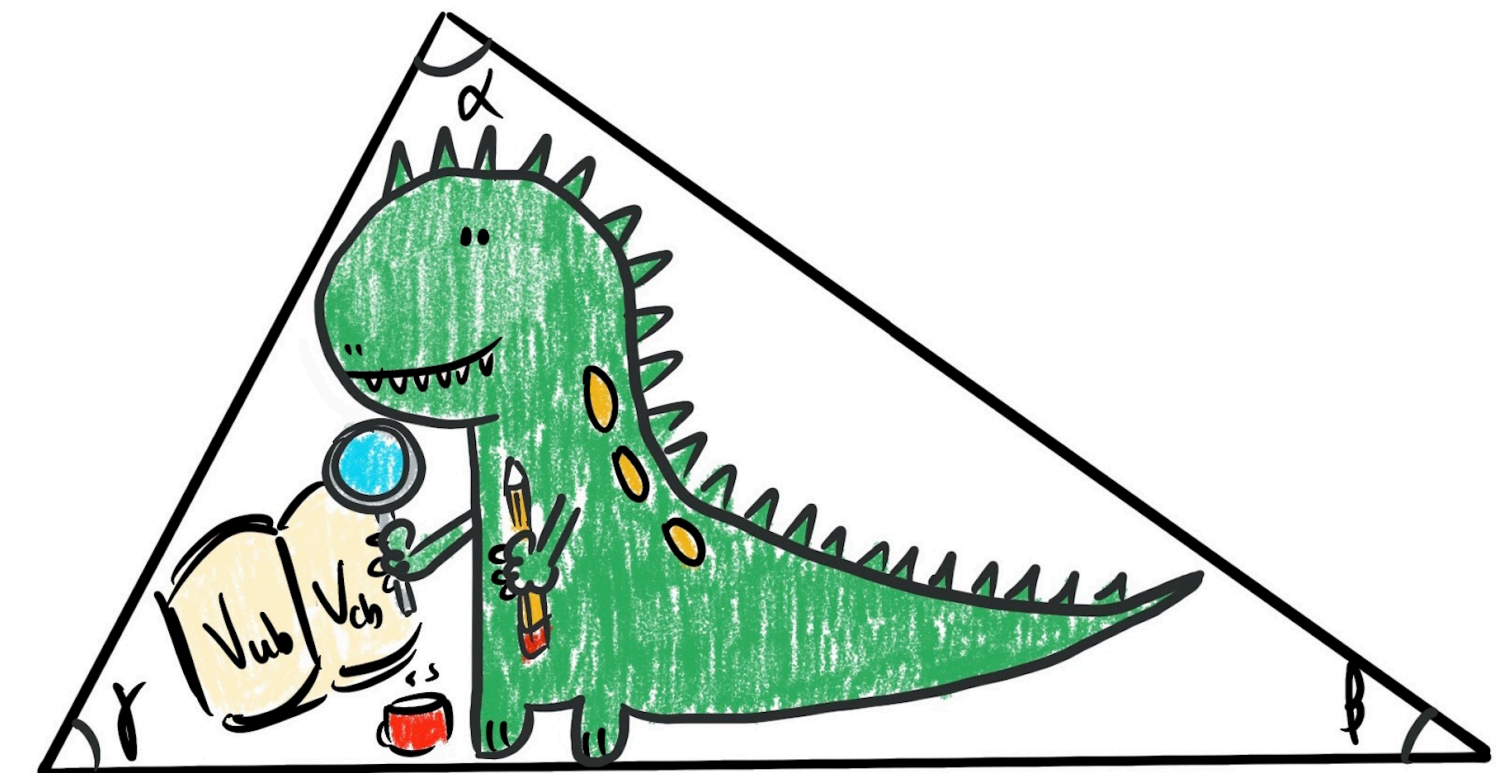


Recent results on matter and antimatter asymmetries at LHCb

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...

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

Motivation for BSM

Plausible EFT Solutions

- Dark matter
- Baryon asymmetry
- Strong CP
- Fermion masses and mixings
- Grand unification

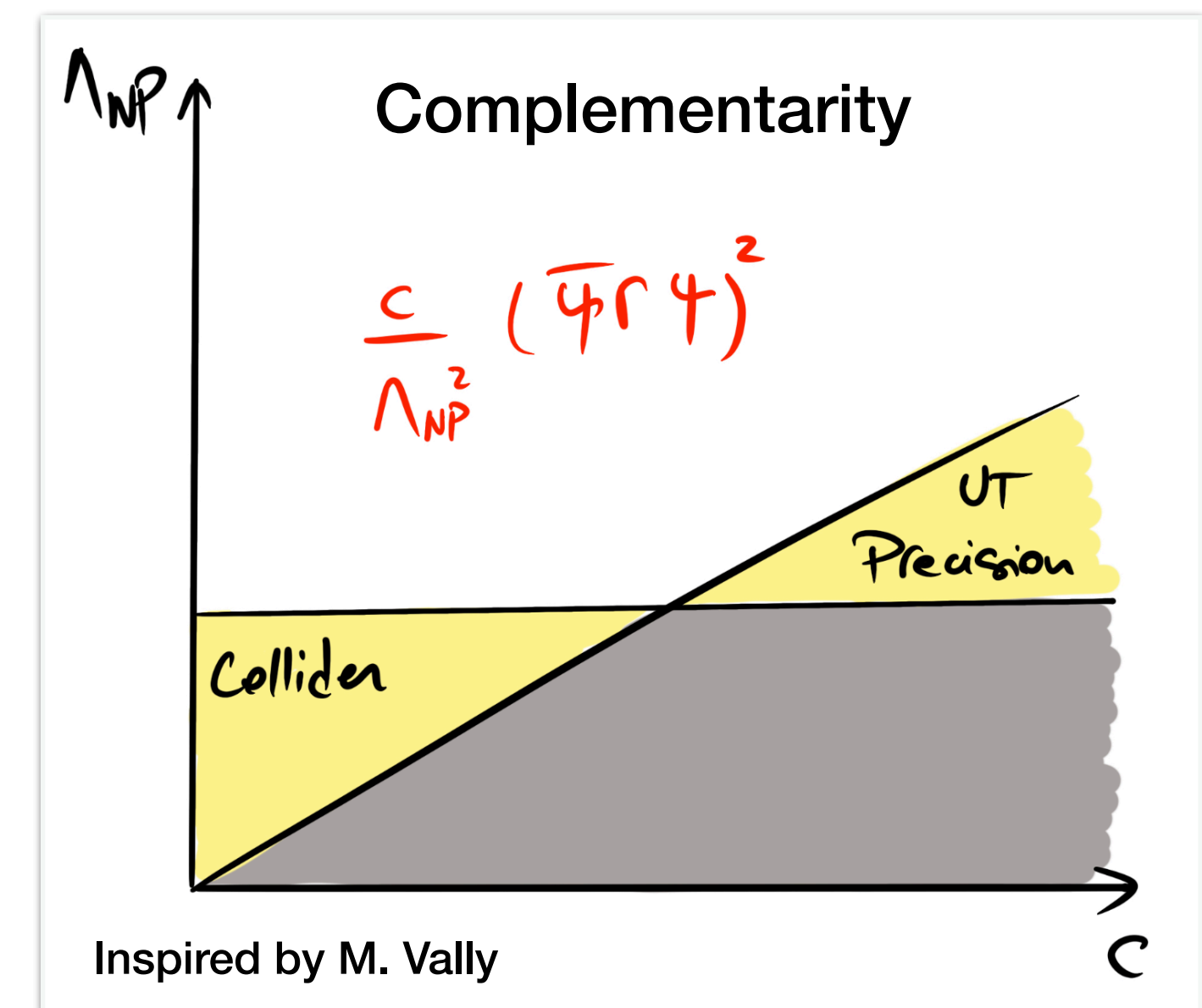
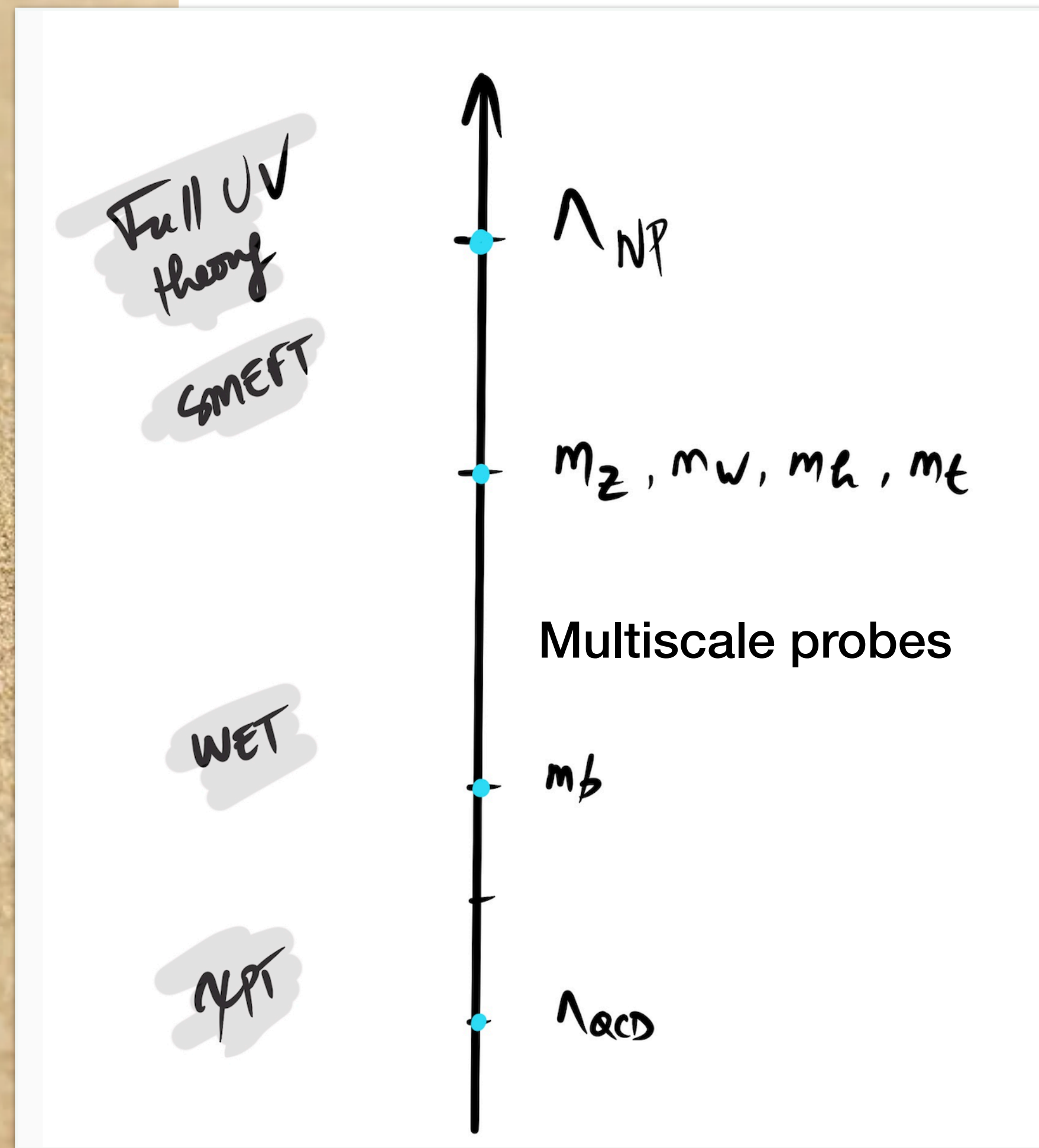
Challenge EFT Paradigm

- Hierarchy problem
- Cosmological constant
- Initial conditions for inflation / Eternal inflation
- UV completion of gravity





Flavour Physics as probe



Many observables & techniques are available

Examples of Flavored Discoveries

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

Y. Nir

The strength of flavour physics and indirect searches

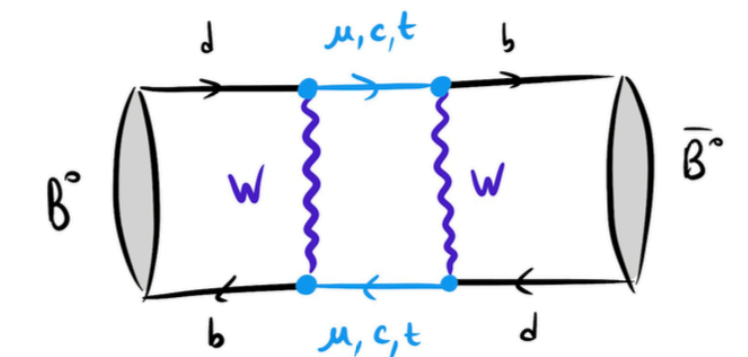
PLB 192 (1987)

OBSERVATION OF B^0 - \bar{B}^0 MIXING

ARGUS Collaboration

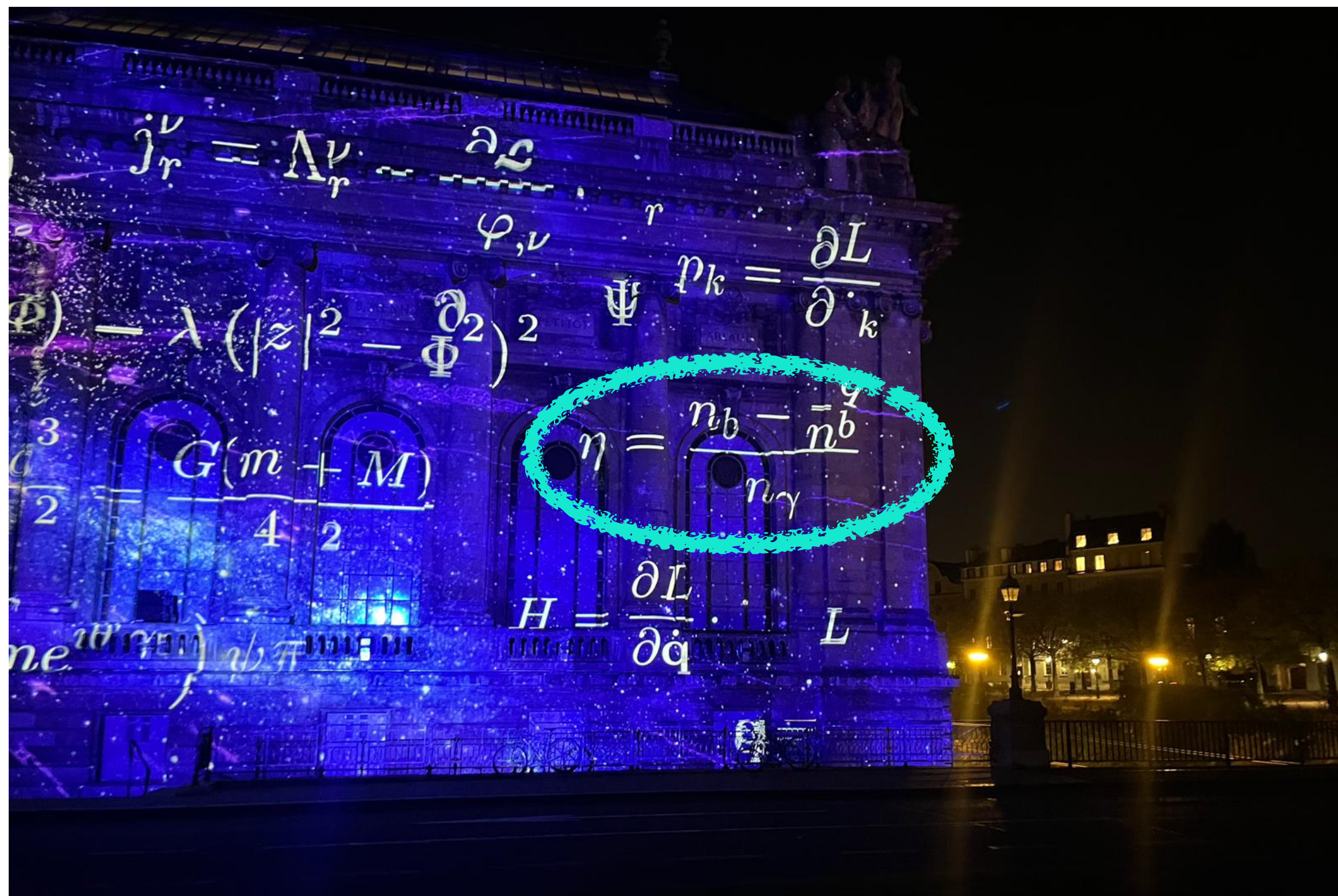
In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the Υ (4S) leads to the conclusion that B^0 - \bar{B}^0 mixing has been observed and is substantial.

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
$ V_{ub} < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{\text{QCD}} < 0.86$	QCD correction factor ^{a)}
$m_t > 50$ GeV/c ²	t quark mass



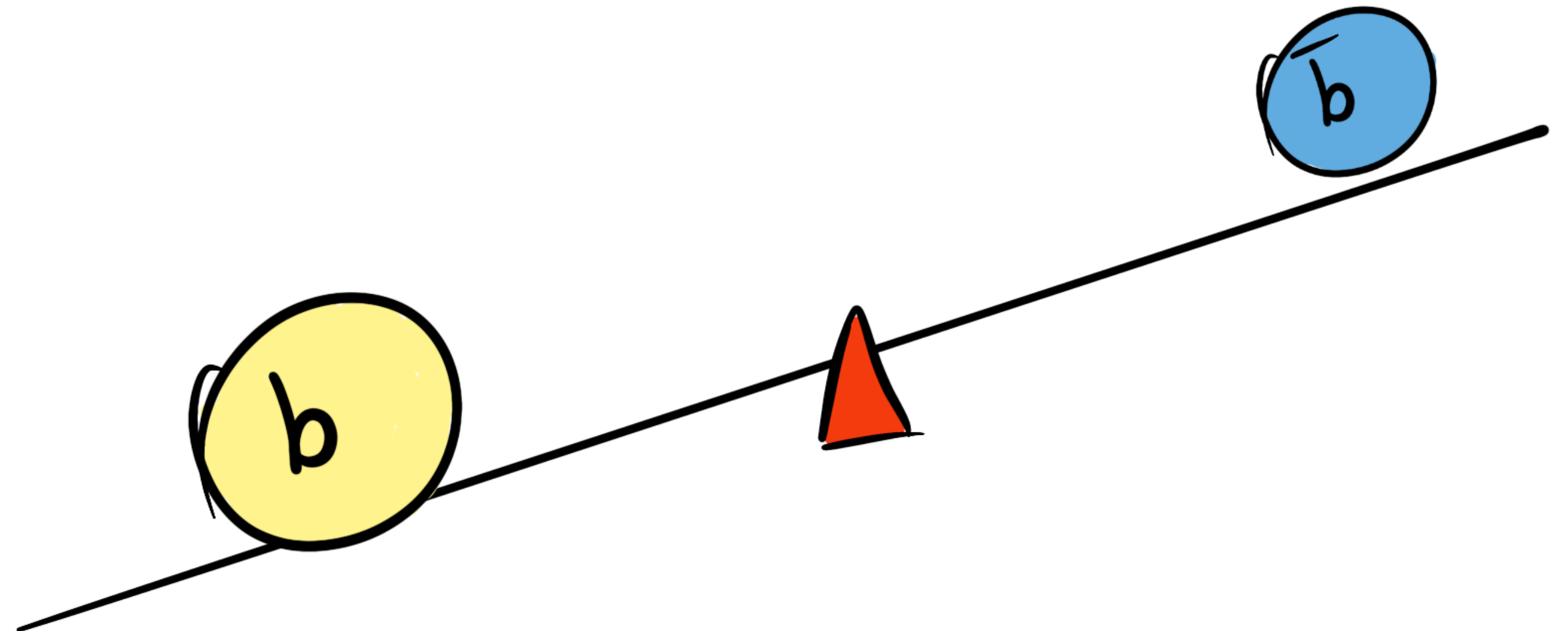
$$\mathcal{M}(B^0 - \bar{B}^0) \propto \sum_j (V_{ub} V_{ud}^*) (V_{jb} V_{jd}^*) F(m_{\mu_j}^2, m_{u_j}^2)$$

Emphasis the complementarity of direct vs indirect searches



Art & History Museum in Geneva

Towards Baryogenesis



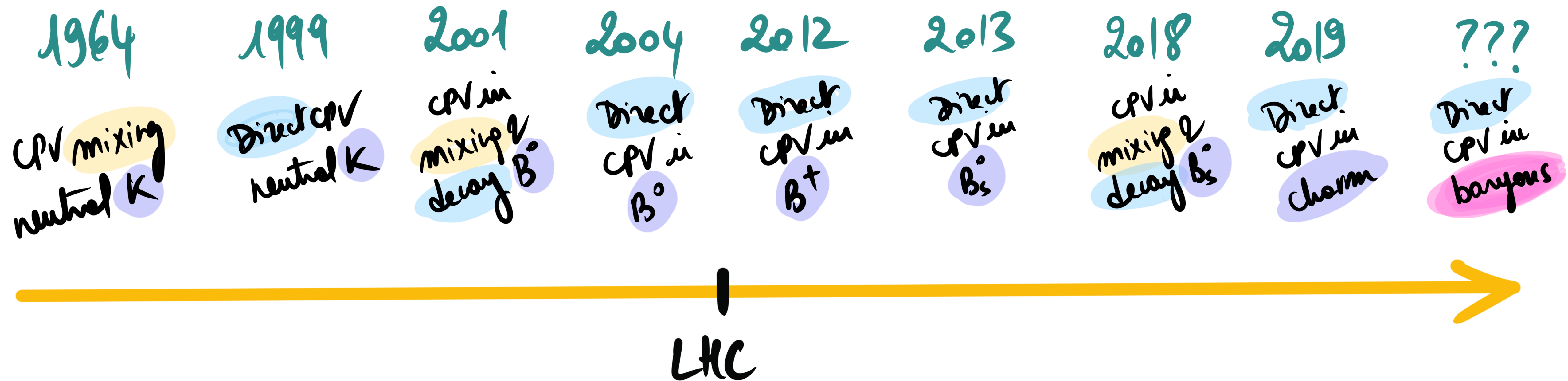
Sakharov conditions [\[edit\]](#)

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:

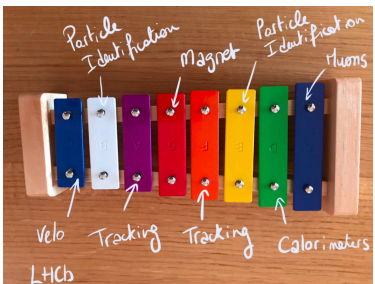
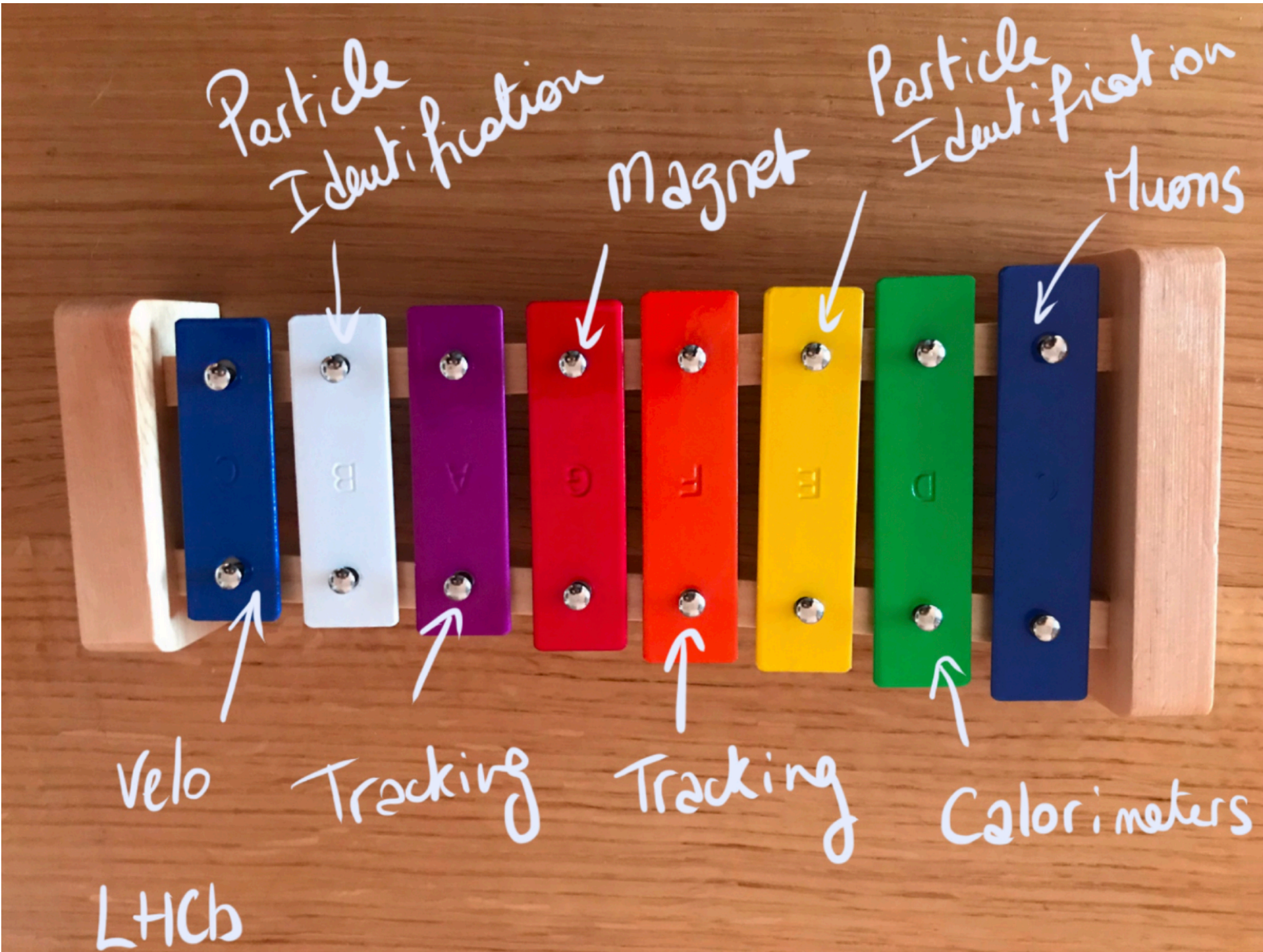
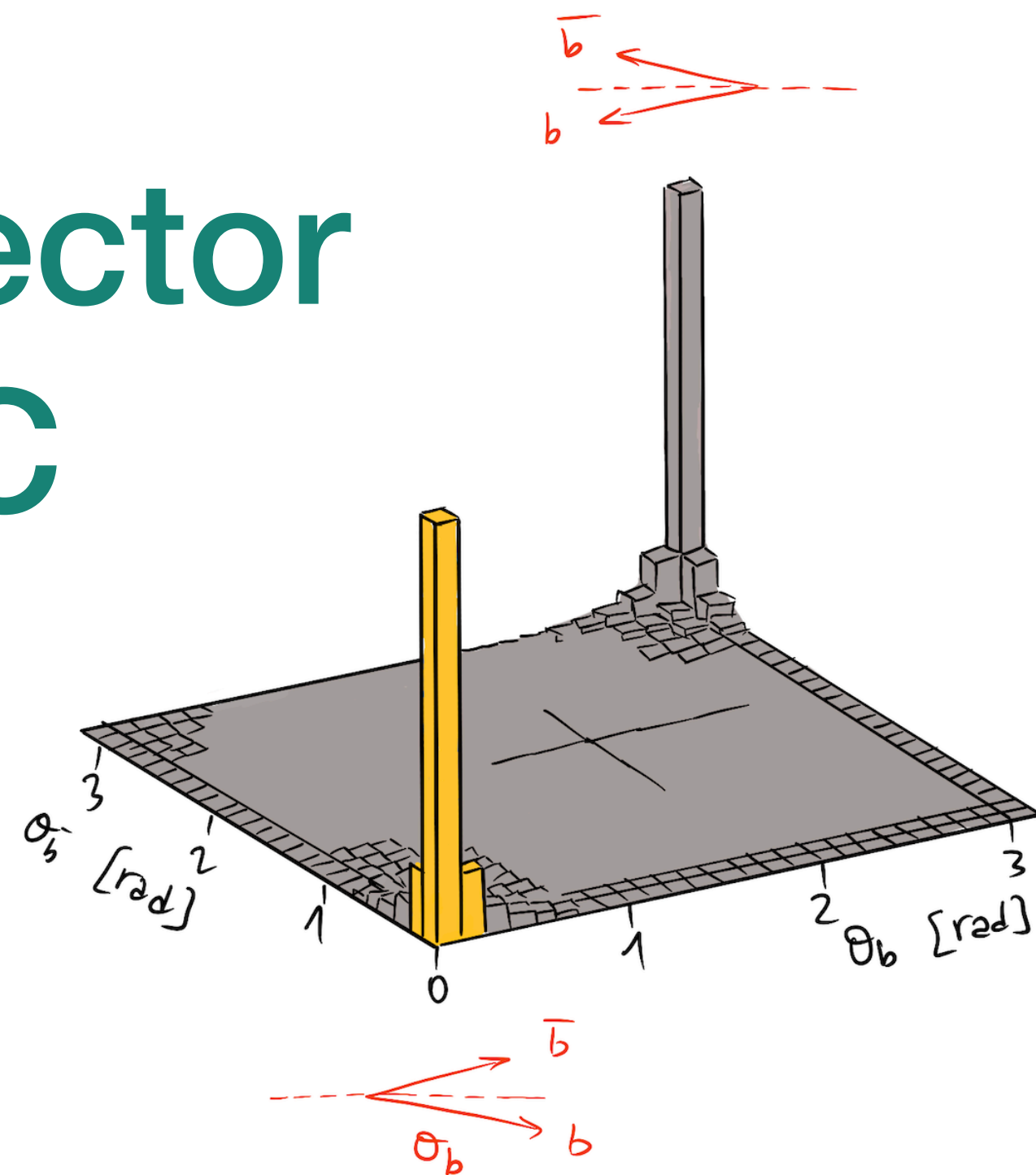
- [Baryon number](#) B violation.
- [C-symmetry](#) and [CP-symmetry](#) violation.
- Interactions out of [thermal equilibrium](#).

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

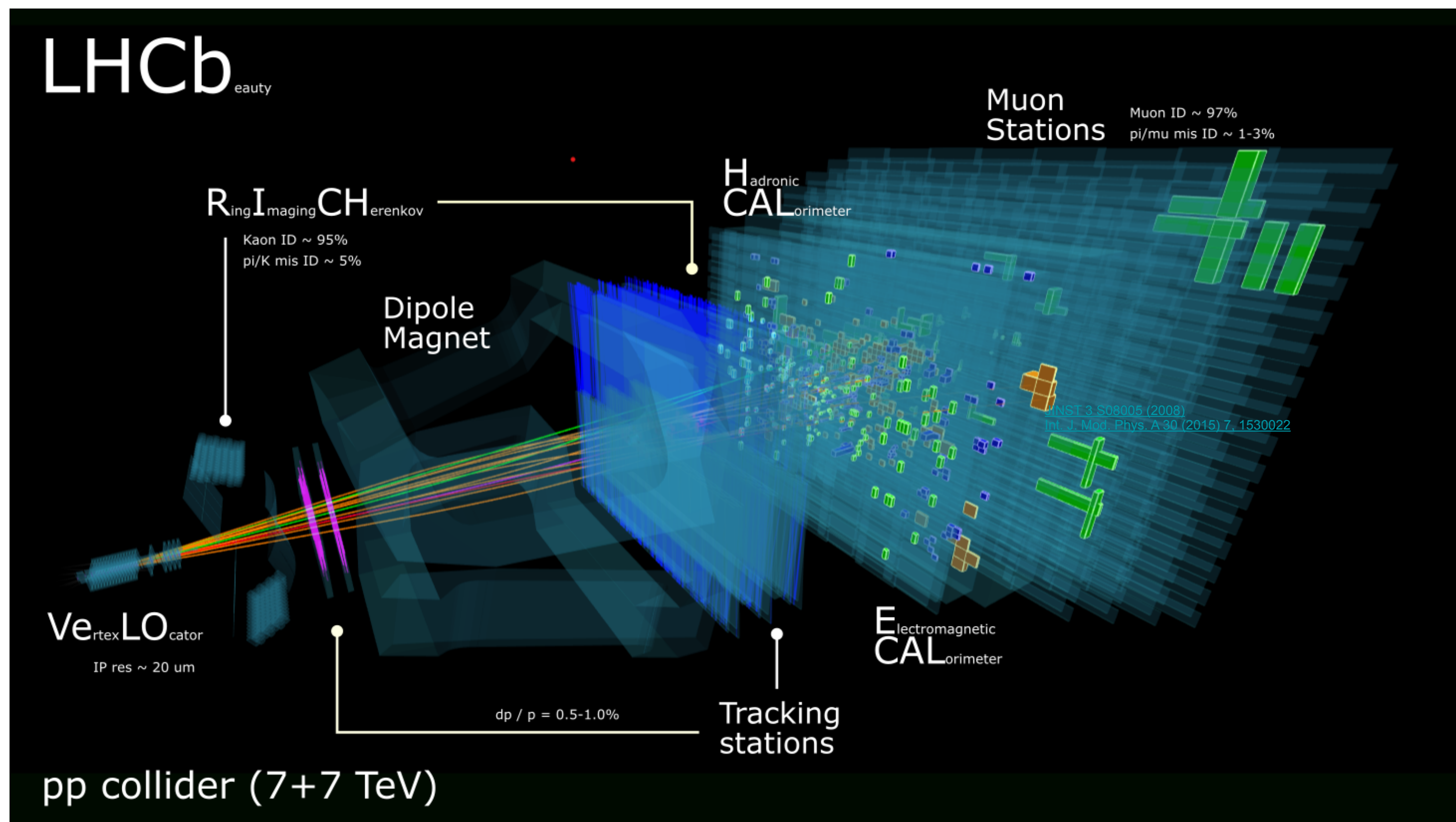


A flavour detector at the LHC

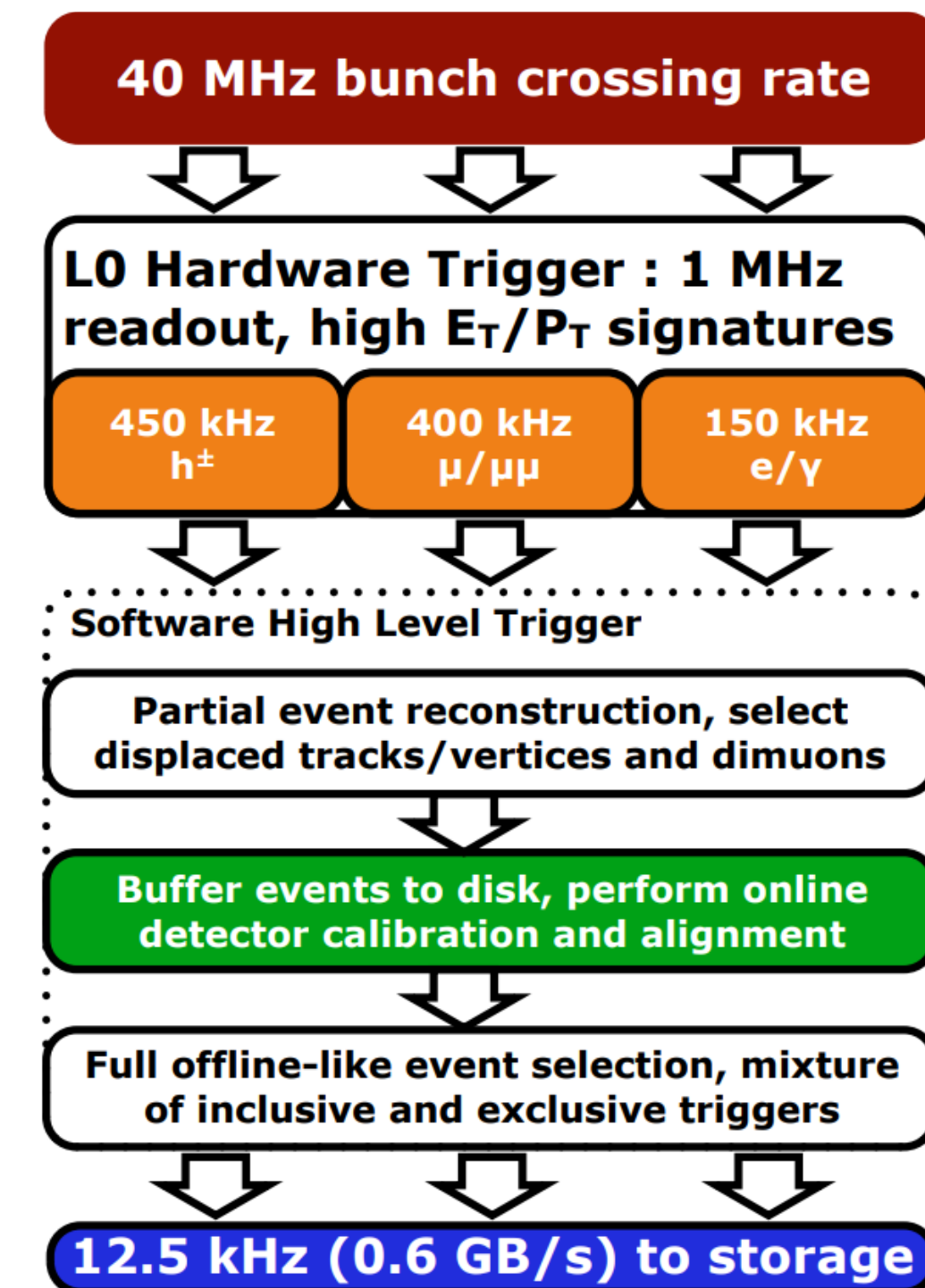


Run 1				LS1		Run 2				LS2		Run 3				LS3		Run 4				LS4		Run 5								
2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041
3 fb ⁻¹						9 fb ⁻¹						23 fb ⁻¹						50 fb ⁻¹						>300 fb ⁻¹								

The LHCb detector



Run 2 trigger



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

- ❖ Good vertex and impact parameter resolution $\sigma(\text{IP}) = 15 + 29/p_T$ mm.
- ❖ Excellent momentum resolution $\sim 25 \text{ MeV}/c^2$ two-body decays.
- ❖ Excellent particle ID (μ -ID 97% for $(\pi \rightarrow \mu)$ misID of 1-3%).
- ❖ Versatile & efficient trigger.

