CEPC2024 workshop

Global Fits at CEPC

Updates on the Global Fit Session of the New Physics White Paper for CEPC

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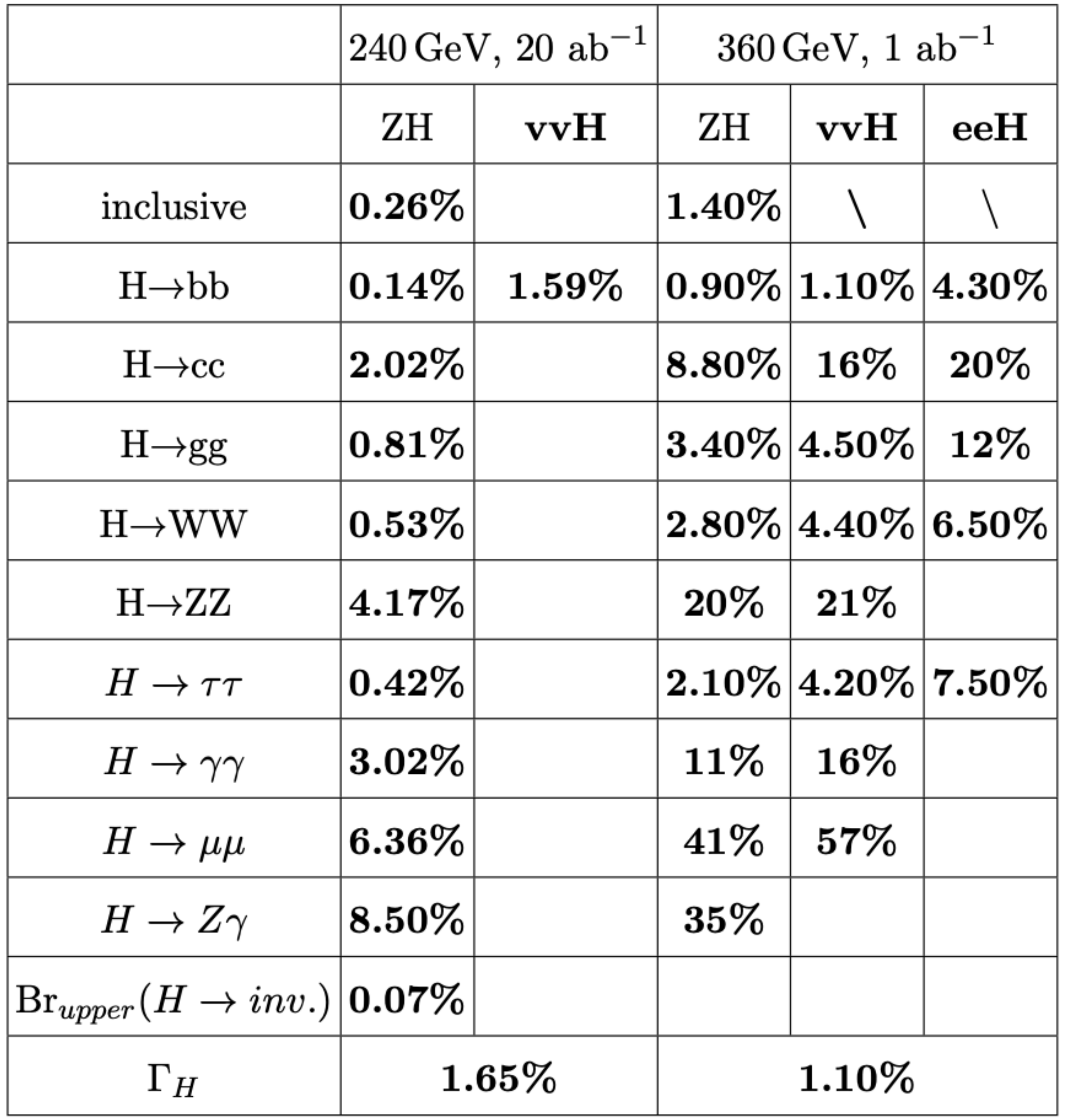
Content

- ➤What is and why global fit?
- ➤CEPC Global Fits of SUSY
- ➤CEPC Global Fits of 2HDM
- ➤CEPC Global Fits of SMEFT
- ➤Summary

Global Fit of Higgs data

Projected precision at the CEPC



	240 GeV, 20 ab^{-1}		360 GeV, 1 ab^{-1}		
	ZH	**vvH**	ZH	**vvH**	**eeH**
inclusive	**0.26%**		**1.40%**	\	\
H→bb	**0.14%**	**1.59%**	**0.90%**	**1.10%**	**4.30%**
H→cc	**2.02%**		**8.80%**	**16%**	**20%**
H→gg	**0.81%**		**3.40%**	**4.50%**	**12%**
H→WW	**0.53%**		**2.80%**	**4.40%**	**6.50%**
H→ZZ	**4.17%**		**20%**	**21%**	
$H \to \tau\tau$	**0.42%**		**2.10%**	**4.20%**	**7.50%**
$H \to \gamma\gamma$	**3.02%**		**11%**	**16%**	
$H \to \mu\mu$	**6.36%**		**41%**	**57%**	
$H \to Z\gamma$	**8.50%**		**35%**		
$\mathrm{Br}_{upper}(H \to inv.)$	**0.07%**				
Γ_H	**1.65%**		**1.10%**		

- Overlay 95% regions:

$$\frac{\sigma_{ZH} \times \mathrm{Br}(h \to b\bar{b})}{\sigma_{ZH}^{\mathrm{SM}} \times \mathrm{Br}(h \to b\bar{b})^{\mathrm{SM}}} = 1 \pm 2 \times 0.14\,\%$$

$$\frac{\sigma_{ZH} \times \mathrm{Br}(h \to c\bar{c})}{\sigma_{ZH}^{\mathrm{SM}} \times \mathrm{Br}(h \to c\bar{c})^{\mathrm{SM}}} = 1 \pm 2 \times 2.02\,\%$$

……

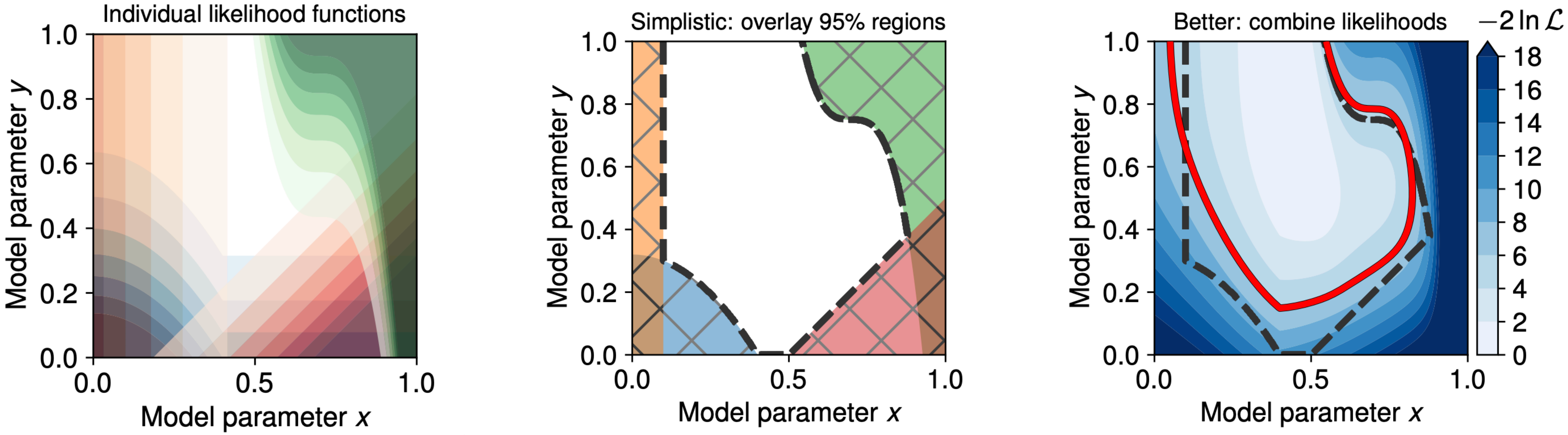
- Global fit:

$$-2 \ln \mathscr{L} = \chi^2$$

$$= \frac{\left(1 - \frac{\sigma_{ZH} \times \mathrm{Br}(h \to c\bar{c})}{\sigma_{ZH}^{\mathrm{SM}} \times \mathrm{Br}(h \to c\bar{c})^{\mathrm{SM}}}\right)^2}{(0.14\%)^2} + \cdots$$

Introduction

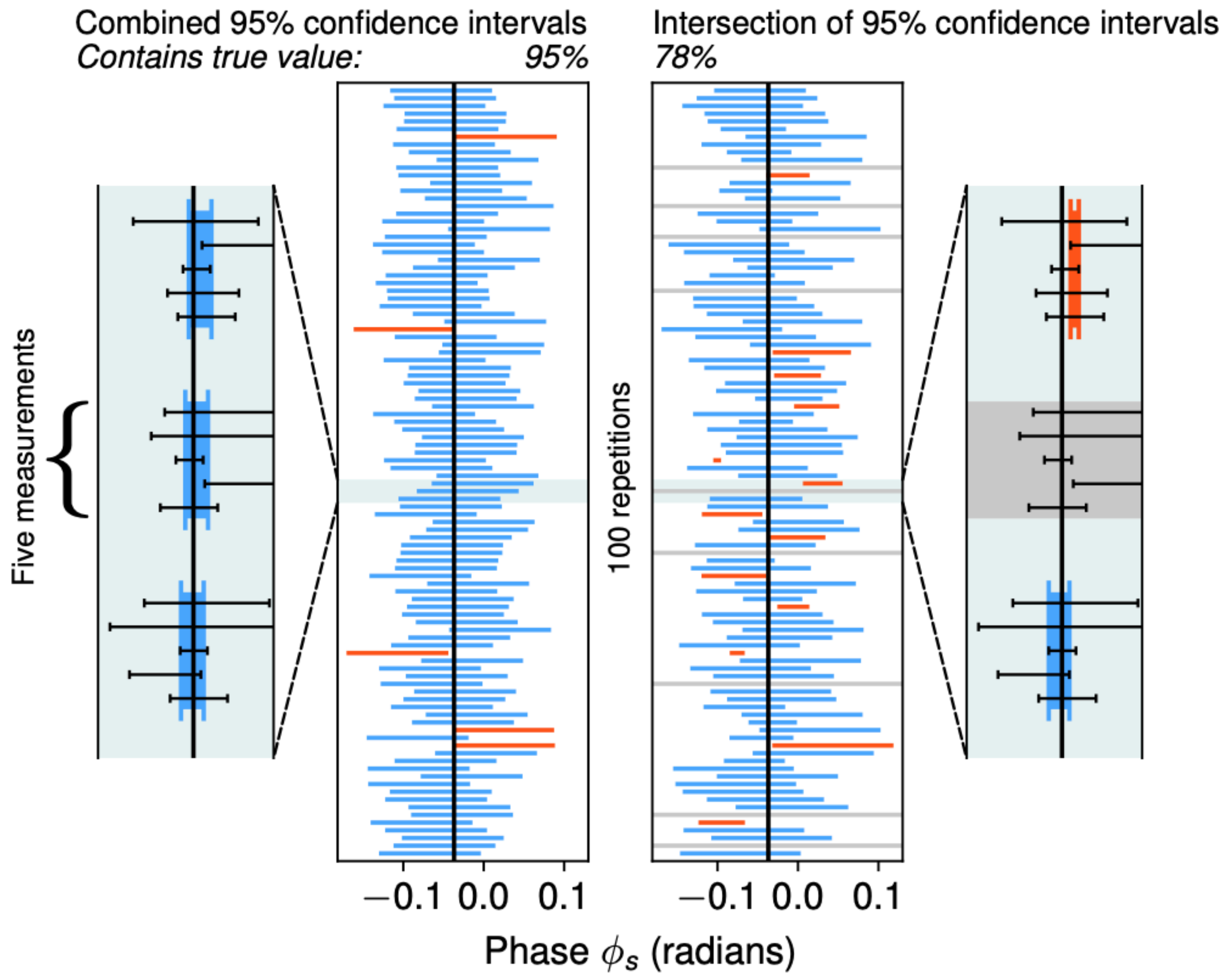
- What is global fit?
  - Perform a statistical fit to all available data.



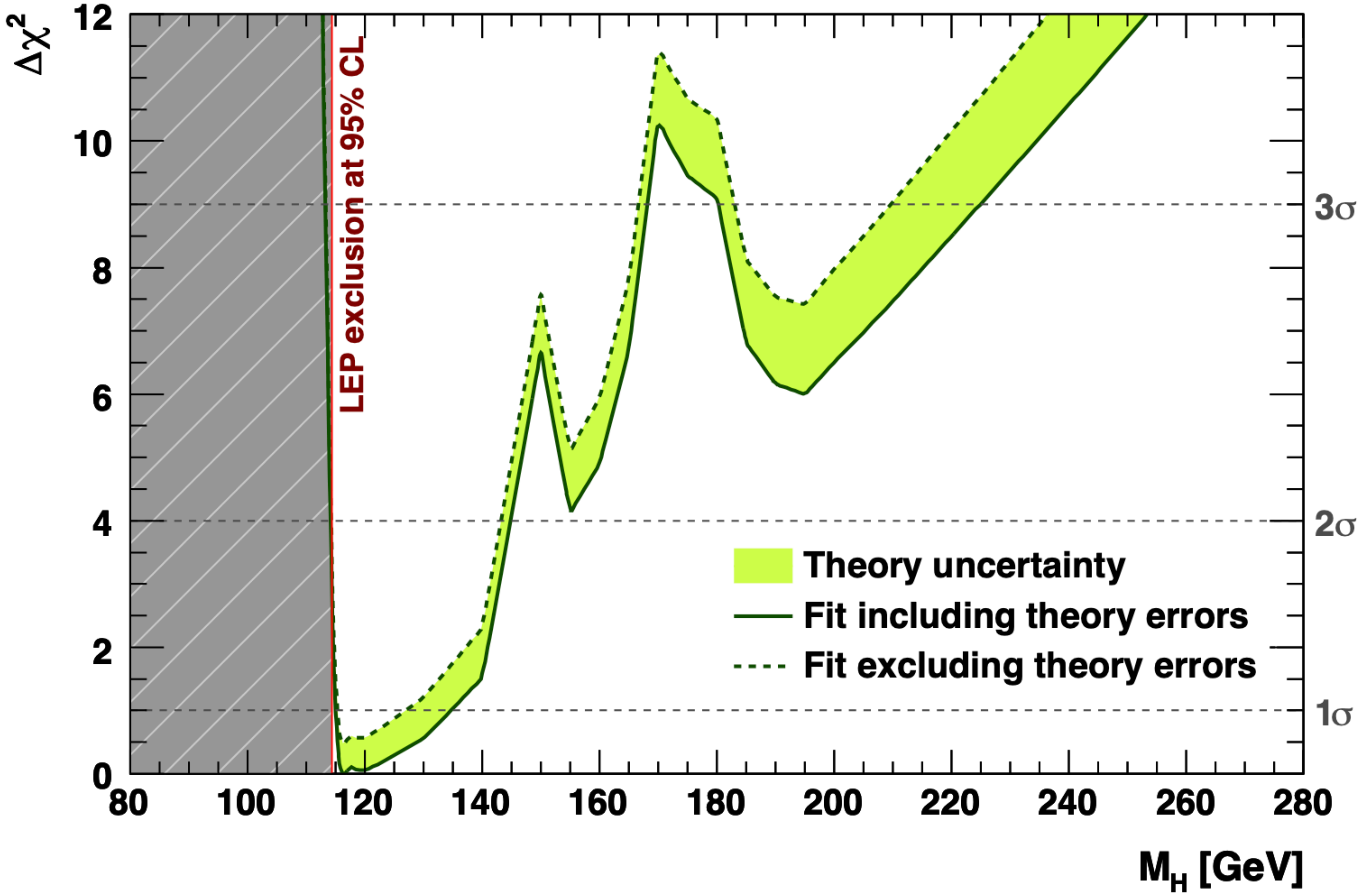
- Parameter estimation: given a particular theory, determine which parameter combinations fit all experiments, and how well.
- Model comparison: given multiple theories, determine which fit the data better, and quantify how much better.

Introduction

- Why global fit?



