Synergies: Theory Overview

2nd Annual US FCC Workshop at MIT
March 25th 2024

Matthew McCullough
CERN

or…

Status and Plans for Theory Studies of the FCC Physics Programme

2nd Annual US FCC Workshop at MIT

March 25th 2024

Matthew McCullough

CERN

FCC Physics

Physics Programme
McCullough & Simon

Physics Performance
Azzi, Perez & Selvaggi

Higgs/EW/Top

Conveners

Performance	**Programme**
M. Selvaggi, J. Eysermans	C. Grojean, G. Durieux, J. de Blas

Programme Status

We now have a clear picture for the FCC landscape in terms of Higgs/EW/Top measurements.

Higgs/EW/Top

Highlights: 6’000’000’000’000 Clean Z-Bosons

…a quantum leap in our understanding of electroweak physics…

Observable	Present value	±	error	FCC-ee (statistical)	FCC-ee (systematic)
m_Z (keV/c^2)	91 186 700	±	2200	5	100
Γ_Z (keV)	2 495 200	±	2300	8	100
R_ℓ^Z ($\times10^3$)	20 767	±	25	0.06	1
$\alpha_s(m_Z)$ ($\times10^4$)	1196	±	30	0.1	1.6
R_b ($\times10^6$)	216 290	±	660	0.3	<60
σ^0_{had} ($\times10^3$) (nb)	41 541	±	37	0.1	4
$N_\nu(\times10^3)$	2991	±	7	0.005	1
$\sin^2\theta_W^{eff}(\times10^6)$	231 480	±	160	3	2–5
$1/\alpha_{QED}(m_Z)(\times10^3)$	128 952	±	14	4	Small
$A_{FB}^{b,0}$ ($\times10^4$)	992	±	16	0.02	<1
$A_{FB}^{pol,\tau}$ ($\times10^4$)	1498	±	49	0.15	<2
m_W (keV/c^2)	803 500	±	15 000	600	300

Compare these columns.

Higgs/EW/Top

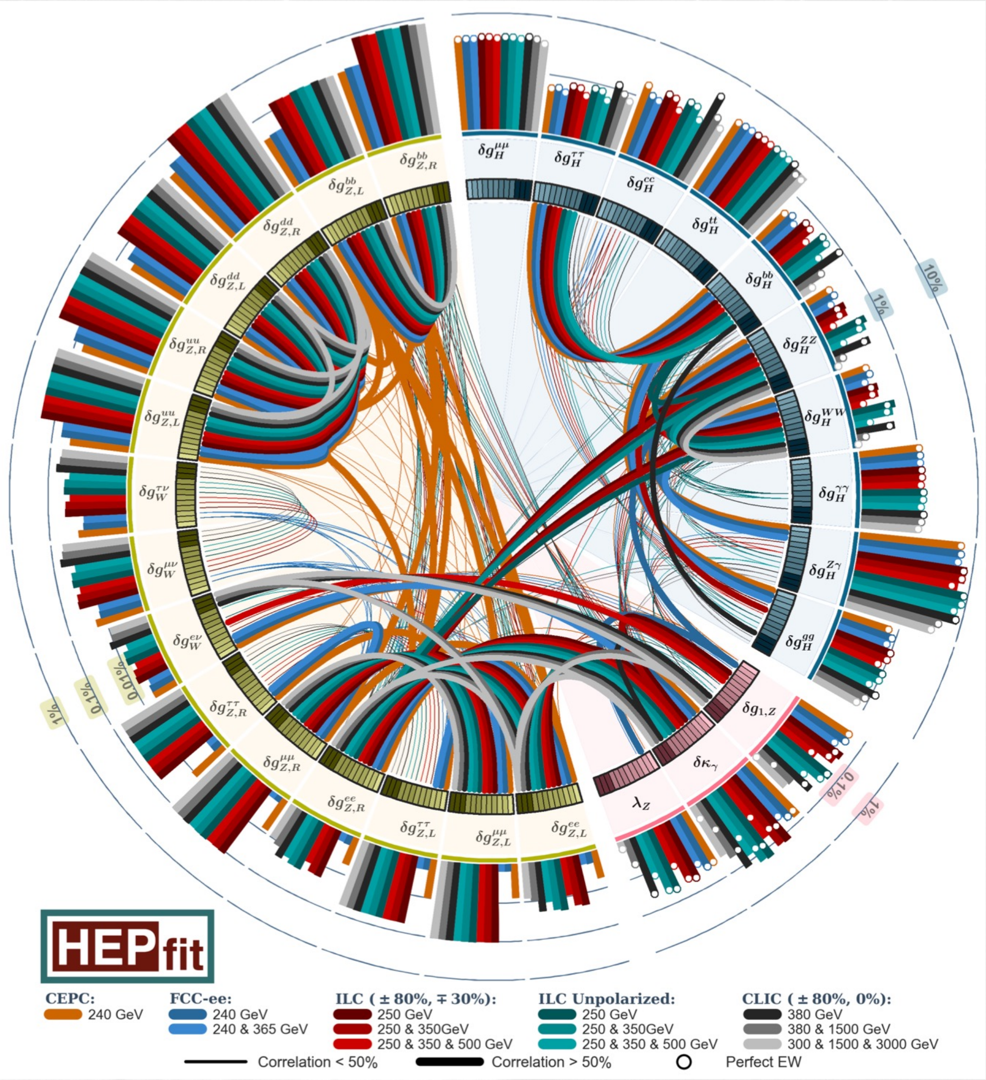
Highlights: 6’000’000’000’000 Clean Z-Bosons

Theory lessons learned:

If new physics resides in the Higgs/EW sector, then a full suite of Higgs/EW measurements are required to fully explore it. **Correlations matter**.

Higgs/EW/Top

Highlights: 6’000’000’000’000 Clean Z-Bosons



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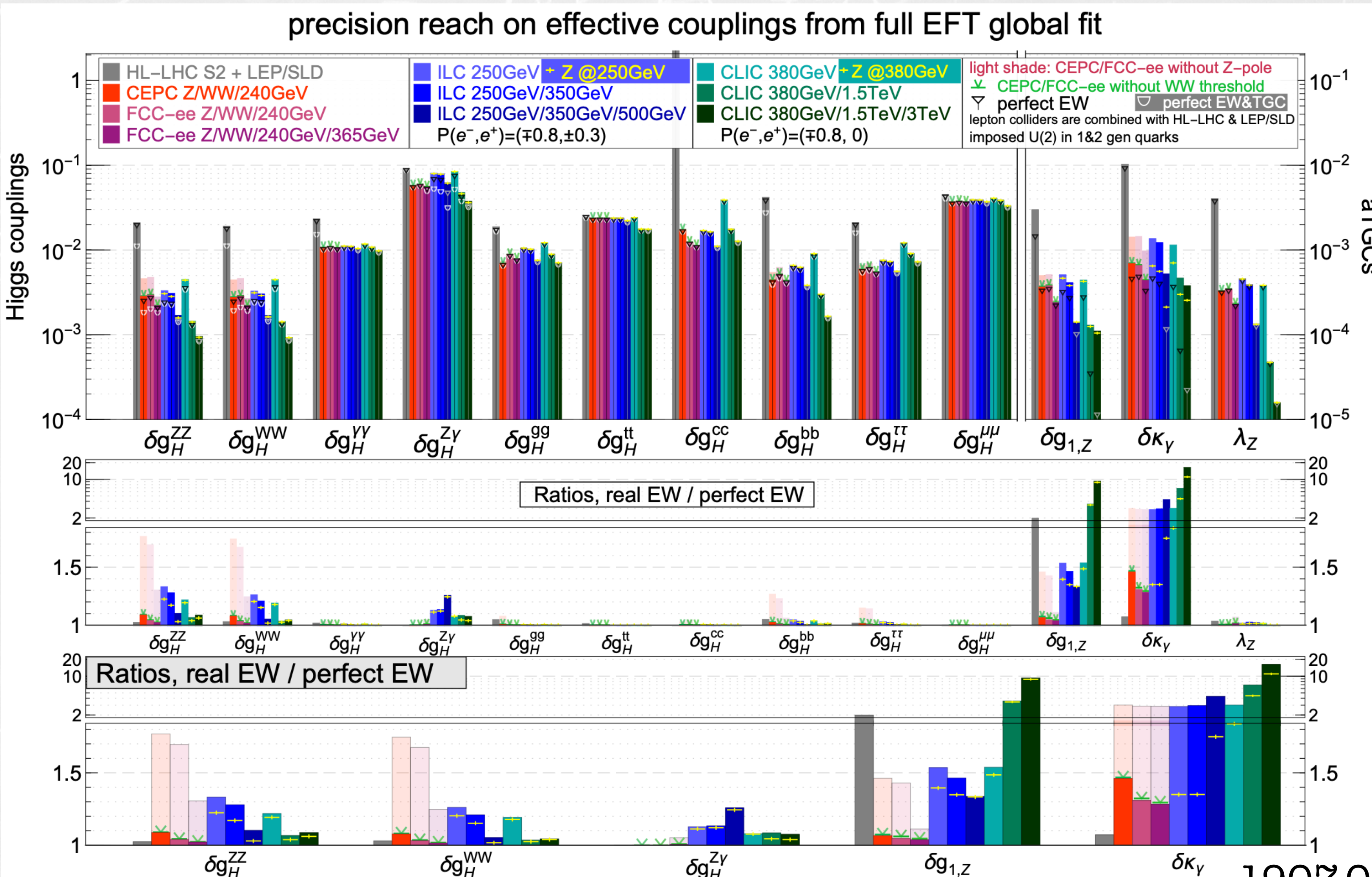
Higgs/EW/Top