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

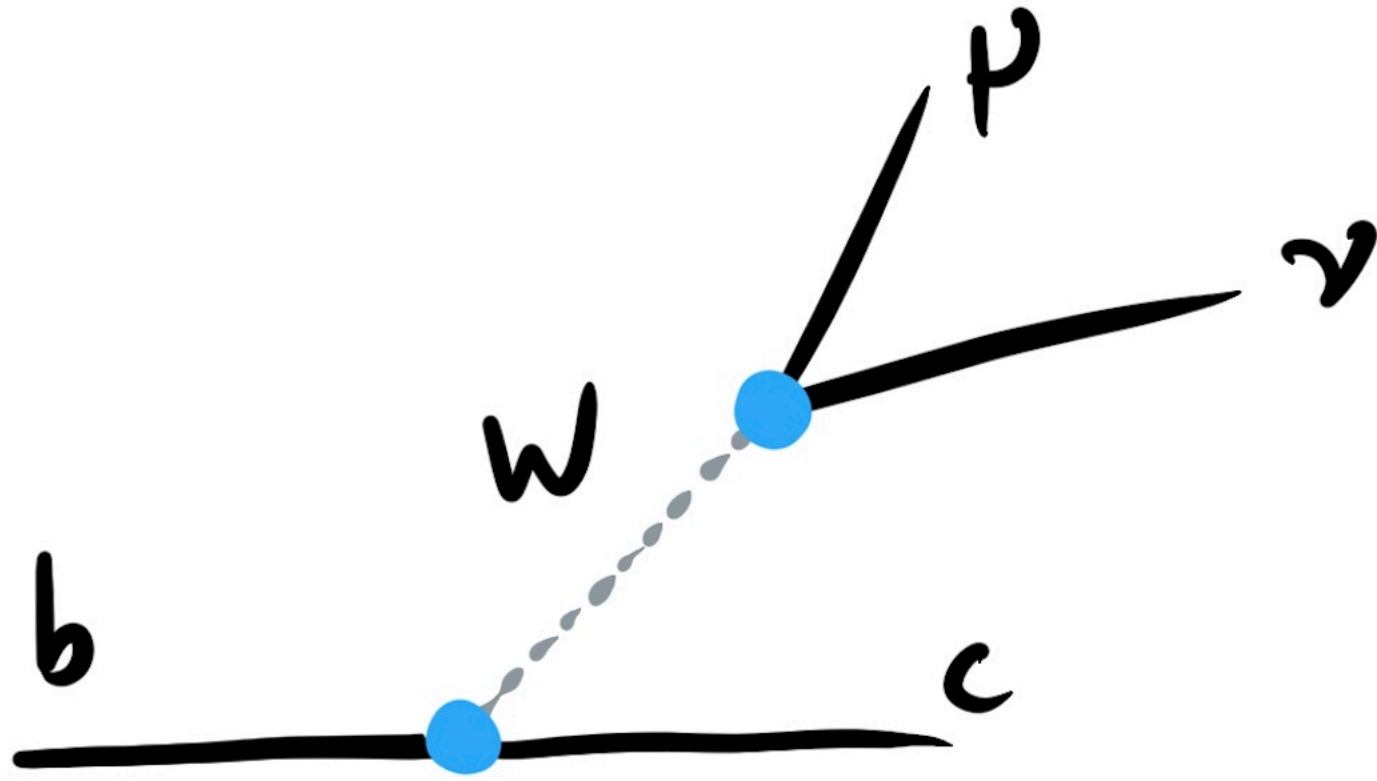
Organised by Maïke Hansen, Saime Gürbüz



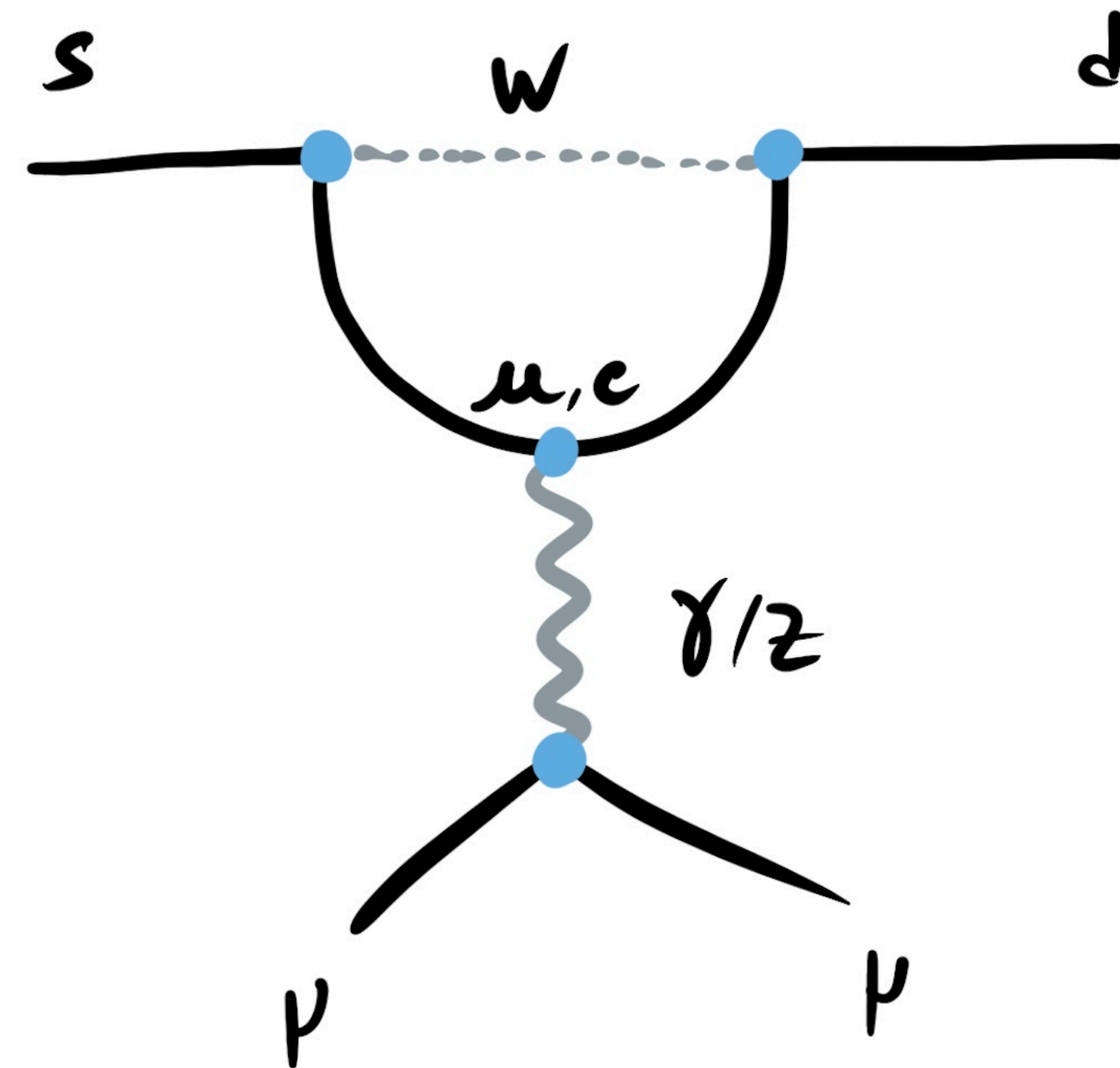
 A. Seha

Trees vs penguins

Flavour Changing Charged Currents



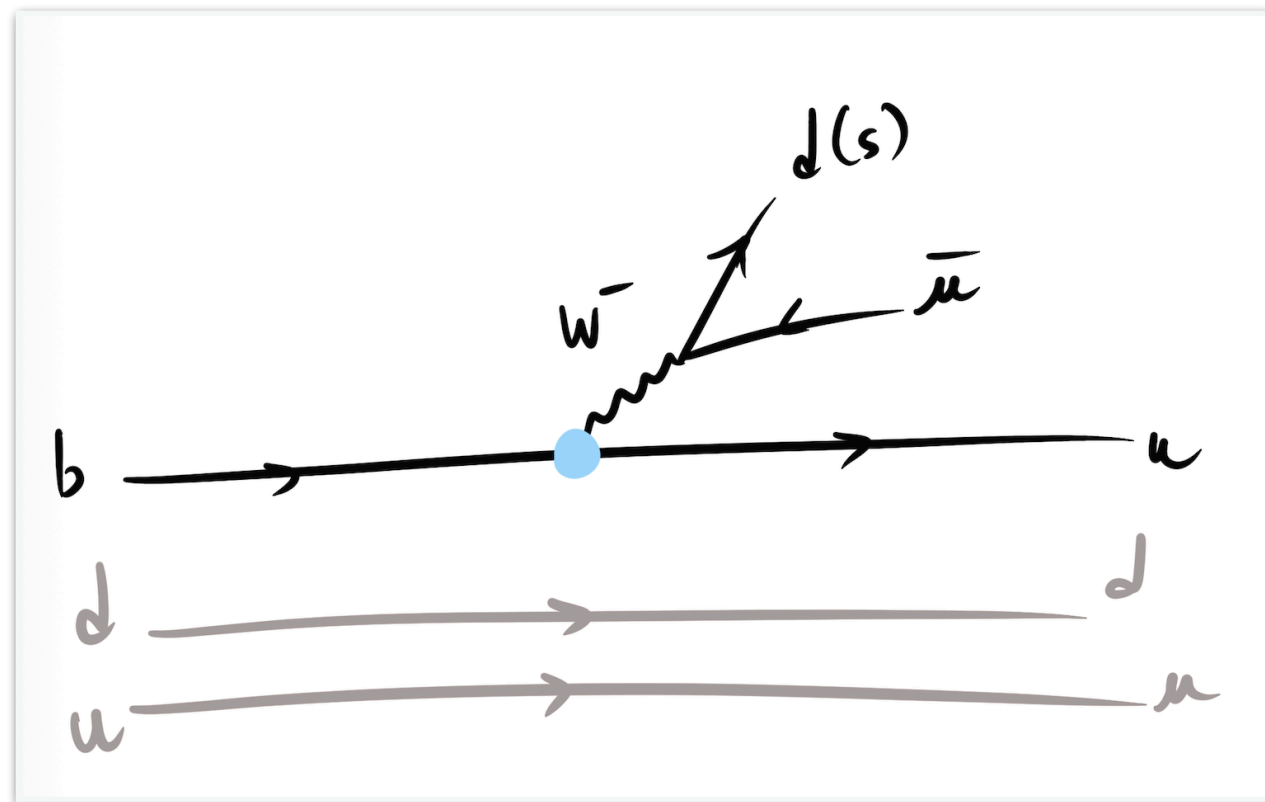
Flavour Changing Neutral Currents



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



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

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

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

Wolfenstein parametrisation

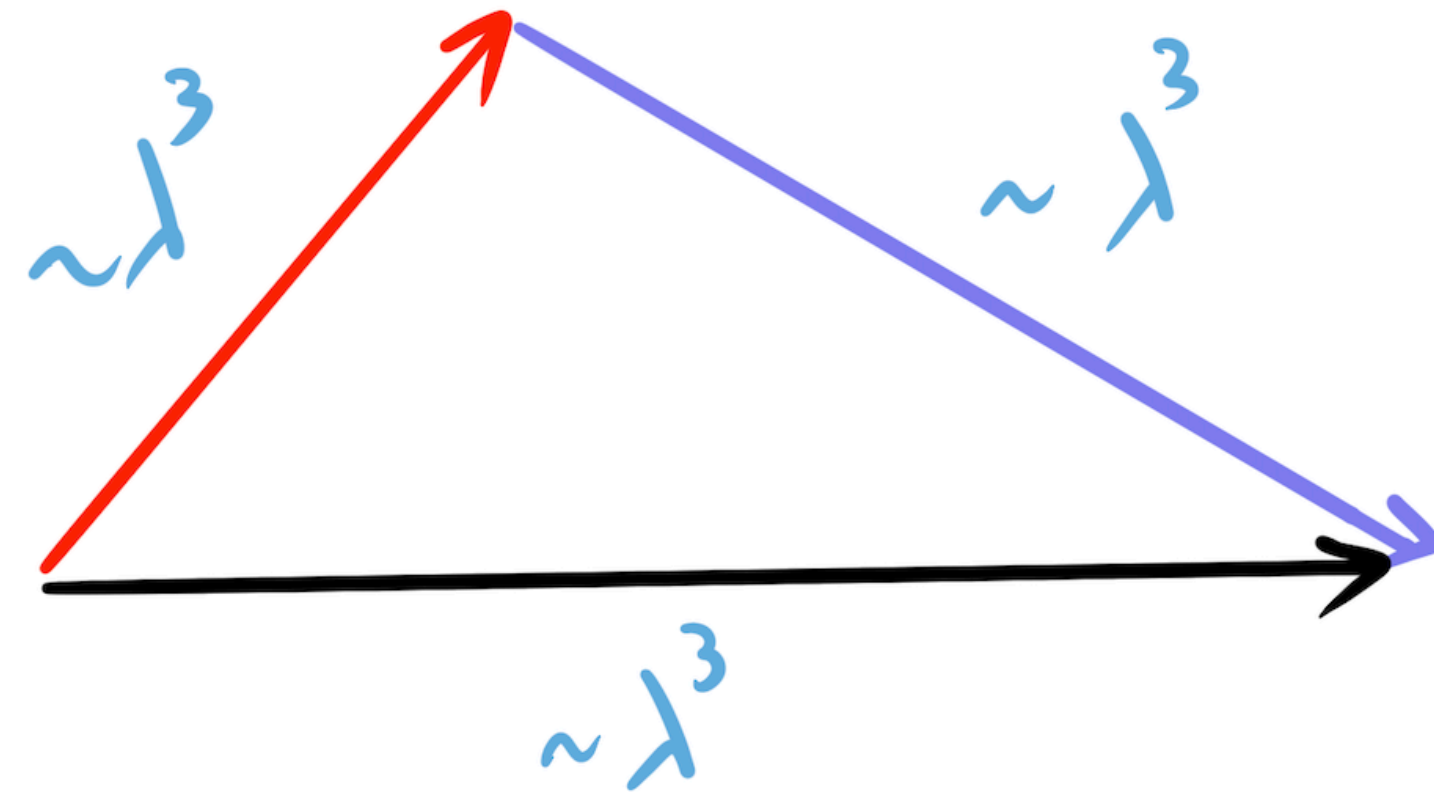
CKM - matrix

$$(V^\dagger V)_{ij} = \delta_{ij}$$

$$i=b, j=d$$



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



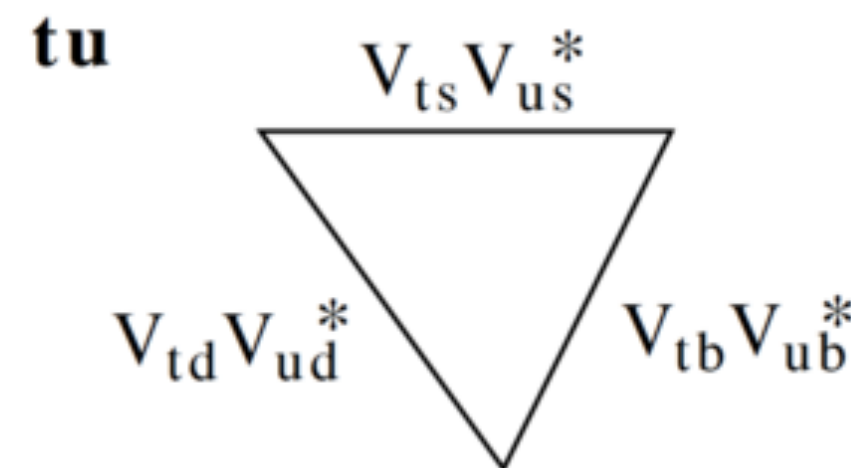
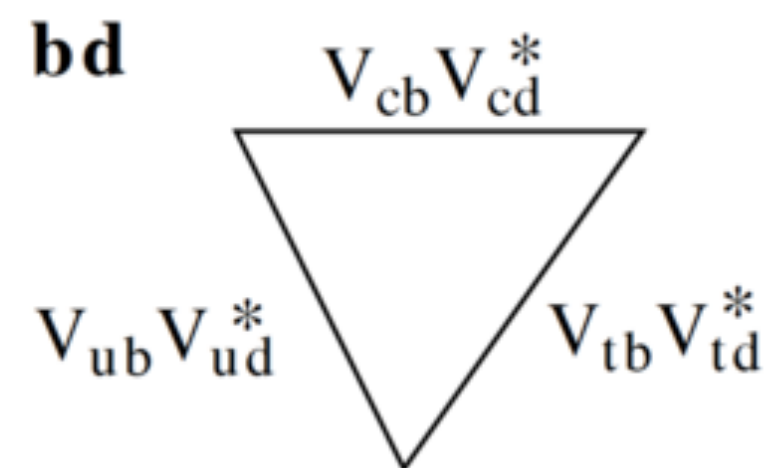
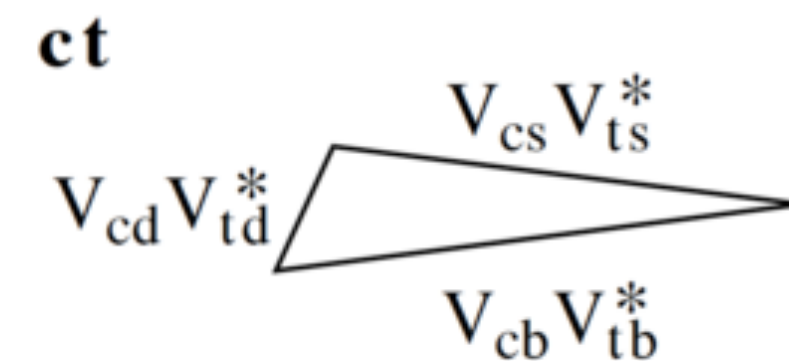
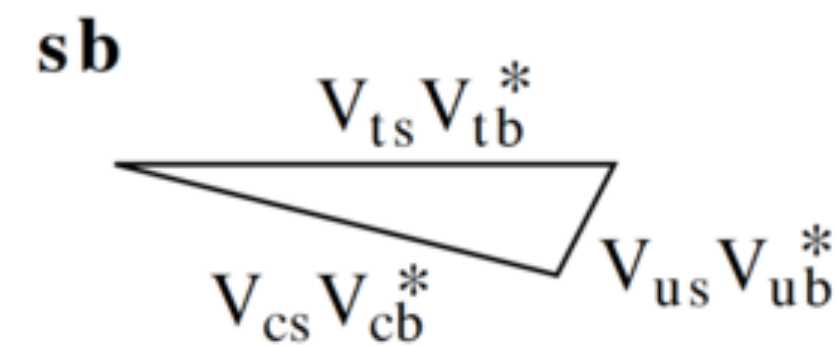
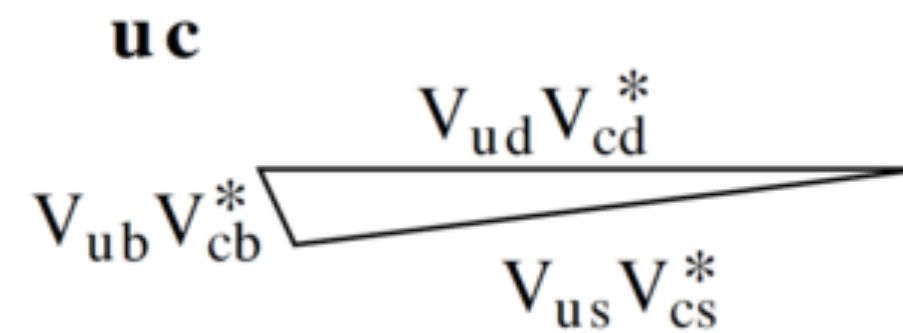
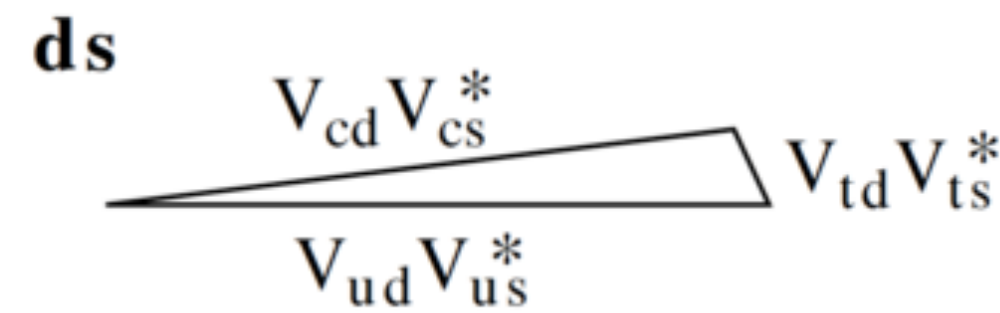
Building the unitarity triangles

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,

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

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



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

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

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

CP Violation in Decay

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

A_f Amplitude $B \rightarrow f$
 \bar{A}_f Amplitude $\bar{B} \rightarrow \bar{f}$

CP Violation in mixing

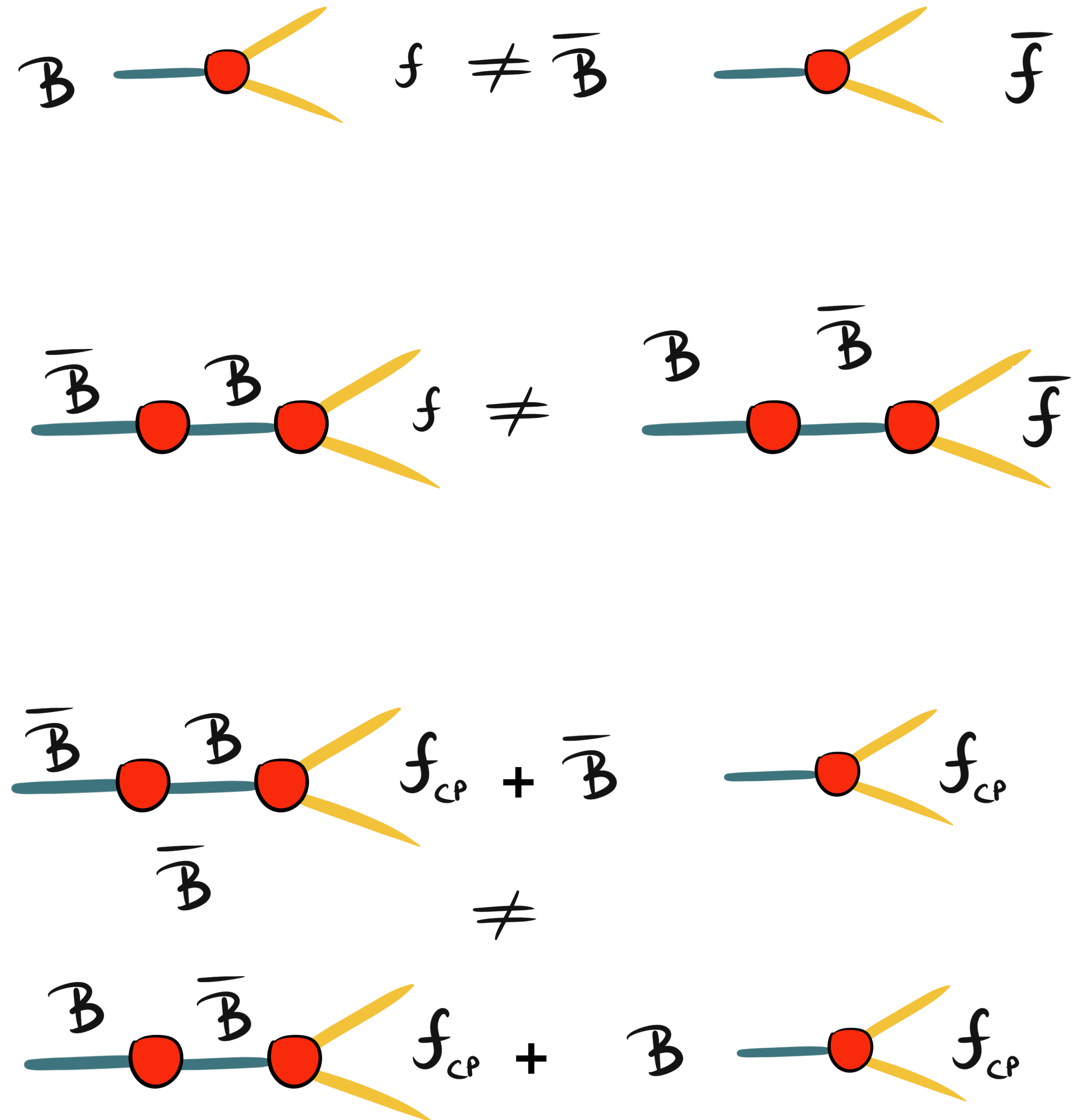
- $|\eta_P| \neq 1$

CP Violation in the interference between mixing and decay

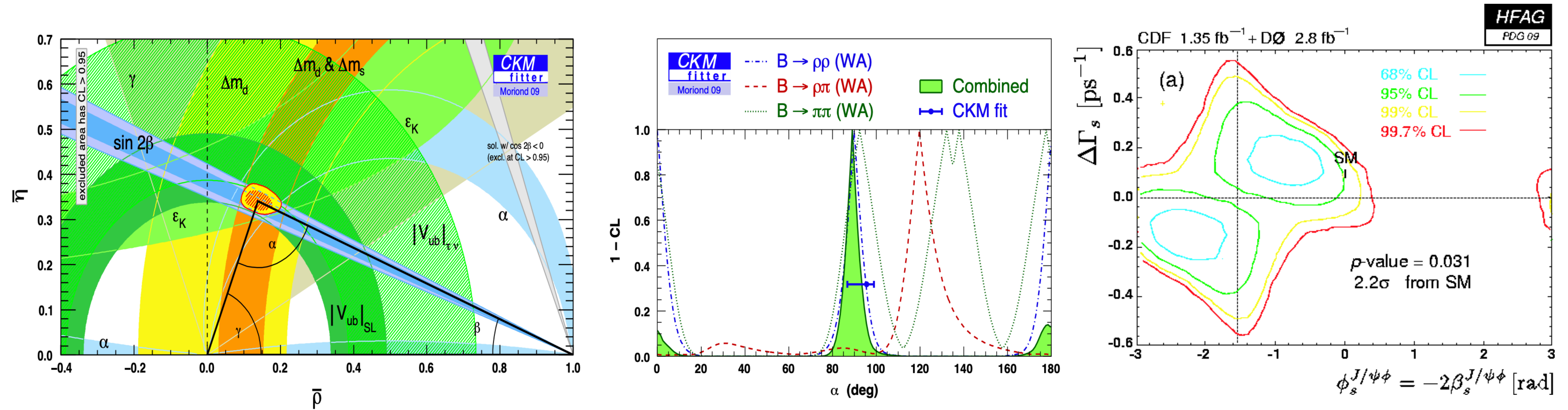
- $\text{Im}(\lambda_f) = \text{Im}\left(\frac{q}{p} \frac{\bar{A}_f}{A_f}\right) \neq 0$

$\lambda_f =$ parameter that quantifies
CP violation

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

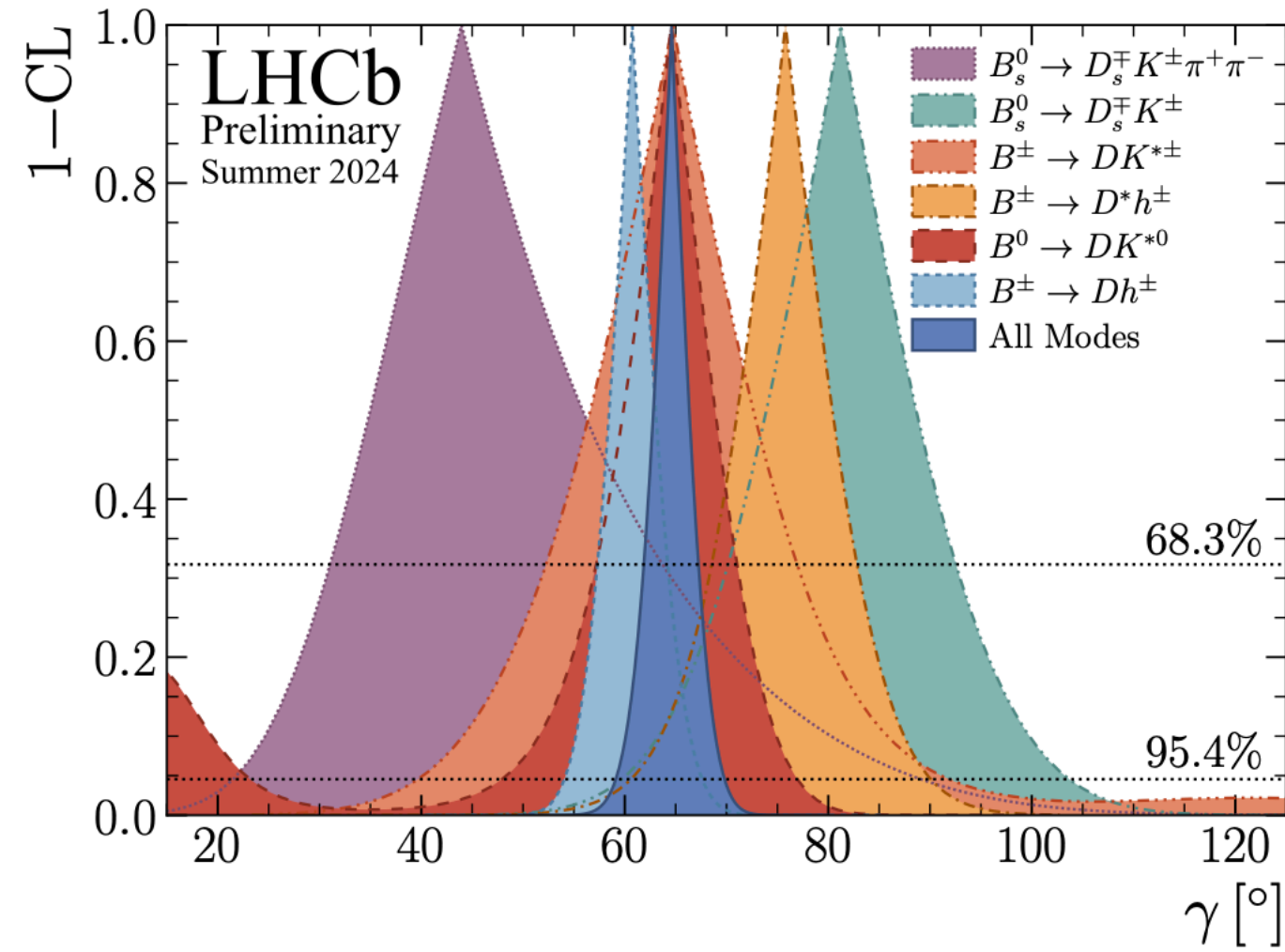
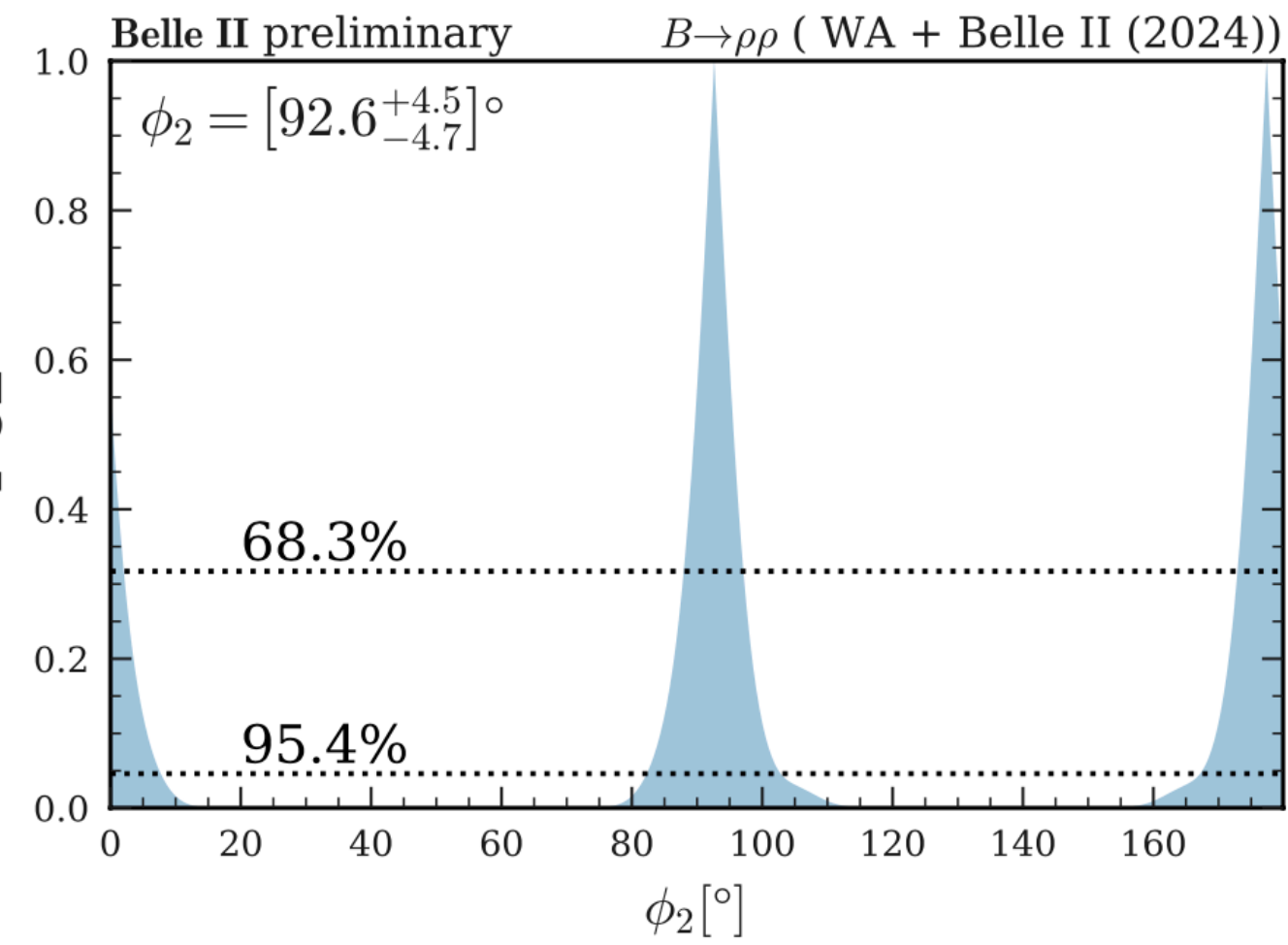


