李政道研究所
TSUNG-DAO LEE INSTITUTE

Electroweak baryogenesis from charged current anomalies in B meson decays

SPCS 2025, TDLI, SJTU, Shanghai

Cristian Sierra, 2025年10月11日

- Motivation
- General Two Higgs Doublet Model (G2HDM)
- Flavour constraints
- Collider constraints
- Parameter space scan
- EWBG
- Results
- Summary

- **Motivation**
- General Two Higgs Doublet Model (G2HDM)
- Flavour constraints
- Collider constraints
- Parameter space scan
- EWBG
- Results
- Summary

李政道研究所 TSUNG-DAO LEE INSTITUTE

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.

- Motivation
- **General Two Higgs Doublet Model (G2HDM)**
- Flavour constraints
- Collider constraints
- Parameter space scan
- EWBG
- Results
- Summary

General 2HDM

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

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

General 2HDM

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

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

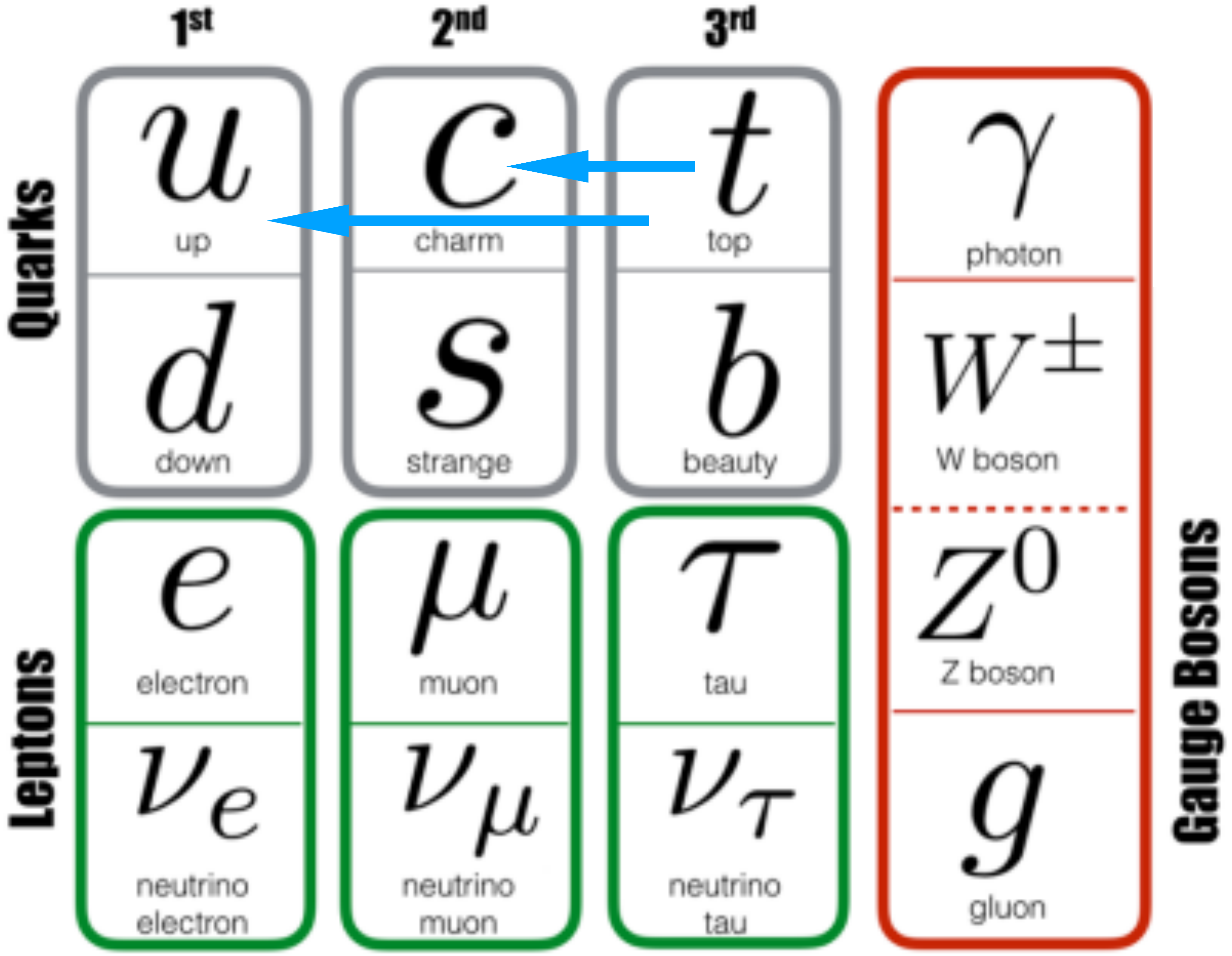
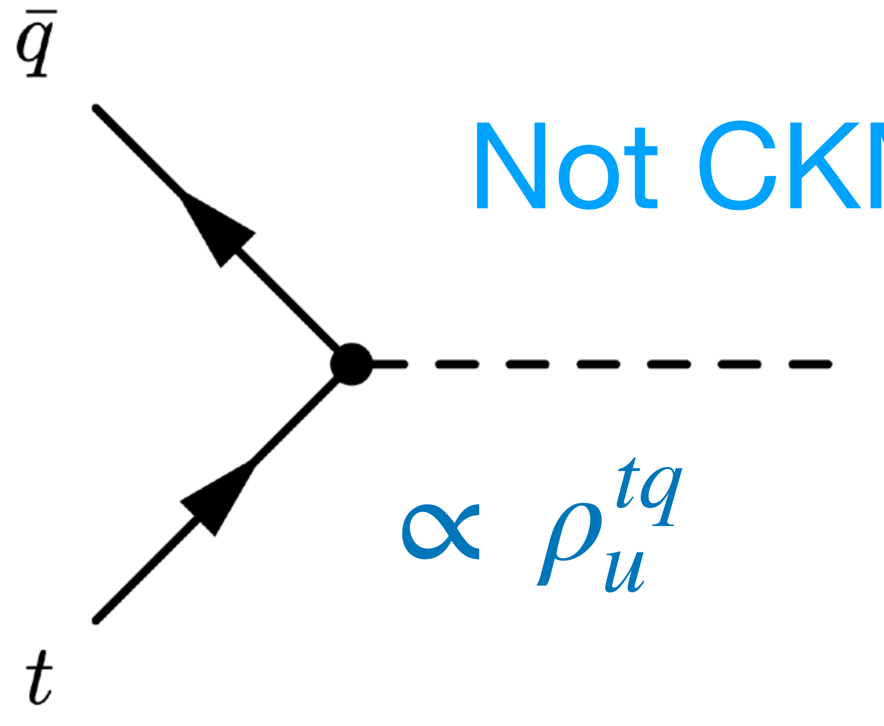


Image credit: Physik-Institut - UZH

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

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

Not CKM suppressed



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

$\propto \rho_u^{tq}$

$q = u, c$

General 2HDM

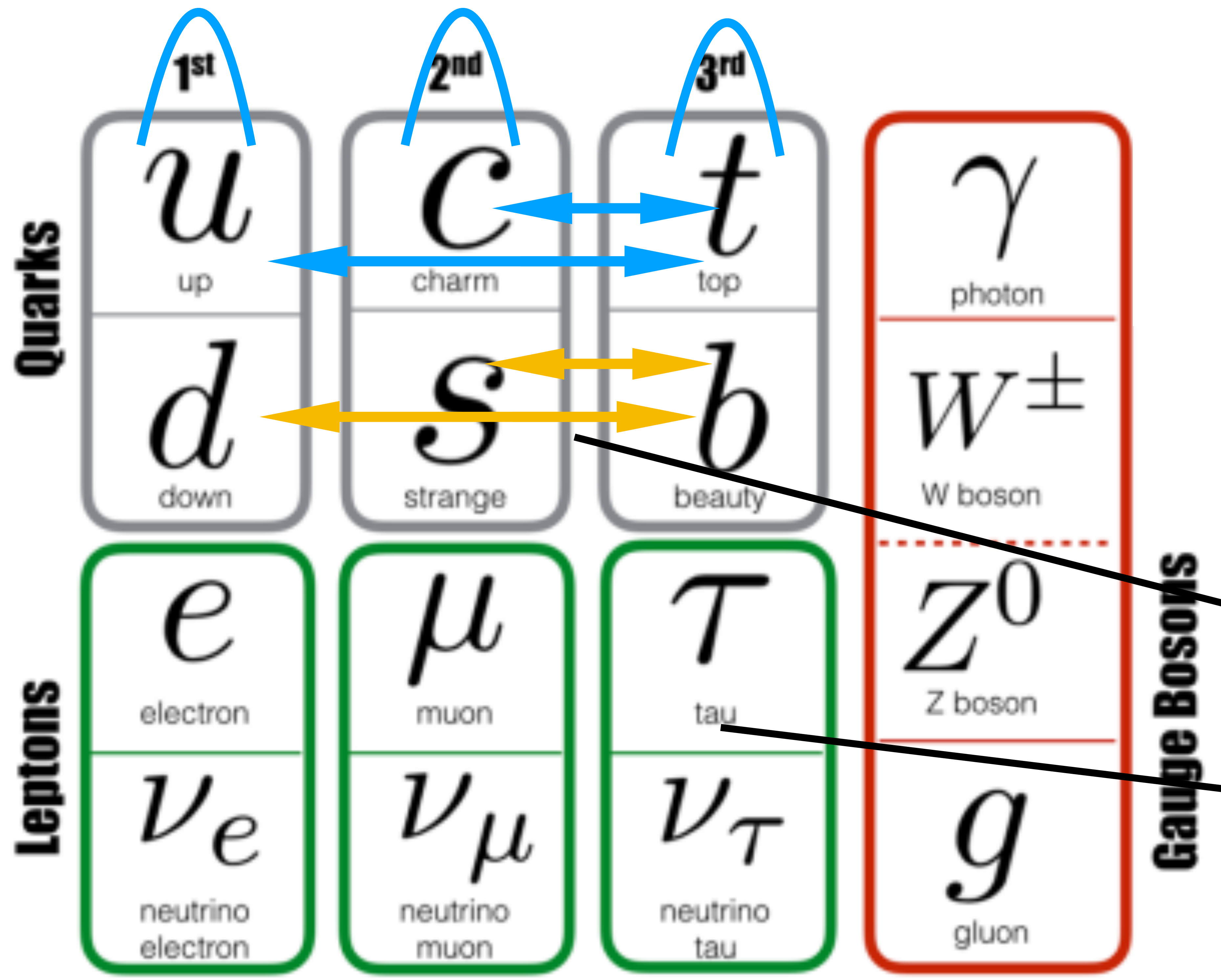
Adding a second Higgs doublet adds more degrees of freedom needed for a strong 1st PT (departure of thermal equilibrium.)

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

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

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

$$\rho_u = \left(\begin{array}{ccc} \rho_u^{uu} & \rho_u^{uc} & \rho_u^{ut} \\ \rho_u^{cu} & \rho_u^{cc} & \rho_u^{ct} \\ \rho_u^{tu} & \rho_u^{tc} & \rho_u^{tt} \end{array} \right)$$



