XXXV International School "Francesco Romano"
on Nuclear, Subnuclear and Astroparticle Physics

UNIVERSITY OF COPENHAGEN

Future Lepton Colliders

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Preliminaries

- These lectures will invariable be somewhat biased towards the FCC-ee e^+e^- collider
  - For about 40 years, there have been plans for a next generation high-energy e^+e^- collider
    - For many years, it was thought that such a collider would be linear: ILC, CLIC
    - This changed with the discovery in 2012 of the *light* 125-GeV Higgs boson

      ⇒ The Higgs boson came within reach at a circular collider
  - I have been involved in the FCC-ee project from even before it was called FCC-ee
  - From the official kick-off of the FCC project in February 2014, the FCC-ee project has been gradually gathered more and more momentum

First Look at the Physics Case of TLEP
The TLEP Design Study Working Group
arXiv:1308.6176v3 [hep-ex] 11 Dec 2013

ESPP 2020 deliberations

An **electron-positron Higgs factory is the highest-priority next collider**.

Europe, together with its international partners, should investigate the **technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV** and with an **electron-positron Higgs and electroweak factory as a possible first stage**.

ESPP 2026 process

- Overwhelming support (21/24 CERN MS HEP communities) in favour of the integrated FCC-ee/hh programme

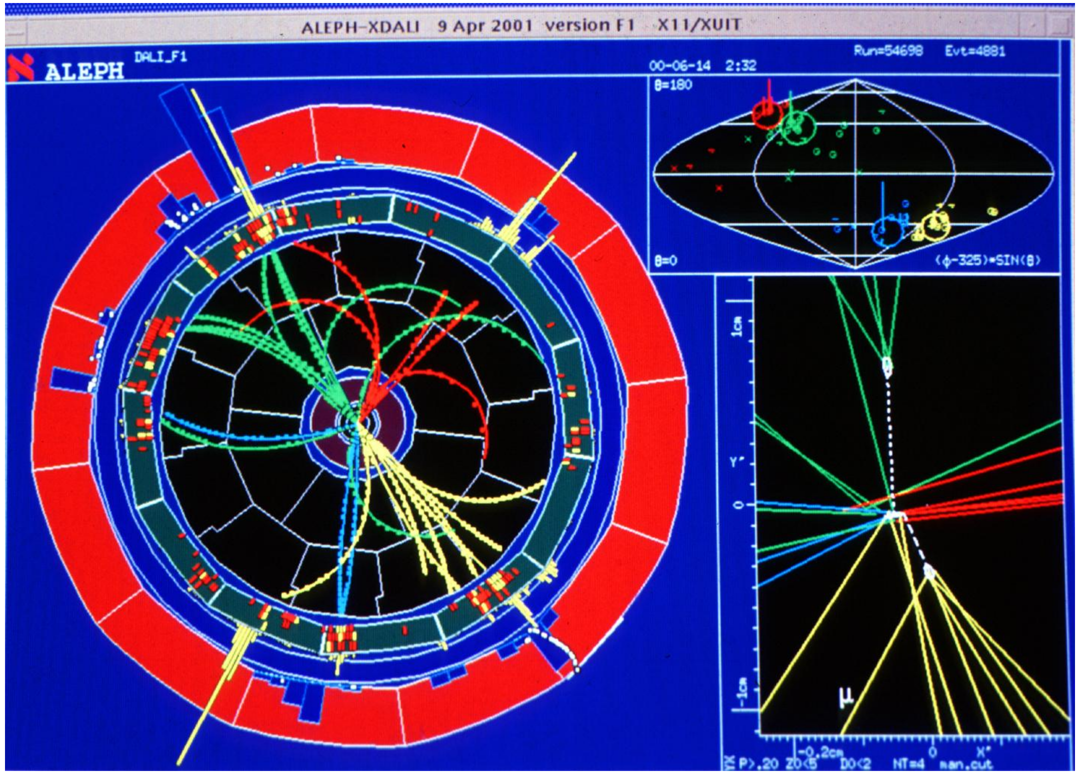
K.Jakobs, Summary talk, ESPP Open Symposiu, Venice, Jun. 2025

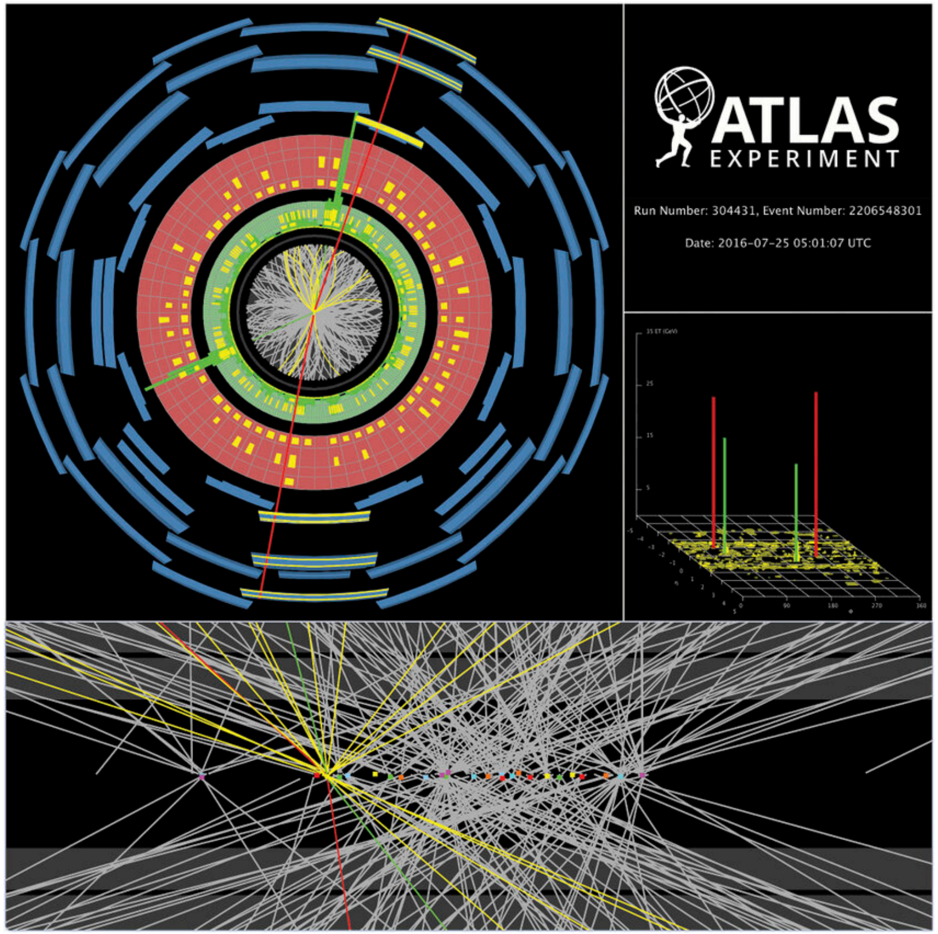
- Besides, I am really not an expert on muon colliders …

Outline

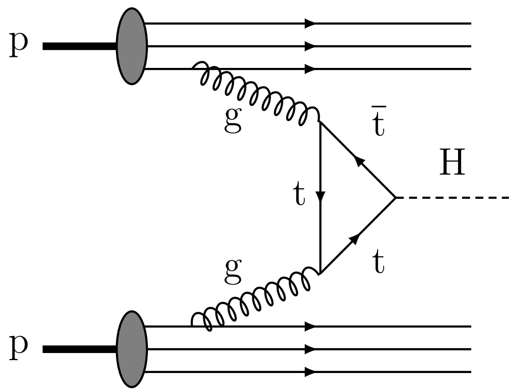
- Lepton Collisions vs. Proton Colissions
- The Rise of Precision
- Precision Higgs Physics
- Electroweak Precision Physcis – Tera-Z
- Tera-Z: Flavour Physics and Direct Discoveries
- CLIC: High Energy e^+e^- Physics
- Detectors for e^+e^- Collisions
- Muon Colliders
- Main Points

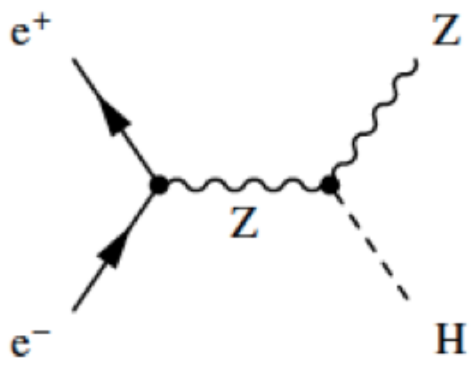
Lepton Collisions vs. proton Collisions





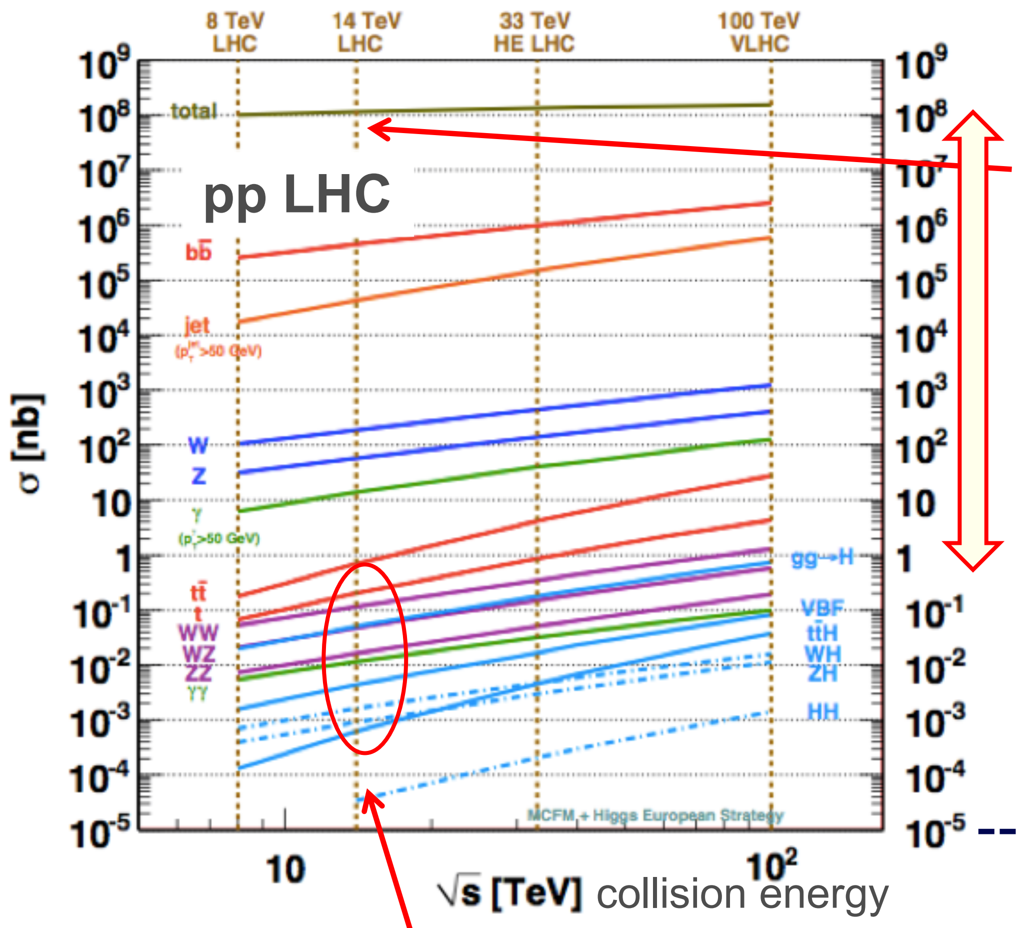
pp collisions vs. e^+e^- collisions





p-p collisions	e^+e^- collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	e^+/e^- are point-like → Initial state well defined (E, **p**), polarisation → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	Clean experimental environment → Trigger-less readout → Low radiation levels
High cross-sections for colored-states	Superior sensitivity for electro-weak states
High-energy circular pp colliders feasible	- At lower energies ($\lesssim$ 350 GeV) , circular e^+e^- colliders can deliver very large luminosities. - Higher energy e^+e^- requires linear collider.

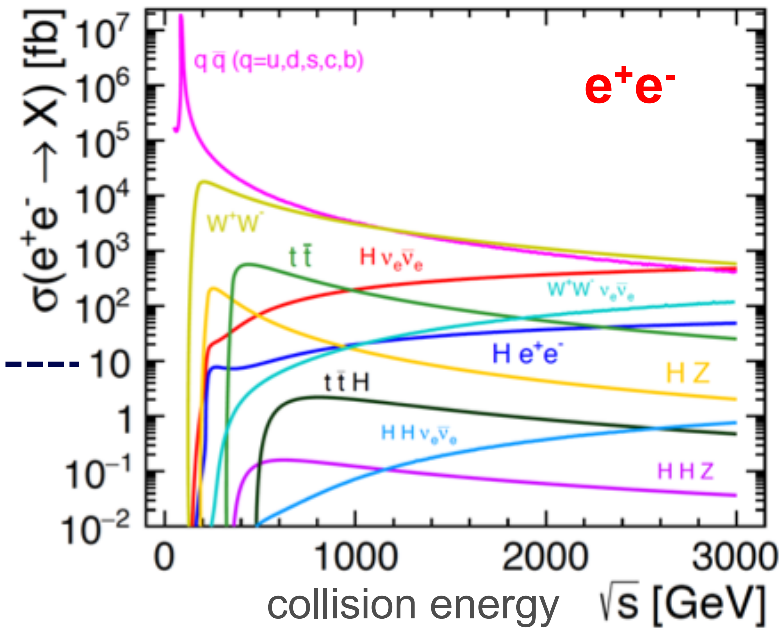
pp collisions vs. e^+e^- collisions



LHC total cross section factor > 100 million !!

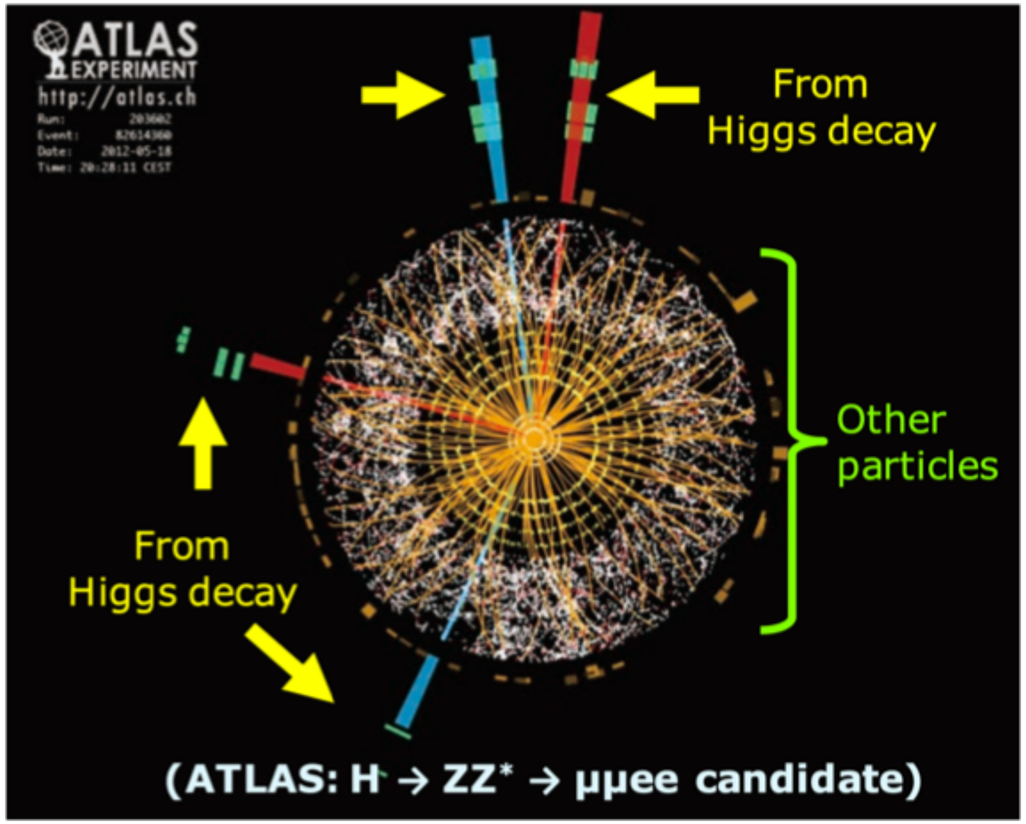
At LHC, much of the interesting physics needs to be found among a huge number of collisions

e^+e^- events are "clean"

