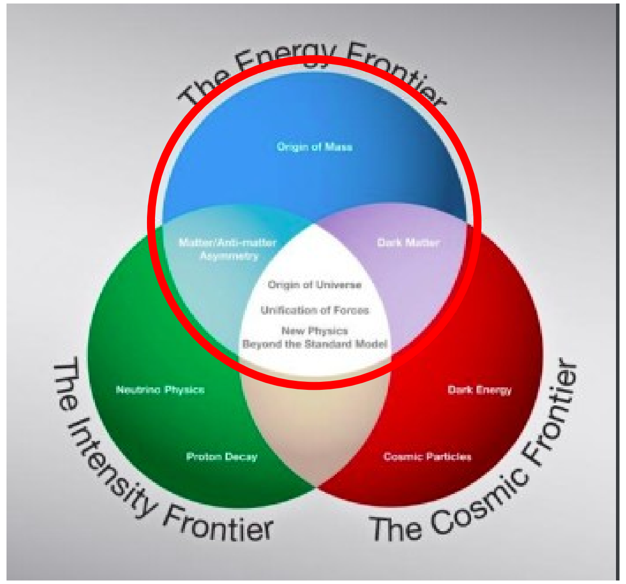
Physics at Future (Energy Frontier) Colliders



Frontier Cartoon of US Snowmass Study

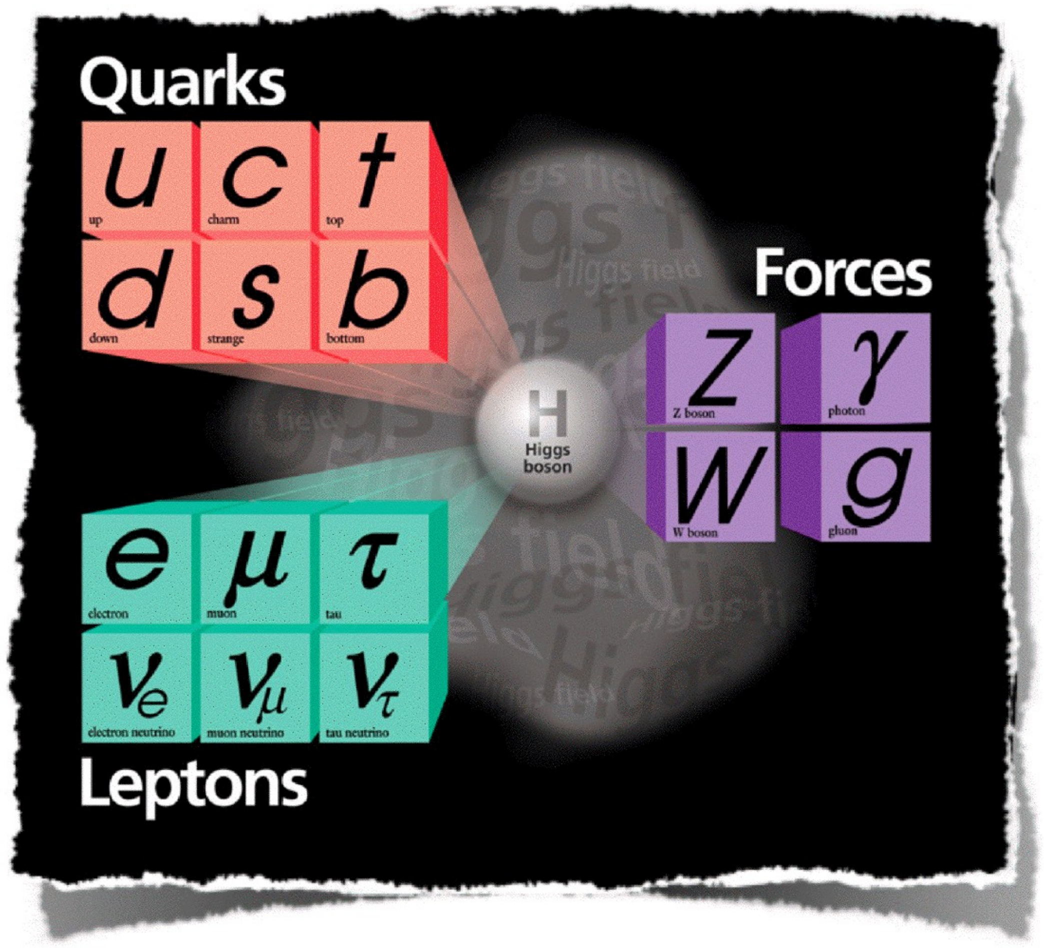
Roman Pöschl

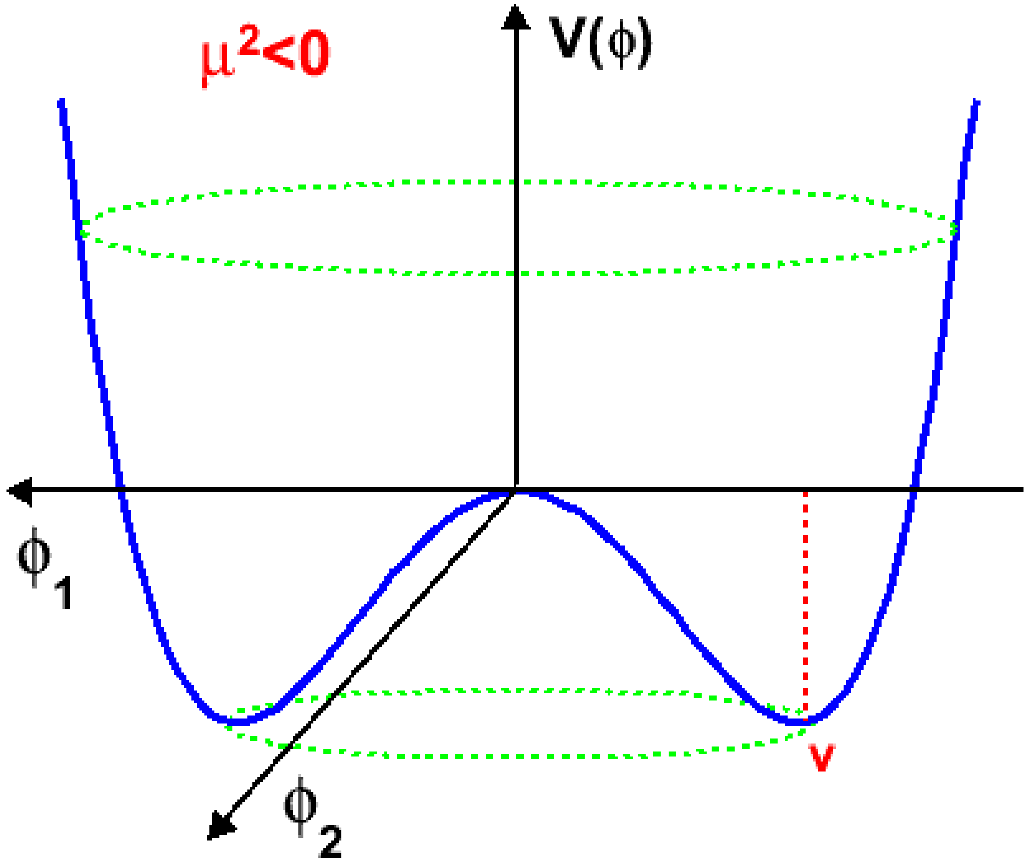
IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis
CNRS IN2P3 Les deux infinis
université PARIS-SACLAY GRADUATE SCHOOL Physique
P2I Physique des deux Infinis

P2I Annual Meeting November 2024

Sorry for covering only the tip of the iceberg

The Standard Model is complete





- We know that there exists at least one fundamental scalar with a non-vanishing expectation value
- We don't know what shapes the potential and whether the potential is the footprint of a larger mass scale

Open questions

New physics?

EFT: Two distinct observations

Observables at fixed mass m
(e.g. Z pole of Higgs decays)

$$\frac{\sigma}{\sigma_{SM}} \approx |1 + \frac{c_6 m^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing the measurement precision

$c_6 \sim (g^*)^2$

Typical experimental precision 0.1-1%

High energy tails of distributions
(e.g. Drell-Yan Productions

$$\frac{\sigma}{\sigma_{SM}} \approx |1 + \frac{c_6 E^2}{\Lambda^2}|^2$$

Increasing UV scales probed in EFT achieved solely by increasing the energy scale of measurement precision

Typical experimental precision 10%

A. Falkowski, Journée Grands Accél., LAL

Time Scale of Future Projects

Snowmass EF-Vision (L. Reina)

Higgs Factories

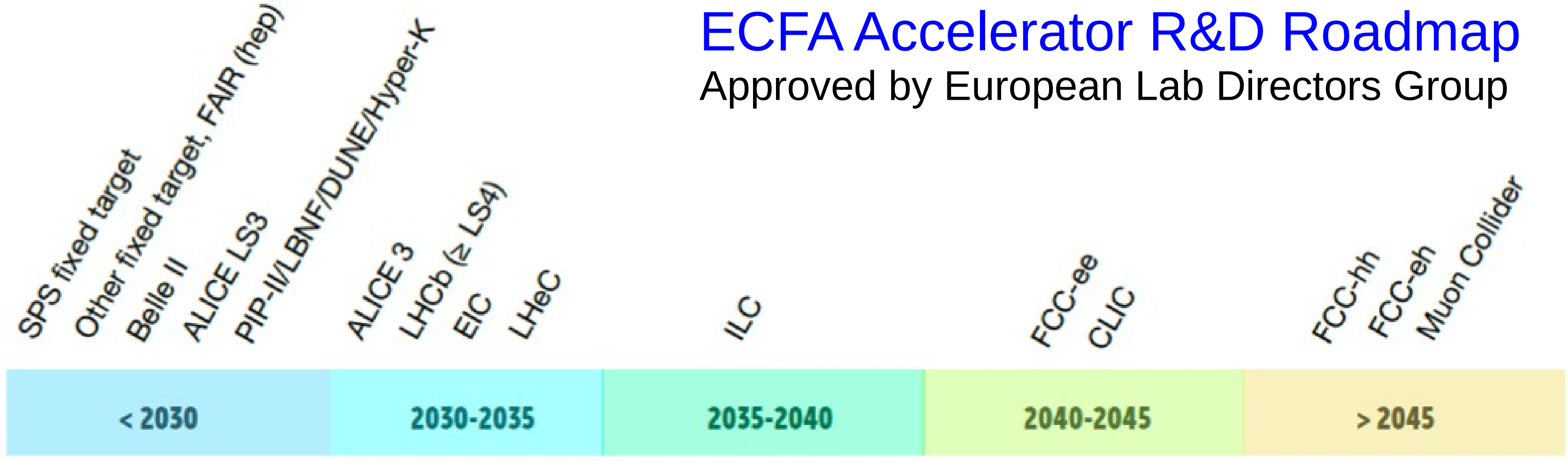
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{int}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV	$\pm80/\pm30$	2	2028	2038
		350 GeV	$\pm80/\pm30$	0.2		
		500 GeV	$\pm80/\pm30$	4		
		1 TeV	$\pm80/\pm20$	8		
CLIC	ee	380 GeV	$\pm80/0$	1	2041	2048
CEPC	ee	M_Z		50	2026	2035
		$2M_W$		3		
		240 GeV		10		
		360 GeV		0.5		
FCC-ee	ee	M_Z		75	2033	2048
		$2M_W$		5		
		240 GeV		2.5		
		$2\ M_{top}$		0.8		
μ-collider	$\mu\mu$	125 GeV		0.02		

>1 TeV pCOM

Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$. e^-/e^+	$\mathcal{L}_{int}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC	ep	1.3 TeV		1		
FCC-eh		3.5 TeV		2		
CLIC	ee	1.5 TeV	$\pm80/0$	2.5	2052	2058
		3.0 TeV	$\pm80/0$	5		
μ-collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		

ECFA Accelerator R&D Roadmap

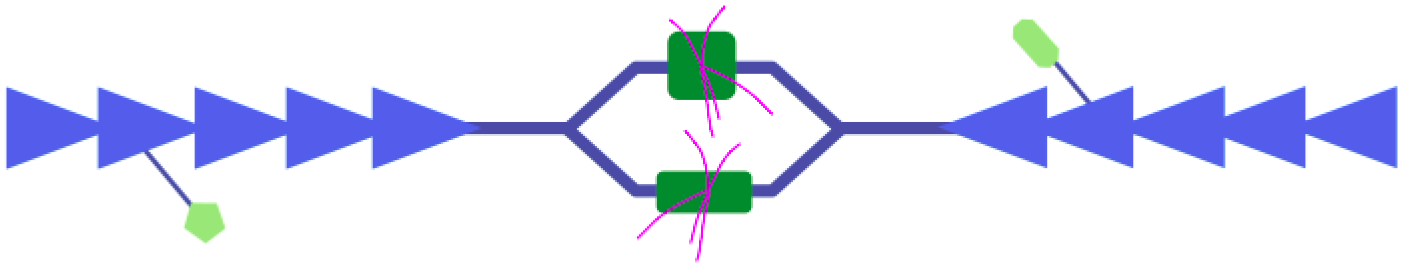
Approved by European Lab Directors Group



- Future projects can be broadly sudivided into ...
- “Higgs Factories to study in depth the properties of the Higgs Boson, the top and the electroweak sector
  - Mainly lepton colliders but also HL-LHC of course
- ...> 1 TeV parton Centre-of-Mass machines
  - To extend the reach for new physics searches or to study
  - the properties of new particles (if they are any)
    - Mainly pp colliders
- Muon and ep-colliders interpolate between these two “extremes”

5

Future Projects – Linear Colliders



ilc · clic · C^3 · **HALHF and PWA**

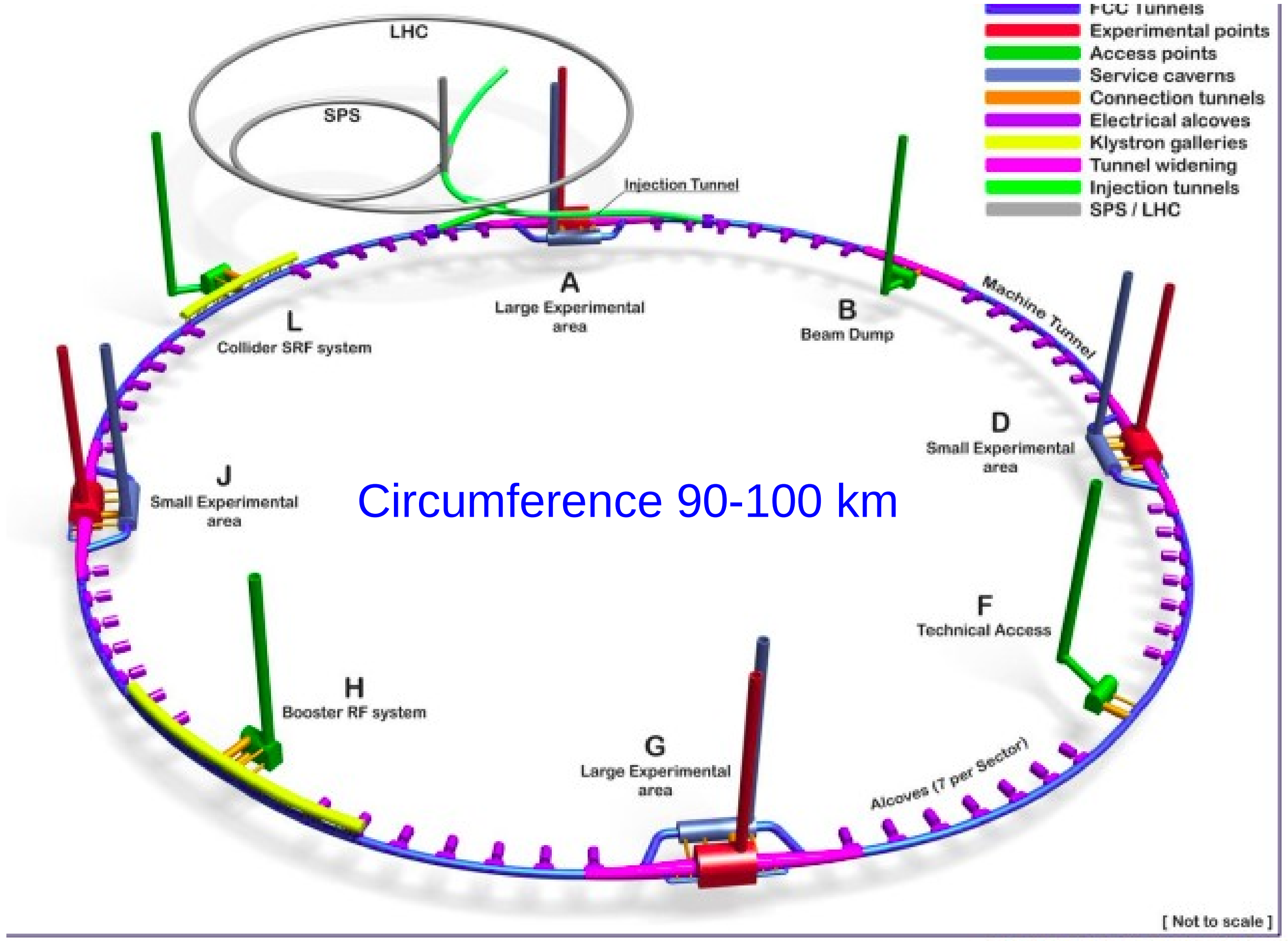
↓

Linear Collider Facility - LCF

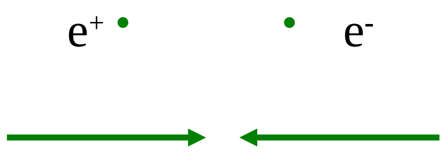
- Linear Colliders could cover in a staged approach centre-of-mass energies between the Z-pole until multi-TeV
- Polarised beams

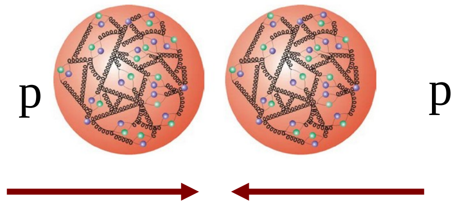
Future Projects – Circular Colliders

FCC-ee and FCC-hh (or CEPC and SppC)



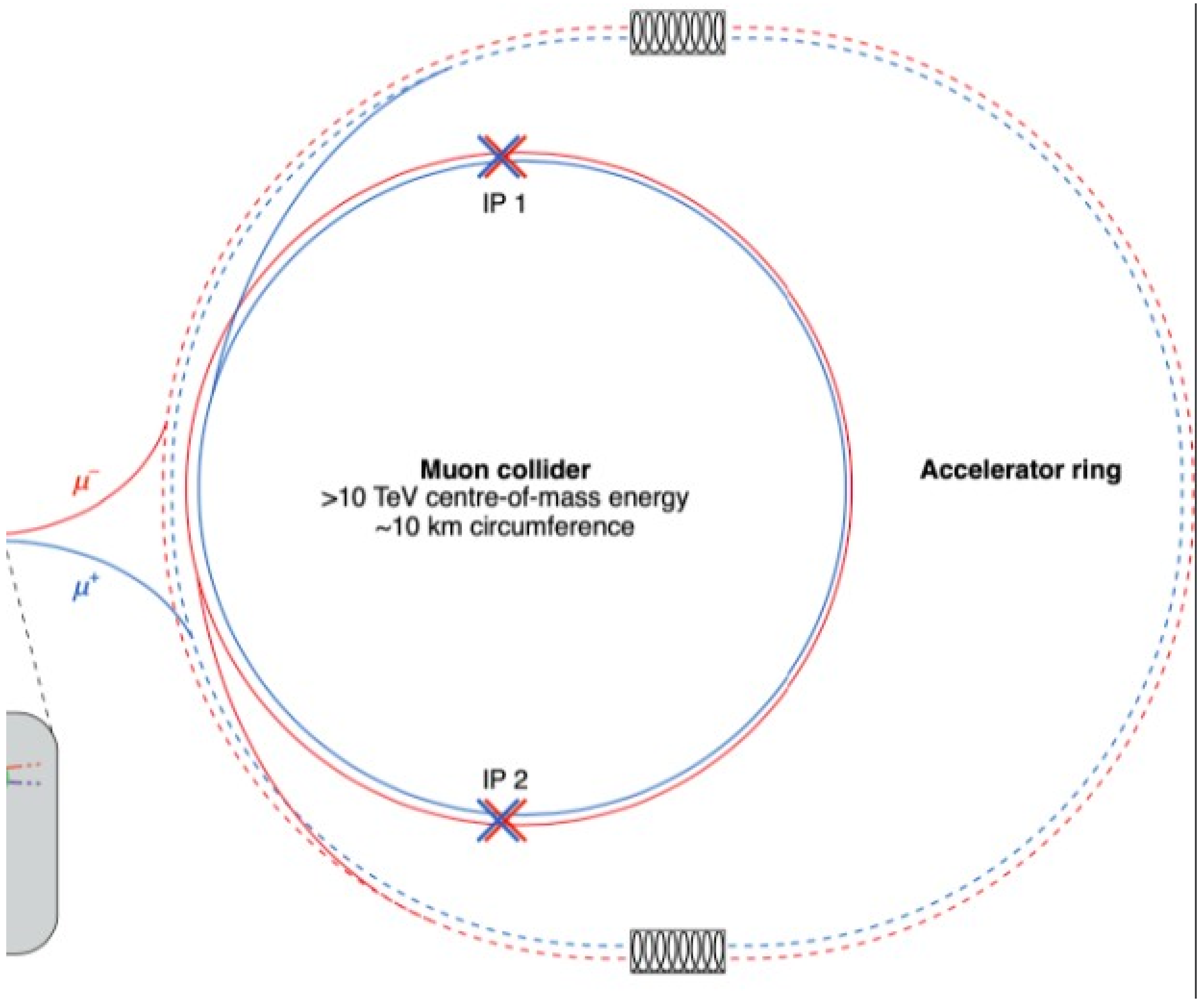
Credit: Angel Navascues Cornago





- Electron positron collider at $\sqrt{s}= M_Z - m_{tt}$
- … followed by pp collisions at √s O(100 TeV)
- Option ep collisions at √s~ O(1-3 TeV)

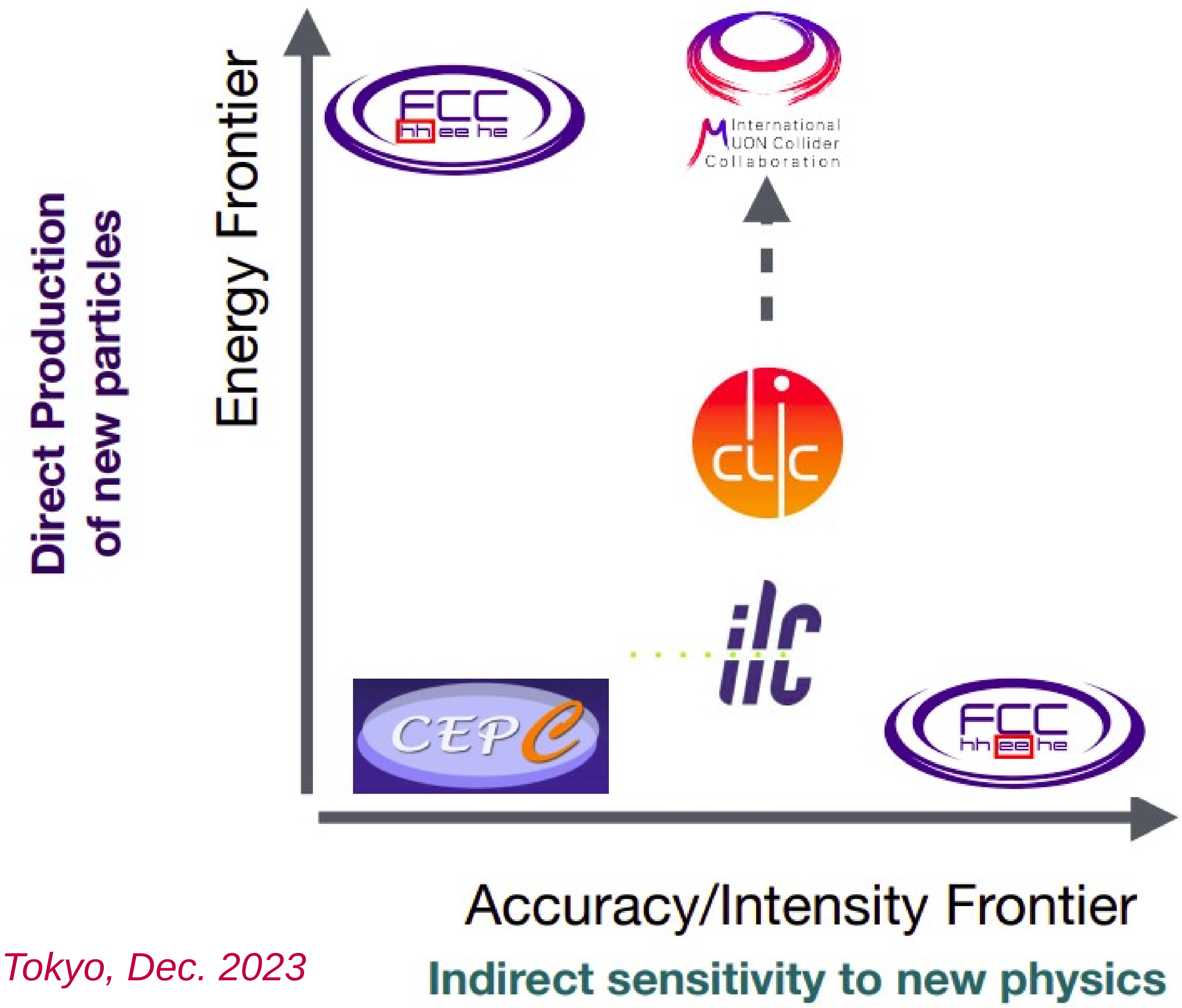
Muon Collider Facility



- Muon collission at √s~3-10 TeV
- Would combine advantages of ee collisions with higher energy reach
- Challenge: Muons are unstable particles

7

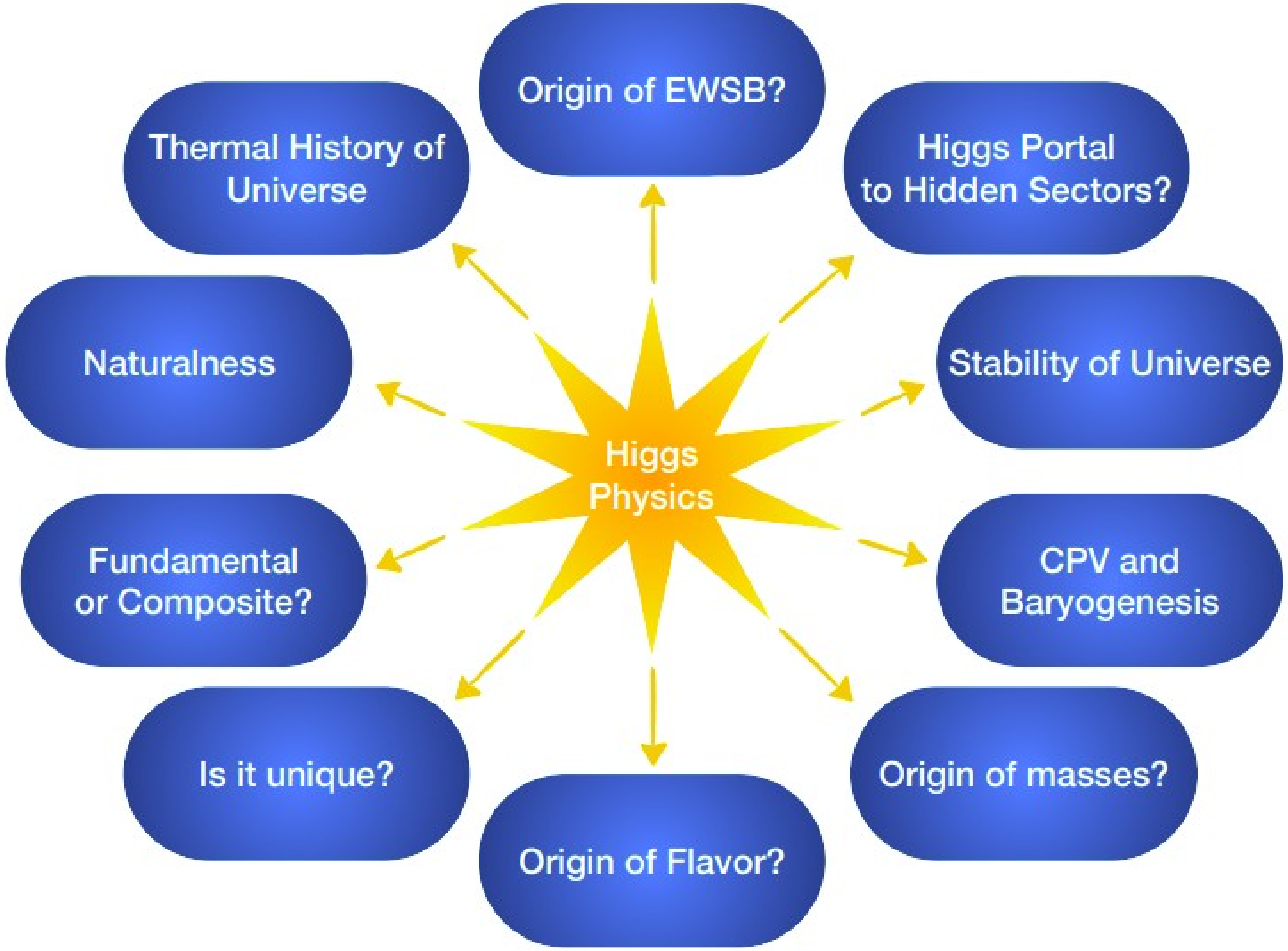
Future Projects – "The Frontiers"



Cartoon J. de Blas, ICEPP Tokyo, Dec. 2023

8

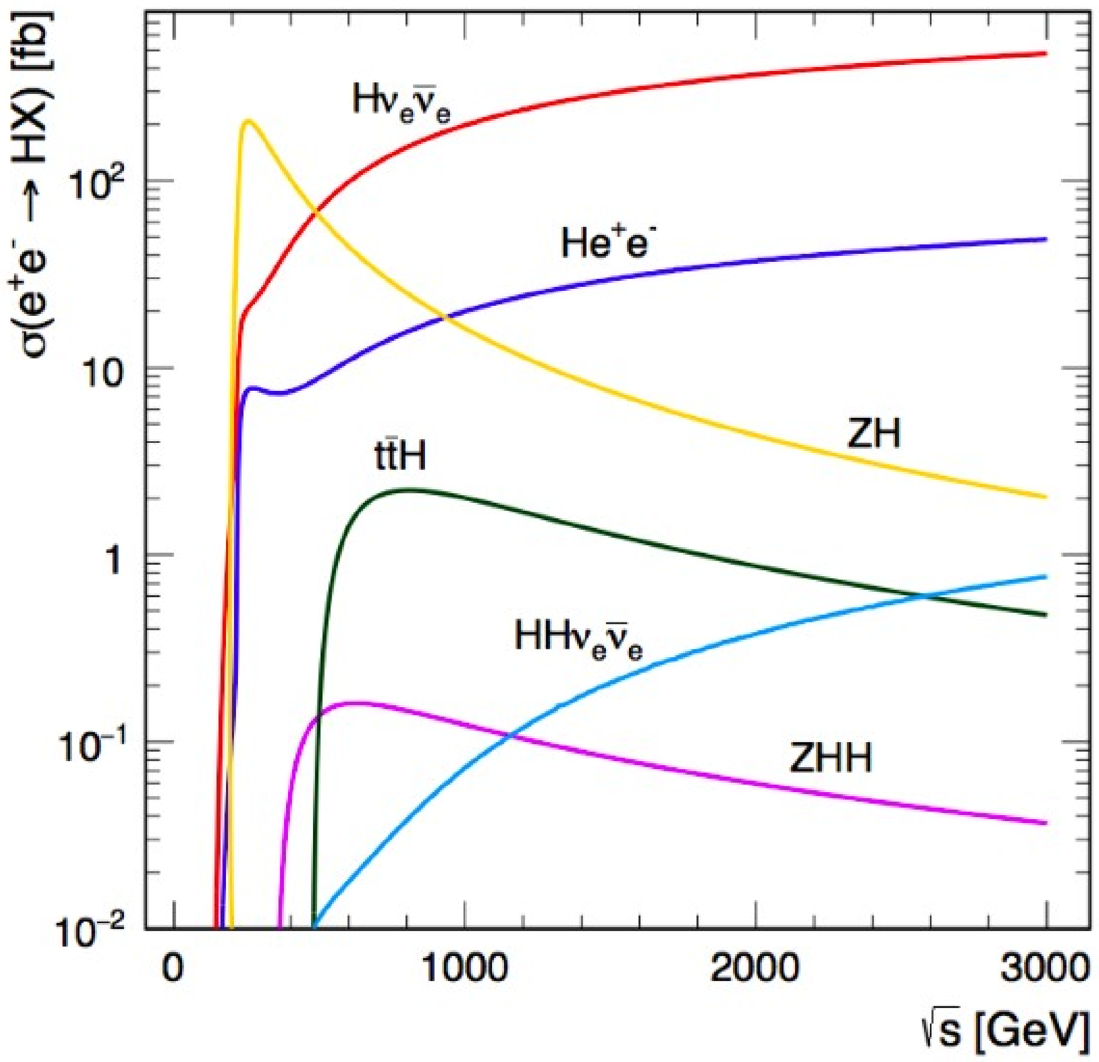
Science Driver Higgs Boson

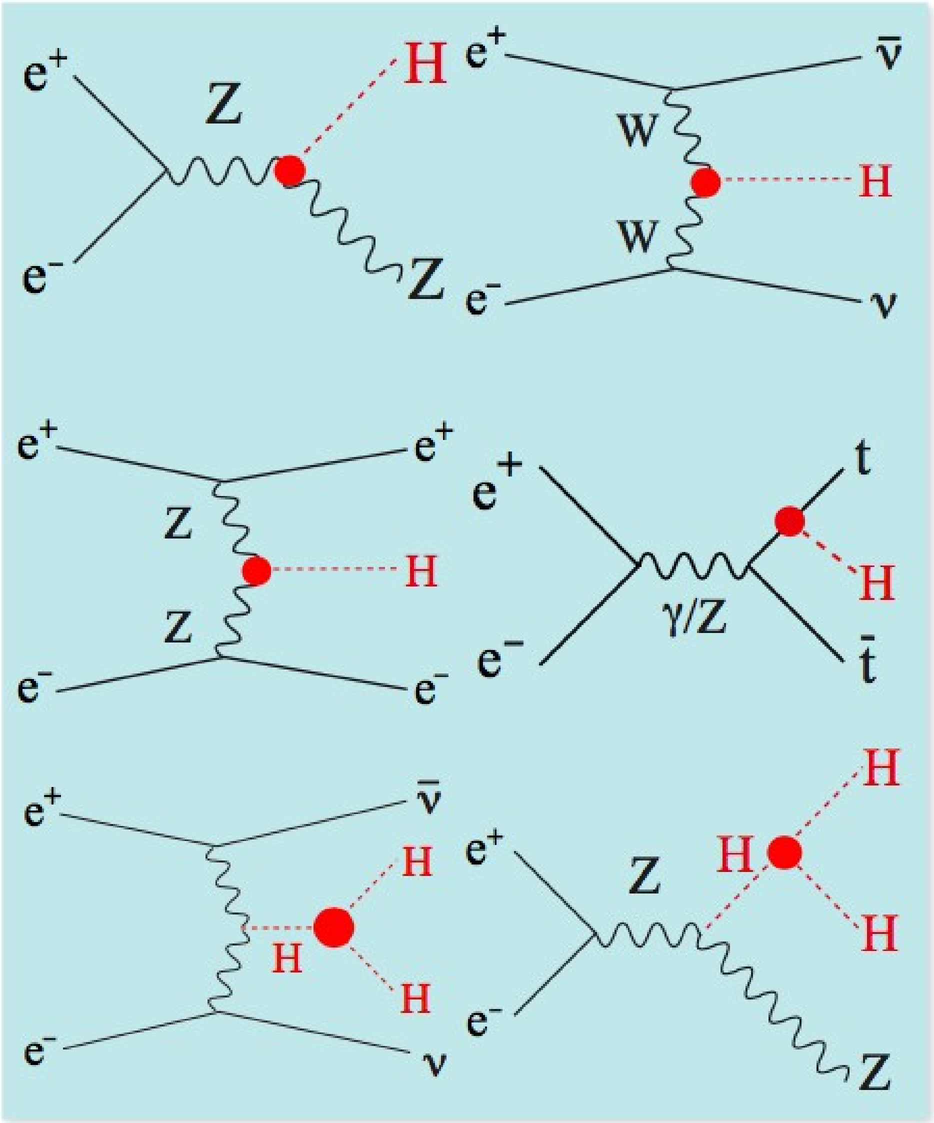


9

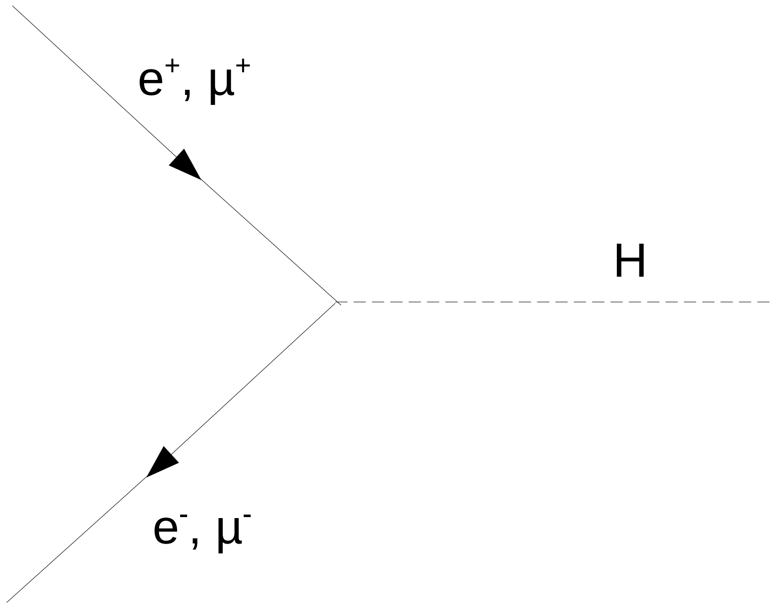
Higgs production at e+e- colliders

Associated and t-channel production





s-channel production

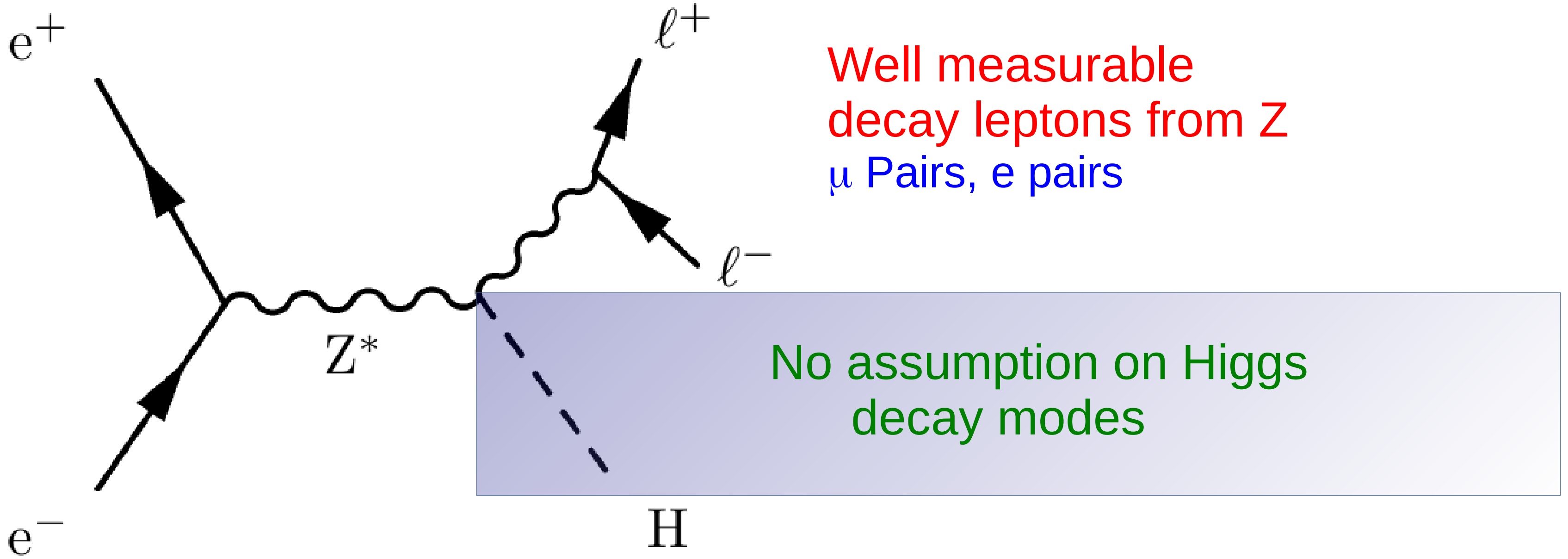


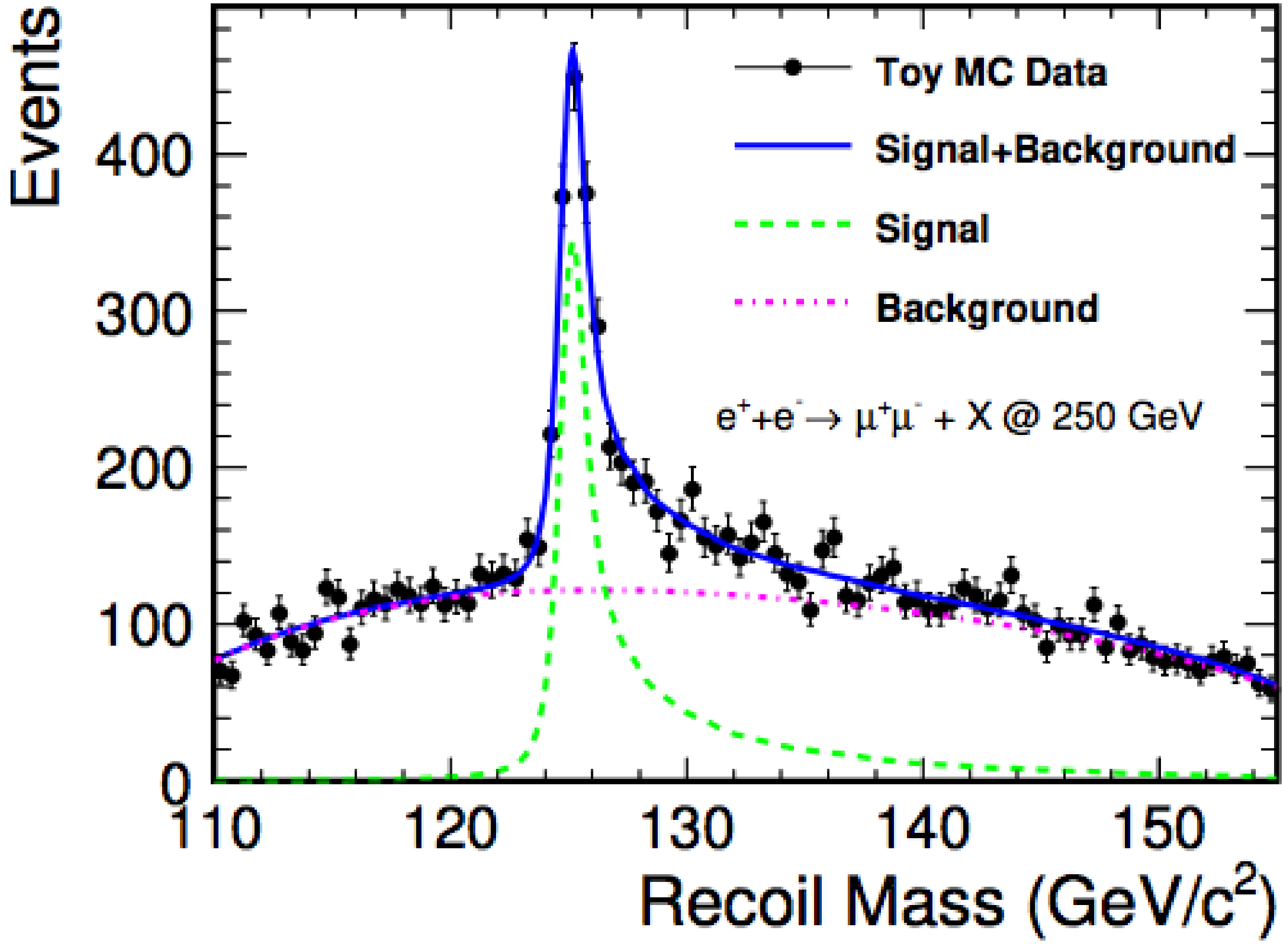
- Monochromatic beams
- Looks "easier" with muons
  - Higgs Lineshape scan?

two important thresholds:
$\sqrt{s}$ ~ 250 GeV for ZH, ~500 GeV for ZHH and ttH

Higgs-strahlung at lepton colliders

- Powerful channel for unbiased tagging of Higgs Events
- Absolute normalisation of Higgs couplings
- Sensitivity to invisible Higgs decays



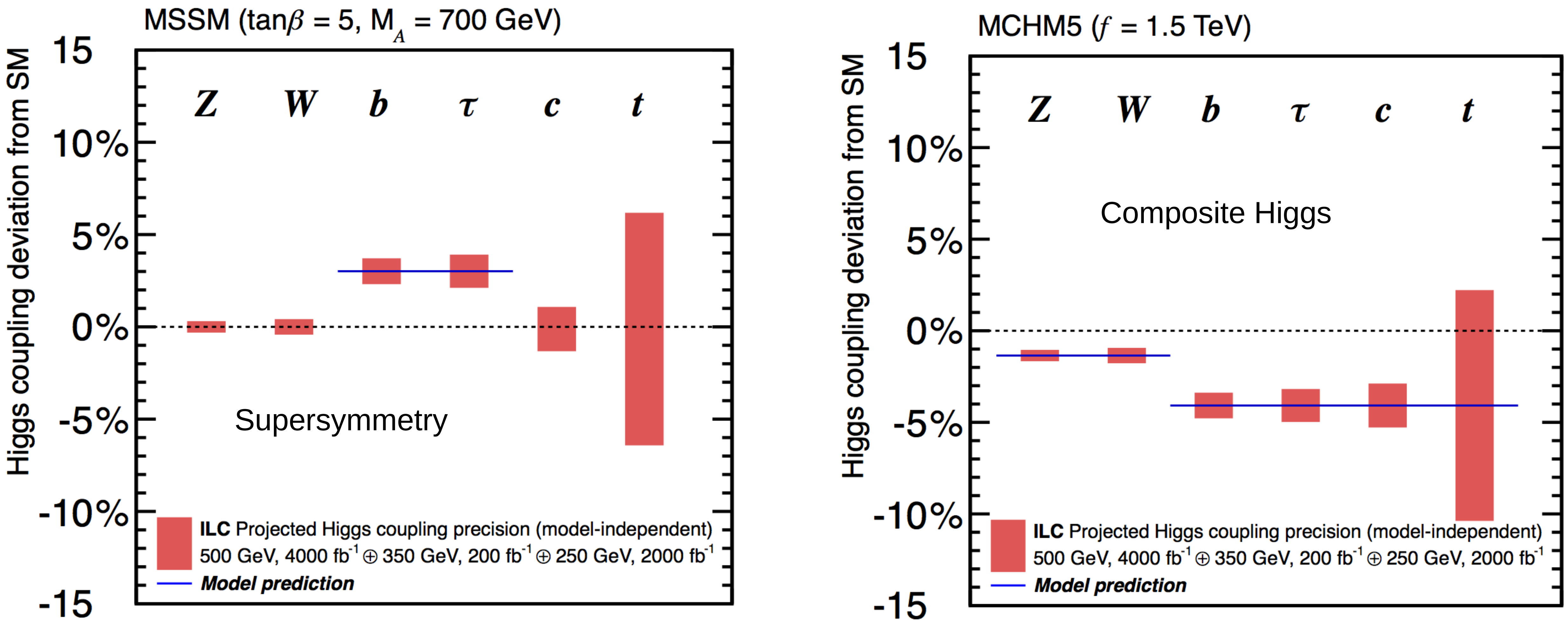


Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2 E_Z \sqrt{s}$

- Clean and sharp peak in Z recoil spectrum
- Illustrates precision that can be expected from e+e- colliders

Precision matters ...

- Example for illustration: Coupling precision after full ILC programme
- Couplings are (of course) also accessible at circular e+e- colliders

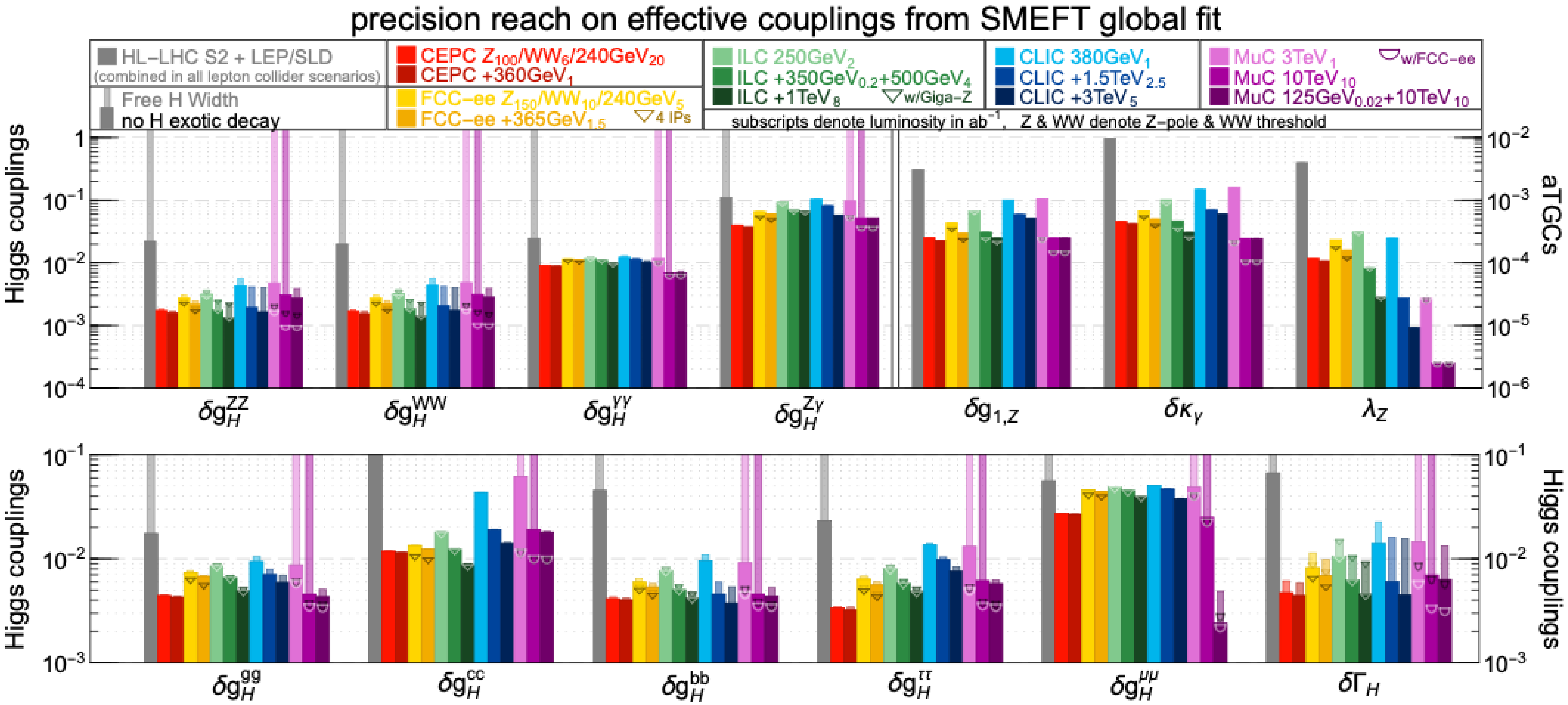


- Different new physics models lead to different patterns

Expected precision at future lepton colliders

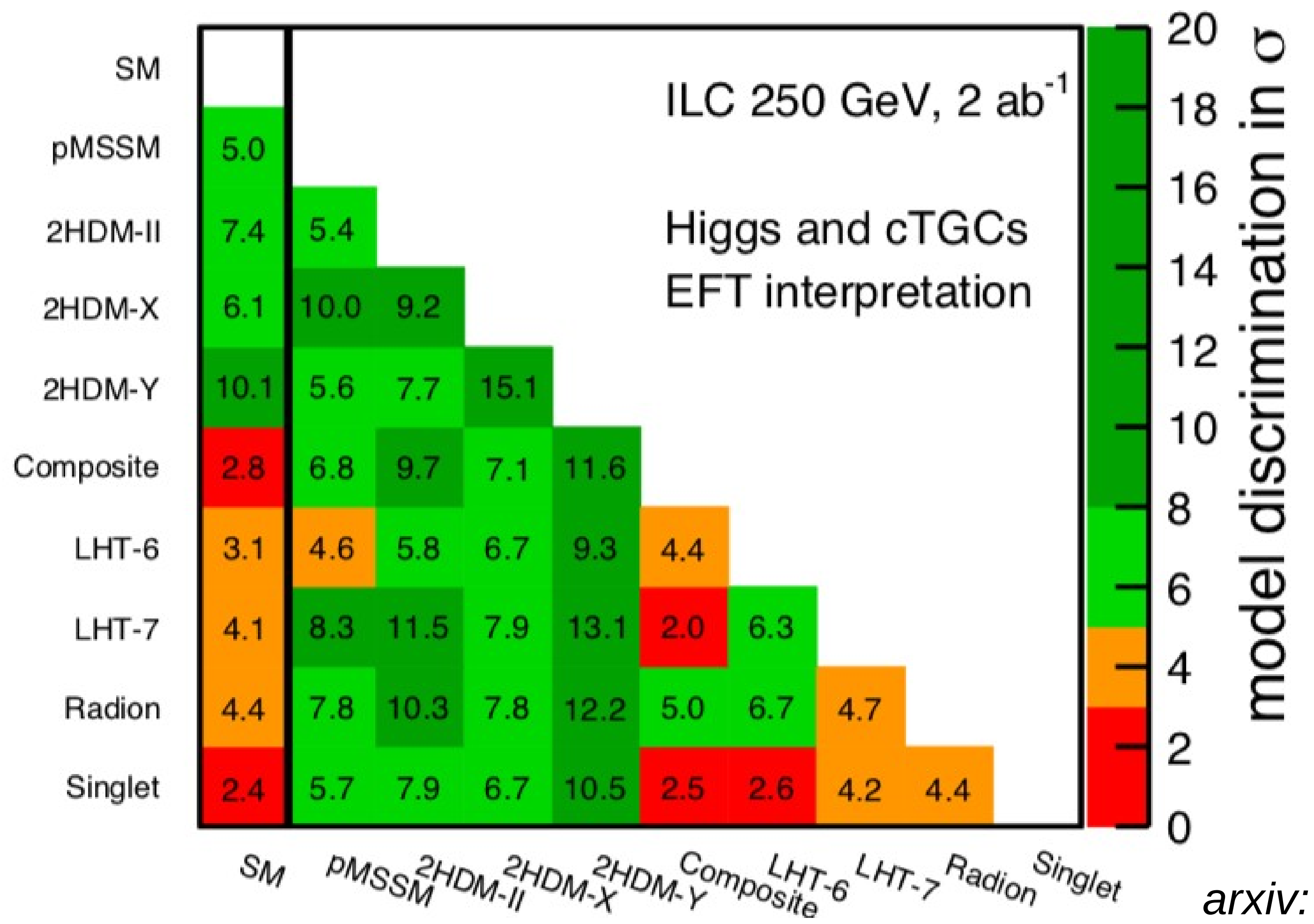
Arxiv: 2206.08326

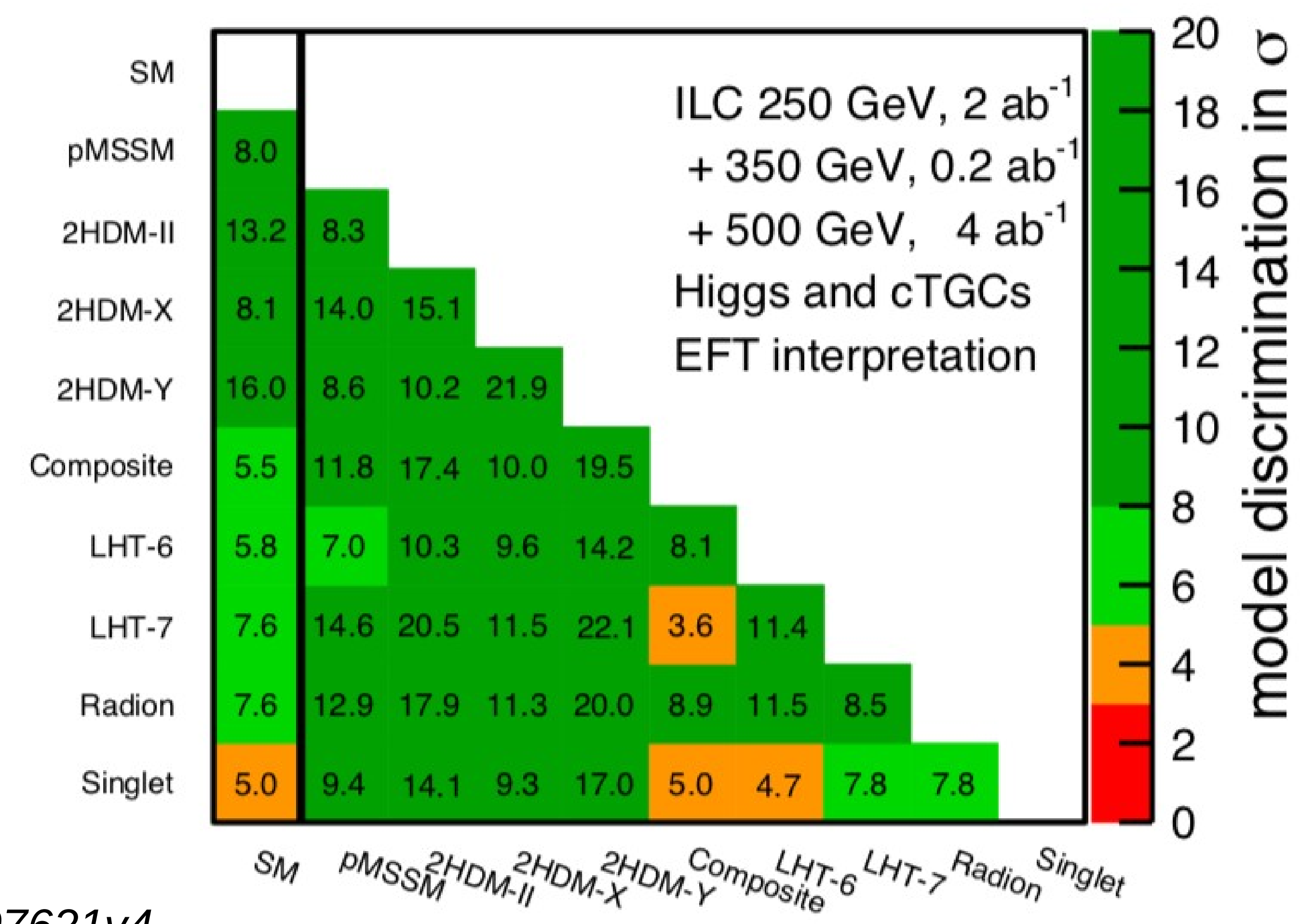
Higgs interactions



- All planned e+e- machines will deliver O(1%) precision on Higgs couplings
  - Beam polarisation at LC catches up for smaller luminosity
- Muon Collider makes excellent job on trilinear couplings and Hμμ coupling

Higgs – Discovery by precision



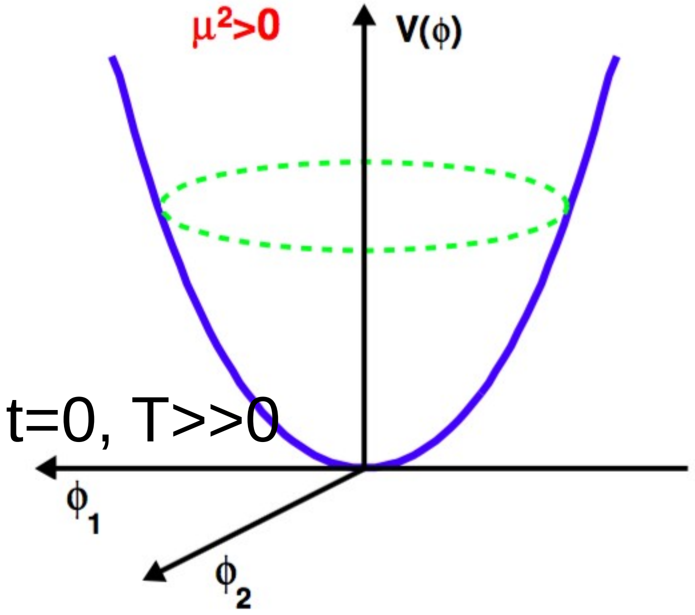


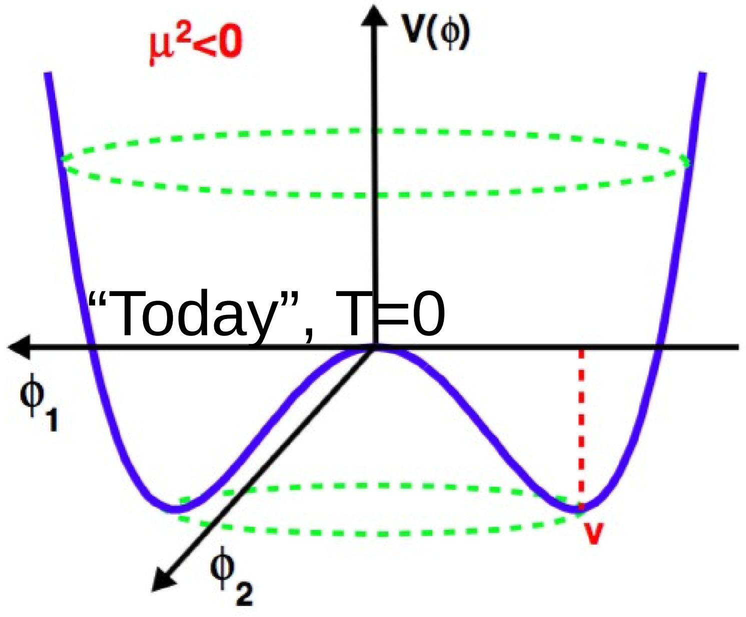
arxiv: 1710.07621v4

- Already large discriminative power at 250 GeV
- Full discovery potential developed at higher energies (e.g. 500 GeV)
- “Anomalies” observed at 250 GeV could be followed up by future hadron or muon colliders

14

The Higgs Potential





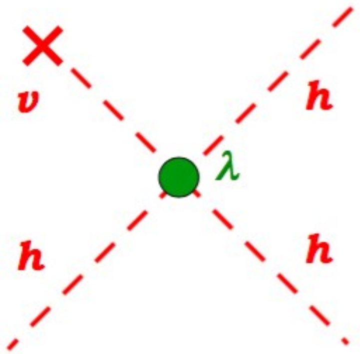
Perfect (electroweak) symmetry and massless particles

Broken (electroweak) symmetry and massive particles

Two questions:

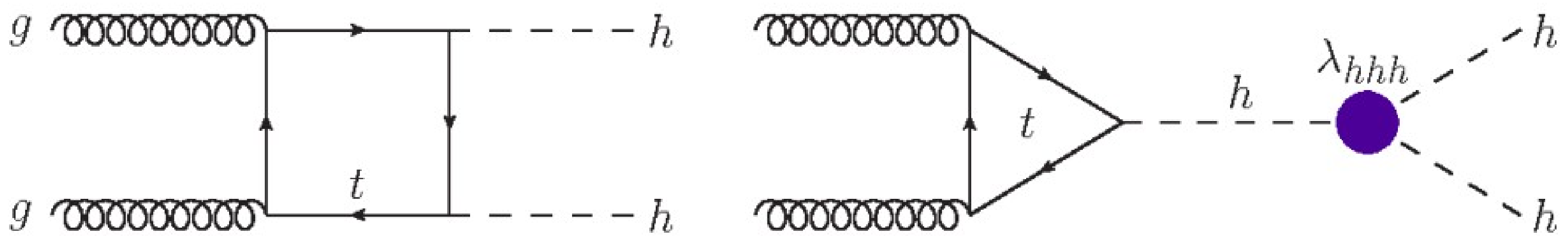
- Shape of "today's" Higgs Potential?

$$V(\eta) = \frac{1}{2}m^2\eta^2 + \lambda v\eta^3 + \frac{1}{4}\lambda\eta^4$$ => Triple Higgs-self coupling

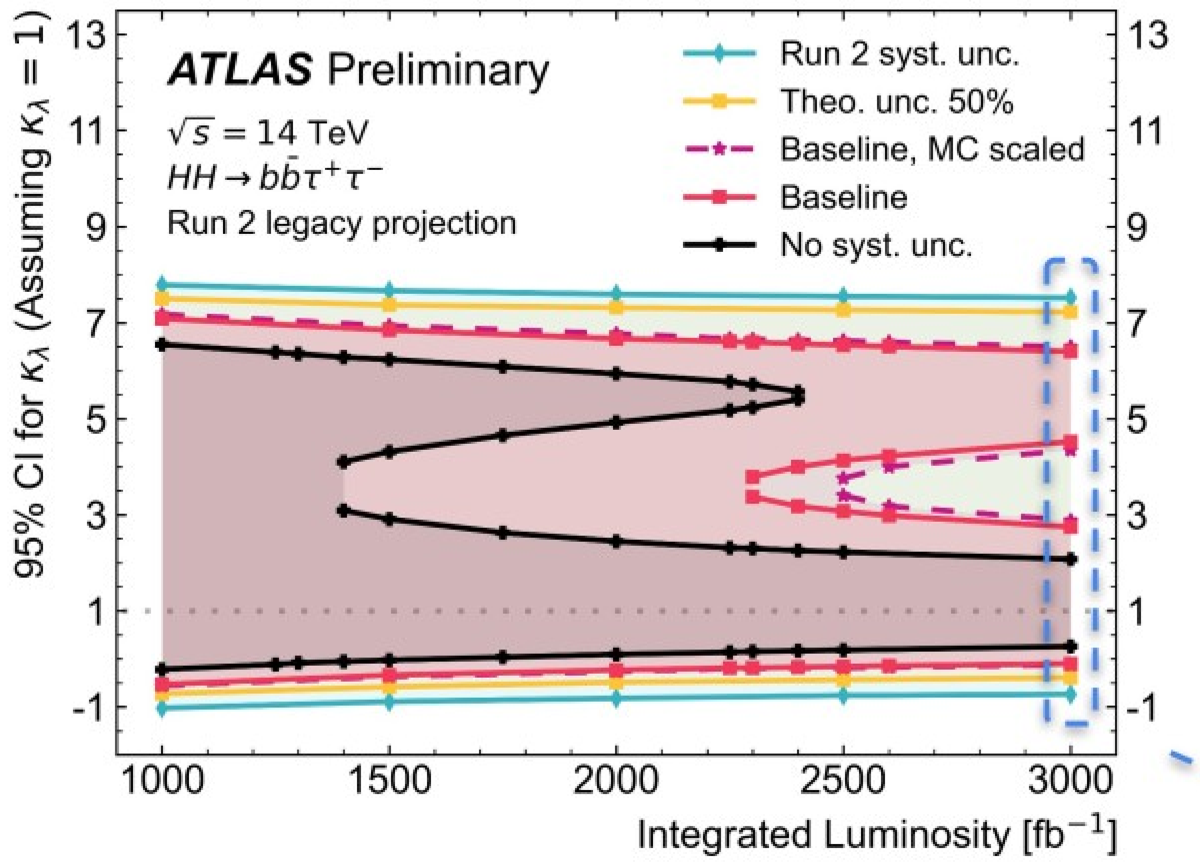


- Transition from symmetric, unbroken to broken phase?

