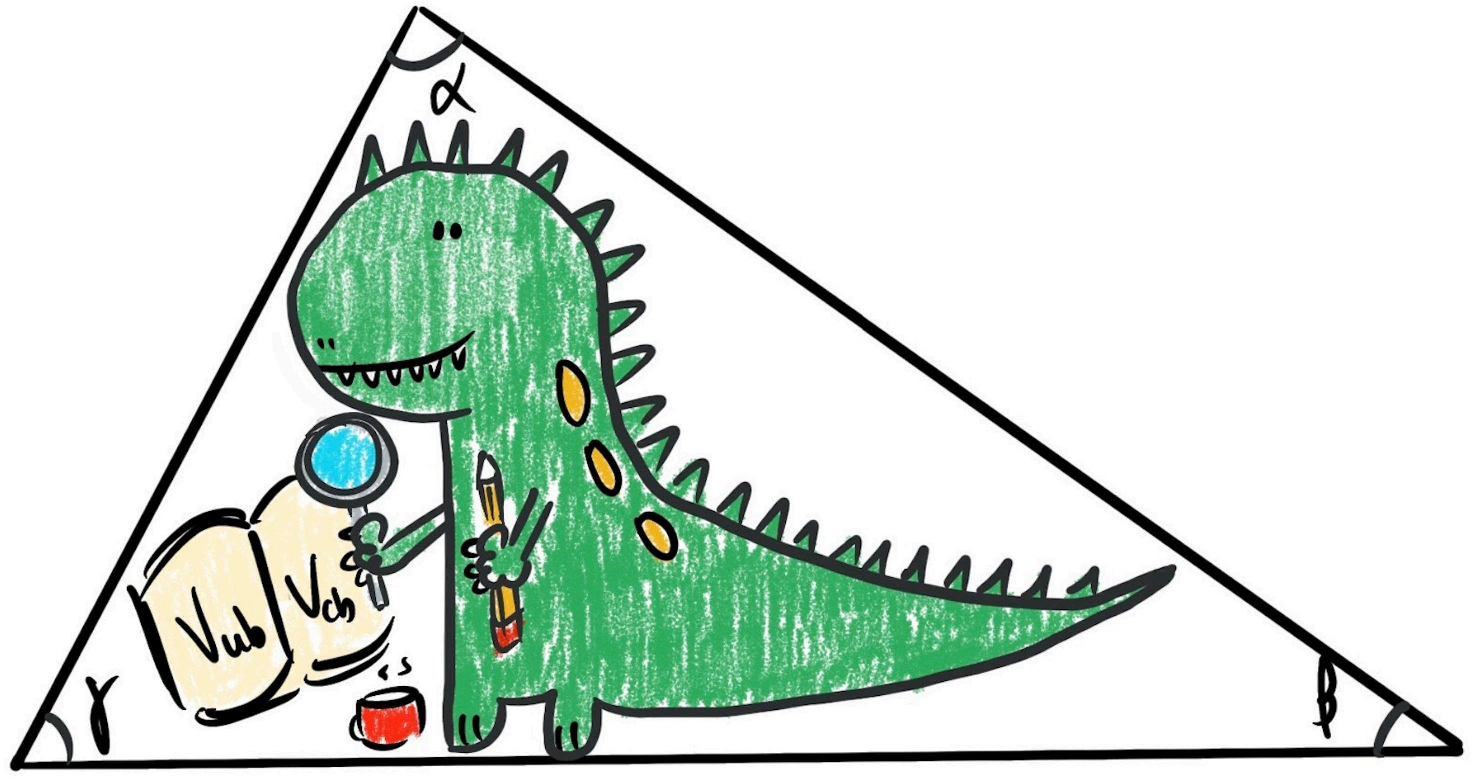
IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

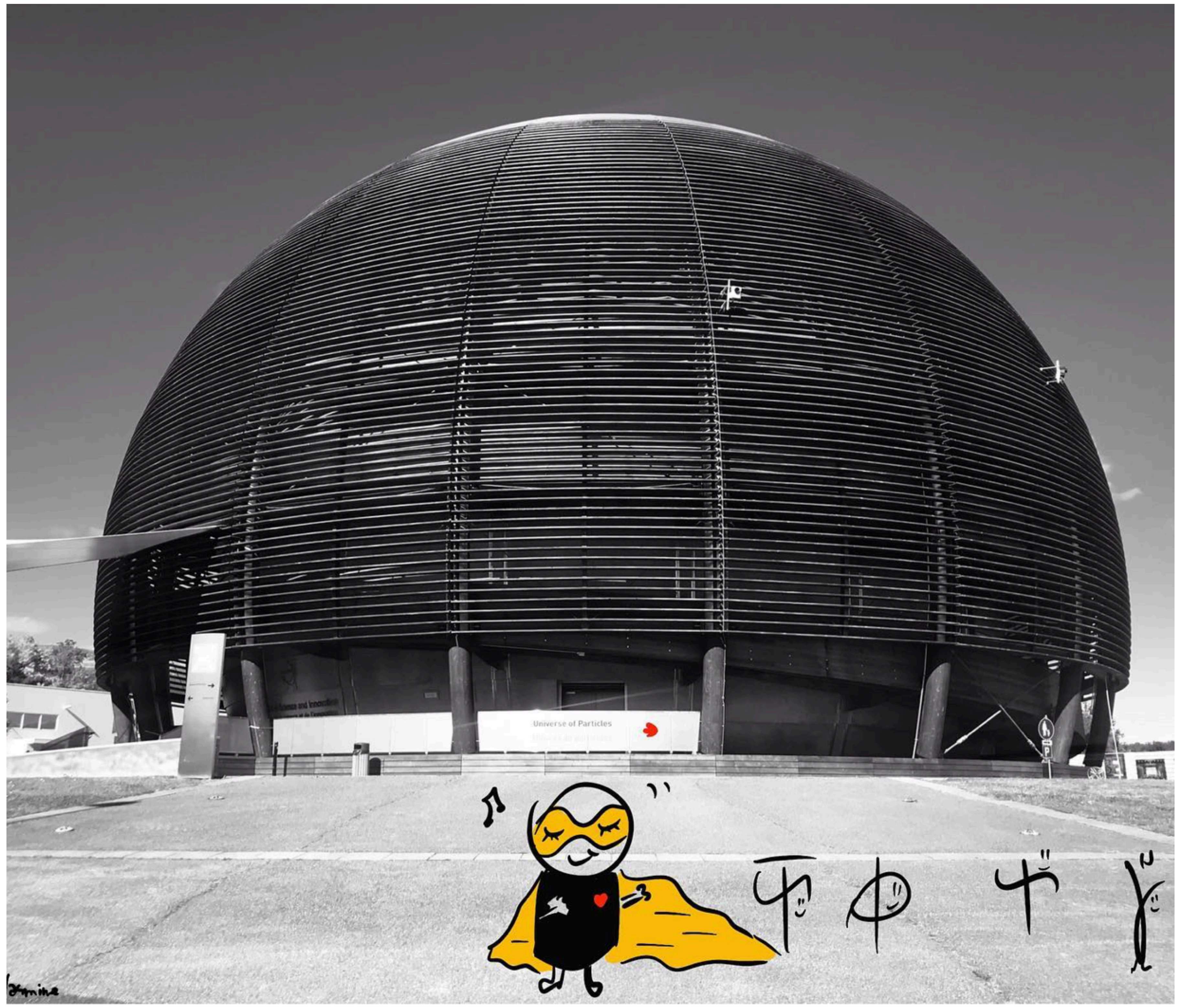
Recent results on matter and antimatter asymmetries at LHCb



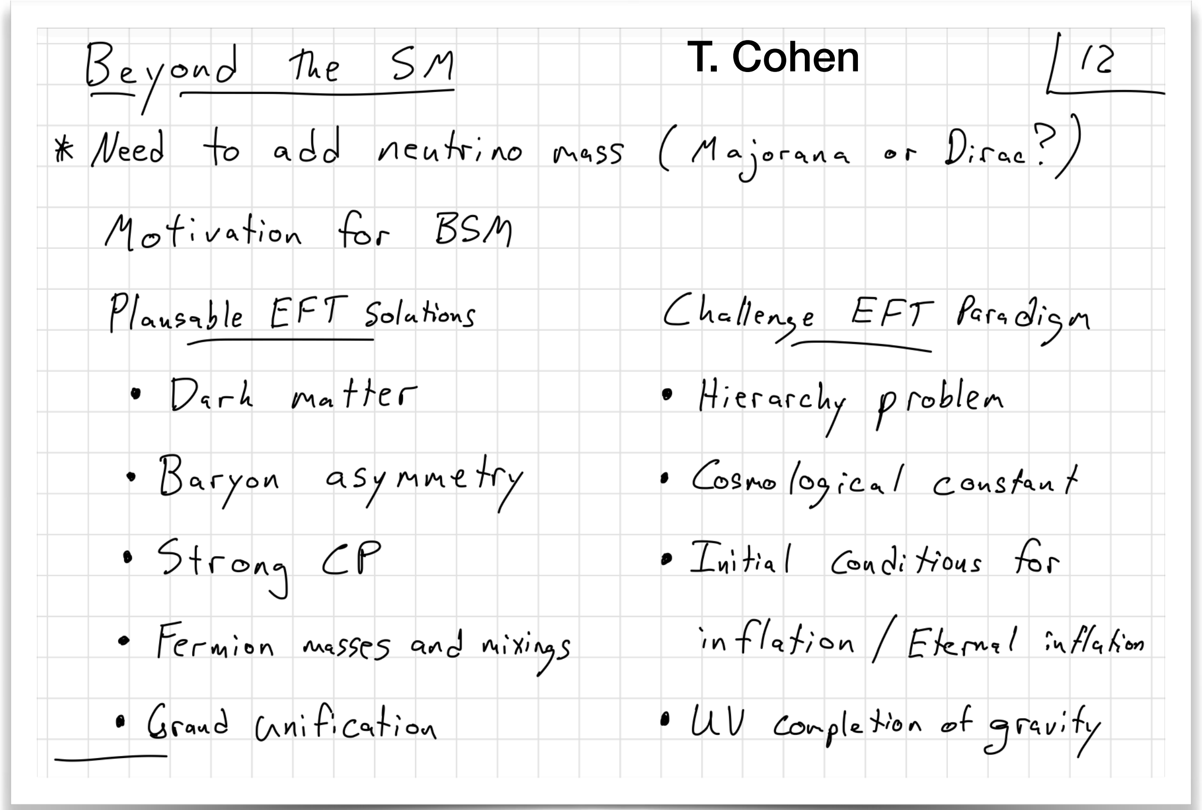
Yasmine Amhis

June 2025
Particle Physics Seminar - Bonn

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

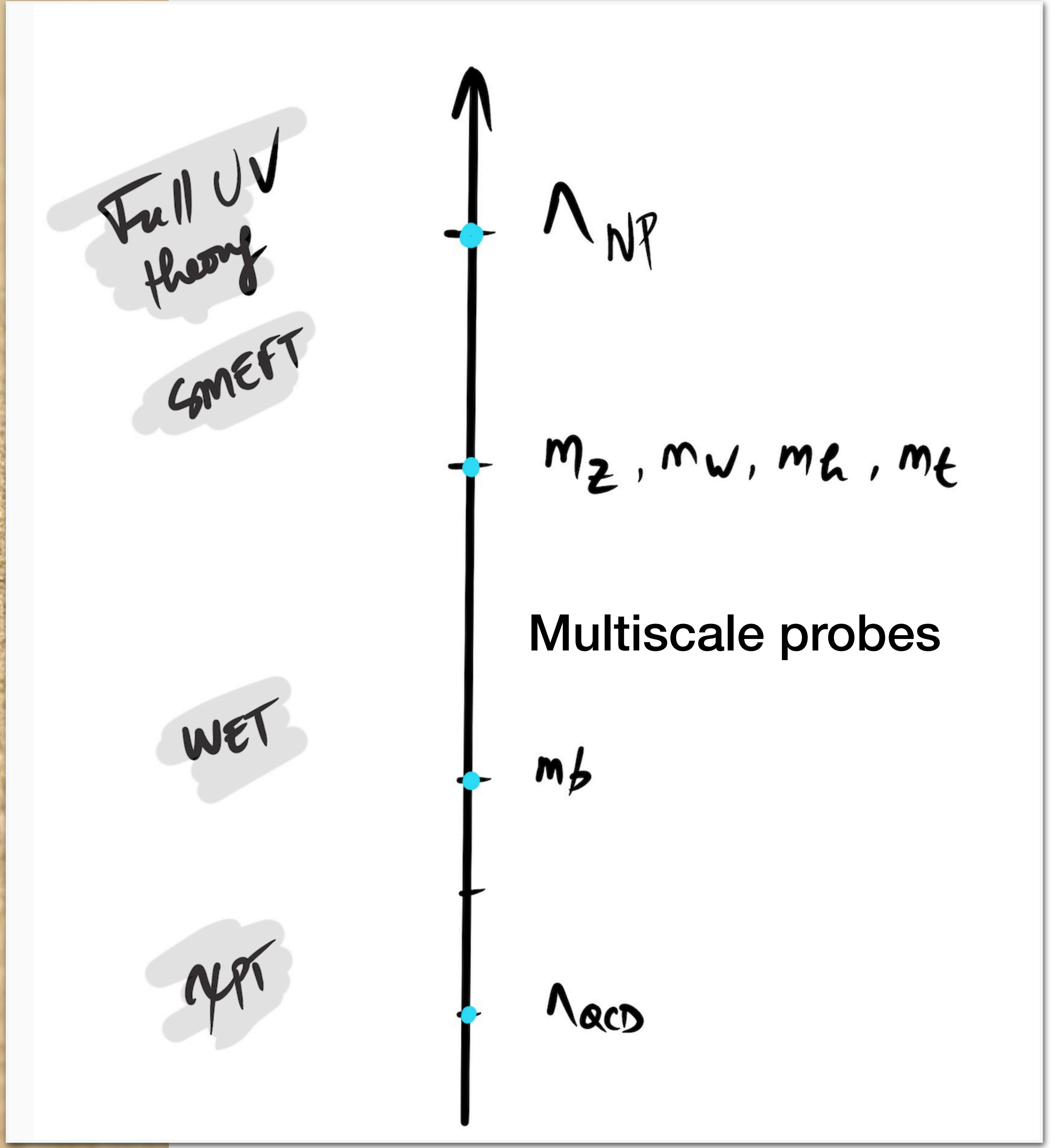
* Need to add neutrino mass (Majorana or Dirac?)

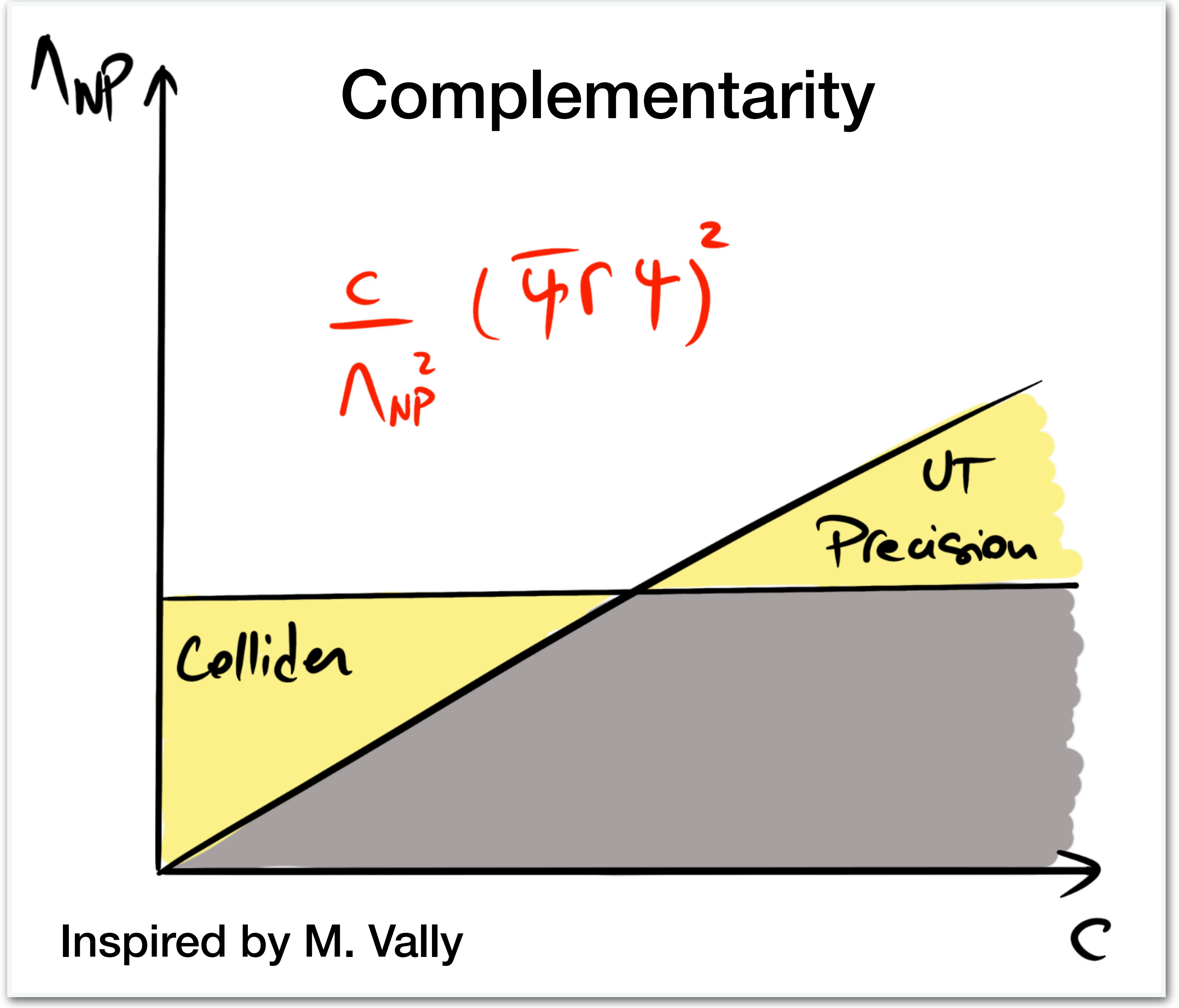
Motivation for BSM

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





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

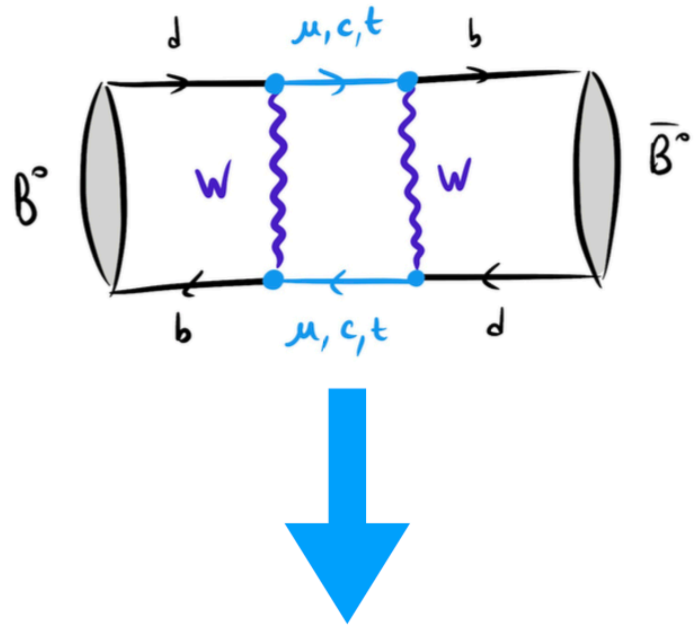
PLB 192 (1987)

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.

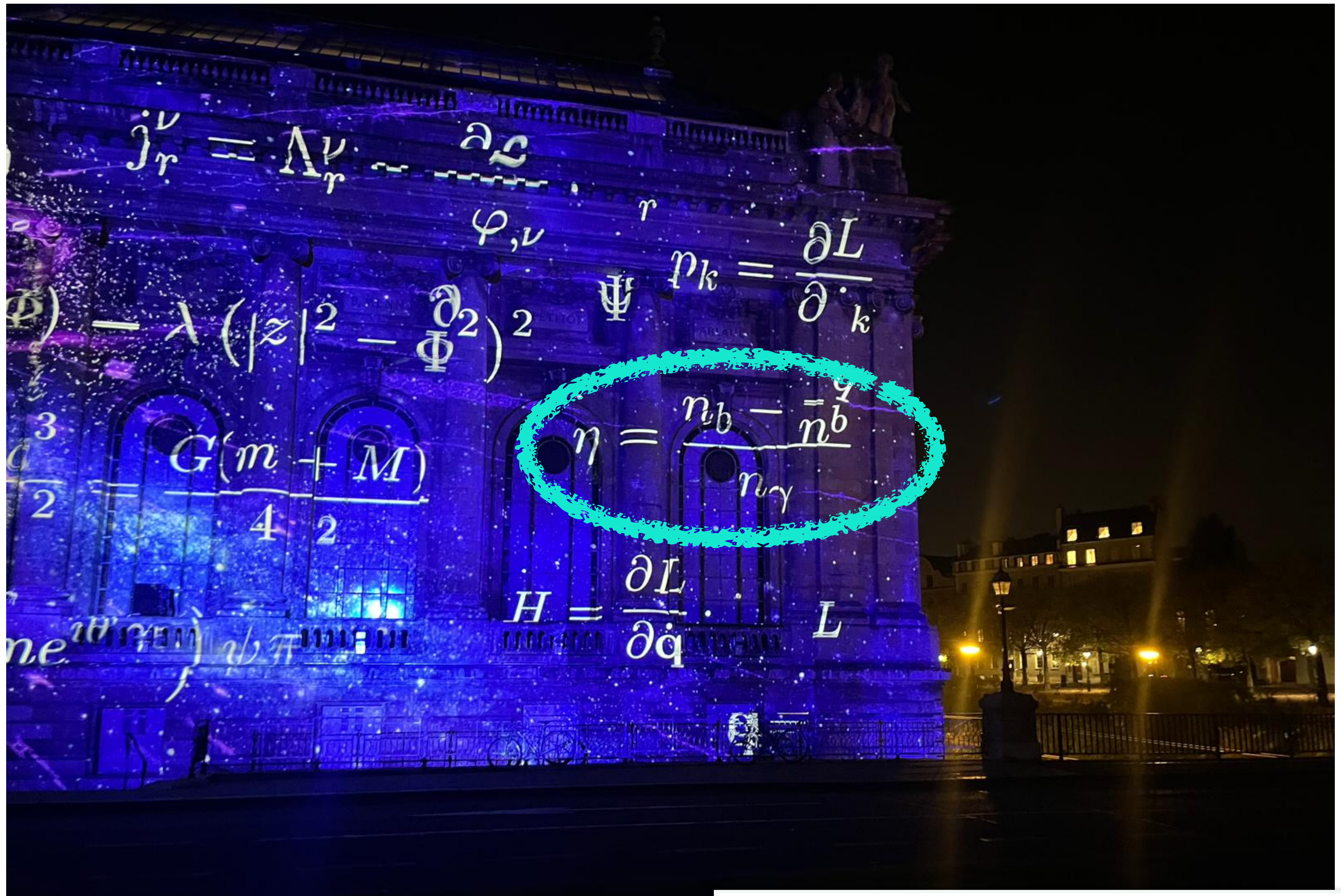
Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$ GeV/c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element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



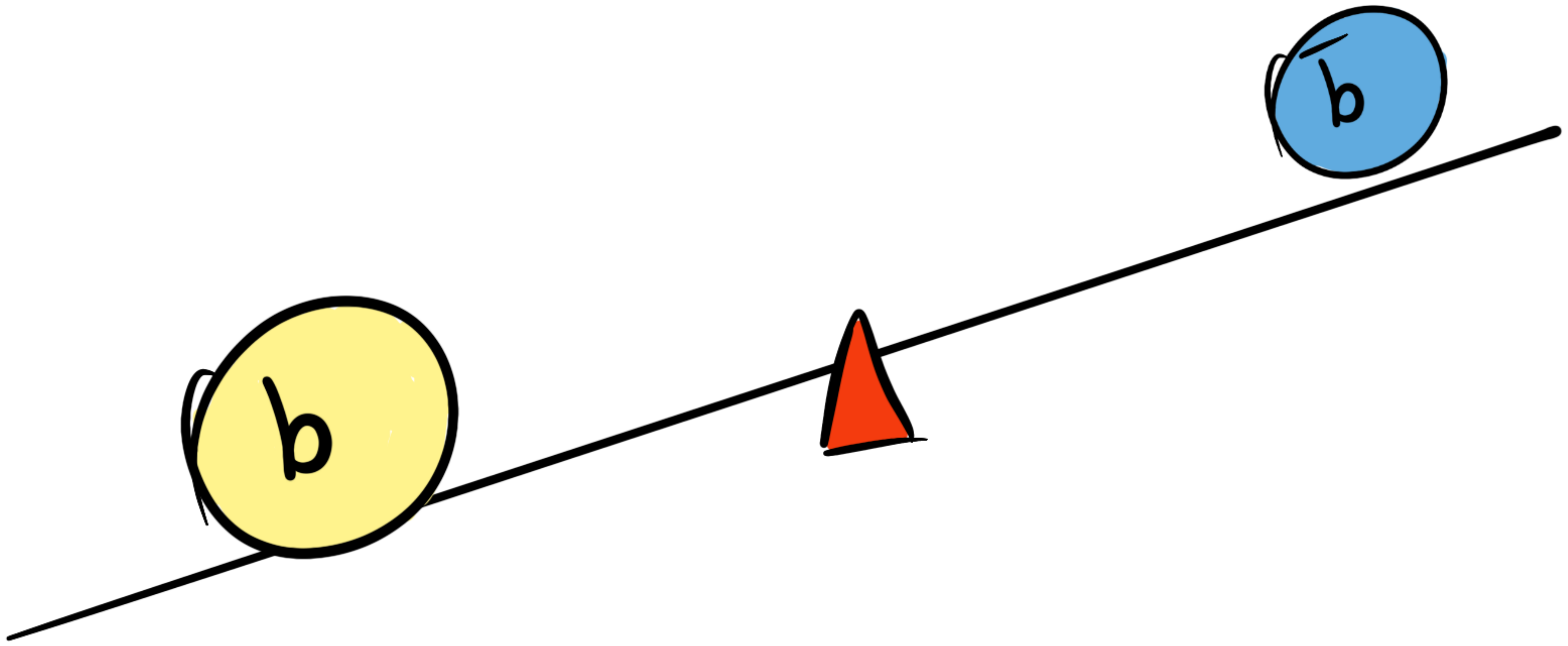
$$\mathcal{M}(B^0 - \bar{B}^0) \propto \sum_{ij} (V_{ib} V_{id}^*)(V_{jb} V_{jd}^*) F(m_{u_i}^2, m_{u_j}^2)$$

Emphasis the complementarity of direct vs indirect searches

Towards Baryogenesis



Art & History Museum in Geneva



Sakharov conditions [edit]

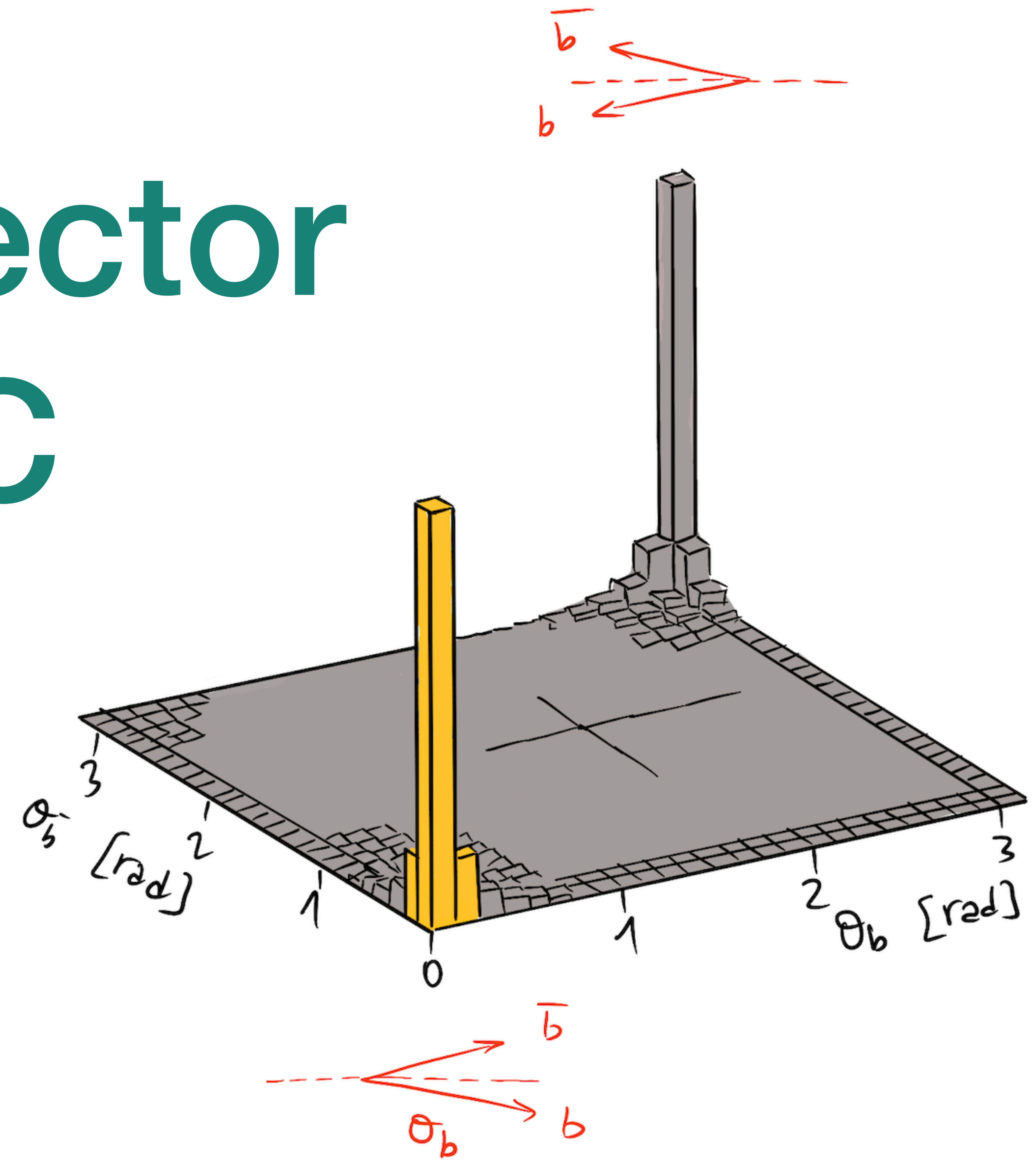
In 1967, Andrei Sakharov proposed[11] a set of three necessary conditions that a baryon-generating interaction must satisfy to produce matter and antimatter at different rates. These conditions were inspired by the recent discoveries of the cosmic microwave background[12] and CP-violation in the neutral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

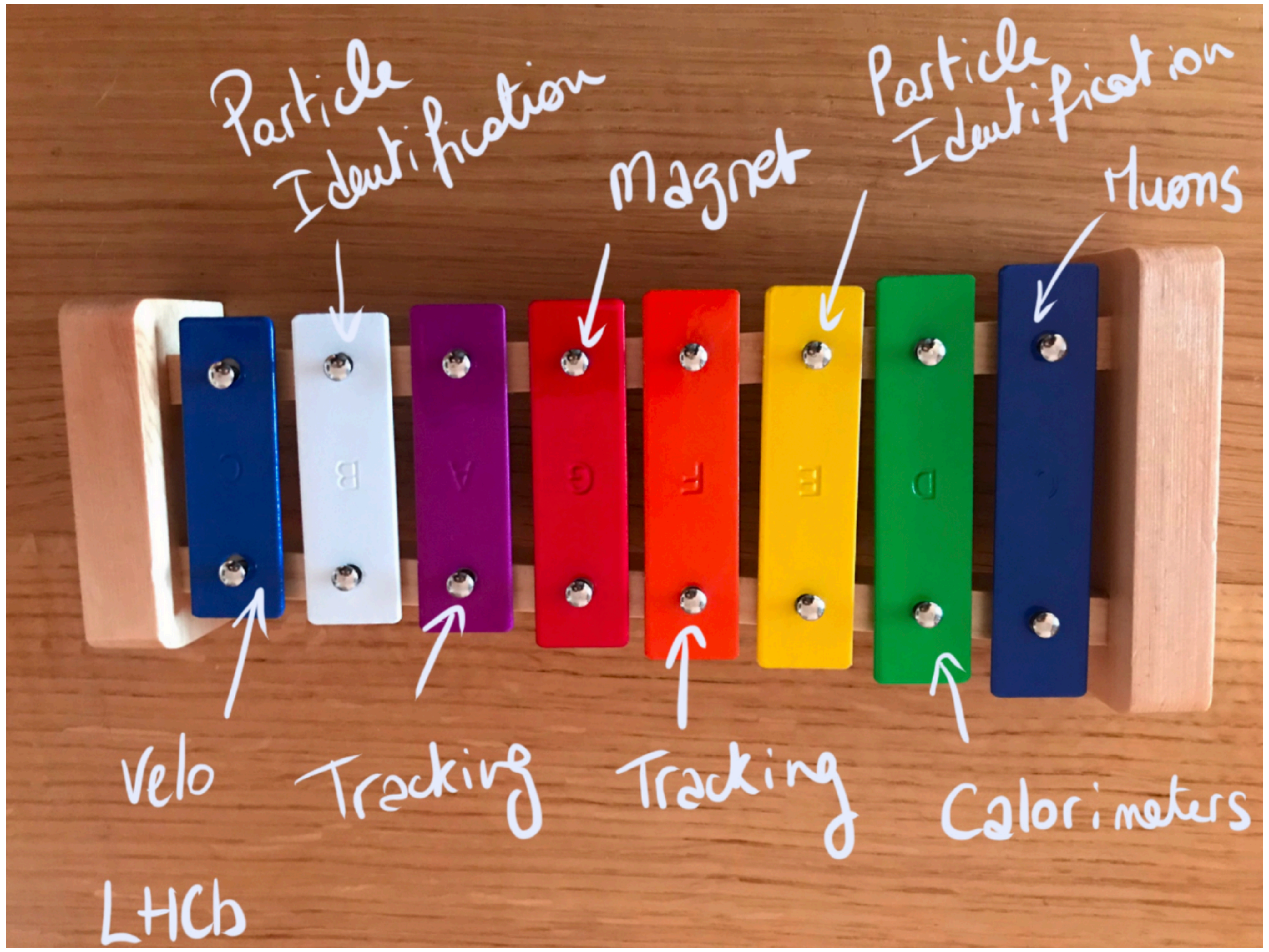
- Baryon number B violation.
- C-symmetry and CP-symmetry violation.
- Interactions out of thermal equilibrium.