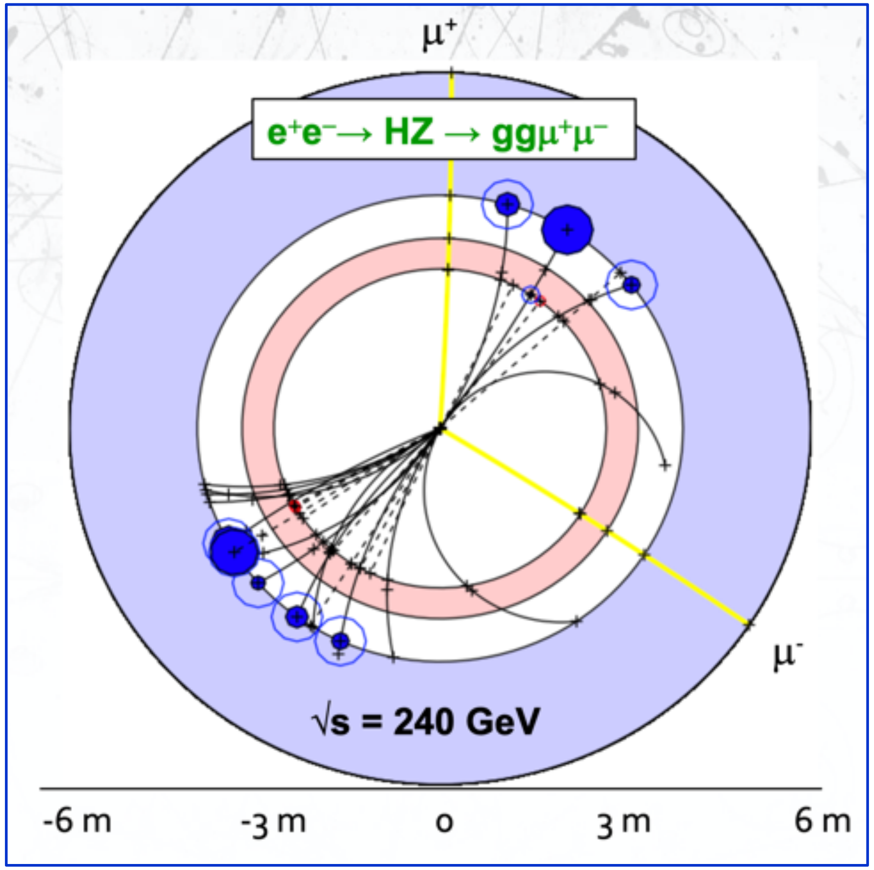


pp collisions vs. e^+e^- collisions

Higgs event in pp



Higgs event in e^+e^-

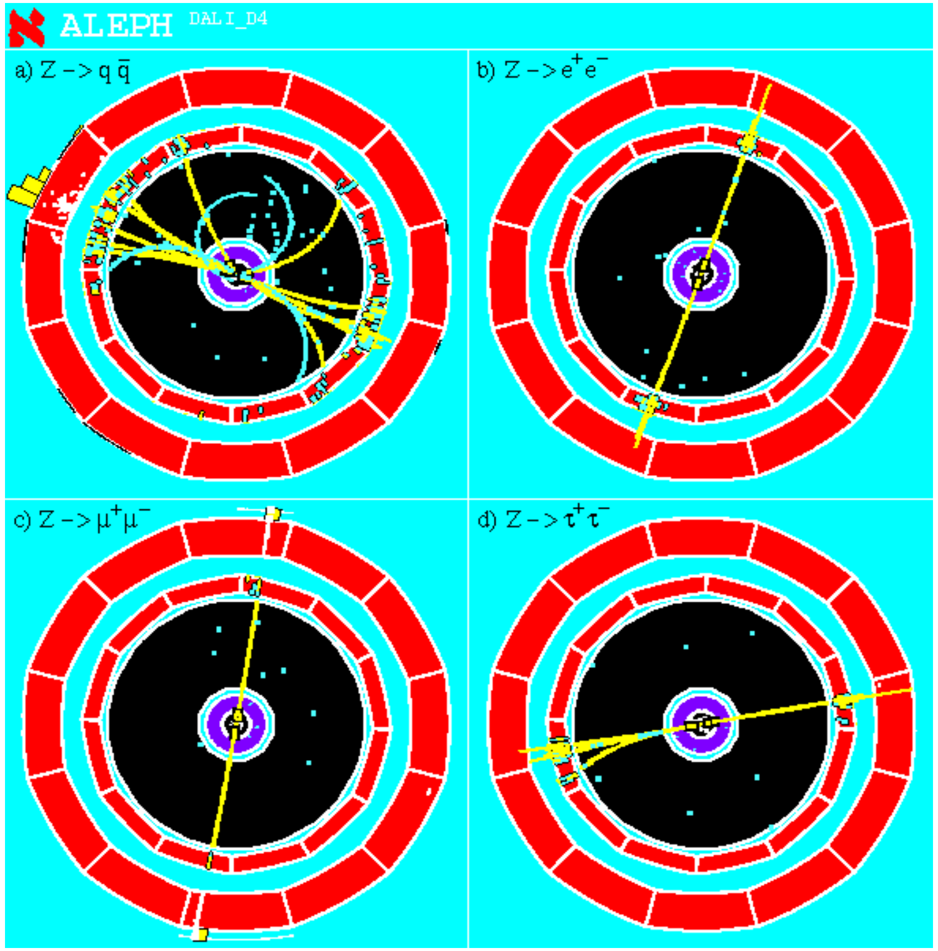


pp: look for striking signal in large background

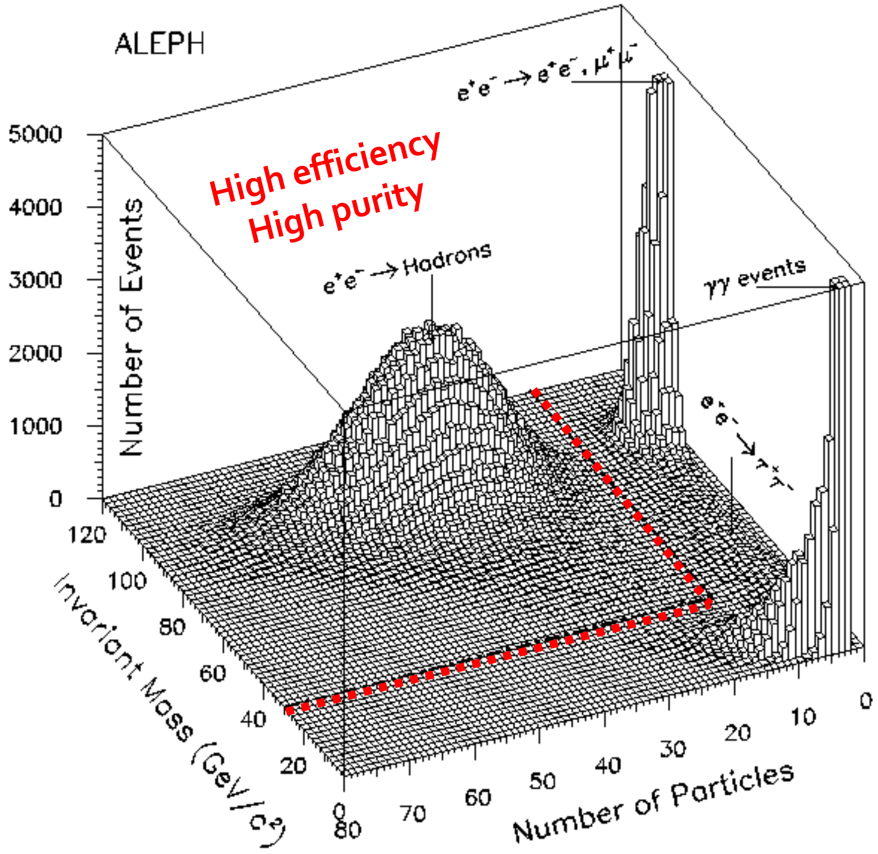
e^+e^-: detect everything; measure precisely

e⁺e⁻ collisions

- No pile-up collisions, no underlying events
  - Final state is clean and cozy, triggering is easy (100% efficient)



Analysis is a waking dream



arXiv:hep-ex/0509008v3

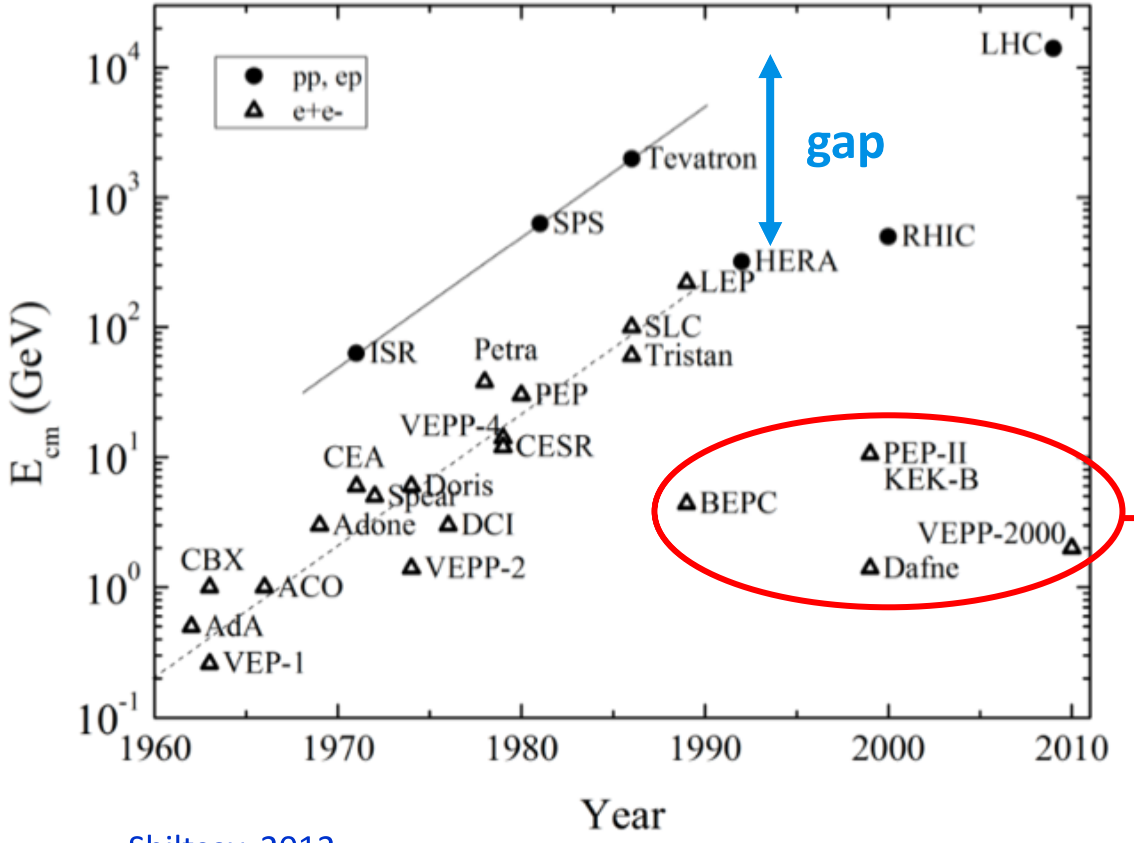
  - No huge QCD cross section: All events are signal

A look in the rear mirror

- Historic overview over important discoveries

Year	Discovery	Experiment	√s [GeV]	Observation
1974	c quark (m~1.5 GeV)	e^+e^- ring (SLAC) Fixed target (BNL)	3.1 8	$\sigma(e^+e^- \to J/\Psi)$ $J/\Psi \to \mu^+\mu^-$
1975	τ lepton (m=1.777 GeV)	e^+e^- ring (SPEAR/SLAC)	8	$e^+e^- \to \tau^+\tau^-$ $e^+\mu^-$ events
1977	b quark (m~4.5 GeV)	Fixed target (FNAL)	25	$\Upsilon \to \mu^+\mu^-$
1979	gluon (m = 0)	e^+e^- ring (PETRA/DESY)	30	$e^+e^- \to qqg$ Three-jet events
1983	W, Z (m ~ 80, 91 GeV)	pp ring (SPS/CERN)	900	$W \to \ell\nu$ $Z \to \ell^+\ell^-$
1989	Three neutrino generations	e^+e^- ring (LEP/CERN)	91	Z-boson lineshape *measurement*
1995	t quark (m=173 GeV)	pp ring (Tevatron/FNAL)	1960	Two semileptonic t-quark decays
2012	Higgs boson (m=125 GeV)	pp ring (LHC/CERN)	8000	$H \to \gamma\gamma$, $H \to Z^*Z \to 4\ell$

Colliders over time, pp and e^+e^-

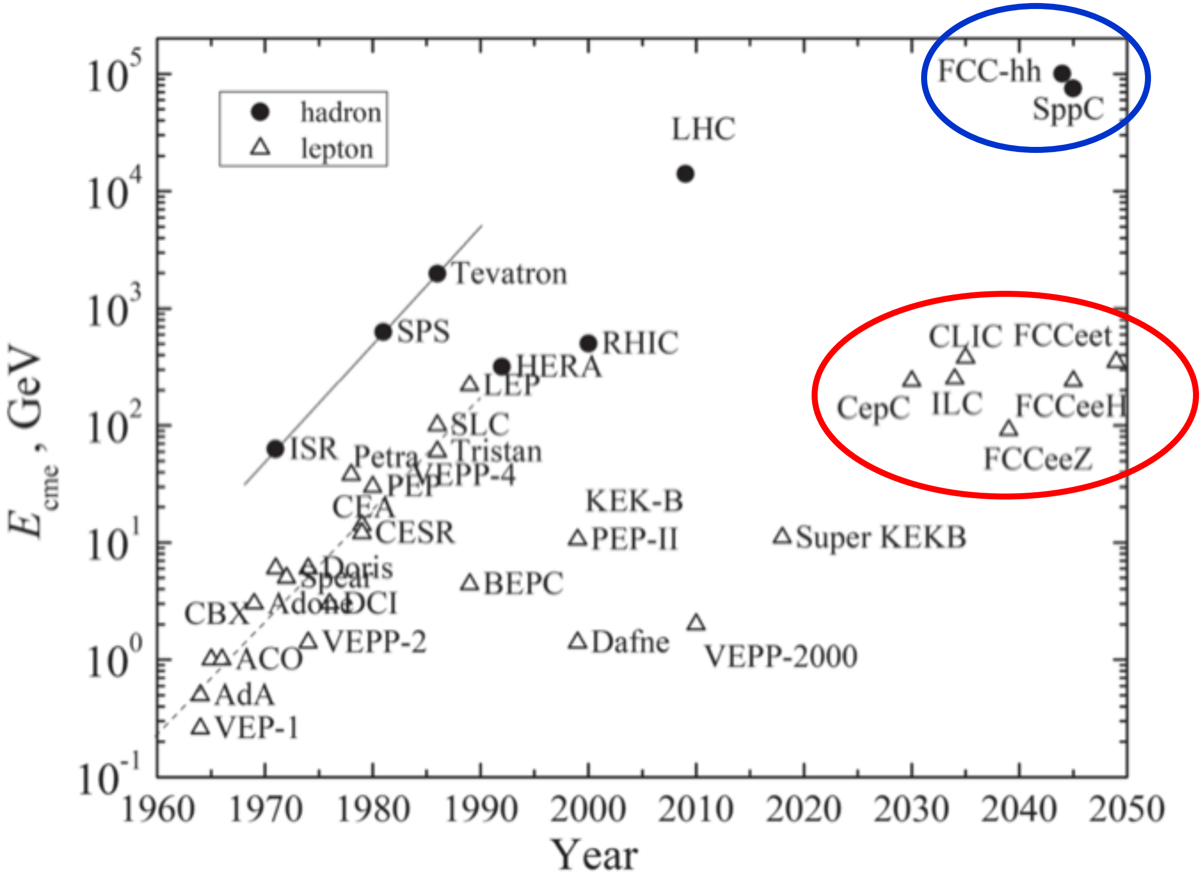


Shiltsev, 2012

- Historically there has been a **gap** in energy reach between pp and e^+e^- colliders
  - Synchrotron radiation; electron is light
    - Energy lost per turn grows as $\boxed{\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4}$

      e.g., 3.5 GeV per turn at LEP2 for E_{BEAM} = 104 GeV
- Since the 1990s, highly productive e^+e^- colliders ("factories") have focused on precise exploration of rare phenomena at low energies

