Precision and Discovery
Physics Potential of Linear Electron-Positron Colliders

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Based on the results of a number of distinguished colleagues

LISHEP 2023 – Rio de Janeiro (BRA) – March 2023

For a comprehensive overview of newest result, see the ILC Snowmass Report
550 signees!!!!

Open questions

How to make progress?

1) Collisions at energies well above the electroweak scale
  - Requires now and in the foreseeable future Hadron colliders
  - Direct production of new particles
  - Produce large number of rare particles and study rare decays
  - First precision measurements of key particles of electroweak theory

-> High energy, High luminosity LHC

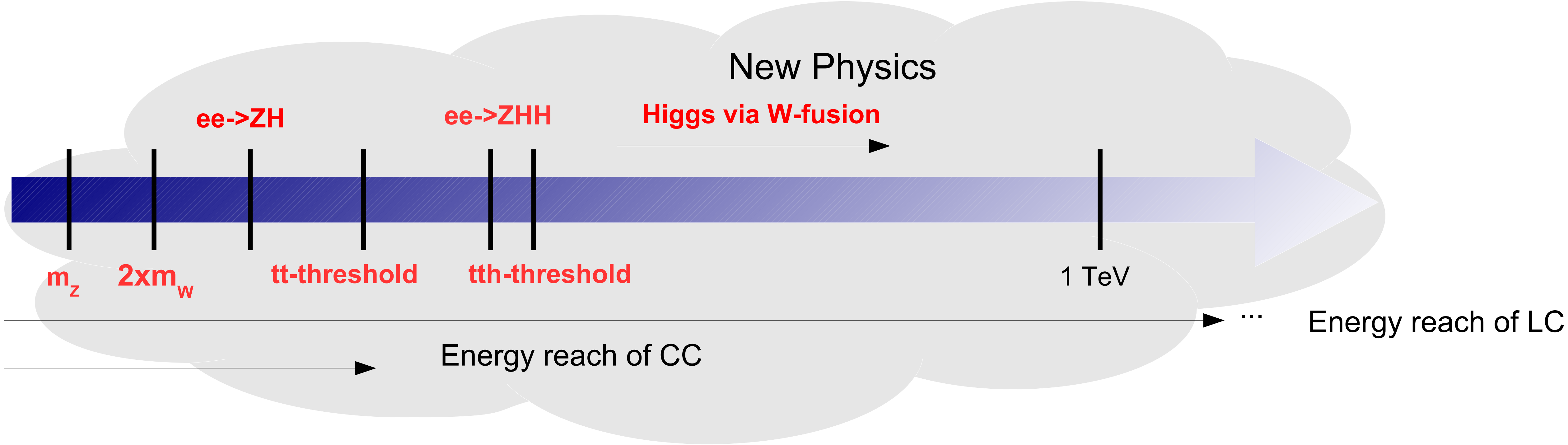
2) e+e-Collisions at energies at the electroweak scale and above
  - Probe the electroweak scale with high precision
  - ... in particular particles that carry the “imprint of the Higgs Field such as W, Z and top”

-> LC

3) e+e- collisions at 'smaller' energies
  - Requires high luminosity to get sensitive to tiny quantum effects

-> SuperKEKB

e+e- Physics program

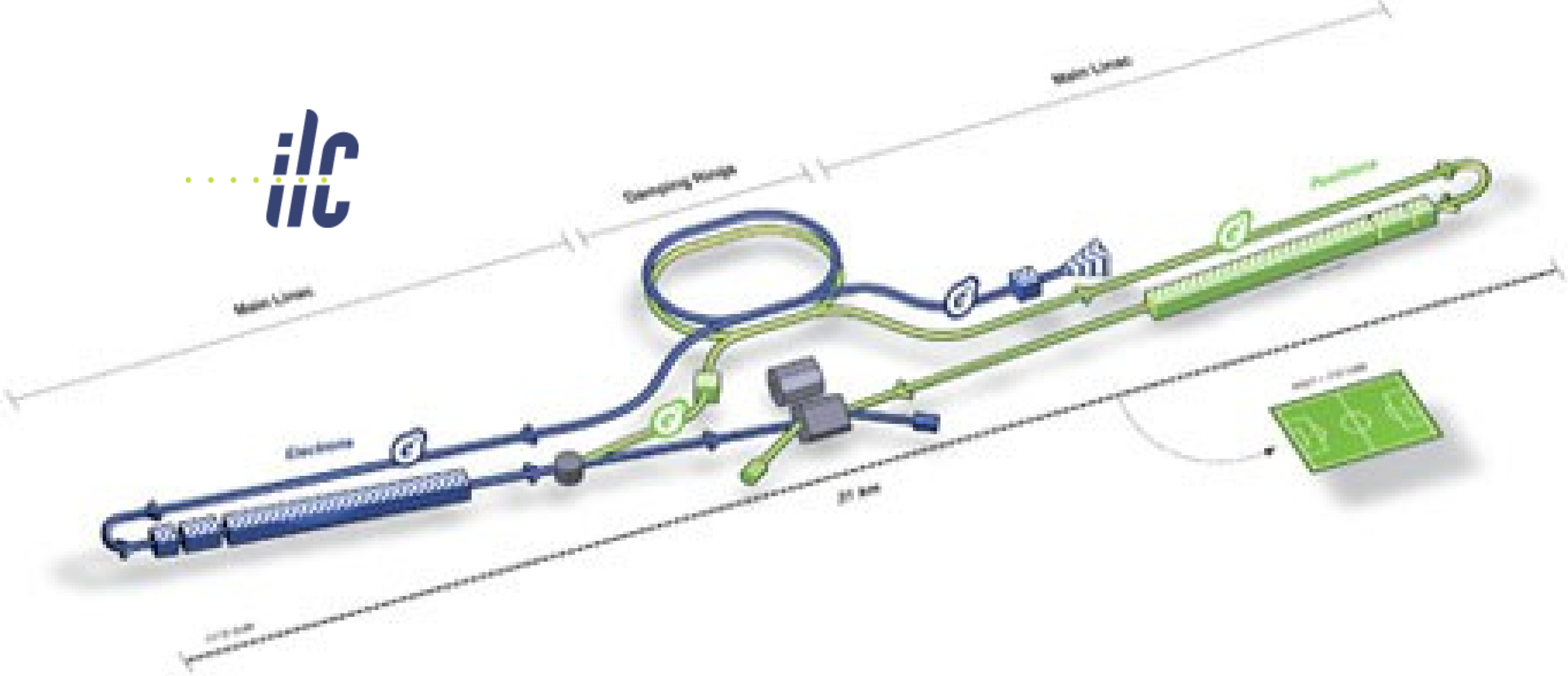


- All Standard Model particles within reach of planned e+e- colliders
- High precision tests of Standard Model over wide range to detect onset of New Physics
- Machine settings can be “tailored” for specific processes
  - Centre-of-Mass energy
  - Beam polarisation (straightforward at linear colliders)

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

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

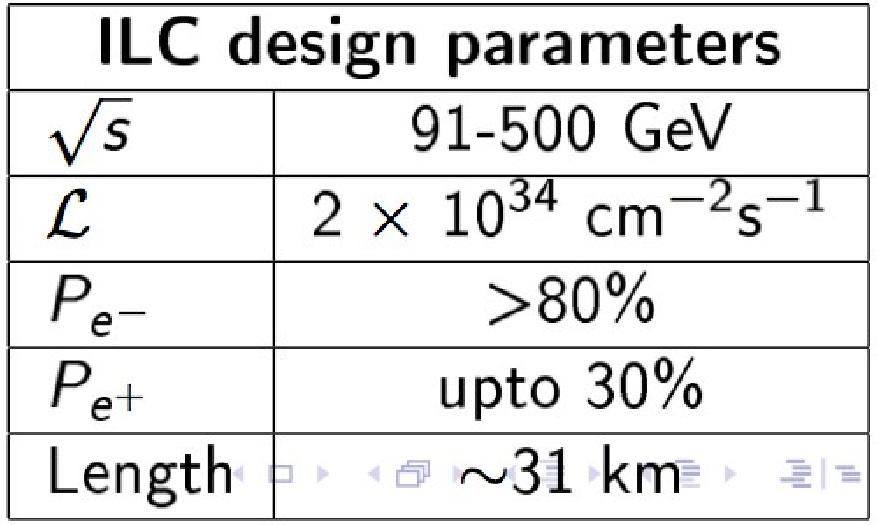
Linear Electron Positron Colliders - ILC



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)



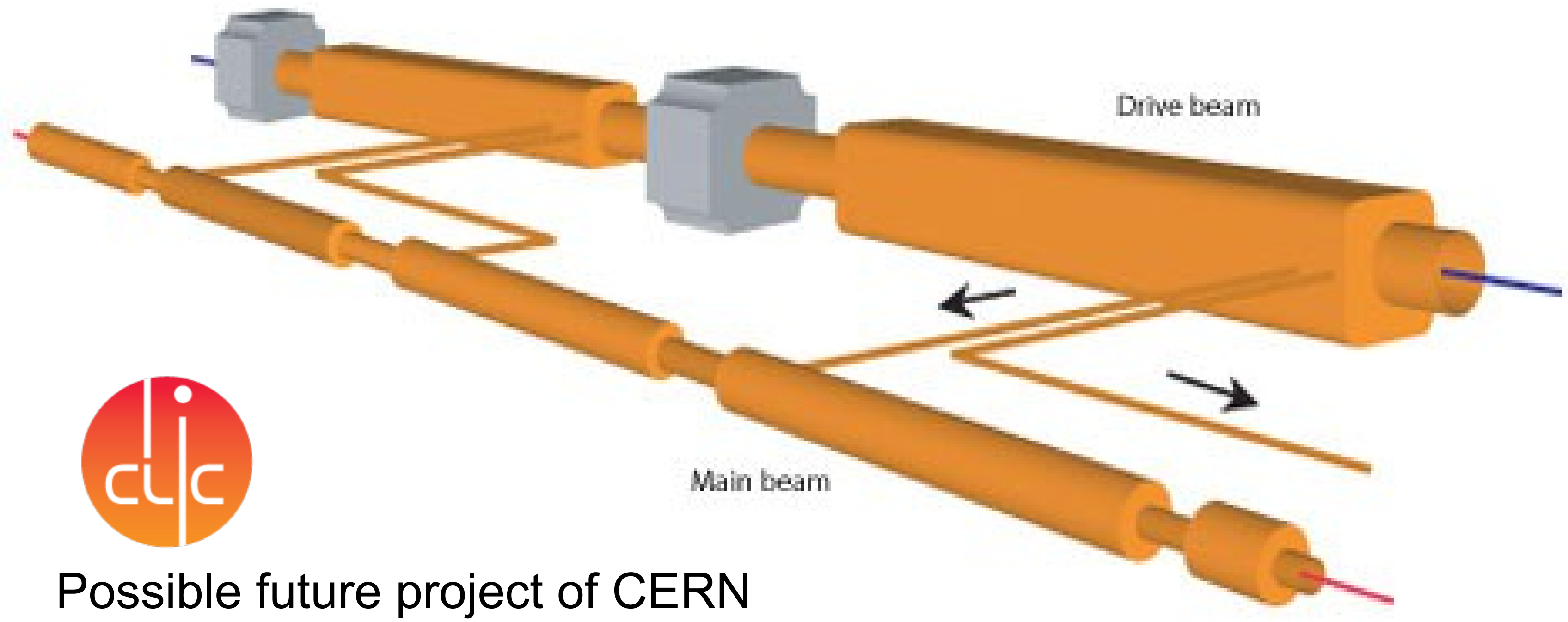
ILC design parameters	
$\sqrt{s}$	91-500 GeV
$\mathcal{L}$	$2 \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
P_{e^-}	>80%
P_{e^+}	upto 30%
Length	~31 km

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/

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

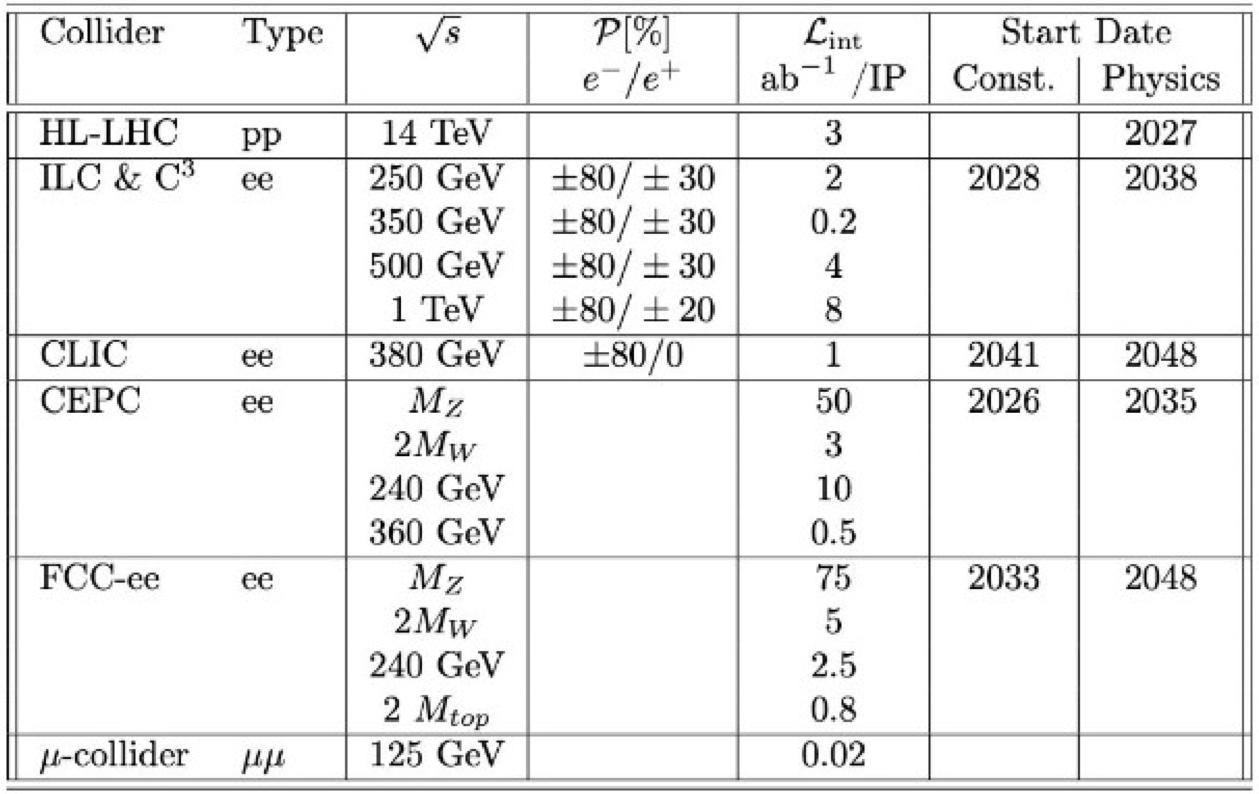

First C^3 structure at SLAC

Cool Copper Collider

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

Time Scale of Future Projects

Snowmass EF-Vision (L. Reina)



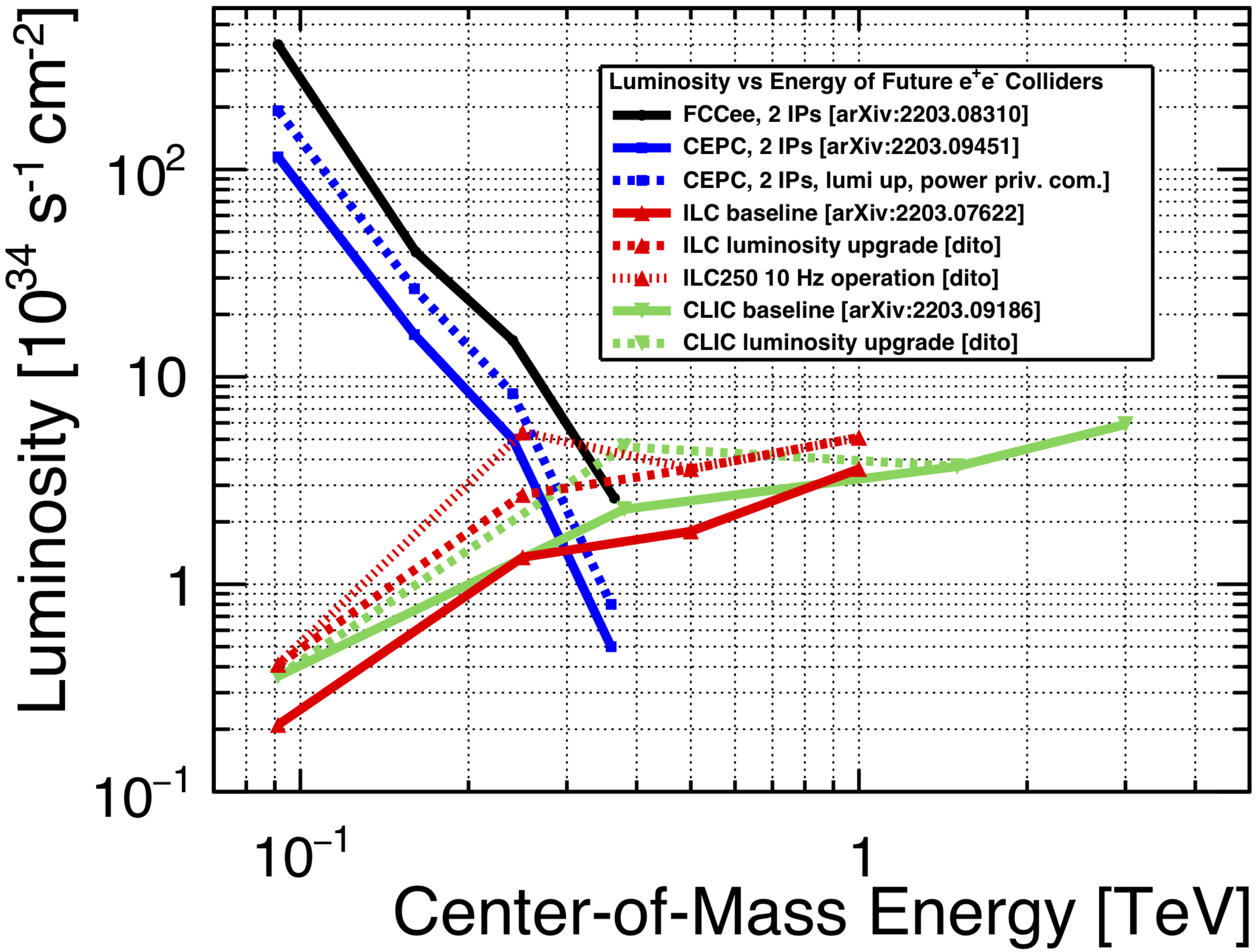
Collider	Type	$\sqrt{s}$	$\mathcal{P}[\%]$ e^-/e^+	$\mathcal{L}_{\rm int}$ ab^{-1}/IP	Start Date Const.	Start Date Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C^3	ee	250 GeV 350 GeV 500 GeV 1 TeV	$\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm30$ $\pm80/\pm20$	2 0.2 4 8	2028	2038
CLIC	ee	380 GeV	$\pm80/0$	1	2041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

ECFA Detector R&D Roadmap

Approved by European Lab Directors Group

- International roadmaps consider construction of a linear collider towards the end of this decade
- We may seek to combine the beast of all (linear) worlds into a linear facility
  - Avoids entangling of a electron-positron collider and a hadron machine
- It would be the parallel running of a TeV hadron machine and a electron positron collider at the TeV scale that “maximises scientific output “

Linear vs. circular e+e- machines – Instantaneous luminosities



- High energies ~above tt-threshold
  Domain of linear colliders

- Low energies e.g. Z-pole
  Domain of circular machines
  However, see later ...

- Transition region, i.e. HZ threshold
  … not so clear
  Comparable numbers for all proposals
  and N = σL

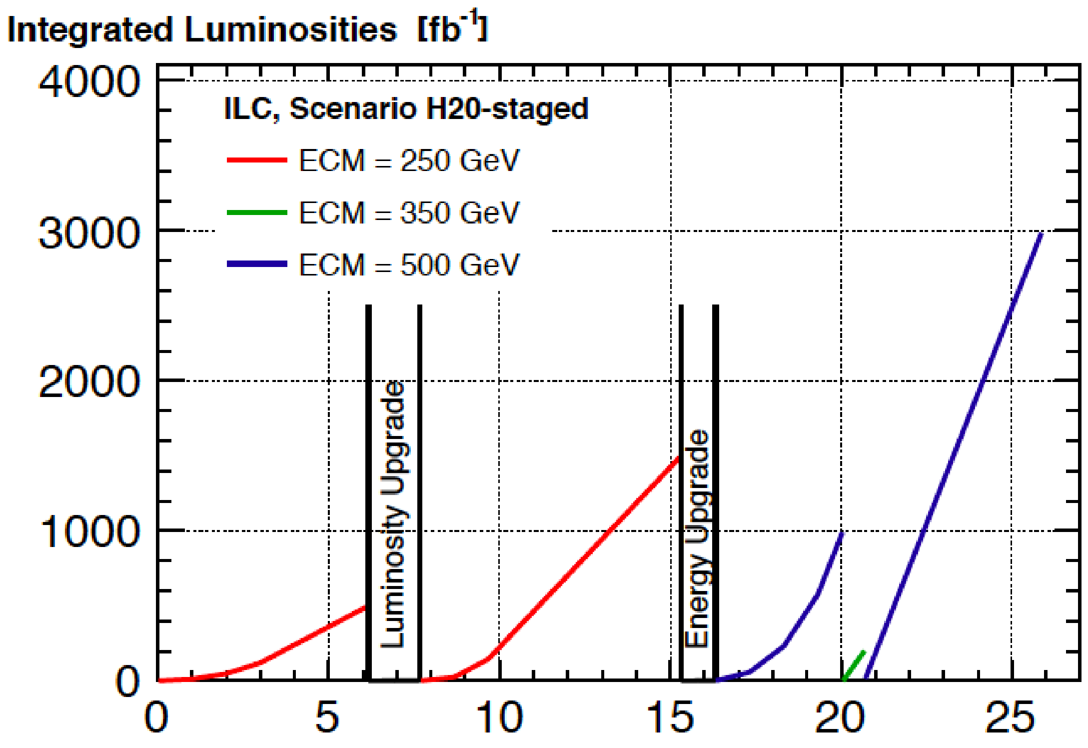
- Linear colliders are more versatile
  to test chiral theory due to polarised
  beams

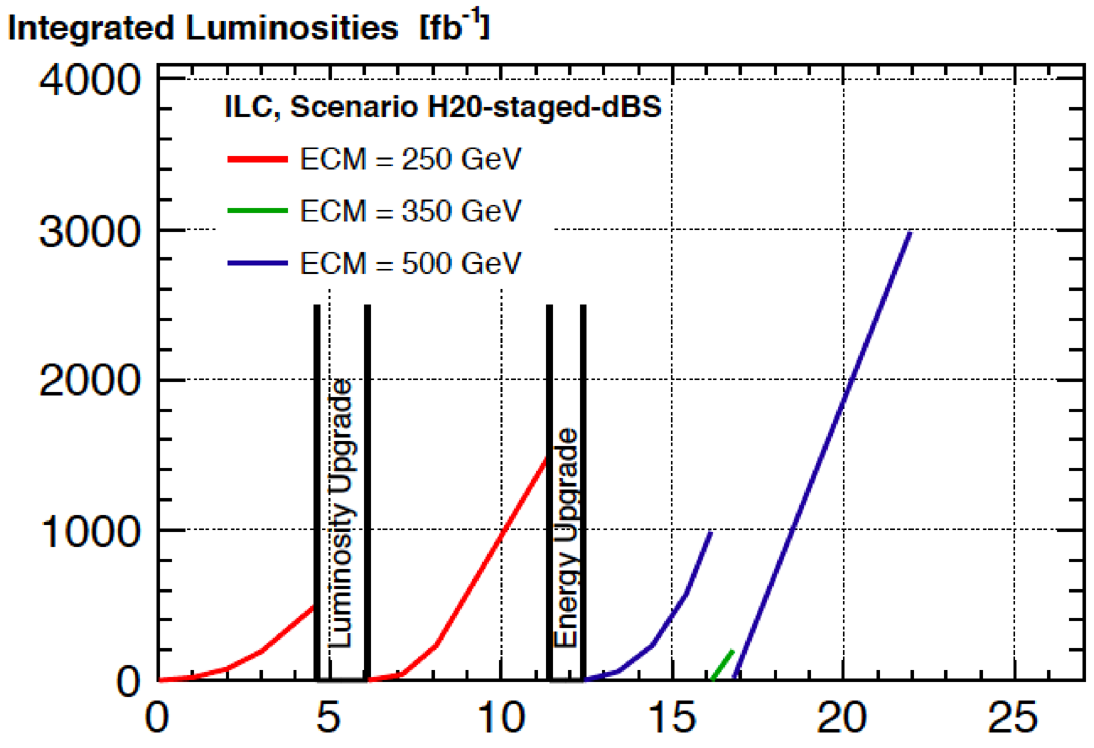
- Plot on power consumption see backup

Figure J. List

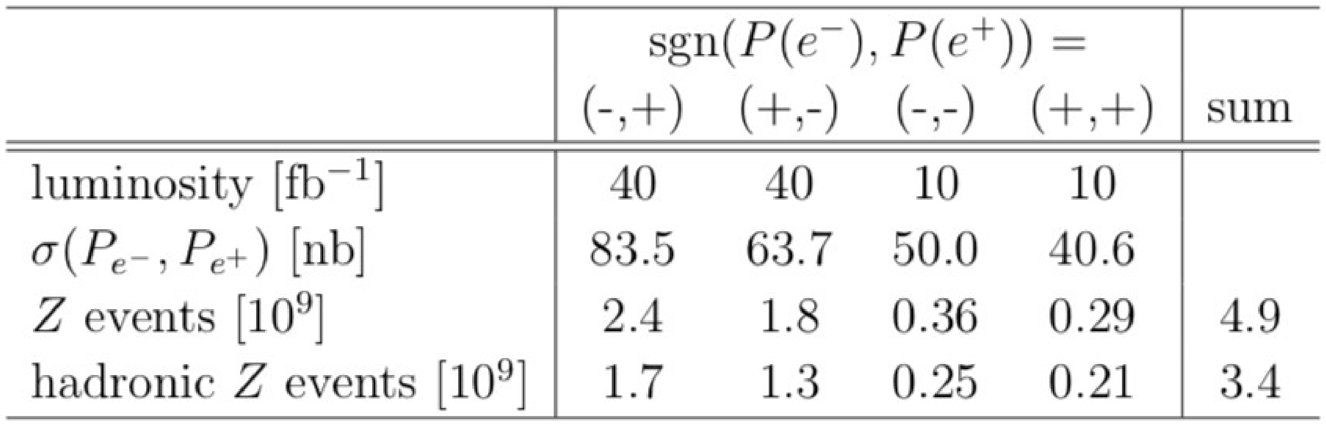
ILC Running Scenarios

arXiv:1506.07830





In 2019 – Revision of capabilities to run on the Z Pole - GigaZ



	$\mathrm{sgn}(P(e^-), P(e^+)) =$				
	(-,+)	(+,-)	(-,-)	(+,+)	sum
luminosity [fb^{-1}]	40	40	10	10	
$\sigma(P_{e^-}, P_{e^+})$ [nb]	83.5	63.7	50.0	40.6	
Z events [10^9]	2.4	1.8	0.36	0.29	4.9
hadronic Z events [10^9]	1.7	1.3	0.25	0.21	3.4

- Pole running can happen before and after the luminosity upgrade
- Further details see arxiv: 2203.07622

Detector requirements

Track momentum: $\sigma_{1/p}$ < 5×10^{-5}/GeV (1/10 x LEP)

(e.g. Measurement of Z boson mass in Higgs Recoil)

Impact parameter: $\sigma_{d0} < [5 \oplus 10/(p[\mathrm{GeV}]\sin^{3/2}\theta)]$ μm (1/3 x SLD)

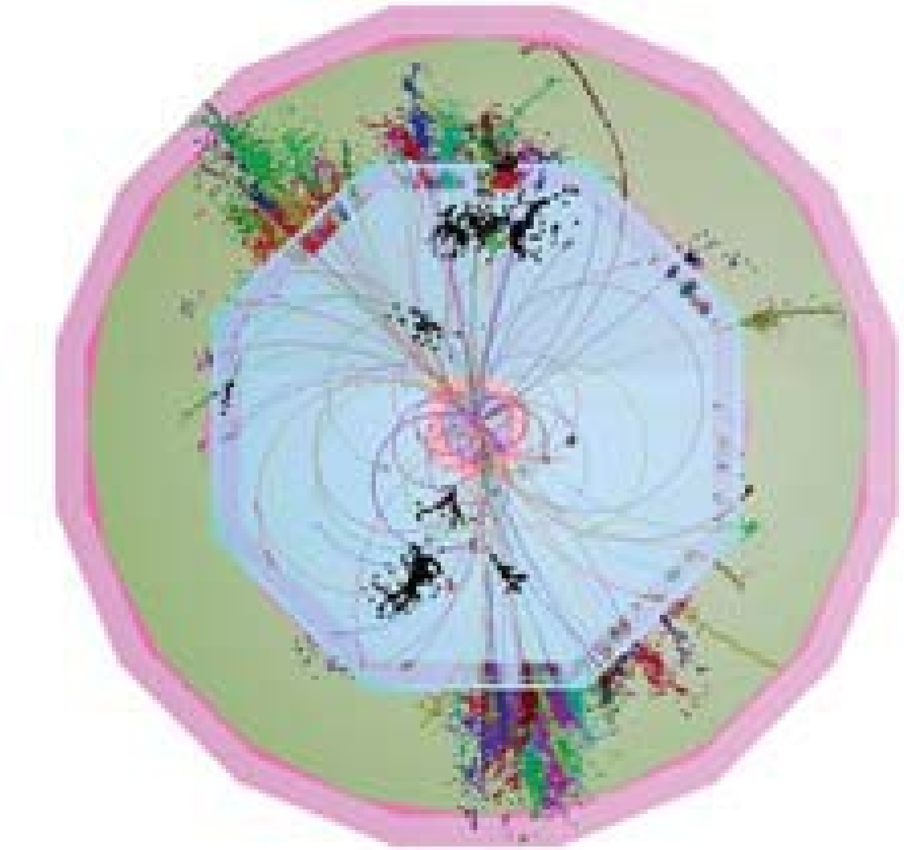
(Quark tagging c/b)

Jet energy resolution : $dE/E = 0.3/(E(\mathrm{GeV}))^{1/2}$ (1/2 x LEP)

(W/Z masses with jets)

Hermeticity : θ_{min} = 5 mrad

(for events with missing energy e.g.dark sector/ invisible decays)



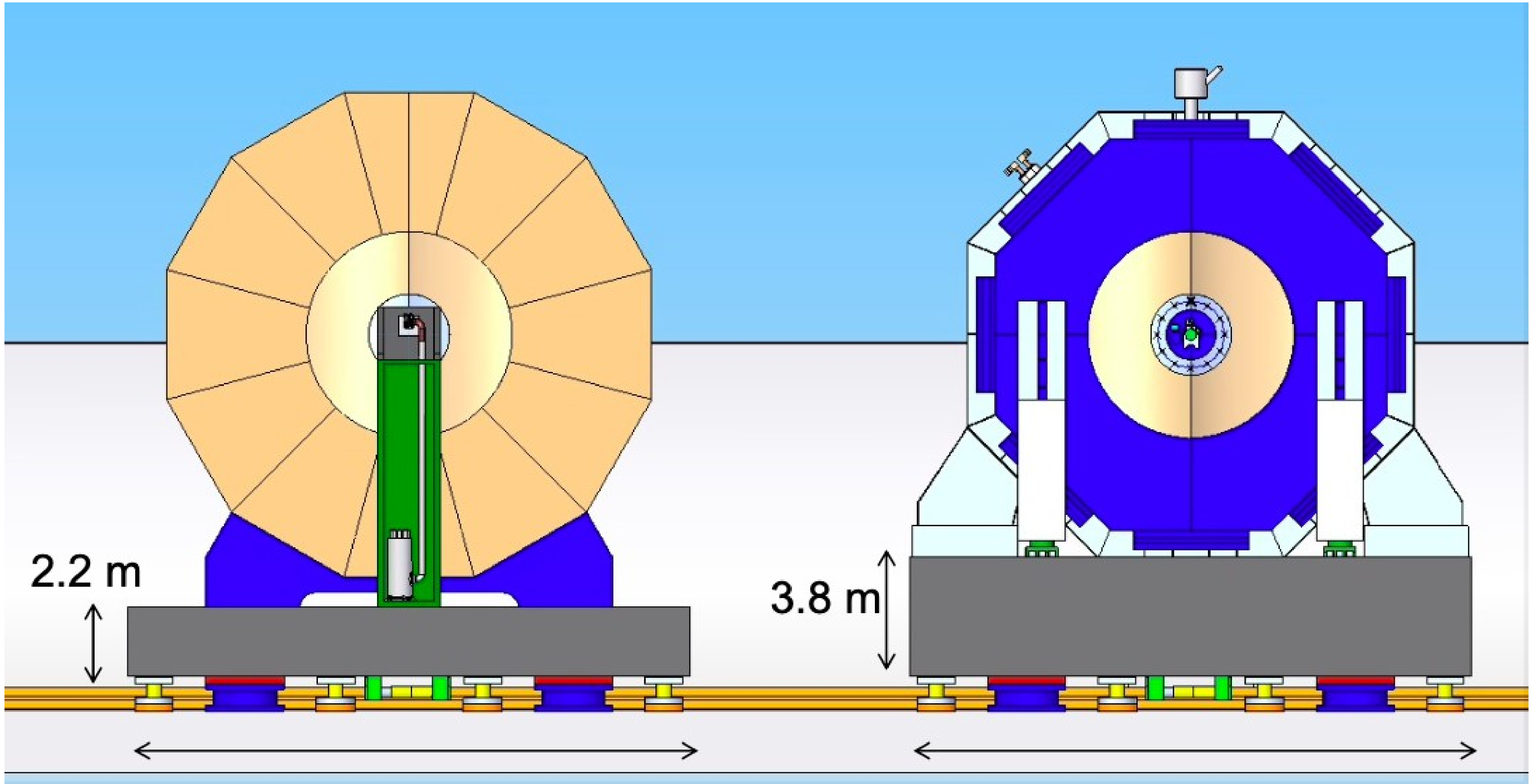
Final state will comprise events with a large number of charged tracks and jets(6+)

- High granularity
- Excellent momentum measurement
- High separation power for particles

- Particle Flow Detectors
- Detector Concepts: ILD, SiD and CLICdp

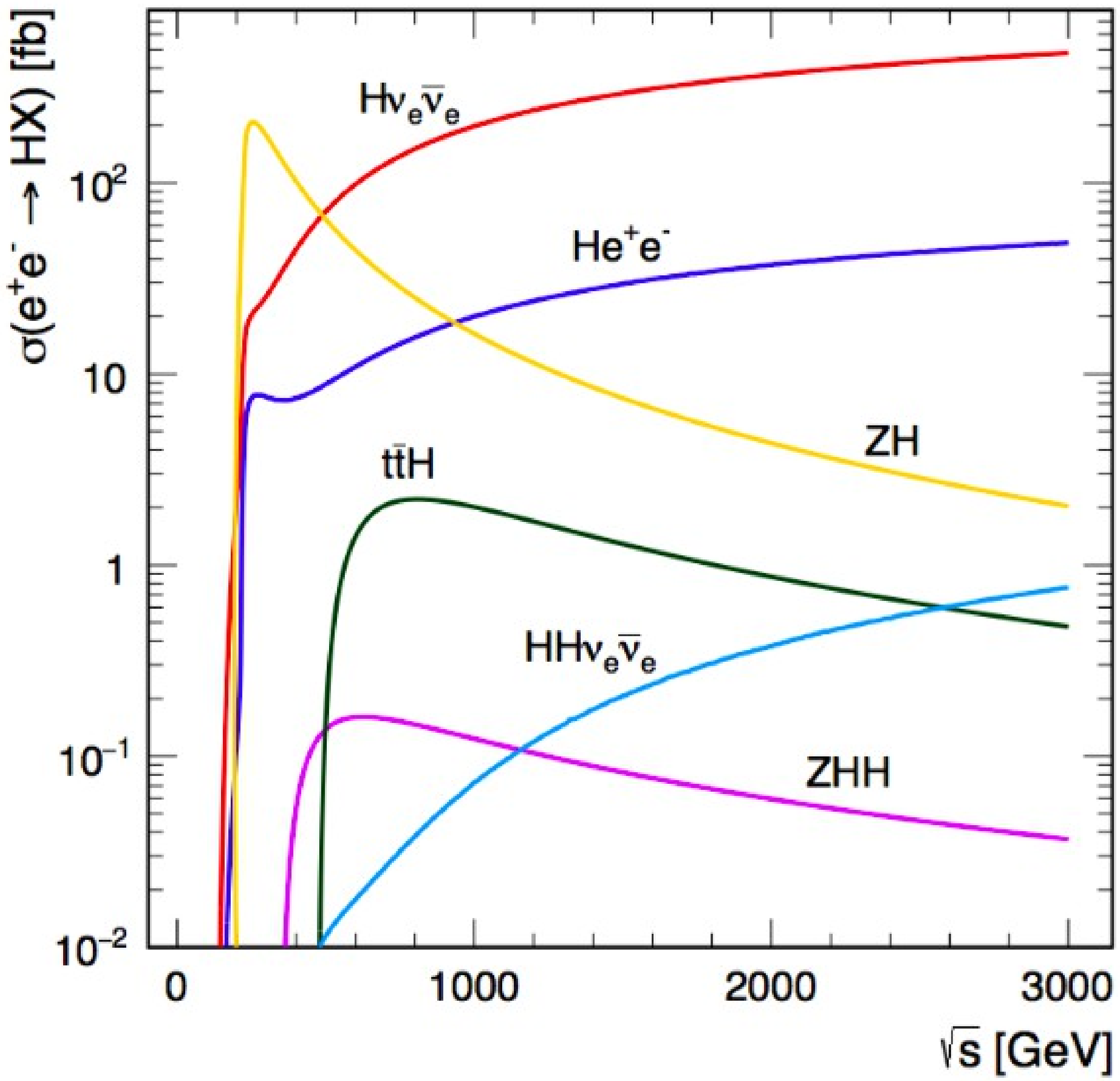
+New ideas!!!!

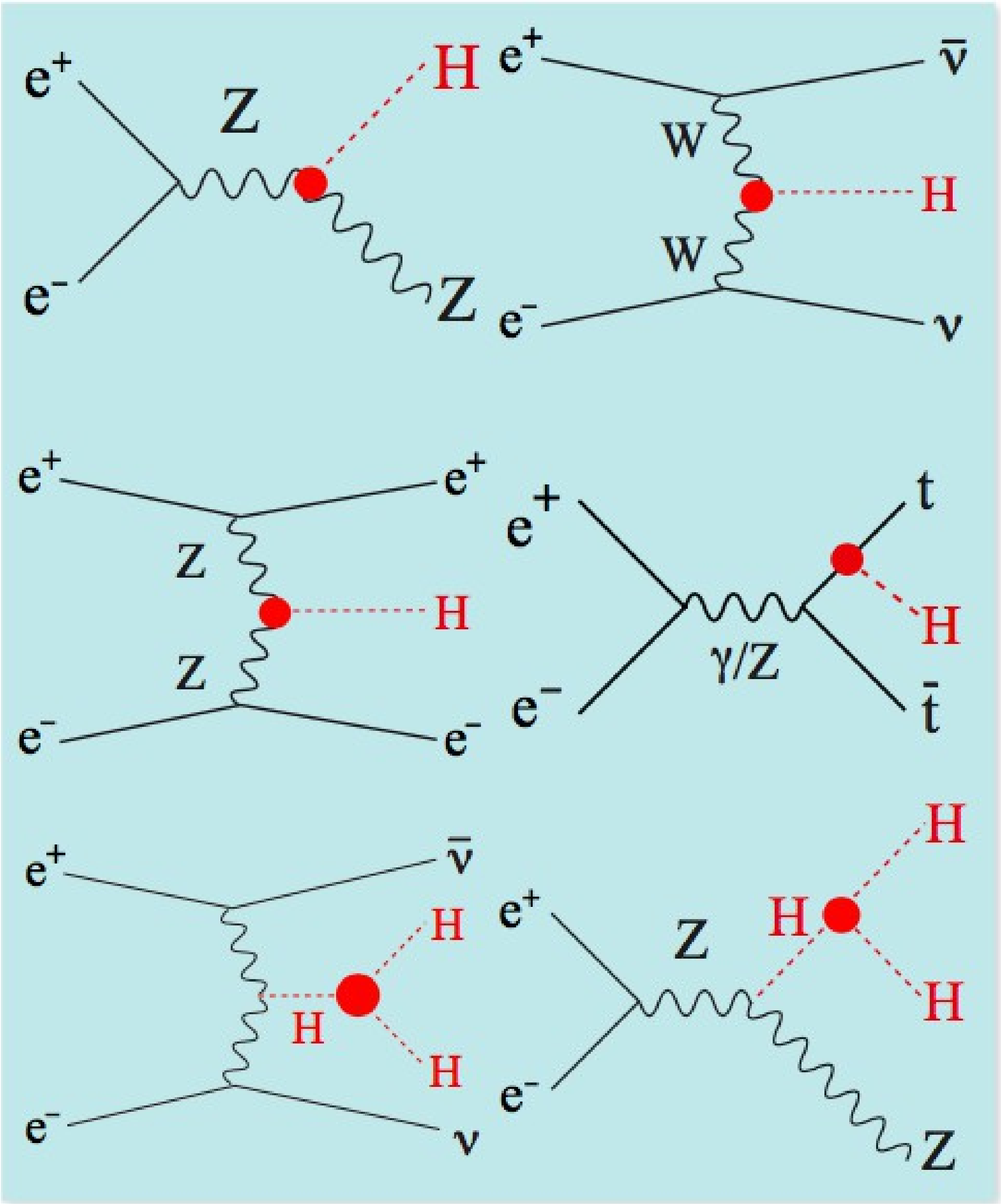
Two Detectors – Push Pull Operation



- The baseline of ILC foresees two detectors
  - One interaction region
- Detectors will be operated in push-pull mode

Higgs production at e+e- colliders

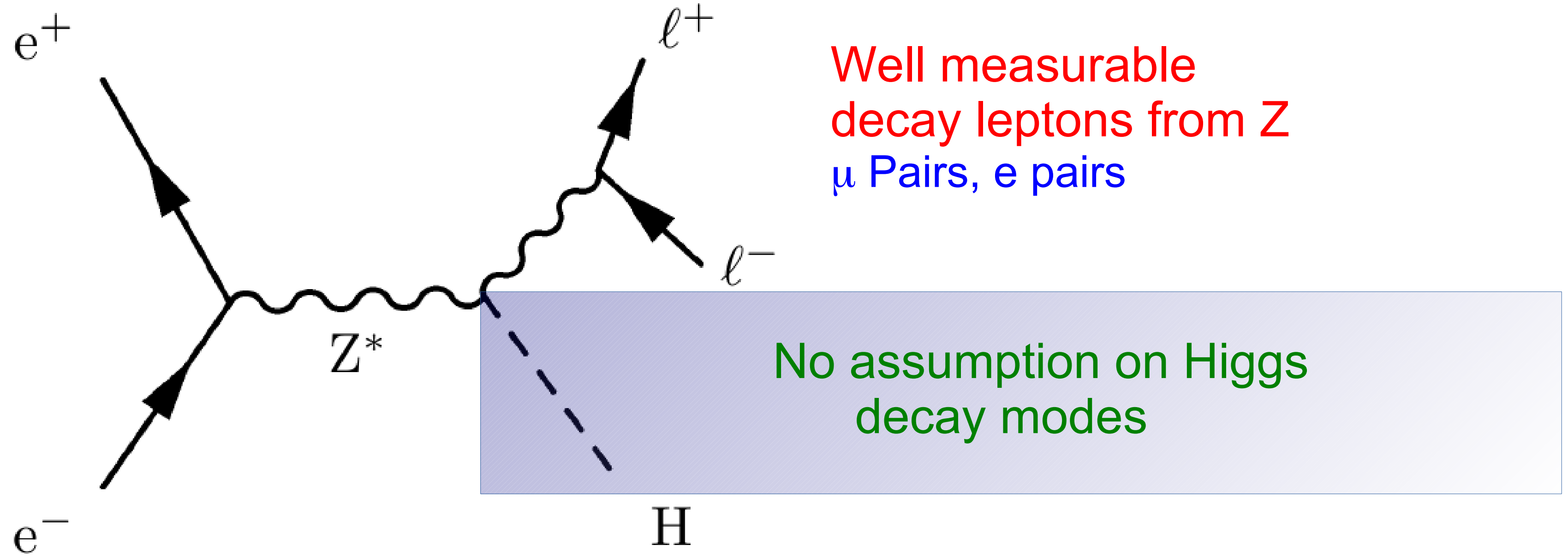




two important thresholds:
$\sqrt{s}$ ~ 250 GeV for ZH, ~500 GeV for ZHH and ttH

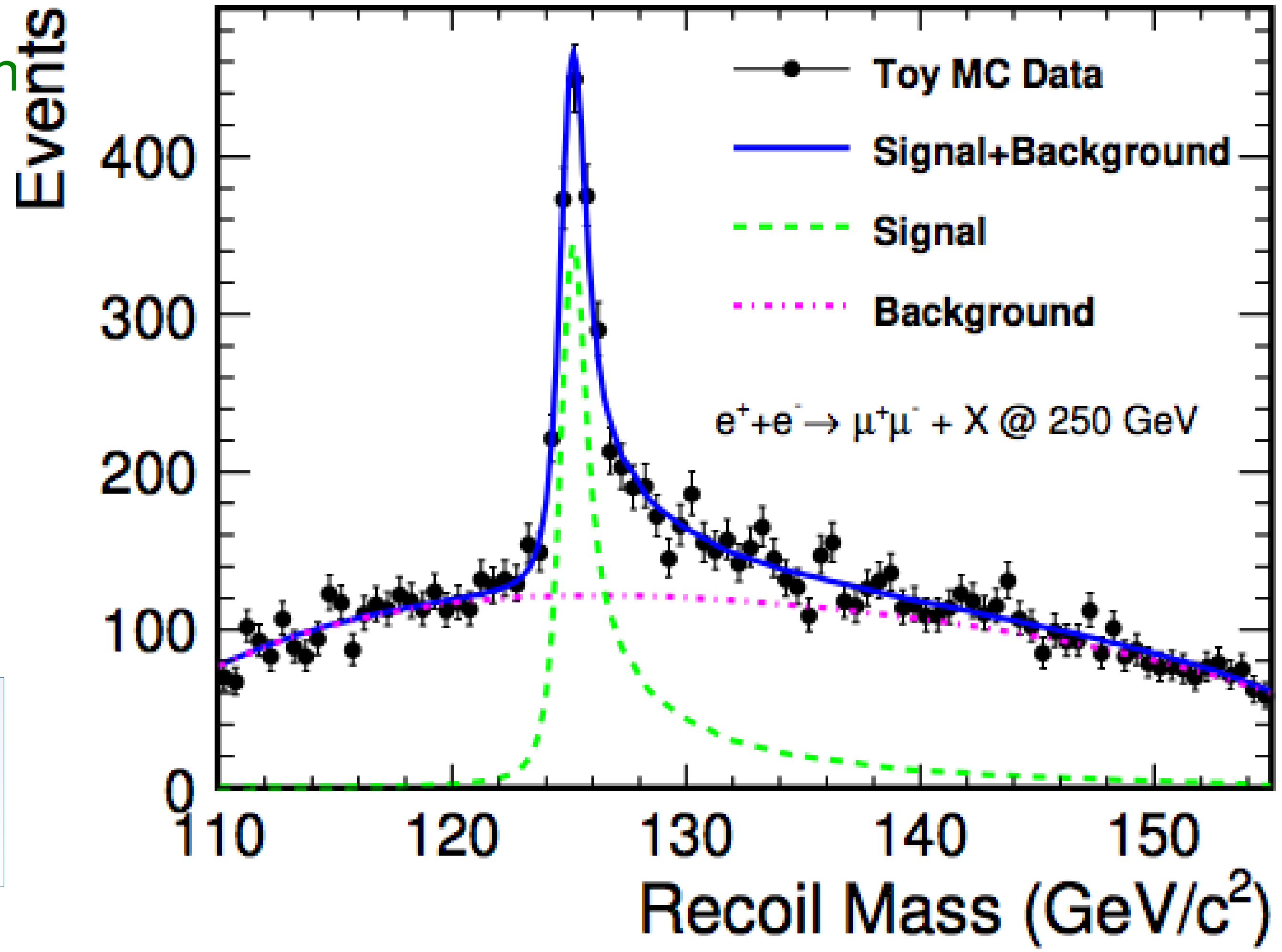
Higgs-strahlung at lepton colliders

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



Well measurable
decay leptons from Z
μ Pairs, e pairs

No assumption on Higgs
decay modes

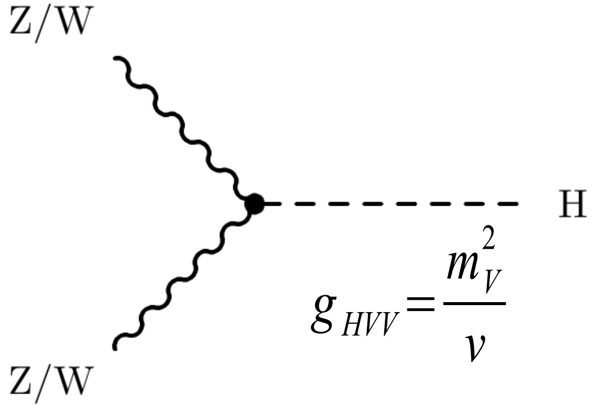


Higgs Recoil Mass: $M_h^2 = M_{recoil}^2 = s + M_Z^2 - 2E_Z\sqrt{s}$

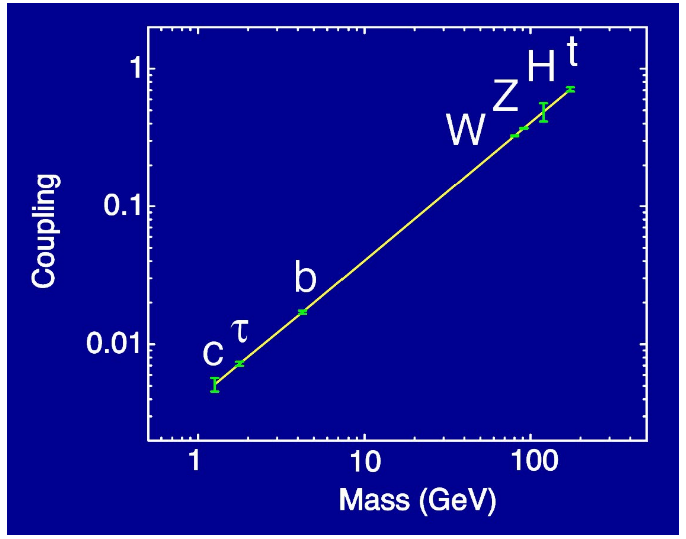
- Clean and sharp peak in Z recoil spectrum
- Illustrates precision that can be expected from e+e- colliders

