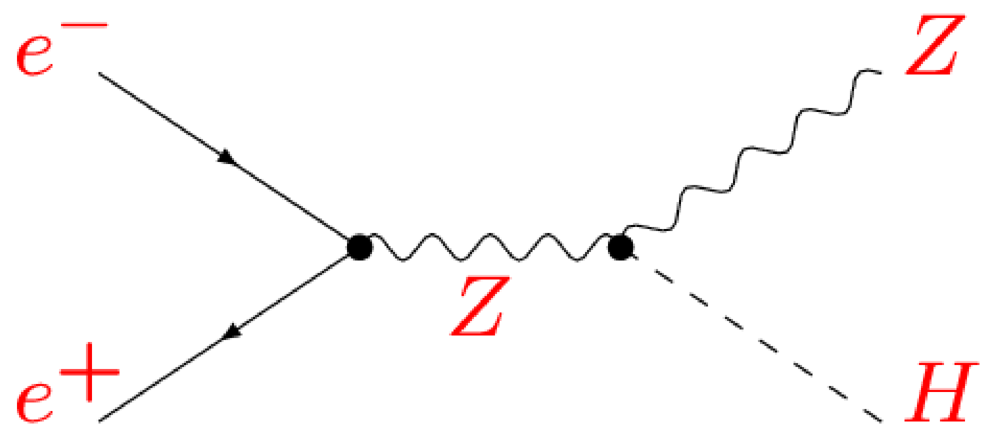
BSM opportunities at e^+e^- colliders

Georg Weiglein, DESY

03 / 2021

Introduction: electron-positron (e^-e^+) colliders

Electron, positron: elementary particles, not affected by strong interaction



Clean experimental environment:

Well-defined initial state, complete knowledge of energy and momentum of the collision process

Tuneable energy, polarisation of the electron and positron beams

Very small backgrounds

High-precision physics

Hadron colliders and lepton colliders provide complementary information, both needed for the understanding of nature; long success story of interplay of hadron and lepton colliders

Scope of this talk

Physics at an e^+e^- collider comprises

- high-precision physics involving known particles (h125, t, Z, W, …)
  ⇒ High sensitivity to (indirect) effects of new physics

- direct searches for the production of new particles,
  characterisation of the possible structure of new physics

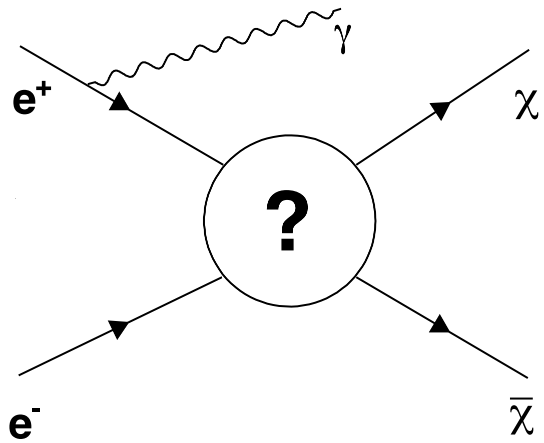
All parts of this programme contribute to the ``BSM opportunities at e^+e^- colliders", which the organisers asked me to talk about.

I interpret the charge for this talk as ``BSM physics at e^+e^- colliders beyond the property determination of the Higgs signal at 125 GeV (h125) at a 250 GeV Higgs factory"

BSM physics at a 250 GeV e^+e^- collider

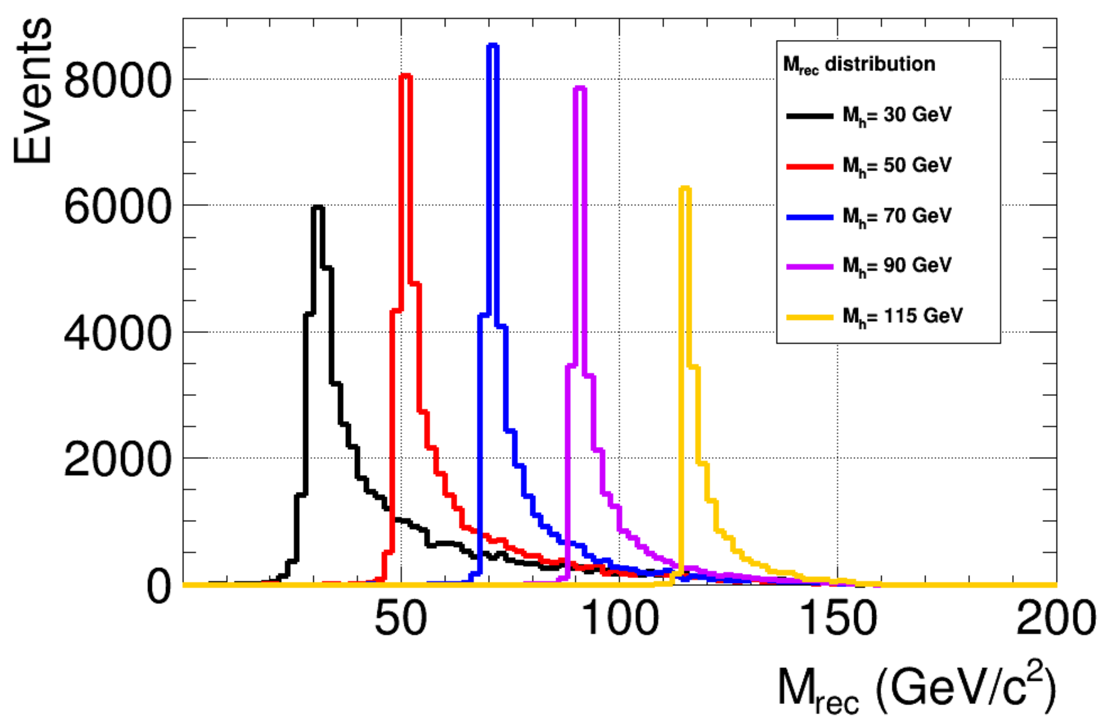
Example: dark matter

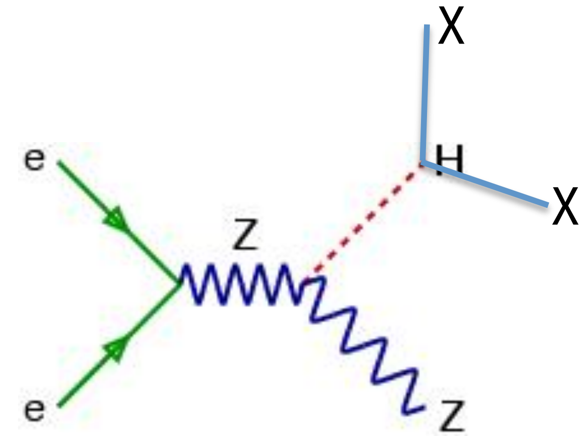
+ Higgs as mediator



yields complementary sensitivity to the LHC and to direct detection experiments

Example: invisible Higgs decays





⇒ Unique sensitivity at an e^+e^- Higgs factory

Search for additional (light) Higgs bosons

In a large variety of models with extended Higgs sectors the squared couplings to gauge bosons fulfill a ``sum rule”:

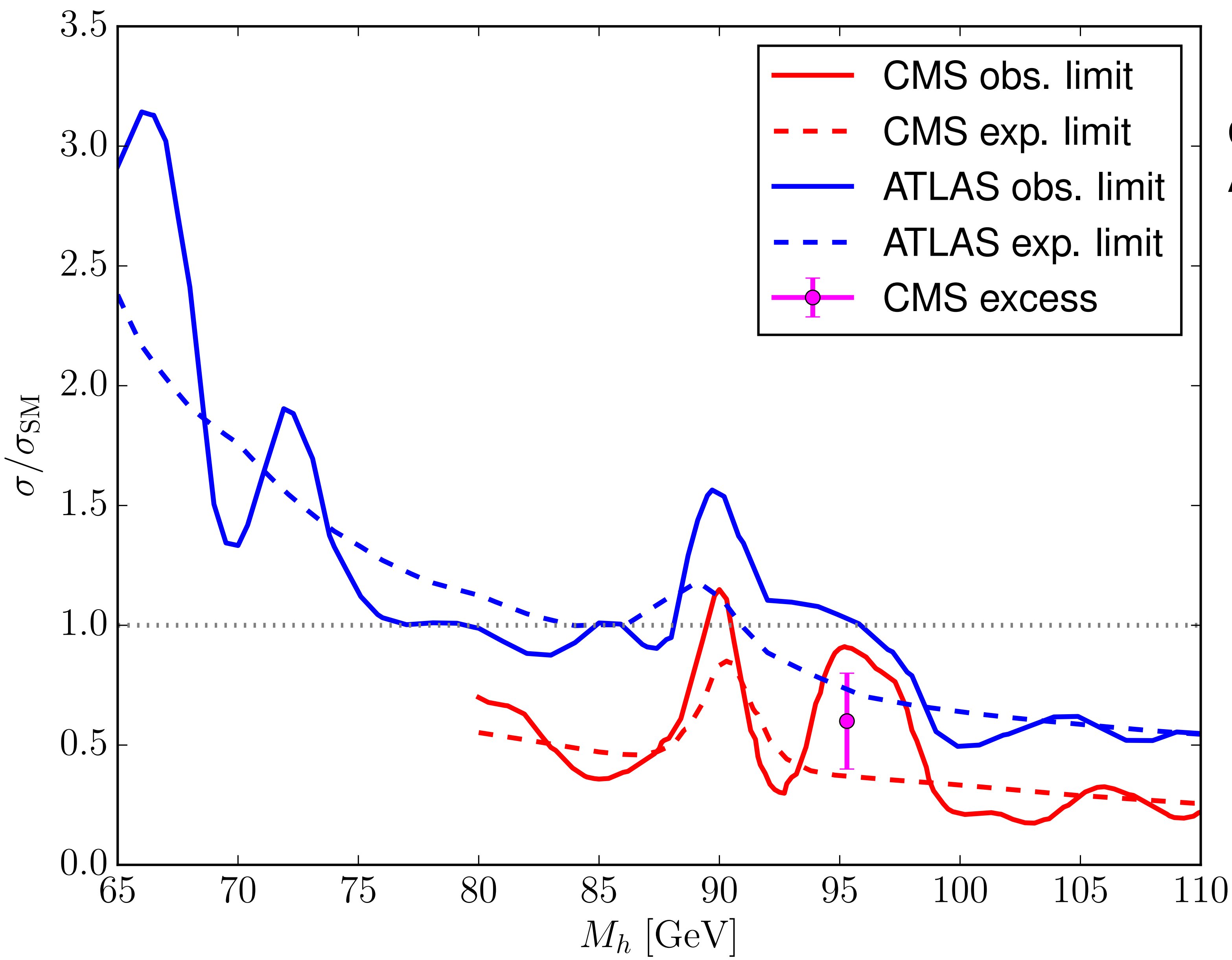
$$\sum_i g^2_{H_i VV} = \left(g^{\rm SM}_{HVV}\right)^2$$

⇒ The SM coupling strength is ``shared” between the Higgses of an extended Higgs sector, $\varkappa_V \leqq 1$

The more SM-like the couplings of the state at 125 GeV turn out to be, the more suppressed are the couplings of the other Higgses to gauge bosons

Hint for a light additional Higgs boson? CMS excess in the h → $\gamma\gamma$ search vs. ATLAS limit

[T. Stefaniak ’18]



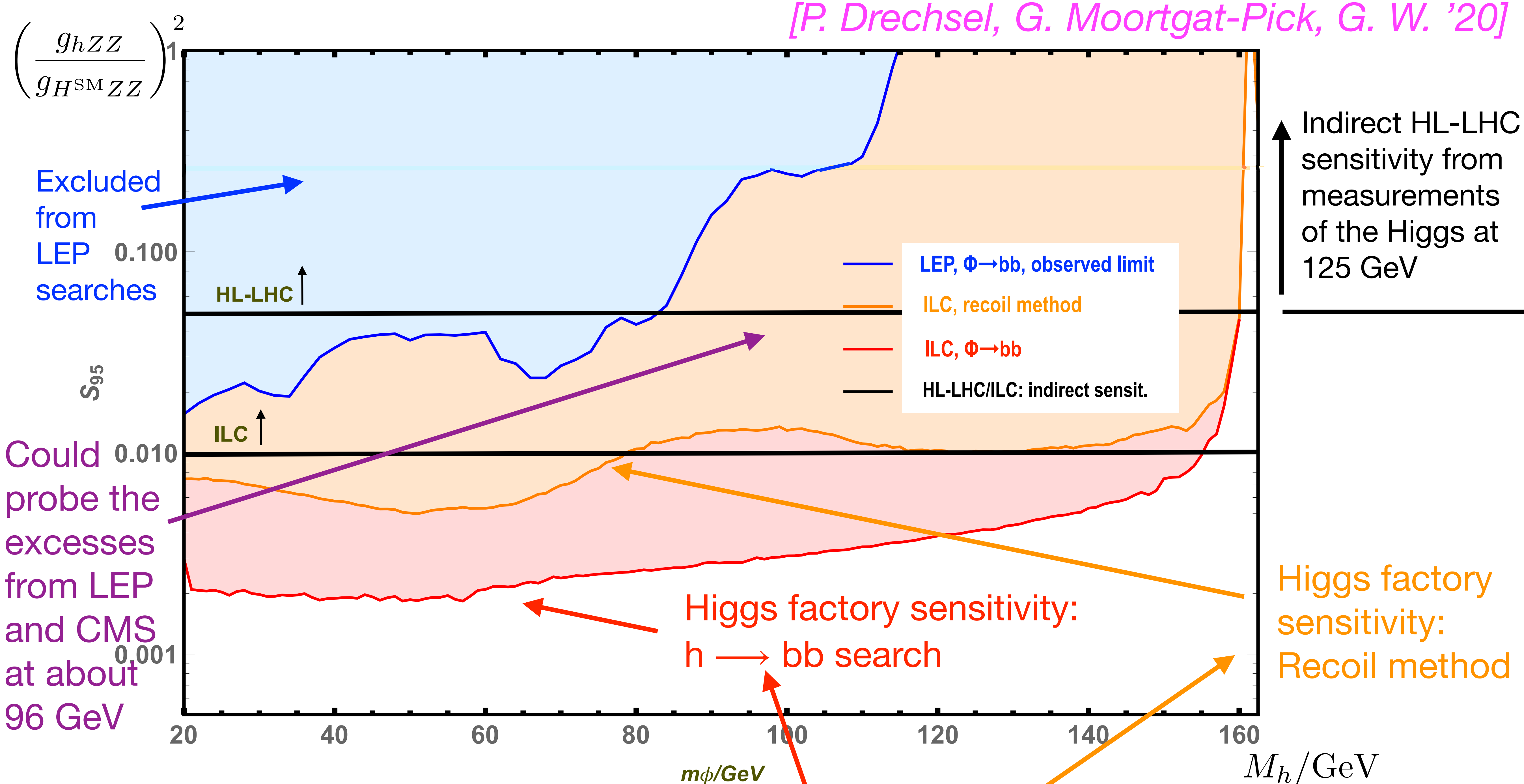
CMS-PAS-HIG 17-013,
ATLAS-CONF-2018-025

Note: also LEP reported a small excess at approximately the same mass in the h→bb channel

⇒ It is important to search for light additional Higgs bosons at the LHC and future facilities!

