FCC-ee

phenomenology status and future plans

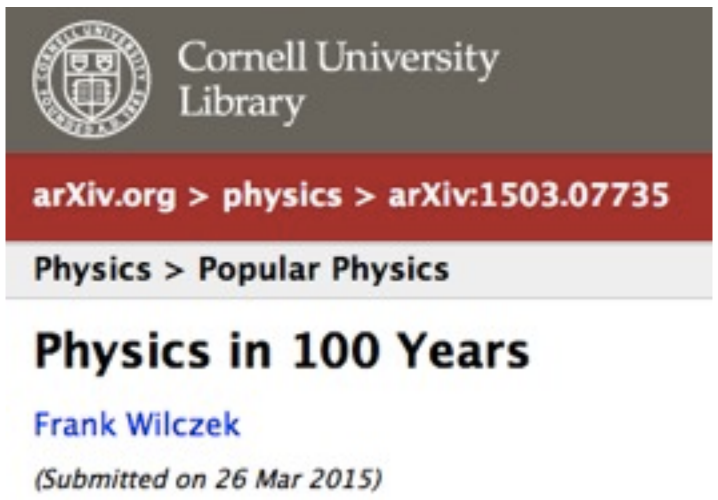
A. Blondel, J. Ellis, C. Grojean and P. Janot

Physics vidyo meeting

May 4, 2015

Still some important physics questions

with the Higgs, the SM can be extrapolated to very high energy (up M_{Planck}?)



The equations of the [SM] have been tested with far greater accuracy, and under far more extreme conditions, than are required for applications in chemistry, biology, engineering, or astrophysics. While there certainly are many things we don't understand, we do understand the Matter we're made from, and that we encounter in normal life - even if we're chemists, engineers, or astrophysicists (sic: DM!)

The SM is not free of inadequacies:

1) Only a description of EW symmetry breaking, not an explanation
   furthermore Higgs field requires a delicate cancelation of large radiative corrections
2) No place for the particle(s) that make up the cosmic DM
3) Does not explain the asymmetry matter-antimatter
4) No understanding of origin of flavor, in particular in the ν sector

FCC-ee has a rather unique potential to provide answers

The physics questions are at the root of the science drivers for politics...

The Science Drivers

- P5 distilled the 11 groups of physics questions formulated at Snowmass into 5 compelling lines of inquiry that show great promise for discovery over the next 10 to 20 years.

- **The Science Drivers**:
  - **Use the Higgs boson as a new tool for discovery.**
  - **Pursue the physics associated with neutrino mass.**
  - **Identify the new physics of dark matter.**
  - **Understand cosmic acceleration: dark energy and inflation.**
  - **Explore the unknown: new particles, interactions, & physical principles.**

- *Recommendation 2:* ***Pursue a program to address the 5 science drivers.***

- The **drivers** are deliberately **not prioritized** because they are **intertwined**, probably more deeply than currently understood.
- A selected set of different experimental approaches that reinforce each other is required. **Projects are prioritized**.
- The vision for addressing each of the drivers using a selected set of experiments is given in the report, along with their approximate timescales and how they fit together.

- Explored at Energy Frontier with colliders

FCC Week 2015 - Lankford: US HEP community perspective 5

A. Lankford @ Washington '15

The handles that FCC-ee can play with to achieve its physics goals: luminosity, beam polarization, energy

Input from Physics to the accelerator design

0. Nobody complains that the luminosity is too high (the more you get, the more you want)

1. Do we need polarized beams?

-1- transverse polarization:

continuous beam Energy calibration with resonant depolarization
central to the precision measurements of m_Z , m_W , Γ_Z
requires 'single bunches'
a priori doable up to W energies -- workarounds exist above (e.g. γZ events)
large ring with small emittance offers *a priori* excellent prospects
need wigglers; simulations ongoing (E. Gianfelice, M. Koratzinos)

-2- longitudinal polarization requires spin rotators and is very difficult at high energies
-- We recently found that it is not necessary to extract top couplings (Janot, Azzi)
-- improves Z peak measurements *if loss in luminosity is not too strong*
but brings no information that is not otherwise accessible

2. What energies are necessary?

-- in addition to Z, W, H and top listed the following are being considered
-- e+e- → H(125.2) (requires monochromatization A. Faus) (under study)
-- e+e- at ~70 GeV (Z-γ interference)
-- e+e- at top threshold + <~20 GeV for top couplings (E_max up to 180 -185 GeV)
-- no obvious case for going to 500 GeV

A. Blondet @ Washington

Phenomenology @ FCC-ee

1. Discovery via EW/Higgs physics
   - potential of Higgs precision measurements
   - EW precision measurements
2. EWSB and flavor probes of BSM
   - sensitivity to new physics of precision EW/H observables
   - direct searches
   - rare phenomena: rare Higgs/Z decays, flavor violating decays
3. Indirect probes of high-mass frontier
   - precision measurements of input parameters
4. DM @ FCC-ee

FCC-ee/eh/hh complementarity/interplay?

1

Discovery via EW/Higgs physics

Higgs agenda

The successes have been breathtaking:

- in O(2) years, the Higgs mass has been measured to 0.2% (vs 1% for the 20-year old top)
- some of its couplings, e.g. κ_γ, have been measured with LEP accuracy (10^{-3})

Higgs agenda for the LHC-II, HL-LHC, ILC/CLIC, FCC, SHiP

multiple independent, synergetic and complementary approaches to achieve **precision** (couplings), **sensitivity** (rare and forbidden decays) and **perspective** (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, naturalness, etc)

M.L. Mangano @ Washington '15

- rare Higgs decays: h→$\mu\mu$, h→γZ LHC, ILC, FCC-ee
- Higgs flavor violating couplings: h→$\mu\tau$ and t→hc FCC-ee
- Higgs CP violating couplings FCC-ee
- exclusive Higgs decays (e.g. h→J/Ψ+γ) and measurement of couplings to light quarks FCC-ee
- exotic Higgs decay channels: LHC, FCC-ee, ILC

  h→ $\not{E}_T$, h→4b, h→2b2μ, h→4τ,2τ2μ, h→4j, h →2γ2j, h→4γ, h→γ/2γ+ $\not{E}_T$,

  h→isolated leptons+ $\not{E}_T$, h→2l+ $\not{E}_T$, h→one/two lepton-jet(s)+X, h→bb+ $\not{E}_T$, h→$\tau\tau$+ $\not{E}_T$ ...

- searches for extended Higgs sectors (H, A, $H^\pm$,$H^{\pm\pm}$...) FCC-hh
- Higgs self-coupling(s) ILC/CLIC, FCC-hh
- Higgs width ILC, FCC-ee
- Higgs/axion coupling? ?
- ...

Higgs agenda

FCC-ee benefits from H reconstruction before decay,
high tagging efficiencies and low background
and the absence of trigger need!

multiple independent, synergetic and complementary approaches to achieve **precision** (couplings), **sensitivity** (rare and forbidden decays) and **perspective** (role of Higgs dynamics in broad issues like EWSB and vacuum stability, baryogenesis, naturalness, etc)

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- Higgs CP violating couplings FCC-ee
- exclusive Higgs decays (e.g. $h \to J/\Psi + \gamma$) and measurement of couplings to light quarks FCC-ee
- exotic Higgs decay channels: LHC, FCC-ee, ILC

  $h \to \not{E}_T$, $h \to 4b$, $h \to 2b2\mu$, $h \to 4\tau, 2\tau 2\mu$, $h \to 4j$, $h \to 2\gamma 2j$, $h \to 4\gamma$, $h \to \gamma/2\gamma + \not{E}_T$,

  $h \to$ isolated leptons+ $\not{E}_T$, $h \to 2l + \not{E}_T$, $h \to$ one/two lepton-jet(s)+X, $h \to bb + \not{E}_T$, $h \to \tau\tau + \not{E}_T$ ...

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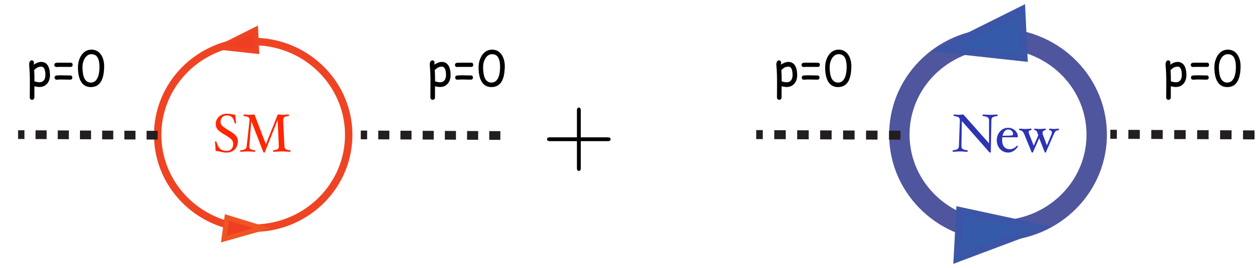
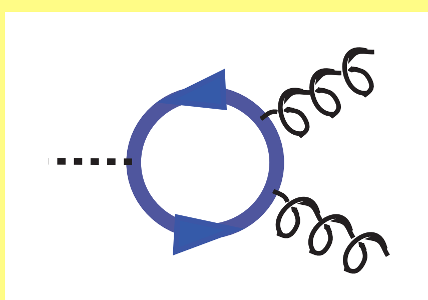
- ...

