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NANJING NORMAL UNIVERSITY

Flavourful global fit to LHCb data with the general 2HDM: An update

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Peter Athron, Andreas Crivellin, Tomas Gonzalo, Syuhei Iguro, **CS** [WIP]

- **SM**
  - Electroweak interactions
- **Second Higgs: Yukawa Lagrangian**
  - Flavour changing transitions
- **Flavour Anomalies**
  - Charged anomalies
  - Neutral anomalies
    - New diagrams from G2HDM
    - Wilson coefficients at LO
- **Scans and Results**
- **Summary**

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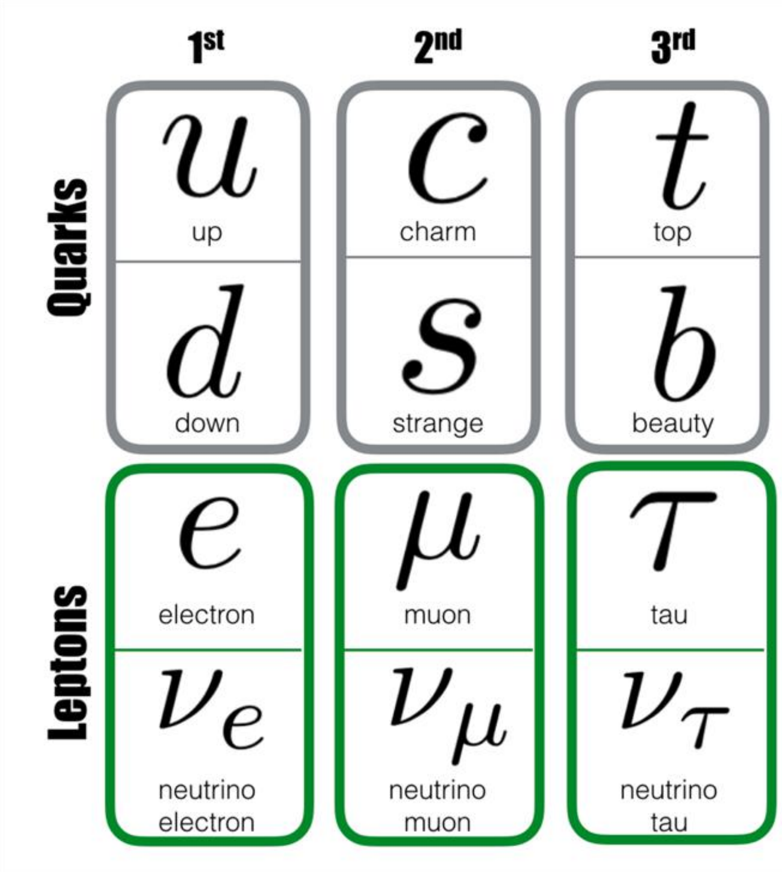
Fermions

Flavour states

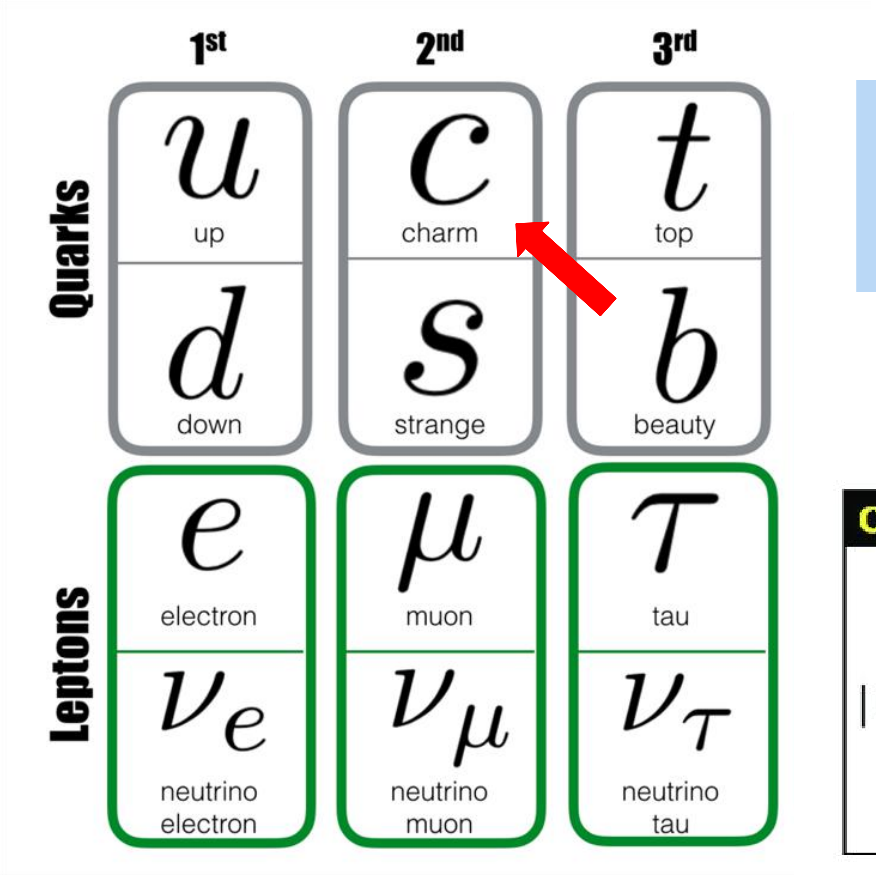


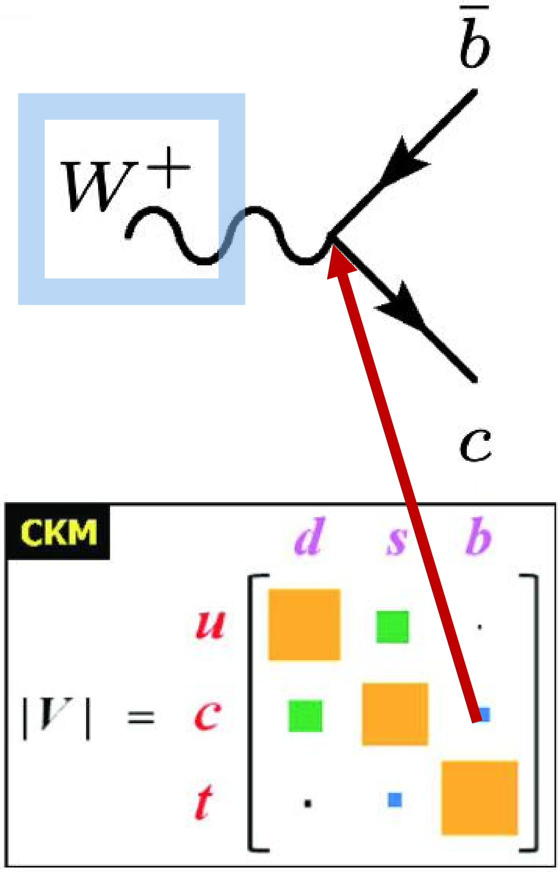
	1st	2nd	3rd
Quarks	u up	c charm	t top
	d down	s strange	b beauty
Leptons	e electron	μ muon	τ tau
	ν_e neutrino electron	ν_μ neutrino muon	ν_τ neutrino tau

12 flavours

Image credit: Physik-Institut - UZH

Flavour changing transitions





Suppressed in the SM

Cabibbo-Kobayashi-Maskawa (CKM)

Image credit: Physik-Institut - UZH

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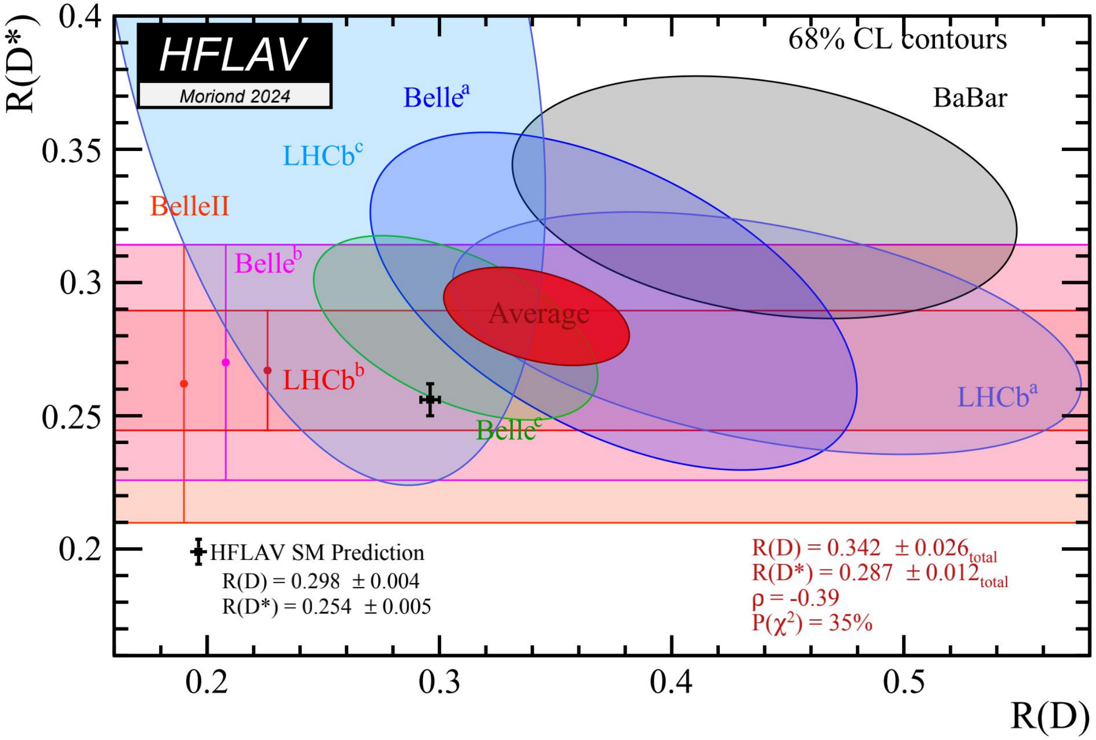
Charged anomalies

$$R_D = \frac{\Gamma(\overline{B} \to D\tau\overline{\nu})}{\Gamma(\overline{B} \to Dl\overline{\nu})} \qquad R_{D^*} = \frac{\Gamma(\overline{B} \to D^*\tau\overline{\nu})}{\Gamma(\overline{B} \to D^*l\overline{\nu})}$$

$$\boxed{R^{\text{exp}}_{D(*)} > R^{\text{SM}}_{D(*)}}$$



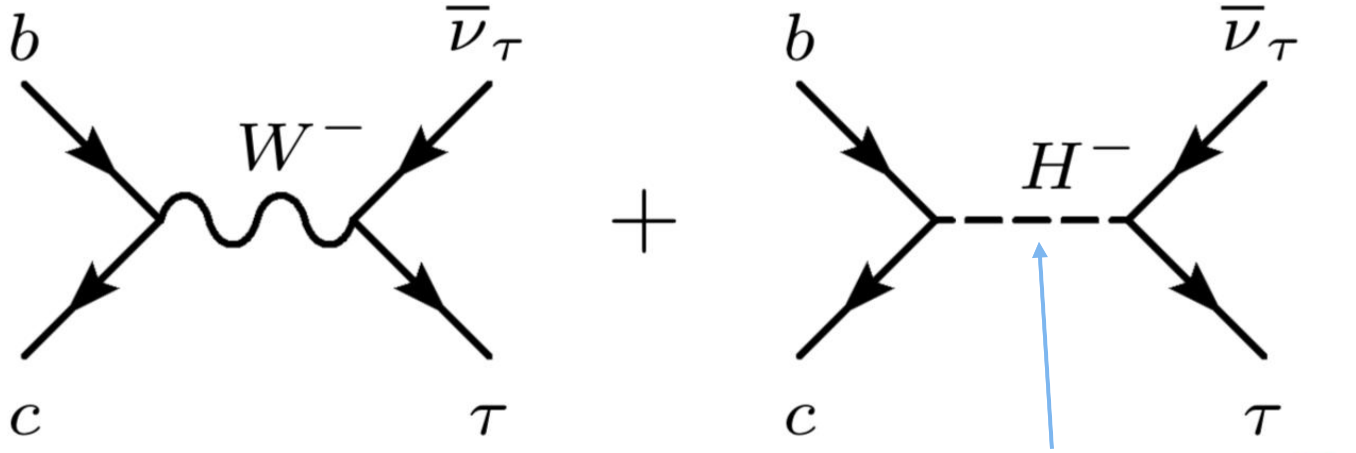
At 3.2 σ

Interference with NP?