Example for discovery potential for new light states: Sensitivity at 250 GeV with 500 fb^{-1} to a new light Higgs

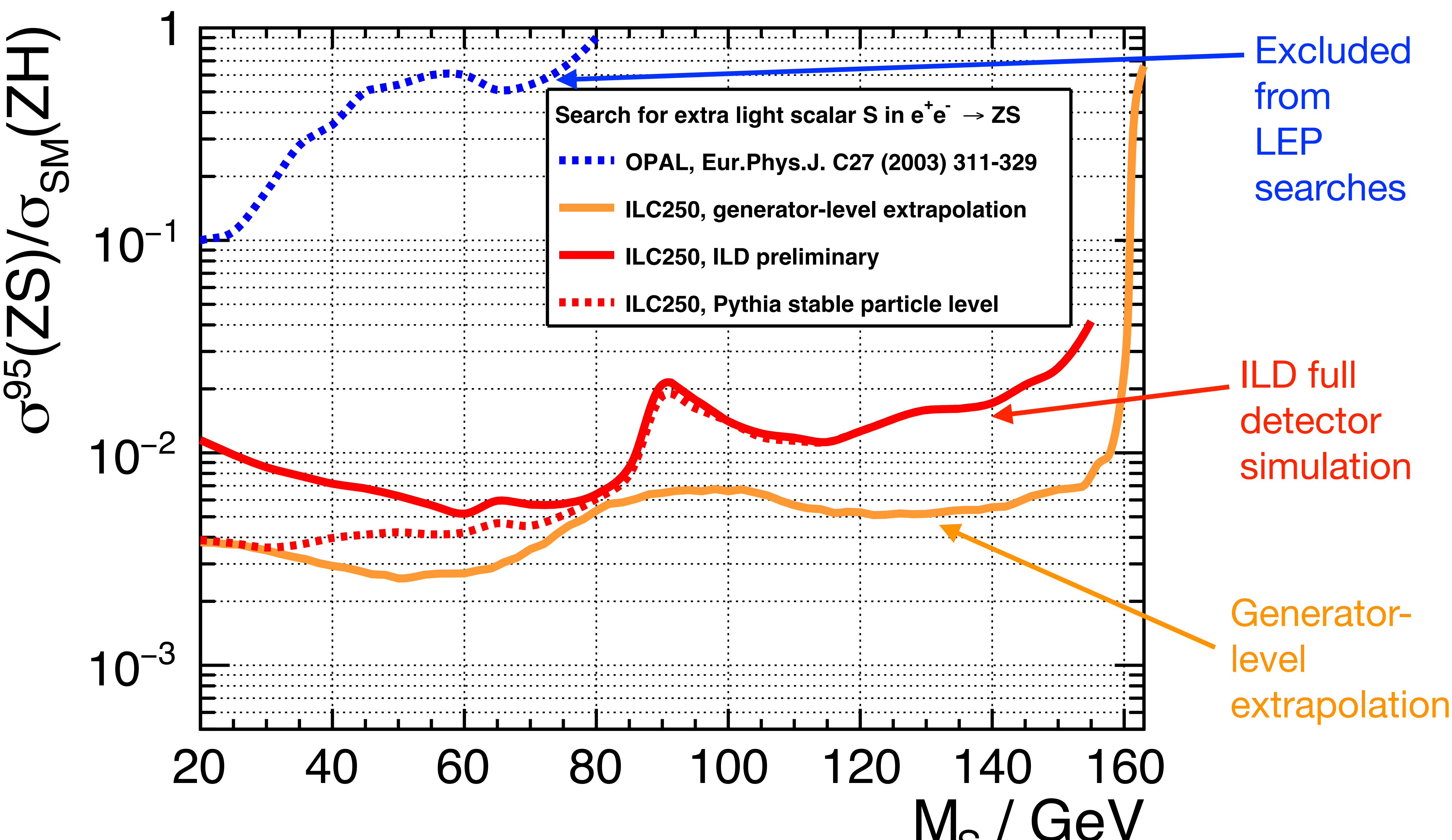
[P. Drechsel, G. Moortgat-Pick, G. W. '20]



⇒ Higgs factory at 250 GeV will explore a large untested region!

e^+e^- collider at 250 GeV with 2 ab^{-1}, recoil method: generator-level extrapol. + ILD full detector simulation

[P. Drechsel, G. Moortgat-Pick, G. W. '20] [Y. Wang, J. List, M. Berggren '19]

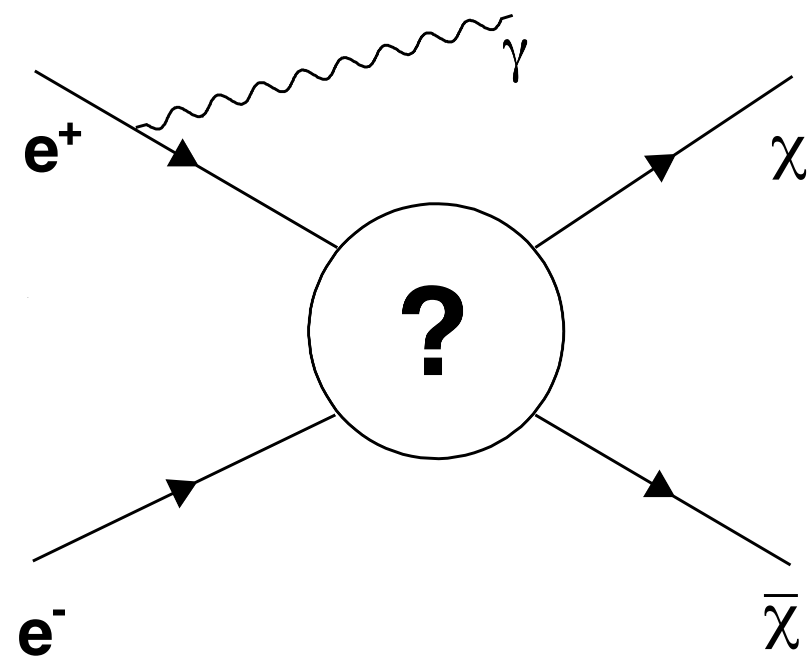


⇒ Higgs factory at 250 GeV will explore a large untested region!

BSM physics at higher or lower collider energies

Searches for new particles:

A LC with 500 GeV or more will have an improved sensitivity in particular in the searches for dark matter and new weakly interacting particles, which is complementary to the sensitivity of the HL-LHC.



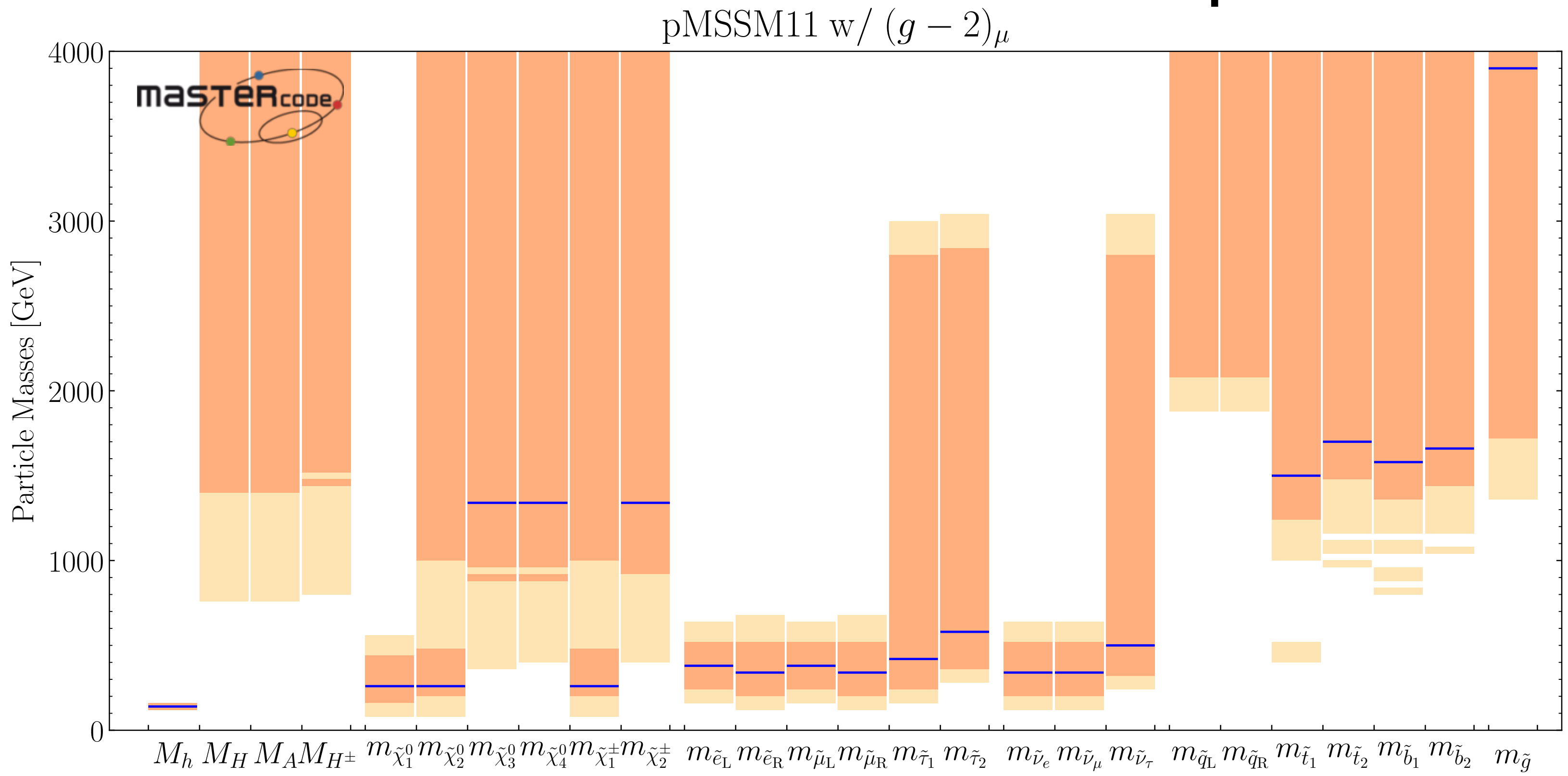
Electroweak physics:

The higher collider energy increases the indirect sensitivity to some effects from new physics.

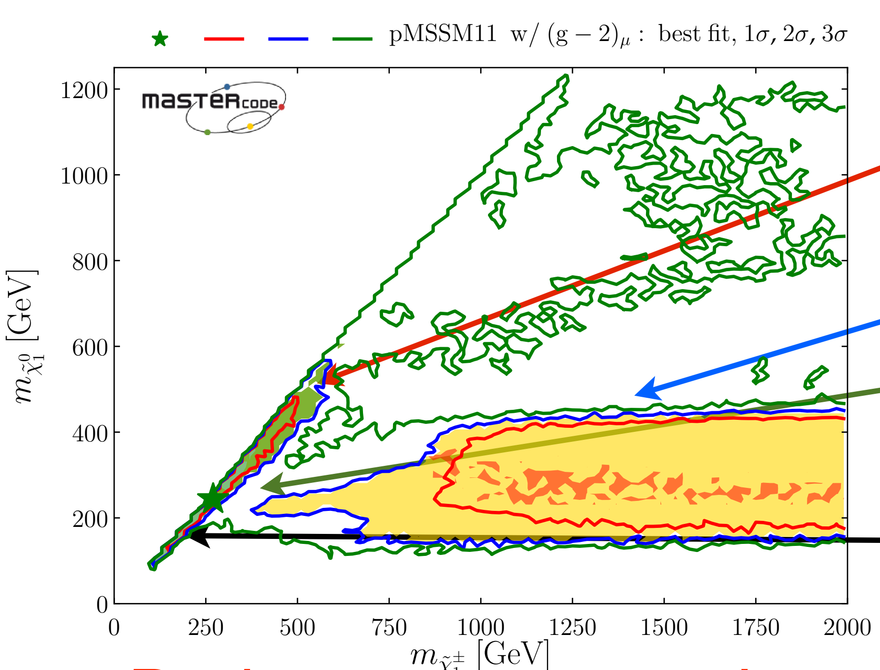
Where are the new particles?
Example: global SUSY fit

[E. Bagnaschi et al '18, 19]

MasterCode: Global fit in the MSSM with 11 parameters



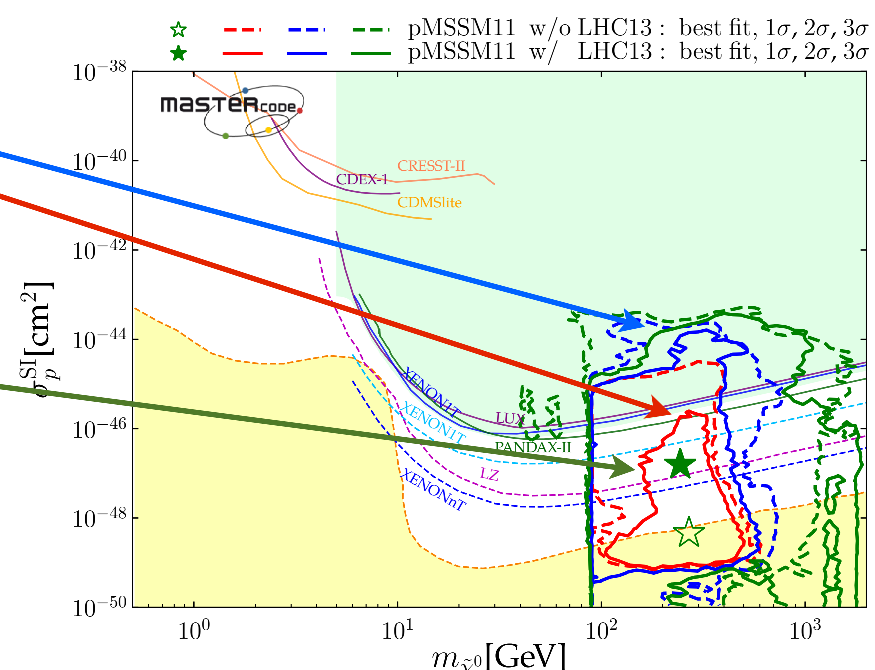
Best fit region and implications for collider and dark matter searches:



68% / 95%
C.L. contours

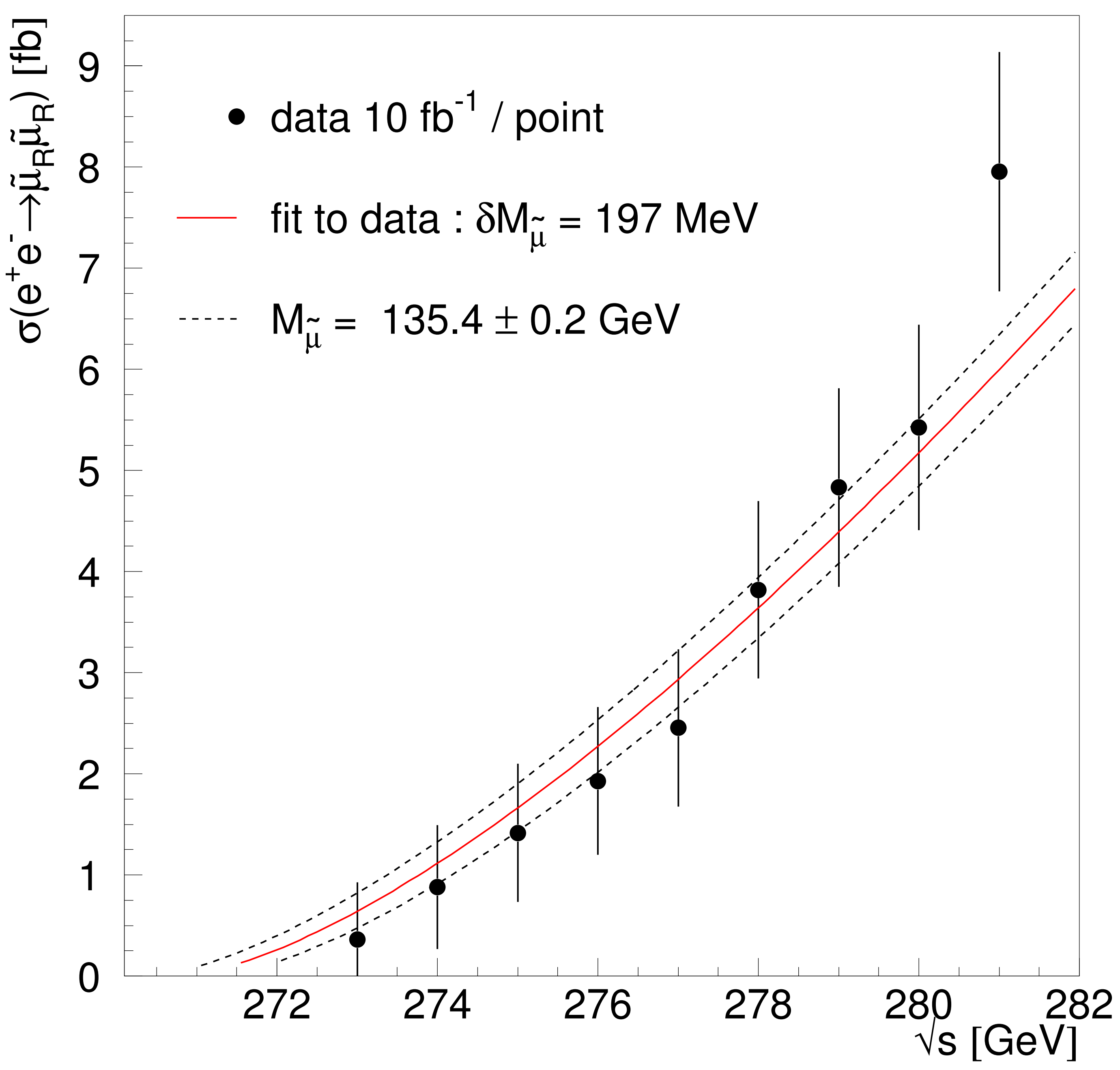
Best fit points

Compressed
spectrum



⇒ Dark matter constraint and $(g\text{-}2)_\mu$ favour light ew particles, compressed spectra

