



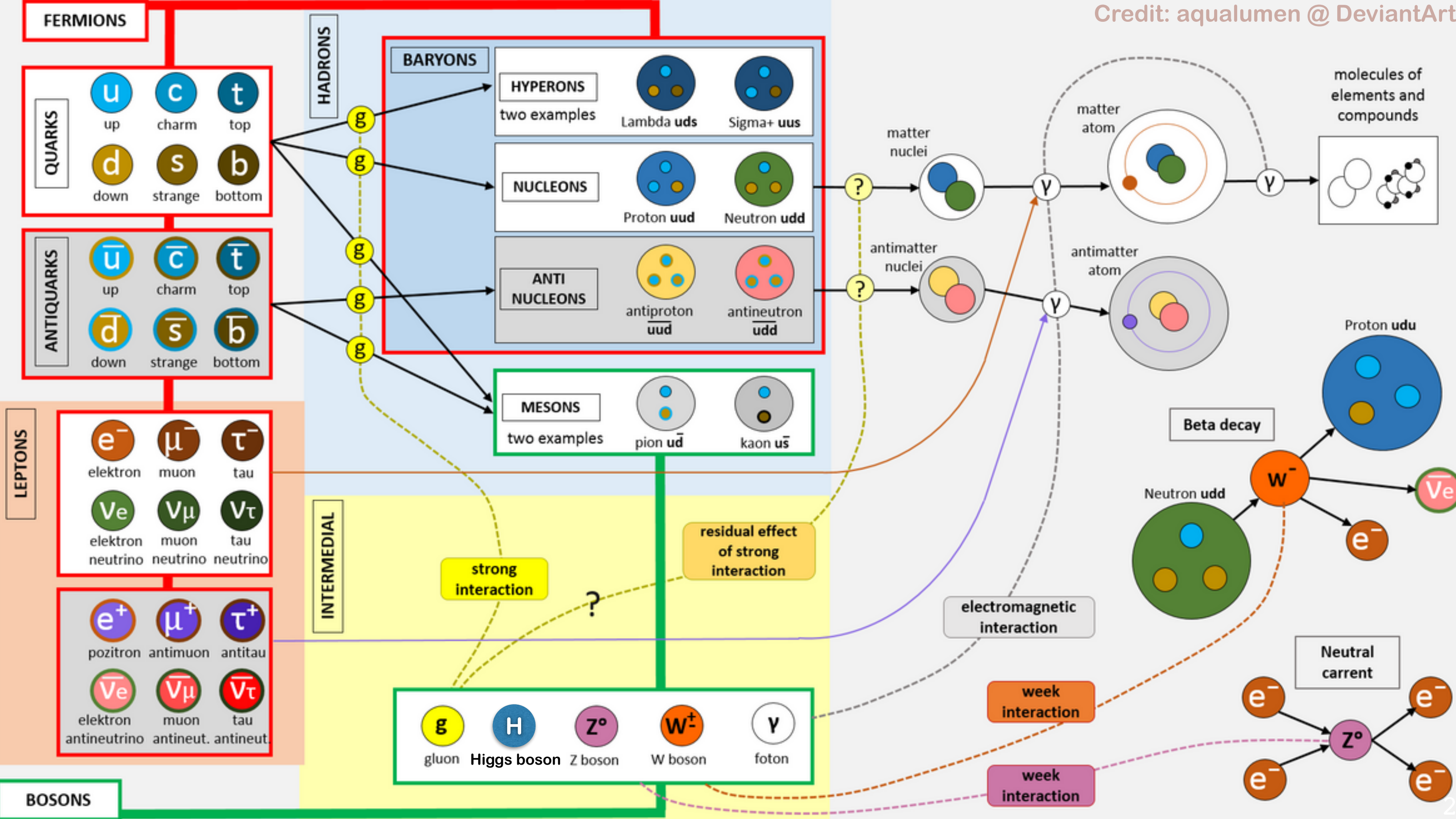
Djbel Aissa

Mirages, Oases, Mountains a journey through the Standard Model

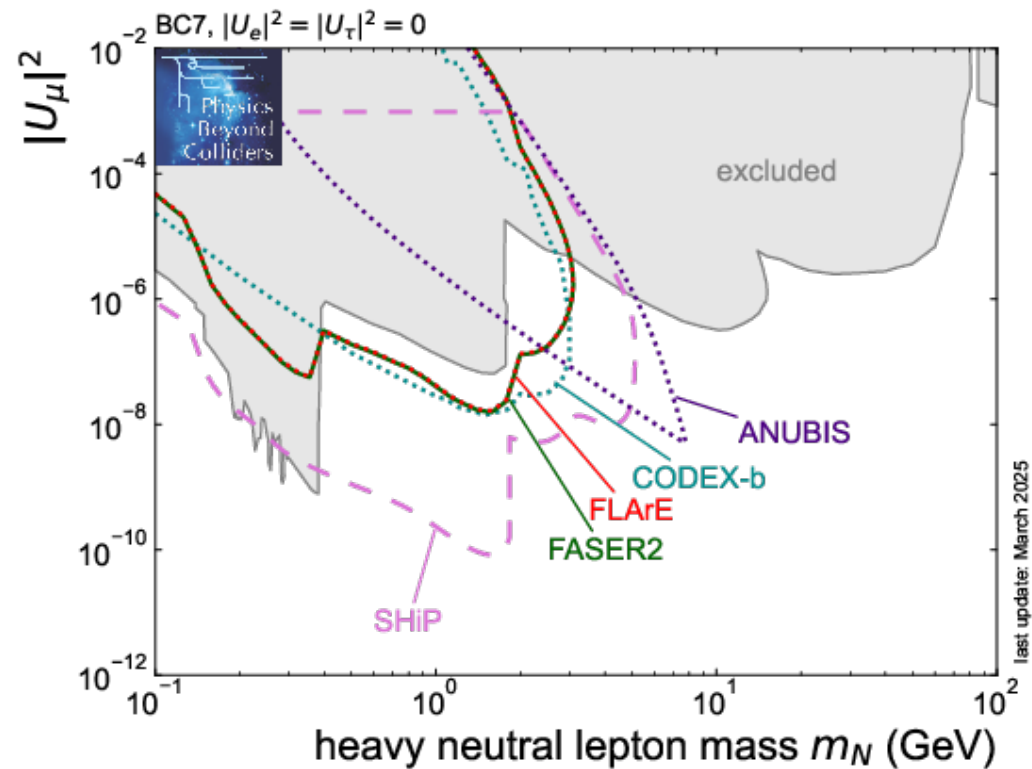


Vladimir V. Gligorov, CNRS/LPNHE
Seminar @ U of Warwick Physics Department 22.05.2025

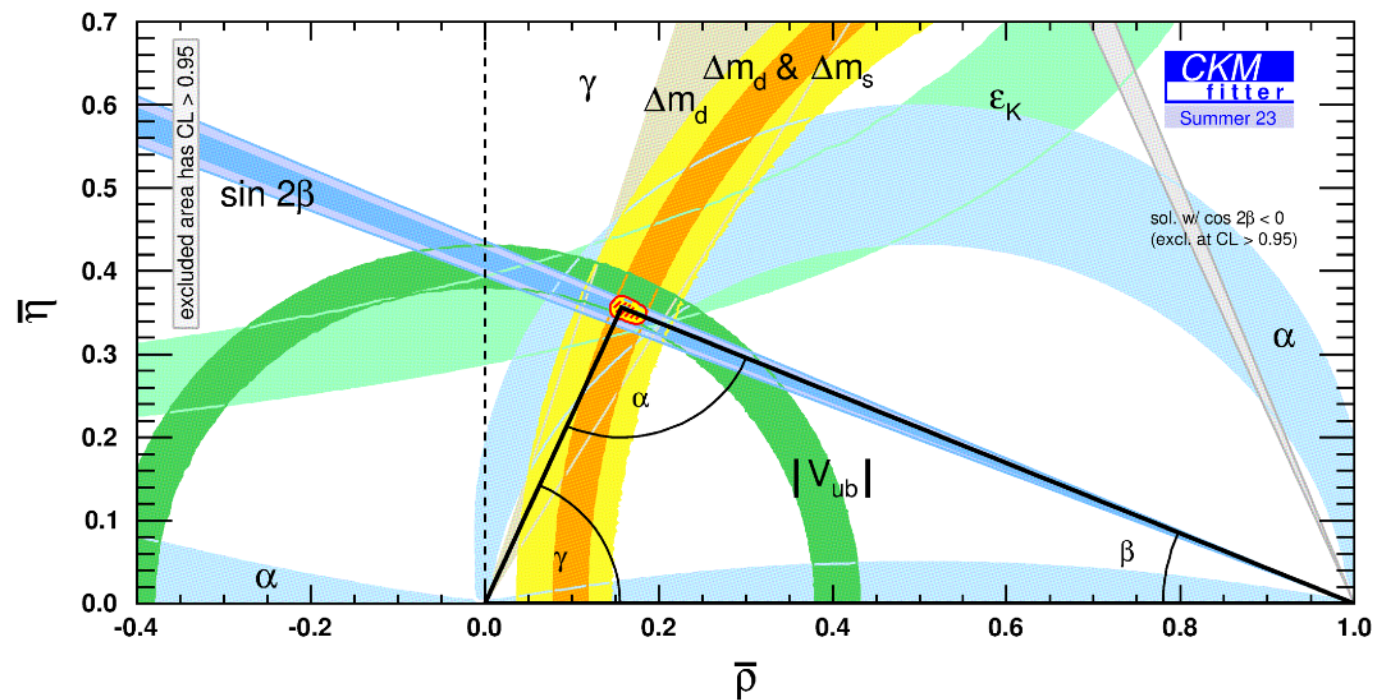
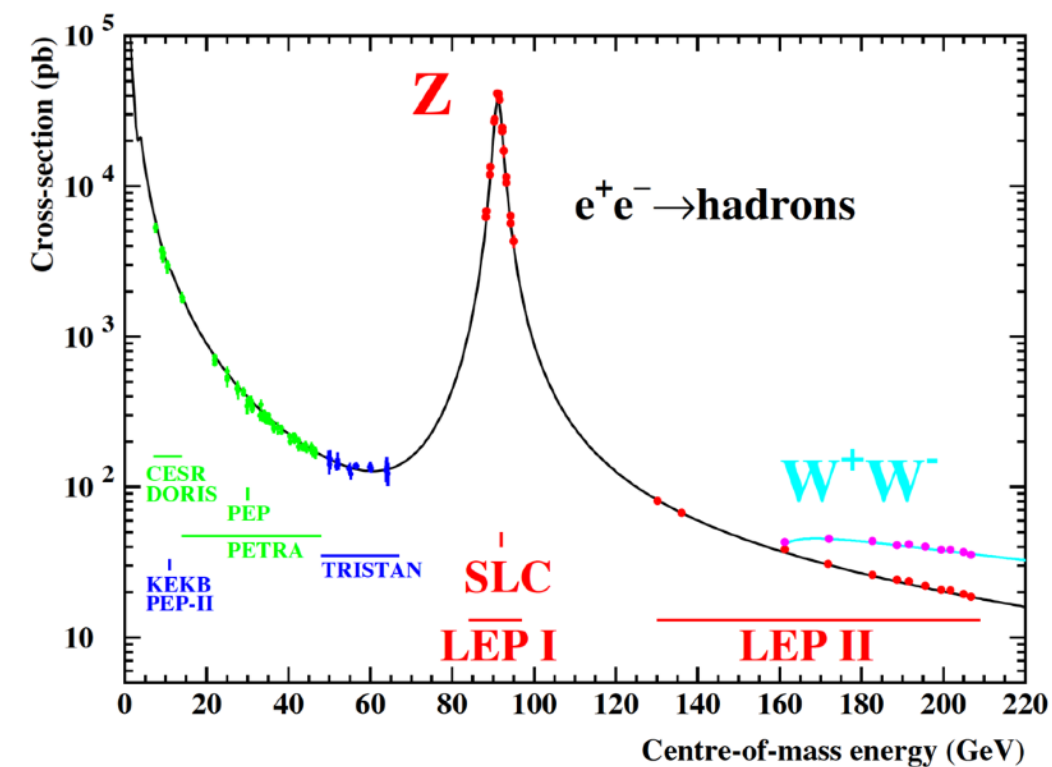
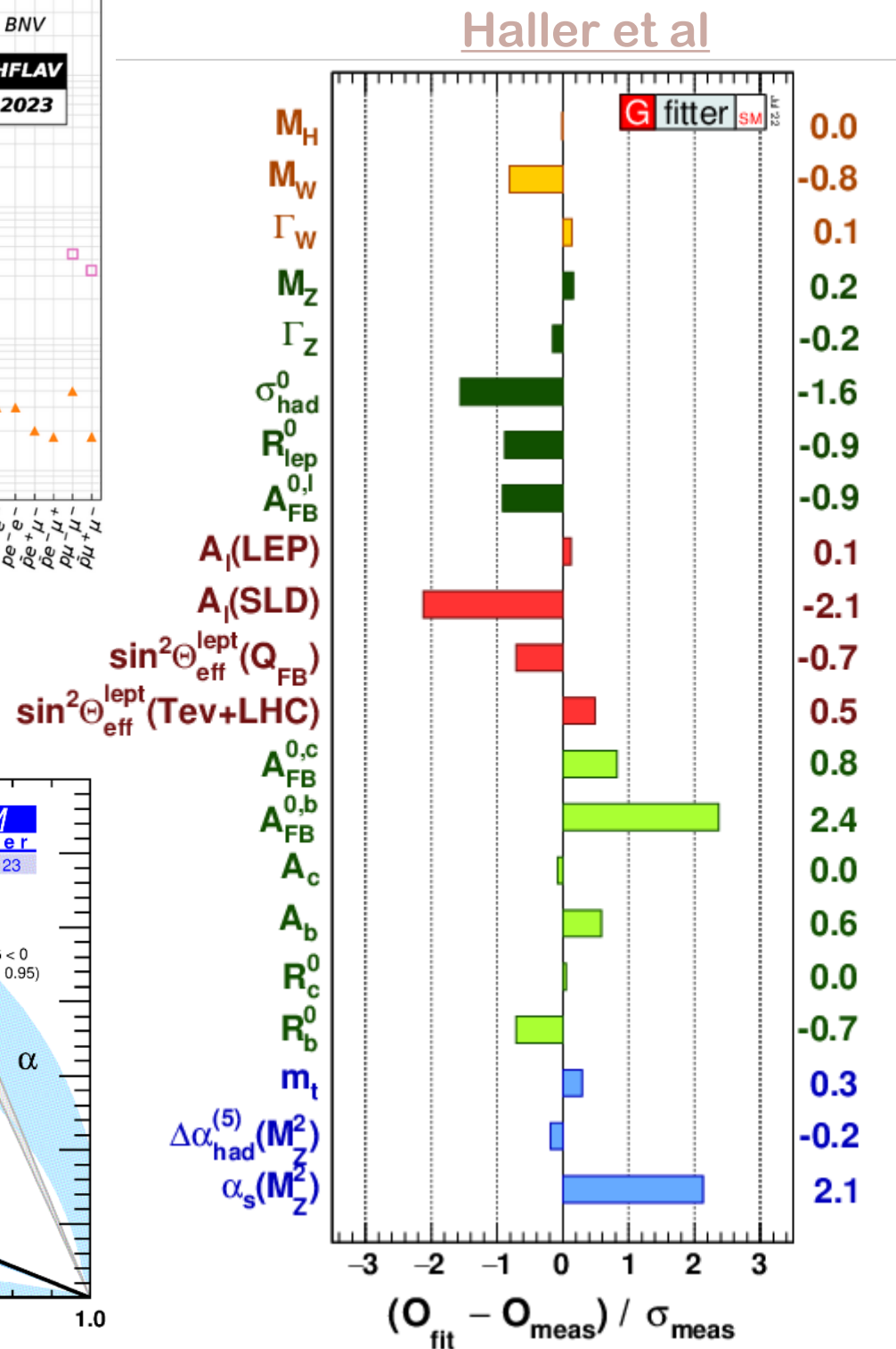
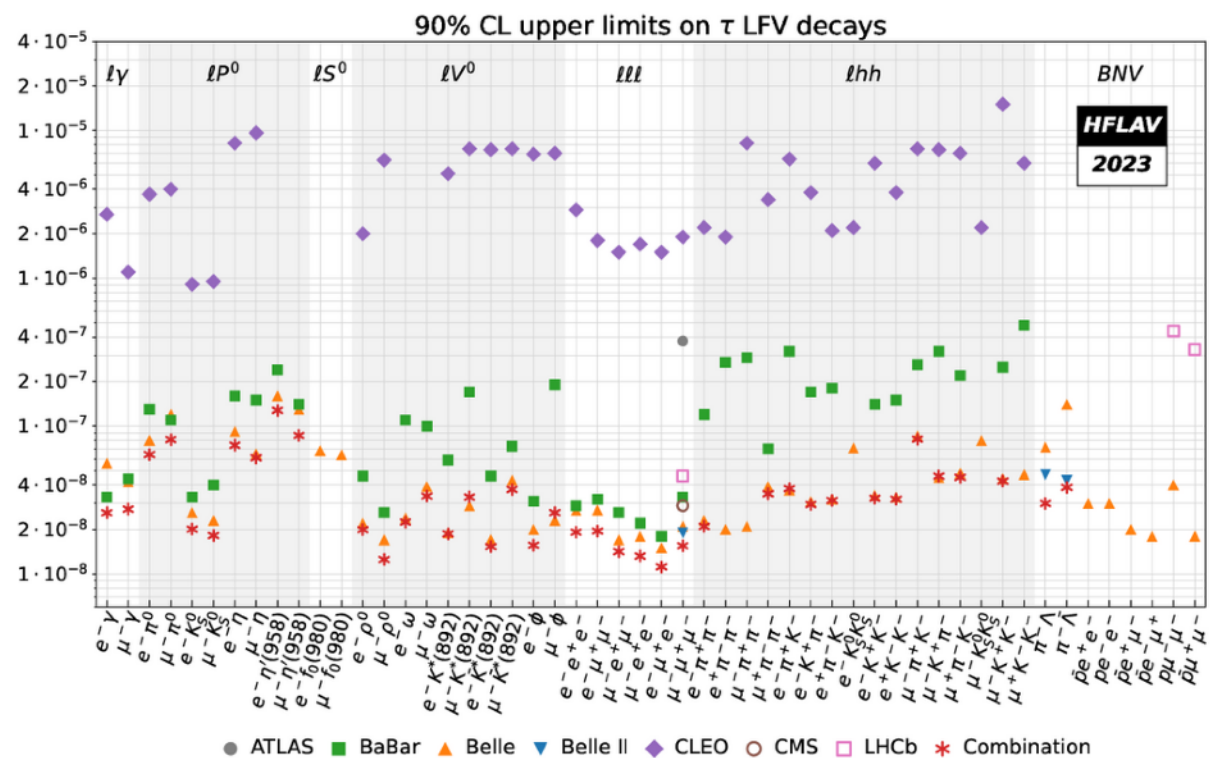




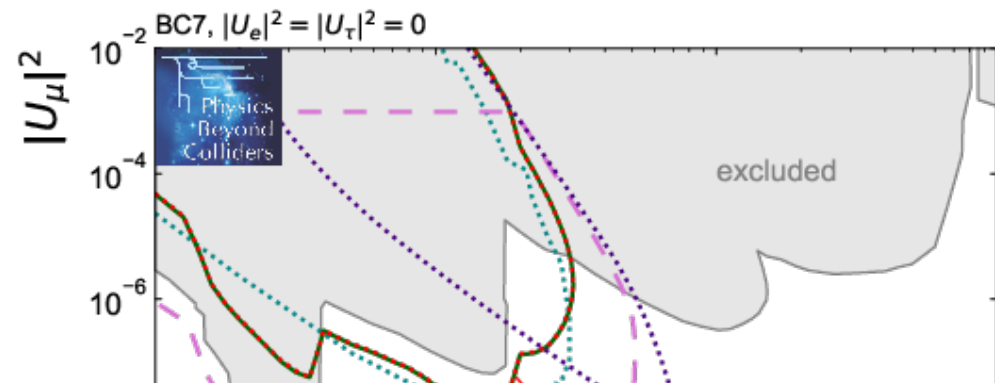
A century in the standard model desert



Alemany Fernandez et al



A century in the standard model desert



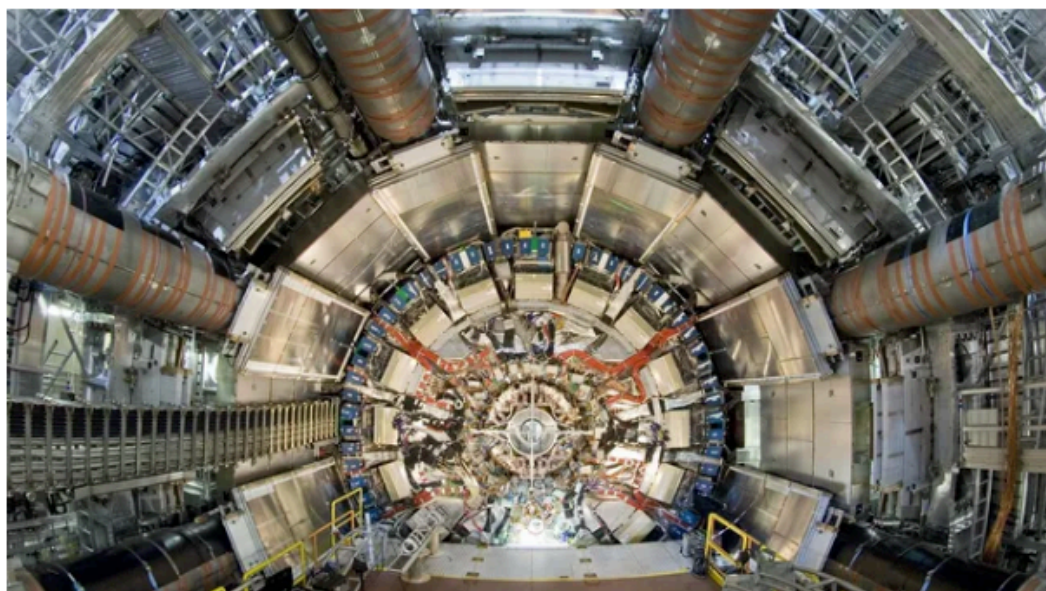
Famous Higgs boson behaves just as expected, 'most comprehensive studies' confirm

News By Tereza Pultarova published July 10, 2022

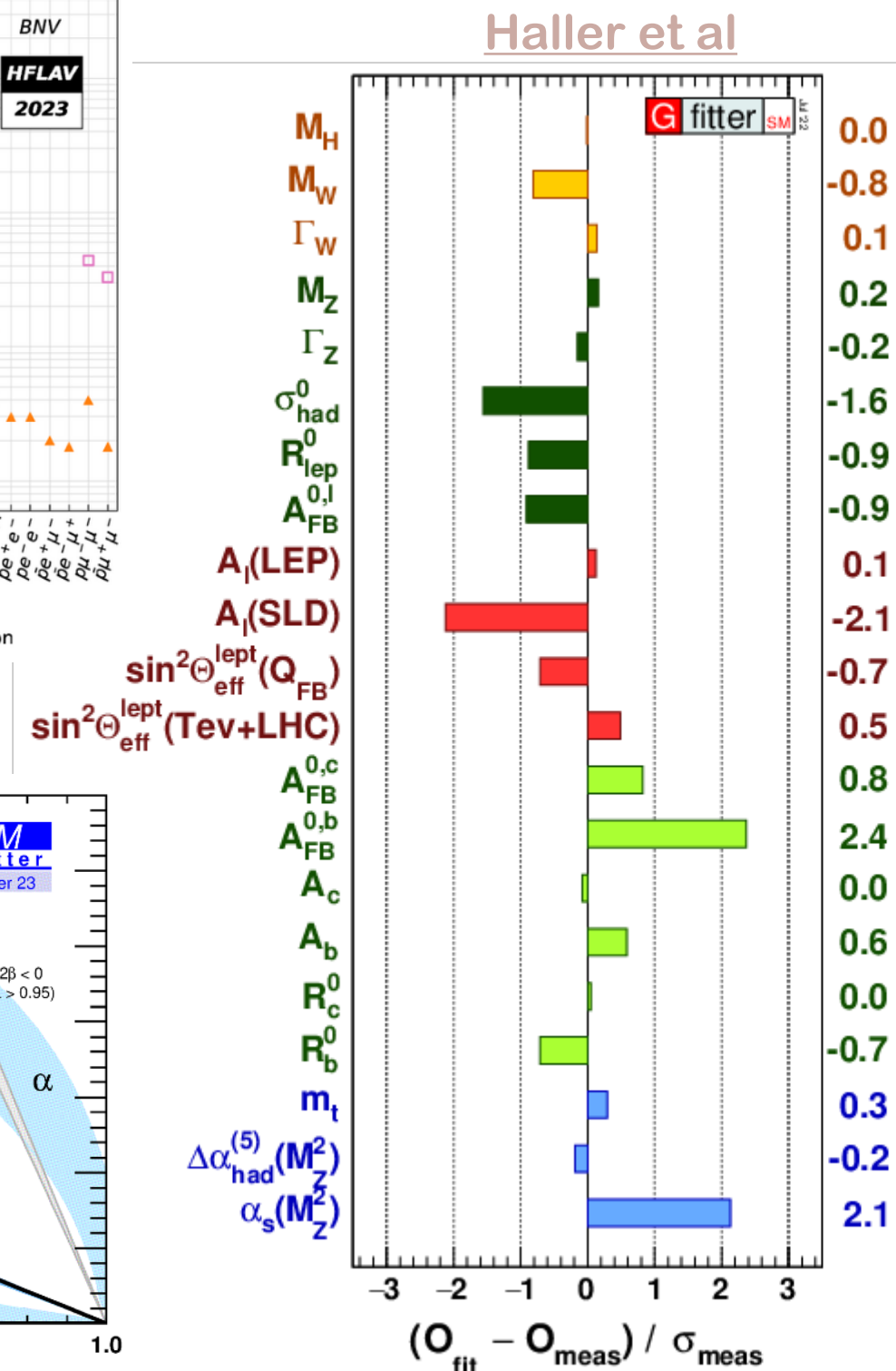
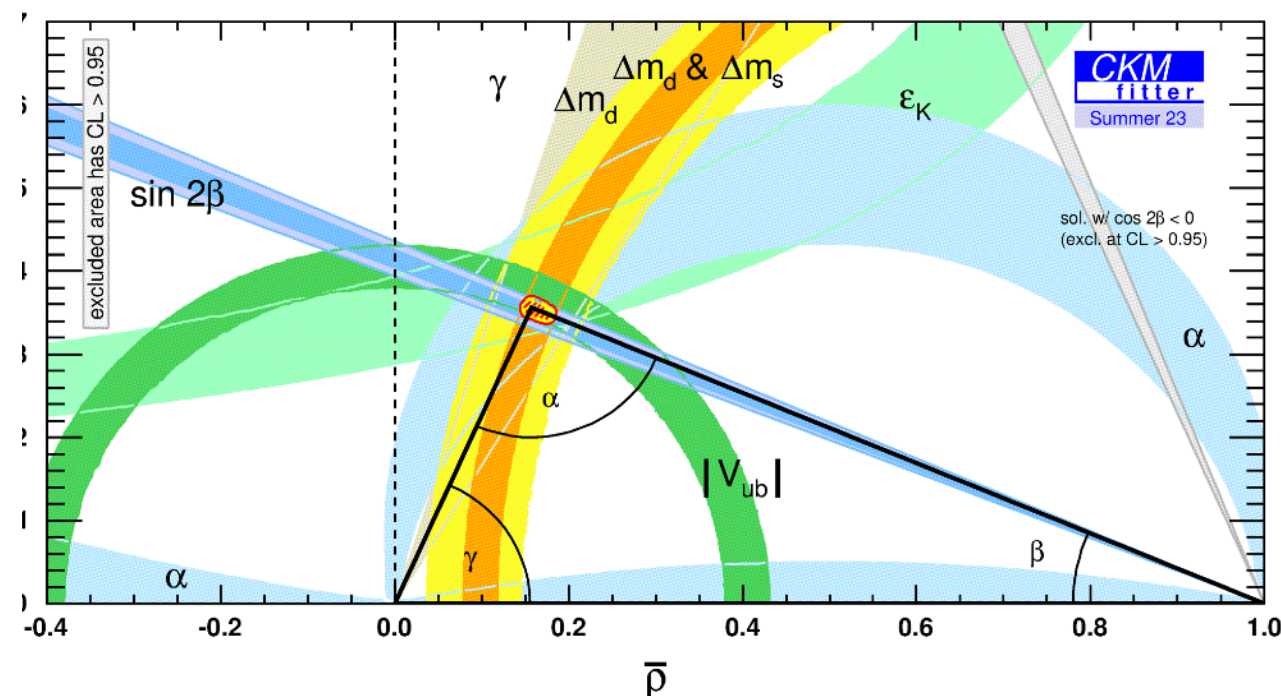
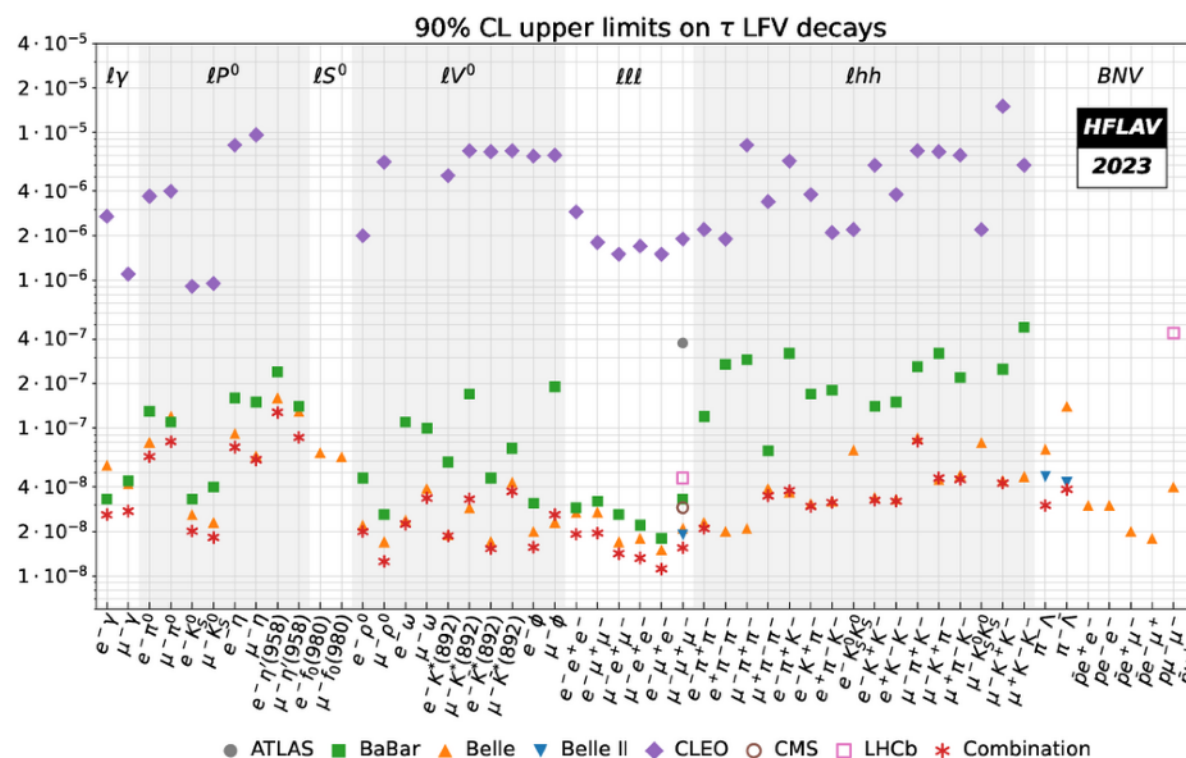
Scientists seem to understand the famous 'God Particle.'



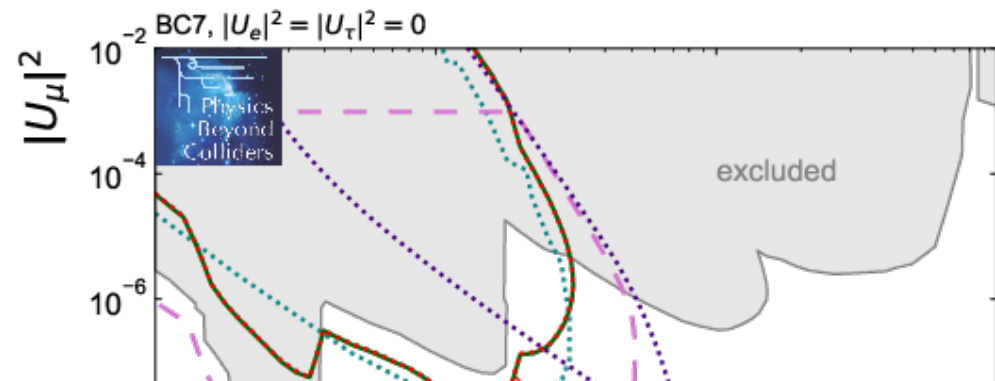
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The ATLAS instrument at CERN's Large Hadron Collider has detected millions of Higgs boson particles. (Image credit: CERN/Claudia Marcelloni/Max Brice)



A century in the standard model desert



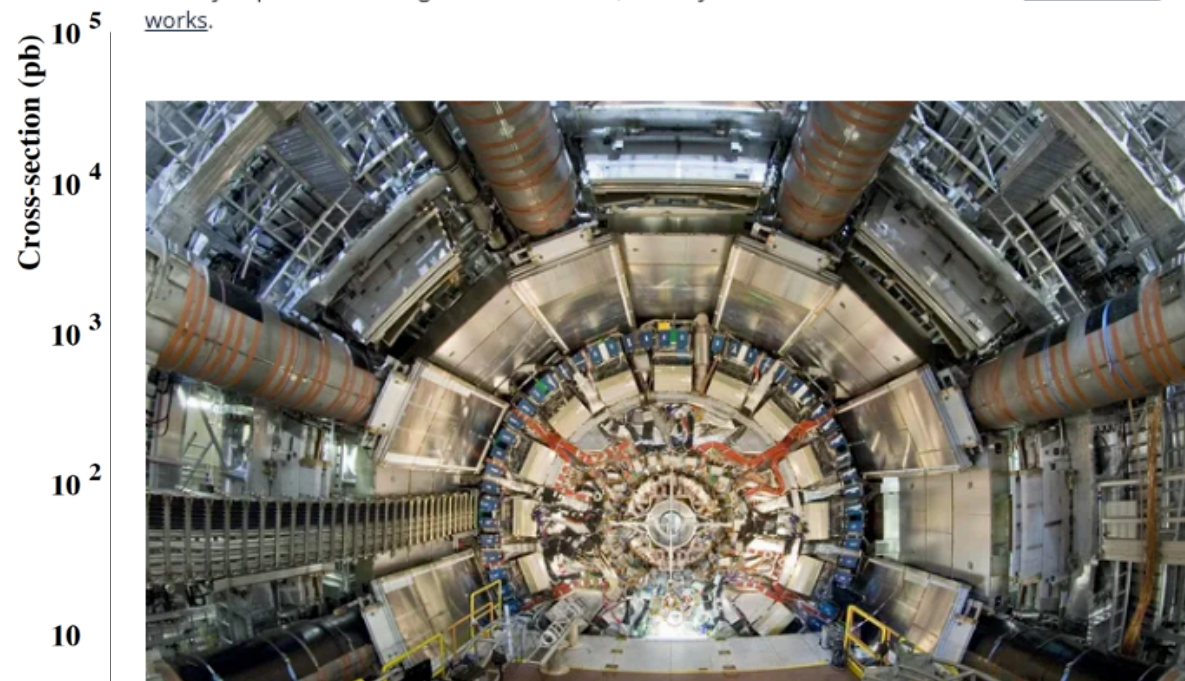
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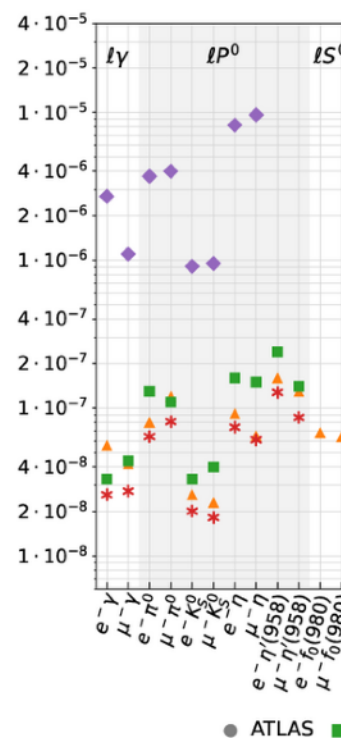
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STARTS WITH A BANG — DECEMBER 21, 2022

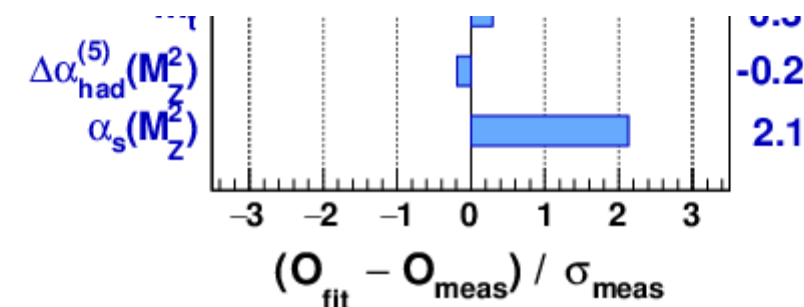
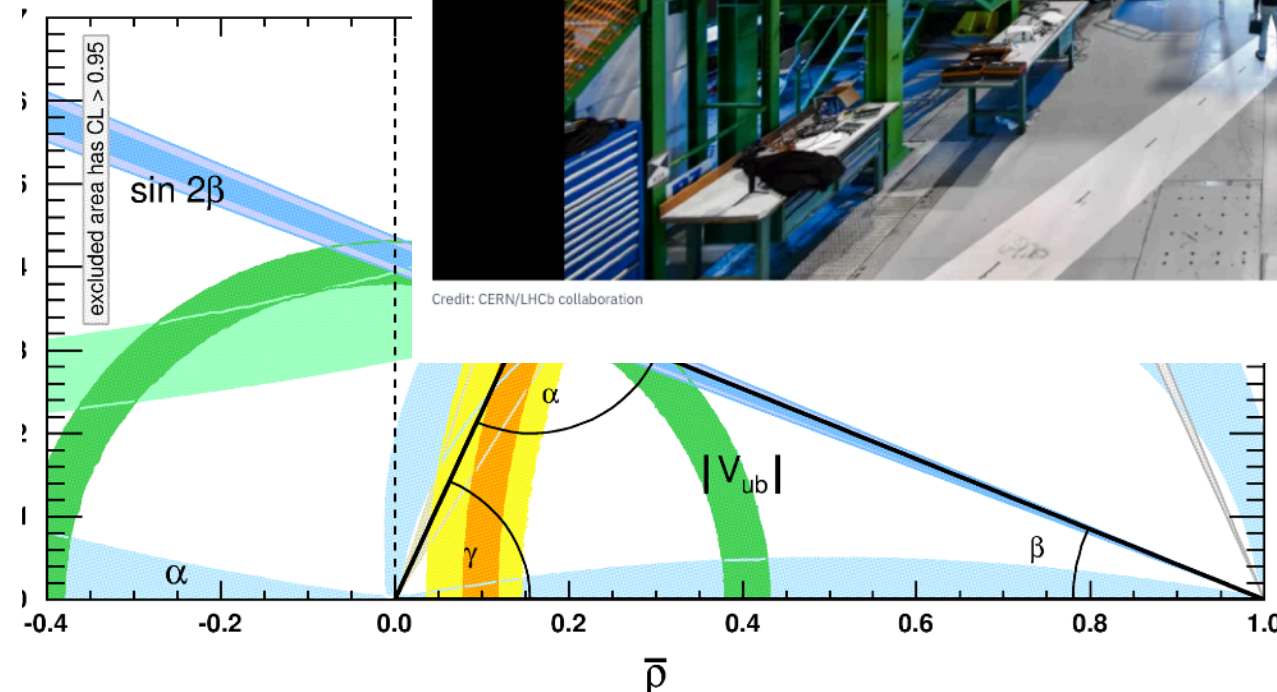
Standard Model survives its biggest challenge yet

For years and over three separate experiments, "lepton universality" appeared to violate the Standard Model. LHCb at last proved otherwise.

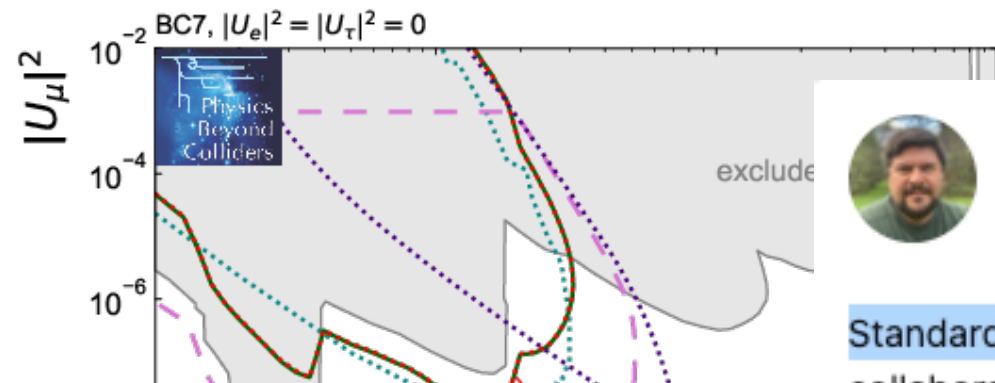


Credit: CERN/LHCb collaboration

The LHCb detector, at 5600 metric tonnes, is 21 meters long, 10 meters high, and 13 meters wide, optimized for detecting and studying particles (and their subsequent decays) that contain b-quarks inside them. At present, there are over 1500 scientists, engineers, and technicians that work on the LHCb collaboration.



A century in the standard model desert



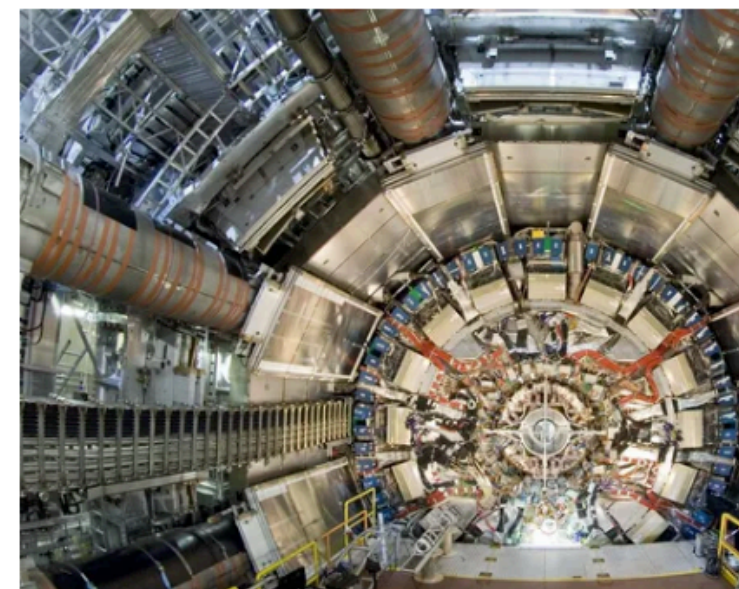
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Alexey Petrov

USC Endowed Chair in Physics, University of South Carolina
8mo

Standard Model wins again... the new measurement of the W-boson mass by the CMS collaboration is consistent with all previous measurements, except for the one by the CDF collaboration. Beautiful result!

LEP combination

Phys. Rep. 532 (2013) 119

D0

PRL 108 (2012) 151804

CDF

Science 376 (2022) 6589

LHCb

JHEP 01 (2022) 036

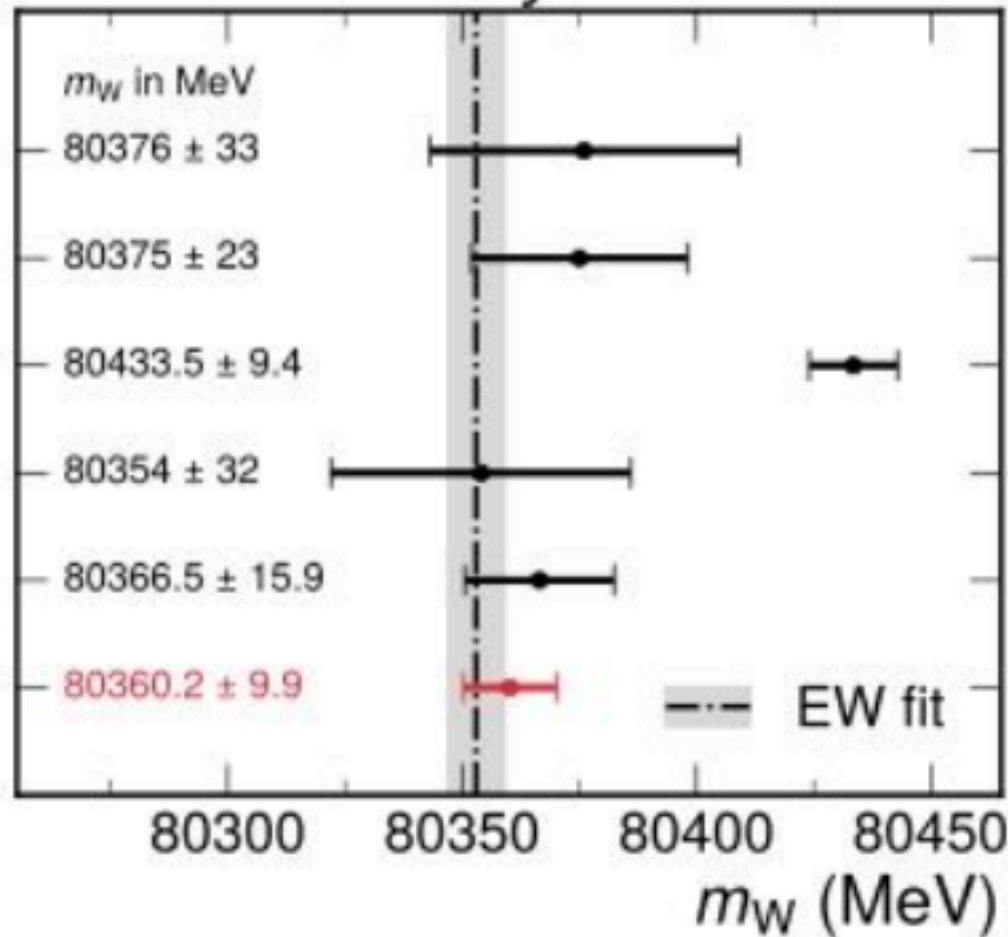
ATLAS

arxiv:2403.15085, subm. to EPJC

CMS

This Work

CMS Preliminary

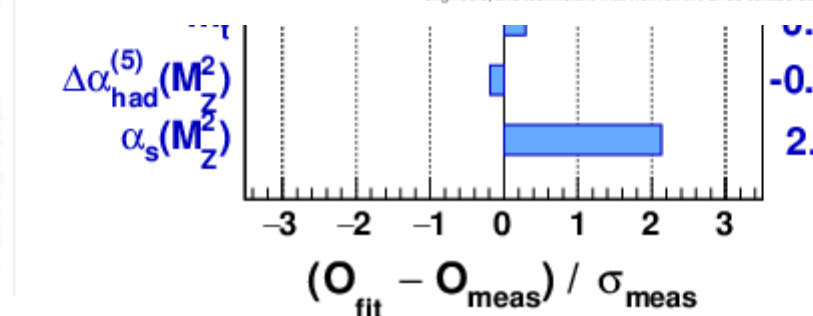


biggest challenge yet

Standard Model. LHCb



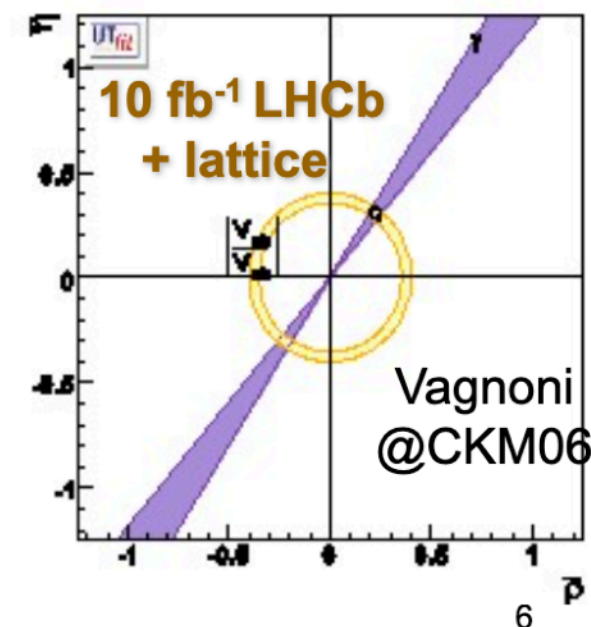
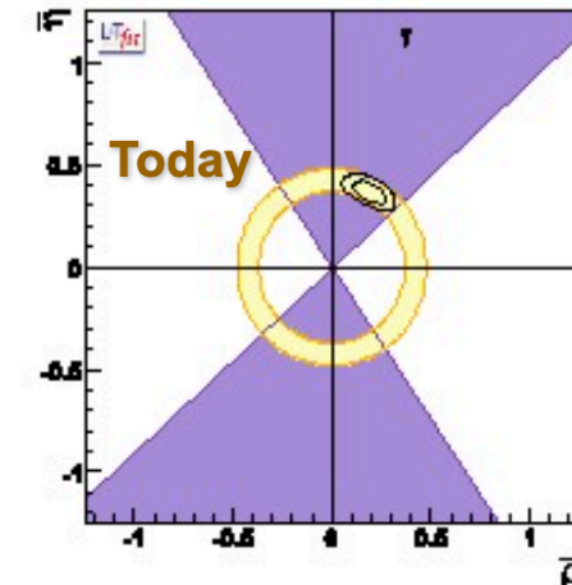
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A scenario formerly known as wasteland

The particle physics landscape in 2013

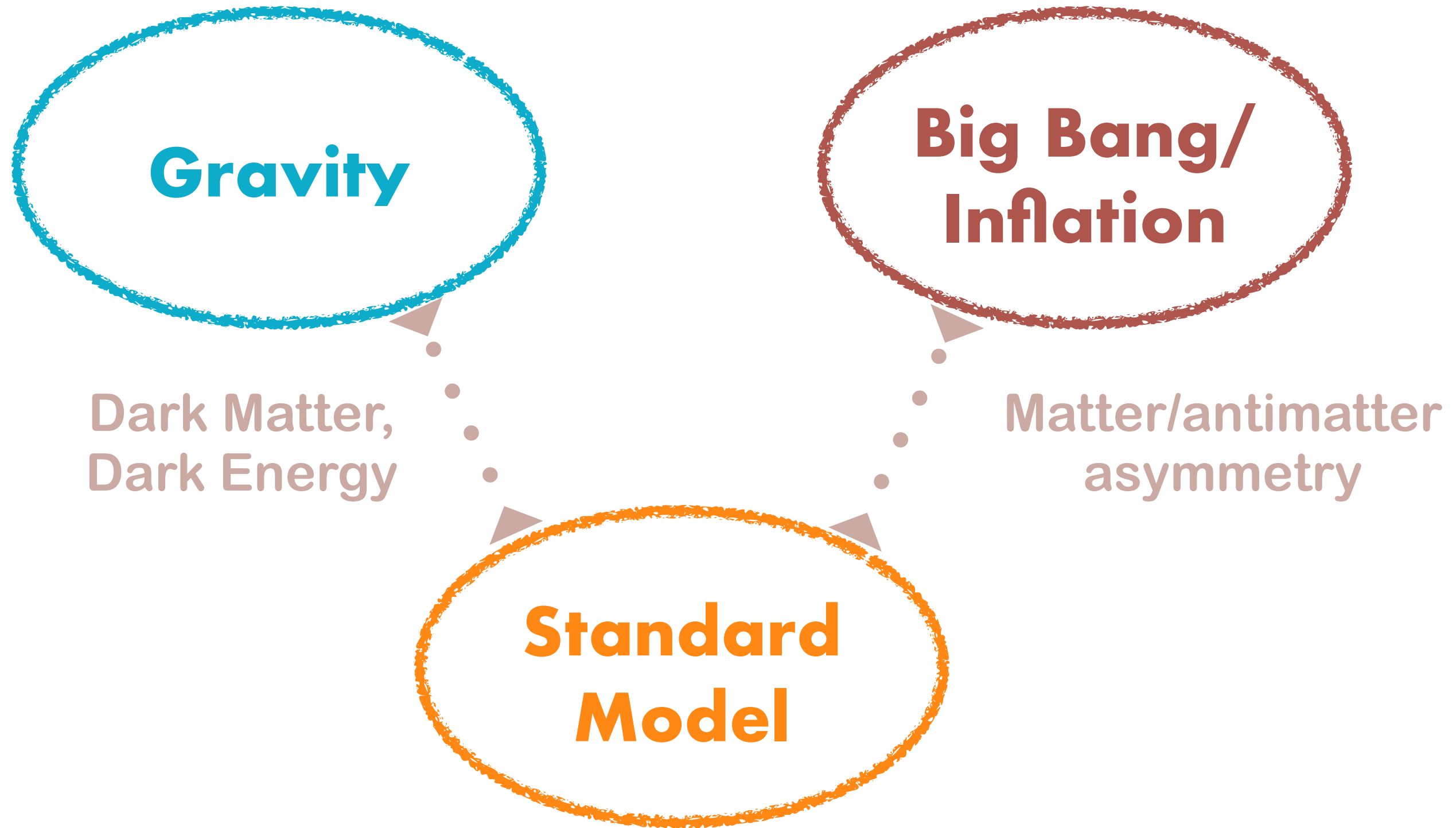
- All measurements listed on previous slide very sensitive to virtual NP effects
- Three tangible scenarios in 2013
 1. NP at GPDs and LHCb
 2. NP at LHCb but not at GPDs
 3. NP at GPDs not at LHCb
 - But maybe a few 2-3 σ effects
- **Trivial to motivate upgrade in first two**
- If we can build a powerful case for scenario 3 then we can justify upgrade before we see any NP signature
- There is a scenario 4 (LHC wasteland)
 - No one wants this!
 - However, virtual effects will be the only way to set scale of NP



22/6/2007

Cosener's Heavy Flavour Forum

And still we press on... why?