Higgs couplings and tests of naturalness

$$-(125\ \text{GeV})^2\left(\frac{\Lambda}{600\ \text{GeV}}\right)^2 \qquad\qquad \frac{g_*^2}{16\pi^2}\Lambda^2$$

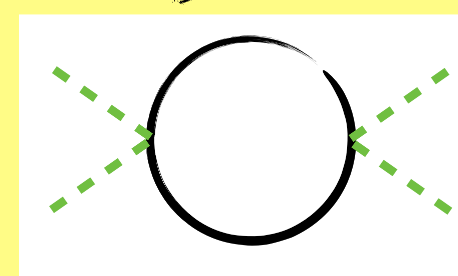
$\delta m_H^2 =$  $\sim m_H^2$

charged particles — *generically* — neutral particles



$$\frac{g_s^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 G_{\mu\nu}^2 \qquad \frac{e^2 g_*^2}{16\pi^2}\frac{1}{m_*^2}|H|^2 F_{\mu\nu}^2$$

$$\frac{\Delta BR(h\to\gamma\gamma, Z\gamma, gg)}{\text{SM}} \sim \frac{g_*^2 v^2}{m_*^2}$$



$$\frac{g_*^2}{16\pi^2}\frac{1}{m_*^2}\left(\partial_\mu |H|^2\right)^2$$

$$BR(h\to ii) = BR_{\text{SM}} \qquad \Gamma = \left(1-\frac{g_*^2 v^2}{16\pi^2 m_*^2}\right)\Gamma_{\text{SM}}$$

$$\delta\sigma_{Zh} = -\frac{g_\star^2}{8\pi^2}\frac{v^2}{m_\star^2}$$

nice to be able to measure Zh & Γ

Colorful naturalness probed @ LHC

Neutral naturalness (invisible?) @ LHC

Color naturalness & FCC-ee

J. Fan @ Washington

New Physics Reach:
natural SUSY (stop + Higgsino sector)

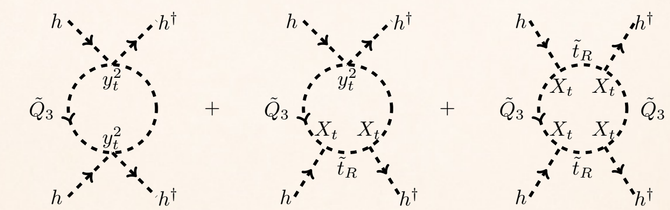
Lepton colliders are limited in kinematic reach of stops compared to proton colliders;

On the other hand, stops can be hidden due to some non-minimal decay modes and/or kinematics of the decay products (RPV, stealth SUSY, folded SUSY...)

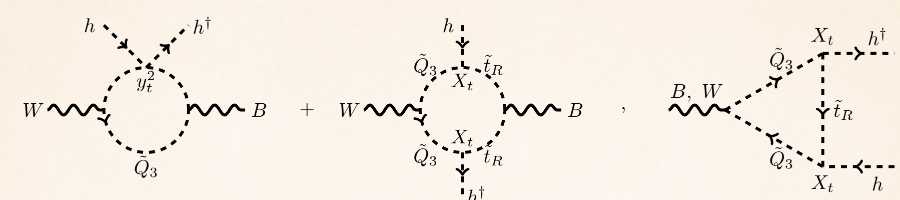
Precision measurements at lepton colliders could provide powerful complementary probes independent of the details of stop decays.

New Physics Reach:
natural SUSY (stop + Higgsino sector)

$$T\left(\frac{2\alpha}{v^2}\right)\left|h^\dagger D_\mu h\right|^2,$$



$$T \approx \frac{m_t^4}{16\pi \sin^2\theta_W m_W^2 m_{\tilde{Q}_3}^2} + \mathcal{O}\left(\frac{m_t^2 X_t^2}{4\pi m_{\tilde{Q}_3}^2 m_{\tilde{u}_3}^2}\right).$$



$$S\left(\frac{\alpha}{4\sin\theta_W\cos\theta_W v^2}\right) h^\dagger W^{i\mu\nu}\sigma^i h B_{\mu\nu}$$

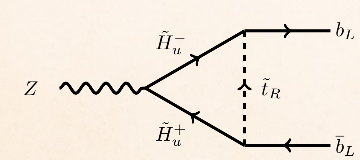
$$i\partial^\nu B_{\mu\nu} h^\dagger \overleftrightarrow{D}^\mu h$$

$$iD^\nu W^i_{\mu\nu} h^\dagger \sigma^i \overleftrightarrow{D}^\mu h$$

$$S \approx -\frac{1}{6\pi}\frac{m_t^2}{m_{\tilde{Q}_3}^2} + \mathcal{O}\left(\frac{m_t^2 X_t^2}{4\pi m_{\tilde{Q}_3}^2 m_{\tilde{u}_3}^2}\right).$$

Henning, Lu, Murayama 2014

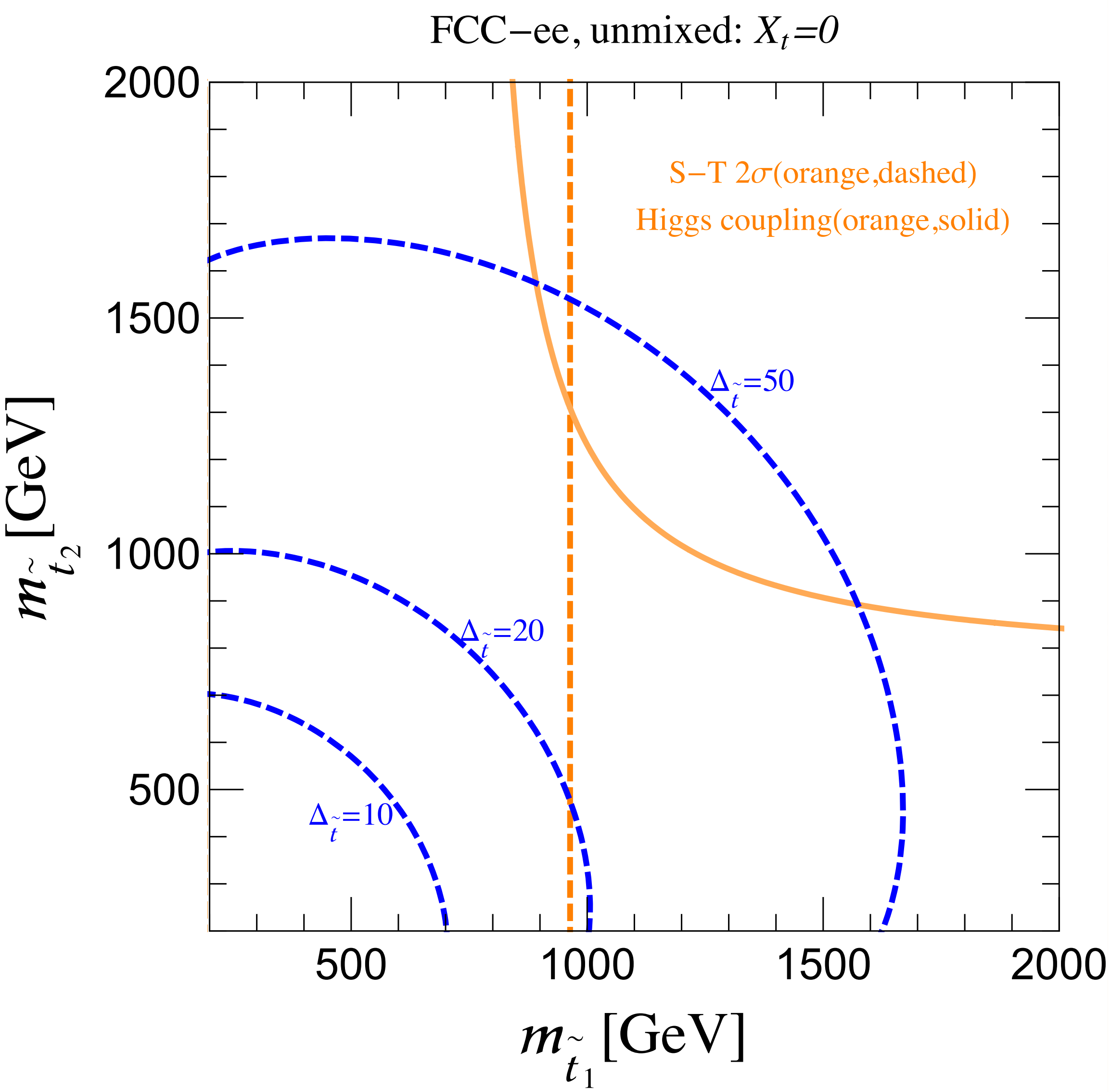
Rb

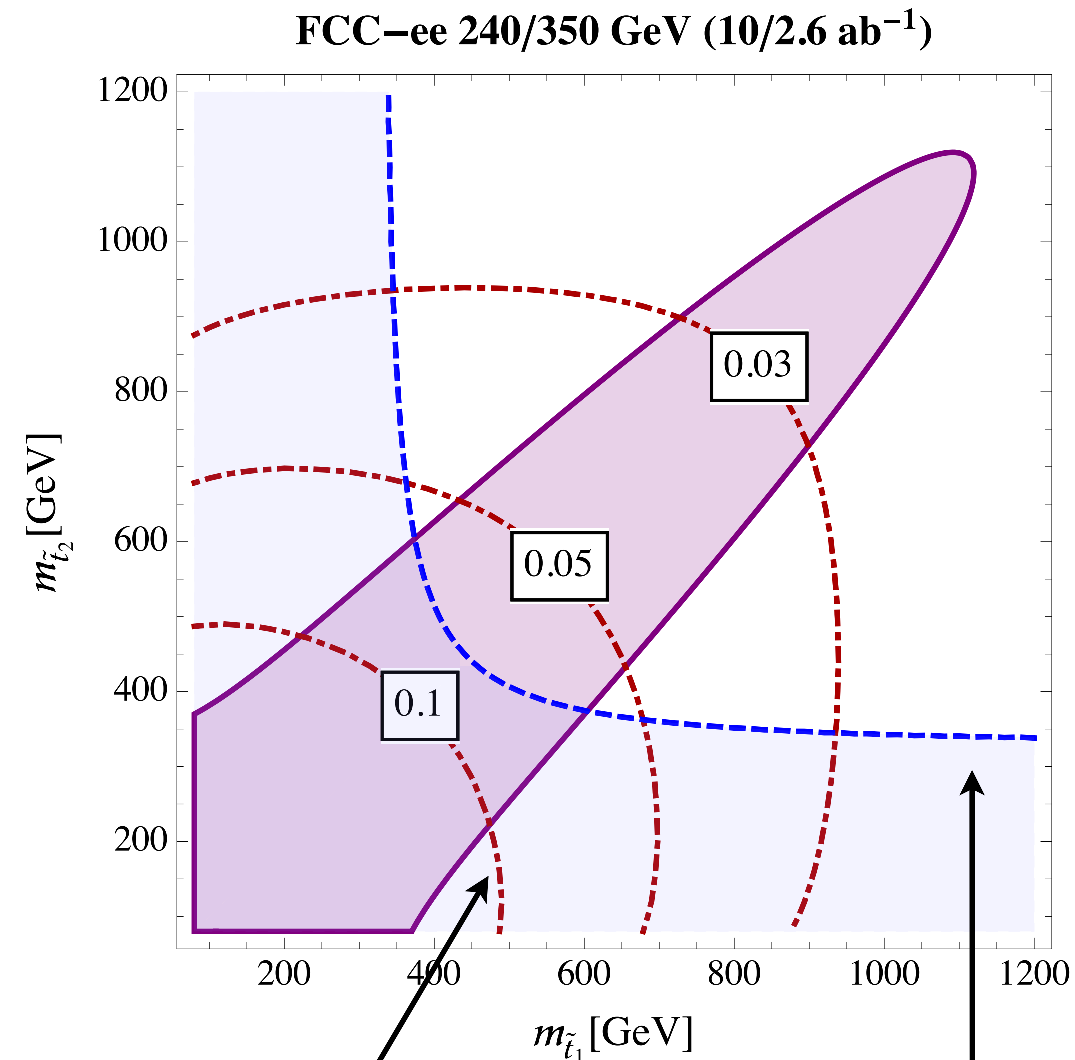


$$\frac{y_t^2}{m_{\tilde{t}_R}^2} W^i_{\mu\nu} Q_3^\dagger \sigma^i \bar{\sigma}^\mu i D^\nu Q_3 \,\log\frac{m_{\tilde{t}_R}}{\mu}.$$

