—but, very surprisingly, we discovered two pentaquark states.

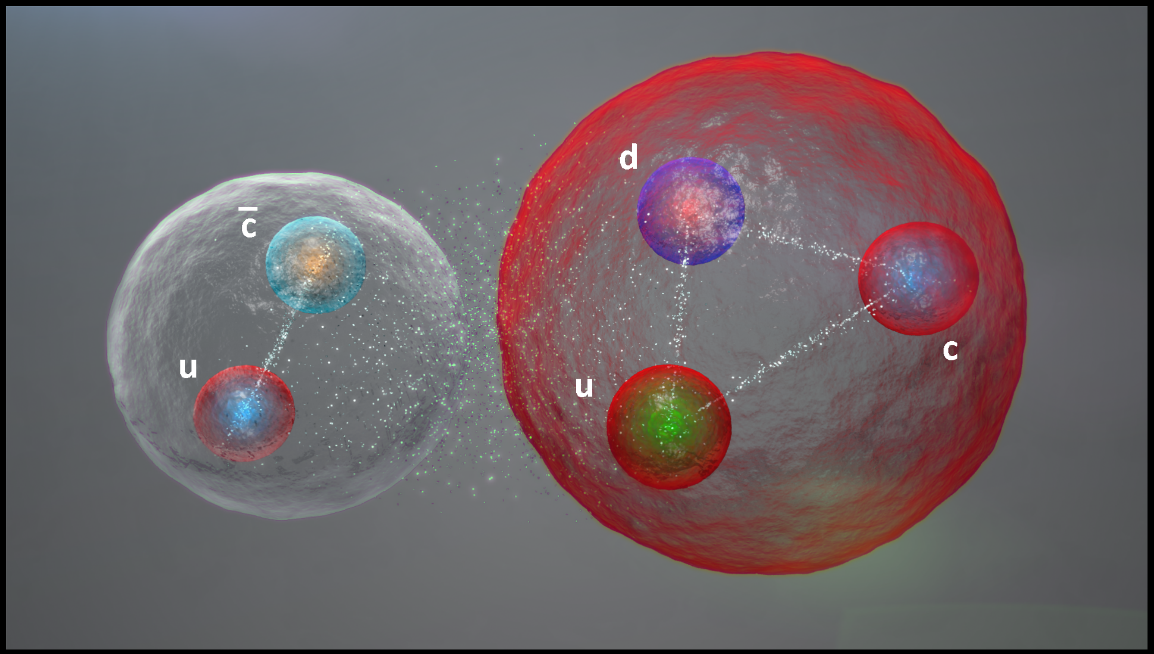
LHCb-PAPER-2015-029, PRL 115 (2015) 072001
LHCb-PAPER-2016-009, PRL 117 (2016) 082002



$$P_c(uud c\bar{c}) \to J/\psi(c\bar{c})p(uud)$$

Are these tightly bound 5-quark states?





Are these baryon-meson molecules?

Are they something else?

LHCb has also discovered ~5 tetraquarks, again with each containing charm/anti-charm.

See, e.g., LHCb-PAPER-[2018-043,2016-018,2015-038,2014-014,…]