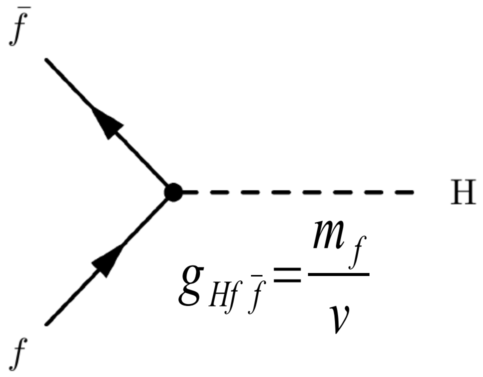
Fitting Higgs Couplings – Kappa and EFT

Couplings to Higgs Boson in Standard Model



$$g_{HVV} = \frac{m_V^2}{v}$$





$$g_{Hf\bar{f}} = \frac{m_f}{v}$$

Analysis using Kappa-fit:

- Simple scaling of SM-couplings
- Implies that Higgs coupling to Z in production and decay are identical
- No new operators

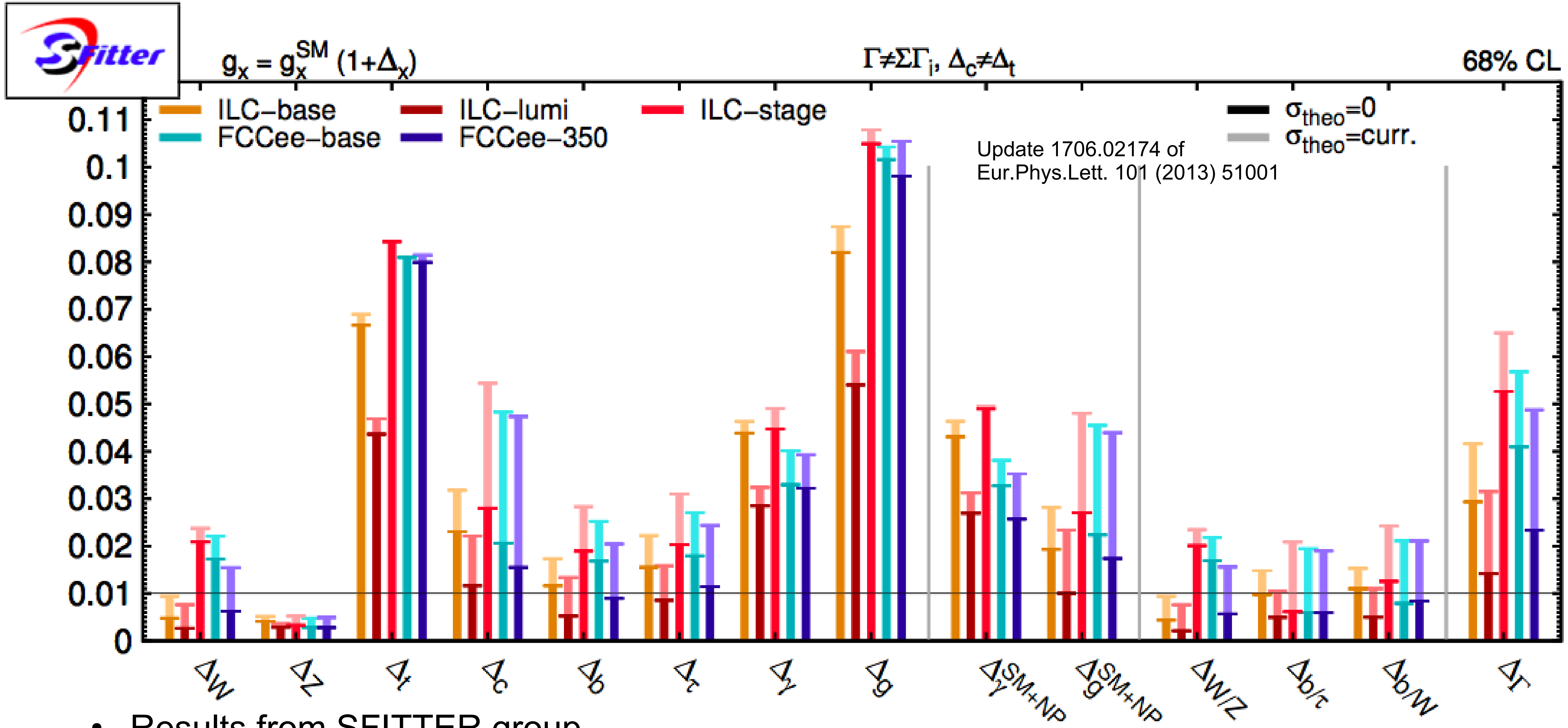
$$\frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \; , \qquad \frac{\sigma(e^+e^- \to Zh)}{SM} = \kappa_Z^2$$

Analysis using EFT-fit:

- Introducing set of SU(2)xU(1) compatible operators
- e.g. breaks simple relation between Higgs production and decay
- Total width and Higgs to invisible as free parameters
- Receives additional input from e.g. ee->WW and EWPO

$$\Gamma(h \to ZZ^*)/SM = (1 + 2\eta_Z - 0.50\zeta_Z)$$
$$\sigma(e^+e^- \to Zh)/SM = (1 + 2\eta_Z + 5.7\zeta_Z)$$

Precision on Higgs Physics – Kappa framework



- Results from SFITTER group
  Assumption: HL-LHC basically completed before e+e- machine starts

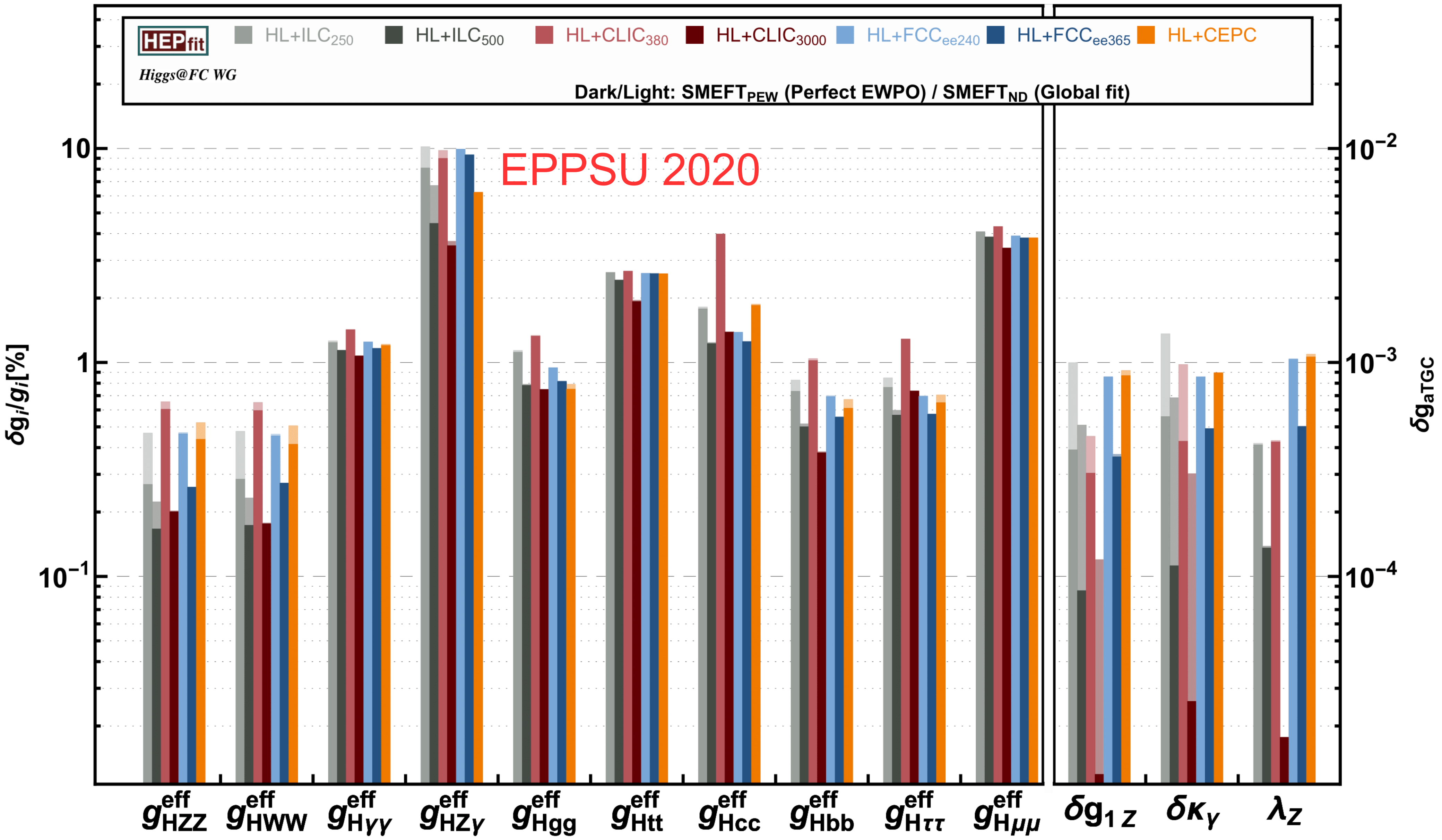
- ILC250 already powerful program (needs however e.g. top-Yukawa as input)

- Higher energies beneficial for total width
  and top-Yukawa couplings (fit constraints and H->γγ)

Precision on Higgs Couplings – EFT Framework

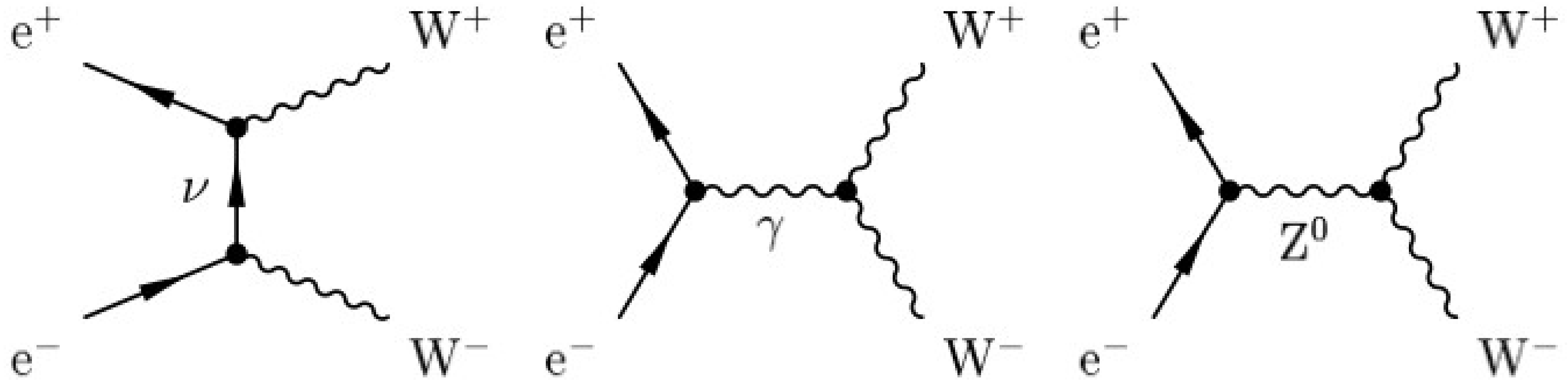
Actual Higgs couplings

aTGCs (=> Constraints in EFT Framework)



- Analysis in EFT Framework
- No clear winner among lepton colliders
- Polarisation at Linear Colliders compensates for higher integrated luminosity at Circular Machines

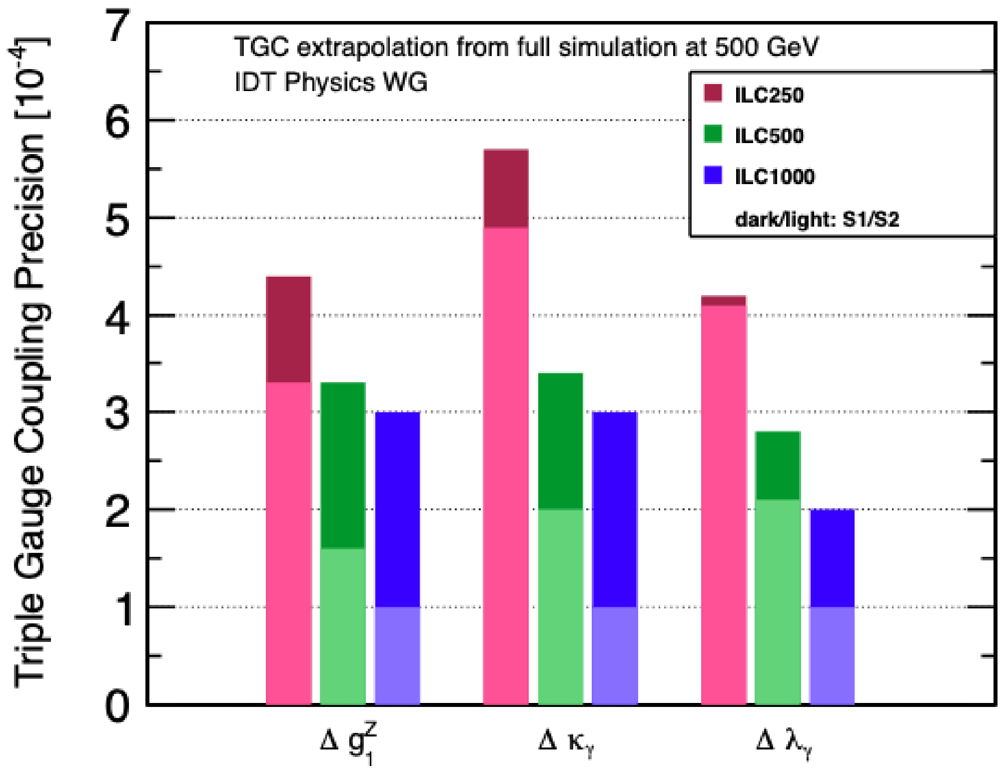
Anomalous Triple Gauge Couplings

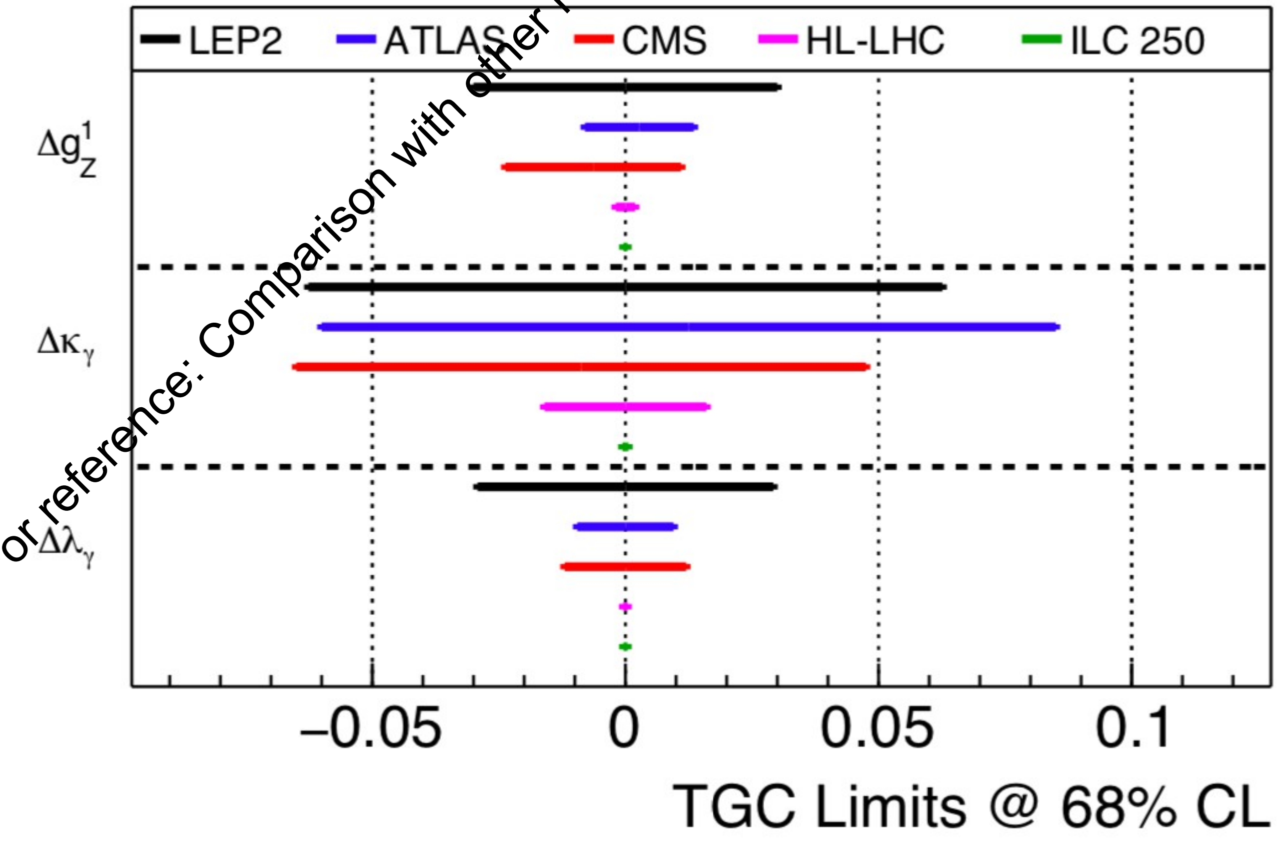


- Sensitivity to triple and quartic gauge Boson couplings (TGC and QGC)
- Observables depend strongly on beam polarisation

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

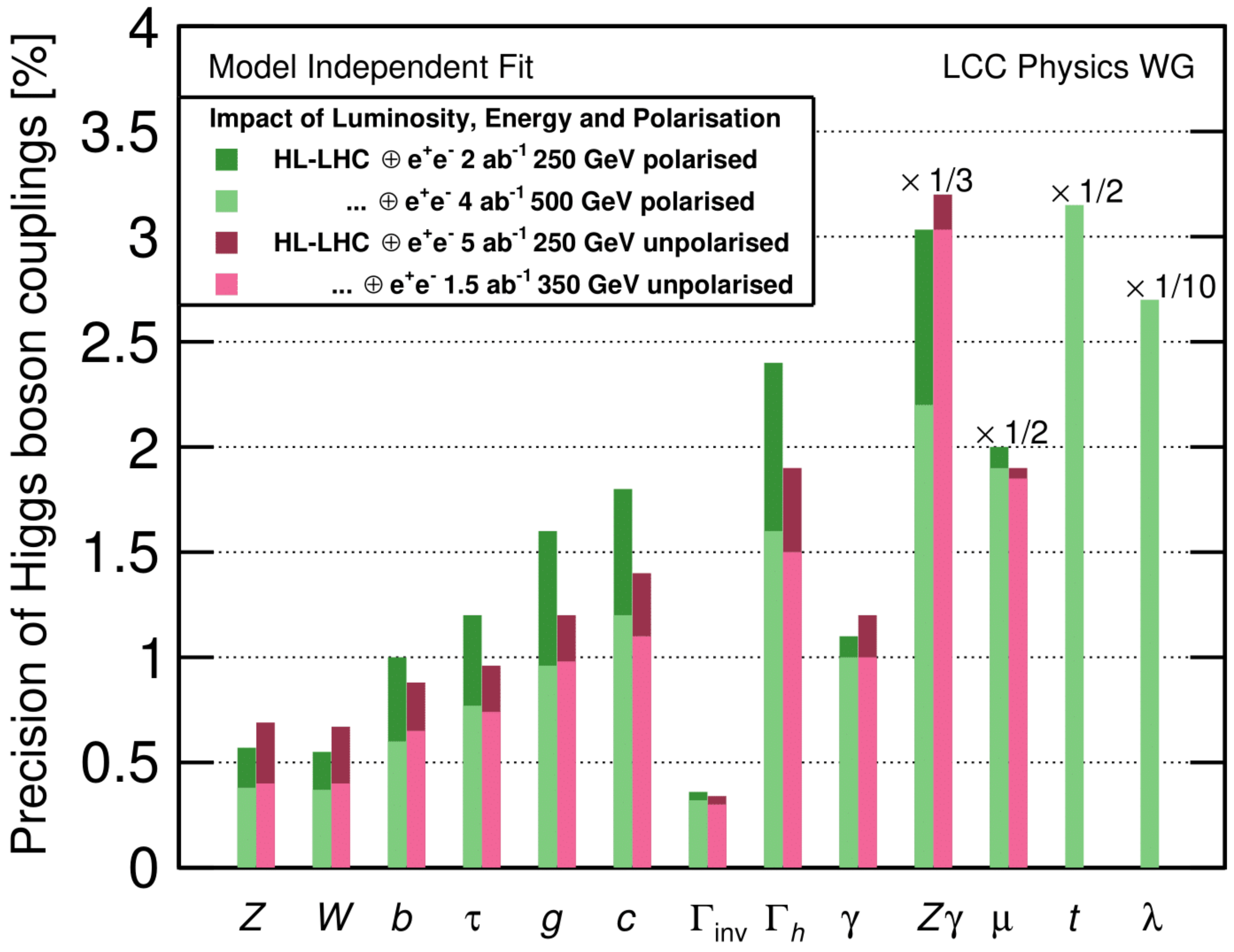
Limits on Triple Gauge Couplings@250 GeV



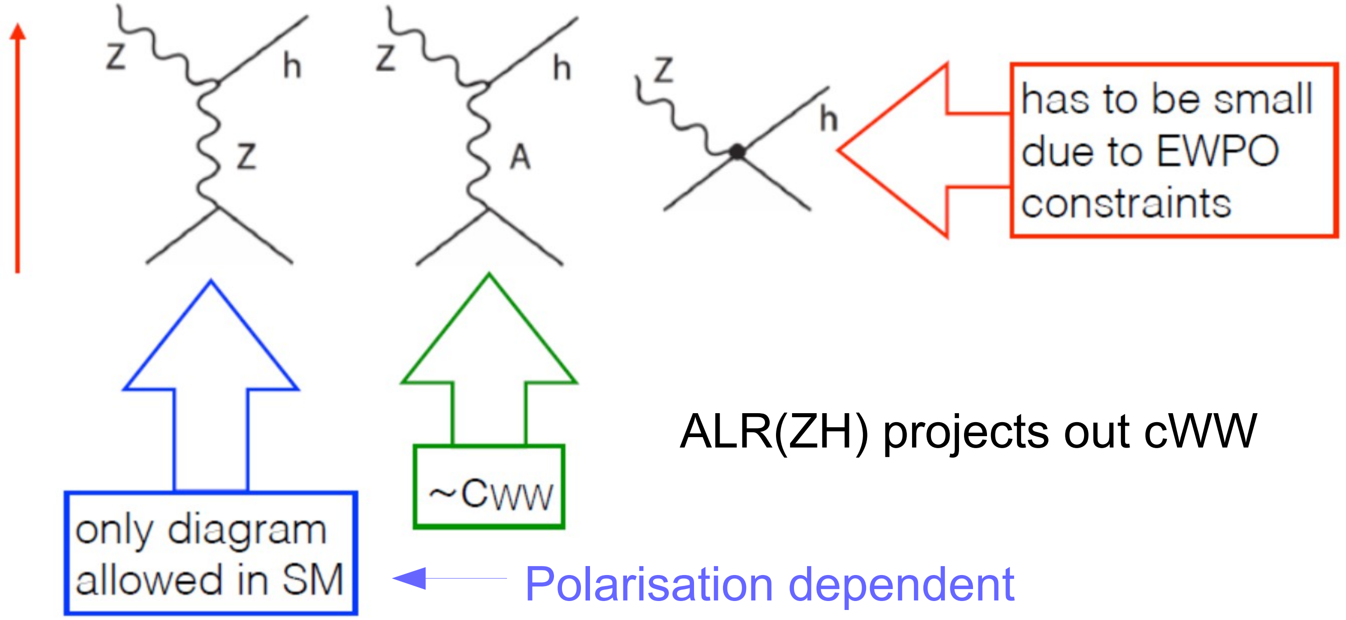


For reference: Comparison with other results

EFT Framework and beam polarisation



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



has to be small due to EWPO constraints

only diagram allowed in SM

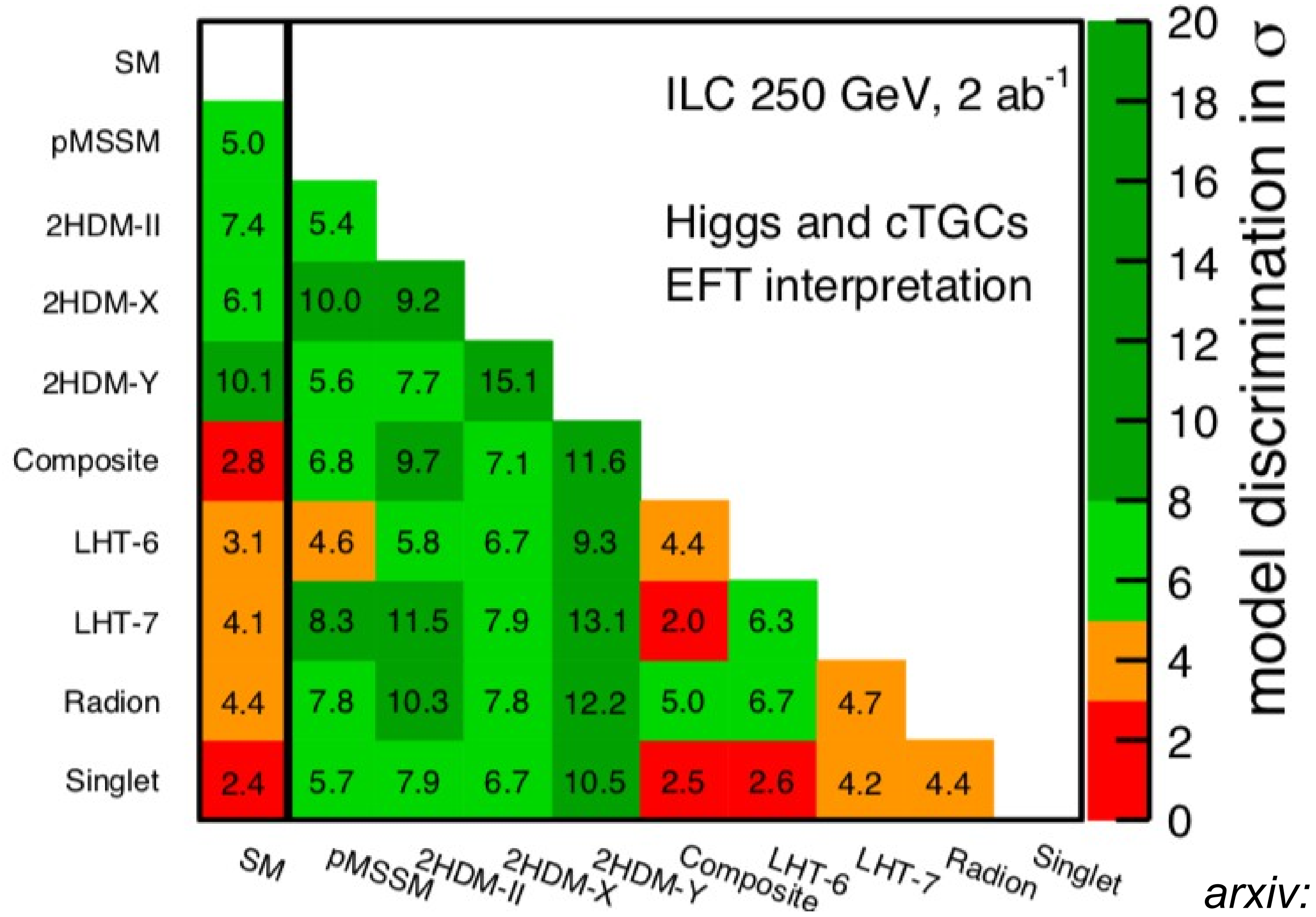
~Cww

ALR(ZH) projects out cWW

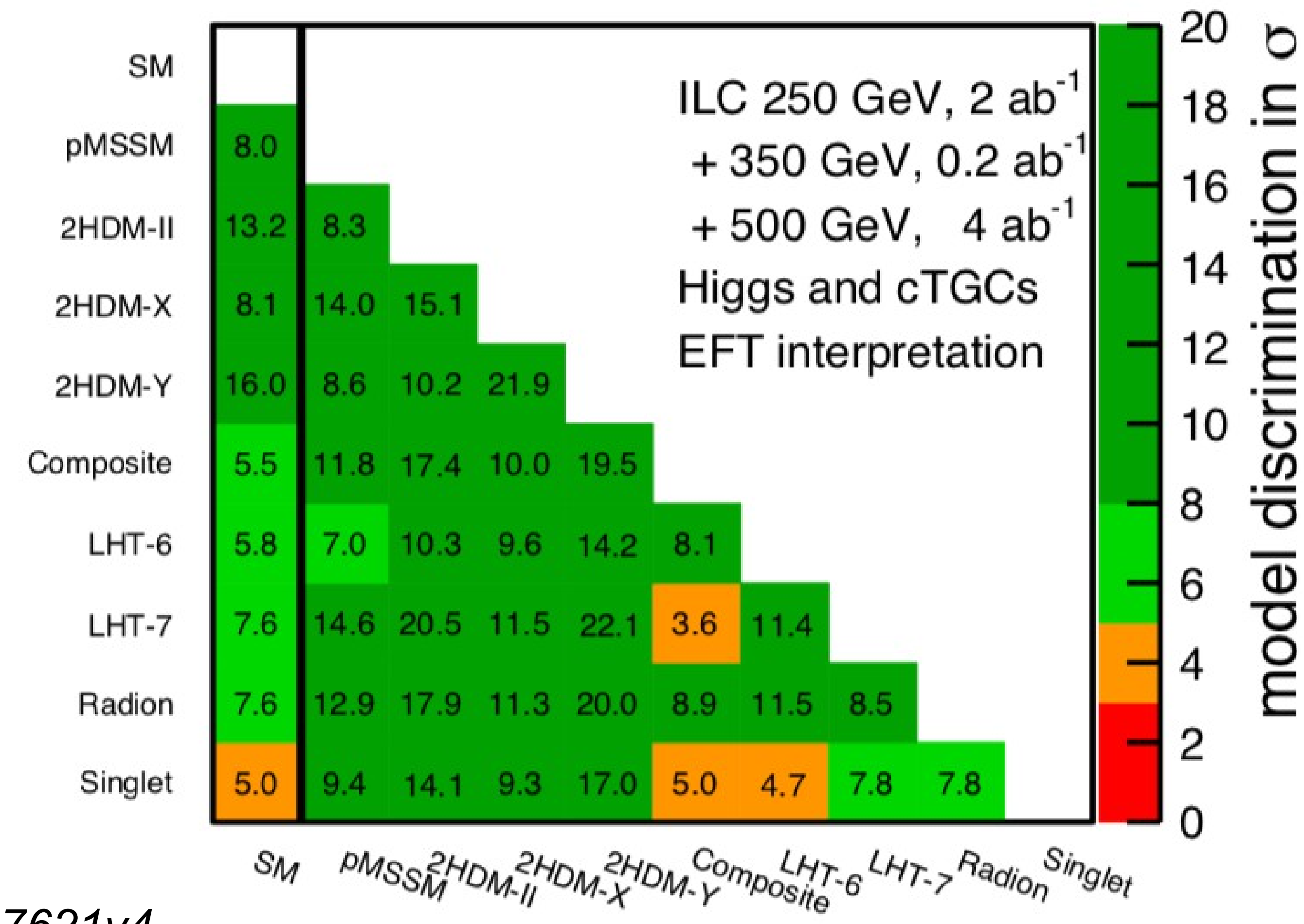
Polarisation dependent

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

Higgs – Discovery by precision



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.0									
2HDM-II	7.4	5.4								
2HDM-X	6.1	10.0	9.2							
2HDM-Y	10.1	5.6	7.7	15.1						
Composite	2.8	6.8	9.7	7.1	11.6					
LHT-6	3.1	4.6	5.8	6.7	9.3	4.4				
LHT-7	4.1	8.3	11.5	7.9	13.1	2.0	6.3			
Radion	4.4	7.8	10.3	7.8	12.2	5.0	6.7	4.7		
Singlet	2.4	5.7	7.9	6.7	10.5	2.5	2.6	4.2	4.4	

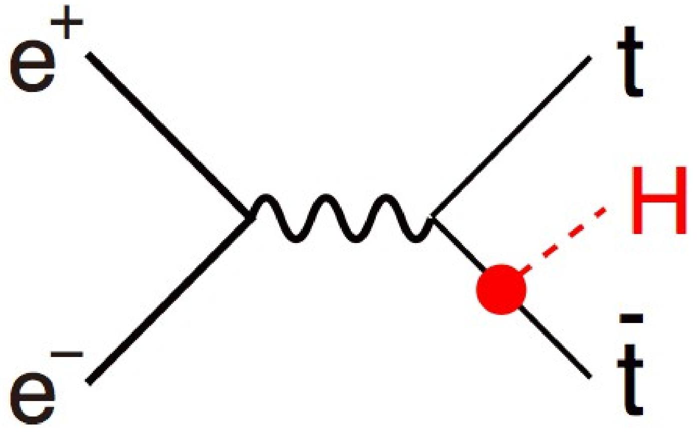


	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	8.0									
2HDM-II	13.2	8.3								
2HDM-X	8.1	14.0	15.1							
2HDM-Y	16.0	8.6	10.2	21.9						
Composite	5.5	11.8	17.4	10.0	19.5					
LHT-6	5.8	7.0	10.3	9.6	14.2	8.1				
LHT-7	7.6	14.6	20.5	11.5	22.1	3.6	11.4			
Radion	7.6	12.9	17.9	11.3	20.0	8.9	11.5	8.5		
Singlet	5.0	9.4	14.1	9.3	17.0	5.0	4.7	7.8	7.8	

arxiv: 1710.07621v4

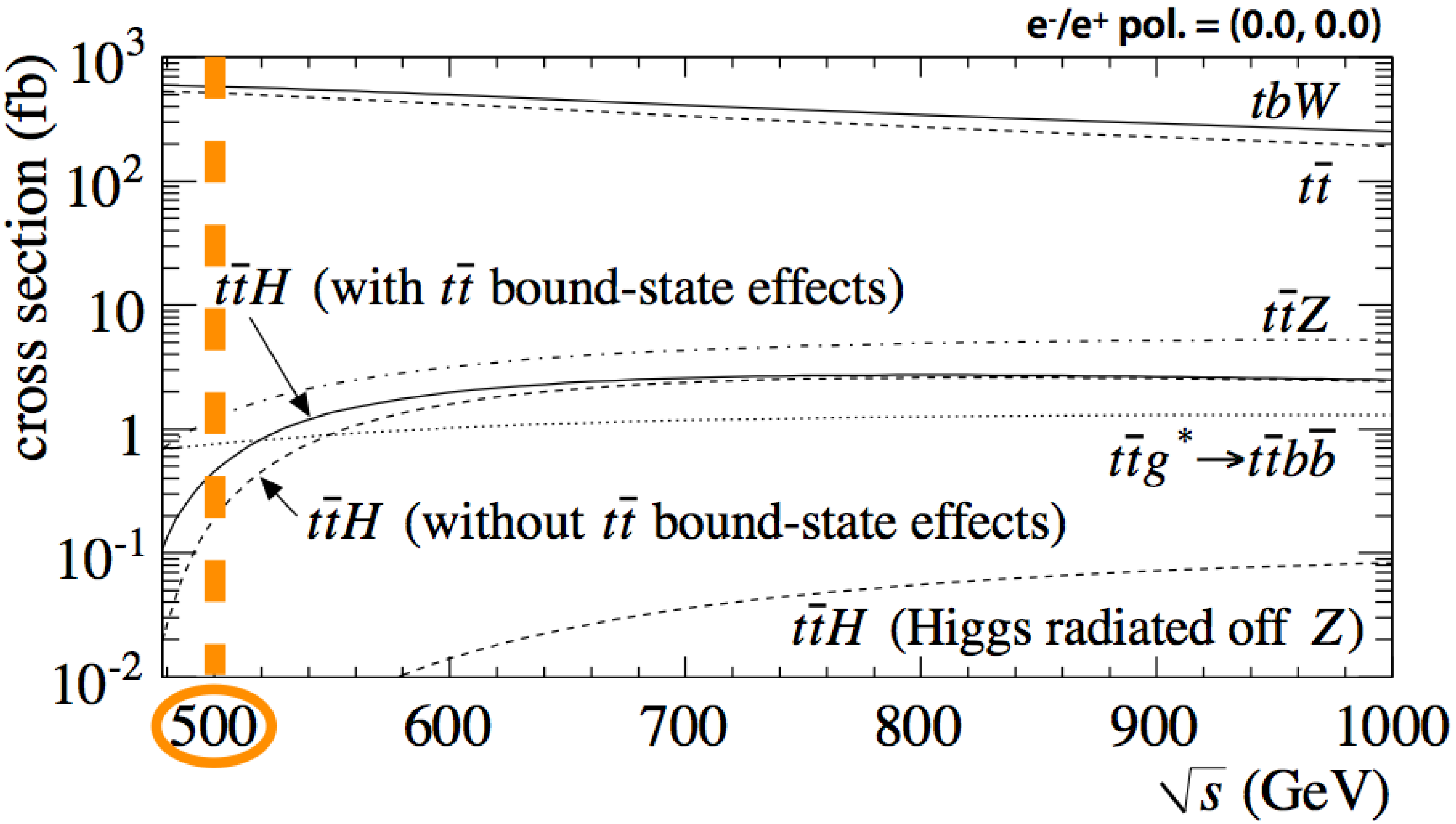
- Already large discriminative power at 250 GeV
- Full discovery potential developed at higher energies (e.g. 500 GeV)
- Consult ILC Snowmass report (2203.07622 for potential on Higgs exotic decays

Top Yukawa Coupling



- Coupling of Higgs to heaviest particle known today

- Up to eight final state jets

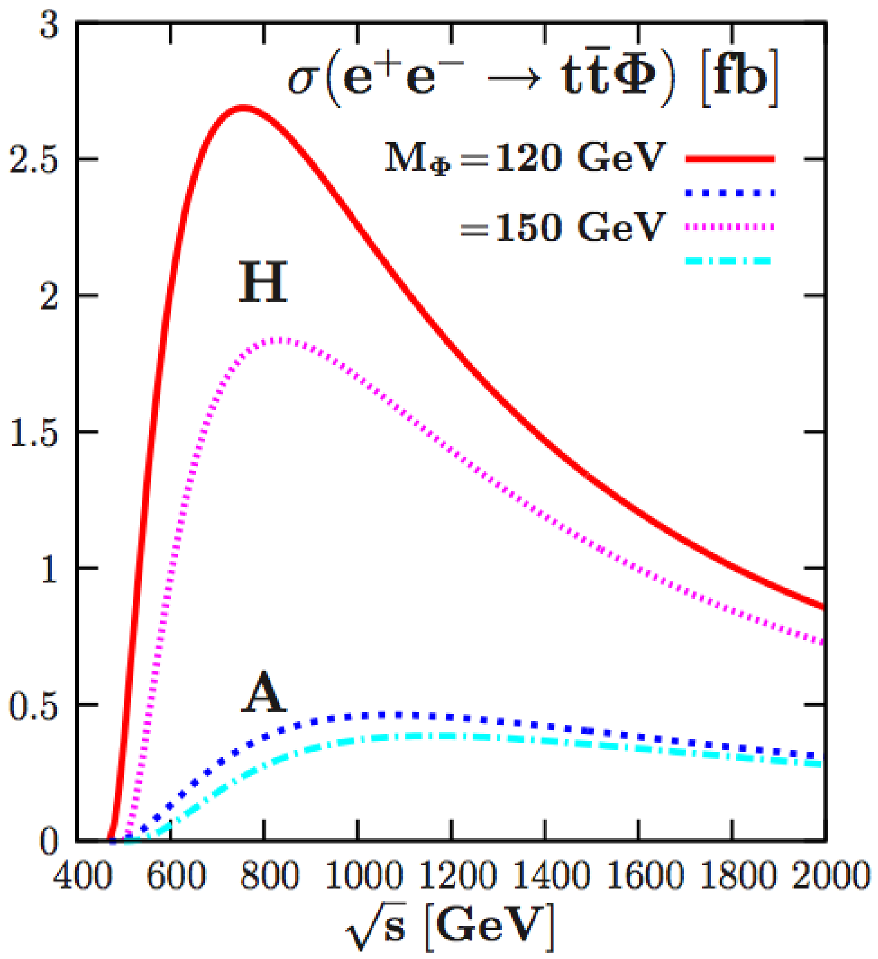


√s[GeV]	550	1000	1400
L[ab-1]	4	8	2
δyt/yt[%]	2.8	2.0	2.7

Higgs Quantum Number – CP via tth

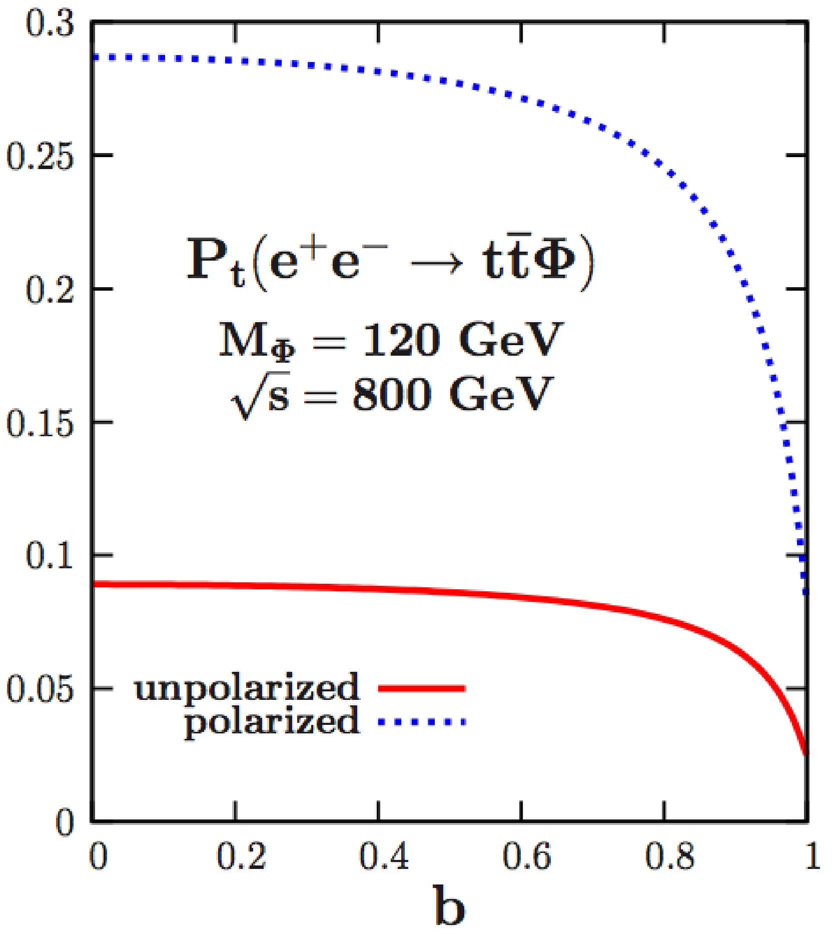
Direct coupling of top quark to CP odd and CP even scalar

Cross section



Dramatic differences for
CP odd and CP even scalar

Top quark polarisation

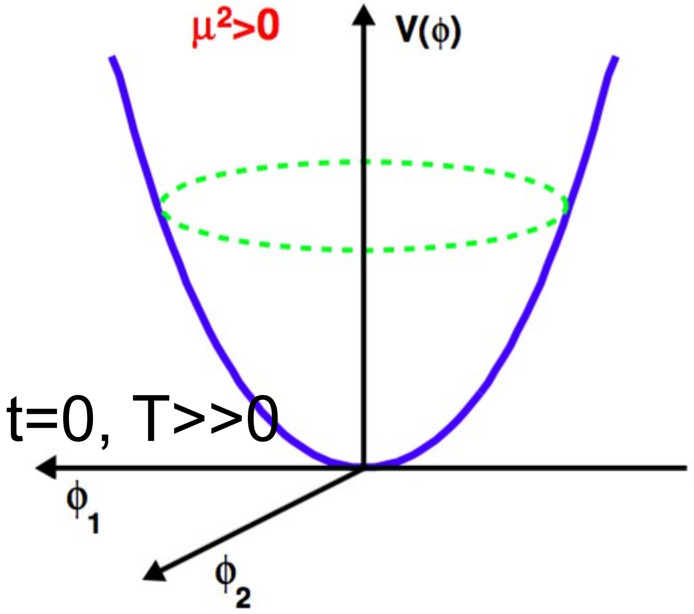


Sensitivity to CP odd admixture b
Merit of beam polarisation

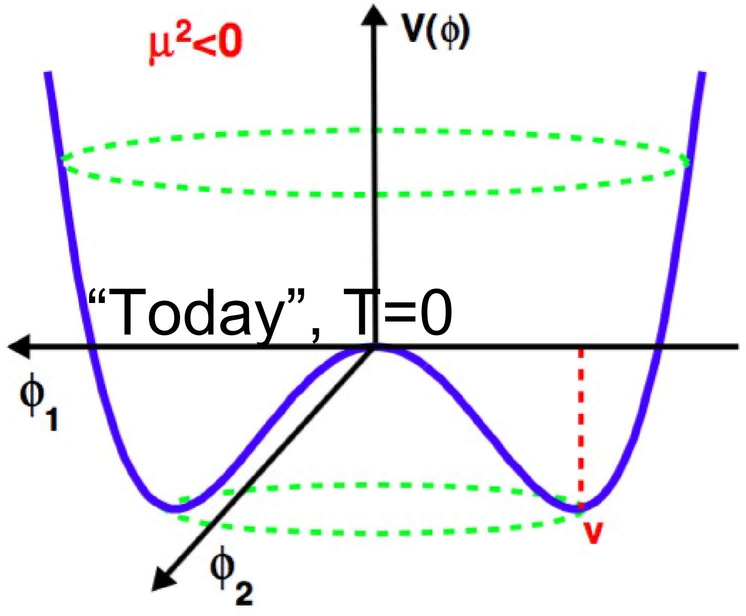
Determination of CP nature of scalar boson in an unambiguous way

Godbole et al., LCWS07

The Higgs Potential



Perfect (electroweak) symmetry
and massless particles

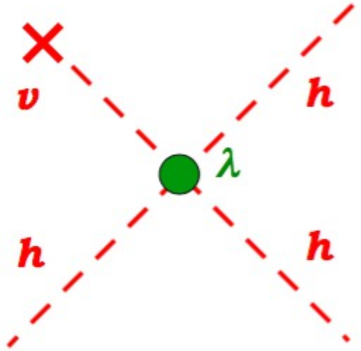


Broken (electroweak) symmetry
and massive particles

Two questions:

- Shape of "today's" Higgs Potential?

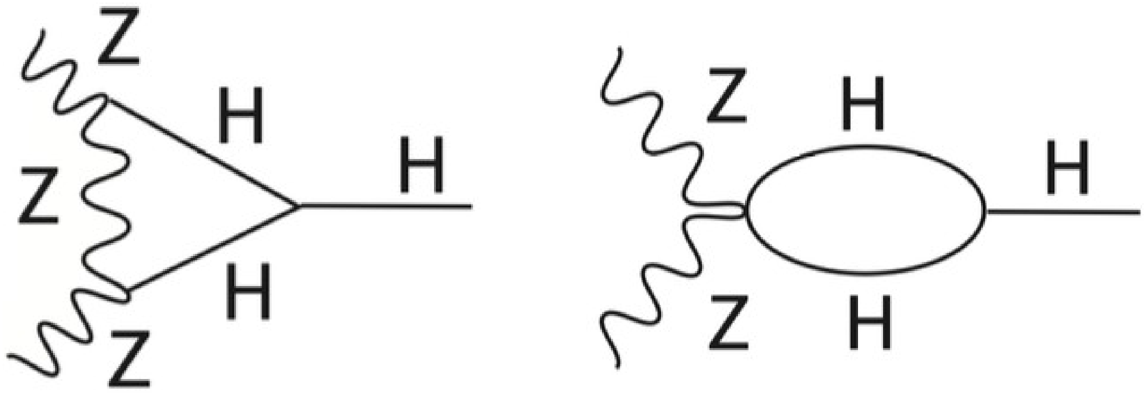
$$V(\eta)=\frac{1}{2}m^2\eta^2+\boxed{\lambda}v\eta^3+\frac{1}{4}\lambda\eta^4$$ => Triple Higgs-self coupling



- Transition from symmetric, unbroken to broken phase?