Highlights: 6’000’000’000’000 Clean Z-Bosons



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Higgs/EW/Top

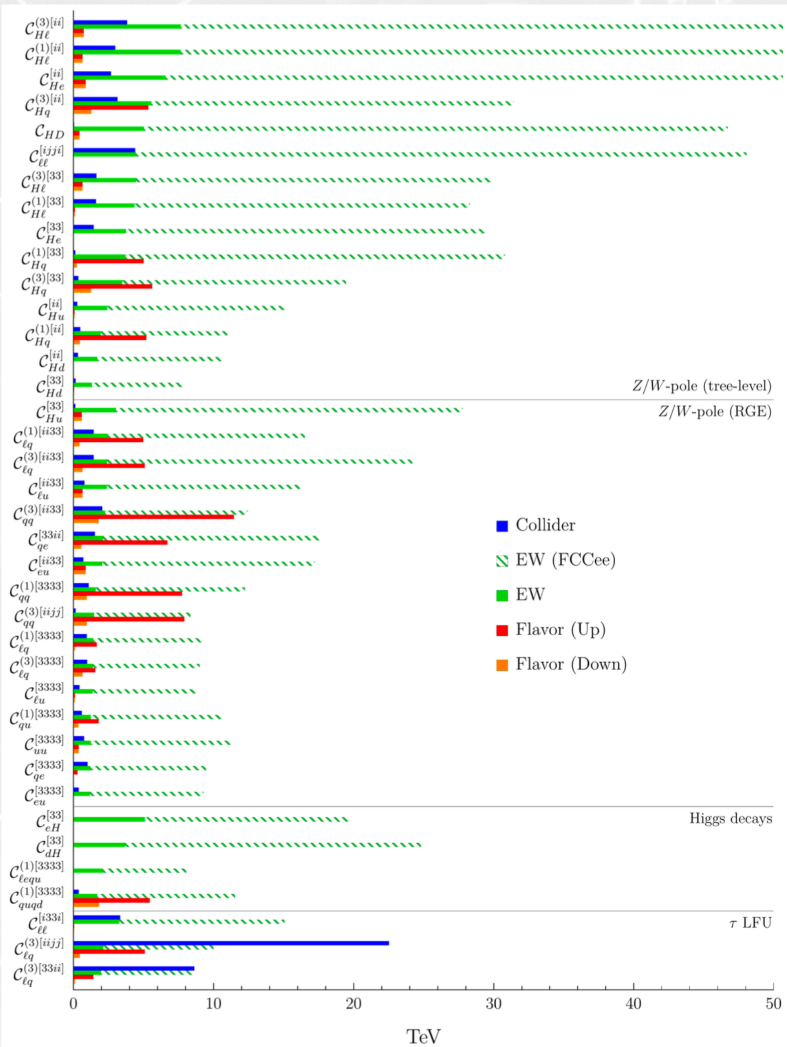
Highlights: 6’000’000’000’000 Clean Z-Bosons

Lessons learned:

If new physics resides in the flavour sector then, due to eye-watering precision, it cannot generically be sequestered from precision electroweak. **RG running matters at FCC**.

Higgs/EW/Top

Highlights: 6’000’000’000’000 Clean Z-Bosons



Many interactions generated by new heavy states would be <u>most deeply explored</u> by Tera-Z!

Tera-Z is not a LEP re-run, but a literal <u>quantum leap</u> towards the smallest distance scales…

Taken from 2311.00020

Higgs/EW/Top

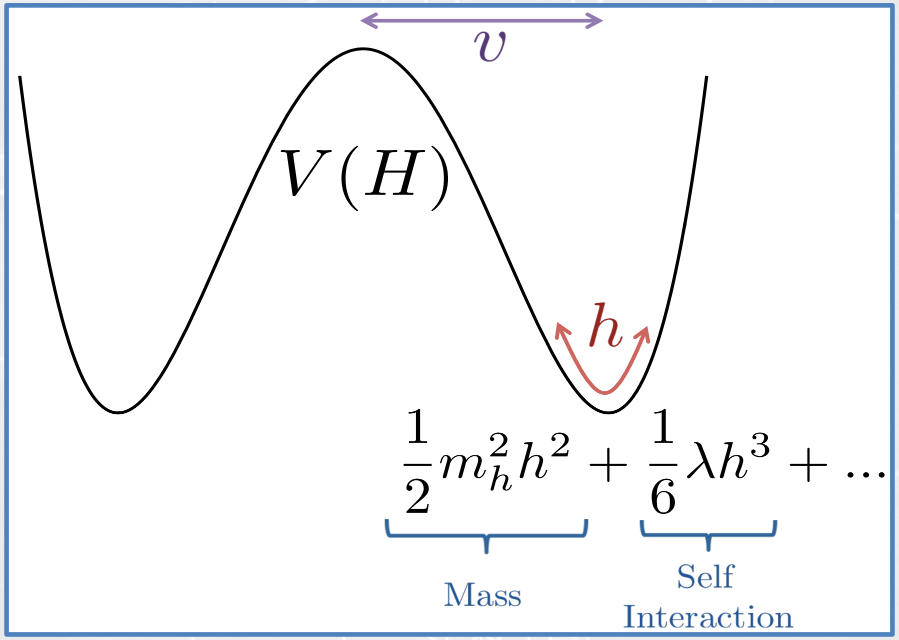
Highlights: 2'000'000 Clean Higgs Bosons

Lessons learned:

FCC would comprehensively explore the Higgs vacuum.

Higgs/EW/Top

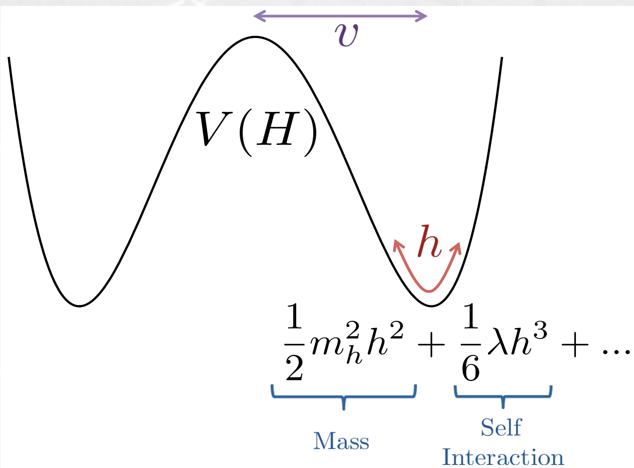
Highlights: Higgs Potential

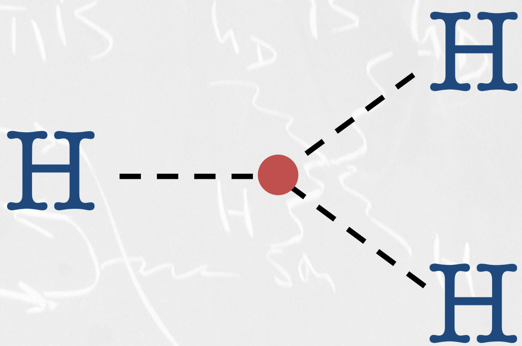


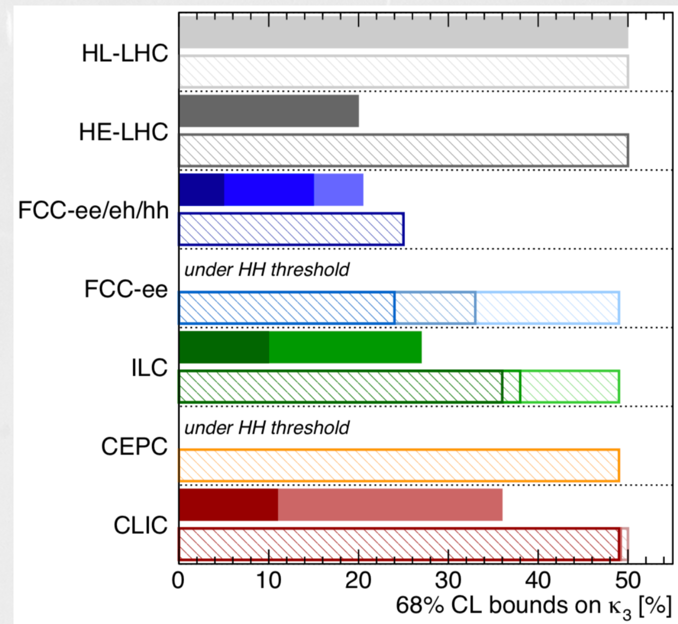
Important because it determines how the Universe froze in the EW sector, giving mass to gauge bosons, fermions, the Higgs…
…because it determines how the Universe will end…

Higgs/EW/Top

Highlights: Higgs Potential







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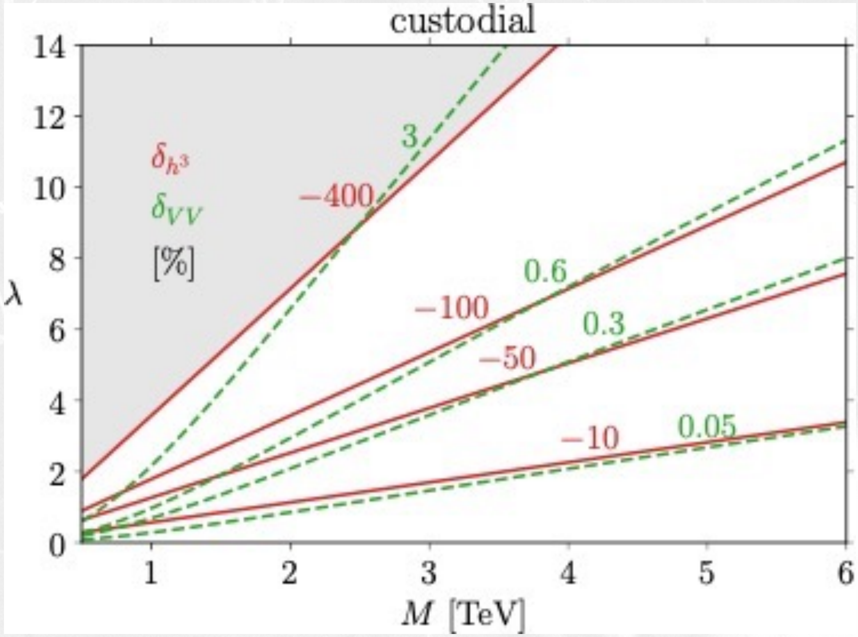
See also talk by Taliercio and Stapf, Annecy 2024.