Including proposed pp and e^+e^- colliders



V.Shiltsev, F.Zimmermann, 2021

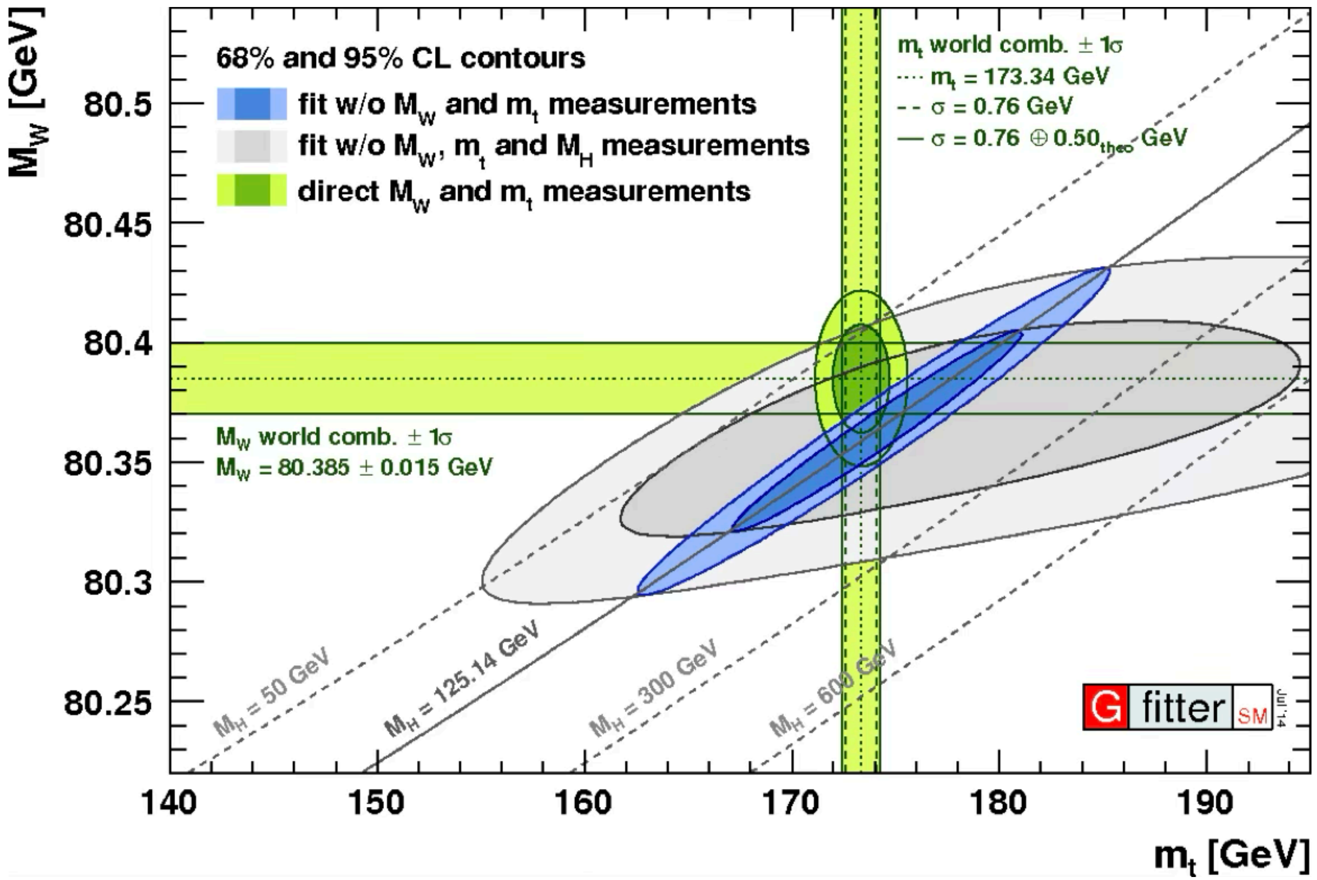
100 TeV pp colliders

e^+e^- Higgs factories
- also electroweak and top factories

Linear:
- CLIC, ILC, LCF, C^3

Circular:
- FCC-ee, CEPC

The Rise of Precision



LEP and the Rise of Precision

- 27 km circumference e^+e^- collider : "LEP tunnel", now "LHC tunnel"
- 1989-1995: Operation as *Z factory* at $\sqrt{s} \simeq 91$ GeV (17×10^6 Z decays)
  - 1989: Only three species of light, active neutrinos

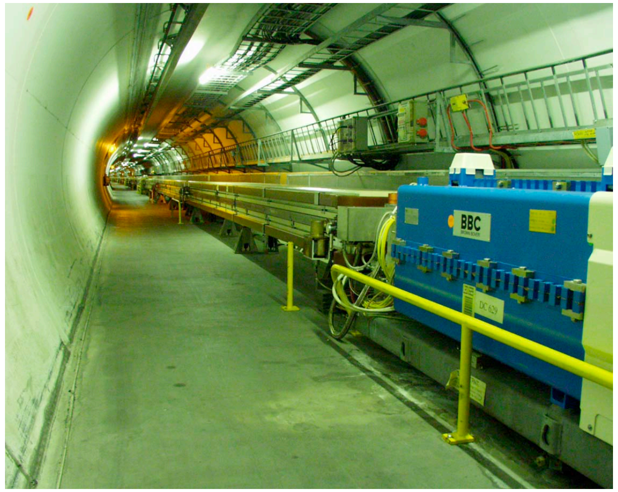
    $\boxed{\nu_e, \nu_\mu, \text{and } \nu_\tau}$

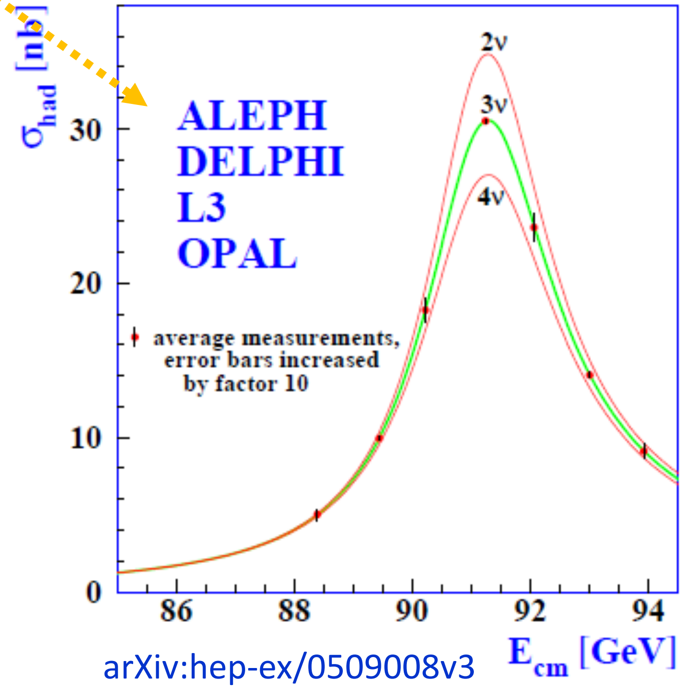
    - $e^+e^- \to Z \to$ hadrons at LEP1; measurement of the Z boson lineshape
  - After 5 years at LEP1: per-mille level precision

$$\left.\begin{aligned} N_\nu &= 2.984 \pm 0.008 \\ \Gamma_Z &= 2495.2 \pm 2.3 \text{ MeV} \\ m_Z &= 91187.5 \pm 2.1 \text{ MeV} \end{aligned}\right\} \text{no updates since LEP}$$

$$\alpha_s = 0.1190 \pm 0.0025$$

- 1996-2000: Operation at WW threshold and above (4×10^4 WW events)
  - W mass, Higgs search



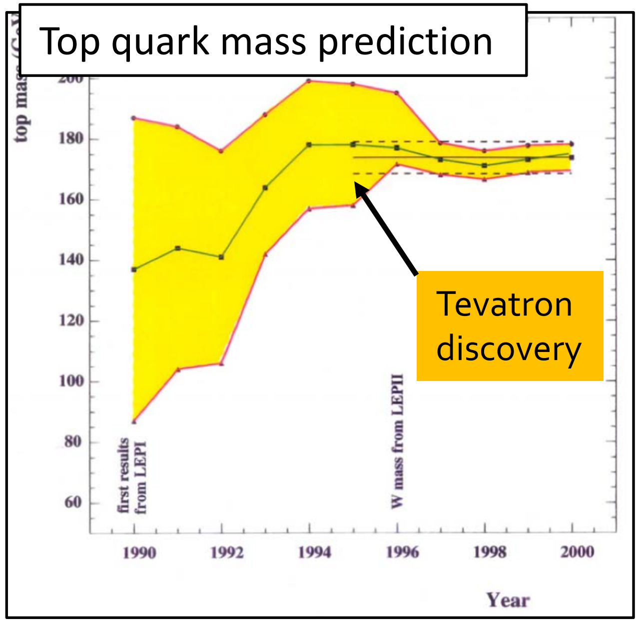


arXiv:hep-ex/0509008v3

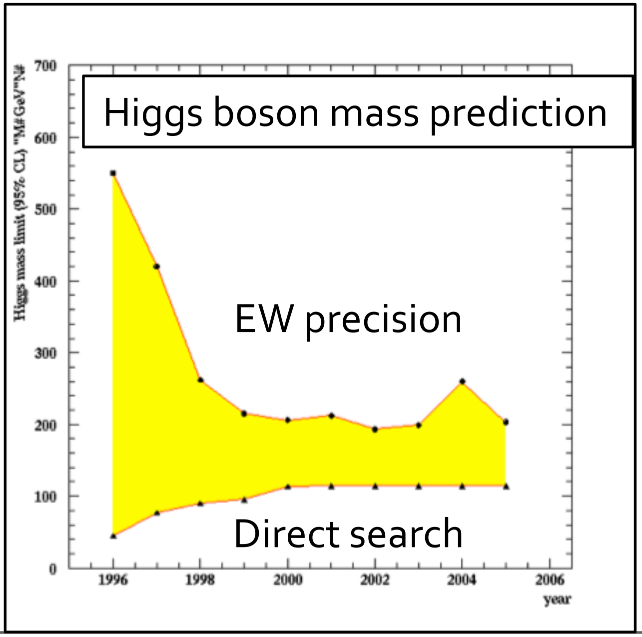
Herwig Schopper, CERN Director 1981-1988, in CERN Courier:
LEP was a transformative machine
"It changed high-energy physics from a 10% to a 1% science."

Indirect evidence from Precision Measurements

- Top quark
  - 1990-1994: Mass predicted from quantum loops
    - m_{top}(pred.) = 178.0 ± 10 GeV
  - 1995: Discovered at the Tevatron (DØ, CDF)
    - Today: m_{top}(obs.) = 172.52 ± 0.33 GeV



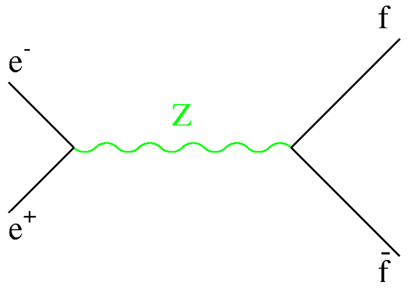
- Higgs boson
  - 1996-2011: Mass predicted from quantum loops
    - m_{Higgs}(pred.) = 98^{+25}_{-21} GeV
  - 2012: Discovery at the LHC (ATLAS, CMS)
    - Today: m_{Higgs}(obs.) = 125.11 ± 0.11 GeV



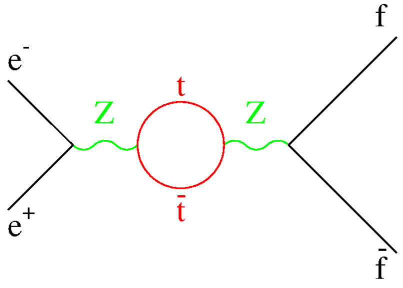
- Lesson:
  - Precision measurements interpreted via quantum loop corrections can give strong constraints on particles at higher masses than what can be directly probed!

Why precision measurements are interesting

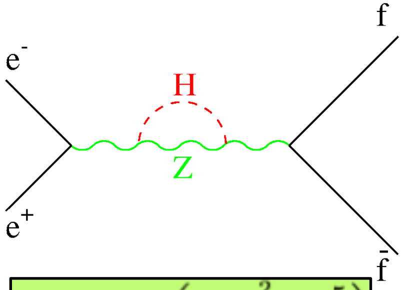
- Electroweak observables can be calculated / predicted with precision
  - They are sensitive to heavier particles through quantum corrections



Tree level



$$\boxed{0.002 \times \frac{m_t^2}{m_W^2} \simeq 1\%}$$



$$\boxed{-0.0006 \times \left(\ln \frac{m_H^2}{m_W^2} - \frac{5}{6}\right)}$$

[small correction]

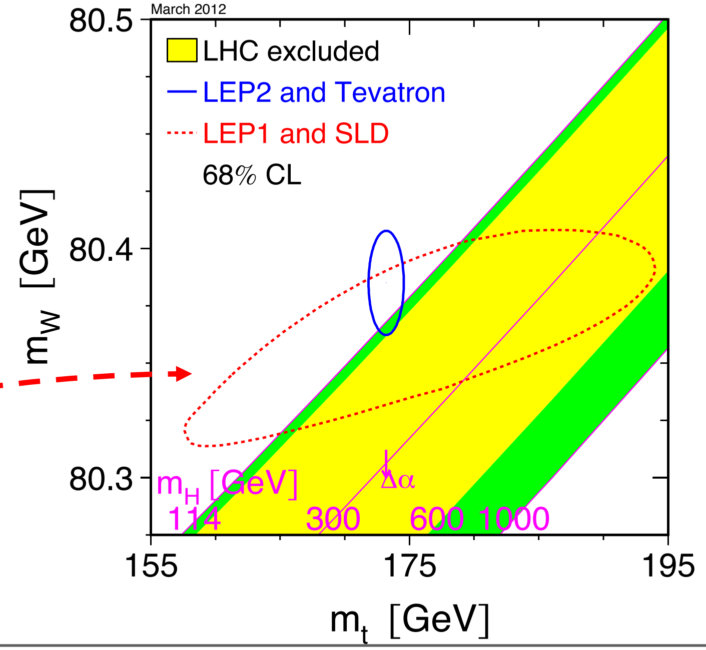
  - Example: $\Gamma_Z \rightarrow \Gamma_Z \times (1+\Delta\rho)$

$$\boxed{\Delta\rho = 0.0020 \times \frac{m_t^2}{m_W^2} - 0.0006 \times \left(\ln \frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \ldots}$$