From **Moriond 2024**

Charged anomalies

$$\boxed{R^{\mathrm{exp}}_{D^{(*)}} > R^{\mathrm{SM}}_{D^{(*)}}}$$



A second Higgs doublet can provide answers: **Charged Higgs!**

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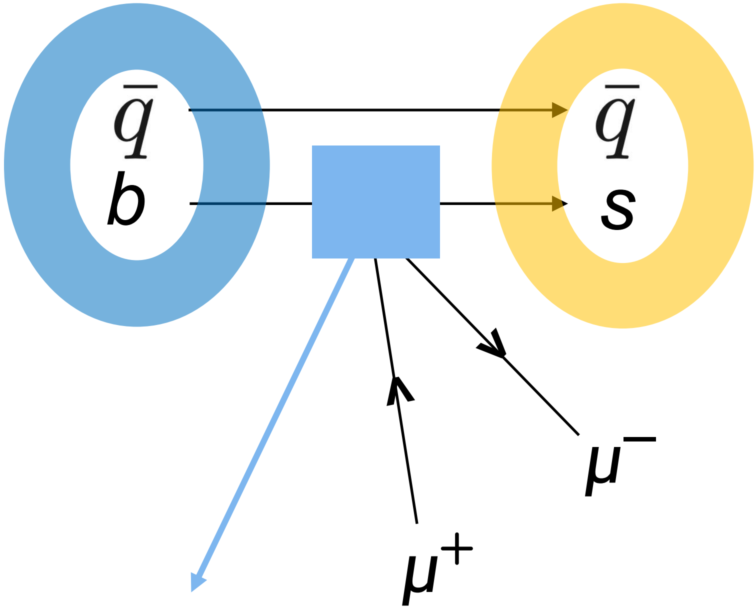
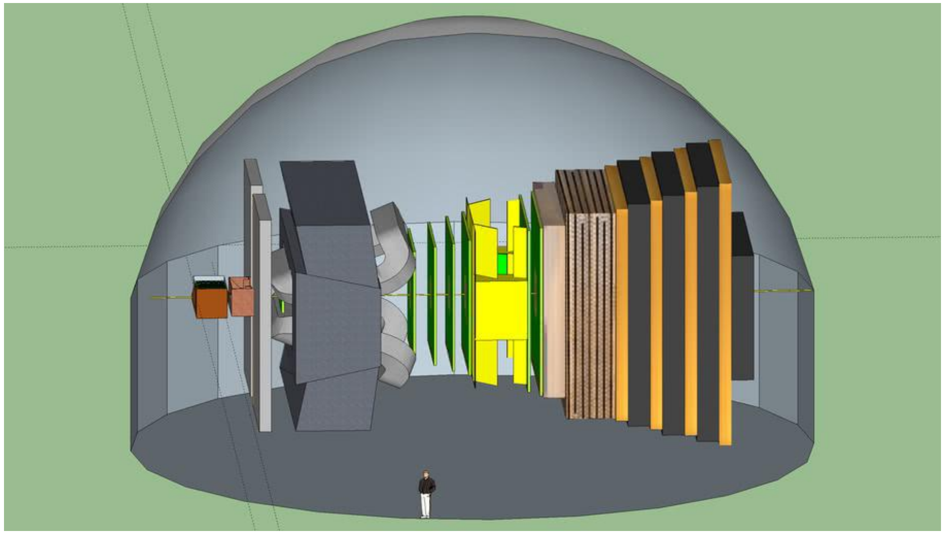
Neutral anomalies

Most precise measurements
come from the LHCb detector

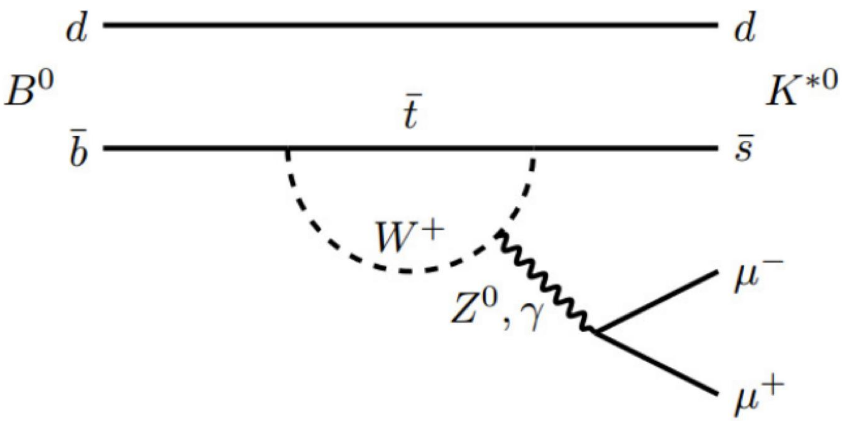
$$B \to K^{(*)}\mu^+\mu^-$$

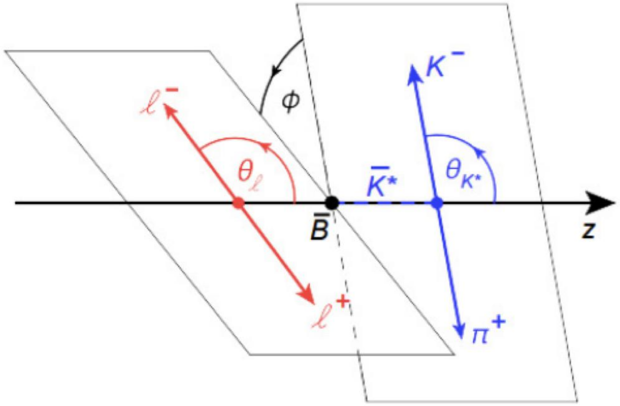




Explanations from the NP point of view of any anomaly will be via effective ***Wilson coefficients***

B meson semilep. decays: Angular observables





Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

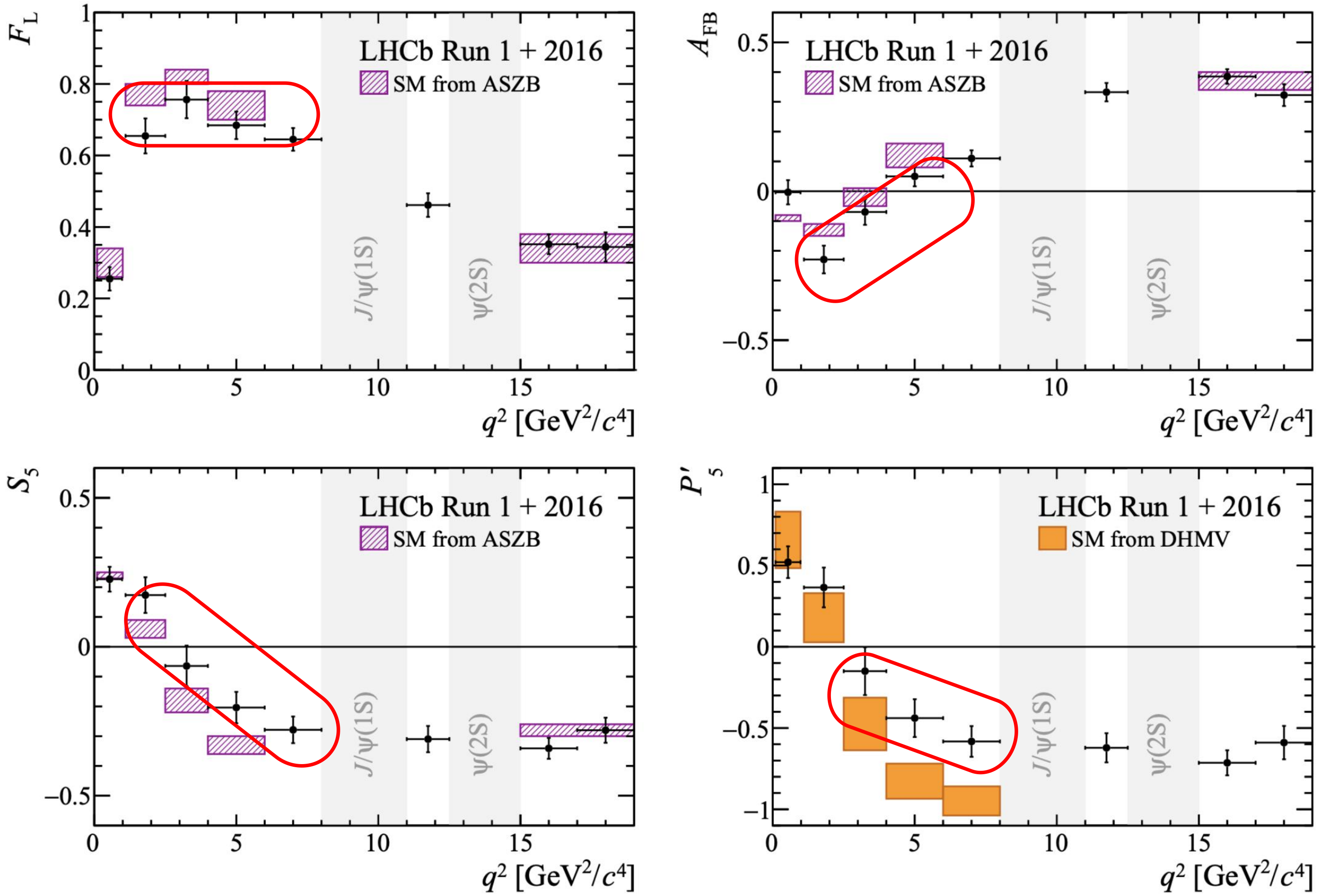
$$\frac{1}{\mathrm{d}(\Gamma+\bar{\Gamma})/\mathrm{d}q^2}\frac{\mathrm{d}^3(\Gamma+\bar{\Gamma})}{\mathrm{d}\vec{\Omega}} = \frac{9}{32\pi}\Big[\tfrac{3}{4}(1-F_{\mathrm{L}})\sin^2\theta_K + F_{\mathrm{L}}\cos^2\theta_K + \tfrac{1}{4}(1-F_{\mathrm{L}})\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_{\mathrm{L}}\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi$$
$$+ S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi + S_5\sin 2\theta_K\sin\theta_\ell\cos\phi$$
$$+ \tfrac{4}{3}A_{\mathrm{FB}}\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$P_5' = \frac{S_5}{\sqrt{F_{\mathrm{L}}(1-F_{\mathrm{L}})}}$$

Most famous

Credit: Stolen from C. Langenbruch at Moriond EW 2023

Anomalies in B meson semileptonic decays



~3σ deviation

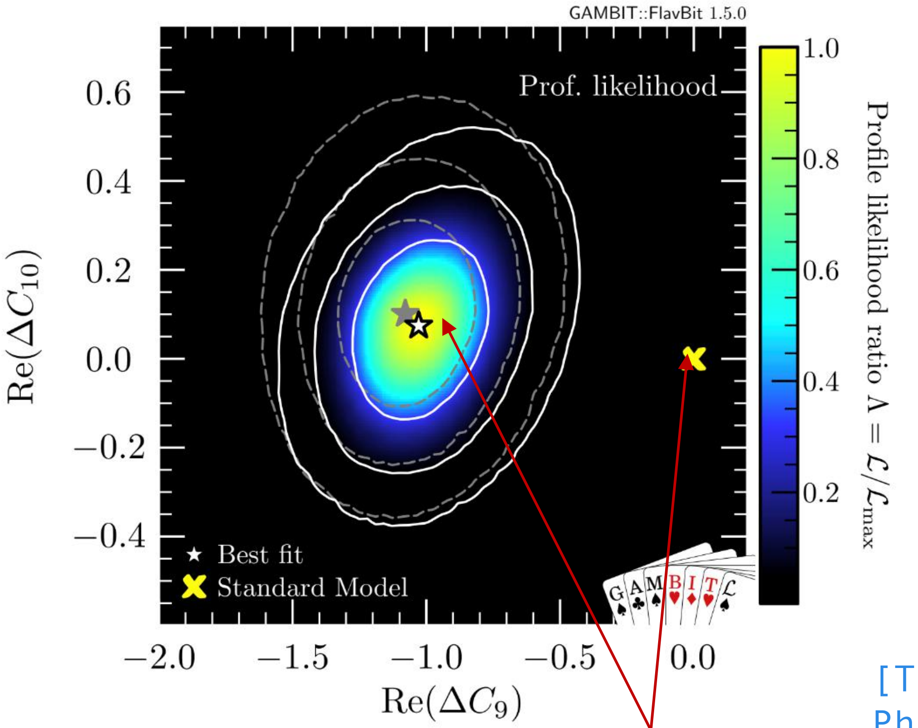
LHCb collaboration, Measurement of CP-averaged observables in the B0 → K*0μ+μ decay, Phys. Rev. Lett. 125 (2020) 011802 [arXiv:2003.04831]

Fit all Wilson Coefficients (WCs)

- $b \to s\mu^+\mu^-$ **observables included in the model independent analysis from** `[J. Bhom et al, arXiv: 2006.03489]` **get modified by the new Wilson coefficients.**

>200 observables on *b* → *s* transitions

(most of them are angular observables)