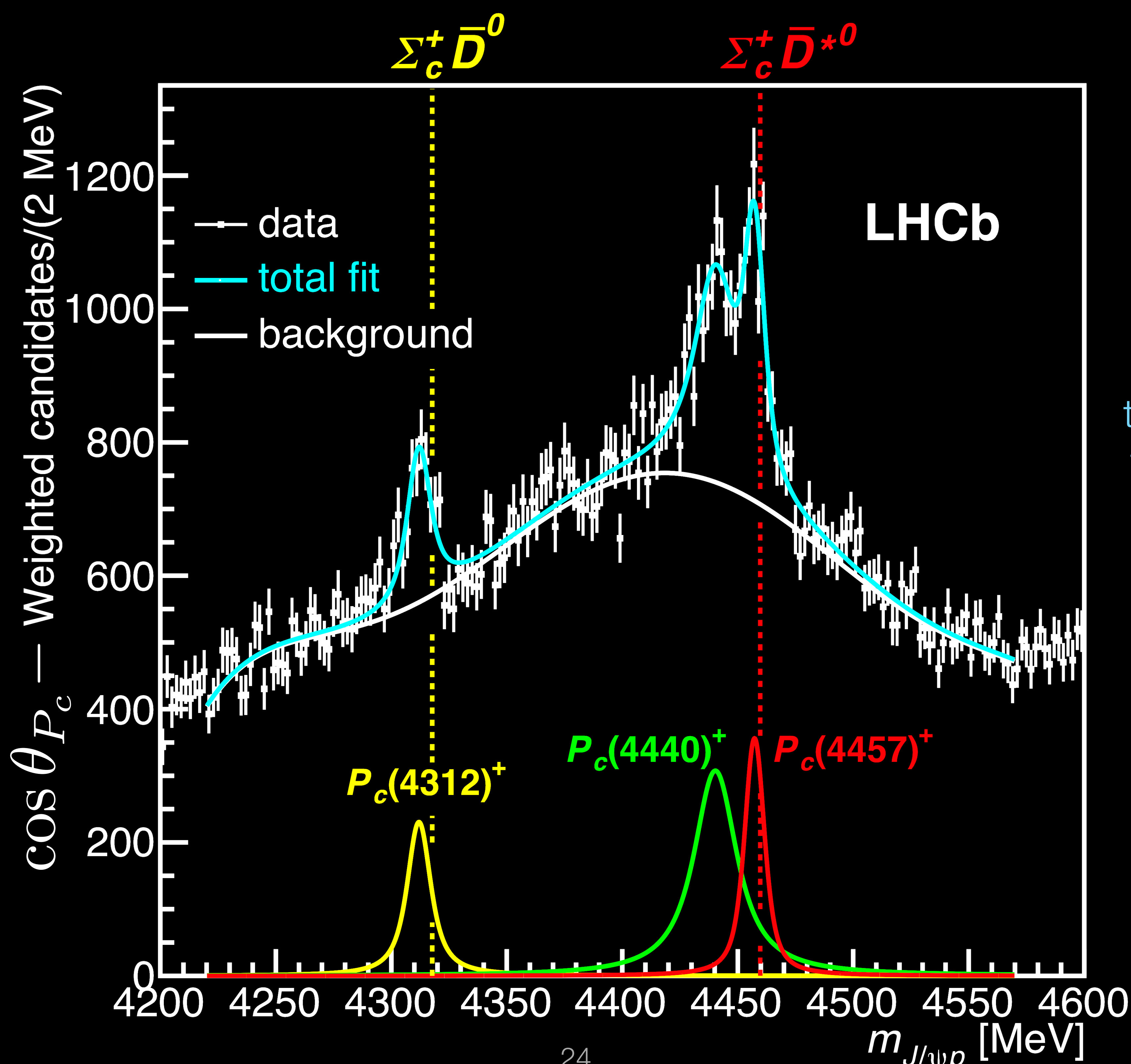
More Pentaquarks!

LHCb-PAPER-2019-014

Full Run 1+2 sample reveals 3 very narrow pentaquark states: the Pc(4450) is resolved into 2 states and a new Pc(4312) emerges. ~10x more signal with same purity

These states are only about 10, 20, and 5 MeV wide.

LHCb mass resolution here is about 2-3 MeV.



Their proximity to the baryon-meson thresholds shown suggests that these play an important role in the Pc-state dynamics.

Long Term Plans

LHCb is dead. Long live LHCb!

