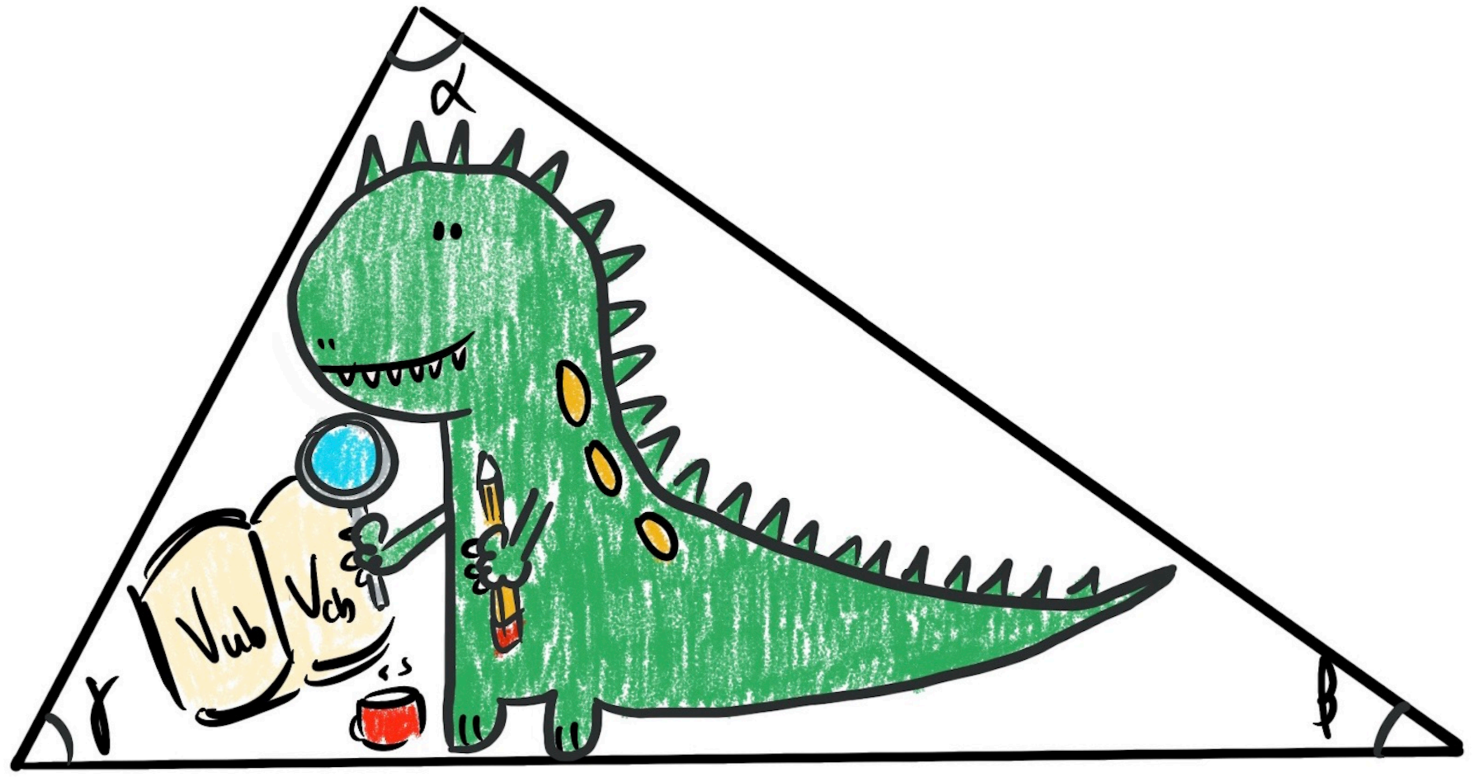
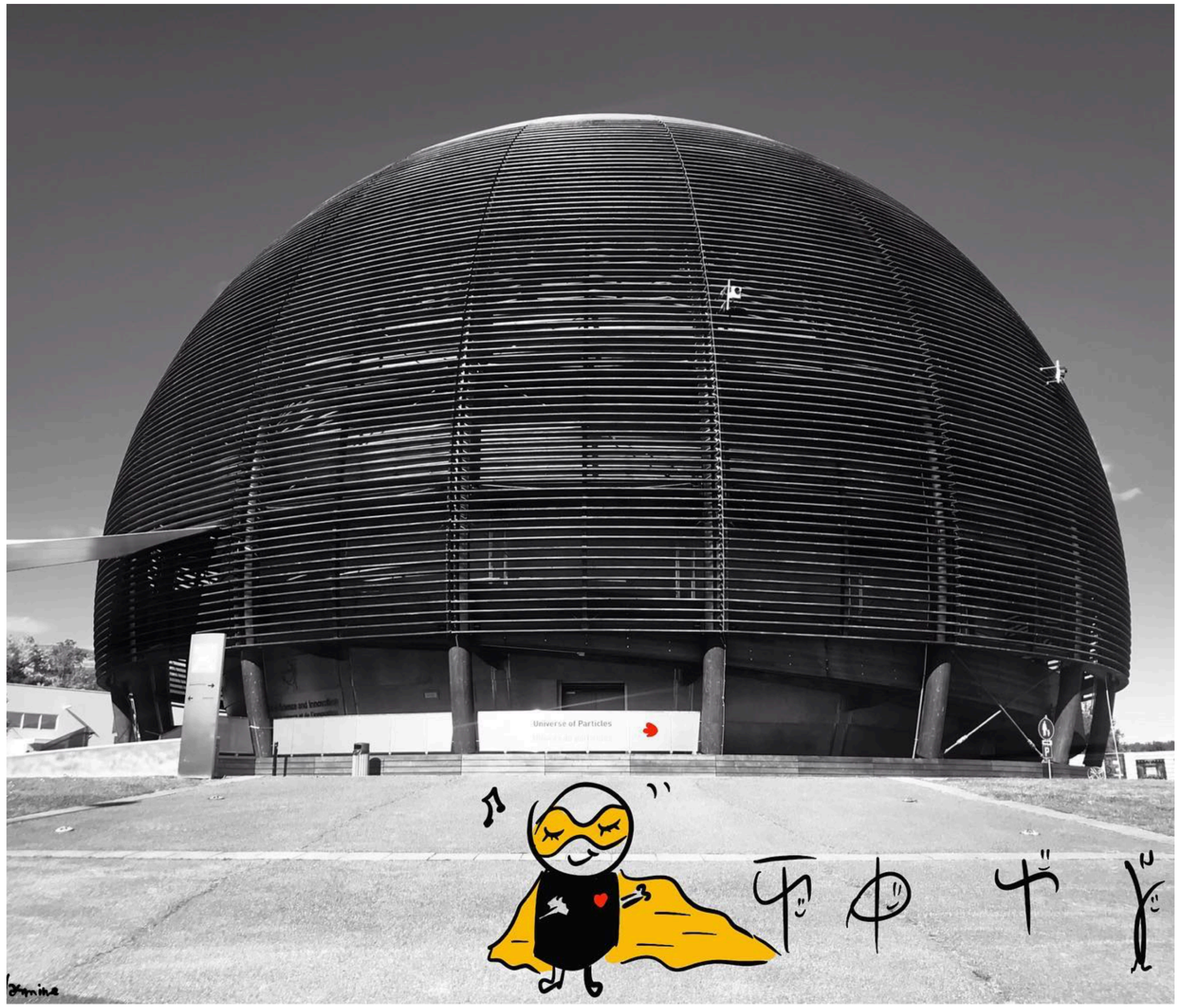
Recent results on matter and antimatter asymmetries at LHCb



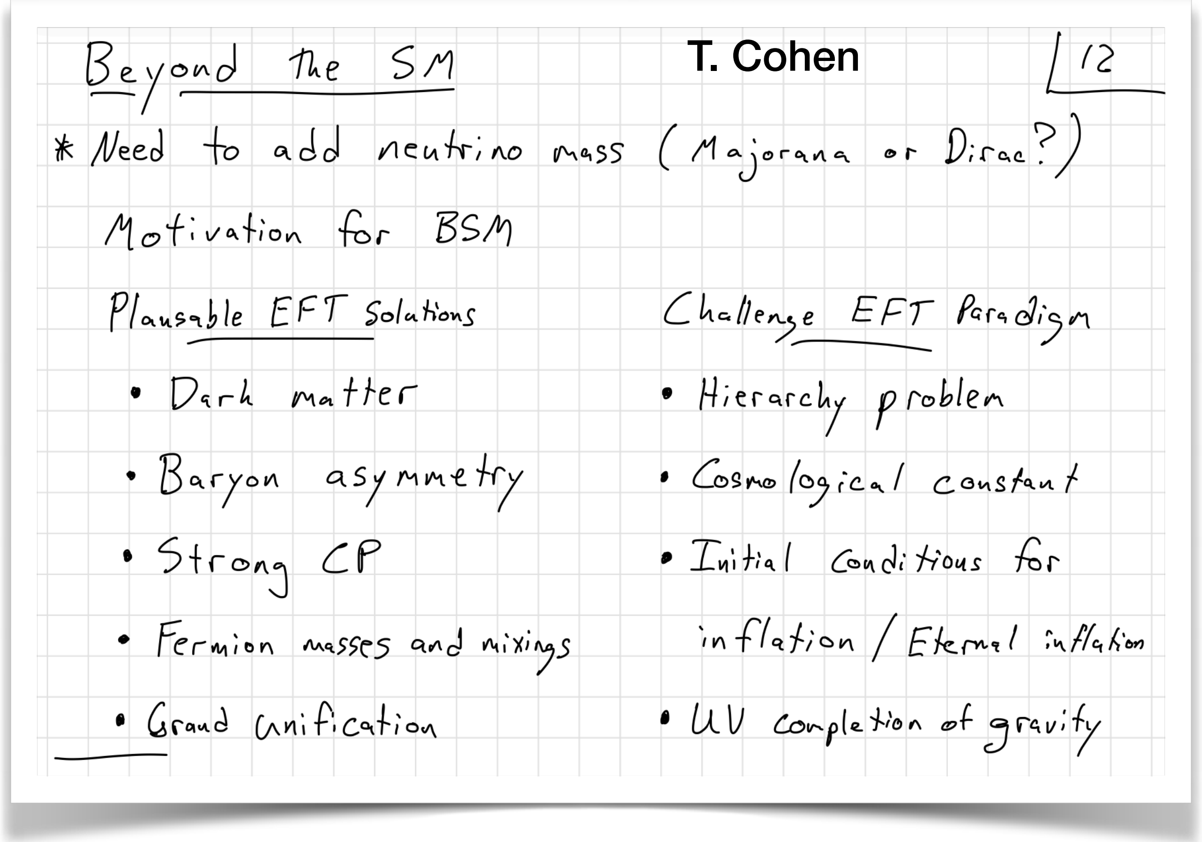
Yasmine Amhis

April 2026
University Queen Mary of London

The Standard Model



A very powerful predictive theory which has resisted many decades of experimentalist trying to “break it”.
Yet, given that the SM can not explain…



Beyond the SM — T. Cohen — L12

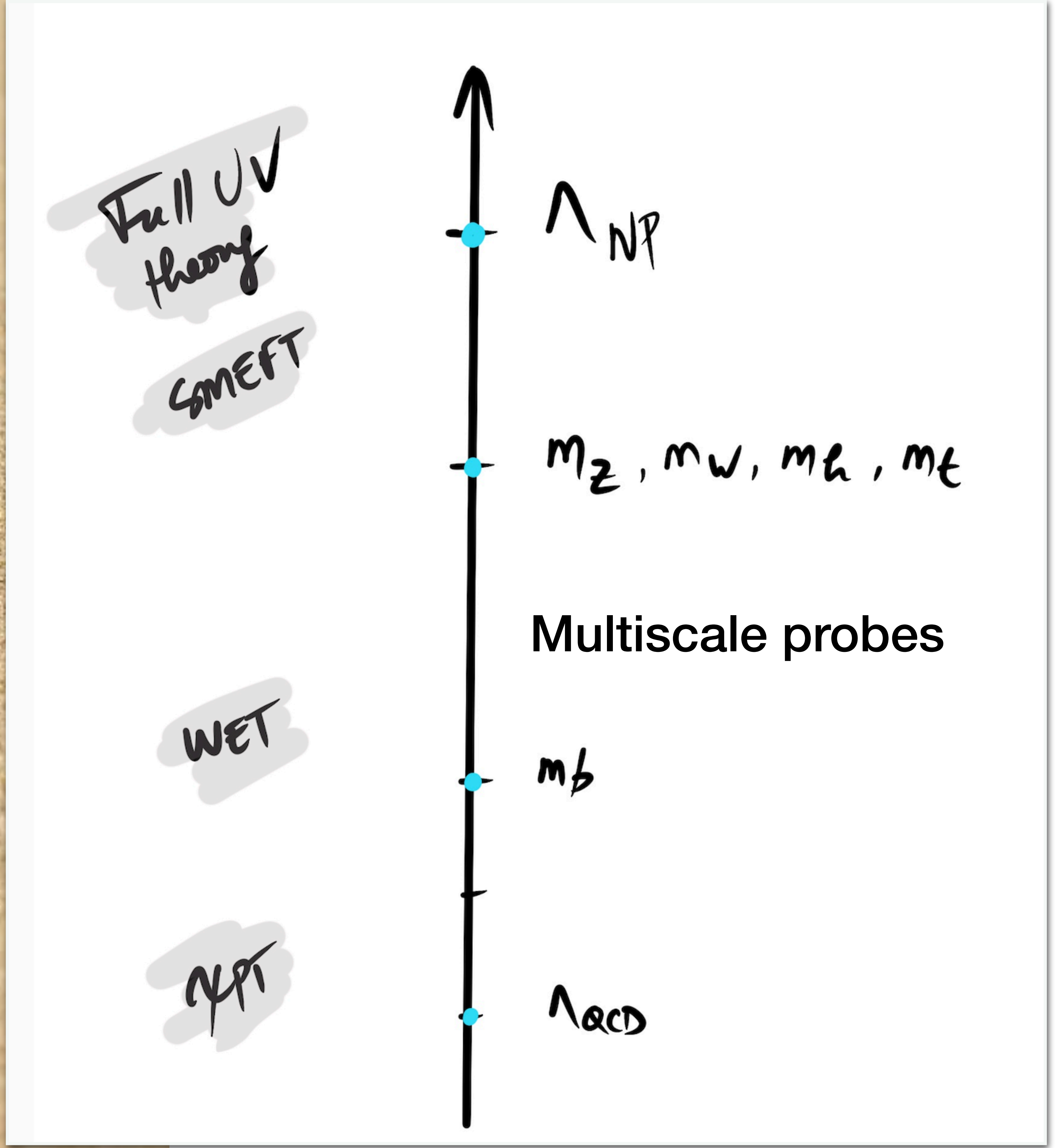
* Need to add neutrino mass (Majorana or Dirac?)

Motivation for BSM

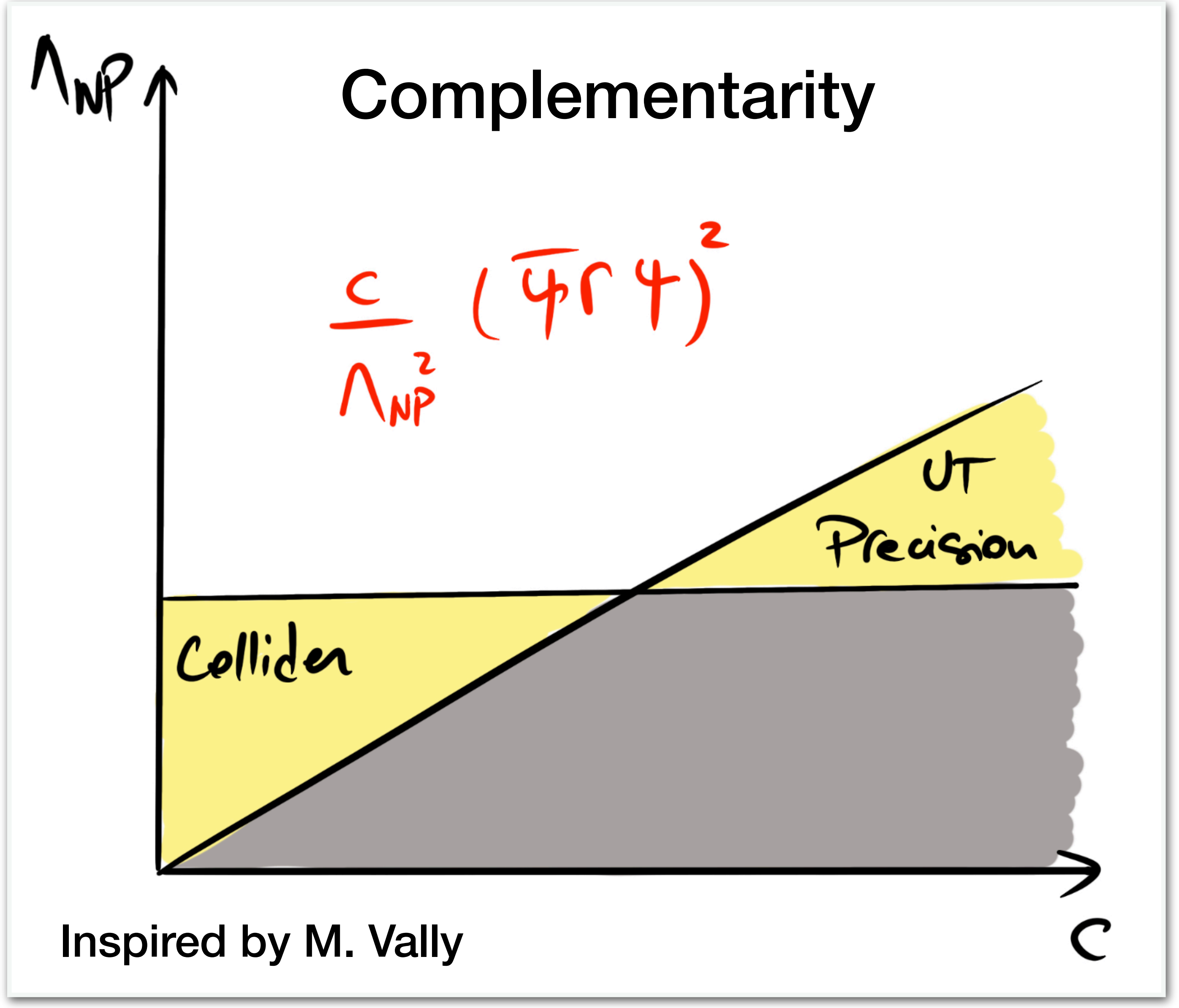
Plausible EFT Solutions	Challenge EFT Paradigm
• Dark matter	• Hierarchy problem
• Baryon asymmetry	• Cosmological constant
• Strong CP	• Initial conditions for inflation / Eternal inflation
• Fermion masses and mixings	
• Grand unification	• UV completion of gravity


Probe
Things we don't understand

Flavour Physics as probe



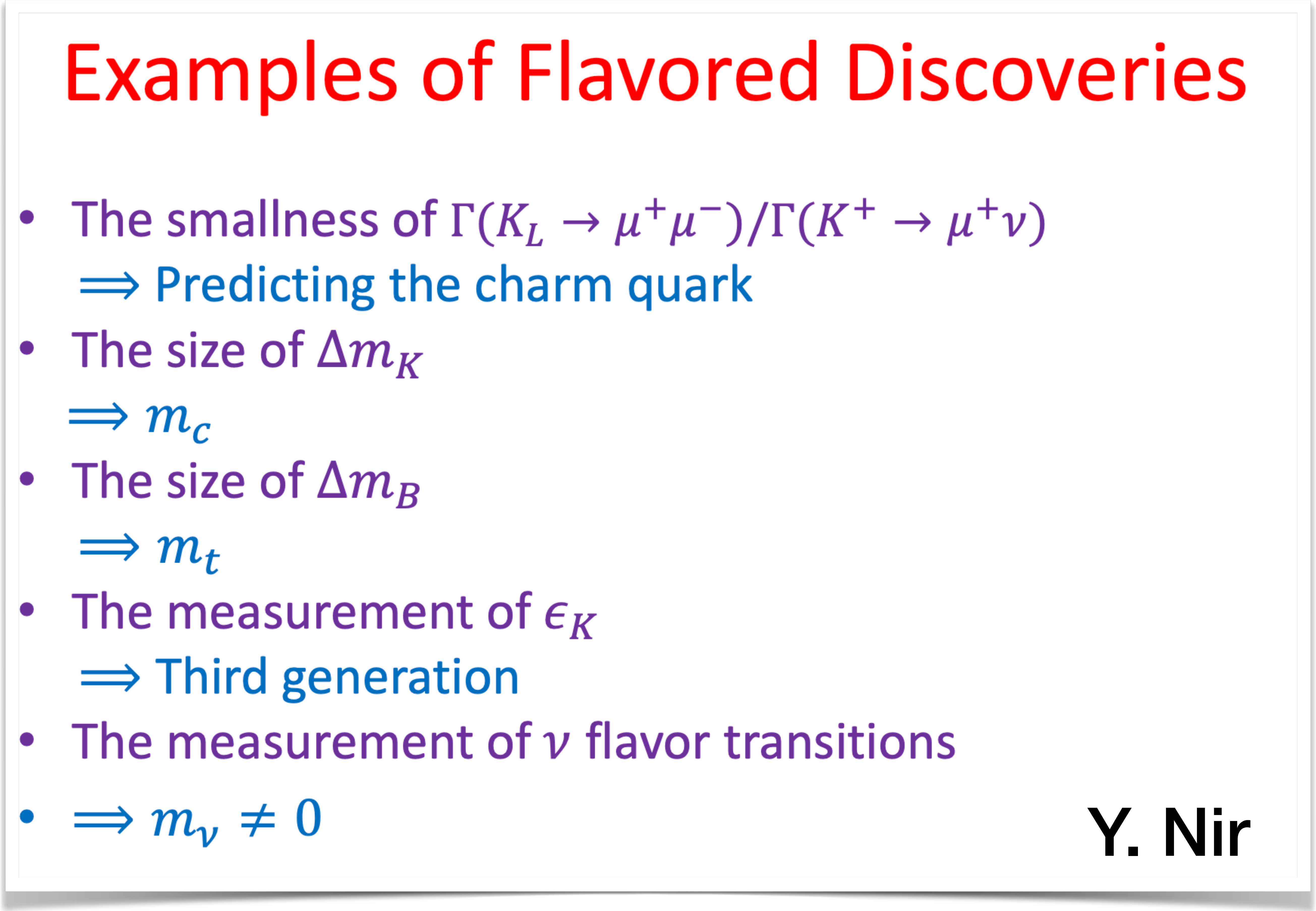
Multiscale probes



Complementarity

Inspired by M. Vally

Many observables & techniques are available

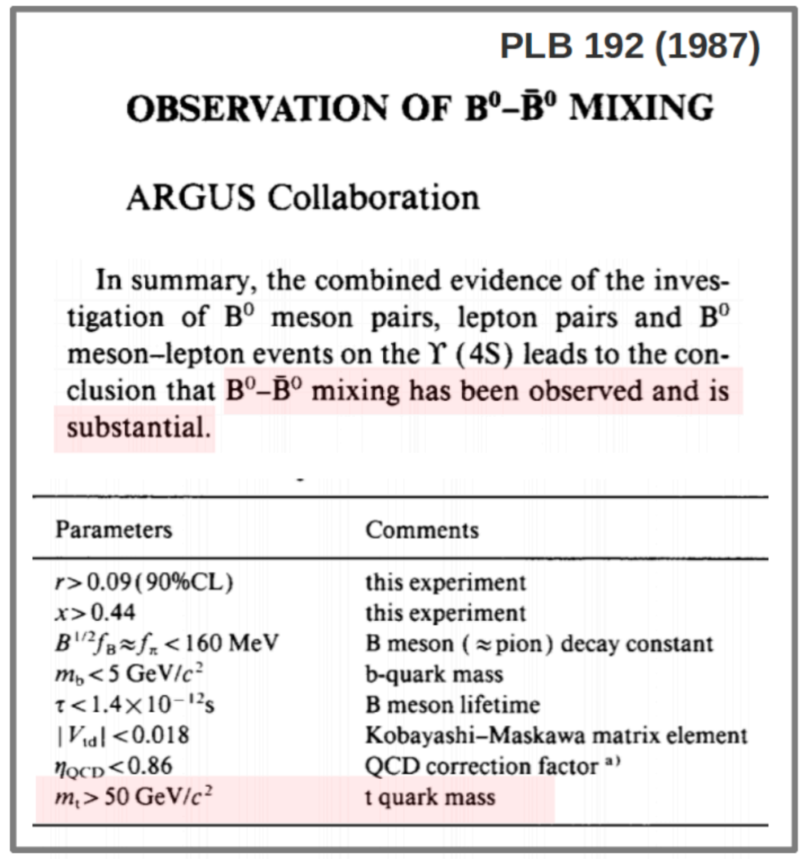


Examples of Flavored Discoveries

- The smallness of $\Gamma(K_L \to \mu^+\mu^-)/\Gamma(K^+ \to \mu^+\nu)$
  $\Longrightarrow$ Predicting the charm quark
- The size of Δm_K
  $\Longrightarrow m_c$
- The size of Δm_B
  $\Longrightarrow m_t$
- The measurement of ϵ_K
  $\Longrightarrow$ Third generation
- The measurement of ν flavor transitions
- $\Longrightarrow m_\nu \neq 0$

Y. Nir

The strength of flavour physics and indirect searches



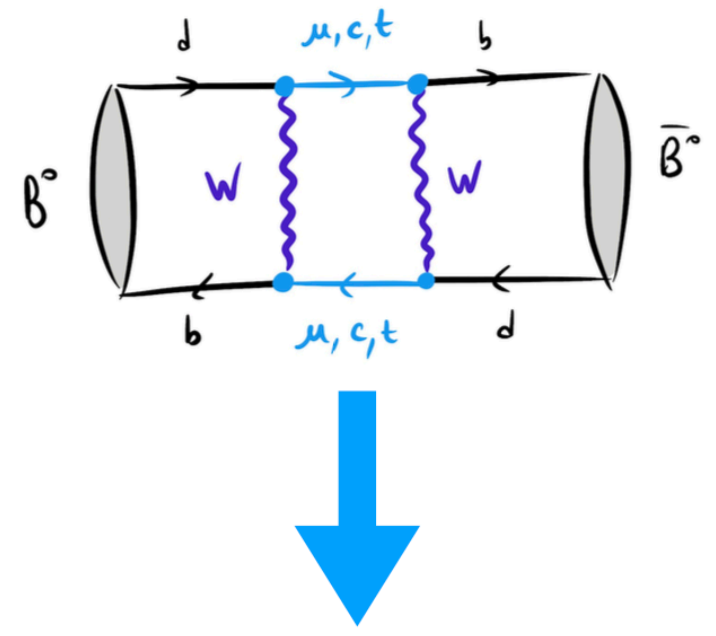
PLB 192 (1987)

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

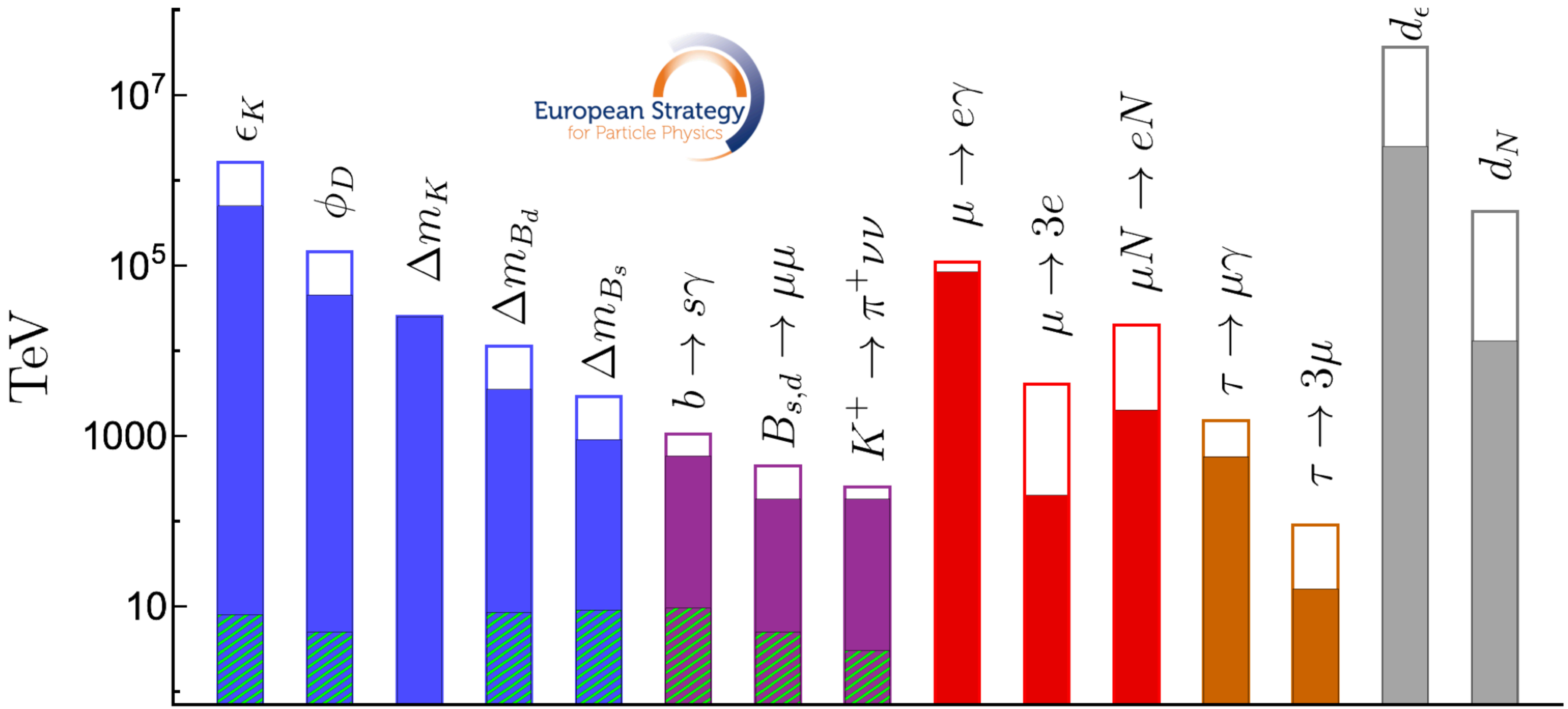
In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson–lepton events on the Υ (4S) leads to the conclusion that B^0–$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$ GeV/c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$ s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [a)]
$m_t > 50$ GeV/c^2	t quark mass



$$\mathcal{M}(B^0 - \bar{B}^0) \propto \sum_{ij} (V_{ib} V_{id}^*)(V_{jb} V_{jd}^*) F(m_{\mu_i}^2, m_{u_j}^2)$$

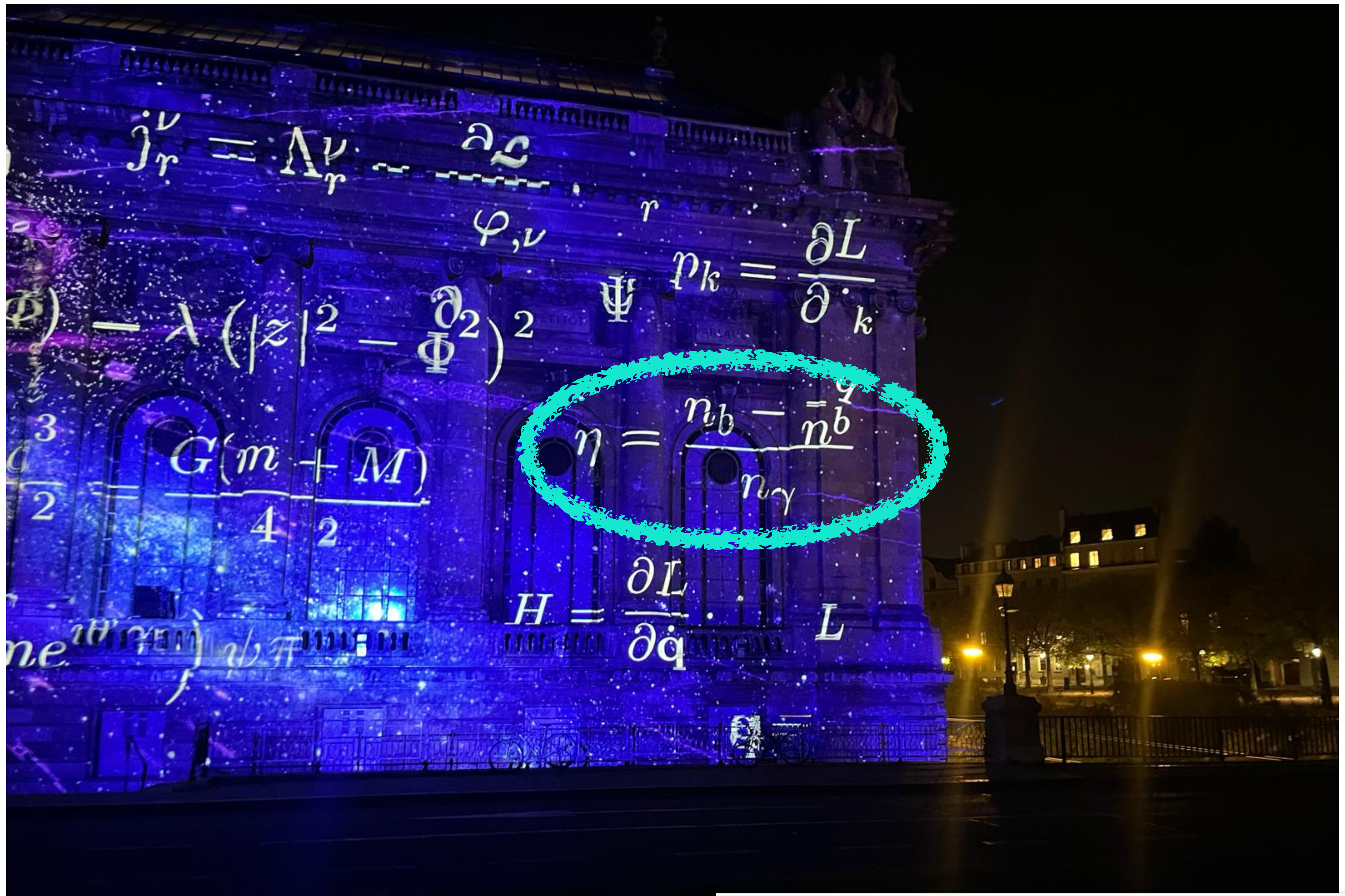
Emphasis the complementarity of direct vs indirect searches



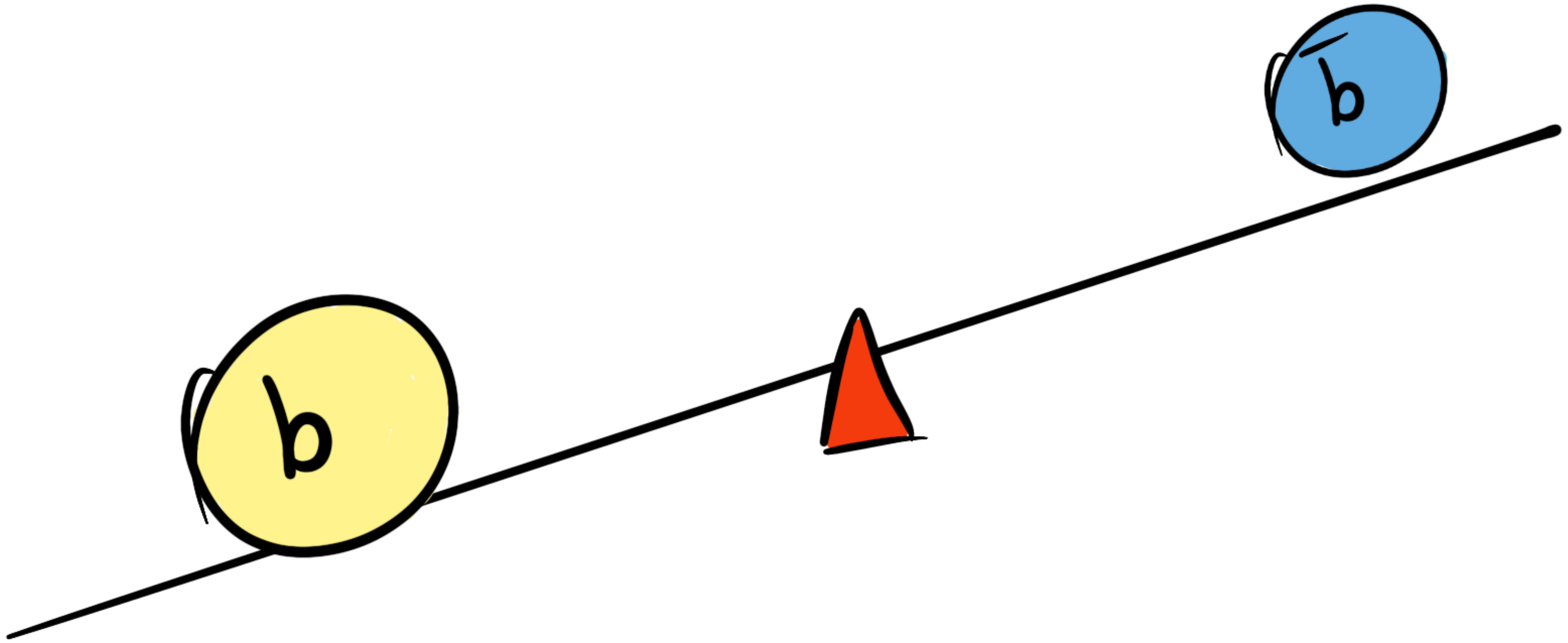
$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{C_5}{\Lambda_M}\mathcal{O}^{(5)} + \sum_a \frac{C_6^a}{\Lambda^2}\mathcal{O}_a^{(6)} + \dots$$

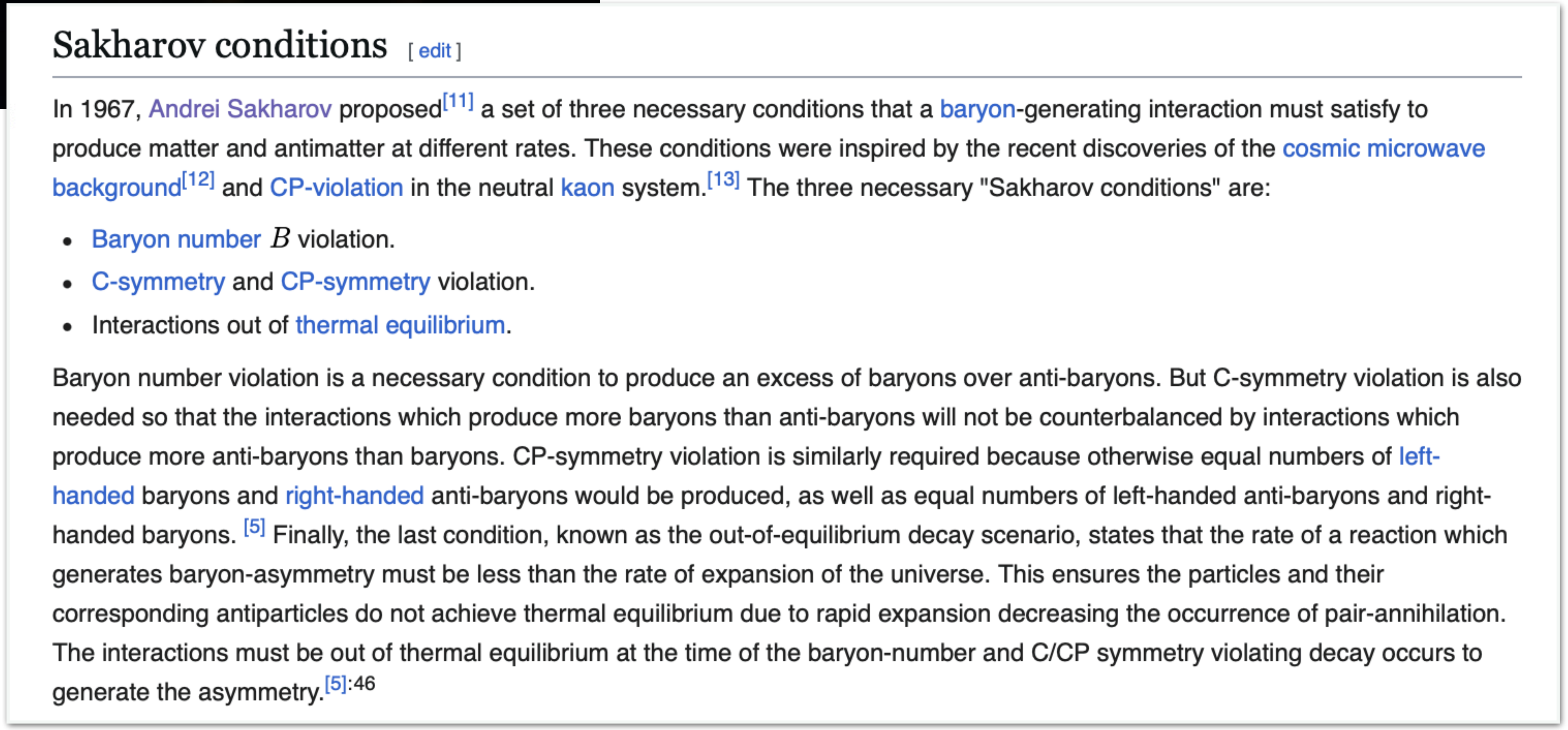
2511.03883

Towards Baryogenesis



Art & History Museum in Geneva





Sakharov conditions [edit]

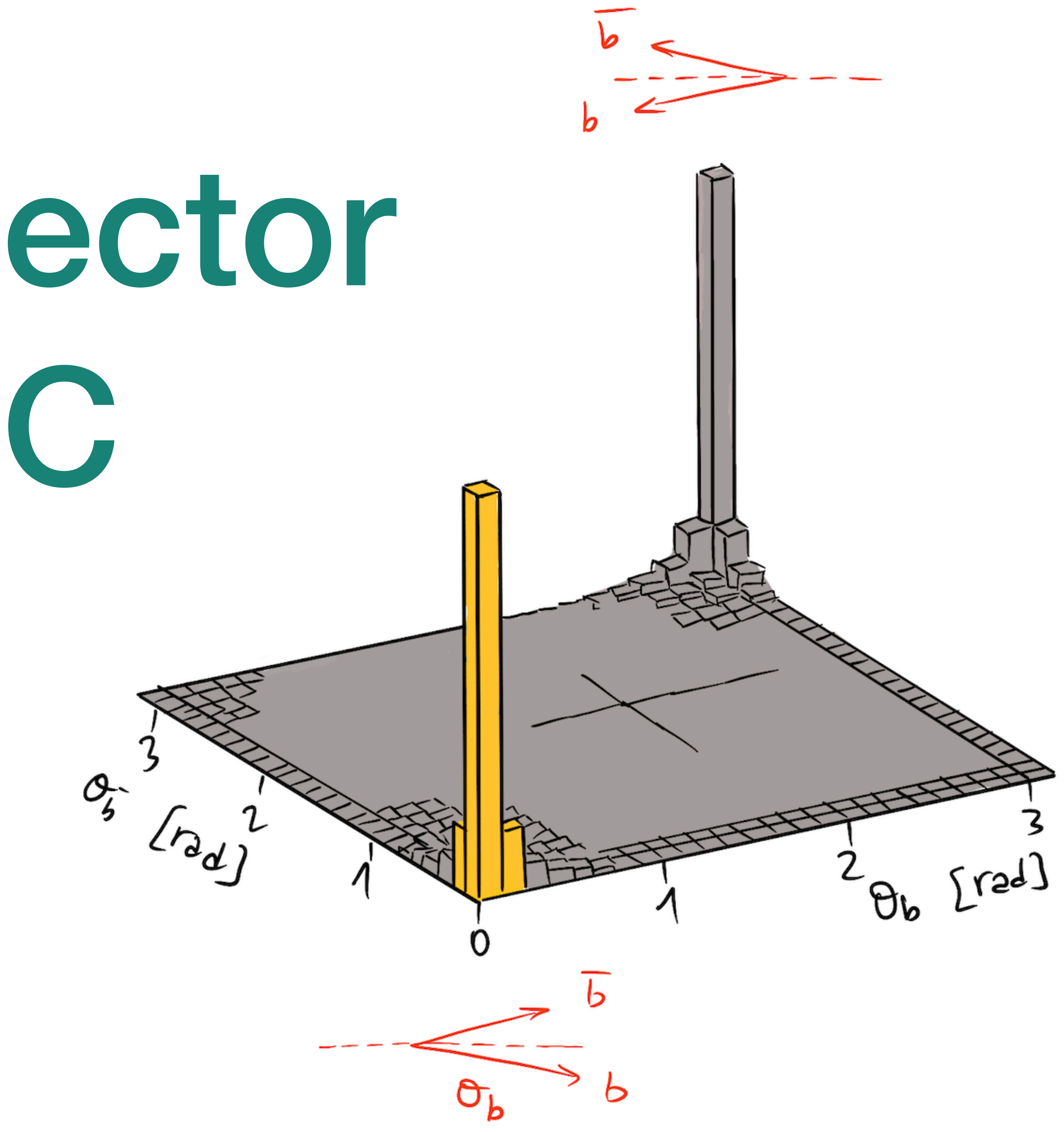
In 1967, Andrei Sakharov proposed[11] a set of three necessary conditions that a baryon-generating interaction must satisfy to produce matter and antimatter at different rates. These conditions were inspired by the recent discoveries of the cosmic microwave background[12] and CP-violation in the neutral kaon system.[13] The three necessary "Sakharov conditions" are:

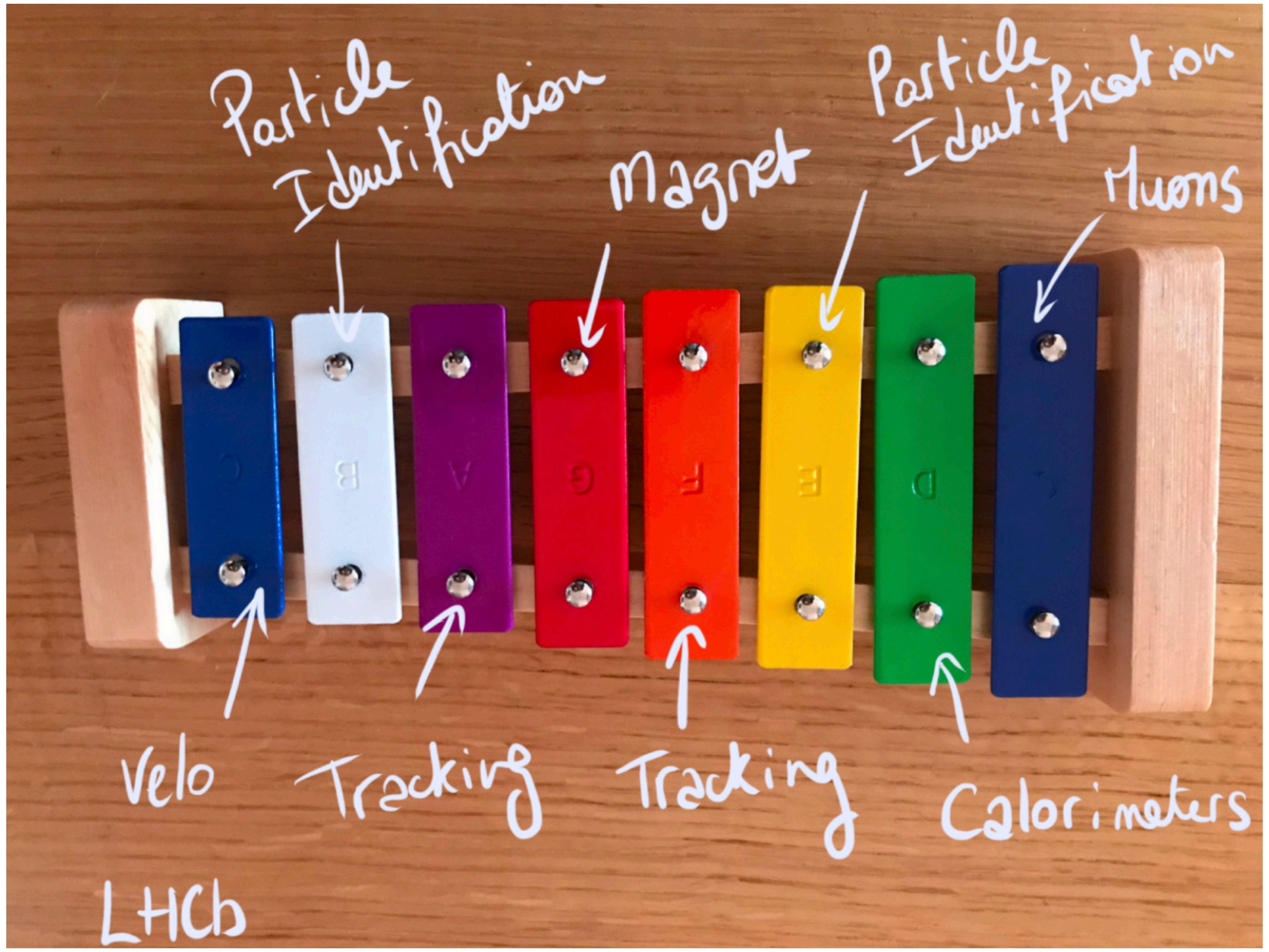
- Baryon number B violation.
- C-symmetry and CP-symmetry violation.
- Interactions out of thermal equilibrium.