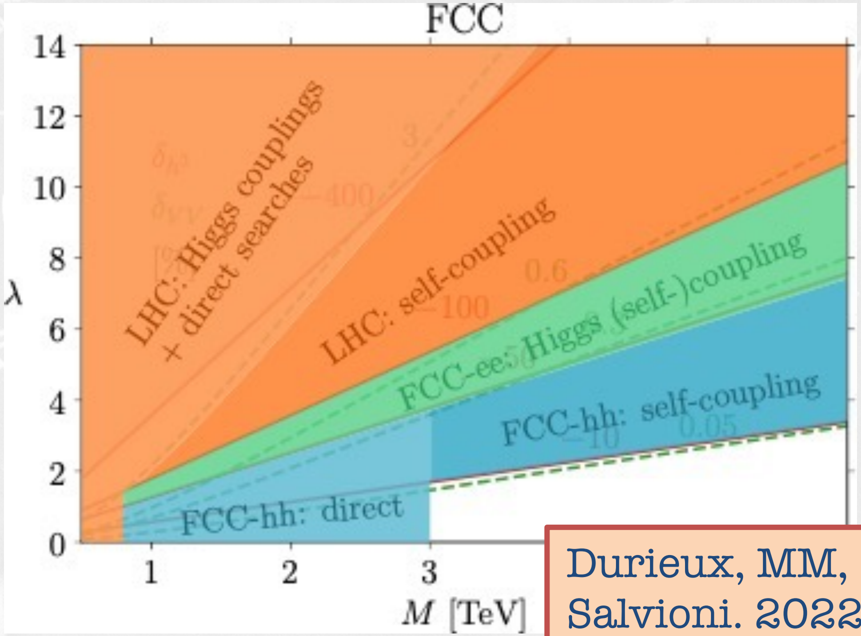
Important because it determines how the Universe froze in the EW sector, giving mass to gauge bosons, fermions, the Higgs…
…because it determines how the Universe will end…

Higgs/EW/Top

Highlights: But is it worth measuring?
"Custodial Quadruplet Model"

$$-\frac{\delta_{VV}}{\delta_{h^3}} = 3\left(\frac{m_h}{4\pi v}\right)^2 + \left(\frac{m_h}{M}\right)^2 \approx \frac{1}{200} + \frac{1}{580}\left(\frac{3\ \text{TeV}}{M}\right)^2$$





Durieux, MM, Salvioni. 2022

Higgs/EW/Top

Conveners

Performance
M. Selvaggi, J. Eysermans

Programme
C. Grojean, G. Durieux, J. de Blas

Programme Plans – Including SAC & SPC

Completed and documented EFT studies with all FCC-ee measurements (incl. CP & flavour?)

Higgs/EW/Top

Conveners

Performance
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Programme Plans – Including SAC & SPC

Continued exploration of the complementarity between FCC-ee and FCC-hh, with complete and correlated analyses (e.g. Ztt measurement at FCC-ee and Htt measurement at FCC-hh).

Higgs/EW/Top

Conveners

Performance	Programme
M. Selvaggi, J. Eysermans	C. Grojean, G. Durieux, J. de Blas

Programme Plans – Including SAC & SPC

Explore uncertainties due to the truncation of the EFT Lagrangian at a given order; likely straightforward…

Deeper comparison of the BSM reach of FCC-ee versus that of FCC-hh in terms of EFT operators.

Precision Electroweak

Conveners

Performance	**Programme**
C. Paus & G. Wilson	A. Freitas

Programme Status

The scope of the theory targets, posed to match or surpass exp statistical and systematic errors, is now clear. The picture for how to meet those targets is emerging.

Precision Electroweak

Highlights: Moving Targets

Observable	present value	±	error	FCC-ee Stat.	FCC-ee Syst.	Comment and leading error
m_Z (keV)	91186700	±	2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200	±	2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff}(\times 10^6)$	231480	±	160	**2**	2.4	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)(\times 10^3)$	128952	±	14	**3**	small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767	±	25	**0.06**	0.2-1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196	±	30	**0.1**	0.4-1.6	From R_ℓ^Z
$\sigma^0_{\rm had}$ $(\times 10^3)$ (nb)	41541	±	37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu(\times 10^3)$	2996	±	7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290	±	660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons Stat. extrapol. from SLD
$A_{FB}^b, 0$ $(\times 10^4)$	992	±	16	**0.02**	1-3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1498	±	49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86	±	0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38	±	0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350	±	15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085	±	42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1010	±	270	**3**	small	From R_ℓ^W
$N_\nu(\times 10^3)$	2920	±	50	**0.8**	small	Ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV)	172740	±	500	**17**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV)	1410	±	190	**45**	small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2	±	0.3	**0.10**	small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings		±	30%	**0.5 – 1.5 %**	small	From $\sqrt{s} = 365$ GeV run

Improving understanding of the exp error has implications for theory challenges.

Older version online: 2106.13885

Precision Electroweak

Highlights: Moving Targets

	Experiment uncertainty			Theory uncertainty
	ILC	**CEPC**	**FCC-ee**	**Current**
$M_W\,[\mathrm{MeV}]$	3-4	3	~~1~~0.3	4
$\sin^2\theta^{l}_{\mathrm{eff}}\,[10^{-5}]$	1	2.3	?0.6	4.5
$\Gamma_Z\,[\mathrm{MeV}]$	0.8	0.5	~~0.1~~0.025	0.4
$R_f\,[10^{-5}]$	14	17	~~6~~1	15

Usovitsch
Annecy 2024

As exp error mitigation strategies evolve, so do theory targets. Require 3 and 4-loop SM predictions.

Precision Electroweak

Highlights: Moving Targets

Theory status

Theory status

Usovitsch
Annecy 2024

- 1-loop and leading 2-loop corrections
  Veltman, Passarino, Sirlin, Marciano, Bardin, Hollik, Riemann, Degrassi, Kniehl, ...
- Completed 2-loop results for M_W, Z-pole observables
  Freitas, Hollik, Walter, Weiglein '00 Awramik, Czakon, Freitas '06 Awramik, Czakon '02 Hollik, Meier, Uccirati '05,07 Onishchenko, Veretin '02 Awramik, Czakon, Freitas, Kniehl '08 Awramik, Czakon, Freitas, Weiglein '04 Freitas '13,14 Dubovyk, Freitas, Gluza, Riemann, Usovitsch '16,18
- Leading 3- and 4-loop results (enhanced by y_t and/or N_f)
  Chetyrkin, Kühn, Steinhauser '95 Schröder, Steinhauser '05 Faisst, Kühn, Seidensticker, Veretin '03 Chetyrkin et al. '06 Boughezal, Tausk, v. d. Bij '05 Boughezal, Czakon '06 Chen, Freitas '20

Progress underway, no obvious showstoppers.

Precision Electroweak

Highlights: Progress

EW NNLO results emerging for 2→2 processes in last 2 years:

Fermionic Electroweak NNLO Corrections to $e^+e^- \to ZH$ with Polarized Beams and Different Renormalization Schemes

Ayres Freitas, Qian Song, Keping Xie

Complete two-loop electroweak corrections to $e^+e^- \to HZ$

Xiang Chen, Xin Guan, Chuan-Qi He, Zhao Li, Xiao Liu, Yan-Qing Ma

Two-Loop Electroweak Corrections with Fermion Loops to $e^+e^- \to ZH$

Ayres Freitas, Qian Song

These are for ee→hZ, but techniques should carry over for ee→ff, ee→WW, etc.

Precision Electroweak

Conveners

Performance	**Programme**
C. Paus & G. Wilson	A. Freitas

Programme Plans – Including SAC & SPC

Developing the coordination and structure to enable the long-term theoretical work needed to match the anticipated experimental precision of the FCC data.

Documenting the theoretical calculation progress and needs in SM and in BSM/EFT.

Precision Electroweak

Conveners

Performance	**Programme**
C. Paus & G. Wilson	A. Freitas

Programme Plans – Including SAC & SPC

Coordination with experimental studies for Prec EW.

MC tool development, and in particular high-precision matching/merging of fixed-order calculations with QED parton showers.

Flavour

Conveners

Performance	**Programme**
S. Monteil, A. Lusiani	G. Isidori, J. Kamenik

Programme Status

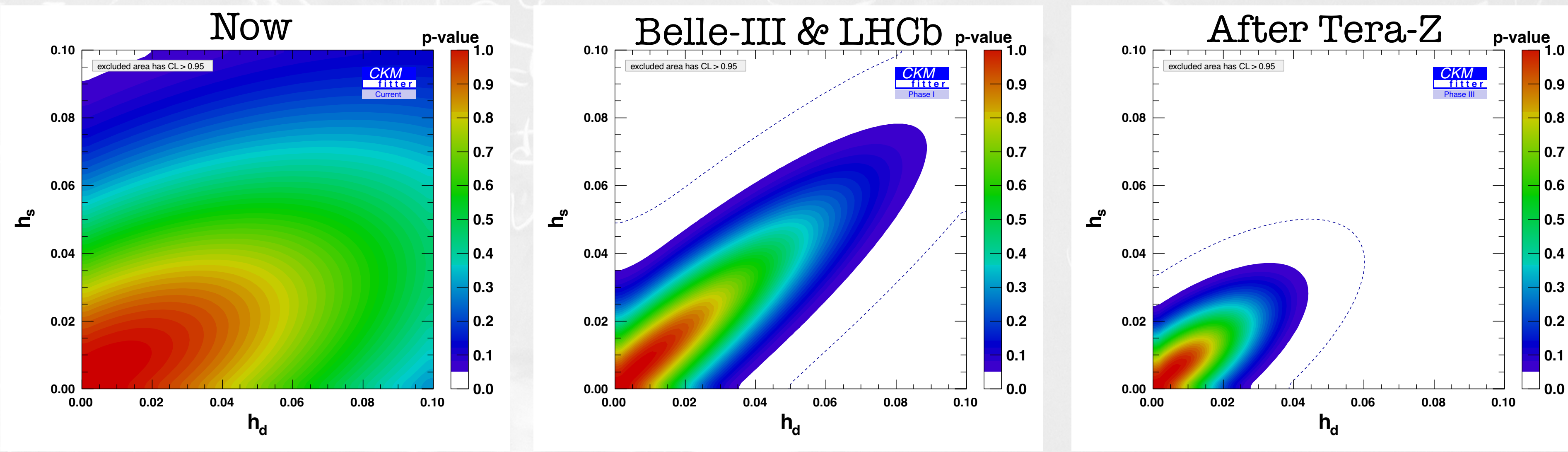
The enormous scope of the flavour programme has begun to emerge, in particular as the most powerful b and τ factory ever constructed.