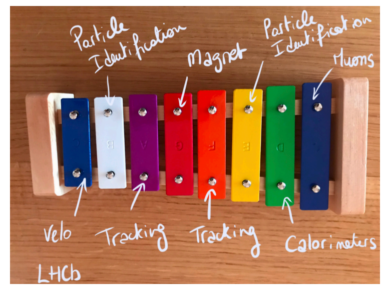
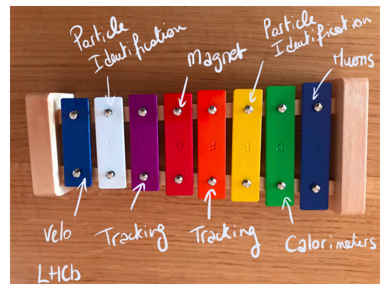
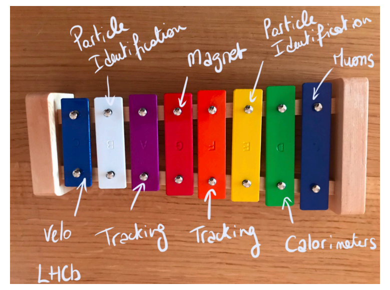
Baryon number violation is a necessary condition to produce an excess of baryons over anti-baryons. But C-symmetry violation is also needed so that the interactions which produce more baryons than anti-baryons will not be counterbalanced by interactions which produce more anti-baryons than baryons. CP-symmetry 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

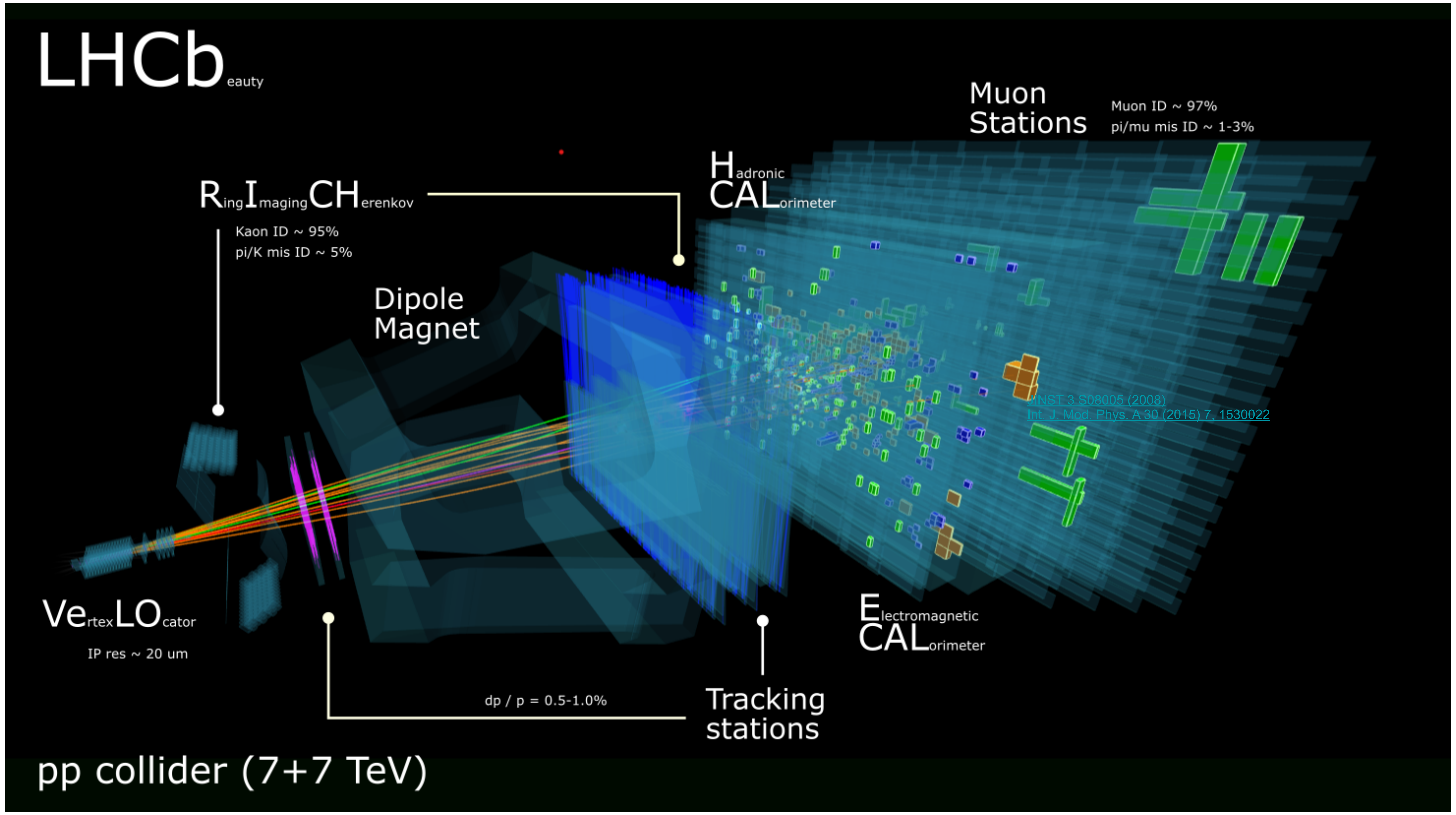




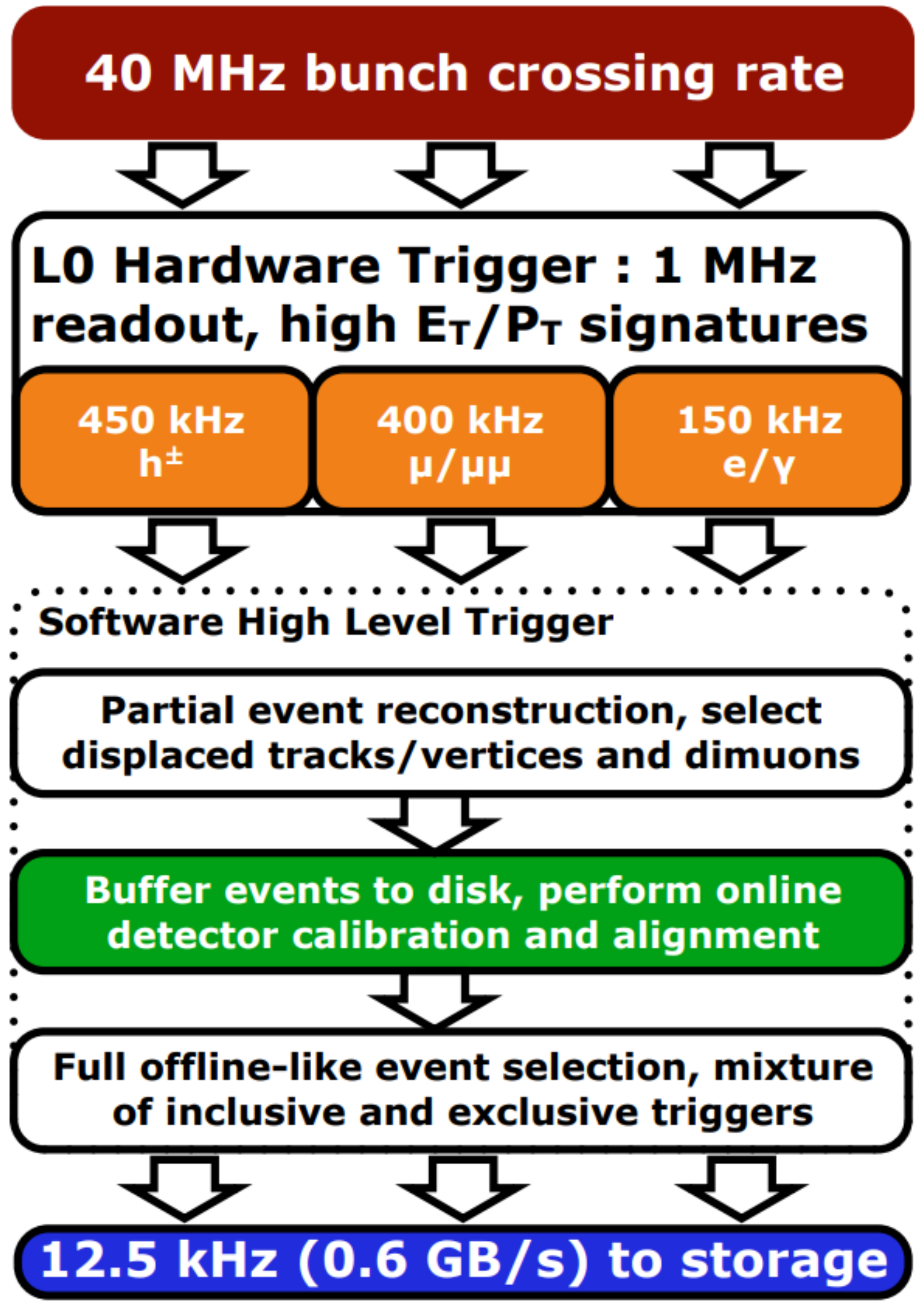




Run 1	2009 2010 2011 2012	3 fb^{-1}
LS1	2013 2014	
Run 2	2015 2016 2017 2018	9 fb^{-1}
LS2	2019 2020 2021	
Run 3	2022 2023 2024 2025 2026	23 fb^{-1}
LS3	2027 2028 2029	
Run 4	2030 2031 2032 2033	50 fb^{-1}
LS4	2034 2035	
Run 5	2036 2037 2038 2039 2040 2041	>300 fb^{-1}

The LHCb detector



Run 2 trigger



- 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

Everything you dreamt to know about LHCb's data !

Particle Physics Seminar

LHCb analysis

by Vava GLIGOROV

Thursday 24 Jul 2025, 10:00 → 12:00 Europe/Berlin

Description Abstract:

Join Zoom Meeting
https://uni-bonn.zoom-x.de/j/66253567797?pwd=R2MrNmNCQnl4K1hSejd6VnBEYXJ2

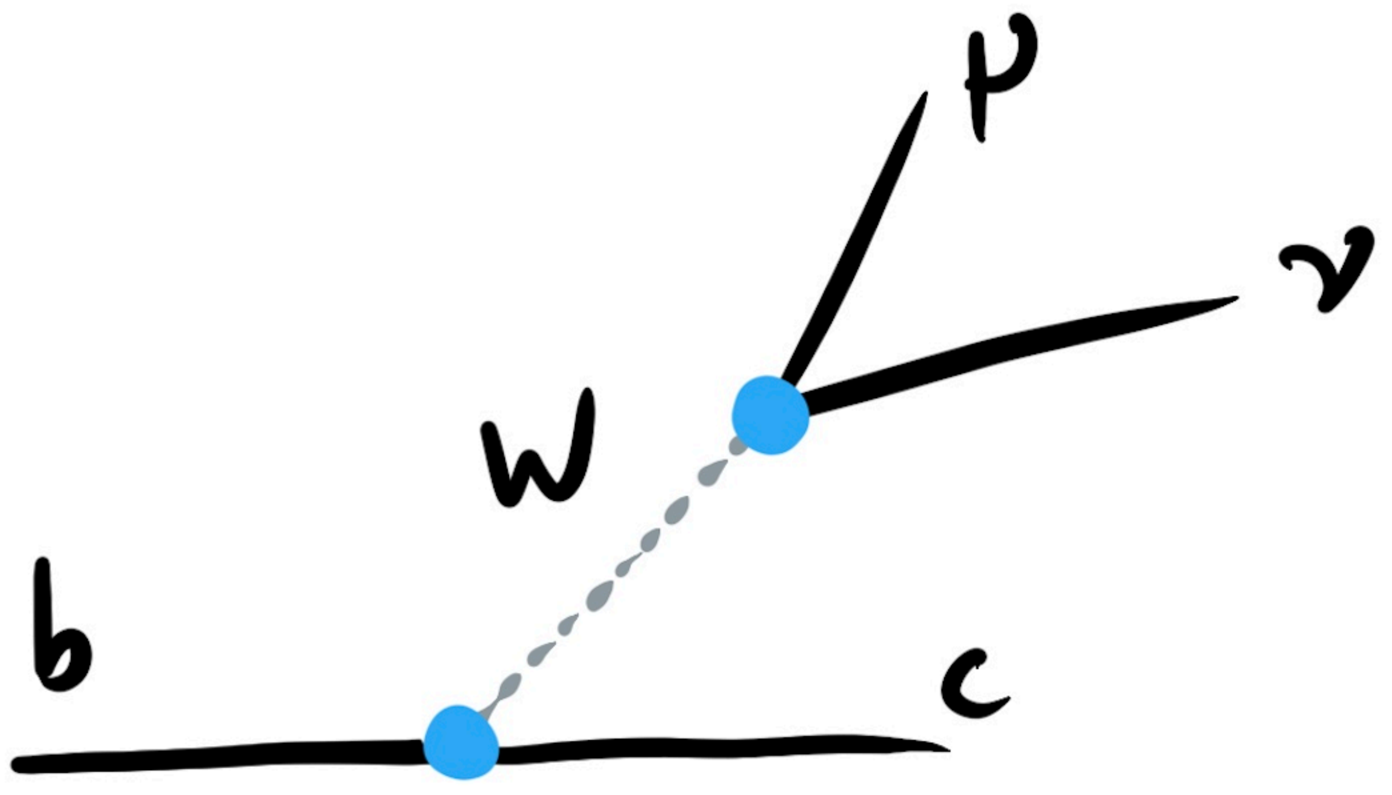
Meeting ID: 662 5356 7797
Passcode: 599591

Organised by Maike Hansen, Saime Gürbüz

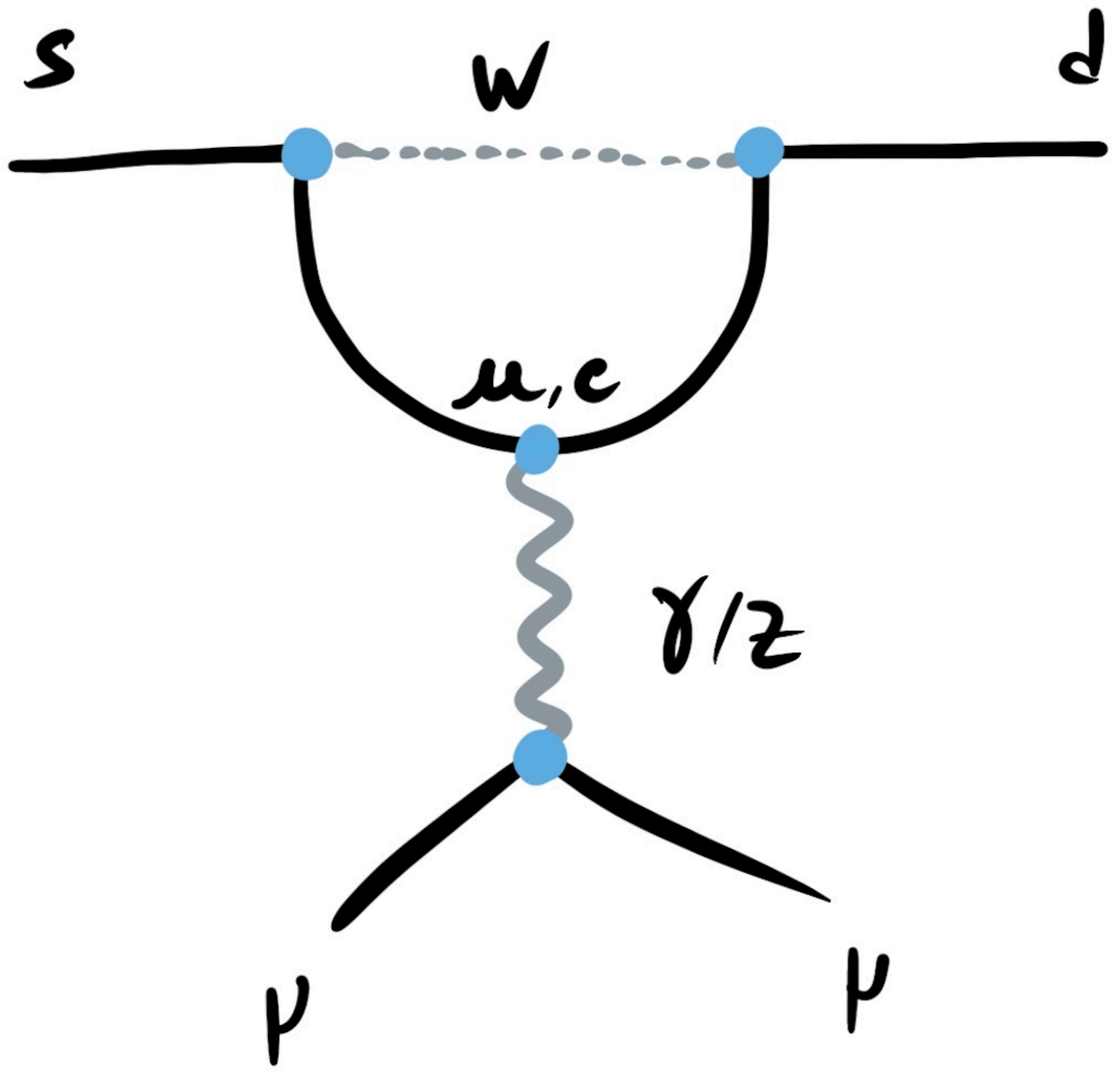
📷 A. Seha

Trees vs penguins

Flavour Changing Charged Currents



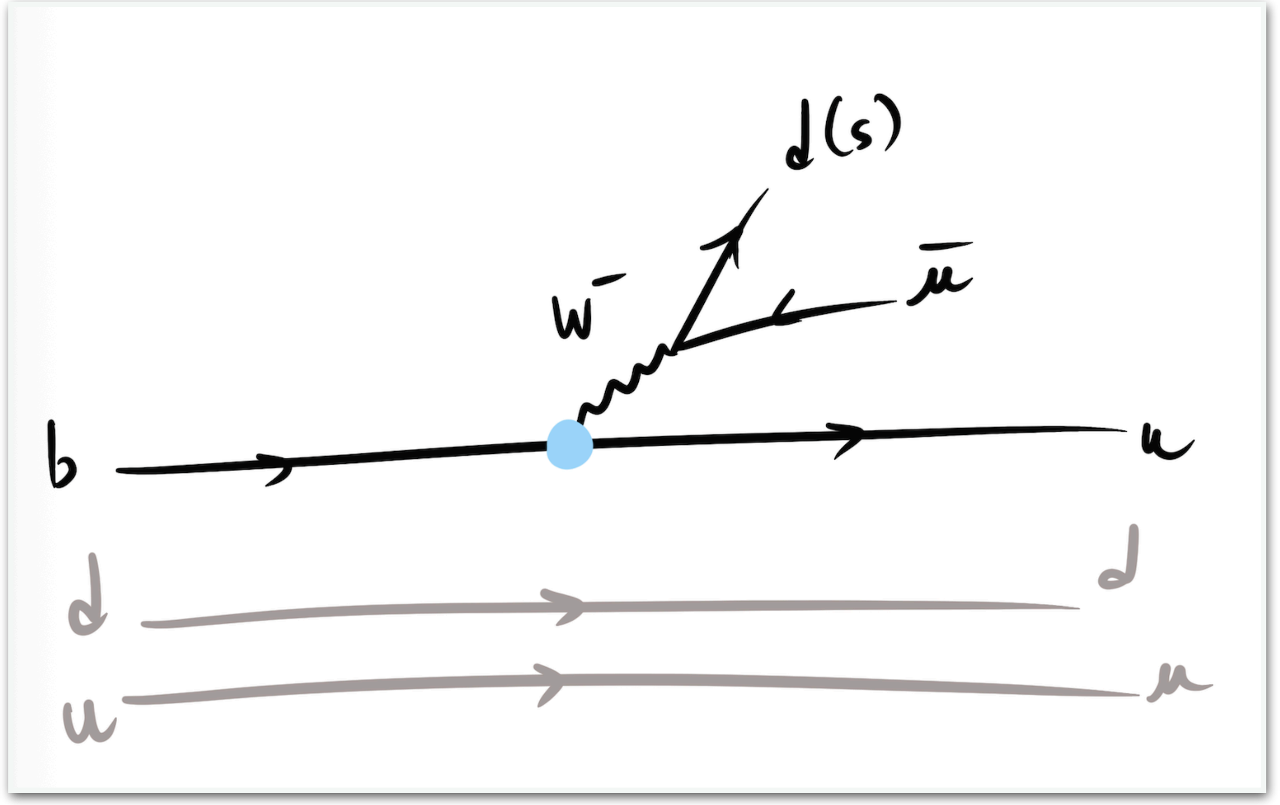
Flavour Changing Neutral Currents



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



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

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

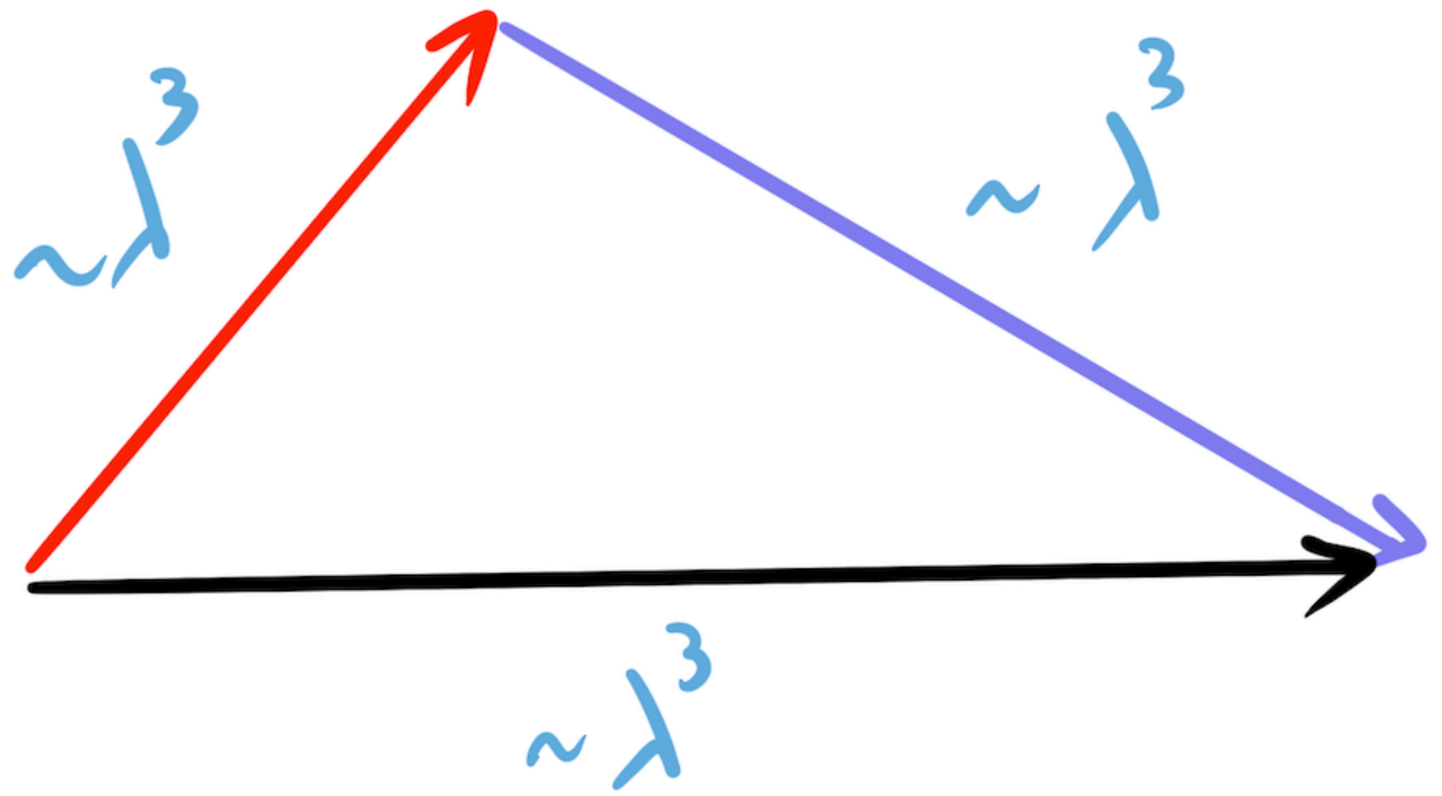
Wolfenstein parametrisation

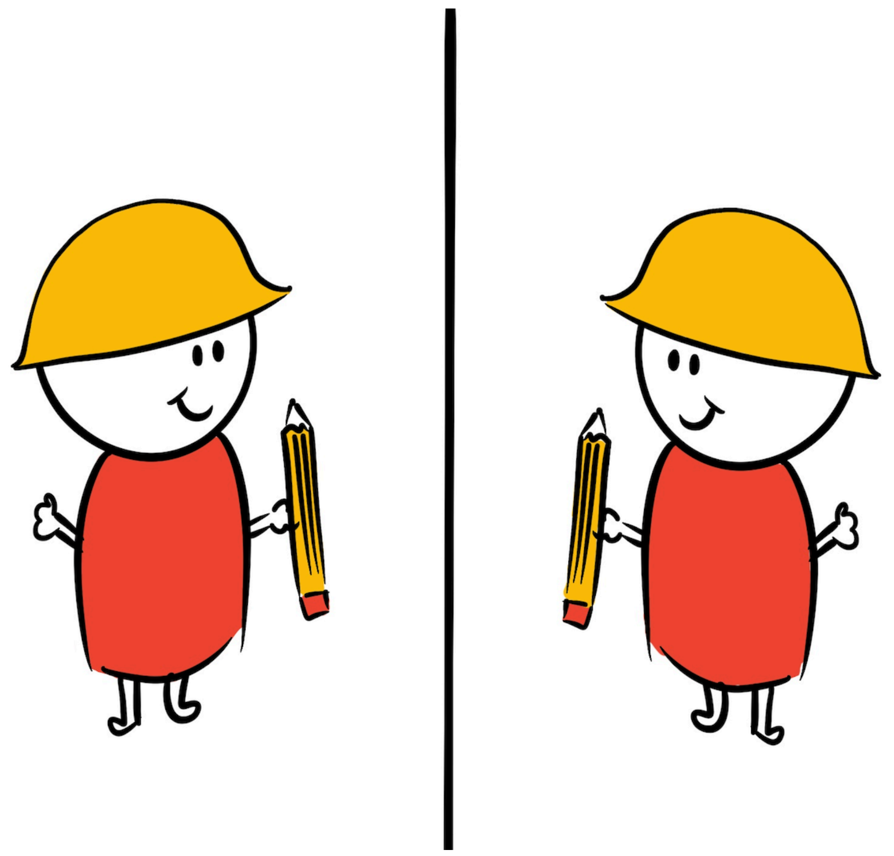
$$\lambda = 0.22 \qquad A, |\rho + i\eta| = \mathcal{O}(1)$$

CKM - matrix

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

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





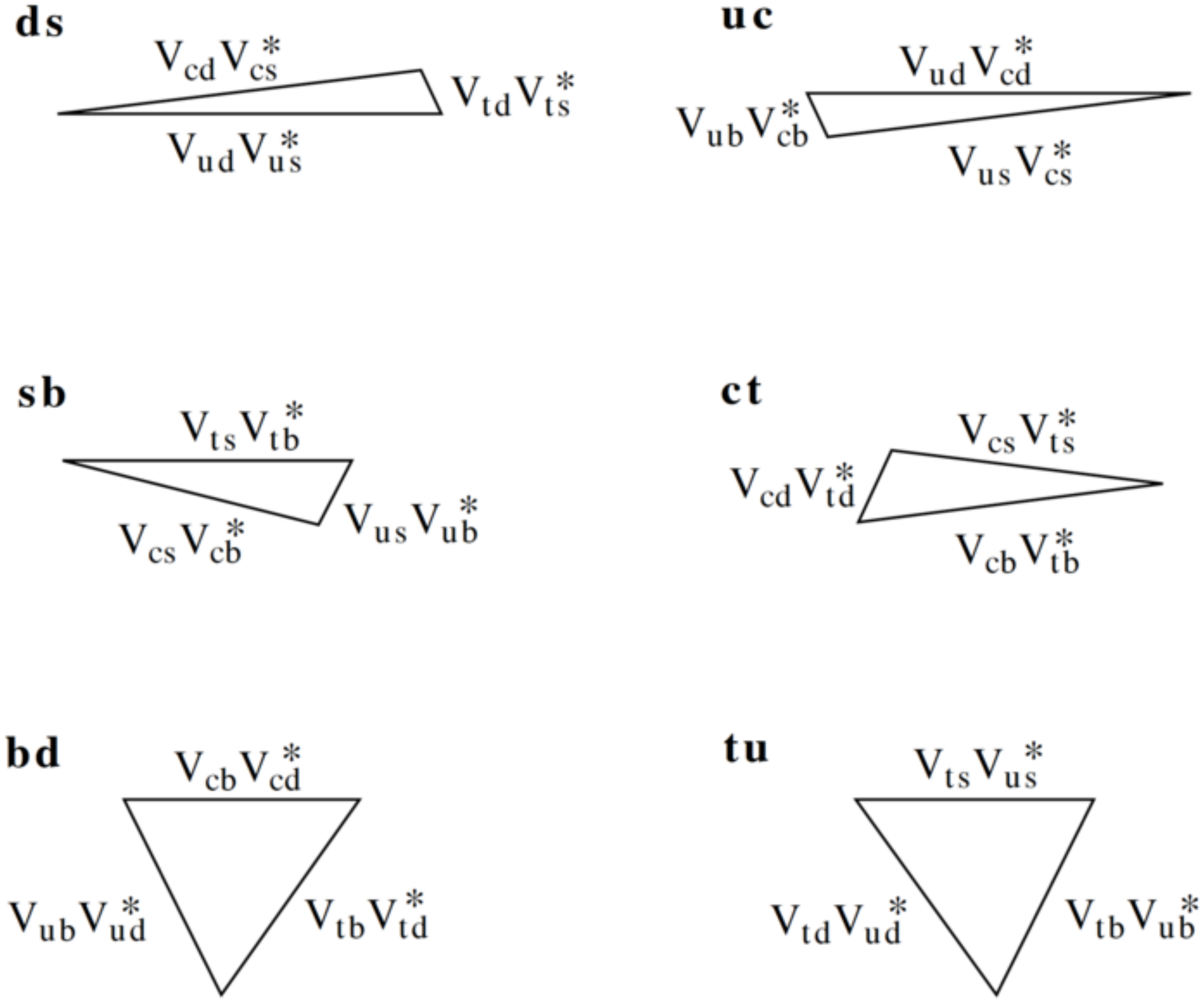
Building the unitarity triangles

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,

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0\ , \qquad (13.35a)$$

$$V_{td}V_{ud}^* + V_{ts}V_{us}^* + V_{tb}V_{ub}^* = 0\ , \qquad (13.35b)$$



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

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

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

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

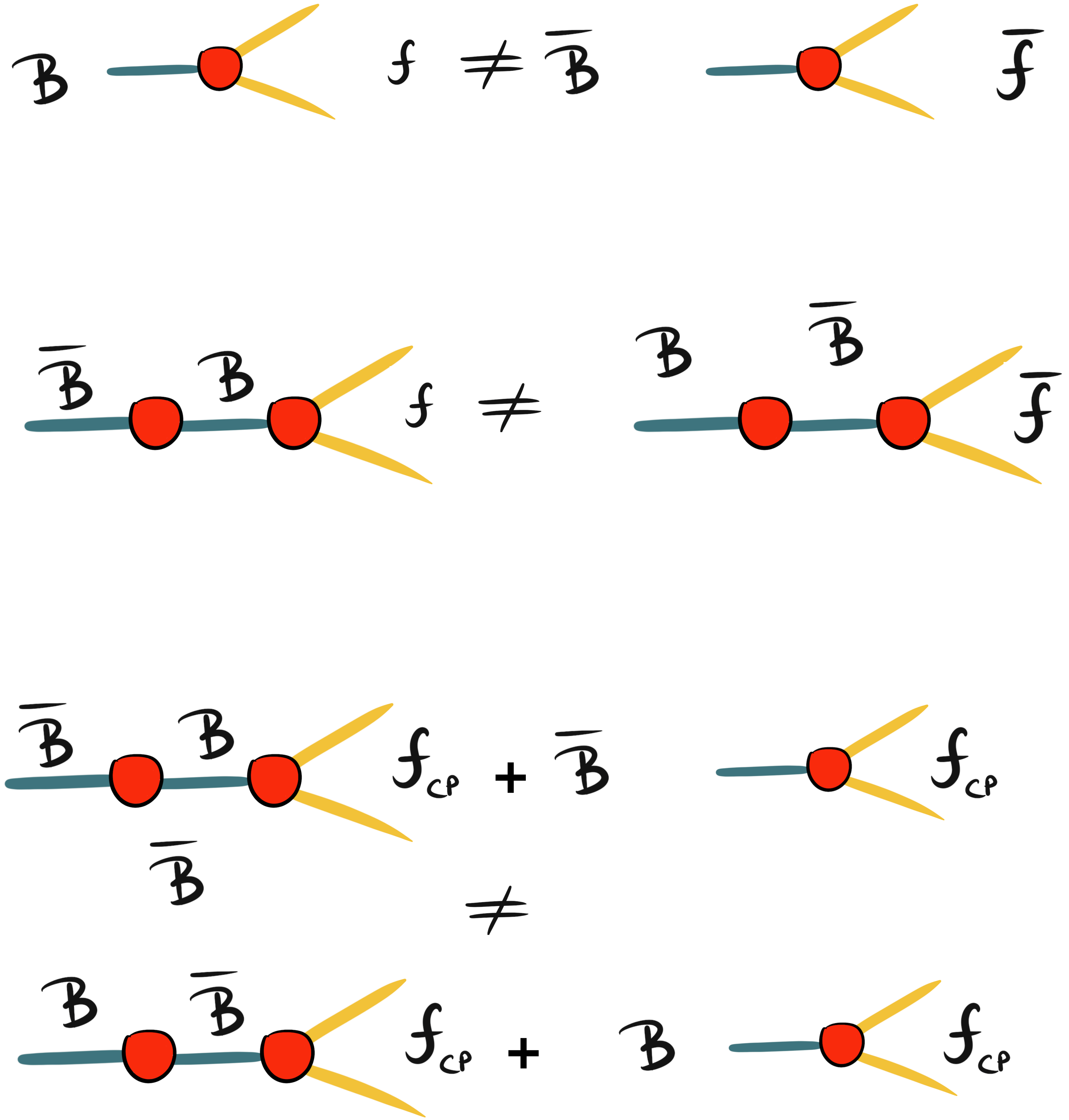
- $|q/p| \neq 1$

CP violation in the interference between mixing and decay

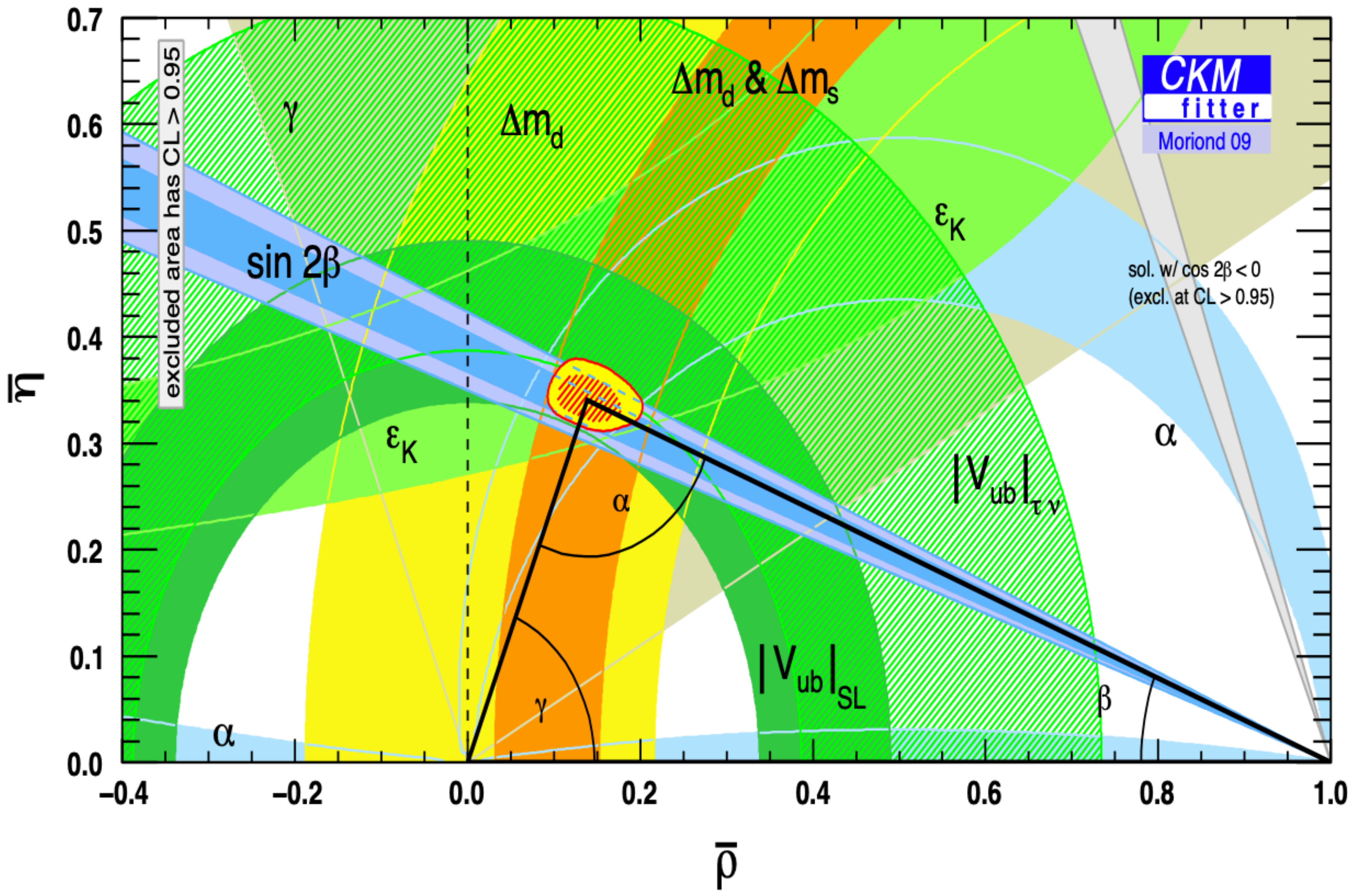
- $\mathrm{Im}(\lambda_f) = \mathrm{Im}\left(\frac{q}{p}\frac{\bar{A}_f}{A_f}\right) \neq 0$