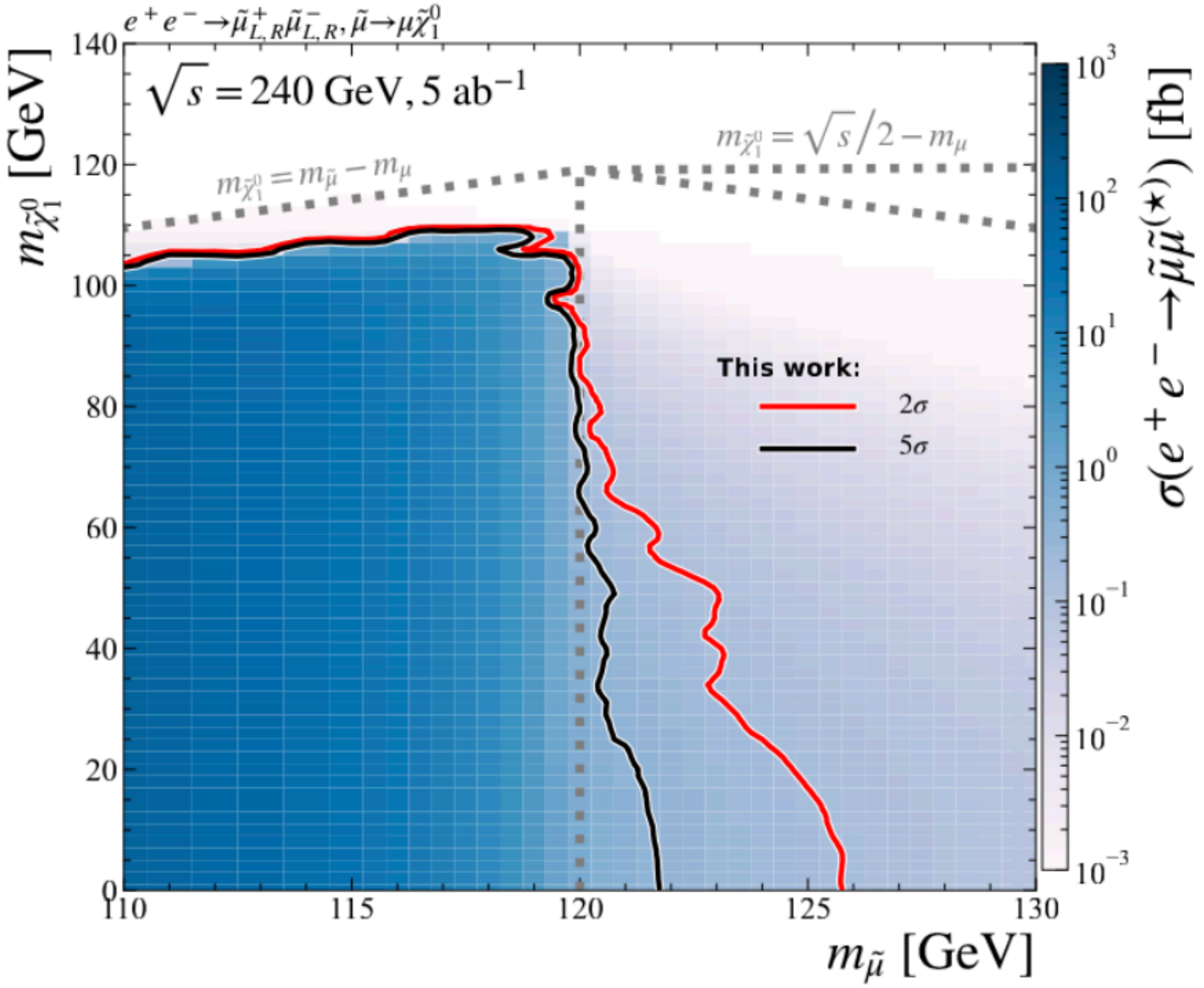
arXiv: 0811.0009v3 (Tue, 24 Feb 2009)



"In the SM fit including the direct Higgs searches, we find $M_H = 116^{18.3}_{1.3}$ GeV".

Direct search vs. Higgs fit at CEPC

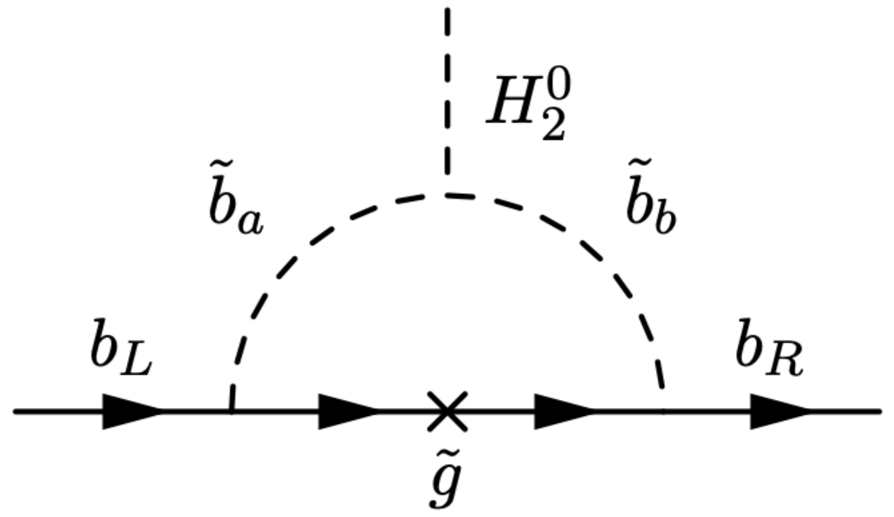
Direct search

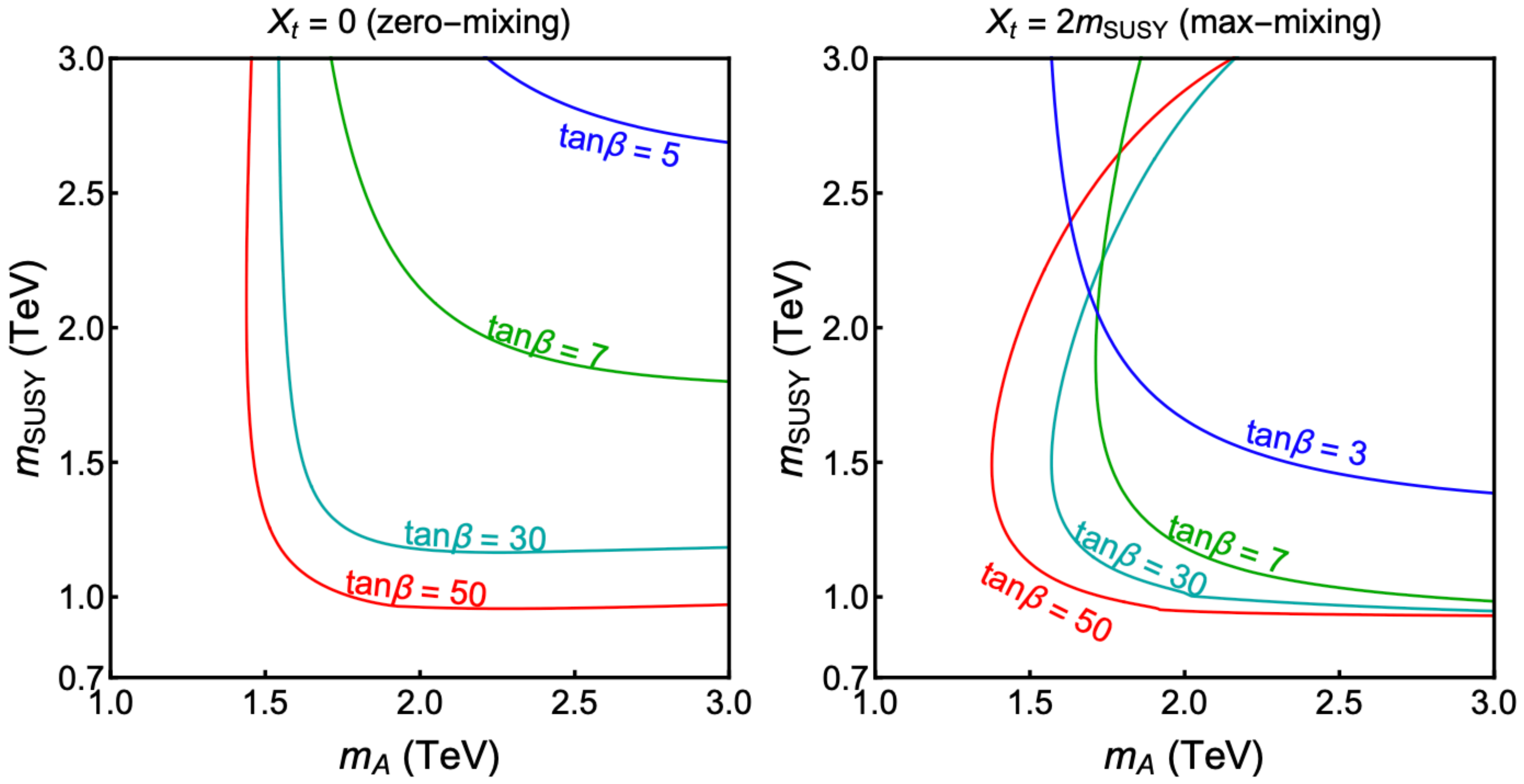


J. M. Yang, Y. Zhang, P. Zhu and R. Zhu, arXiv:2211.08132

vs.

Higgs fit





H. Li, H. Song, S. Su, W. Su and J. M. Yang, arXiv:2211.08132

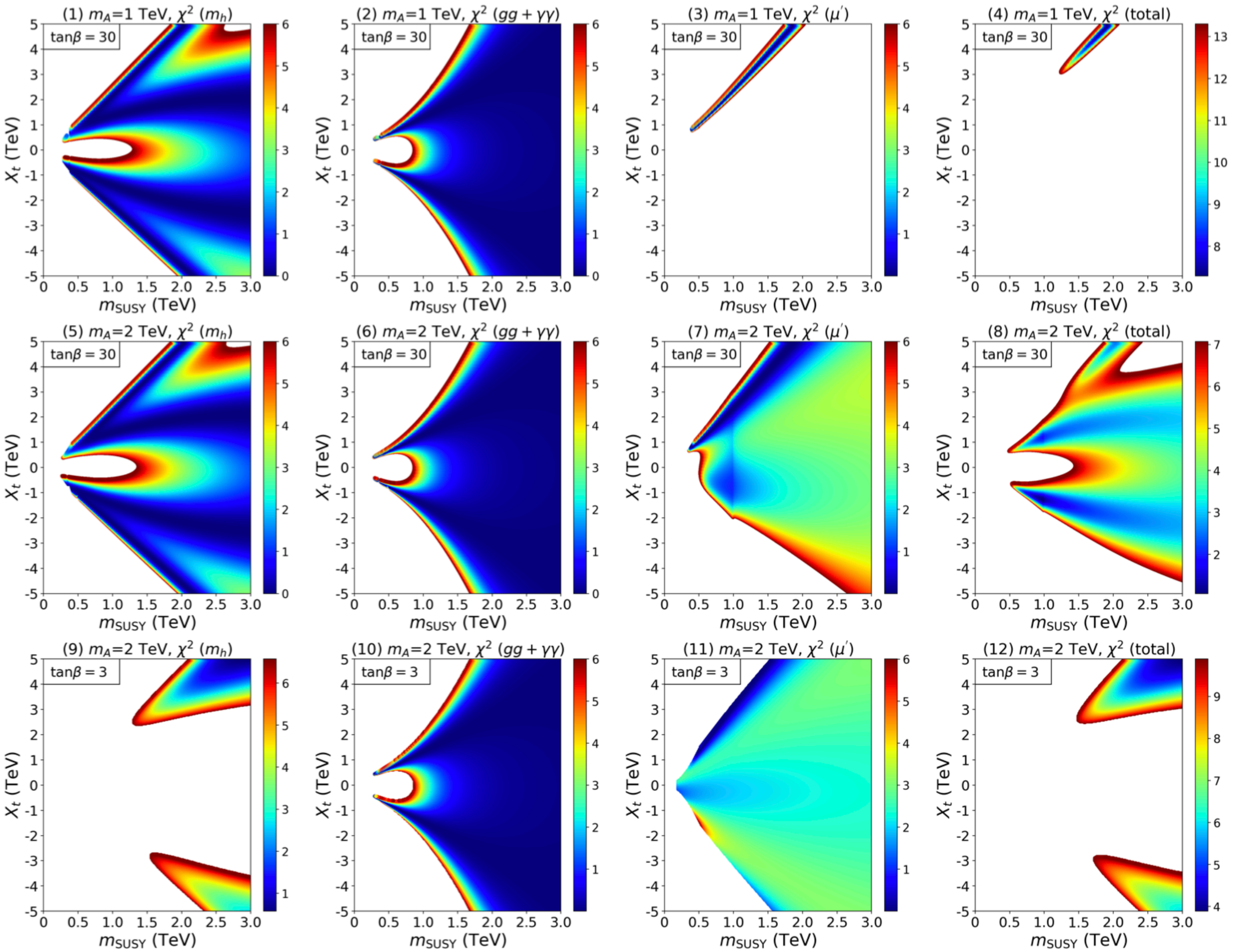
Global fits of SUSY

H. Li, H. Song, S. Su, W. Su and J. M. Yang, arXiv:2211.08132

- ➤ The likelihood includes contribution from

$$\chi^2_{total} = \chi^2_{m_h} + \chi^2_{\mu} = \frac{(m_h^{\mathrm{MSSM}} - m_h^{\mathrm{obs}})^2}{(\Delta m_h)^2} + \sum_{i=f,V..} \frac{(\mu_i^{\mathrm{MSSM}} - \mu_i^{\mathrm{obs}})^2}{(\Delta \mu_i)^2}$$

  - ◉ the Higgs mass
  - ◉ signal strength measurements
    - ✳ loop level decays
    - ✳ tree level decays
- ➤ It will be complementary to the direct searches of SUSY particles at energy frontier machines.



Global fits of SUSY

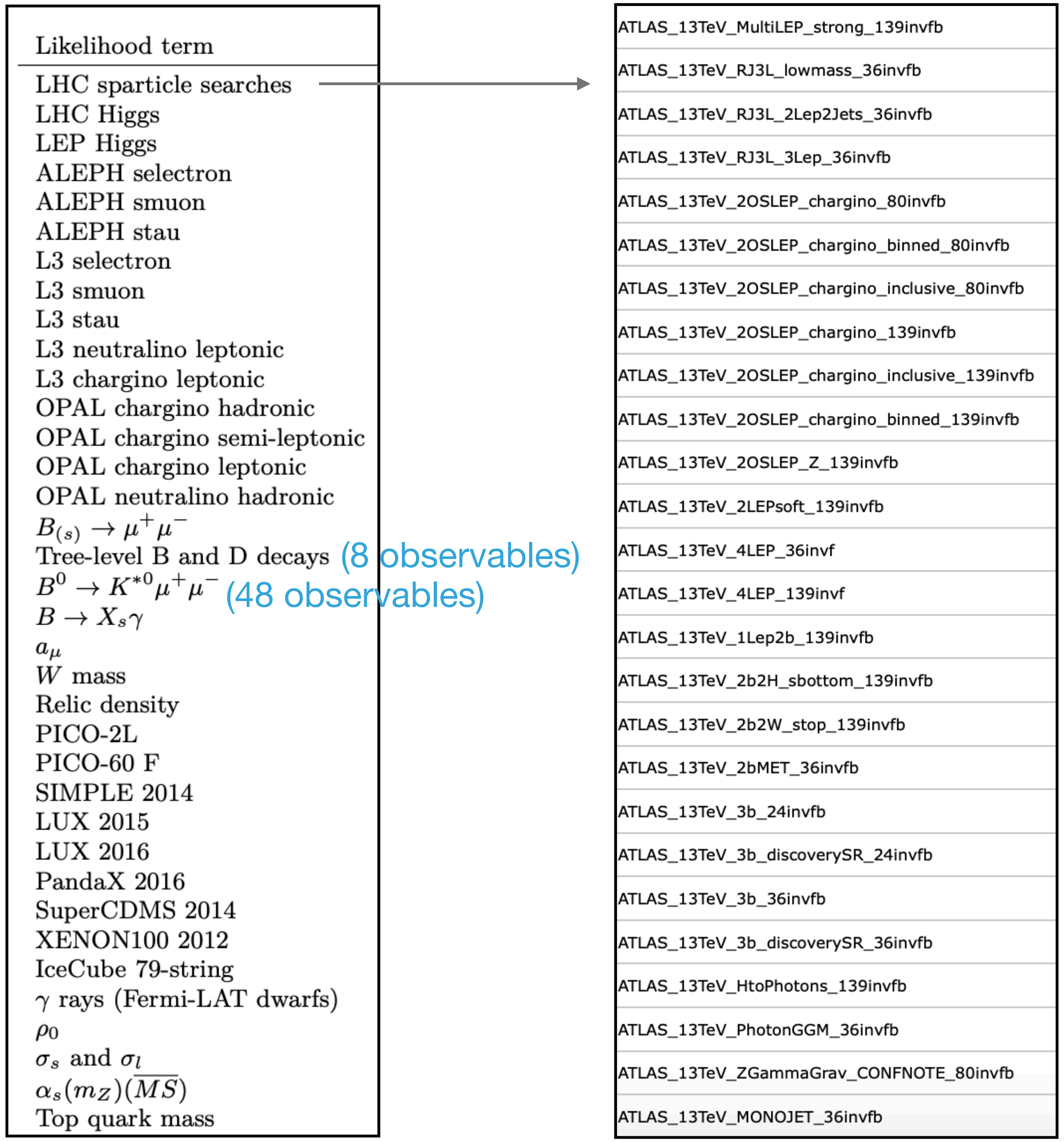
GAMBIT, arXiv:1705.07935, arXiv:1705.07917, arXiv:2203.04828

- All current experimental data should be included in the global fit:

$$\mathscr{L}_{\text{Present+CEPC}} = \mathscr{L}_{\text{CEPC}}\mathscr{L}_{\text{Present}}$$

$$= \mathscr{L}_{\text{CEPC}}\mathscr{L}_{\text{collider}}\mathscr{L}_{\text{DM}}\mathscr{L}_{\text{flavor}}\mathscr{L}_{\text{EWPO}}\cdots$$

- This is extremely time-consuming, especially the simulation involved in calculating the LHC direct search limits.
- We post-process the available data from previous global fits by GAMBIT. It takes several weeks on 1280 supercomputer cores.