Higgs Selfcoupling – HL-LHC in a nutshell

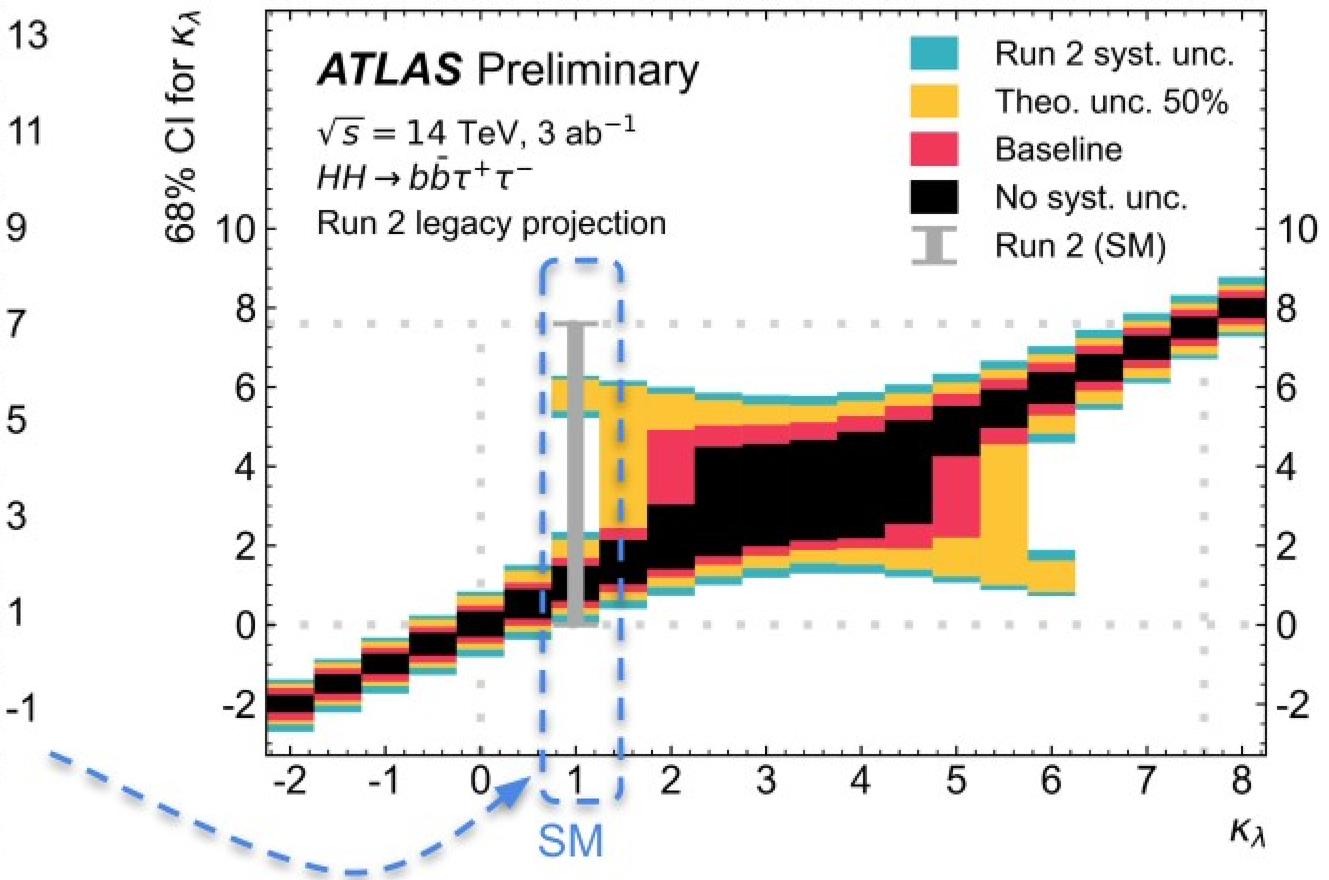


95% CI for κ_λ (assuming **SM**)



F. Haslbeck, Higgs Hunting 2024

68% CI for κ_λ at **3000 fb**$^{-1}$ varying κ_λ

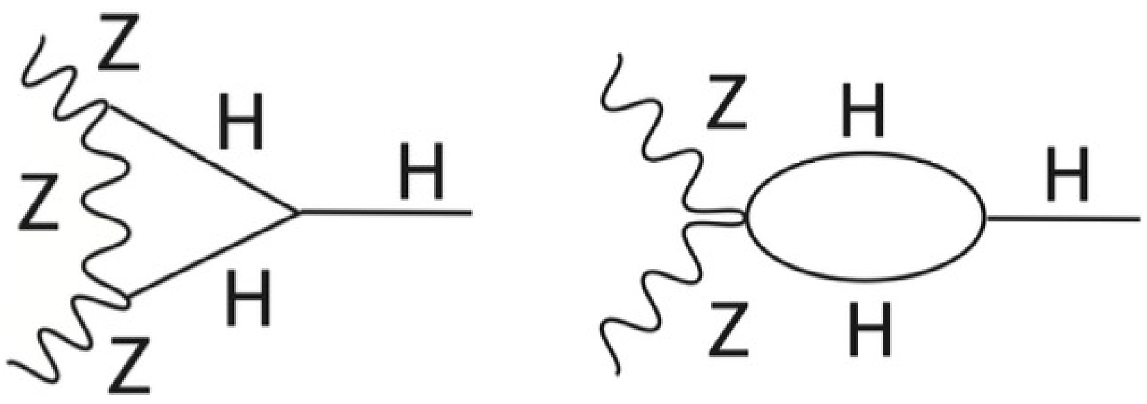


HL-LHC on track to confirm a $\kappa_\lambda \neq 0$

Our knowledge of κ_λ very much will depend on the universe's implementation!

Higgs Selfcoupling measurement in e+e- (μ+μ-)

- Indirect access
  - Through loop order corrections in EFT fits
  - Single Higgs measurements in e+e- at or better than 1%
  - Large number of independent observables
  - Running at two different centre-of-mass energies

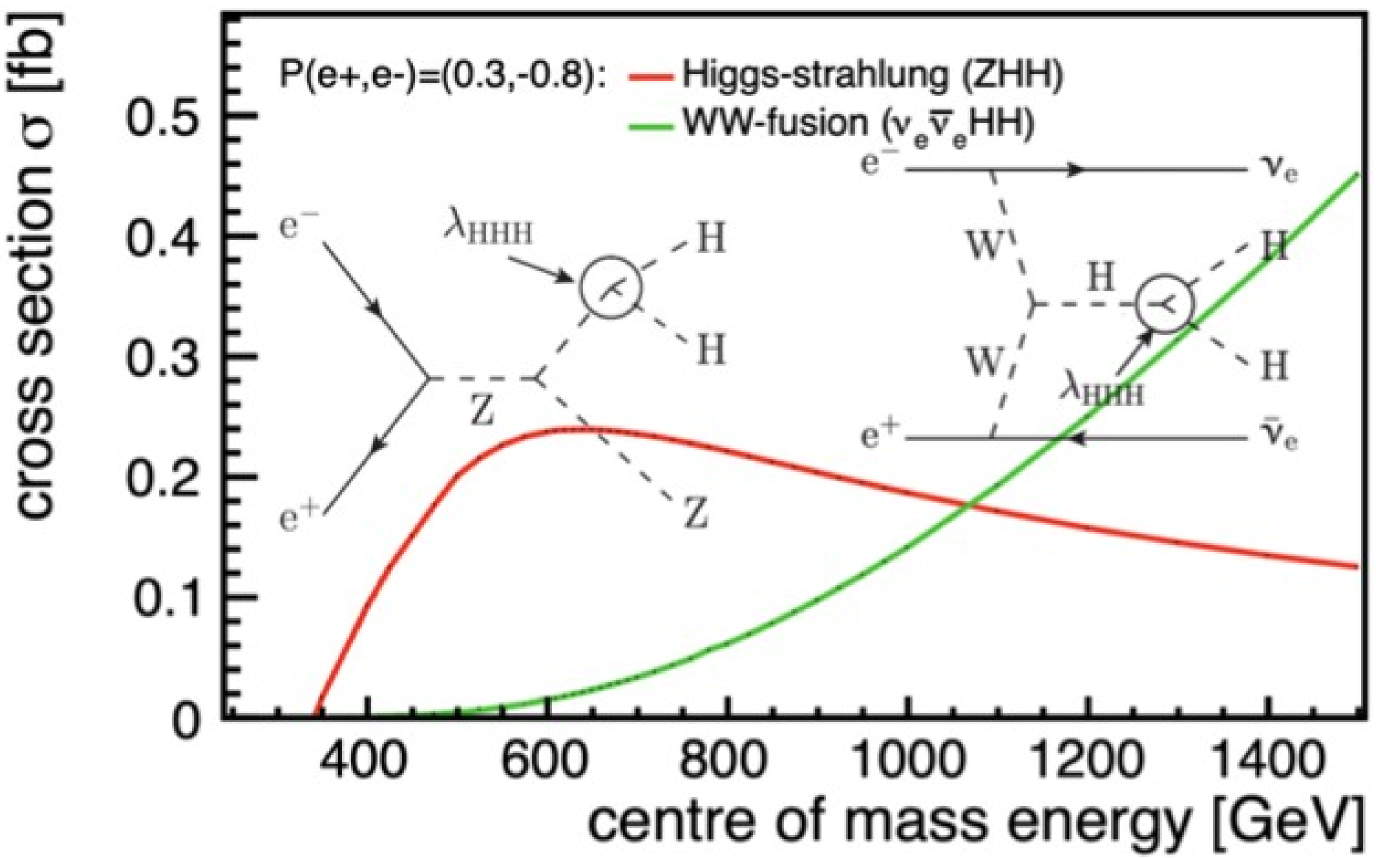


Details see M. Peskin, 12/1/23

- Direct access
  - Through double-Higgs Production

$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} = c \cdot \frac{\Delta\sigma_{HHx}}{\sigma_{HHs}}$$

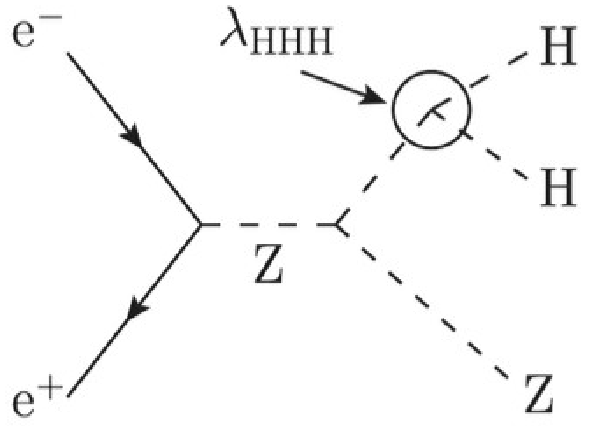
  - Cross section measurement



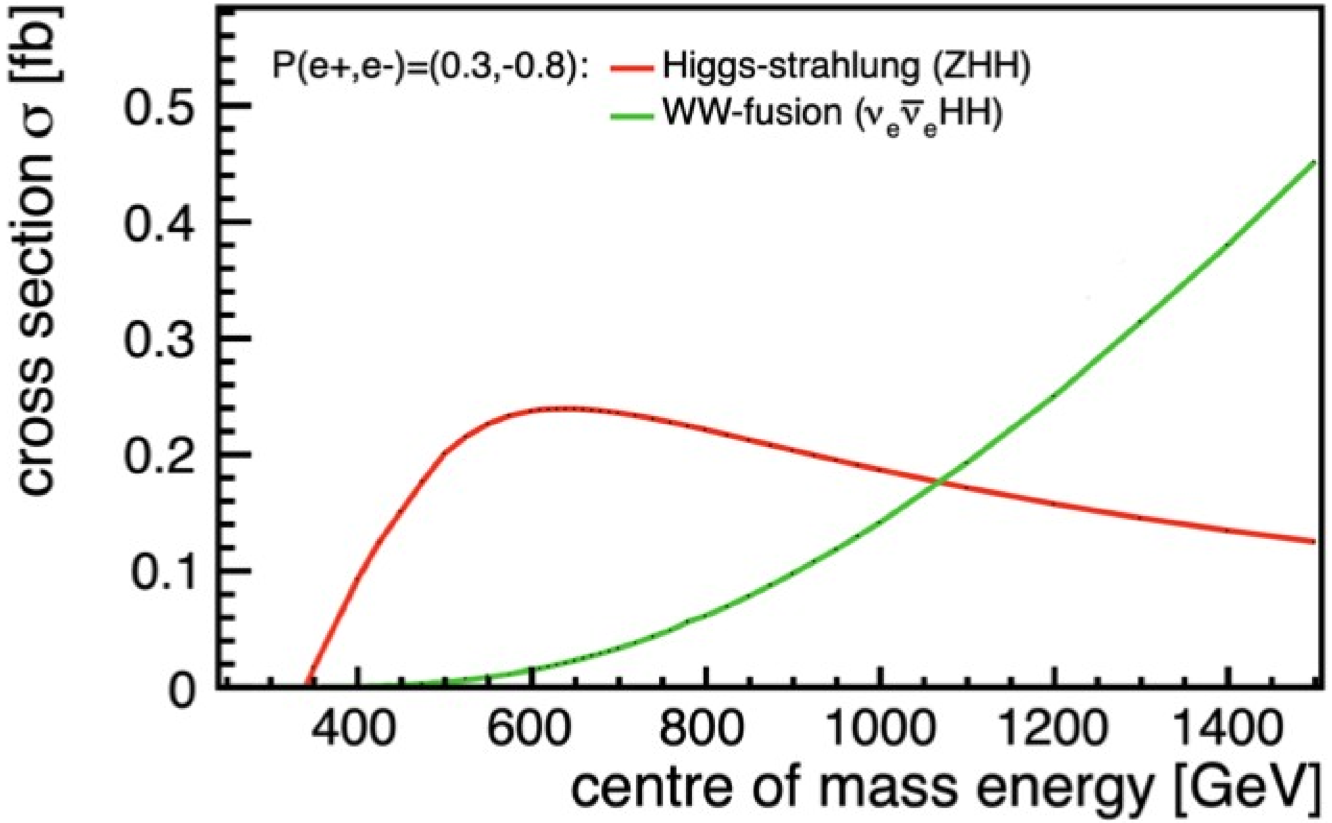
Slide from Julie Munch Torndal

Higgs Self Coupling measurement - Ingredients to cross section

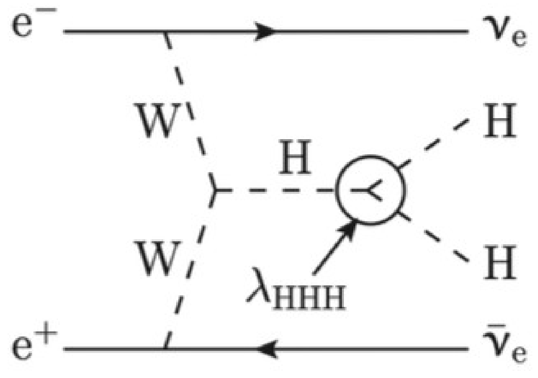
Di-Higgsstrahlung



Dominates below 1 TeV

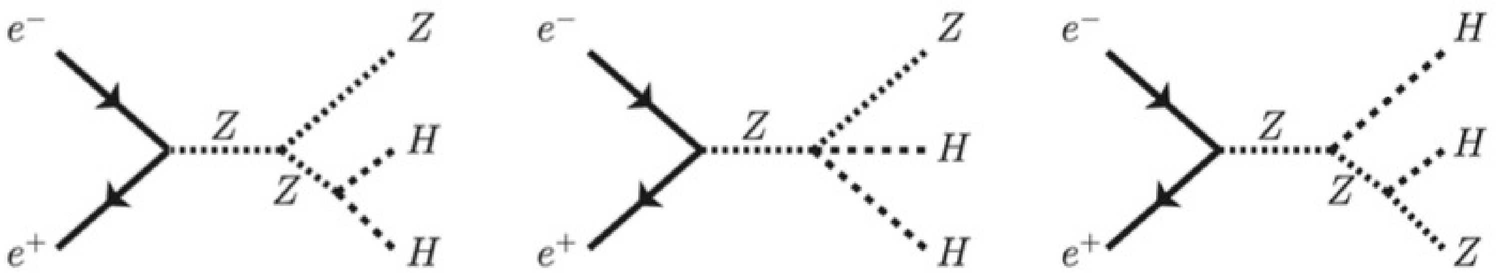


WW Fusion

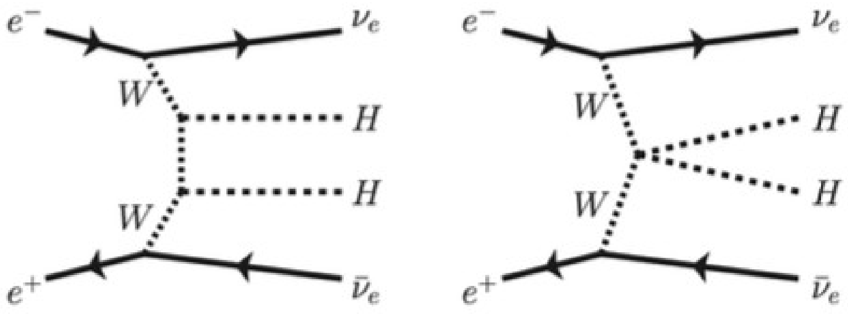


Dominates above 1 TeV

Constructive Interference



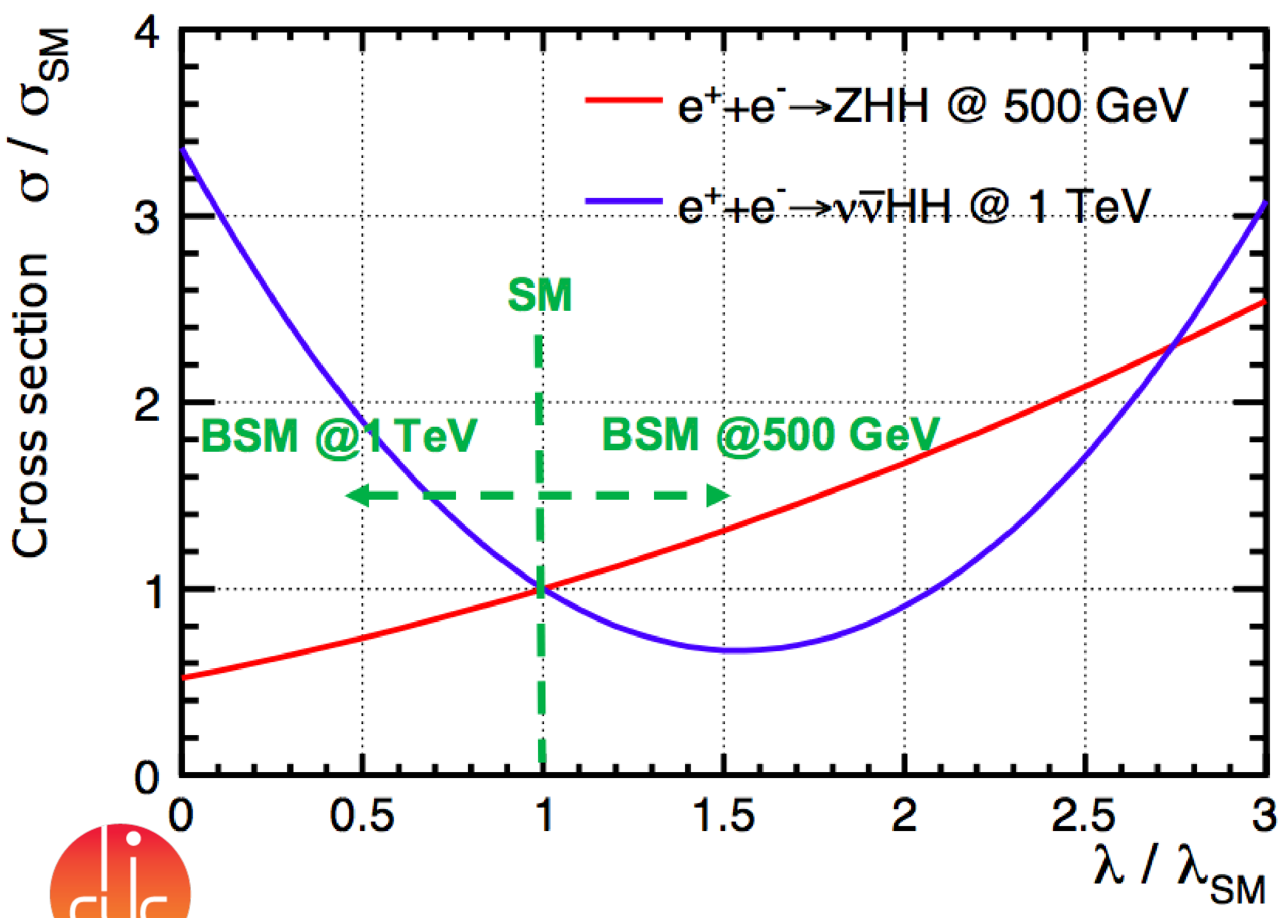
Destructive Interference

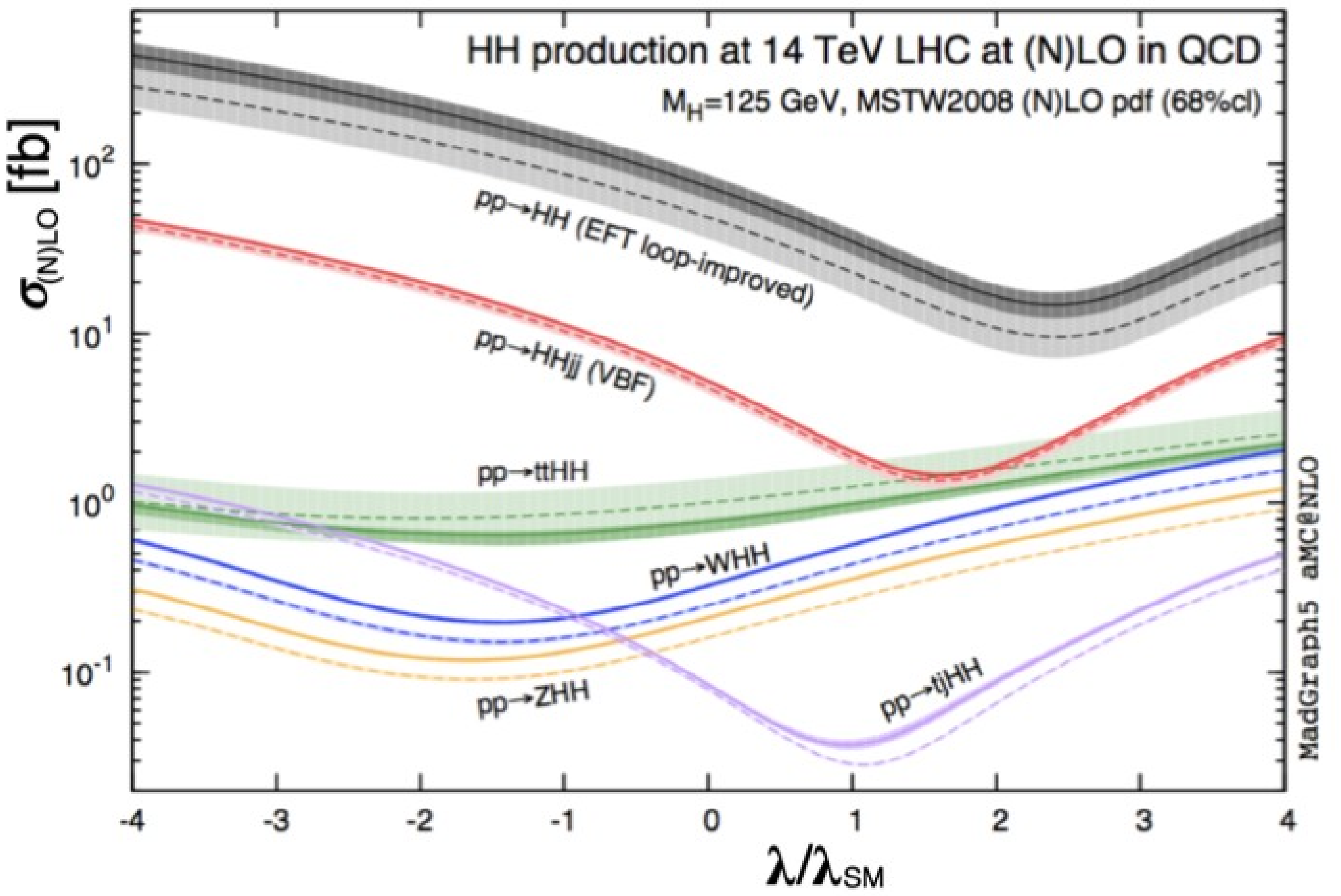


Slide from Julie Munch Torndal

Higgs self-coupling and new physics

Manifestation of new physics in observables and extracted results?





- Remarkable sensitivity of 500 GeV e+e- machine in case of large upward deviation
- 1 TeV machine superior for large upward and downward deviations
- LHC gives stronger constraints in case of $\lambda_{HHH} < \lambda_{HHH,SM}$

Result valid for $\lambda_{HHH} = \lambda_{HHH,SM}$

collider	indirect-h	direct-hh
HL-LHC	100-200%	50%
ILC250	–	–
ILC500	58%	20%*
ILC1000	52%	10%
CLIC380	–	–
CLIC1500	–	36%
CLIC3000	–	9%
FCC-ee 240	–	–
FCC-ee 240/365	44%	–
FCC-ee (4 IPs)	27%	–
FCC-hh	–	3.4-7.8%

[arXiv:1910.00012, arXiv:2211.11084]

Obsolete (see above)

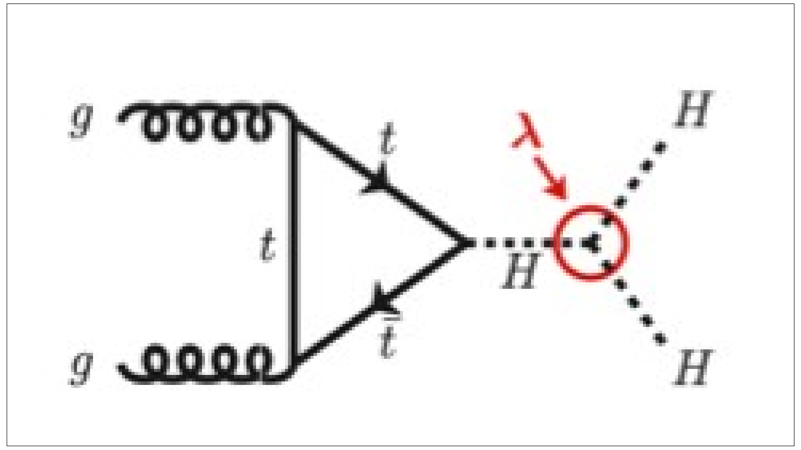
50% sensitivity: establish that $\lambda_{HHH} \neq 0$ at 95% CL
20% sensitivity: 5σ discovery of the SM λ_{HHH} coupling
5% sensitivity: getting sensitive to quantum corrections to Higgs potential

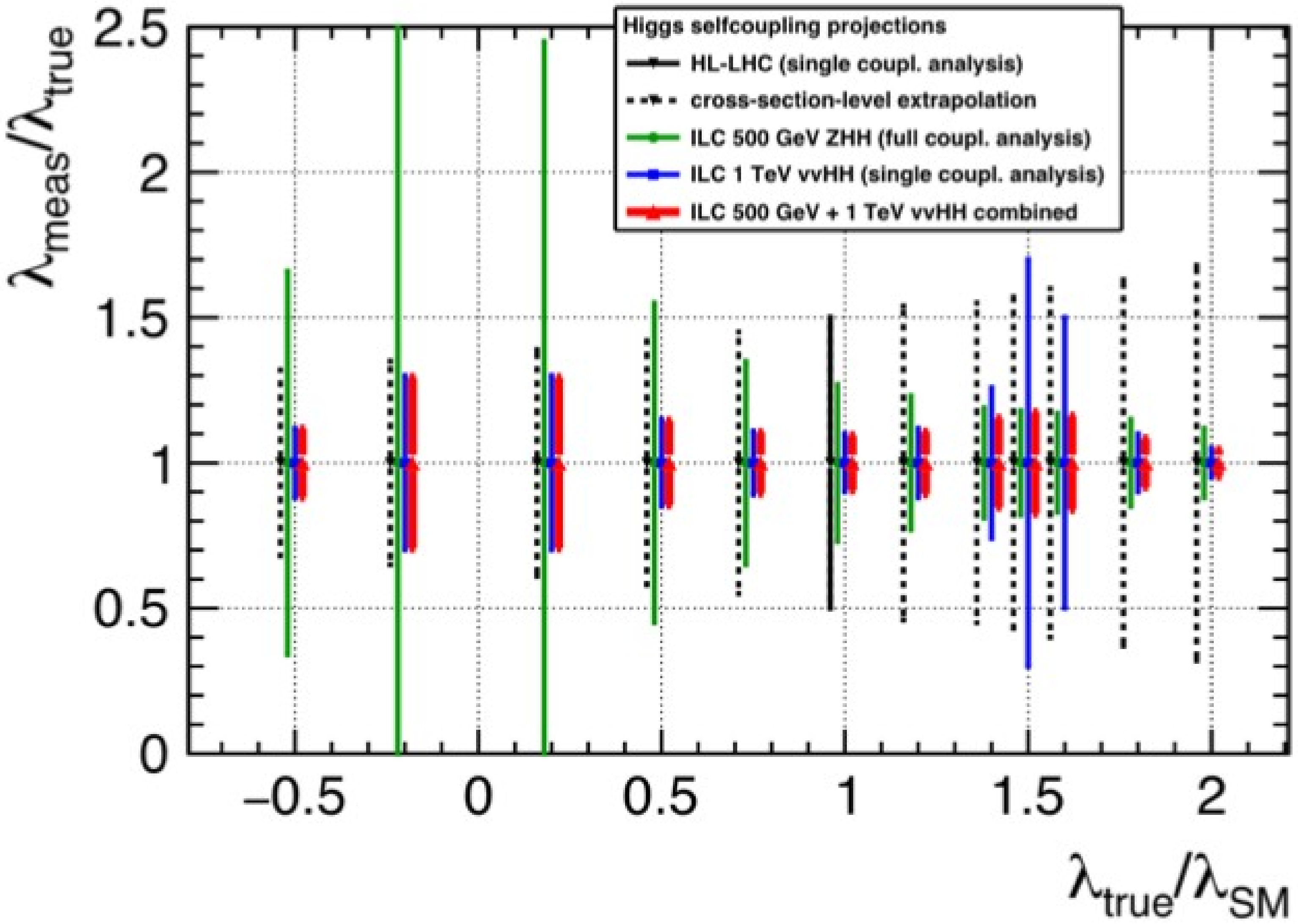
Result of 1-parameter fit for λ_{HHH} is backed-up by SMEFT Analysis

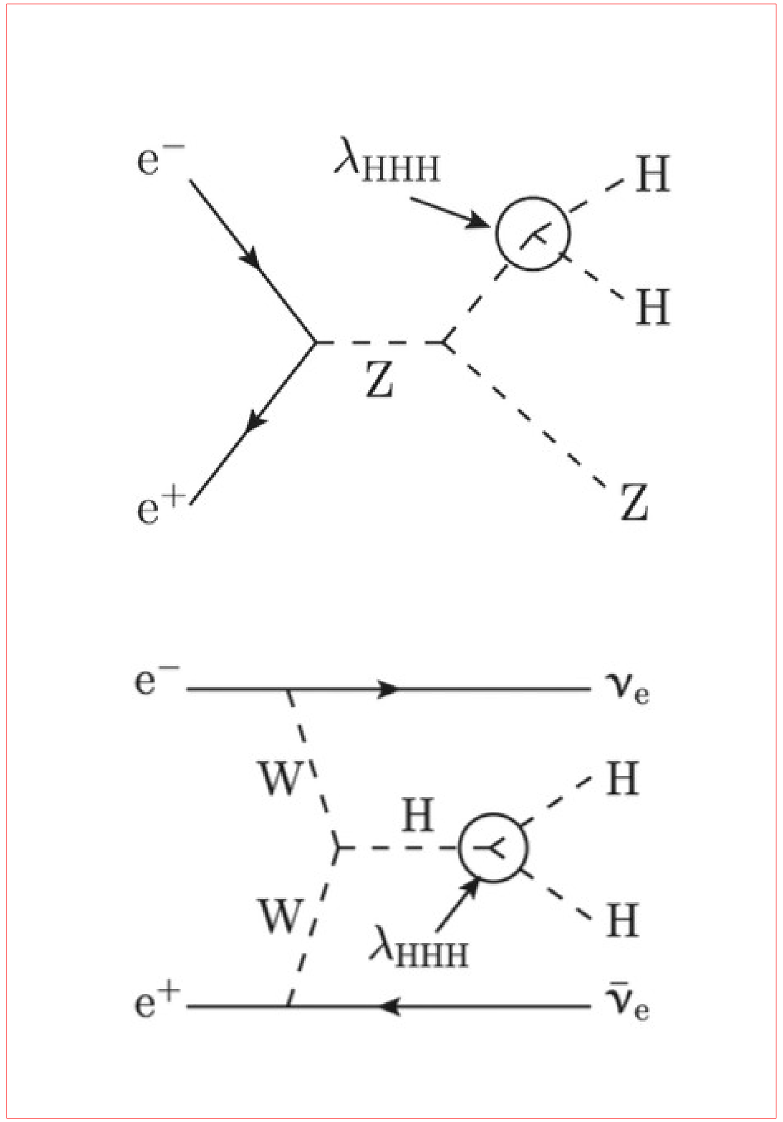
Details see M. Peskin, 12/1/23

Julie Munch Torndal

Higgs self-coupling – Results

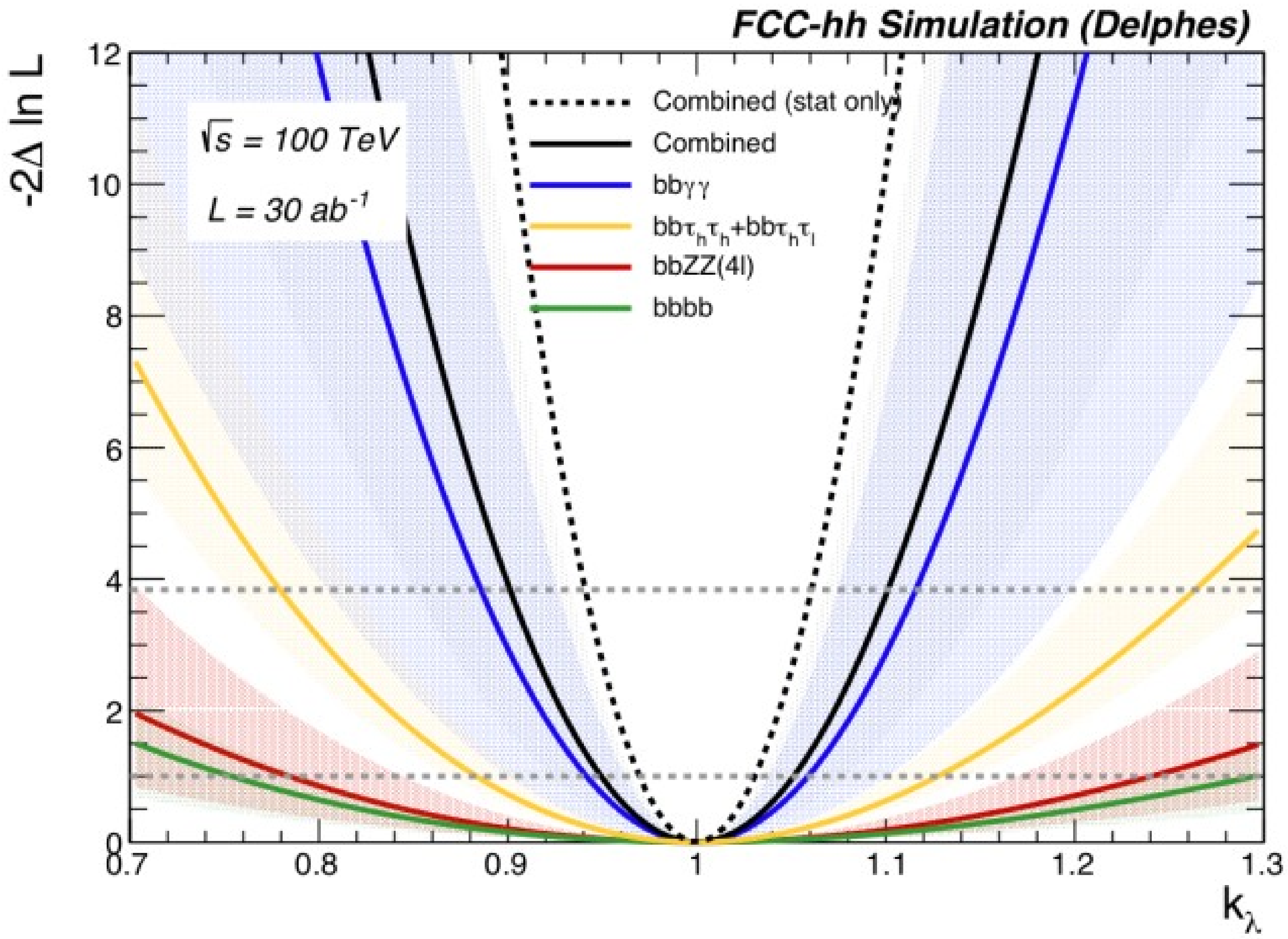






Sufficient centre-of-mass energy allow for 10% accuracy on Higgs self-coupling

Higgs self-coupling – … and FCC-hh?



M. Mangano, FCC-hh studies for ESPPU

80 TeV	s I	s II	s III
stat	3.5	4.7	6.4
syst	1.6	3.0	5.4
tot	**3.8**	**5.6**	**8.4**

100 TeV	s I	s II	s III
stat	3.0	4.1	5.6
syst	1.6	3.0	5.4
tot	**3.4**	**5.1**	**7.8**

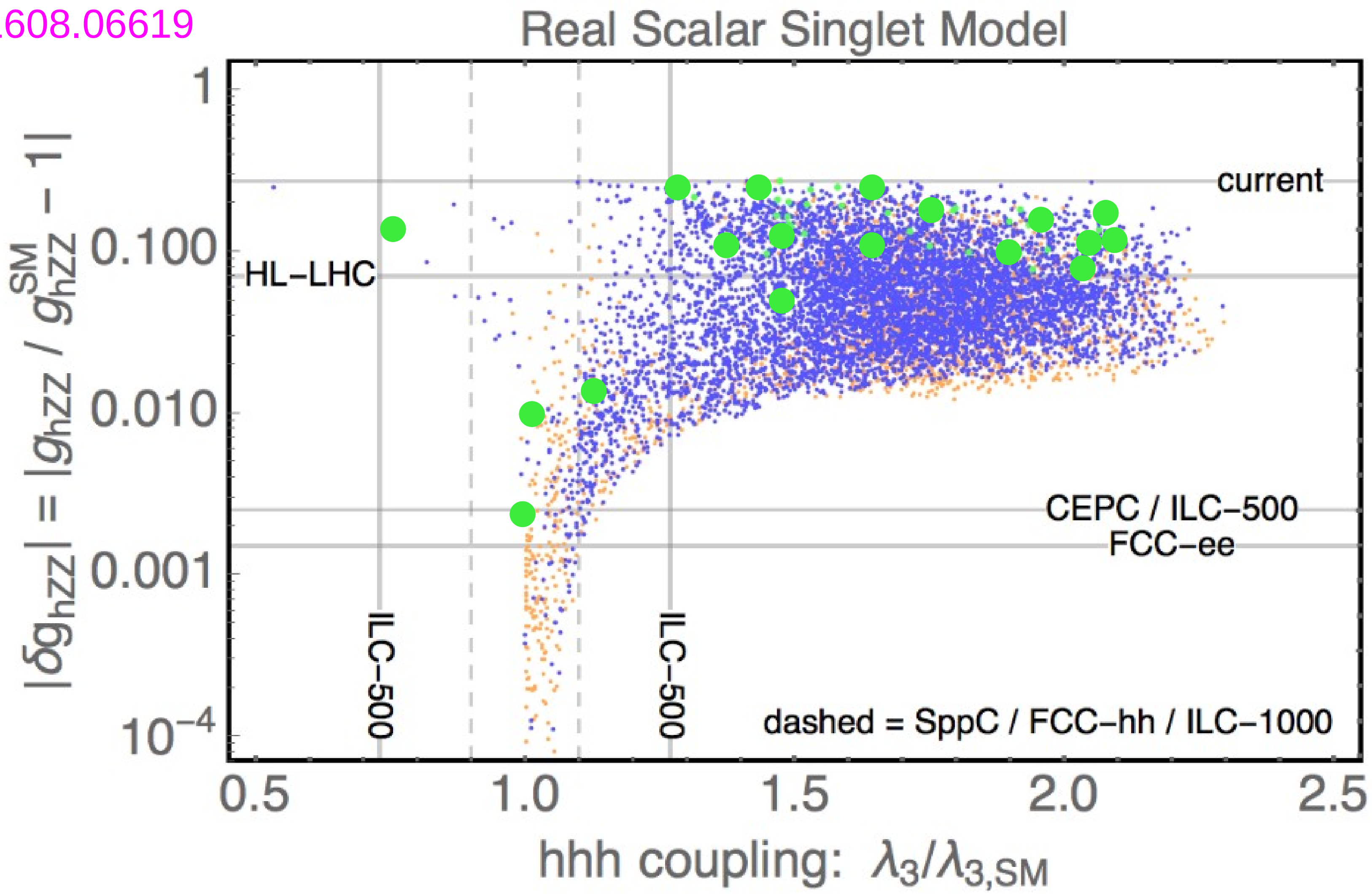
120 TeV	s I	s II	s III
stat	2.6	3.6	4.9
syst	1.6	3.0	5.4
tot	**3.1**	**4.7**	**7.3**

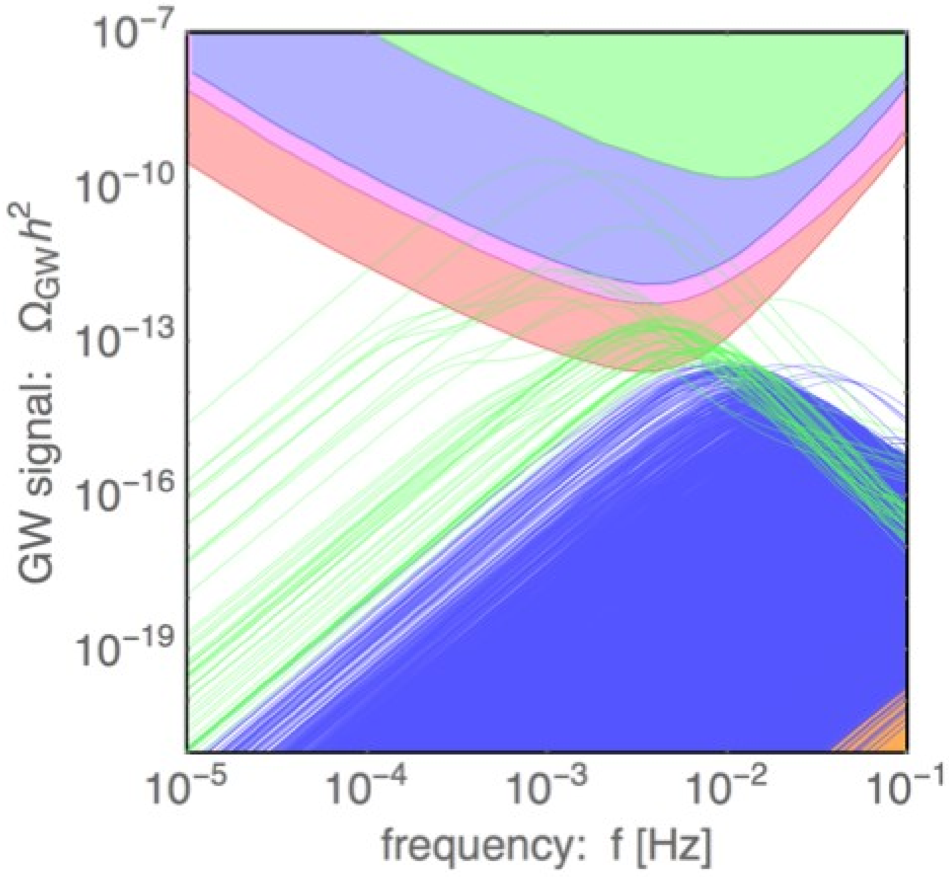
FCC-hh will reach the 3% precision level

… in ~2100 according to today's projections

New particles – Higgs couplings and EWBG

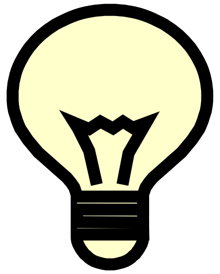
arxiv:1608.06619



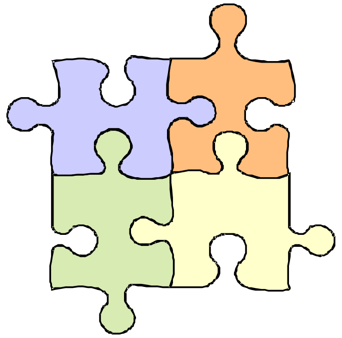


- Adding a singlet that mixes the SM Higgs allows for generating 1st Electroweak Phase transitions
  - Strong EWPT, stronger EWPT, strongest EWPT
- This has an impact on both gHZZ and Higgs self-coupling
- Higgs self-coupling O(10%) by linear colliders
- Strong EWPS may be detectable by eLISA ↔ Complementarity Collider GW experiments?

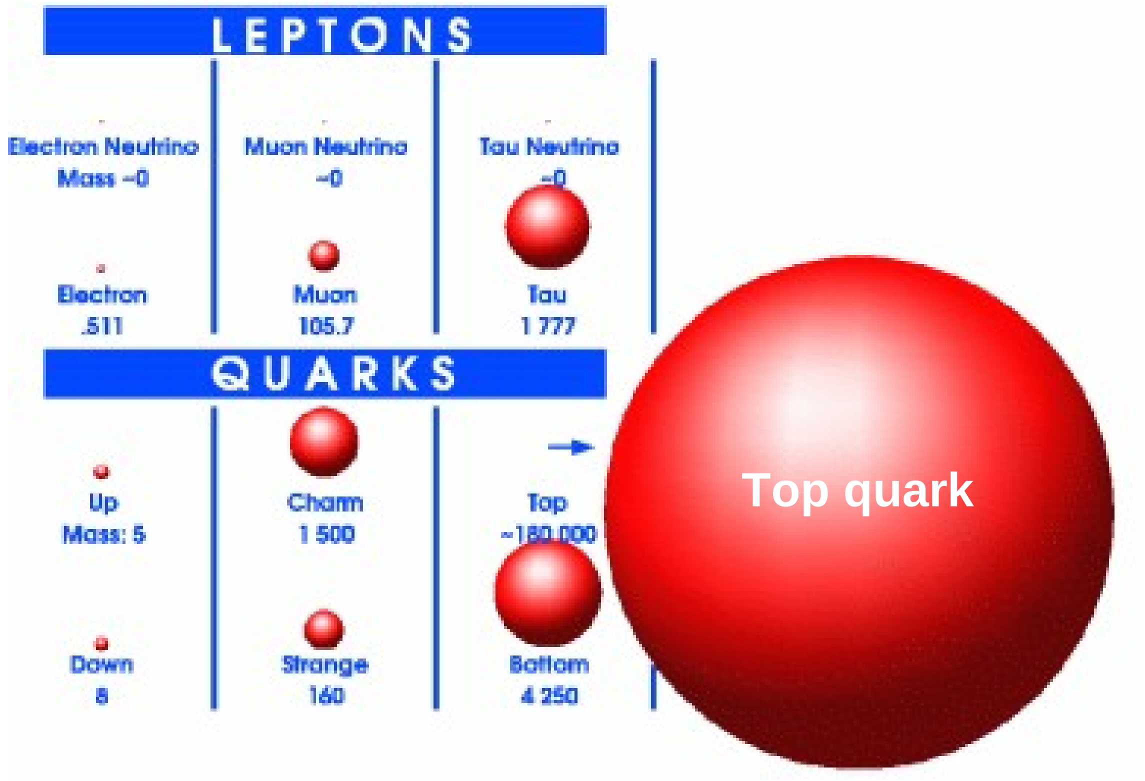
An enigmatic couple



Elementary Scalar?



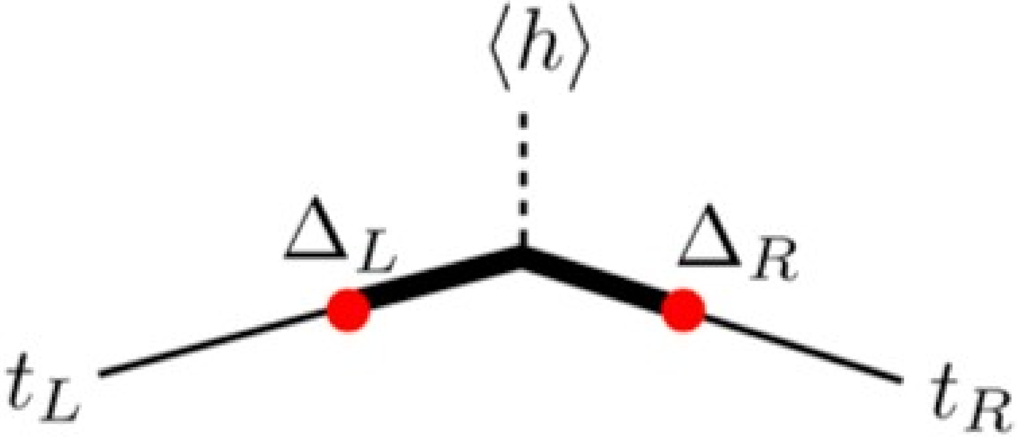
Composite object?



- Higgs and top quark are intimately coupled!
  Top Yukawa coupling O(1) !
  => Top mass important SM Parameter

- New physics by compositeness?
  Higgs <u>and</u> top composite objects?