Higgs Selfcoupling measurement

- 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



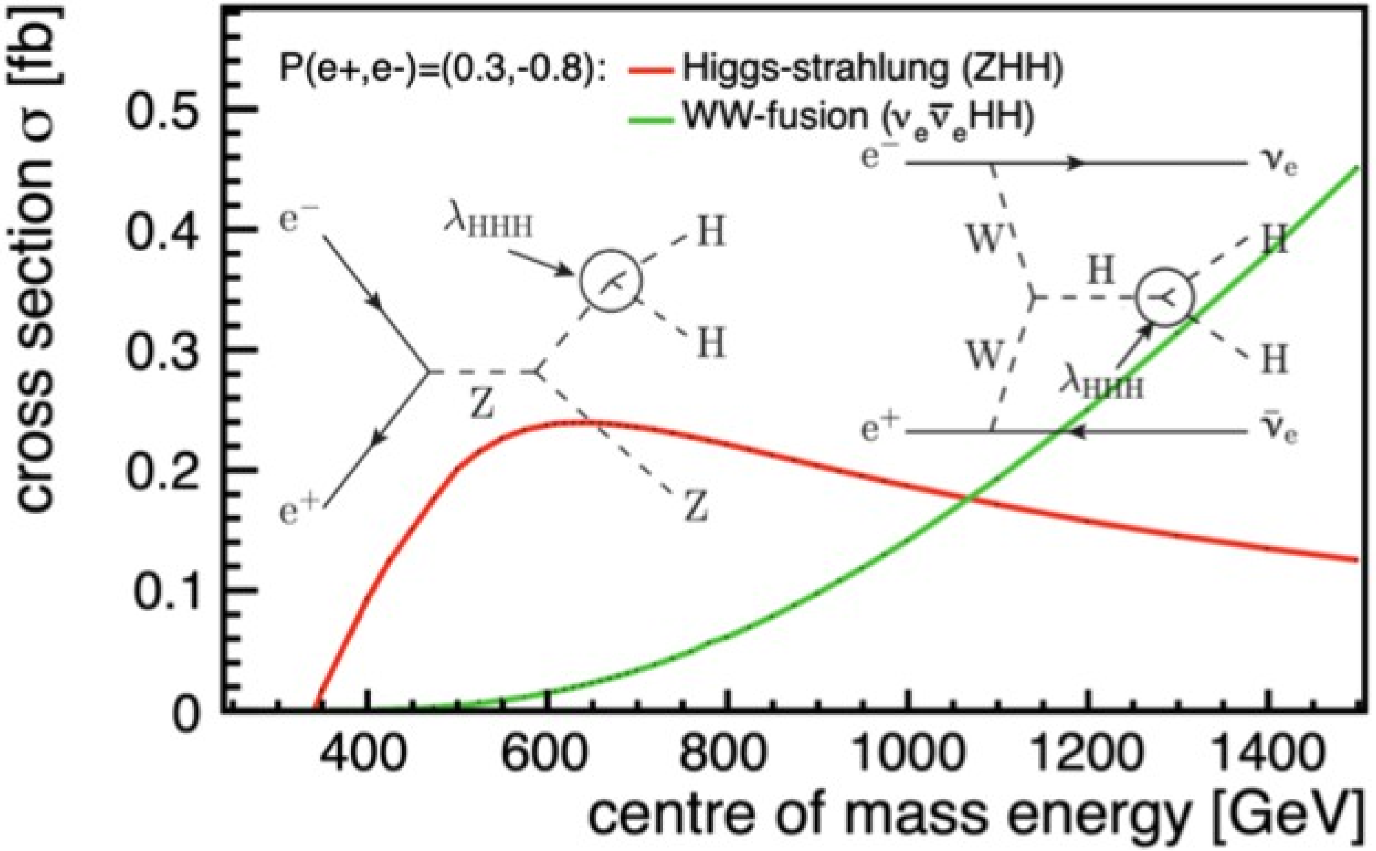
Details see M. Peskin, 12/1/23

Slide from Julie Munch Torndal

- Direct access
  - Through double-Higgs Production

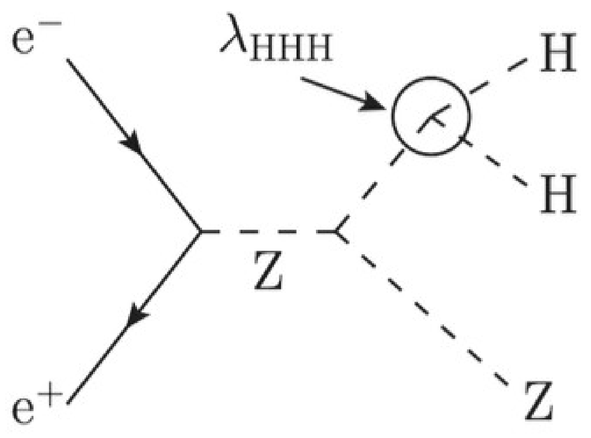
$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} = c \cdot \frac{\Delta\sigma_{HHx}}{\sigma_{HHs}}$$

  - Cross section measurement

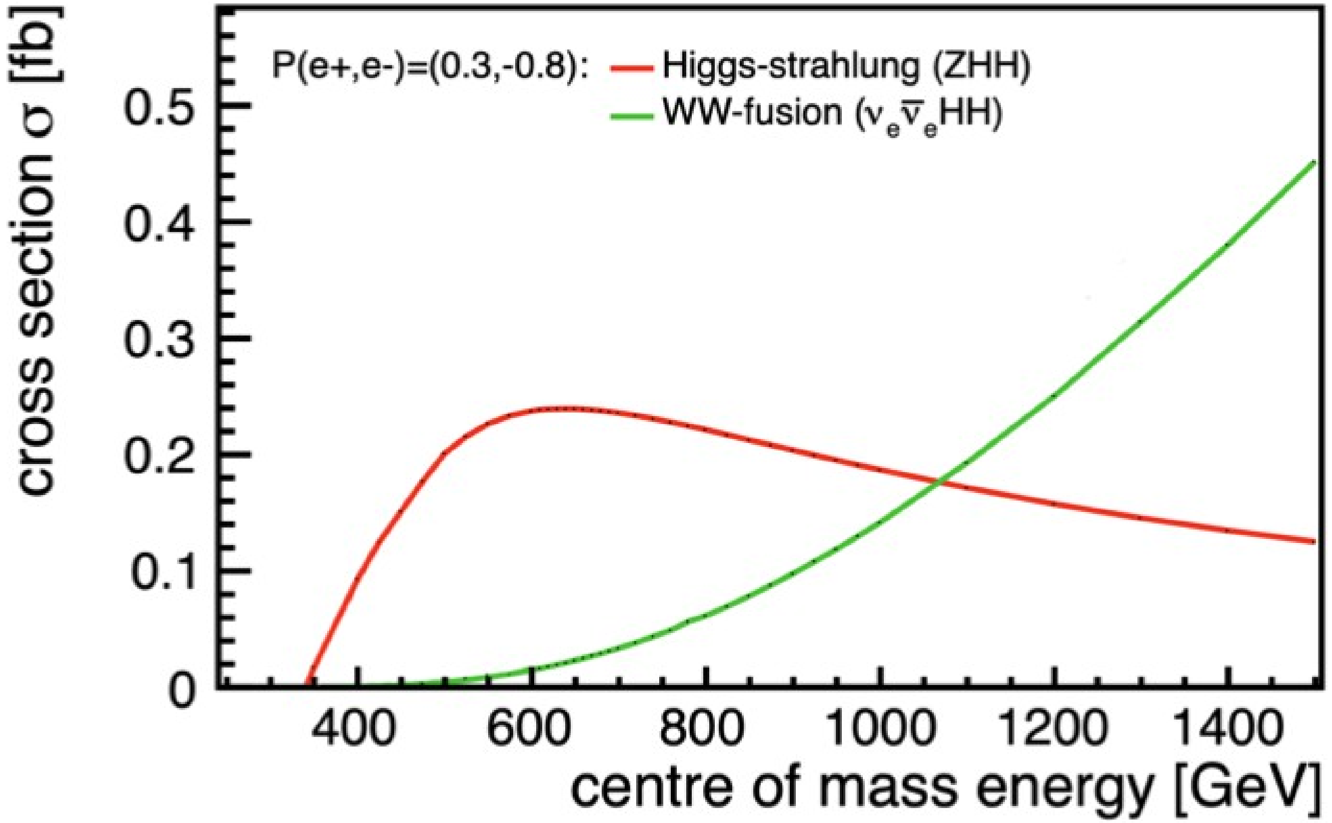


Higgs Selfcoupling measurement - Ingredients to cross section

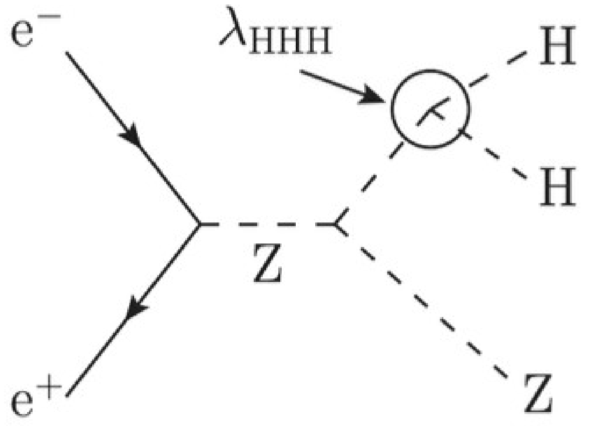
Di-Higgsstrahlung



Dominates below 1 TeV

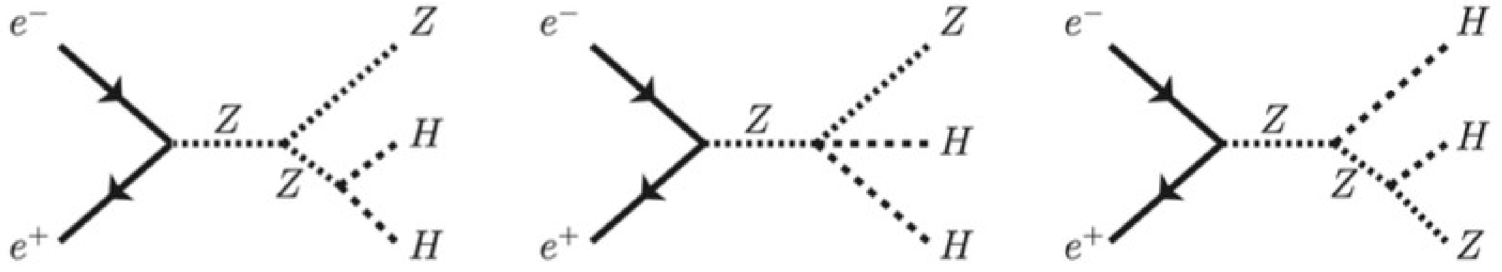


WW Fusion

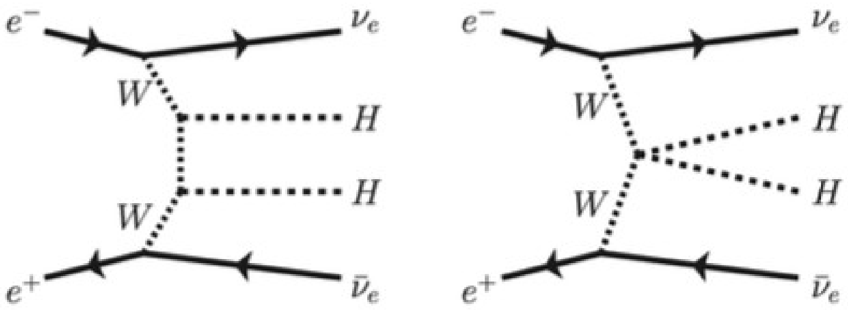


Dominates above 1 TeV

Constructive Interference

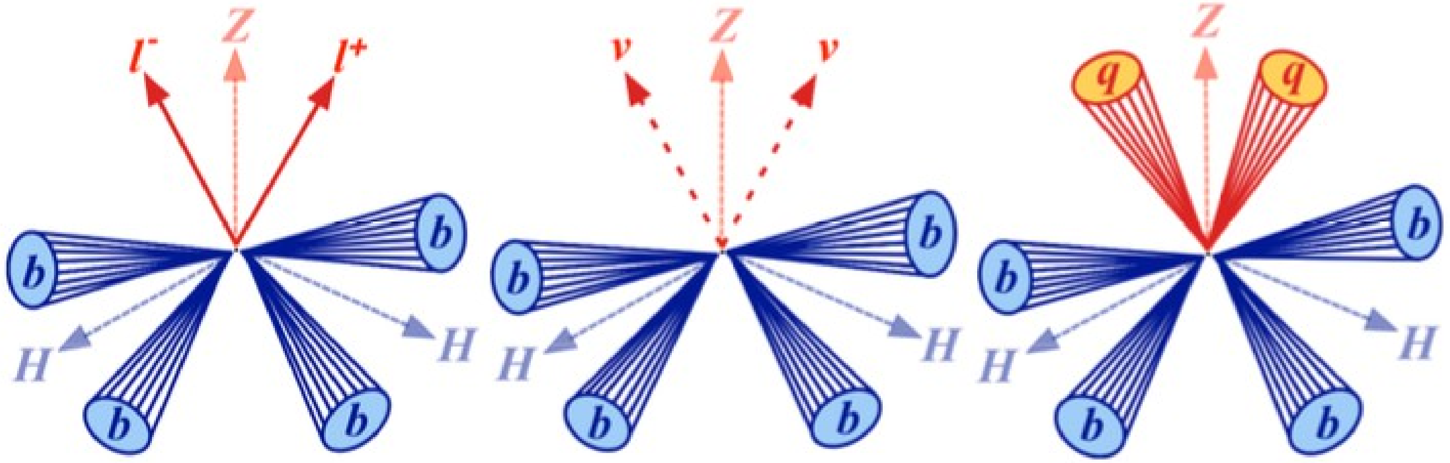


Destructive Interference

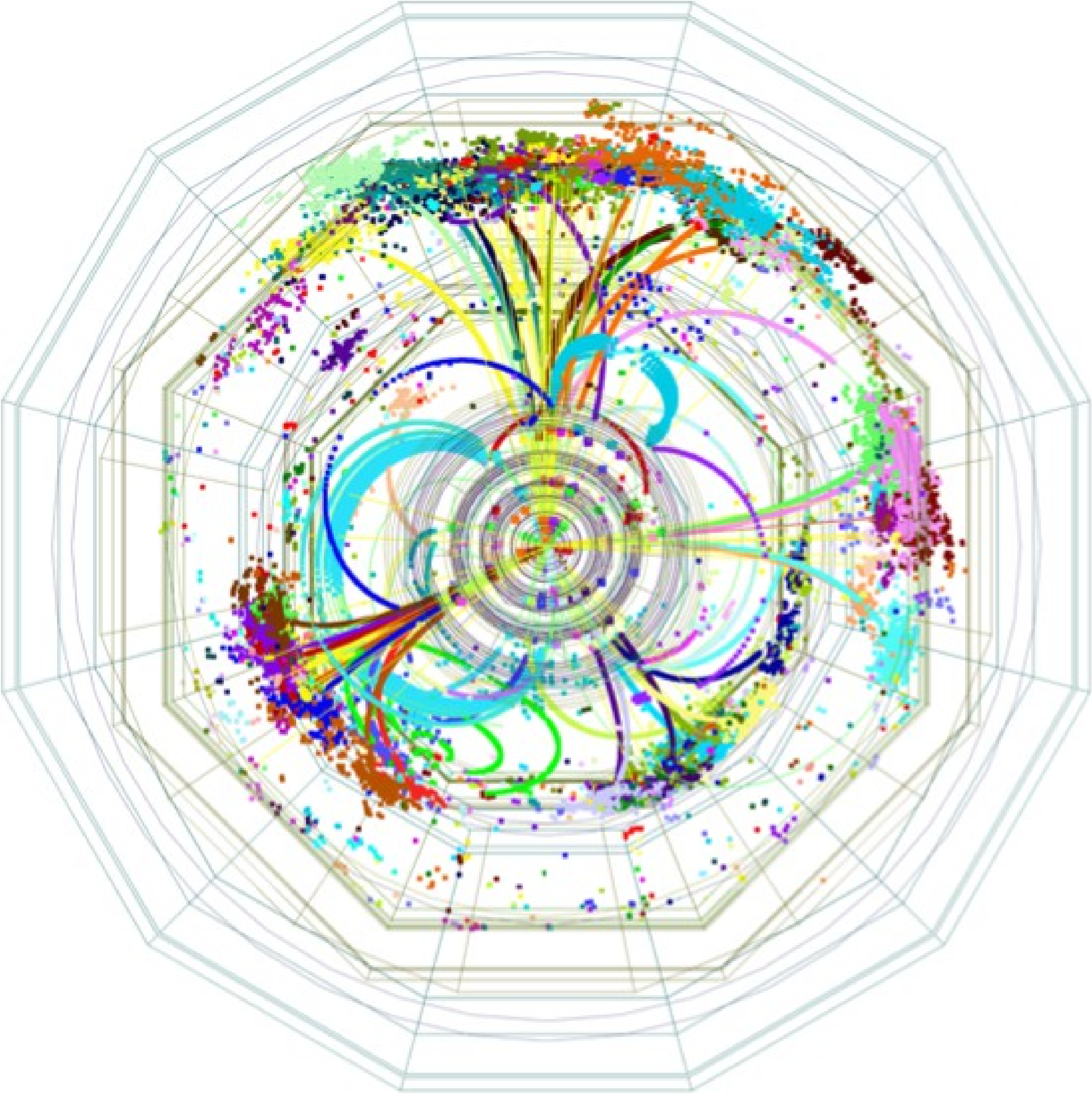


Slide from Julie Munch Torndal

Higgs self-coupling – Experimental issues



ILD Event Display

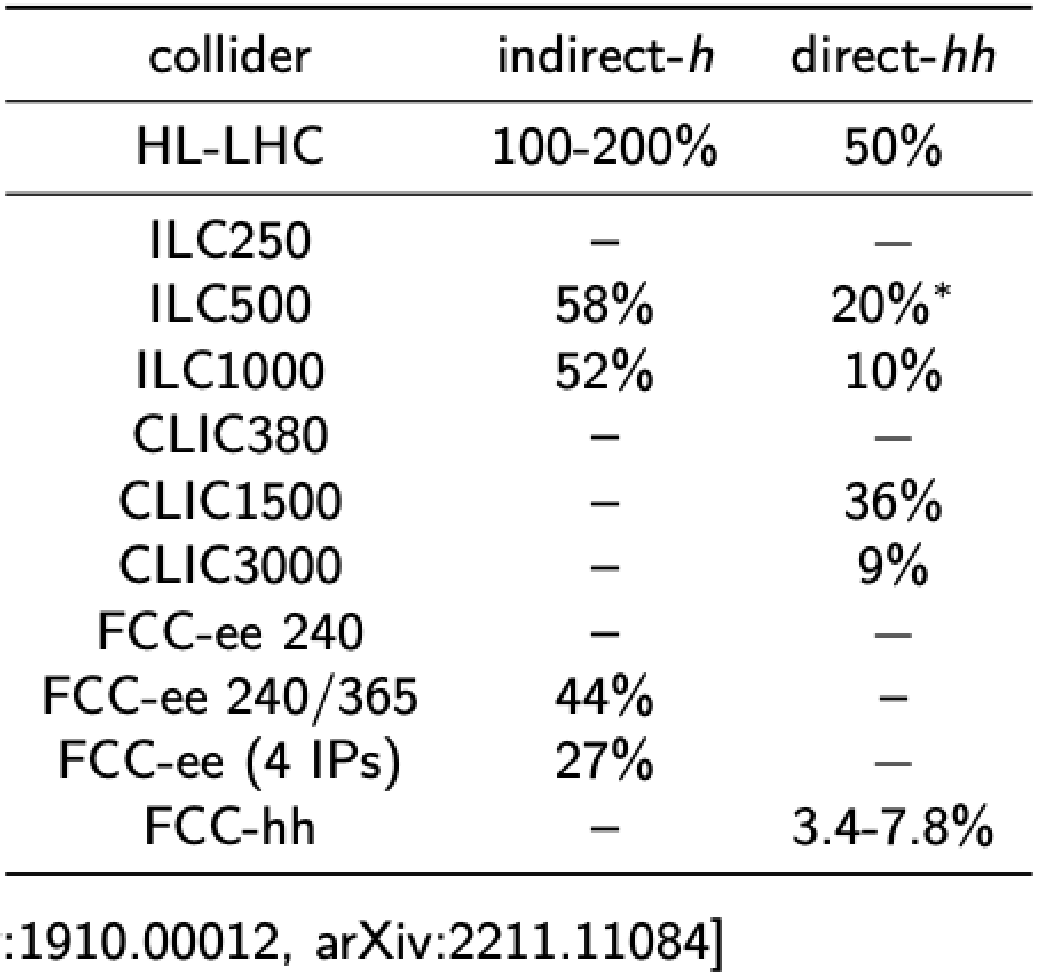


- Up to six jets in final state
  - Excellent jet and particle separation and (nearly) 4pi hermeticity required
- Four b-quarks
  - Excellent flavor tagging
  - Results shown in the following profit from recent improvements

Julie Munch Torndal and DESY-THESIS-2016-027

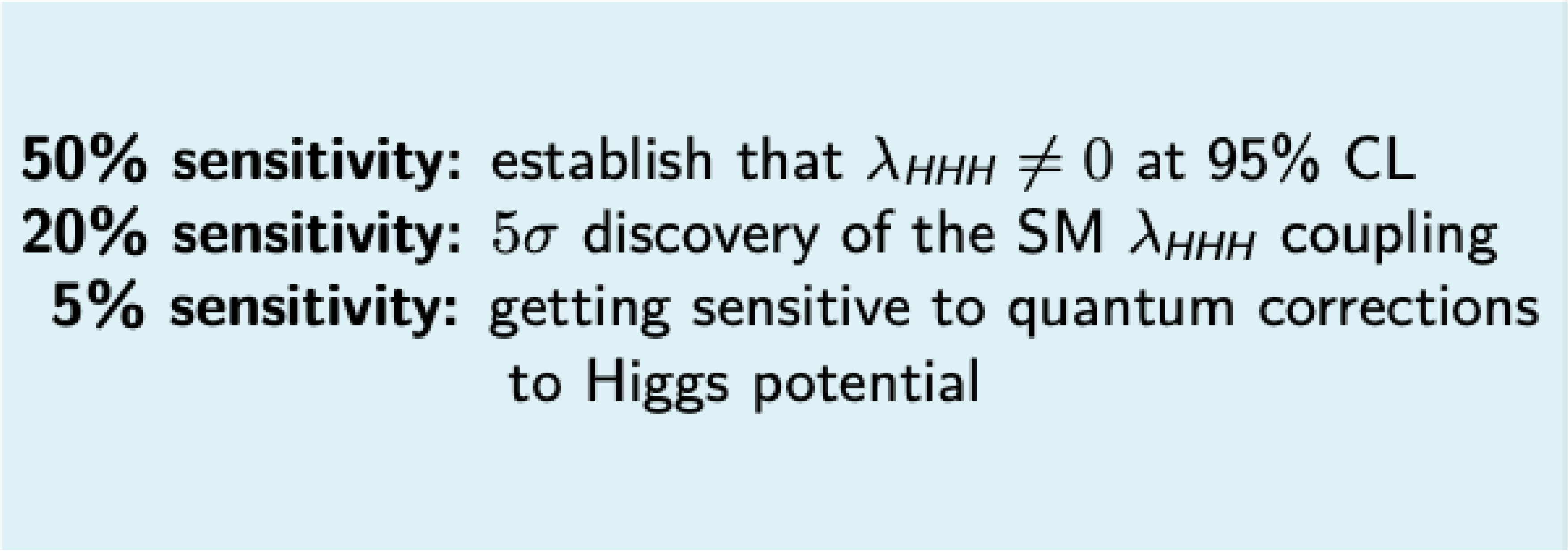
Higgs self-coupling – Experimental issues

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]



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

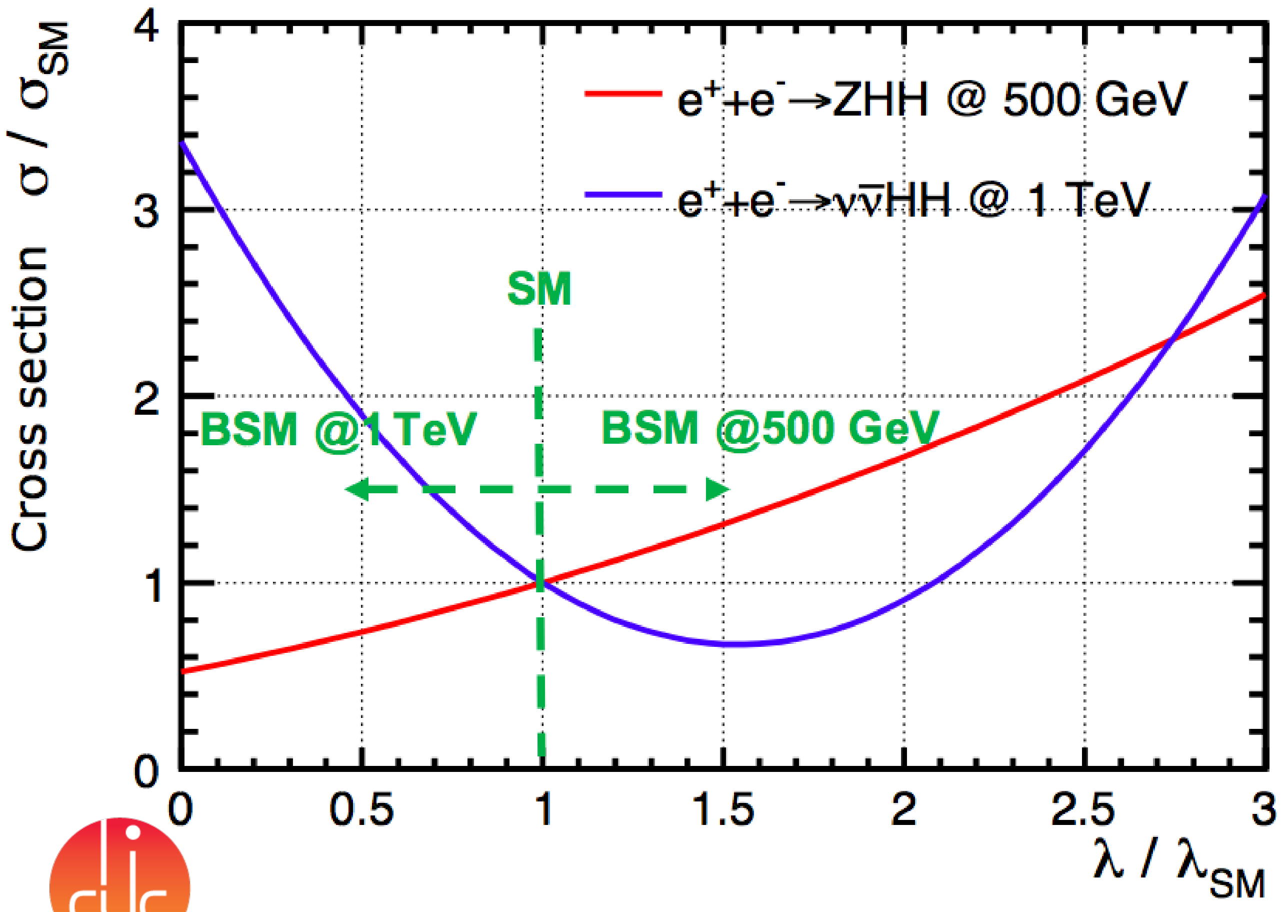
Result of 1-parameter fit for λ_{HHH} b is backed-up by SMEFT Analysis

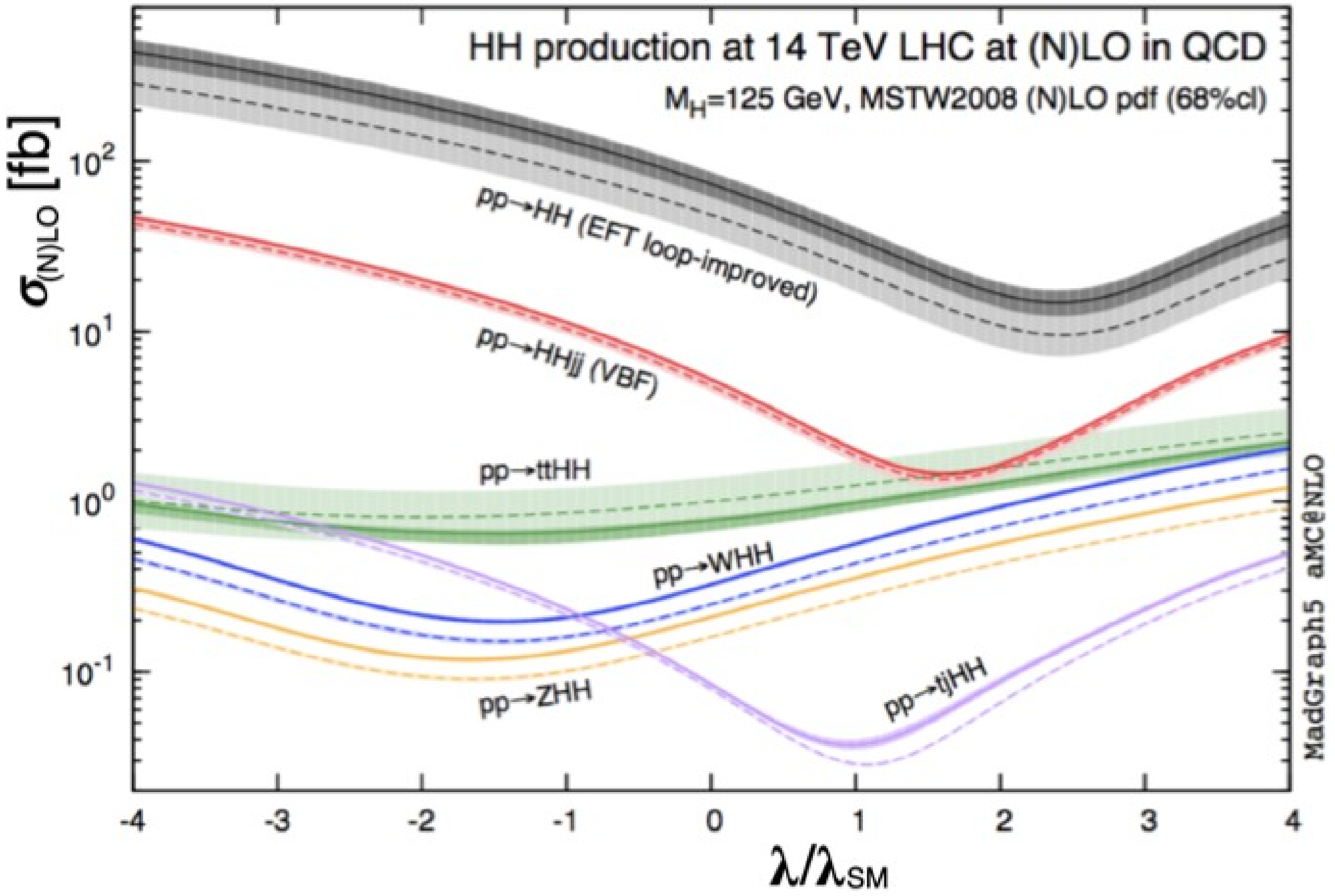
Details see M. Peskin, 12/1/23

Julie Munch Torndal

Higgs self-coupling and new physics

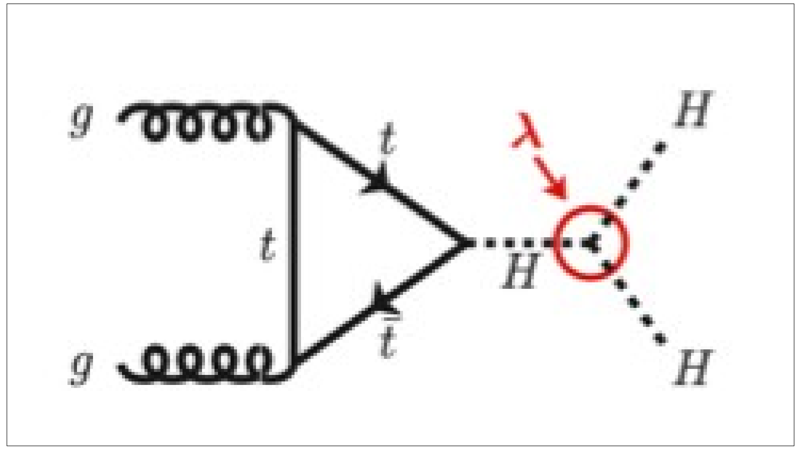
Manifestation of new physics in observables and extracted results?

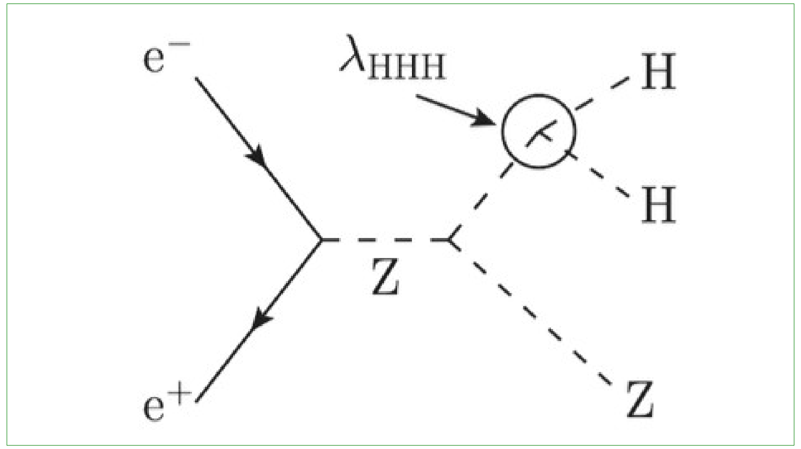


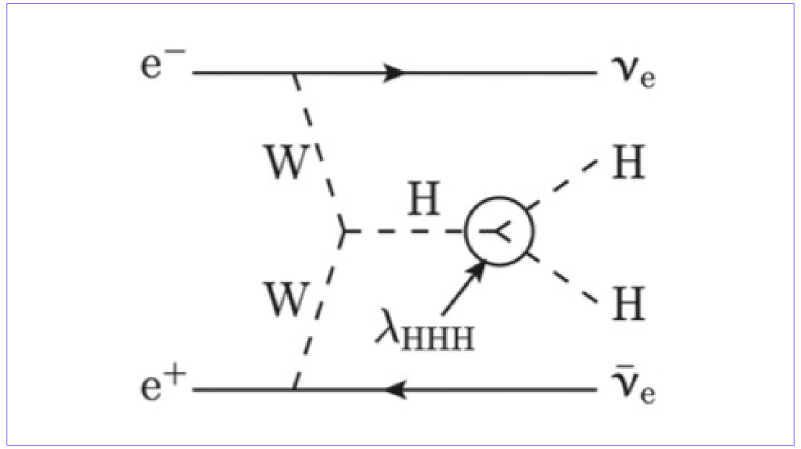


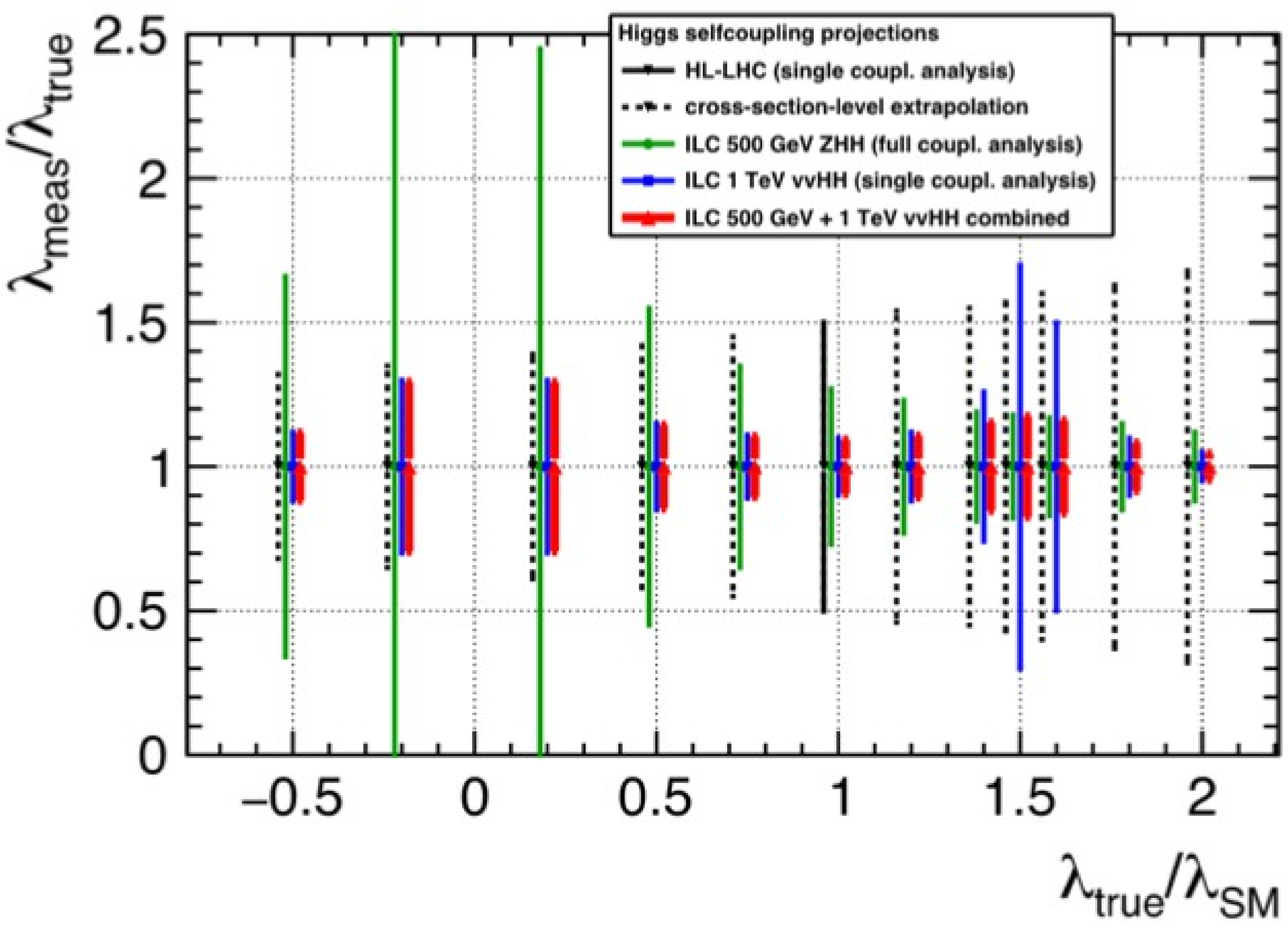
- Remarkable sensitivity of 500 GeV machine in case of large upward deviation
- 1 TeV machine superior for large upward and downward deviations
- LHC gives stronger constraints in case of $\lambda_{HHH} < \lambda_{HHH,SM}$

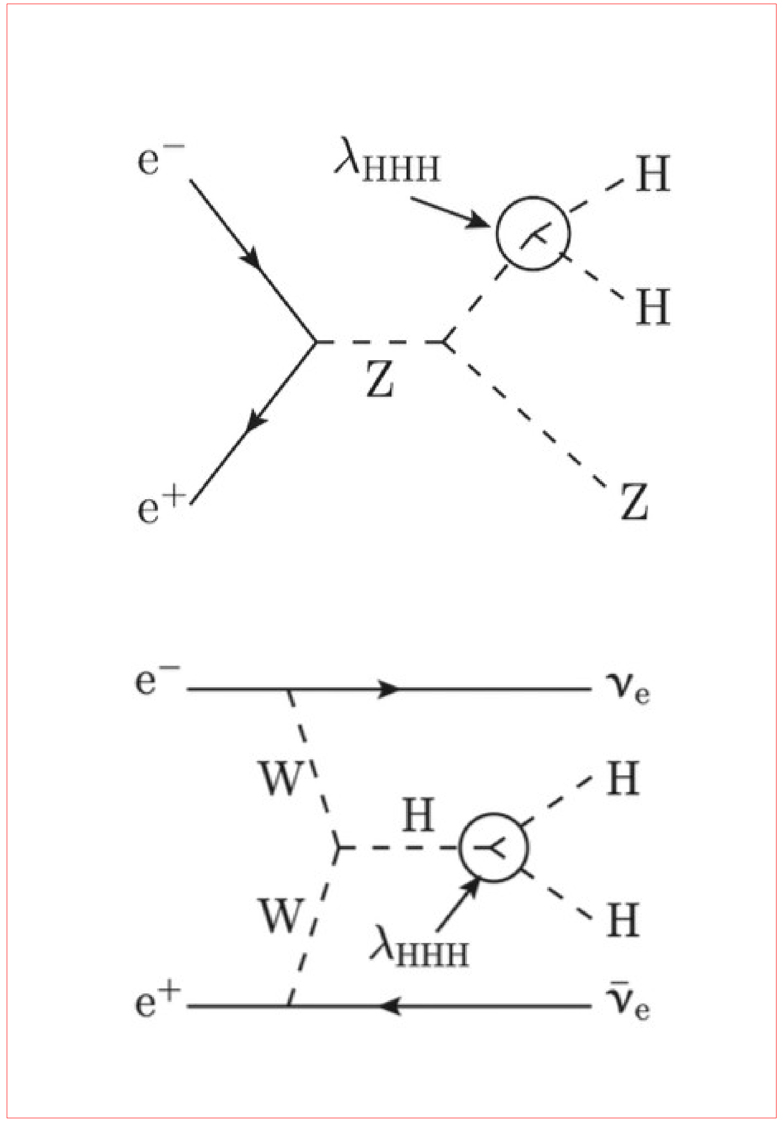
Higgs self-coupling – Different Scenarios and Combinations









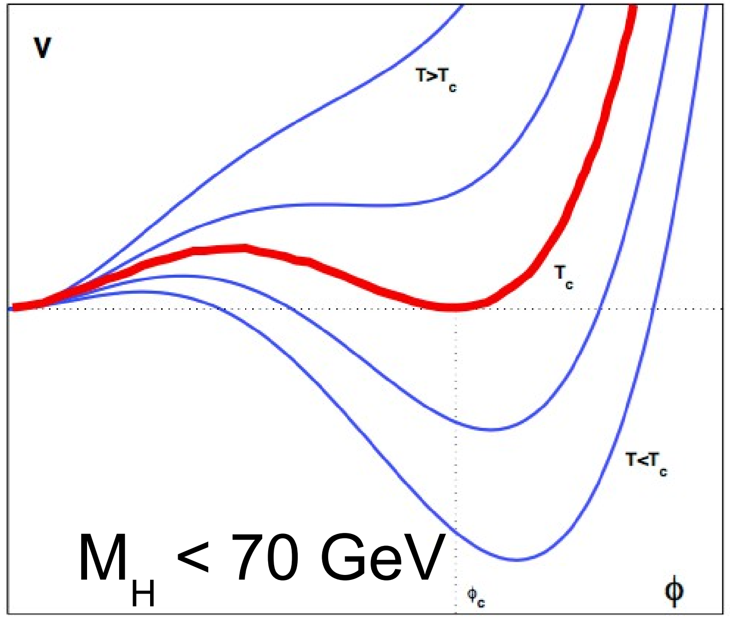


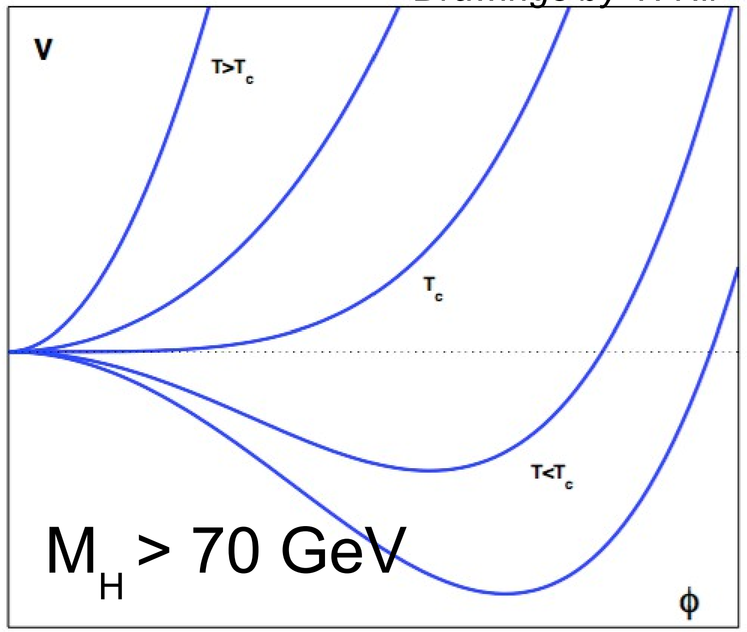
Sufficient centre-of-mass energy allow for 10% accuracy on Higgs self-coupling

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$_c$**

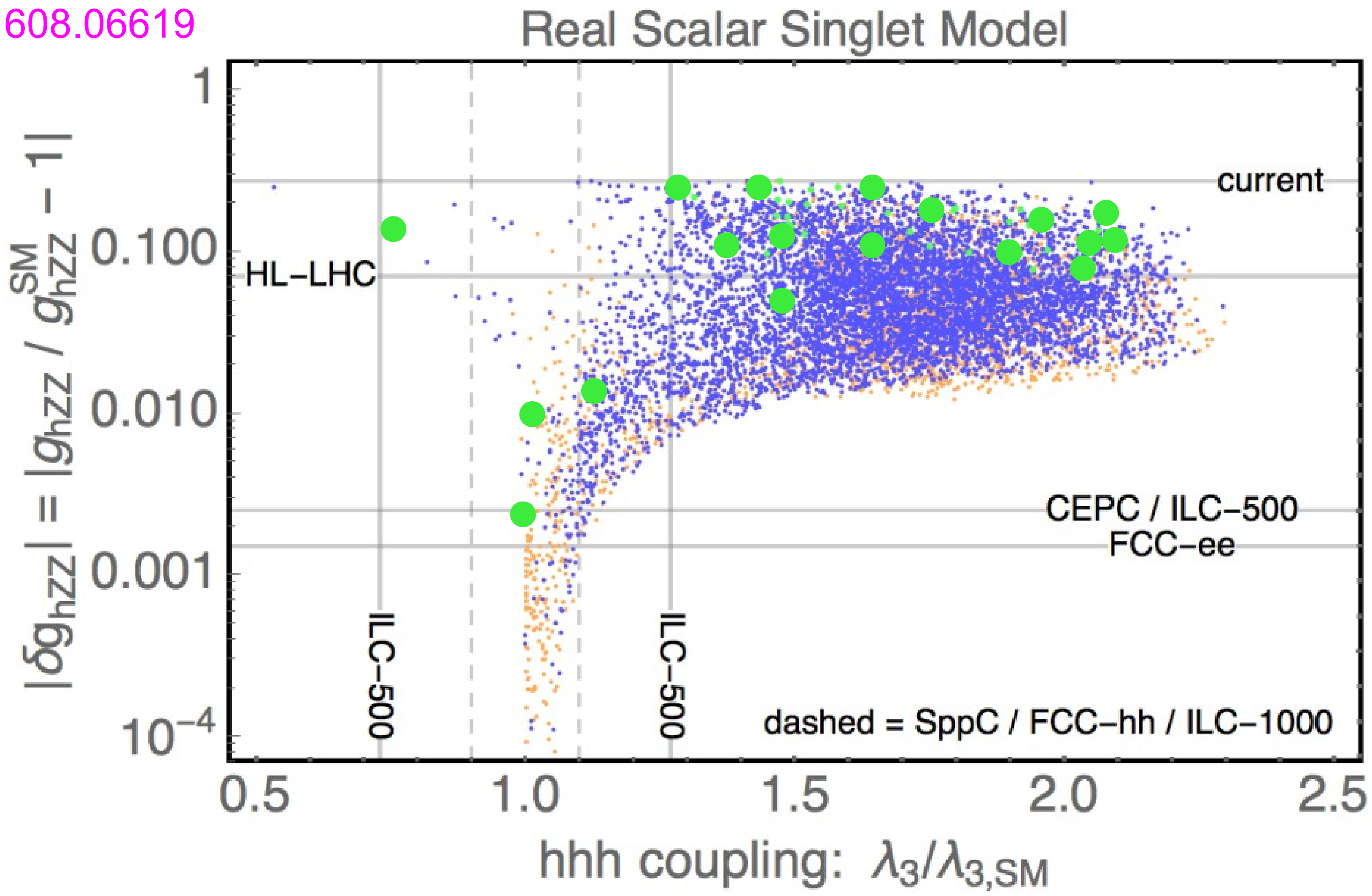
=> Cross over into “today's” shape at T=0

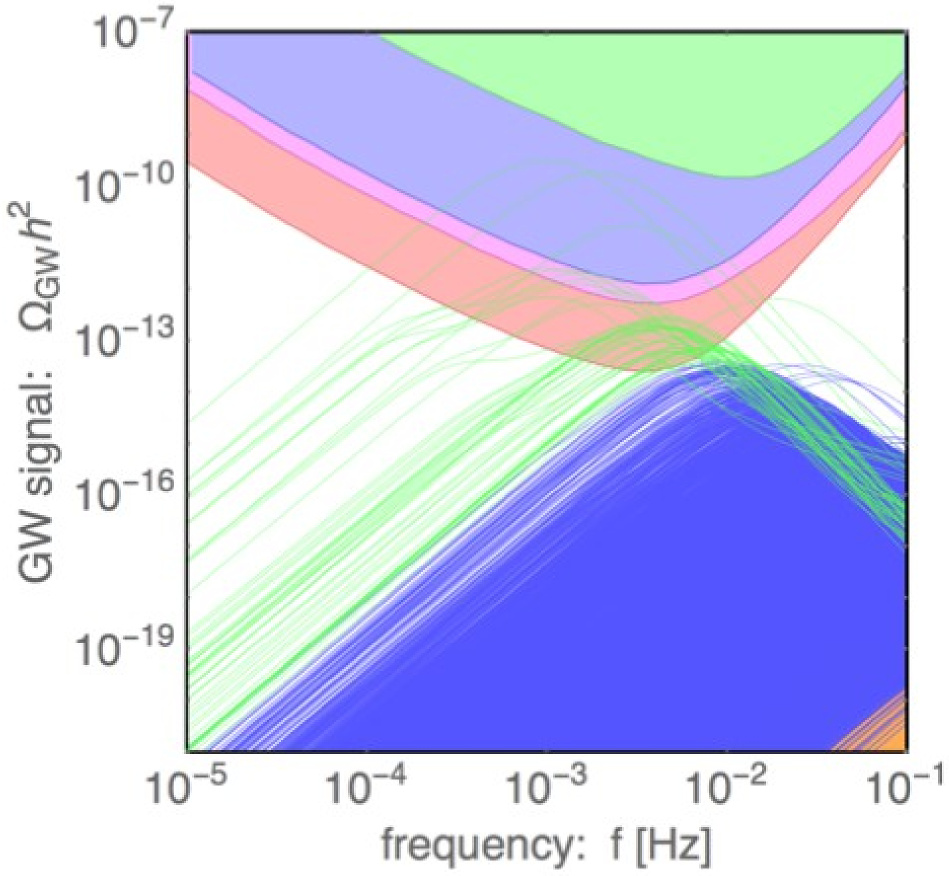
The discovered Higgs is too heavy to provoke a 1st order phase transition

