Global fit to 2HDMs with generic flavour violation

Cristian Sierra

Nanjing Normal University, School of Physics and Technology

GAMBIT XVI at Frascati

2024年09月19日

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

Almost ready for submitting it to the arXiv (!)
(Next week hopefully)

- **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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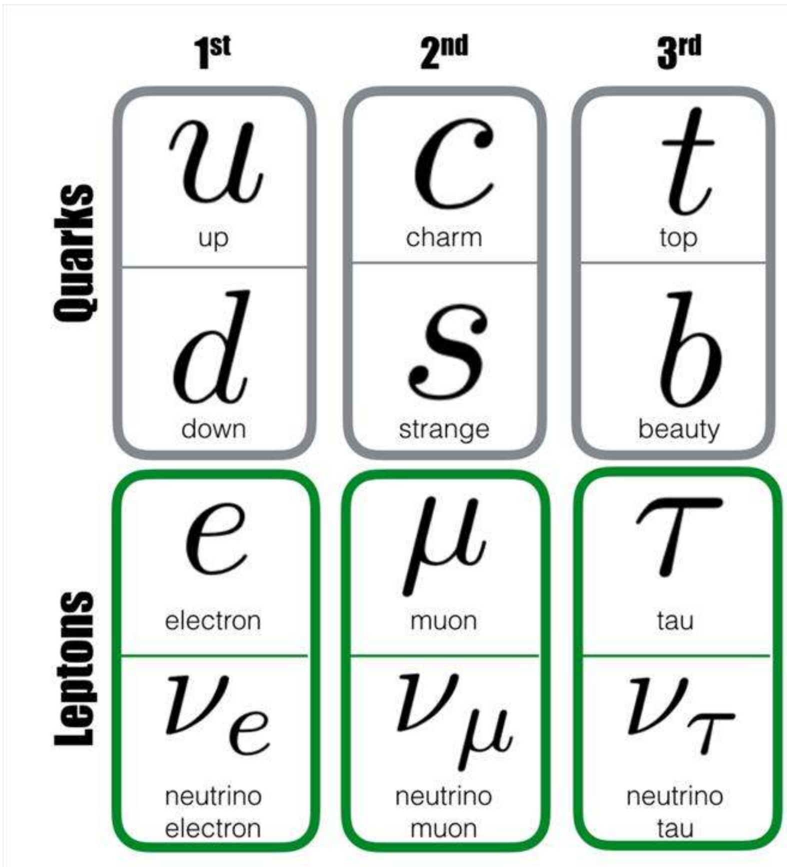
Fermions

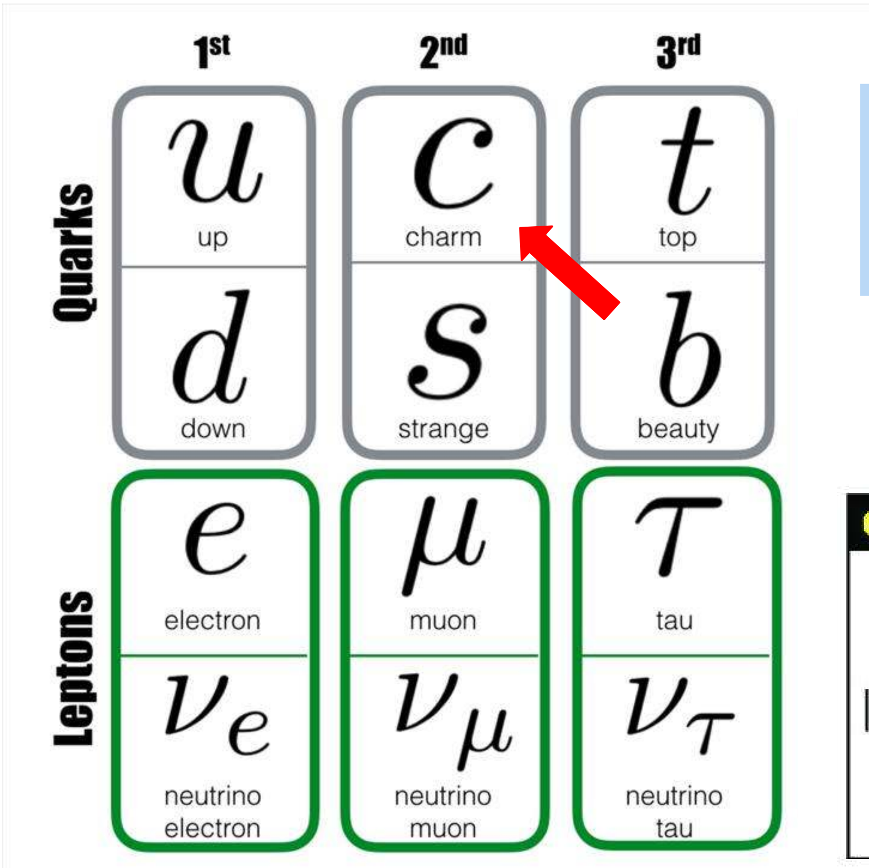
Flavour states

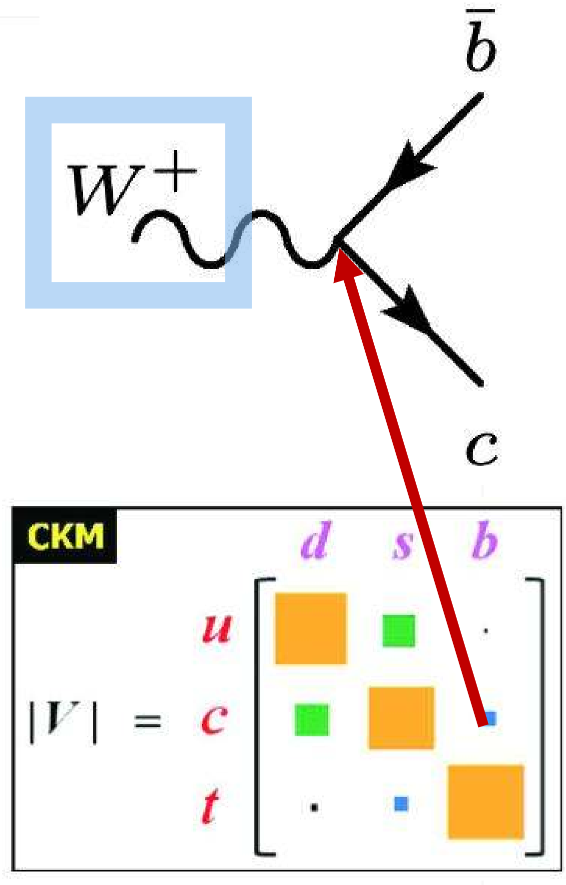


12 flavours

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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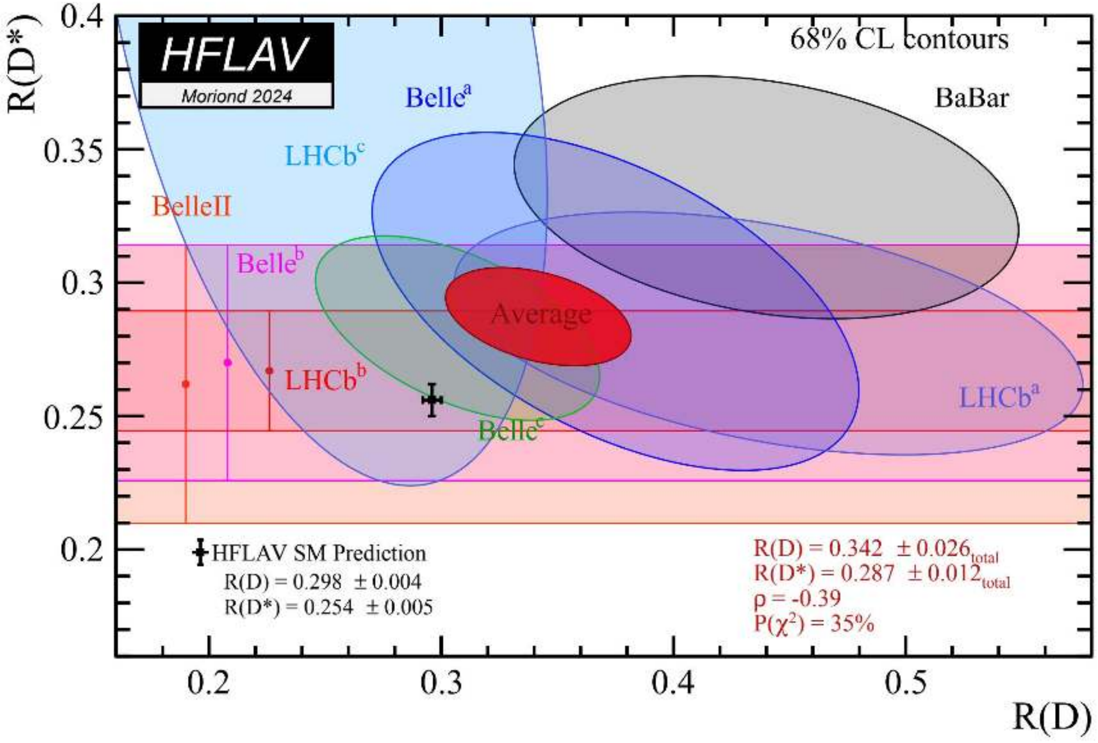
Charged anomalies

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



$$R_{D(*)}^{\mathrm{exp}} > R_{D(*)}^{\mathrm{SM}}$$

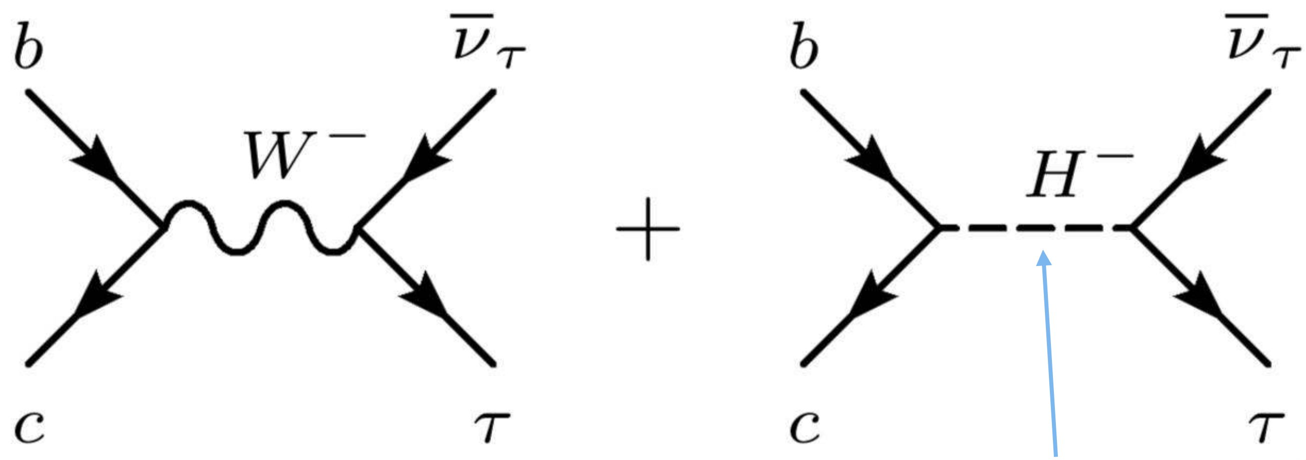
At 3.2 σ

Interference with NP?