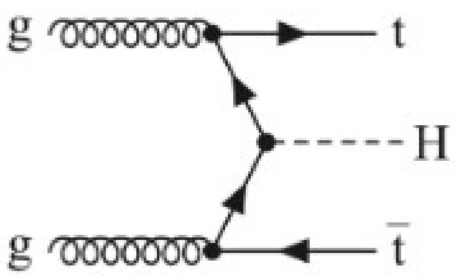
- Future colliders perfectly suited to decipher both particles

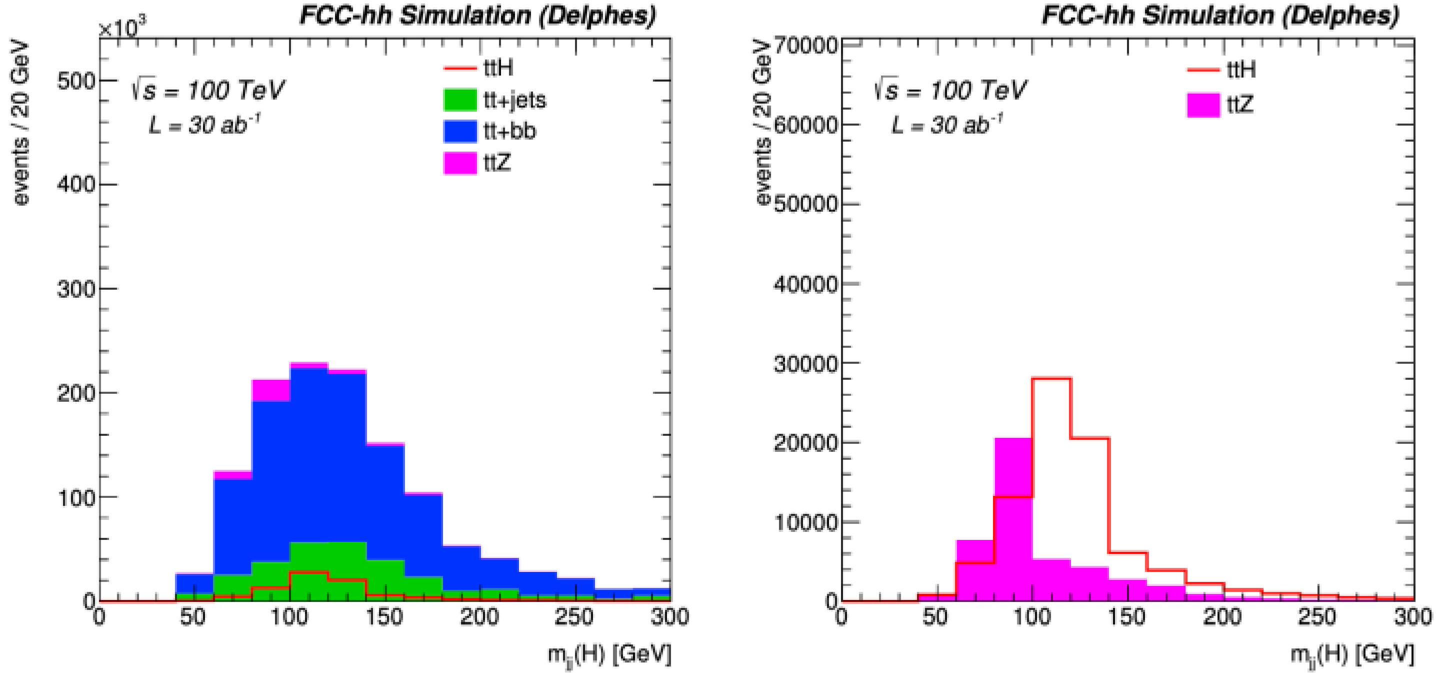


Courtesy of S. Rychkov

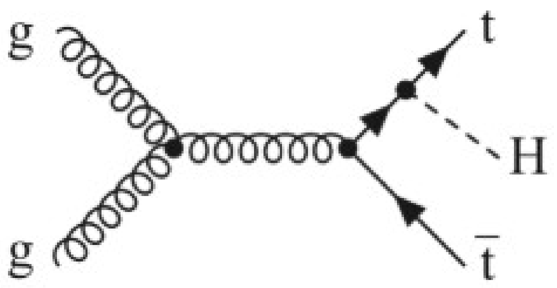
Top Yukawa Coupling at FCC-hh

ttH coupling from ttH/ttZ





- Exploit boosted top and Higgs topologies, with $p_T(H,t) \gtrsim 250$ GeV
- Assumes ttZ coupling precisely known from FCC-ee
- No bg-subtraction syst's included
- 1% stat uncertainty quoted



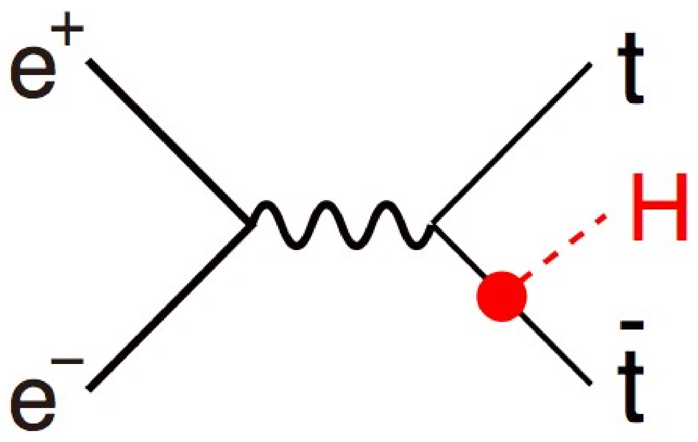
ECM dependence of rates for boosted final states [pt(H), pt(top) > ptmin]

$p_{T,min}$ (GeV)	0	100	200	400
σ(80)/σ(100)	0.68	0.67	0.67	0.57
σ(120)/σ(100)	1.36	1.38	1.38	1.48

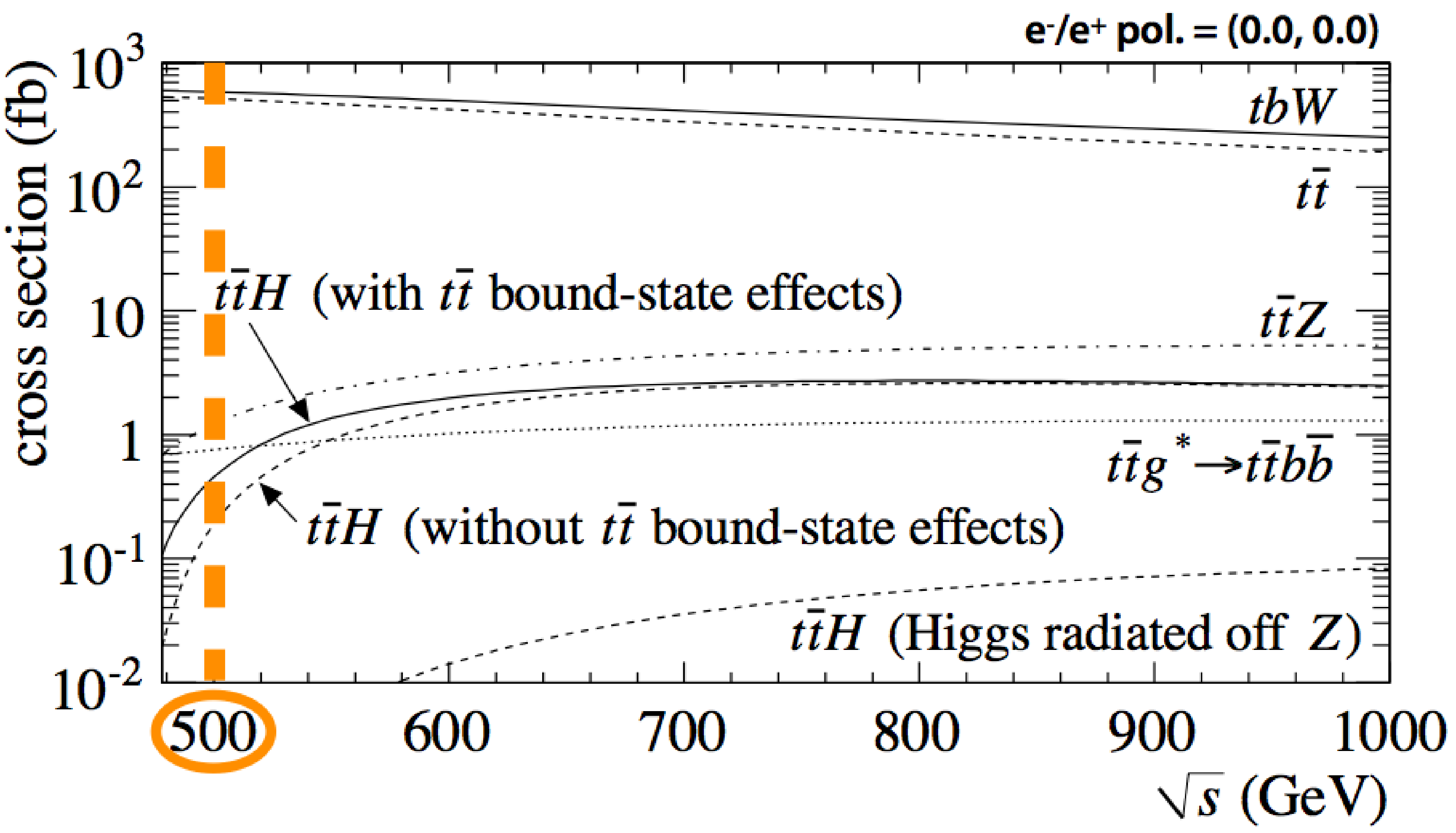
At 80 TeV expect stat degradation of precision from 1% to 1.2% …
At 120 TeV expect stat improvement of precision from 1% to 0.85% …
But systematics will likely remain the critical item, more work, even for 100 TeV, is needed

M. Mangano, FCC-hh studies for ESPPU

Top Yukawa Coupling – e+e-



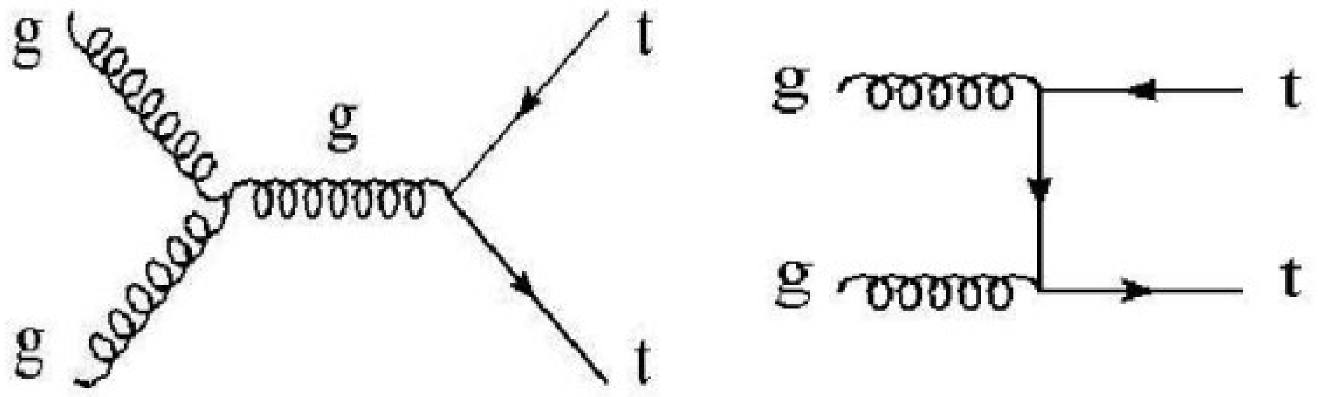
- Coupling of Higgs to heaviest particle known today
- Up to eight final state jets

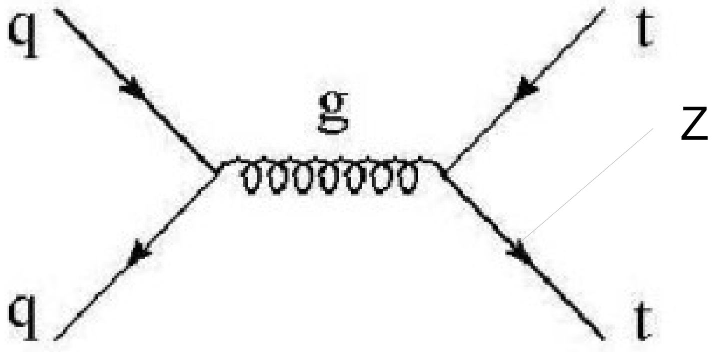


√s[GeV]	550	1000	1400
L[ab-1]	4	8	2
δyt/yt[%]	2.8	1.0	2.7

Top Pair Production

Pair production in pp collisions

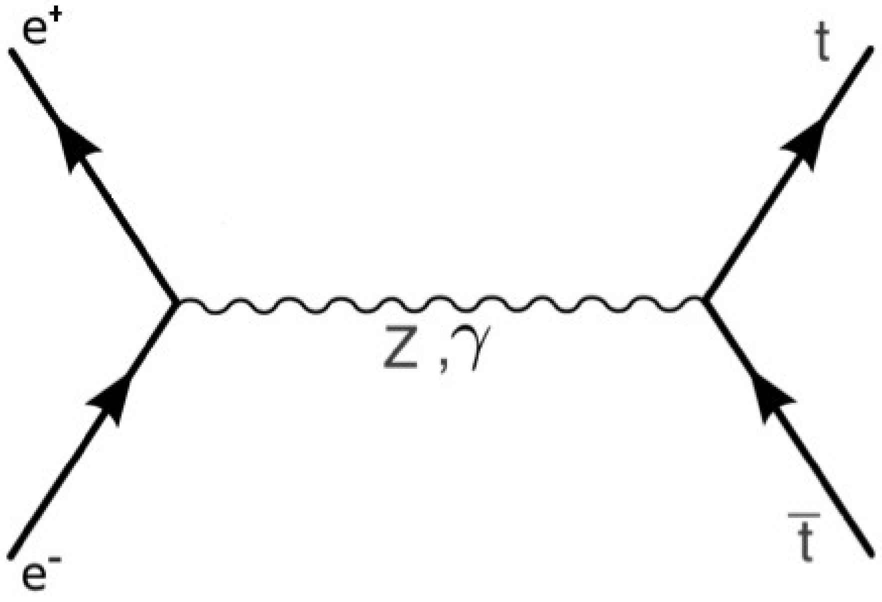




Assoc. prod. for
Top ttZ couplings

- Cross section ~1nb@13 TeV
  - … but QCD dominated

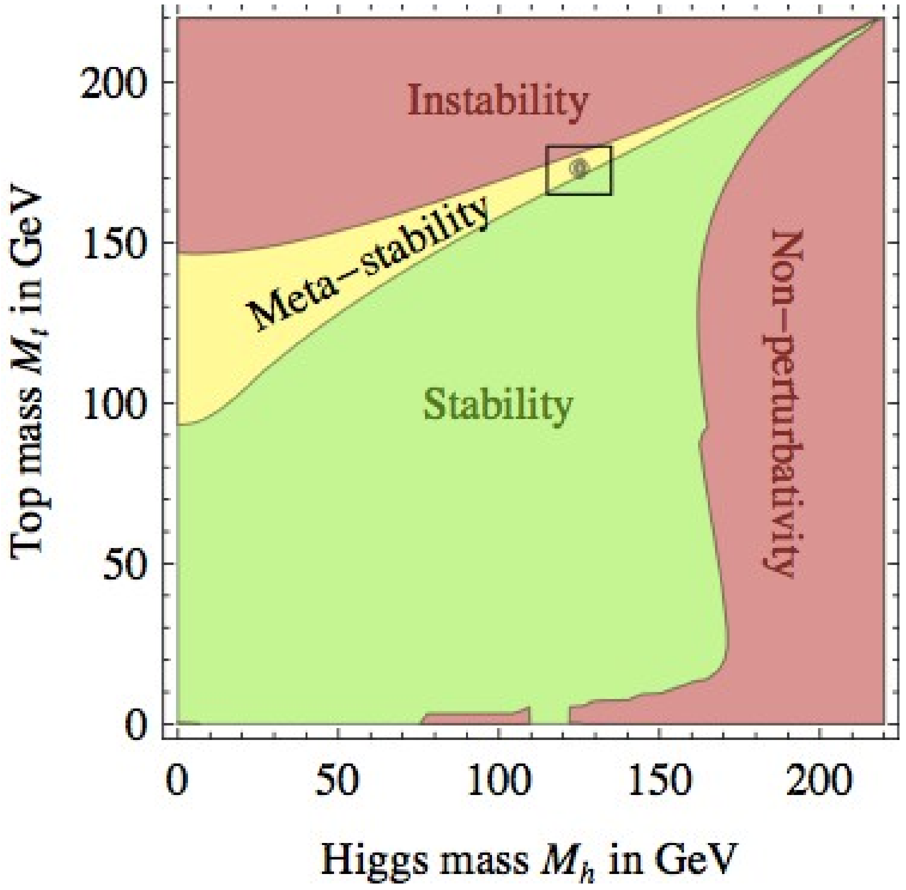
Pair production in e+e- collisions

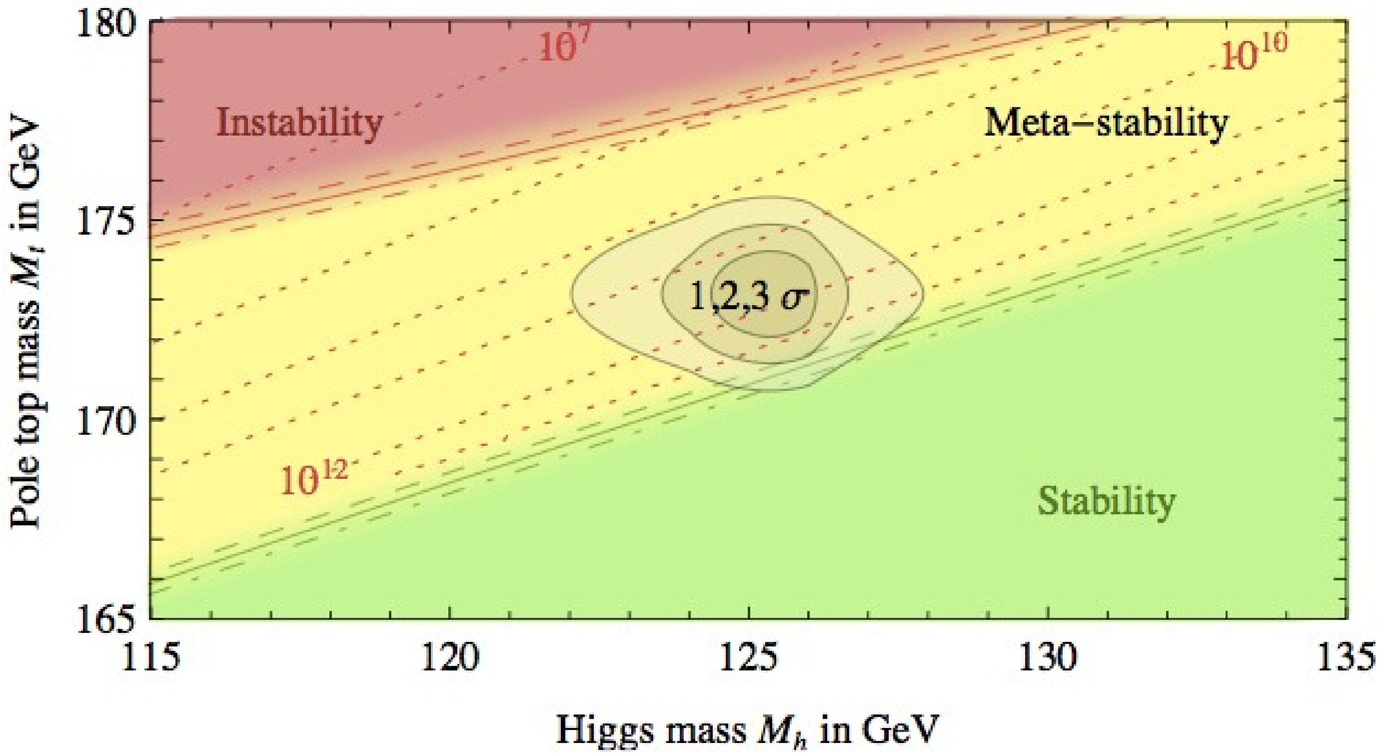


- Cross section ~500 fb@500 GeV
  - … pure electroweak process

Vacuum Stability and Top Quark Mass

$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\mathrm{th}}\ .$$

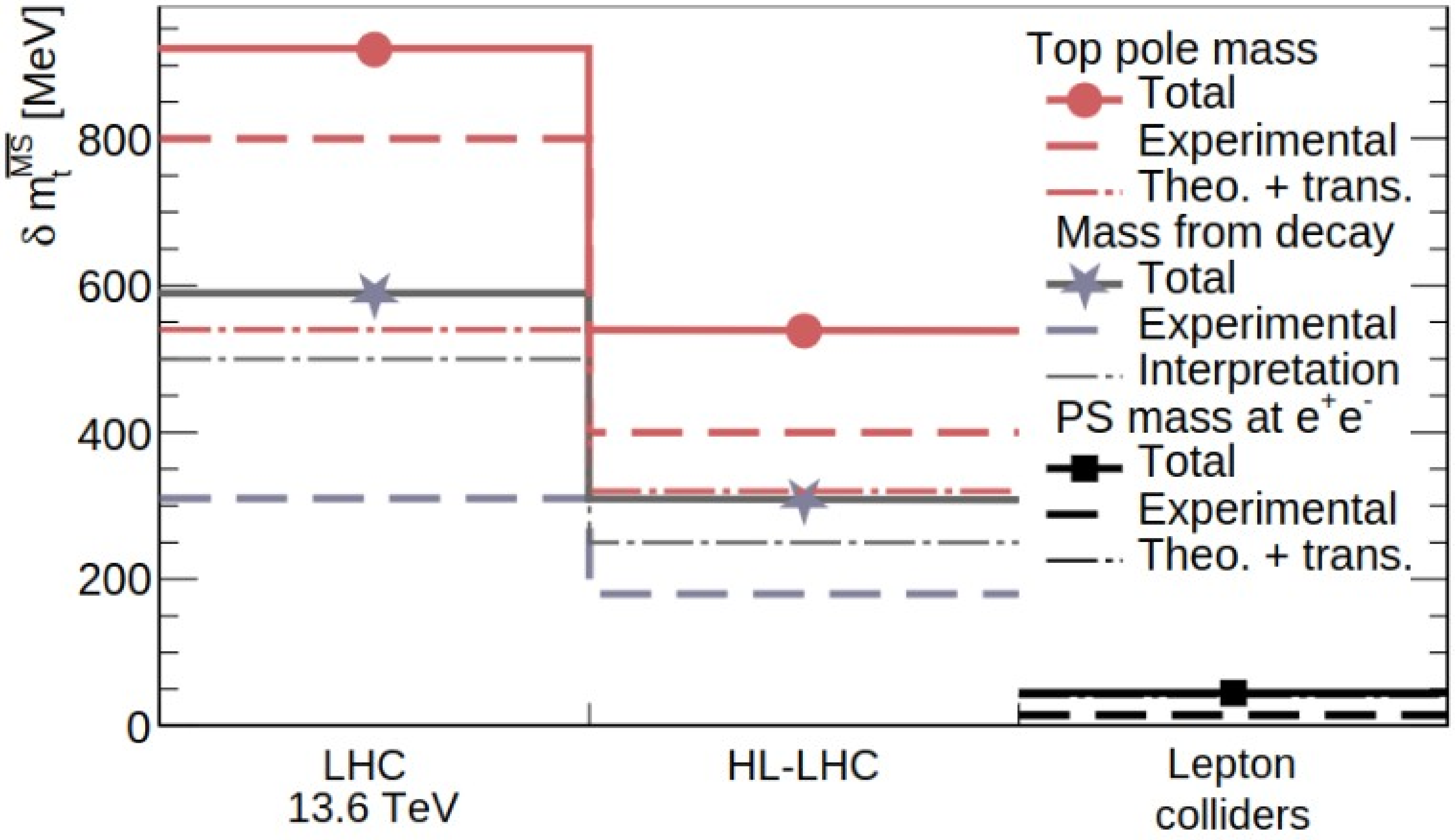




Uncertainty on (pole) top quark mass determines uncertainty on stability conditions

Top Mass Summary

Snowmass report, arXiv:2209.11267



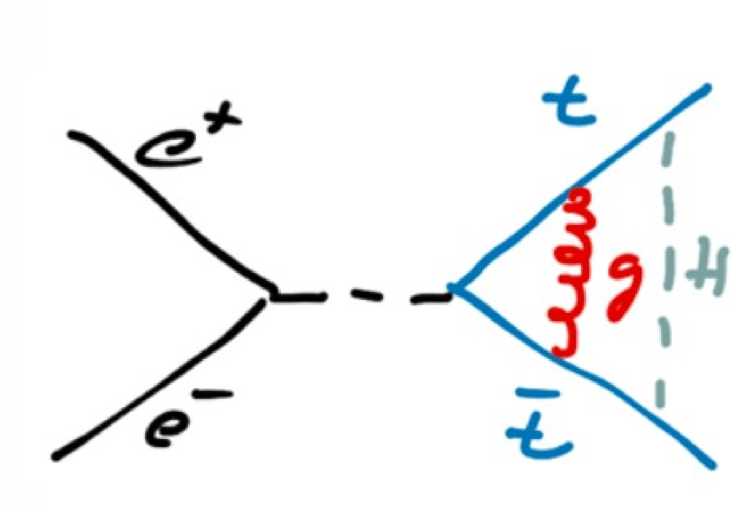
All future lepton (e+e- colliders) will improve considerably the precision on m_{top}

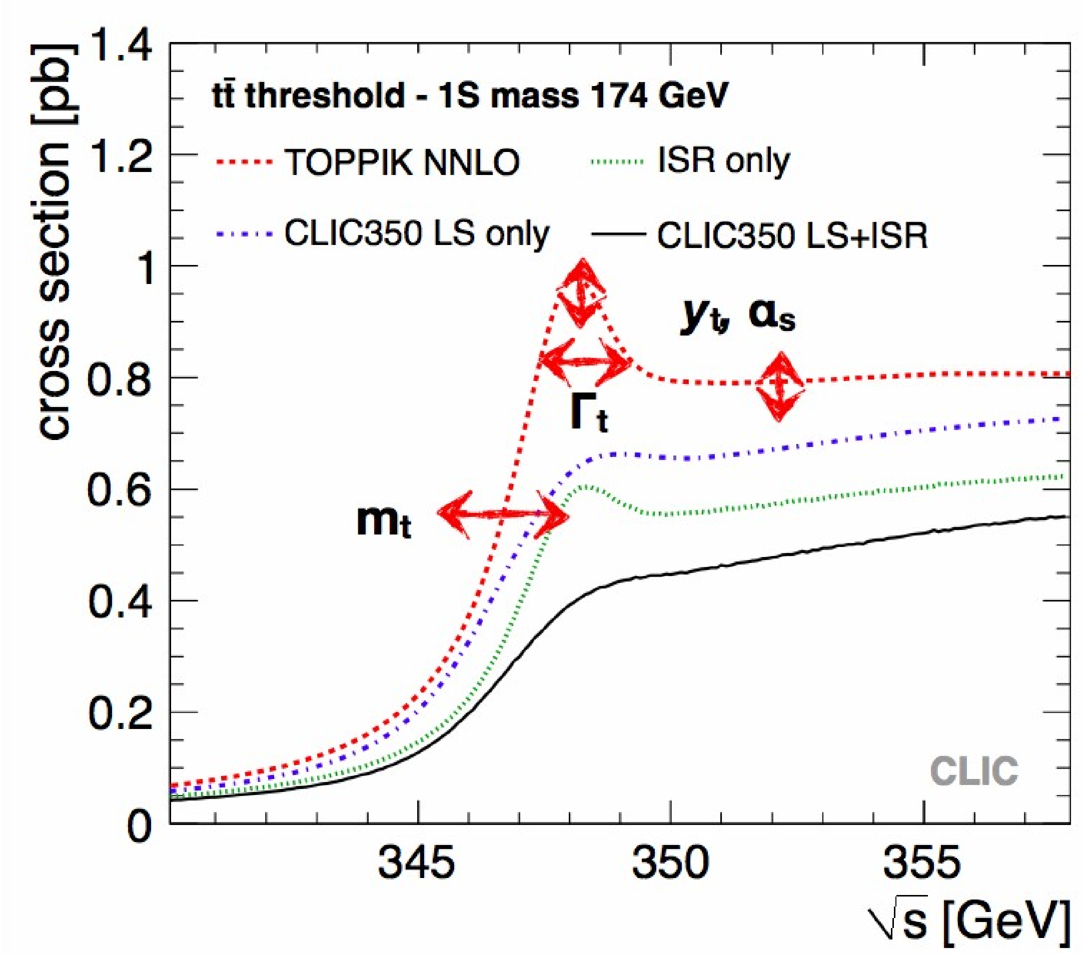
Marcel Vos@Top23

Small size of ttbar “bound state” at threshold ideal premise for precision physics

Cross section around threshold is affected by several properties of the top quark and by QCD

- Top mass, width Yukawa coupling
- Strong coupling constant

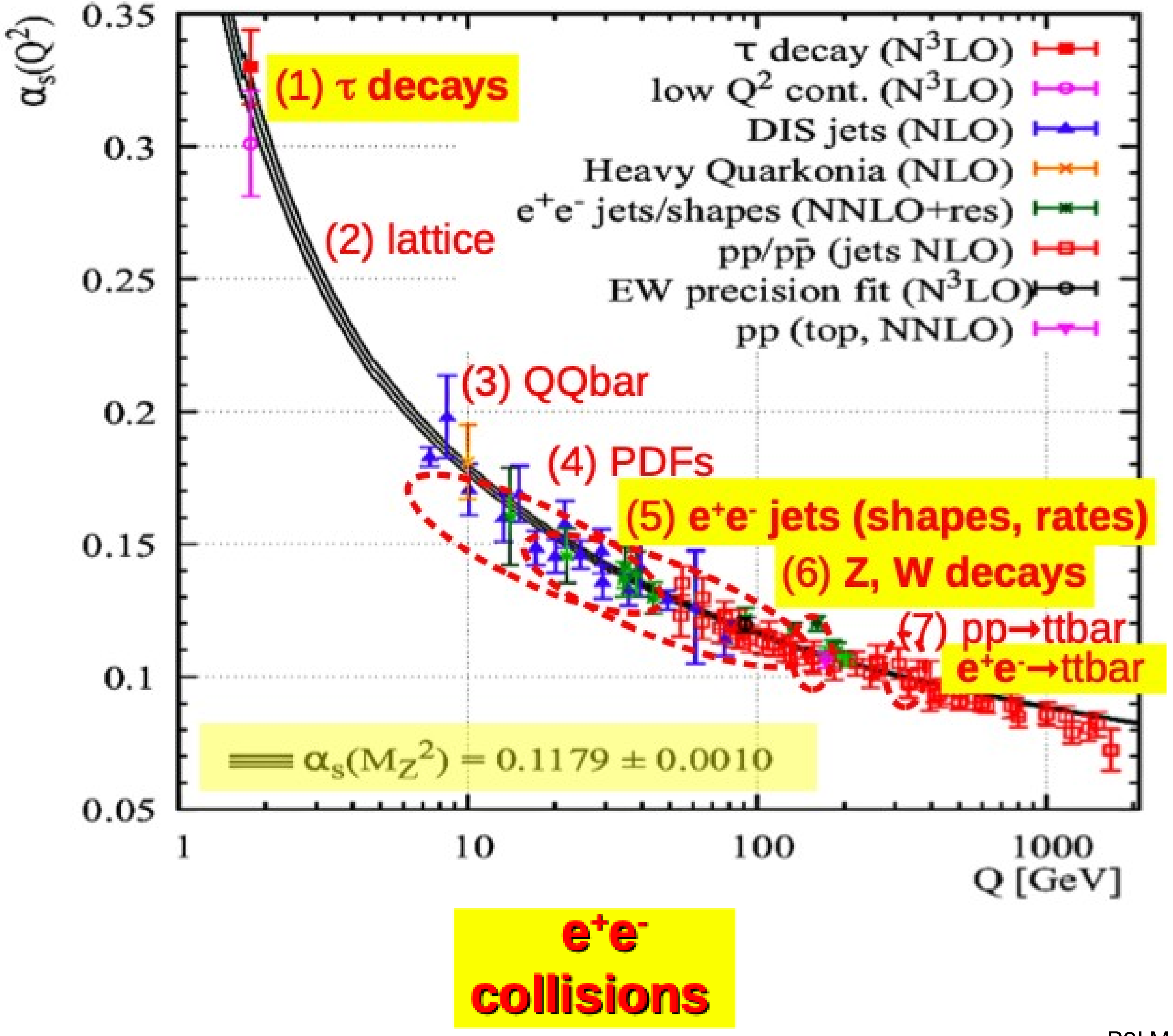




- Effects of some parameters are correlated:
- Dependence on Yukawa coupling rather weak,
- Precise external α_s helps

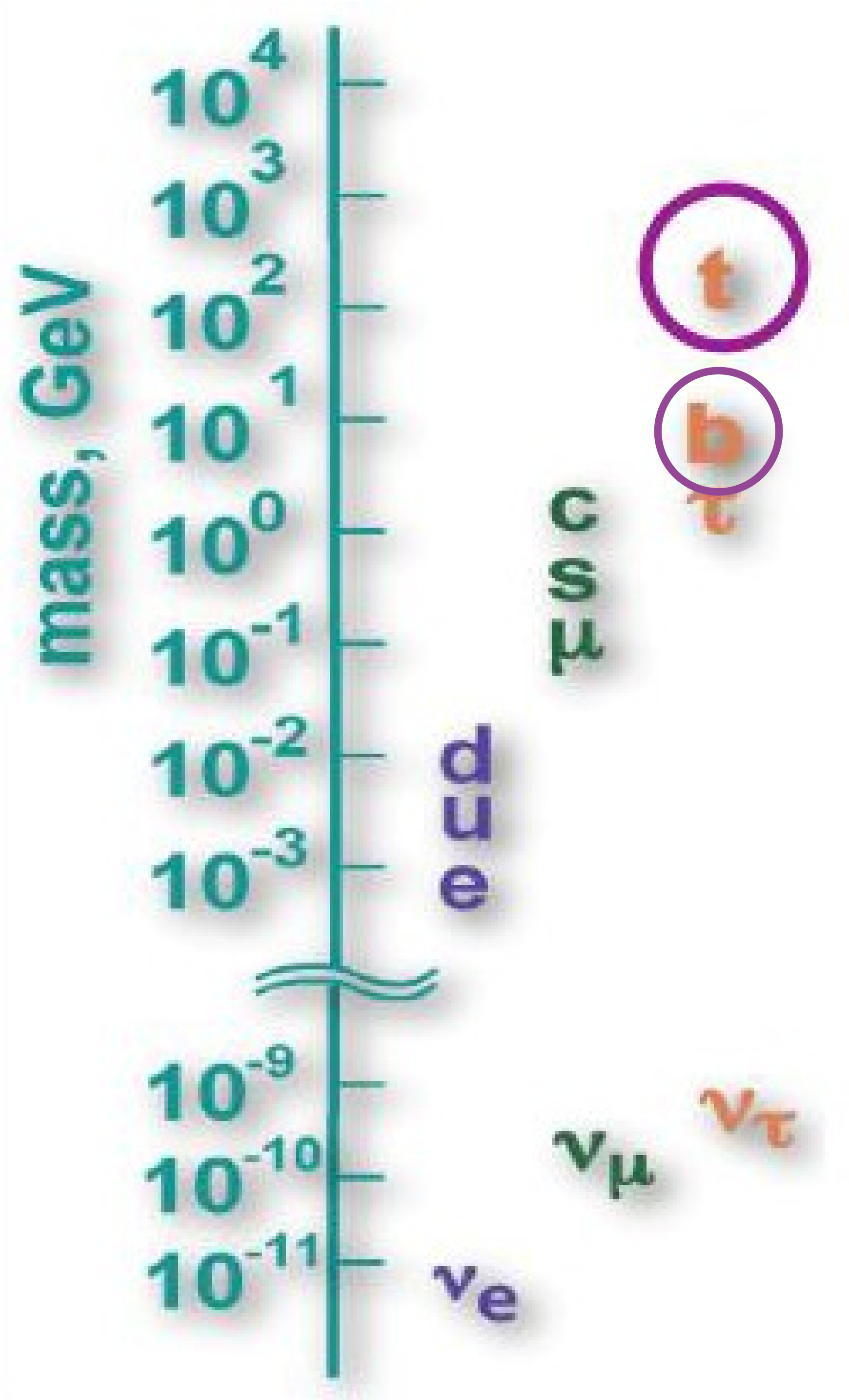
F. Simon, Top@LC15 Valencia

Uncertainty driver α_s



- See talk by Francesco Giuli LCF2022
  - https://indico.ectstar.eu/event/149/contributions
  - /3058/attachments/1919/2513/FCC_LFC_FGiuli_2022.pdf
- Best prospects from e+e- collisions
  - $\Delta\alpha/\alpha$ ~0.1% for FCCee hadronic Z-decays
    - Comparable with QCD Lattice Results
  - Status for ILC $\Delta\alpha/\alpha$ ~0.6% (arXiv:1512.05194)
    - Worth another look ?!

Vaccum Stability and Top Quark Mass



- SM does not provides no explanation for mass spectrum of fermions (and gauge bosons)

- Fermion mass generation closely related to the origin electroweak symmetry breaking

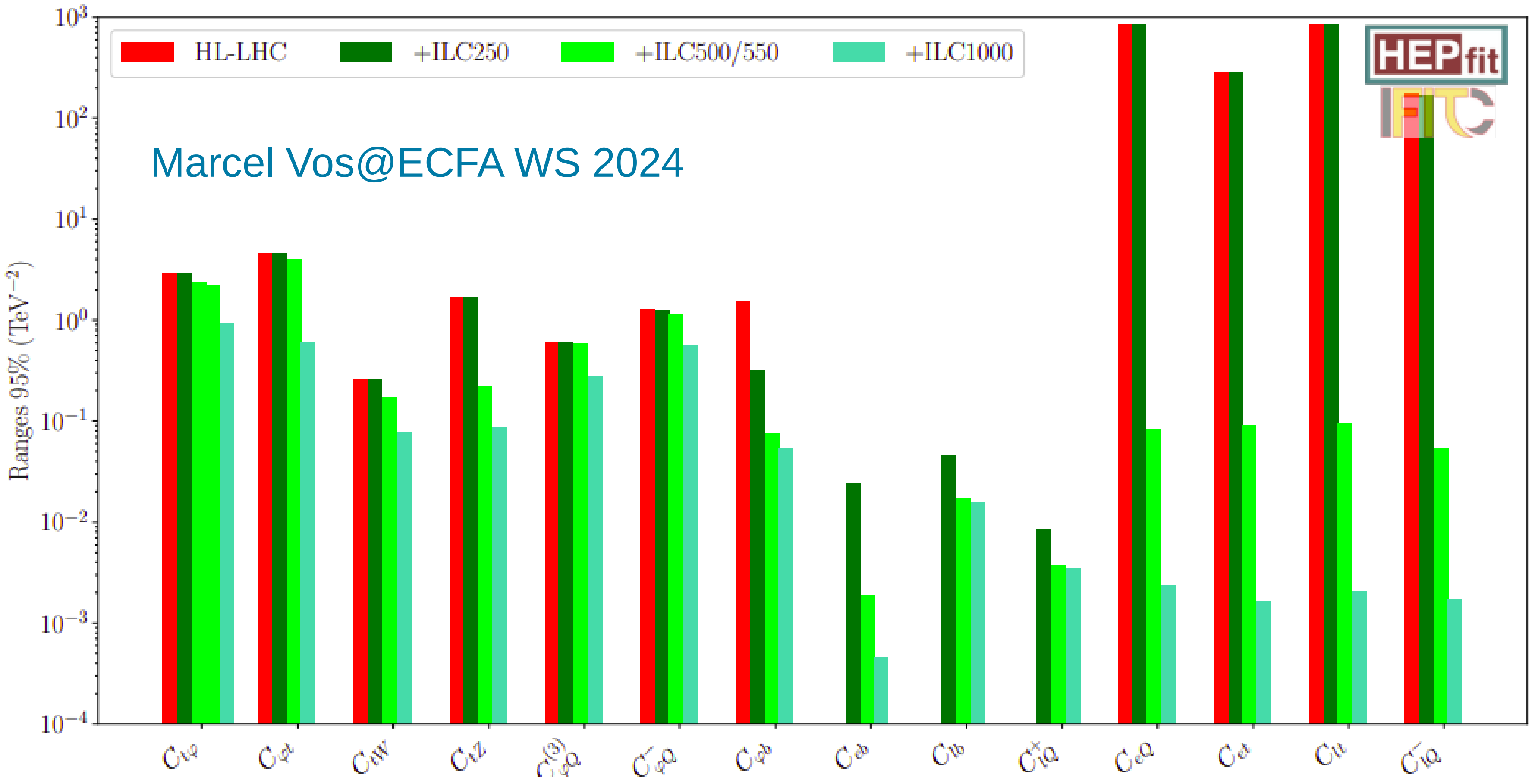
- Expect residual effects for particles with masses closest to symmetry breaking scale

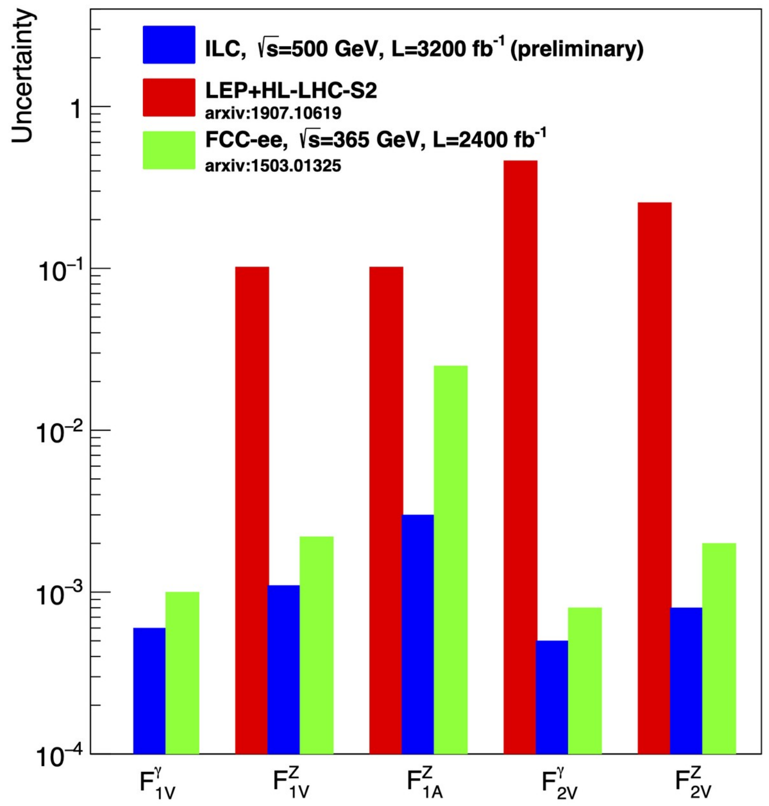
$$\begin{pmatrix} t \\ b \end{pmatrix}_L$$

- Heavy quark effect or effect on all fermions?

Strong motivation to study chiral structure of (heavy) quark vertices

Precision on electroweak form factors and couplings





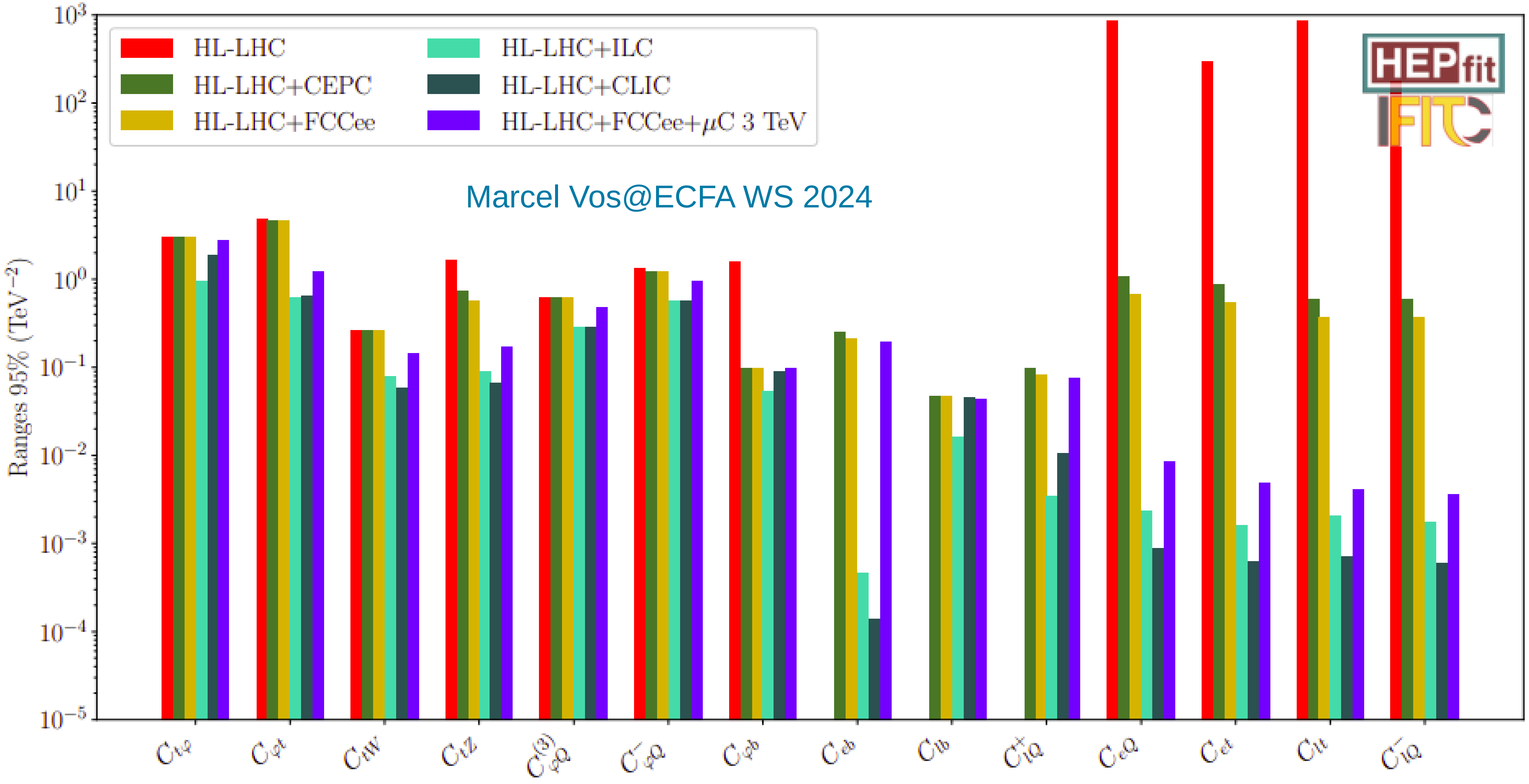
The 250 GeV run provides some information (interplay bottom-top)

Top production at an e+e- collider yields dramatic improvement

The fit benefits from a 2nd top run at high energy (2-vs-4 fermion operators)

- e+e- collider way superior to LHC ($\sqrt{s}$ = 14 TeV)
  - True for both, analysis in terms of Form Factors and Wilson Coefficients
- Polarised beams at ILC, final state analysis at FCCee
  - Final stat analysis also possible at LC => Redundancy should be checked again (see arxiv 1503.04247)
- :500 GeV is nicely away from QCD matching regime (see backup)
  - Less systematic uncertainties
- Axial form factors are ~β and benefit therefore from higher energies

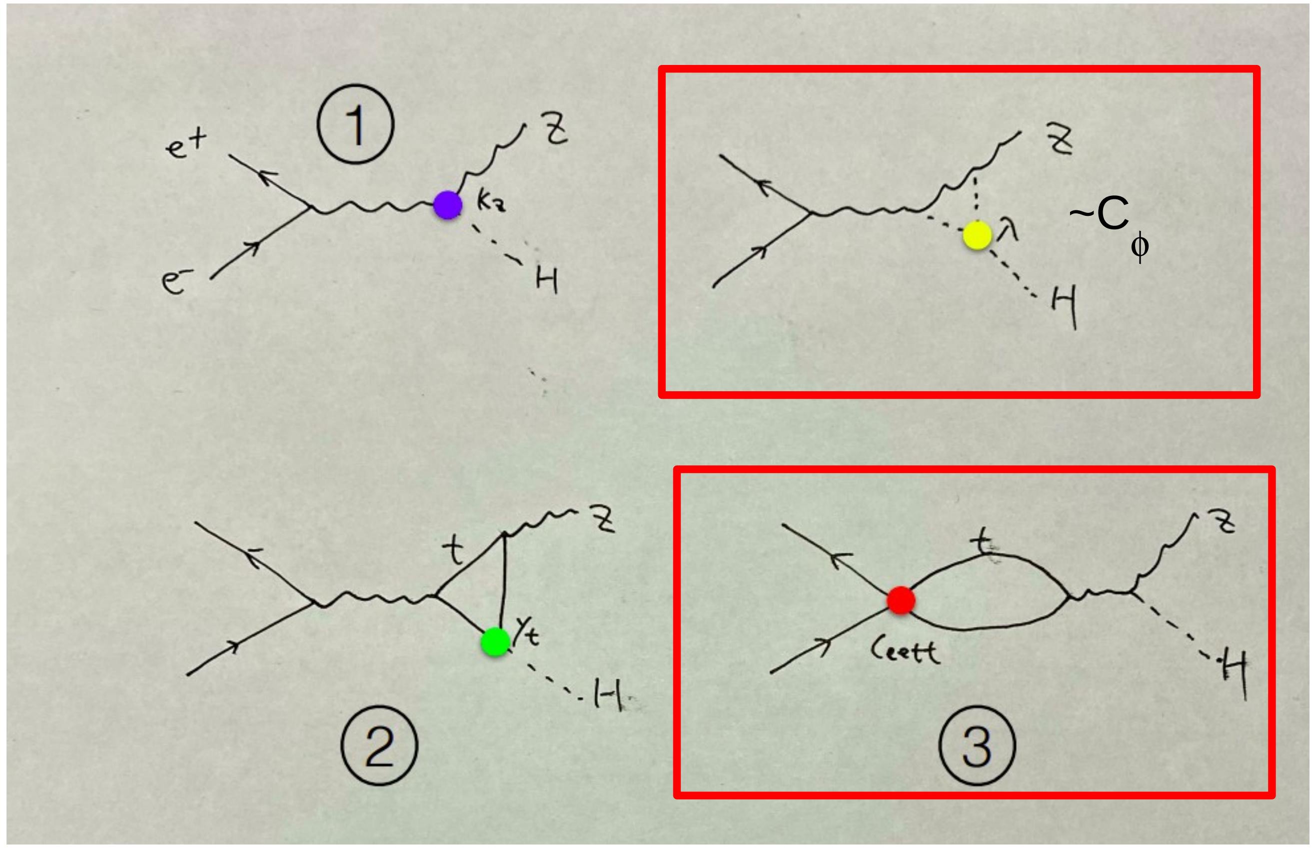
SMEFT Fit for different colliders



All e+e- colliders improve the bounds on the top sector dramatically
High-energy operation is important to provide the strongest global bounds

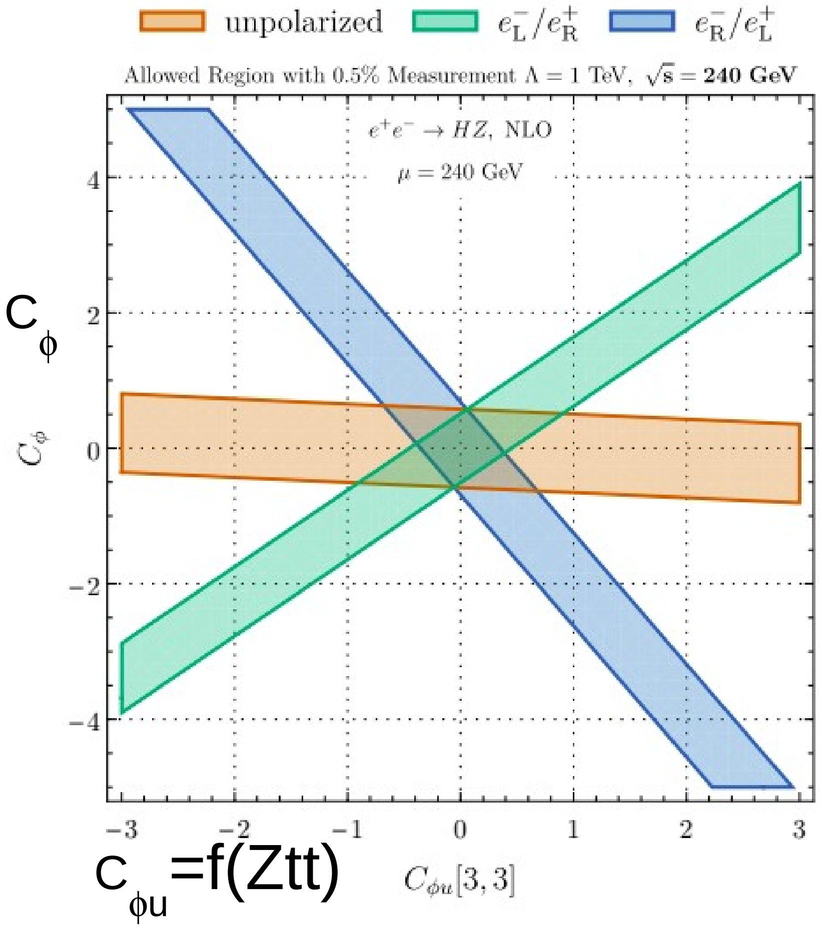
Entanglement SMEFT NLO

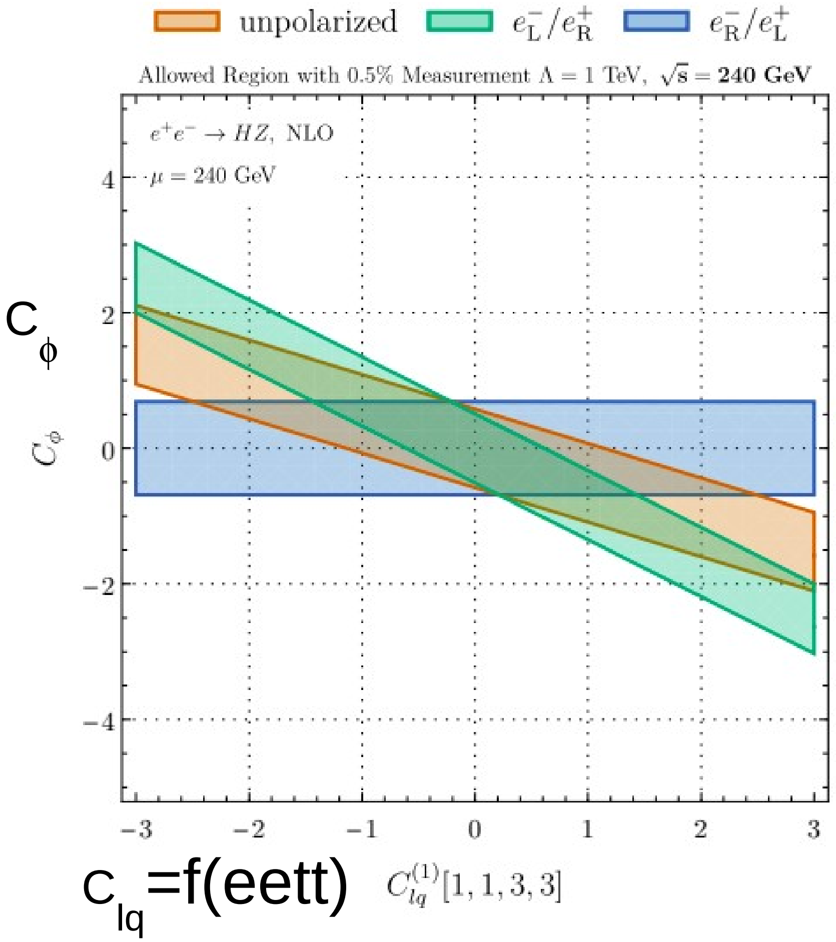
NLO Contributions to ee->HZ



One important contribution is eett Vertex

Correlation C_ϕ to tt-Vertices arxiv:2409.11466

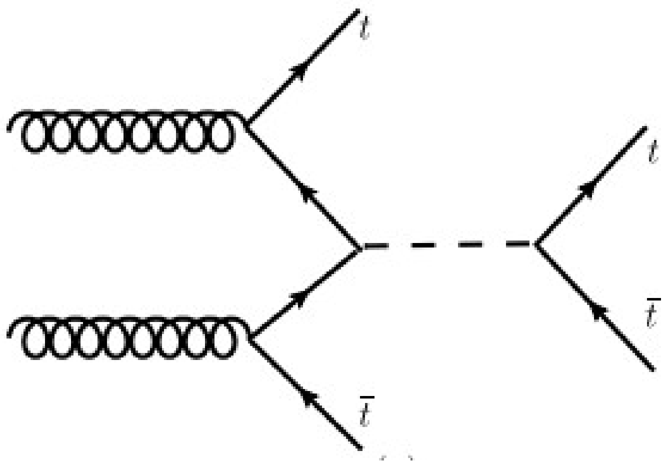


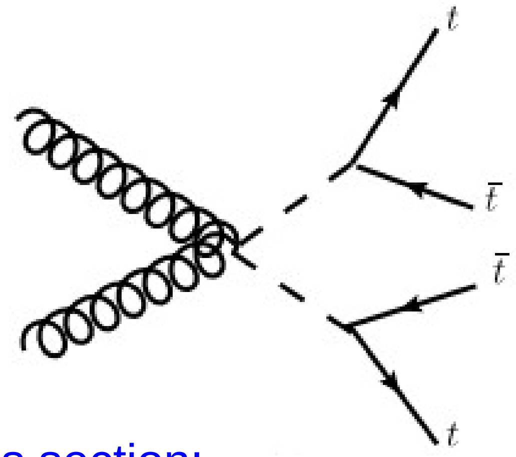


- NLO SMEFT introduces sensitivity to and constrains C_ϕ and operators involving top vertices
- Disentangling of constraints using beam polarisation
- Final word would come from higher energy measurements
- Note that C_{lq} is strongly energy dependent (-> would benefit from higher energies)

(New) Physics with four top production

4-top in pp





Cross section:

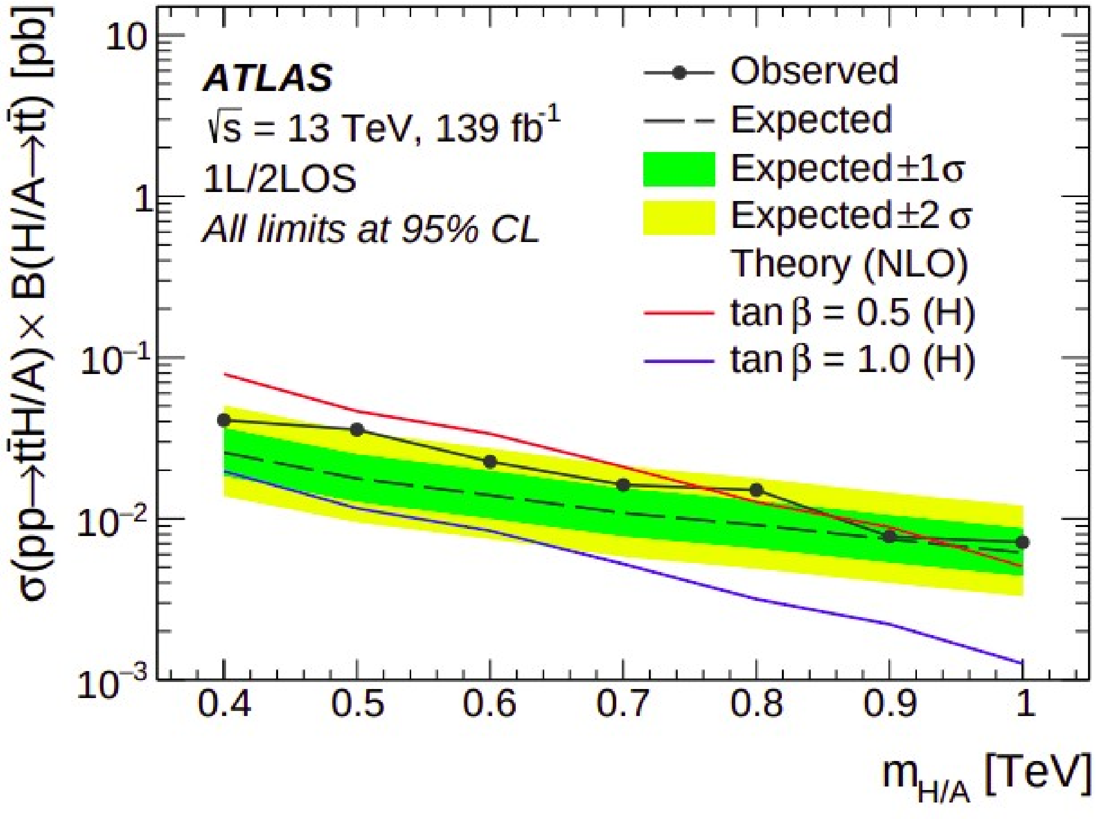
ATLAS: $22.5^{+4.7}_{-4.3}(\text{stat.})^{+4.6}_{-3.4}(\text{syst.})$ fb

