Global fits of UV complete models in future e^+e^- colliders

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Outline

UV vs EFT

UV vs EFT

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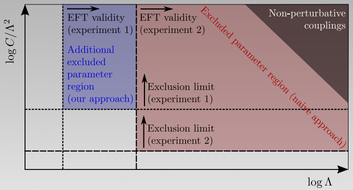
- EFTs are better at quantified deviations from SM
  - → What happens when a deviation is measured? (e.g. $\mathcal{C}_{9,10}$)
  - → How to reconstruct a UV model from the EFT? ⇝ Ricardo's talk
- Not all UV models correspond to an EFTs (e.g. decays to dark sectors)
- Issues with EFT validity

$$\mathcal{L}_{\rm EFT} = \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)}$$

  - → Misisng low Λ in weakly coupled
  - → Redundant dependency on $\mathcal{C}$ & Λ
  - → Inclear clear cutoffs ($m_{\chi\chi} < \Lambda$)



[GAMBIT, Eur.Phys.J.C 81 (2021) 11, 992]

- UV complete models are valid at many energy scales, they can be tested by colliders, precision experiments, astrophysical and cosmological observatories

Global fits

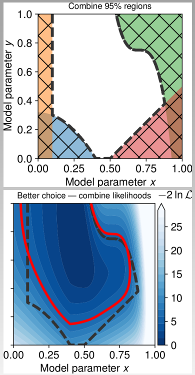
[GAMBIT, MasterCode, Fittino, HEPfit et al, Rept.Prog.Phys. 85 (2022) 5, 052201]

Global fits

- Combine all constraints into a composite likelihood (e.g. existing LHC searches with e^+e^- Higgs measurements)

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

- Perform an extensive parameter scan
  - → Old-school sampling methods (random, grid) are inefficient
  - → Harder to make statement about statistics
  - → Need smart sampling strategies (differential, nested, genetic,. . .)
- Rigorous statistical interpretation (frequentist/Bayesian)
  - → Goodness-of-fit
  - → Parameter estimation
  - → Model comparison
- BSM global fitting tools (GAMBIT, HEPFit,...)



[arXiv:2012.09874 [hep-ph]]

Global fits

GAMBIT: The Global And Modular BSM Inference Tool

gambit.hepforge.org   github.com/GambitBSM   EPJC 77 (2017) 784   arXiv:1705.07908

- Extensive model database, beyond SUSY
- Fast definition of new datasets, theories
- Extensive observable/data libraries
- Plug&play scanning/physics/likelihood packages
- Various statistical options (frequentist /Bayesian)
- Fast LHC likelihood calculator
- Massively parallel
- Fully open-source

Members of: ATLAS, Belle-II, CLiC, CMS, CTA, Fermi-LAT, DARWIN, IceCube, LHCb, SHiP, XENON

Authors of: BubbleProfiler, Capt'n General, Contur, DarkAges, DarkSUSY, DDCalc, DirectDM, Diver, EasyScanHEP, ExoCLASS, FlexibleSUSY, gamLike, GM2Calc, HEPLike, IsaTools, MARTY, nuLike, PhaseTracer, PolyChord, Rivet, SOFTSUSY, Superlso, SUSY-AI, xsec, Vevacious, WIMPSim

Recent collaborators: P Athron, C Balázs, A Beniwal, S Bloor, T Bringmann, A Buckley, J-E Camargo-Molina, C Chang, M Chrzaszcz, J Conrad, J Cornell, M Danninger, J Edsjö, T Emken, A Fowlie, T Gonzalo, W Handley, J Harz, S Hoof, F Kahlhoefer, A Kvellestad, P Jackson, D Jacob, C Lin, N Mahmoudi, G Martinez, MT Prim, A Raklev, C Rogan, R Ruiz, P Scott, N Serra, P Stöcker , W. Su, A Vincent, C Weniger, M White, Y Zhang, ++