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

Image credit: Physik-Institut - UZH

李政道研究所
TSUNG-DAO LEE INSTITUTE

General 2HDM

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

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

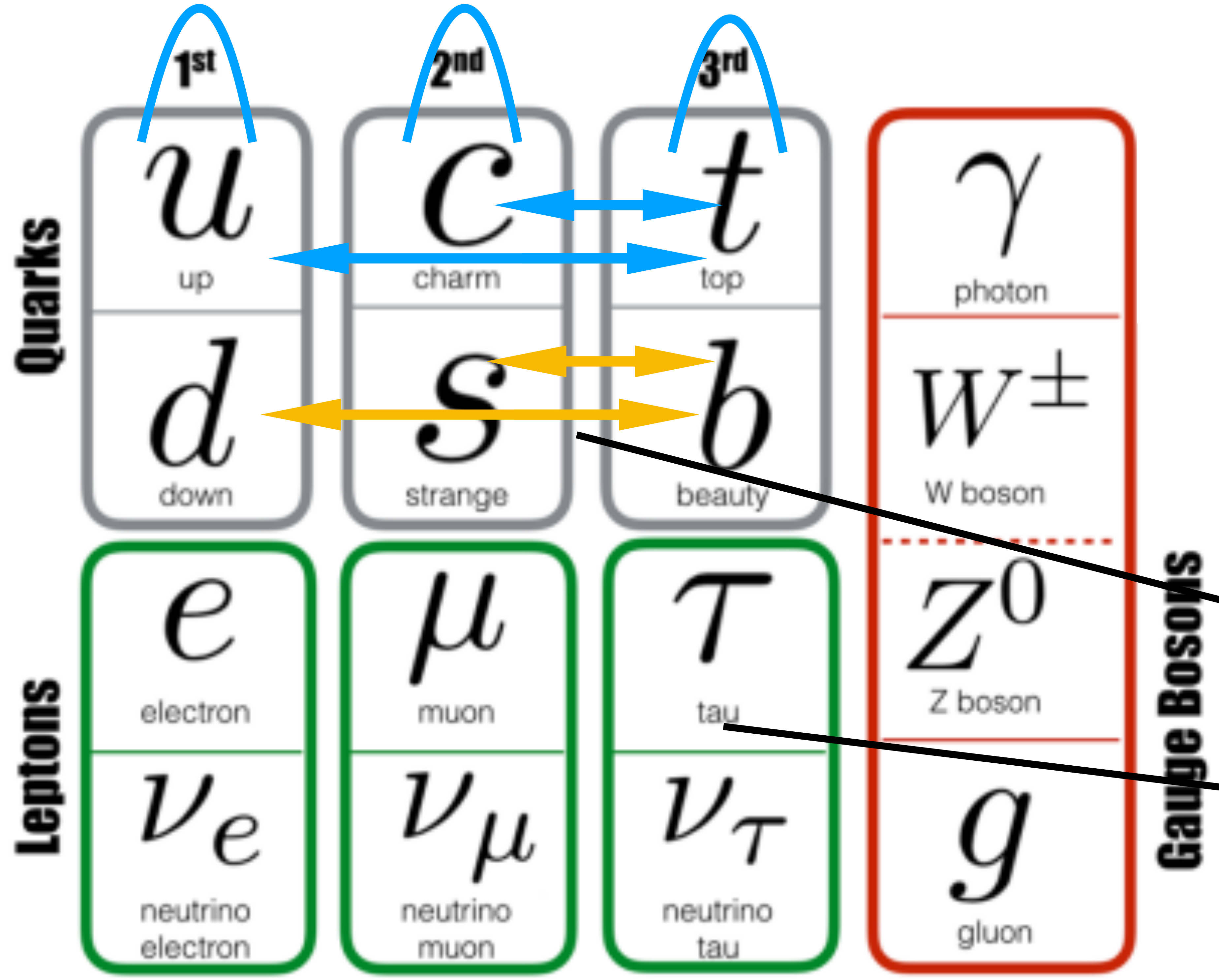


Image credit: Physik-Institut - UZH

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

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

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

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

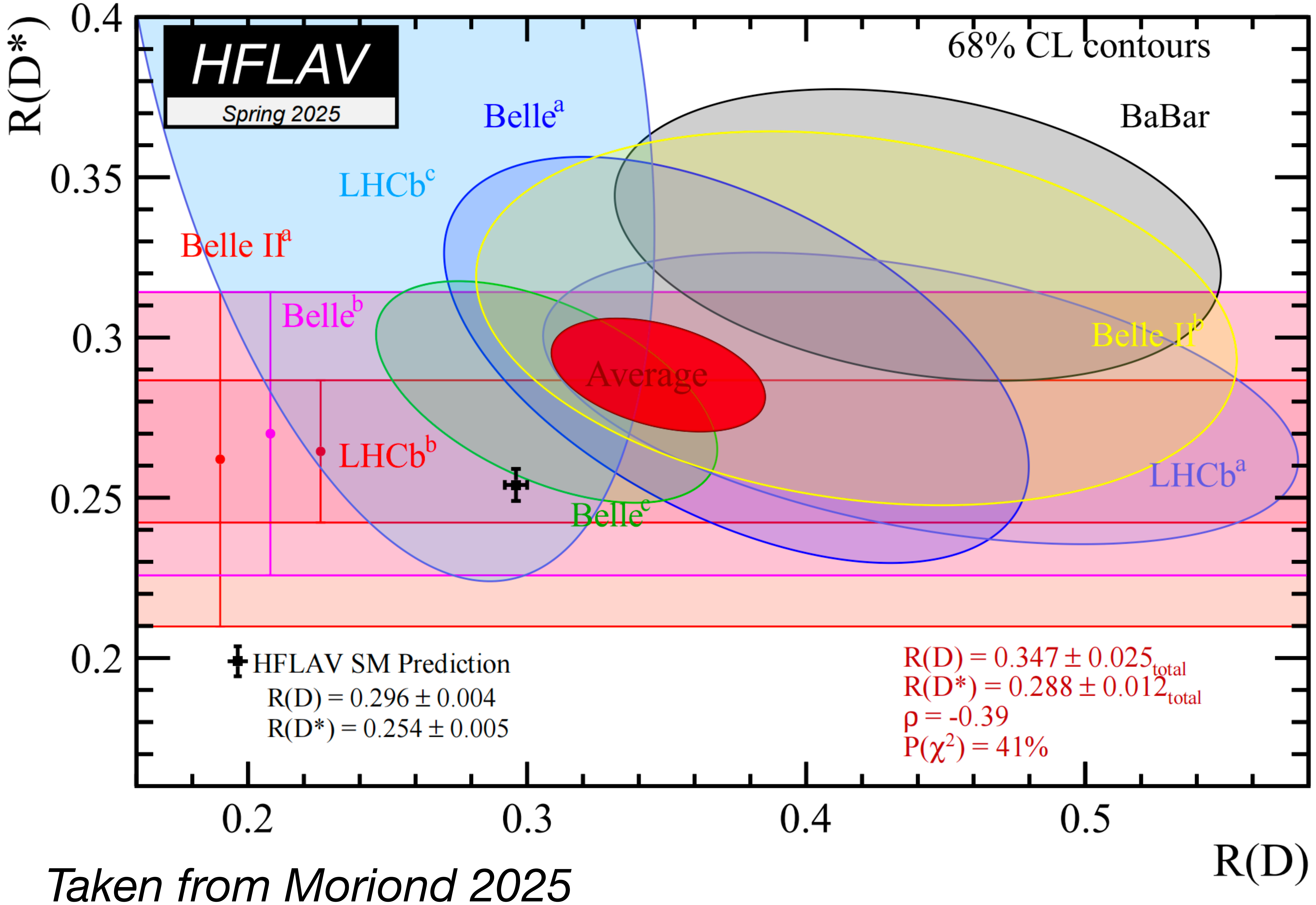
李政道研究所
TSUNG-DAO LEE INSTITUTE

- Motivation
- General Two Higgs Doublet Model (G2HDM)
- **Flavour constraints**
- Collider constraints
- Parameter space scan
- EWBG
- Results
- Summary

Charged current anomalies

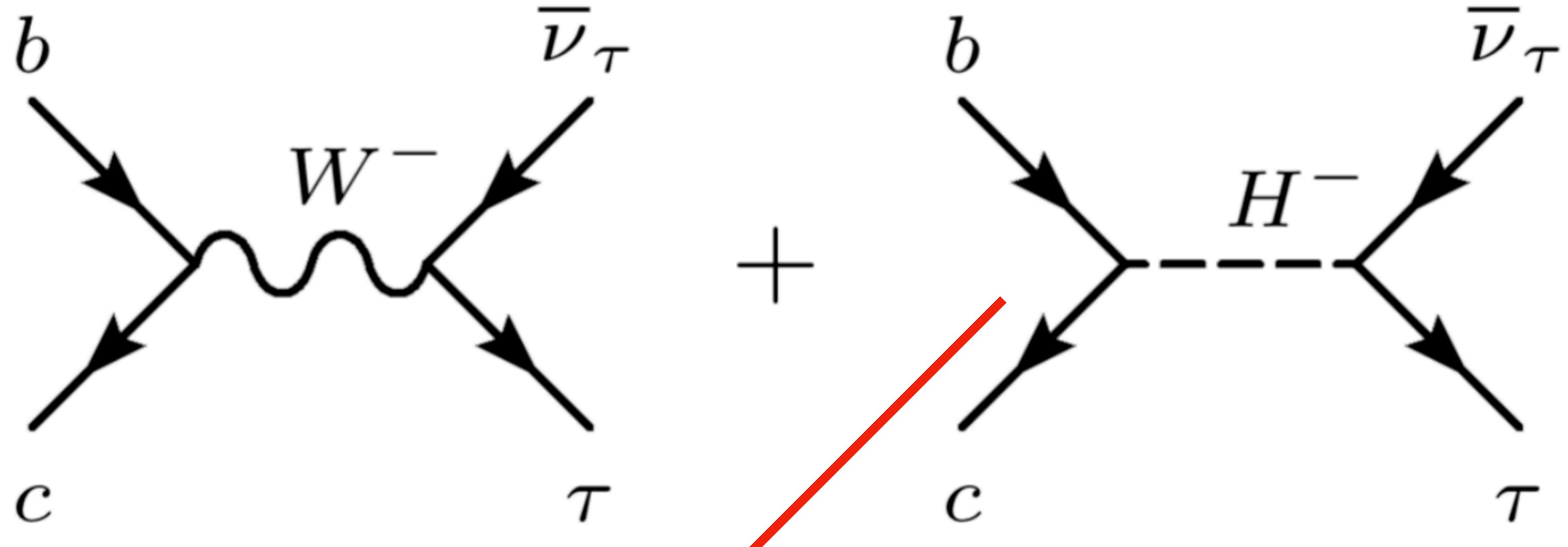
$$R_D = \frac{\Gamma(\overline{B} \to D\tau\overline{\nu})}{\Gamma(\overline{B} \to Dl\overline{\nu})} \qquad R_{D^*} = \frac{\Gamma(\overline{B} \to D^*\tau\overline{\nu})}{\Gamma(\overline{B} \to D^*l\overline{\nu})}$$

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



Taken from Moriond 2025

Possible interference with NP?



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

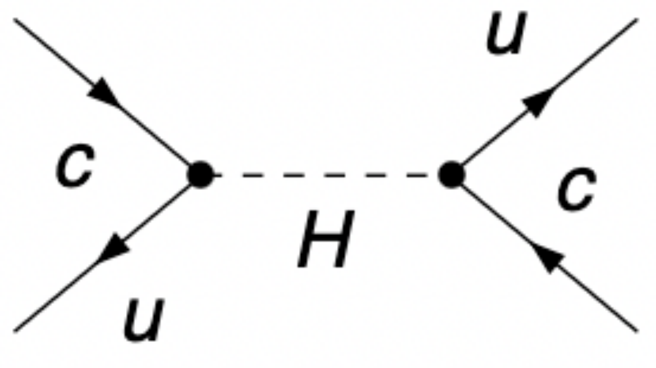
Non-zero ρ_u^{tc} and $\rho_\ell^{\tau\tau}$ are needed.

TSUNG-DAO LEE INSTITUTE

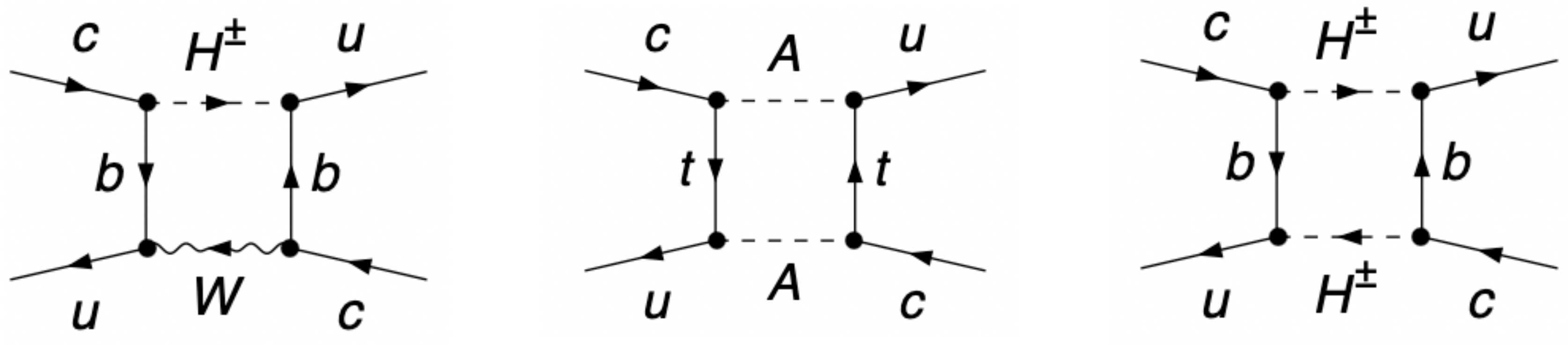
Flavour constraints

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

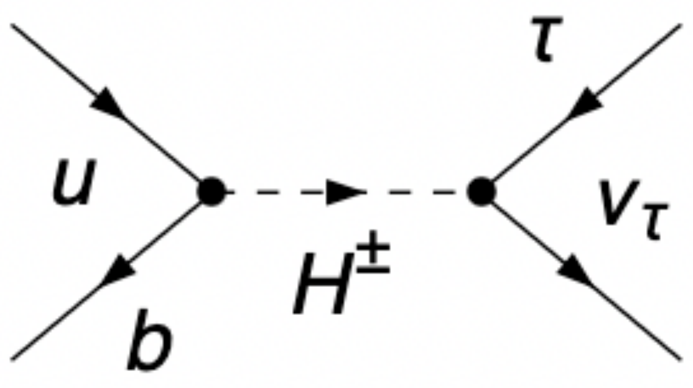
-$D^0 - \bar{D}^0$ mixing at tree level.



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



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



李政道研究所
TSUNG-DAO LEE INSTITUTE

Flavour constraints

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

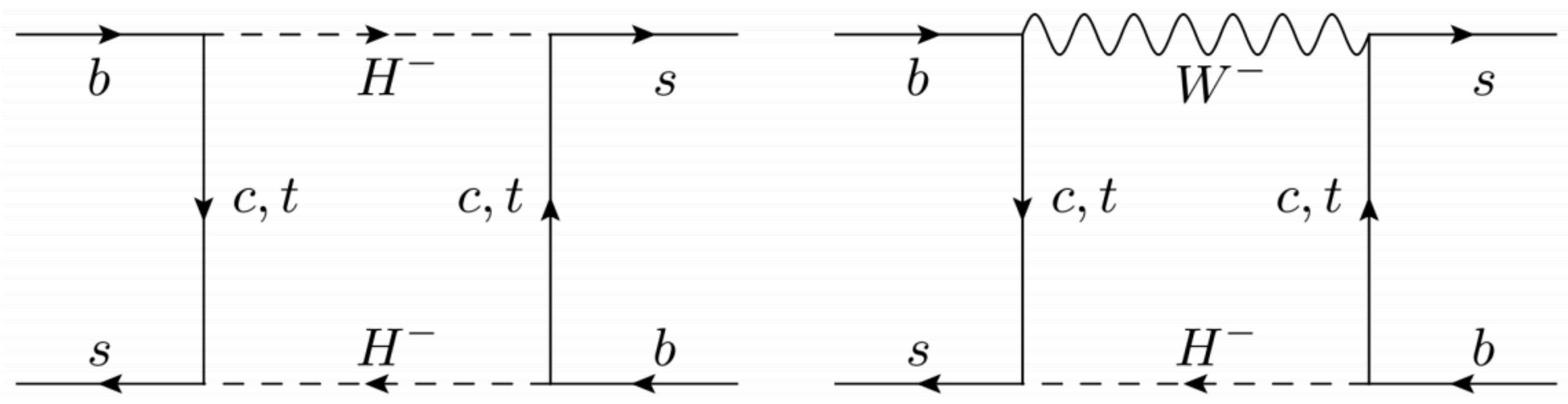
$$\rho_u = \begin{pmatrix} 0 & 0 & \rho_u^{ut} \\ 0 & \rho_u^{cc} & 0 \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

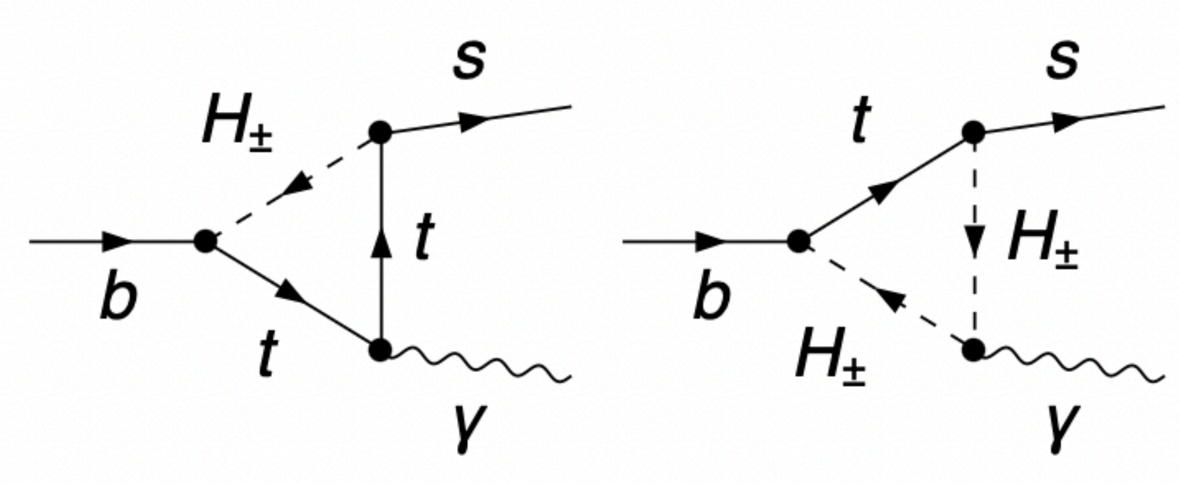
Flavour constraints

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

(Constrain all four couplings)