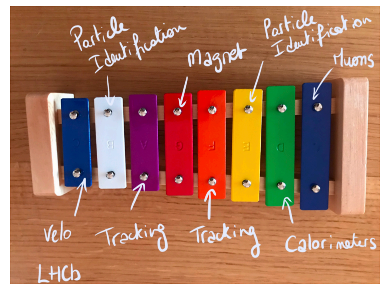
Baryon number violation is a necessary condition to produce an excess of baryons over anti-baryons. But C-symmetry violation is also needed so that the interactions which produce more baryons than anti-baryons will not be counterbalanced by interactions which produce more anti-baryons than baryons. CP-symmetry violation is similarly required because otherwise equal numbers of left-handed baryons and right-handed anti-baryons would be produced, as well as equal numbers of left-handed anti-baryons and right-handed baryons. [5] Finally, the last condition, known as the out-of-equilibrium decay scenario, states that the rate of a reaction which generates baryon-asymmetry must be less than the rate of expansion of the universe. This ensures the particles and their corresponding antiparticles do not achieve thermal equilibrium due to rapid expansion decreasing the occurrence of pair-annihilation. The interactions must be out of thermal equilibrium at the time of the baryon-number and C/CP symmetry violating decay occurs to generate the asymmetry.[5]:46

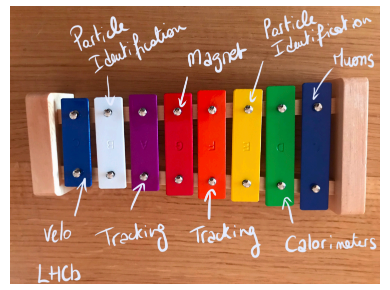
CPV violation timeline

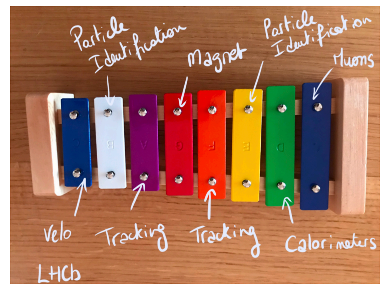
A flavour detector at the LHC





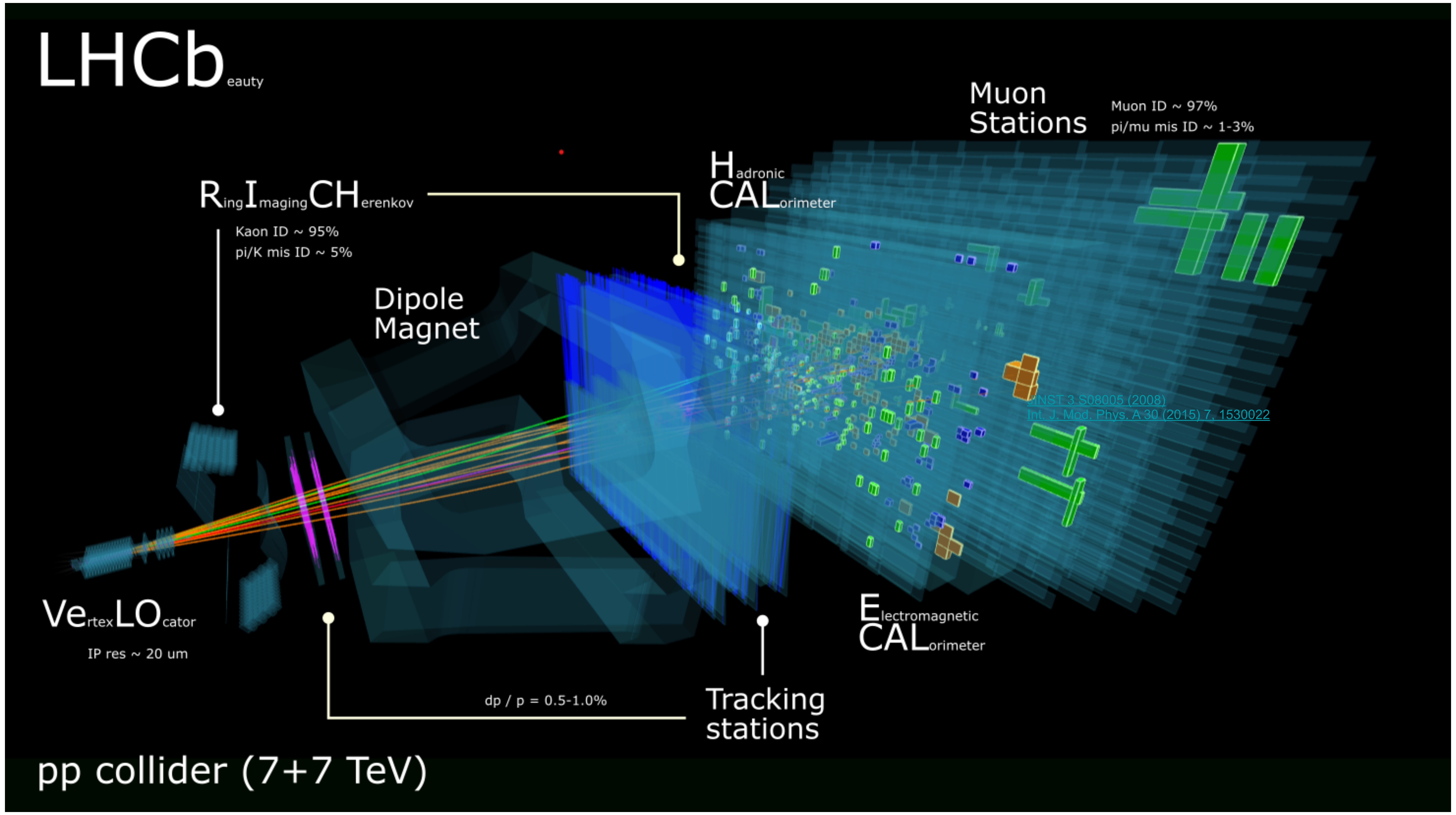




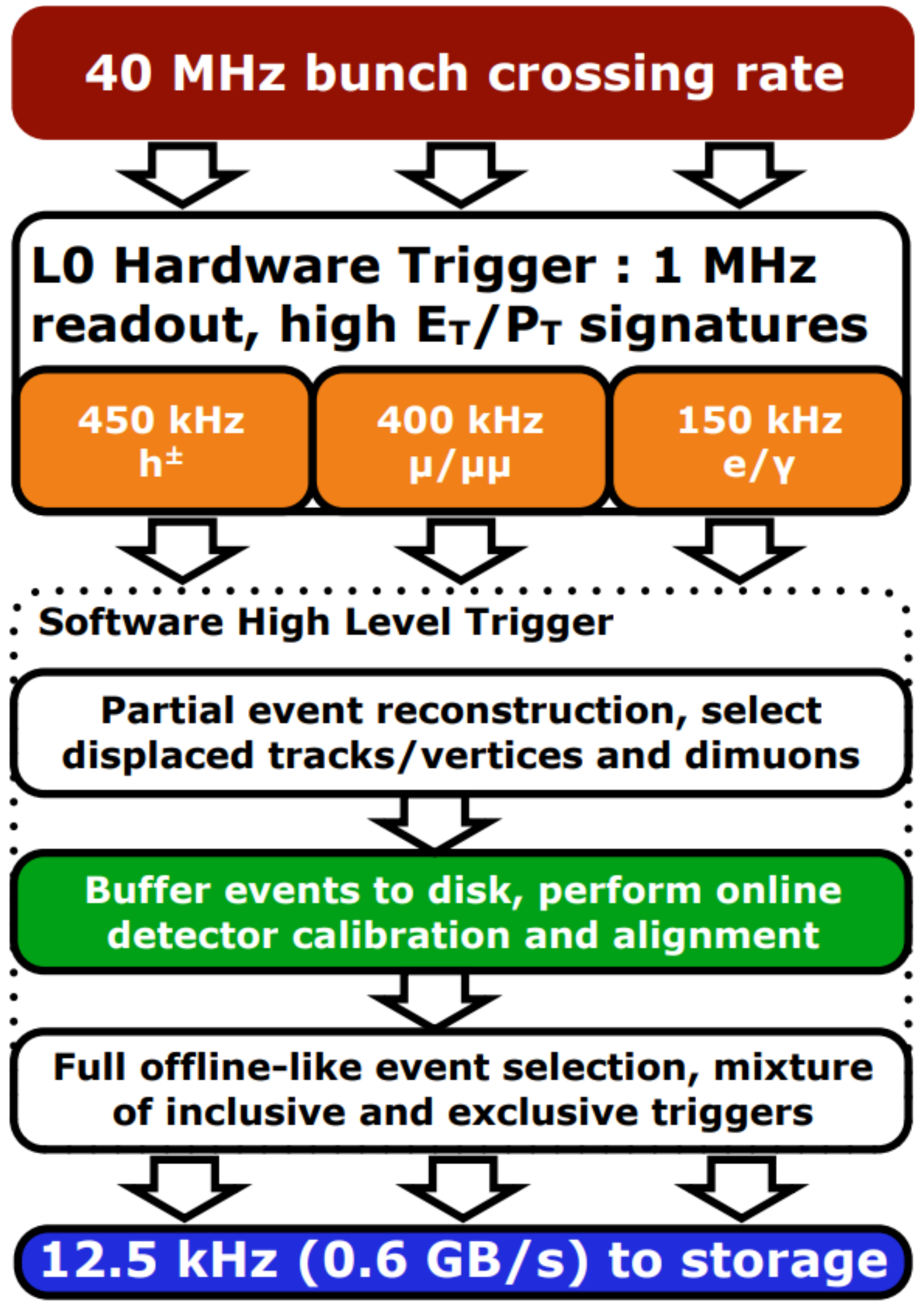


Run 1	LS1	Run 2	LS2	Run 3	LS3	Run 4	LS4	Run 5
2009 2010 2011 2012	2013 2014	2015 2016 2017 2018	2019 2020 2021	2022 2023 2024 2025 2026	2027 2028 2029	2030 2031 2032 2033	2034 2035	2036 2037 2038 2039 2040 2041
3 fb^{-1}		9 fb^{-1}		23 fb^{-1}		50 fb^{-1}		>300 fb^{-1}

The LHCb detector



Run 2 trigger



40 MHz bunch crossing rate

L0 Hardware Trigger : 1 MHz readout, high E_T/P_T signatures

450 kHz $h^{\pm}$

400 kHz $\mu/\mu\mu$

150 kHz e/γ

Software High Level Trigger

Partial event reconstruction, select displaced tracks/vertices and dimuons

Buffer events to disk, perform online detector calibration and alignment

Full offline-like event selection, mixture of inclusive and exclusive triggers

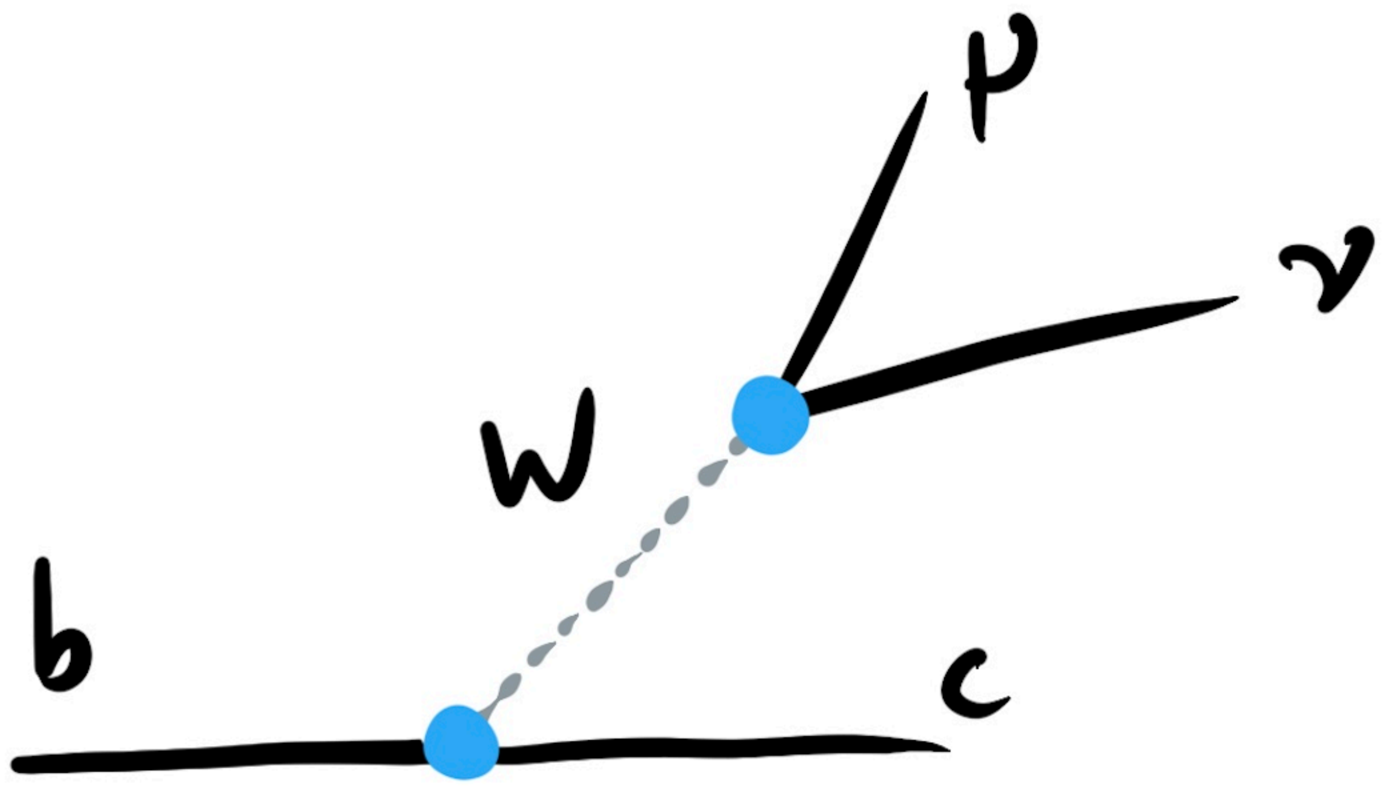
12.5 kHz (0.6 GB/s) to storage

- Good vertex and impact parameter resolution σ (IP) = 15+29/p_T mm.
- Excellent momentum resolution ~ 25 MeV/c^2 two-body decays.
- Excellent particle ID (μ-ID 97% for (π → μ) misID of 1-3%).
- Versatile & efficient trigger.

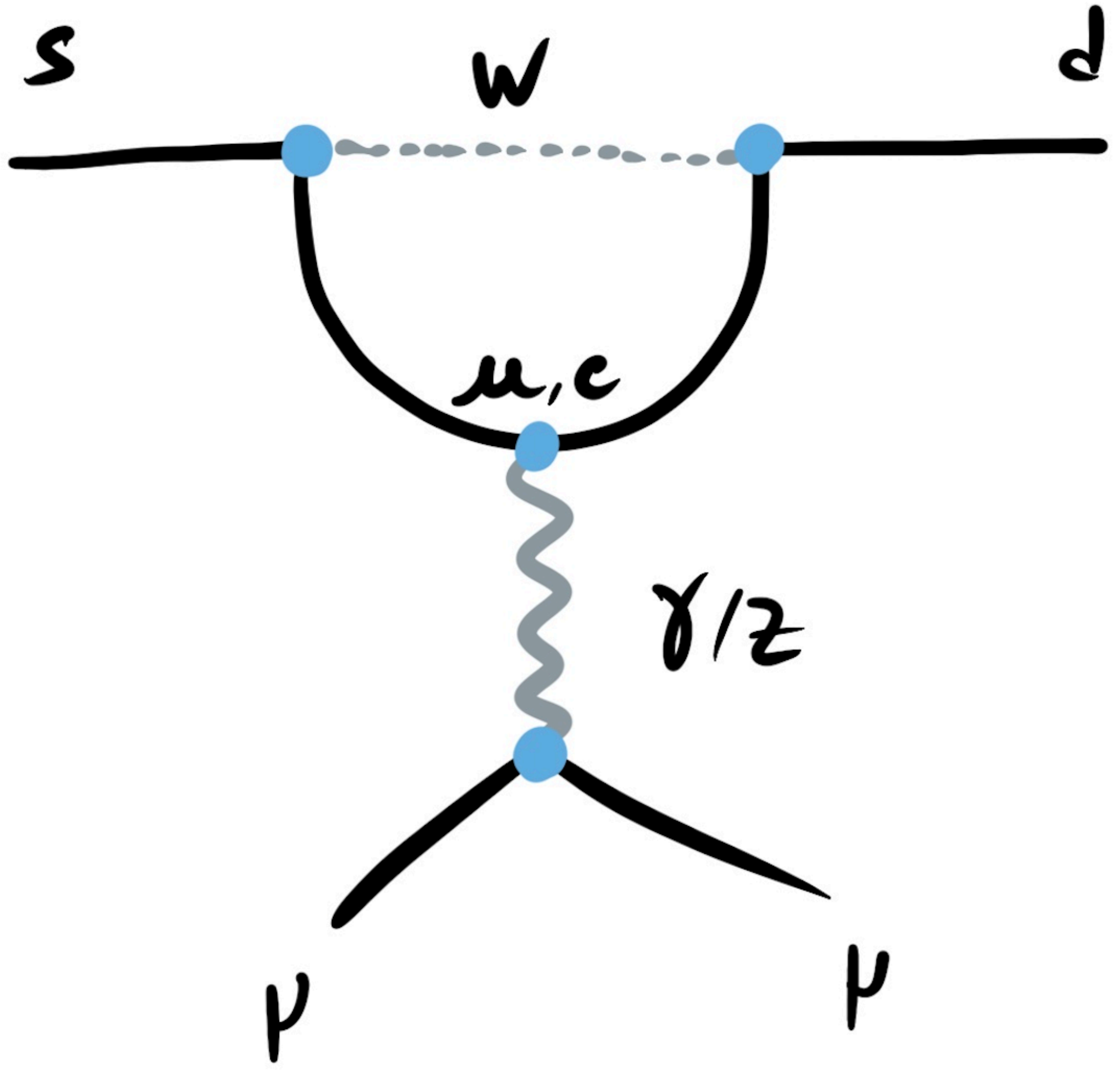
JINST 3 S08005 (2008)
Int. J. Mod. Phys. A 30 (2015) 7, 1530022
Comput.Phys.Commun. 208 (2016) 35-42

Trees vs penguins

Flavour Changing Charged Currents



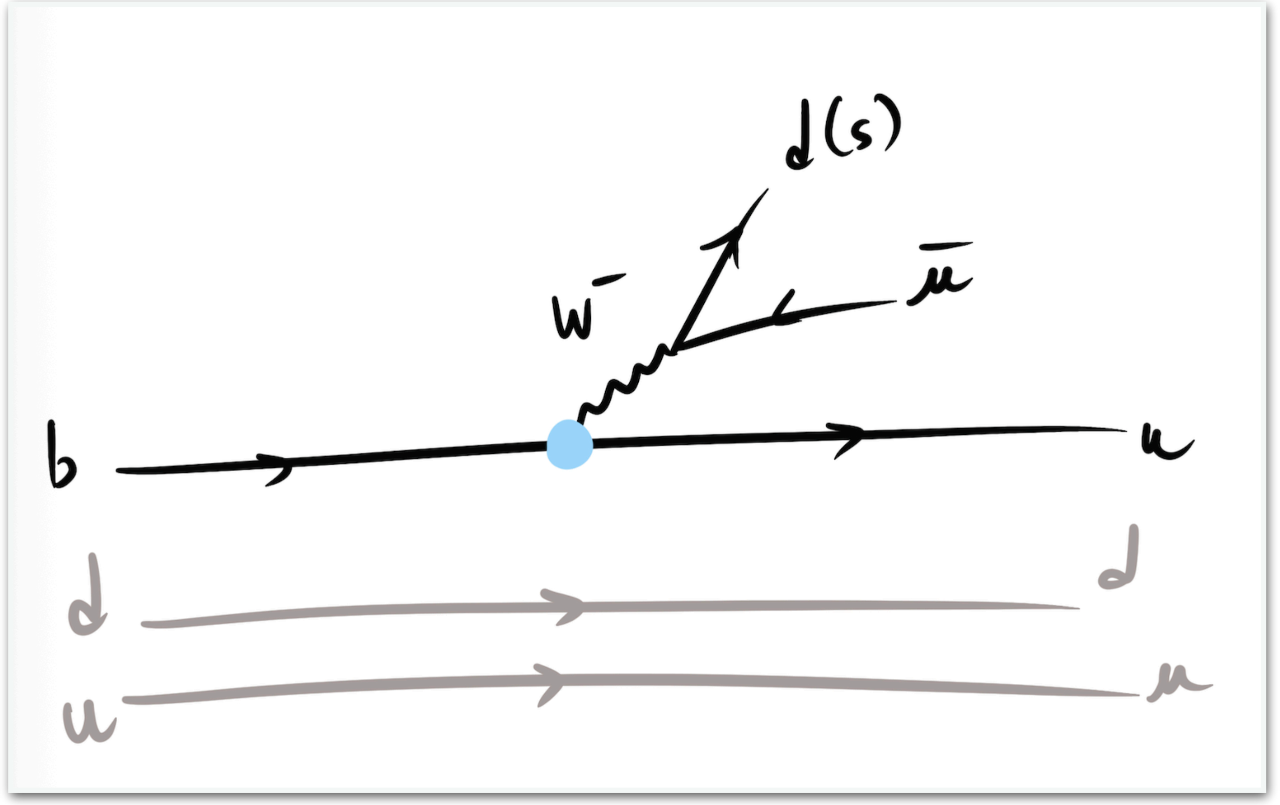
Flavour Changing Neutral Currents



Rule of thumb: you can’t access all the parameters at once
you have to pick your battles

CKM - matrix

Let’s consider this current



$\lambda = 0.22 \qquad A, |\rho + i\eta| = \mathcal{O}(1)$

$$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

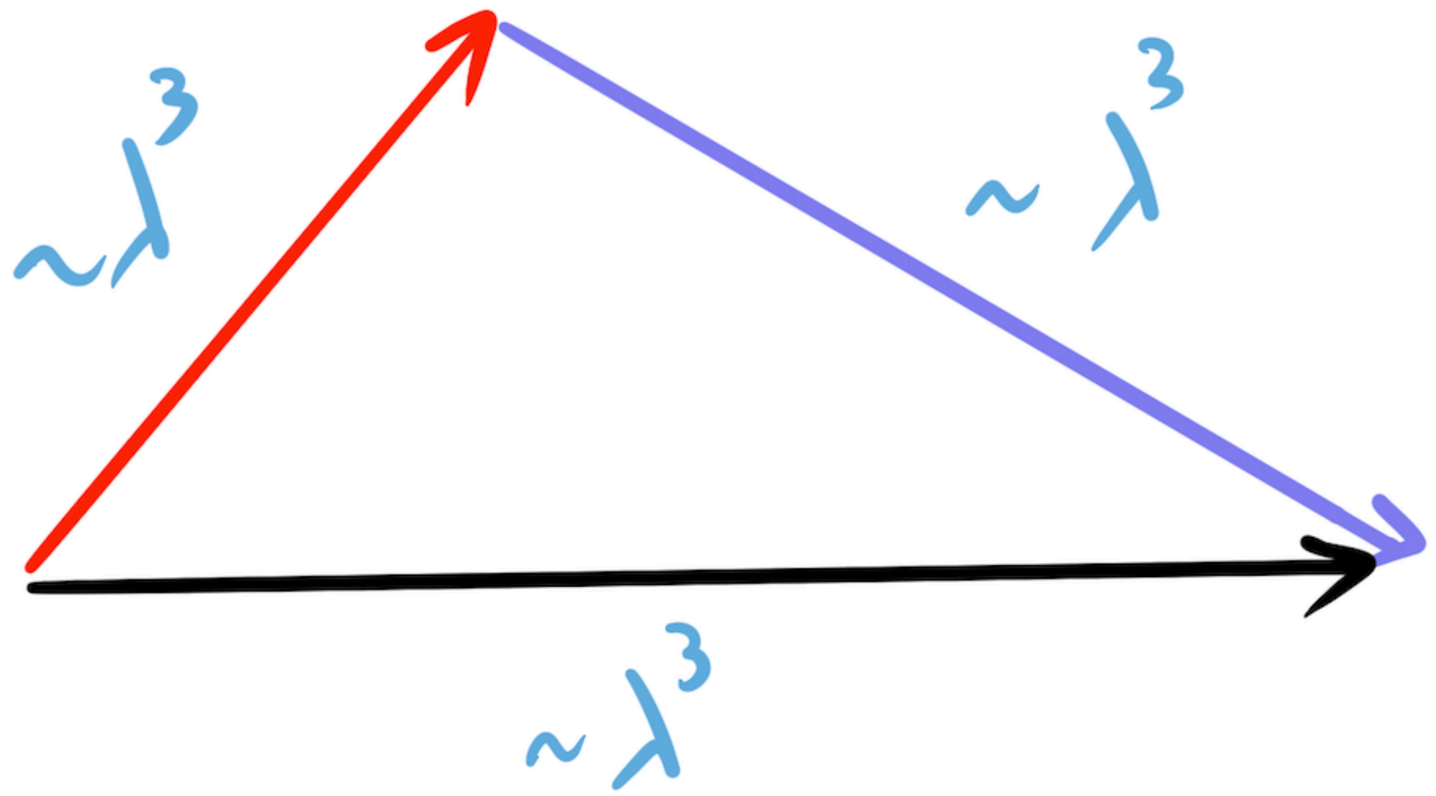
$$V_{CKM} \approx \begin{bmatrix} 1 - \lambda^2/2 & \lambda & \lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

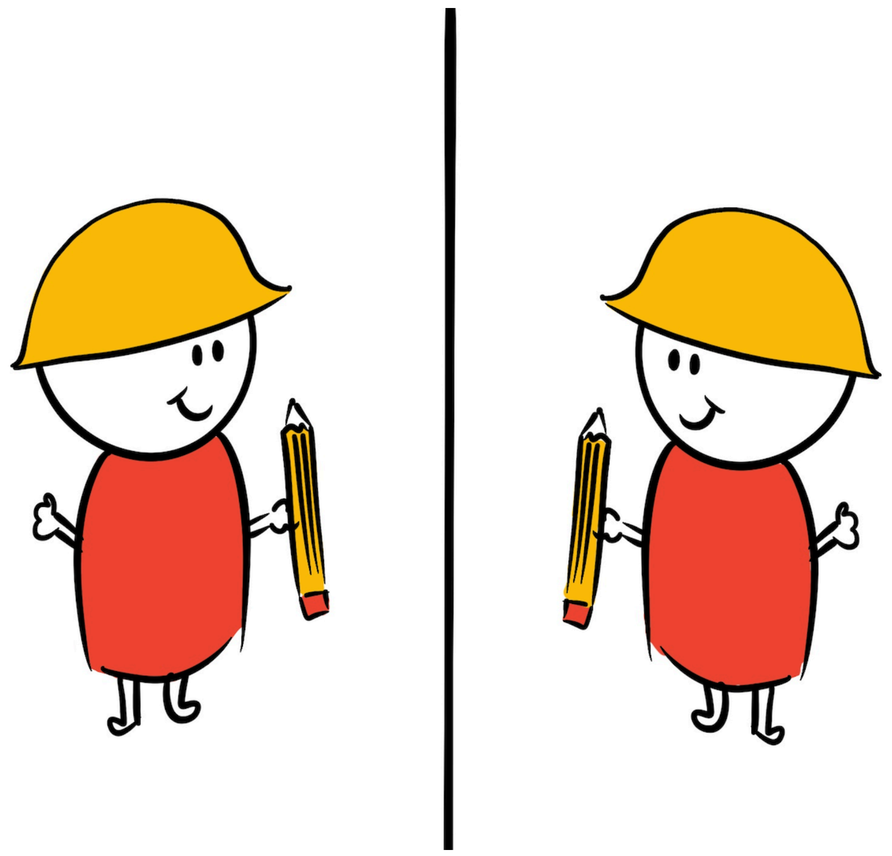
Wolfenstein parametrisation

CKM - matrix

$$\underline{V_{ub}^{*} V_{ud}} + \underline{V_{cb}^{*} V_{cb}} + \underline{V_{tb}^{*} V_{td}} = 0$$

$$(V^{\dagger} V)_{ij} = \delta_{ij} \qquad i = b,\ j = d$$





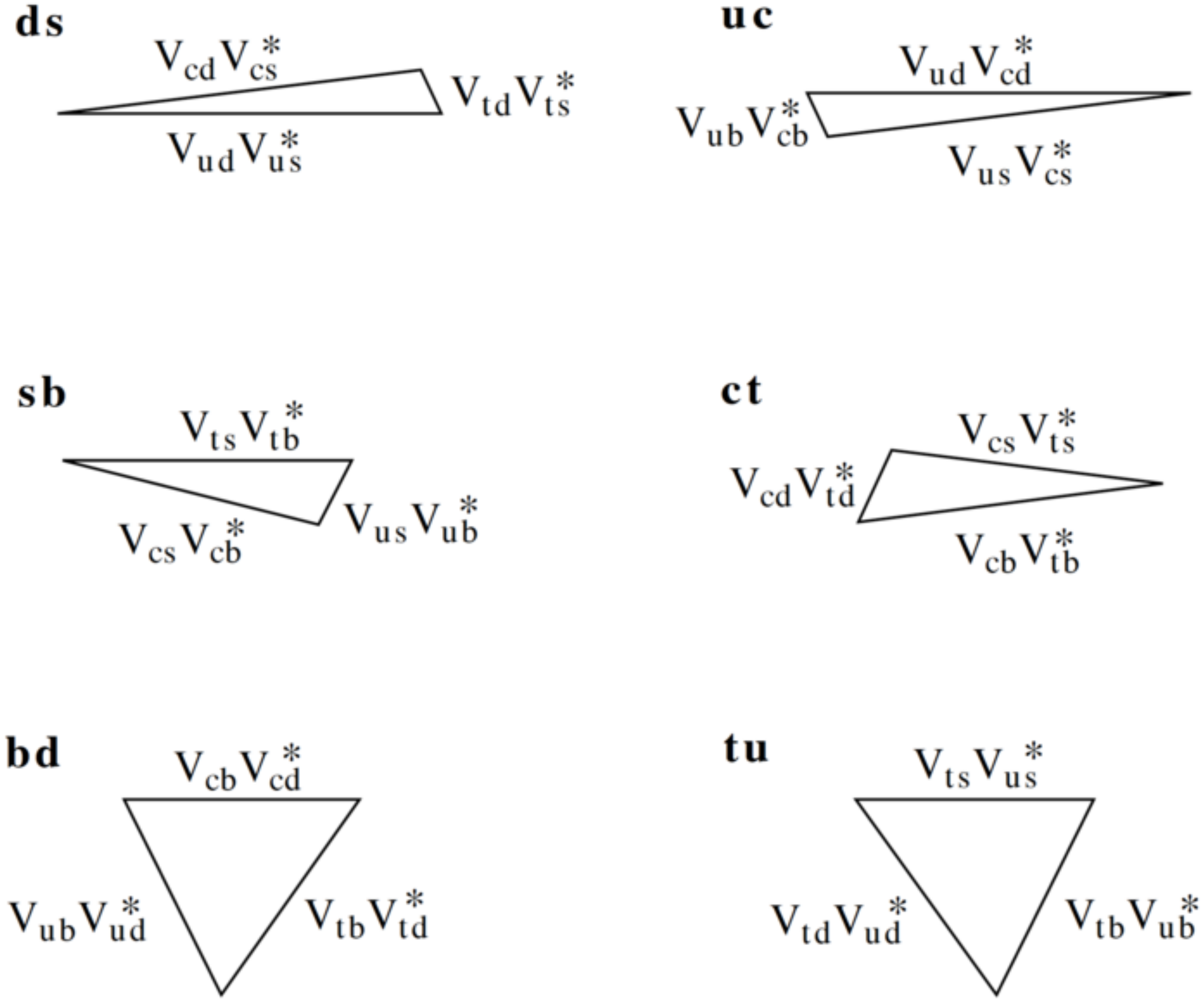
Building the unitarity triangles

The other triangles

The unitarity of the CKM matrix, $(VV^\dagger)_{ij} = (V^\dagger V)_{ij} = \delta_{ij}$, leads to twelve distinct complex relations among the matrix elements. The six relations with $i \neq j$ can be represented geometrically as triangles in the complex plane. Two of these,

$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0\,, \tag{13.35a}$$

$$V_{td}V^*_{ud} + V_{ts}V^*_{us} + V_{tb}V^*_{ub} = 0\,, \tag{13.35b}$$



$$\alpha \equiv \varphi_2 \equiv \arg\left(-\frac{V_{td}V^*_{tb}}{V_{ud}V^*_{ub}}\right) \simeq \arg\left(-\frac{1-\rho-i\eta}{\rho+i\eta}\right)\,,$$

$$\beta \equiv \varphi_1 \equiv \arg\left(-\frac{V_{cd}V^*_{cb}}{V_{td}V^*_{tb}}\right) \simeq \arg\left(\frac{1}{1-\rho-i\eta}\right)\,,$$

$$\gamma \equiv \varphi_3 \equiv \arg\left(-\frac{V_{ud}V^*_{ub}}{V_{cd}V^*_{cb}}\right) \simeq \arg\left(\rho+i\eta\right)\,.$$

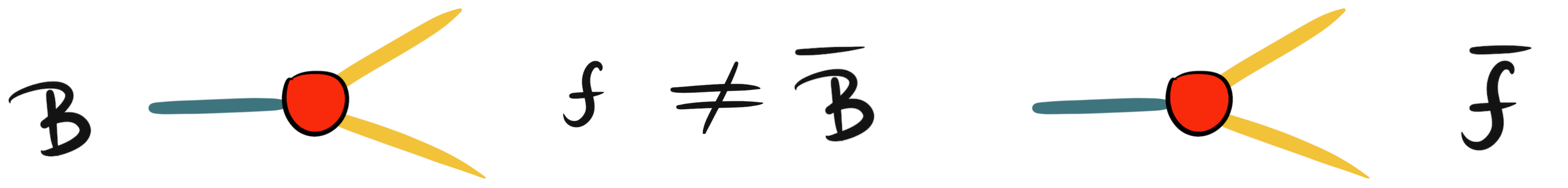
http://www.scholarpedia.org/article/Experimental_determination_of_the_CKM_matrix

CP Violation in Decay

- $\left| \frac{A_f}{\bar{A}_f} \right| \neq 1$

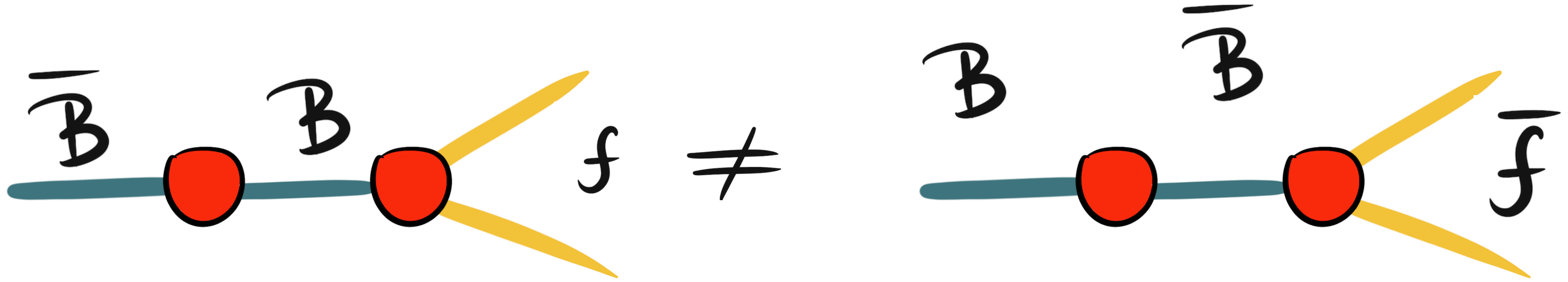
A_f Amplitude $B \to f$

$\bar{A}_f$ Amplitude $\bar{B} \to \bar{f}$



CP Violation in mixing

- $|q/p| \neq 1$

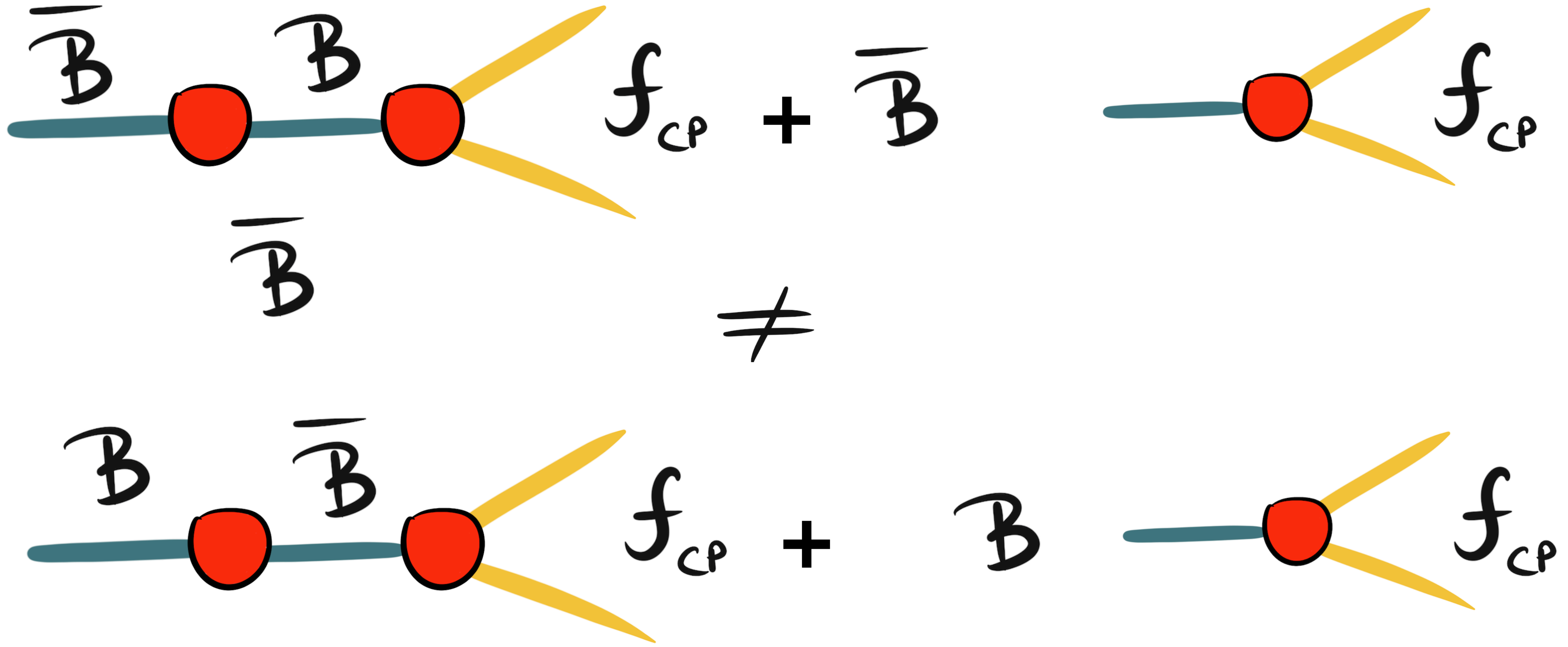


CP violation in the interference between mixing and decay

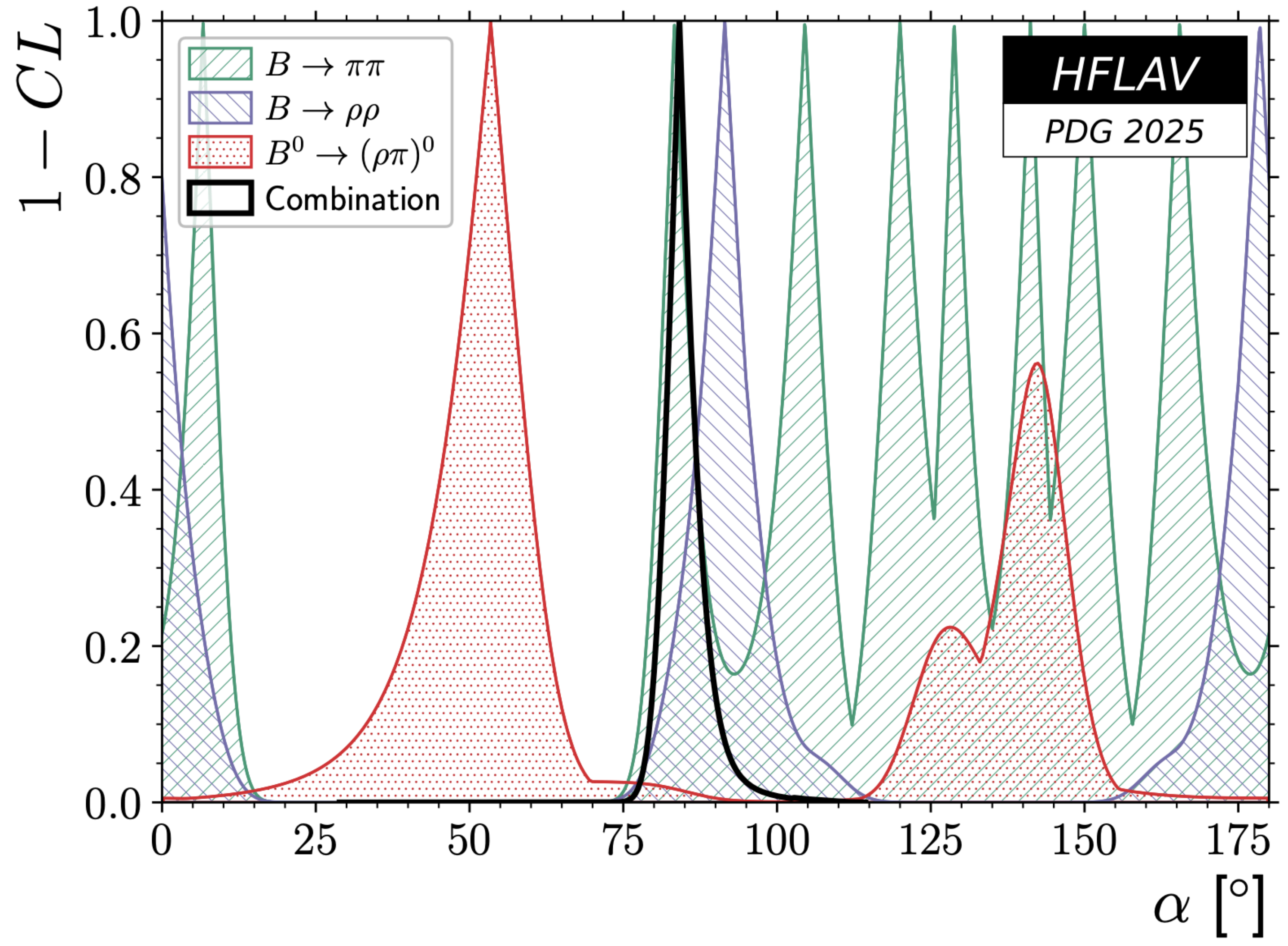
- $\mathrm{Im}(\lambda_f) = \mathrm{Im}\left(\frac{q}{p} \frac{\bar{A}_f}{A_f} \right) \neq 0$