All the phases...in 2009

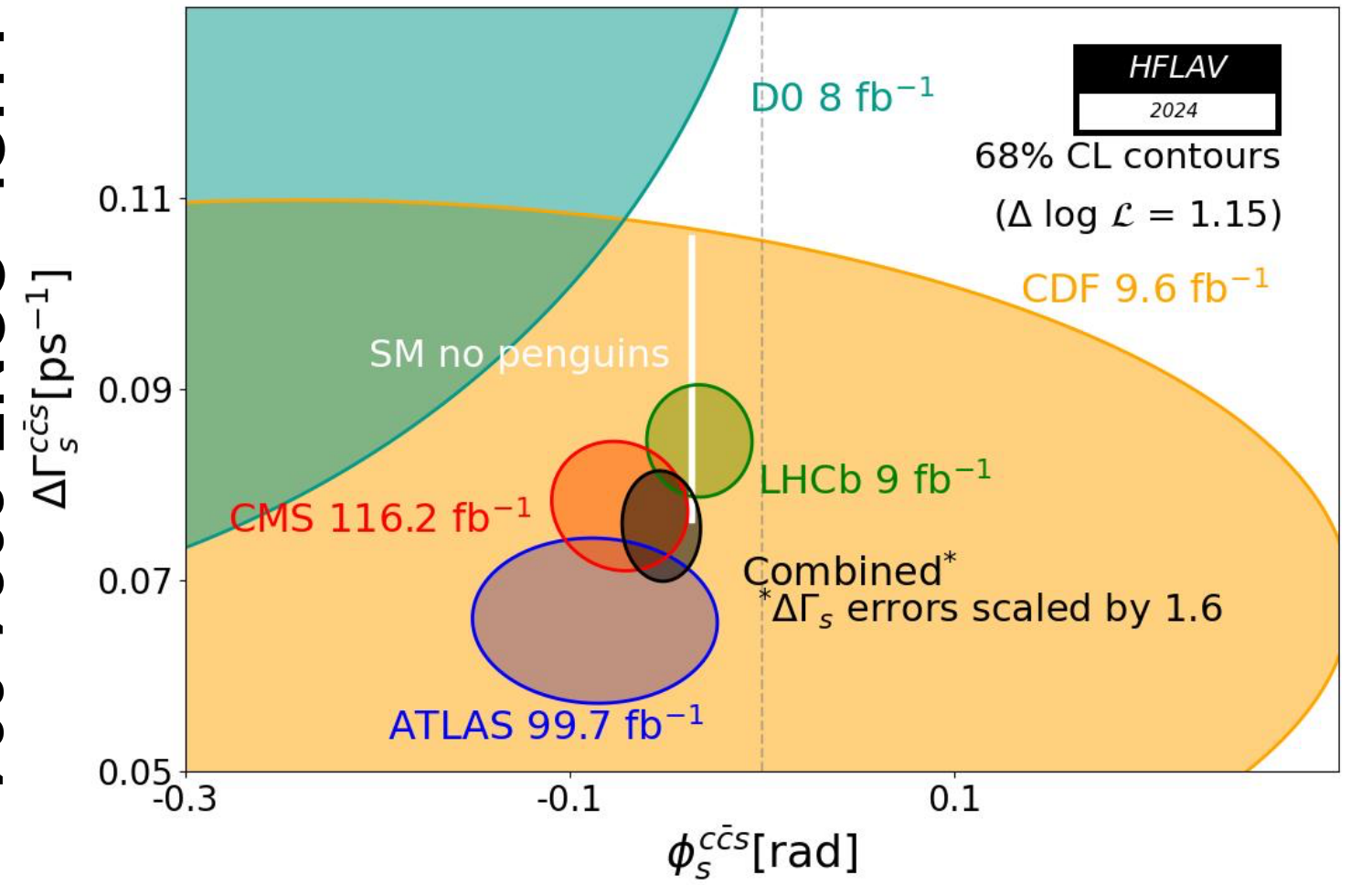


All the phases...Today

2412.19624v1



LHCb-CONF-2024-004

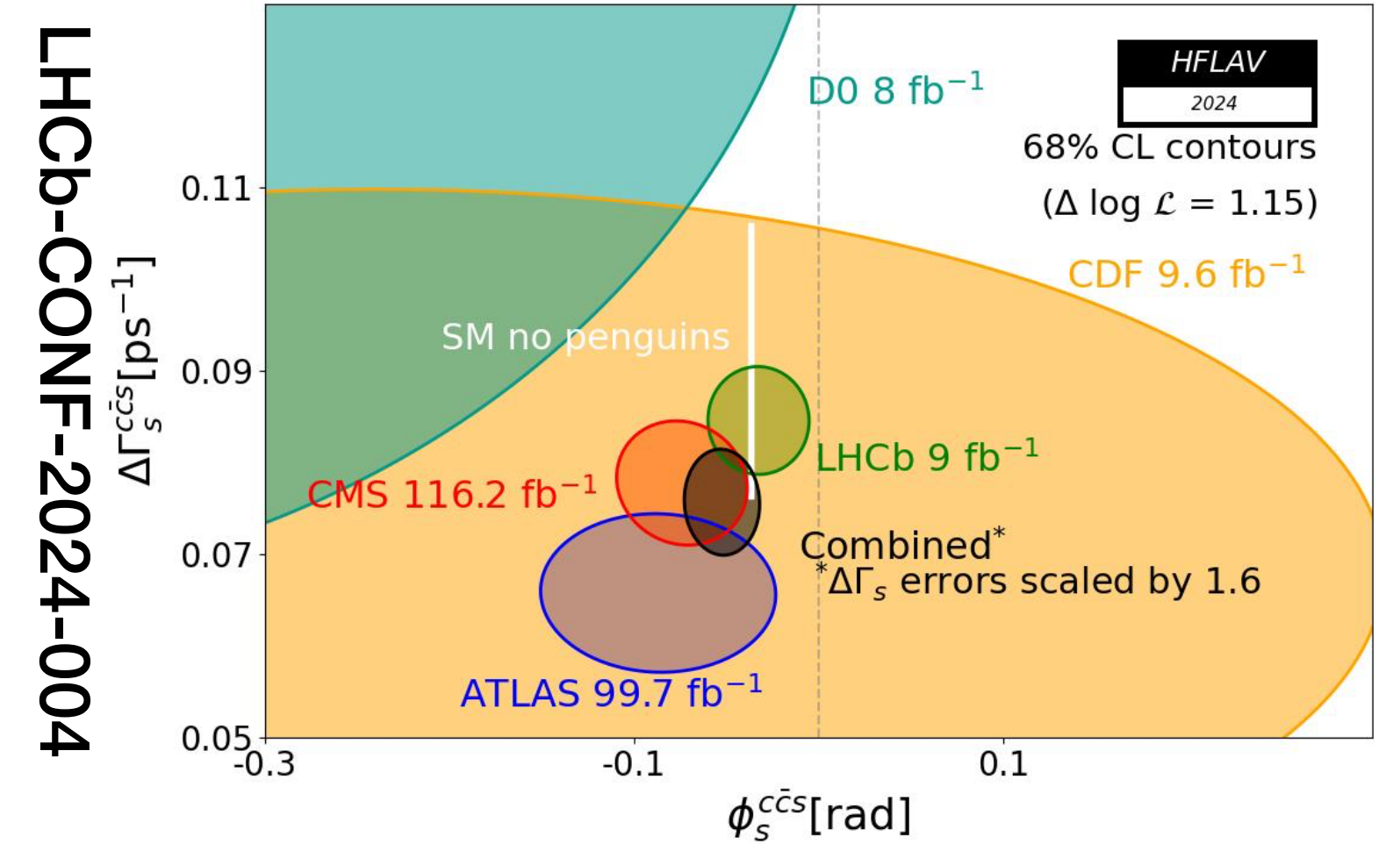
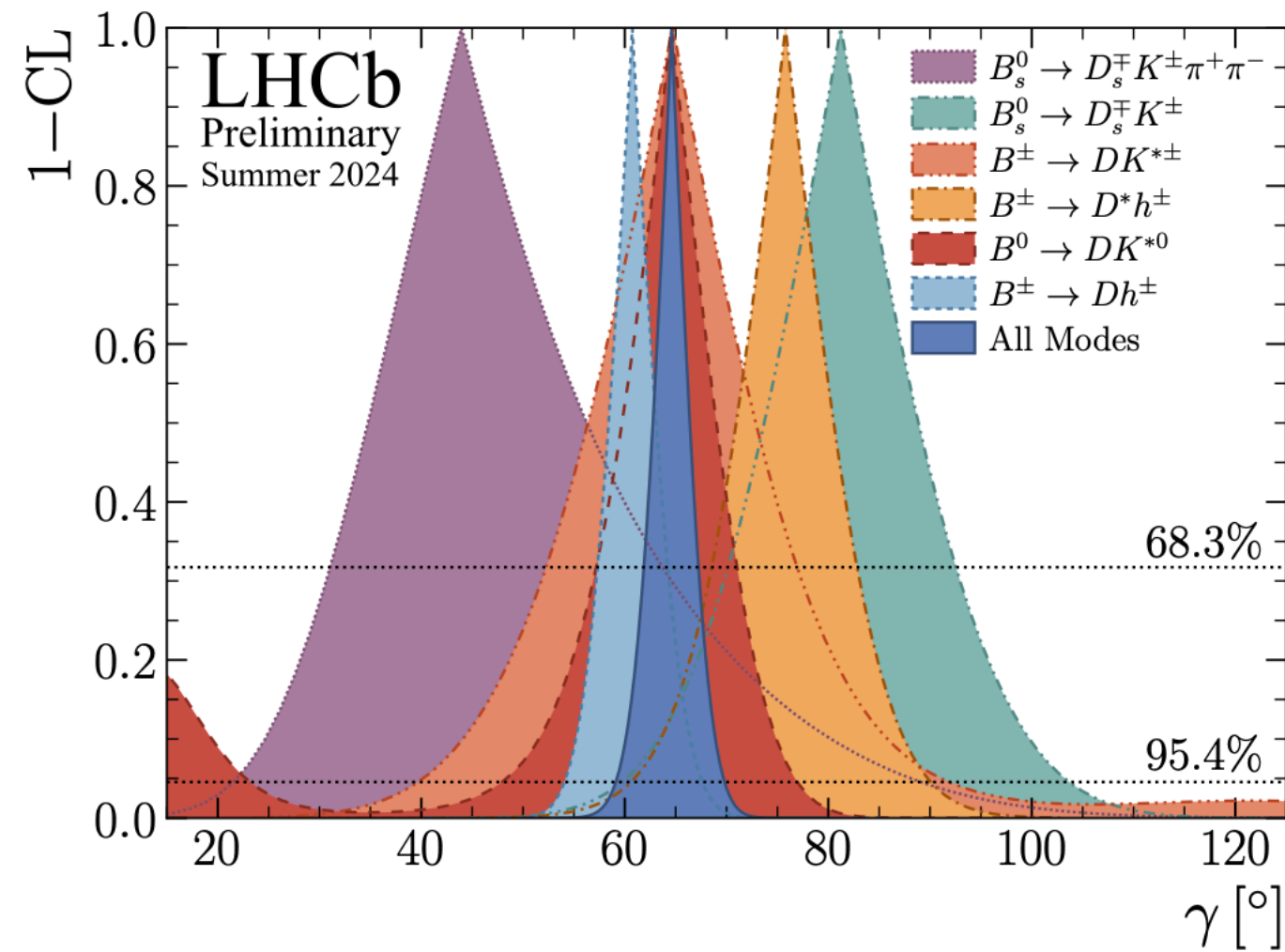
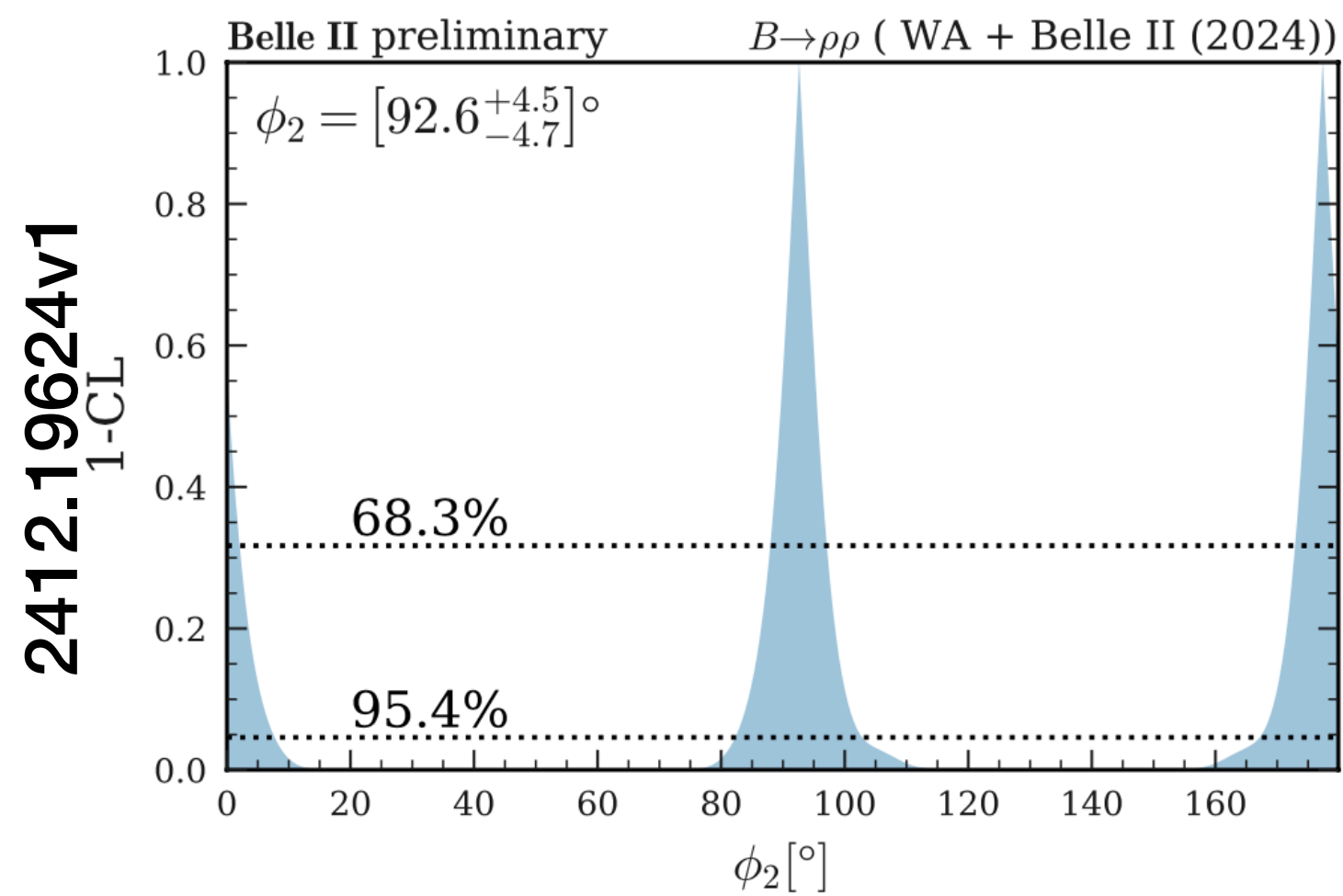


arXiv:2411.18639

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?



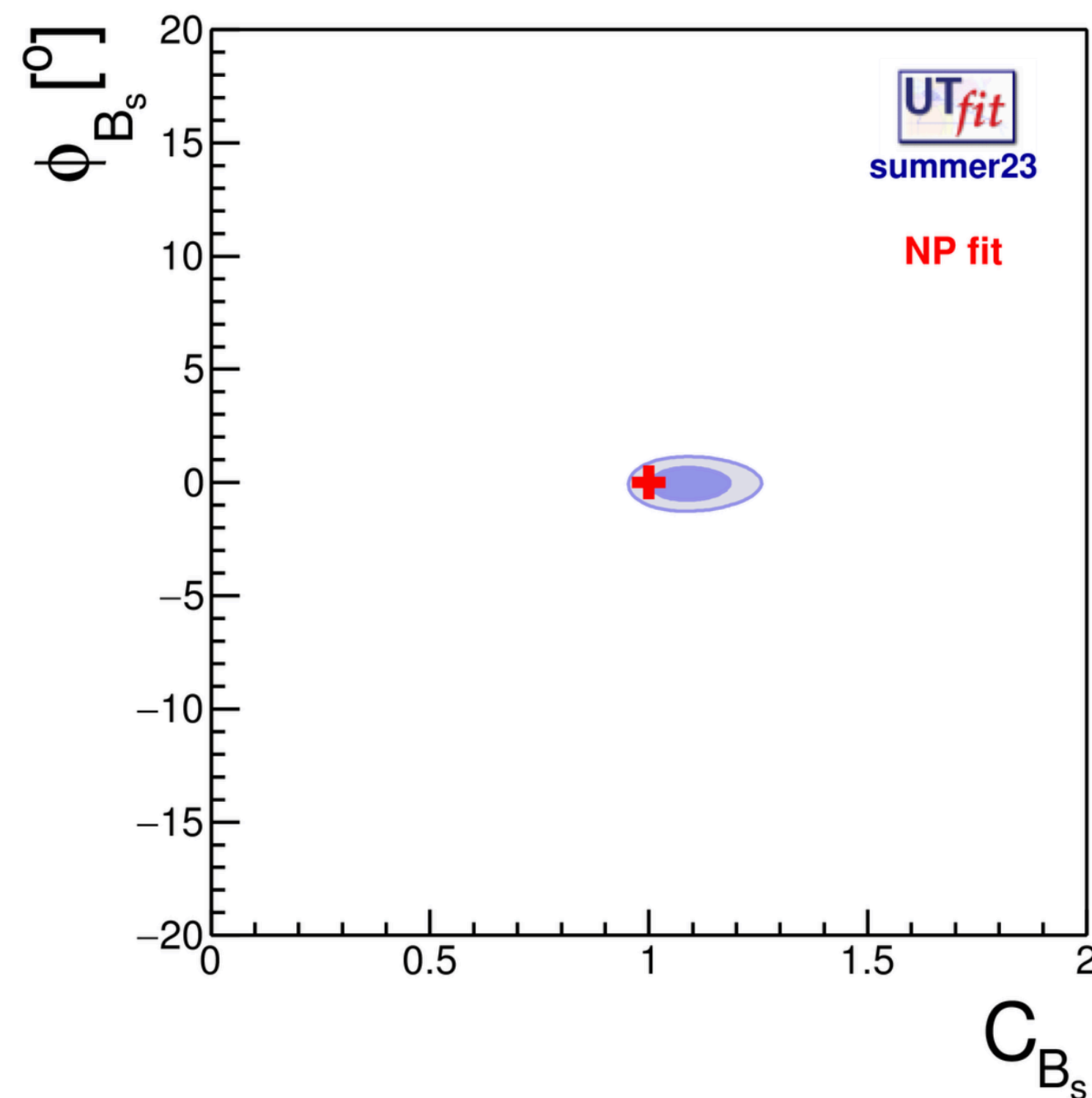
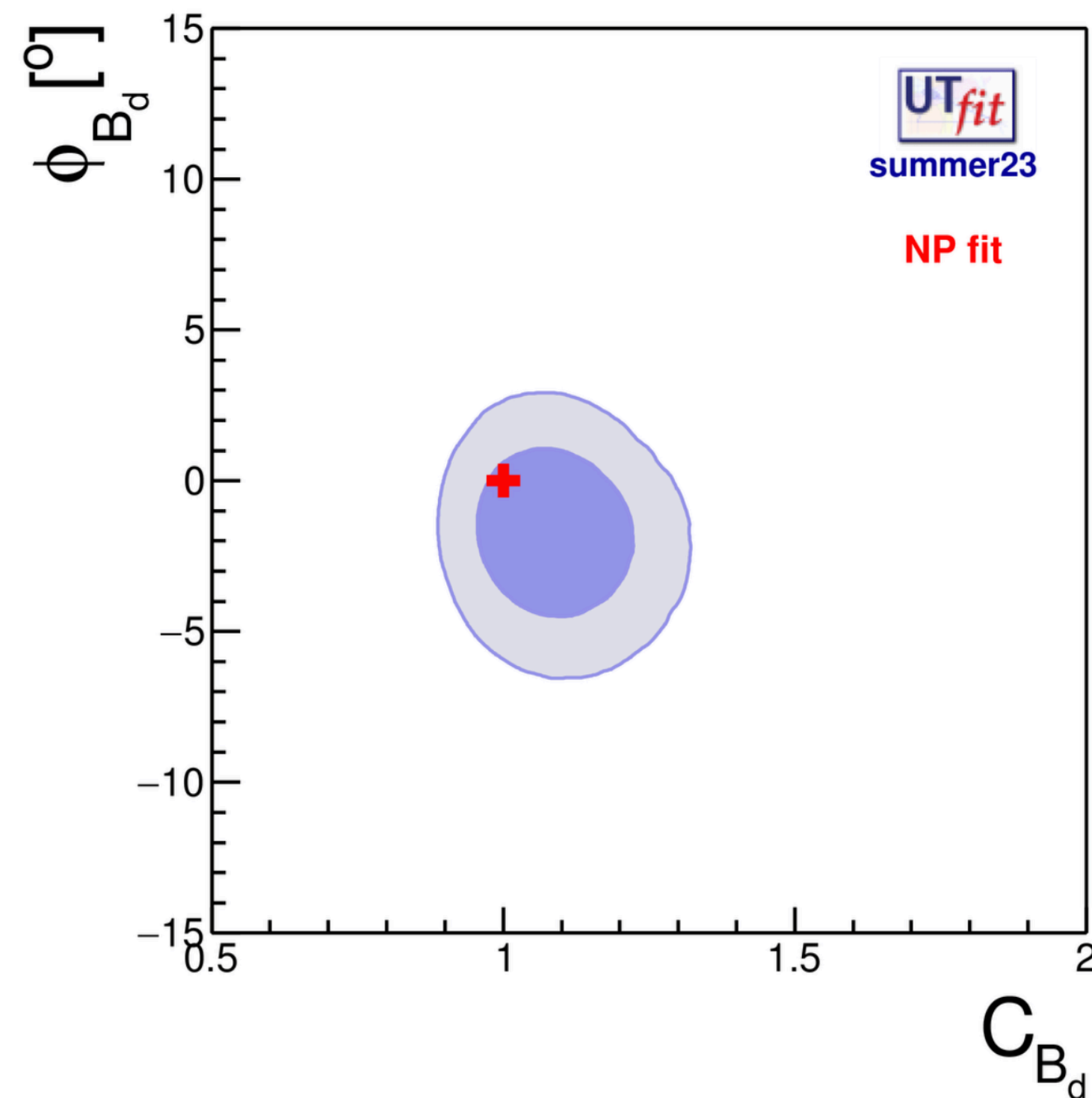
arXiv:2411.18639

An example of a UT fit

Adopt a given parametrisation

$$A_1 = C_{B_q} e^{2i\phi_{B_q}} A_1^{\text{SM}} e^{2i\phi_1^{\text{SM}}}$$

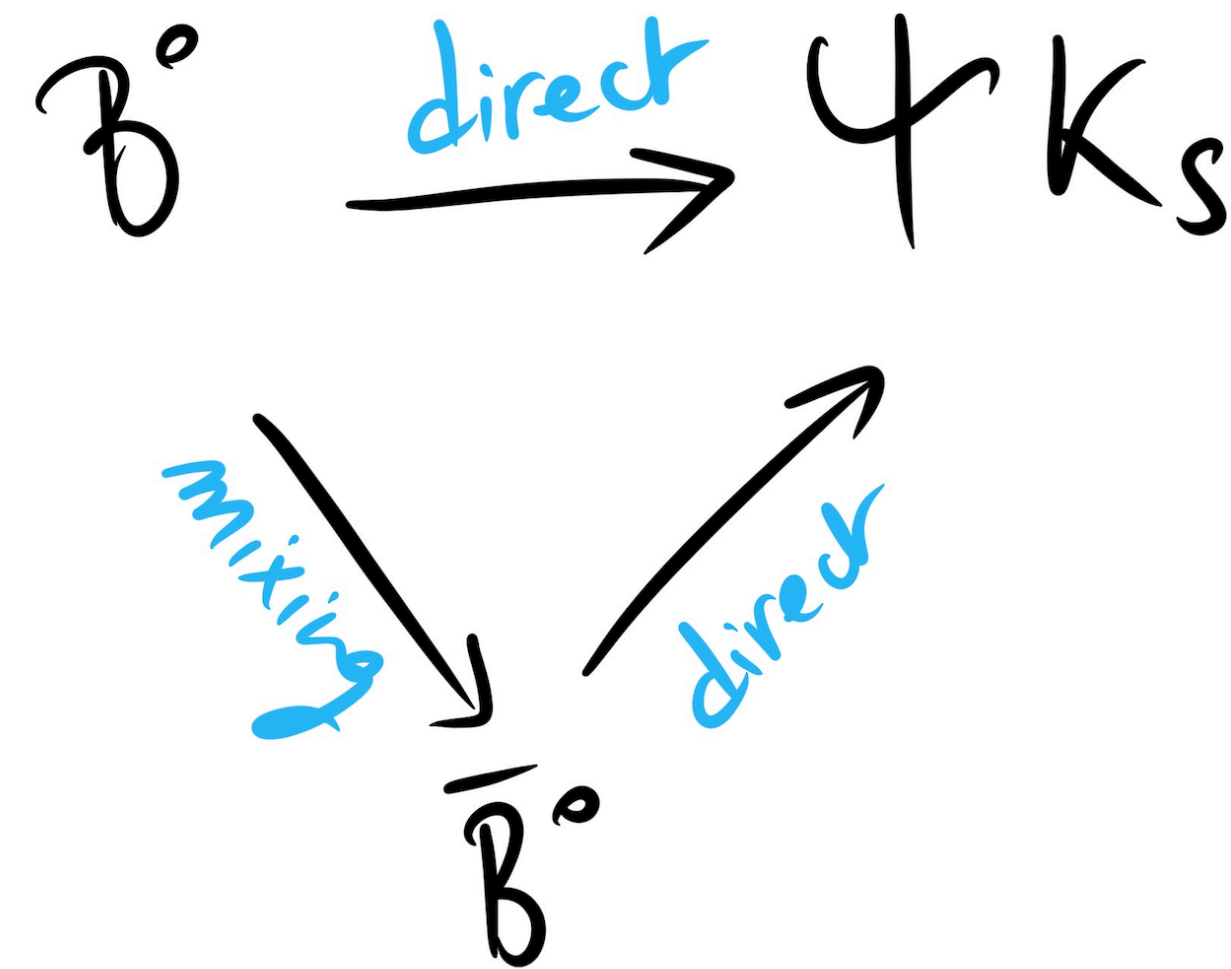
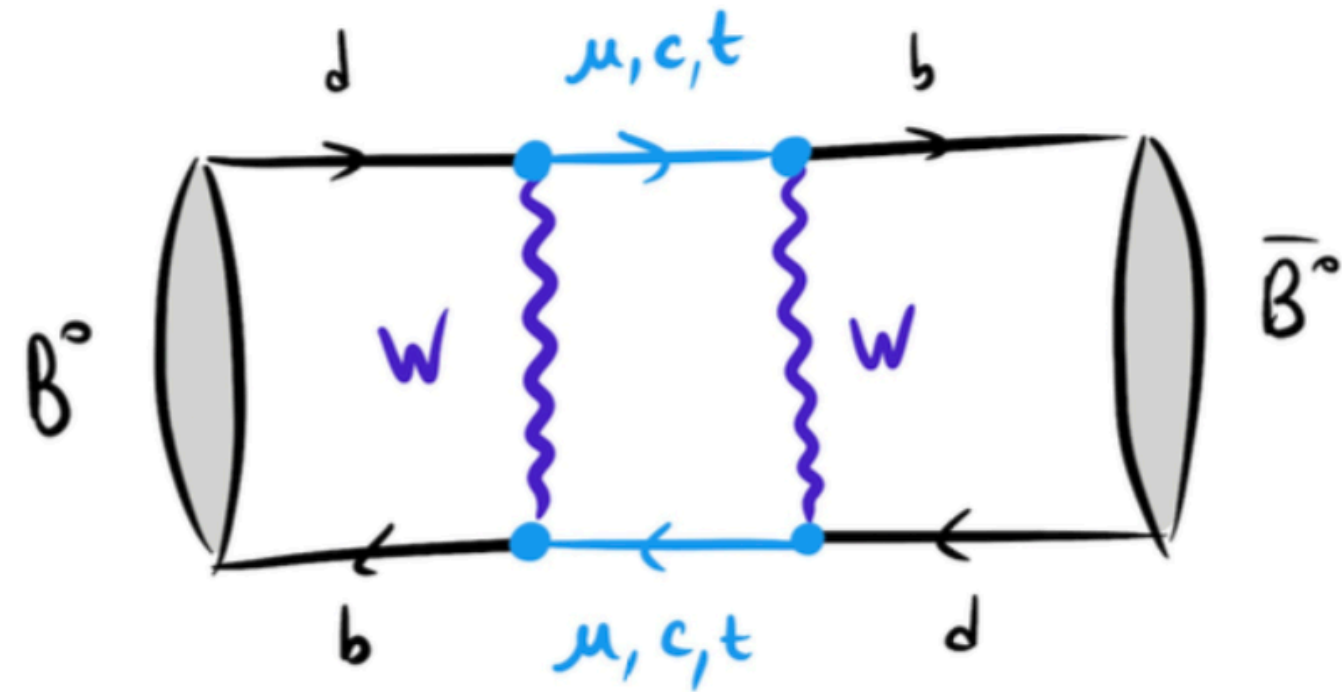
+ SM



Let's dive in



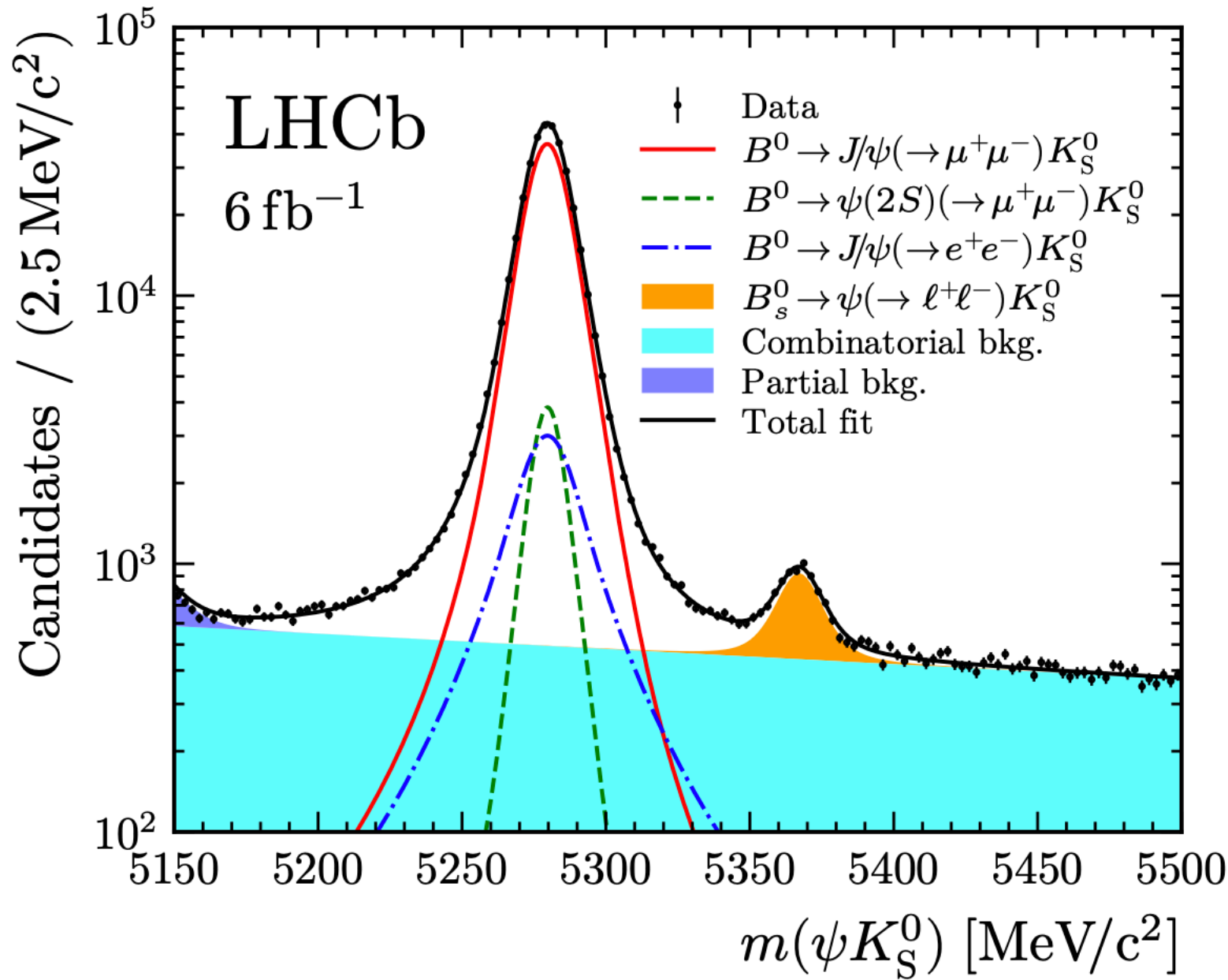
Let's start with sin2beta with the “golden” mode $B^0 \rightarrow \psi(\ell^+\ell^-)K_S^0(\pi^+\pi^-)$



Time dependent analysis \rightarrow requires flavour tagging

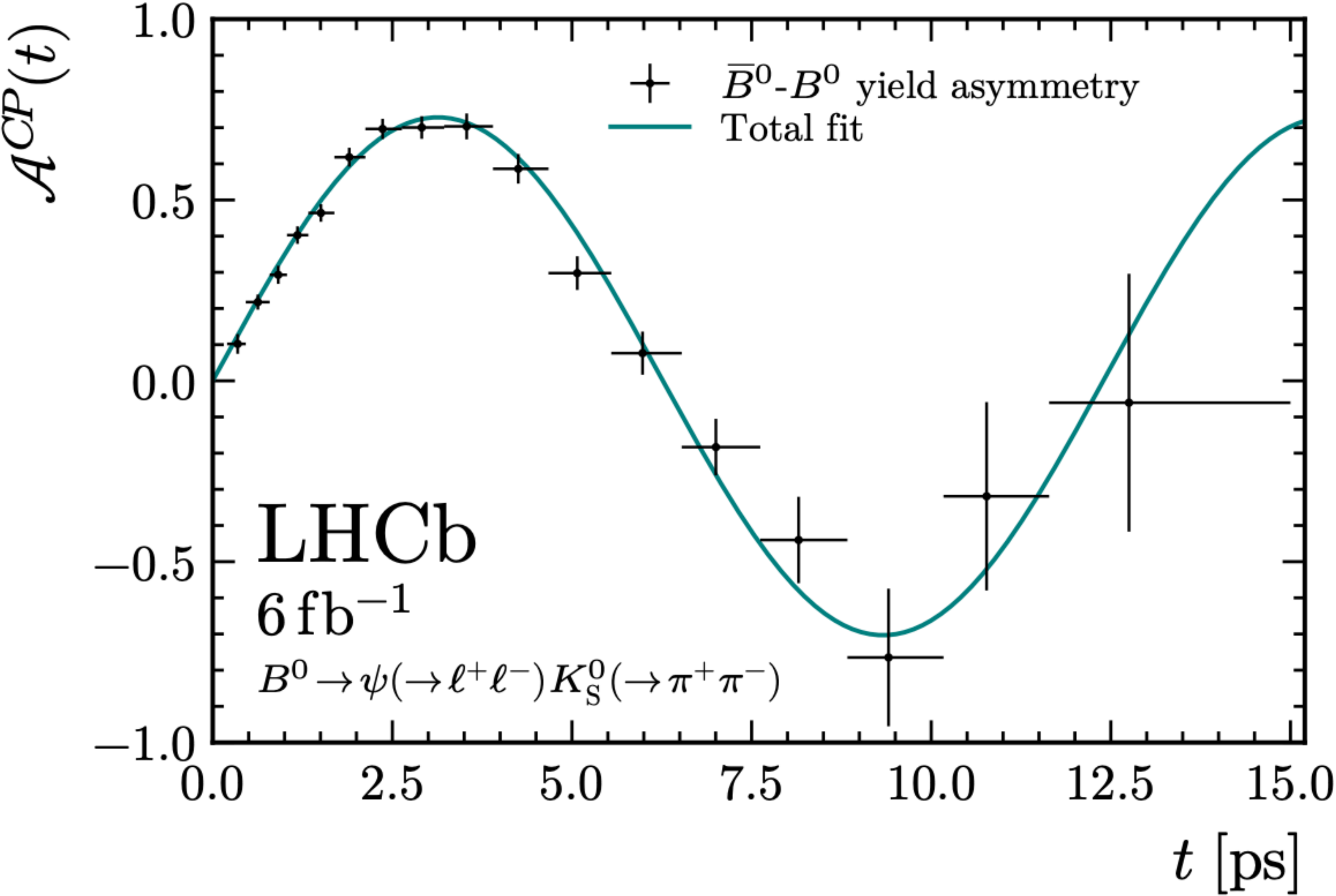
$$A^{\psi}(t) = \frac{\Gamma(\bar{B}^0 \rightarrow \psi K_S) - \Gamma(B^0 \rightarrow \psi K_S)}{\Gamma(\bar{B}^0 \rightarrow \psi K_S) + \Gamma(B^0 \rightarrow \psi K_S)} \approx \underbrace{D_{\Delta t} D_{FT}}_{\text{Experimental dilution}} S \sin(\Delta m_d t)$$

Text book like result !

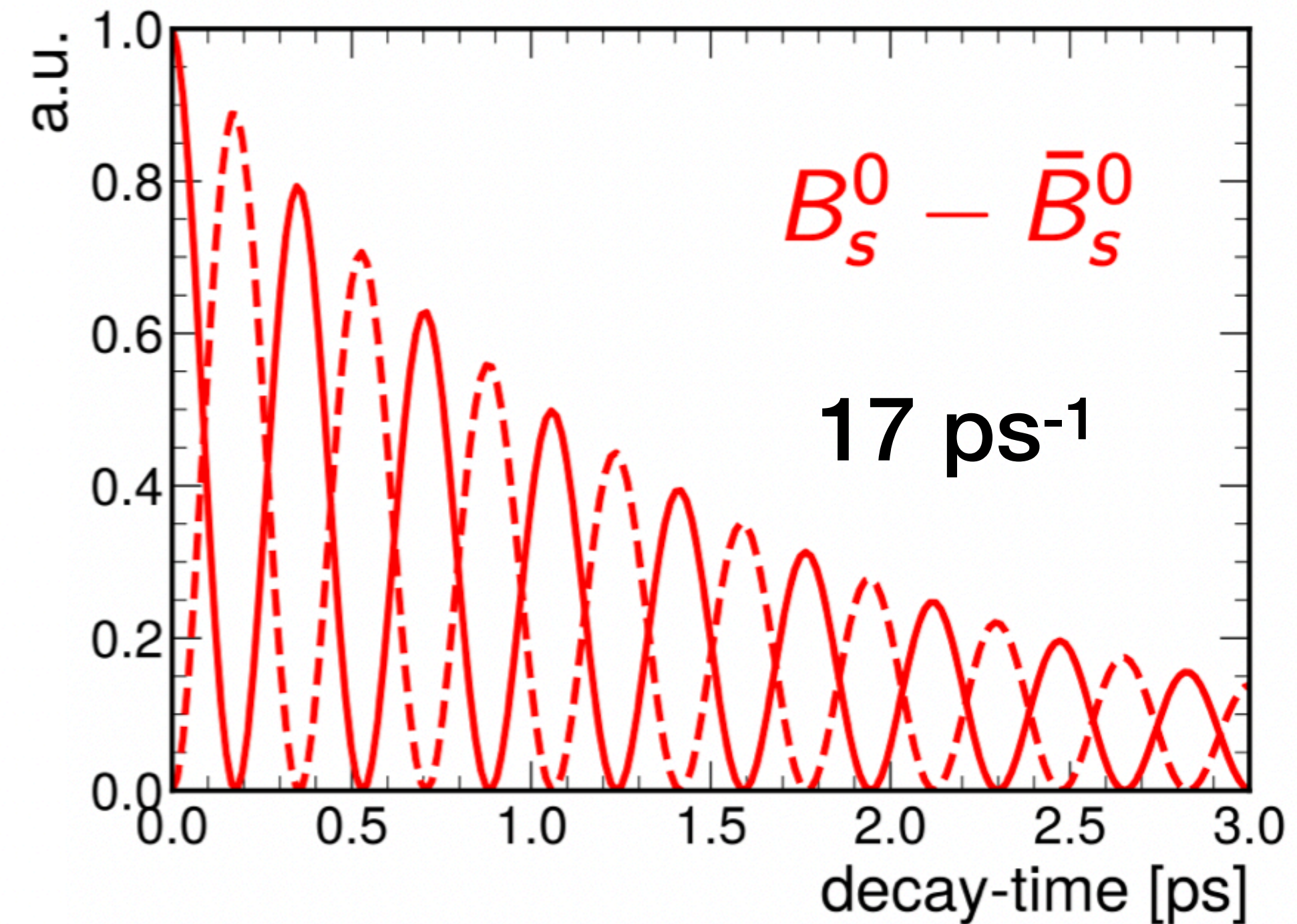
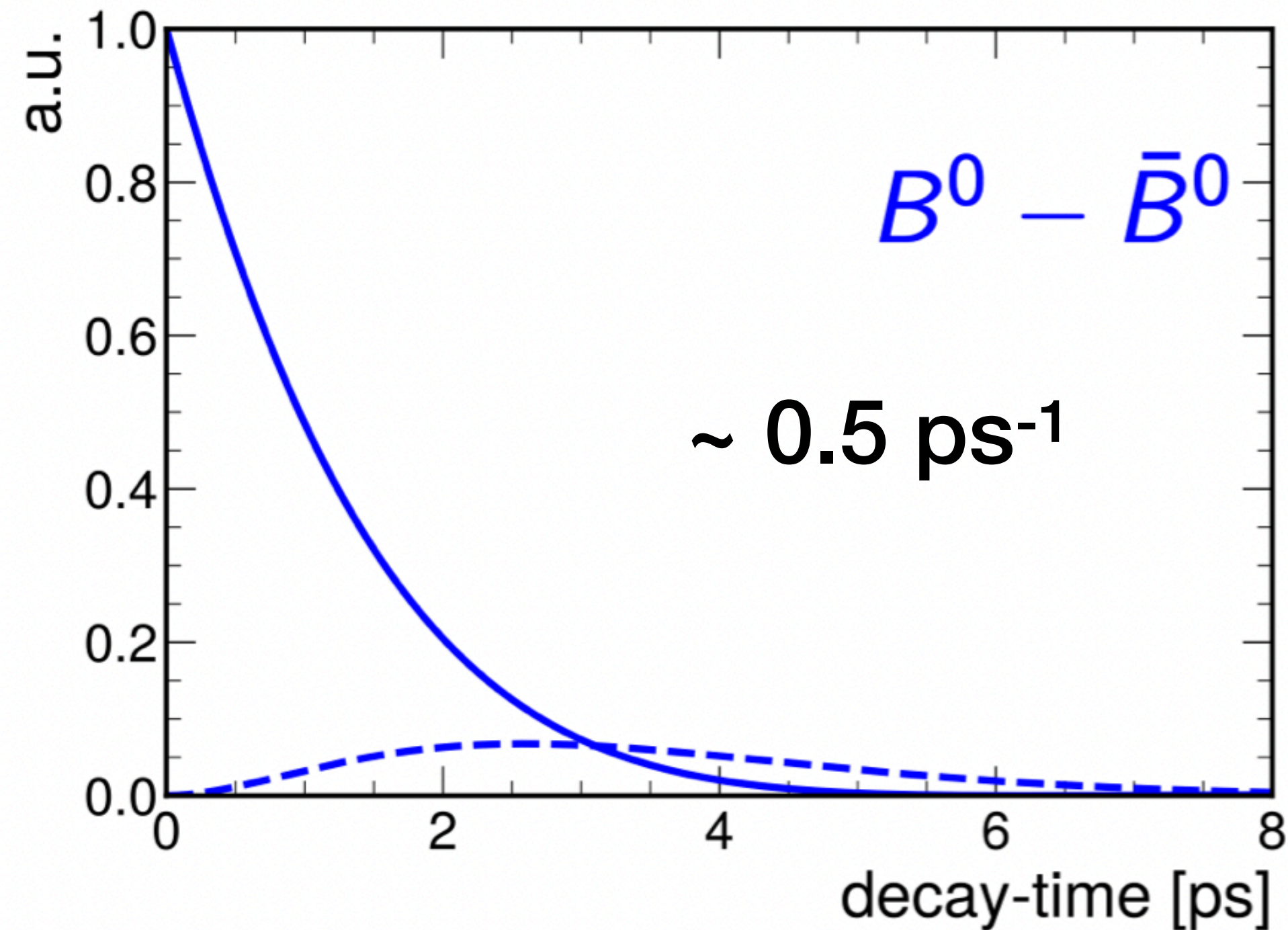


Trigger wise dilepton decays
are a day at the beach

Combination of a few decay channels



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

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 =

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

$$|B_L\rangle \propto p |\bar{B}_q'\rangle - q |B_q'\rangle$$

The time evolution =

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

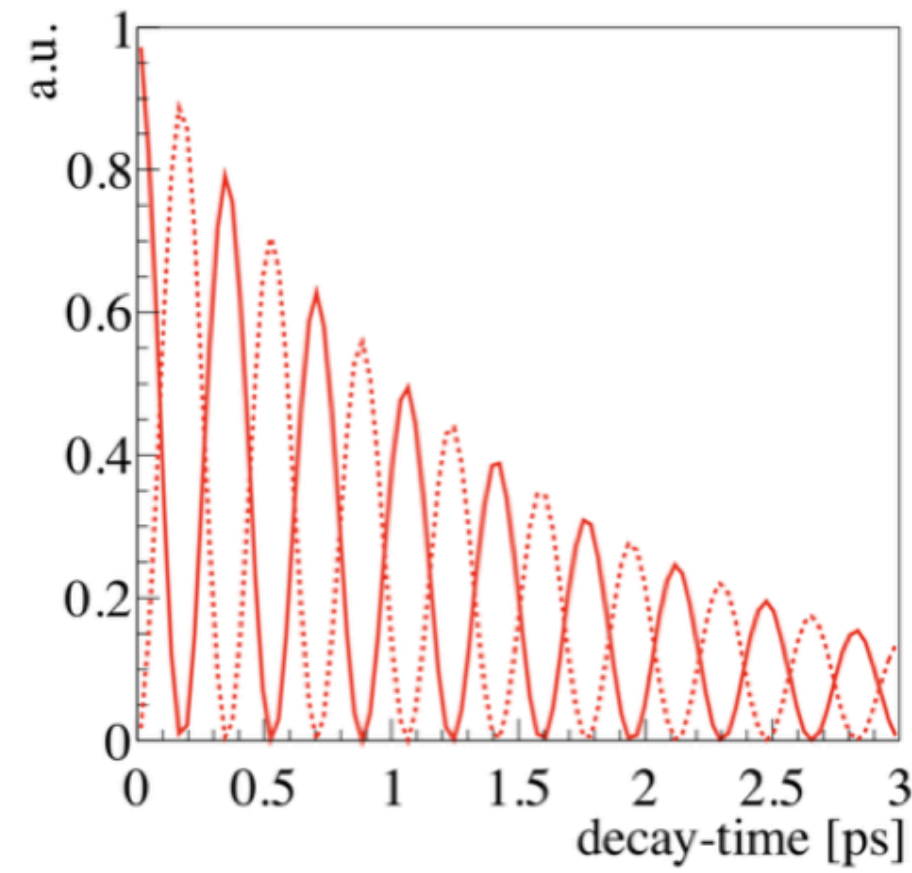
$$m_q = \frac{m_H + m_L}{2}, \quad \Gamma_q = \frac{\Gamma_L + \Gamma_H}{2} = \frac{1}{2}$$

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

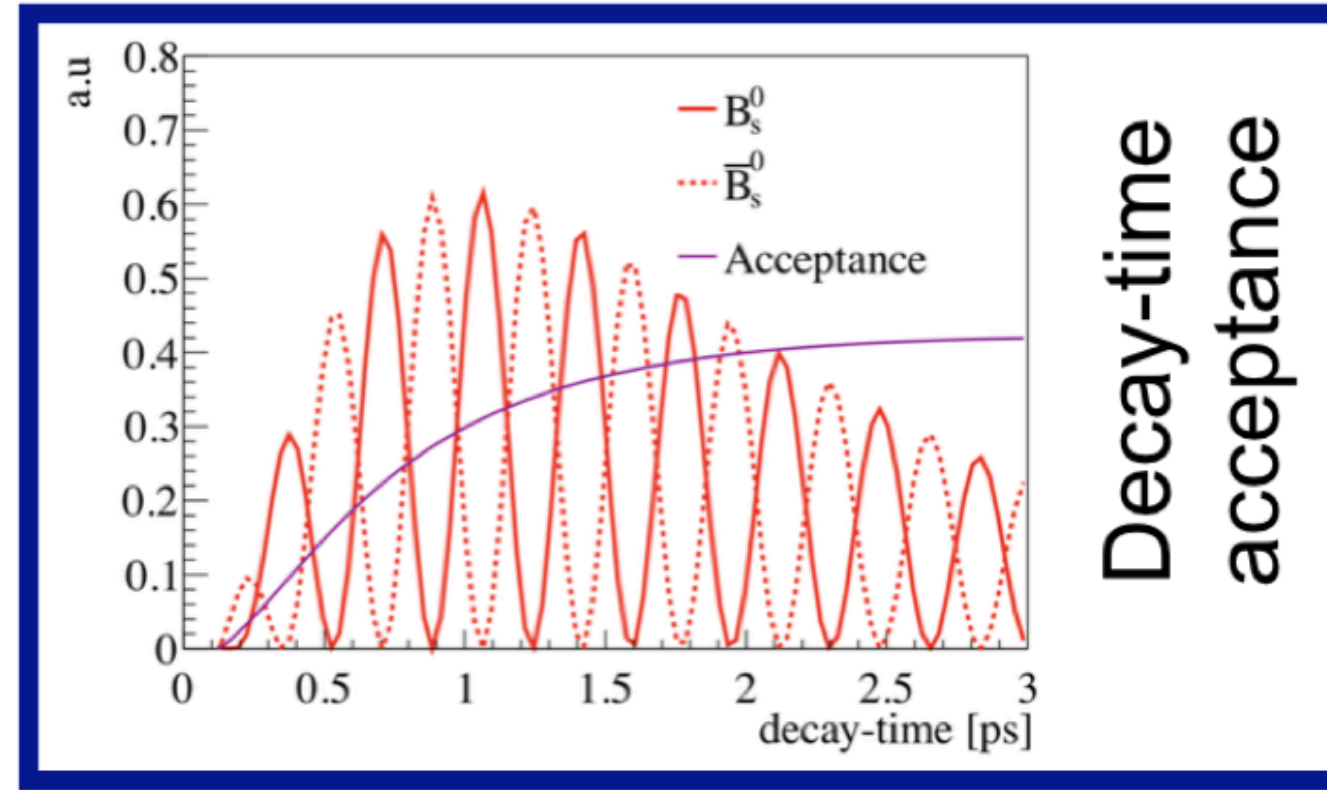
CERN-THESIS-2014-361 a very pedagogical reference.