From **Moriond 2024**

Charged anomalies

$$R_{D^{(*)}}^{\mathrm{exp}} > R_{D^{(*)}}^{\mathrm{SM}}$$



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

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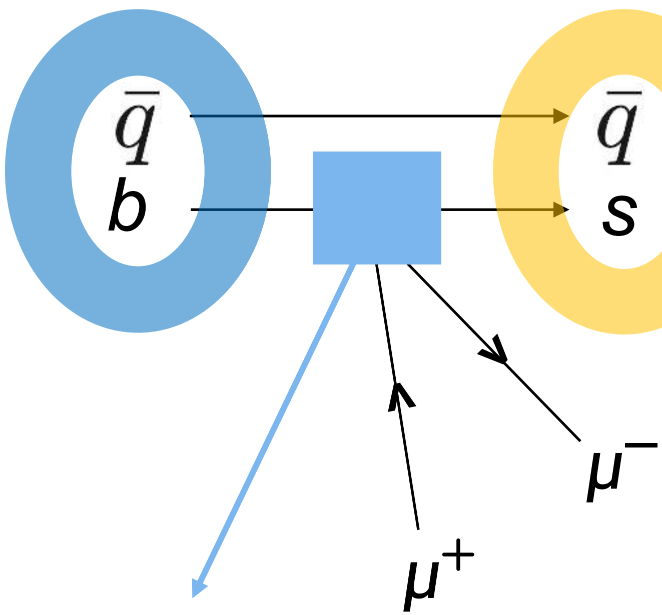
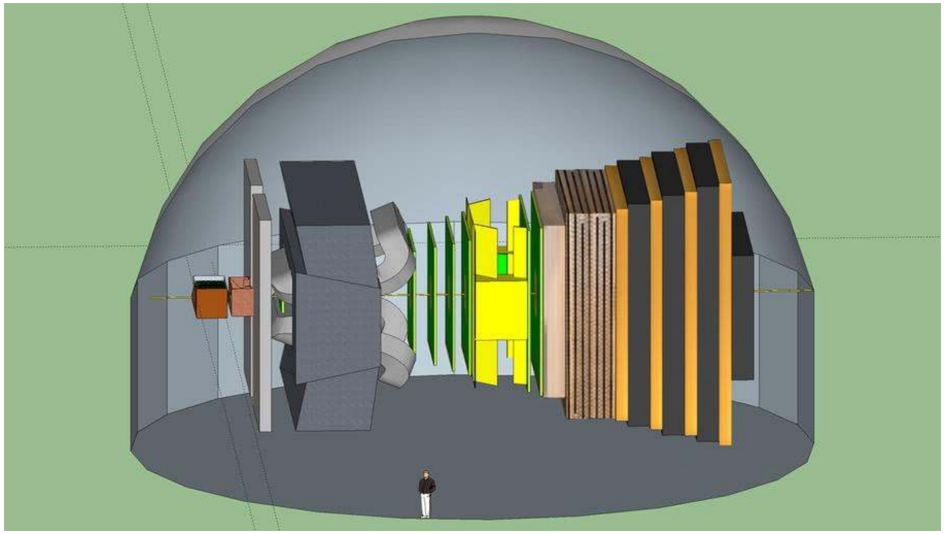
Neutral anomalies

Most precise measurements
come from the LHCb detector

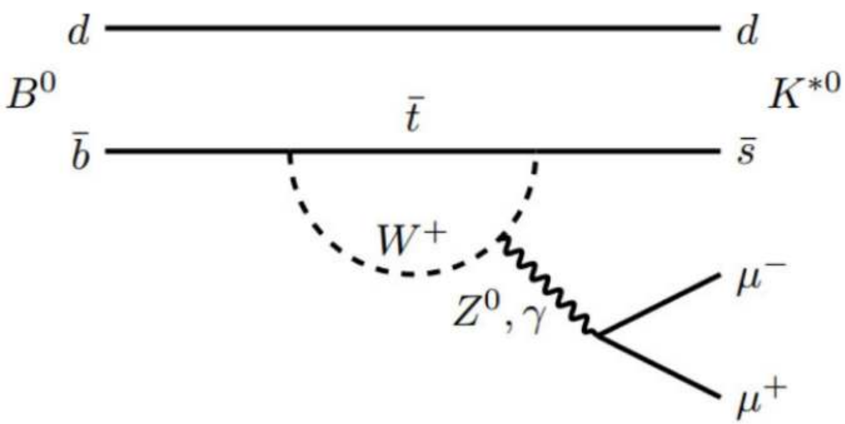
$$B \to K^{(*)}\mu^+\mu^-$$

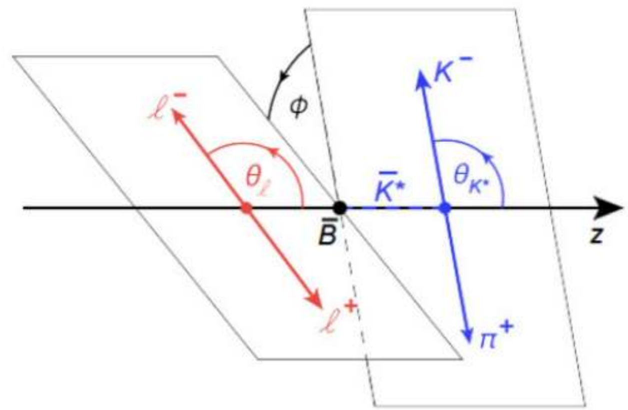




Explanations from the NP point of view of any anomaly will be via effective ***Wilson coefficients***

B meson semilep. decays: Angular observables





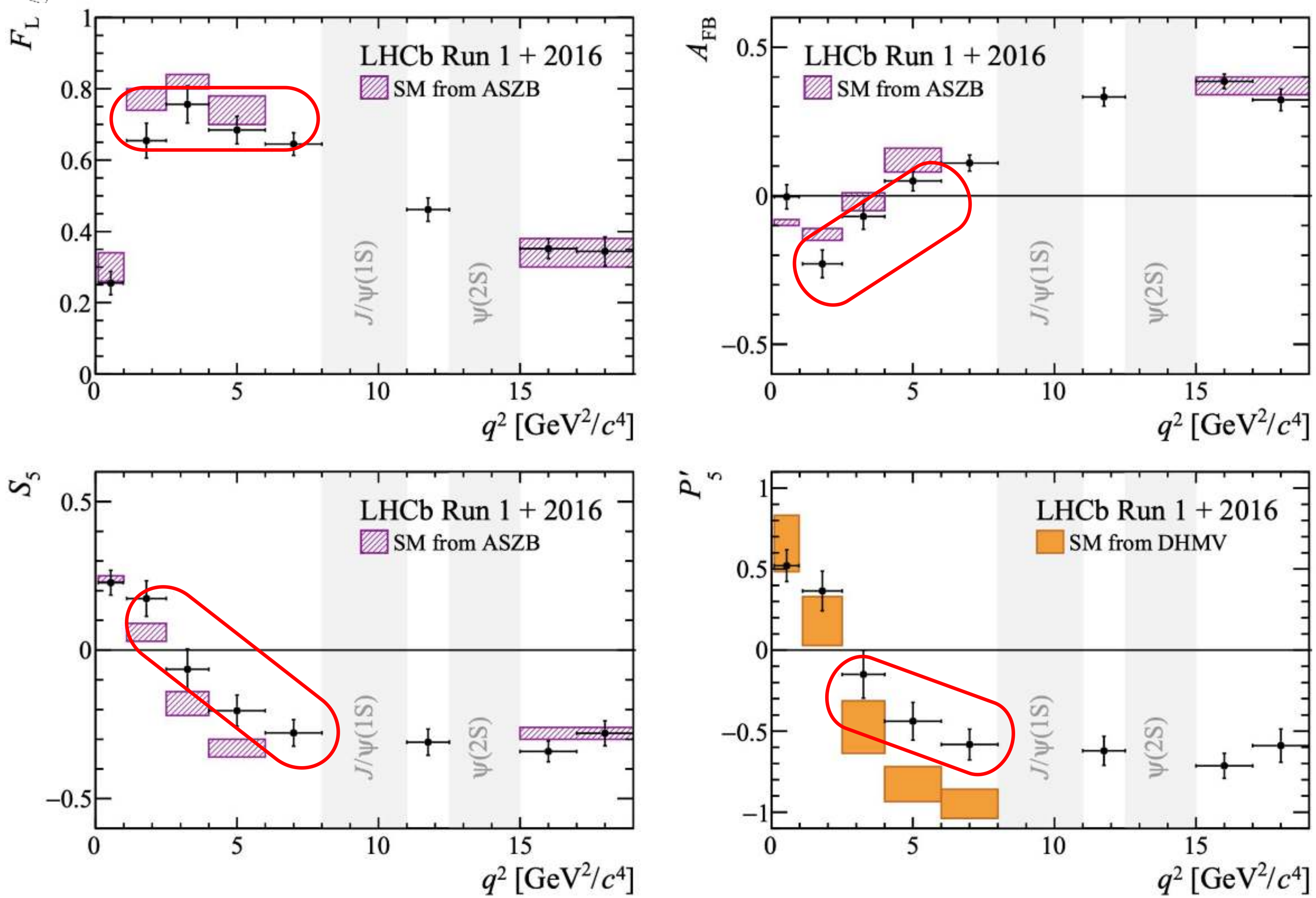
Decay fully described by three helicity angles $\vec{\Omega} = (\theta_\ell, \theta_K, \phi)$ and $q^2 = m^2_{\mu\mu}$

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

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

Most famous

B meson anomalies at LHCb

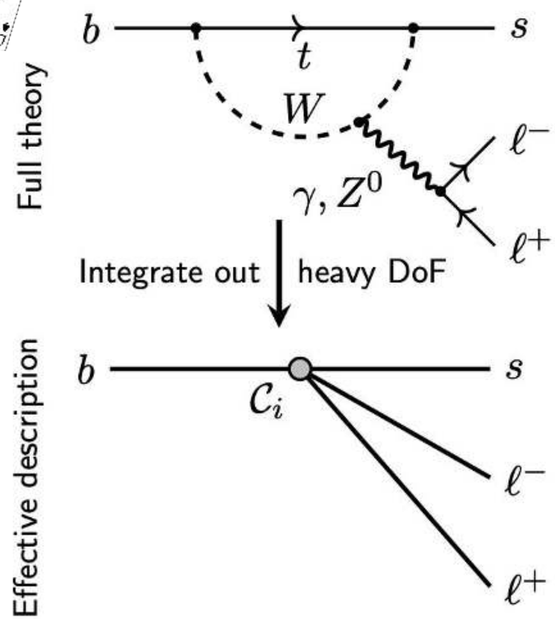


~3σ deviation

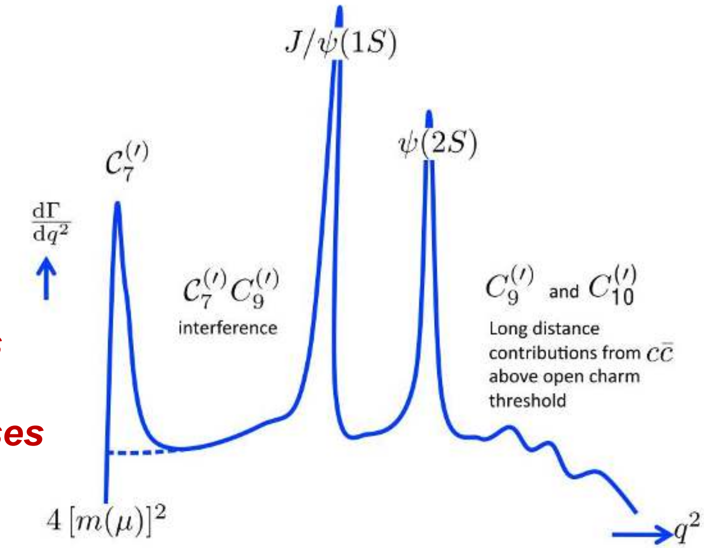
Confirmed by CMS, CMS-PAS-BPH-21-002

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

How to explain them?: *New Physics Story*



-Leptoquarks
-Z' bosons
-Heavy Higgses
-?