=> New physics needed

New particles – Higgs couplings and EWBG

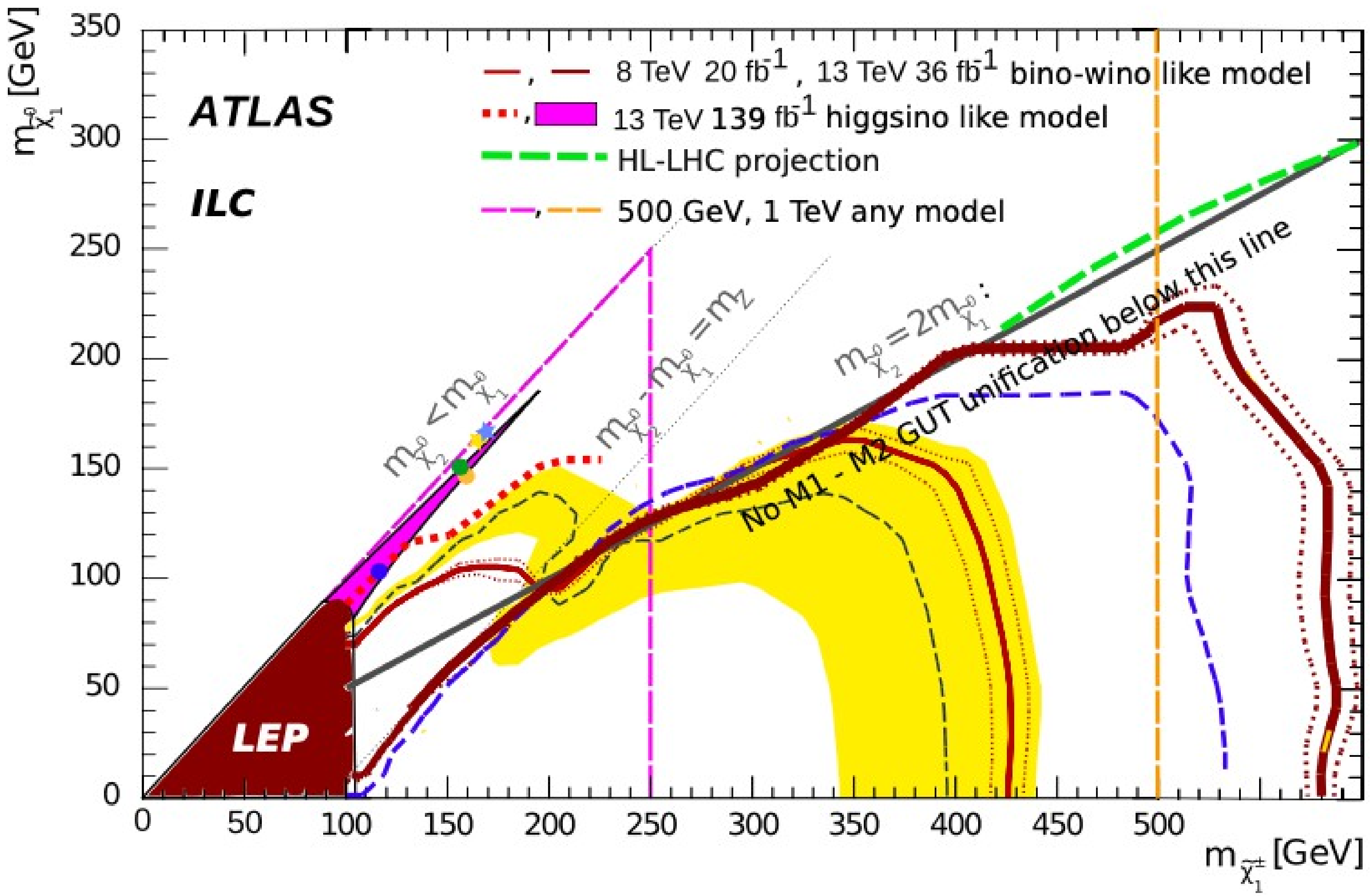
arxiv:1608.06619





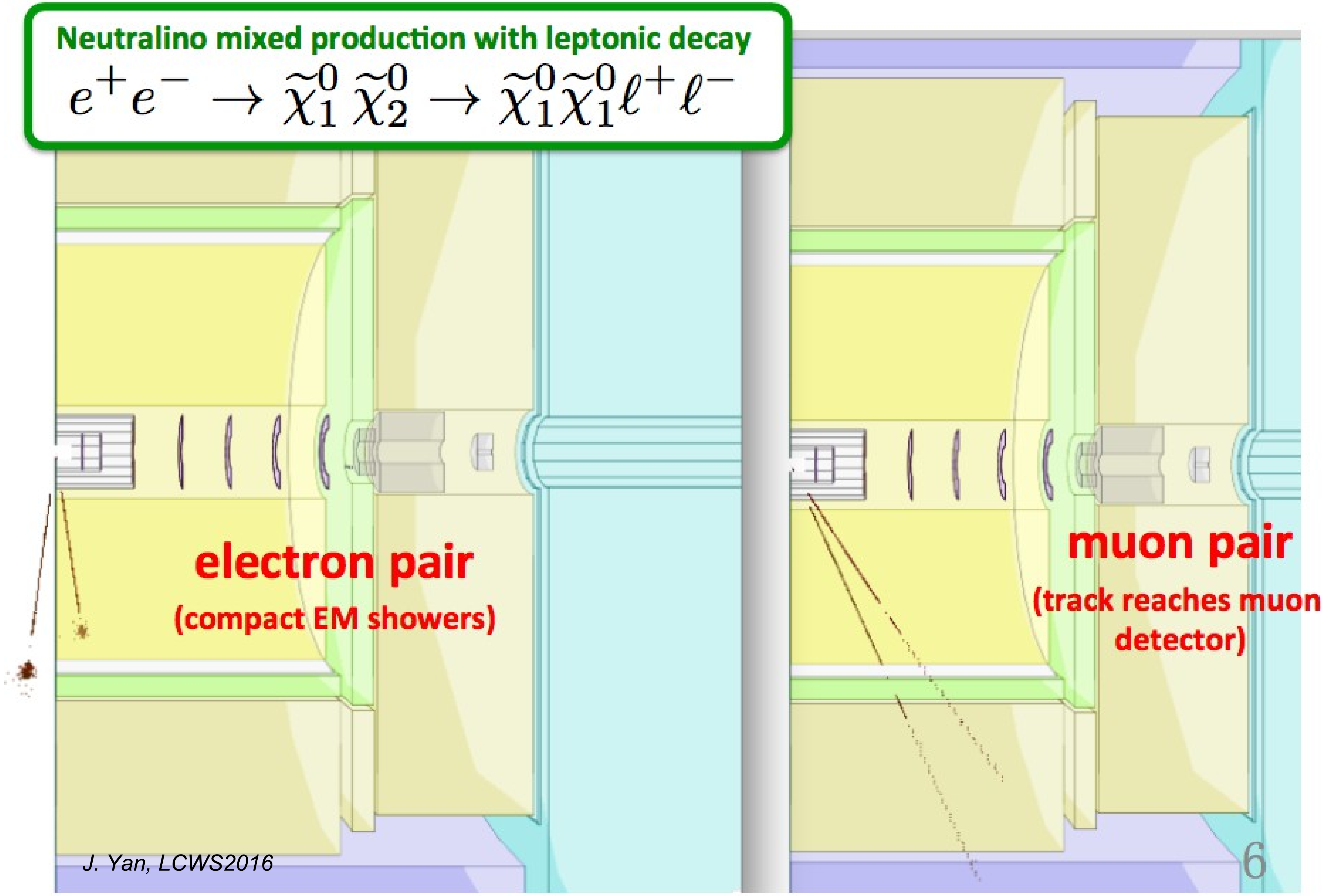
- Adding a singlet that mixes the SM Higgs allow for generating 1st Electroweak Phase transitions
  - Strong EWPT, stronger EWPT, strongest EWPT
- This has an impact on both gHZZ and Higgs self-coupling
- Higgs self-coupling O(10%) by linear colliders
- Strong EWPS may be detectable by eLISA ↔ Complementarity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

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



Neutralino mixed production with leptonic decay

$$e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell^+\ell^-$$

J. Yan, LCWS2016

Light Higgsinons- Event Display

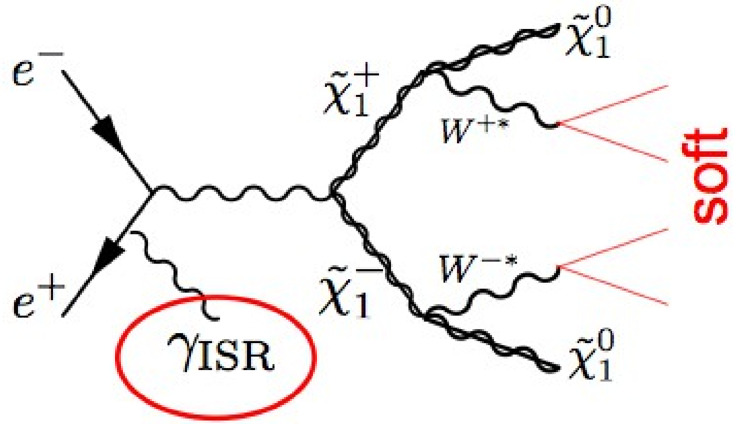
Study of Higgsino pair production, with ISR tag

Benchmark models with

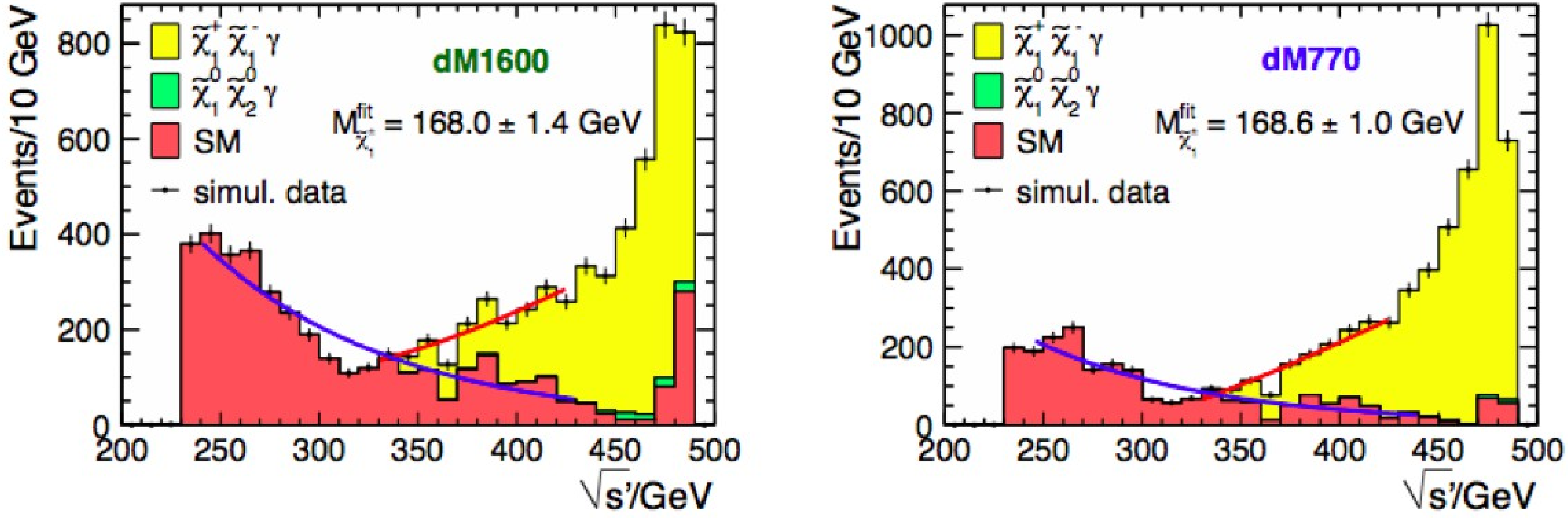
m(NLSP) – M(LSP) = 1.6 GeV and 0.8 GeV

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

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



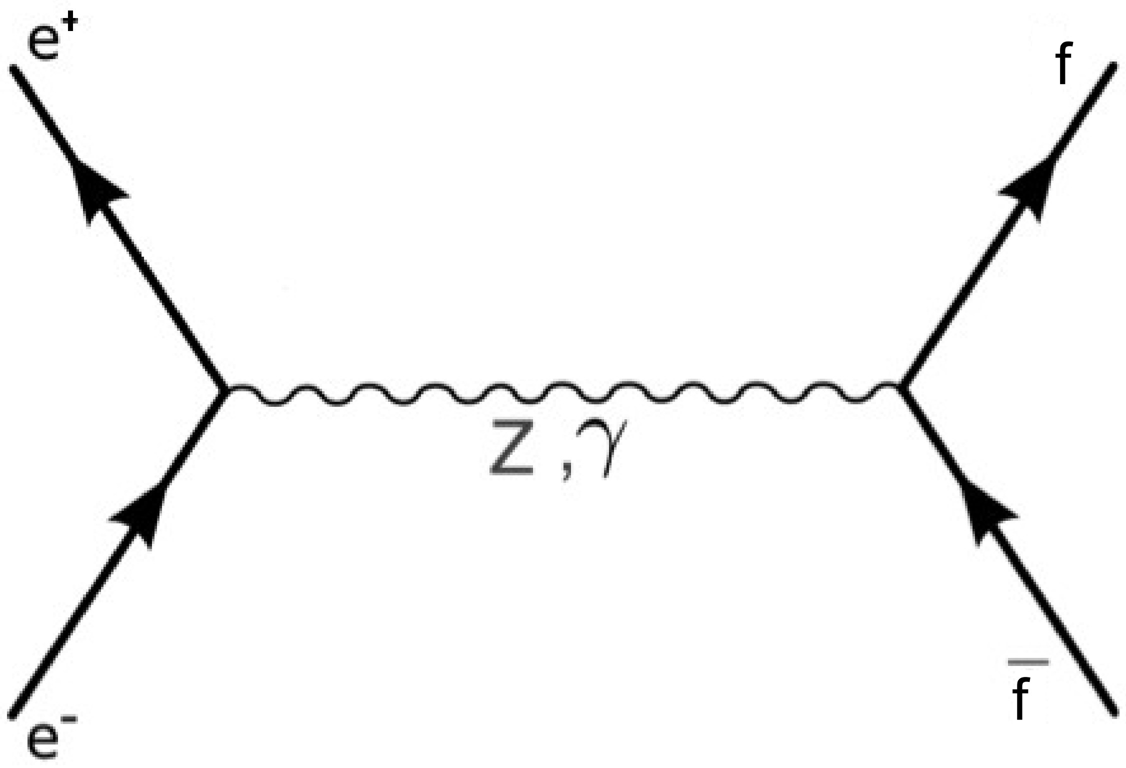
Berggren, Bruemmer, List, Moortgat-Pick, Robens, Rolbiecki, Sert, EPJ C73 (2013) 2660 [arXiv:1307.3566]



$\sqrt{s}$=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

Two fermion processes



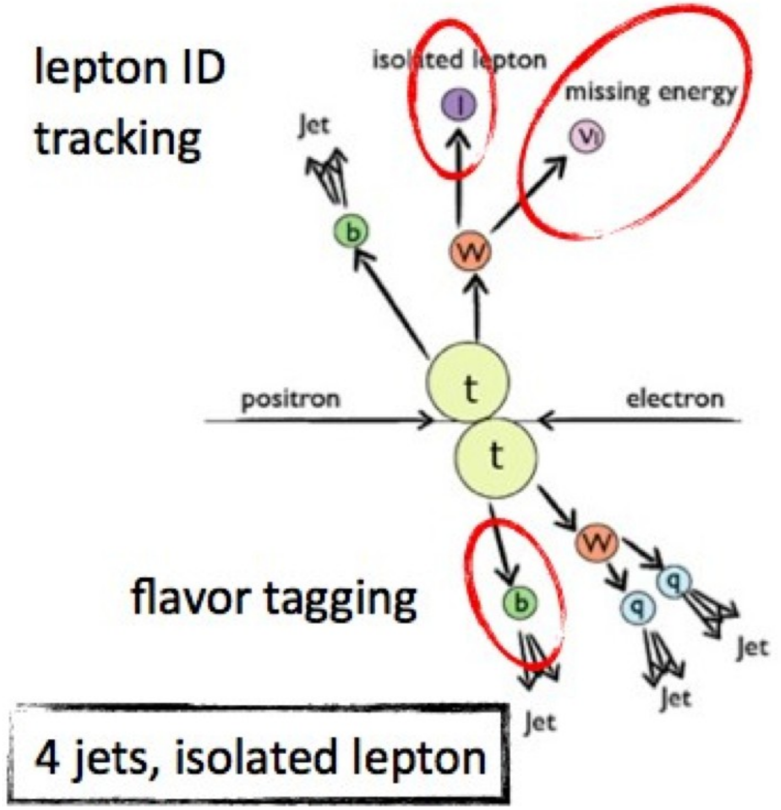
- Important threshold tt => top mass
- Sensitivity to new physics at all cms energies

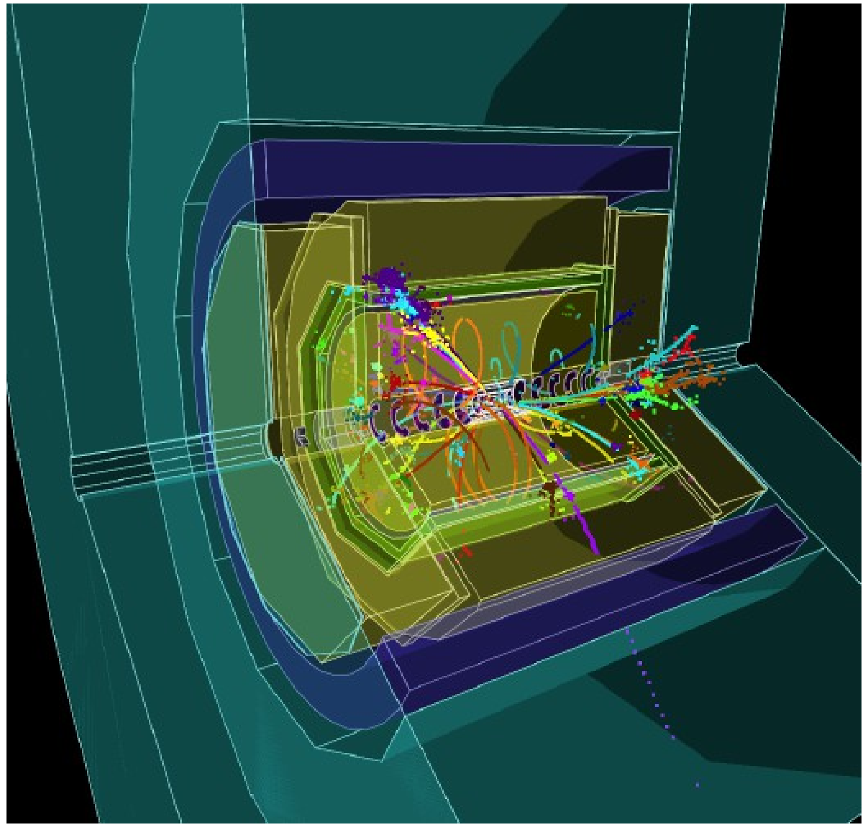
Elements of top quark reconstruction

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

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

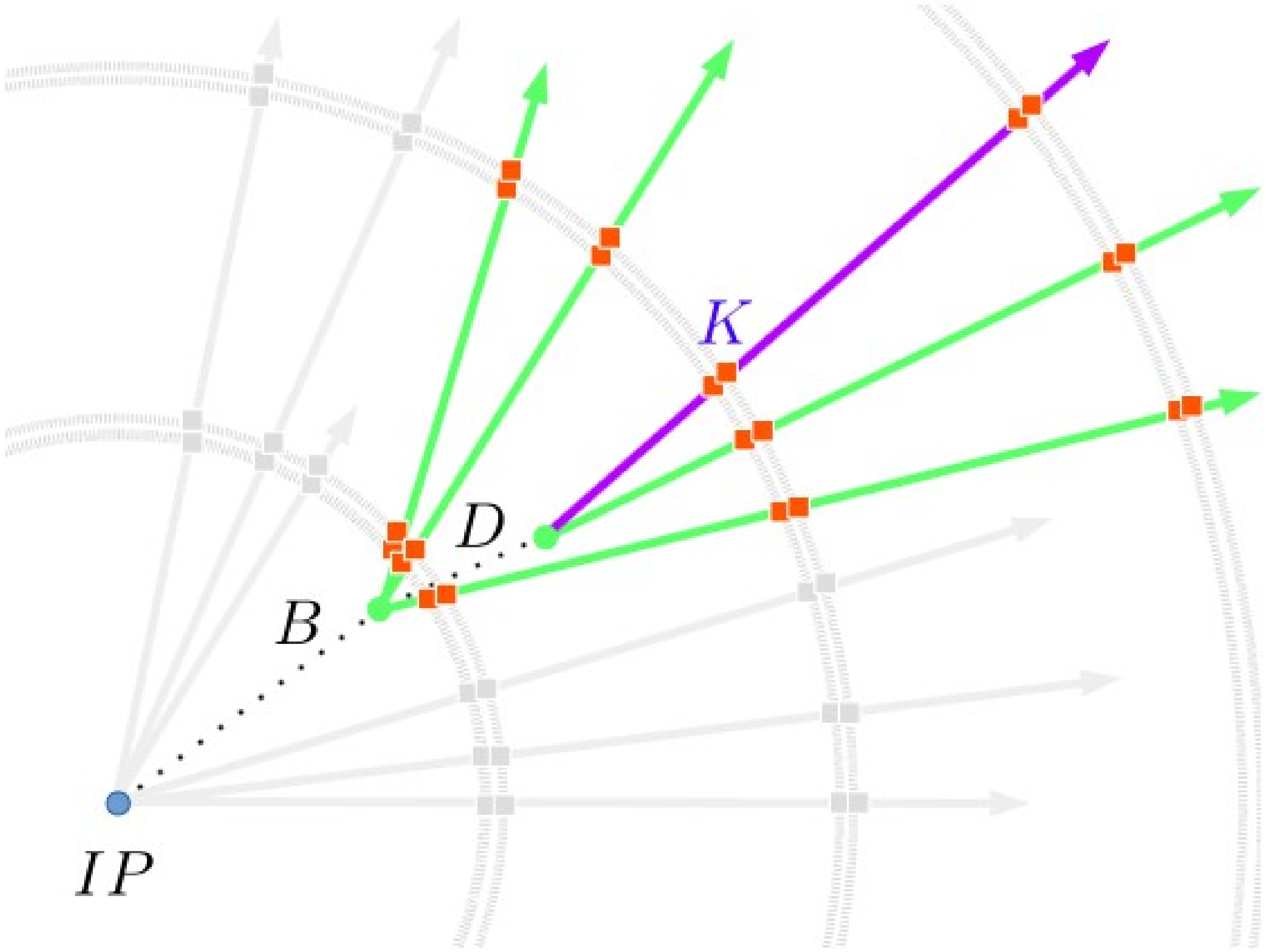




Final state reconstruction uses all detector aspects

Results shown in the following are based on full simulation of LC Detectors

Experimental challenges - Flavor tagging and charge measurement



- 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

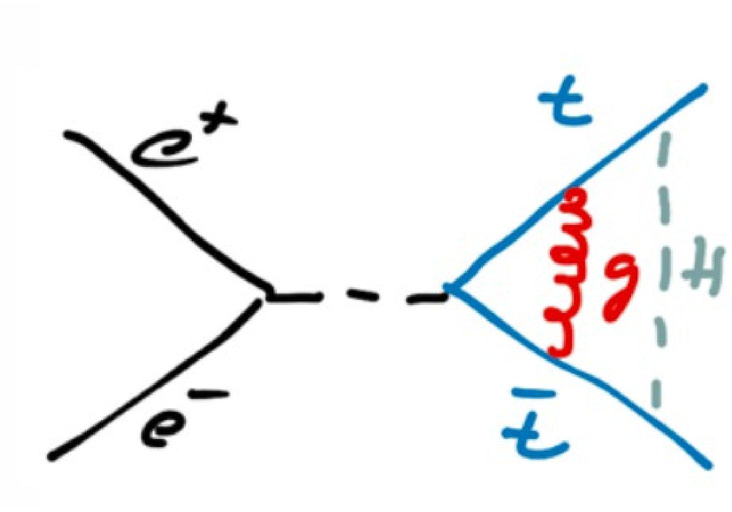
PhD thesis: S. Bilokin
A. Irles

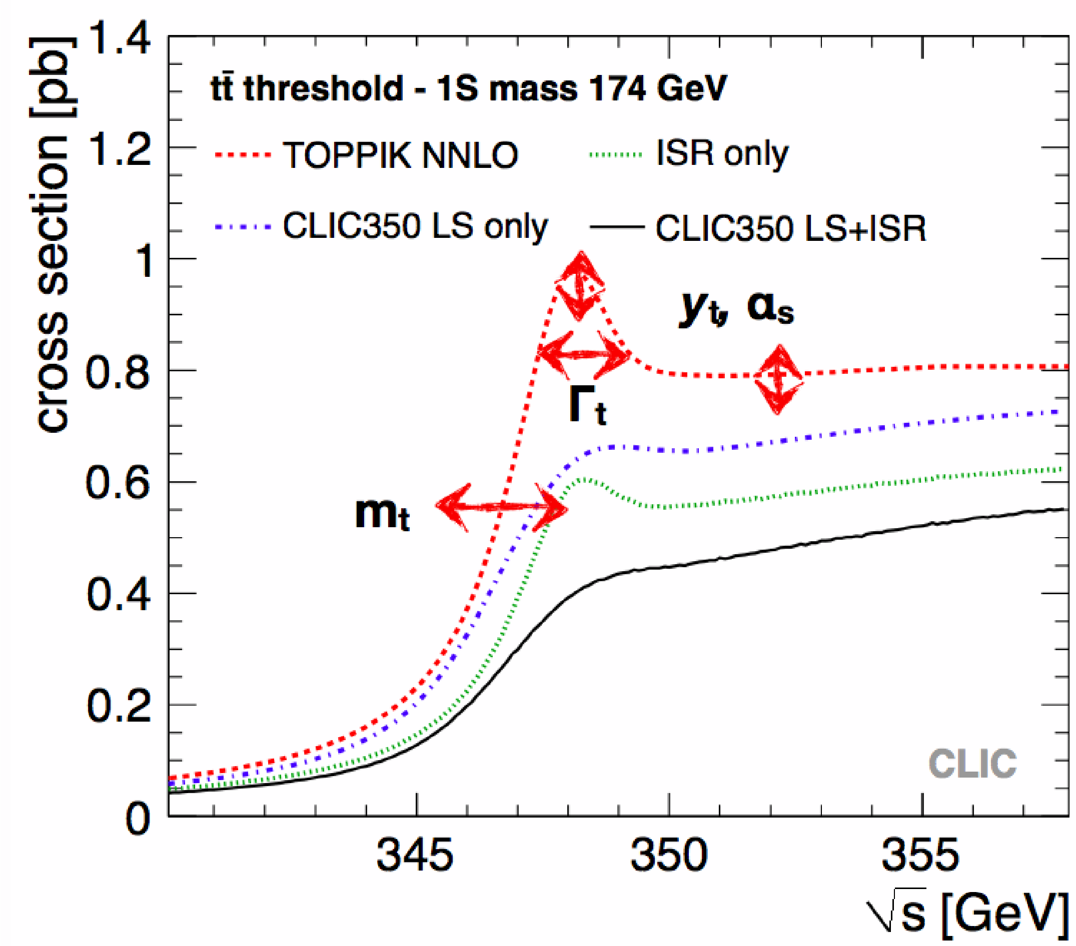
Top pair production at threshold

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

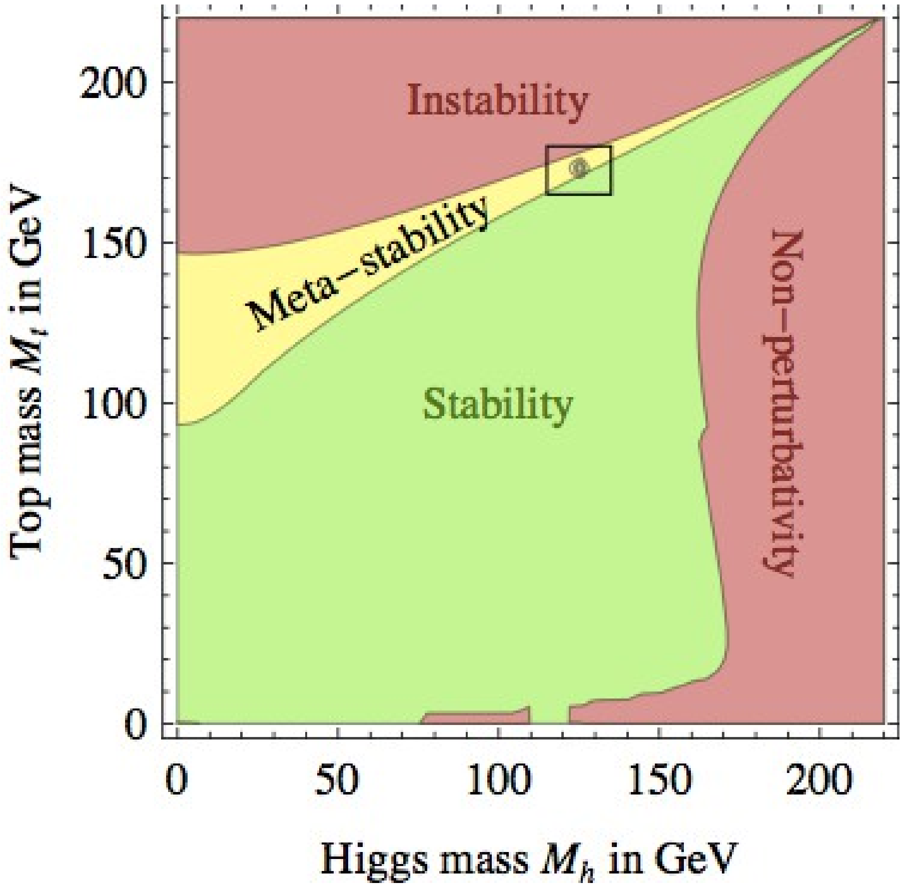


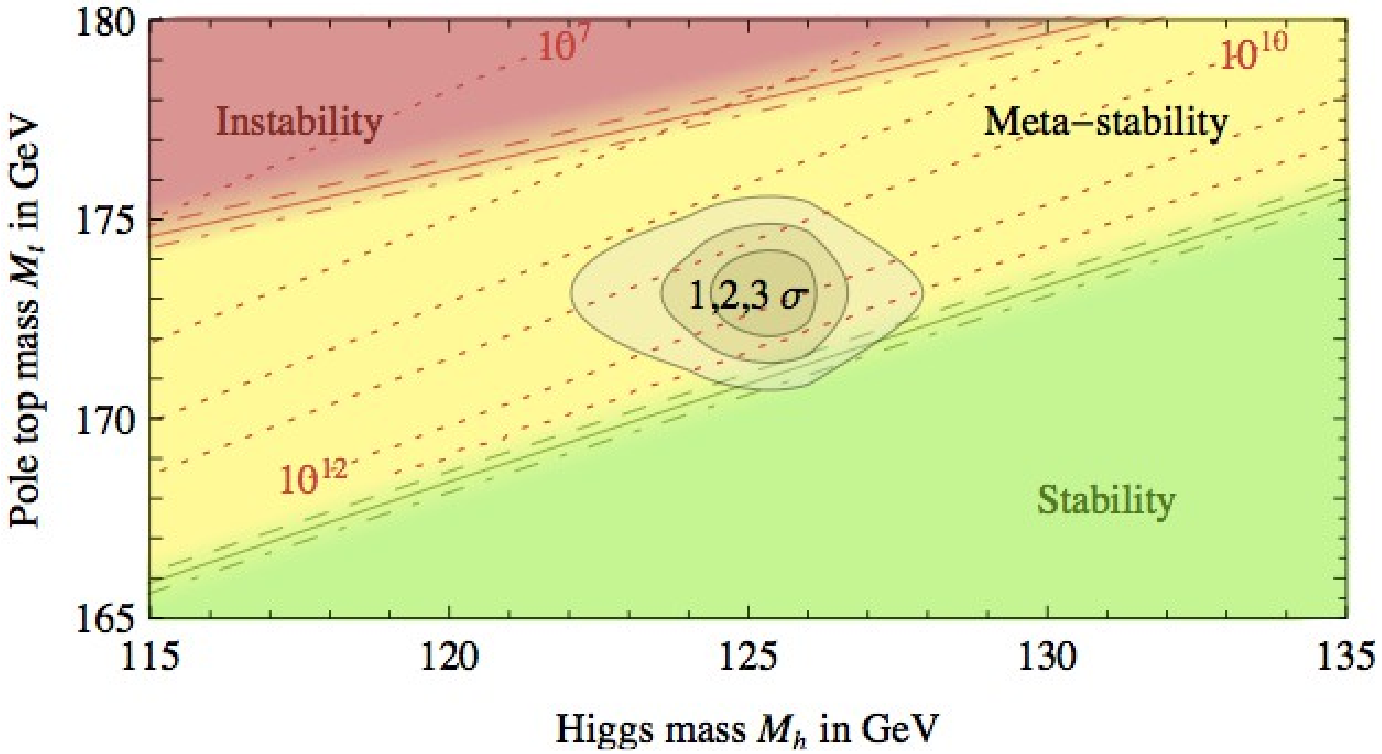


- Effects of some parameters are correlated:
- Dependence on Yukawa coupling rather weak,
- Precise external α_s helps

Vaccum Stability and Top Quark Mass

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



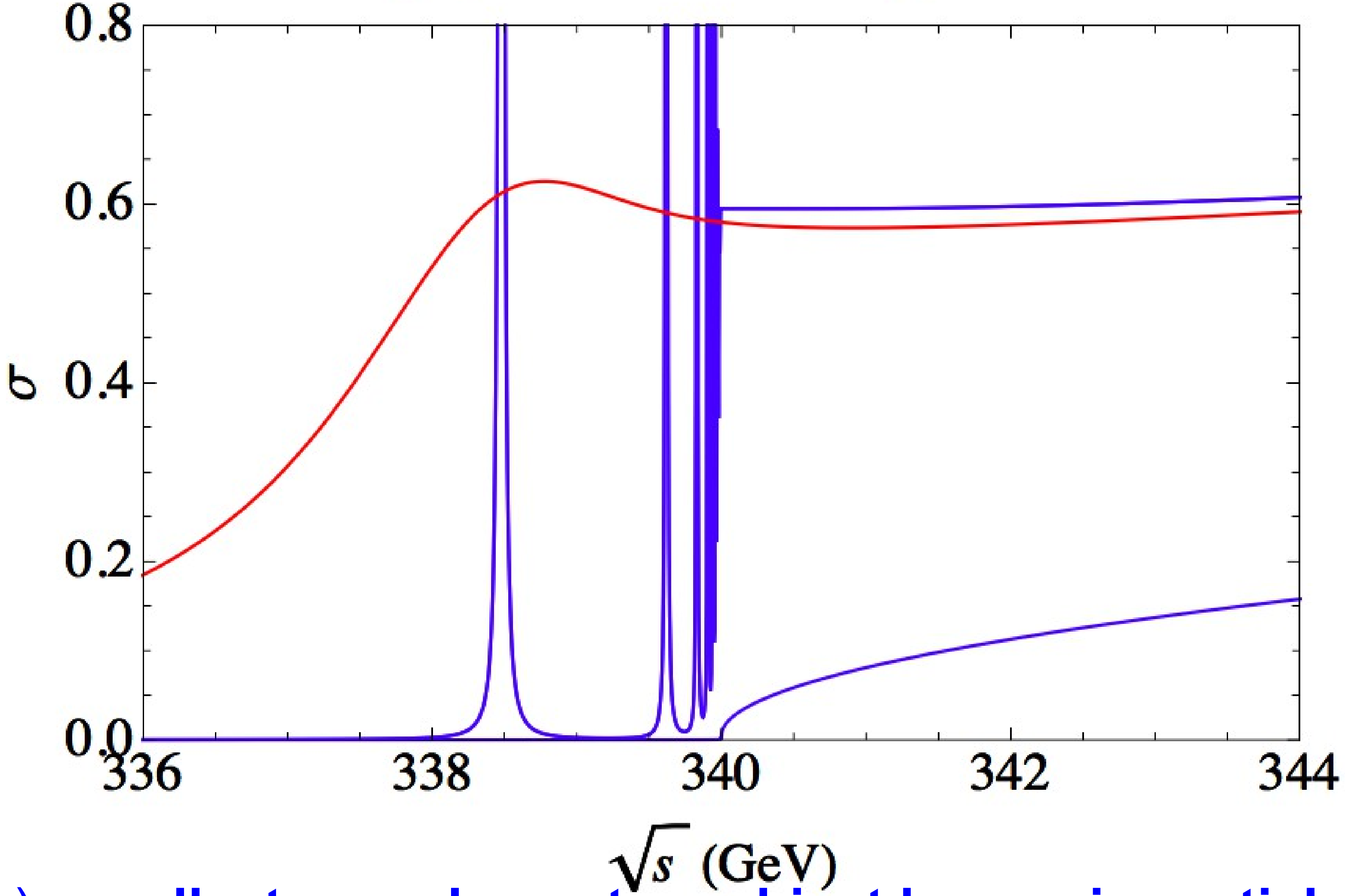


Uncertainty on (pole) top quark mass determines uncertainty on stability conditions

Top pair production at threshold

“Bound states” at tt threshold

Hydrogen atom of strong interaction



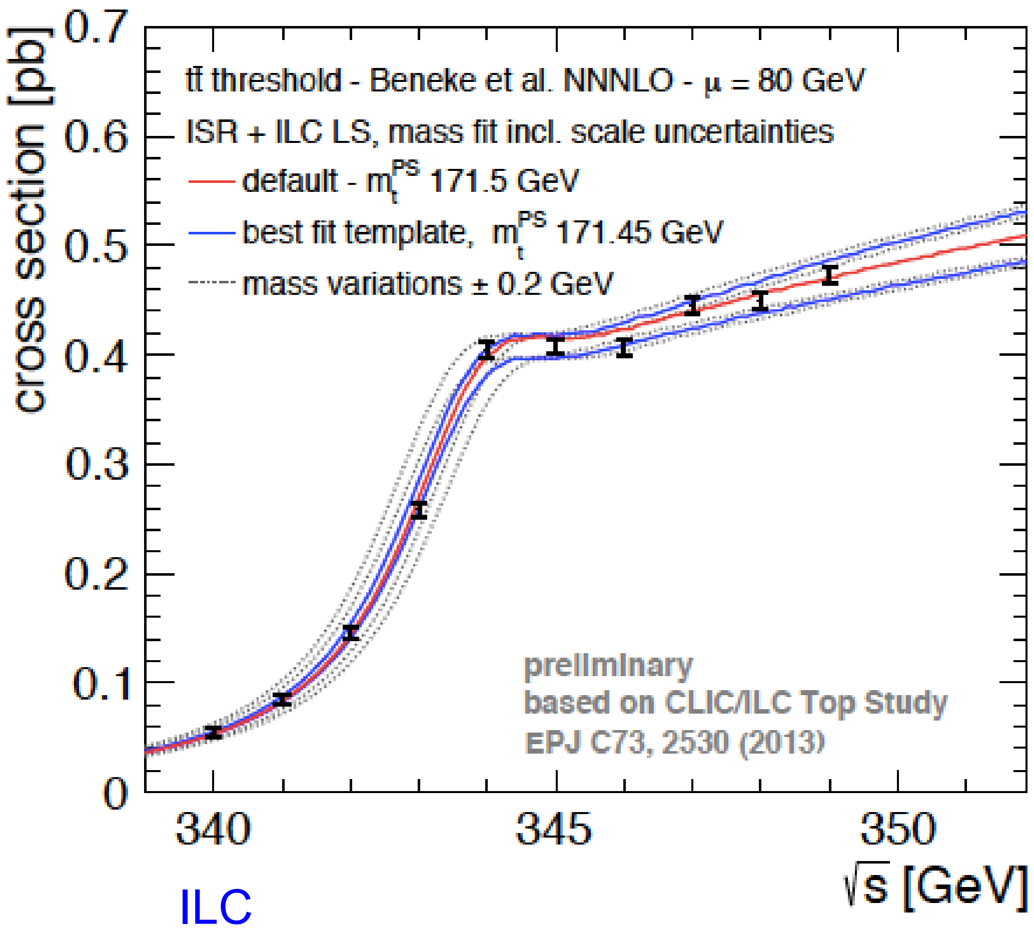
- Size O(10^{-17}m), **smallest non-elementary object known in particle physics**

  Small scale => Free of confinement effects => Ideal premise for precision calculations

  Measurement of (a hypothetical) 1^3S_1 State

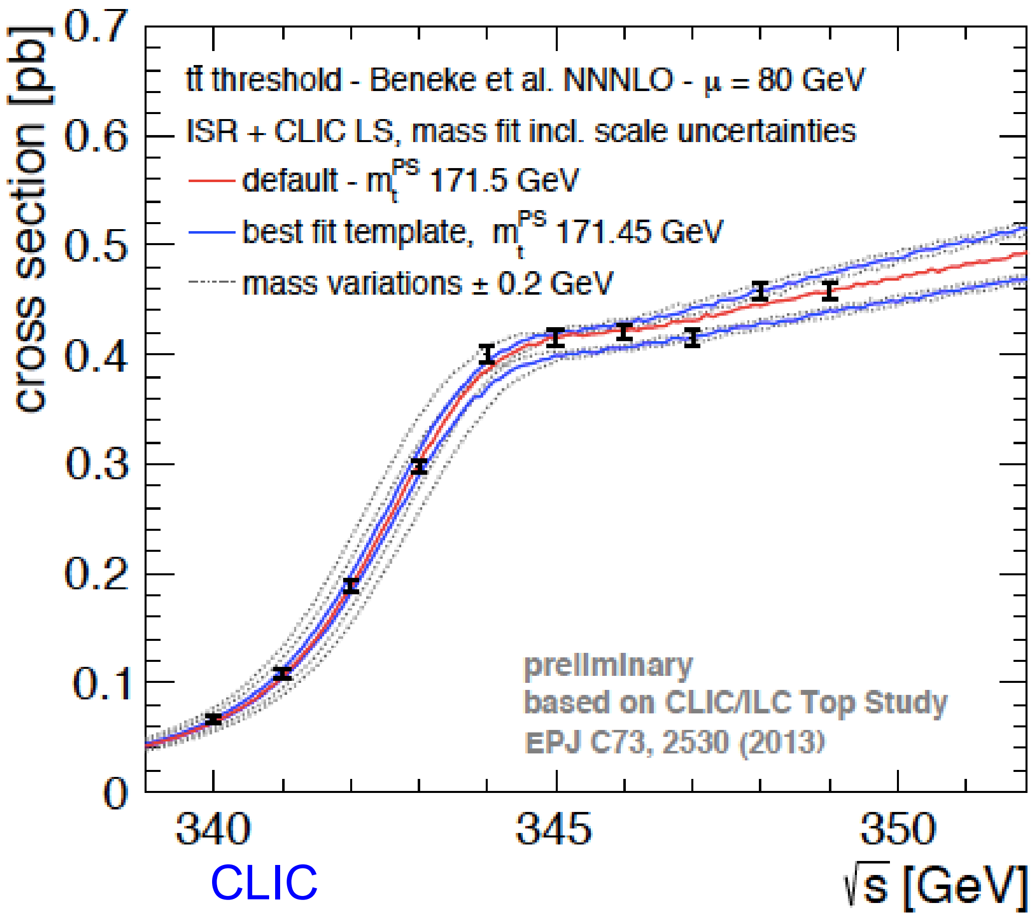
- Decay of top quark smears out resonances in a well defined way

Top threshold scans at different e+e- colliders



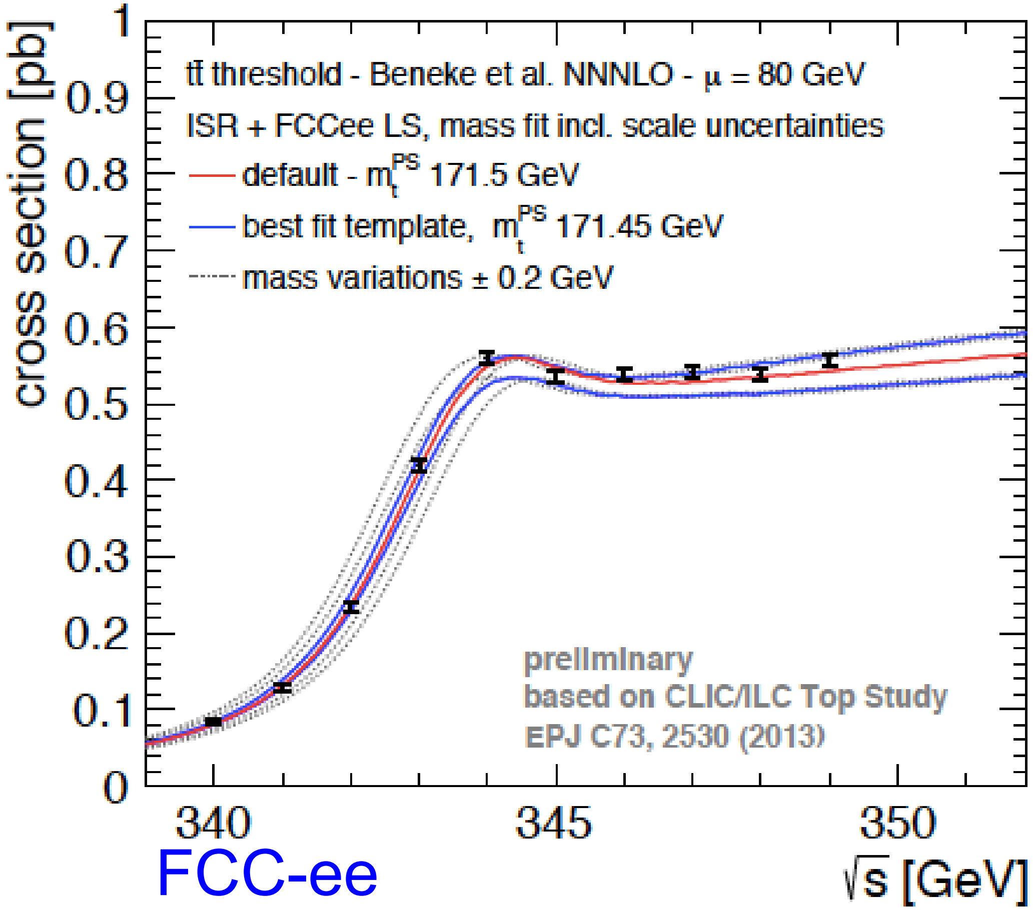
ILC

Fit uncertainty:
28.5 MeV (18 MeV stat)



CLIC

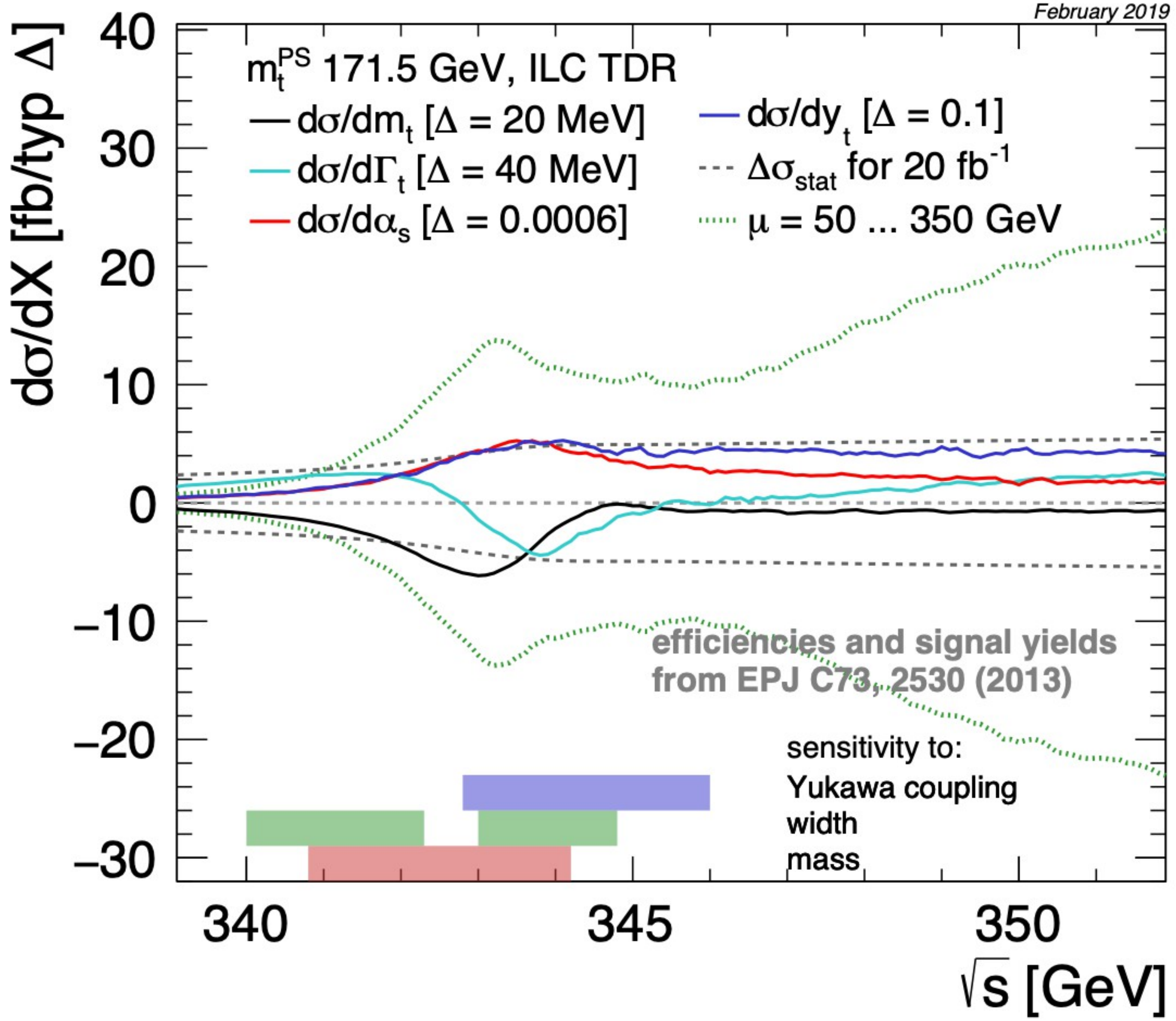
Fit uncertainty:
31 MeV (21 MeV stat)



FCC-ee

Fit uncertainty:
27 MeV (15 MeV stat)

Sensitivity and error breakdown

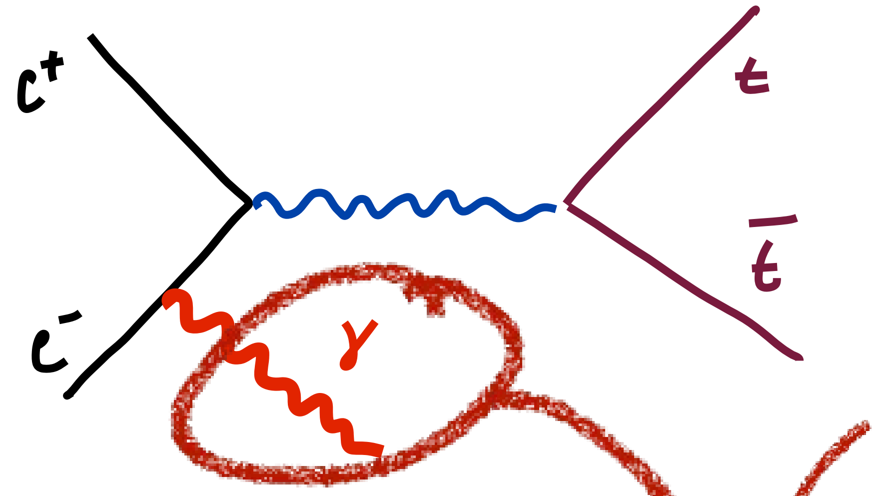


error source	Δm_t^{PS} [MeV]
stat. error (200 fb^{-1})	13
theory (NNNLO scale variations, PS scheme)	40
parametric (α_s, current WA)	35
non-resonant contributions (such as single top)	< 40
residual background / selection efficiency	10 – 20
luminosity spectrum uncertainty	< 10
beam energy uncertainty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