Example: scalar muon production at the ILC



⇒ Determination of mass and spin of the new particle

Direct searches for new particles at CLIC

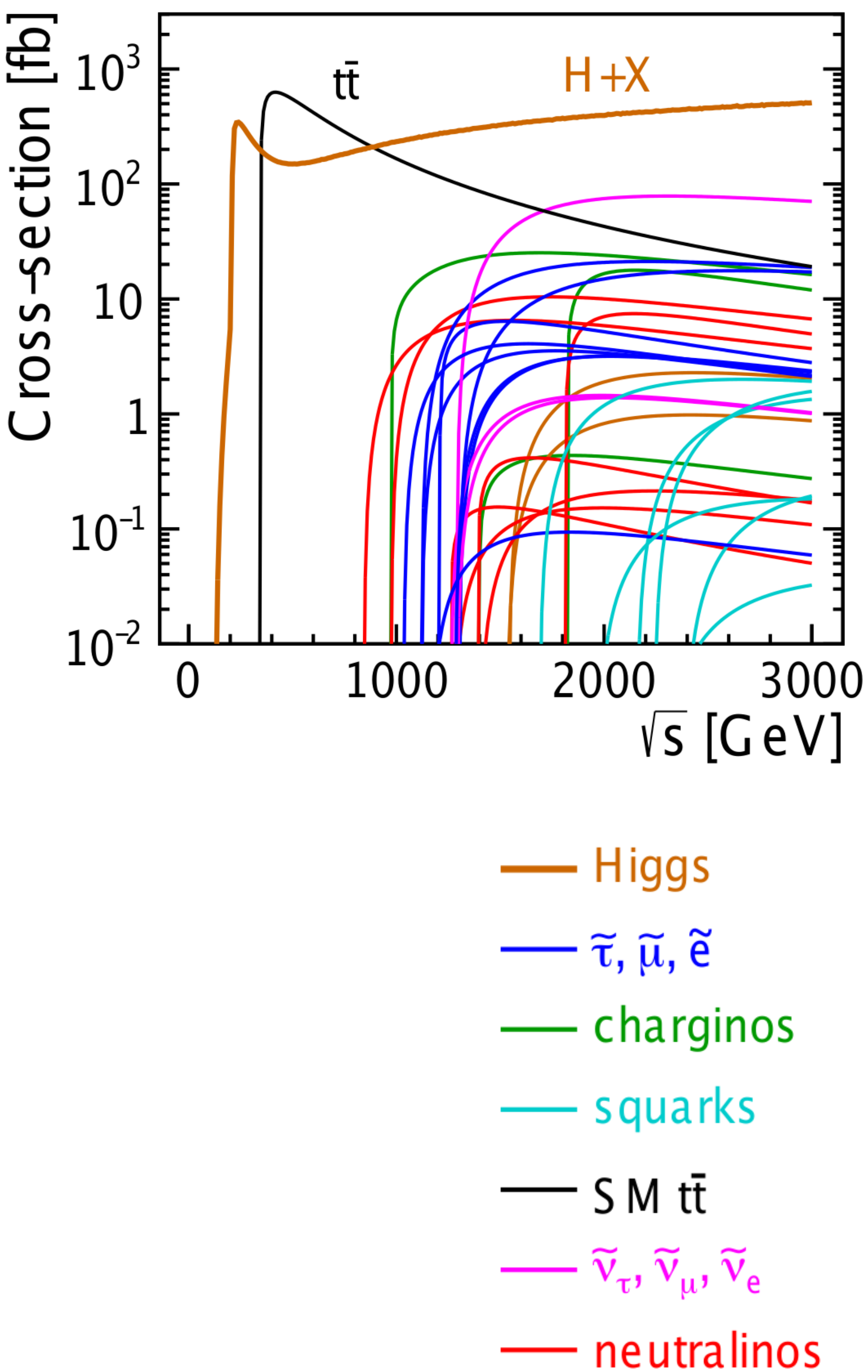
[P. Roloff '18]

- Direct observation of new particles coupling to γ*/Z/W
→ precision measurement of new particle masses and couplings

- The sensitivity often extends up to the kinematic limit
(e.g. M ≤ $\sqrt{s}$ / 2 for pair production)

- Very rare processes accessible due to low backgrounds (no QCD)
→ CLIC especially suitable for electroweak states

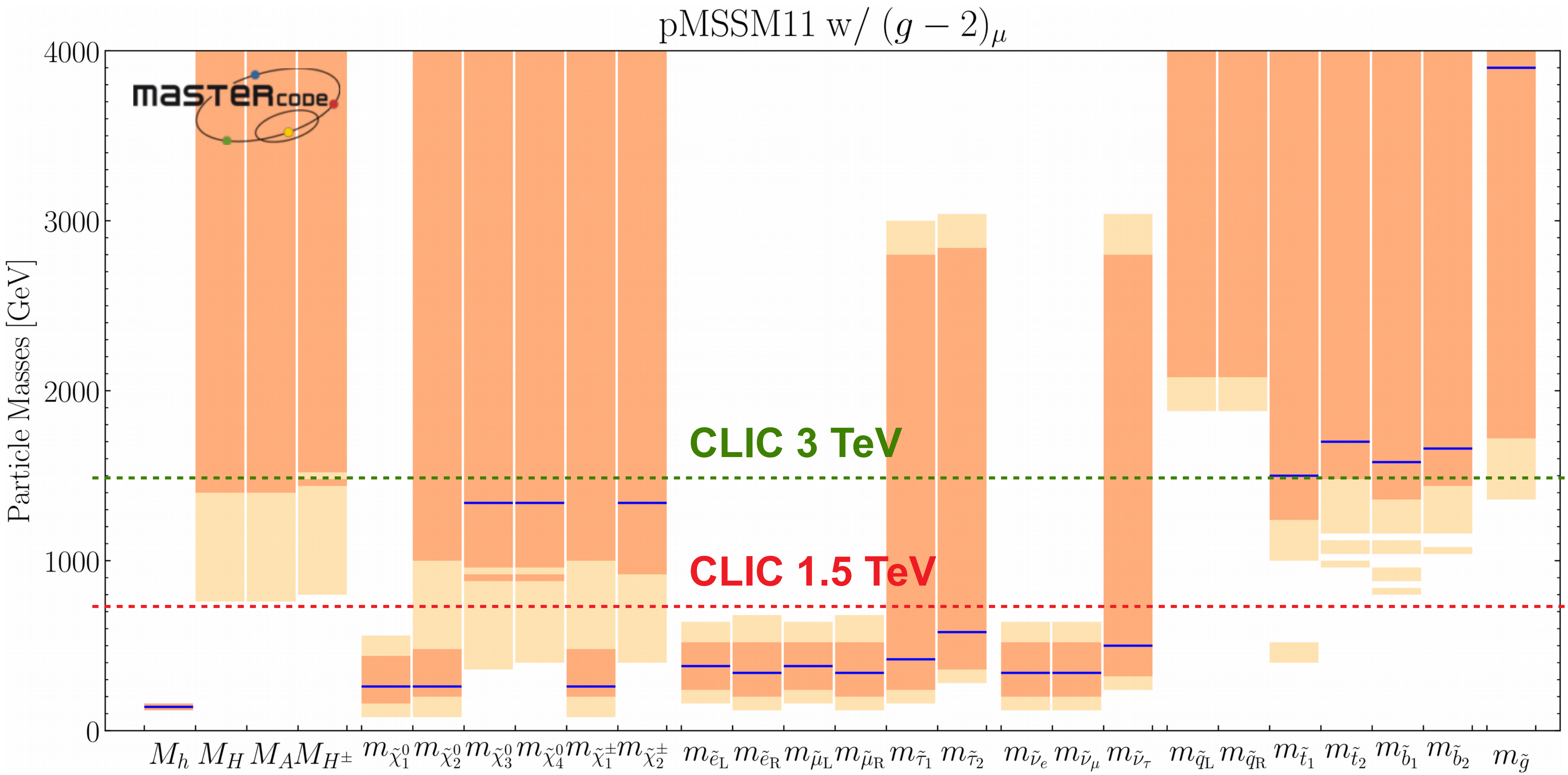
- Polarised electron beam and threshold scans might be useful to constrain the underlying theory



Comparison with SUSY fit

[P. Roloff ’18]

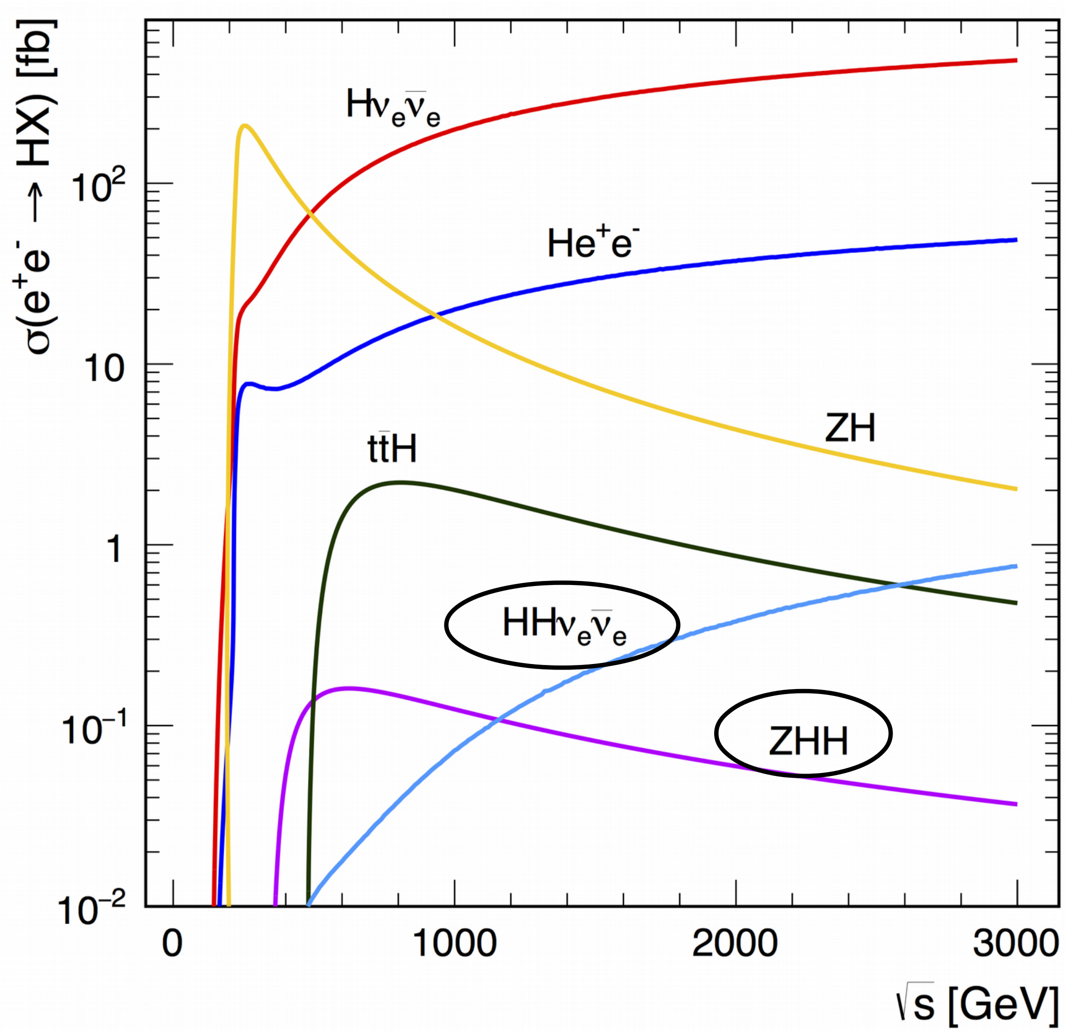
Example: Phenomenological MSSM with 11 parameters



arXiv:1710.11091

Higgs pair production and Higgs self-coupling λ

Higgs pair production: LC energies of 500 GeV or higher needed



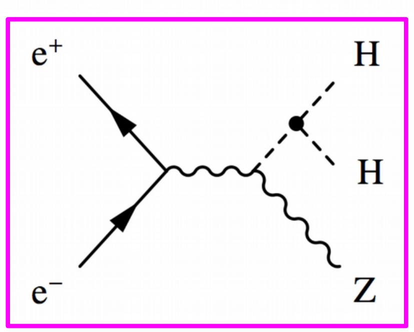
$e^+e^- \to$ ZHH:
• Cross section maximum ≈ 600 GeV, but very small number of events ($\sigma \lesssim 0.2$ fb)

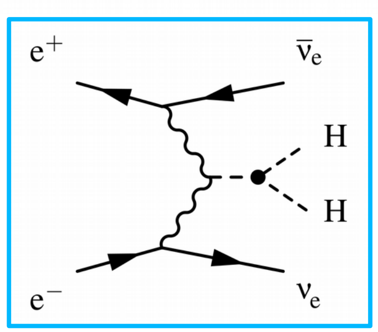
[P. Roloff '18]

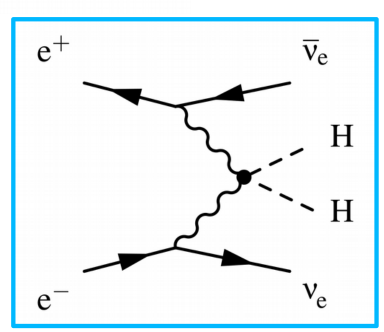
$e^+e^- \to HH\nu_e\bar{\nu}_e$:
• Allows simultaneous extraction of triple Higgs coupling, λ, and quartic HHWW coupling
• Benefits from high-energy operation

Projected precisions:
• Δ(λ) = 16% for CLIC from total cross section assuming 3 ab^{-1} at 3 TeV
(→ Δ(λ) ≈ 10% from differential distributions)

Eur. Phys. J. C 77, 475 (2017)







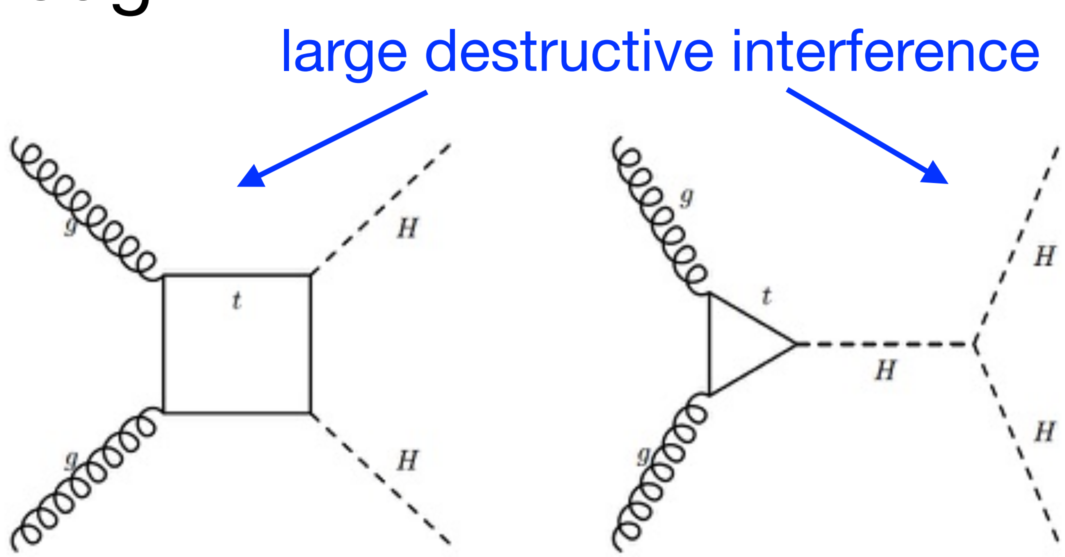
Model	$\Delta g_{hhh}/g_{hhh}^{SM}$
Mixed-in Singlet	$-18\,\%$
Composite Higgs	tens of %
Minimal Supersymmetry	$-2\,\%^a$ $\quad -15\,\%^b$
NMSSM	$-25\,\%$

Phys. Rev. D 88, 055024 (2013)

Recent discussion regarding Higgs self-coupling

Does one really need an e^+e^- Linear Collider with at least 500 GeV to precisely measure the Higgs self-coupling?