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

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

Local operator ($\mathcal{O}_i$)

Wilson coefficient ("effective coupling") ($\mathcal{C}_i$)

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

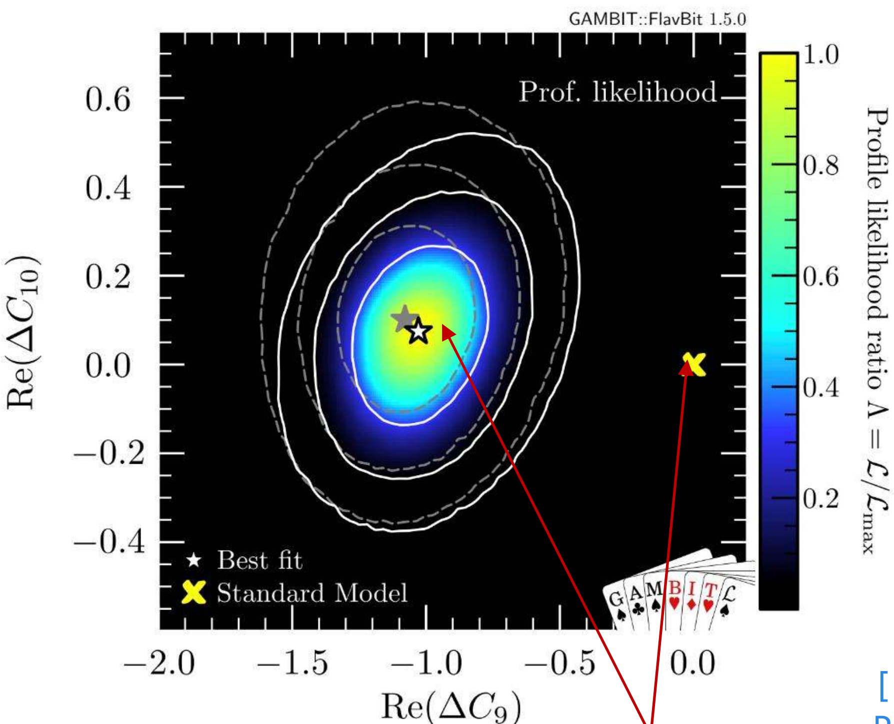
- Different $q^2 = m^2(\ell^+\ell^-)$ regions probe different operator combinations

Credit: Stolen from C. Langenbruch at Moriond EW 2023

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 $b \to s$ transitions
(most of them are angular observables)



All observables with $\chi^2_{\rm SM} = 157.28$ ($\chi^2_{\min} = 100.34$; 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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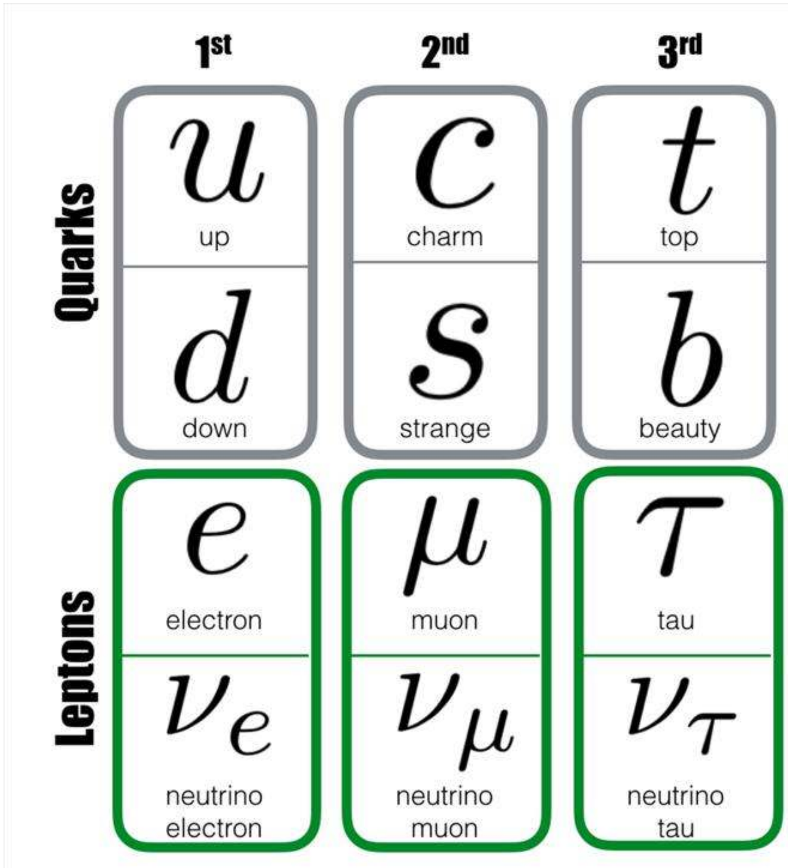
Fermions + second Higgs doublet



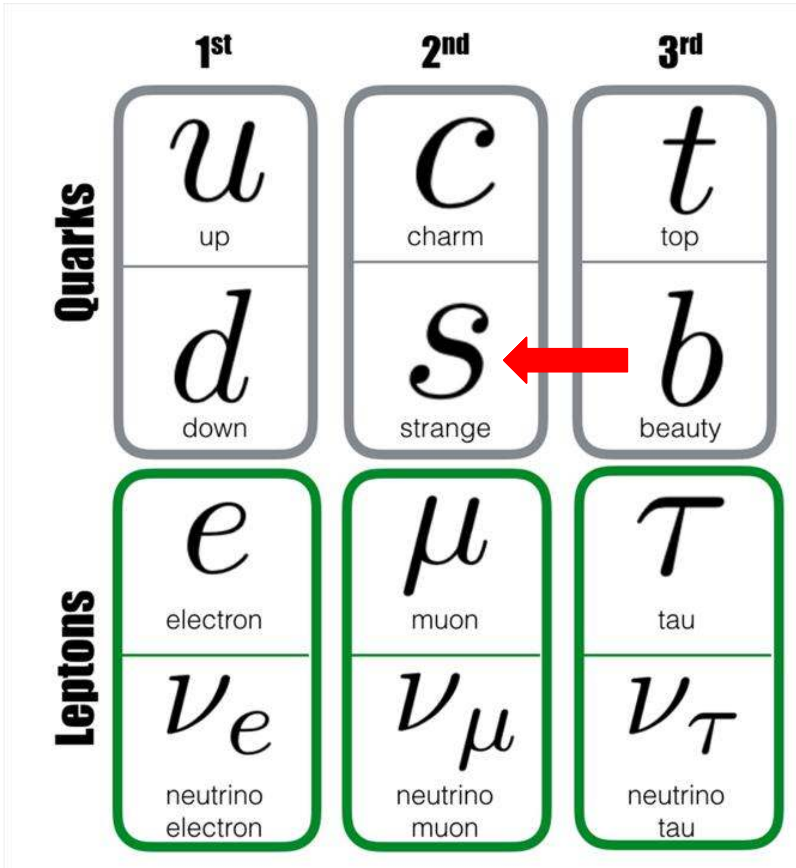
$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1 + H_1 + i\eta_1) \end{pmatrix}$$

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

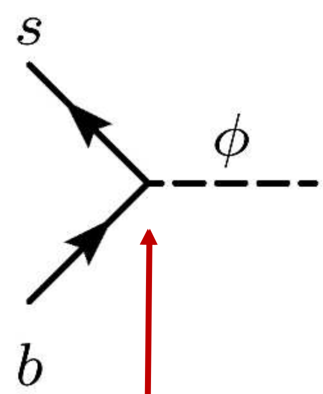
Adding a second Higgs doublet is one of the simplest extensions of the SM

Image credit: Physik-Institut - UZH

Flavour changing transitions



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



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

Not CKM suppressed!

Can be complex numbers (*general 2HDM*)

Image credit: Physik-Institut - UZH

Yukawa Lagrangian

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

general 2HDM (G2HDM)

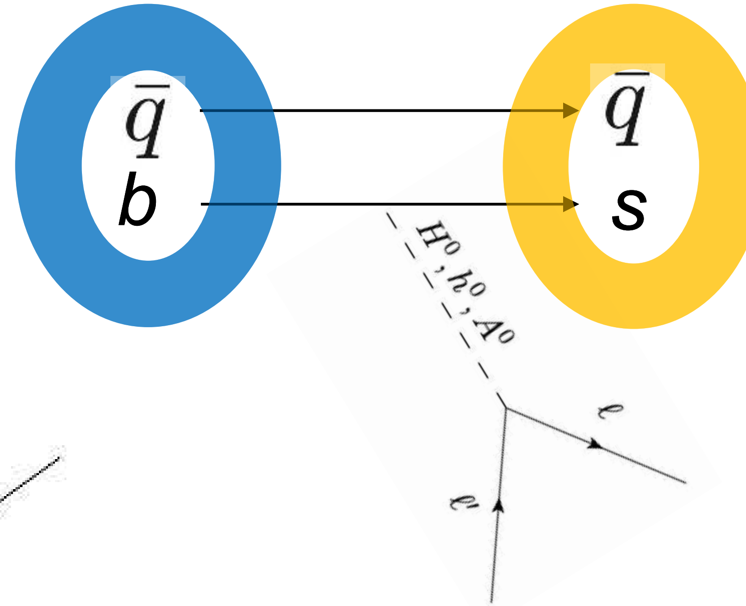
New couplings constrained by

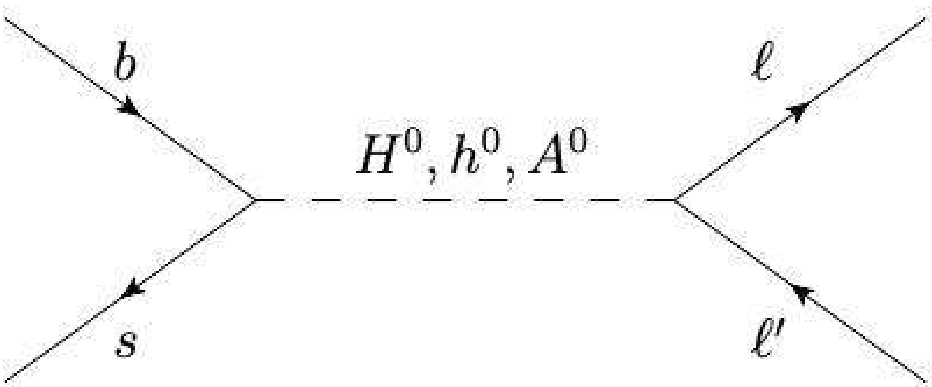
- ***Stability, perturbativity and unitarity***
- ***Strong flavour constraints***

WCs with in the G2HDM

Tree level diagrams

树
Shù

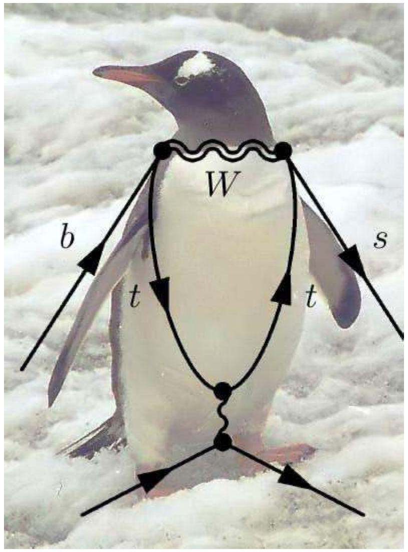




Neutral currents

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

Penguin diagrams



企鹅 - Qì'é

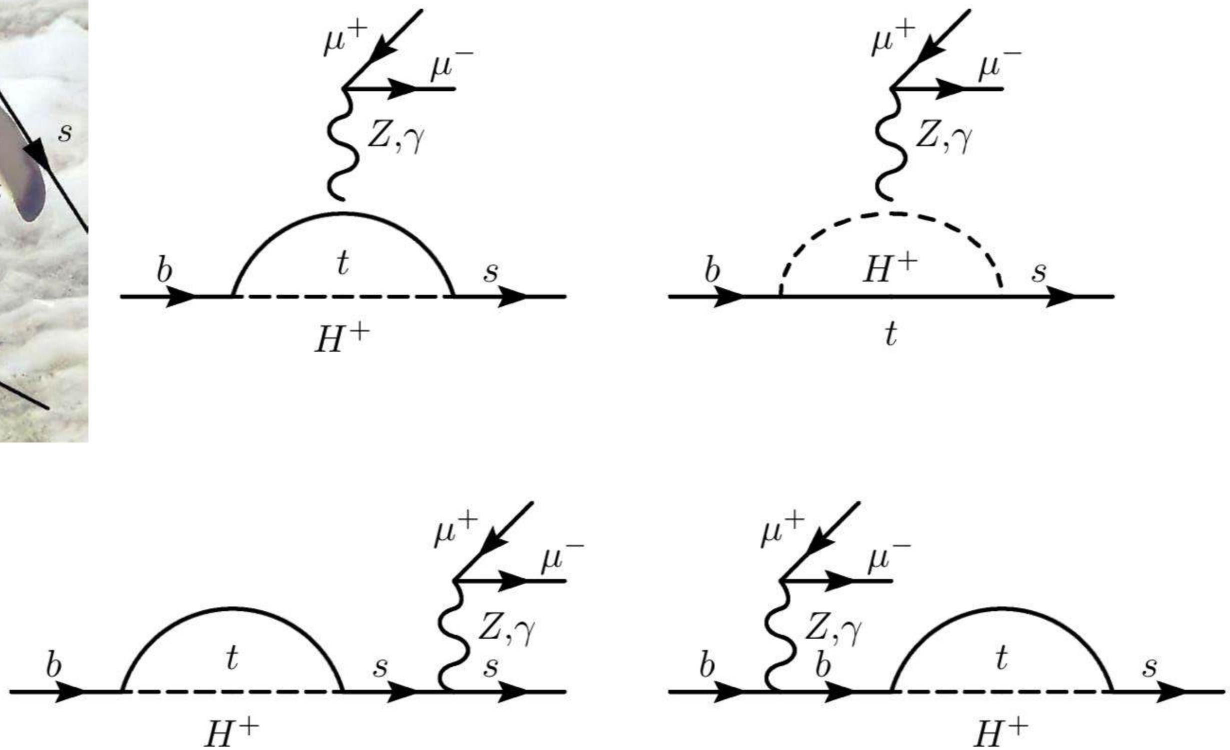


Figure 2: Penguin diagrams at one loop level for $b \to s\mu^+\mu^-$ transitions.