Flavour physics: mapping the desert

**Charm
physics**

**CKM
apex**

**Top
physics**

**Exotic
hadrons**

**Rare &
forbidden
processes**

Why do (yet) more flavour physics?

- 1. Necessary to precisely measure properties of fundamental particles (quarks & leptons)**
- 2. Complementary to precision Higgs&EW program in establishing beyond SM physics**
- 3. Leaves a legacy of knowledge about reality whether physics beyond the SM is readily accessible in a laboratory or not**

But aren't indirect searches overrated?

The TeraZ Mirage: New Physics Lost in Blind Directions

Mikael Chala, Juan Carlos Criado, Michael Spannowsky

The next generation of high-luminosity electron-positron colliders, such as FCC-ee and CEPC operating at the Z pole (TeraZ), is expected to deliver unprecedented precision in electroweak measurements. These precision observables are typically interpreted within the Standard Model Effective Field Theory (SMEFT), offering a powerful tool to constrain new physics. However, the large number of independent SMEFT operators allows for the possibility of blind directions, parameter combinations to which electroweak precision data are largely insensitive. In this work, we demonstrate that such blind directions are not merely an artefact of agnostic effective field theory scans, but arise generically in realistic ultraviolet completions involving multiple heavy fields. We identify several concrete multi-field extensions of the Standard Model whose low-energy SMEFT projections align with known blind subspaces, and show that these persist even after accounting for renormalisation group evolution and finite one-loop matching effects. Our analysis highlights that the apparent sensitivity to new physics of TeraZ may be significantly overestimated, and that indirect searches alone are often insufficient to rule out broad classes of ultraviolet physics. Complementary high-energy collider probes are therefore essential to fully explore the SMEFT parameter space.

With the preliminaries out of the way...

...let's meet three major components of our desert

Mirages: glimpses of the world beyond which vanish over time

Oases: refuges filled with fascinating curiosities

Mountains: intimidating boundaries (or are they?) to be crossed

Mirages



Many observables, many curiosities

[Submitted on 5 Mar 2008 ([v1](#)), last revised 23 Dec 2009 (this version, v2)]

First Evidence of New Physics in $b \leftrightarrow s$ Transitions

The UTfit Collaboration: [M. Bona](#), [M. Ciuchini](#), [E. Franco](#), [V. Lubicz](#), [G. Martinelli](#), [F. Parodi](#), [M. Pierini](#), [C. Schiavi](#), [L. Silvestrini](#), [V. Sordini](#), [A. Stocchi](#), [V. Vagnoni](#)

We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of B_s to $J/\psi \phi$ by the CDF and D0 collaborations. We find that the phase of the B_s mixing amplitude deviates more than 3 sigma from the Standard Model prediction. While no single measurement has a 3 sigma significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavors New Physics models with Minimal Flavour Violation with the same significance.

Comments: 5 pages, 2 figures, 2 tables. v2: added a note on more recent Tevatron results

Subjects: **High Energy Physics – Phenomenology (hep-ph)**

Cite as: [arXiv:0803.0659](#) [hep-ph]
(or [arXiv:0803.0659v2](#) [hep-ph] for this version)
<https://doi.org/10.48550/arXiv.0803.0659> 

Journal reference: PMC Phys.A3:6,2009

Related DOI: <https://doi.org/10.1186/1754-0410-3-6> 

Submission history

From: Luca Silvestrini [[view email](#)]

[v1] Wed, 5 Mar 2008 13:43:04 UTC (106 KB)

[v2] Wed, 23 Dec 2009 16:51:41 UTC (135 KB)

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[Submitted on 16 May 2010]

This is a first evidence of physics beyond the Standard Model with Minimal Flavour Violation with the same significance

Evidence for an anomalous like-sign dimuon charge asymmetry

The D0 Collaboration: [V.M. Abazov](#), et al

We measure the charge asymmetry A of like-sign dimuon events in 6.1 fb^{-1} of $p\bar{p}$ collisions recorded with the D0 detector at a center-of-mass energy $\sqrt{s} = 1.96 \text{ TeV}$ at the Fermilab Tevatron collider. From A , we extract the like-sign dimuon charge asymmetry in semileptonic b -hadron decays: $A_{\text{SL}} = -0.00957 \pm 0.00251 (\text{stat}) \pm 0.00146 (\text{syst})$. This result differs by 3.2 standard deviations from the standard model prediction $A_{\text{SL}}(\text{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$ and provides first evidence of anomalous CP-violation in the mixing of neutral B mesons.

Comments: 5 pages, 2 figures, 2 tables. v2: added a
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Cite as: [arXiv:0803.0659](#) [**hep-ph**]
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<https://doi.org/10.48550/arXiv.0803.0659>
Journal reference: PMC Phys.A3:6,2009
Related DOI: <https://doi.org/10.1186/1754-0410-3-6>

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[v1] Wed, 5 Mar 2008 13:43:04 UTC (106 KB)

[v2] Wed, 23 Dec 2009 16:51:41 UTC (135 KB)

Comments: Submitted to Phys. Rev. D
Subjects: **High Energy Physics – Experiment (hep-ex)**
Report number: Fermilab-Pub-10/114-E
Cite as: [arXiv:1005.2757](#) [**hep-ex**]
(or [arXiv:1005.2757v1](#) [**hep-ex**] for this version)
<https://doi.org/10.48550/arXiv.1005.2757> 
Journal reference: Phys.Rev.D82:032001,2010
Related DOI: <https://doi.org/10.1103/PhysRevD.82.032001> 

Submission history

From: Guennadi Borissov [[view email](#)]

[v1] Sun, 16 May 2010 16:18:52 UTC (183 KB)

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Cite as: [arXiv:0803.0659](#) [hep-ph]

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Journal reference: PMC Phys.A3:6,2009

Related DOI: <https://doi.org/10.1186/1754-0410-3-6>

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[v2] Wed, 23 Dec 2009 16:51:41 UTC (135 KB)

Comments: Submitted to Phys. Rev. D
Subjects: High Energy Physics - Experiment
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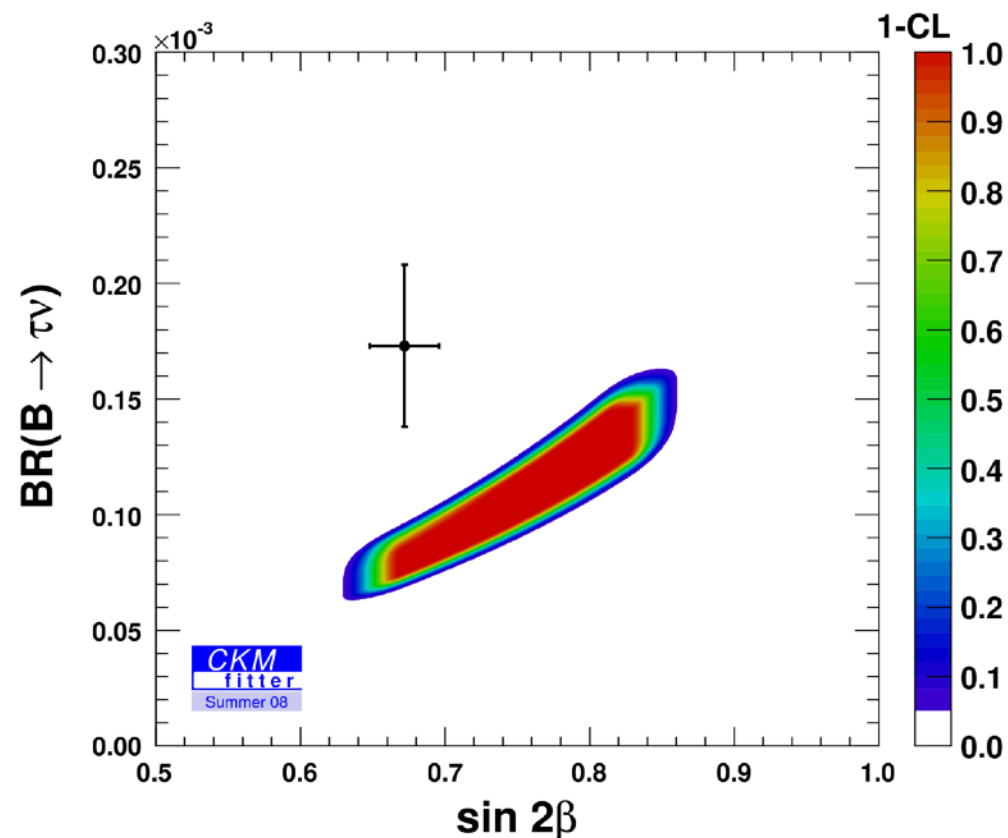
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Evidence for an anomalous like-sign dimuon charge asymmetry

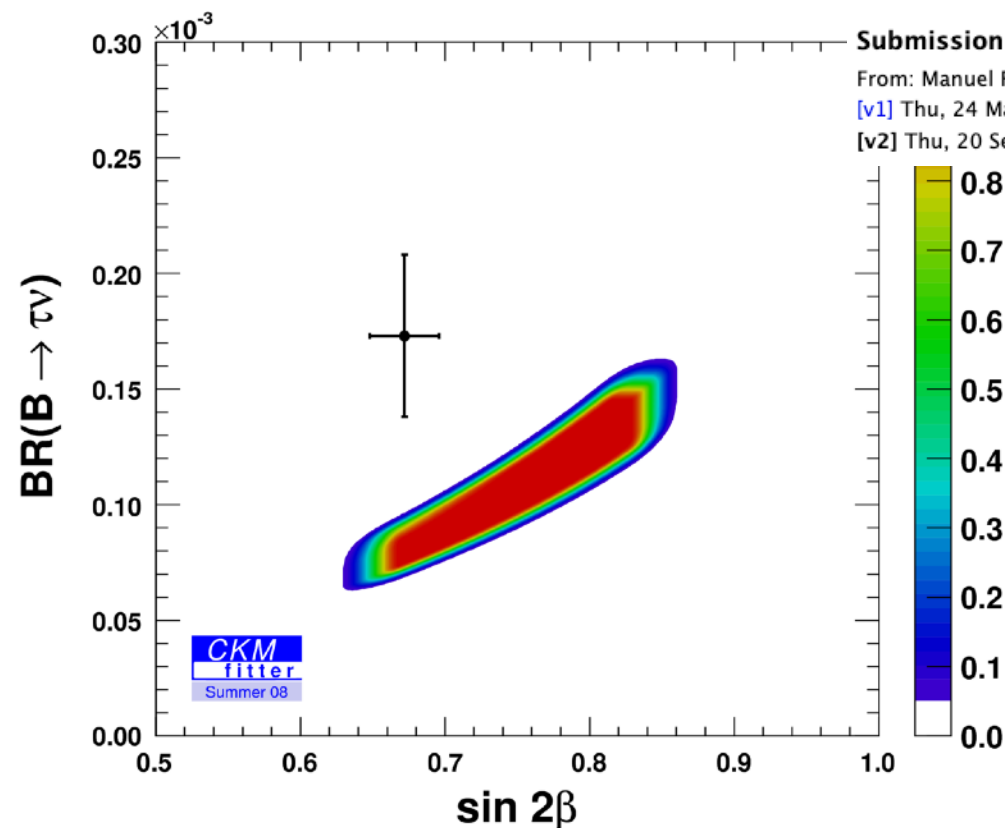
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Comments: Submitted to Phys. Rev. D
Subjects: **High Energy Physics – Experiment**
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Cite as: [arXiv:1005.2757 \[hep-ex\]](#)
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Submission history

From: Guennadi Borissov [[view email](#)]
[v1] Sun, 16 May 2010 16:18:52 UTC (183 KB)



[Submitted on 24 May 2012 (v1), last revised 20 Sep 2012 (this version, v2)]

Evidence for an excess of $B \rightarrow D^{(*)} \tau \nu$ decays

The BaBar Collaboration

Based on the full BaBar data sample, we report improved measurements of the ratios $R(D^{(*)}) = \mathcal{B}(B \rightarrow D^{(*)} \tau \nu) / \mathcal{B}(B \rightarrow D^{(*)} \ell \nu)$, where ℓ is either e or μ . These ratios are sensitive to new physics contributions in the form of a charged Higgs boson. We measure $R(D) = 0.440 \pm 0.058 \pm 0.042$ and $R(D^{*}) = 0.332 \pm 0.024 \pm 0.018$, which exceed the Standard Model expectations by 2.0 sigma and 2.7 sigma, respectively. Taken together, our results disagree with these expectations at the 3.4 sigma level. This excess cannot be explained by a charged Higgs boson in the type II two-Higgs-doublet model. We also report the observation of the decay $B \rightarrow D \tau \nu$, with a significance of 6.8 sigma.

Comments: Expanded section on systematics, text corrections, improved the format of Figure 2 and included the effect of the change of the Tau polarization due to the charged Higgs
Subjects: **High Energy Physics – Experiment (hep-ex)**
Report number: BABAR-PUB-12/012; SLAC-PUB-15028
Cite as: [arXiv:1205.5442 \[hep-ex\]](#)
(or [arXiv:1205.5442v2 \[hep-ex\]](#) for this version)
<https://doi.org/10.48550/arXiv.1205.5442>
Journal reference: Phys. Rev. Lett. 109, 101802 (2012)
Related DOI: <https://doi.org/10.1103/PhysRevLett.109.101802>

Submission history

From: Manuel Franco Sevilla [[view email](#)]
[v1] Thu, 24 May 2012 13:43:06 UTC (444 KB)
[v2] Thu, 20 Sep 2012 19:54:26 UTC (370 KB)

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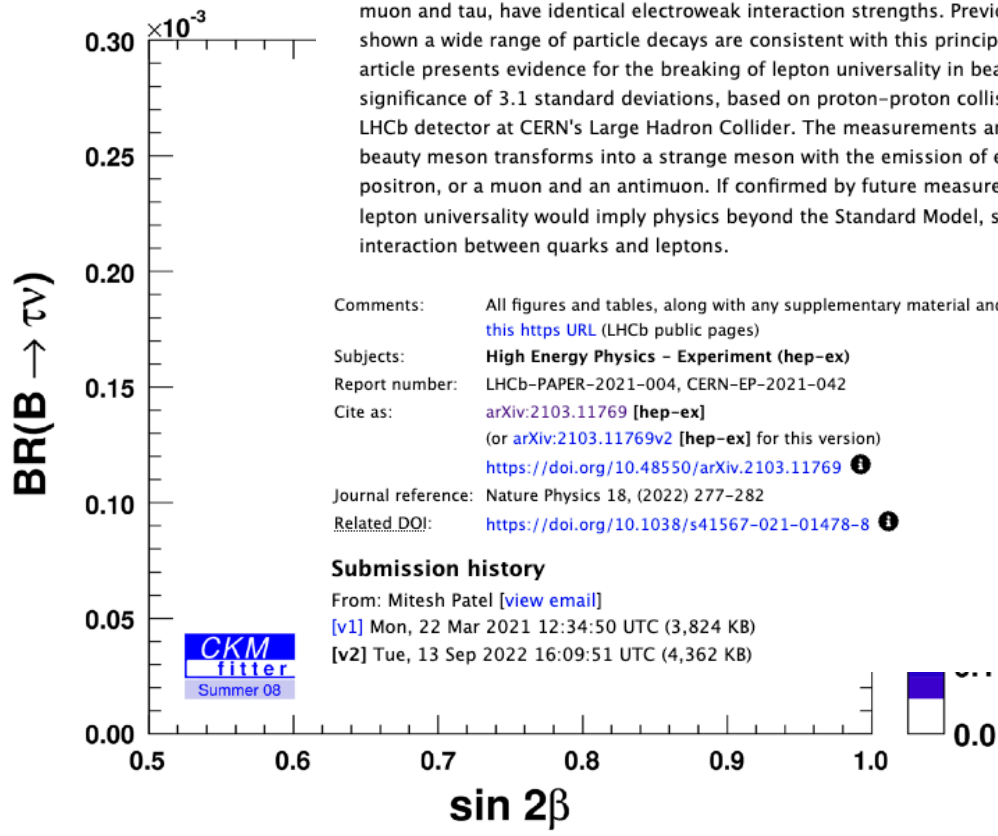
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Evidence for an excess of $B \rightarrow D^{(*)} \tau \nu$ decays

[Submitted on 22 Mar 2021 (v1), last revised 13 Sep 2022 (this version, v2)]

Test of lepton universality in beauty-quark decays

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The Standard Model of particle physics currently provides our best description of fundamental particles and their interactions. The theory predicts that the different charged leptons, the electron, muon and tau, have identical electroweak interaction strengths. Previous measurements have shown a wide range of particle decays are consistent with this principle of lepton universality. This article presents evidence for the breaking of lepton universality in beauty-quark decays, with a significance of 3.1 standard deviations, based on proton-proton collision data collected with the LHCb detector at CERN's Large Hadron Collider. The measurements are of processes in which a beauty meson transforms into a strange meson with the emission of either an electron and a positron, or a muon and an antimuon. If confirmed by future measurements, this violation of lepton universality would imply physics beyond the Standard Model, such as a new fundamental interaction between quarks and leptons.

Comments: All figures and tables, along with any supplementary material and additional information, are available at [this https URL](#) (LHCb public pages)
Subjects: **High Energy Physics – Experiment (hep-ex)**
Report number: LHCb-PAPER-2021-004, CERN-EP-2021-042
Cite as: [arXiv:2103.11769 \[hep-ex\]](#)
(or [arXiv:2103.11769v2 \[hep-ex\]](#) for this version)
<https://doi.org/10.48550/arXiv.2103.11769>
Journal reference: Nature Physics 18, (2022) 277–282
Related DOI: <https://doi.org/10.1038/s41567-021-01478-8>

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[v2] Tue, 13 Sep 2022 16:09:51 UTC (4,362 KB)

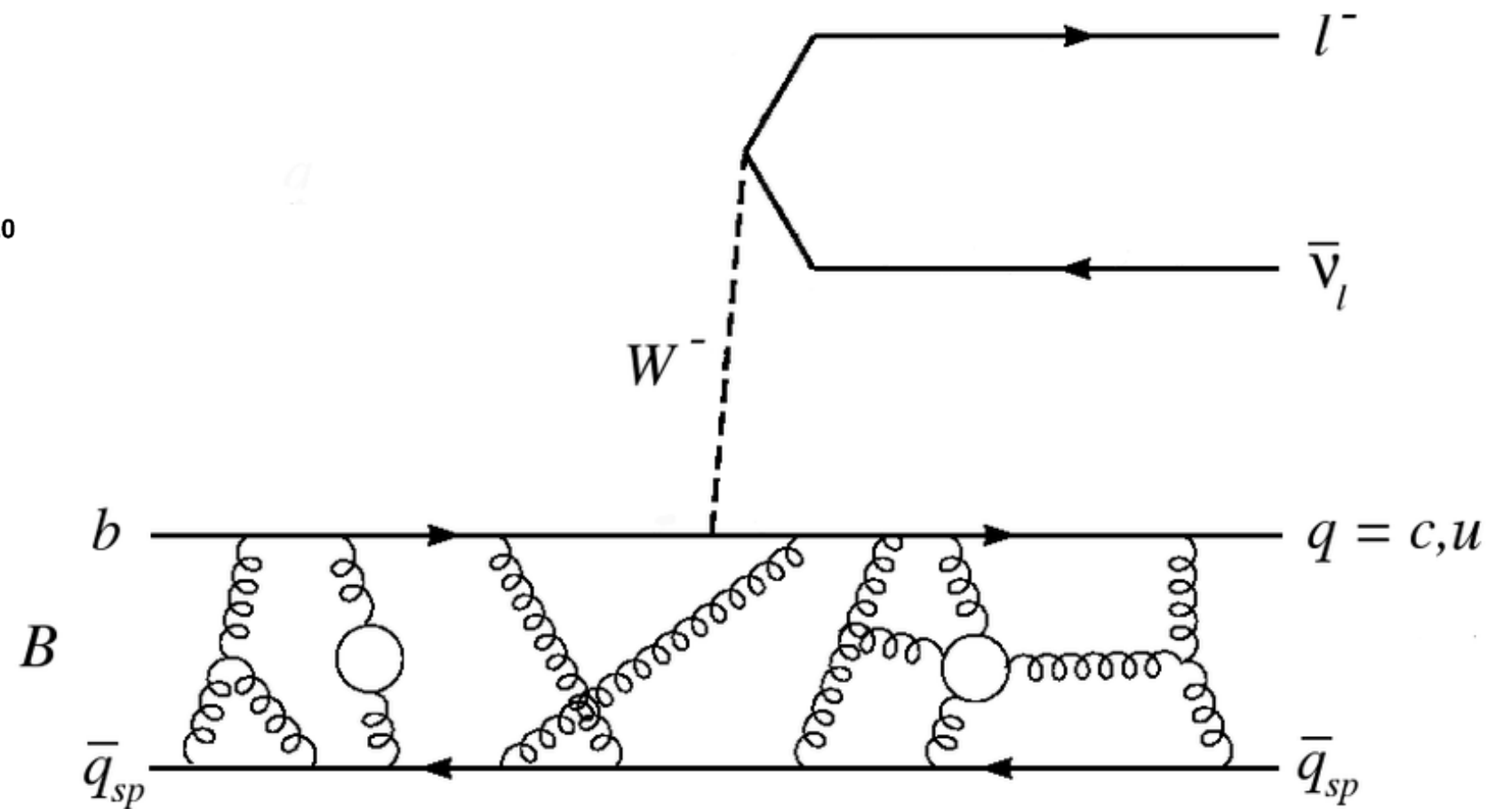
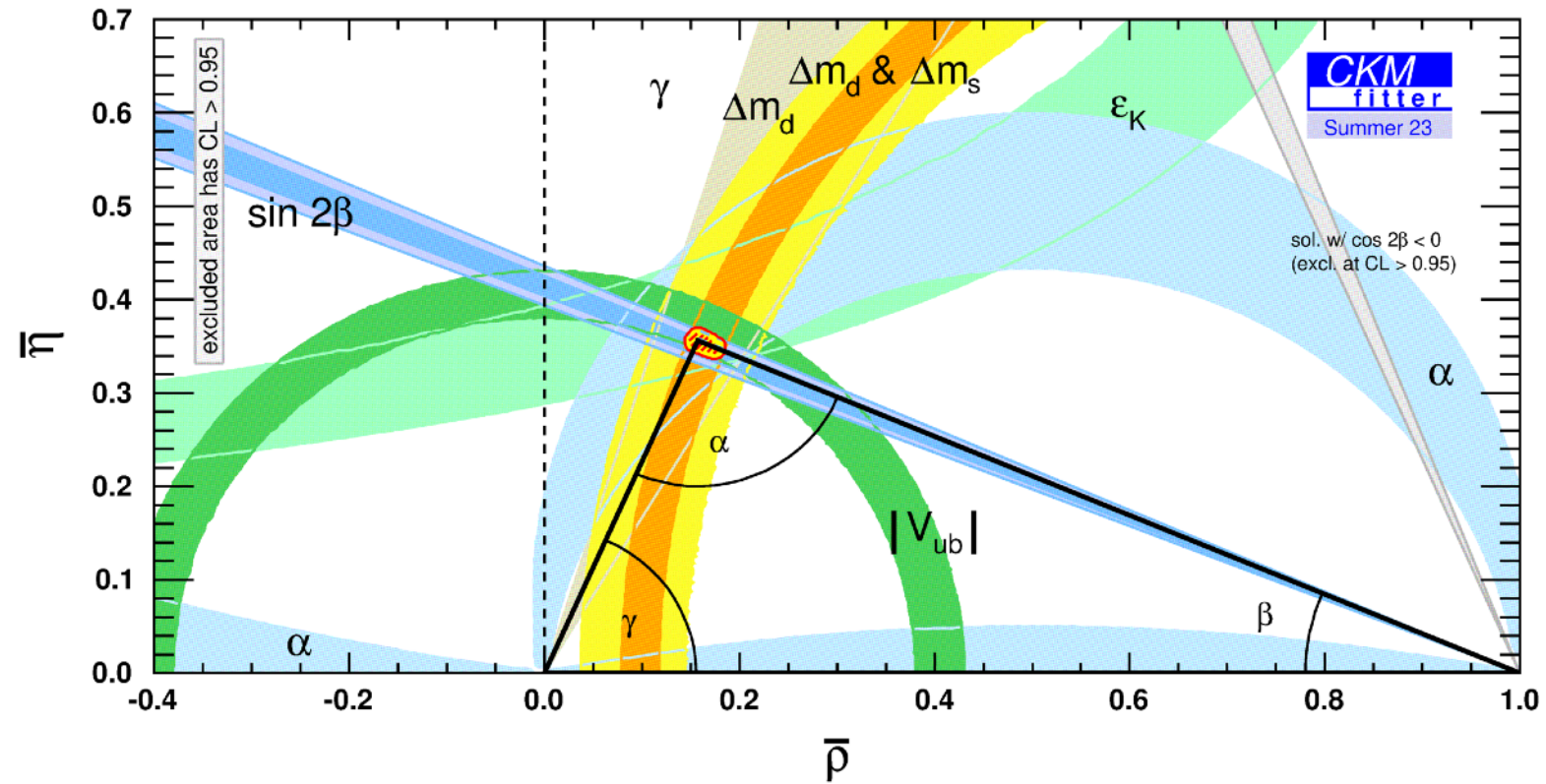
port improved measurements of the ratios $R(D^{(*)}) = \mathcal{B}(B \rightarrow D^{(*)} \tau \nu) / \mathcal{B}(B \rightarrow D^{(*)} \ell \nu)$ where ℓ is either e or mu. These ratios are sensitive to new physics beyond the Standard Model, such as a charged Higgs boson. We measure $R(D) = 0.440 \pm 0.058$ (stat) ± 0.018 (syst), which exceed the Standard Model expectations by 3.1 standard deviations. When taken together, our results disagree with these expectations. This excess cannot be explained by a charged Higgs boson in the Standard Model. We also report the observation of the decay $B \rightarrow D \tau \nu$.

text corrections, improved the format of Figure 2 and included the polarization due to the charged Higgs

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5028

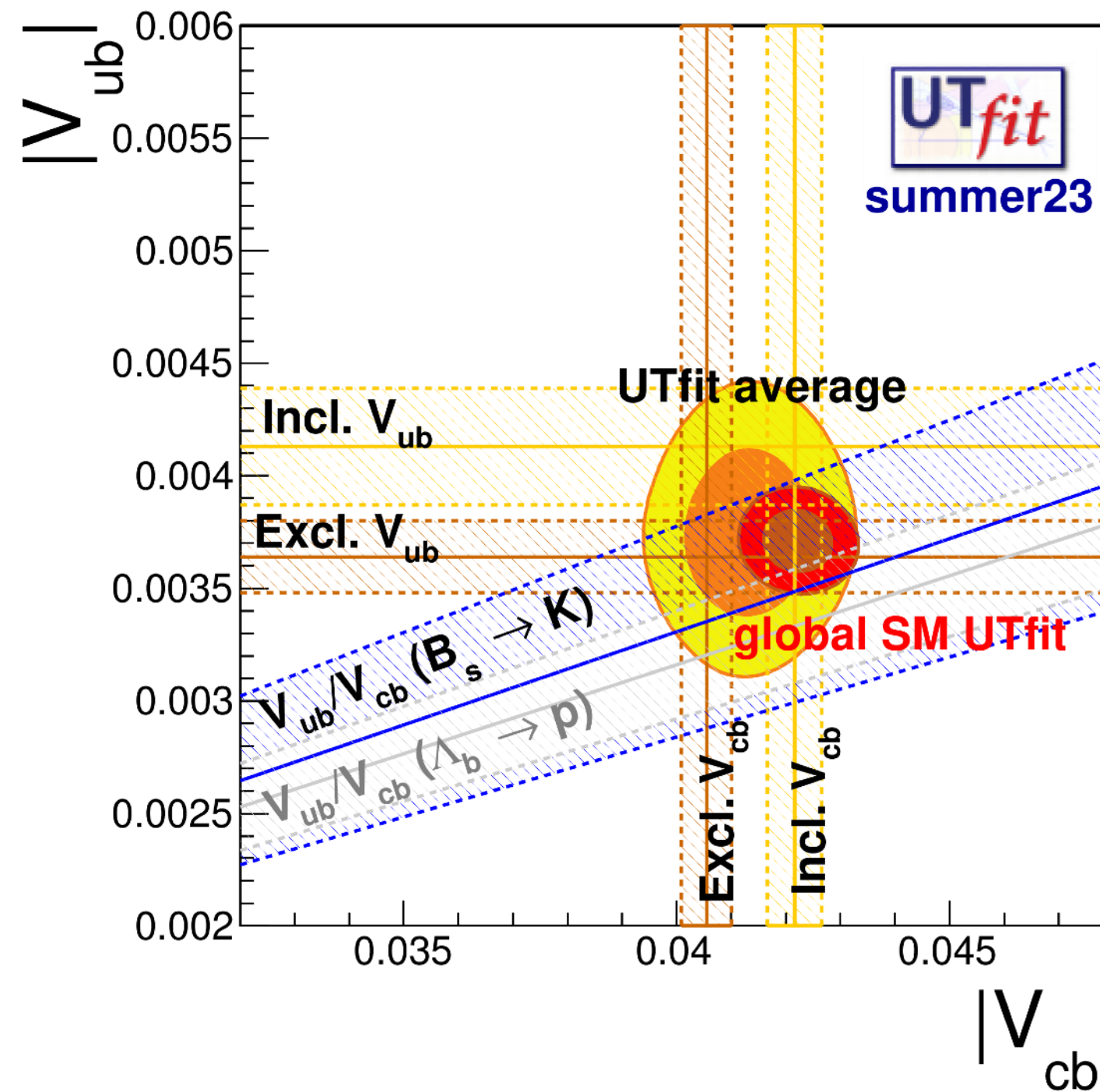
or this version)
[205.5442](#)
2)
[Lett.109.101802](#)

V_{ub} and V_{cb}

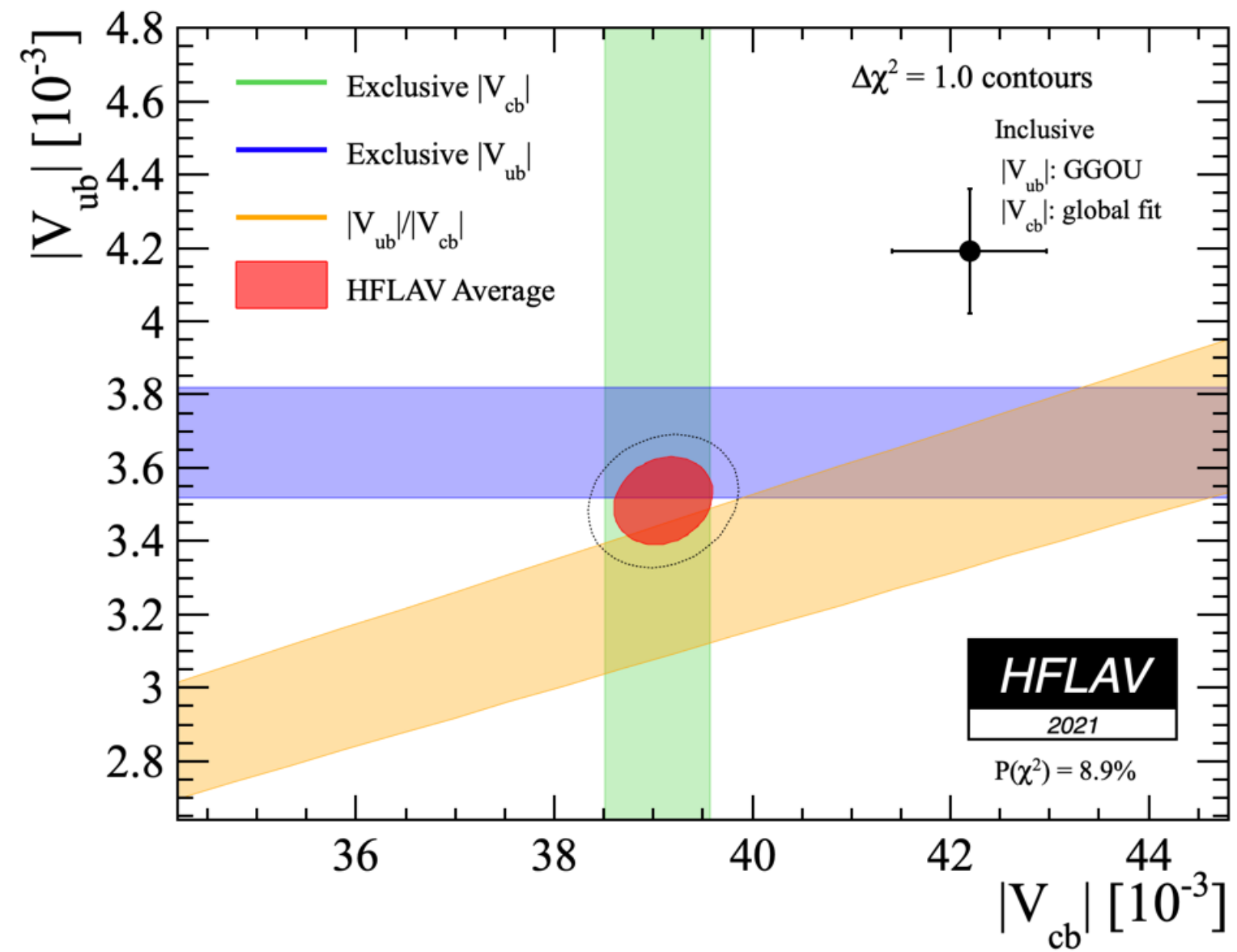


Measure using inclusive or exclusive semi-leptonic beauty hadron decays and fix the CKM triangle apex

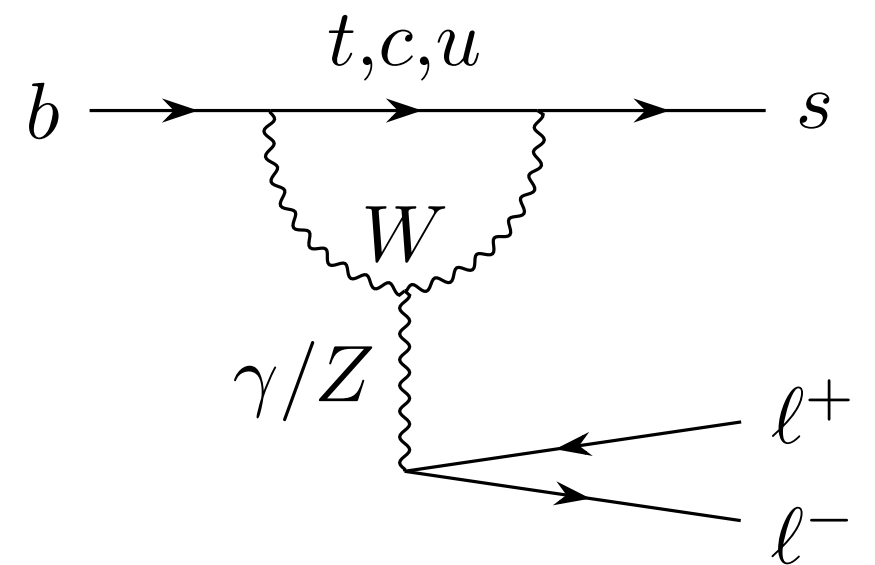
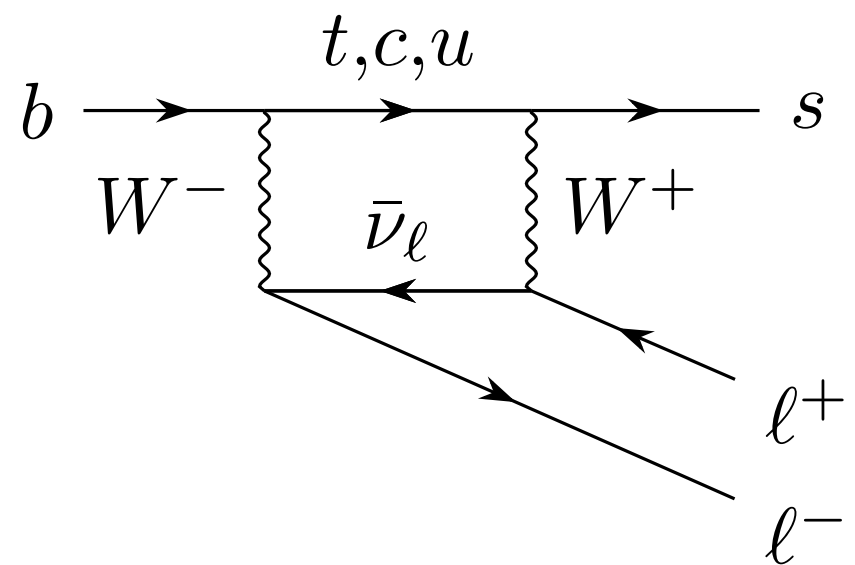
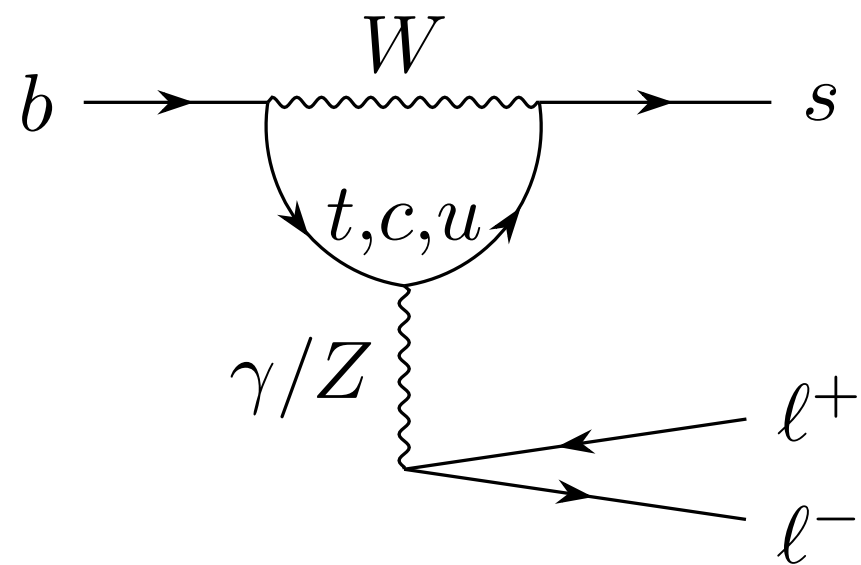
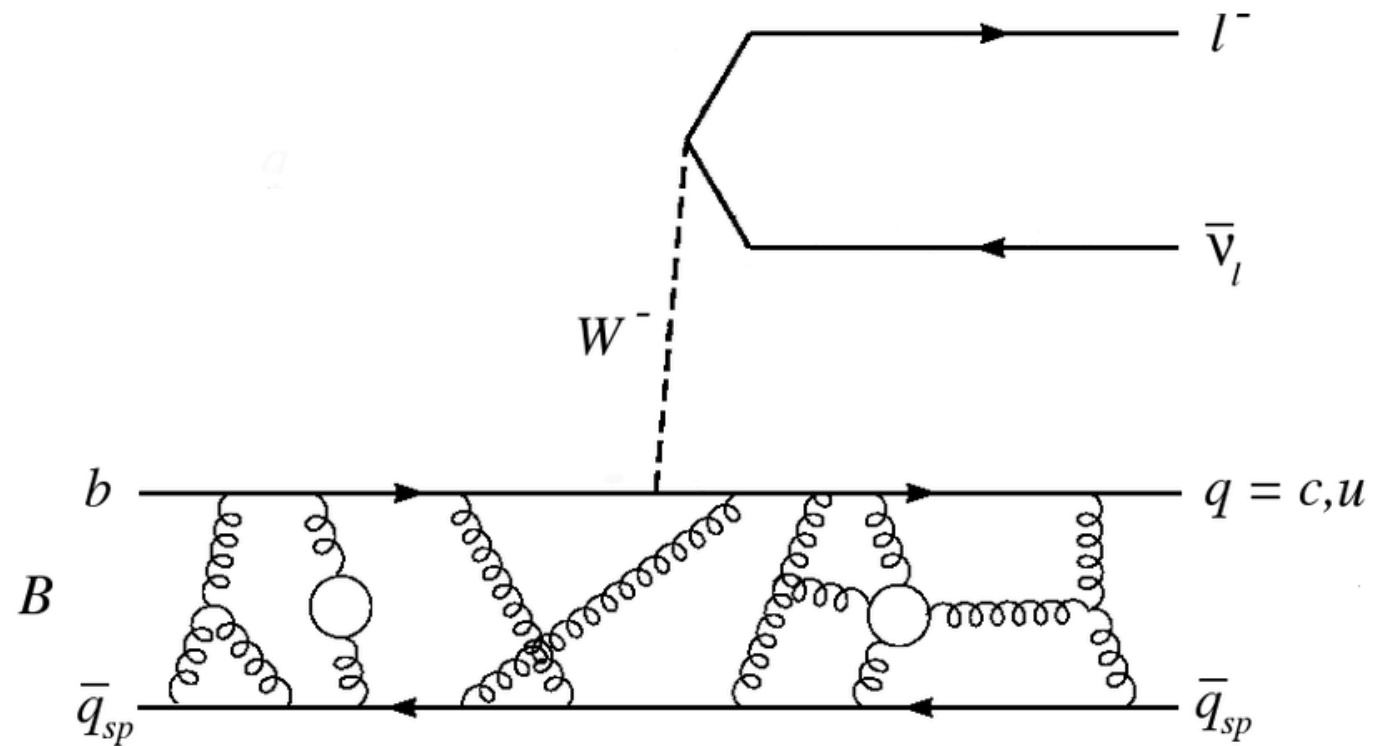
V_{ub} and V_{cb}



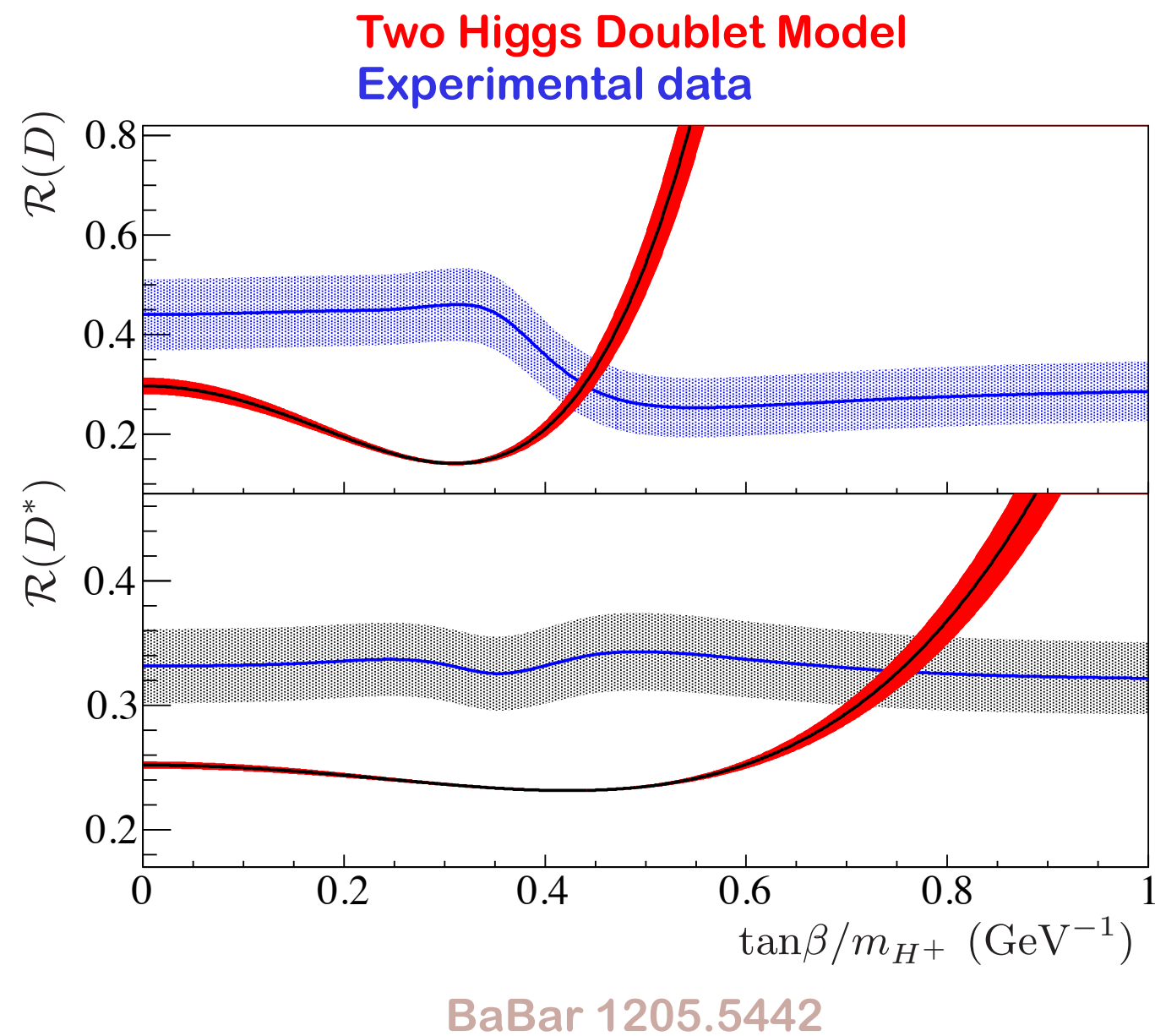
V_{ub} and V_{cb}



Tests of lepton universality (LU)