Likelihood term
LHC sparticle searches
LHC Higgs
LEP Higgs
ALEPH selectron
ALEPH smuon
ALEPH stau
L3 selectron
L3 smuon
L3 stau
L3 neutralino leptonic
L3 chargino leptonic
OPAL chargino hadronic
OPAL chargino semi-leptonic
OPAL chargino leptonic
OPAL neutralino hadronic
$B_{(s)} \to \mu^+\mu^-$
Tree-level B and D decays (8 observables)
$B^0 \to K^{*0}\mu^+\mu^-$ (48 observables)
$B \to X_s\gamma$
a_μ
W mass
Relic density
PICO-2L
PICO-60 F
SIMPLE 2014
LUX 2015
LUX 2016
PandaX 2016
SuperCDMS 2014
XENON100 2012
IceCube 79-string
γ rays (Fermi-LAT dwarfs)
ρ_0
σ_s and σ_l
$\alpha_s(m_Z)(\overline{MS})$
Top quark mass

ATLAS_13TeV_MultiLEP_strong_139invfb
ATLAS_13TeV_RJ3L_lowmass_36invfb
ATLAS_13TeV_RJ3L_2Lep2Jets_36invfb
ATLAS_13TeV_RJ3L_3Lep_36invfb
ATLAS_13TeV_2OSLEP_chargino_80invfb
ATLAS_13TeV_2OSLEP_chargino_binned_80invfb
ATLAS_13TeV_2OSLEP_chargino_inclusive_80invfb
ATLAS_13TeV_2OSLEP_chargino_139invfb
ATLAS_13TeV_2OSLEP_chargino_inclusive_139invfb
ATLAS_13TeV_2OSLEP_chargino_binned_139invfb
ATLAS_13TeV_2OSLEP_Z_139invfb
ATLAS_13TeV_2LEPsoft_139invfb
ATLAS_13TeV_4LEP_36invf
ATLAS_13TeV_4LEP_139invf
ATLAS_13TeV_1Lep2b_139invfb
ATLAS_13TeV_2b2H_sbottom_139invfb
ATLAS_13TeV_2b2W_stop_139invfb
ATLAS_13TeV_2bMET_36invfb
ATLAS_13TeV_3b_24invfb
ATLAS_13TeV_3b_discoverySR_24invfb
ATLAS_13TeV_3b_36invfb
ATLAS_13TeV_3b_discoverySR_36invfb
ATLAS_13TeV_HtoPhotons_139invfb
ATLAS_13TeV_PhotonGGM_36invfb
ATLAS_13TeV_ZGammaGrav_CONFNOTE_80invfb
ATLAS_13TeV_MONOJET_36invfb

Global fits of SUSY

GAMBIT, arXiv:1705.07935, arXiv:1705.07917, arXiv:2203.04828

- GUT scale MSSM

$$\mathcal{L}_{soft} \sim M^2_{H_{u,d}}|H_{u,d}|^2 + m_0^2 \tilde{F}_i^\dagger \tilde{F}_i + \frac{1}{2} m_{1/2} \tilde{G}_j \tilde{G}_j + A_0 \tilde{F}_i^c H_{u,d} \tilde{F}_i + \cdots$$

  - CMSSM: $m_0^2 = M^2_{H_{u,d}}$ — 7.1×10^7 samples
  - NUHM1: $m_0^2 \neq M^2_{H_{u,d}}$, $M^2_{H_u} = M^2_{H_d}$ — 9.4×10^7 samples
  - NUHM2: $m_0^2 \neq M^2_{H_{u,d}}$, $M^2_{H_u} \neq M^2_{H_d}$ — 1.2×10^8 samples

- Weak scale MSSM

$$\mathcal{L}_{soft} \sim M^2_{H_{u,d}}|H_{u,d}|^2 + m^2_{\tilde{f}_i} \tilde{F}_i^\dagger \tilde{F}_i + \frac{1}{2} M_j \tilde{G}_j \tilde{G}_j + A_{f_i} \tilde{F}_i^c H_{u,d} \tilde{F}_i + \cdots$$

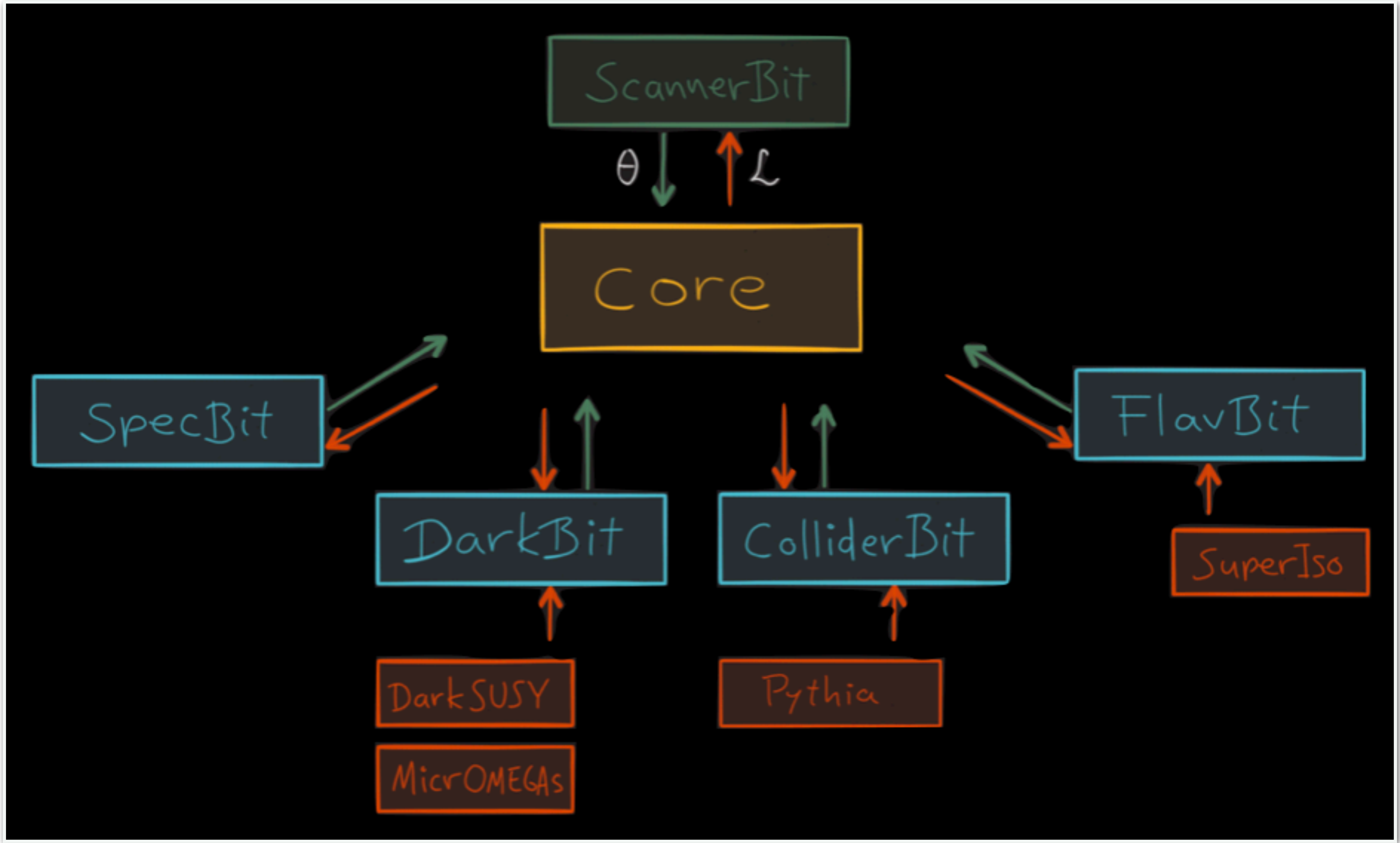
  - MSSM-7: $\tan\beta$, $A_u = A_d = A_e = 0$, — 1.8×10^8 samples

    except for $(A_u)_{33} = A_{u3}$, $(A_d)_{33} = A_{d3}$.

Global fits of SUSY

GAMBIT, arXiv:1705.07935, arXiv:1705.07917, arXiv:2203.04828

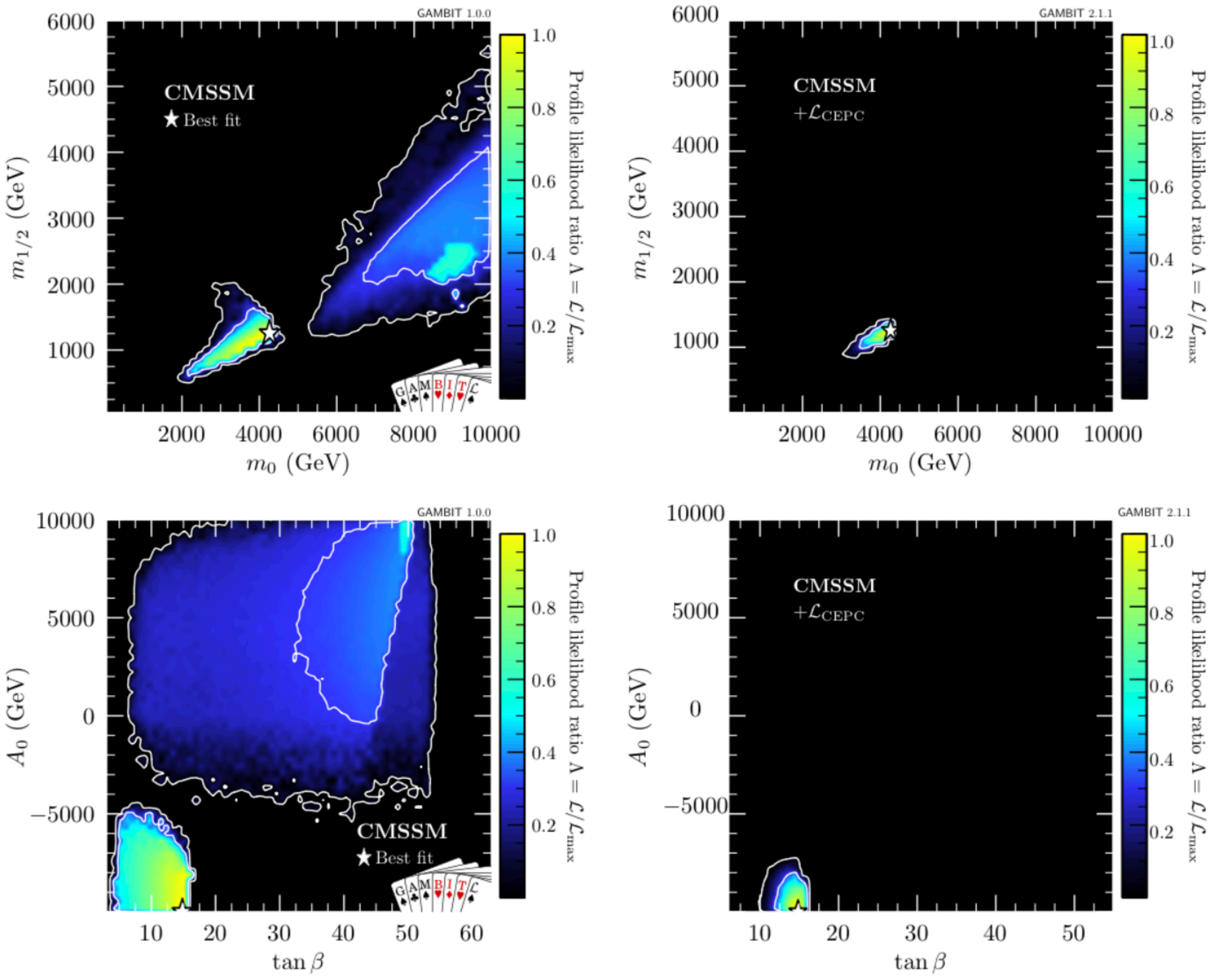
- Present constraints:
  - DM abundance (upper bound)
  - DM direct det. (8 experiments)
  - DM indirect det. (Fermi-LAT, IceCube79)
  - EW precision (W mass, muon g-2, …)
  - 59 flavor observables *(old one)*
  - LHC Higgs data, SUSY searches, …



- 5 nuisances:
  - local DM density, nuclear physics parameters, top mass, strong coupling.

Global fits of SUSY

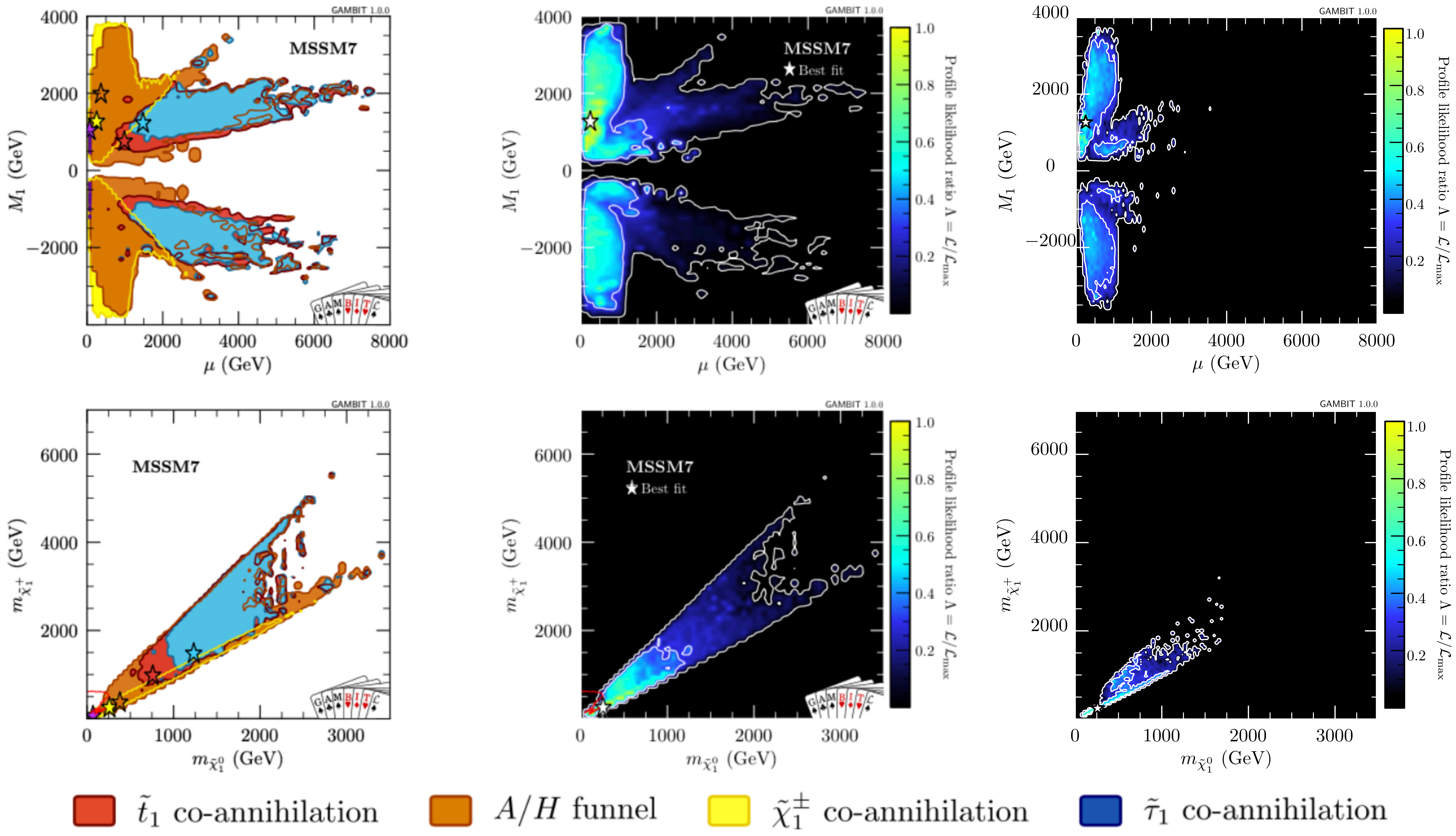
GAMBIT, arXiv:1705.07935, arXiv:1705.07917, arXiv:2203.04828



- Profile likelihood ratio in planes of the CMSSM parameters
- Left panels: present likelihood
- Right panels: present likelihood + $\mathscr{L}_{\rm CEPC}$
- The central values of measurements at CEPC are values of the best-fit point, and the theoretical uncertainties are $k=1/5$ times smaller than the current SM value.
- The position of the best-fit point holds still, and the preferred regions shrink significantly towards the best-fit point.