Detector effects

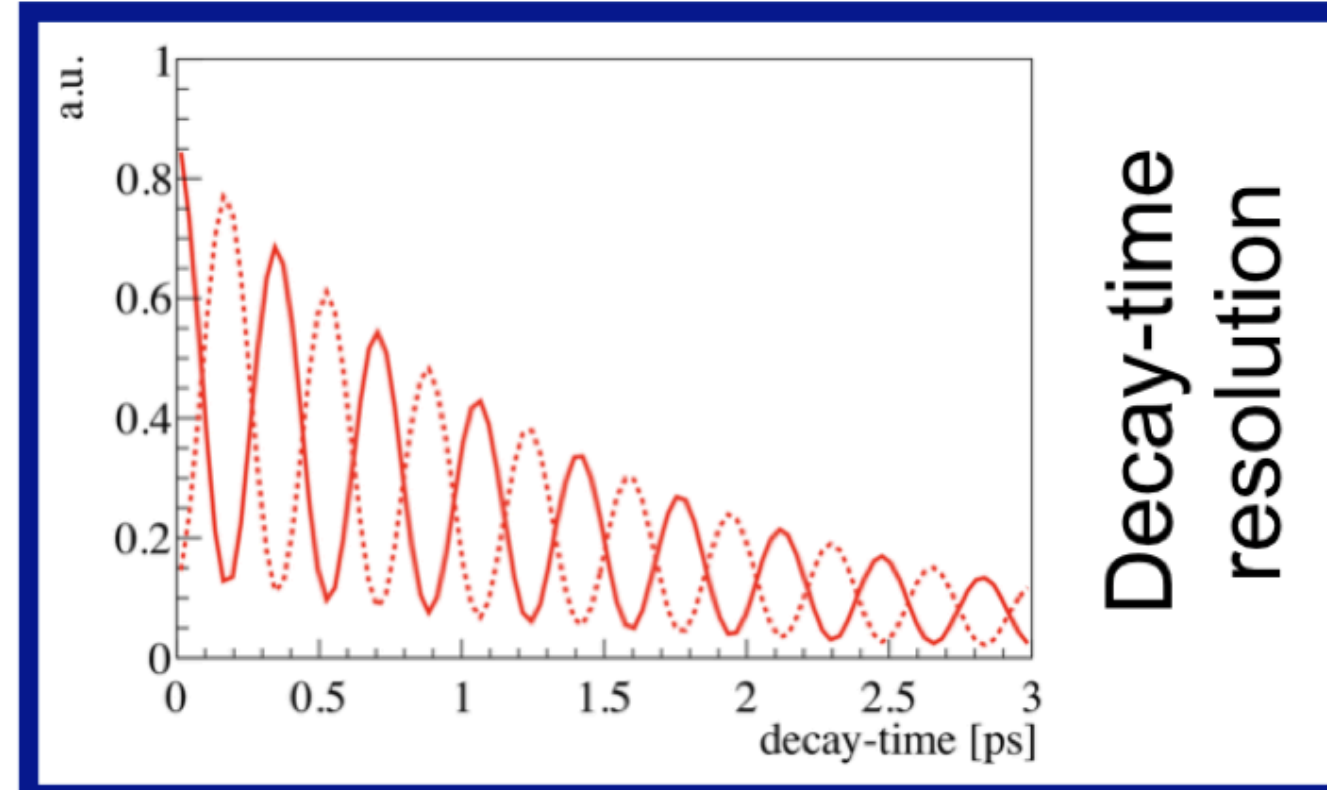
Perfect



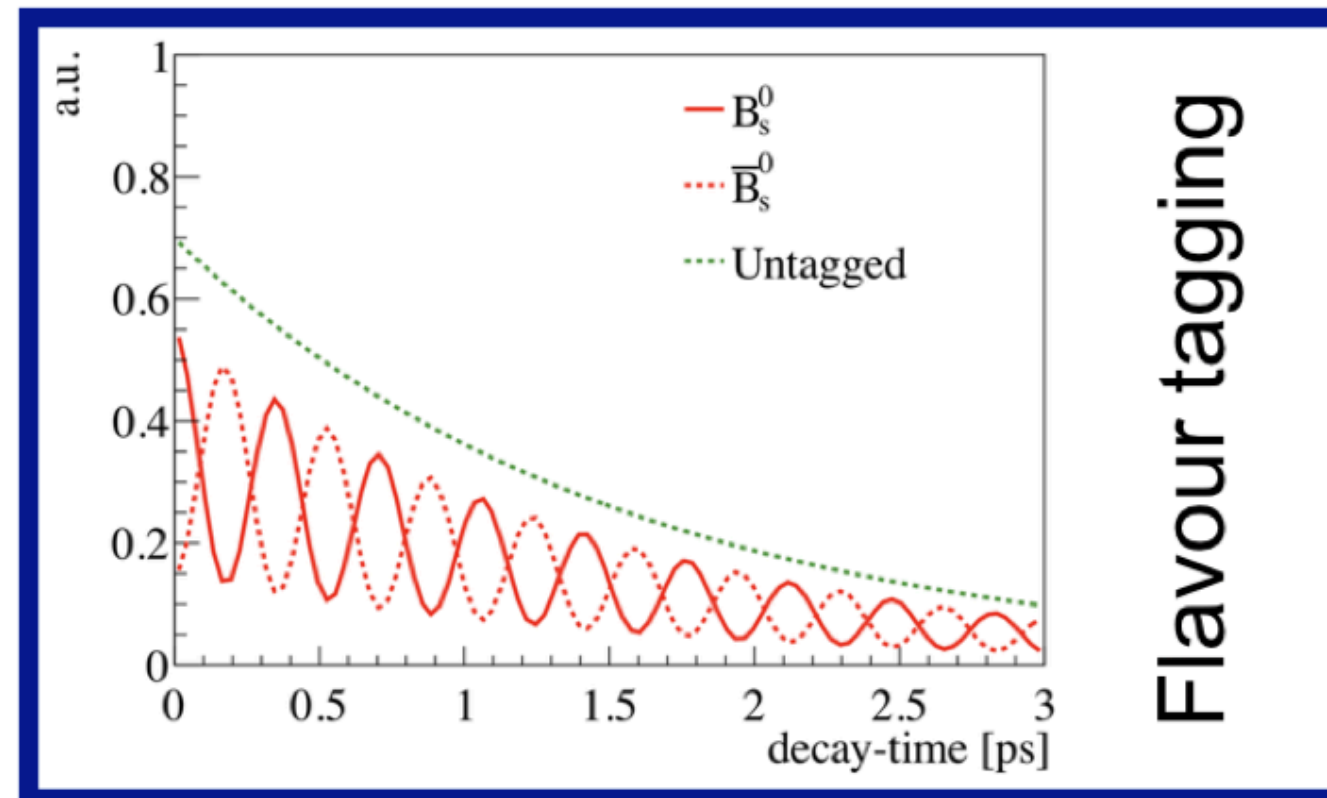
$$P(t) \sim e^{-\Gamma_s t} \left(\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) \pm \cos(\Delta m_s t) \right)$$



Decay-time acceptance

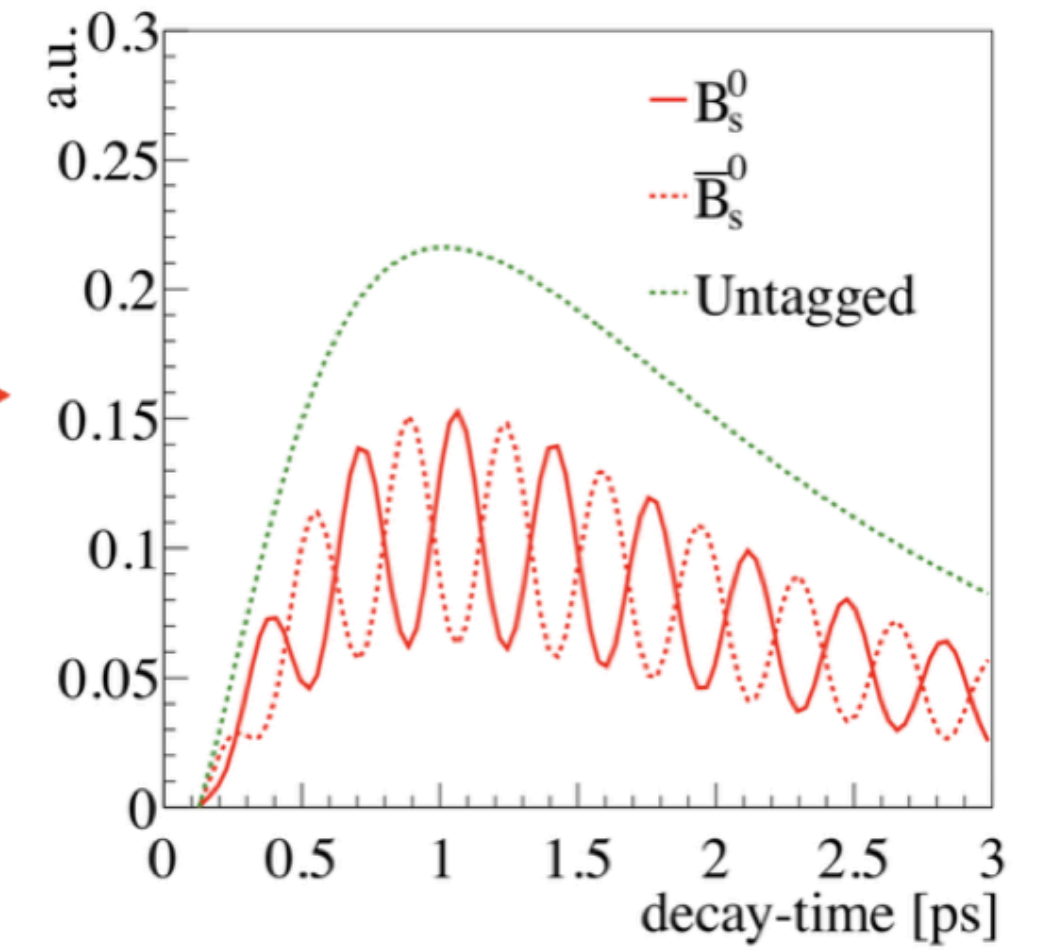


Decay-time resolution



Flavour tagging

Data



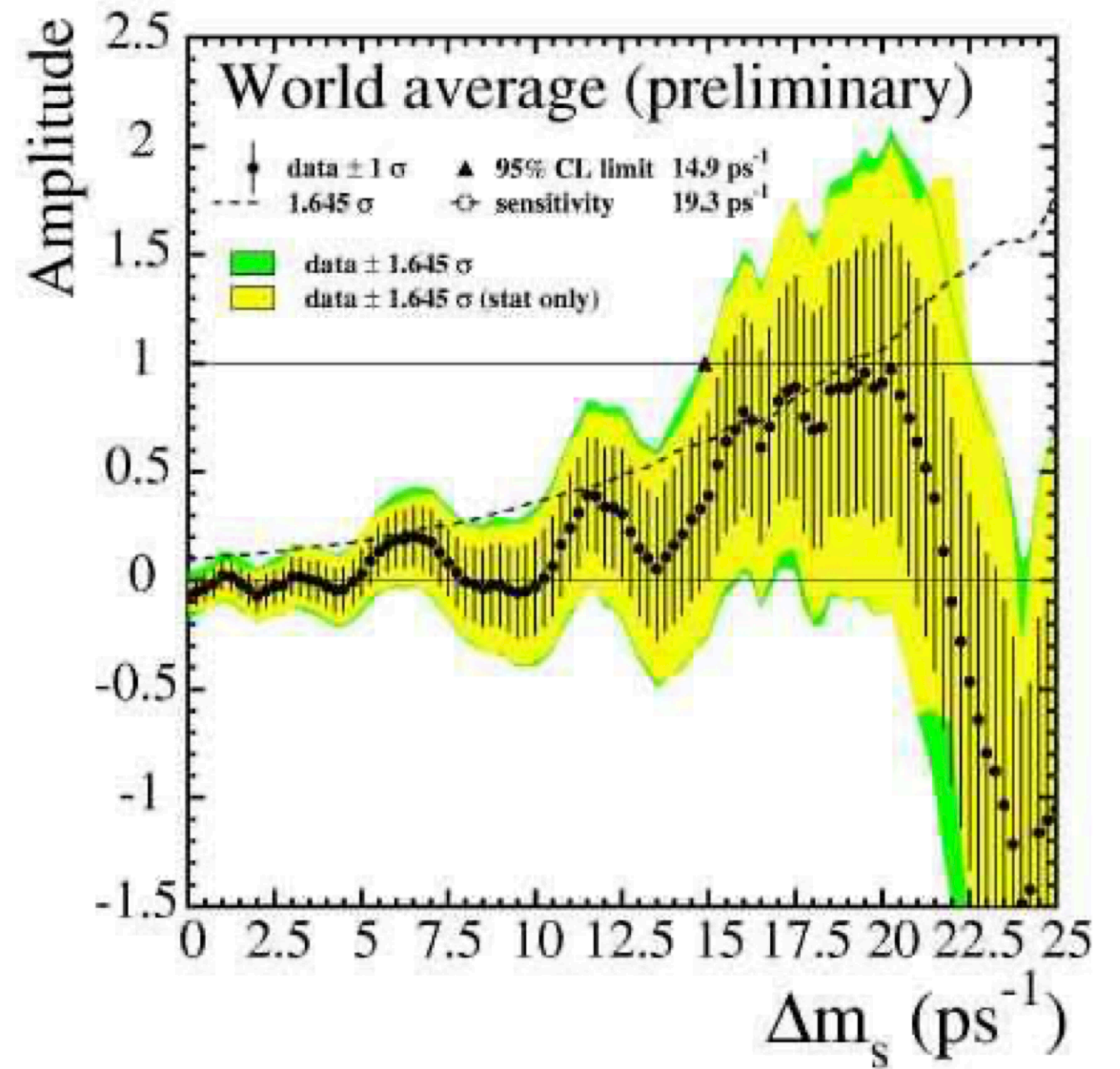
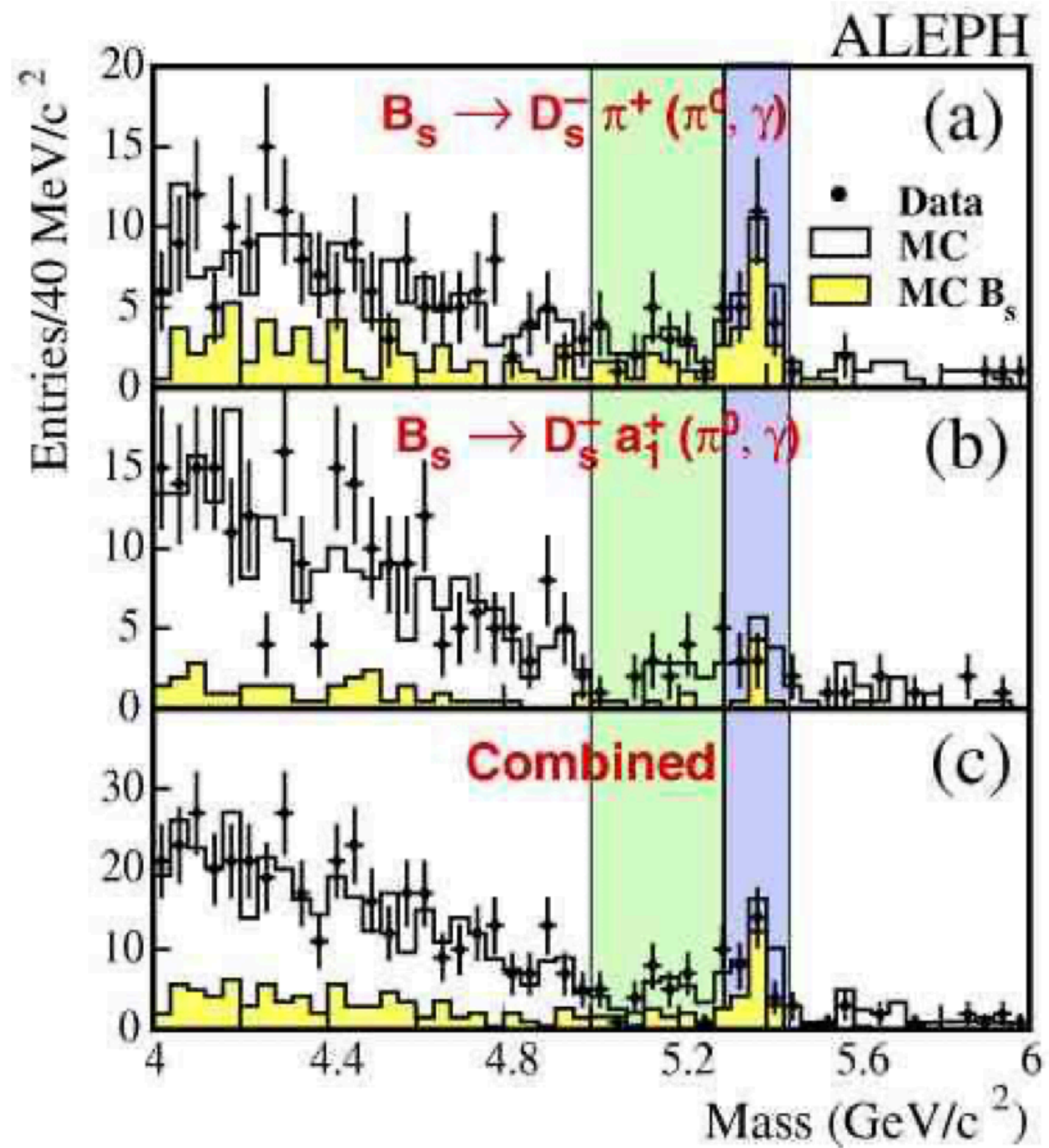
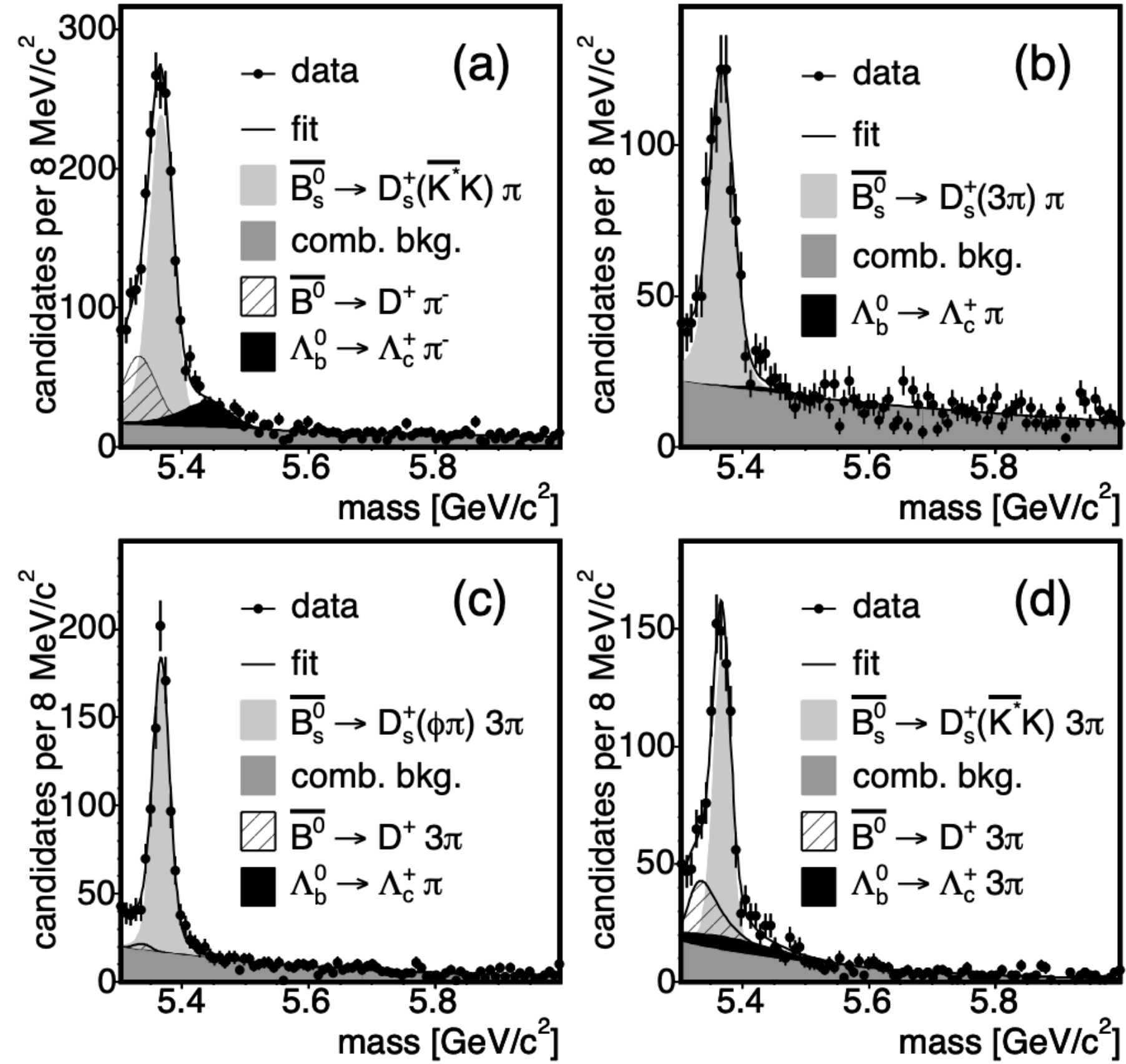


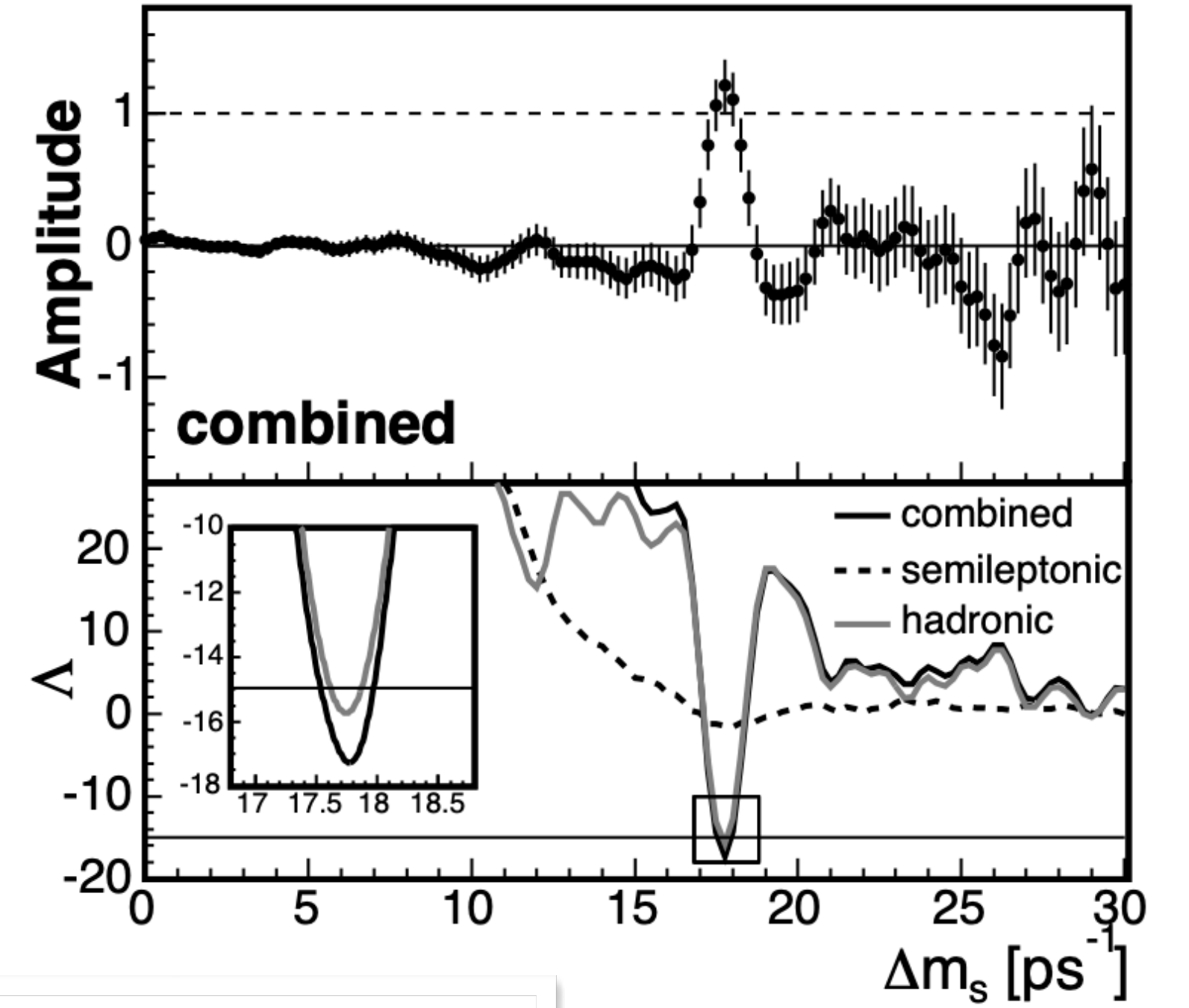
Figure 7: The combined B_s^0 oscillation results from ALEPH, CDF, DELPHI, OPAL, and SLD shown as amplitude versus hypothesized Δm_s [11]. The dots with error bars show the fitted amplitude values and uncertainties. An observed (expected) 95% C.L. lower limit on Δm_s of 14.9 ps⁻¹ (19.3 ps⁻¹) is obtained.

arXiv:0209007

My personal end of the universe at the time



- (a) $\bar{B}_S^0 \rightarrow D_S^+(\bar{K}^* K) \pi$
- (b) $\bar{B}_S^0 \rightarrow D_S^+(3\pi) \pi$
- (c) $\bar{B}_S^0 \rightarrow D_S^+(\phi\pi) 3\pi$
- (d) $\bar{B}_S^0 \rightarrow D_S^+(\bar{K}^* K) 3\pi$
- (e) $\bar{B}_S^0 \rightarrow D_S^+(3\pi) 3\pi$

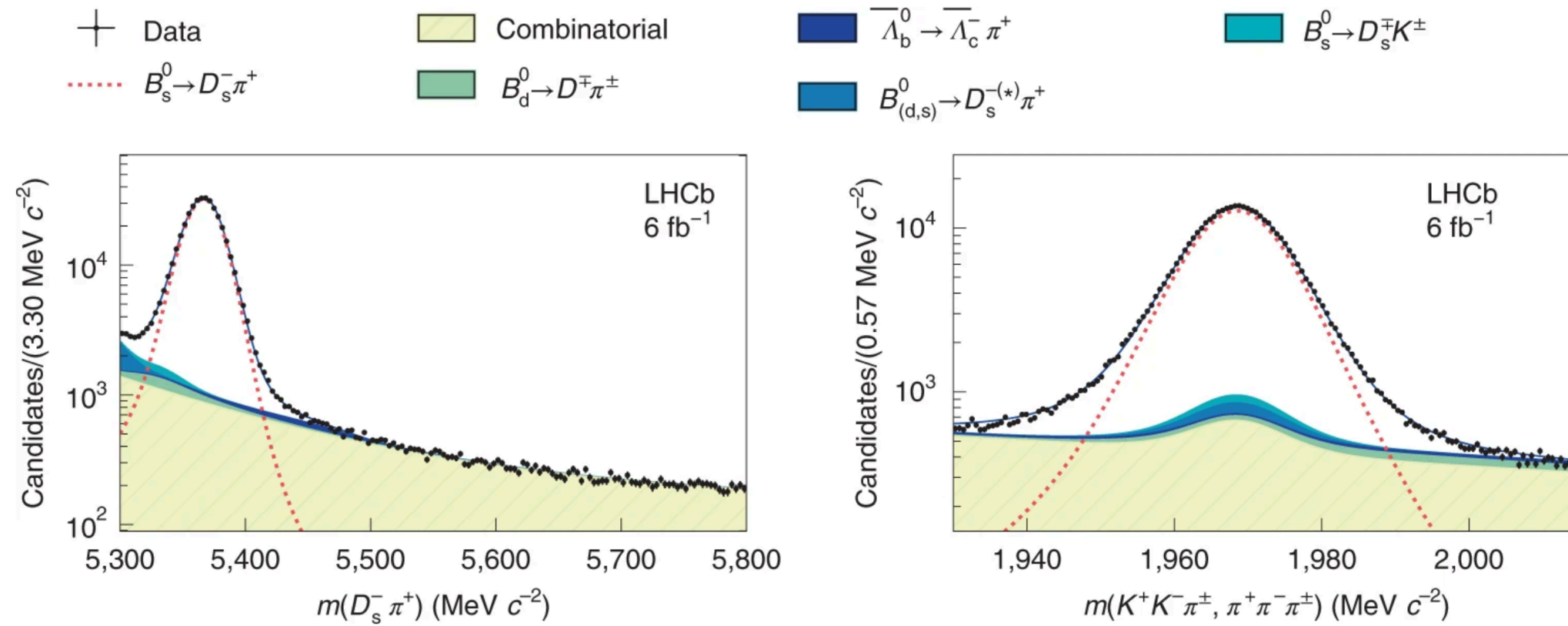


Observation of B_S^0 - \bar{B}_S^0 Oscillations

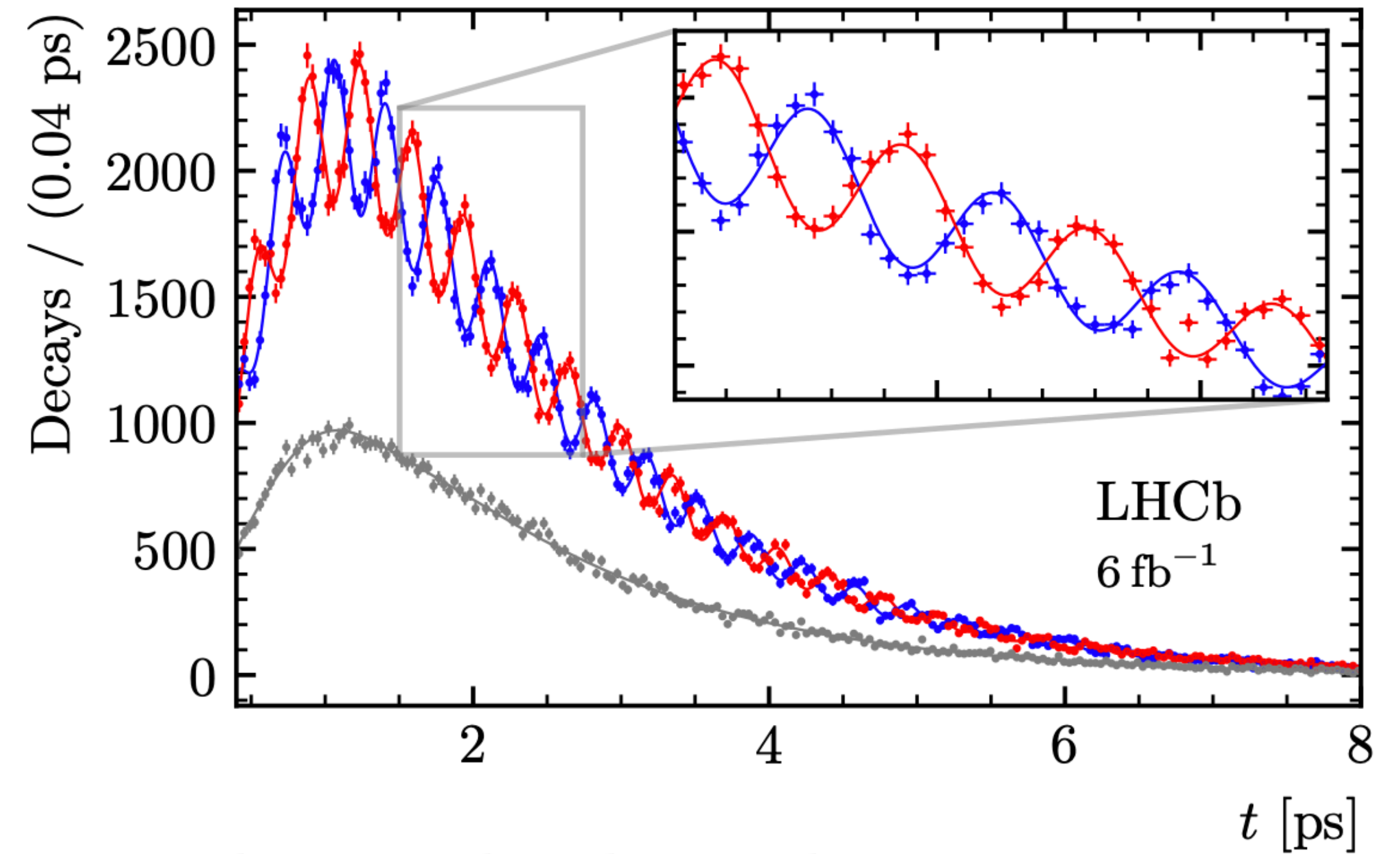
A. Abulencia,²³ J. Adelstein,¹³ T. Affolder,¹⁰ T. Akimoto,⁵⁰ M.G. Albrow,¹⁶ D. Ambrose,¹⁶ S. Amerio,⁴³ D. Amidei,³⁴ A. Anastassov,⁵² K. Anikeev,¹⁶ A. Annovi,¹⁸ J. Antos,¹ M. Aoki,⁵³ G. Apollinari,¹⁶ J.-F. Arguin,³³ T. Arisawa,⁵⁷ A. Artikov,¹⁴ W. Ashmanskas,¹⁶ A. Attal,⁸ F. Azfar,⁴² P. Azzi-Bacchetta,⁴³ P. Azzurri,⁴⁶ N. Bacchetta,⁴³ W. Badgett,¹⁶ A. Barbaro-Galtieri,²⁸ V.E. Barnes,⁴⁸ B.A. Barnett,²⁴ S. Baroiant,⁷ V. Bartsch,³⁰ G. Bauer,⁵⁰ F. Bedeschi,⁴⁶ S. Behari,²⁴ S. Bellocchi,⁵⁴ G. Bellotti,⁴⁶ J. Bellinger,⁵⁰ A. Belloni,⁵² D. Benjamin,¹⁶ A. Bercvas,¹⁶ J. Beringer,²⁸ T. Berry,²⁹ A. Bhatti,⁵⁰ M. Binkley,⁴⁶ D. Biselli,⁴³ R.E. Blair,⁷ C. Blocker,⁵ B. Blumenfeld,²⁴ A. Bocci,¹⁵ A. Bodek,⁴⁹ V. Boesvert,⁴⁹ G. Bolla,⁴⁸ A. Bolshov,³² D. Bortoletto,⁴⁸ J. Boudreau,⁴⁷ A. Boveia,¹⁰ B. Bran,¹⁰ L. Brigliadori,² C. Bromberg,³⁵ E. Brubaker,¹³ J. Budagov,¹⁴ H.S. Budd,⁴⁹ S. Budd,²³ S. Budroni,⁴⁶ K. Burkett,¹⁶ G. Busetto,⁴³ P. Bussey,²⁰ K. L. Byrum,² S. Cabrera,¹⁵ M. Campanelli,¹⁹ M. Campbell,³⁴ F. Canelli,¹⁶ A. Canepa,⁴⁸ S. Carrillo,¹⁷ D. Carlsmith,⁵⁰ R. Carosi,⁴⁶ S. Carron,³³ B. Casal,¹¹ M. Casarsa,⁵⁴ A. Castro,⁵ P. Catastini,⁴⁶ D. Cauz,⁵⁴ M. Cavalli-Sforza,³ A. Cerri,²⁸ L. Cerrito,³⁰ S.H. Chang,²⁷ Y.C. Chen,¹ M. Chertok,⁷ G. Chiarelli,⁴⁶ G. Chlachidze,¹⁴ F. Chlebana,¹⁶ I. Cho,²⁷ K. Cho,²⁷ D. Chokheli,¹⁴ J.P. Chou,²¹ G. Choudalakis,³² S.H. Chuang,⁵⁹ K. Chung,¹² W.H. Chung,⁵⁹ Y.S. Chung,⁴⁹ M. Cijlak,⁴⁶ C.I. Ciobanu,²³ M.A. Ciocci,⁴⁶ A. Clark,¹⁹ D. Clark,⁶ M. Coca,¹⁵ G. Compostella,⁴³ M.E. Convery,⁵⁰ J. Conway,⁷ B. Cooper,³⁵ K. Copie,³⁴ M. Cordelli,¹⁸ G. Cortiana,⁴³ F. Crescioli,⁴⁶ C. Cuenca Almenar,⁷ J. Cuevas,¹¹ R. Culbertson,¹⁶ J.C. Cully,³⁴ D. Cyr,³⁹ S. DaRonco,²¹ S. D'Auria,²⁰ T. Davies,²⁰ M. D'Onofrio,⁷ D. Dagenhart,⁴⁶ P. de Barbaro,⁴⁹ S. De Cecco,⁵¹ A. Delchev,²⁸ G. De Lentdeker,⁴⁹ M. Dell'Orso,⁴⁶ F. Delli Paoli,⁴³ L. Demortier,⁵⁰ J. Deng,¹⁵ M. Desimino,³ D. De Pedis,⁵¹ P.F. Derwent,¹⁶ G.P. Di Giovanni,¹⁴ C. Dionisi,⁵¹ B. Di Ruzza,⁵⁴ J.R. Dittmann,⁴ P. DiToro,³² C. Dörz,²⁵ S. Donati,⁴⁶ M. Donega,¹⁹ P. Dong,² J. Douini,⁴³ D. Dorigo,⁴³ S. Dube,⁵² J. Efron,³⁹ R. Erbacher,⁷ D. Errede,²³ S. Errede,²³ R. Eusebi,¹⁶ H.C. Fang,²⁸ S. Farrington,²⁹ I. Fedorko,⁴⁶ W.T. Fedorko,¹³ R.G. Feild,⁶⁰ M. Feindt,²⁵ J.P. Fernandez,³¹ R. Field,¹⁷ G. Flanagan,⁴⁸ A. Foland,²¹ S. Forrester,⁷ G.W. Foster,¹⁶ M. Franklin,¹⁰ J.C. Freeman,²⁸ H. J. Frisch,¹³ I. Furic,¹³ M. Gallinaro,⁵⁰ J. Galyardt,¹² J.E. Garcia,⁴⁶ F. Garbersson,¹⁰ A.F. Garfinkel,⁴⁸ C. Gay,⁶⁰ H. Gerberich,²³ D. Gerdes,³⁴ S. Giagu,⁵¹ P. Giannetti,⁴⁶ A. Gibson,²⁸ K. Gibson,⁴⁷ J.L. Gimmell,⁴⁹ C. Ginsburg,¹⁶ N. Giokaris,¹⁴ M. Giordani,⁵⁴ P. Giromini,¹⁸ M. Giunta,⁴⁶ G. Giurgiu,¹² V. Glagolev,¹⁴ D. Glezinski,¹⁶ M. Gold,³⁷ N. Goldschmidt,¹⁷ J. Goldstein,⁴² G. Gomez,¹¹ G. Gomez-Ceballos,¹¹ M. Goncharov,⁵³ O. González,³¹ I. Gorelov,³⁷ A.T. Goshaw,¹⁵ K. Goulianos,⁵⁰ A. Gressle,⁴³ M. Griffiths,²⁹ S. Grinstein,²¹ C. Grosso-Pilcher,¹³ R.C. Group,¹⁷ U. Grunler,²³ J. Guimaraes da Costa,²¹ Z. Gunay-Unalan,⁵⁰ C. Haber,³² K. Hahn,⁵⁰ S.R. Hahn,¹⁰ E. Halkiadakis,⁴² A. Hamilton,³³ B.-Y. Han,⁴⁹ J.Y. Han,⁴⁹ R. Handerl,⁵⁰ F. Happacher,¹⁸ K. Hara,⁵⁰ M. Hase,⁵⁶ S. Harper,⁴² R.F. Harr,¹⁸ R.M. Harris,¹⁶ M. Hartz,⁴⁷ K. Hatakeyama,³⁰ J. Hauser,⁸ A. Heijboer,²⁵ B. Heinemann,²⁹ J. Heinrich,²⁵ C. Henderson,³² M. Herndon,⁵⁹ J. Heuser,²⁵ D. Hidas,¹⁵ C.S. Hill,¹⁹ D. Hirschbuhl,²⁵ A. Hocker,¹⁶ A. Holloway,²¹ S. Hou,¹ M. Houlden,²⁹ S.-C. Hsu,⁹ B.T. Huffman,⁴² R.E. Hughes,³⁹ U. Husemann,⁴⁹ J. Huston,³⁵ J. Incandella,¹⁰ G. Introzzi,⁴⁶ M. Iori,⁵¹ Y. Ishizawa,⁵⁰ A. Ivanov,⁷ B. Iyutin,³² E. James,¹⁶ D. Jang,⁵² B. Jayatilaka,³⁴ D. Jeans,⁵¹ H. Jensen,¹⁶ E.J. Jeon,²⁷ S. Jindariani,¹⁷ M. Jones,⁴⁸ K.K. Joo,²⁷ S.Y. Jun,¹² J.E. Jung,²⁷ T.R. Junk,²³ T. Kamon,⁵³ P.E. Karchin,⁵⁸ Y. Kato,⁴¹ Y. Kemp,²⁵ R. Kephart,¹⁶ U. Kerzel,²⁵ V. Khotilovich,⁵³ B. Kilminster,²⁹ D.H. Kim,²⁷ H.S. Kim,²⁷ J.E. Kim,²⁷ M.J. Kim,¹² S.B. Kim,²⁷ S.H. Kim,⁵⁵ Y.K. Kim,¹³ N. Kimura,⁵⁵ L. Kirsch,⁵ S. Klimentenko,¹⁷ M. Klute,³² B. Knuteson,³² B.R. Ko,¹⁵ K. Kondo,⁵⁷ D.J. Kong,²⁷ J. Konigsberg,¹⁷ A. Korytov,¹⁷ A.V. Kotwal,¹⁵ A. Kovalev,⁴⁵ A.C. Kraan,⁴⁵ J. Kraus,²³ I. Kravchenko,³² M. Kreps,²⁵ J. Kroll,⁴⁵ N. Krummacker,¹ M. Kruse,¹⁵ V. Krutelyov,¹⁰ T. Kubo,³⁵ S. E. Kuhlmann,² T. Kuhr,²⁵ Y. Kusaka,²¹ S. Kwang,⁵³ A.T. Laassanen,⁴⁸ S. Lai,⁵⁰ S. Lami,⁴⁸ S. Lammell,¹⁴ M. Lancaster,²⁹ R.L. Lander,⁷ K. Lannon,³⁹ A. Lath,⁵² G. Latino,⁴⁹ I. Lazzizzera,⁴³ T. LeCompte,² J. Lee,⁴⁹ J. Lee,²⁷ V.J. Lee,²⁷ S.W. Lee,⁵³ R. Lefevre,³ N. Leonard,³² S. Leone,⁴⁸ S. Levy,¹³ J.D. Lewis,¹⁴ C. Lin,⁶⁰ C.S. Lin,¹⁶ M. Lindgren,¹⁶ E. Lippe,⁹ T.M. Liss,²³ A. Lister,⁷ D.O. Litvinov,¹⁶ T. Liu,¹⁶ N.S. Lockyer,⁴² A. Logunov,³⁶ M. Loret,⁴³ P. Loverre,⁵¹ R.-S. Lu,¹ D. Lucchesi,³ P. Lujan,²⁸ P. Lukens,¹⁶ G. Lungu,¹⁷ L. Lyons,⁴² J. Lys,²⁸ R. Lysak,¹ E. Lytken,⁴⁸ P. Mack,²⁵ D. MacQueen,³³ R. Madrak,¹⁶ K. Maeshima,¹⁶ K. Makhoul,³² T. Maki,²² P. Maksimovic,²⁴ S. Malde,⁴² G. Manca,²⁹ F. Margaroli,¹⁶ R. Marginean,¹⁶ C. Marino,²⁰ C.P. Marino,²³ A. Martin,⁶⁰ M. Martin,²⁴ V. Martin,²⁰ M. Martinez,³ T. Maruyama,⁵⁵ P. Mastrandrea,⁵¹ T. Masubuchi,⁵⁵ H. Matsunaga,⁵⁰ M.E. Mattson,²⁸ R. Mazini,³³ P. Mazzanti,⁵ K.S. McFarland,⁴⁹ P. McIntyre,⁵³ R. McNulty,²⁹ A. Mehta,²⁹ P. Mehtala,²² S. Menzemer,¹¹ A. Menzione,⁴⁶ P. Merik,⁴⁸ C. Mesropian,⁵⁰ A. Messina,⁵¹ T. Miao,¹⁶ N. Miladinovic,⁶ J. Miles,³² R. Miller,³⁵ C. Mills,¹⁰ M. Milnik,²⁵ A. Mitra,¹ G. Mitselmakher,¹⁷ A. Miyamoto,²⁶ S. Moed,¹⁹ N. Moggi,⁵ B. Mohr,⁸

