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Electroweak baryogenesis from charged current anomalies in B meson decays

Scalars 2025, University of Warsaw, Faculty of Physics, Warsaw, Poland

Cristian Sierra, 2025年09月24日

- Motivation
- General Two Higgs Doublet Model (G2HDM)
- Flavour observables and constraints
    - Charged current anomalies
    - B meson oscillations and decays
- Parameter space scan
- EWBG
- Results
- Summary

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Motivation

1. ***Baryon asymmetry of the universe (BAU)***: Where did all the antimatter go? CP and baryon number were violated in the early universe, along a departure from thermal equilibrium **(Sakharov conditions)**.
2. ***CPV in the SM is not enough***. New sources of CPV are required (and thermal equilibrium departure).
3. ***Scalar or fermionic CPV?*** Scalar sector often selected, fermions offer rich pheno too if using complex Yukawas (will use the **general 2HDM**).
4. ***CPV in quarks or leptons?*** Quark CPV constrained by both EDMs, meson decays and oscillations. Let's use leptons (less constrained and can be linked to semi-leptonic decays.)
5. ***Electroweak baryogenesis (EWBG)***. Lepton CPV sources can generate the required BAU.

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General 2HDM

Adding a second Higgs doublet adds more degrees of freedom needed for a strong 1st PT (departure of thermal equilibrium.)

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \xi_i + i\eta_i) \end{pmatrix}, \quad i = 1, 2.$$

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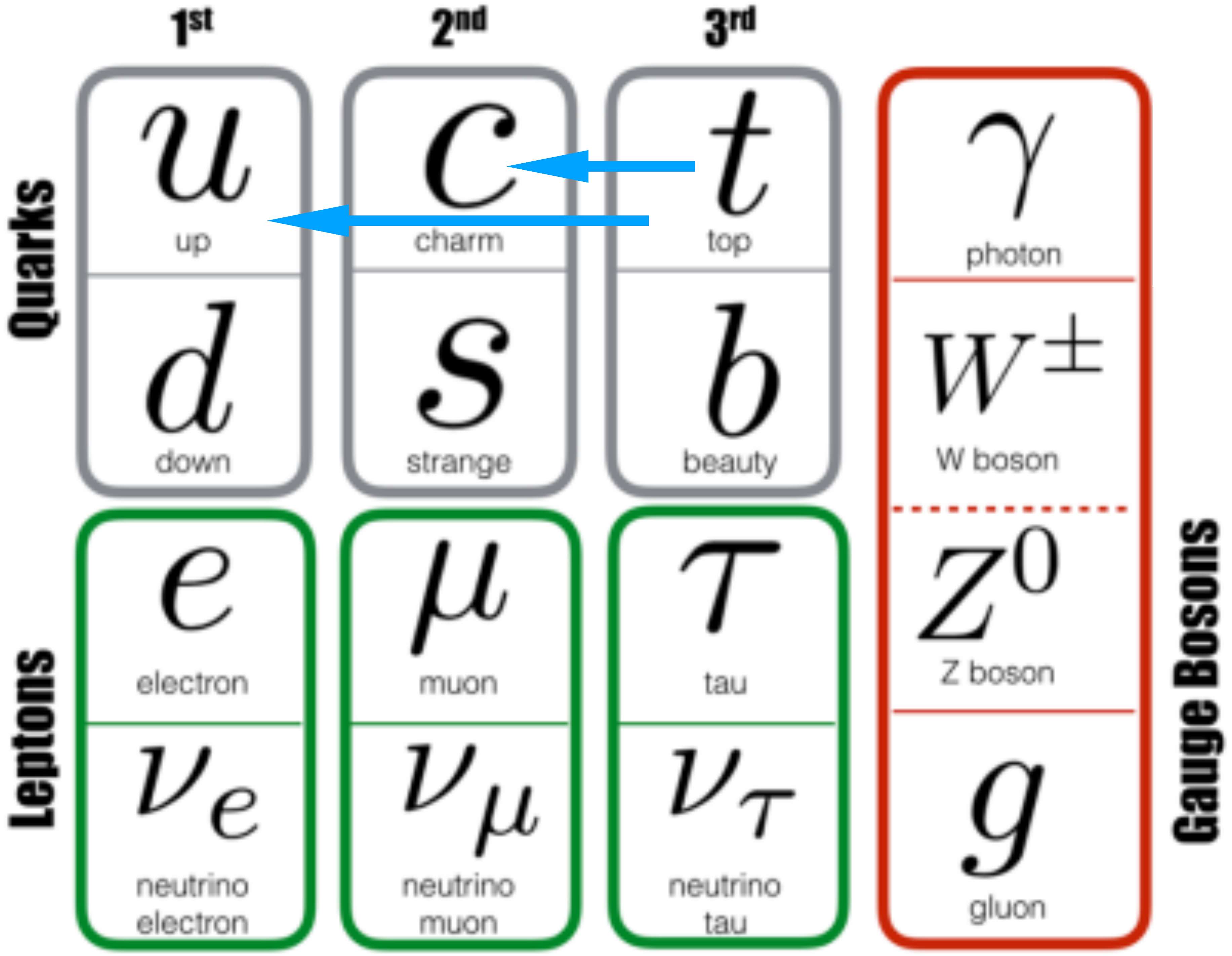


Image credit: Physik-Institut - UZH

In the mass basis, the Yukawa Lagrangian has the following flavour violating couplings (complex in general)

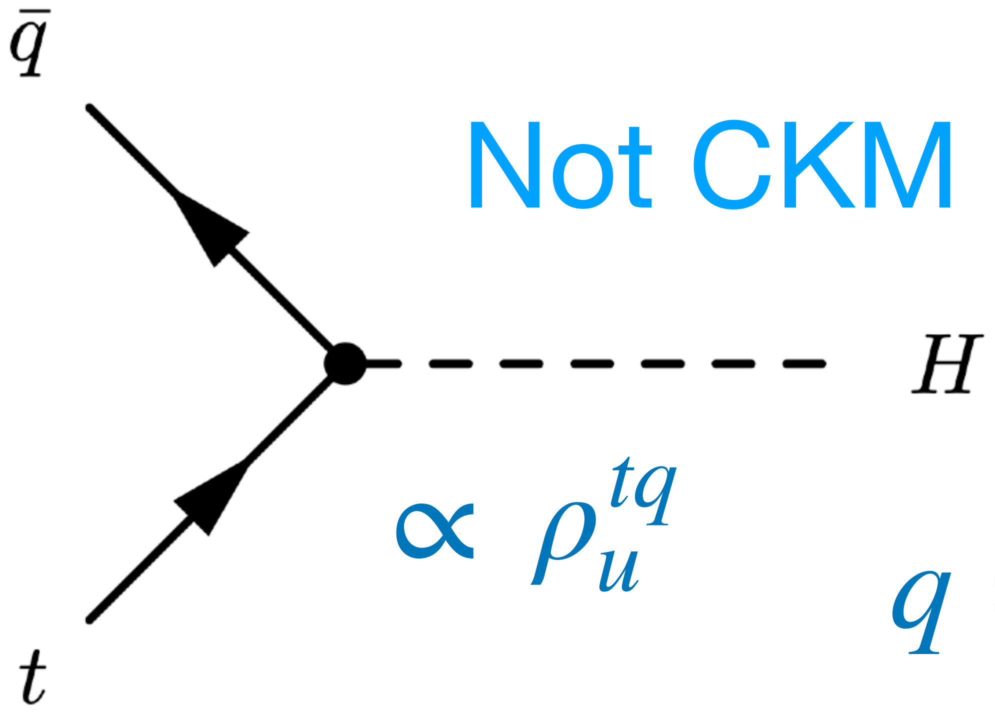
$$-\mathcal{L}_{Yukawa} = \bar{u}_b \left(V_{bc} \rho_d^{ca} P_R - V_{ca} \rho_u^{cb*} P_L \right) d_a H^+ + \bar{\nu}_b \rho_\ell^{ba} P_R l_a H^+ + \text{h.c.}$$
$$+ \sum_{f=u,d,\ell} \sum_{\phi=h,H,A} \bar{f}_b \Gamma_f^{\phi ba} P_R f_a \phi + \text{h.c.},$$

$$\rho_f^{ba} \equiv \frac{Y_f^{2,ba}}{\cos\beta} - \frac{\sqrt{2}\tan\beta\, \bar{M}_f^{ba}}{v}$$

$\tan\beta$ is absorbed in ρ_f^{ba}

$$\Gamma_f^{Hba} \equiv \frac{\bar{M}_f^{ba}}{v} c_{\beta\alpha} - \frac{1}{\sqrt{2}} \rho_f^{ba} s_{\beta\alpha}$$

Not CKM suppressed



$$= -i\Gamma_u^{Htq} P_R$$

$\propto \rho_u^{tq}$

$q = u, c$

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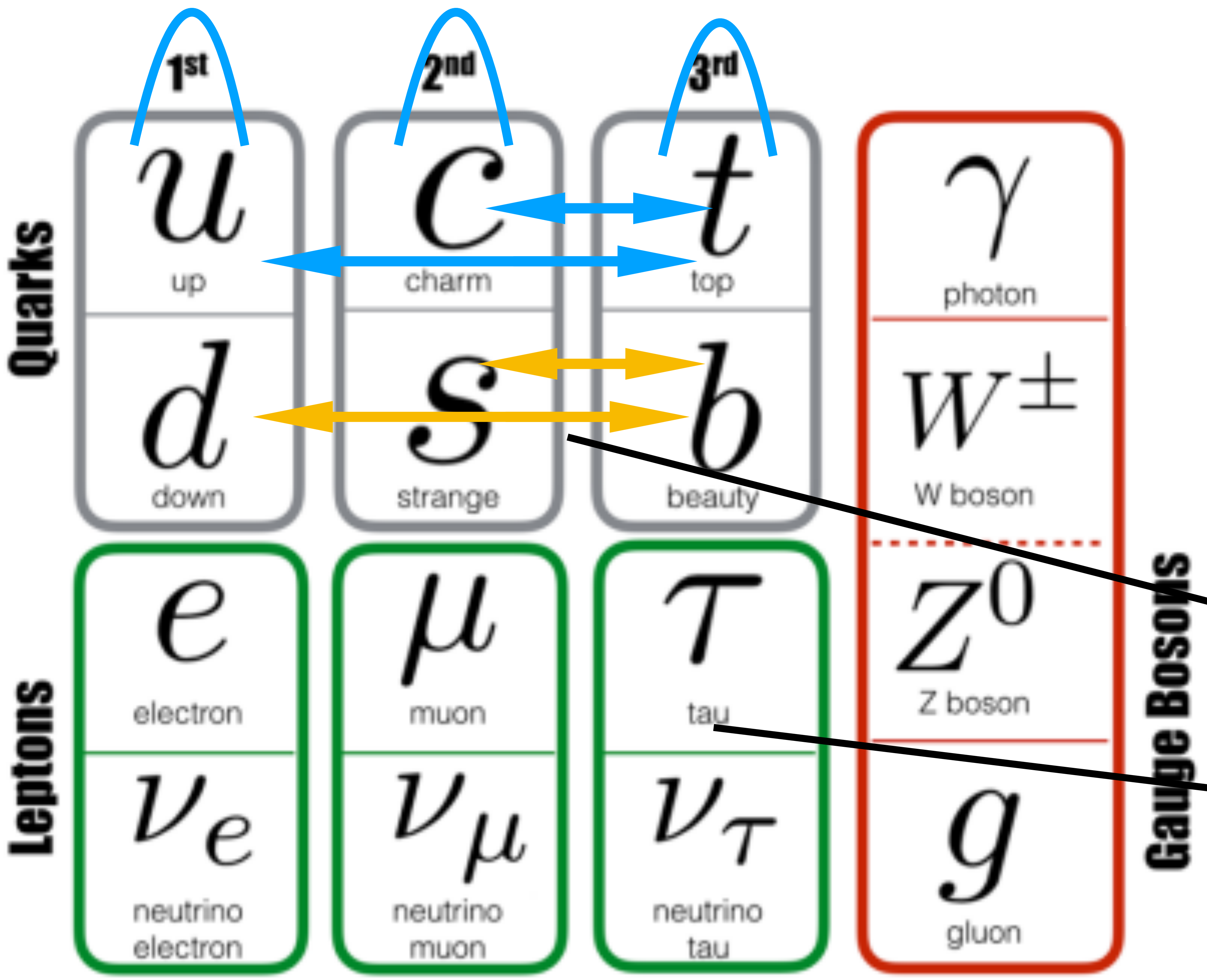

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$$+ \sum_{f=u,d,\ell} \sum_{\phi=h,H,A} \bar{f}_b \Gamma_f^{\phi ba} P_R f_a \phi + \text{h.c.},$$

$$\rho_u = \begin{pmatrix} \rho_u^{uu} & \rho_u^{uc} & \rho_u^{ut} \\ \rho_u^{cu} & \rho_u^{cc} & \rho_u^{ct} \\ \rho_u^{tu} & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

Very suppressed at tree level, only non-zero can be ρ_d^{bb}.