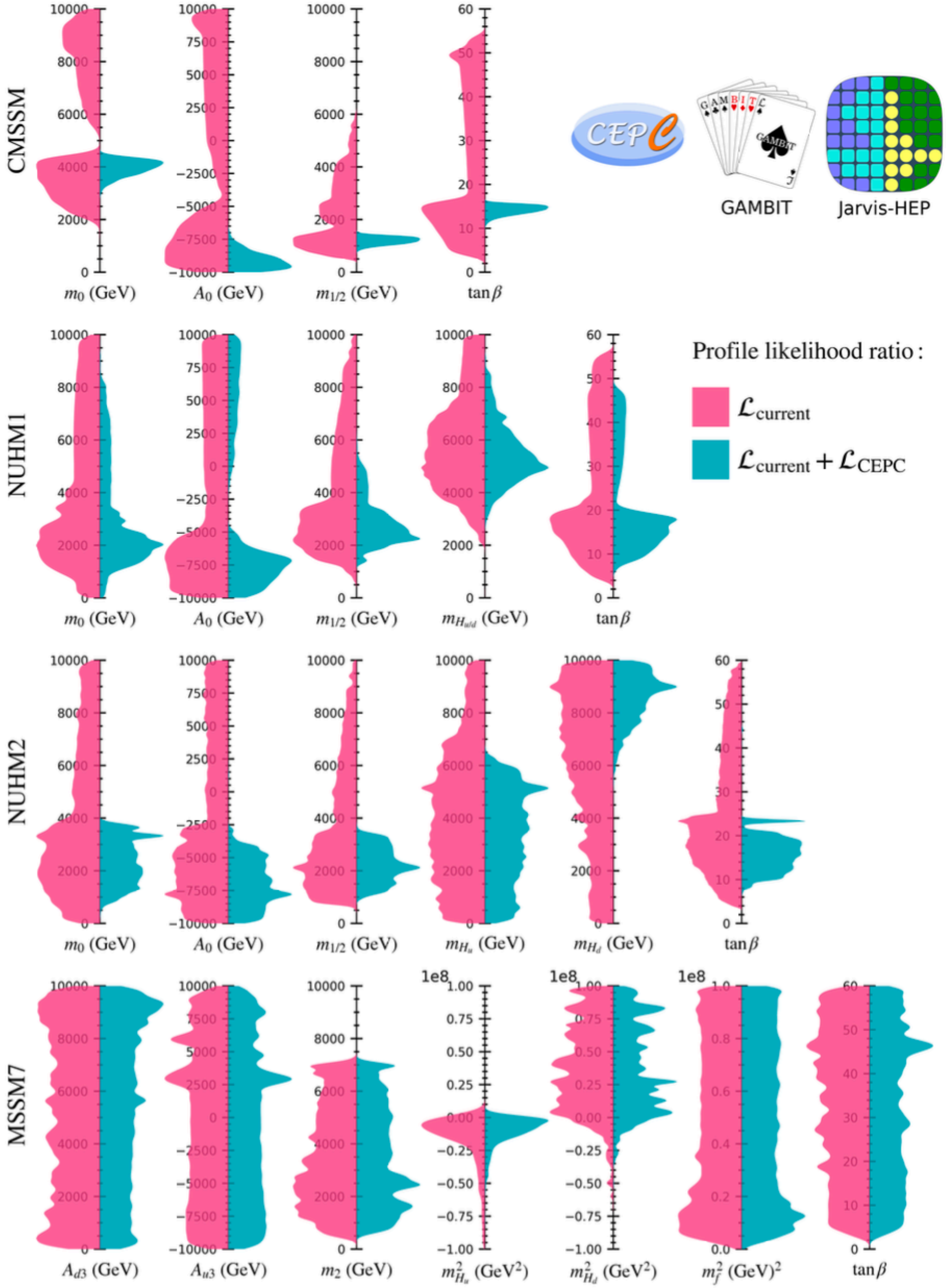
Global fits of SUSY

GAMBIT, arXiv:1705.07935, arXiv:1705.07917, arXiv:2203.04828



- ➤ Two new regions, sbottom co-annihilation region and light higgs funnel region, appears.
- ➤ The best fit point is located in chargino co-annihilation region.
- ➤ It is hard to distinguish between chargino co-annihilation region and A/H funnel region by Higgs measurements.
- ➤ Moreover, both negative and positive mu are found in the 95% CL region.

Global fits of SUSY



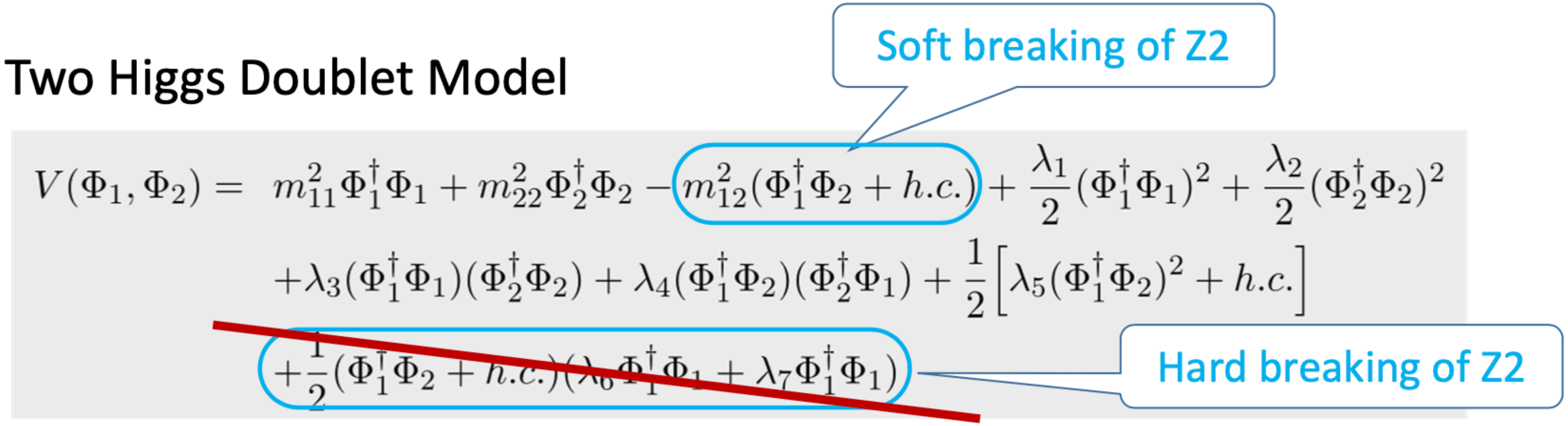
A new summary plot for SUSY global fit, generated by Pengxuan Zhu.

Global fits of 2HDM

Provided by 苏伟

2HDM: Brief Introduction

- Two Higgs Doublet Model



Soft breaking of Z2

$$V(\Phi_1,\Phi_2) = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - \boxed{m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.)} + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$

$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\right]$$

$$\cancel{\boxed{+\frac{1}{2}(\Phi_1^\dagger\Phi_2 + h.c.)(\lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_1^\dagger\Phi_1)}}$$

Hard breaking of Z2

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix}$$

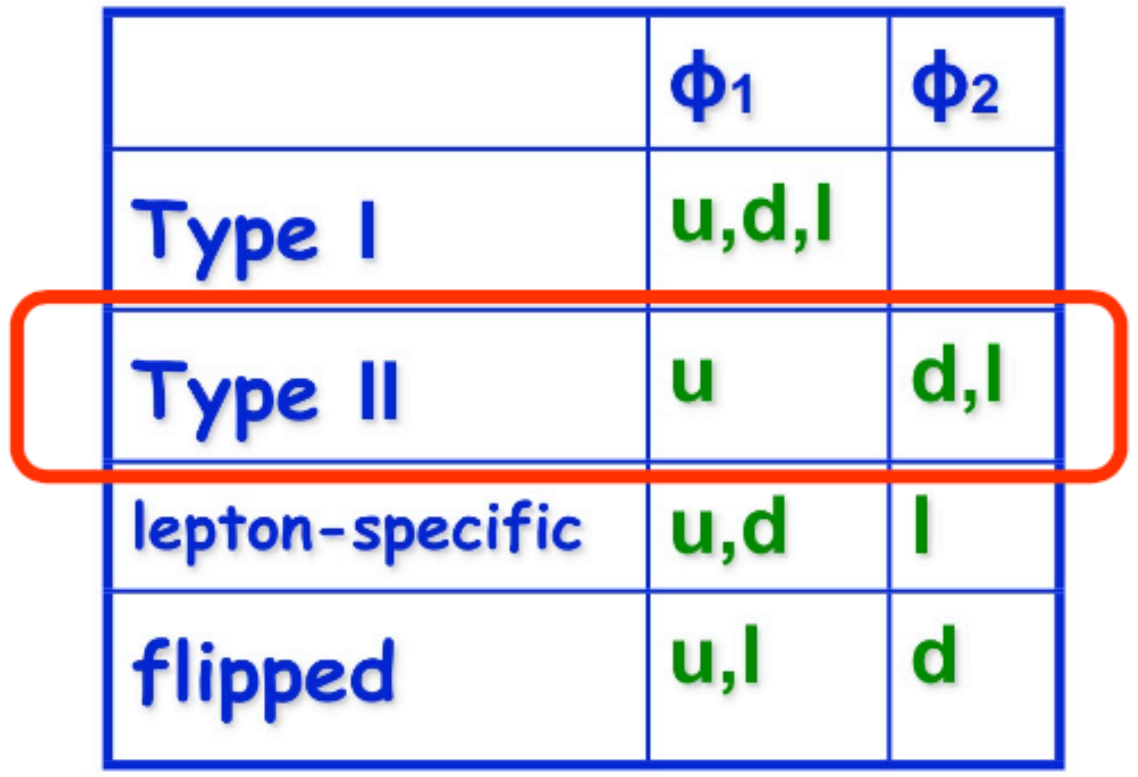
$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \quad \begin{aligned} A &= -G_1\sin\beta + G_2\cos\beta \\ H^\pm &= -\phi_1^\pm\sin\beta + \phi_2^\pm\cos\beta \end{aligned}$$

Global fits of 2HDM

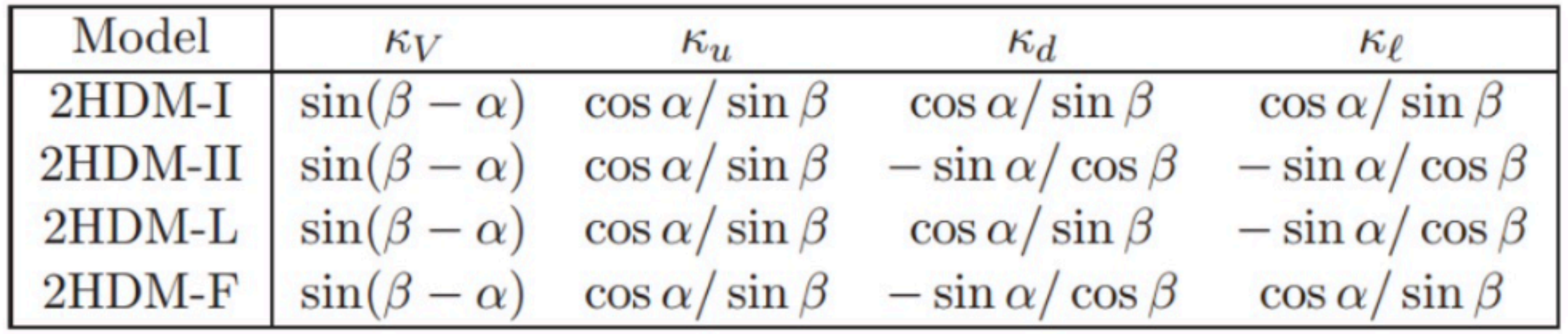
Provided by 苏伟

2HDM: Brief Introduction



	Φ1	Φ2
Type I	u,d,l	
Type II	u	d,l
lepton-specific	u,d	l
flipped	u,l	d

$$\kappa_i = g_{hii}^{BSM} / g_{hii}^{SM}$$



Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

- Parameters (CP-conserving, Flavor Limit, Z_2 Symmetry)

$$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \Rightarrow v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$$

Soft Z_2 symmetry breaking: m_{12}^2

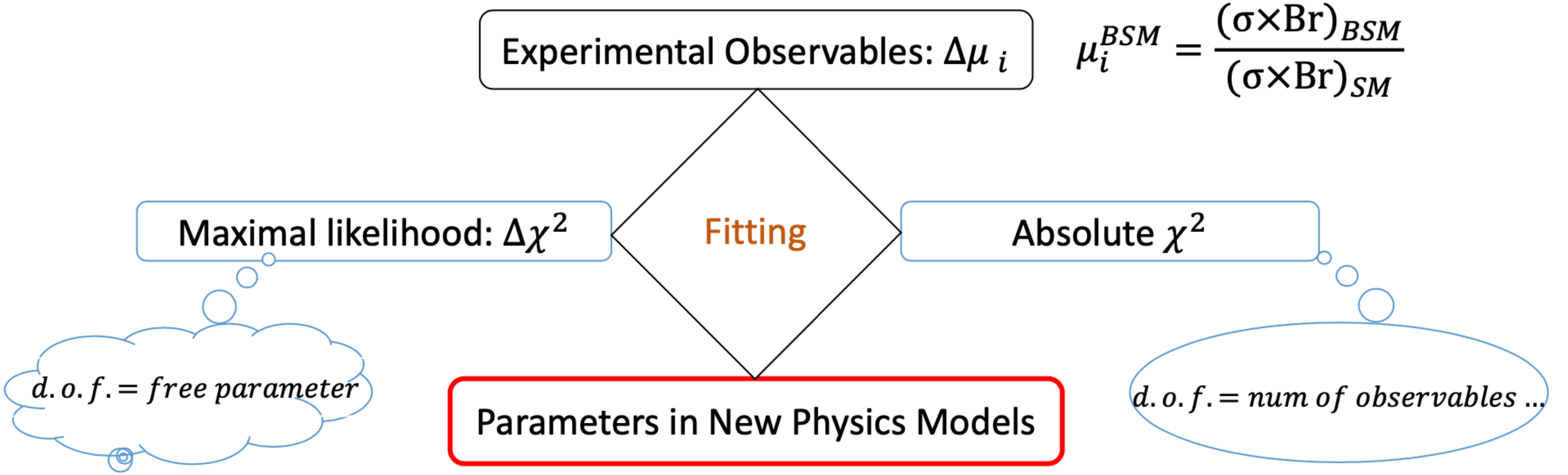
v → 246 GeV

m_h → 125. GeV

Global fits of 2HDM

Provided by 苏伟

Exclusion ability : Study strategies



Experimental Observables: $\Delta\mu_i$

$$\mu_i^{BSM} = \frac{(\sigma\times Br)_{BSM}}{(\sigma\times Br)_{SM}}$$

Fitting

Maximal likelihood: $\Delta\chi^2$

$d.o.f. = free\ parameter$

Absolute χ^2

$d.o.f. = num\ of\ observables$ ...

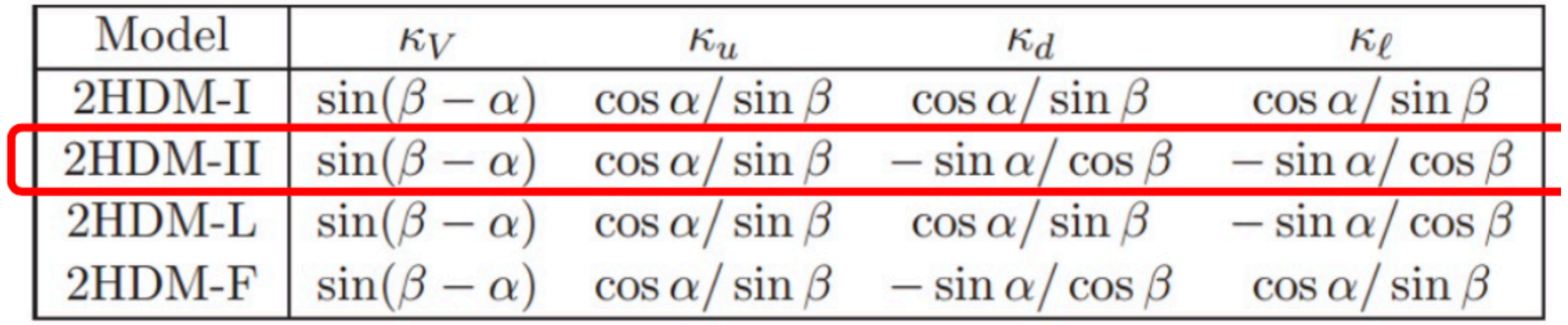
Parameters in New Physics Models

$$\chi^2 = \frac{(\mu_i^{BSM} - \mu_i^{obs})^2}{(\Delta\mu_i)^2}, \quad \mu_i^{obs} = 1$$