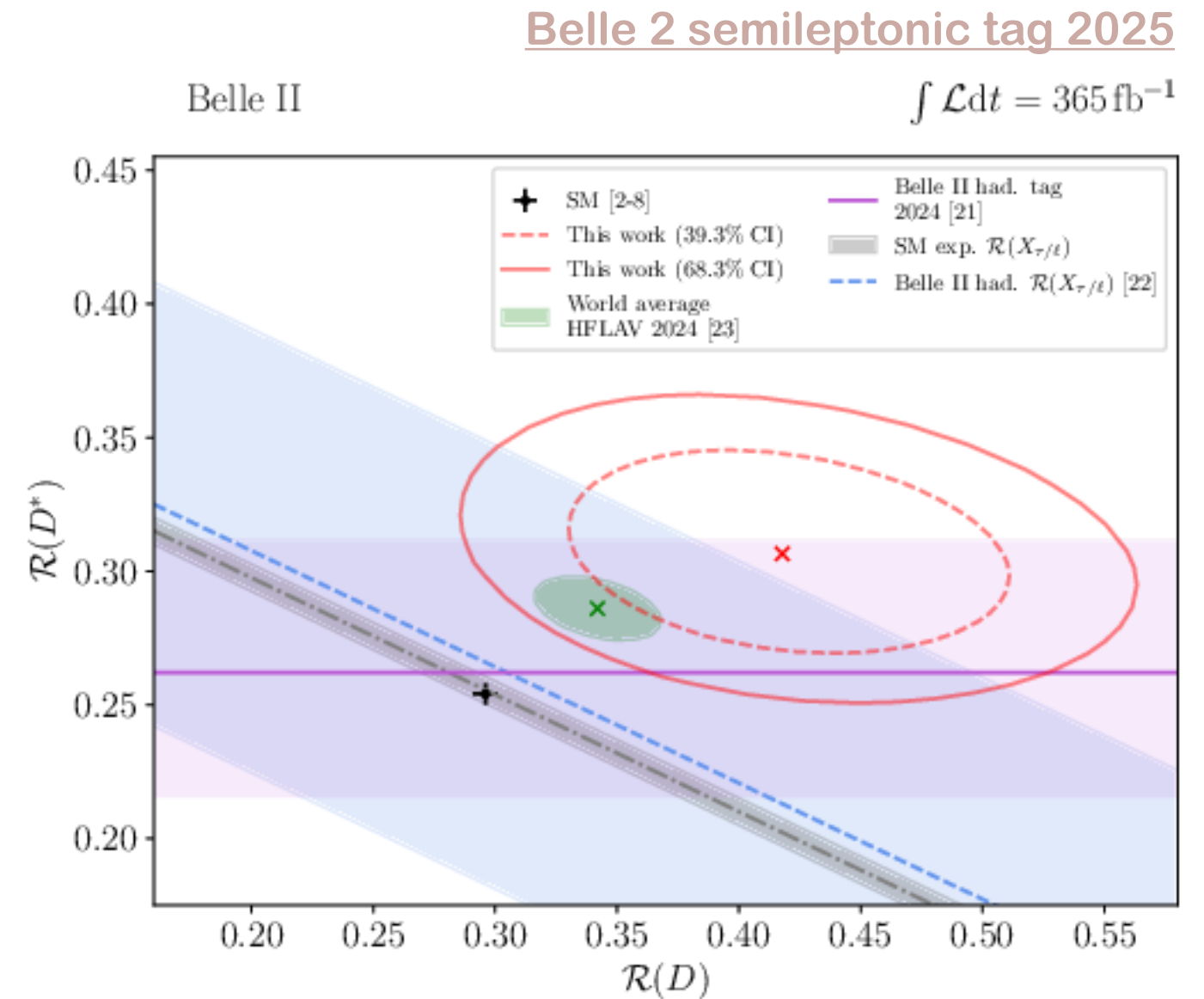
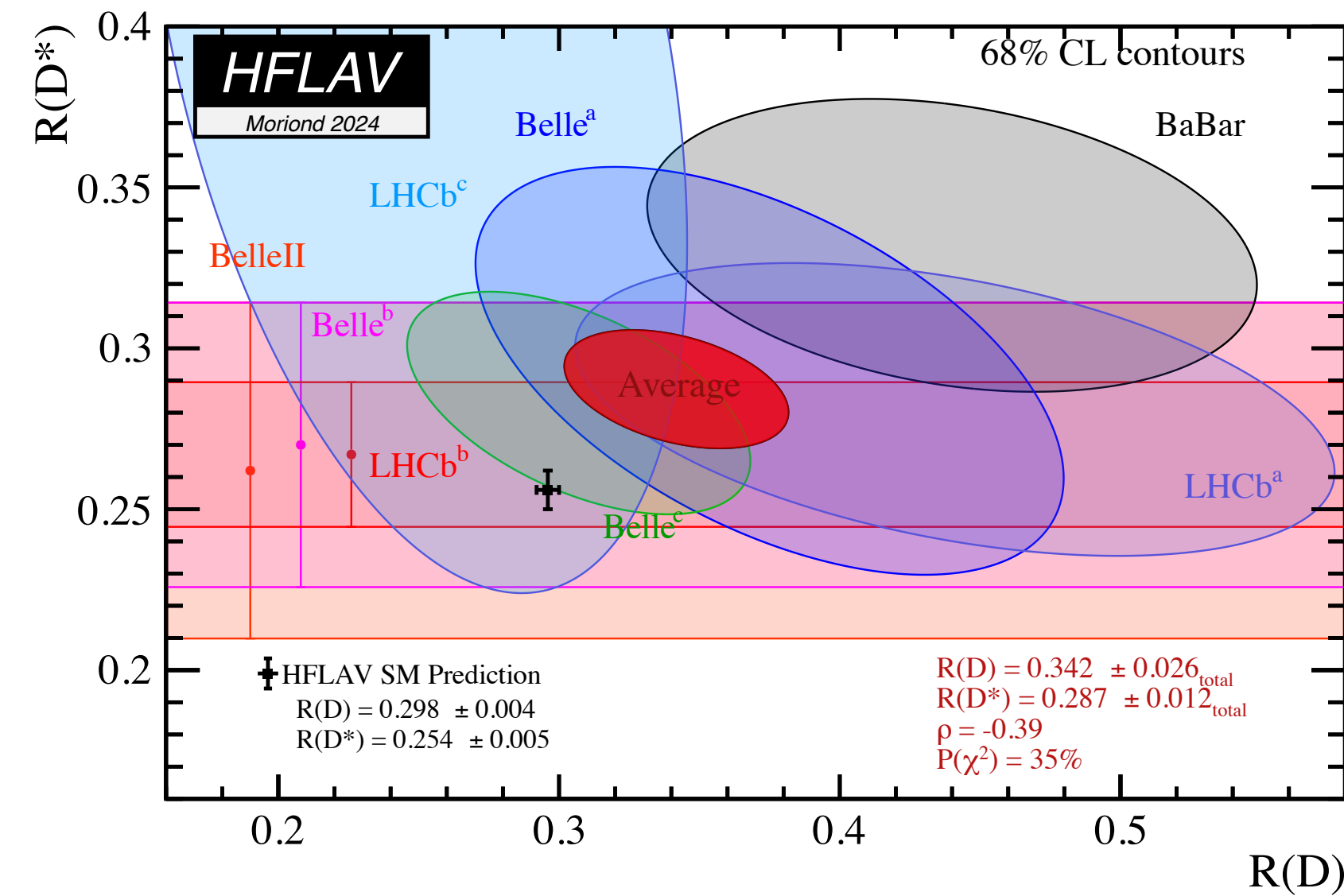
Reach of LU measurements



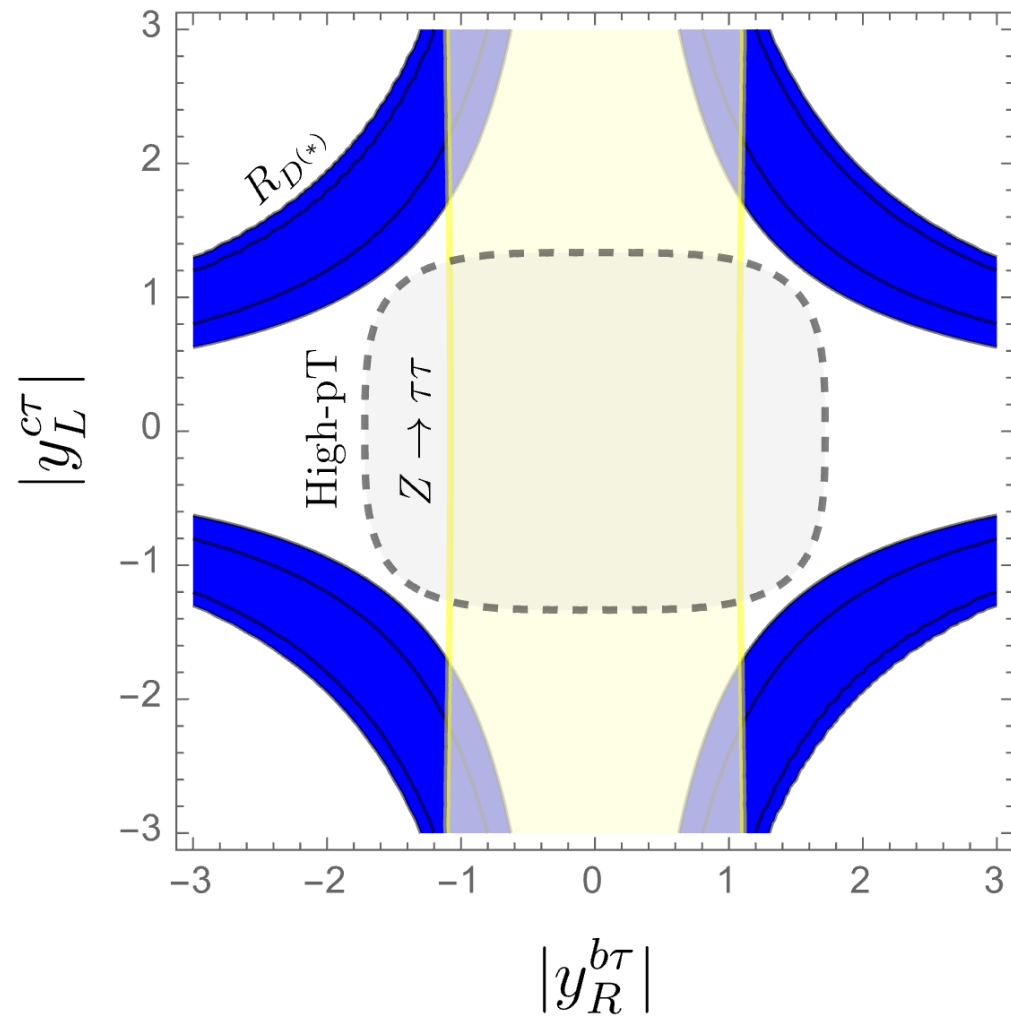
Integrated Luminosity	3 fb^{-1}	23 fb^{-1}	300 fb^{-1}
R_K and R_{K^*} measurements			
$\sigma(C_9)$	0.44	0.12	0.03
$\Lambda_{\text{NP}}^{\text{tree generic}} [\text{TeV}]$	40	80	155
$\Lambda_{\text{NP}}^{\text{tree MFV}} [\text{TeV}]$	8	16	31
$\Lambda_{\text{NP}}^{\text{loop generic}} [\text{TeV}]$	3	6	12
$\Lambda_{\text{NP}}^{\text{loop MFV}} [\text{TeV}]$	0.7	1.3	2.5

Taken from the LHCb Upgrade 2 physics case

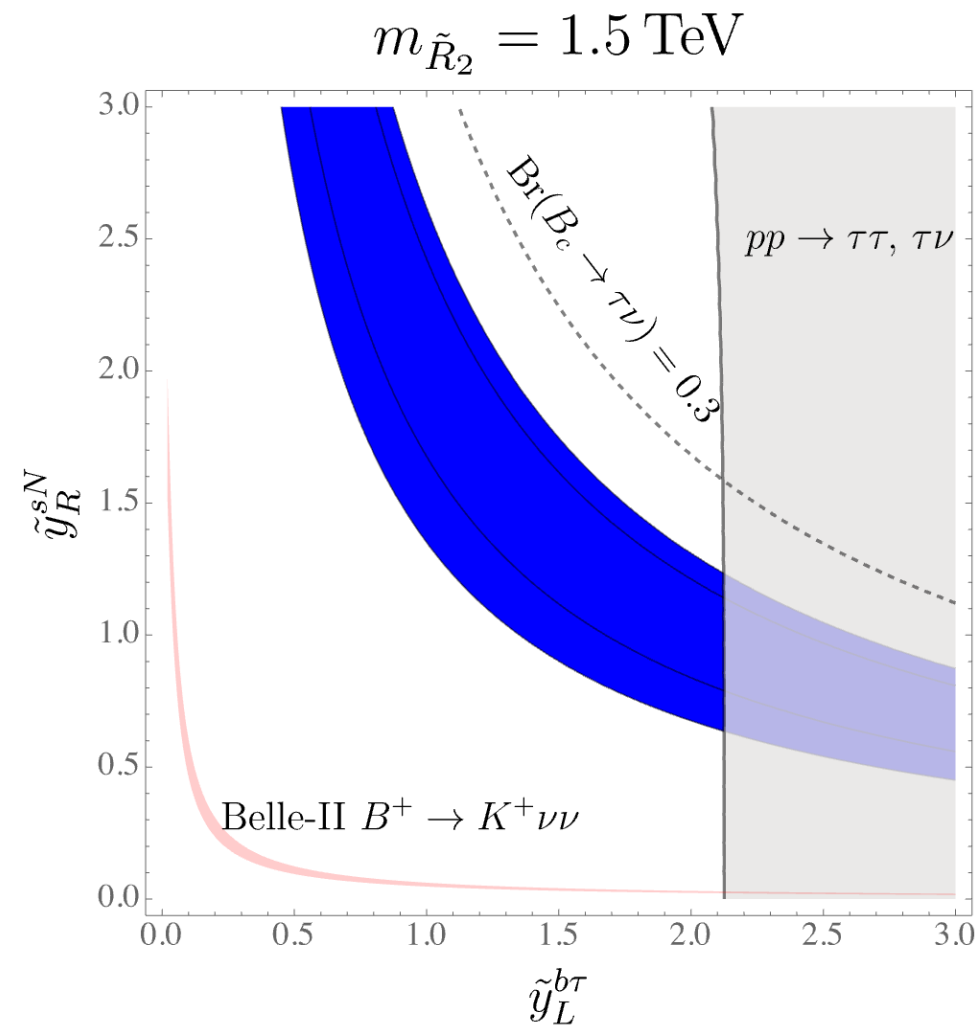
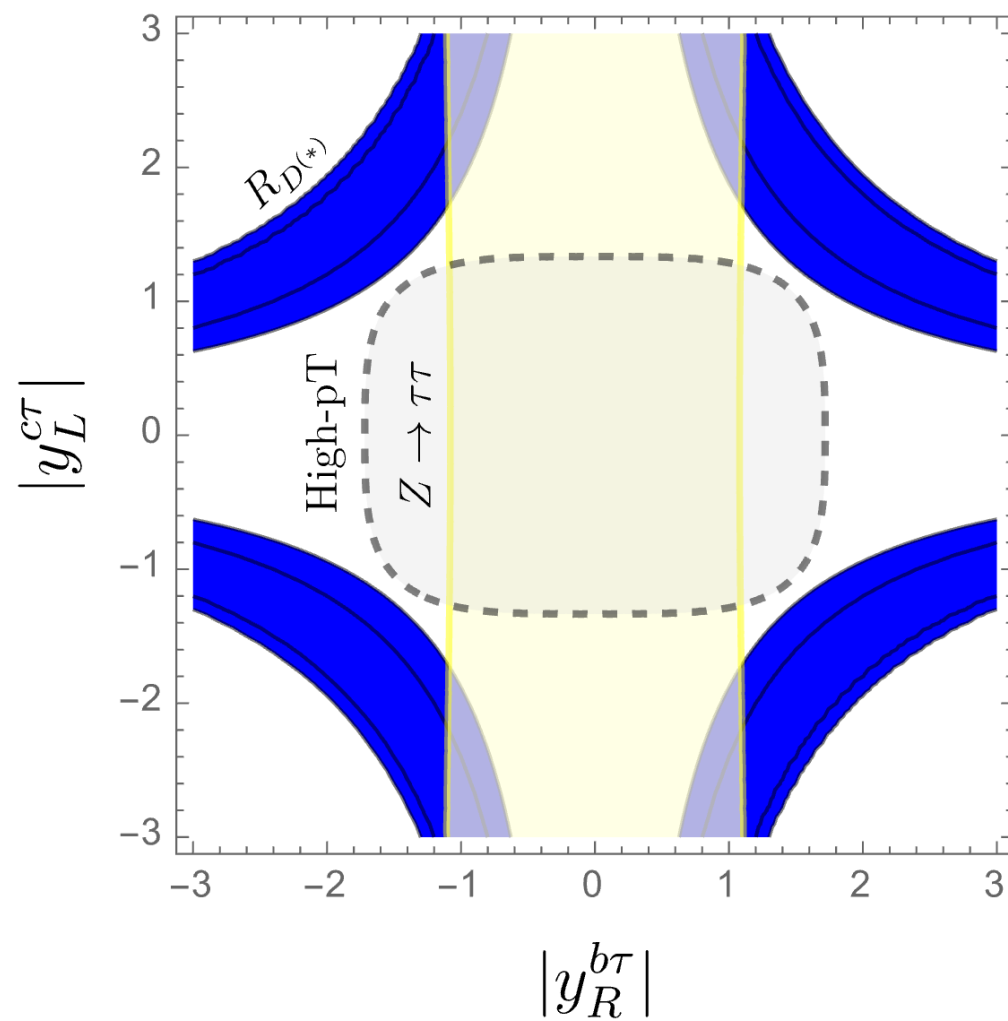
LU in semileptonic decays as of 2025



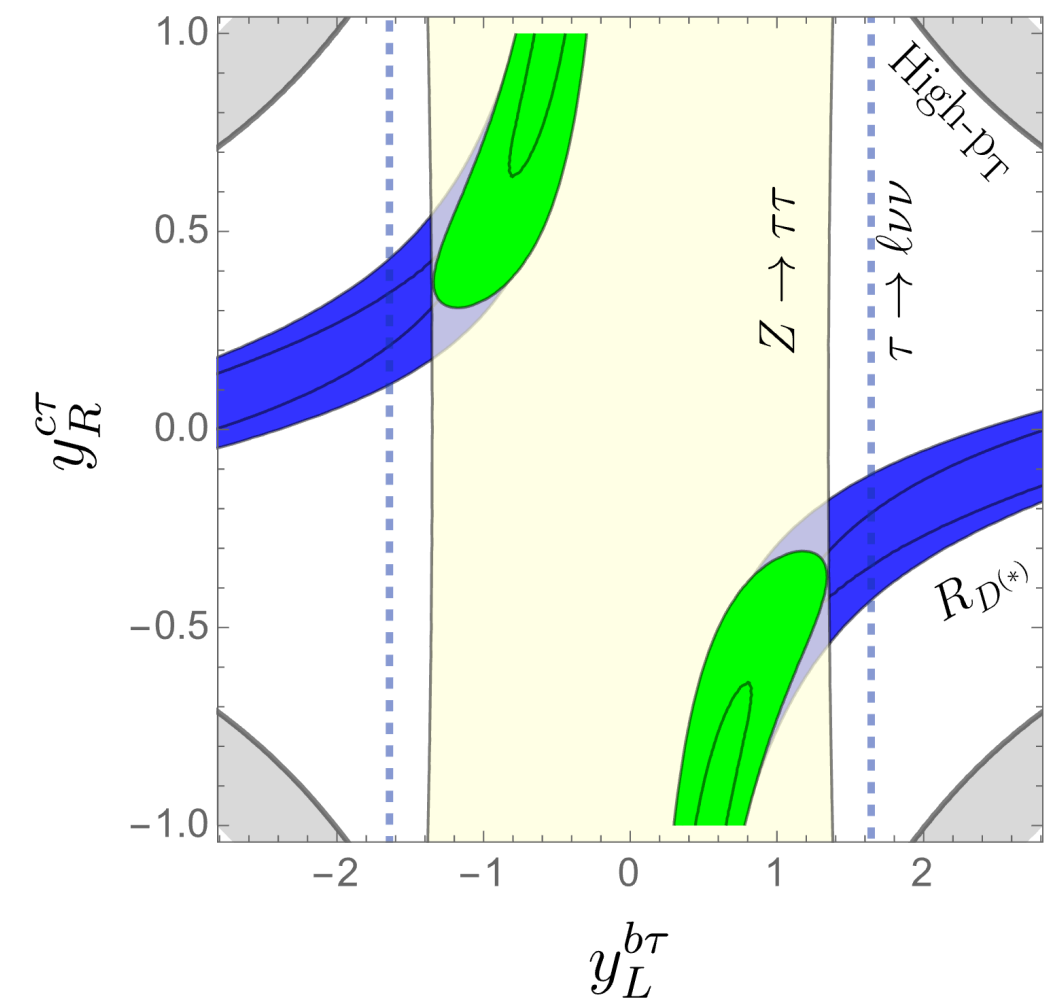
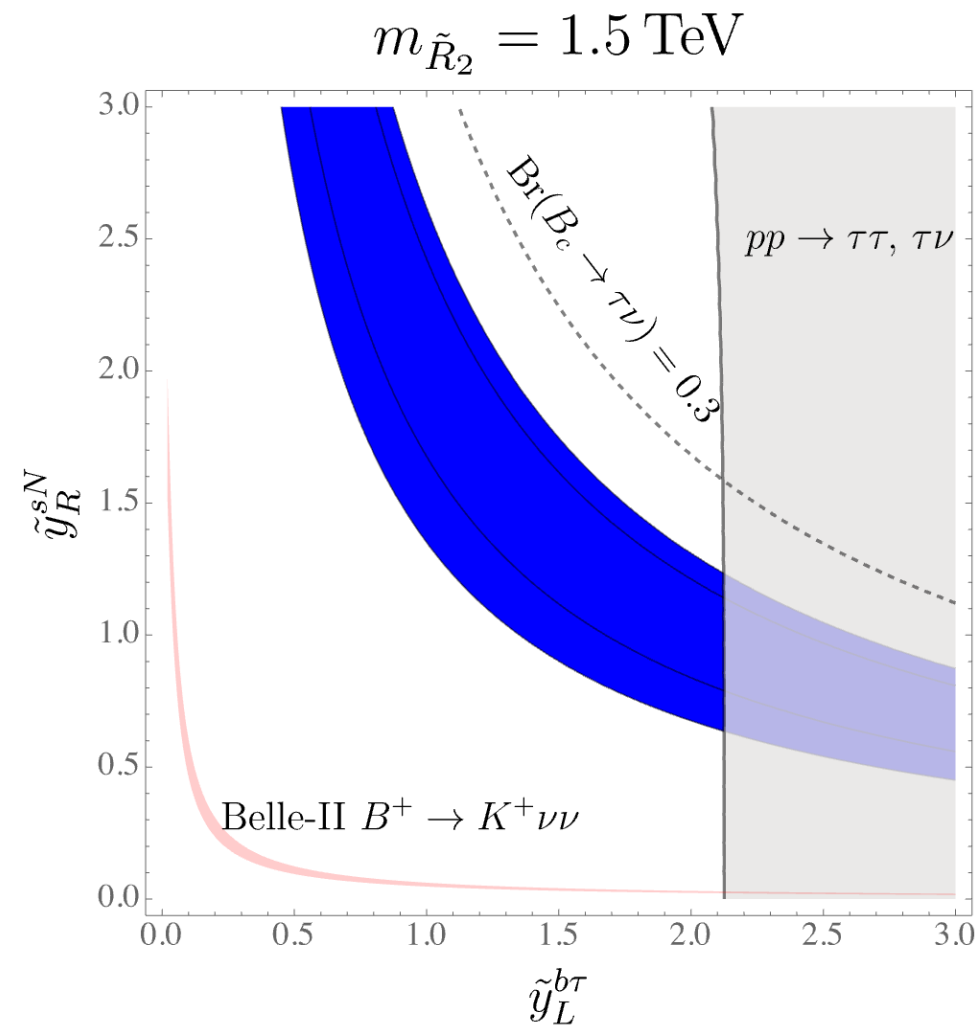
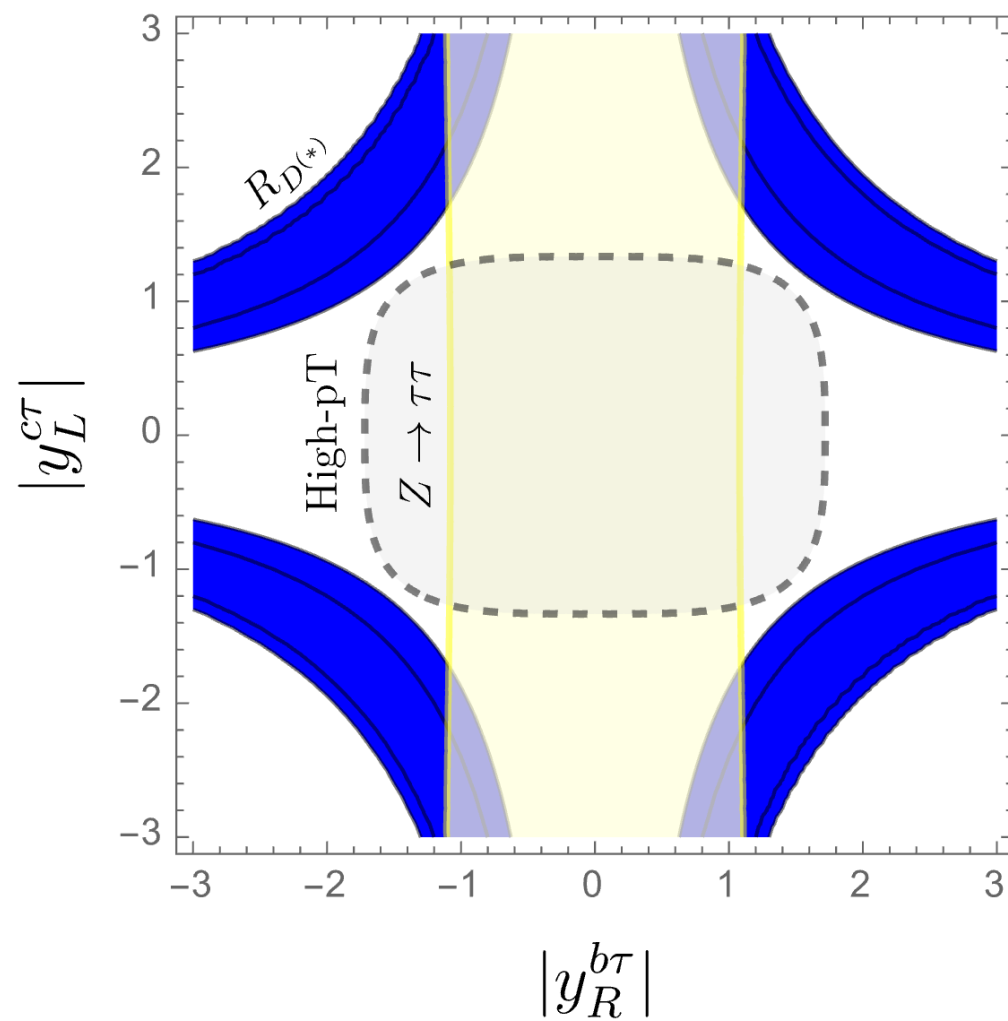
If this is BSM, what implications?



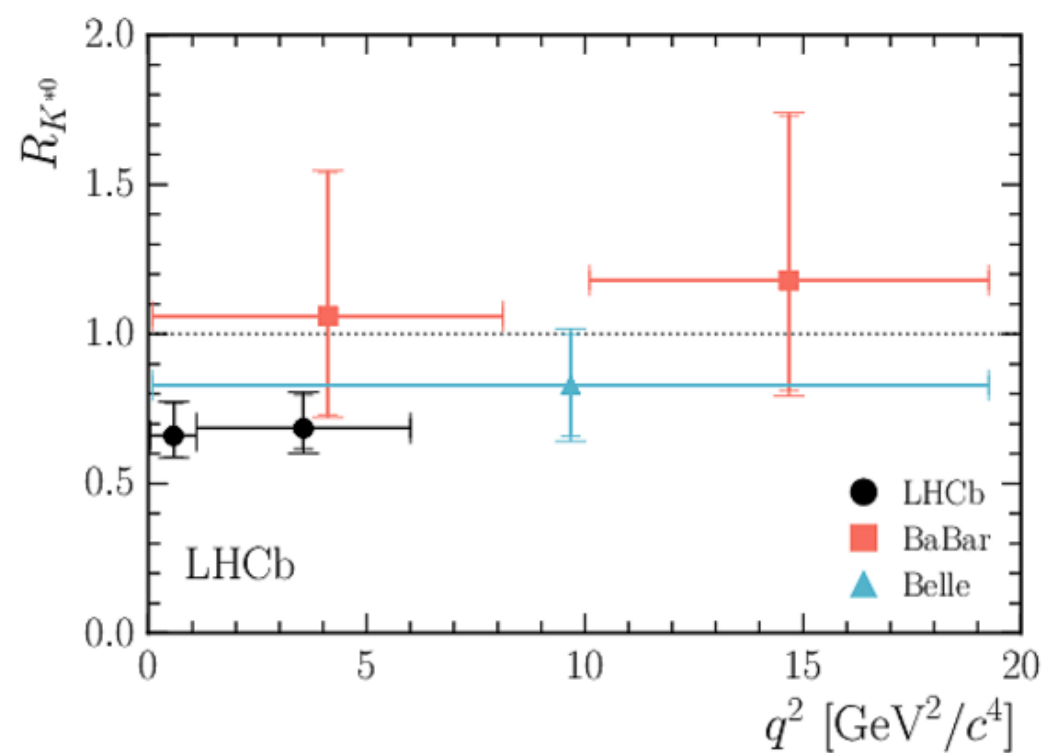
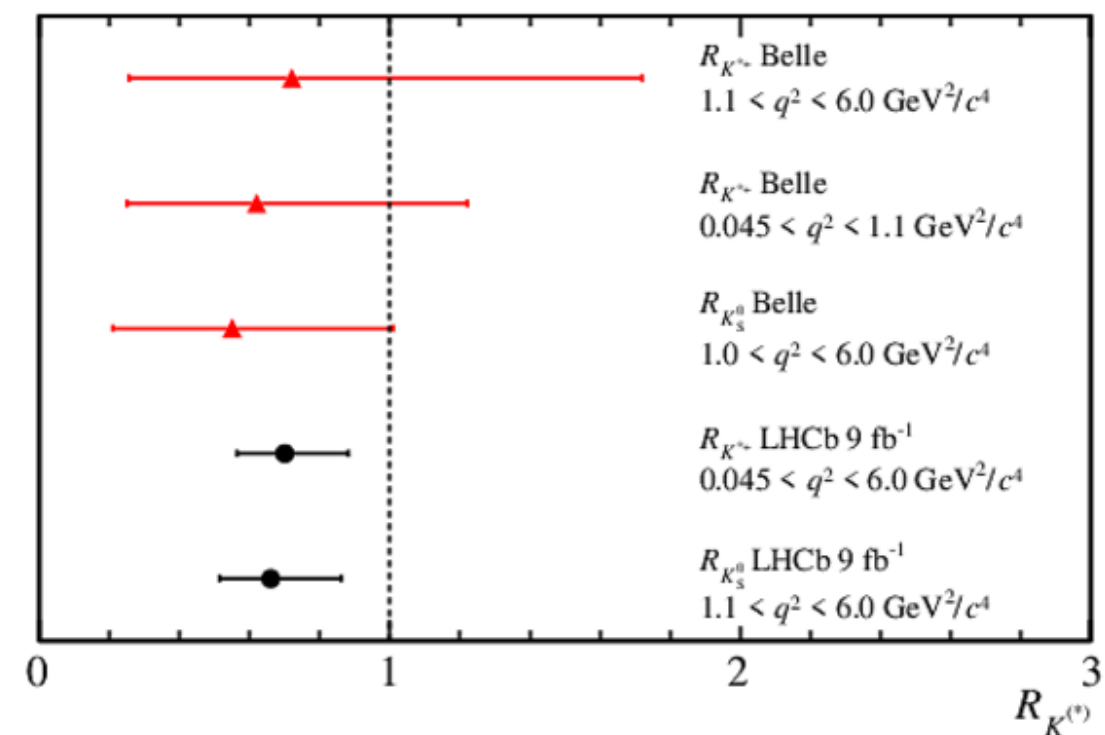
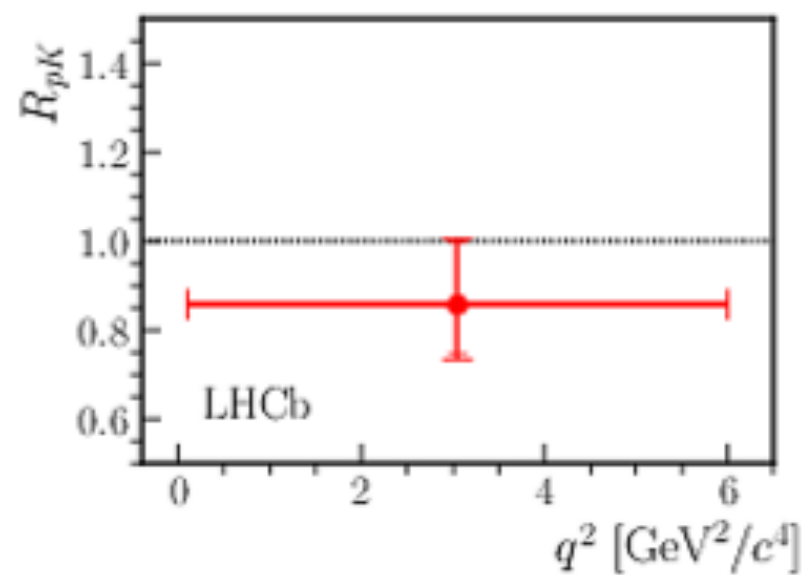
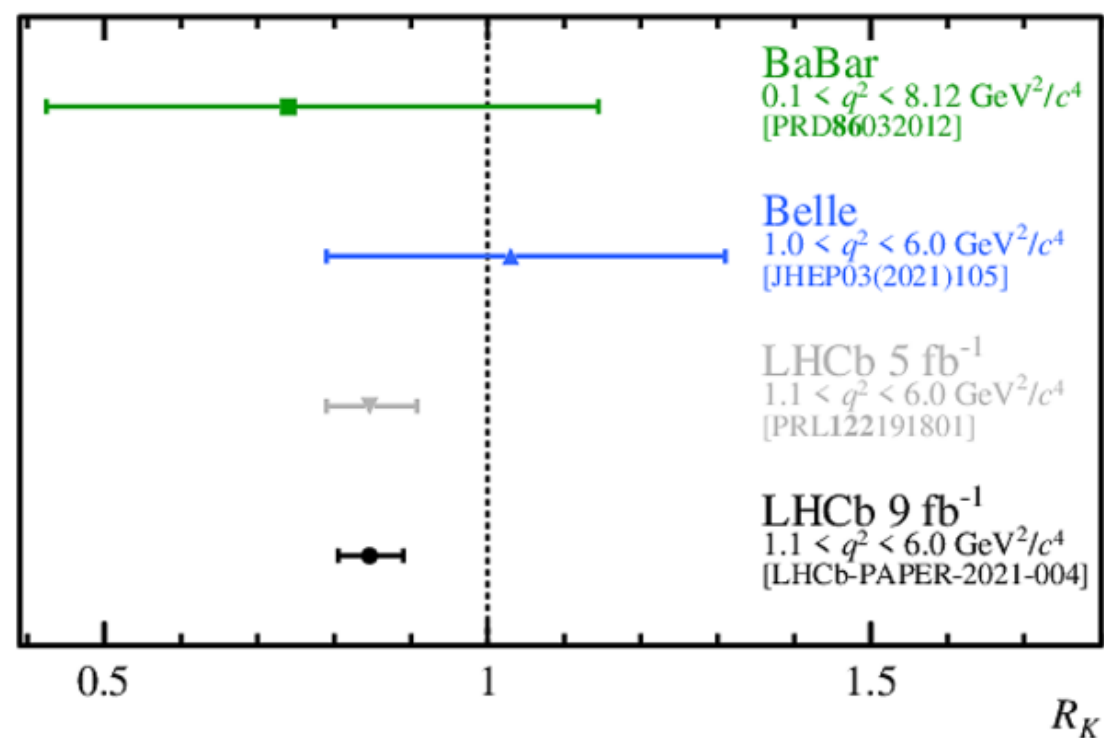
If this is BSM, what implications?



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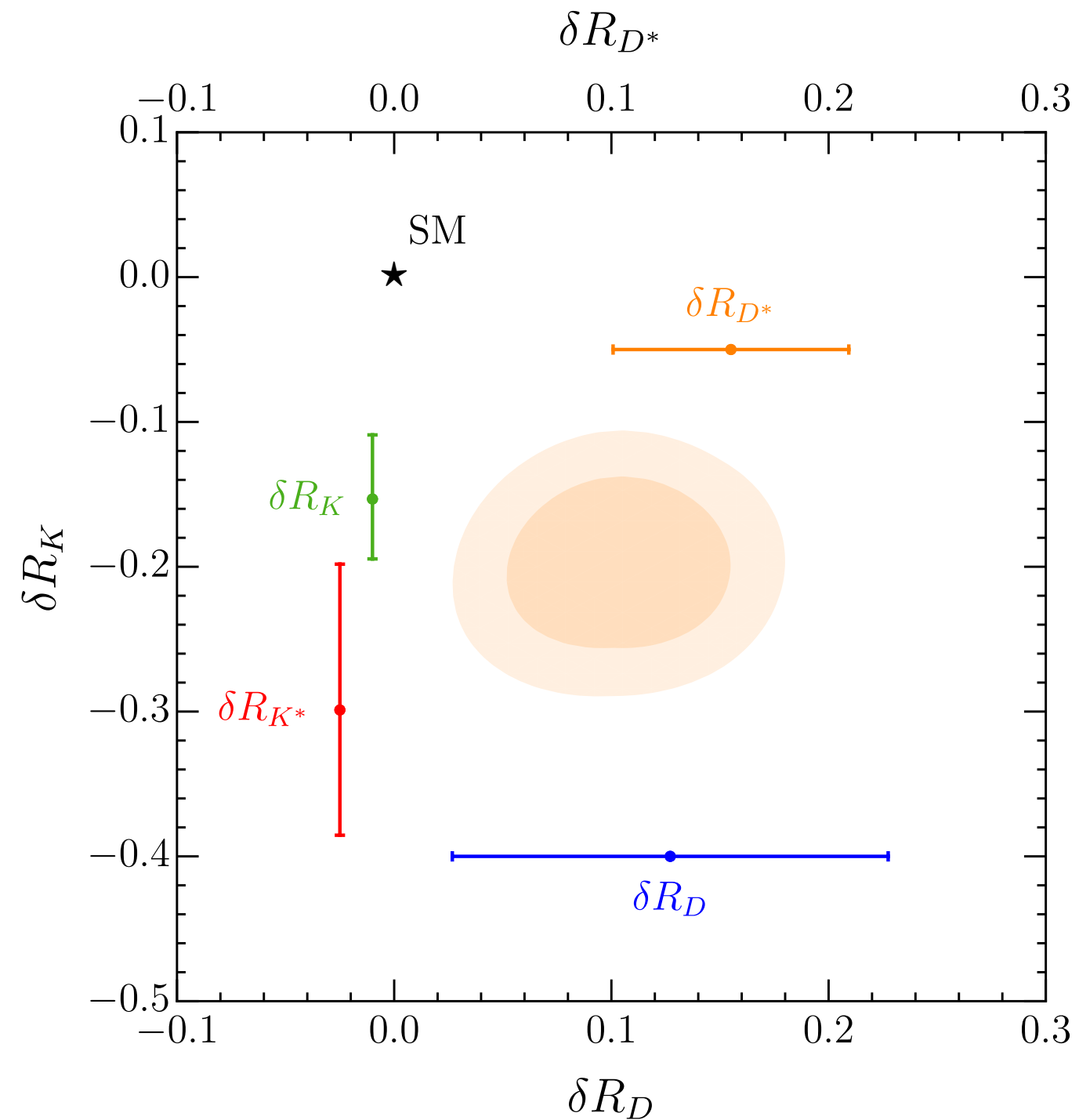
LU in $b \rightarrow s \ell \ell$ decays – quite the mirage



As of 2021, this was generating a great deal of excitement...

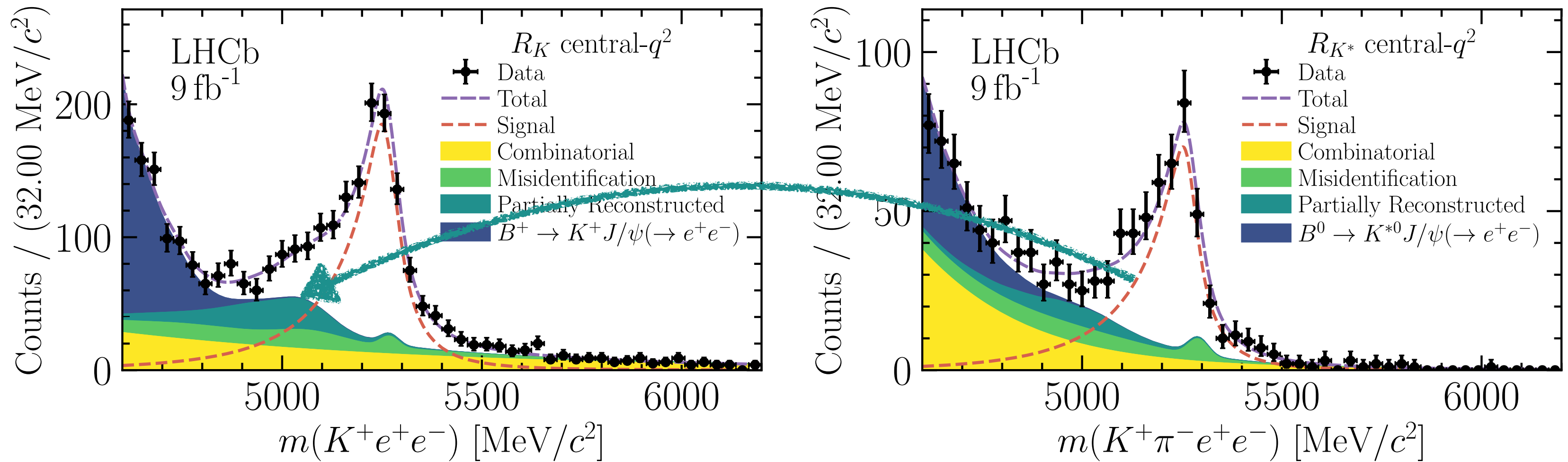
LU in $b \rightarrow s \ell \ell$ decays – quite the mirage

Cornella et al 2103.16558

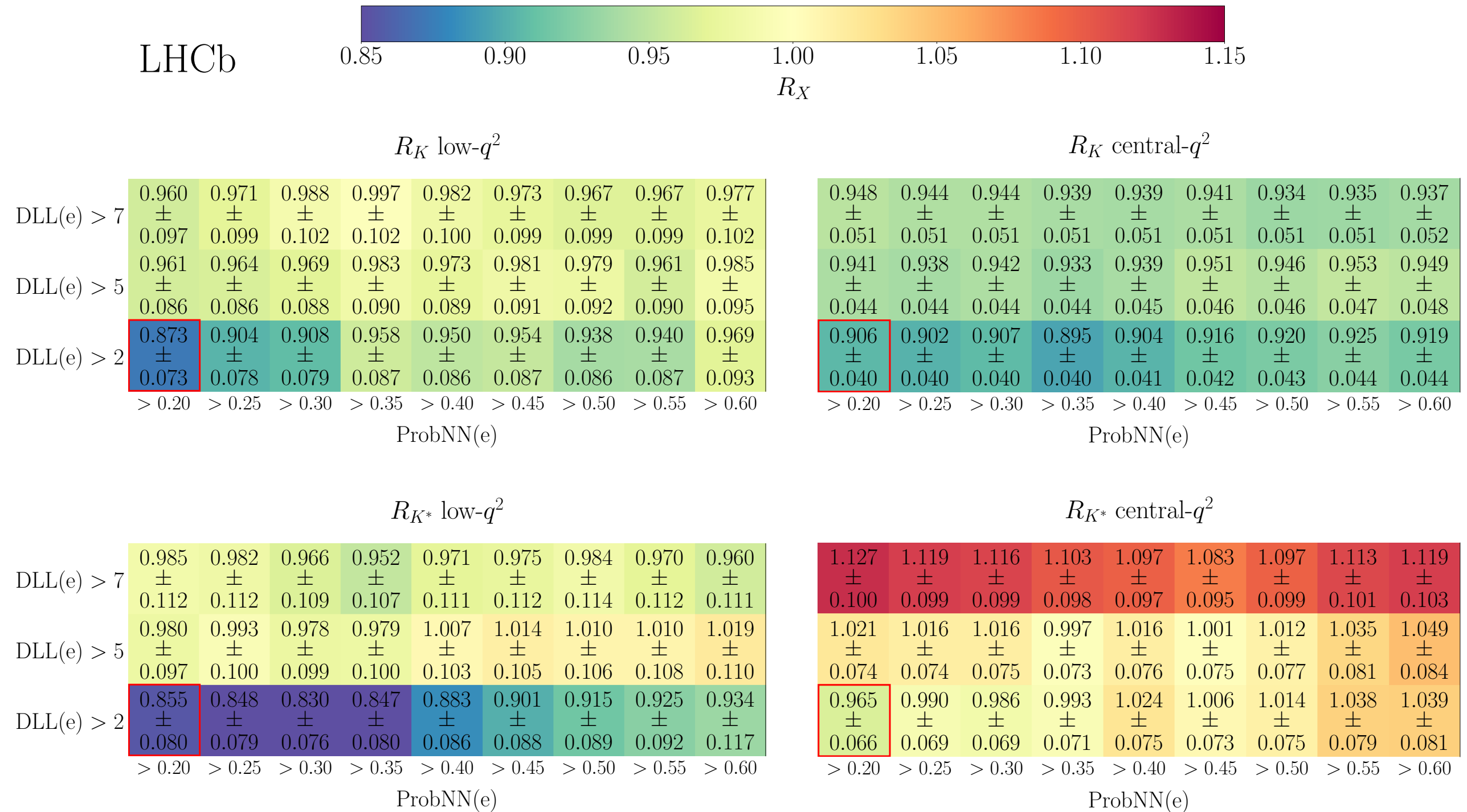


Including a range of fairly strong global fit statements

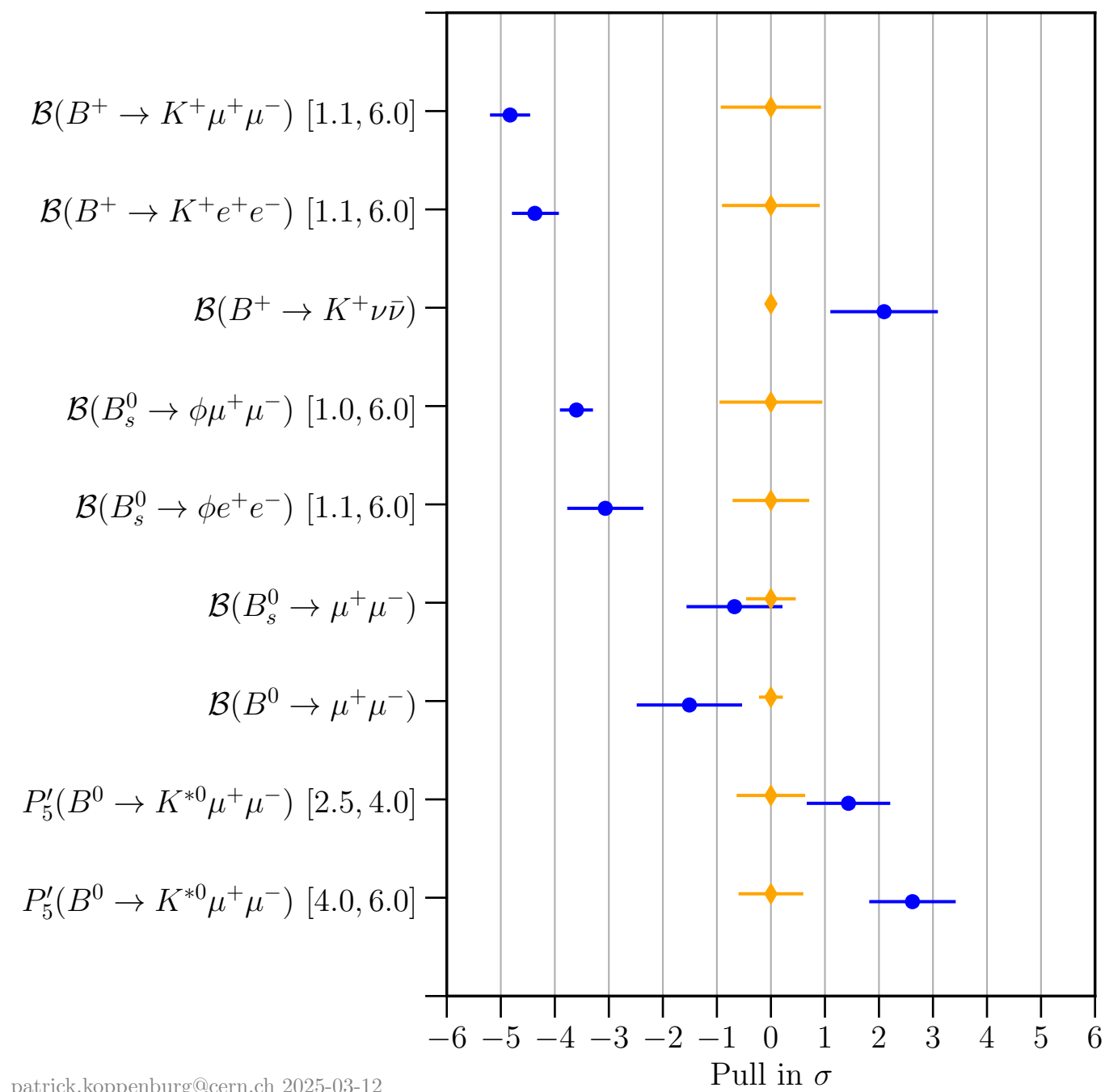
The mirage fades away



A lesson in experimental coherence

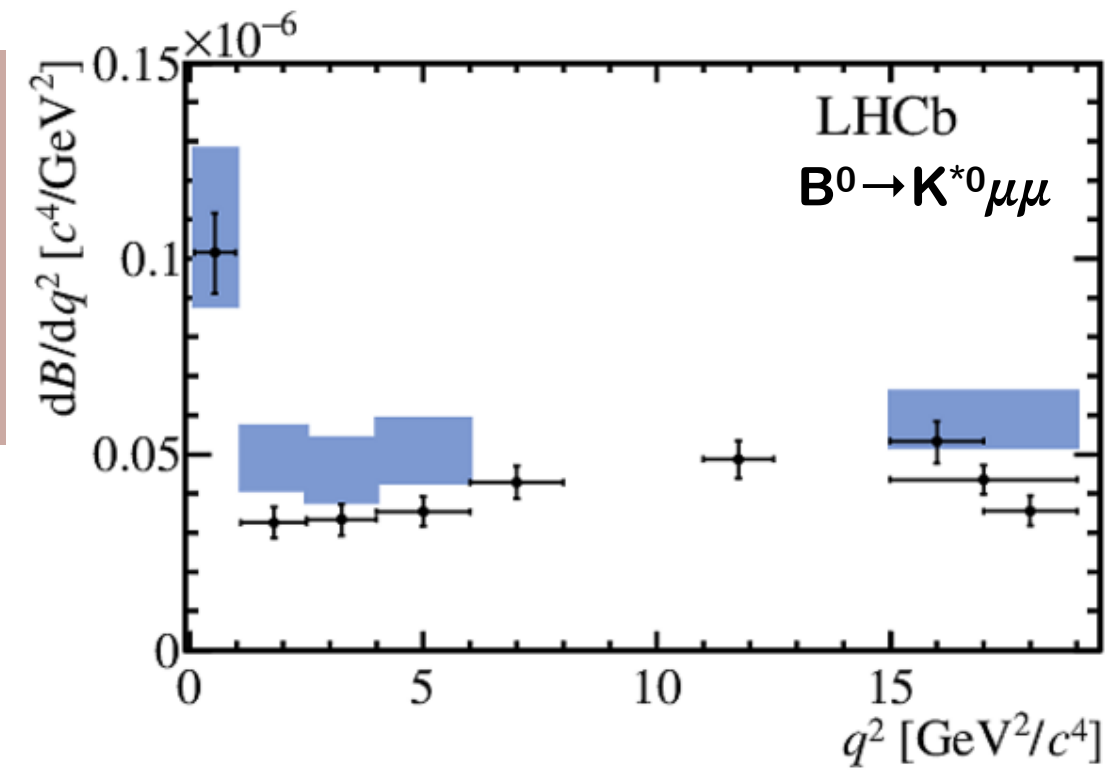


$b \rightarrow s \ell \ell$ transitions beyond LU



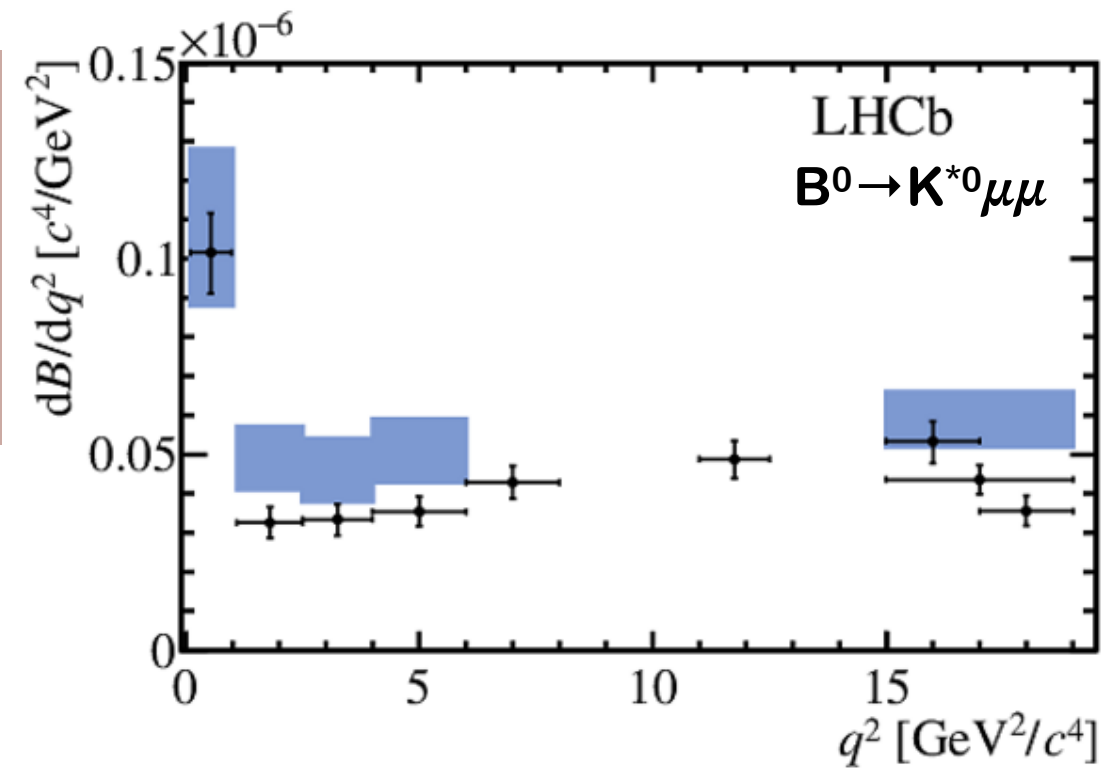
$b \rightarrow s \ell \ell$ transitions beyond LU