CMS: $17.7^{+3.7}_{-3.5}(\text{stat.})^{+2.3}_{-1.9}(\text{syst.})$ fb

… for multi-lepton final states

Probing new physics at LHC

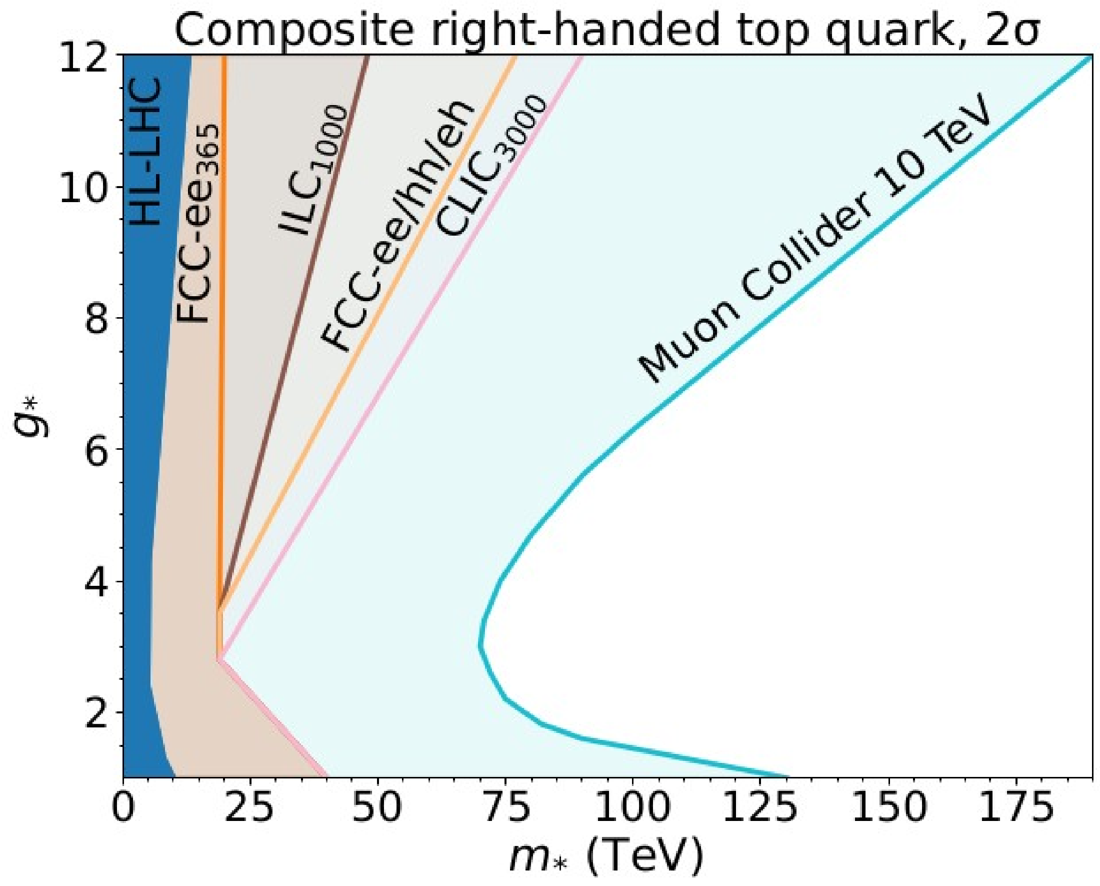
ATLAS: 2408.17164



Limits on production within
2 Higgs Doublet Model (2HDM)

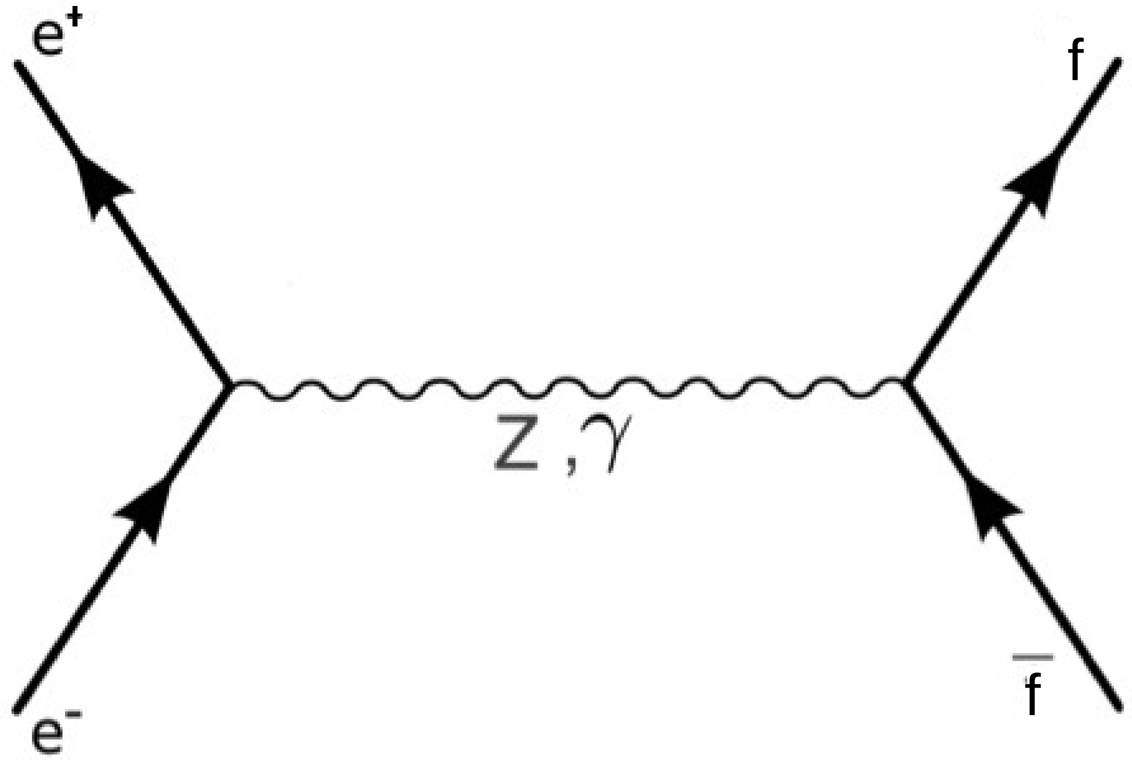
The "ultimate" probe for compositess

Snowmass Energy Frontier Report



- Compositeness gives rise to sizeable 4-top Wilons Coefficients
- Tests of compositeness improve with Centre-of-mass energy

Two fermion processes



Differential cross sections for (relativistic) di-fermion production*:

$$\frac{d\sigma}{d\cos\theta}(e^-_L e^+_R \to f\bar{f}) = \Sigma_{LL}(1+\cos\theta)^2 + \Sigma_{LR}(1-\cos\theta)^2$$

$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \to f\bar{f}) = \Sigma_{RL}(1-\cos\theta)^2 + \Sigma_{RR}(1+\cos\theta)$$

*add term ~*sin*$^2\theta$ in case of non-relativistic fermions e.g. top close to threshold

- Σ_{IJ} are helicity amplitudes that contain couplings g_L, g_R *(or F_V, F_A)*
- $\Sigma_{IJ} \neq \Sigma_{I'J}'$ => (characteristic) asymmetries for each fermion
- Forward-backward in angle, general left-right in cross section
- **All four** helicity amplitudes for all fermions **only available with polarised beams**

- **tt production see above**

Electroweak Precision Observables

Copied from deBlas, Higgs-Hunting 2016

- Precise measurements of W&Z properties taken at e+e- colliders and in part also at Tevatron/LHC

$$M_Z,\ \Gamma_Z,\ \sigma^0_{had},\ \sin^2\theta^{\rm lept}_{\rm eff},\ P^{Pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f$$

$$M_W,\ \Gamma_W$$

W-observables
LEP2
0.02 - O(1%)

Tevatron/LHC but in future also from e+e- colliders

$$M_W,\ \Gamma_W$$

0.02-O(1%)

$$m_t$$

0.4%

$$M_H$$

0.2%

38

e+e- Colliders – Uncertainties and their drivers

	experimental accuracy			intrinsic theory uncertainty		
	current	ILC	FCC-ee	current	current source	prospect
ΔM_Z[MeV]	2.1	0.2	0.1			
$\Delta \Gamma_Z$[MeV]	2.3	0.1	0.03	0.4	$\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$	0.15
$\Delta \sin^2\theta^\ell_{\rm eff}[10^{-5}]$	23	1.3	0.2	4.5	$\alpha^3, \alpha^2\alpha_s$	1.5
$\Delta R_b[10^{-5}]$	66	14	6	11	$\alpha^3, \alpha^2\alpha_s$	5
$\Delta R_\ell[10^{-3}]$	25	3	1	6	$\alpha^3, \alpha^2\alpha_s$	1.5

FCCee: 2203.06520 *ILC: 2203.07622*

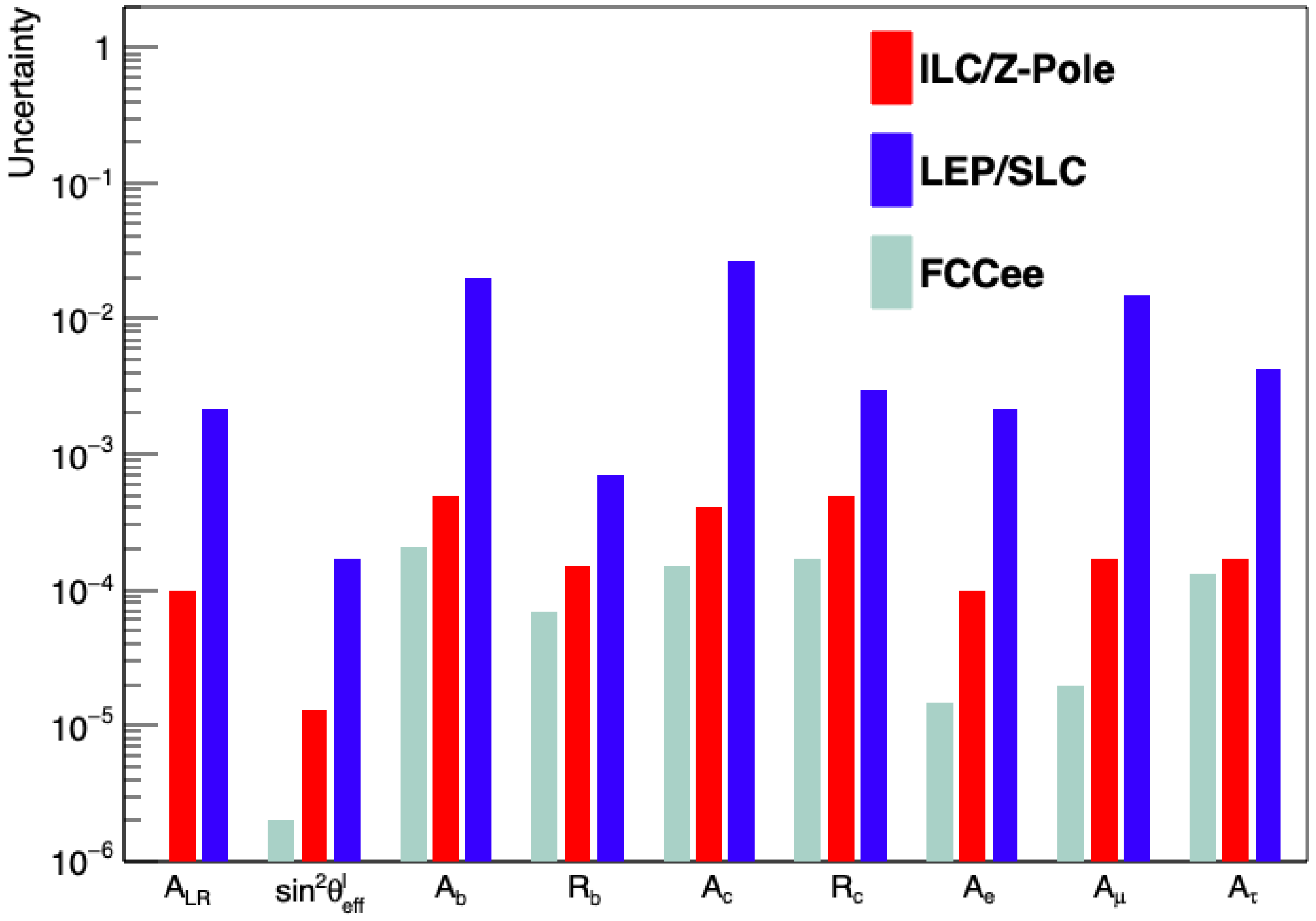
Theory requires 3-loop calculations

Experimental uncertainty drivers:

- M_Z, Γ_Z: Beam energy, detector calibration and acceptance
  - Would require a reduction of a factor 20-25 to match FCCee statistics w.r.t current estimates
- $\sin^2\theta^\ell_{\rm eff}$:Beam energy (FCCee, CEPC), beam polarisation (ILC)
- R_b: Detector acceptance, QCD (gluon radiation?)
  - Difficult to judge on “the error source”, it's rather a sum of many
- R_l: Detector acceptance

39

Z-pole – Comparison future e+e- colldiers



Numbers FCCee*: "Mixture" of FCC CDR and
P. Janot at Precision Workshop/CERN
https://indico.cern.ch/event/1140580/timetable/

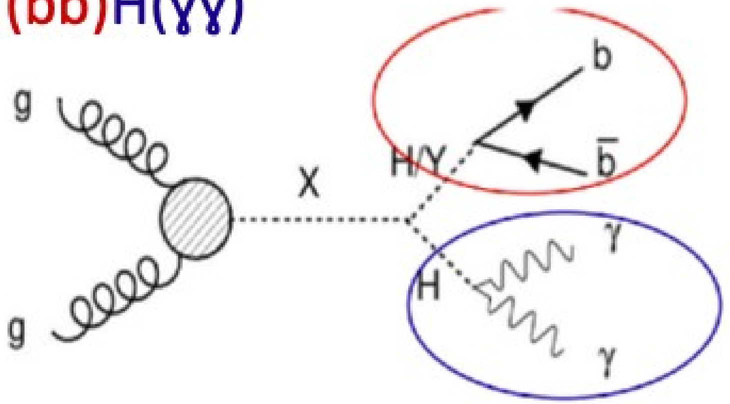
Numbers ILC: arxiv: 2203.07622 (ILC Snowmsss report)

- All future e+e- colliders will improve significantly precision compared with LEP/SLC
- Comparable precisions despite differences in luminosity
  - Polarisation catches up in case of LC
  - Systematics will play a major role
  - e.g. beam polarisation for LC
- High precision is sensitive probe to quantum Fluctuations
  - 10-100 (?) TeV in reach
  - (see recent talk by M. McCullough)

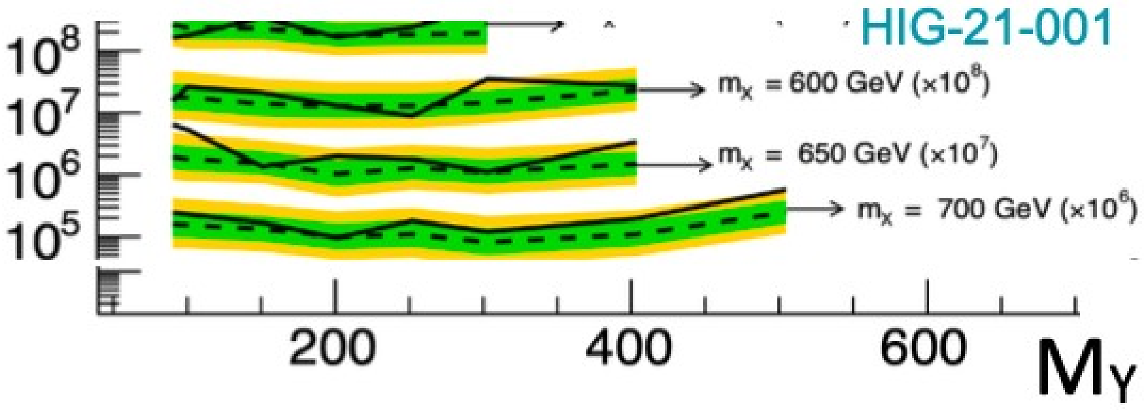
**cross checked with M. McCollough IDT-WG3 talk Nov. 24 → no major changes*

What if … the LHC makes a discovery?

Search for resonances (X) decaying to H/Y(bb)H(γγ)

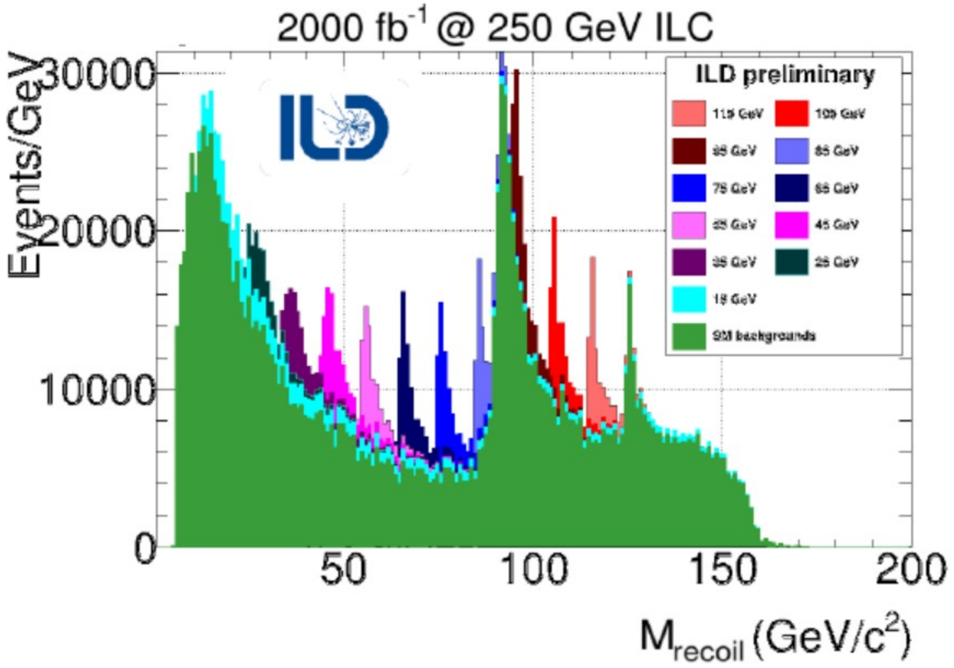


Excess at (90,100) with 650 GeV heavy resonance mass (~3.8 σ local and 2.8 σ global)

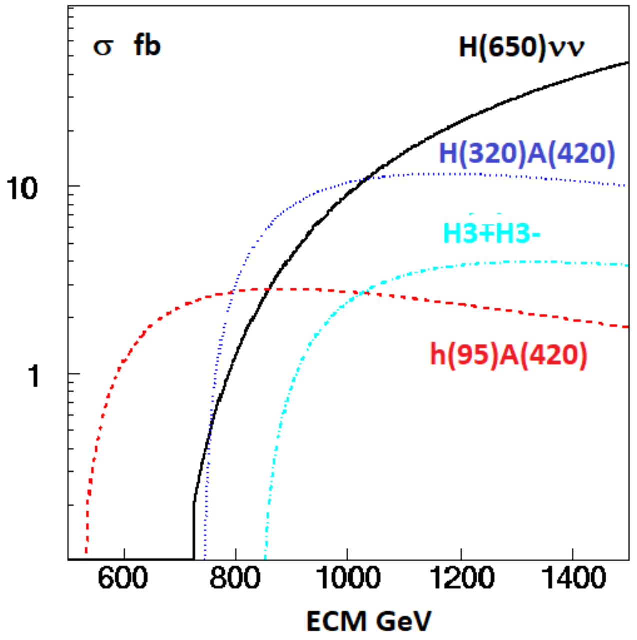


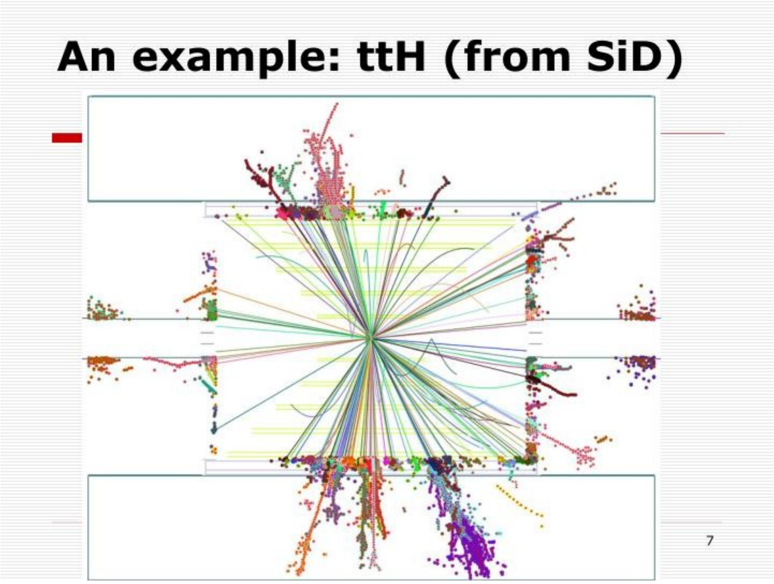
Tantalising excesses common to $\gamma\gamma$ and ττ final states!

Light scalars are "easy" to measure



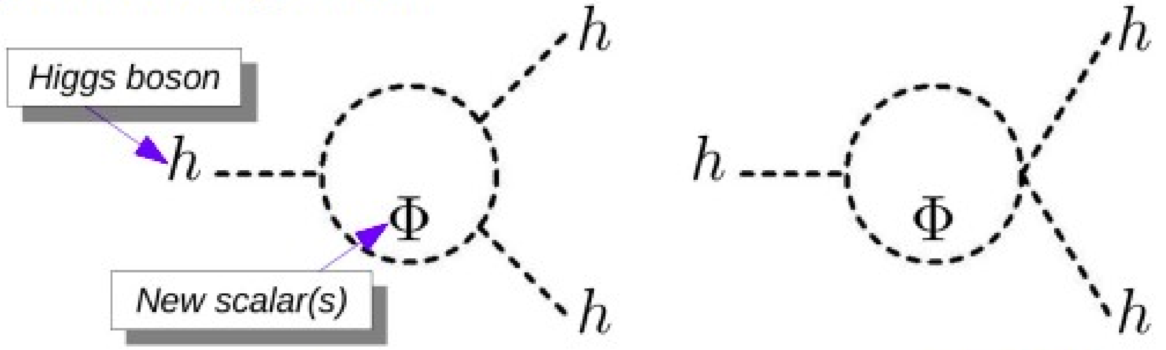
Sufficient centre-of-mass energy and hermetic detectors





J. Braathen, IDT-WG3 Physics Meeting

- **Large effects from New Physics possible in λ_{hhh}** due to radiative corrections from extra scalars, e.g. at leading order



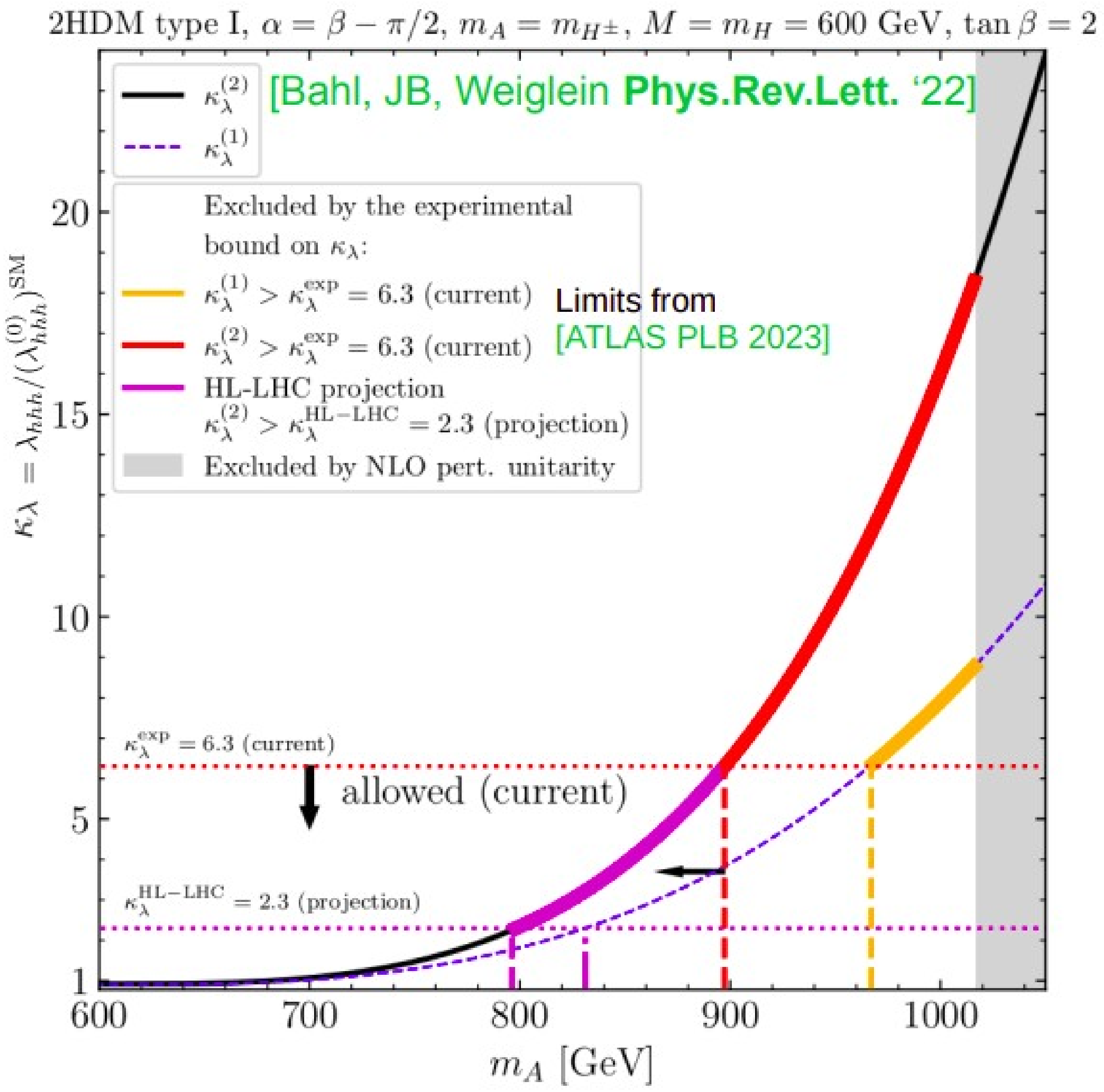
$$m_\Phi^2 = M^2 + \frac{1}{2} g_{hh\Phi\Phi} v^2 \quad \Leftrightarrow \quad g_{hh\Phi\Phi} = -\frac{2(M^2 - m_\Phi^2)}{v^2}$$

- Comparing latest exp. bounds

$$-1.2 < \kappa_\lambda = \frac{\lambda_{hhh}}{(\lambda_{hhh}^{(0)})^{\mathrm{SM}}} < 7.2$$

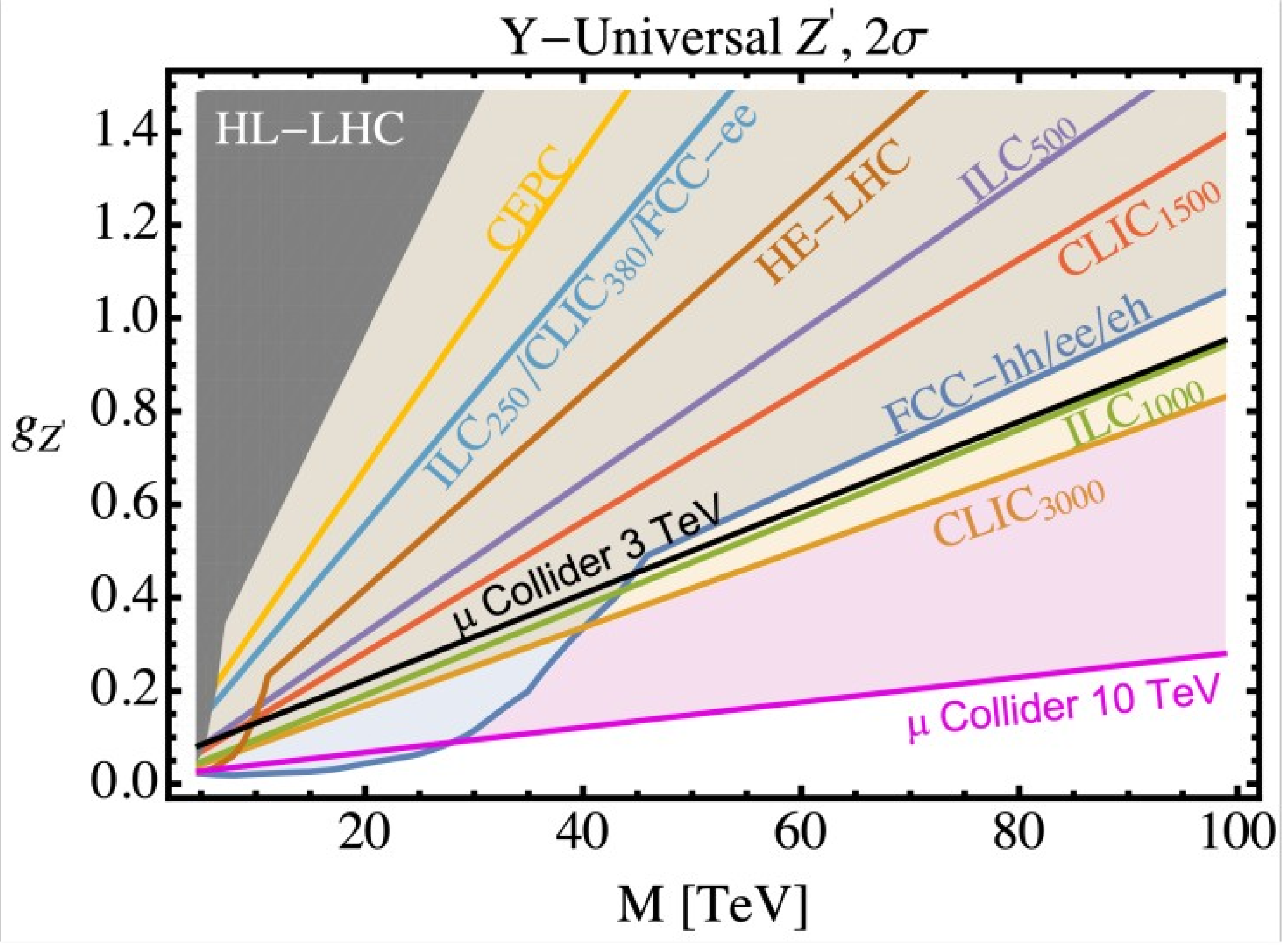
[ATLAS 2024]

with precise theory predictions for λ_{hhh} provides a **powerful new tool to constrain BSM models**
[Bahl, JB, Weiglein **Phys.Rev.Lett.** '22]



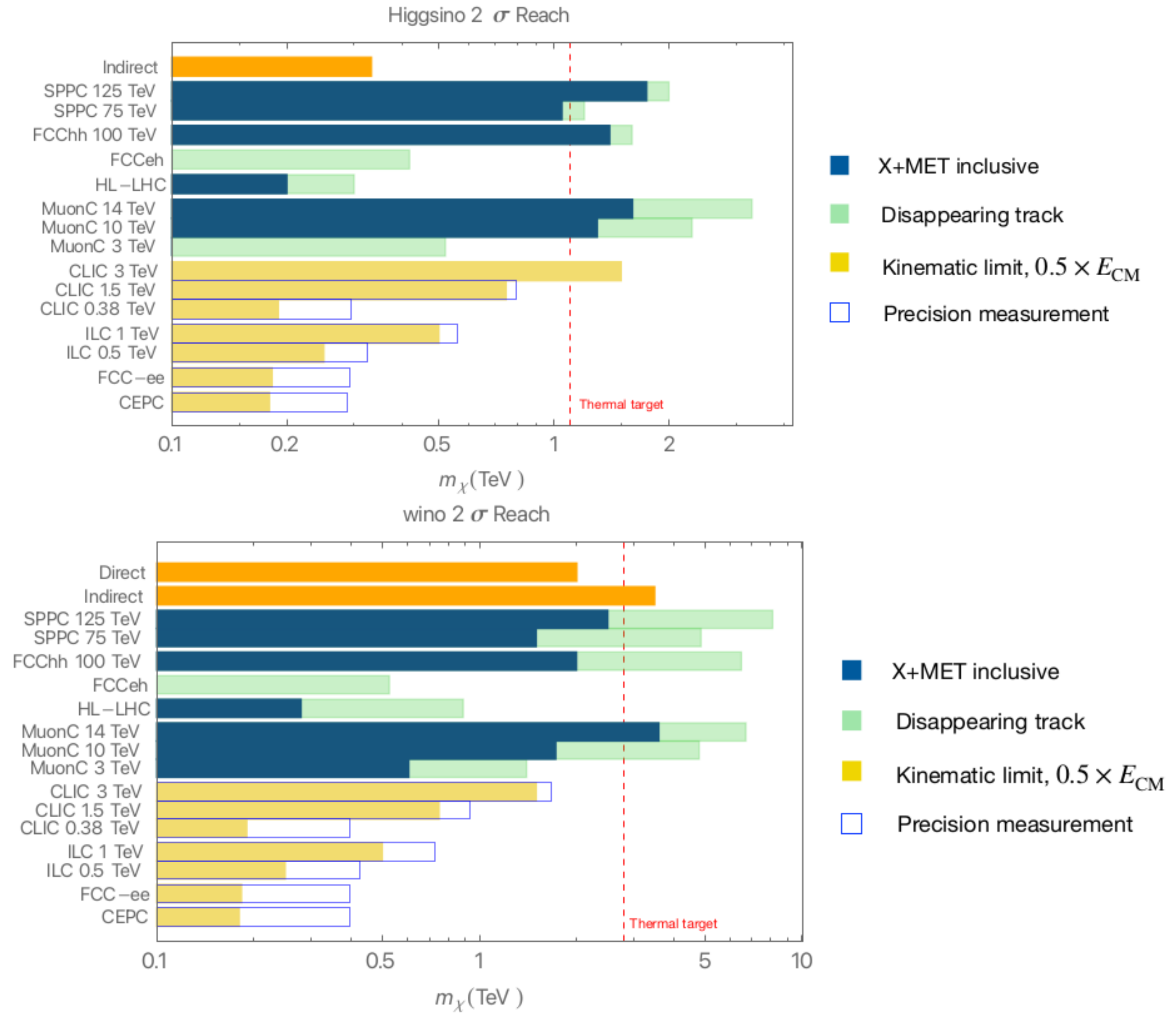
Mass reaches of future colliders (from Snowmass EF Report)

Generic Z' Model



Z' are expected for in compositeness models or in (dual) models with extra dimensions

Dark Matter 2σ exclusion limits



- Example for light Higgsino search in backup
- High centre-of-mass energy helps (here)
- Don't forget light states (see backup)

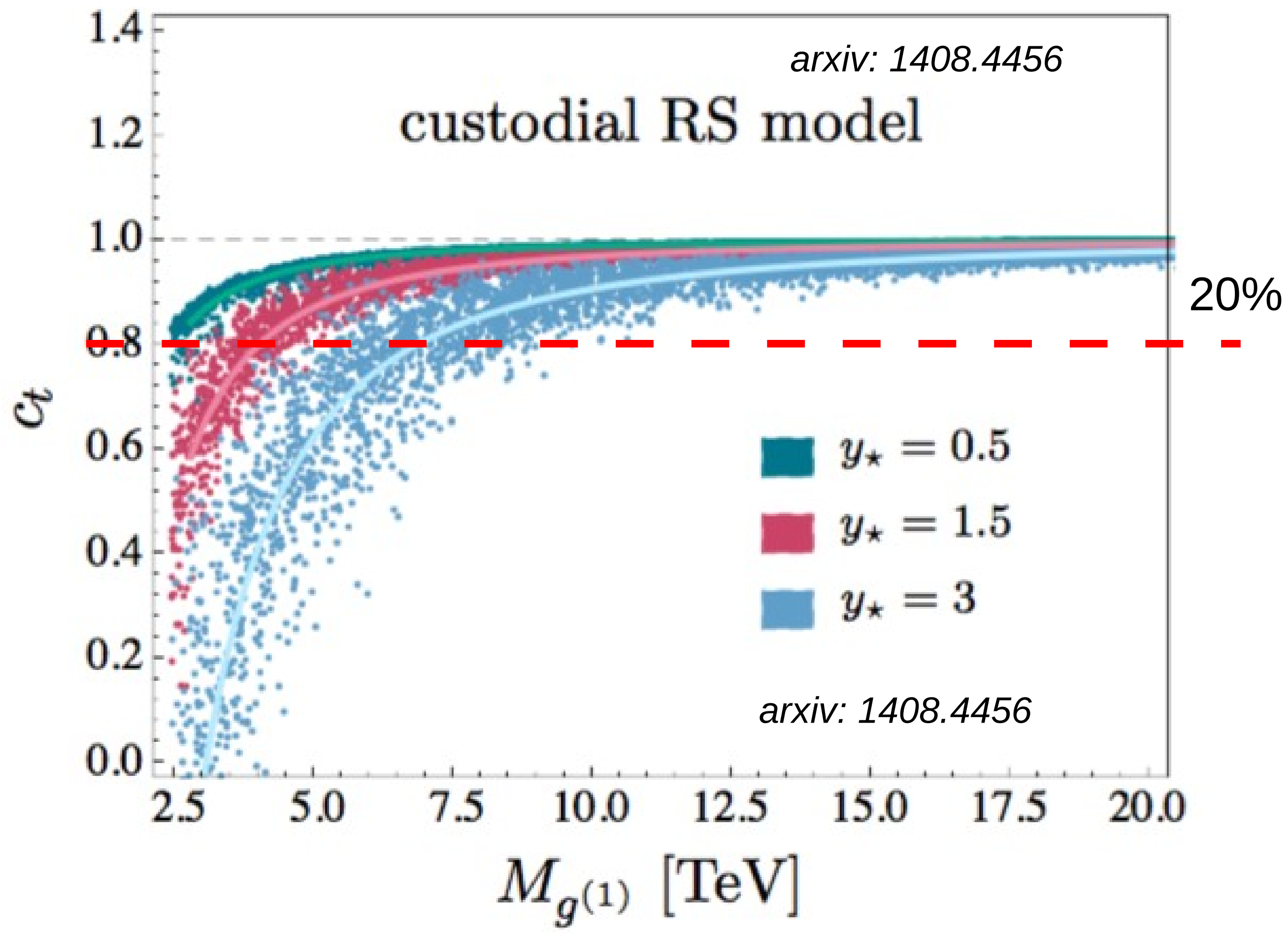
Summary and Conclusion

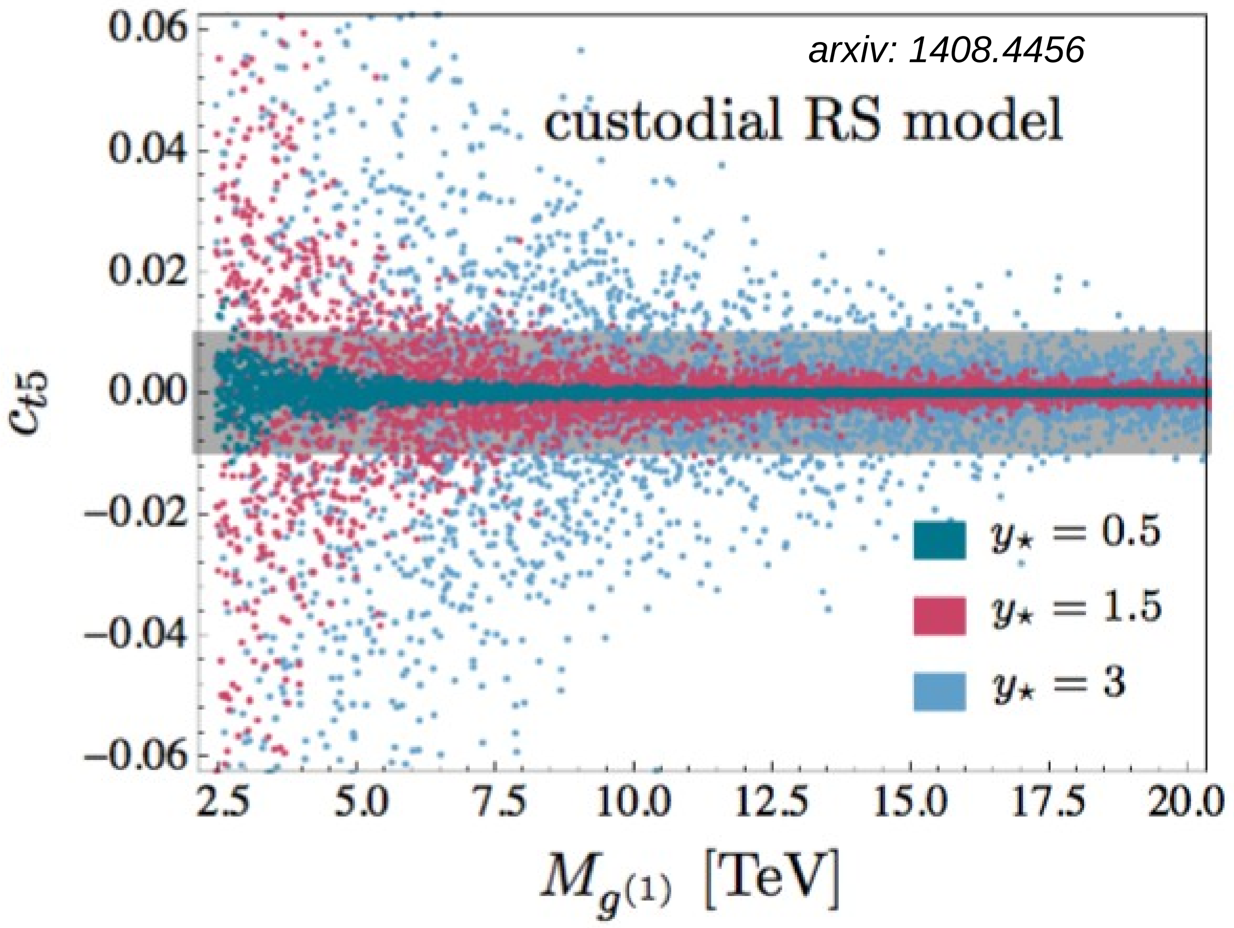
- Higgs is still the least known particle of the Standard Model
  - … and most likely a portal to new physics
- Therefore, Higgs Boson needs to be studied in full depth
- Need to improve electroweak precision
- Good prospects on HL-LHC to prove the existence of Higgs self-couplings
- Future colliders could study Higgs self-coupling in further depth O(5%) precision in reach
  - Note: O(10%) on Higgs self-coupling competes with ~O(1%) on g_{HZZ} (see backup)
  - Check interplay with other fields of science
- Top quark is intimately coupled to Higgs boson
  - Future colliders could carry out a vast top programme including 4-top production
- LHC has only gathered 10% of its data
  - Future colliders could (should be able) to react to surprises by HL-LHC
- Future colliders allow for “attacking” the 100 TeV mass scale (~40xelectroweak scale)

Backup

Top Yukawa Coupling and New Physics

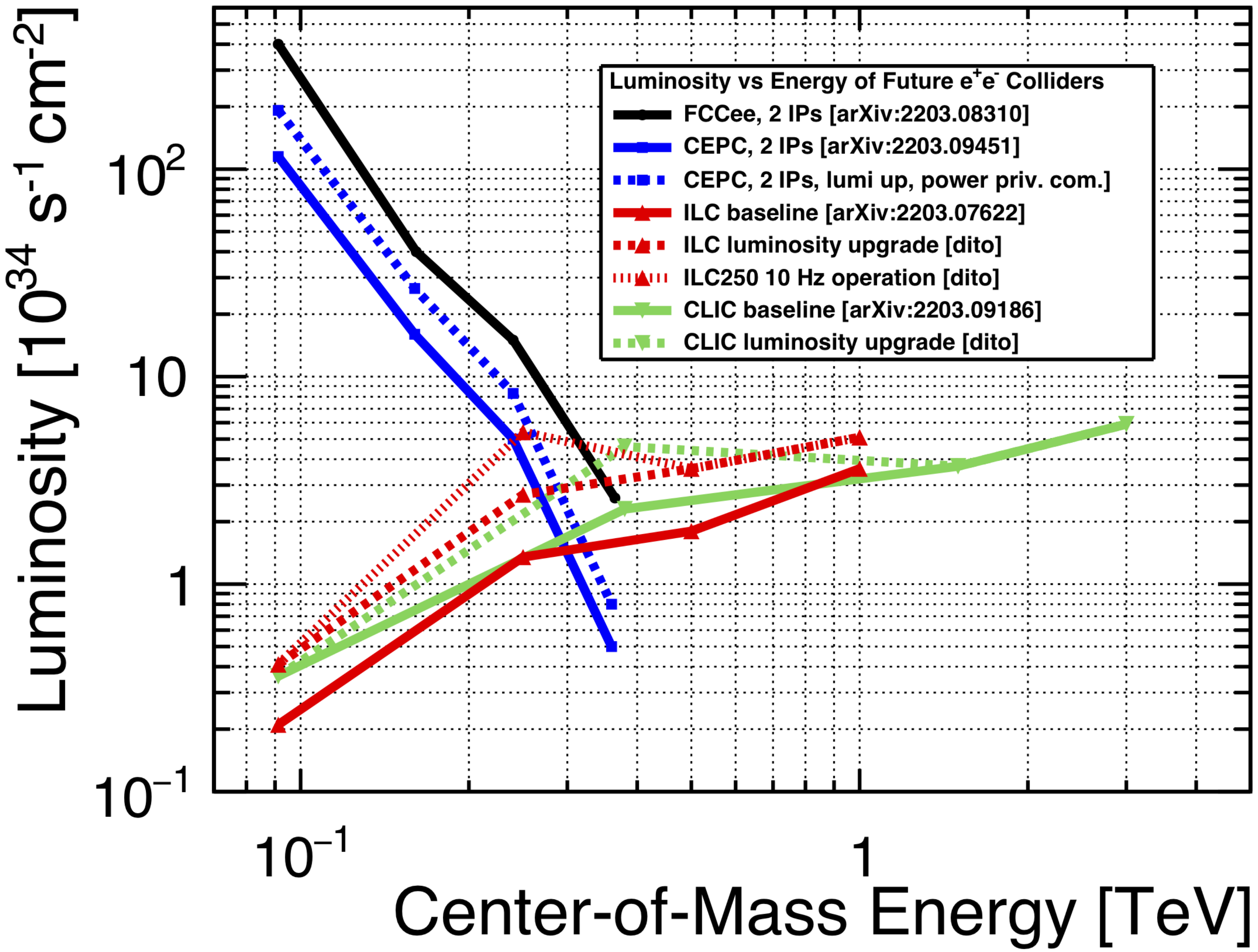
Top-Higgs couplings in “presence” of heavy particles





- Heavy particles, e.g. (Kaluza Klein) “duplicas” of SM particles provoke sizable effects
- Sensitivity to CP Violation !?
- Caveat: R.P. did not check against current LHC constraints!

Top Yukawa Coupling and New Physics

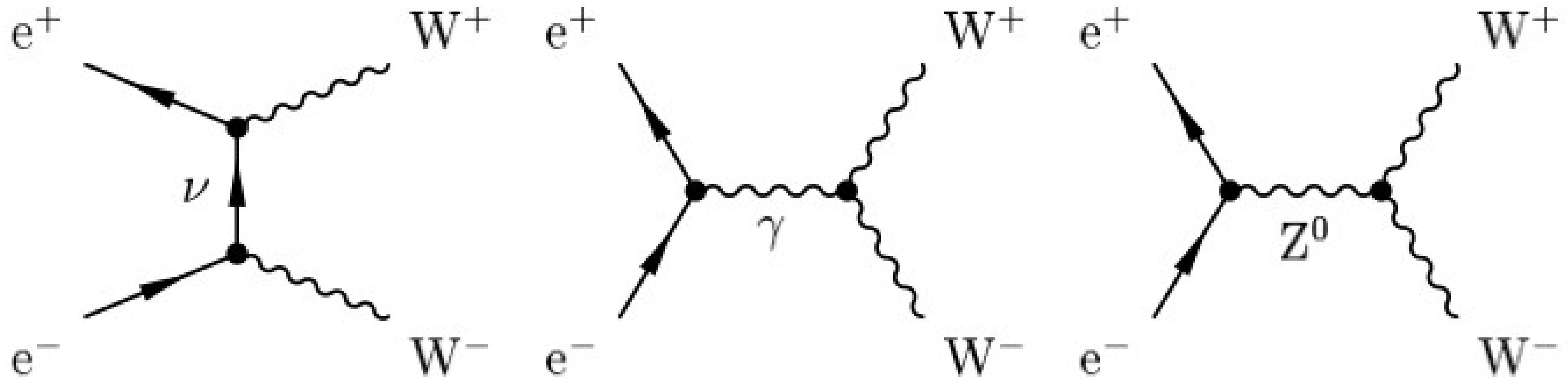


- High energies ~above tt-threshold
  Domain of linear colliders
- Low energies e.g. Z-pole
  Domain of circular machines
  However, ...
- Transition region, i.e. HZ threshold
  Comparable Higgs Couplings uncertainties for all proposals (see later)
- Linear colliders are more versatile to test chiral theory due to polarised beams

$$\sigma_{P,P'} = \frac{1}{4}\left[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})\right]$$

Figure J. List

Anomalous Triple Gauge Couplings

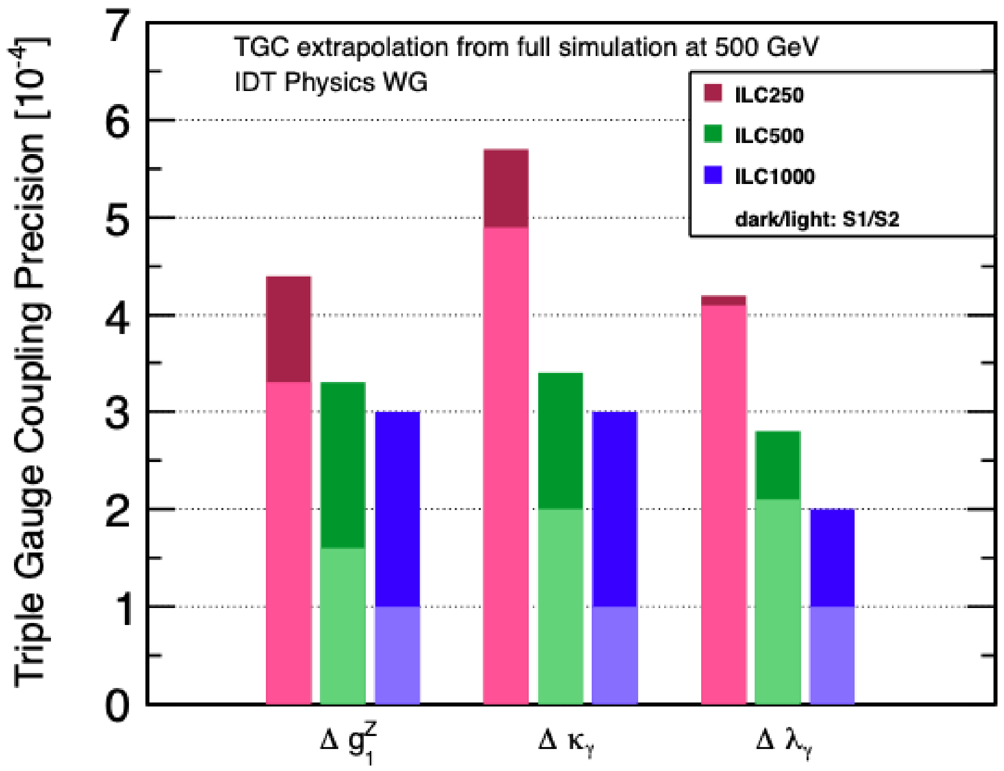


- Sensitivity to triple and quartic gauge Boson couplings (TGC and QGC)

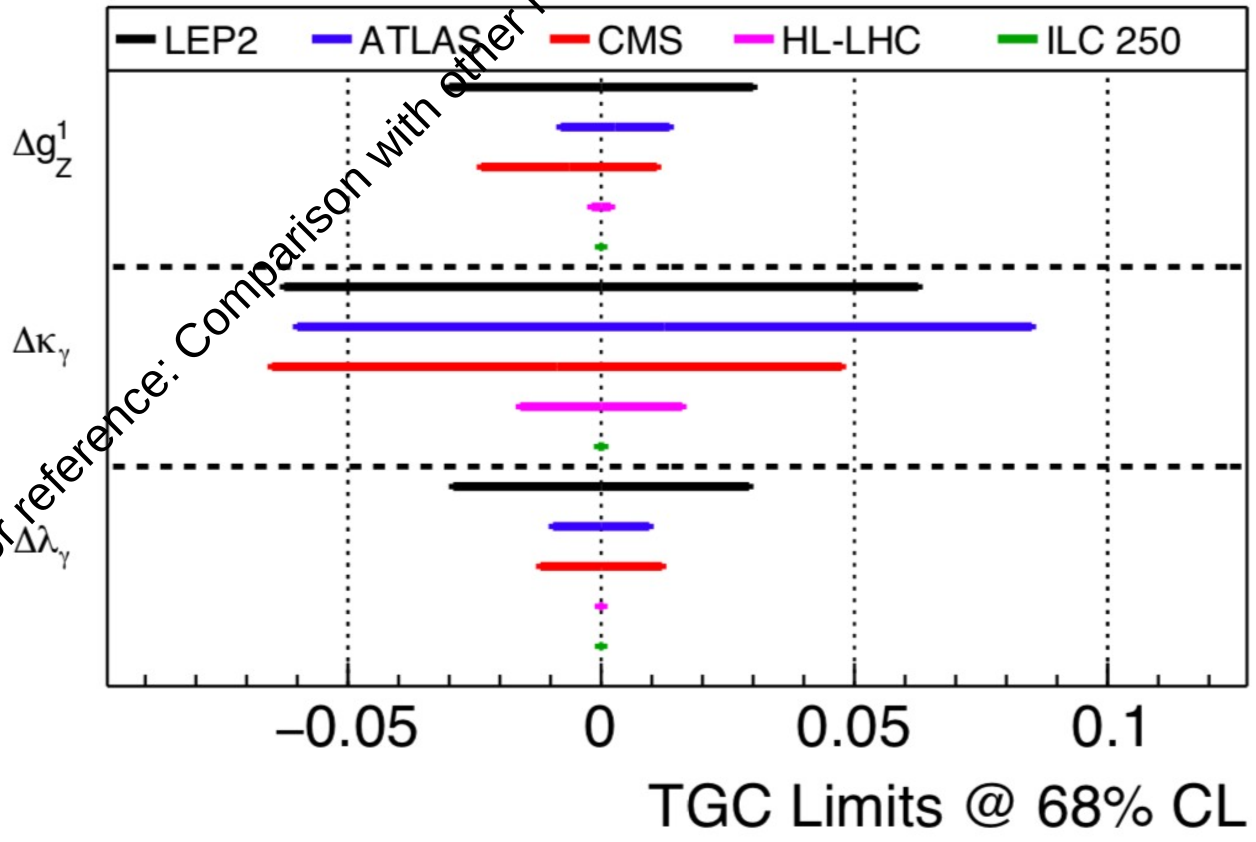
- Observables depend strongly on beam polarisation

=> Enrich different helicity modes of W
=> Disentangling of couplings to Z and γ
=> in situ measurement of beam polarisation (and luminosity)

Limits on Triple Gauge Couplings@250 GeV



For reference: Comparison with other results



Light Higgsinons- Event Display

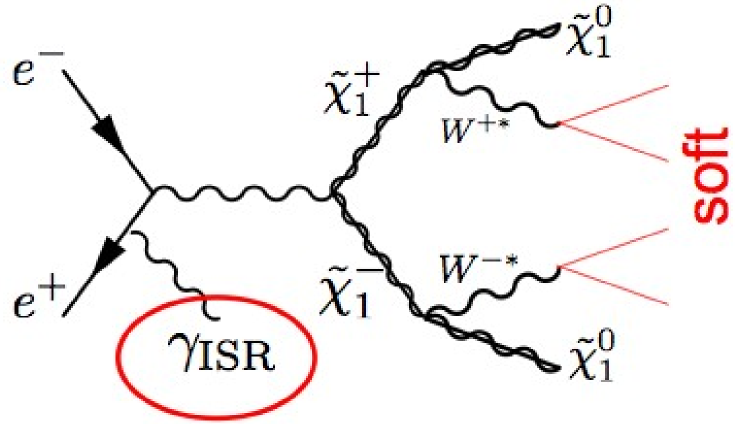
Study of Higgsino pair production, with ISR tag

Benchmark models with

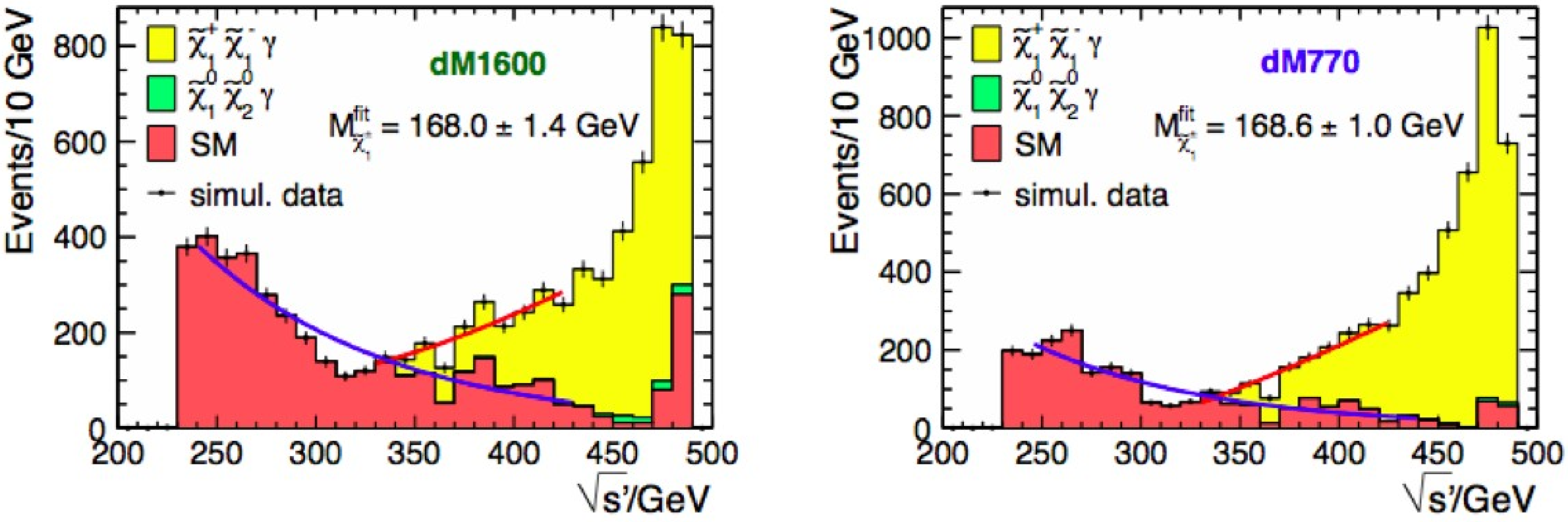
m(NLSP) – M(LSP) = 1.6 GeV and 0.8 GeV

$$\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-) = 78.7\ (77.0)\ \text{fb}$$

$$\Delta M = 1.60\ (0.77)\ \text{GeV}$$



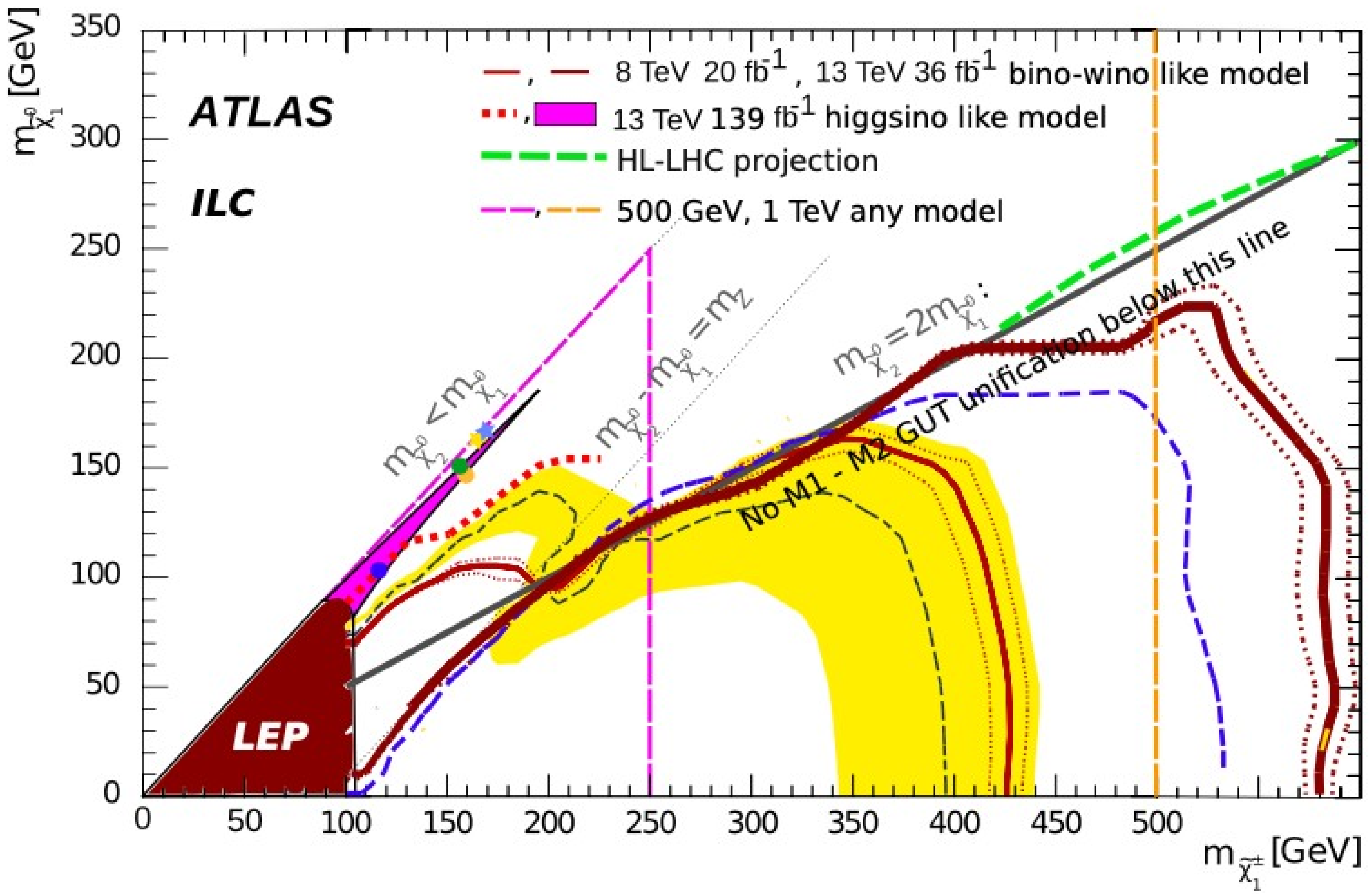
Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert, EPJ C73 (2013) 2660 [arXiv:1307.3566]