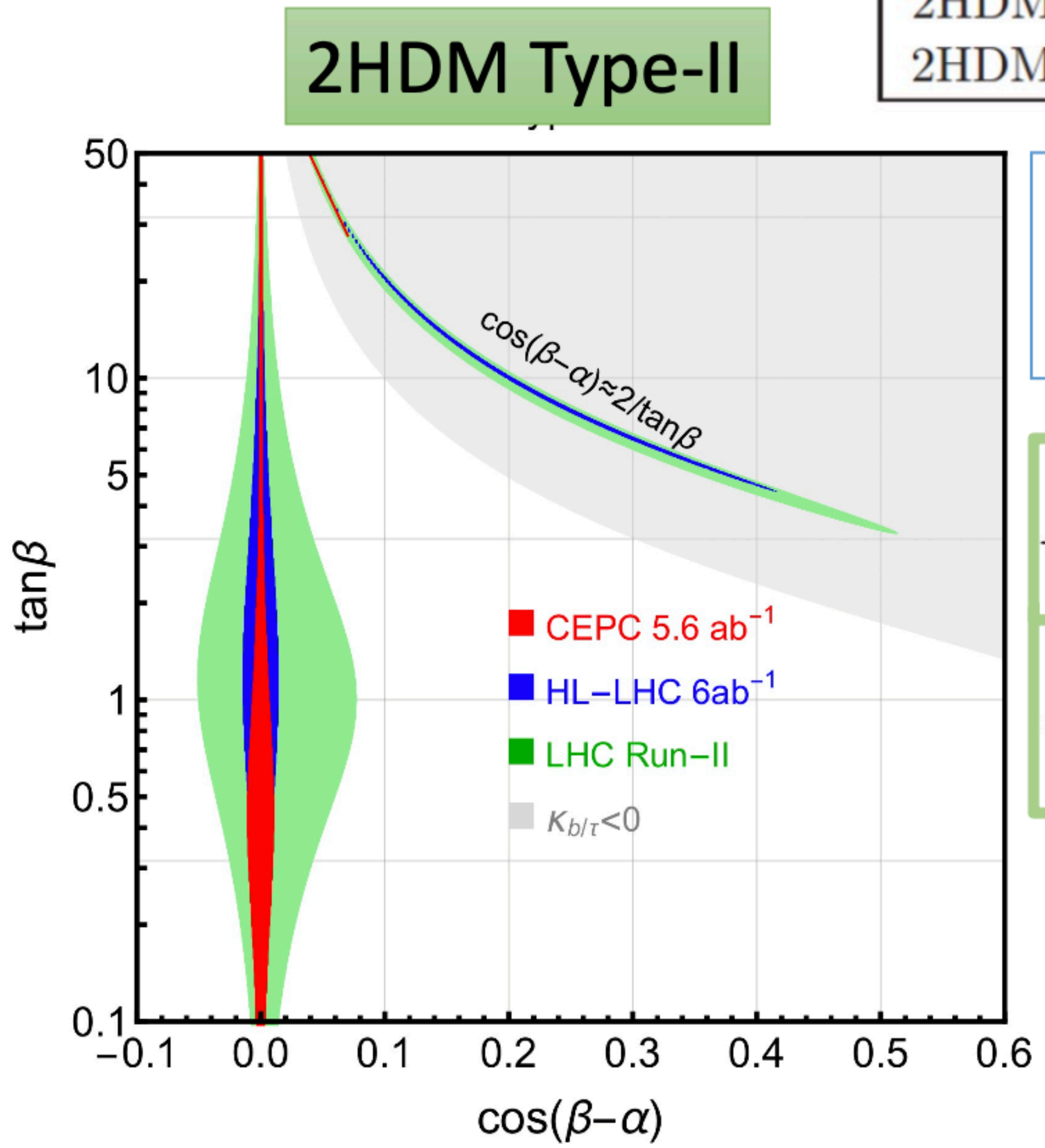
Global fits of 2HDM

Provided by 苏伟

2HDM: Tree Level



Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$



Alignment limit :
$\cos(\beta-\alpha)=0$
$g(2HDM)=g(SM)$

[1910.06269](1910.06269)
WS

$$-\frac{\sin\beta}{\cos\alpha}-1=-\frac{1}{2}\cos^2(\beta-\alpha)-\cos(\beta-\alpha)\times\tan\beta$$

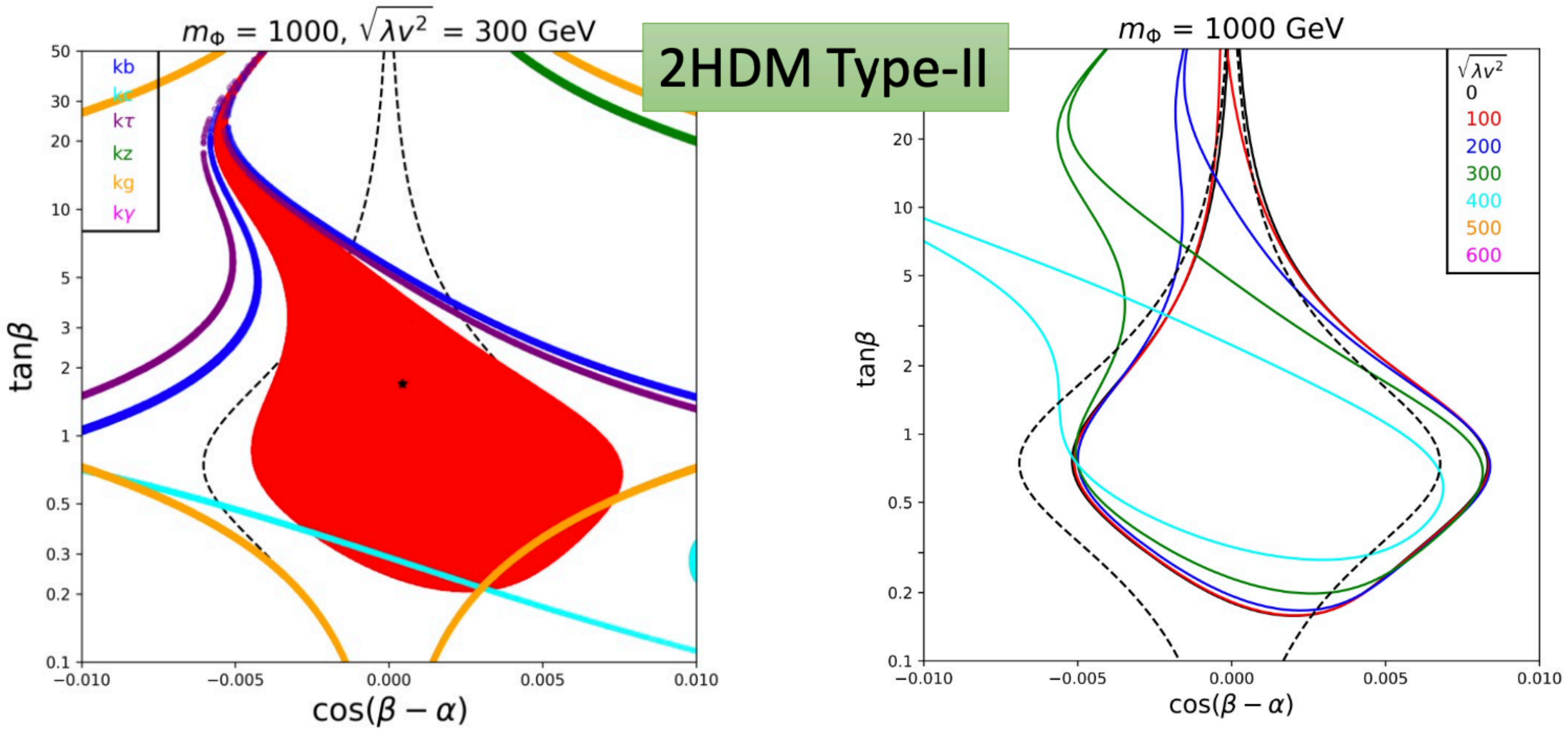
$$\frac{\cos\alpha}{\sin\beta}-1=-\frac{1}{2}\cos^2(\beta-\alpha)+\frac{\cos(\beta-\alpha)}{\tan\beta}$$

Global fits of 2HDM

Provided by 苏伟

2HDM: Loop Level

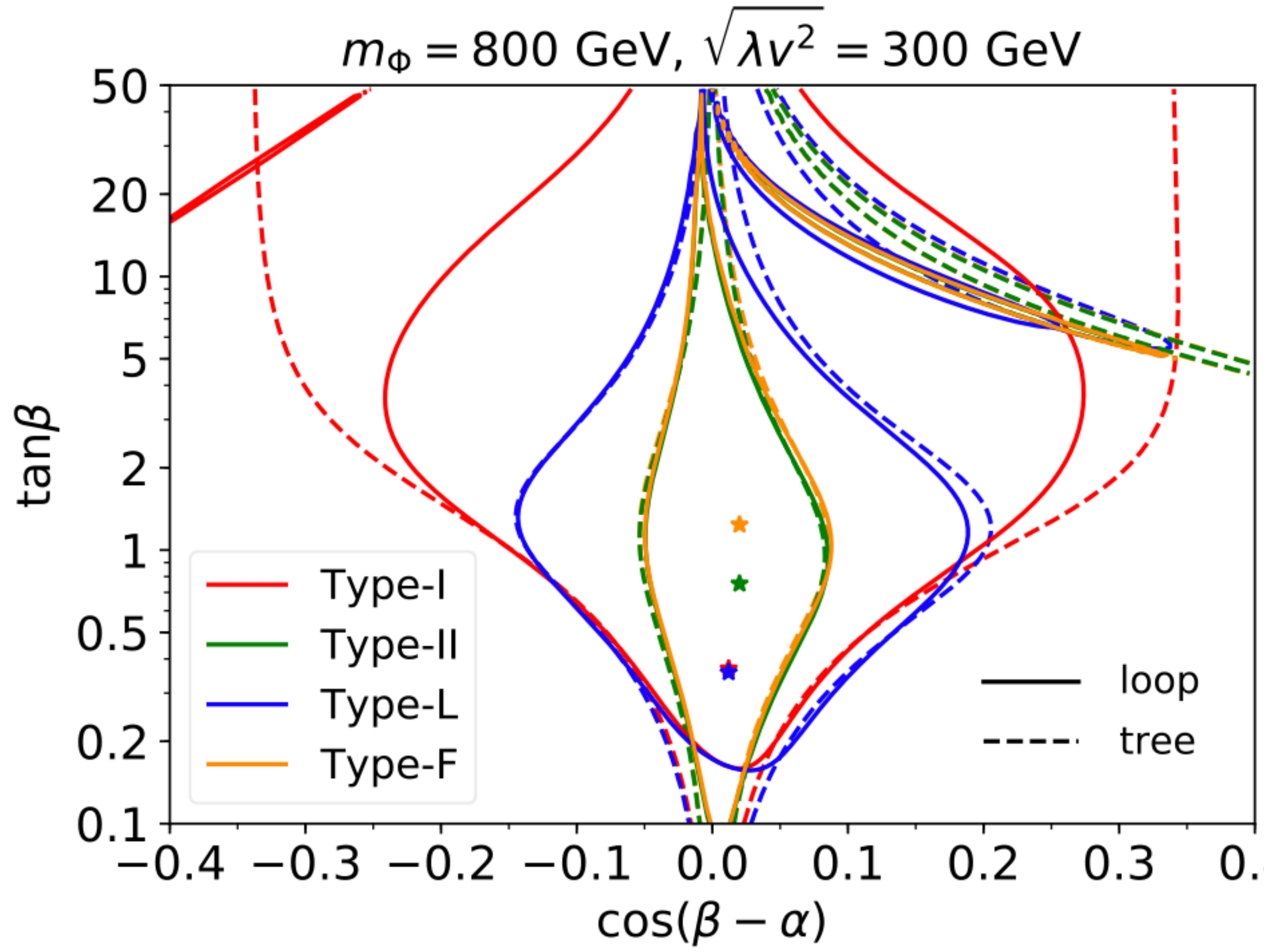
2HDM Type-II

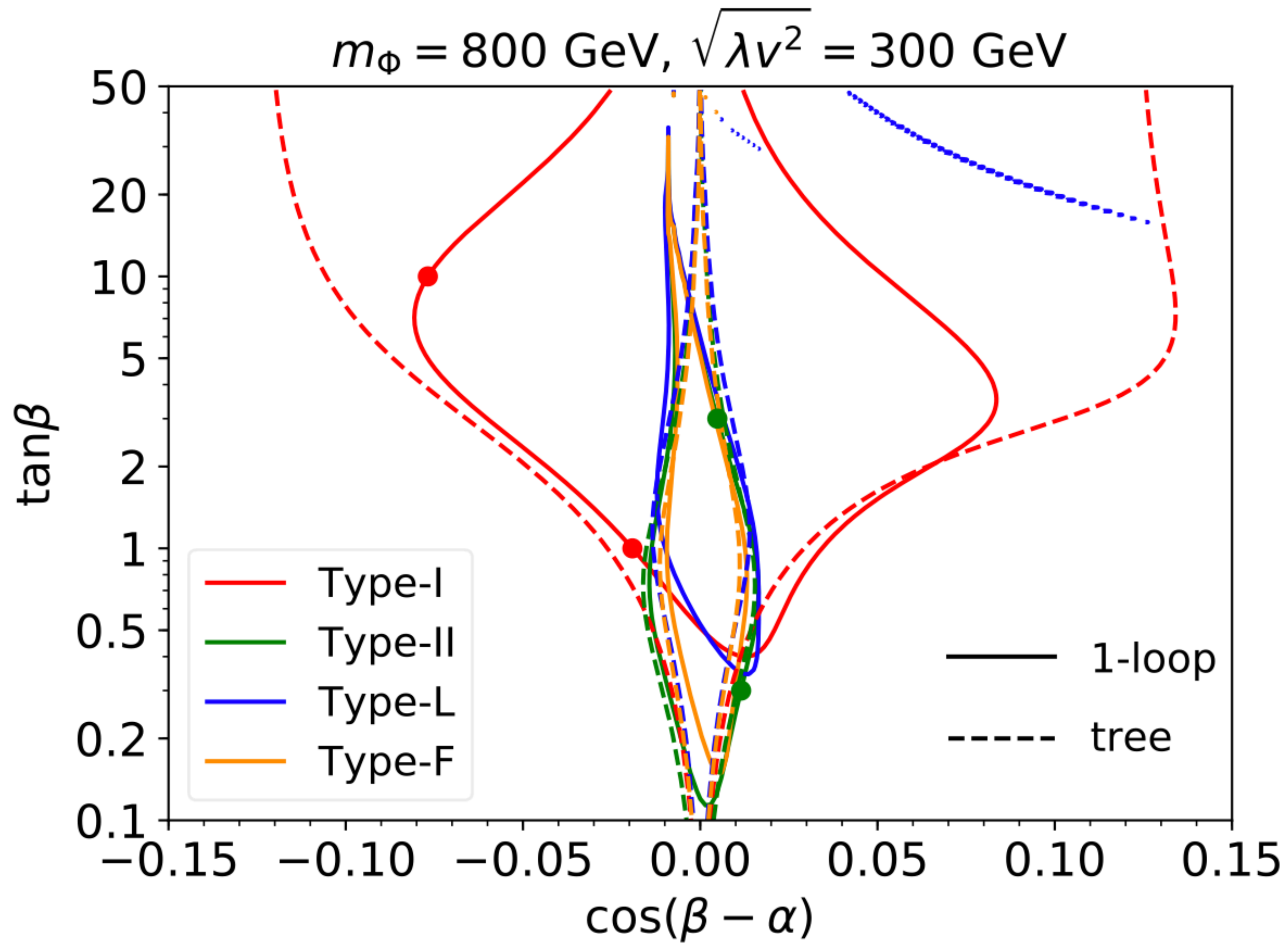


Global fits of 2HDM

Provided by 苏伟

- ➤ Four types of 2HDMs at the proposed Higgs factories.