Non-zero couplings are $\rho_\ell^{\tau\tau}$, $\rho_\ell^{\mu\tau}$ and $\rho_\ell^{e\tau}$.

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General 2HDM

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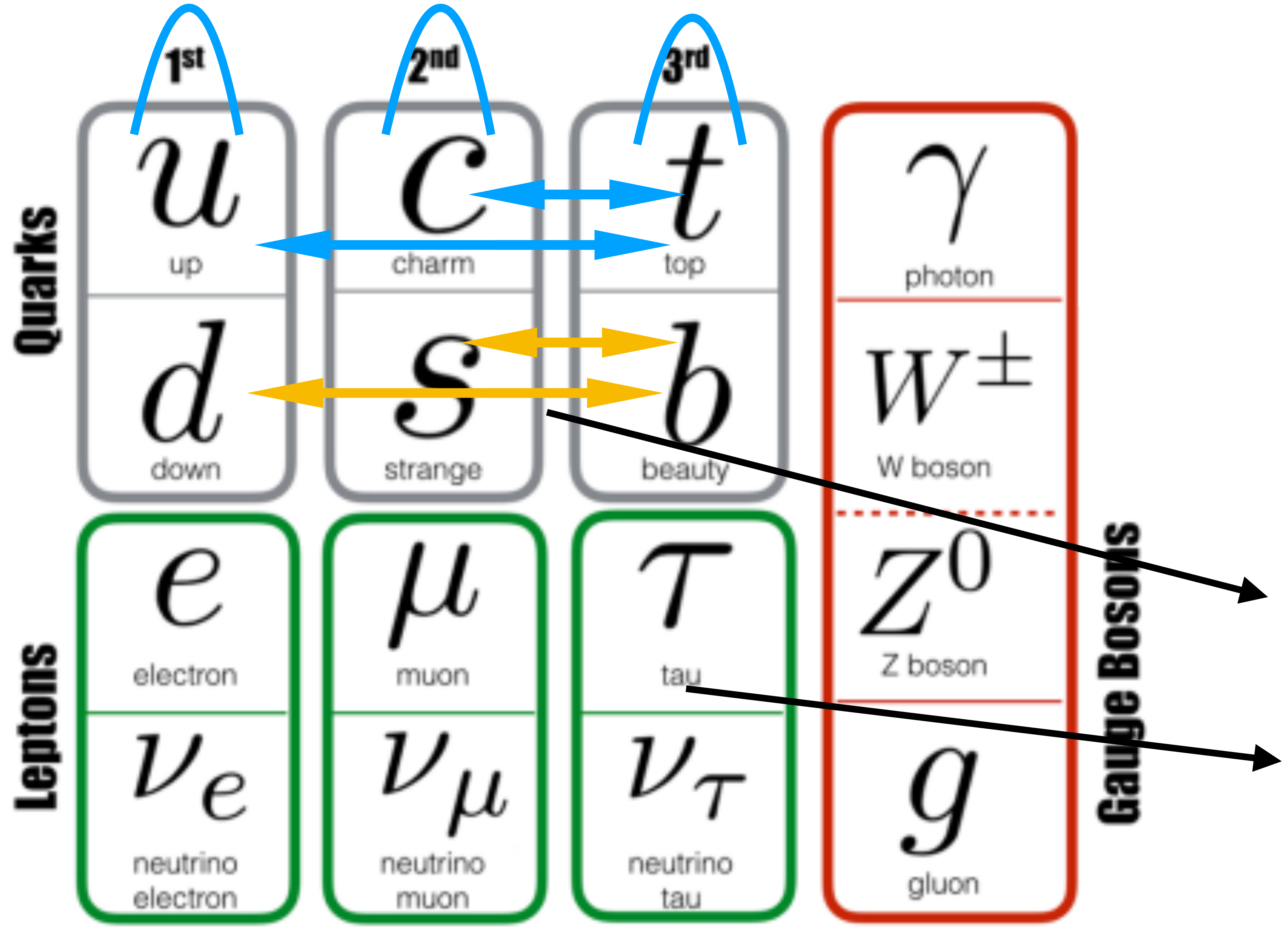

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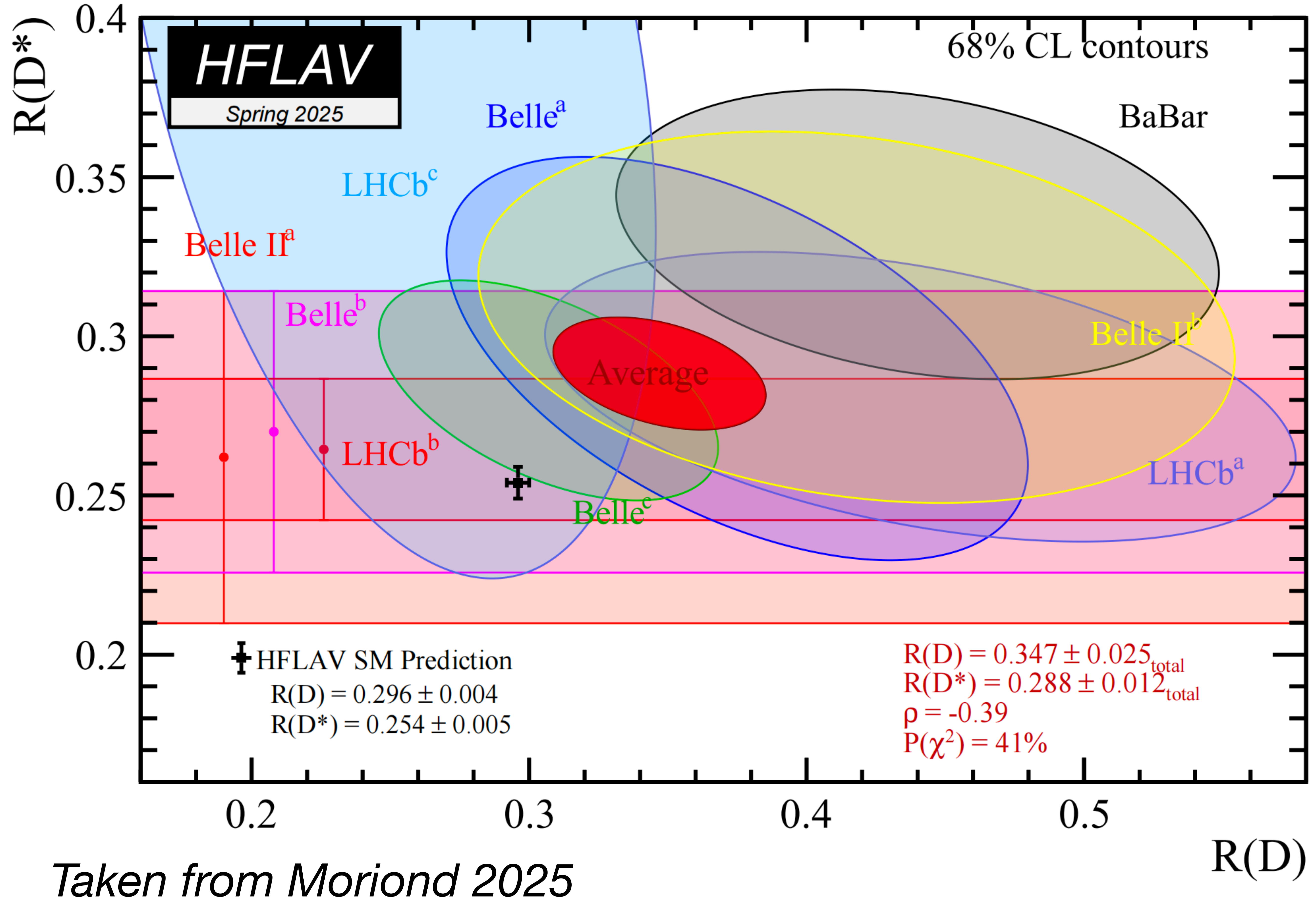
Charged current anomalies

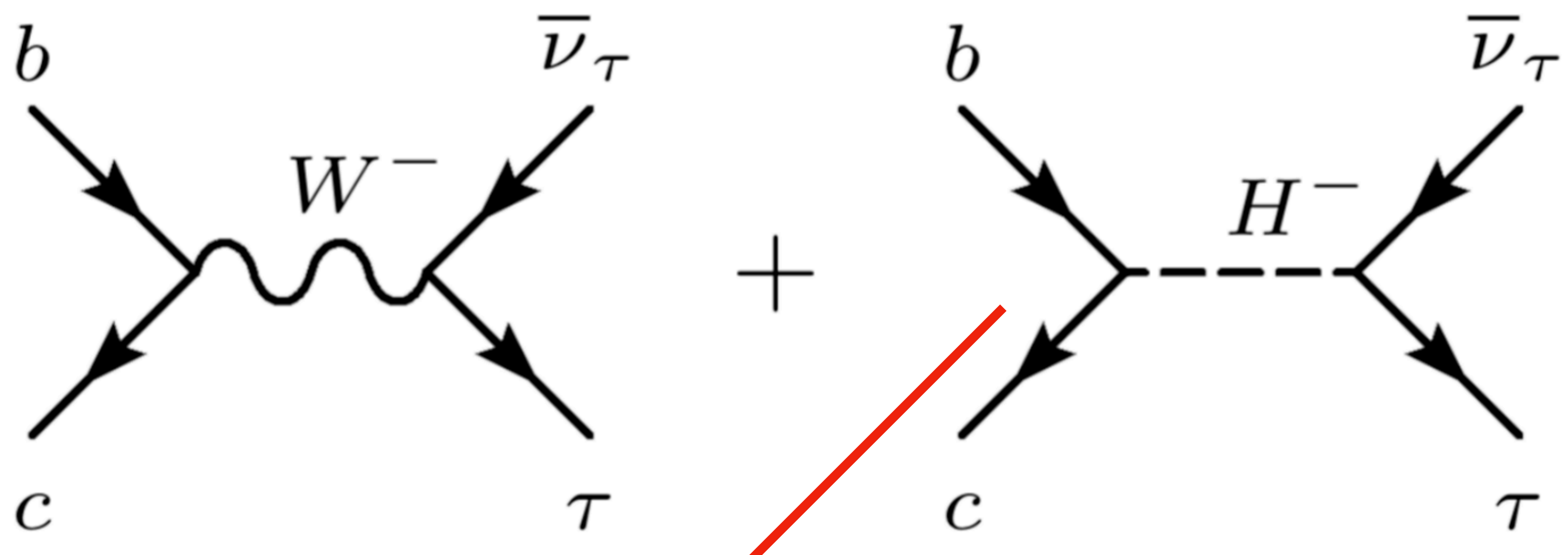
$$R_D = \frac{\Gamma(\overline{B} \to D\tau\overline{\nu})}{\Gamma(\overline{B} \to Dl\overline{\nu})} \quad R_{D^*} = \frac{\Gamma(\overline{B} \to D^*\tau\overline{\nu})}{\Gamma(\overline{B} \to D^*l\overline{\nu})}$$



Taken from Moriond 2025

$$R^{\text{exp}}_{D^{(*)}} > R^{\text{SM}}_{D^{(*)}} \quad \text{at } 3.8\,\sigma$$

Possible interference with NP?