Flavour

Highlights: 6’000’000’000’000 Clean Z-Bosons

Particle production (10^9)	B^0 / $\overline{B}^0$	B^+ / B^-	B^0_s / $\overline{B}^0_s$	Λ_b / $\overline{\Lambda}_b$	$c\bar{c}$	τ^-/τ^+
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	300	300	80	80	600	150

Incredible flavour factory!

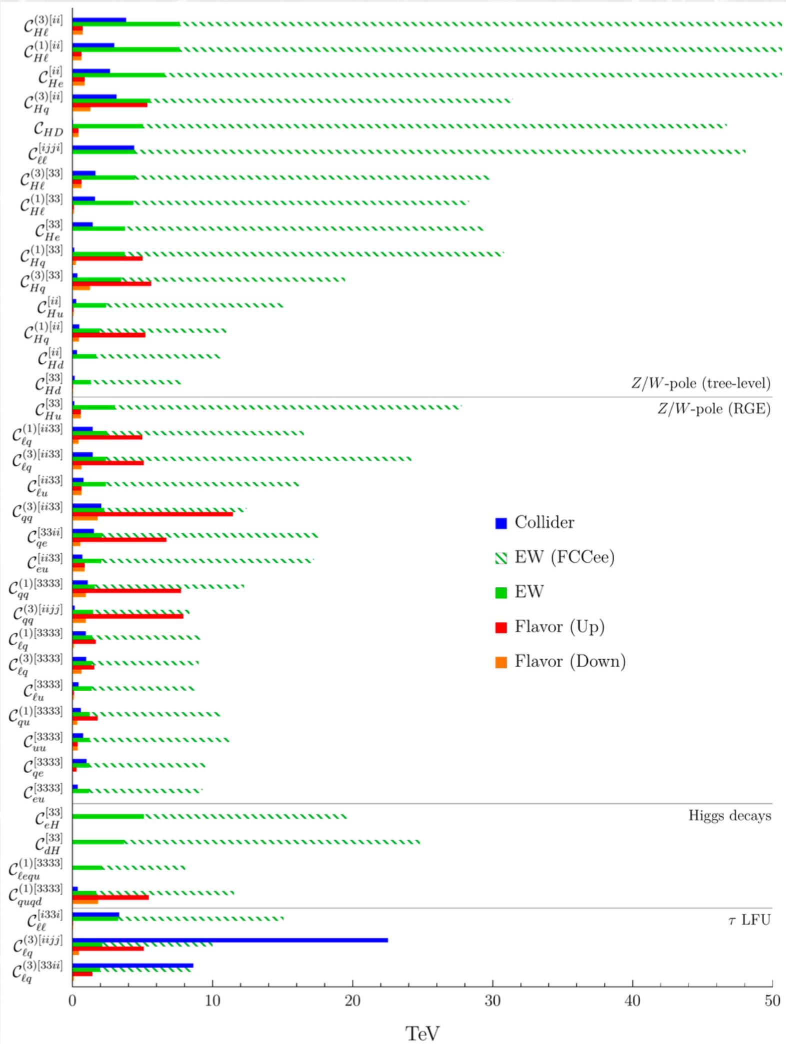


Taken from 2106.01259

$$M_{12} = (M_{12})_{\text{SM}} \times \left(1 + h_{d,s}\, e^{2i\sigma_{d,s}}\right)$$

Flavour

Highlights: Strong synergetic interplay with EW precision.



Note the important roles played by EW and Higgs in mapping out the full space of flavoured new physics at high energy.

Taken from 2311.00020

Flavour

Conveners

Performance	Programme
S. Monteil, A. Lusiani	G. Isidori, J. Kamenik

Programme Plans – Including SAC & SPC

We need to expand the flavour studies significantly, in particular with respect to charm, tau physics.

There remains scope to develop the impact of flavour programme in respect of concrete scenarios.

QCD

Conveners

Performance	Programme
D. d'Enterria	P. Monni

Programme Status

The landscape of theory challenges and physics opportunities is emerging.

Many areas of theory required (fixed order QCD + EW, resum in QCD & QED, EFTs, non-perturbative QCD, event generators, new observables,...)

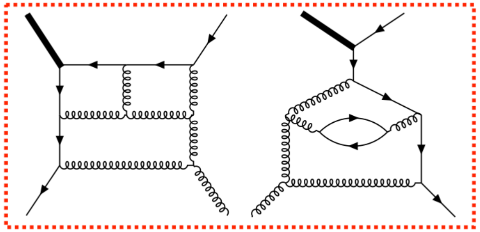
Monni, Annecy 2024

QCD

Highlights

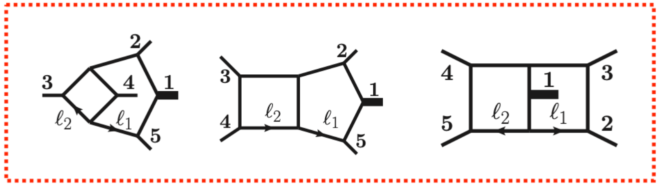
Z/γ to light jets:

- Significant improvement needed in FO QCD calculations
  - 3 jets @ N^{3}LO QCD: amplitudes in the making (planar limit), but IR subtraction is an open challenge



[Gehrmann et al. 2023]

  - 4 jets @ NNLO QCD: likely within reach in next O(few) years



[Abreu et al. 2023]

Monni, Annecy 2024

QCD

Conveners

Performance	Programme
D. d'Enterria	P. Monni

Programme Needs – Including SAC & SPC

Need significant breakthroughs to improve understanding: e.g. non-perturbative QCD (hadronisation), EFT calculations, high-order QCD+EW, MCs currently a bottleneck.

Huge step forward demanded for MCs (QCD/EW, ISR, for jet processes, NR QCD, resonances).

Monni, Annecy 2024

QCD

Conveners

Performance	Programme
D. d'Enterria	P. Monni

Programme Plans – Including SAC & SPC

Study of the prospect of runs below the Z peak to improve the modelling (e.g. event generators) and understanding (e.g. via analytic methods) of hadronization corrections to QCD observables. These aspects will impact the description of jet observables at higher-energy runs of FCC-ee.

QCD
Conveners

Performance	Programme
D. d'Enterria	P. Monni

Programme Plans – Including SAC & SPC

(In collaboration with the Higgs performance conveners) - Study of the extraction of the strange-quark Yukawa coupling from hadronic Higgs decays. Assessment of theoretical challenges in the description of kinematical distributions and study of the performance of flavour taggers.

QCD

Conveners

Performance	Programme
D. d'Enterria	P. Monni

Programme Plans – Including SAC & SPC

(On a longer timeline) - Study of the possibility to identify high-purity jet data of specific flavour (e.g. b/c, gluon, light-quark jets), and their potential use for the training of jet taggers and the tuning of MC generators.

Beyond the Standard Model

Conveners

Performance
R. Gonzalez-Suarez, G. Polesello

Programme
T. You

Programme Status

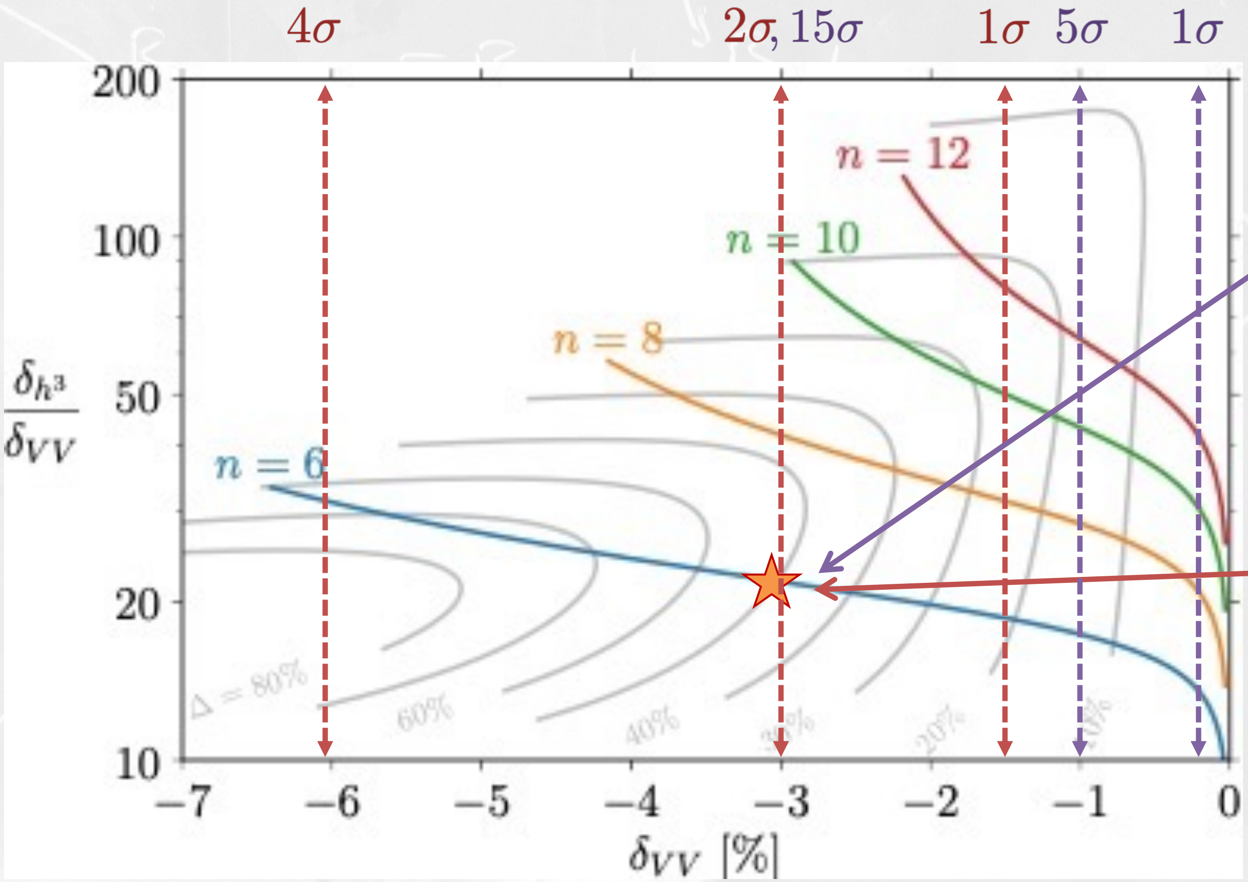
A depth of interconnections between all FCC-ee runs, as pertains to exploring new physics, is emerging.