JHEP 04 (2017) 142

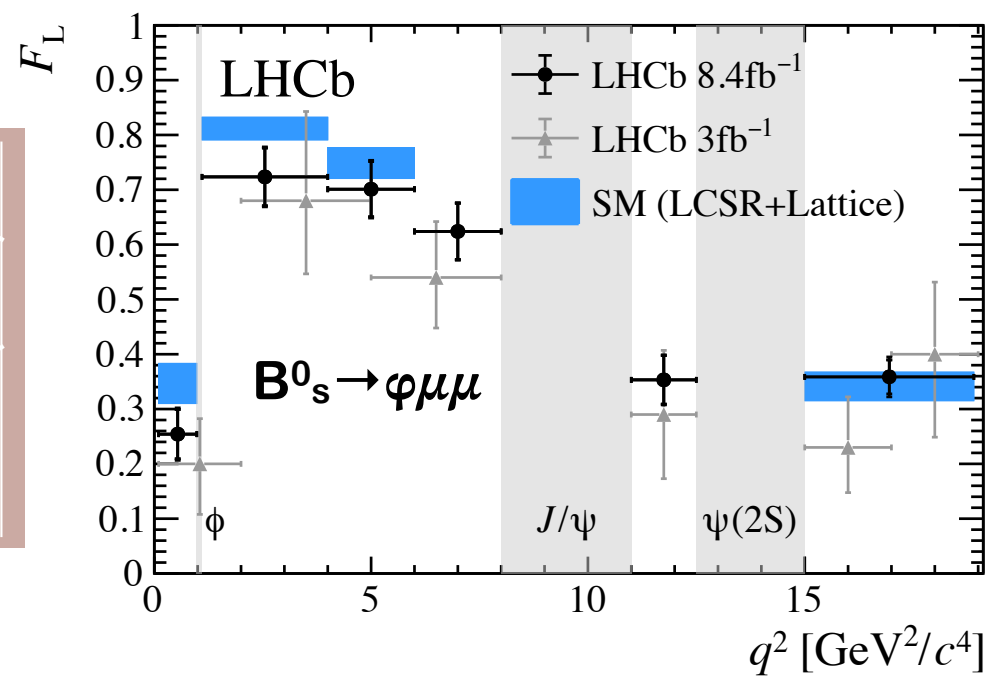


$b \rightarrow s \ell \ell$ transitions beyond LU

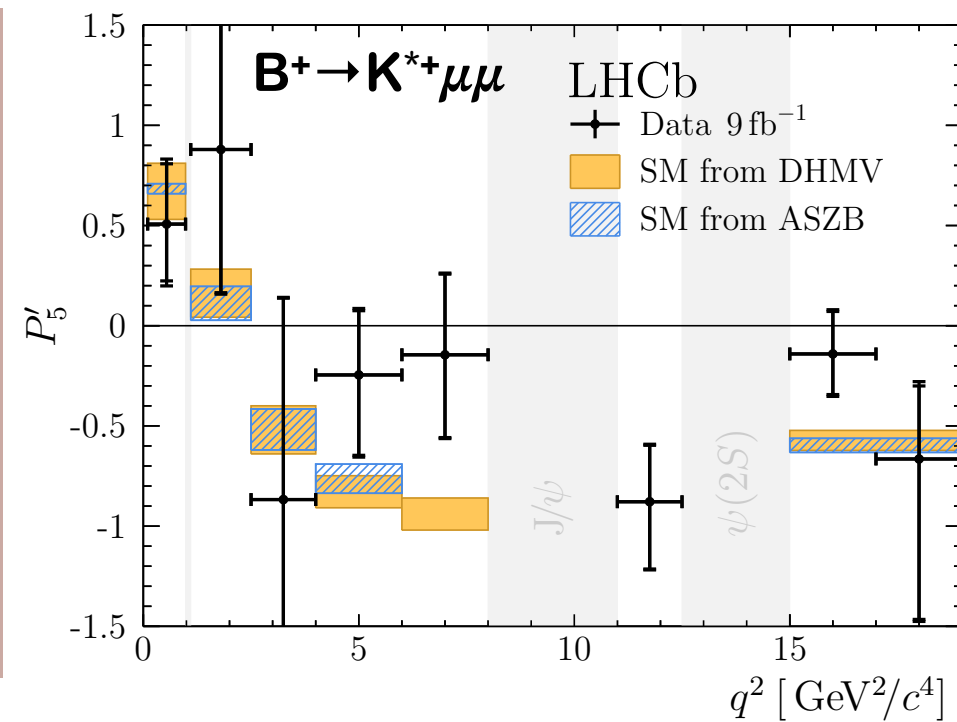
JHEP 04 (2017) 142



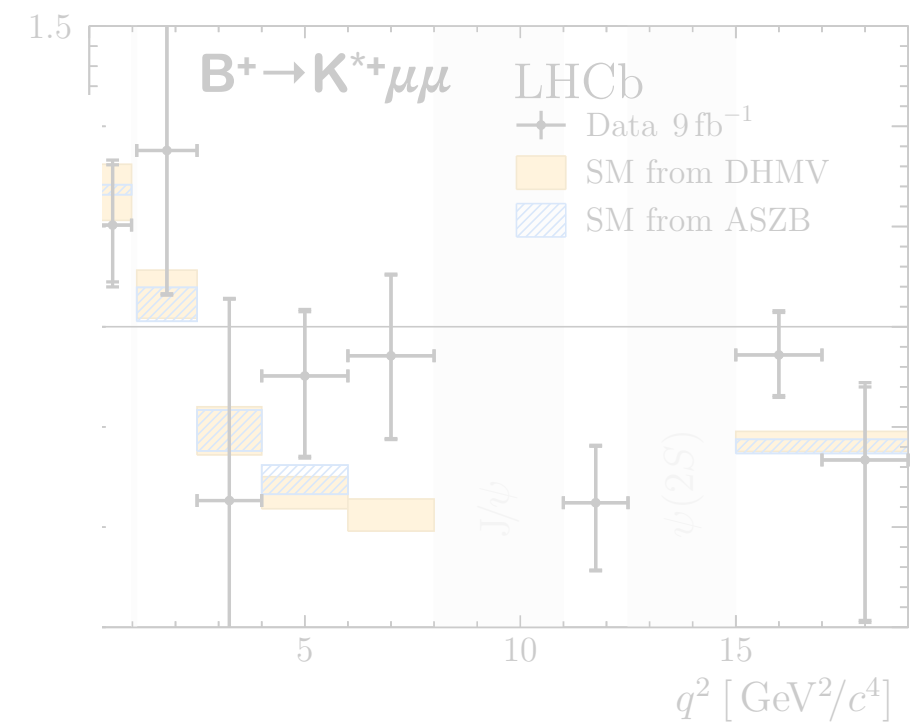
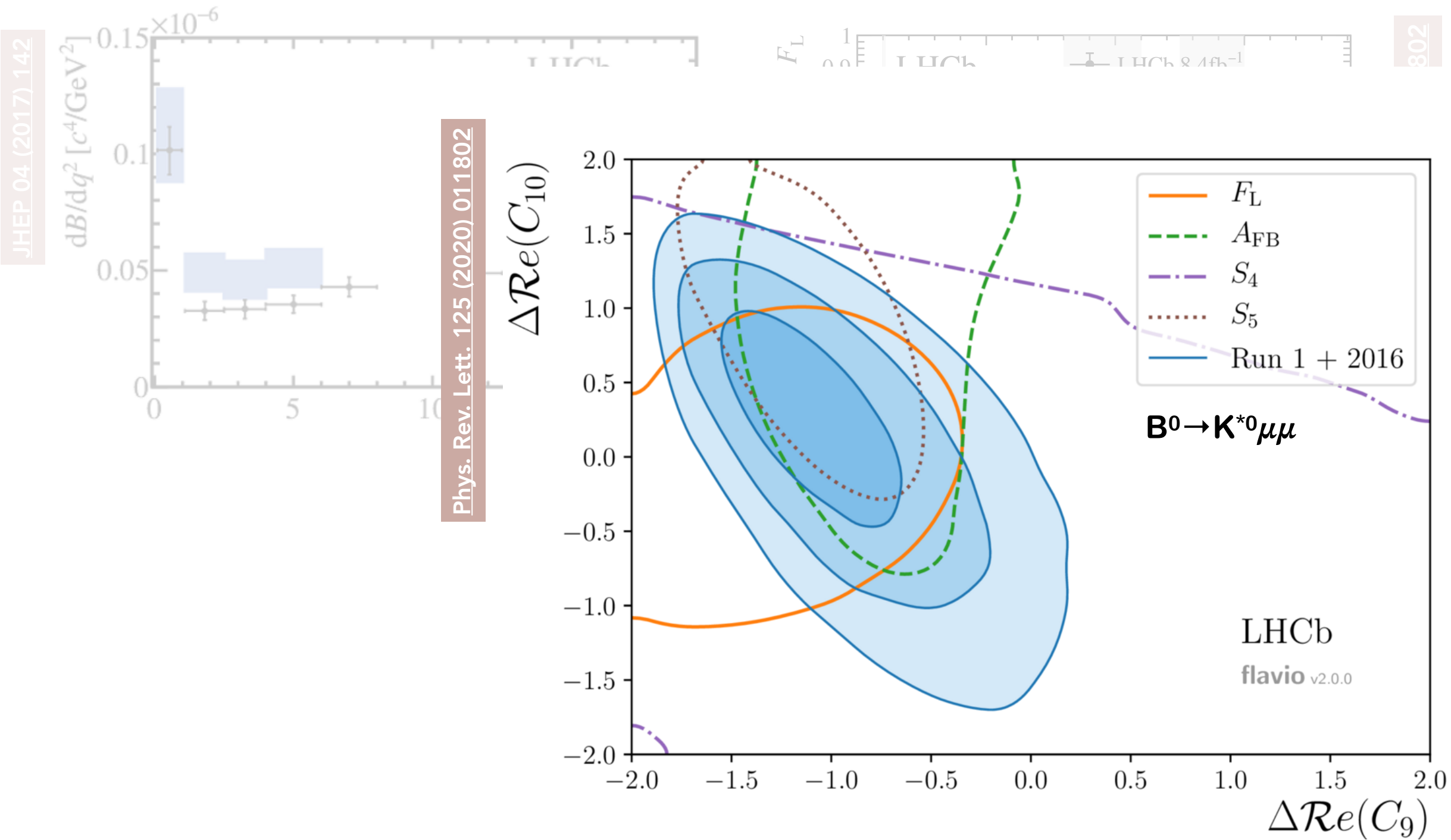
JHEP 11 (2021) 043



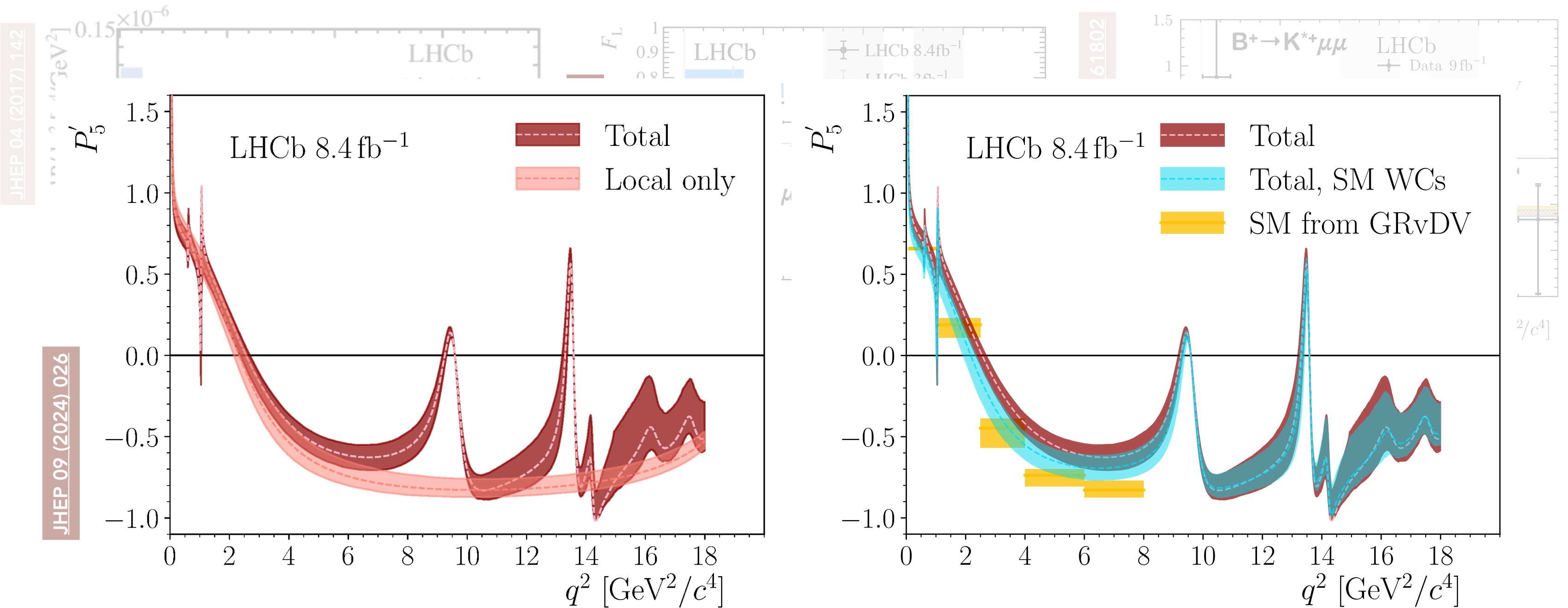
Phys.Rev.Lett.126(2021):161802



$b \rightarrow s \ell \ell$ transitions beyond LU



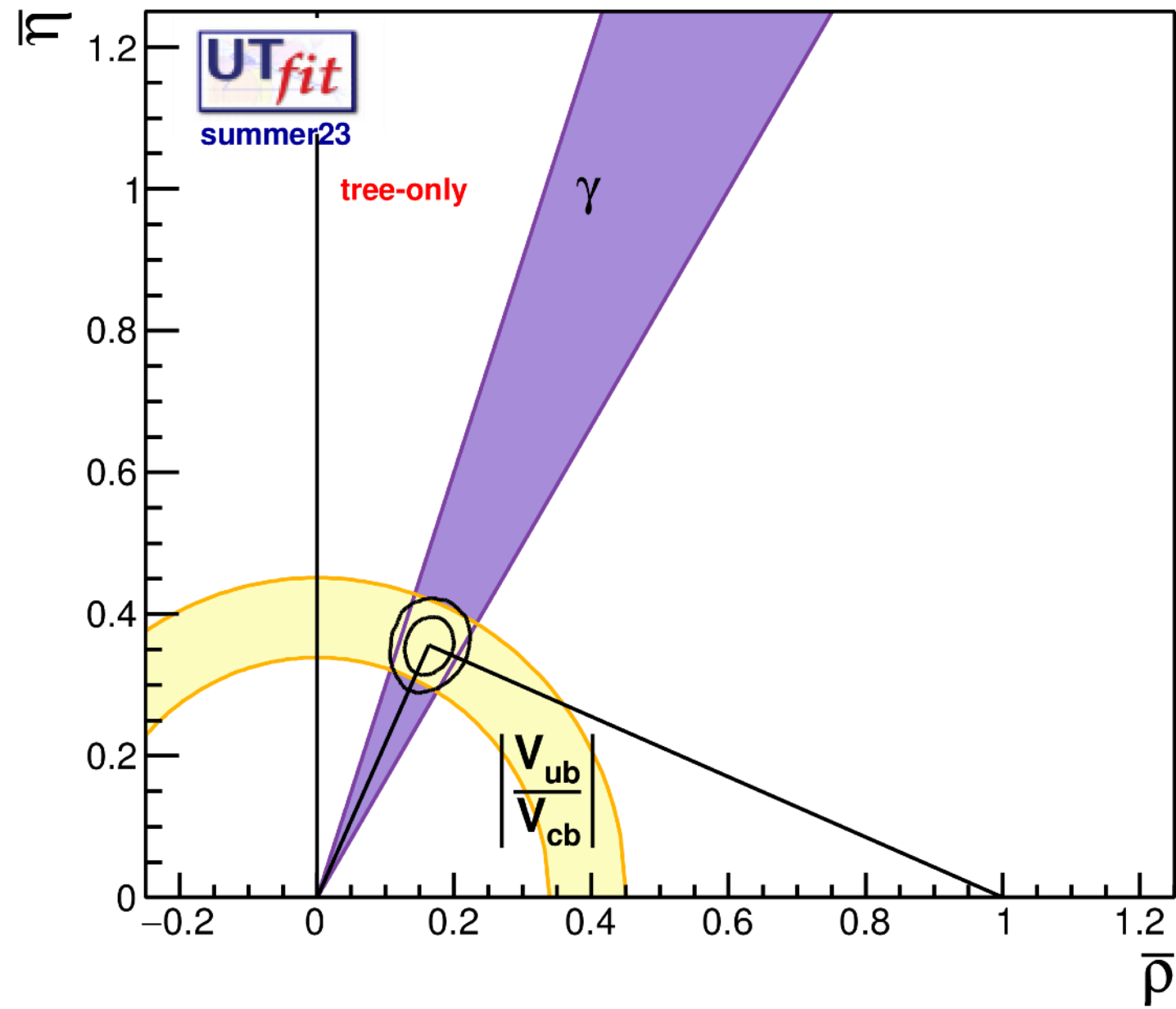
$b \rightarrow s \ell \ell$ transitions beyond LU



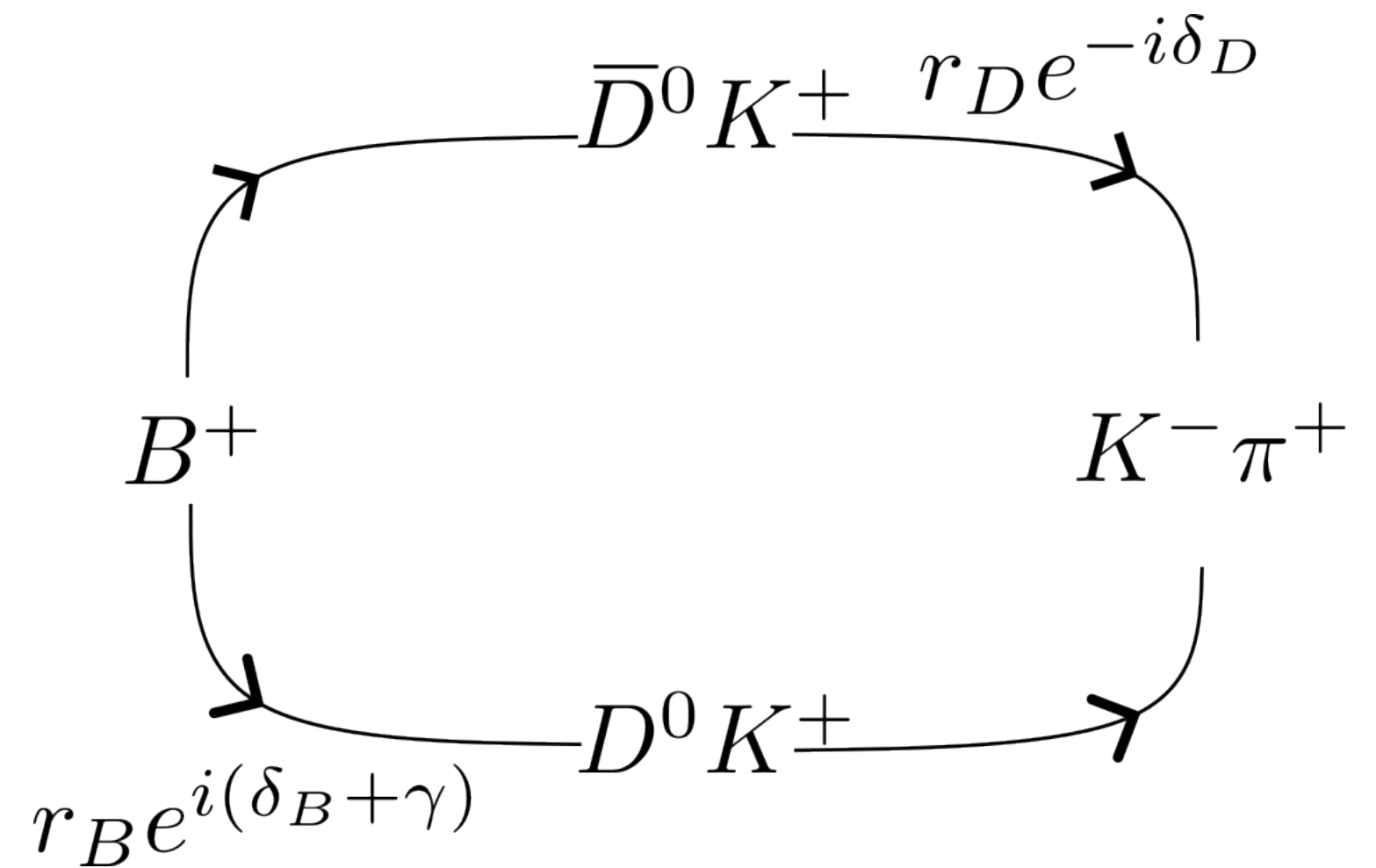
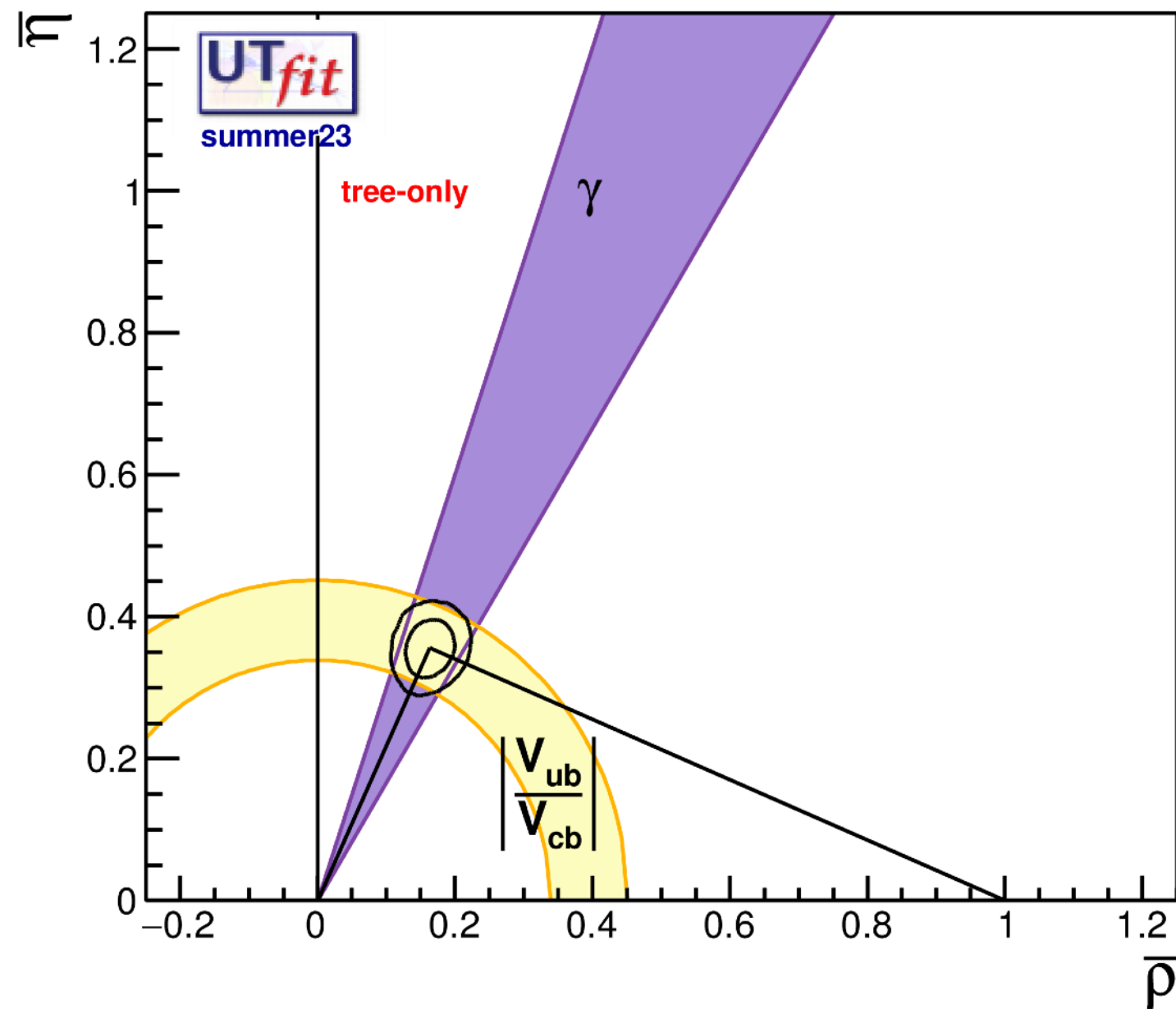


Oases

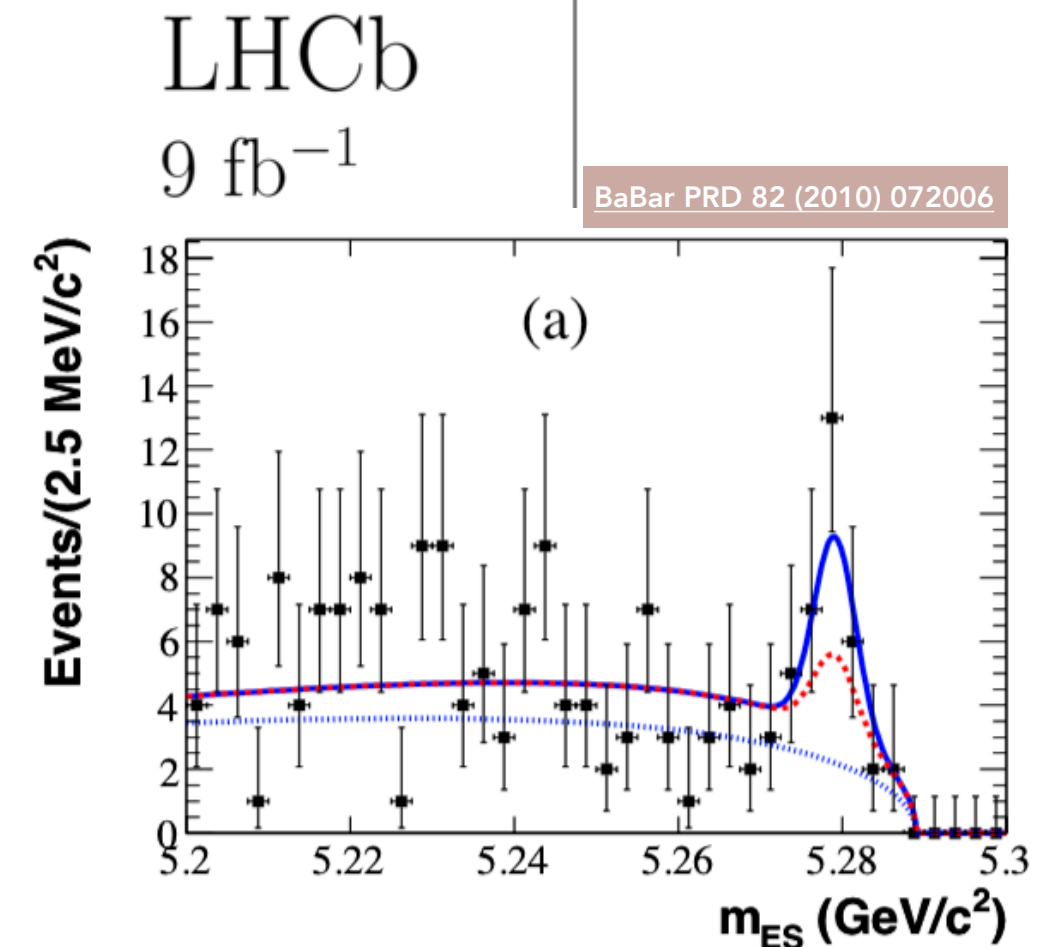
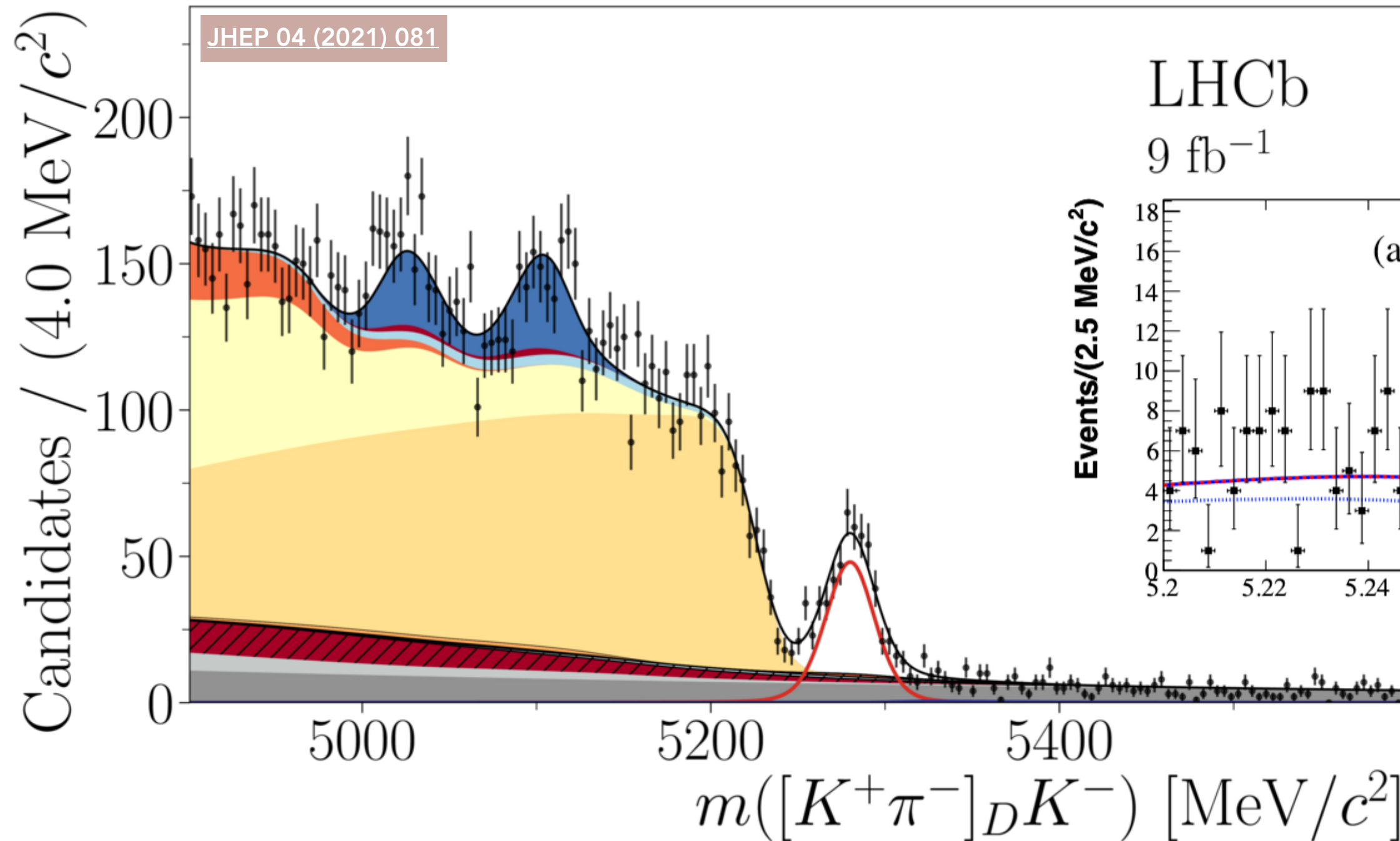
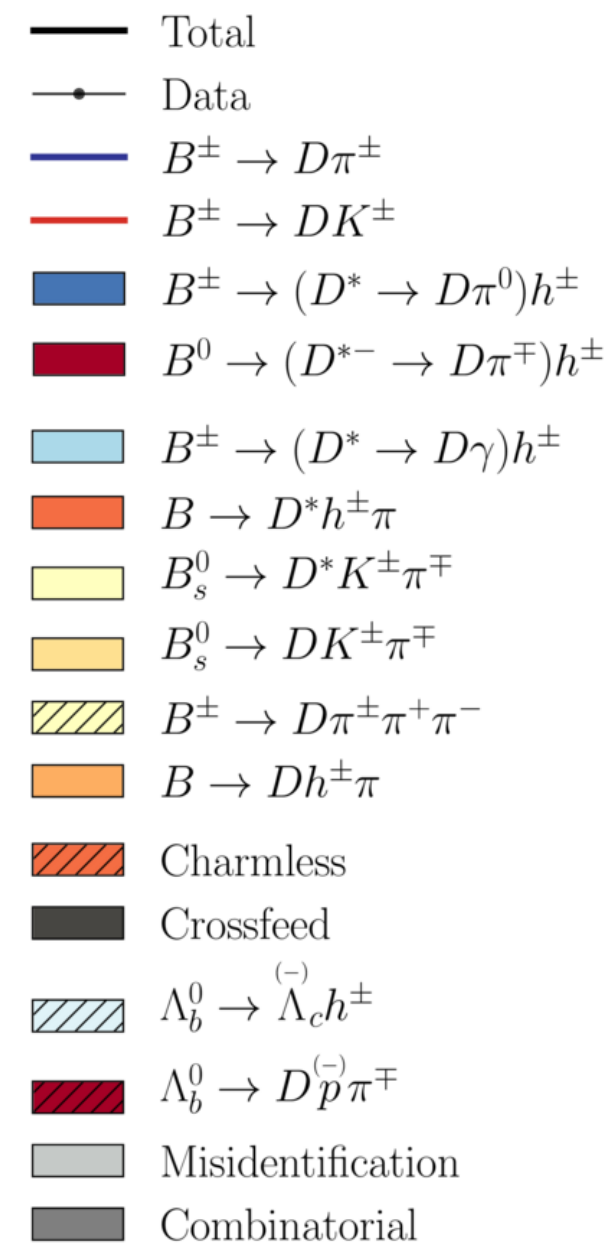
The unitarity triangle apex



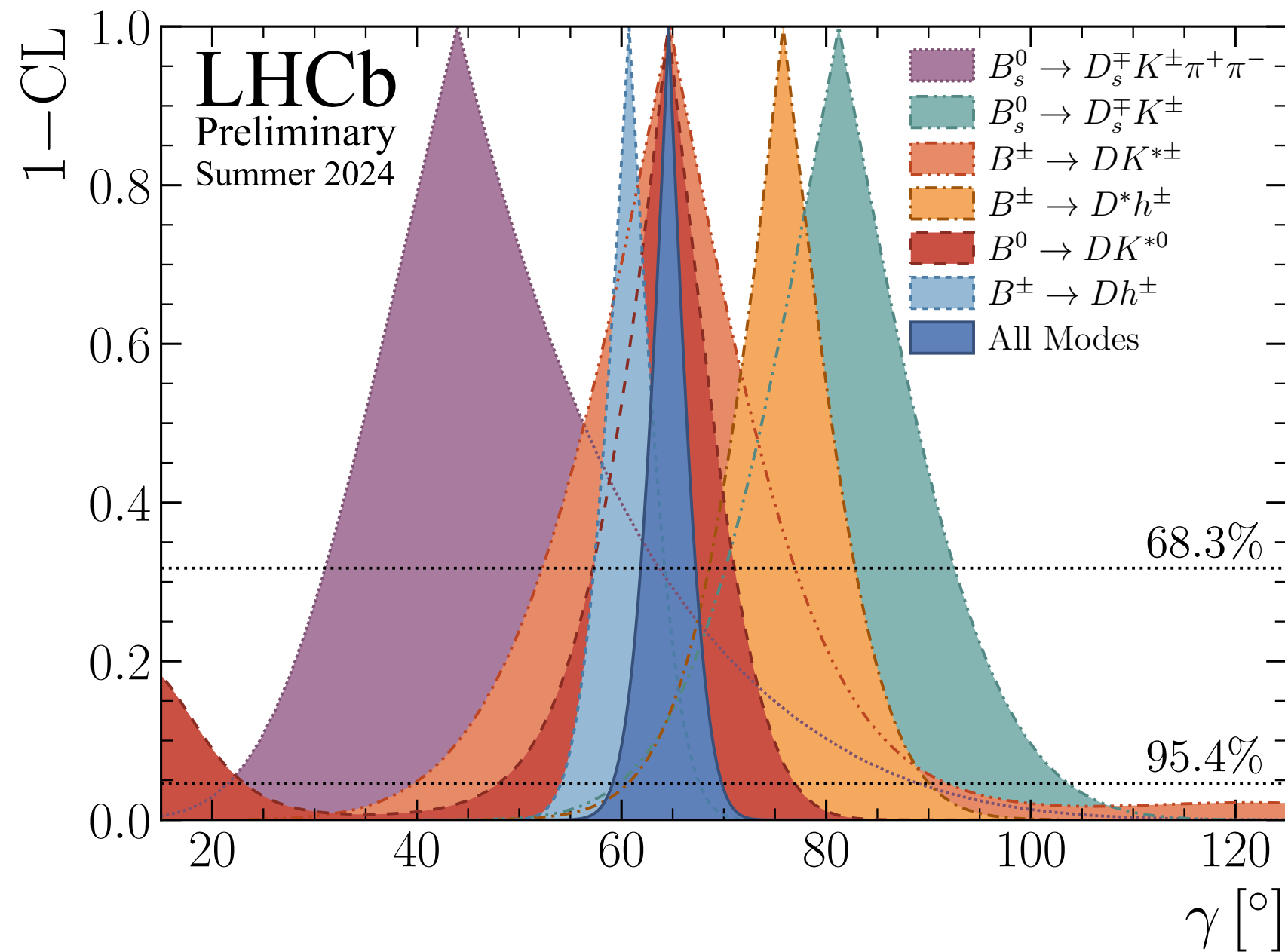
The unitarity triangle apex



We have come quite a way in 15 years



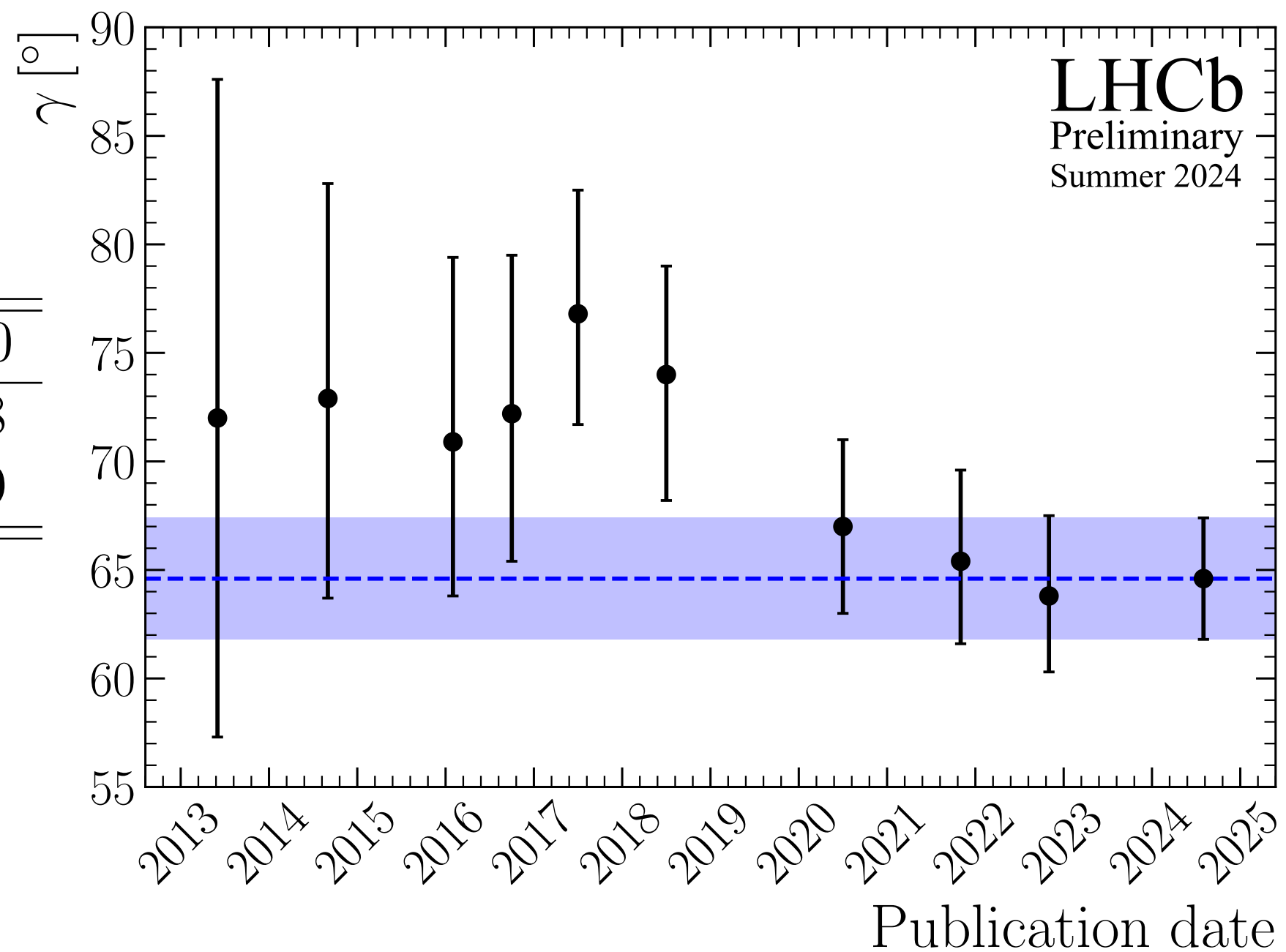
A cornucopia of methods



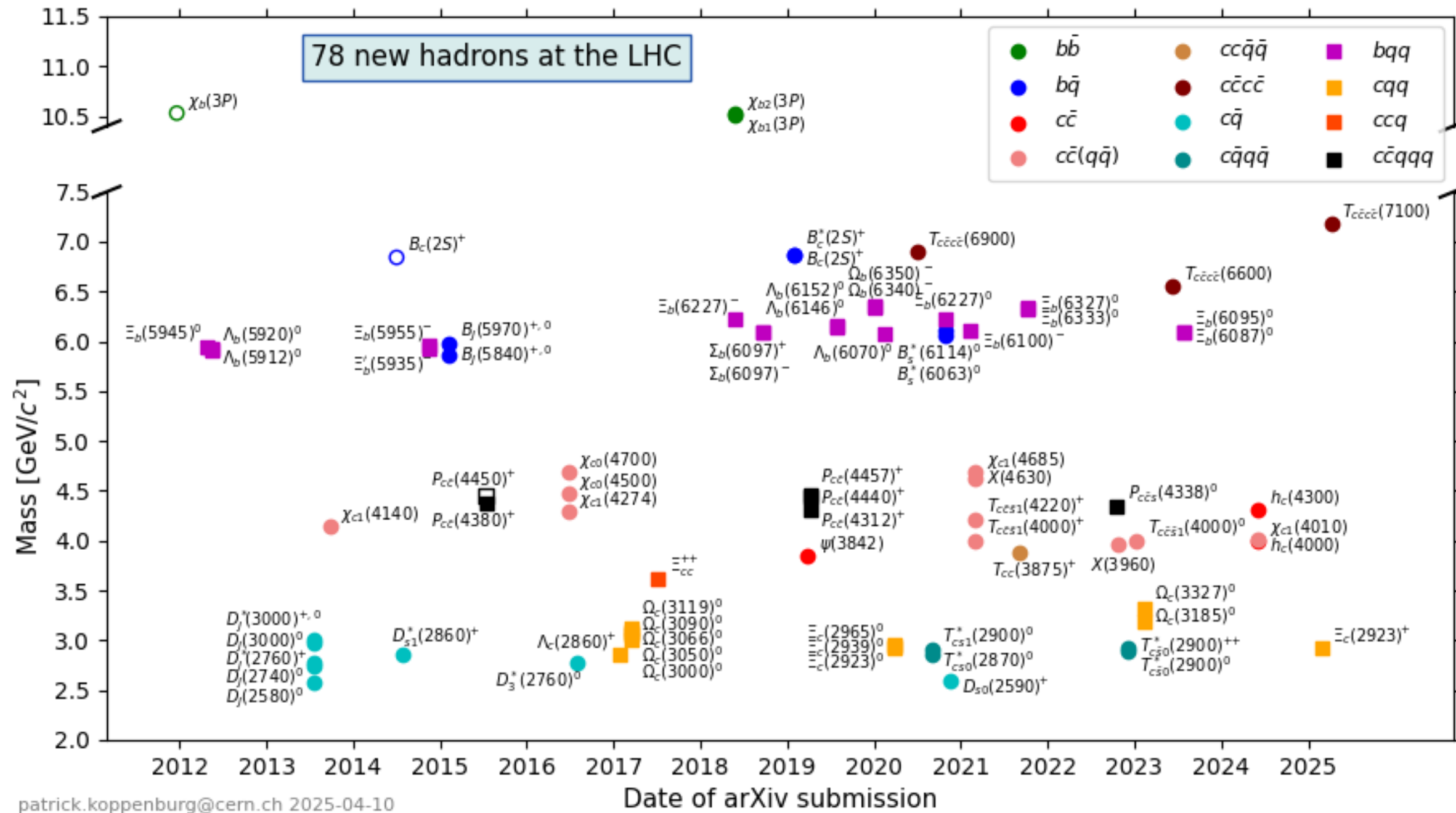
And definitely not a wasteland

LHCb 2009 measurements roadmap
Statistical uncertainty only!

$\delta_{B^0} \text{ (}^\circ\text{)}$	0	45	90	135	180
$\sigma_\gamma \text{ for } 0.5 \text{ fb}^{-1} \text{ (}^\circ\text{)}$	8.1	10.1	9.3	9.5	7.8
$\sigma_\gamma \text{ for } 2 \text{ fb}^{-1} \text{ (}^\circ\text{)}$	4.1	5.1	4.8	5.1	3.9

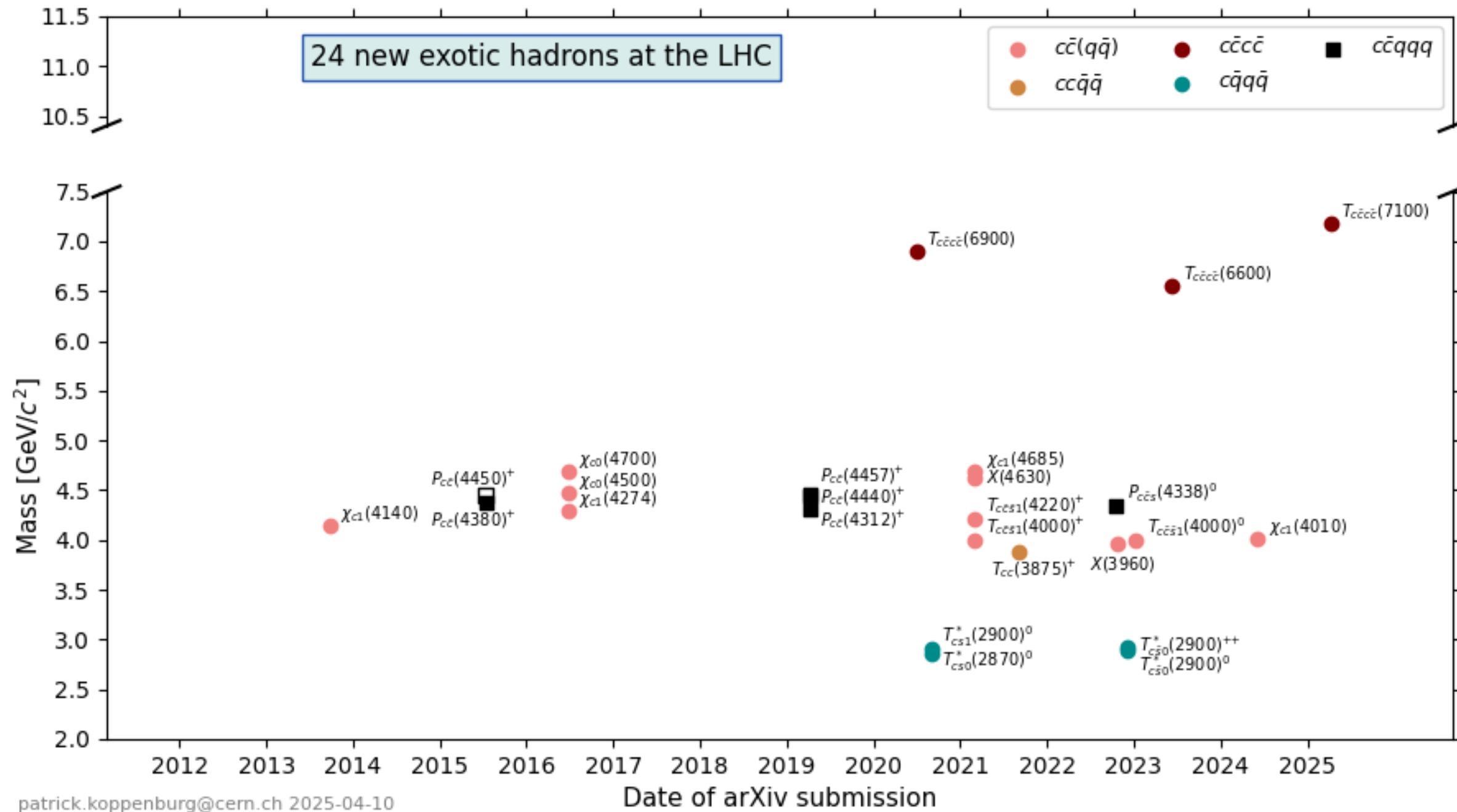


Exotic hadron spectroscopy



Credit to Patrick Koppenburg for the figure

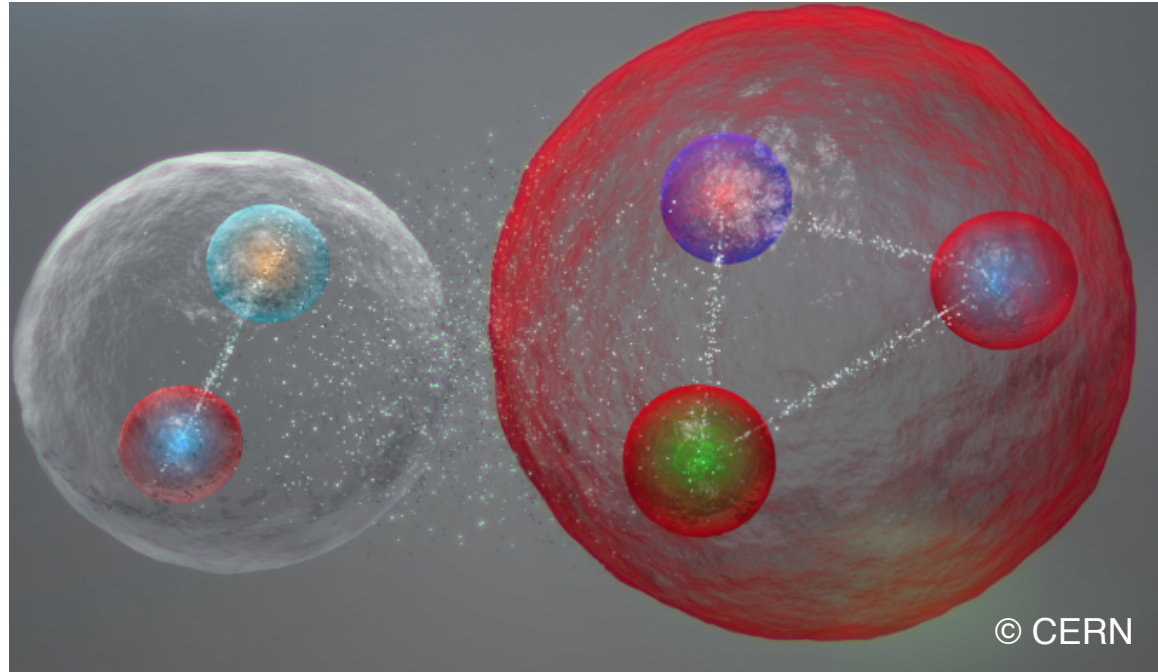
Exotic hadron spectroscopy



Credit to Patrick Koppenburg for the figure

What are these 4 and 5 quark states?