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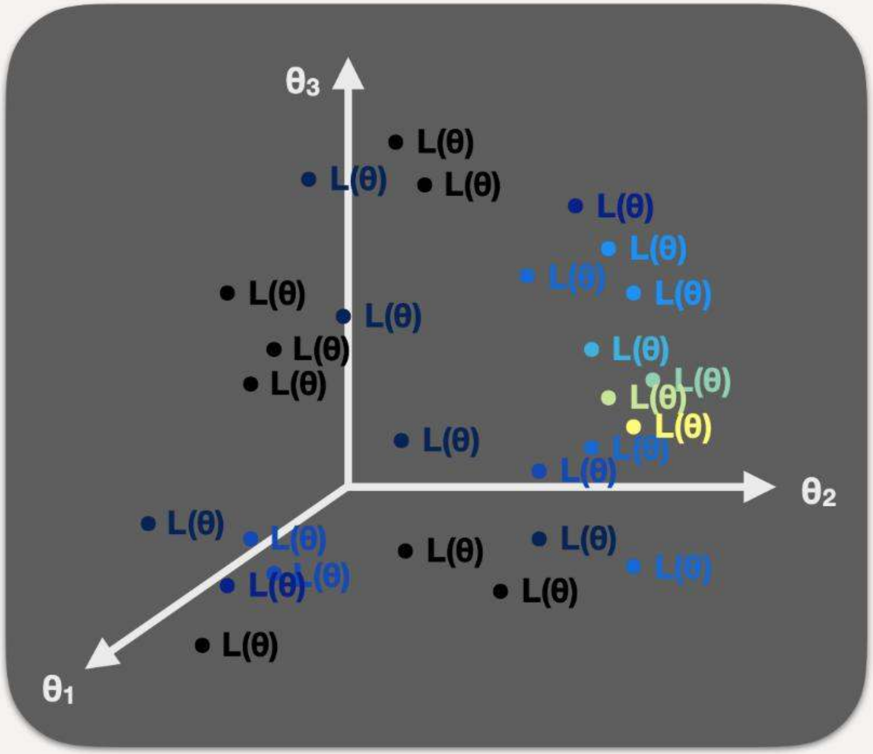
The code: GAMBIT

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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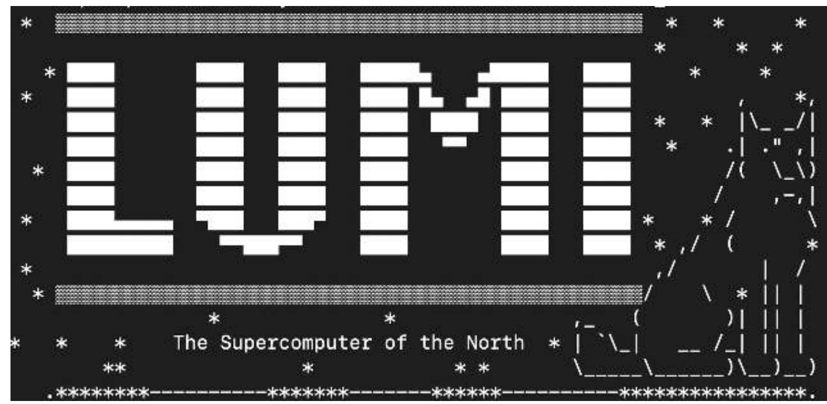
Scans

