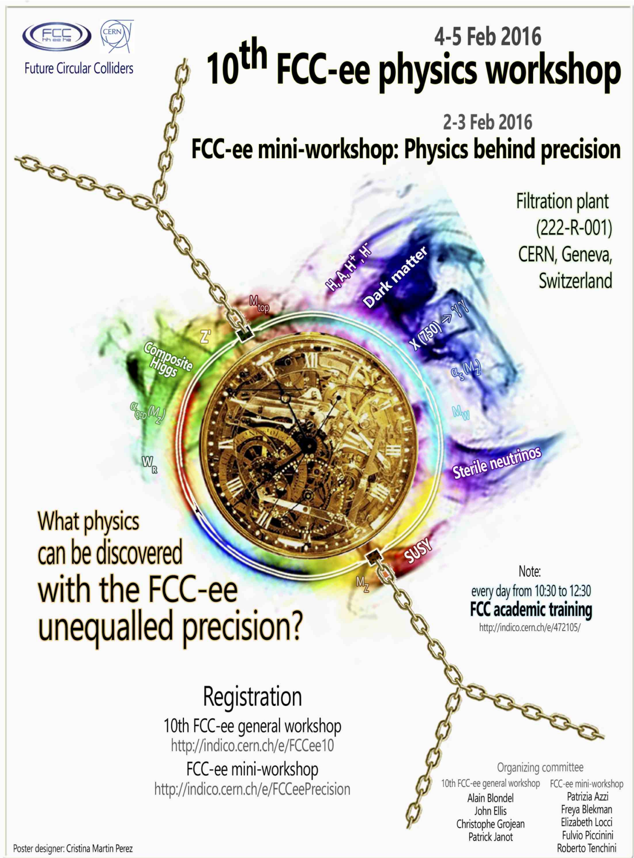
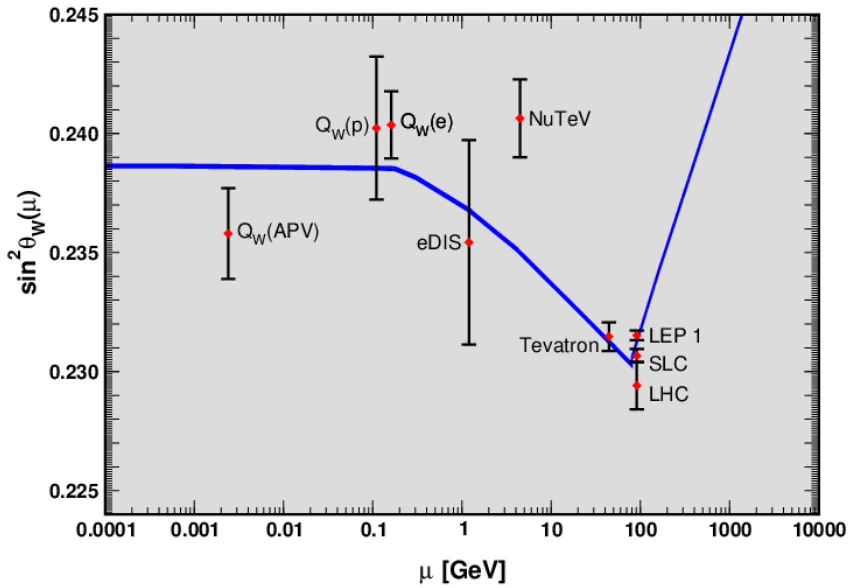
Precision Measurements & Their Sensitivity to New Physics



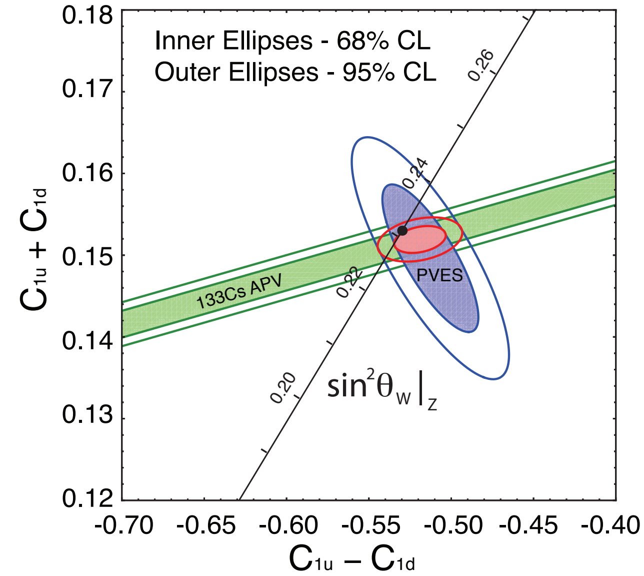
- Precision experiments
- Implications for the SM and beyond
- Paradigms and realizations
- The FCC-ee

Precision Physics: Past and Present

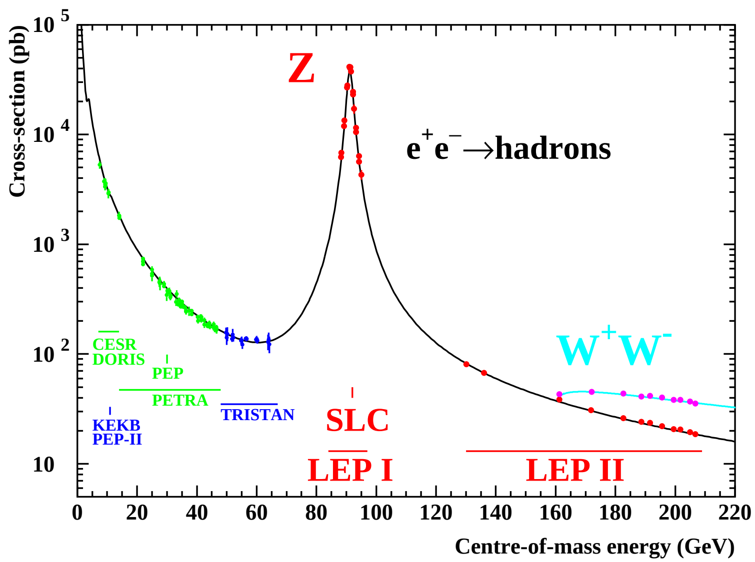
- **Weak neutral current** (ν scattering; APV; polarized e^-; e^+e^-; $\cdots$)
- **Z, W** (S$p\bar{p}$S, LEP, SLC, Tevatron, LHC)
- **Higgs**
- **Triple/quartic gauge vertices; $W_L W_L \to W_L W_L$**
- **Weak charged current** (β, μ, $\cdots$ decay; CP violation; unitarity triangle)
- **QED** (classic tests; $g_\mu - 2$; μ Lamb shift (proton radius))
- **t physics**
- **EDMs**
- **Flavor physics, rare decays, FCNC, neutrinos**
- **Precision cosmology**



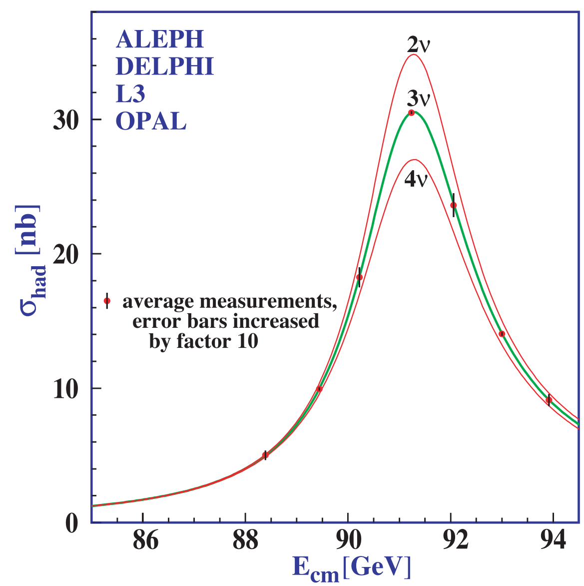
0.245
0.240
0.235
0.230
0.225
$\sin^2\theta_W(\mu)$
$Q_W(p)$
$Q_W(e)$
NuTeV
$Q_W(APV)$
eDIS
Tevatron
LEP 1
SLC
LHC
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
μ [GeV]



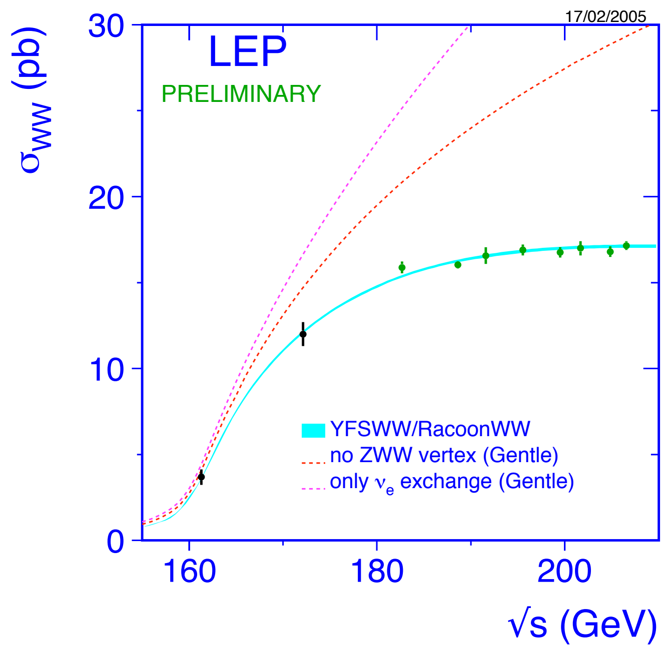
Inner Ellipses - 68% CL
Outer Ellipses - 95% CL
0.26
0.24
0.22
0.20
PVES
133Cs APV
$\sin^2\theta_W|_Z$
$C_{1u} + C_{1d}$
$C_{1u} - C_{1d}$
0.18
0.17
0.16
0.15
0.14
0.13
0.12
-0.70
-0.65
-0.60
-0.55
-0.50
-0.45
-0.40