Strategy for communicating the BSM case is evolving.

Beyond the Standard Model

Highlights: Expanding landscape of composite Higgs understanding and importance of precision.

Example: Gegenbauer's Twin



Only 2σ at HL-LHC but 15σ at FCC-ee!

Example point. Low tuning, 3% single-coupling correction, 70% self-coupling correction.

Durieux, MM, Salvioni. 2022

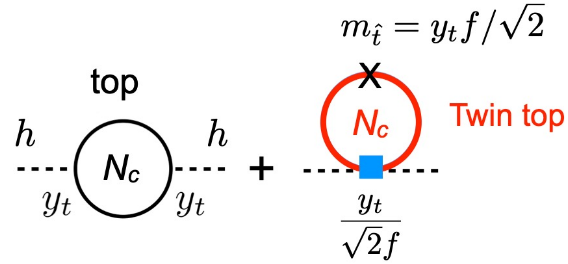
Beyond the Standard Model

Highlights: More complete picture emerging for connection to big questions, e.g. naturalness.

Probing the Twin top directly

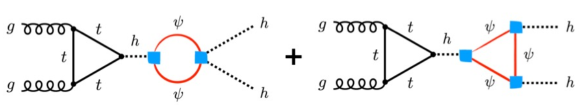
Twin top is SM-neutral, but <u>must</u> couple to the Higgs as:

$$\mathcal{L} = -m_{\hat{t}}\bar{\hat{t}}\hat{t} + \frac{y_t}{\sqrt{2}}\frac{|H|^2}{f}\bar{\hat{t}}\hat{t}$$

$\delta m_h^2 \sim$ 

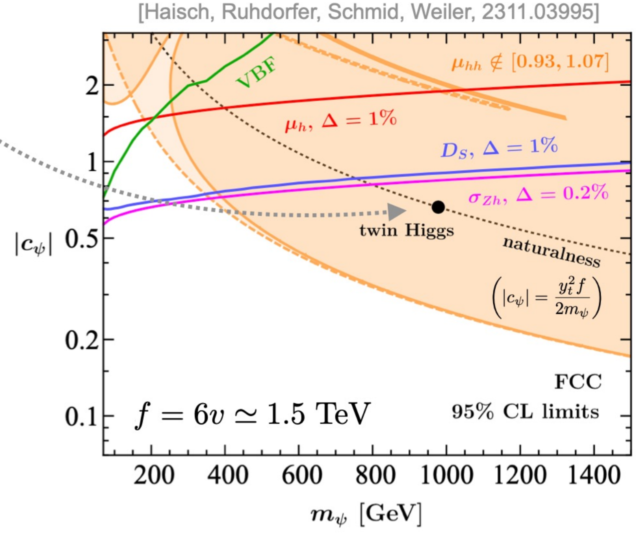
Probes at LHC, HE-LHC, FCC have been studied very recently

Interestingly, double Higgs production appears to be sensitive at loop level



(see paper for assumptions on dim-6 ops.)

[Haisch, Ruhdorfer, Schmid, Weiler, 2311.03995]



Salvioni, Annecy 2024

Beyond the Standard Model

Highlights: More complete picture emerging for probes of dark sectors through precision.

Model	Scenario	Main LHC prod. channel	(HL-)LHC constraint	$\delta\sigma^{y\leq 2}_{\rm ZH,max}$	oblique para.
DSDM	large Δm_{Dl}	$pp \to \chi_D^\pm \chi_h^0$	$pp \to 4q$, [68]	$< 3\%$	relevant
			$pp \to 1lbb$, [69]		
	small Δm_{Dl}	$pp \to \chi_D^\pm \chi_D^\mp$	$pp \to 2l_{\rm soft}$, [71]	$< 1\%$	relevant
MSDM	χ_h^0 doublet-dominant	$pp \to \chi_{h,D}^0 \chi_D^\pm, \chi_D^\pm \chi_D^\mp$	$pp \to 4q$, [68]	$< 6\%$	not relevant
			$pp \to 1lbb$, [69]		
	χ_h^0 singlet-dominant	$pp \to \chi_D^0 \chi_D^\pm$	$pp \to 3l_{\rm soft}$,[79]	$< 1\%$	not relevant
			$pp \to \leq 2l_{\rm soft}$,[76]		
DDTM1	$\chi_l^\pm$ doublet-dominant	$pp \to \chi_l^\pm \chi_l^\mp$	$pp \to 2l_{\rm soft}$,[71]	$< 3\%$	relevant
	$\chi_l^\pm$ triplet-dominant	$pp \to \chi_l^\pm \chi_l^\mp$	$pp \to 2l_{\rm soft}$, [71]	$< 3\%$	relevant
DDTM0	χ_h^0 triplet-dominant	$pp \to \chi_h^0 \chi_{h,T}^\pm, \chi_{h,T}^\pm \chi_{h,T}^\mp$	$pp \to 4q$, [68]	$< 1\%$	relevant
			$pp \to 1lbb$, [69]		
	χ_h^0 doublet-dominant is forbidden				
MDTM	χ_h^0 doublet-dominant	$pp \to \chi_{h,D}^0 \chi_h^\pm, \chi_h^\pm \chi_h^\mp$	$pp \to 4q$, [68]	$< 4\%$	relevant
			$pp \to 1lbb$, [69]		
	χ_h^0 triplet-dominant	$pp \to \chi_h^0 \chi_h^\pm, \chi_h^\pm \chi_h^\mp$	$pp \to 4q$, [68]	$< 3\%$	relevant
			$pp \to 1lbb$, [69]		

TABLE I. Summary table for the scenarios with stable lightest fermions considered in this work. $\delta\sigma^{y\leq 2}_{\rm ZH,max}$ denotes the size of the possible deviations of the $e^+e^- \to ZH$ cross-section within current constraints from electroweak precision and LHC data.

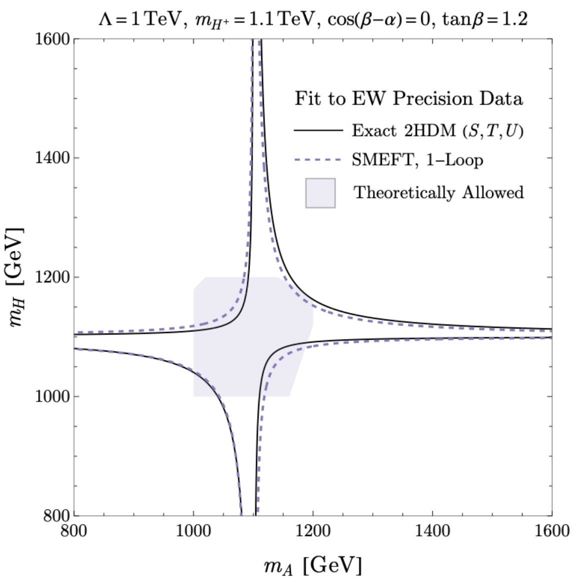
Ayres, Song, 2308.13030.

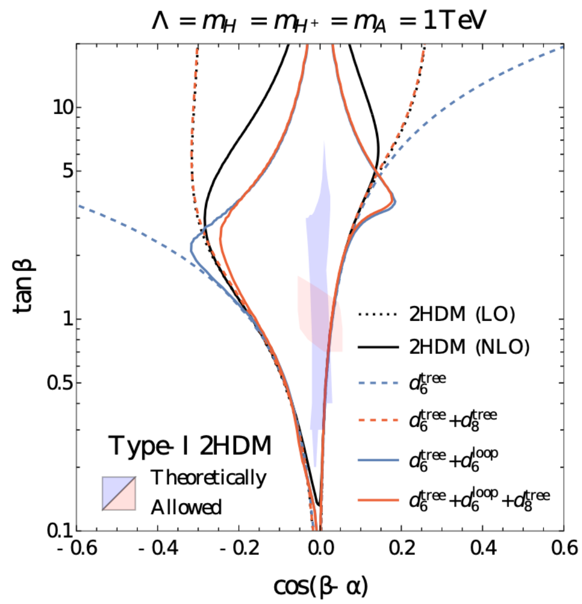
Beyond the Standard Model

Highlights: More complete, and FCC-ee appropriate, matching of EFTs to specific BSM emerging.