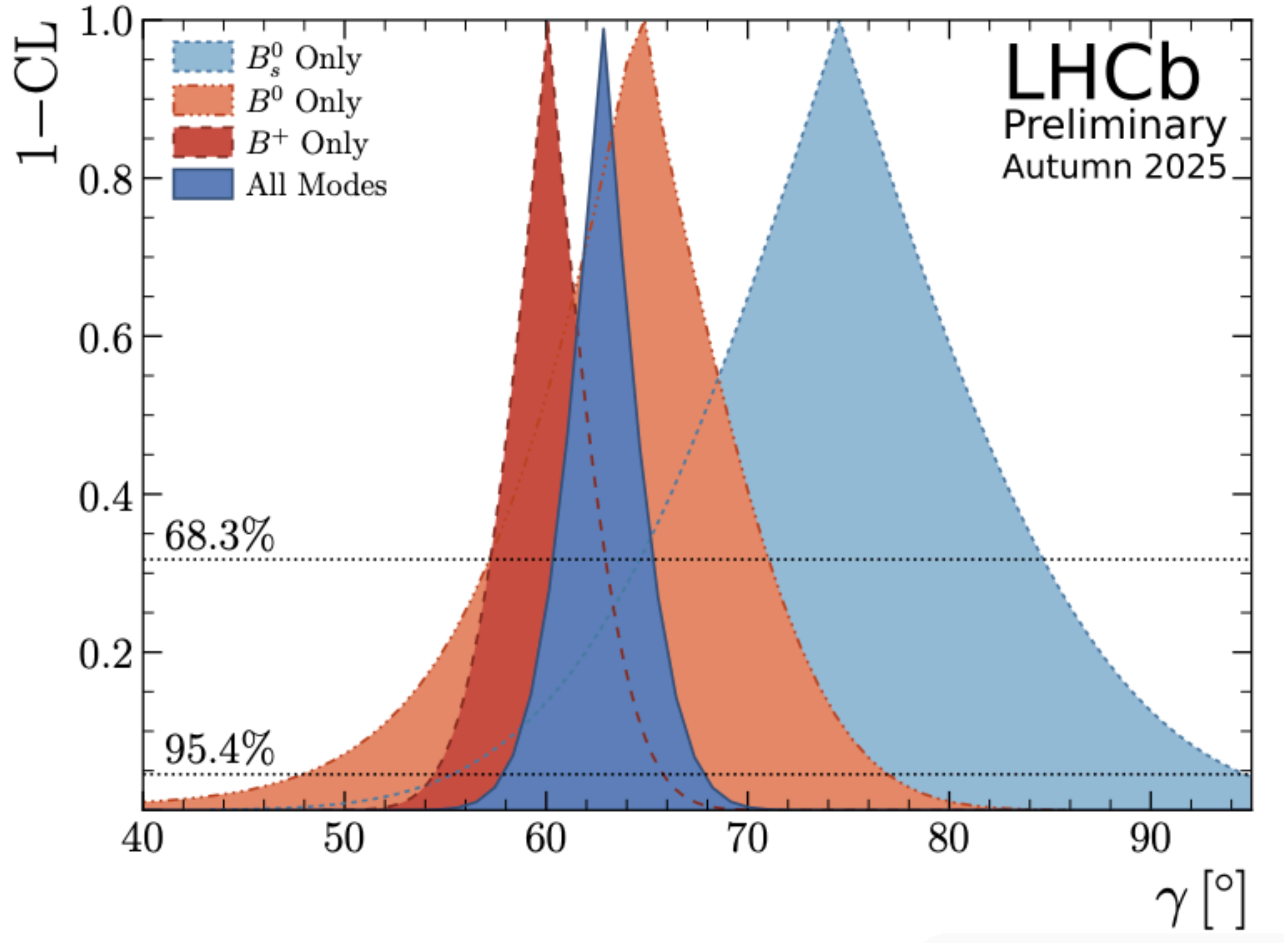
λ_f = parameter that quantifies CP violation

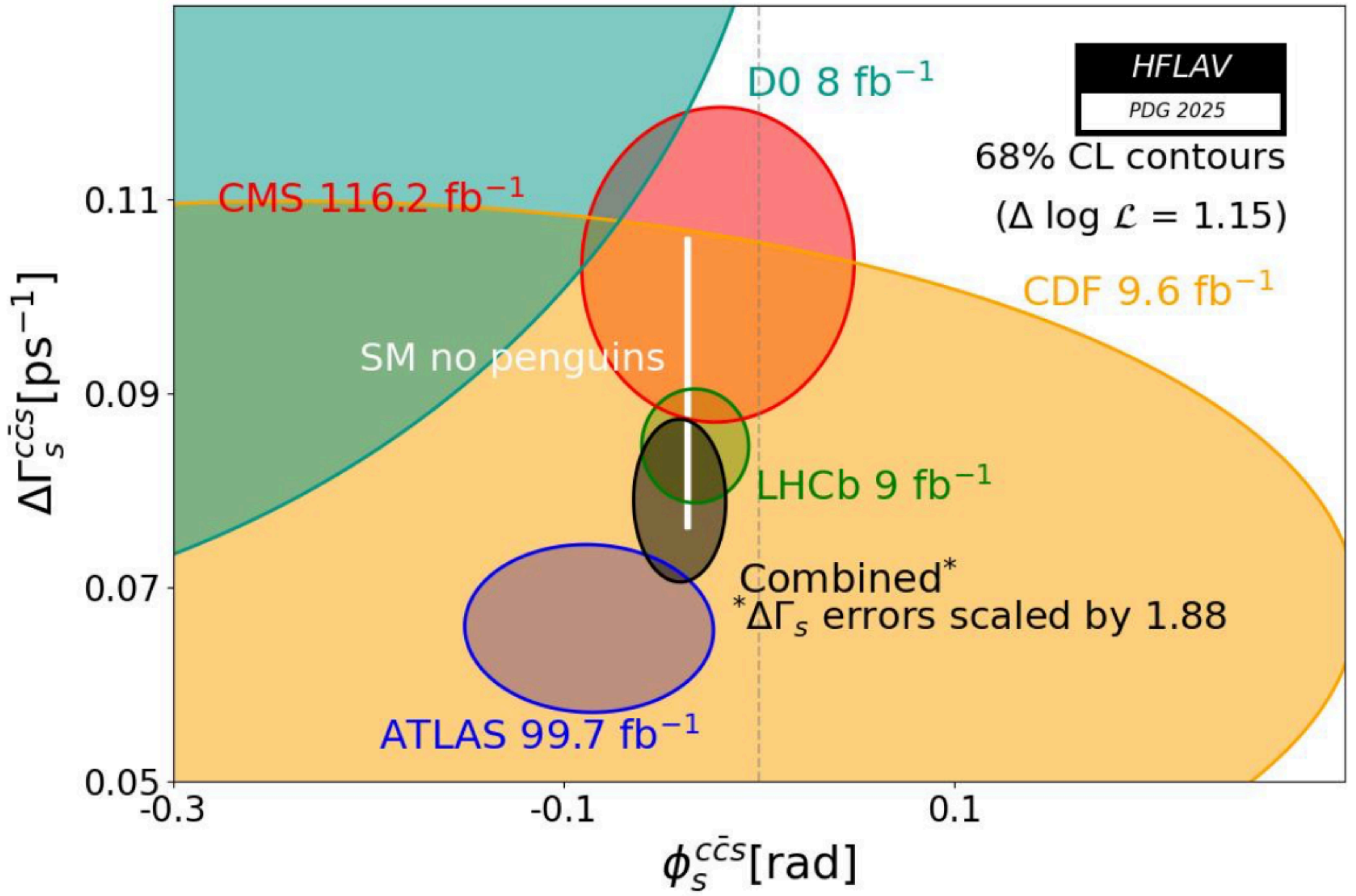
$CP|f_{cp}\rangle = \eta_f^{CP} |f_{cp}\rangle$ with $\eta_{cp} = \pm 1$



All the phases…Today



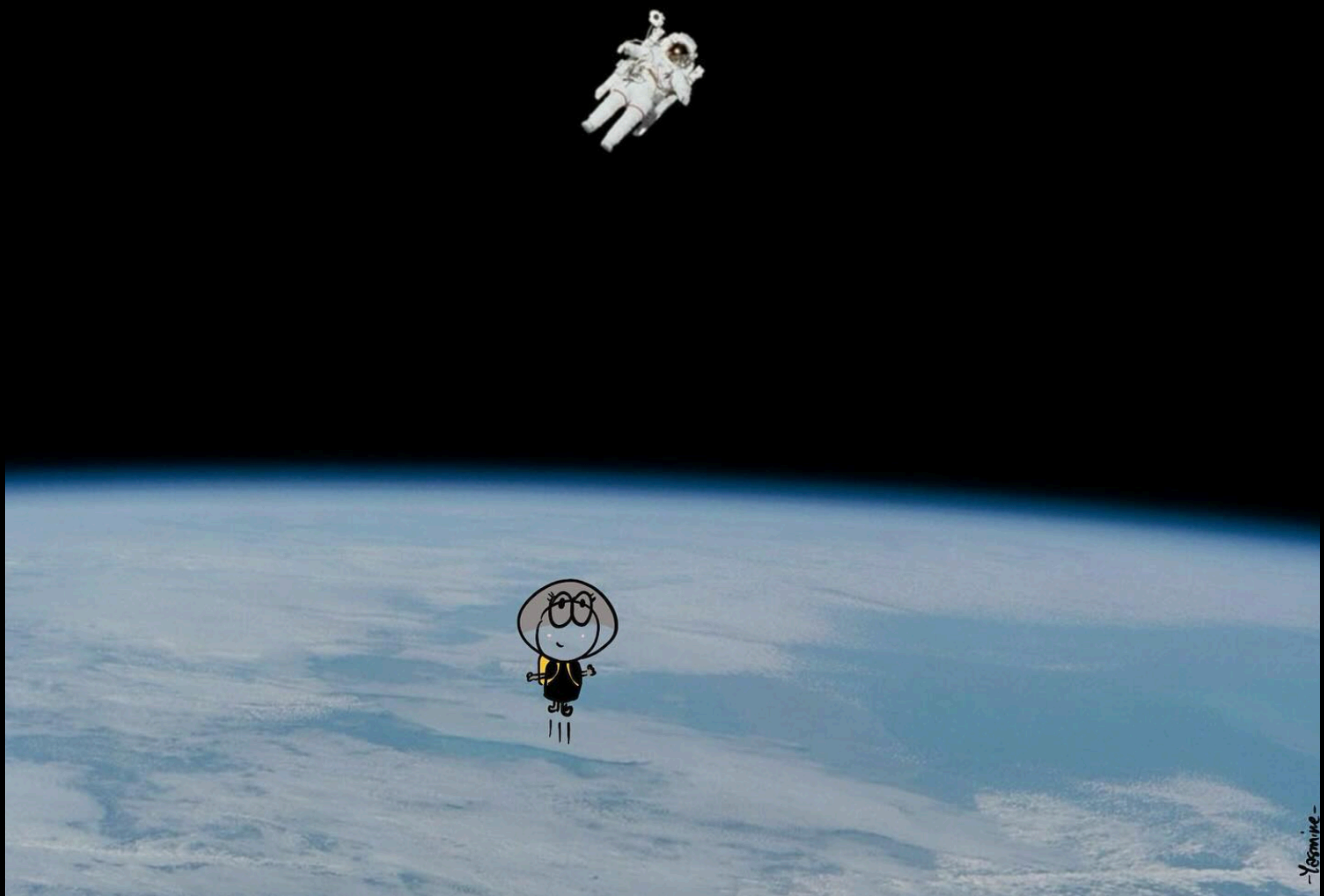




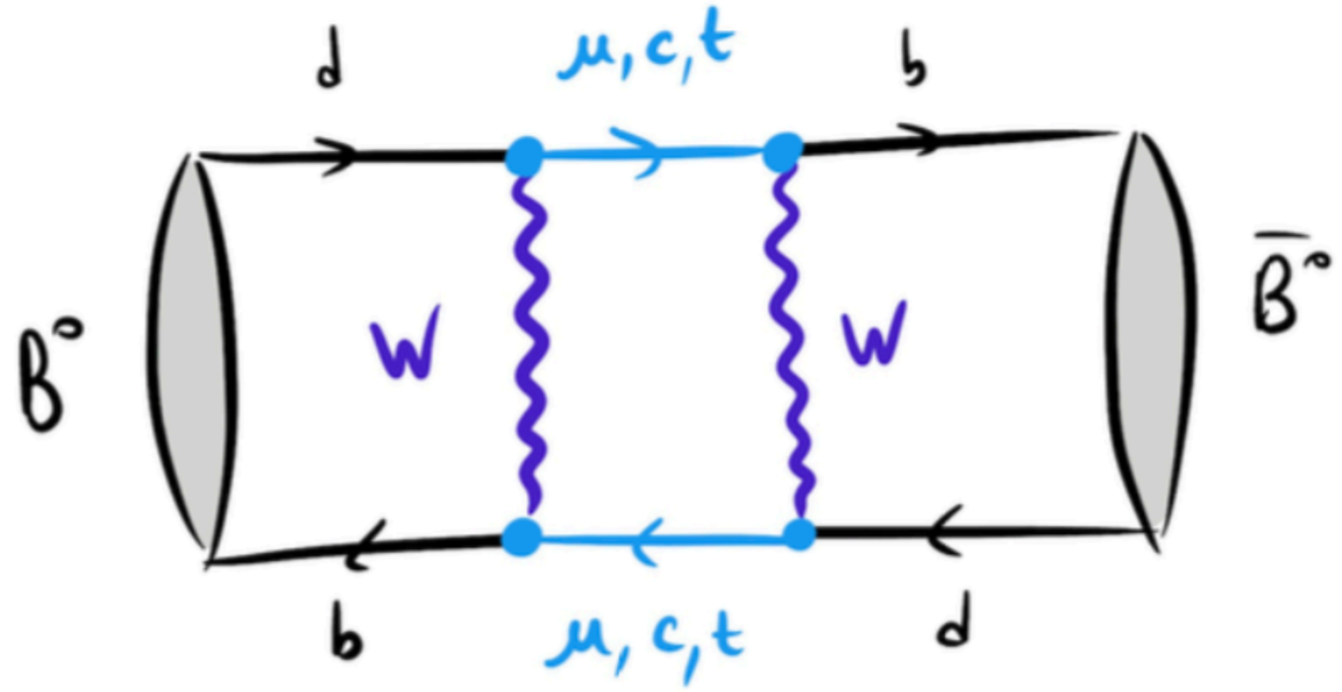
LHCb-CONF-2025-003

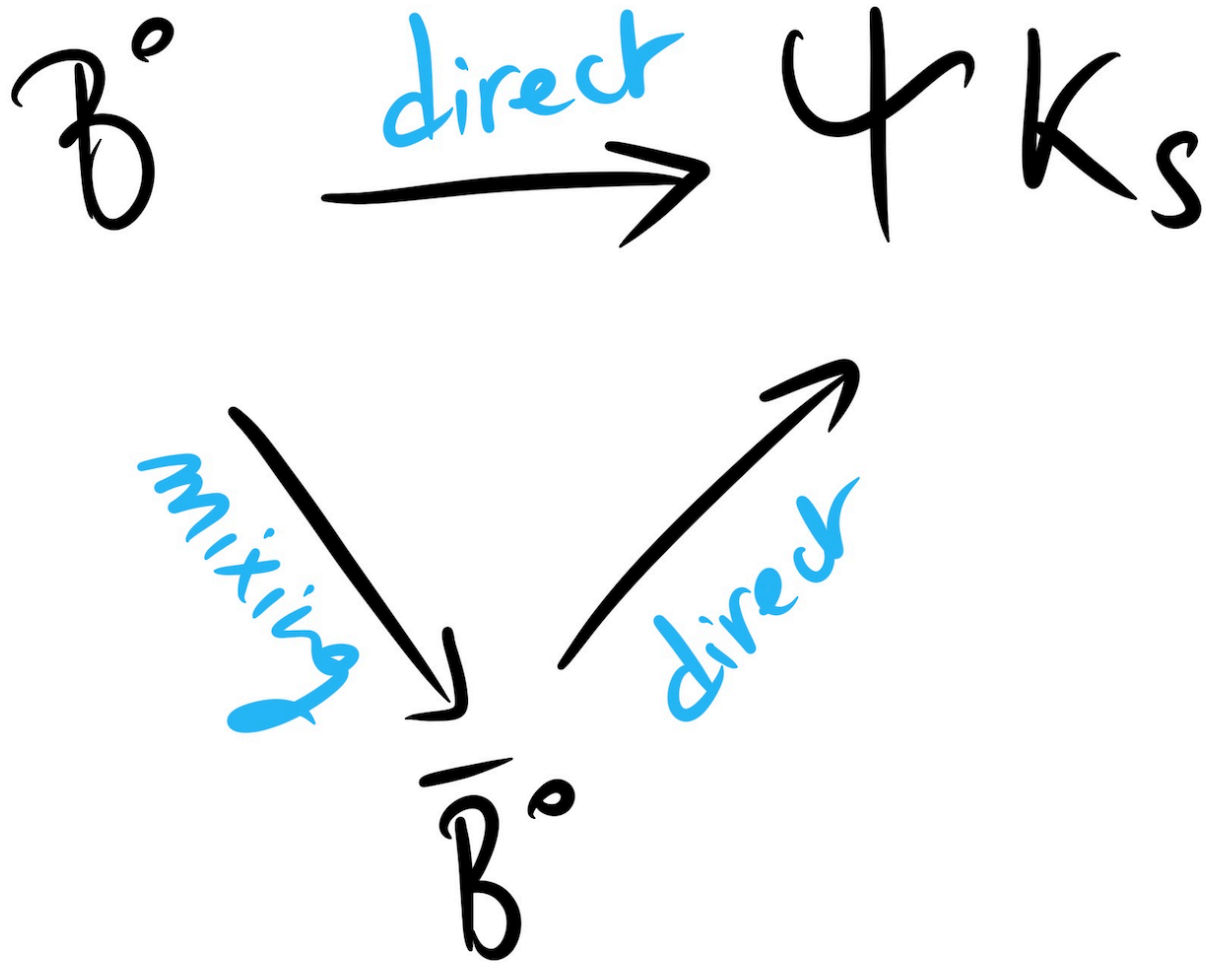
https://hflav-eos.web.cern.ch/hflav-eos/osc/PDG_2025/

Let’s dive in



Let's start with sin2beta with the "golden" mode $B^0 \to \psi(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$

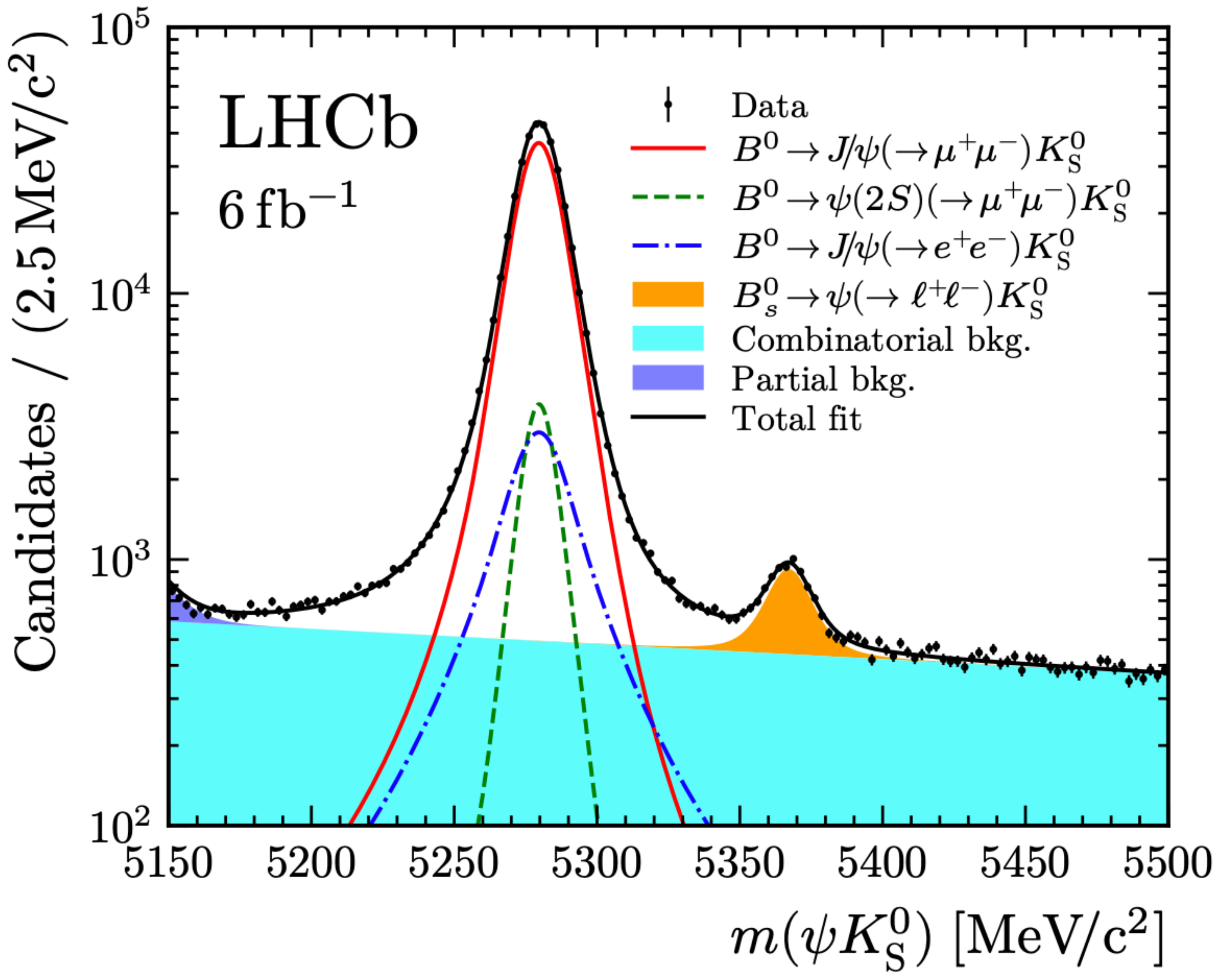




Time dependent analysis → requires flavour tagging

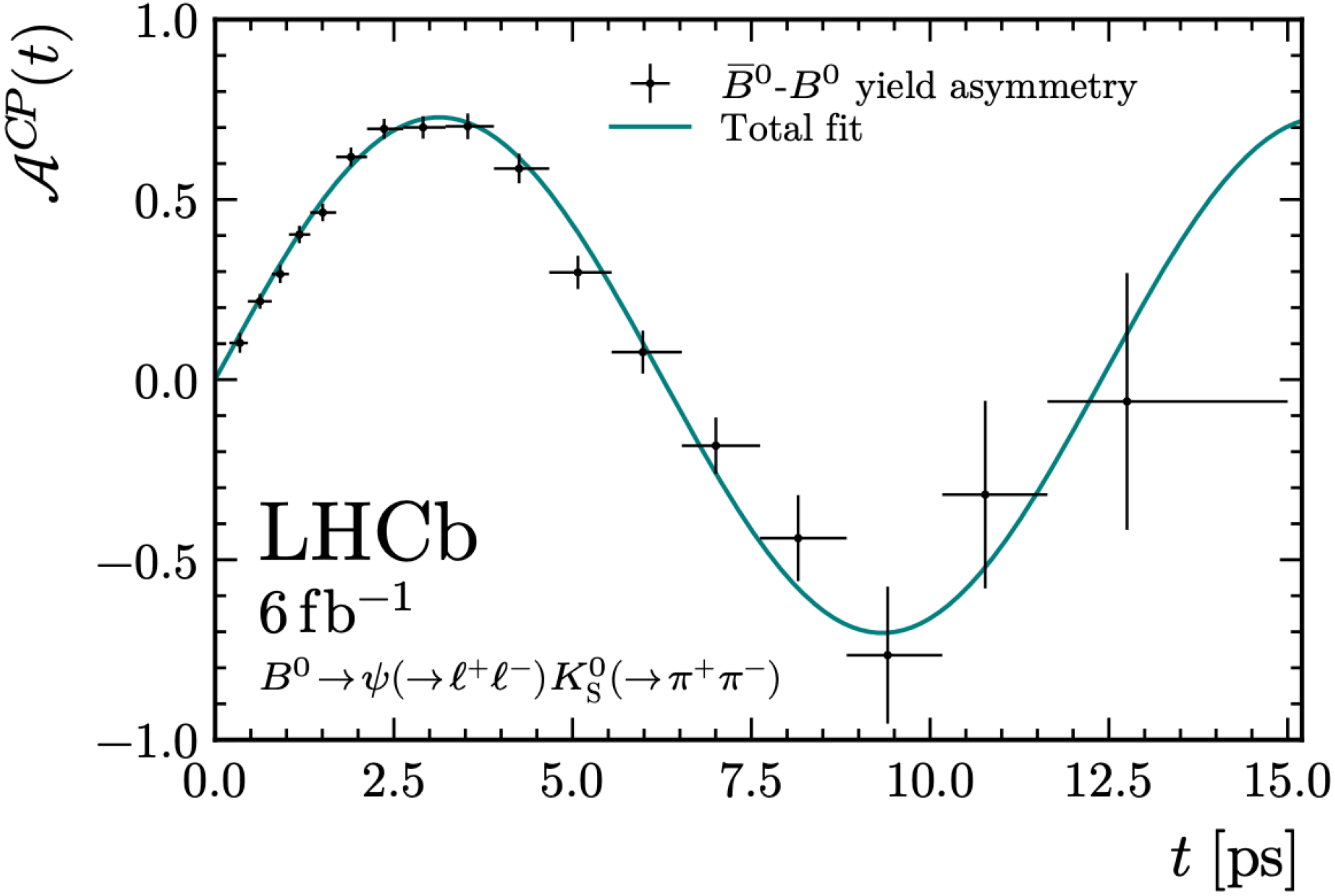
$$A^{CP}(t) = \frac{\Gamma(\bar{B}^0 \to \psi K_S) - \Gamma(B^0 \to \psi K_S)}{\Gamma(\bar{B}^0 \to \psi K_S) + \Gamma(B^0 \to \psi K_S)} \simeq \underbrace{D_{\Delta t}\, D_{FT}}_{\text{Experimental dilution}} S \sin(\Delta m_d t)$$

Text book like result !



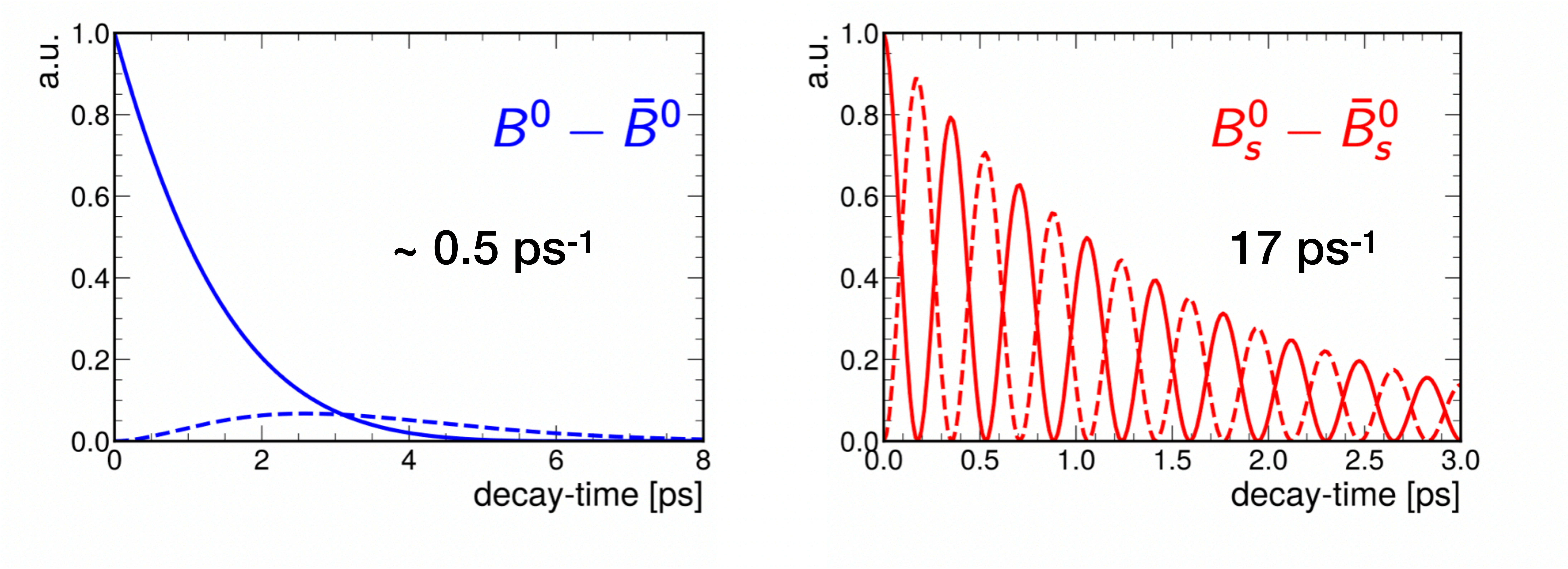
Trigger wise dilepton decays
are a day at the beach

Combination of a few decay channels



arXiv:2309.09728

It’s interesting to see what a “just” a difference in the spectator quark can do



$\sim 0.5\ \mathrm{ps}^{-1}$

$17\ \mathrm{ps}^{-1}$

An other fascinating topic is “simple” lifetime measurements.

A few lines about the mixing formalism

- $$i\frac{d}{dt}\begin{pmatrix}|B_q^0(t)\rangle\\ |\bar{B}_q^0(t)\rangle\end{pmatrix} = \mathcal{H}\begin{pmatrix}|B_q^0(t)\rangle\\ |\bar{B}_q^0(t)\rangle\end{pmatrix}$$

where $$\mathcal{H} = \left(M - \frac{i}{2}\Gamma\right) = \begin{pmatrix}M_{11} & M_{12}\\ M_{12}^* & M_{22}\end{pmatrix} - \frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma_{12}^* & \Gamma_{22}\end{pmatrix}$$

Mass Matrix

Dispersive

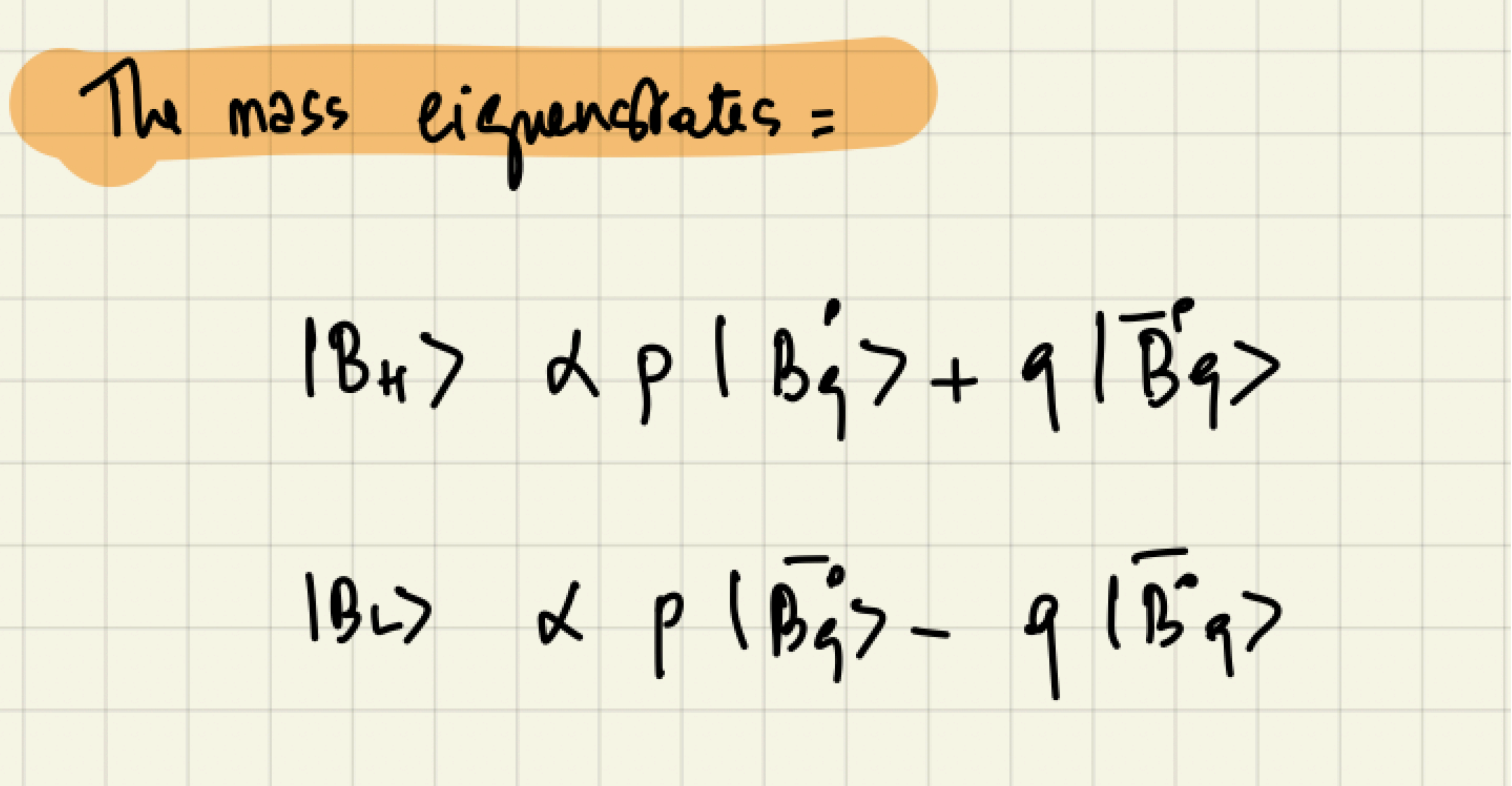
Decay Matrix

Absorptive

$M = M^\dagger$ and $\Gamma = \Gamma^\dagger$, CPT $\Rightarrow M_{11} = M_{22} = m_q$ and $\Gamma_{11} = \Gamma_{22} = \Gamma_q$

in case of mixing: M_{12} and Γ_{12} are non-zero

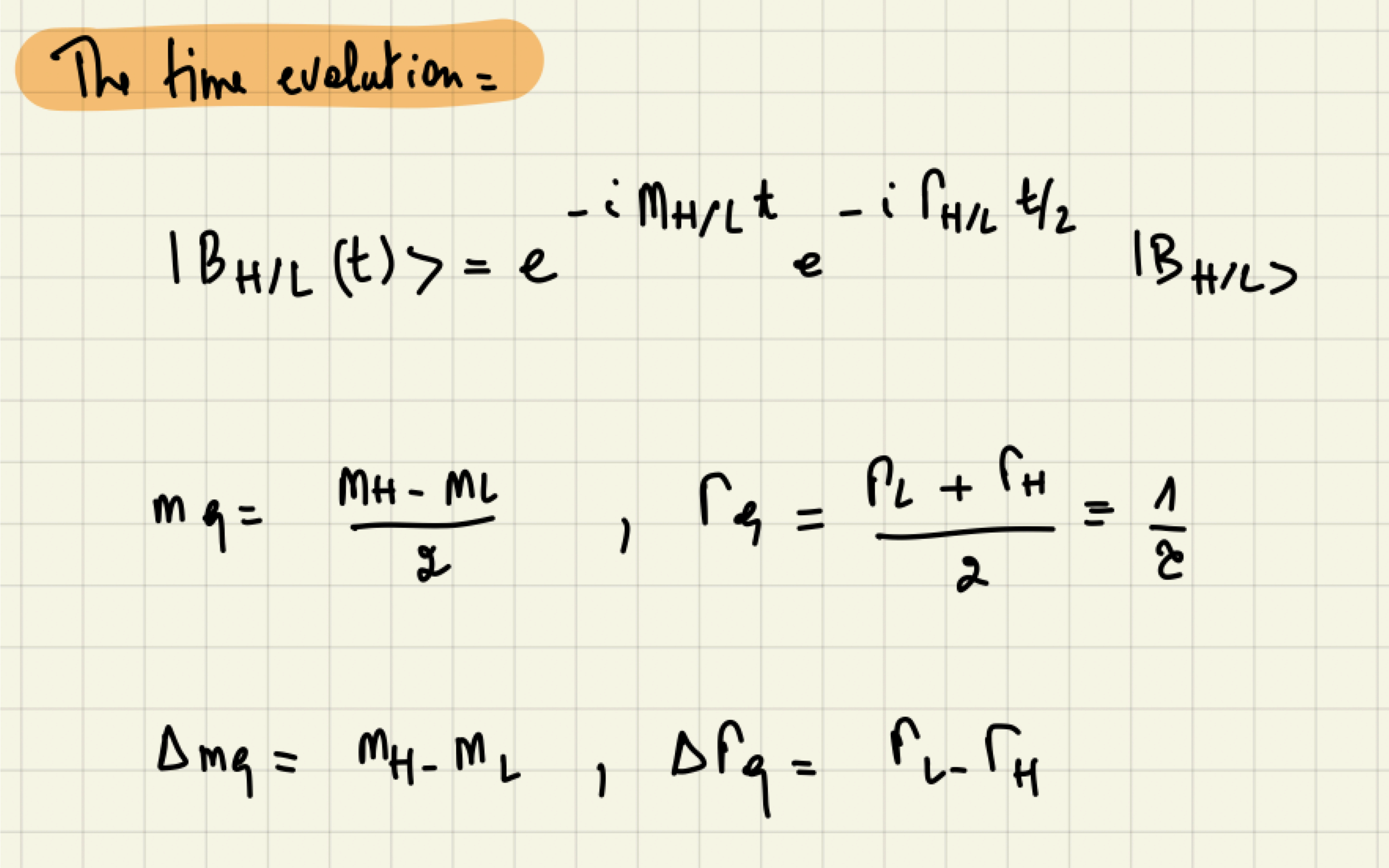
A few lines about the mixing formalism



The mass eigenstates :

$$|B_H\rangle \propto p|B_q^0\rangle + q|\bar{B}_q^0\rangle$$

$$|B_L\rangle \propto p|\bar{B}_q^0\rangle - q|\bar{B}_q^0\rangle$$



The time evolution :

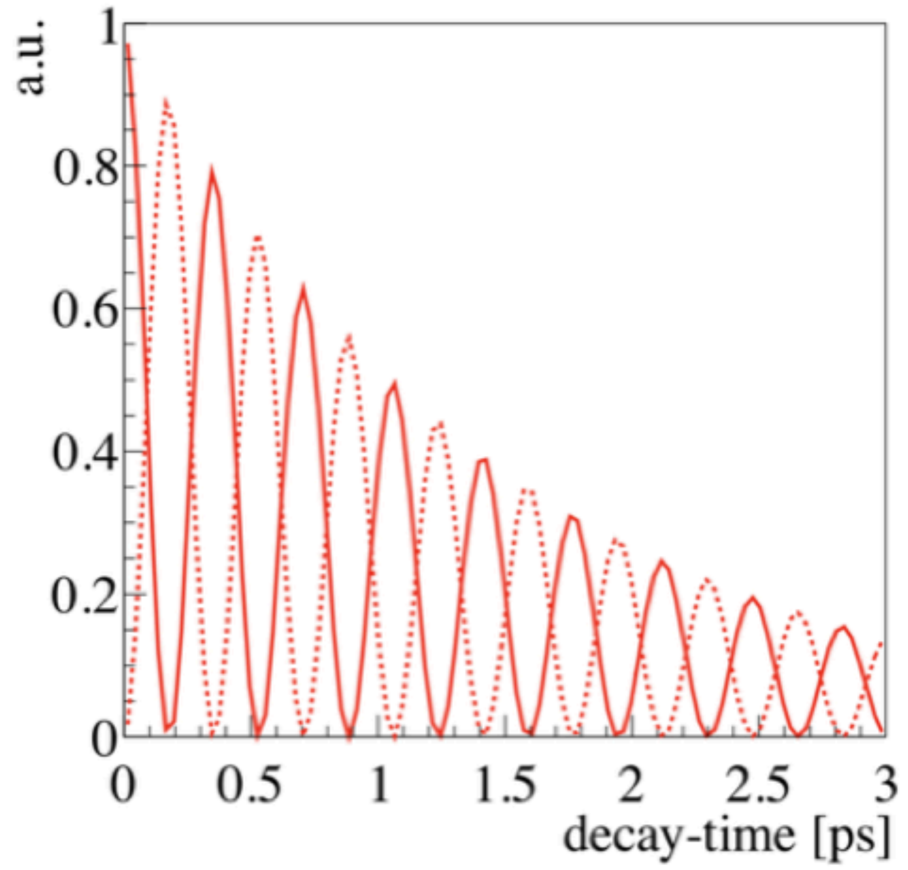
$$|B_{H/L}(t)\rangle = e^{-i m_{H/L} t} e^{-i \Gamma_{H/L} t/2} |B_{H/L}\rangle$$

$$m_q = \frac{m_H - m_L}{2} , \quad \Gamma_q = \frac{\Gamma_L + \Gamma_H}{2} = \frac{1}{\tau}$$

$$\Delta m_q = m_H - m_L , \quad \Delta\Gamma_q = \Gamma_L - \Gamma_H$$

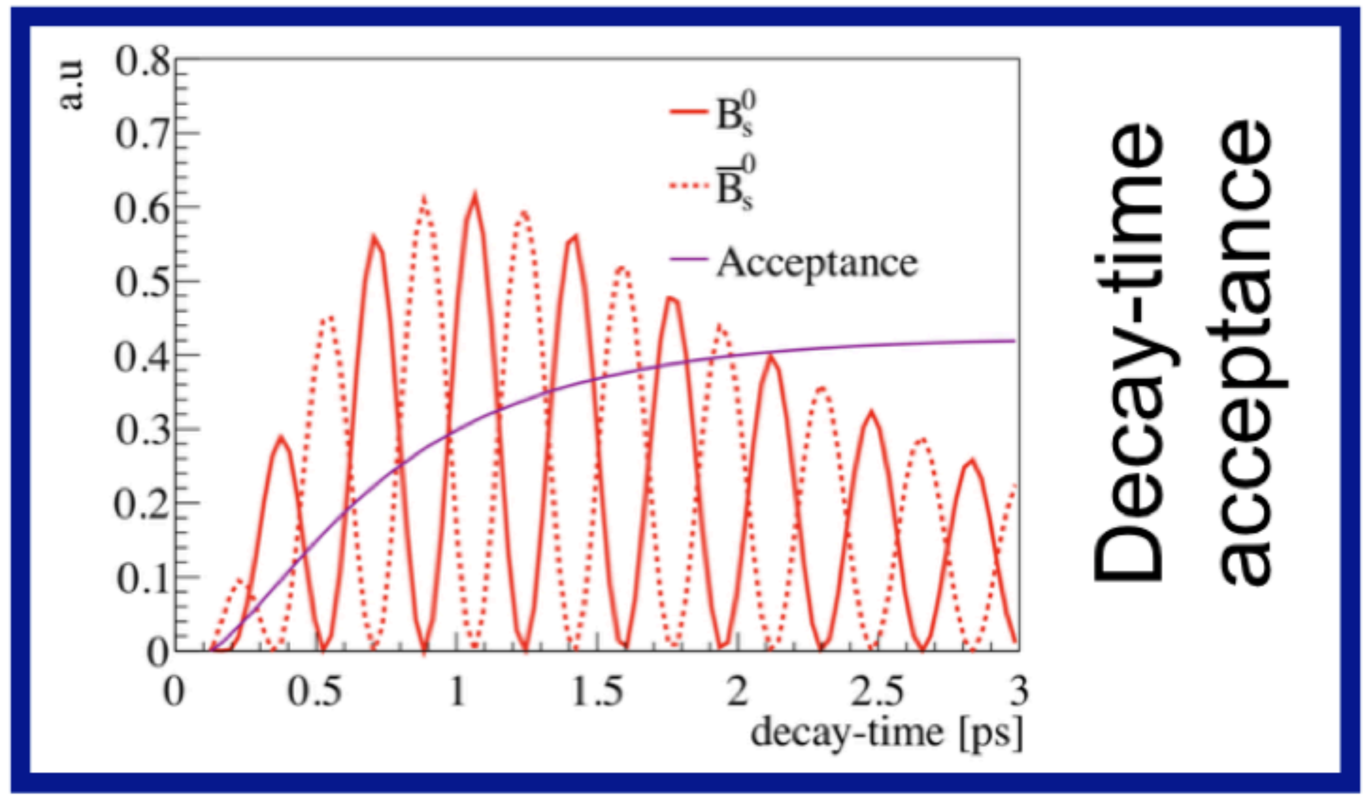
CERN-THESIS-2014-361 a very pedagogical reference.