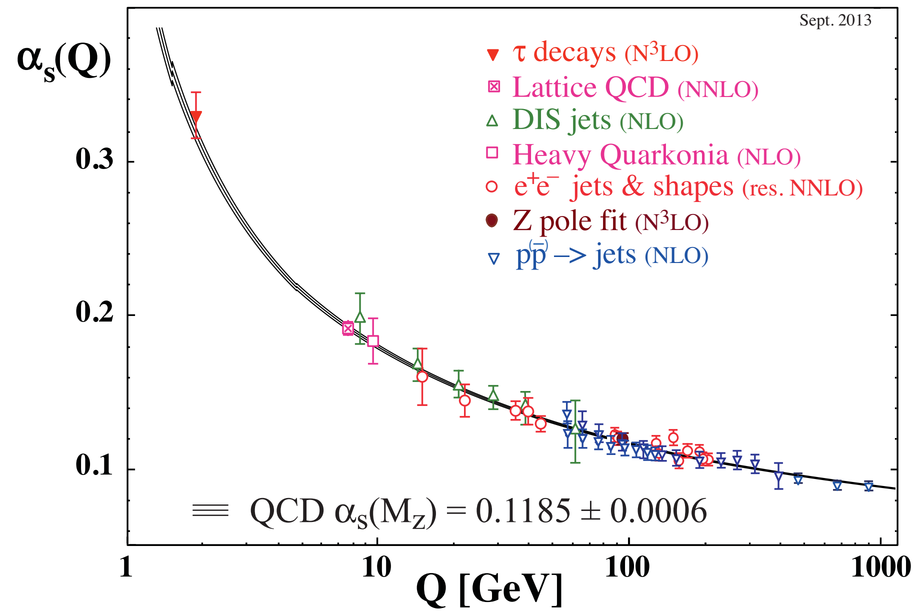


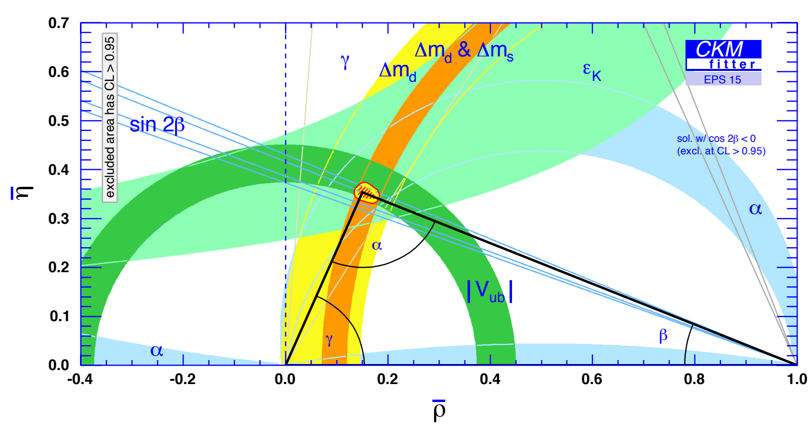
Cross-section (pb)
10^5
10^4
10^3
10^2
10
Z
$e^+e^- \to$hadrons
W^+W^-
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
LEP II
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

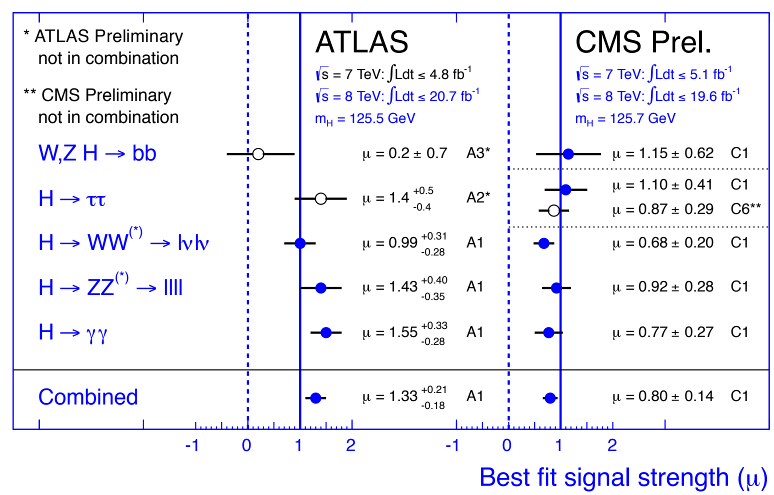


ALEPH
DELPHI
L3
OPAL
2ν
3ν
4ν
average measurements,
error bars increased
by factor 10
σ_{had} [nb]
30
20
10
0
86
88
90
92
94
E_{cm}[GeV]


17/02/2005
LEP
PRELIMINARY
σ_{WW} (pb)
YFSWW/RacoonWW
no ZWW vertex (Gentle)
only ν_e exchange (Gentle)
$\sqrt{s}$ (GeV)


Sept. 2013
$\alpha_s(Q)$
τ decays (N^3LO)
Lattice QCD (NNLO)
DIS jets (NLO)
Heavy Quarkonia (NLO)
e^+e^- jets & shapes (res. NNLO)
Z pole fit (N^3LO)
$p\bar{p}$ –> jets (NLO)
QCD $\alpha_s(M_Z) = 0.1185 \pm 0.0006$
Q [GeV]

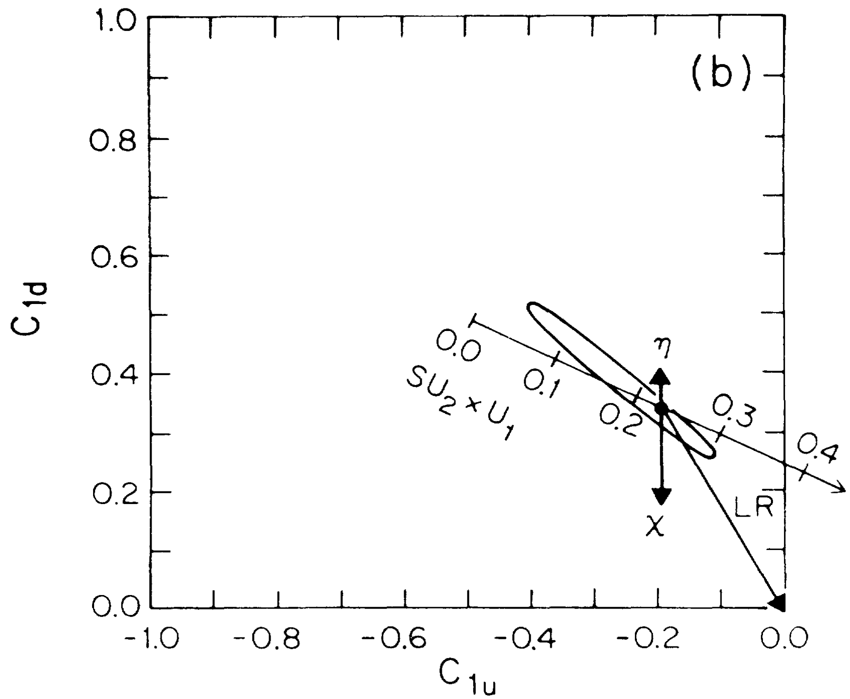

CKM fitter
EPS 15
excluded area has CL > 0.95
sin 2β
γ
Δm_d
Δm_d & Δm_s
ε_K
sol. w/ cos 2β < 0 (excl. at CL > 0.95)
α
$|V_{ub}|$
β
$\bar{\eta}$
$\bar{\rho}$