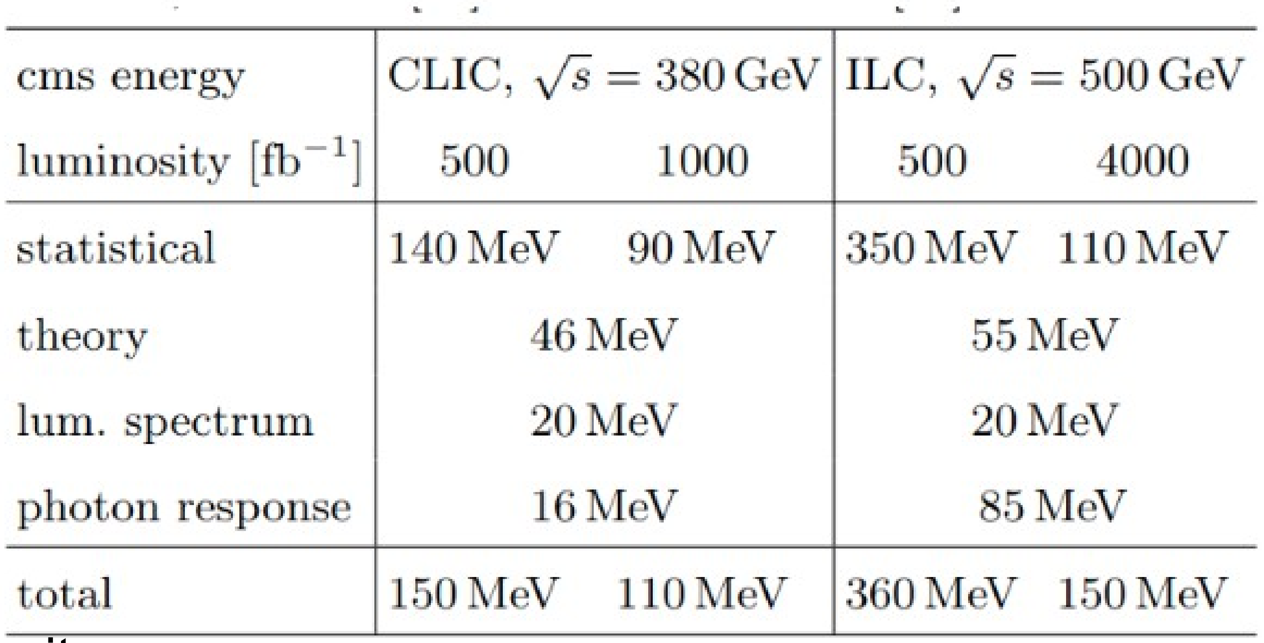
- Numbers for ILC/CLIC, some numbers get better for FCCee
  - e.g. Beam energy uncertainty < 3 [MeV]
- Uncertainty driver α_s
  - $\Delta m \sim 2.6$ per 10^{-4} in α_s

Running top mass

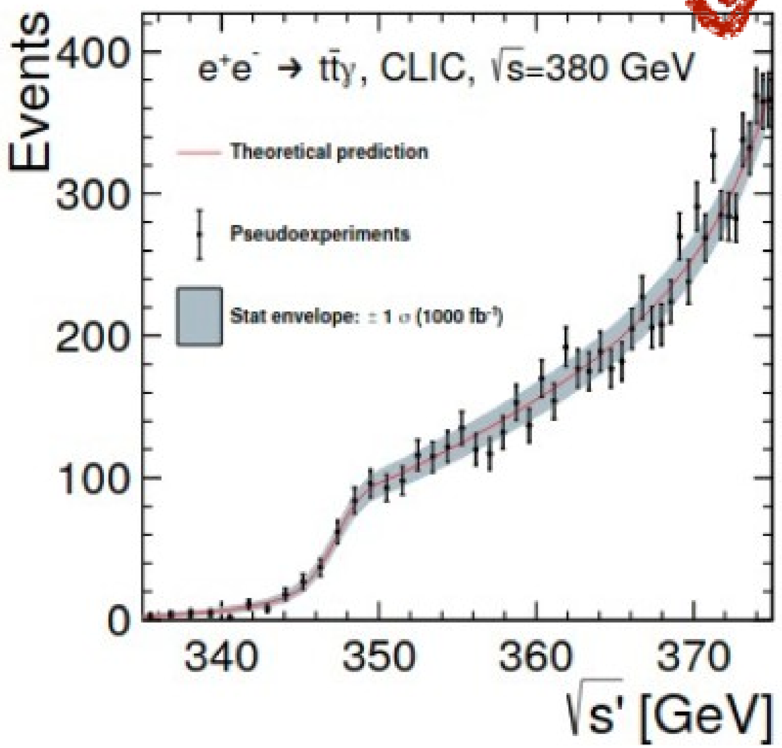
- A new(er) idea to measure the top mass in a theoretically well-defined scheme in high-energy running above the threshold

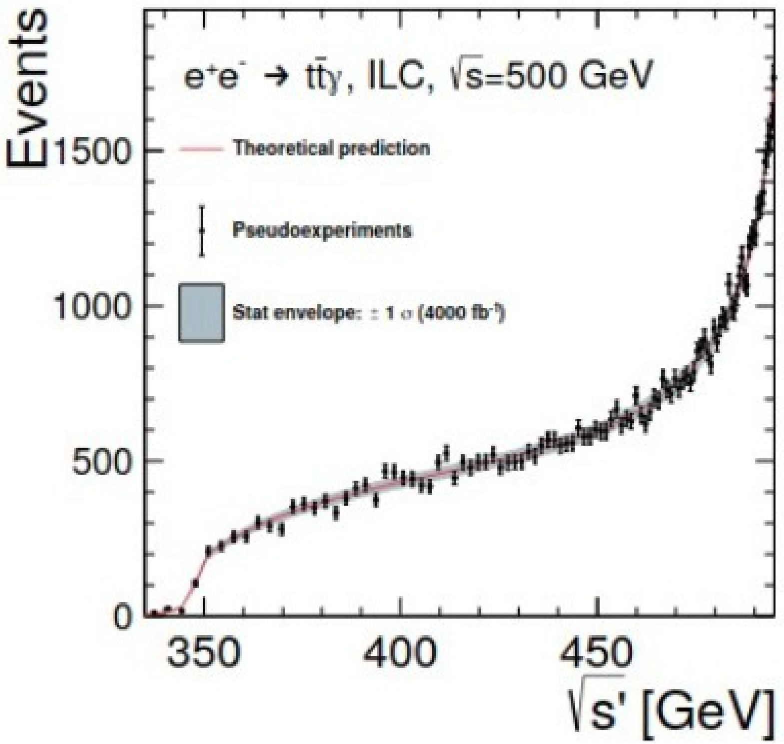


matched NNLO + NNLL calculation, luminosity spectrum folded in explicitly;
Extraction of short distance MSR mass

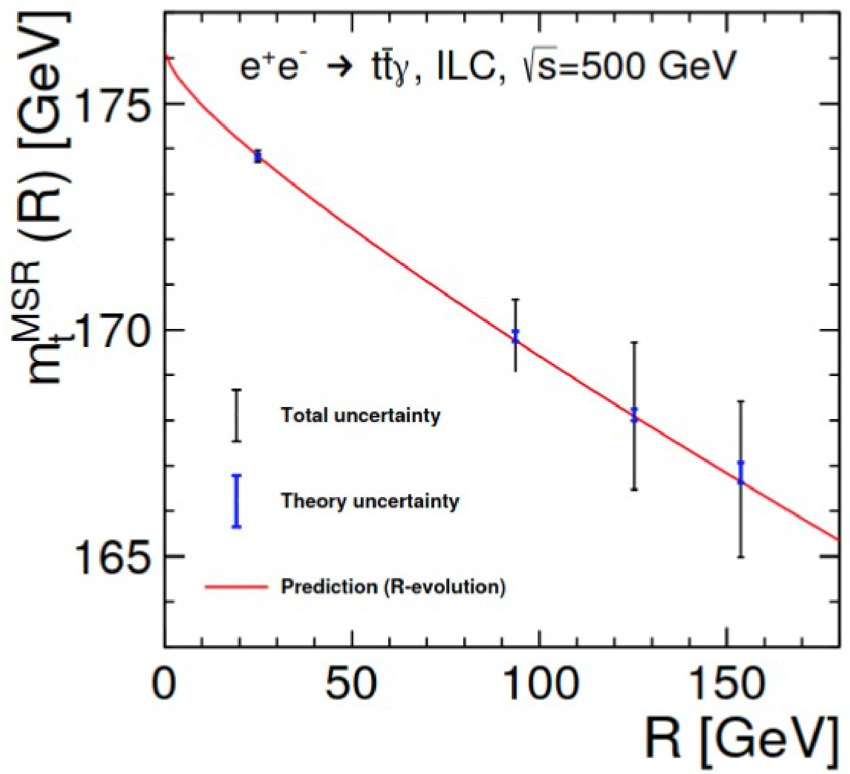


cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV

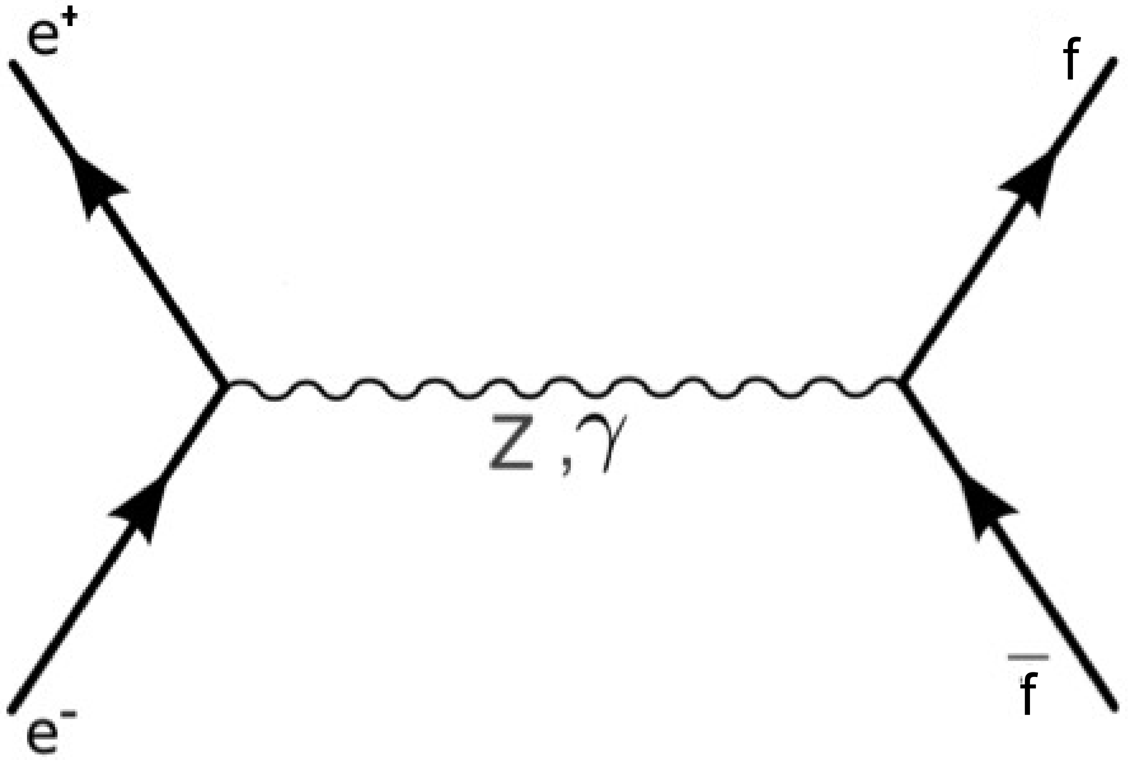




can provide 5σ evidence for scale evolution (“running”) of the top quark MSR mass from ILC500 data alone



Two fermion processes



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

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

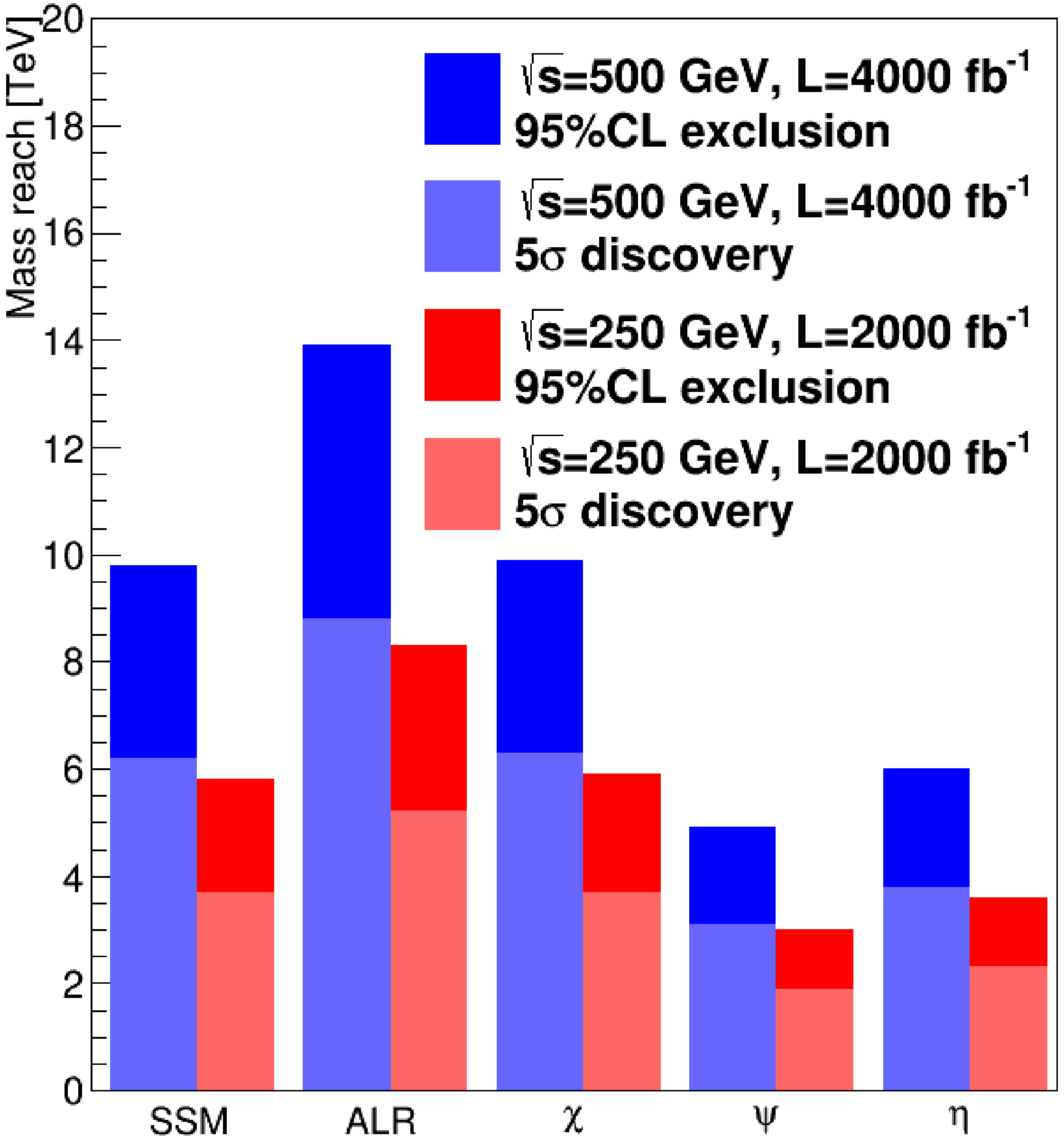
$$\frac{d\sigma}{d\cos\theta}(e^-_R e^+_L \rightarrow f\bar{f}) = \Sigma_{RL}(1+\cos\theta)^2 + \Sigma_{RR}(1-\cos\theta)^2$$

*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**

- **Here we focus on tt, bb and cc pair production**

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



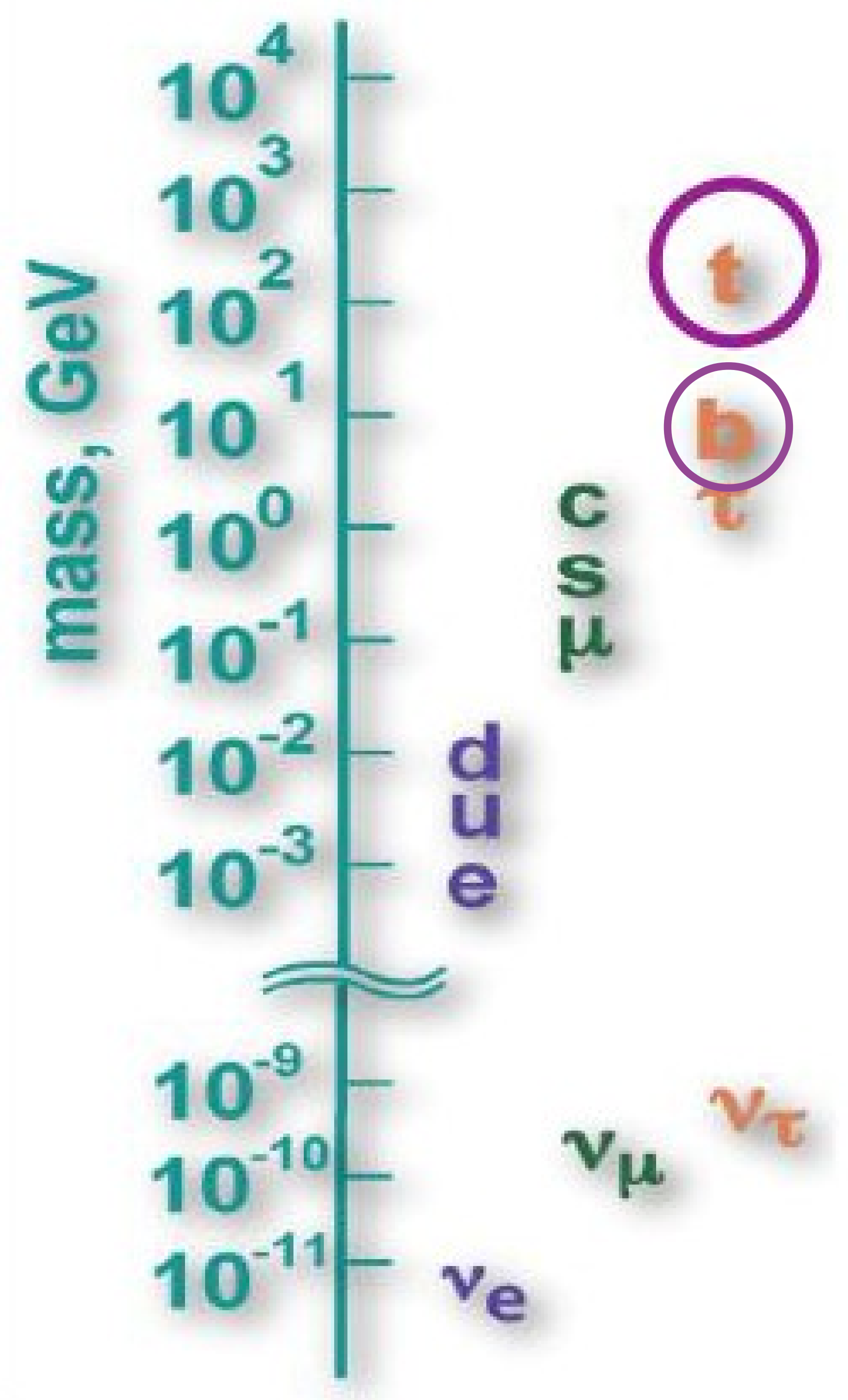
Study by Kyushu group and KEK group within TYL/FJPPL HEP01 Project

- 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 Z

Typical mass reach 5-10 TeV

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

Electroweak couplings of heavy quarks



- 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

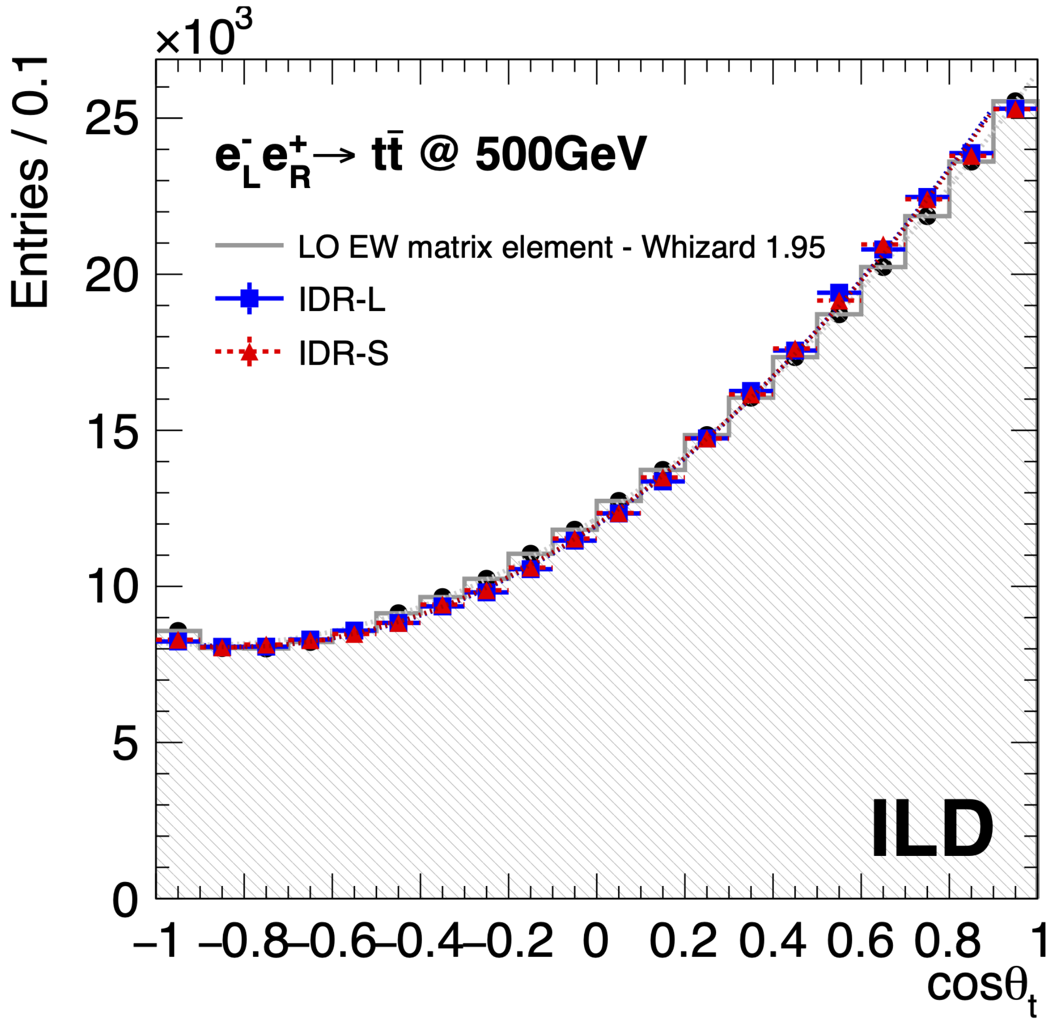
- Expect residual effects for particles with masses closest to symmetry breaking scale

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

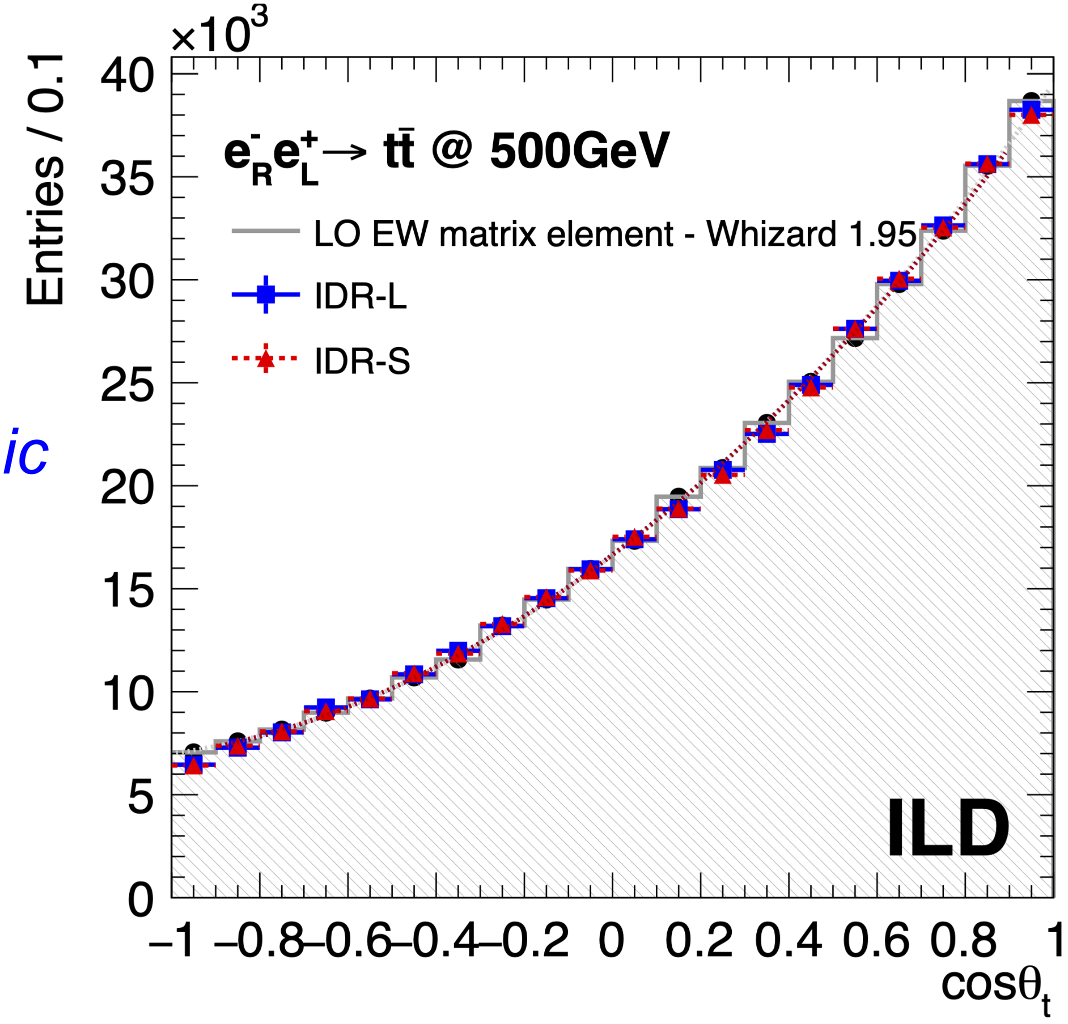
- Heavy quark effect or effect on all fermions?

Strong motivation to study chiral structure of (heavy) quark vertices in high energy e+e- collisions

Top quark polar angle spectrum at 500 GeV



Semi-leptonic channel

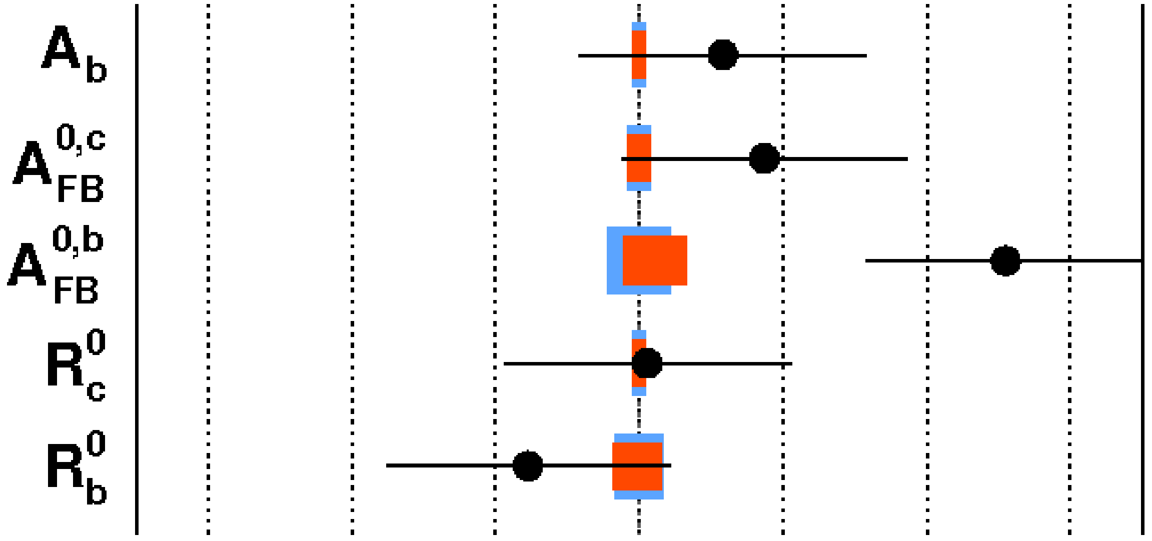


ILD-Note-2019-007

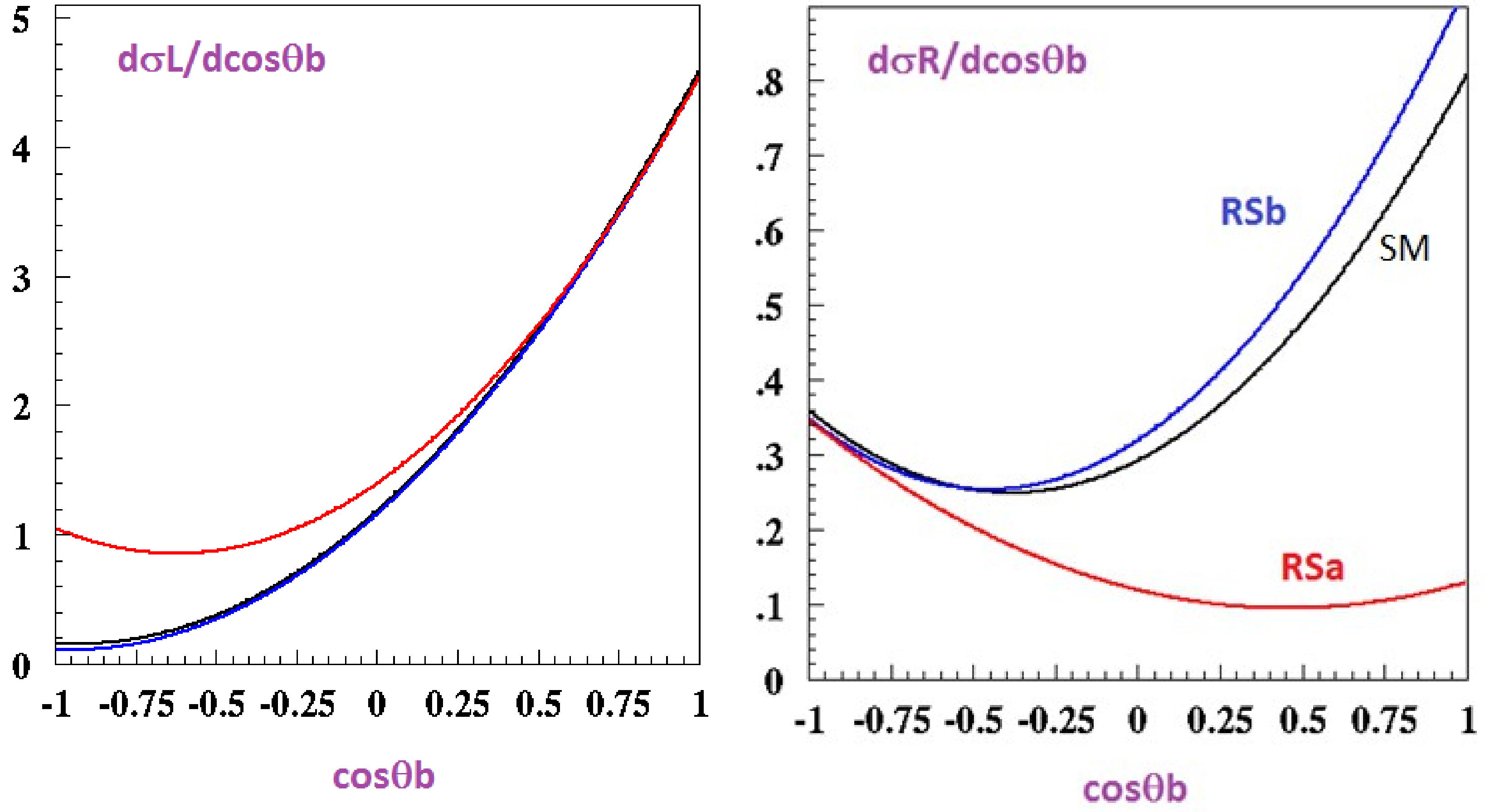
- Integrated Luminosity 4 fb^{-1}
- Exact reproduction of generated spectra
- Statistical precision on cross section: ~0.1%
- Statistical precision on A_{FB}: ~0.5%
  - Can expect that systematic errors will match statistical precision (but needs to be shown)

New physics below tt threshold? - Example b quark couplings

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



ee->bb@250 GeV

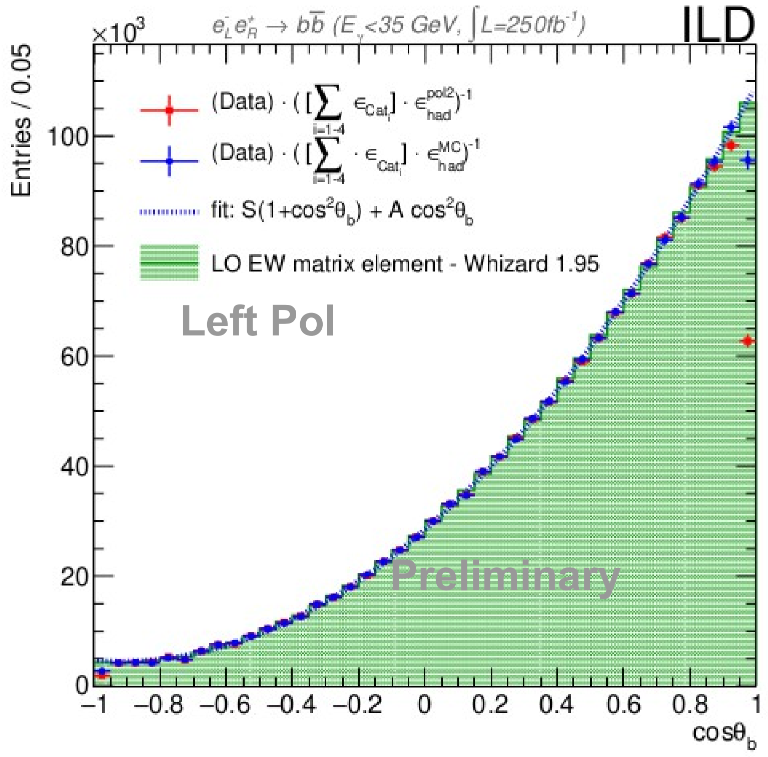


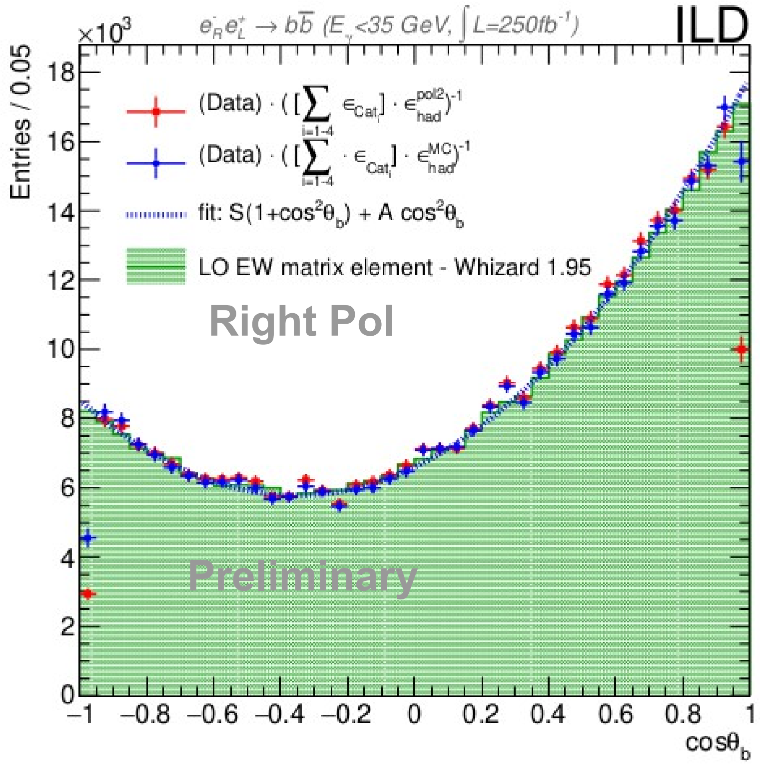
Randall Sundrum Models Djouadi/Richard '06

- 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*

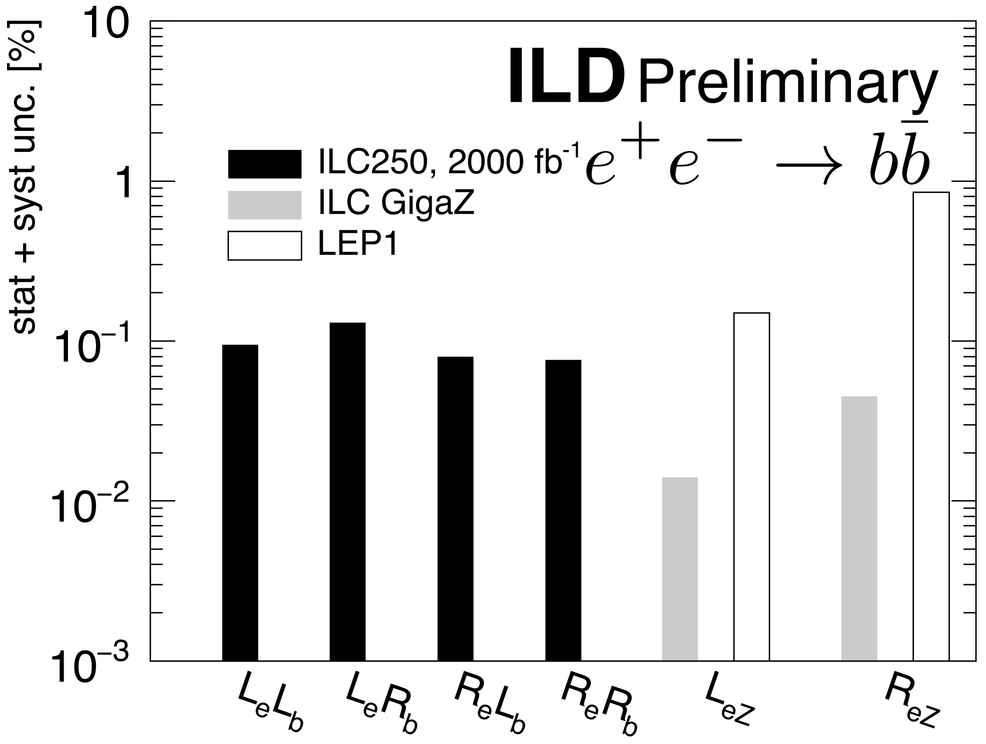
Systematic uncertainties under scrutiny:

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

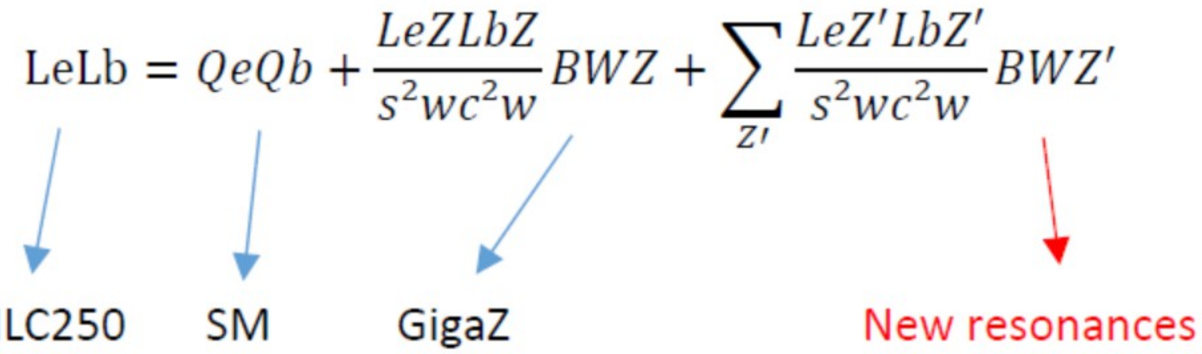
Additional complication in continuum: Rejection of ISR events – Uncertainty ~5x10^{-4} (doesn't apply on Z-pole)

Precision on electroweak form factors and couplings

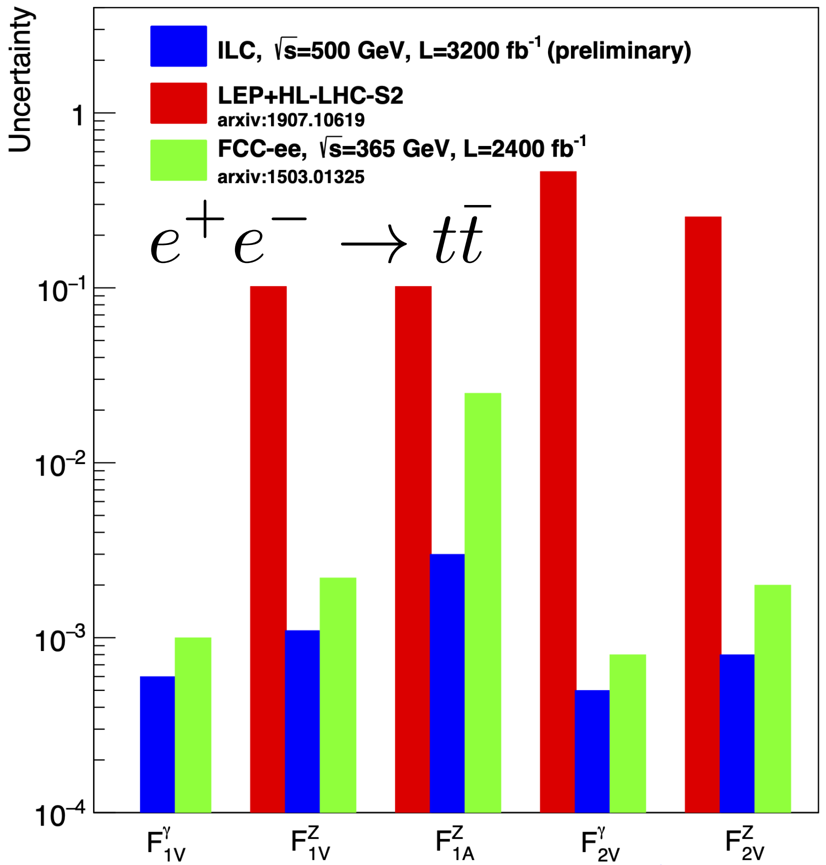
Arxiv:1709.04289, ILD Paper in progress



- Couplings are order of magnitude better than at LEP



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



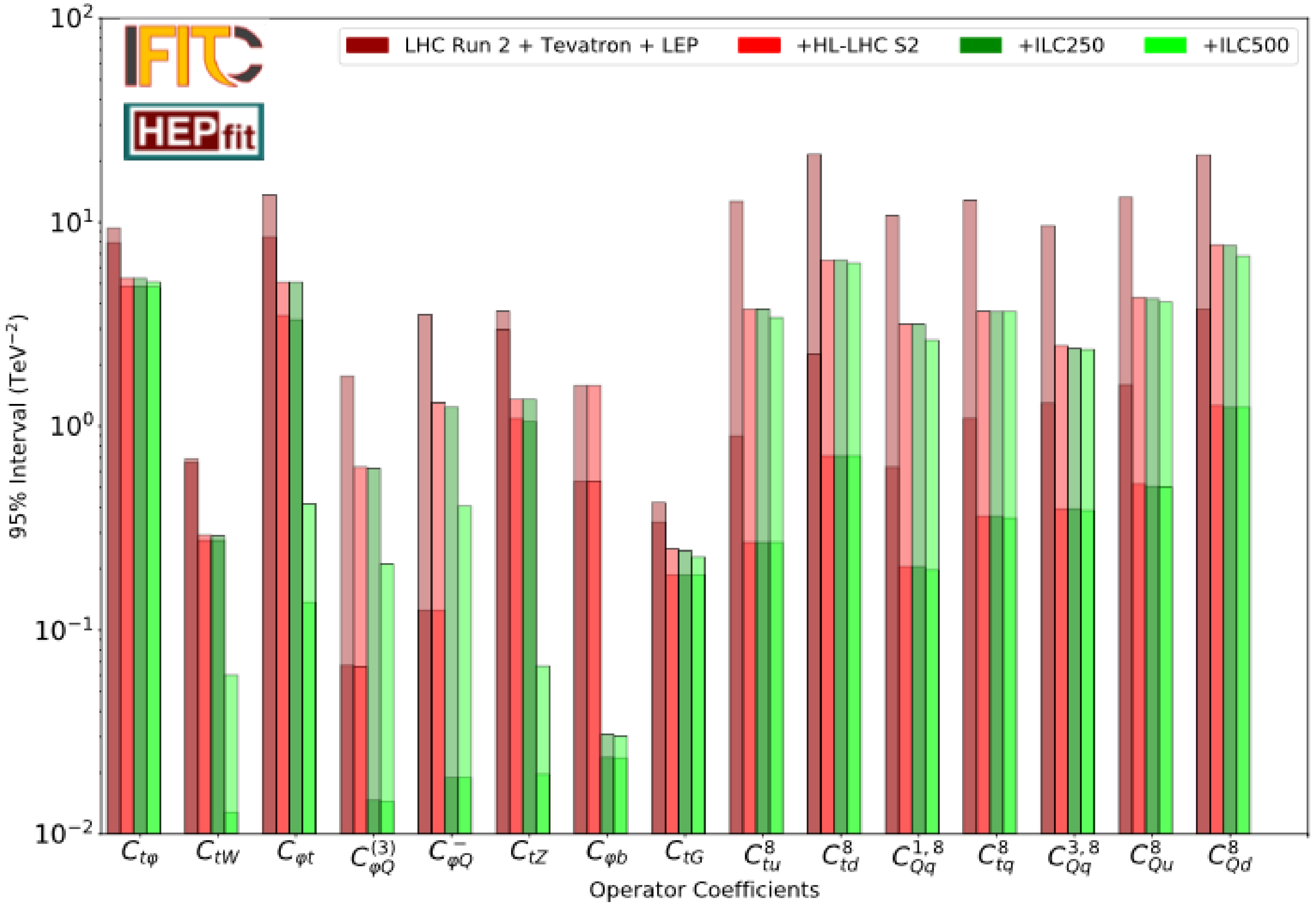
- e+e- collider way superior to LHC (√s = 14 TeV)

- 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!!