$\sqrt{s}$=500 GeV, Lumi=500 fb^{-1}, P(e-,e+)=(-0.8,+0.3) → LSP mass resolution ~1%

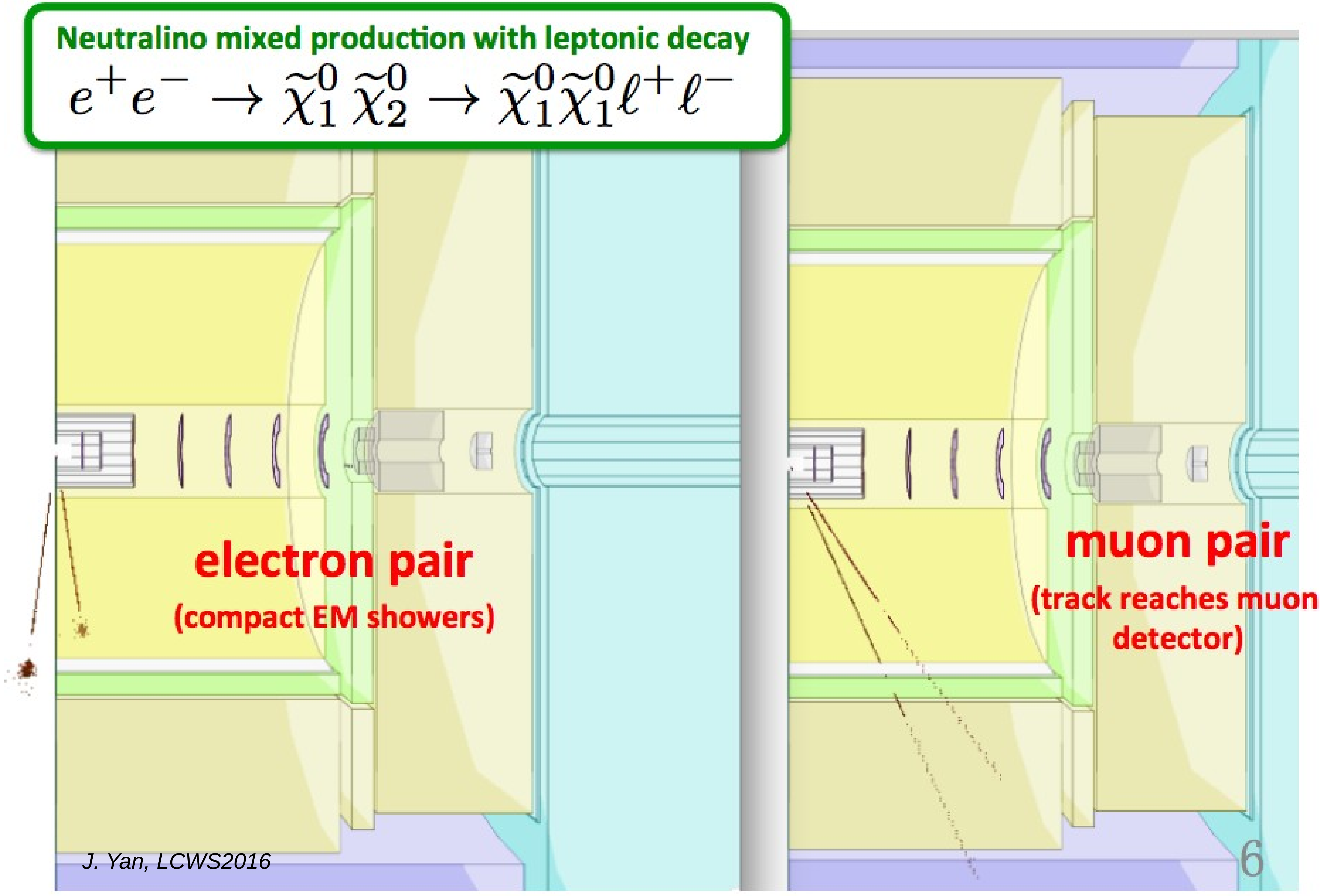
Clear signal => ILC covers important corner of phase space for SUSY Searches

Direct Searches for New Particles - SUSY

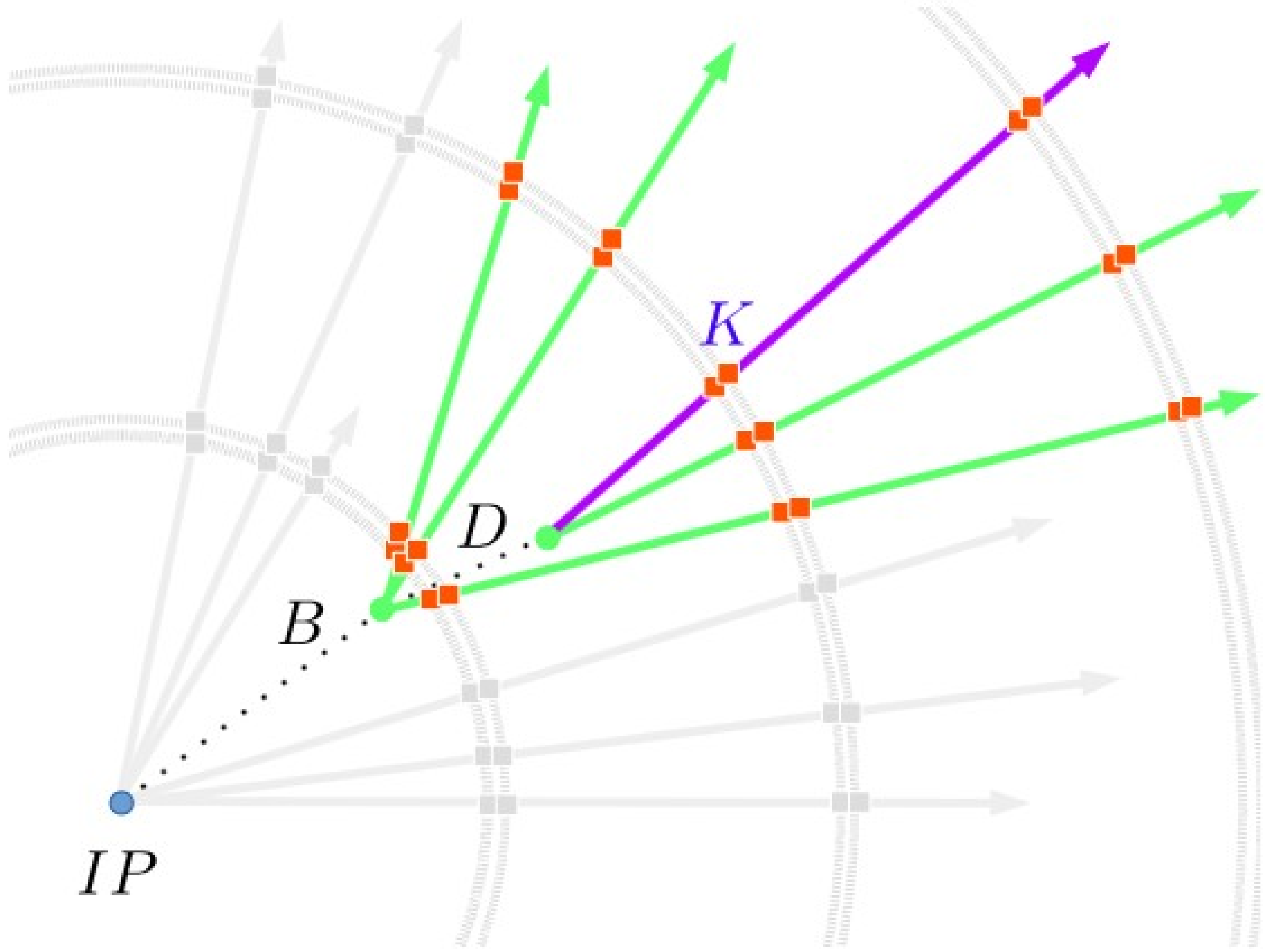


- Hadron Colliders have a great potential to discover supersymmetric particles
- Hadron Colliders cannot exclude low mass SUSY with light neutralinos and charginos
  - … that are degenerated in mass

Light Higgsinons- Event Display



Experimental challenges - Flavor tagging and charge measurement



PhD thesis: S. Bilokin
A. Irles

- Flavor tagging
  - Indispensable for analyses with final state quarks
- Quark charge measurement
  - Important for top quark studies,
  - indispensable for ee->bb, cc, ss, ...
- Control of migrations:
  - Correct measurement of vertex charge
  - Kaon identification by dE/dx (and more)
- Future detectors can base the entire measurements on double Tagging and vertex charge
  - LEP/SLC had to include single tags and Semi-leptonic events

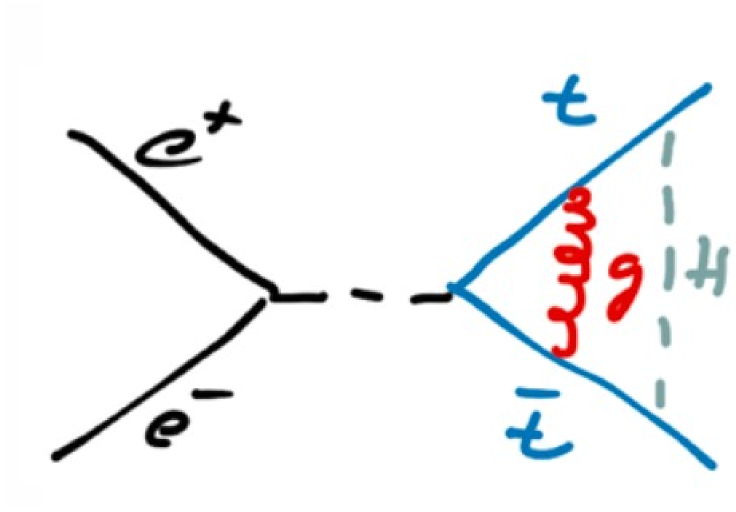
52

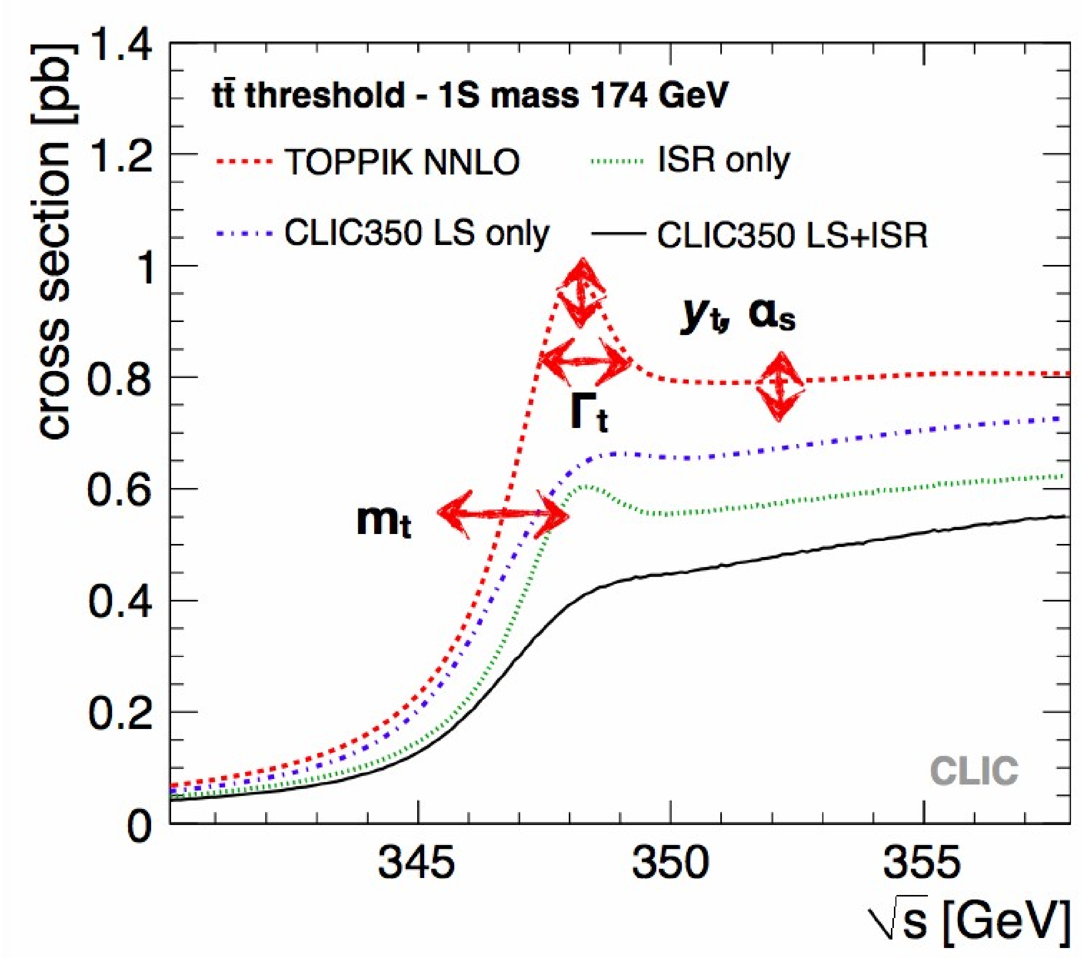
Top pair production at threshold

Small size of ttbar “bound state” at threshold ideal premise for precision physics

Cross section around threshold is affected by several properties of the top quark and by QCD

- Top mass, width Yukawa coupling
- Strong coupling constant

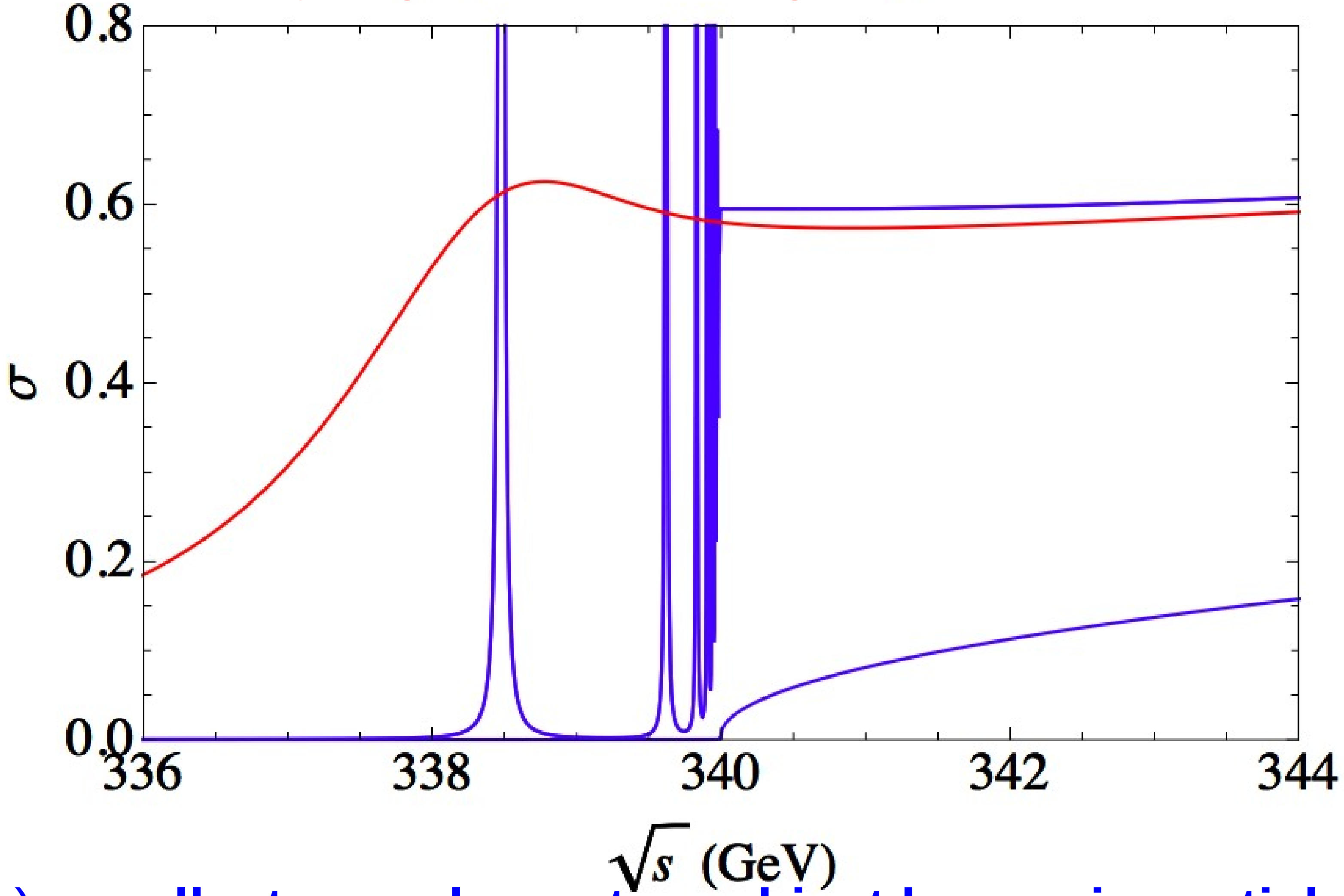




- Effects of some parameters are correlated:
- Dependence on Yukawa coupling rather weak,
- Precise external α_s helps

"Bound states" at $t\bar{t}$ threshold

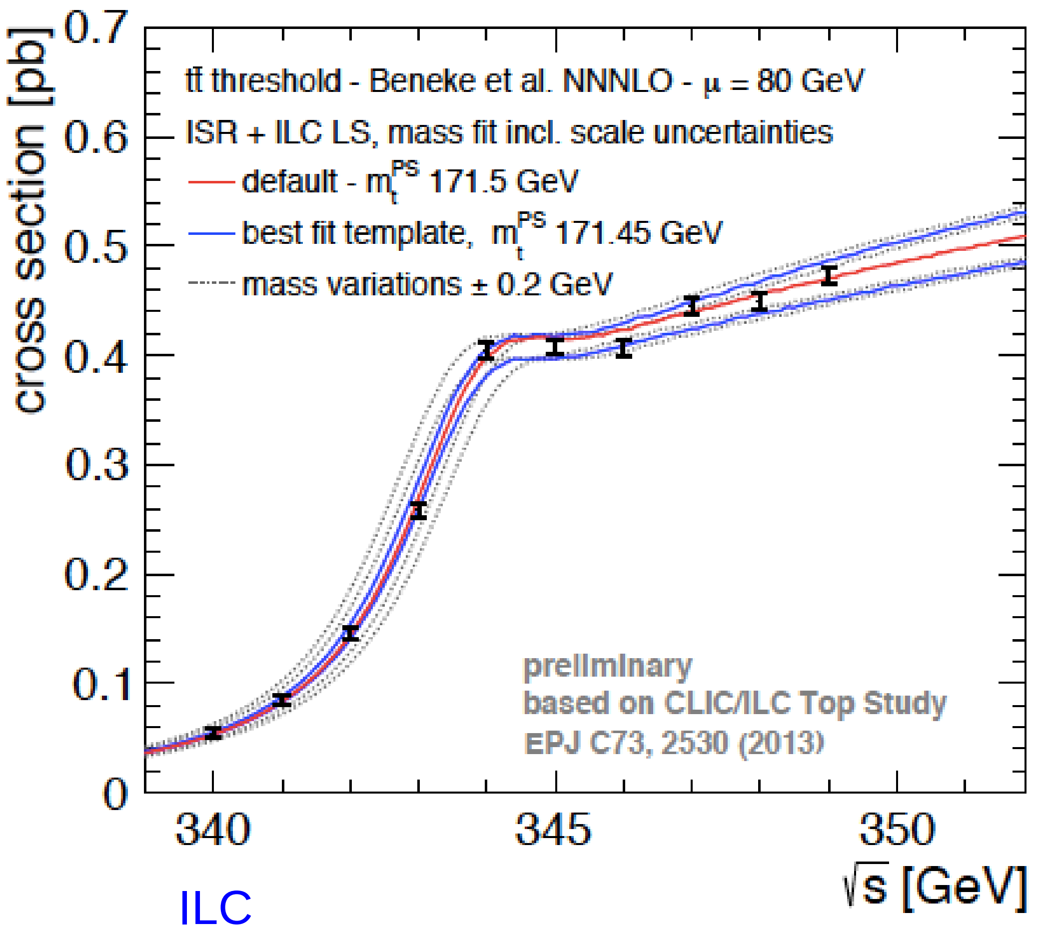
Hydrogen atom of strong interaction



- Size O(10^{-17}m), **smallest non-elementary object known in particle physics**
  Small scale => Free of confinement effects => Ideal premise for precision calculations
  Measurement of (a hypothetical) 1^3S_1 State

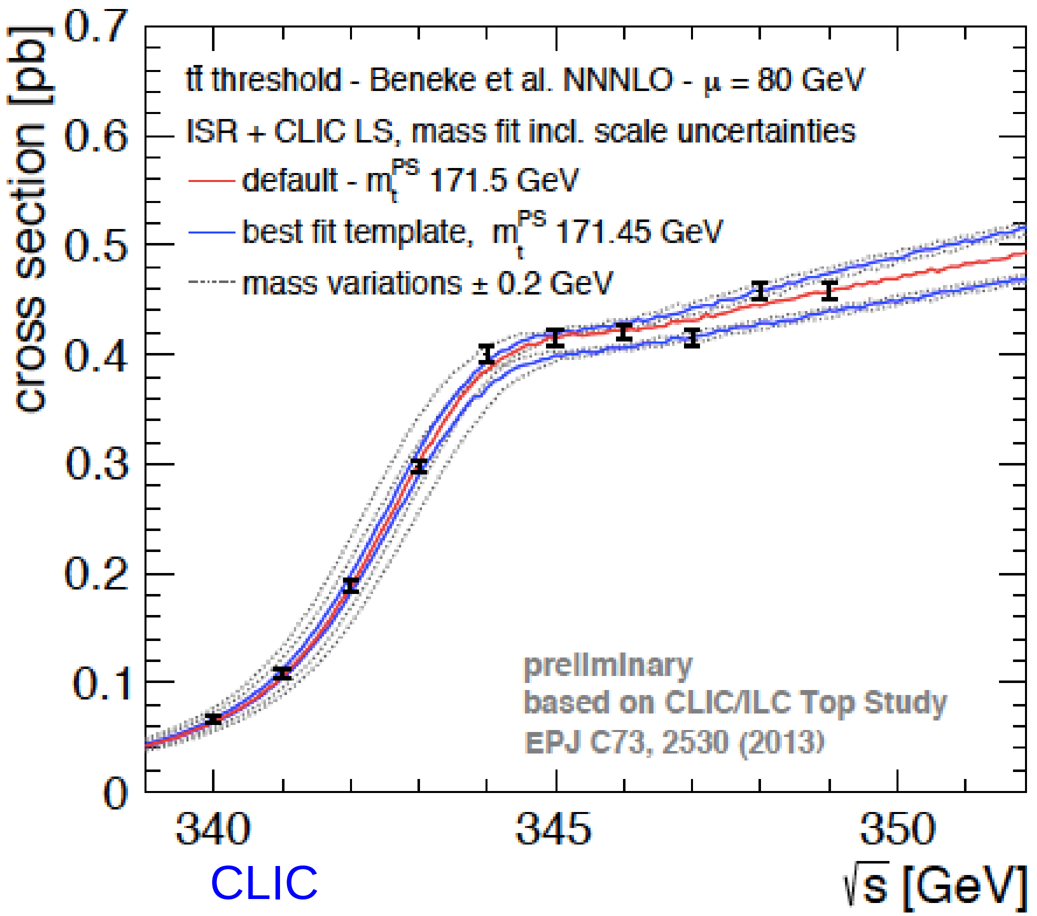
- Decay of top quark smears out resonances in a well defined way

Top threshold scans at different e+e- colliders



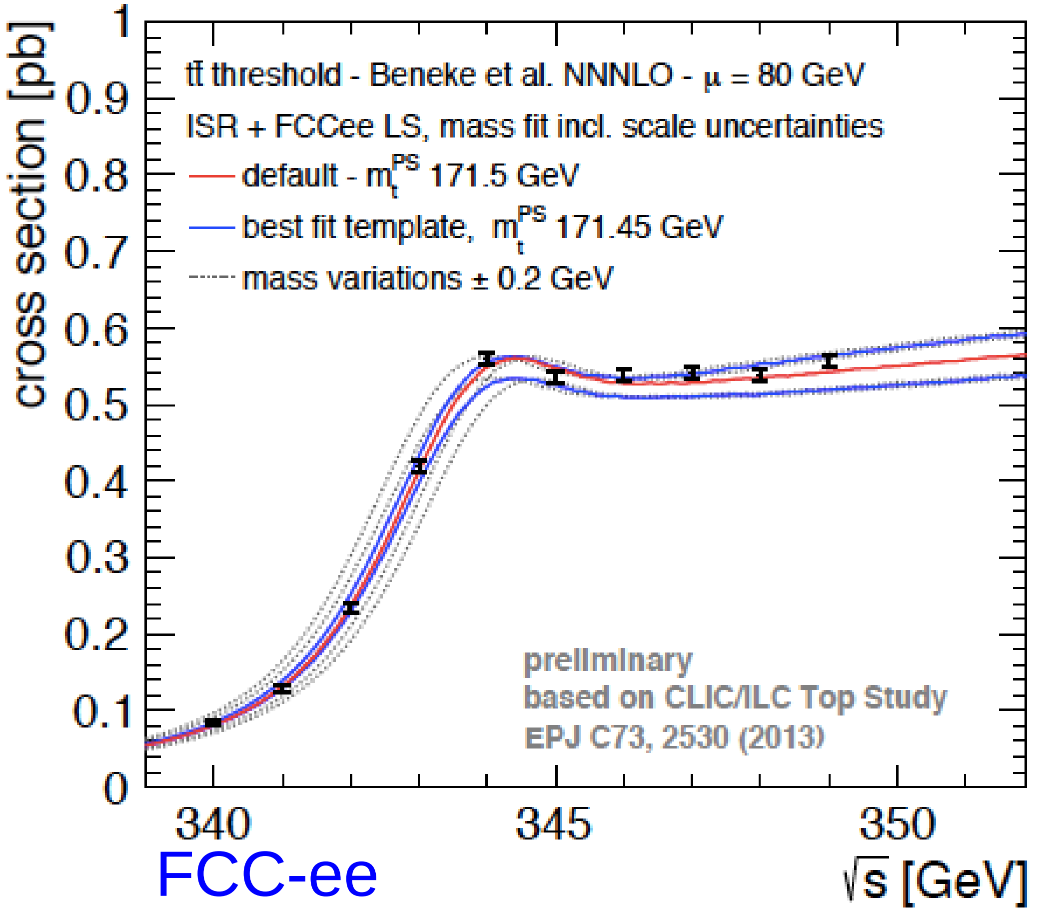
ILC

Fit uncertainty:
28.5 MeV (18 MeV stat)



CLIC

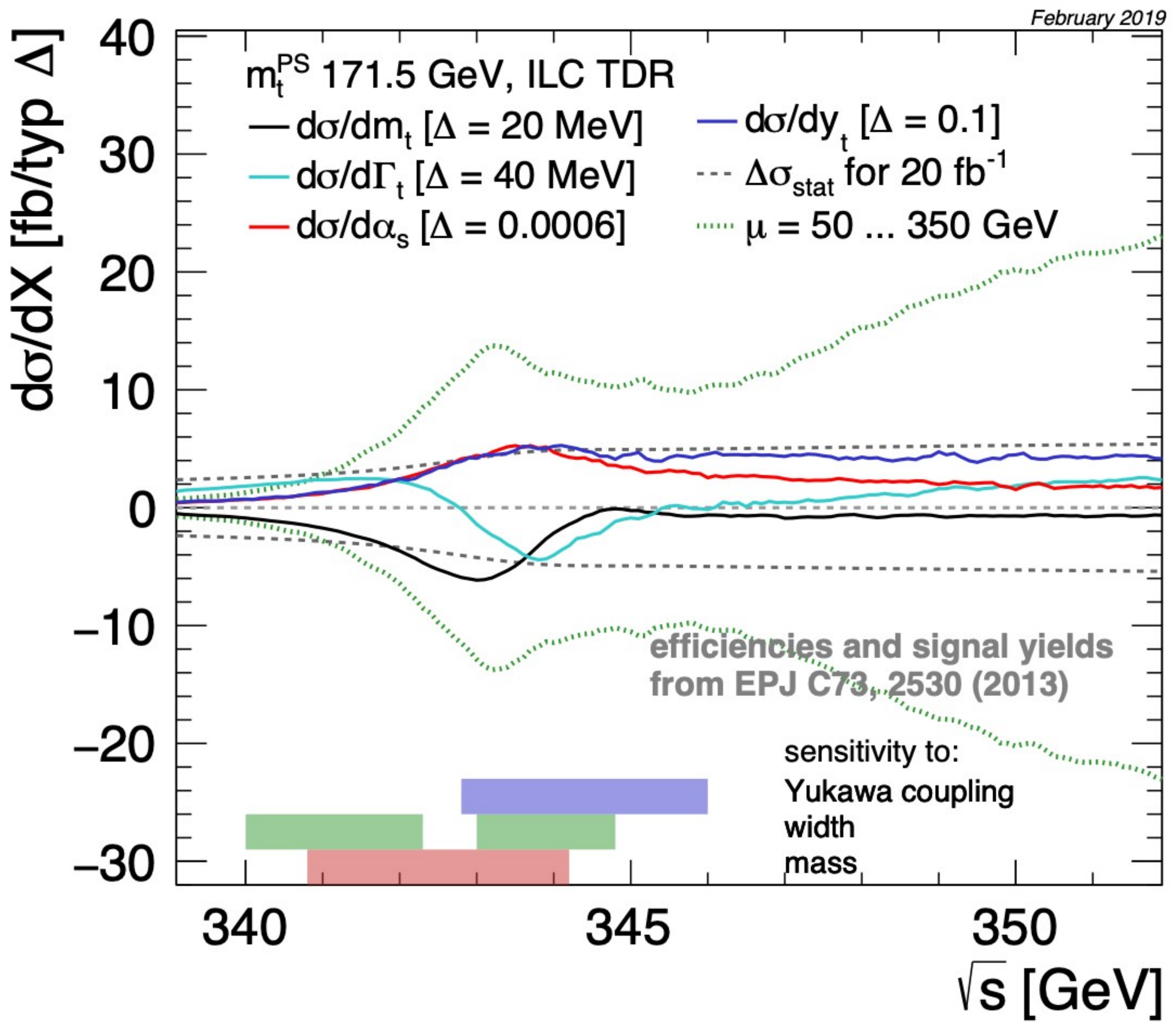
Fit uncertainty:
31 MeV (21 MeV stat)



FCC-ee

Fit uncertainty:
27 MeV (15 MeV stat)

Sensitivity and error breakdown

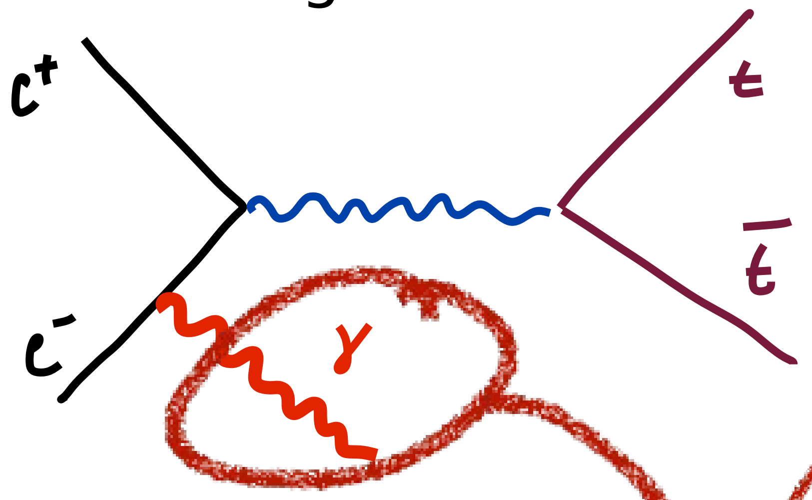


error source	Δm_t^{PS} [MeV]
stat. error (200 fb^{-1})	13
theory (NNNLO scale variations, PS scheme)	40
parametric (α_s, current WA)	35
non-resonant contributions (such as single top)	< 40
residual background / selection efficiency	10 – 20
luminosity spectrum uncertainty	< 10
beam energy uncertainty	< 17
combined theory & parametric	30 – 50
combined experimental & backgrounds	25 - 50
total (stat. + syst.)	40 – 75

- Numbers for ILC/CLIC, some numbers get better for FCCee
  - e.g. Beam energy uncertainty < 3 [MeV]
- Uncertainty driver α_s
  - $\Delta m \sim 2.6$ per 10^{-4} in α_s

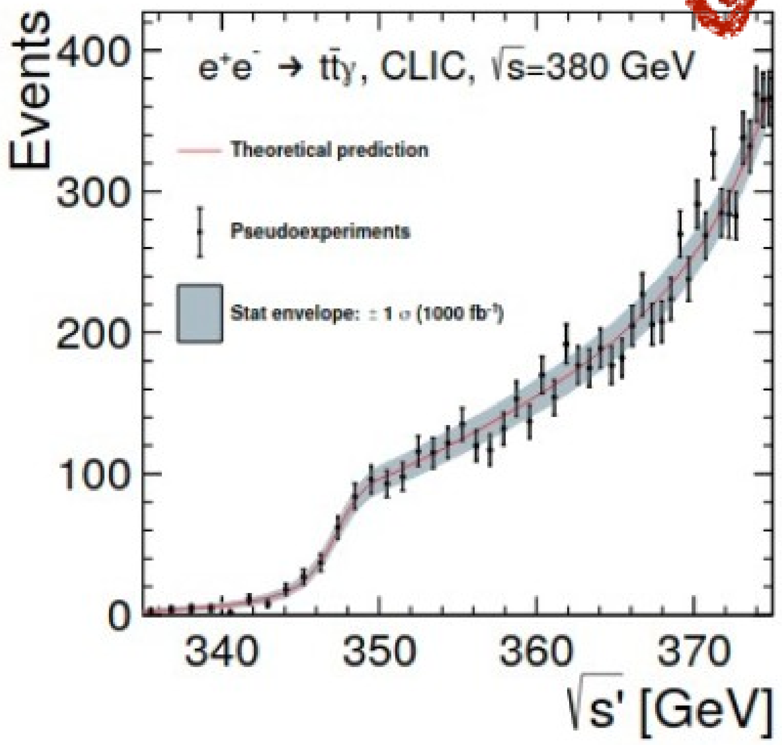
Running top mass

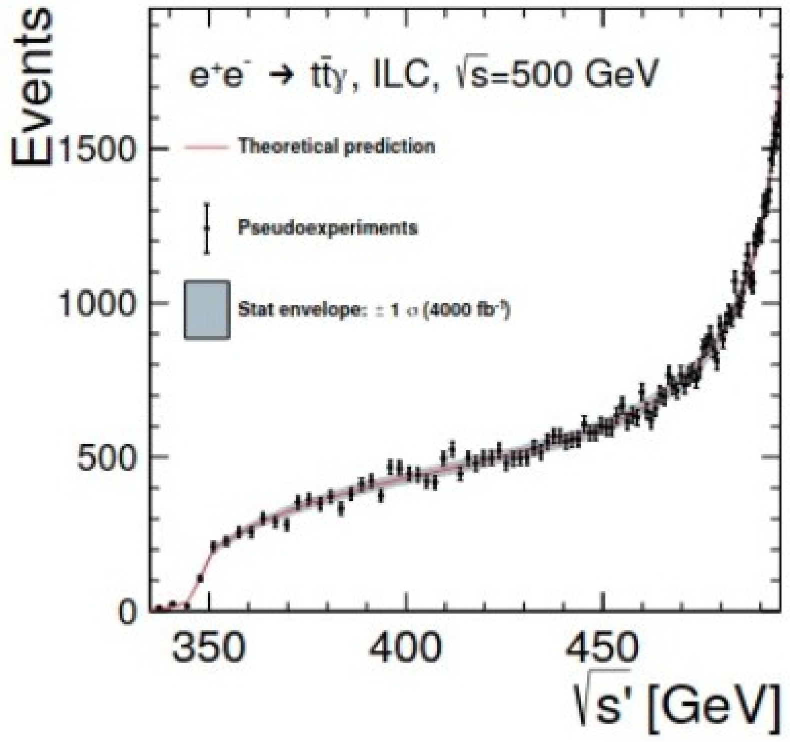
- A new(er) idea to measure the top mass in a theoretically well-defined scheme in high-energy running above the threshold



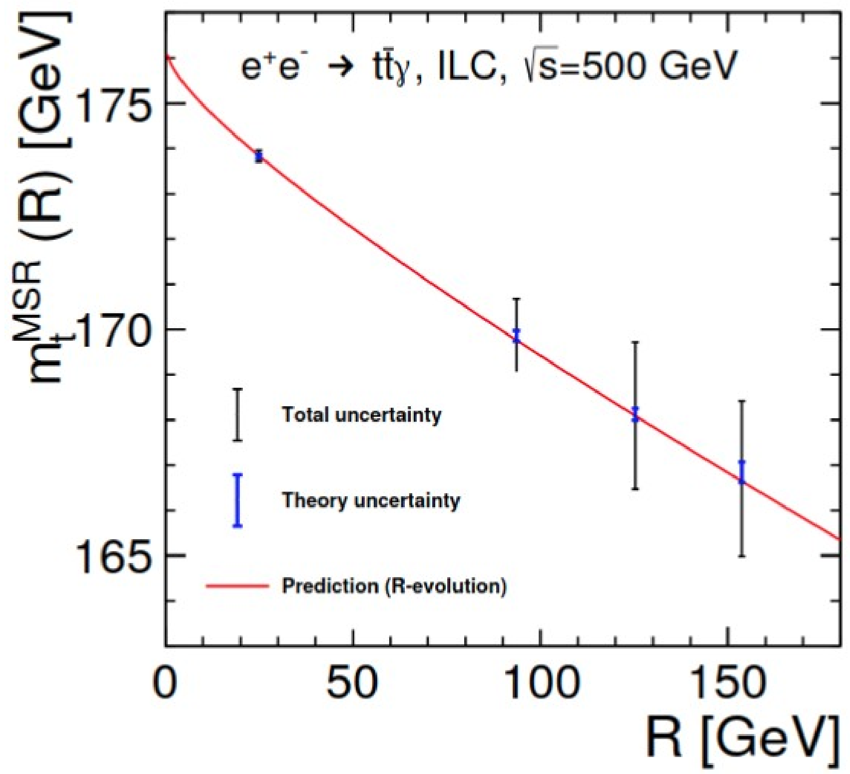
cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV

matched NNLO + NNLL calculation, luminosity spectrum folded in explicitly;
Extraction of short distance MSR mass

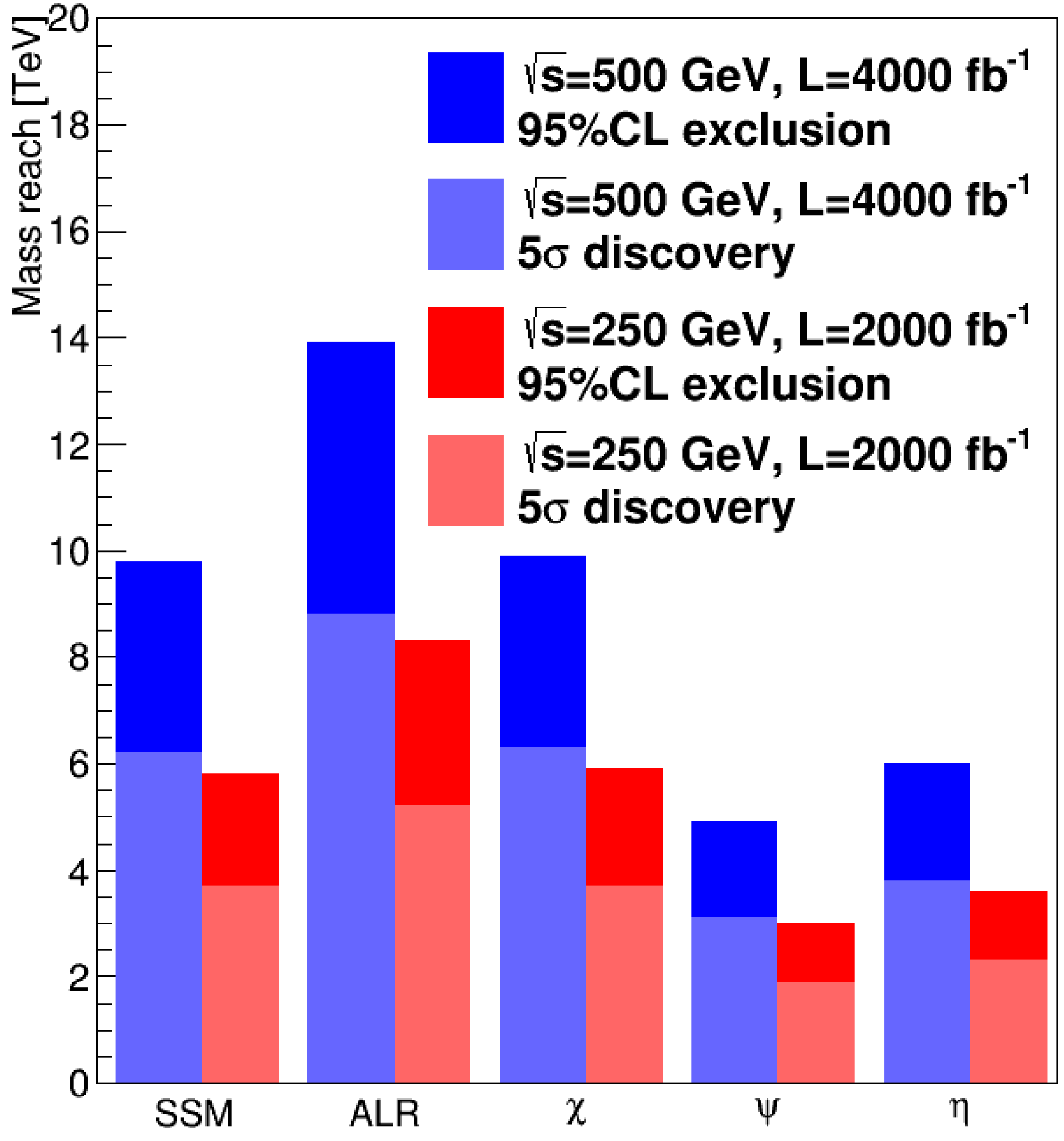




can provide 5σ evidence for scale evolution (“running”) of the top quark MSR mass from ILC500 data alone



Mass reach for vector new bosons (Z') in 2-fermion production



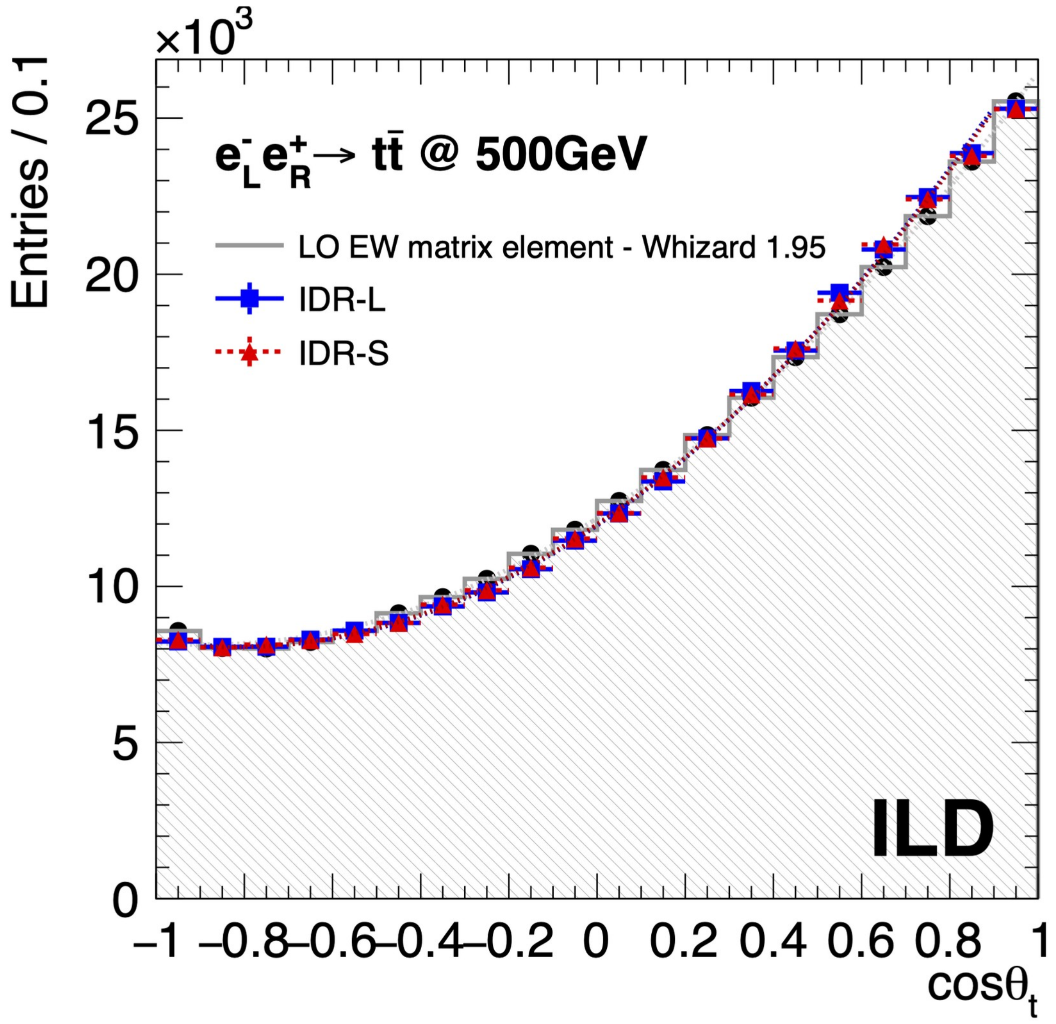
Study by Kyushu group and KEK group within TYL/FJPPL HEP01 Project

- SSM is “carbon” copy of SM Z and used as common metric in generic Z' searches
- ALR introduces an “ad hoc” $SU(2)_R$ and a Z' with orthogonal couplngs to the fermions
- X, ψ, η are linear combinations of bosons appearing in Grand Unified Theories with couplings orthogonal to the SM

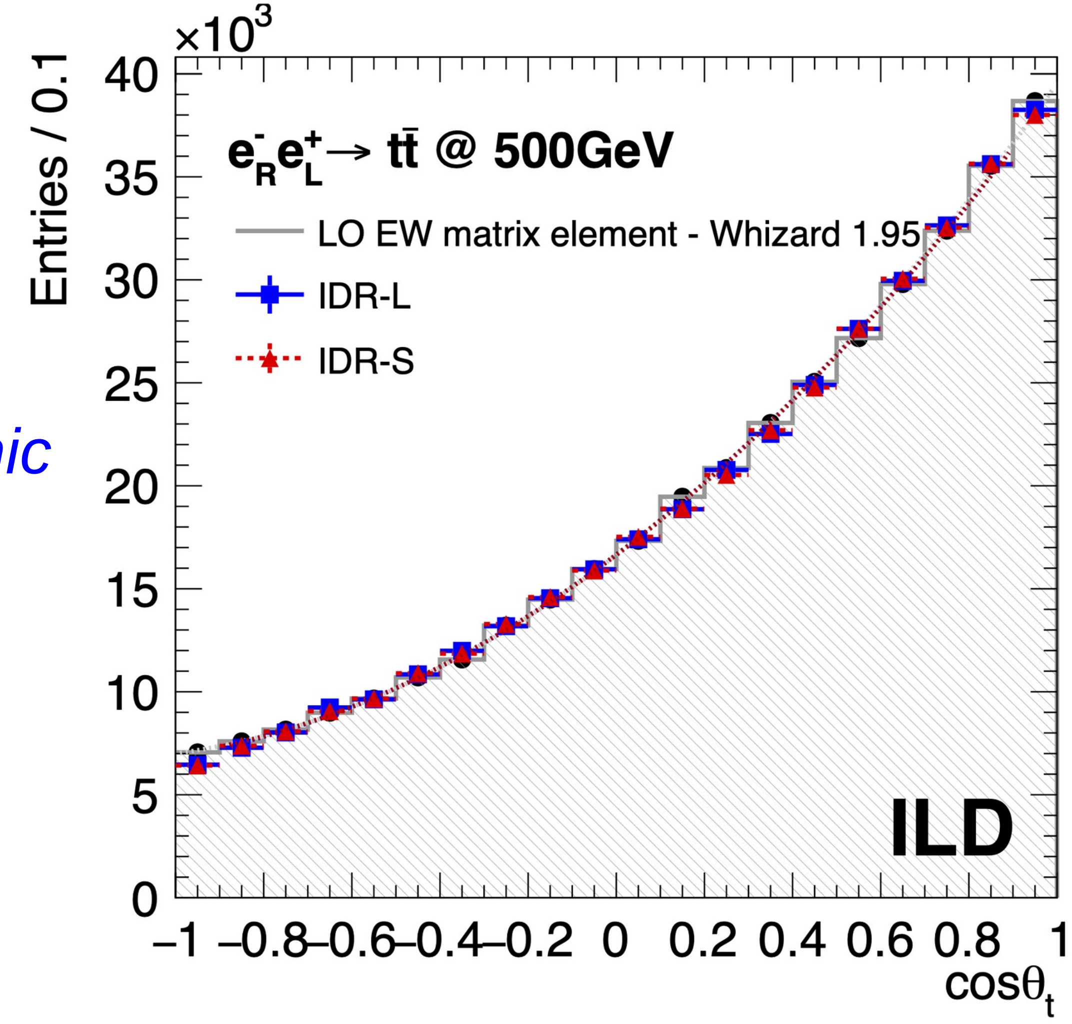
Typical mass reach 5-10 TeV

- Reach shown for e, μ, τ
- Adding quarks would improve limits

Top quark polar angle spectrum at 500 GeV



Semi-leptonic channel



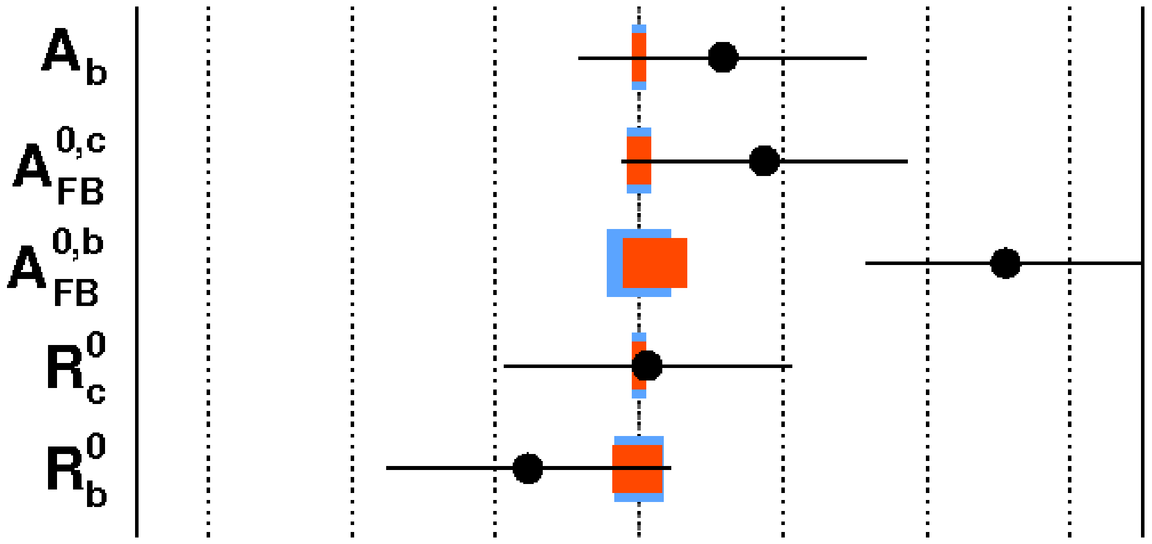
ILD-Note-2019-007

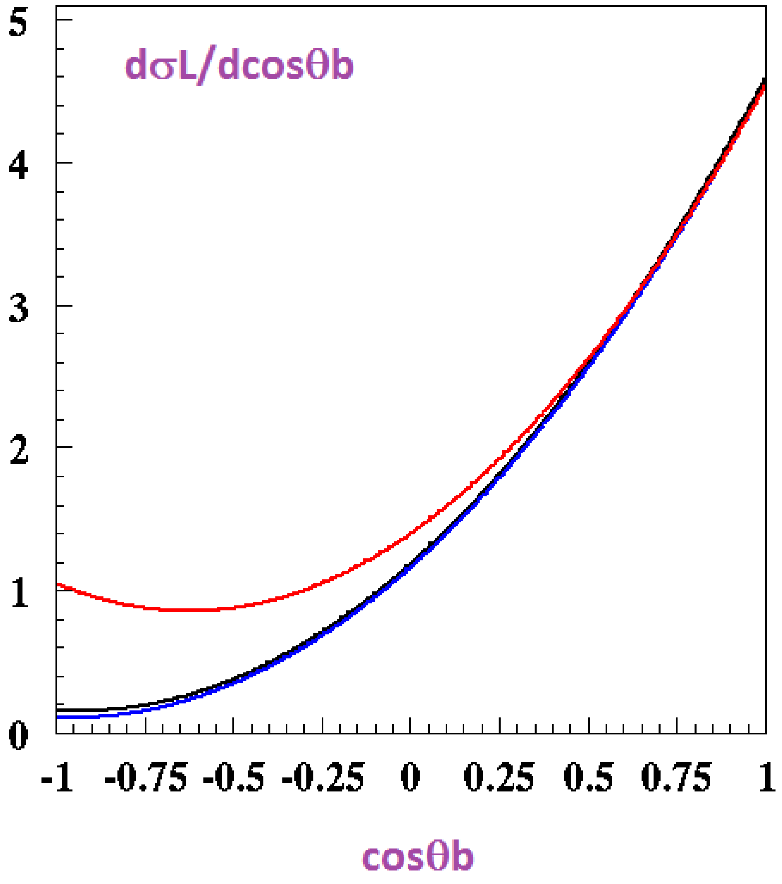
- Integrated Luminosity 4 fb^{-1}
- Exact reproduction of generated spectra
- Statistical precision on cross section: ~0.1%
- Statistical precision on A_{FB}: ~0.5%
  - Can expect that systematic errors will match statistical precision (but needs to be shown)

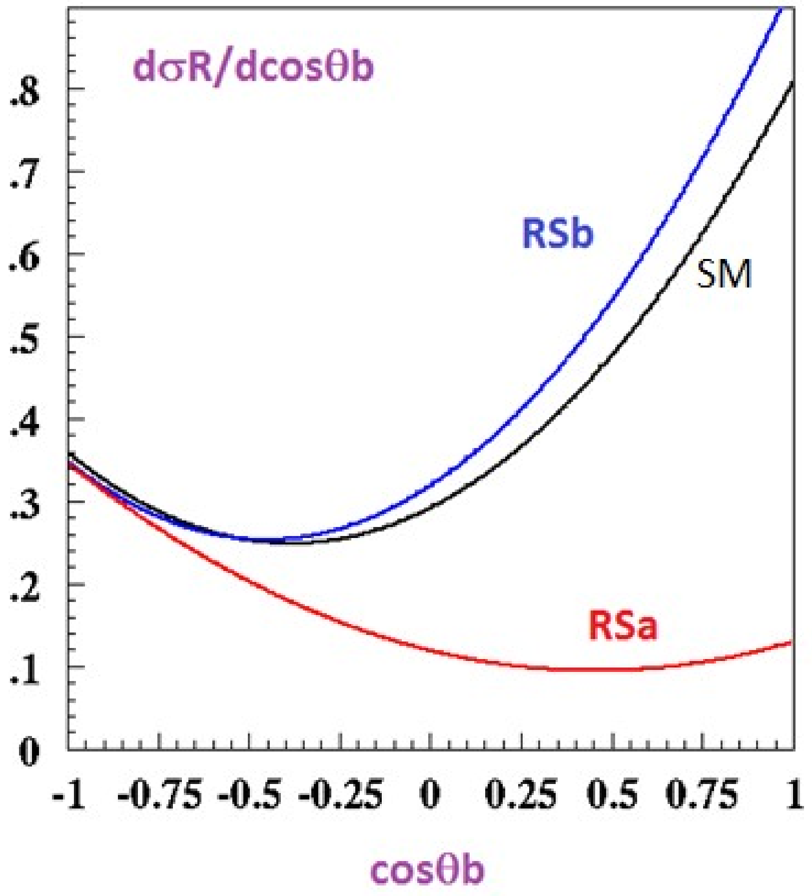
New physics below tt threshold? - Example b quark couplings