[Das Bakshi, Dawson, Fontes, Homiller '24]

2HDM matched at one-loop

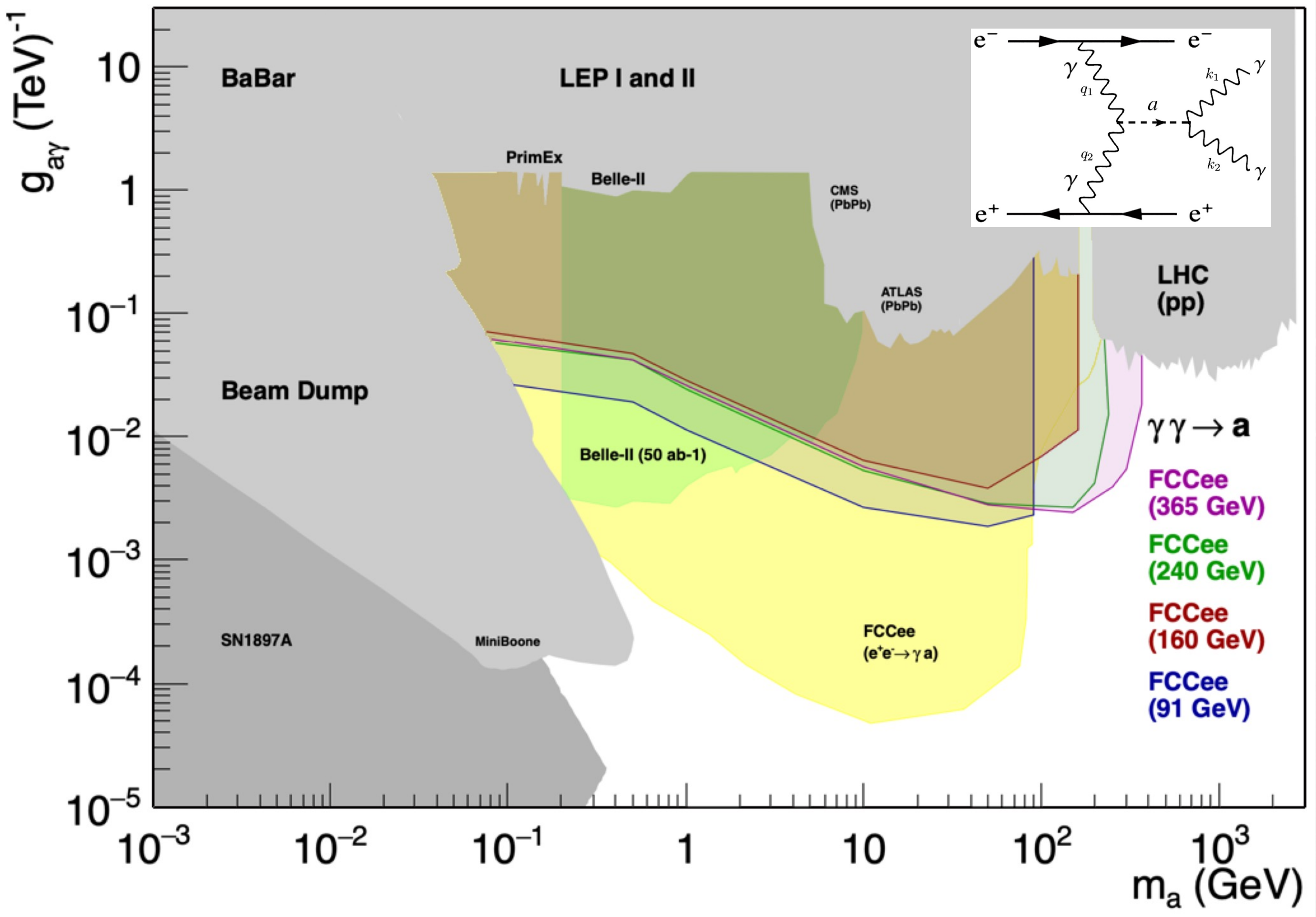




- EWPO constraints arising first at one-loop
  - mild impact so far; more important with new Z pole?
- more accurate large-tan β description
  - from Yukawa operators; probed with new Higgs measurements

Beyond the Standard Model

Highlights: Intensity frontier picture expanding, especially due to efforts from performance folks!



2310.17270

Beyond the Standard Model

Conveners

Performance	**Programme**
R. Gonzalez-Suarez, G. Polesello	T. You

Programme Plans – Including SAC & SPC

We plan to illustrate the BSM physics reach in terms of some chosen specific ultraviolet complete models to illuminate the discovery potential of FCC ee+hh and to clarify the physics gain from Higgs coupling measurements.

Beyond the Standard Model

Conveners

Performance	**Programme**
R. Gonzalez-Suarez, G. Polesello	T. You

Programme Plans – Including SAC & SPC

We plan to deepen analyses on both the flavour and dark sector programs, exploring the new capabilities offered by FCC-ee.

Beyond the Standard Model

Conveners

Performance	**Programme**
R. Gonzalez-Suarez, G. Polesello	T. You

Programme Plans – Including SAC & SPC

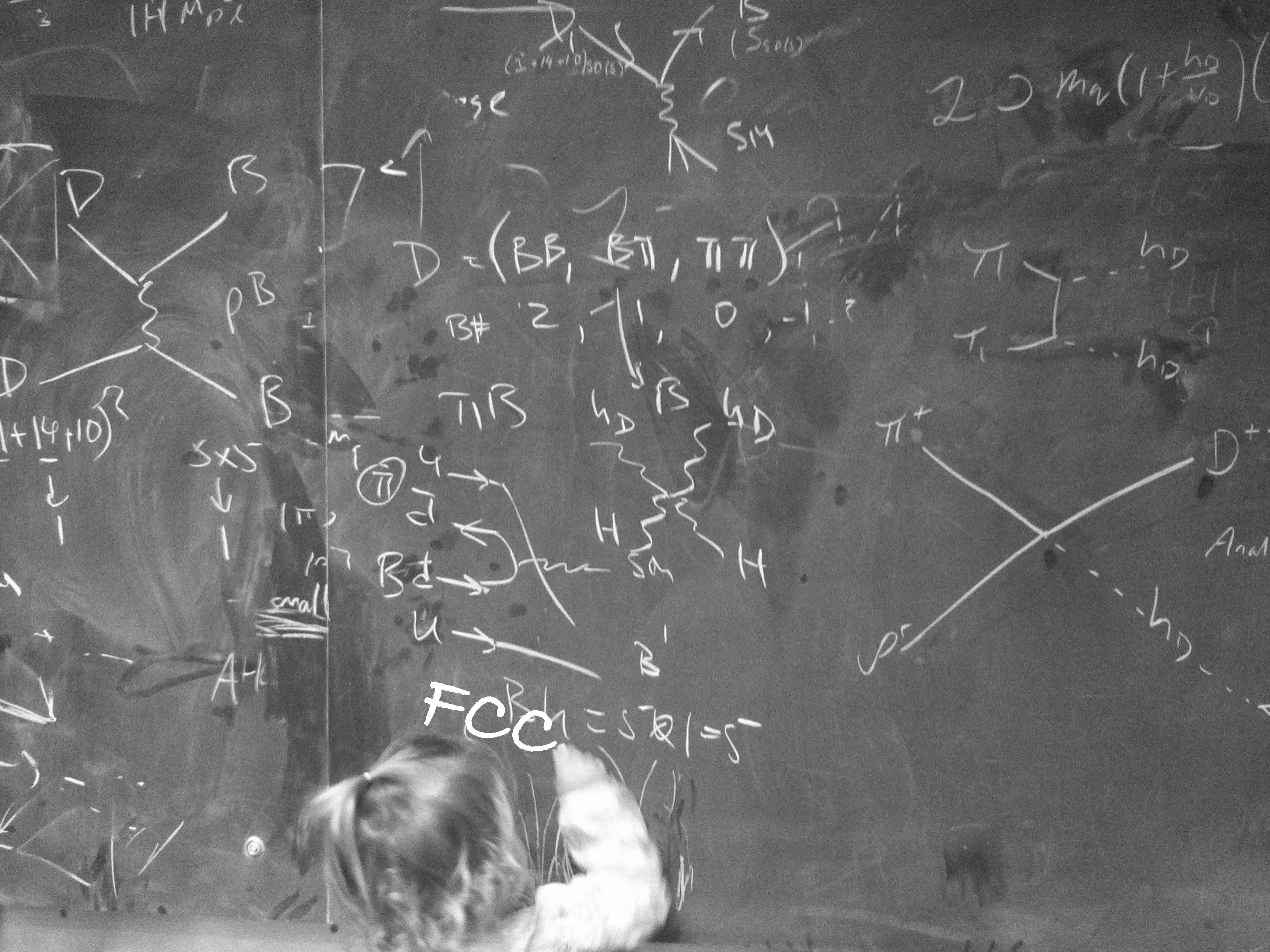
Remains to document FCC-ee (direct and indirect) reach for a few specific BSM models

Explore physics case of parasitic detectors

Conclusions

Theory develops organically, driven by a combination of curiosity and the joy of solving challenging problems.

FCC offers a bounty of interesting, difficult, and achievable theory challenges.


FCC

Further Activities

Exploring synergy with FCC-hh and muon collider.

Across photon, gluon, (W&Z) and five-flavour scheme for quarks, FCC-hh collides

$$N = 144\,,\,196$$

different initial states. Broad exploration. Writing cross section as

$$\sigma = r\frac{C_{yy}}{s}$$

where

$$C_{gg} = \frac{\pi^2}{8}\int_\tau^1 \frac{dx}{x}\, f_g(x)f_g(\tau x)\;, \quad C_{q\bar{q}} = \frac{4\pi^2}{9}\int_\tau^1 \frac{dx}{x}\,\left[f_q(x)f_{\bar{q}}(\tau x) + f_{\bar{q}}(x)f_q(\tau x)\right]$$