CP conserving potential close to the alignment limit

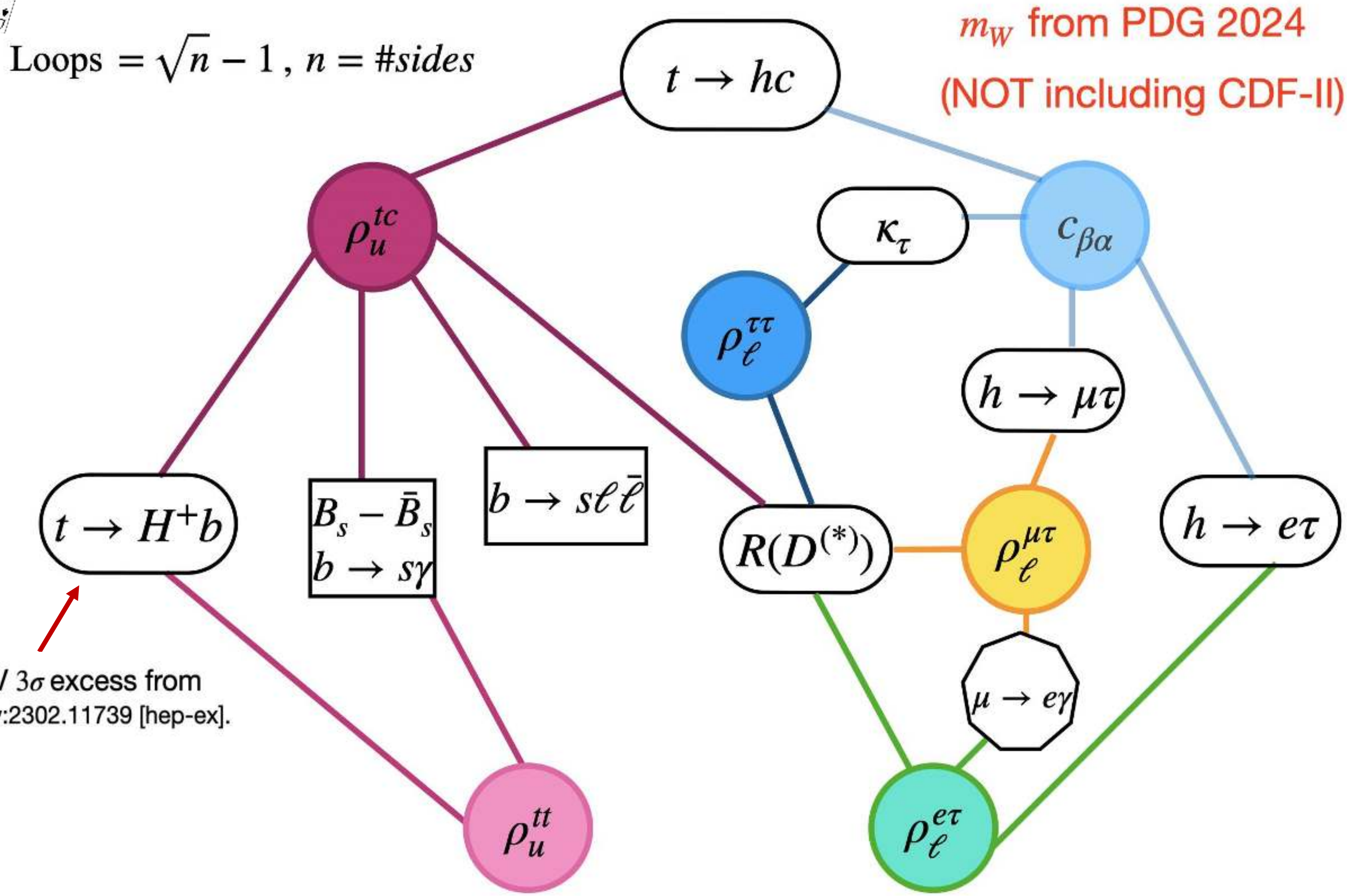
LUMI supercomputer (Large Unified Modern Infrastructure) in Kajaani (LUMI also means snow in Finnish.). 5th most powerful in the world.

```yaml
Scanner:

  use_scanner: de

  scanners:

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



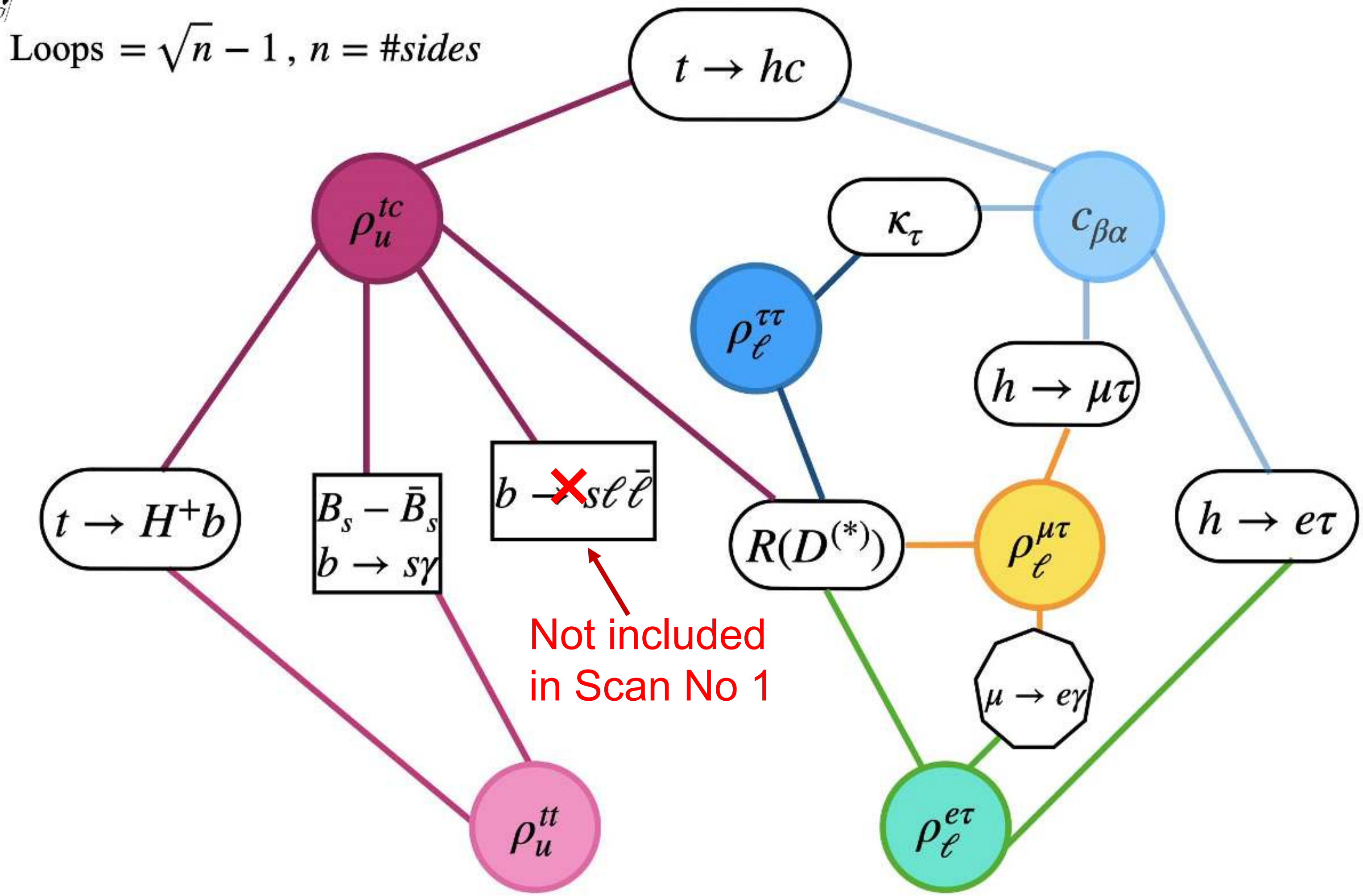
(~22 hours/scan with 512 cores on the small partition)
So far I have used more than 2000 hours.

Observables and couplings



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

Scan No 1



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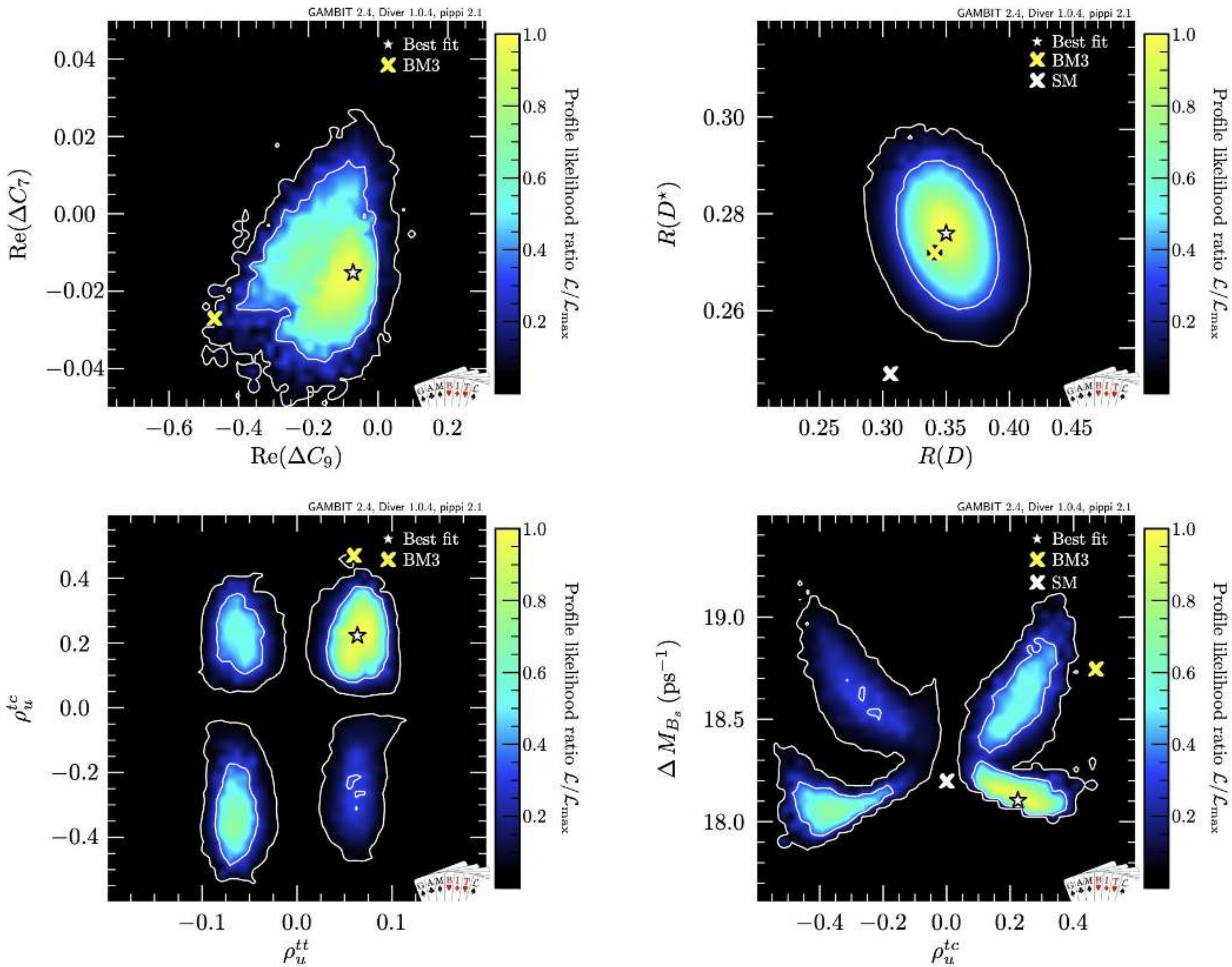
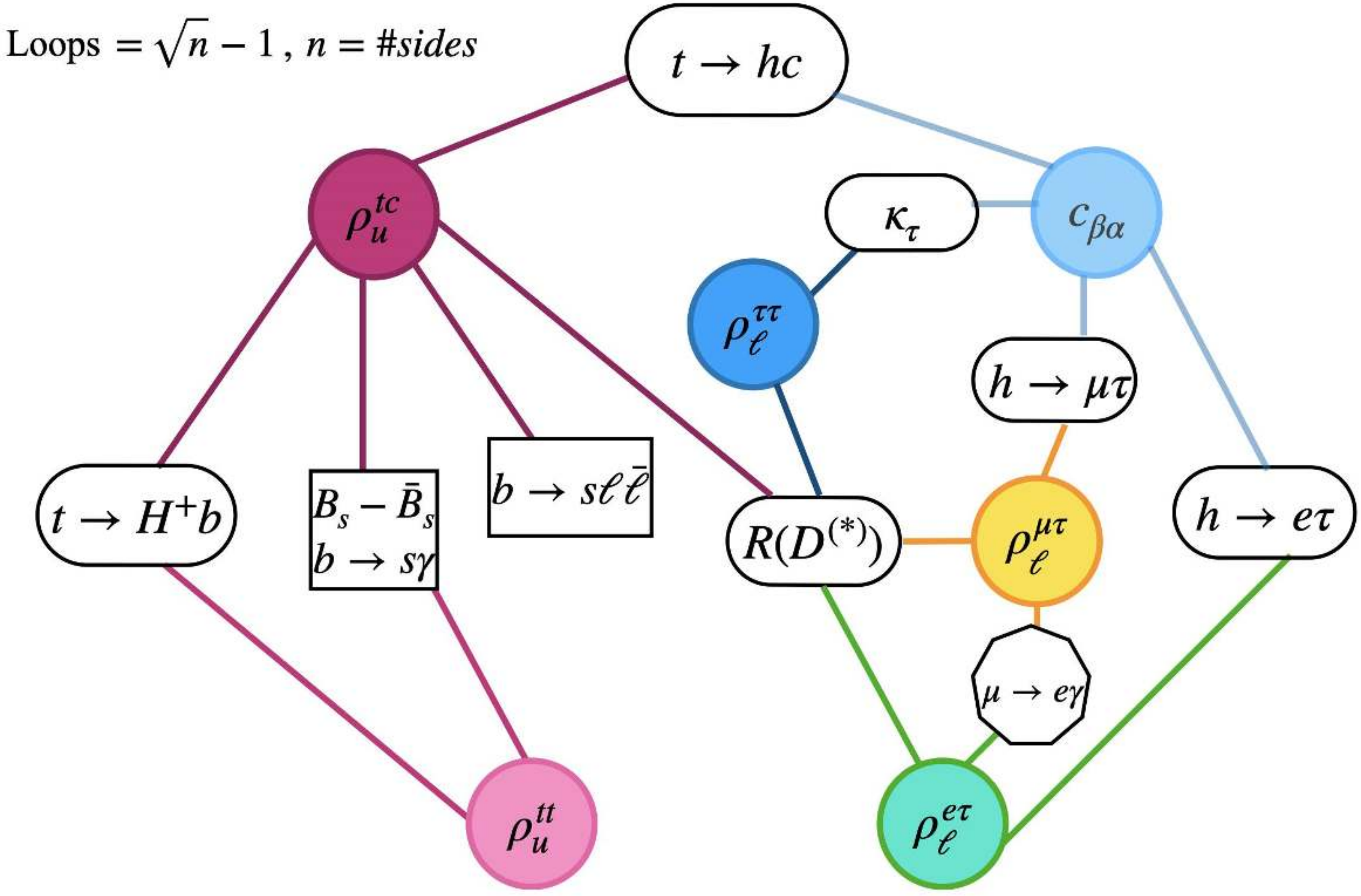
Scan No 1

Parameter space and best fit values



Scan No 2