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



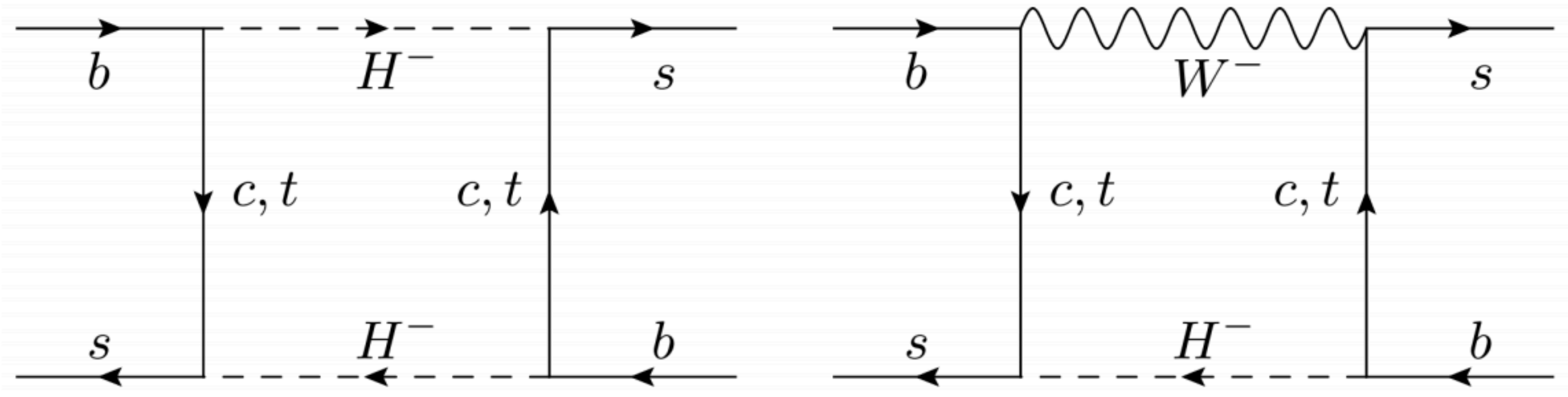


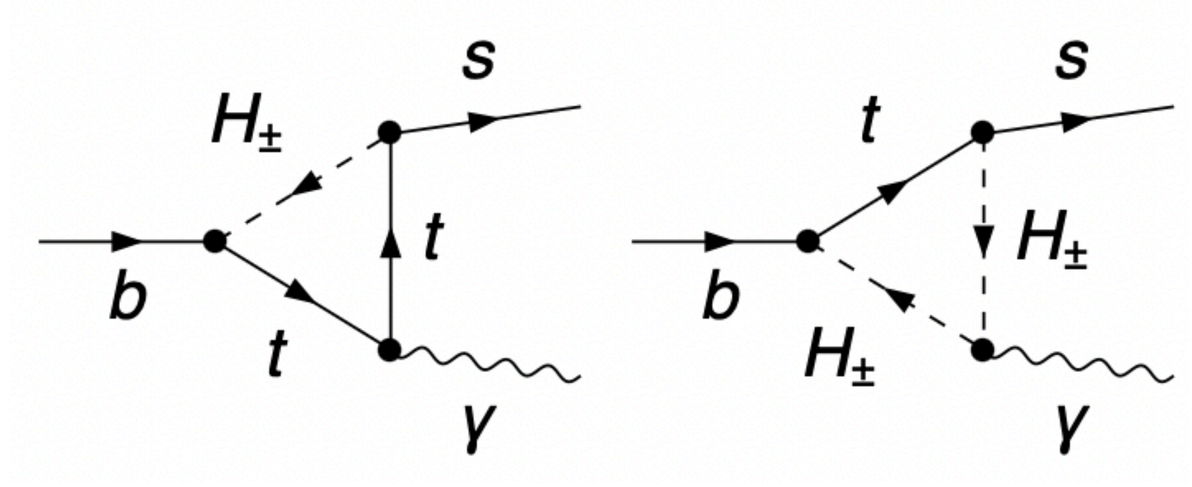
$$\rho_u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \rho_u^{cc} & 0 \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

李政道研究所 TSUNG-DAO LEE INSTITUTE

Flavour constraints

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





(Constrain all four couplings)

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

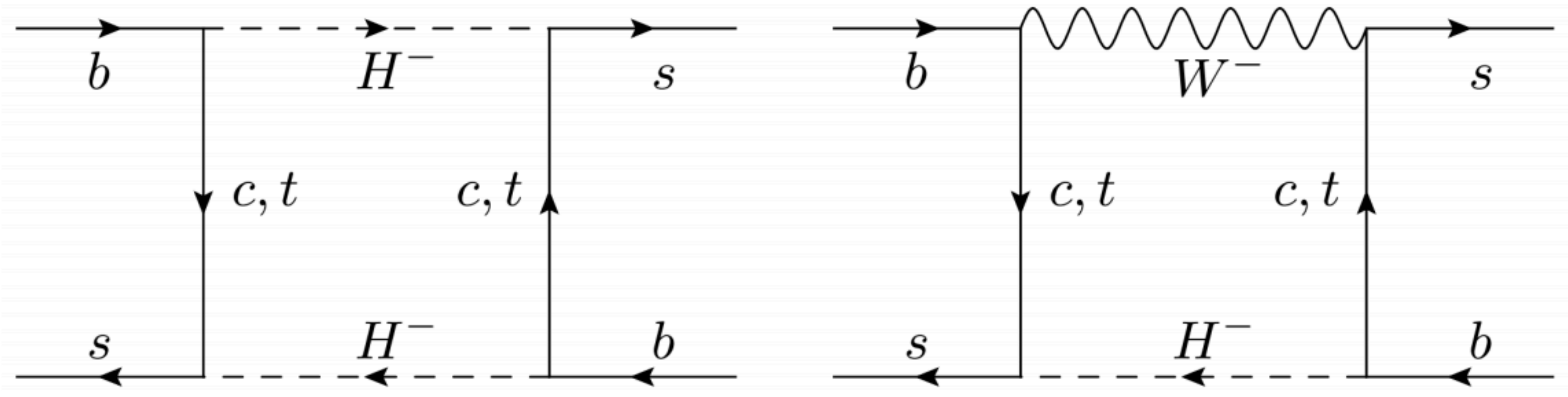
$$\rho_u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \rho_u^{cc} & 0 \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

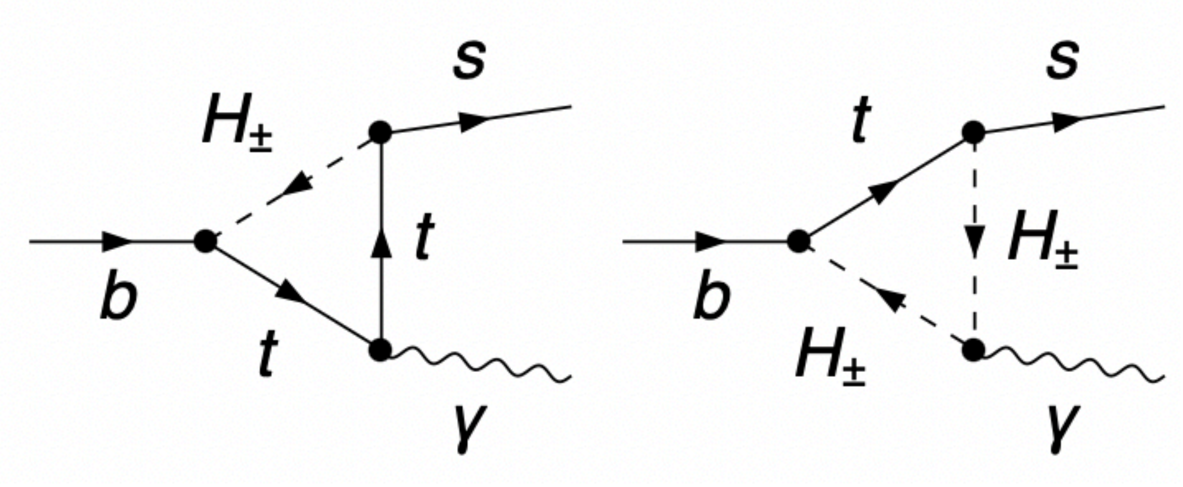
$R(D^{(*)})$

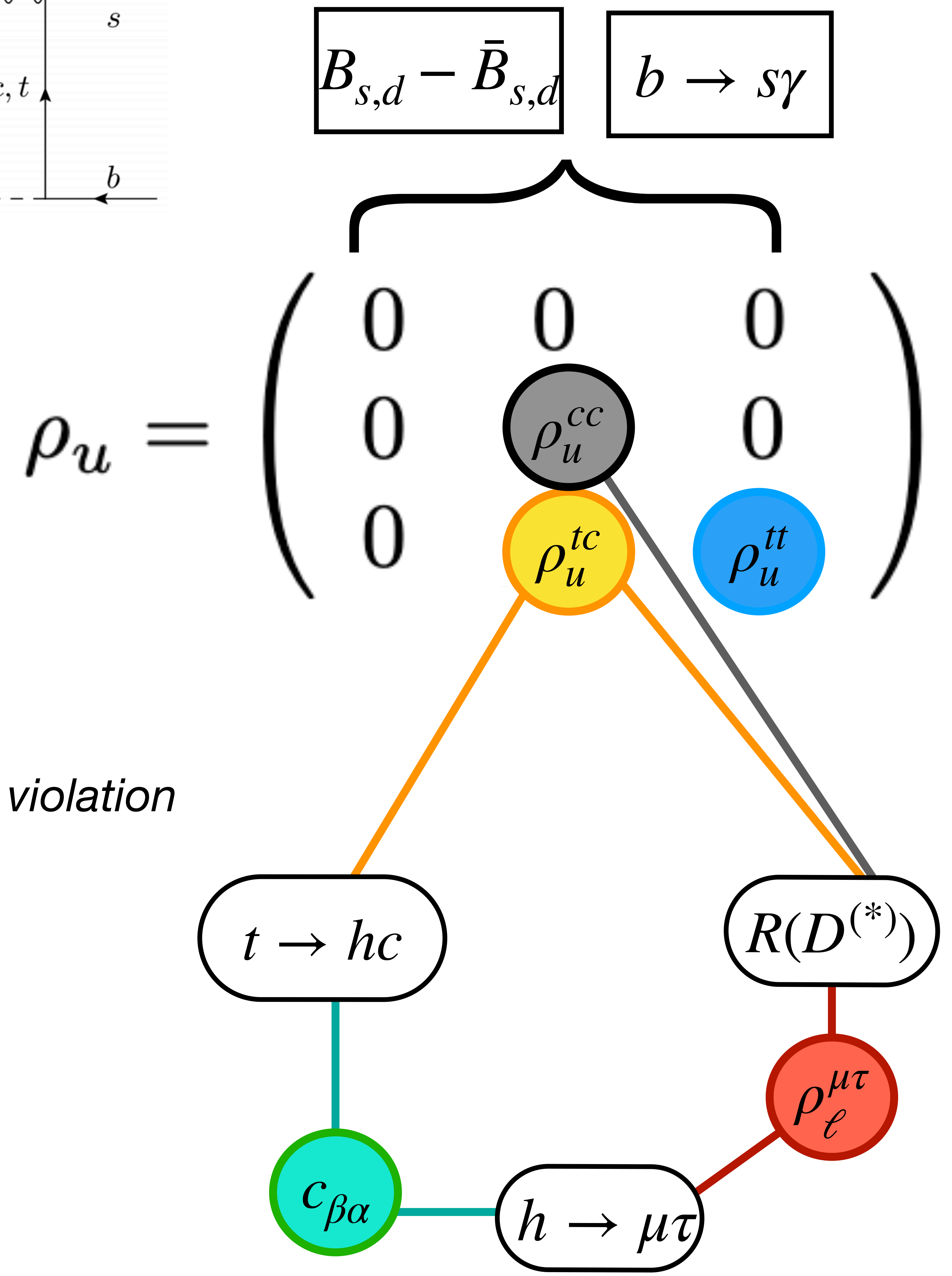
Flavour constraints

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

(Constrain all four couplings)