  - Similarly, $m^2_W = m^2_Z \cos^2\theta_W^{eff} (1+\Delta\rho)$

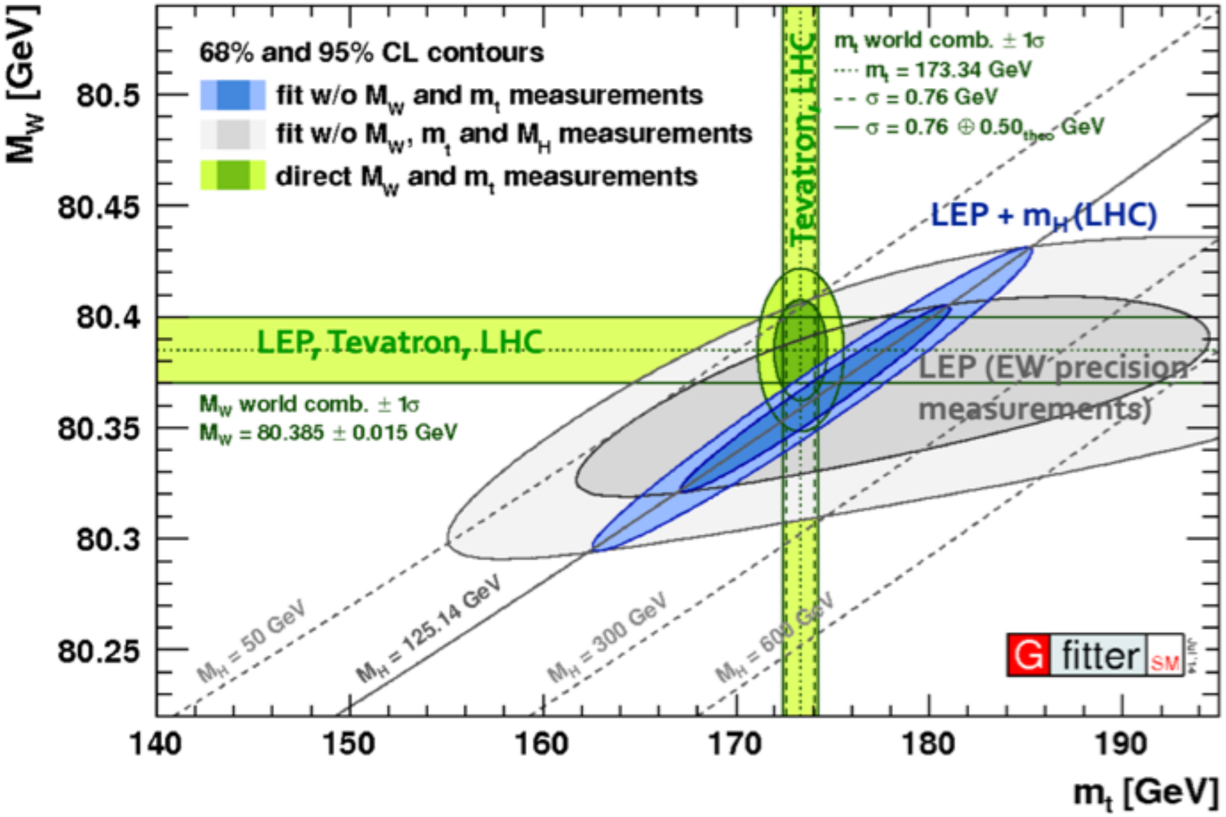
    ($\sin^2\theta_W^{eff}$ from, e.g., asymmetries)

  - Precict m_W and m_{top} from Z measurements



Precision Measurements

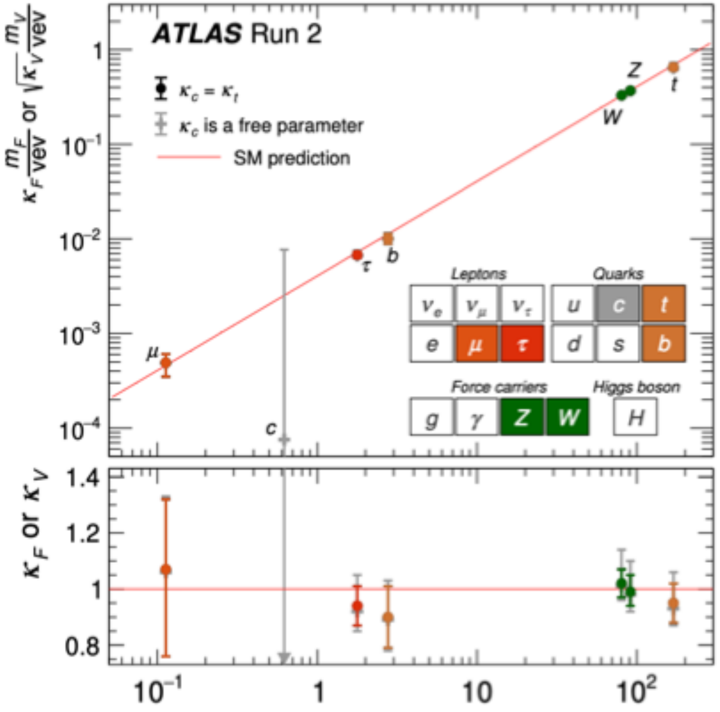
- With m_{top}, m_W and m_H known, the Standard Model has nowhere to go



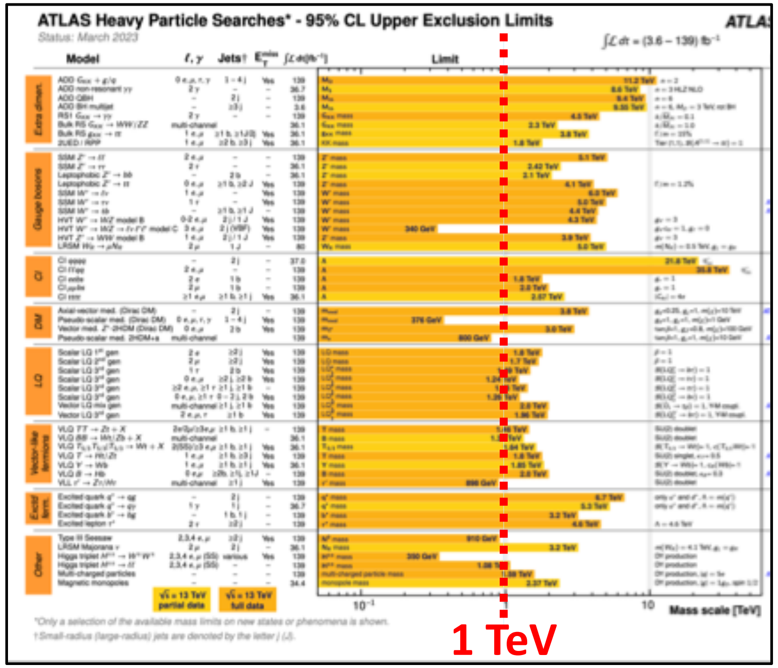
- Within current precision, direct and indirect constraints are consistent
  - No evidence for the need for BSM physics
- But what if measurements precisions were improved ?
  - Strong incentive to significantly improve the precision of all measurement

The LHC Legacy (so far)

LHC = Higgs + Nothing*)



[ATLAS Collab.]

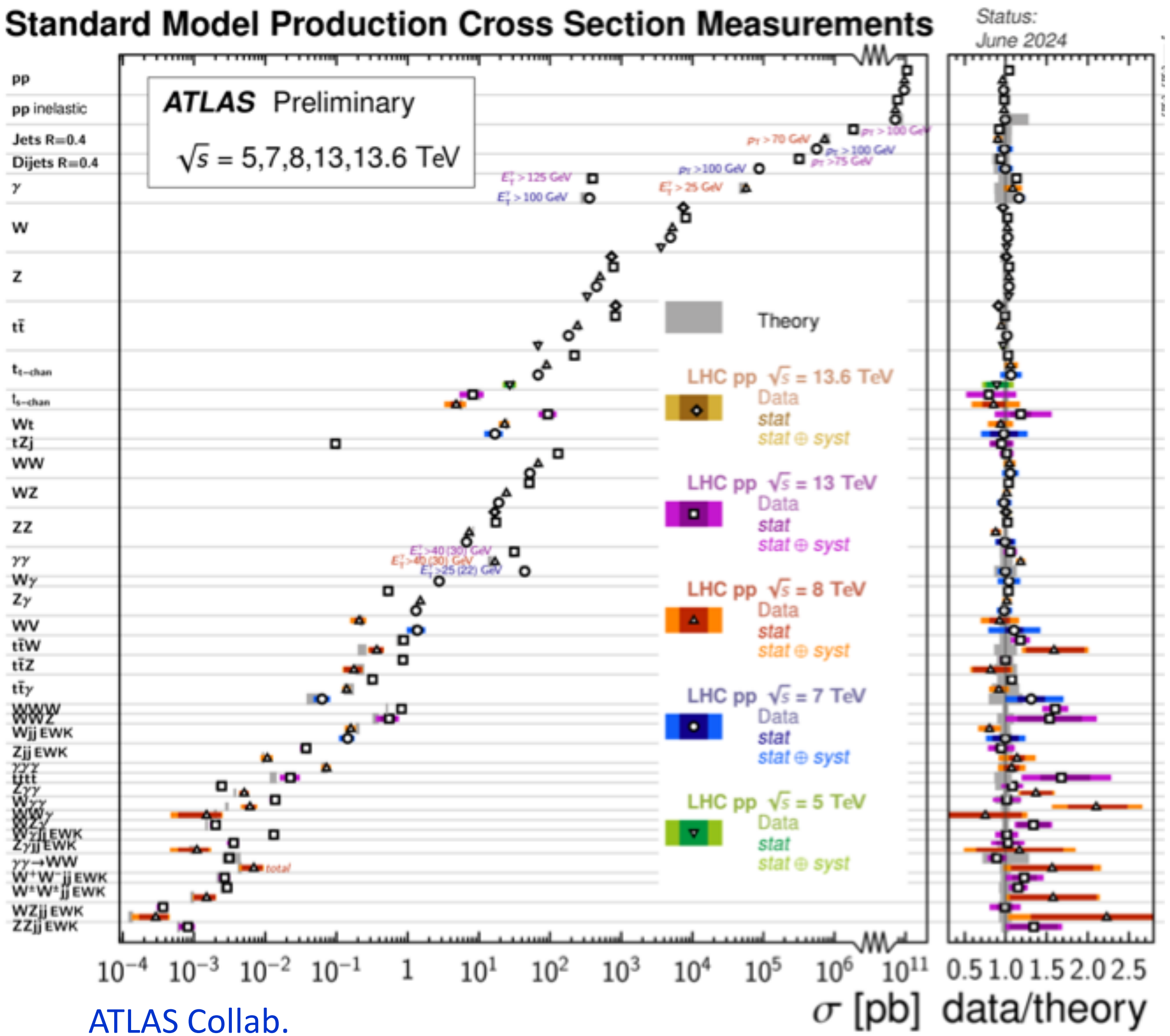


[ATLAS Collab.]

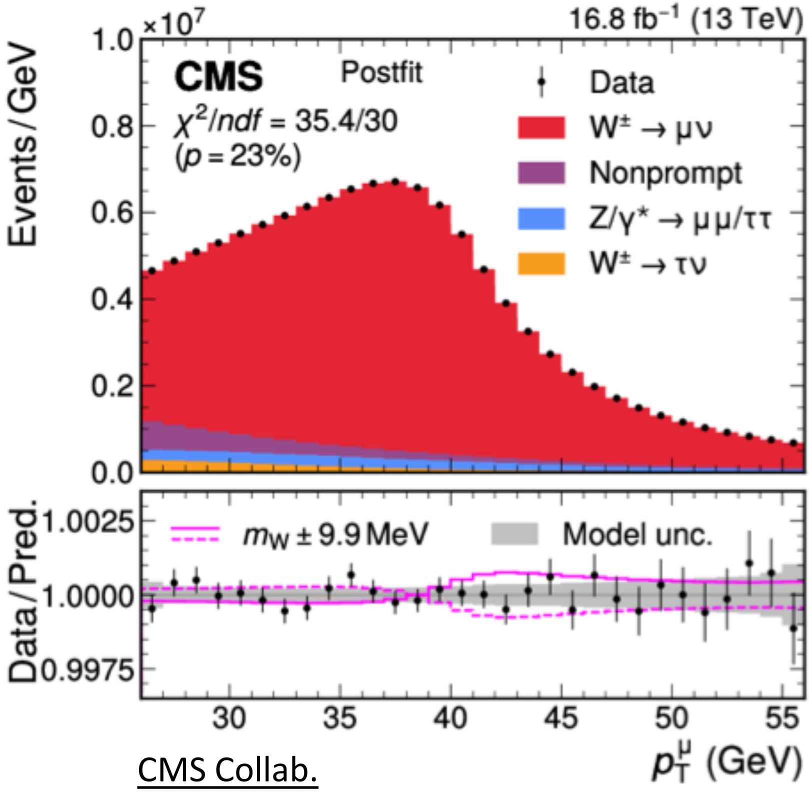
*) Actually, a lot progress in our understanding of the SM:
1) Improved measurements of SM processes; 2) Precise measurements in flavour physics; 3) New frontiers in heavy-ion studies.

The LHC Legacy (so far)

- Thanks to a firm control of EXP & TH systematic uncertainties, the LHC has become a precision machine.



[ATLAS Collab.]



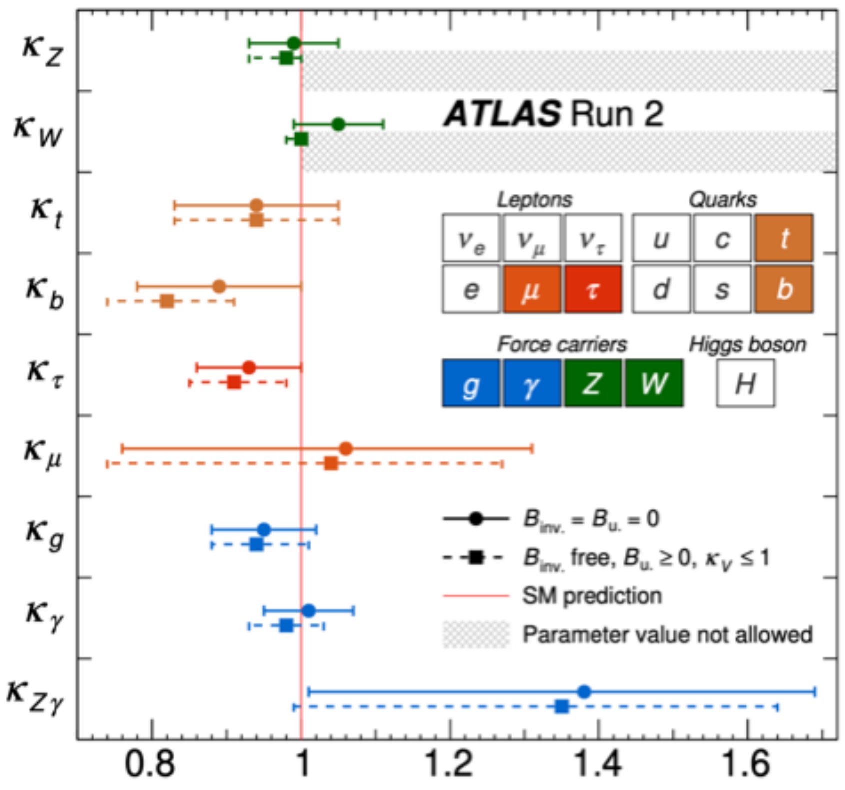
[CMS Collab.]

m_W = 80 360.2 ± 9.9 MeV

Better by factor 3 relative to LEP average

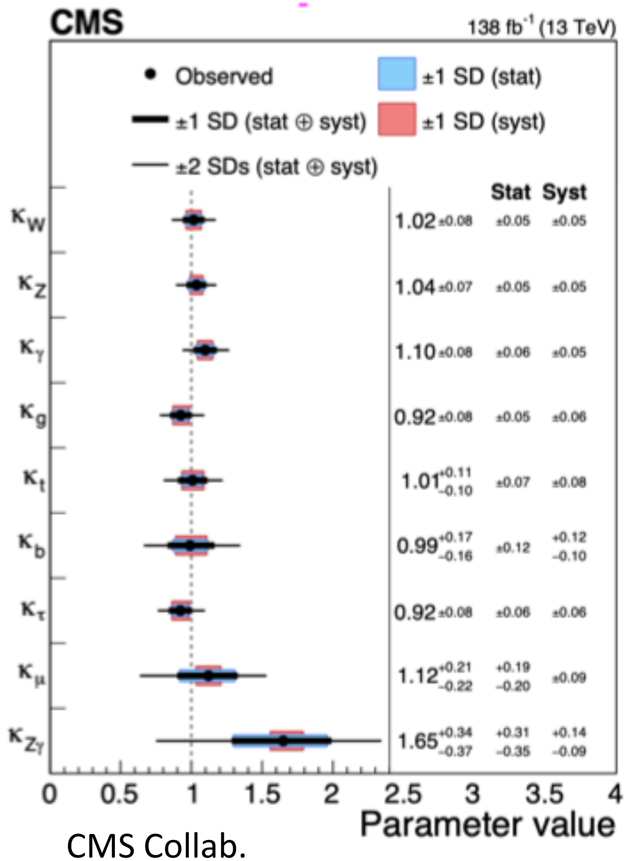
Higgs couplings @ LHC and projections for HL-LHC

ATLAS, '22



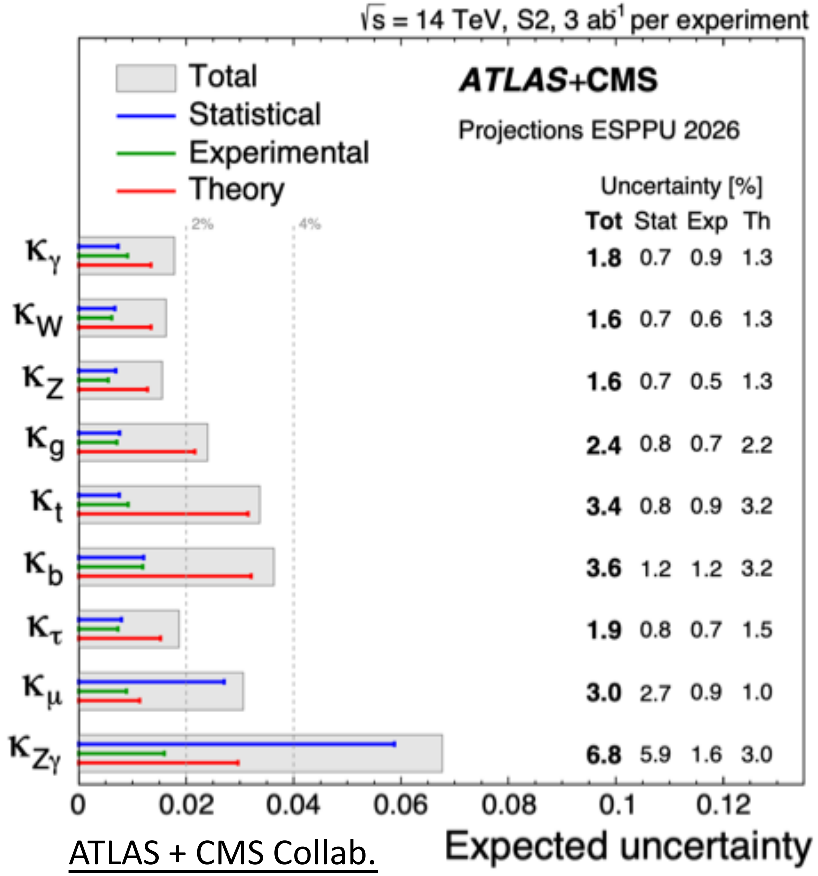
ATLAS Collab.