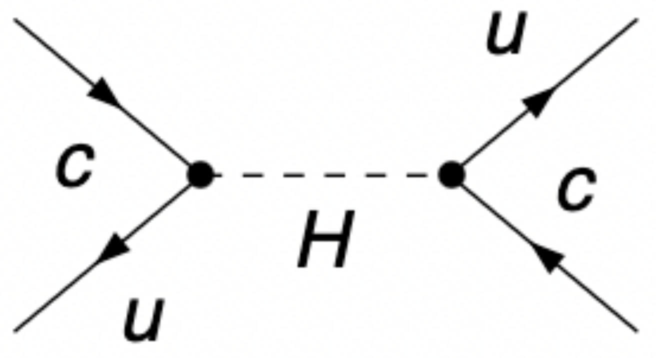
$$C_L^{cb} = \frac{(V_{tb}\rho_u^{tc} + V_{cb}\rho_u^{cc})\rho_\ell^{\tau\tau}}{m_{H^\pm}^2}$$

Non-zero ρ_u^{tc} and $\rho_\ell^{\tau\tau}$ are needed.

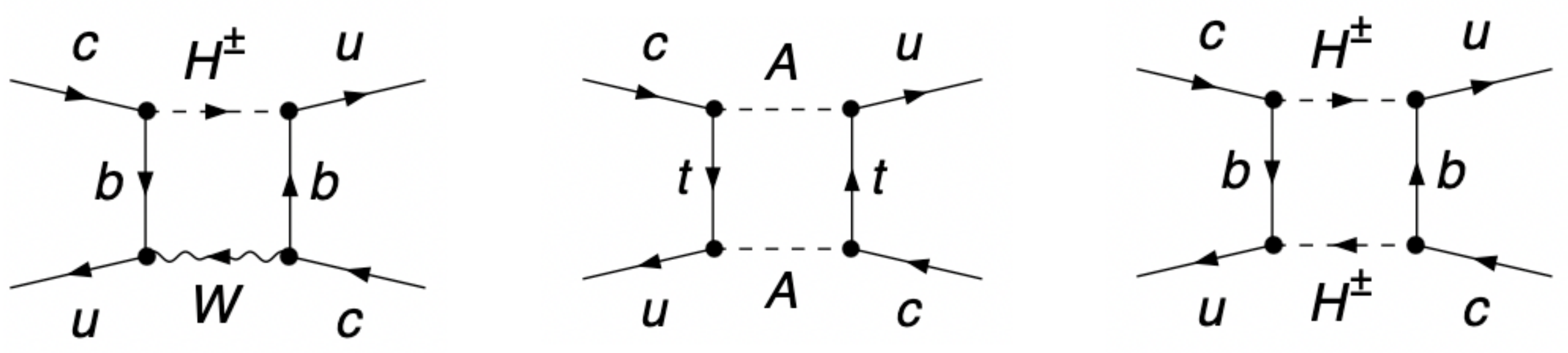
Flavour constraints

$$\rho_u = \begin{pmatrix} \rho_u^{uu} & \rho_u^{uc} & \rho_u^{ut} \\ \rho_u^{cu} & \rho_u^{cc} & \rho_u^{ct} \\ \rho_u^{tu} & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

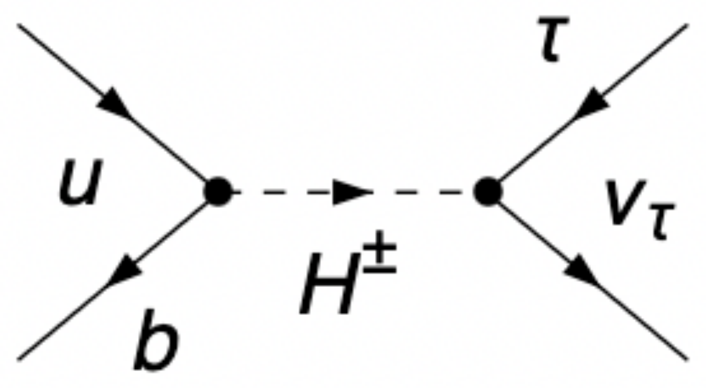
-$D^0 - \bar{D}^0$ mixing at tree level.



-$D^0 - \bar{D}^0$ mixing at one-loop.



-$B_u \to \tau\nu$ at tree level.

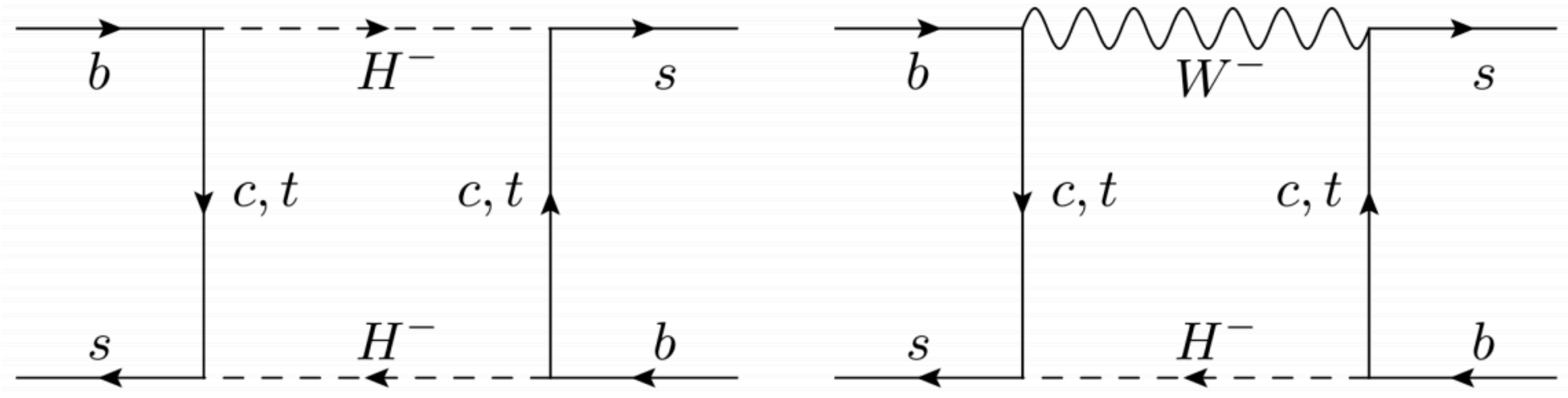


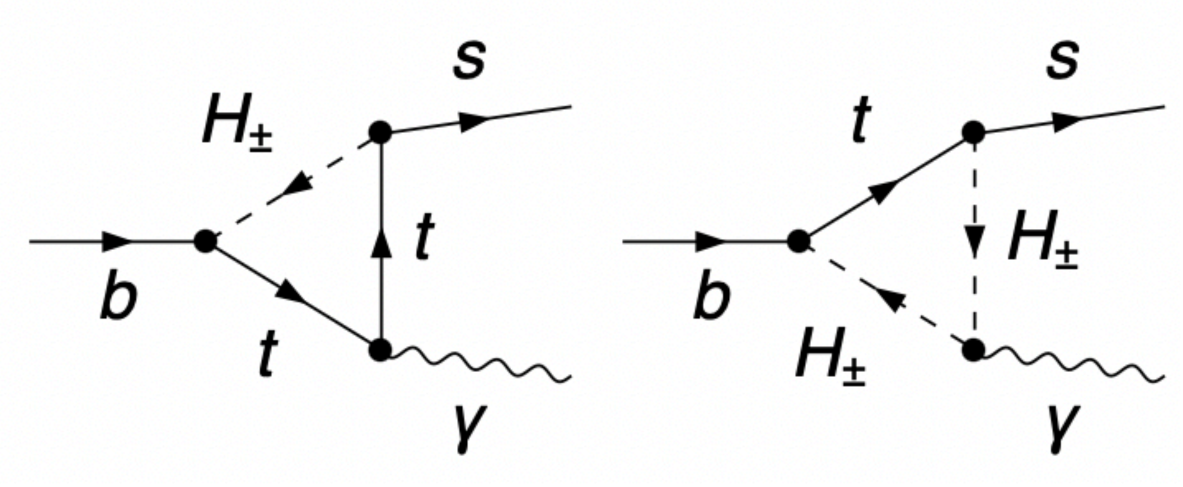
Flavour constraints

$$\rho_u = \begin{pmatrix} 0 & 0 & \rho_u^{ut} \\ 0 & \rho_u^{cc} & 0 \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

Flavour constraints

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





(Constrain all four couplings)

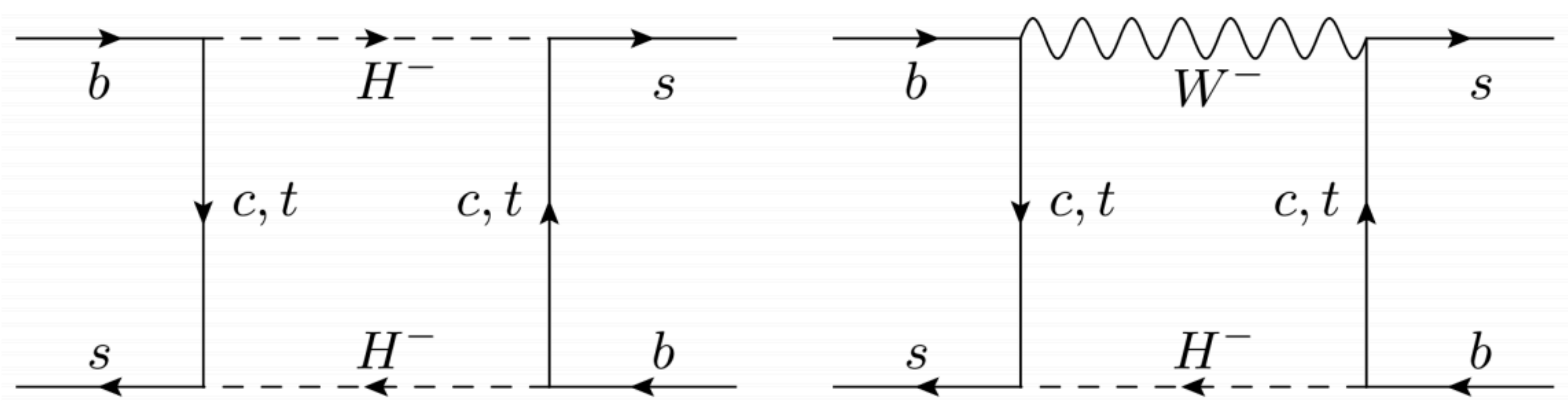
$B_{s,d} - \bar{B}_{s,d}$ | $b \to s\gamma$ | $b \to d\gamma$

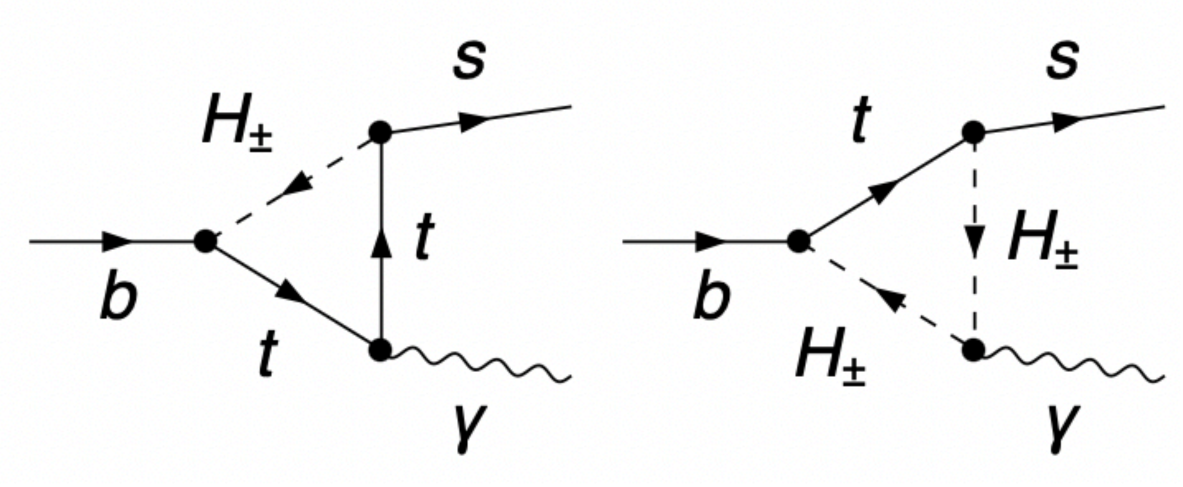
$$\rho_u = \begin{pmatrix} 0 & 0 & \rho_u^{ut} \\ 0 & & 0 \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