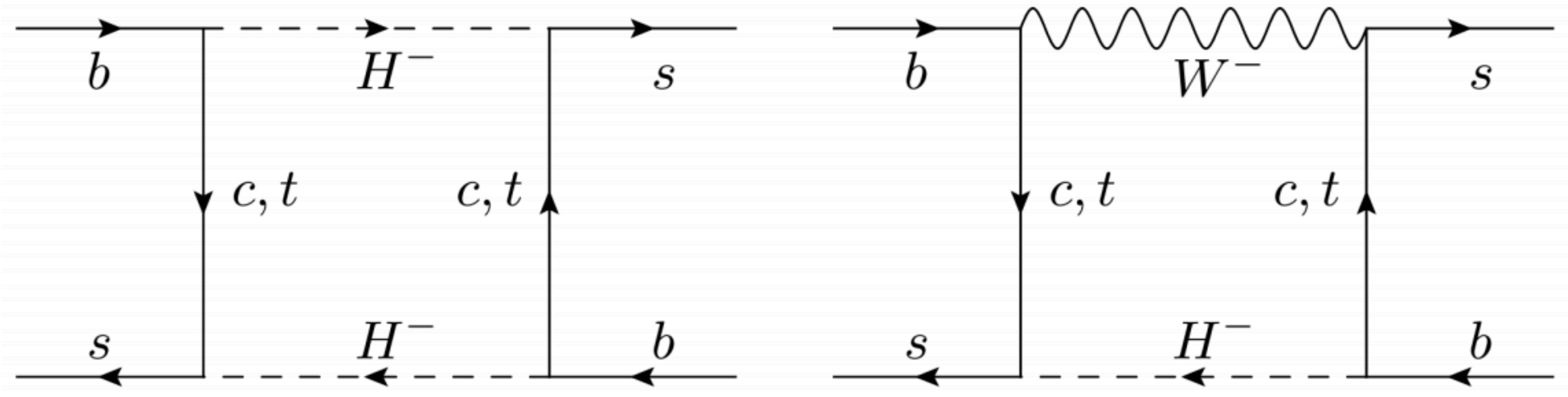


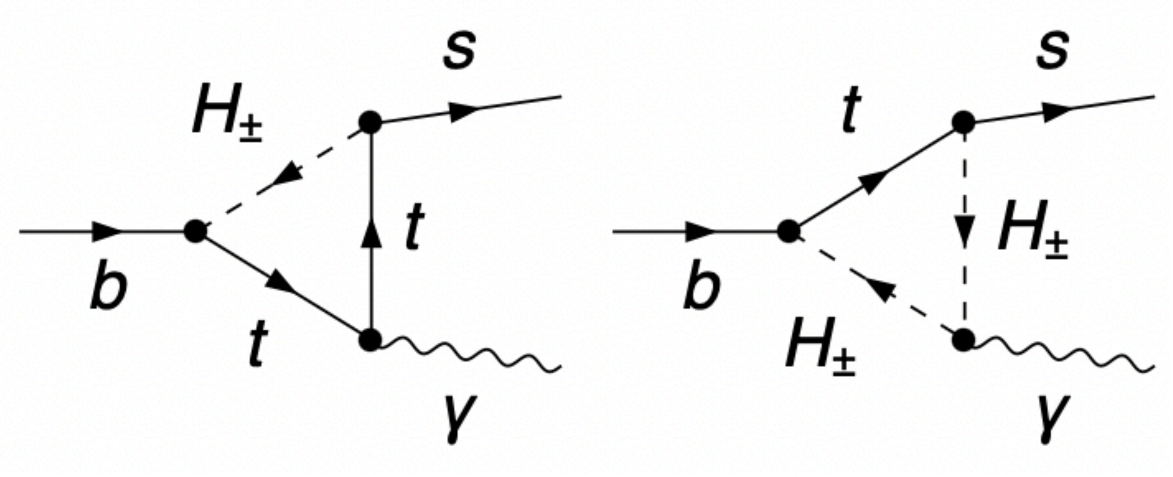
- *Direct flavour violation*

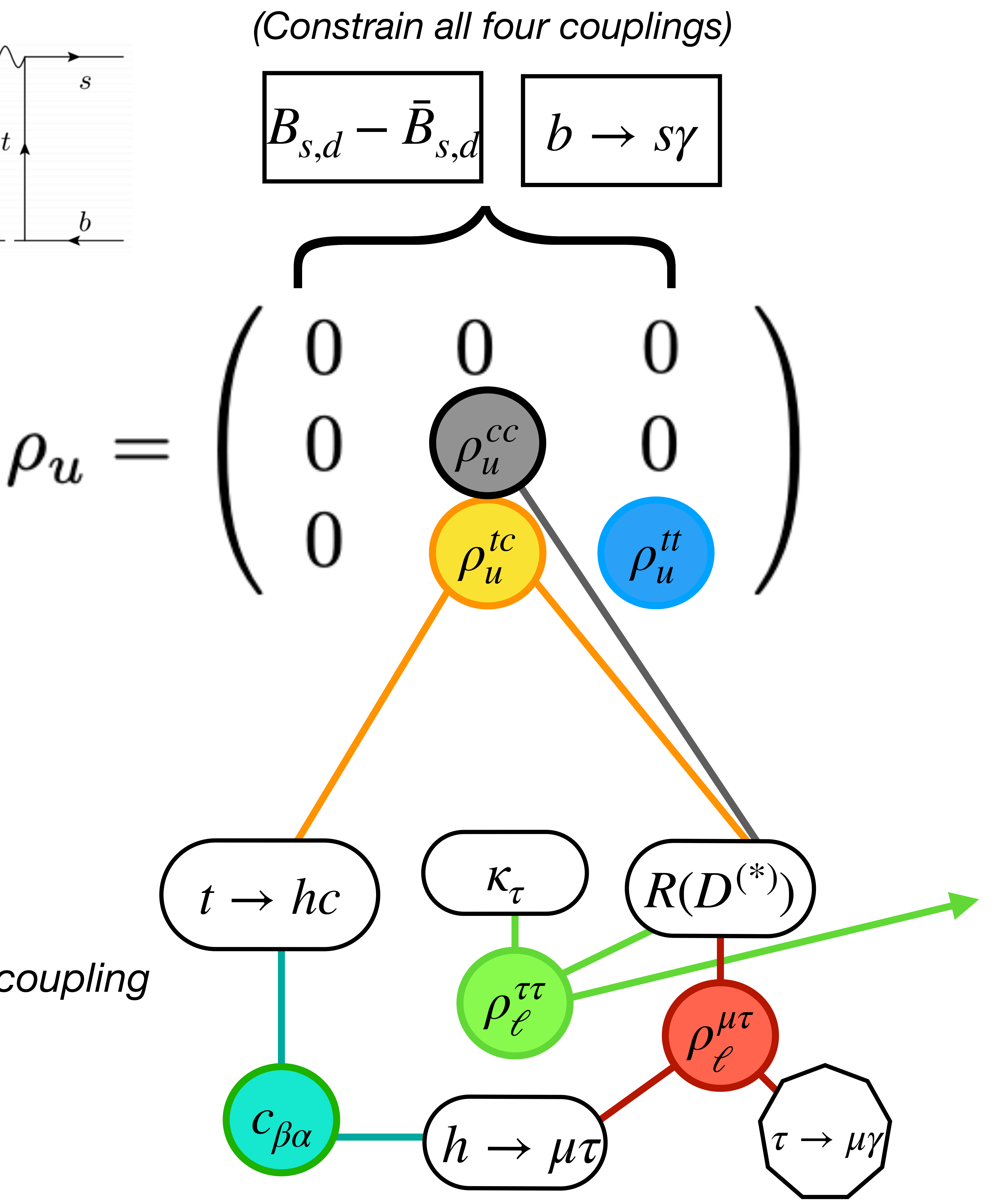
李政道研究所 TSUNG-DAO LEE INSTITUTE

Flavour constraints

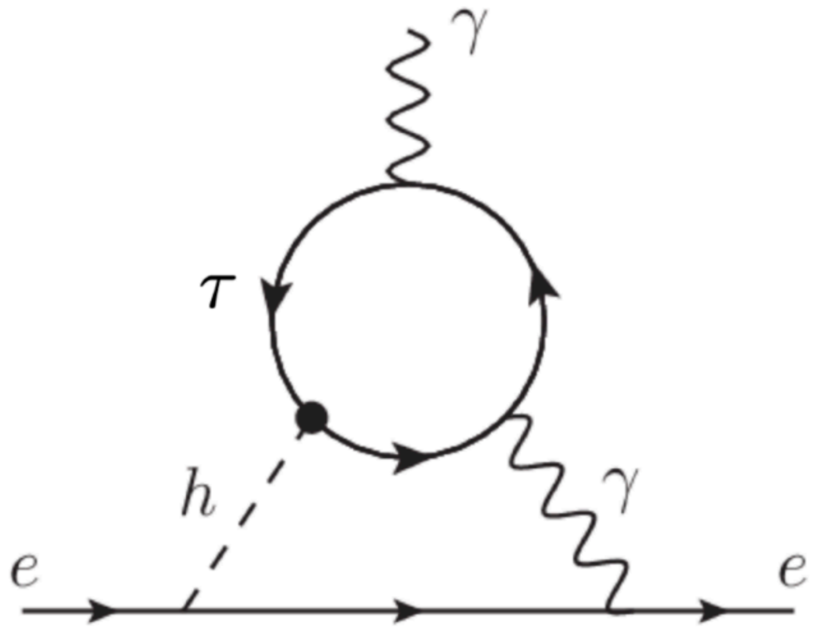
$\text{Loops} = \sqrt{n} - 1\,,\ n = $ #"**sides**"







- *Constraints on tau coupling*



- *eEDM constrains the imaginary part of* $\rho_\ell^{\tau\tau}$.

- Motivation
- General Two Higgs Doublet Model (G2HDM)
- Flavour constraints
- **Collider constraints**
- Parameter space scan
- EWBG
- Results
- Summary

Collider constraints

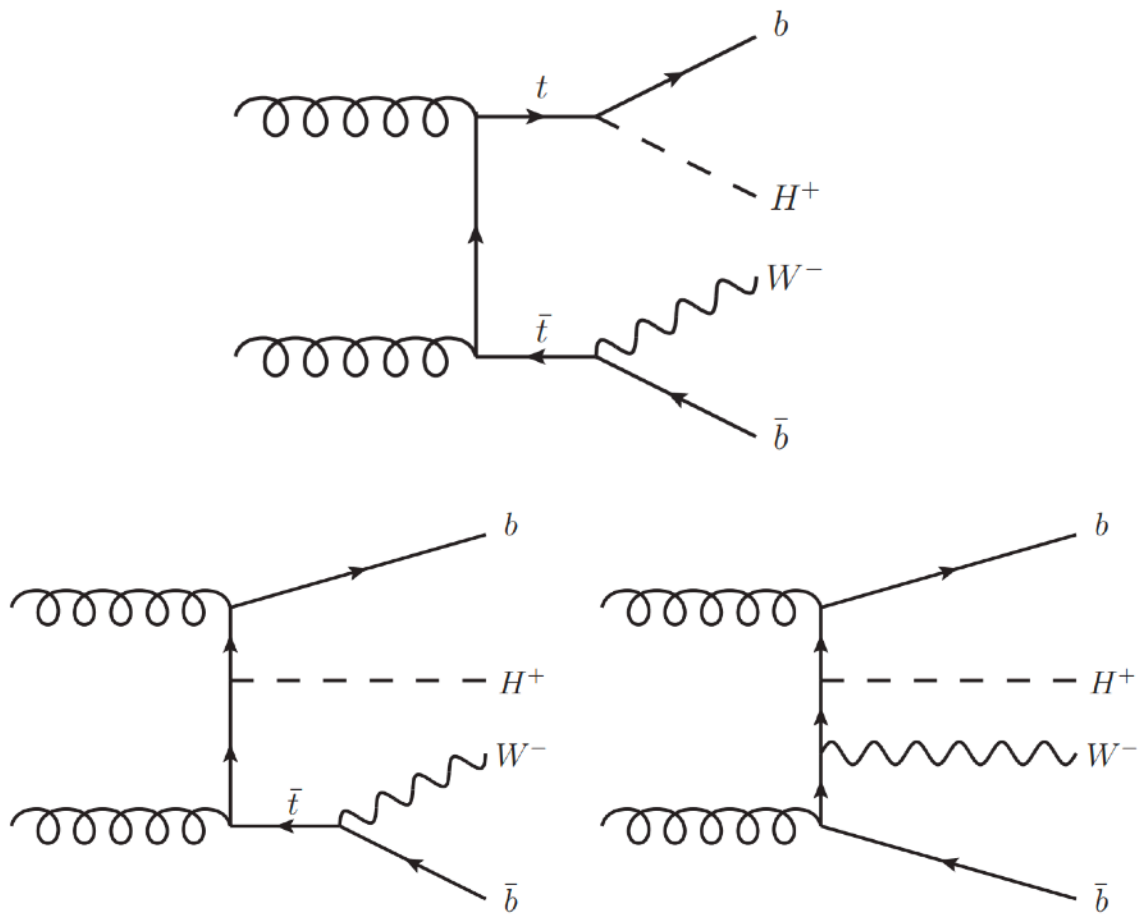
$$\rho_u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \rho_u^{cc} & 0 \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

