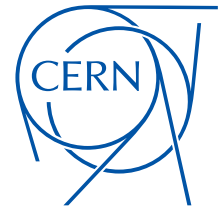
Higgs physics programme

Gauthier Durieux
(CERN)

with Higgs programme and performance conveners:
J. de Blas, C. Grojean,
J. Eysermans, M. Selvaggi

contact us
mailing list subscription
Indico category
next meeting towards July
mini-workshop envisioned after ECFA one towards Nov.

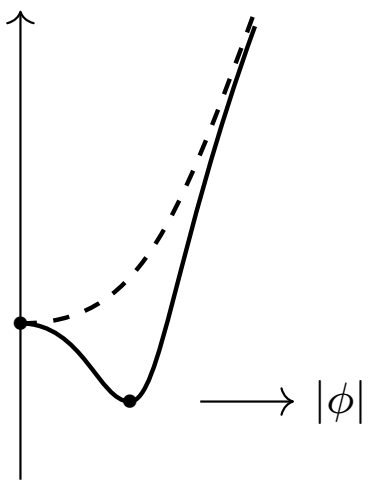


FCC Week, 31 May 2022

The Higgs at 10

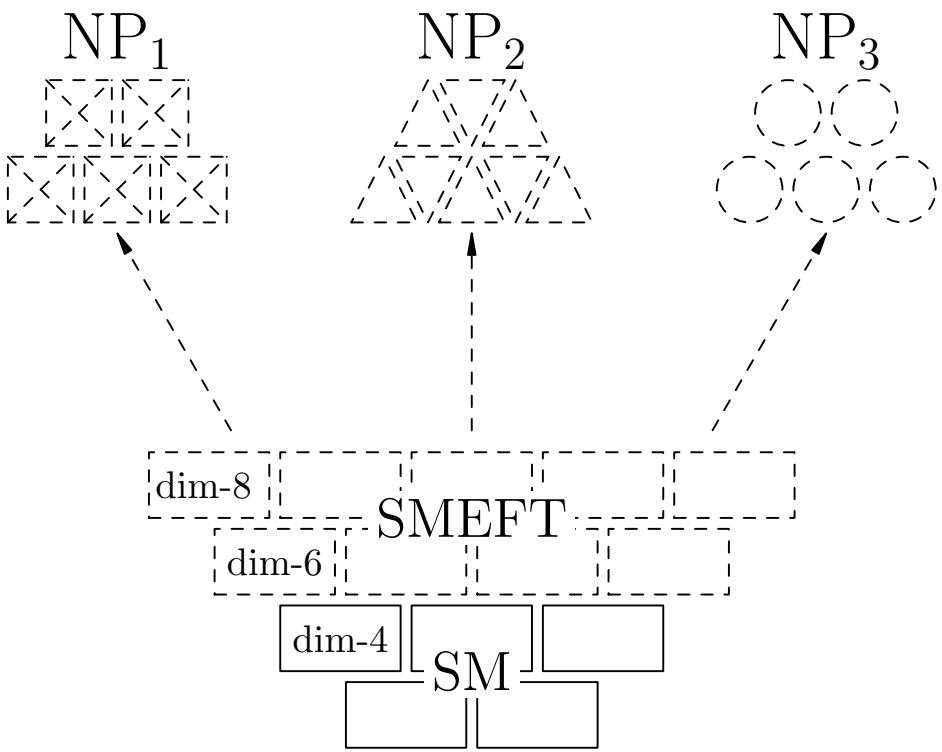
Is it elementary? Is its mass protected by a symmetry?

Phenomenological description of a more microscopic dynamics like the Ginzburg-Landau theory of superconductivity?



$$V(\phi) = \pm\mu^2|\phi|^2 + \lambda|\phi|^4$$

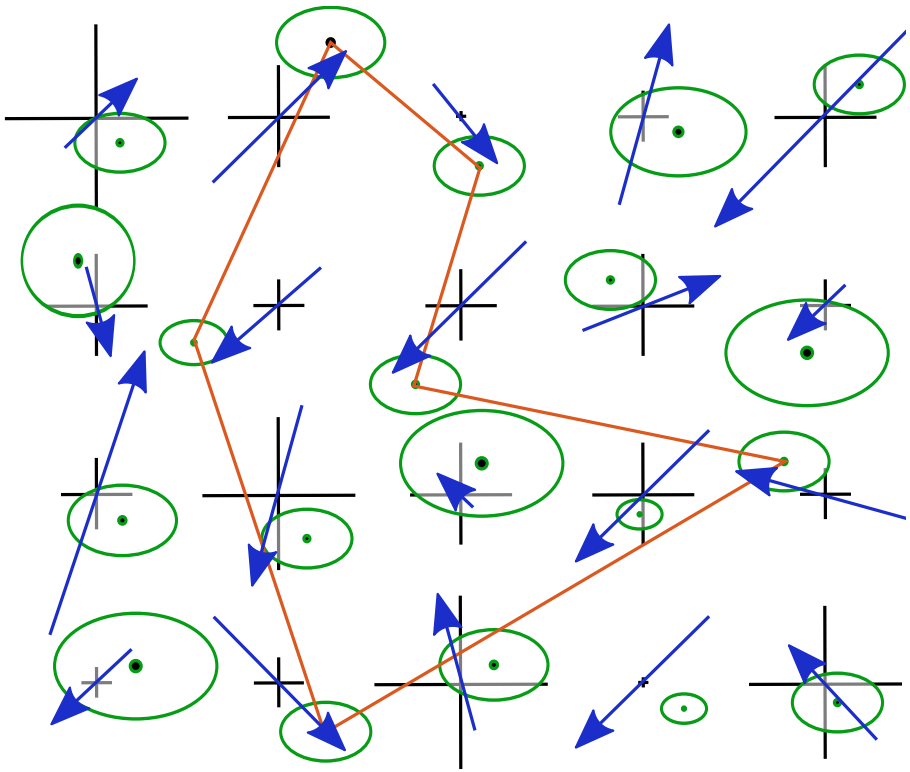
Taking the SM to higher dimensions



- using established bricks (fields and symmetries)
- organised by relevance (operator dimension)
- full coverage of heavy new physics (finite operator set)

systematic strategy through a global approach

Isolating patterns of new physics



array of sensitive observables

precise measurements

precise SMEFT predictions

$\rightarrow$ correlate deviations

Global SMEFT analyses

Global SMEFT analyses for e^+e^-

Higgs and EW

- Ellis, Roloff, Sanz, You '15, '17
- de Blas, Ciuchini, Franco, Mishima, Pierini, Reina, Silvestrini '16
- GD, Grojean, Gu, Wang '17
- Di Vita, GD, Grojean, Gu, Liu, Panico, Riembau, Vantalon '17
- de Blas, GD, Grojean, Gu, Paul '19
- Barklow, Fujii, Jung, Karl, List, Ogawa, Peskin, Tian '17
- Barklow, Fujii, Jung, Peskin, Tian '17

→ ECFA Higgs Study Group '19

Top

- Amjad et al. '13, '15
- Grzadkowski, Hioki '00; Janot '15
- GD, Perello, Vos, Zhang '18
- GD, Irles, Miralles, Penuelas, Poeschl, Perello, Vos '19

Top and Higgs

- GD, Gu, Vryonidou, Zhang '18
- Jung, Lee, Perello, Tian, Vos '20

Higgs & EW

[Ellis, Roloff, Sanz, You '15; '17]

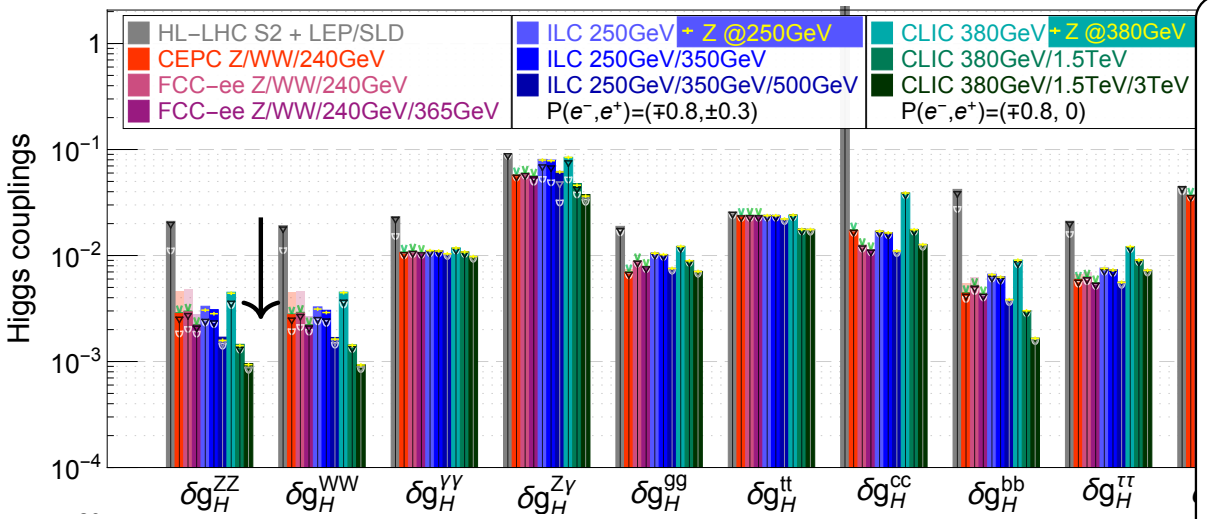
[de Blas, Ciuchini, Franco, Mishima, Pierini, Reina, Silvestrini '16]