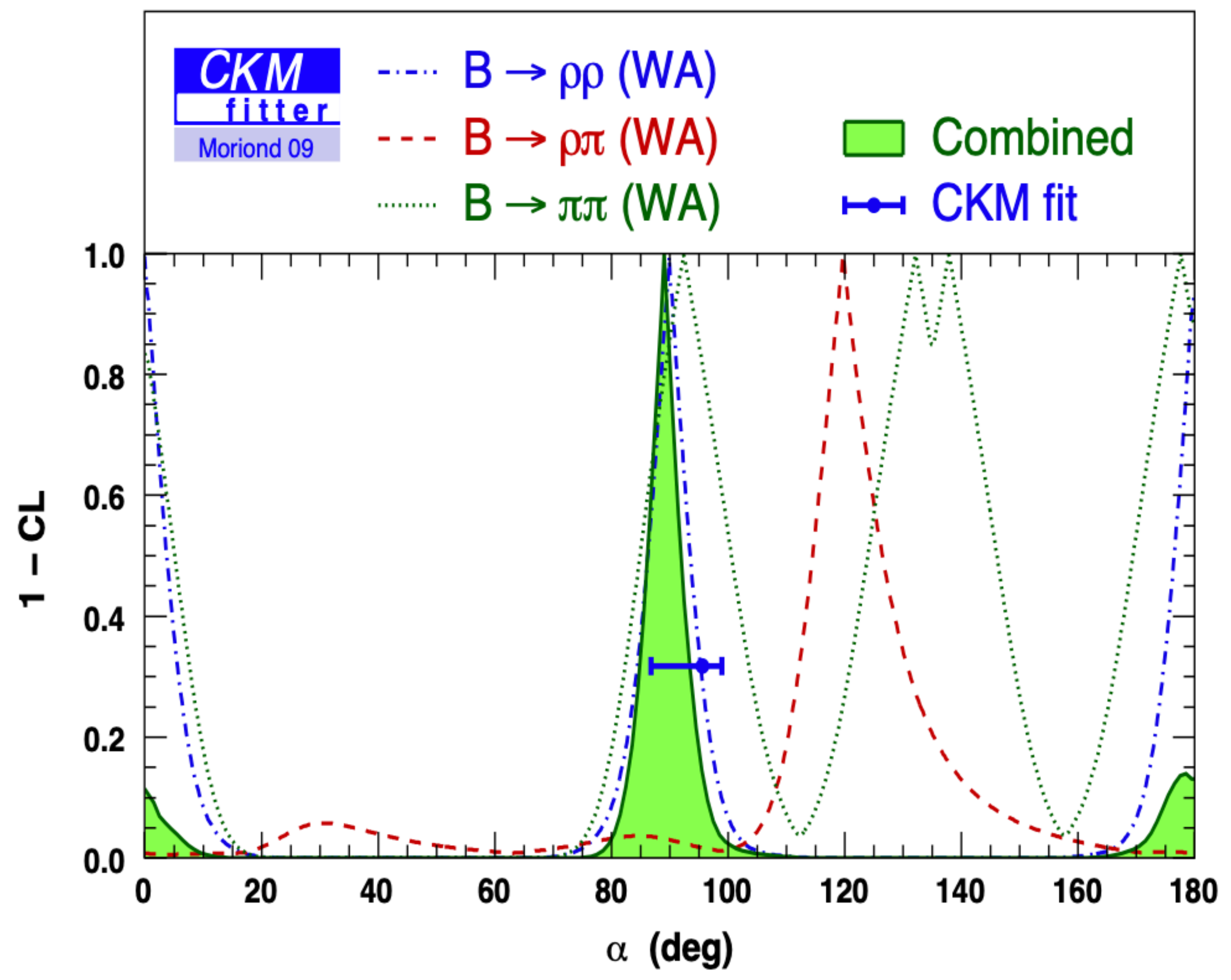
λ_f = parameter that quantifies CP violation

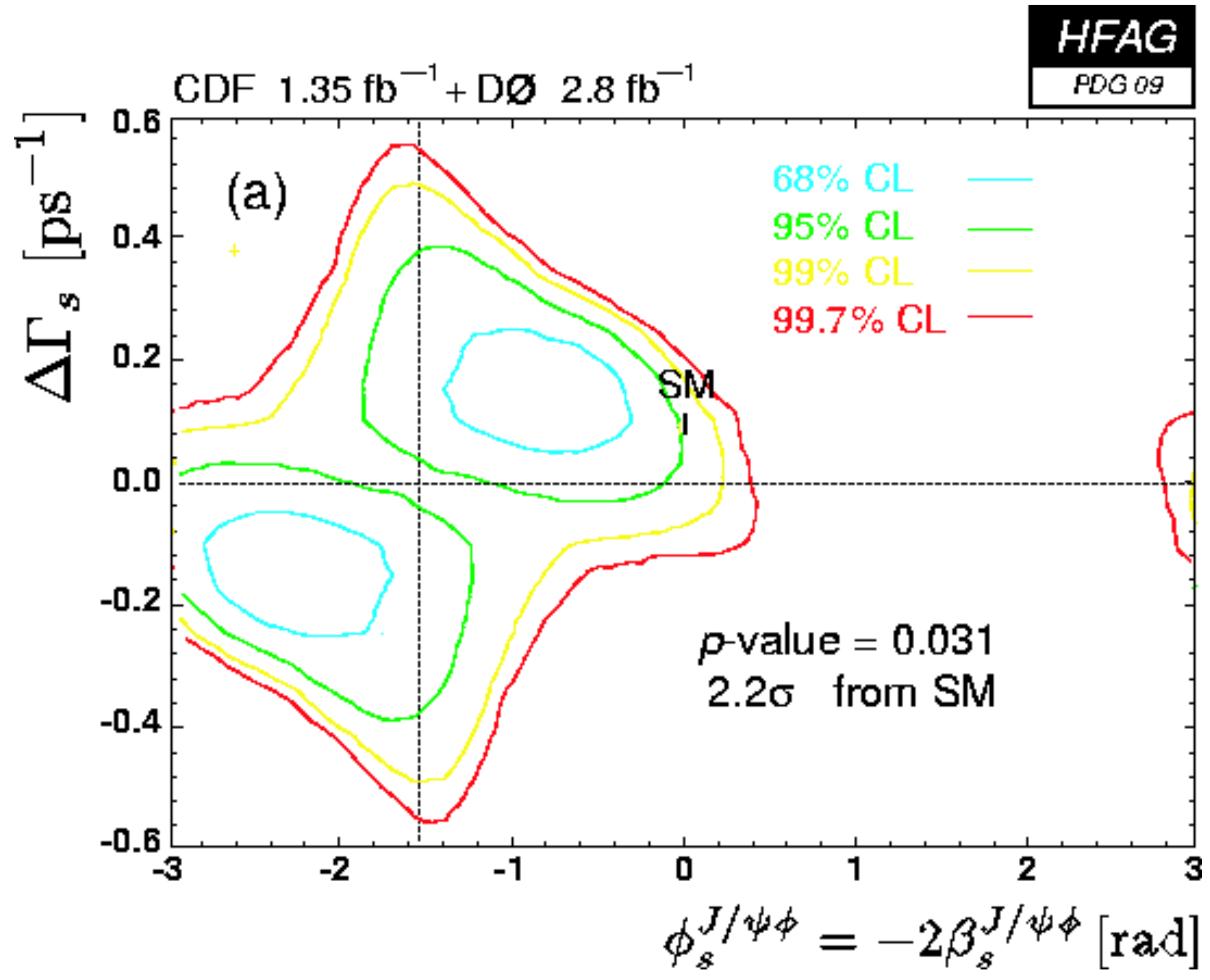
$CP|f_{CP}\rangle = \eta_f^{CP}|f_{CP}\rangle$ with $\eta_{CP} = \pm 1$



All the phases…in 2009



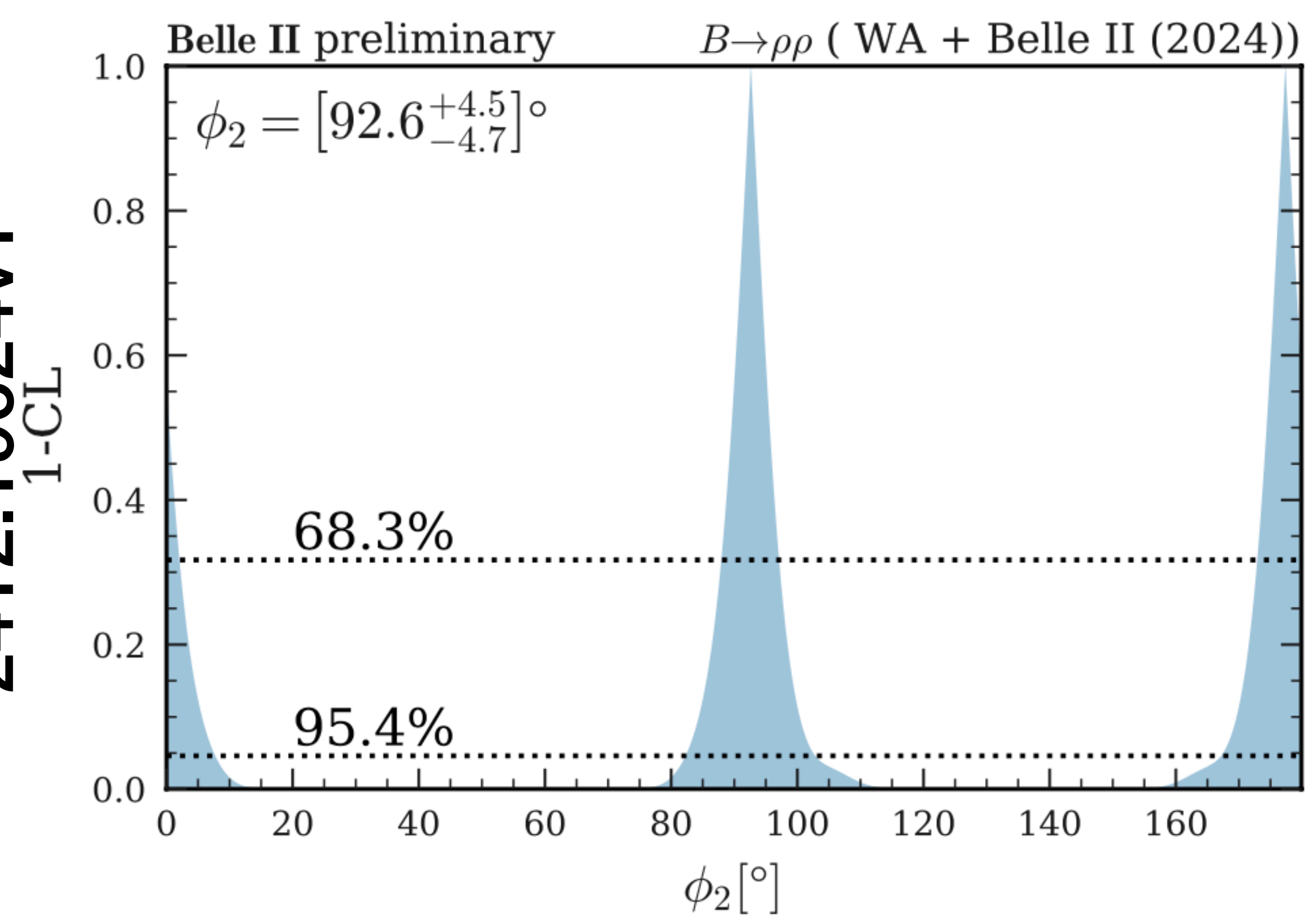


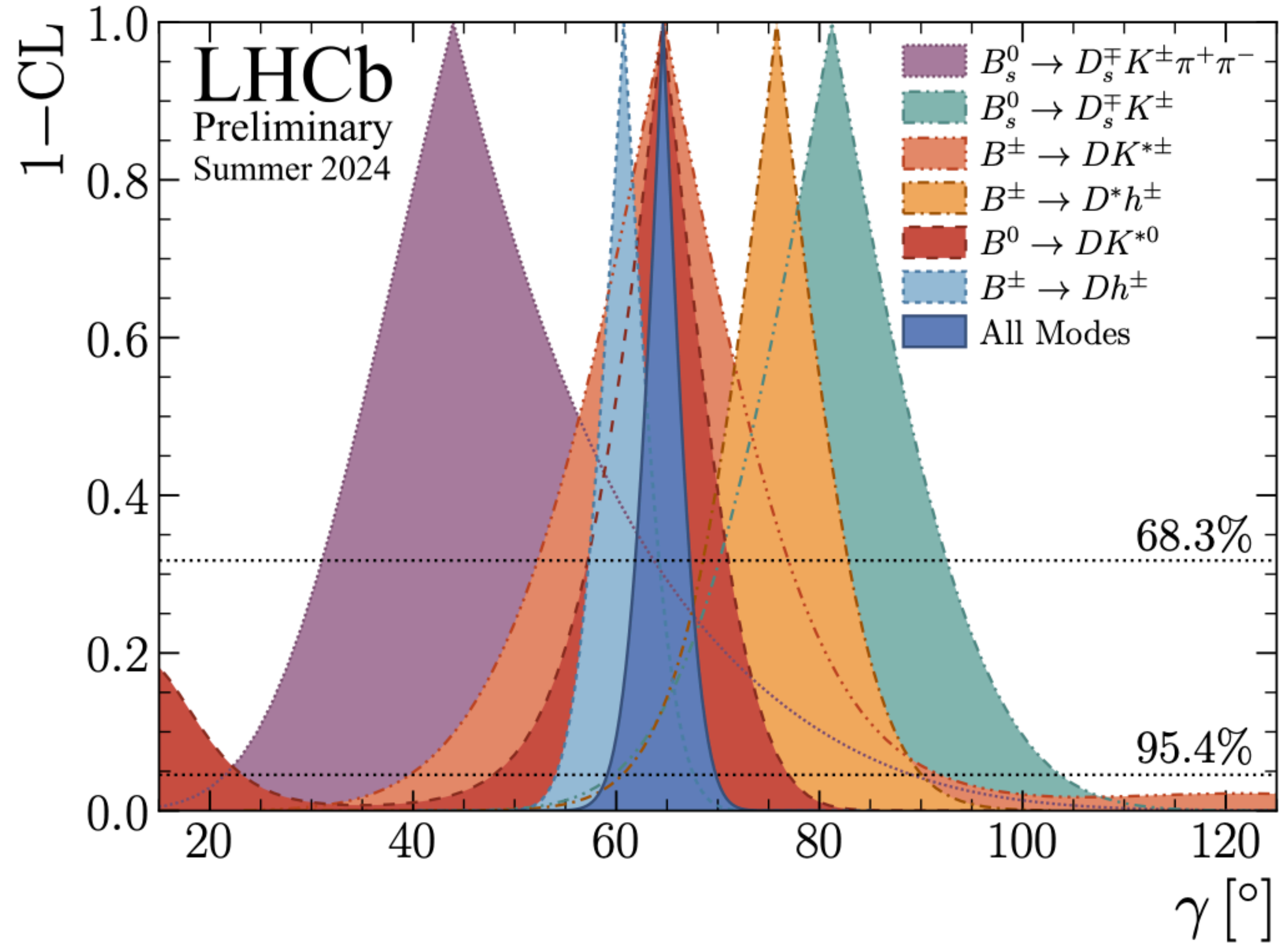


arXiv:0905.1572

All the phases…Today

2412.19624v1





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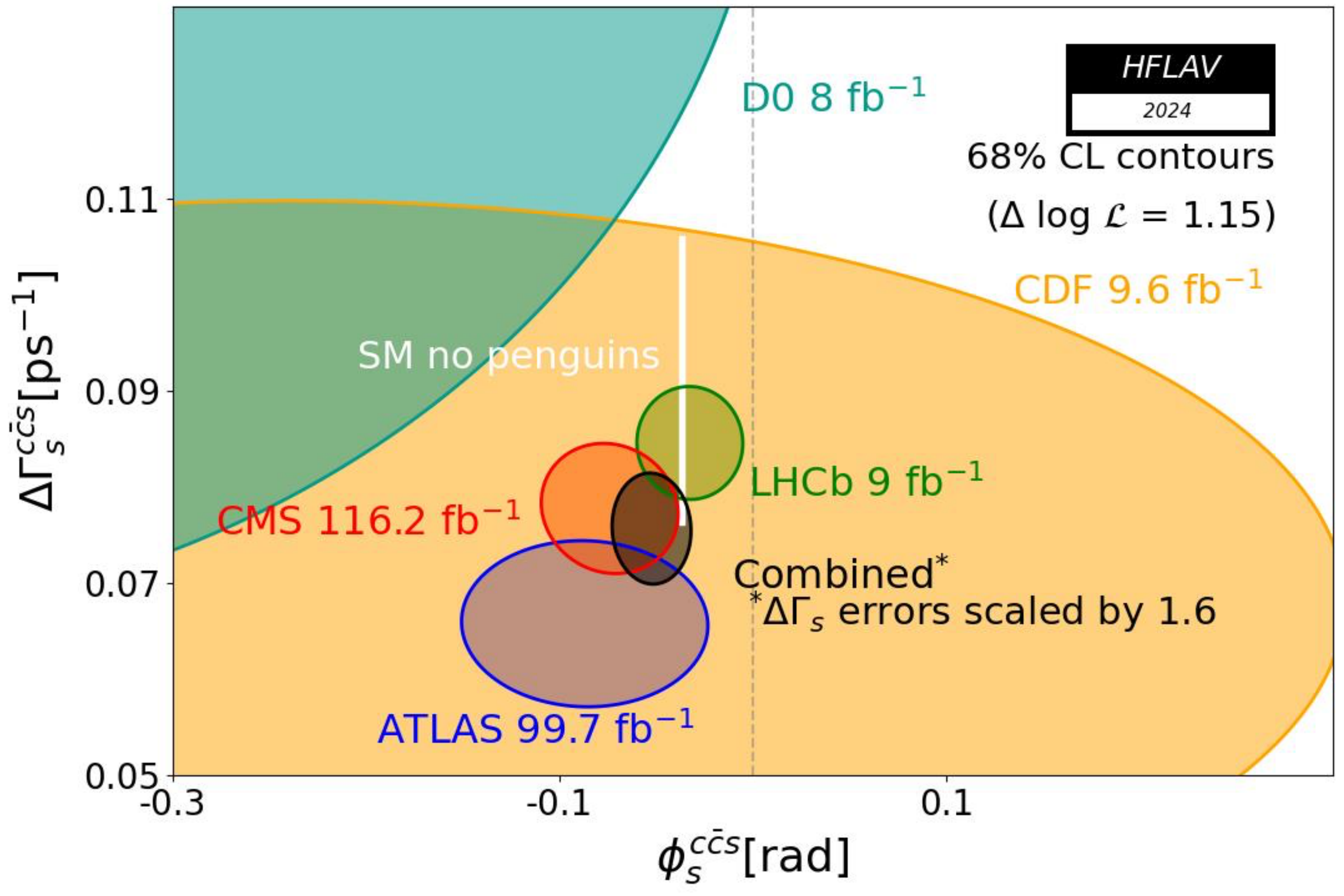
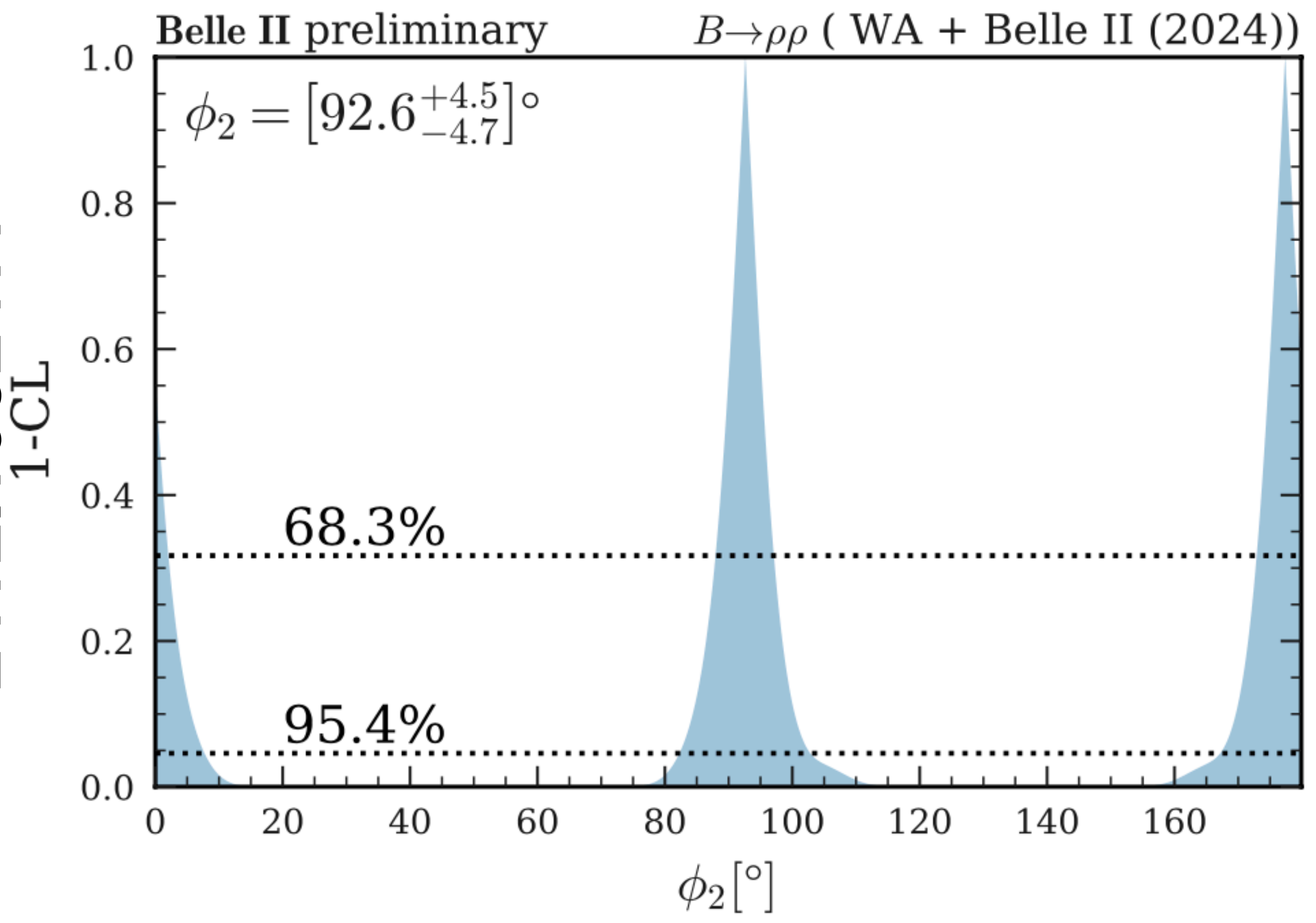


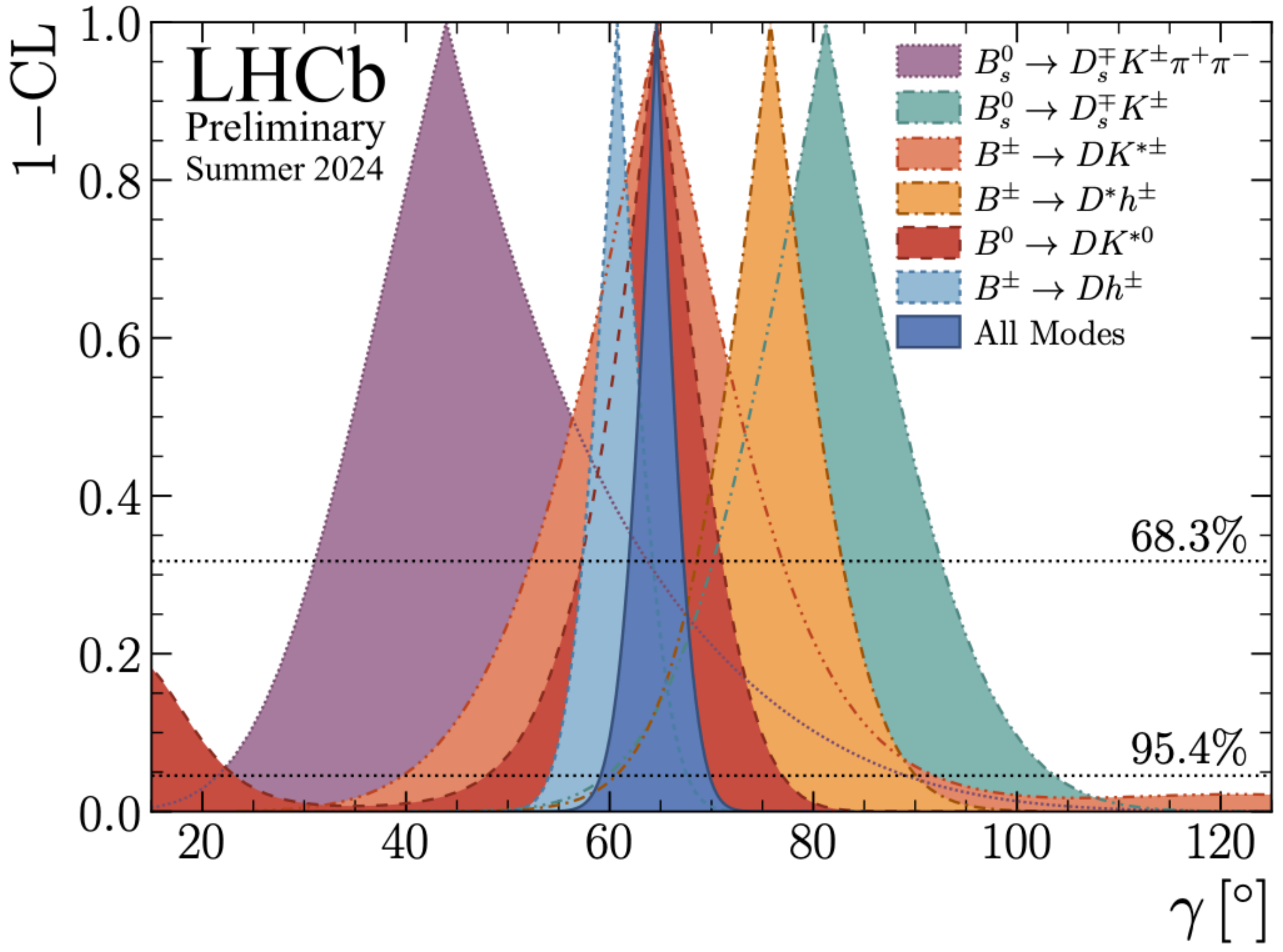
arXiv:2411.18639

All the phases…Today

Question to my theory/phenomenology colleagues:
While the overall picture is looking very SM-like do we believe there is room for NP in these observables?

2412.19624v1





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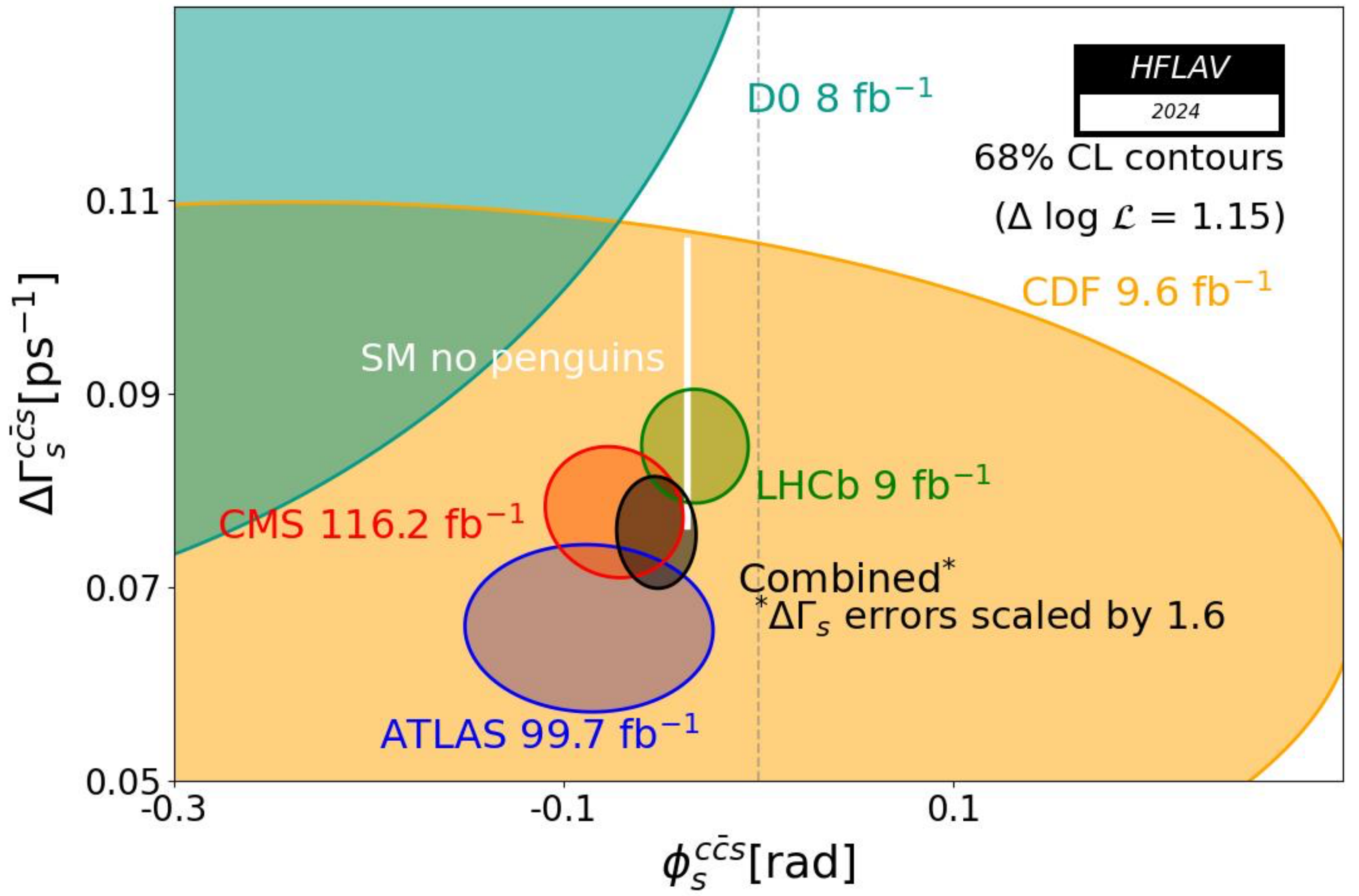


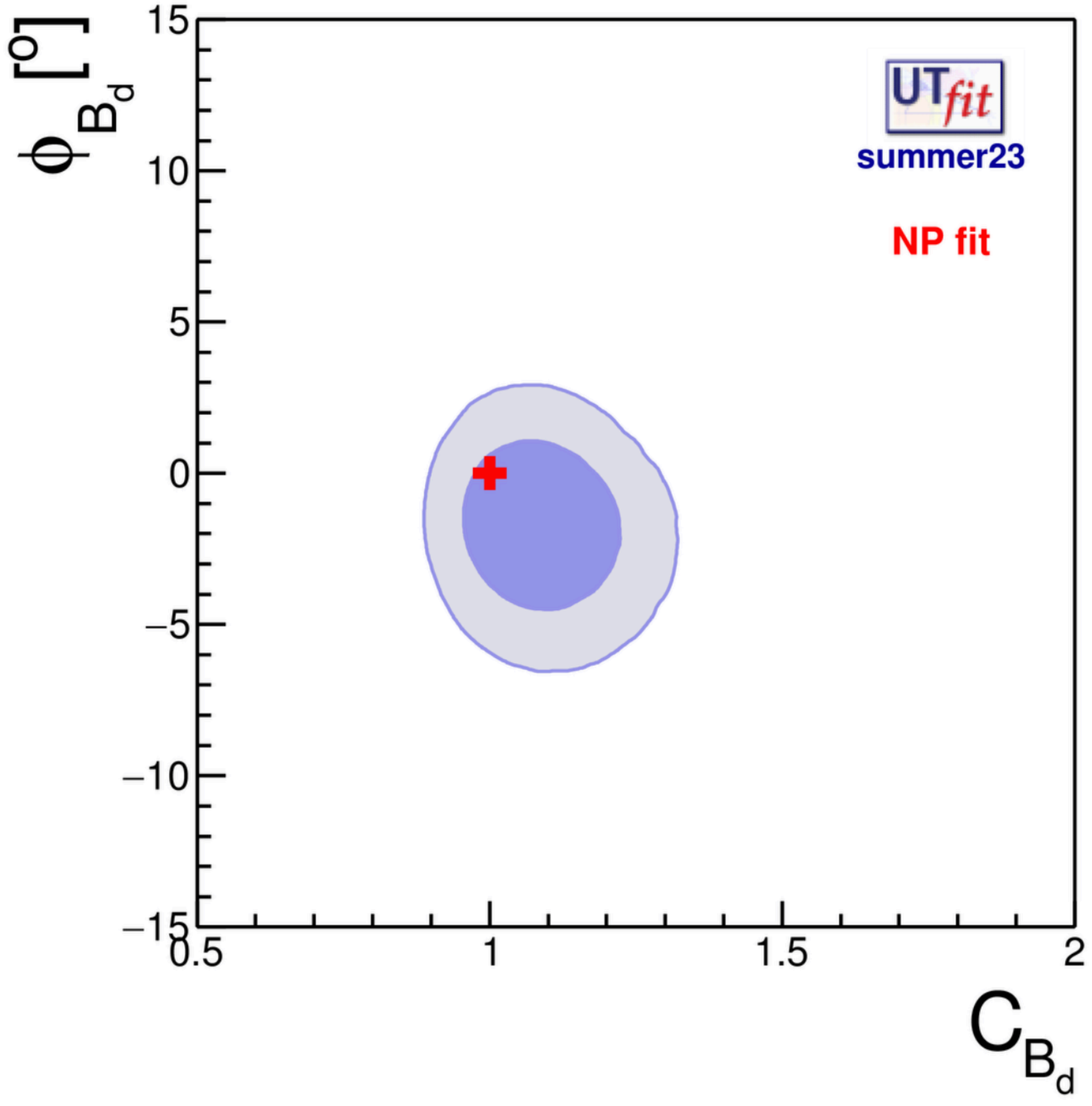
arXiv:2411.18639

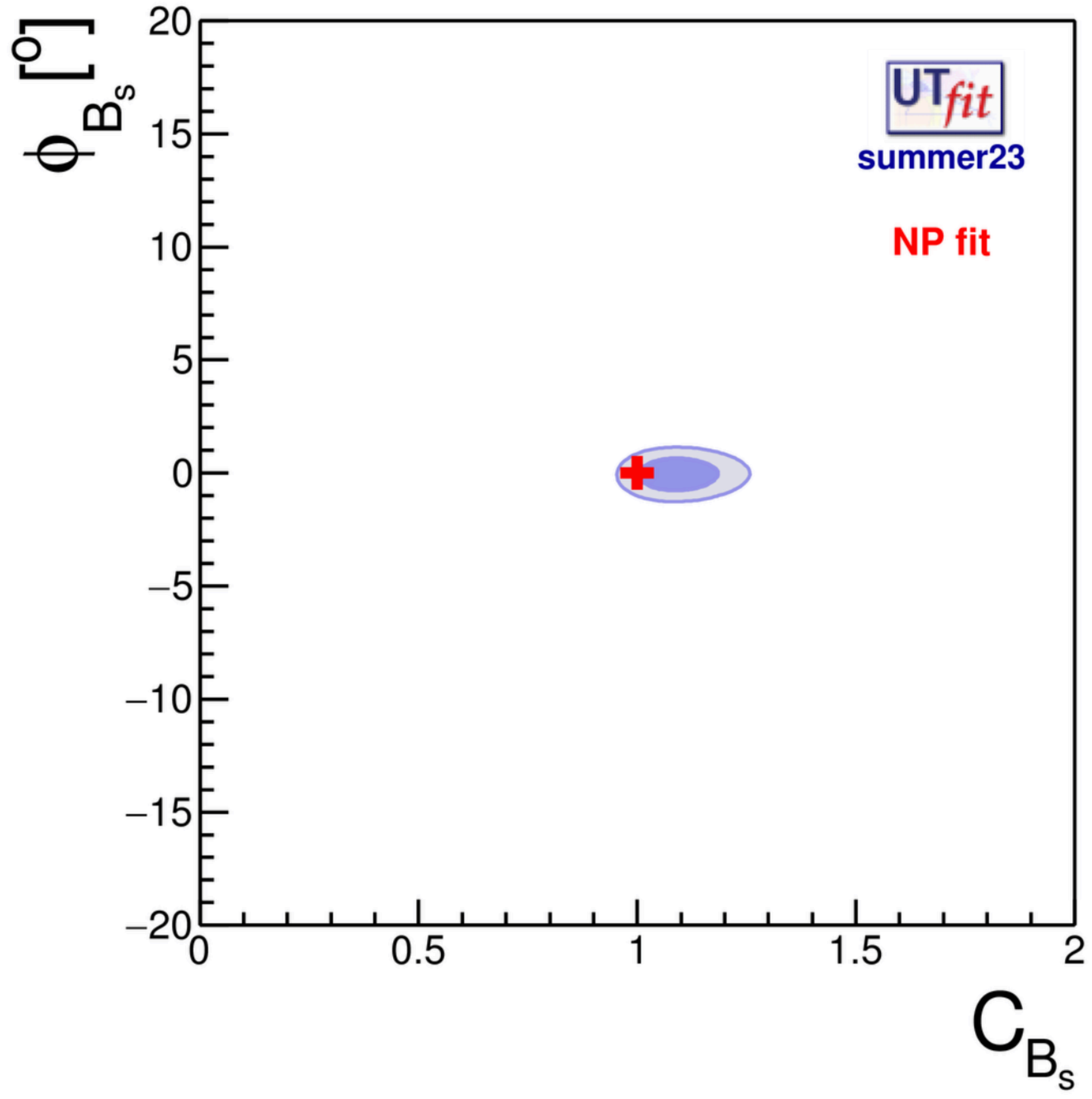
An example of a UT fit

Adopt a given parametrisation

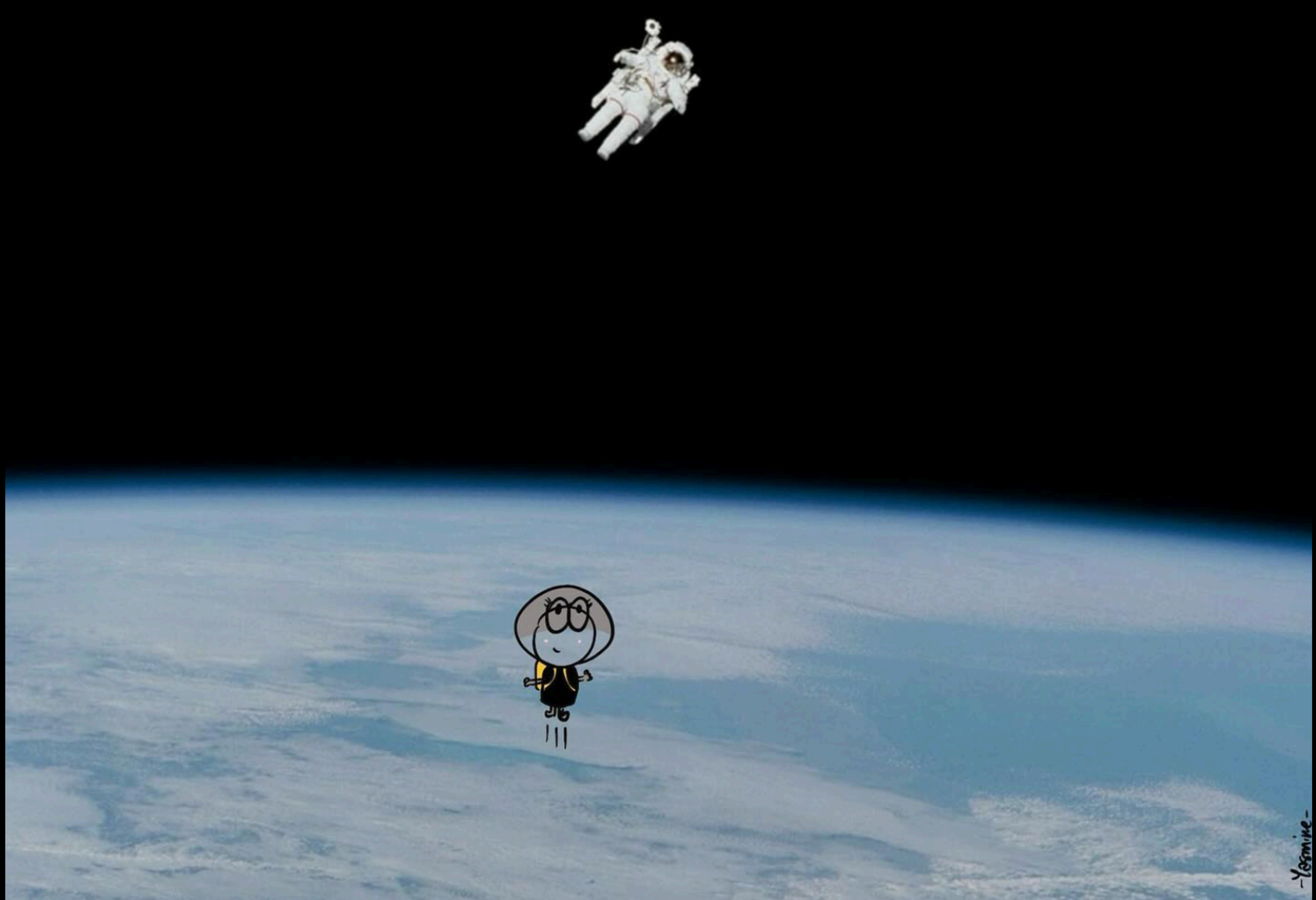
$$A_q = C_{B_q} e^{2i\phi_{B_q}} A_q^{SM} e^{2i\phi_q^{SM}}$$