~3σ in heavy quark observable A^{b}_{FB}

ee->bb@250 GeV





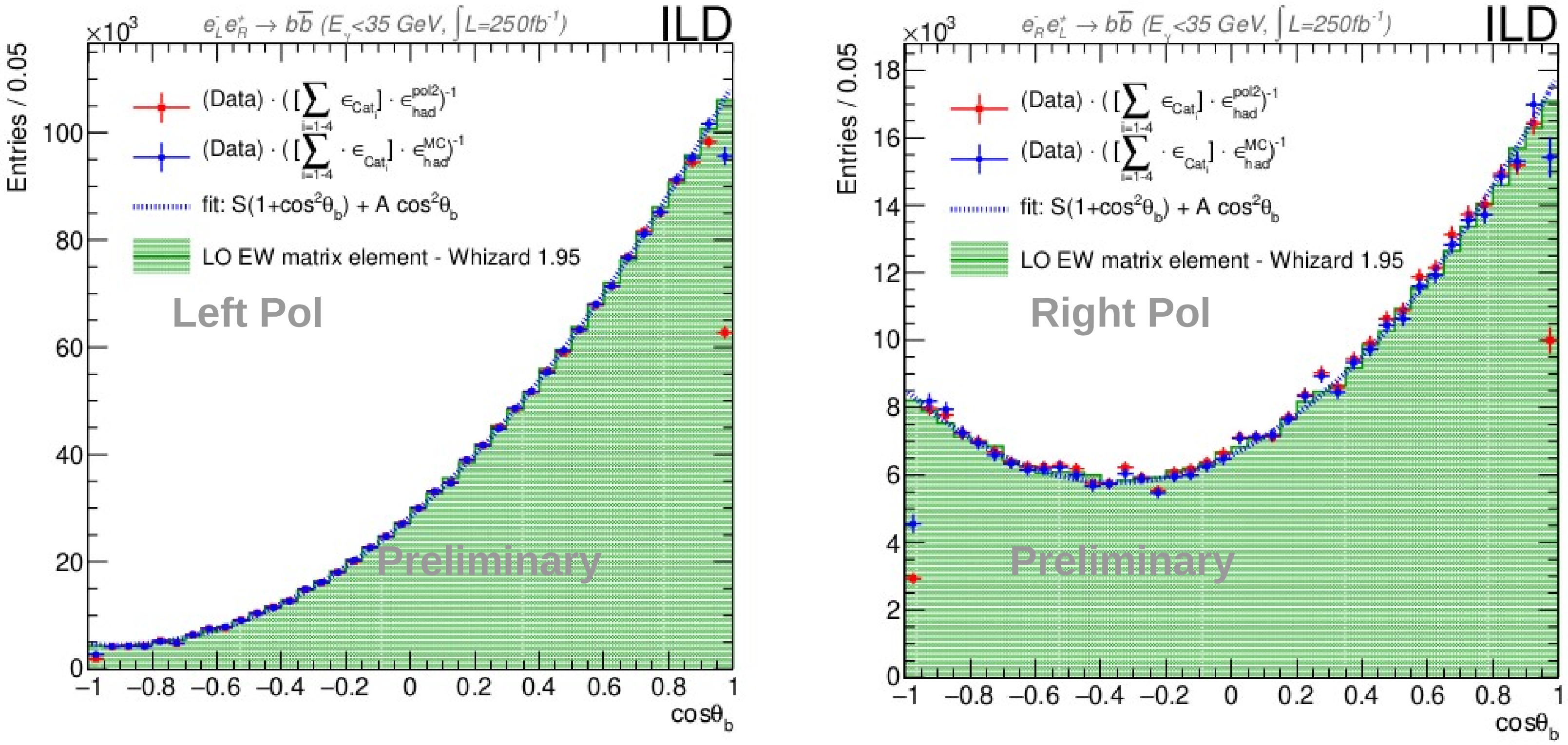


Randall Sundrum Models Djouadi/Richard '06

- Is tension due to underestimation of errors or due to new physics?
- High precision e+e- collider will give final word on anomaly
- In case it will persist polarised beams will allow for discrimination between effects on left and right handed couplings
- Randall Sundrum Models generate basically automatically a symmetry group of type $SU(2)_R$

Decomposing ee->bb – Differential cross section

Full simulation study within ILD Concept allows for educated guess on uncertainties on Z-Pole



Arxiv:1709.04289, ILD Paper in progress
A. Irles, SUSY2021

Excellent agreement between predicted and reconstructed distributions

- Gap between red dots and green histogram = acceptance drop.
- Blue dots = corrected acceptance
- The fit is restricted to |costheta|<0.8
  - *Minimal impact of the corrections*

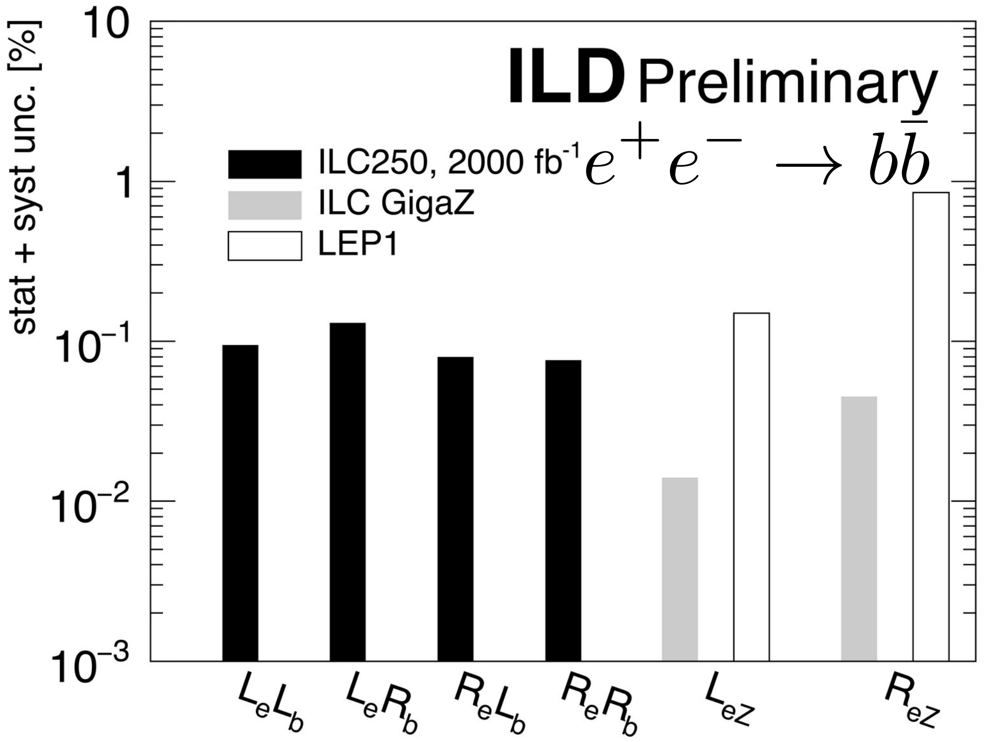
Systematic uncertainties under scrutiny:

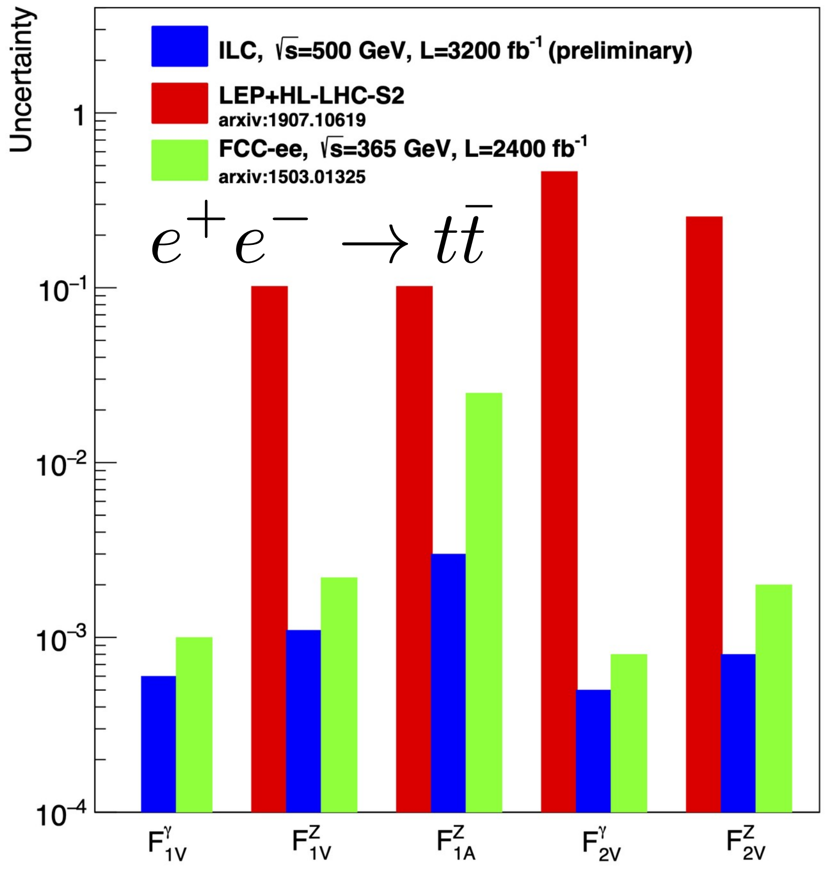
- Selection and background rejection
- quark tagging/mistagging (modelisation, QCD, correlations)
- Luminosity
- Polarisation

Additional complication in continuum: Rejection of ISR events – Uncertainty ~5x10^{-4} (doesn't apply on Z-pole)

Precision on electroweak form factors and couplings

Arxiv:1709.04289, ILD Paper in progress





- Couplings are order of magnitude better than at LEP

$$\mathrm{LeLb} = QeQb + \frac{LeZLbZ}{s^2wc^2w}BWZ + \sum_{Z'}\frac{LeZ'LbZ'}{s^2wc^2w}BWZ'$$

ILC250 SM GigaZ New resonances

- e+e- collider way superior to LHC ($\sqrt{s}$ = 14 TeV)
- Final state analysis at FCCee
  - Also possible at LC => Redundancy
- Two remarks:
  - 500 GeV is nicely away from QCD Matching regime
    - Less systematic uncertainties
  - Axial form factors are ~β and benefit therefore from higher energies

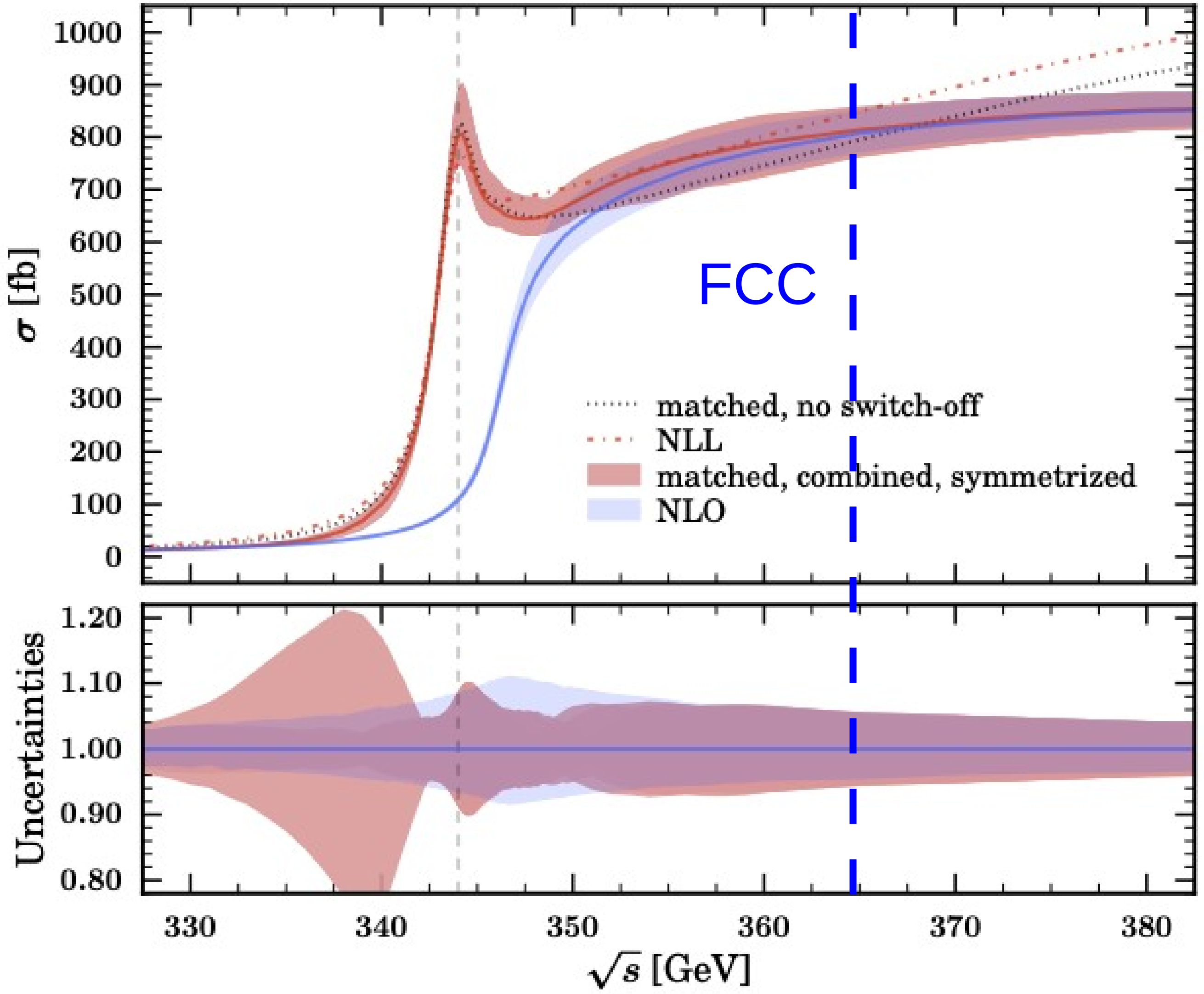
- Full disentangling of helicity structure for all fermions only possible with polarised beams!!

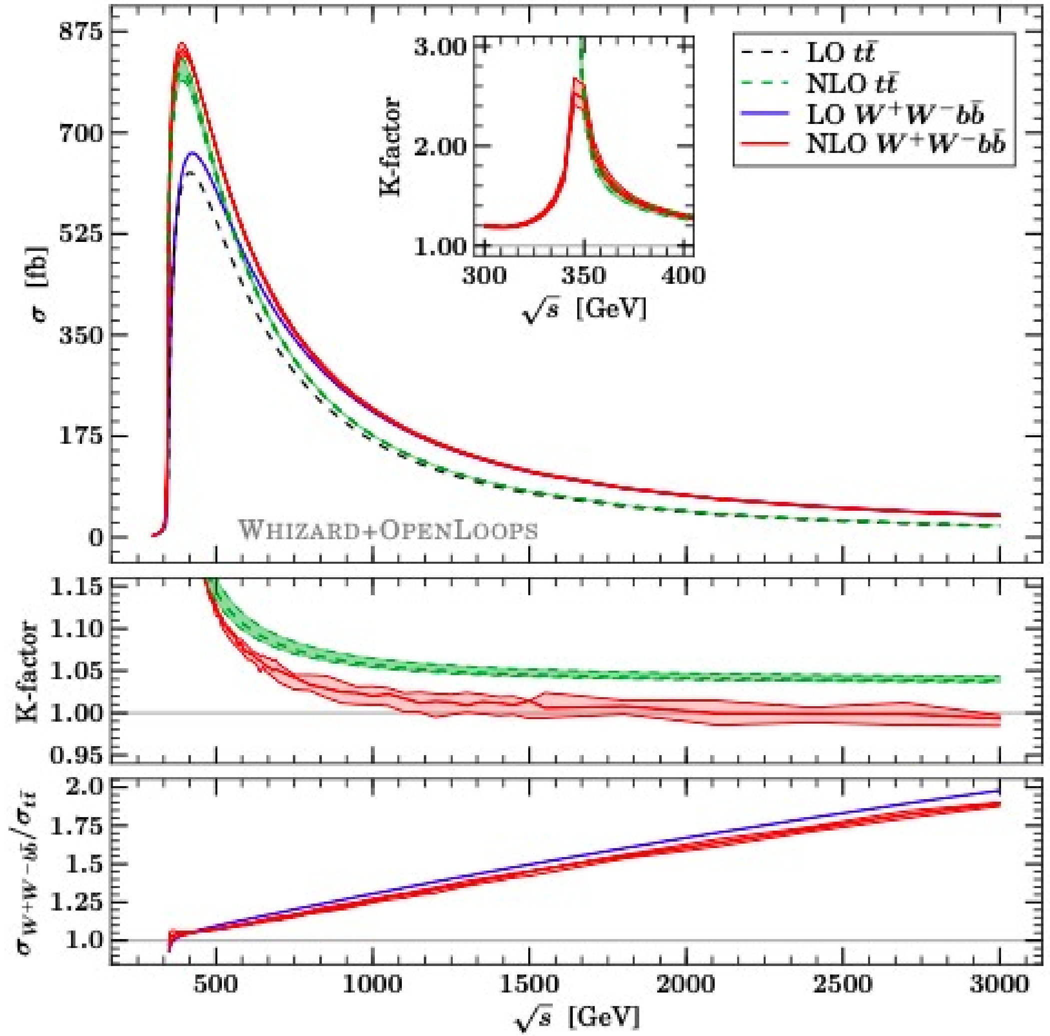
62

QCD uncertainties on ee->tt cross section

Linear Colliders →

$$e^+e^- \to W^+bW^-\bar{b}$$





- Marching non-relativistic calculations in threshold region with tt-continuum is theoretical challenge
- QCD uncertainties shrink as energy increases
- Non resonant contributions are important (i.e. ee->tt --> ee->WbWb)

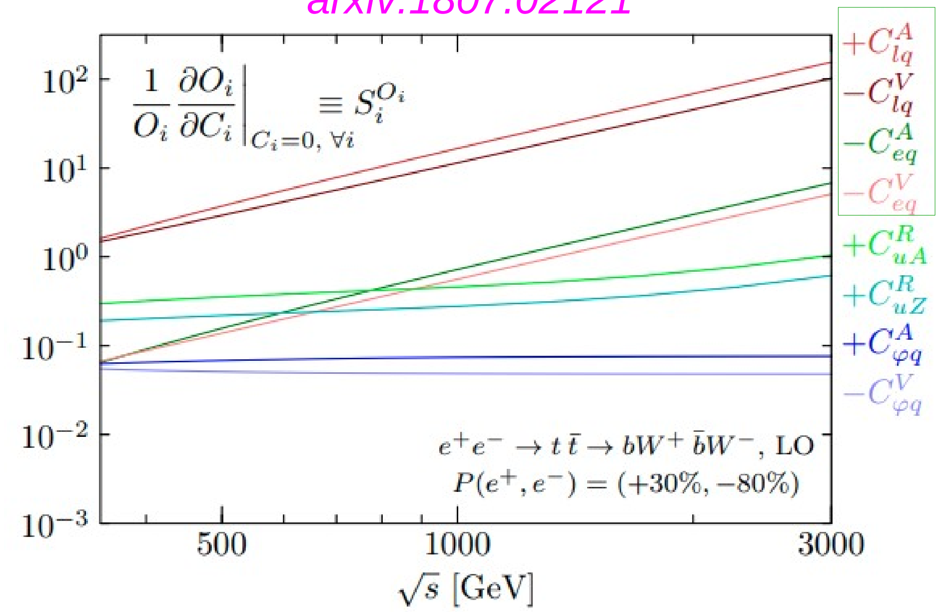
63

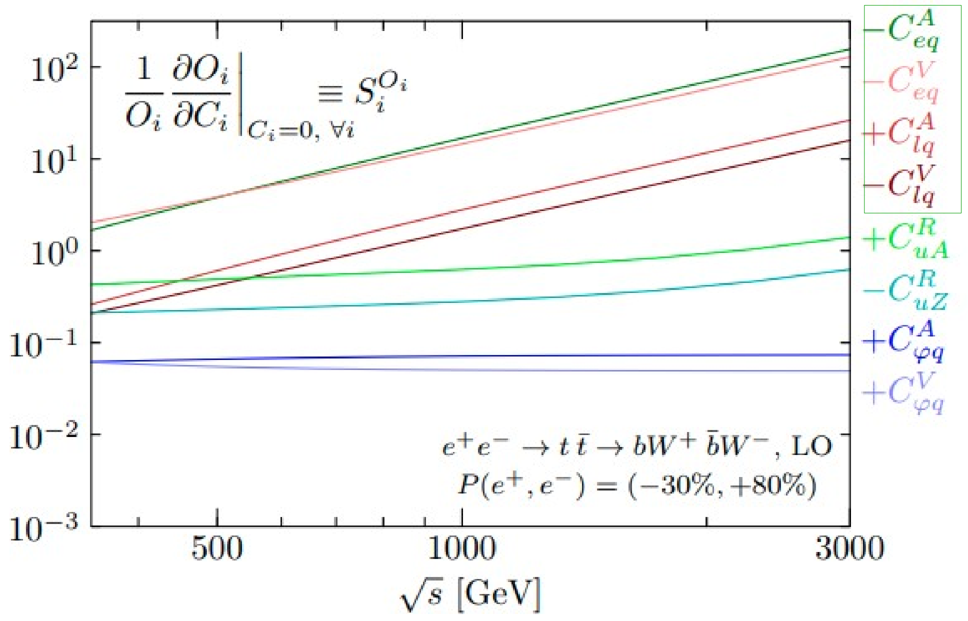
J. Reuter, FCCee-France Workshop, Annecy and arXiv: 1609.03390

Effects at higher energies

Development of EFT Operators

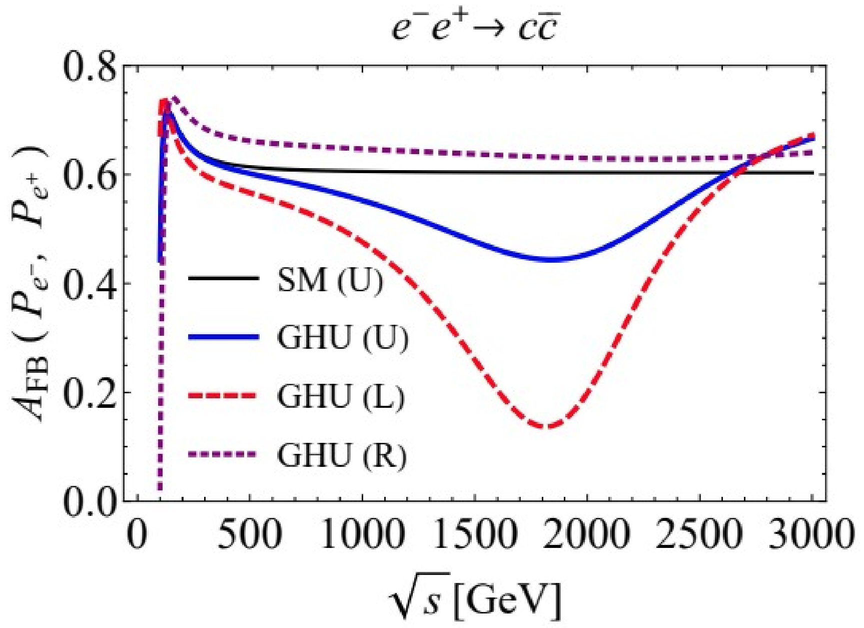
arxiv:1807.02121

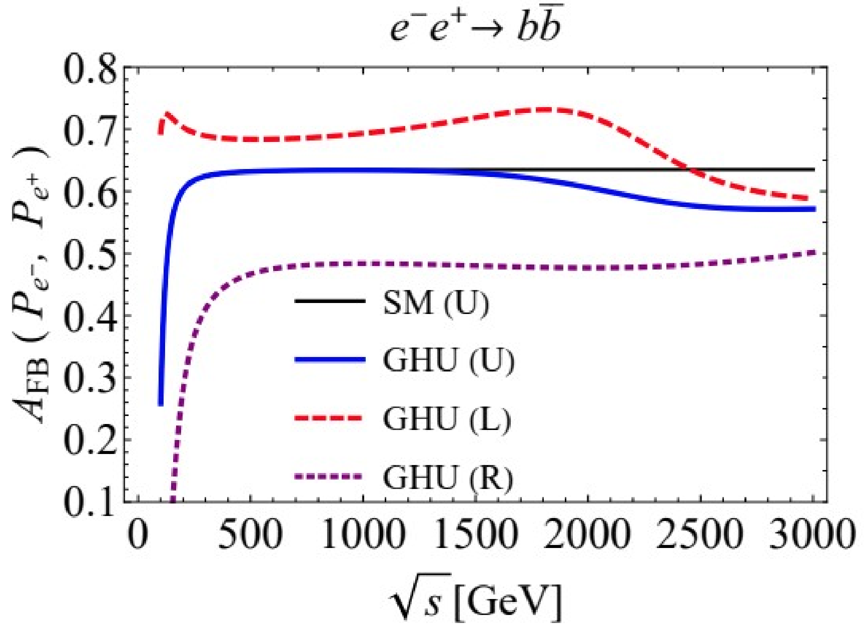


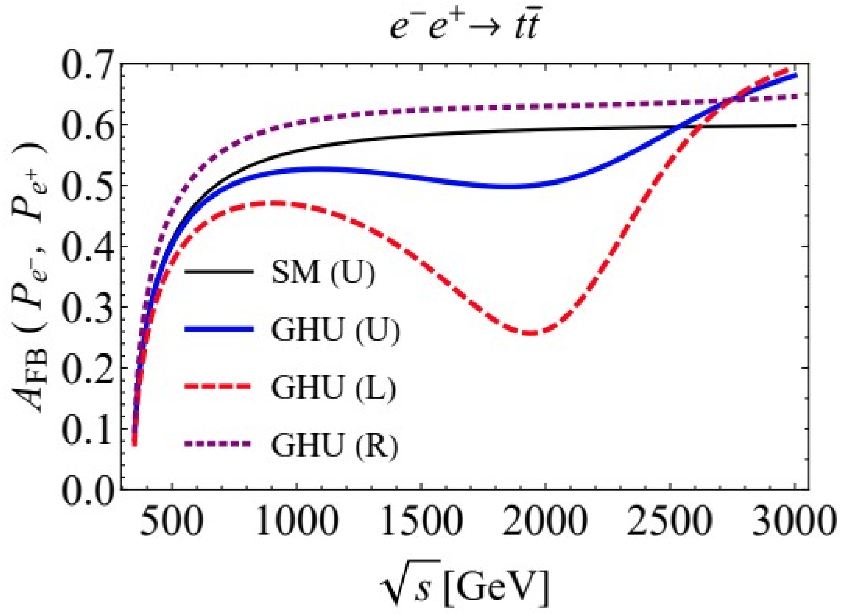


Increased sensitivity to operators representing four-fermion interactions

GUT Inspired GHU Model (Hosotani et al.)





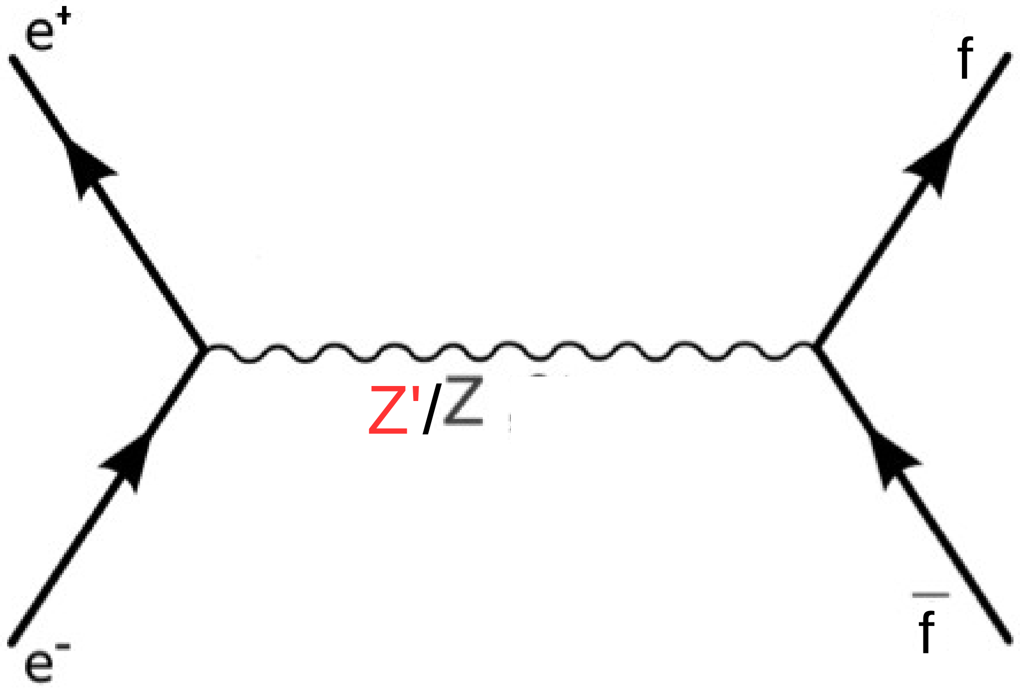


- Effects amplified at higher energies
- Different patterns for different beam polarisations (L, U, R)
- Different patterns for different fermions

64

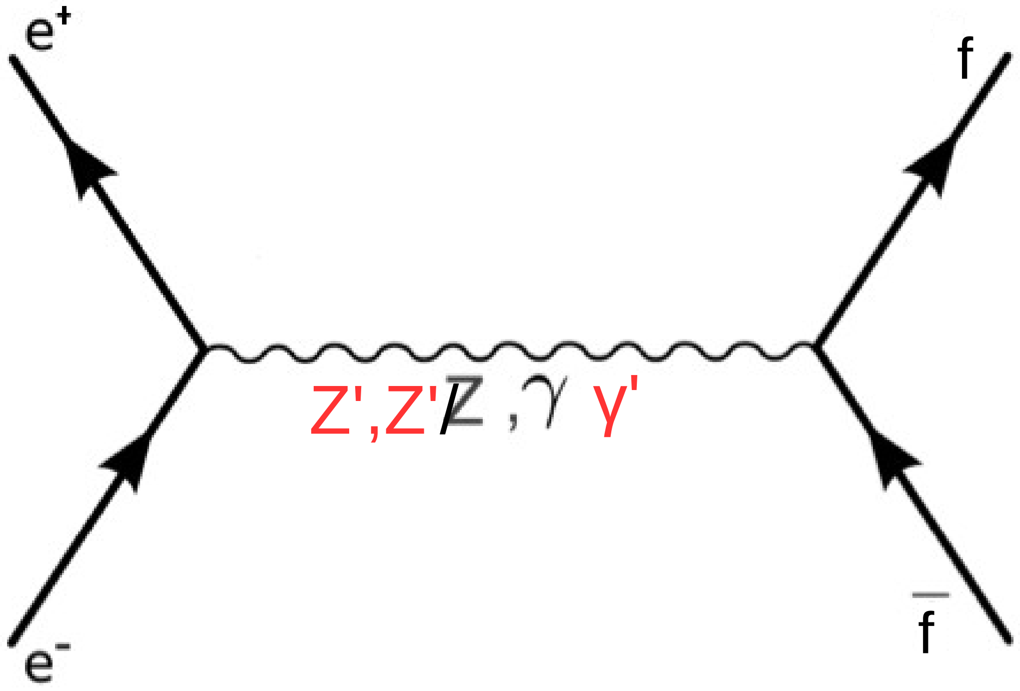
How can the Z-pole help?

On the Z-pole



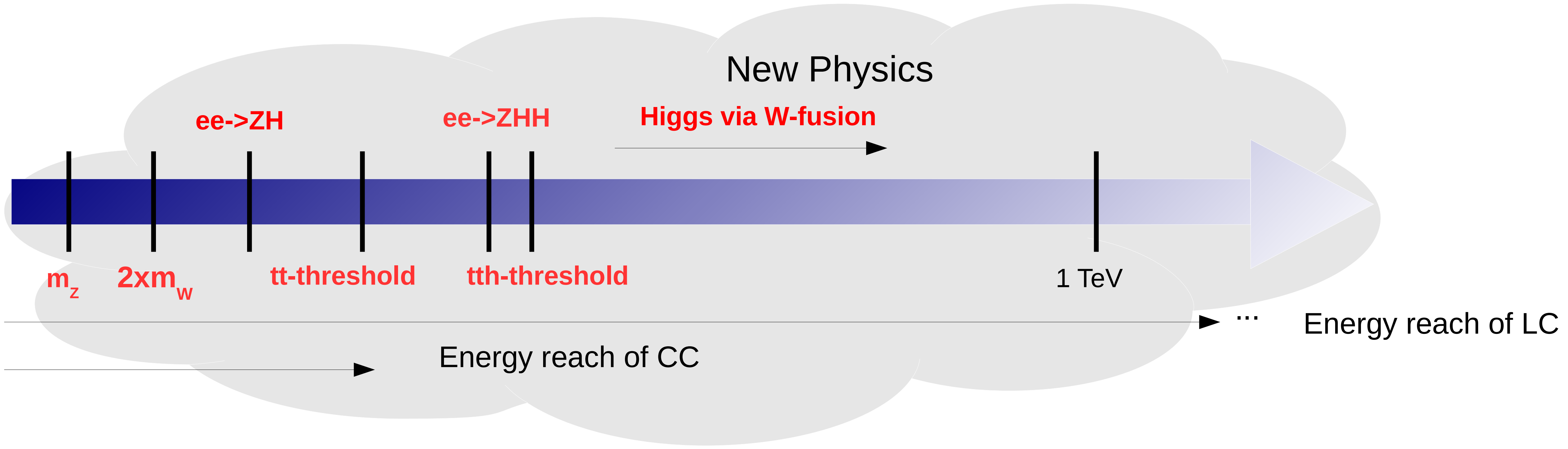
- ILC/GigaZ with ~10^9 Z
- Sensitivity to Z/Z' mixing
- Sensitivity to vector (and tensor) couplings of the Z
  - the photon does not "disturb"

Above the Z-pole



- Sensitivity to interference effects of Z and photon!!
- Measured couplings of photon and Z can be influenced by new physics effects
- Interpretation of result is greatly supported by precise input from Z pole

e+e- Physics program

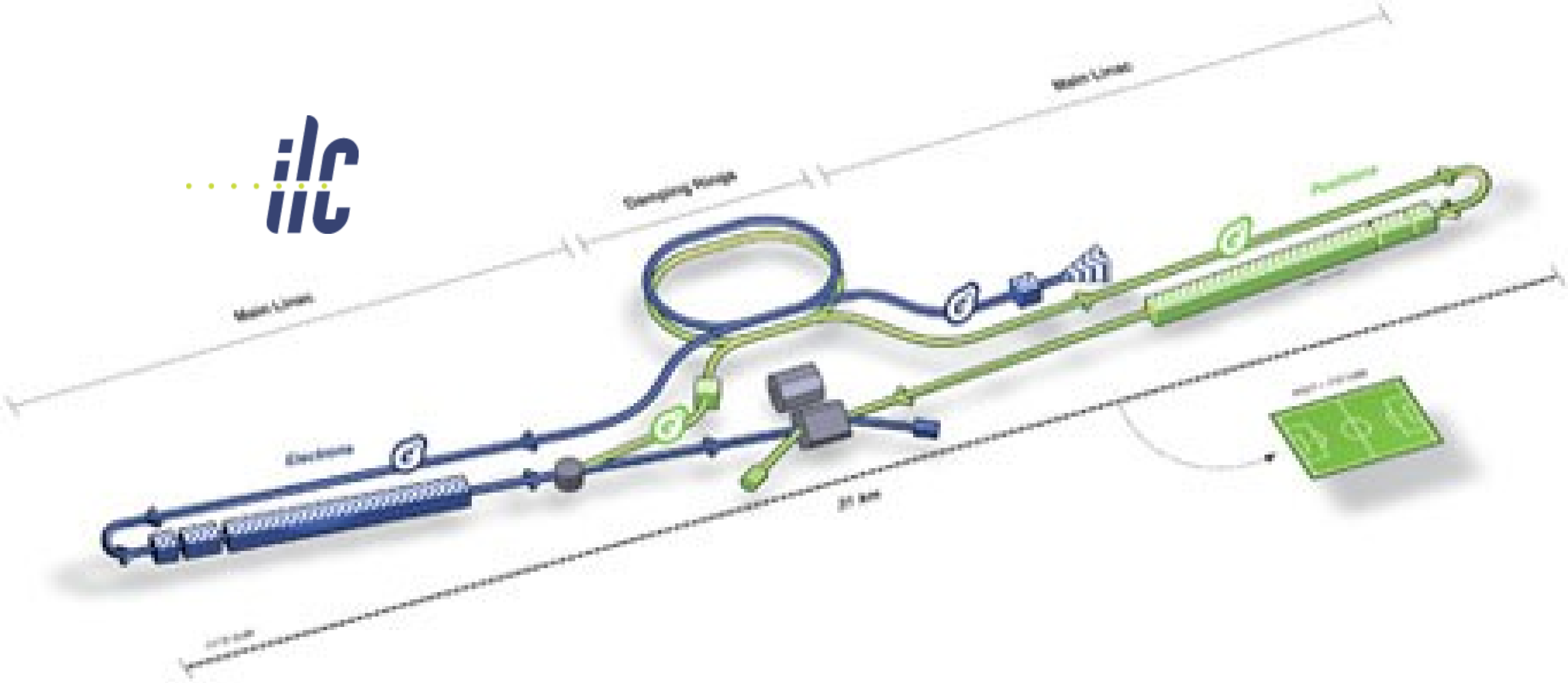


- All Standard Model particles within reach of planned e+e- colliders
- High precision tests of Standard Model over wide range to detect onset of New Physics
- Machine settings can be “tailored” for specific processes
  - Centre-of-Mass energy
  - Beam polarisation (straightforward at linear colliders)

$$\sigma_{P,P'} = \frac{1}{4}\left[(1 - PP')(\sigma_{LR} + \sigma_{RL}) + (P - P')(\sigma_{RL} - \sigma_{LR})\right]$$

- **Background free** searches for BSM through beam polarisation

Linear Electron Positron Colliders - ILC



Energy: 0.1 - 1 TeV
Electron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Footprint 31 km

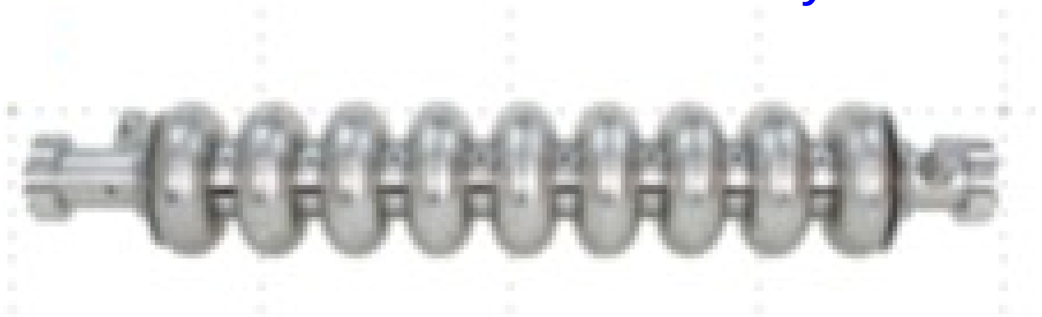
Initial Energy 250 GeV – Footprint ~20km

Under discussion in Japanese Gouvernment and inernational community
Recently: Budget request by Japanese Government of for ILC related accelerator studies (10 Oku Yen = doubling of budget)

ILC design parameters	
$\sqrt{s}$	91-500 GeV
$\mathcal{L}$	2×10^{34} cm^{-2}s^{-1}
P_{e-}	>80%
P_{e+}	upto 30%
Length	~31 km

Design Gradient: 31,5 MV/m

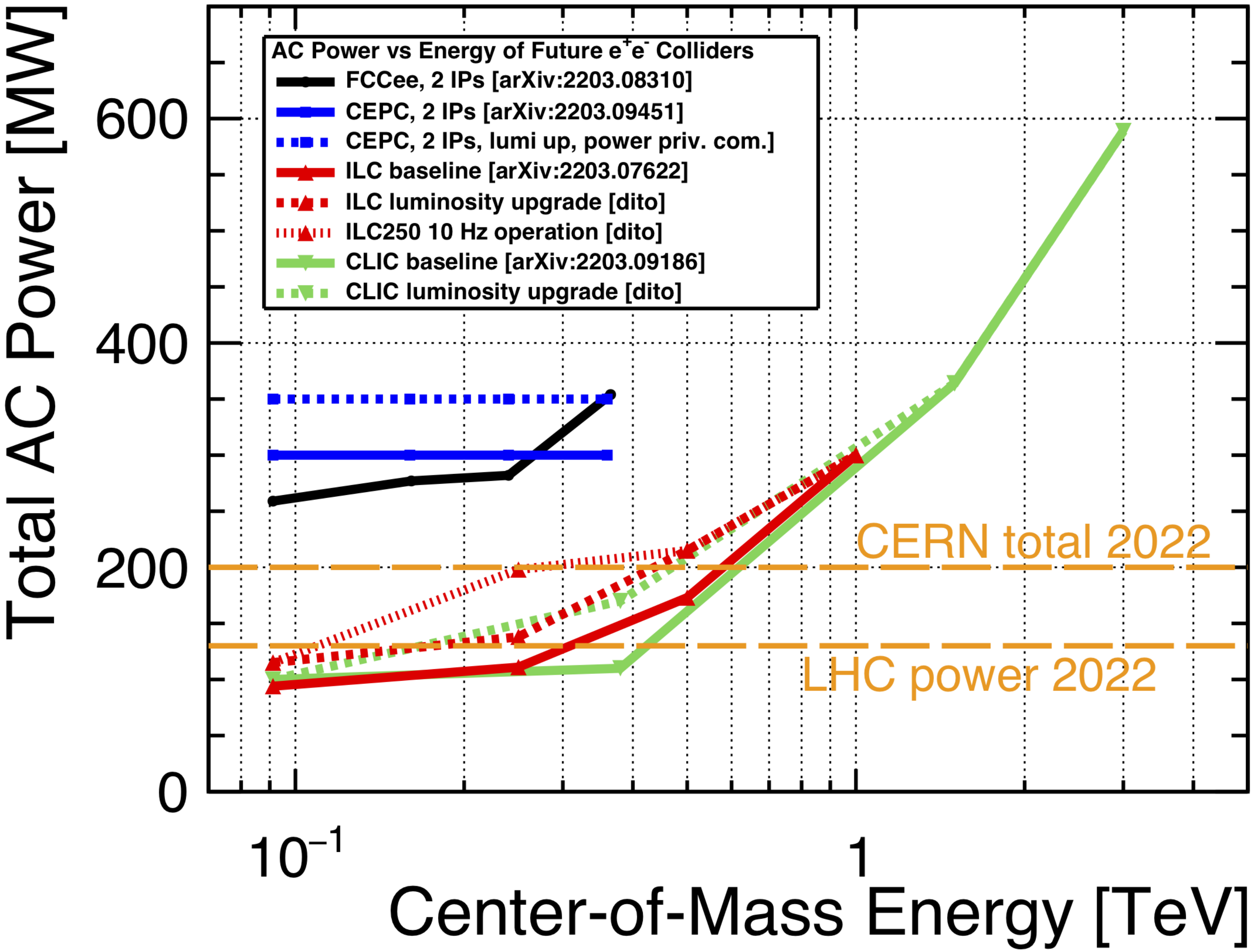
ILC Nine-Cell SRF Cavity



- Since 2020 ILC Development is organised within International Development Team
https://linearcollider.org/team/

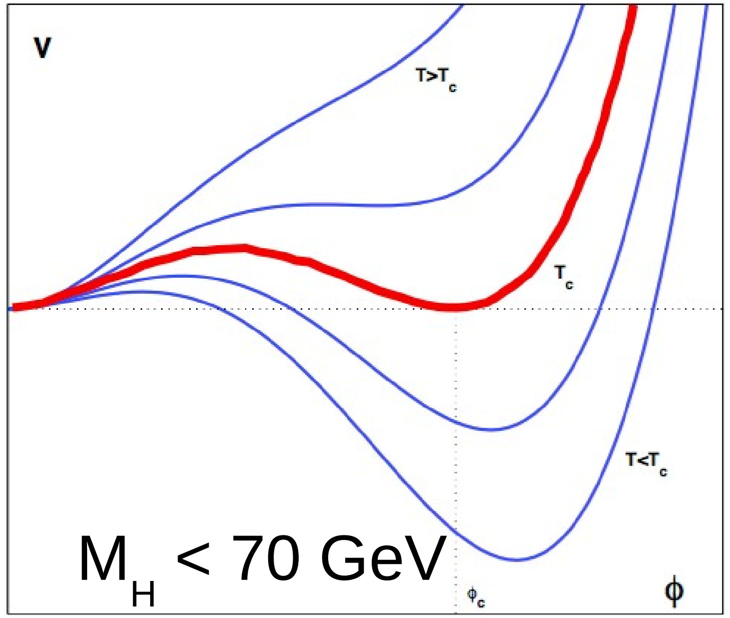
67

Higgs Factories – AC Power Consumption

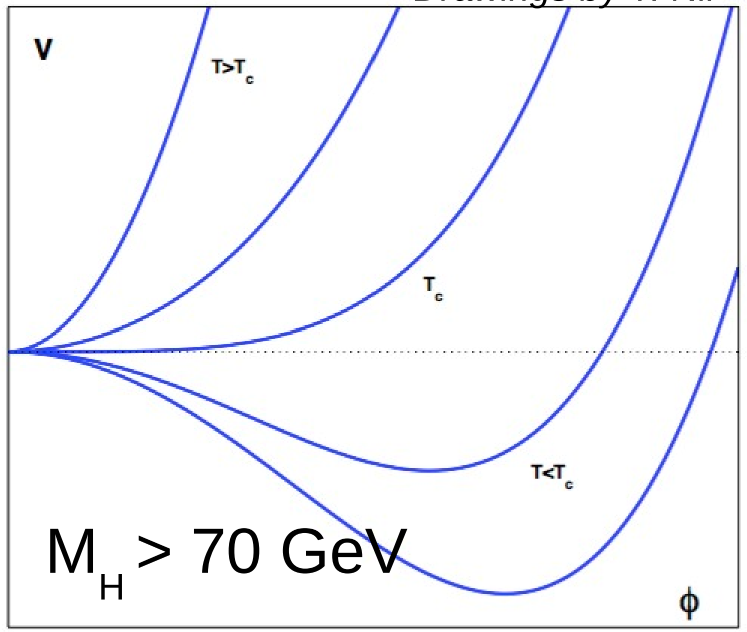


Phase Transition in Standard Model

Electroweak Baryogenesis requires 1st Order PT



Drawings by Y. Nir



- Coexistence Two minima at **0 and v_c at T_C**

=> 1st order phase transition
and development into “today's” shape at T=0

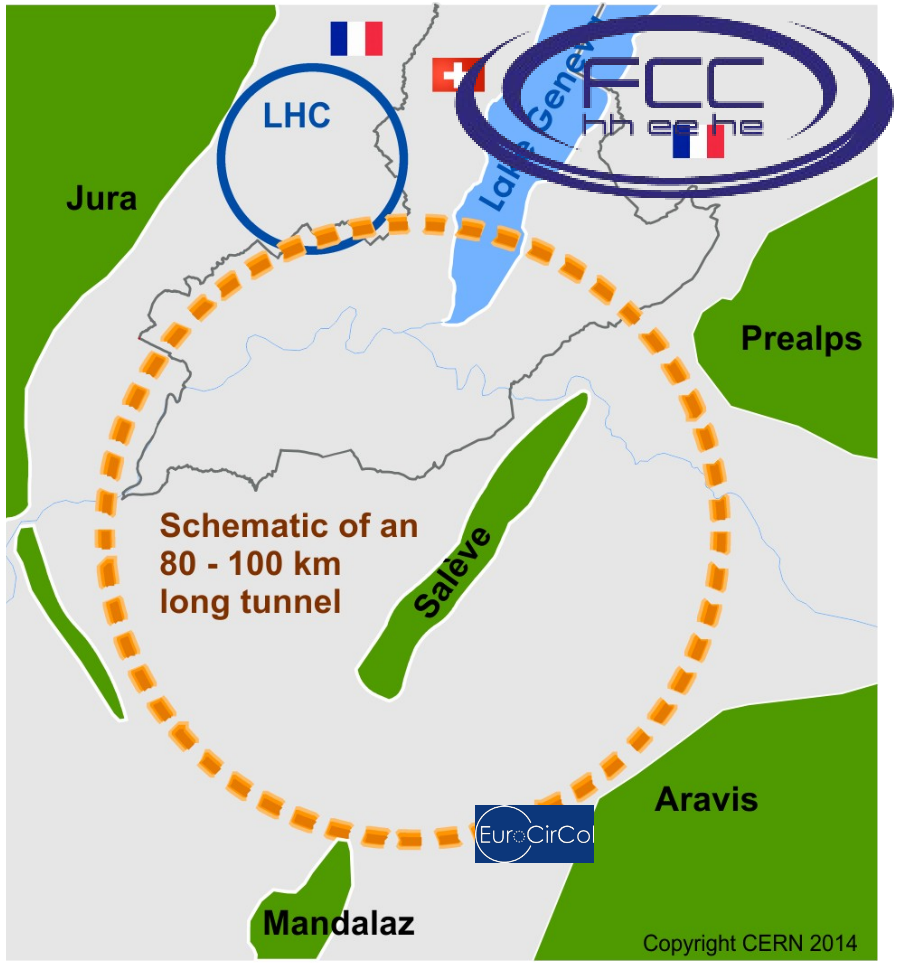
- No coexistence of two minima at **0 and v_c**

=> Cross over into “today's” shape at T=0

The discovered Higgs is too heavy to provoke a 1st order phase transition

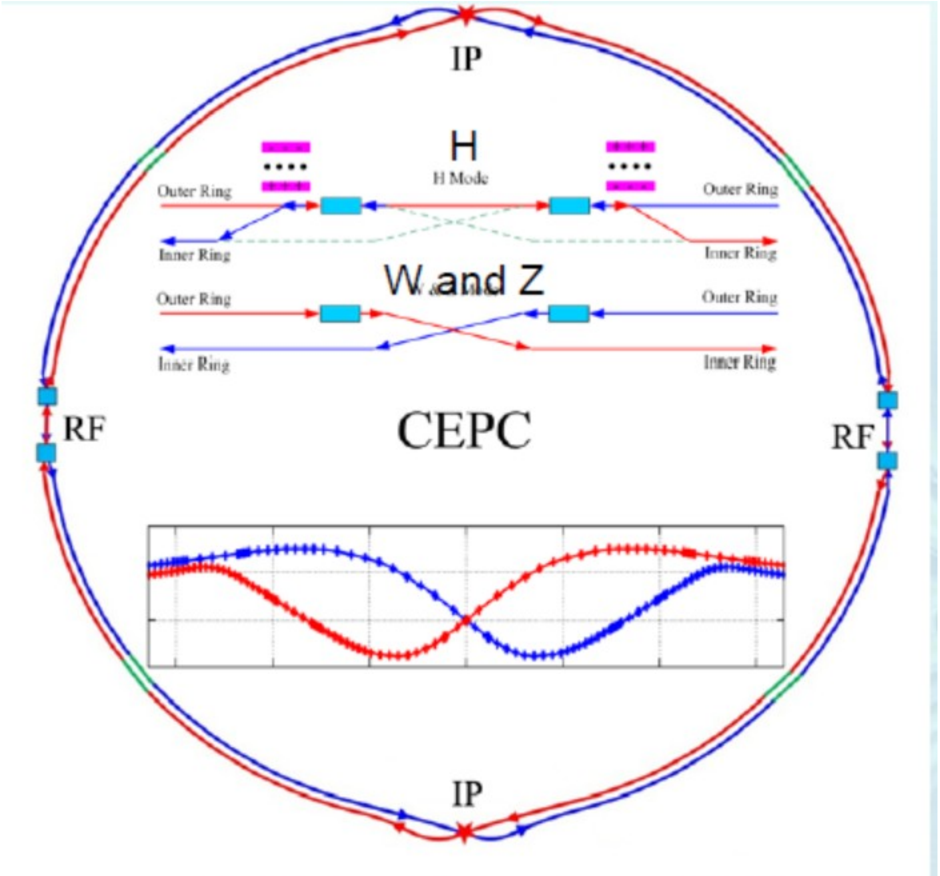
=> New physics needed

Circular Electron-Positron Colliders



- ~100 km storage rings
- Coupled to hadron collider proposal
- 90 – 350 GeV cms energy
- No long. beam polarisation
- CDR completed January 2019
  http://fcc-cdr.web.cern.ch

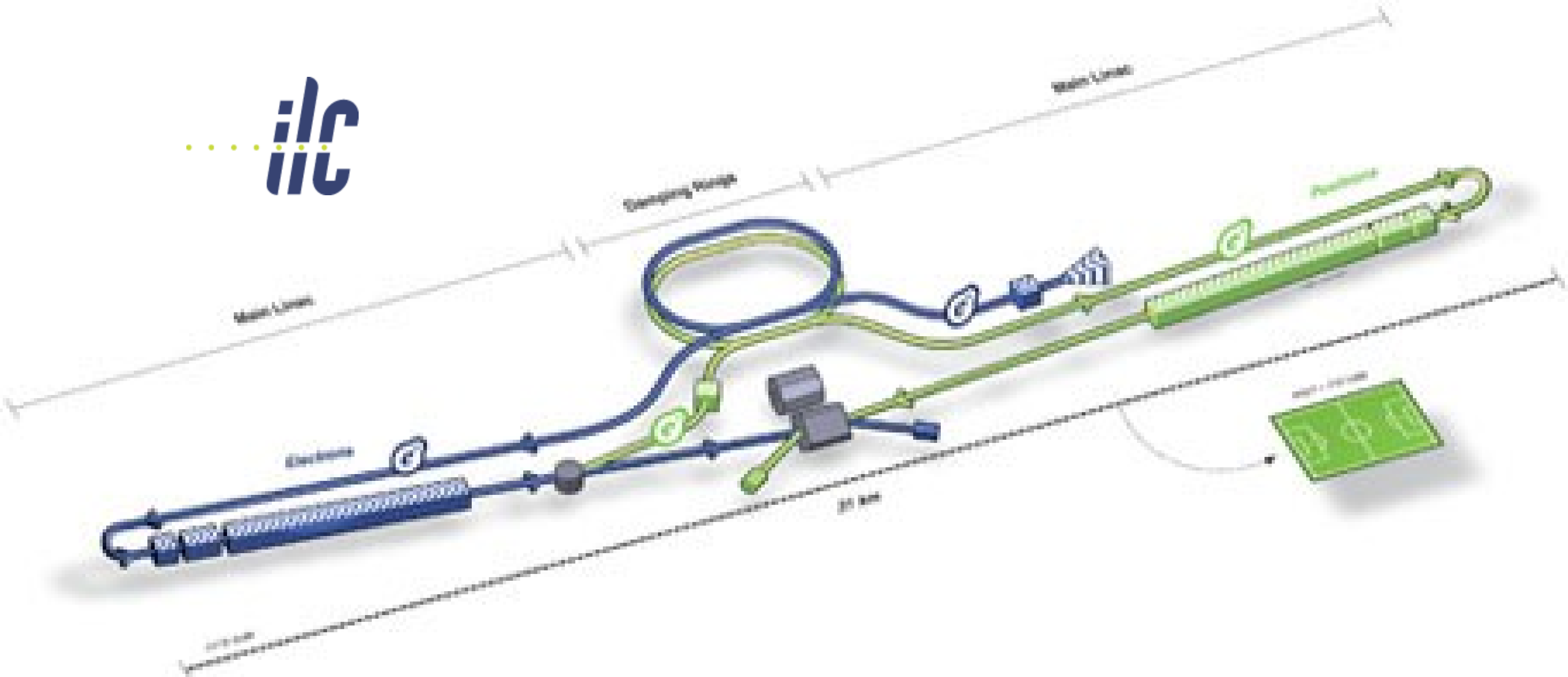
CEPC



CEPC collider ring (100km)

- ~100 km storage rings
- Coupled to hadron collider proposal
- 90 – 240 GeV cms energy
- No long. beam polarisation
- CDR completed September 2018
- Arxiv:1809.00285

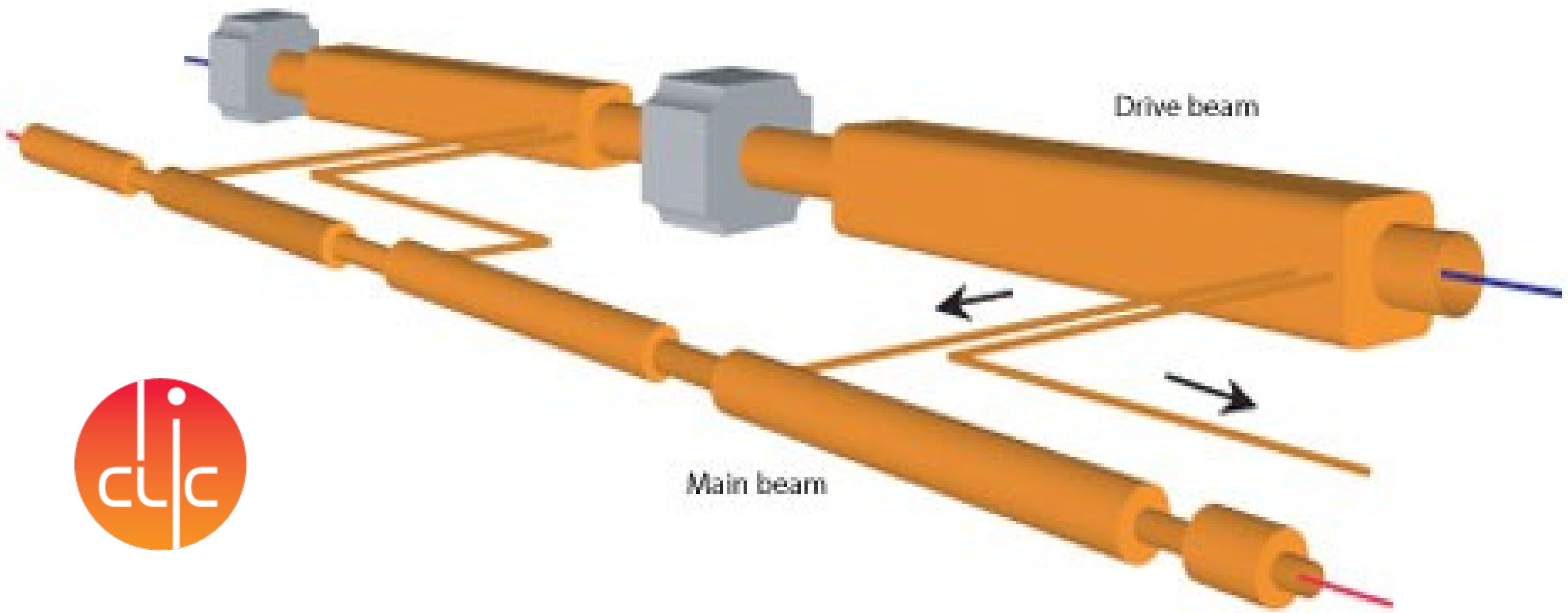
Linear Electron-Positron Colliders



Japanese Gouvernment expressed its interest in project in March 2019

Energy: 0.1 - 1 TeV
Electron (and positron) polarisation
TDR in 2013
+ DBD for detectors
Footprint 31 km

Initial Energy 250 GeV – Footprint ~20km



Possible future project at CERN

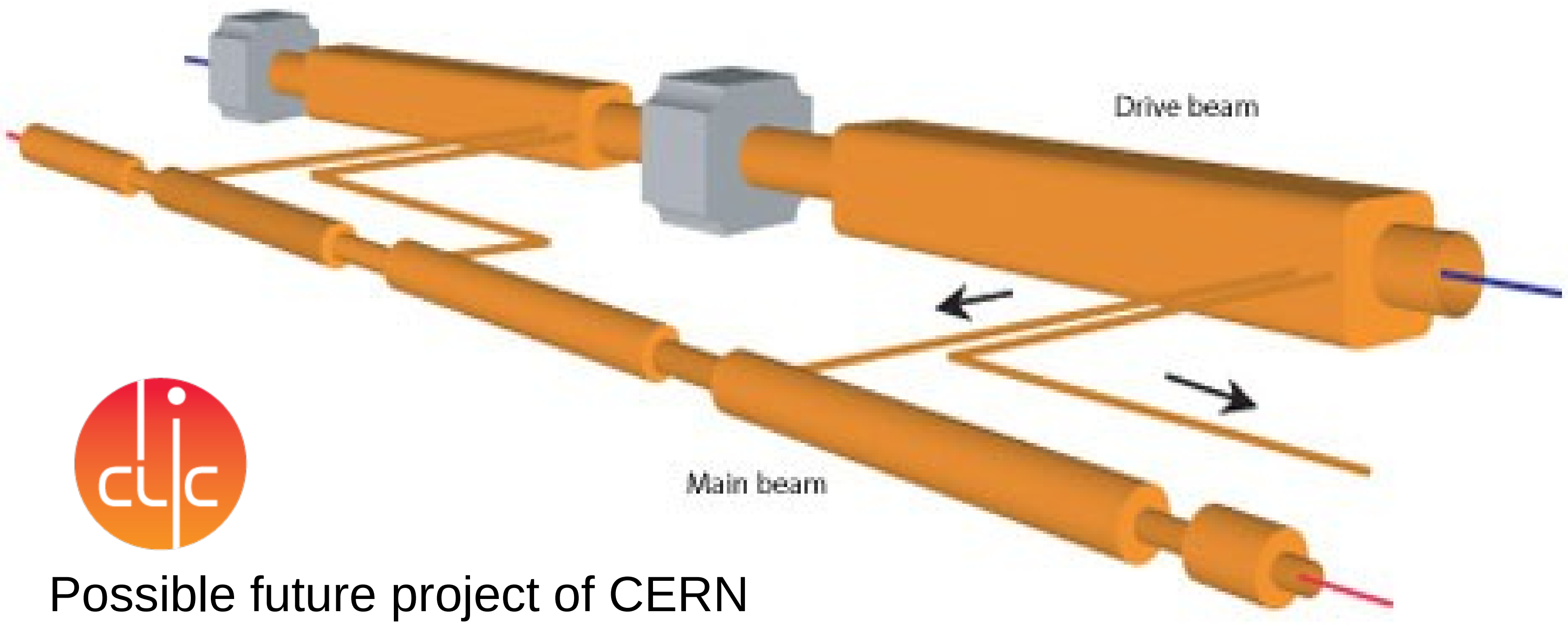
Energy: 0.4 - 3 TeV

CDR in 2012

Footprint 48km

Initial Energy 380 GeV

Linear Electron Positron Colliders



Possible future project of CERN

Energy: 0.4 - 3 TeV

CDR in 2012
Update 2016

Footprint 48km

Initial Energy 380 GeV

Cool Copper Collider

- Based on new RF Technology
- Operation at Cryogenic temperature (LN2 ~ 80K)
- Aiming at gradients of 120 MV/m

New physics?