[Barklow, Fujii, Jung, Karl, List, Ogawa, Peskin, Tian '17; '17]

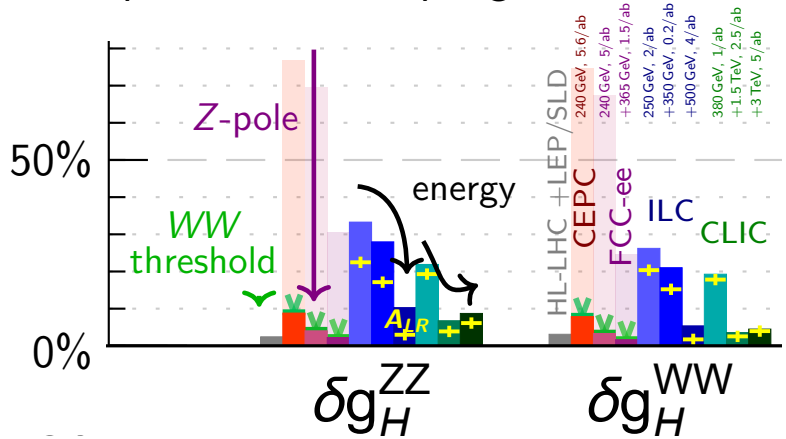
[GD, Grojean, Gu, Wang '17; + Di Vita, Liu, Panico, Riembau, Vantalon '17; + de Blas, Paul '19]

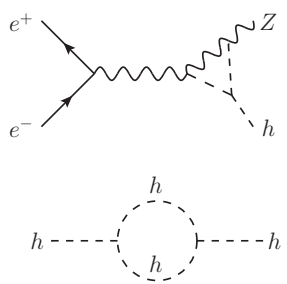
[ECFA Higgs Study Group '19]

order-of-magnitude improvement wrt. HL-LHC

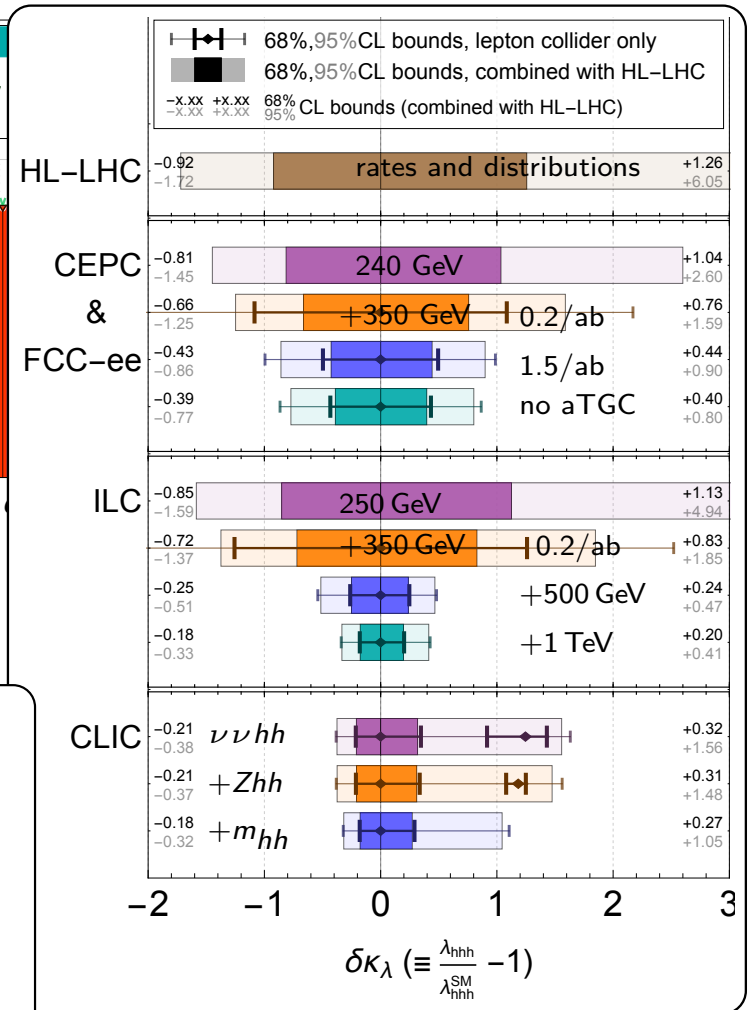


impact of EW coupling uncertainties





[McCullough '13]



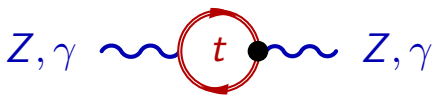
indirect λ_{hhh} determination requires two energy runs

Top quark & Higgs

[Vryonidou, Zhang '18; + GD, Gu '18]
[Jung, Lee, Perelló, Tian, Vos '20]

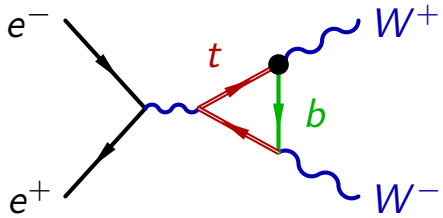
EWPO

[Zhang, Greiner, Willenbrock '12]



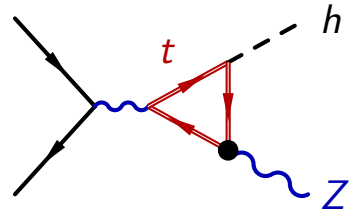
Diboson

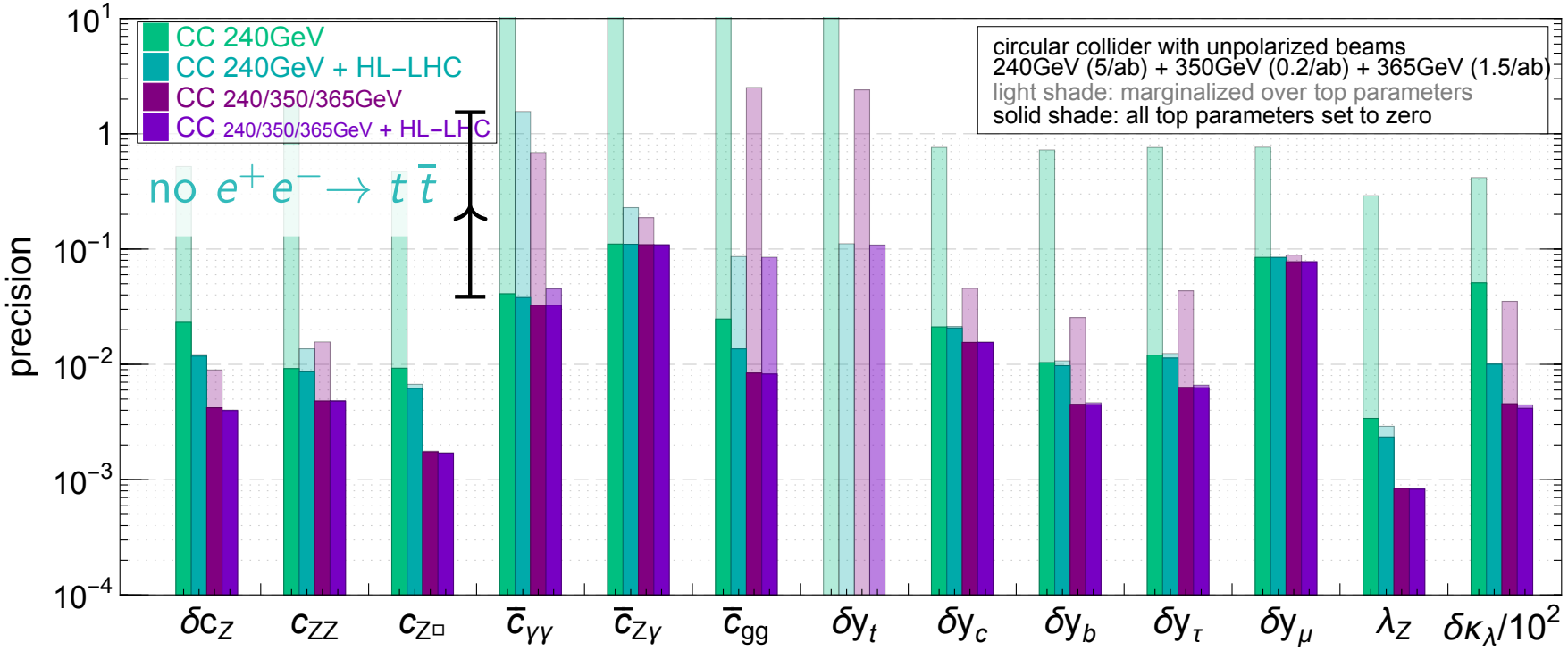
[GD, Gu, Vrionidou, Zhang '18]



Higgs

[Vrionidou, Zhang, '18]
[see also Boselli et al '18]





Top-quark uncertainties can impede Higgs precision!