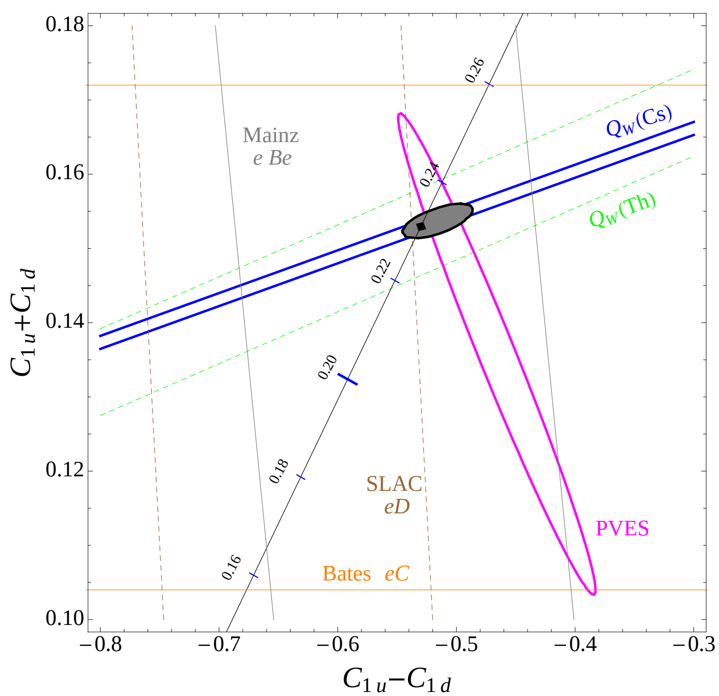

* ATLAS Preliminary not in combination
** CMS Preliminary not in combination
ATLAS
$\sqrt{s}$ = 7 TeV: $\int Ldt \le 4.8\ fb^{-1}$
$\sqrt{s}$ = 8 TeV: $\int Ldt \le 20.7\ fb^{-1}$
m_H = 125.5 GeV
CMS Prel.
$\sqrt{s}$ = 7 TeV: $\int Ldt \le 5.1\ fb^{-1}$
$\sqrt{s}$ = 8 TeV: $\int Ldt \le 19.6\ fb^{-1}$
m_H = 125.7 GeV
W,Z H → bb
$\mu = 0.2 \pm 0.7$ A3*
$\mu = 1.15 \pm 0.62$ C1
H → ττ
$\mu = 1.4^{+0.5}_{-0.4}$ A2*
$\mu = 1.10 \pm 0.41$ C1
$\mu = 0.87 \pm 0.29$ C6**
$H \to WW^{(*)} \to l\nu l\nu$
$\mu = 0.99^{+0.31}_{-0.28}$ A1
$\mu = 0.68 \pm 0.20$ C1
$H \to ZZ^{(*)} \to llll$
$\mu = 1.43^{+0.40}_{-0.35}$ A1
$\mu = 0.92 \pm 0.28$ C1
H → γγ
$\mu = 1.55^{+0.33}_{-0.28}$ A1
$\mu = 0.77 \pm 0.27$ C1
Combined
$\mu = 1.33^{+0.21}_{-0.18}$ A1
$\mu = 0.80 \pm 0.14$ C1
Best fit signal strength (μ)

Results of the Precision Program

- **Established electroweak SM to first approximation**

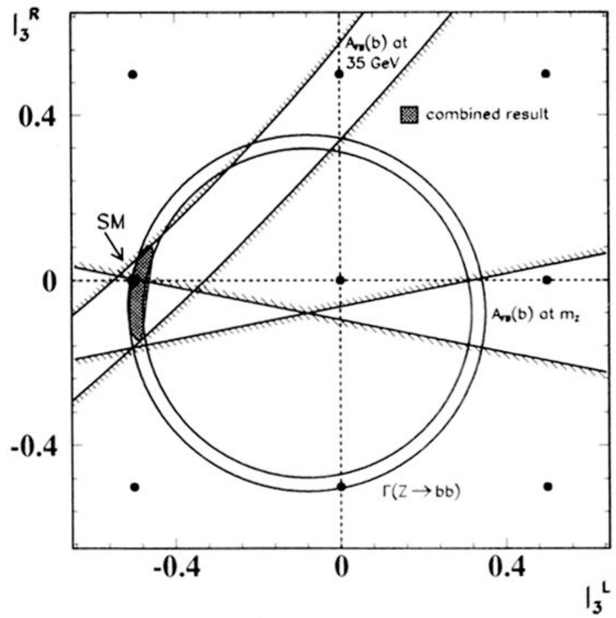
gauge theory (V, A; W, Z); $SU(2) \times U(1)$;
fermion reps., chiralities; $\sin^2\theta_W$; t; ν_τ required



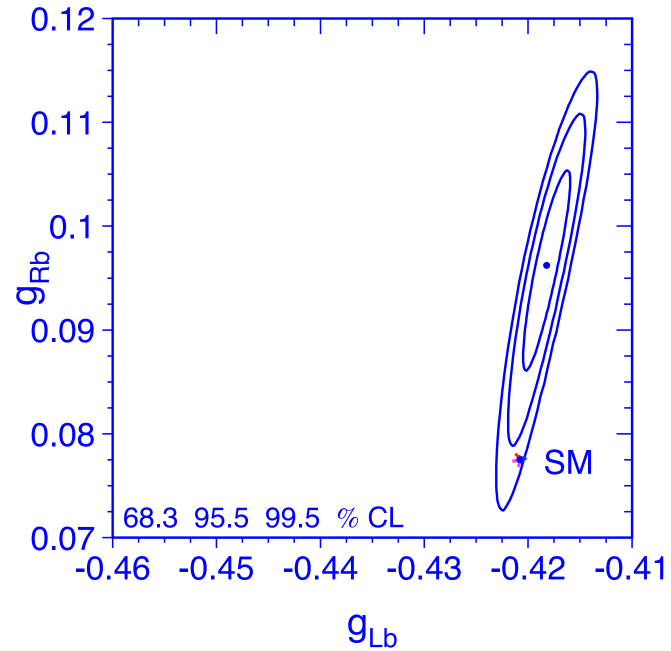


Amaldi et al., Phys.Rev. D36 (1987)

$(-\frac{1}{2}, 0)$, SM
$(0, -\frac{1}{2})$, mirror
$(0, 0)$, topless
$(-\frac{1}{2}, -\frac{1}{2})$, vector doublet

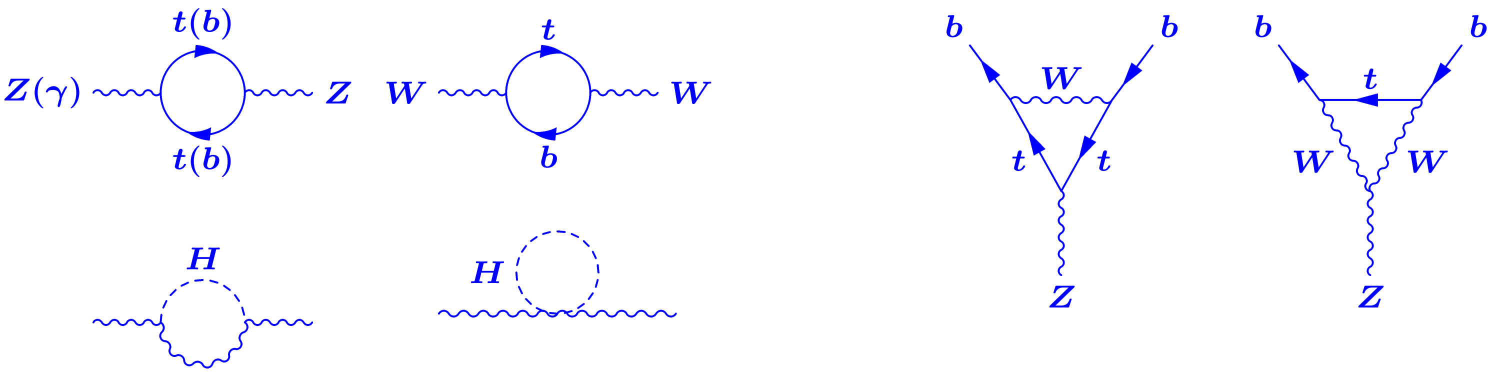


Schaile and Zerwas, Phys.Rev. D45 (1992)

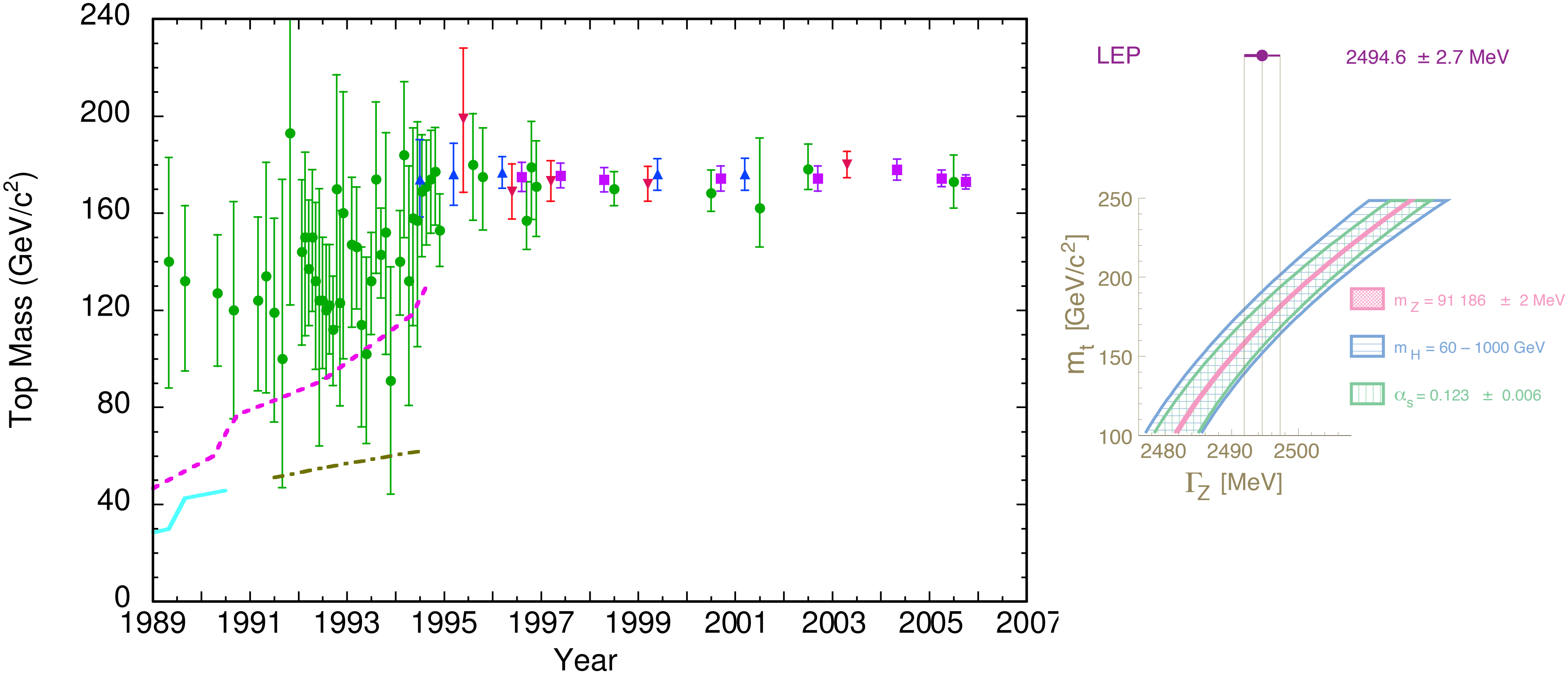


LEPEWWG

- **Established SM at loop level** **(QED, EW, QCD, mixed)**
  - Renormalization theory vindicated
  - m_t, M_H successfully predicted