Electroweak top couplings EFT-operators



arxiv:2203.07622
Updated from arxiv:1907.10619

Mapping between FF and EFT Coefficients

$$F^Z_{1V} = \frac{\frac{1}{4} - \frac{2}{3}s^2_W}{s_W c_W} - \frac{m_t^2}{\Lambda^2}\frac{1}{2s_W c_W}\left[C^V_{\varphi q} = C^{(33)}_{\varphi u} + (C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q})\right],$$

$$F^Z_{1A} = \frac{-\frac{1}{4}}{s_W c_W} - \frac{m_t^2}{\Lambda^2}\frac{1}{2s_W c_W}\left[C^A_{\varphi q} = C^{(33)}_{\varphi u} - (C^{1(33)}_{\varphi q} - C^{3(33)}_{\varphi q})\right],$$

$$F^Z_{2V} = 4\frac{m_t^2}{\Lambda^2}\left[C^R_{uZ} = \mathrm{Re}\{c^2_W C^{(33)}_{uW} - s^2_W C^{(33)}_{uB}\}/s_W c_W\right],$$

$$F^Z_{2A} = 4\frac{m_t^2}{\Lambda^2}i\left[C^I_{uZ} = \mathrm{Im}\{c^2_W C^{(33)}_{uW} - s^2_W C^{(33)}_{uB}\}/s_W c_W\right],$$

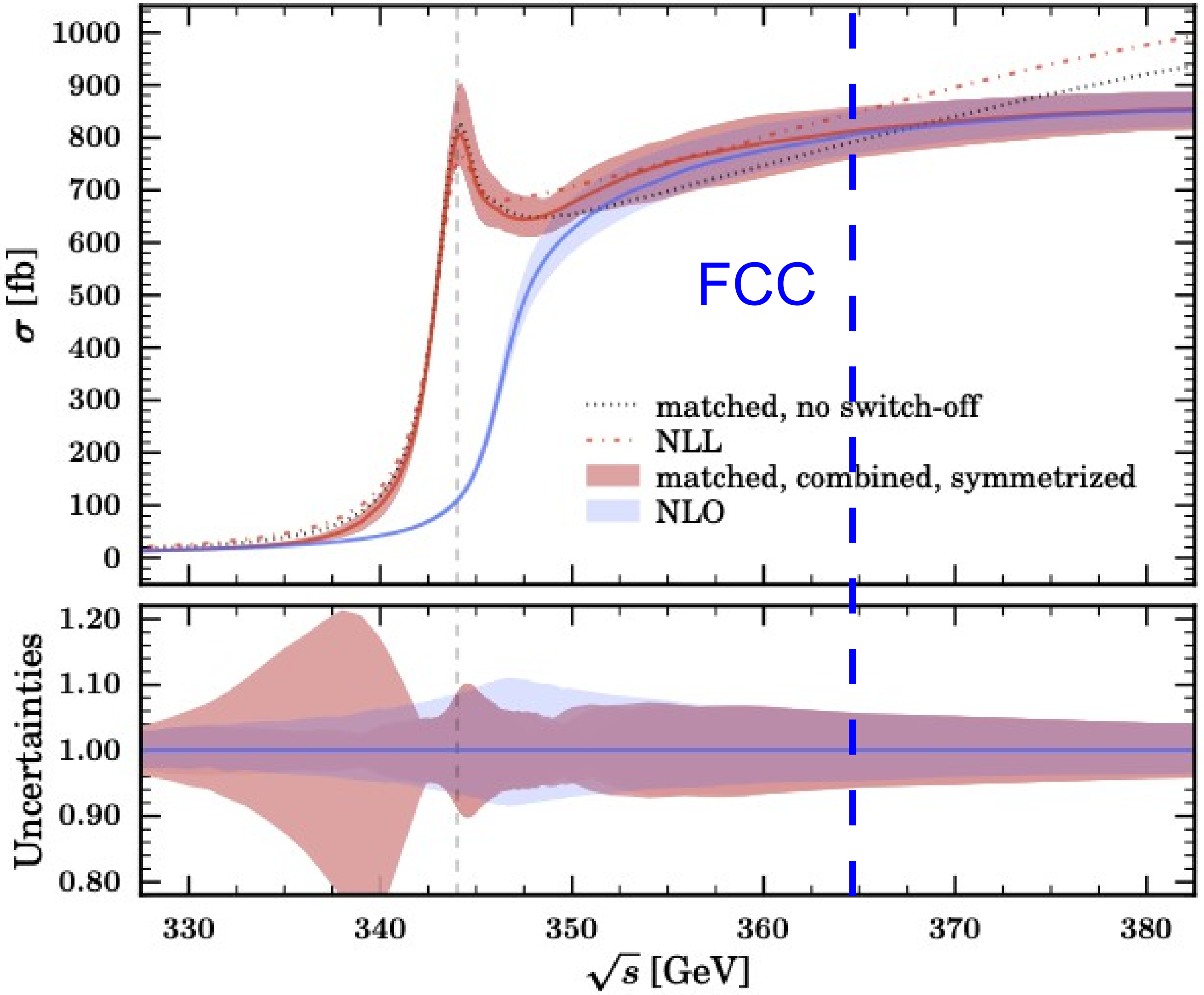
arxiv:1807.02121

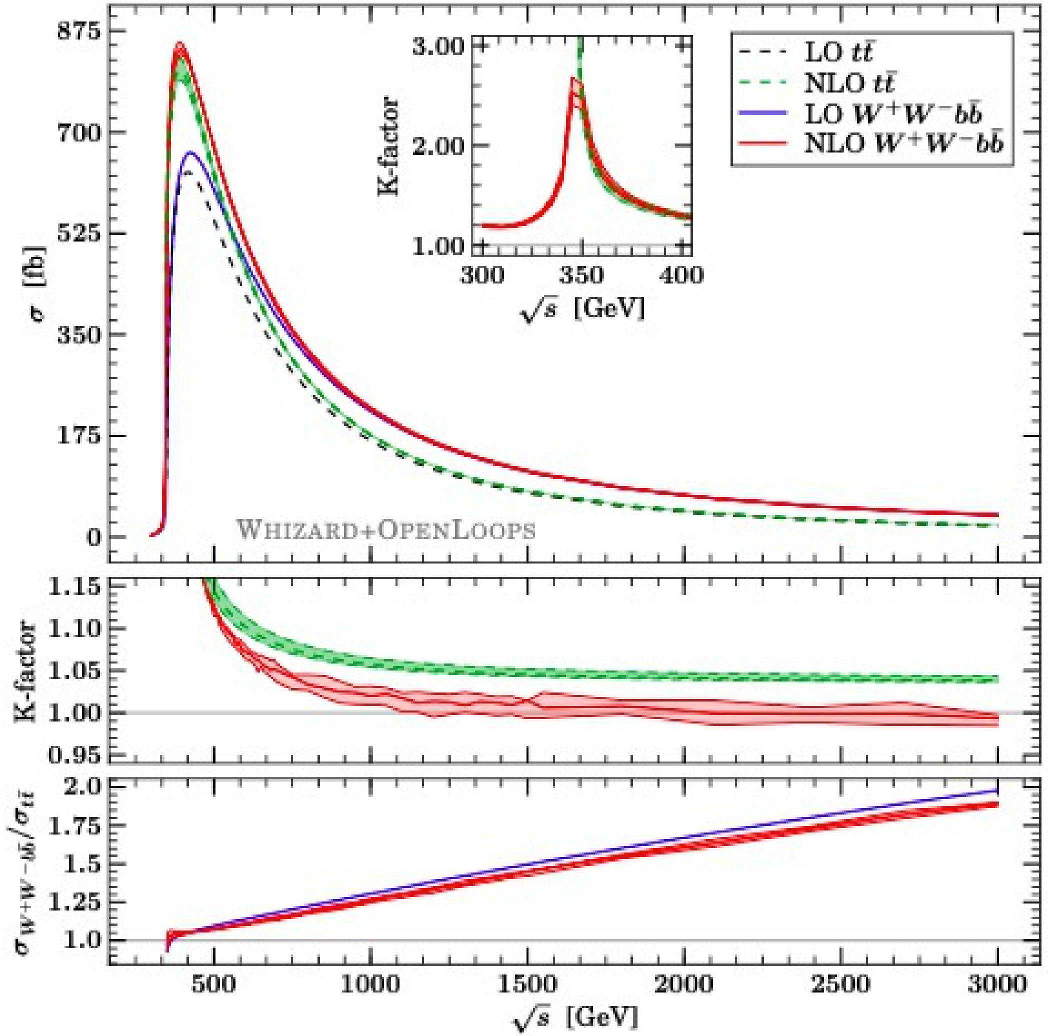
- Translation of results into EFT language confirm superiority of e+e- w.r.t. LHC
- Several operators benefit already from 250 GeV running
- Top specific operators constrained by running at 500 GeV

QCD uncertainties on ee->tt cross section

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

Linear Colliders





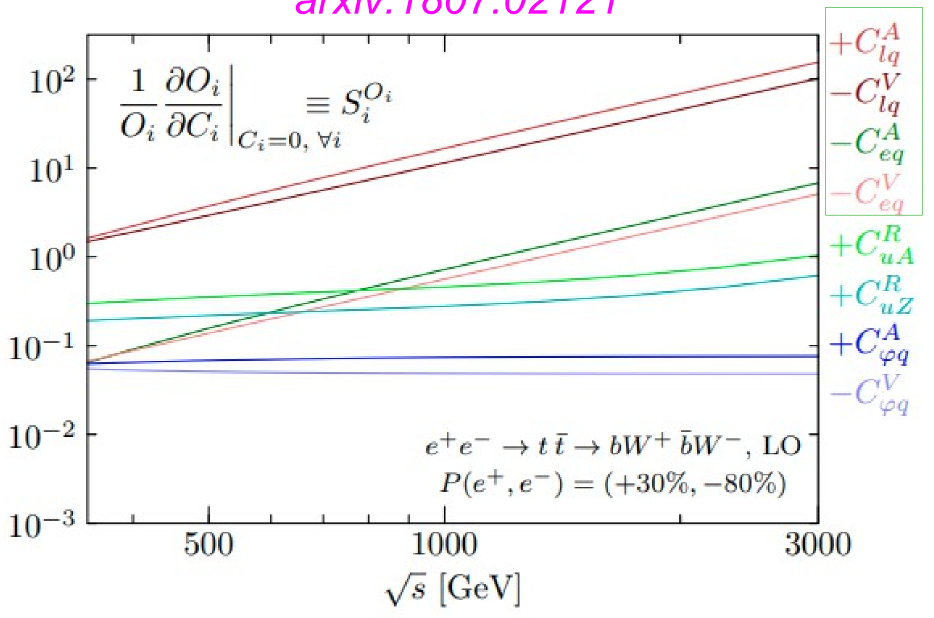
- Marching non-relatistic calculations in threshold region with tt-continuum is theoretical challenge
- QCD uncertainties shrink as energy increases
- Non resonant contributions are important (i.e. ee->tt --> ee->WbWb)

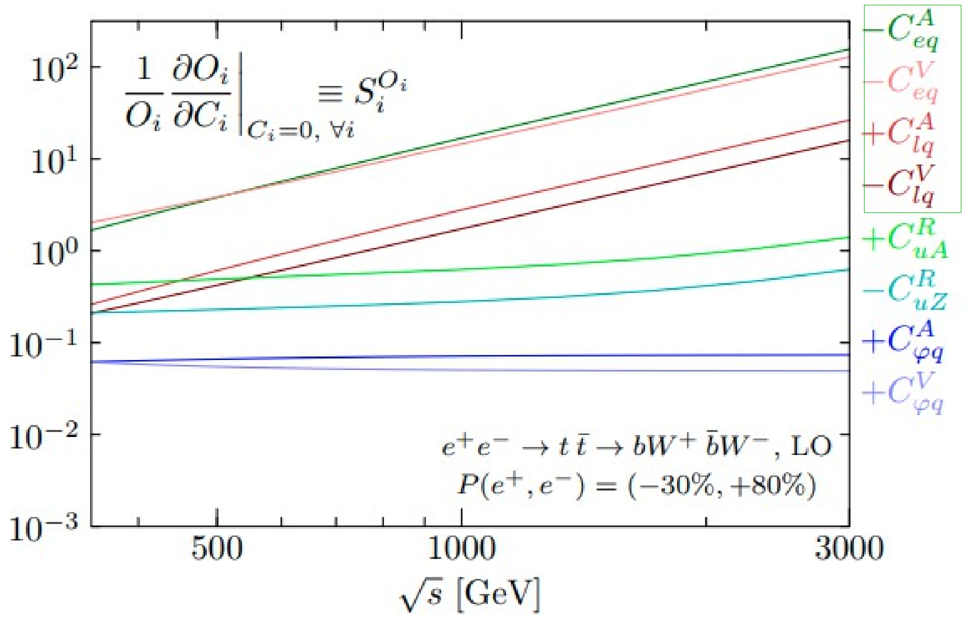
J. Reuter, FCCee-France Workshop, Annecy and arXiv: 1609.03390

Effects at higher energies

Development of EFT Operators

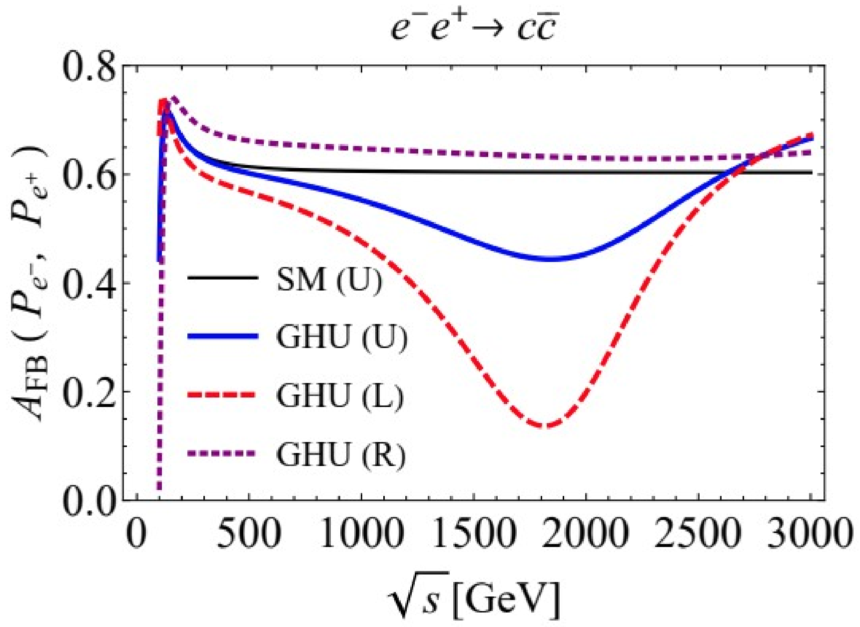
arxiv:1807.02121

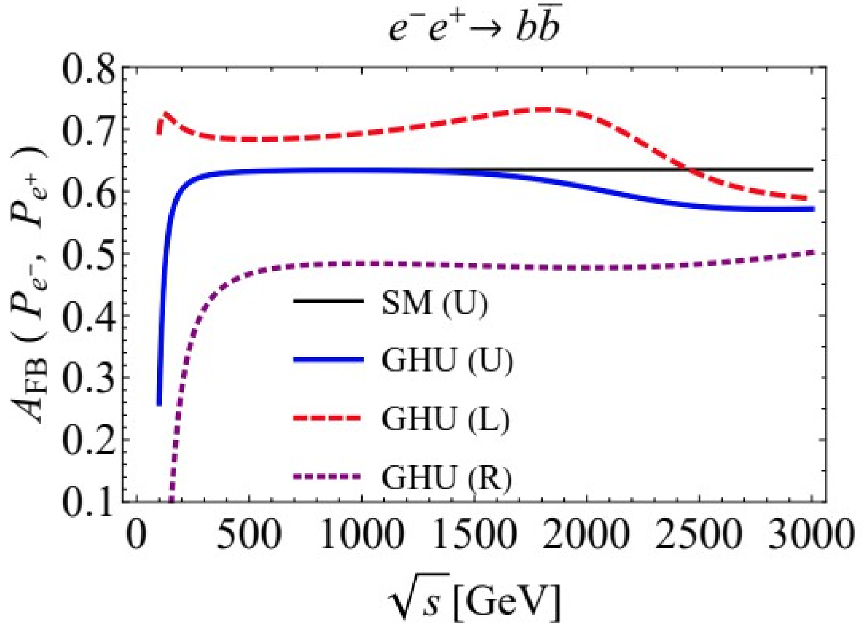


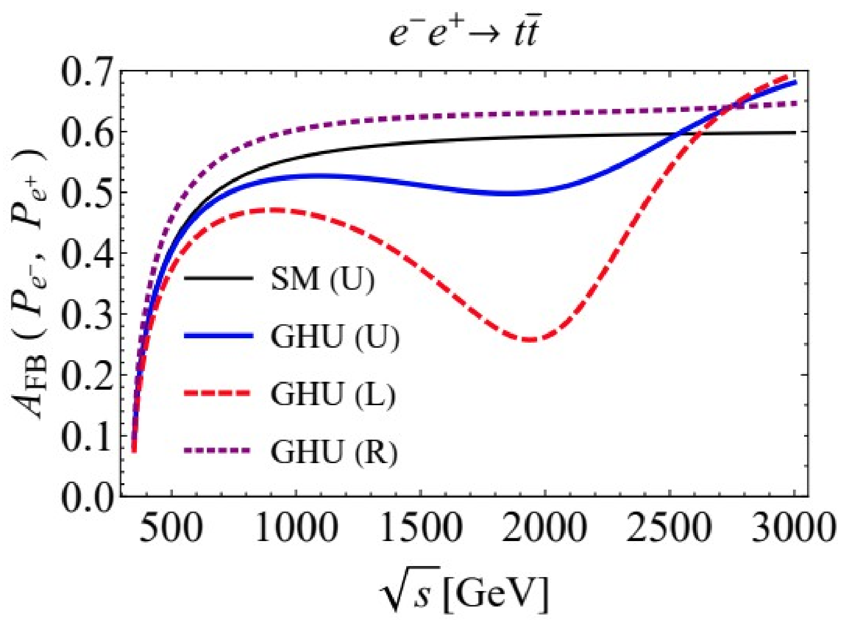


Increased sensitivity to operators representing four-fermion interactions

GUT Inspired GHU Model (Hosotani et al.)



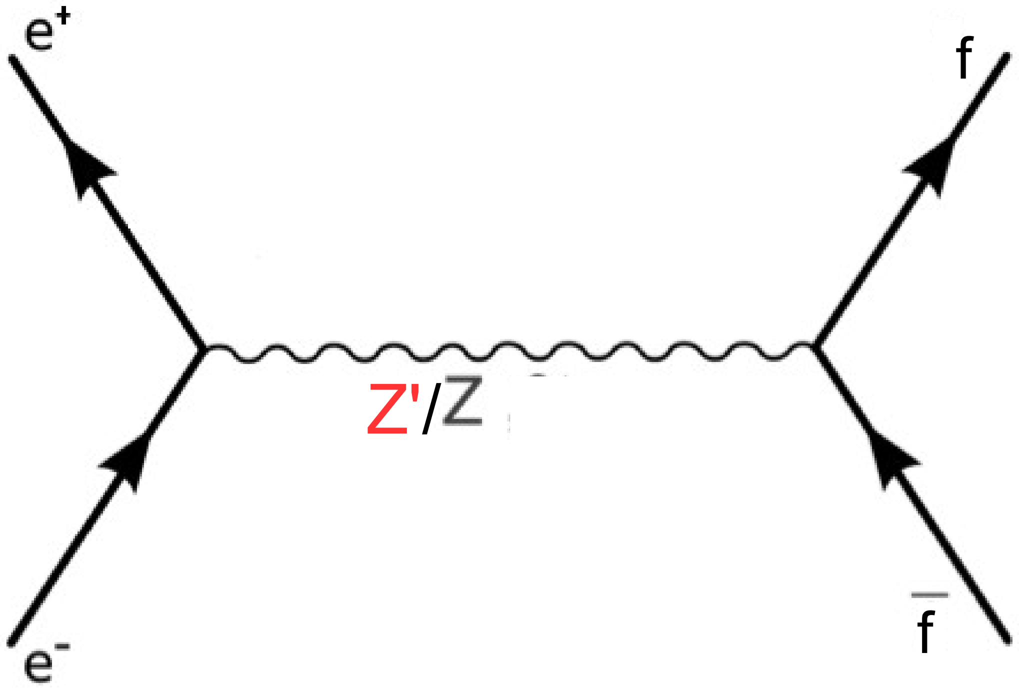




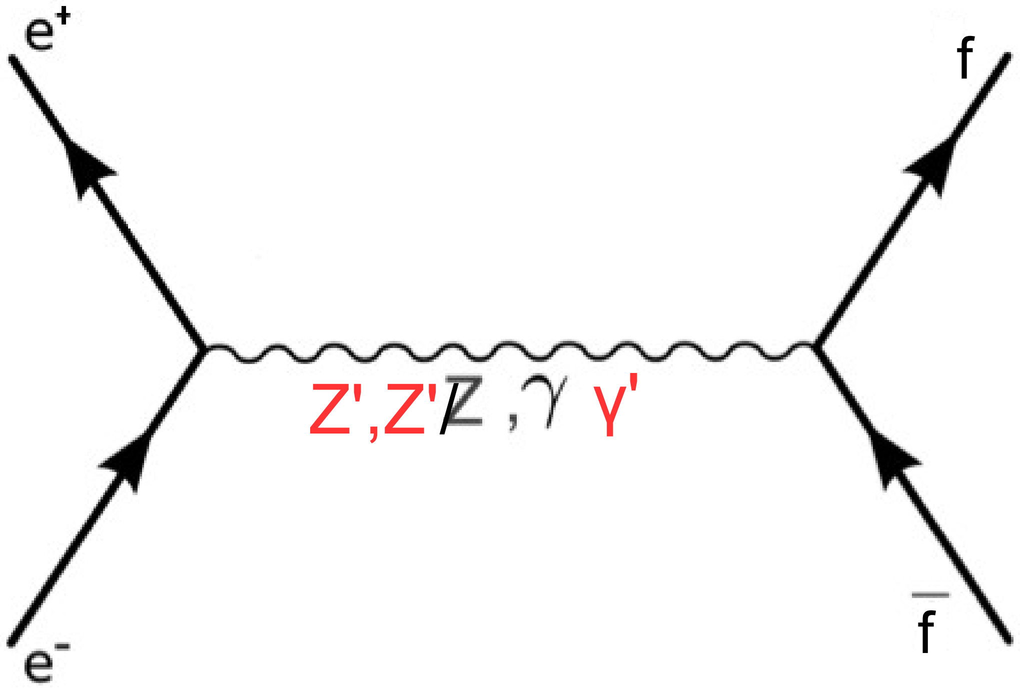
- Effects amplified at higher energies
- Different patterns for different beam polarisations (L, U, R)
- Different patterns for different fermions

How can the Z-pole help?

On the Z-pole



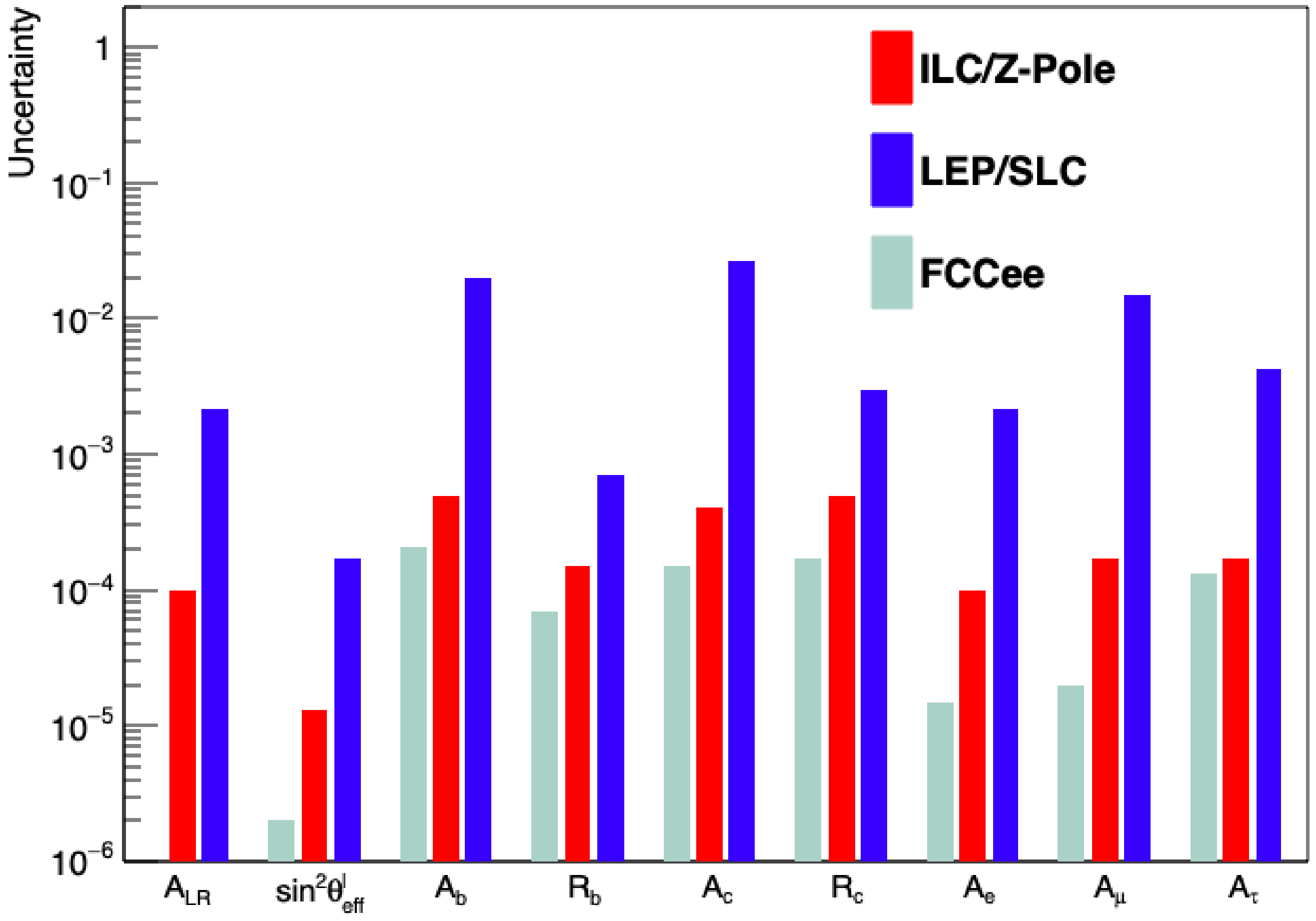
Above the Z-pole



- 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”

- 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

Z-Pole input?

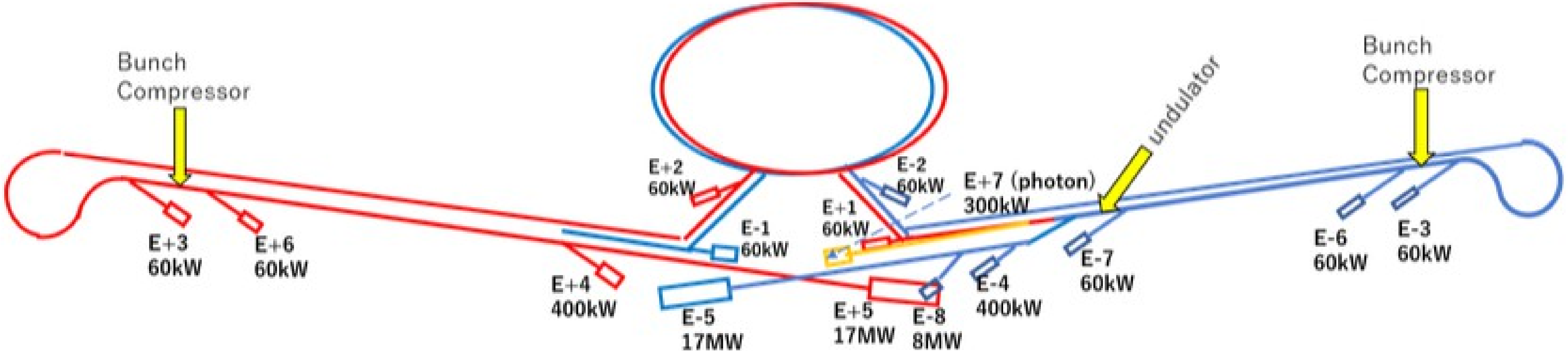


Numbers FCCee: “Mixture” of FCC CDR and
P. Janot at Precision Workshop/CERN
https://indico.cern.ch/event/1140580/timetable/

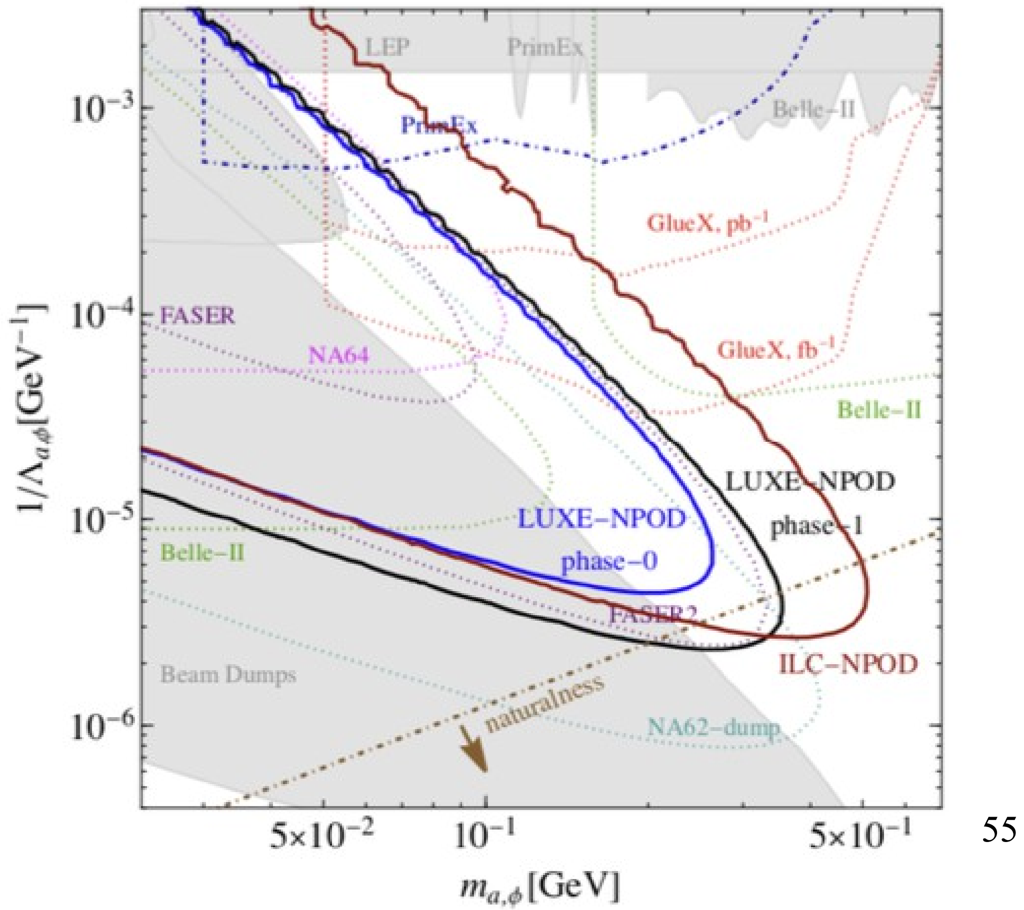
Numbers ILC: arxiv: 2203.07622 (ILC Snowmsss report)

- All future colliders will improve significantly precision compared with LEP/SLC
- Comparable precisions despite differences in luminosity
  - Systematics will play a major role
- Main error sources for heavy quarks
  - Beam polarisation (Linear Collider)
  - QCD corrections that dilute forward-backward asymmetries (arXiv:2010.06604) (all colliders)
    - not considered for ILC here but needs to be looked at once more

ILC – More than a collider



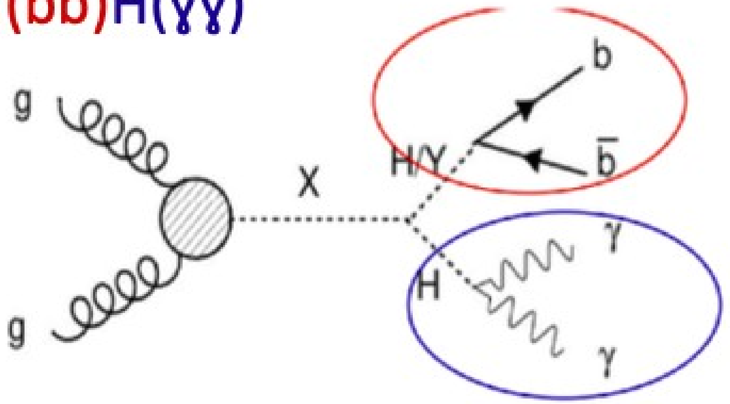
Light axion search at LUXE and ILC



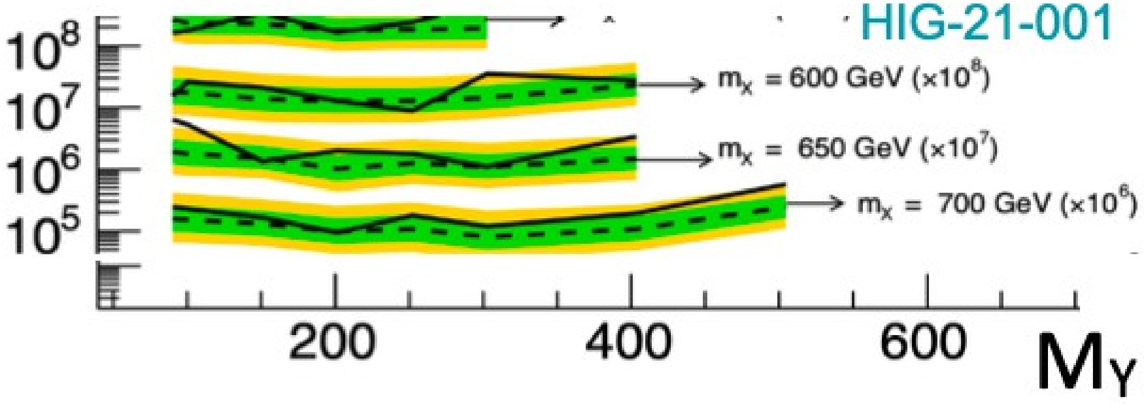
- The colliding beam experiments can be complemented with a series of fixed targat experiments
  - Enabling nuclear, hadron physics experiments and resources for accelerator development
  - Material science?
- Details see 2203.07622

What if … the LHC makes a discovery?

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

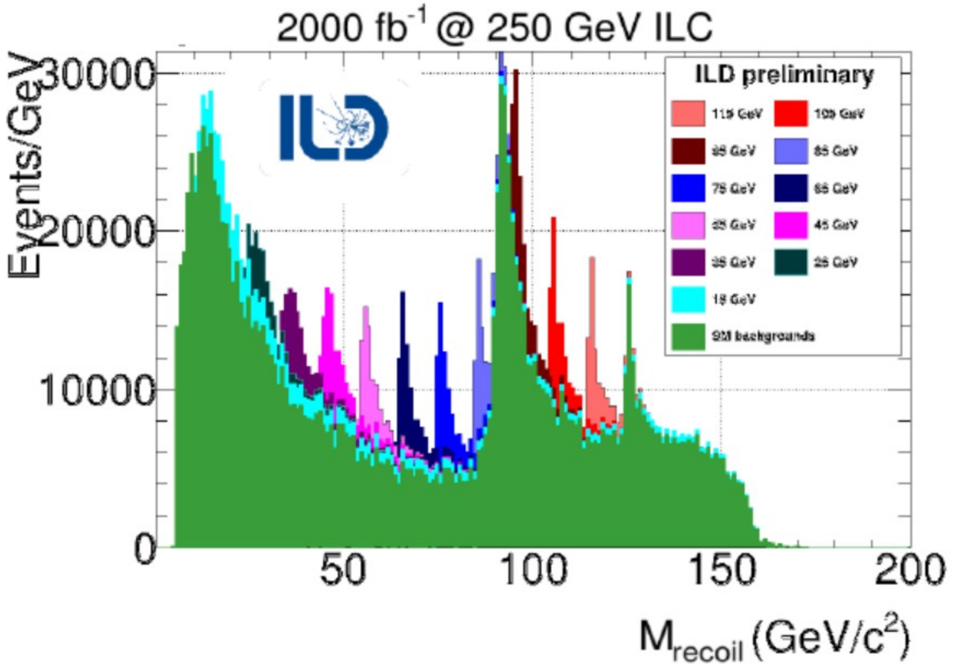


Excess at (90,100) with 650 GeV heavy resonance mass (~3.8 σ local and 2.8 σ global)

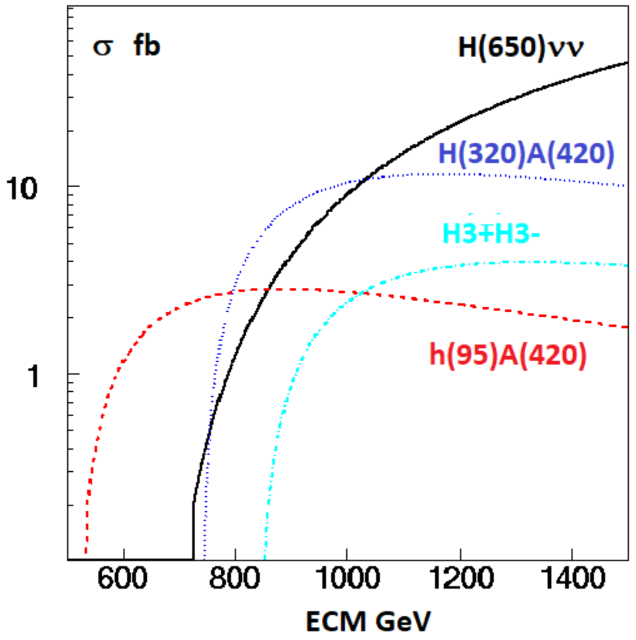


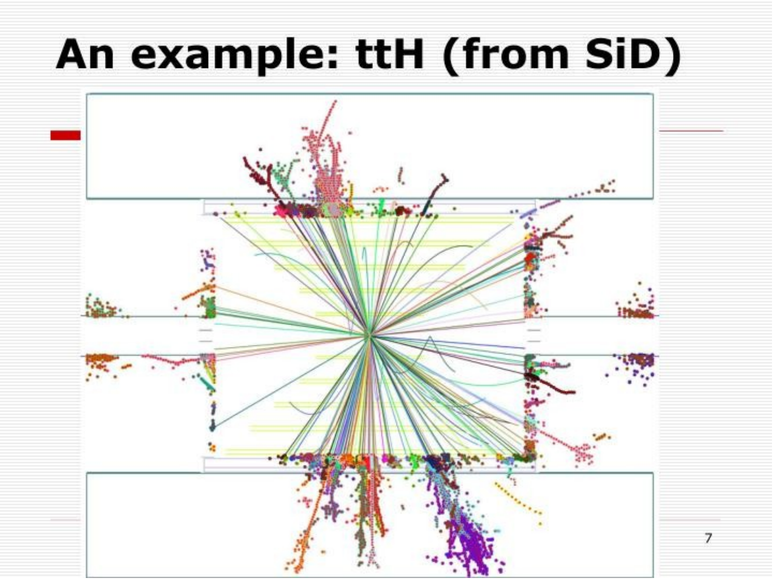
Tantalising excesses common to *γγ* and ττ final states!

Light scalars are "easy" to measure



Sufficient centre-of-mass energy and hermetic detectors





LI

Summary and conclusion

- e+e- colliders are indispensable tools to understand and/or discover the nature of new physics
  - Precision on Higgs couplings at or below 1% level
  - Indrect and direct discovery potential at all centre-of-mass energies
  - Light scalars or vector bosons with different gauge symmetry

- Full exploitation of physics potential requires large energy coverage and polarised beams
  - Both premises are fulfiled only by linear e+e- colliders
  - Effects at HZ threshold and below are expected to become more prominent at higher energies
  - New physics signals and relevant operators depend on chiral state of initial and final state fermions
  - (“Early”) direct measurement of the Higgs-selfcoupling
  - Sufficient lever arm to react to HL-LHC results
  - Remember also the “LEP disaster”, Higgs missed by 30 GeV in centre-of-mass

- A clear pattern of anomalies would be an excellent (and maybe the only) motivation for a large hadron machine

- ILC is s shovel ready. Why don't we build it?
  - Could be turned into a linear facility with attractive options for innovative accelerator and detector concepts

International Workshop on Future Linear Colliders

15-19 May 2023

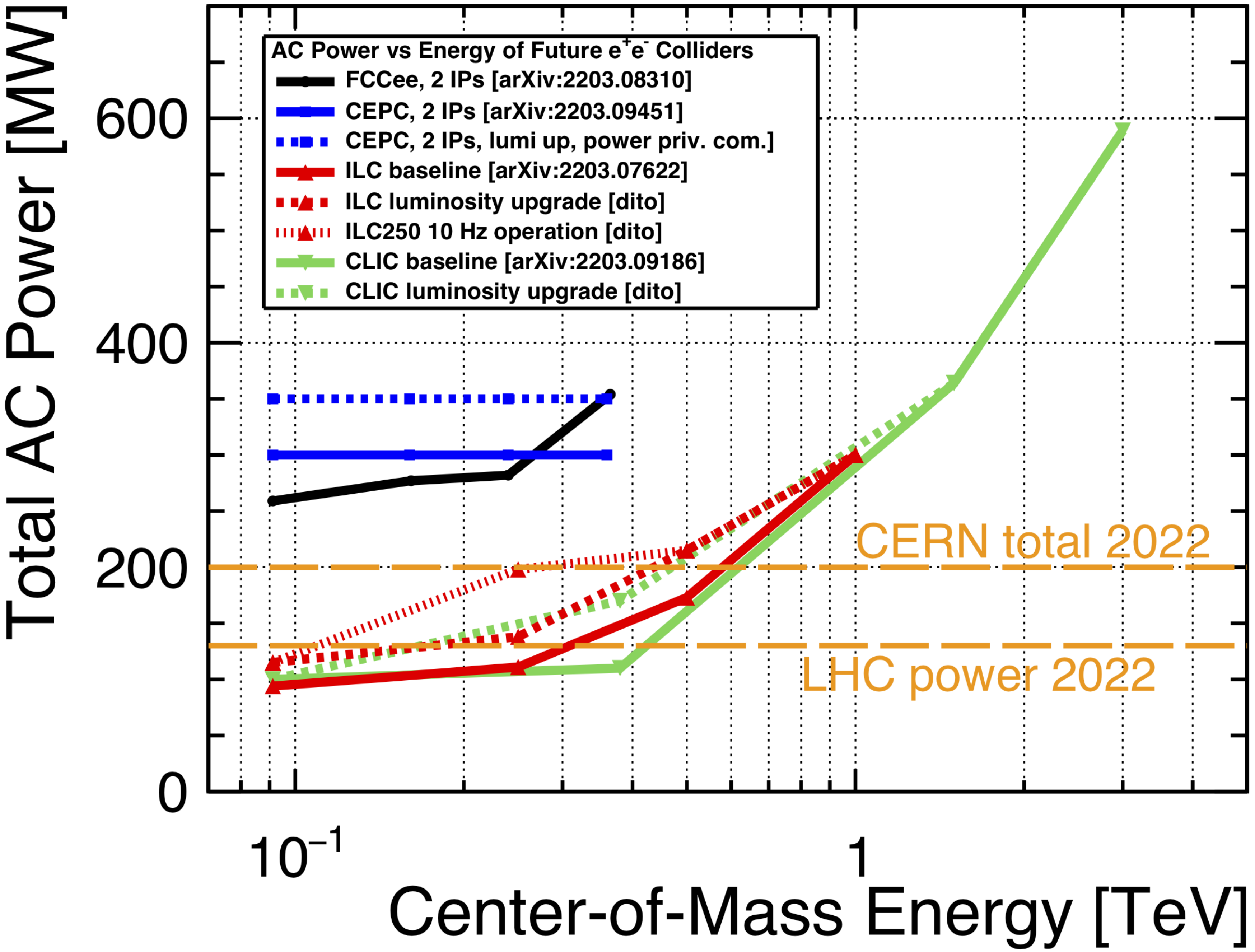
America/Los_Angeles timezone

The 2023 International Workshop on Future Linear Colliders (LCWS2023), continue the series devoted to the study of the physics, detectors, and accelerator issues relating to the high-energy linear electron-positron colliders. A linear collider will operate as a Higgs factory during its initial stage, while maintaining a clear path for future energy upgrades.

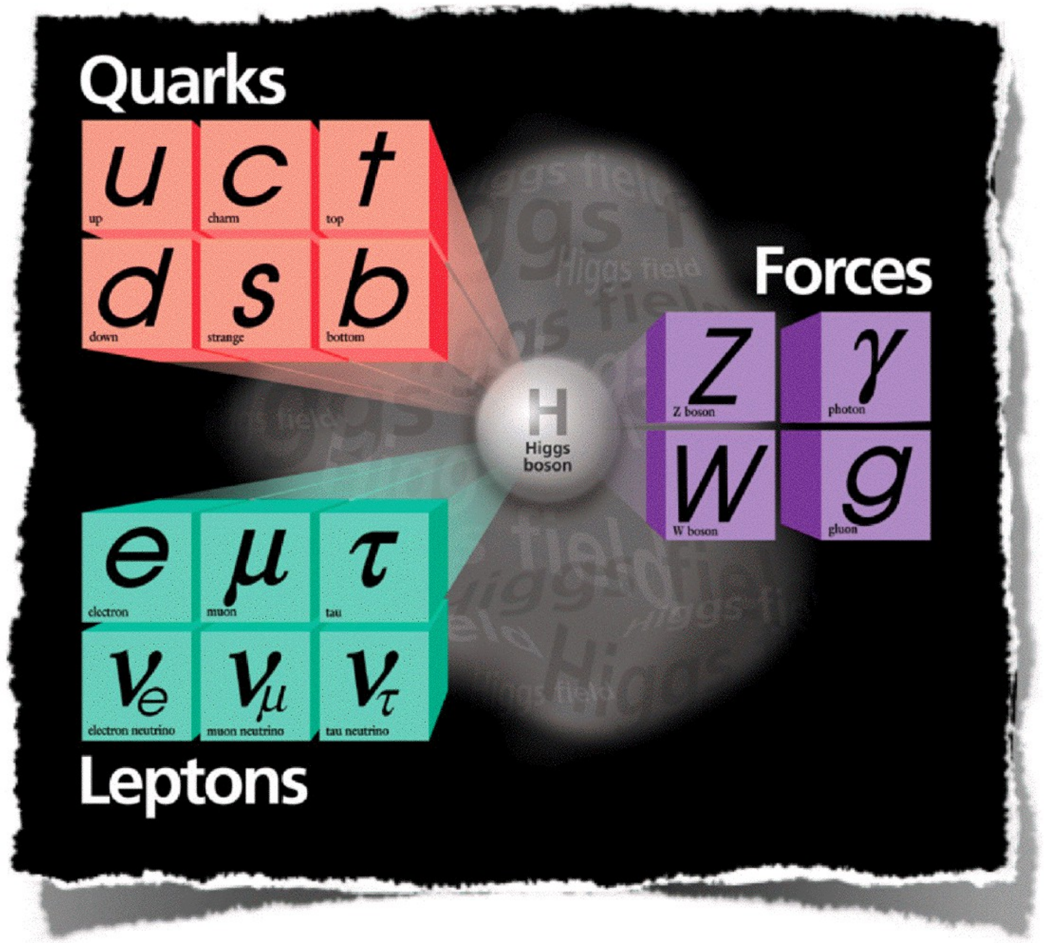
Since the last workshop (LCWS2021), many significant steps have been made. With a wide

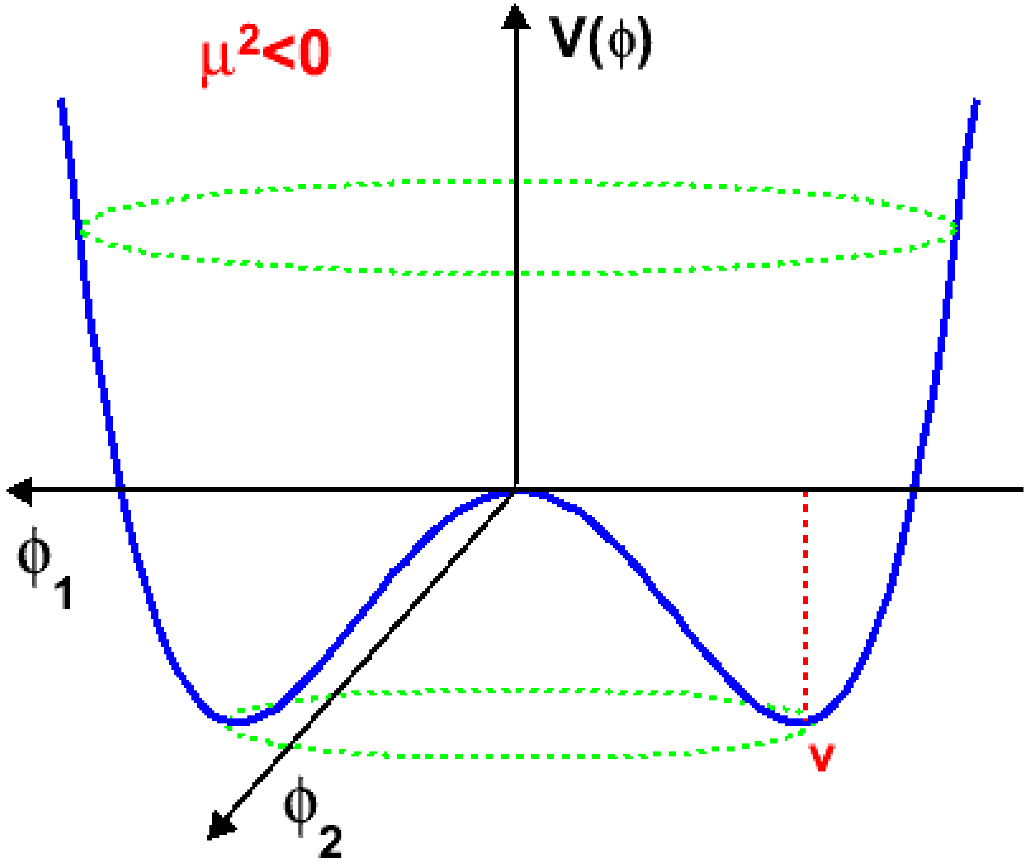
Backup

Higgs Factories – AC Power Consumption



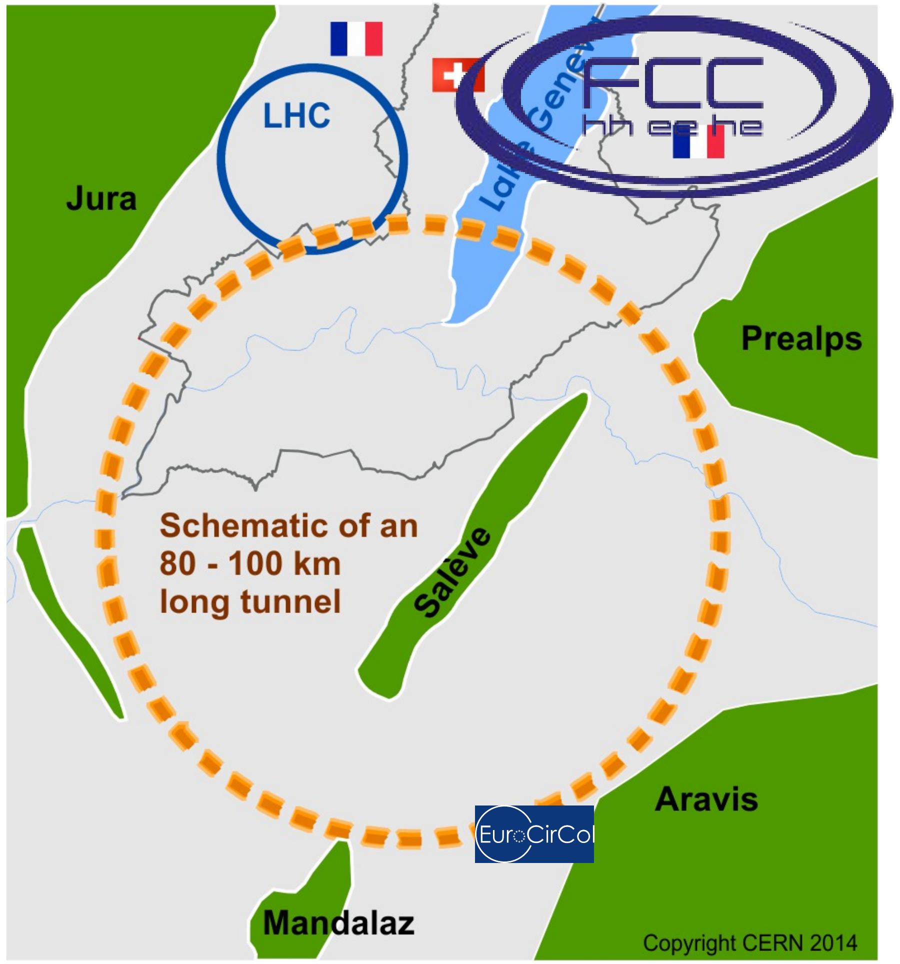
The Standard Model is complete





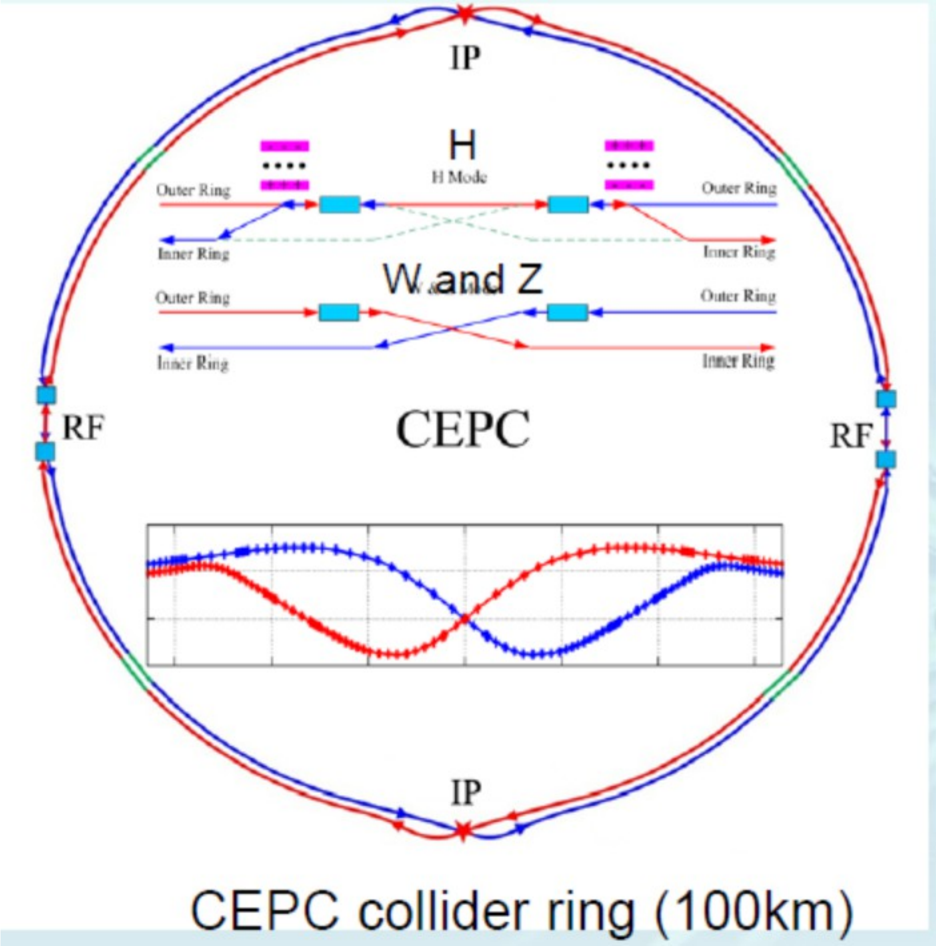
- We know that there exists at least one fundamental scalar with a non-vanishing expectation value
- We don't know what shapes the potential and whether the potential is the footprint of a larger mass scale

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

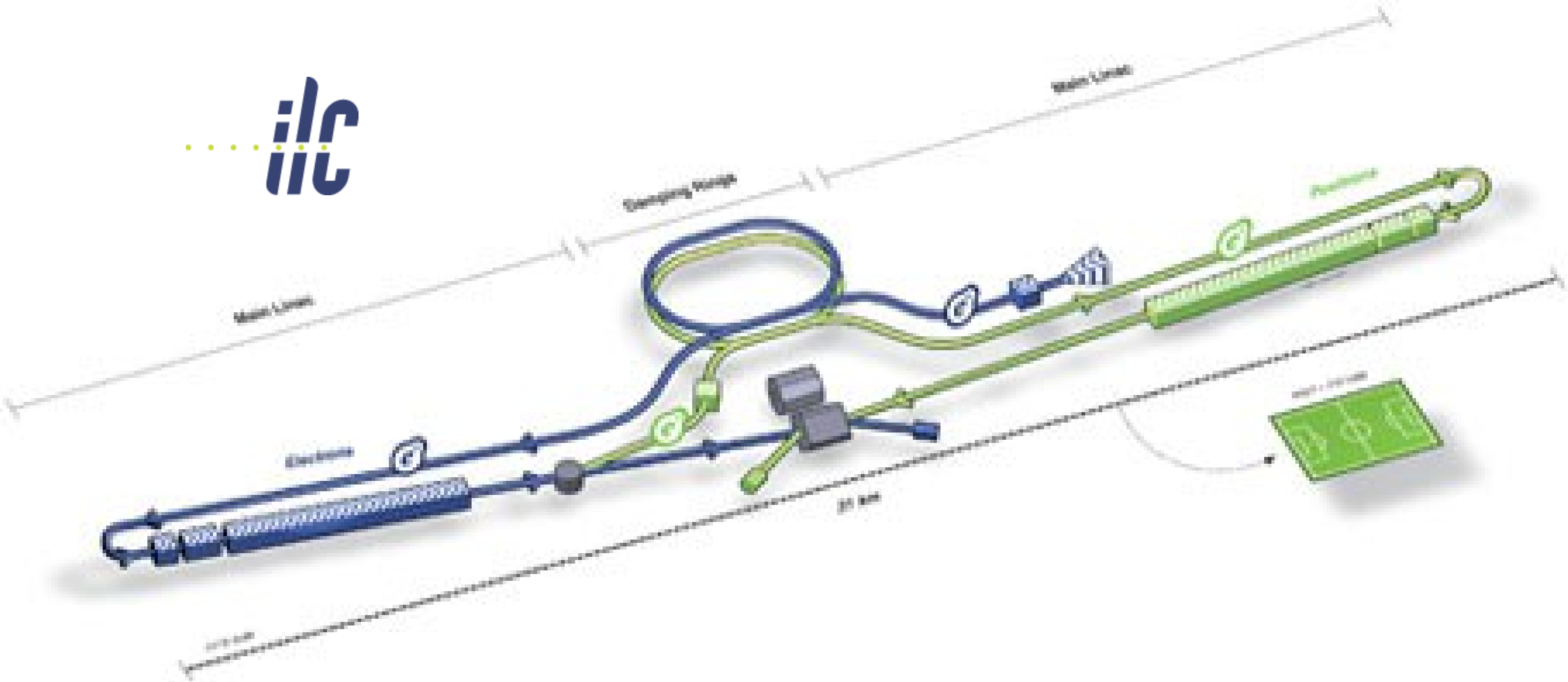
CEPC



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

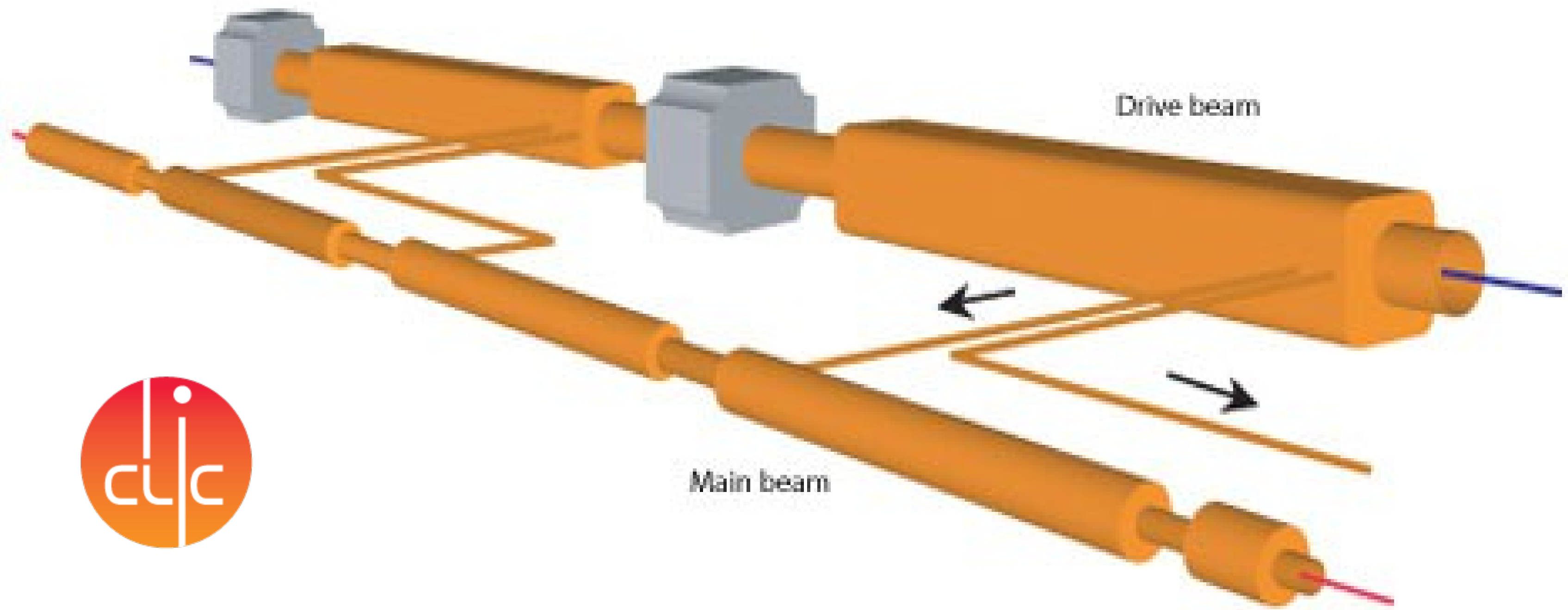
Linear Electron-Positron Colliders



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

New physics?