Finally...

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



— $B_s^0 \rightarrow D_s^- \pi^+$ — $\bar{B}_s^0 \rightarrow B_s^0 \rightarrow D_s^- \pi^+$ — Untagged



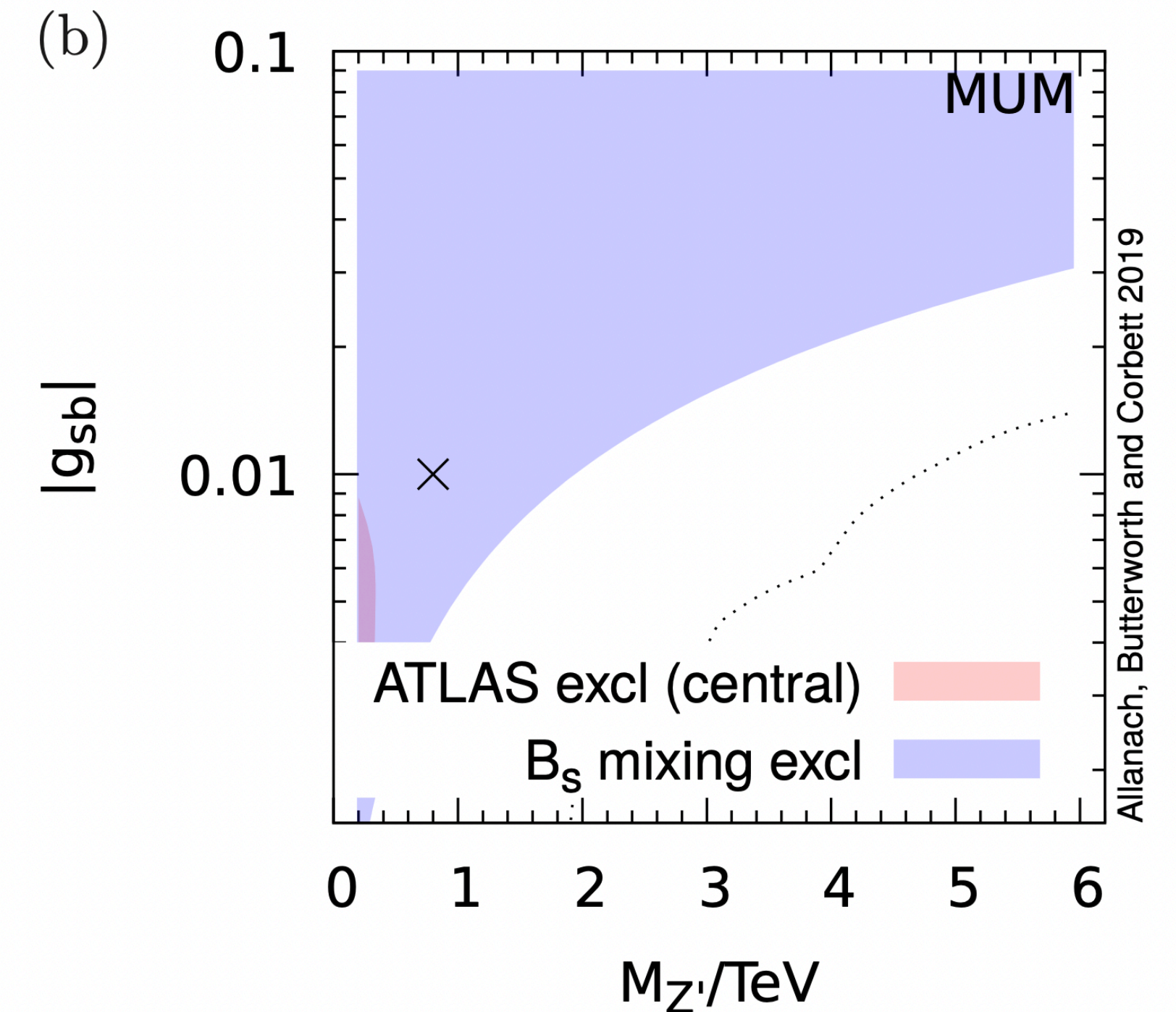
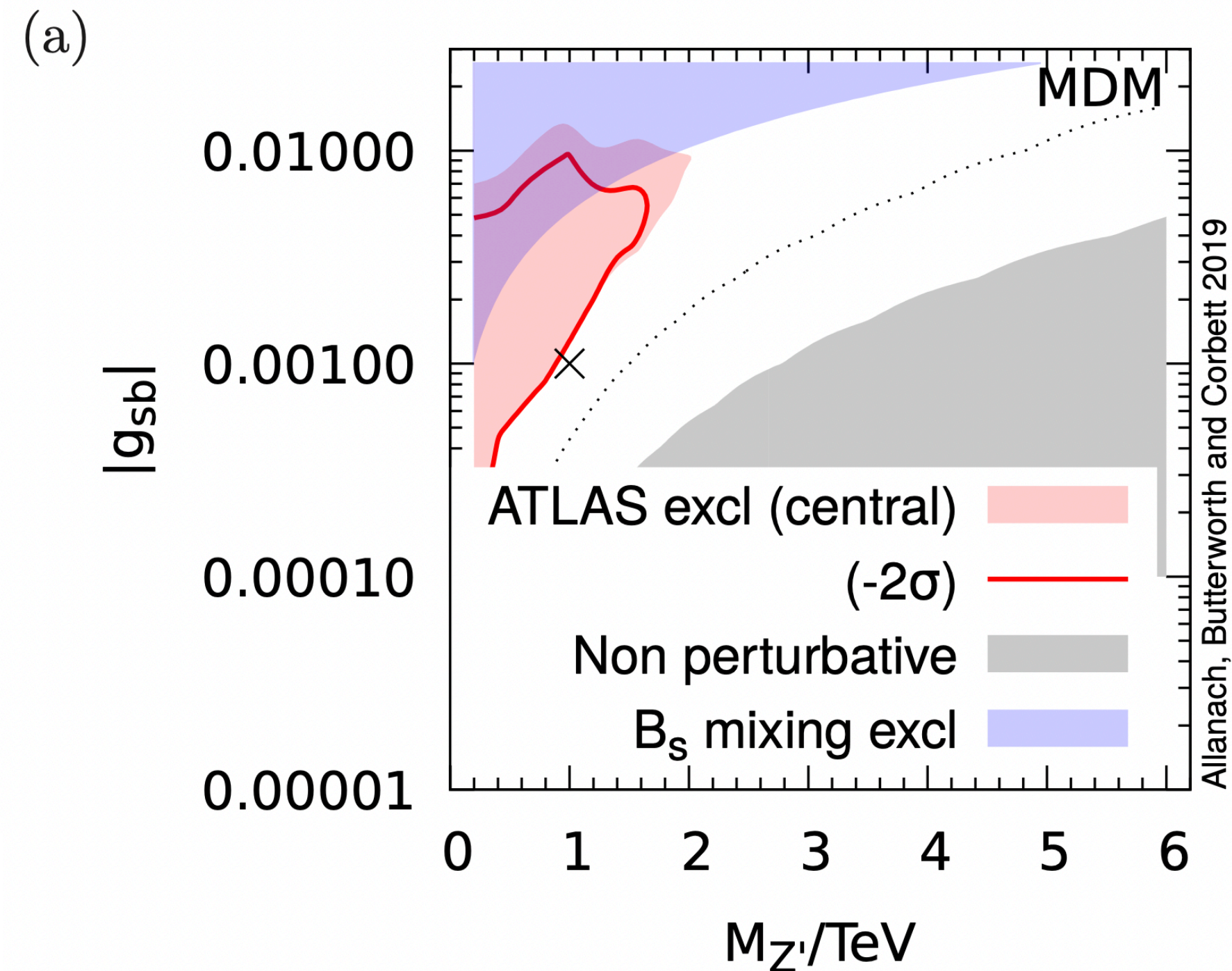
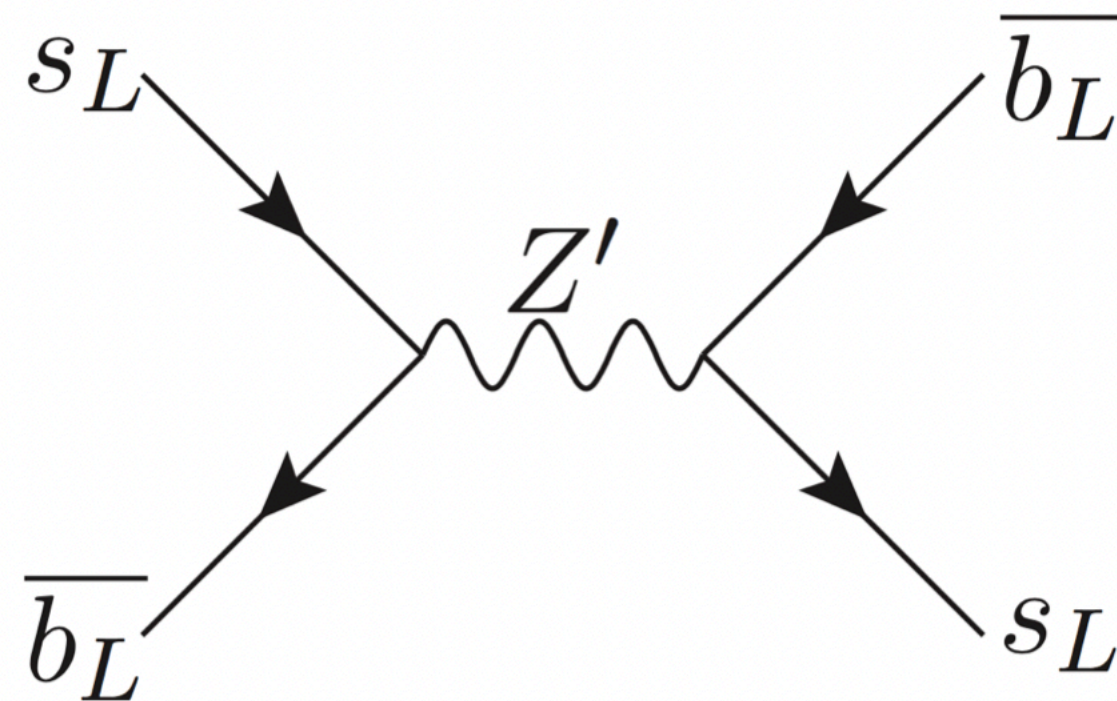
The value of the B_s^0 – \bar{B}_s^0 oscillation frequency determined in this article:

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

Loop back to the models

Standard
Model

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

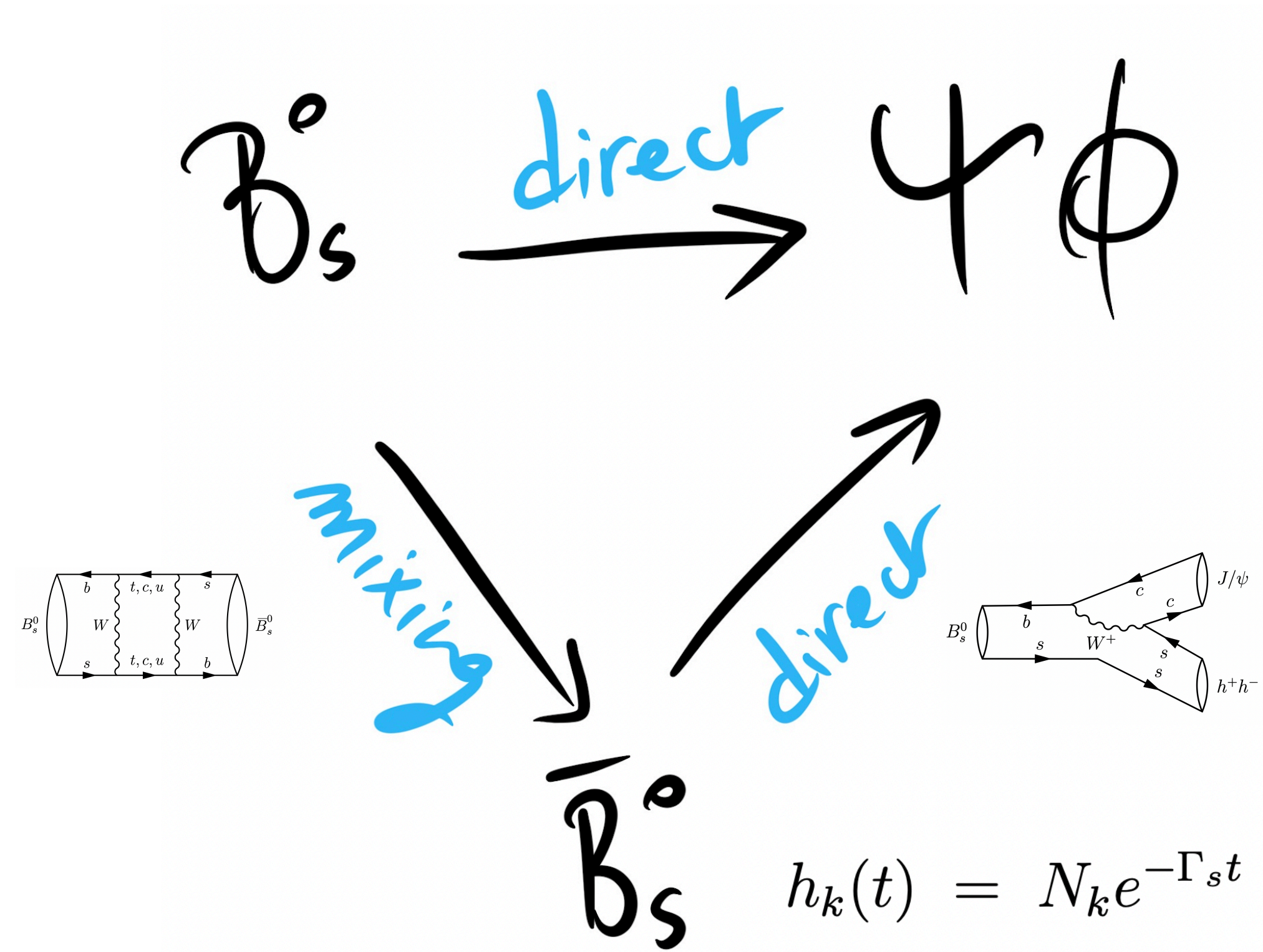


arXiv:1904.10954 one example out of the billion out there.

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

Mixture of CP odd and CP even eigenstates

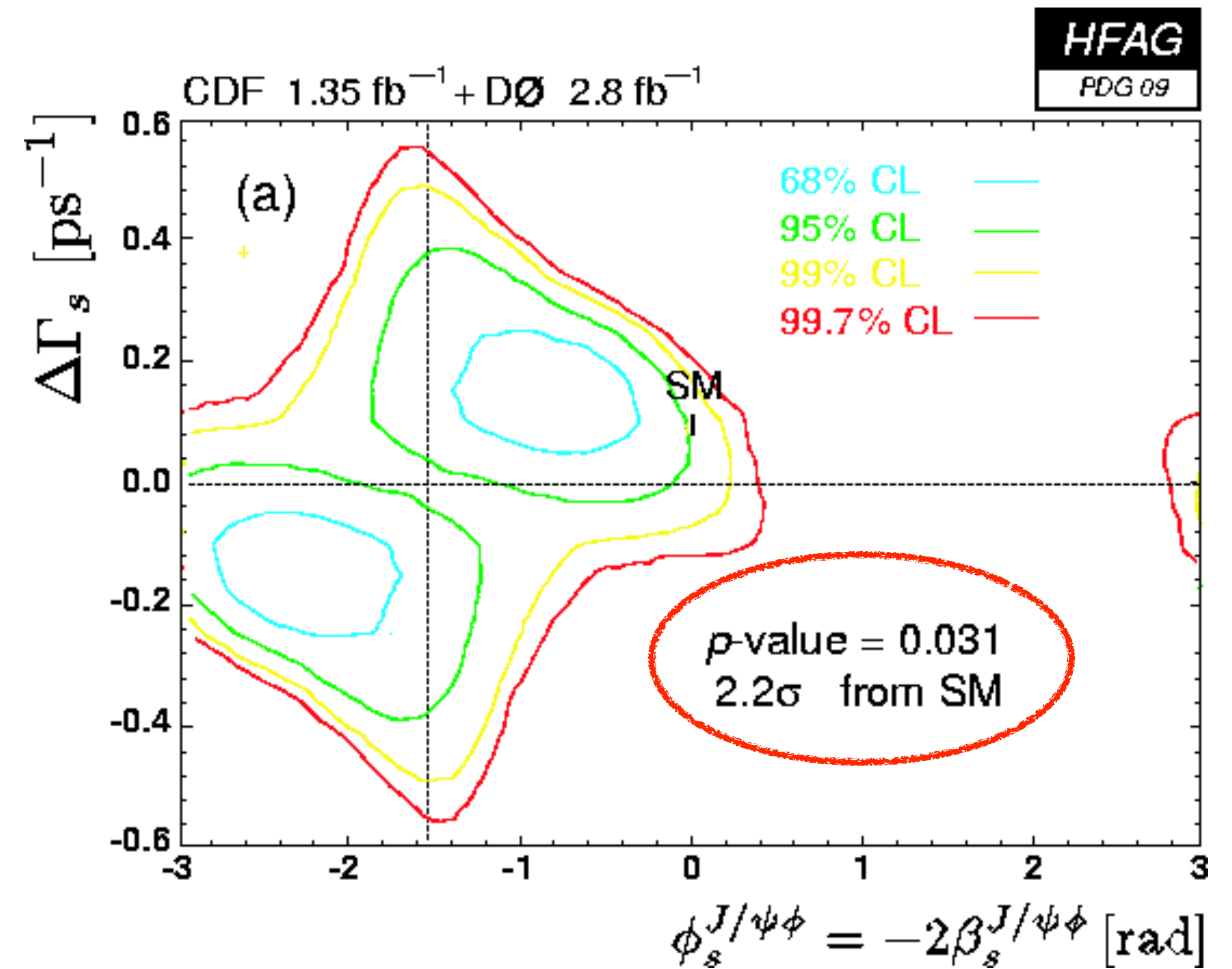
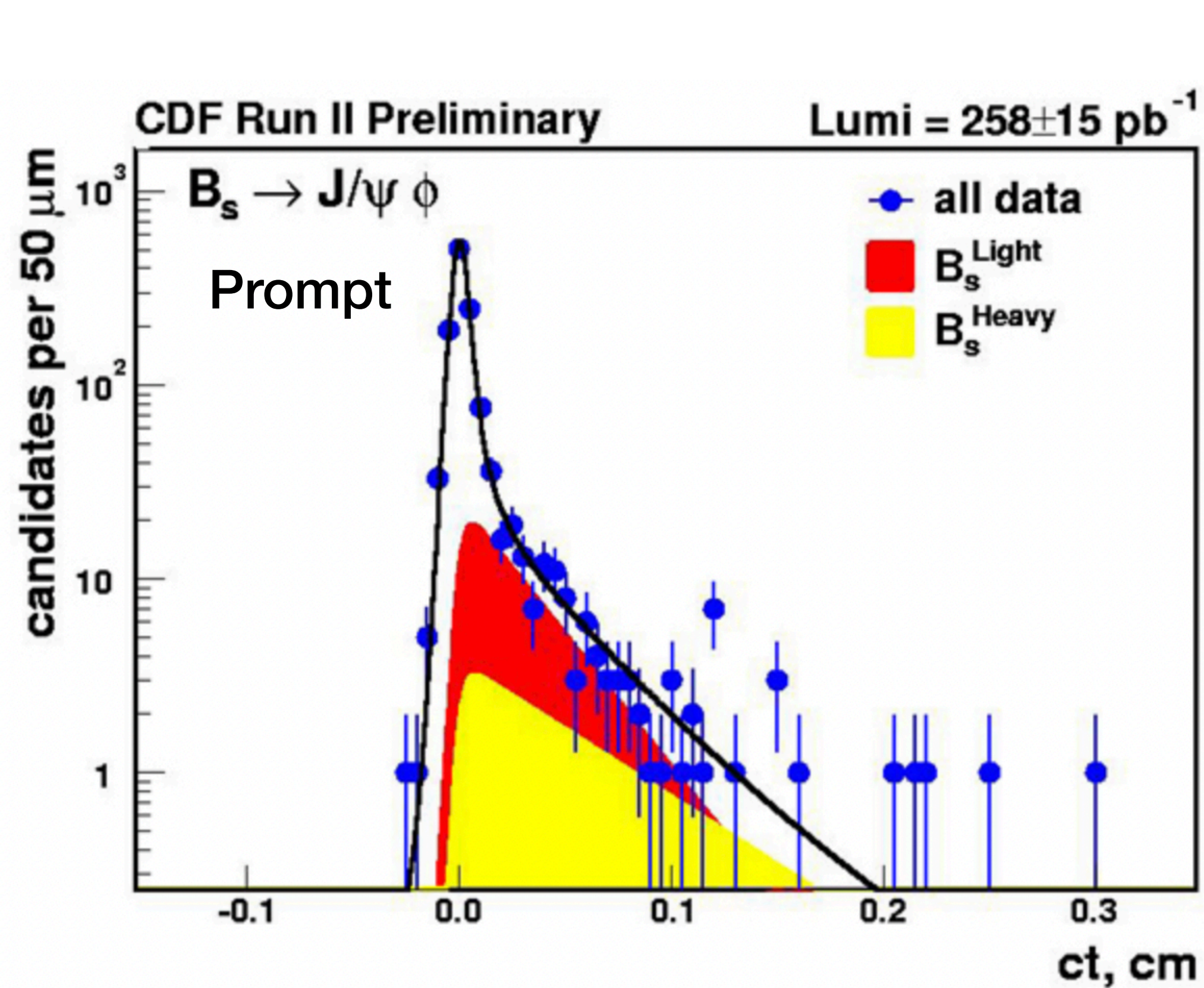
None negligible difference between the heavy and the light state of your the B_s^0 mesons $\Delta\Gamma_s$



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

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

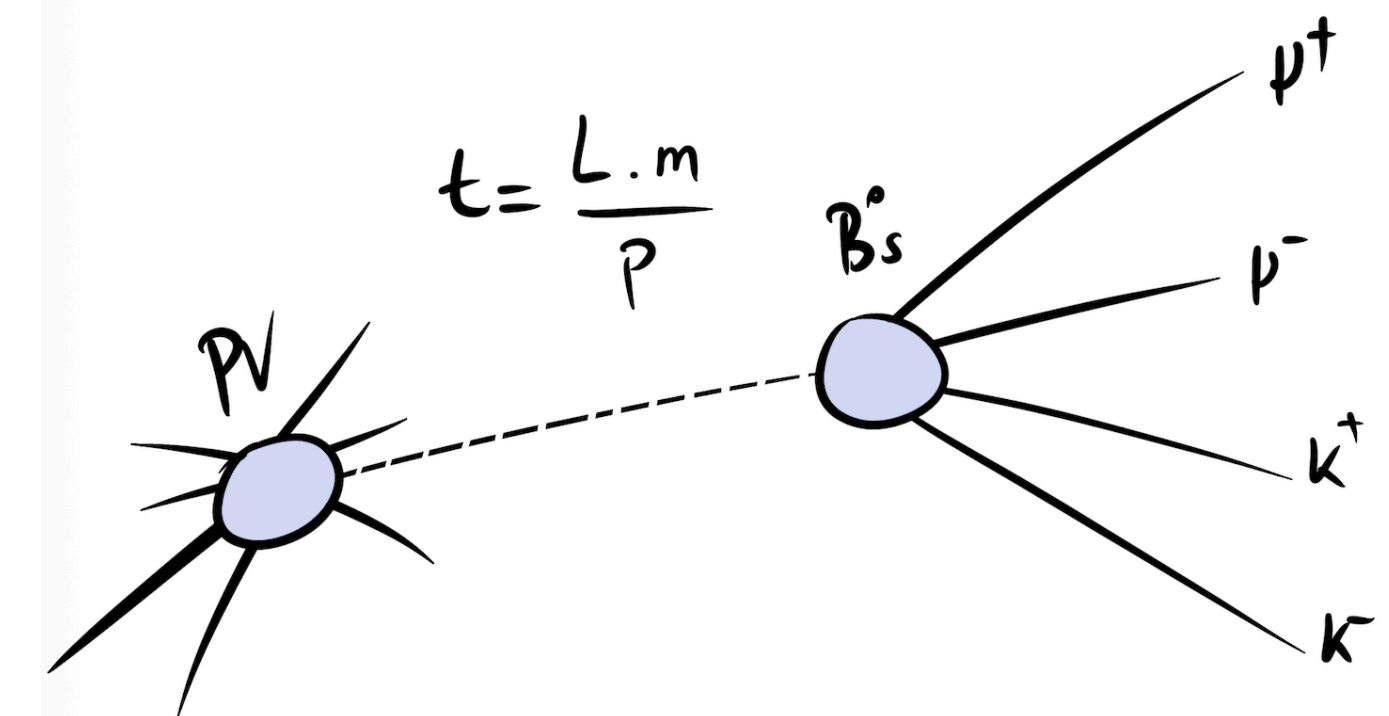
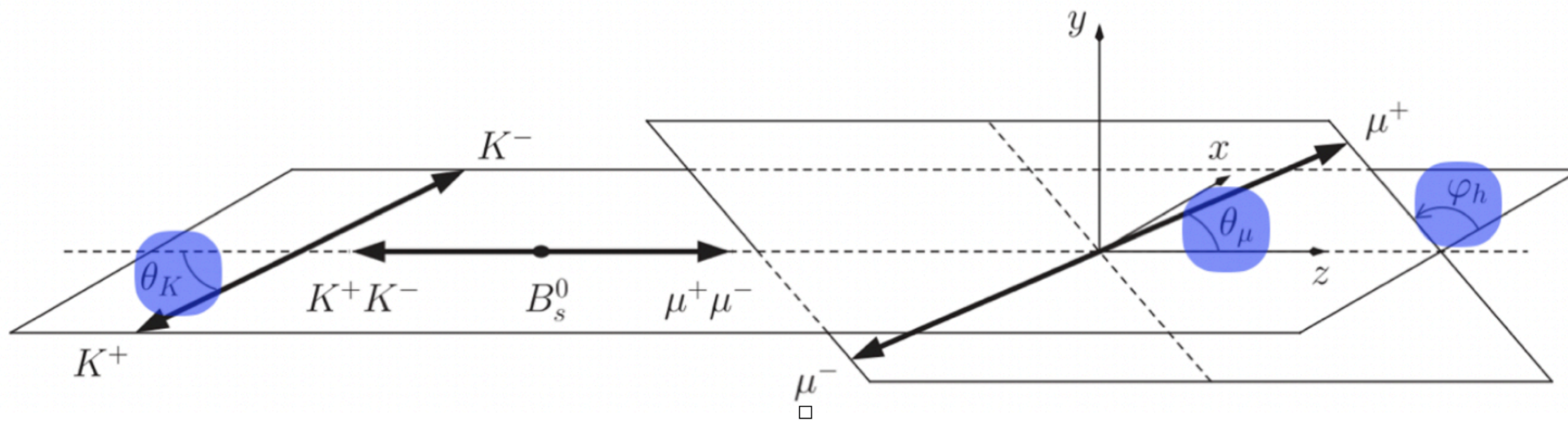
Fermilab paved the path of B_s^0 physics



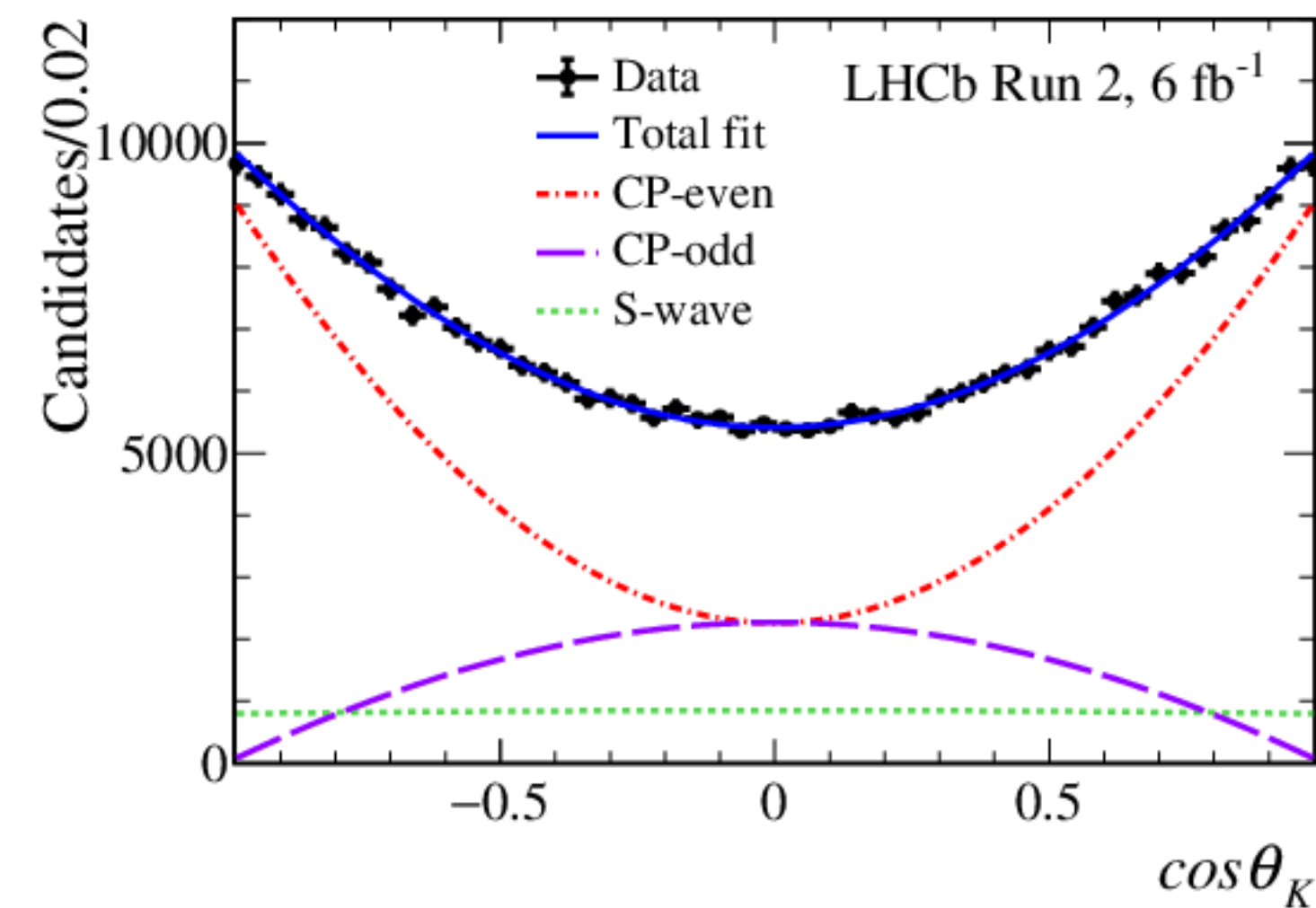
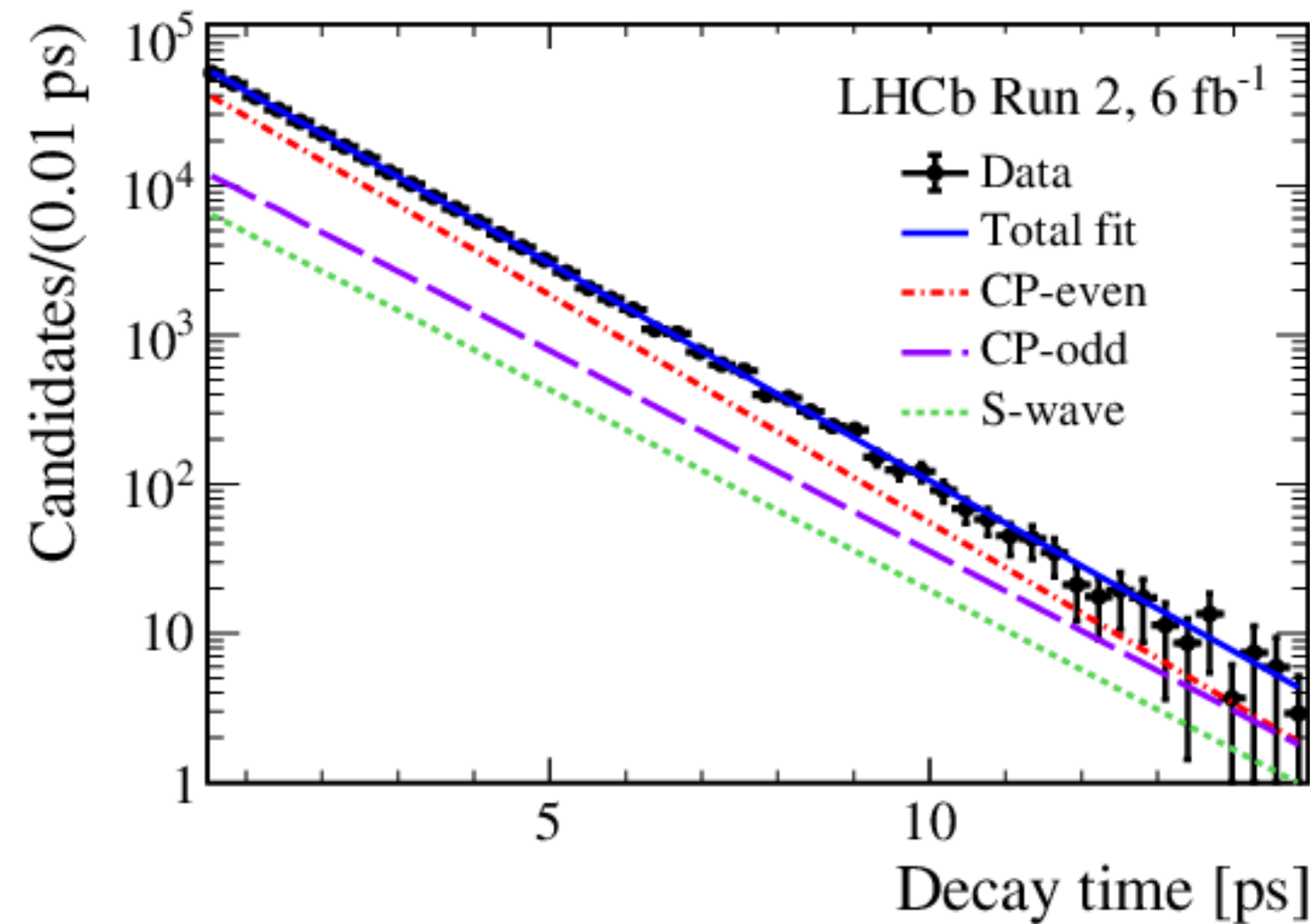
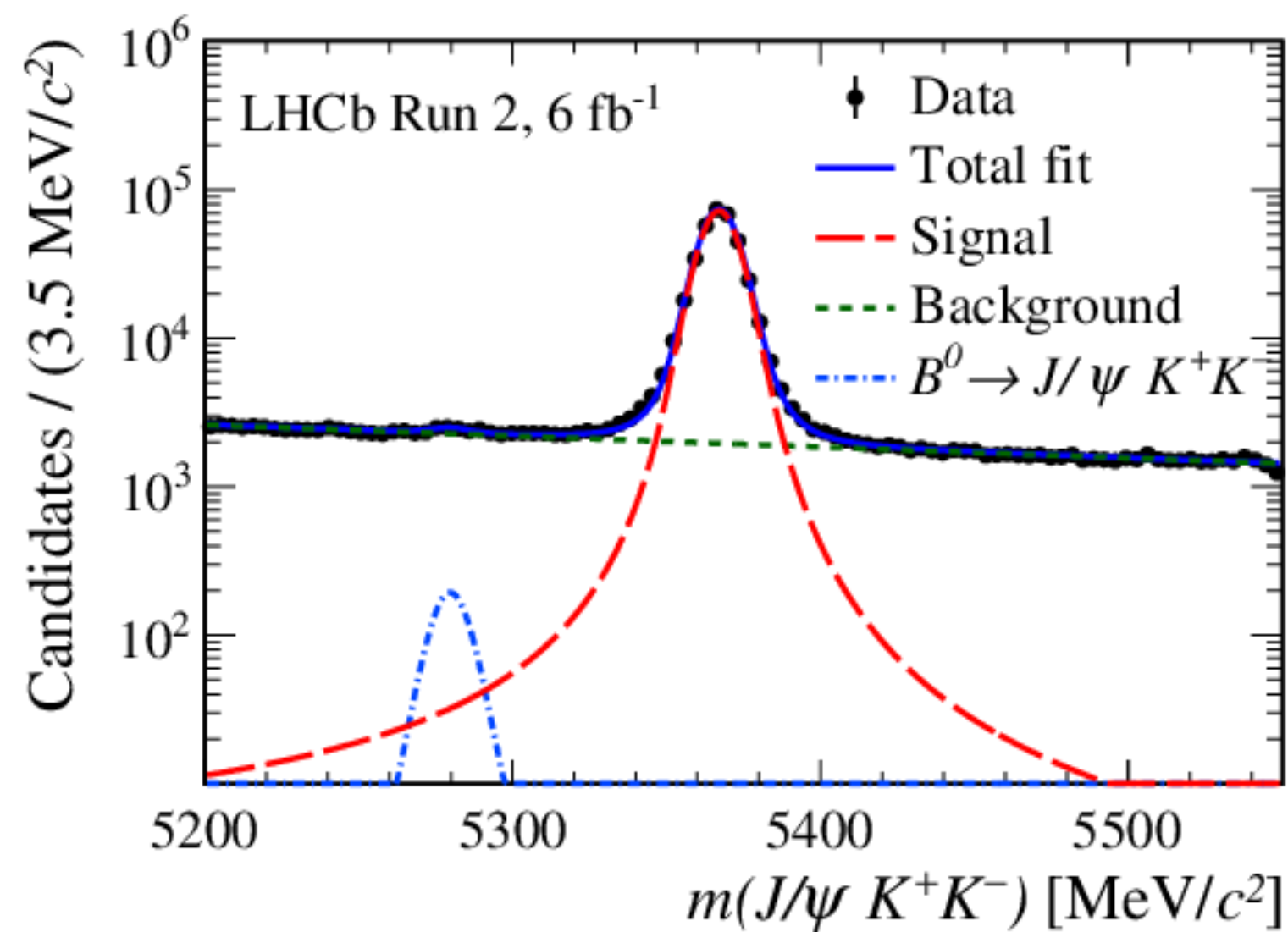
It's “just” yet another counting experiment