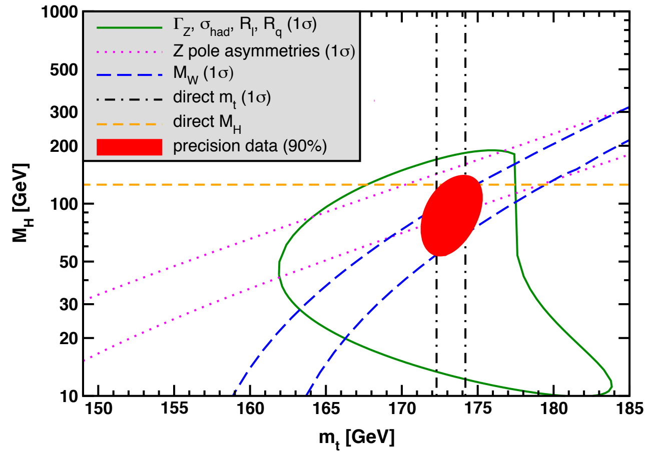


• **The top quark prediction**

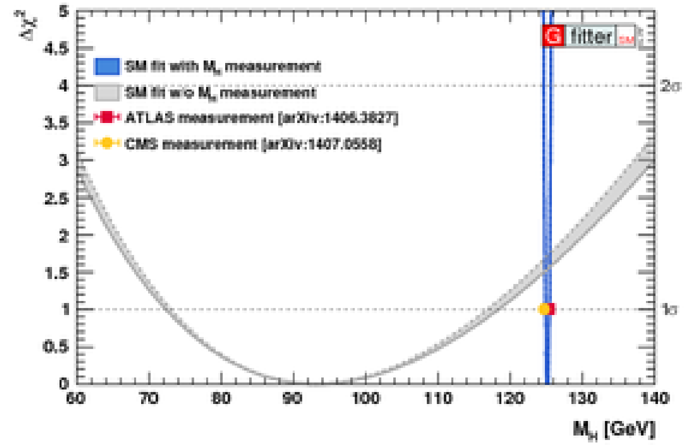


– **Updated from** **Chris Quigg, Phys.Today (1997), hep-ph/9704332**

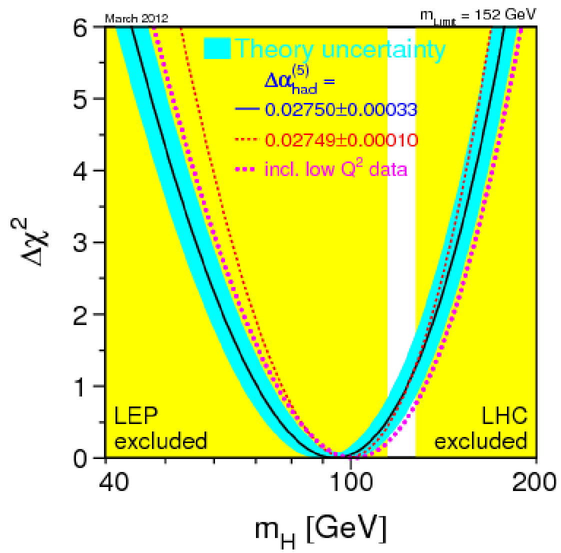
– **Current indirect value: $177.0(2.1)$ GeV** **(Erler and Freitas, PDG); direct: $173.21(0.87)$ GeV** **(LHC/Tevatron, PDG)**



Erler and Freitas, PDG



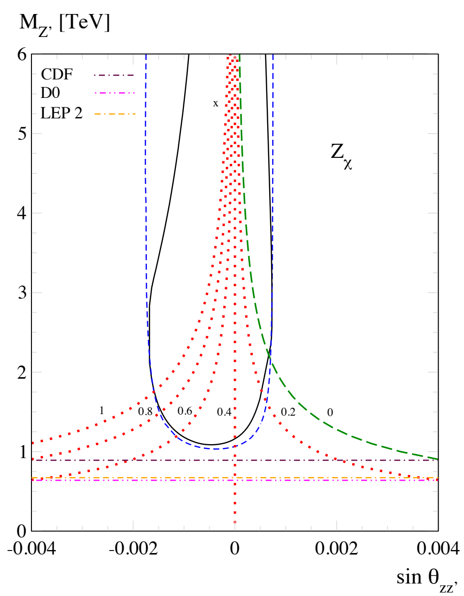
Gfitter

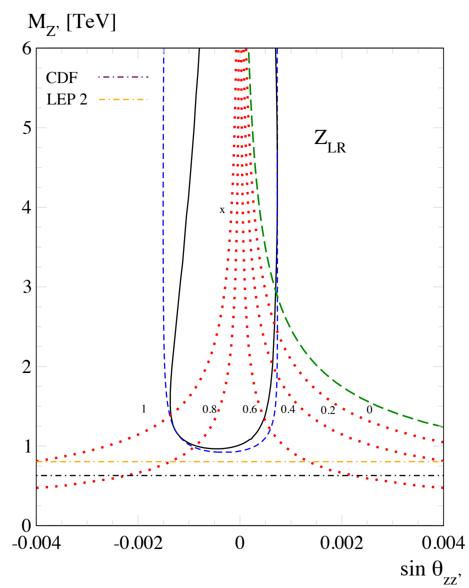


LEPEWWG

- **The Z pole watershed:** **new TeV-scale physics severely constrained**
  - **Nondecoupling** **(many forms of strong coupling, DSB): several %**
  - **Decoupling** **(e.g., SUSY): $< 1\%$**

- **Limits on weak coupling** **(oblique: EWSB, chiral fermions; Z', exotics)**





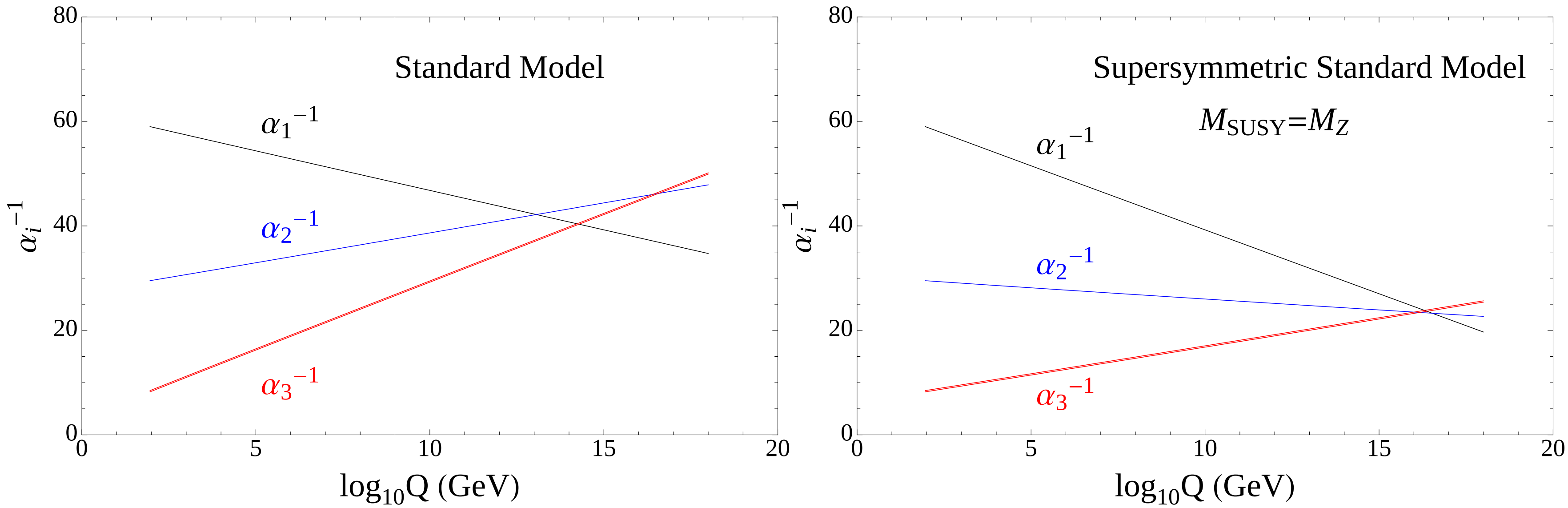
Z'	EW	ATLAS	CMS	CDF	DØ	LEP 2	M_H
Z_χ	1,141	2,540	–	930	903	785	$171^{+493}_{-\ 89}$
Z_ψ	147	2,380	2,600	917	891	500	$97^{+\ 31}_{-\ 25}$
Z_η	427	2,440	–	938	923	500	423^{+577}_{-350}
Z_{LR}	998	–	–	–	–	825	$804^{+174}_{-\ 35}$
Z_S	1,257	2,470	–	858	822	–	$149^{+353}_{-\ 68}$
Z_{SM}	1,403	2,860	2,960	1,071	1,023	1,760	331^{+669}_{-246}