- The projections for the HL-LHC have significantly improved recently. Isn't that enough?



- During the update of the European Strategy for Particle Physics some proponents claimed a high sensitivity to the trilinear Higgs coupling from its effects in loop contributions to observables that are measured at a 250 GeV Higgs factory ($e^+e^- \to Z\,h125$)

Higgs self-coupling λ

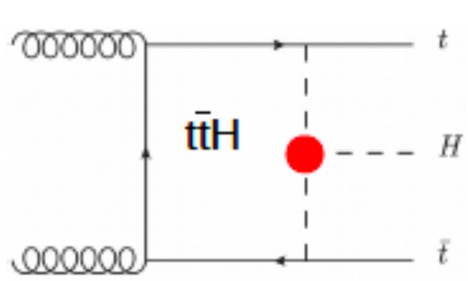
Sensitivity of different processes crucially depends on the actual value of λ

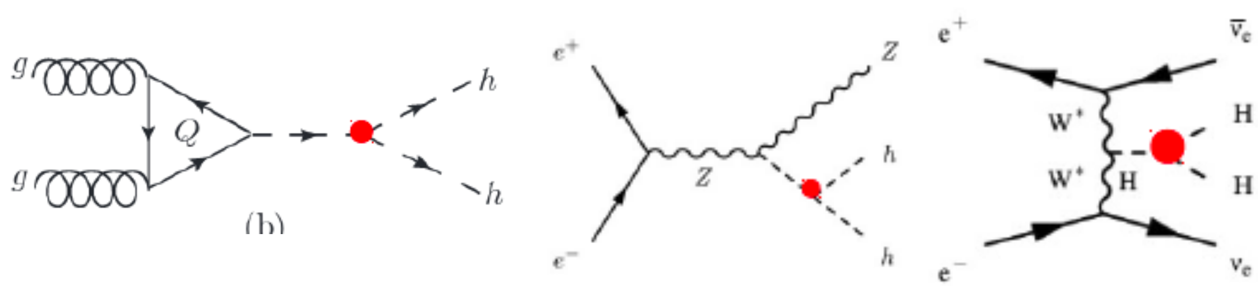
[B. Heinemann '19]

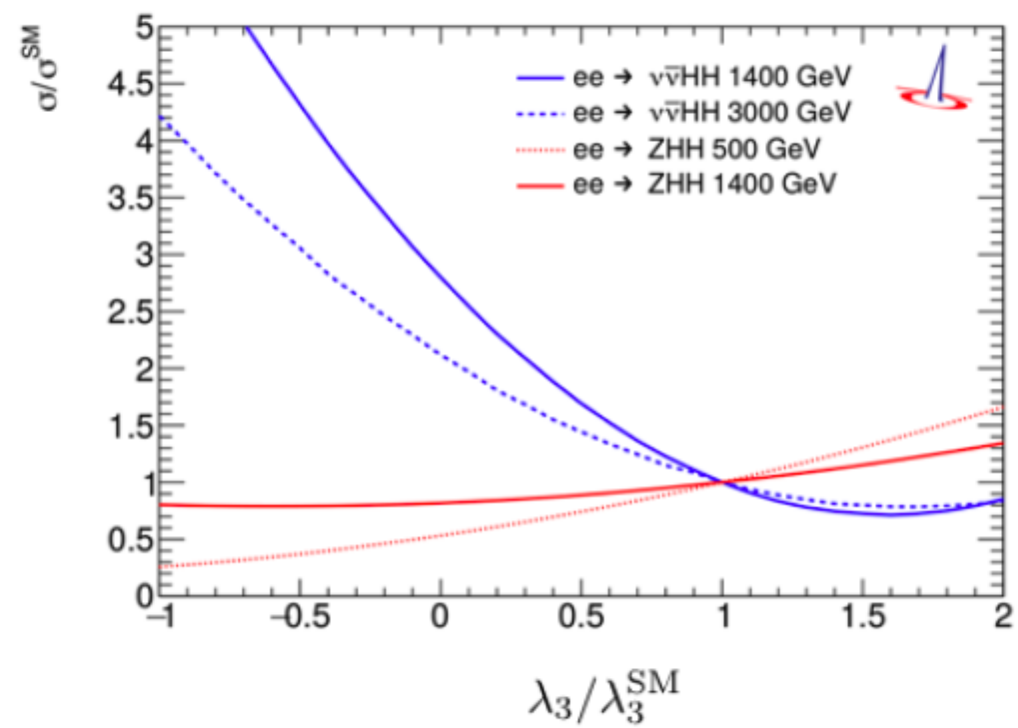
Di-Higgs processes at hadron colliders:
- $\sigma(HH) \approx 0.01\times\sigma(H)$
- Important to use differential measurements

Di-Higgs processes at lepton colliders
- ZHH or VBF production complementary

Single-Higgs production sensitive through loop effects, e.g. for $\kappa_\lambda = 2$:
- Hadron colliders: ~3%
- Lepton colliders: ~1%

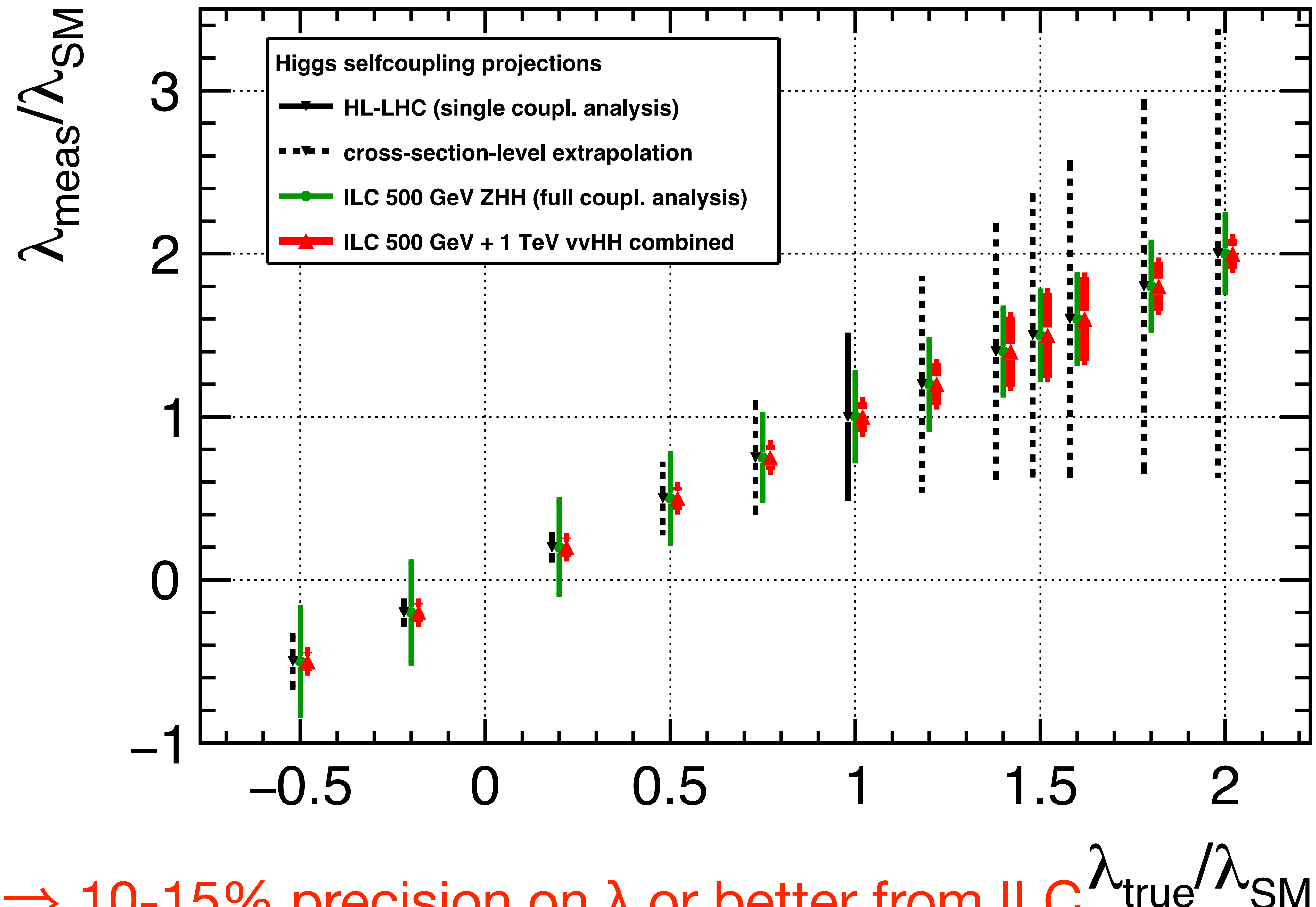






Higgs self-coupling sensitivity: ILC vs. HL-LHC

[J. List et al. '21]



⇒ 10-15% precision on λ or better from ILC with ZHH (500 GeV) + $\nu\nu$HH (1 TeV)

Single-Higgs processes: λ enters at loop level

[E. Petit '19]

How to measure deviations of λ_3

Note: this is based on the assumption that there is a large shift in λ, but no change anywhere else!

- The Higgs self-coupling can be assessed using di-Higgs production and single-Higgs production
- The sensitivity of the various future colliders can be obtained using four different methods:

	di-Higgs	single-H
exclusive	**1. di-H, excl.** • Use of σ(HH) • only deformation of κλ	**3. single-H, excl.** • single Higgs processes at higher order • only deformation of κλ
global	**2. di-H, glob.** • Use of σ(HH) • deformation of κλ + of the single-H couplings (a) do not consider the effects at higher order of κλ to single H production and decays (b) these higher order effects are included	**4. single-H, glob.** • single Higgs processes at higher order • deformation of κλ + of the single Higgs couplings

Single-Higgs processes: λ enters at loop level

[B. Heinemann '19]

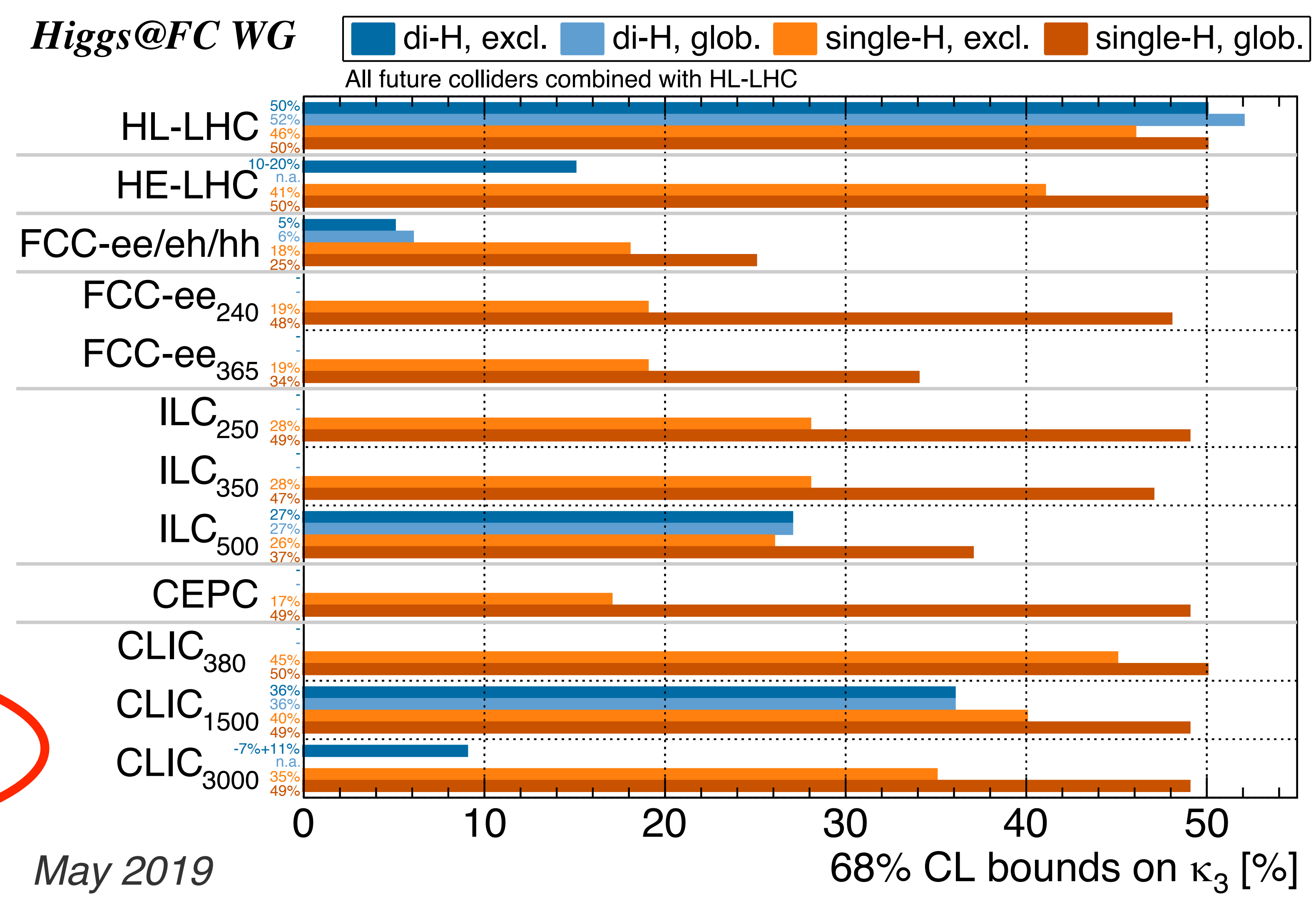
Sensitivity to λ: via single-H and di-H production

Di-Higgs:

- HL-LHC: ~50% or better?
- Improved by HE-LHC (~15%), ILC_{500} (~27%), $CLIC_{1500}$ (~36%)
- Precisely by $CLIC_{3000}$ (~9%), FCC-hh (~5%),
- Robust w.r.t other operators

Single-Higgs:

- **Global** analysis: FCC-ee365 and ILC500 sensitive to ~35% when combined with HL-LHC
  - ~21% if FCC-ee has 4 detectors
- **Exclusive** analysis: too sensitive to other new physics to draw conclusion

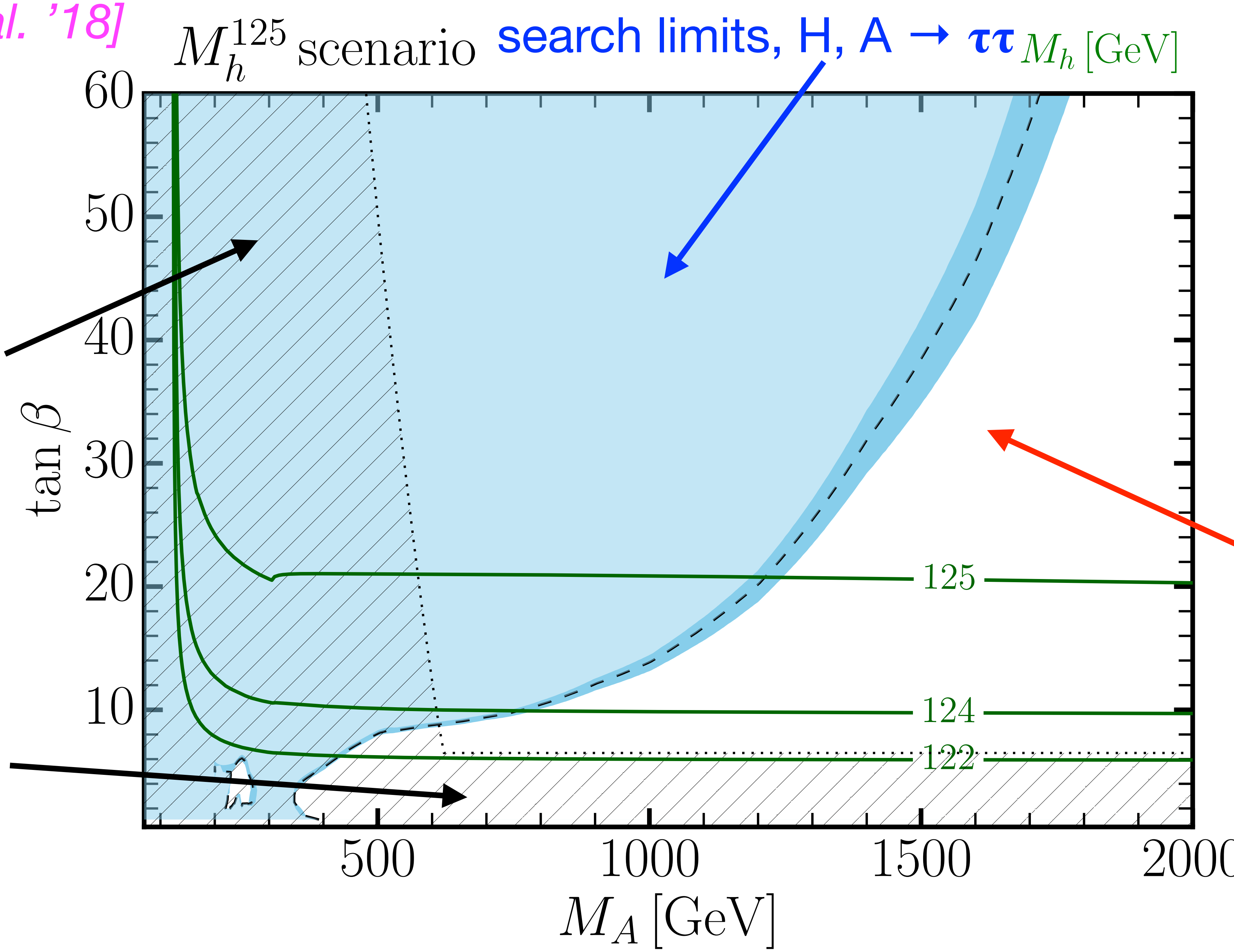


Search for additional (heavy) Higgs bosons

MSSM example: M_h^{125} benchmark scenario

[H. Bahl et al. '18]

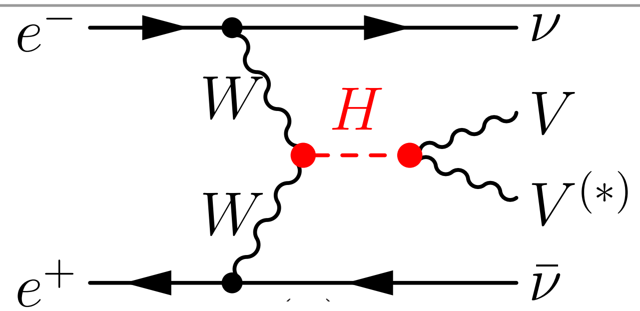
HiggsBounds: area excluded by Higgs search limits, H, A → **ττ**



HiggsSignals: area is not compatible with the properties of the detected Higgs signal h125

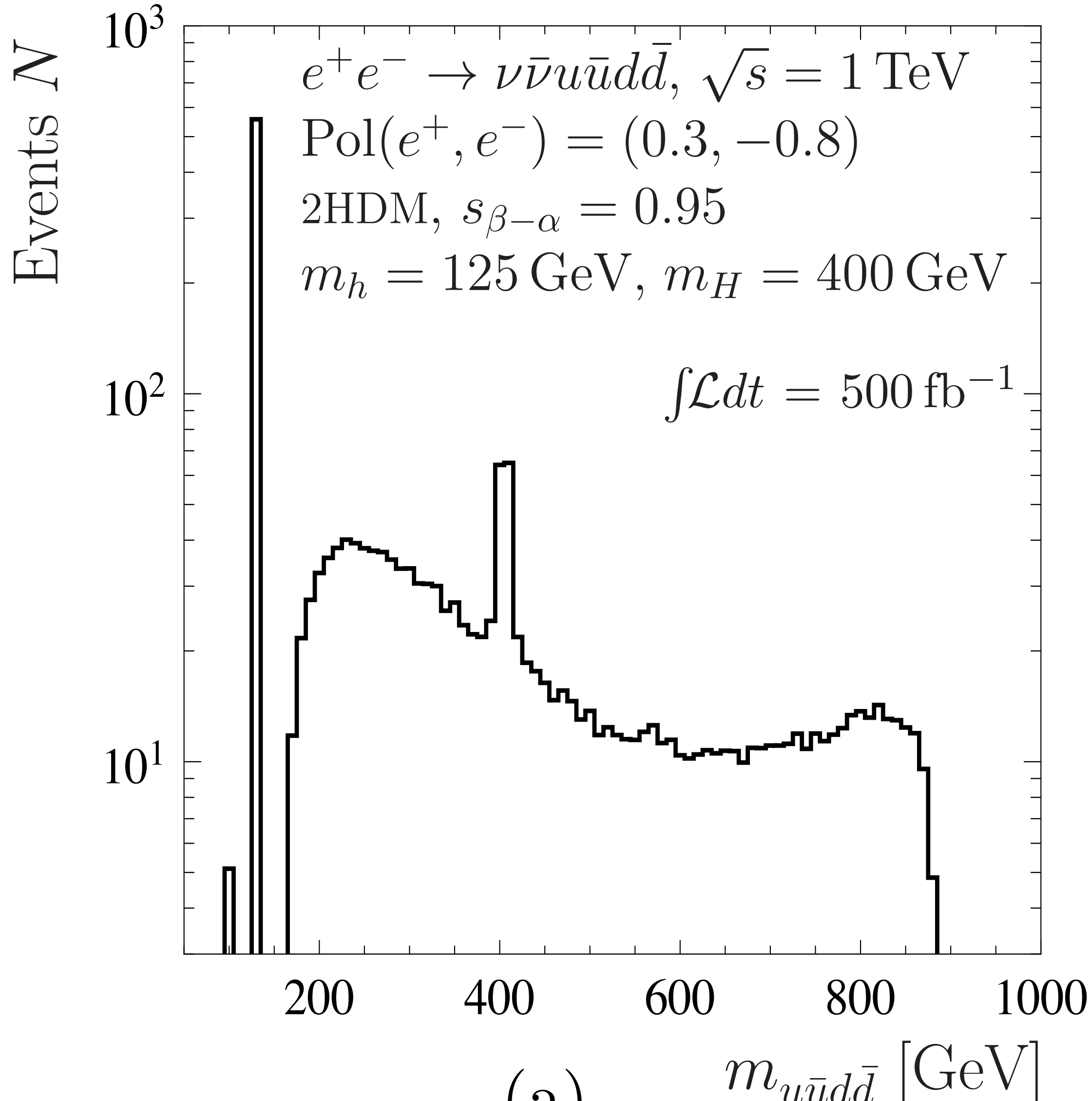
Allowed region, can be reduced with improved precision of M_h prediction

LC sensitivity to the small signal of an additional heavy Higgs boson in a Two-Higgs-Doublet model (2HDM)

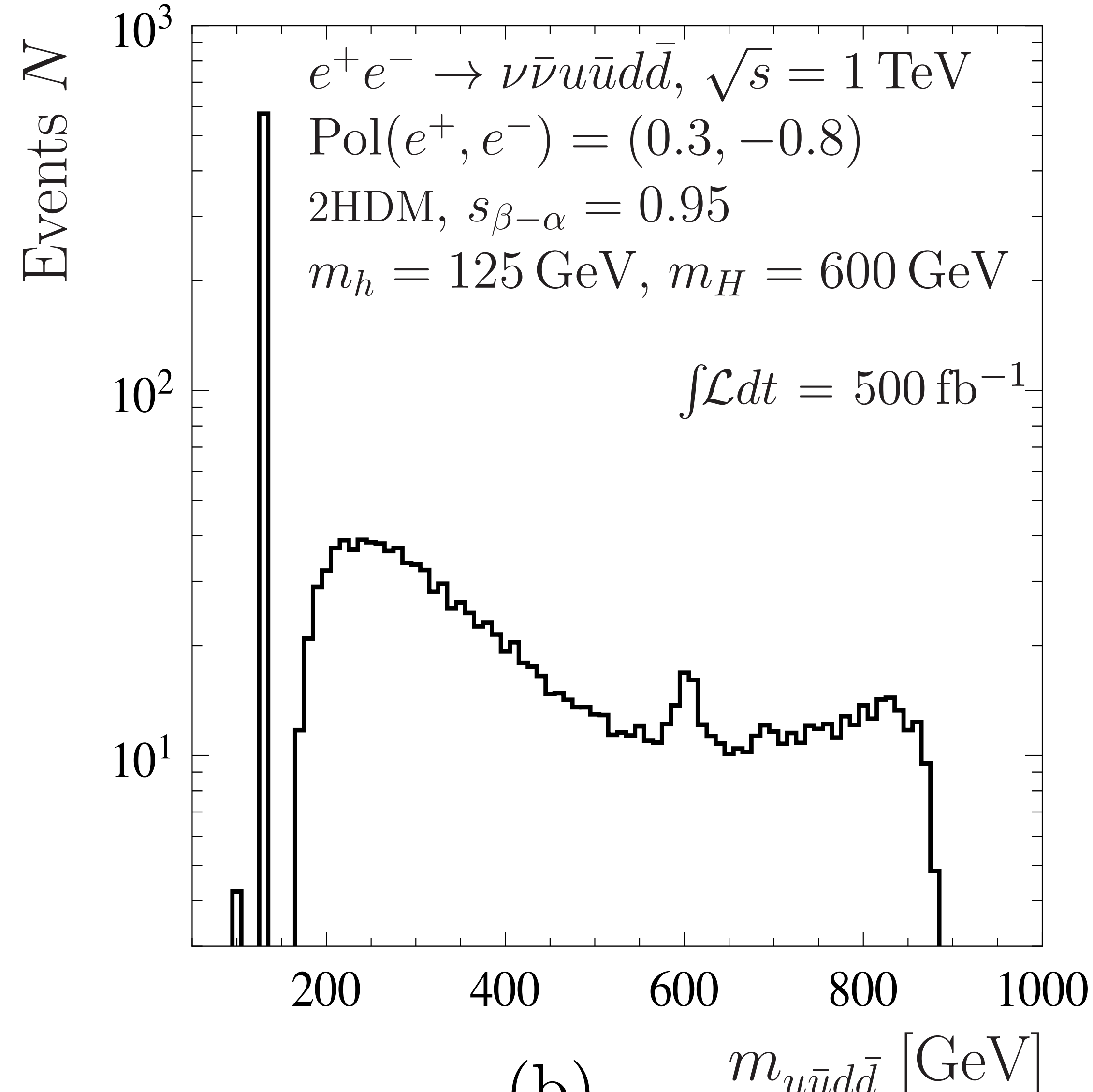


[S. Liebler et al. '15]

$$g_{\mathrm{hVV}} = \sin(\beta-\alpha)\, g^{\mathrm{SM}}_{\mathrm{HVV}}, \quad g_{\mathrm{HVV}} = \cos(\beta-\alpha)\, g^{\mathrm{SM}}_{\mathrm{HVV}}, \quad V = W^{\pm}, Z$$



(a)



(b)

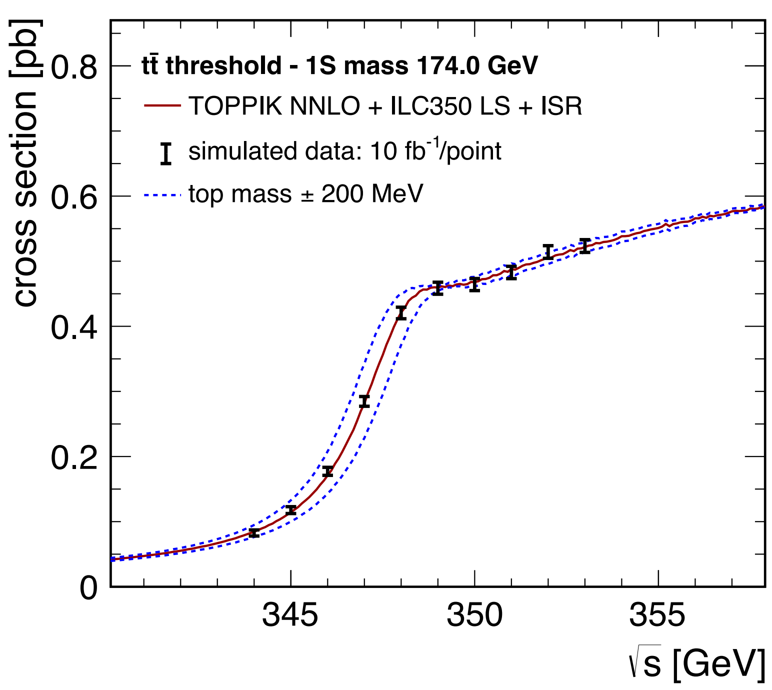
$\Rightarrow$ ILC: Potential sensitivity beyond the kinematic reach of Higgs pair production

Physics at the top threshold

The top-quark mass is a crucial input parameter entering comparisons between experiment and theory either directly or via quantum effects.

At the LHC top quarks are produced with high statistics. The measurement of the top-quark mass, however, is affected by a rather large systematic uncertainty in relating the measured quantity (which is a ``Monte Carlo mass") to a theoretically well-defined top-quark mass. Large efforts are currently made at the LHC with the goal to improve on this situation.

At an e^+e^- collider a ``threshold mass" will be measured with an unprecedented precision of about 50 MeV. It is theoretically well-defined and can be translated into the top-quark mass value used in theoretical predictions at the same level of accuracy.