70+ participants in many experiments and numerous major theory codes

Supersymmetric models

[GAMBIT, Eur.Phys.J.C 77 (2017) 12, 824, Eur.Phys.J.C 77 (2017) 12, 879]

[P. Athron et al, Phys.Rev.D 105 (2022) 11, 115029]

SUSY

- Most "current" global fit results for CMSSM, NUHM1 and MSSM7

→ LHC searches

→ Higgs measurements

→ Flavour constraints

→ Relic Density

→ DM direct and indirect detection

→ EW precision measurements

- Future e^+e^- colliders can improve Higgs measurements $e^+e^- \to hZ$

$$\mathcal{L}_{\text{Higgs}} = -\frac{(\sigma_{hZ} - \sigma_{hZ}^{\text{obs}})^2}{2\sigma_{\sigma_{hZ}}^2} - \sum_i \frac{(\mu_i - \mu_i^{\text{obs}})^2}{2\sigma_{\mu_i}}, \quad \mu_i = \frac{(\sigma BR)_i}{(\sigma BR)_i^{\text{SM}}}$$

- Can also perform very precise measurements of EW observables

$$\mathcal{L}_{\text{EW}} = -\frac{(m_t - m_t^{\text{obs}})^2}{2\sigma_{m_t}^2} - \frac{(\alpha_s - \alpha_s^{\text{obs}})^2}{2\sigma_{\alpha_s}} - \frac{(m_W - m_W^{\text{obs}})^2}{2\sigma_{m_W}^2} - \frac{(\sin^2\theta_W - \sin^2\theta_W^{\text{obs}})^2}{2\sigma_{\sin^2\theta_W}}$$

- Central values x^{obs} are taken as those predicted by best fit point

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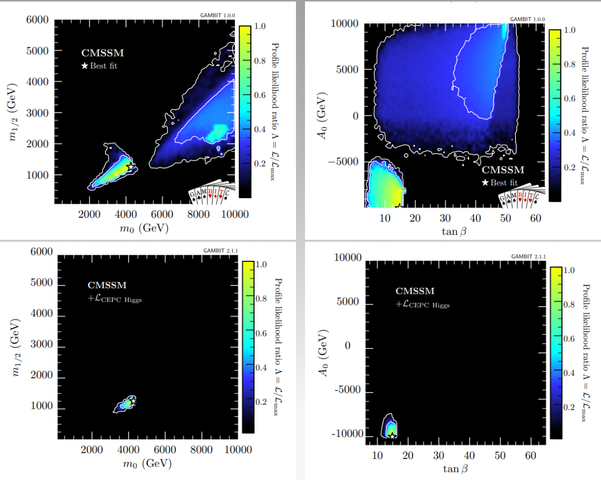
- Estimated precisions for Higgs measurements and EW observables