Color naturalness & FCC-ee

Fan, Reece, Wang '14





Higgs mass fine-tuning

Higgs coupling fit

EW precision and Higgs data probe TeV-stops

Can exclude the 10% fine-tuned region and significantly constrain the 5% fine-tuned region

Neutral naturalness & FCC-ee

D. Curtin @ Washington

Singlet Naturalness

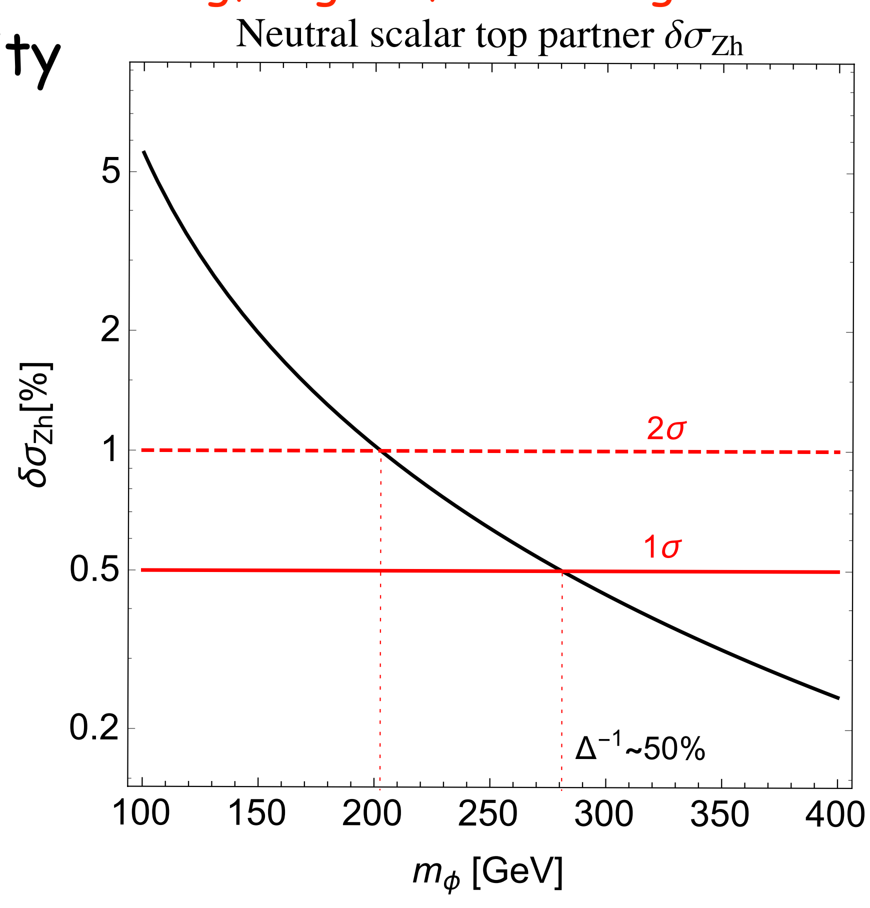
Fermionic top partners *without* any SM charge *always* lead to tree-level Higgs coupling shifts. ⇛ Detectable at lepton colliders for partner masses ≲ 1-2 TeV!

What about SM singlet scalar top partners? No theory yet, but can probably write one down....

In that case, would have to rely on *Higgs Portal Observables* at future colliders:

- **h*→SS production** (100 TeV) ⟵ surprisingly low sensitivity
- **σ(Zh) shift** by partner loops (ILC/TLEP)
- **triple higgs coupling shift** by partner loops (100 TeV)

Craig, Englert, McCullough '13

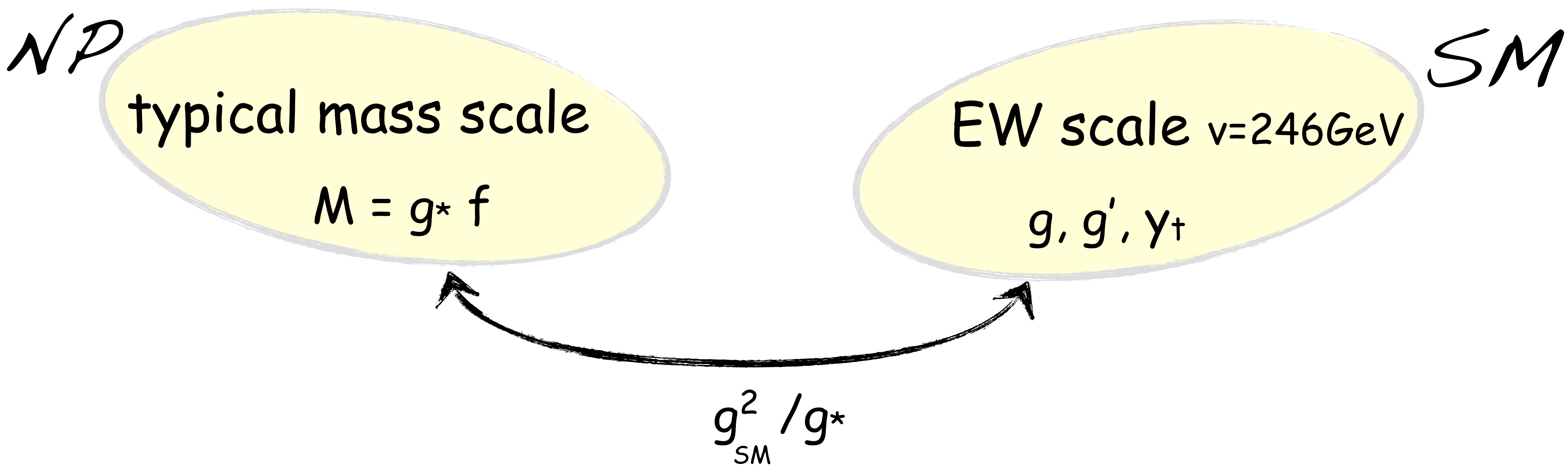


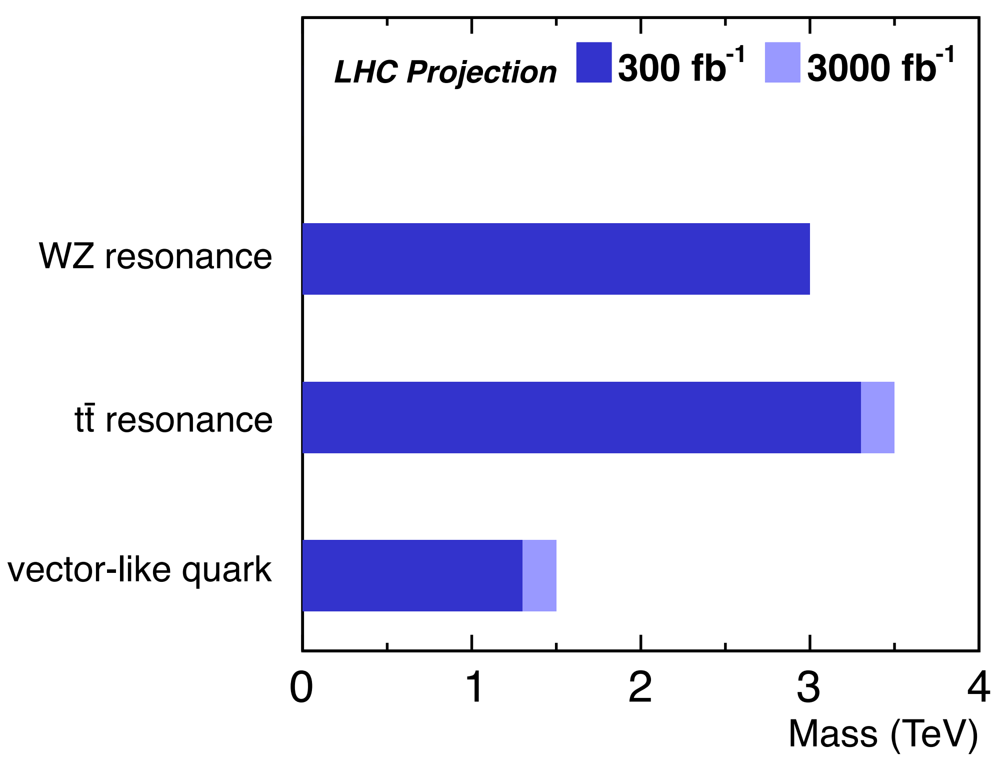
Sensitive to singlet scalar top partners at ~ 300 GeV

If there is a mirror QCD, h→invisible decays at lepton colliders *might* be sensitive to ~ 400 GeV

Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)





LHC direct search

- Precision Higgs study: $\xi \equiv \frac{\delta g}{g} = \frac{v^2}{f^2}$
- Direct searches for resonances: $m_\rho \approx g_* f$