- Set to zero for simplicity (affects $B_s - \bar{B}_s$ mainly, large uncertainty in the SM)

Flavour constraints

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





(Constrain all four couplings)

$B_{s,d} - \bar{B}_{s,d}$ $\quad$ $b \to s\gamma$ $\quad$ ρ_d^{bb}

$$\rho_u = \begin{pmatrix} 0 & 0 & \rho_u^{ut} \\ 0 & & 0 \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

$b \to d\gamma$

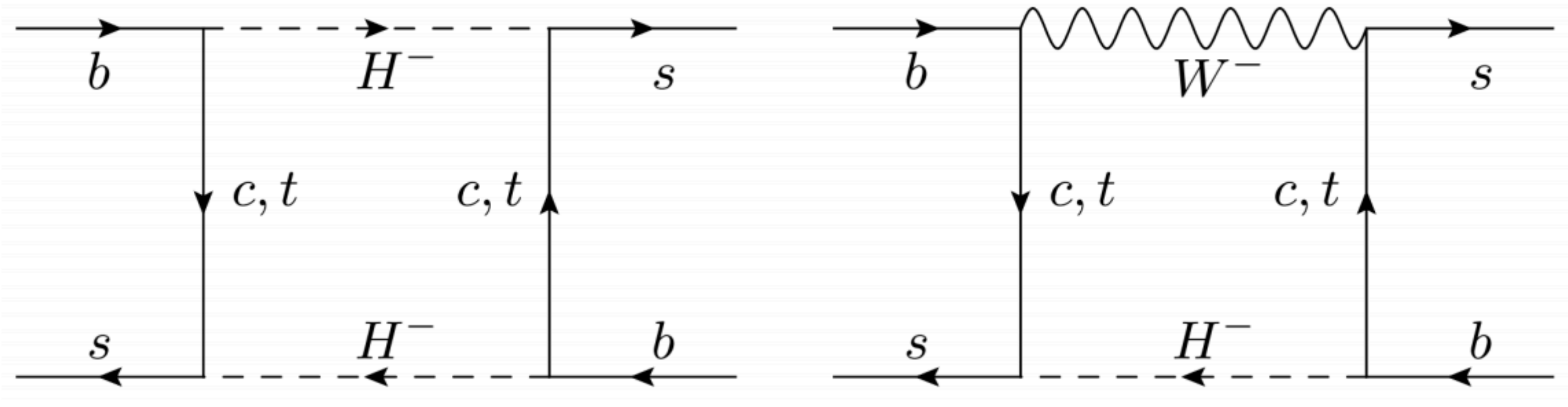
$R(D^{(*)})$

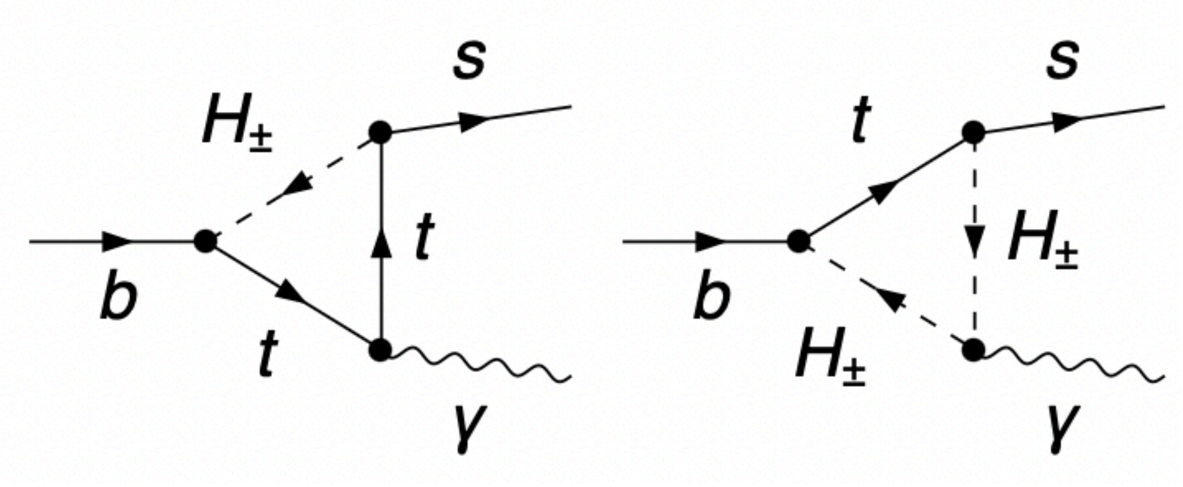
- *Set to zero for simplicity (affects $B_s - \bar{B}_s$ mainly, large uncertainty in the SM)*

Flavour constraints

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

(Constrain all four couplings)





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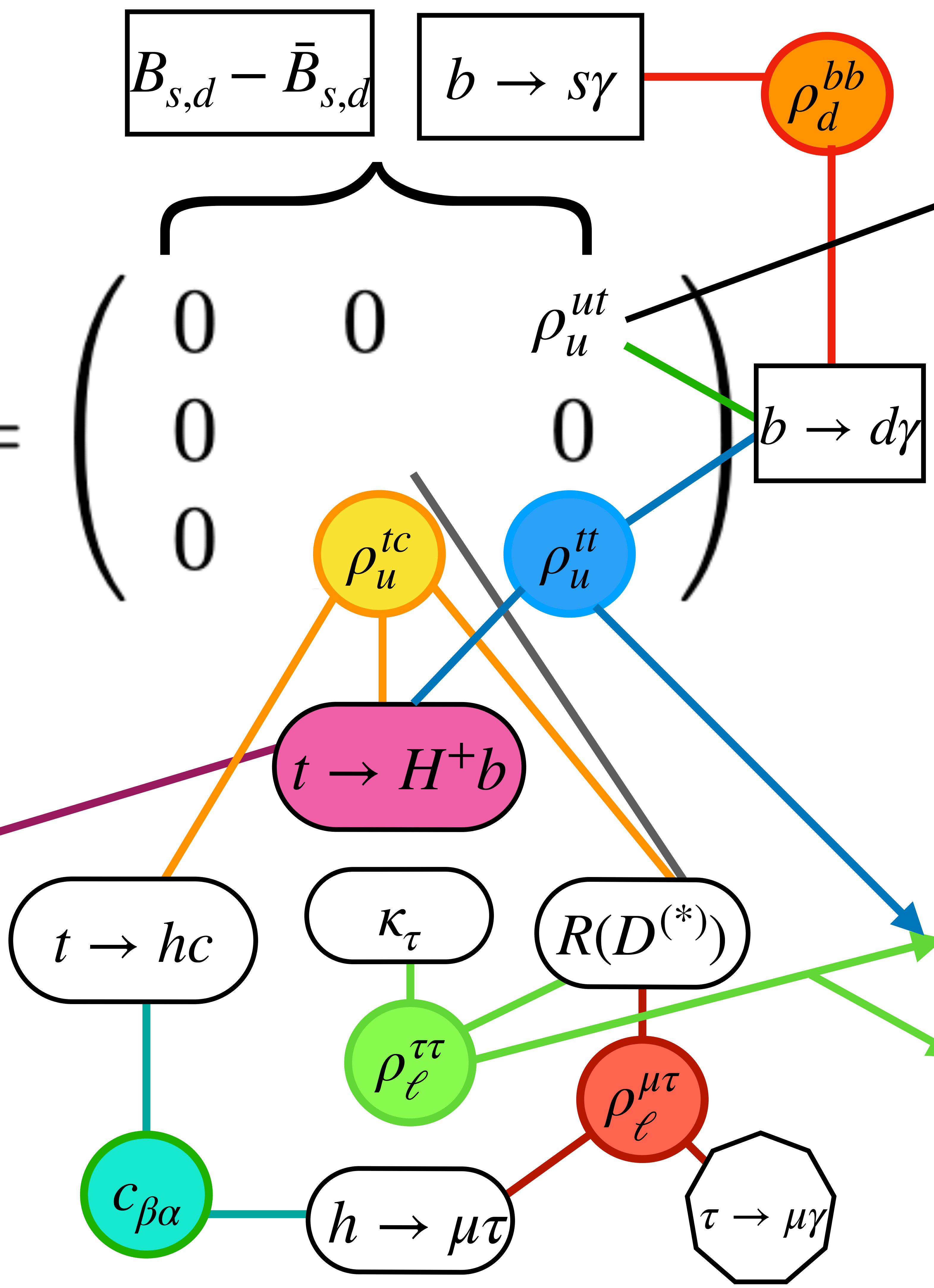


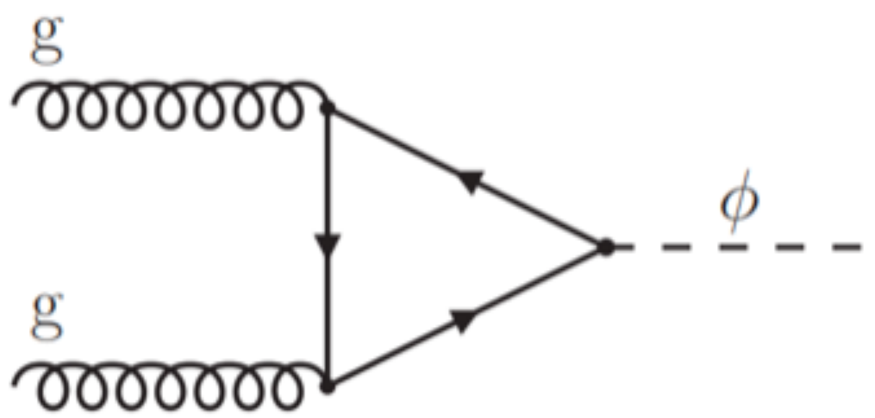
- Set to zero for simplicity (affects $B_s - \bar{B}_s$ mainly, large uncertainty in the SM)

$$m_{H^\pm} = 130\,\mathrm{GeV}$$

130 GeV 3σ excess from

ATLAS arXiv:2302.11739 [hep-ex].

Collider constraints



$$\sigma(gg \to \phi \to \tau^+\tau^-) = \sigma(gg \to \phi) \cdot \mathrm{BR}(\phi \to \tau^+\tau^-)$$

- Multi-tau decays from CMS.
- eEDM constrains the imaginary part of $\rho_\ell^{\tau\tau}$.