- Polarized beams play a crucial role in disentangling the two spin structures

$$\sigma = \frac{2}{3}\frac{\pi\alpha_w^2}{c_w^4}\frac{m_Z^2}{(s-m_Z^2)}\frac{2k_Z}{\sqrt{s}}(2+\frac{E_Z^2}{m_Z^2})\cdot Q_Z^2\cdot\left[1+2a+2\,\frac{3\sqrt{s}E_Z/m_Z^2}{(2+E_Z^2/m_Z^2)}\,b\right]$$

The a and b coefficients depend on beam polarization:

$e_L^- e_R^+$

$$Q_{ZL} = (\frac{1}{2} - s_w^2)\ , \qquad a_L = -c_H$$

$$b_L = c_w^2(1 + \frac{s_w^2}{1/2 - s_w^2}\frac{s - m_Z^2}{s})(8c_{WW})$$

$e_R^- e_L^+$

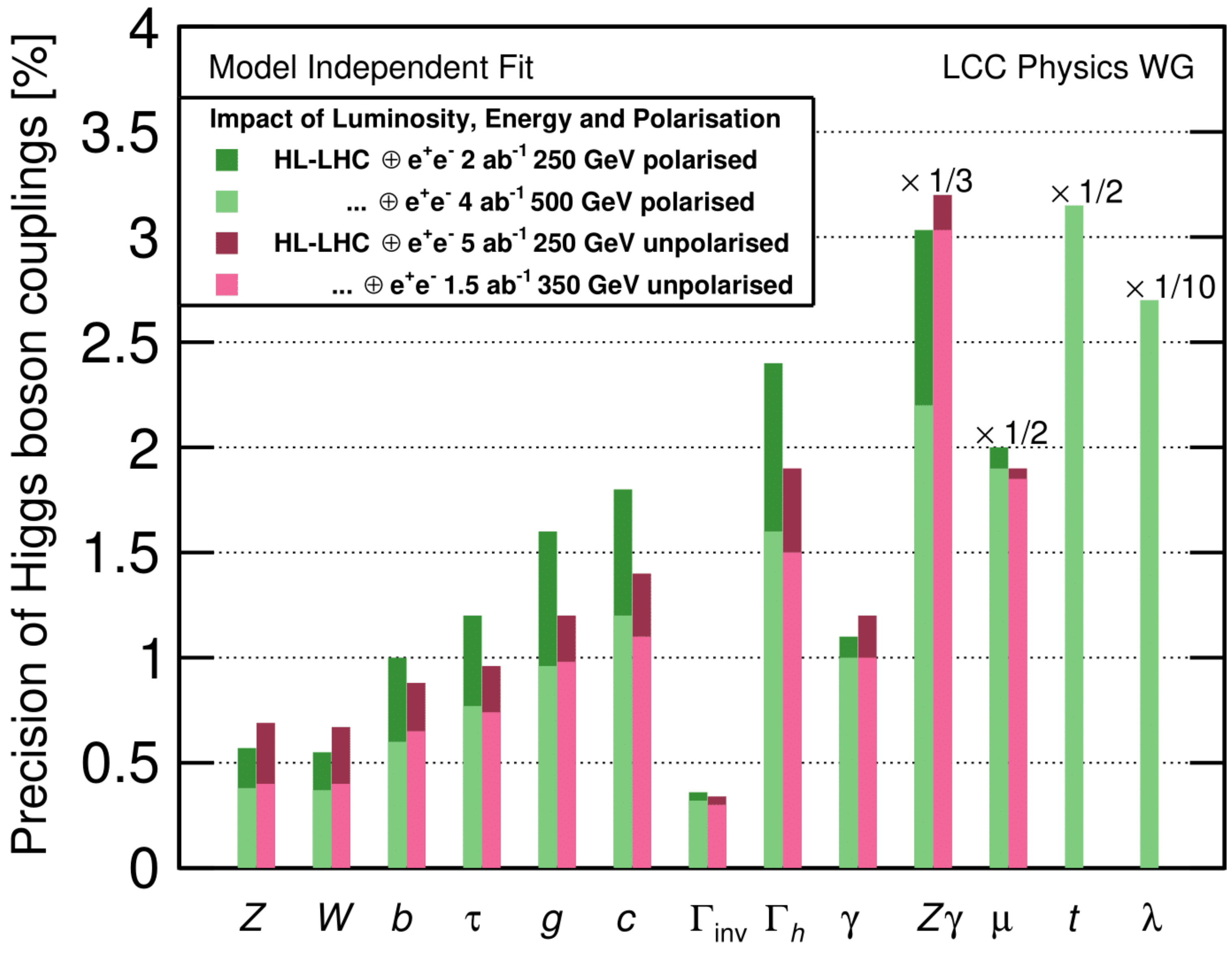
$$Q_{ZR} = (-s_w^2)\ , \qquad a_R = -c_H$$

$$b_R = c_w^2(1 - \frac{s - m_Z^2}{s})(8c_{WW})$$

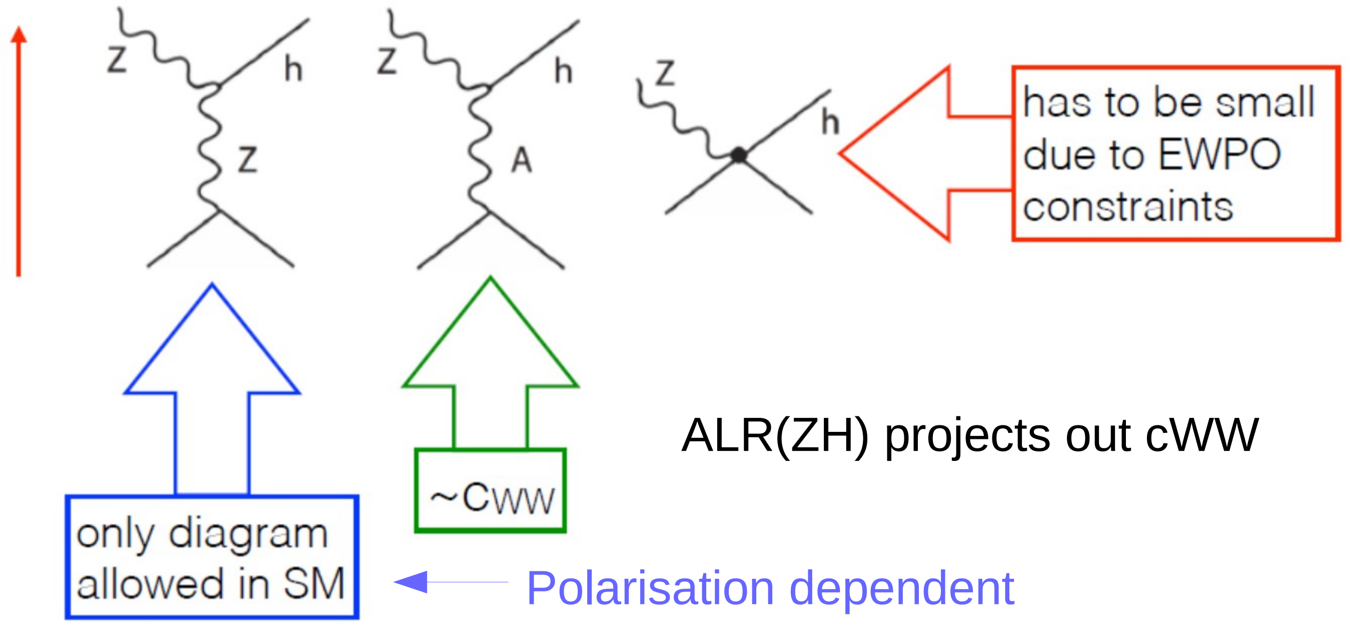
- Angular distributions in $e^+e^- \to hZ$ can also be used, but have weaker analyzing power and require more luminosity to achieve the same result

M. Perelstein: AWLC2017

EFT Framework and beam polarisation

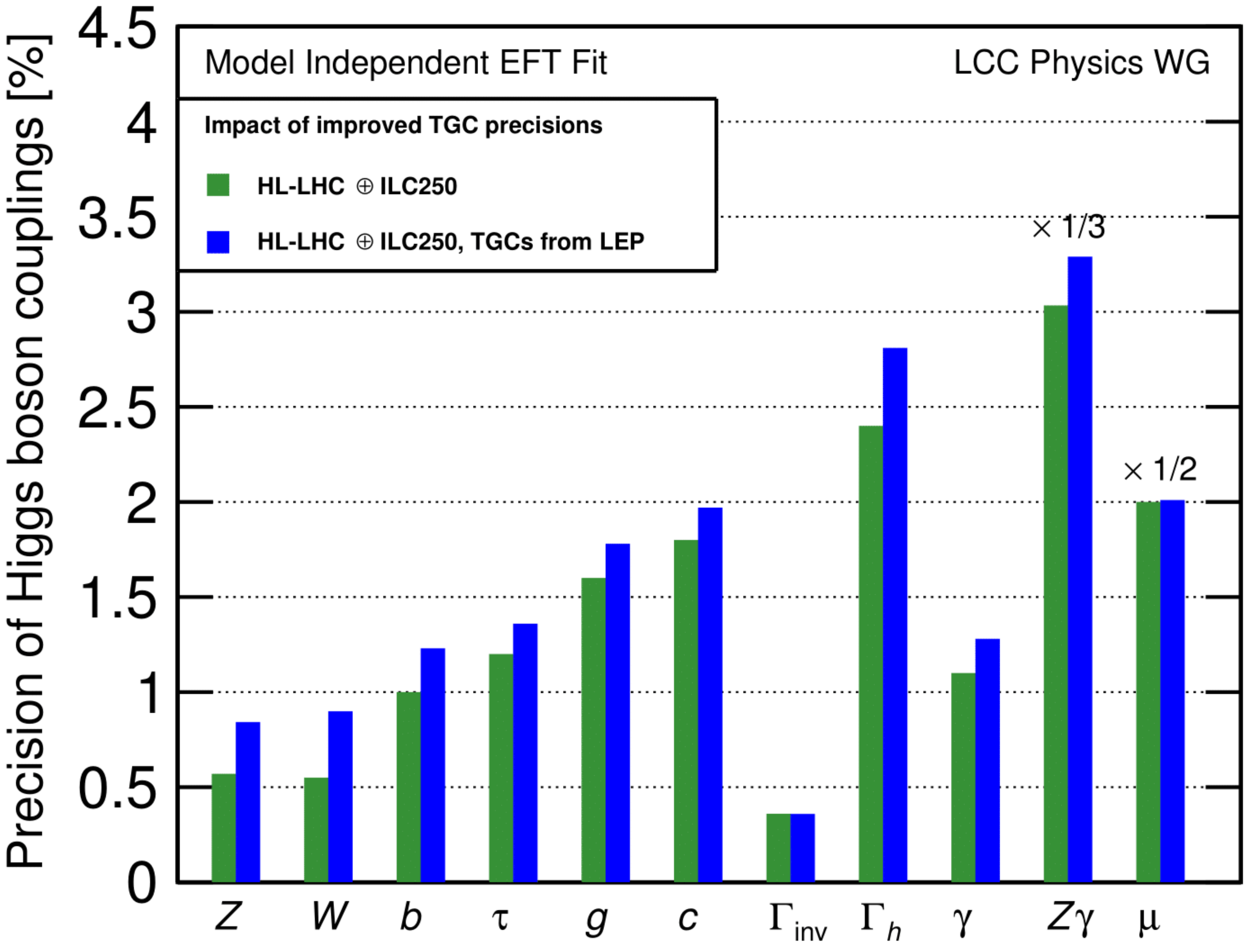


- EFT adds additional spin structure to ZH production cross section (see backup)

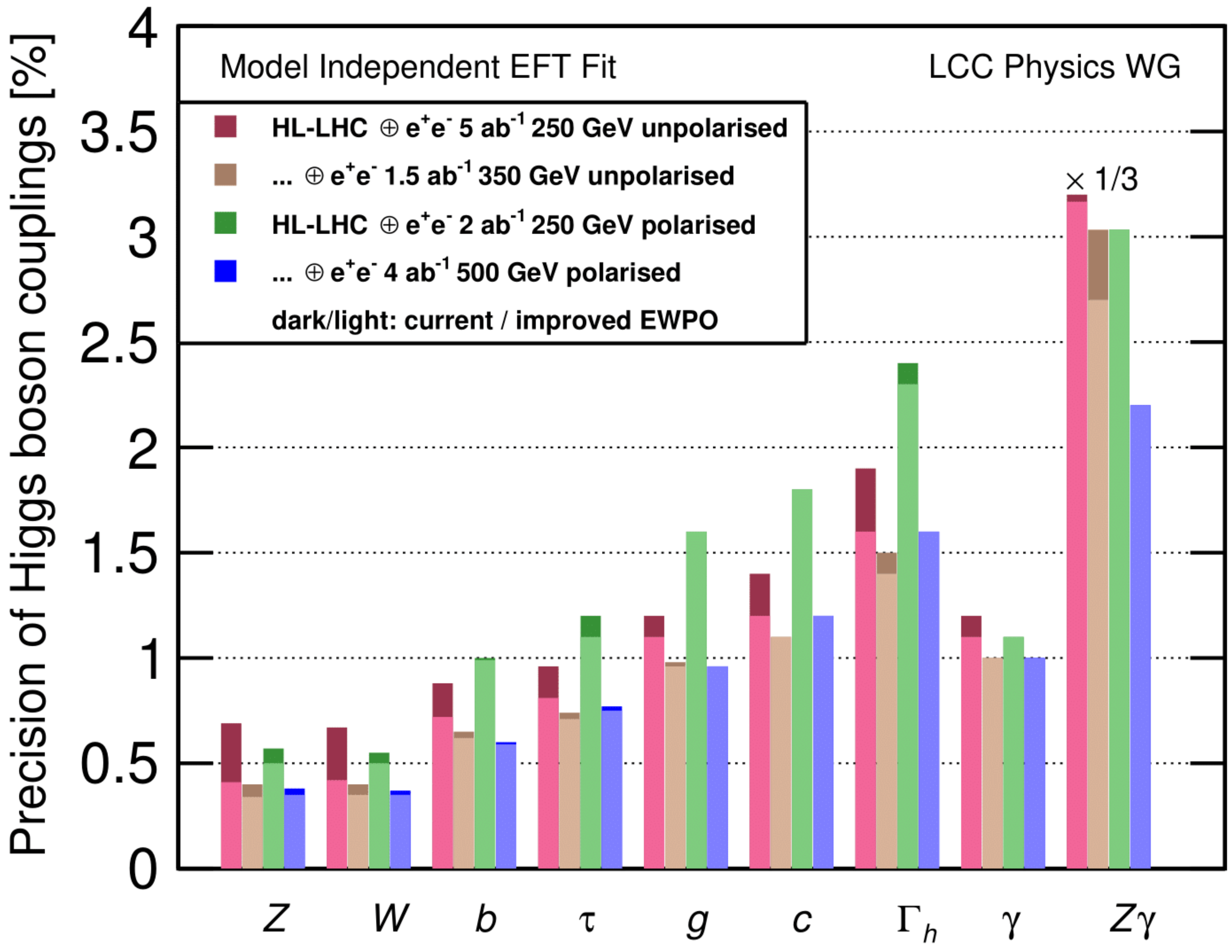


- Precision for 2ab-1 polarised = 5ab-1 unpolarised

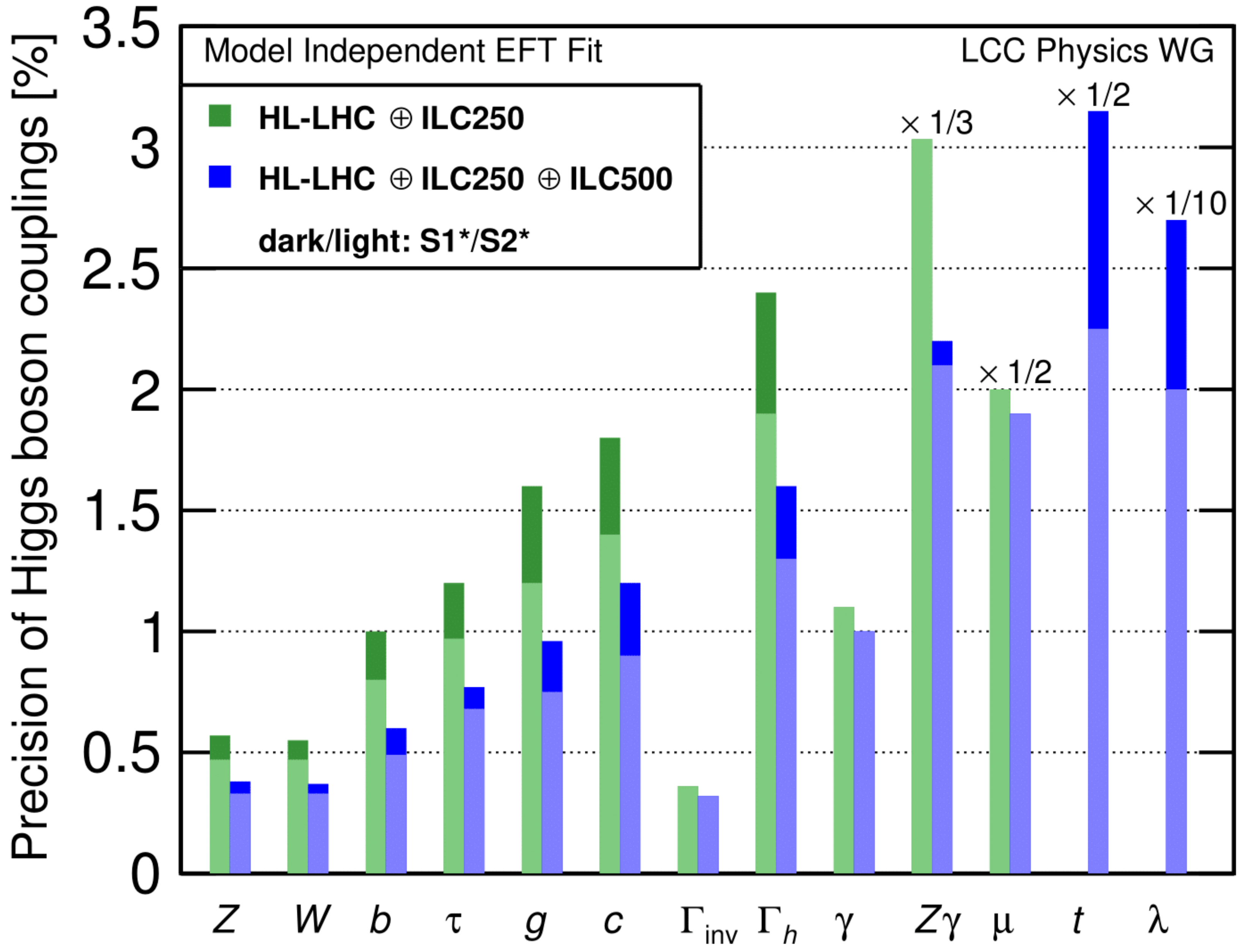
Higgs couplings – Impact of TGC



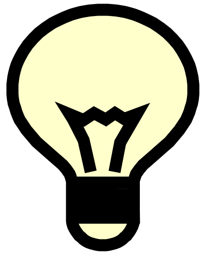
Higgs couplings – Polarisation + EWPO



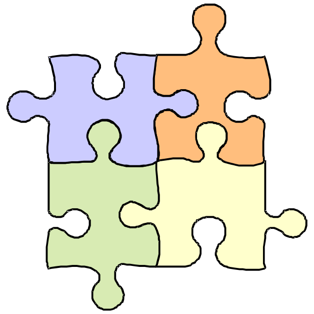
Higgs couplings – Polarisation + EWPO



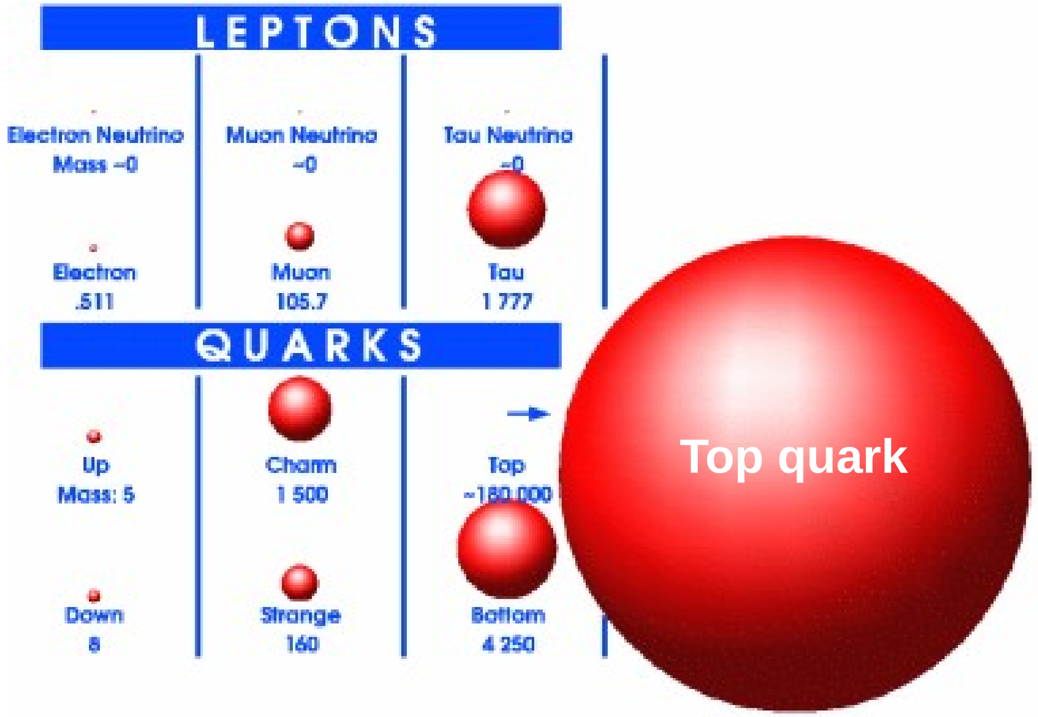
Science drivers



Elementary Scalar?



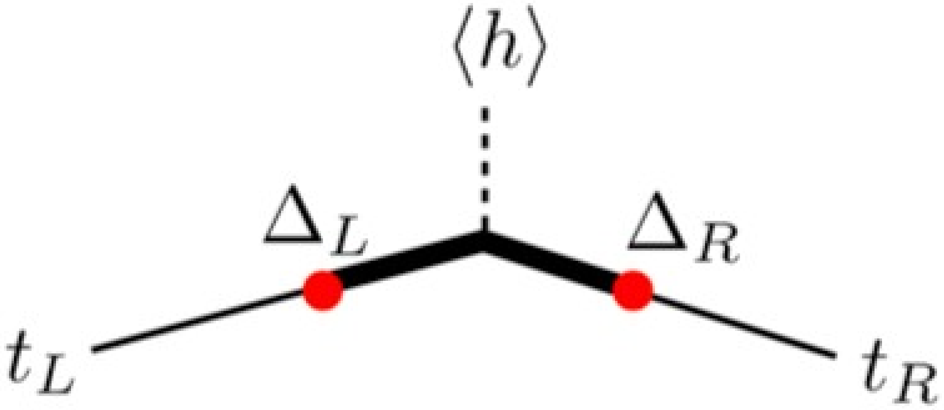
Composite object?



- Higgs and top quark are intimately coupled!
  Top Yukawa coupling O(1) !
  => Top mass important SM Parameter

- New physics by compositeness?
  Higgs and top composite objects?

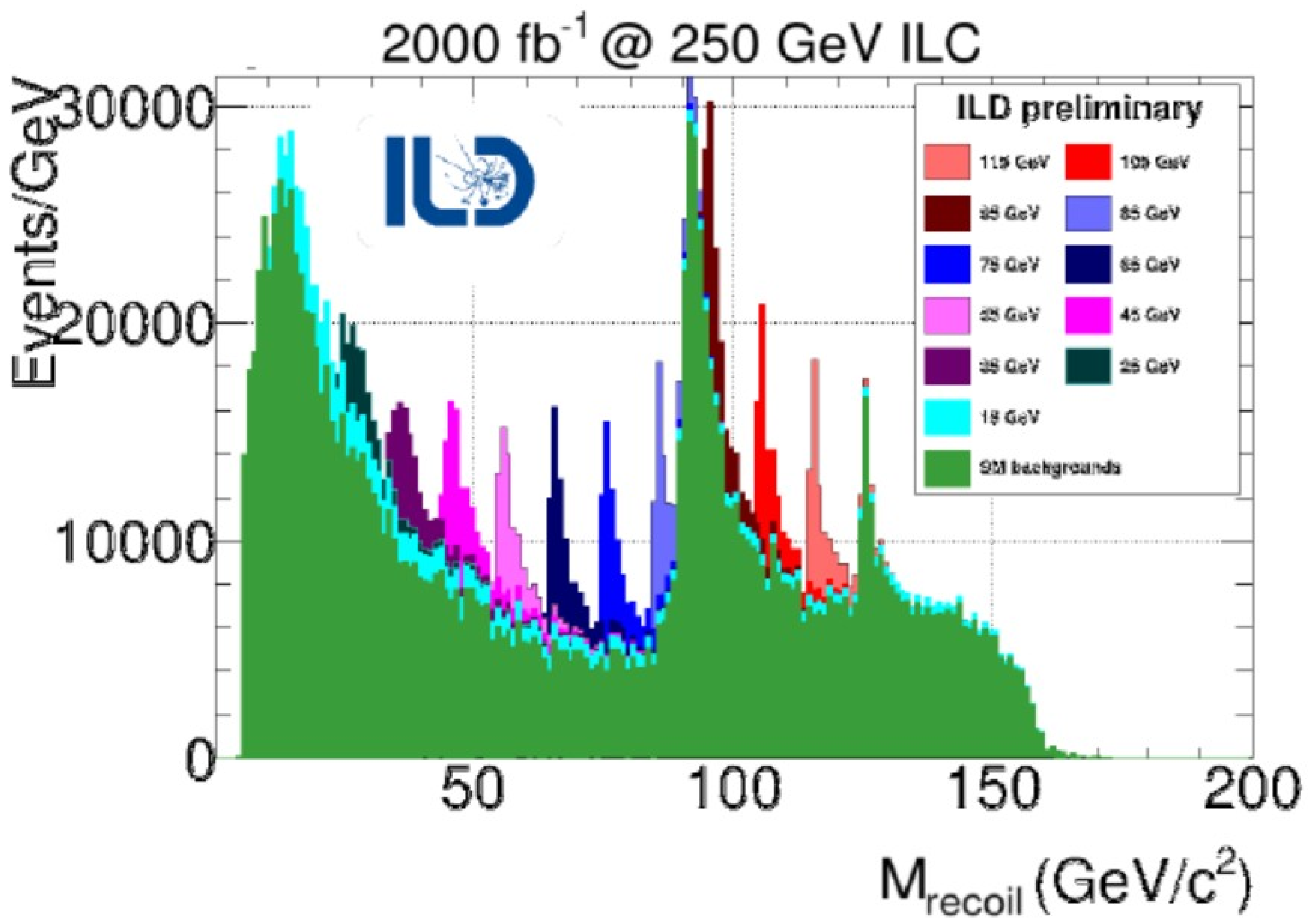
- e+e- collider perfectly suited to decipher both particles

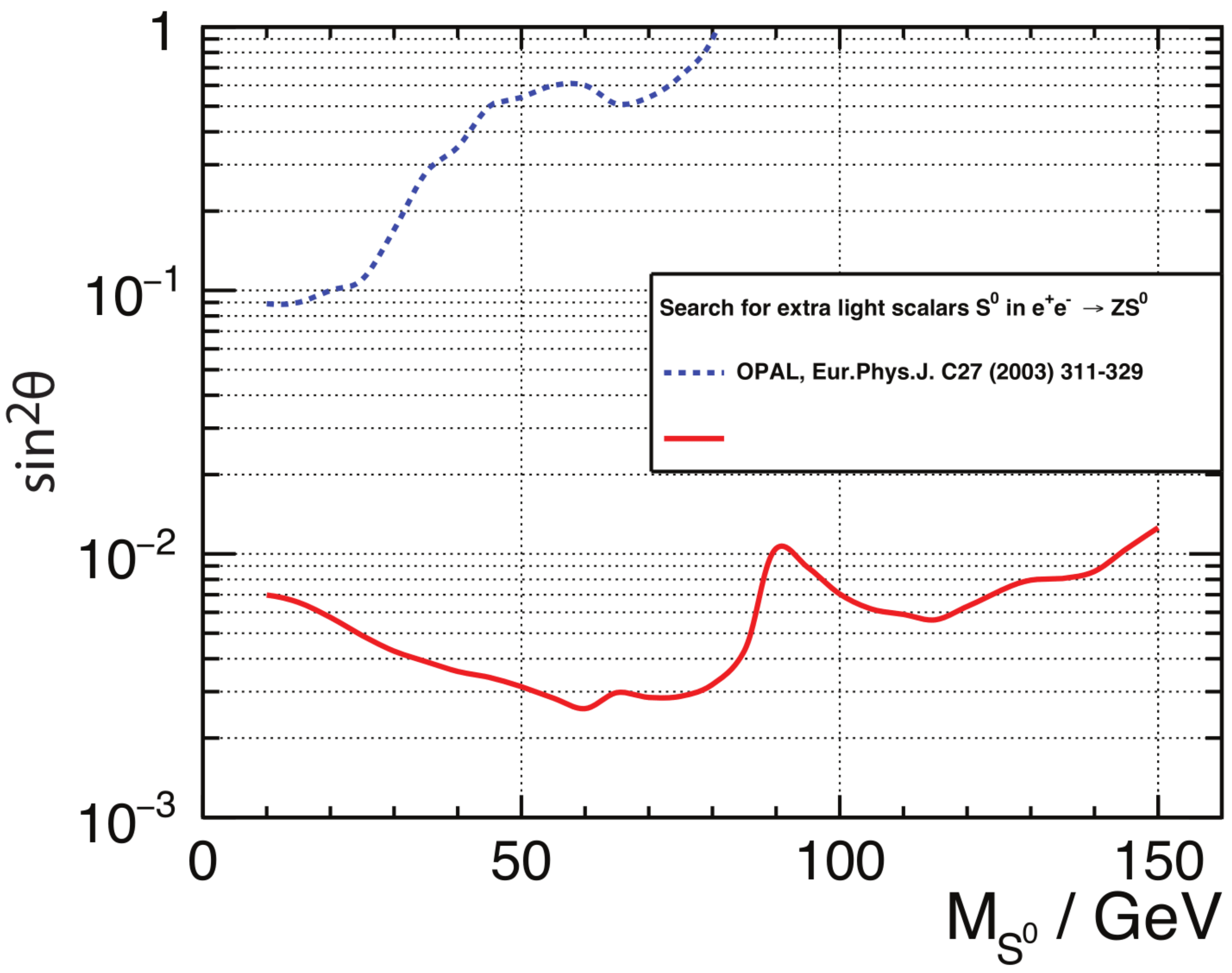


Courtesy of S. Rychkov

Light scalar study in ILD

Light scalar may be missing piece to trigger first order 1st transition and/or the being the radion in extra dimension theories

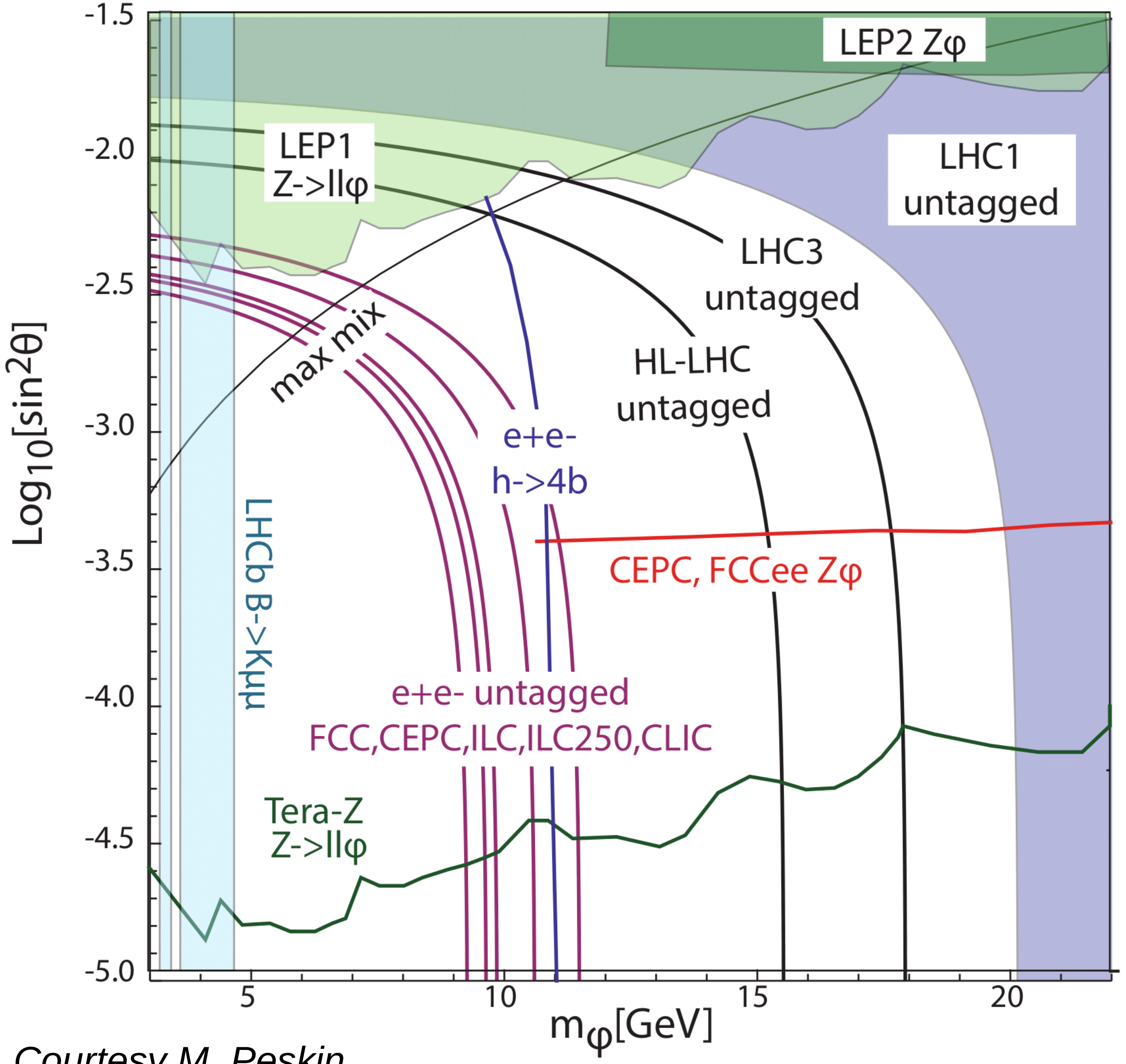




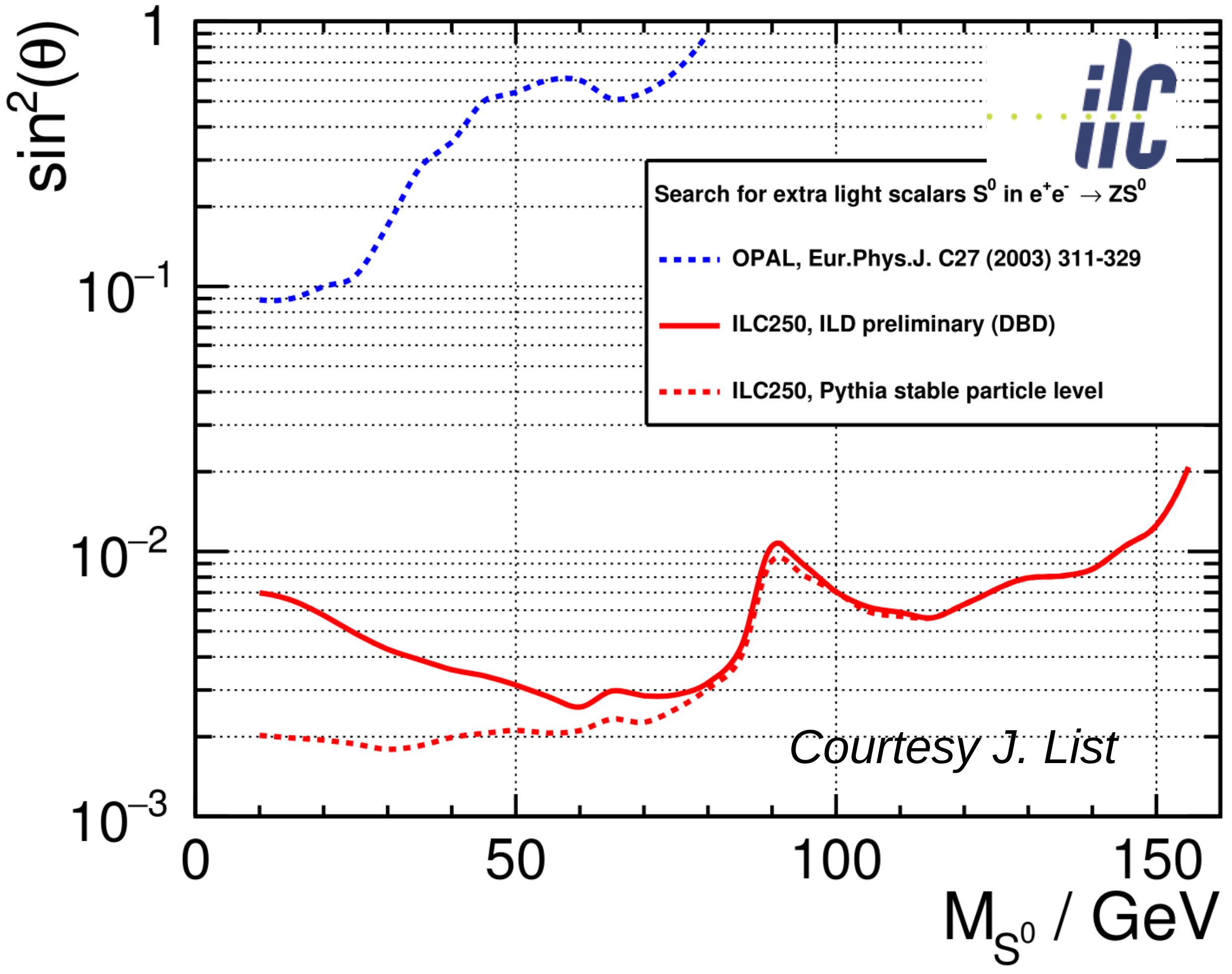
- New resonances cleanly dinstiguishable for large range of masses
- Sensitivity to mixing angle θh down to 10^{-2} (taking all relevant backgrounds into account)
- └new scalar would count as "Feebly interacting Particle" (FIPS)

Feebly interacting particles – A summary

Light scalar may be missing piece to trigger first order 1st phase transition and/or being the radion in extra dimension theories

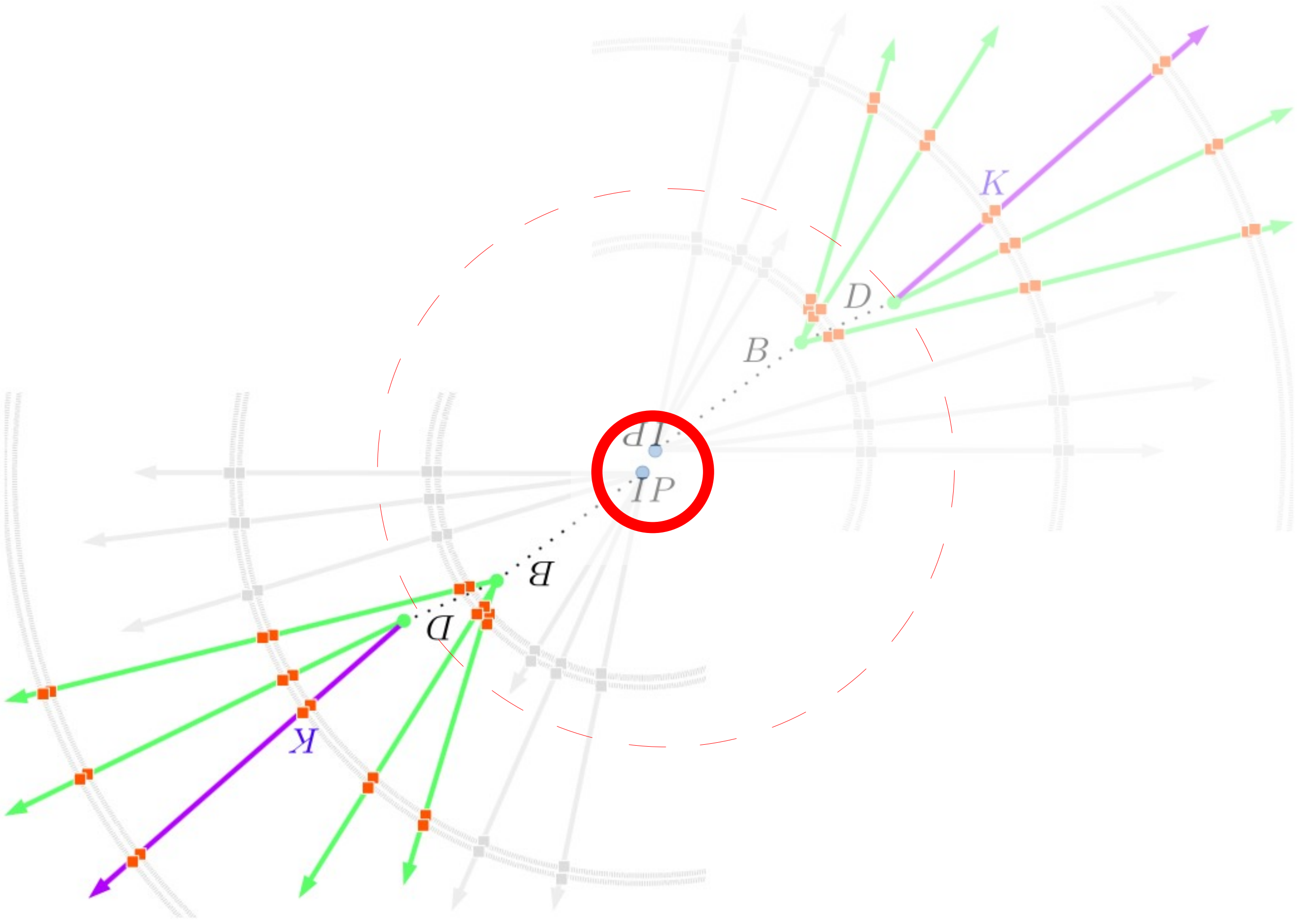


Courtesy M. Peskin



- e+e- colliders extend limits considerably w.r.t. LHC
  - Statistics helps at lowest masses
- CEPC, FCCee (>Z pole) limits order of magnitude better than ILC
  - Backgrounds taken correctly into account?
  - Similar at stable particle level

Double tagging



Important systematic error is knowledge of tagging efficiency ε_q

Can be derived from data if tagging is independent in two hemispheres, i.e. if

$$C_q = \frac{\epsilon_{double}}{\epsilon_q^2} \approx 1$$

If $C_q \neq 1$ => Hemisphere correlations => systematic error

For example:

LEP (large beam spot): C_q-1 ≈ 3% => ΔR_b ≈ 0.2%

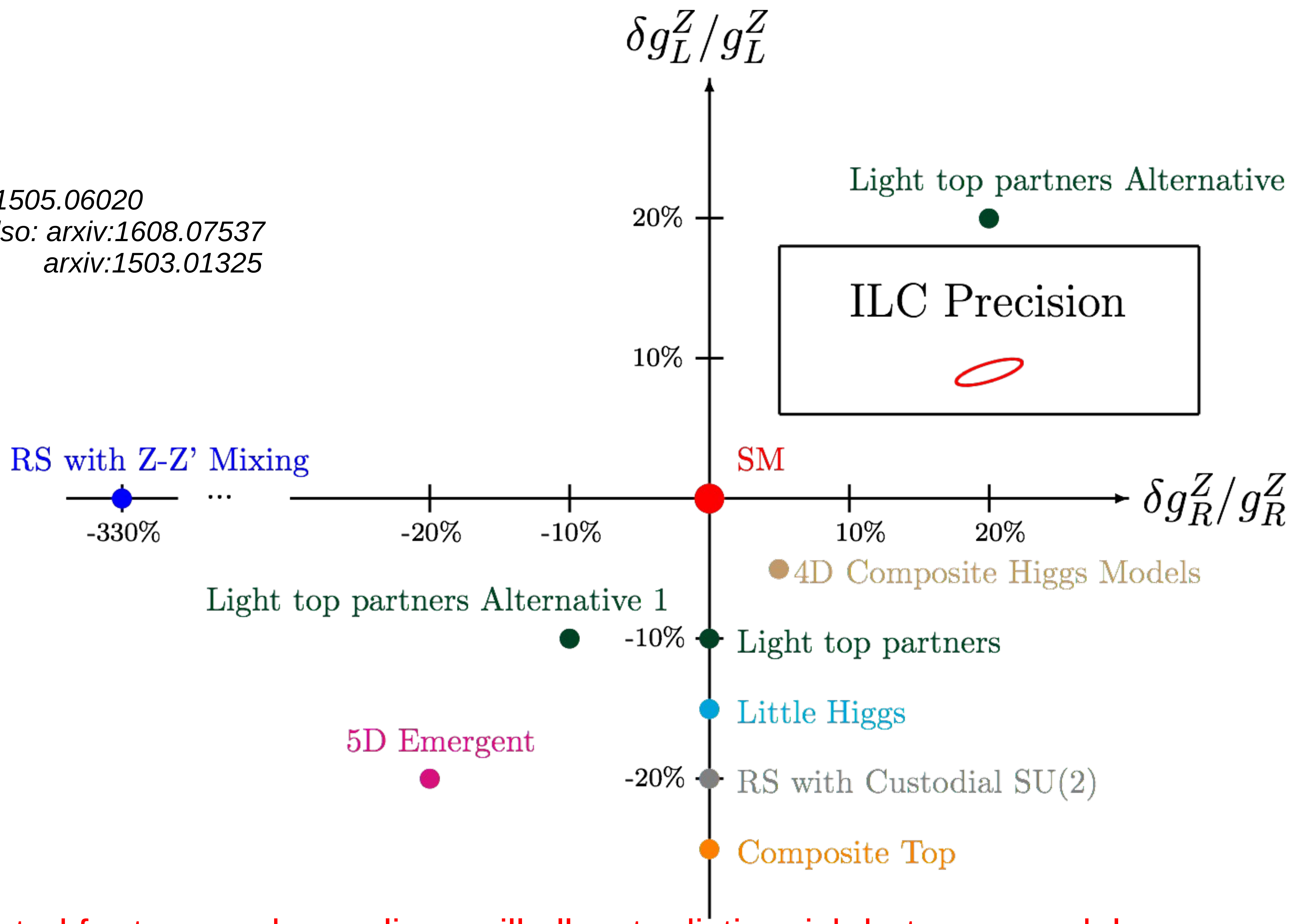
SLC (smaller beam spot): C_q -1 < 1% => ΔR_b ≈ 0.07%

Future (small/tiny beam spot): Expect C_q -1 = 0 => ΔR_b ≈ 0
to be verified however

Electroweak top couplings

Top is primary candidate to be a messenger new physics in many BSM models

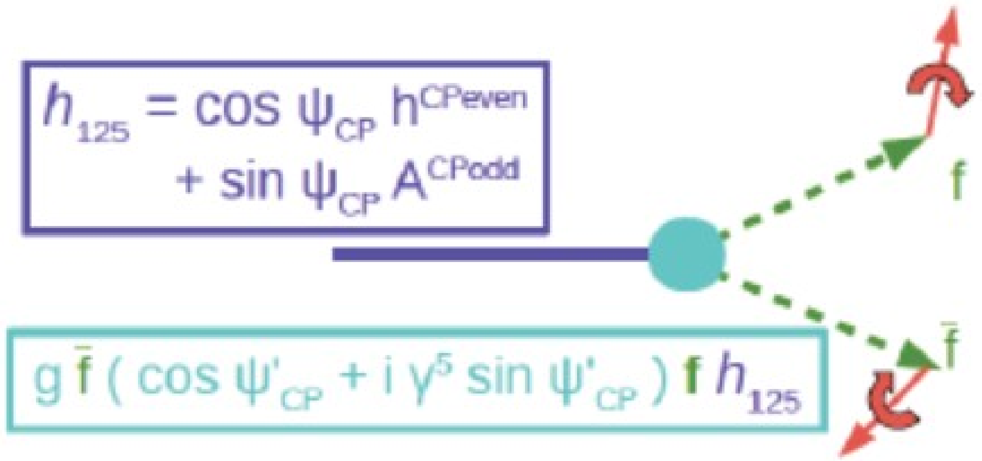
arxiv:1505.06020
see also: arxiv:1608.07537
arxiv:1503.01325



Statistical error:
$\sqrt{s}$ ~ 500 GeV
L = 500 fb^{-1}

Precision expected for top quark couplings will allow to distinguish between models

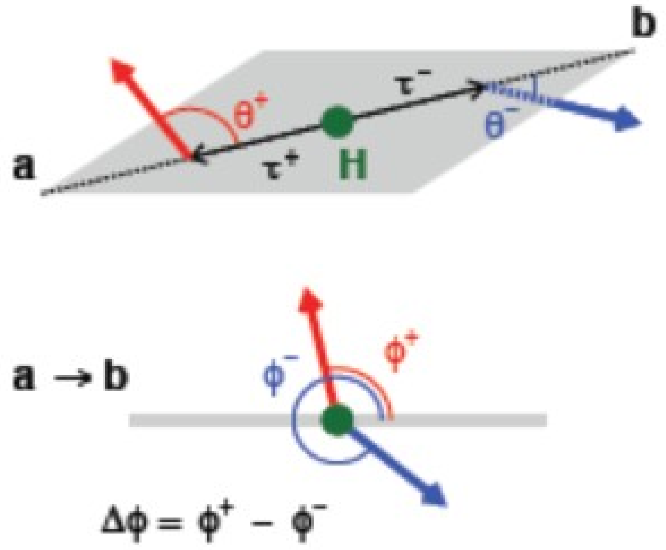
Remark: All presented models are compatible with LEP elw. precision data

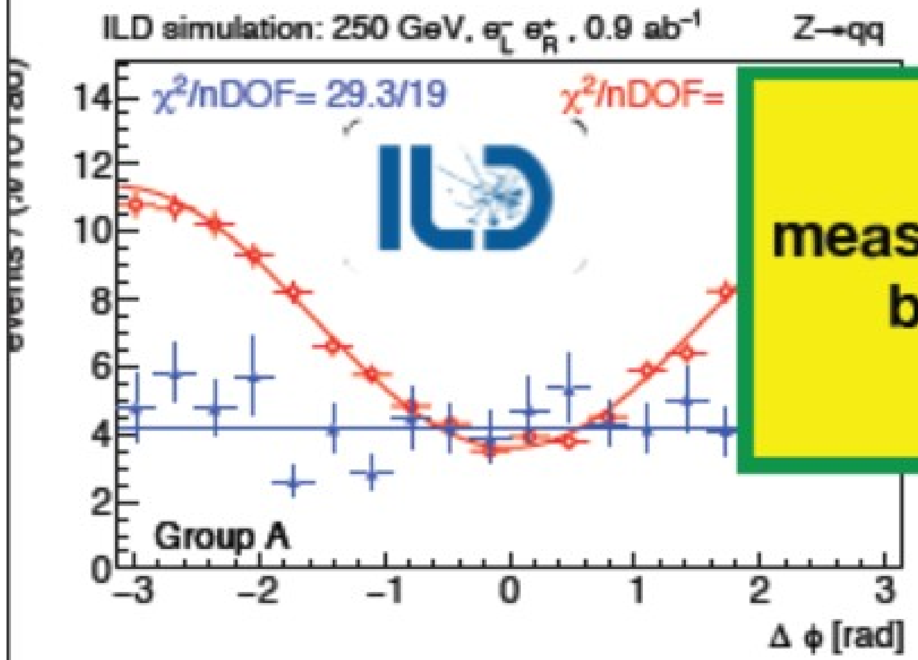


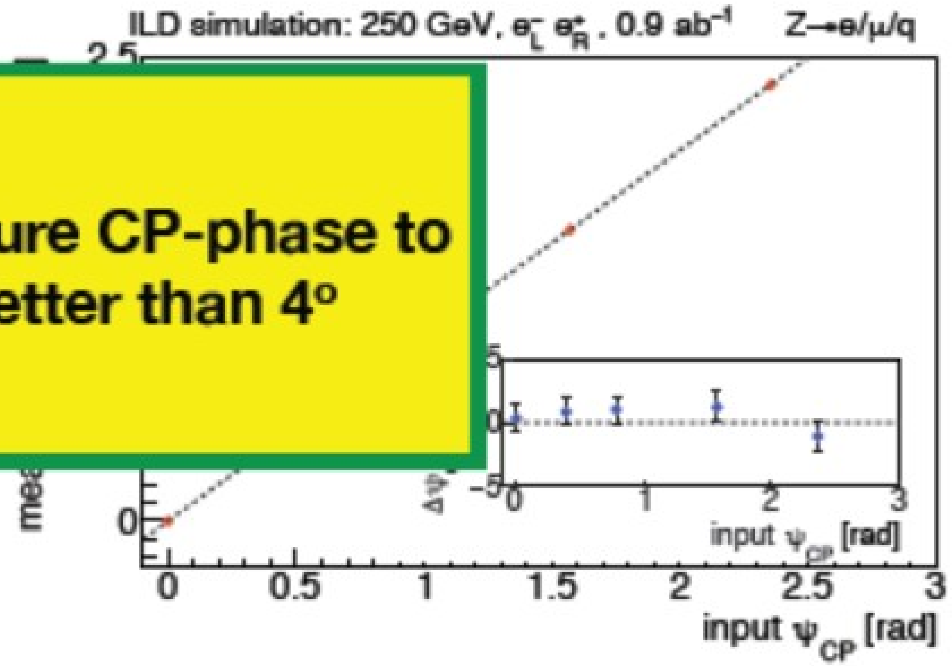
h is a spin 0 state:

$|f\,\bar{f}\rangle = |\uparrow\downarrow\rangle + e^{2i\psi}\,|\downarrow\uparrow\rangle$

[ψ = 0 CP even, $\pi/2$ CP odd]







measure CP-phase to better than 4°

..and CPV in Zh coupling:

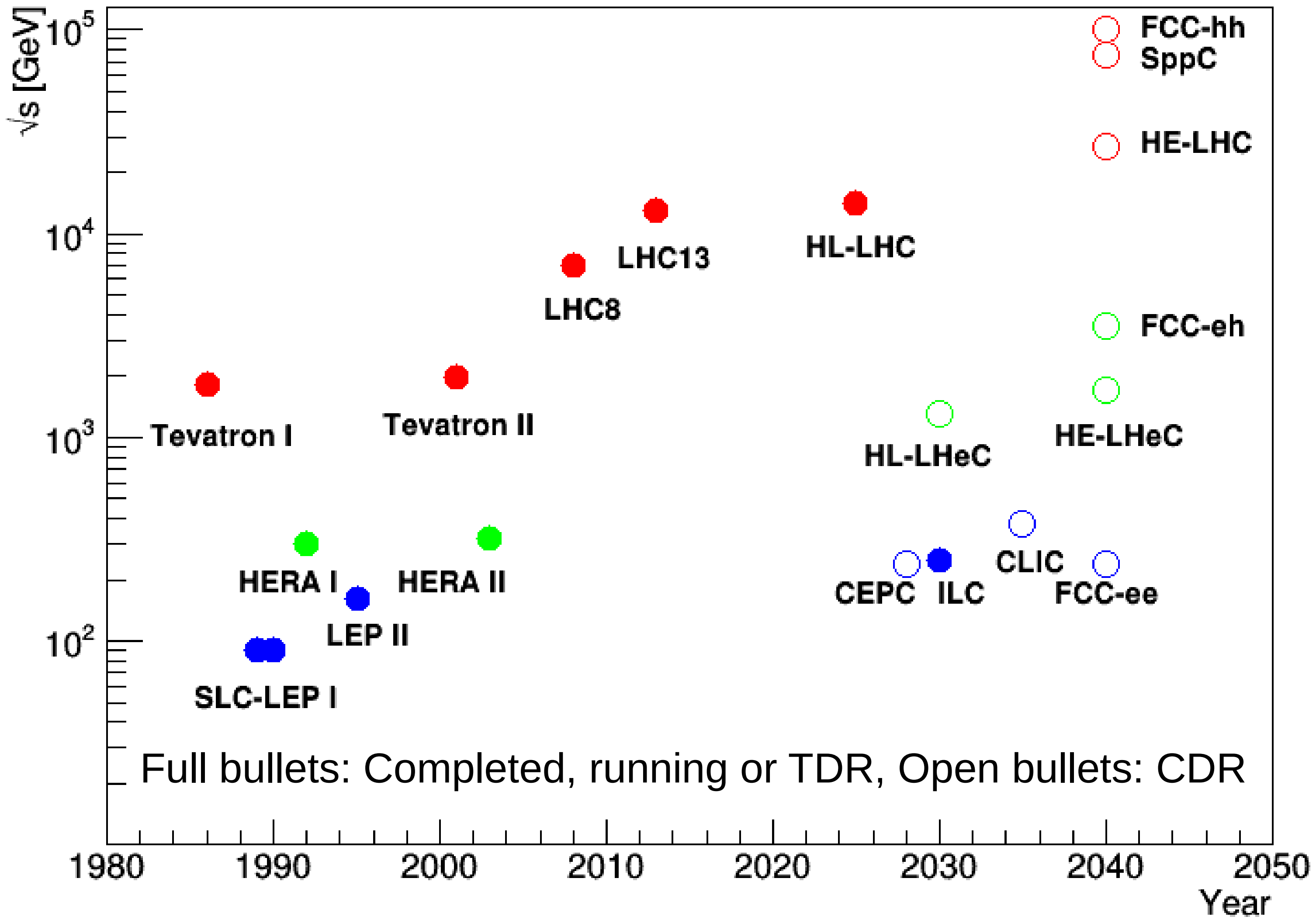
$$\Delta\mathcal{L}_{hZZ} = \frac{1}{2}\frac{\tilde{b}}{v} h Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

=> $\tilde{b}$ **to ±0.005**

arxiv:1804.01241

based on NIM A810 (2016) 51-58

e+e- machines (and others) - Readiness



- ILC is the only machine that can be built now
  - European XFEL gives credbility for construction

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

Points 1,2,4:

- Exploit LHC and implement HiLumi. Well underway.
- High field magnets and high gradient acceleration, project planning for CLIC and FCC/He-LHC. Studies being summarized for the European Strategy update in 2019-20.
- Develop a neutrino programme at CERN. Neutrino platform implementation.