~6σ deviation

All observables with $\chi^2_{\rm SM} = 157.28$ ($\chi^2_{\rm min} = 100.34$; Pull$_{\rm SM} = 4.3\sigma$)			
δC_7 0.05 ± 0.03		δC_8 -0.71 ± 0.43	
$\delta C_7'$ -0.01 ± 0.02		$\delta C_8'$ -0.09 ± 0.86	
δC_9^μ -1.11 ± 0.19	δC_9^e -6.69 ± 1.37	δC_{10}^μ 0.08 ± 0.25	δC_{10}^e 3.97 ± 4.99
$\delta C_9'^\mu$ 0.18 ± 0.35	$\delta C_9'^e$ 1.84 ± 1.75	$\delta C_{10}'^\mu$ -0.13 ± 0.21	$\delta C_{10}'^e$ 0.05 ± 5.01
$C_{Q_1}^\mu$ -0.07 ± 0.12	$C_{Q_1}^e$ -1.52 ± 0.98	$C_{Q_2}^\mu$ -0.10 ± 0.14	$C_{Q_2}^e$ -4.36 ± 1.46
$C_{Q_1}'^\mu$ 0.05 ± 0.12	$C_{Q_1}'^e$ -1.40 ± 1.56	$C_{Q_2}'^\mu$ -0.17 ± 0.15	$C_{Q_2}'^e$ -4.33 ± 2.33

`[T. Hurtha, F. Mahmoudi, S. Neshatpour Phys.Rev.D 102 (2020) 5, 055001]`

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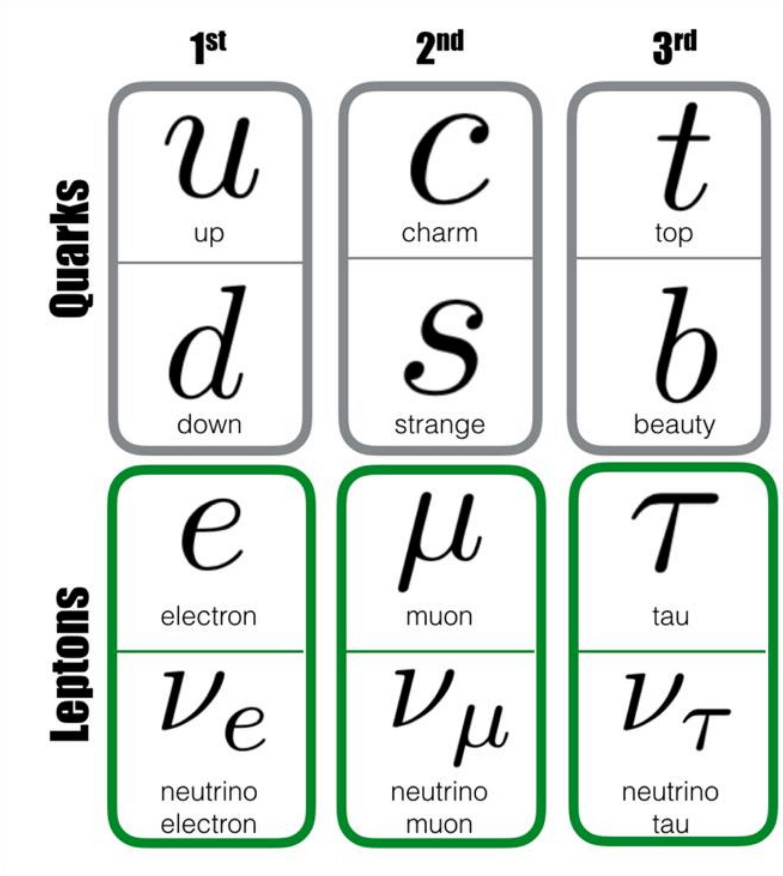
Fermions + second Higgs doublet



$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + H_1 + i\eta_1) \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + H_2 + i\eta_2) \end{pmatrix}$$

Adding a second Higgs doublet is one of the simplest extensions of the SM

Image credit: Physik-Institut - UZH

Flavour changing transitions

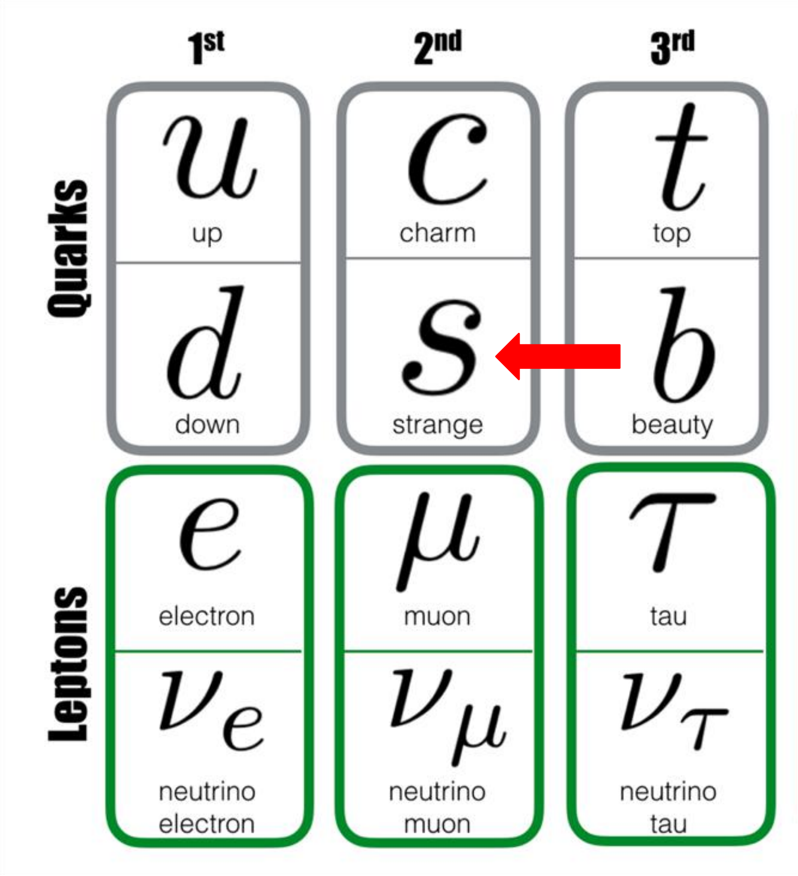
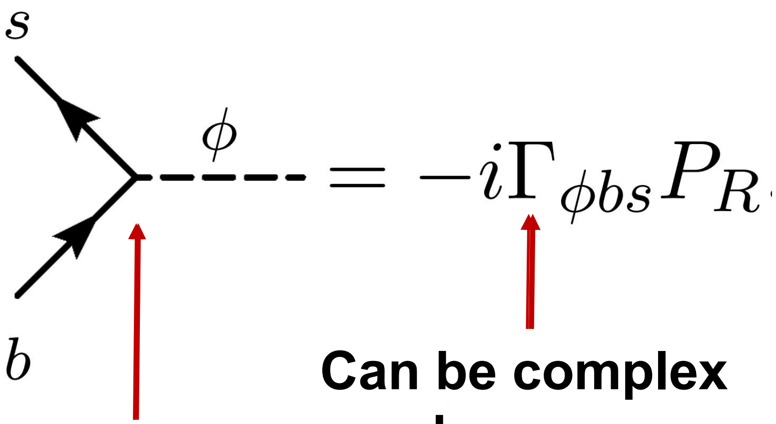


Image credit: Physik-Institut - UZH

$$\phi = h,\, H,\, A$$



$$= -i\Gamma_{\phi bs} P_R$$

Not CKM suppressed!

Can be complex numbers (*general 2HDM*)

Yukawa Lagrangian

$$
\begin{aligned}
-\mathcal{L}_{Yukawa} =& \bar{u}_b \left(V_{bc}\boxed{\rho_d^{ca}} P_R - V_{ca}\boxed{\rho_u^{cb*}} P_L \right) d_a \, H^+ + \bar{\nu}_b \boxed{\rho_\ell^{ba}} P_R l_a \, H^+ + \text{h.c.} \\
&+ \sum_{f=u,d,\ell} \sum_{\phi=h,H,A} \bar{f}_b \boxed{\Gamma_f^{\phi ba}} P_R f_a \phi + \text{h.c.},
\end{aligned}
$$

general 2HDM (G2HDM)

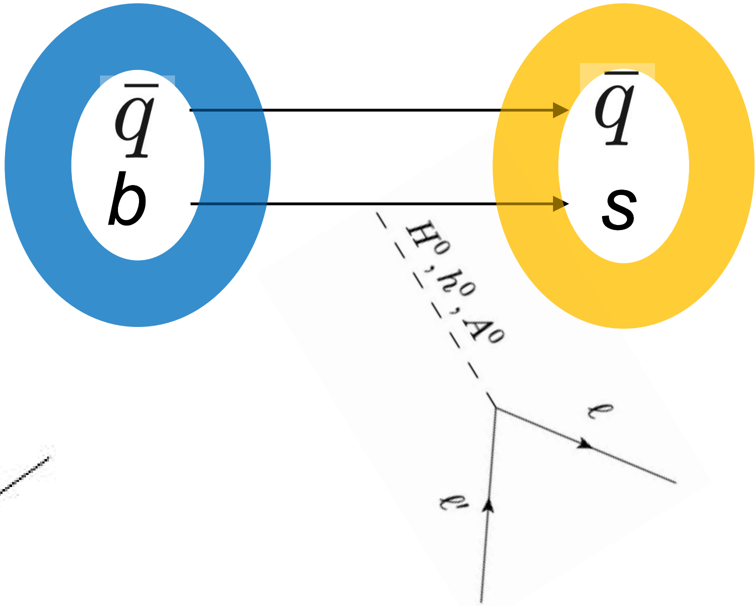
New couplings constrained by

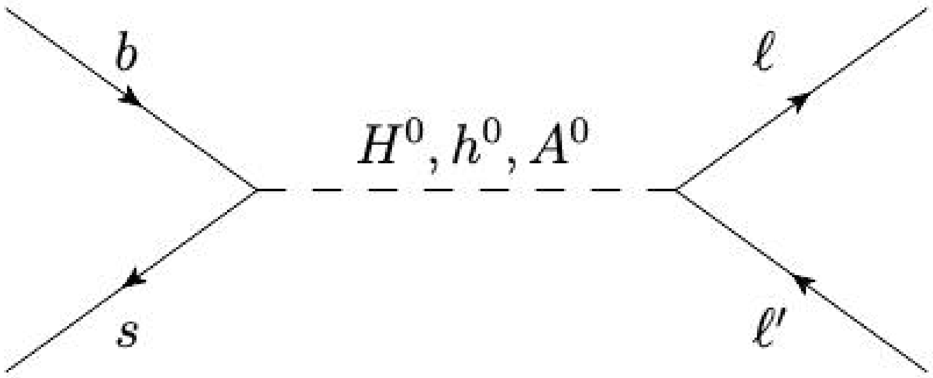
- ***Stability, perturbativity and unitarity***
- ***Strong flavour constraints***

WCs with in the G2HDM

Tree level diagrams

树
Shù

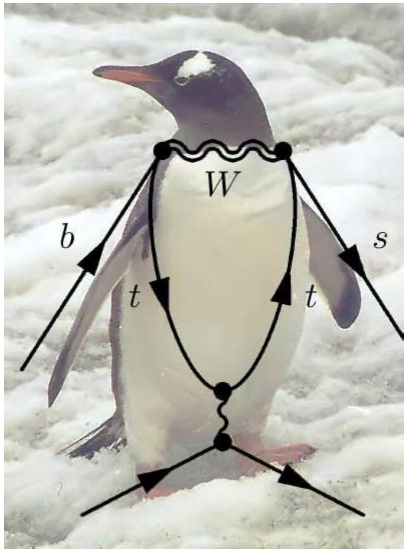




Neutral currents

Pseudo-scalar and scalar NP encoded in $C_{P,S}$

Penguin diagrams



企鹅 - Qì'é

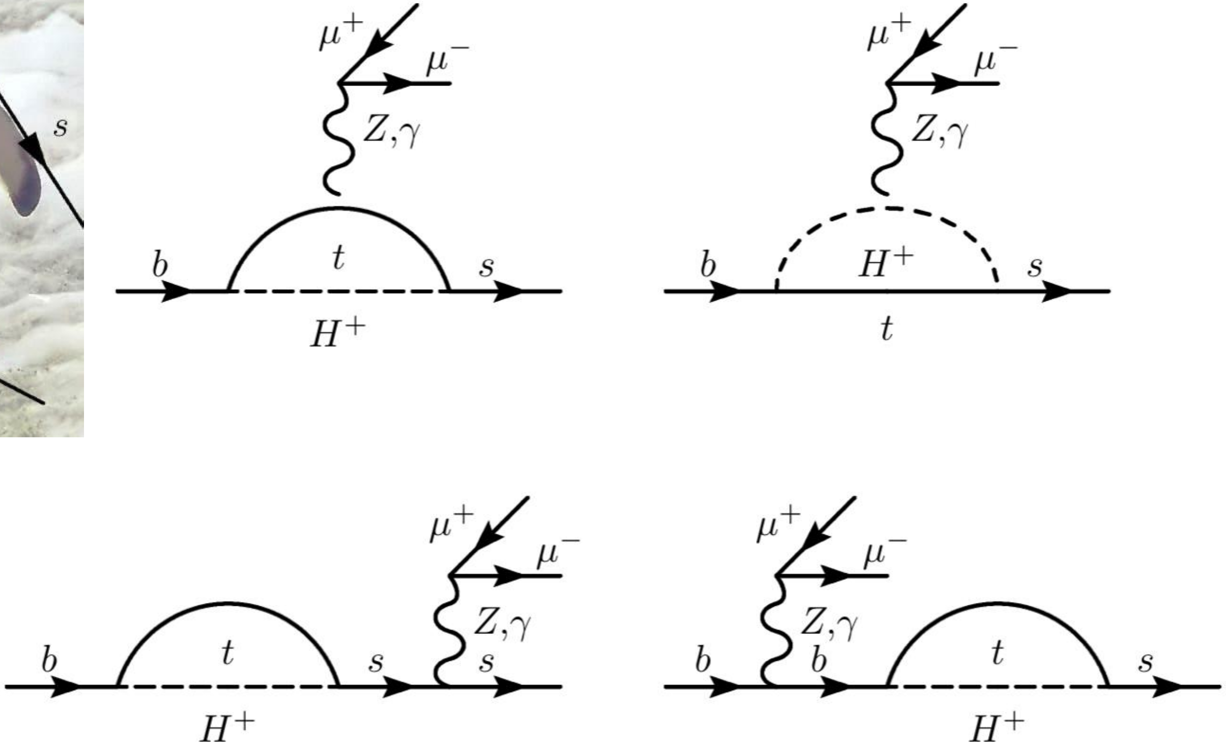


Figure 2: Penguin diagrams at one loop level for $b \to s\mu^+\mu^-$ transitions.