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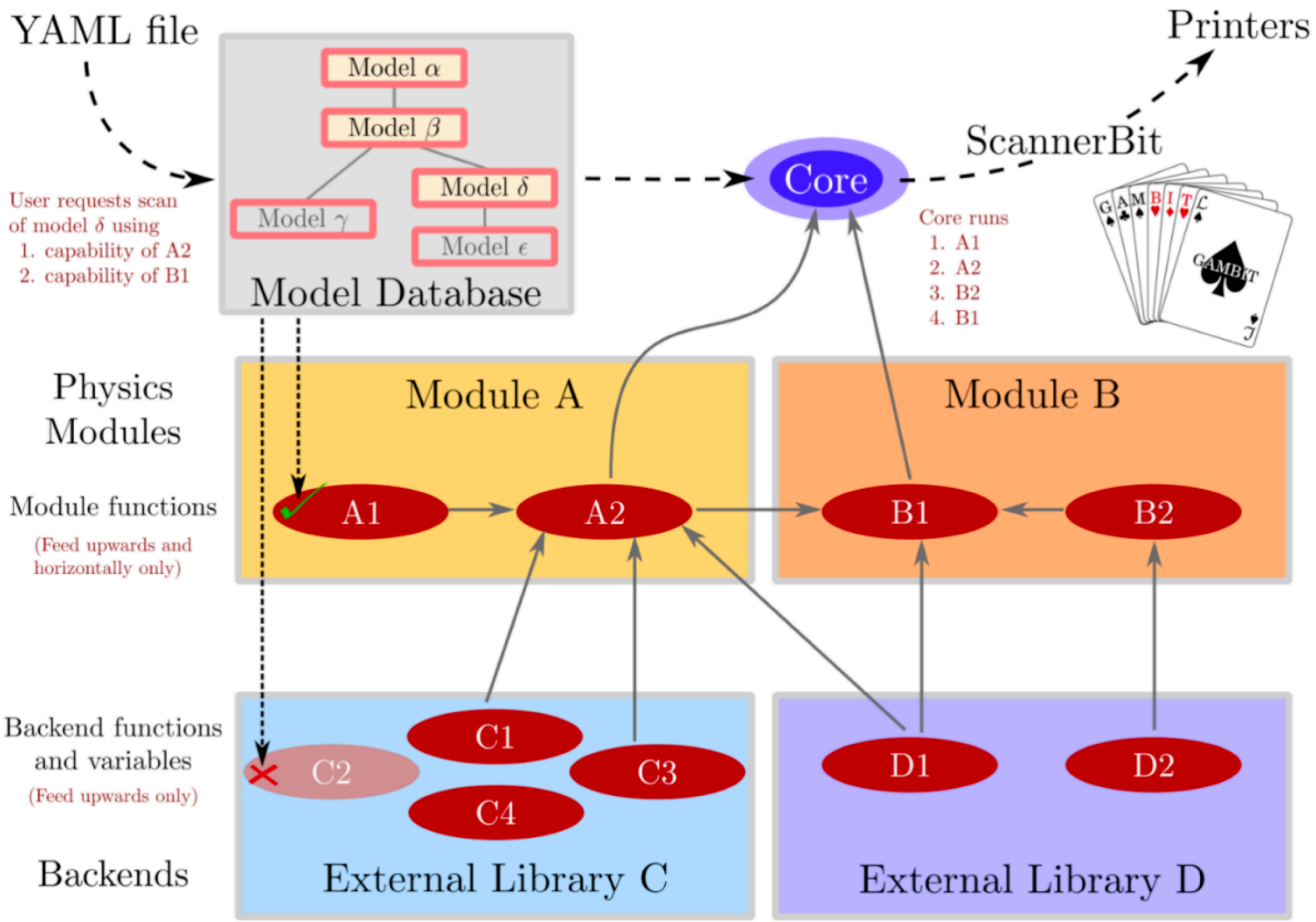
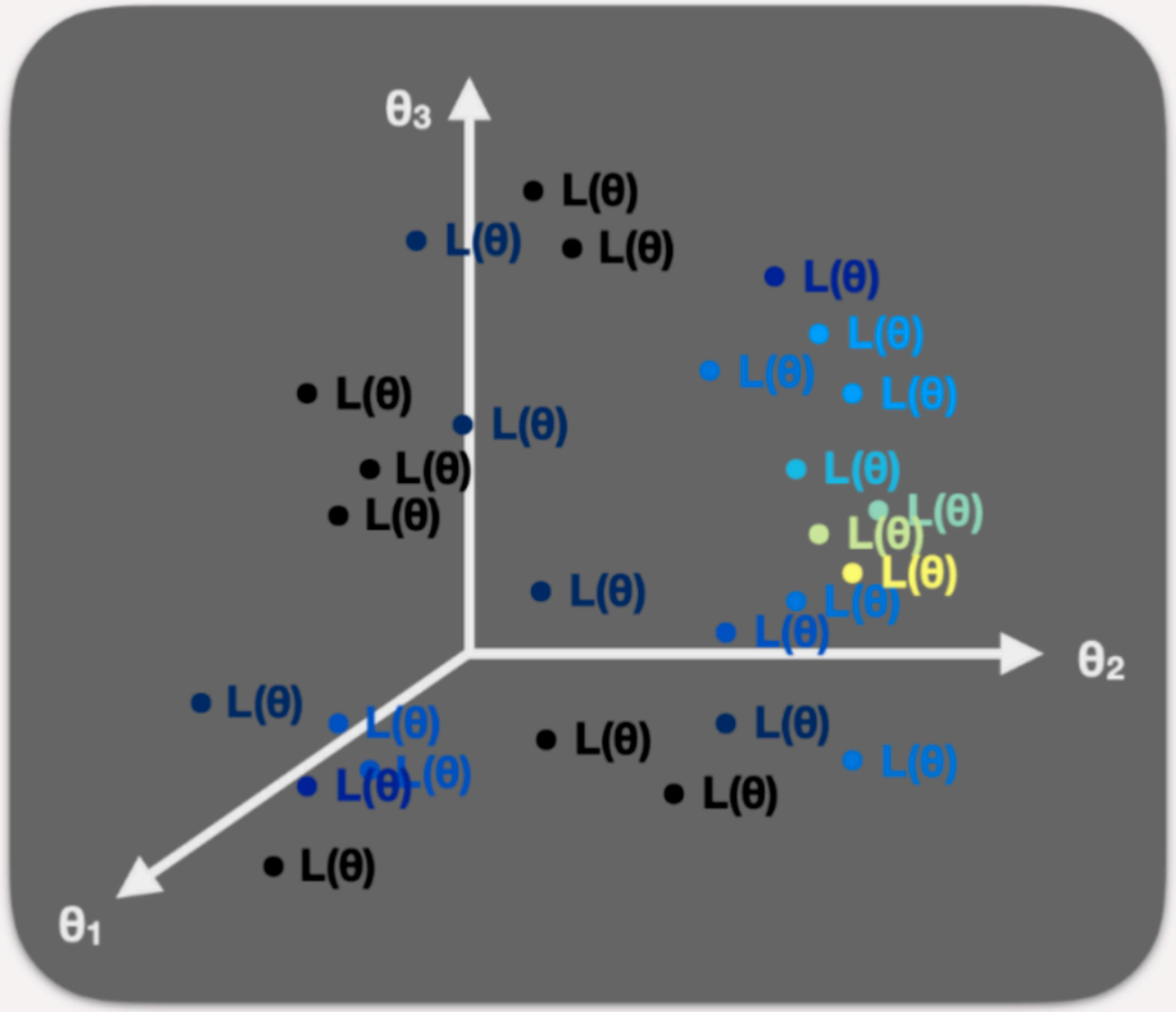
GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org