SM

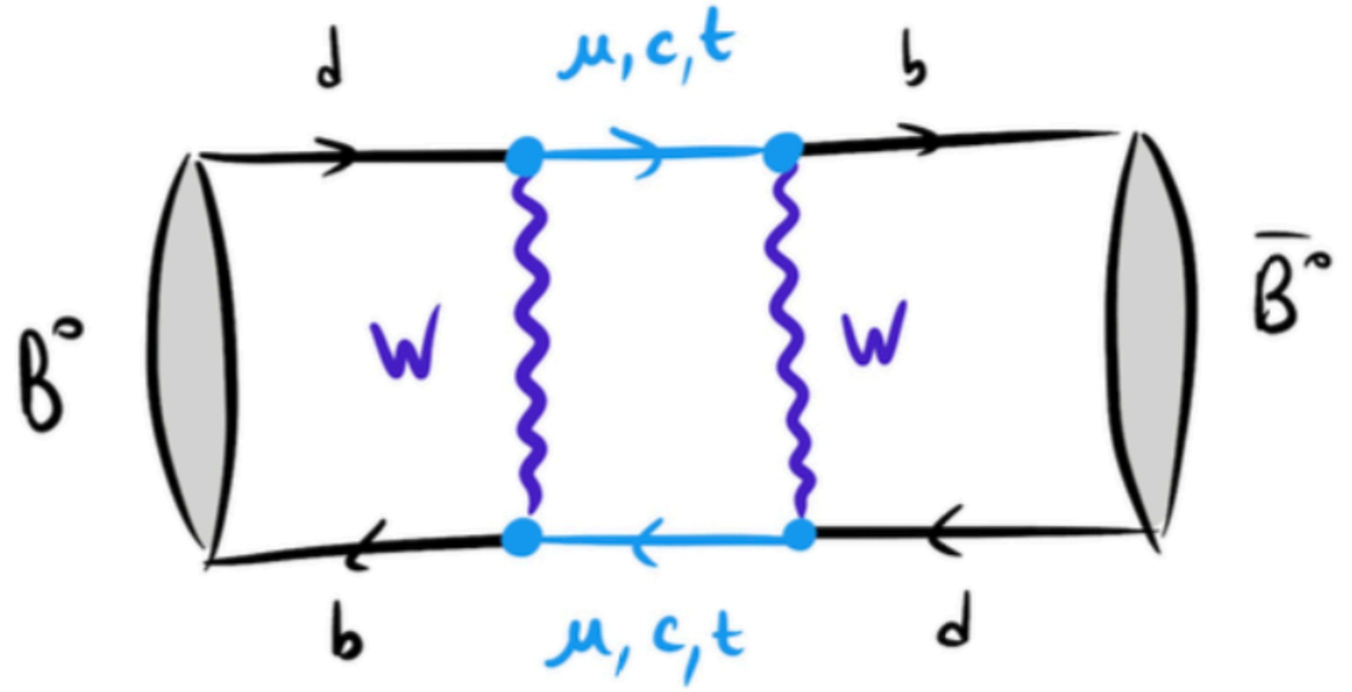


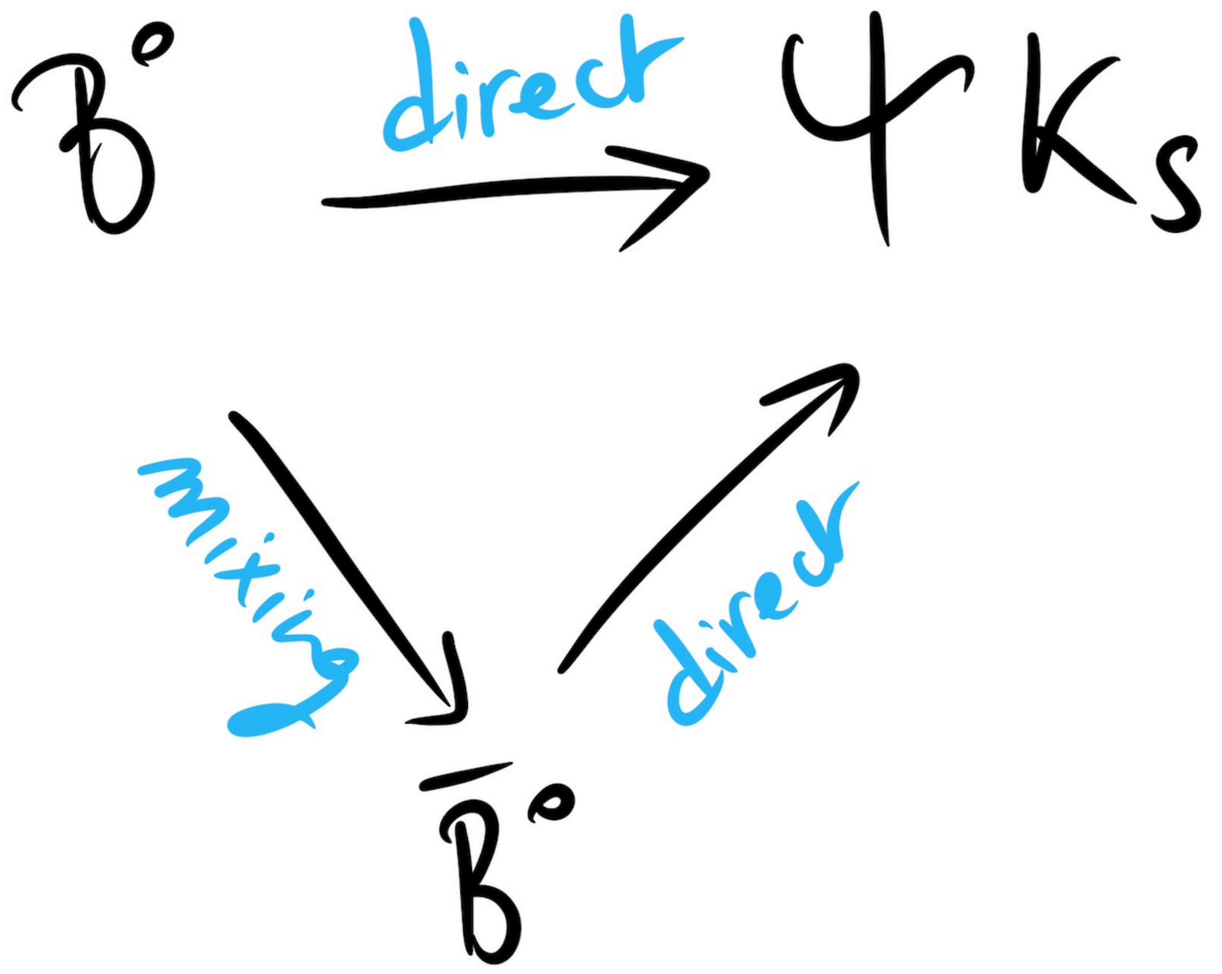


Let’s dive in



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



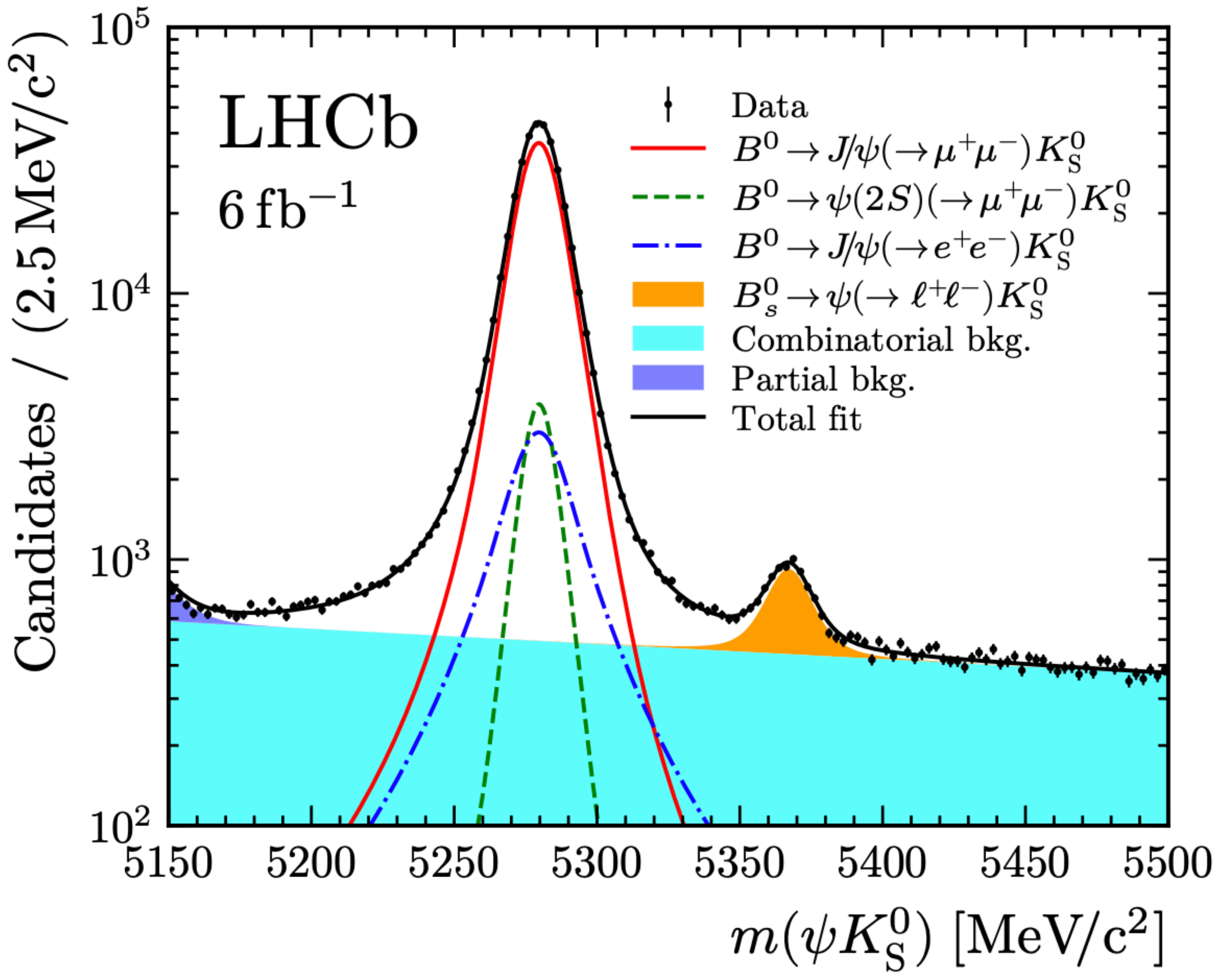


Time dependent analysis → requires flavour tagging

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

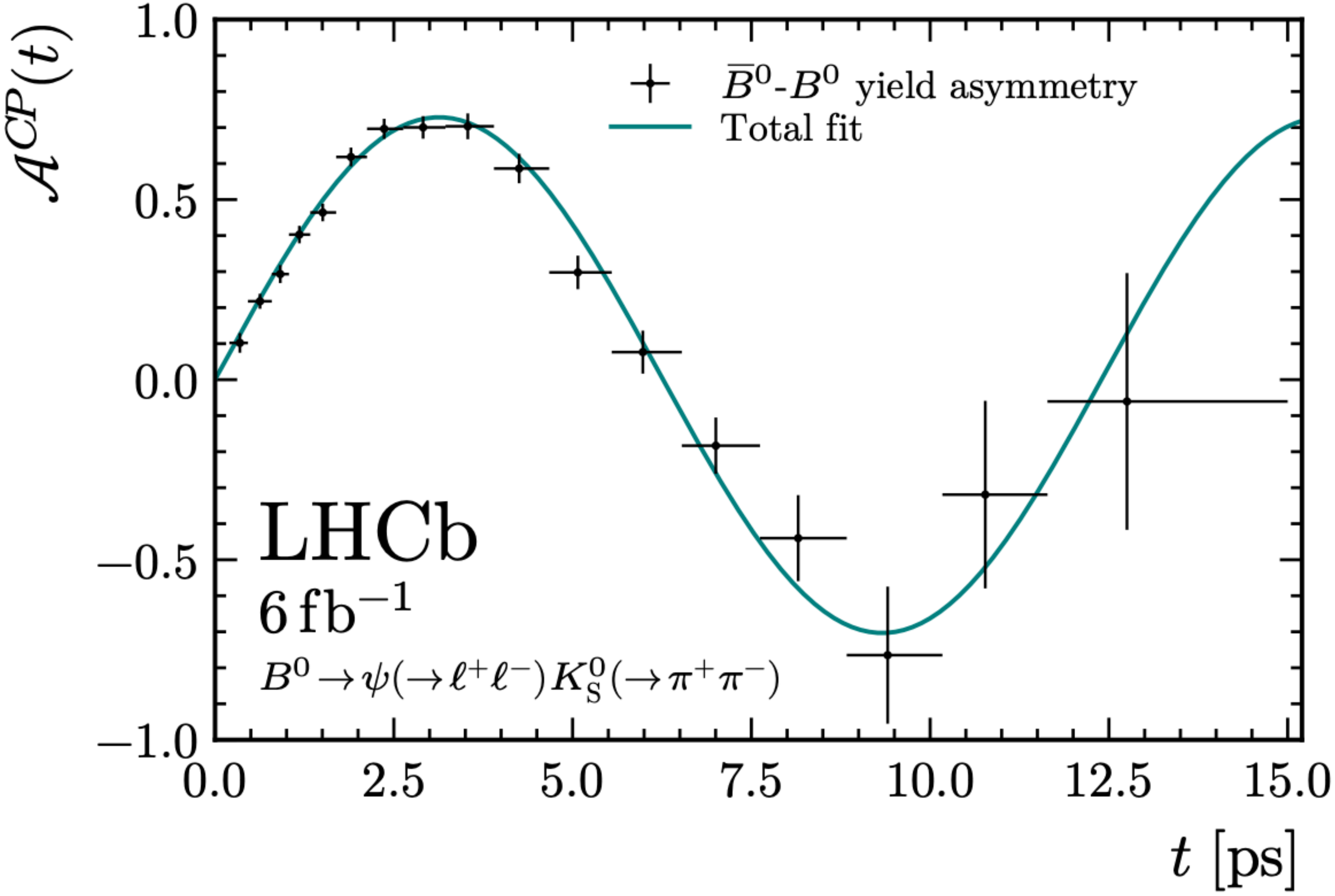
Experimental dilution

Text book like result !



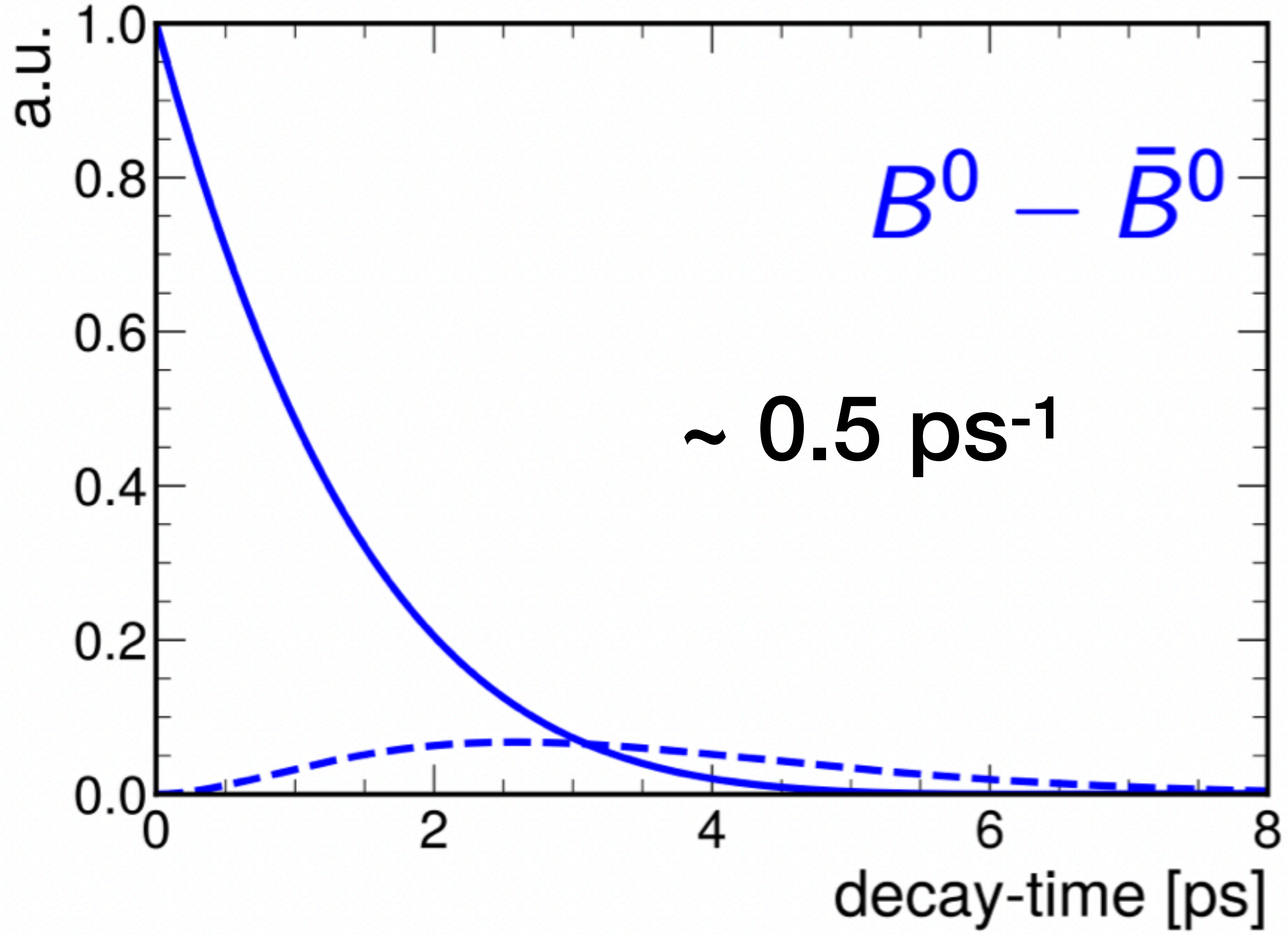
Trigger wise dilepton decays
are a day at the beach

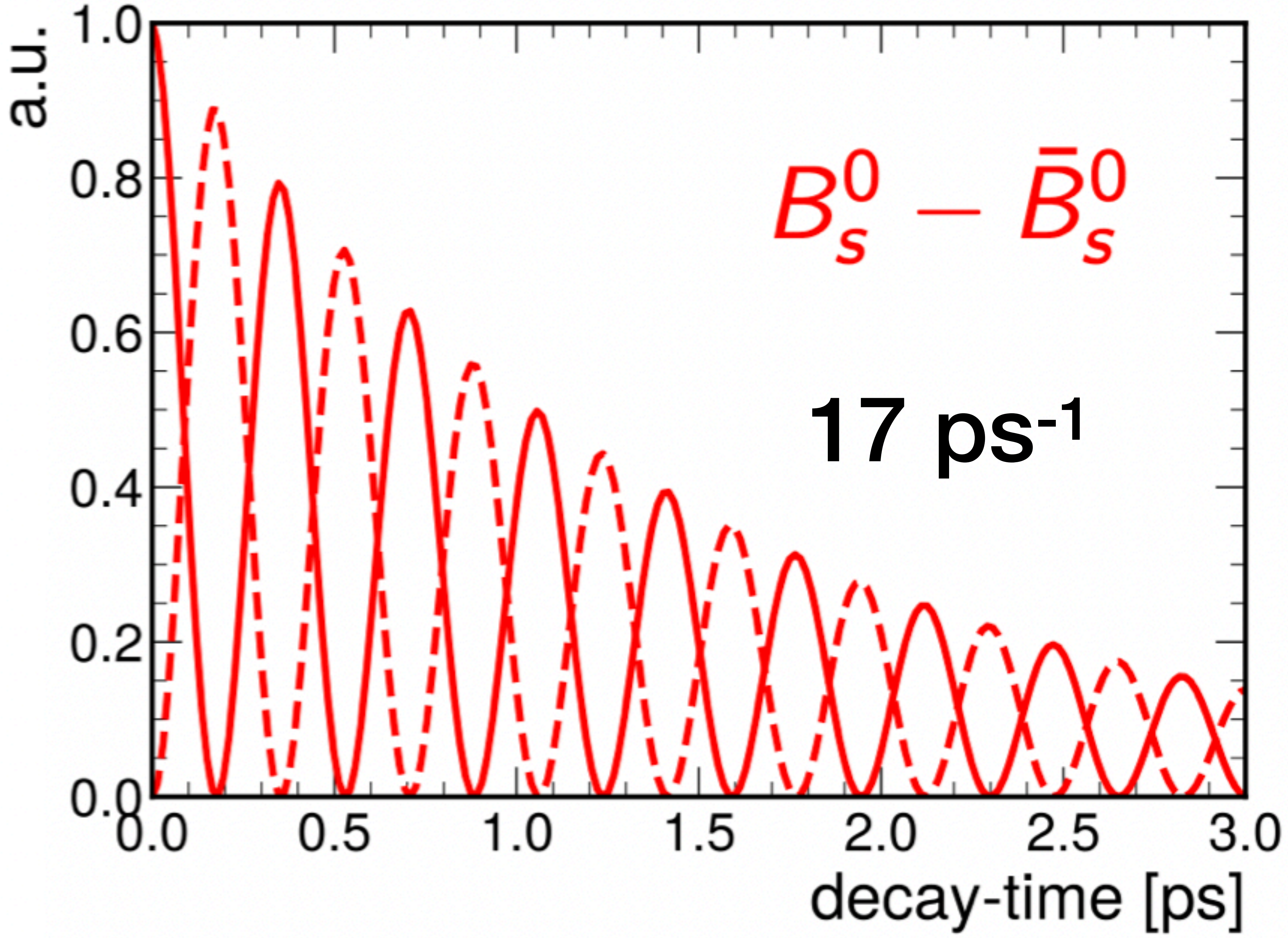
Combination of a few decay channels



arXiv:2309.09728

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





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

M: Mass Matrix — Dispersive

Γ: 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:

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

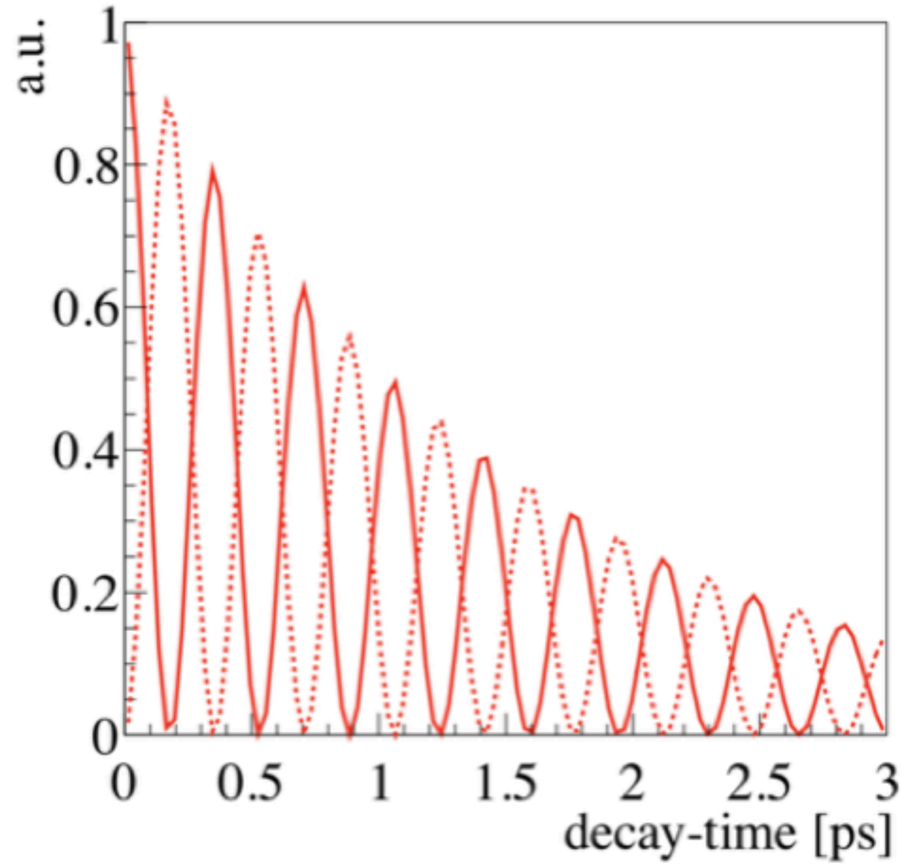
$$m_q = \frac{m_H - m_L}{2}\,, \quad \Gamma_q = \frac{\Gamma_L + \Gamma_H}{2} = \frac{1}{\tau}$$

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

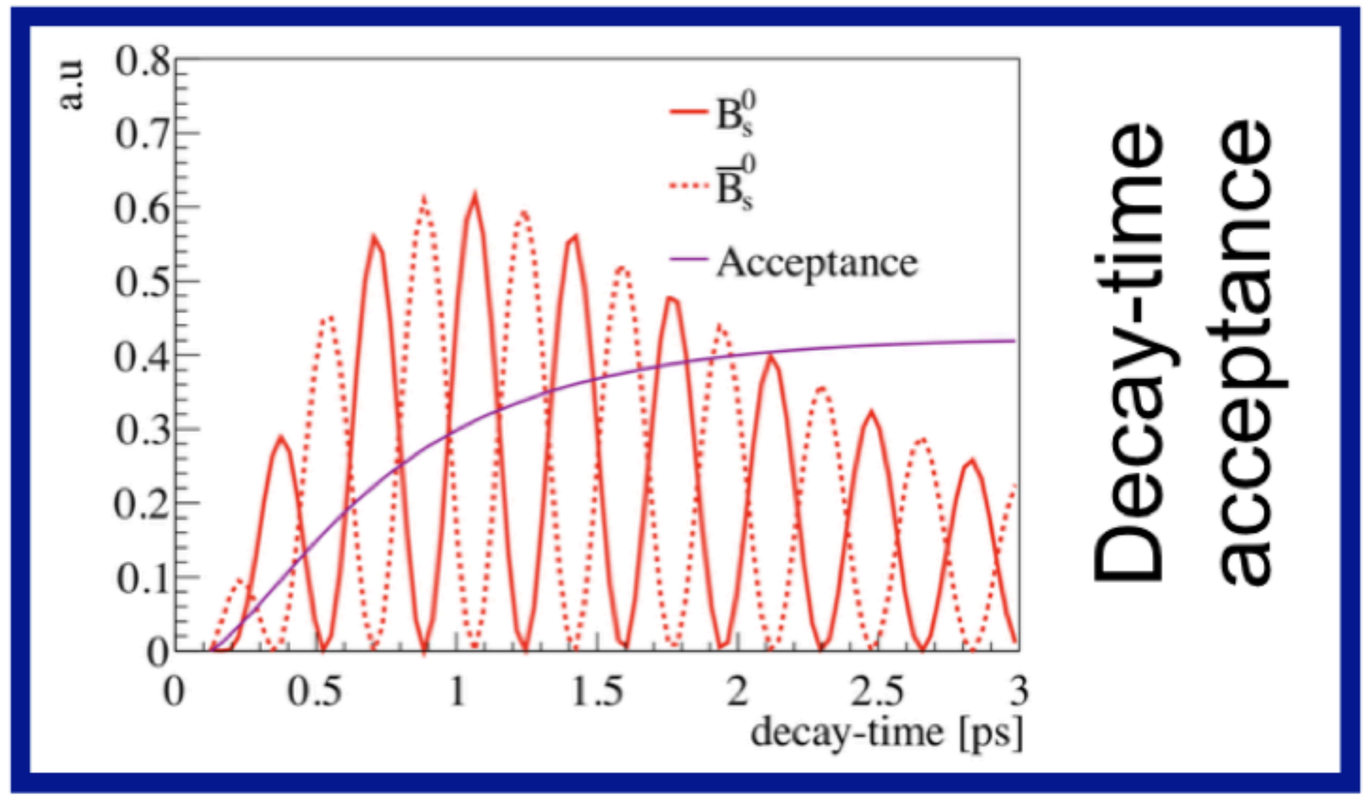
CERN-THESIS-2014-361 a very pedagogical reference.

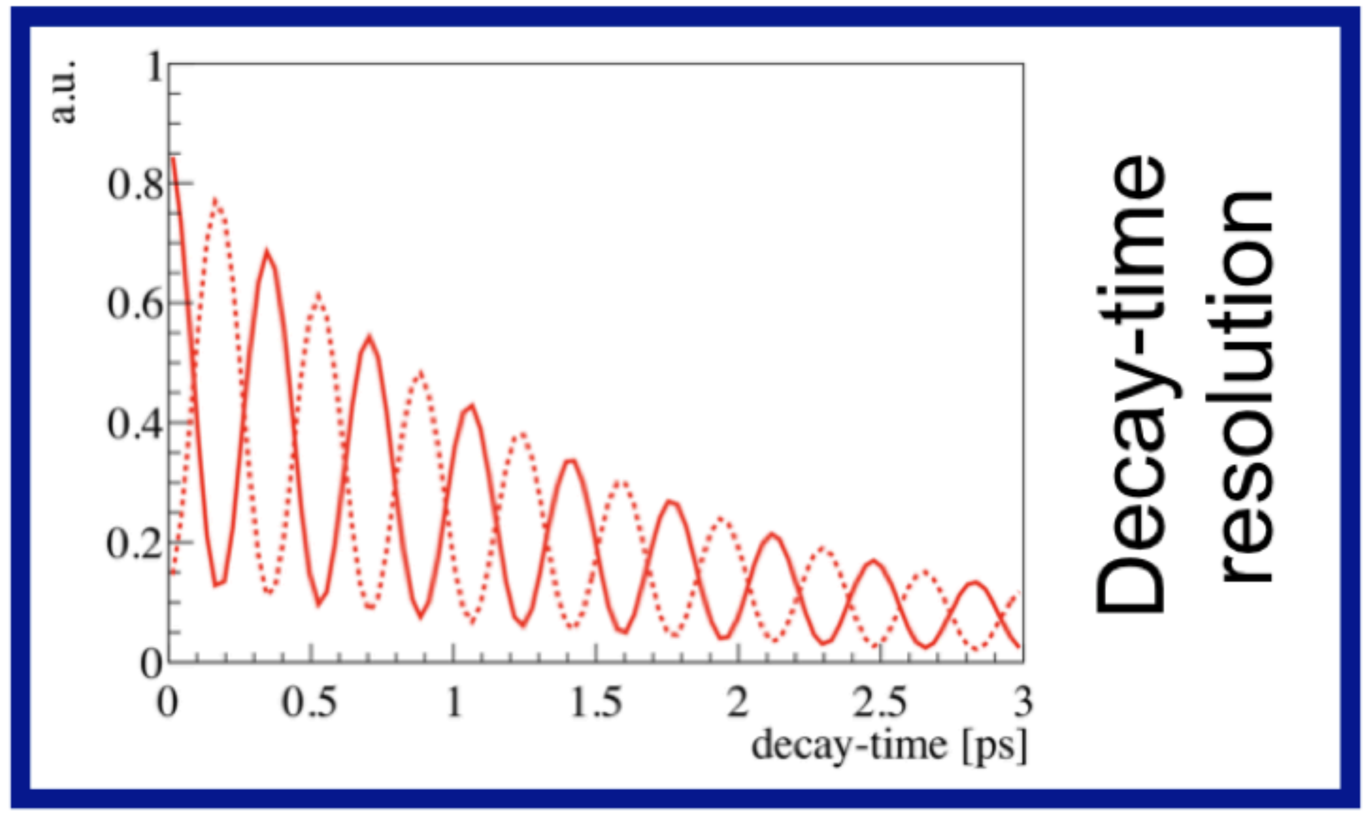
Detector effects

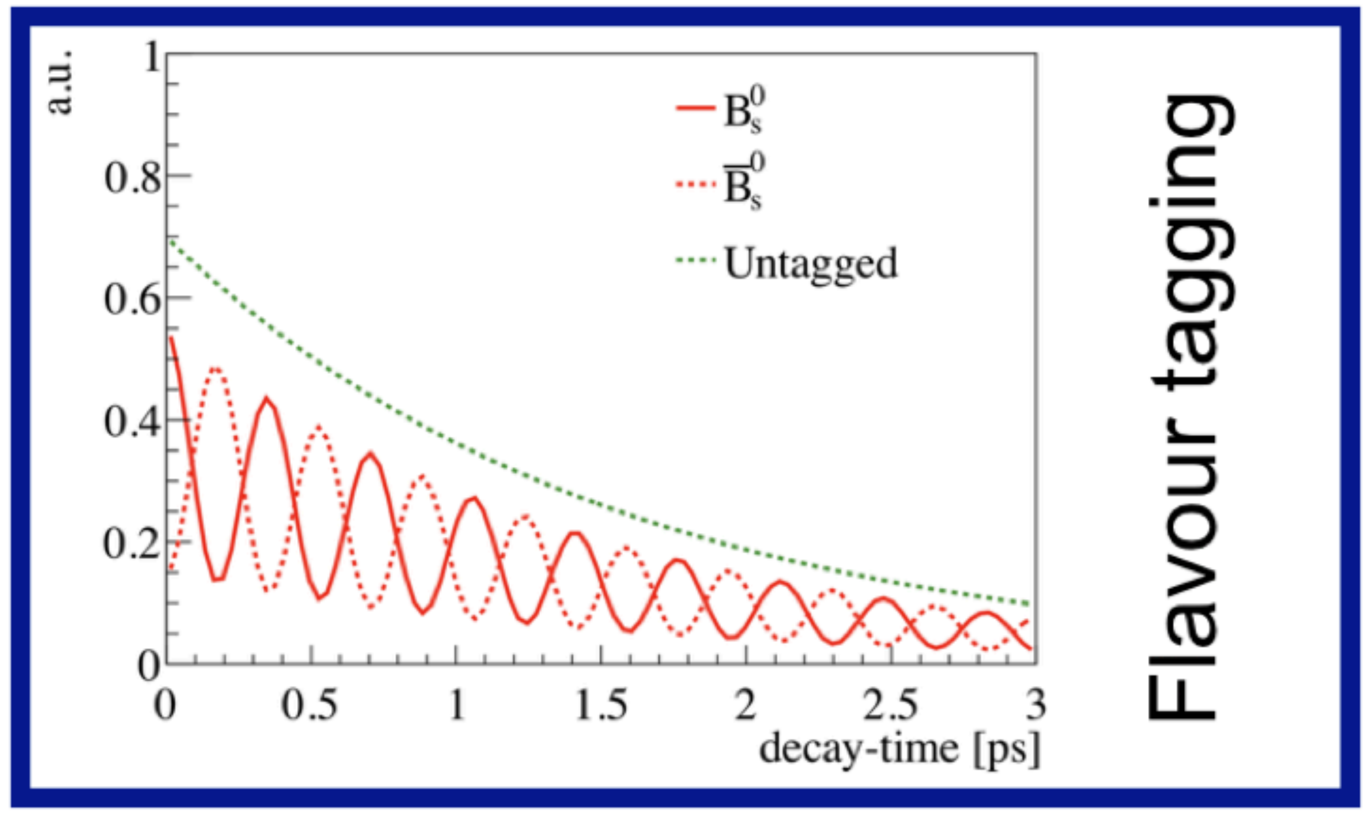
Perfect



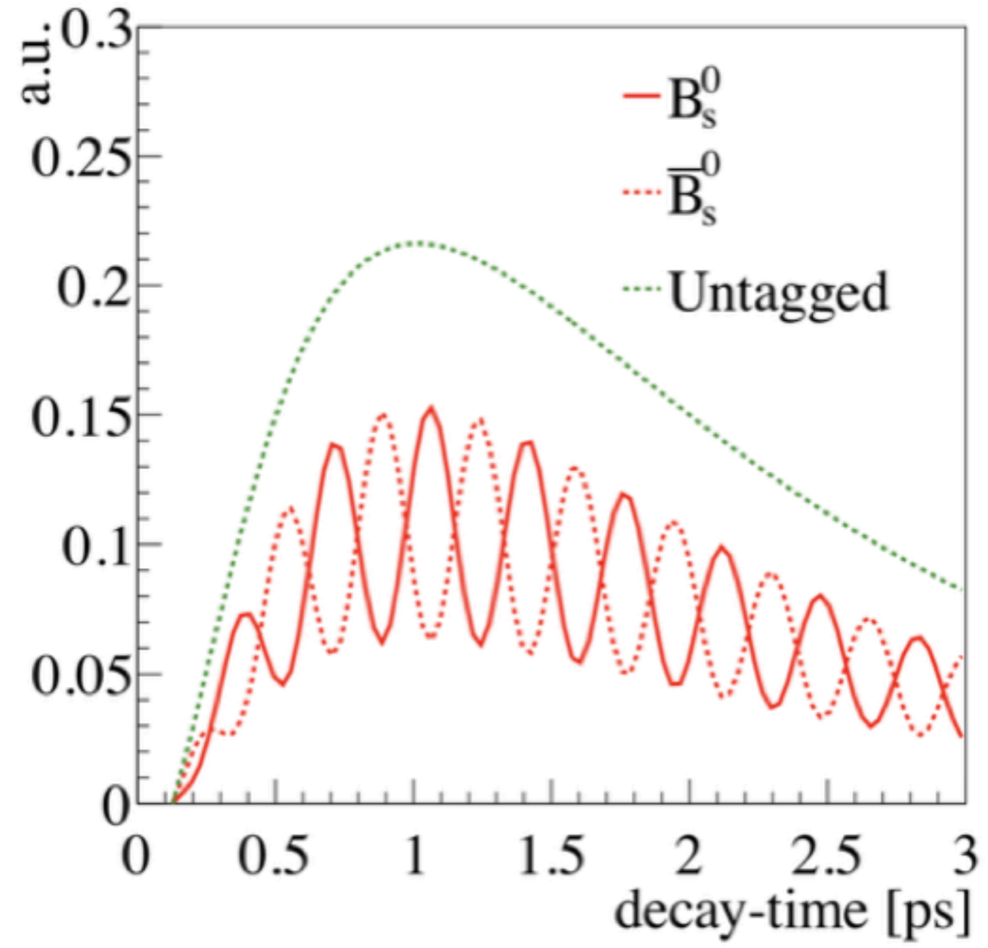
$$P(t) \sim e^{-\Gamma_s t}(\cosh(\frac{\Delta\Gamma_s t}{2}) \pm \cos(\Delta m_s t))$$