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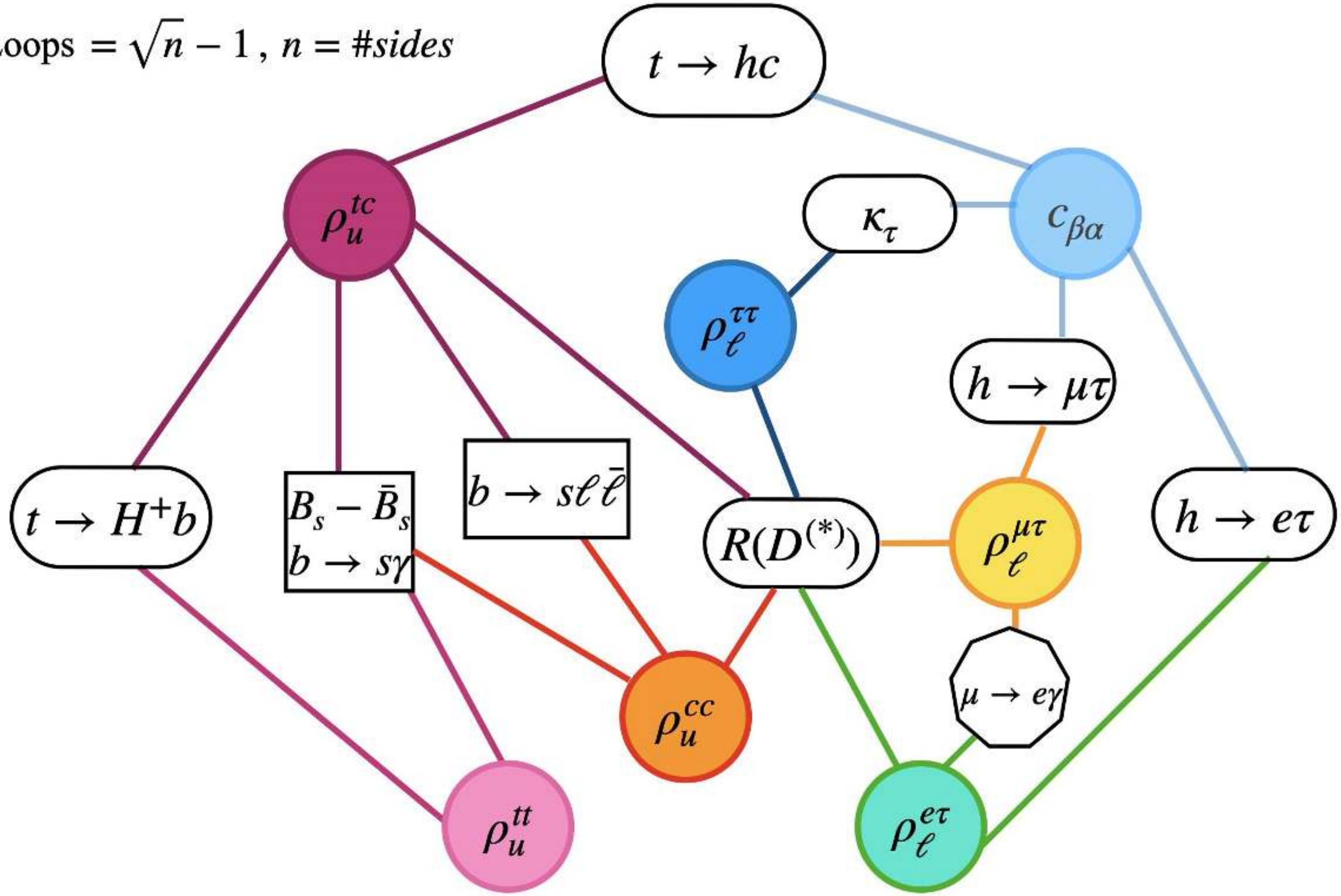
Scan No 2

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



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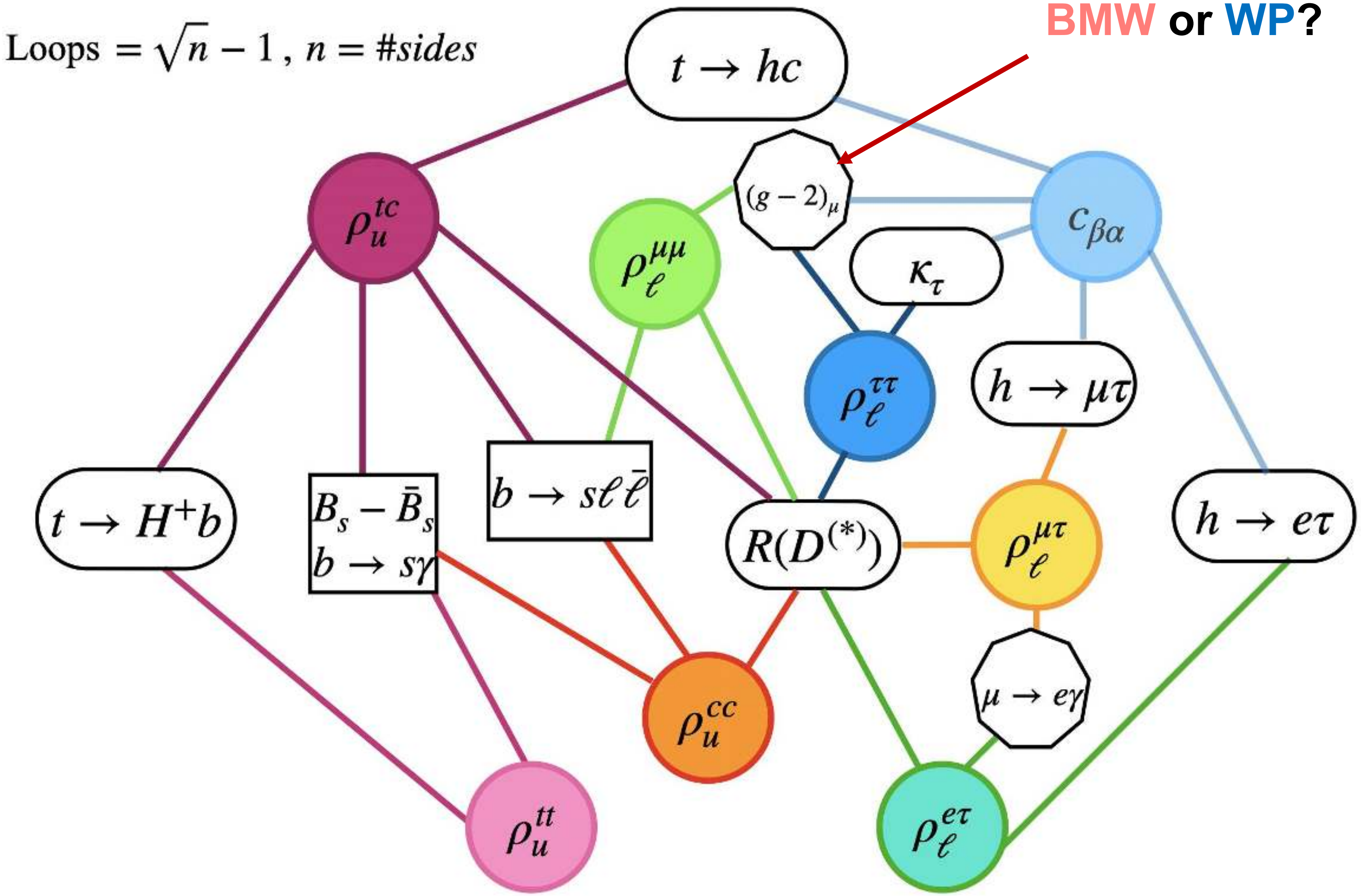
Scan No 2

g-2 in the game, BMW or WP?



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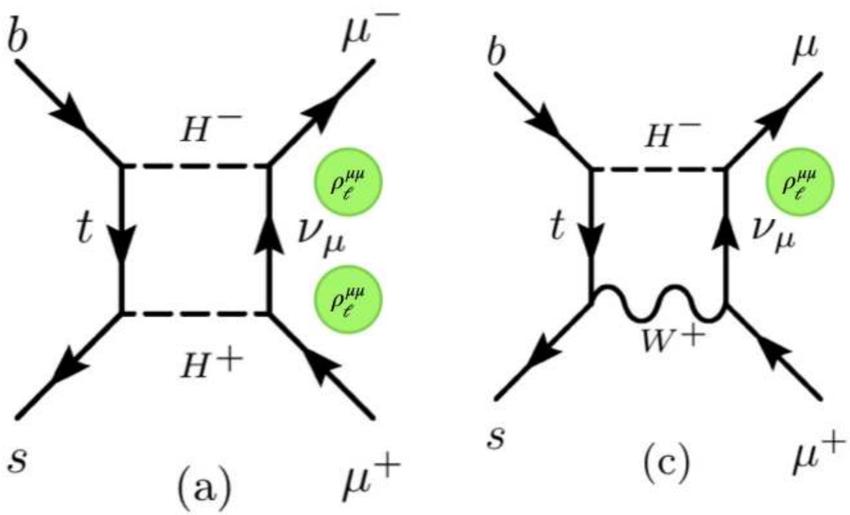
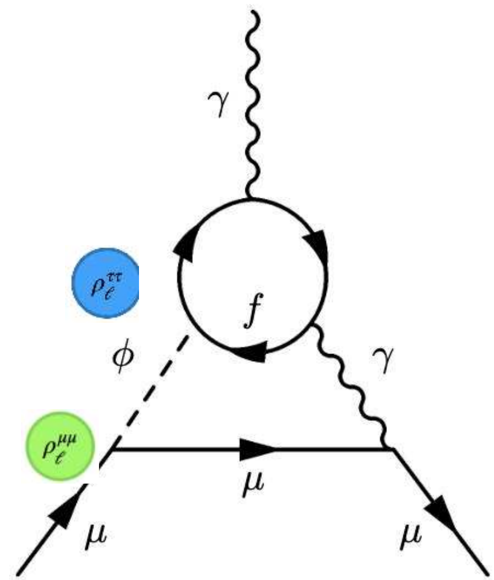
New diagrams!

Box diagrams



Barr-Zee diagrams
in muon g-2

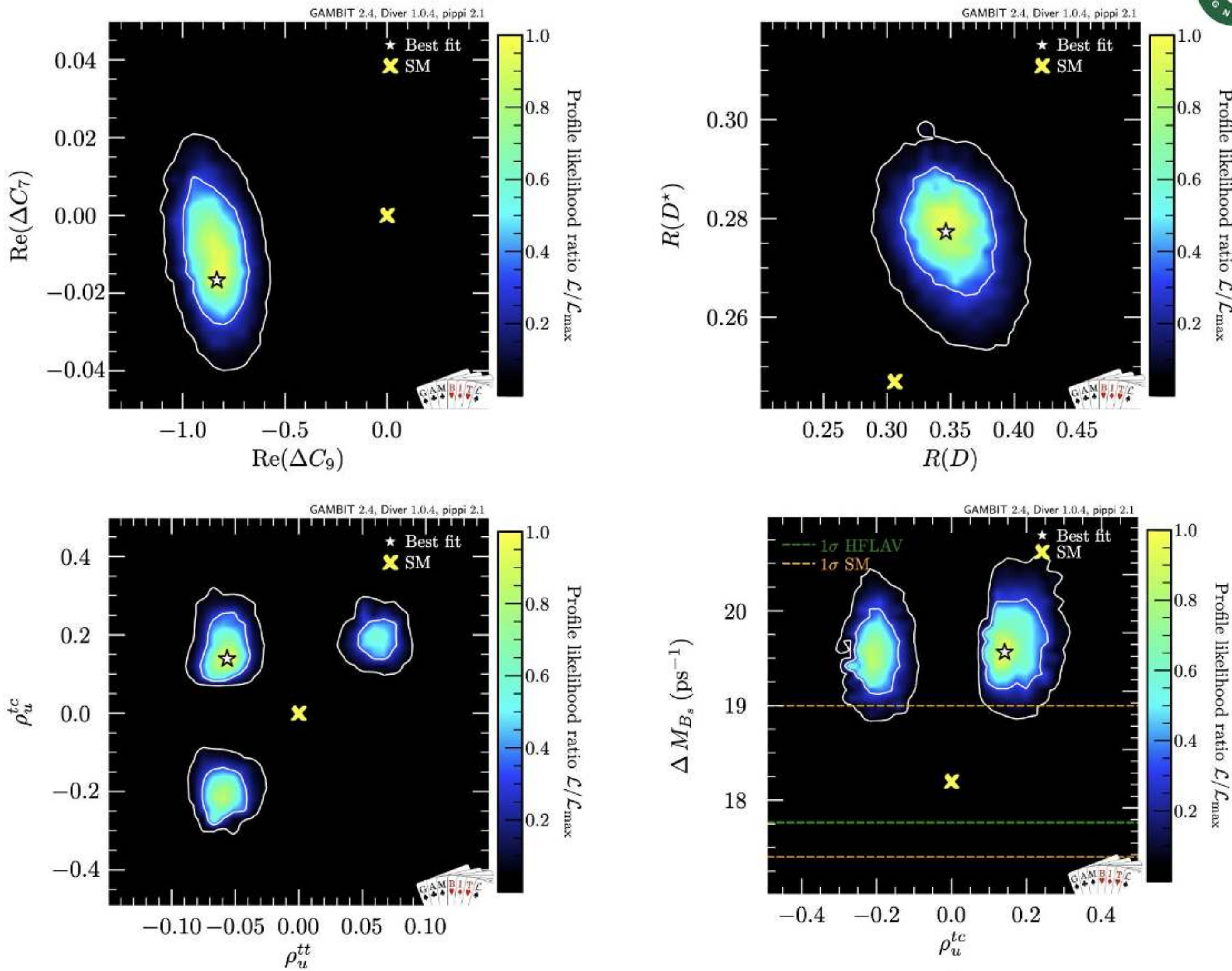


$$\phi = h, H, A$$

Scan No 2

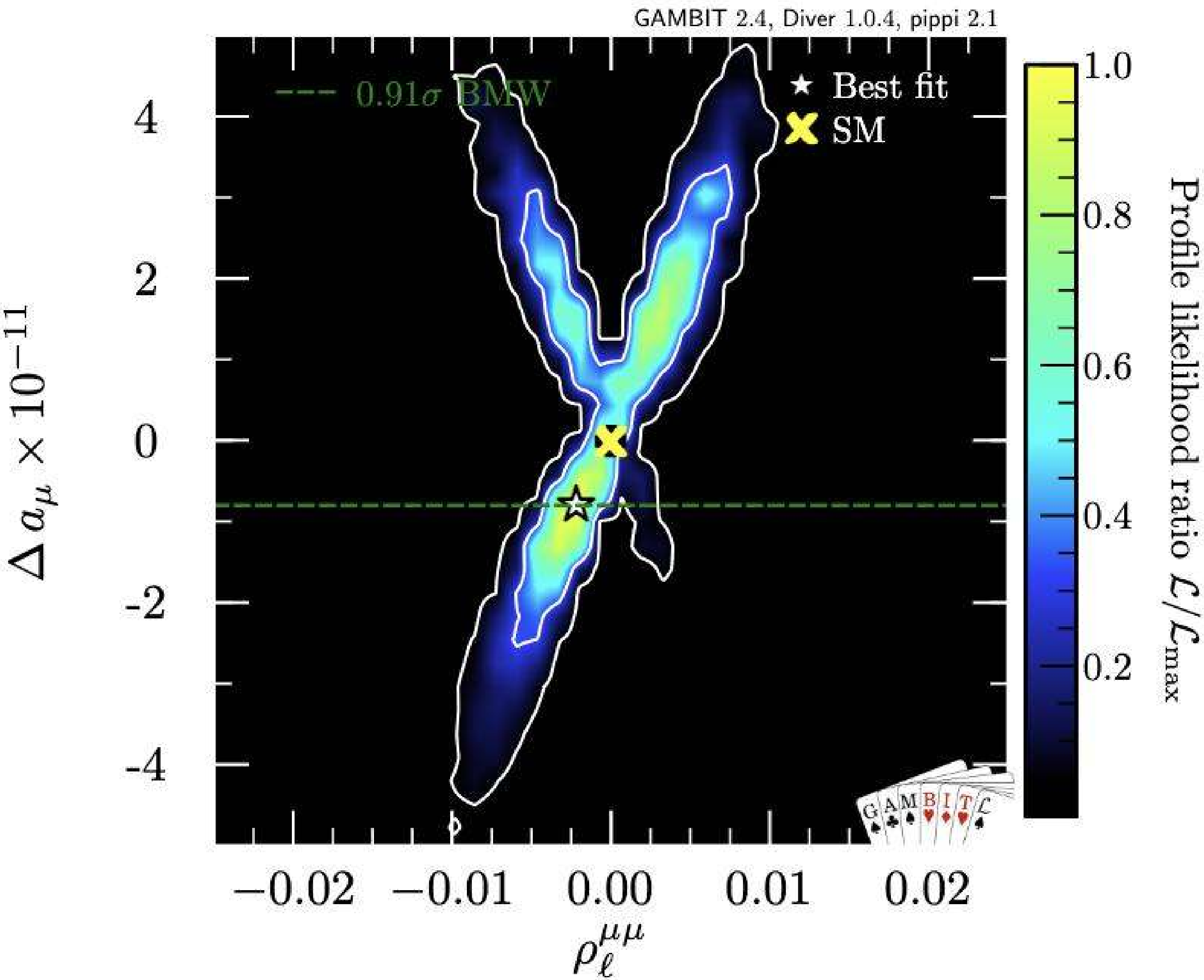
g-2 in the game, BMW, latest HVP from 2407.10913

Parameter space and best fit values



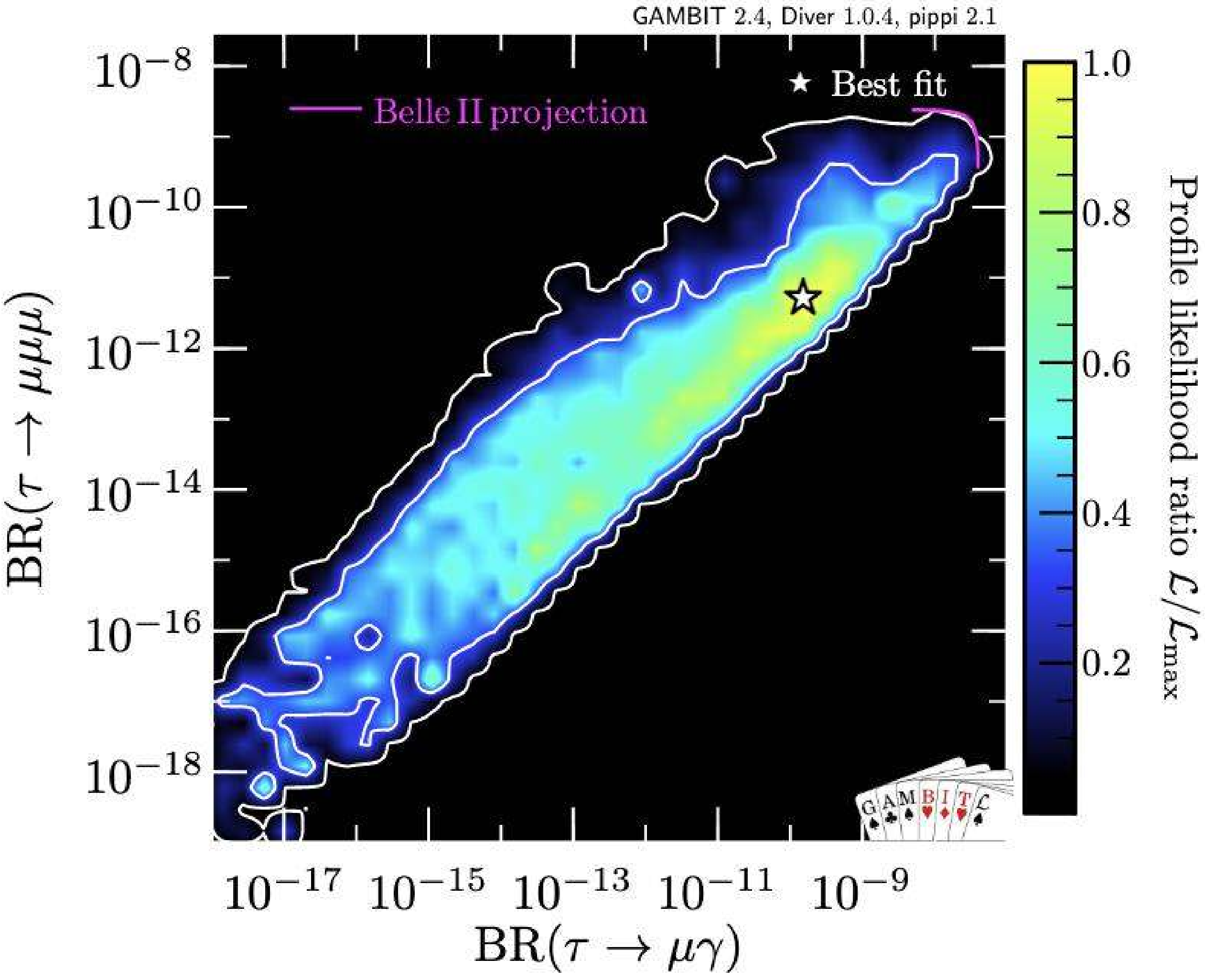
Scan No 2

g-2 in the game, BMW, latest HVP from 2407.10913