Which one is doing best?
it depends on value of g*

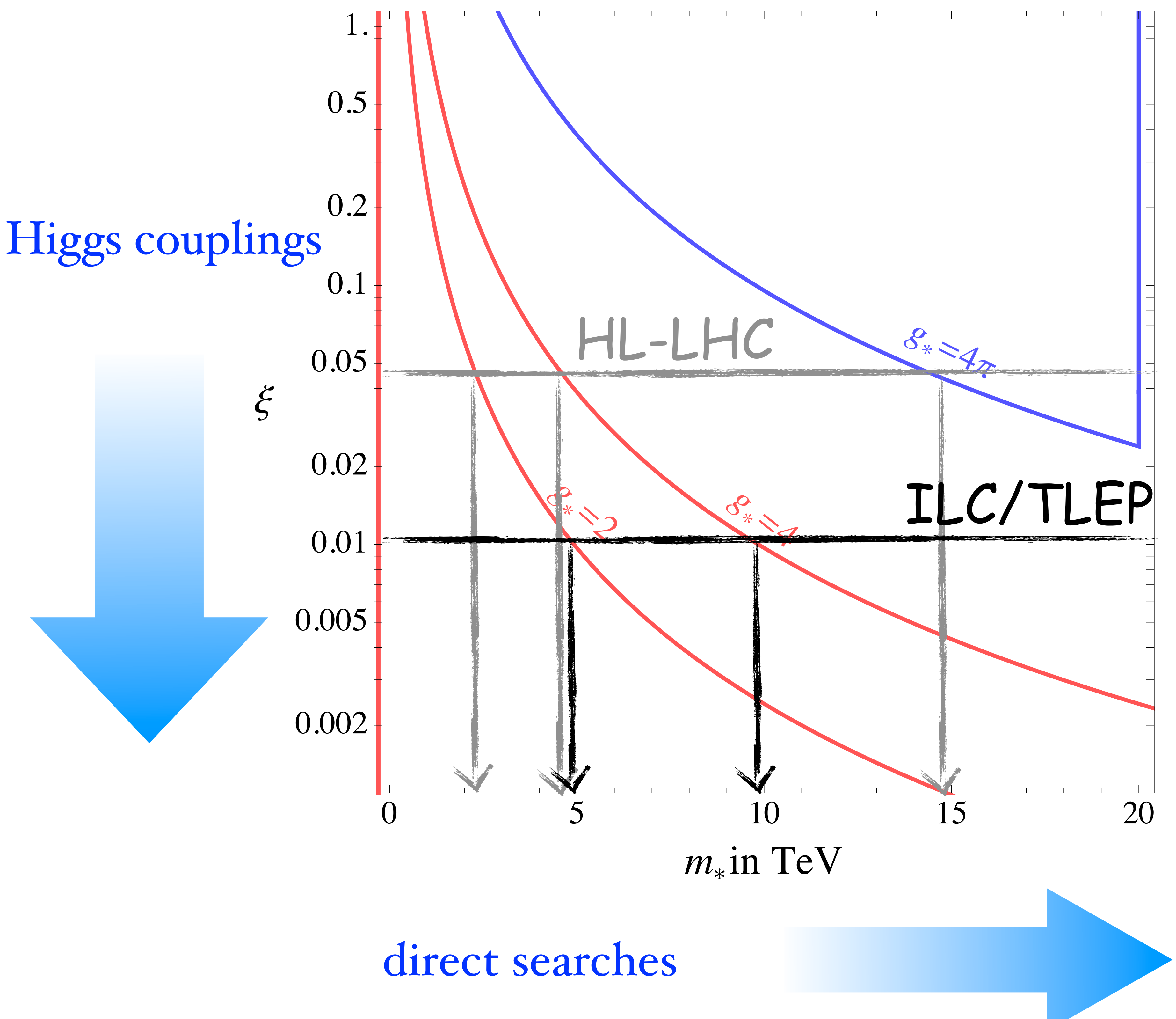
Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

Mass reach:

ee machines are best to test strongly coupled NP

pp machines are best to test weakly coupled NP



Rattazzi, BSM@100TeV, CERN '14

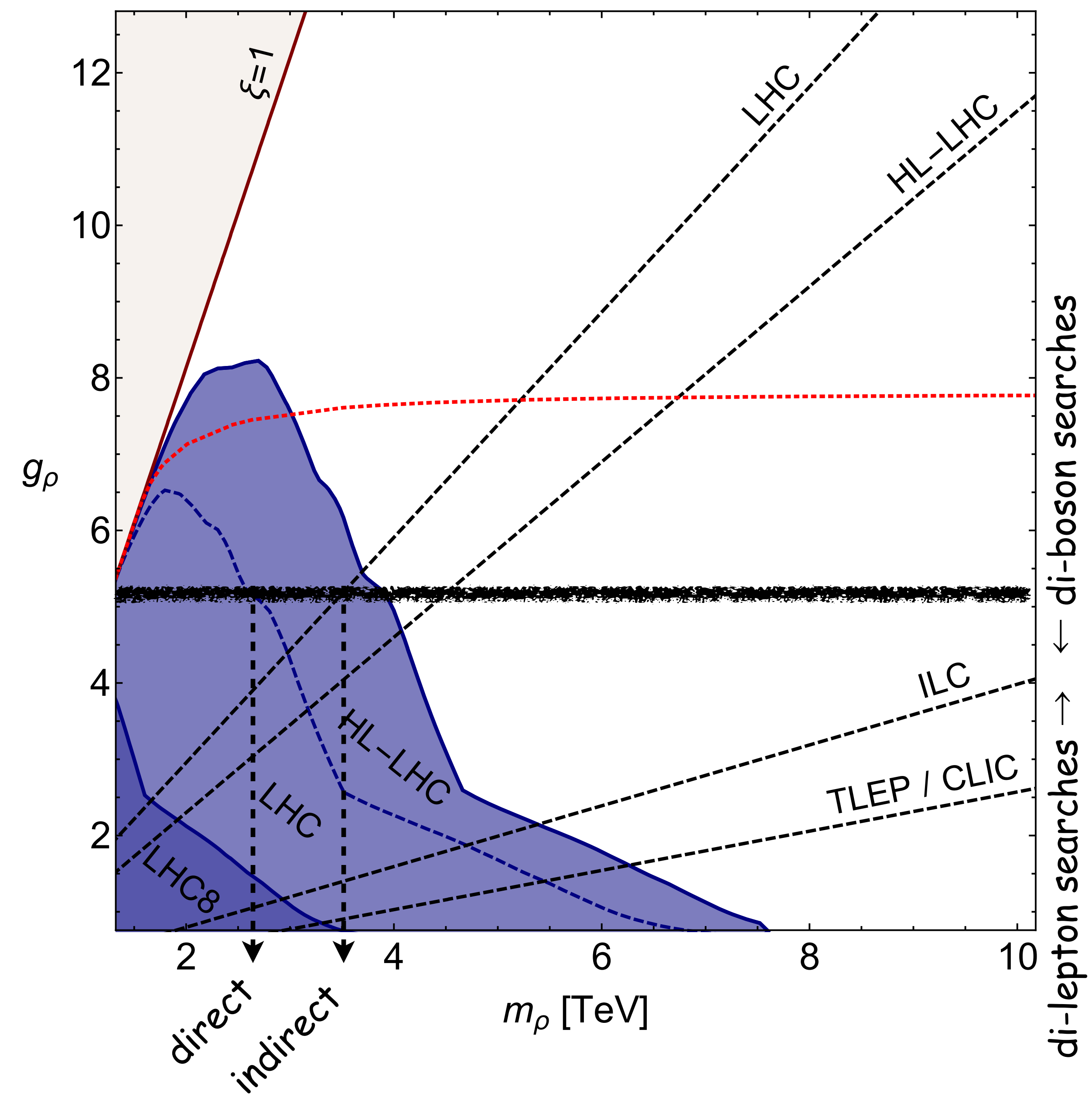
Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

DY production xs of resonances decreases as $1/g_\rho^2$

Torre, Thamm, Wulzer '15

Collider	Energy	Luminosity	ξ [1σ]
LHC	14 TeV	300 fb^{-1}	$6.6 - 11.4 \times 10^{-2}$
LHC	14 TeV	3 ab^{-1}	$4 - 10 \times 10^{-2}$
ILC	250 GeV + 500 GeV	250 fb^{-1} 500 fb^{-1}	4.8-7.8 $\times 10^{-3}$
CLIC	350 GeV + 1.4 TeV + 3.0 TeV	500 fb^{-1} 1.5 ab^{-1} 2 ab^{-1}	2.2 $\times 10^{-3}$
TLEP	240 GeV + 350 GeV	10 ab^{-1} 2.6 ab^{-1}	2 $\times 10^{-3}$



- **complementarity:**
  - direct searches win at small couplings
  - indirect searches probe new territory at large coupling

e.g.

indirect searches at LHC over-perform direct searches for g > 4.5

indirect searches at FCC-ee over-perform direct searches at HL-LHC for g > 1.5

Higgs & New Physics

Precision /indirect searches (high lumi.) vs. direct searches (high energy)