$t \to H^+ b$

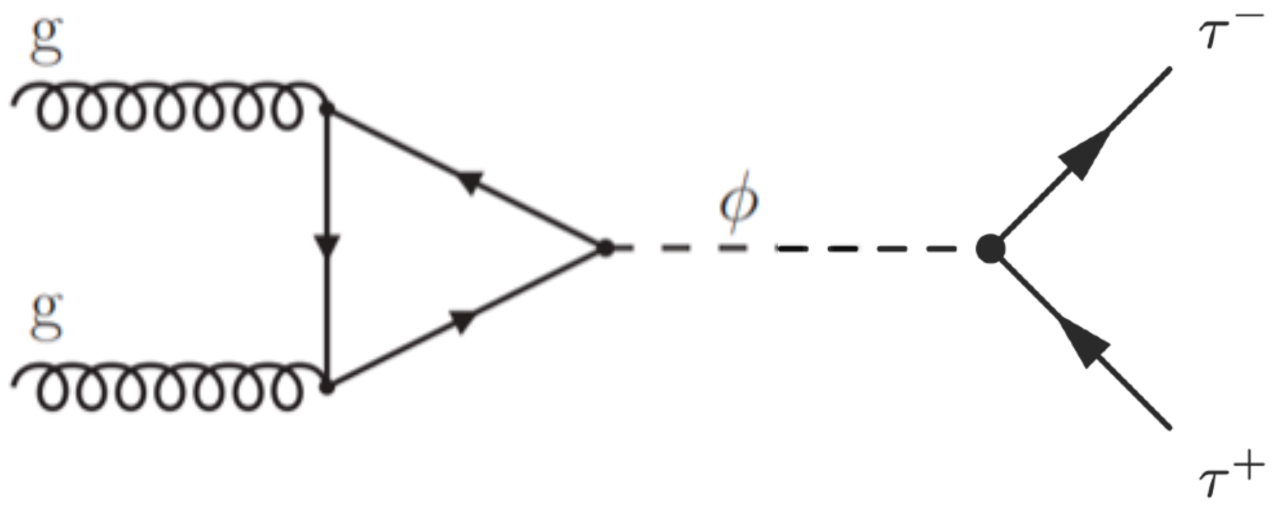
$\rho_\ell^{\tau\tau}$

CMS data, Charged Higgs production,

arXiv:2412.17584

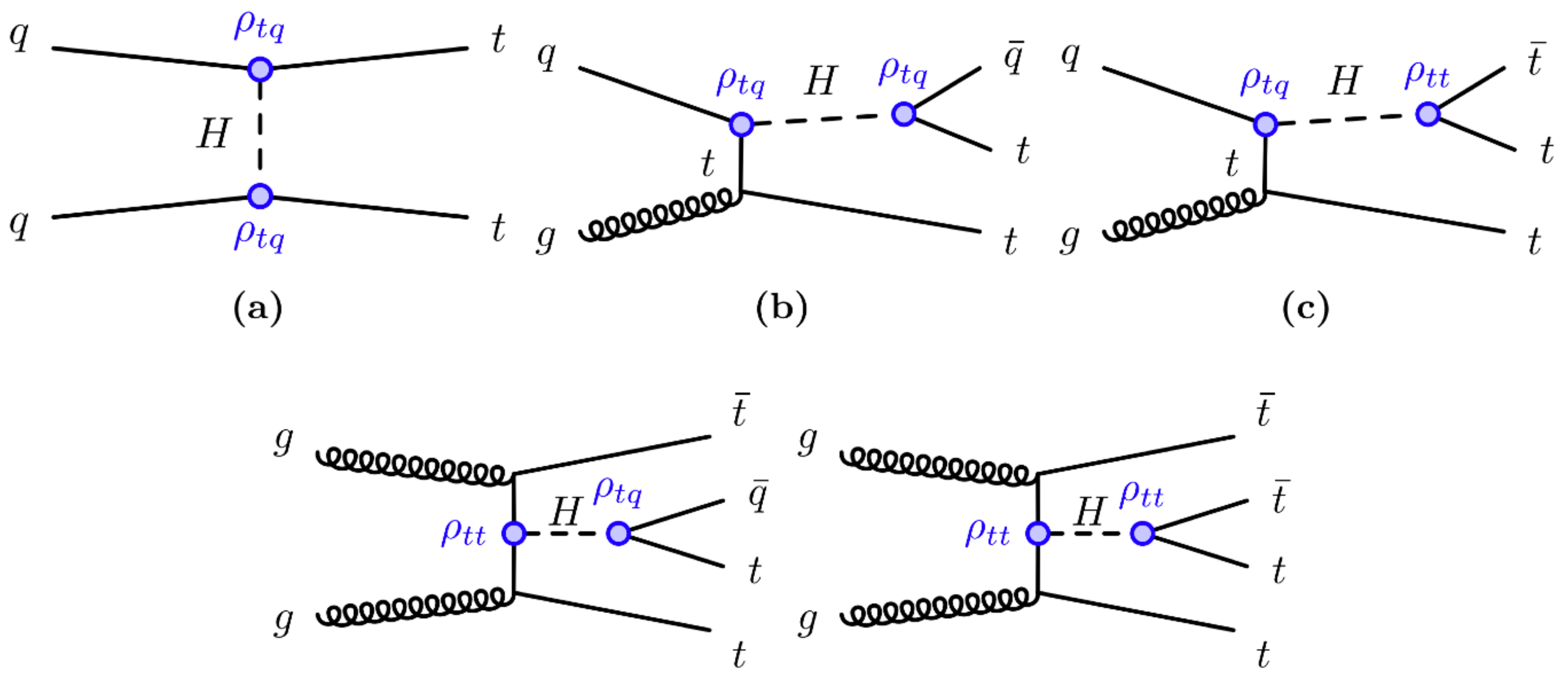


- ***CMS multi-tau decays search arXiv:2208.02717***



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

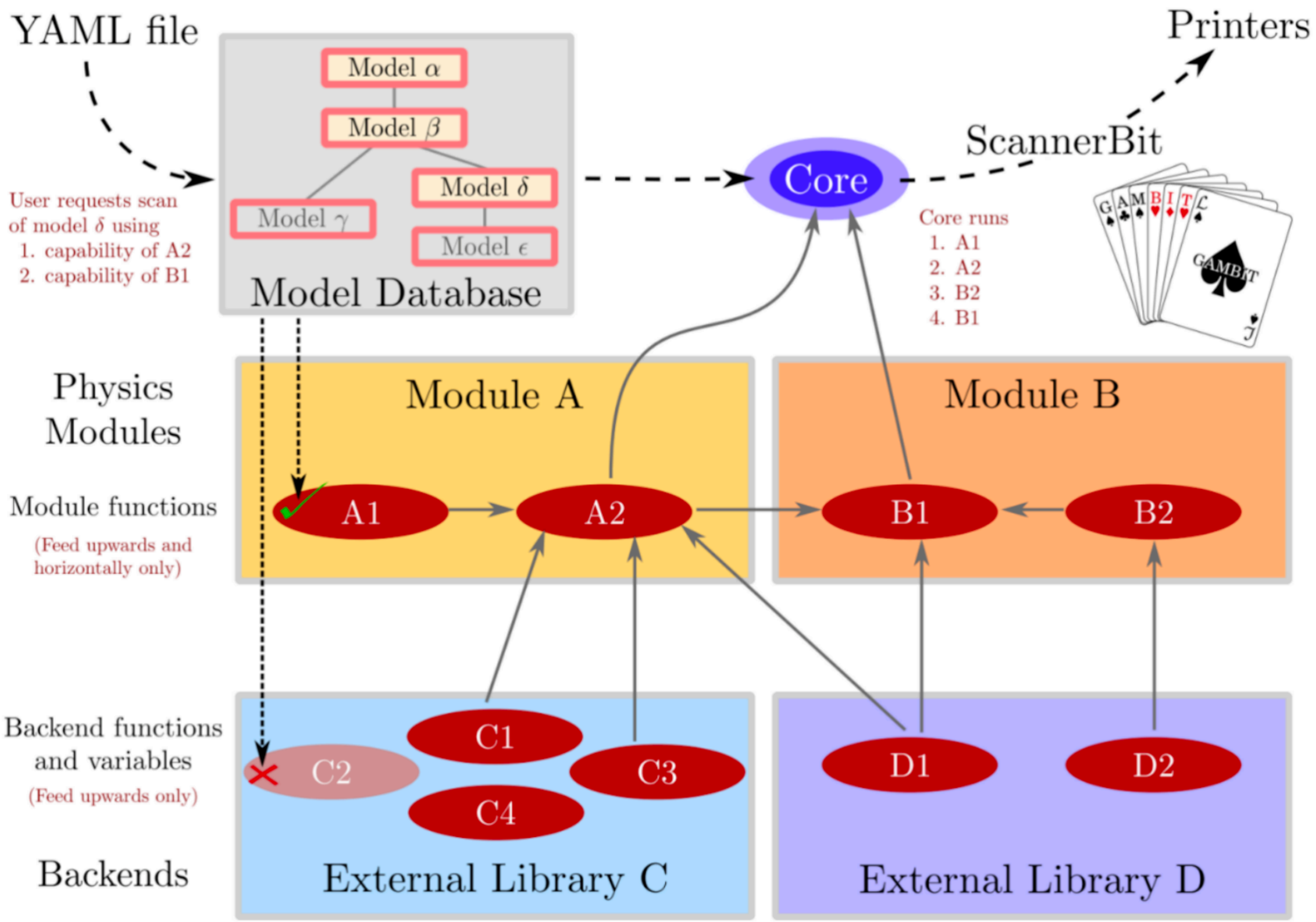
ATLAS search for neutral Higgses, arXiv:2307.14759



- Motivation
- General Two Higgs Doublet Model (G2HDM)
- Flavour constraints
- Collider constraints
- **Parameter space scan**
- EWBG
- Results
- Summary

GAMBIT: The Global And Modular BSM Inference Tool

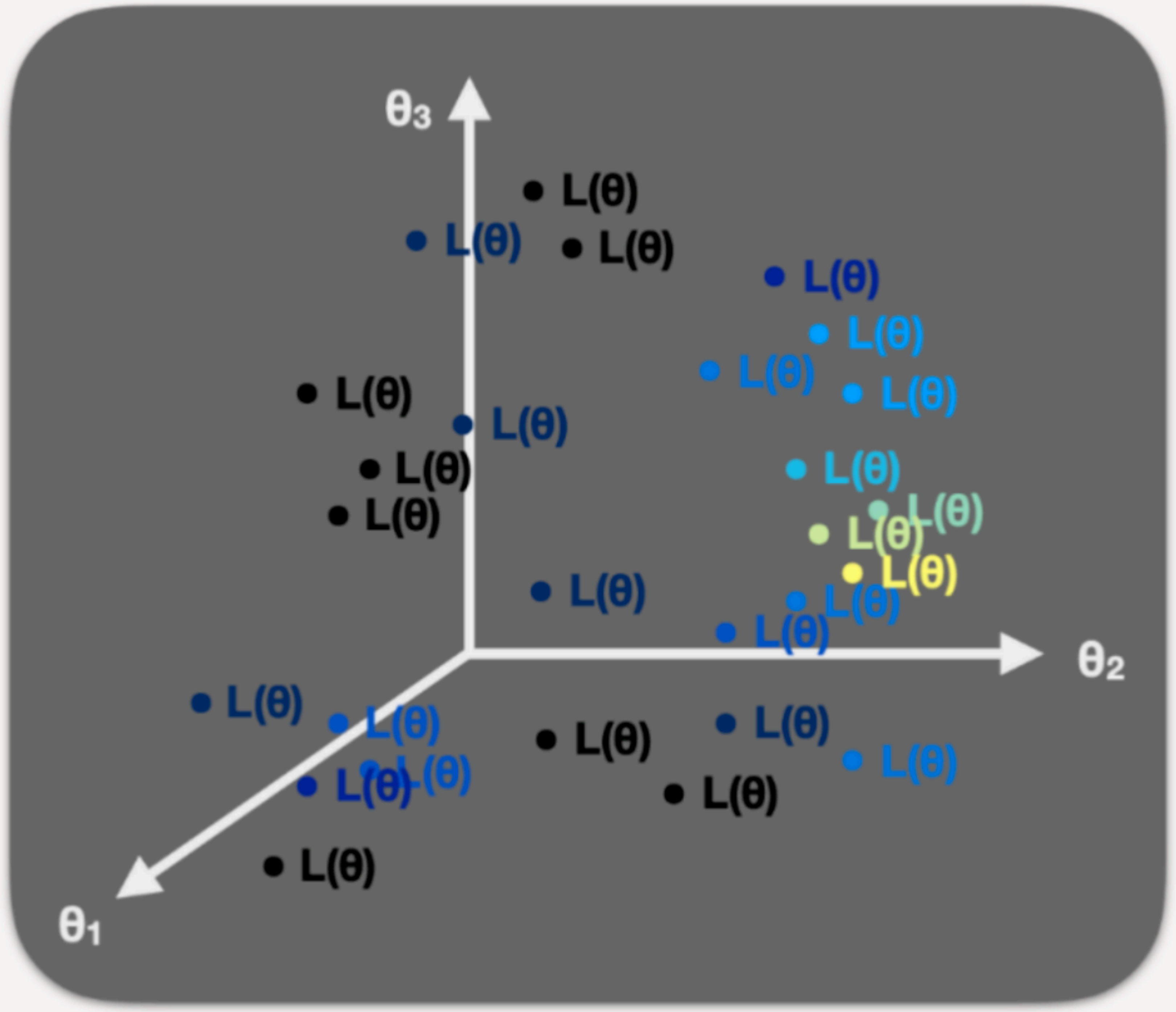
gambit.hepforge.org



李政道研究所 TSUNG-DAO LEE INSTITUTE

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)**



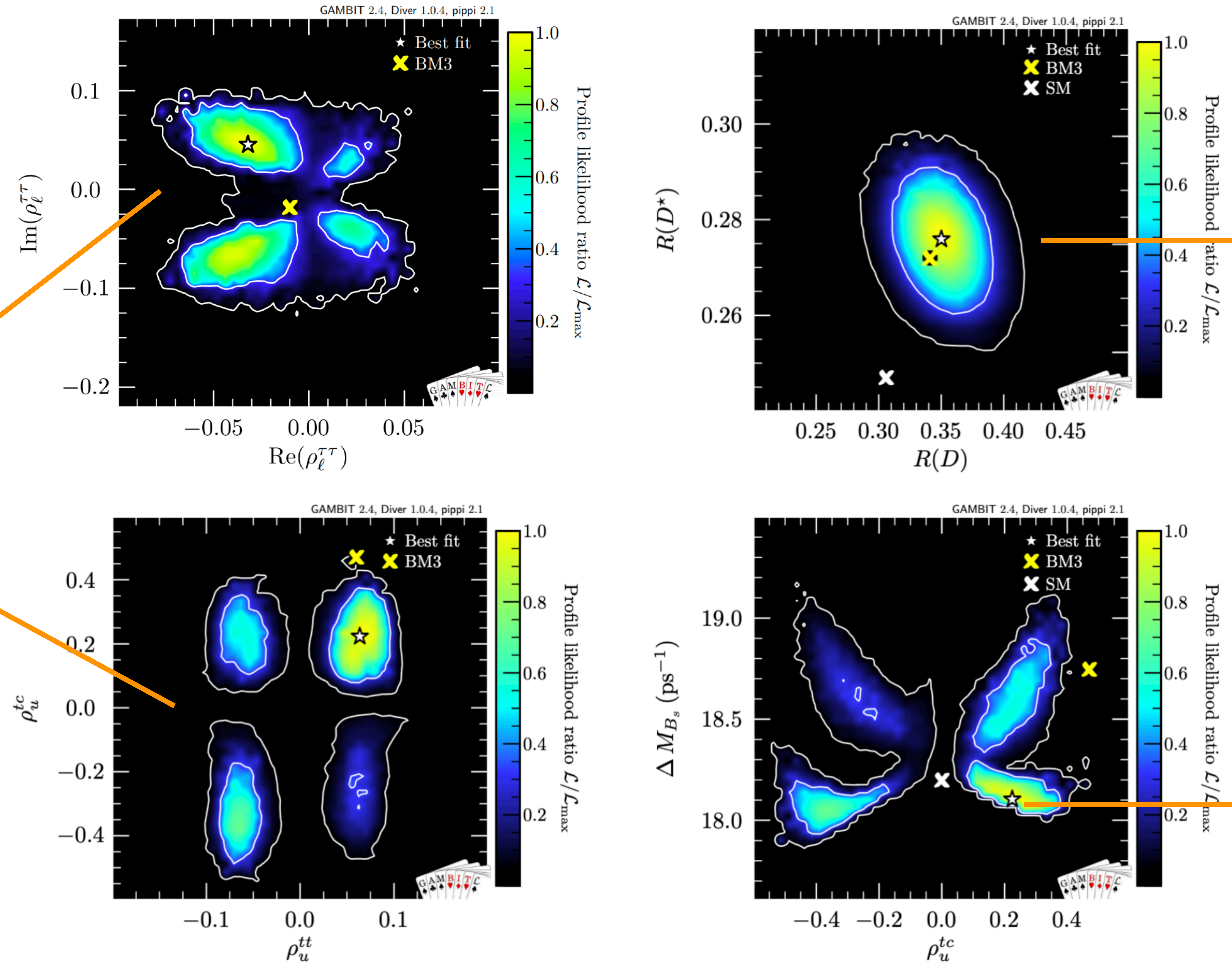
- Region of highest L(θ) or lnL(θ): **model's best simultaneous fit to all data**
(but not necessarily a *good* fit, or the most probable θ…)

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)

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



Charged anomalies are fitted

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

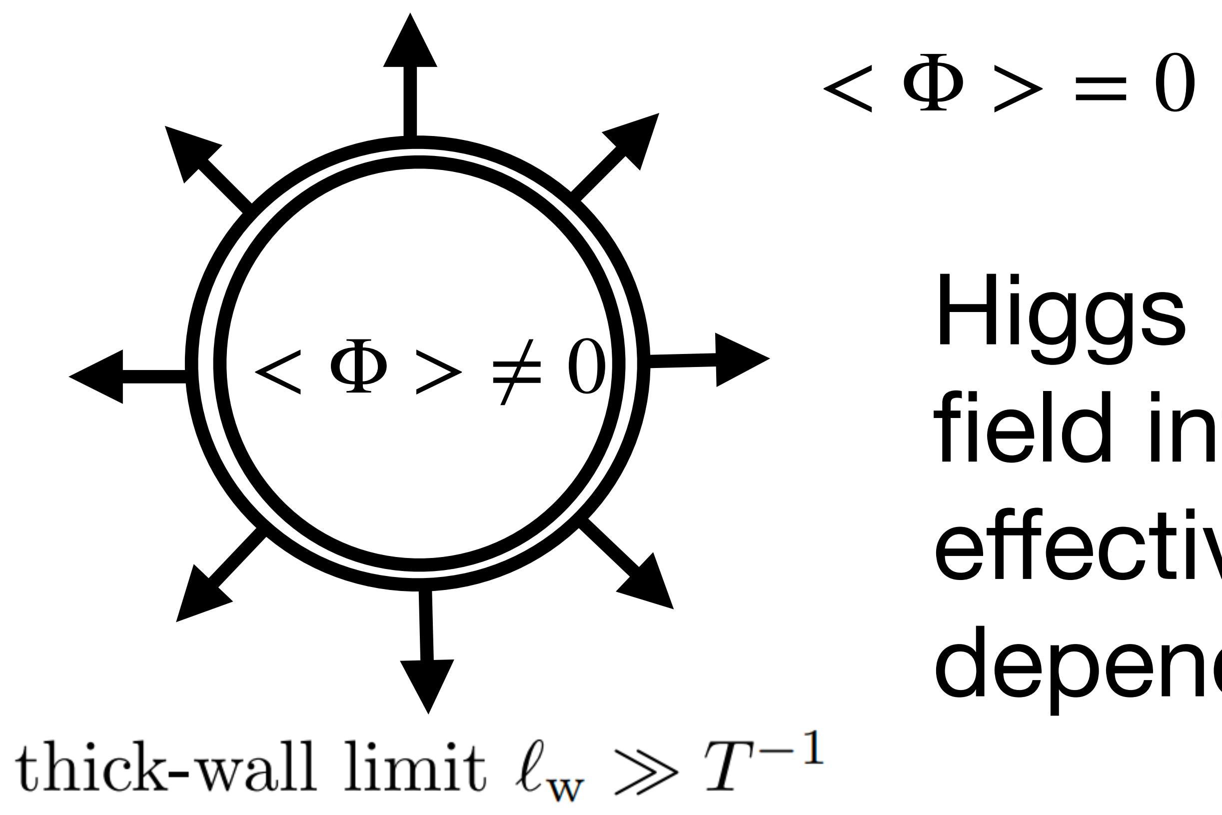
Plots from P. Athron, A. Crivellin, T. Gonzalo, S. Iguro, **CS**. *JHEP* 11 (2024) 133 • e-Print: 2410.10493 [hep-ph]

李政道研究所
TSUNG-DAO LEE INSTITUTE

- Motivation
- General Two Higgs Doublet Model (G2HDM)
- Flavour constraints
- Collider constraints
- Parameter space scan
- **EWBG**
- Results
- Summary