Erler and Freitas, PDG

Erler et al: 0906.2435

- **Hints of new physics?** **(A_{LR} vs $A_{FB}^{b\bar{b}}$; $g_\mu - 2$; proton radius)**

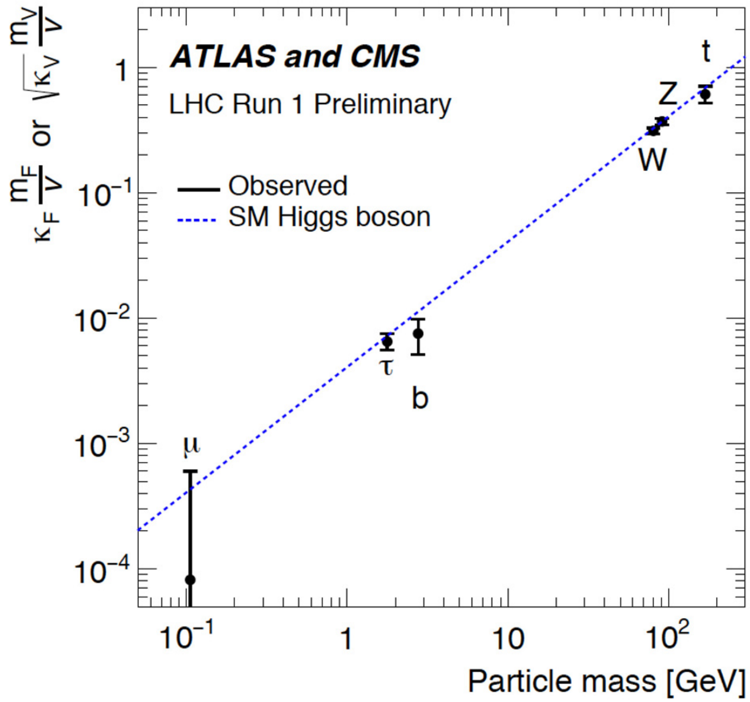
- **Precise SM parameters**
  - $\sin^2\hat{\theta}_W(M_Z^2) \;= 0.23126(5)$ **(PDG)**
  - $\alpha_s(M_Z) = 0.1193(16)$ **(Z-pole)** vs $0.1185(6)$ **(all), (PDG)**
  - **Gauge couplings** **(consistent with SUSY gauge unification)**



  - **Neutrino counting** **($2.984(8)$ light active ν)**

The Standard Model

- Spectacularly successful/unsuccessful
- Mathematically consistent
- Describes nature to 10^{-16} cm
- Higgs discovery
  (not DSB; but composite/extra dim?, EFT?)



- But, complicated, fine-tuned, families, many parameters
- Missing: dark matter and energy, $n_B - n_{\bar{B}}$, quantum gravity, m_ν type

The Paradigms

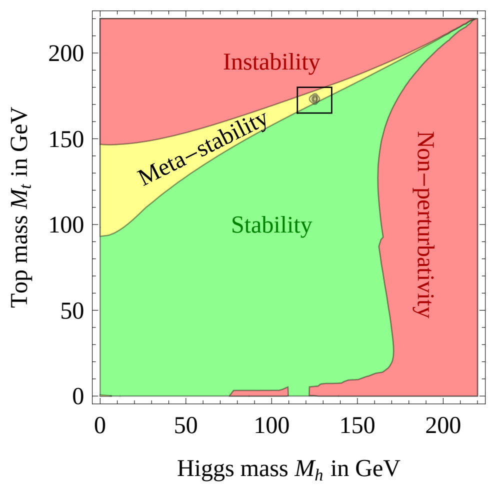
naturalness (TeV physics) — tuning (landscape?)

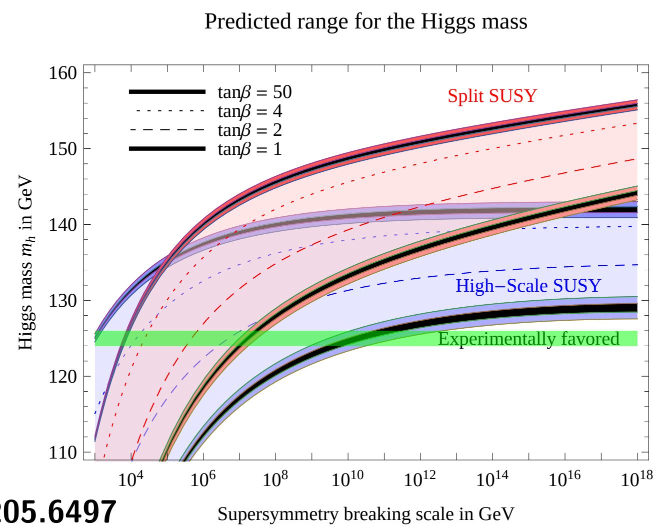
- **Naturalness or tuning**
- **Uniqueness or environment**
- **Minimality or remnants**

Naturalness or Tuning

- **ATLAS/CMS/LHCb:** no clear sign of supersymmetry, strong dynamics, or other new physics
  - 750 GeV diphoton? 2 TeV diboson? B anomalies?

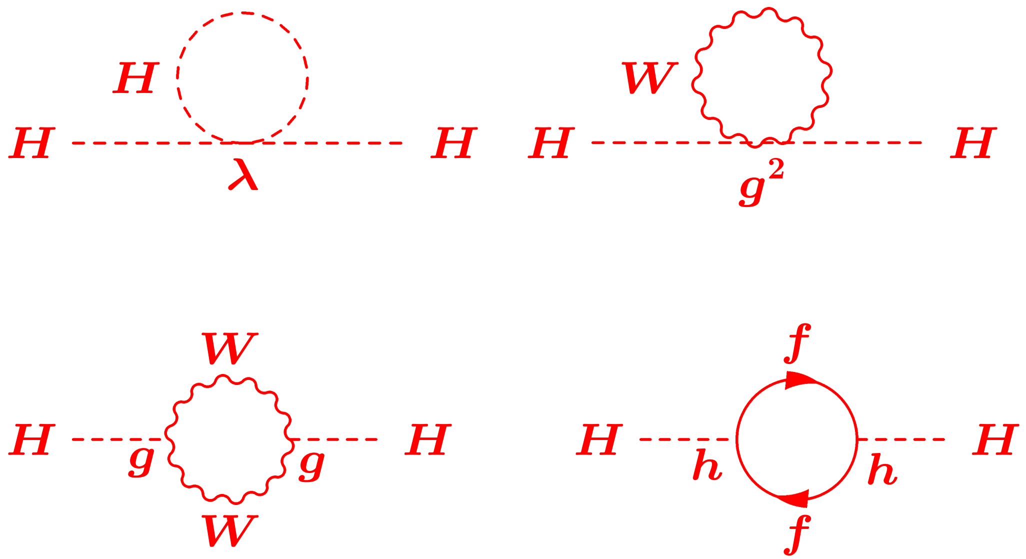
- Higgs-like particle: consistent with elementary Higgs
  - SM: rather light (metastable vacuum or new physics below 10^{11} GeV)
  - MSSM: rather heavy (need heavy stop or large mixing)





Degrassi et al, 1205.6497

- **Higgs mass^2 very unnatural (tuning by 10^{34}) unless TeV physics**
  (supersymmetry, composite Higgs, extra dimensions)



- **Is naturalness a good guide? cf dark energy (tuning by 10^{120})**
  (environmental solution?)

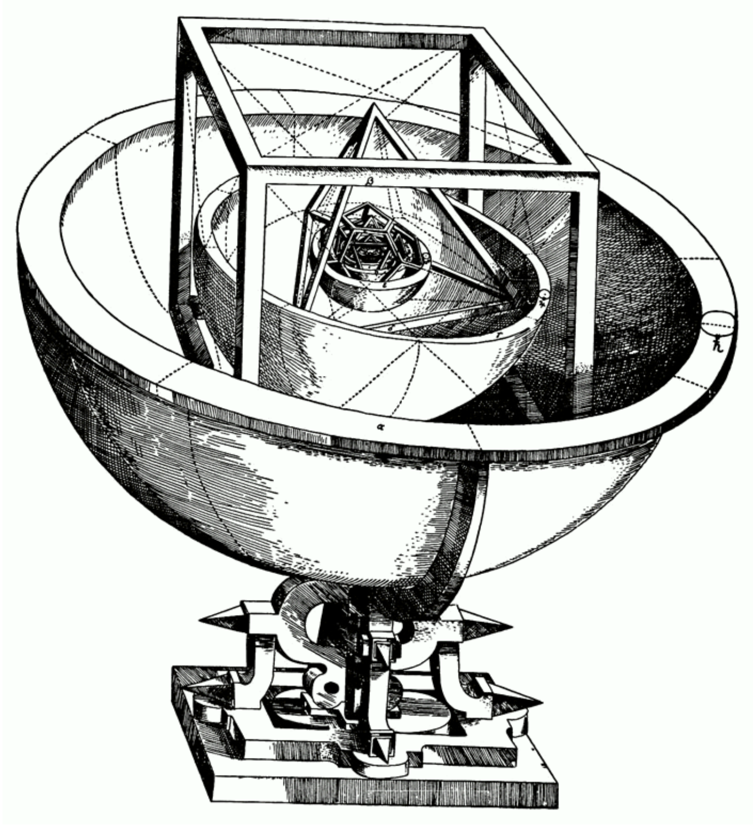
- **Even for higher-scale new physics: little (baby) hierarchy problem**
  (but reduces FCNC, EDM constraints)