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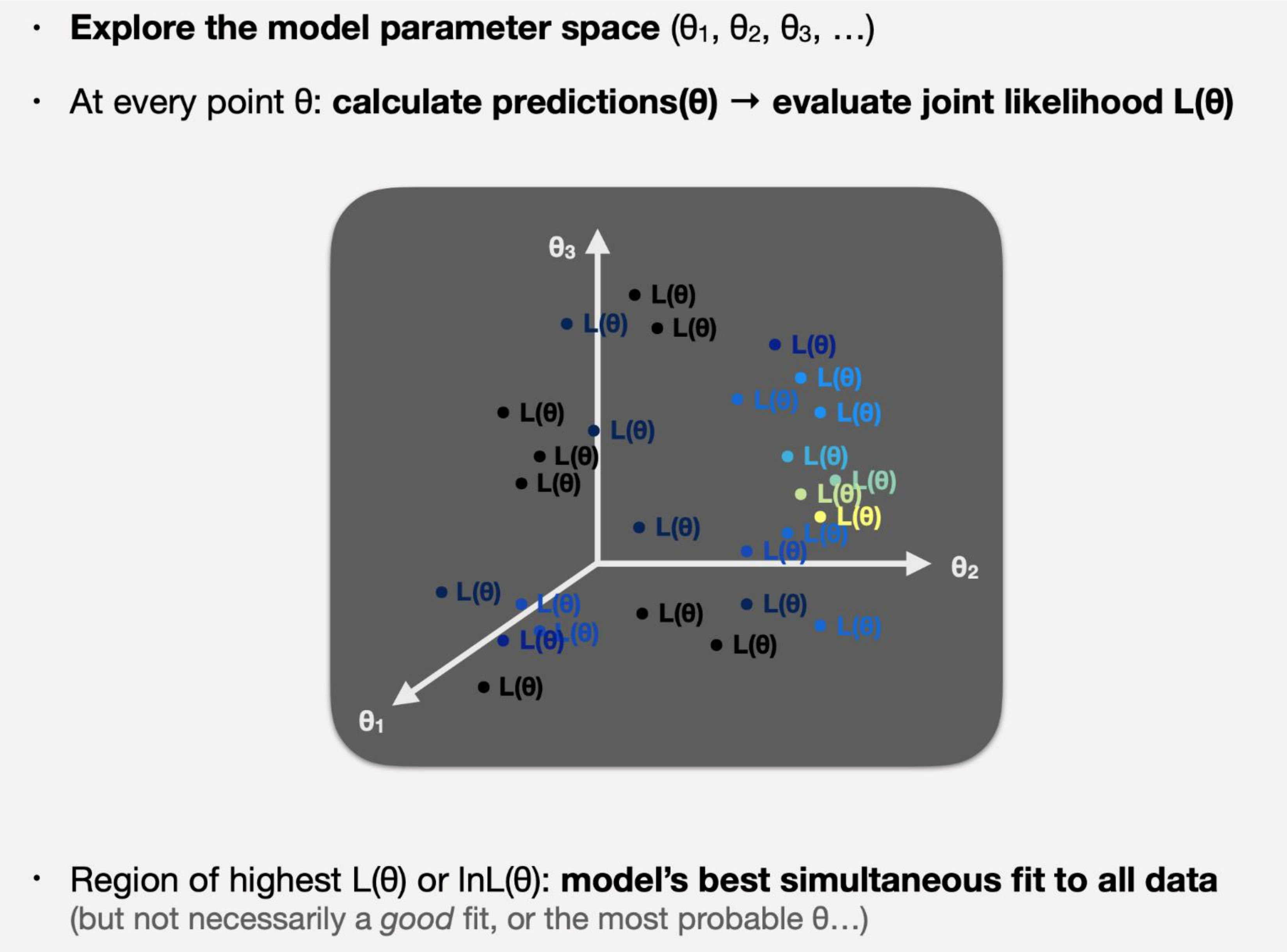
The code: GAMBIT

The **G**lobal **A**nd **M**odular **B**SM **I**nference **T**ool

- Open-source code in **C++** to calculate observables and ***likelihoods*** for generic Beyond the Standard Model(s) theories.
- Modular: ***modules*** provide **GAMBIT** with a range of functions (capabilities) to calculate a certain quantity.
- **GAMBIT** samples the parameter space by calling the necessary modules and backend functions for each parameter point, e.g., performing a global fit.

Likelihood functions and Global fits



- **Explore the model parameter space** (θ_1, θ_2, θ_3, …)
- At every point θ: **calculate predictions(θ) → evaluate joint likelihood L(θ)**
- Region of highest L(θ) or lnL(θ): **model's best simultaneous fit to all data** (but not necessarily a *good* fit, or the most probable θ…)

Taken from Anders Kvellestad' s talk at the Norwegian Physical Society

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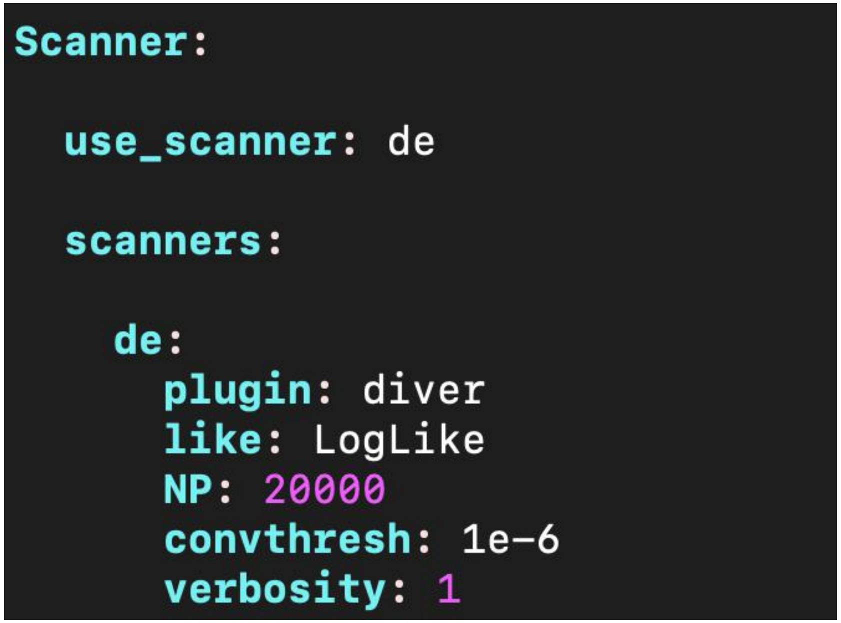
Scans

CP conserving potential close to the alignment limit

LUMI supercomputer (Large Unified Modern Infrastructure) in Kajaani (LUMI also means snow in Finish.). 5th most powerful in the world.

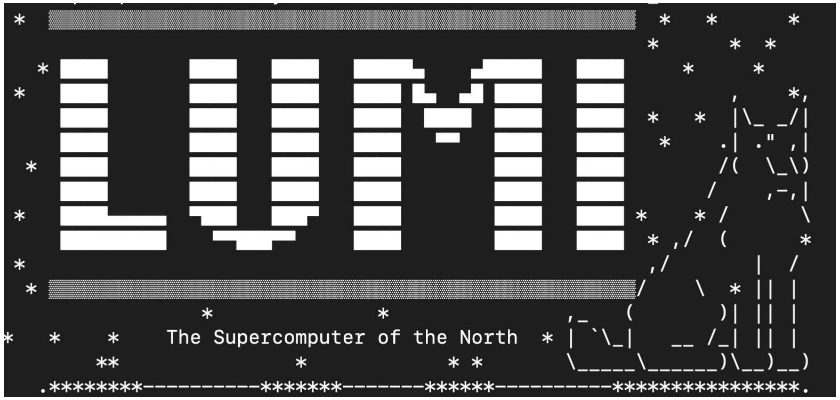


```
Scanner:

  use_scanner: de

  scanners:

    de:
      plugin: diver
      like: LogLike
      NP: 20000
      convthresh: 1e-6
      verbosity: 1
```



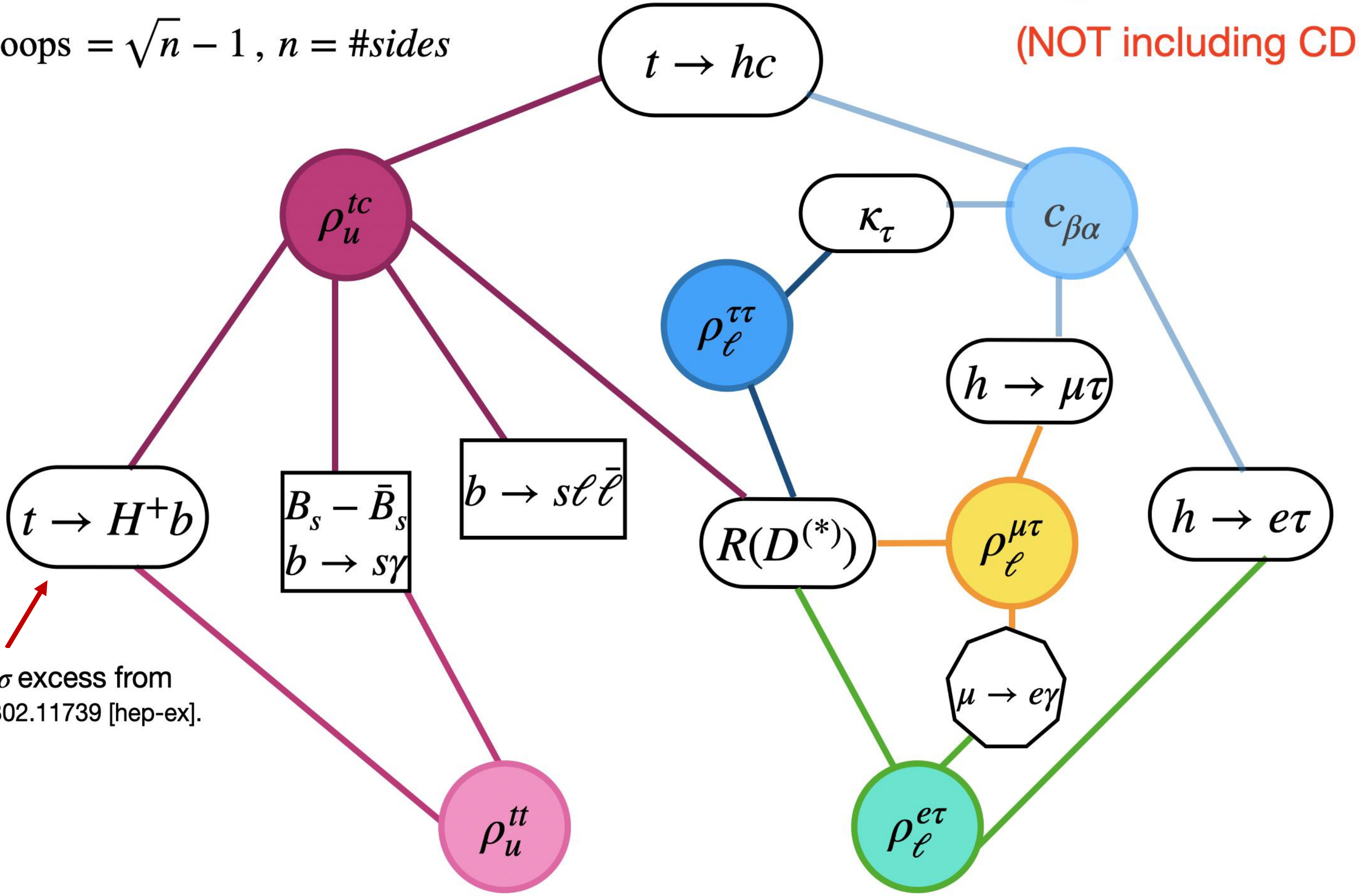
(~22 hours/scan with 512 cores on the small partition)
So far I have used more than 300 hours.