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)**

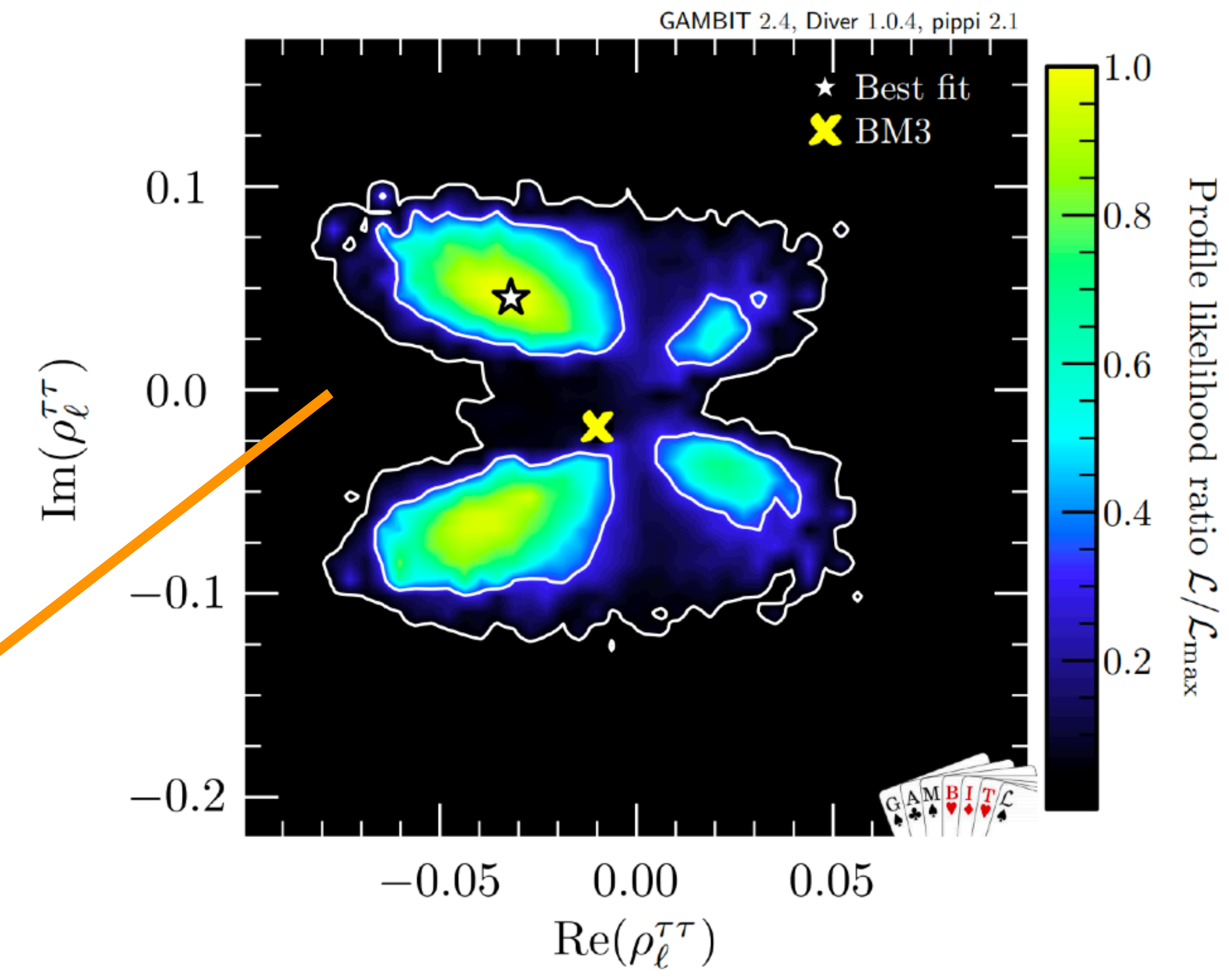


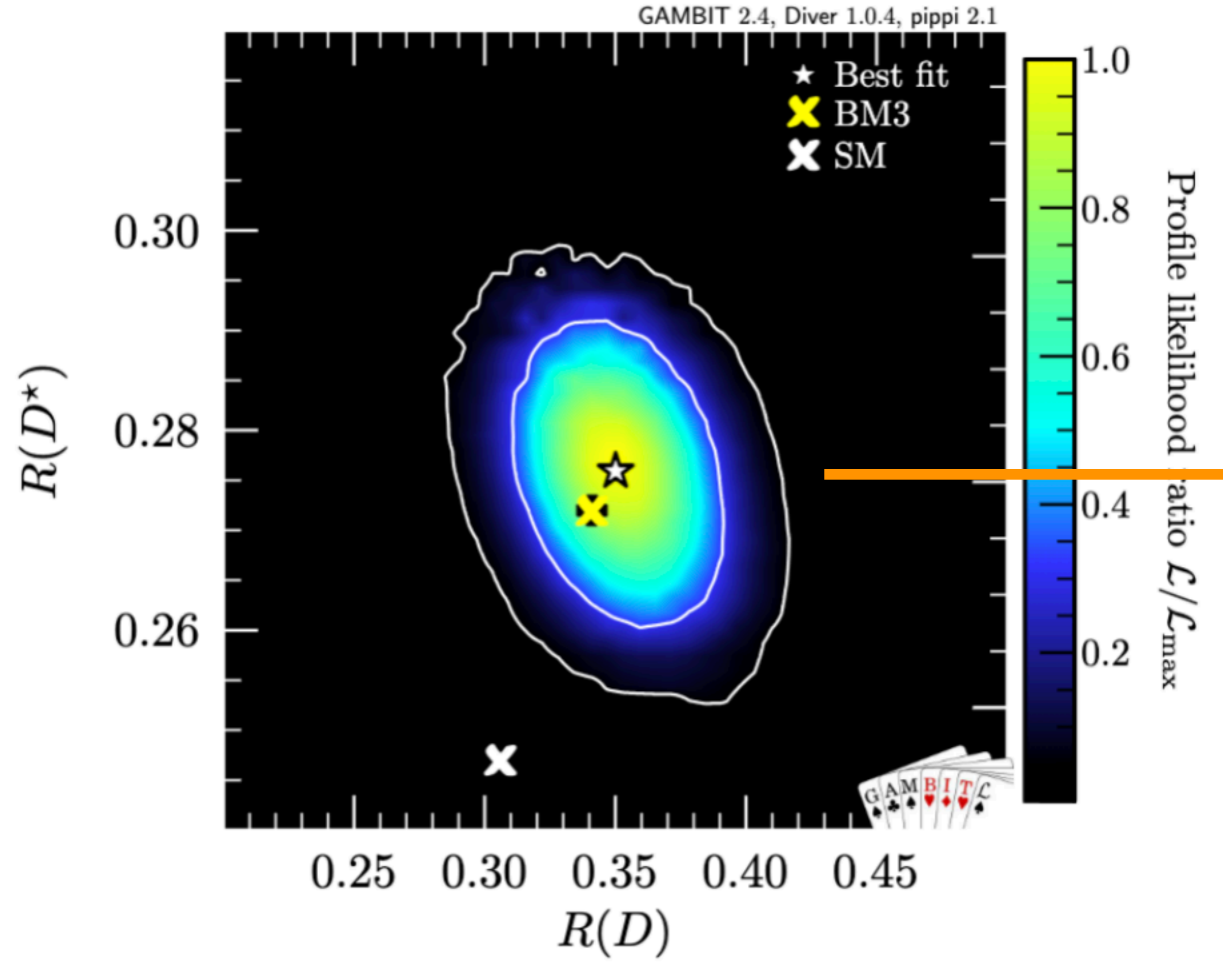
- Region of highest L(θ) or lnL(θ): **model's best simultaneous fit to all data**
  (but not necessarily a *good* fit, or the most probable θ…)

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

Parameter space scan

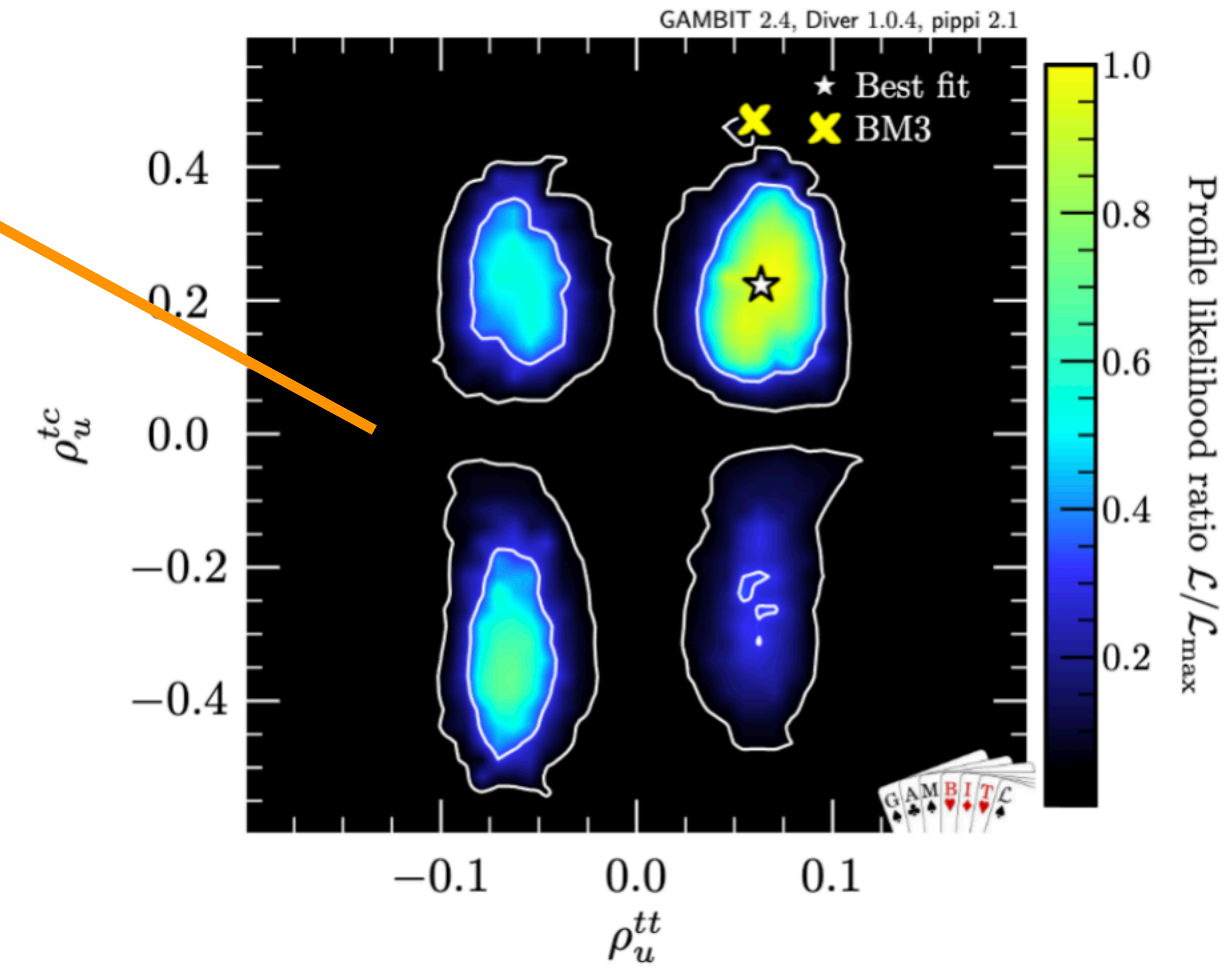
We use complex $\rho_\ell^{\tau\tau}$
(will have the CPV)

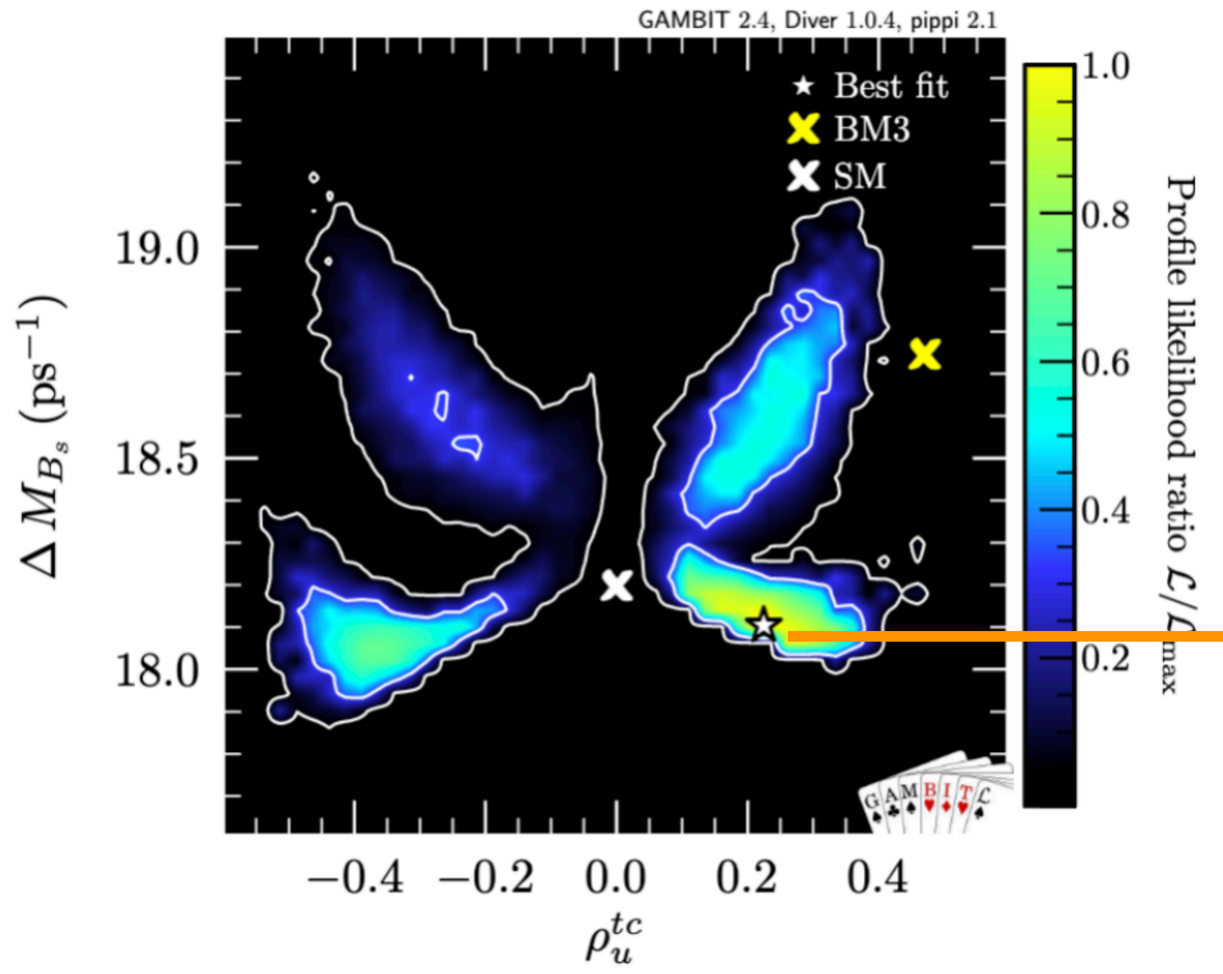




Charged anomalies are fitted

Non-zero ρ_u^{tc} and $\rho_\ell^{\tau\tau}$





$B_s - \bar{B}_s$ oscillations fit better the exp. value.