CMS, '22



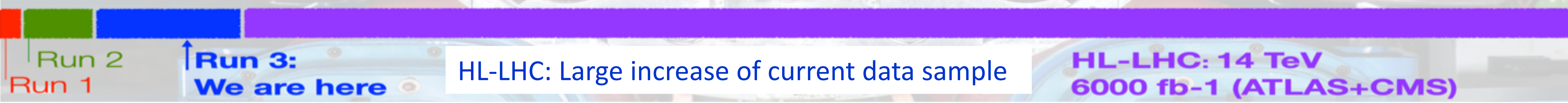
CMS Collab.

ATLAS + CMS projection, full HL-LHC



ATLAS + CMS Collab.

Current $\mathcal{O}$(10%) level → $\mathcal{O}$(few %) level



Precision Higgs physics – The need for a Higgs Factory

- The Higgs boson is different from all other SM particles (the only scalar)
  - May possibly open a window to ***new physics*** *?*
  - Study precisely its properties to look for possible deviations from SM predictions
- The (HL-)LHC is already a *"Higgs factory"*
  - Fabulous statistics: > 10^8 Higgs bosons will be produced at HL-LHC
  - Main challenge is backgrounds: Many decay modes are hard to identify
  - Expected ultimate HL-LHC precisions at the *few percent level*
- Is this precision good enough to make a "discovery" ?
- Higgs couplings are sensitive to New Physics (NP)
  - Expected deviations from SM coupling strengths depend on NP scale:

An e^+e^- Higgs factory identified as highest-priority next collider, by the European Strategy Update 2020 and by the US P5 process 2023

$$\frac{g_{HXX}}{g_{HXX}^{SM}} \approx 1 + \delta \times \left(\frac{1\ \mathrm{TeV}}{\Lambda_{\mathrm{NP}}}\right)^2$$

with δ =

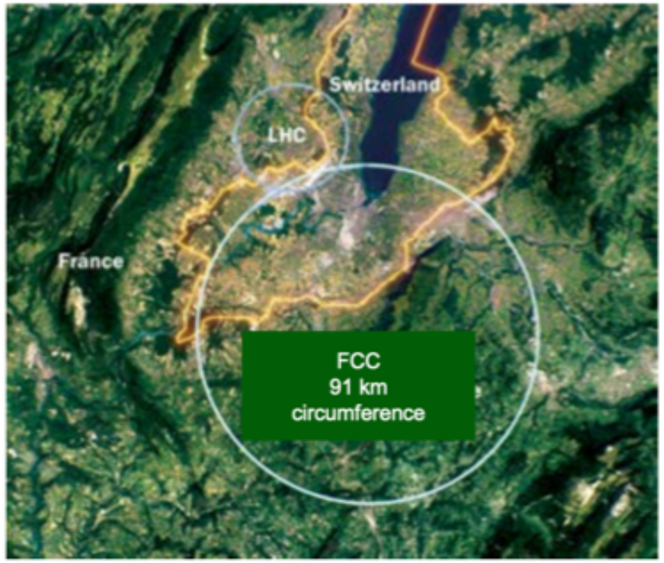
Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

arxiv:1301.8361

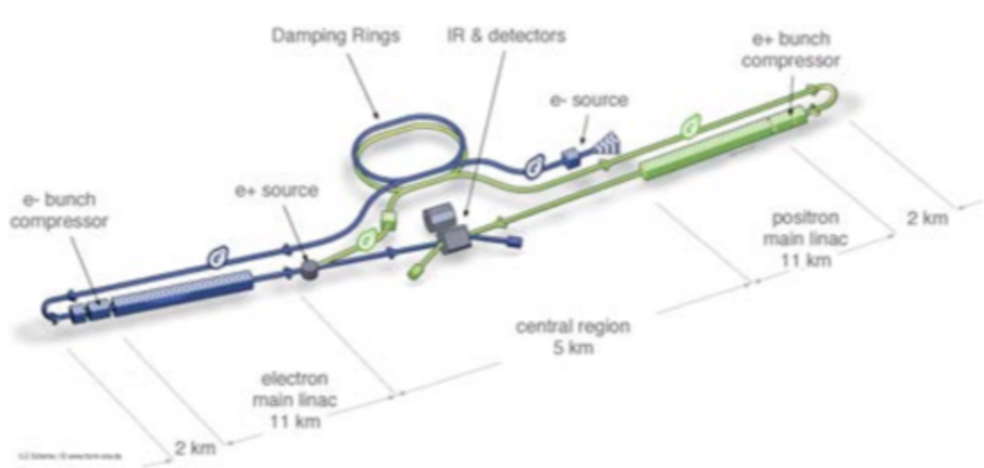
- Need a <u>*minimum*</u> of 1% precision on couplings for a 5σ discovery if Λ_{NP} = 1 TeV
  - And better for heavier New Physics

Proposed e^+e^- Higgs factories (at CERN)

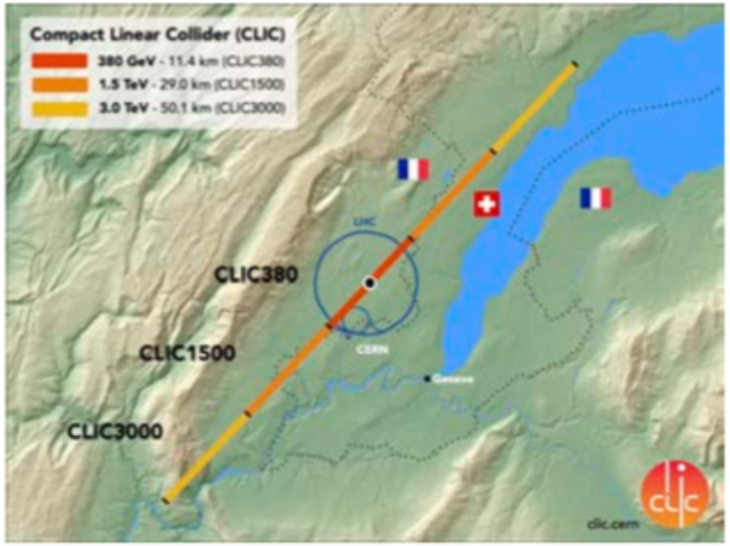
FCC-ee (e^+e^-, circular, 91 – 365 GeV)



LCF (e^+e^-, linear, 91 – 240, 550 GeV)



CLIC (e^+e^-, linear, 380 GeV, 1.5 TeV)



Circular

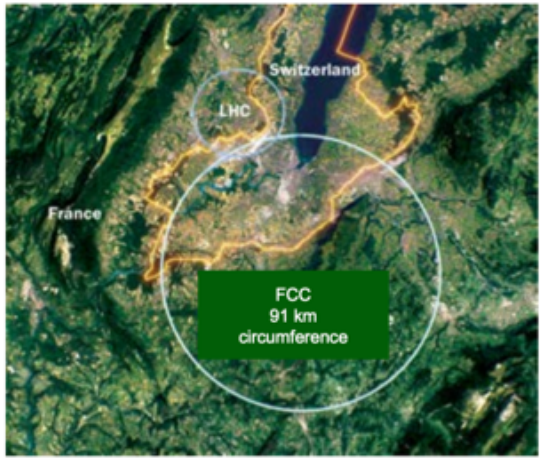
Beam goes in circle
- Reused many times for higher luminosity
- Synchrotron radiation limits energy reach
- Non-destructive focussing, moderate collision-energy dispersion

Linear

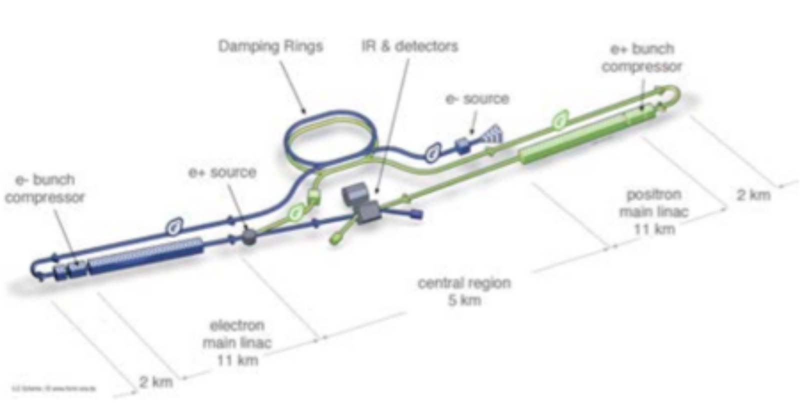
One pass only
- Lower luminosity
- Avoids synchrotron radiation – *can* go to higher energies
- Extreme focussing – large collision energy dispersion

Proposed e^+e^- Higgs factories (at CERN)

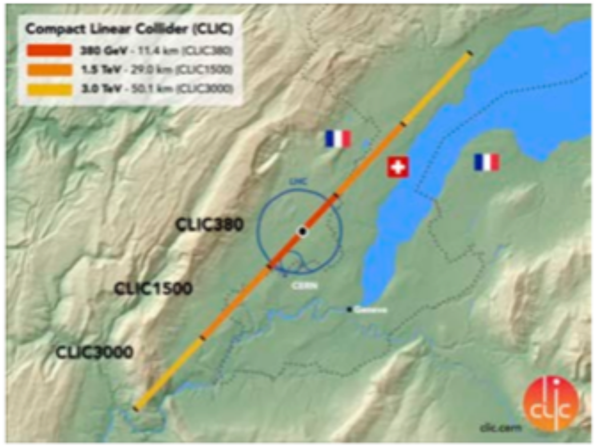
FCC-ee (e^+e^-, circular, 91 – 365 GeV)



LCF (e^+e^-, linear, 91 – 240, 550 GeV)

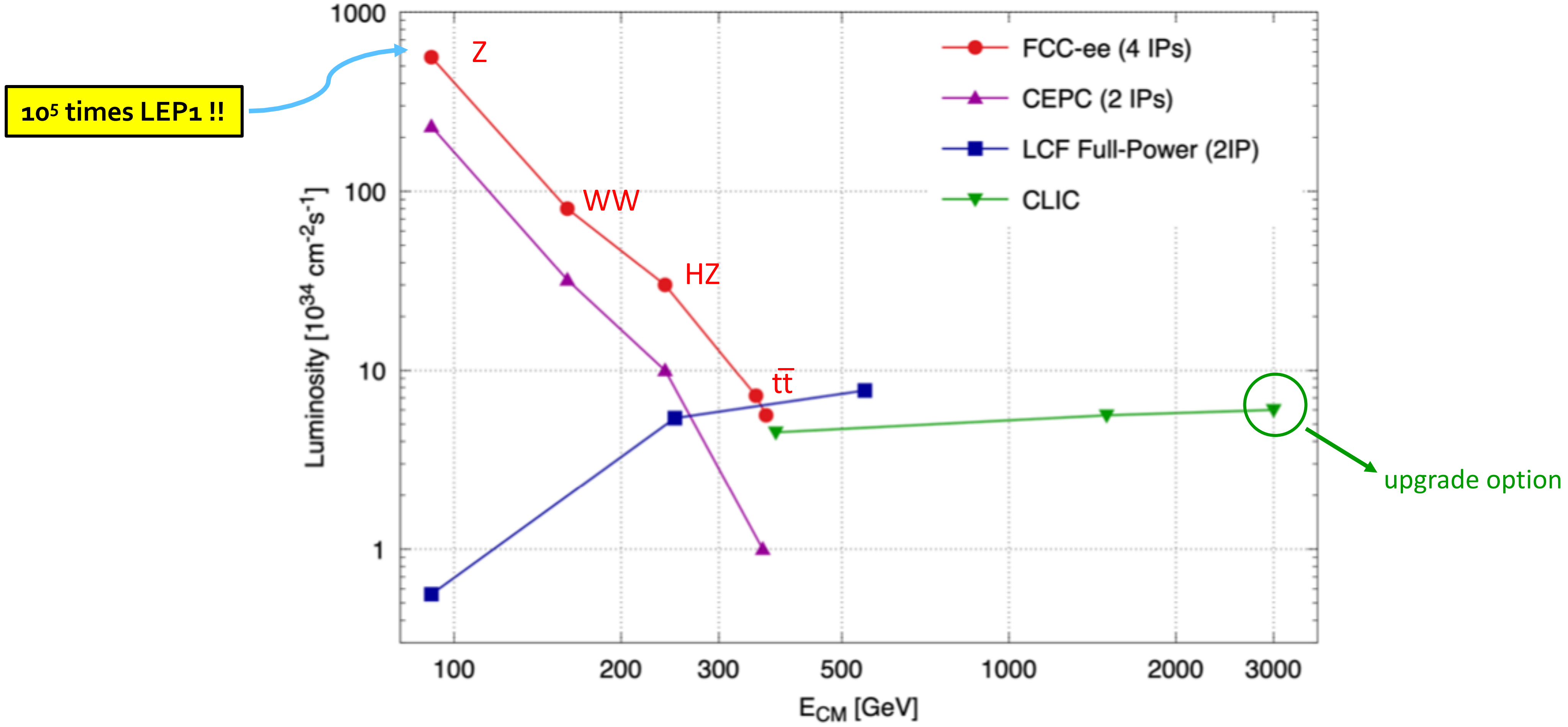


CLIC (e^+e^-, linear, 380 GeV, 1.5 TeV)