$e^+e^- \to t\,\bar{t}$ measurements required at two c.o.m. energies!

Lessons from global analyses

- Order-of-magnitude improvement from HL-LHC to future e^+e^- (excepted on rare but clean $h\gamma\gamma$, $hZ\gamma$, $h\mu\mu$ or on $ht\bar{t}$) and $hc\bar{c}$
- Triple-Higgs coupling robustly probed at the loop-level with 250 and 350 GeV runs, or above the $e^+e^- \to Zhh$ threshold
- Good control over EW couplings is required for Higgs coupling extractions (Z-pole, or radiative return and higher energies)
- Without $e^+e^- \to t\,\bar{t}$, top electroweak coupling uncertainties impede Higgs precision (two c.o.m. energies needed to constrain simultaneously $t\bar{t}V$ and $e^+e^-t\bar{t}$ interactions)

Possible improvements

[J. de Blas @Snowmass, 4 June & 24 Sept. '20]

Important topics not covered in ESU studies

Some topics related to EW/Higgs physics

- **EW precision observables:**
  - ✓ Detailed assessment of impact of SM uncertainties for EWPO in SMEFT fits.
  - ✓ Clarify systematics for heavy flavor observables (A_q, R_q).
  - ✓ Exploit EW obs. outside the Z-pole (low and high energy) ⇒ add 4-fermion ops.
  - ✓ NLO EFT [Dawson, Giardino '19]
  - ✓ Flavor (and CP violation): not explored in the ESU SMEFT fits.
- **Higgs and Multi-boson processes:**
  - ✓ Boosted Higgs, Higgs off-shell measurements, …
  - ✓ Full EFT studies of $e^+e^- \to W^+W^-$. Use of "optimal" observables.
  - ✓ High-E probes of EFT effects that grow with the energy.
  - ✓ Vector boson scattering: not included in ESU studies.
- **Interplay EW/Higgs/Top:** Top sector only explored superficially:
  - ✓ Consider effects from 4-fermion operators or top dipole operators.
  - ✓ Exploit NLO effects of Top couplings in H/EW.
- **SMEFT assumptions:**
  - ✓ Impact of SMEFT uncertainties: NLO, (dim-6)^2 vs. dim 8, …
  - ✓ Non-universality: combine with flavor data to explore more flavor BSM scenarios
  - ✓ exotic Higgs decays?
  - ✓ HEFT?

J. de Blas
C. Grojean

Snowmass 2021 - EF01 & EF04 WG meeting
Sept 24, 2020

4

Possible improvements

[C. Grojean @Snowmass, 13 May & 24 Sept. '20]

Future Directions - II

- Consider HEFT setups? Which expansion parameter? Which BSM scenarios do we want to test? Generically, HEFT doesn't predict that $\kappa_i \sim 1$.
- Estimate EFT uncertainties (NLO, dim-8 effects, linear vs quadratic…), NP in backgrounds, theoretical constraints (positivity, analyticity)
- Explore more flavour scenarios (and make connection with flavour data)
- Full-fledged EFT analysis of diboson data (away from TGC dominance assumption) with statistically optimised observables
- More combined Higgs and top analysis
  1. effects of top dipoles or 4 fermion ops. with tops
  2. constraints on top EW couplings from their NLO effects in Higgs and diboson processes (particularly relevant for low-energy colliders below ttH threshold)
- Don't forget correlations
- Provide more BSM interpretations, i.e., match to different models/UV dynamics. Which physics hypotheses do we want to test? Which consequences for cosmo?

Possible improvements

[M. Peskin @Snowmass, 24 Sept. '20]

- New-physics interpretations
- EFT validity and truncation independence
- New sensitivities from higher orders
- EFT in backgrounds (e.g. four-fermion operators)
- Exotic Higgs decays

Experimental study targets

Ongoing activities

[performance meetings: Nov, March and May]
[more details in J. Eysermans' talk]

- ZH cross section and m_h (recoil of $Z \to \mu^+\mu^-$ and hadrons)
- $H \to b\bar{b}, c\bar{c}, gg$ and $s\bar{s}$ ($Z \to \ell^+\ell^-, \nu\bar{\nu}, jj$)
- $H \to \tau\tau$ (+ CPV + light scalars at Z pole)
- $H \to$ invisible ($Z \to e^+e^-, \mu^+\mu^-, b\bar{b}, q\bar{q}$)
- self-coupling through loops
  - recoil with $Z \to \mu^+\mu^-, q\bar{q}$ at 240 & 365 GeV
  - VFB $\nu\bar{\nu}H(b\bar{b})$ and $e^+e^-H(b\bar{b})$ at 365 GeV
  - combination with di-Higgs at FCC-hh
- differential $ZH \to 4f$ for anomalous couplings [Beneke, Boito, Wang '14] [Craig, Gu, Liu, Wang '15]
- $e^+e^- \to H$

SM couplings: check list

[ECFA Higgs Study Group '19]

	FCC-ee$_{240}$	FCC-ee$_{365}$
$\delta\sigma_{ZH}$	0.005 ✓	0.009
$\delta\mu_{ZH,bb}$	0.003 ✓	0.005
$\delta\mu_{ZH,cc}$	0.022 ✓	0.065
$\delta\mu_{ZH,gg}$	0.019 ✓	0.035
$\delta\mu_{ZH,WW}$	0.012	0.026
$\delta\mu_{ZH,ZZ}$	0.044	0.12
$\delta\mu_{ZH,\tau\tau}$	0.009 ✓	0.018
$\delta\mu_{ZH,\gamma\gamma}$	0.09	0.18
$\delta\mu_{ZH,\mu\mu}$	0.19	0.40
$\delta\mu_{ZH,Z\gamma}$	–	–
$\delta\mu_{\nu\nu H,bb}$	0.031	0.009 ✓
$\delta\mu_{\nu\nu H,cc}$	–	0.10
$\delta\mu_{\nu\nu H,gg}$	–	0.045
$\delta\mu_{\nu\nu H,ZZ}$	–	0.10
$\delta\mu_{\nu\nu H,\tau\tau}$	–	0.08
$\delta\mu_{\nu\nu H,\gamma\gamma}$	–	0.22
$\mathrm{BR}_{\mathrm{inv}}$	$<$0.0015 ✓	$<$0.003

$H \to VV^*$ and width
(in separate $4f$ channels)

rare $\gamma\gamma, \gamma Z, \mu\mu$ decays

$+$
combination
with correlations

Exotica largely untouched

[see BSM talks this afternoon]

- CPV
  - $H \to \tau\tau$ (planned)
  - differential ZH
- Quark flavour violation

  $H \to bs, bd, cu$ (extending $H \to$ hadrons analyses)
  and four-body?
- Lepton flavour violation

  $H \to \tau\mu, \tau e, \mu e$ (extending $H \to \tau\tau$ analysis)
  and four-body?
- More exotic decay?
  - $H \to xx, Zx \to 4f$ [Curtin, Essig, Gori, Jaiswal, Katz et al. '13]
  - displaced, long-lived, invisible [Cepeda, Gori, Outschoorn, Shelton '21]

TGC study needed in W^+W^-!

overlap with EW group:
A. Freitas, C. Paus, G. Wilson

- Crucial interplay with Higgs measurements

  [de Blas, GD, Grojean, Gu, Paul '19]

- Benefiting from optimal observables
  - used at LEP already [Opal, L3, ALEPH, DELPHI]
  - and in latest ILC studies [Karl PhD Thesis '19] [sec. 10.2 of Snowmass input]

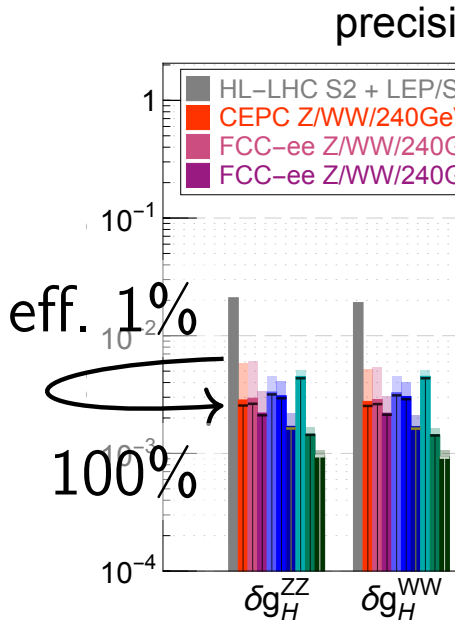
- Sensitivity driven by high energies (240, 365 GeV)

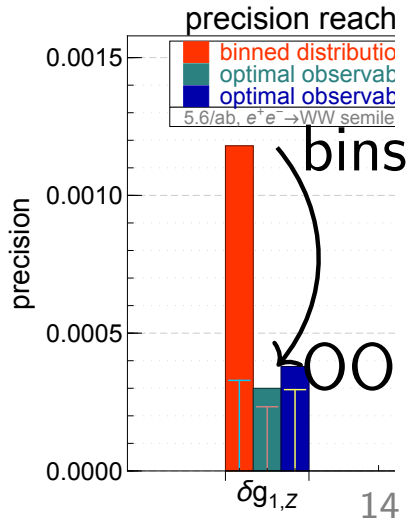
  enough forward detector coverage?