Plots from P. Athron, A. Crivellin, T. Gonzalo, S. Iguro, **CS**. *JHEP* 11 (2024) 133 • e-Print: 2410.10493 [hep-ph]

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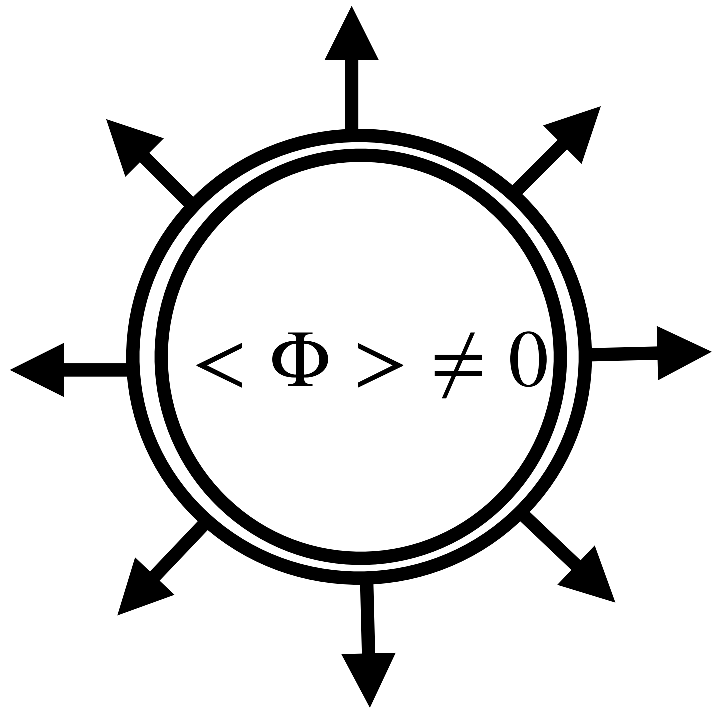
Electroweak baryogenesis

WKB formalism

$< \Phi > = 0$

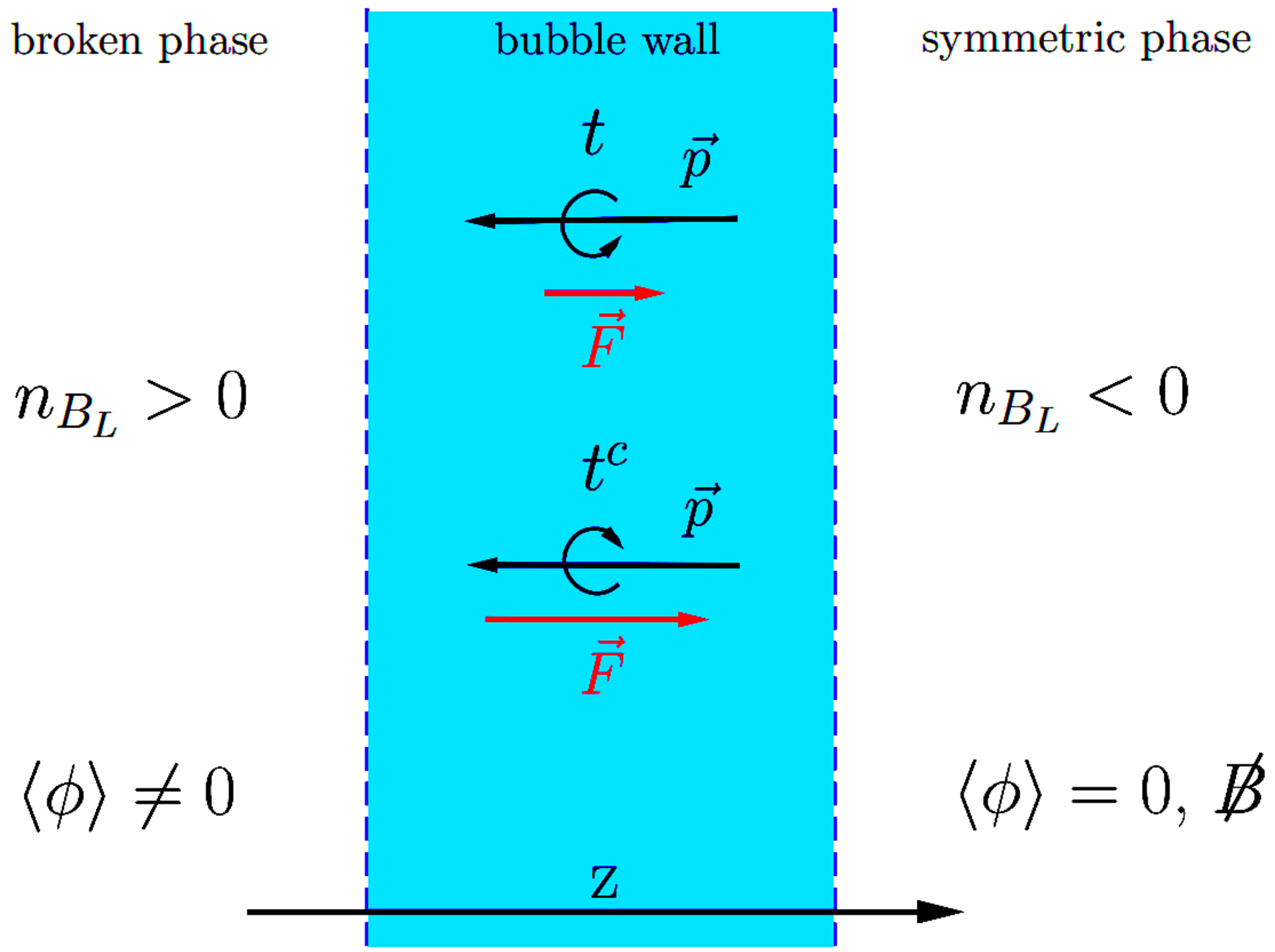


thick-wall limit $\ell_w \gg T^{-1}$

Higgs plasma and fermion field interactions generate an effective force from space-dependent mass terms

$$F_z = -\frac{\left(|m|^2\right)'}{2E} + s\left[\frac{\left(|m|^2\theta'\right)'}{2EE_z}\right]$$

$E = (\mathbf{p}^2 + |m|^2)^{1/2}$, $E_z = (p_z^2 + |m|^2)^{1/2}$, and $s = \pm 1$



The effect of this force can be translated into a CPV source $\bar{S}_l$ in a diffusion equation for the lepton number density l:

$$\bar{D}_l\, l''(z) + v_w\, l'(z) + \bar{\Gamma}_l\, l(z) = \bar{S}_l$$

Diffusion coeff. bubble wall vel. Collision term

The solution for l will depend on a convolution of $\bar{S}_l$ which will be a function of the lepton CPV phase

Taken from Dietrich Bodeker, Wilfried Buchmuller, *Rev.Mod.Phys.* 93 (2021) 3, 3 • e-Print: 2009.07294 [hep-ph]

Electroweak baryogenesis

WKB formalism

Lorentz factor

"K" factors from transport equations

$$S_j = -v_w \gamma_w \, Q_j^{8o} \, (\mathrm{Im}(A_{22}))' , \quad j = 1, 2$$

Depends on the imaginary part of A

Matrix A borrowed from SUSY solutions for charginos

$$A = U M_l \partial_z M_l^{-1} U^\dagger$$

Matrix U diagonalizing the square of the mass profile

$$U = \frac{\sqrt{2}}{\sqrt{\Lambda(\Lambda+\Delta)}} \begin{pmatrix} \frac{1}{2}(\Lambda+\Delta) & a \\ -a^* & \frac{1}{2}(\Lambda+\Delta) \end{pmatrix}$$

$$\Lambda = \sqrt{\Delta^2 + 4\,|a|^2} \qquad a = (M_l^\dagger M_l)_{12}$$

$$\Delta = (M_l^\dagger M_l)_{11} - (M_l^\dagger M_l)_{22}$$

Lepton mass profile

$$M_l(z) = \frac{1}{\sqrt{2}} \left[\begin{pmatrix} y_{\mu\mu} & y_{\mu\tau} \\ 0 & y_{\tau\tau} \end{pmatrix} h_1 + \begin{pmatrix} y_{\mu\mu} & y_{\mu\tau} \\ 0 & y_{\tau\tau}\, e^{i\theta} \end{pmatrix} h_2 \right]$$

Higgs profiles (kink type)

$$h_1(z) = \frac{v_n \cos\beta}{2} \left[1 + \tanh\left(\frac{z}{L_w} \right) \right],$$

$$h_2(z) = \frac{v_n \sin\beta}{2} \left[1 + \tanh\left(\frac{z}{L_w} - \Delta\beta \right) \right],$$

Electroweak baryogenesis

BAU calculation

Diffusion equation for the baryon number density

$$n_B''(z) - \frac{v_w}{D_q} n_B'(z) = \frac{\Gamma_{ws}}{D_q}\left(\mathcal{R}\, n_B(z) + \frac{3}{2} n_L(z)\right)$$

Weak sphaleron rate

Quarks diffusion coefficient

SM relaxation term (15/4)

Solution with $Y_B \equiv n_B/s$ and $n_L(z) \simeq l(z)$

$$Y_B = -\frac{3\,\Gamma_{ws}}{2\,s}\frac{1}{D_q \lambda_+}\int_{-\infty}^{-L_w} l(z)\, e^{-\lambda_- z} dz,$$

Entropy density

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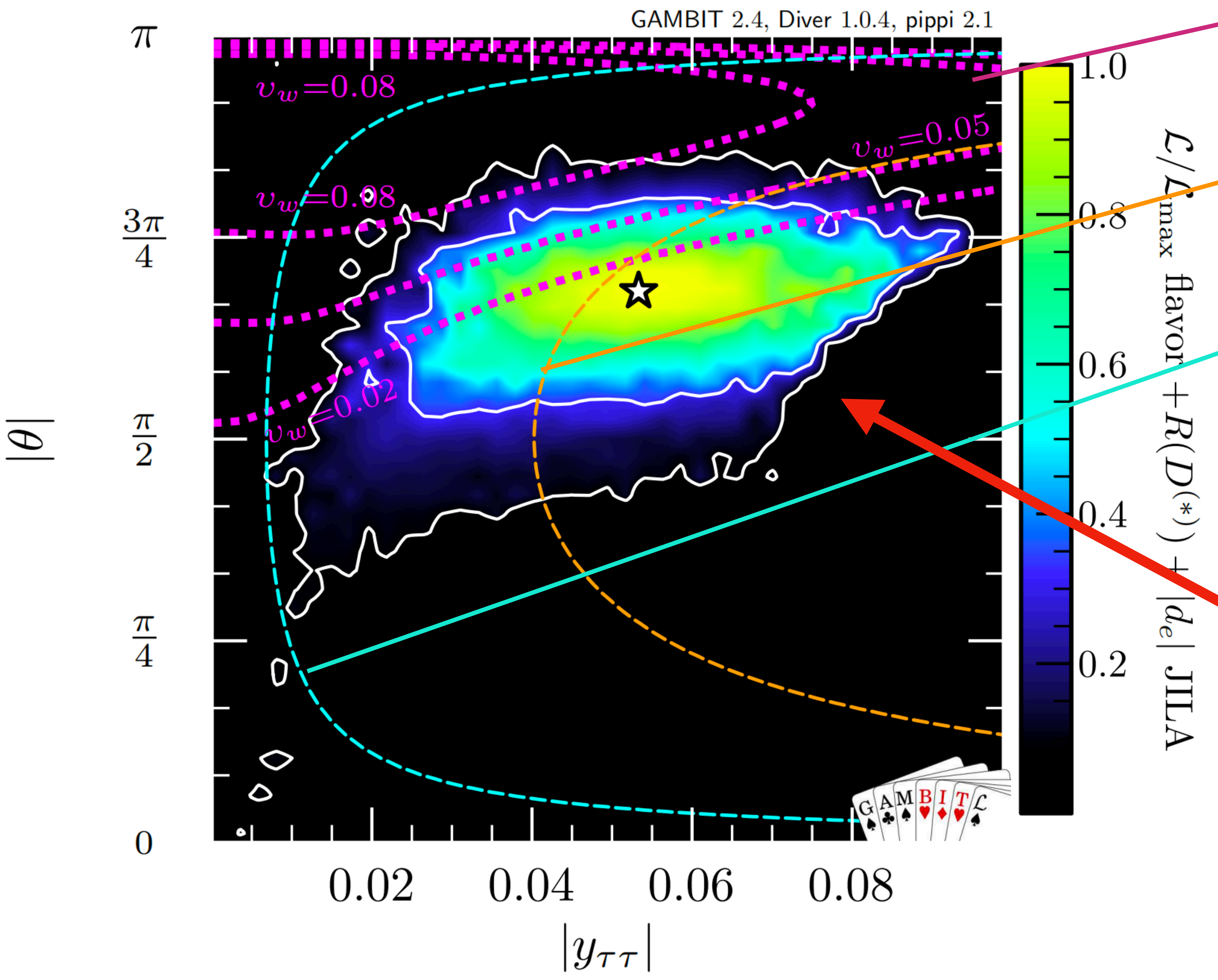
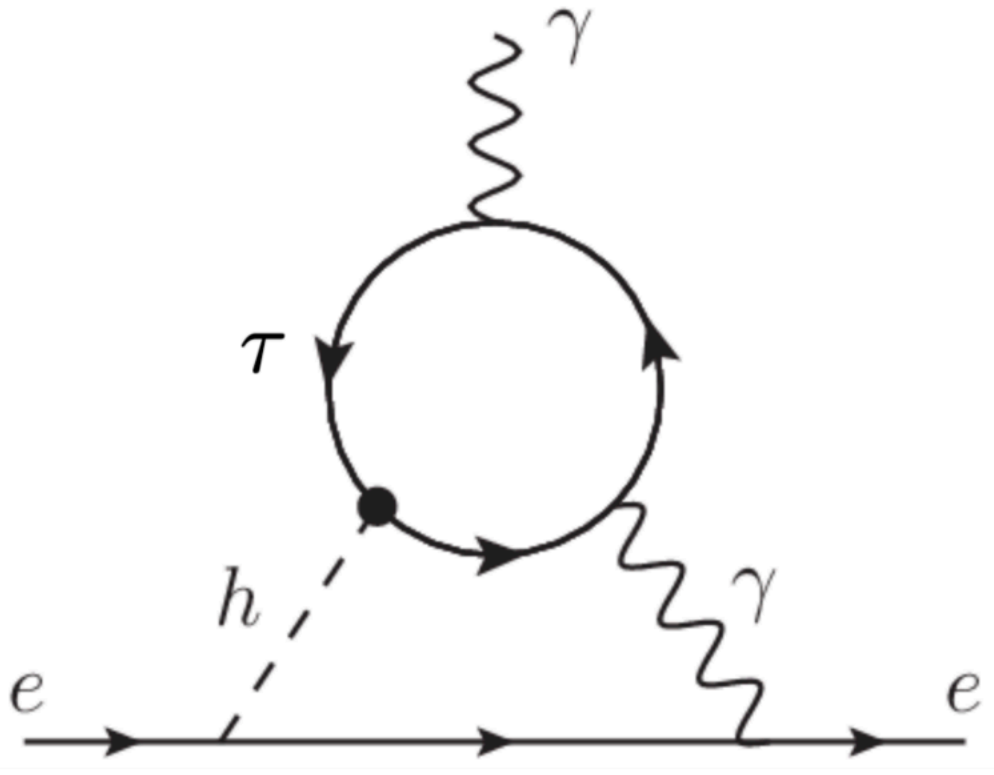
Electroweak baryogenesis