	ILC 250 GeV 2 ab^{-1}	ILC 350 GeV 200 fb^{-1}		ILC 500 GeV 4 ab^{-1}		FCC-*ee* 240 GeV 5 ab^{-1}	FCC-*ee* 365 GeV 1.5 ab^{-1}		CEPC 240 GeV 20 ab^{-1}	CEPC 360 GeV 1 ab^{-1}	
σ_{Zh}	0.71%	2.0%		1.05%		0.5%	0.9%		0.26%	1.4%	
Decay mode	σ_{Zh}Br	σ_{Zh}Br	$\sigma_{\nu\bar{\nu}h}$Br	σ_{Zh}Br	$\sigma_{\nu\bar{\nu}h}$Br	σ_{Zh}Br	σ_{Zh}Br	$\sigma_{\nu\bar{\nu}h}$Br	σ_{Zh}Br	σ_{Zh}Br	$\sigma_{\nu\bar{\nu}h}$Br
$h \to b\bar{b}$	0.46%	1.7%	2.0%	0.63%	0.23%	0.3%	0.5%	0.9%	0.14%	0.9%	1.1%
$h \to c\bar{c}$	2.9%	12.3%	21.2%	4.5%	2.2%	2.2%	6.5%	10%	2.02%	8.8%	16%
$h \to gg$	2.5%	9.4%	8.6%	3.8%	1.5%	1.9%	3.5%	4.5%	0.81%	3.4%	4.5%
$h \to WW^*$	1.6%	6.3%	6.4%	1.9%	0.85%	1.2%	2.6%	3.0%	0.53%	2.8%	4.4%
$h \to \tau^+\tau^-$	1.1%	4.5%	17.9%	1.5%	2.5%	0.9%	1.8%	8.0%	0.42%	2.1%	4.2%
$h \to ZZ^*$	6.4%	28.0%	22.4%	8.8%	3.0%	4.4%	12%	10%	4.17%	20%	21%
$h \to \gamma\gamma$	12.0%	43.6%	50.3%	12.0%	6.8%	9.0%	18%	22%	3.02%	11%	16%
$h \to \mu^+\mu^-$	25.5%	97.3%	178.9%	30.0%	25.0%	19%	40%	-	6.36%	41%	57%
$(\nu\bar{\nu})h \to b\bar{b}$	3.7%	-	-	-	-	3.1%	-	-	1.58%	-	-

	CMSSM BF point	Present central value	Precision ILC	Precision FCC-*ee*	Precision CEPC
m_Z	91.1876 GeV	91.1876 GeV	2.1 MeV	0.1 MeV	0.5 MeV
m_t	173.267 GeV	173.34 GeV	0.03 GeV	0.6 GeV	0.6 GeV
$\alpha_s^{\overline{\rm MS}}(m_Z)$	0.11862	0.1185	1.0×10^{-4}	1.0×10^{-4}	1.0×10^{-4}
m_W	80.3786 GeV	80.385 GeV	5 MeV	8 MeV	3 MeV
$\sin^2\theta_W$	0.231424	0.23155	1.3×10^{-5}	0.3×10^{-5}	4.6×10^{-5}