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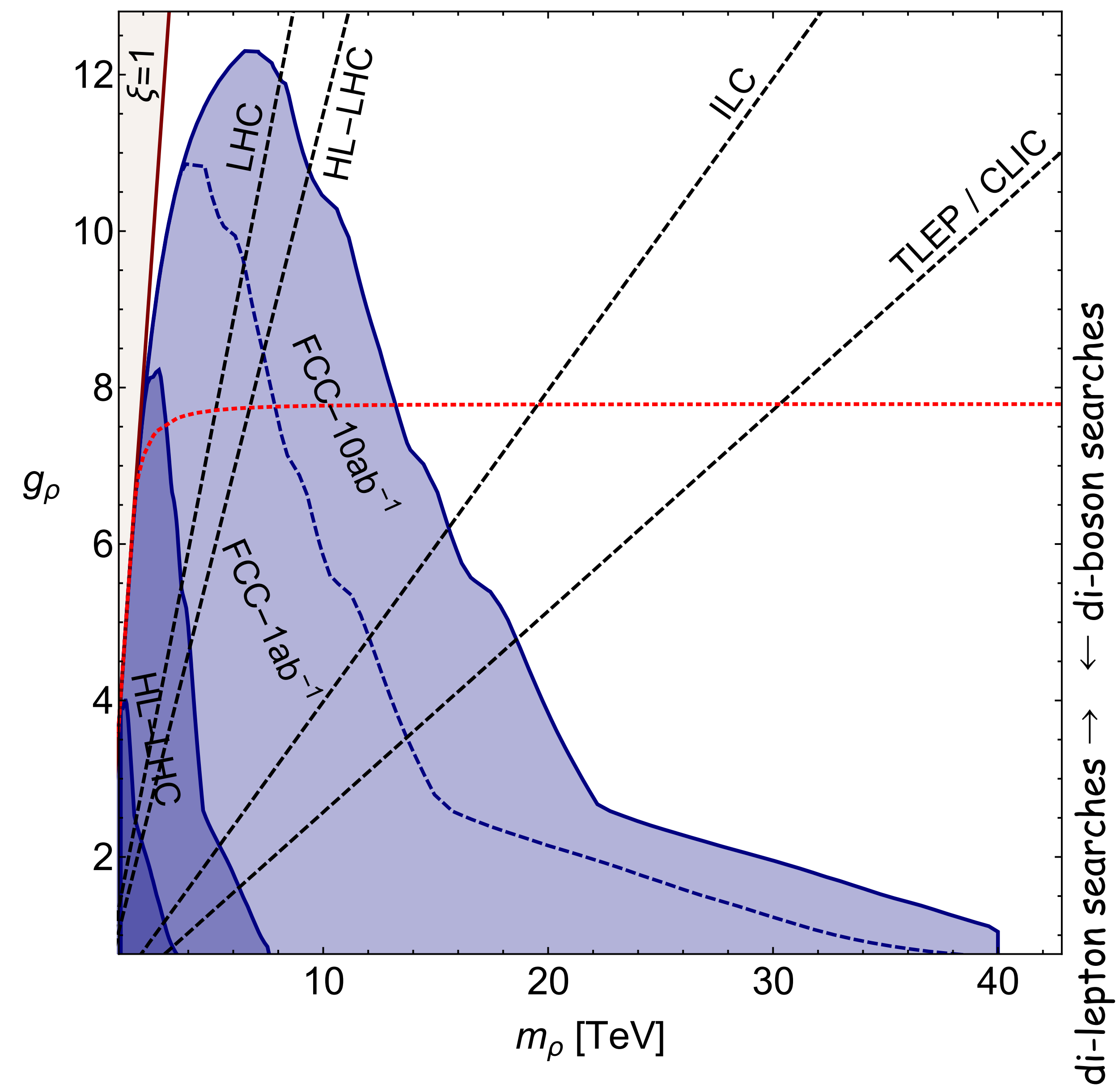
DY production xs of resonances decreases as $1/g_\rho^2$



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2 + 3

EWSB and flavor probes of BSM
(In)direct probes of high-mass frontier

The Twin Frontiers of FCC-ee Physics

Precision Measurements

- Springboard for sensitivity to new physics
- Experimental issues:
  - Systematics
- Theoretical issues:
  - Higher-order QCD
  - Higher-order EW
  - Mixed QCD + EW

Heinemeyer, Freitas, Degrassi, Salvarezza, Soreq, Matsedonskyi, Riemann, Schwinn, De Curtis

Rare Decays

- Direct searches for new physics
- Many opportunities
- Z: 10^{13}
- b, c, τ: 10^{12}
- W: 10^{8}
- H: 10^{6}
- t: 10^{6}

Soreq, Nemevsek, Azzi, Strumia, Fischer

Improving EW fit

LEP: 10^6 Z's ➠ TLEP: 10^{12} Z's

TLEP (physics case) '13

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Ratio TLEP/LEP
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6)	< 100	20
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{had}$)	2495200 ± 2300	Z Line shape scan	8 (10)	< 100	20
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001	25
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004	
N_ν	... and sterile ν's	2.92 ± 0.05	Zγ, 161 GeV	0.0010 (12)	< 0.001	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060	10
A_{LR}	$\Delta\rho$, ϵ_3, $\Delta\alpha_{had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015	100
m_W (MeV)	$\Delta\rho$, ϵ_3, ϵ_2, $\Delta\alpha_{had}$	80385 ± 15	WW threshold scan	0.3 (0.4)	< 0.5	3
m_{top} (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 (12)	< 10	100

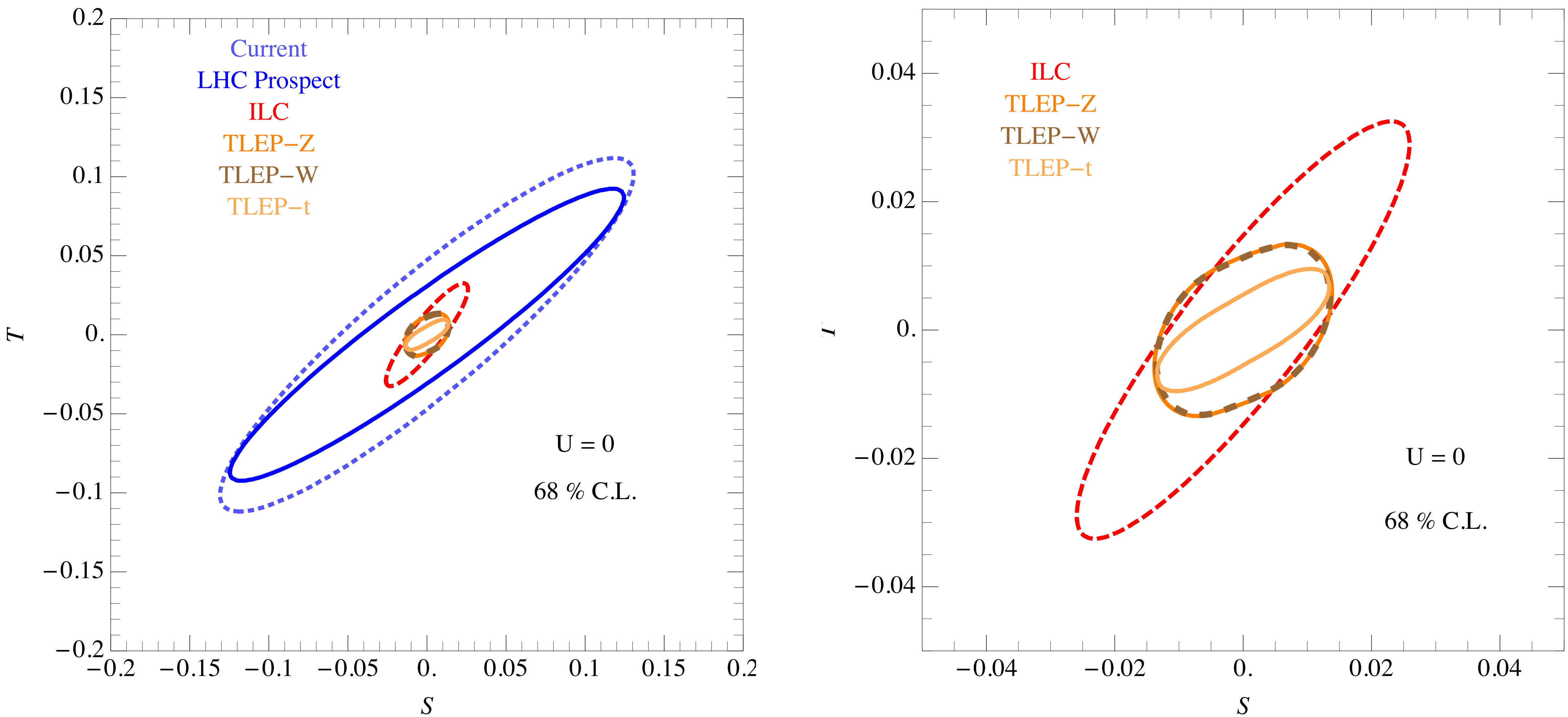
Table 9. Selected set of precision measurements at TLEP. The statistical errors have been determined with *(i)* a one-year scan of the Z resonance with 50% data at the peak, leading to 7×10^{11} Z visible decays, with resonant depolarization of single bunches for energy calibration at O(20min) intervals; *(ii)* one year at the Z peak with 40% longitudinally-polarized beams and a luminosity reduced to 20% of the nominal luminosity; *(iii)* a one-year scan of the WW threshold (around 161 GeV), with resonant depolarization of single bunches for energy calibration at O(20min) intervals; and *(iv)* a five-years scan of the $t\bar{t}$ threshold (around 346 GeV). The statistical errors expected with two detectors instead of four are indicated between brackets. The systematic uncertainties indicated below are only a "first look" estimate and will be revisited in the course of the design study.

Measurements of EW observables improved by ~20÷30 @TLEP/now

➠ oblique parameters (S,T,W,Y) uncertainty better by same amount (ILC/now≈2÷3)

Improving EW fit

LEP: 10^6 Z's ➠ TLEP: 10^{12} Z's



Fan, Reece, Wang '14

A. Blondel @ Washington

-- full use of precision measurements requires a considerable improvement in the theory calculations

- -- for the measurements themselves (e.g. Full two loops exponentiated for the QED ISR)
- -- for the interpretation; full three loop calculations for EWRCs and on inputs ($\Delta\alpha$_QED(m_Z)) *Was, Gluza, Heynemeyer, Kuhn, Frietas, Jadach, Ward..*

J. Fan @ Washington

To do list for a successful electroweak program

- ✦ Determine m_W to better than 5 MeV precision (15 MeV now) and $\sin^2\theta$ to better than 2×10^{-5} precision (16×10^{-5} now);
- ✦ Determine m_t to 100 MeV precision (0.76 GeV now) and m_Z to 500 KeV precision (2.1 MeV now).
- ✦ The precision goals apply to both experimental and theory uncertainties. For theory uncertainties, this means for m_W, $\sin^2\theta$, complete three-loop SM electroweak correction computations are desirable (two-loop calculations so far).