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

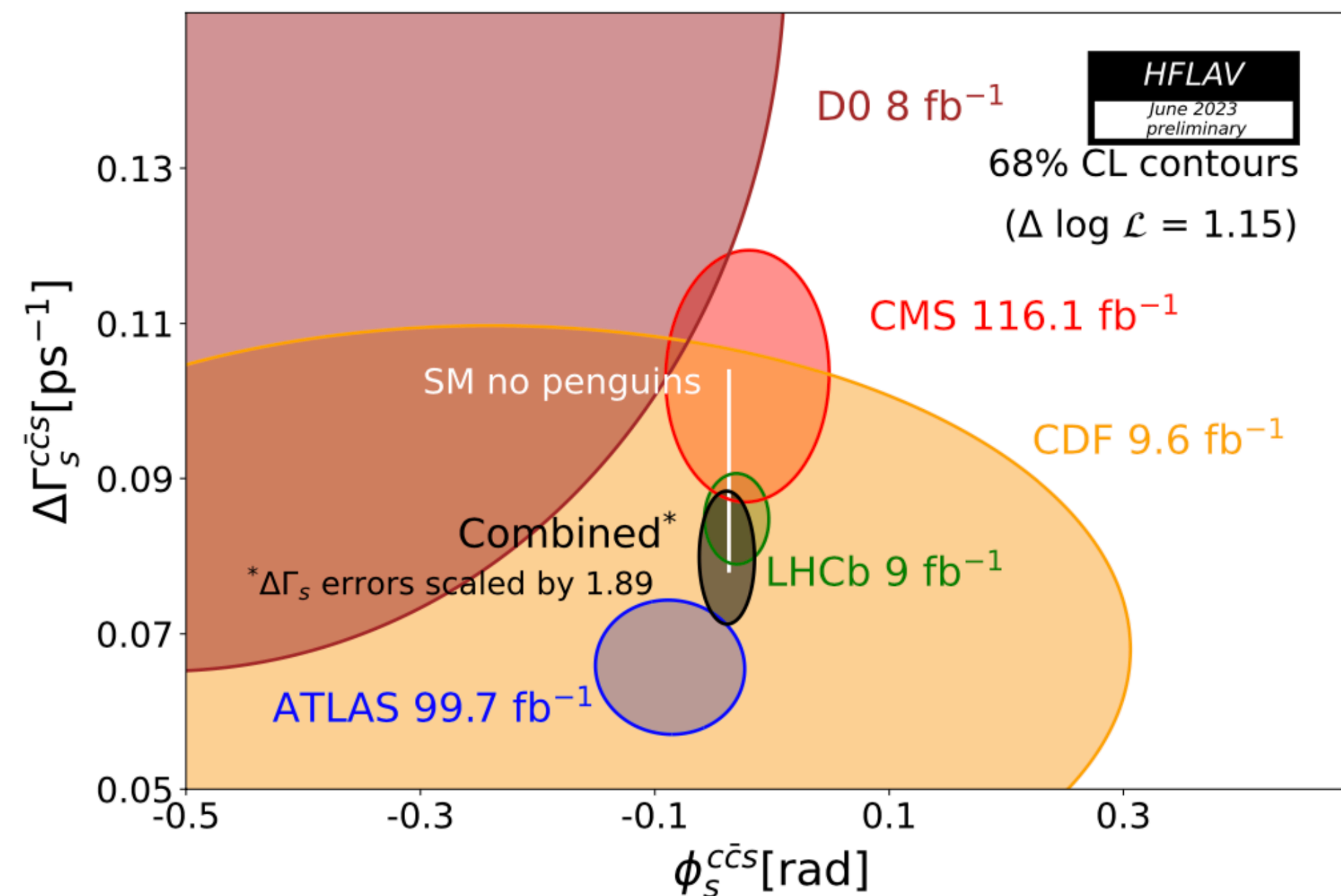
$\eta_f = (-1)^L$ CP eigenvalues of the final state



Mixture of CP odd and CP even requires an angular analysis

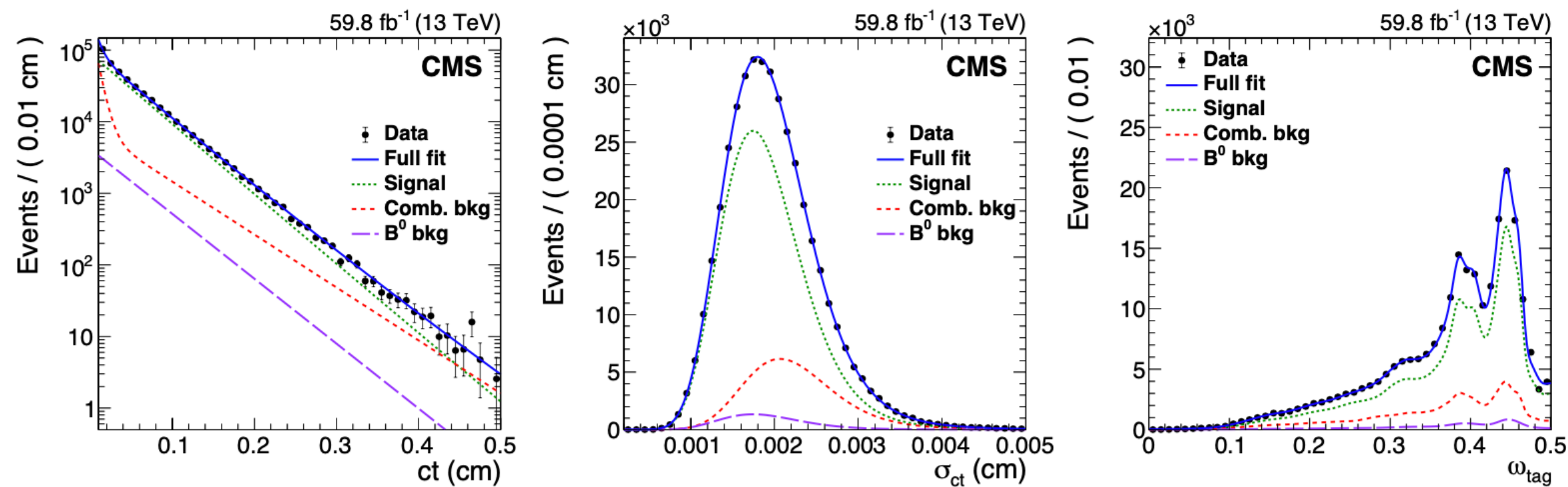


Very similar experimental techniques between the LHC three collaborations

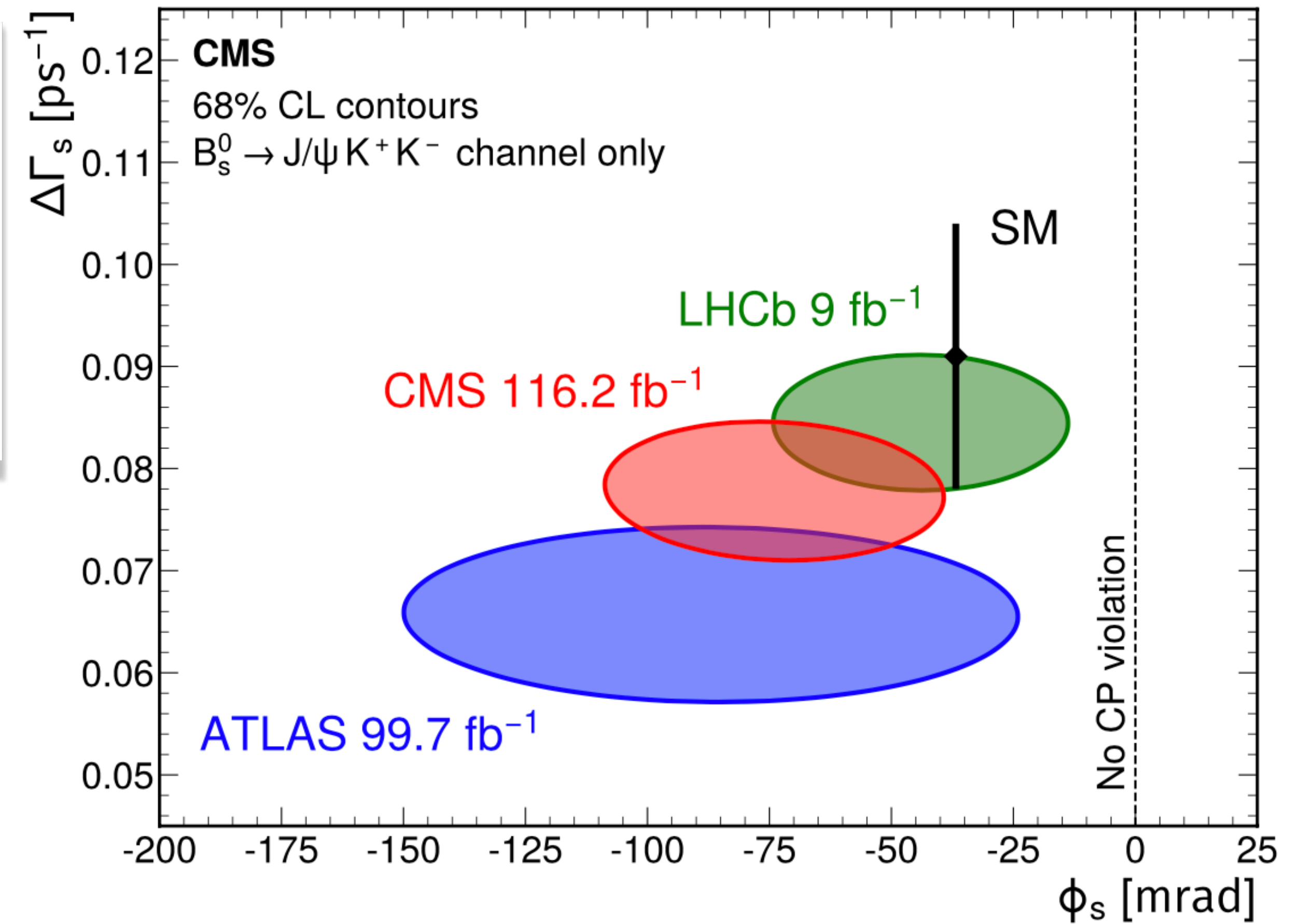


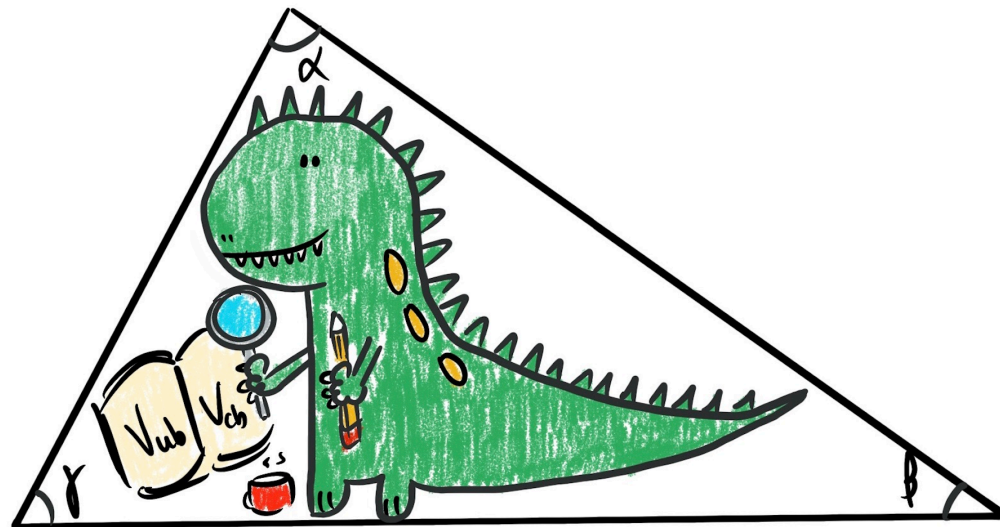
Evidence for CP violation and measurement of
 CP -violating parameters in $B_s^0 \rightarrow J/\psi \phi(1020)$ decays in pp
 collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*



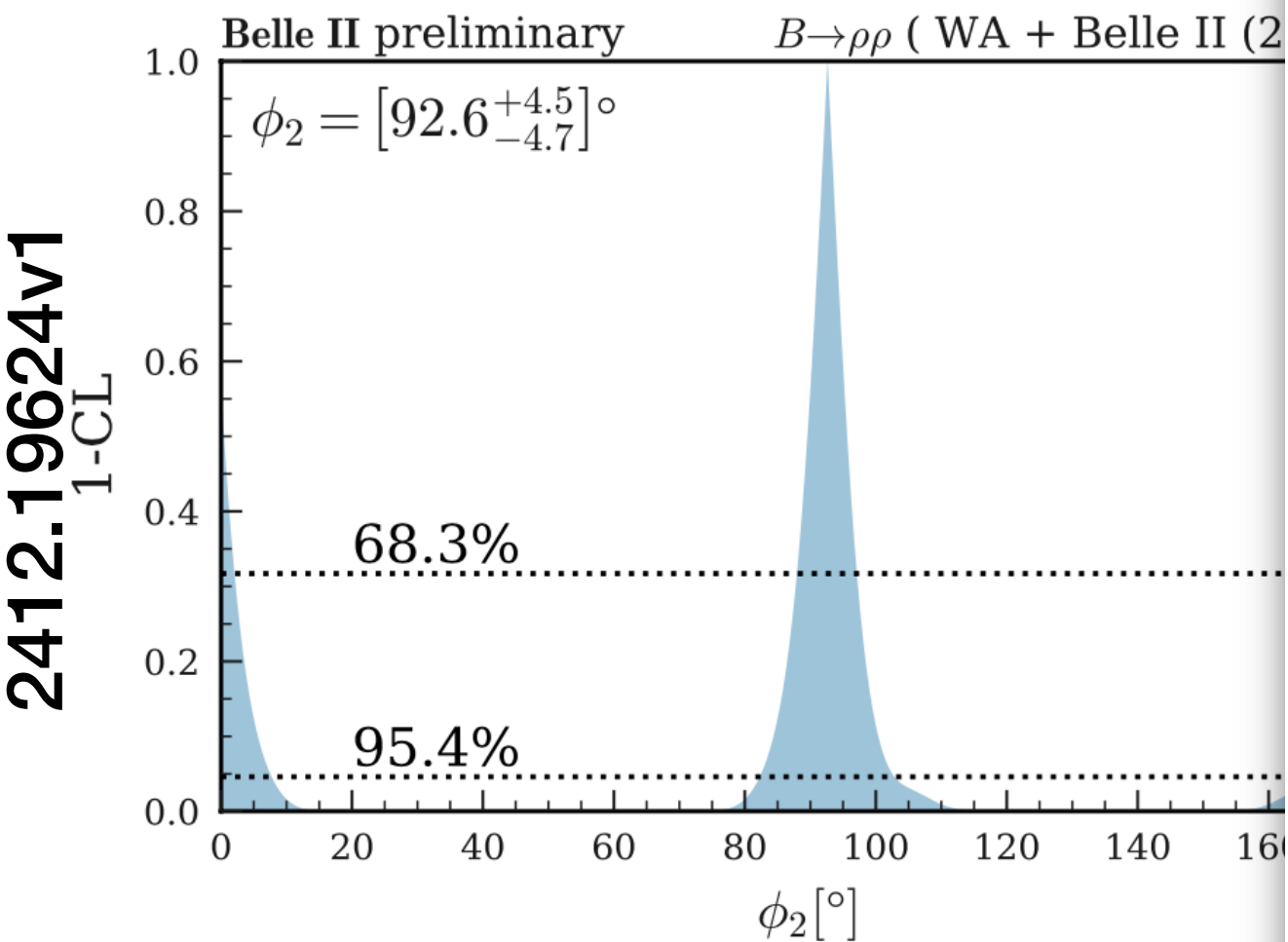
arXiv:2412.19952v1





All the phases...Today

Question to my theory colleagues:
While the overall picture is looking good 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...

[Details](#)

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

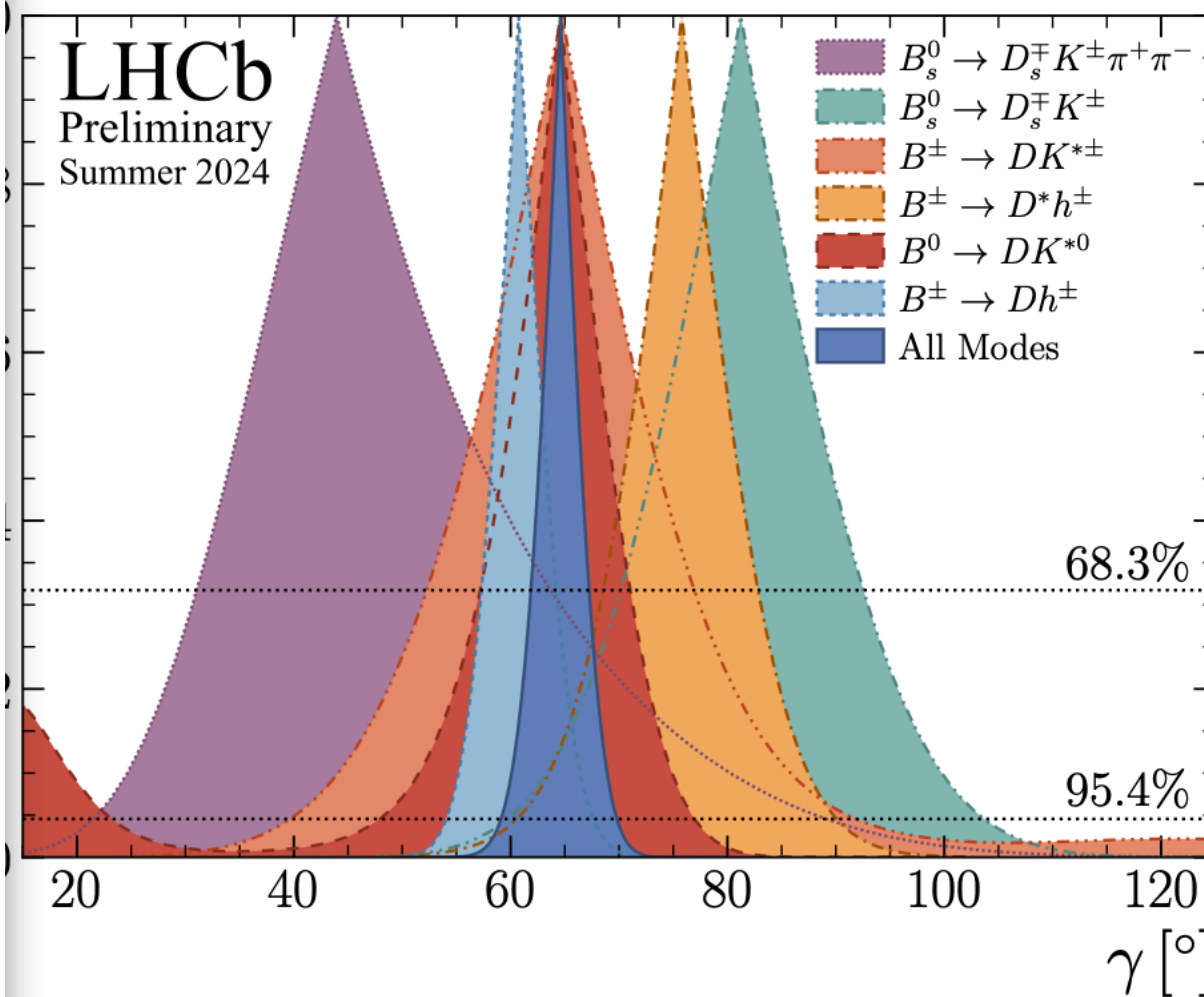
A new piece in the matter-antimatter puzzle

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.

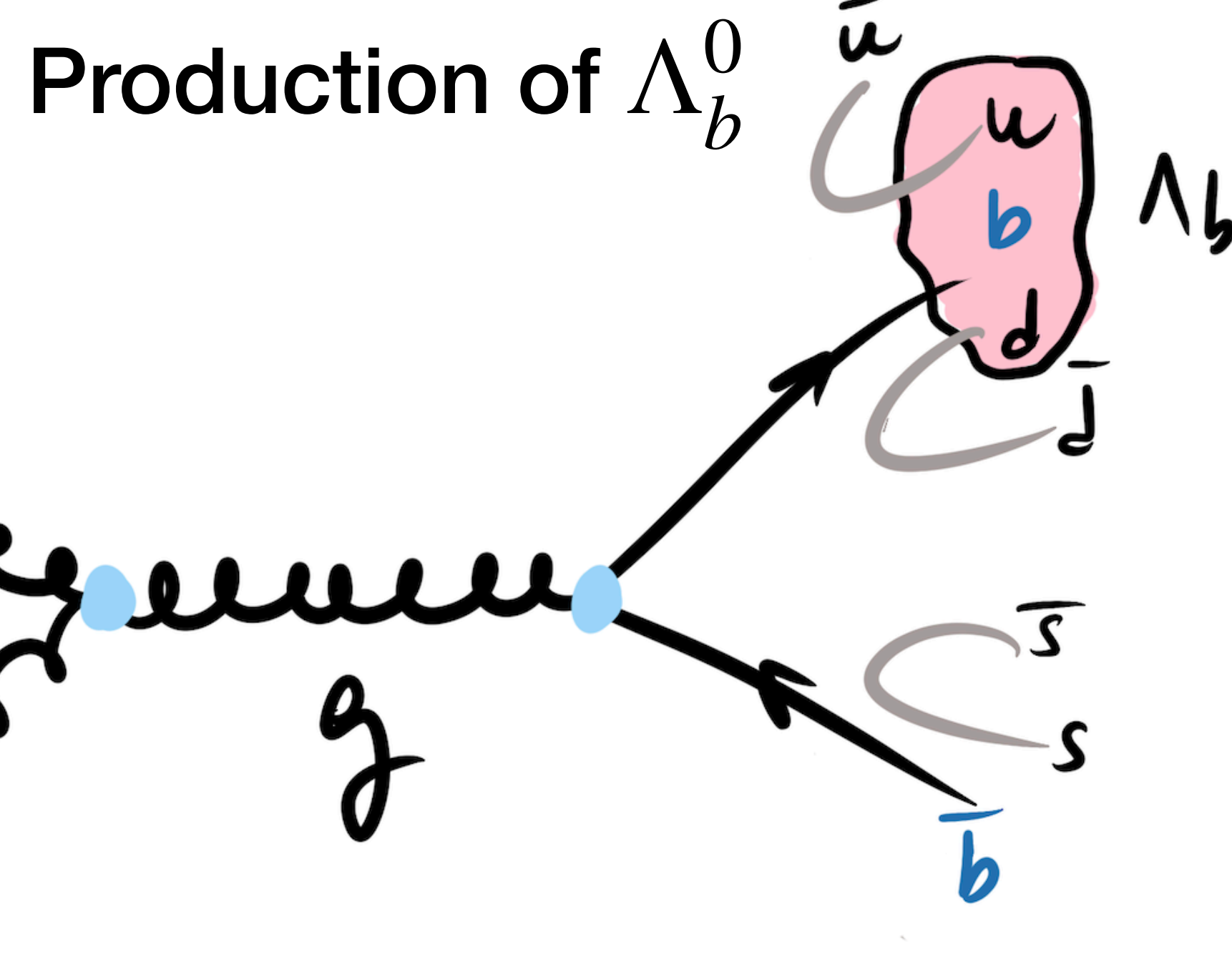
"The reason why it took longer to observe CP violation in baryons than in mesons is down to the size of the effect and the available data," explains LHCb spokesperson Vincenzo Vagnoni. "We needed a machine like the LHC capable of producing a large enough number of beauty baryons and their antimatter 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."

om for NP in these observables?



LHCb-CONF-2024-004

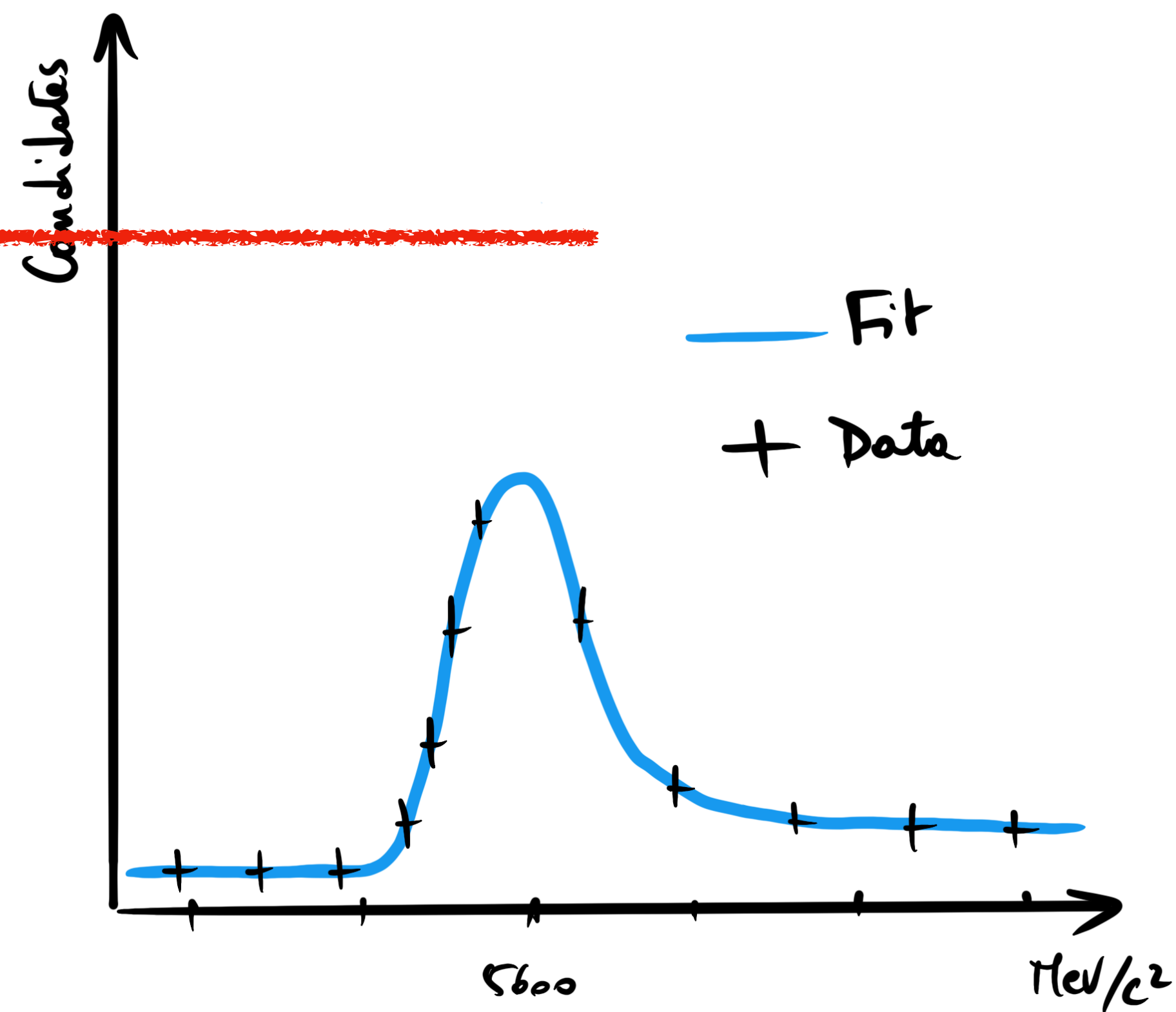
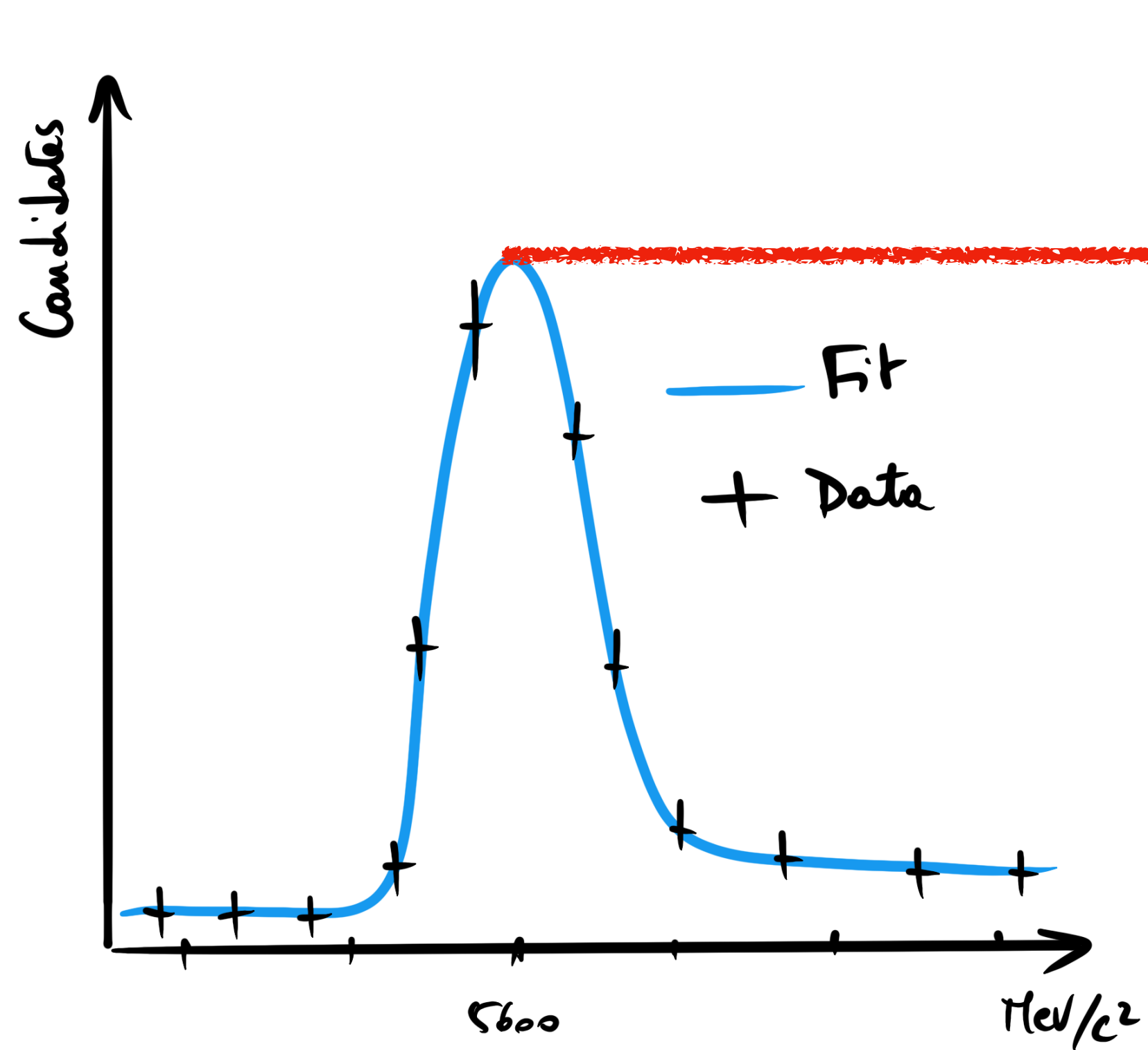
Observation of charge-parity symmetry breaking in baryon decays



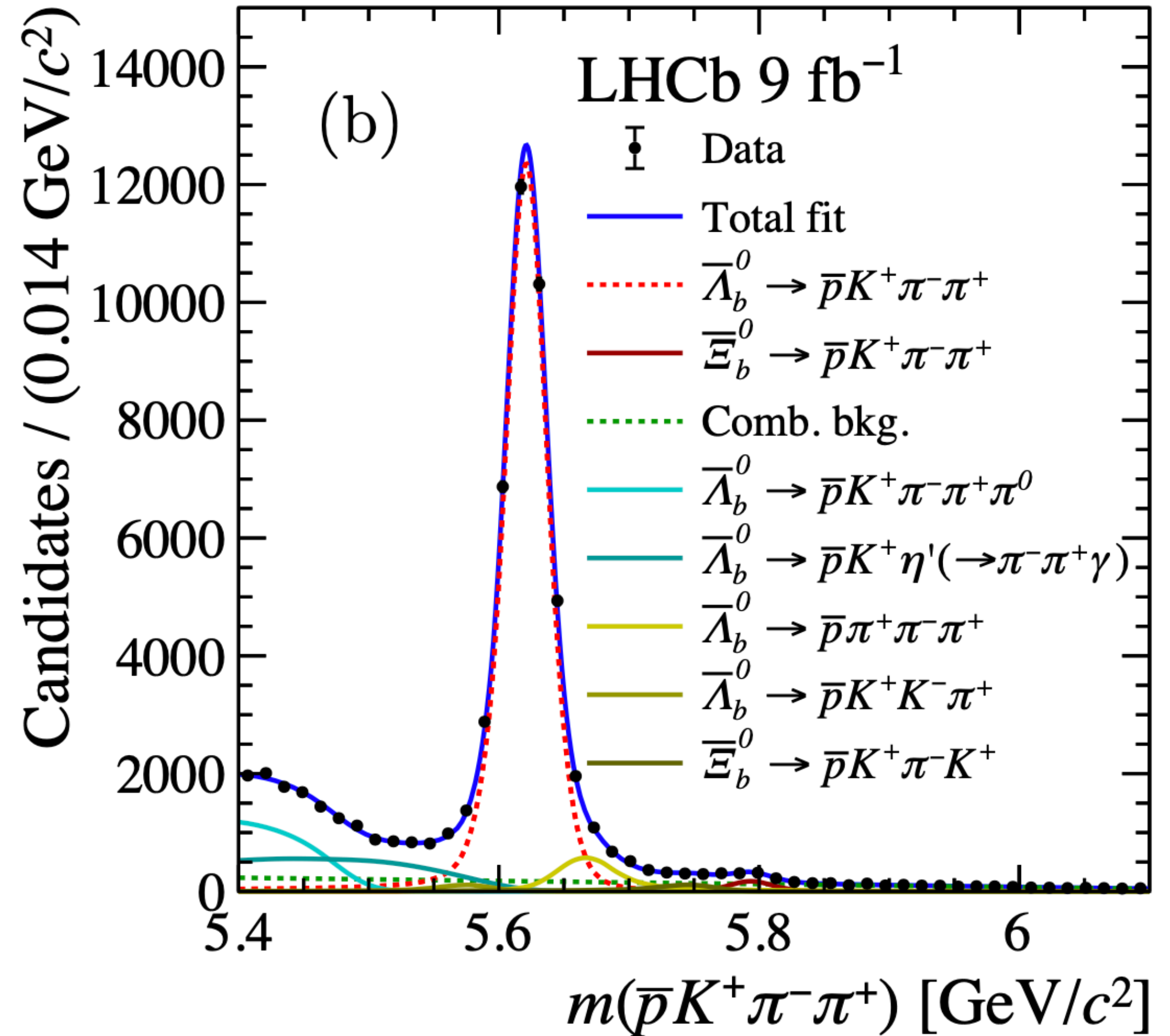
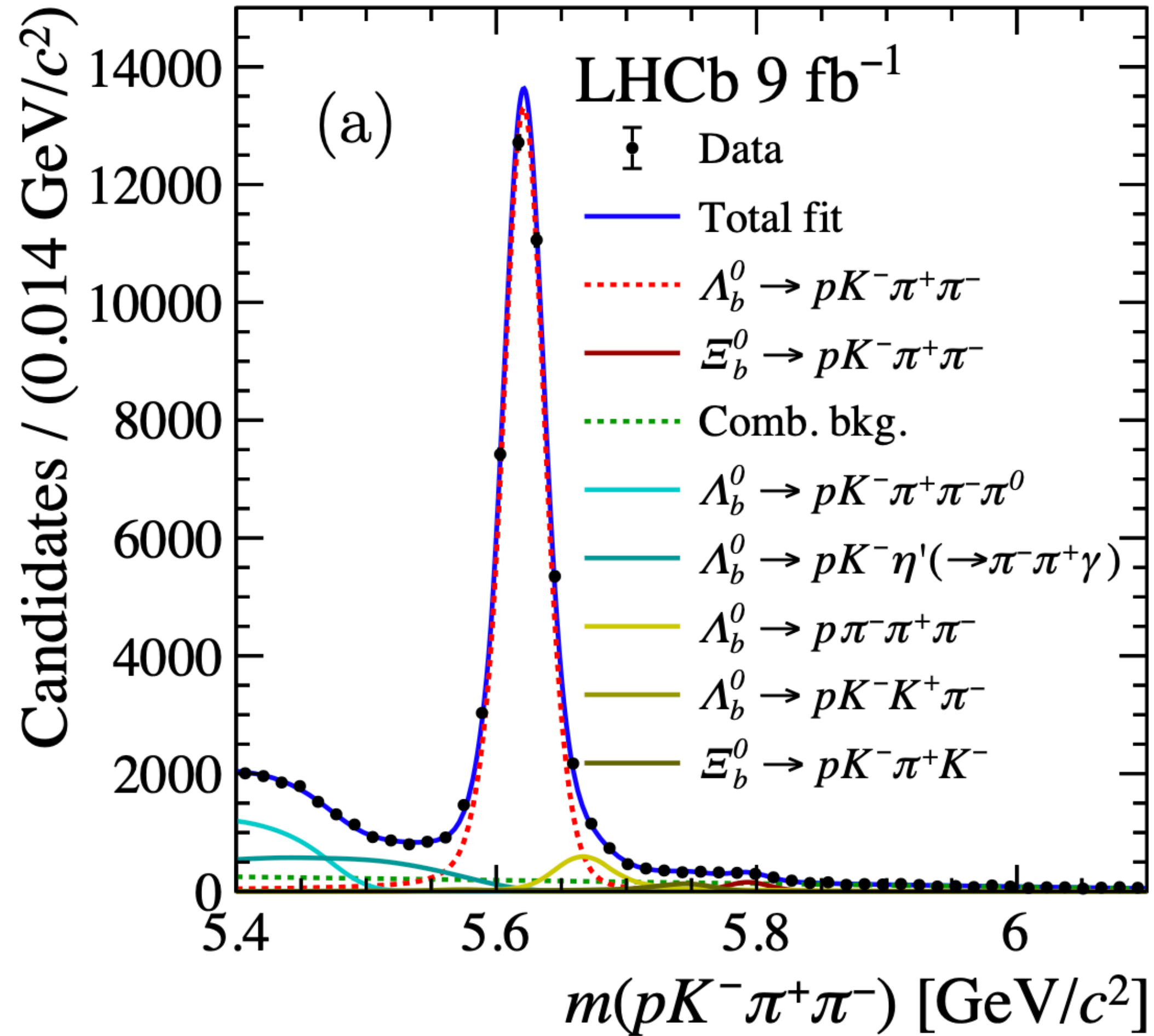
Expression of the asymmetry