- Also sensitive to *Vff* couplings

  dependence often unduly neglected

  [GD, Grojean, Gu, Wang '17]





Theory calculations and Monte Carlo generators

What theory precision?

[Freitas, Heinemeyer, et al. '19]

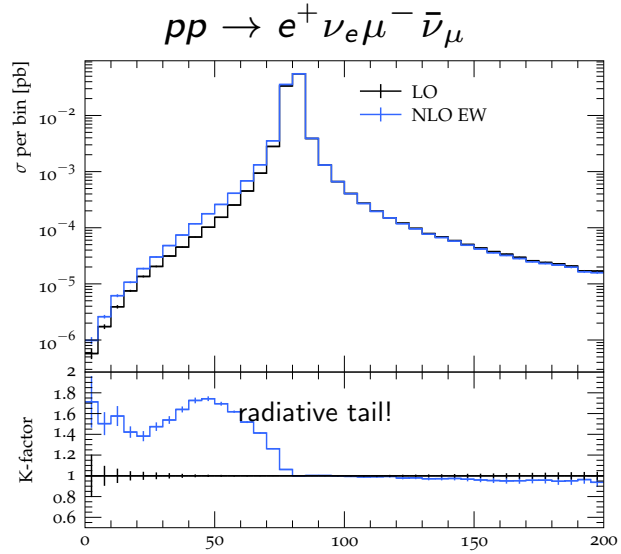
- 2-loop ZH needed for $< 1\%$ unc. and possibly achievable
  - off-shell Z effects?
- Partial 2-loop VBF possibly achievable and sufficient
- Off-shell WW production at 2-loop requiring significant effort
- Factorisable NNLO QCD to $H \to VV^* \to 4f$ decay achievable
- N^{4}LO $H \to gg$ and m_b dependence at N^{3}LO needed for $< 1\%$ unc. and possibly reachable
- One-loop SMEFT automation ongoing

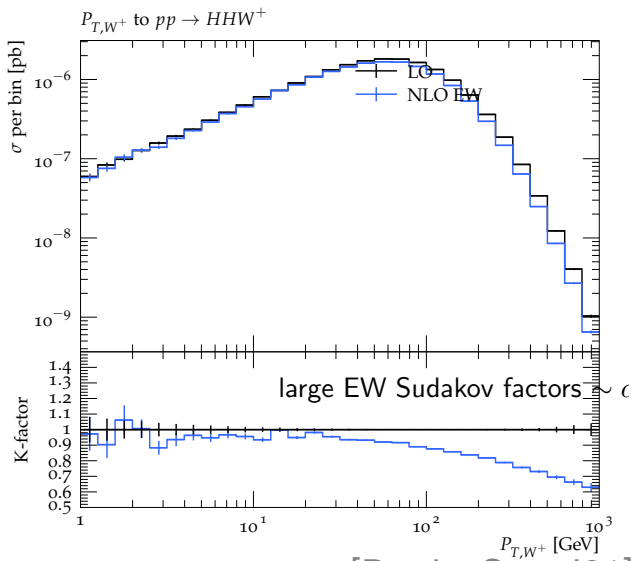
[Degrande, GD, Maltoni, Mimasu, Vryonidou, Zhang '20]

Whizard

[Stienemeier, March '21]

- UFO support for BSM completed
- ISR & beamsstrahlung,
  also for polarized beams
- automated NLO QCD
  (FKS subtraction, resonance aware)
- Powheg matching to Pythia8 shower
- NLO EW developments ongoing
  implementing NLL electron PDFs



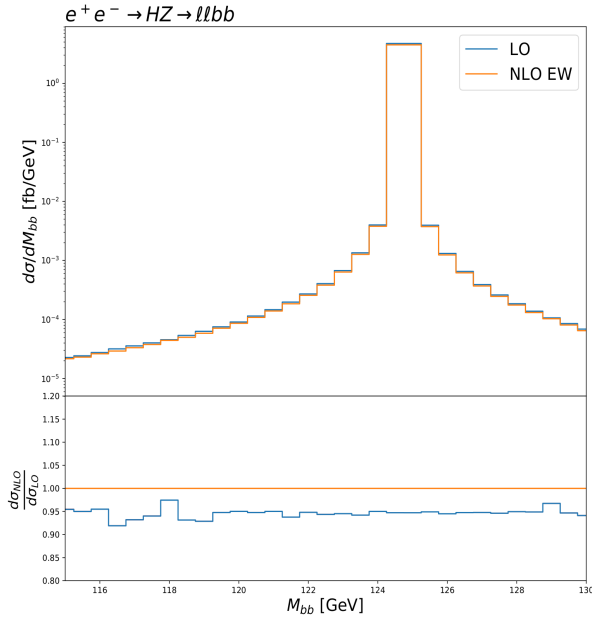


[Bredt, Sept '21]

[Frixione et al. '19, '19]

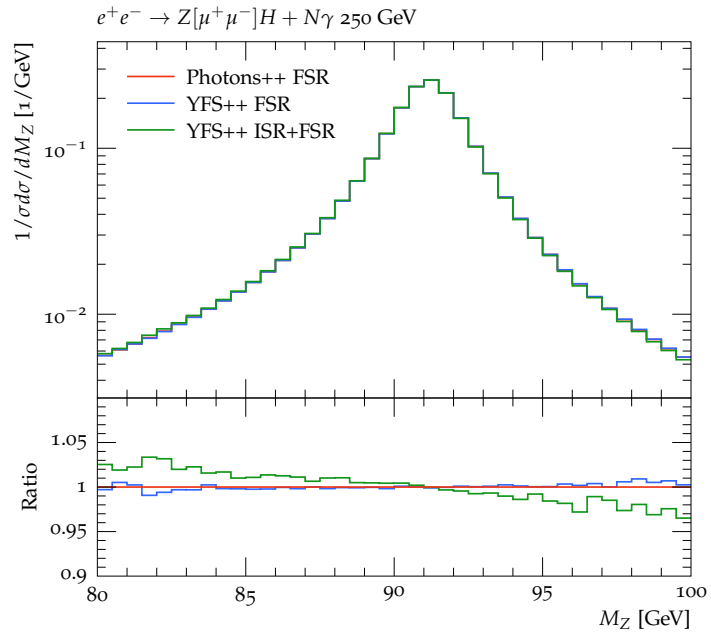
Sherpa

[Price, March '21]



- UFO support for BSM
- automated NLO QCD and EW (CS subtraction)
- mc@nlo matching to parton shower
- YFS resummation of soft&collinear photons
  - to be matched to NLO EW
  - ISR/FSR interference planned

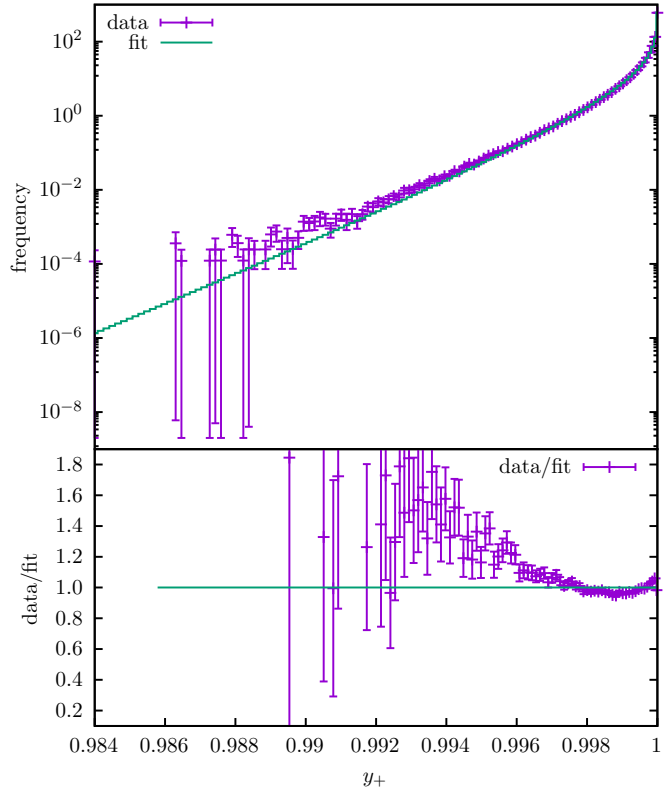
[Krauss, Price, Schönherr '22]