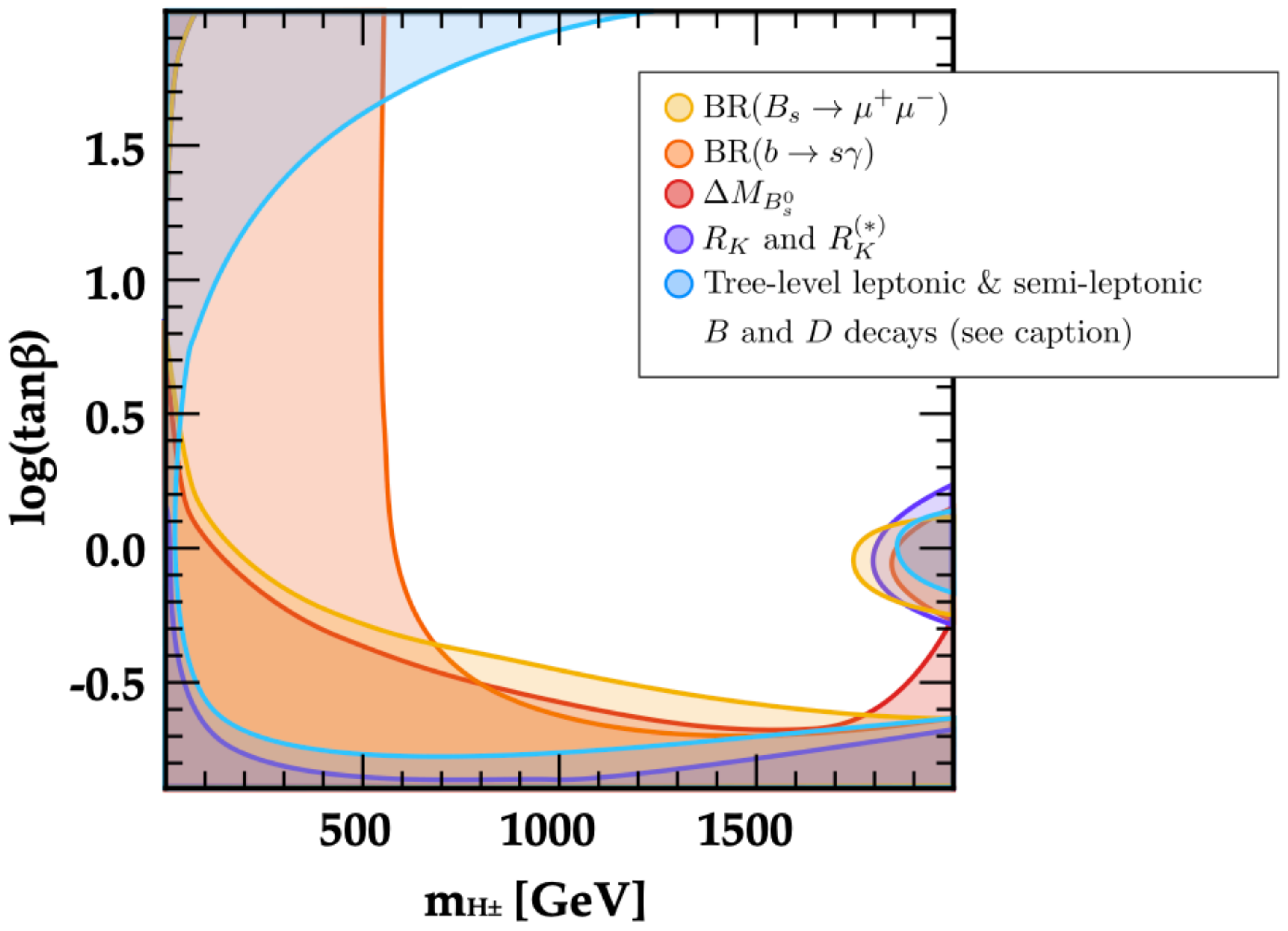


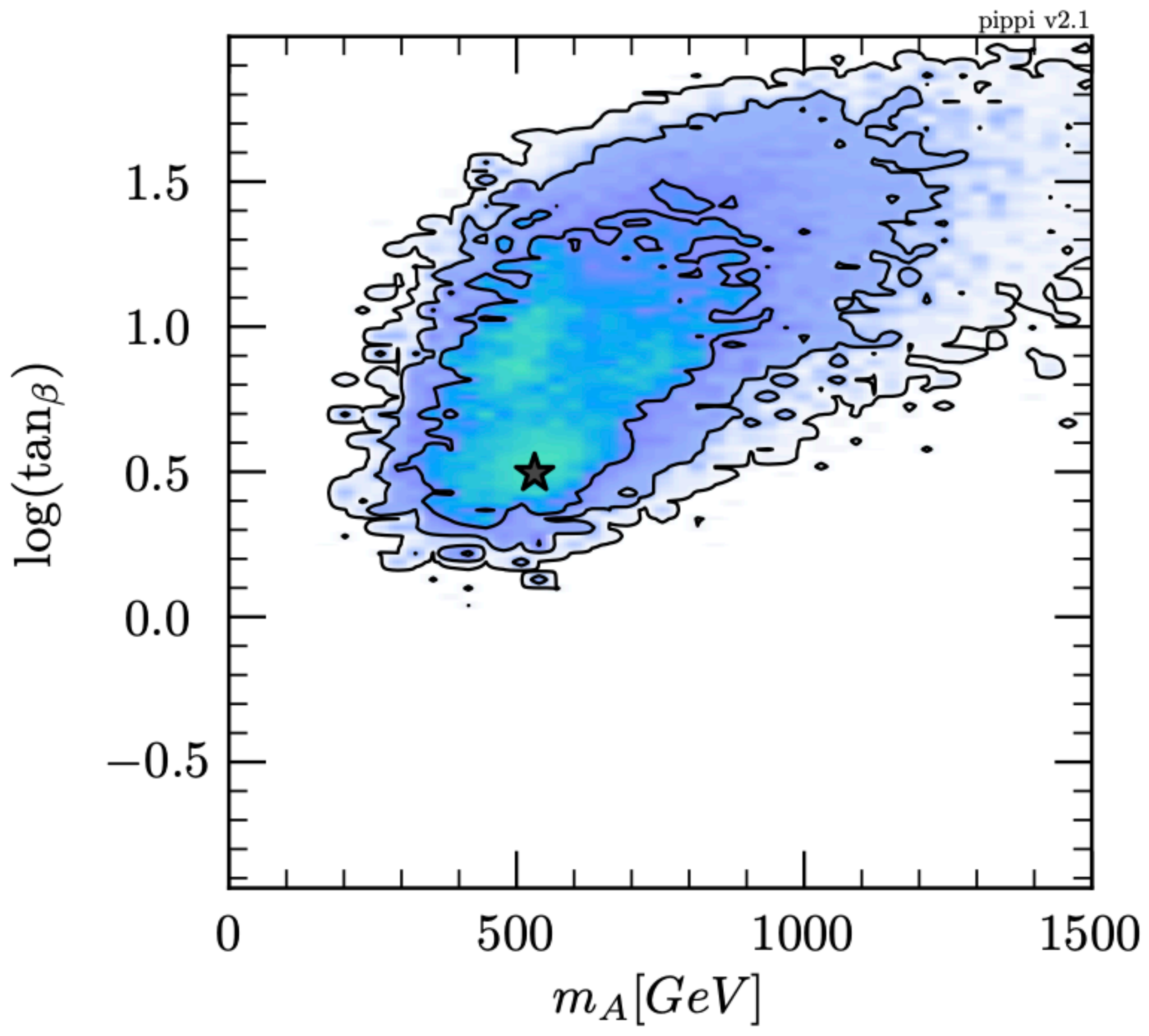
- ➤ Most of the currently allowed region permits a discovery at the CEPC and HL-LHC

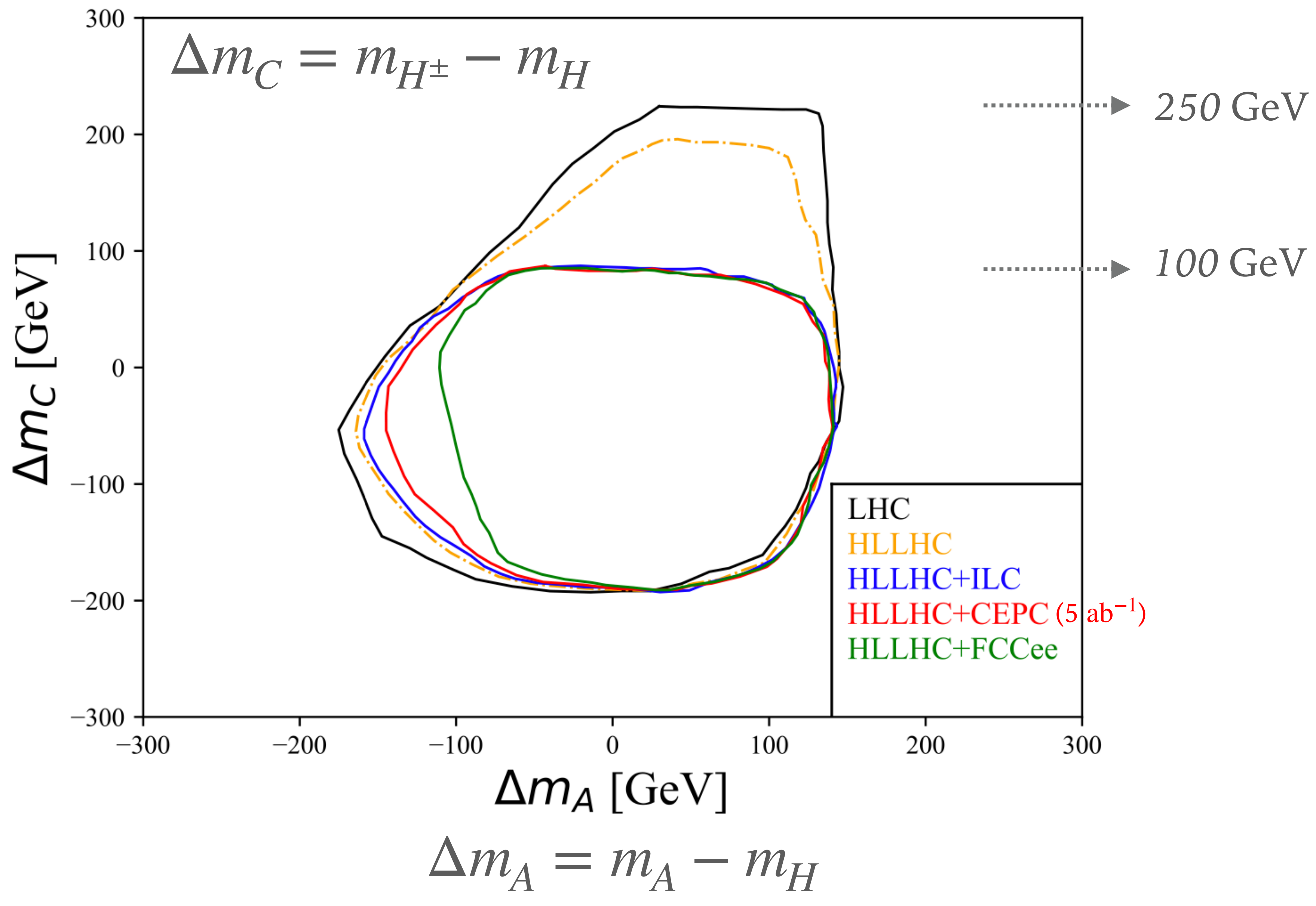
Global fits of 2HDM

A.Beniwal, F. Rajec, M. T. Prim, P. Scott, W. Su, M. White, A. G. Williams and A. Woodcock, arXiv:2203.07883

- Preliminary results of the type- II 2HDM with GAMBIT
- Theoretical constraints, Higgs searches, EW physics and flavour constraints







- There are strong constraints on the mass splittings from Higgs and Z-pole precision measurements.

Global SMEFT Fits

From 顾嘉荫's slides at the CEPC Shanghai workshop

- Under the hypothesis that new physics has a high mass scale, the new fields of any particular model can be integrated out, producing an effective Lagrangian.
- Assuming Baryon and Lepton numbers are conserved,

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots .$$

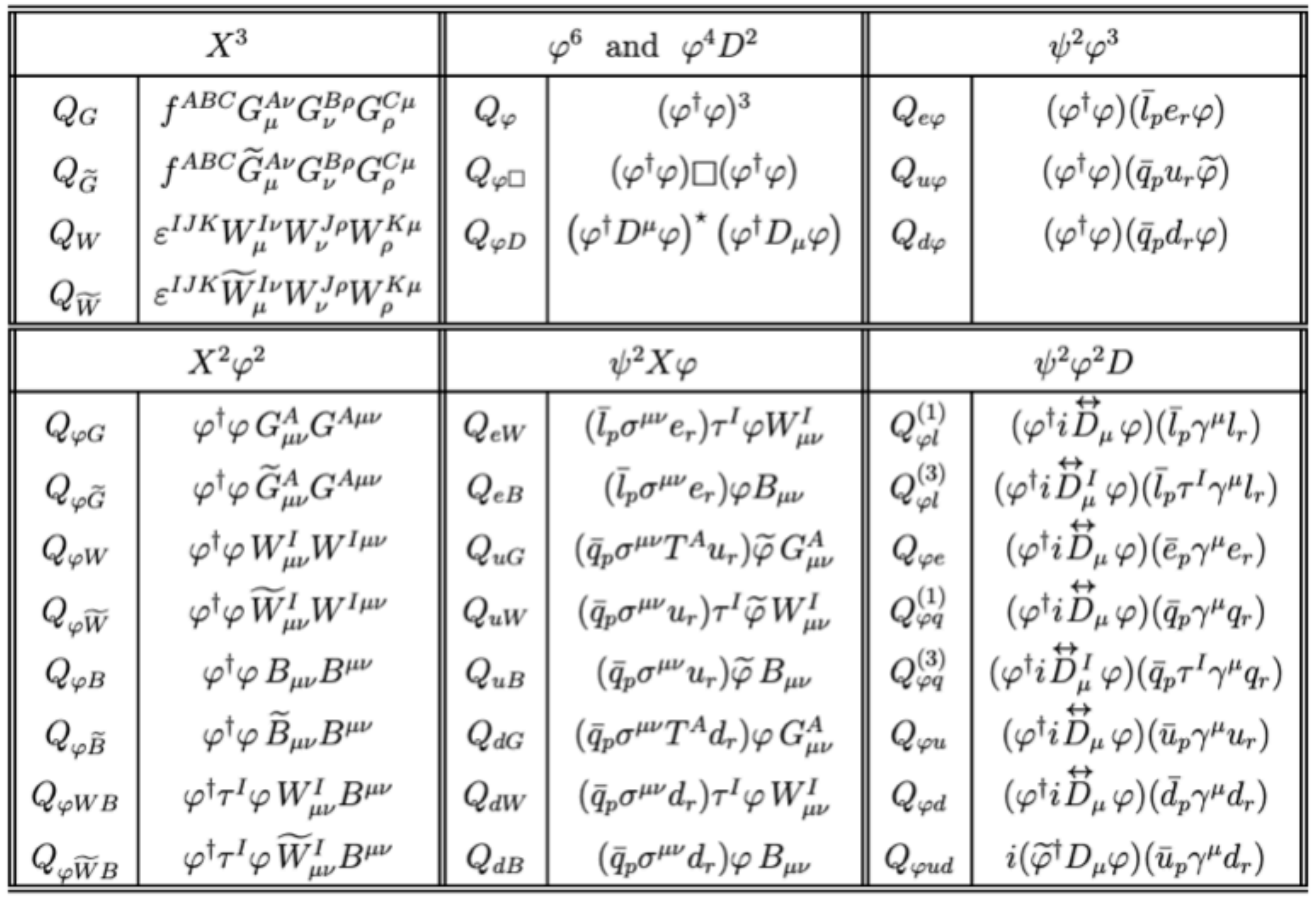
- If $\Lambda \gg v$, then SM + dimension-6 operators are sufficient to parameterize the physics around the electroweak scale.
- Standard Model Effective Field Theory provides a good model-independent framework to study the physics potential of the CEPC.

Global SMEFT Fits

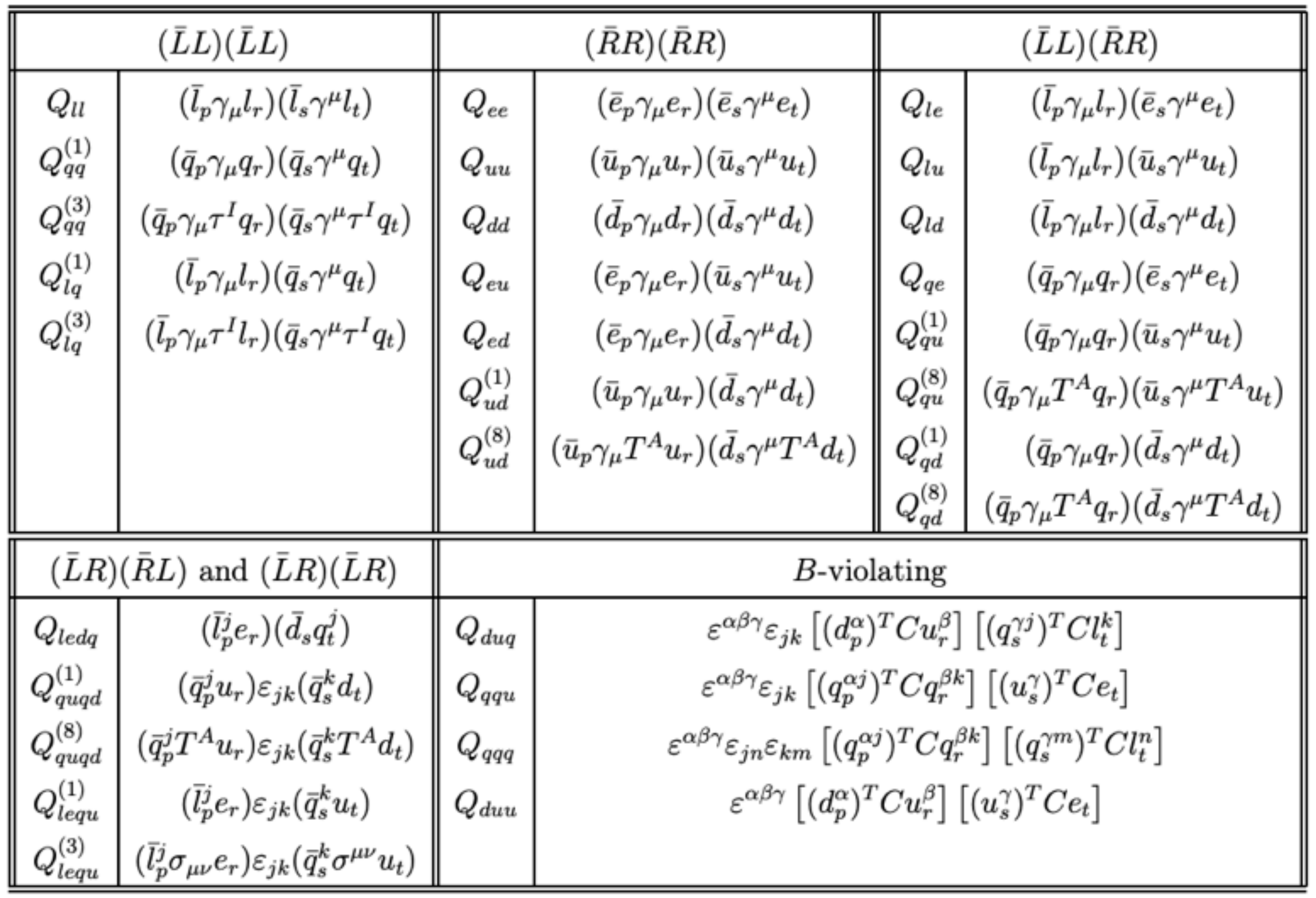
Provided by 杜勇

Operators in the Warsaw basis:

Buchmuller and Wyler, Nucl.Phys.B 268 (1986) 621
Grzadkowski, Iskrzynski, Misiak and Rosiek, JHEP 10 (2010) 085



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger \varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger \varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger \varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) \varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$



$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

59 operators (+ 4 B-violating ones)

2499 operators: 1350 (CP-even) + 1149 (CP-odd)

No flavor assumptions are made.