implemented real-time alignment & calibration

Today

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
2021-2023
+15/fb @ 14 TeV

Run 4
2026-2029
+25/fb @ 14 TeV

Run 5
2031-2033
+100/fb @ 14 TeV

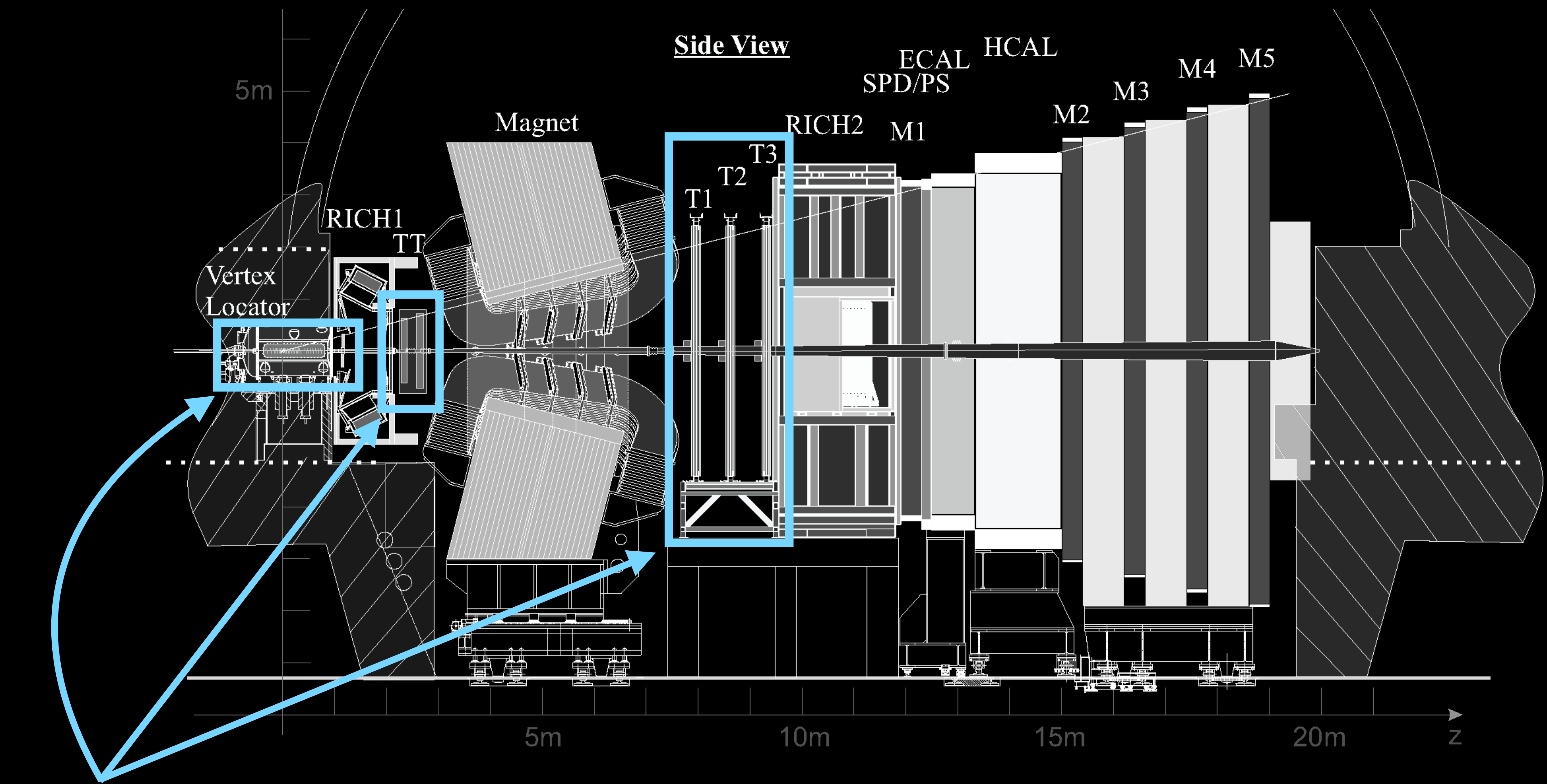
Run(s) ???
2035-20??
Total: 300/fb

a miracle occurs?
ramping up serious R&D efforts to make this possible

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

Upgrade I

Run 3: Increasing the luminosity by a factor of 5 and removing the hardware trigger. We'll need to process 5 TB/s in software, do tracking at 40 MHz, etc.



all tracking systems being upgraded to handle higher occupancy

all electronics being upgraded to readout at 40 MHz

LS3: new magnet tracking stations, possibly other improvements.
LS4: Upgrade II (major upgrade)

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 $b \to s\mu\mu$ penguin decays, which suggest nature may posses new (possibly lepton-flavor non-universal) interactions — though we need more data to be sure.
- LHCb has world-leading results for some regions of dark photon and Higgs portal parameter space, with great potential to expand these searches and to start exploring other hidden-sector models.
- Using Run 1 data, LHCb discovered 2 pentaquark structures. Including Run 2 data resolves one of these structures into 2 narrow pentaquark states, and reveals another new pentaquark. (The wide Pc(4380) state seen in Run 1 awaits confirmation from a 6-D amplitude analysis of this data sample, which is underway.)
- 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