- Beamsstrahlung being implemented
- Underlying events (e.g. $\gamma\gamma$) planned

MadGraph

- UFO support for BSM (also at NLO)
- automated NLO QCD and EW (FKS, resonance aware)
- mc@nlo matching to parton shower
- ISR and beamsstrahlung (from v3.2.0)
  - for unpolarised beams
  - no spread above partonic beam energy
- NLL electron PDFs
  - computed for unpolarised beams
  - NLO EW being finalised



[Frixione, Mattelaer, Zaro, Zhao '21]

[Bertone, Cacciari, Frixione, Stagnitto '19, '19]

Higgs physics programme

The Higgs at 10 remains a mystery.

FCC(-ee) rich programme will bring a new level of precision.

Plenty of interesting TH & EX challenges!

Experimental studies not covered yet:

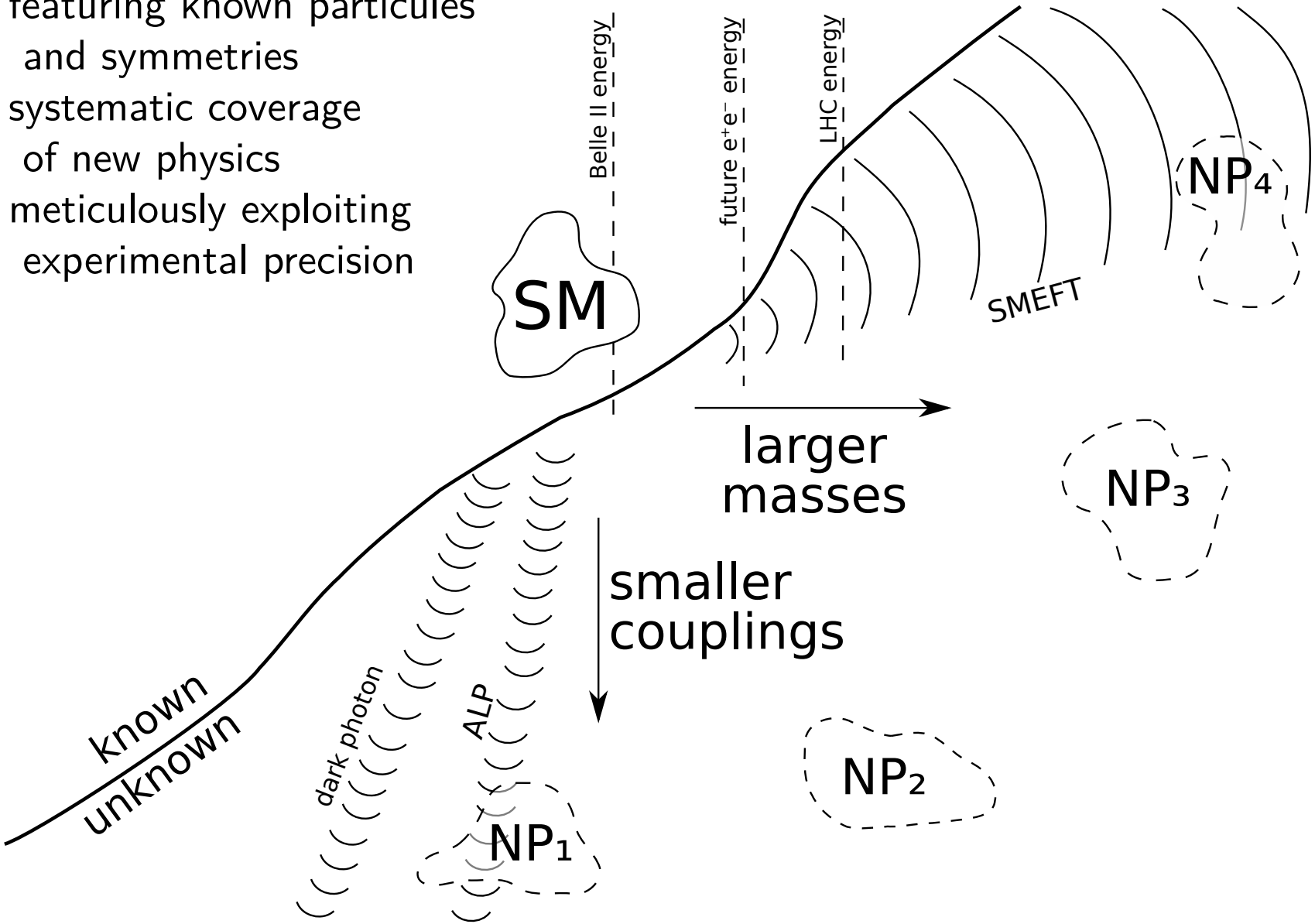
- $H \to VV^*$
- $H \to \gamma Z, \gamma\gamma, \mu\mu$
- channel combination
- TGC in $e^+e^- \to W^+W^-$
- CPV
- quark and lepton flavour violation
- ...

Lots of room for your contribution!

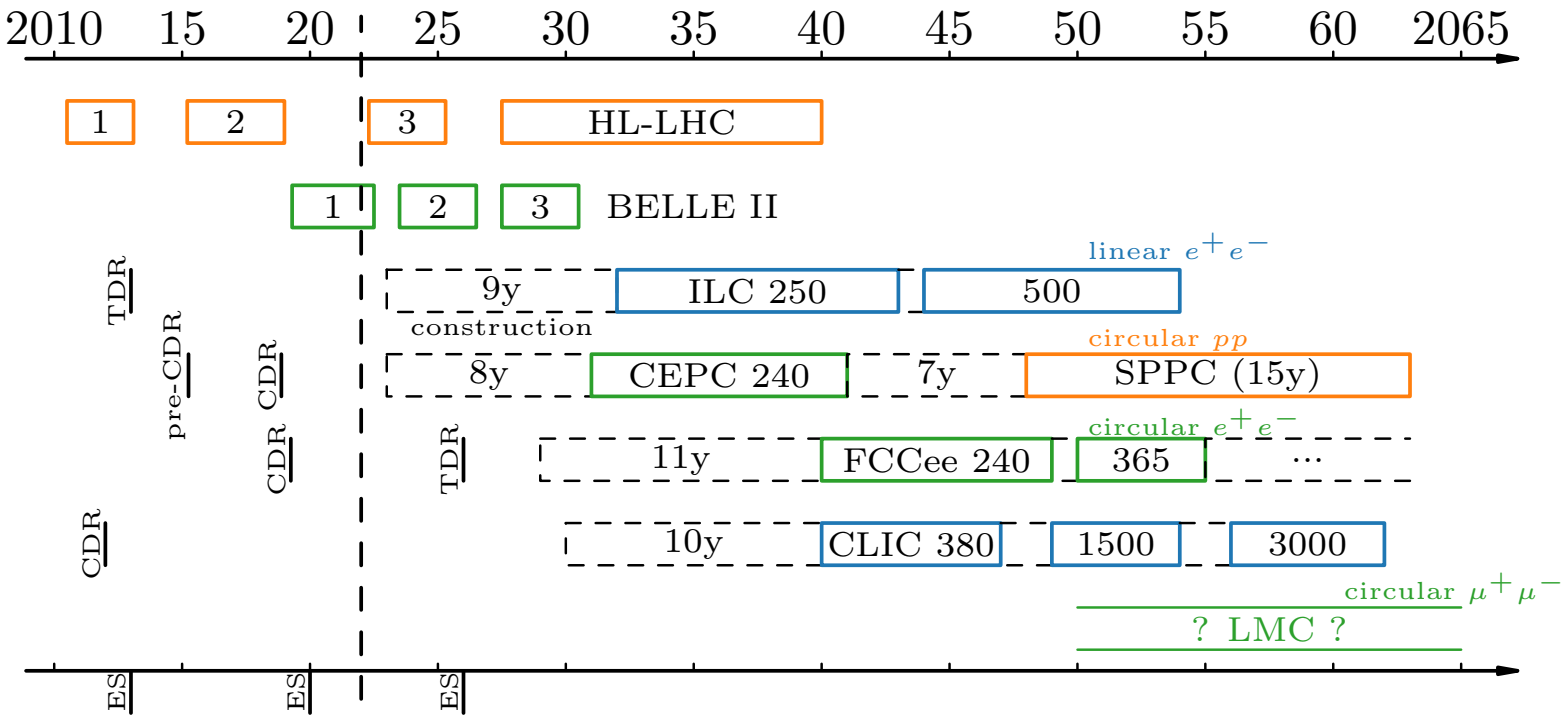
Extras

Standard-model effective field theory

- featuring known particules and symmetries
- systematic coverage of new physics
- meticulously exploiting experimental precision