Observables and couplings

m_W from PDG 2024

(NOT including CDF-II)

Loops $= \sqrt{n} - 1\,,\ n = \#sides$



$t \to hc$

ρ_u^{tc}

$c_{\beta\alpha}$

κ_τ

$\rho_\ell^{\tau\tau}$

$h \to \mu\tau$

$t \to H^+ b$

$B_s - \bar{B}_s$

$b \to s\gamma$

$b \to s\ell\bar{\ell}$

$R(D^{(*)})$

$\rho_\ell^{\mu\tau}$

$h \to e\tau$

$\mu \to e\gamma$

ρ_u^{tt}

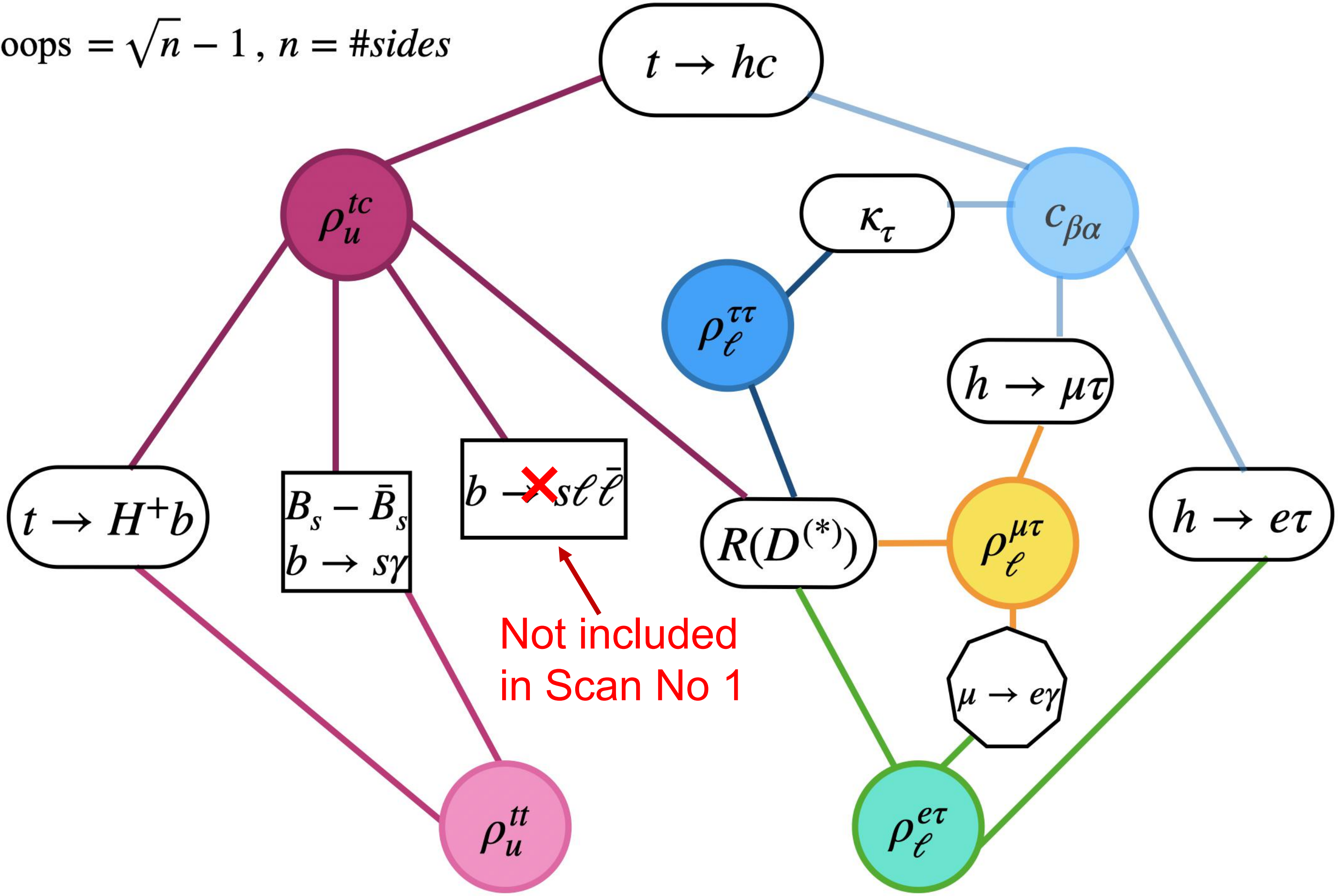
$\rho_\ell^{e\tau}$

130 GeV 3σ excess from ATLAS arXiv:2302.11739 [hep-ex].

Adapted from Phys.Rev.D 110 (2024) 1, 015014 • e-Print: 2311.03430 [hep-ph]

Scan No 1

$\text{Loops} = \sqrt{n} - 1\,,\ n = \#sides$

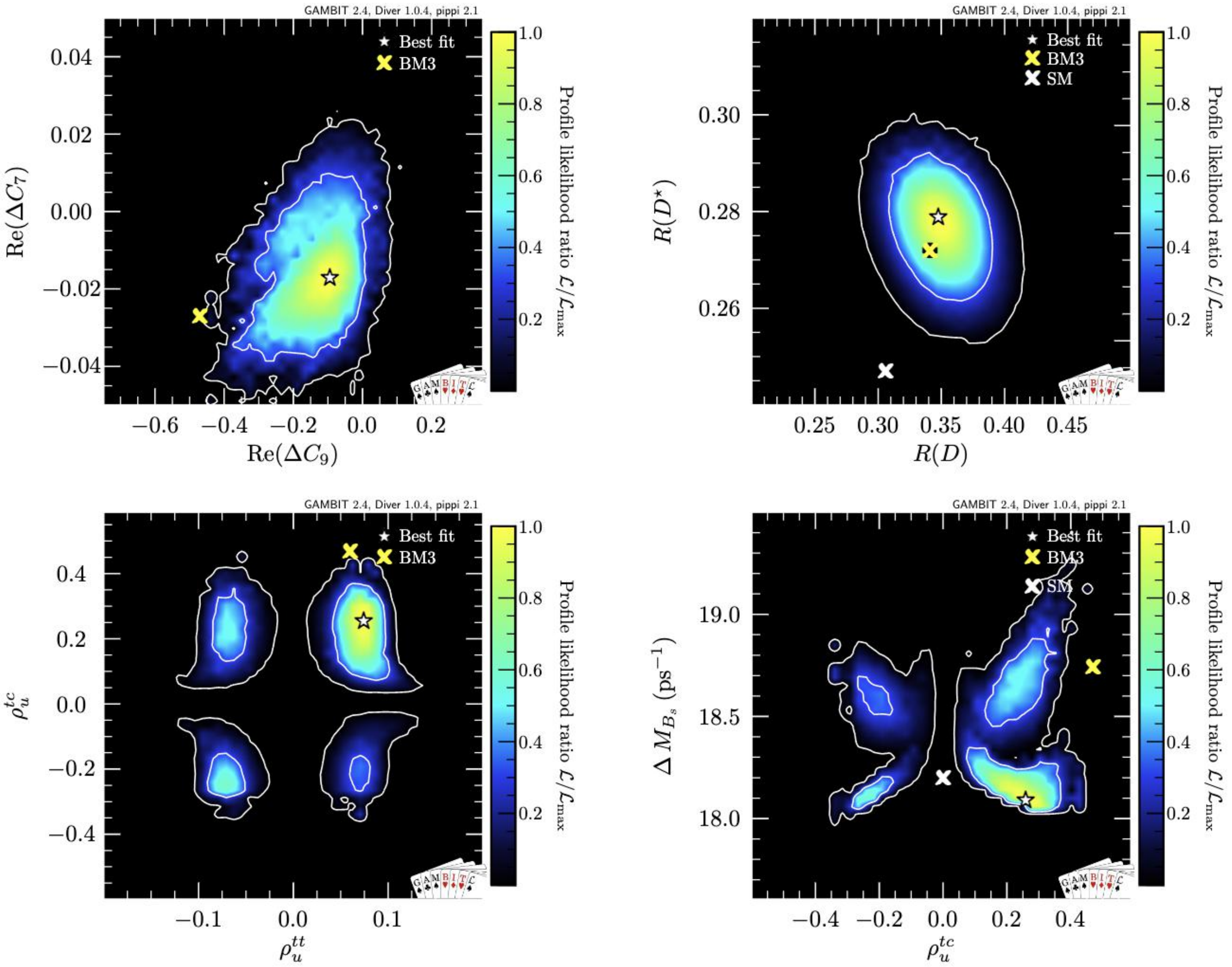


Not included in Scan No 1

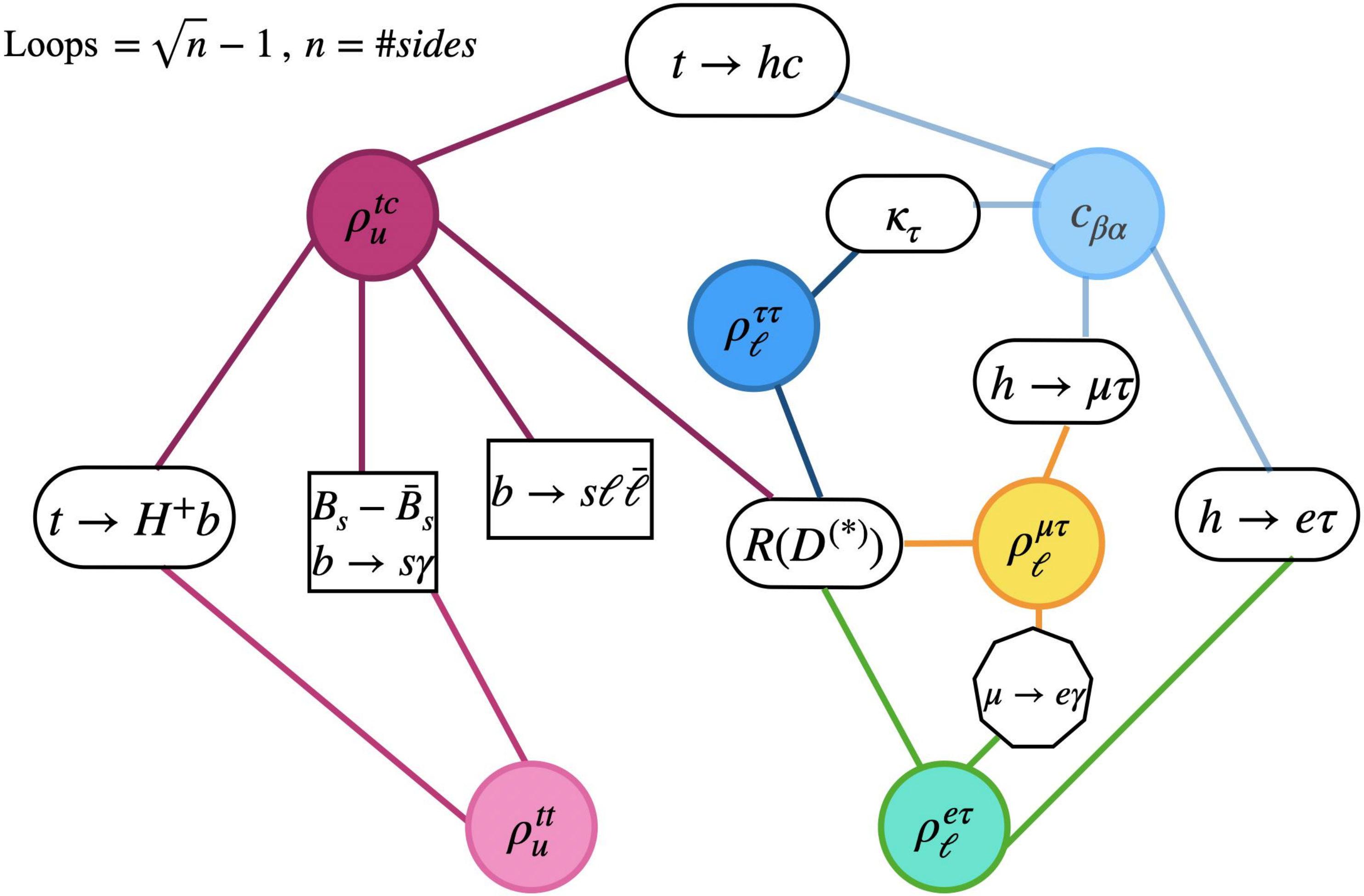
Adapted from Phys.Rev.D 110 (2024) 1, 015014 • e-Print: 2311.03430 [hep-ph]