EFT: Two distinct observations

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

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

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

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

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

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

Typical experimental precision 0.1-1%

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

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:

$e_L^- e_R^+$

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

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

$e_R^- e_L^+$

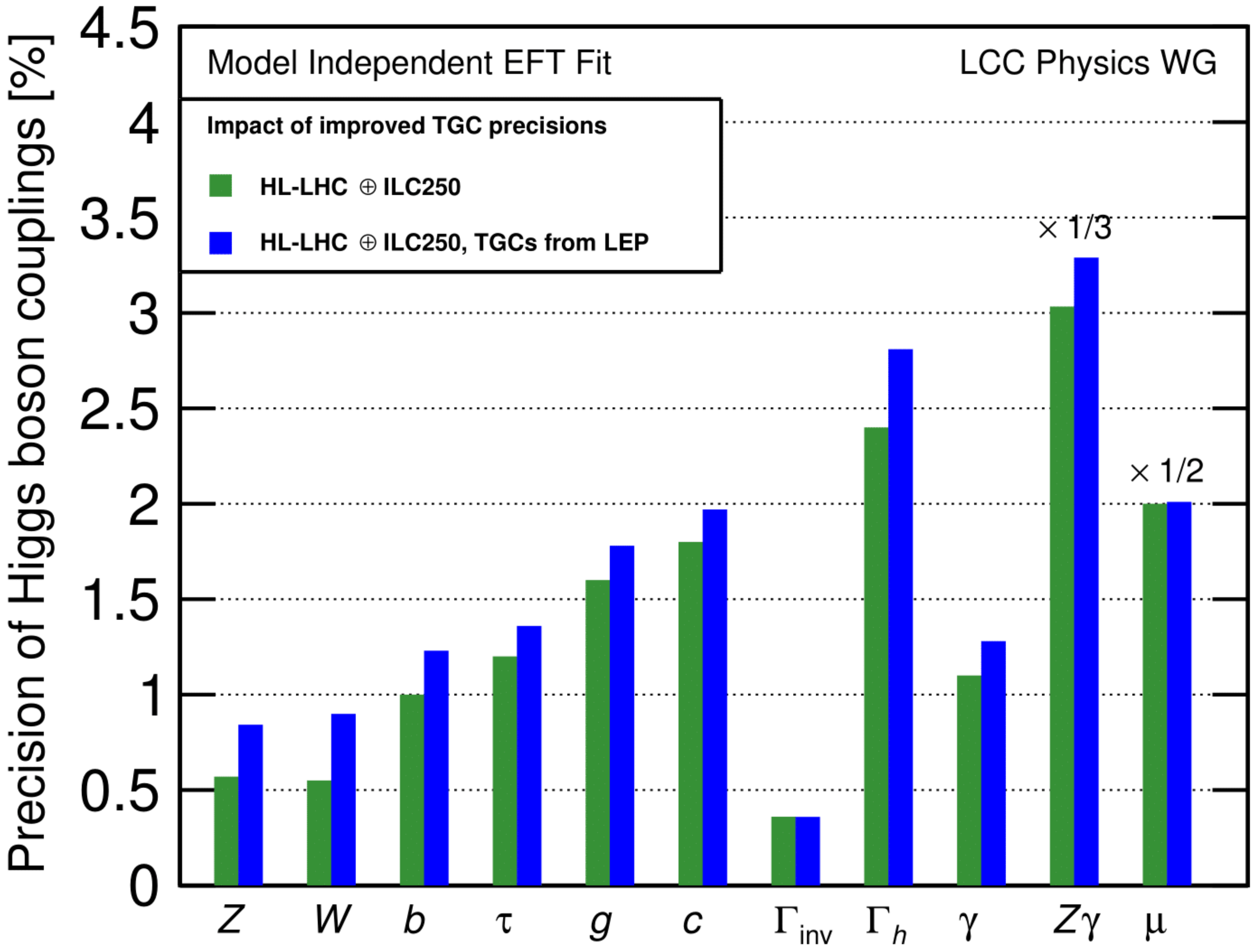
$$Q_{ZR} = (-s_w^2)\ , \qquad a_R = -c_H$$

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

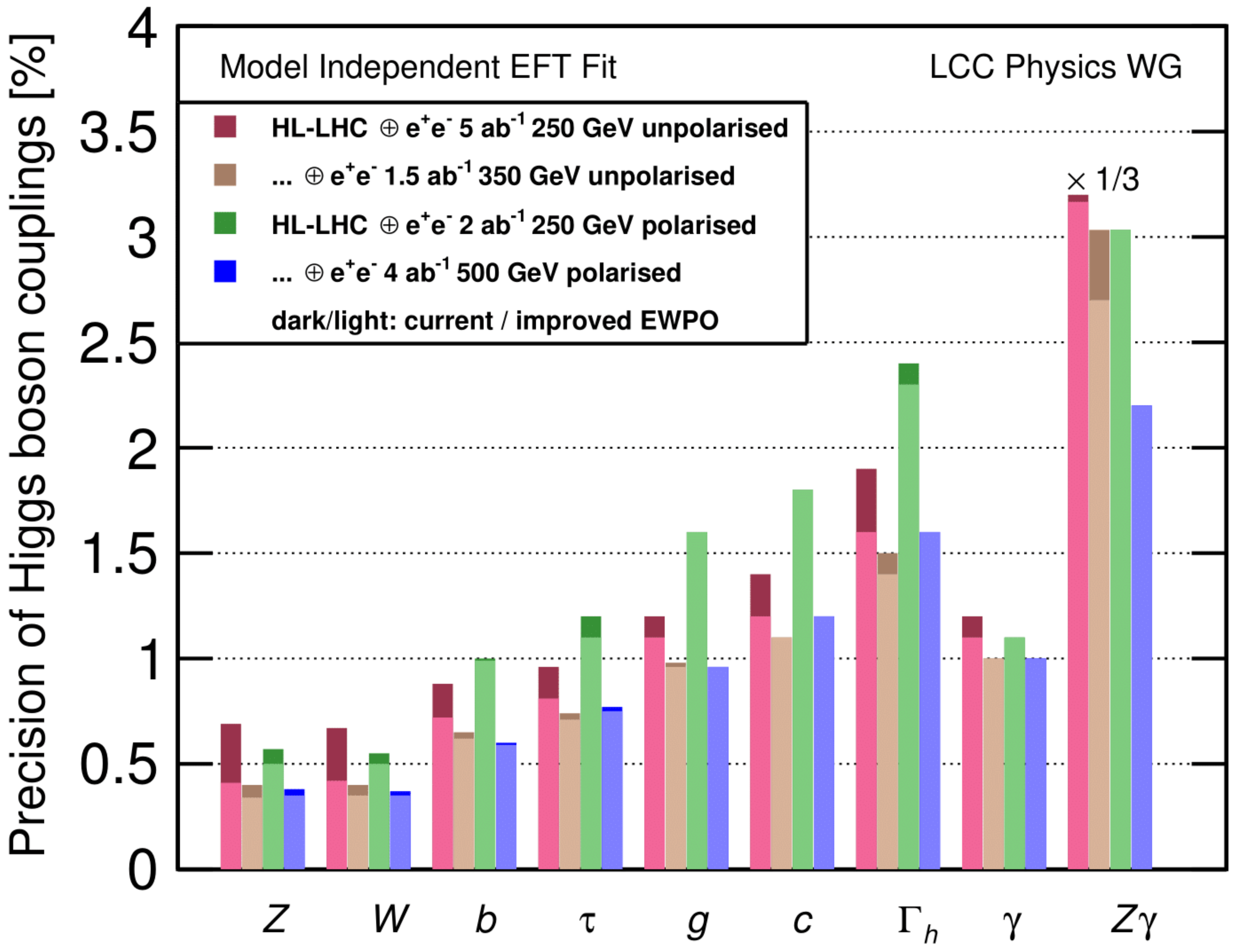
- Angular distributions in $e^+e^- \to hZ$ can also be used, but have weaker analyzing power and require more luminosity to achieve the same result

M. Perelstein: AWLC2017

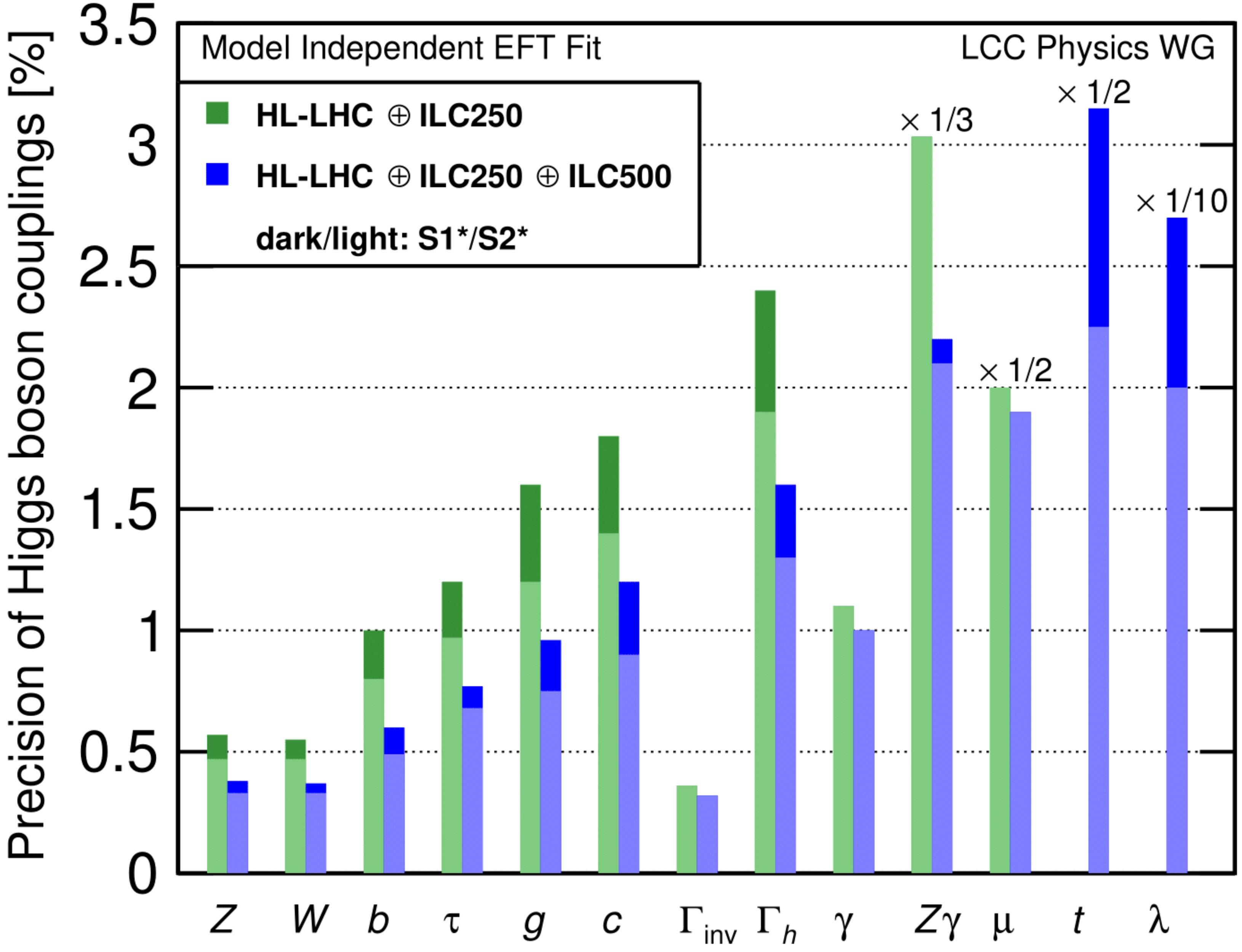
Higgs couplings – Impact of TGC



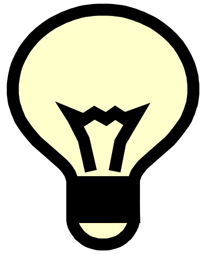
Higgs couplings – Polarisation + EWPO



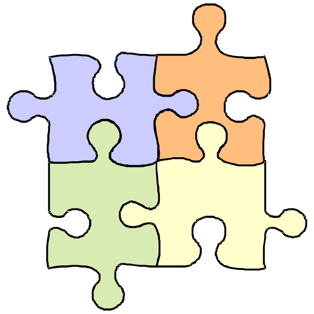
Higgs couplings – Polarisation + EWPO



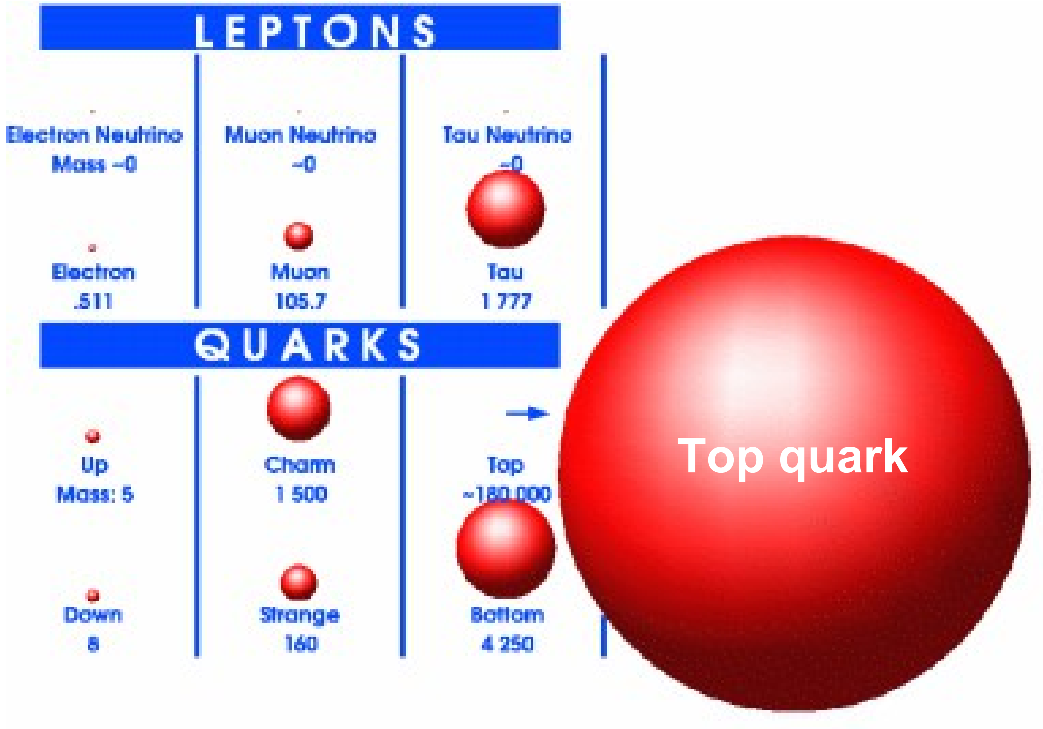
Science drivers



Elementary Scalar?



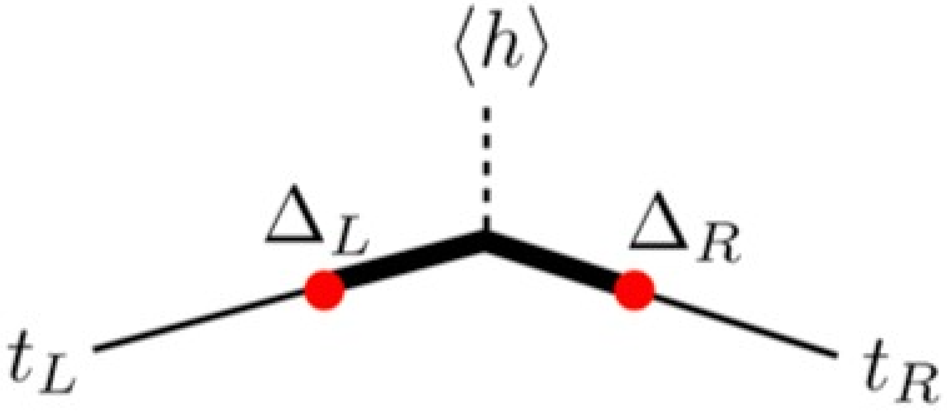
Composite object?



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

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

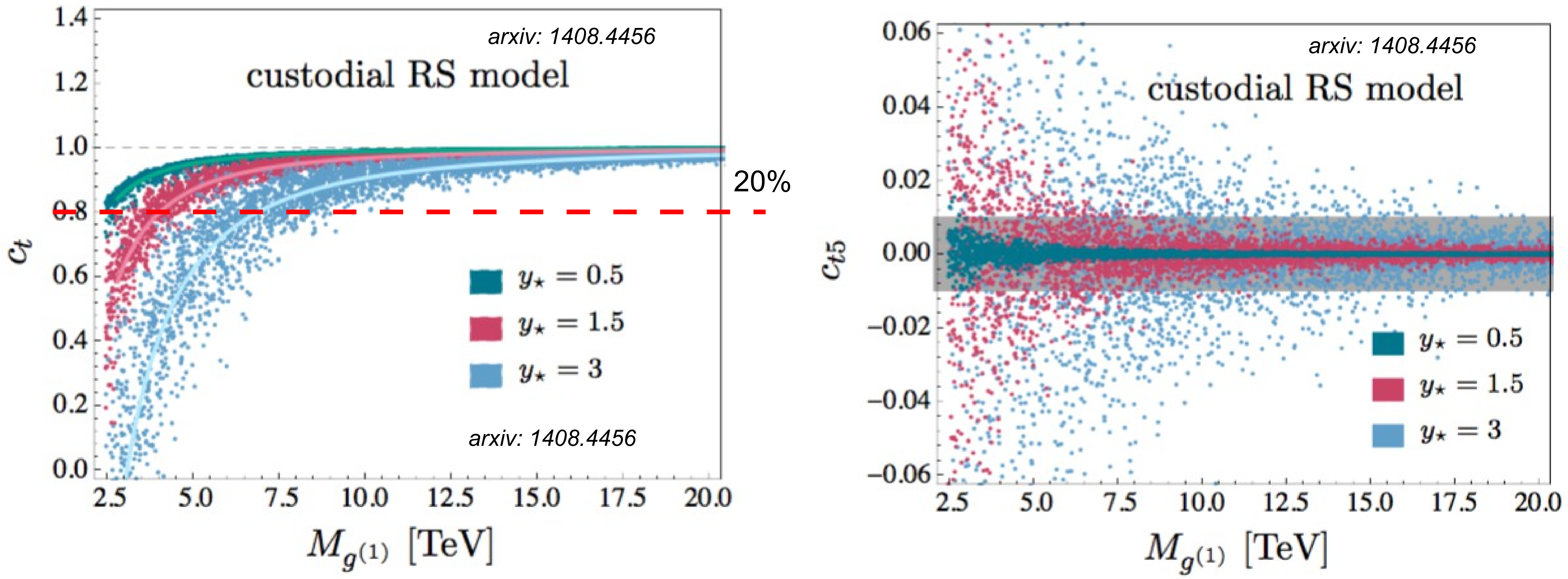
- e+e- collider perfectly suited to decipher both particles



Courtesy of S. Rychkov

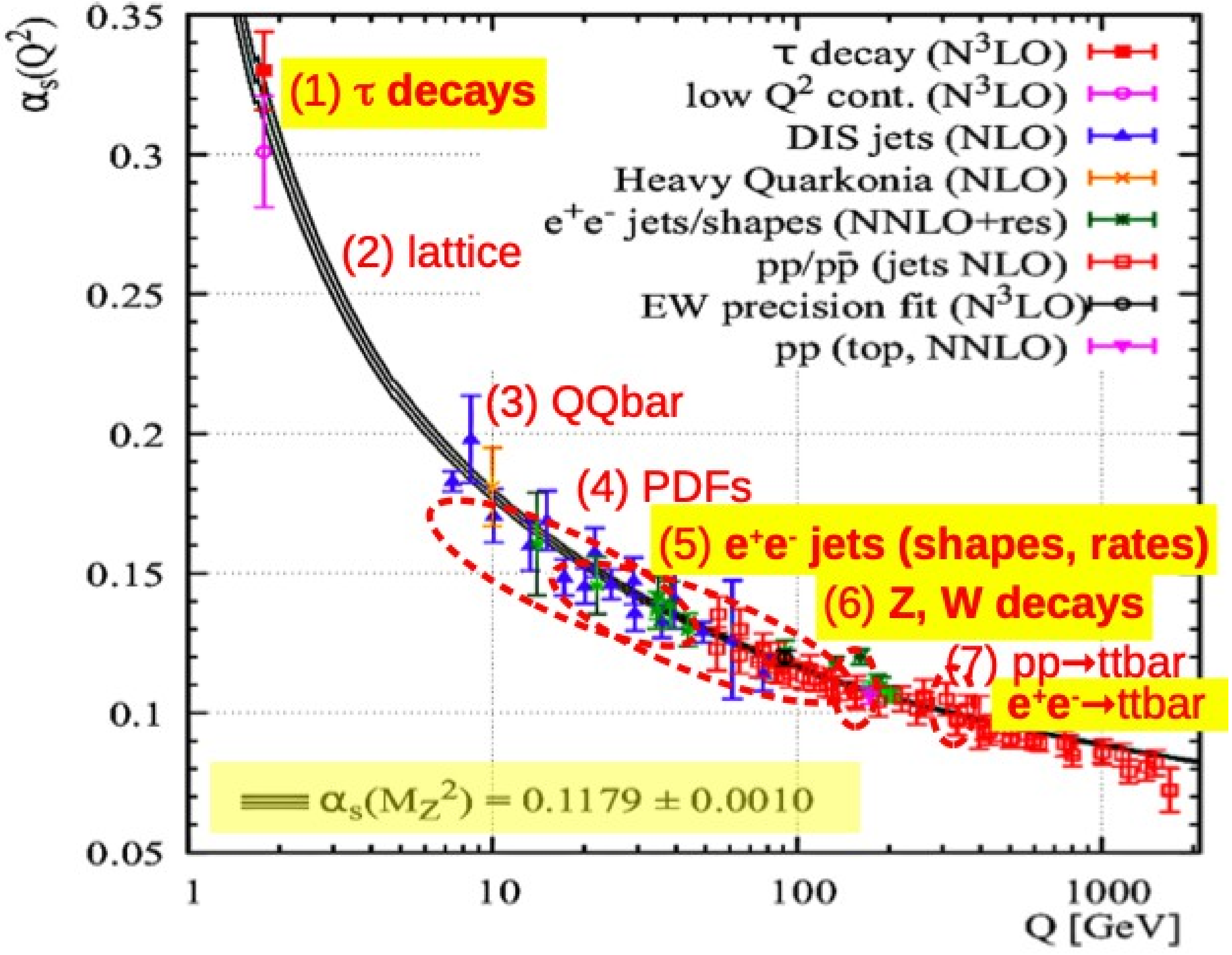
Top Yukawa Coupling and New Physics

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 !?

Uncertainty driver α_s

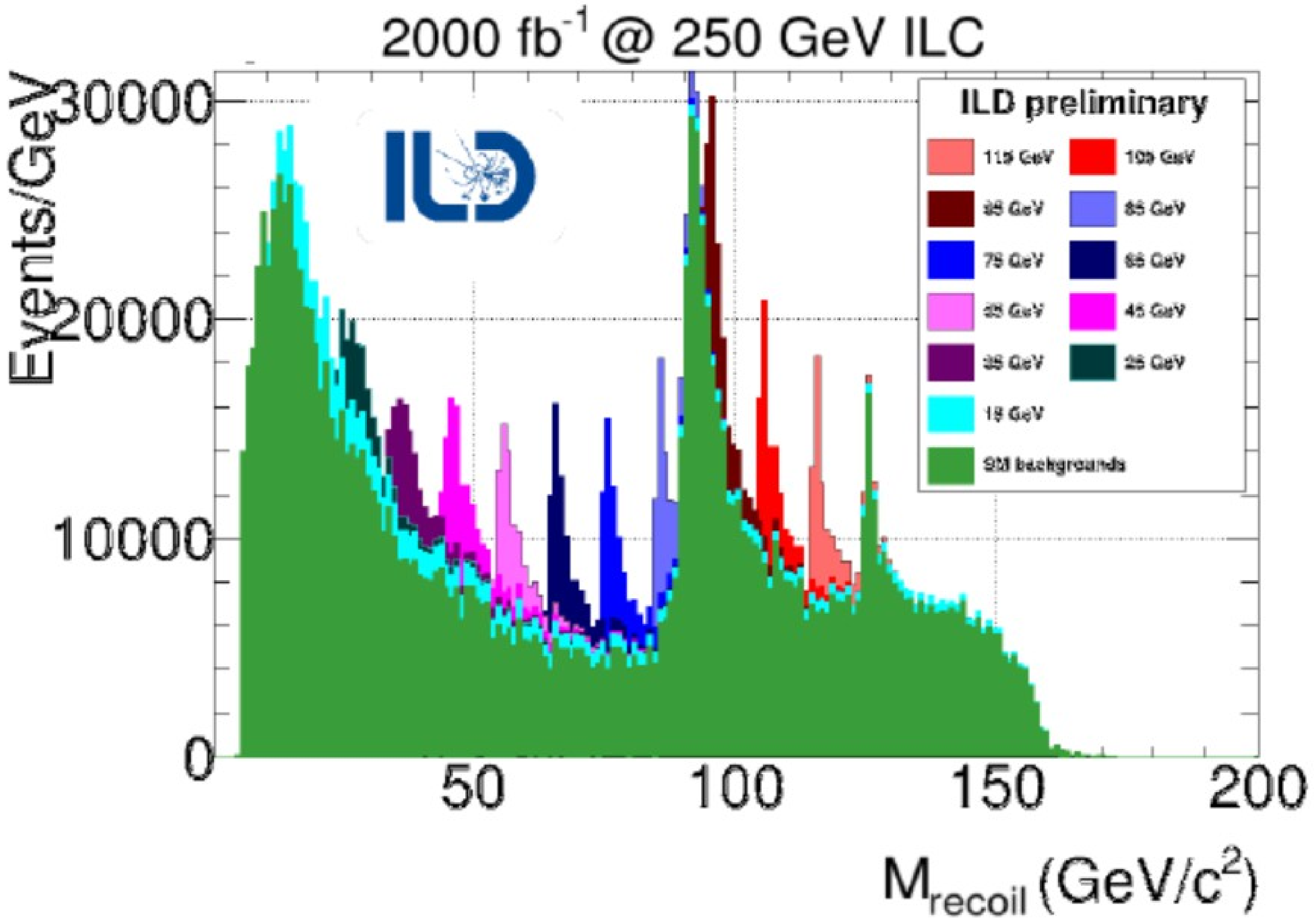


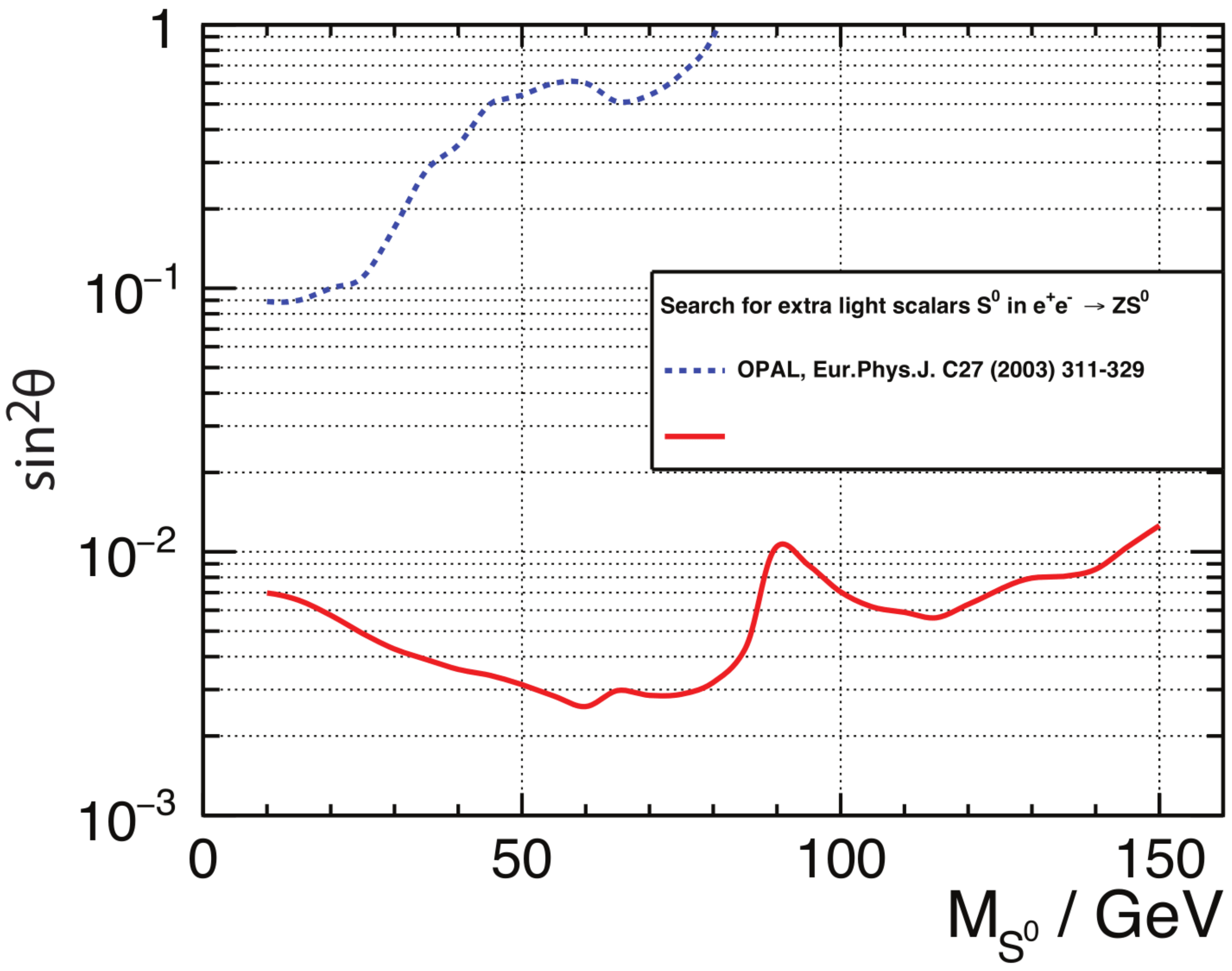
e^+e^- collisions

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

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

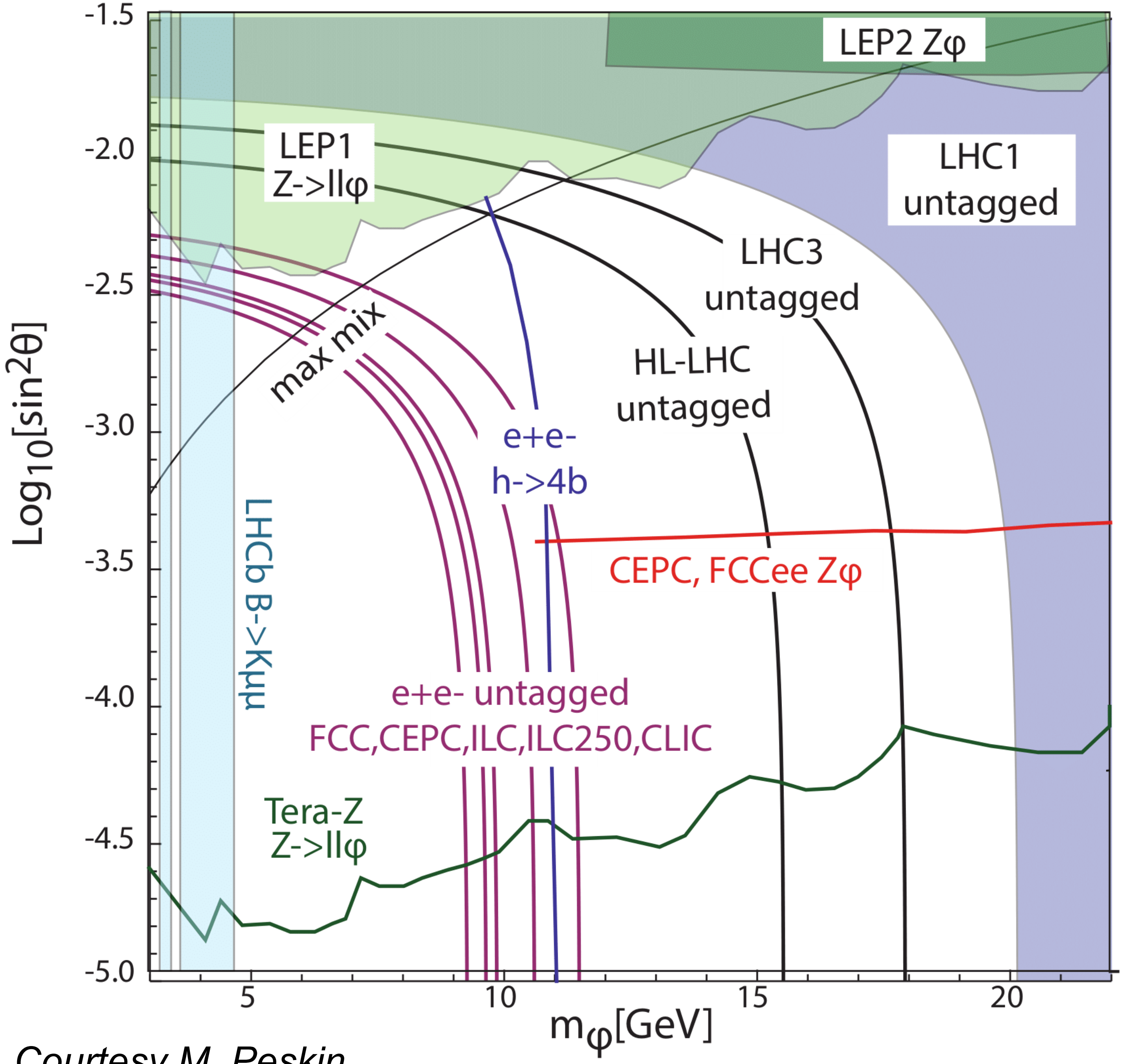




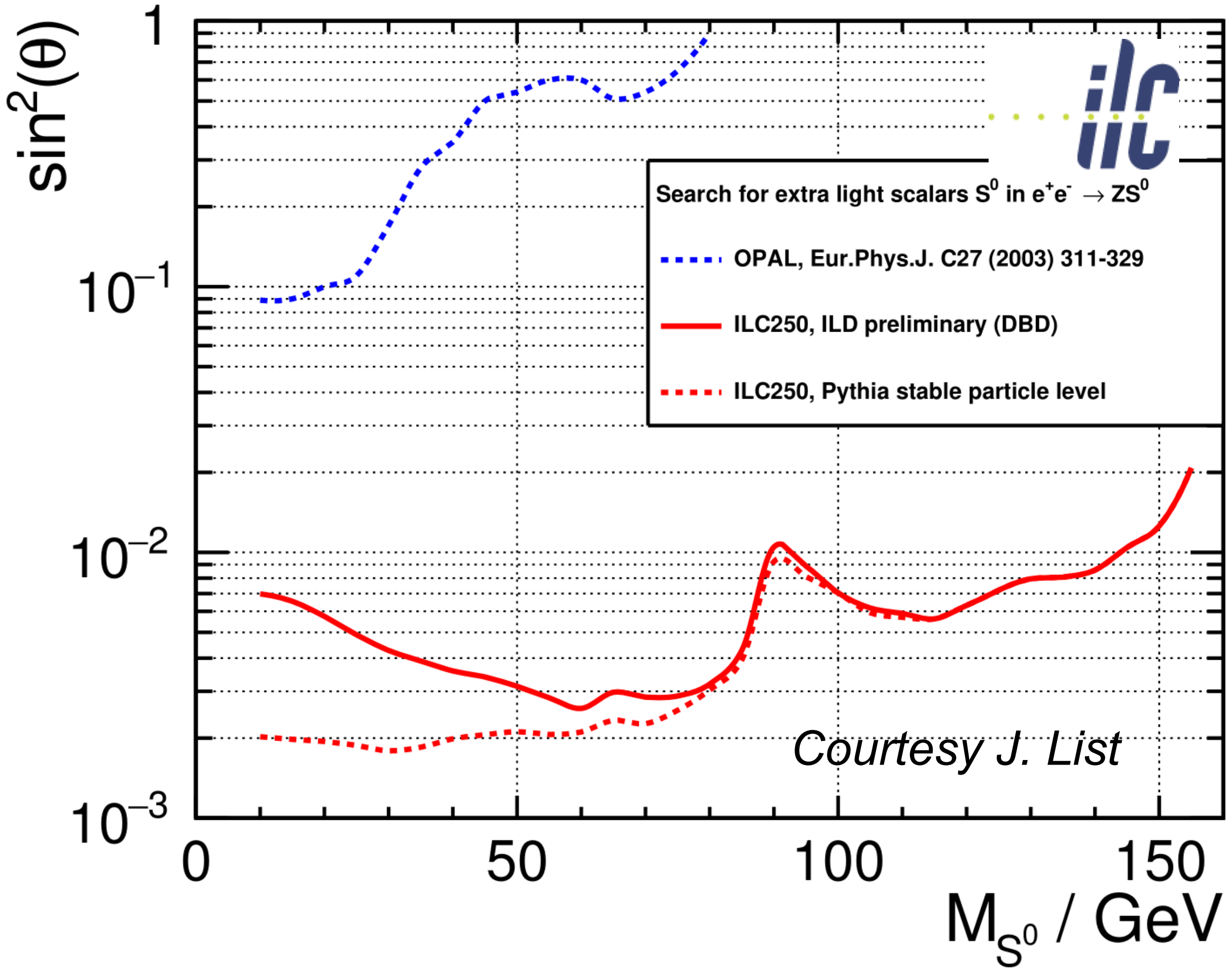
- New resonances cleanly dinstiguishable for large range of masses
- Sensitivity to mixing angle θh down to 10^{-2} (taking all relevant backgrounds into account)
- └new scalar would count as “Feebly interacting Particle” (FIPS)

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



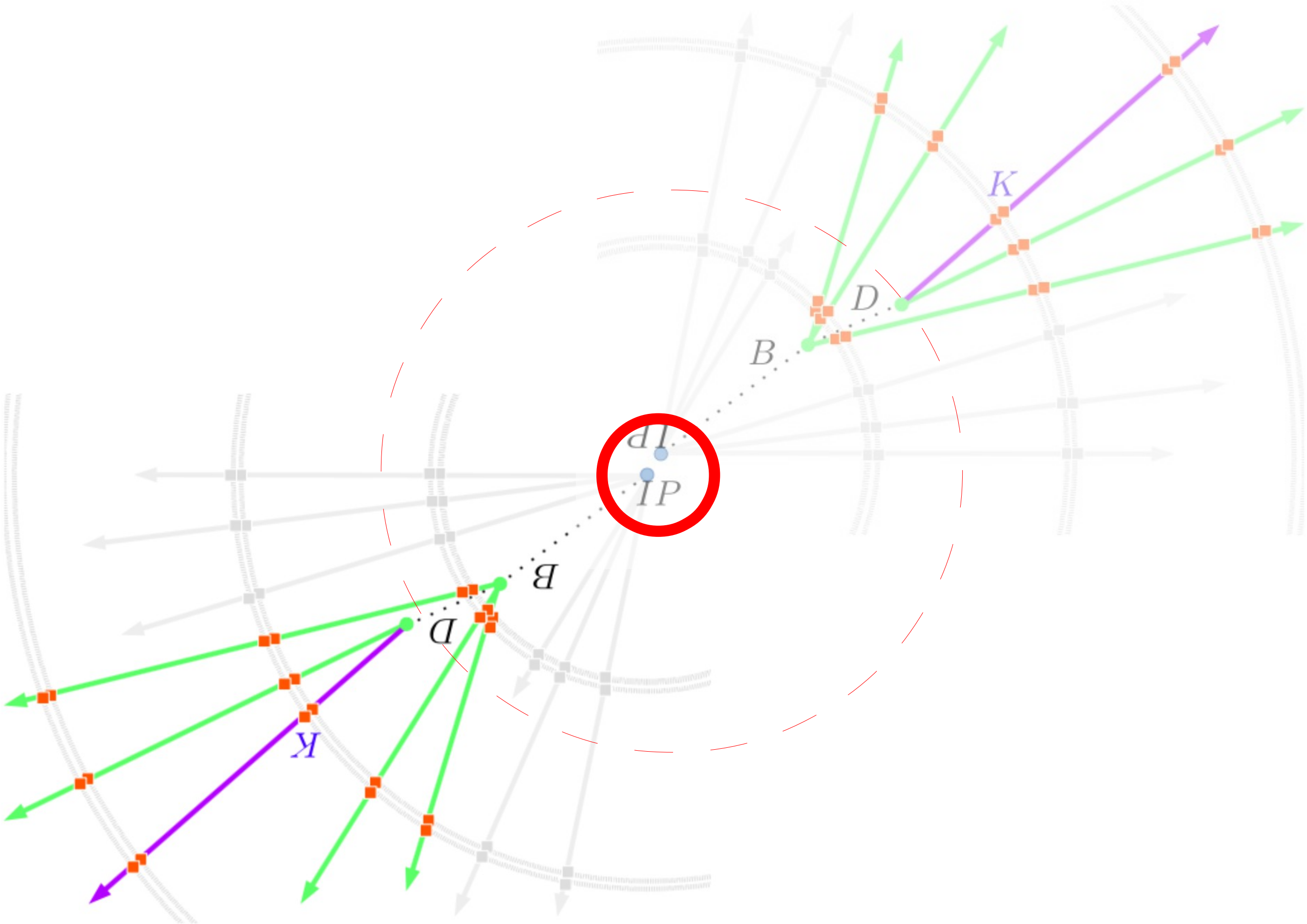
Courtesy M. Peskin



Courtesy J. List

- 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% => $\Delta R_b \approx 0.2\%$

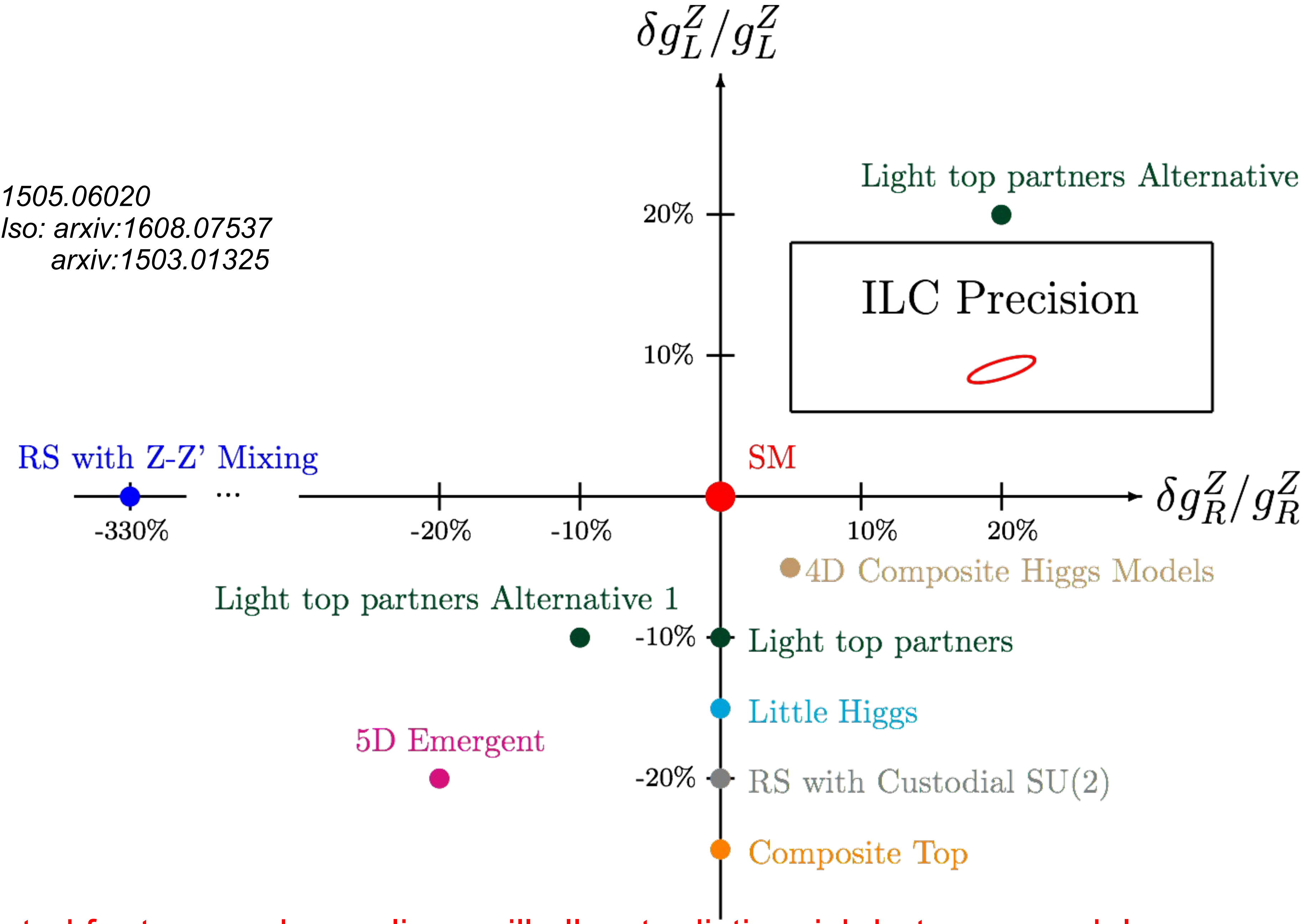
SLC (smaller beam spot): C_q -1 < 1% => $\Delta R_b \approx 0.07\%$