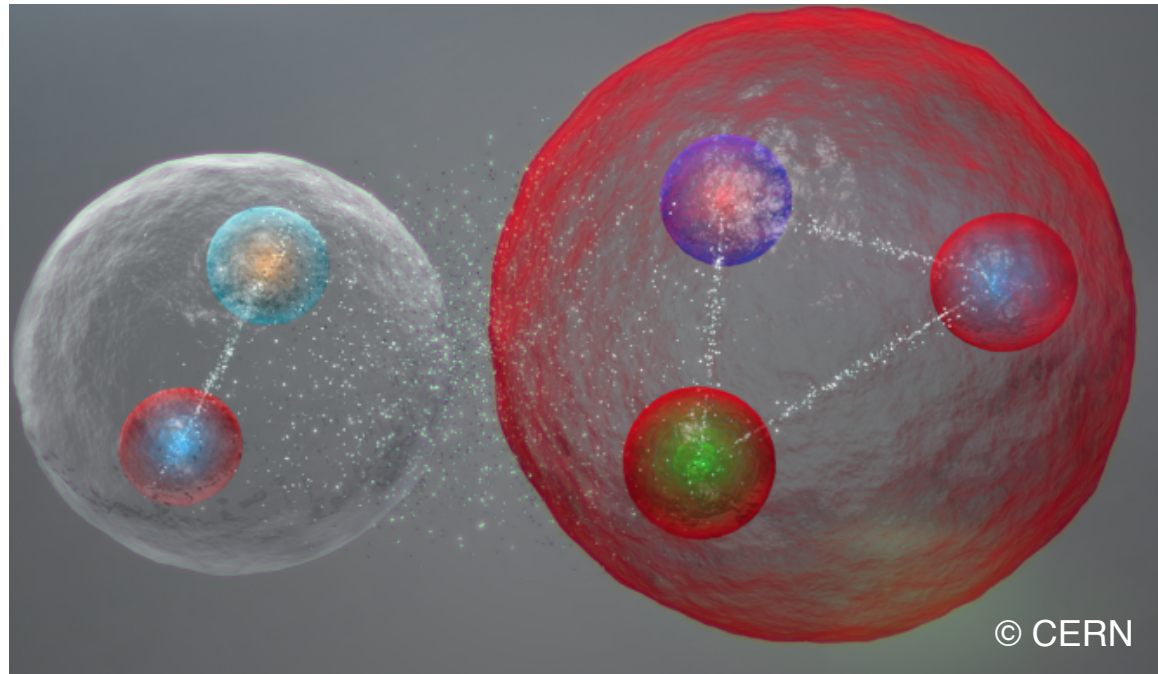
Molecule model - nuclear forces



F.-K. Guo et al., Rev. Mod. Phys. 90 (2018) 015004

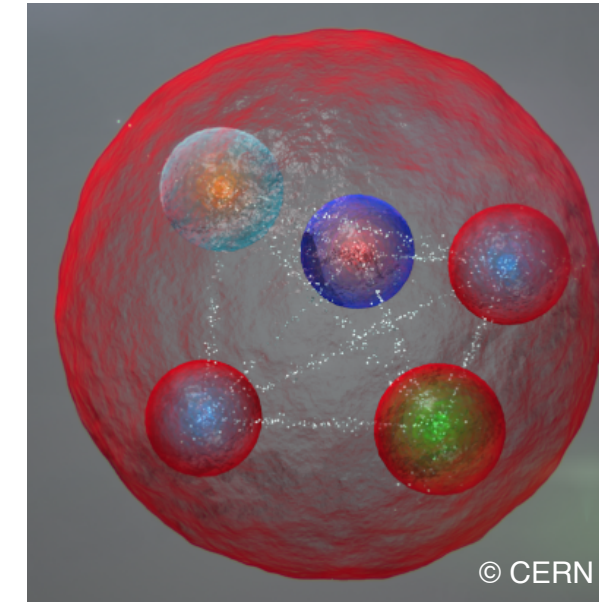
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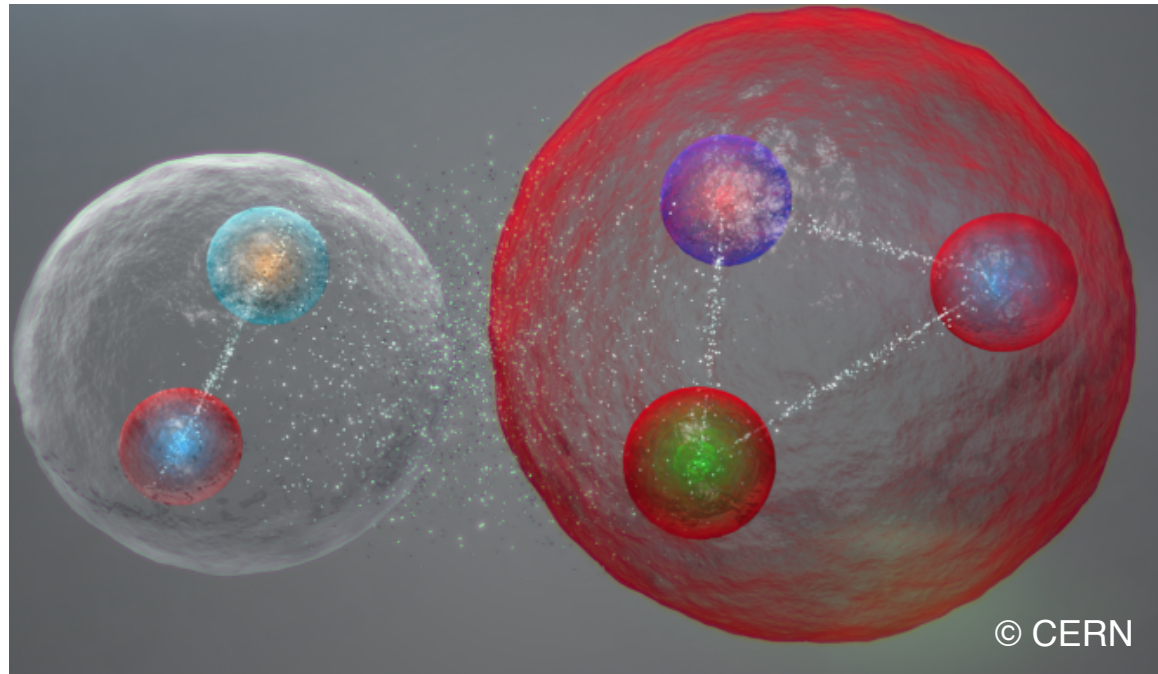
Tightly bound quarks - color forces



A. Esposito, A Pilloni, A. D. Polosa, Phys. Rept. 668 (2017) 1
J.-M. Richard, Few Body Syst. 57 (2016) 1185

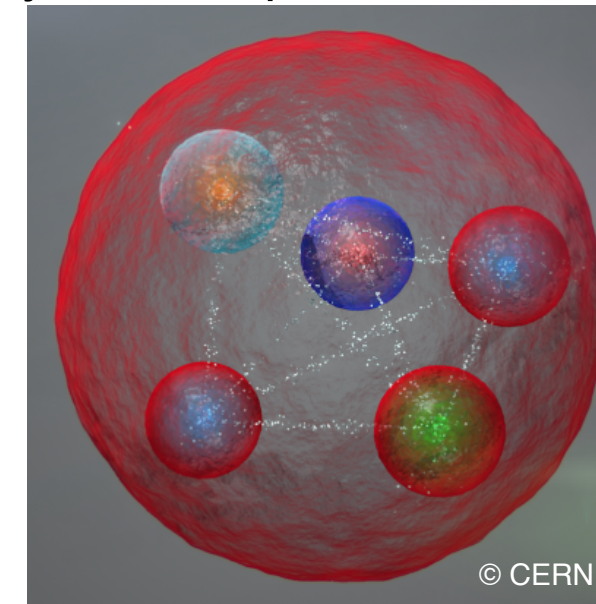
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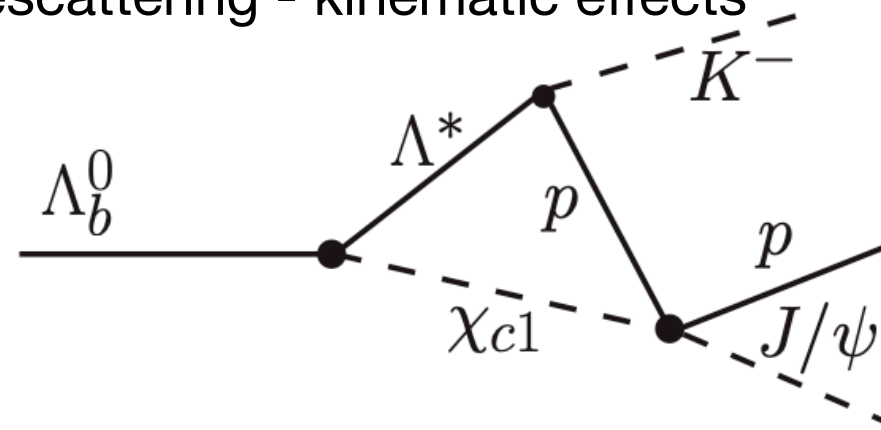
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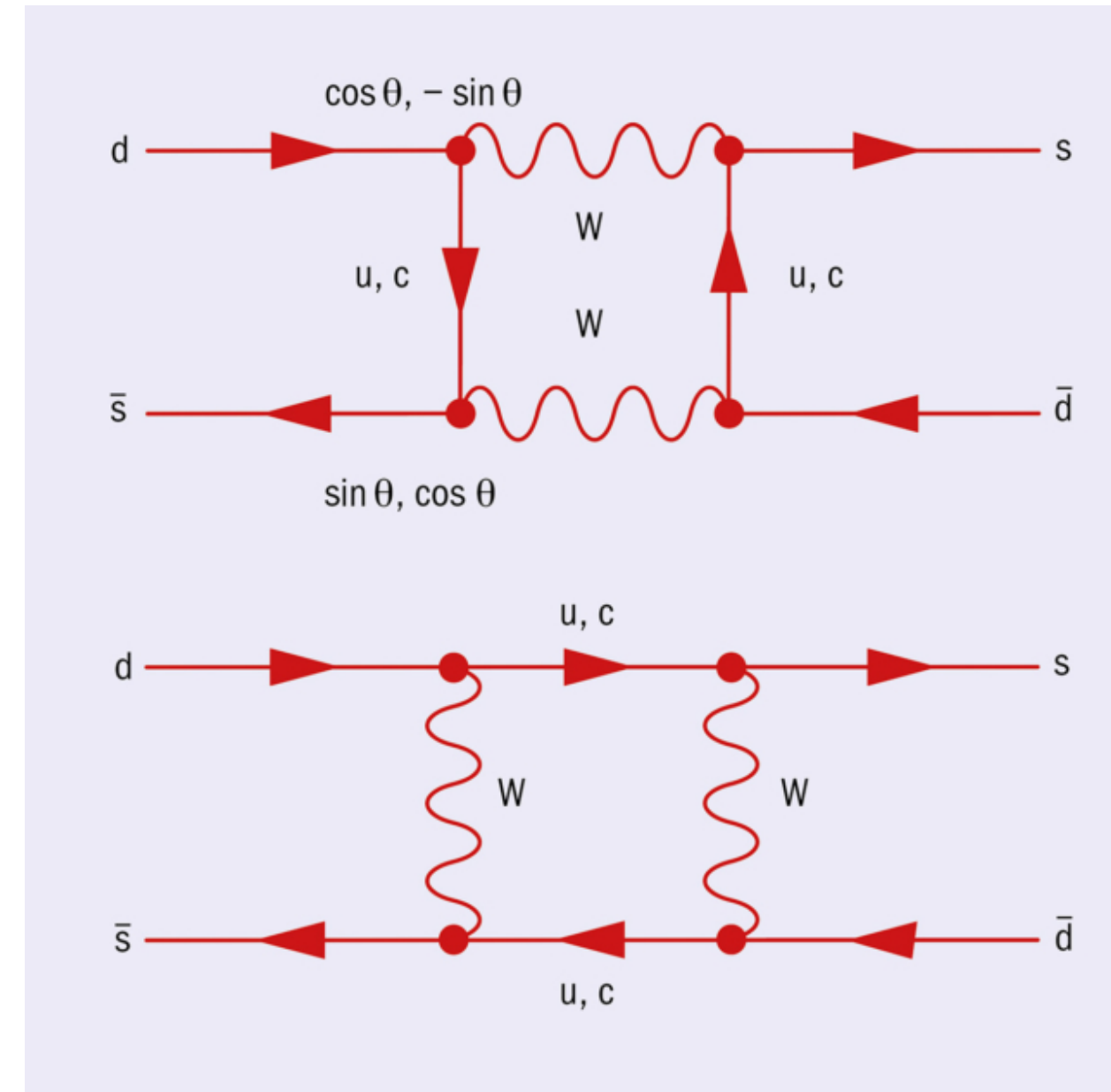
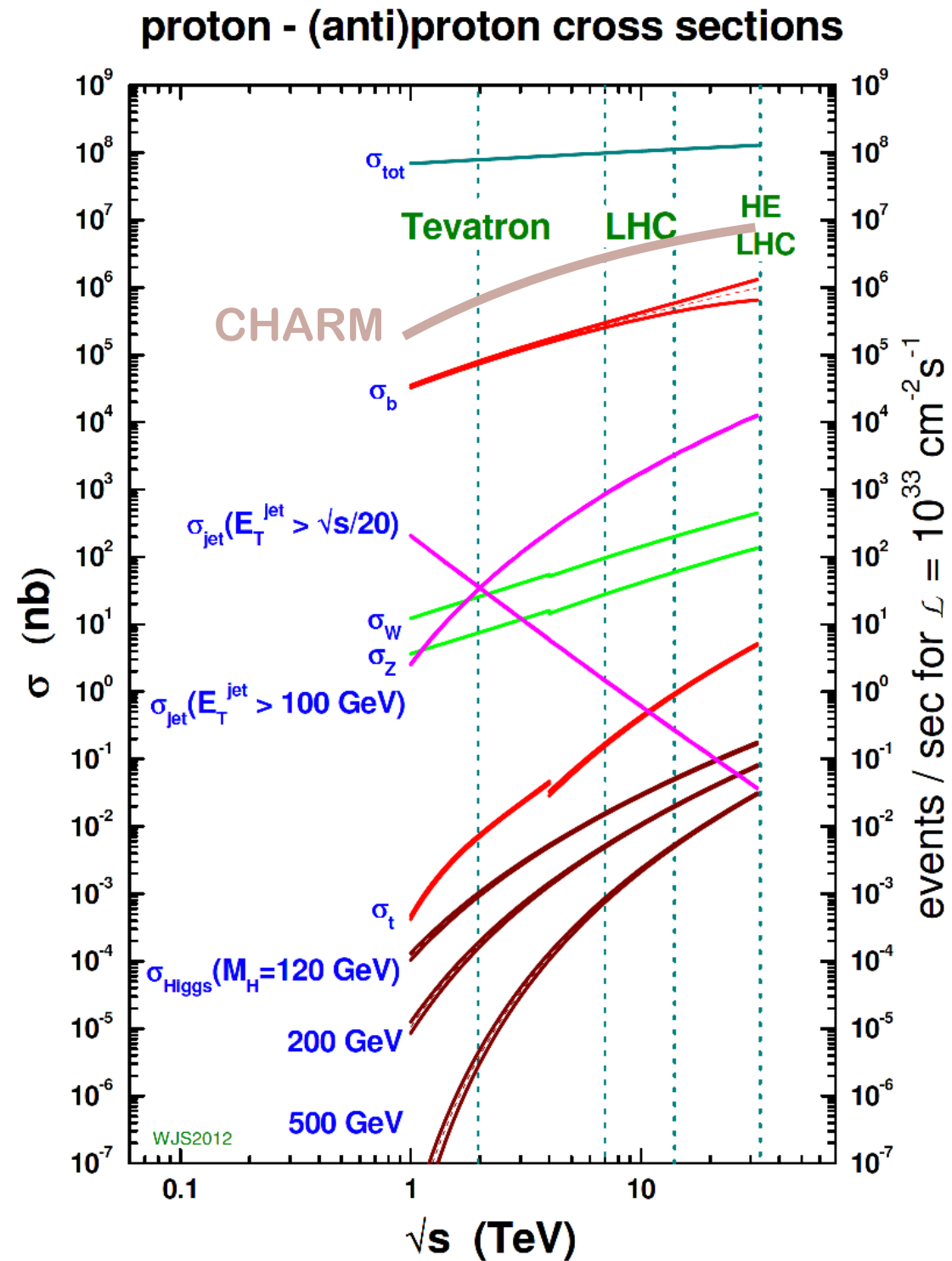
Rescattering - kinematic effects



F. Guo et al., Phys. Rev. D 92, 071502 (2015)

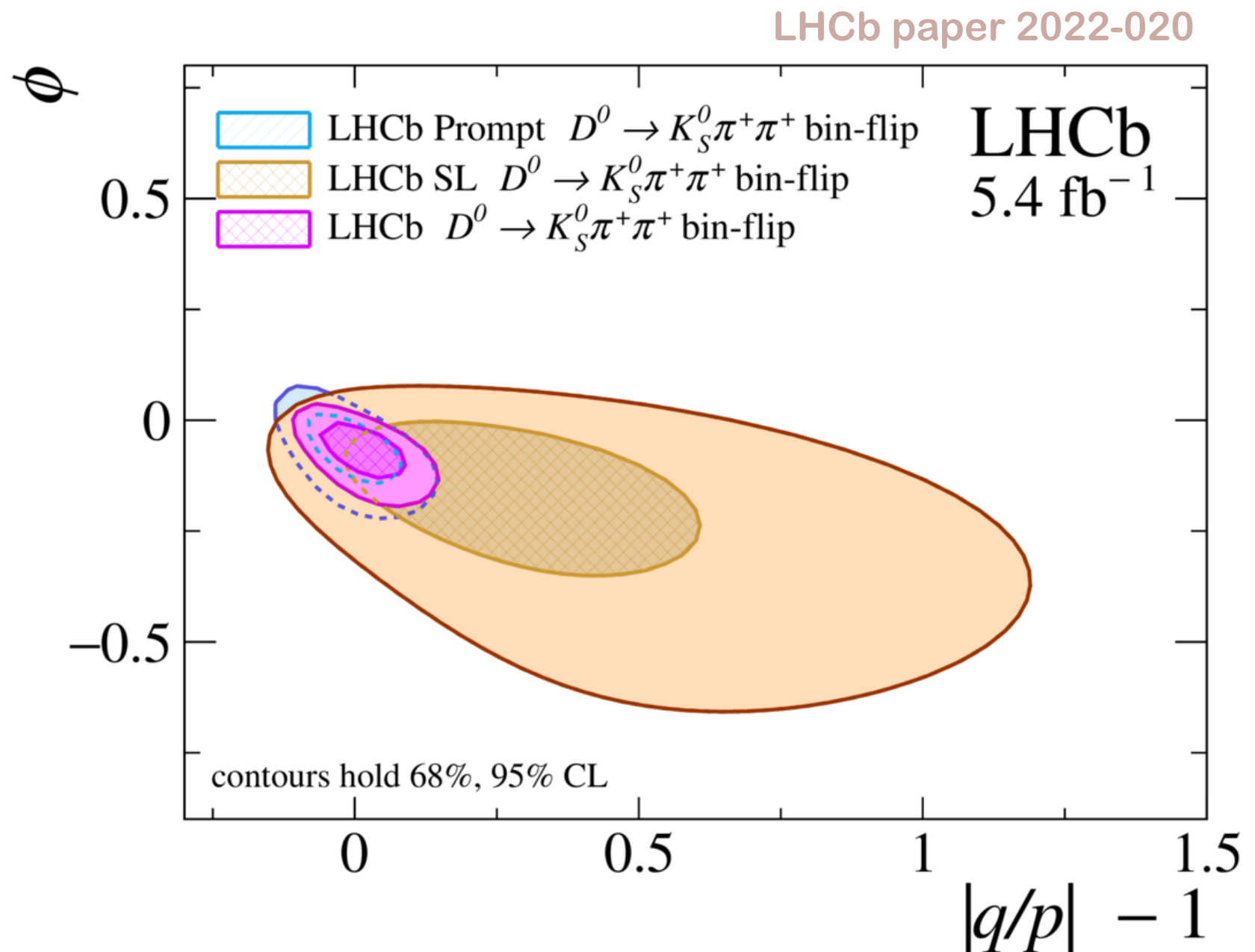
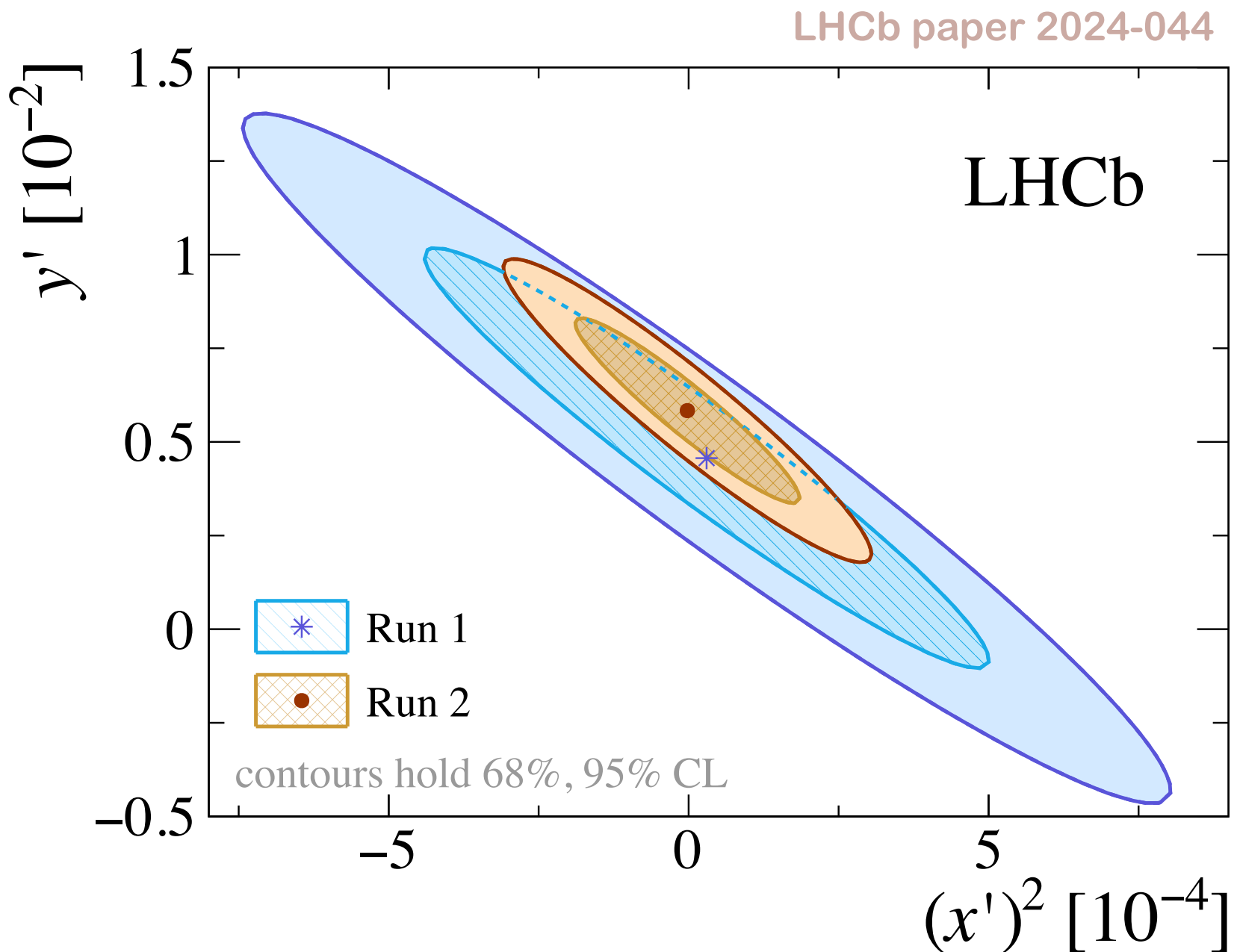
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Charm hadrons – the up sector



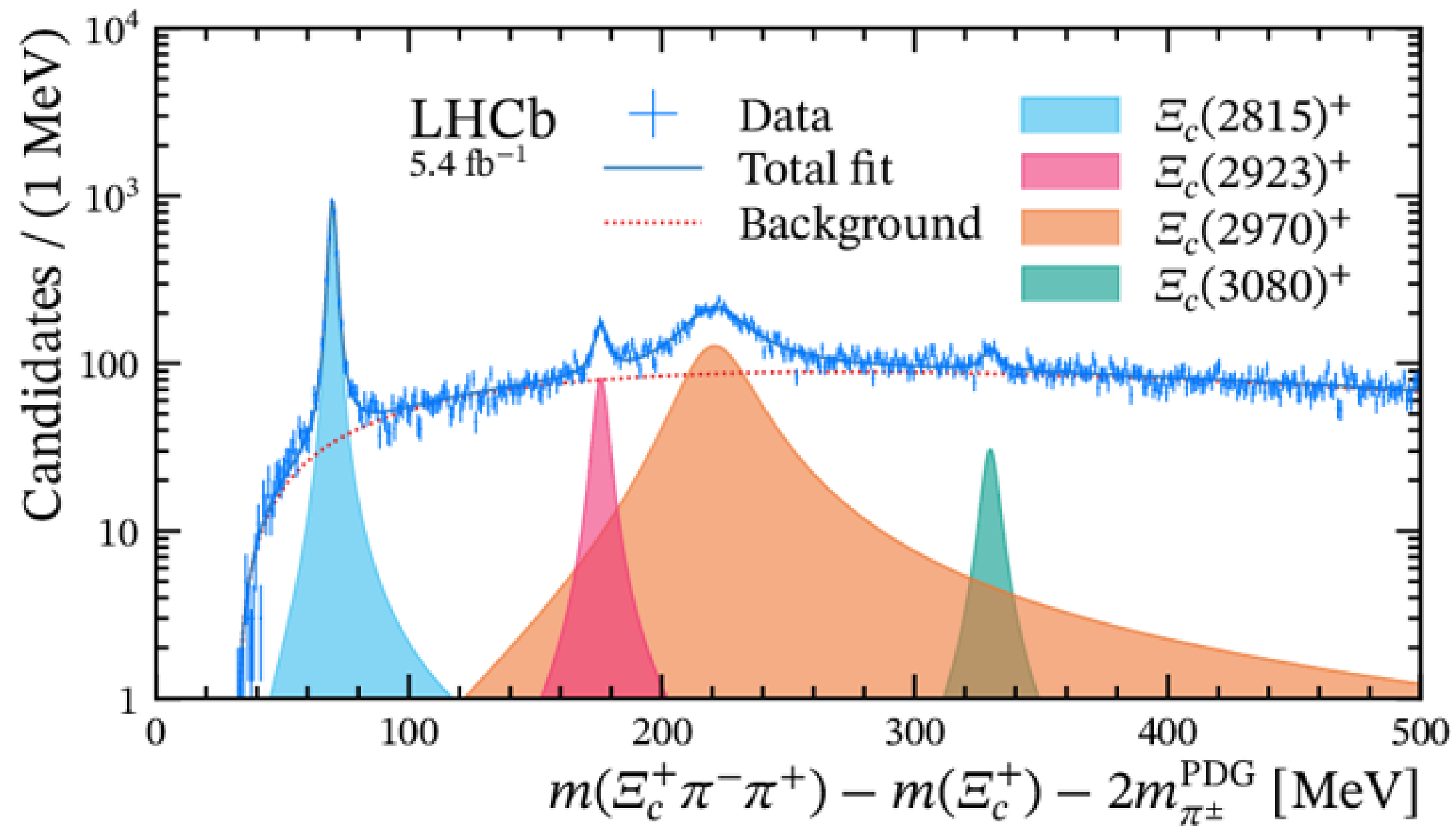
The only up-type quark which forms weakly-decaying hadrons

Precisely characterising charm mixing

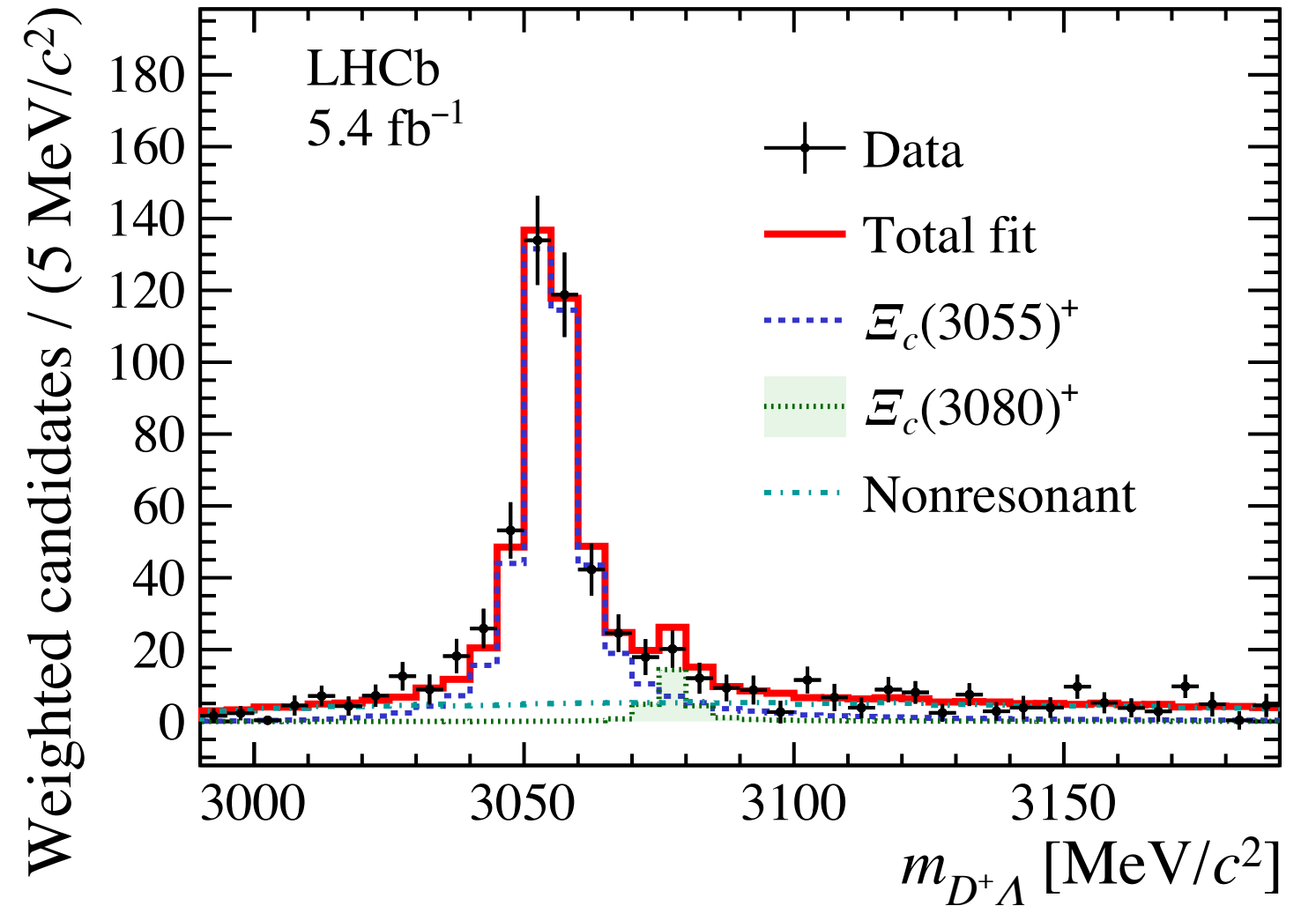
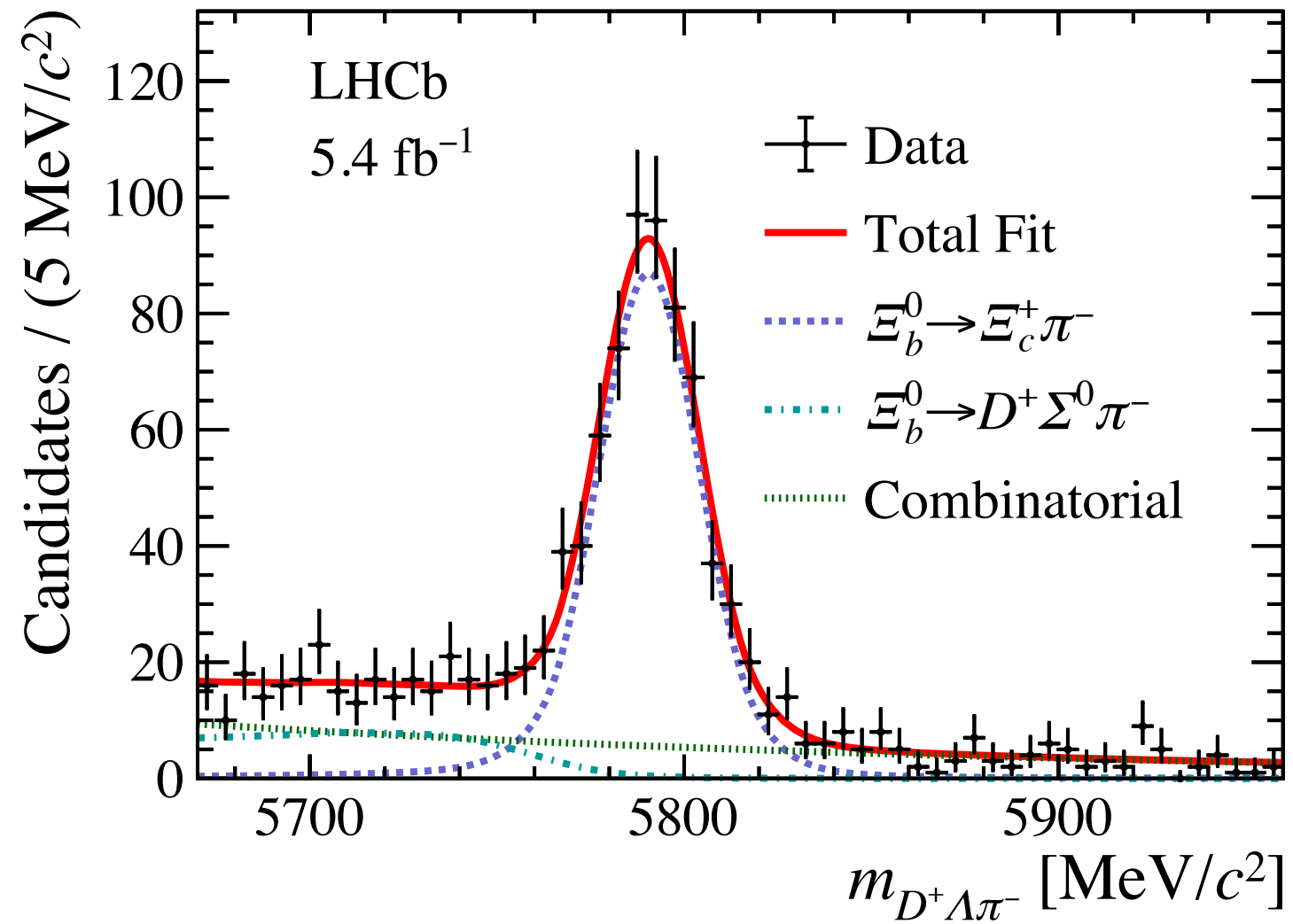


An area where the LHC production cross-section gives LHCb unique reach
Two production mechanisms – a challenge but also an opportunity for understanding systematics

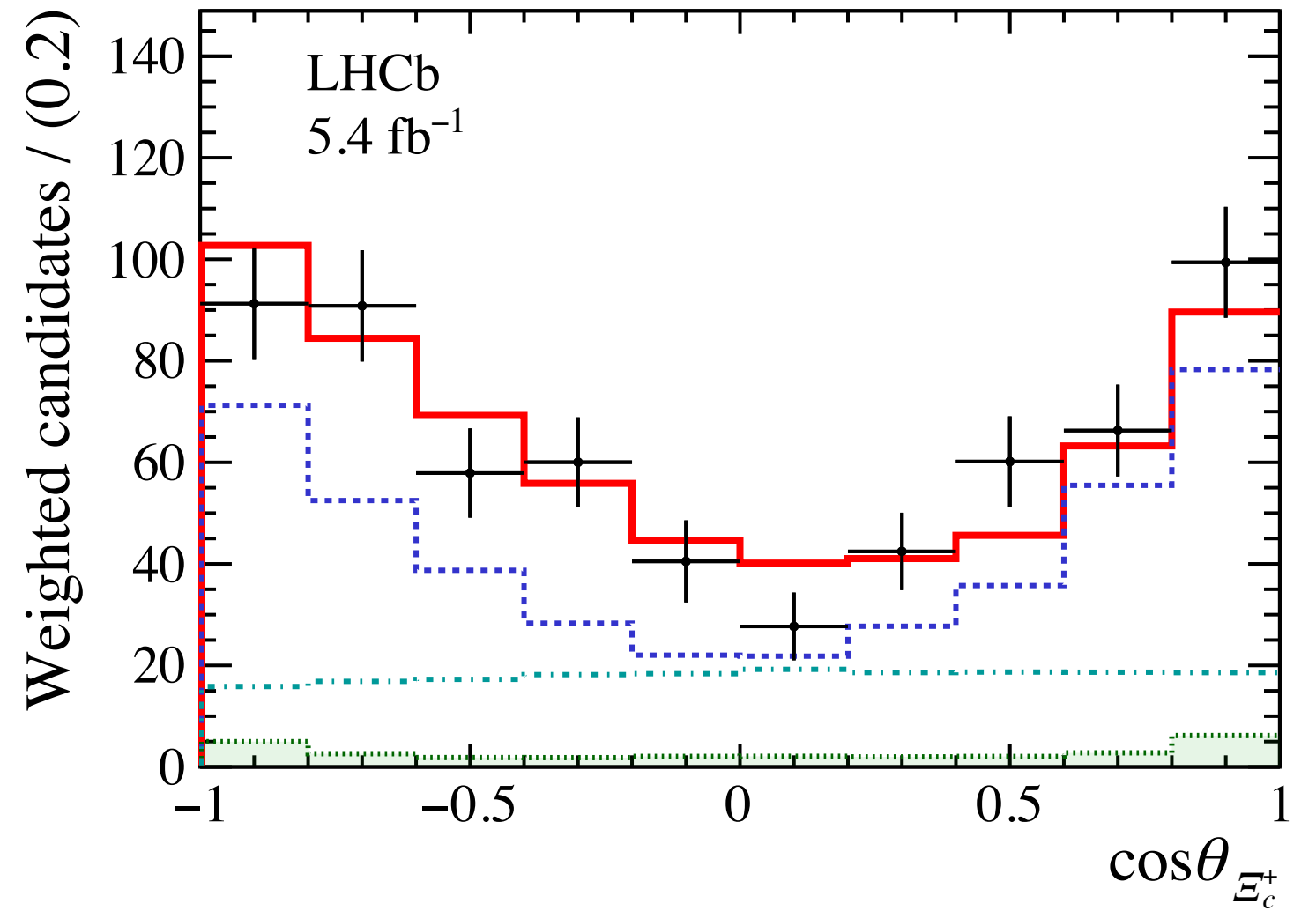
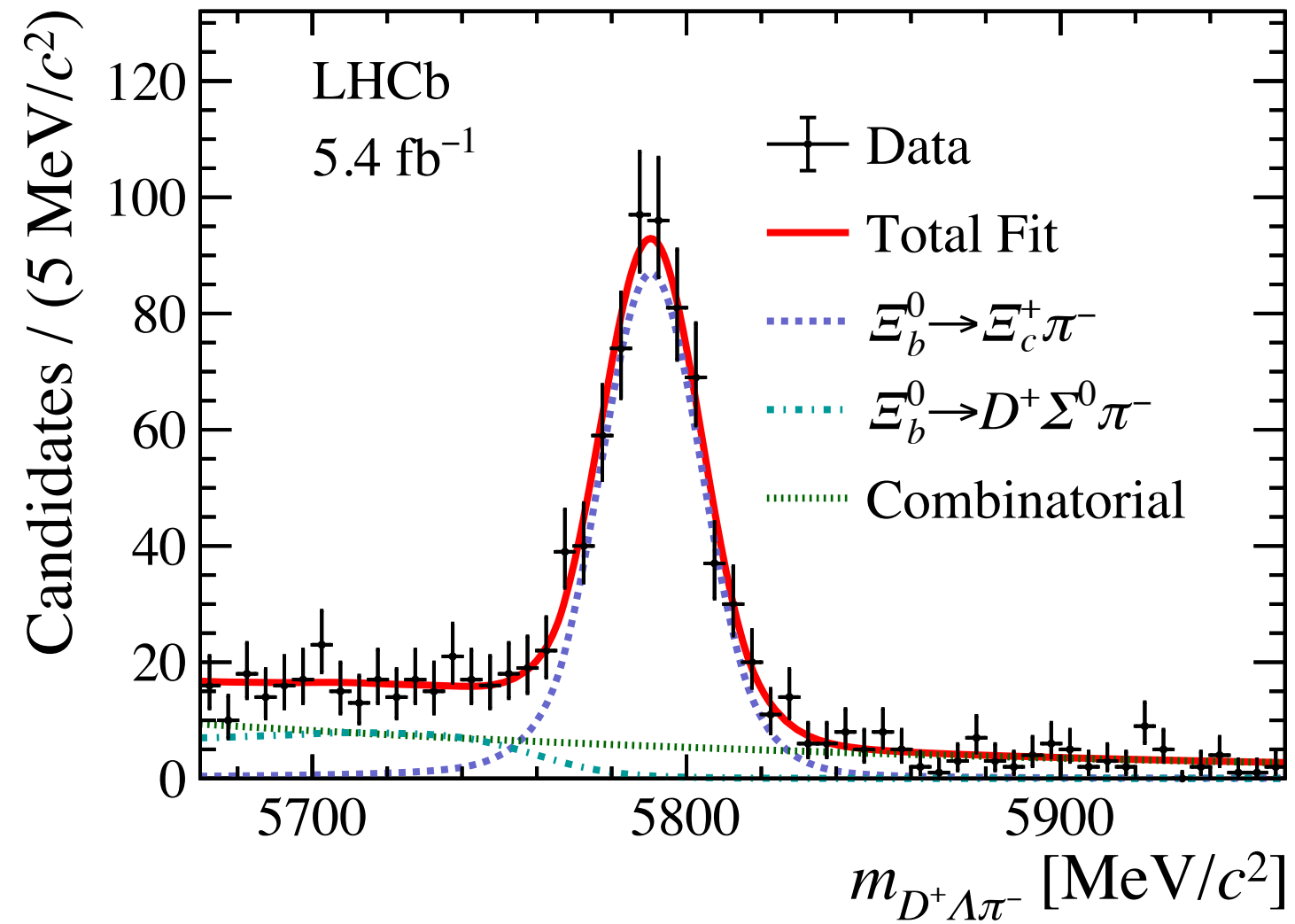
Cataloguing the charmed baryons



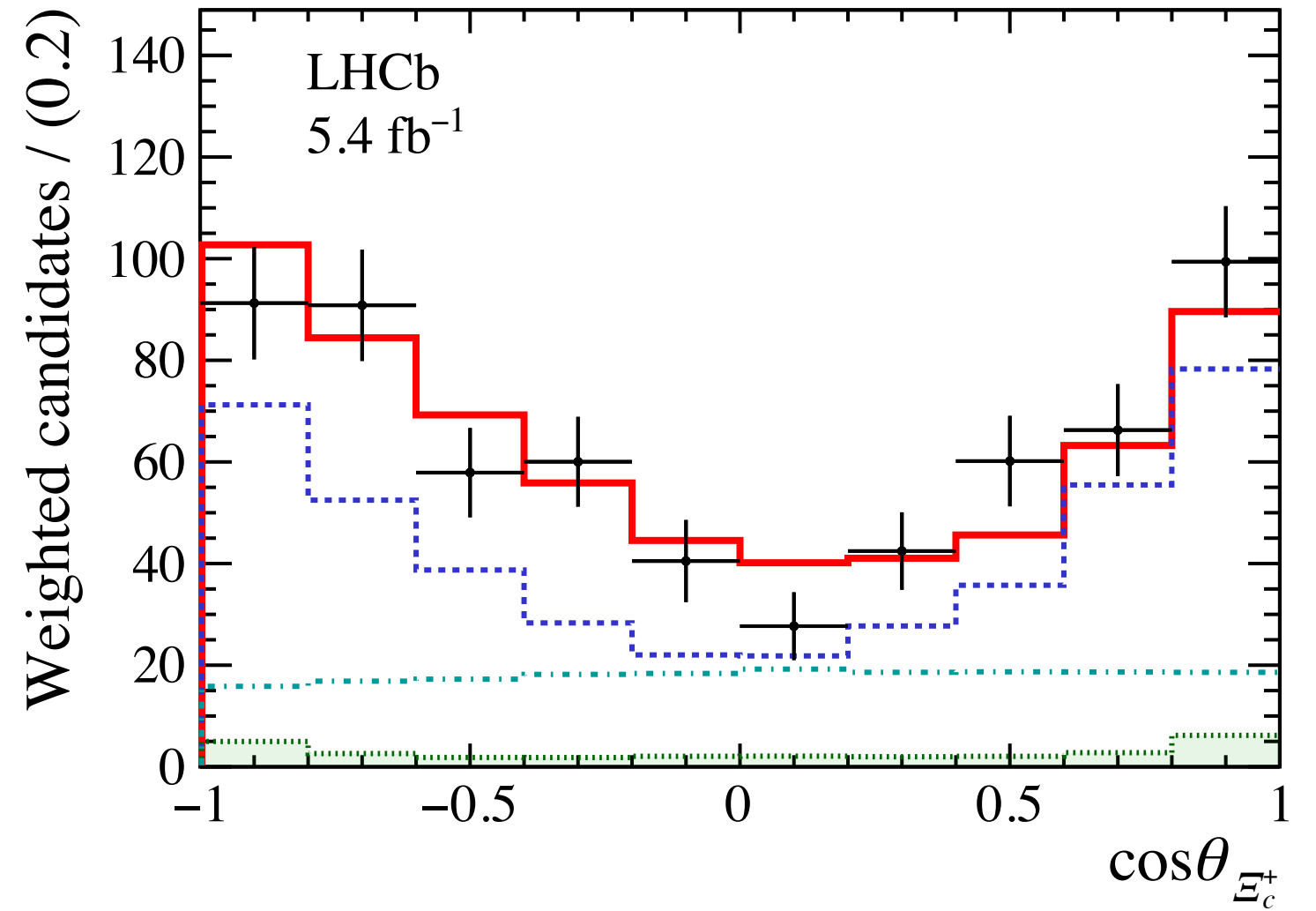
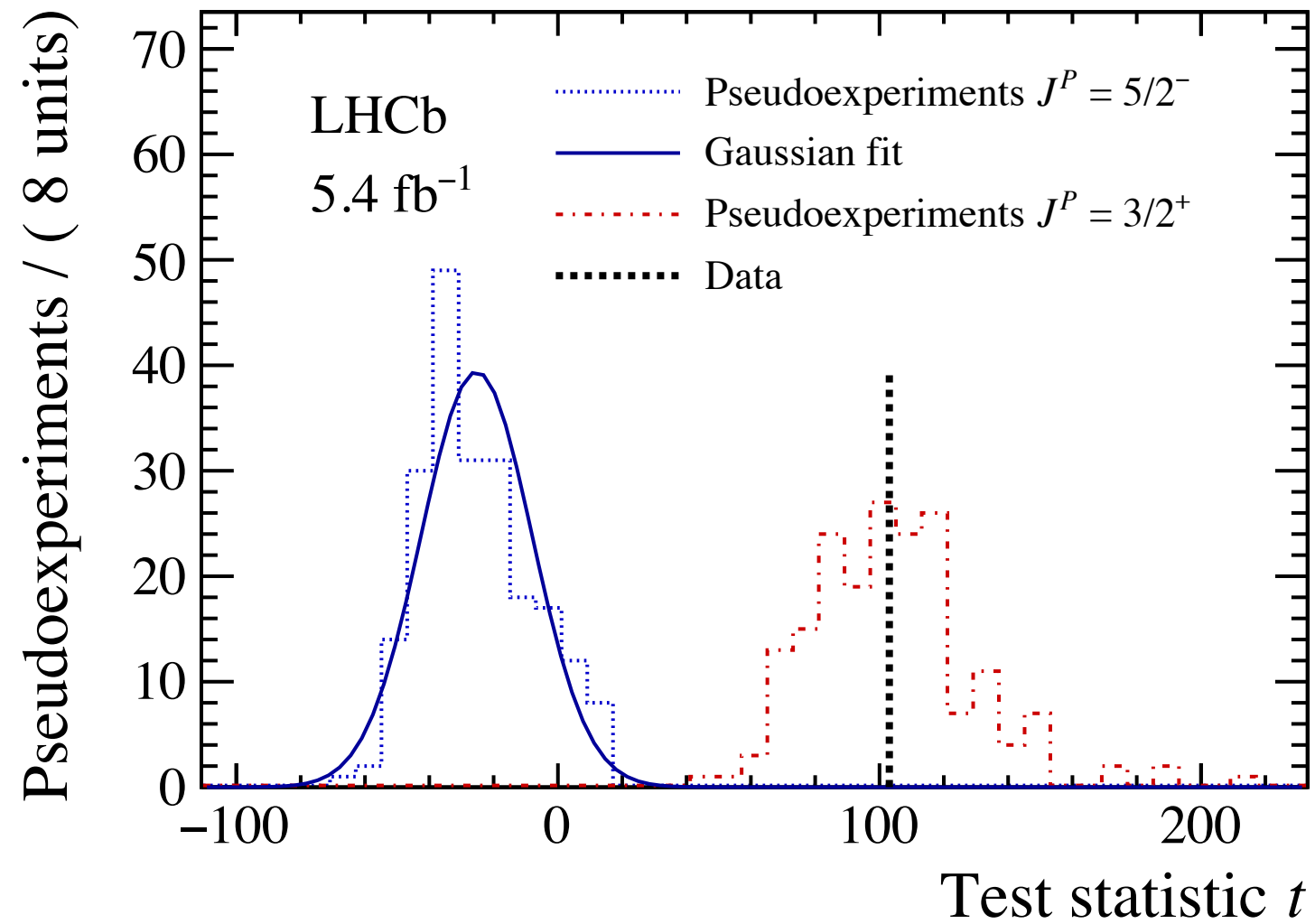
And measuring their properties