Scan No 1

Parameter space and best fit values



Scan No 2



$\text{Loops} = \sqrt{n} - 1\,,\ n = \#sides$

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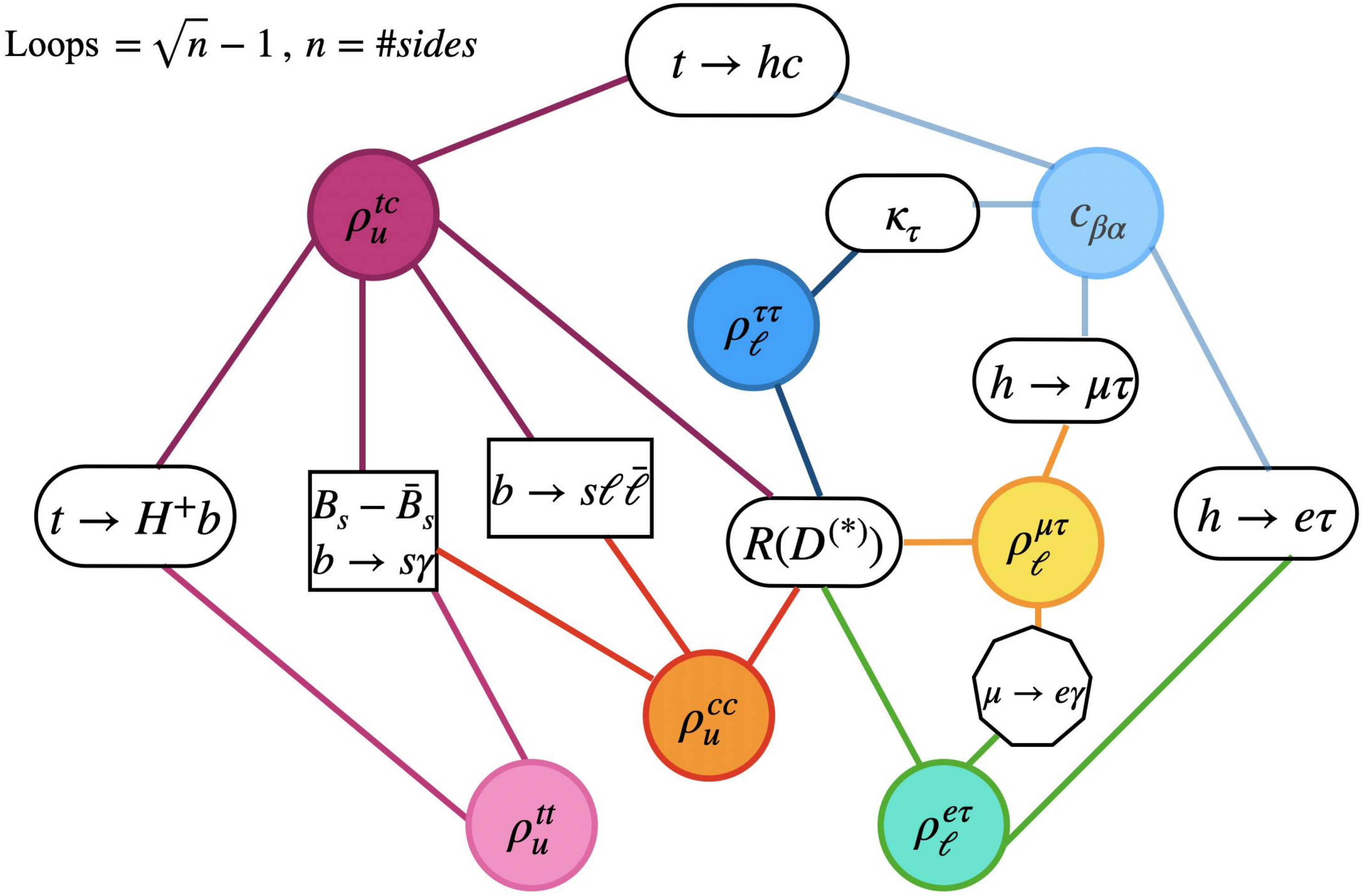
Scan No 2



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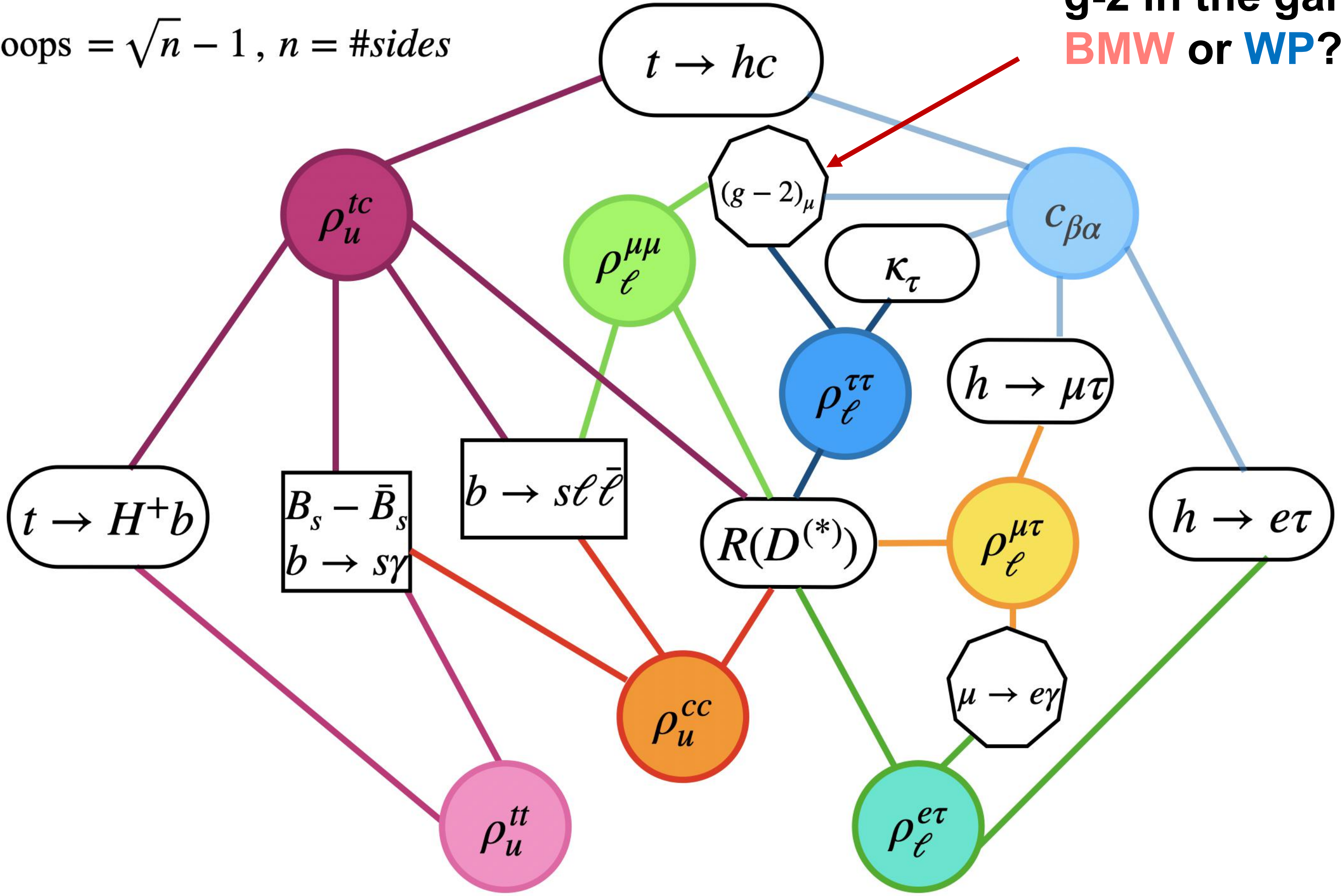
Scan No 2

Loops $= \sqrt{n} - 1$, $n = \#sides$

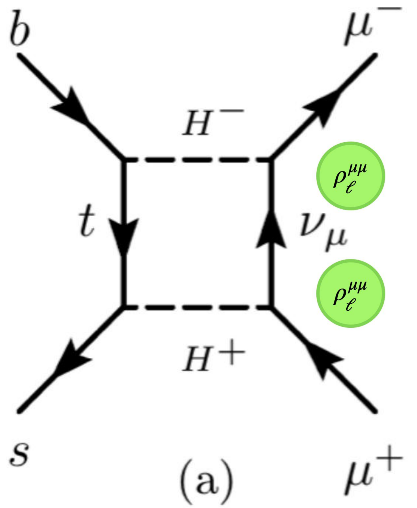


g-2 in the game,
BMW or WP?

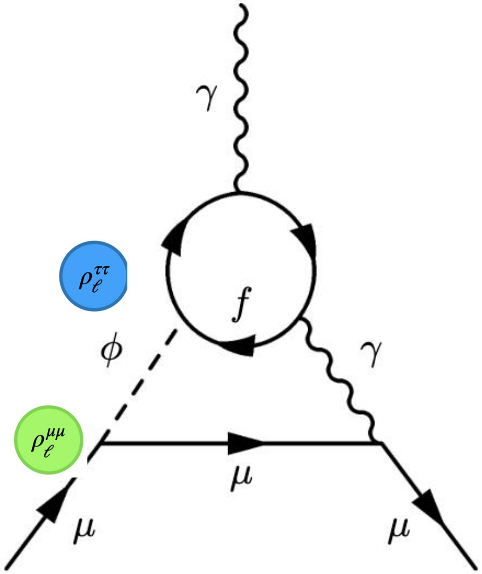
Adapted from Phys.Rev.D 110 (2024) 1, 015014 • e-Print: 2311.03430 [hep-ph]

New diagrams!