Electroweak baryogenesis

WKB formalism



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

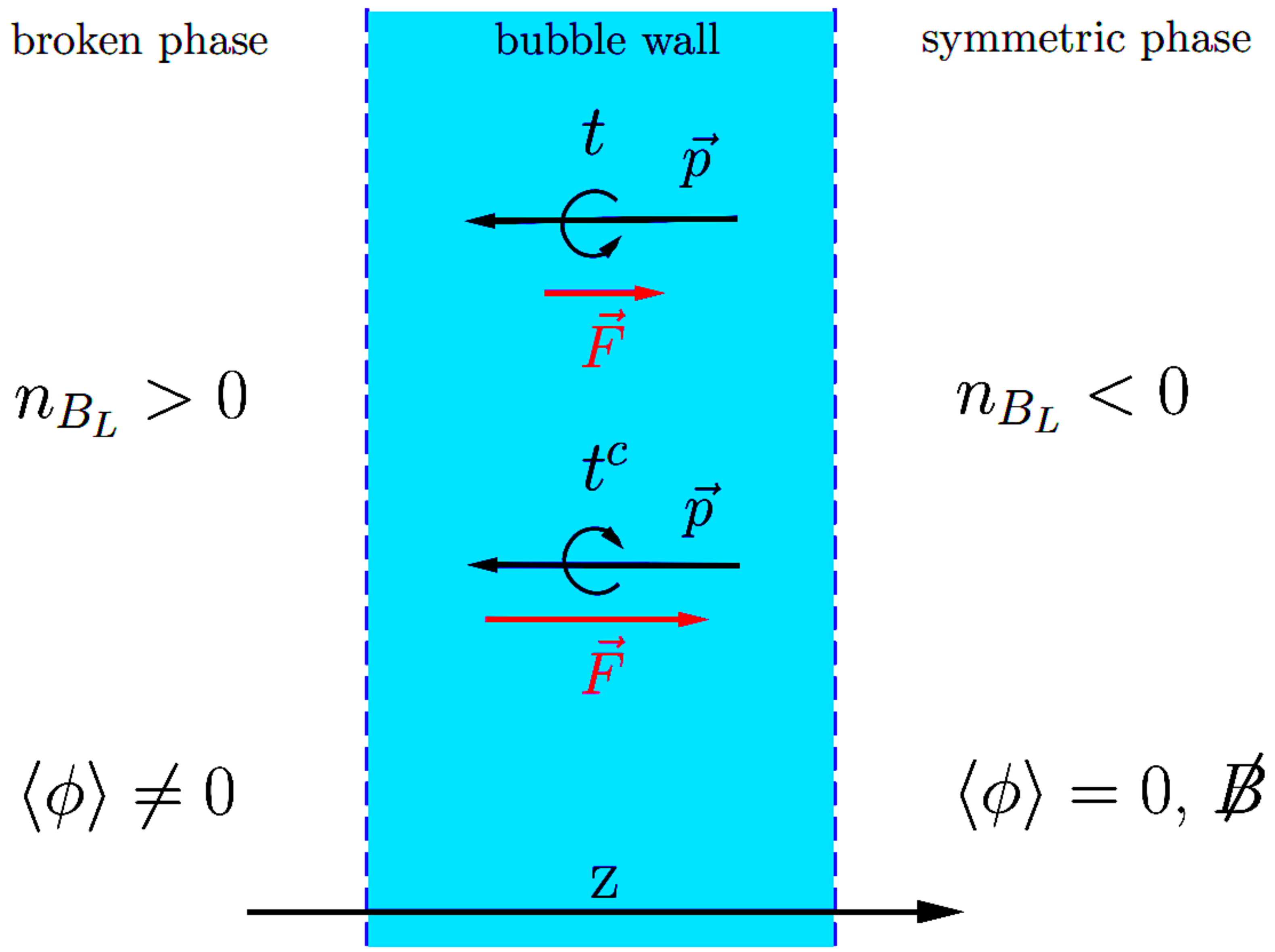
$$F_z = -\frac{\left(|m|^2\right)'}{2E} + s\left[\frac{\left(|m|^2\theta'\right)'}{2EE_z}\right]$$

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

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:

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

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]

李政道研究所
TSUNG-DAO LEE INSTITUTE

Electroweak baryogenesis

WKB formalism

Lorentz factor

"K" factors from transport equations

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

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

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

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

Weak sphaleron rate

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

Quarks diffusion coefficient

SM relaxation term (15/4)

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

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

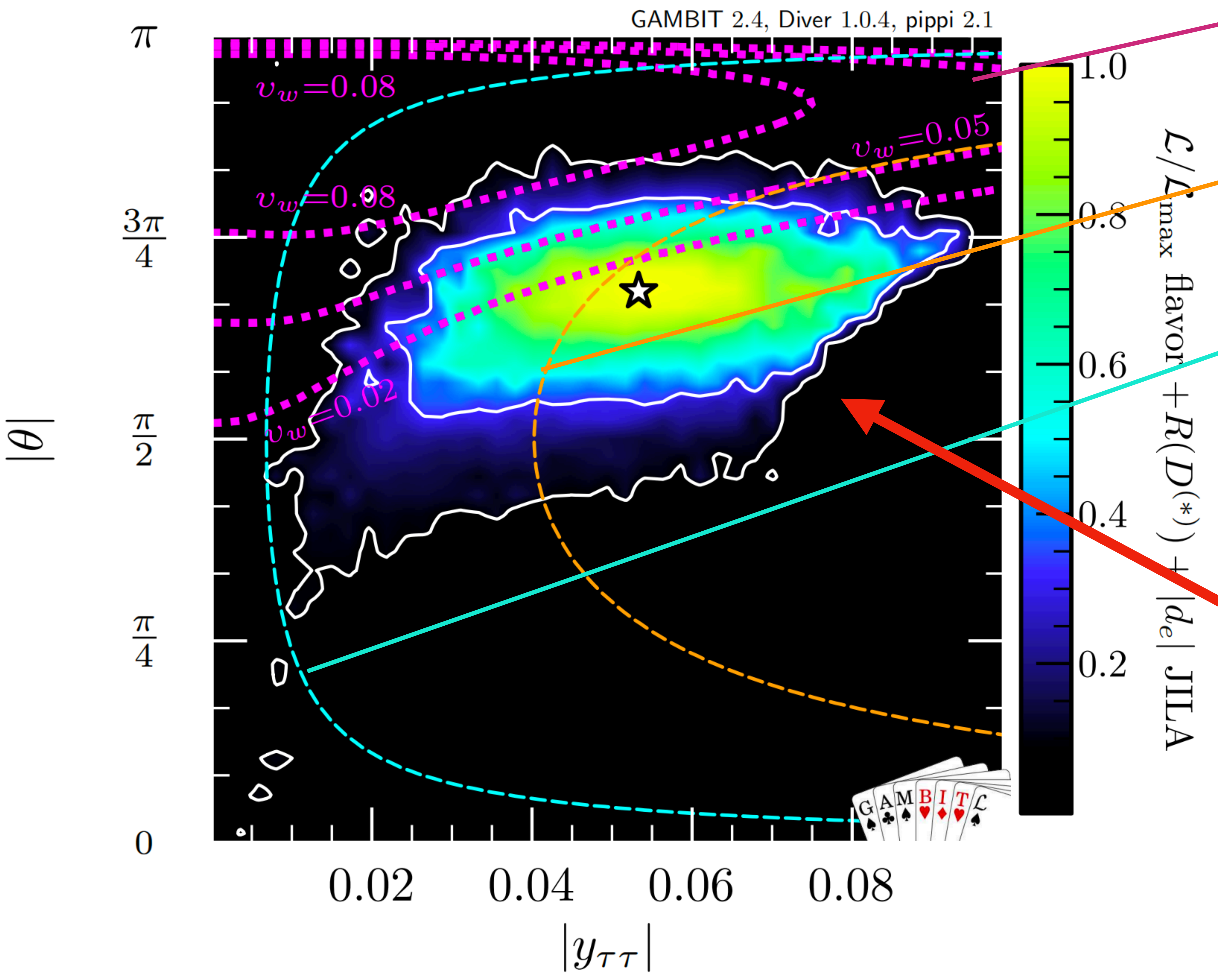
Entropy density

李政道研究所
TSUNG-DAO LEE INSTITUTE

- Motivation
- General Two Higgs Doublet Model (G2HDM)
- Flavour constraints
- Collider constraints
- Parameter space scan
- EWBG
- **Results**
- Summary

Electroweak baryogenesis

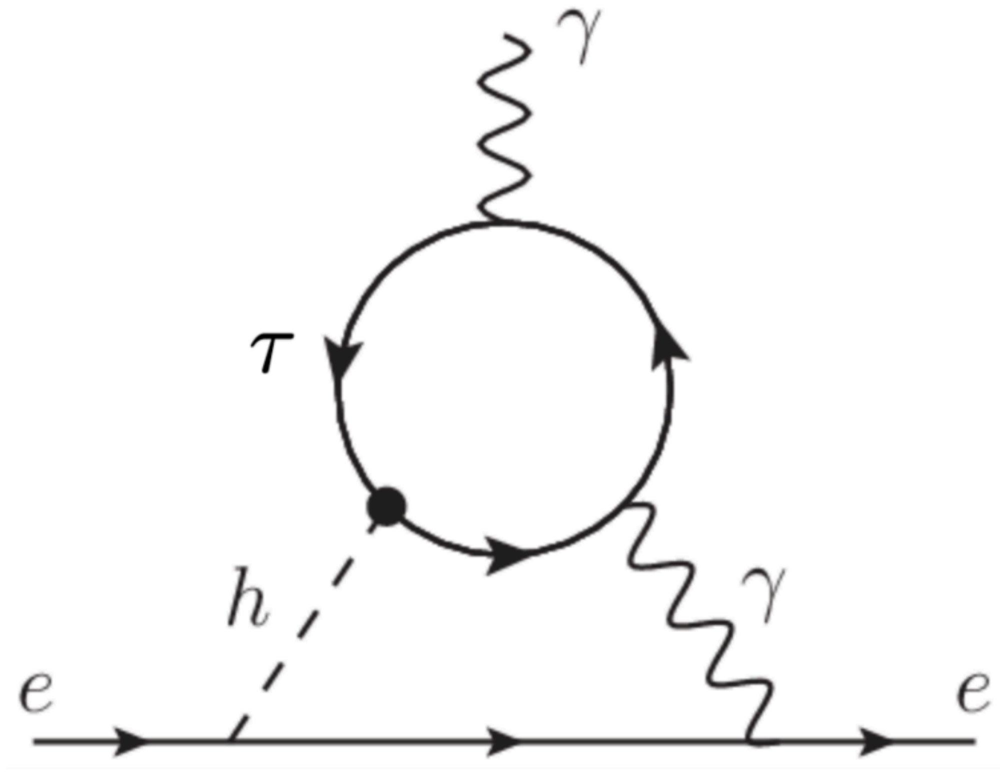
Projecting the BAU in the parameter space



- 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

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



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

李政道研究所
TSUNG-DAO LEE INSTITUTE

- Motivation
- General Two Higgs Doublet Model (G2HDM)
- Flavour constraints
- Collider constraints
- Parameter space scan
- EWBG
- Results
- **Summary**

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 $Y_B = Y_B^{obs}$.

谢谢你！

Backup

李政道研究所 TSUNG-DAO LEE INSTITUTE

General 2HDM

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

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

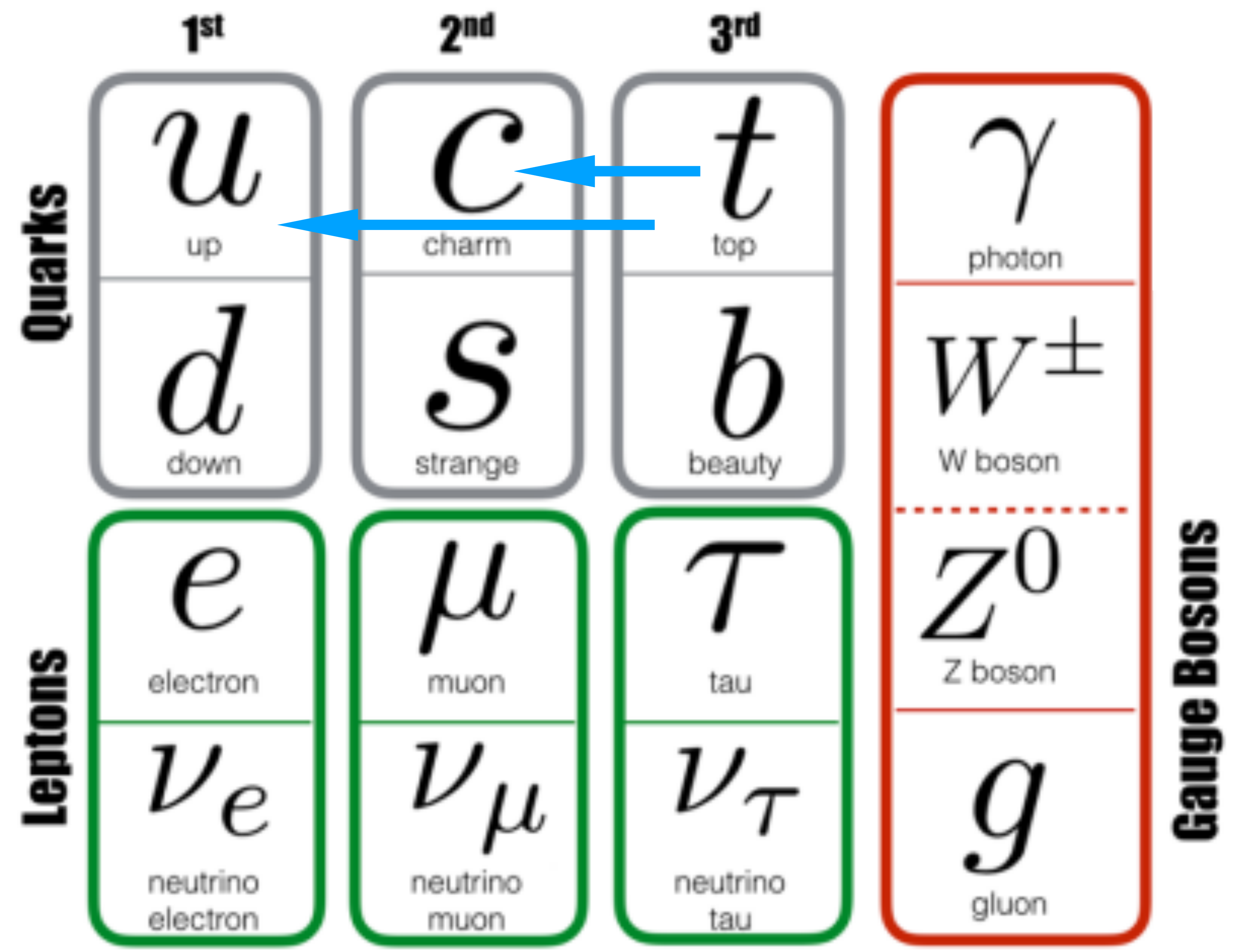


Image credit: Physik-Institut - UZH

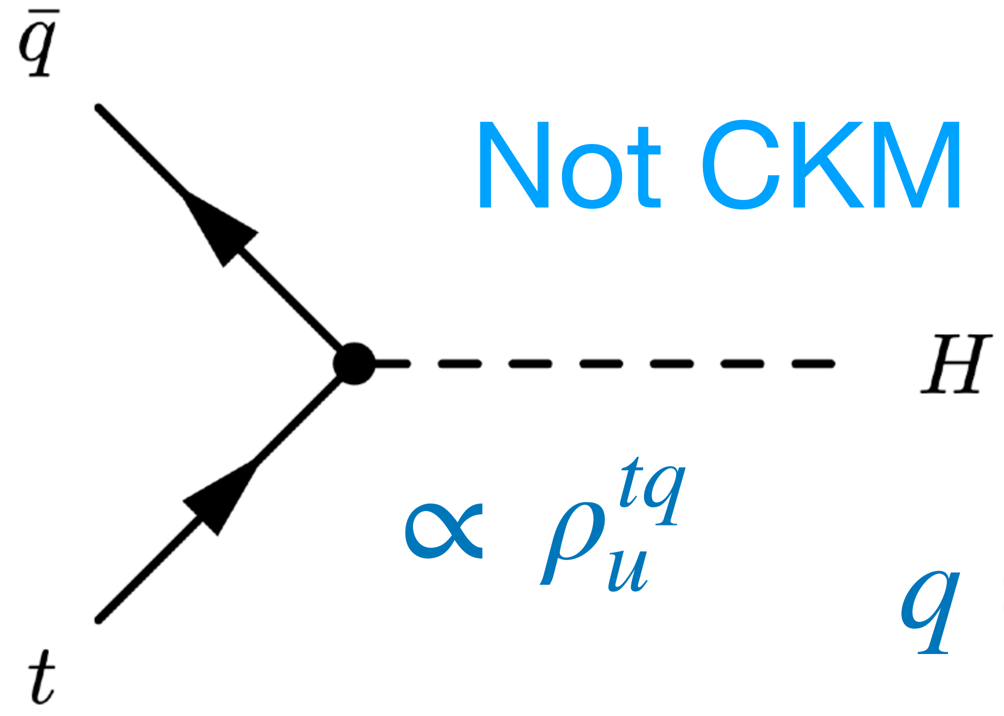
In the mass basis, the Yukawa Lagrangian has the following flavour violating couplings (complex in general)