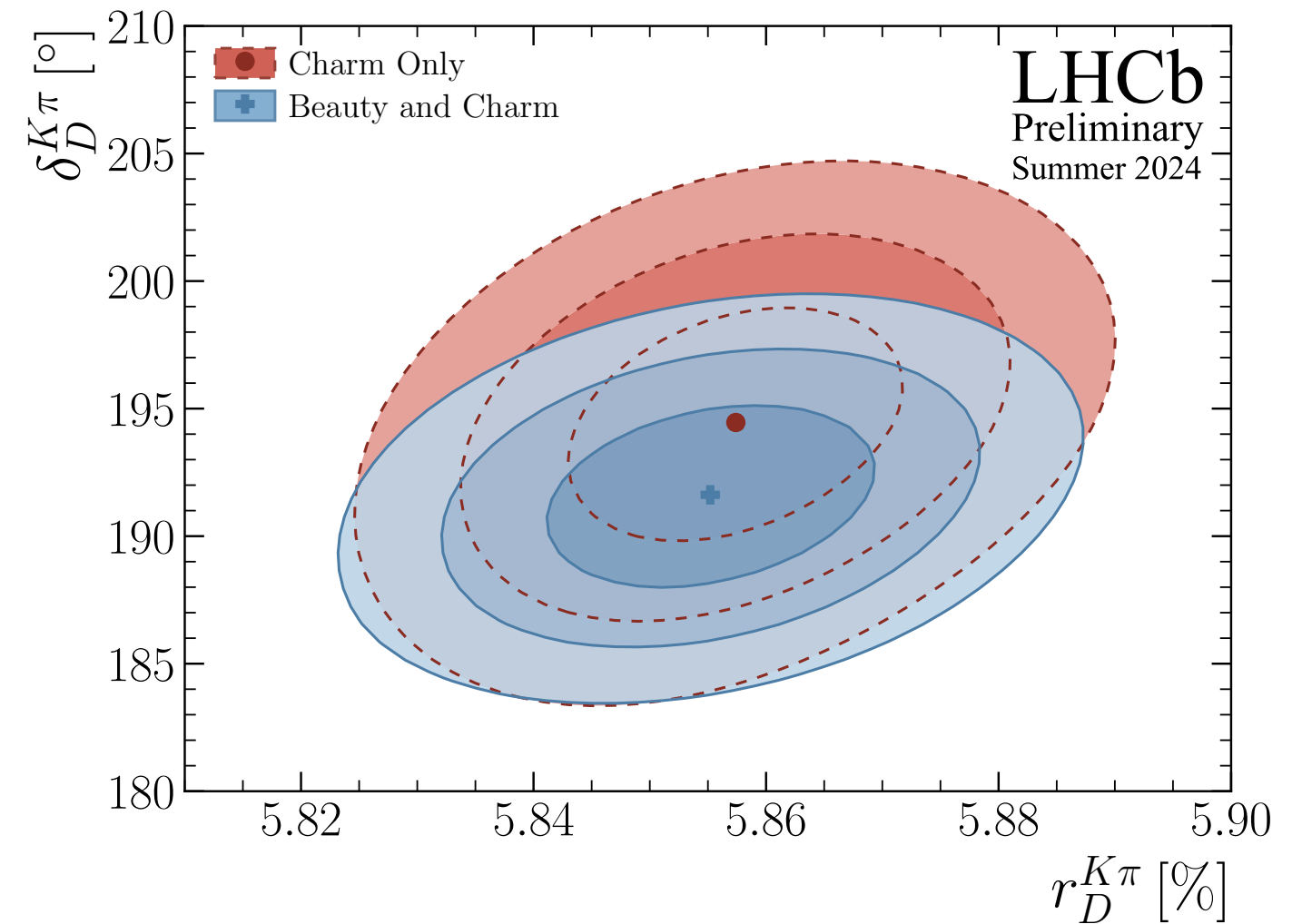
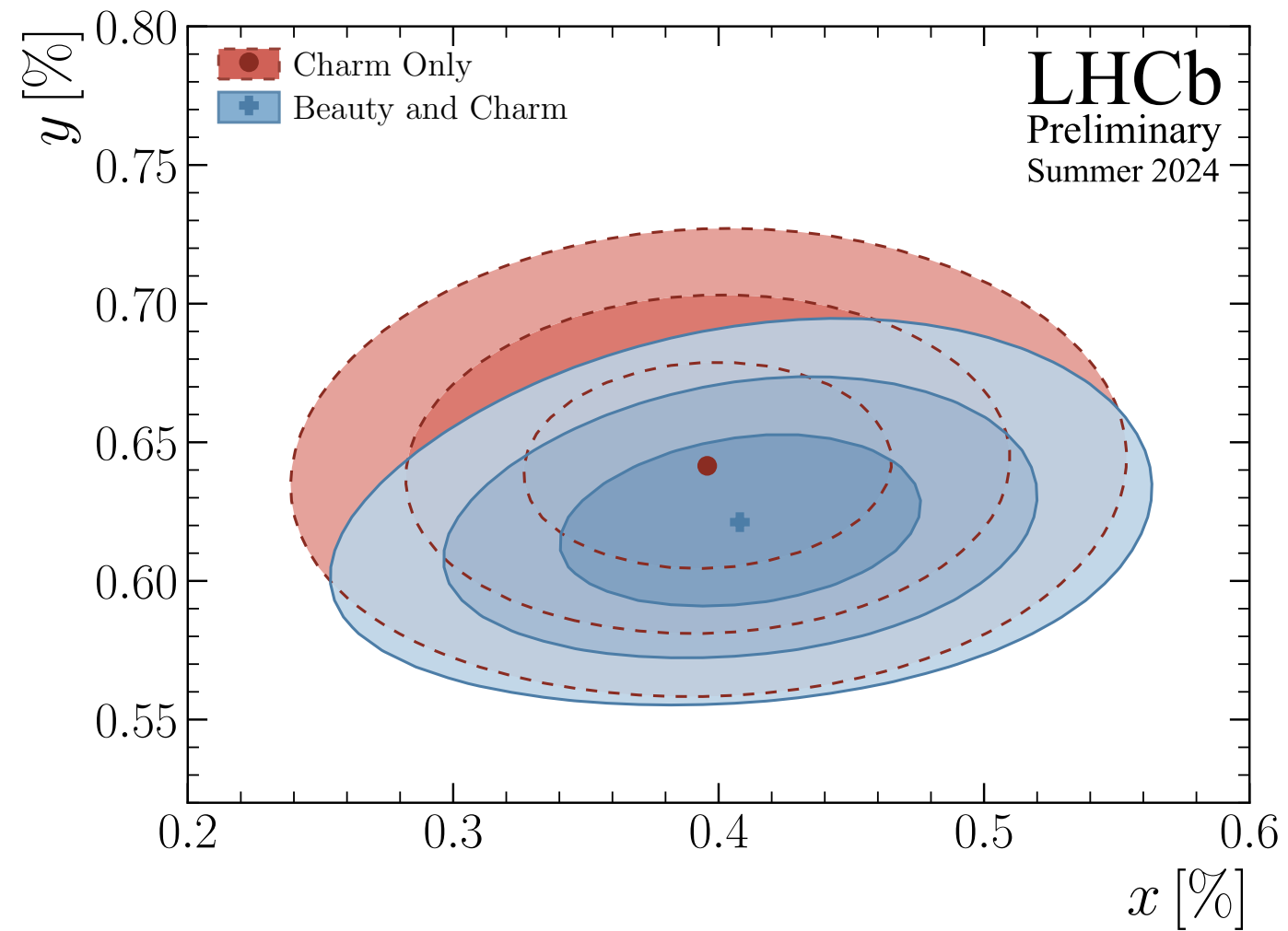
And measuring their properties



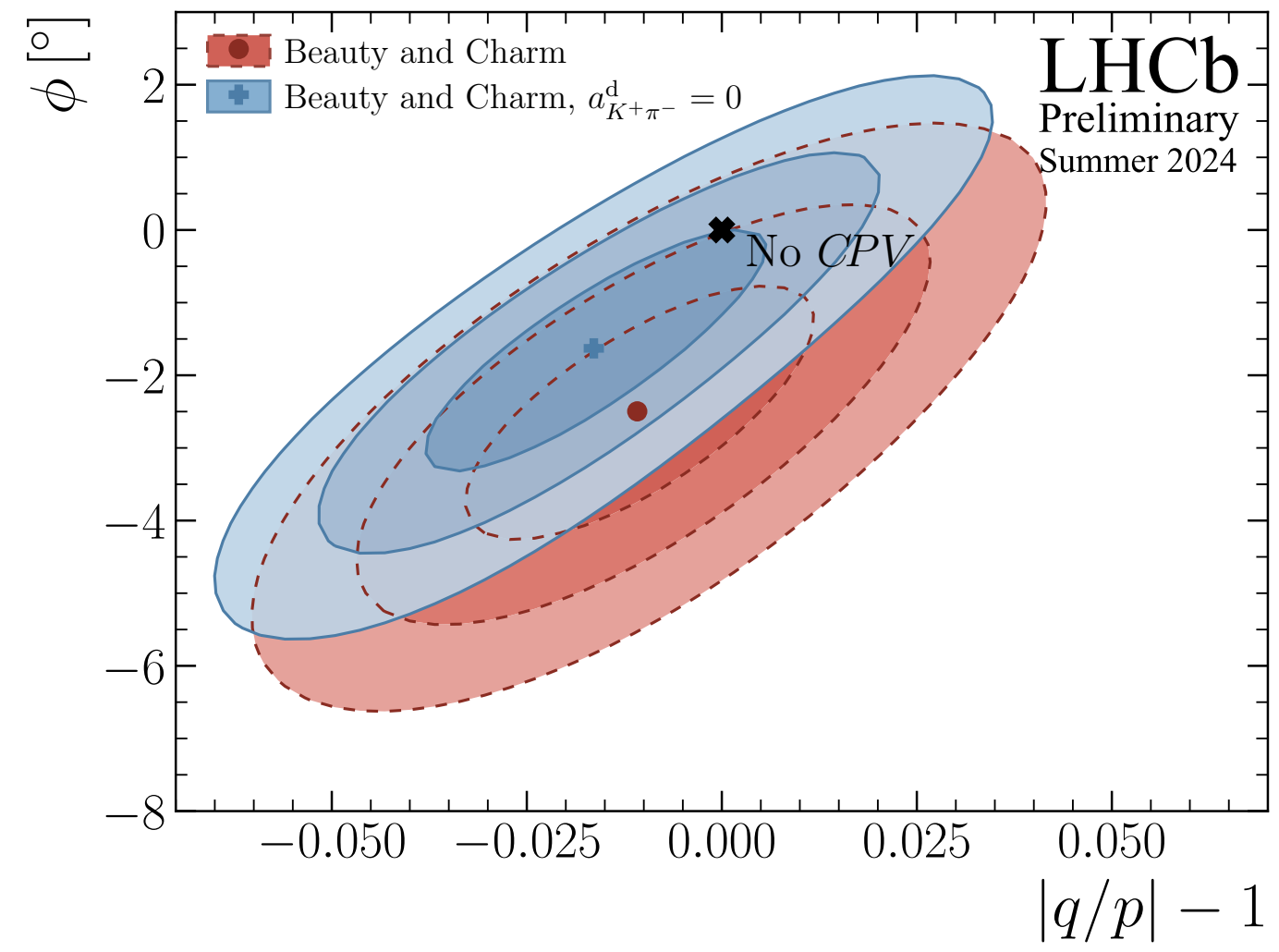
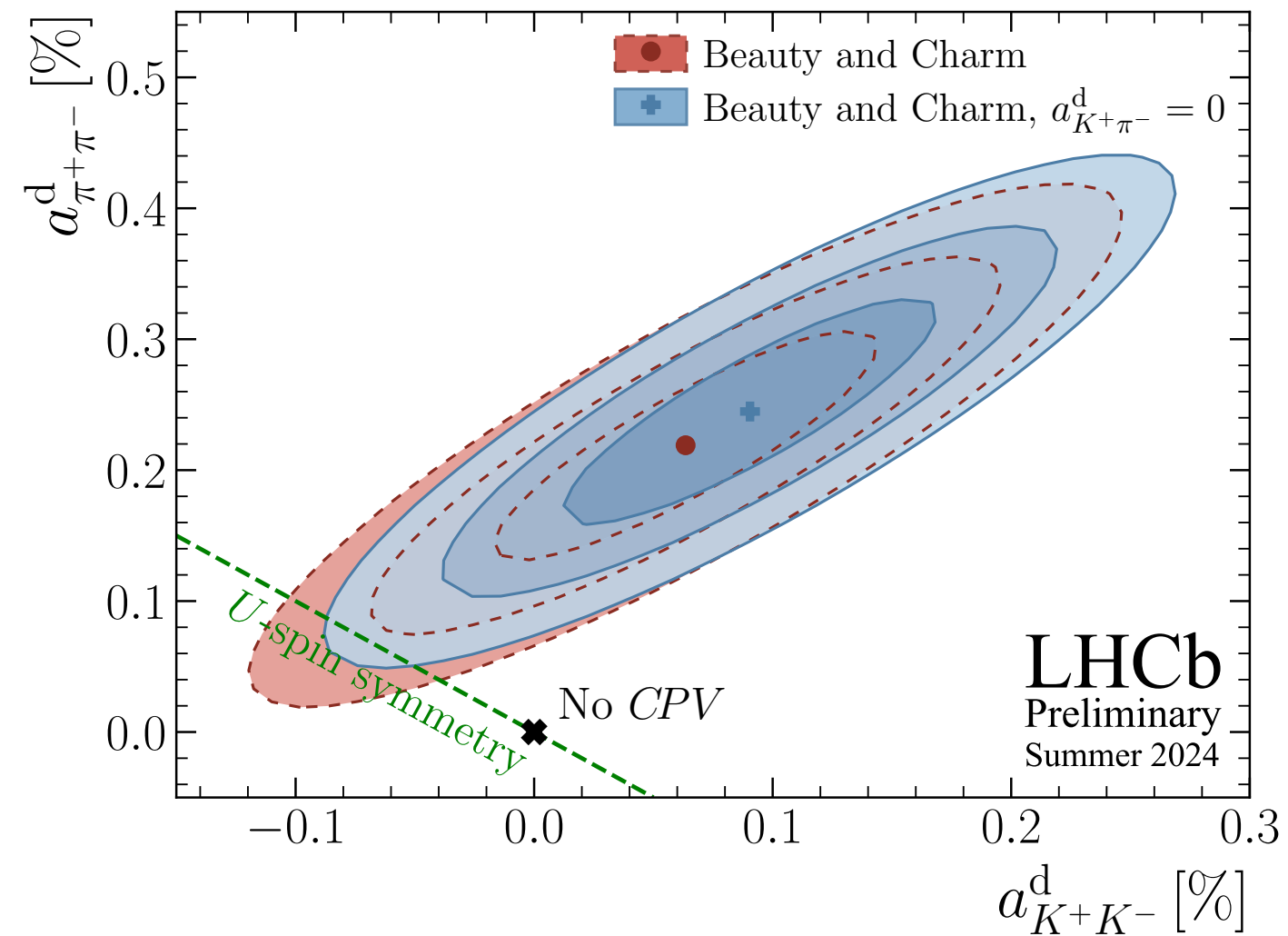
And measuring their properties



The symbiosis of beauty and charm



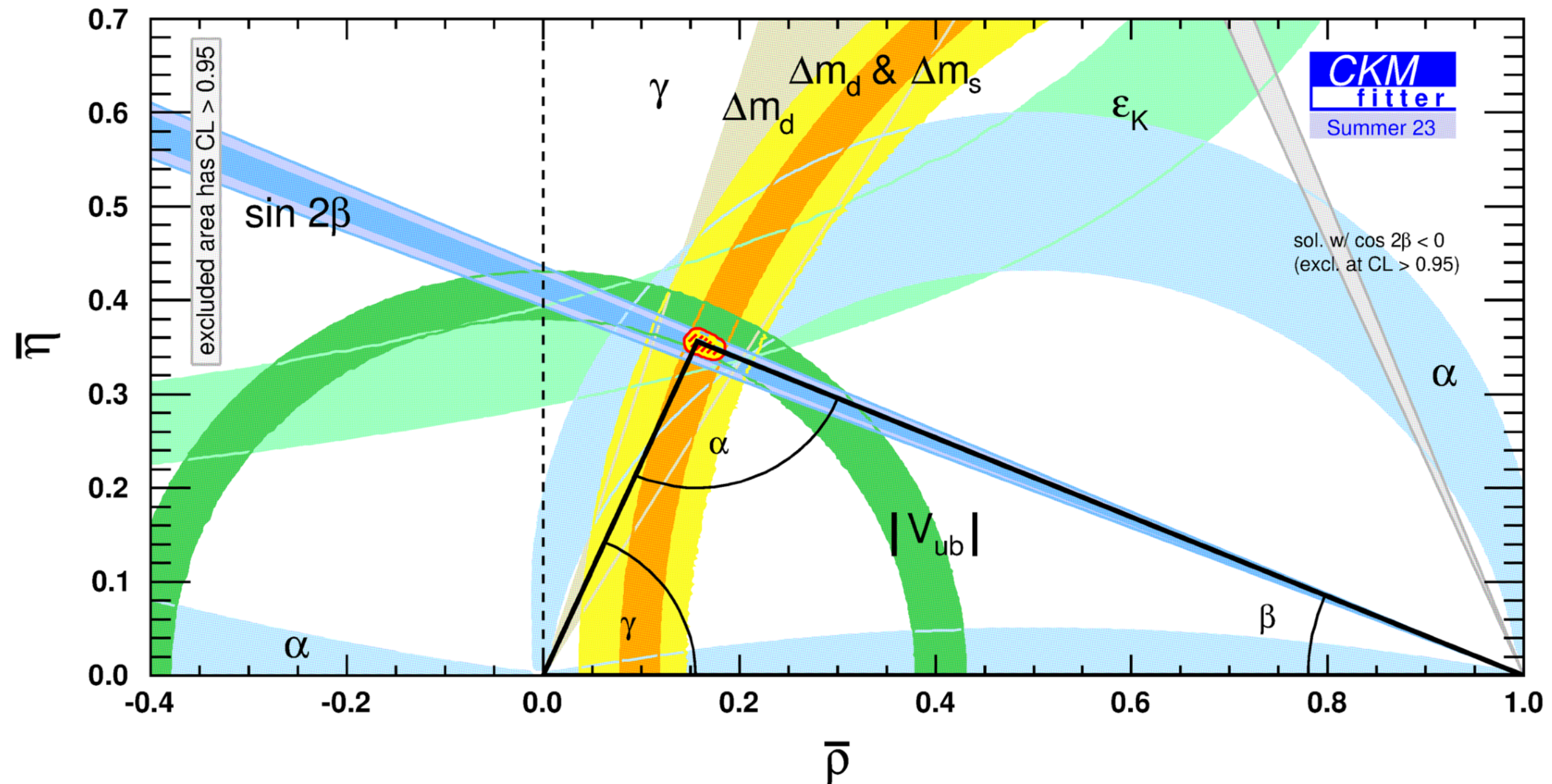
The symbiosis of beauty and charm



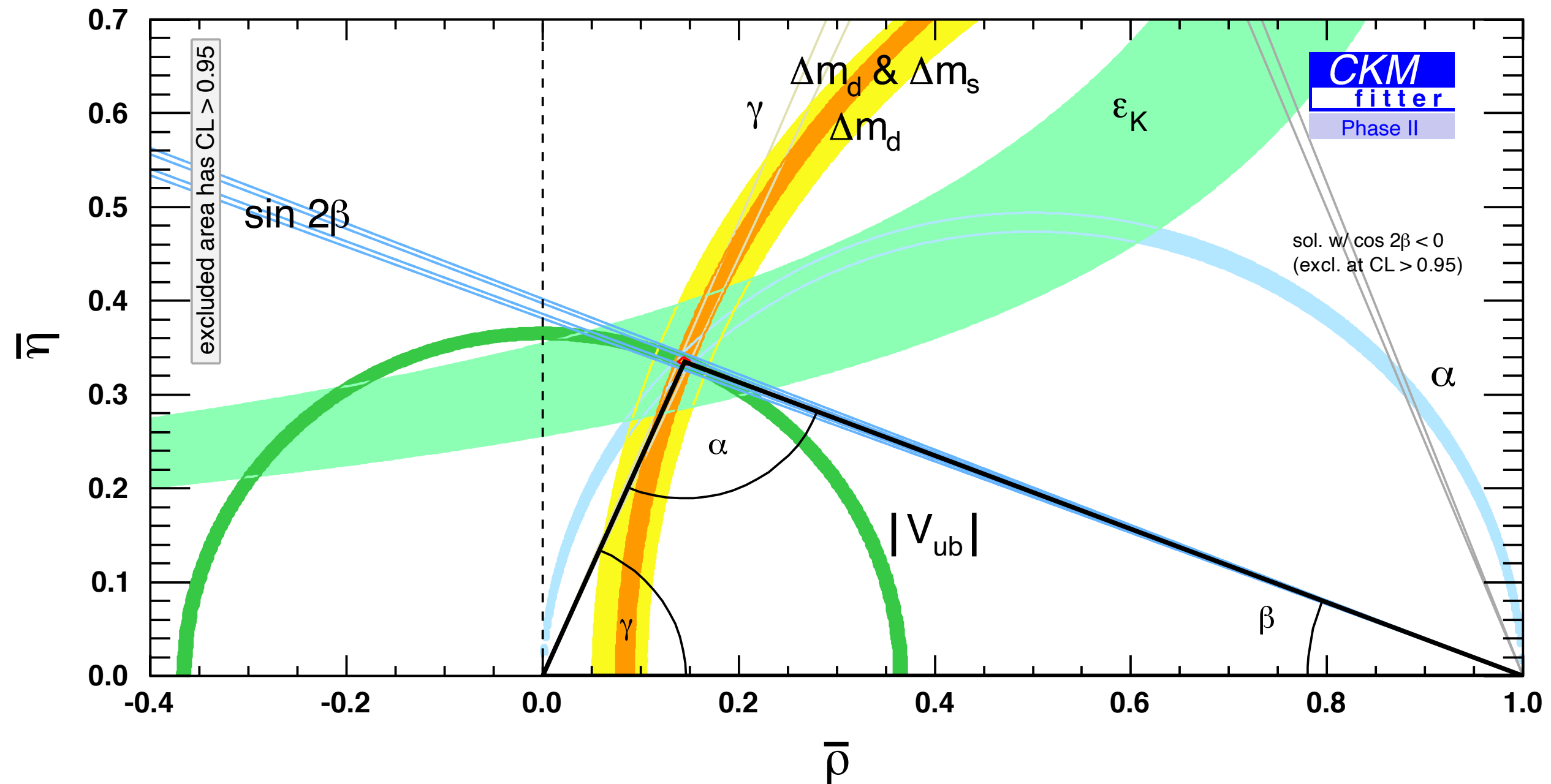
Mountains



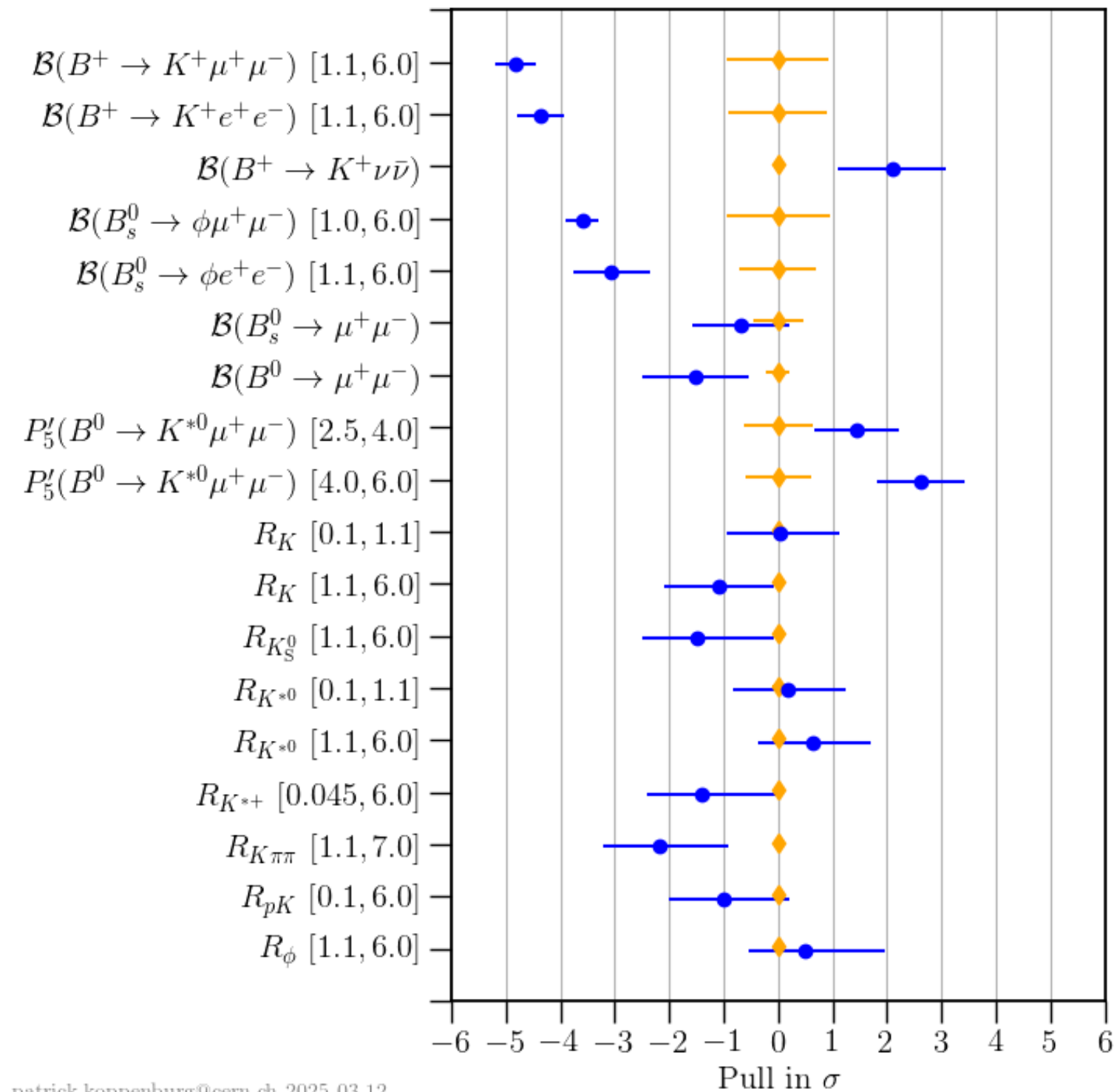
A permille knowledge of the CKM apex



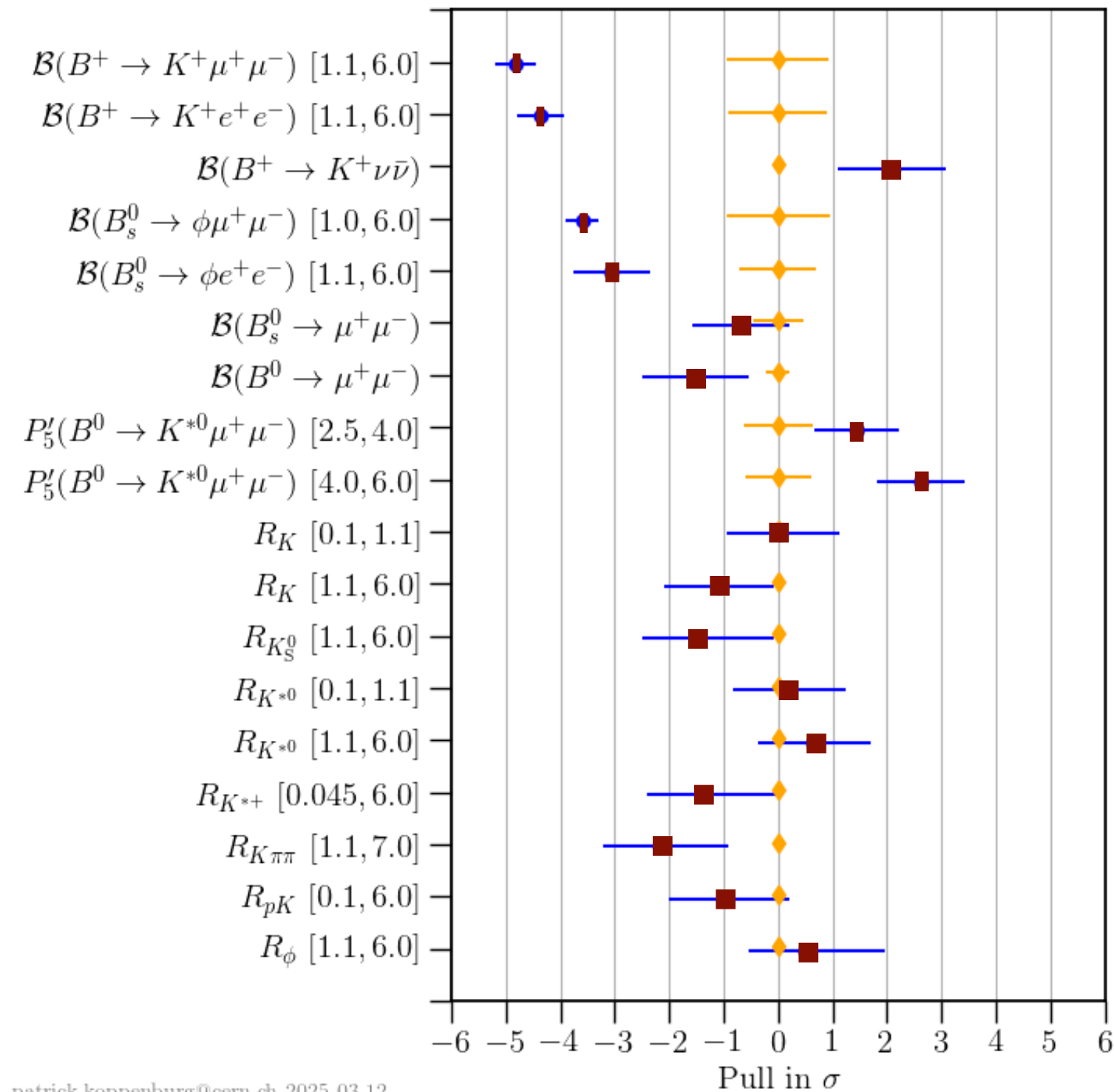
A permille knowledge of the CKM apex



A percent-level map of $b \rightarrow s \ell \ell$ transitions



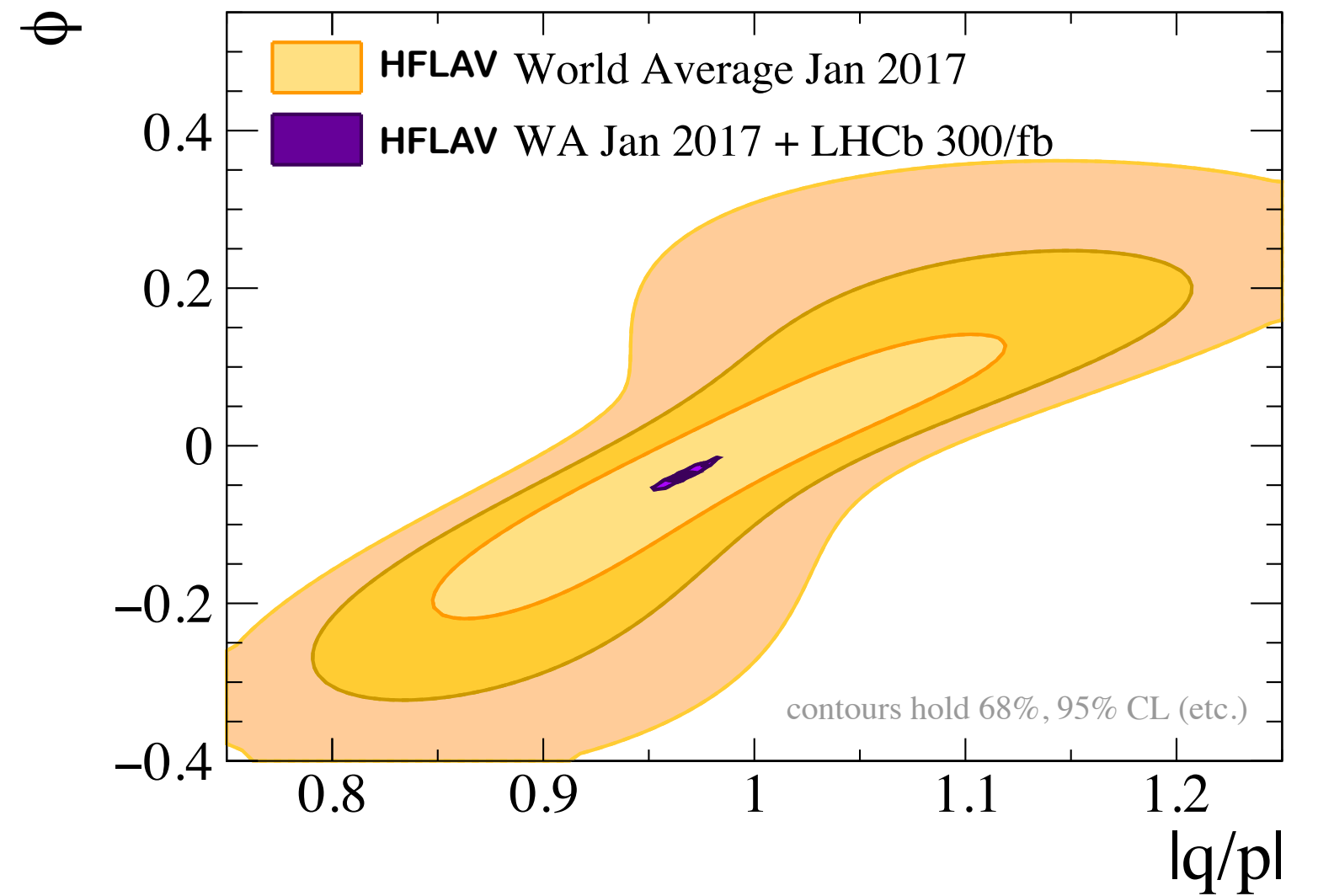
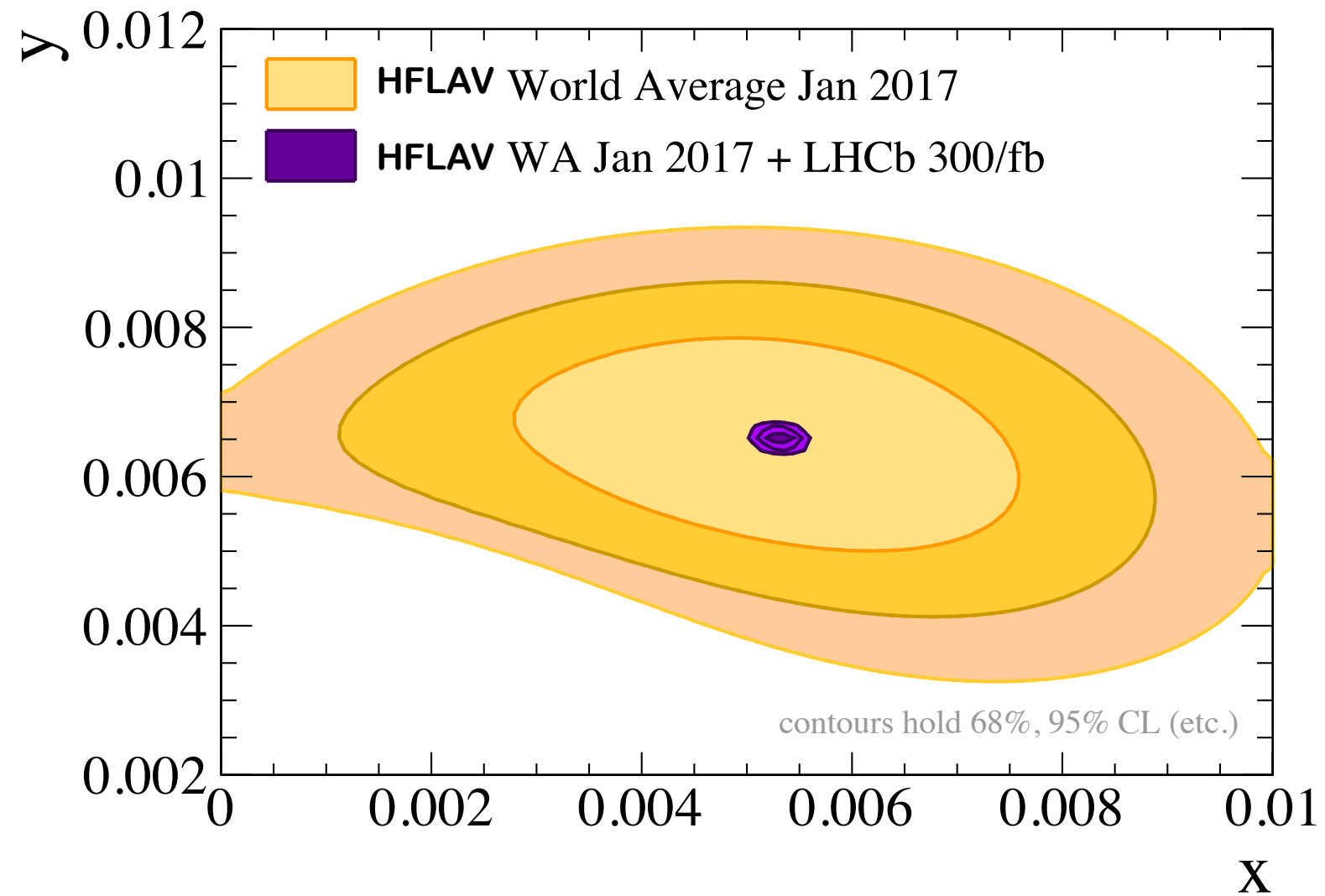
A percent-level map of $b \rightarrow s \ell \ell$ transitions



patrick.koppenburg@cern.ch 2025-03-12

Red bars are projected sensitivities (roughly drawn) at the end of the HL-LHC era

Charm beyond 10^{-5}



The pack camels of flavour physics

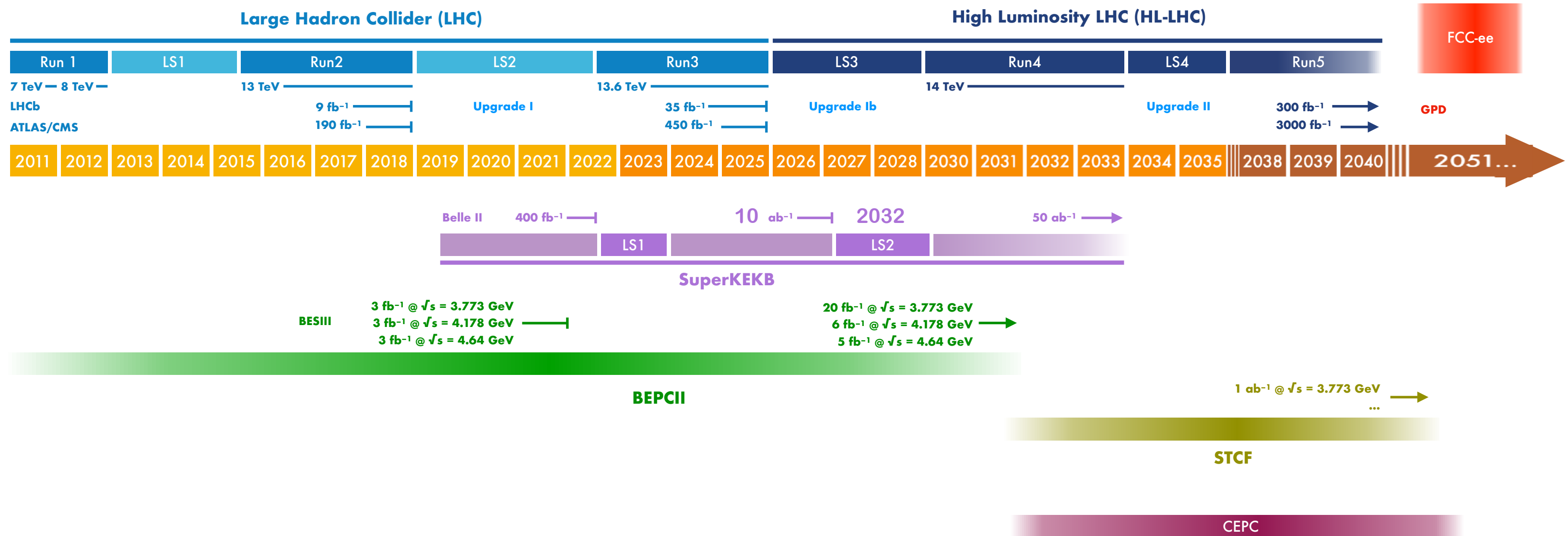
Belle (2, 3)

LHCb (I, II) BES III

ATLAS,
CMS

FCCee

Dreams and timelines

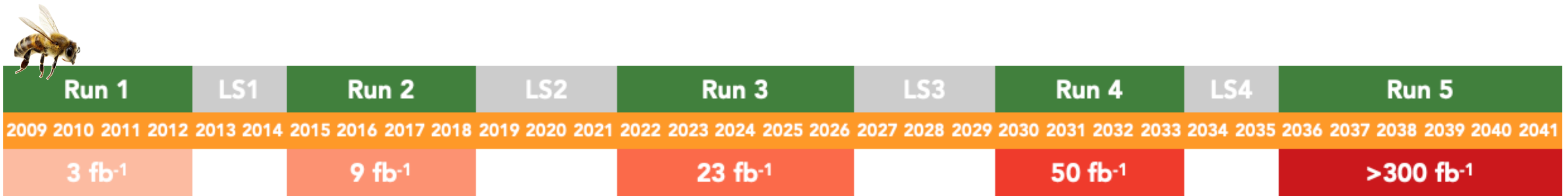


Timeline has been lightly adjusted from the original for assorted delays...

LHCb's ascent

Run 1				LS1		Run 2				LS2			Run 3						LS3			Run 4				LS4		Run 5						
2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041		
3 fb ⁻¹						9 fb ⁻¹							23 fb ⁻¹									50 fb ⁻¹						>300 fb ⁻¹						

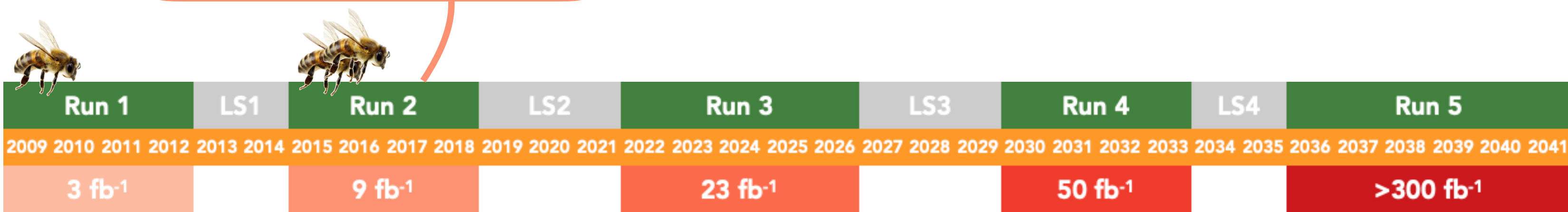
LHCb's ascent



It works! Concept of forward flavour detector validated, many world-best measurements

LHCb's ascent

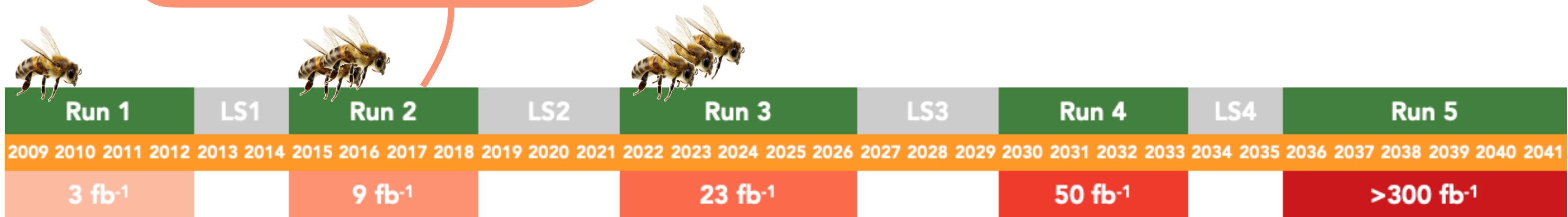
Align and calibrate detector in quasi-real time, full detector reconstruction and pileup suppression in trigger



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LHCb's ascent

Align and calibrate detector in quasi-real time, full detector reconstruction and pileup suppression in trigger



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Greatly improved tracker & PID granularity, 30 MHz detector readout & GPU tracking trigger

LHCb's ascent

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Enhance PID with precise timing and improved granularity, explore enhanced readout boards with fast tracking



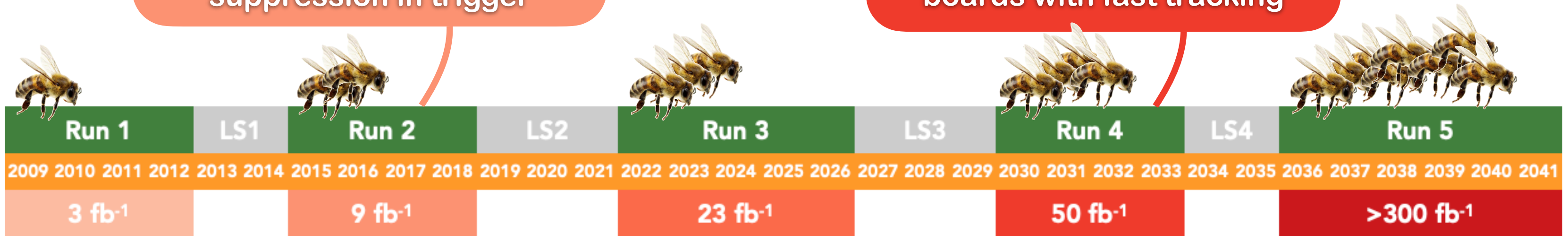
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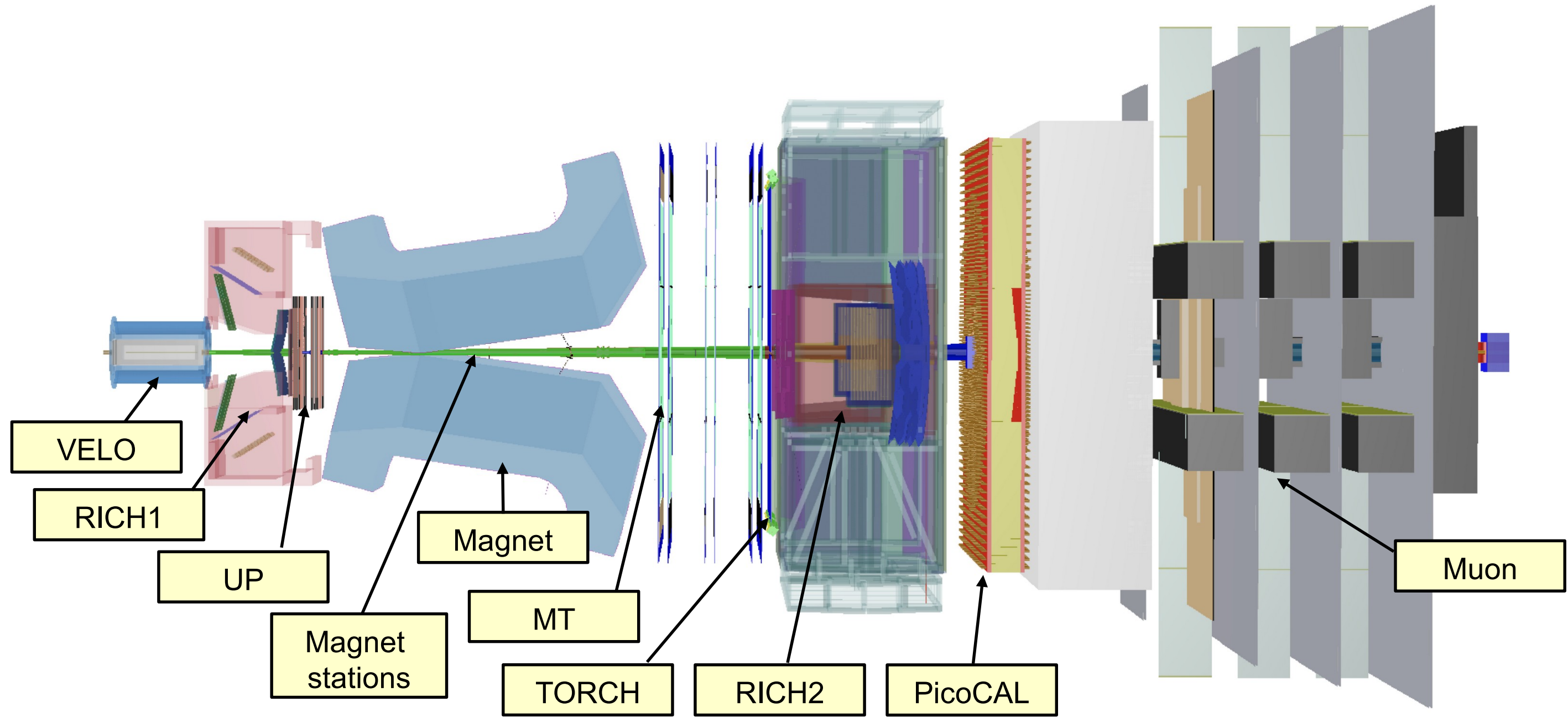


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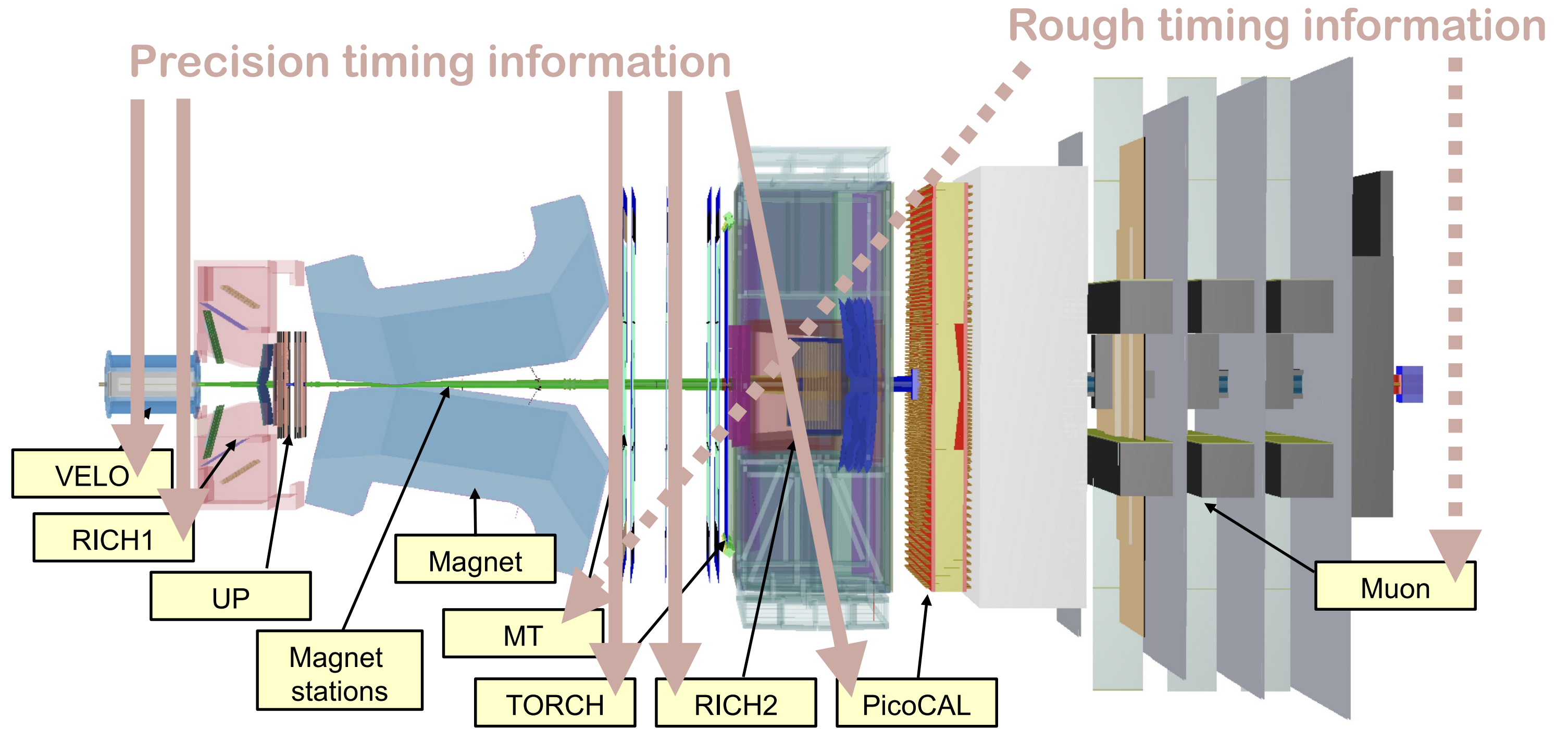
Greatly improved tracker & PID granularity, 30 MHz detector readout & GPU tracking trigger

Deploy 4D tracking, PID, and calorimetry + a highly granular pixel tracker to be processed by a heterogenous trigger

LHCb Upgrade 2 detector layout



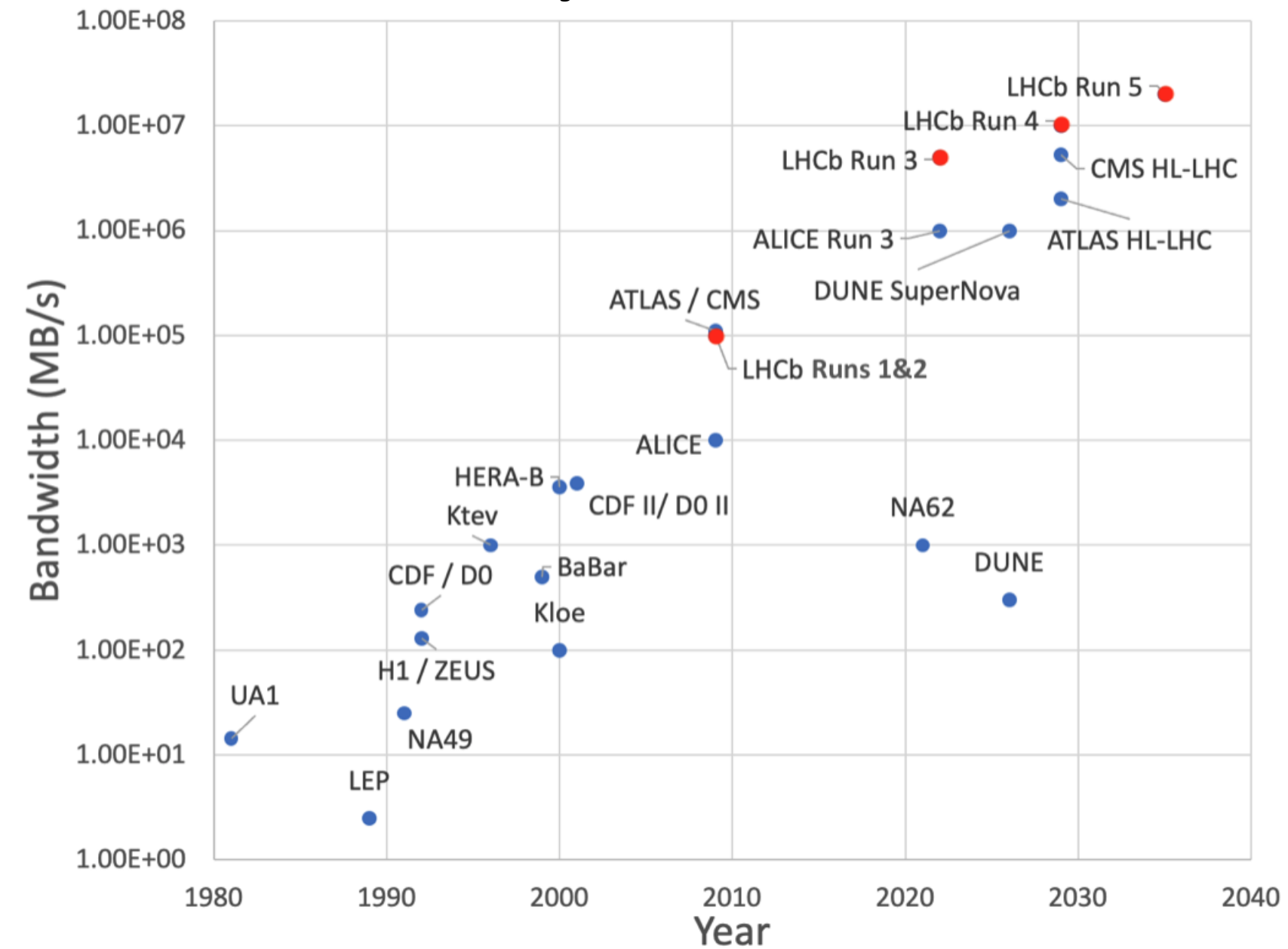
LHCb Upgrade 2 detector layout



A nearly 4-dimensional detector and thus a pathfinder for the future!