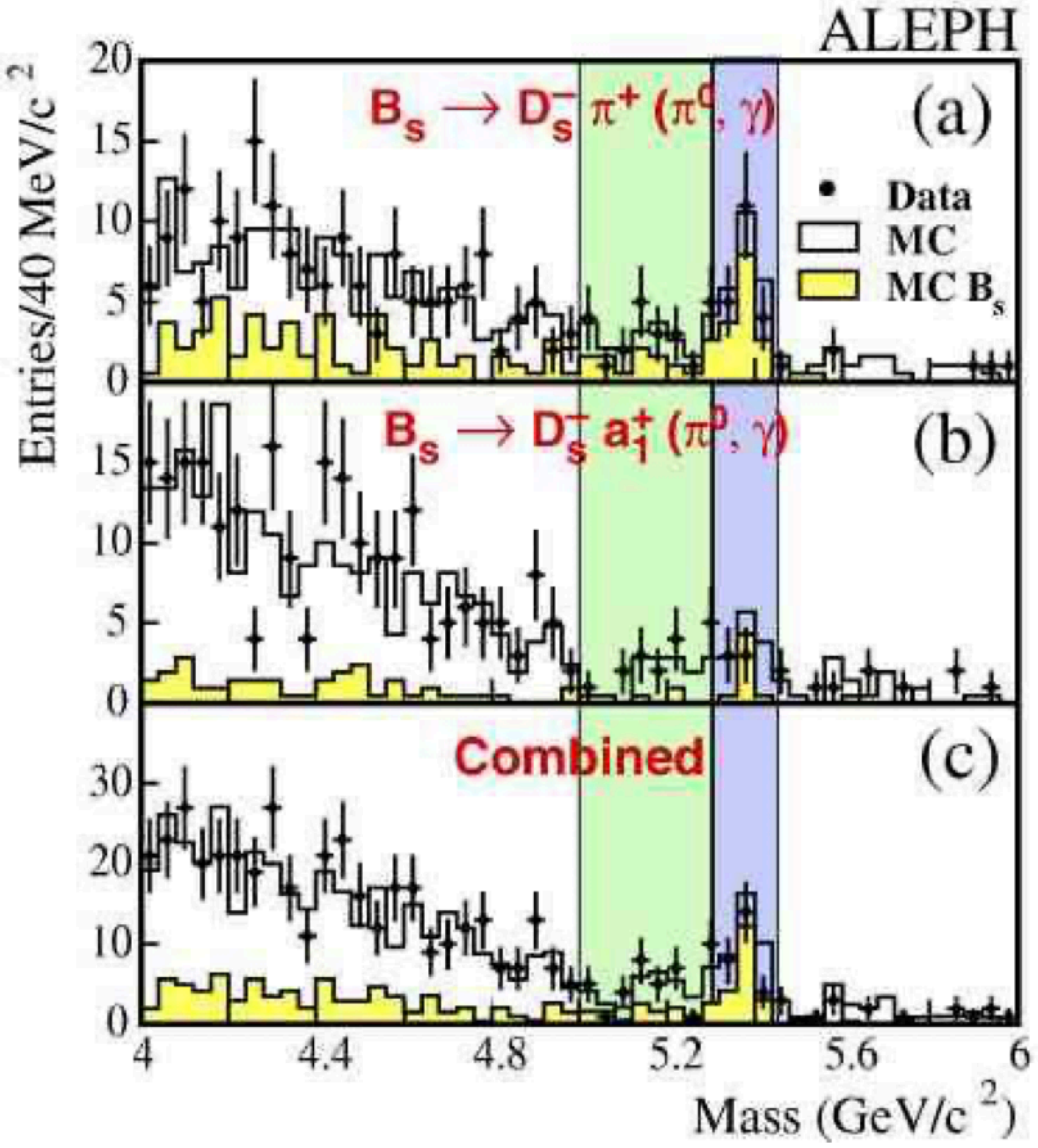






Data





arXiv:0209007

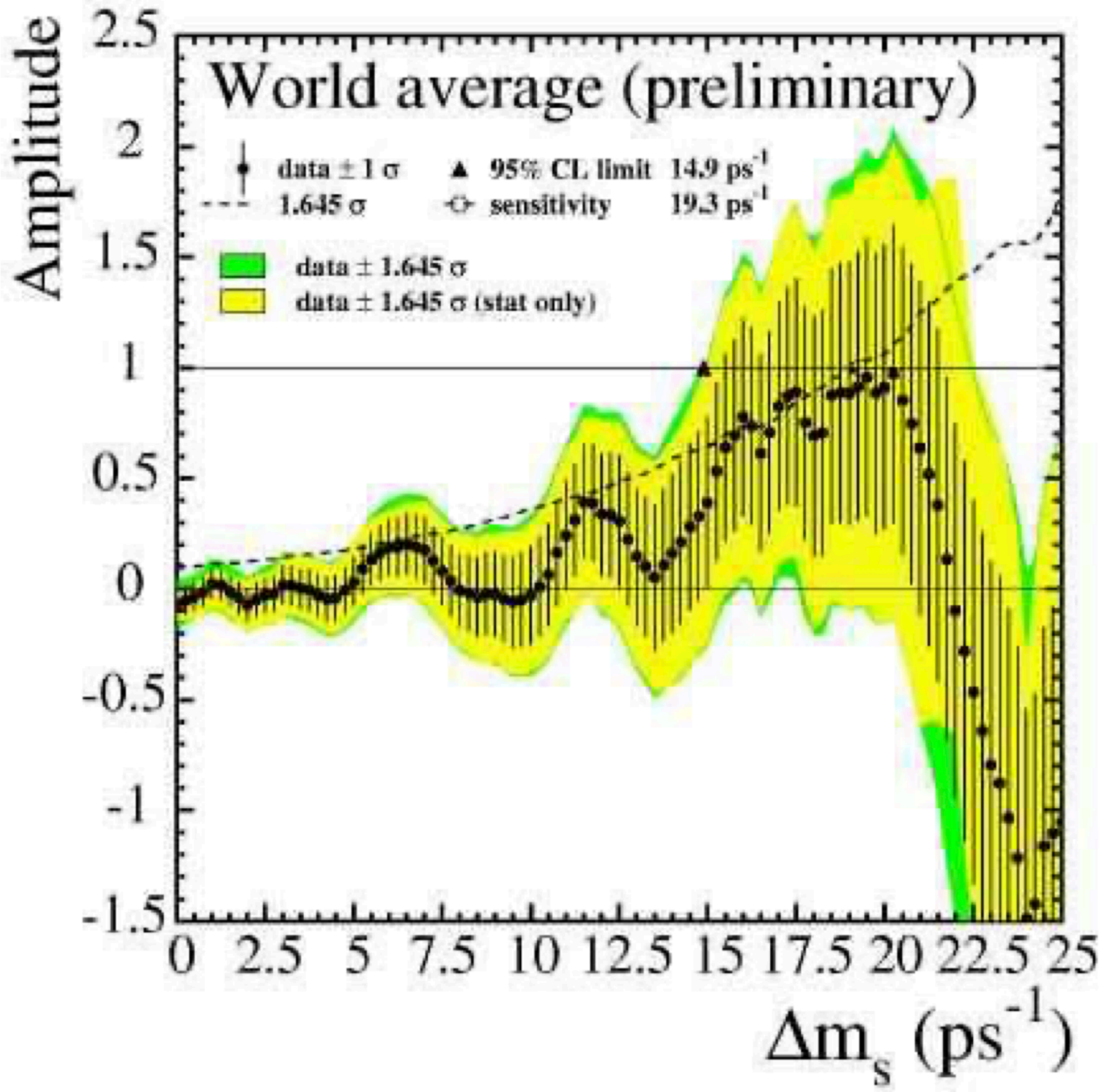
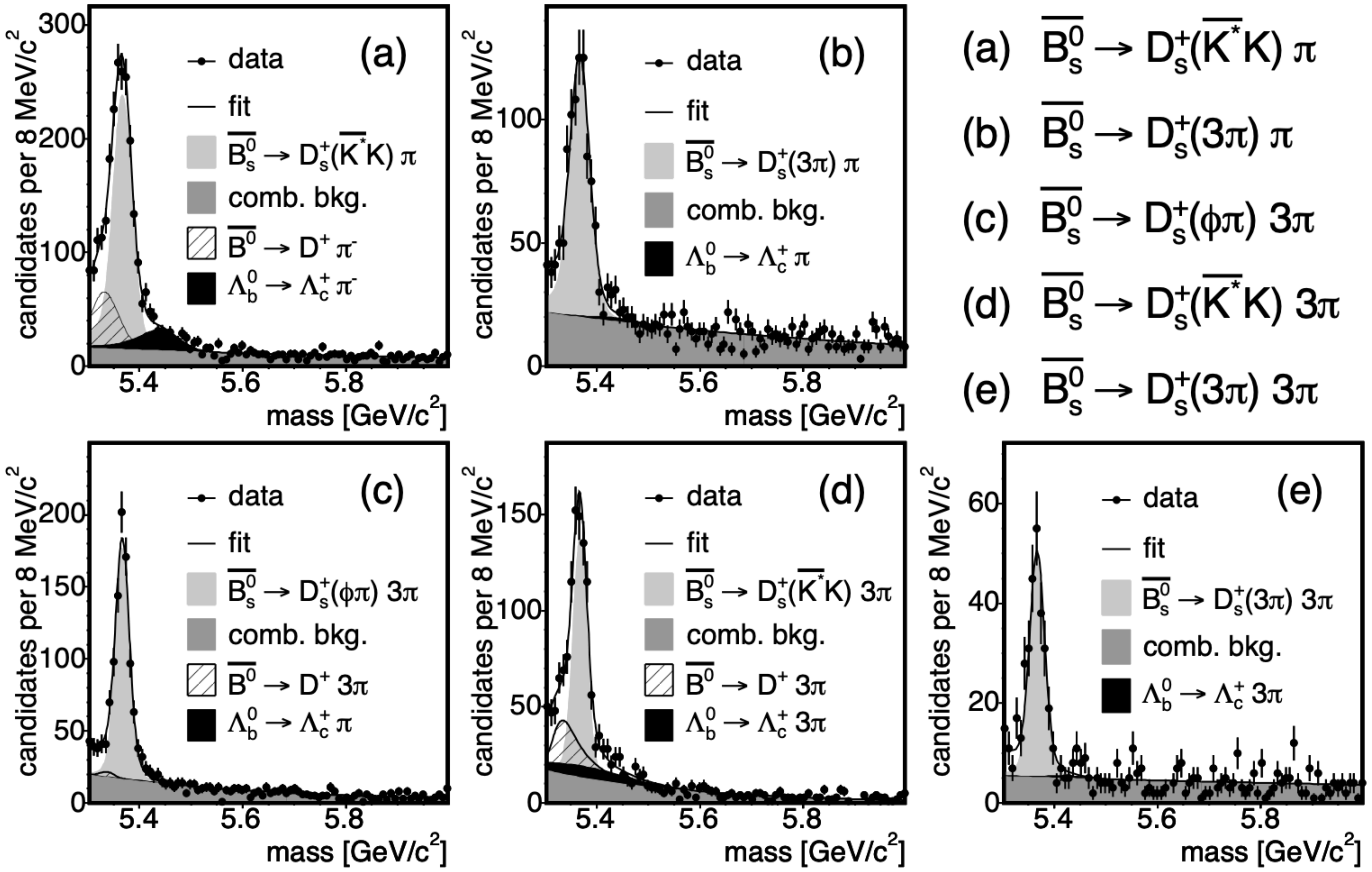
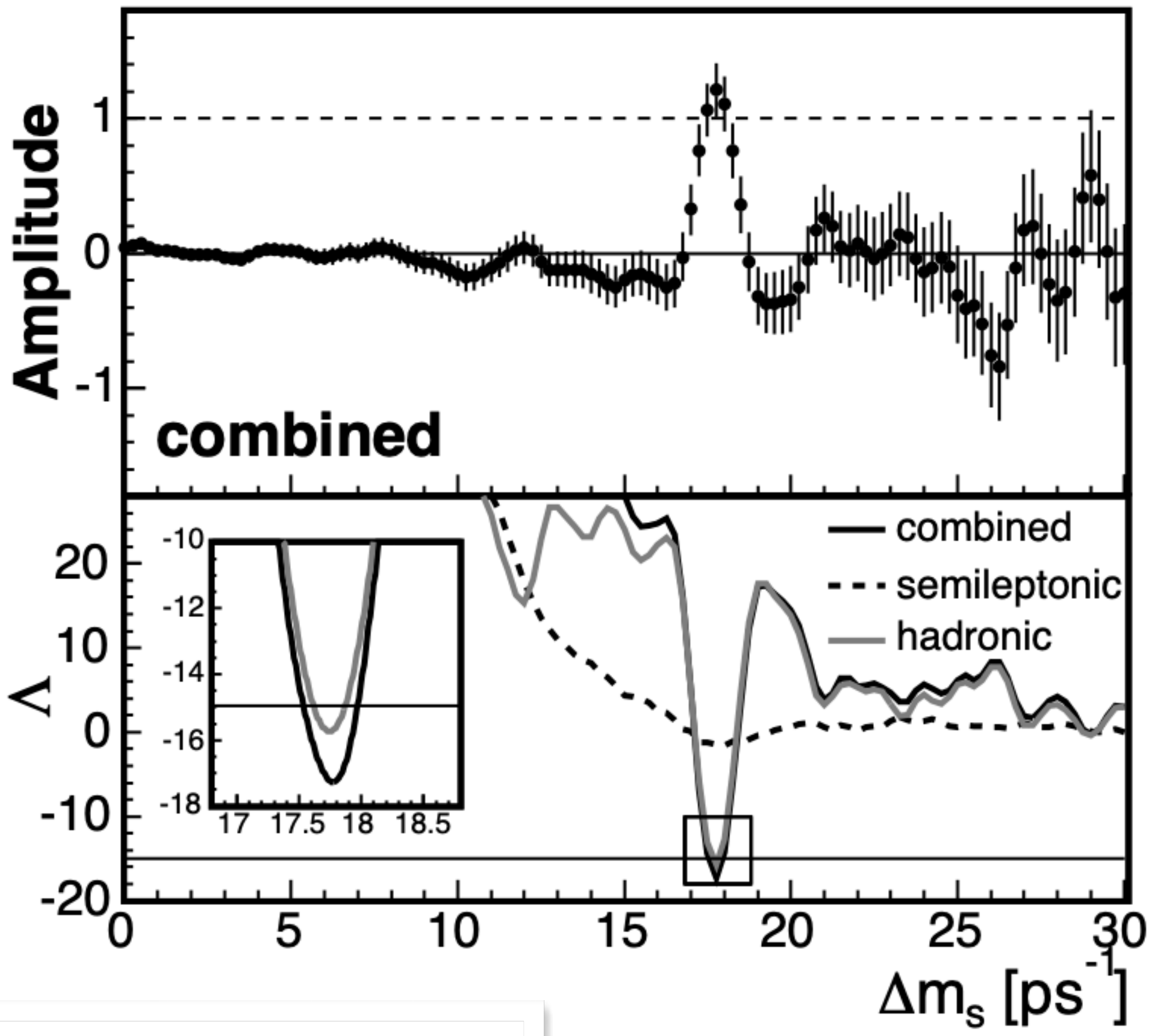


Figure 7: The combined B_s^0 oscillation results from ALEPH, CDF, DELPHI, OPAL, and SLD shown as amplitude versus hypothesized Δm_s [11]. The dots with error bars show the fitted aplitude values and uncertainties. An observed (expected) 95% C.L. lower limit on Δm_s of 14.9 ps^{-1} (19.3 ps^{-1}) is obtained.

My personal end of the universe at the time



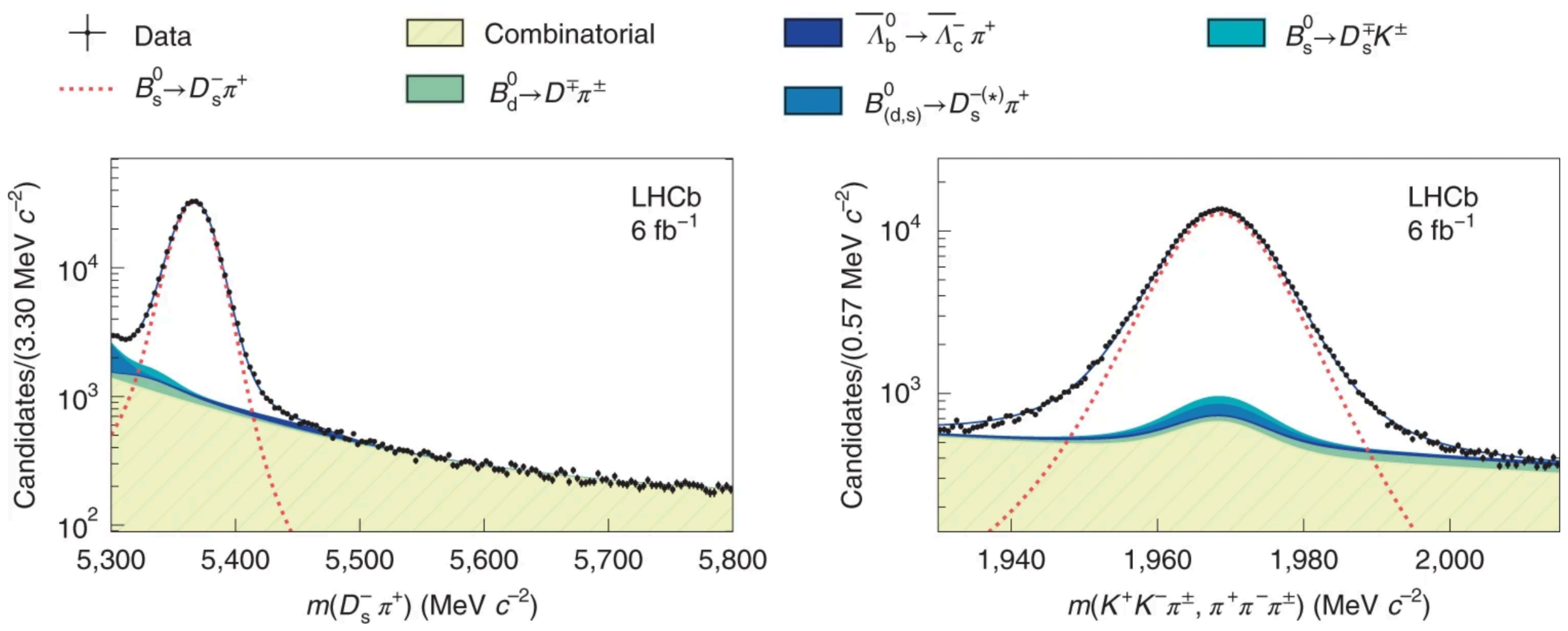


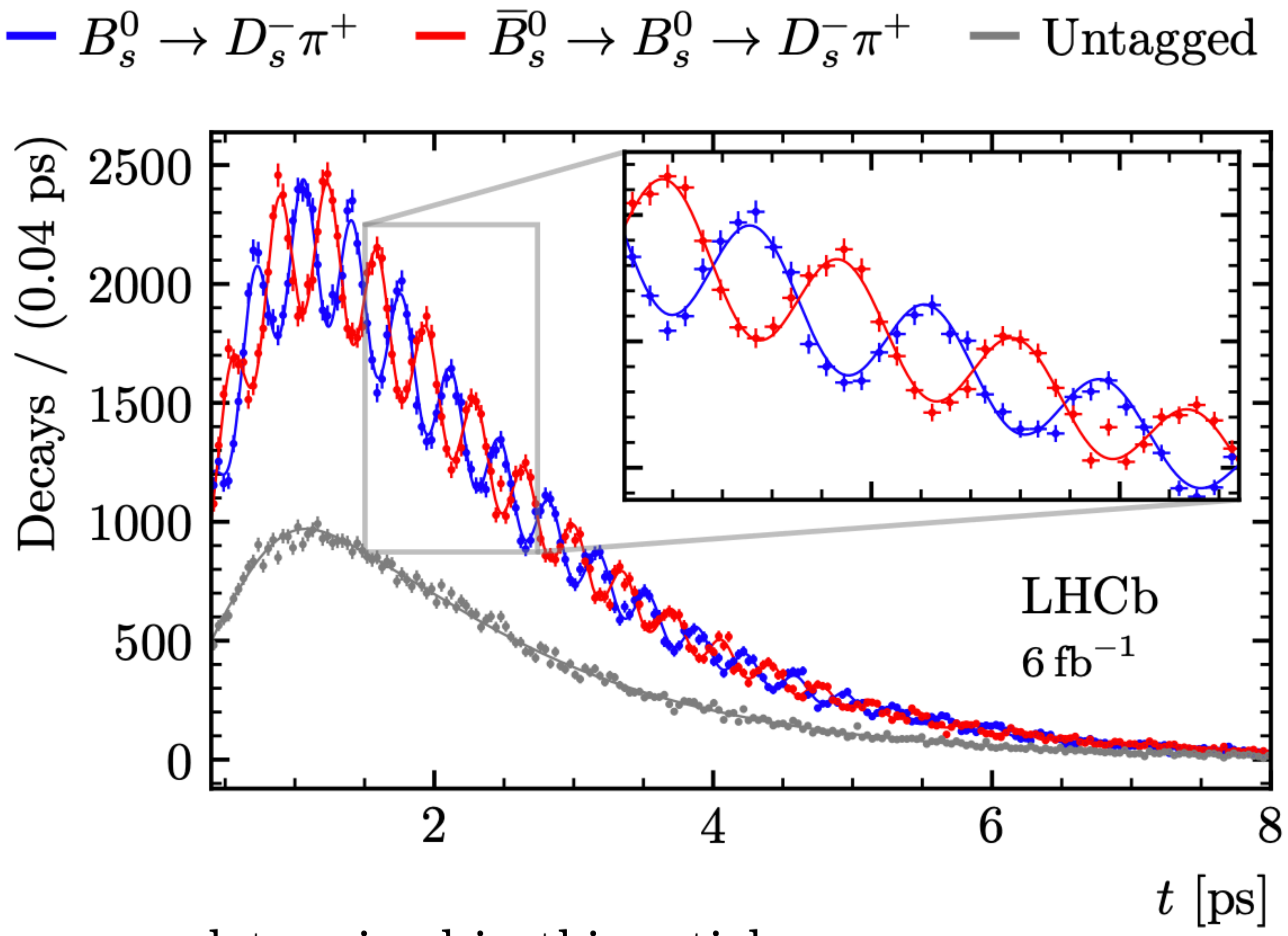

Observation of B_s^0-$\bar{B}_s^0$ Oscillations

arXiv:hep-ex/0609040v1 22 Sep 2006

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:

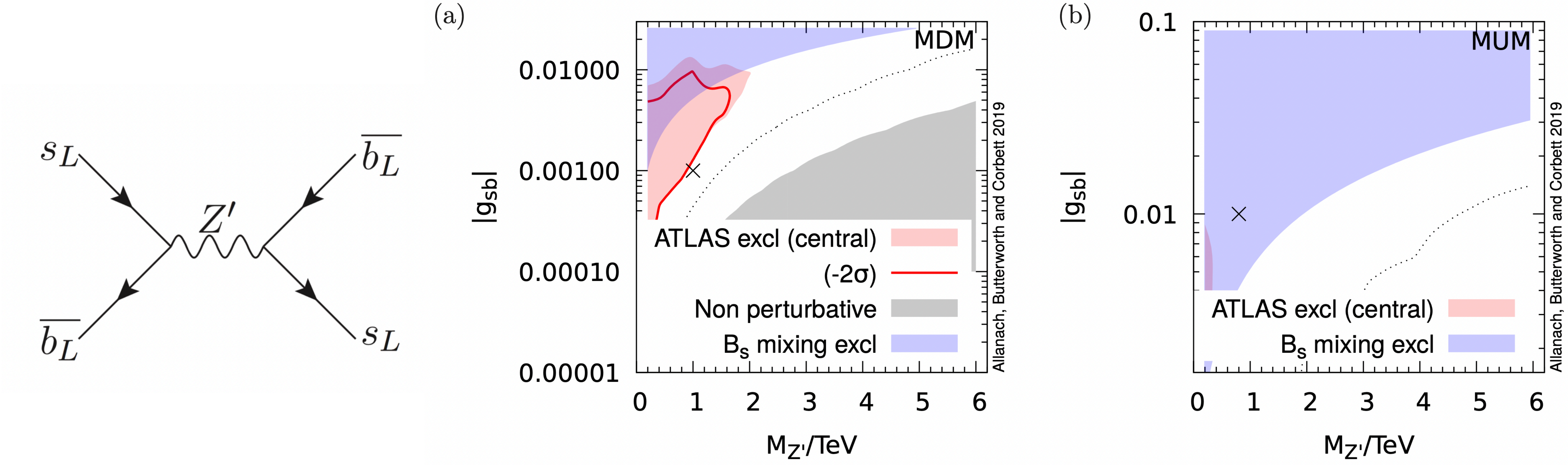
$$\Delta m_s = 17.7683 \pm 0.0051\,(\text{stat}) \pm 0.0032\,(\text{syst})\,\text{ps}^{-1}$$

arXiv:2104.04421

Loop back to the models

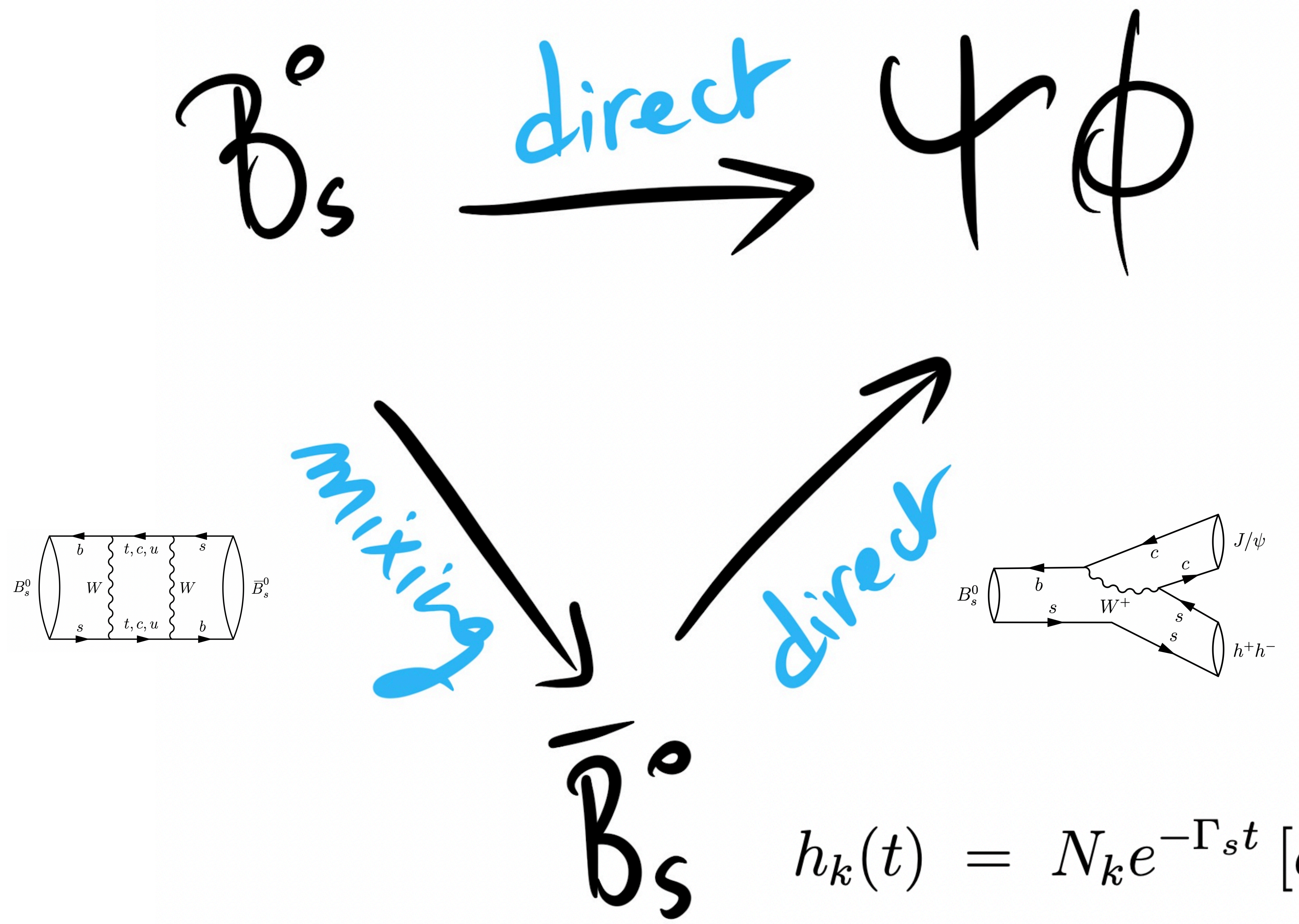
Standard Model

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



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

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



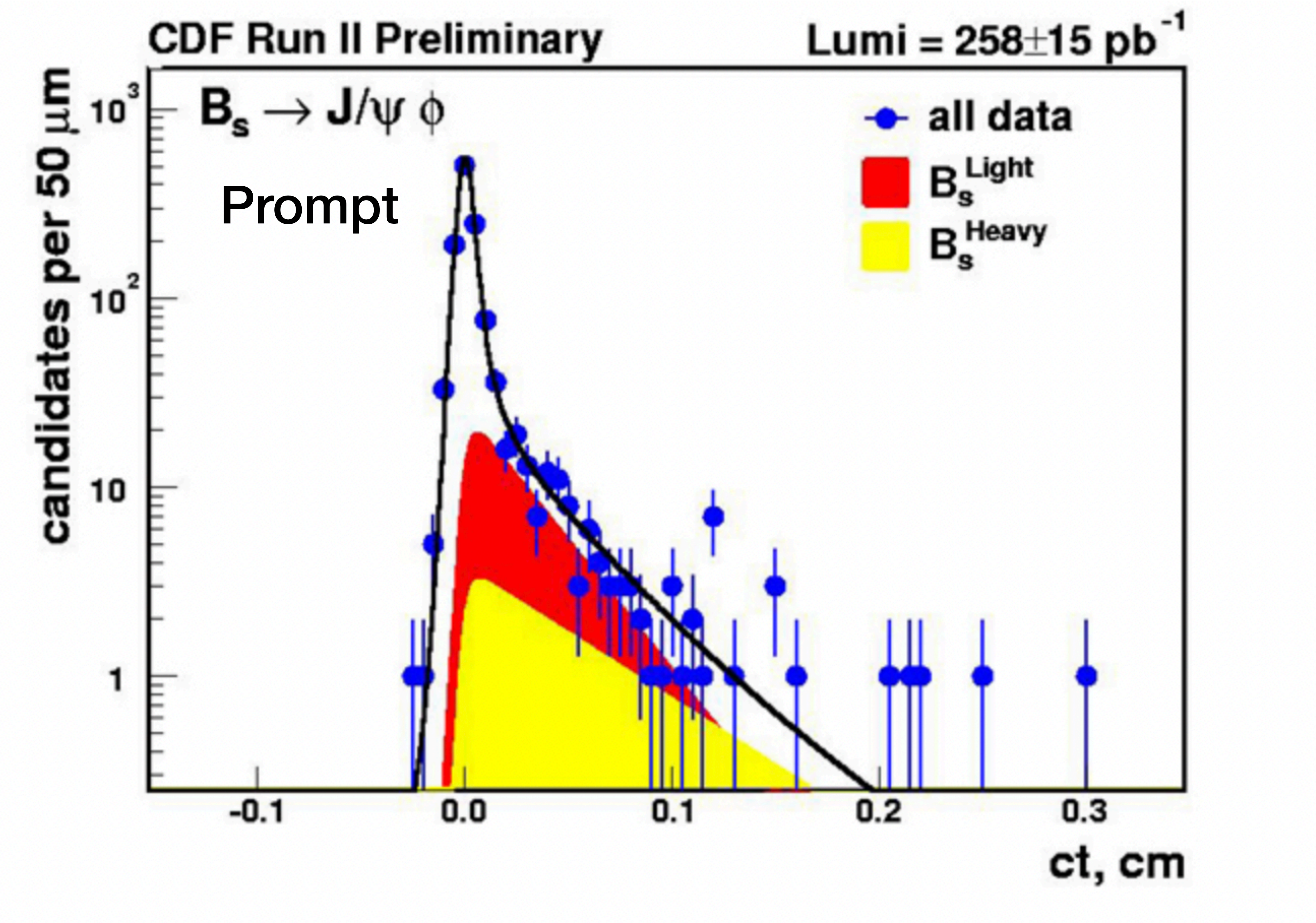
Mixture of CP odd and CP even eigenstates