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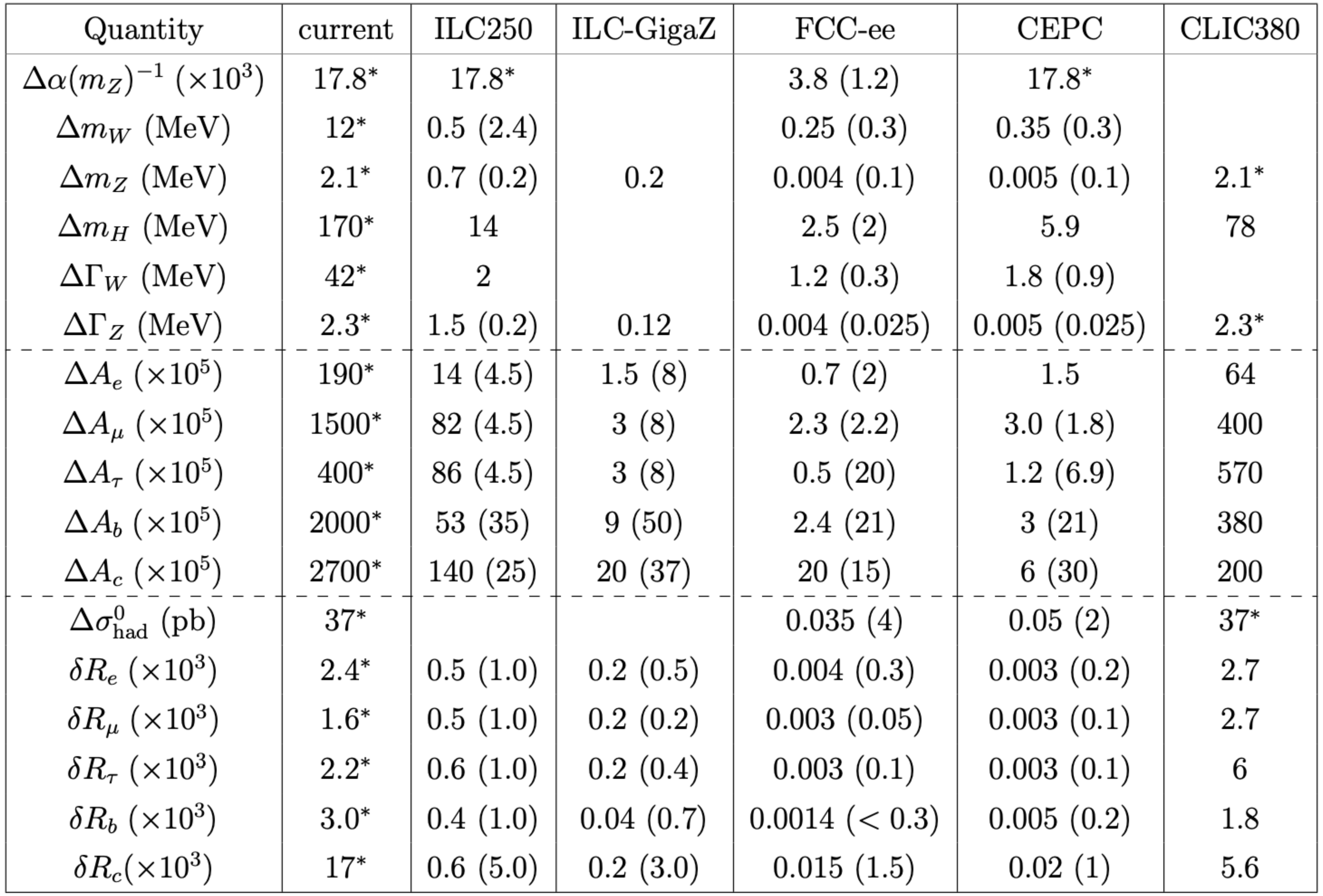

Quantity	current	ILC250	ILC-GigaZ	FCC-ee	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	17.8*	17.8*		3.8 (1.2)	17.8*	
Δm_W (MeV)	12*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1*
Δm_H (MeV)	170*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3*
ΔA_e ($\times 10^5$)	190*	14 (4.5)	1.5 (8)	0.7 (2)	1.5	64
ΔA_μ ($\times 10^5$)	1500*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	400
ΔA_τ ($\times 10^5$)	400*	86 (4.5)	3 (8)	0.5 (20)	1.2 (6.9)	570
ΔA_b ($\times 10^5$)	2000*	53 (35)	9 (50)	2.4 (21)	3 (21)	380
ΔA_c ($\times 10^5$)	2700*	140 (25)	20 (37)	20 (15)	6 (30)	200
$\Delta\sigma^0_{\text{had}}$ (pb)	37*			0.035 (4)	0.05 (2)	37*
δR_e ($\times 10^3$)	2.4*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.7
δR_μ ($\times 10^3$)	1.6*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.7
δR_τ ($\times 10^3$)	2.2*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	6
δR_b ($\times 10^3$)	3.0*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.8
δR_c($\times 10^3$)	17*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	5.6

Recent improvement after Snowmass2021 deadline not implemented.

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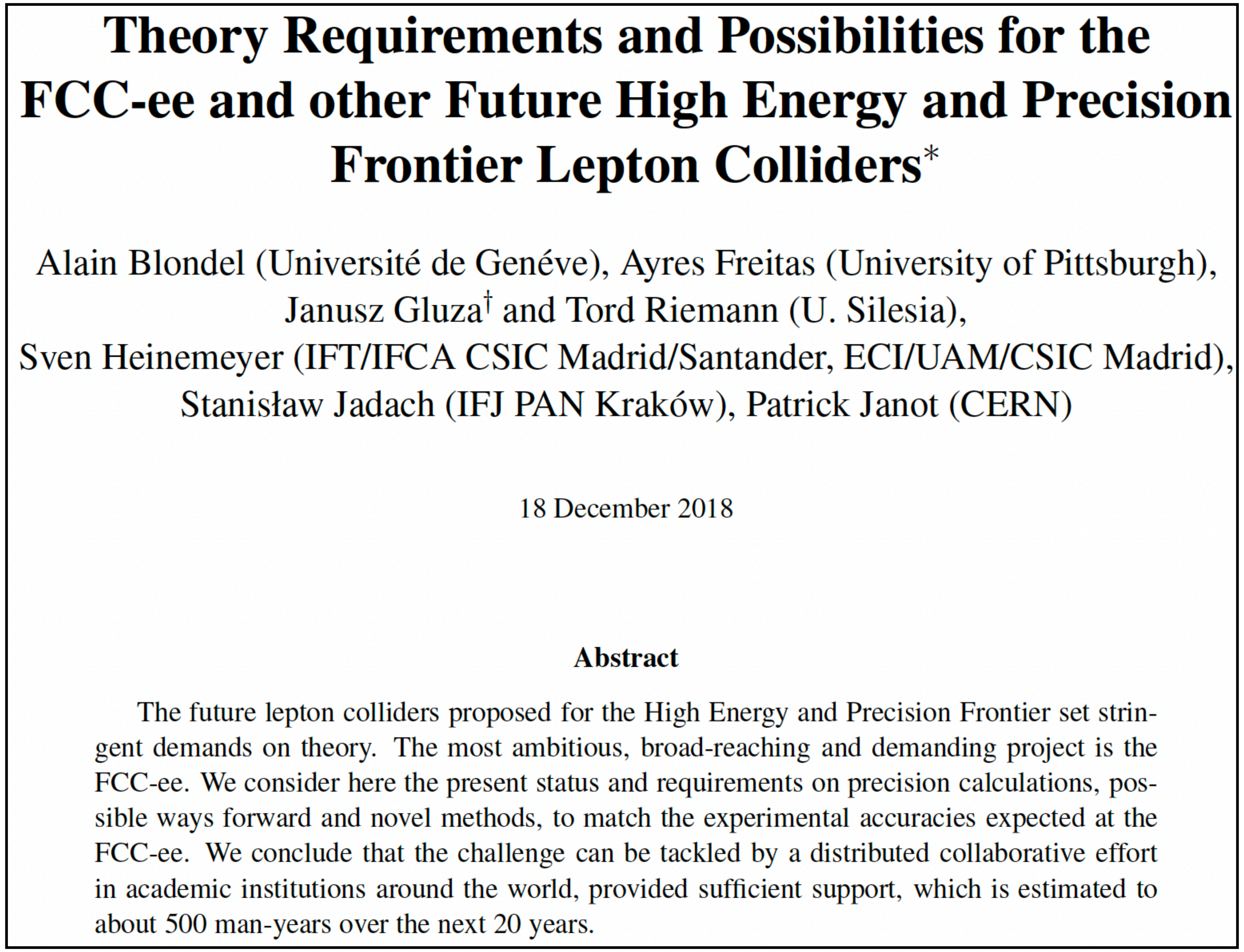

Theory Requirements and Possibilities for the FCC-ee and other Future High Energy and Precision Frontier Lepton Colliders*

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Janusz Gluza† and Tord Riemann (U. Silesia),
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18 December 2018

Abstract

The future lepton colliders proposed for the High Energy and Precision Frontier set stringent demands on theory. The most ambitious, broad-reaching and demanding project is the FCC-ee. We consider here the present status and requirements on precision calculations, possible ways forward and novel methods, to match the experimental accuracies expected at the FCC-ee. We conclude that the challenge can be tackled by a distributed collaborative effort in academic institutions around the world, provided sufficient support, which is estimated to about 500 man-years over the next 20 years.

Theoretical uncertainties are yet to be reduced, which are computationally expensive and considered as well under control by the operation time and thus neglected in the global fit.

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Presenting the results will be basis dependent. We choose to work in the Higgs basis to disentangle physics in different sectors

$$
\begin{aligned}
\mathcal{L} \supset\; & e A^{\mu} \sum_{f=u,d,e} Q_f \left(\bar{f}_I \bar{\sigma}_\mu f_I + f_I^c \sigma_\mu \bar{f}_I^c\right) \\
& + \frac{g_L}{\sqrt{2}} \left[W^{\mu+} \bar{\nu}_I \bar{\sigma}_\mu \left(\delta_{IJ} + [\delta g_L^{W\ell}]_{IJ}\right) e_J + W^{\mu+} \bar{u}_I \bar{\sigma}_\mu \left(V_{IJ} + \left[\delta g_L^{Wq}\right]_{IJ} \right) d_J + \text{h.c.} \right] \\
& + \frac{g_L}{\sqrt{2}} \left[W^{\mu+} u_I^c \sigma_\mu \left[\delta g_R^{Wq}\right]_{IJ} \bar{d}_J^c + \text{h.c.} \right] \\
& + \sqrt{g_L^2 + g_Y^2}\, Z^{\mu} \sum_{f=u,d,e,\nu} \bar{f}_I \bar{\sigma}_\mu \left((T_3^f - s_w^2 Q_f)\delta_{IJ} + \left[\delta g_L^{Zf}\right]_{IJ} \right) f_J \\
& + \sqrt{g_L^2 + g_Y^2}\, Z^{\mu} \sum_{f=u,d,e} f_I^c \sigma_\mu \left(-s_w^2 Q_f \delta_{IJ} + \left[\delta g_R^{Zf}\right]_{IJ} \right) \bar{f}_J^c,
\end{aligned}
$$

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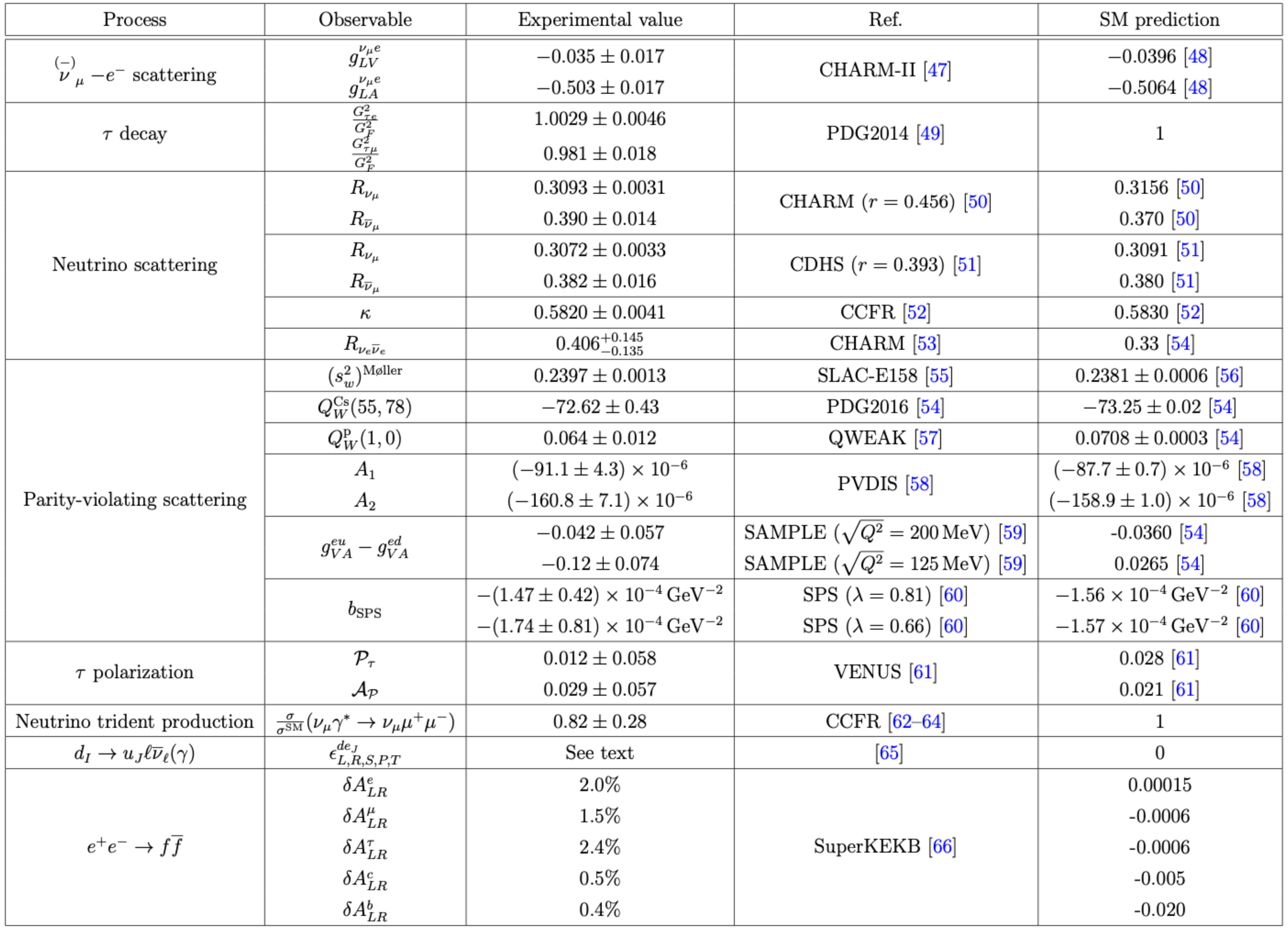
Without any flavor assumption, many flat directions exist. Low-energy observables are thus included, and we focus on the complementarity in the following slides.



Process	Observable	Experimental value	Ref.	SM prediction
$\overset{(-)}{\nu}_\mu - e^-$ scattering	$g_{LV}^{\nu_\mu e}$	-0.035 ± 0.017	CHARM-II [47]	-0.0396 [48]
	$g_{LA}^{\nu_\mu e}$	-0.503 ± 0.017		-0.5064 [48]
τ decay	$\frac{G_{\tau e}^2}{G_F^2}$	1.0029 ± 0.0046	PDG2014 [49]	1
	$\frac{G_{\tau\mu}^2}{G_F^2}$	0.981 ± 0.018		
Neutrino scattering	R_{ν_μ}	0.3093 ± 0.0031	CHARM ($r = 0.456$) [50]	0.3156 [50]
	$R_{\overline{\nu}_\mu}$	0.390 ± 0.014		0.370 [50]
	R_{ν_μ}	0.3072 ± 0.0033	CDHS ($r = 0.393$) [51]	0.3091 [51]
	$R_{\overline{\nu}_\mu}$	0.382 ± 0.016		0.380 [51]
	κ	0.5820 ± 0.0041	CCFR [52]	0.5830 [52]
	$R_{\nu_e\overline{\nu}_e}$	$0.406^{+0.145}_{-0.135}$	CHARM [53]	0.33 [54]
Parity-violating scattering	$(s_w^2)^{\text{Møller}}$	0.2397 ± 0.0013	SLAC-E158 [55]	0.2381 ± 0.0006 [56]
	$Q_W^{\text{Cs}}(55, 78)$	-72.62 ± 0.43	PDG2016 [54]	-73.25 ± 0.02 [54]
	$Q_W^{\text{p}}(1, 0)$	0.064 ± 0.012	QWEAK [57]	0.0708 ± 0.0003 [54]
	A_1	$(-91.1 \pm 4.3) \times 10^{-6}$	PVDIS [58]	$(-87.7 \pm 0.7) \times 10^{-6}$ [58]
	A_2	$(-160.8 \pm 7.1) \times 10^{-6}$		$(-158.9 \pm 1.0) \times 10^{-6}$ [58]
	$g_{VA}^{eu} - g_{VA}^{ed}$	-0.042 ± 0.057	SAMPLE ($\sqrt{Q^2} = 200$ MeV) [59]	-0.0360 [54]
		-0.12 ± 0.074	SAMPLE ($\sqrt{Q^2} = 125$ MeV) [59]	0.0265 [54]
	b_{SPS}	$-(1.47 \pm 0.42) \times 10^{-4}\,\text{GeV}^{-2}$	SPS ($\lambda = 0.81$) [60]	$-1.56 \times 10^{-4}\,\text{GeV}^{-2}$ [60]
		$-(1.74 \pm 0.81) \times 10^{-4}\,\text{GeV}^{-2}$	SPS ($\lambda = 0.66$) [60]	$-1.57 \times 10^{-4}\,\text{GeV}^{-2}$ [60]
τ polarization	$\mathcal{P}_\tau$	0.012 ± 0.058	VENUS [61]	0.028 [61]
	$\mathcal{A}_\mathcal{P}$	0.029 ± 0.057		0.021 [61]
Neutrino trident production	$\frac{\sigma}{\sigma^{\text{SM}}}(\nu_\mu\gamma^* \to \nu_\mu\mu^+\mu^-)$	0.82 ± 0.28	CCFR [62–64]	1
$d_I \to u_J \ell \overline{\nu}_\ell(\gamma)$	$\epsilon_{L,R,S,P,T}^{de_J}$	See text	[65]	0
$e^+e^- \to f\overline{f}$	δA_{LR}^e	2.0%	SuperKEKB [66]	0.00015
	δA_{LR}^μ	1.5%		-0.0006
	δA_{LR}^τ	2.4%		-0.0006
	δA_{LR}^c	0.5%		-0.005
	δA_{LR}^b	0.4%		-0.020