LHCb U2: DAQ & real-time analysis

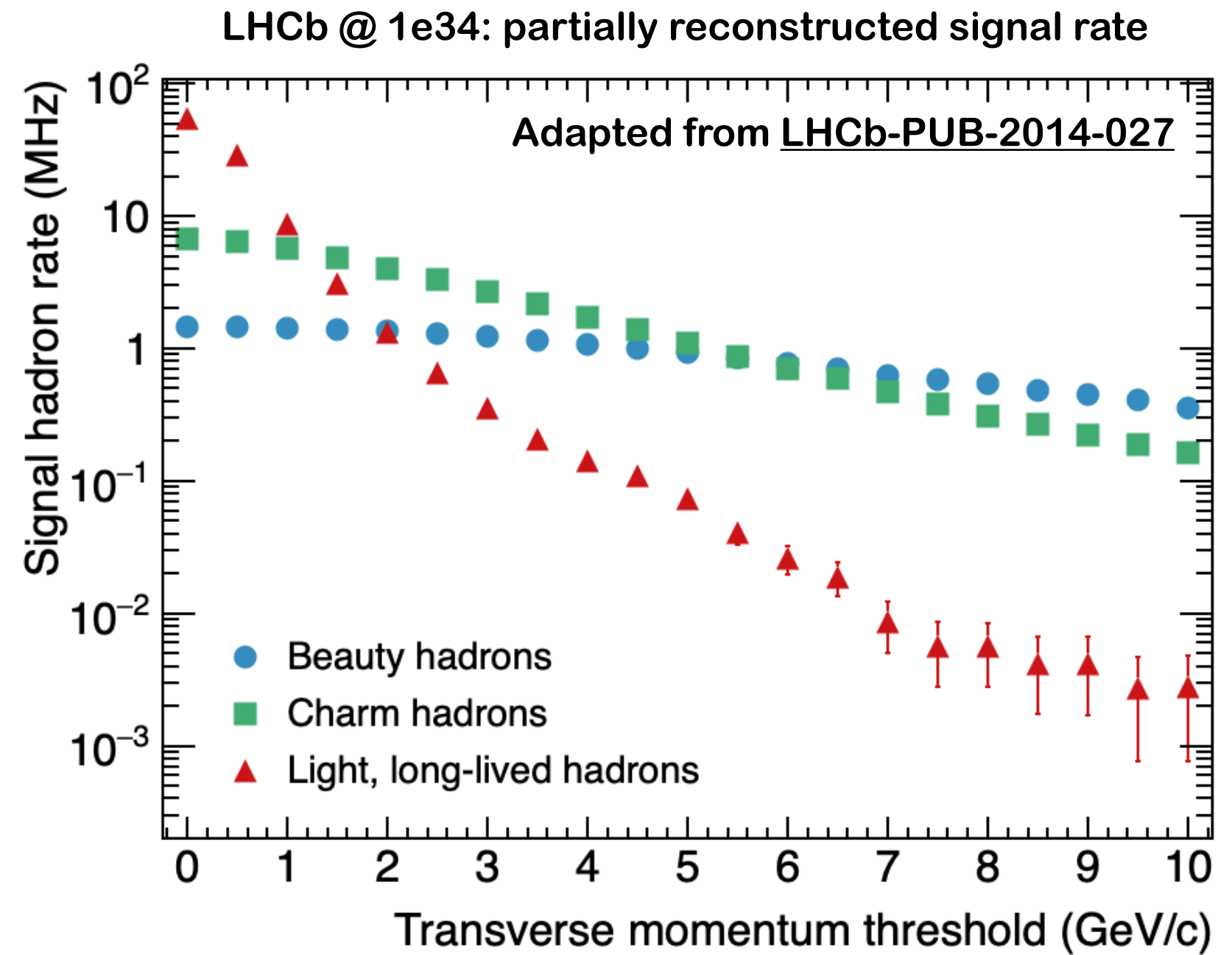
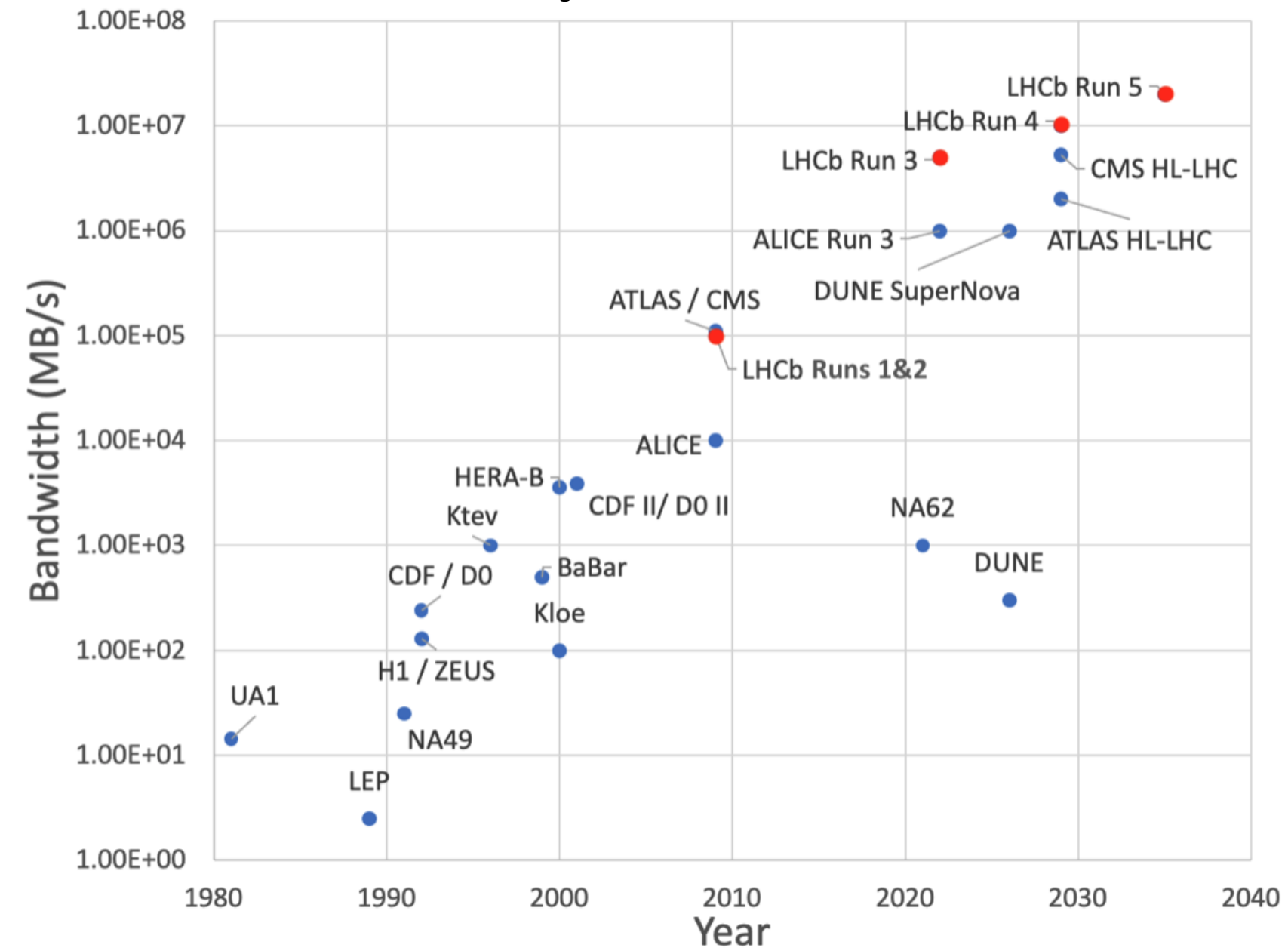
A. Cerri, University of Sussex



LHCb Upgrade 2 will be the biggest data processing challenge attempted in HEP

LHCb U2: DAQ & real-time analysis

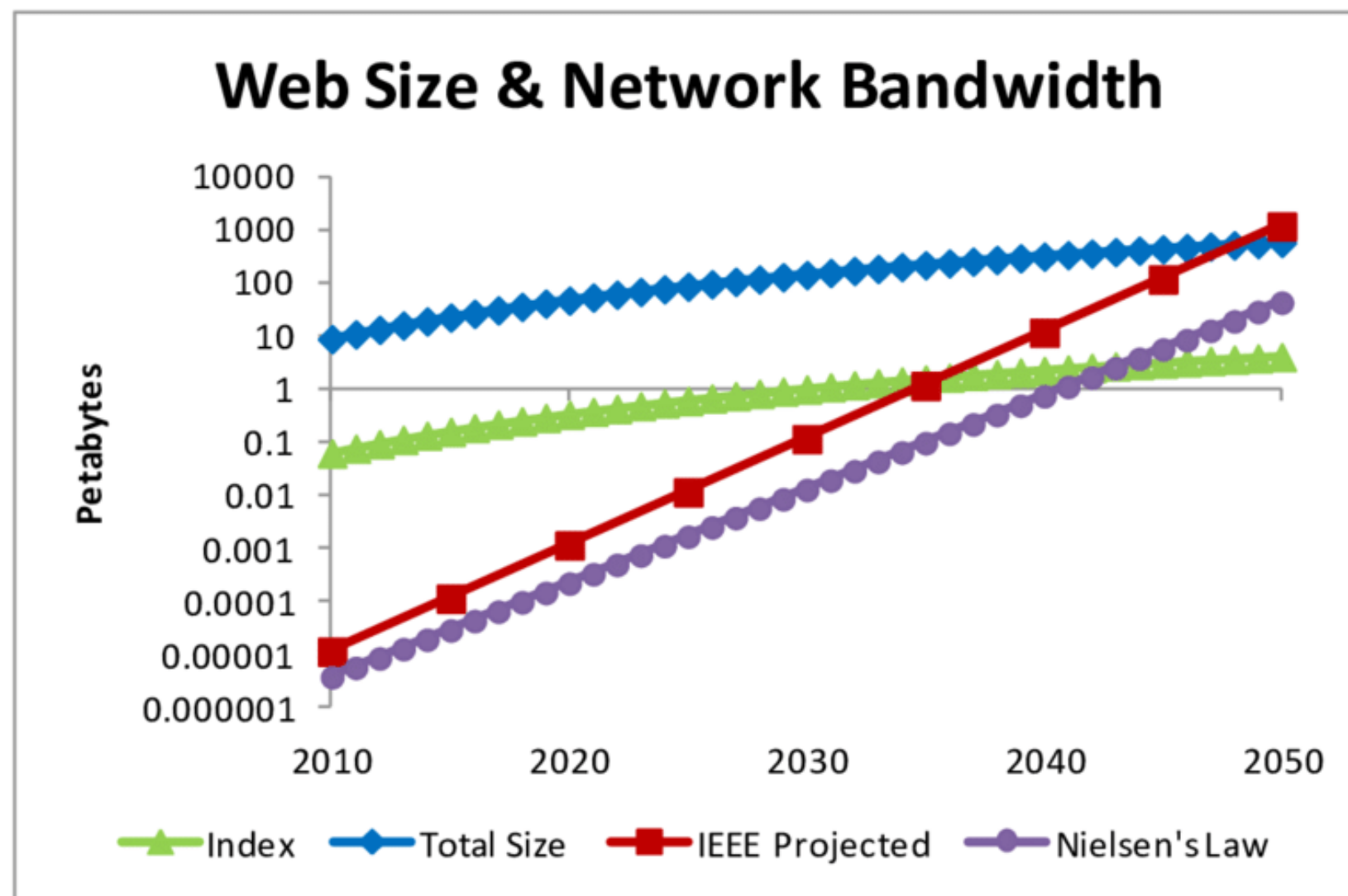
A. Cerri, University of Sussex



Trigger saturated by signal – must perform real-time analysis!

An ascent with a view to the future

Trotman & Zhang 1307.1179



Triggerless readout and real-time data analysis is the future for all HEP detectors
Requires both a technological and sociological shift in community thinking, but this is underway

Together towards the summit



Together towards the summit

Gligorov & Robinson 2503.09772



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Gligorov & Robinson 2503.09772

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Simultaneous analysis of flavour data from the ultimate experiments is essential.

Work to enable it must get underway now and be baked into the data processing logic by the 2030s!

What lies beyond the mountains ahead?



What lies beyond the mountains ahead?

We would all of course like it to be a world of new wonders



What lies beyond the mountains ahead?

Yet knowledge advances through bursts and plateaus: the rapid gains of the 20th century are no guarantee for the 21st



What lies beyond the mountains ahead?

If we are on a plateau, then we must record the fundamental constituents of nature as precisely as our skill allows.
Our camels (detectors) have a great deal of life in them!



What lies beyond the mountains ahead?

And even if we do not see its end, one day technology will
allow others to advance beyond the plateau.
Our measurements will be their companions on that journey.



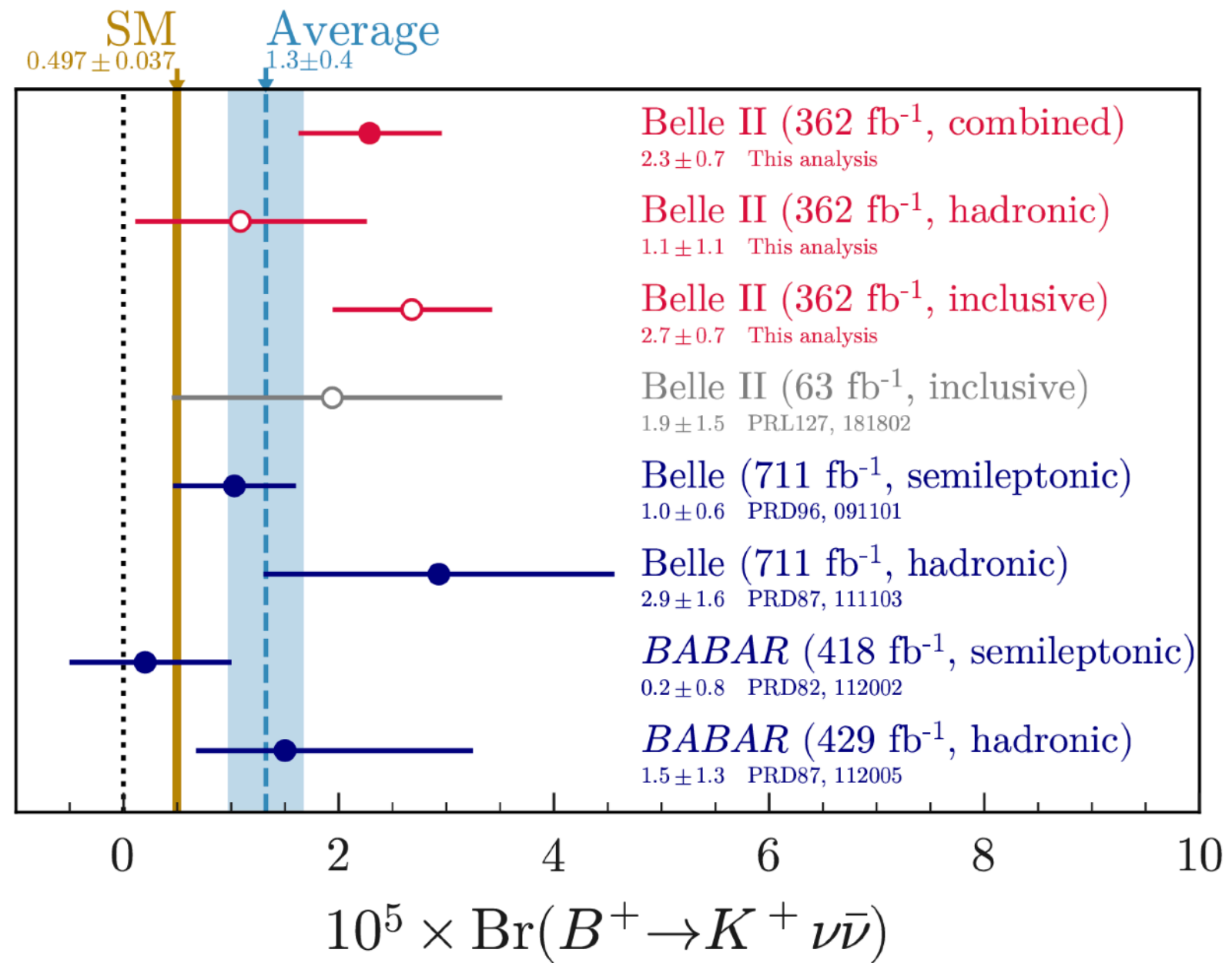
What lies beyond the mountains ahead?

This is justification & mandate enough to press onwards.

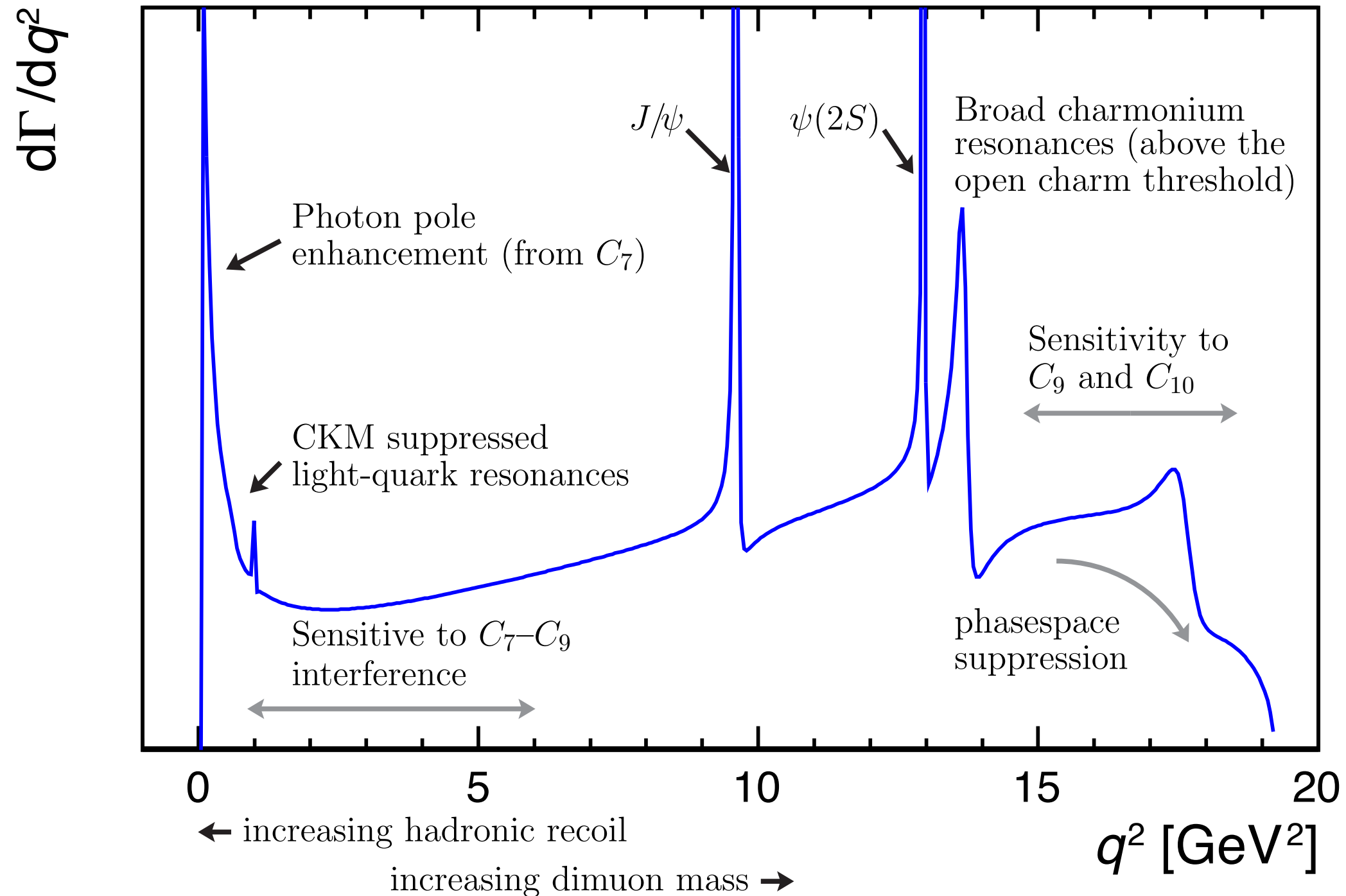


BACKUP

Evidence for $B \rightarrow K \nu \nu$

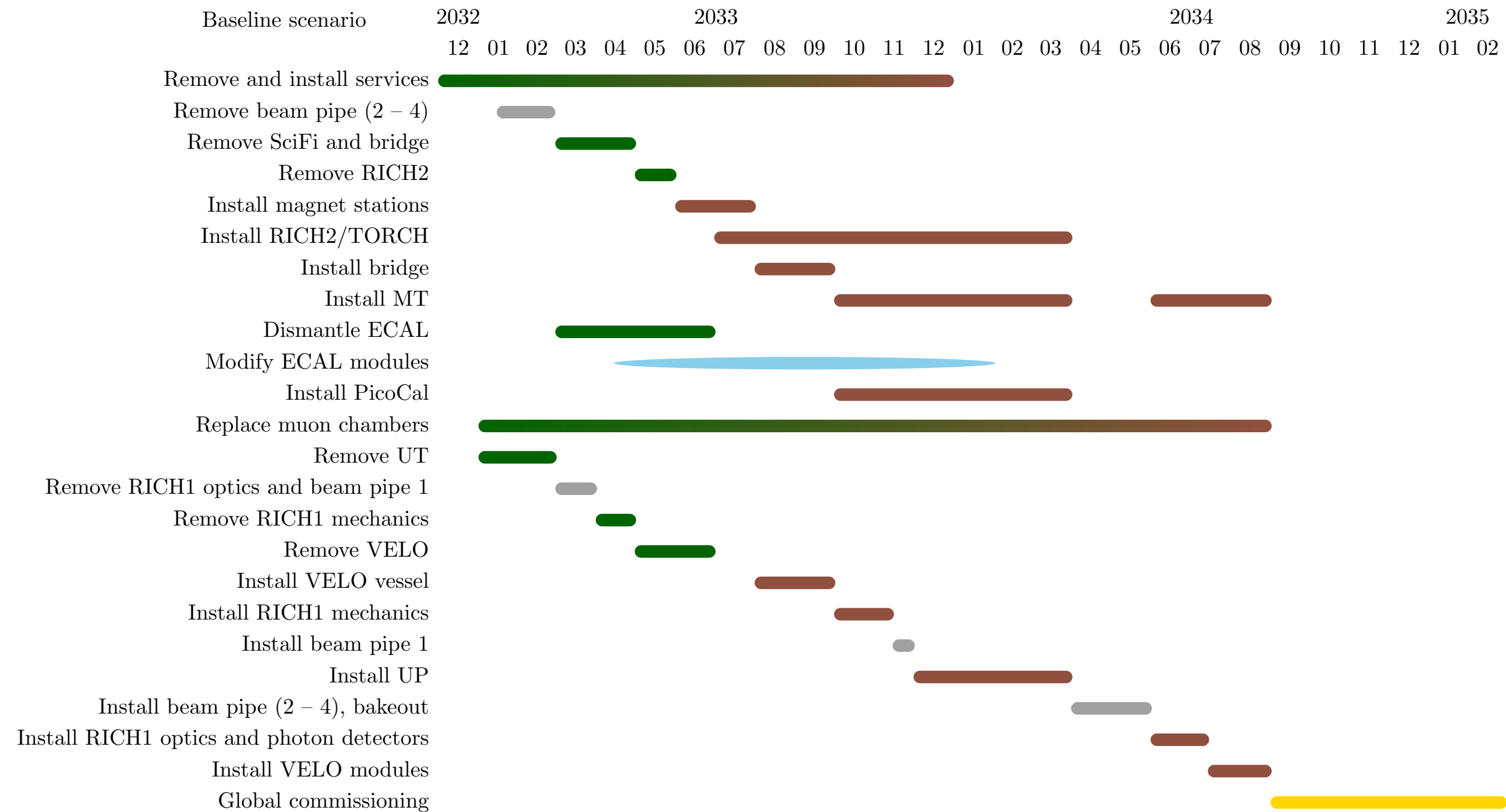


Phenomenology of $b \rightarrow s \ell \ell$ transitions



U2 installation schedule

LHCb Upgrade 2 Scoping Document



Downstream
of
Magnet

Upstream
of
Magnet

Completing all work in 2 years is challenging but achievable

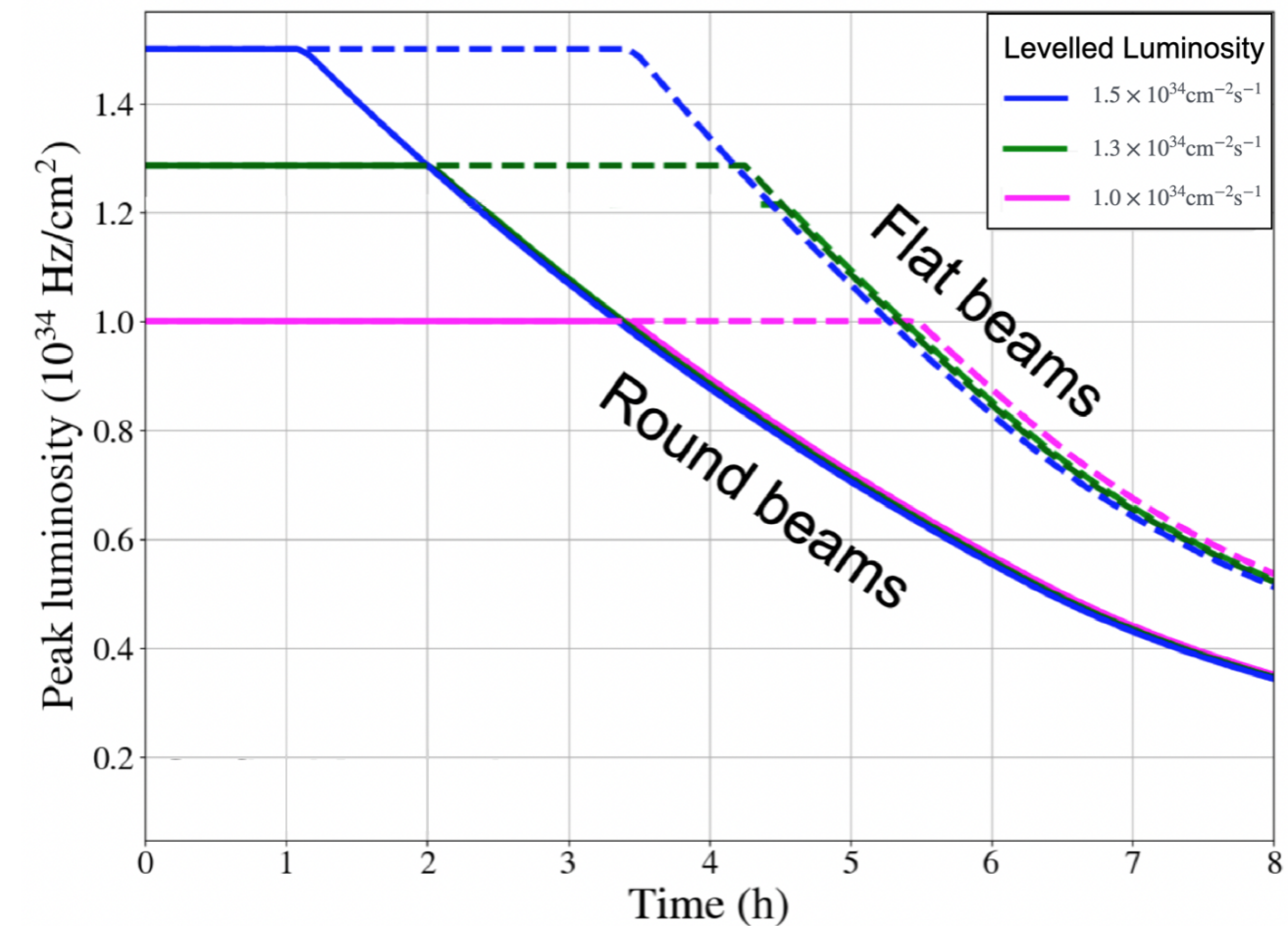
Why another LHCb upgrade?

Observable	Old LHCb (up to 9 fb ⁻¹)	LHCb Upgrade 2 Scoping Document		
		Upgrade I (23 fb ⁻¹)	Upgrade I (50 fb ⁻¹)	Upgrade II (300 fb ⁻¹)
CKM tests				
γ ($B \rightarrow DK$, <i>etc.</i>)	2.8° [18, 19]	1.3°	0.8°	0.3°
ϕ_s ($B_s^0 \rightarrow J/\psi\phi$)	20 mrad [22]	12 mrad	8 mrad	3 mrad
$ V_{ub} / V_{cb} $ ($\Lambda_b^0 \rightarrow p\mu^-\bar{\nu}_\mu$, <i>etc.</i>)	6% [55, 56]	3%	2%	1%
Charm				
ΔA_{CP} ($D^0 \rightarrow K^+K^-, \pi^+\pi^-$)	29×10^{-5} [25]	13×10^{-5}	8×10^{-5}	3.3×10^{-5}
A_Γ ($D^0 \rightarrow K^+K^-, \pi^+\pi^-$)	11×10^{-5} [29]	5×10^{-5}	3.2×10^{-5}	1.2×10^{-5}
Δx ($D^0 \rightarrow K_S^0\pi^+\pi^-$)	18×10^{-5} [57]	6.3×10^{-5}	4.1×10^{-5}	1.6×10^{-5}
Rare decays				
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$	69% [30, 31]	41%	27%	11%
$S_{\mu\mu}$ ($B_s^0 \rightarrow \mu^+\mu^-$)	—	—	—	0.2
$A_{\text{T}}^{(2)}$ ($B^0 \rightarrow K^{*0}e^+e^-$)	0.10 [58]	0.060	0.043	0.016
$S_{\phi\gamma}(B_s^0 \rightarrow \phi\gamma)$	0.32 [59]	0.093	0.062	0.025
$\alpha_\gamma(\Lambda_b^0 \rightarrow \Lambda\gamma)$	$^{+0.17}_{-0.29}$ [60]	0.148	0.097	0.038

Key precision observables remain statistically limited + unique reach for ions, baryons & exotic hadrons
After showing that systematics scale with luminosity in Run 3 – aim to build the best quality U2 detector! 90

LHCb Upgrade 2 luminosity scenarios

	Round optics			Flat optics		
Levelled $\mathcal{L}_{\text{peak}}$ ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	1.0	1.3	1.5	1.0	1.3	1.5
β_x^*/β_y^* (m)	1.5/1.5			0.5/1.5		
N_{bunch} total/colliding in LHCb	2760/2574			2760/2574		
Levelled pile-up	28	36	42	28	36	42
Delivered $\mathcal{L}_{\text{int}}$ per year (fb^{-1})	42.16	47.25	49.34	48.73	57.89	63.36
Levelling time t_{lev} (h)	3.42	2.00	1.08	5.42	4.25	3.42
Optimal fill length t_{opt} (h)	7.67	7.58	7.58	7.58	7.50	7.42
$t_{\text{lev}}/t_{\text{opt}}$	0.45	0.26	0.14	0.72	0.57	0.46
RMS luminous region (z) at $t = 0$ (mm)	43.30	43.31	43.31	38.41	38.44	38.45
Peak pile-up density at $t = 0$ (mm^{-1})	0.29	0.35	0.40	0.41	0.49	0.54



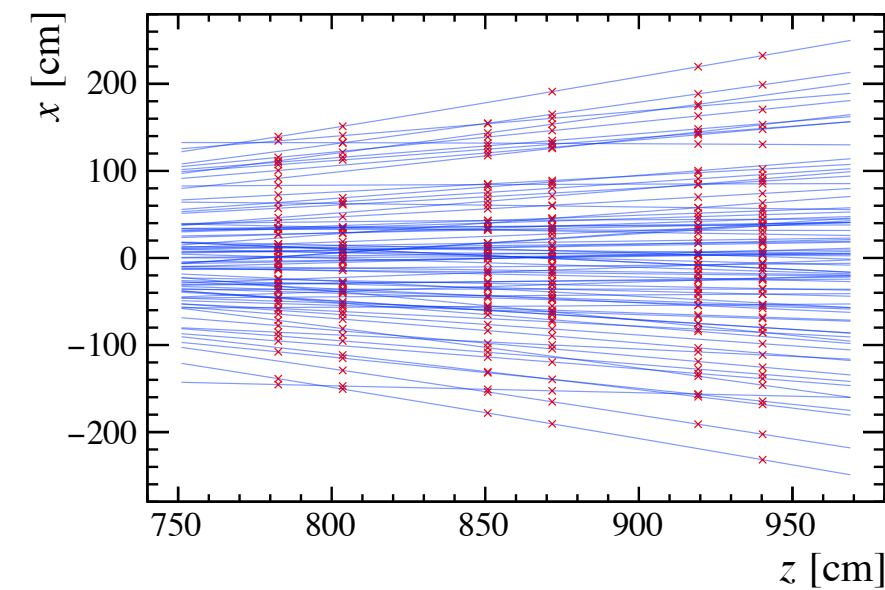
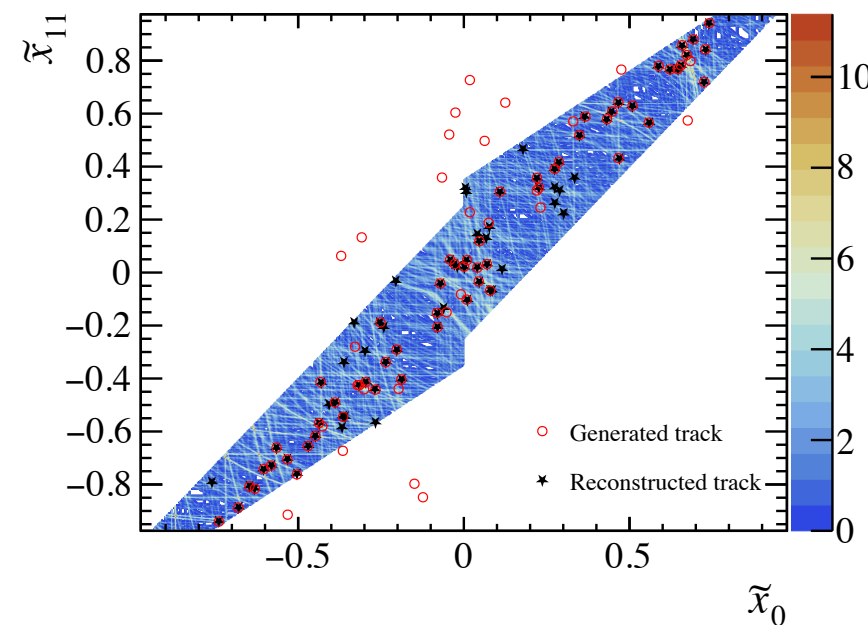
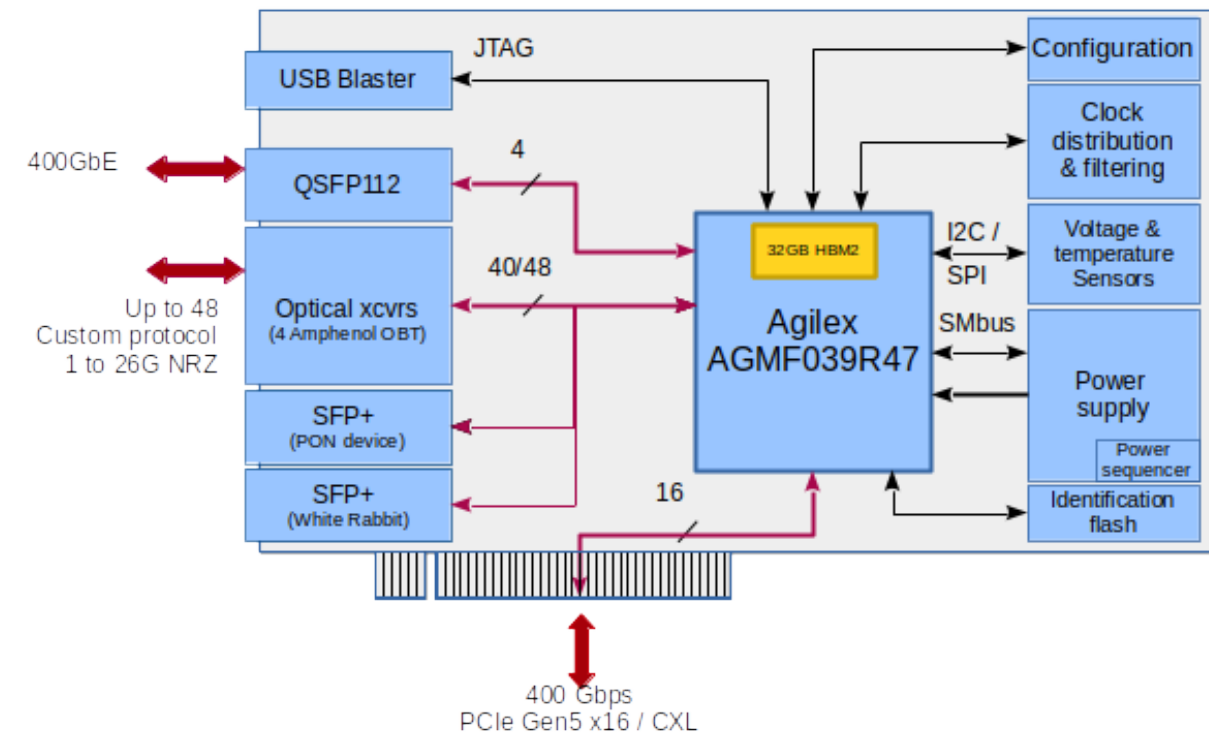
Many thanks to our LHC machine colleagues for their hard work and support!
Looking forward to the results of machine tests to understand if flat optics are feasible.

LS3 enhancements: data acquisition

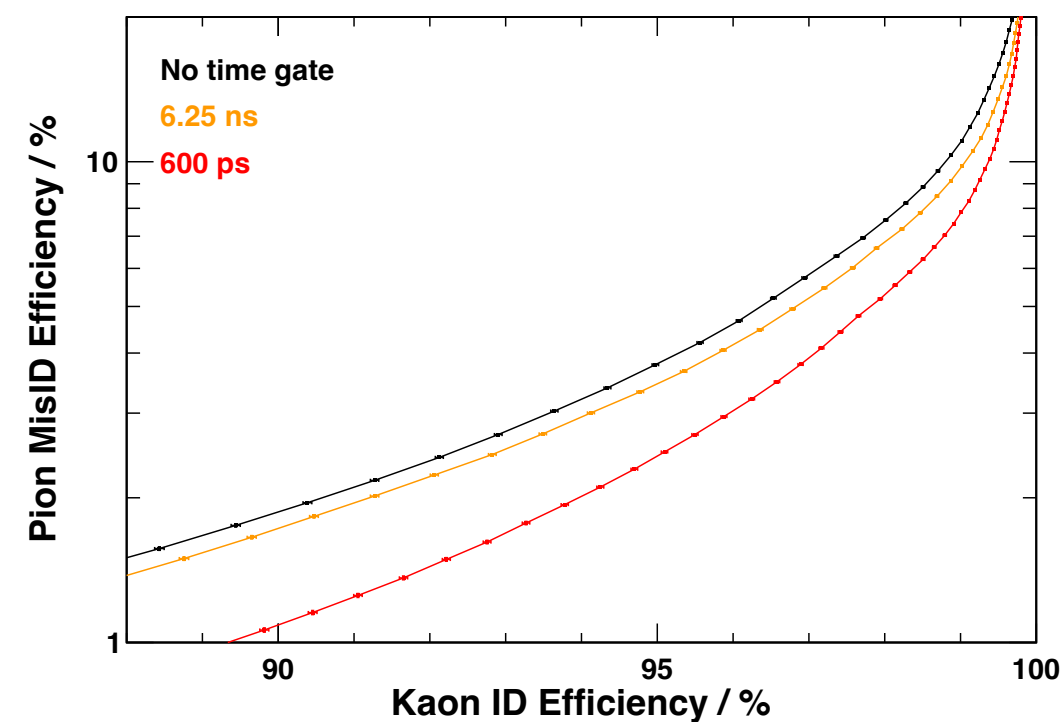
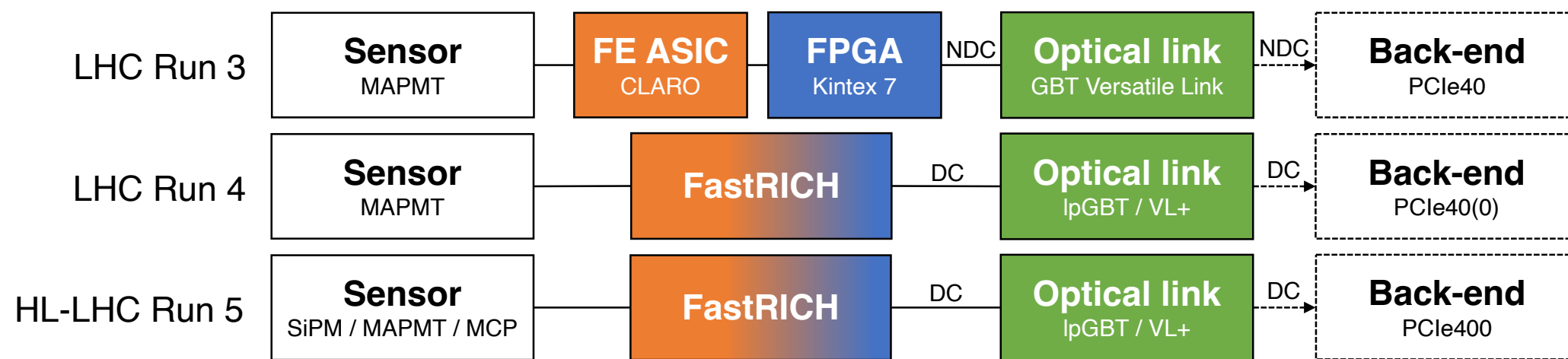
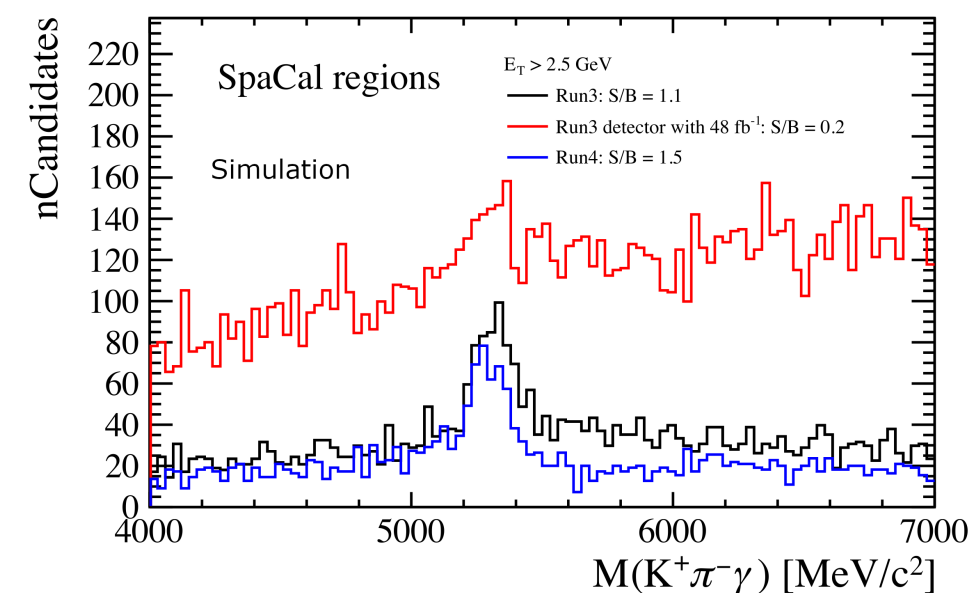
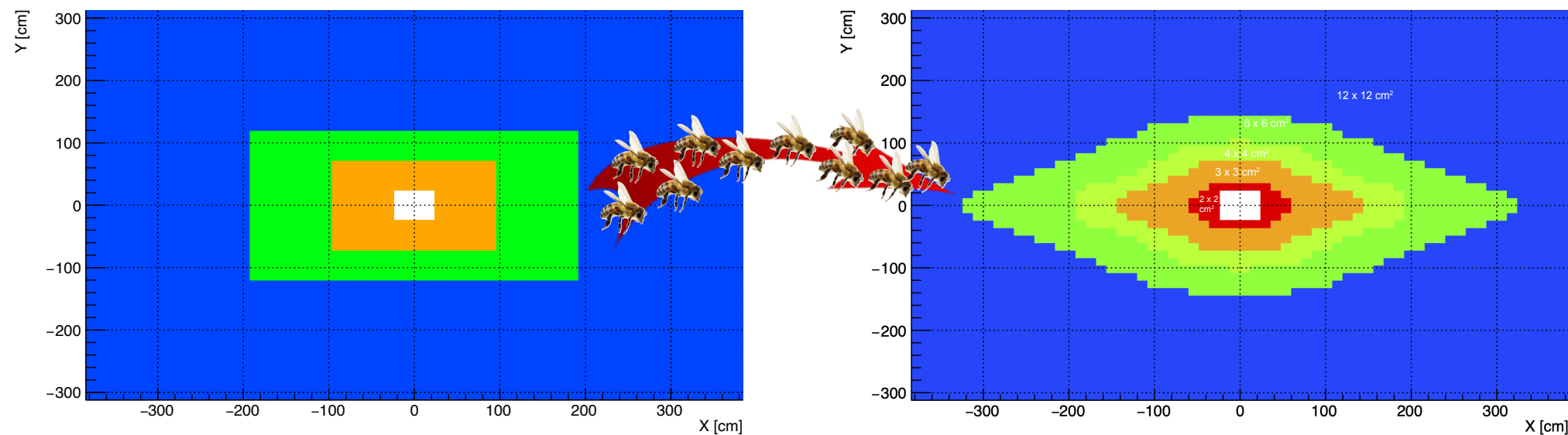
The aim is to exercise the following features ahead of Run 5

1. Clock distribution with jitter and deterministic phase of $O(10)$ ps
2. The usage of IpGBT links
3. The usage of very high speed links running at 100Gbit/s using data-centre protocols like Ethernet 400 or PCIe Gen5
4. Creation and use of reconstruction primitives embedded within the readout, with potential gains for triggering already in Run 4.