Collider timeline

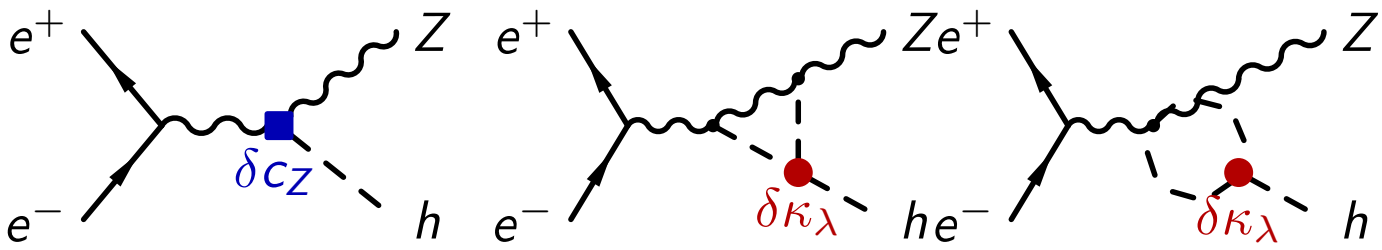


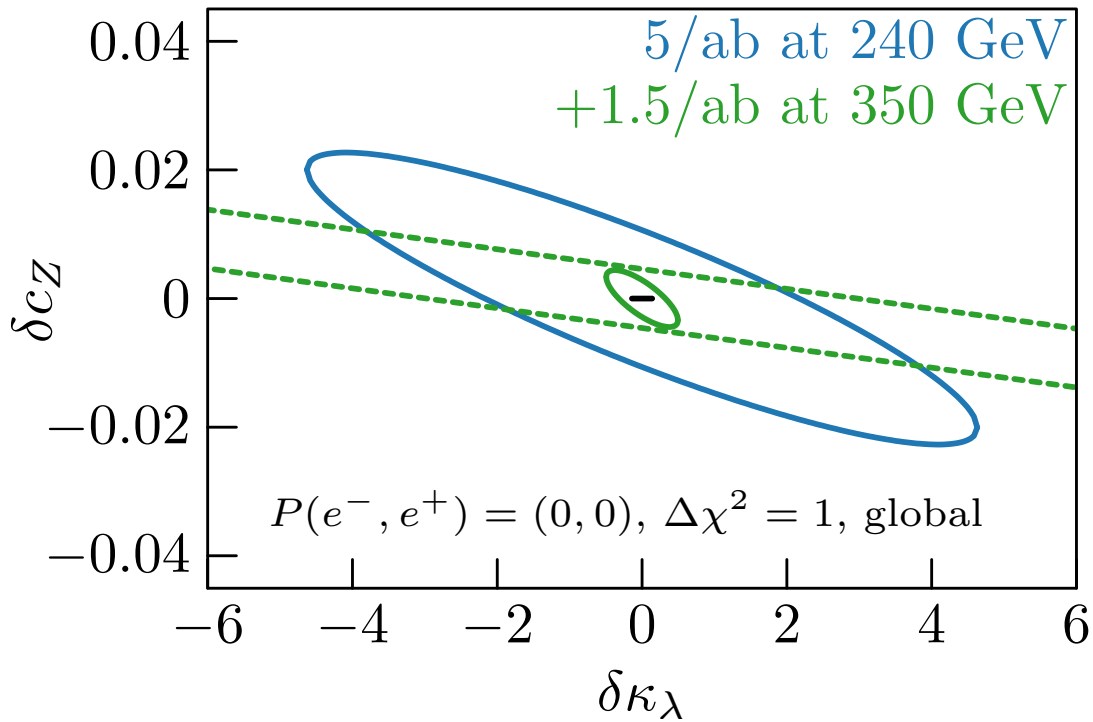
precision as target for LHC and future lepton colliders

Trilinear Higgs self-coupling

[Di Vita, GD, Grojean, Gu, Liu, et al. '17]

[McCullough '13]
[Gorbahn, Haisch '16]
[Degrassi et al. '16]
[Bizon et al. '16]
[Degrassi et al. '17]
[Kribs et al. '17]
[Maltoni et al. '17]



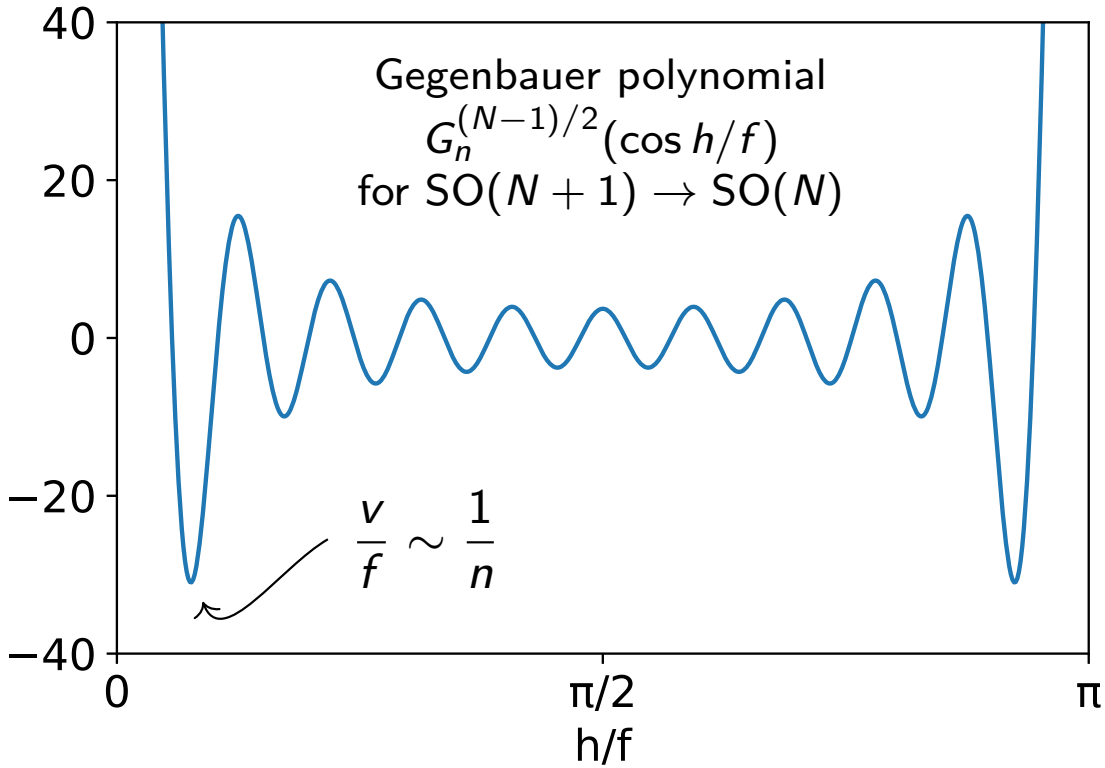


Correlations with single-Higgs couplings require two $\sqrt{s}$.

Large self-coupling deviations?

[GD, McCullough, Salvioni '21, '22]

Radiatively stable potential for pseudo-Nambu-Goldstone Higgs.



Naturally features $\mathcal{O}(1\%)$ Higgs deviations,

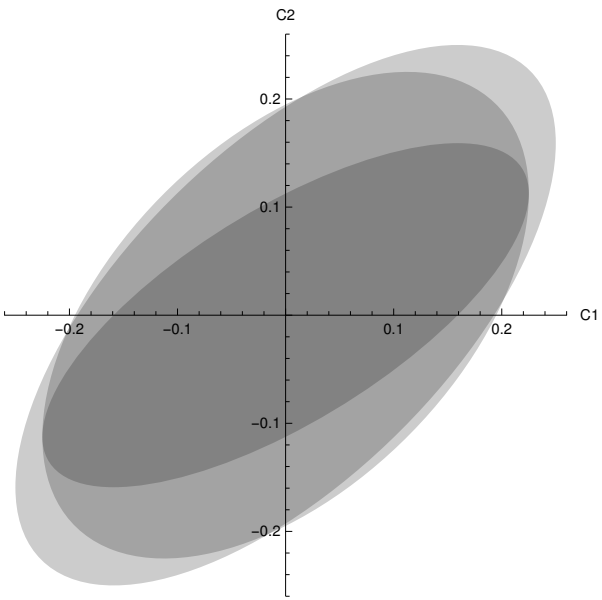
but yields $\mathcal{O}(100\%)$ self-coupling modifications.