Perfect

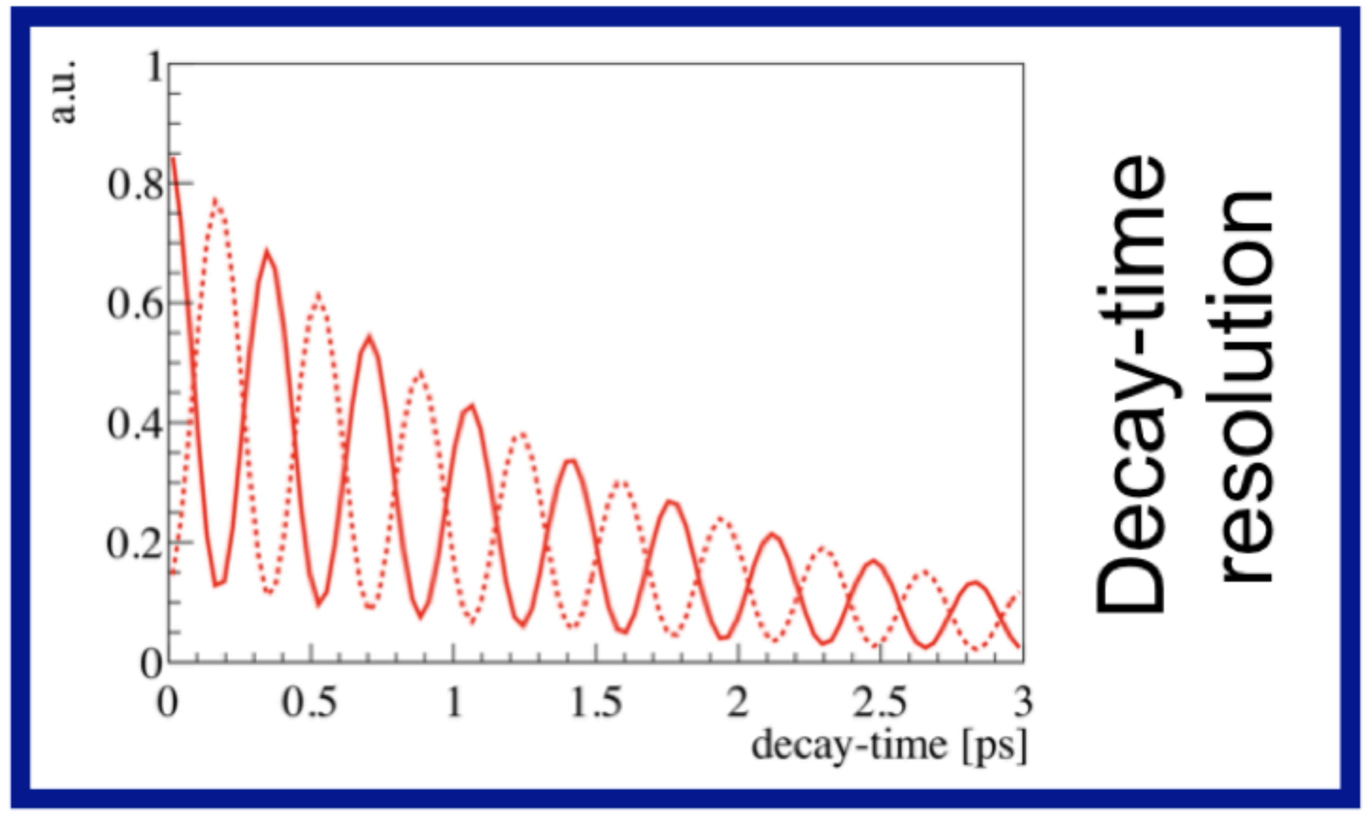


$$P(t) \sim e^{-\Gamma_s t}(\cosh(\frac{\Delta\Gamma_s t}{2}) \pm \cos(\Delta m_s t))$$

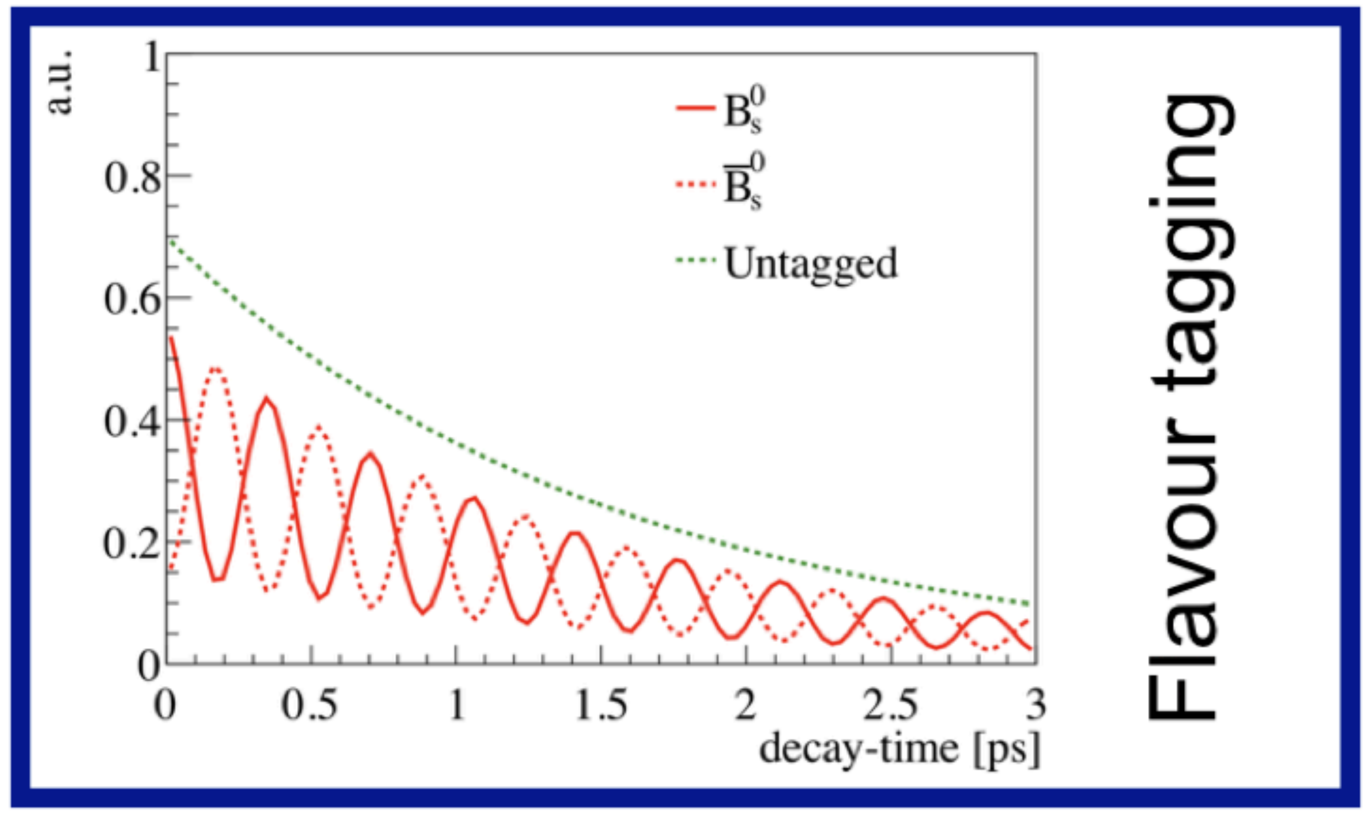
Detector effects



Decay-time acceptance

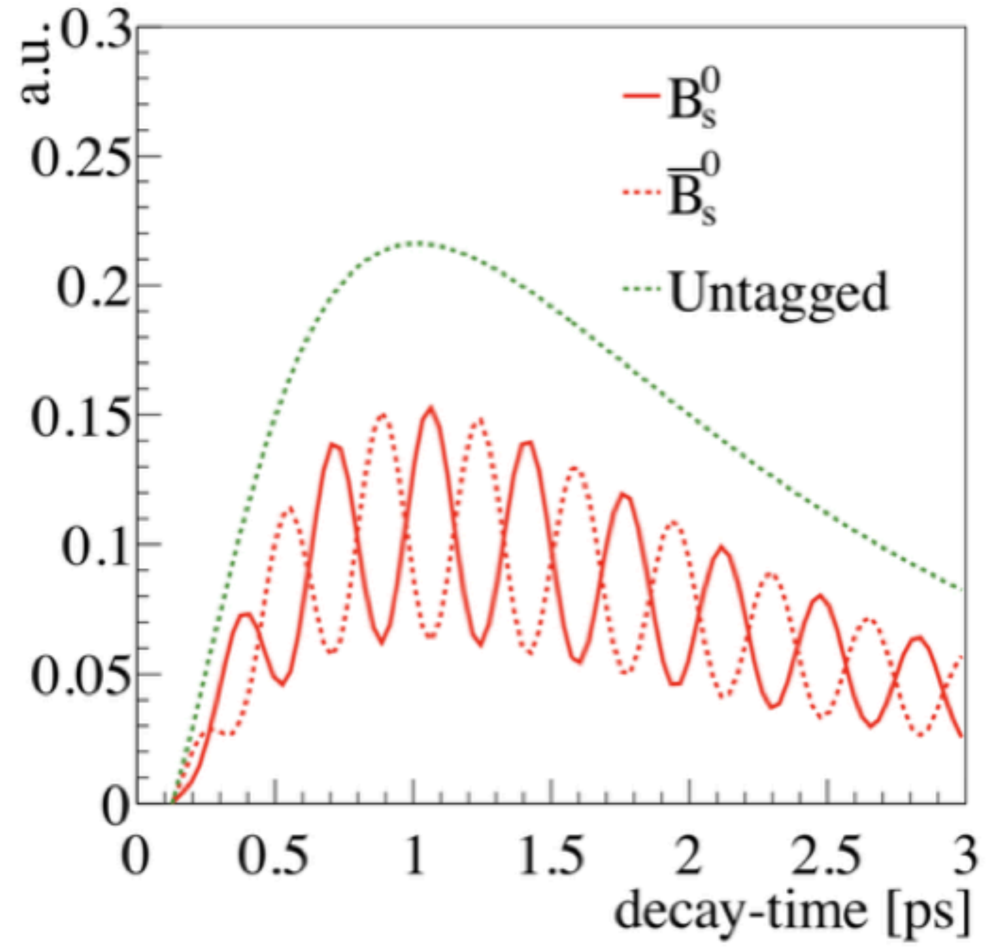


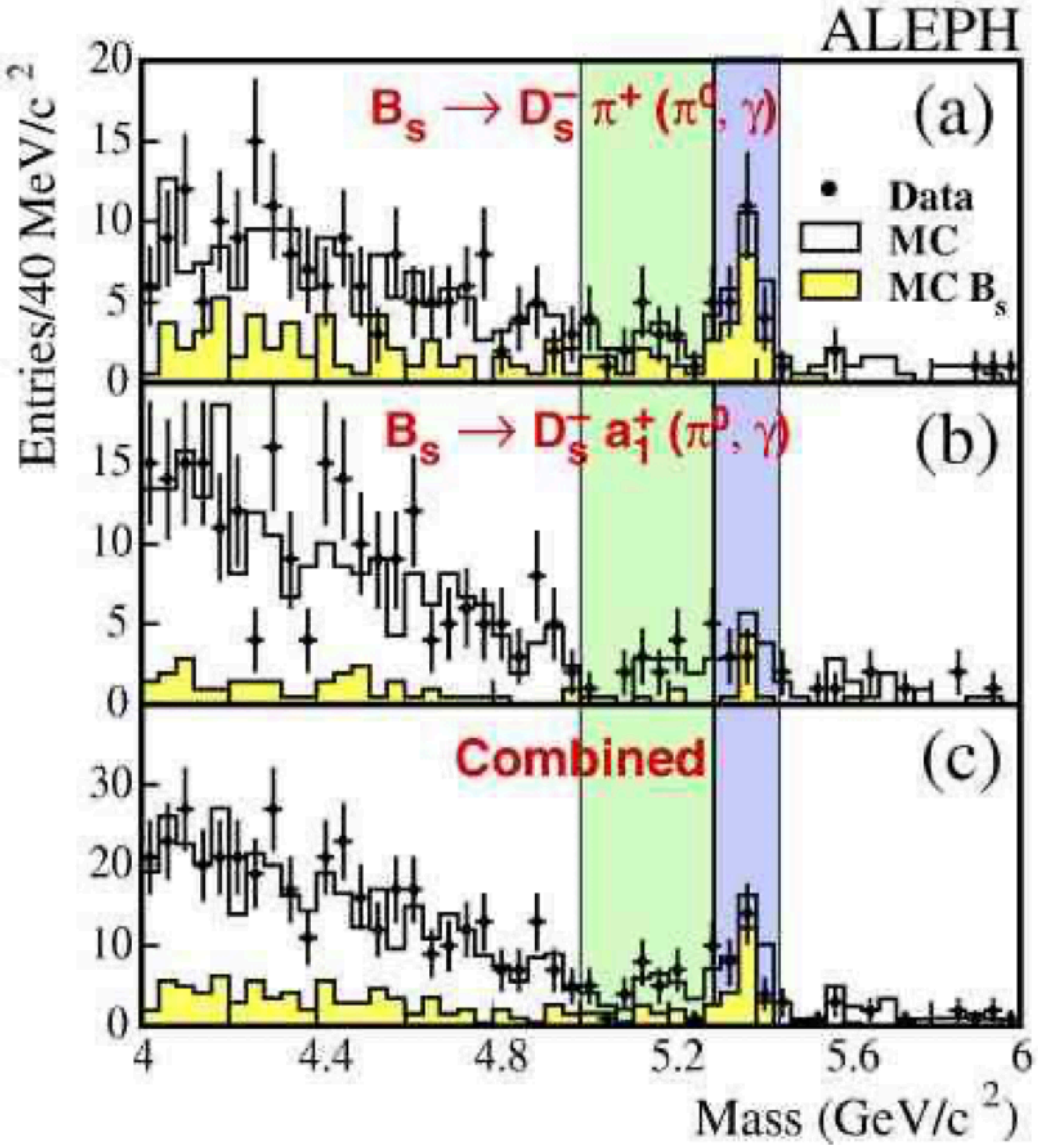
Decay-time resolution



Flavour tagging

Data





arXiv:0209007

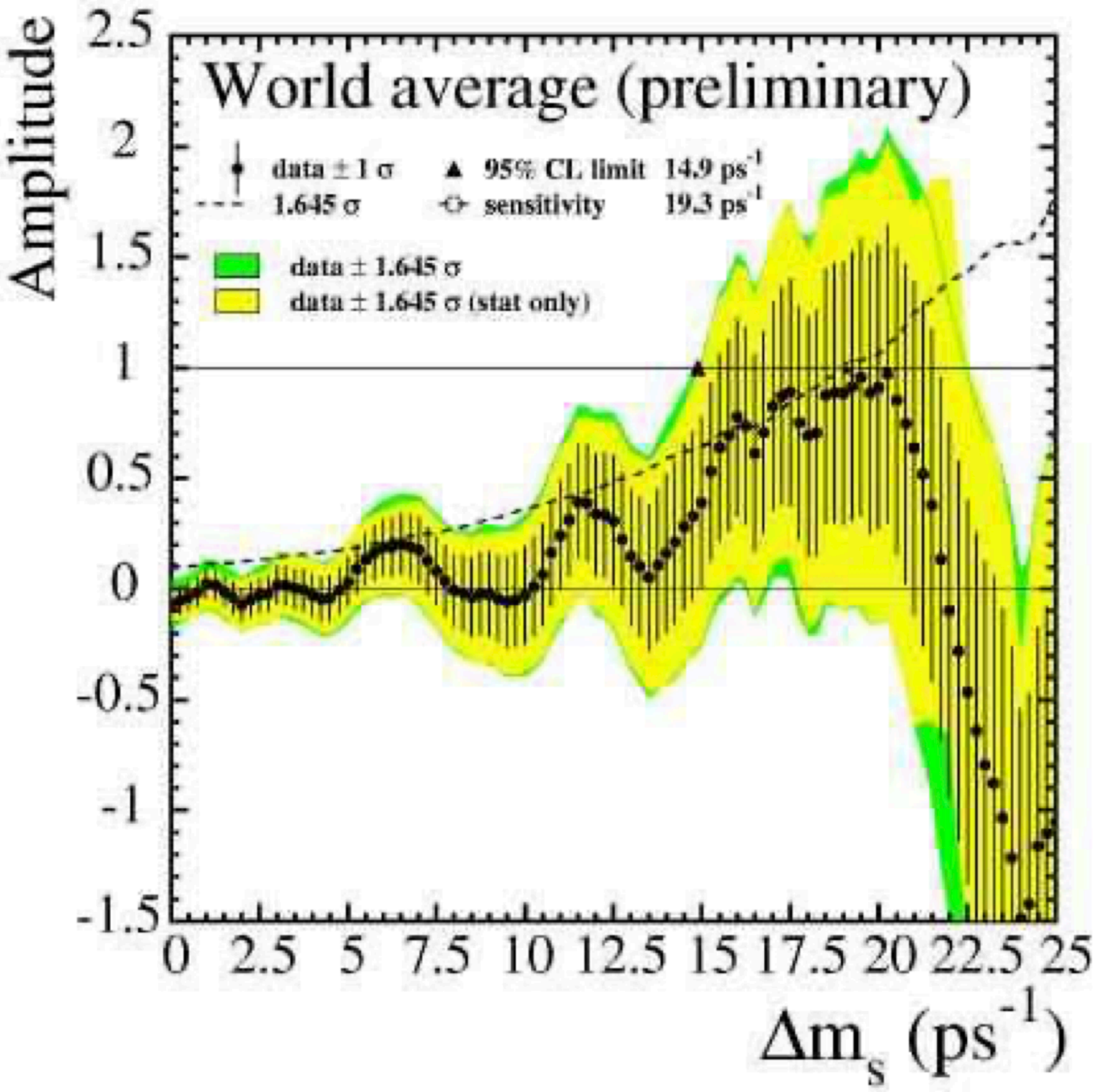
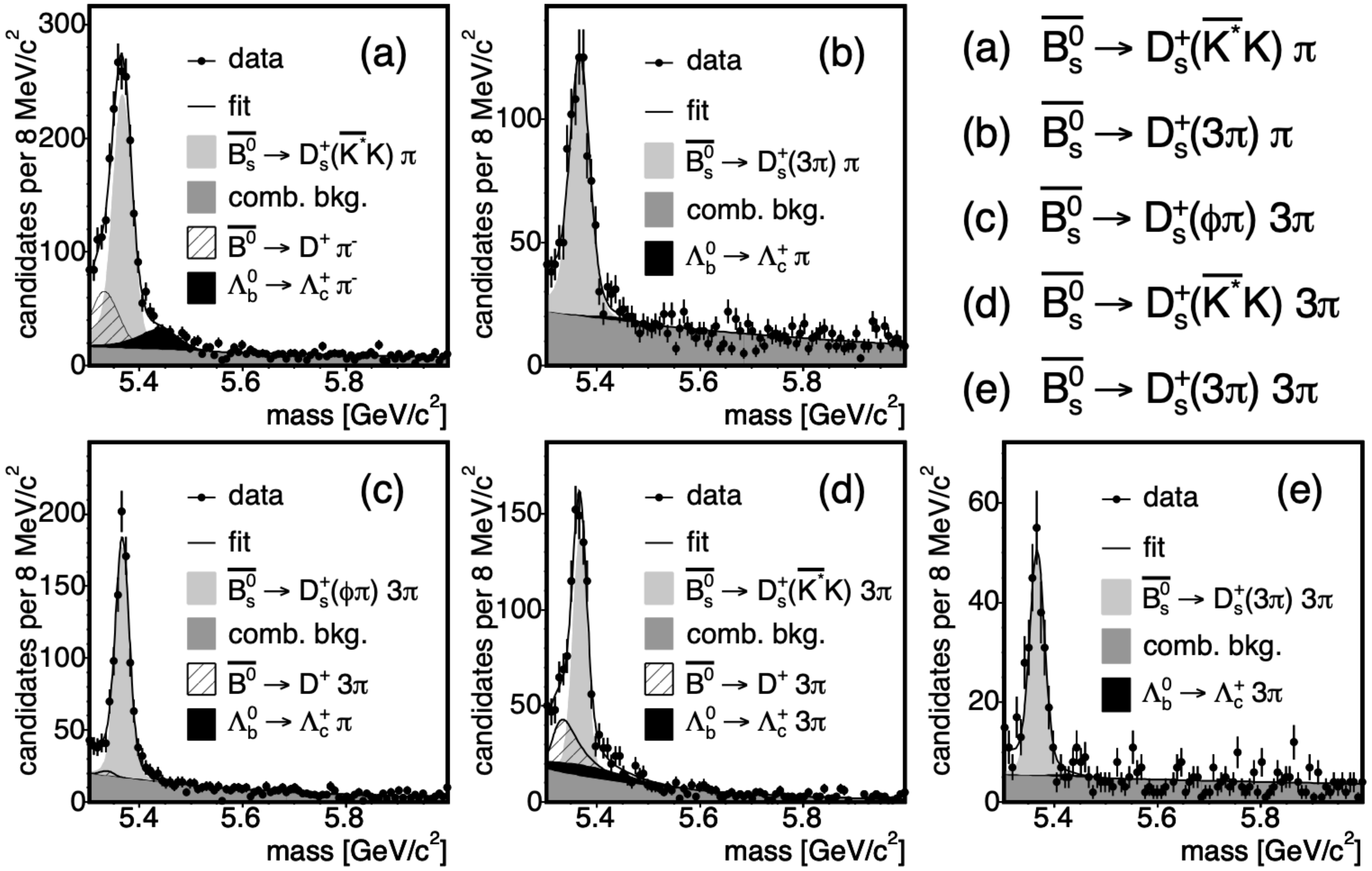


Figure 7: The combined B_s^0 oscillation results from ALEPH, CDF, DELPHI, OPAL, and SLD shown as amplitude versus hypothesized Δm_s [11]. The dots with error bars show the fitted aplitude values and uncertainties. An observed (expected) 95% C.L. lower limit on Δm_s of 14.9 ps^{-1} (19.3 ps^{-1}) is obtained.

My personal end of the universe at the time



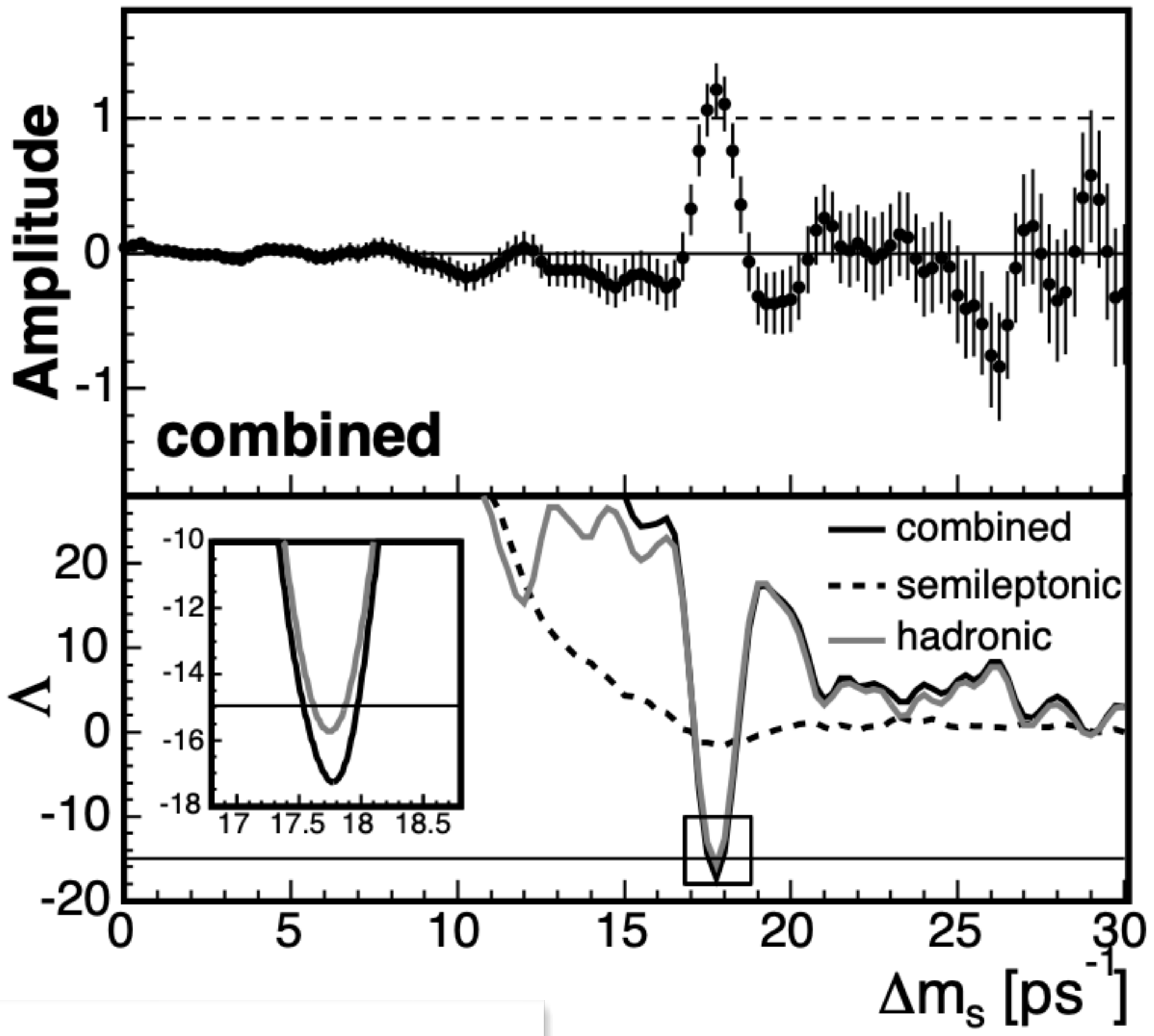
(a) $\overline{B^0_s} \to D_s^+(\overline{K^*}K)\,\pi$

(b) $\overline{B^0_s} \to D_s^+(3\pi)\,\pi$

(c) $\overline{B^0_s} \to D_s^+(\phi\pi)\,3\pi$

(d) $\overline{B^0_s} \to D_s^+(\overline{K^*}K)\,3\pi$

(e) $\overline{B^0_s} \to D_s^+(3\pi)\,3\pi$



arXiv:hep-ex/0609040v1 22 Sep 2006

Observation of B^0_s-$\bar{B}^0_s$ Oscillations

A. Abulencia,[23] J. Adelman,[13] T. Affolder,[10] T. Akimoto,[55] M.G. Albrow,[16] D. Ambrose,[16] S. Amerio,[43]
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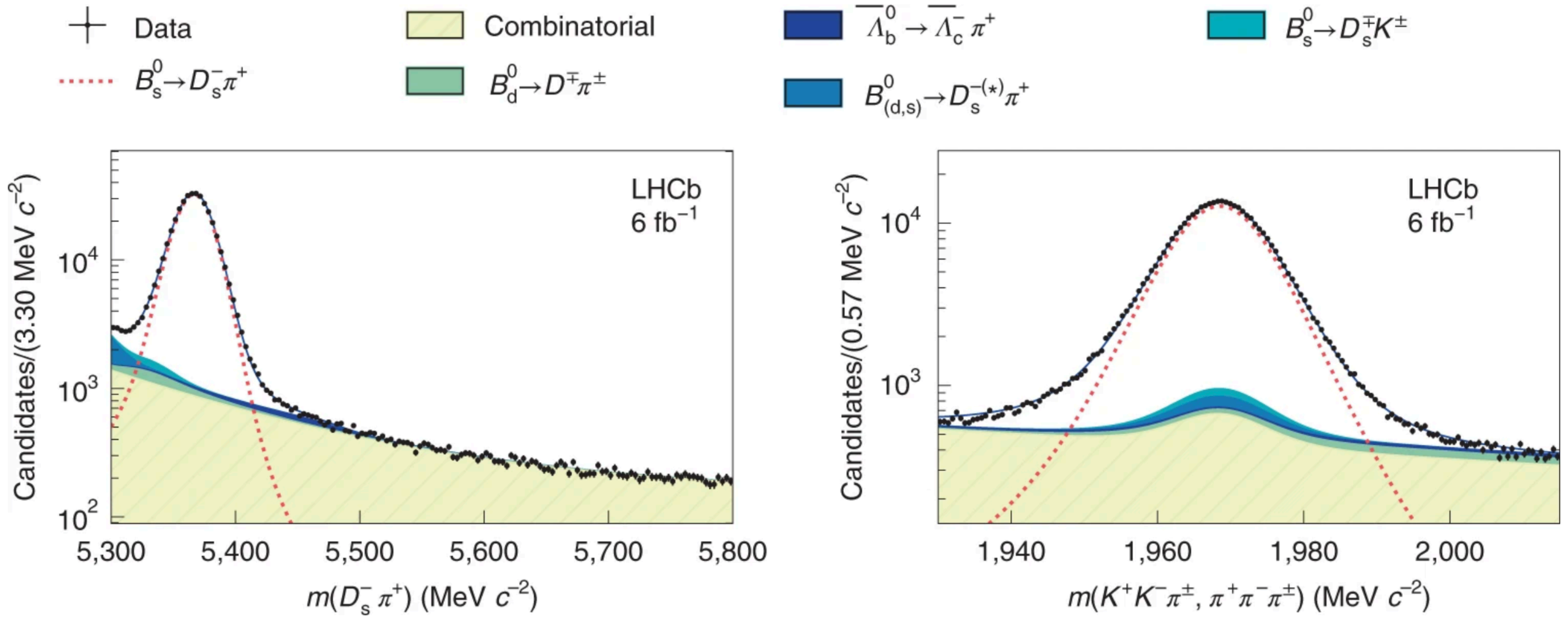
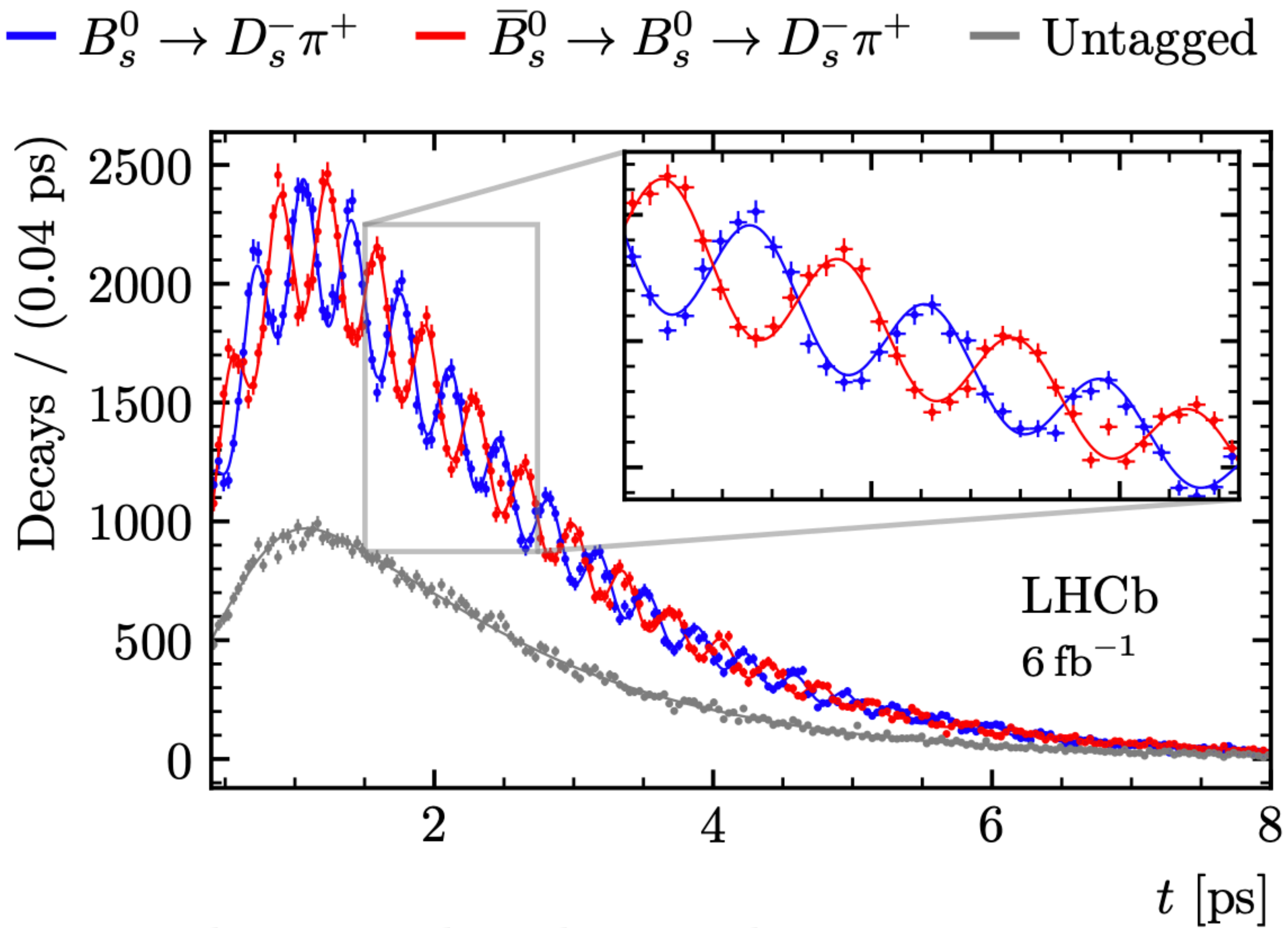
Finally…

$$A(t) = \frac{N(B_s^0 \to D_s^- \pi^+, t) - N(\overline{B}_s^0 \to D_s^- \pi^+, t)}{N(B_s^0 \to D_s^- \pi^+, t) + N(\overline{B}_s^0 \to D_s^- \pi^+, t)},$$





The value of the B_s^0–$\overline{B}_s^0$ oscillation frequency determined in this article:

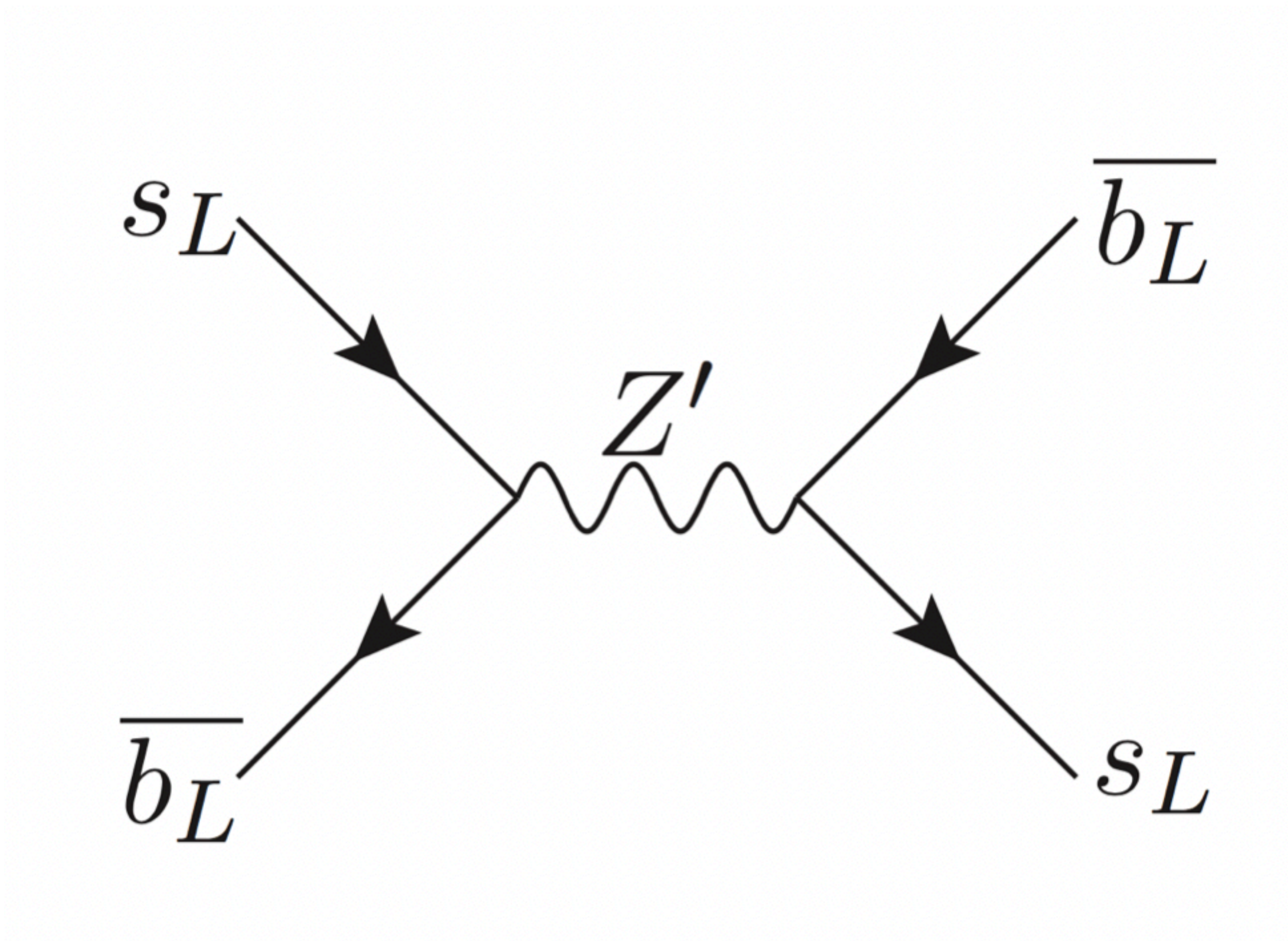
$$\Delta m_s = 17.7683 \pm 0.0051\,(\text{stat}) \pm 0.0032\,(\text{syst})\,\text{ps}^{-1}$$

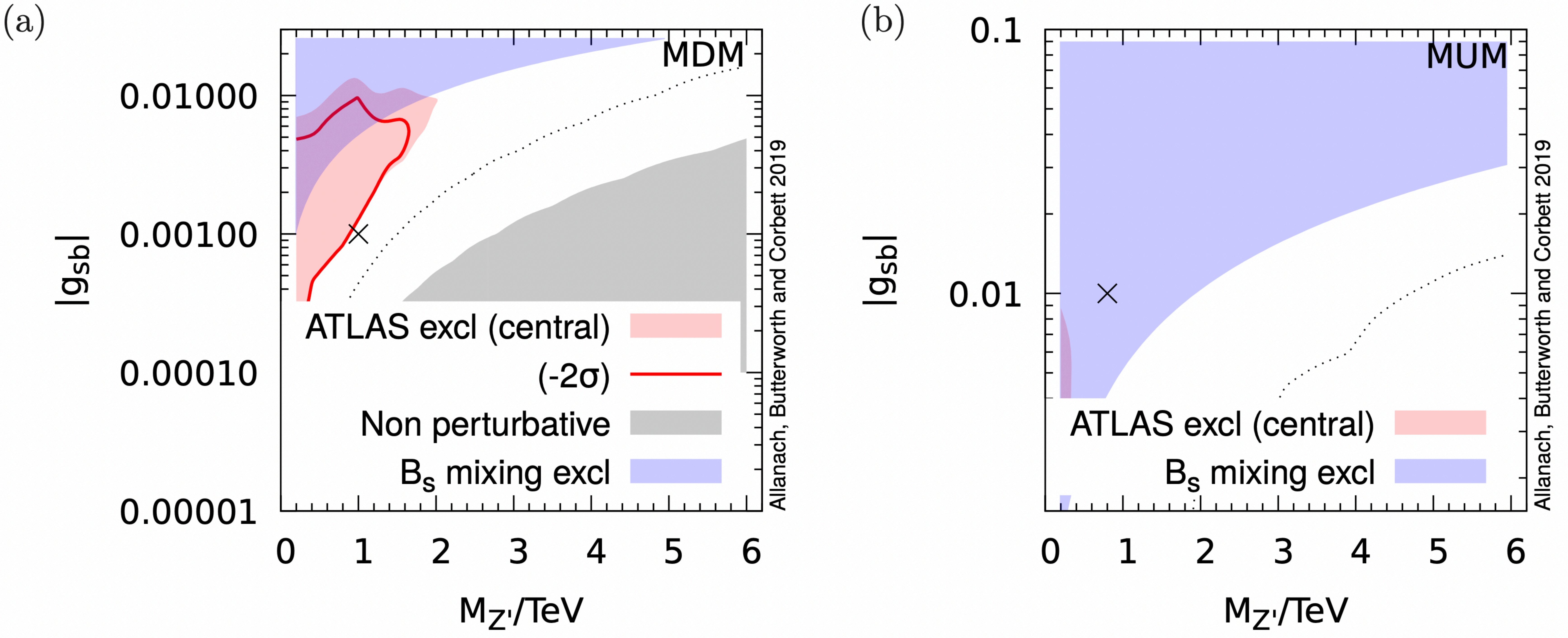
arXiv:2104.04421

Loop back to the models

Standard Model

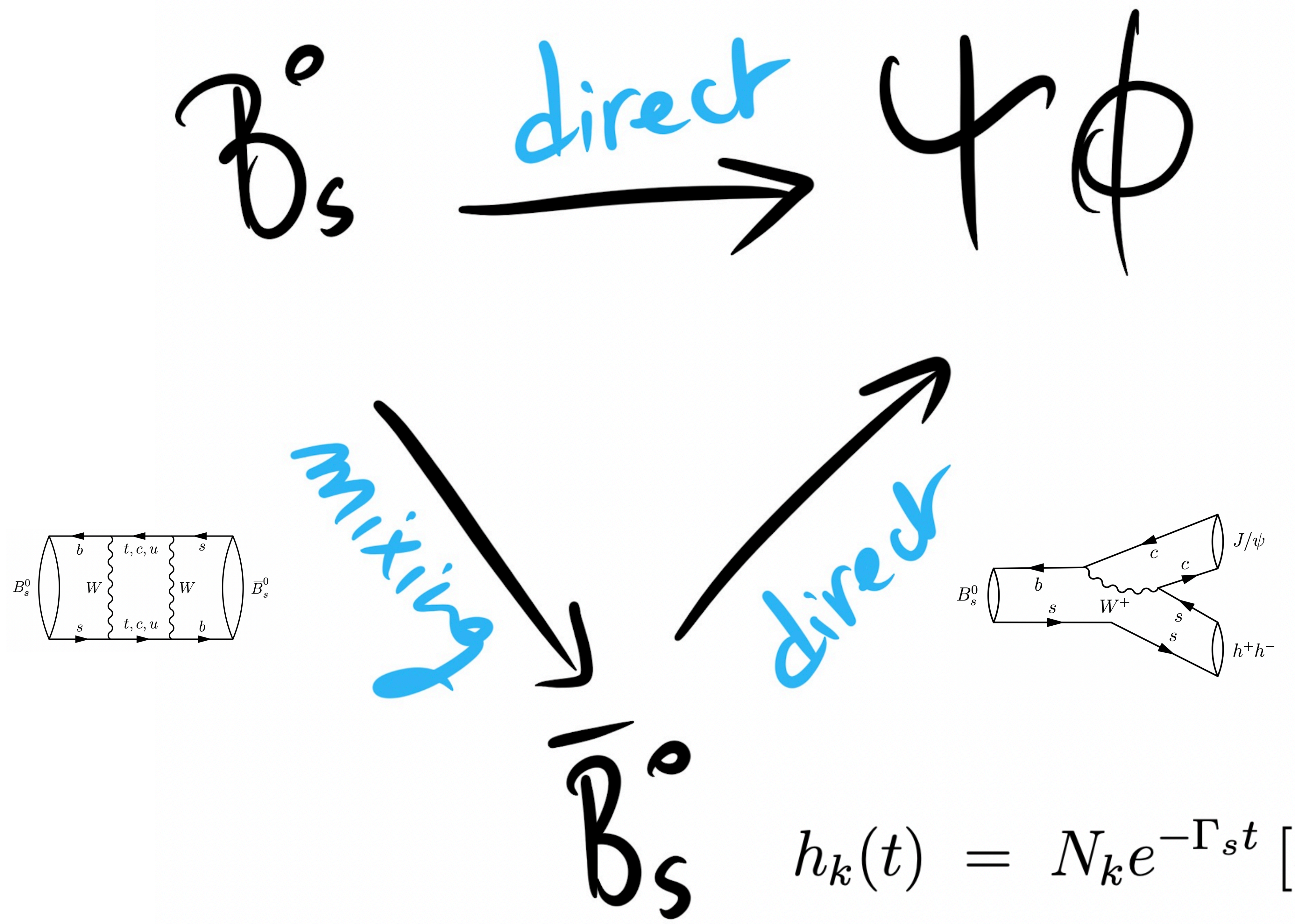
$$\Delta m_q = \frac{G_f^2}{6\pi^2} m_{B_q} M_W^2 f\left(\frac{m_t^2}{M_W^2}\right) \eta_{QCD} B_{B_q} f_{B_q}^2 |V_{tb}^* V_{tq}|^2 \qquad q = d, s$$





arXiv:1904.10954 one example out of the billion out there.