Top couplings: sensitivity to new physics

[P. Roloff '18]

Top electroweak couplings

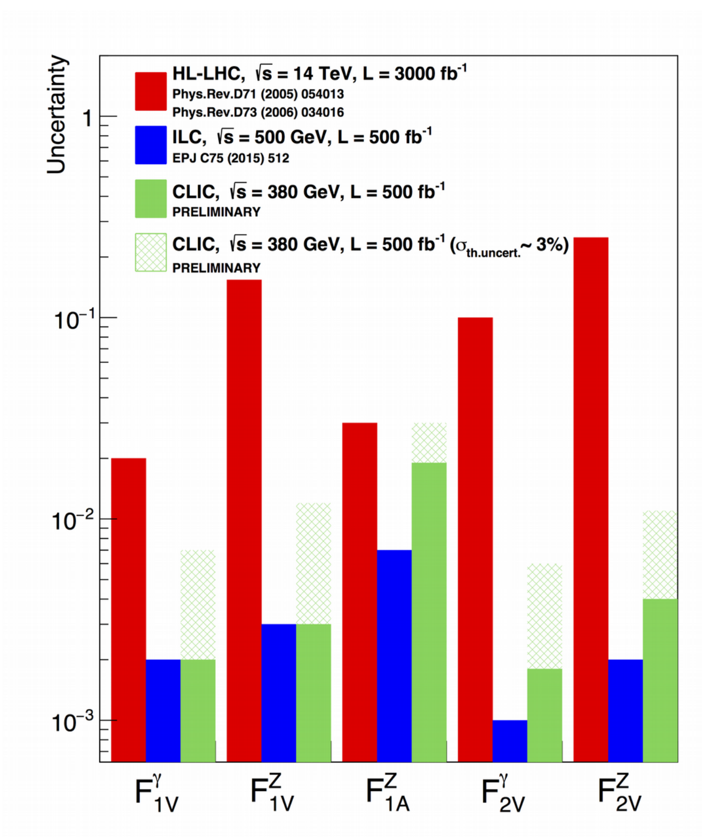
- Top quark pairs are produced via Z/γ* in electron-positron collisions
- The general form of the coupling can be described as:

arXiv:hep-ph/0601112

CP conserving

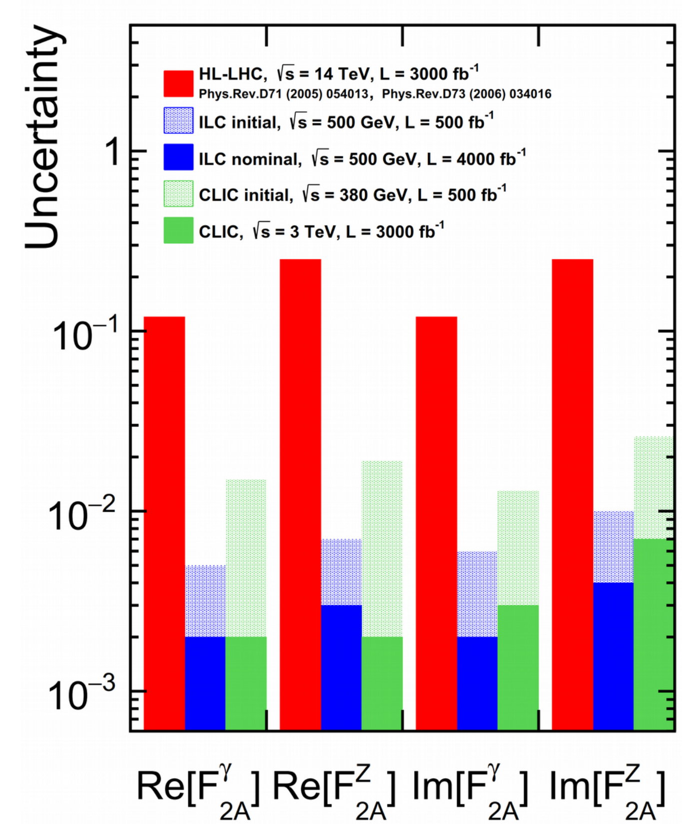
CPV

$$\Gamma_{\mu}^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu \left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$



CERN-2016-004

- New physics would modify the $t\bar{t}V$ vertex
- CLIC typically 1-2 orders of magnitude better than HL-LHC



Eur. Phys. J. C 78, 155 (2018)

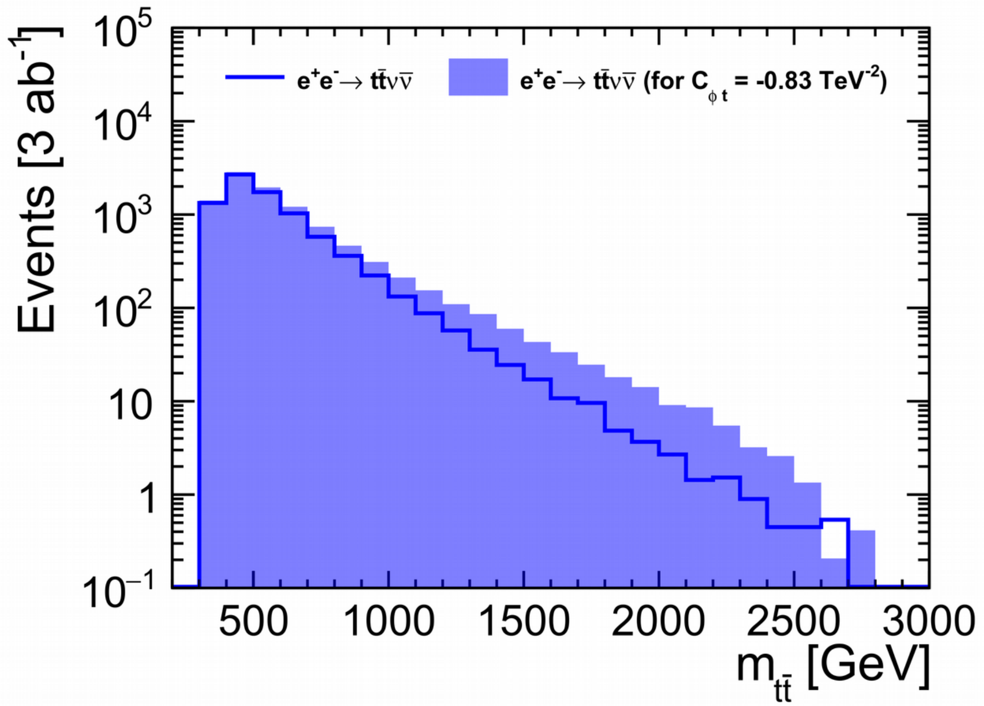
Electroweak physics at higher energies (CLIC)

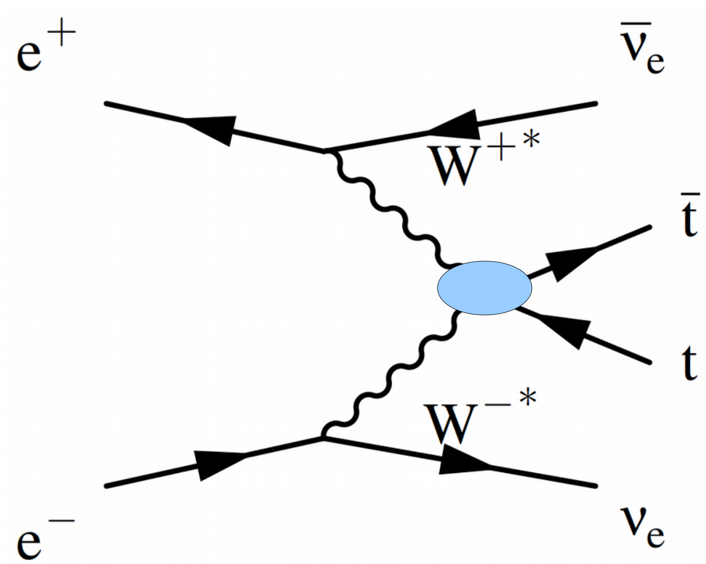
[P. Roloff '18]

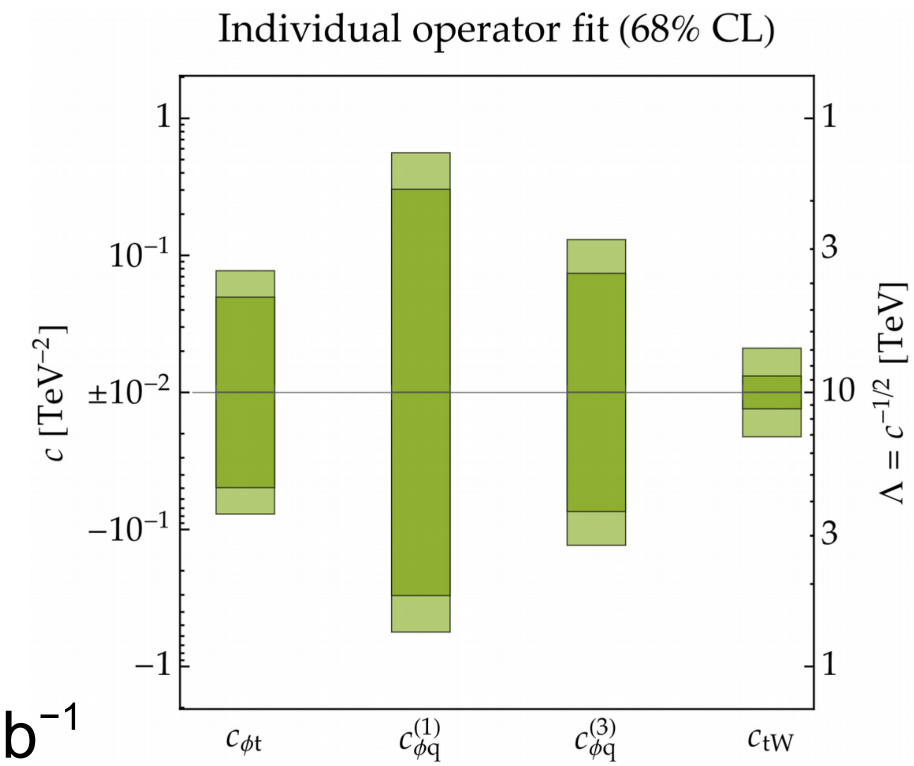
- Generator-level study and EFT interpretation

- Contributions of considered operators grow quadratically with energy

- Potential high-energy probe of the top Yukawa coupling







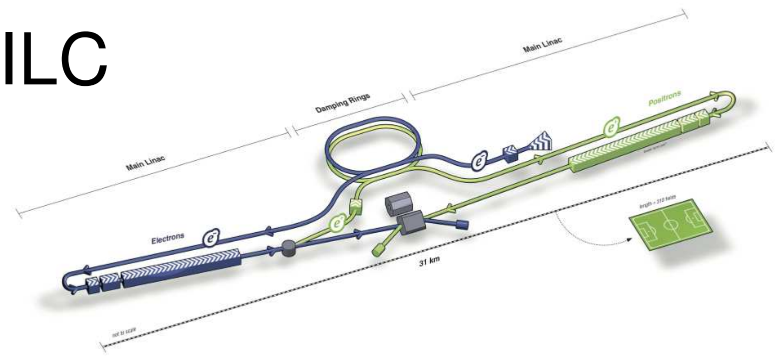
Grojean, You, Wulzer, Zhang

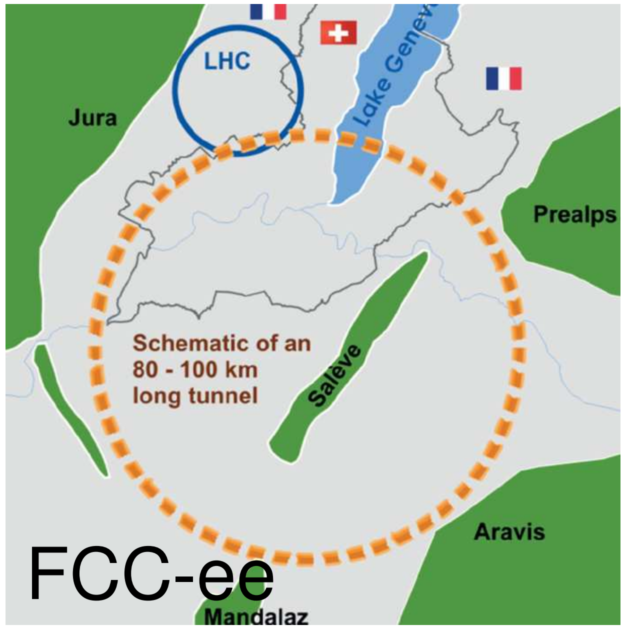
$\sqrt{s}$ = 3 TeV, L = 3 ab^{-1}

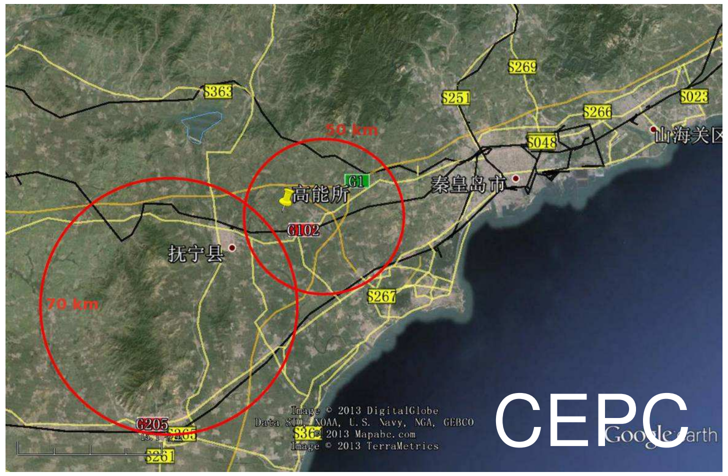
Electroweak physics at Z pole and WW threshold

[A. Freitas '21]

ILC







$\sqrt{s}$	M_Z	$2M_W$	
ILC/GigaZ	100 fb^{-1}	500 fb^{-1} (6 pts.)	beam pol. (P_{e^-}=0.8, P_{e^+}=0.3)
FCC-ee	230 ab^{-1}	10 ab^{-1} (2 pts.)	2 detectors
CEPC	45 ab^{-1}	2.6 ab^{-1} (3 pts.)	2 detectors

Electroweak physics at Z pole and WW threshold

Anticipated precision for EWPOs:

[A. Freitas '21]

	Current exp.	ILC/GigaZ	CEPC	FCC-ee
M_{W} [MeV]	15	1–2 ^{a,e}	1 ^{e}	1 ^{e}
M_{Z} [MeV]	2.1	–	0.5 ^{e}	0.1 ^{e}
Γ_Z [MeV]	2.3	1 ^{a}	0.5 ^{e}	0.1 ^{e}
$R_\ell = \Gamma_{\mathrm{Z}}^{\mathrm{had}}/\Gamma_{\mathrm{Z}}^{\ell}$ [10^{-3}]	25	6 ^{b}	2 ^{b}	1 ^{b}
$R_b = \Gamma_{\mathrm{Z}}^{b}/\Gamma_{\mathrm{Z}}^{\mathrm{had}}$ [10^{-5}]	66	15 ^{c}	4.3 ^{c}	6 ^{c}
$\sin^2\theta_{\mathrm{eff}}^{\ell}$ [10^{-5}]	16	1 ^{d}	$<$1 ^{e}	0.5 ^{e}

Systematics:

^{a} energy scale

^{b} acceptance

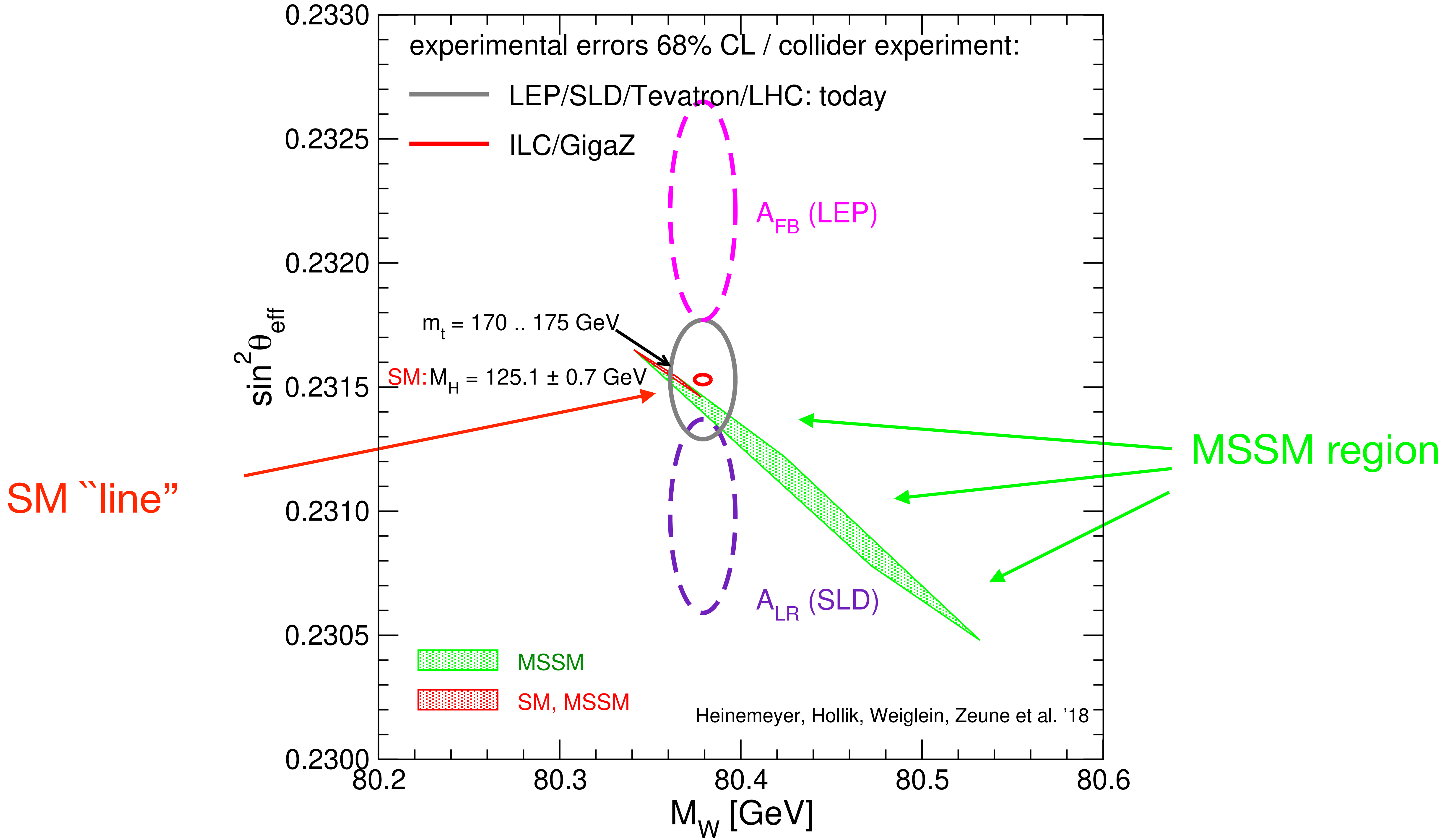
^{c} flavor tagging

^{d} polarization

^{e} beam energy calibration / beam-beam interactions

Electroweak precision physics: Prediction for M_W and $\sin^2\theta_{\mathrm{eff}}$ in SM and MSSM vs. exp. accuracies

[S. Heinemeyer, W. Hollik, G. W., L. Zeune '18]



⇒ M_W and $\sin^2\theta_{\mathrm{eff}}$ have high sensitivity for model discrimination

Further experimental opportunities at a LC facility

- Beam dump experiments
- Fixed-target experiments
- Detectors near the interaction point
- …

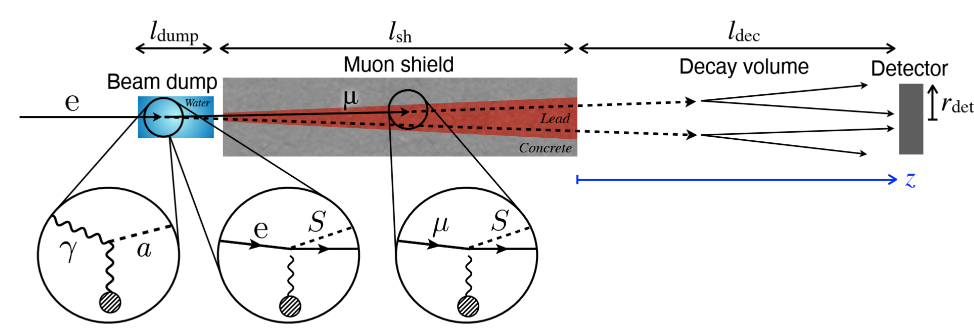
Further experimental opportunities at a LC facility

[S. Michizono '21]

Use of ILC Beam for Fixed Target Experiment

There are many possible experiments using the ILC beam other than the colliding experiment

- Experiments using the main dump
  - ✓ Observe particles created in the main beam dump
  - ✓ Dark photon, dark lepton, ALP (axion-like particle), Higgs-portal particles, ……
  - ✓ Positron main dump
    - Positron annihilation with atomic electrons
  - ✓ Parasitic with the main collision experiment



- Experiments using Extracted beam
  - ✓ Extract the strong ILC beam somewhere for e.g., strong QED experiment
    - This is perhaps difficult (the beam is too strong to ontercept)
  - ✓ Or, create and extract a weak beam
    - Low bunch intensity but many (>> 1312) bunches
    - Ideally, CW
    - Missing energy experiment to search for dark photons
    - Lots of accelerator issues such as beam creation, to avoid damping in DR, control of very weak beam, etc.

By Kaoru Yokoya on Tuesday 10PM (Europe)
"N1: Dark Sector, Fixed-Target and Beam Dump Experiments"

- Far detector
  - ✓ Long-lived particles may be produced at the IP
  - ✓ They may be detected by a detector behind 50-200m shield (natural rocks)
  - ✓ Need to construct a cavern (near the main beamline, or along the access tunnel)

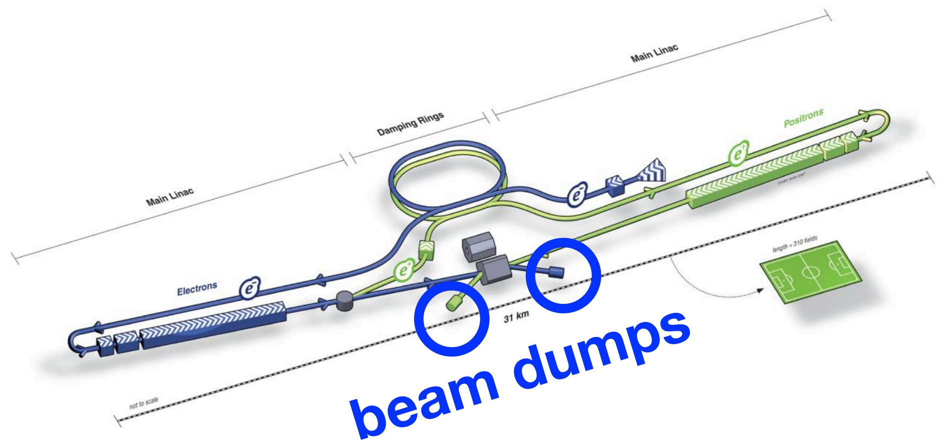
We would be happy to discuss the further possibilities of the ILC accelerator.

LCWS2021 (Mar.15,2021) 18

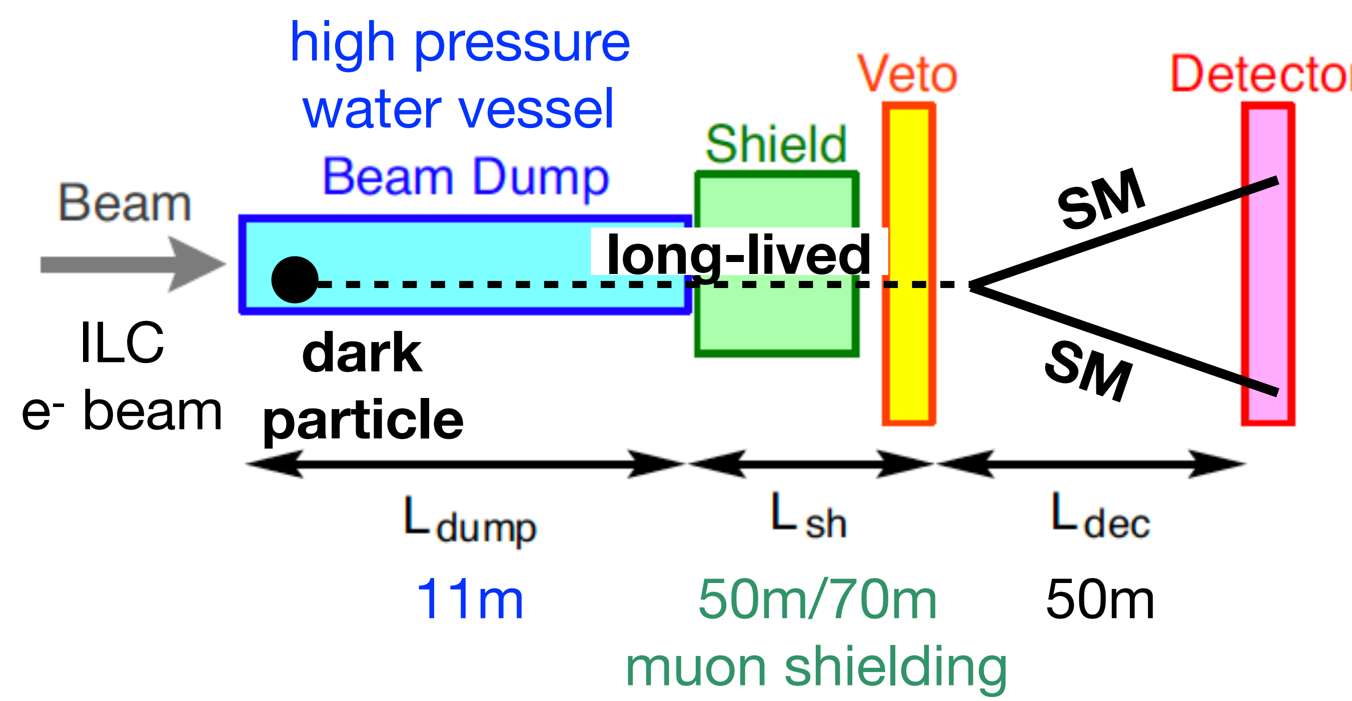
Beam dump experiments at a Linear Collider

[S. Gori '20]

ILC beam-dump setup



Kanemura, Moroi, Tanabe, 1507.02809



- Much **larger energy:** 125 GeV, 250 GeV, 500 GeV, 1.5 TeV electron beams compared to past/present e^- beam dump experiments:
  - E137 @ SLAC: ~20 GeV electron beam (past)
  - HPS @ JLAB: ~ (1-6) GeV electron beam (present)

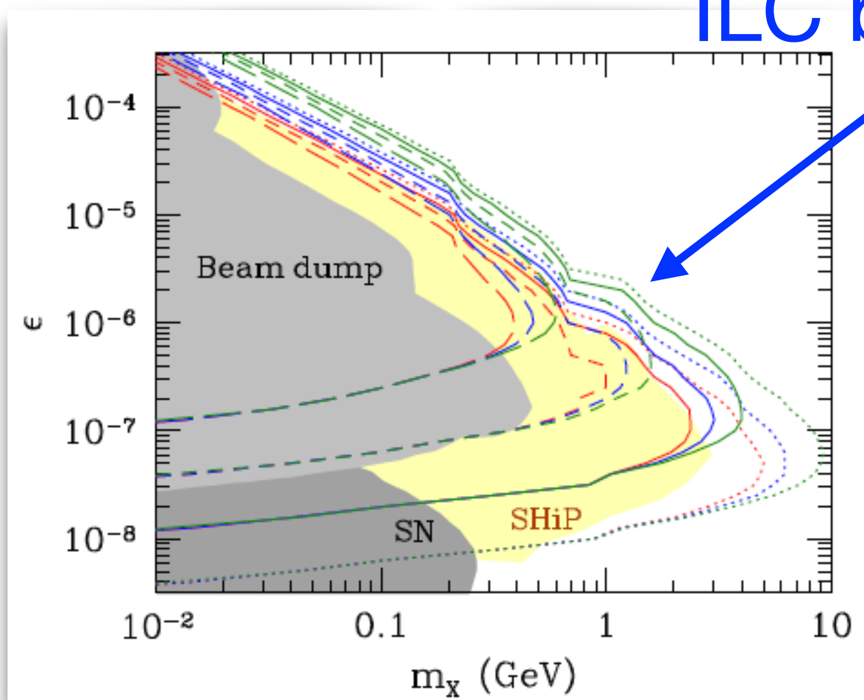
- **Very high luminosities**: ~$4*10^{21}$ electrons on target (EOT)/year compared to
  - E137 @ SLAC: ~$2*10^{20}$ EOT
  - HPS @ JLAB: ~10^{18} EOT

Dark photon searches via beam dump experiments

[S. Gori ’20]

Complementarity with other experiments

ILC beam dump

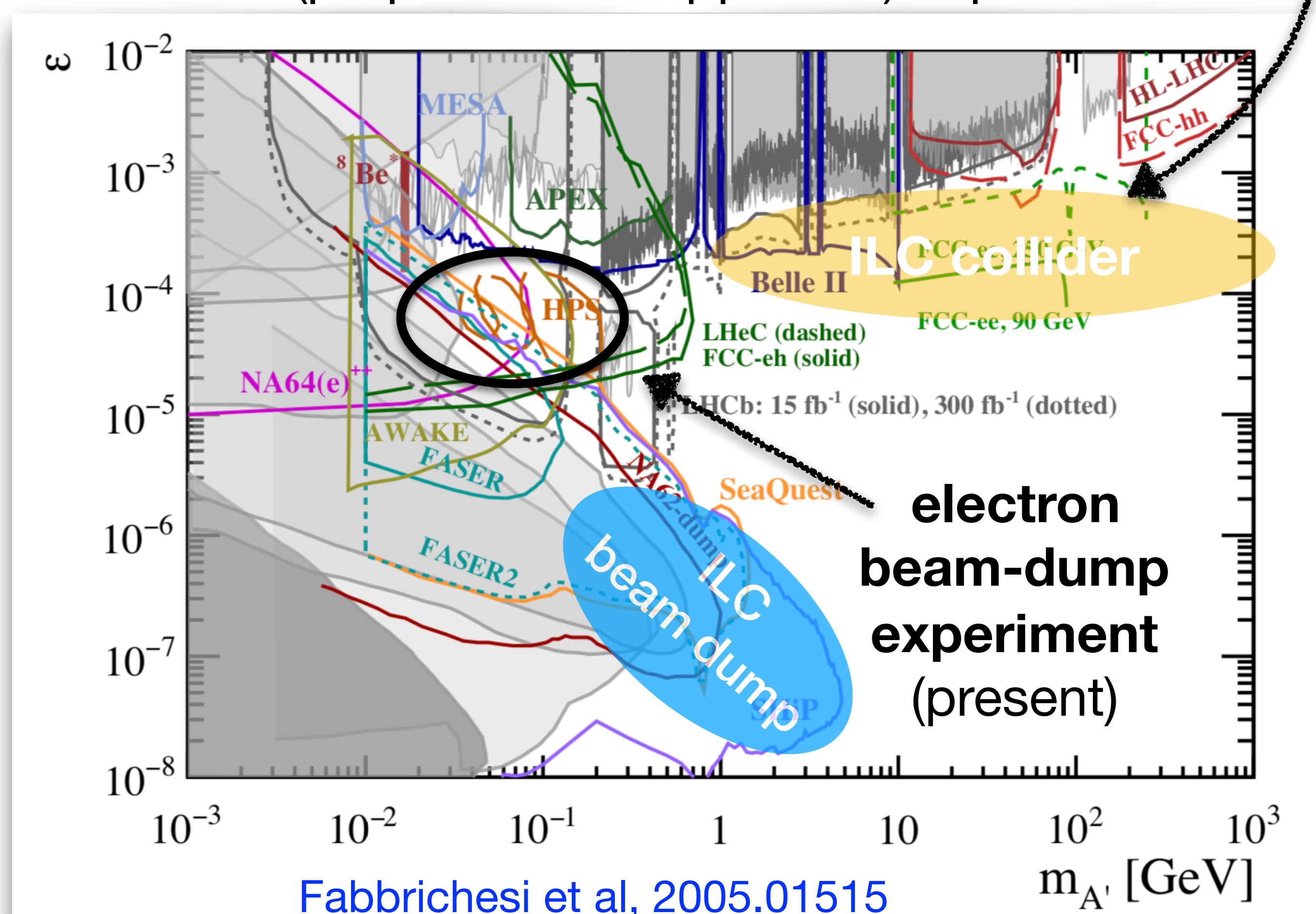


Kanemura et al.,1507.02809

Additional opportunities for the ILC here!