Future (small/tiny beam spot): Expect C_q -1 = 0 => $\Delta R_b \approx 0$ 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

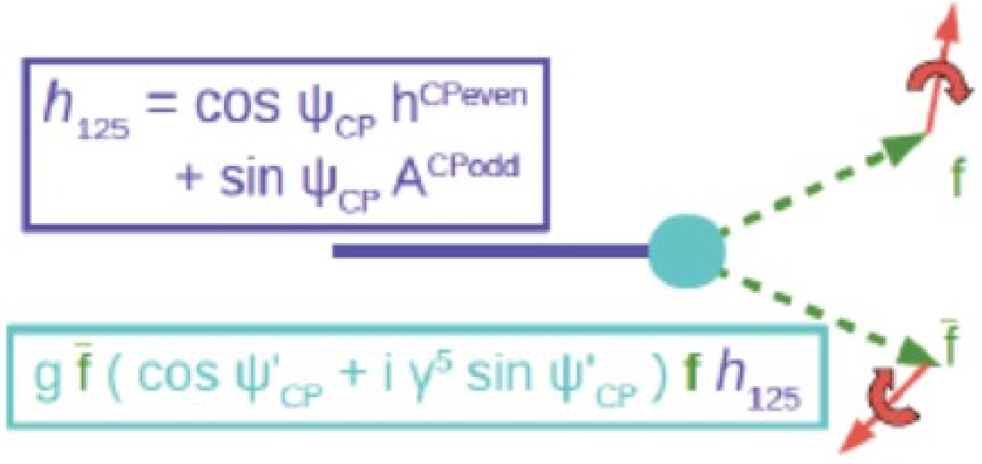


Statistical error:
√s ~ 500 GeV
L = 500 fb^{-1}

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

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

htautau



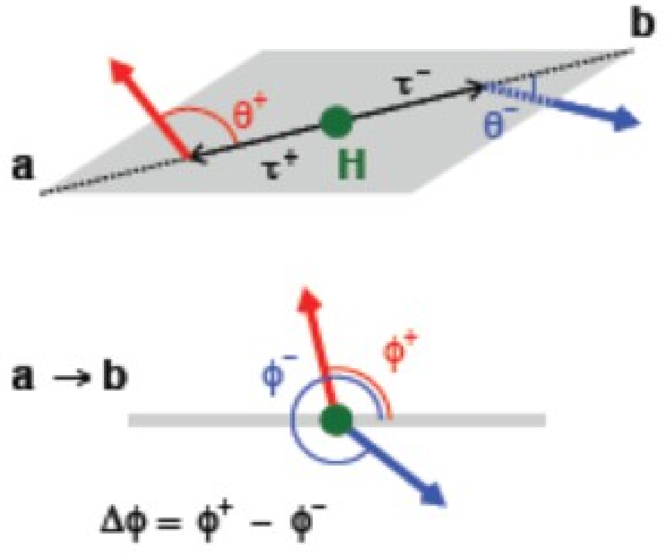
$h_{125} = \cos\psi_{CP}\, h^{CPeven} + \sin\psi_{CP}\, A^{CPodd}$

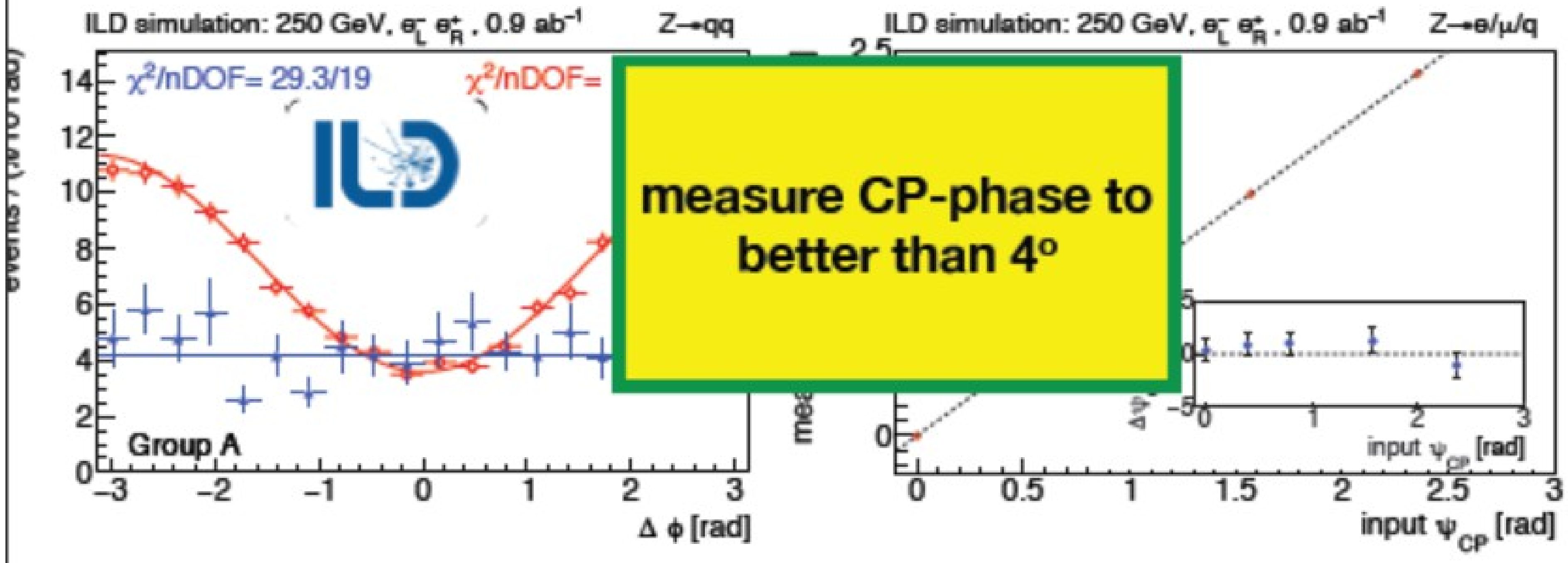
$g\bar{f}\,(\cos\psi'_{CP} + i\gamma^5 \sin\psi'_{CP})\, f\, h_{125}$

h is a spin 0 state:

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

[ψ = 0 CP even,
π/2 CP odd]





measure CP-phase to better than 4°

..and CPV in Zh coupling:

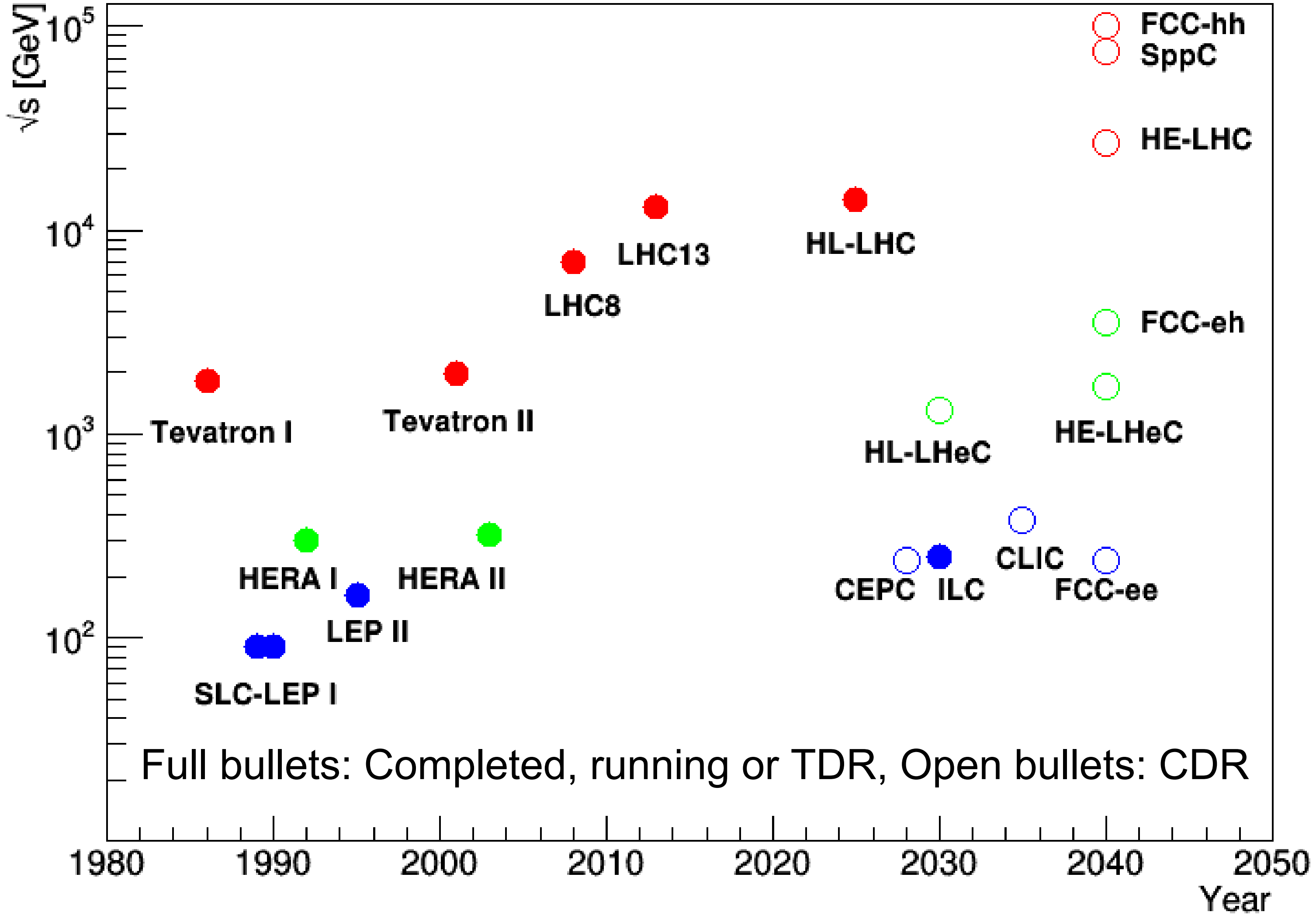
$$\Delta\mathcal{L}_{hZZ} = \frac{1}{2}\frac{\tilde{b}}{v} h Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

=> $\tilde{b}$ 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

European Strategy - Reminder

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.

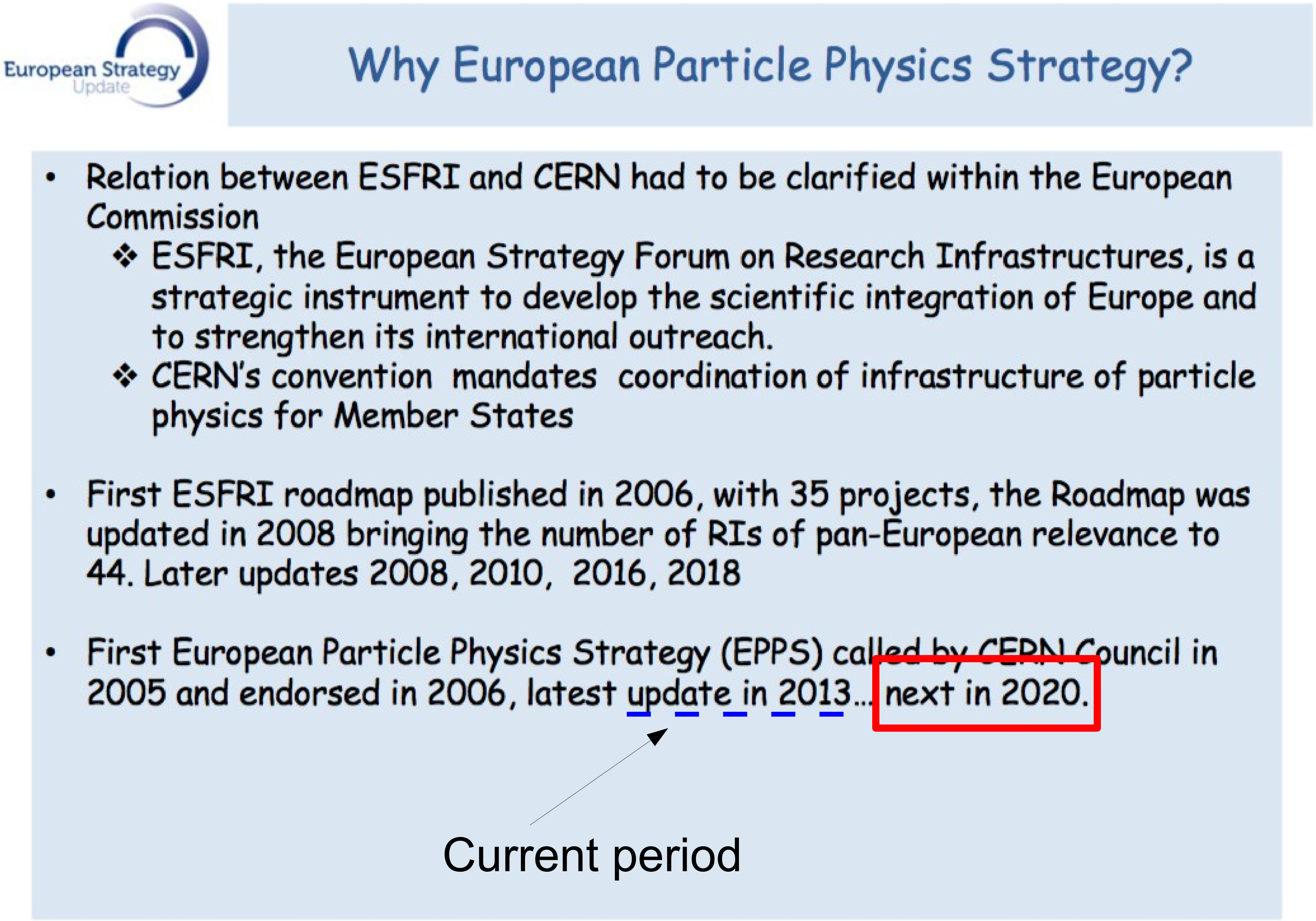
Points 1,2,4:

- 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.***

Update of European Strategy of Particle Physics



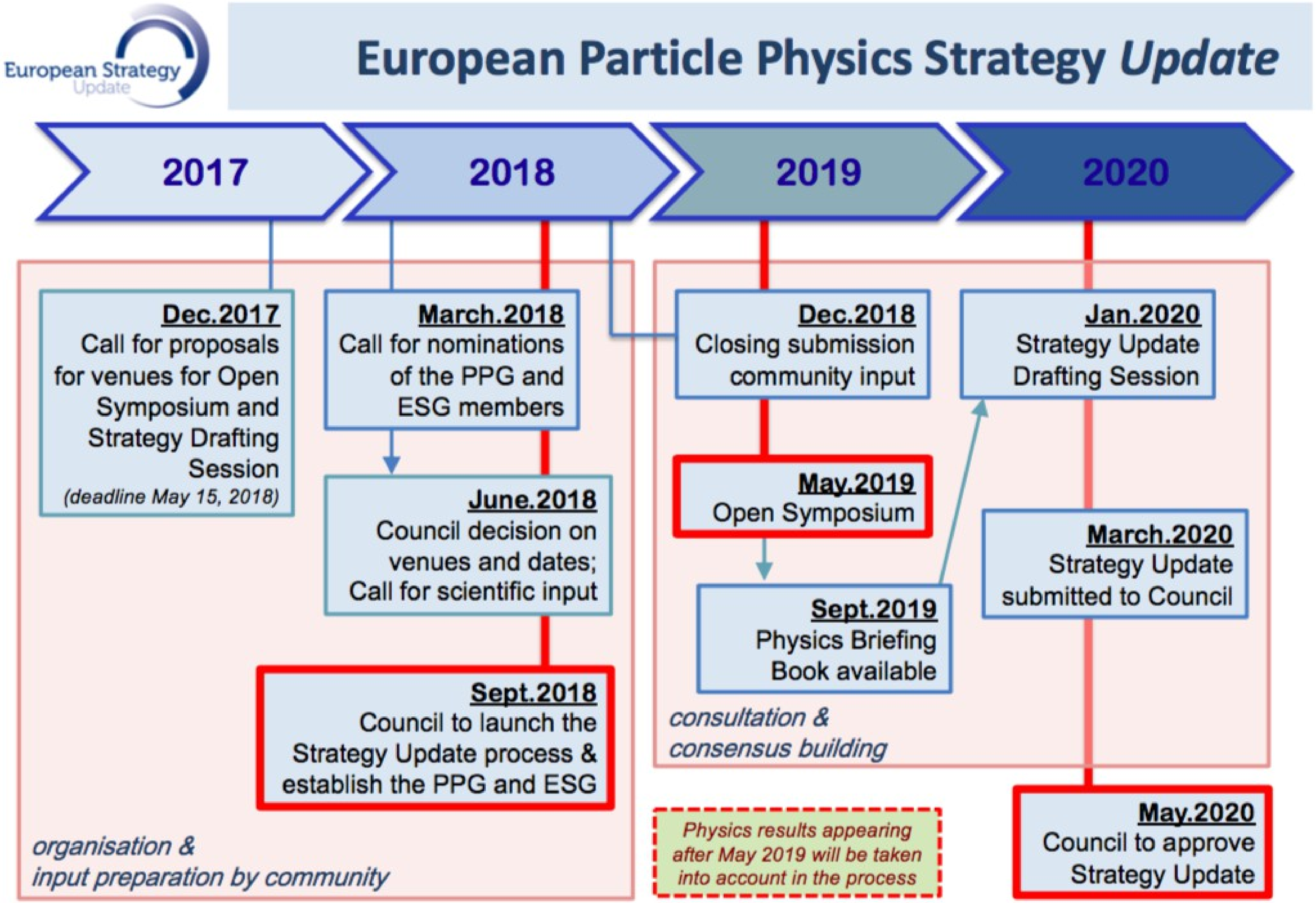
Why European Particle Physics Strategy?

- Relation between ESFRI and CERN had to be clarified within the European Commission
  - ❖ ESFRI, the European Strategy Forum on Research Infrastructures, is a strategic instrument to develop the scientific integration of Europe and to strengthen its international outreach.
  - ❖ CERN's convention mandates coordination of infrastructure of particle physics for Member States
- First ESFRI roadmap published in 2006, with 35 projects, the Roadmap was updated in 2008 bringing the number of RIs of pan-European relevance to 44. Later updates 2008, 2010, 2016, 2018
- First European Particle Physics Strategy (EPPS) called by CERN Council in 2005 and endorsed in 2006, latest update in 2013… next in 2020.

Current period

EPPSU – The Schedule

EPPSU Secretary:
H. Abramowicz



European Strategy Update

European Particle Physics Strategy *Update*

2017 | 2018 | 2019 | 2020

Dec.2017
Call for proposals for venues for Open Symposium and Strategy Drafting Session
(deadline May 15, 2018)

March.2018
Call for nominations of the PPG and ESG members

June.2018
Council decision on venues and dates; Call for scientific input

Sept.2018
Council to launch the Strategy Update process & establish the PPG and ESG

organisation &
input preparation by community

Dec.2018
Closing submission community input

May.2019
Open Symposium

Sept.2019
Physics Briefing Book available

consultation &
consensus building

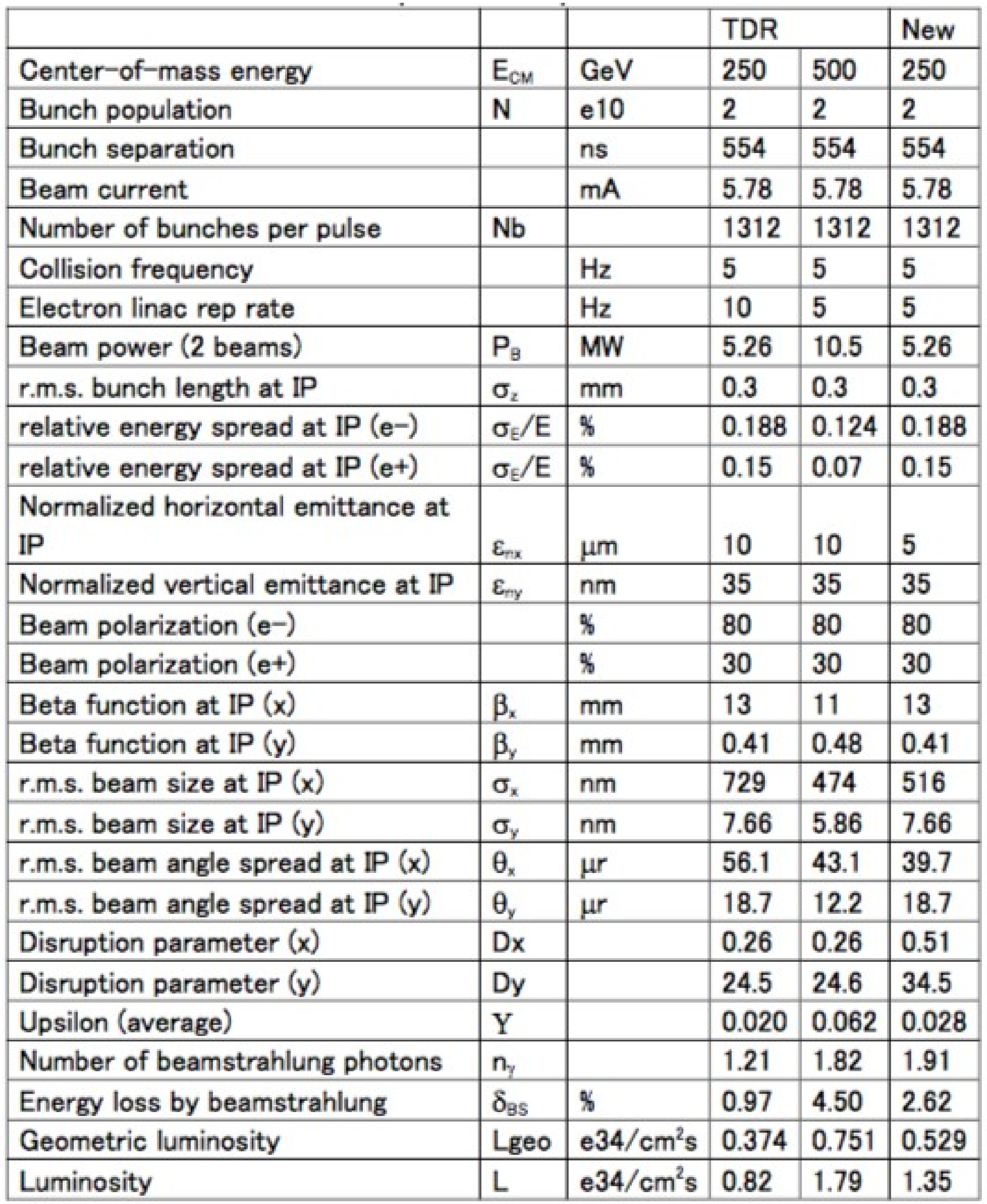
Physics results appearing after May 2019 will be taken into account in the process

Jan.2020
Strategy Update Drafting Session

March.2020
Strategy Update submitted to Council

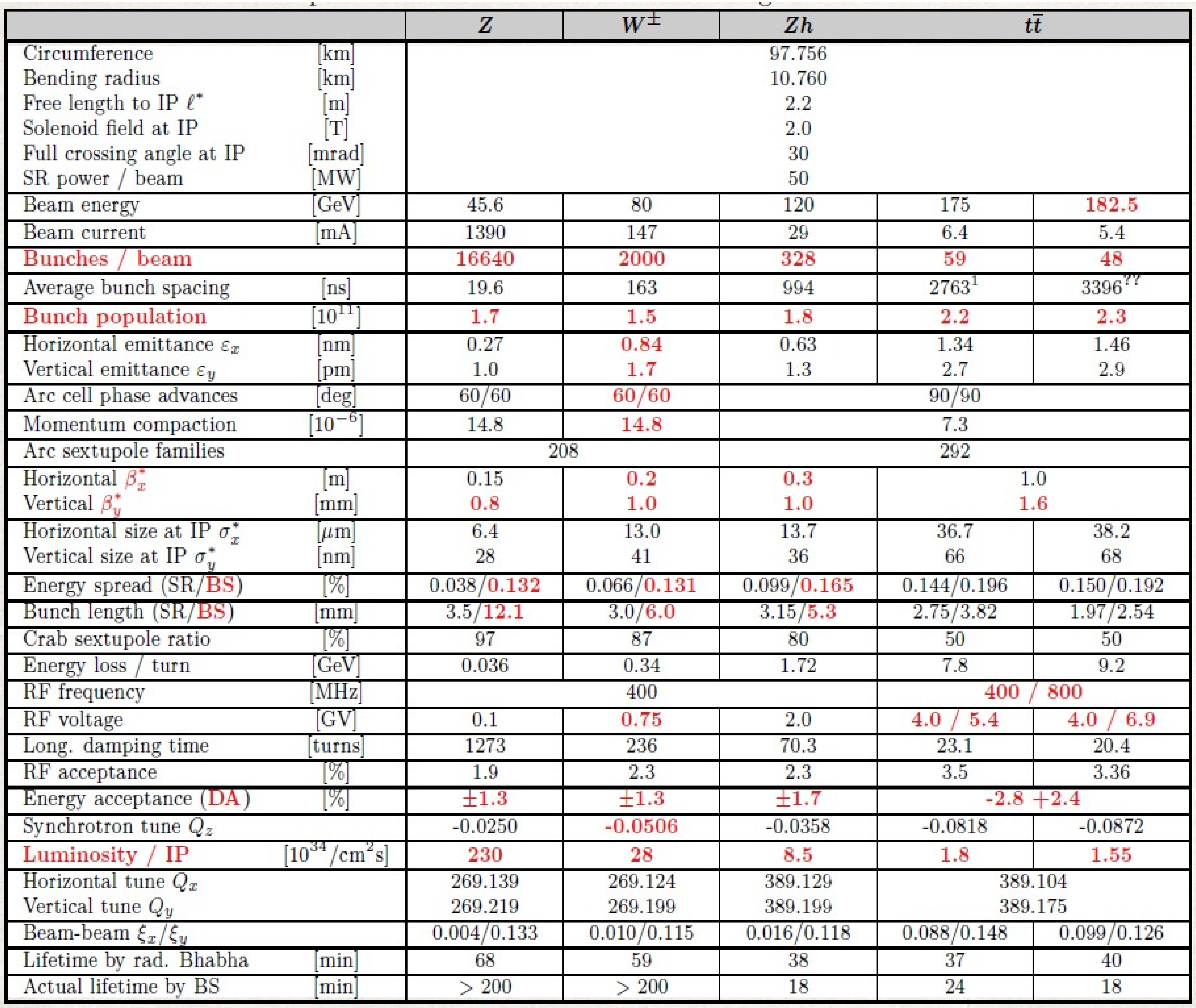
May.2020
Council to approve Strategy Update

ILC Parameters

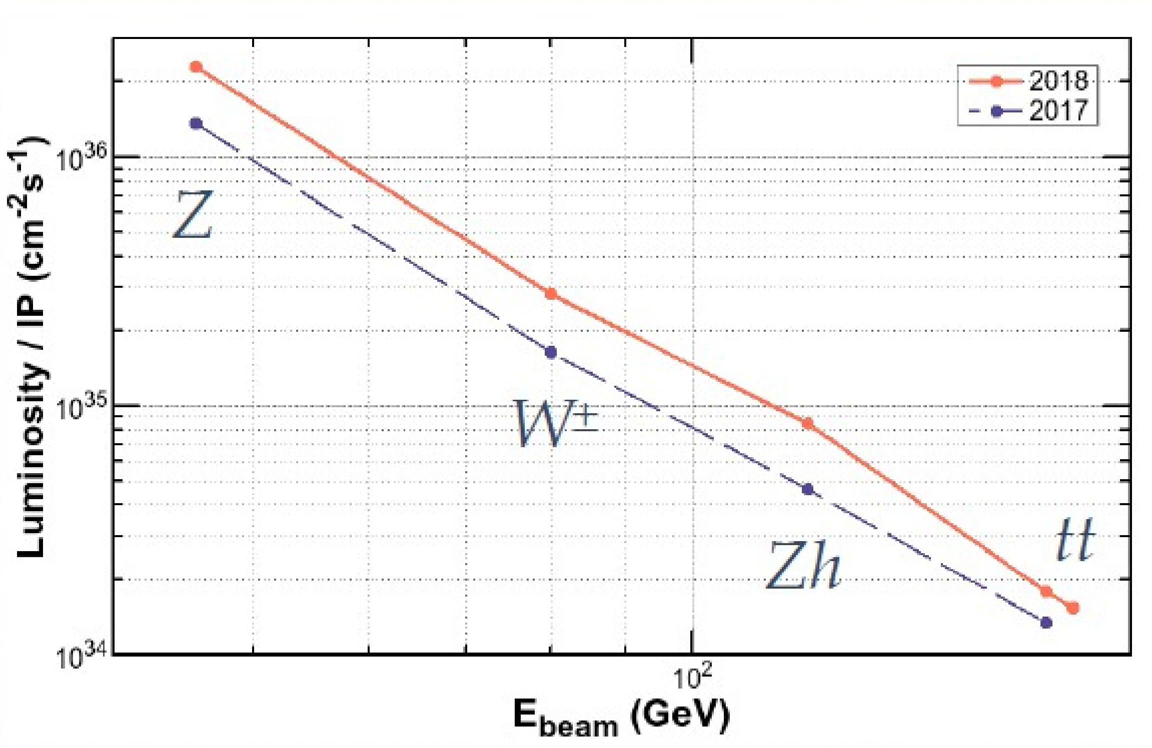


			TDR		New
Center-of-mass energy	E_{CM}	GeV	250	500	250
Bunch population	N	e10	2	2	2
Bunch separation		ns	554	554	554
Beam current		mA	5.78	5.78	5.78
Number of bunches per pulse	Nb		1312	1312	1312
Collision frequency		Hz	5	5	5
Electron linac rep rate		Hz	10	5	5
Beam power (2 beams)	P_B	MW	5.26	10.5	5.26
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	$e34/cm^2s$	0.374	0.751	0.529
Luminosity	L	$e34/cm^2s$	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}/cm^{2}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

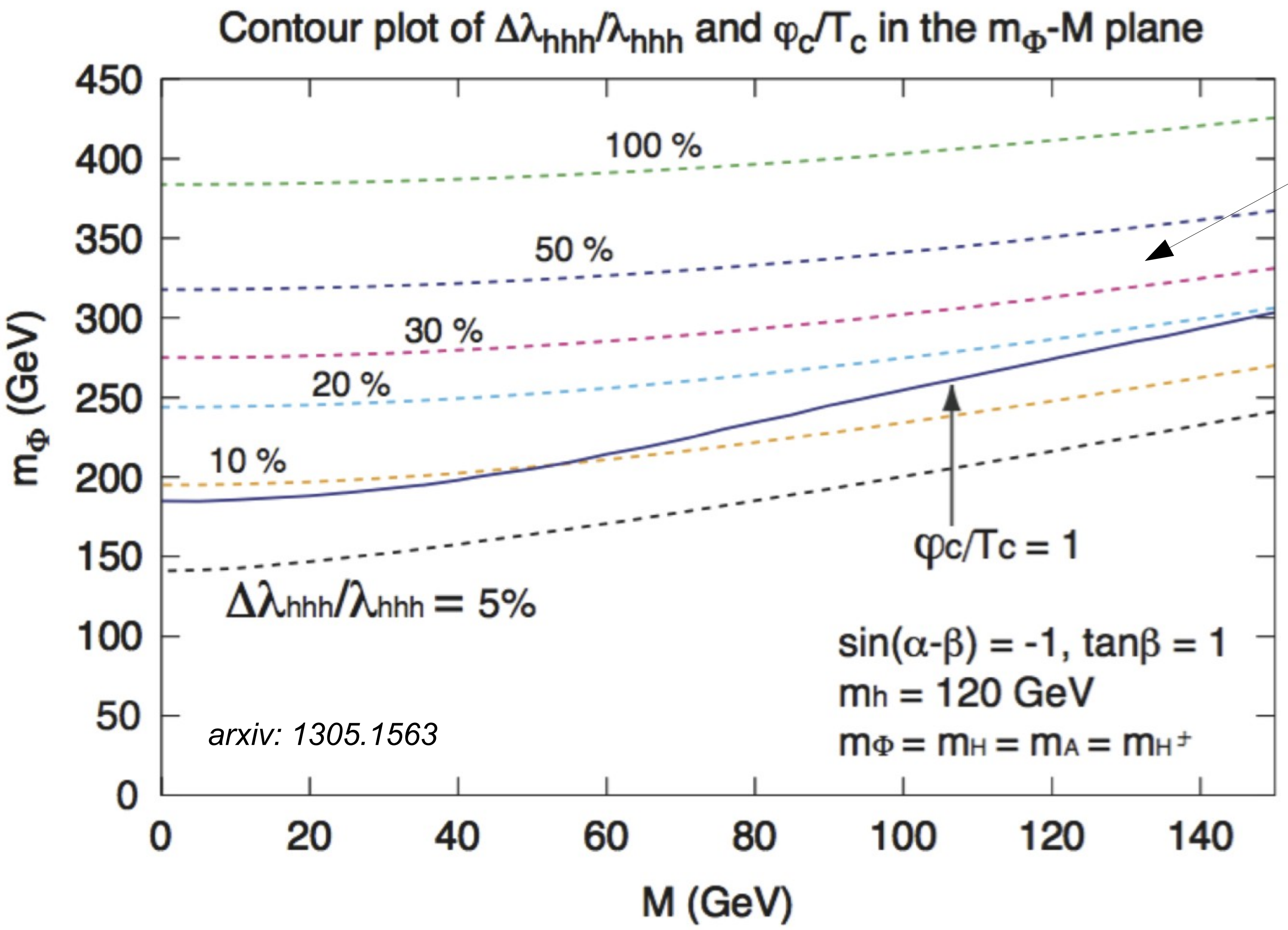
CEPC Parameters

	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



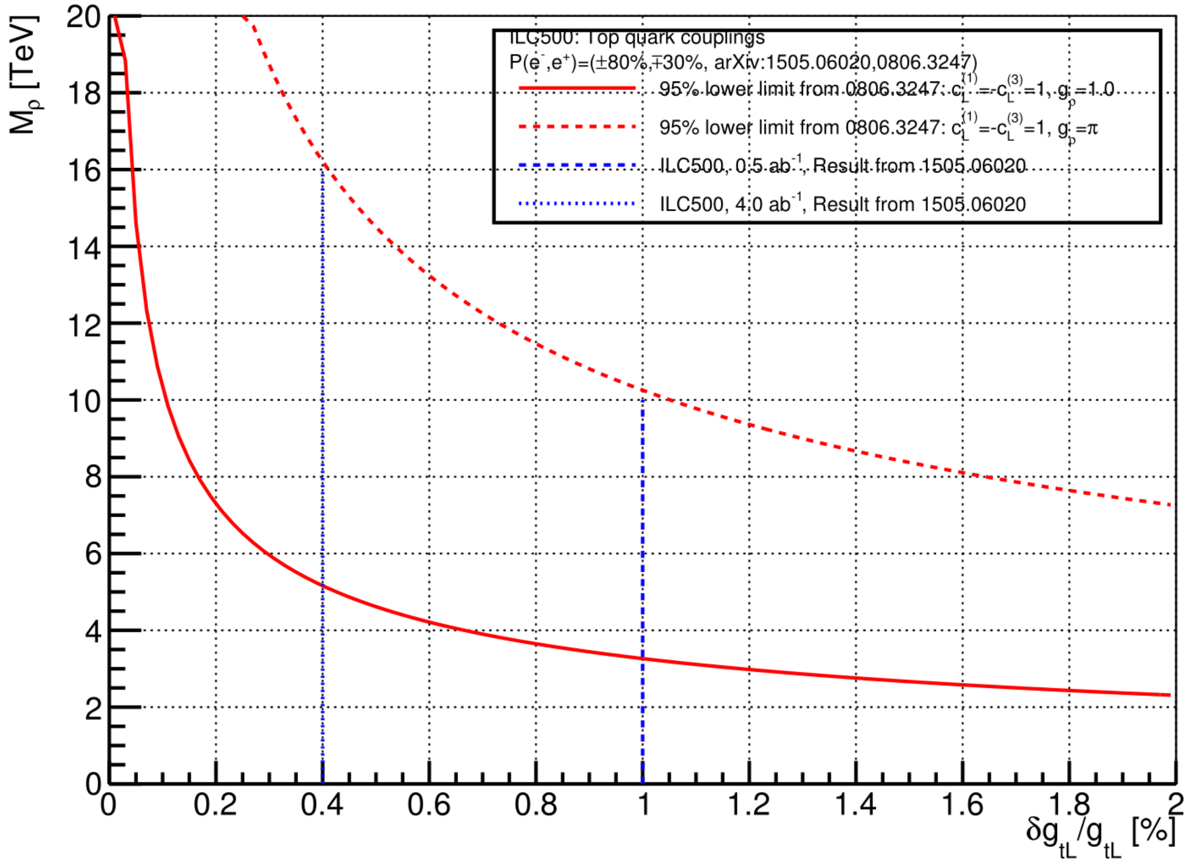
Deviations
of λ from
SM Value

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

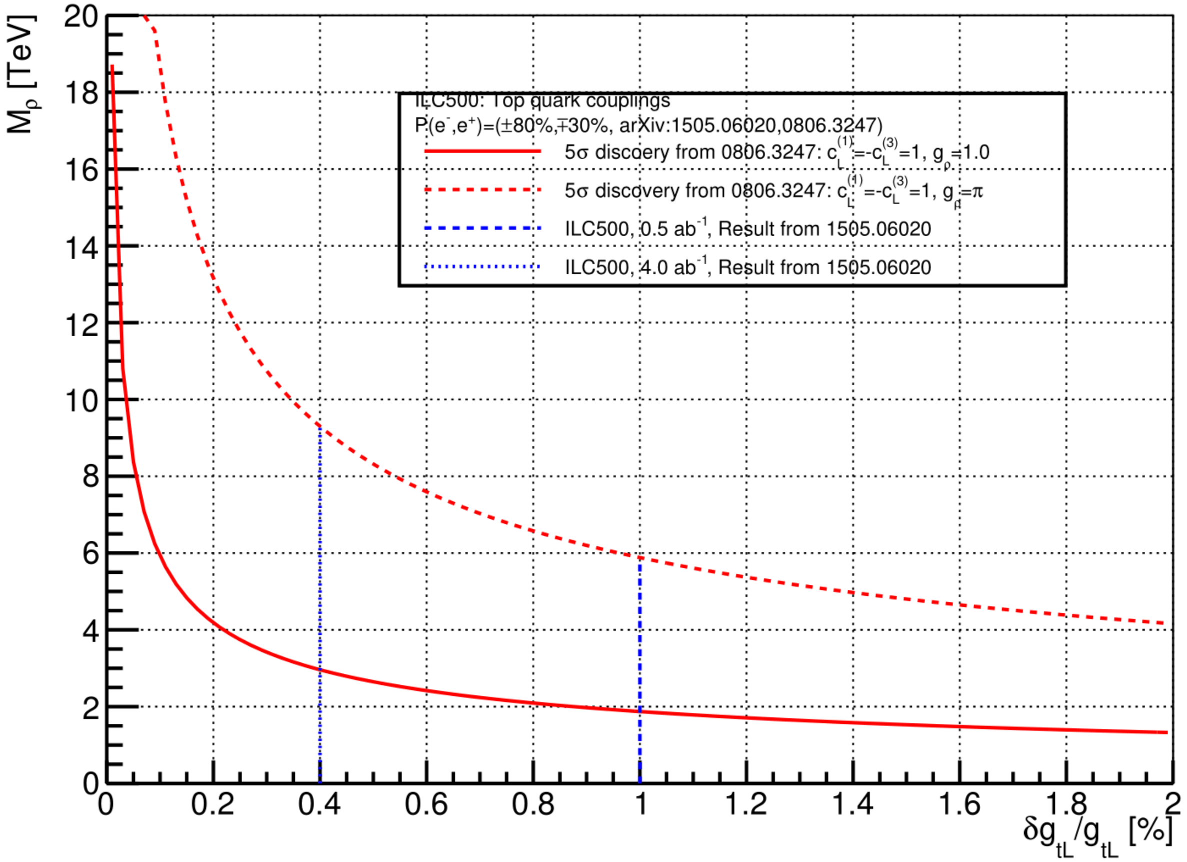
Electroweak top couplings and discovery reach

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



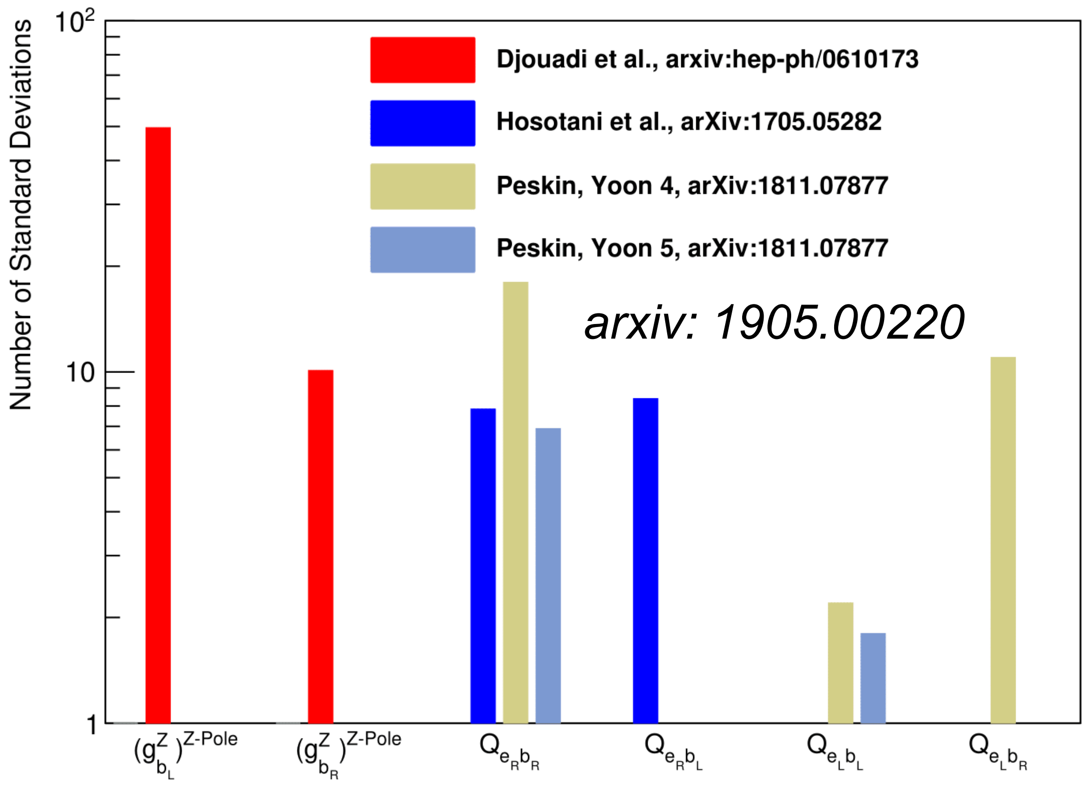
5σ discovery

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

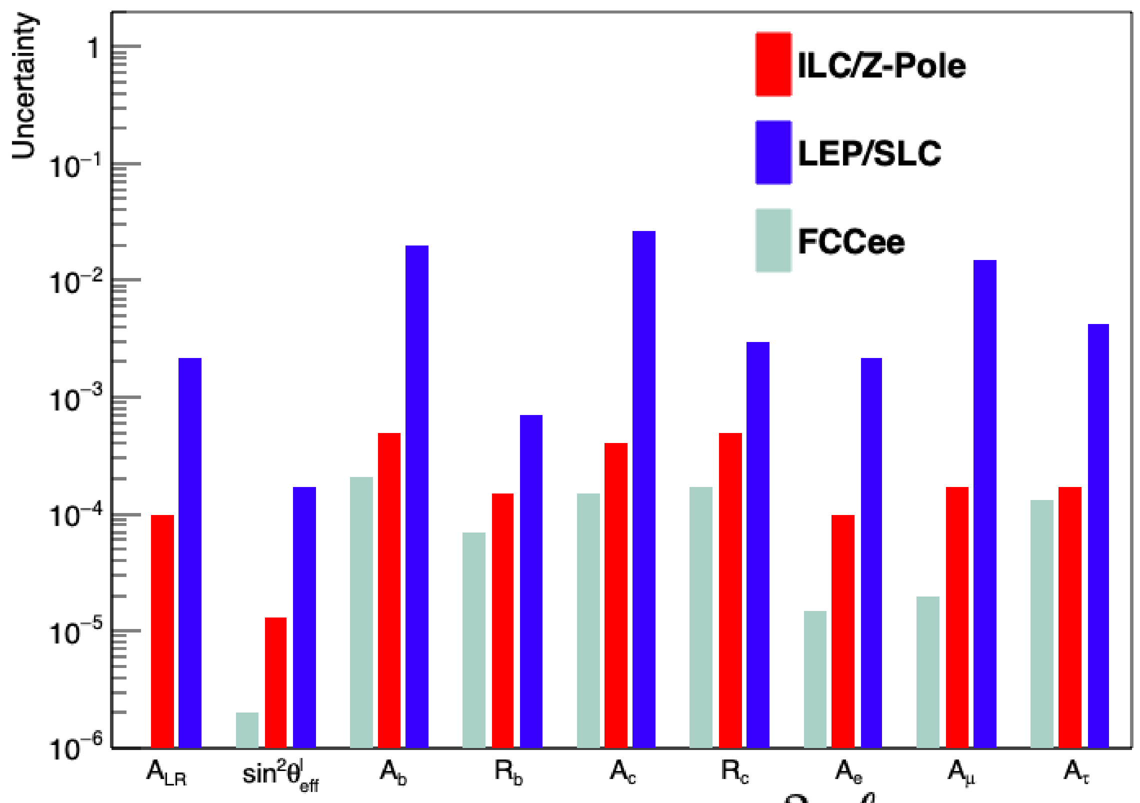
Example: b couplings and helicity amplitudes



arxiv: 1905.00220

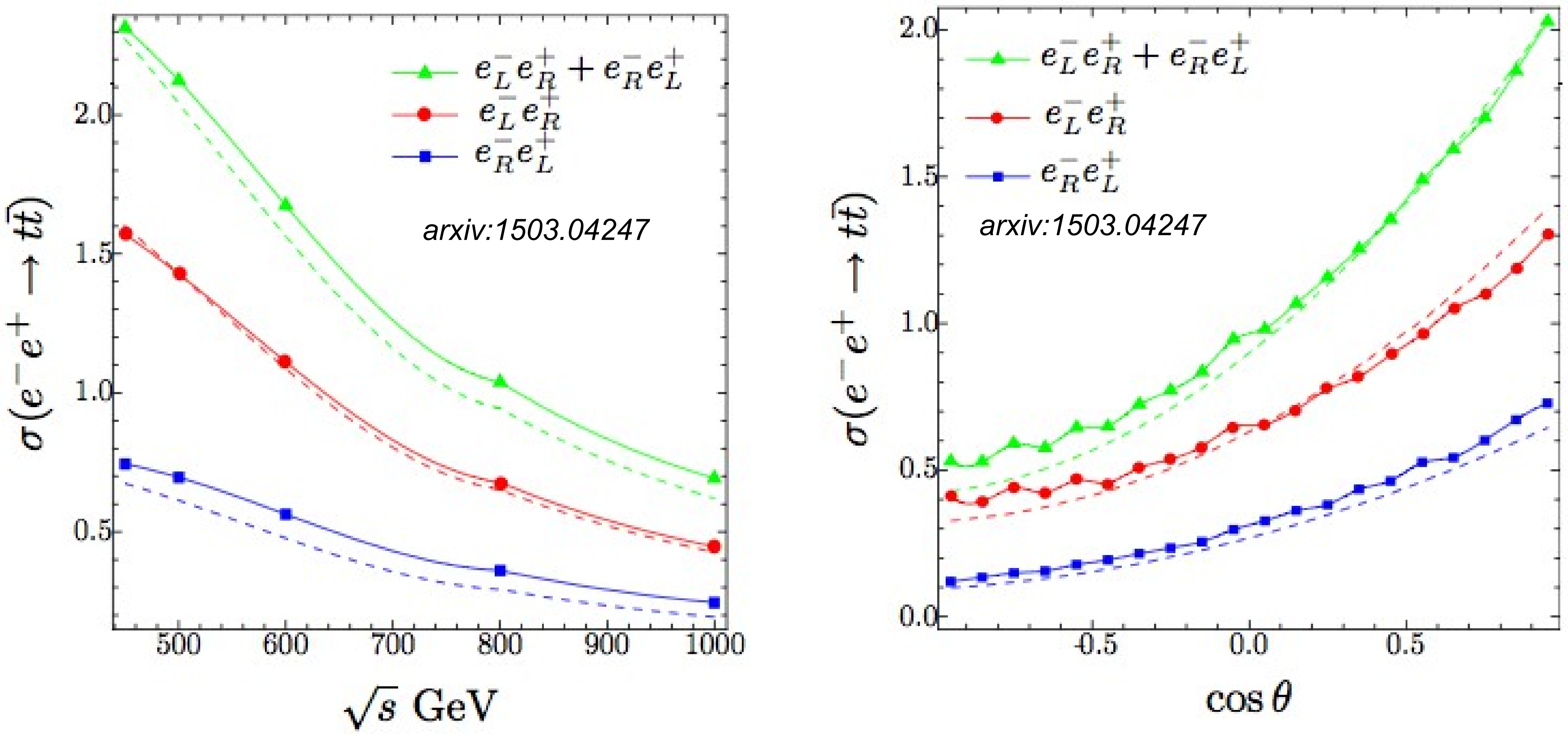
- Spectacular sensitivity to new physics in RS Models
  - **Complete tests only possible at LC**
  - **Discovery reach O(10 TeV)@250 GeV and O(20 TeV)@500 GeV**
- Pole measurements critical input
  - Only poorly constrained by LEP
- Pole measurements will (most likely) influence also top electroweak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

Don't forget: Electroweak observables



- Precise measurement of $\sin^2\theta^\ell_{\rm eff}$.
  - 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

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