Scan No 2

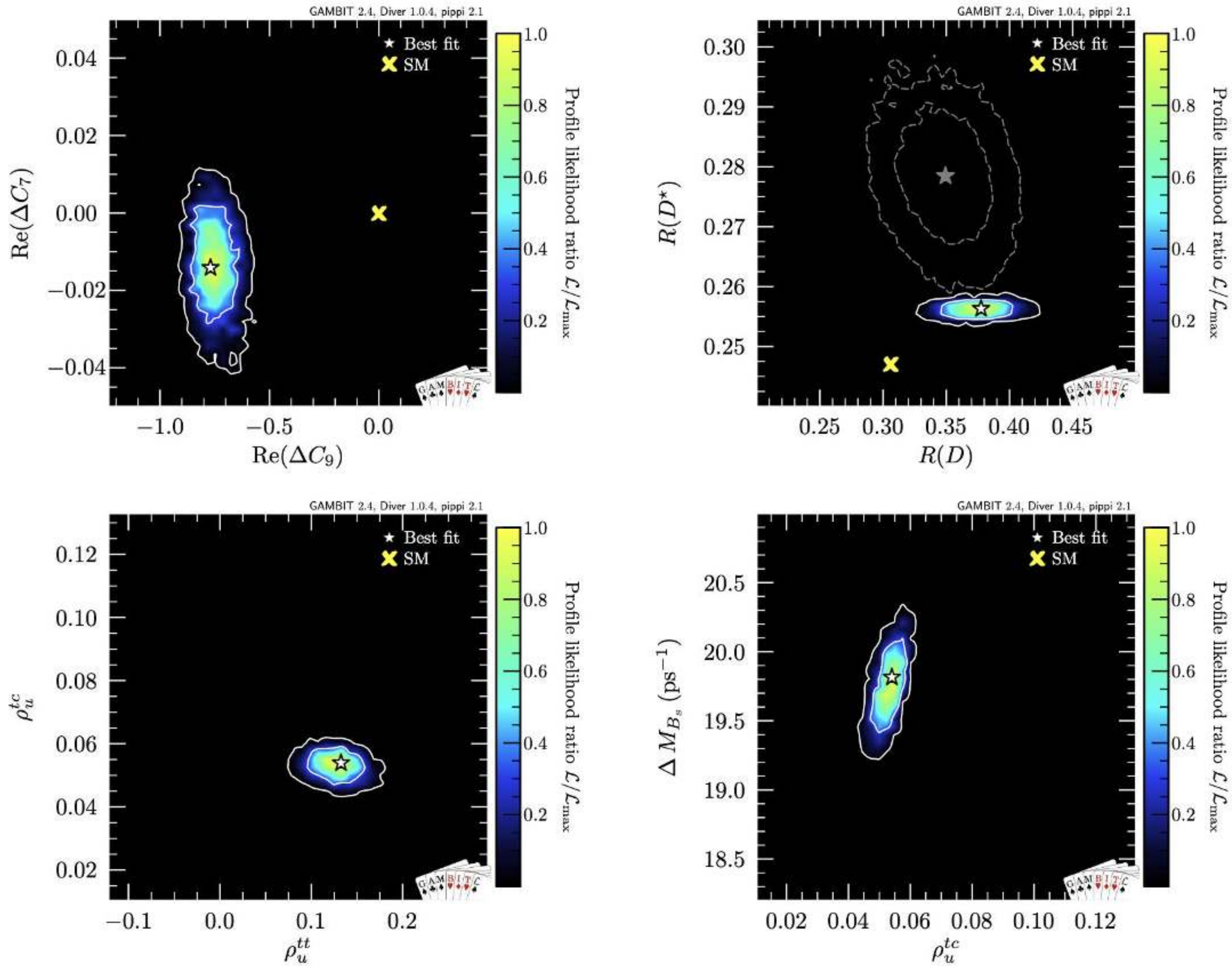
g-2 in the game, BMW, latest HVP from 2407.10913



Scan No 3

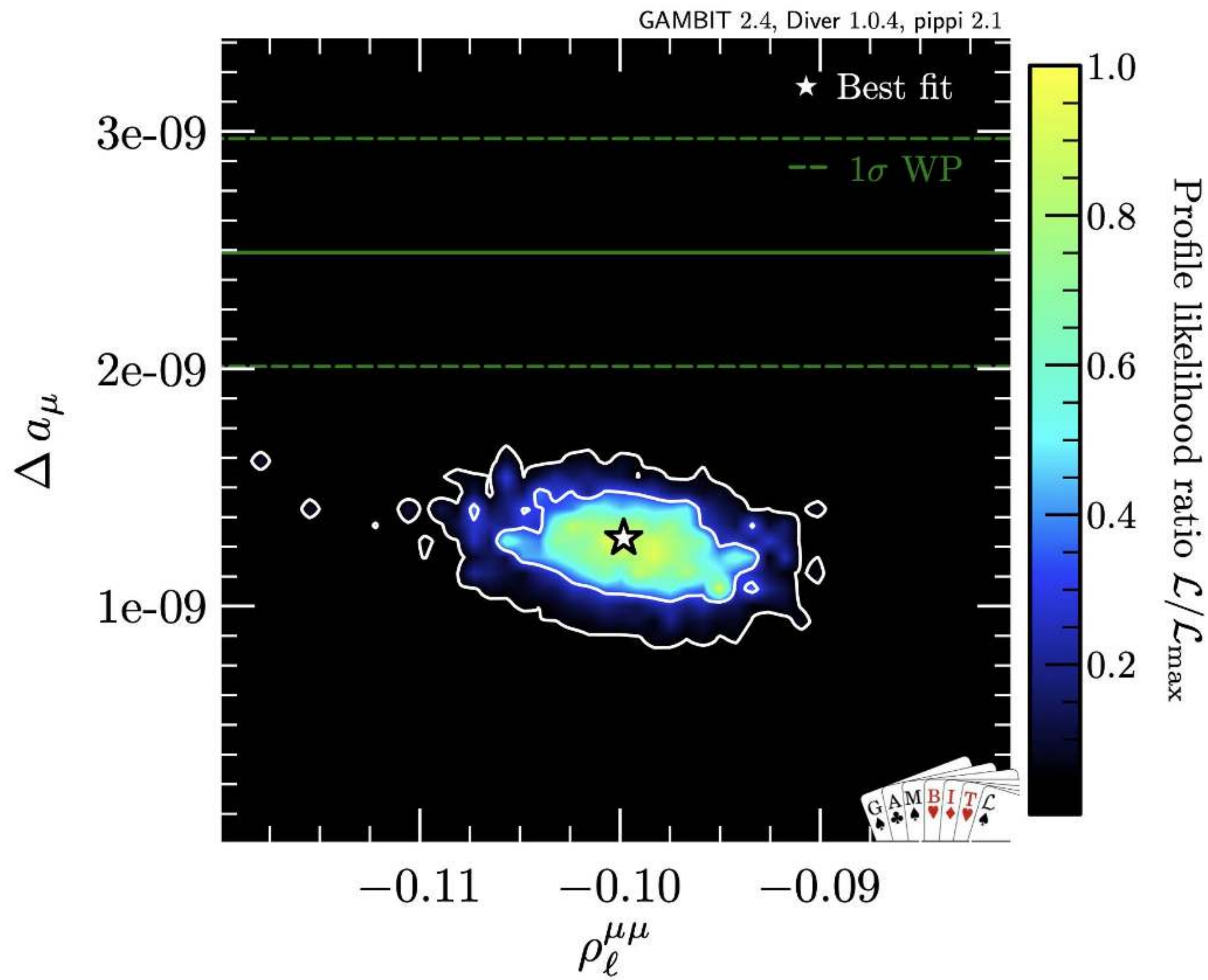
g-2 in the game, WP

Parameter space and best fit values



Scan No 3

g-2 in the game, WP



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Summary

- We 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 PDG 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.

Grazie!

(谢谢您!)

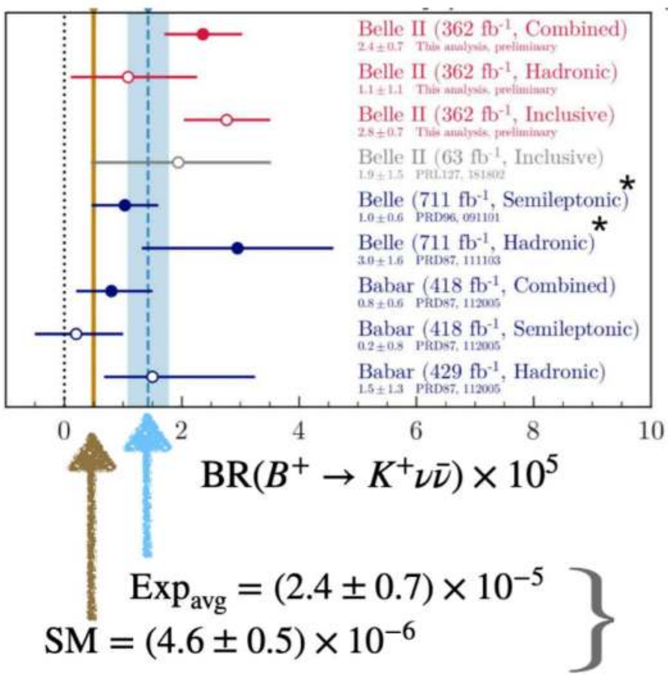
FlavBit WG Update

Convenors: Nazila Mahmoudi, Cristian Sierra

GAMBIT XVI

B -> K nunu form factors in SuperIso

- **Pletora of new observables for b->snunu transitions (greatly motivated by the observation of $B^+ \to K^+ \nu\bar{\nu}$ by Belle II)**



2.8σ deviation from SM