Let's us add complexity: $B_s \to \psi(\ell^+\ell^-)\phi(K^+K^-)$



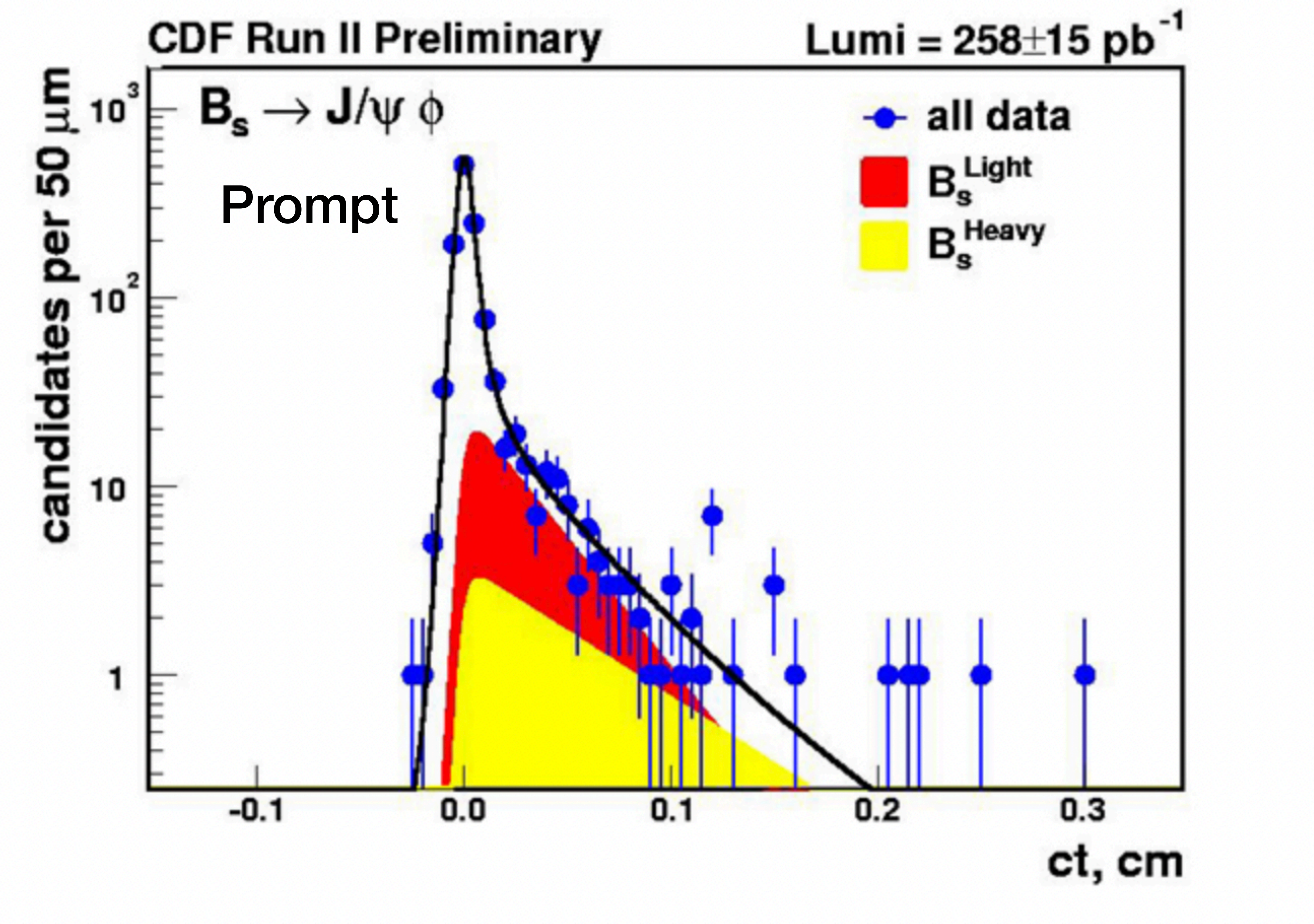
Mixture of CP odd and CP even eigenstates

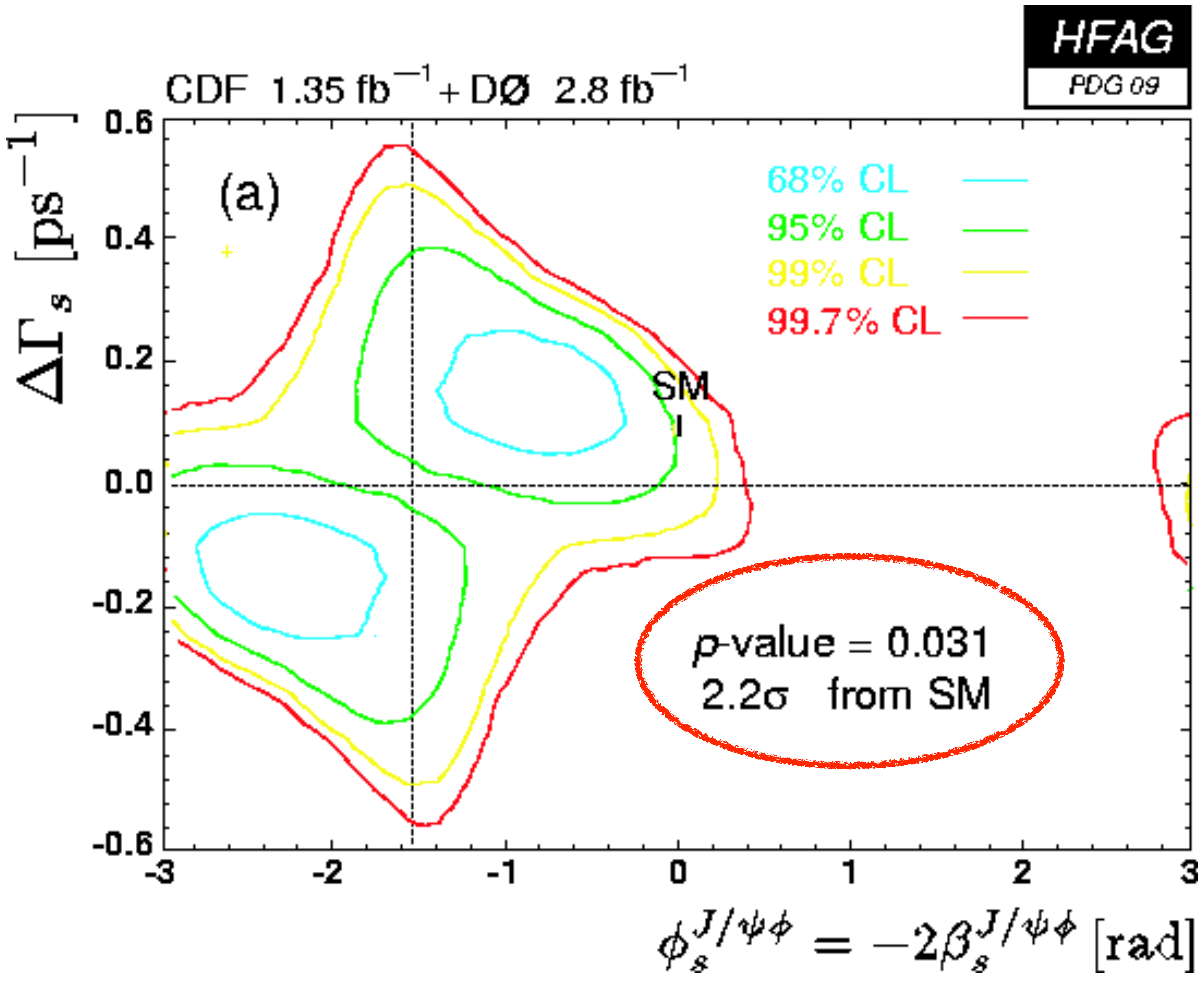
None negligible difference between the heavy and the light state of your the B_s^0 mesons $\Delta\Gamma_s$

$$\frac{d^4\Gamma(B_s^0 \to J/\psi K^+K^-)}{dt\, d\Omega} \propto \sum_{k=1}^{10} h_k(t)\, f_k(\Omega)\,.$$

$$h_k(t) = N_k e^{-\Gamma_s t}\left[a_k \cosh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + b_k \sinh\left(\tfrac{1}{2}\Delta\Gamma_s t\right) + c_k \cos(\Delta m_s t) + d_k \sin(\Delta m_s t)\right],$$

Fermilab paved the path of B_s^0 physics

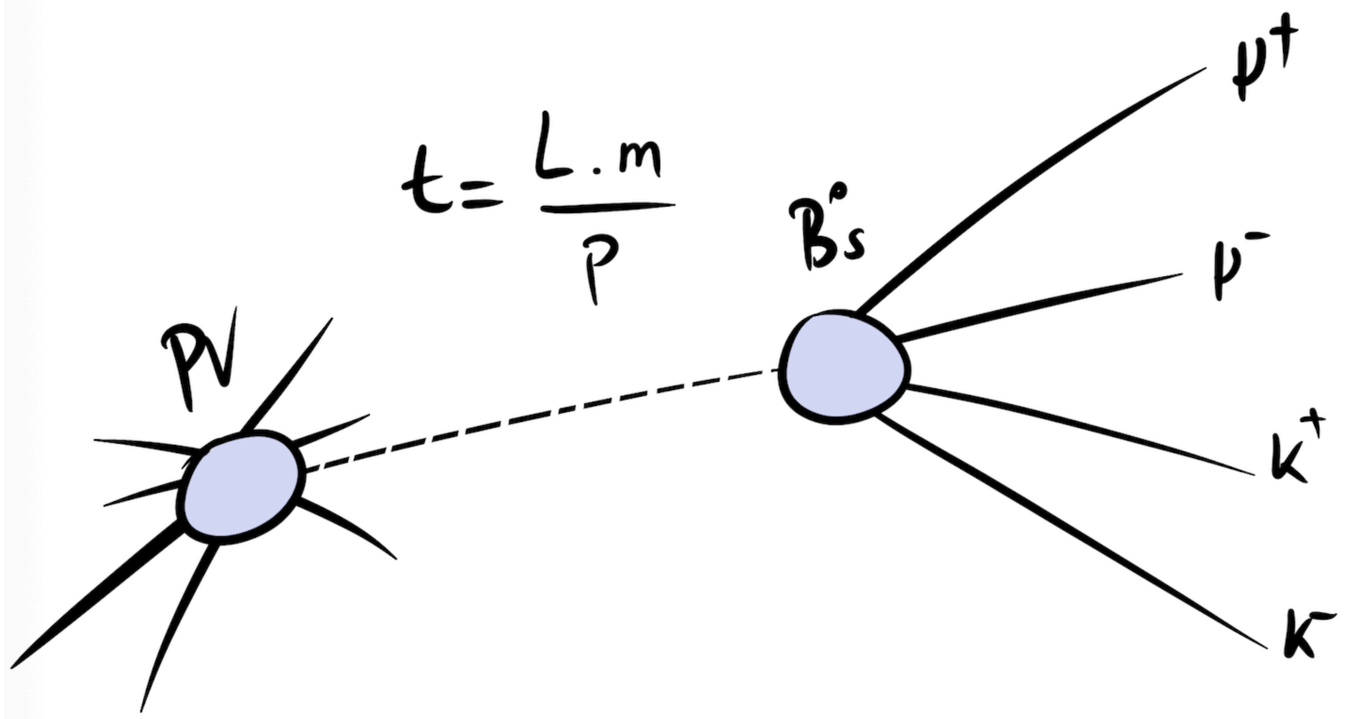


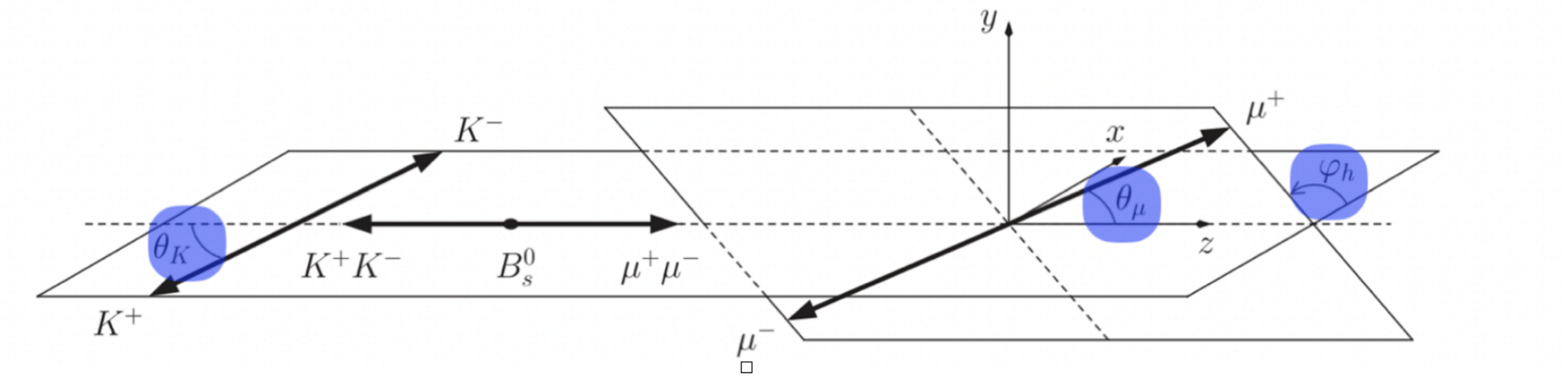


It’s “just” yet an other counting experiment

$$A_{cp}(t) = \frac{\Gamma(\bar{B}_s^0 \to \psi\phi) - \Gamma(B_s^0 \to \psi\phi)}{\Gamma(\bar{B}_s^0 \to \psi\phi) + \Gamma(B_s \to \psi\phi)} = \eta_f \sin \phi_s \sin(\Delta m_s t)$$

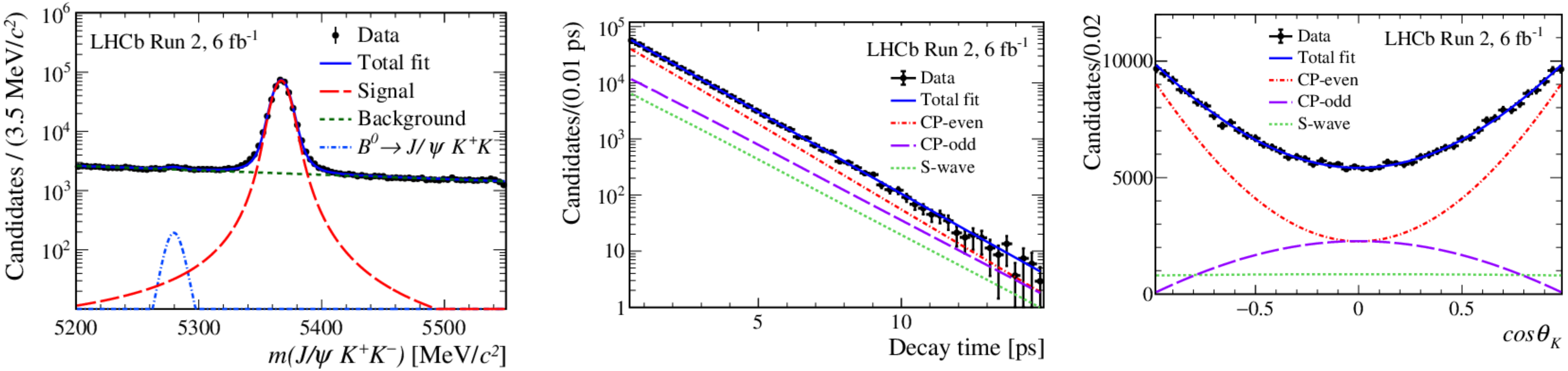
$\eta_f = (-1)^L$ CP eigenvalues of the final state



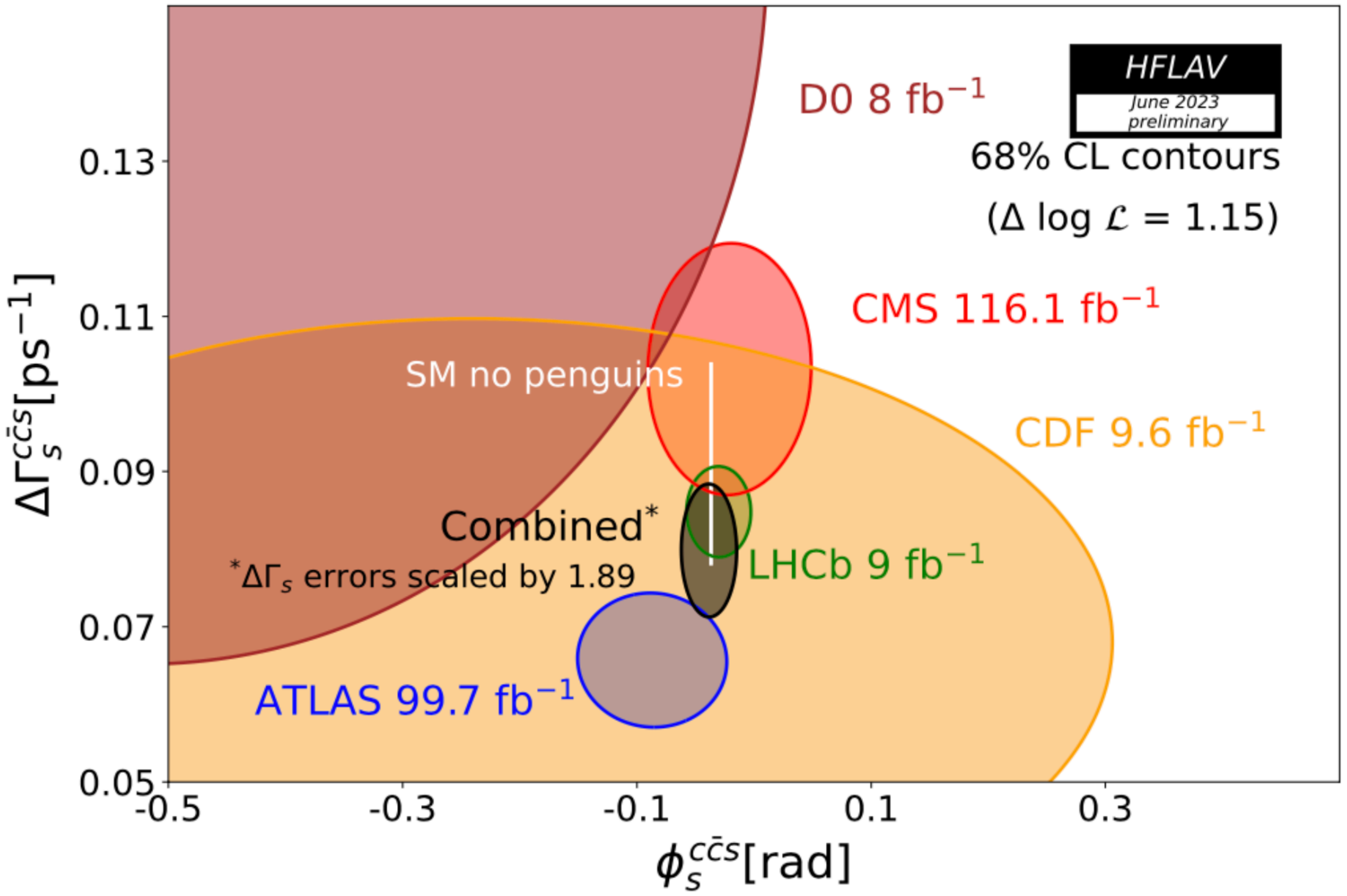


Mixture of CP odd and CP even requires an angular analysis

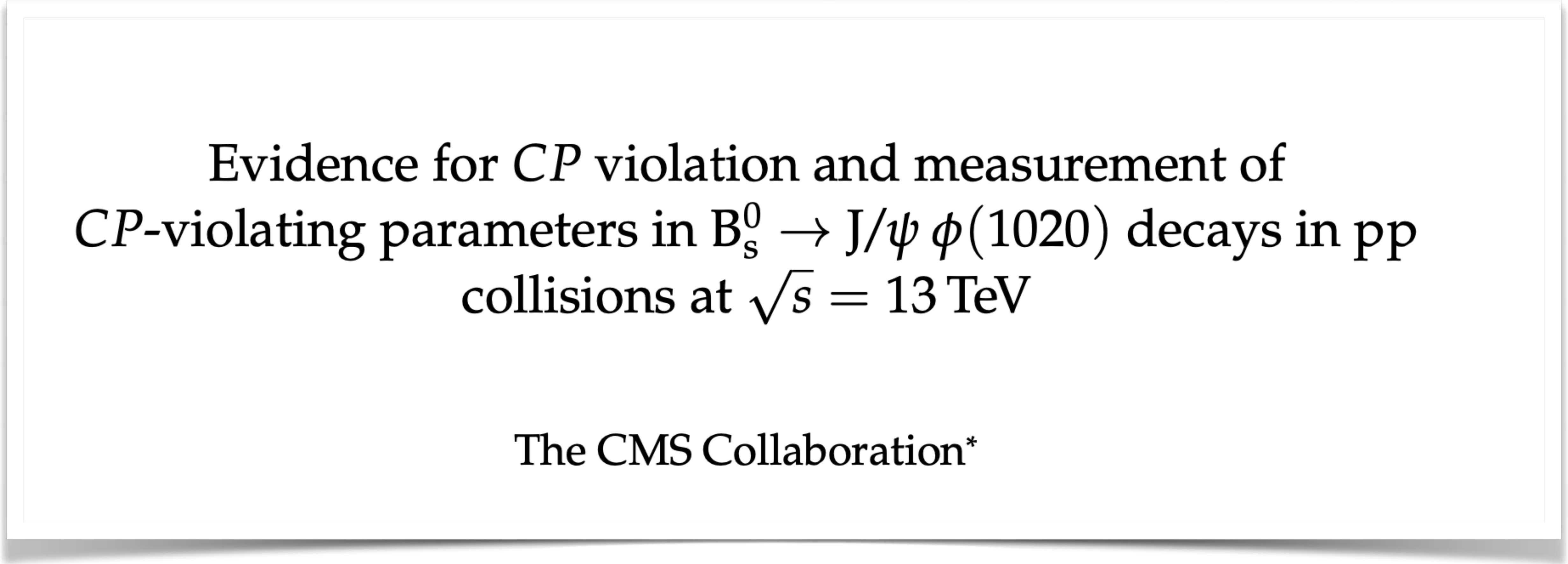
arXiv:2308.01468



Very similar experimental techniques between the LHC three collaborations

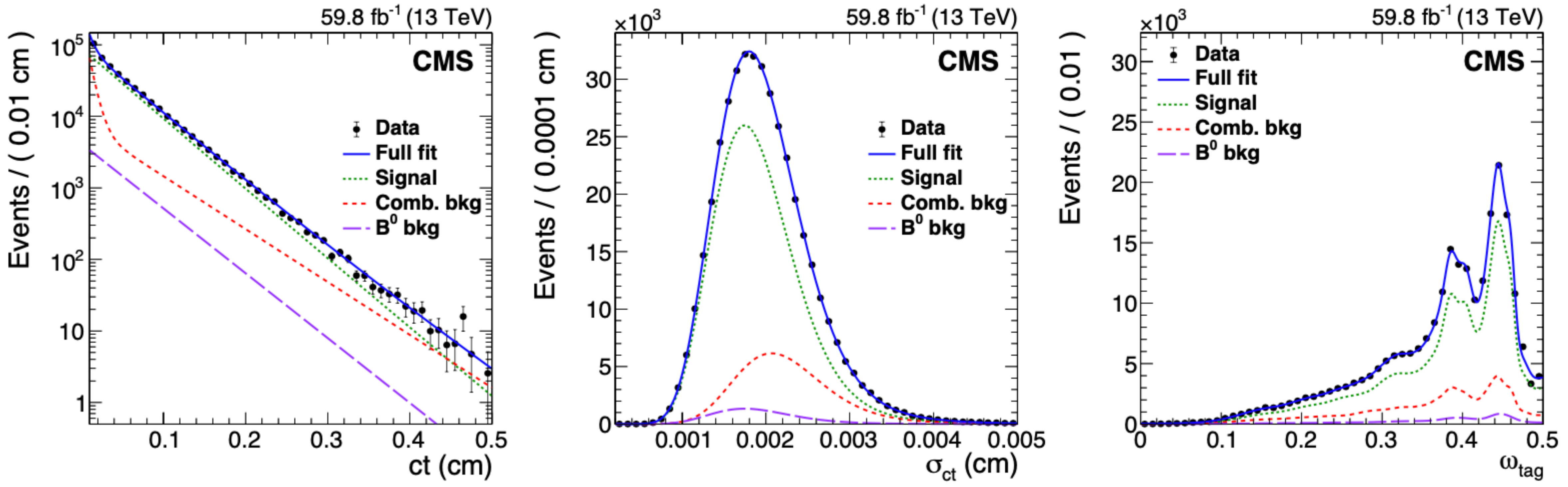


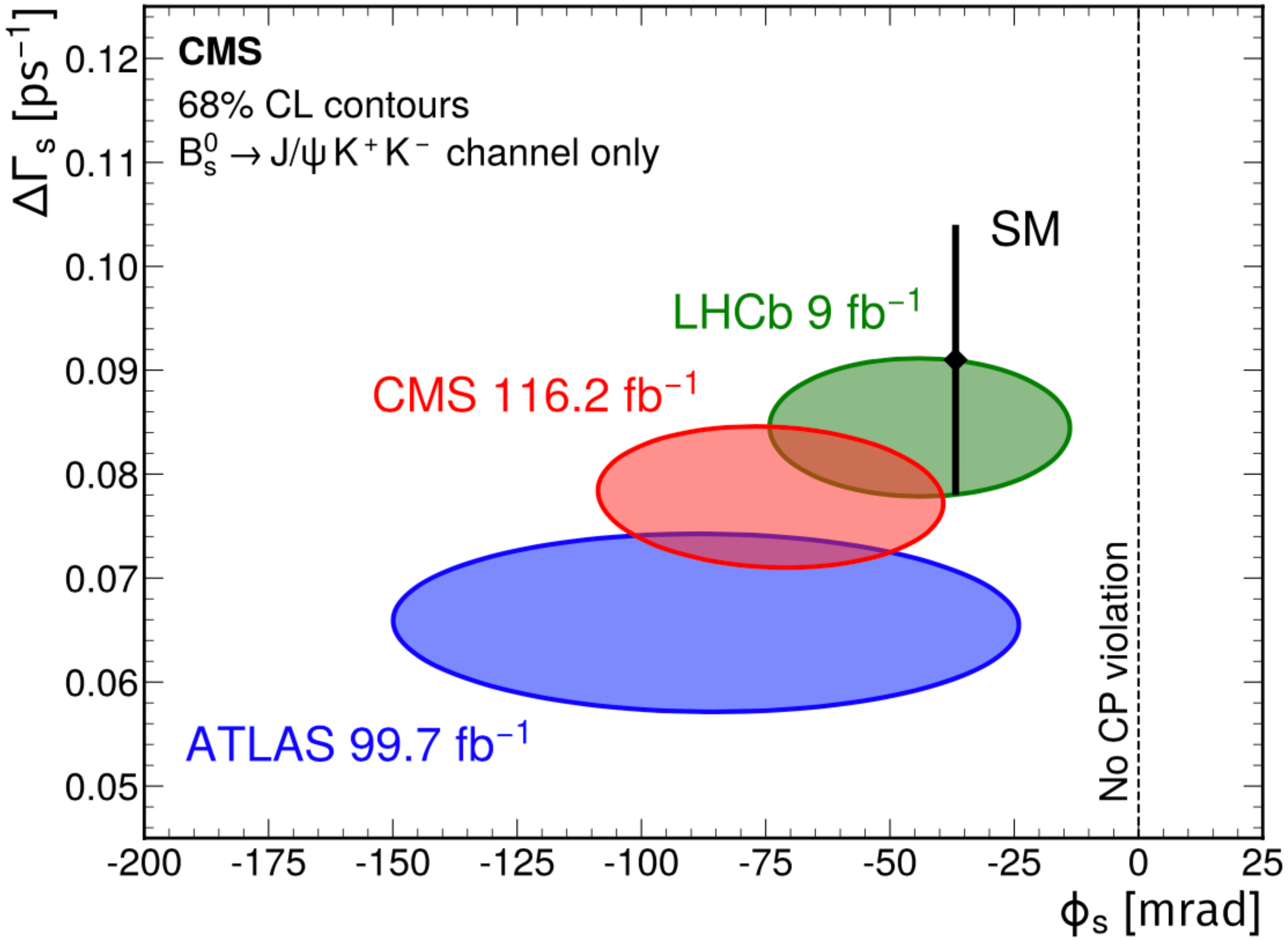
arXiv:2308.01468



Evidence for *CP* violation and measurement of *CP*-violating parameters in $B_s^0 \rightarrow J/\psi\,\phi(1020)$ decays in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*





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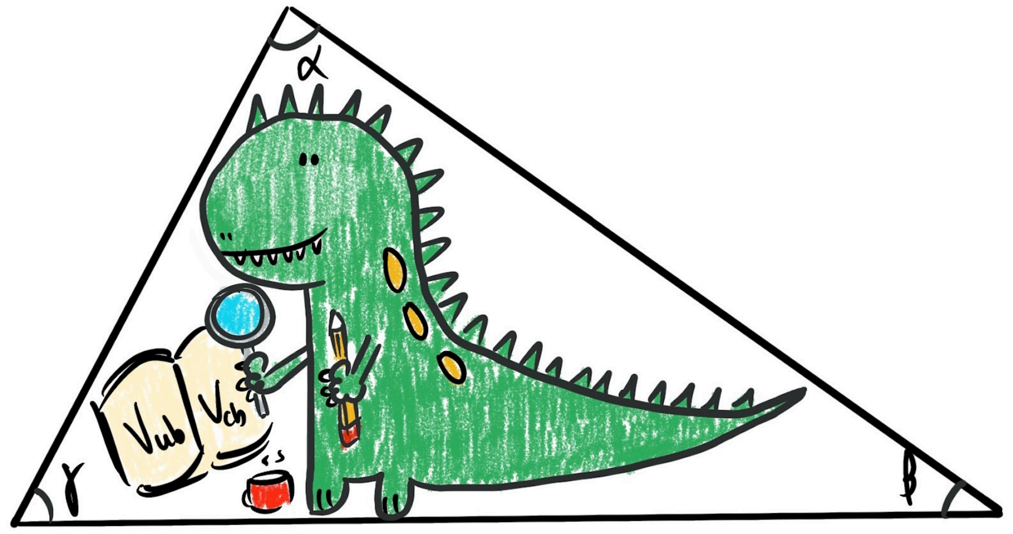
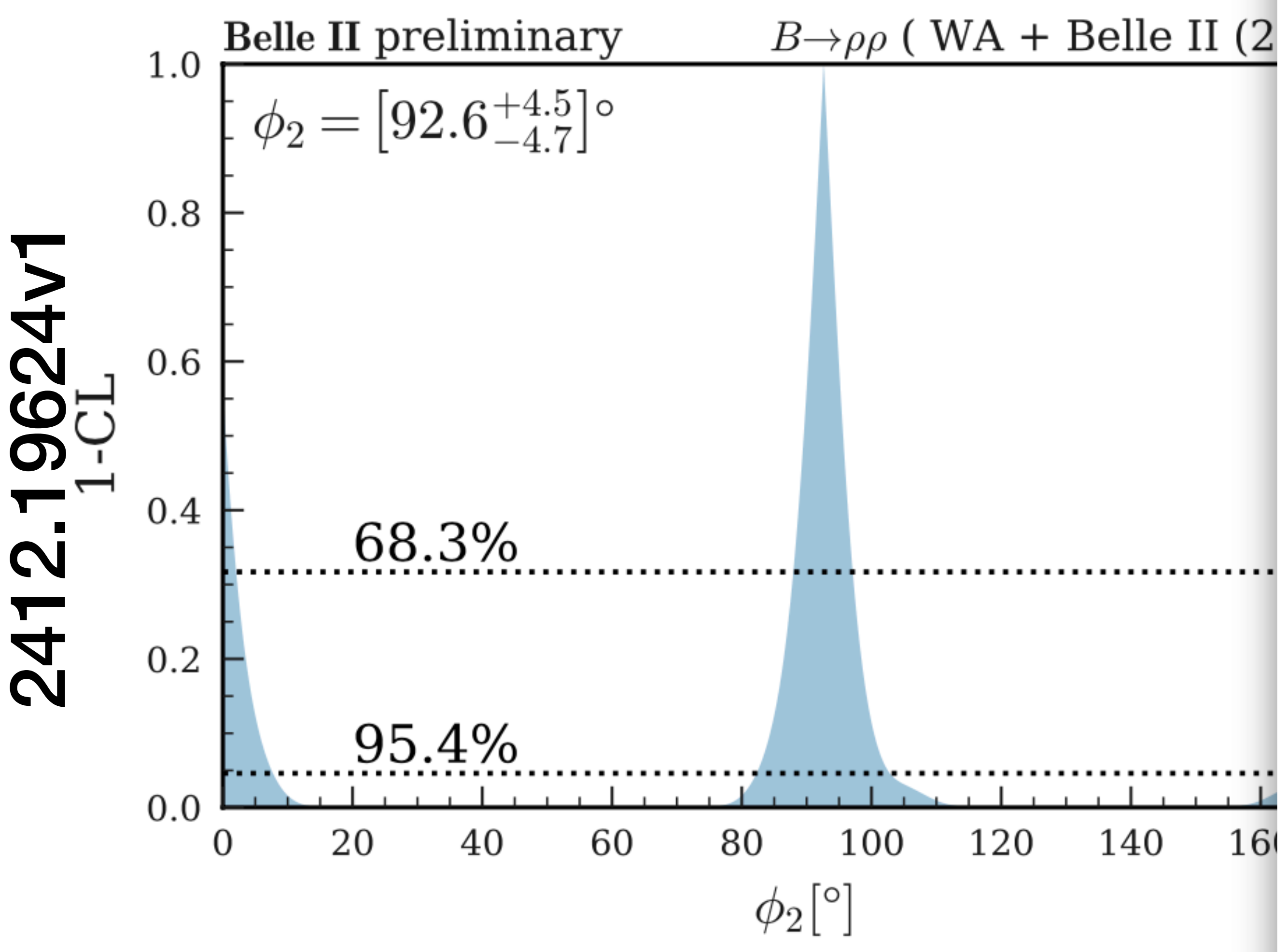
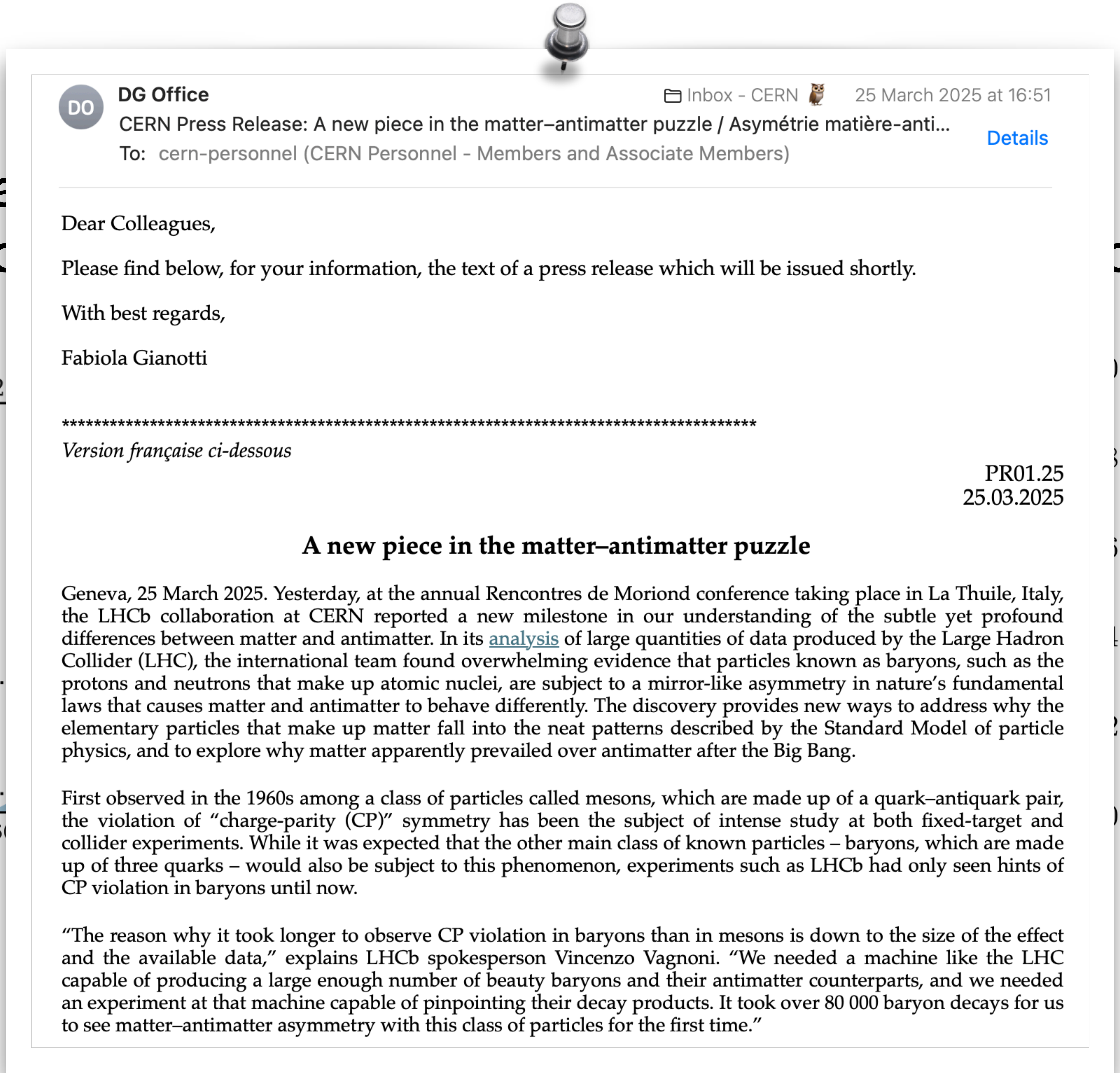


All the phases…Today

Question to my theory collea
While the overall picture is lo om for NP in these observables?





DG Office 25 March 2025 at 16:51

CERN Press Release: A new piece in the matter–antimatter puzzle / Asymétrie matière-anti...

To: cern-personnel (CERN Personnel - Members and Associate Members)

Dear Colleagues,

Please find below, for your information, the text of a press release which will be issued shortly.

With best regards,

Fabiola Gianotti

****

Version française ci-dessous

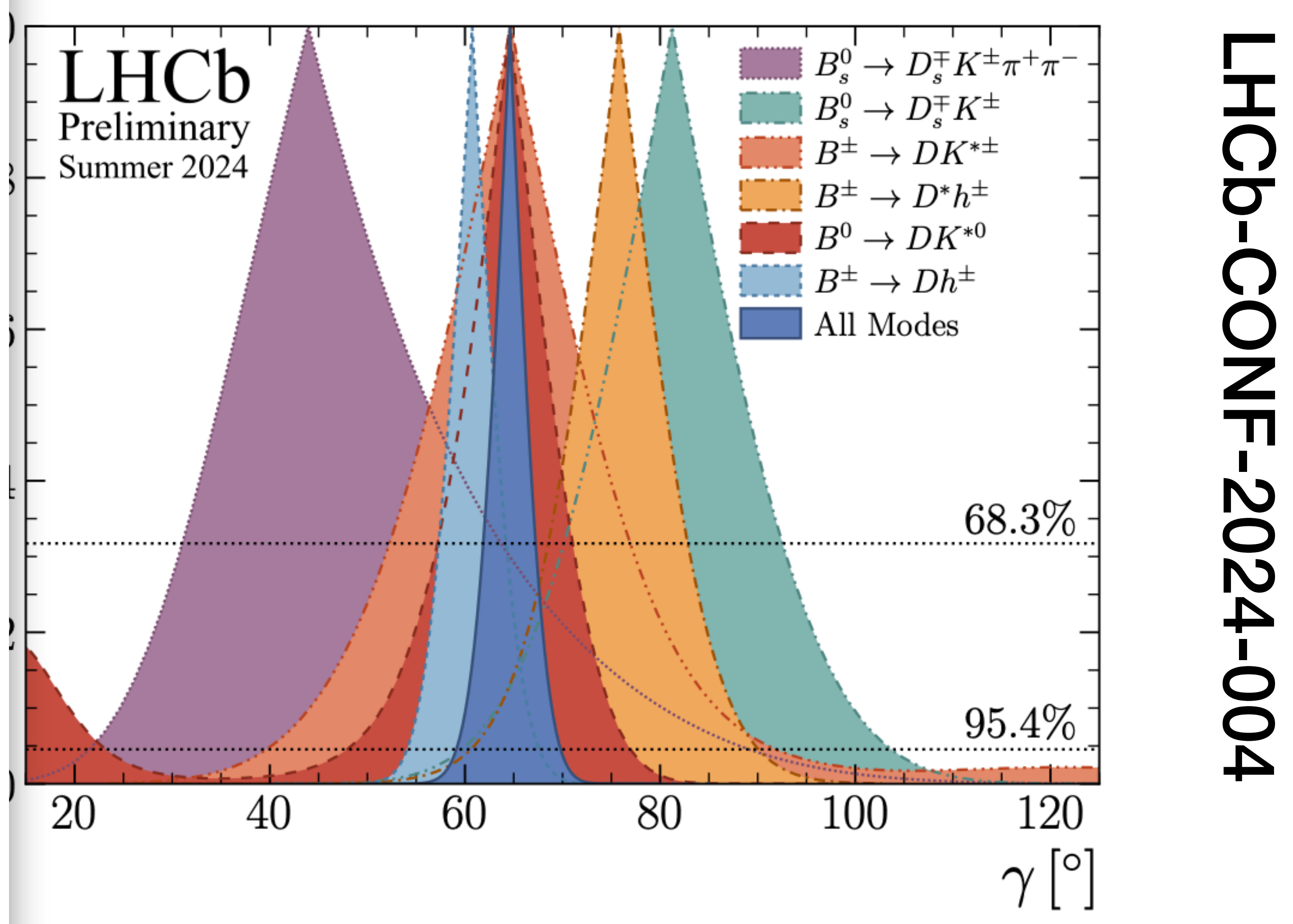
PR01.25
25.03.2025

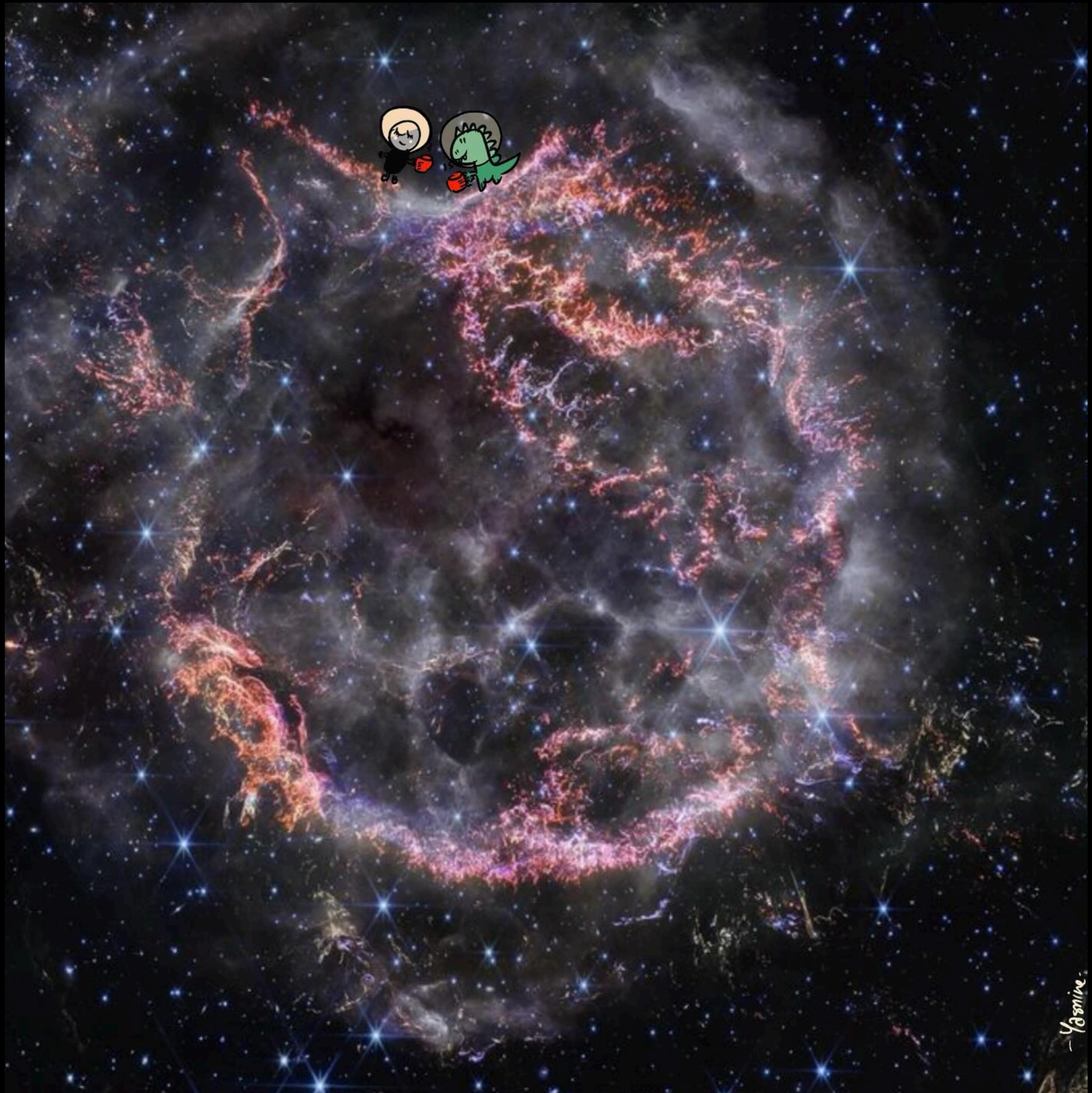
A new piece in the matter–antimatter puzzle

Geneva, 25 March 2025. Yesterday, at the annual Rencontres de Moriond conference taking place in La Thuile, Italy, the LHCb collaboration at CERN reported a new milestone in our understanding of the subtle yet profound differences between matter and antimatter. In its analysis of large quantities of data produced by the Large Hadron Collider (LHC), the international team found overwhelming evidence that particles known as baryons, such as the protons and neutrons that make up atomic nuclei, are subject to a mirror-like asymmetry in nature's fundamental laws that causes matter and antimatter to behave differently. The discovery provides new ways to address why the elementary particles that make up matter fall into the neat patterns described by the Standard Model of particle physics, and to explore why matter apparently prevailed over antimatter after the Big Bang.