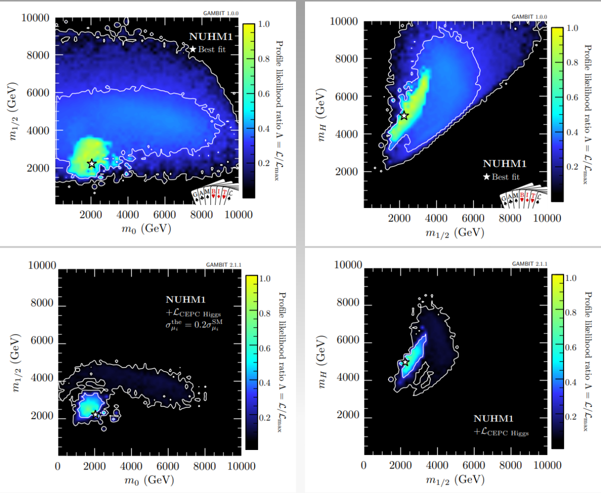
SUSY

- CMSSM $\{m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)\}$



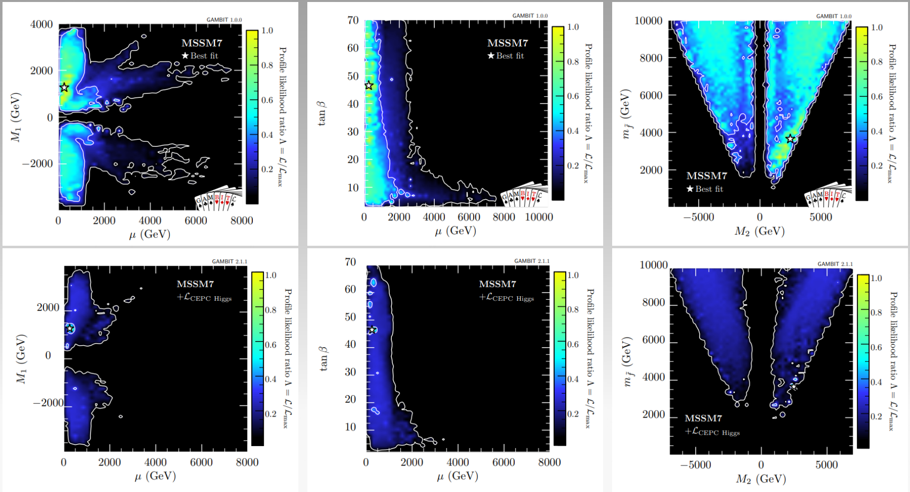
SUSY

- NUHM1 $\{m_0, m_H, m_{1/2}, A_0, \tan\beta, \mathrm{sign}(\mu)\}$



SUSY

- MSSM7 $\{M_2, A_t, A_b, m^2_{\tilde{f}}, m^2_{H_u}, m^2_{H_d}, \tan\beta, \text{sign}(\mu)\}$



THDM

[GAMBIT, *in preparation*]

[A. Beniwal et al, 2203.07883 [hep-ph]]

THDM

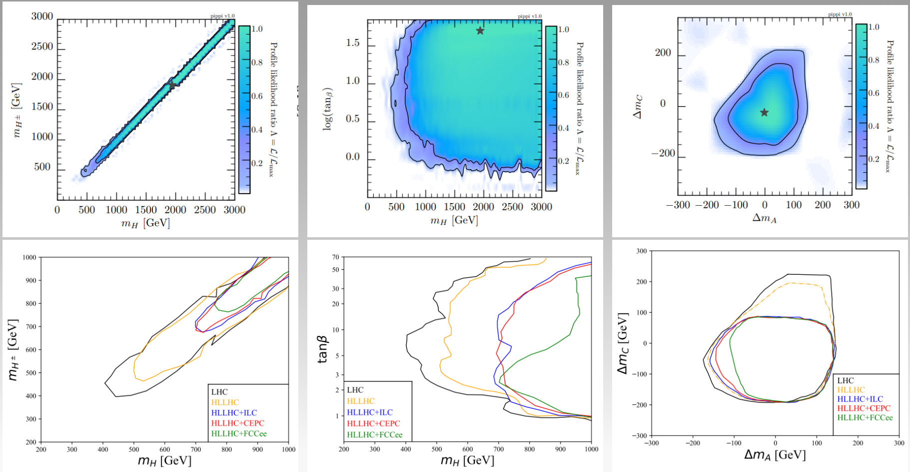
- Type II Two Higgs doublet model in preparation with
  - → Theoretical constraints
  - → EW precision measurements
  - → Higgs measurements
  - → Flavour constraints
- Future e^+e^- colliders can improve Higgs measurements $e^+e^- \to hZ$
- EW precision corrections are codified in oblique parameters S, T, U

	Current (1.7×10^7 Z's)				CEPC ($10^{10} Z$'s)				FCC-ee ($7 \times 10^{11} Z$'s)				ILC ($10^9 Z$'s)			
	σ	correlation			σ	correlation			σ	correlation			σ	correlation		
		S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U
S	0.04 ± 0.11	1	0.92	-0.68	2.46	1	0.862	-0.373	0.67	1	0.812	0.001	3.53	1	0.988	-0.879
T	0.09 ± 0.14	–	1	-0.87	2.55	–	1	-0.735	0.53	–	1	-0.097	4.89	–	1	-0.909
U	-0.02 ± 0.11	–	–	1	2.08	–	–	1	2.40	–	–	1	3.76	–	–	1

$$\mathcal{L}_{\text{Future}} = -\sum_i \frac{(\mu_i - \mu_i^{\text{obs}})^2}{2\sigma_{\mu_i}^2} - \sum_{ij} (X_i - X_i^{\text{obs}})(\sigma^2)^{-1}_{ij}(X_j - X_j^{\text{obs}})$$