On-going efforts

	ILC	TLEP	perturb. error with 3-loop†	Param. error ILC*	Param. error TLEP**
M_W [MeV]	3–5	~ 1	1	2.6	1
Γ_Z [MeV]	~ 1	~ 0.1	$\lesssim 0.2$	0.5	?
R_b [10^{-5}]	15	$\lesssim 5$	5–10	< 1	< 1
$\sin^2\theta^{\ell}_{\rm eff}$ [10^{-5}]	1.3	0.3	1.5	2	2

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^2\alpha_s)$

(N_f^n = at least n closed fermion loops)

Parametric inputs:

* **ILC:** $\delta m_t = 100$ MeV, $\delta\alpha_s = 0.001$, $\delta M_Z = 2.1$ MeV

****TLEP:** $\delta m_t \lesssim 50$ MeV, $\delta\alpha_s =?$, $\delta M_Z = 0.1$ MeV

also: $\delta(\Delta\alpha) = 5 \times 10^{-5}$

A. Freitas @ Pisa '15

- Subtraction of QED radiation contributions
  - → Known to $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha^3 L^3)$ for **ISR**, $\mathcal{O}(\alpha^2)$ for **FSR** and $\mathcal{O}(\alpha^2 L^2)$ for $\mathbf{A_{FB}}$
    ($L = \log \frac{s}{m_e^2}$)
    Berends, Burgers, v.Neerven '88
    Kniehl, Krawczyk, Kühn, Stuart '88
    Beenakker, Berends, v.Neerven '89
    Skrzypek '92; Montagna, Nicrosini, Piccinini '97
  - → $\mathcal{O}(0.1\%)$ uncertainty on σ_Z, A_{FB}
  - → Improvement needed for ILC/TLEP
- Subtaction of non-resonant γ-exchange, γ–Z interf., box contributions, Bhabha scattering
  see, e.g., Bardin, Grünewald, Passarino '99
  - → $\mathcal{O}(0.01\%)$ uncertainty within SM (improvements may be needed)
  - → Sensitivity to some NP beyond EWPO

Other precision fronts

R. Tenchini @ Washington '15

- Z line shape -> mZ and GammaZ
- Z asymmetries (ALR, AFB) -> 10^{-6} on sin2theta, need long. pola?
- W mass from WW threshold scan (0.5 MeV vs 5 MeV LHC), need 4l final state rates: include non-resonant and off-shell effects
- top mass from tt threshold scan -> 5 MeV 1/ab vs 100 MeV LHC

Other topics non covered

- Neutrino counting
- Triple and quartic gauge couplings
- Measurements of α_s from lineshape and W hadronic decays
- Potential of FCC-hh for, e.g., dibosons

Don't leave QCD to hadronic machine

V. Radescu @ Washington

Strong coupling from e+e-

- **Hadronic final states:**
    - The theoretical predictions up to NNLO and the re-summation up to NNLL or N3LL
        - theoretical uncertainties though 1-3% , hadronisation effects ~1-2%
    - Typical experimental uncertainty about 1%
    - **For FCC prospects —> difficult to foresee that the overall uncertainty on alphas <1%**
- **Hadronic Z, W decay widths:**
    - An accurate determination of α_s due to precise theoretical calculations up to N3LO and suppressed non-perturbative effects

$$R_Z \equiv R_l^0 \equiv \frac{\Gamma(Z \to \text{hadrons})}{\Gamma(Z \to \text{leptons})} = R_Z^{\text{EW}} N_C (1 + \delta_{\text{QCD}} + \delta_{\text{m}} + \delta_{\text{np}}),$$

QCD, mass, NP corrections

- LEP results using NNLO calculations —>

$$\alpha_s(M_Z^2) = 0.1226 \pm 0.0038(\text{exp}) {}^{+0.0028}_{-0.0005}(\mu = {}^{2}_{0.25} M_Z) \; {}^{+0.0033}_{-0.0...}(M_H = {}^{900}_{100} \text{ GeV})$$
$$\pm 0.0002(M_{\text{top}} = \pm 5 \text{ GeV}) \pm 0.0002(\text{renormal. schemes})$$

- **The LEP measurement is mainly limited by lepton statistics —> FCC ee expect 10^{12} Z event stat**
- Use the W hadronic width , statistical limited for LEP, but an interesting prospect for FCC ee
- **Hadronic τ decay width**

$$R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\text{EW}} N_C (1 + \delta_{\text{QCD}} + \delta_{\text{np}}),$$

- LEP fit simultaneously α_s and the non-perturbative coefficients by measuring various moments of the τ spectral function
- **challenging to get uncertainty <1%**

22 Voica Radescu | Washington, D.C. | 2015

At LEP limited by TH uncertainties or statistics. New opportunities at FCC-ee, such as use of Γ_W

15

- QCD physics objectives at FCC ee:
    - High-precision (<1% uncertainty) strong coupling determination

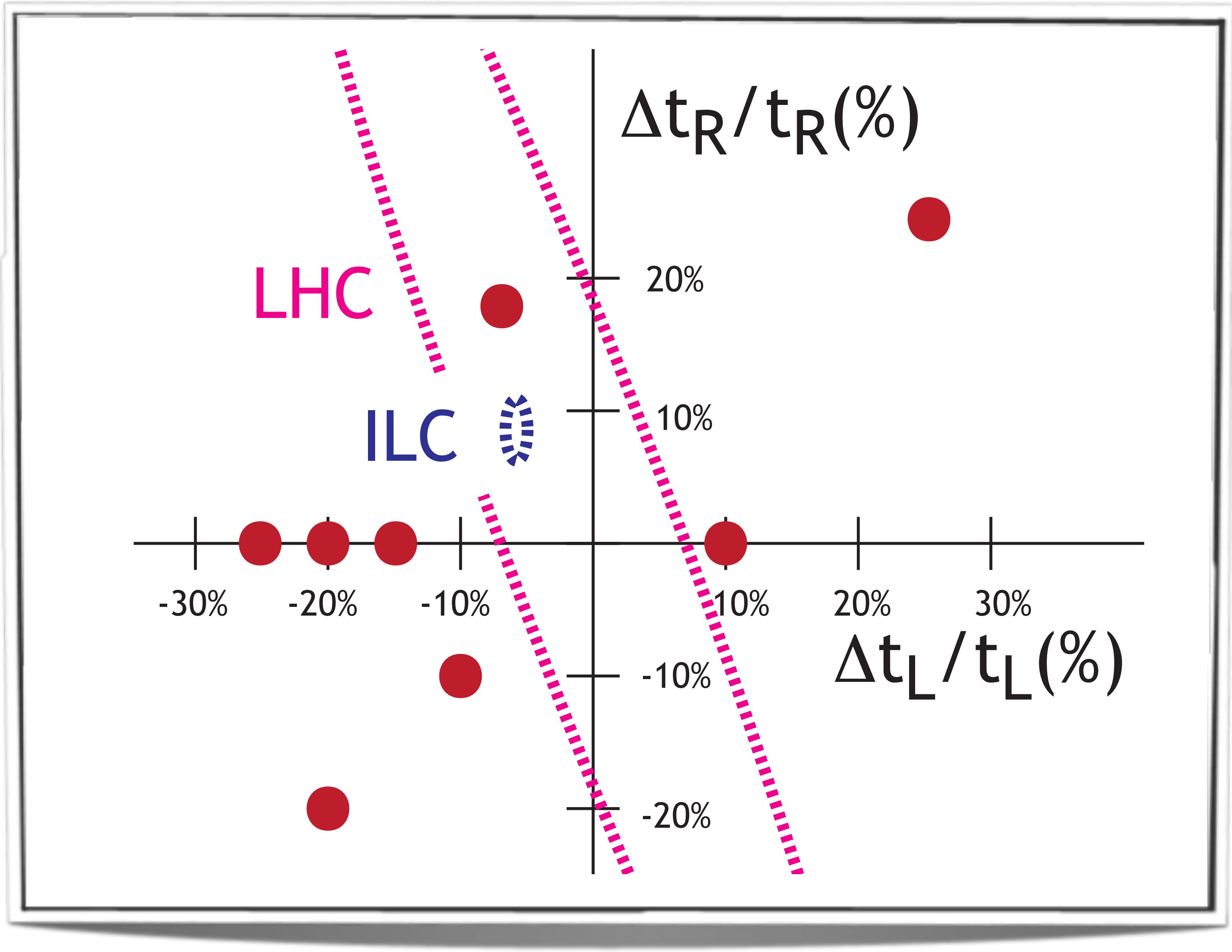
Top EW couplings

important to access the EW top couplings

chiral gauge symmetries are the only one to be spontaneously broken?