First observed in the 1960s among a class of particles called mesons, which are made up of a quark–antiquark pair, the violation of "charge-parity (CP)" symmetry has been the subject of intense study at both fixed-target and collider experiments. While it was expected that the other main class of known particles – baryons, which are made up of three quarks – would also be subject to this phenomenon, experiments such as LHCb had only seen hints of CP violation in baryons until now.

"The reason why it took longer to observe CP violation in baryons than in mesons is down to the size of the effect and the available data," explains LHCb spokesperson Vincenzo Vagnoni. "We needed a machine like the LHC capable of producing a large enough number of beauty baryons and their antimatter counterparts, and we needed an experiment at that machine capable of pinpointing their decay products. It took over 80 000 baryon decays for us to see matter–antimatter asymmetry with this class of particles for the first time."





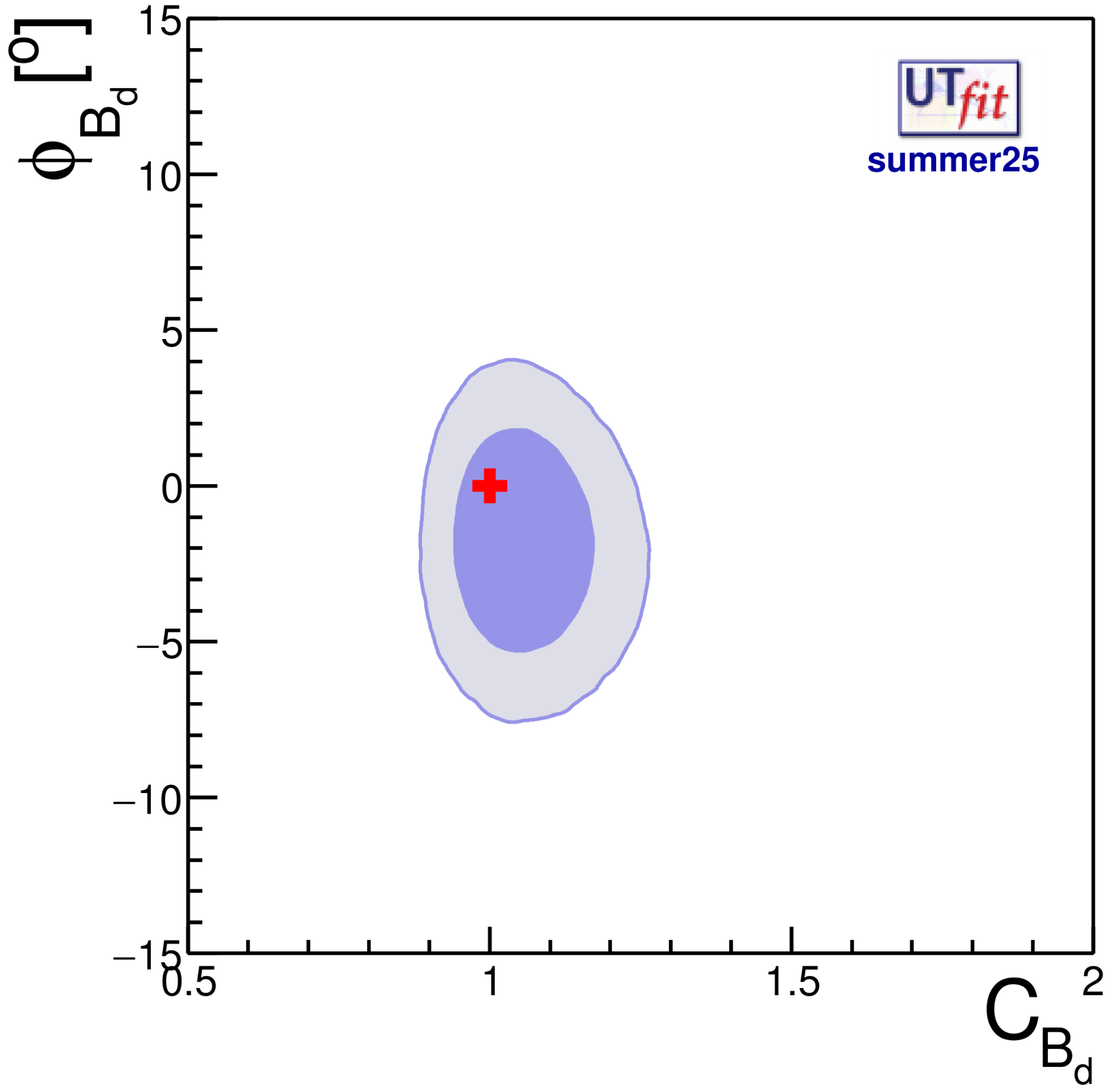
NP ?

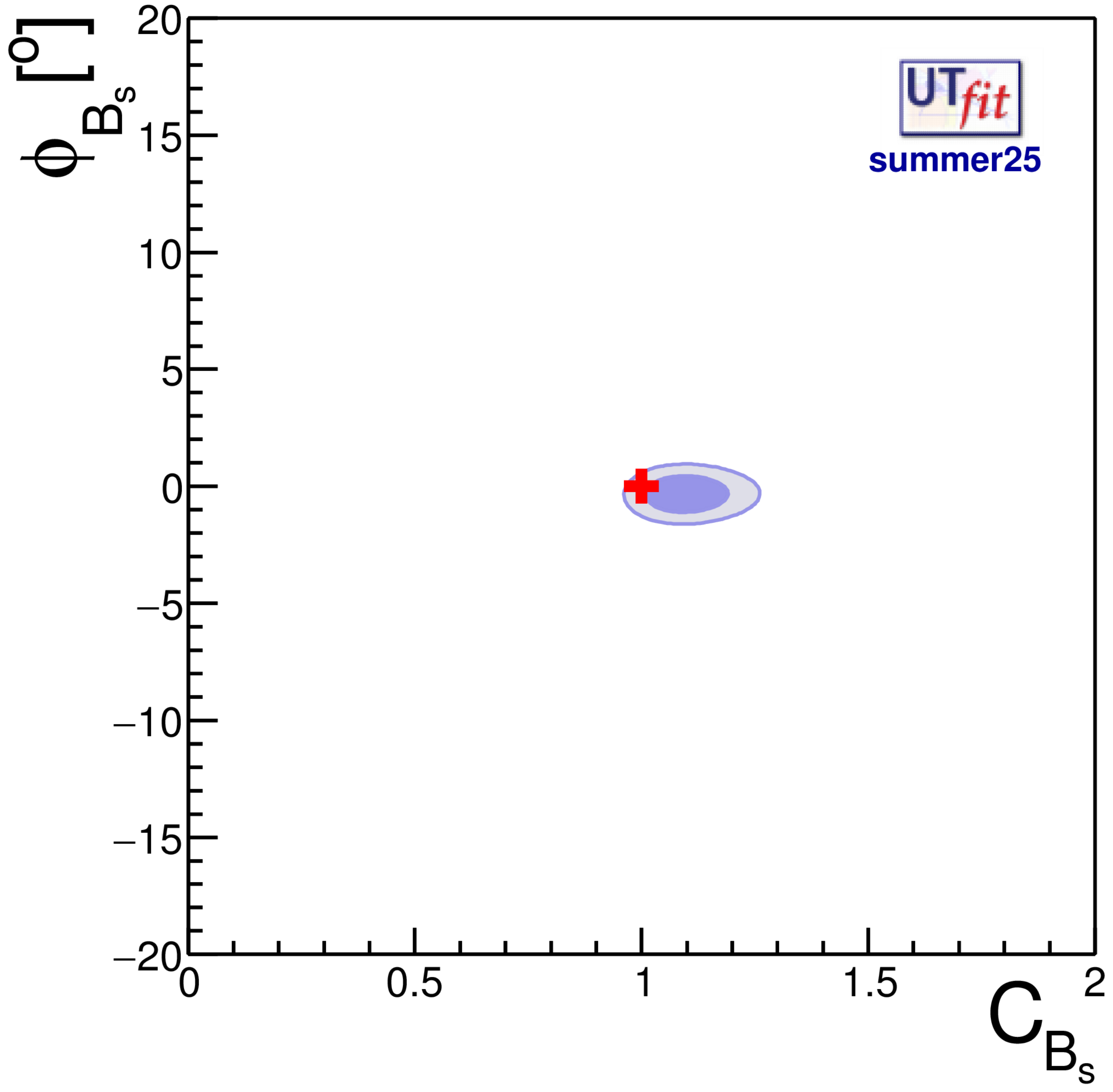
Now what about NP physics?

Adopt a given parametrisation

$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{sm} e^{2i\phi_q^{sm}}$$

✚ SM

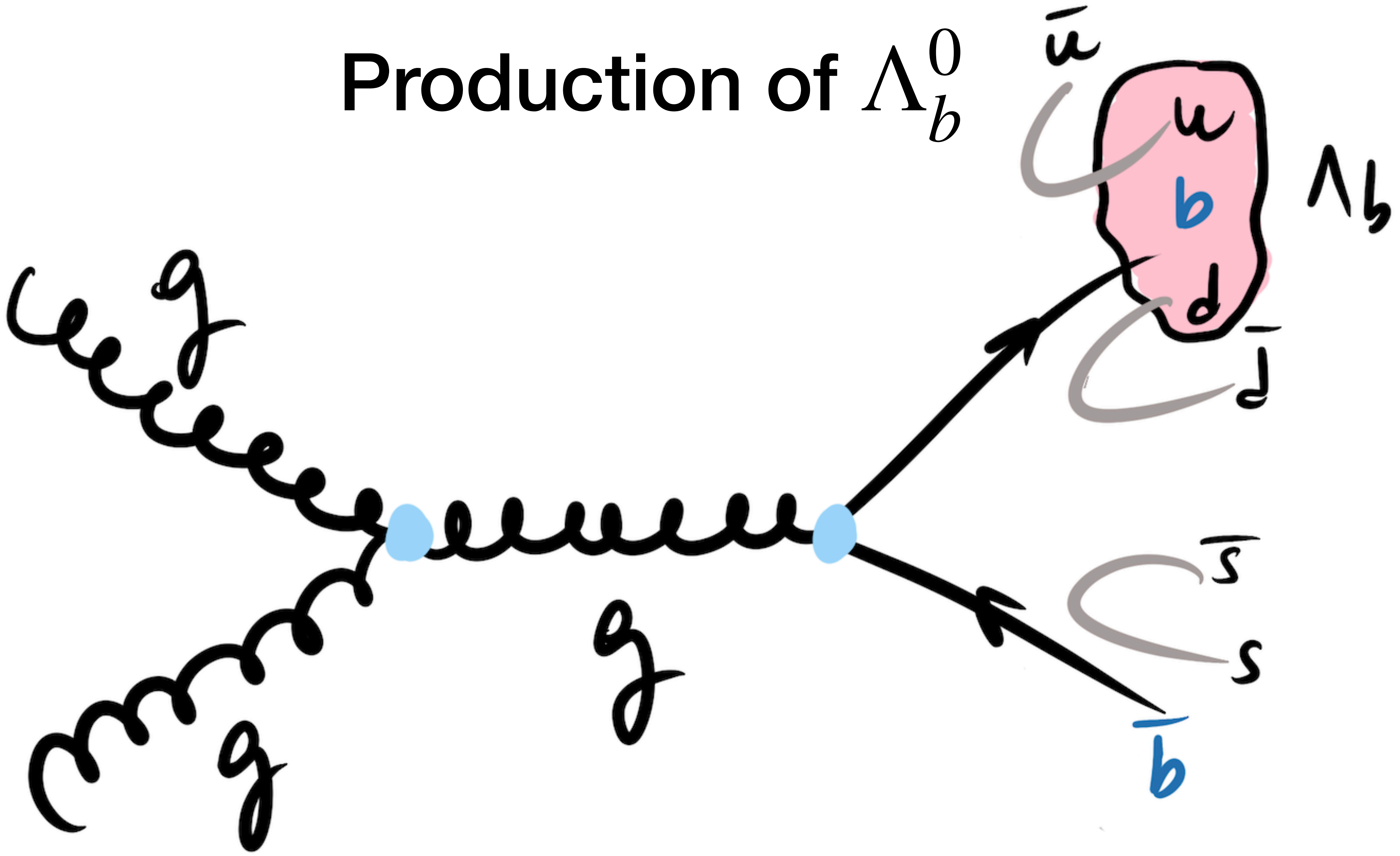




http://www.utfit.org/UTfit/ResultsSummer2025

Observation of charge-parity symmetry breaking in baryon decays

Production of Λ_b^0

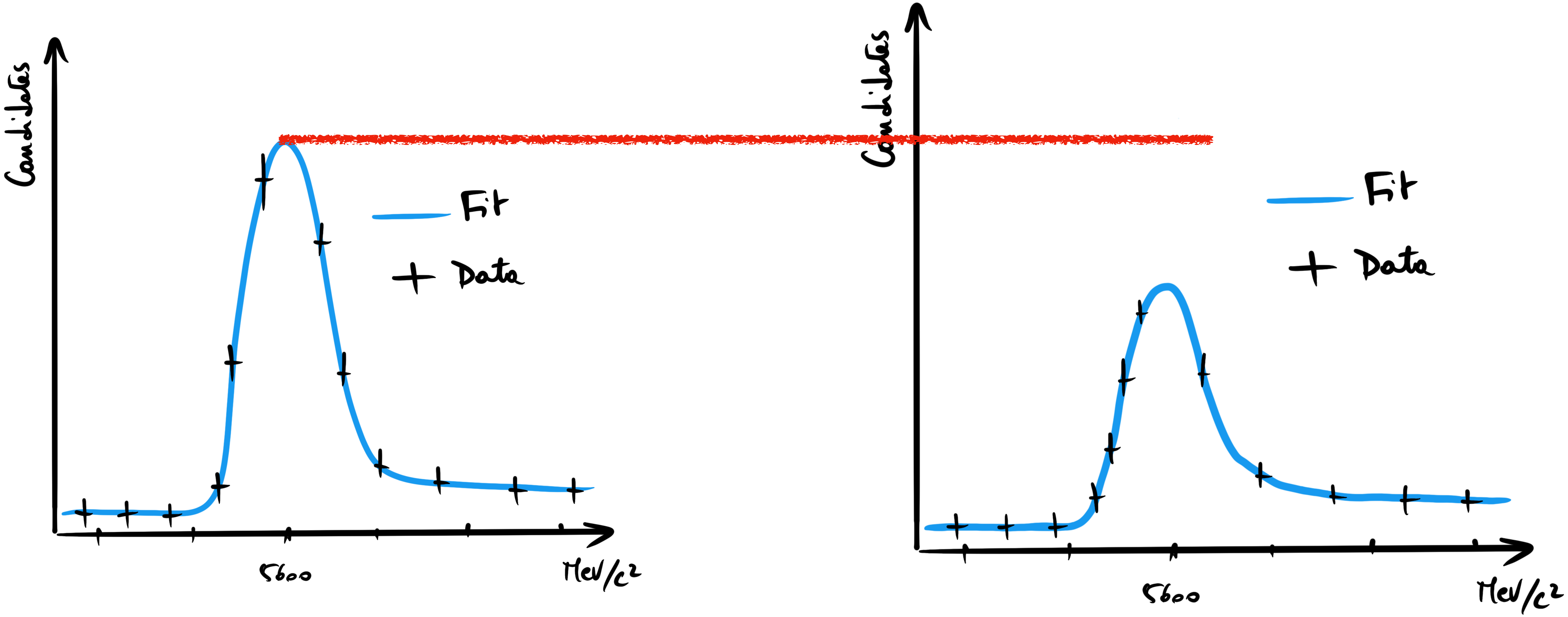


Expression of the asymmetry

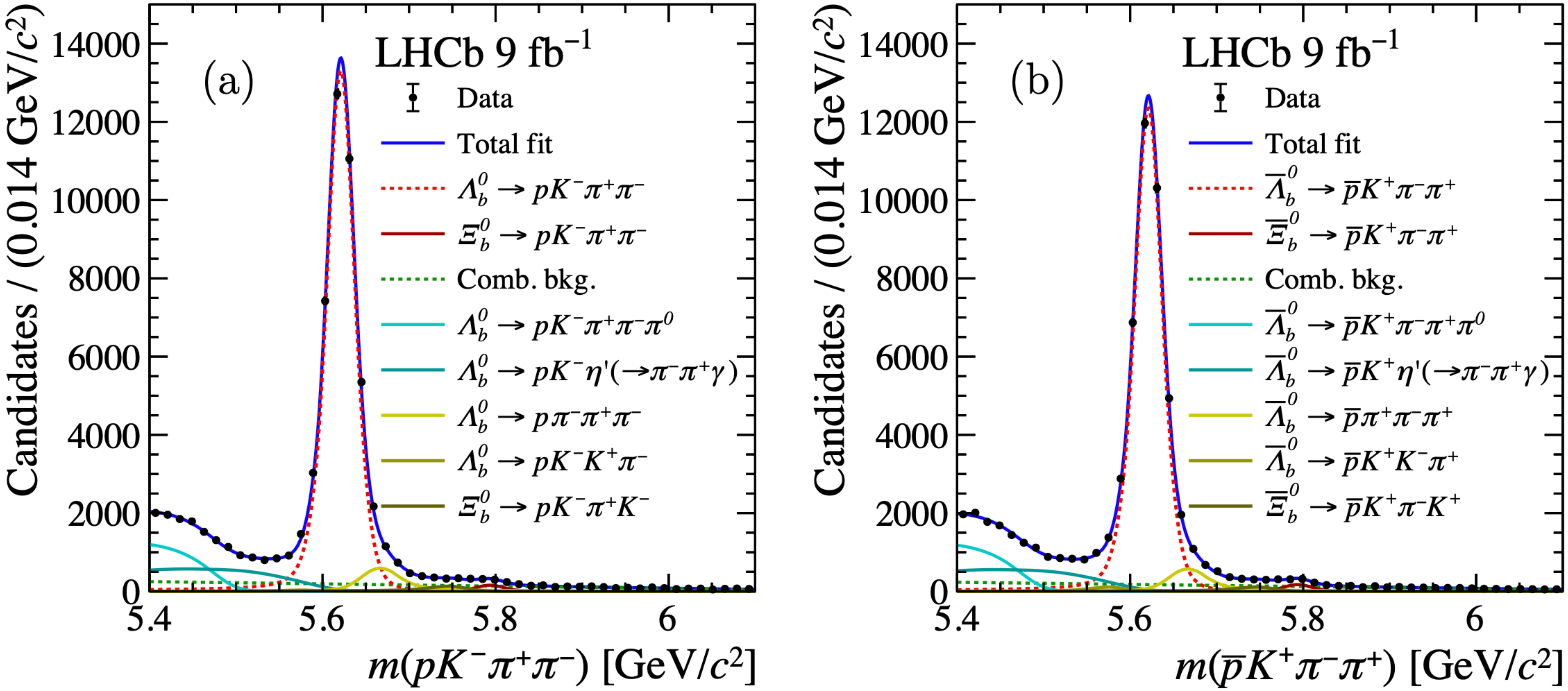
$$A_{CP}^{f} = \frac{\Gamma(\Lambda_b^0 \to f) - \Gamma(\bar{\Lambda}_b \to \bar{f})}{\Gamma(\Lambda_b \to f) + \Gamma(\bar{\Lambda}_b \to \bar{f})}$$

arXiv:2503.16954

$$A^{f}_{Raw} = \frac{N(\Lambda_b^0 \rightarrow f) - N(\bar{\Lambda}_b^0 \rightarrow \bar{f})}{N(\Lambda_b^0 \rightarrow \bar{f}) + N(\bar{\Lambda}_b^0 \rightarrow \bar{f})}$$



Signal mode



Very pure selection & careful modelling of the backgrounds

From Raw to CP observable

$$A_{CP}^{f} = A_{Raw}^{f} - A_{P}^{\Lambda_b^0} - A_{D}^{f}$$

Production asymmetry

$$A_{P}^{\Lambda_b^0} = \frac{\sigma(\Lambda_b^0) - \sigma(\bar{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\bar{\Lambda}_b^0)}$$

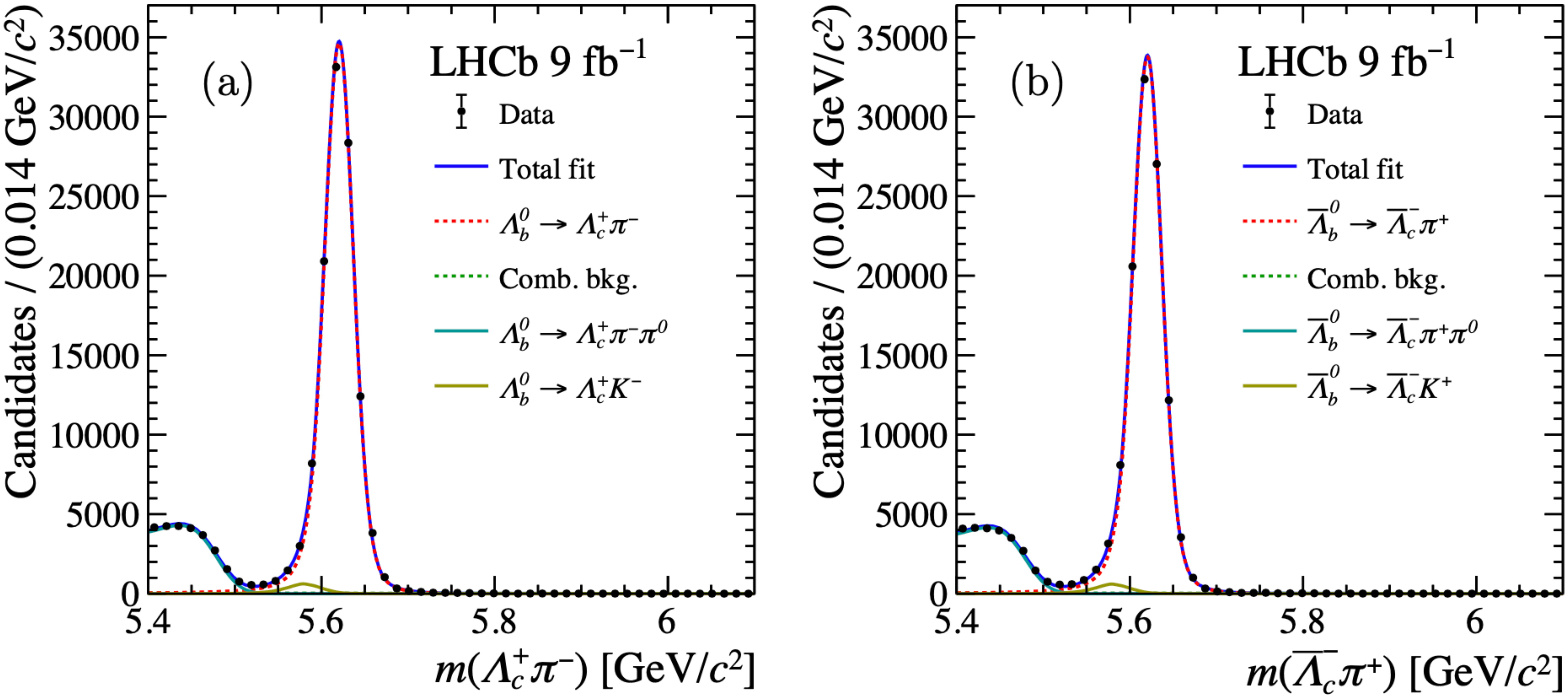
Detection asymmetry

$$A_{D}^{f} = \frac{\epsilon(f) - \epsilon(\bar{f})}{\epsilon(f) + \epsilon(\bar{f})}$$

$A_{CP}^{c} = A_{Raw}^{c} - A_{P}^{\Lambda_b^0} - A_{D}^{c}$ ➤ Measured for the control mode for which $\boxed{A_{CP} \sim 0}$

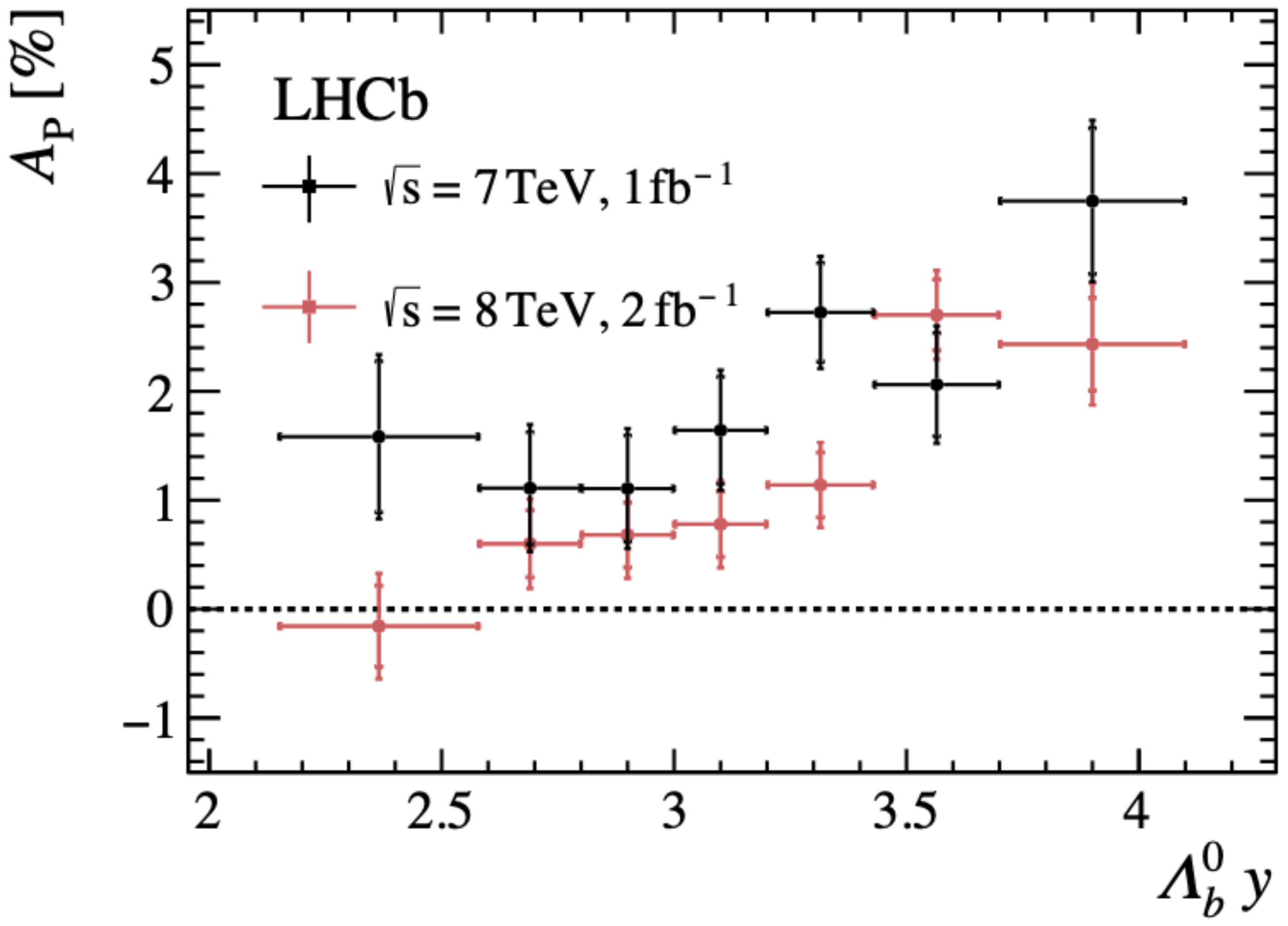
$A_{CP}^{f} = A_{Raw}^{f} - A_{P}^{\Lambda_b^0} - A_{D}^{f}$ ➤ Measured for the signal

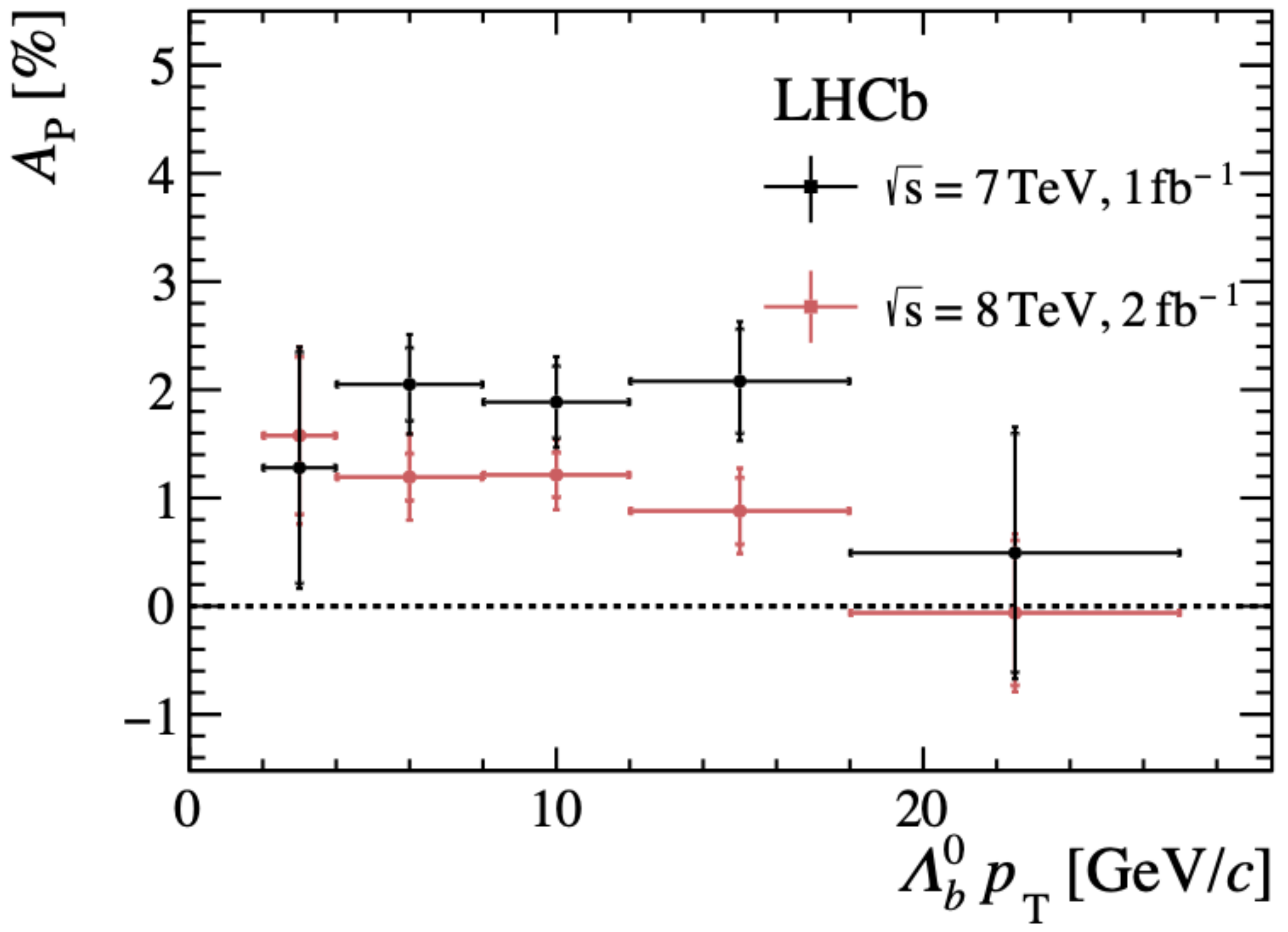
Control mode



Production asymmetries

- Production asymmetry dominated by gluon fusion.
- Hadronization asymmetry of Λ_b^0 and $\bar{\Lambda}_b^0$ in pp collisions.
- A_p 1-2% measured by LHCb as a function of kinematics.
- ΔA_p vanishes





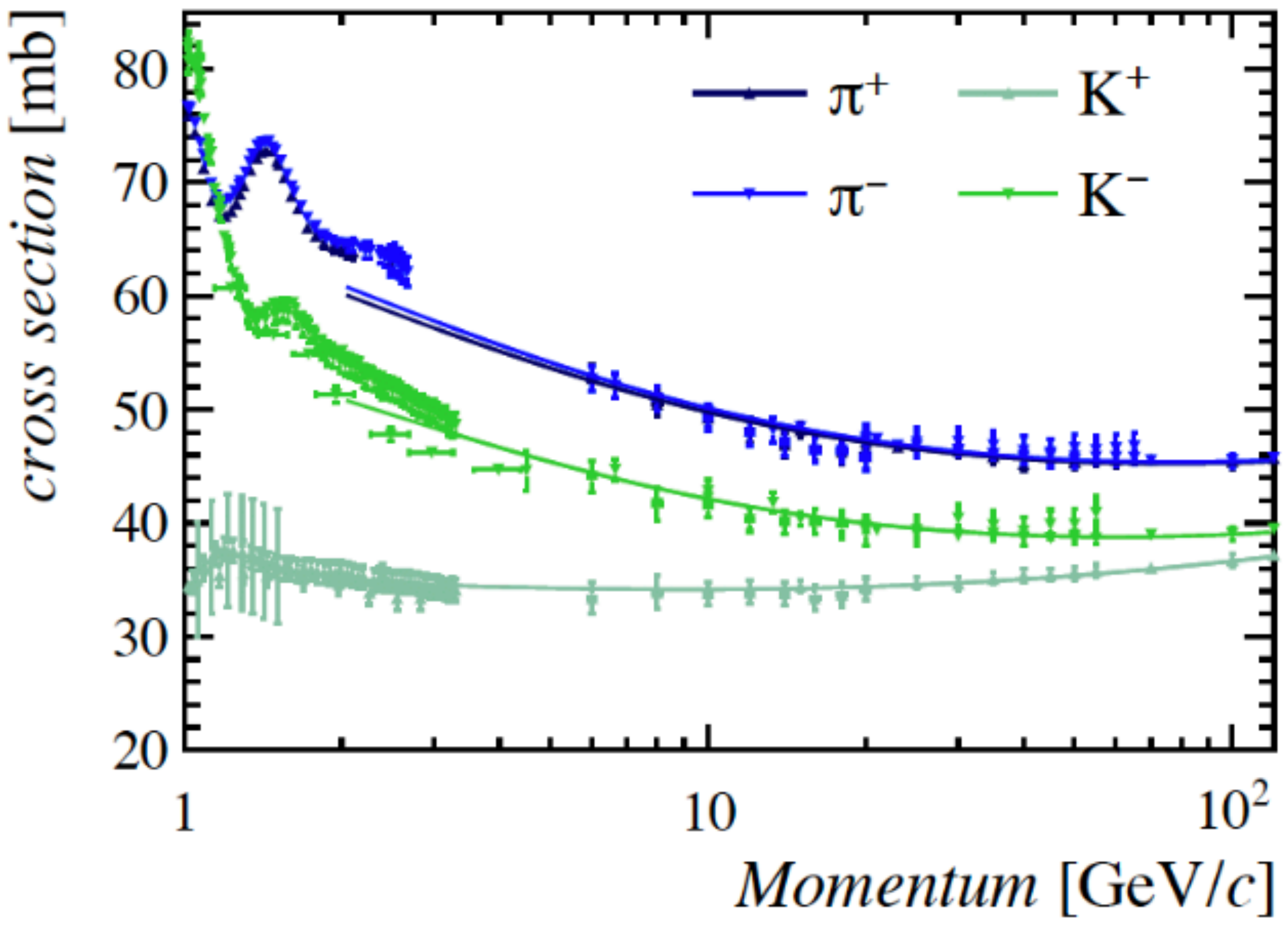
LHCb-PAPER-2021-016

Detector asymmetries

Matter, antimatter interact with detector (made by matter) differently

- $\boldsymbol{f}$: different combinations of $\boldsymbol{p}$, $\boldsymbol{K}$, $\boldsymbol{\pi}$ etc.

- Including effects from reconstruction of particles, PID, trigger effects


[Chin. Phys. C 40 (2016) 100001]

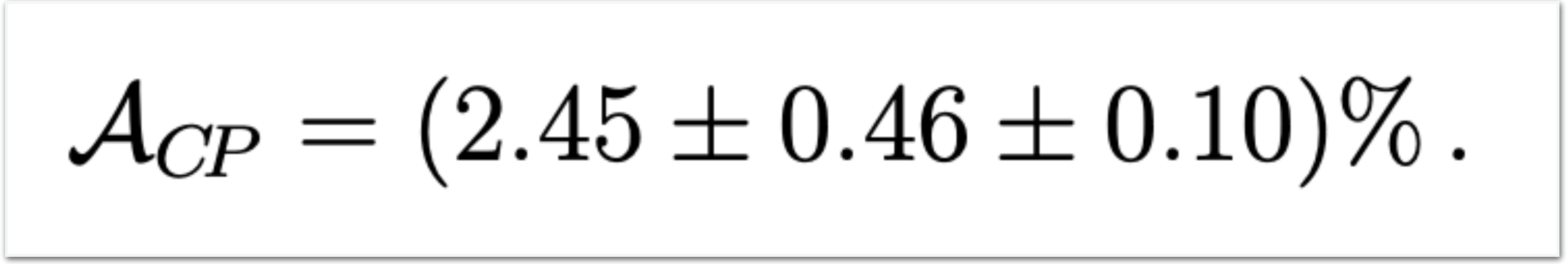
,

Obtained using data-driven method with calibration channels

$$A_D(\pi^\pm) \approx 0.1\%, A_D(K^\pm) \approx 1\%, A_D(p/\overline{p}) \approx 1-2\%$$

- ΔA_D vanishes

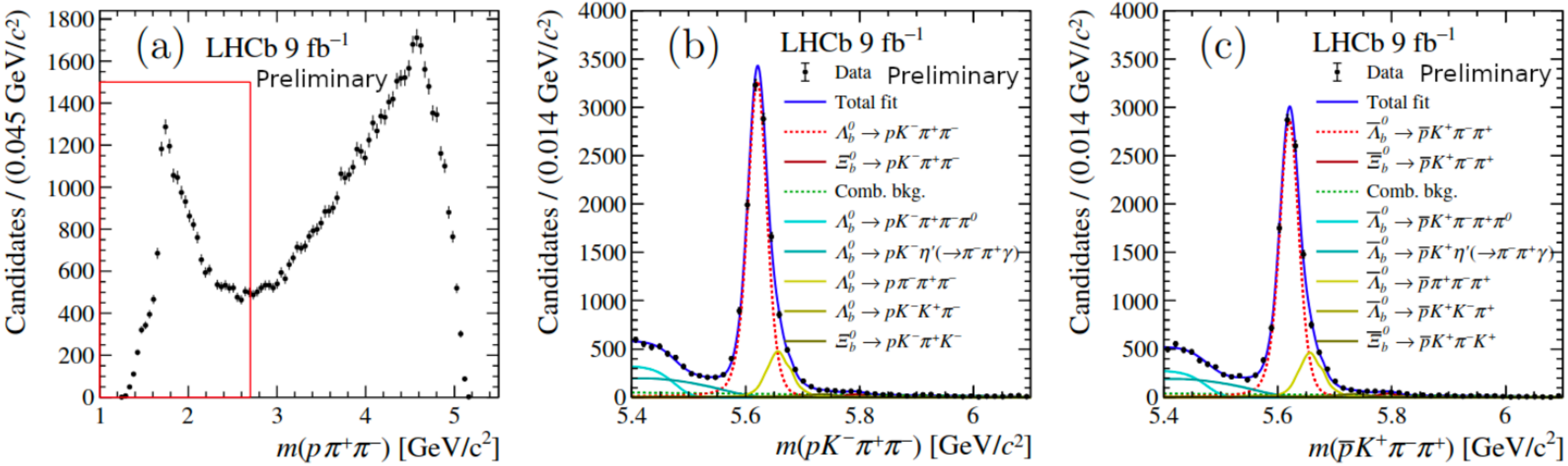
Putting everything together



$$\mathcal{A}_{CP} = (2.45 \pm 0.46 \pm 0.10)\% \,.$$

This CP asymmetry differs from zero by 5.2 standard deviations, marking the observation of CP violation !