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

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

$\tan\beta$ is absorbed in ρ_f^{ba}

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



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

Not CKM suppressed

$\propto \rho_u^{tq}$

$q = u, c$

Collider constraints

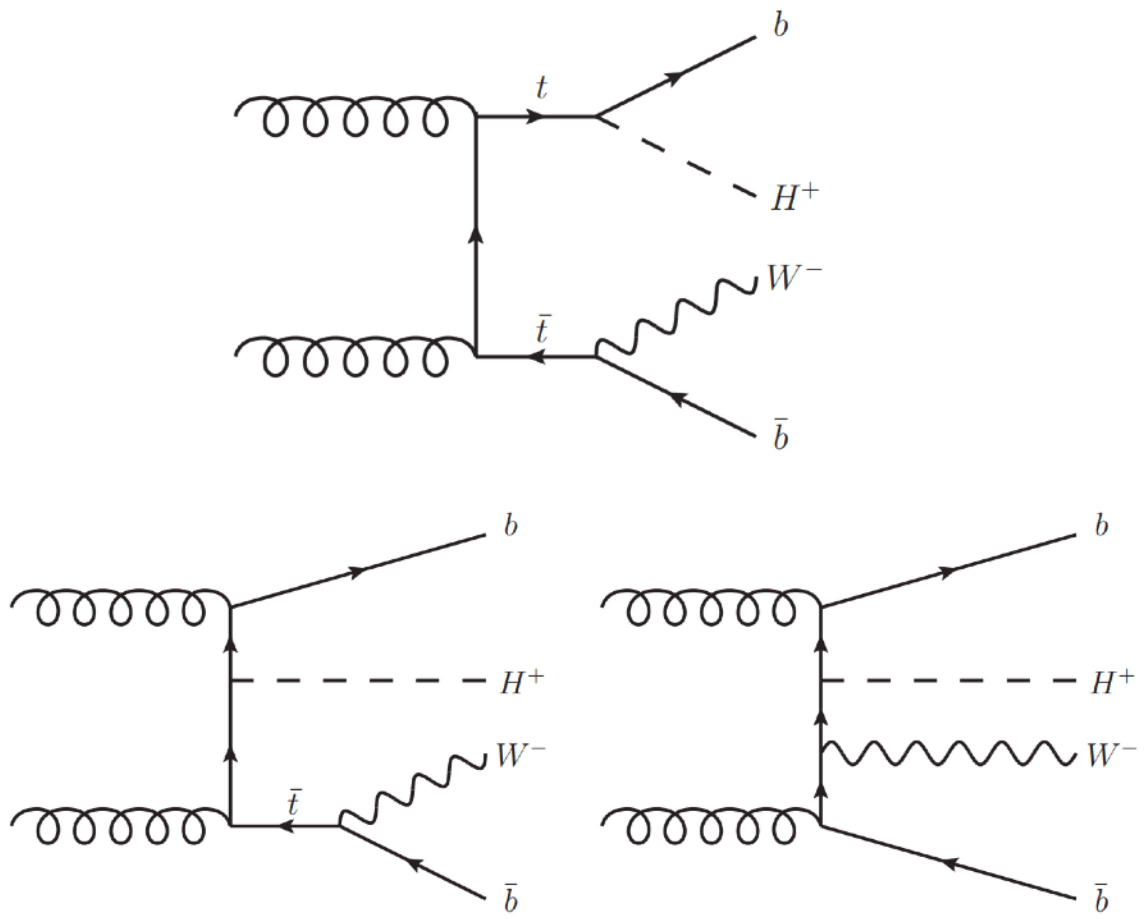
$$\rho_u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \rho_u^{cc} & 0 \\ 0 & \rho_u^{tc} & \rho_u^{tt} \end{pmatrix}$$

$t \to H^+ b$

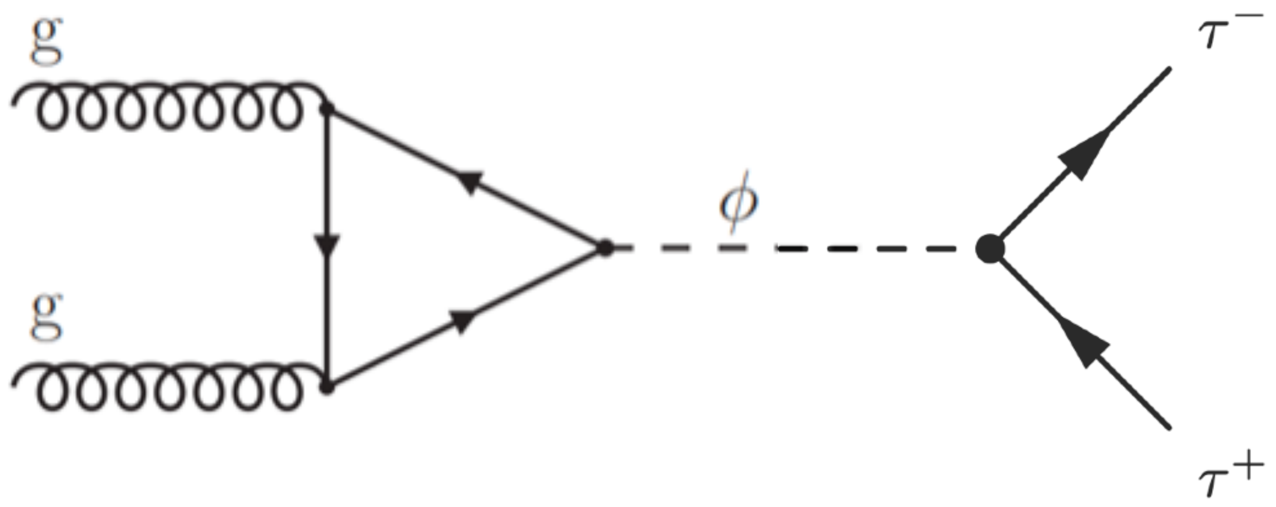
$\rho_\ell^{\tau\tau}$

CMS data, Charged Higgs production,

arXiv:2412.17584

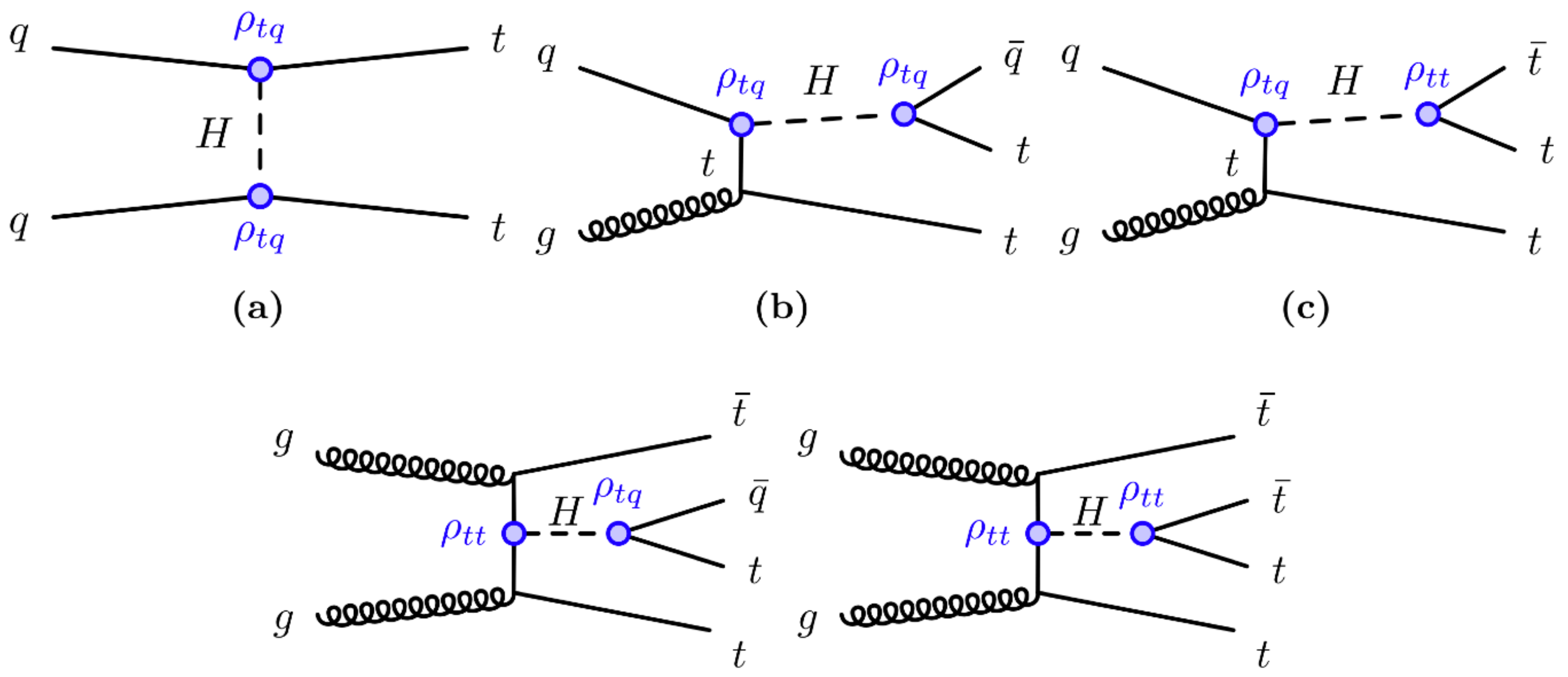


- ***CMS multi-tau decays search arXiv:2208.02717***



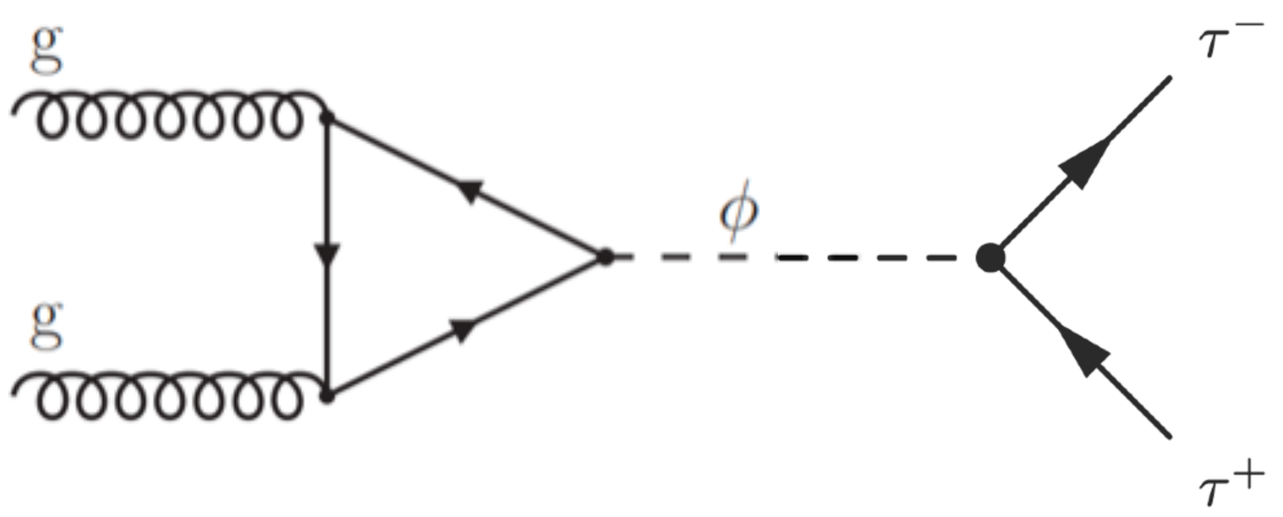
$$\boxed{\sigma(gg \to \phi \to \tau^+\tau^-) = \sigma(gg \to \phi) \cdot \mathrm{BR}(\phi \to \tau^+\tau^-)}$$

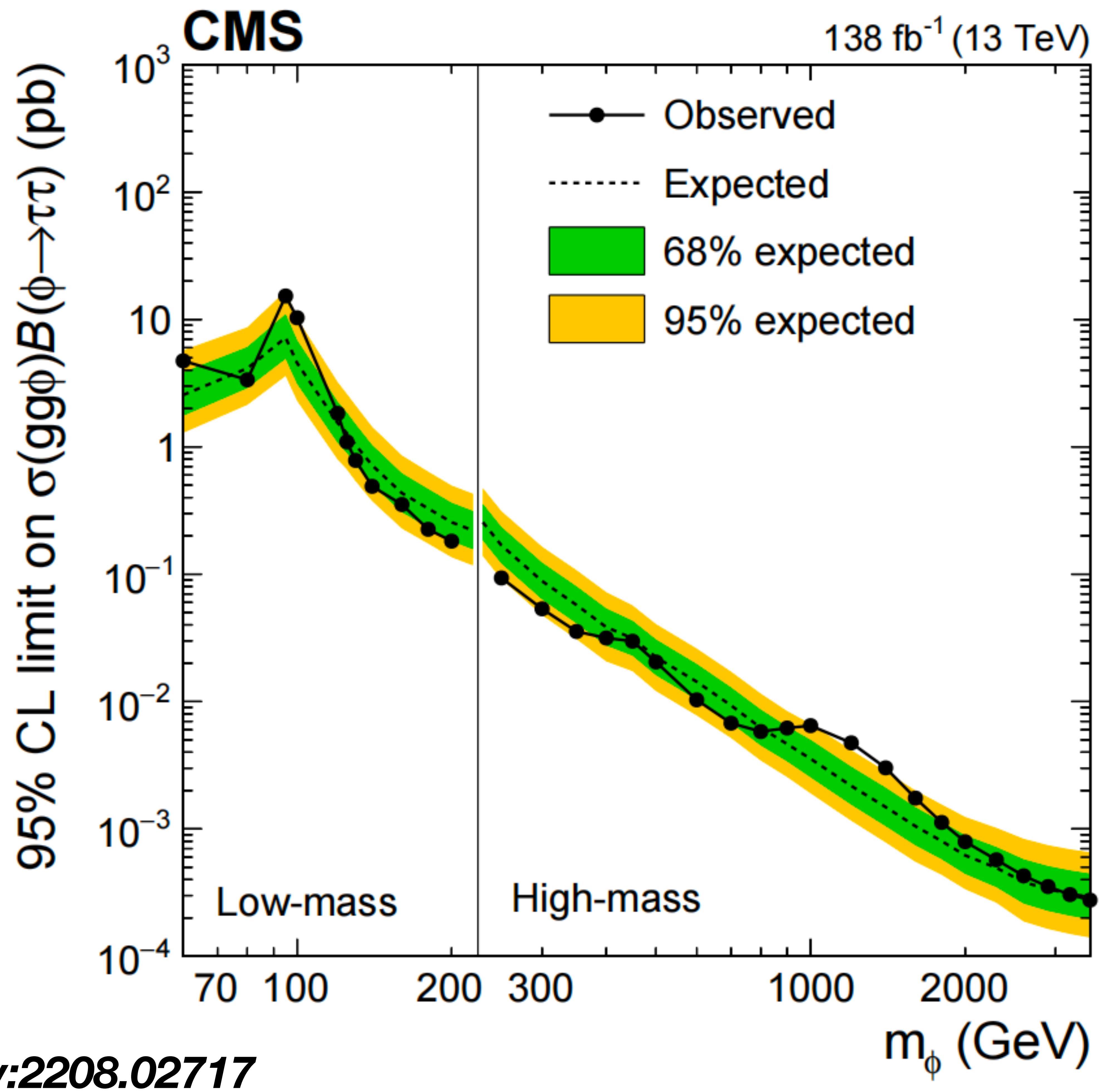
ATLAS search for neutral Higgses, arXiv:2307.14759