Uniqueness or Environment

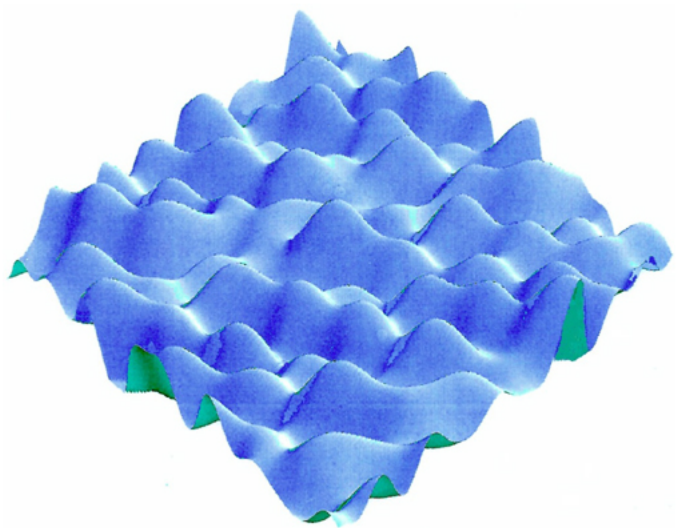
- **Gauge interactions: determined by symmetry**
  (but groups, representations, SSB)

- **Yukawa interactions: unconstrained, unless new symmetries/principles**
  (local, global, discrete, stringy)

- **The uniqueness paradigm: simple, unique, underlying theory**



Kepler's Mysterium Cosmographicum



- **The environmental paradigm**
  (cf., planetary orbits)
  - **No simple explanation of parameters**
  - **String landscape: may be $\gtrsim 10^{600}$ vacua (de Sitter?); no known selection principle**
  - **Subset habitable, with different groups, remnants, hierarchy mechanisms, parameters**
  - **Multiverse sampled by eternal inflation?**
  - **Environmental selection? (A word?)**

Minimality or Remnants

- **Bottom up: minimality often assumed**
- **Top down: new particles/interactions** (remnants) **often "slip through net"**
  - Z', vector fermions, extended Higgs, leptoquarks, diquarks; dark sectors

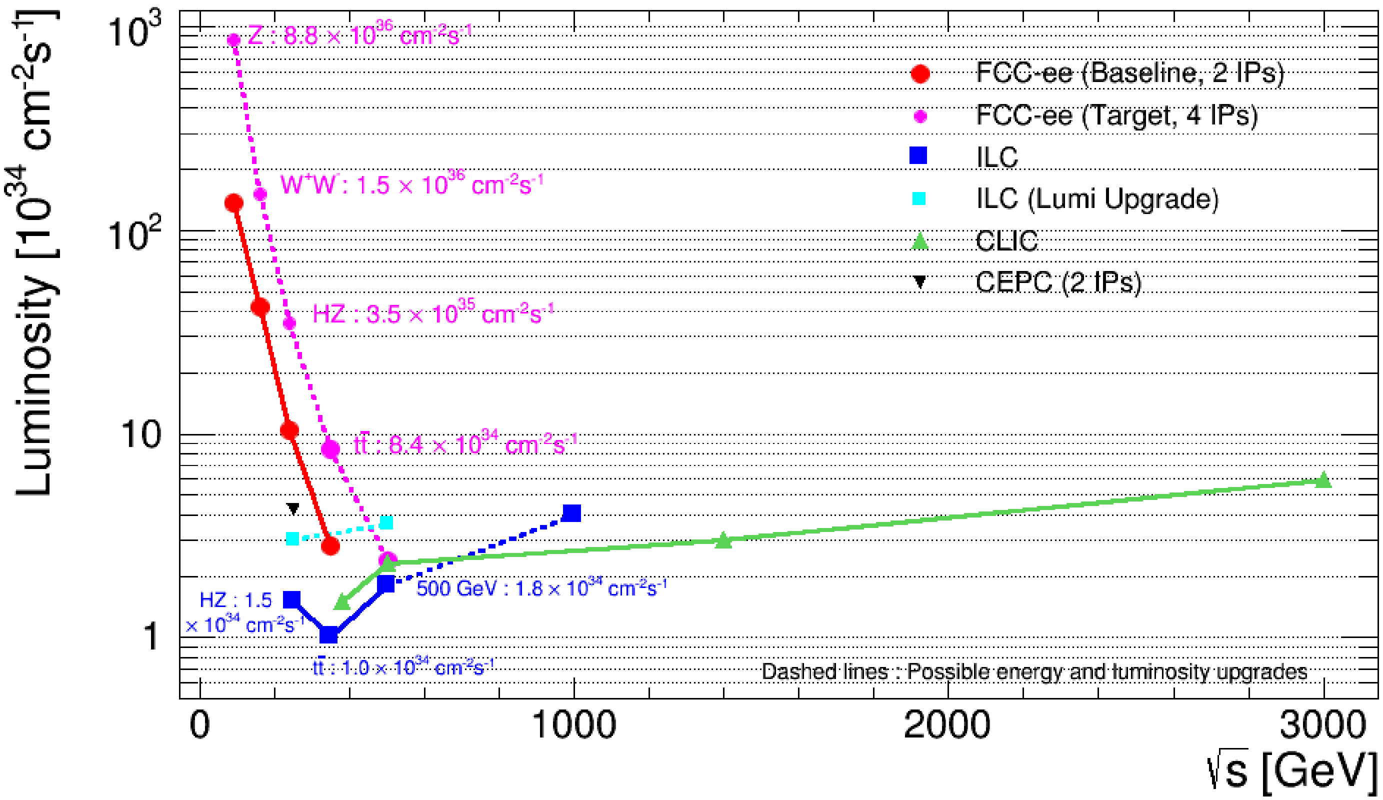
The Realizations

- **Strong dynamics at low scale** (composite Higgs, $\cdots$)
- **Low fundamental scale** (large or warped dimensions, low string scale)
- **Perturbative connection to high scale** (string, GUT)
  - Supersymmetry (nonminimal?), $\cdots$
  - Remnants?
  - Nothing
- **Multiverse?** (not exclusive)

Future Collider Proposals

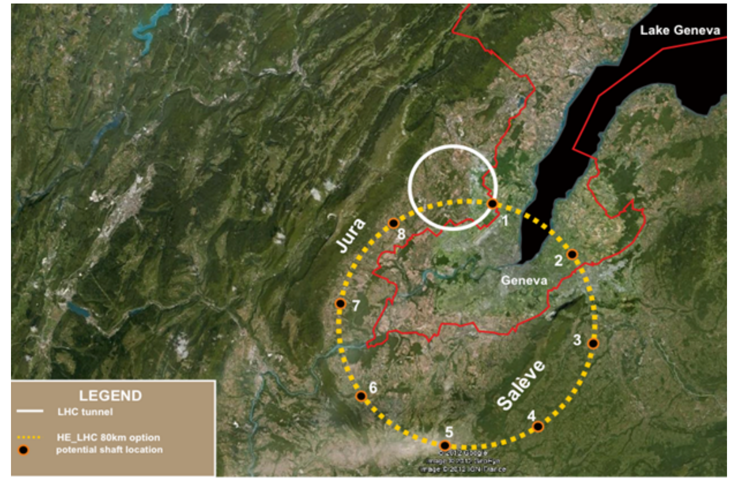
- **HL-LHC (CERN):** (pp, 14 TeV, 3000 fb^{-1})
- **ILC (Japan):** (e^+e^-; 250, 350, 500 GeV ($\longrightarrow$ 1 TeV),) ILC Higgs: 1310.0763
- **CLIC (CERN):** (e^+e^-; 350 GeV $\longrightarrow$ 3 TeV,) CLIC: 1209.2543, 1307.5288
- **CEPC (China):** (e^+e^-; 240 GeV,) CEPP: cepc.ihep.ac.cn
- **SPPC (China):** (pp, 100 TeV?)
- **FCC (CERN)**

The FCC-ee



Luminosity [10^{34} cm^{-2}s^{-1}]
10^3
10^2
10
1
0
1000
2000
3000
$\sqrt{s}$ [GeV]
Z : 8.8 × 10^{36} cm^{-2}s^{-1}
W^+W^- : 1.5 × 10^{36} cm^{-2}s^{-1}
HZ : 3.5 × 10^{35} cm^{-2}s^{-1}
$t\bar{t}$: 8.4 × 10^{34} cm^{-2}s^{-1}
HZ : 1.5 × 10^{34} cm^{-2}s^{-1}
$t\bar{t}$: 1.0 × 10^{34} cm^{-2}s^{-1}
500 GeV : 1.8 × 10^{34} cm^{-2}s^{-1}
FCC-ee (Baseline, 2 IPs)
FCC-ee (Target, 4 IPs)
ILC
ILC (Lumi Upgrade)
CLIC
CEPC (2 IPs)
Dashed lines : Possible energy and luminosity upgrades

- **FCC-ee (TLEP)**
- **$\sim$100 km**
- **e^+e^-: precision EW, Higgs, t, BSM**
- **90 (Z), 125 (H)?, 160 (WW), 240 (H), 350 ($t\bar{t}$) GeV**
- **$e^\pm$ polarization?**
- **$10^{12} - 10^{13}$ Z's (Tera-Z)**
  $2 \times 10^8\, WW$, $10^5\, H$, $10^6\, t\bar{t}$