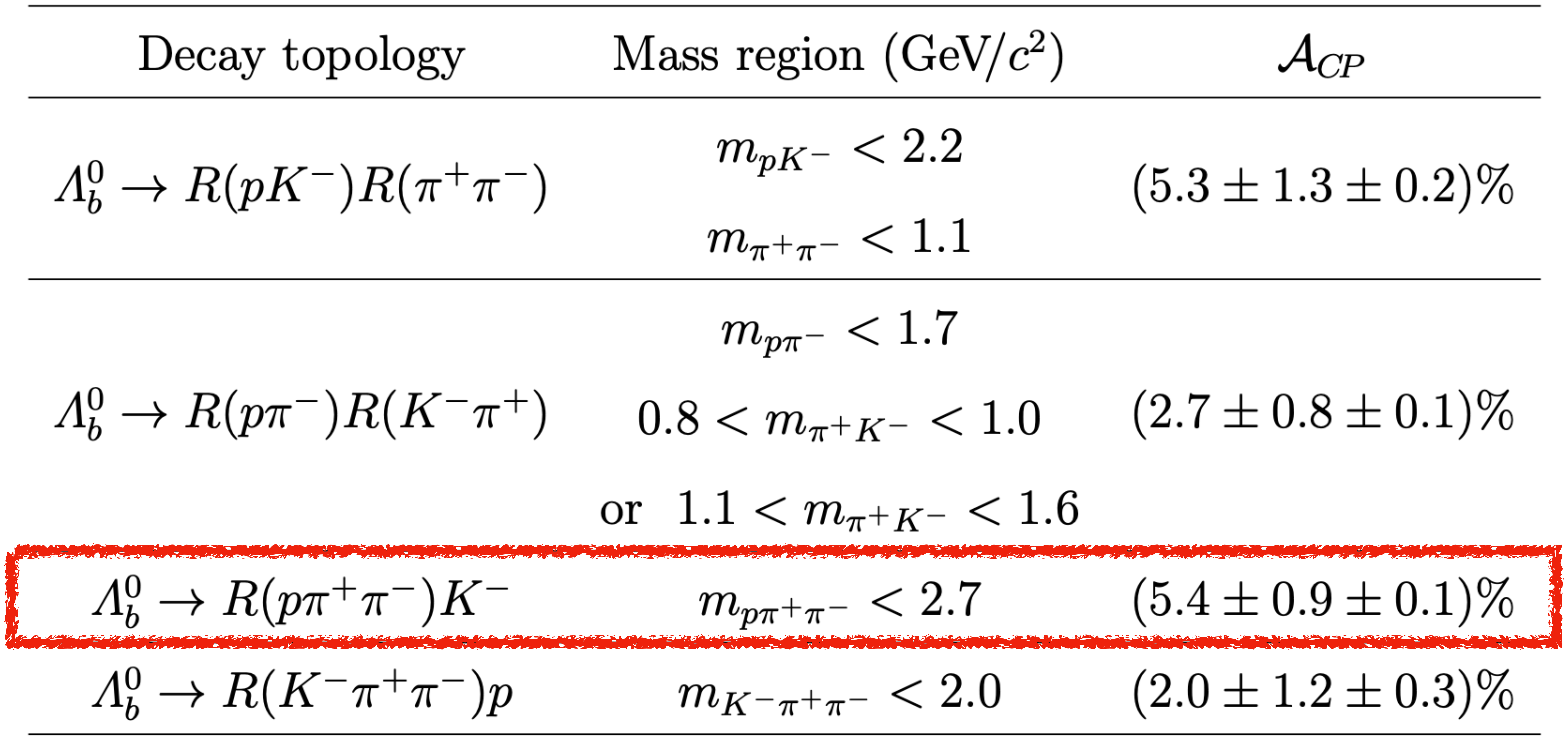
Taking it one step further



Studies in different mass region to study local effects

Taking it one step further

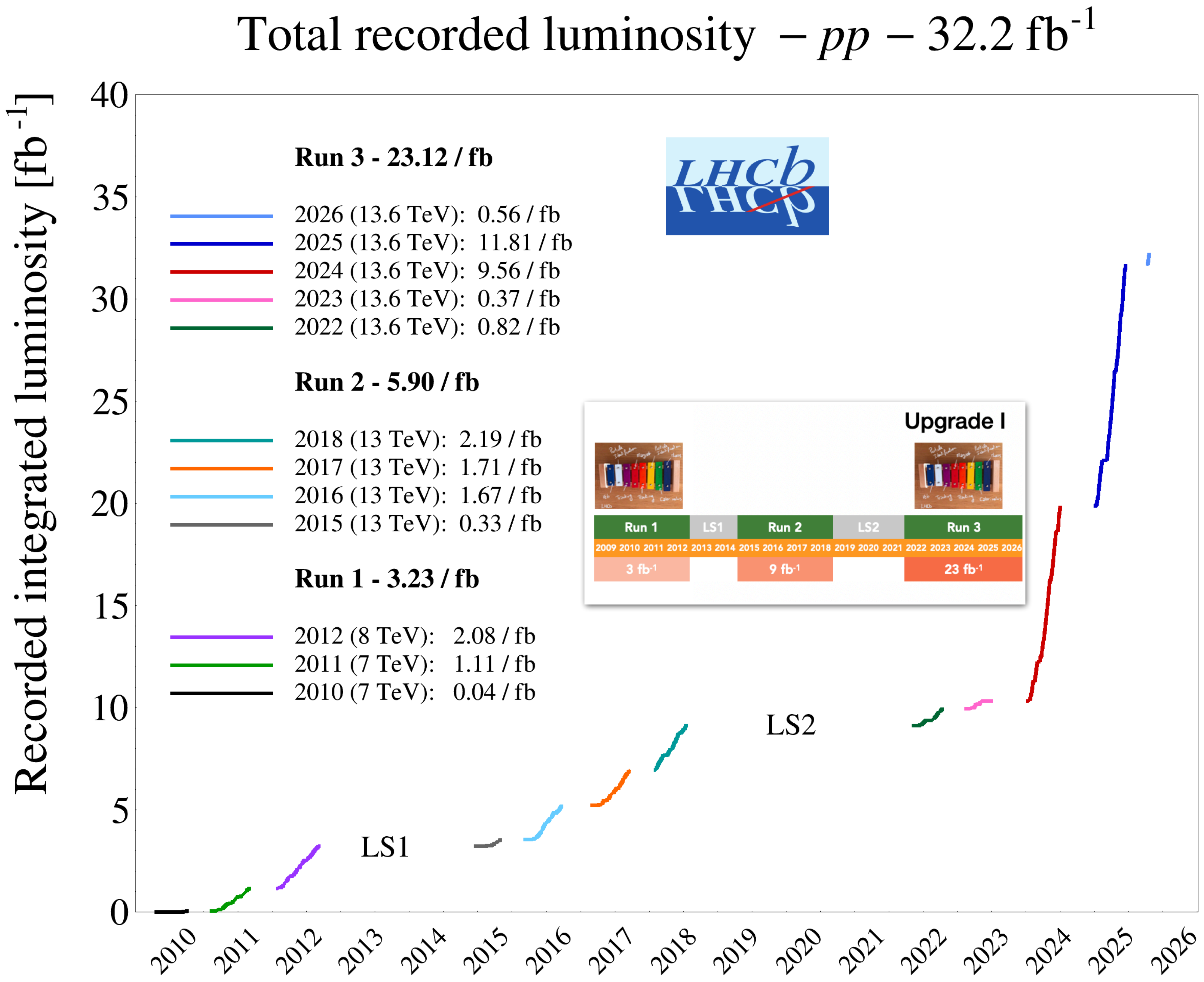
Observe up to 6 standard deviations locally



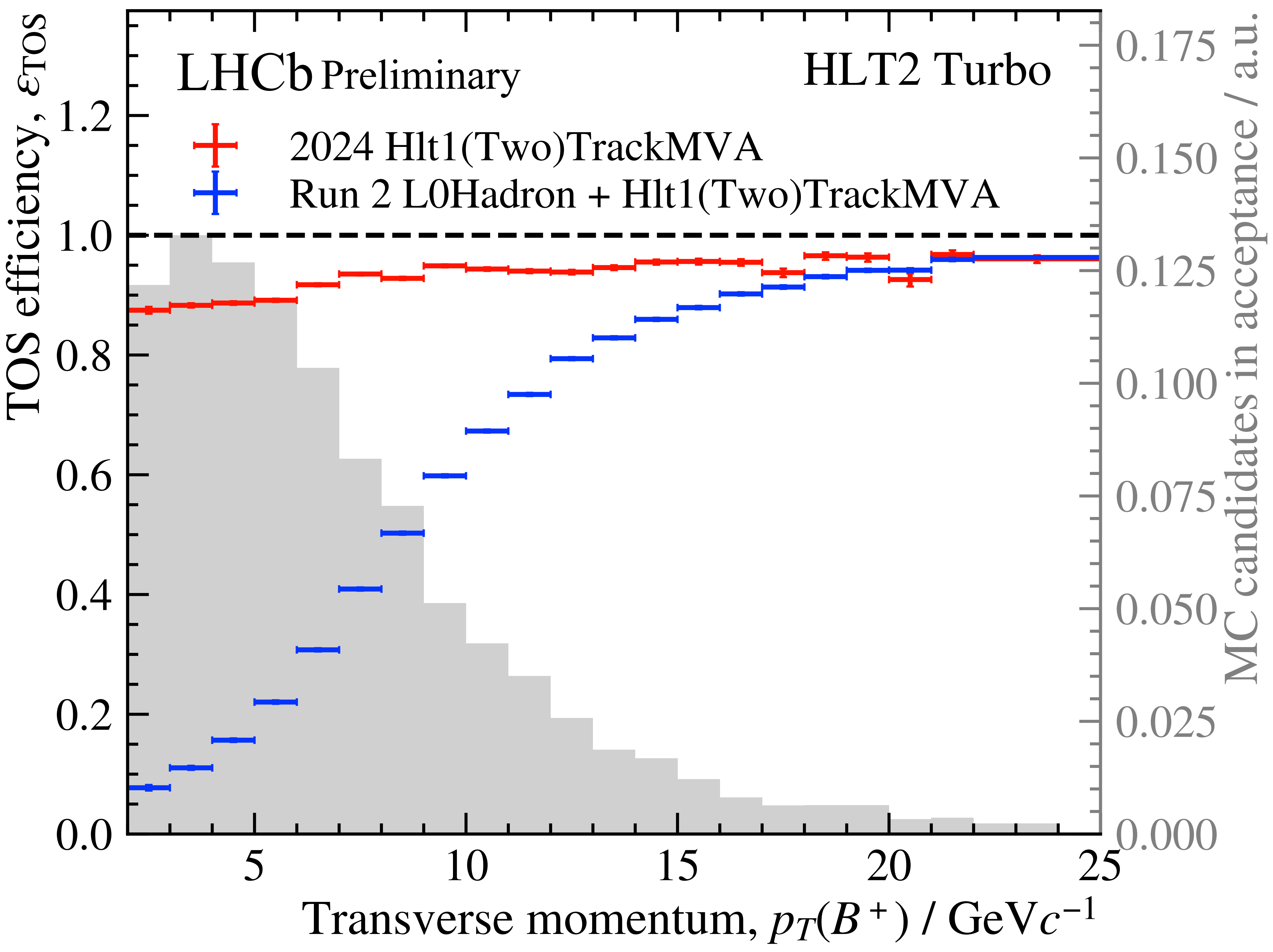
Decay topology	Mass region (GeV/c^2)	$\mathcal{A}_{CP}$
$\Lambda_b^0 \to R(pK^-)R(\pi^+\pi^-)$	$m_{pK^-} < 2.2$ $m_{\pi^+\pi^-} < 1.1$	$(5.3 \pm 1.3 \pm 0.2)\%$
$\Lambda_b^0 \to R(p\pi^-)R(K^-\pi^+)$	$m_{p\pi^-} < 1.7$ $0.8 < m_{\pi^+K^-} < 1.0$ or $1.1 < m_{\pi^+K^-} < 1.6$	$(2.7 \pm 0.8 \pm 0.1)\%$
$\Lambda_b^0 \to R(p\pi^+\pi^-)K^-$	$m_{p\pi^+\pi^-} < 2.7$	$(5.4 \pm 0.9 \pm 0.1)\%$
$\Lambda_b^0 \to R(K^-\pi^+\pi^-)p$	$m_{K^-\pi^+\pi^-} < 2.0$	$(2.0 \pm 1.2 \pm 0.3)\%$

This discovery strongly suggests that
specific intermediate resonances play a key role in
generating CP violation

LHCb in Run 3



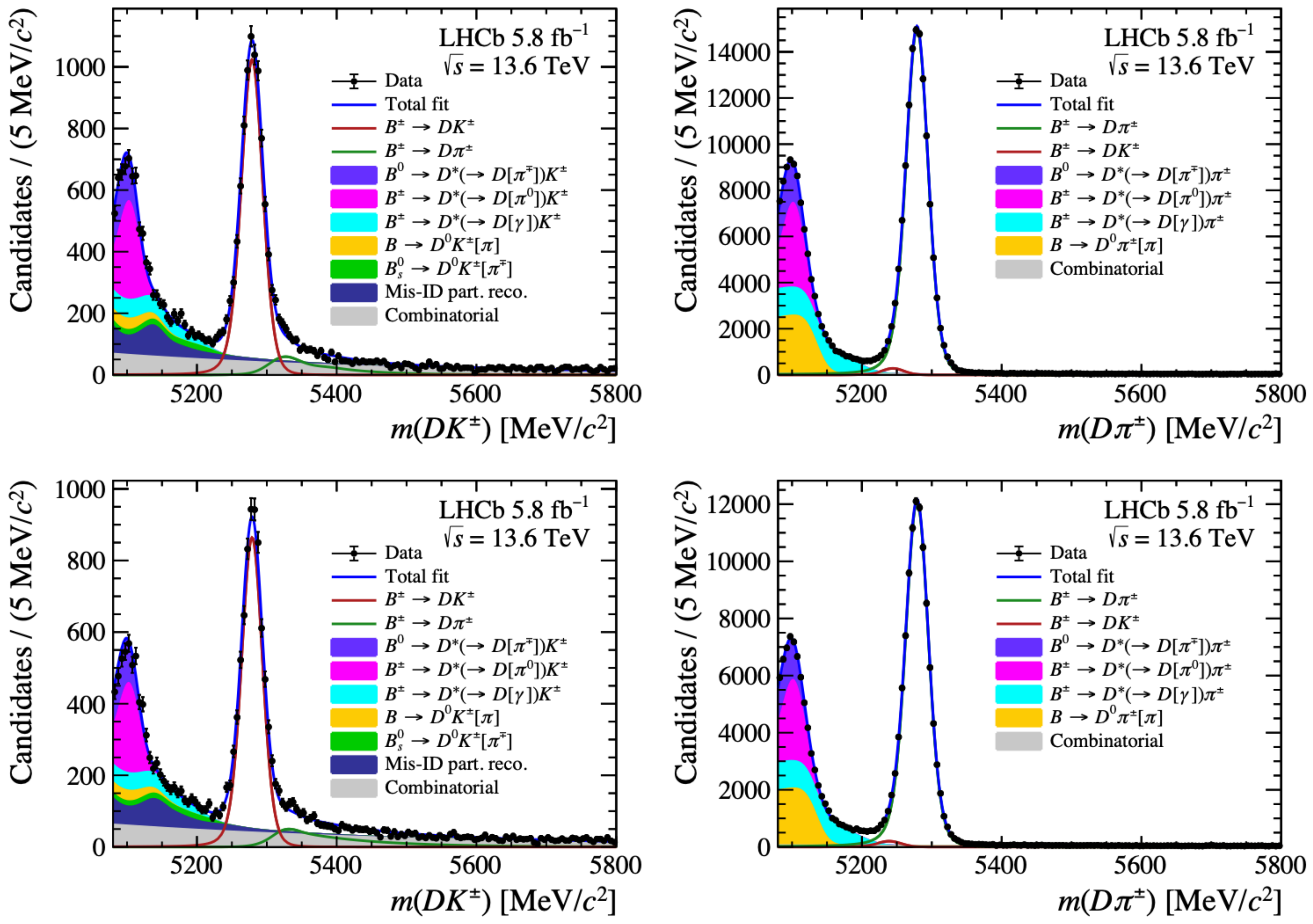
LHCb-FIGURE-2024-030



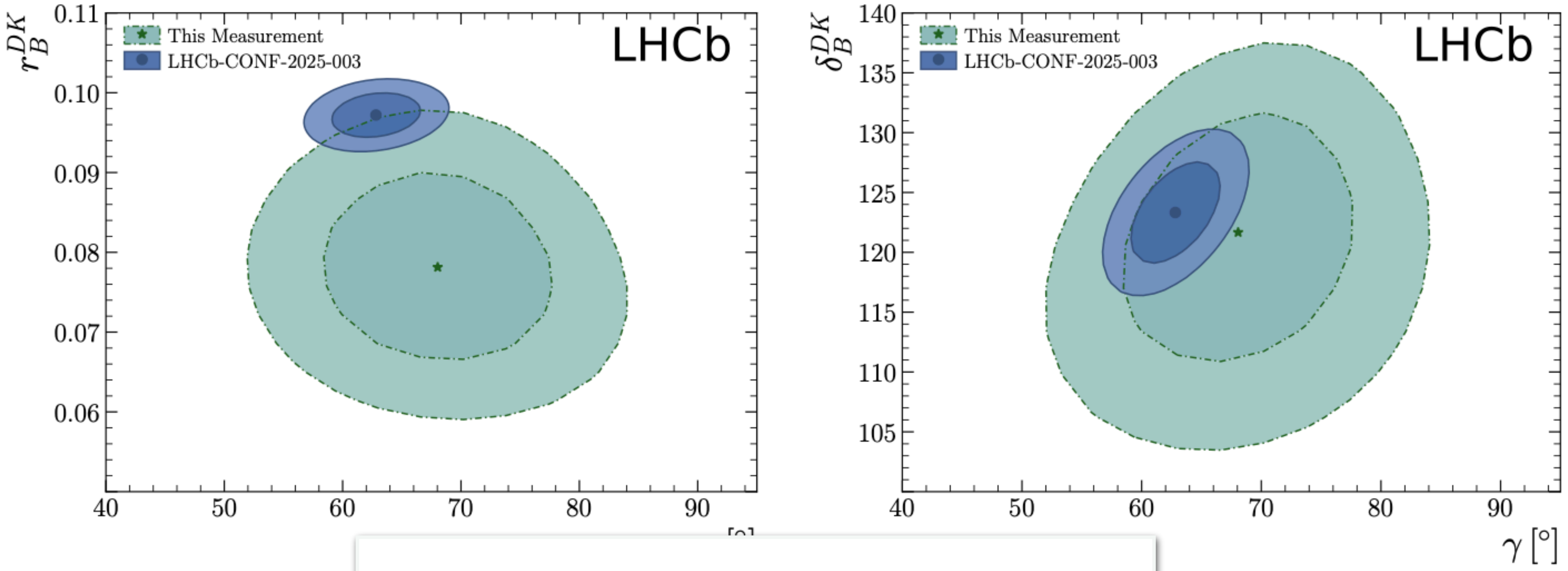
Doubled the recorded integrated luminosity thanks to excellent detector&LHC performance

More than doubled the efficiency for hadronic signals thanks to 30 MHz GPU tracking trigger

A measurement of γ using $B^{\pm} \to DK^{\pm}$ and $B^{\pm} \to D\pi^{\pm}$ decays with $D \to K^0_S\pi^+\pi^-$ and $D \to K^0_S K^+ K^-$



LHCb-PAPER-2026-010

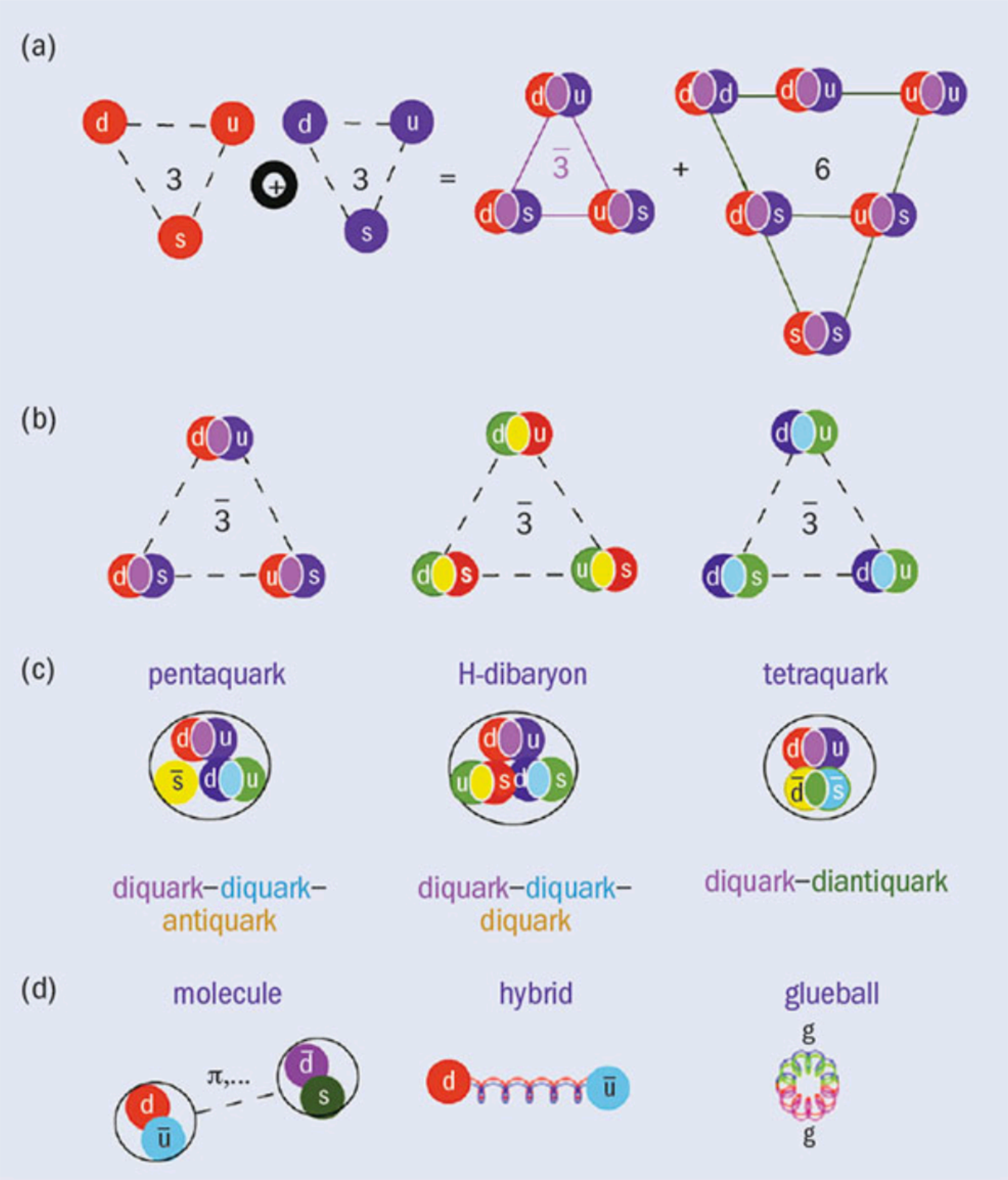


$$\gamma = (68.1 \pm 6.7)^\circ,$$
$$r_B^{DK} = 0.0781^{+0.0078}_{-0.0079},$$
$$\delta_B^{DK} = (121.5^{+6.9}_{-7.4})^\circ,$$
$$r_B^{D\pi} = 0.0073^{+0.0016}_{-0.0015},$$
$$\delta_B^{D\pi} = (286^{+20}_{-23})^\circ,$$

- ✦ It is the first γ measurement with Run3 !
- ✦ Higher signal yields observed with less integrated luminosity
- ✦ These results show good agreement with the previous measurement

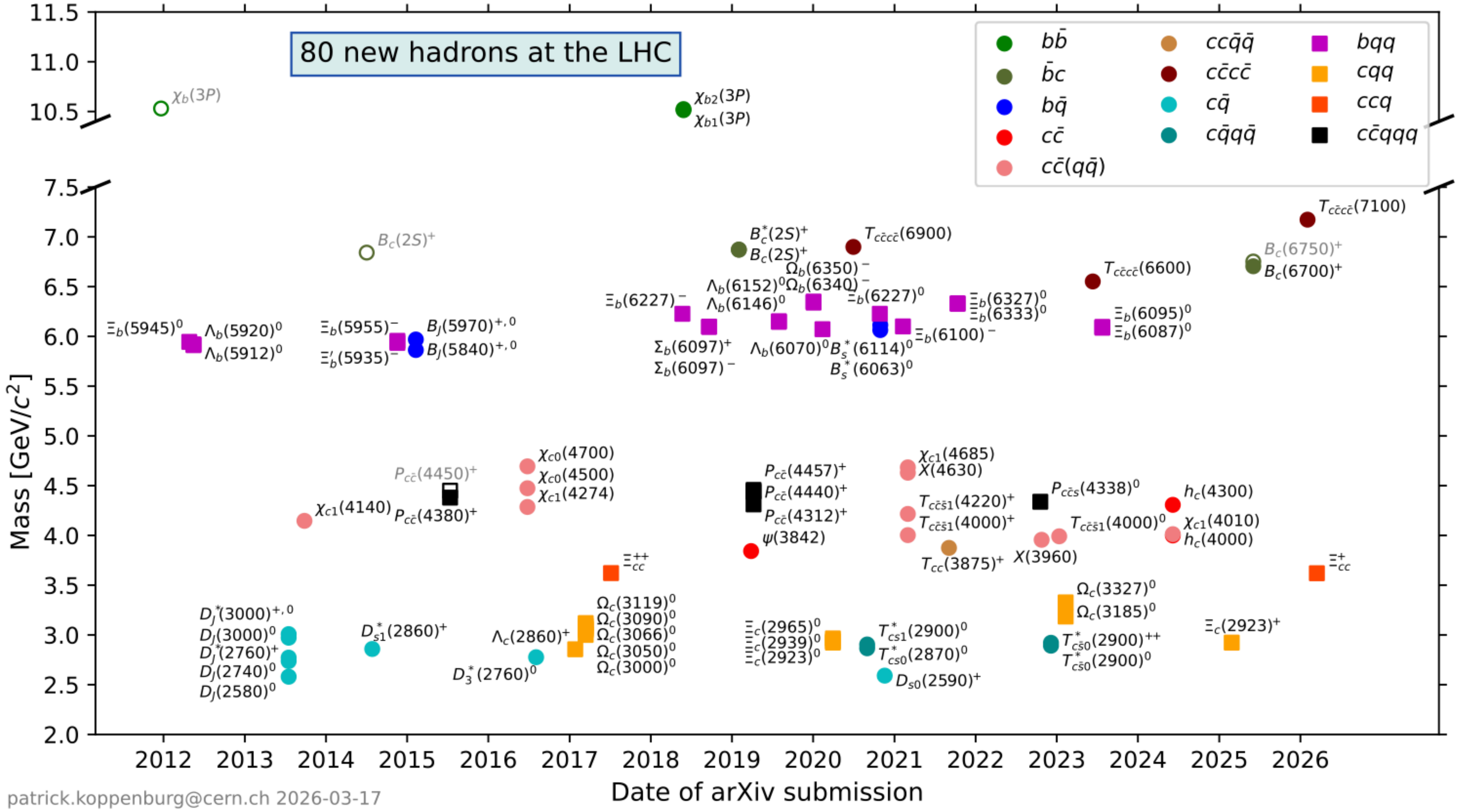
Hadrons !

One fundamental particle was discovered at the LHC so far…but also ~~75~~ new hadrons at the LHC

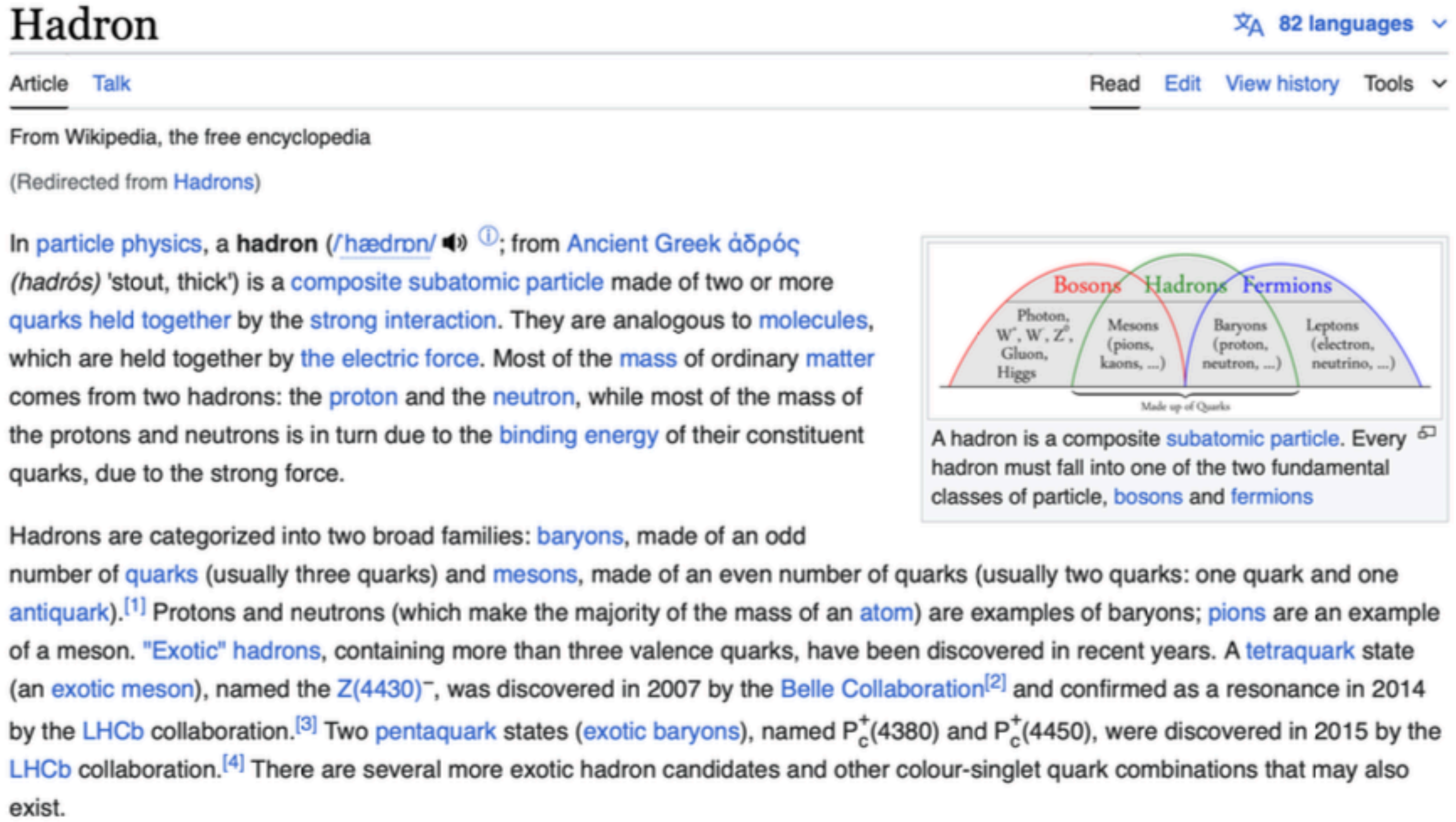


This is the land of spectroscopy !

https://cerncourier.com/a/exotic-hadrons-bend-the-rules/



patrick.koppenburg@cern.ch 2026-03-17



Hadron

From Wikipedia, the free encyclopedia

(Redirected from Hadrons)

In particle physics, a **hadron** (/ˈhædrɒn/; from Ancient Greek ἁδρός *(hadrós)* 'stout, thick') is a composite subatomic particle made of two or more quarks held together by the strong interaction. They are analogous to molecules, which are held together by the electric force. Most of the mass of ordinary matter comes from two hadrons: the proton and the neutron, while most of the mass of the protons and neutrons is in turn due to the binding energy of their constituent quarks, due to the strong force.

A hadron is a composite subatomic particle. Every hadron must fall into one of the two fundamental classes of particle, bosons and fermions

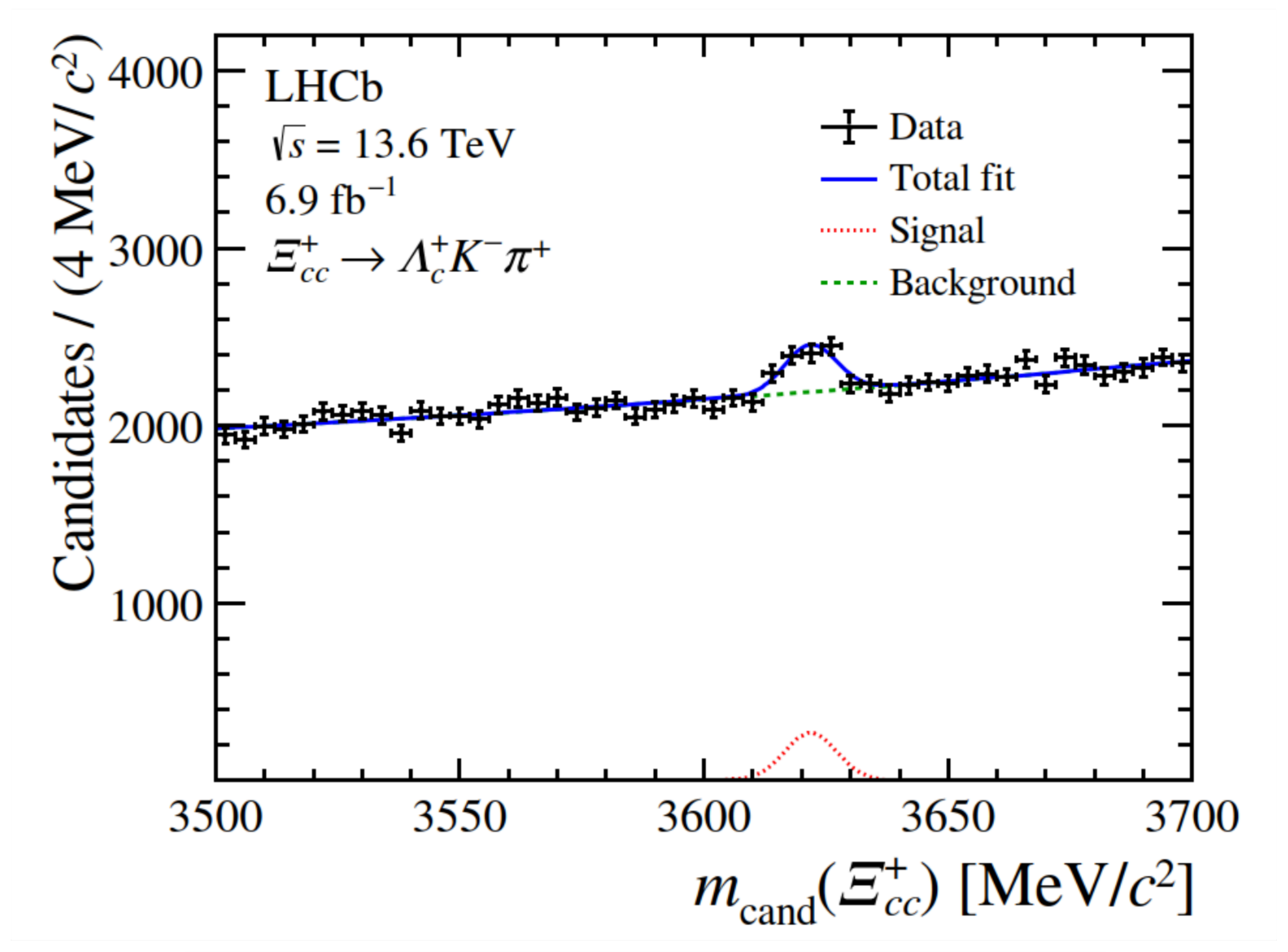
Hadrons are categorized into two broad families: baryons, made of an odd number of quarks (usually three quarks) and mesons, made of an even number of quarks (usually two quarks: one quark and one antiquark).[1] Protons and neutrons (which make the majority of the mass of an atom) are examples of baryons; pions are an example of a meson. "Exotic" hadrons, containing more than three valence quarks, have been discovered in recent years. A tetraquark state (an exotic meson), named the Z(4430)⁻, was discovered in 2007 by the Belle Collaboration[2] and confirmed as a resonance in 2014 by the LHCb collaboration.[3] Two pentaquark states (exotic baryons), named $P_c^+(4380)$ and $P_c^+(4450)$, were discovered in 2015 by the LHCb collaboration.[4] There are several more exotic hadron candidates and other colour-singlet quark combinations that may also exist.

New discovery !

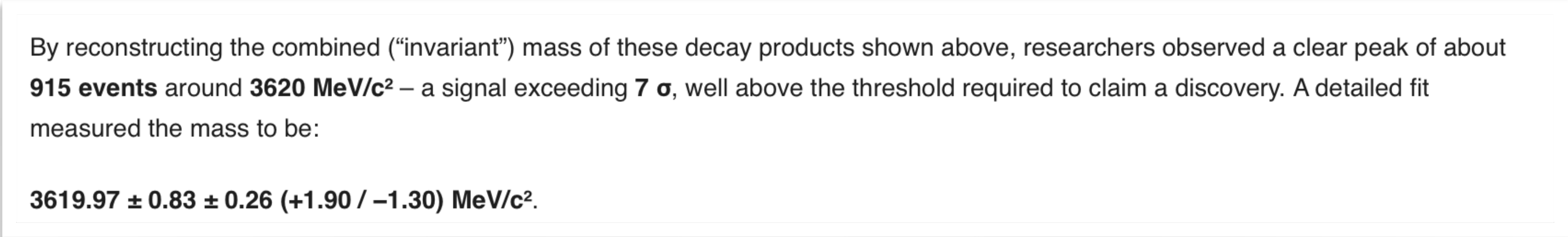
Scientists discover heavier version of proton with upgraded detector

Snappily named Xi-cc-plus, Cern physicists spotted the particle in shower of debris that lit up Large Hadron Collider

Illustration of the newly discovered Xi-cc-plus particle. Photograph: Cern



[LHCb-PAPER-2026-009, in preparation]



By reconstructing the combined ("invariant") mass of these decay products shown above, researchers observed a clear peak of about **915 events** around **3620 MeV/c²** – a signal exceeding **7 σ**, well above the threshold required to claim a discovery. A detailed fit measured the mass to be:

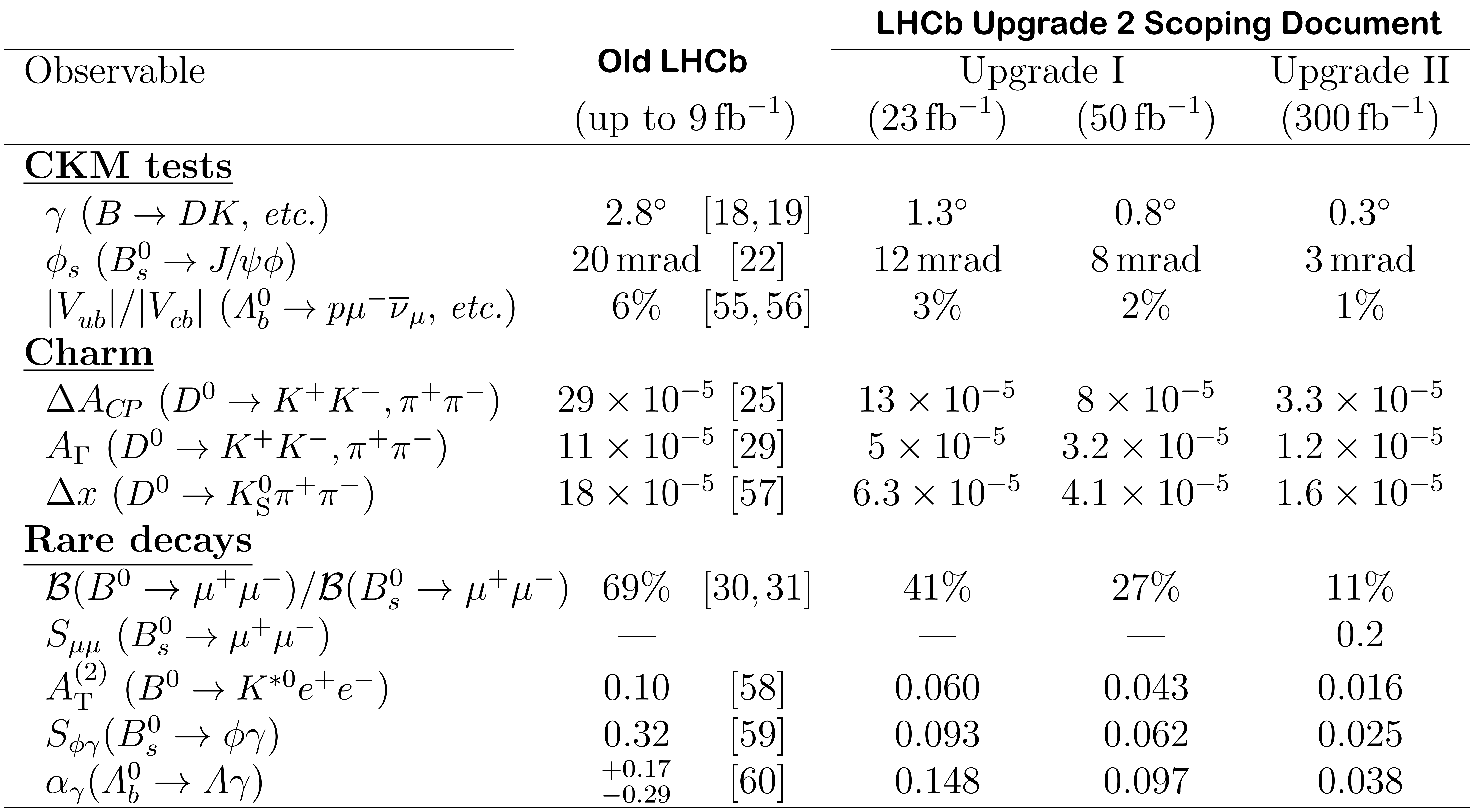
3619.97 ± 0.83 ± 0.26 (+1.90 / −1.30) MeV/c².

Preparing the future…now


Upgrade II workshop @Heidelberg March 25

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}

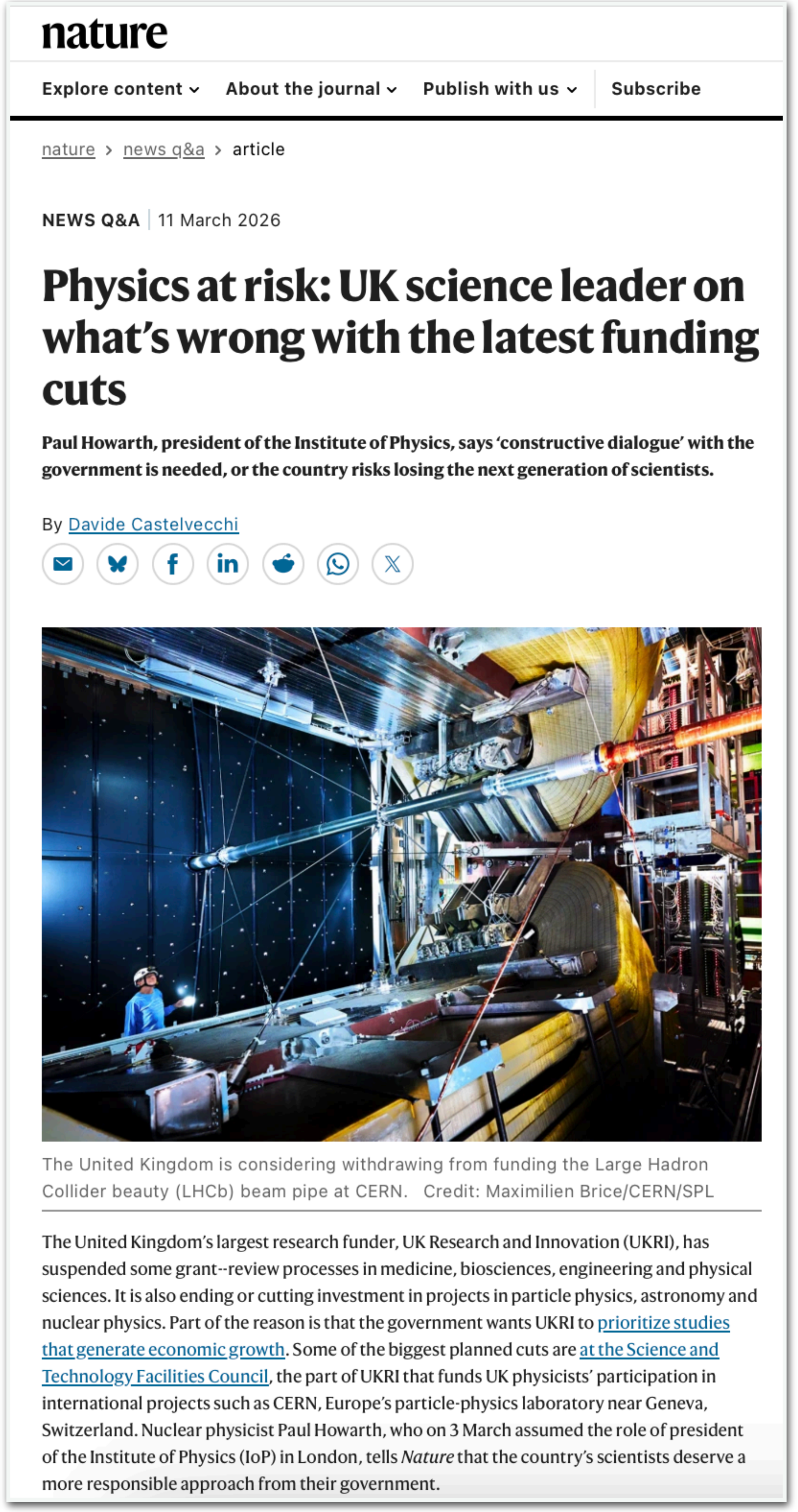
Why another LHCb upgrade?



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



NEWS Q&A | 11 March 2026

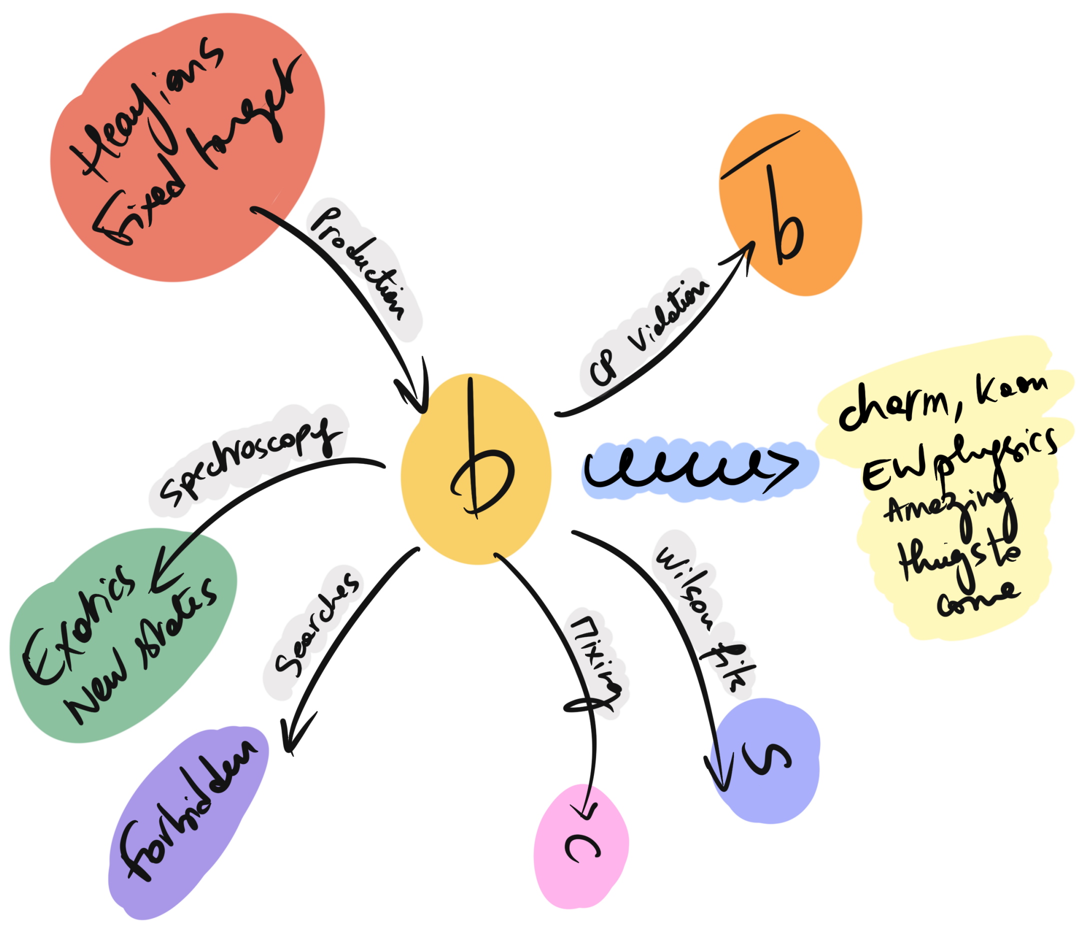
Physics at risk: UK science leader on what's wrong with the latest funding cuts

Paul Howarth, president of the Institute of Physics, says 'constructive dialogue' with the government is needed, or the country risks losing the next generation of scientists.

By Davide Castelvecchi

The United Kingdom is considering withdrawing from funding the Large Hadron Collider beauty (LHCb) beam pipe at CERN. Credit: Maximilien Brice/CERN/SPL

The United Kingdom's largest research funder, UK Research and Innovation (UKRI), has suspended some grant--review processes in medicine, biosciences, engineering and physical sciences. It is also ending or cutting investment in projects in particle physics, astronomy and nuclear physics. Part of the reason is that the government wants UKRI to prioritize studies that generate economic growth. Some of the biggest planned cuts are at the Science and Technology Facilities Council, the part of UKRI that funds UK physicists' participation in international projects such as CERN, Europe's particle-physics laboratory near Geneva, Switzerland. Nuclear physicist Paul Howarth, who on 3 March assumed the role of president of the Institute of Physics (IoP) in London, tells *Nature* that the country's scientists deserve a more responsible approach from their government.