and

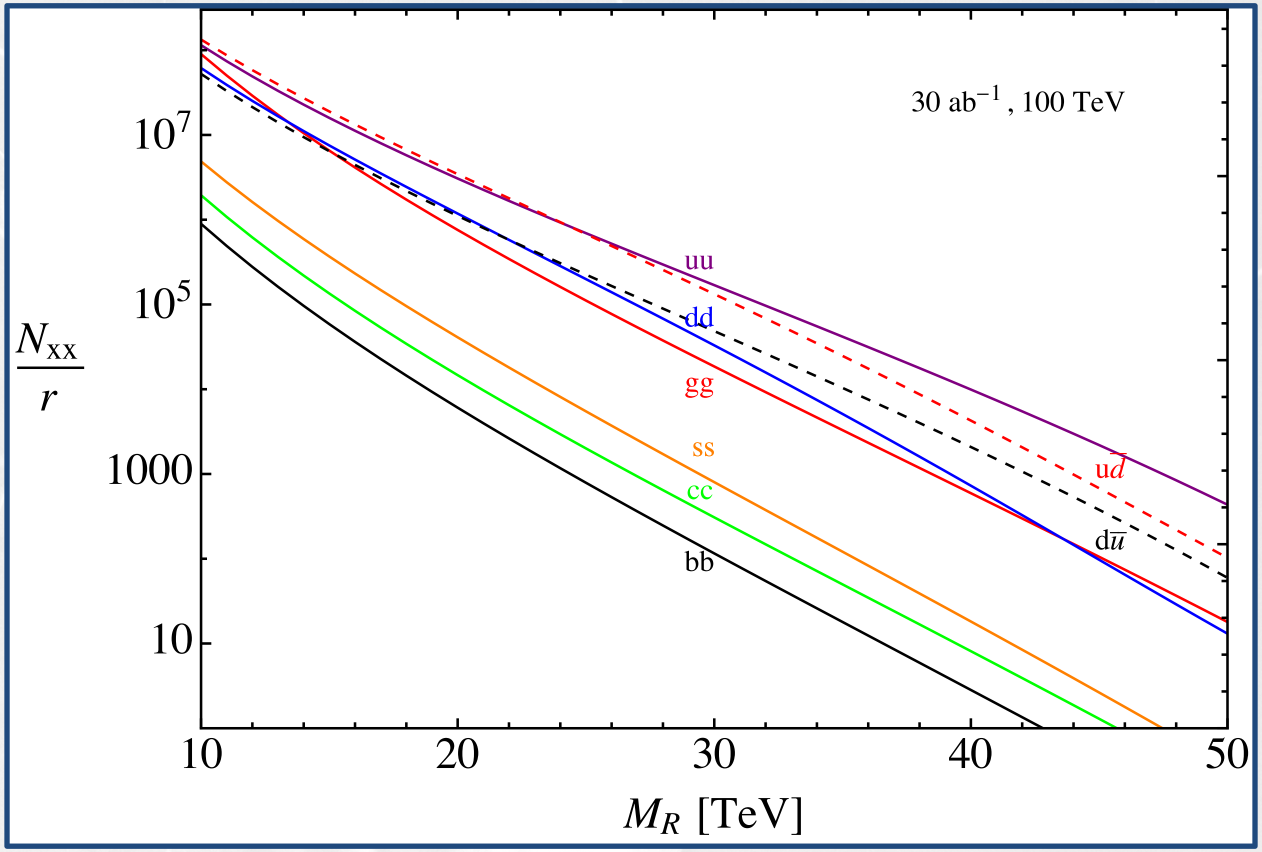
$$r = (2S+1)B_{yy}B_{xx}\frac{\Gamma_R}{M_R}$$

Further Activities

Then, recalling,

$$r = (2S+1) B_{yy} B_{xx} \frac{\Gamma_R}{M_R}$$

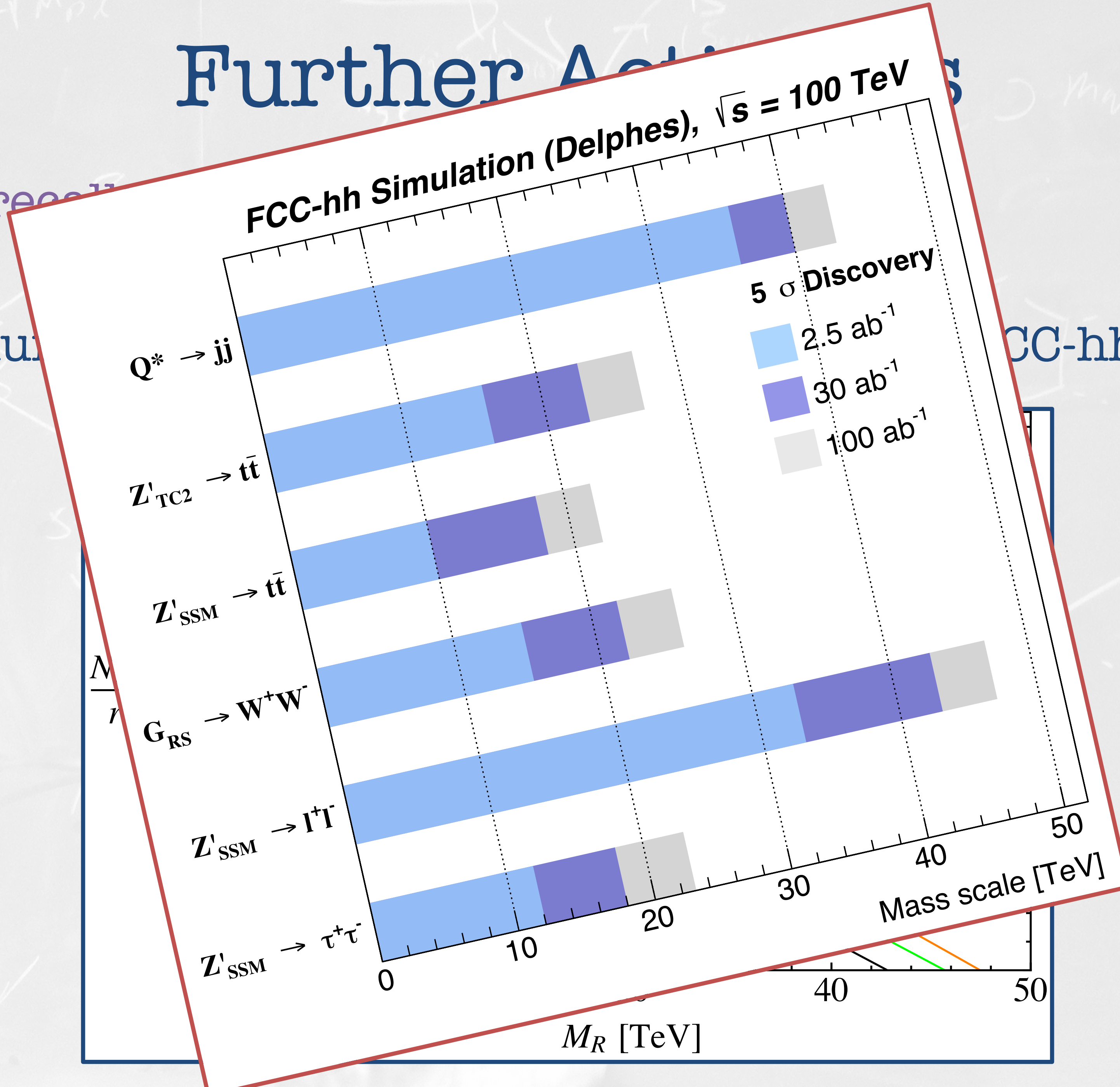
...the number of events you get above 10 TeV at FCC-hh is:



Further Act... s

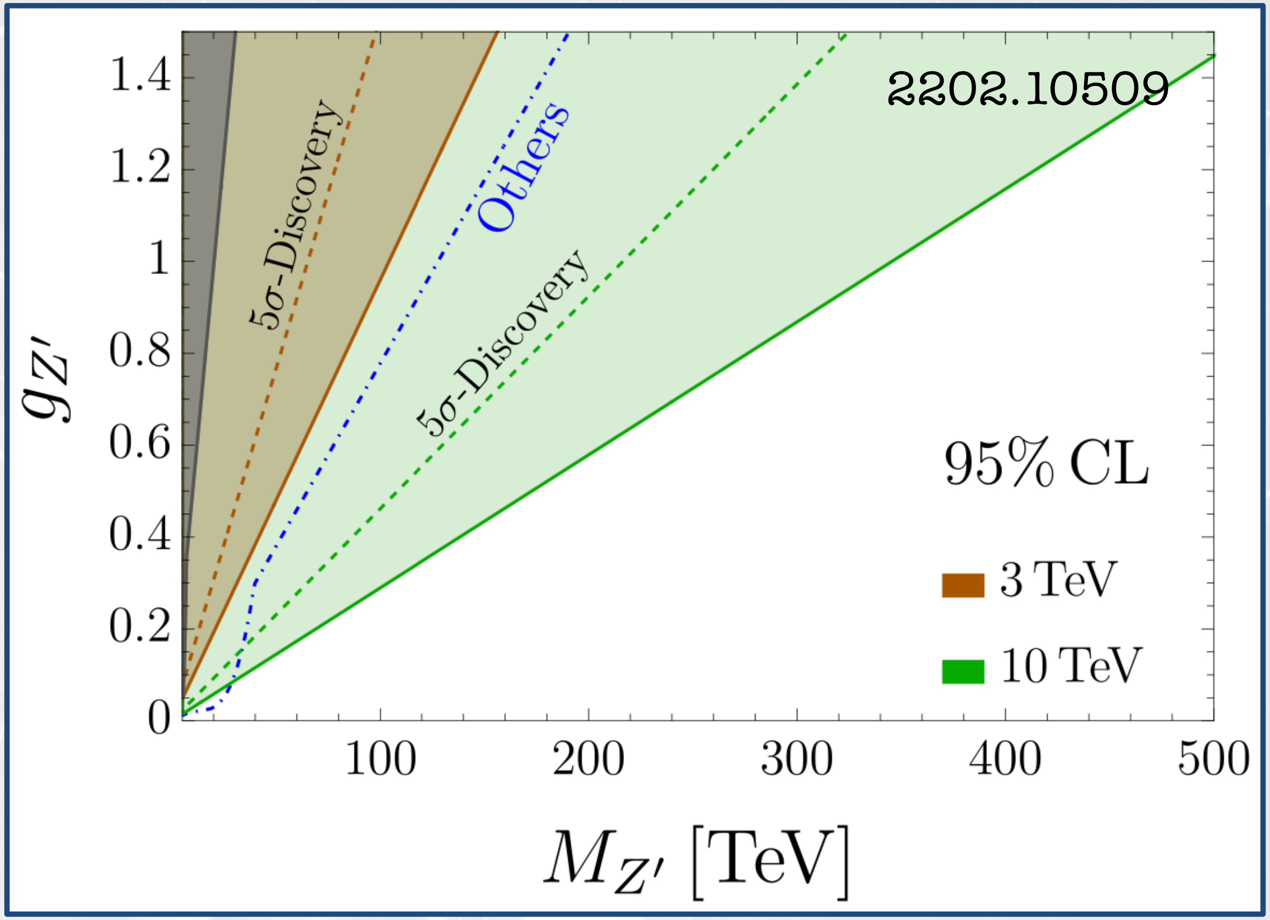
Then, reca...