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

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



Signal mode



Very pure selection & careful modelling of the backgrounds

From Raw to CP observable

$$A_{CP}^f = A_{Raw}^f - A_P^{f, \Lambda_b^0} - A_D^f$$

Production asymmetry

$$A_P^{f, \Lambda_b^0} = \frac{\sigma(\Lambda_b^0) - \sigma(\bar{\Lambda}_b^0)}{\sigma(\Lambda_b^0) + \sigma(\bar{\Lambda}_b^0)}$$

Detection asymmetry

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

$$A_{CP}^c = A_{Raw}^c - A_P^{c, \Lambda_b^0} - A_D^c \rightarrow$$

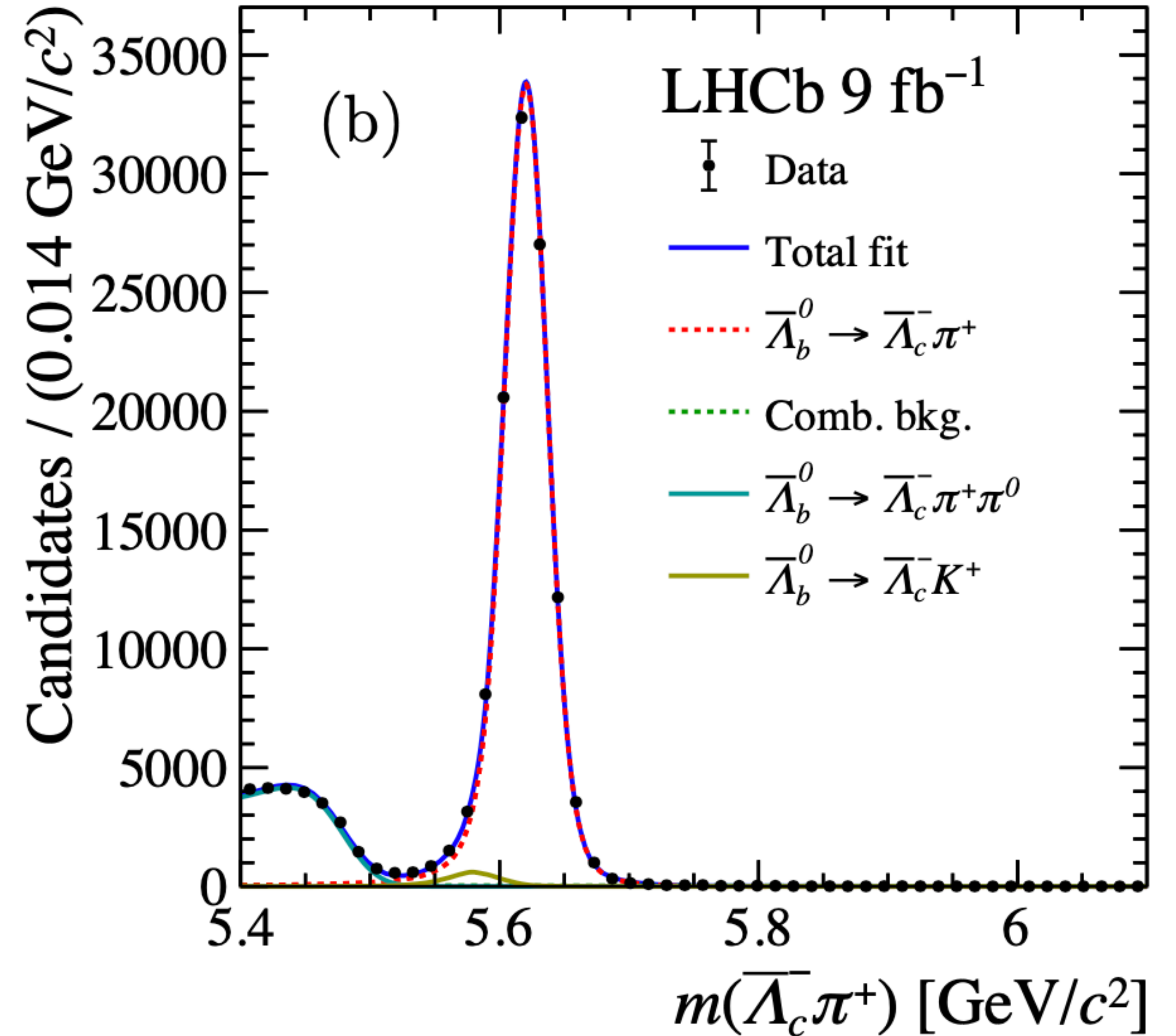
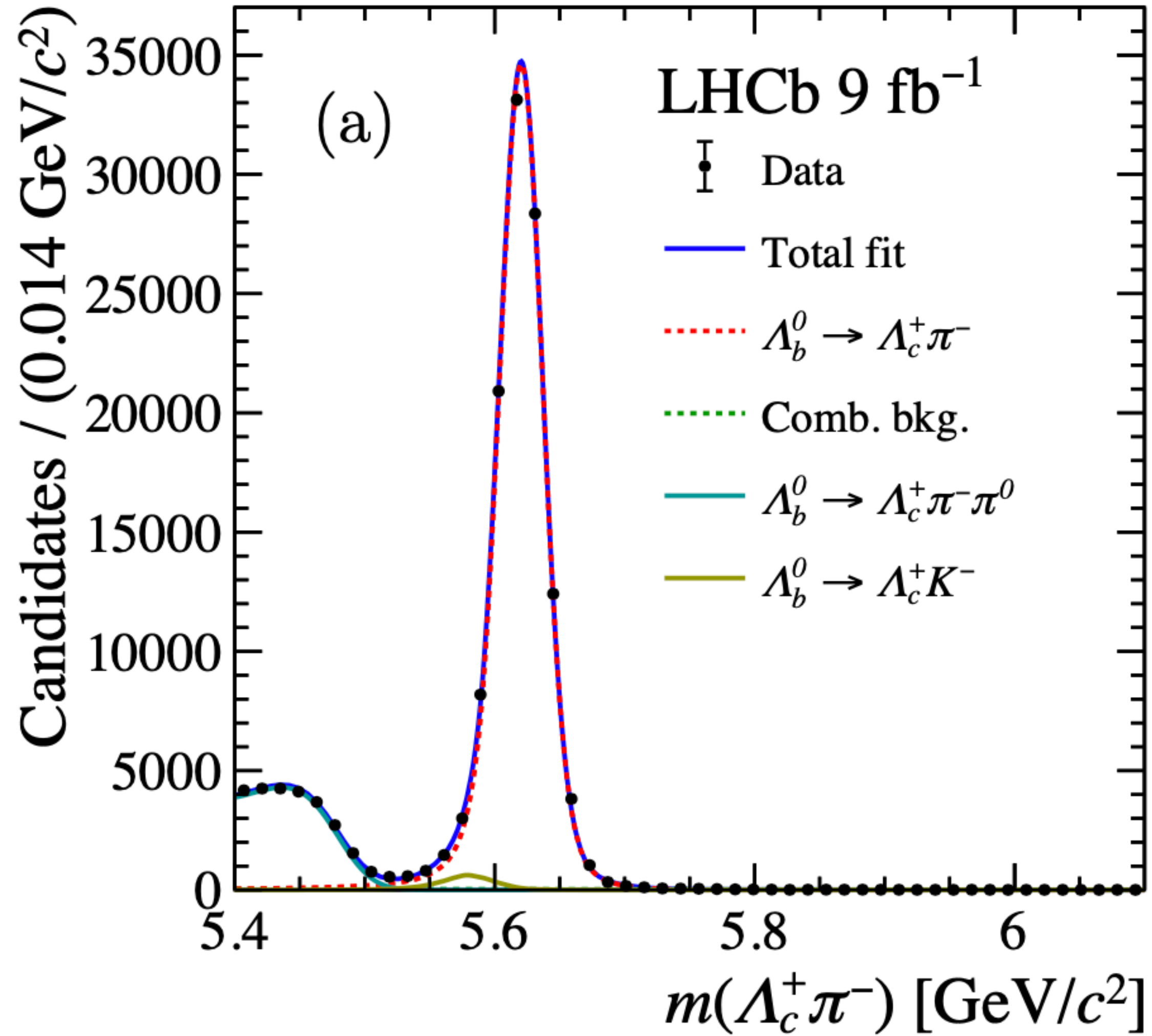
$$A_{CP}^f = A_{Raw}^f - A_P^{f, \Lambda_b^0} - A_D^f \rightarrow$$

Measured for the control mode for which

$$A_{CP} \sim 0$$

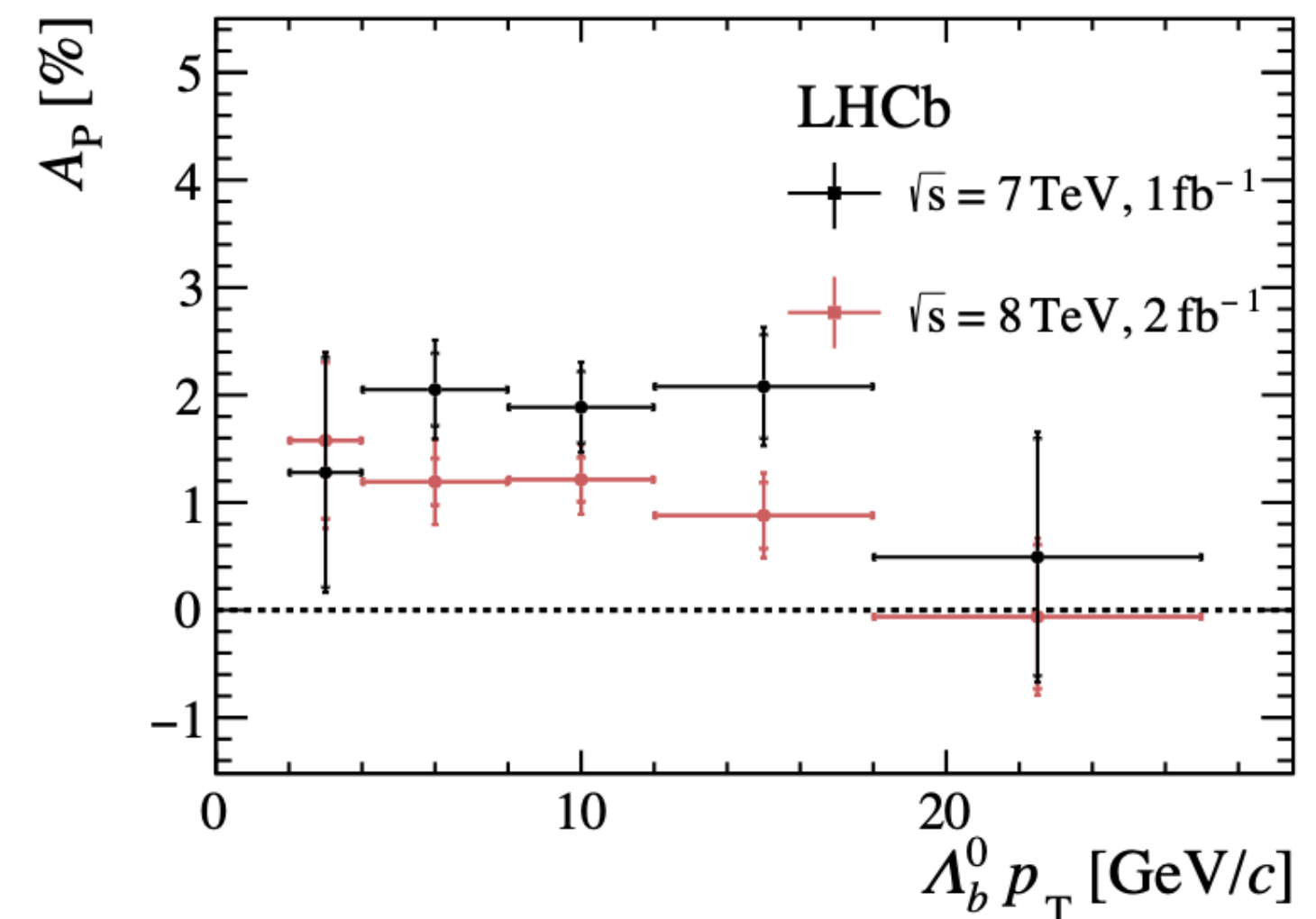
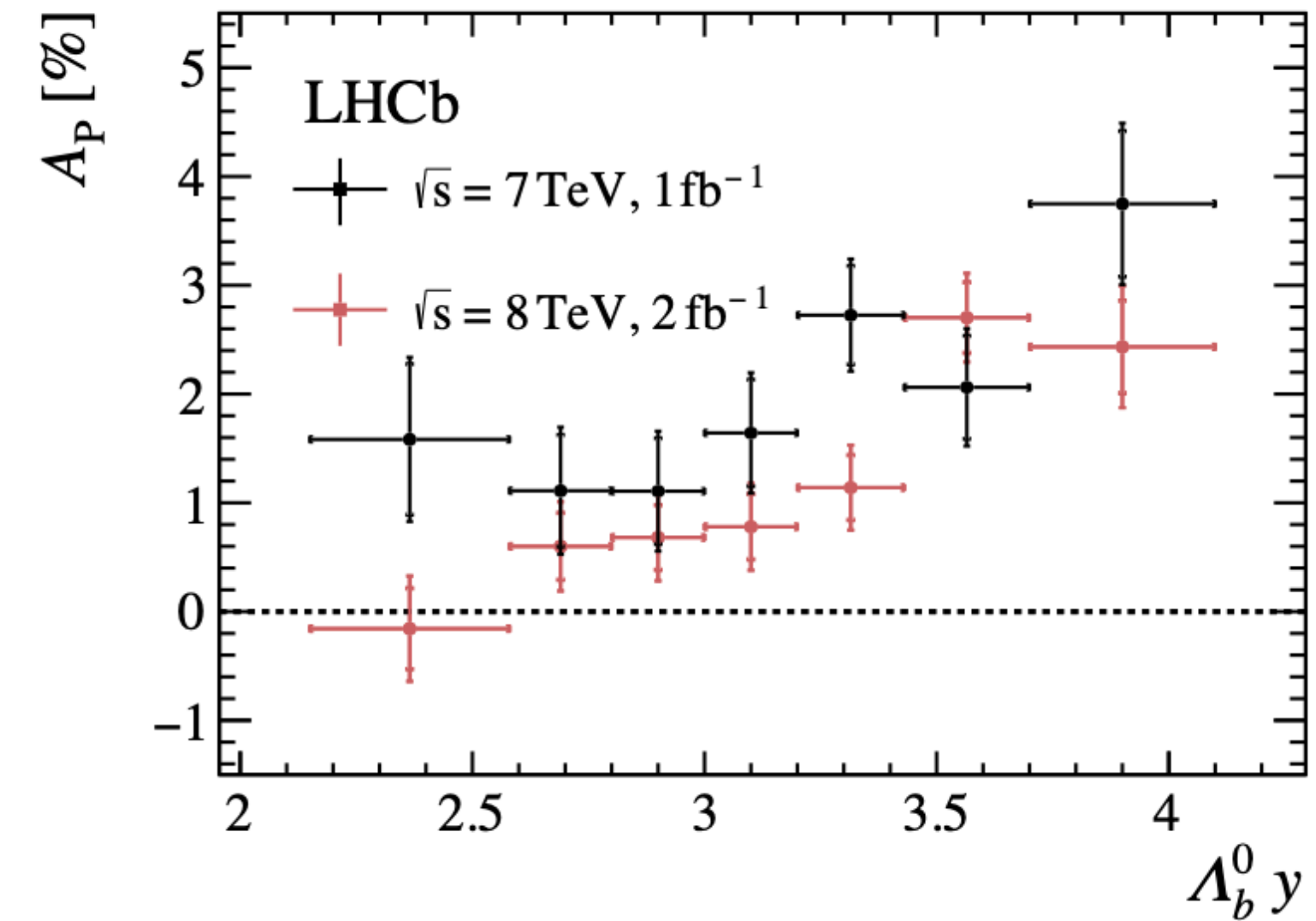
Measured for the signal

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



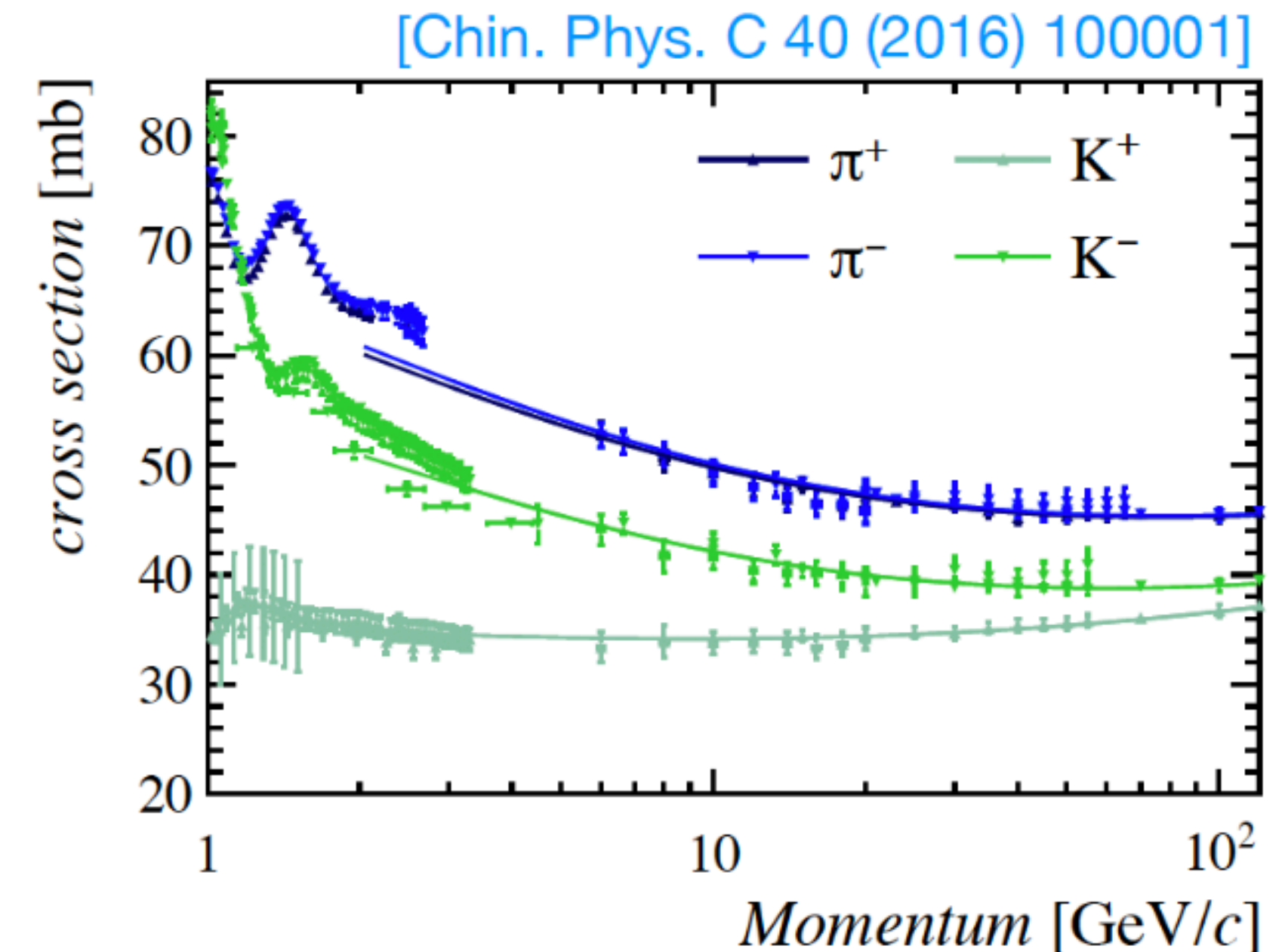
Detector asymmetries

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

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



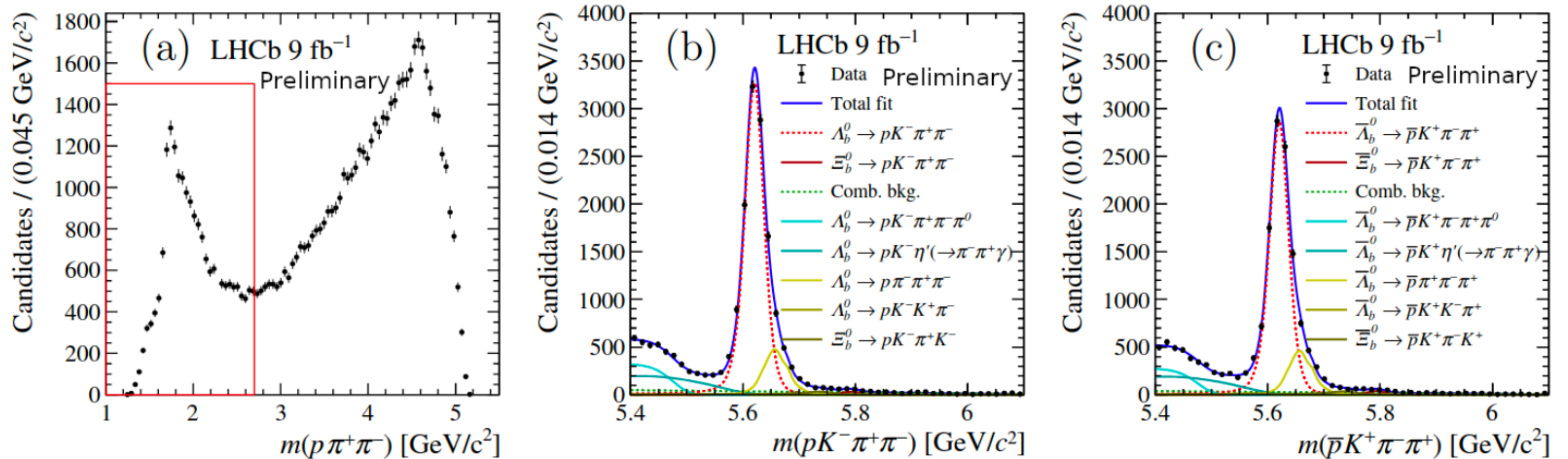
- ΔA_D vanishes

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

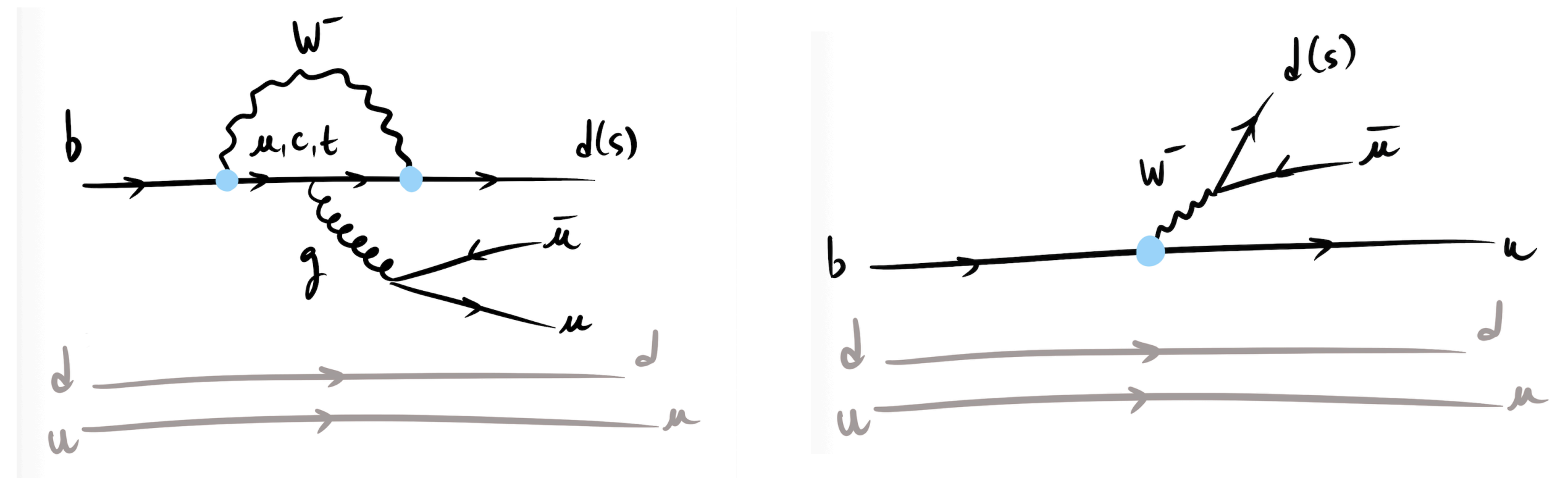
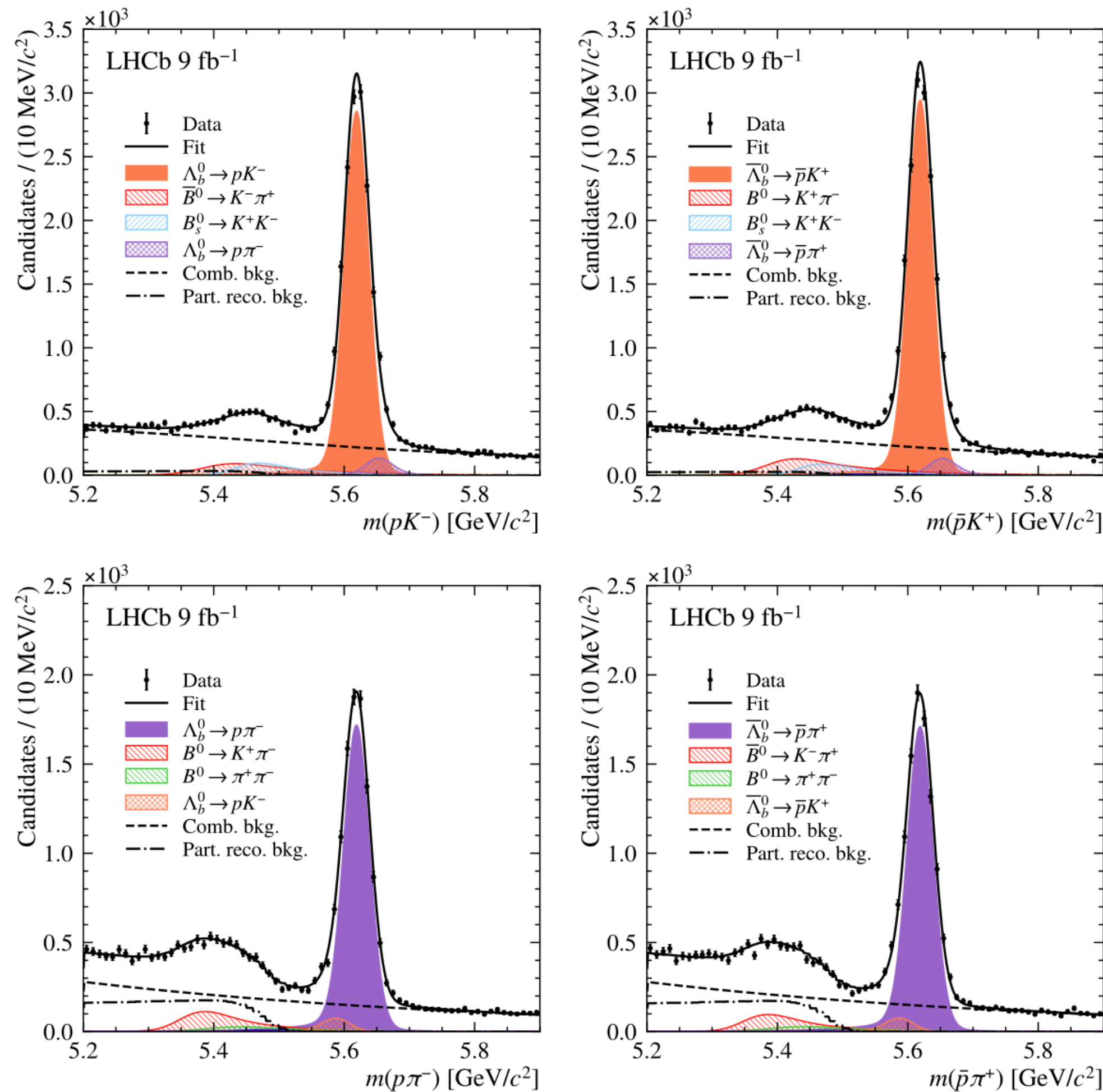
Taking it one step further

Observe up to 6 standard deviations locally

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

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

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



Experimental techniques are very similar

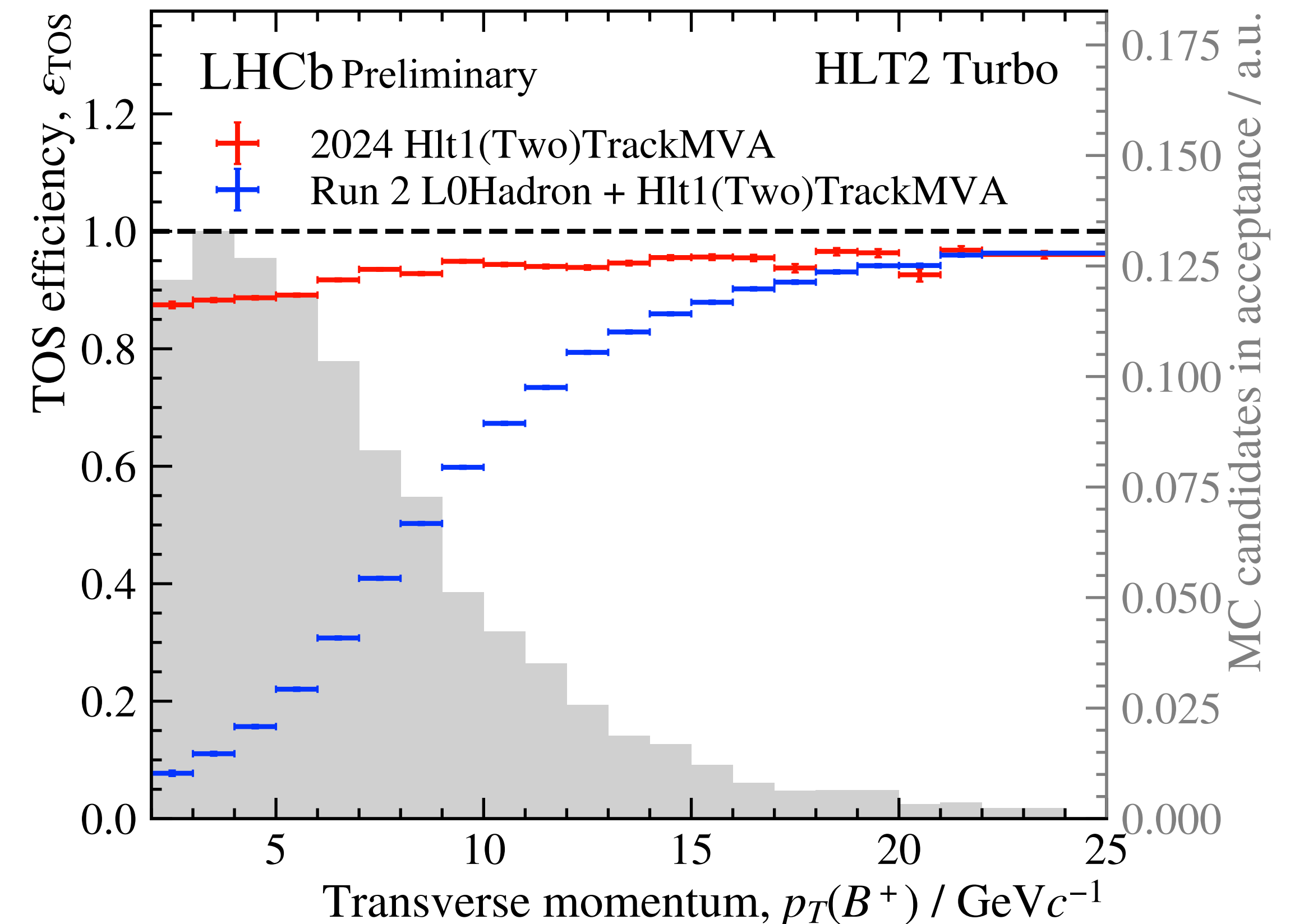
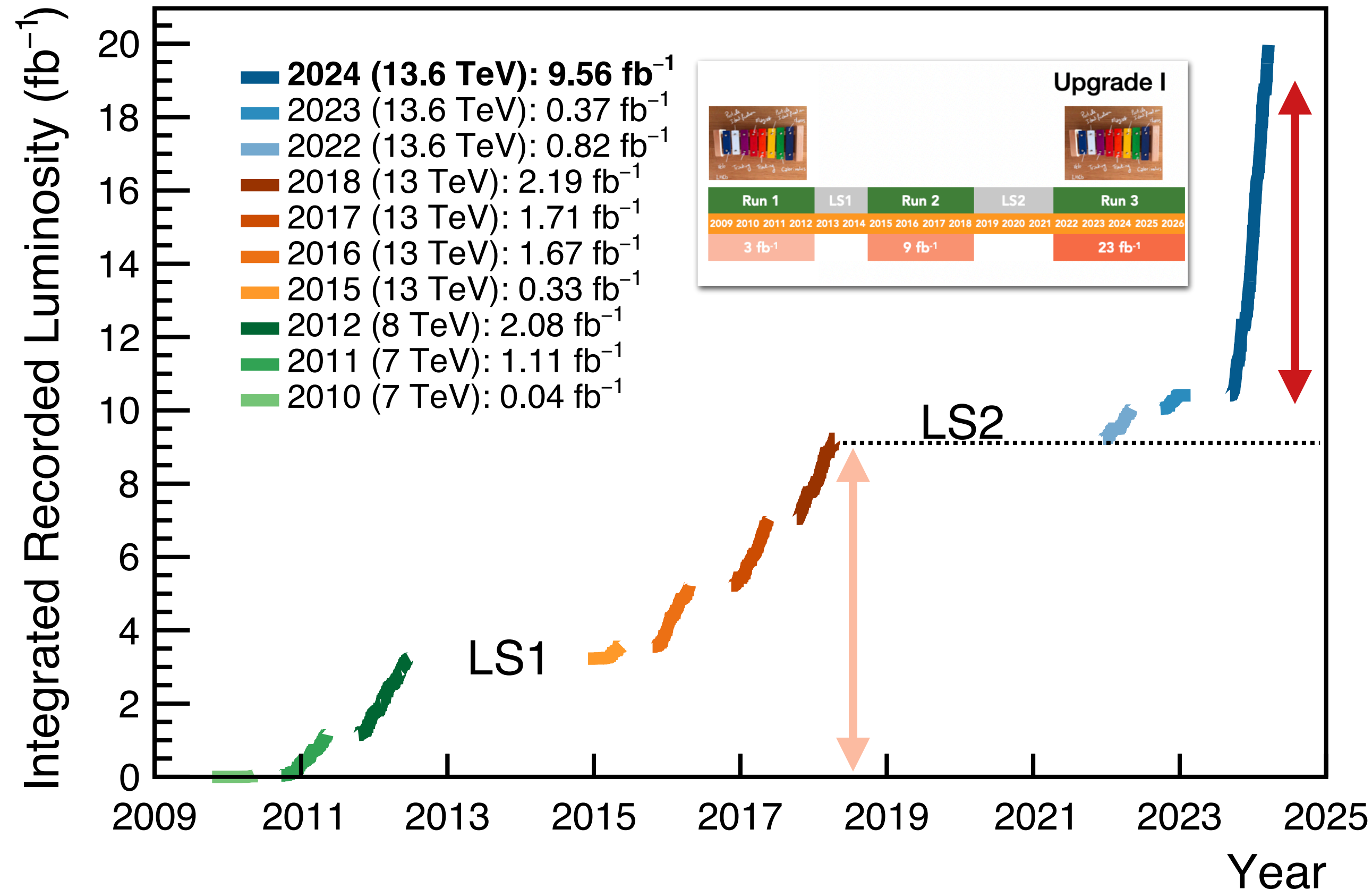
$$A_{CP}^{pK^-} = (-1.1 \pm 0.7 \pm 0.4)\%,$$

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

No evidence of CP violation is found

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 ($B \rightarrow DK$, <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!