Point 3:

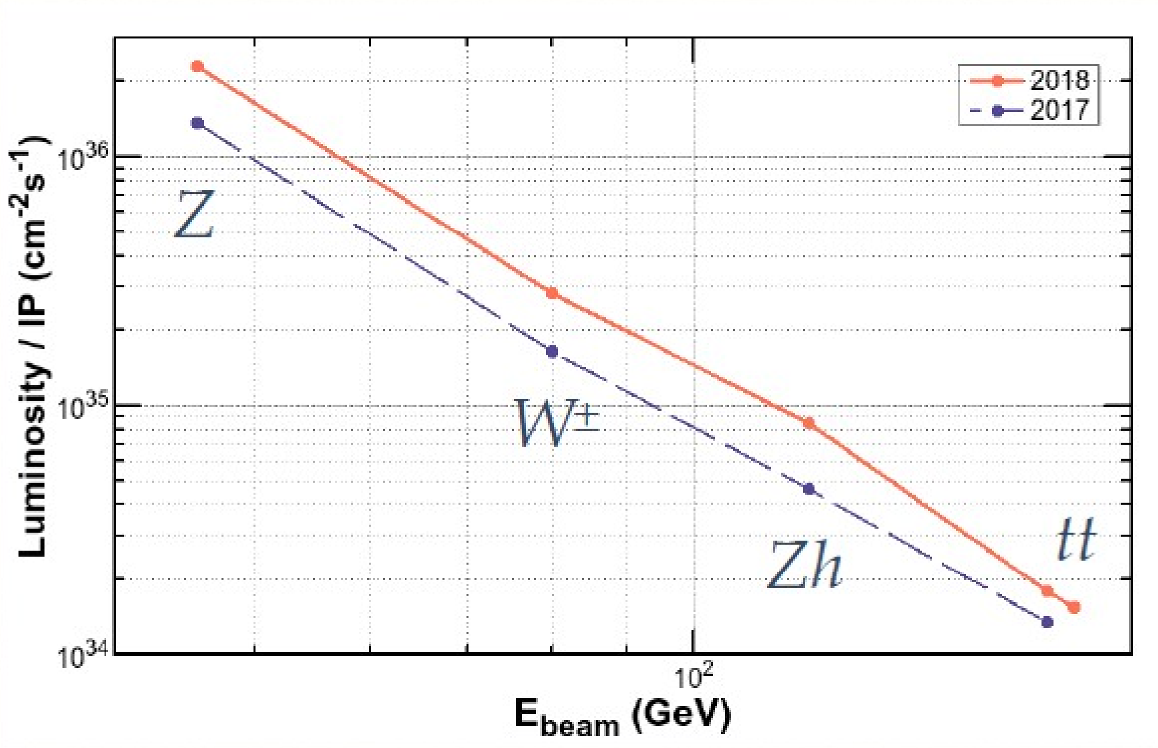
- There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. ***Europe looks forward to a proposal from Japan to discuss a possible participation.***

ILC Parameters

			TDR		New
Center-of-mass energy	E_{CM}	GeV	250	500	250
Bunch population	N	e10	2	2	2
Bunch separation		ns	554	554	554
Beam current		mA	5.78	5.78	5.78
Number of bunches per pulse	Nb		1312	1312	1312
Collision frequency		Hz	5	5	5
Electron linac rep rate		Hz	10	5	5
Beam power (2 beams)	P_B	MW	5.26	10.5	5.26
r.m.s. bunch length at IP	σ_z	mm	0.3	0.3	0.3
relative energy spread at IP (e−)	σ_E/E	%	0.188	0.124	0.188
relative energy spread at IP (e+)	σ_E/E	%	0.15	0.07	0.15
Normalized horizontal emittance at IP	ε_{nx}	μm	10	10	5
Normalized vertical emittance at IP	ε_{ny}	nm	35	35	35
Beam polarization (e−)		%	80	80	80
Beam polarization (e+)		%	30	30	30
Beta function at IP (x)	β_x	mm	13	11	13
Beta function at IP (y)	β_y	mm	0.41	0.48	0.41
r.m.s. beam size at IP (x)	σ_x	nm	729	474	516
r.m.s. beam size at IP (y)	σ_y	nm	7.66	5.86	7.66
r.m.s. beam angle spread at IP (x)	θ_x	μr	56.1	43.1	39.7
r.m.s. beam angle spread at IP (y)	θ_y	μr	18.7	12.2	18.7
Disruption parameter (x)	Dx		0.26	0.26	0.51
Disruption parameter (y)	Dy		24.5	24.6	34.5
Upsilon (average)	Υ		0.020	0.062	0.028
Number of beamstrahlung photons	n_γ		1.21	1.82	1.91
Energy loss by beamstrahlung	δ_{BS}	%	0.97	4.50	2.62
Geometric luminosity	Lgeo	e34/cm^{2}s	0.374	0.751	0.529
Luminosity	L	e34/cm^{2}s	0.82	1.79	1.35

FCC-ee Parameters

		Z	$W^\pm$	Zh	$t\bar{t}$	
Circumference	[km]	97.756				
Bending radius	[km]	10.760				
Free length to IP ℓ^*	[m]	2.2				
Solenoid field at IP	[T]	2.0				
Full crossing angle at IP	[mrad]	30				
SR power / beam	[MW]	50				
Beam energy	[GeV]	45.6	80	120	175	182.5
Beam current	[mA]	1390	147	29	6.4	5.4
Bunches / beam		16640	2000	328	59	48
Average bunch spacing	[ns]	19.6	163	994	2763[1]	3396[??]
Bunch population	$[10^{11}]$	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x	[nm]	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y	[pm]	1.0	1.7	1.3	2.7	2.9
Arc cell phase advances	[deg]	60/60	60/60	90/90		
Momentum compaction	$[10^{-6}]$	14.8	14.8	7.3		
Arc sextupole families		208		292		
Horizontal β^*_x	[m]	0.15	0.2	0.3	1.0	
Vertical β^*_y	[mm]	0.8	1.0	1.0	1.6	
Horizontal size at IP σ^*_x	[μm]	6.4	13.0	13.7	36.7	38.2
Vertical size at IP σ^*_y	[nm]	28	41	36	66	68
Energy spread (SR/BS)	[%]	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.196	0.150/0.192
Bunch length (SR/BS)	[mm]	3.5/12.1	3.0/6.0	3.15/5.3	2.75/3.82	1.97/2.54
Crab sextupole ratio	[%]	97	87	80	50	50
Energy loss / turn	[GeV]	0.036	0.34	1.72	7.8	9.2
RF frequency	[MHz]	400			400 / 800	
RF voltage	[GV]	0.1	0.75	2.0	4.0 / 5.4	4.0 / 6.9
Long. damping time	[turns]	1273	236	70.3	23.1	20.4
RF acceptance	[%]	1.9	2.3	2.3	3.5	3.36
Energy acceptance (DA)	[%]	±1.3	±1.3	±1.7	-2.8 +2.4	
Synchrotron tune Q_z		-0.0250	-0.0506	-0.0358	-0.0818	-0.0872
Luminosity / IP	$[10^{34}/\mathrm{cm}^2\mathrm{s}]$	230	28	8.5	1.8	1.55
Horizontal tune Q_x		269.139	269.124	389.129	389.104	
Vertical tune Q_y		269.219	269.199	389.199	389.175	
Beam-beam ξ_x/ξ_y		0.004/0.133	0.010/0.115	0.016/0.118	0.088/0.148	0.099/0.126
Lifetime by rad. Bhabha	[min]	68	59	38	37	40
Actual lifetime by BS	[min]	> 200	> 200	18	24	18



E. Levichev, FCC Week 2018

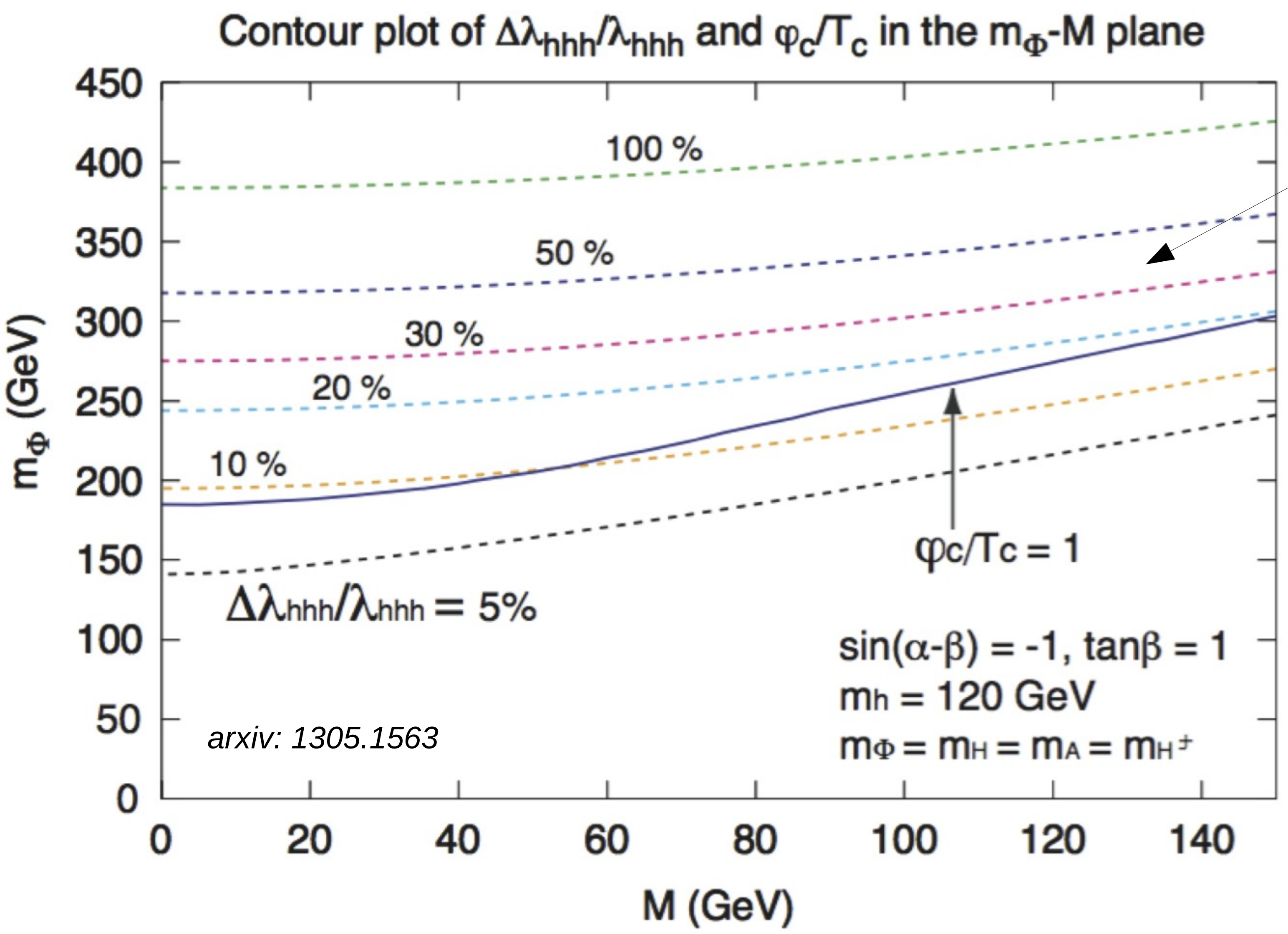
CEPC Parameters

	Higgs	*W*	*Z* (3T)	*Z* (2T)
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5×2			
Piwinski angle	2.58	7.0	23.8	
Number of particles/bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number (bunch spacing)	242 (0.68μs)	1524 (0.21μs)	12000 (25ns+10%gap)	
Beam current (mA)	17.4	87.9	461.0	
Synchrotron radiation power /beam (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compact (10^{-5})	1.11			
β function at IP β_x^* / β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance $\varepsilon_x/\varepsilon_y$ (nm)	1.21/0.0031	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.068	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.031/0.109	0.013/0.106	0.0041/0.056	0.0041/0.072
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz) (harmonic)	650 (216816)			
Natural bunch length σ_z (mm)	2.72	2.98	2.42	
Bunch length σ_z (mm)	3.26	5.9	8.5	
Betatron tune ν_x/ν_y	363.10 / 365.22			
Synchrotron tune ν_s	0.065	0.0395	0.028	
HOM power/cavity (2 cell) (kw)	0.54	0.75	1.94	
Natural energy spread (%)	0.1	0.066	0.038	
Energy acceptance requirement (%)	1.35	0.4	0.23	
Energy acceptance by RF (%)	2.06	1.47	1.7	
Photon number due to beamstrahlung	0.29	0.35	0.55	
Lifetime simulation (min)	100			
Lifetime (hour)	0.67	1.4	4.0	2.1
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP L (10^{34}cm^{-2}s^{-1})	2.93	10.1	16.6	32.1

E. Levichev, Y. Wang
FCC Week 2018

New particles – Extended Higgs Sector

Heavy Higgs Mass



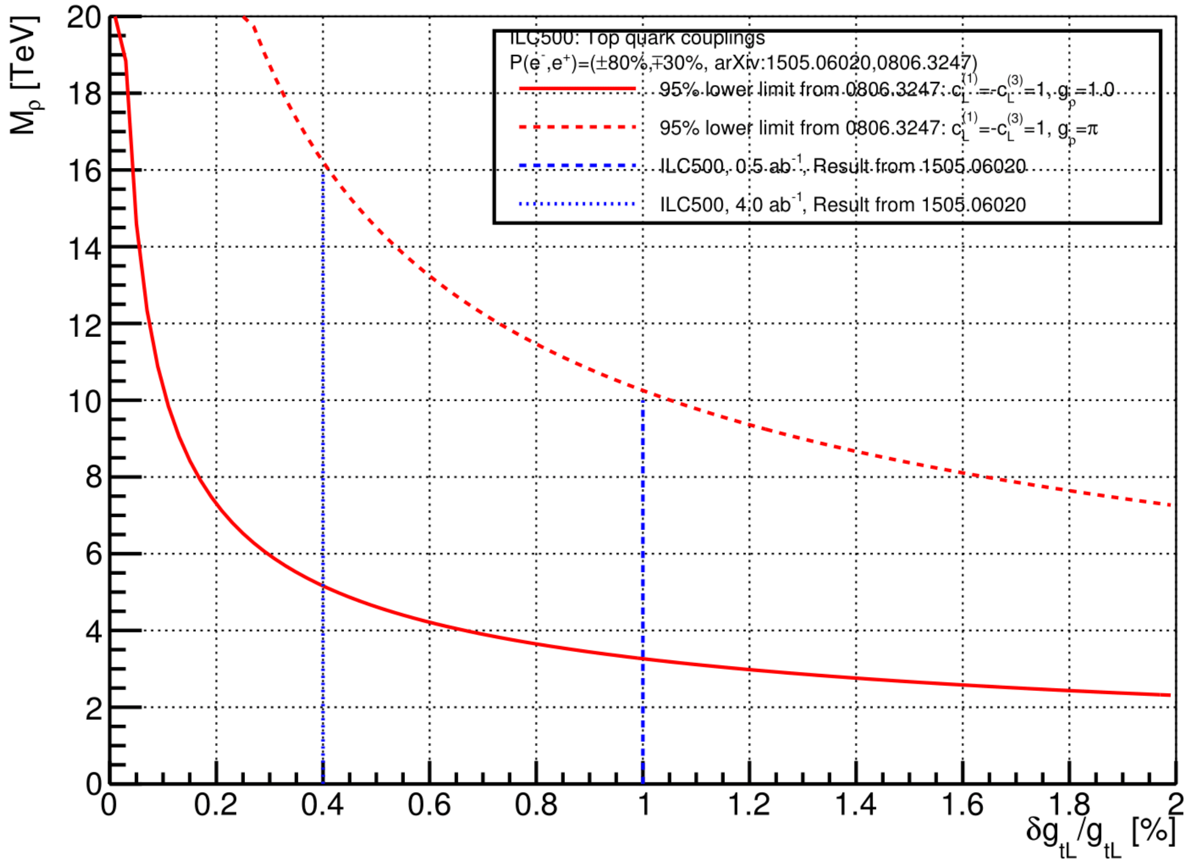
Deviations of λ from SM Value

- New (bosonic) particle may modify λ and enable 1st order phase transition
- Impact on measurements and achievable precisions of λ ?

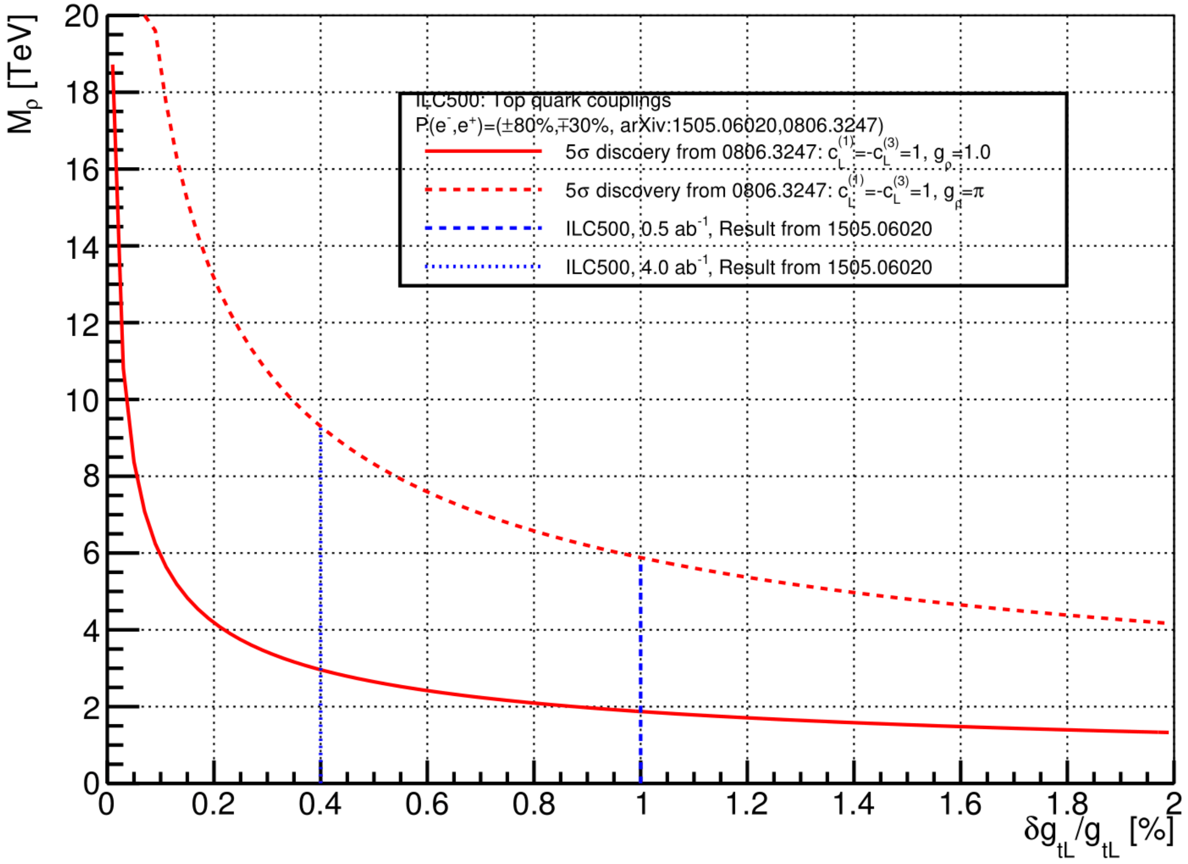
Electroweak top couplings and discovery reach

New physics reach for typical BSM scenarios with composite Higgs/Top and/or extra dimensions
Based on phenomenology described in Pomerol et al. arXiv:0806.3247

95% Exclusion Limit



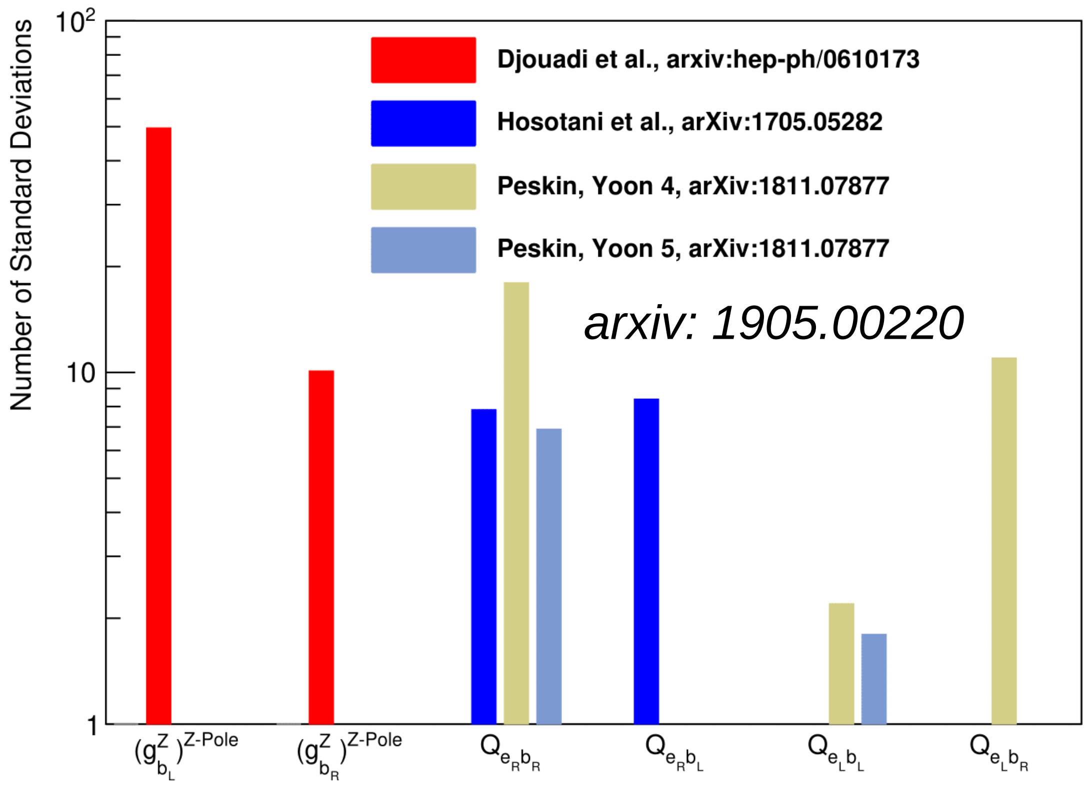
5σ discovery



ILC@500 has discovery potential up to 10 TeV for typical BSM scenario
More cms e.g. at CLIC would of course help a great deal (also for disentangling effects)

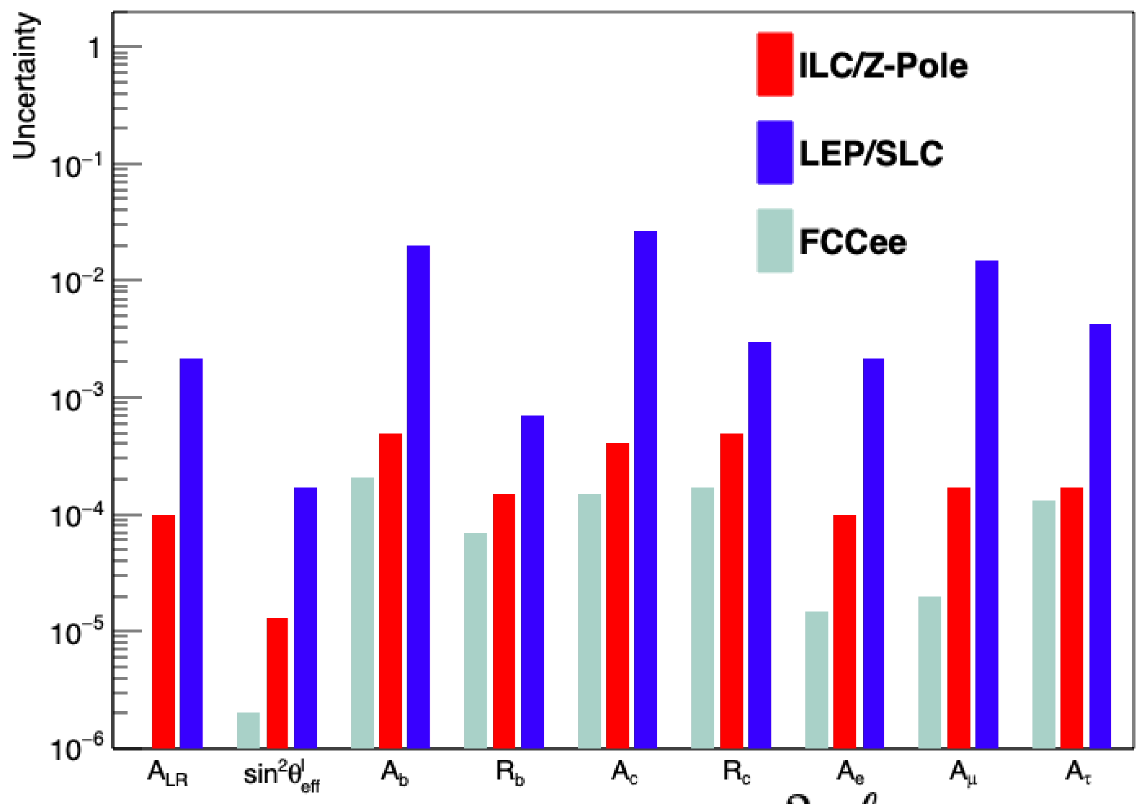
Precision on Z-pole and interplay with measurements above pole

Example: b couplings and helicity amplitudes



- Spectacular sensitivity to new physics in RS Models
  - **Complete tests only possible at LC**
  - **Discovery reach O(10 TeV)@250 GeV and O(20 TeV)@500 GeV**
- Pole measurements critical input
  - Only poorly constrained by LEP
- Pole measurements will (most likely) influence also top electroweak precision program
  - (t,b) doublet

Don't forget: Electroweak observables

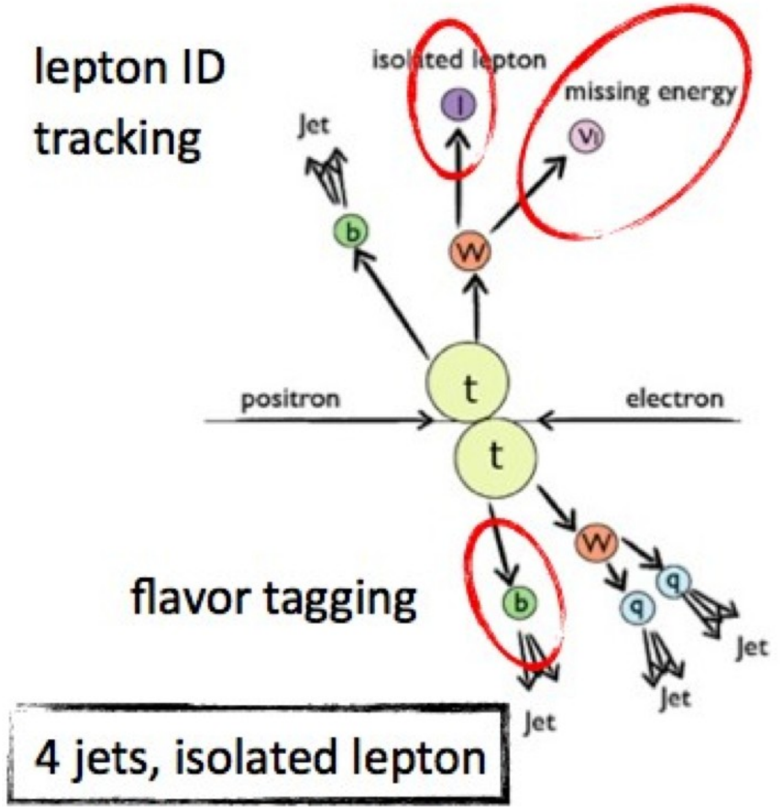


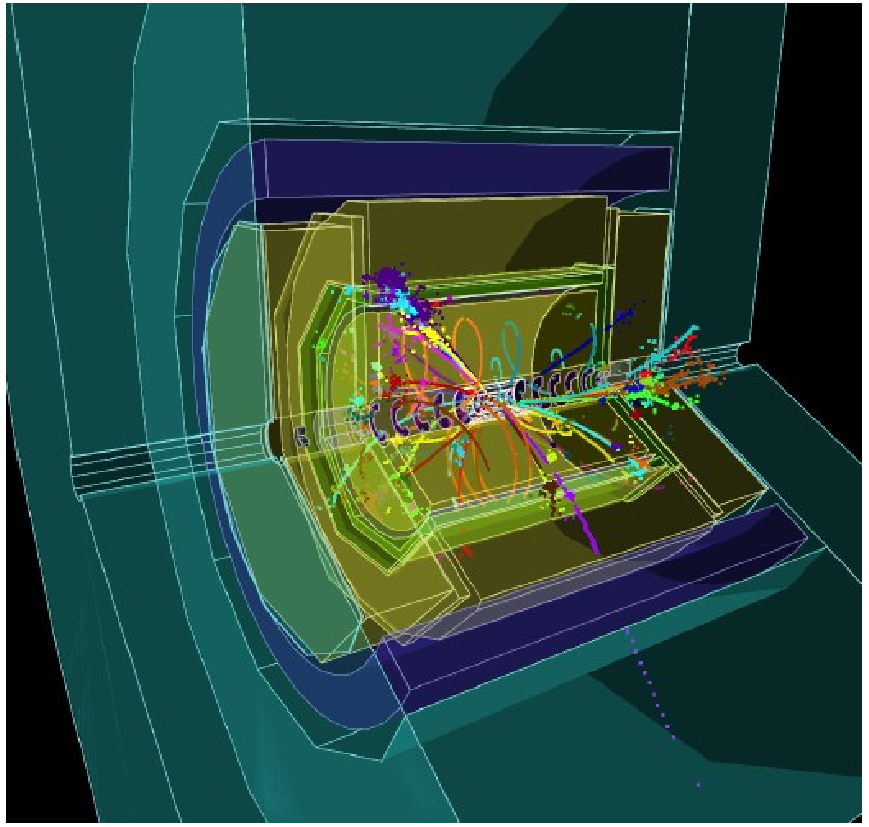
- Precise measurement of $\sin^2\theta^\ell_{\text{eff}}$.
  - Ten times better than LEP/SLD
  - Polarisation compensates for ~30 times luminosity
  - ... and ALR at LC can benefit from hadronic Z decays
  - **No assumption on lepton universality at LC**
- Complete test of lepton universality
  - Precisions of order 0.05%
- Excellent control of beam polarisation(dP/P ~ 5×10^{-4}) and beam energy (~MeV or better) required

Elements of top quark reconstruction

Three different final states:
1) Fully hadronic (46.2%) → 6 jets
2) Semi leptonic (43.5%) → 4 jets + 1 charged lepton and a neutrino
3) Fully leptonic (10.3%) → 2 jets + 4 leptons

$$t\bar{t} \rightarrow (bW)(bW) \rightarrow (bqq')(b\ell\nu)$$



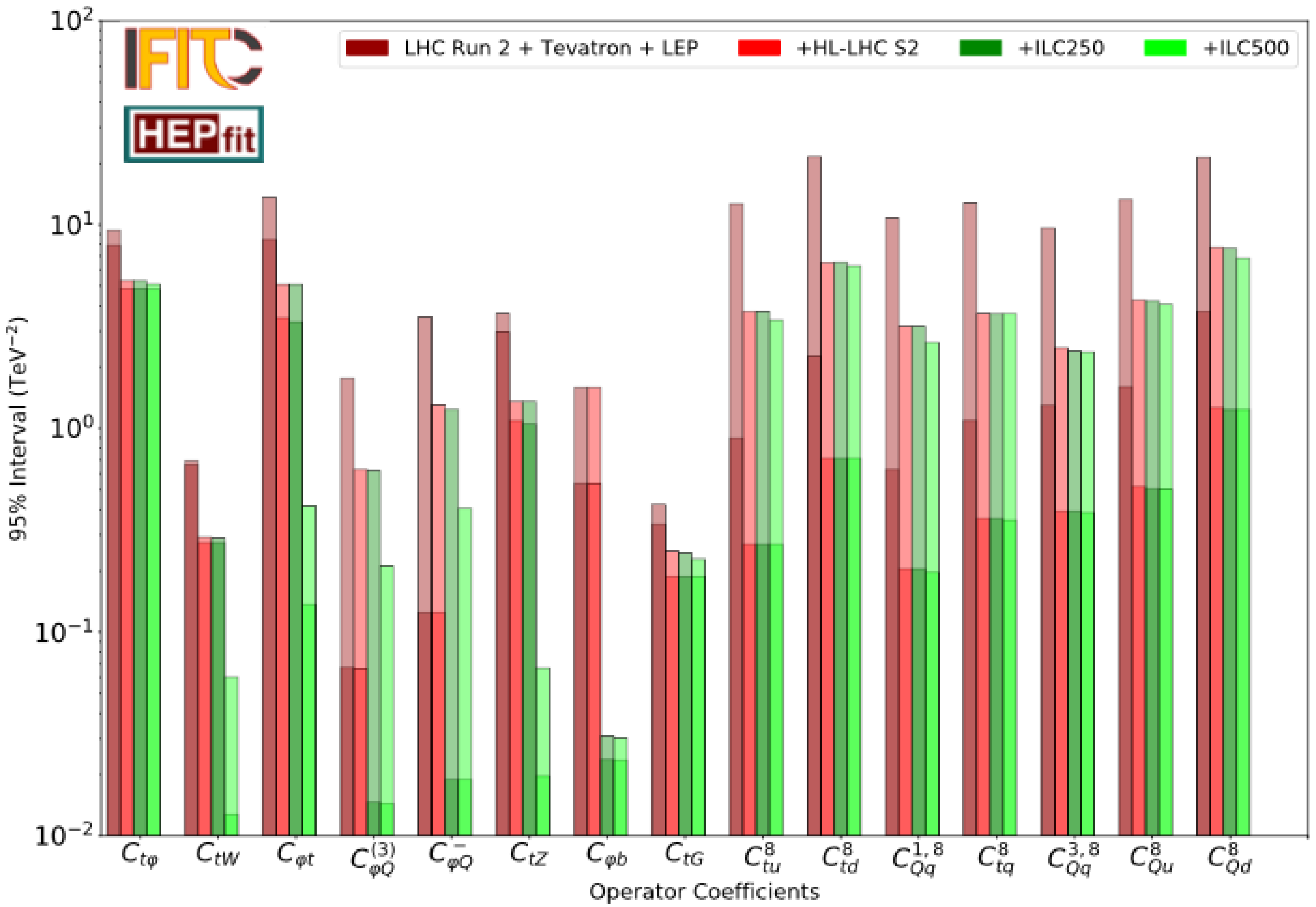


Final state reconstruction uses all detector aspects
Results shown in the following are based on <u>full simulation</u> of LC Detectors

92

92

Electroweak top couplings EFT-operators



arxiv:2203.07622
Updated from arxiv:1907.10619

Mapping between FF and EFT Coefficients

$$F_{1V}^Z = \frac{\frac{1}{4} - \frac{2}{3}s_W^2}{s_W c_W} - \frac{m_t^2}{\Lambda^2}\frac{1}{2 s_W c_W}\left[C_{\varphi q}^V = C_{\varphi u}^{(33)} + (C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)})\right],$$

$$F_{1A}^Z = \frac{-\frac{1}{4}}{s_W c_W} - \frac{m_t^2}{\Lambda^2}\frac{1}{2 s_W c_W}\left[C_{\varphi q}^A = C_{\varphi u}^{(33)} - (C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)})\right],$$

$$F_{2V}^Z = 4\frac{m_t^2}{\Lambda^2}\left[C_{uZ}^R = \mathrm{Re}\{c_W^2 C_{uW}^{(33)} - s_W^2 C_{uB}^{(33)}\}/s_W c_W\right],$$

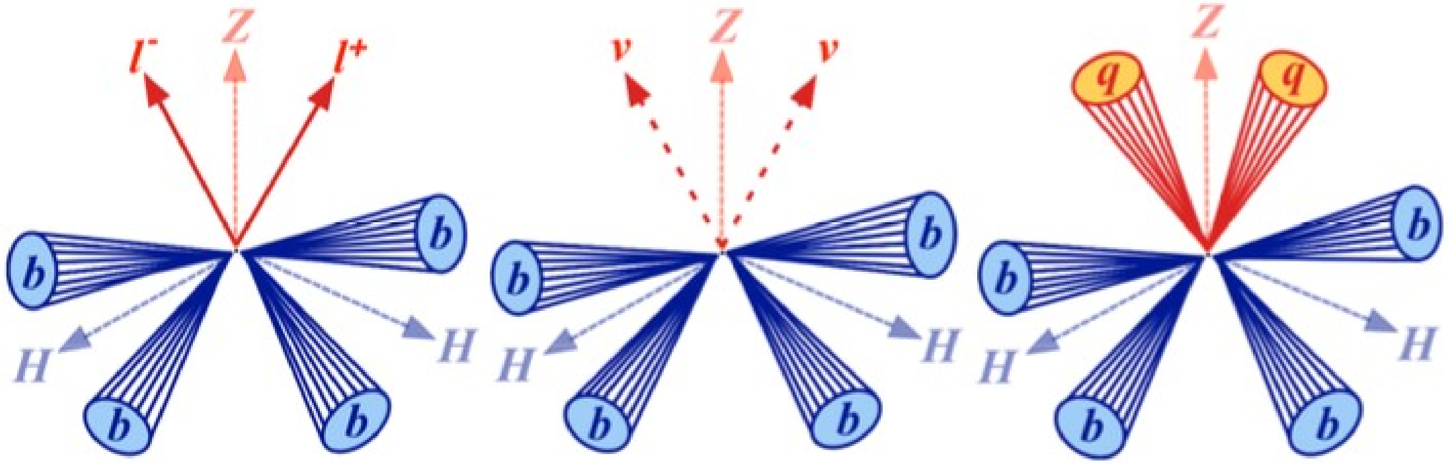
$$F_{2A}^Z = 4\frac{m_t^2}{\Lambda^2} i\left[C_{uZ}^I = \mathrm{Im}\{c_W^2 C_{uW}^{(33)} - s_W^2 C_{uB}^{(33)}\}/s_W c_W\right],$$

arxiv:1807.02121

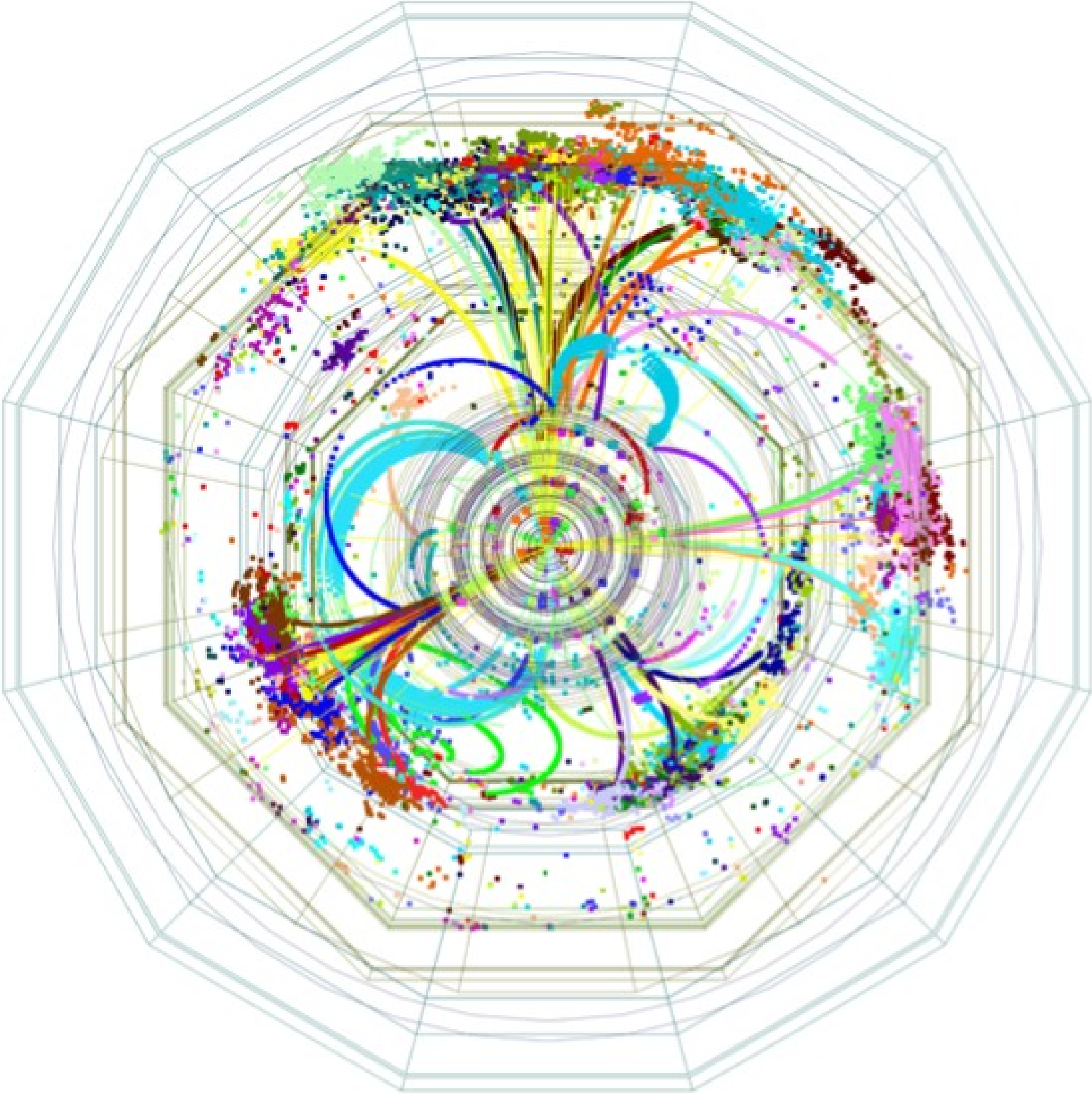
- Translation of results into EFT language confirm superiority of e+e- w.r.t. LHC
- Several operators benefit already from 250 GeV running
- Top specific operators constrained by running at 500 GeV

93

Higgs self-coupling – Experimental issues



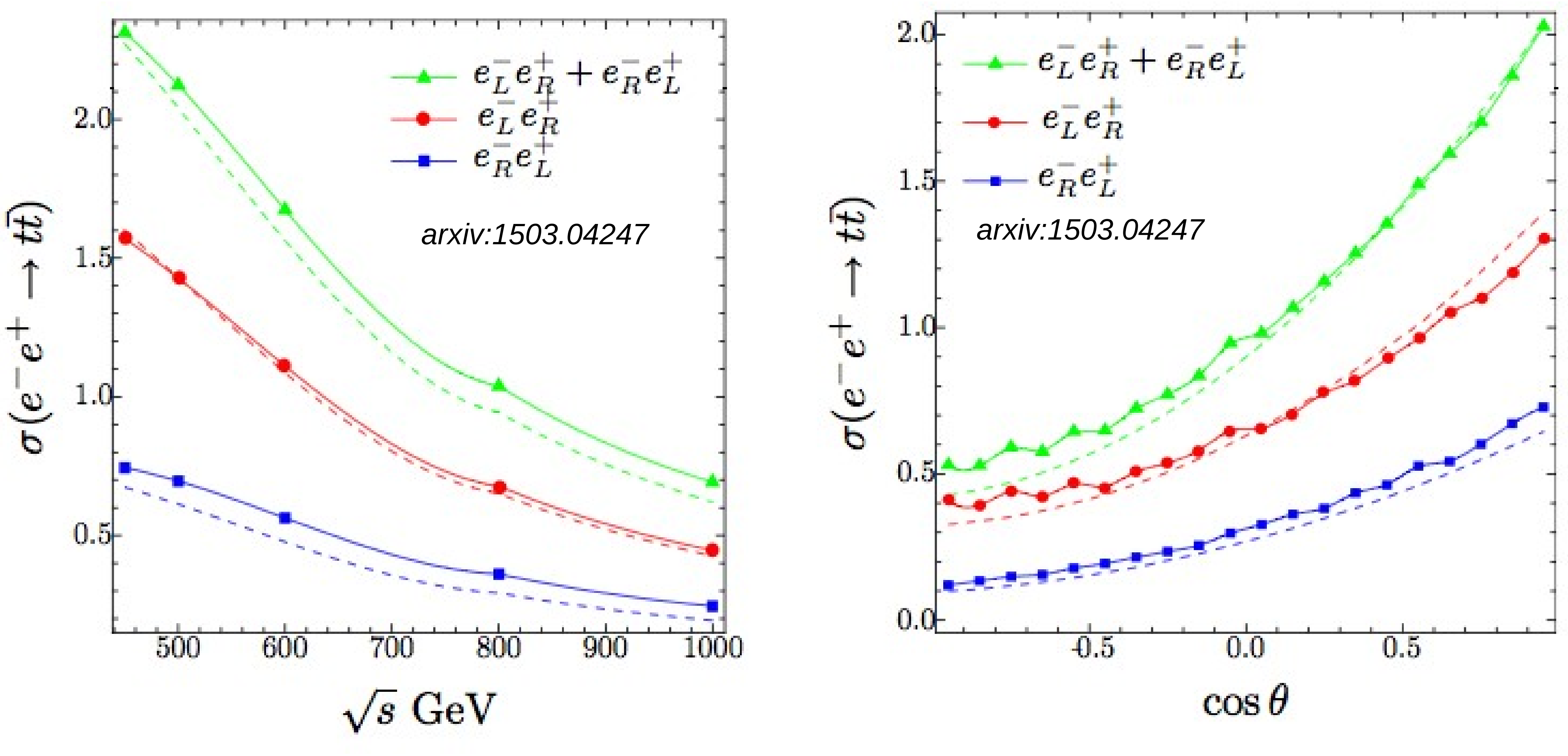
ILD Event Display



- Up to six jets in final state
  - Excellent jet and particle separation and (nearly) 4pi hermeticity required
- Four b-quarks
  - Excellent flavor tagging
  - Results shown in the following profit from recent improvements

Julie Munch Torndal and DESY-THESIS-2016-027

High Order Electroweak Corrections



- Electroweak corrections manifest themselves differently for different beam polarisations

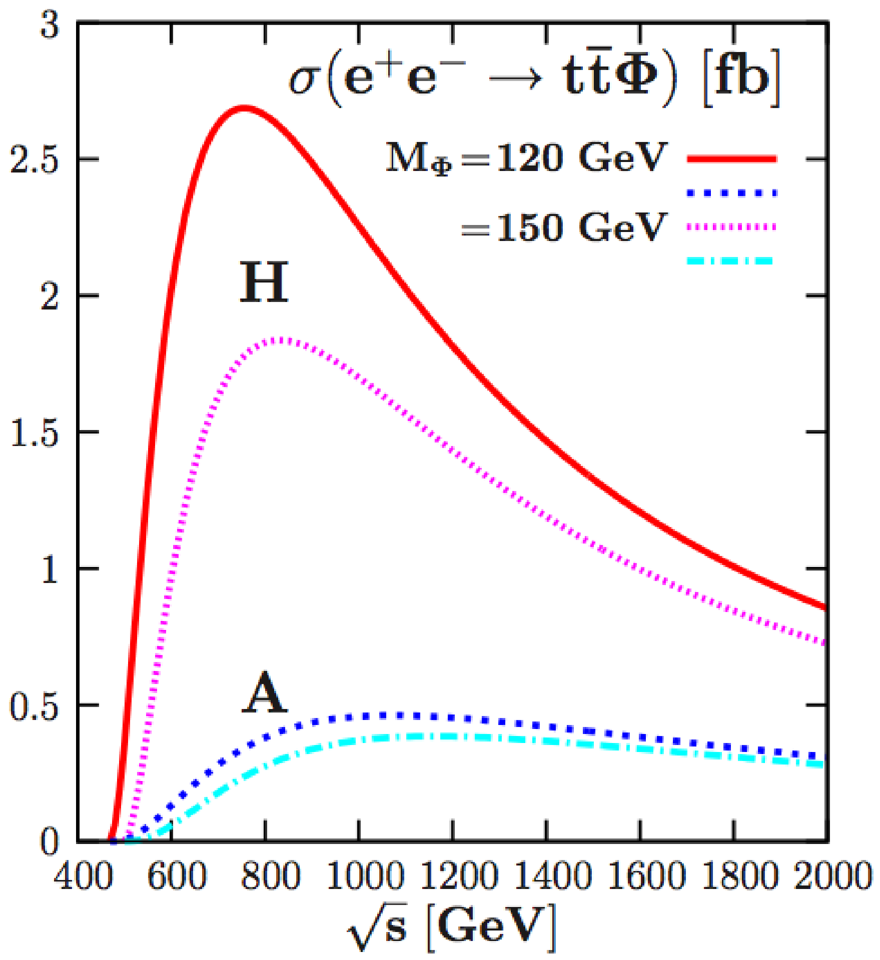
Beam polarisation important asset to disentangle SM and effects of new physics

Configuration $e_R^- e_L^+$ seems to lead to "simpler" corrections

Higgs Quantum Number – CP via tth

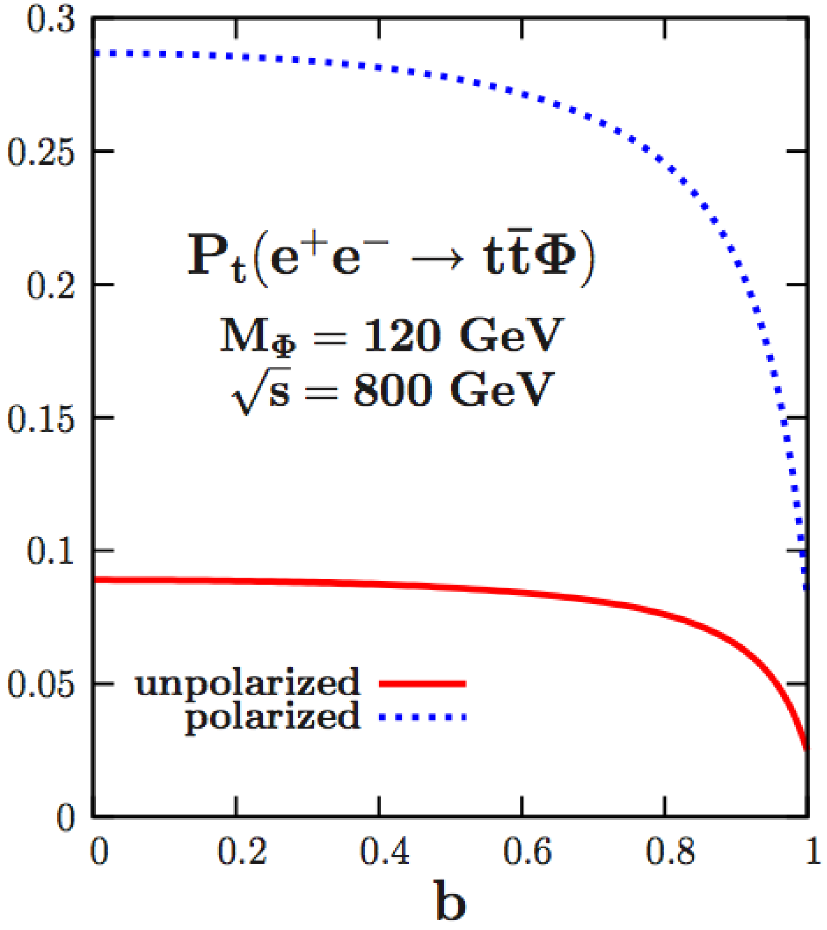
Direct coupling of top quark to CP odd and CP even scalar

Cross section



Dramatic differences for
CP odd and CP even scalar

Top quark polarisation



Sensitivity to CP odd admixture b
Merit of beam polarisation

Determination of CP nature of scalar boson in an unambiguous way

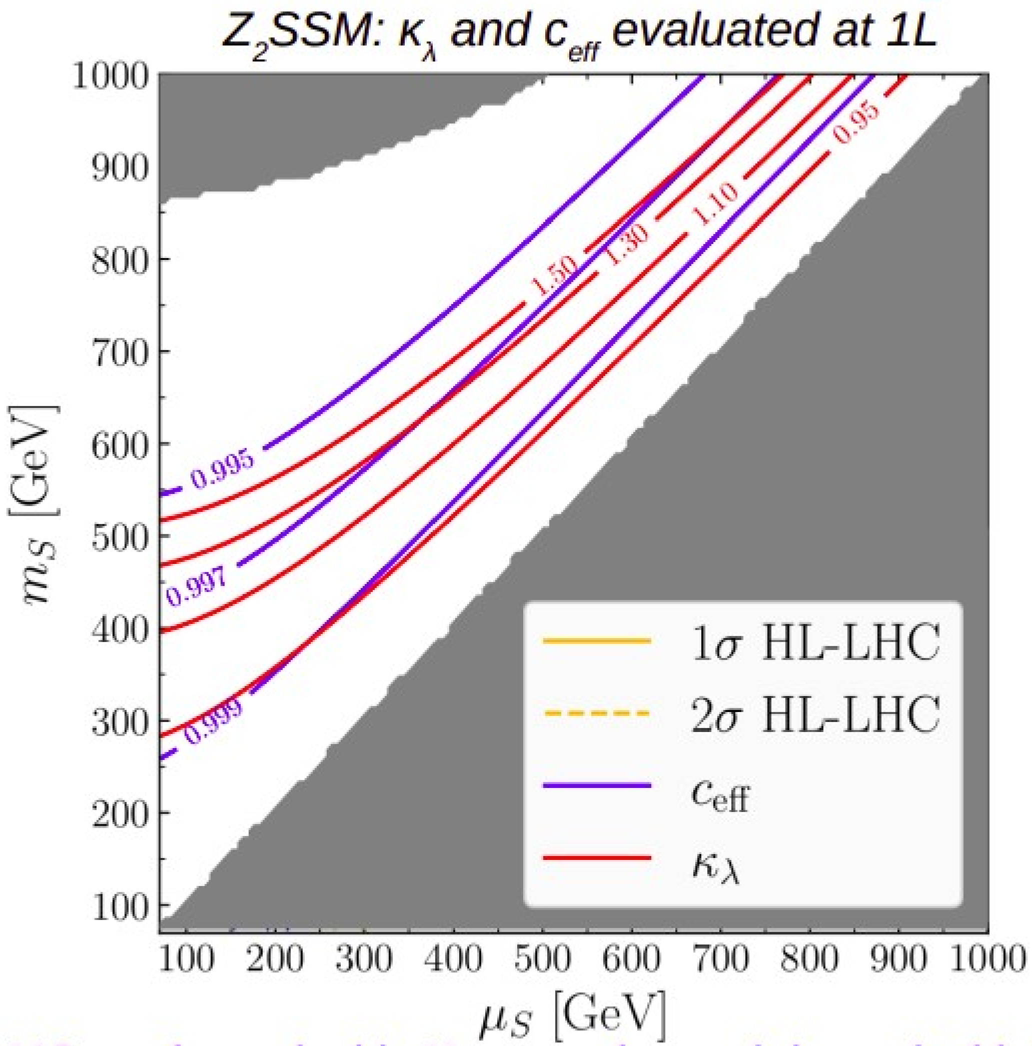
Godbole et al., LCWS07

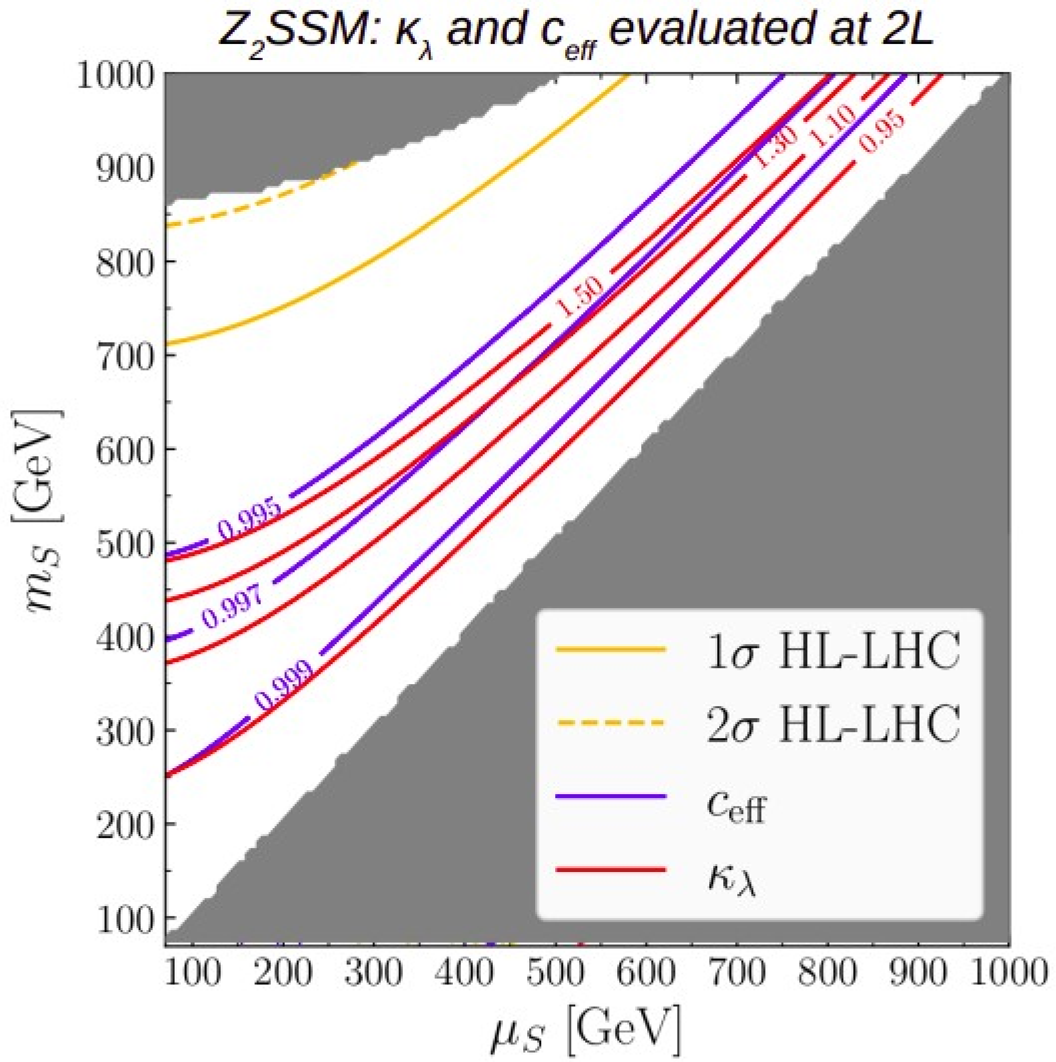
Probing New Physics with the trilinear Higgs Coupling

J. Braathen, IDT-WG3 Physics Meeting

Effective couplings in the Z_2SSM

[Bahl, JB, Gabelmann, Heinemeyer, Radchenko Serdula, Verduras Schaeidt, Weiglein *WIP*]





- HL-LHC: no bound with 1L c_{eff}, only weak bound with 2L c_{eff}
- O(50%) accuracy on κ_λ is stronger than O(0.5%) accuracy on c_{eff} (i.e. g_{hVV})
- O(20%) accuracy on κ_λ is competitive with O(0.3%) accuracy on c_{eff} (i.e. g_{hVV}) for most of the parameter plane

DESY. | IDT-WG3-Phys Open Meeting | Johannes Braathen (DESY) | 15 November 2024 Page 24

Higgs production at e+e- colliders