Statistically optimal observables

[Atwood,Soni '92]
[Diehl,Nachtmann '94]

minimize the one-sigma ellipsoid in EFT parameter space.
(*joint efficient* set of estimators, saturating the Rao-Cramér-Fréchet bound: $V^{-1} = I$)

For small C_i, with a phase-space distribution $\sigma(\Phi) = \sigma_0(\Phi) + \sum_i C_i\, \sigma_i(\Phi)$,
the statistically optimal set of observables is: $O_i(\Phi) = \sigma_i(\Phi)/\sigma_0(\Phi)$.



e.g. $\sigma(\phi) = 1 + \cos(\phi) + C_1 \sin(\phi) + C_2 \sin(2\phi)$

1. asymmetries: $O_i \sim \text{sign}\{\sin(i\phi)\}$
2. moments: $O_i \sim \sin(i\phi)$
3. statistically optimal: $O_i \sim \dfrac{\sin(i\phi)}{1+\cos\phi}$

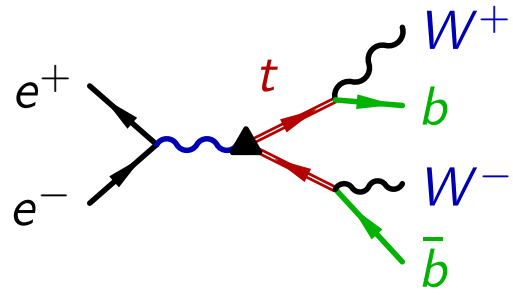
$\Longrightarrow$ area ratios 1.9 : 1.7 : 1

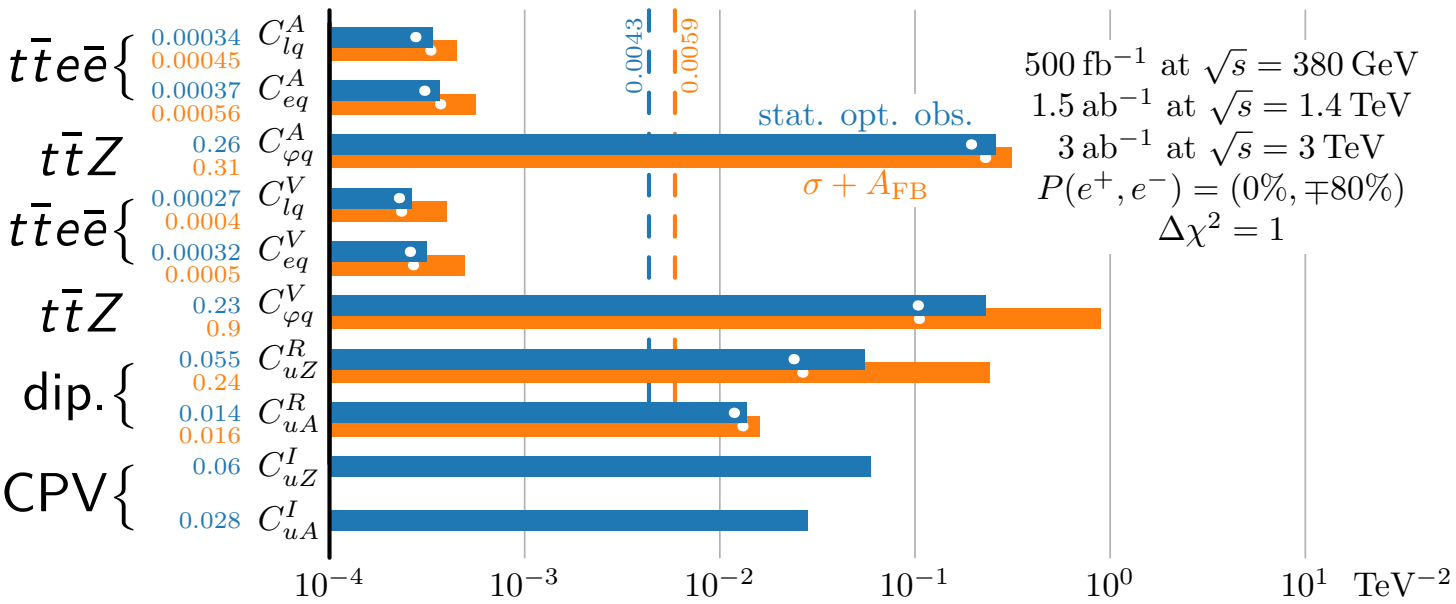
Previous applications in $e^+e^- \to t\,\bar{t}$:
[Grzadkowski, Hioki '00] [Janot '15] [Khiem et al '15]

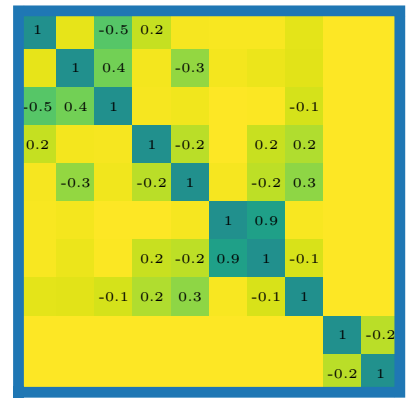
Statistically optimal observables

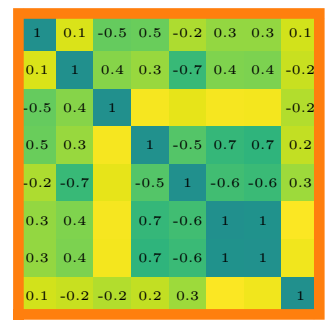
[GD, Perelló, Vos, Zhang '18]
[CLICdp '18]

- exploiting differential distributions
- covering multidimensional parameter spaces
- enhancing linear terms and EFT validity





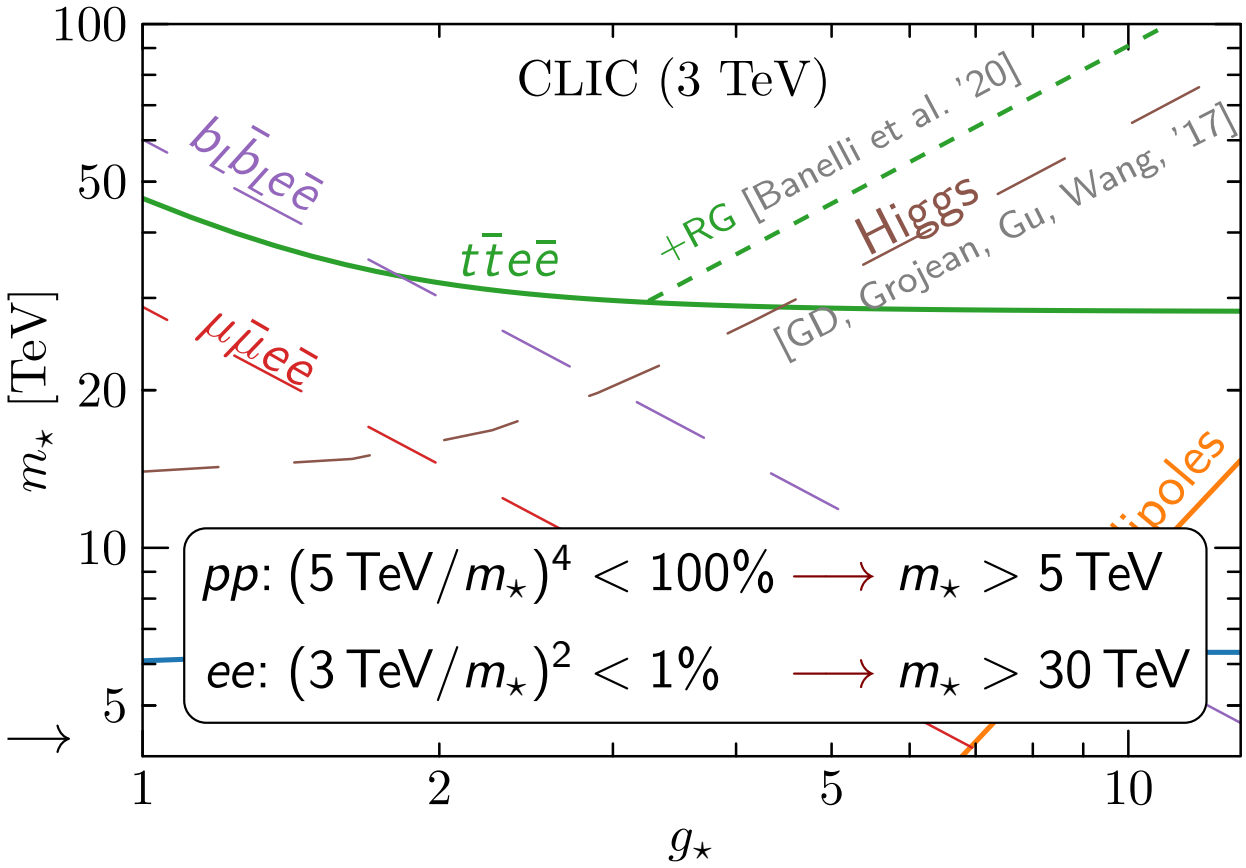




Composite Higgs scenario

[GD, Matsedonskyi '18]