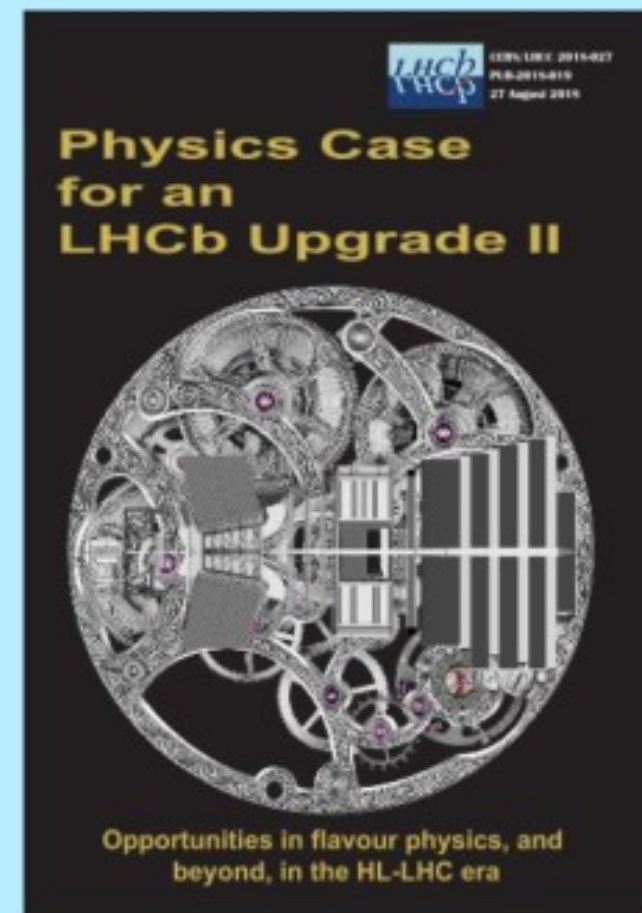
And an other Upgrade

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

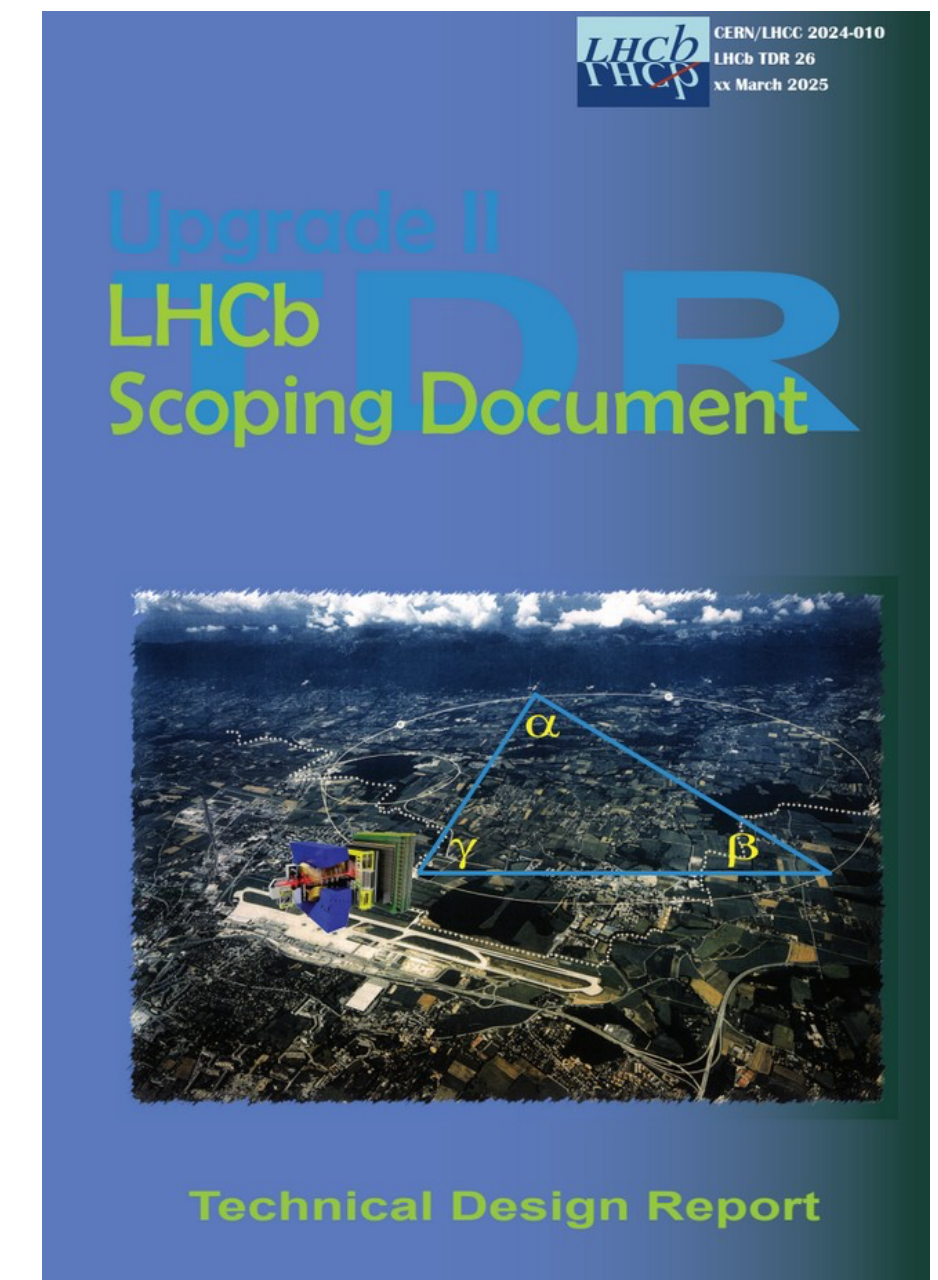
Approved by LHCC March 2022

"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 descopeing 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."

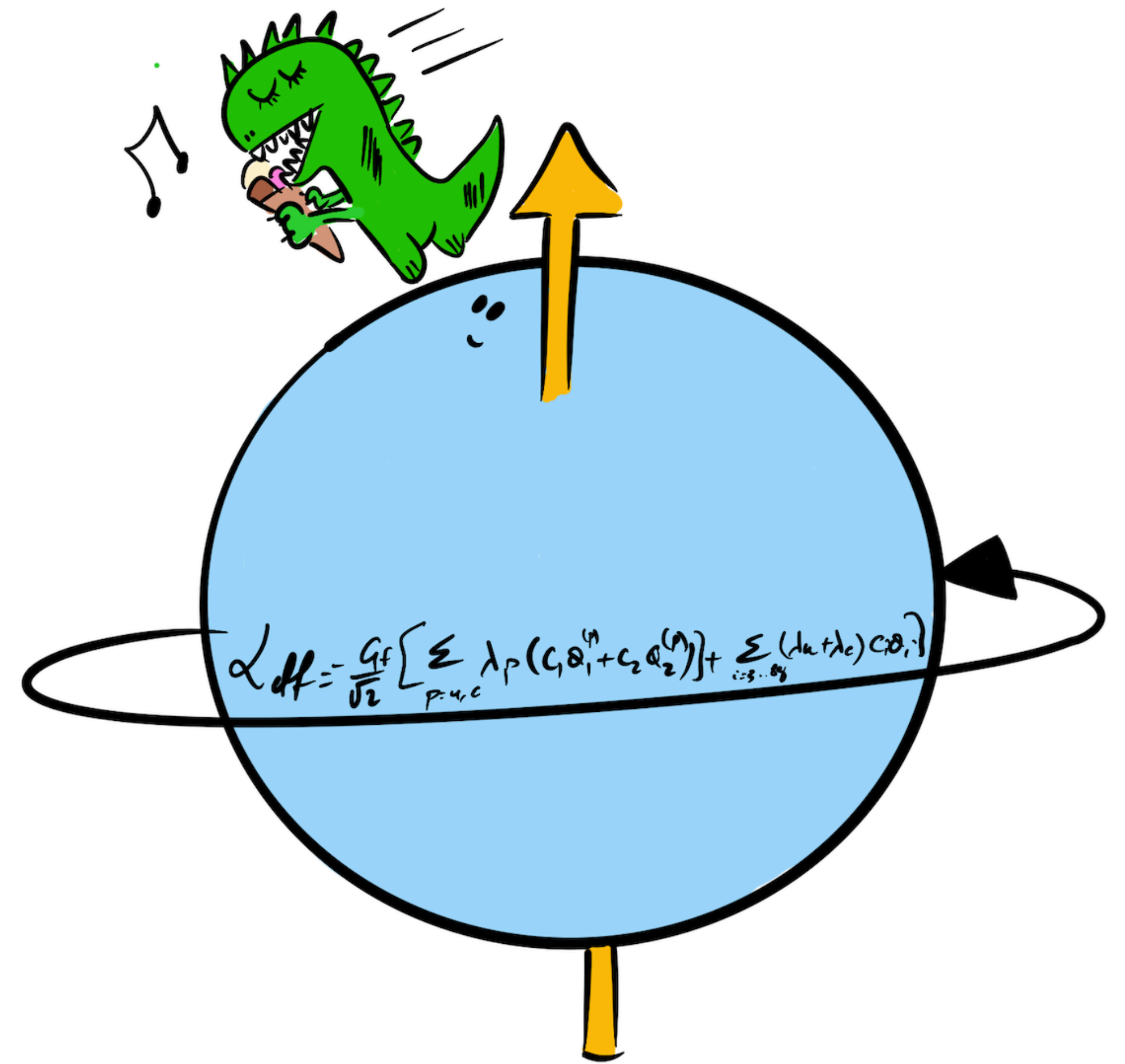
Scoping document



**Submitted to LHCC
(Sept 2024)
Under review**

Conclusions

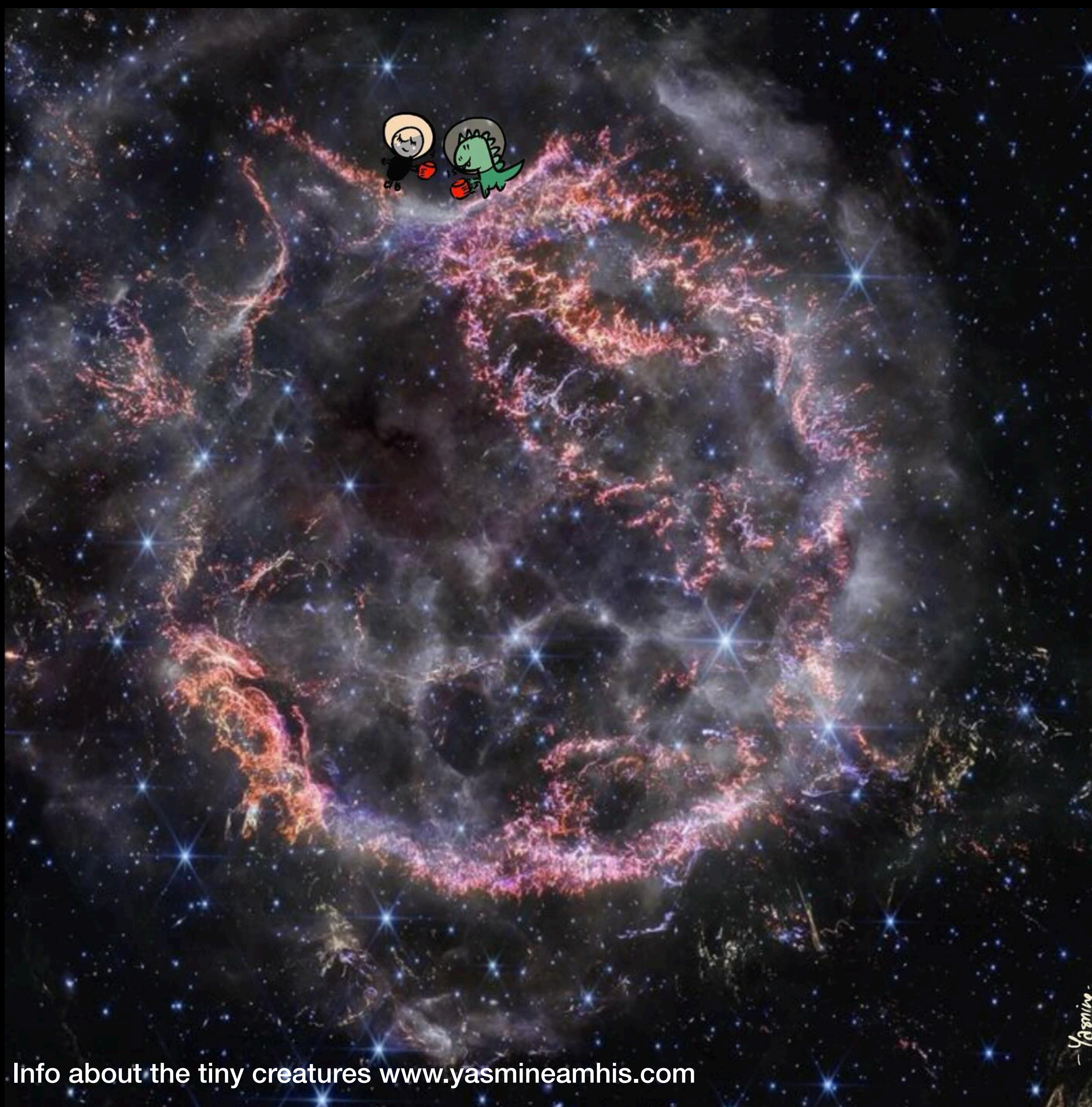
- Flavour physics is an excellent approach to help us shed the light on many unknowns.
- LHCb is a powerful environment to answer (some) of these questions.
- There is enough left to understand to keep us busy for at least a couple of decades (probably more).
- Thank you for the invitation !



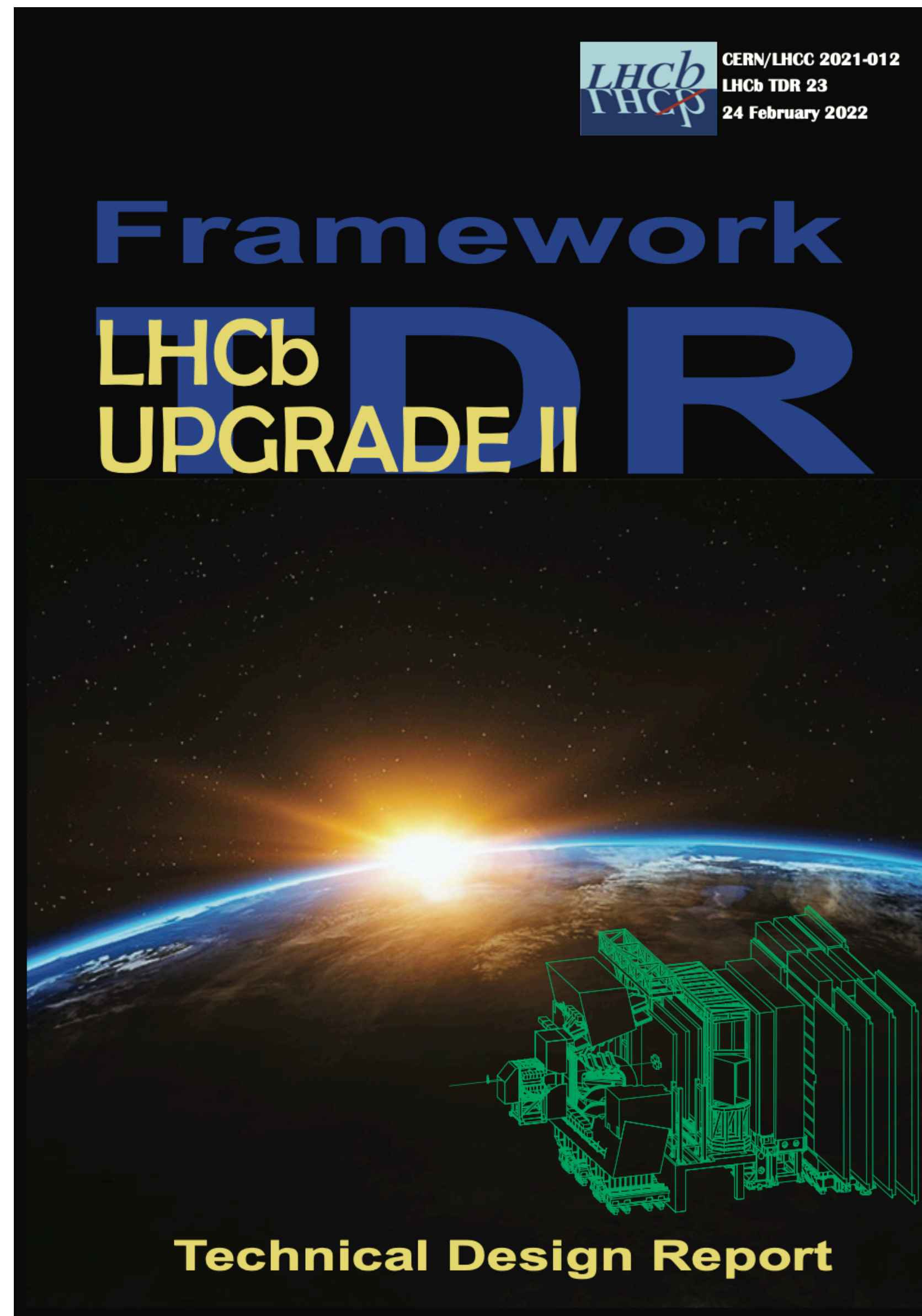
A colouring book for children is available at the CERN Science Gateway - also in German



More information yasmineamhis.com



Backup slides



Upgrades

[LHCC-2021-012](#)

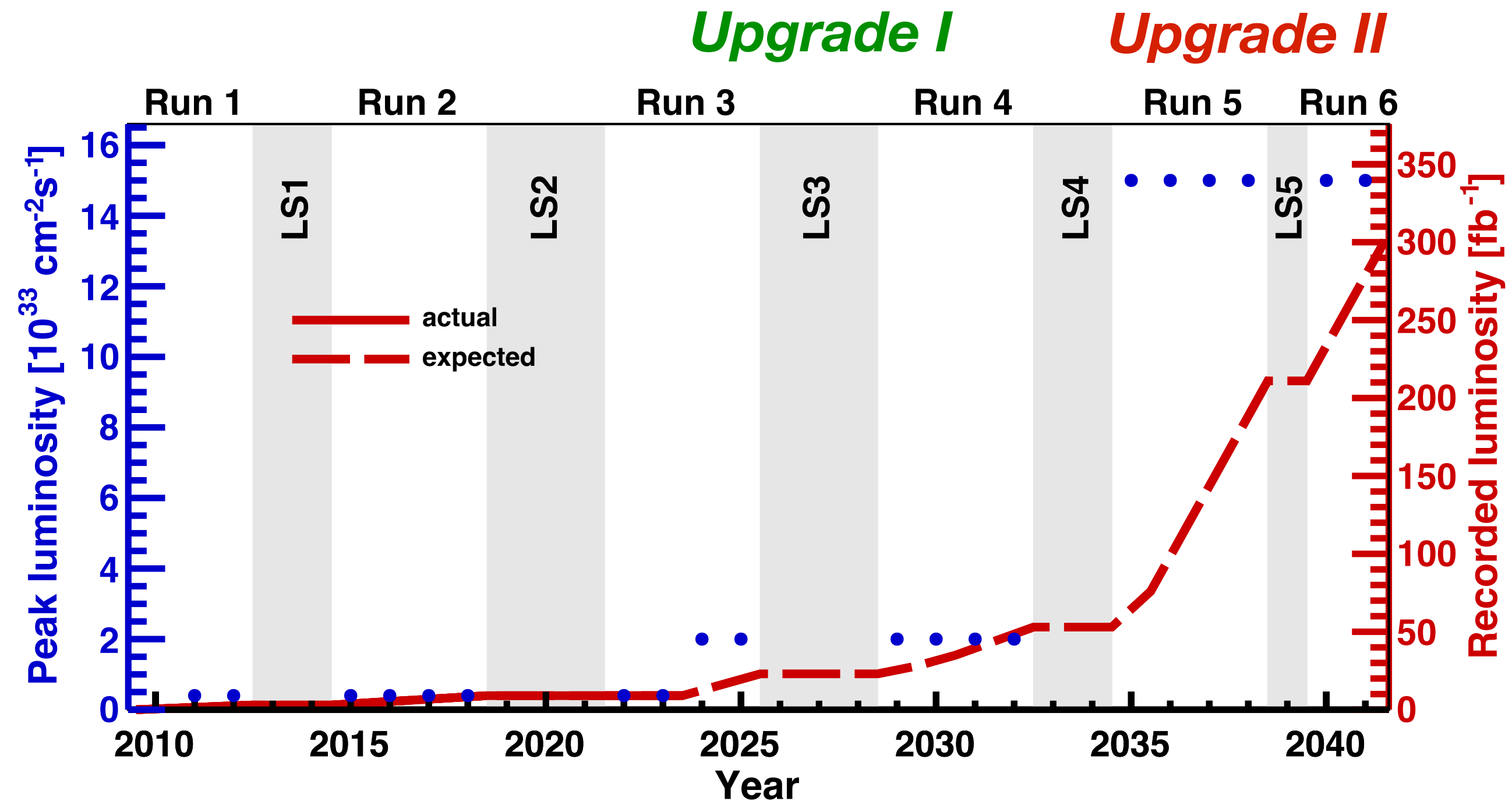
Framework TDR

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

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



Upgrade II, installation at LS4

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

LHCb Upgrade II

- Unprecedented sensitivity for B and D physics
 - Beyond \sqrt{N} scaling with new subdetectors and reconstruction techniques

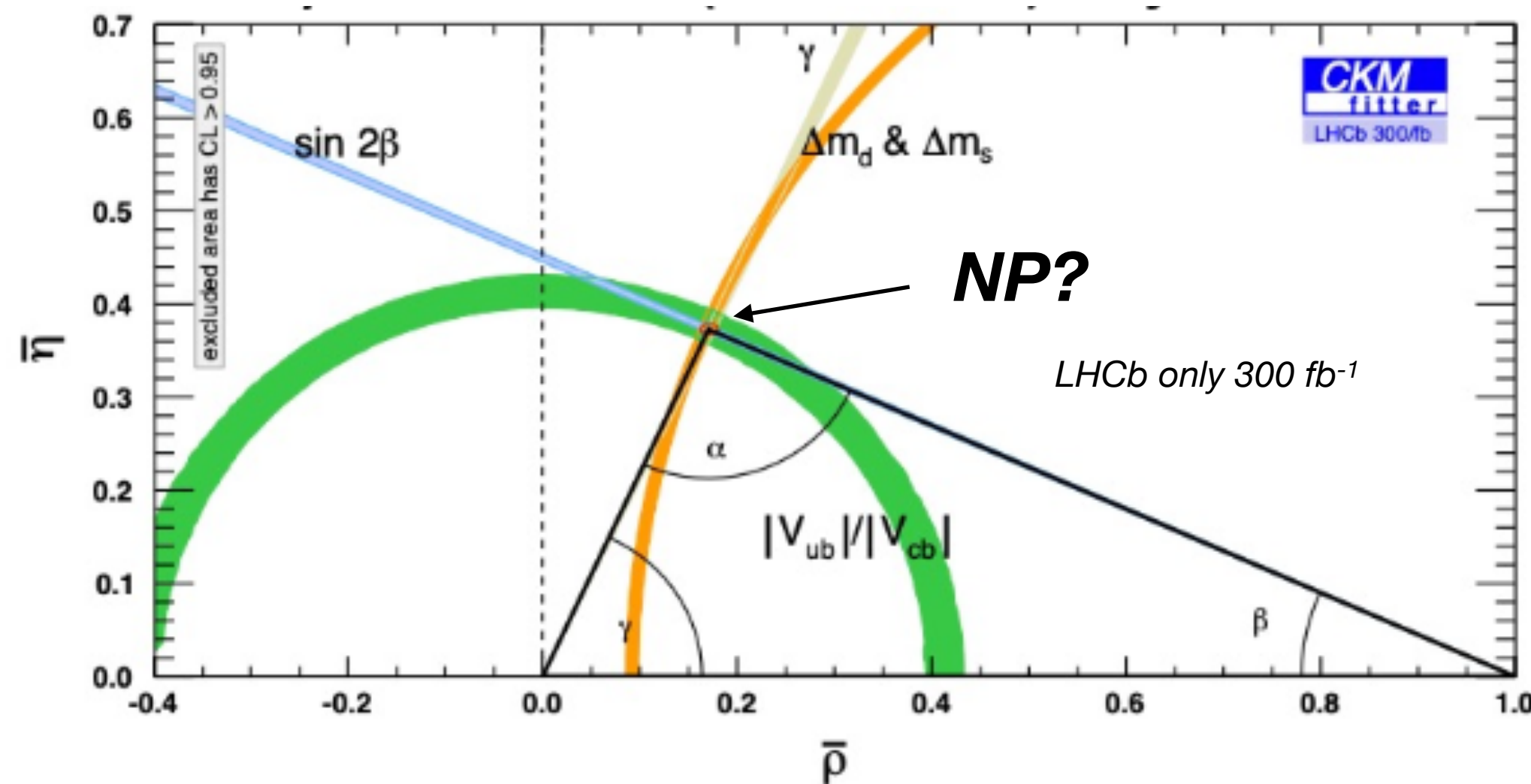
[LHCC-2018-027](#)

Physics case

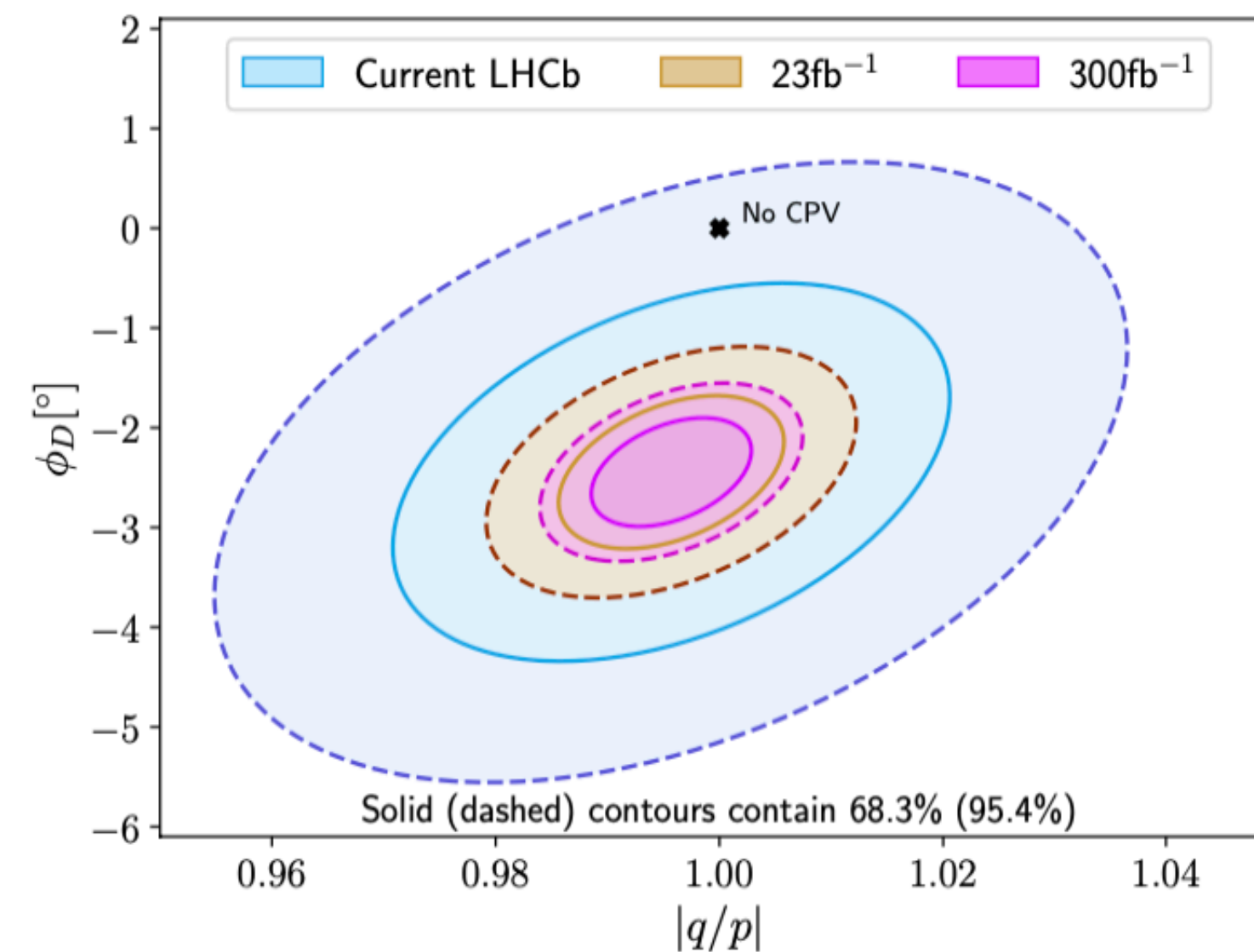
- Broad general purpose programme with unique forward acceptance

- Spectroscopy, EW precision measurements, top quark and Higgs physics, dark sector, heavy ions and fixed target

Impressive precision on CP violating phases

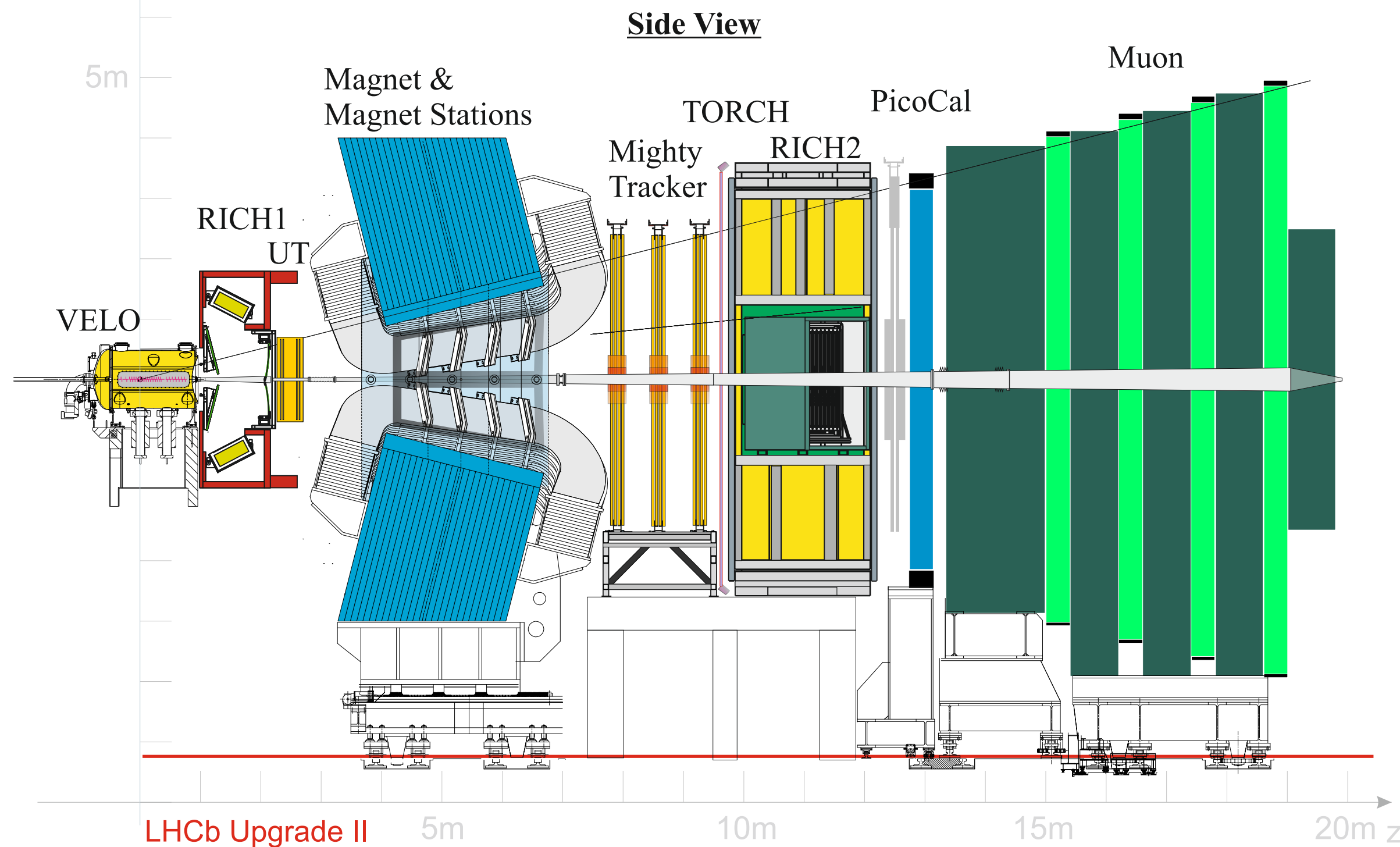


The only planned facility with a realistic possibility to observe CPV in charm mixing



The detector challenge

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



Same spectrometer footprint, innovative technology for detector and data processing

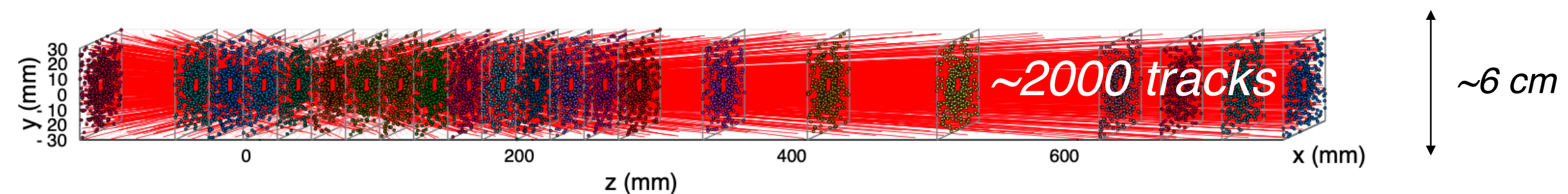
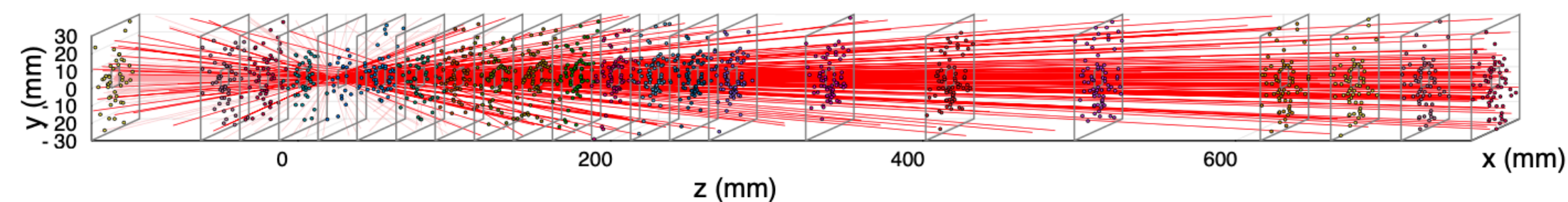
Key ingredients:

- 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)

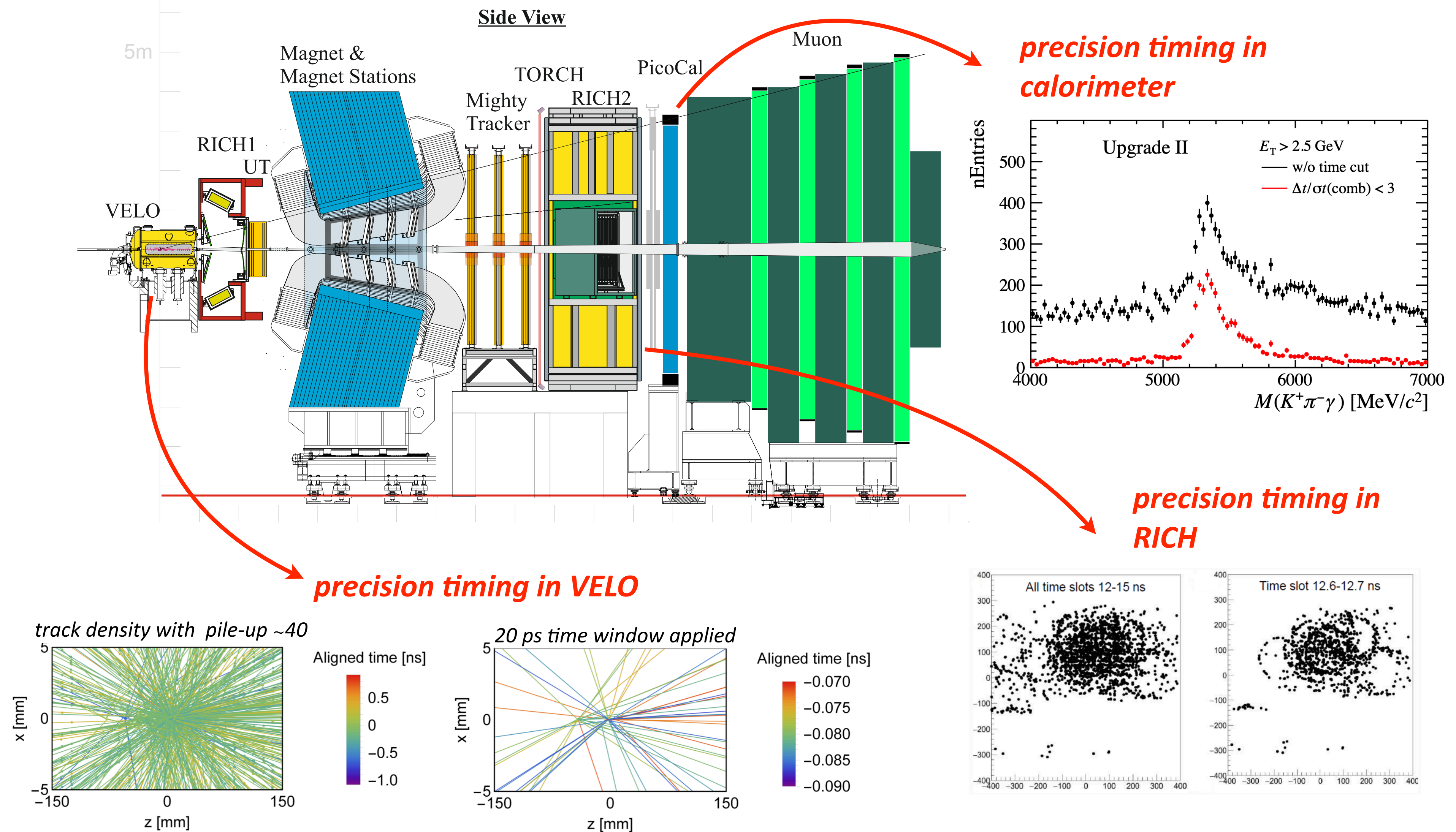
Run 3: pile-up ~ 6

Upgrade II: pile-up ~ 40

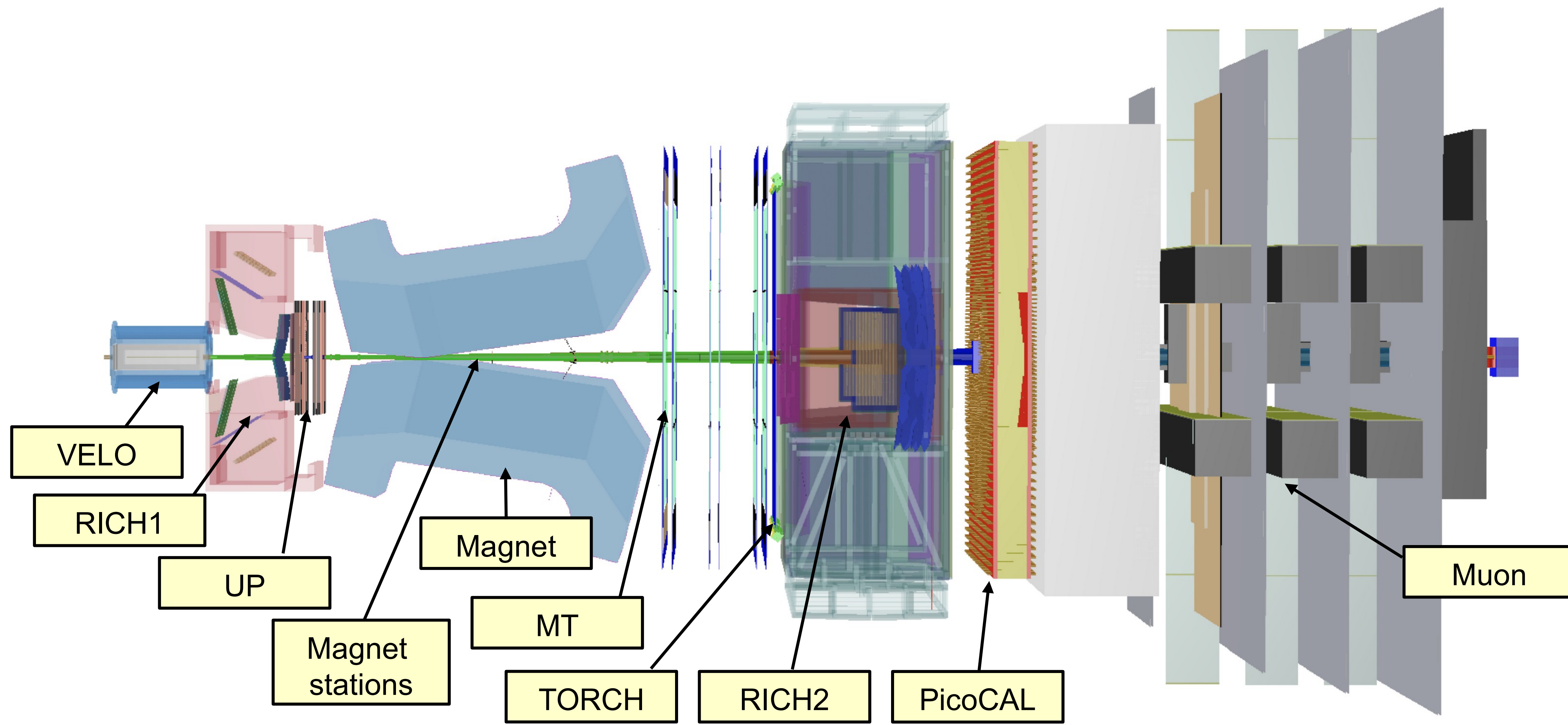


The role of timing

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



LHCb Upgrade 2 detector layout



Flavour Tagging @ LHCb