```
# ------------------------- #
# B -> K nu nu likelihoods #
# ------------------------- #

- purpose: LogLike
  capability: BKnunu_LogLikelihood_Belle_sl

- purpose: LogLike
  capability: BKnunu_LogLikelihood_Belle_had

- purpose: LogLike
  capability: BuKnunu_LogLikelihood_Belle_sl

- purpose: LogLike
  capability: BuKnunu_LogLikelihood_Belle_had

- purpose: LogLike
  capability: BuKnunu_LogLikelihood_BelleII

- purpose: LogLike
  capability: BKnunu_LogLikelihood_BaBar

- purpose: LogLike
  capability: BuKnunu_LogLikelihood_BaBar
```

Branches

THDM_development branch

- src/FlavBit.cpp
  - t2bbc @FlavBit::THDM_t2bbc *from ATLAS*
  - t2mutauc @FlavBit::THDM_t2mutauc *from ATLAS*
- src/WCs.cpp
  - Hack by Tomas: DeltaC9_mu_LogLikelihood : Useful for *quickly scanning* (Alex was optimizing likelihoods for speeding up scans...) the parameter space and cornering it. **Do not use it for actual results!**
- src/FCNC.cpp
  - Tomas added correlations for RK and RKstar based *on latest LHCb* data, likelihood in HEPLike.

THDM_development branch

- src/FCCC.cpp
  - RD and RDstar need correlations to be computed from SuperIso, not supported currently, doing it with flav_data.yaml

```
/// HEPLike LogLikelihood RD RDstar
// TODO: Recognised sub-capabilities:
//    RD
//    RDstar
void HEPLike_RDRDstar_LogLikelihood(double& result)
{
  using namespace Pipes::HEPLike_RDRDstar_LogLikelihood;
  static const std::string inputfile = path_to_latest_heplike_data() + "/data/HFLAV_19/Semileptonic/RD_RDstar.yaml";
  static HepLike_default::HL_nDimGaussian nDimGaussian(inputfile);
  static bool first = true;
  if (first)
  {
    if (flav_debug) std::cout << "Debug: Reading HepLike data file: " << inputfile << std::endl;
    nDimGaussian.Read();
    first = false;
  }

  // TODO: SuperIso is not ready to give correlations for these observables. So currently we fall back to the old way.
  //       Below code is for future reference.
  // static std::vector<str> obs_list = Downstream::subcaps->getNames();
  // flav_prediction prediction = *Dep::prediction_RDRDstar;
  // flav_observable_map theory = prediction.central_values;
  // flav_covariance_map theory_covariance = prediction.covariance;

  // result = nDimGaussian.GetLogLikelihood(get_obs_theory(prediction, obs_list), get_obs_covariance(prediction, obs_list));
  const std::vector<double> theory{*Dep::RD, *Dep::RDstar};
  result = nDimGaussian.GetLogLikelihood(theory /* , theory_covariance */);
```

THDM_development branch

- data/flav_data.yaml
  - Updated almost (the ones used in our scans) all observables to HFLAV 2024.


```yaml
- name: RDstar
  islimit: false
  exp_value: 0.285
  exp_stat_error: 0.012
  exp_sys_error: 0.00
  exp_source: HFLAV2024
  th_error: 0.005
  th_error_type: M
  th_error_source: HFLAV
  correlation:
  - name: RD
    value: -0.39

- name: RD
  islimit: false
  exp_value: 0.344
  exp_stat_error: 0.026
  exp_sys_error: 0.00
  exp_source: HFLAV2024
  th_error: 0.004
  th_error_type: M
  th_error_source: HFLAV
  correlation:
  - name: RDstar
    value: -0.39
```

Other branches

- **smeft_vlq_hacked**
  - Updates are welcome! *Tomas?*

Backup slides

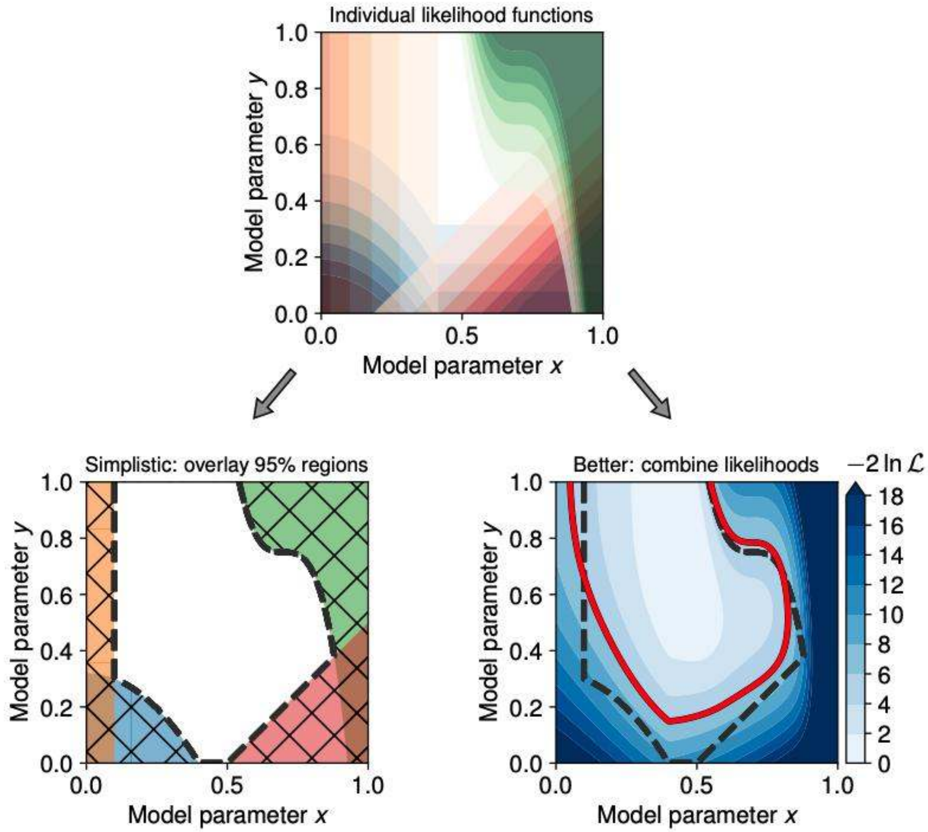
Likelihood functions and Global fits

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

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

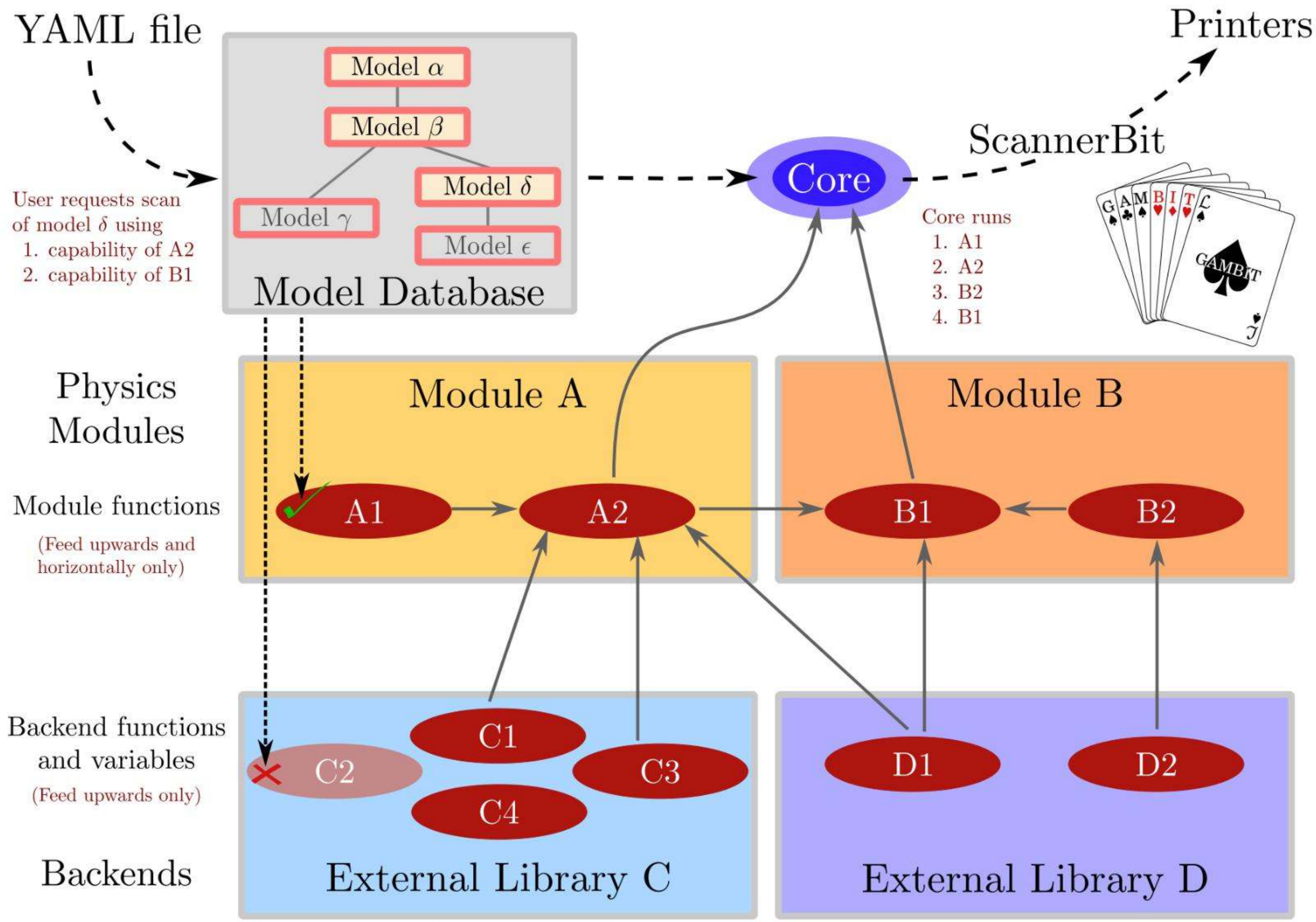
$$\mathcal{L} = \mathcal{L}_{Flavour}\mathcal{L}_{Higgs}\mathcal{L}_{Collider}\cdots$$

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



GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org



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

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

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

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

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

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

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

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

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

and prime operators from $P_R \to P_L$.

Fermions + second Higgs doublet

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

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

NEW PARTICLES!

h A H $H^{\pm}$

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

Mixing parameters

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