Box diagrams



Barr-Zee diagrams
in muon g-2

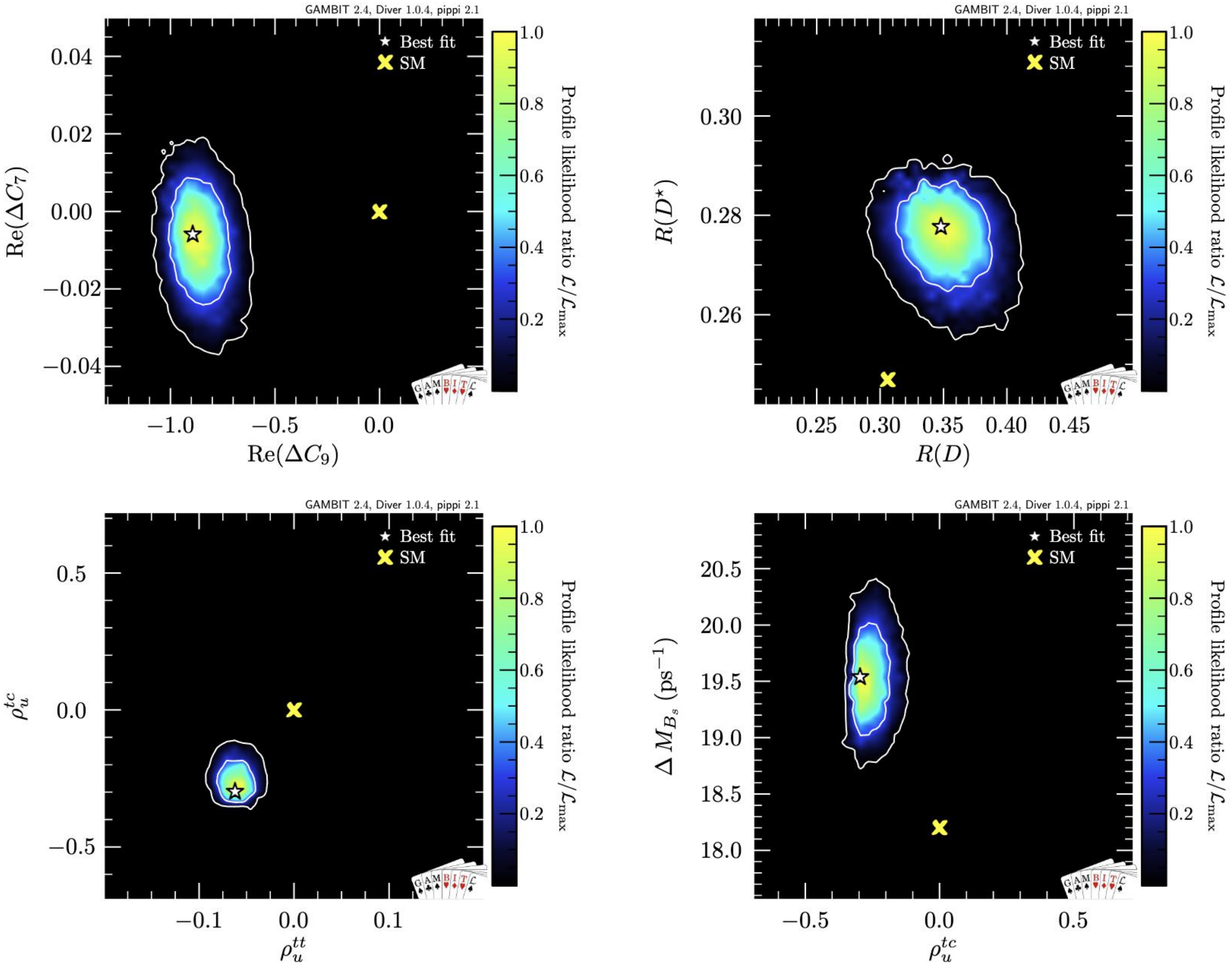


$$\phi = h, H, A$$

Scan No 2

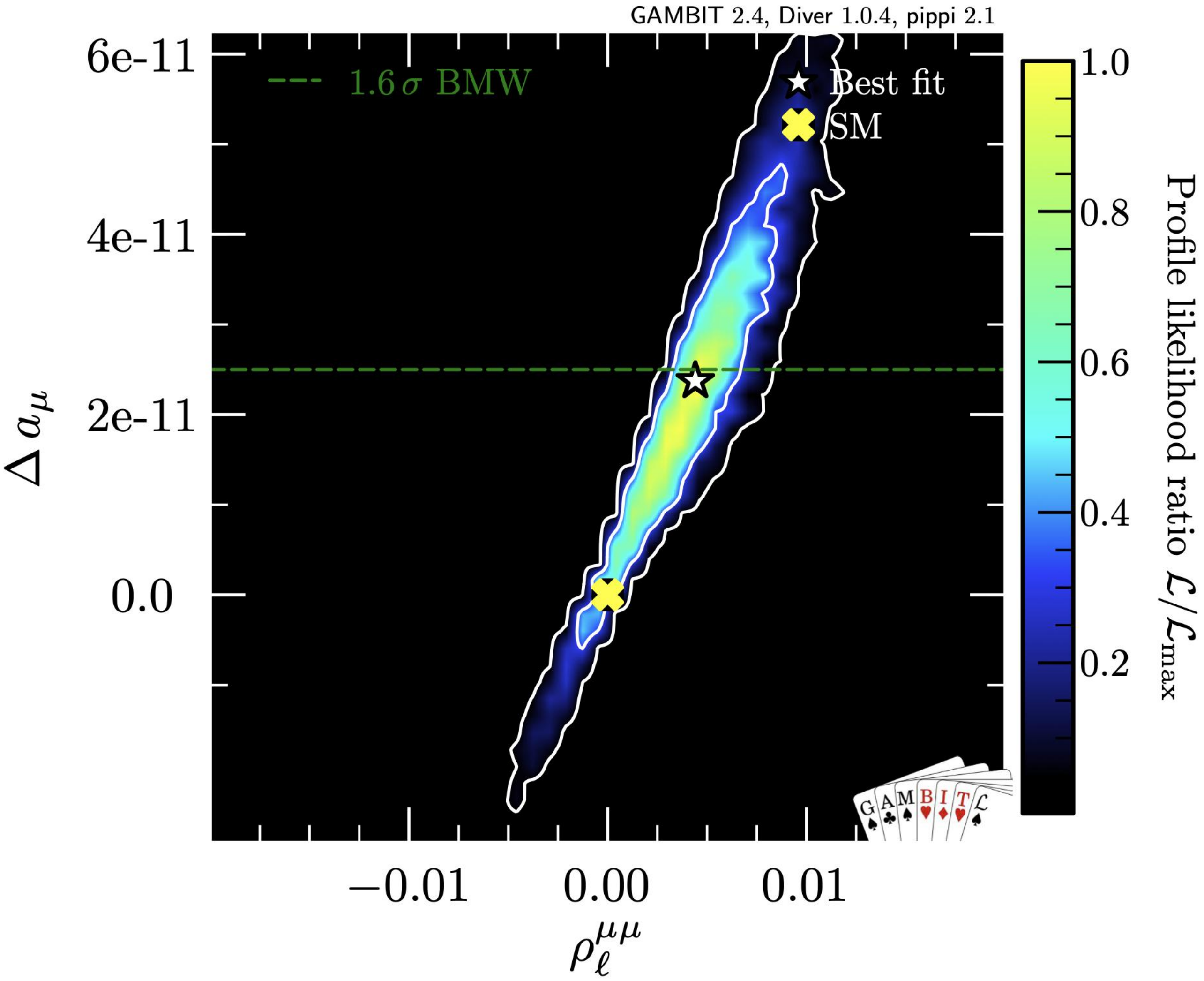
g-2 in the game, BMW

Parameter space and best fit values



Scan No 2

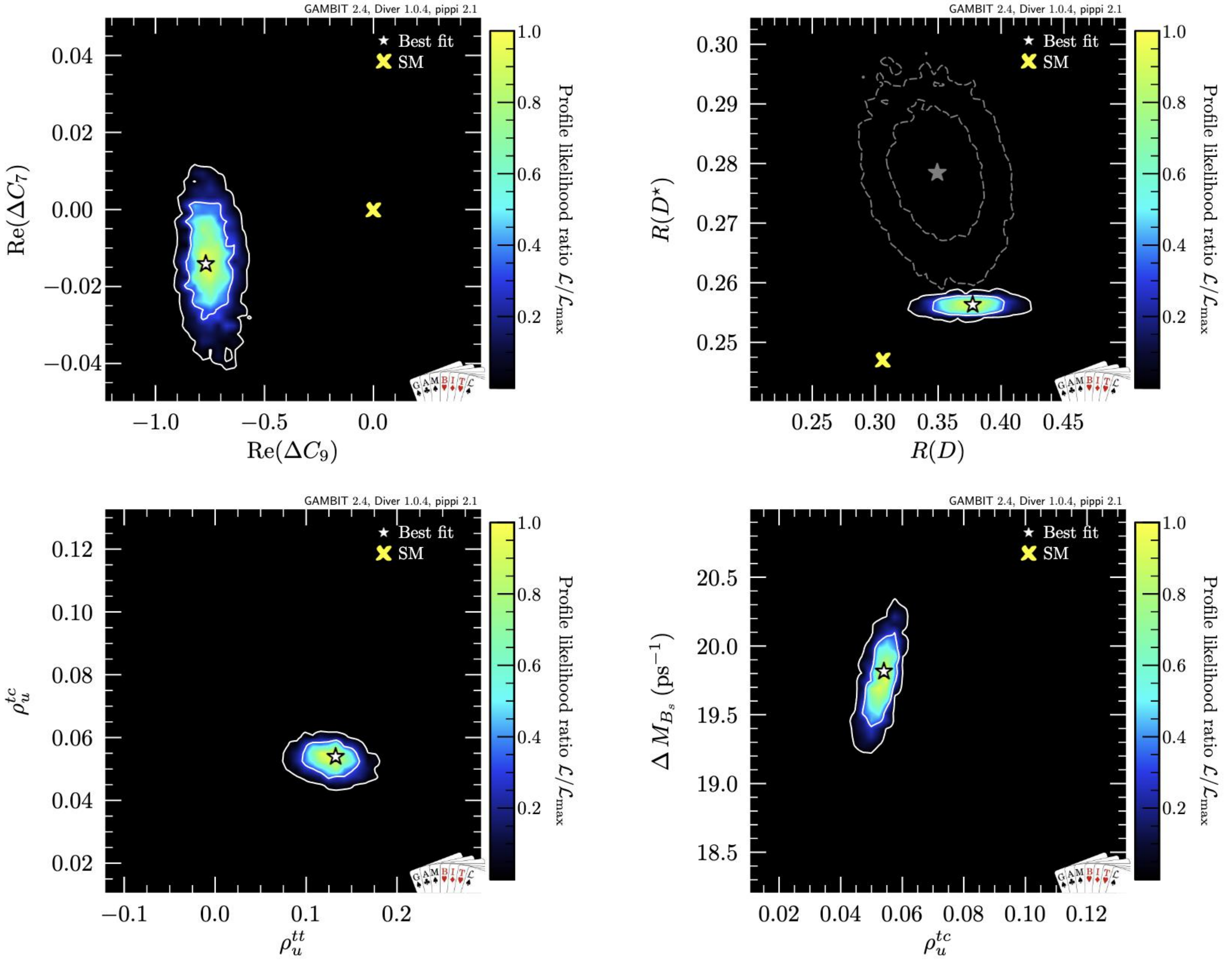
g-2 in the game, BMW



Scan No 3

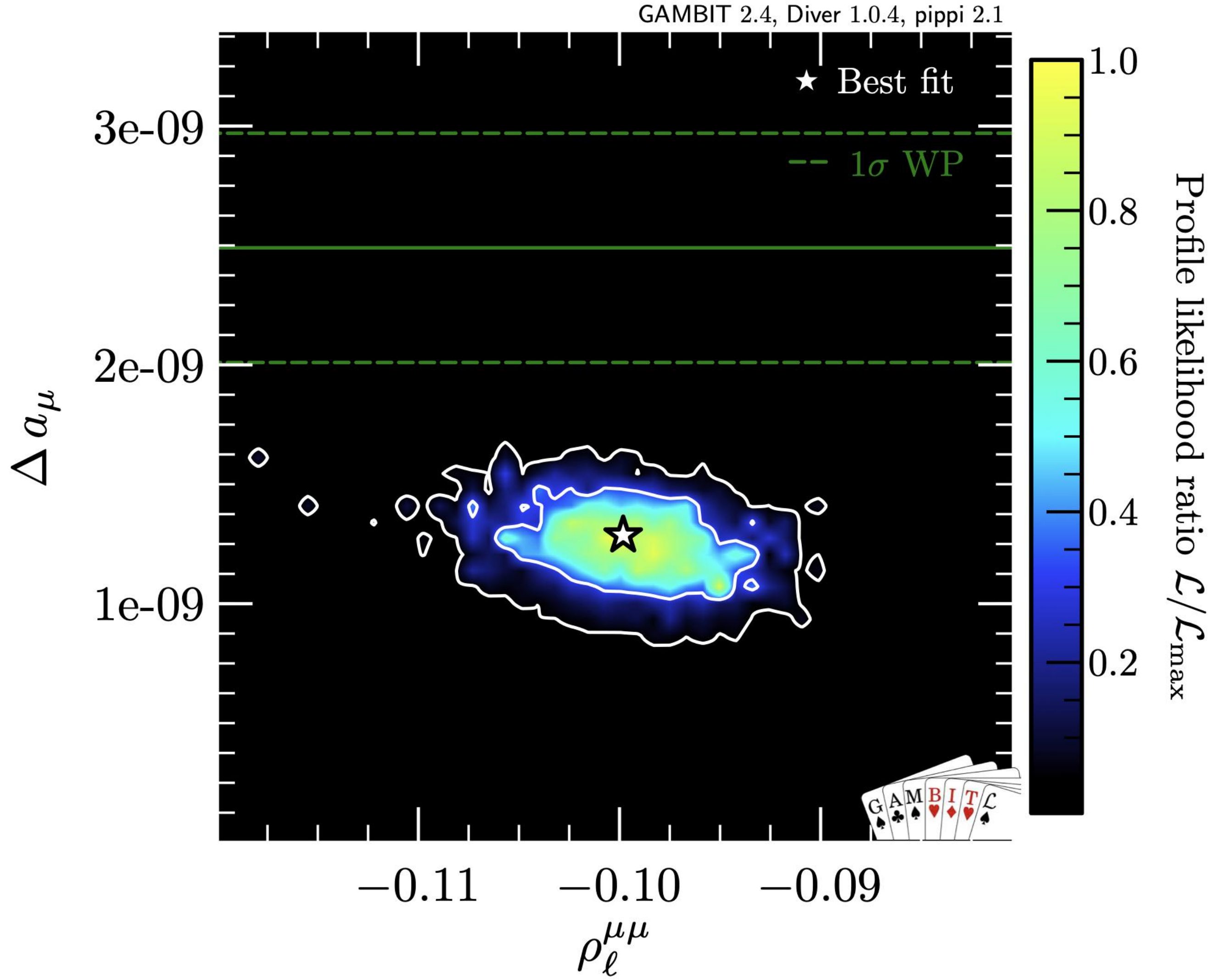
g-2 in the game, WP

Parameter space and best fit values



Scan No 2

g-2 in the game, WP



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Summary

- I presented a likelihood analysis for the G2HDM including both the charged and neutral anomalies along other flavour observables.

- We found that the model can explain the neutral anomalies at the 1 sigma level at the same time that the BMW muon g-2 value and the PDG 2024 data for the mW mass (not including CDF-II data).

- The model will require small b-s flavour violation at tree level in order to explain Bs-Bs mixing.

- When using PDF 2024 data, the model can explain WP value at the 2 sigma level altough large charm-charm extra Yukawas are needed and the charged anomalies can not be explained.