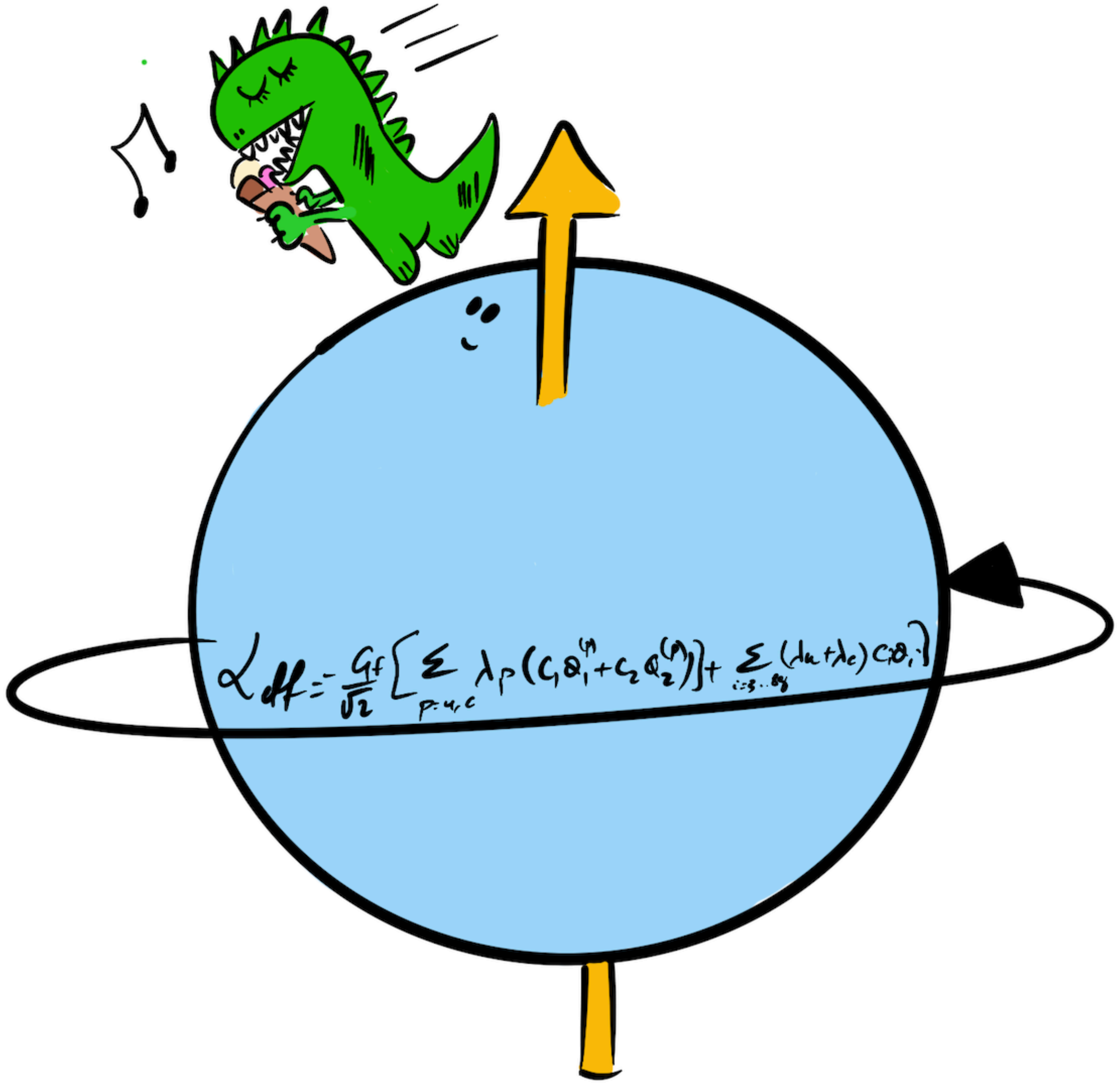
IOP responds to cancellation of UK funding for major international science projects

UK Research and Infrastructure (UKRI) has confirmed that it is cancelling UK funding for four major physics infrastructure projects: the Large Hadron Collider b (LHCb) upgrade; the US-based Electron-Ion Collider (EIC) particle accelerator; and two UK-based national facilities: the Relativistic Ultrafast Electron Diffraction and Imaging (RUEDI) and the Critical Mass (C-MASS) spectrometry facility.

The news, first reported by **Research Professional News** (RPN) and **confirmed in RPN** and then the ***Financial Times*** yesterday following a media briefing from UKRI Chief Executive Sir Ian Chapman - comes on top of **severe concerns expressed by the physics community** over funding cuts announced on 28 January by the Science and Technology Facilities Council (STFC).

Conclusions

- Flavour physics is an excellent approach to help us shed the light on many unknowns.
- LHCb is a powerful environment to answer (some) of these questions.
- There is enough left to understand to keep us busy for at least a couple of decades (probably more).
- Thank you for the invitation !



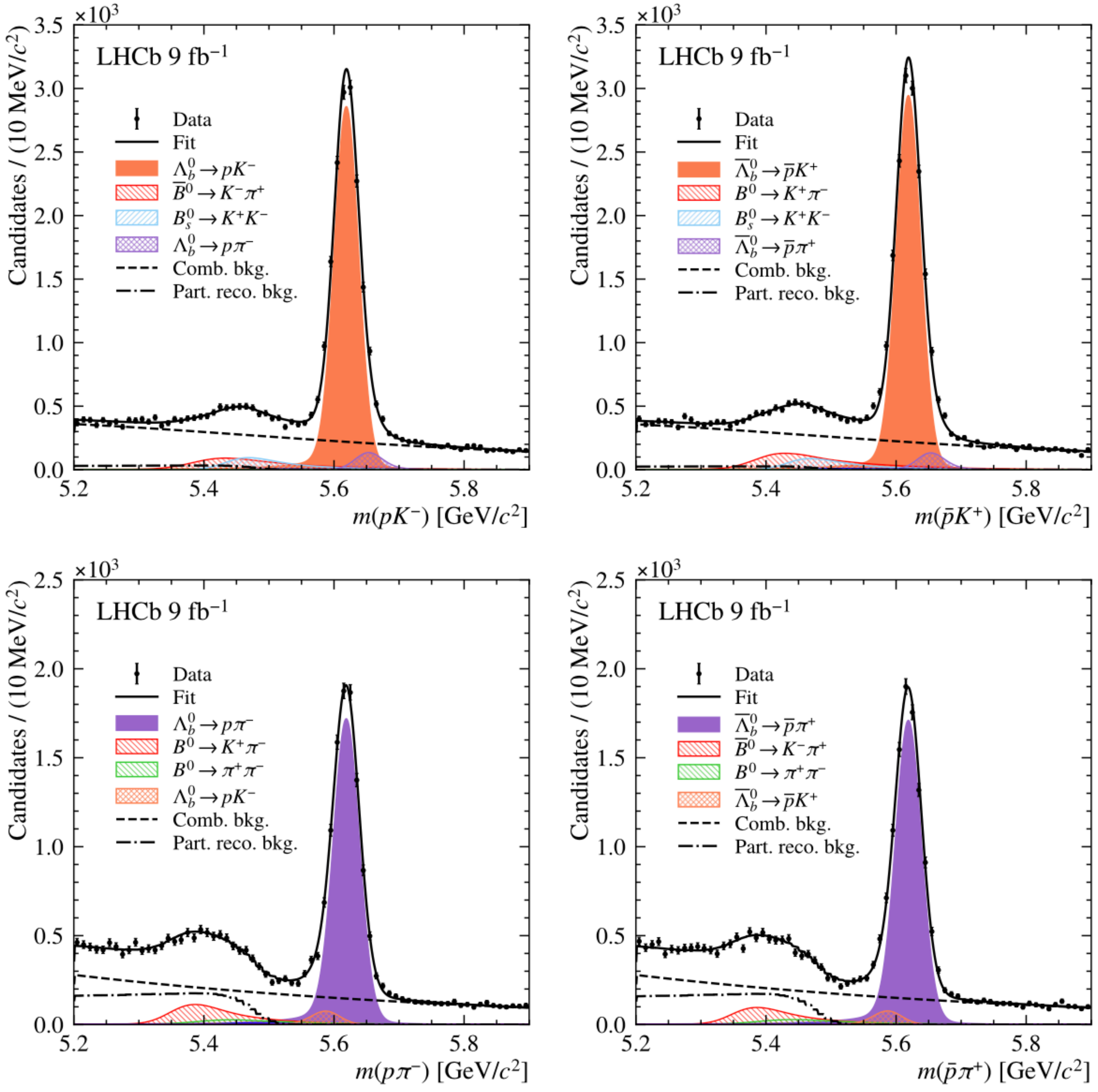
A colouring book available at the CERN Science Gateway : French, English, German and Italian
Online : also Spanish, Basque, Portuguese, Serbo-Croate, Chinese

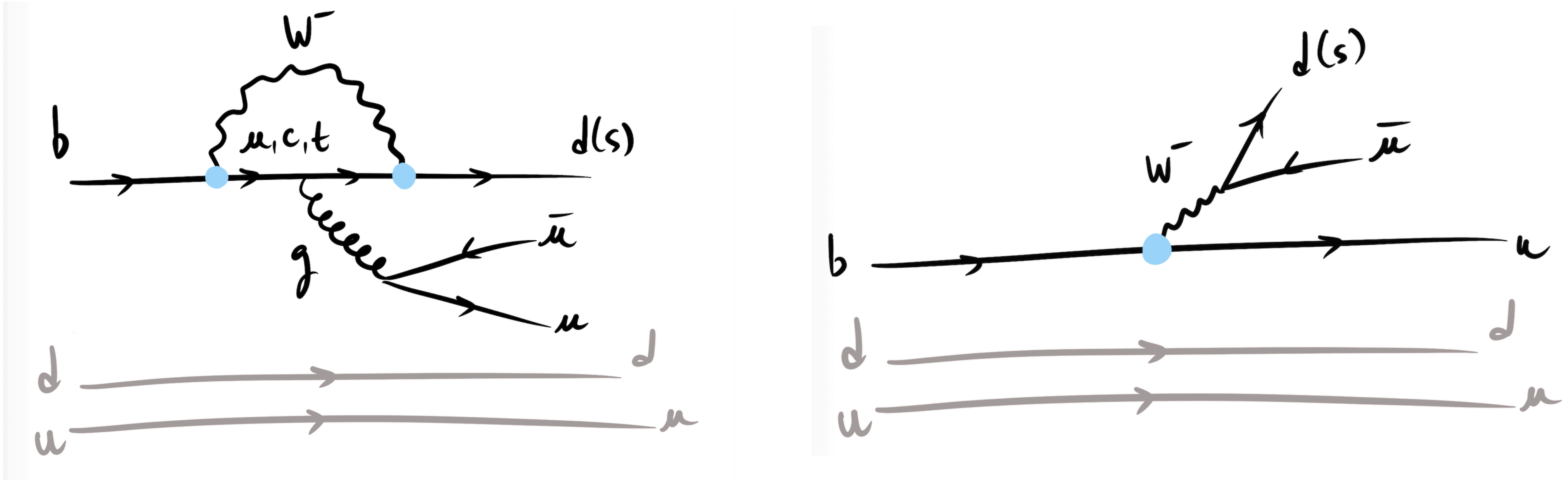
More information yasmineamhis.com
Kids can now send their drawings too https://lhcb-outreach.web.cern.ch/lhcbkidbook/

A colouring book for children is available at the CERN Science Gateway - also in German

More information yasmineamhis.com

Measurement of CP asymmetries in $\Lambda_b^0 \to p h^-$ decays





Experimental techniques are very similar

$$A_{CP}^{pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%,$$
$$A_{CP}^{p\pi^-} = (\ \ 0.2 \pm 0.8 \pm 0.4)\%,$$

No evidence of CP violation is found

arXiv:2412.13958

Info about the tiny creatures www.yasmineamhis.com

Backup slides

Upgrades

CERN/LHCC 2021-012
LHCb TDR 23
24 February 2022

Framework TDR

LHCb UPGRADE II

Technical Design Report

[LHCC-2021-012]

Framework TDR

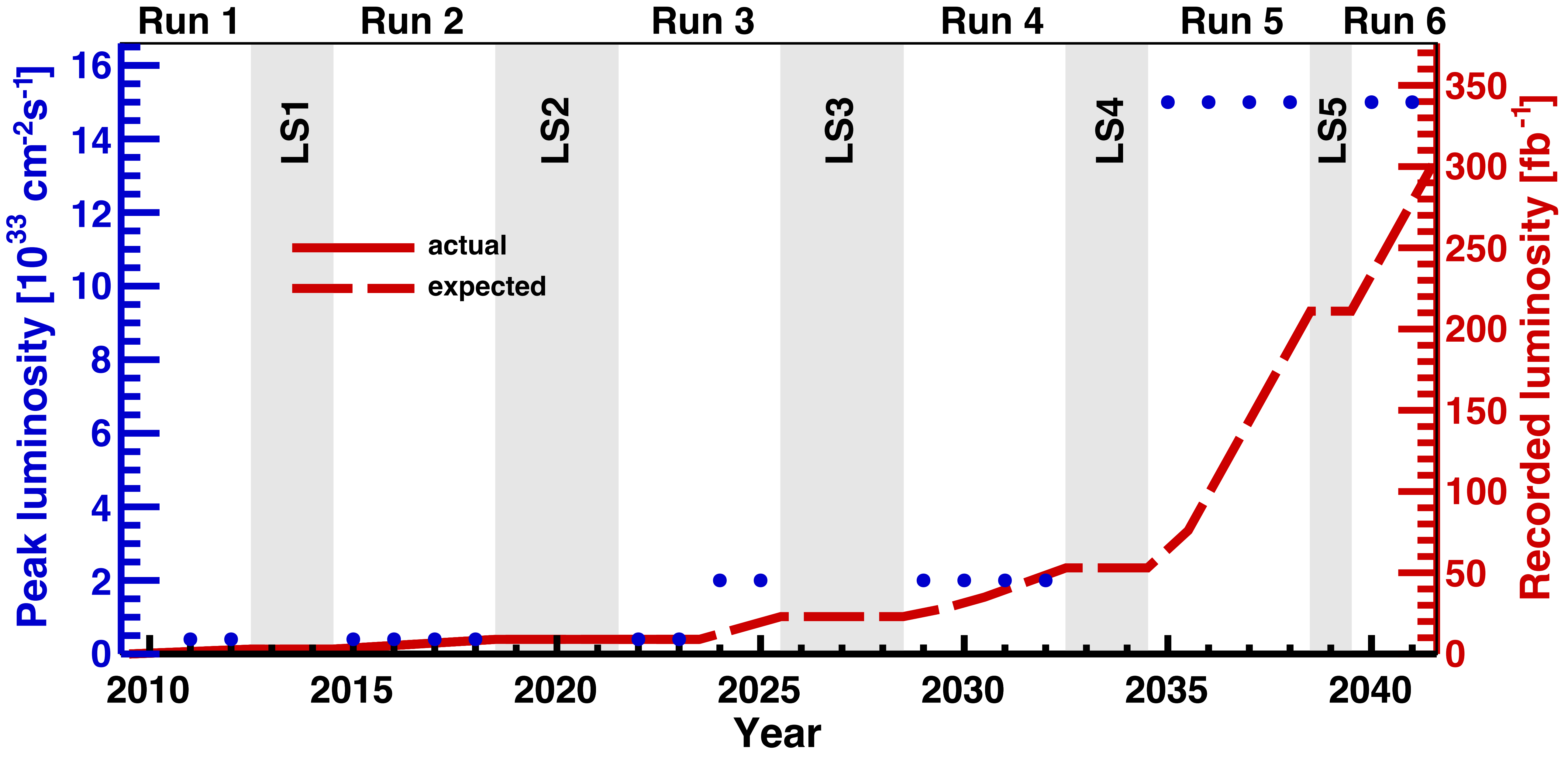
The LHCb upgrades

Physics programme limited by detector, so there's a clear case for an ambitious plan of upgrades covering the full HL-LHC phase

Upgrade I just started

- $L_{peak} = 2 \times 10^{33}\ cm^{-2}\ s^{-1}$
- $L_{int} = 50\ fb^{-1}$ *during Run 3 & 4*
- *Move to full software trigger, improved efficiency on hadronic modes*

Upgrade I ***Upgrade II***



Upgrade II, installation at LS4

- $L_{peak} = 1.5 \times 10^{34}\ cm^{-2}\ s^{-1}$, $L_{int} = \sim 300\ fb^{-1}$ *during Run 5 & 6*
- *Upgrade I will not saturate precision in many key observables ⇒ Upgrade II will fully realise the flavour-physics potential of the HL-LHC*

endorsed by the European Strategy Update 2020

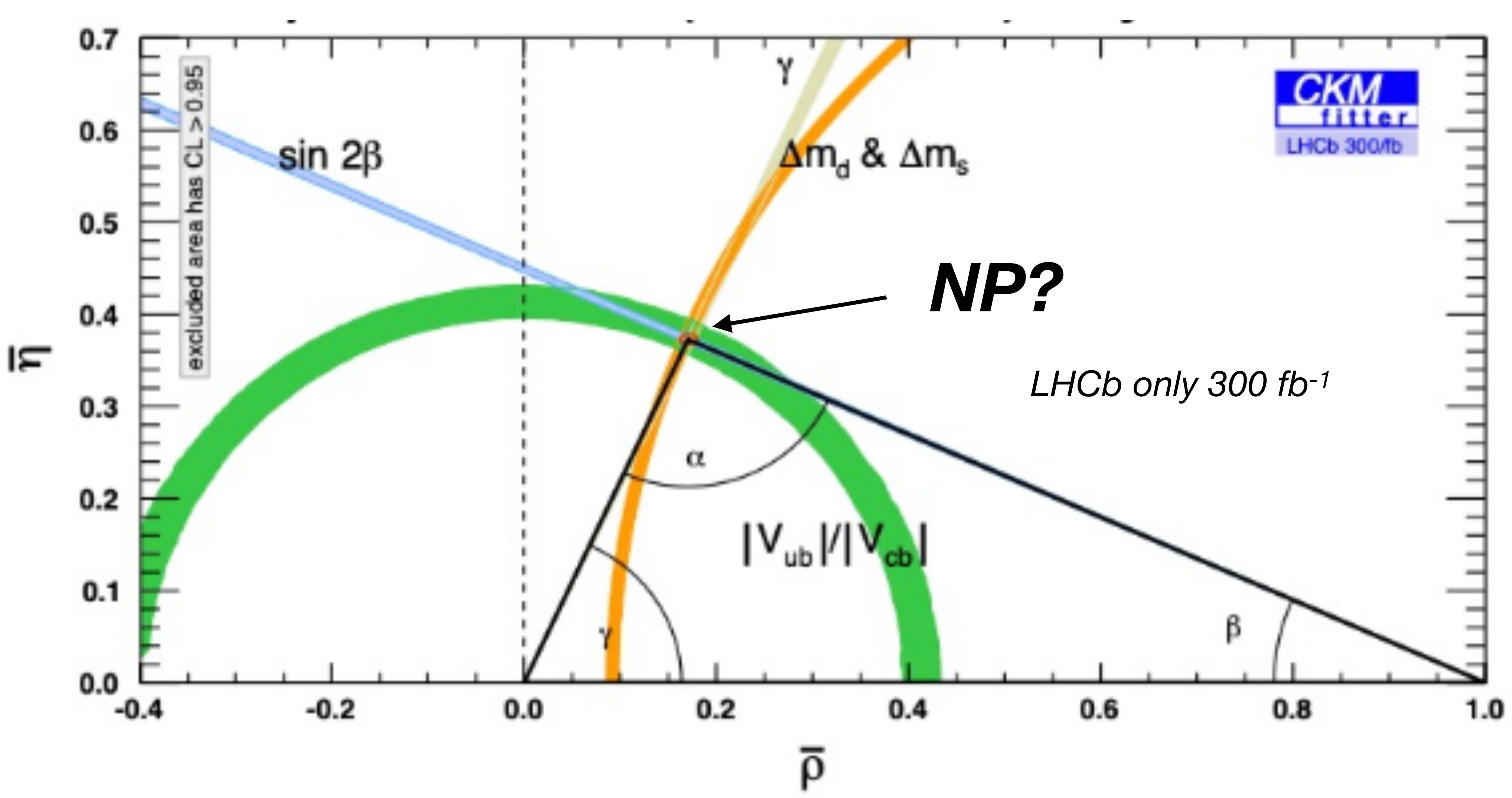
LHCb Upgrade II

- Unprecedented sensitivity for B and D physics
    - Beyond √N scaling with new subdetectors and reconstruction techniques
- Broad general purpose programme with unique forward acceptance
    - Spectroscopy, EW precision measurements, top quark and Higgs physics, dark sector, heavy ions and fixed target

LHCC-2018-027

Physics case

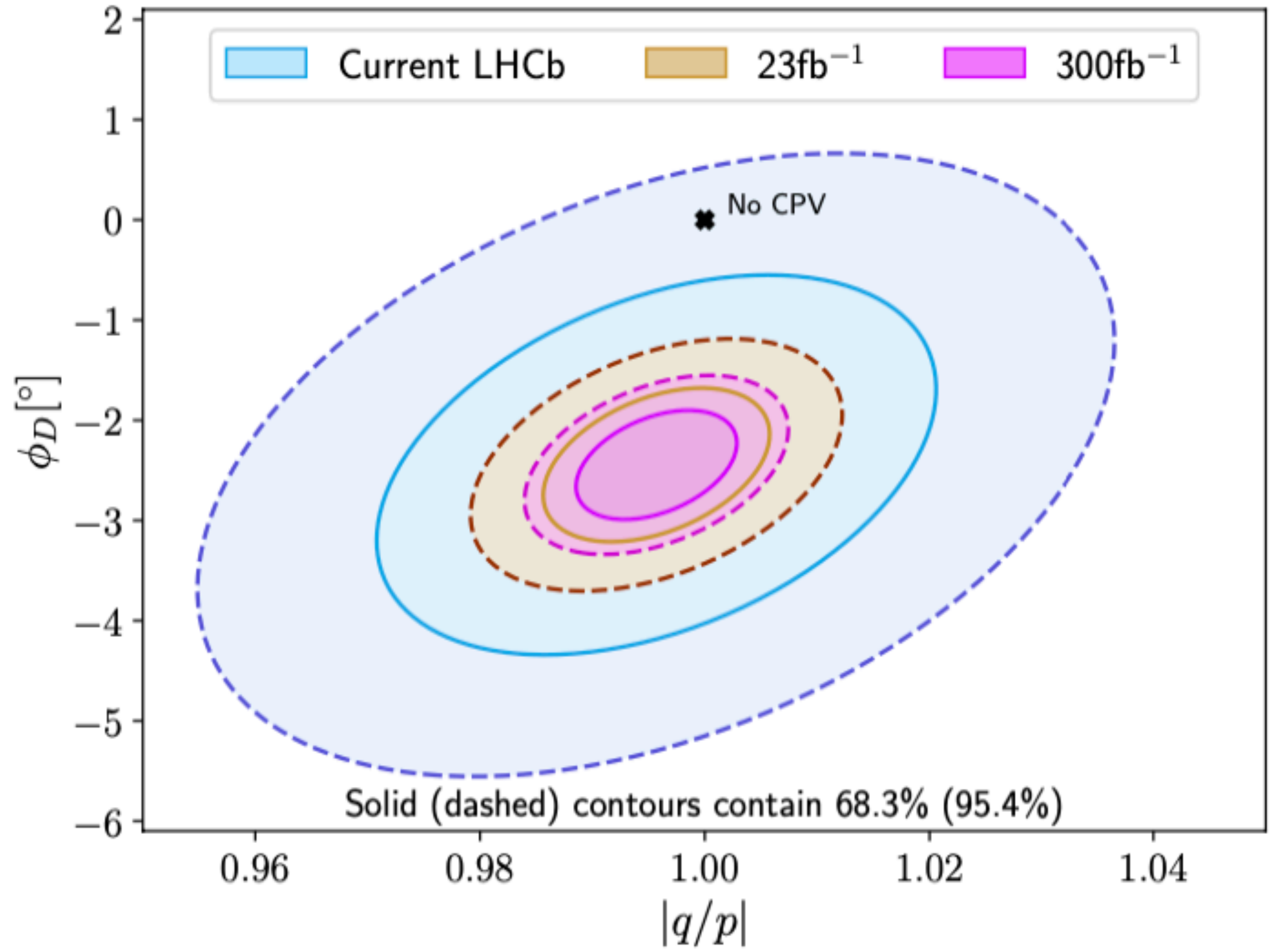
Impressive precision on CP violating phases



NP?

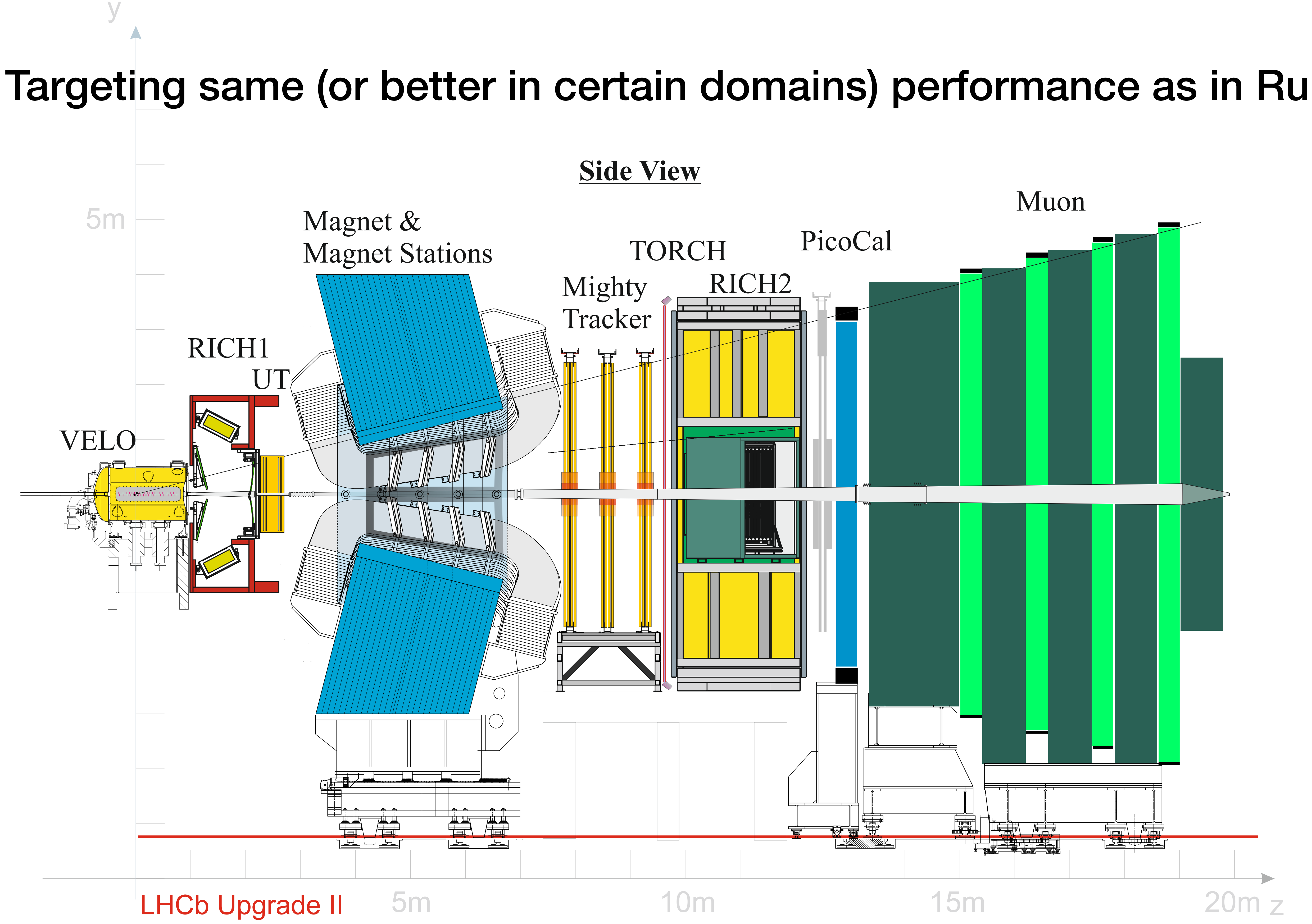
LHCb only 300 fb^{-1}

The only planned facility with a realistic possibility to observe CPV in charm mixing



The detector challenge

Targeting same (or better in certain domains) performance as in Run 3, but with pile-up ×7!



Same spectrometer footprint, innovative technology for detector and data processing

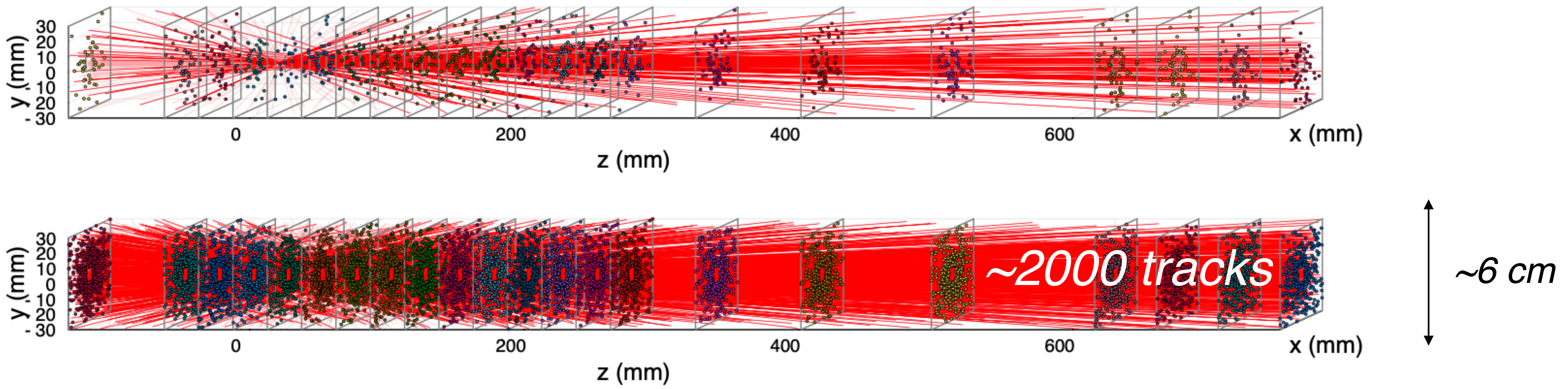
Key ingredients:

- granularity
- fast timing (few tens of ps)
- radiation hardness (up to few $10^{16} n_{eq}/cm^2$)
- data throughput ~200 Tb/s

VErtex LOcator (VELO)

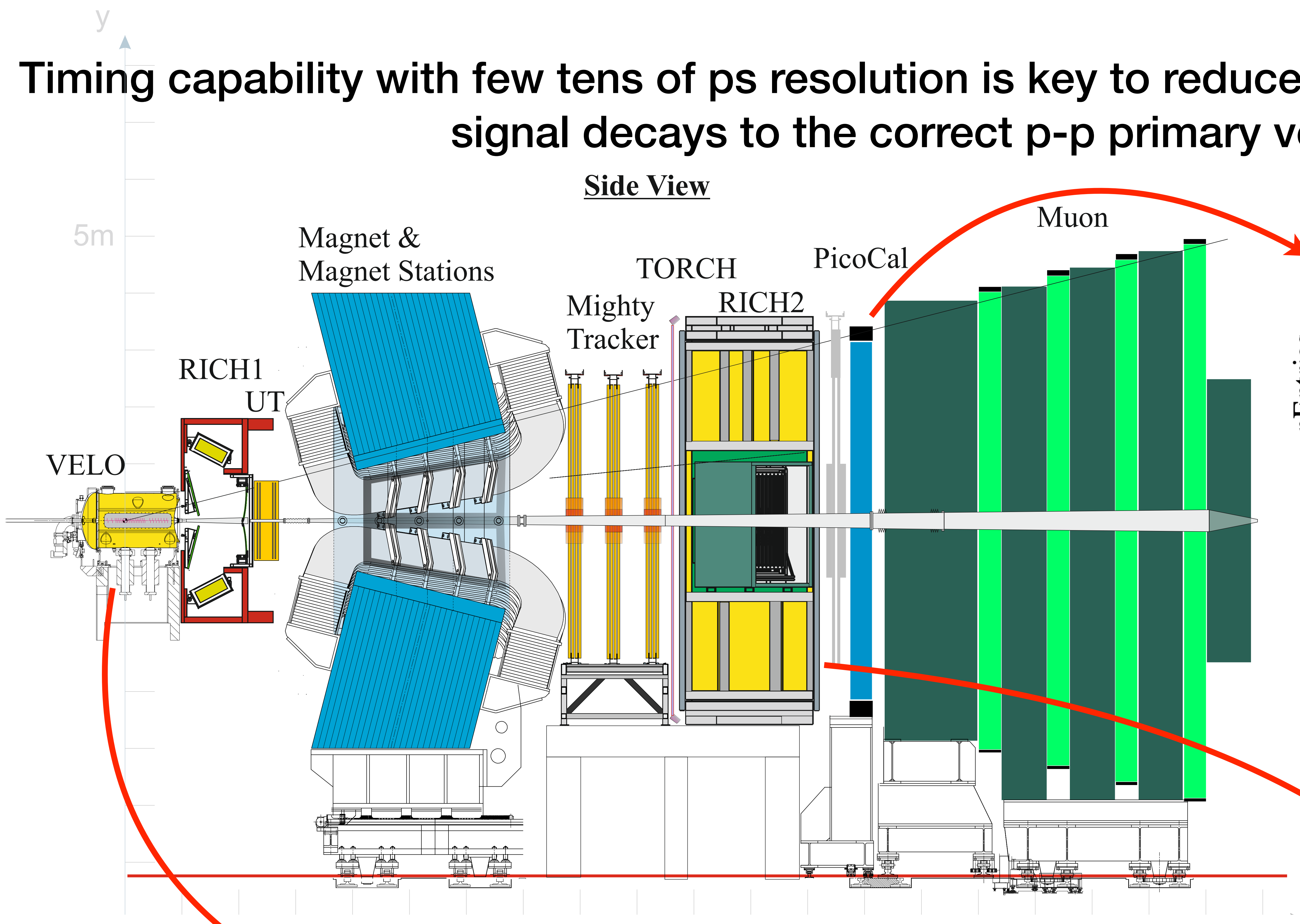
Run 3: pile-up ~6

Upgrade II: pile-up ~40

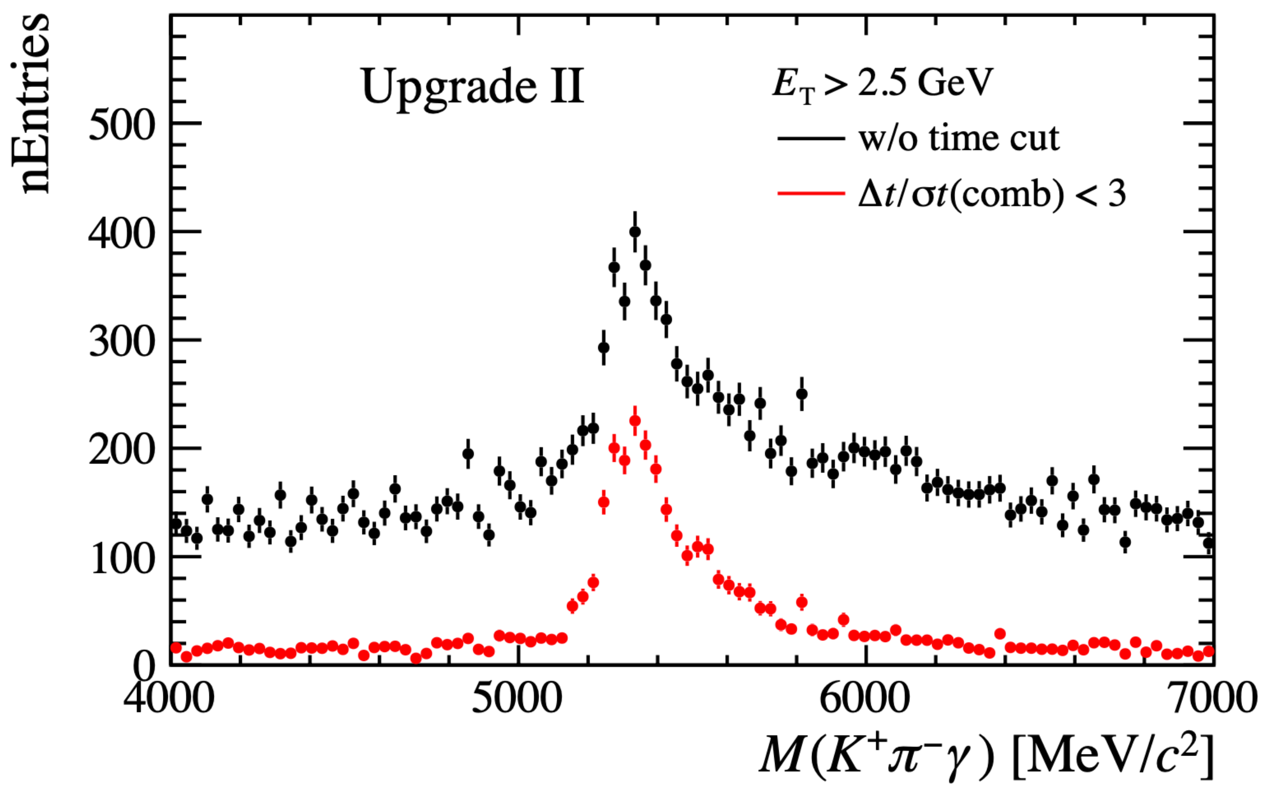


The role of timing

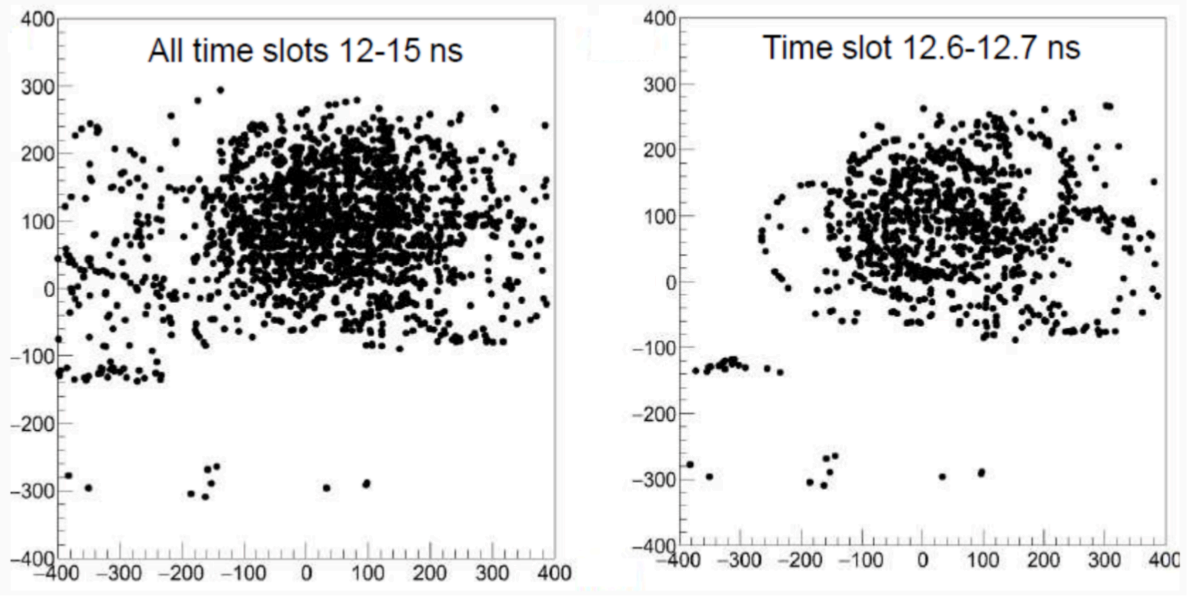
Timing capability with few tens of ps resolution is key to reduce background and associate signal decays to the correct p-p primary vertices



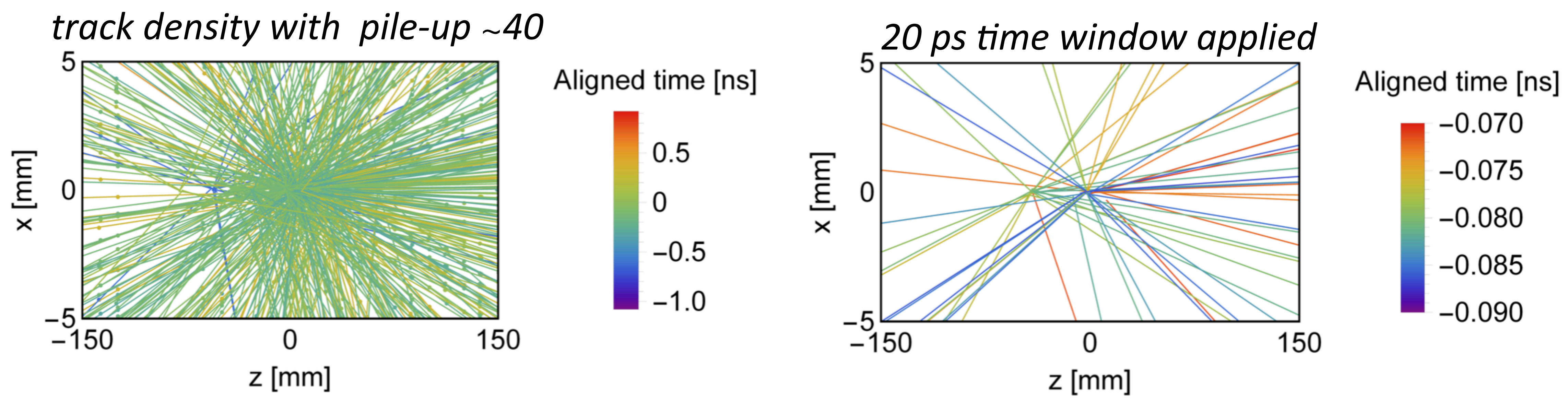
precision timing in calorimeter



precision timing in RICH

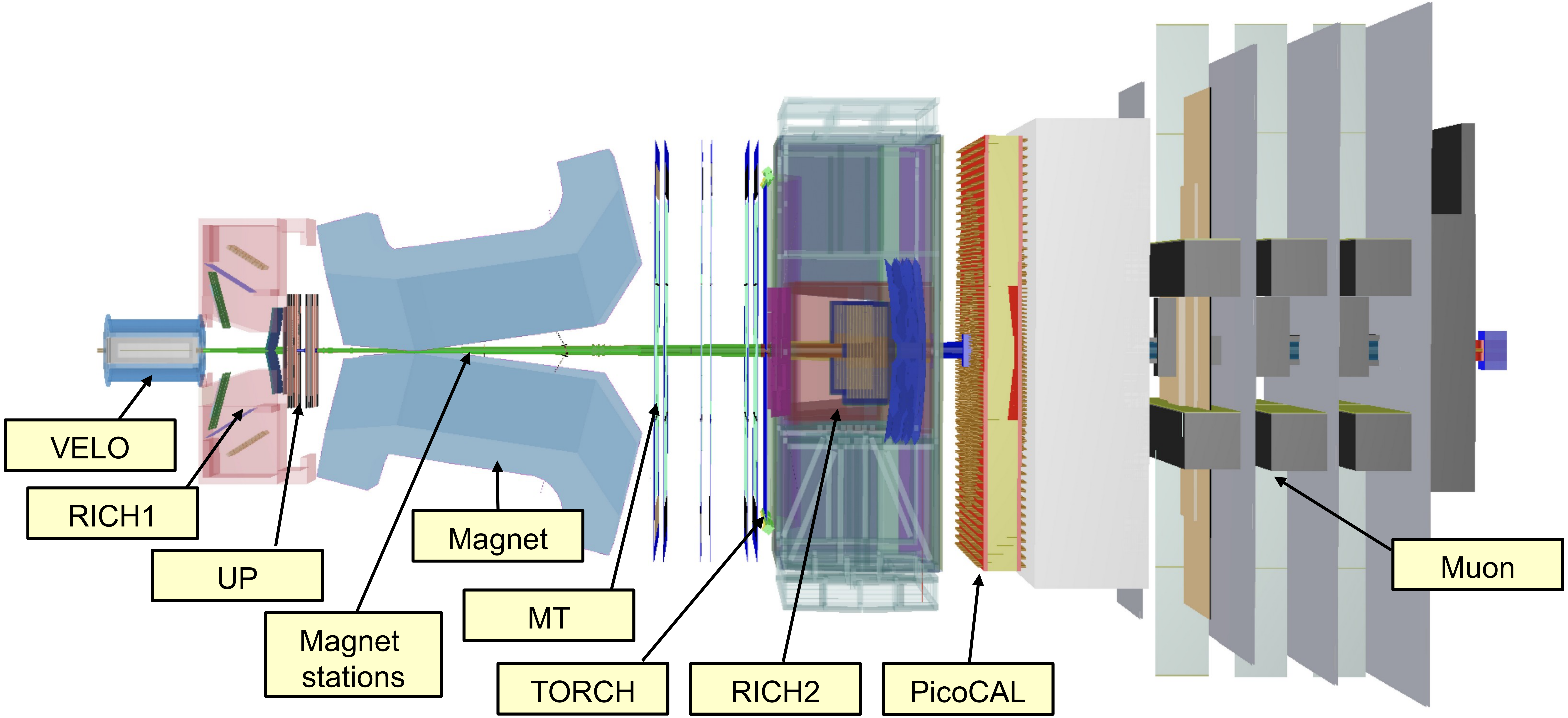


precision timing in VELO


track density with pile-up ~40

20 ps time window applied

LHCb Upgrade 2 detector layout



Flavour Tagging @ LHCb