$e^+e^- \to A'\,\gamma \to \gamma\, l^+\, l^-$ (prompt dark photon)

Future (proposed and approved) experiments



Fabbrichesi et al, 2005.01515

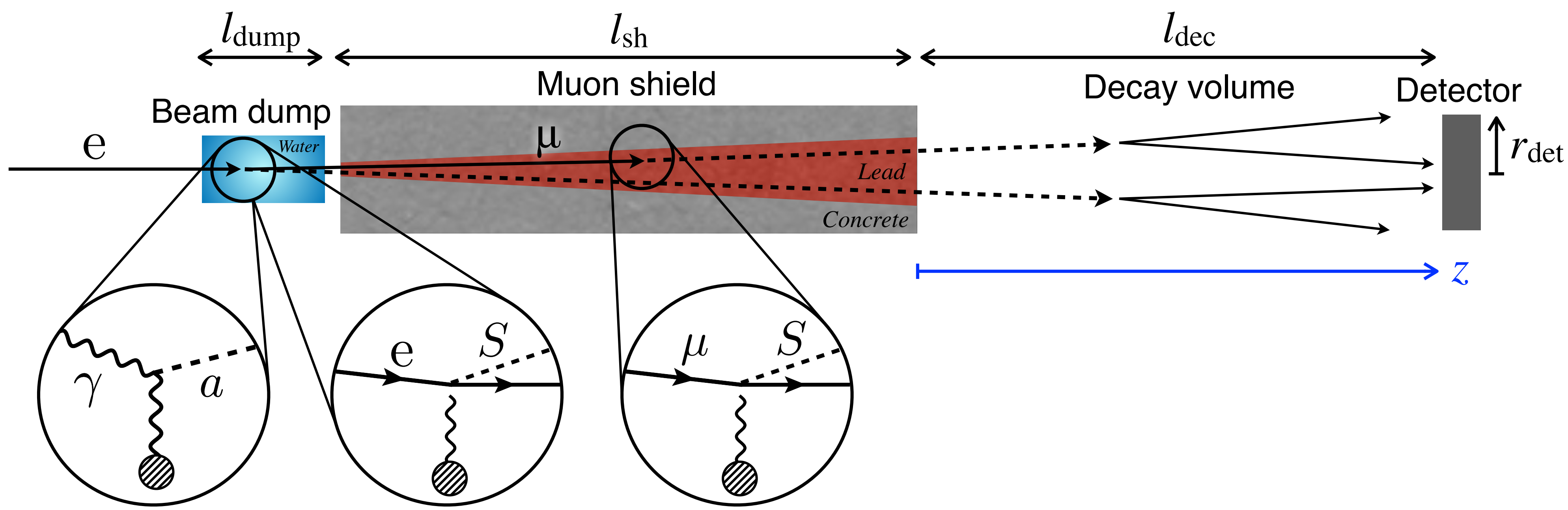
Few references:

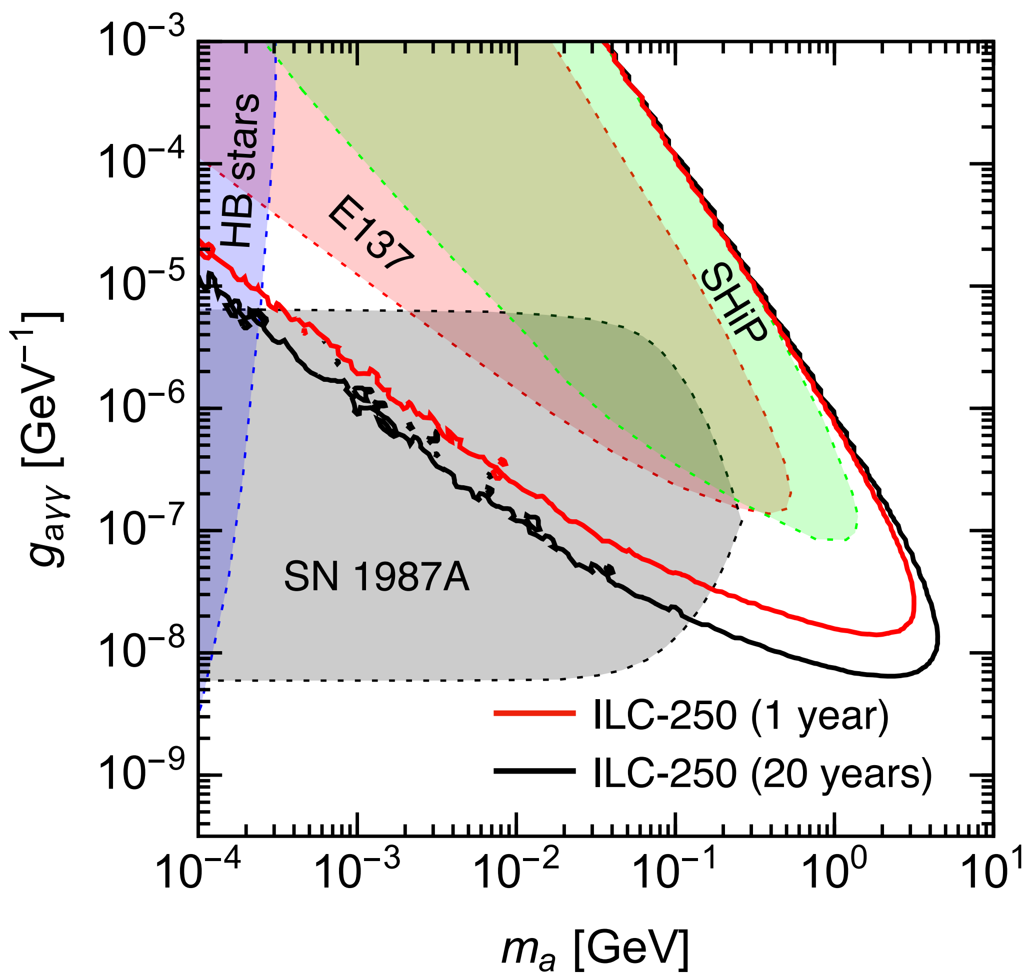
- SeaQuest: Berlin, SG, Schuster, Toro, 1804.00661
- FCC: Karliner et al., 1503.07209
- SHiP: Alekhin et al., 1504.04855
- FASER: Feng et al., 1708.09389

+ Proposal for the Belle II experiment: Gazelle (Evans et al.)

Search for axion-like particles with LC beam dump

[Y. Sakaki, D. Ueda '20]





⇒ Large improvements over other beam dump experiments in the small coupling region

Conclusions

An e^+e^- collider will allow the exploration of the observed Higgs signal with the highest precision and provide a very high sensitivity to direct and indirect effects of new physics

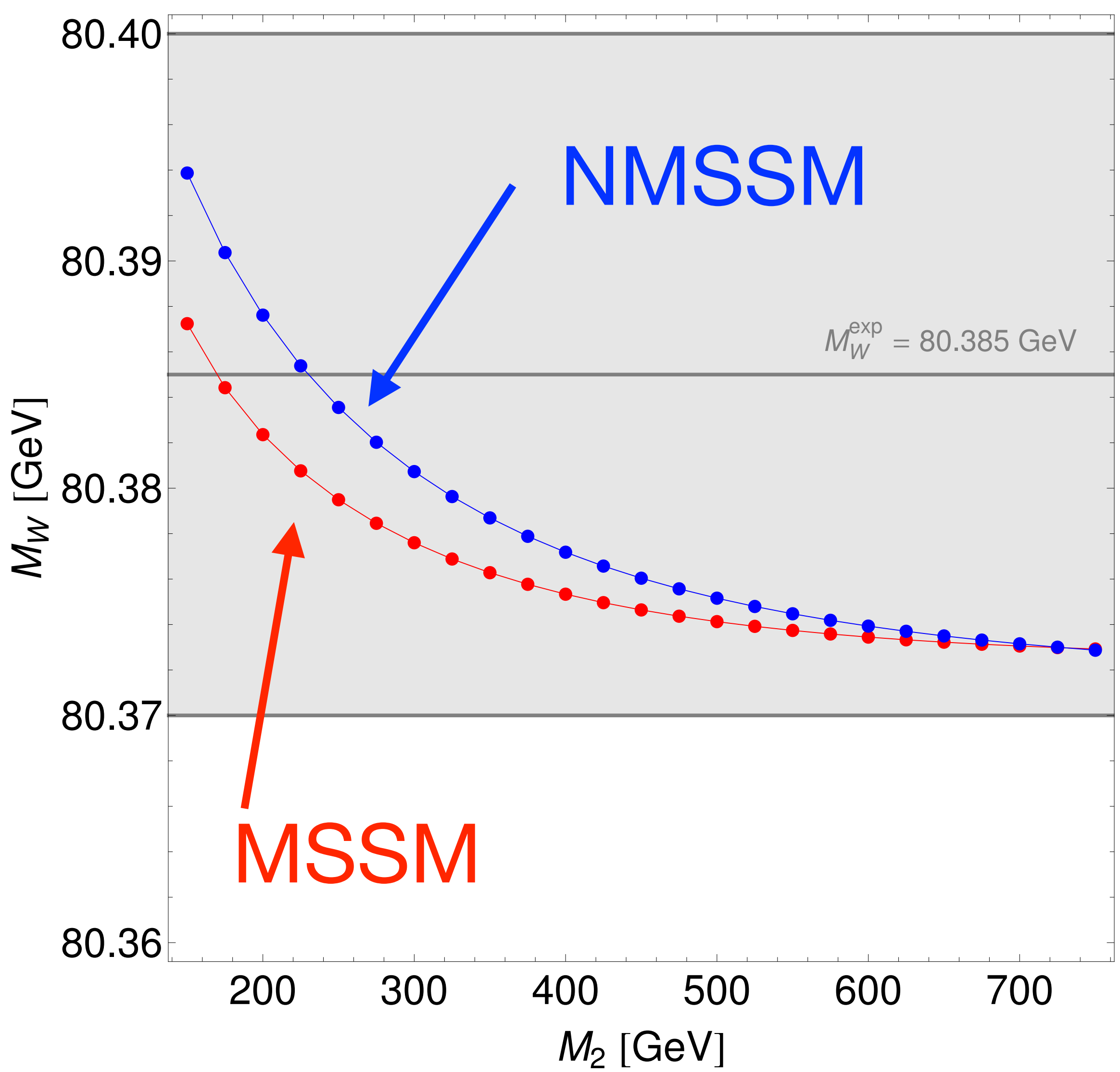
It has a great potential for discovering new physics, in particular colour-neutral particles, and for precisely determining its nature

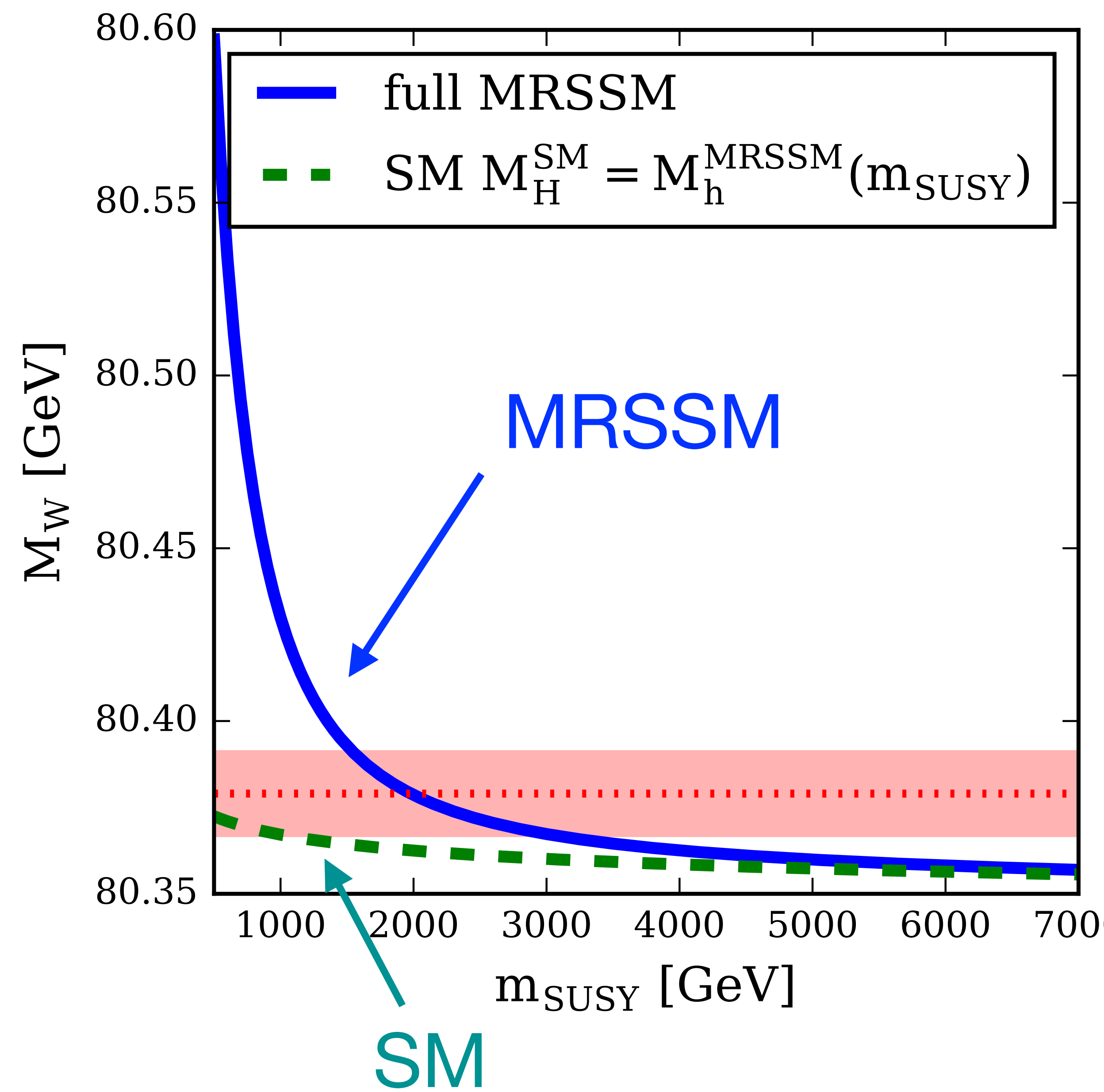
Besides running in ``Higgs factory" mode at 250 GeV, the opportunities for BSM physics profit from running at higher energies (top threshold, 500 GeV and beyond) and at lower energies (Z pole, WW threshold), as well as from exploring non-collider options (LC beam dump experiments, etc.)

Backup

M_W prediction in the SM, MSSM, NMSSM, MRSSM

NMSSM: *[O. Stål, G. W., L. Zeune '15]* MRSSM: *[P. Diessner, G. W. '19]*





⇒ MRSSM prediction for M_W: pronounced dependence on SUSY parameters, sizeable deviations from the SM even for large m_{SUSY}