- **FCC-hh (VHE-LHC)**
  - **pp: EWSB, BSM**
  - **2040-2050: 80-100 TeV**

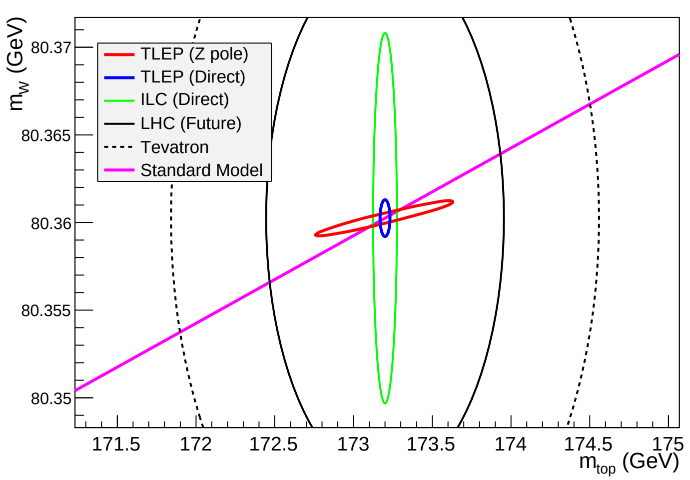
FCC-ee (TLEP): 1308.6176

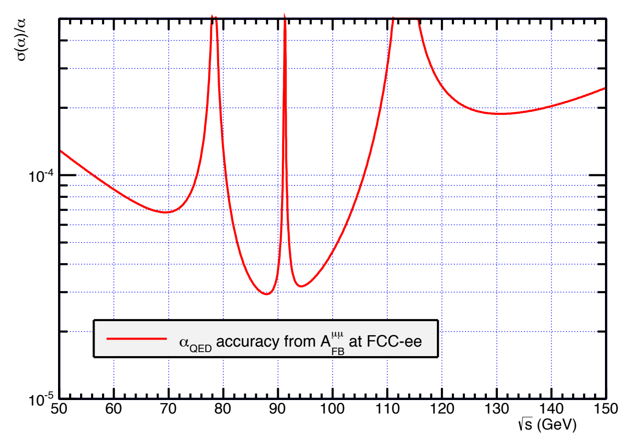
- **$10^{12} - 10^{13}$ Z's**
  (LEP: 1.7×10^7; SLC: 6×10^5, $P_{e^-} \gtrsim 0.75$)

- **Combine with WW and $t\bar{t}$ threshold scans**

- **Need significant improvement in theory calculations (3 loop)**

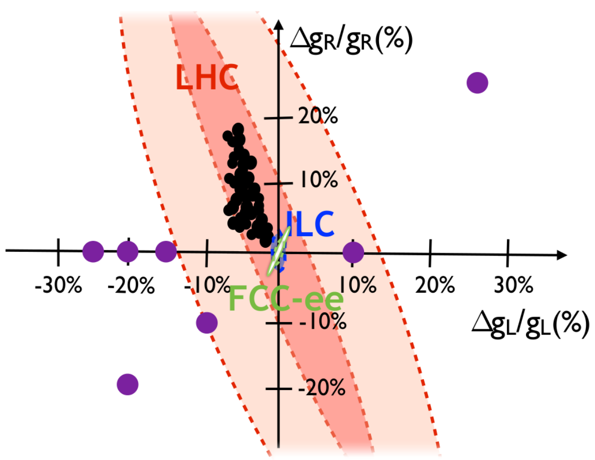
quantity	precision	current
M_Z	100 keV	2.1 MeV
Γ_Z	100 keV	2.3 MeV
$\sin^2 \hat{\theta}_W(M_Z^2)$	6×10^{-6}	5×10^{-5}
$\Delta\alpha(M_Z)/\alpha$	1.1×10^{-4}	3×10^{-5}
M_W	300 keV	15 MeV
$\alpha_s(M_Z)$	0.0001	0.0006
m_t	10 MeV	0.9 GeV
N_ν $(Z\gamma)$	0.001	0.008



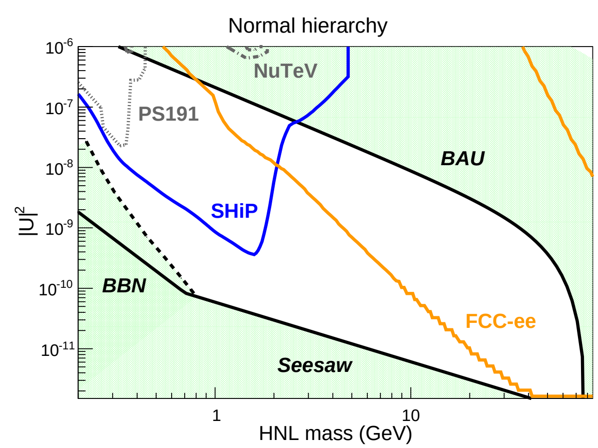


P. Janot: 1512.05544

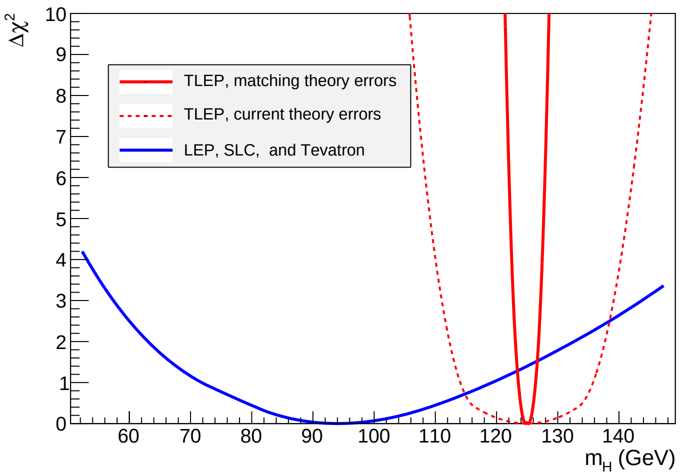
- Sensitive to $Z-Z'$, $W-W'$, $f-f'$ mixing (vector exotics, composite Higgs, $\cdots$); unitarity violation
- Rare/invisible decays: $Z, H \to$ dark matter; sterile ν; FCNC; universality violation
- Oblique corrections: Higgs; EWSB; chiral fermions; multiplet splitting
- Effective operators; triple gauge couplings

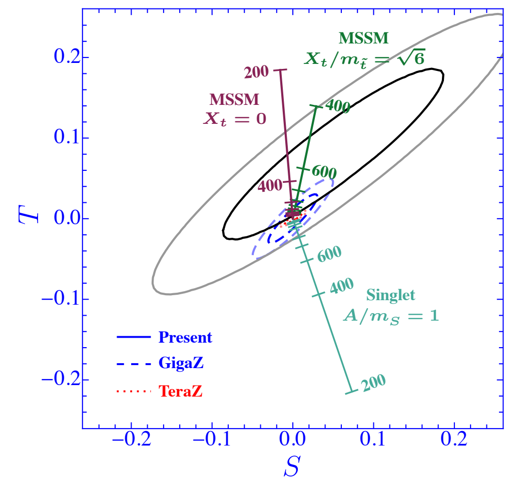


Barducci et al: 1504.05407

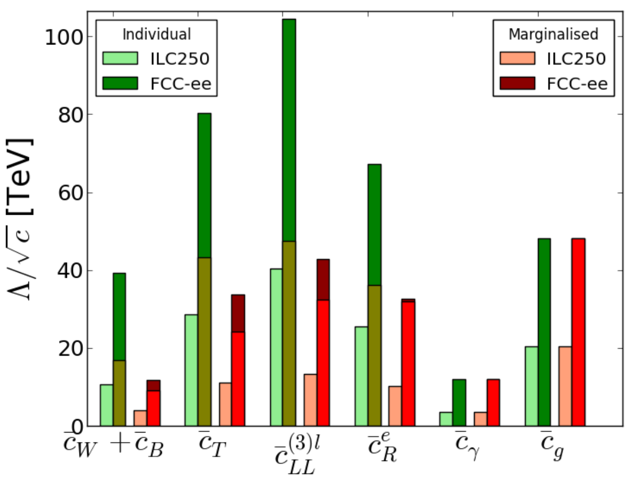


Blondel et al: 1411.5230

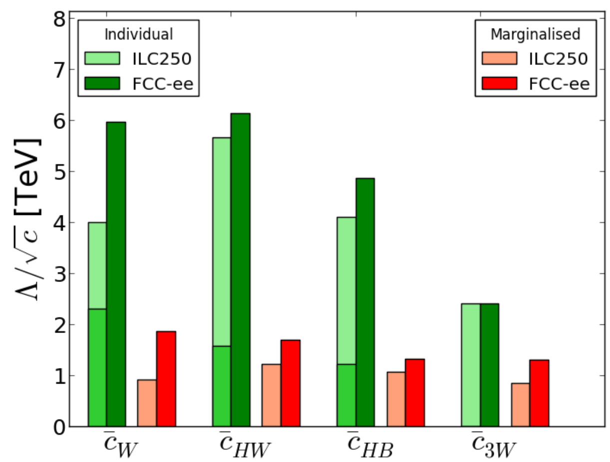




Henning ea, 1404.1058



Ellis, You: 1510.04561



Z-Pole and Higgs Factory Reach

- **Composite Higgs at scale f**

  $\kappa_{W,Z} = \sqrt{1 - \frac{v^2}{f^2}}, \; S \sim \frac{v^2}{4f^2}$

- **MSSM $\tilde{t}_L$**

  $\kappa_g - 1 \sim \frac{m_t^2}{4m_{\tilde{t}_L}^2}$

  $T \sim \frac{m_t^4}{16\pi s_W^2 M_W^2 m_{\tilde{t}_L}^2}$

Experiment	κ_Z (68%)	f (GeV)	κ_g (68%)	$m_{\tilde{t}_L}$ (GeV)
HL-LHC	3%	1.0 TeV	4%	430 GeV
ILC500	0.3%	3.1 TeV	1.6%	690 GeV
ILC500-up	0.2%	3.9 TeV	0.9%	910 GeV
CEPC	0.2%	3.9 TeV	0.9%	910 GeV
TLEP	0.1%	5.5 TeV	0.6%	1.1 GeV