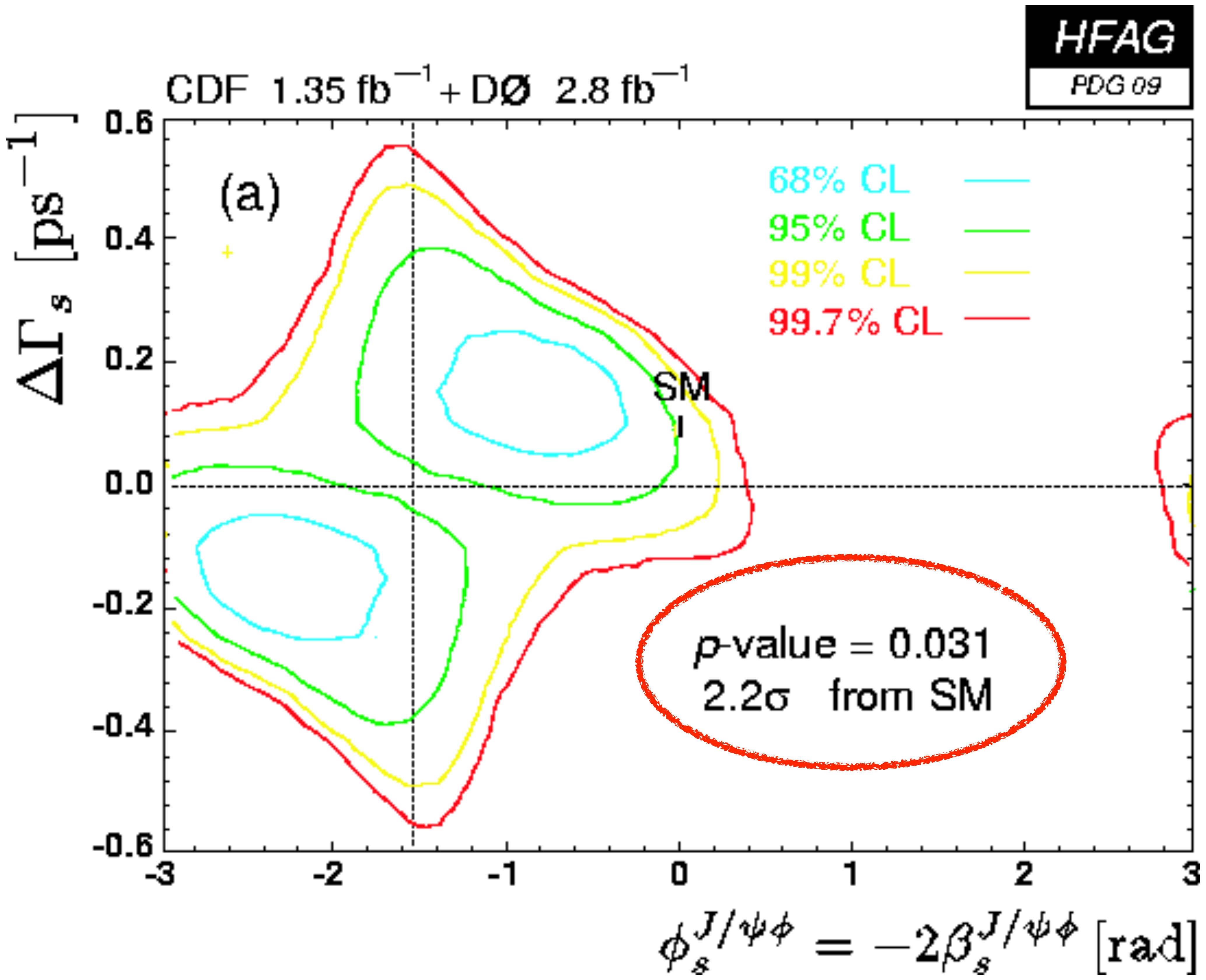
None negligible difference between the heavy and the light state of your the B_s^0 mesons $\Delta\Gamma_s$

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

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

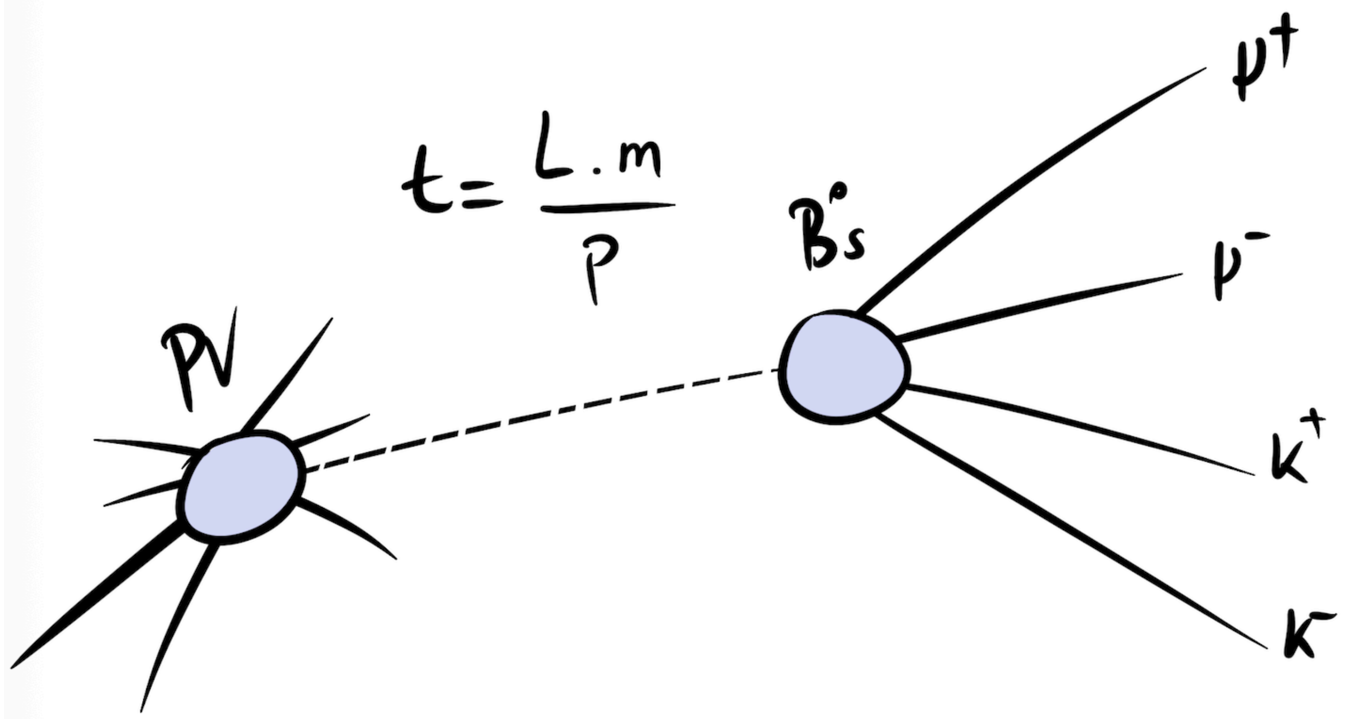
Fermilab paved the path of B_s^0 physics



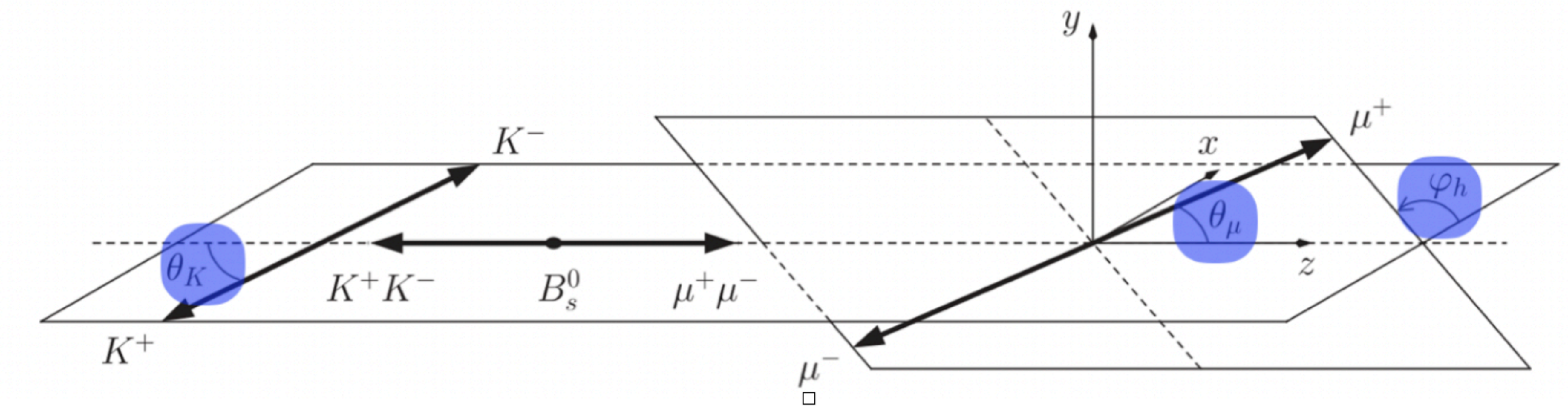


It’s “just” yet an other counting experiment

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

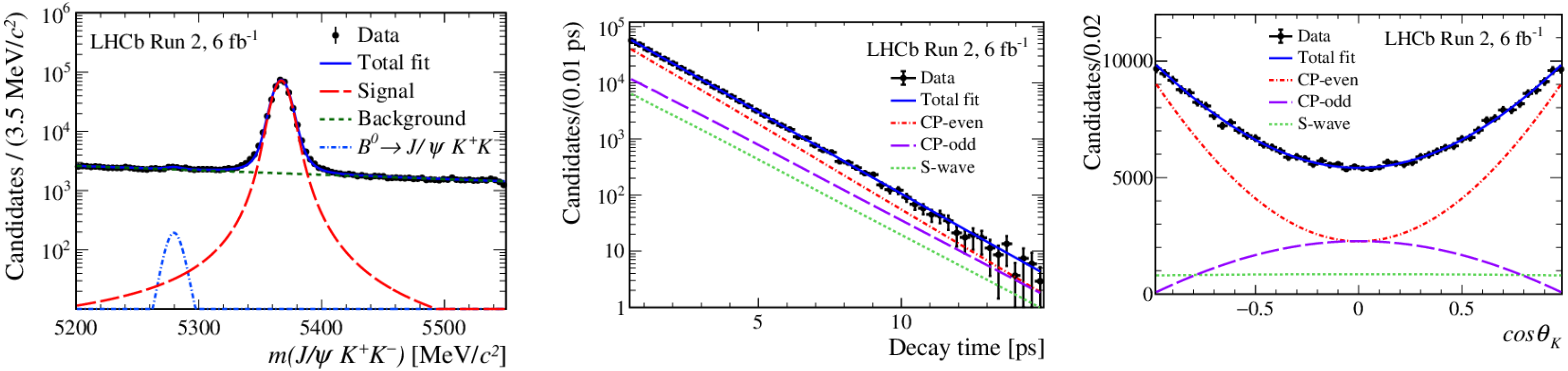


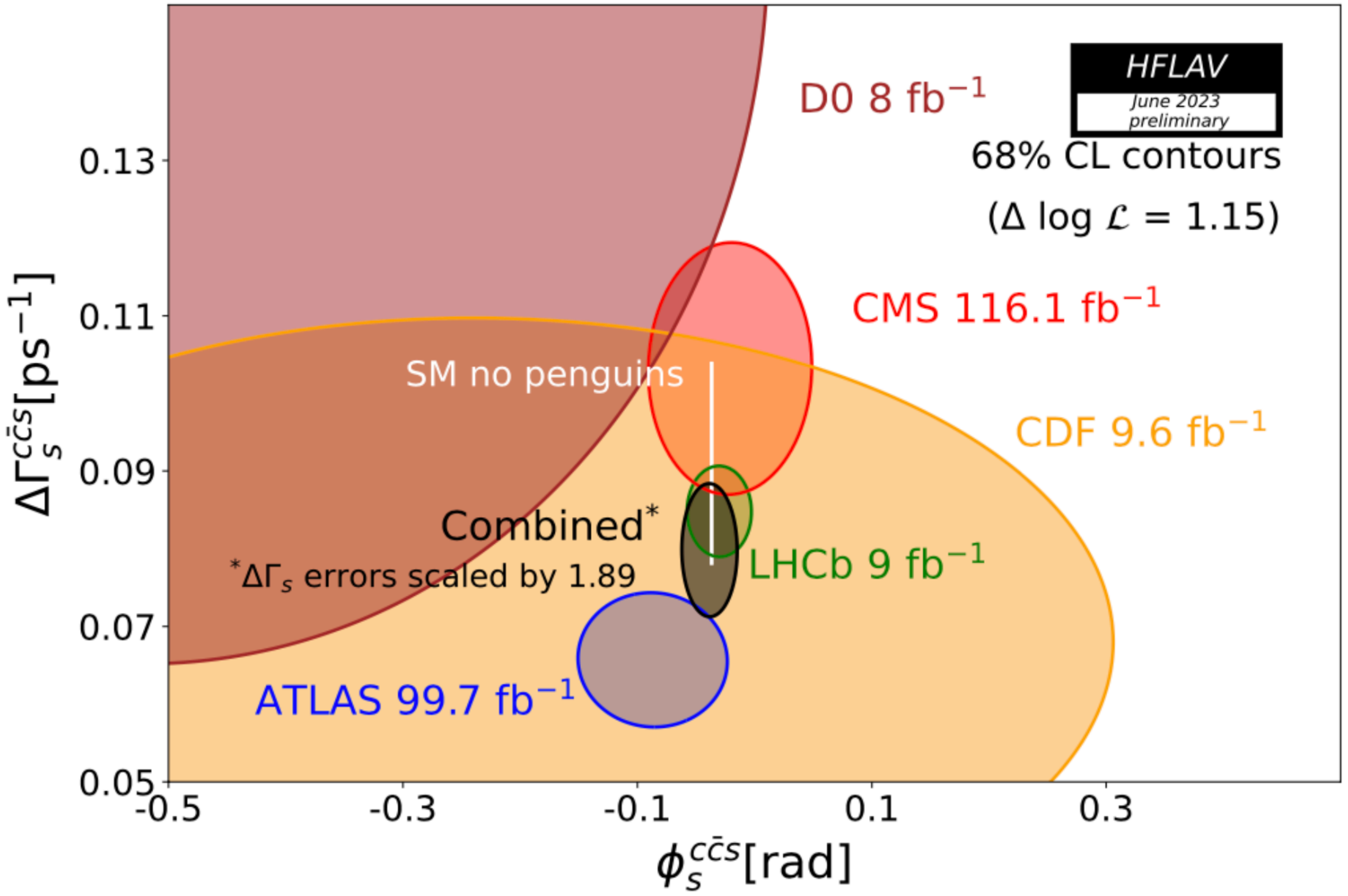
$\eta_f = (-1)^L$ CP eigenvalues of the final state



Mixture of CP odd and CP even requires an angular analysis

arXiv:2308.01468



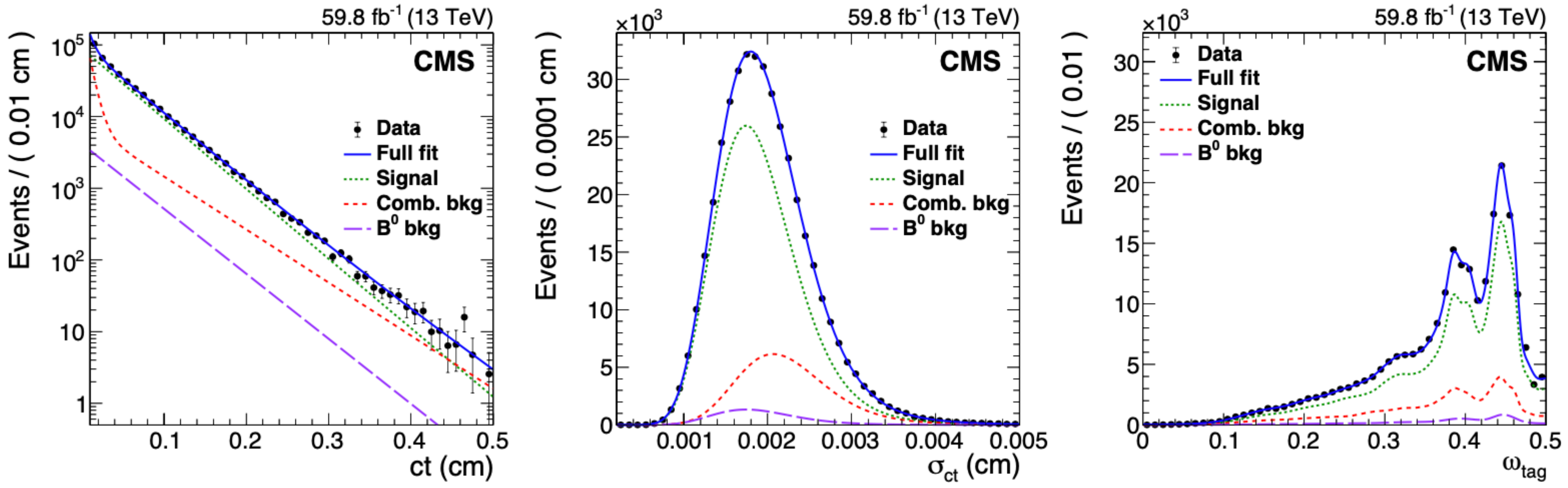


Very similar experimental techniques between the LHC three collaborations

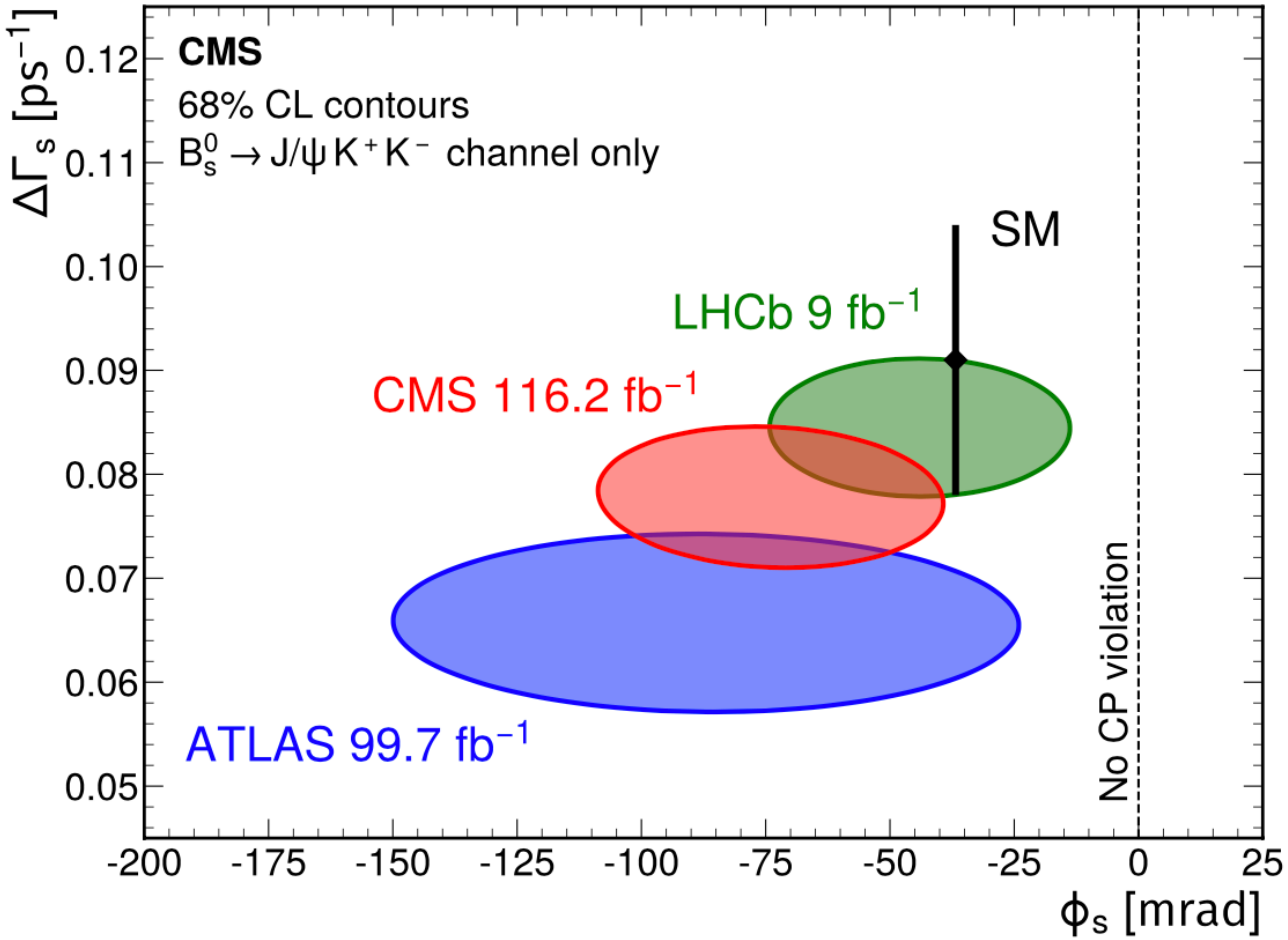
arXiv:2308.01468

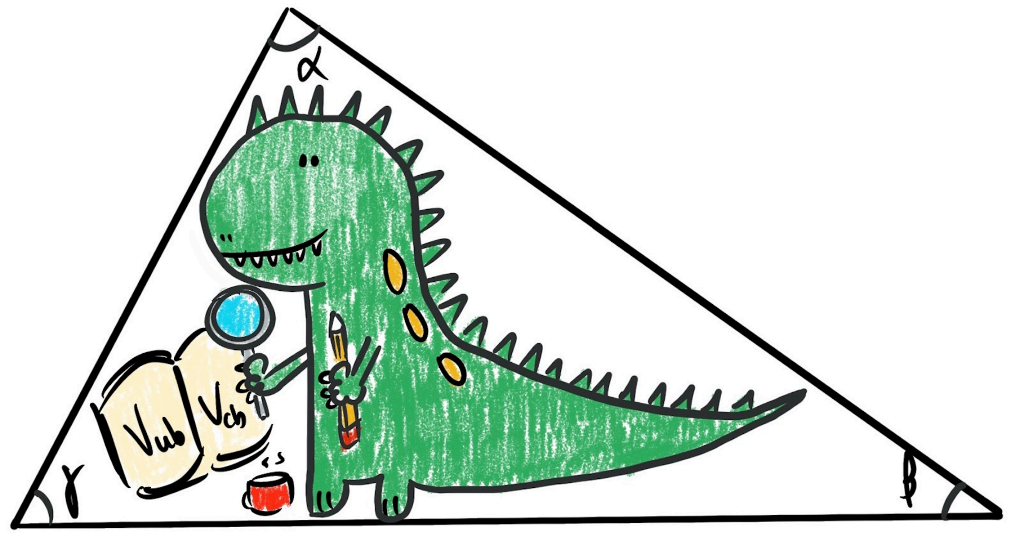
Evidence for CP violation and measurement of CP-violating parameters in $B_s^0 \to J/\psi\,\phi(1020)$ decays in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*



arXiv:2412.19952v1

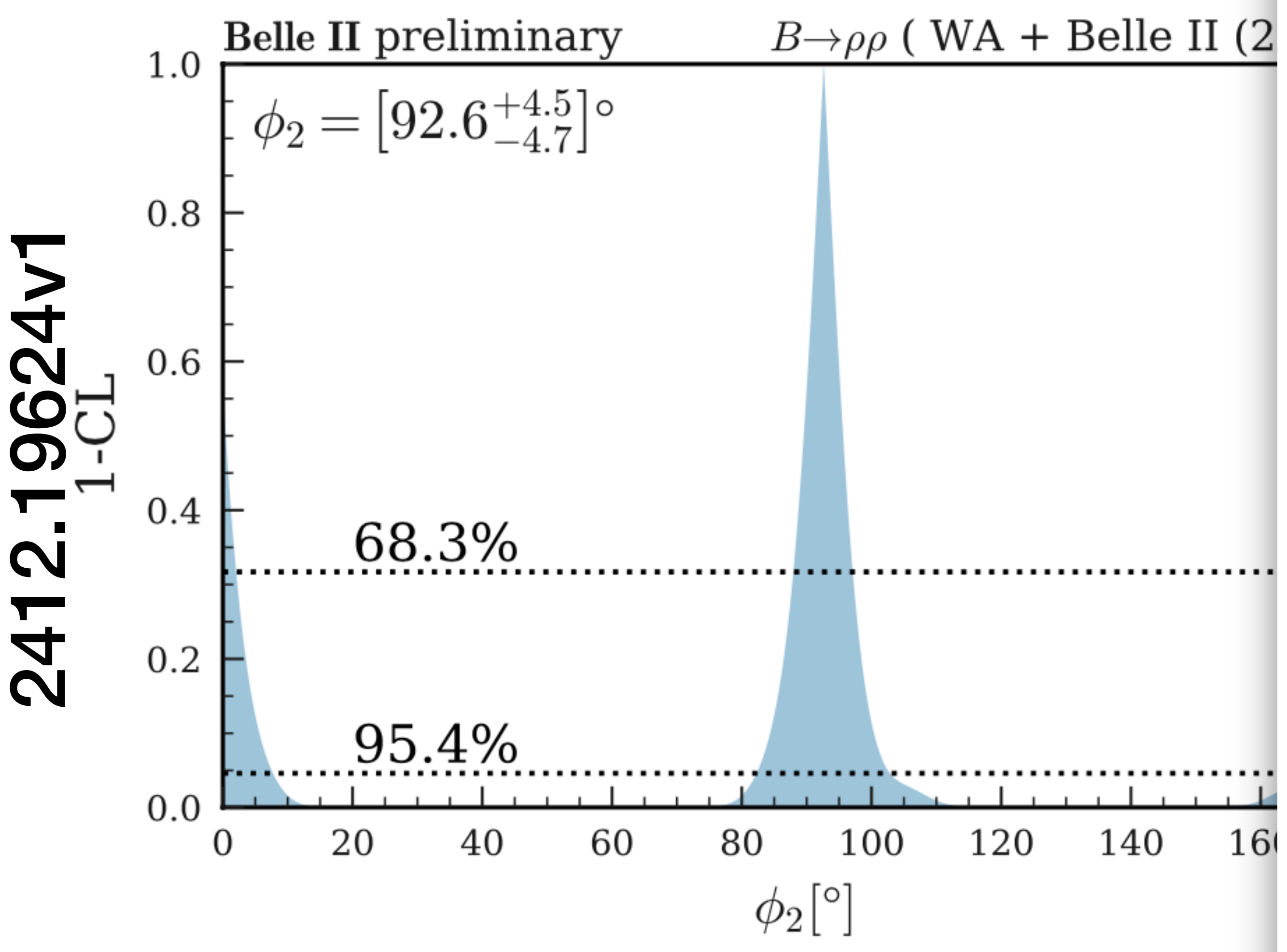




All the phases…Today

Question to my theory collea

While the overall picture is lo … om for NP in these observables?




DG Office
Inbox - CERN 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)
Details

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

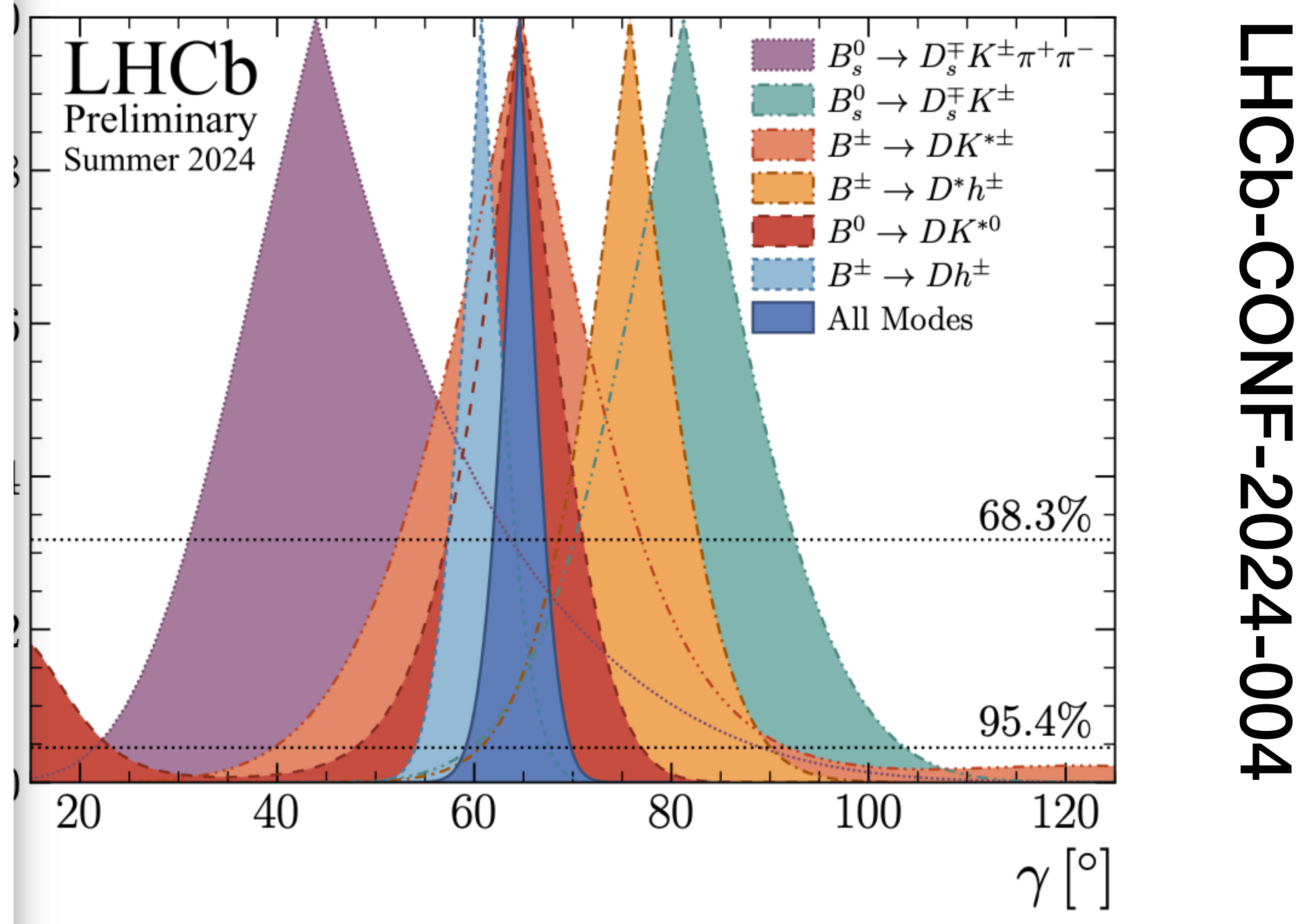
PR01.25
25.03.2025

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.

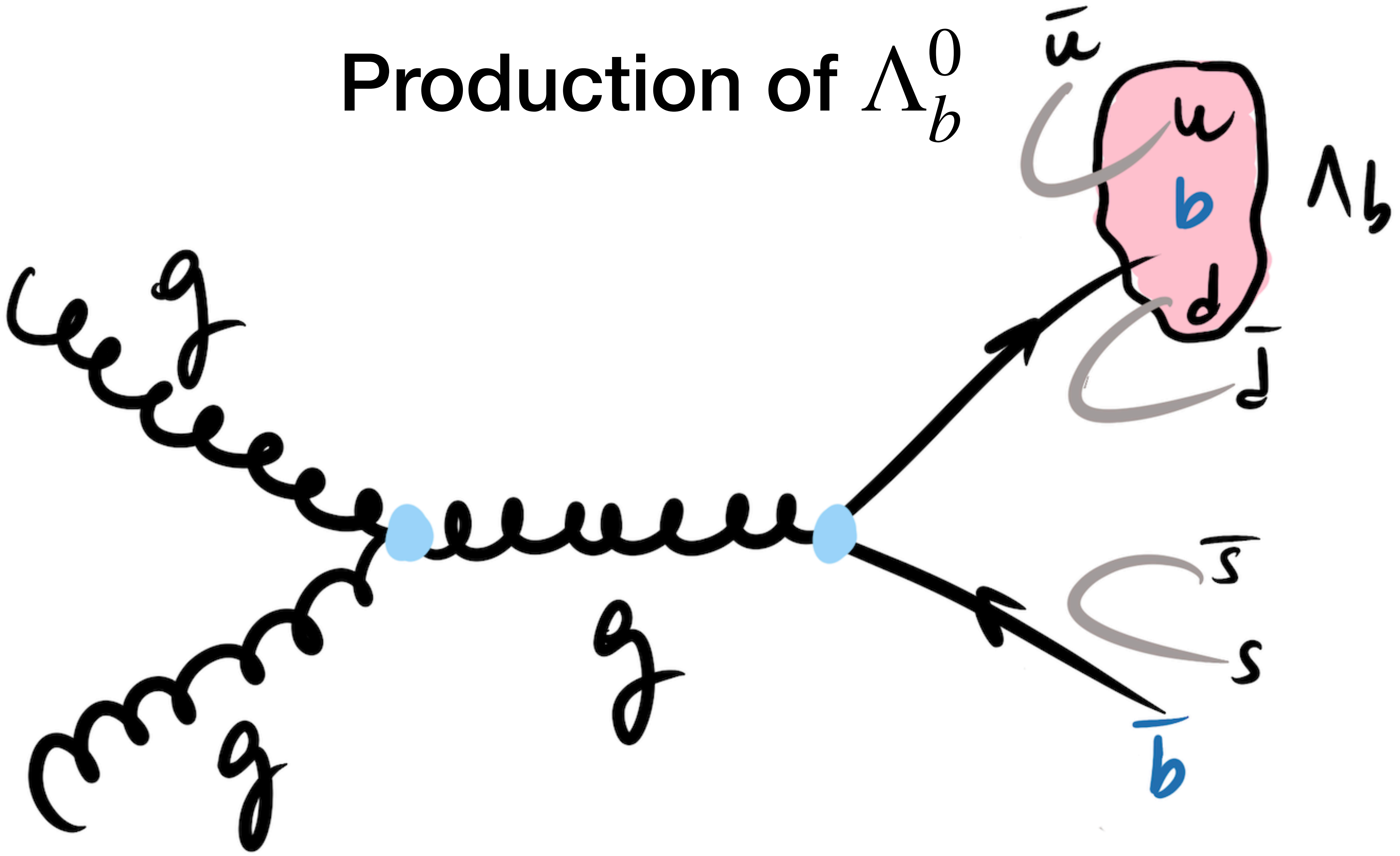
First observed in the 1960s among a class of particles called mesons, which are made up of a quark–antiquark pair, the violation of "charge-parity (CP)" symmetry has been the subject of intense study at both fixed-target and collider experiments. While it was expected that the other main class of known 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."