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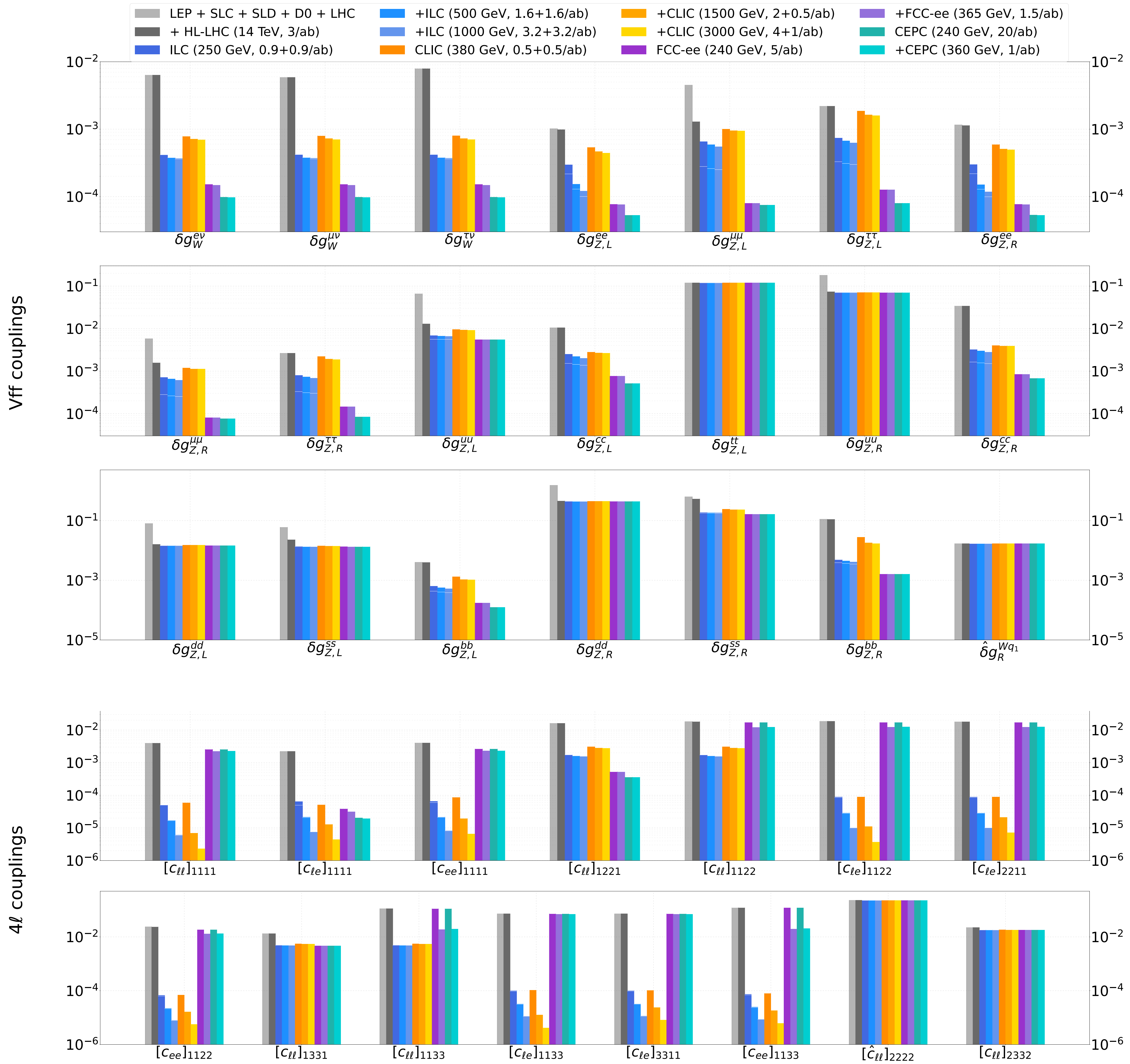
- ➢ Unprecedented precision reached at the FCCee machine (same for Higgs couplings)
- ➢ Still much room left for new physics generating large 1st and 2nd (could be improved with σ_s and A_{FB}^{s}) generation $Zq\bar{q}$ couplings (possible tagging improvement with the help of AI (Chai, Gu, Li, 2401.02474 for example)?)
- ➢ Also much room left for 4-fermion operators at FCC-ee or CEPC (same for top, see backup), mainly due to the difficulty in telling the right from the left.
- ➢ Merging data from neutrino experiments (e.g. CEvNS) can also make a difference.
- ➢ Polarized option of CEPC? (CEPC TDR: 2312.14363)



Global SMEFT Fits — CPV

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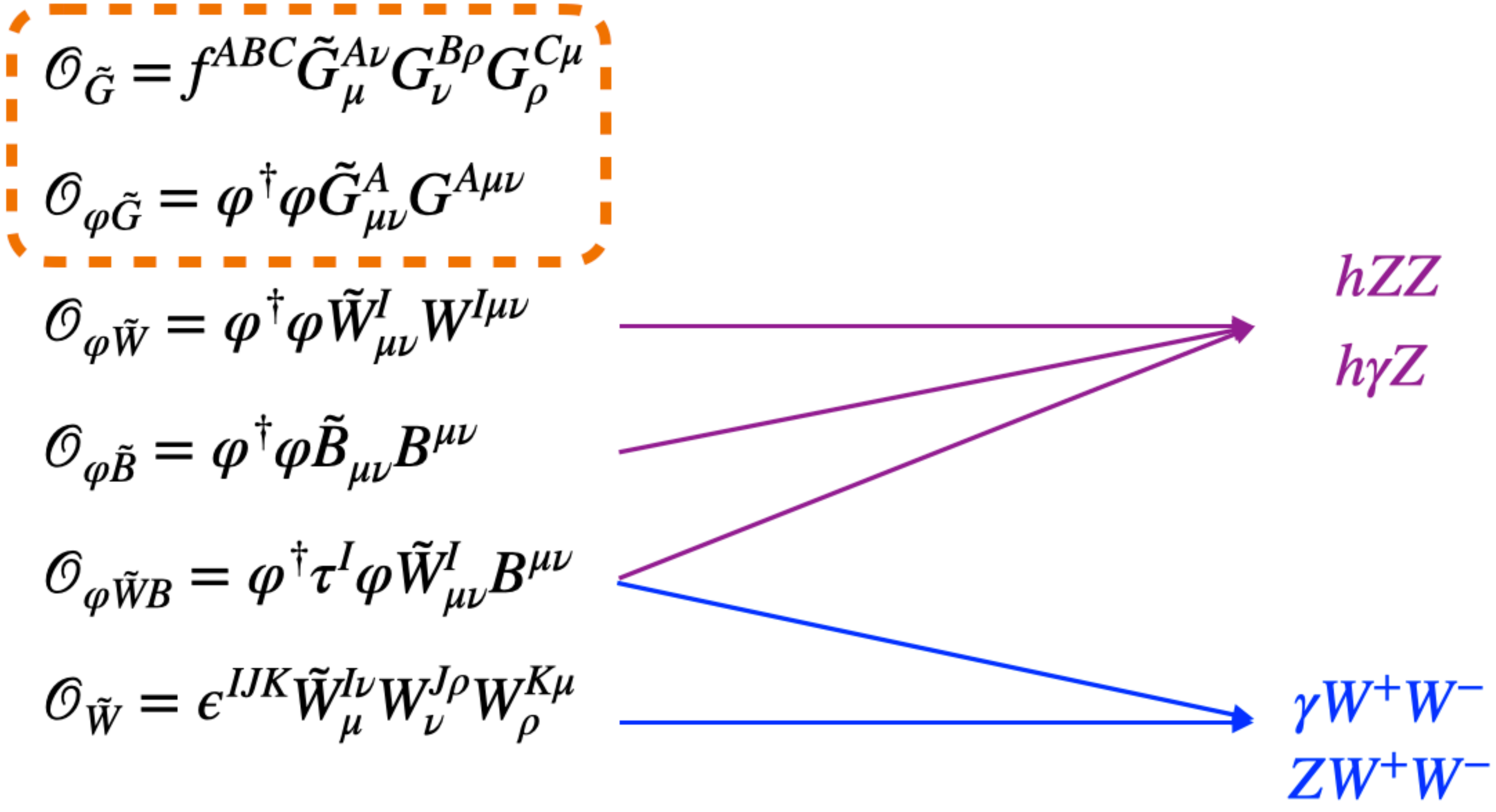

$$\mathcal{O}_{\tilde{G}} = f^{ABC}\tilde{G}_{\mu}^{A\nu}G_{\nu}^{B\rho}G_{\rho}^{C\mu}$$

$$\mathcal{O}_{\varphi\tilde{G}} = \varphi^{\dagger}\varphi\tilde{G}_{\mu\nu}^{A}G^{A\mu\nu}$$

$$\mathcal{O}_{\varphi\tilde{W}} = \varphi^{\dagger}\varphi\tilde{W}_{\mu\nu}^{I}W^{I\mu\nu}$$

$$\mathcal{O}_{\varphi\tilde{B}} = \varphi^{\dagger}\varphi\tilde{B}_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{O}_{\varphi\tilde{W}B} = \varphi^{\dagger}\tau^{I}\varphi\tilde{W}_{\mu\nu}^{I}B^{\mu\nu}$$

$$\mathcal{O}_{\tilde{W}} = \epsilon^{IJK}\tilde{W}_{\mu}^{I\nu}W_{\nu}^{J\rho}W_{\rho}^{K\mu}$$

hZZ

$h\gamma Z$

γW^+W^-

ZW^+W^-

(Statistically limited at OPAL)

CEPC is well suited for both Zh and W^+W^- studies!

Also helps V_{cb} extraction by running at the W^+W^- threshold.

Global SMEFT Fits — CPV

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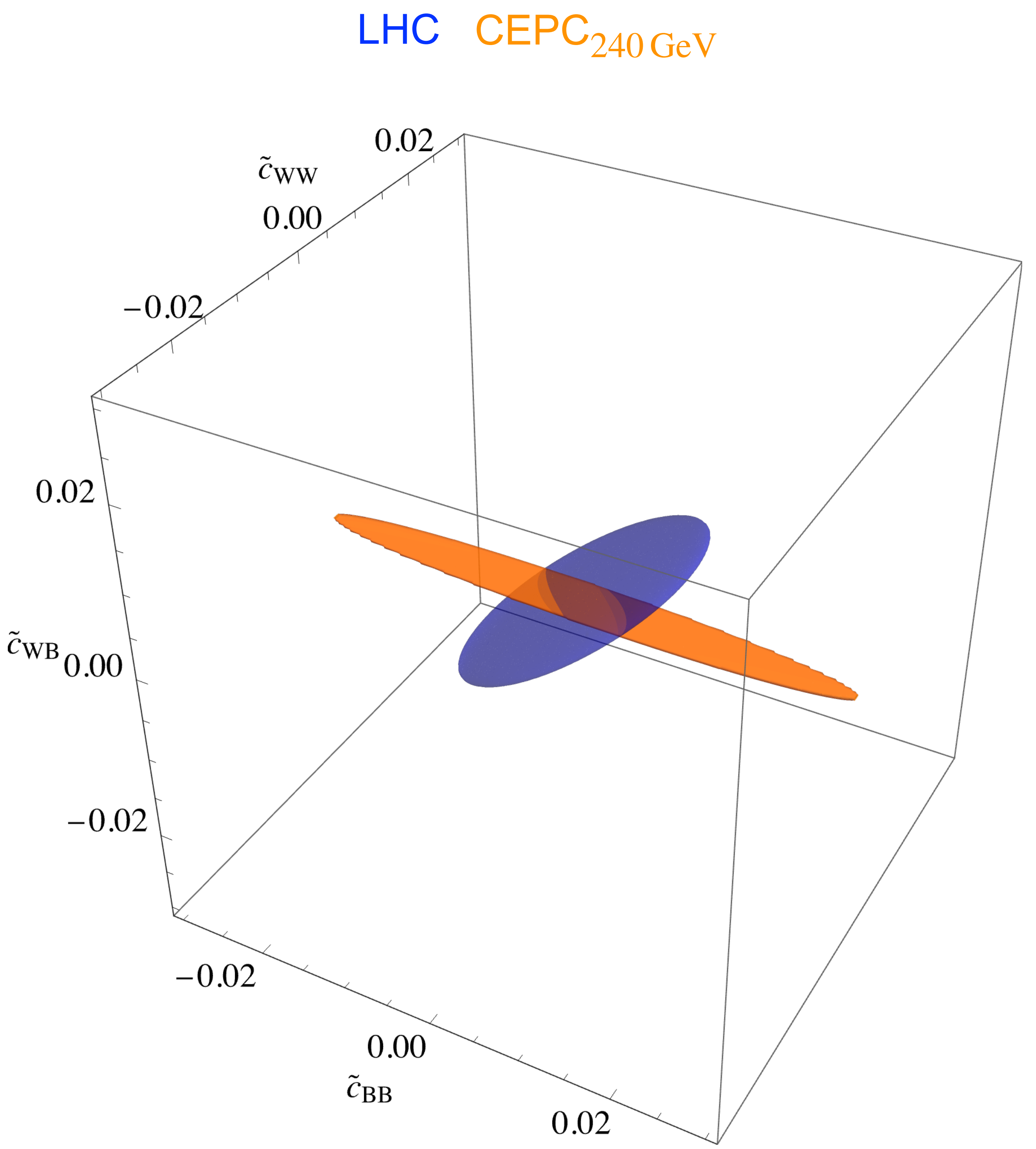
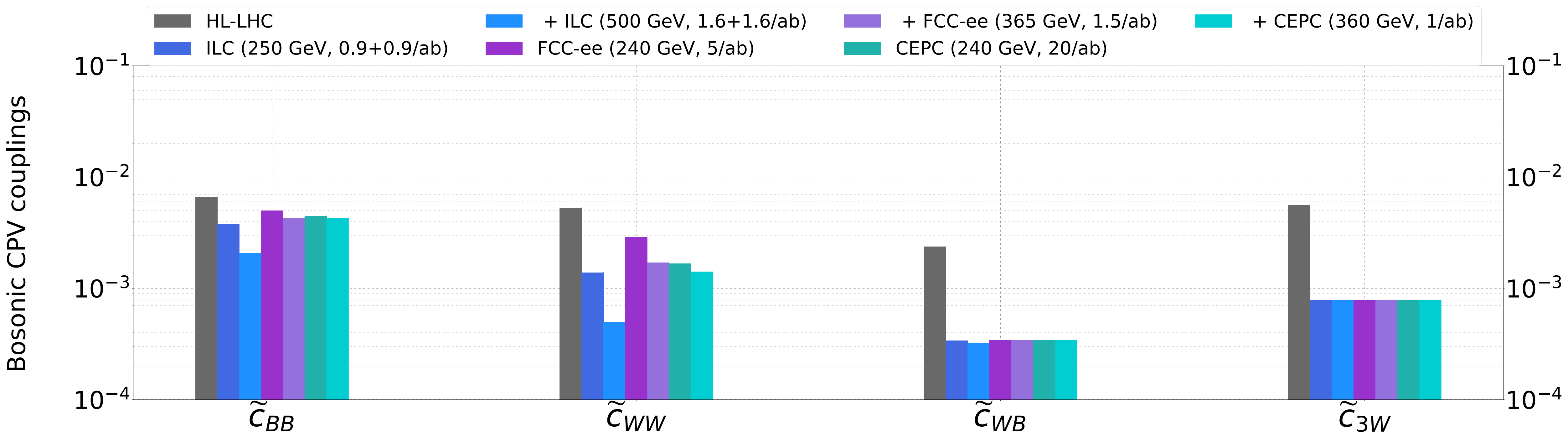
Using angular asymmetries of Zh and aTGC measurements for W^+W^-, the CPV parameters can be extracted, for which we use the optimal observable approach (see backup) to improve the sensitivity





Per-mille level precision reach

Global SMEFT Fits

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- CEPC is an ideal precision machine for new physics studies, as studied model-independently within the SMEFT framework.

  - Unprecedented precision reach for Higgs and EW physics (except 1st gen quarks)

  - New direction probe of CEPC for bosonic CPV operators, complementary to the LHC.

  - Significant improvement on parameter space for specific models (such as leptoquark)

  - Sensitivity reach increase with beam polarization at CEPC? How well in polar. control?

Thank you!

Yang Zhang