probe various scenarios of physics beyond the SM

adapted from Richard '14
see also Agashe et al '13

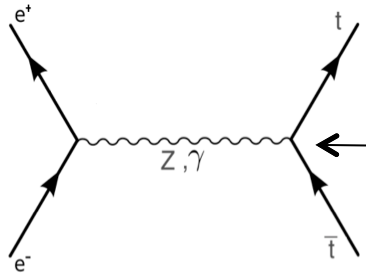


FCC sensitivity down to 0.5%

⇒ probe New Physics resonances up to 15-20 TeV, way above direct LHC access

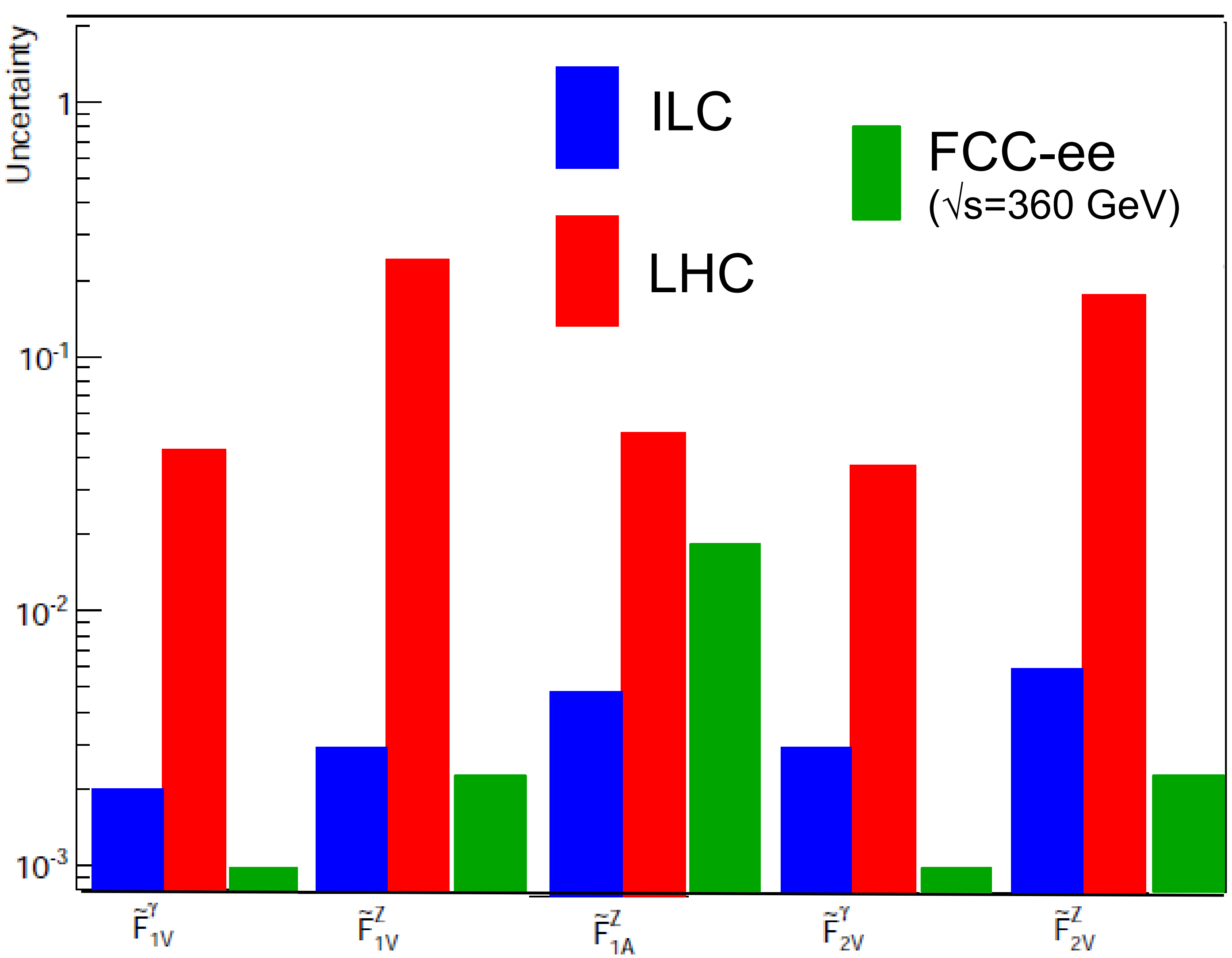
Top EW couplings

Janot '15



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

7 (gauge invariant) form factors, 5 CP-even & 2 CP-odd



To scrutinize:

S-wave contribution to ttbar @ threshold?

S-T-waves interference

see also P. Azzi @ Washington

top/Higgs flavor violating decays

		ATLAS	CMS
$h \to \mu\tau$		✔	✔
$t \to hq$ w/	$h \to \mu\tau$	✔	✔
	$h \to$ multilepton		✔
	$h \to bb$	✔	

Assuming a simple universal scaling: $Y_{ij} \sim \sqrt{(m_i m_j / v^2)}$,

$BR(h \to \mu\tau) = (0.89 \pm 0.40)\%$ implies $BR(t \to hc) \sim 0.25\%$

while direct constrain is currently ~0.5%, but can improve by combining various channels

LFV in rare Z-decays

- In the minimal SM (with massive neutrinos and PMNS mass mixing matrix), the LFV leptonic Z decays are beyond experimental reach

$$\mathcal{B}(Z \to e^\pm\mu^\mp) \sim \mathcal{B}(Z \to e^\pm\tau^\mp) \sim 10^{-54} \text{ and } \mathcal{B}(Z \to \mu^\pm\tau^\mp) \sim 4.10^{-60}$$

- Many NP models do foresee LFV Z decays: SUSY, Little Higgs etc...

- The current experimental bounds:

$$\mathcal{B}(Z \to e^\pm\mu^\mp) < 7.5\ 10^{-7},$$
$$\mathcal{B}(Z \to e^\pm\tau^\mp) < 9.8\ 10^{-6},$$
$$\mathcal{B}(Z \to \mu^\pm\tau^\mp) < 1.2\ 10^{-5}.$$

- We could potentially go more than 5 orders of magnitude beyond.

- Illustration: study these decays in the context of additional sterile neutrinos and relate their constraints to other observables. arXiv:1412.6322 [hep-ph], V. De Romeri et al. to appear in JHEP.

S. Monteil @ Washington '15

Indirect search for ν_R

O. Fischer @ Paris '14

Presence of massive right-handed neutrinos (ν_R):

$$\mathscr{L}_{\text{Theory}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{\nu_R}$$

Leads to mixing of the neutral states (ν_L, ν_R):

$$\mathcal{U} = \begin{pmatrix} \begin{pmatrix} & N & \end{pmatrix} & \cdots \\ \vdots & \ddots \end{pmatrix} \quad \text{with} \quad \mathcal{U}^\dagger \mathcal{U} = 1$$

- $N \sim$ Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- PMNS as submatrix in general **not** unitary

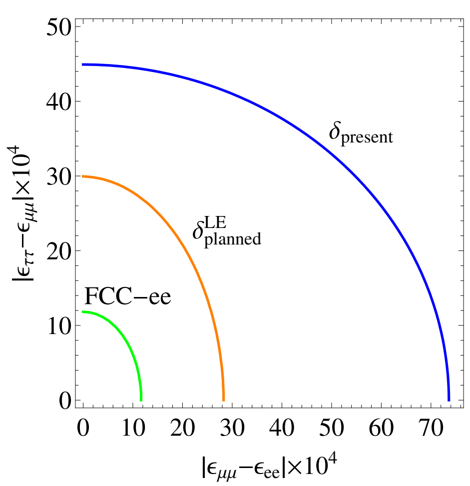
$$(NN^\dagger)_{\alpha\beta} = \mathbb{1}_{\alpha\beta} + \varepsilon_{\alpha\beta}$$

current bounds

-0.0021	$\leq \varepsilon_{ee} \leq$	-0.0002	$\lvert\varepsilon_{e\mu}\rvert$	$<$	1.0×10^{-5}
-0.0004	$\leq \varepsilon_{\mu\mu} \leq$	0	$\lvert\varepsilon_{e\tau}\rvert$	$<$	2.1×10^{-3}
-0.0053	$\leq \varepsilon_{\tau\tau} \leq$	0	$\lvert\varepsilon_{\mu\tau}\rvert$	$<$	8.0×10^{-4}

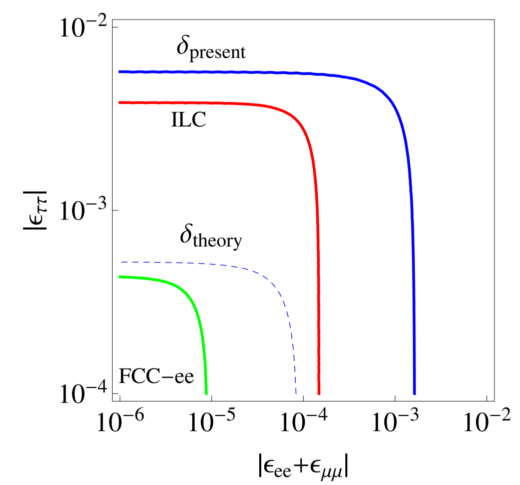
future prospects

Sensitivity to Non-Unitarity from Lepton Universality Tests



- Assumption: SM is true ($\varepsilon \equiv 0$ & $O^{exp} = O^{SM}$).
- Blue line: experimental constrains (present).
- Orange line: experimental sensitivity (planned). *MOLLER, TRIUMF, PSI, NA62, Tau/Charm factories*
- Green line: W decays at the FCC-ee.

Sensitivity to Non-Unitarity from EWPOs

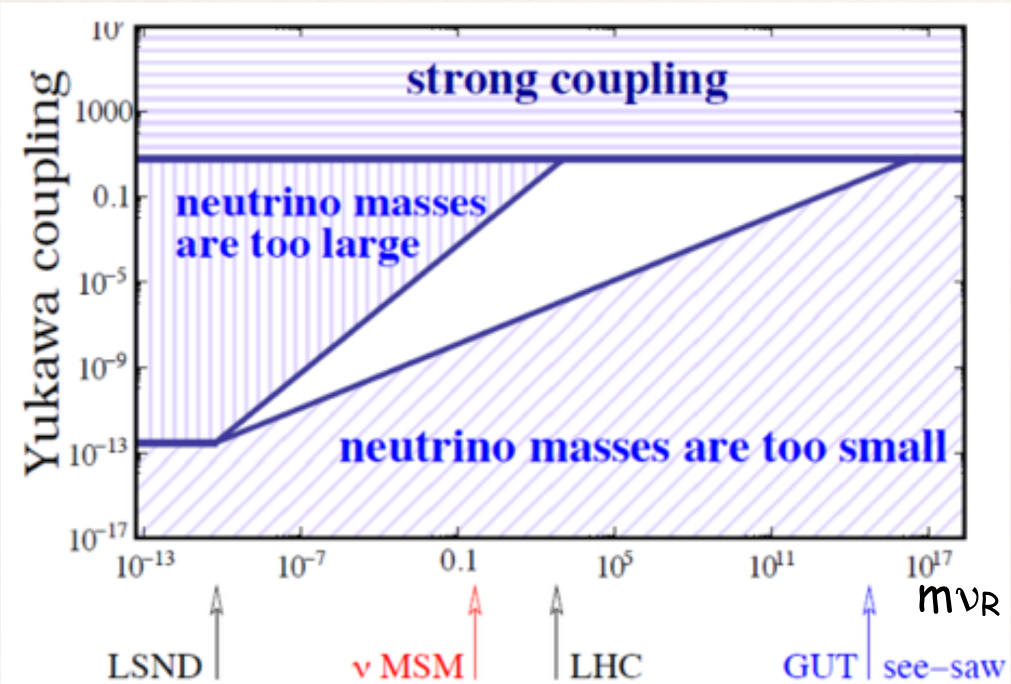


- Non-unitarity of the EWPO only.
- Blue lines: theoretical and experimental constrains (present).
- Red/Green line: ILC/FCC-ee sensitivity, see Backup VI.
- $\varepsilon_{\alpha\beta} = -y^*_\alpha y_\beta v^2_{EW}/(2\, m^2_{\nu_R}) \Rightarrow$ Test m_{ν_R} up to $\sim$ 60 TeV.