LHCb data acquisition enhancements TDR



LS3 enhancements: particle identification



LHCb particle identification enhancements TDR

Enhanced calorimeter granularity & SpaCal modules: maintain performance despite radiation damage

Fast timing information in the RICH: improved hadron identification and gain experience for Run 5

LHCb U2: detector scenarios

LHCb Upgrade 2 Scoping Document

Three detector scenarios considered

Baseline: ultimate acceptance, granularity, and material budget leading to maximal instantaneous luminosity headroom.

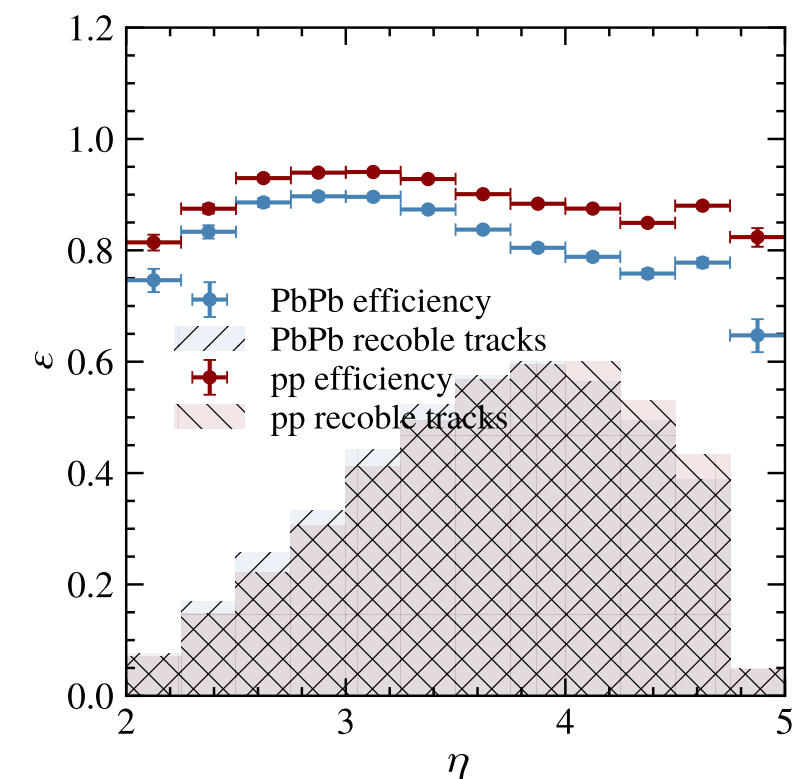
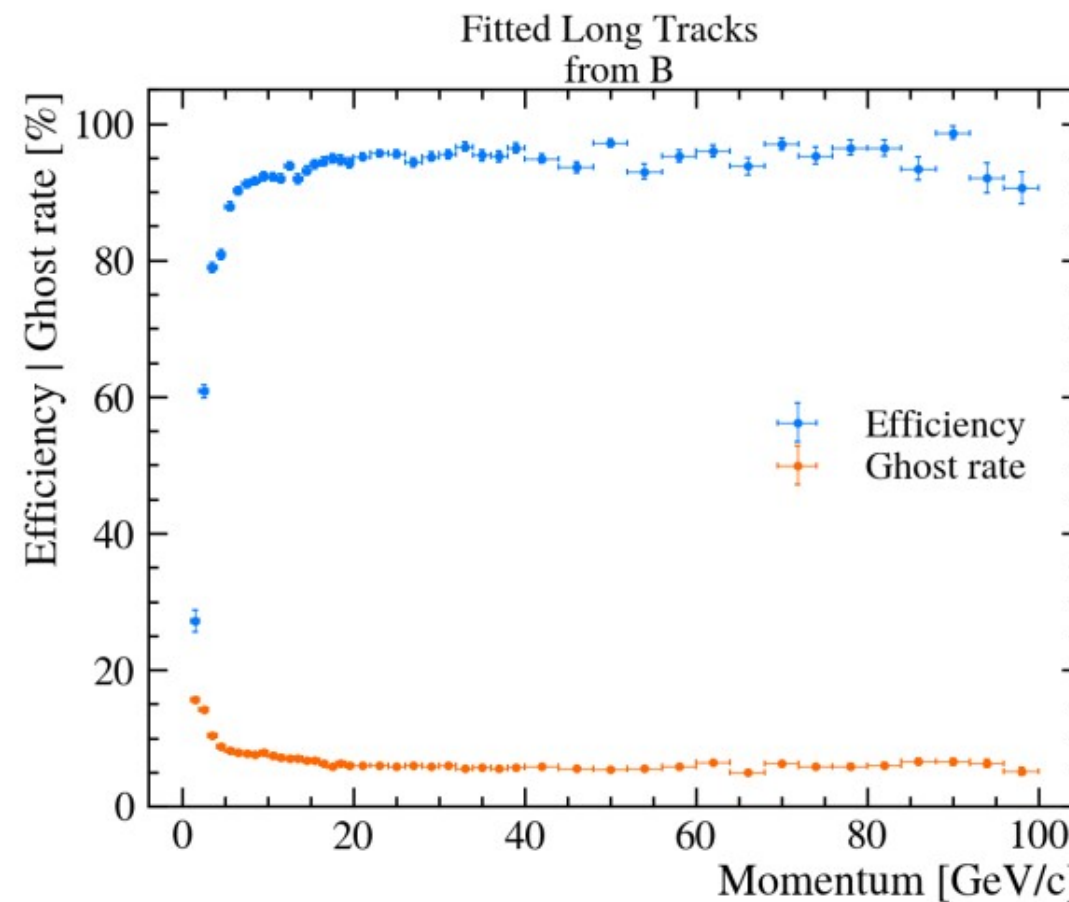
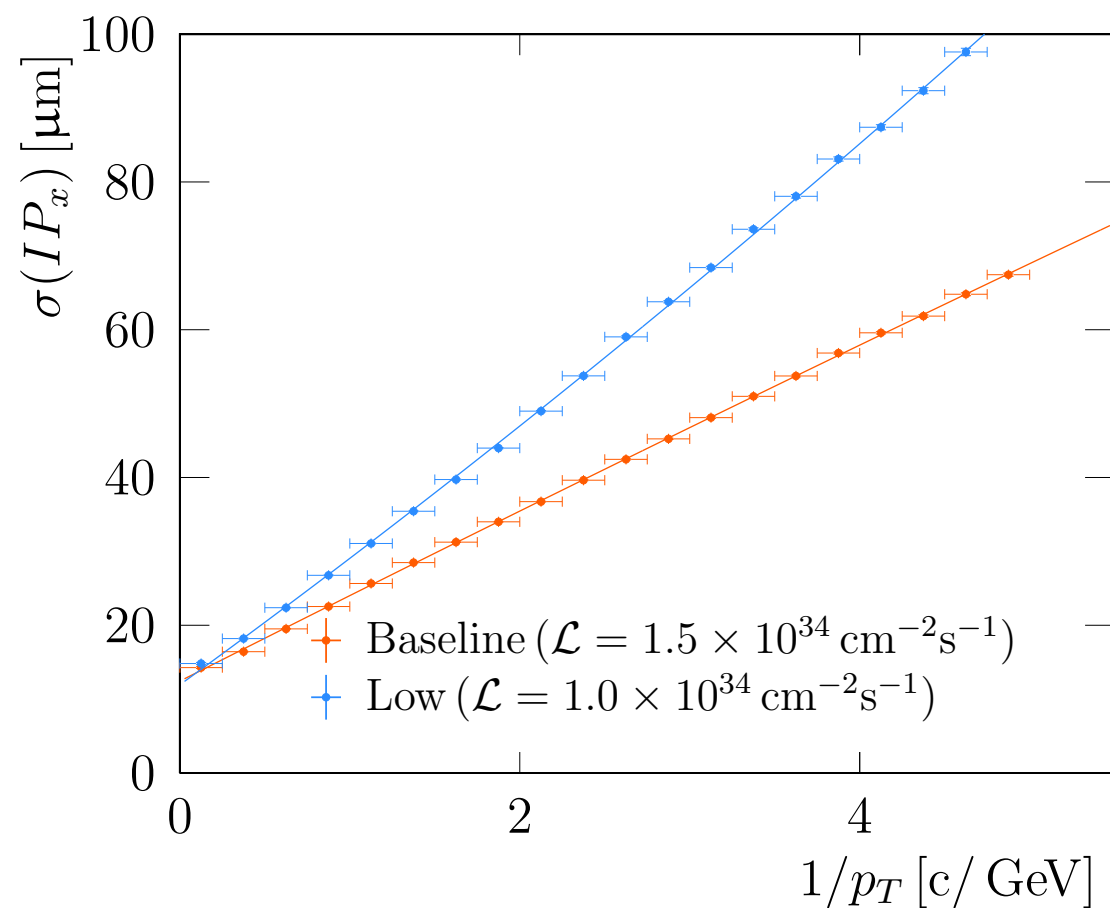
Middle: keeps all subsystems but in some cases reduces their acceptance. Lower instantaneous luminosity leads to significant savings in data processing cost.

Low: worse acceptance, granularity, and material budget depending on the detector. Two detectors fully removed. Highest risk and least robust option.

	Baseline	Middle	Low
$\mathcal{L}_{\text{peak}}$ ($10^{34} \text{ cm}^{-2} \text{ s}^{-1}$)	1.5	1.0	1.0
	(kCHF)	(kCHF)	(kCHF)
VELO	16672	15906	13753
UP	8077	7719	6887
Magnet Stations	2592	2234	0
Mighty-SciFi	21767	21273	17388
Mighty-Pixel	15994	11641	11061
RICH	21450	18415	14794
TORCH	12508	8756	0
PicoCal	27607	27607	21584
Muon	9785	8266	8266
RTA	18800	11700	9500
Online	11800	9467	8993
Infrastructure	14463	13284	12430
Total	181515	156268	124656

LHCb U2: tracking

LHCb Upgrade 2 Scoping Document

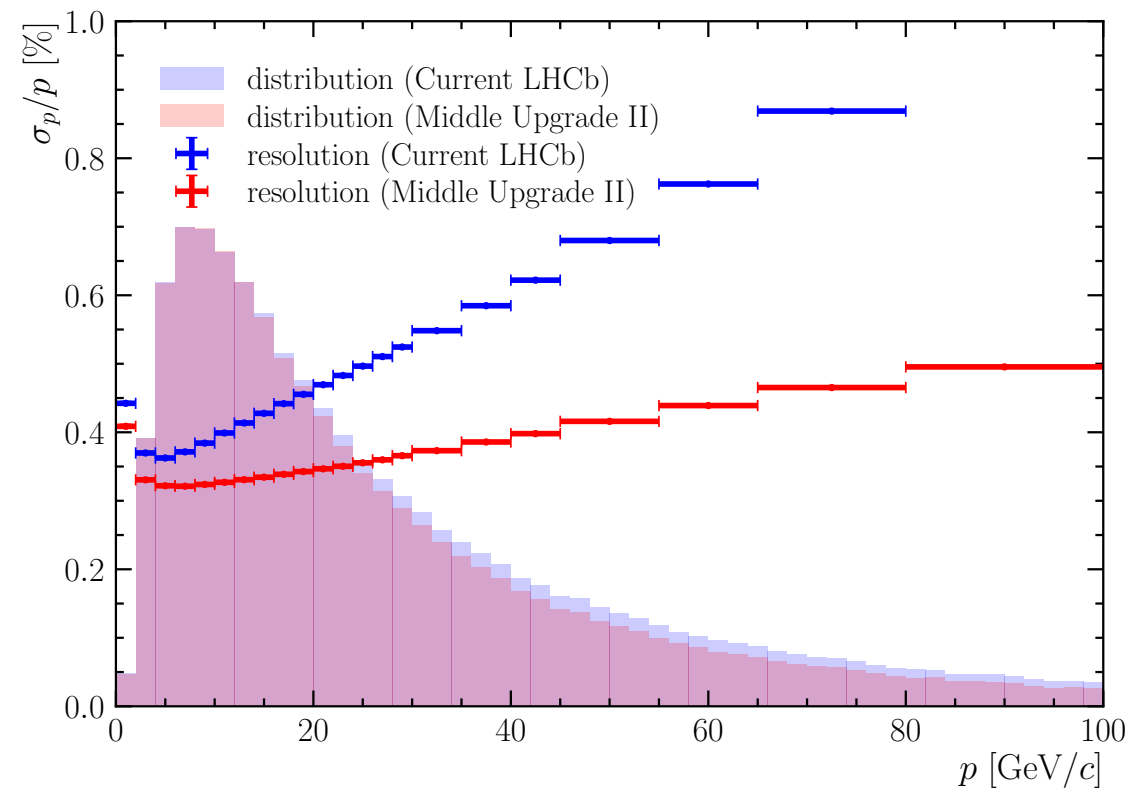
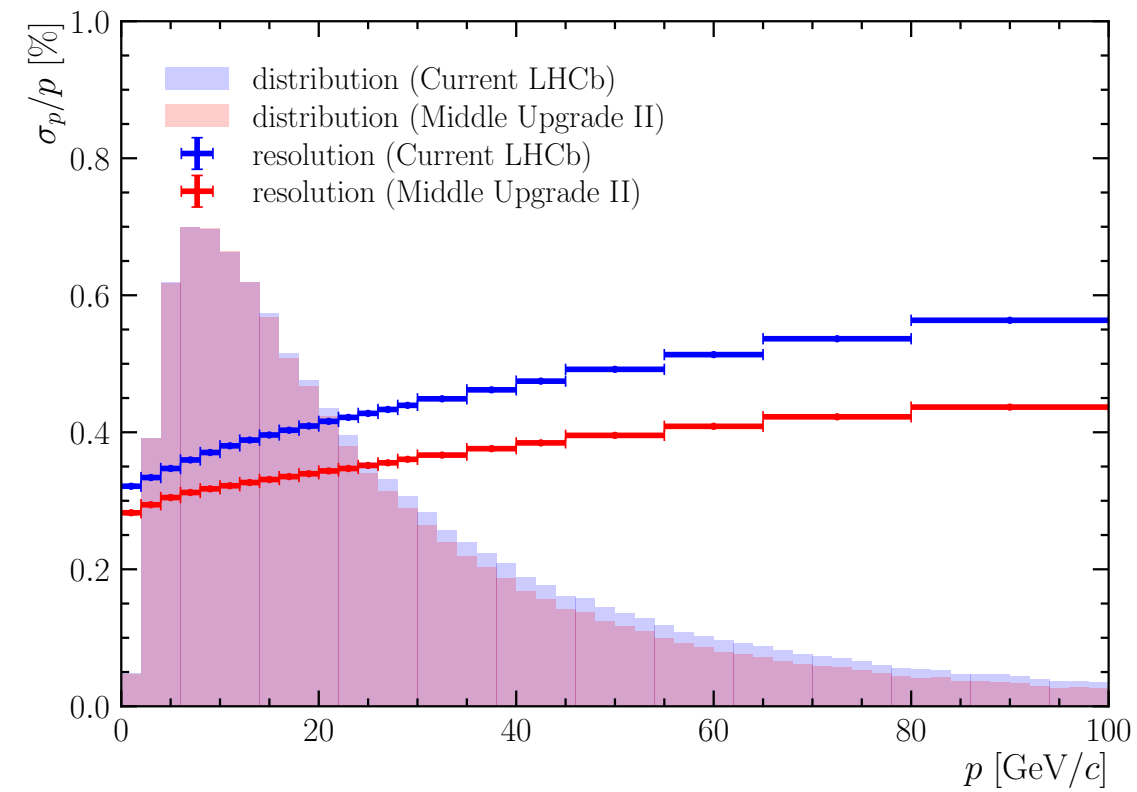


The baseline design ensures high efficiencies with acceptable fake rates!

Similar tracking efficiencies for pp and PbPb will allow reconstruction of the most central collisions.

Channel	Relative acceptance %	
	Middle	Low
$B_s^0 \rightarrow \mu^+ \mu^-$	99.3 ± 0.1	95.3 ± 0.1
$B_s^0 \rightarrow \phi(\rightarrow K^+ K^-) \phi(\rightarrow K^+ K^-)$	99.4 ± 0.1	90.6 ± 0.2
$D^0 \rightarrow K_S^0(\rightarrow \pi^+ \pi^-) \pi^+ \pi^-$	99.7 ± 0.1	84.8 ± 0.8

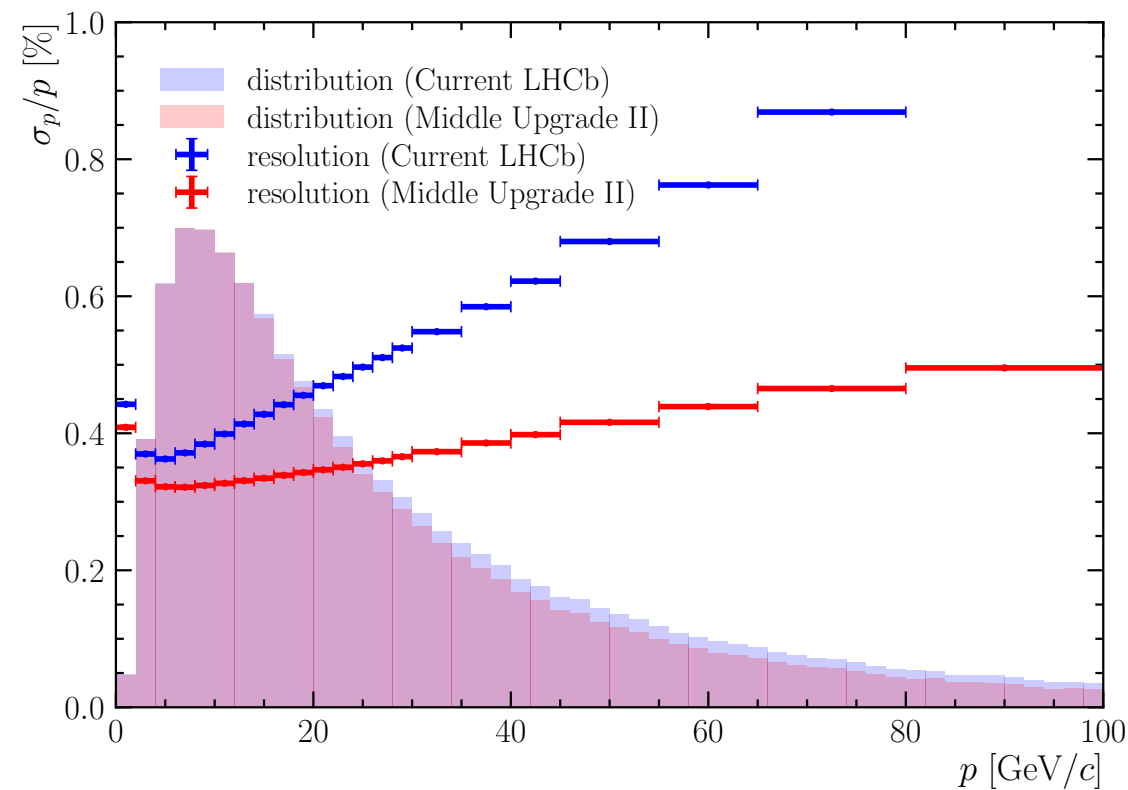
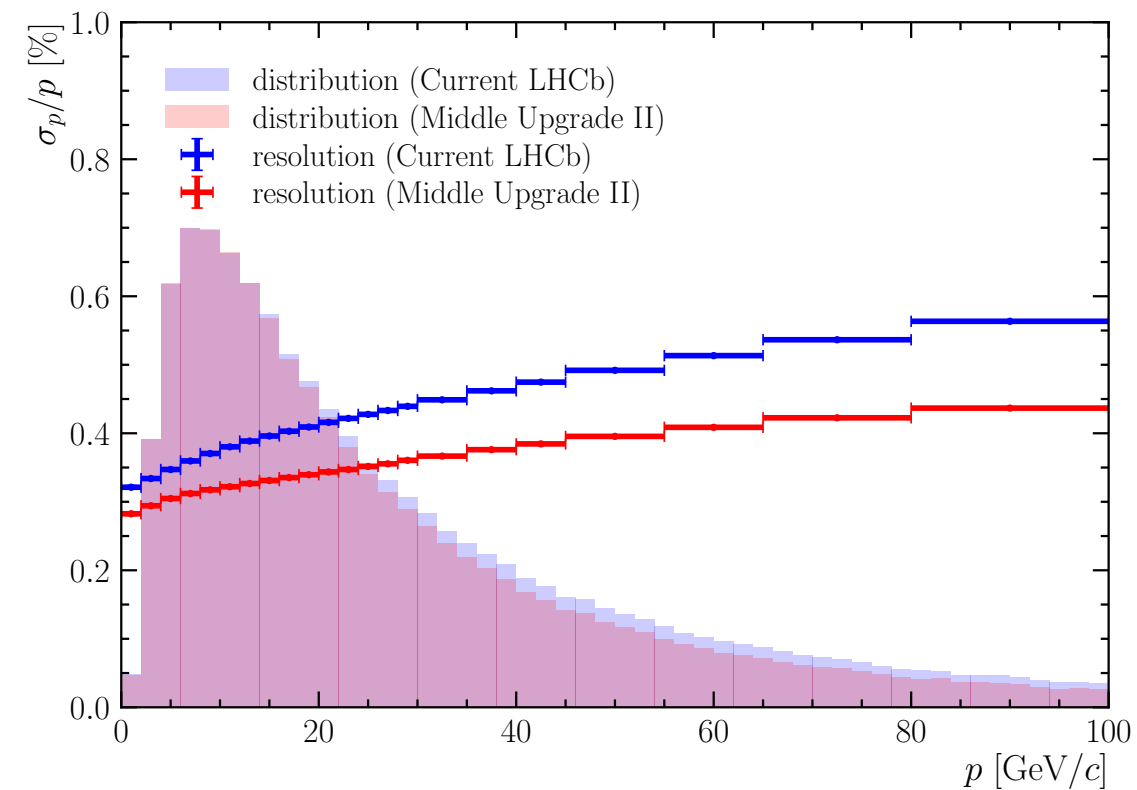
LHCb U2: tracking (2)



LHCb Upgrade 2 Scoping Document

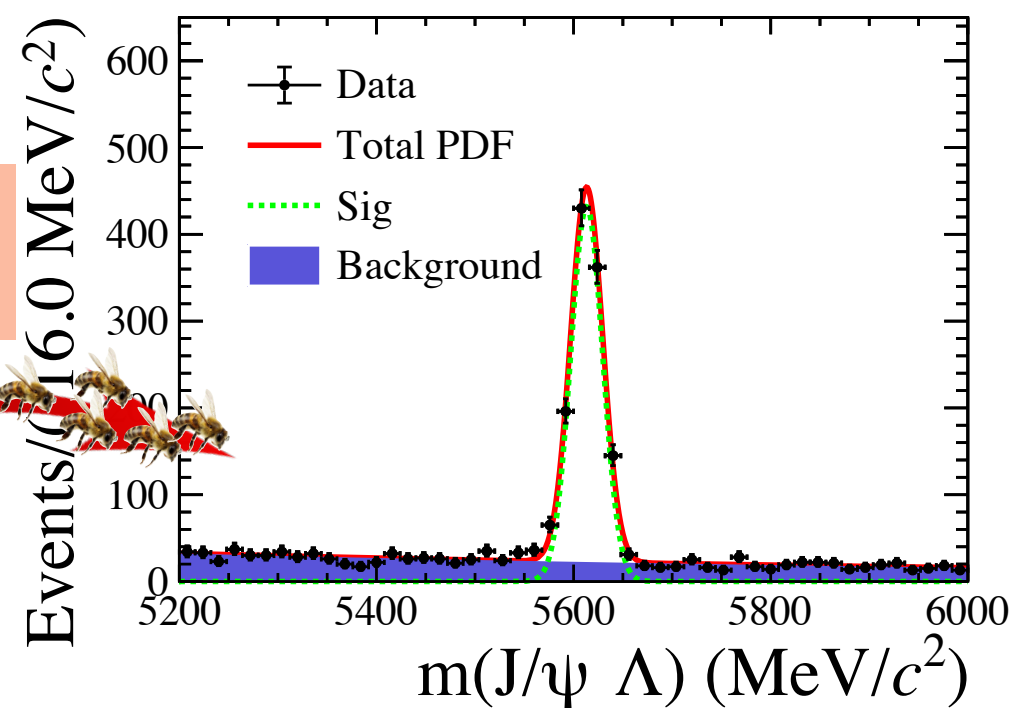
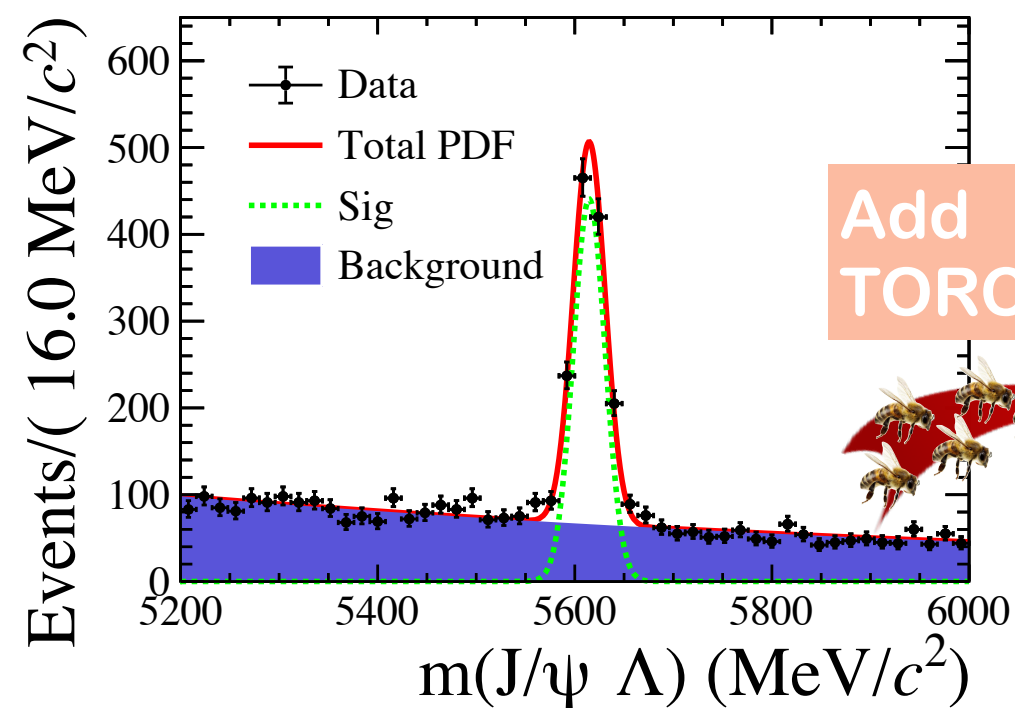
**UP + MT (pixels)
significantly improves
momentum resolution
compared to U1 LHCb!**

LHCb U2: tracking (3)



LHCb Upgrade 2 Scoping Document

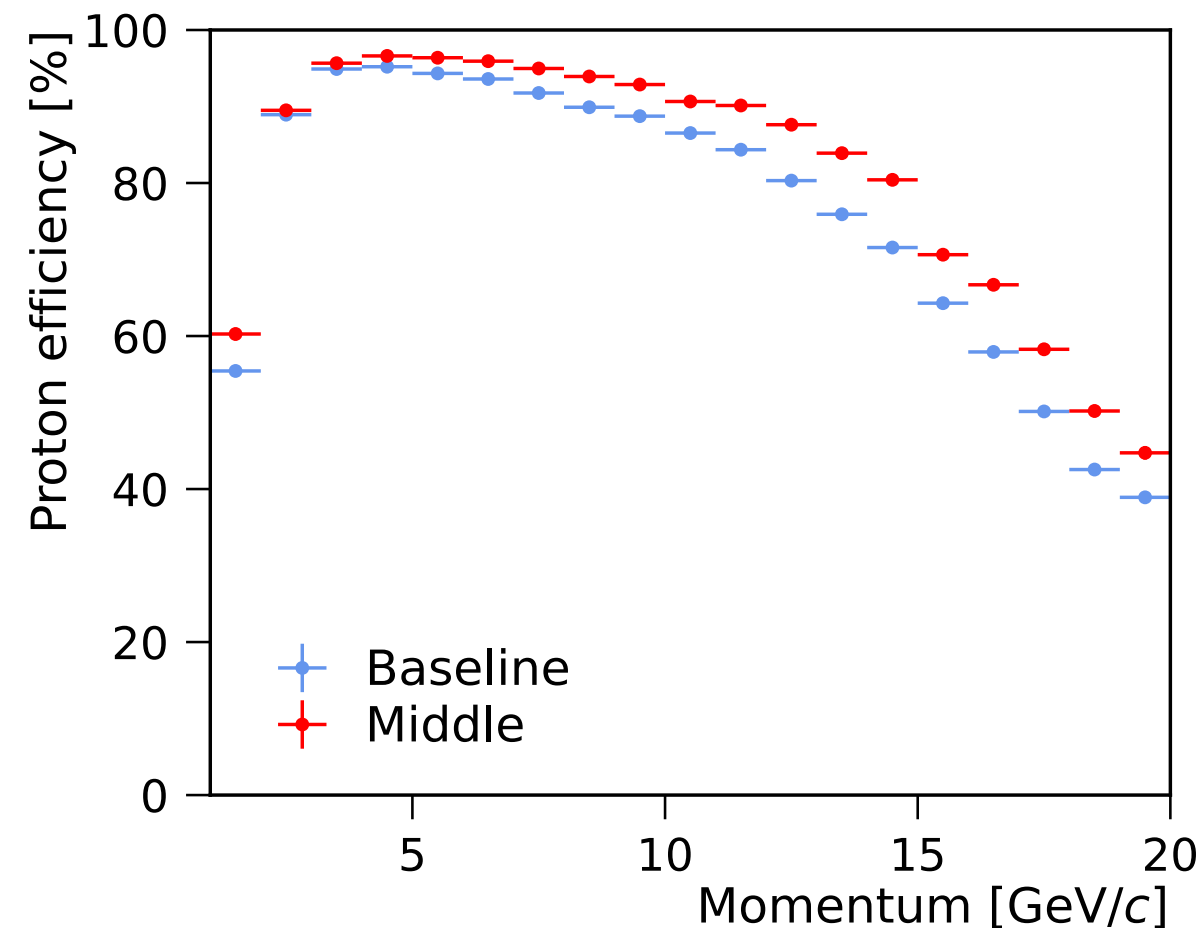
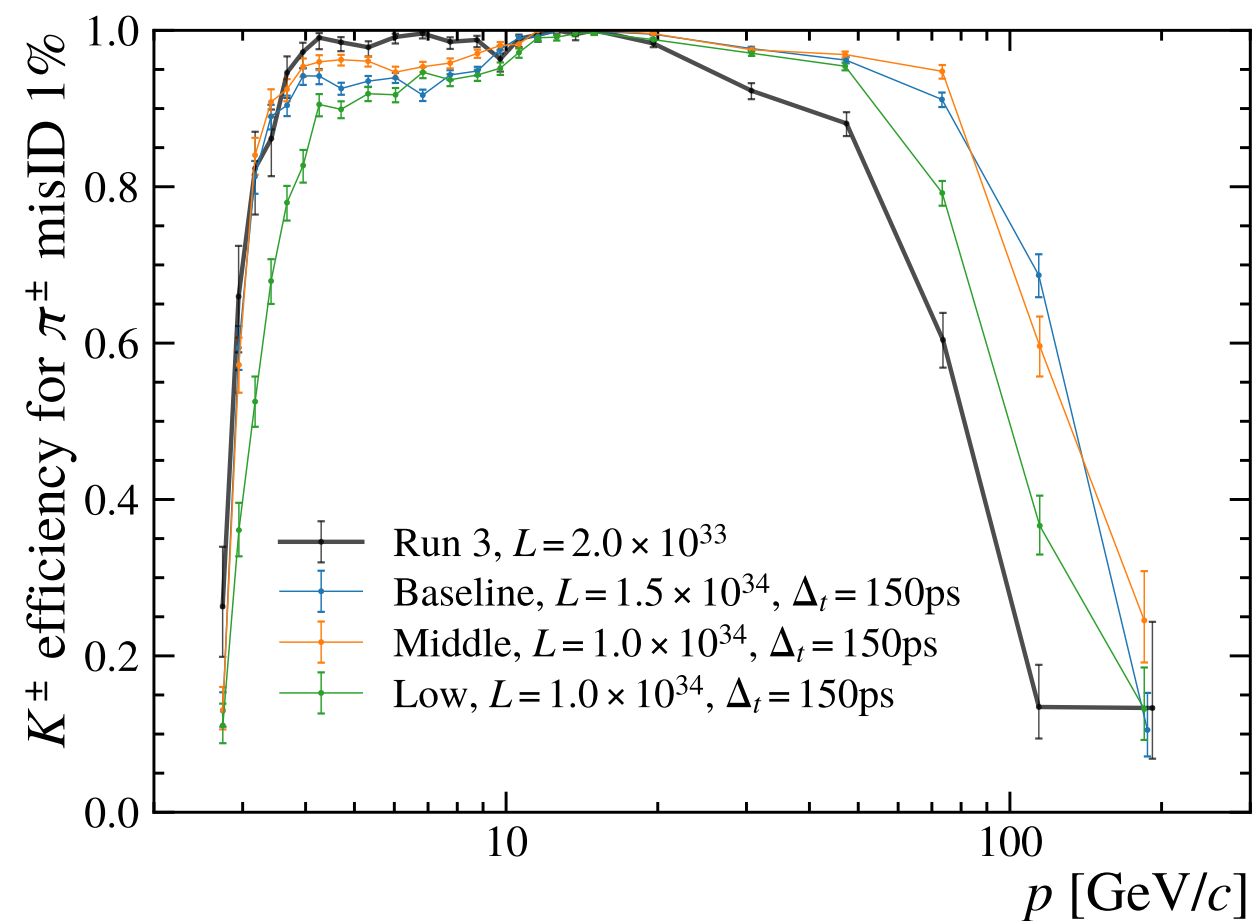
UP + MT (pixels)
significantly improves
momentum resolution
compared to U1 LHCb!



TORCH timing can help
suppress backgrounds
in tracks without a
VELO segment.

LHCb U2: particle identification

LHCb Upgrade 2 Scoping Document



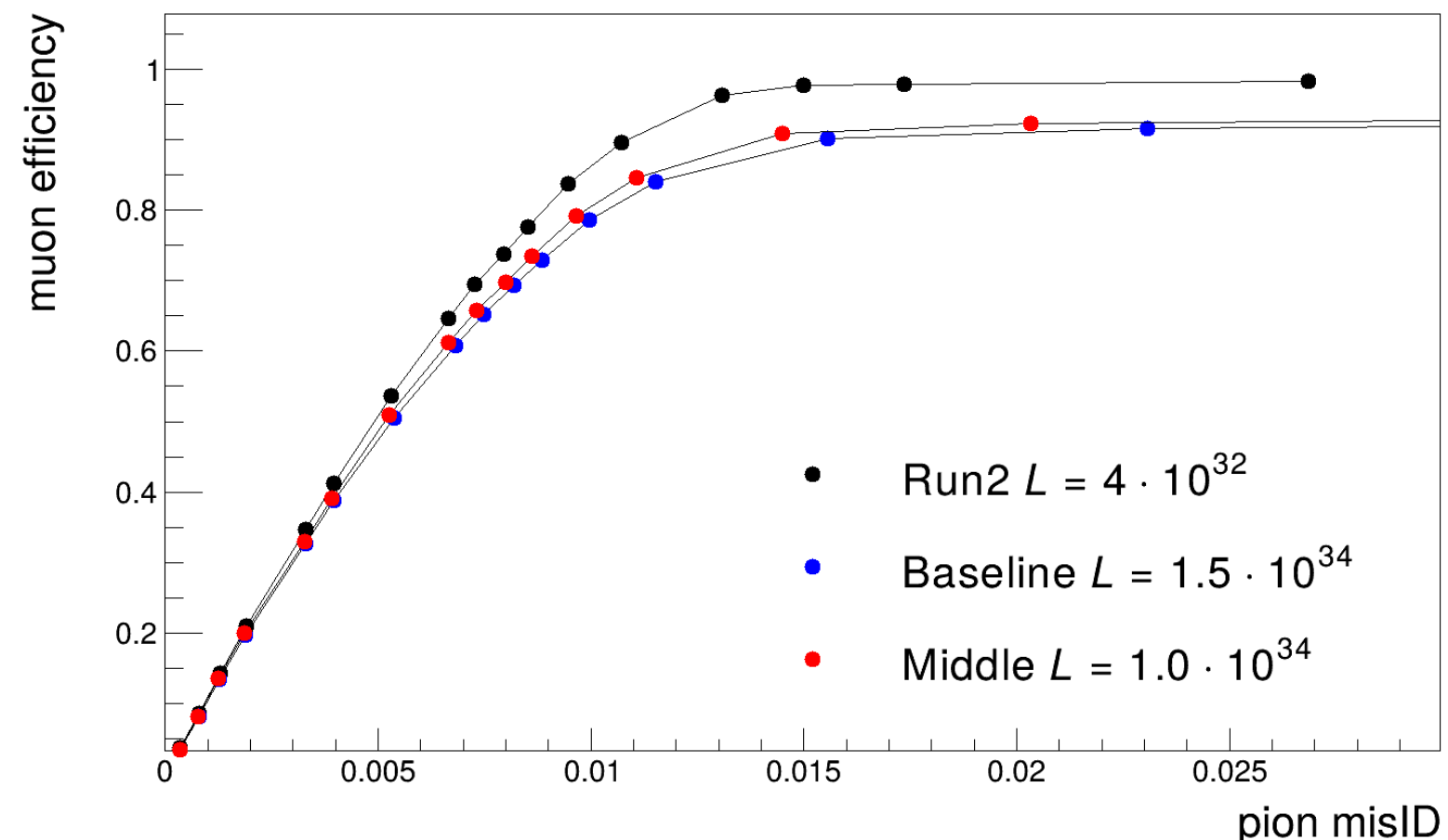
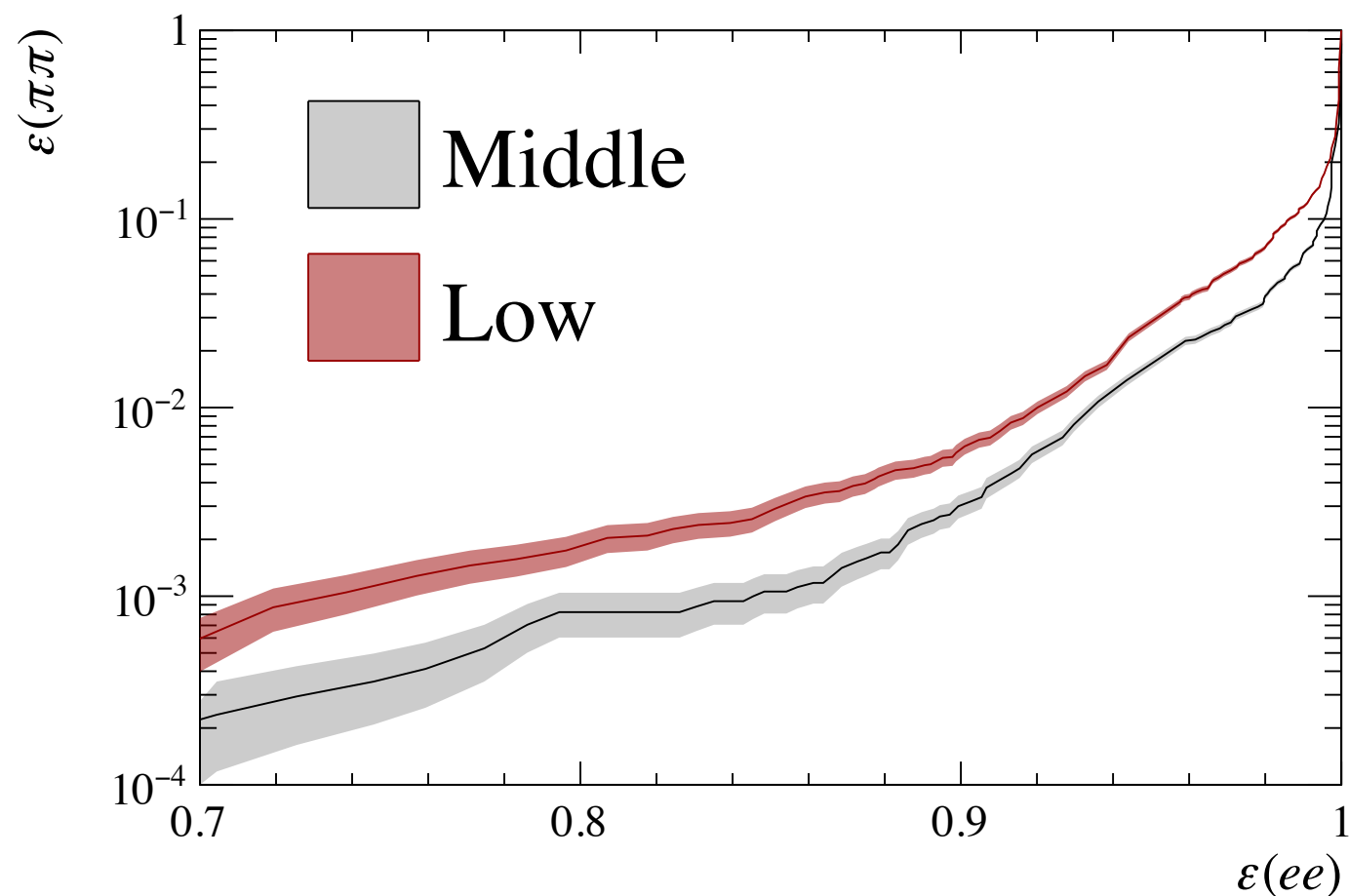
Potential to improve pion-kaon separation at high momenta

Strong impact of reduced RICH photoelectron yield at low momentum, especially for the Low detector scenario

TORCH provides additional capabilities at low momenta

LHCb U2: particle identification (2)

LHCb Upgrade 2 Scoping Document



Electron-pion separation is significantly degraded in the low scenario

The muon ID performance good, but not yet at the excellent levels we are used to. Studies to improve it are ongoing.

Impact of U2 scenarios on sensitivity

Baseline	Middle	Low	
<u>$B_{(s)}^0 \rightarrow \mu^+ \mu^-$</u>			
Improved background rejection from VELO with timing		Worse background rejection	→
Improved mass resolution to separate B^0 and B_s^0 peaks			
Loss of muon identification	Loss of muon identification	Loss of muon identification	→
Acceptance comparable to current detector		Reduced acceptance	→
<u>γ from $B^+ \rightarrow DK^+, D \rightarrow K_S^0 \pi^+ \pi^-$</u>			
Improved high momentum kaon/pion separation		Less or no improvement	→
Background rejection for downstream tracks with RICH2 & TORCH timing	Reduced TORCH acceptance	RICH2 timing only	→
Acceptance comparable to current detector		Reduced acceptance also for downstream tracks	→
<u>$D^{*+} \rightarrow D\pi^+, D \rightarrow K^+ K^-$</u>			
Acceptance for long tracks comparable to current detector		Reduced acceptance	→
Improved slow pion acceptance from Magnet Stations		No improvement	
Trigger throughput comparable to current detector		Reduced online farm capacity	→
<u>ϕ_s from $B_s^0 \rightarrow J/\psi \phi$</u>			
Loss of muon identification	Loss of muon identification	Loss of muon identification	
Improved high momentum kaon/pion separation		Less or no improvement	→
Improved decay time resolution		Worse performance	→
Improved flavour tagging		No improvement	→

Precise impact under study

~5% per track

~10% PID efficiency loss

3x higher background

~10-15% per track

Up to 40% total tracking efficiency loss

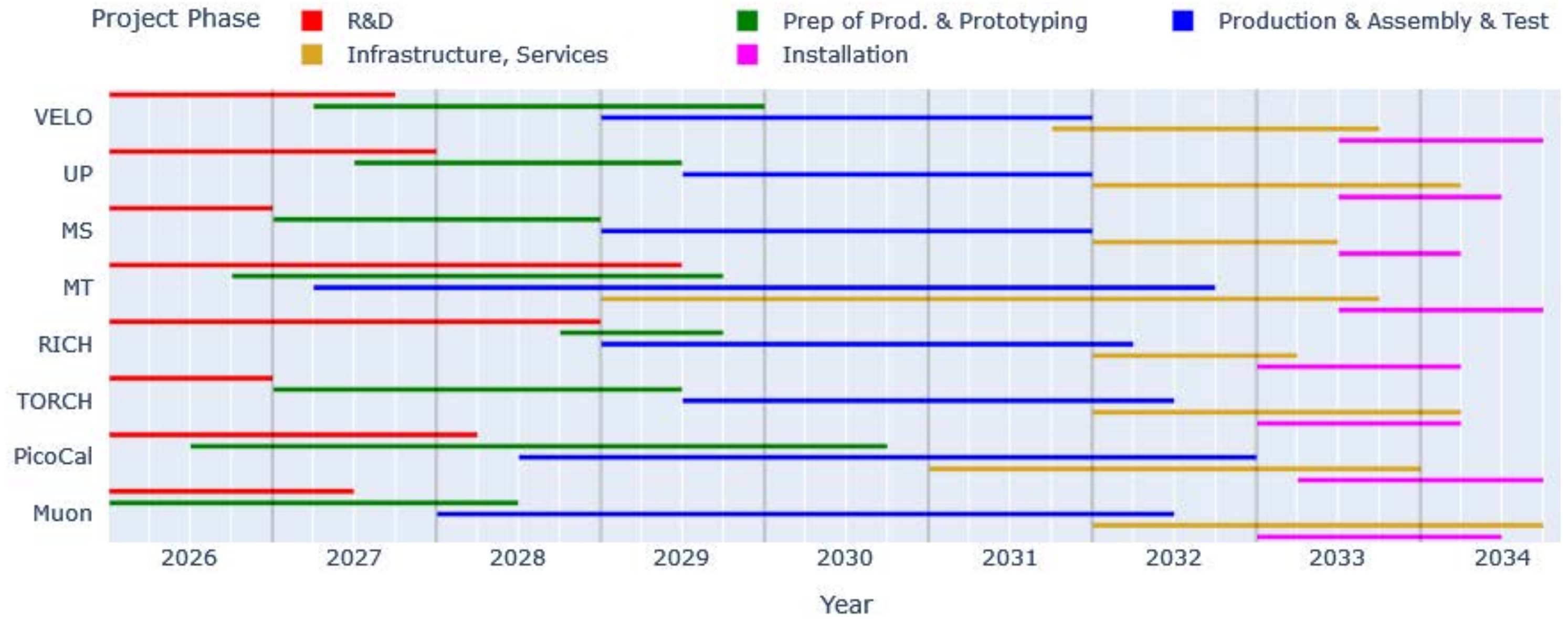
Impact on trigger to be evaluated

~10% sensitivity dilution

~5% flavour tagging loss

U2 detailed schedule

LHCb Upgrade 2 Scoping Document



Ultimate flavour sensitivity projections

Experiment Assumed data sample	ATLAS 3000 fb ⁻¹	CMS 3000 fb ⁻¹	LHCb 300 fb ⁻¹	Belle II 50 ab ⁻¹
CKM angles				
β	—	—	0.08°	0.3°
α	—	—	—	0.6°
γ	—	—	0.3°	1.0°
ϕ_s [mrad]	(4 – 9)	3	3	—
<i>CP</i> violation in loop-dominated decays				
$S(B^0 \rightarrow \eta' K_S^0)$	—	—	—	0.015
$\phi_s(B_s^0 \rightarrow \phi\phi)$ [mrad]	—	—	9	—
$\phi_s(B_s^0 \rightarrow K^{*0}\bar{K}^{*0})$ [mrad]	—	—	8	—
<i>CP</i> violation in $B_{(s)}^0$–$\bar{B}_{(s)}^0$ mixing				
a_{sl}^s	—	—	3	—
a_{sl}^d	—	—	2	6.2
<i>CP</i> violation in the charm sector				
ΔA_{CP} [10 ⁻⁵]	—	—	3.3	60
$A_{CP}(D^{+,0} \rightarrow \pi^{+,0}\pi^0)$ [10 ⁻⁵]	—	—	100, —	130, 70
$A_\Gamma(KK, \pi\pi)$ [10 ⁻⁵]	—	—	1.2	—
$\Delta x(D^0 \rightarrow K_S^0\pi^+\pi^-)$ [10 ⁻⁵]	—	—	1.6	40
Semileptonic <i>B</i> decays				
$ V_{ub} $	—	—	1%	1.2%
$ V_{cb} $	—	—	—	1.0%
$R(D), R(D^*)$	—	—	3.3%, 3.0%	1.4%, 1.0%

Experiment Assumed data sample	ATLAS 3000 fb ⁻¹	CMS 3000 fb ⁻¹	LHCb 300 fb ⁻¹	Belle II 50 ab ⁻¹
Leptonic <i>B</i> decays				
$\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$ [10 ⁻⁹]	(0.33 – 0.40)	0.22	0.16	—
$\mathcal{B}(B^0 \rightarrow \mu^+\mu^-)$ [10 ⁻¹⁰]	(0.32 – 0.48)	0.12	0.12	—
$\tau_{\text{eff}}(B_s^0 \rightarrow \mu^+\mu^-)$ [ps]	^{+(0.07–0.11)} _{–(0.05–0.08)}	0.05	0.05	—
$S(B_s^0 \rightarrow \mu^+\mu^-)$	—	—	0.2	—
$\mathcal{B}(B^+ \rightarrow \tau^+\nu_\tau)$	—	—	—	6%
$\mathcal{B}(B^+ \rightarrow \mu^+\nu_\mu)$	—	—	—	5%
Flavour-changing neutral current <i>b</i> → <i>sll</i> decays				
$P'_5(B^0 \rightarrow K^{*0}\mu^+\mu^-)$ [10 ⁻³] [†]	(47 – 82)	23	12	—
$\mathcal{B}(B^{+,0} \rightarrow K^{+,*0}\nu\bar{\nu})$	—	—	—	8%, 23%
$\mathcal{B}(B^{+,0} \rightarrow K^{+,*0}\tau^+\tau^-)$ [10 ⁻⁴]	—	—	—	< 0.9, < 1.5
Flavour-changing neutral current <i>b</i> → <i>sγ</i> decays				
$\mathcal{B}(B \rightarrow X_s\gamma; E_\gamma > 1.6 \text{ GeV})$	—	—	—	(4.7 – 8.8)%
$S(B^0 \rightarrow K_S^0\pi^0\gamma)$	—	—	—	0.04
$S(B_s^0 \rightarrow \phi\gamma)$	—	—	0.025	—
$A_{\text{T}}^{(2)}(B^0 \rightarrow K^{*0}e^+e^-; \text{very low } q^2)$	—	—	0.016	0.08
$\alpha_\gamma(\Lambda_b^0 \rightarrow \Lambda^0\gamma)$	—	—	0.038	—
Lepton flavour violation in τ decays				
$\mathcal{B}(\tau^+ \rightarrow \mu^+\gamma)$ [10 ⁻⁸]	—	—	—	< 0.7
$\mathcal{B}(\tau^+ \rightarrow \mu^+\mu^+\mu^-)$ [10 ⁻⁸]	< (0.13 – 0.64)	< 0.39	< 0.26	< (0.02 – 0.17)

[†] The sensitivity for the P'_5 variable is quoted for the range $q^2 \in [4.0, 6.0] \text{ GeV}^2$ for ATLAS and LHCb and $q^2 \in [4.3, 6.0] \text{ GeV}^2$ for CMS.