Projecting the BAU in the parameter space



- Contours of $Y_B = Y_B^{obs}$ for different v_w.
- Sensitivity from CEPC/FCCee.
- Projection from ACME-III.
- eEDM constraints from JILA-NIST cuts a piece of the "liver-like" plot

$$|d_e| < 4.1 \times 10^{-30}\ e\text{cm}$$



P. Athron, MJRM, Y. Wu, **CS** 2502.00445 [hep-ph] (under review at PRL)

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Summary

- General 2HDM offers FV couplings with rich phenomenology.
- Computed constraints for quark couplings from tree and loop level observables.
- The resultant parameter space can fit the $R(D^*)$ ratios at 1σ.
- Same CPV Yukawa in $R(D^*)$ can accommodate $Y_B = Y_B^{obs}$.

Dziękuję bardzo!

Backup

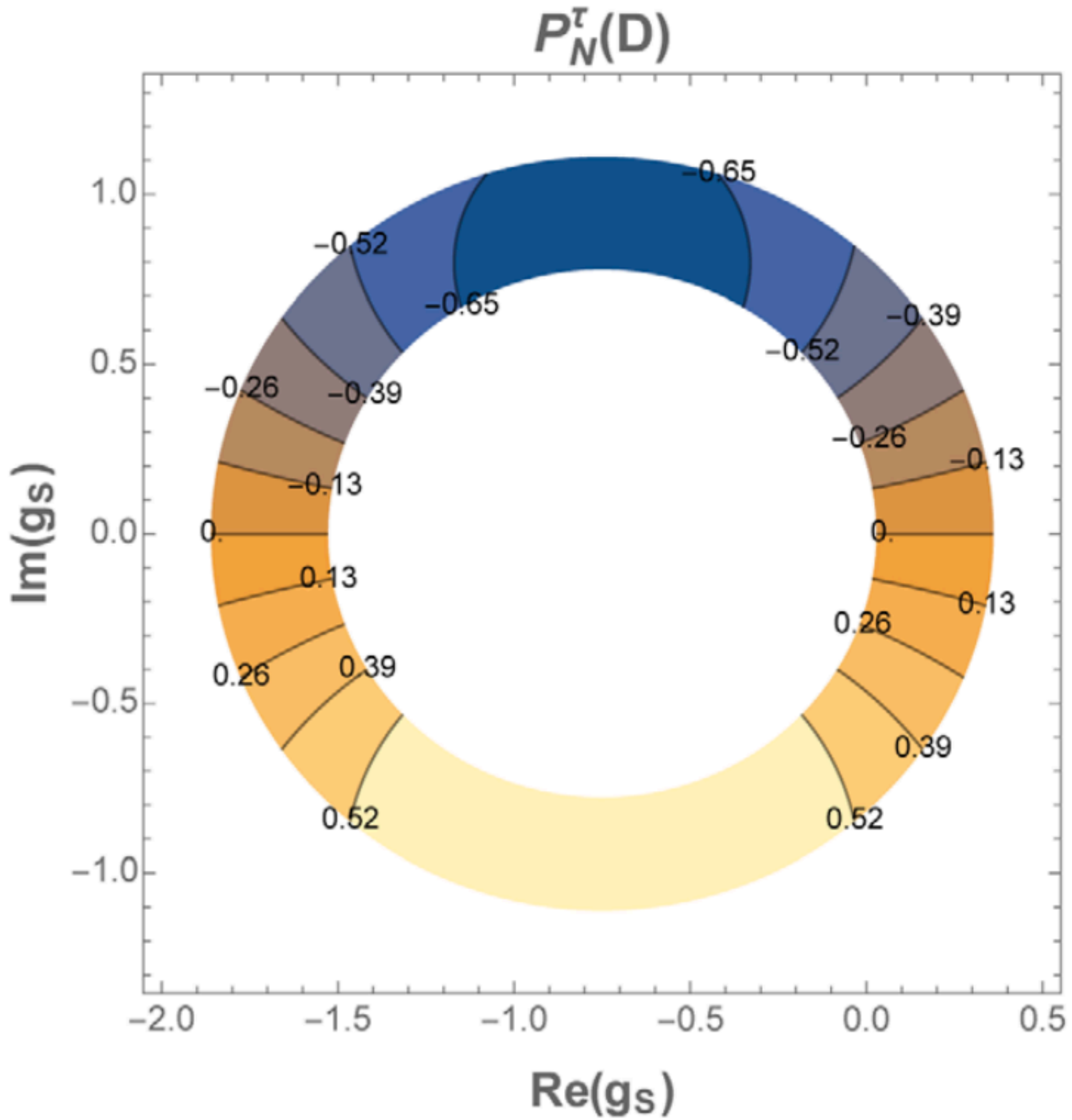
Normal polarizations of the tau lepton

$$P_N^\tau(D) \approx \frac{-1.01\,\mathrm{Im}(g_S)}{1 + 1.47\,\mathrm{Re}(g_S) + 0.98|g_S|^2},$$

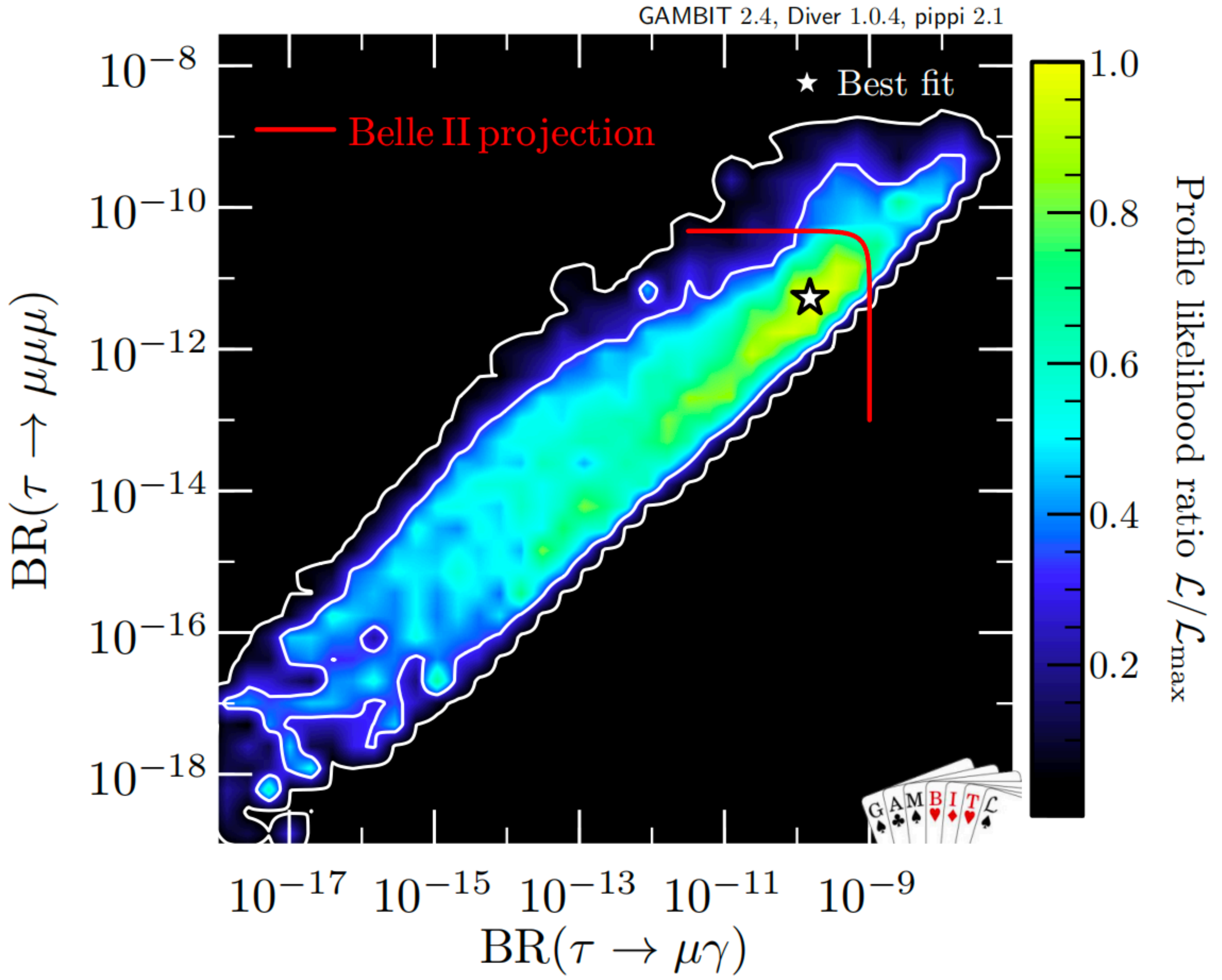
$$P_N^\tau(D^\star) \approx \frac{-0.18\,\mathrm{Im}(g_P)}{1 + 0.1\,\mathrm{Re}(g_P) + 0.03|g_P|^2}.$$

$$g_S \equiv \frac{C_R^{cb} + C_L^{cb}}{C_{\mathrm{SM}}^{cb}}, \qquad g_P \equiv \frac{C_R^{cb} - C_L^{cb}}{C_{\mathrm{SM}}^{cb}}.$$

$$C_L^{cb} = \frac{(V_{tb}\,\rho_u^{tc} + V_{cb}\,\rho_u^{cc})\,\rho_\ell^{\tau\tau}}{m_{H^\pm}^2}$$



Taken from R.Martinez, **CS**, G. Valencia, *Phys.Rev.D* 98 (2018) 11, 115012 • e-Print: 1805.04098 [hep-ph]


GAMBIT 2.4, Diver 1.0.4, pippi 2.1
Best fit
Belle II projection
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-18}
$\mathrm{BR}(\tau \to \mu\mu\mu)$
10^{-17} 10^{-15} 10^{-13} 10^{-11} 10^{-9}
$\mathrm{BR}(\tau \to \mu\gamma)$
1.0
0.8
0.6
0.4
0.2
Profile likelihood ratio $\mathcal{L}/\mathcal{L}_{\max}$