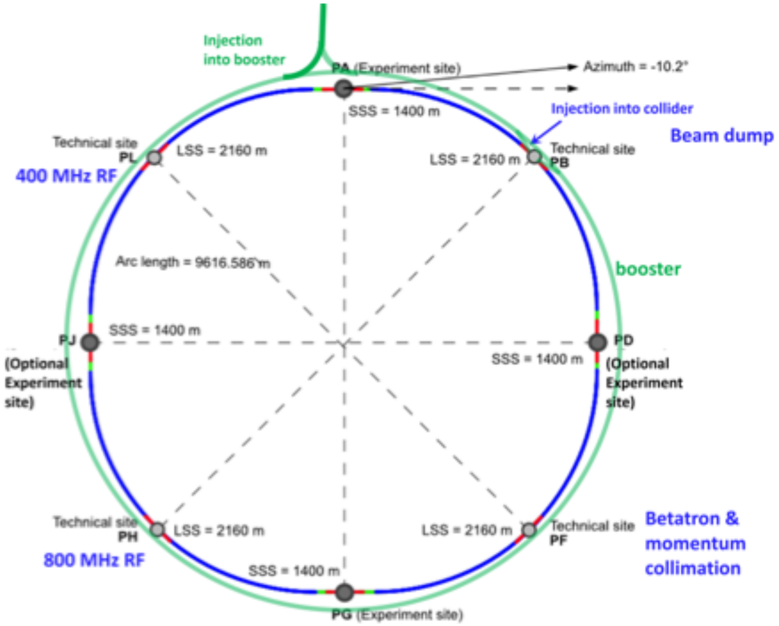
Length [km]	91	33.5	11.4 / 29
Energies [GeV]	91 / 160 / 240 / 350-365	91 / 250 / 550	380 / 1500
Run time [years]	4 / 2 / 3 / 1+4	1 / 10 / 10	10 / 10
Detectors	4	2	2
Possible upgrade	FCC-hh ; ~100 TeV pp	1-3 TeV e^+e^-	3 TeV e^+e^-

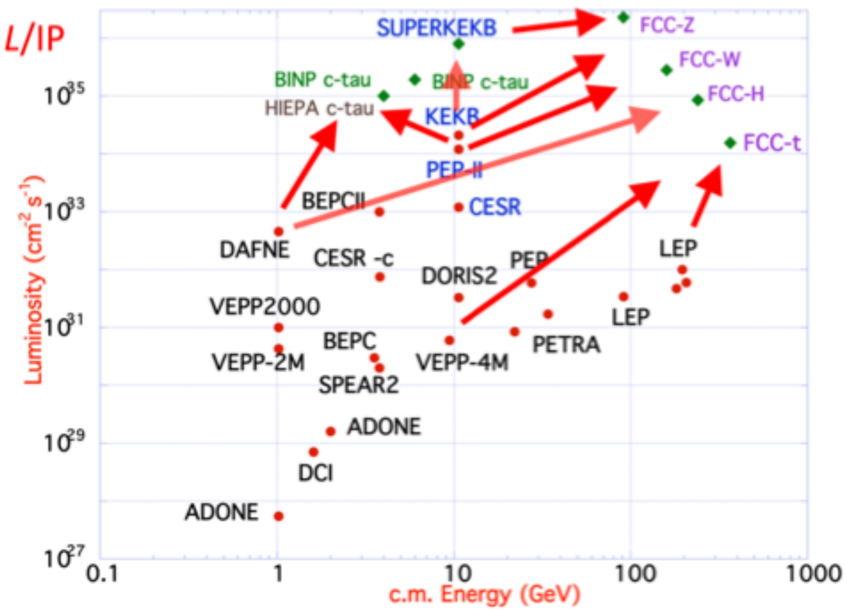
Projected Luminosities of e^+e^- Colliders



- Complementarity
  - Ultimate precision measurements (luminosity!) with circular colliders (FCC-ee)
  - Ultimate e^+e^- energies with linear colliders (CLIC)

FCC-ee: Extremely high luminosities

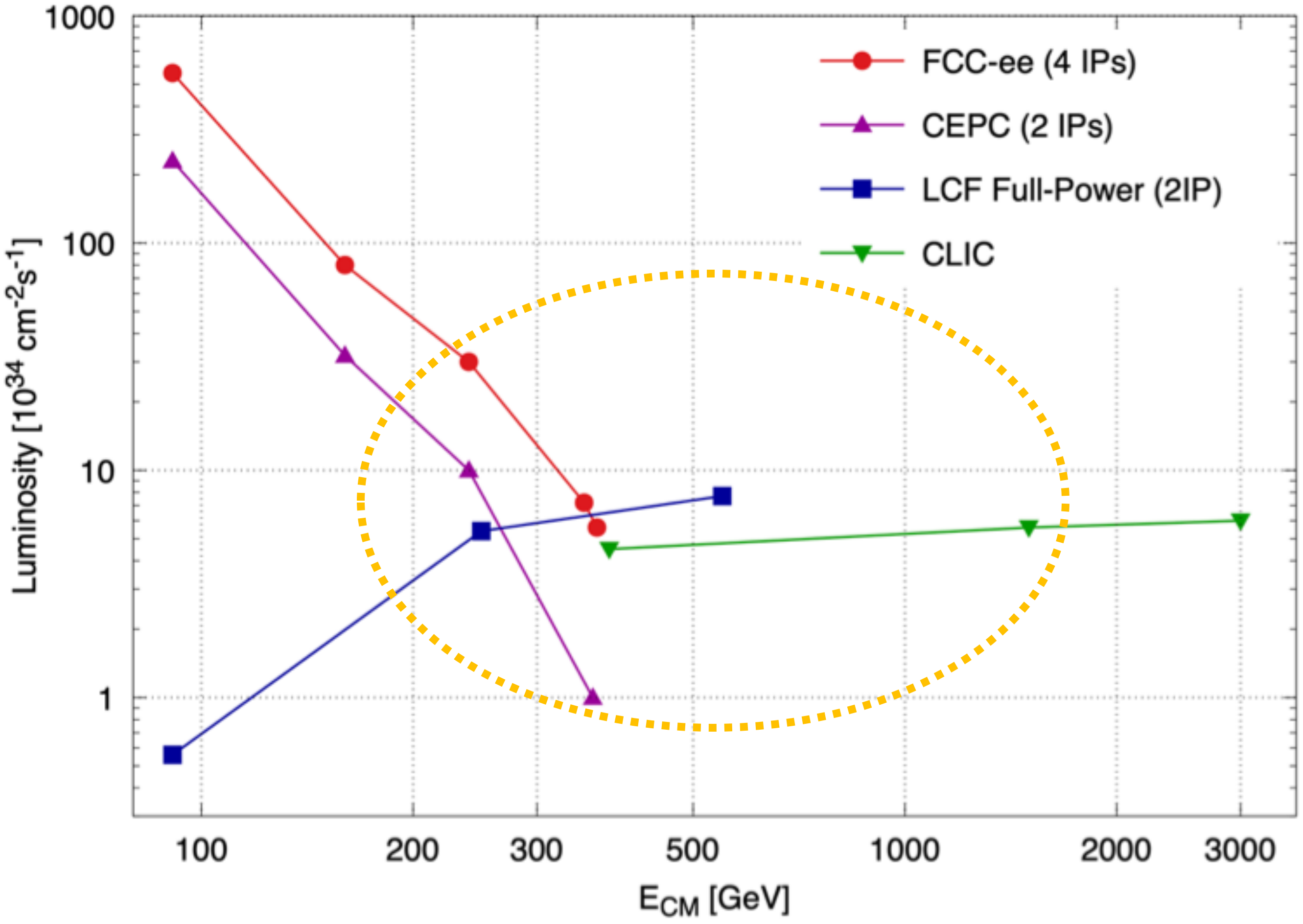




- Basic Layout
  - Double ring collider, 91 km
  - Large horizontal crossing angle 30 mrad, crab-waist optics
  - Top-up injection
    - Separate booster ring
  - Four Interaction Points (IPs)
    - increased integrated luminosity; experimental diversity

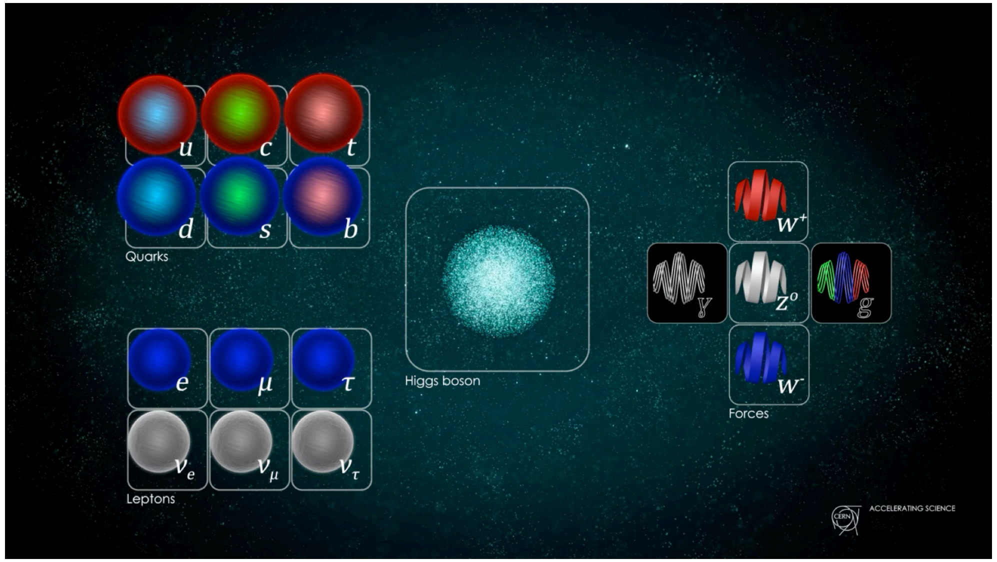
- Exploiting lessons from past & present colliders
  - LEP: high energy, synchrotron radiation effects
  - B-factories: double-ring, high beam currents, top-up injection
  - DAΦNE: crab waist, double ring
  - Super B-factories: e^+ source
  - HERA, LEP, RHIC: spin gymnastics
  - VEPP-4M, LEP: precision energy calibration

Precision Higgs Physics



Higgs Factory mission

- Unravel as much as we can about the properties of the 125-GeV Higgs boson
  - Basic properties
    - Prodution cross section, total width
    - Decay rates to known particles
    - Invisible decays
    - Search for “exotic decays”
  - CP properties of couplings to gauge bosons and fermions
  - Self-coupling

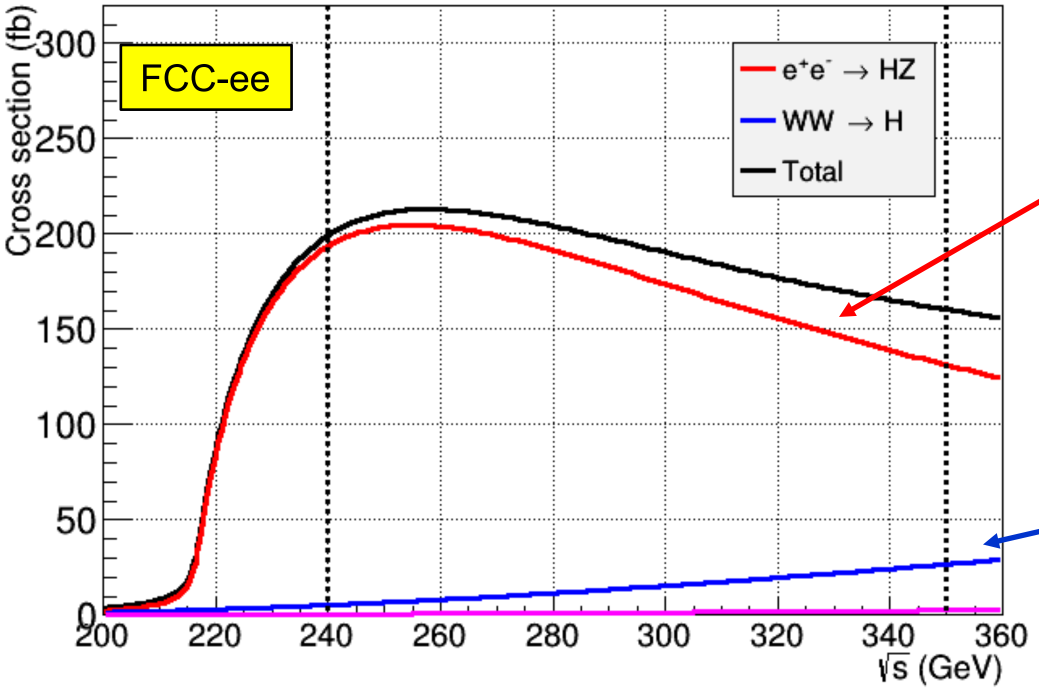


- To interpret Higgs measurements, need matching precisions
  - Top quark: mass, Yukawa & electroweak couplings, CP properties
  - Z / W bosons: masses, couplings to fermions, triple gauge couplings, incl CP, …

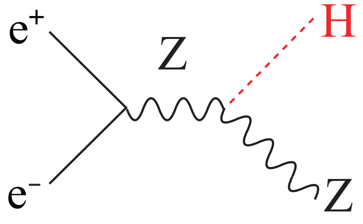
- Search for direct production of new particles – determine their properties
  - Dark matter? Dark sector?
  - Heavy Neutral Leptons
  - SUSY, Higgsino
  - The UNEXPECTED

Higgs Production

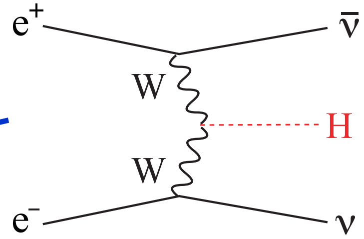
- Higgs production for √s ≤ 500 GeV



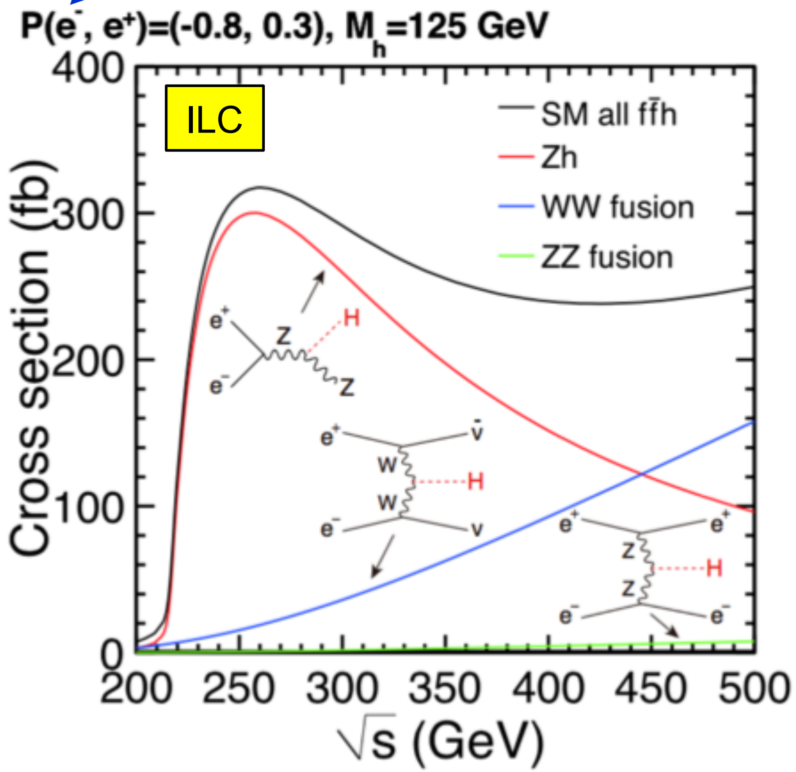
Higgs-strahlung



Boson fusion



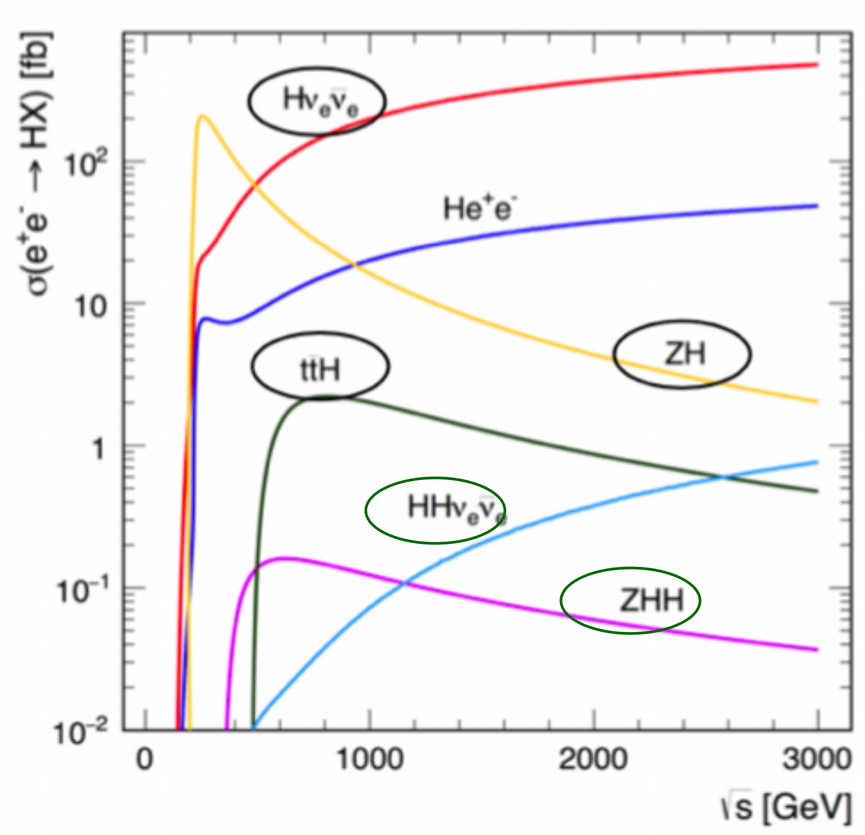
Polarised beams



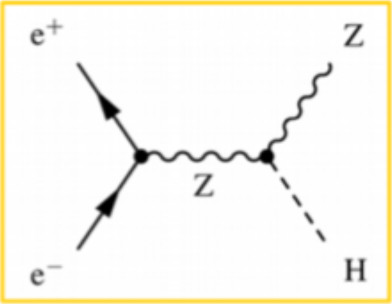
- Effect of beam polarization
  - Higgs-strahlung cross section multiplied by $1 - P_{-}P_{+} - A_e \times (P_{-} - P_{+})$
  - Boson fusion cross section multiplied by $(1 - P_{-}) \times (1 + P_{+})$