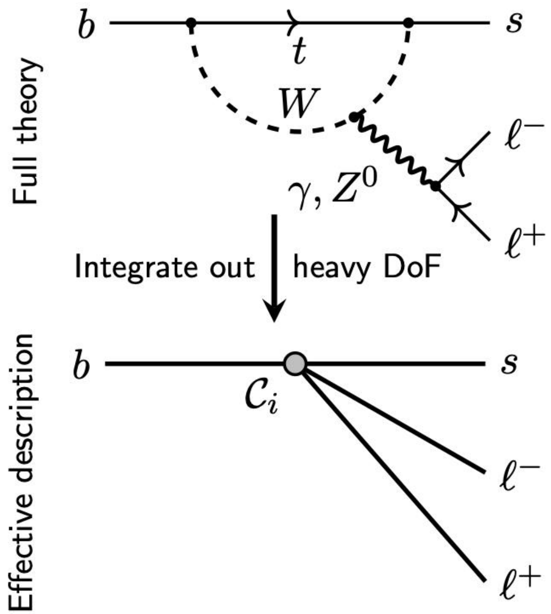
- Next step is to study what happens when using CDF-II data.

Thanks!

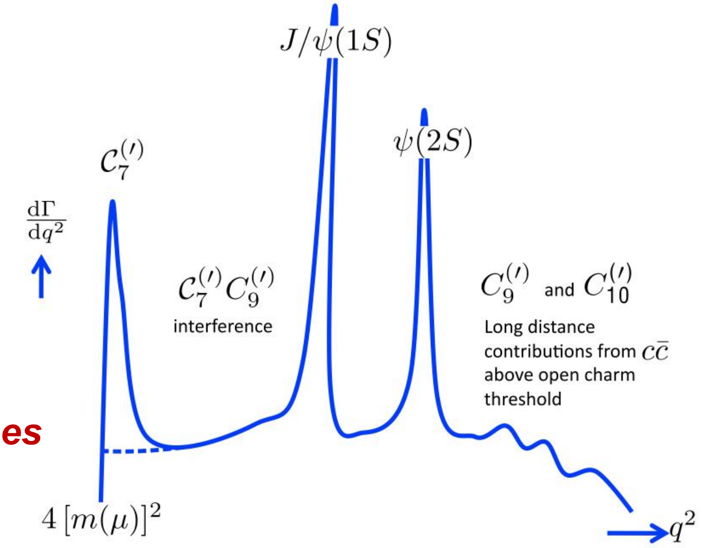
(谢谢您!)

Backup slides

How to explain them?: *New Physics Story*



-Leptoquarks
-Z' bosons
-Heavy Higgses
-?



- $b \to s\ell\ell$ transitions described model-independently in effective theory

Local operator

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{\text{tb}} V_{\text{ts}}^* \frac{e^2}{16\pi^2} \sum_i \boxed{\mathcal{C}_i}\,\boxed{\mathcal{O}_i}$$

Wilson coefficient ("effective coupling")

Effective couplings in $b \to s\ell\ell$ transitions

Wilson coefficient		Operator
γ-penguin	$\mathcal{C}_7^{(\prime)}$	$\frac{e}{g^2} m_b(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$
ew. penguin	$\mathcal{C}_9^{(\prime)}$	$\frac{e^2}{g^2}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\mu)$
	$\mathcal{C}_{10}^{(\prime)}$	$\frac{e^2}{g^2}(\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\mu}\gamma^\mu\gamma_5\mu)$
scalar	$\mathcal{C}_S^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b(\bar{s}P_{R(L)}b)(\bar{\mu}\mu)$
pseudoscalar	$\mathcal{C}_P^{(\prime)}$	$\frac{e^2}{16\pi^2} m_b(\bar{s}P_{R(L)}b)(\bar{\mu}\gamma_5\mu)$

`For completeness`

- Different $q^2 = m^2(\ell^+\ell^-)$ regions probe different operator combinations

Credit: Stolen from C. Langenbruch at Moriond EW 2023

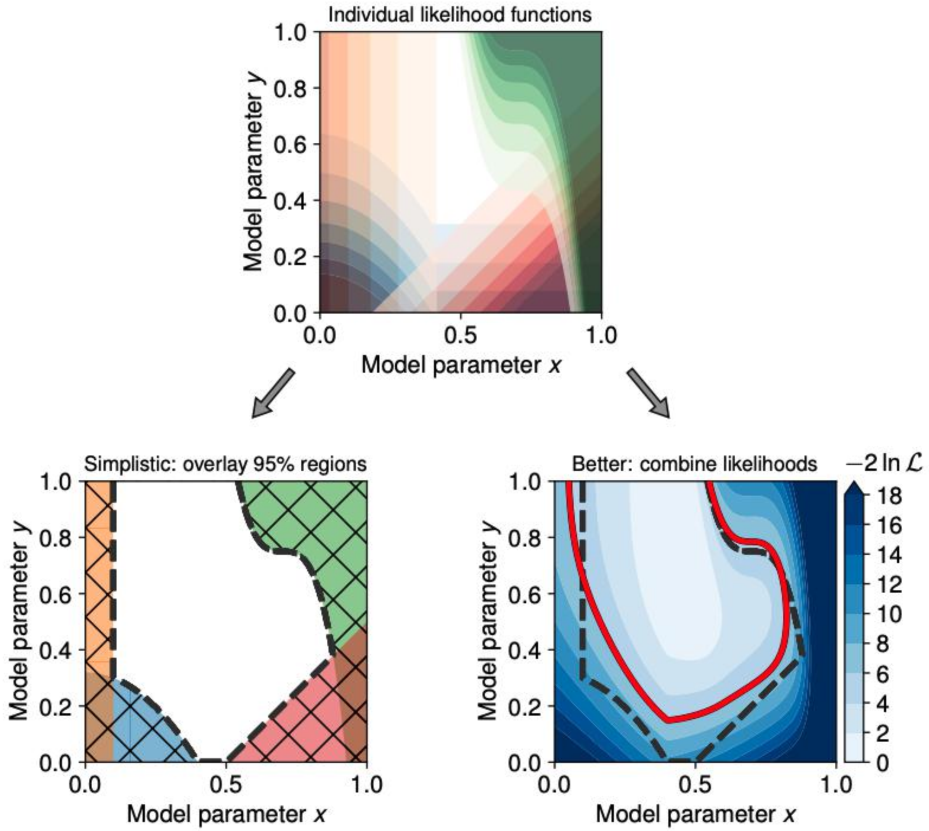
Likelihood functions and Global fits

- In general, we have several likelihood functions from different observables: Combine all constraints into a composite likelihood,

$$\mathcal{L} = \mathcal{L}_{Flavour}\mathcal{L}_{Higgs}\mathcal{L}_{Collider}\cdots$$

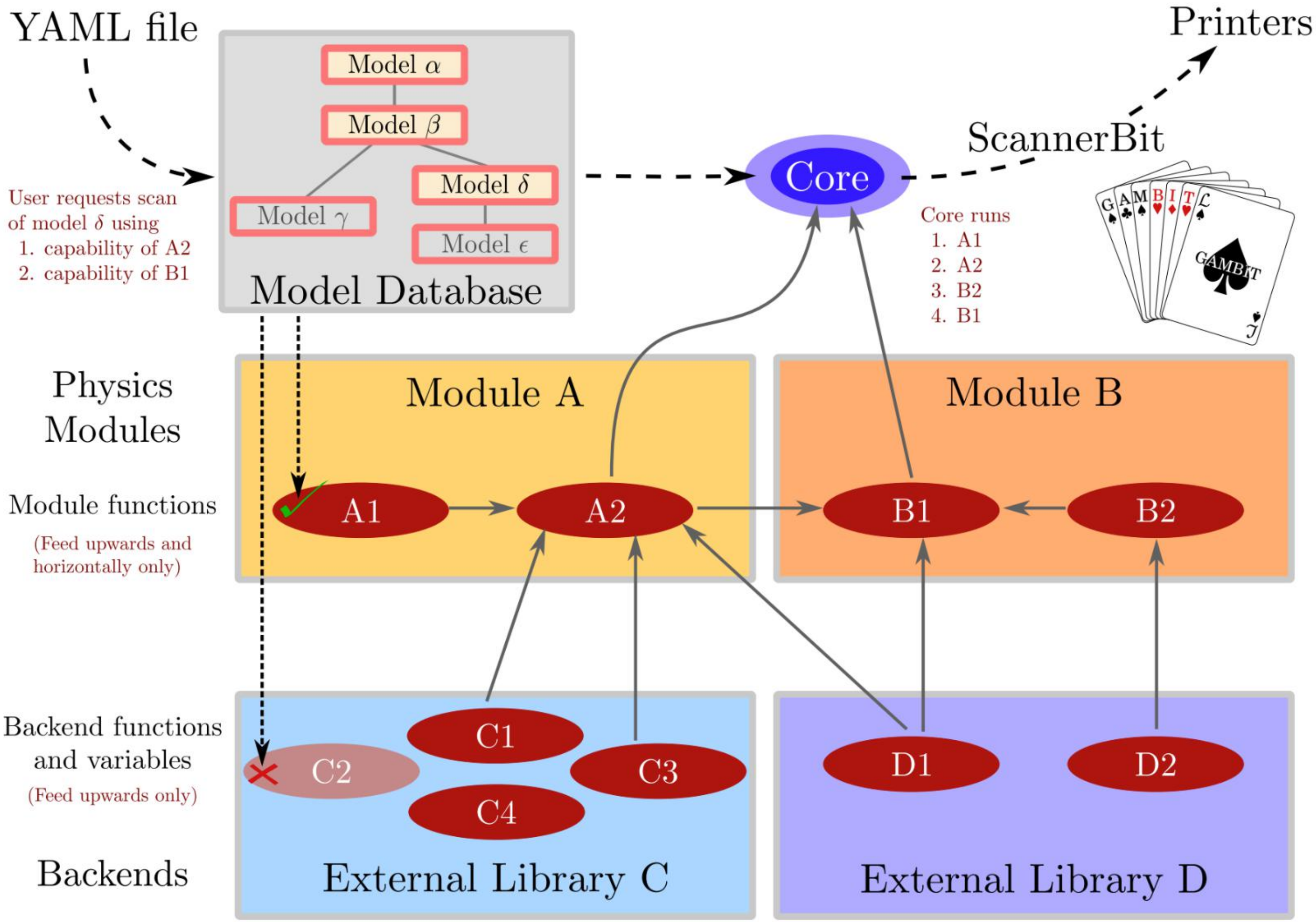
- Perform an extensive parameter scan with rigorous statistical interpretation (frequentist/Bayesian):
  - Parameter estimation.
  - Model comparison.

[GAMBIT Community, arXiv:2012.09874 [hep-ph]]



GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org



User requests scan of model δ using
1. capability of A2
2. capability of B1

(Feed upwards and horizontally only)

(Feed upwards only)

Core runs
1. A1
2. A2
3. B2
4. B1

Cristian Sierra

7/19/2024

Likelihood functions

Probability Distribution Functions (PDFs)

Statistical Model: PDFs for obtaining observations x given a set of params θ. → $p(x|\theta)$

Experiments provide observations of x which are used for inferences about components of θ.

Likelihood: We can compute theory predictions $x^{th}(\theta)$ so that

$$p(x^{exp}|\theta) = p(x^{exp},\, x^{th}(\theta)) \cdot$$

Evaluate the PDF only for the specific x^{exp} that was observed, and examine how it varies with θ

$$\mathcal{L}(\theta) = p(x^{exp},\, x^{th}(\theta))$$

Yukawa textures

- The number of free parameters from the Yukawas will be 54 (3x3x3x2).

$$\xi^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \xi^u_{cc} & \xi^u_{ct} \\ 0 & \xi^u_{tc} & \xi^u_{tt} \end{pmatrix}, \qquad \xi^d = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \xi^d_{ss} & \xi^d_{sb} \\ 0 & \xi^d_{bs} & \xi^d_{bb} \end{pmatrix}, \qquad \xi^l = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \xi^l_{\mu\mu} & \xi^l_{\mu\tau} \\ 0 & \xi^l_{\tau\mu} & \xi^l_{\tau\tau} \end{pmatrix},$$

Effective Hamiltonian for $b \to s\mu^+\mu^-$

$$\mathcal{H}_{\text{eff}}^{NP} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[\sum_{i=S,P} C_i^{(0)}\mathcal{O}_i + C_i^{\prime(0)}\mathcal{O}_i^\prime + \sum_{i=7,9,10} C_i^{(1)}\mathcal{O}_i + C_i^{\prime(1)}\mathcal{O}_i^\prime \right]$$

$$\mathcal{O}_9 = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \qquad \mathcal{O}_{10} = \frac{e^2}{16\pi^2}(\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),$$

$$\mathcal{O}_S = \frac{e^2}{16\pi^2} m_b(\bar{s}P_R b)(\bar{\ell}\ell), \qquad \mathcal{O}_P = \frac{e^2}{16\pi^2} m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5 \ell),$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b(\bar{s}\sigma^{\mu\nu} P_R b)F_{\mu\nu},$$

and prime operators from $P_R \to P_L$.

Fermions + second Higgs doublet

NEW PARTICLES!

h A H $H^{\pm}$

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + H_1 + i\eta_1) \end{pmatrix}$$

$$\Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2 + H_2 + i\eta_2) \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

Mixing parameters

$$\sin(\beta - \alpha)$$

Results

Branching ratios, arXiv: 2111.10464