Experiment	S (68%)	f (GeV)	T (68%)	$m_{\tilde{t}_L}$ (GeV)
ILC	0.012	1.1 TeV	0.015	890 GeV
CEPC (opt.)	0.02	880 GeV	0.016	870 GeV
CEPC (imp.)	0.014	1.0 TeV	0.011	1.1 GeV
TLEP-Z	0.013	1.1 TeV	0.012	1.0 TeV
TLEP-t	0.009	1.3 TeV	0.006	1.5 TeV

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- **P. Janot, Precision measurements of the top quark couplings at the FCC: 1510.09056**

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Conclusions

- **Standard Model is very successful, but complicated, fine-tuned**
- **Precision physics:** major role in establishing SM and restricting BSM
- **Major questions**
  - Naturalness or tuning
  - Uniqueness or environment
  - Minimality or remnants
  - Unification (strings/landscape, GUTs, SUSY, remnants) or strong coupling/compositeness
  - Dark matter/energy; vacuum stability; baryogenesis; ν mass
- **Signatures often similar** (e.g., 750 GeV diphoton)
- **The challenge: distinguishing** (multiple/complementary probes, effects)

- **Complementary probes**
  - e^+e^- **(precision Z-pole and above, Higgs factory)**
  - **Other precision and flavor physics ($g_\mu - 2$, rare decays/processes, heavy quark, neutrino)**
  - **Dark matter searches, cosmology**
  - **Energy frontier (LHC, pp at 100 TeV scale)**
- **The FCC-ee is especially promising**

Typical Stringy Effects

- Z' (or other gauge)
- **Extended Higgs/neutralino** (doublet, singlet)
- **Quasi-chiral exotics**
- **Leptoquark, diquark, $\not{R}_P$ couplings**
- **Family non-universality** (from different origins) (Yukawas, $U(1)'$)
- **Various ν mass mechanisms** (HDO: Majorana or Dirac; D (string) instantons: non-minimal seesaw, Weinberg op, Dirac, sterile)
- **(Quasi-)hidden sectors** (strong coupling? SUSY breaking? dark matter? random?); **may be portals** (exotics, Z', Higgs)

- *Perturbative* **global symmetries from anomalous** $U(1)'$
  (exponentially-suppressed breaking)

- **Nonstandard hypercharge embeddings/normalizations**

- **Fractionally charged color singlets (e.g.,** $\frac{1}{2}$**)**
  (confined?, stable relic? millicharged?)

- **Large/warped dimensions, low string scale**
  (TeV black holes, stringy resonances)

- **Axions, moduli, cosmic strings**

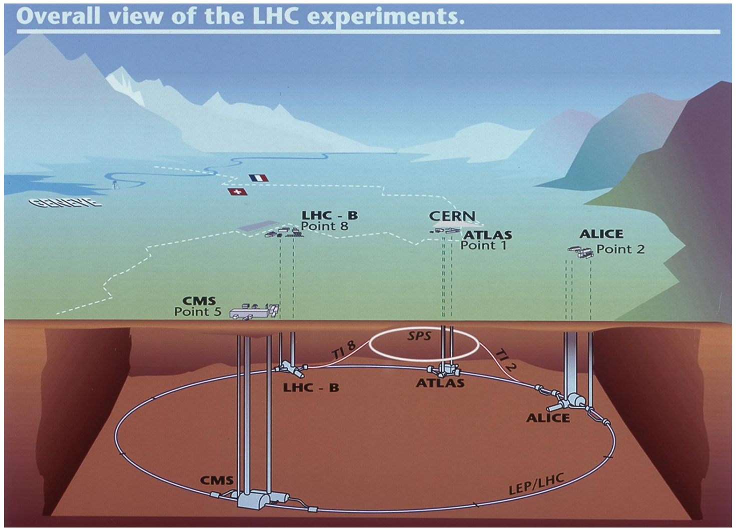
- **Time/space/environment-varying couplings**

- **LIV, VEP (speeds, decays, [oscillations] of HE** γ, e**, gravity waves, [**ν**'s])**

Future/Proposed Precision Program at Colliders

Large Hadron Collider (LHC), CERN

- pp: Higgs, EW, QCD, BSM, $\cdots$
- 2009-2012: 7-8 TeV, 30 fb^{-1}
- 2015-2022: 13-14 TeV, 300 fb^{-1}
- 2025-2035: HL-LHC, 14 TeV, 3000 fb^{-1}
- 33 TeV HE-LHC?



International Linear Collider (ILC), Japan

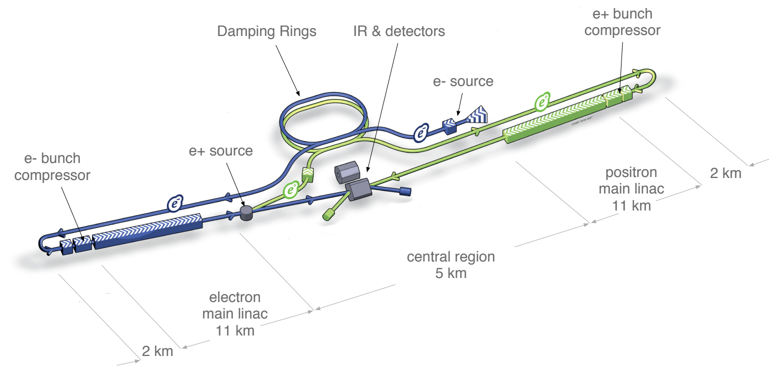
- e^+e^-: Higgs factory, Z-pole, WW, $t\bar{t}$, Z', $\cdots$

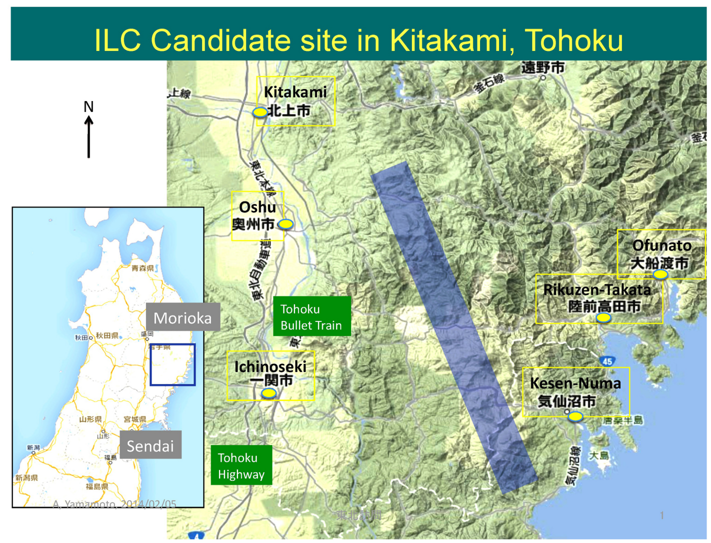
- 31 km ($\rightarrow$ 50)

- 250, 350, 500 GeV ($\rightarrow$ 1 TeV)

- $P_{e^-} \sim$ 80% ($P_{e^+} \sim$ 50-60%)

- Z-pole (Giga-Z)





ILC TDR: www.linearcollider.org/ILC/Publications/Technical-Design-Report

ILC Higgs: 1310.0763

Compact Linear Collider (CLIC), CERN

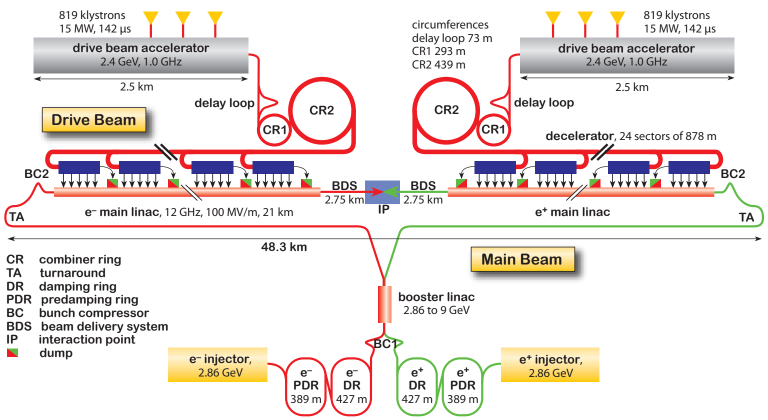


Fig. 3.1: Overview of the CLIC layout at $\sqrt{s} = 3$ TeV.

- e^+e^-: **Higgs, $t\bar{t}$, BSM**
- **Two beam acceleration**
- **48 km**
- ~ 2030: **350 GeV $\rightarrow$ 3 TeV**
- **Polarized e^- (e^+?)**

CLIC CDR: clic-study.web.cern.ch/content/conceptual-design-report

CLIC: 1209.2543, 1307.5288

Circular Electron Positron Collider (CEPC), China

Figure 3.3: Illustration of the CEPC-SPPC ring sited in Qinghuangdao. The small circle is 50 km, and the big one 100 km. Which one will be chosen depends on the funding scenario.

- e^+e^-: Higgs factory, Z, WW, Z', $\cdots$
- 50 or 100 km
- 240 GeV (H)
- Z-pole ($10^{10} - 10^{11}$ Z's)
- Super pp Collider, (SPPC)
  - pp: BSM, naturalness, EWBG, DM
  - 100-140 TeV

CEPP: cepc.ihep.ac.cn