Observation of charge-parity symmetry breaking in baryon decays

Production of Λ_b^0

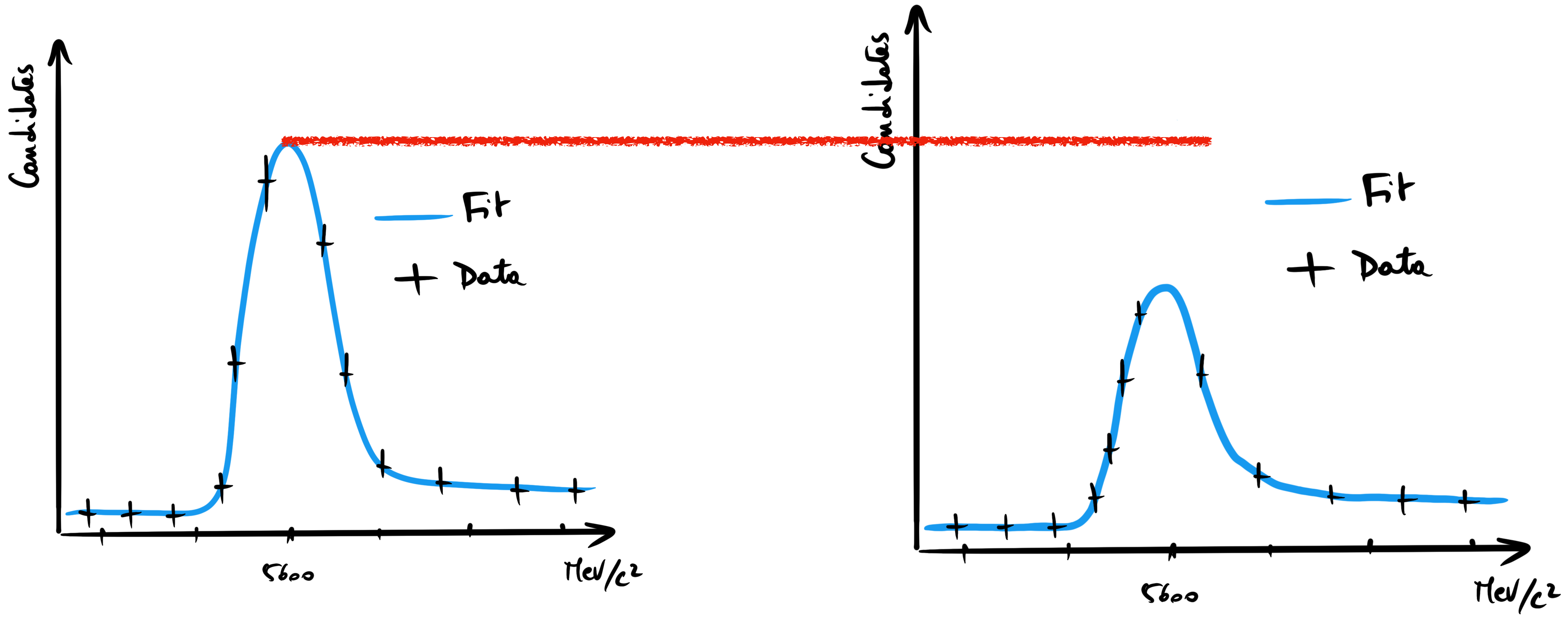


Expression of the asymmetry

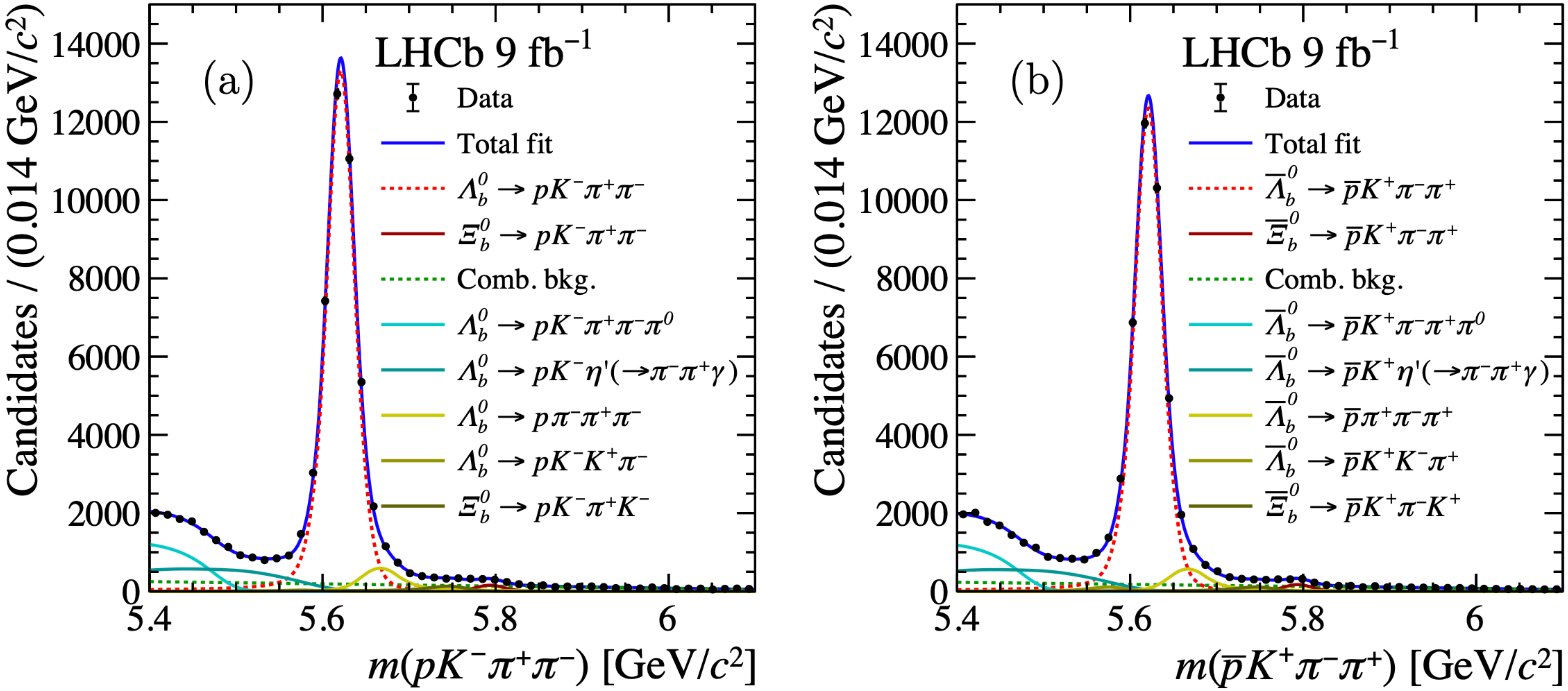
$$A^f_{CP} = \frac{\Gamma(\Lambda_b^0 \to f) - \Gamma(\bar{\Lambda}_b \to \bar{f})}{\Gamma(\Lambda_b \to f) + \Gamma(\bar{\Lambda}_b \to \bar{f})}$$

arXiv:2503.16954

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



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

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

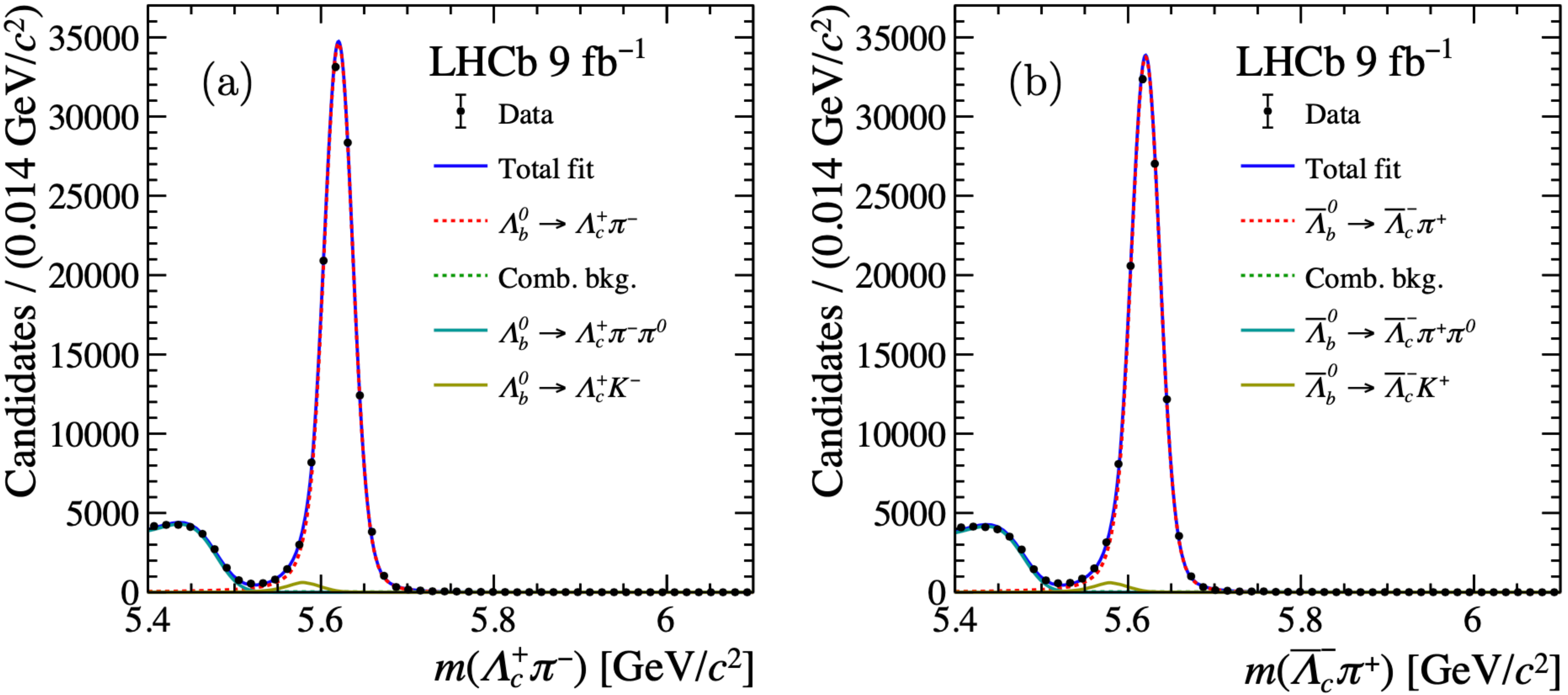
Detection asymmetry

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

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

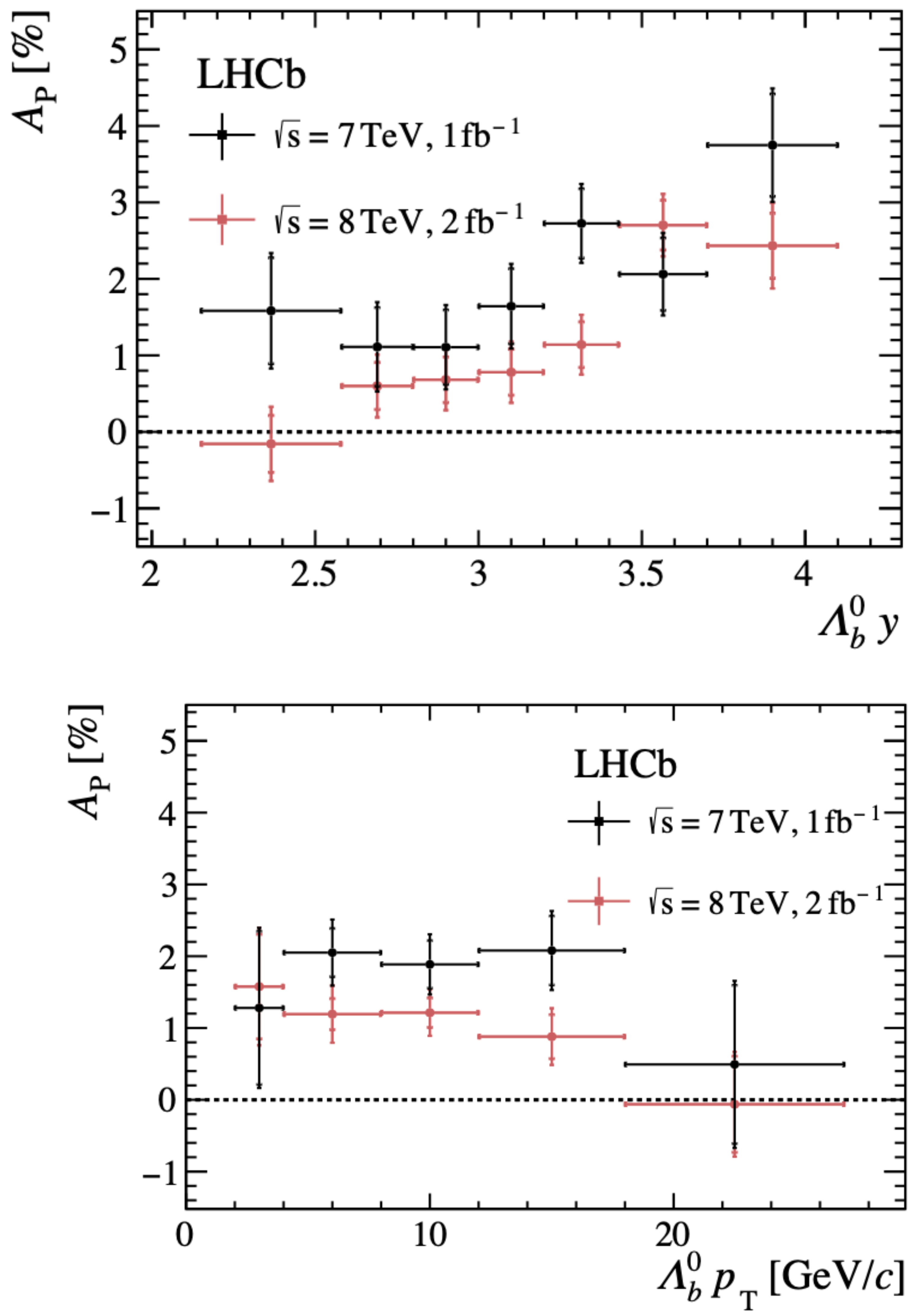
$$A_{CP}^{f} = A_{Raw}^{f} - A_{P}^{\Lambda_b^0} - A_{D}^{f}$$ ➤ Measured for the signal

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



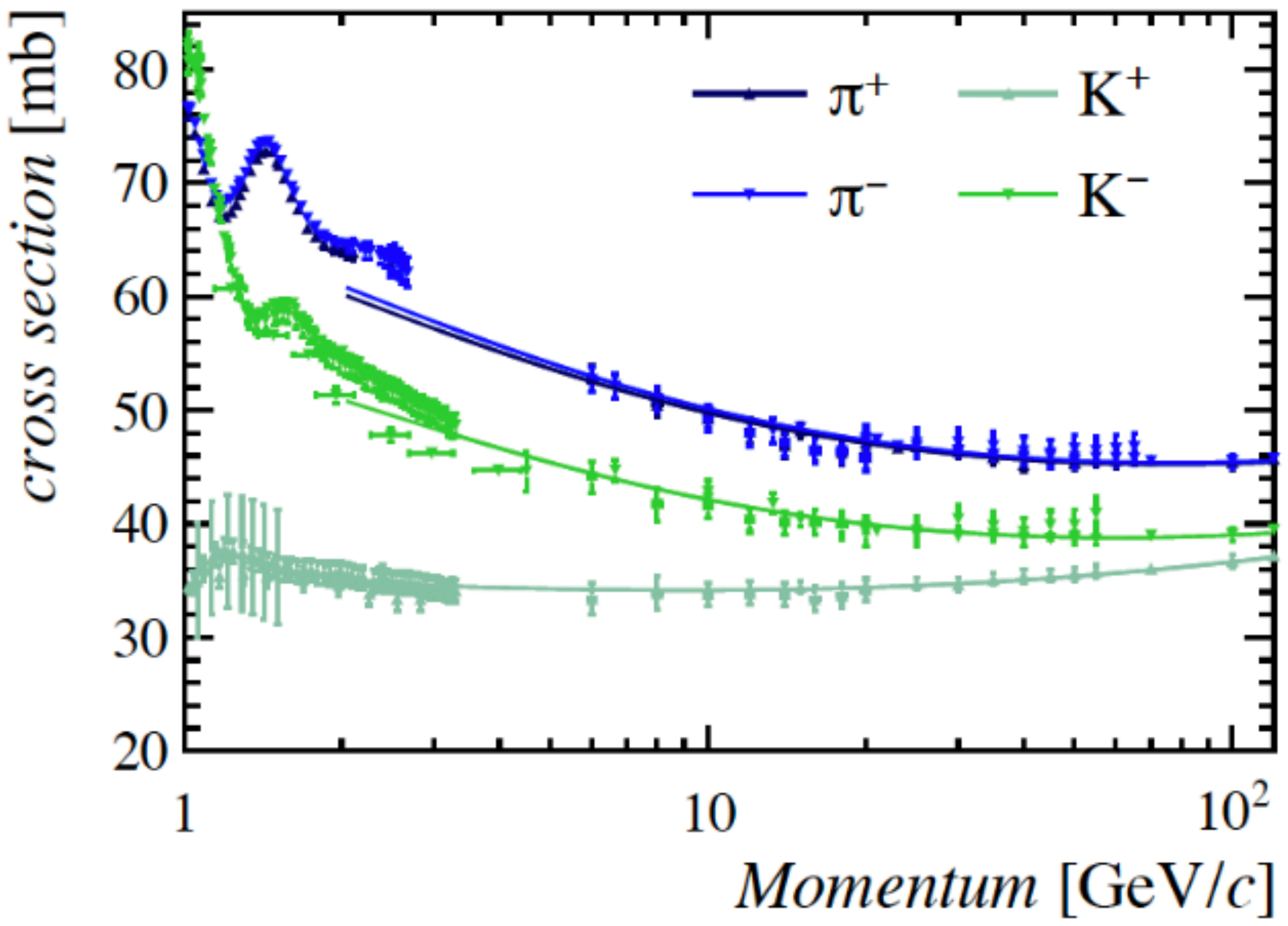
LHCb-PAPER-2021-016

Detector asymmetries

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

- f: different combinations of p, K, π etc.

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



Obtained using data-driven method with calibration channels

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

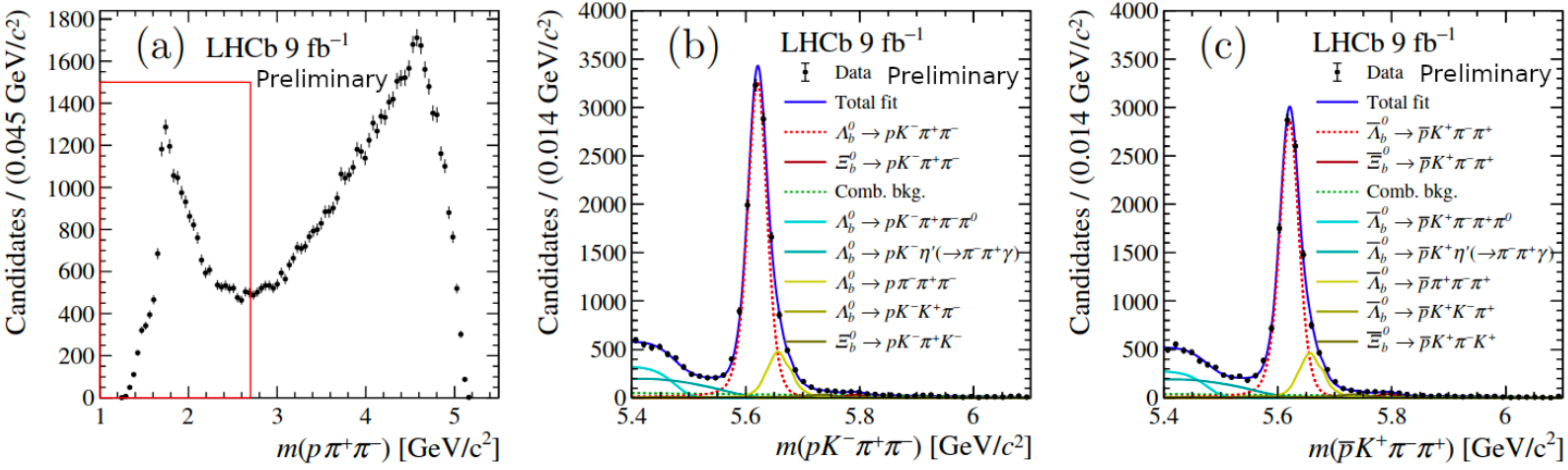
- ΔA_D vanishes

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

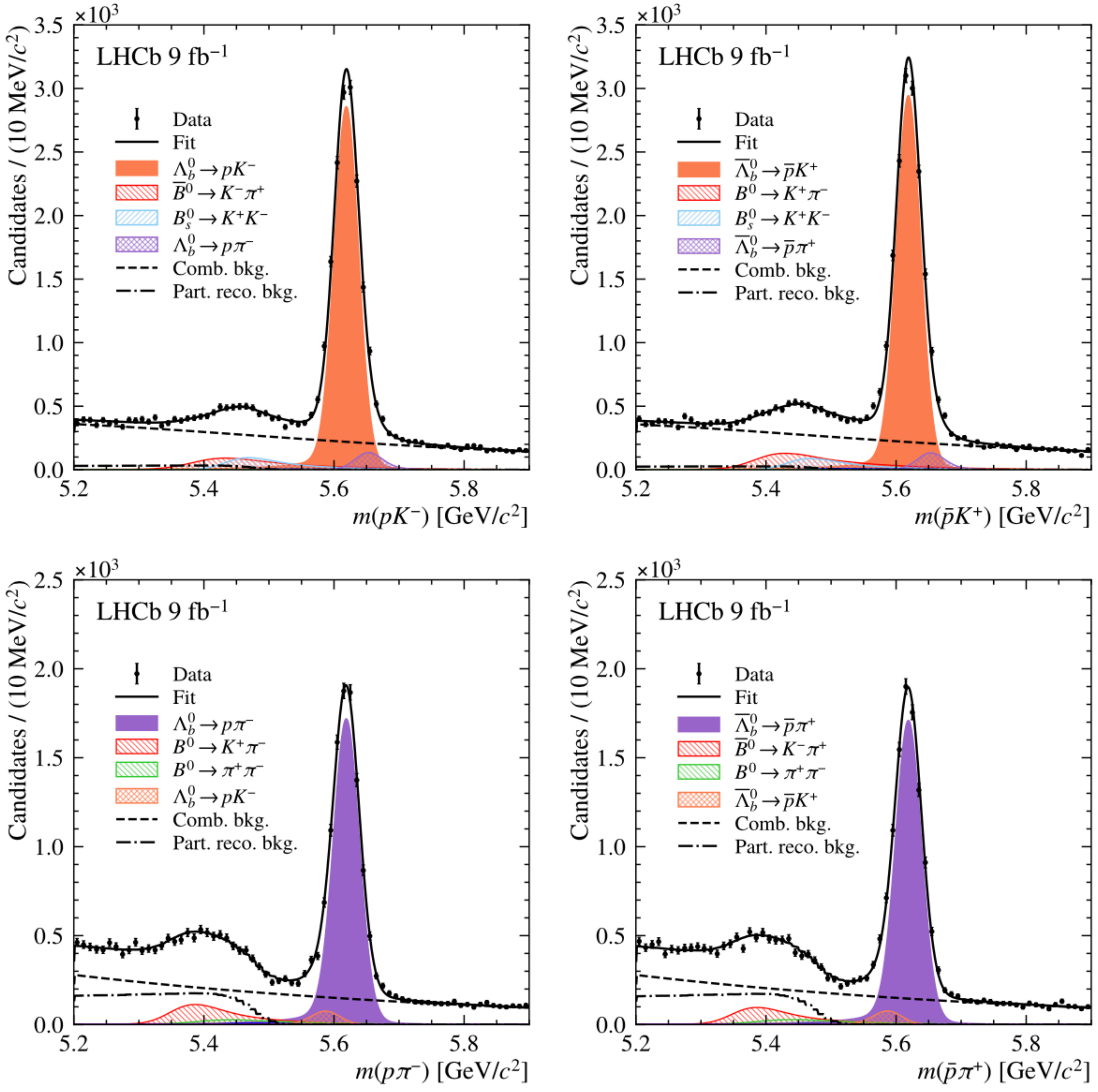
Taking it one step further

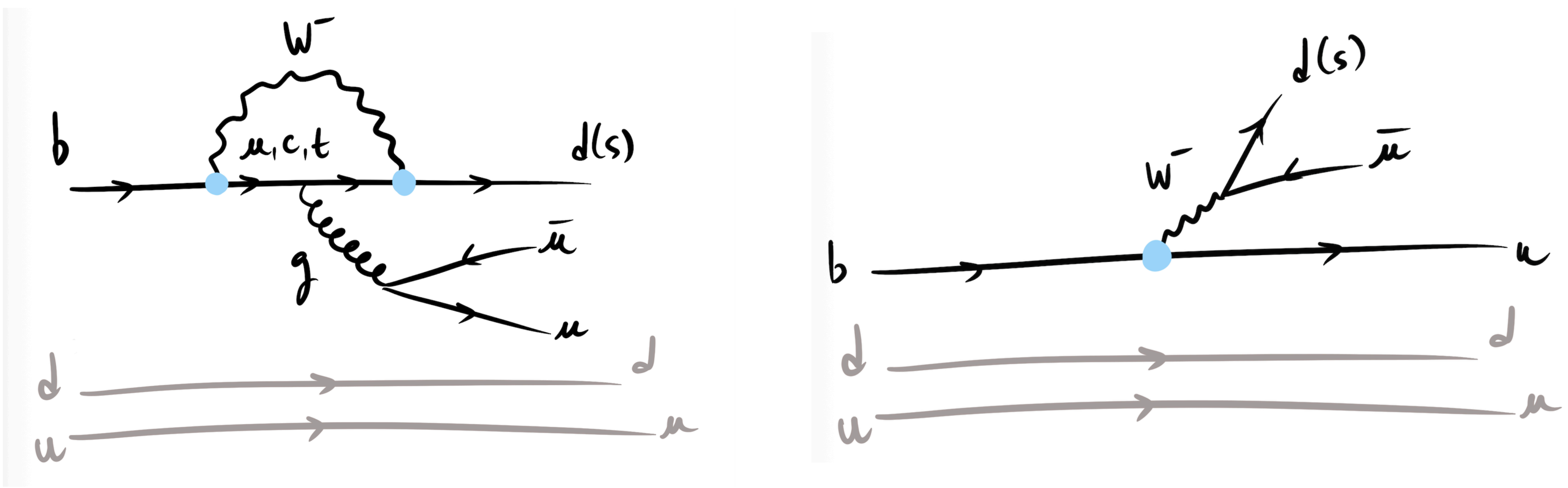
Observe up to 6 standard deviations locally

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

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





Experimental techniques are very similar

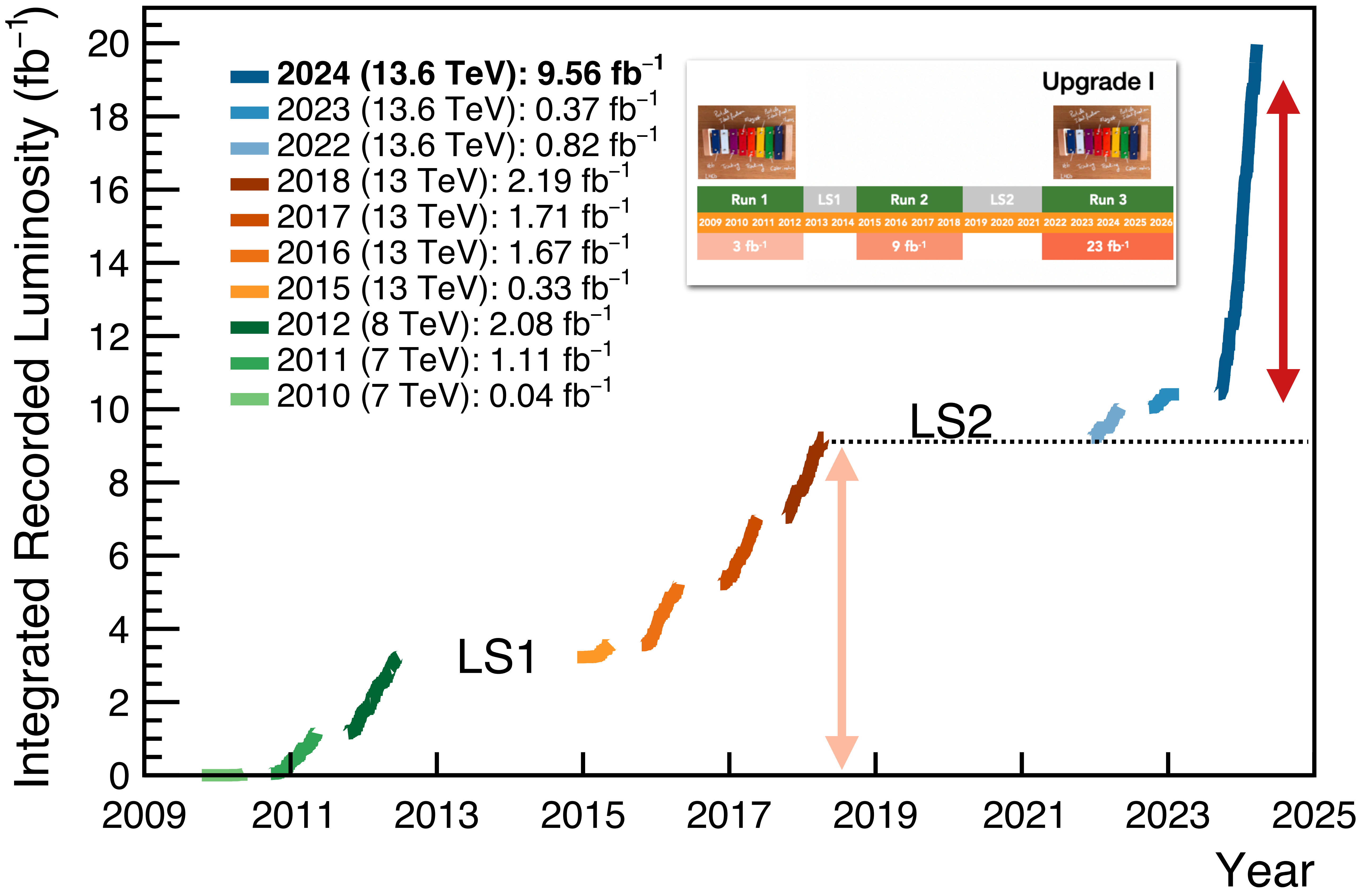
$$A_{CP}^{pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%,$$
$$A_{CP}^{p\pi^-} = (\ \ 0.2 \pm 0.8 \pm 0.4)\%,$$

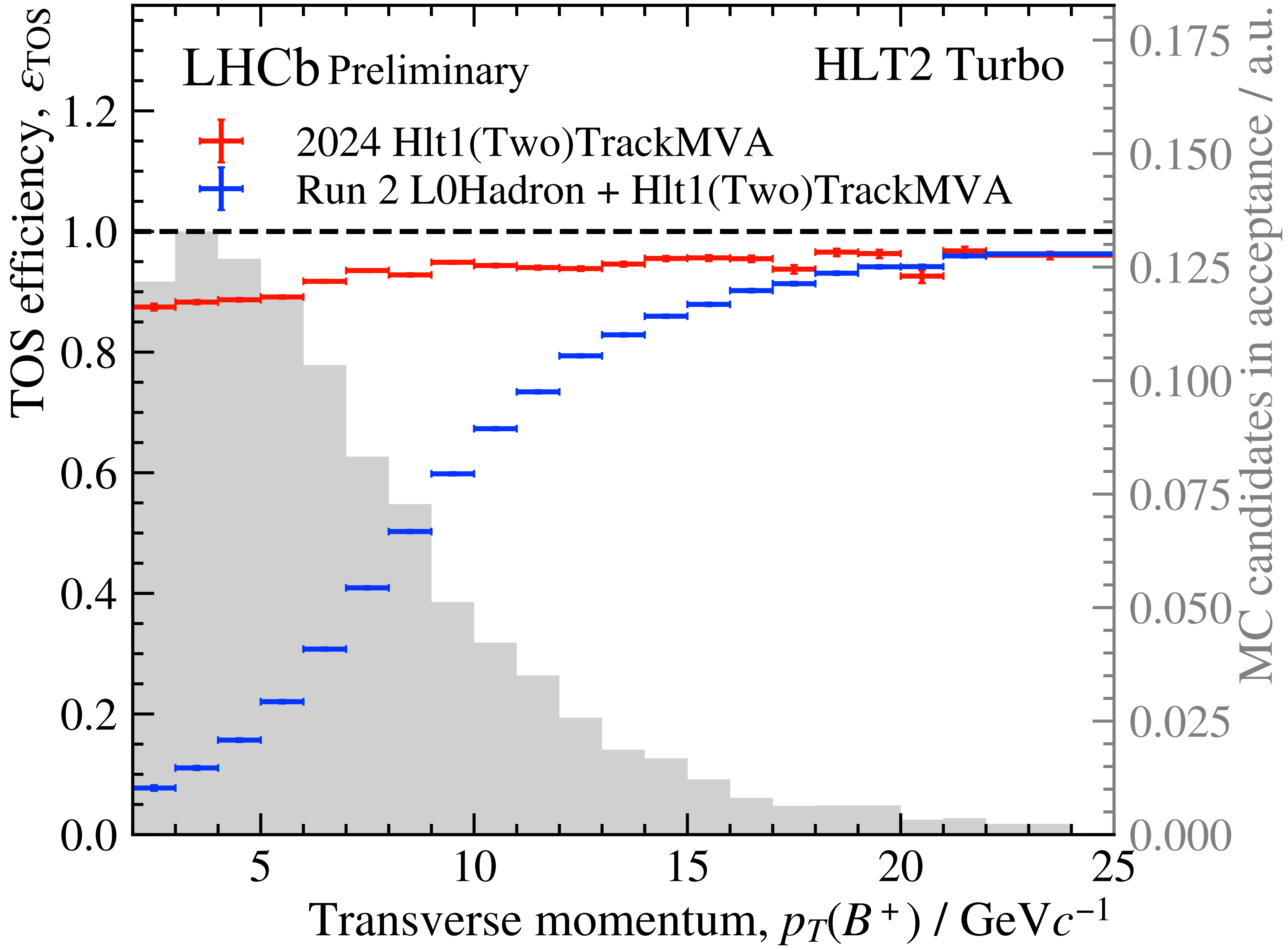
No evidence of CP violation is found

arXiv:2412.13958

LHCb in 2024: twice doubled data

[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

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 ($B \to DK$, *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

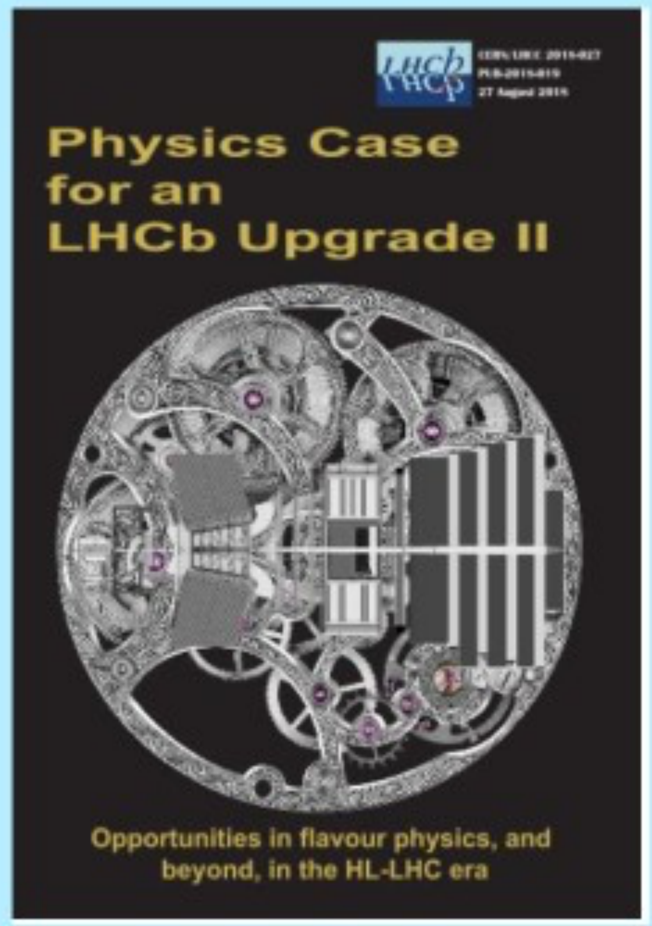
After showing that systematics scale with luminosity in Run 3 – aim to build the best quality U2 detector!

And an other Upgrade

EoI

LHCC-2017-003

Physics case



LHCC-2018-027

Accelerator study CERN-ACC-2018-038

CERN Research Board September 2019

"The recommendation to prepare a framework TDR for the LHCb Upgrade-II was endorsed, noting that LHCb is expected to run throughout the HL-LHC era."

European Strategy update 2020

"The full potential of the LHC and the HL-LHC, including the study of flavour physics, should be exploited."

Framework TDR

LHCC-2021-012

Detector design and technology options

R&D program and schedule

Cost for baseline, options for descoping

National interests

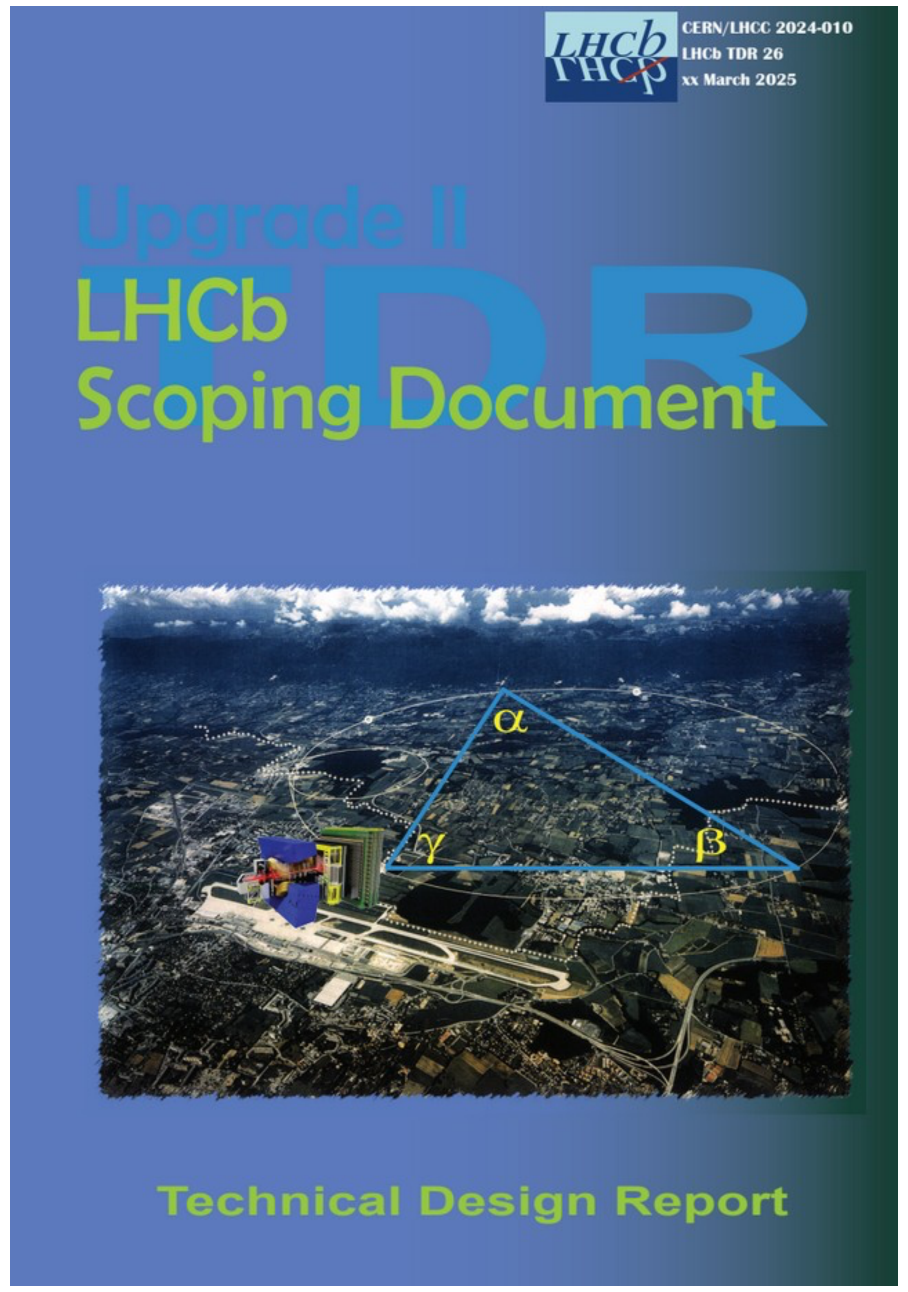
Approved by LHCC March 2022

"The **LHCC recommends** that LHCb continue the R&D necessary to complete technical design reports on the proposed schedule, …"

"The **LHCC recommends** the continued investigation of descoping and other cost-saving possibilities. …"

"The **LHCC recommends** that a well-defined process to establish the financial envelope prior to the preparation of TDRs be set up and notes that close coordination with funding agencies will likely be required in this process.