...the nu... CC-hh is:



Further Activities

Consider universal Hypercharge Z'.



Indirect reach of μ-coll exceeds "Others", including FCC-hh. Why?

Further Activities

In EFT corresponds to O_{2B}...

2202.10509	SILH basis
W&Y	$O_{2W} = (D_\mu W^{\mu\nu,a})^2$ $O_{2B} = (\partial_\mu B^{\mu\nu})^2$
Di-boson	$O_W = \frac{ig}{2}(H^\dagger \sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu}$ $O_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial^\nu B_{\mu\nu}$

Which gives SM-like amplitude with correction scaling as

$$\mathcal{M} \approx \mathcal{M}_{\text{SM}} \left(1 + \frac{E^2}{M^2}\right)$$

so here energy + accuracy powerful.

Further Activities

Programme Plans – Including SAC & SPC

Muon/FCC-hh synergy to be elaborated on further.

Continue developing a clear explanation of the physics case for the FCC project, targeting both non-scientists and scientists in other fields.

Higgs/EW/Top

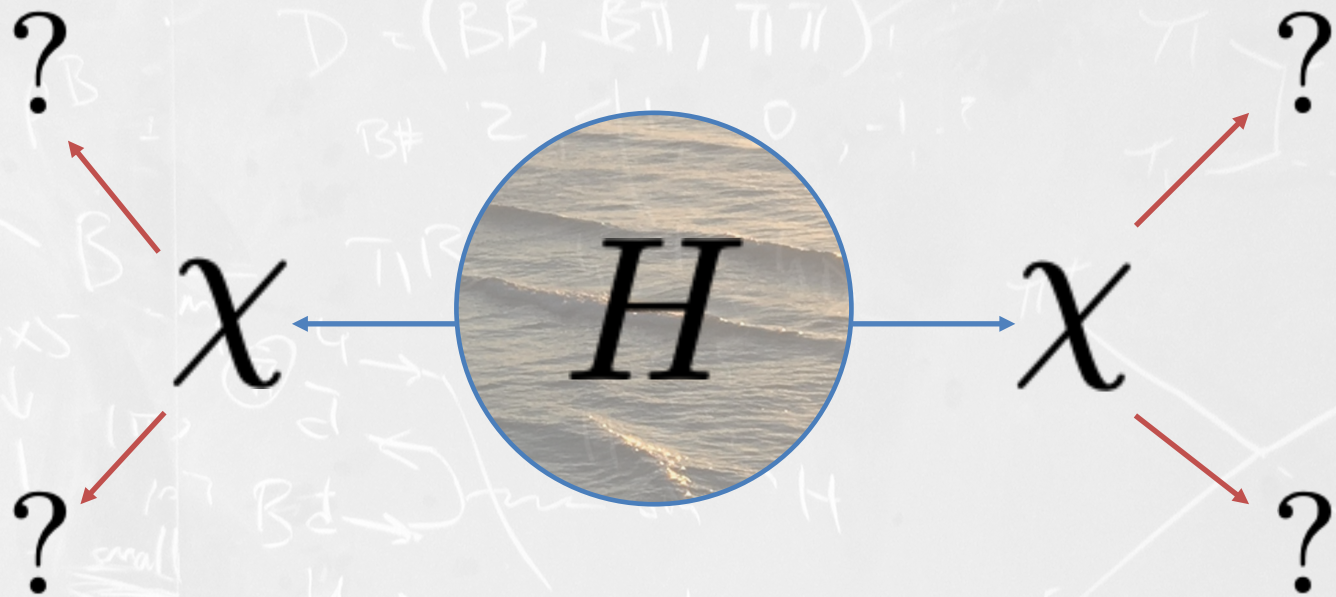
Highlights: 2'000'000 Clean Higgs Bosons

Lessons learned:

Higgs portal comprehensively explored as well.

Higgs/EW/Top

Highlights: Higgs Potential

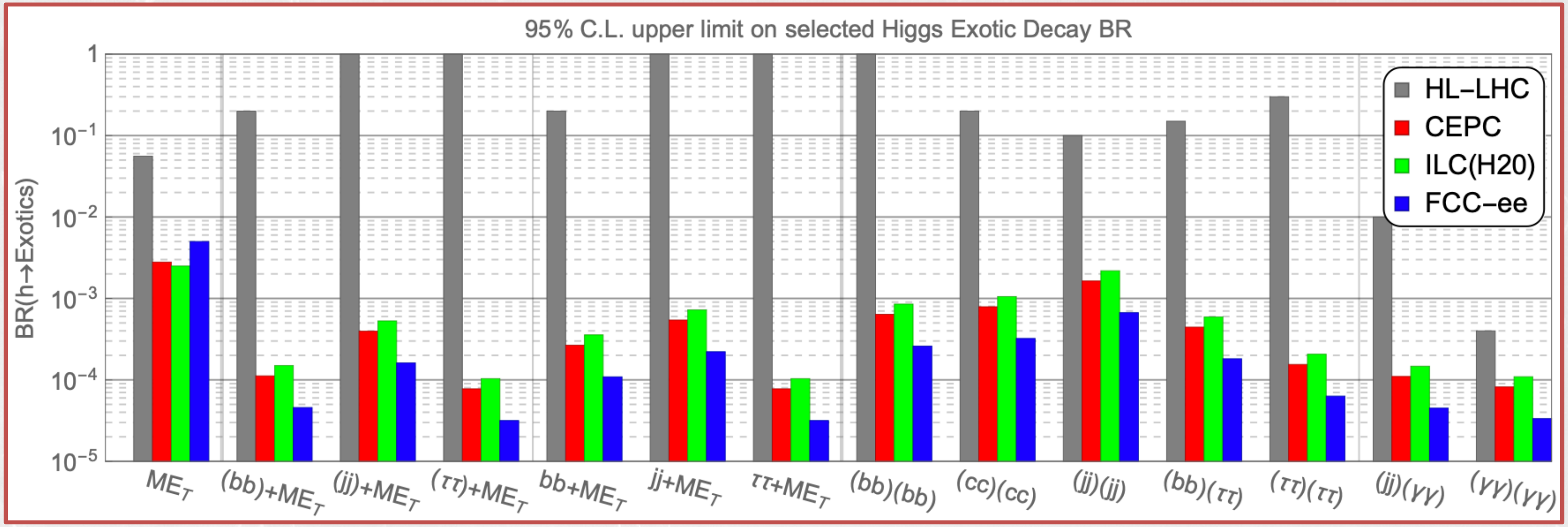


After all, $|H|^2$ is the most relevant interaction involving SM fields! Even if generated at microscopic scales

stays relevant all the way down to the Higgs scale...

Higgs/EW/Top

Highlights: Higgs Potential



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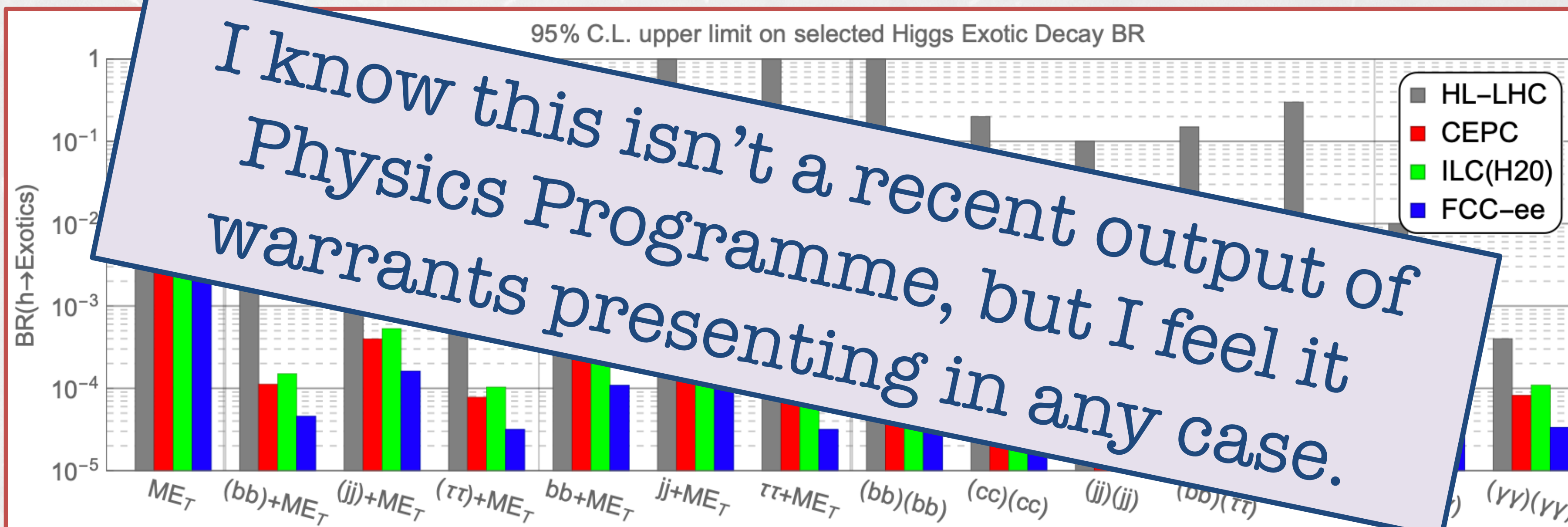
Orders of magnitude improvement in coverage of exotic Higgs decays.

Higgs/EW/Top

Highlights: Higgs Potential



I know this isn't a recent output of Physics Programme, but I feel it warrants presenting in any case.

1612.09284

Orders of magnitude improvement in coverage of exotic Higgs decays.