李政道研究所 TSUNG-DAO LEE INSTITUTE

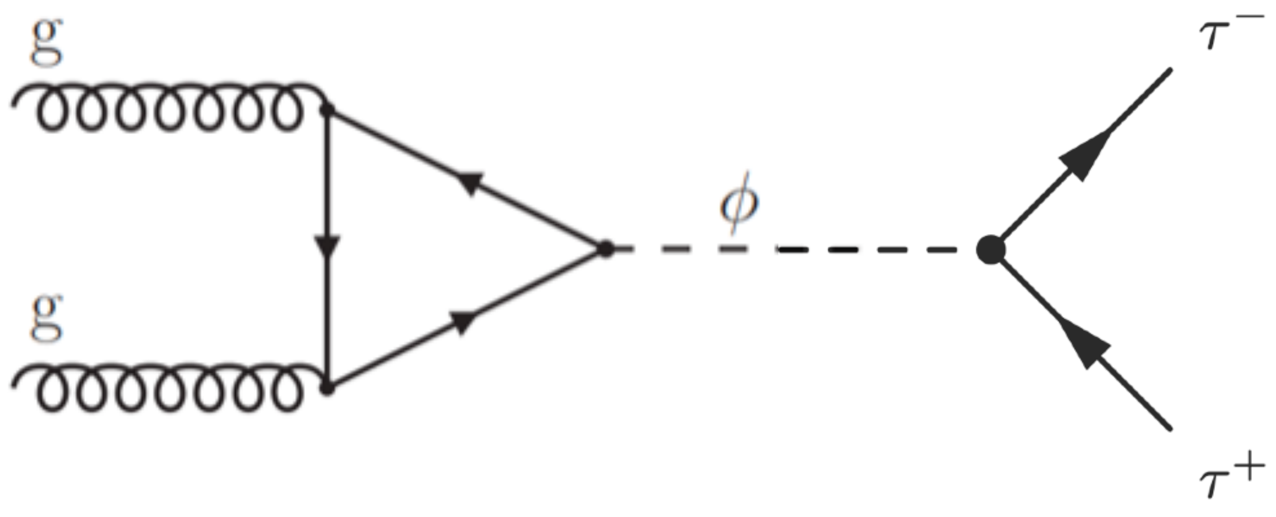
Collider constraints





- ***CMS multi-tau decays search arXiv:2208.02717***

Collider constraints



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

$$\boxed{\Gamma_{\rm total} \approx \Gamma(A \to \tau\tau) + \Gamma(A \to gg)}$$

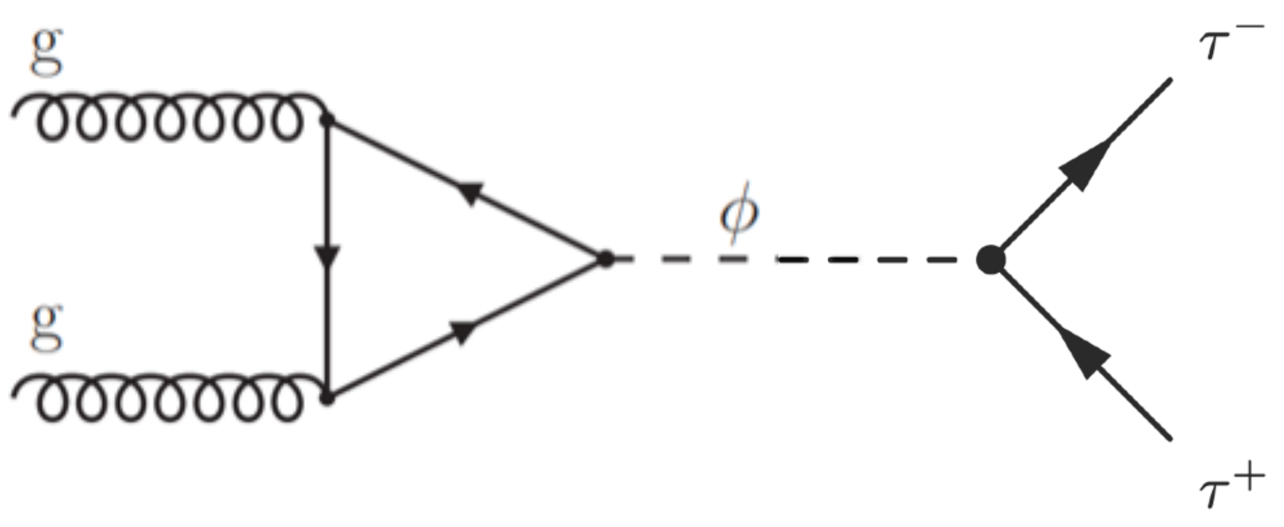
Negligible for small ρ_{bb}

$$\Gamma_{\rm total} \approx \Gamma(A \to \tau\tau) + \Gamma(A \to bb) + \Gamma(A \to tt) + \cancel{\Gamma(A \to ZH)} + \cancel{\Gamma(A \to H^{\pm}W^{\mp})} + \Gamma(A \to gg)$$

Absent for degenerated masses

Only for $m_A > 2\,m_t$

Collider constraints



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

$$\Gamma_{\text{total}} \approx \Gamma(A \to \tau\tau) + \Gamma(A \to gg)$$

How to obtain it?

$$\frac{d\sigma}{dy}(AB \to \phi^0 + X) = \frac{\pi^2 \Gamma(\phi^0 \to gg)}{8m_{\phi^0}^3} g_A\left(x_a, m_{\phi^0}^2\right) g_B\left(x_b, m_{\phi^0}^2\right) \to \tau_\phi \frac{d\mathcal{L}^{gg}}{d\tau_\phi}$$

$$\sigma \propto |\rho_u^{tt}|^2 |\rho_\ell^{\tau\tau}|^2$$

李政道研究所
TSUNG-DAO LEE INSTITUTE

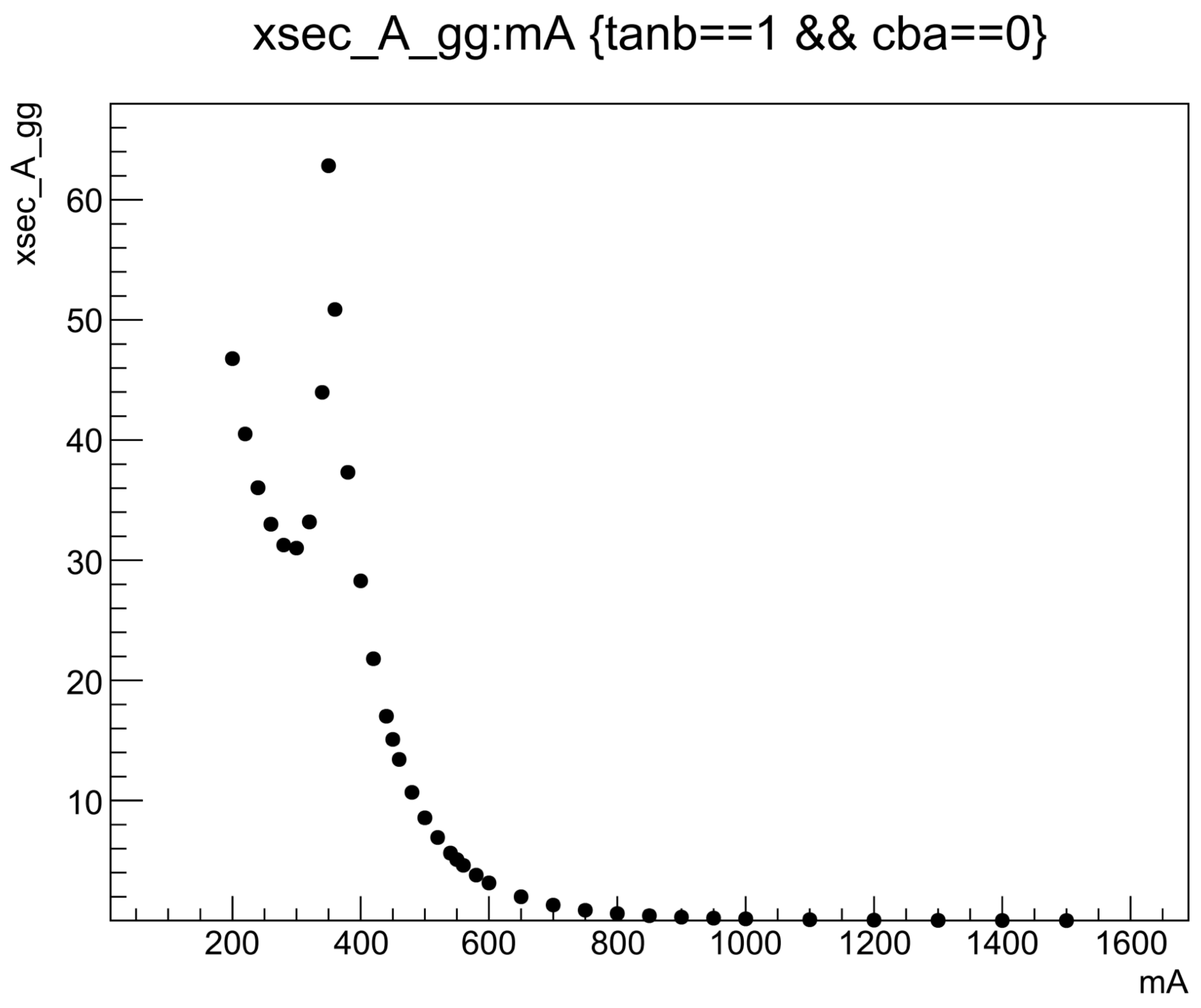
Collider constraints

How to obtain it?

$$\boxed{\tau_\phi \frac{d\mathcal{L}^{gg}}{d\tau_\phi}}$$

Cheating: Use s.o.a calculation kindly provided by CMS: Data for 2HDM type-II at $\sqrt{s}$=13 TeV

$$\sigma(gg \to A) = \frac{\pi^2}{8m_A^3}\Gamma(A \to gg) \cdot \boxed{\tau_\phi \frac{d\mathcal{L}^{gg}}{d\tau_\phi}}$$



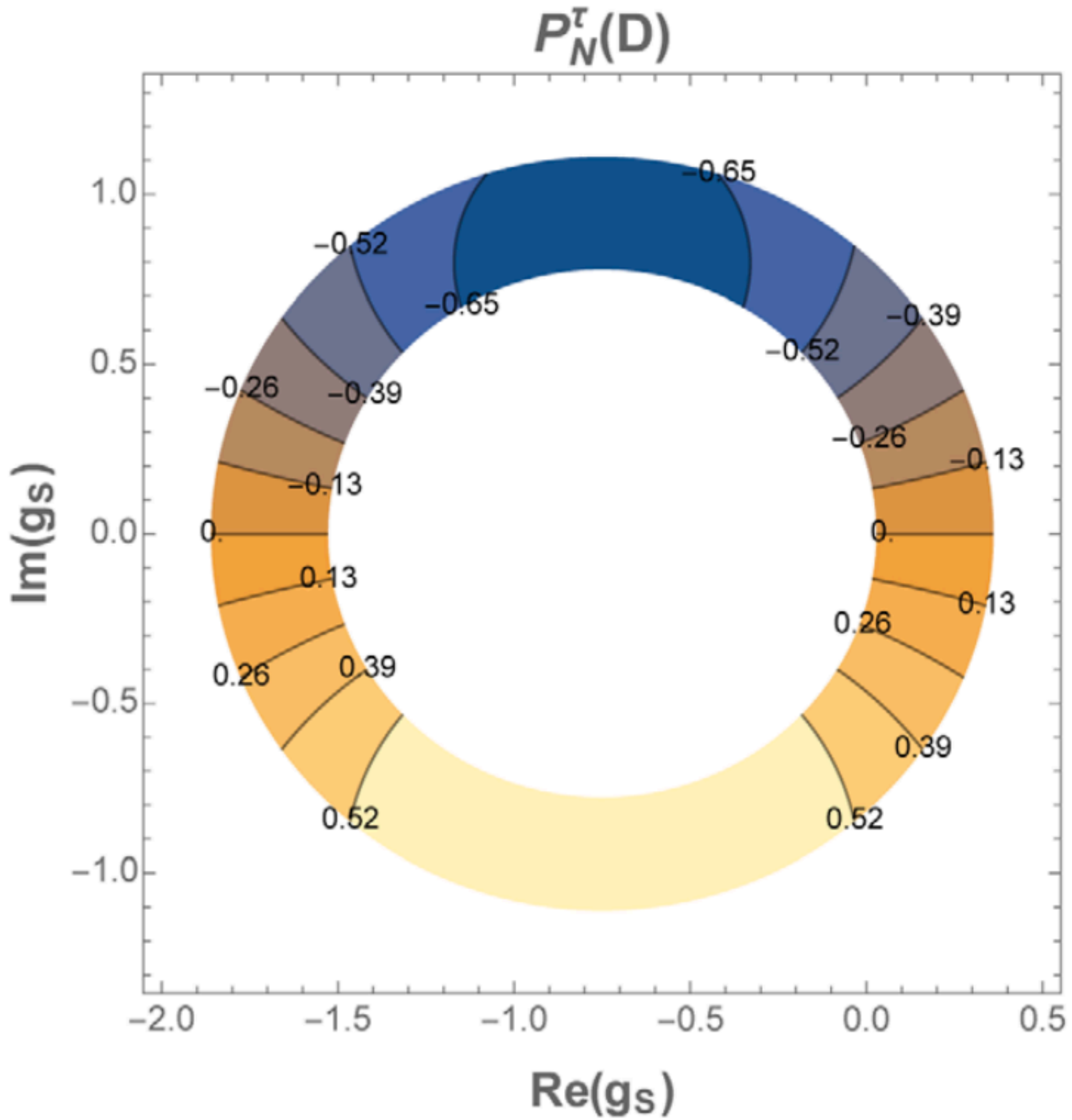
Normal polarizations of the tau lepton

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

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

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

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



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

李政道研究所
TSUNG-DAO LEE INSTITUTE