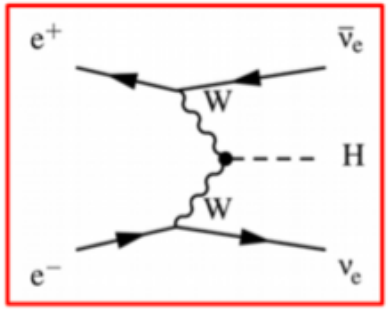
(exercise)

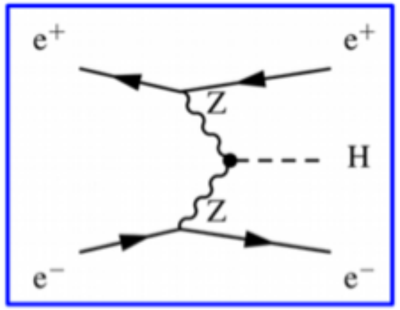
Moving to higher energies

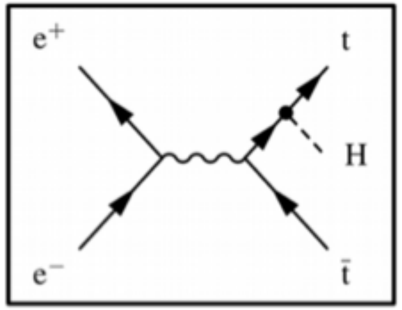


- Higgsstrahlung: $e^+e^- \rightarrow ZH$
  - $\sigma \sim 1/s$, dominant up to ≈ 450 GeV
- WW fusion: $e^+e^- \rightarrow H\nu_e\bar{\nu}_e$
  - $\sigma \sim \log(s)$, dominant above 450 GeV
  - Large statistics at high energy
- $t\bar{t}H$ production: $e^+e^- \rightarrow t\bar{t}H$
  - Accessible ≥ 500 GeV, maximum ≈ 800 GeV
    - Direct extraction of top Yukawa coupling
- ZHH and $HH\nu_e\bar{\nu}_e$ production
  - From 500 GeV (ZHH) and ~800 GeV ($HH\nu_e\bar{\nu}_e$), di-Higgs production
    - Sensitivity to Higgs self coupling









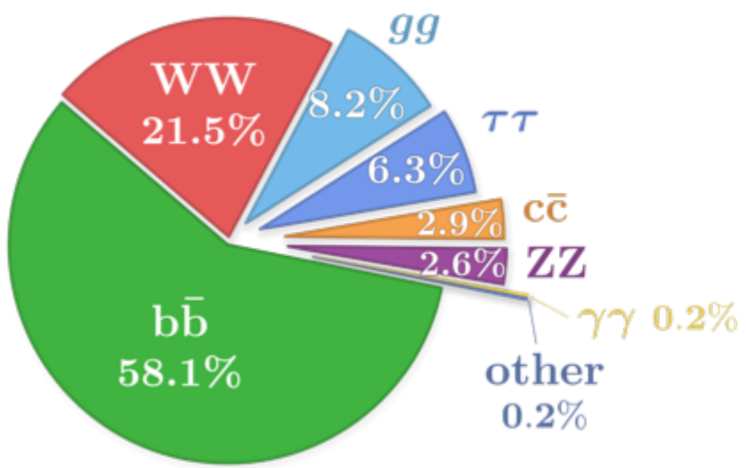
Higgs Decays

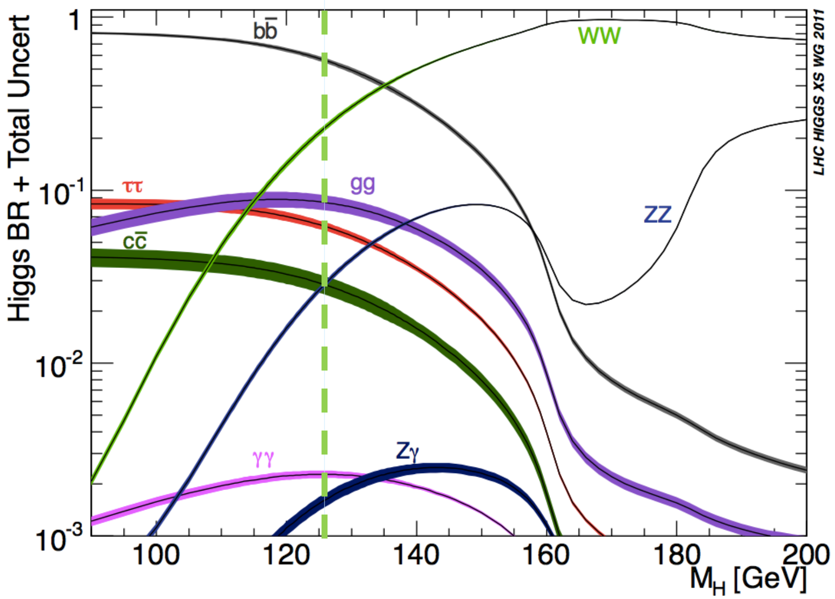
- Run at √s = 240-250 GeV and 350-500 GeV, in order to
  - Determine all Higgs couplings in a model-independent way
  - Infer the Higgs total decay width
  - Evaluate (or set limits on) the Higgs invisible or exotic decays
- Everything via the measurements of

$$\boxed{\sigma(e^+e^- \to H + X) \times BR(H \to YY)}$$

with $Y = b, c, g, W, Z, \gamma, \tau, \mu$, invisible

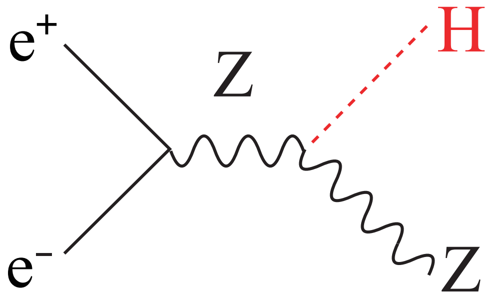
- We are lucky: m_H = 125 GeV is a very good place to be for precision measurements
  - All decay channels open and measurable – can test new physics from many angles





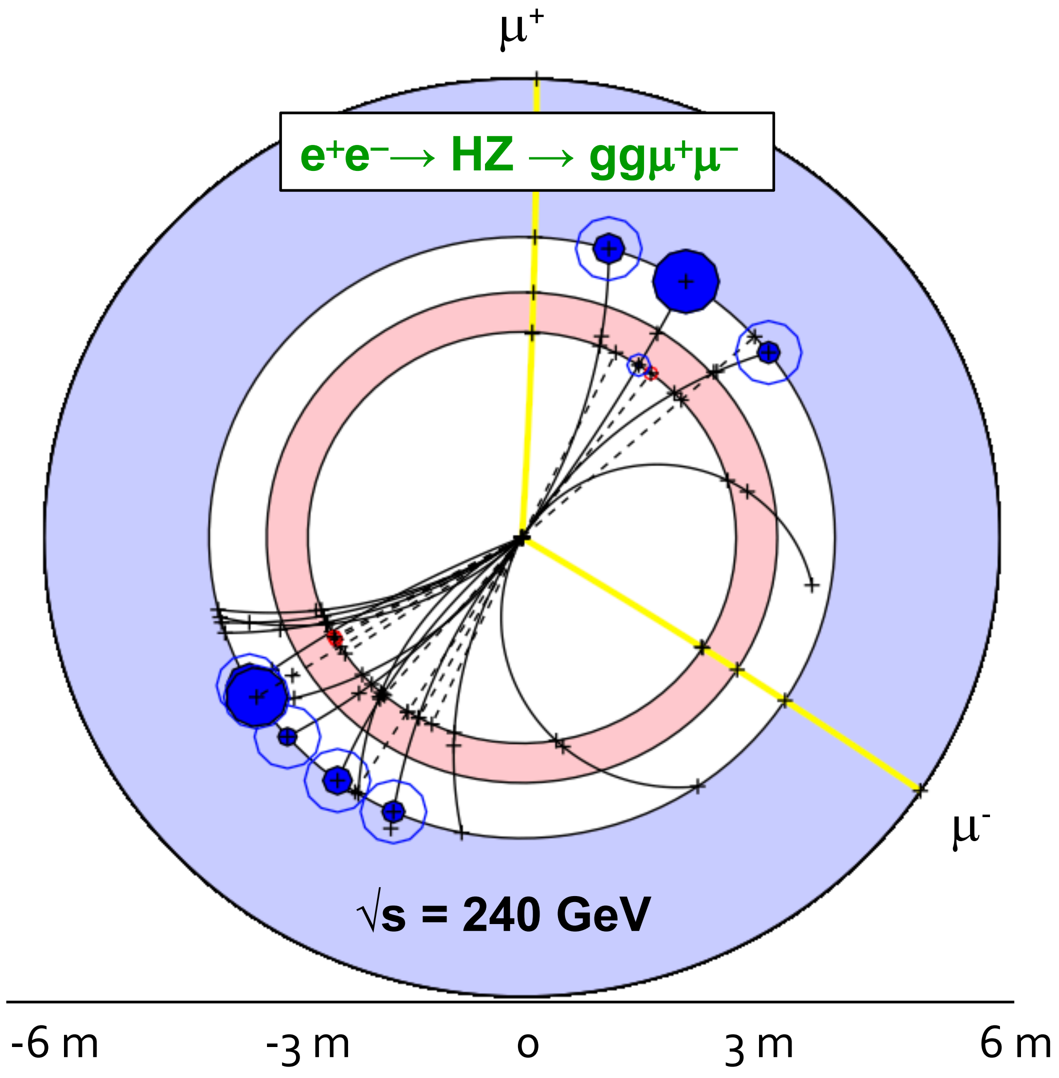
Higgs Events

- ZH events allow the reconstruction of a *tagged sample* of Higgs bosons

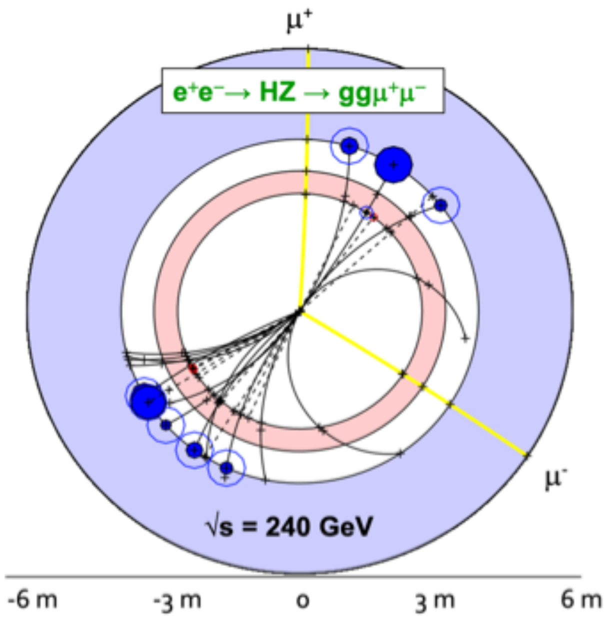


- Example, $Z \to \mu^-\mu^-$
  - Clean signature
  - Tagged with $\mu^-\mu^-$ from Z decay
    - $\mu^-\mu^-$ system mass = Z mass
    - Mass of system recoiling against $\mu^-\mu^-$ = Higgs mass

$$m_{recoil}^2 = s + m_Z^2 - 2\sqrt{s}\,(p_+ + p_-)$$

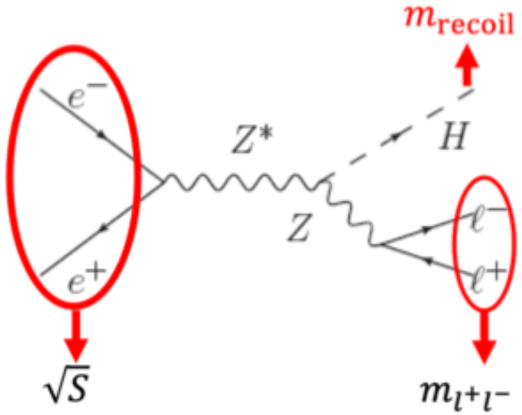


Higgs Physics Analysis



- Model-independent measurement of σ_{HZ} and g_{HZZ}
  - The Higgs boson in HZ events is tagged by the presence of the $Z \rightarrow e^+e^-, \mu^+\mu^-$
    - Select events with a lepton pair ($e^+e^-, \mu^+\mu^-$) with mass compatible with m_Z
    - Apply total energy-momentum conservation to determine the "recoil mass"
    - Plot recoil mass distribution – resolution proportional to momentum resolution
    - No requirement on the Higgs decays: measure $\sigma_{HZ} \times BR(Z \rightarrow e^+e^-, \mu^+\mu^-)$

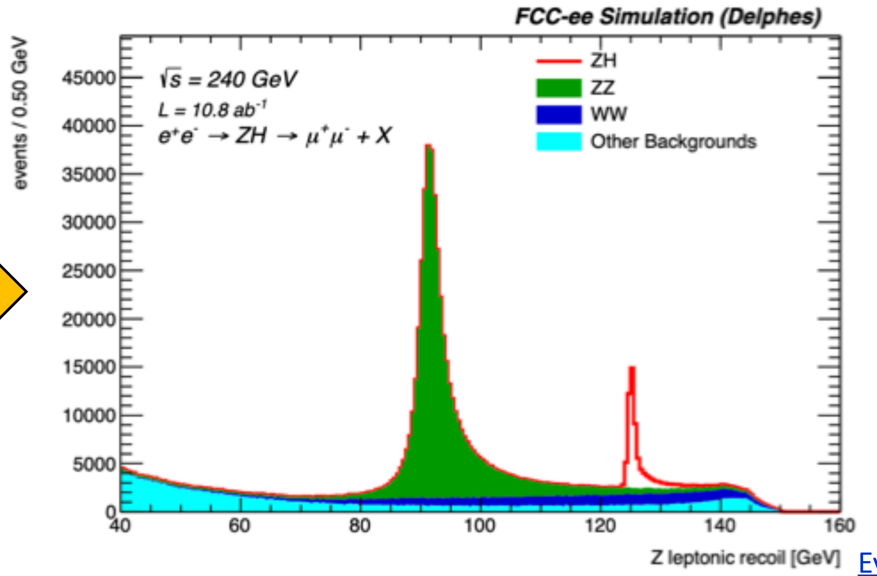
$$m_{recoil}^2 = s + m_Z^2 - 2\sqrt{s}\,(p_+ + p_-)$$



known

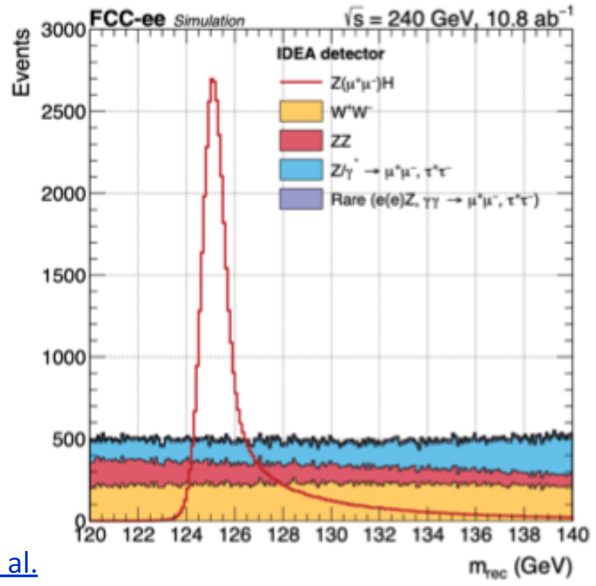
measured

Raw m_{recoil} distribution with only minor cuts



Eysermans et al.