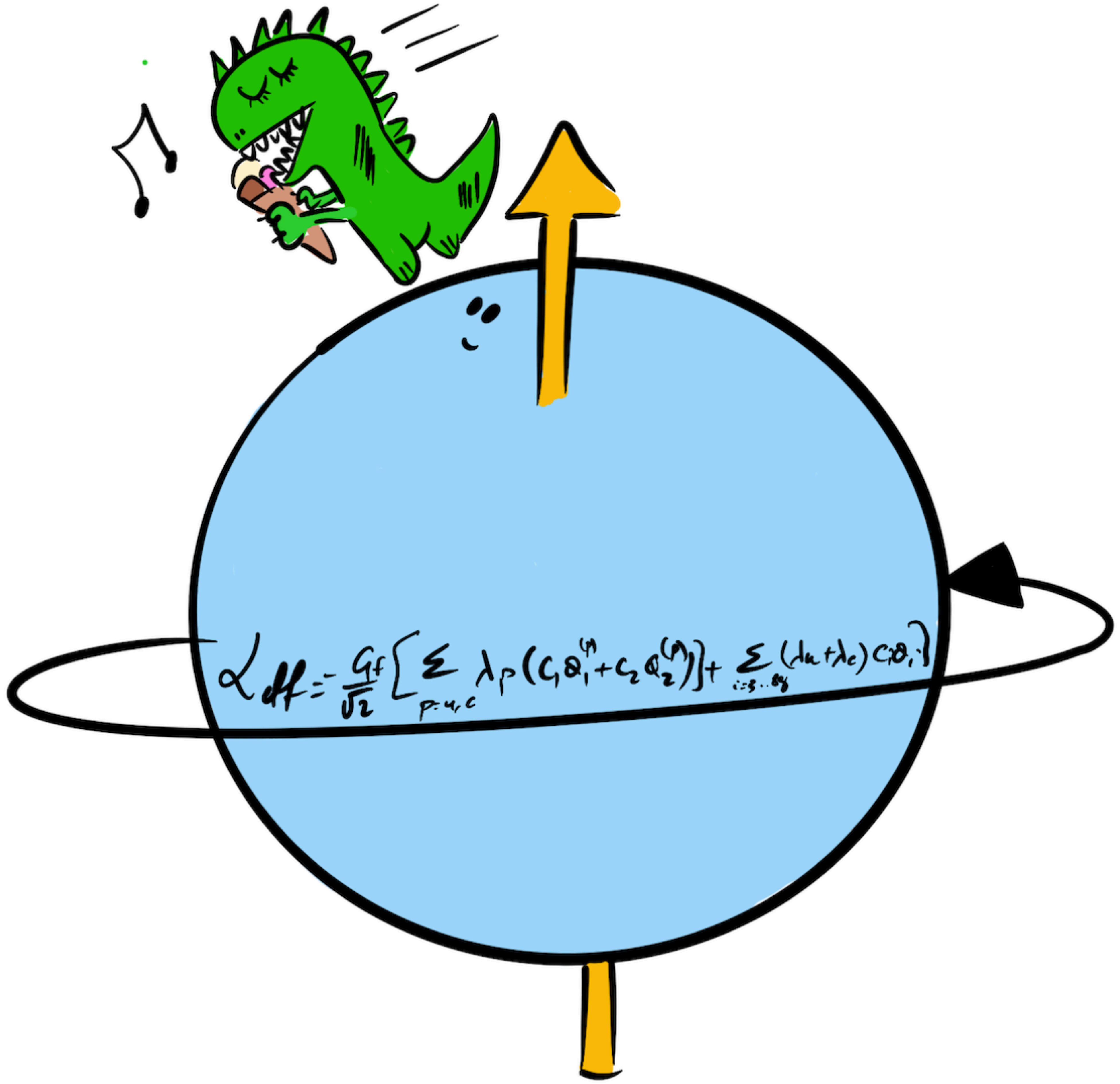
Scoping document



Submitted to LHCC (Sept 2024) Under review

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

More information yasmineamhis.com

Backup slides

LHCC-2021-012

Framework TDR

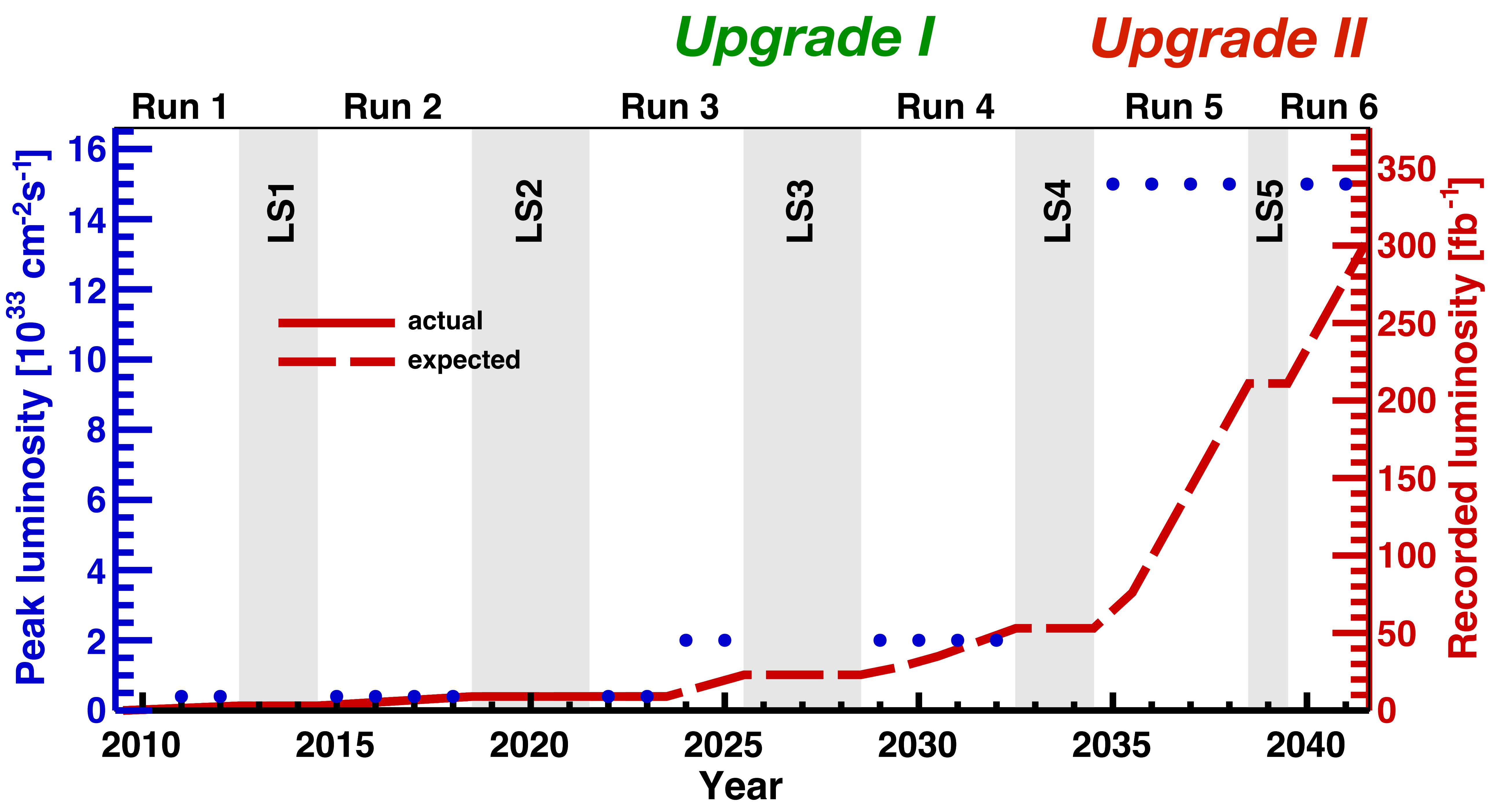
Upgrades

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} = 2x10^{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 II, installation at LS4

- L_{peak} = 1.5x10^{34} cm^{-2} s^{-1} , L_{int} = ~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

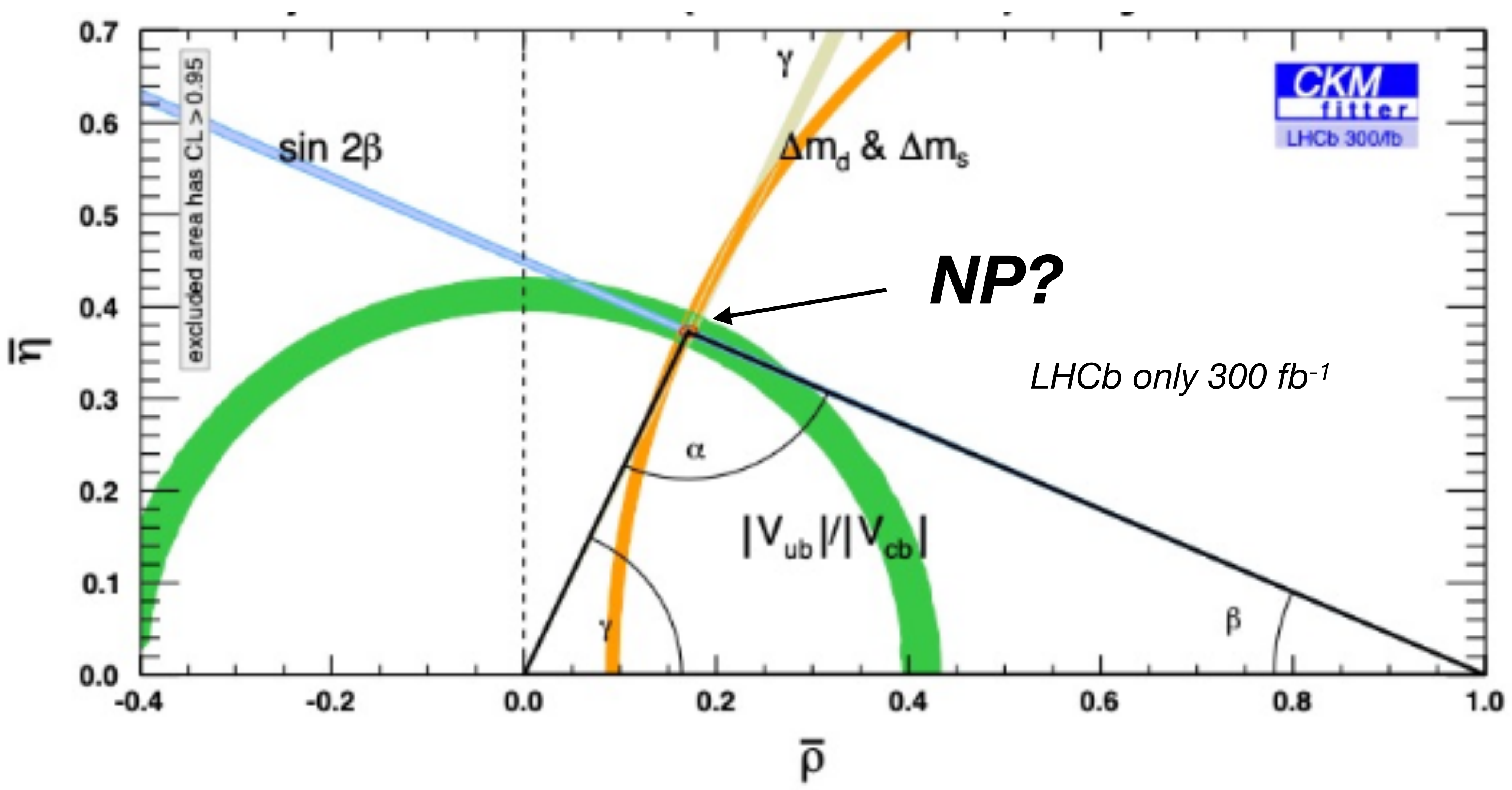
- Unprecedented sensitivity for B and D physics
  - Beyond √N scaling with new subdetectors and reconstruction techniques

- Broad general purpose programme with unique forward acceptance
  - Spectroscopy, EW precision measurements, top quark and Higgs physics, dark sector, heavy ions and fixed target

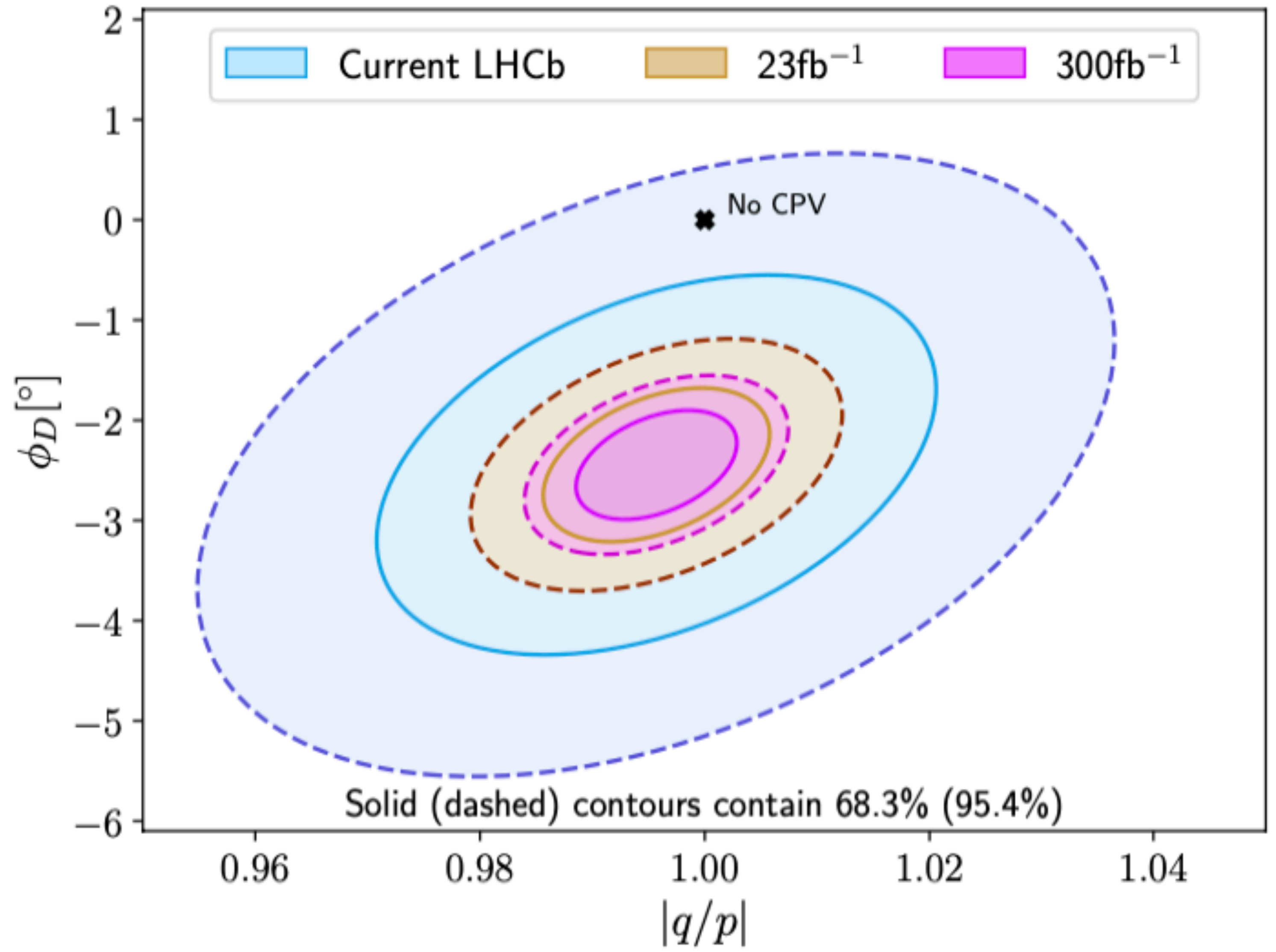
LHCC-2018-027

Physics case

Impressive precision on CP violating phases

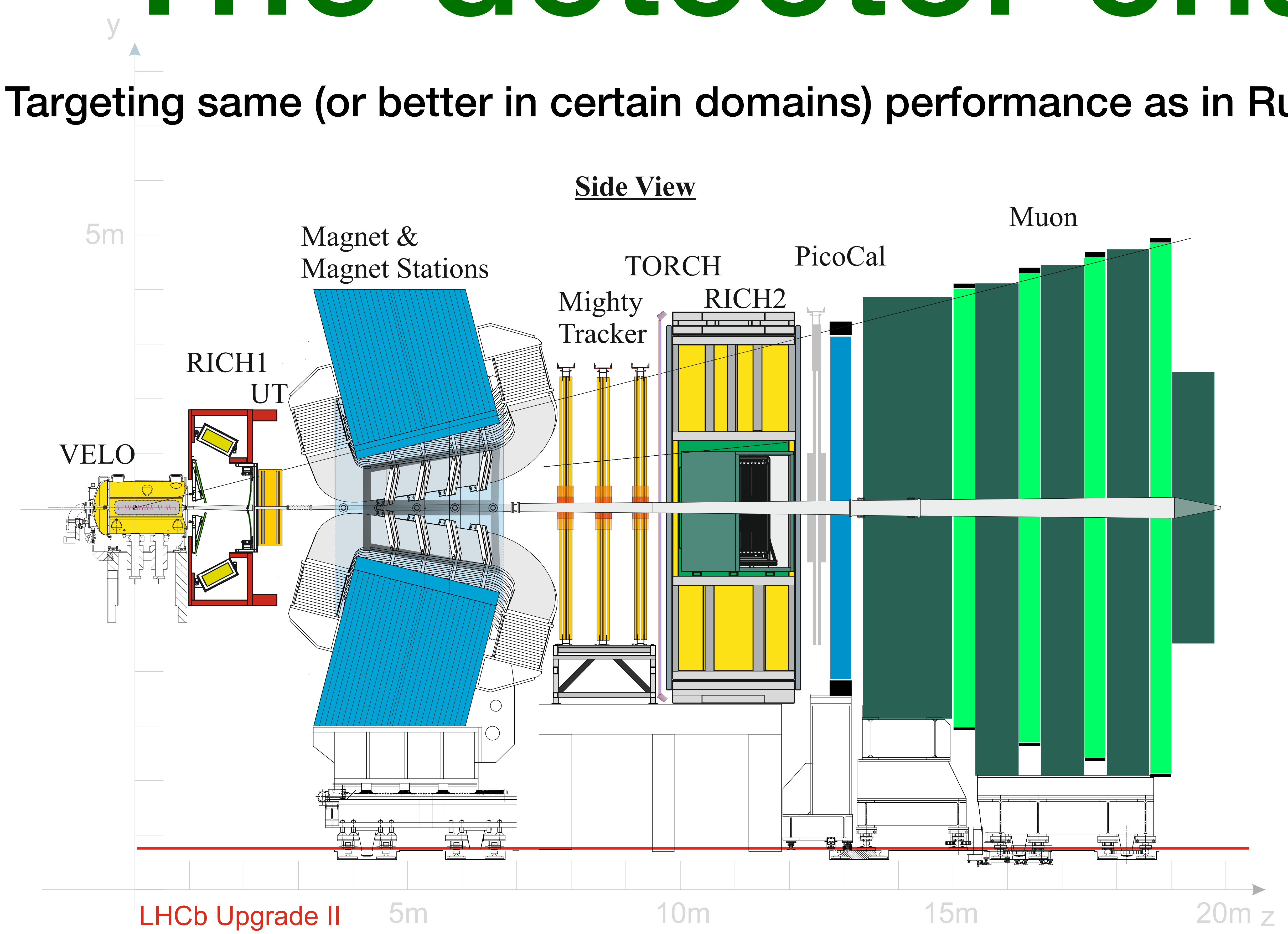


The only planned facility with a realistic possibility to observe CPV in charm mixing



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

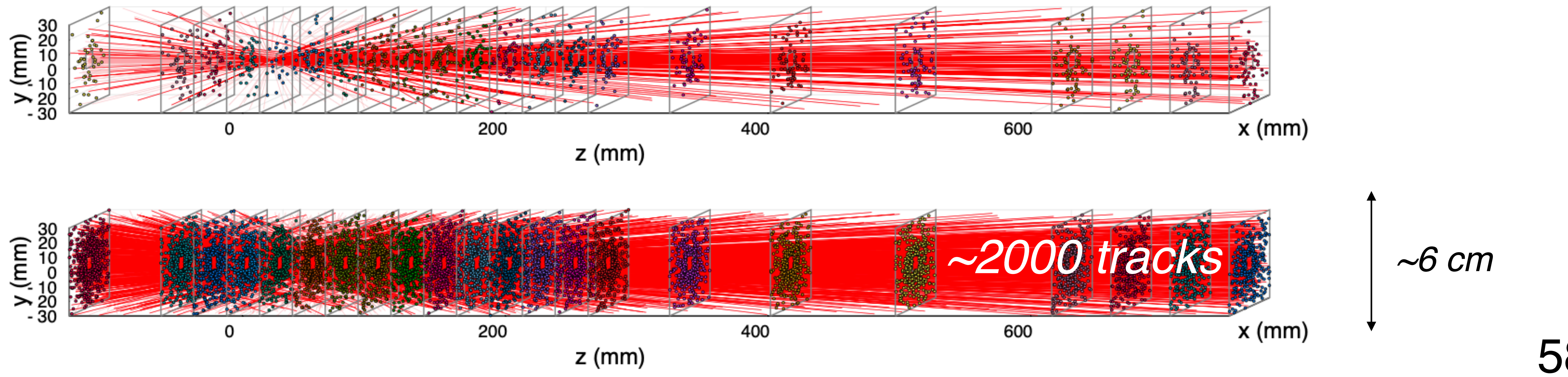
Key ingredients:

- 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)

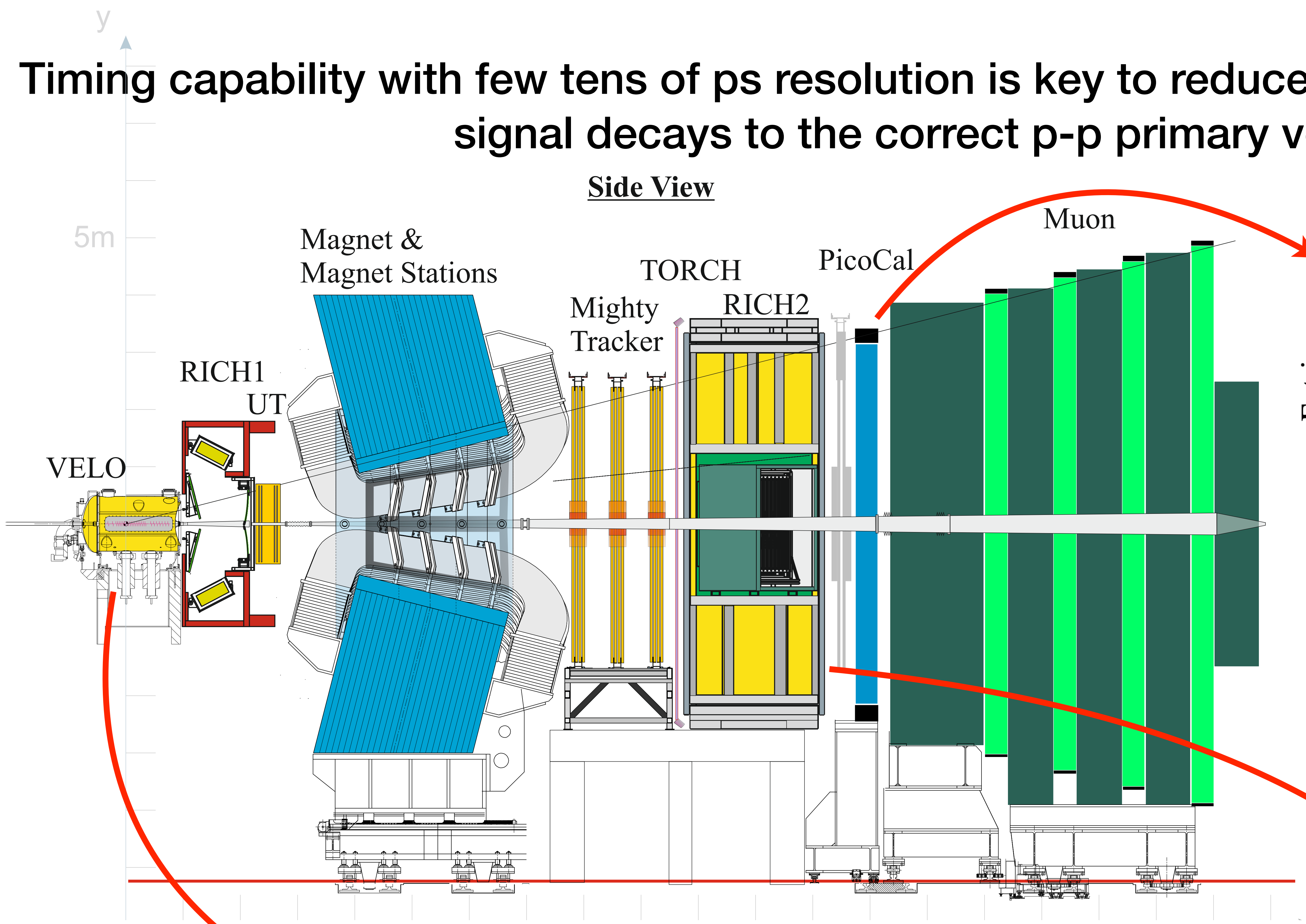
Run 3: pile-up ~6

Upgrade II: pile-up ~40

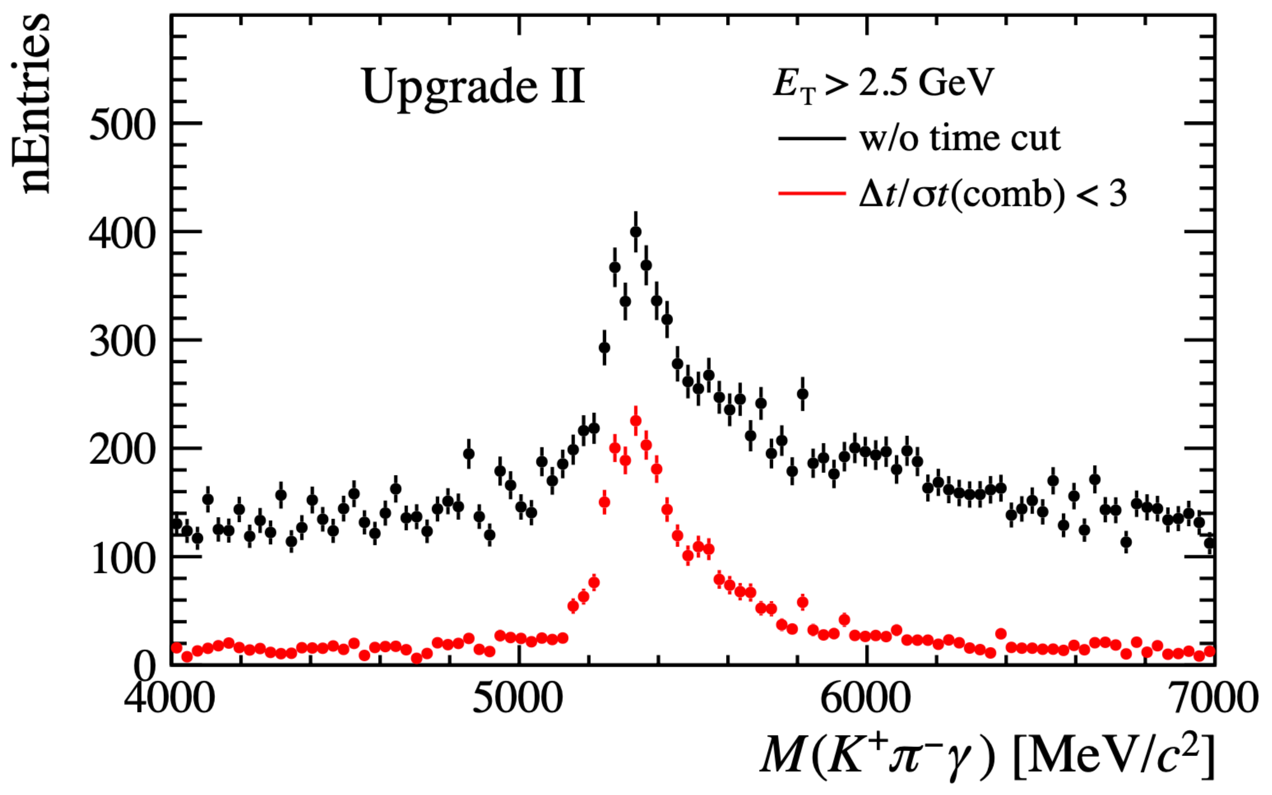


The role of timing

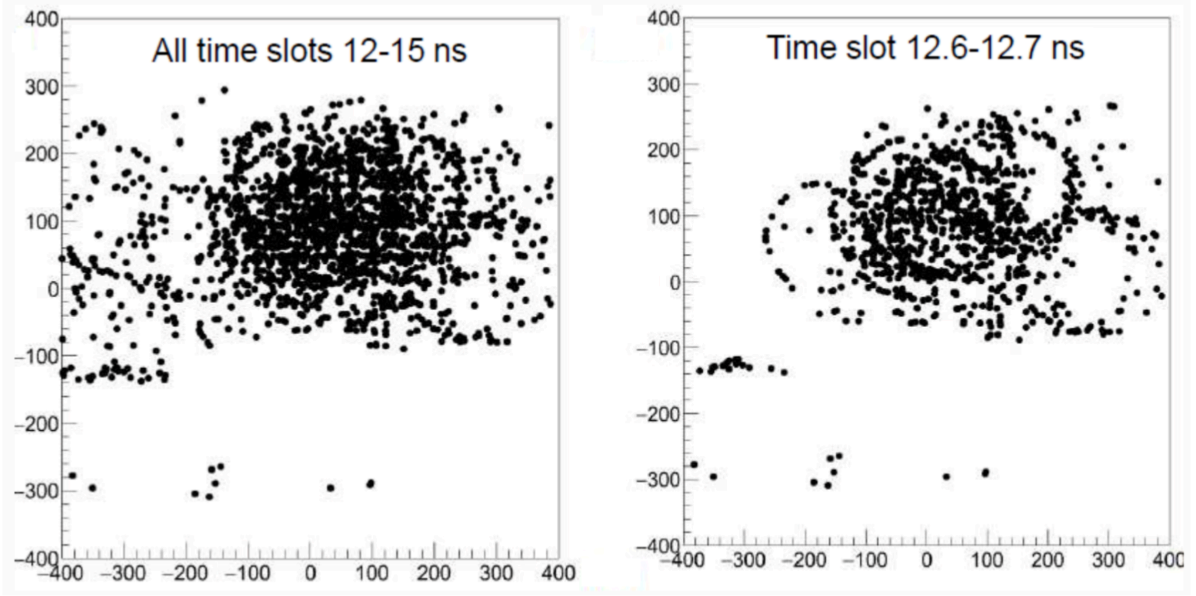
Timing capability with few tens of ps resolution is key to reduce background and associate signal decays to the correct p-p primary vertices



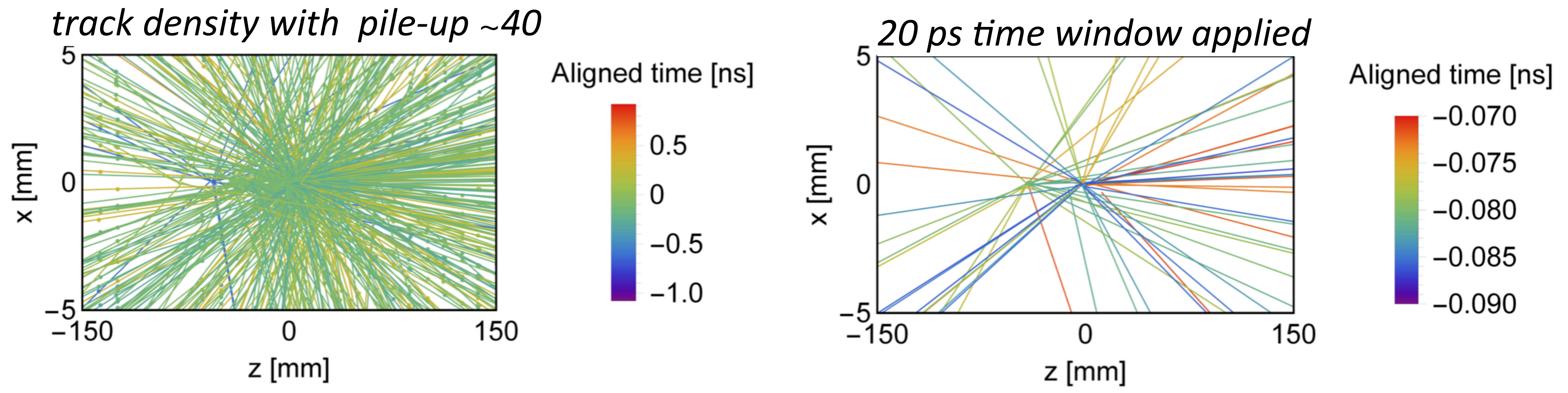
precision timing in calorimeter



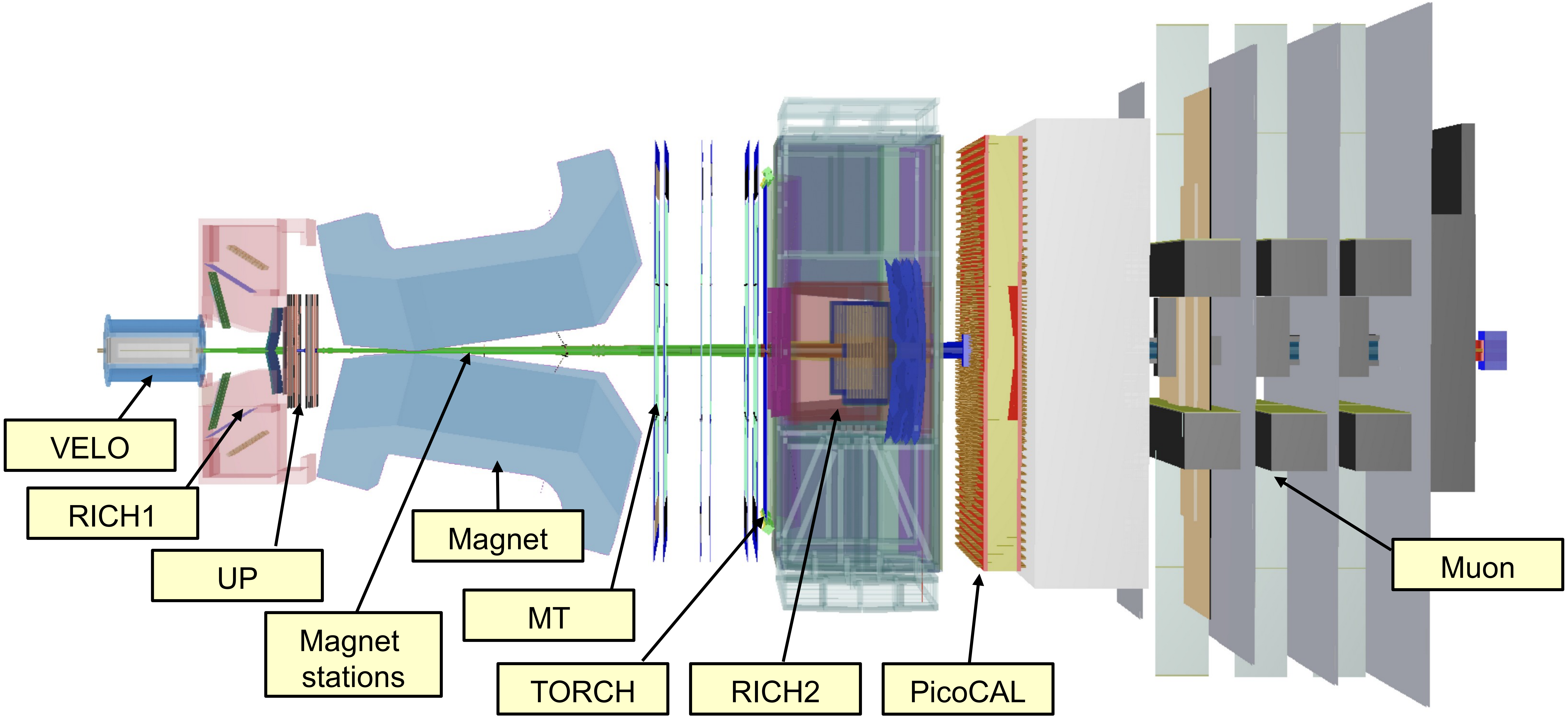
precision timing in RICH



precision timing in VELO



LHCb Upgrade 2 detector layout



Flavour Tagging @ LHCb