- 1σ sensitivities
- fully composite t_R
- up to $\pm\mathcal{O}(1)$ factors

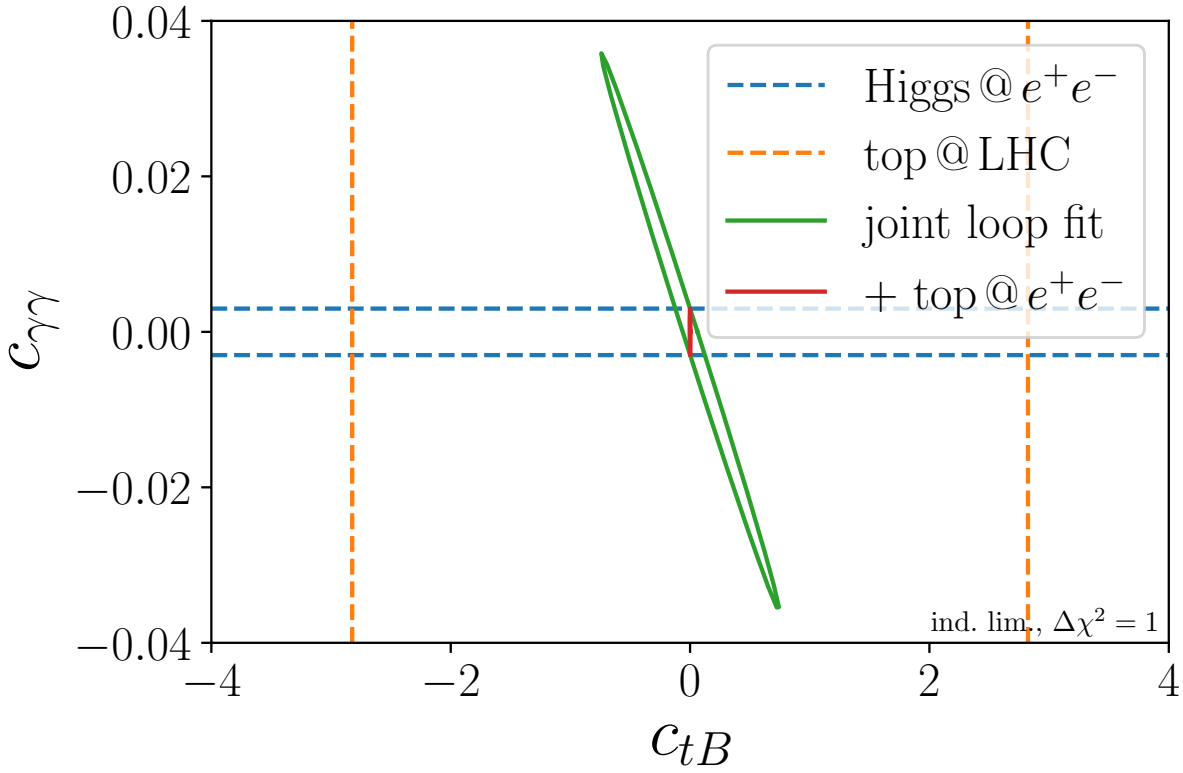


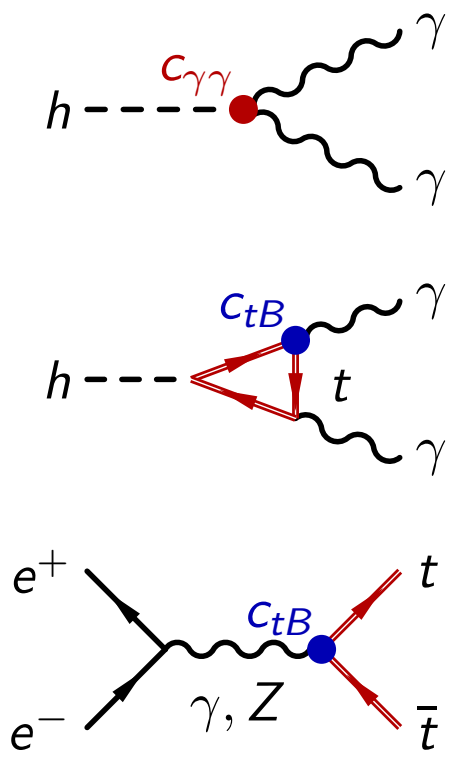
HL-LHC
[Farina et al. '18]
→

Top is complementary to Higgs

Top-Higgs interplay

[GD, Gu, Vryonidou, Zhang '18]





Higgs@e^+e^- helps improving top coupling precision.

Higgs precision is however contaminated by top uncertainties.

Top@e^+e^- is needed to achieve the full potential of Higgs@e^+e^-.

SMEFT at one loop

- $pp \to jj$ $(q\bar{q}q\bar{q})$ [Gao, Li, Wang, Zhu, Yuan '11]
- $pp \to t\bar{t}$ $(q\bar{q}t\bar{t})$ [Shao, Li, Wang, Gao, Zhang, Zhu '11]
- $pp \to VV$ [Dixon, Kunszt, Signer '99] [Melia, Nason, Röntsch, Zanderighi '11] [Baglio, Dawson, Lewis '17, '18, '19] [Chiesa, Denner, Lang '18]

- EWPO (top) [Zhang, Greiner, Willenbrock '12]
- top decays [Zhang '14] [Boughezal, Chen, Petriello, Wiegand '19]
- top FCNCs UFO [Degrande, Maltoni, Wang, Zhang '14] [**GD**, Maltoni, Zhang '14]
- $pp \to t\bar{t}$ (chromo-dipole) [Franzosi, Zhang '15]
- $h \to \gamma\gamma$, VV, γZ [Hartmann, Trott '15] [Ghezzi, Gomez-Ambrosio, Passarino, Uccirati '15] [Dawson, Giardino '18] [Dedes, Paraskevas, Rosiek, Suxho, Trifyllis '18] [Dawson, Giardino '18] [Dedes, Suxho, Trifyllis '19]
- $h \to f\bar{f}$ [Gauld, Pecjak, Scott '15, '16] [Cullen, Pecjak, Scott '19, '20]
- $pp \to tj$ [Zhang '16] [de Beurs, Laenen, Vreeswijk, Vryonidou '18]
- $pp \to t\bar{t}Z$, $gg \to ZH$ [Röntsch, Markus Schulze '14] [Bylund, Maltoni, Vryonidou, Zhang '16]
- $pp \to t\bar{t}H$, $gg \to Hj, HH$ [Maltoni, Vryonidou, Zhang '16]
- $pp \to HV$ [Degrande, Fuks, Mawatari, Mimasu, Sanz '16] [Alioli, Dekens, Girard, Mereghetti '18]
- Z, W poles [Hartmann, Shepherd, Trott '16] [Dawson, Ismail, Giardino '18, '18, '19]
- $pp \to h$ [Grazzini, Ilnicka, Spira, Wiesemann '16] [Deutschmann, Duhr, Maltoni, Vryonidou '17]
- $pp \to tjZ, tjh$ [Degrande, Maltoni, Mimasu, Vryonidou, Zhang '18]
- $pp \to$ jets (triple gluon) UFO [Hirshi, Maltoni, Tsinikos, Vryonidou '18]
- Higgs self-coupling [McCullough '13] [Gorbahn, Haisch '16] [Degrassi et al. '16, '17] [Bizon et al. '16] [Kribs et al. '16] [Maltoni, Pagani, Shivaji, Zhao '17] [Di Vita, **GD**, Grojean, Gu, Liu, Panico, Riembau, Vantalon '17]

- EW Higgs & WW (top) [Vryonidou, Zhang '18] [**GD**, Gu, Vryonidou, Zhang '18] [Boselli, Hunter, Mitov '18]
- EW $pp \to t\bar{t}$ (ttZ,tth) [Martini, Schulze '19] [Martini, Pan, Schulze, Xiao '21]
- all QCD and four-quarks UFO [Degrande, **GD**, Maltoni, Mimasu, Vryonidou, Zhang '20]
- EW $pp \to \ell^+\ell^-$ [Dawson, Giardino '21, '22]
- EW $QQQQ$ in $gg \to h$, $h \to bb$, $pp \to tth$ [Alasfar, de Blas, Gröber '22]