- Central values are set to null hypthesis $\mu_i^{\text{obs}} = 1$, $X_i^{\text{obs}} = 0$

THDM



$m_{H^\pm}$ [GeV]
m_H [GeV]
$\log(\tan_\beta)$
Δm_C
Δm_A
Profile likelihood ratio $\Lambda = \mathcal{L}/\mathcal{L}_{max}$
pippi v1.0
$\tan\beta$
Δm_C [GeV]
Δm_A [GeV]
LHC
HLLHC
HLLHC+ILC
HLLHC+CEPC
HLLHC+FCCee

Heavy Neutral Leptons

[M. Chrzaszcz, M. Drewes, T.G, et al, Eur.Phys.J.C 80 (2020) 6, 569]

[M. Drewes, T.G et al, *in preparation*]

Heavy Neutral Leptons

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- Heavy neutrinos in $\mathcal{O}(100)$ MeV - $\mathcal{O}(10)$ GeV scale

→ Direct searches	→ Oscillations
→ Lepton flavour violation	→ CKM unitarity
→ Lepton universality	→ EW precision observables

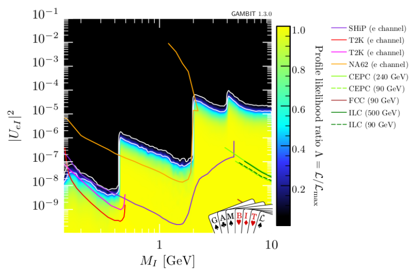
- Current collider searches look at $pp \to W* \to lN$
- Future e^+e^- colliders running at the Z pole can look at $e^+e^- \to Z \to \nu N$

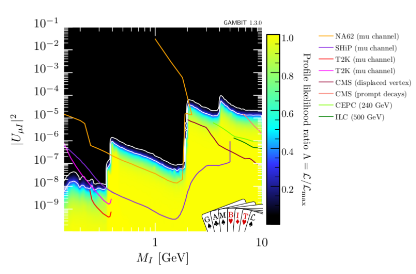
$$BR(Z \to \nu N) = \frac{2}{3}|U_N|^2 BR(Z \to \text{inv}) \left(1 + \frac{m_N^2}{2m_Z^2}\right)\left(1 - \frac{m_N^2}{m_Z^2}\right)$$

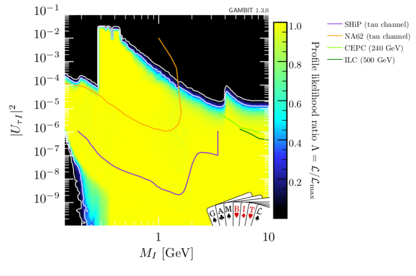
- Subsequent EW decays of N at displaced vertices

$$N_{\text{obs}} \propto L|U_N|^4 M^5$$

Heavy Neutral Leptons







Summary and Conclusions

- UV models are often more suitable candidates than EFT models
  - → UV mapping, EFT validity, applicability of constraints,...
- Global fits are the best solution to explore UV models
  - → Multidisciplinary constraints, smart sampling, existing tools
- Higgs and EW measurements from e^+e^- colliders can signficantly reduce the available parameter space in SUSY and THDM models
  - → CMSSM and NUMH1 almost "excluded" with precision Higgs physics
  - → Strong preference for wino/higgsino-like scenarios in MSSM7
  - → Strong constraints on Higgs masses and splittings in THDM
- Displaced vertex searches very critical in e^+e^- colliders
  - → Searches for HNLs can probe low couplings $|U|^2 \gtrsim 10^{-8} - 10^{-10}$
- Future e^+e^- colliders working at the Higgs and Z poles can be critical to exclude or constrained UV models
- Global fits are fundamental to combine those constraints with new physics searches and other constraints