FCC-ee sensitive to m_{ν_R}~60TeV but not ν_R of traditional seesaw Actually, for **traditional seesaw**: ε~ 10^{-5} x(10keV/m_{ν_R}) ⇛ no visible effects

Direct search for (light) ν_R

N. Serra @ Paris '14
A. Blondel @ Washington '15



$m\nu_R$ [GeV]

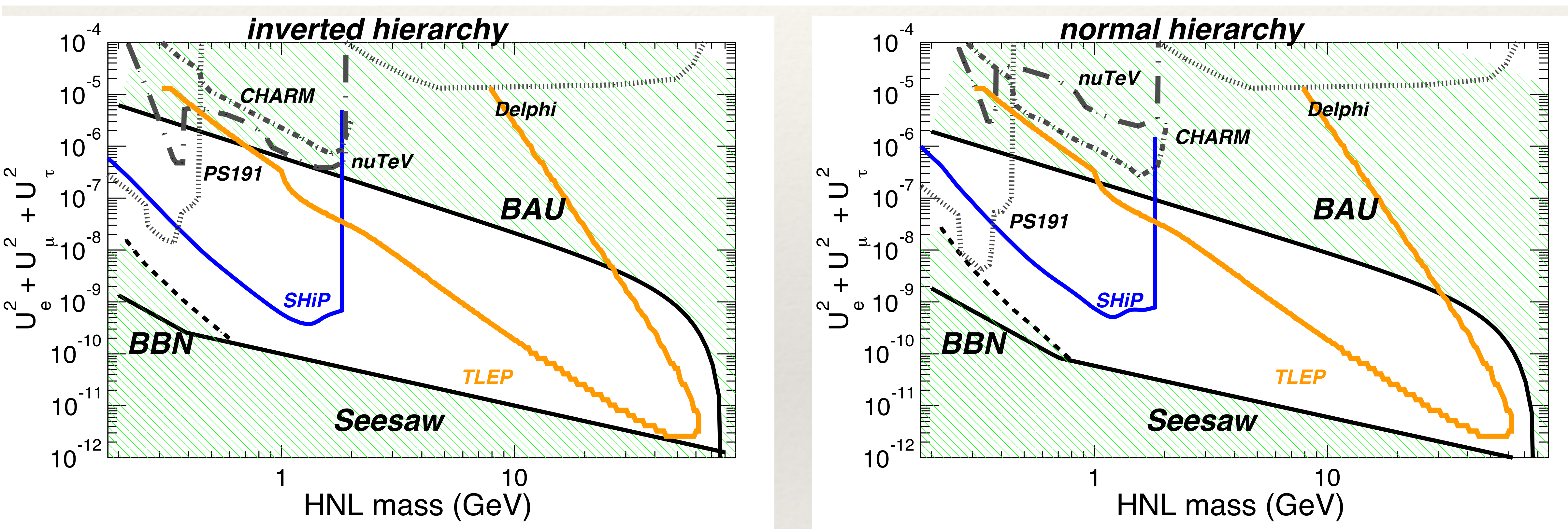
- Assuming $m_\nu = 0.1\text{eV}$
- if $Y \sim 1$ implies $M \sim 10^{14}\text{GeV}$
- if $M_N \sim 1\text{GeV}$ implies $Y_\nu \sim 10^{-7}$

remember $Y_{top} \sim 1.$ and $Y_e \sim 10^{-6}$

Traditional seesaw

$m\nu_L = Y^2\, v^2 / m\nu_R$

ν_R are produced in the 10^{12} TLEP Z decays and can be searched for



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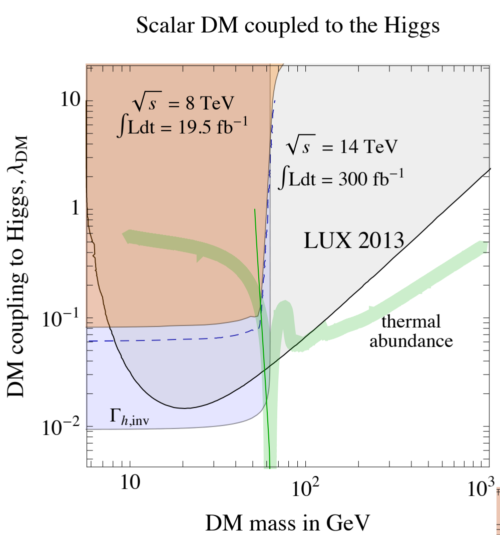
DM @ FCC-ee

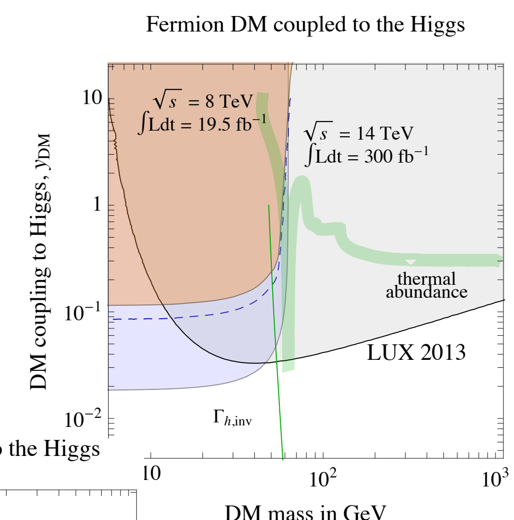
DM & FCC-ee

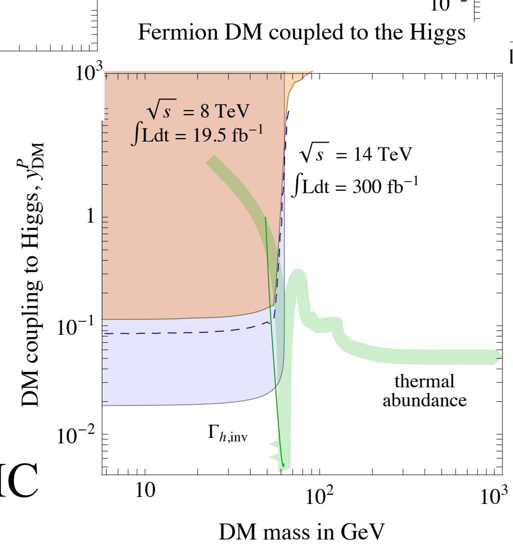
In traditional WIMP model, DM caries SM (weak) charges
Other models where FCC-ee can be particularly relevant:
SM neutral DM + light mediators (could be the Higgs itself!)

Higgs portal: $\mathcal{L} = -hJ_h\,, \quad J_h = \frac{1}{\sqrt{2}}\left[\sum_f y_f \bar{f} f + \bar{\psi}_{\rm DM}(y_{\rm DM} + i y^P_{\rm DM}\gamma_5)\psi_{\rm DM} + \frac{\lambda_{\rm DM} v}{2} s^2_{\rm DM}\right]$ $y\,, y^P\,, \lambda$ arbitrary couplings

current LHC bounds

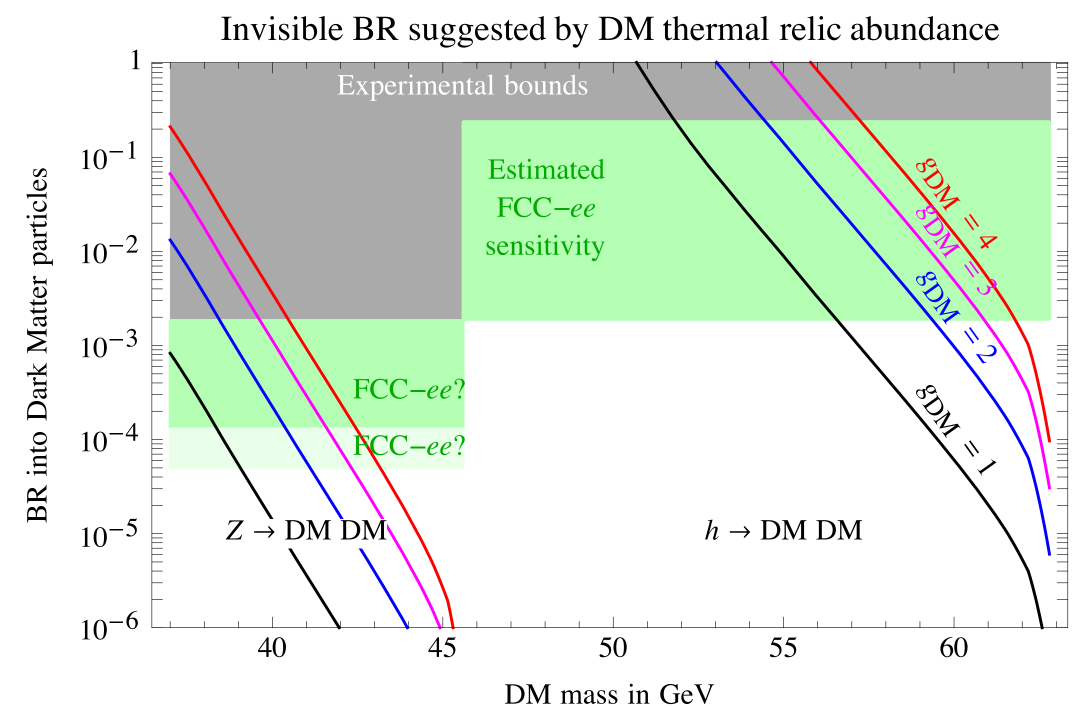






Γ_h invisible &
direct DM
do better than LHC

future bounds



Γ_Z and Γ_h invisible are the most efficient way to explore SM-mediated DM at colliders

De Simone, Giudice, Strumia '14

DM & FCC-ee

on-going analyses by M. Pierini

M. Pierini @ Washington

- Existing bounds from LEP put interesting bounds already
  - Measurement of Γ(Z→invisible)
  - Monophoton search
- Improved sensitivity @FCCee, thanks to large target ∫Lumi
  - Γ(Z→invisible)/Γ(Z→ℓℓ) @ Z pole
  - σ(ννγ)/σ(ℓℓγ) above Z pole with monophoton (Z portal)
  - Study photon spectrum for monophoton events (other DM models)
  - Add extra sensitivity with H→invisible search
- Quantitative conclusions are model dependent: need to establish benchmark simplified models

Conclusions

LHC-FCC interplay

If the LHC does not see any sign of NP, what should be the energy of the next machine?

FCC-hh -> exploration of the unknown/energy frontier
FCC-ee -> dedicated study of the EW+Higgs+top

Do we need to ttH, HH thresholds?