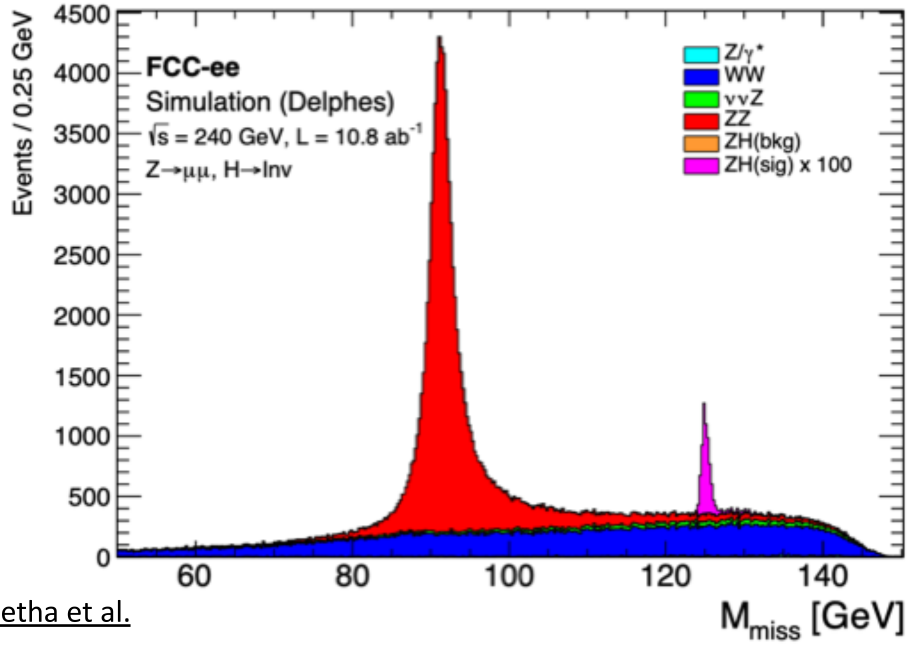
Final m_{recoil} distribution



Higgs Physics Analysis

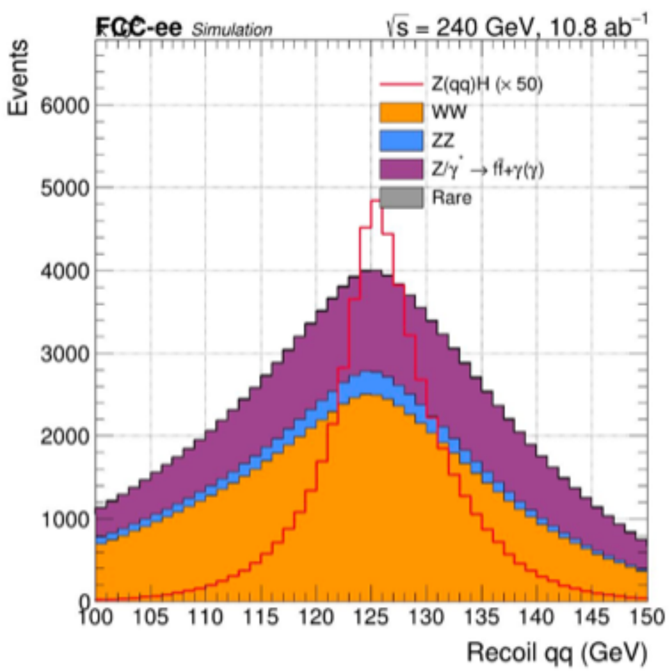
- Repeat analysis for all possible final states
  - For all exclusive decays, YY, of the Higgs boson: measure $\sigma_{HZ} \times BR(H \rightarrow YY)$
    - Including invisible decays
      - event containing only the lepton pair with correct (m_{miss}, m_{recoil}), else empty (SM BF $\simeq$ 0.1%; $H \rightarrow Z^*Z \rightarrow 4\nu$)
    - For all decays of the Z (hadrons, taus, neutrinos) to increase statistics
  - For the WW fusion mode ($H\nu\nu$ final state): measure $\sigma_{WW\rightarrow H} \times BR(H \rightarrow YY)$

Example: Z→μμ, H→inv



Metha et al.

Example: Z→qq, H→inclusive



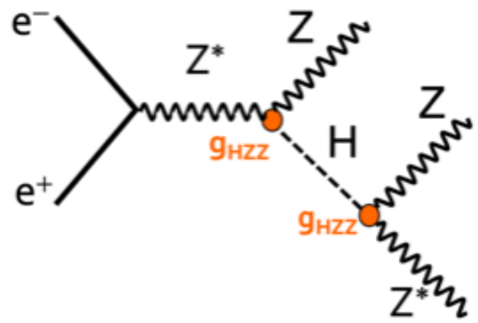
Eysermans et al.

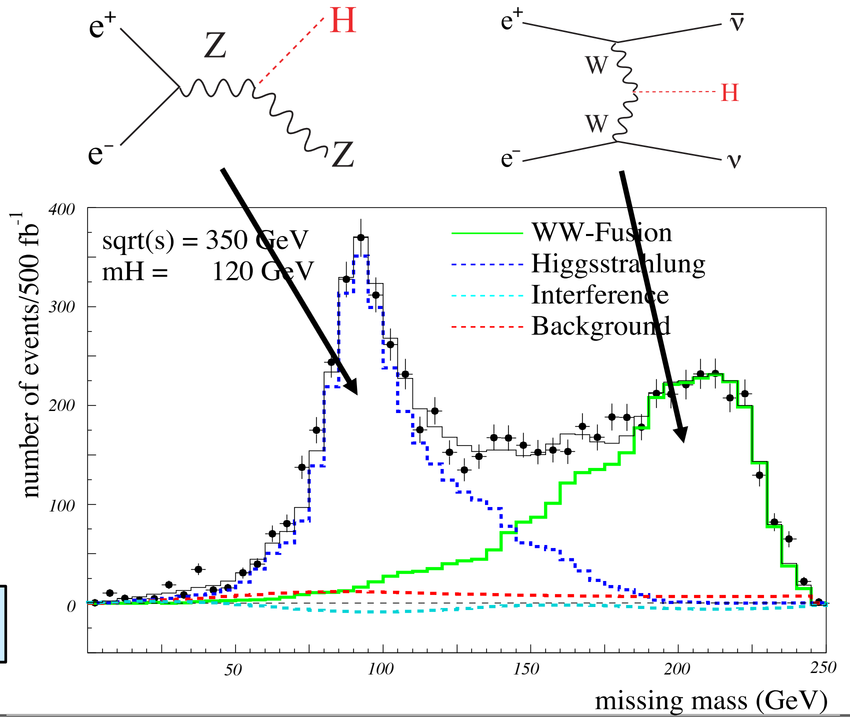
Higgs total Width

- Indirect determination of the total Higgs decay width
  - From a counting of HZ events with H → ZZ at √s = 240 GeV
    - Measure $\sigma_{HZ} \times BR(H \to ZZ)$
    - σ_{HZ} is proportional to g_{HZZ}^2
      - Previous slide
    - $BR(H \to ZZ) = \Gamma(H \to ZZ) / \Gamma_H$ is proportional to g_{HZZ}^2 / Γ_H
      - $\sigma_{HZ} \times BR(H \to ZZ)$ is proportional to g_{HZZ}^4 / Γ_H
    - Infer the total width Γ_H
  - From a counting WW→ H→ bb events at 350-500 GeV in the $bb\nu\nu$ final state:
    - Measure $\sigma(WW \to H \to bb)$
    - Take branching ratios into WW and bb from σ_{HZ} and $\sigma_{HZ} \times BR(H \to WW,bb)$
    - Infer the total width

$$\Gamma_H \propto \sigma_{WW\to H} / BR(H \to WW) = \sigma_{WW\to H\to bb} / BR(H \to WW) \times BR(H \to bb)$$

Final state with three Z's
Almost background free

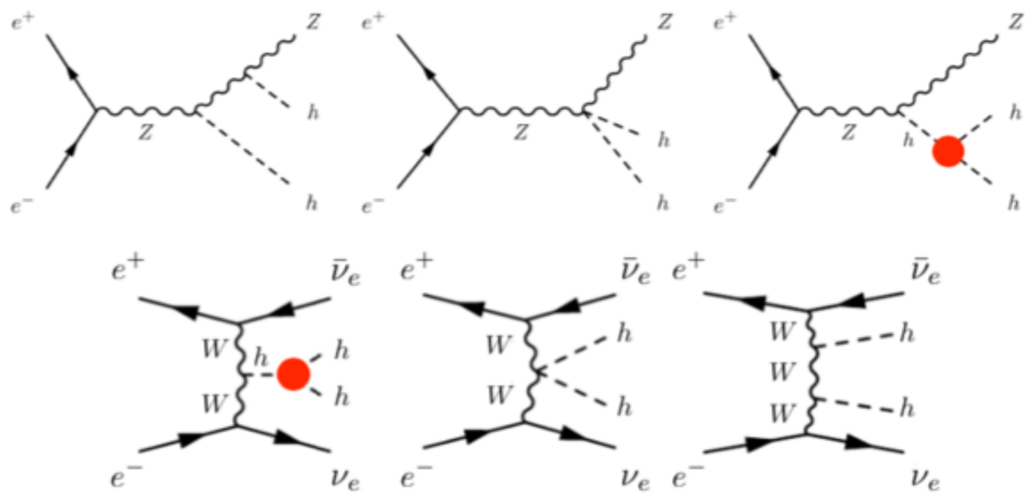


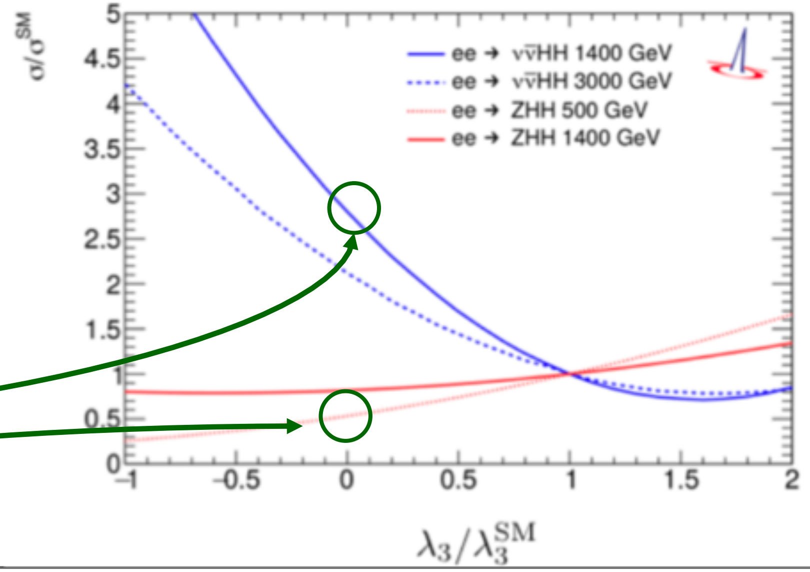


Higgs Self Coupling, λ_3 - Di-Higgs production

- Higgs self-coupling, λ_3, is a fundamental parameter of the SM whos value should be measured
  - Determines the shape of the Higgs potential

- For $\sqrt{s} \gtrsim 500$ GeV, access to di-Higgs production

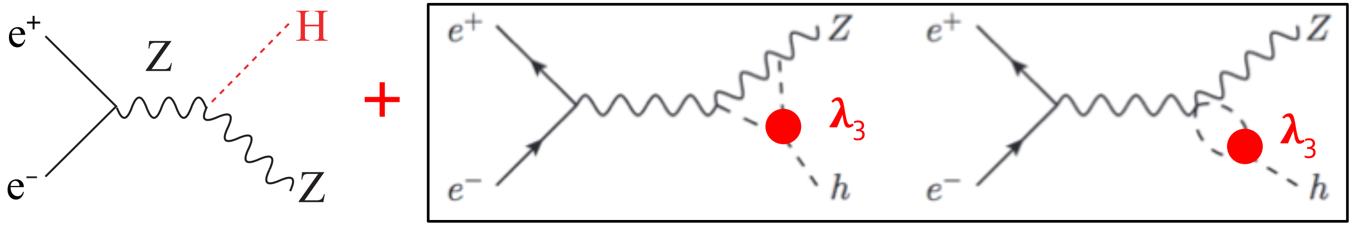




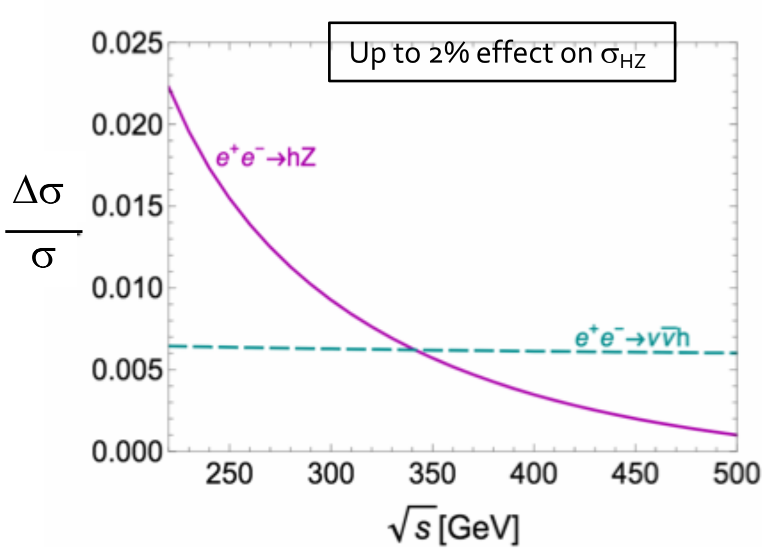
  - In both cases, three interfering diagrams
    - Higgs self coupling, λ_3, extracted from fit to production cross section
      - At 1400 GeV: relatively strong dependence
      - At 550 GeV: weak(er) dependence

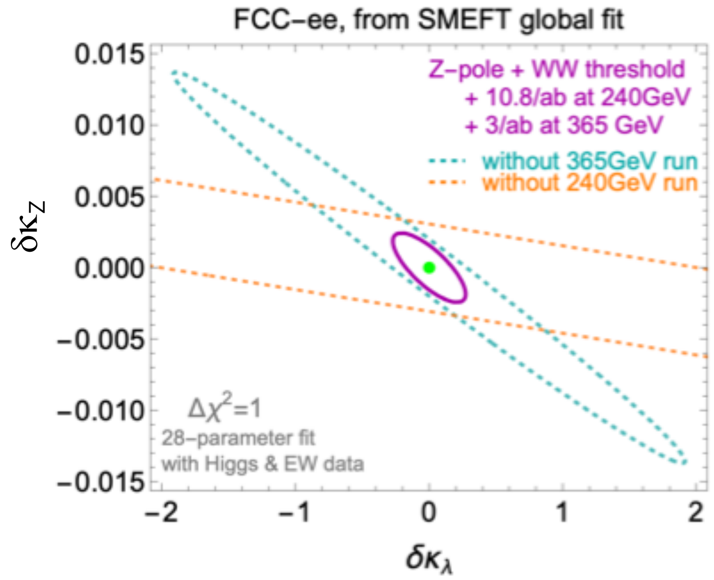
Higgs Self Coupling, λ_3 - Quantum Loop effects

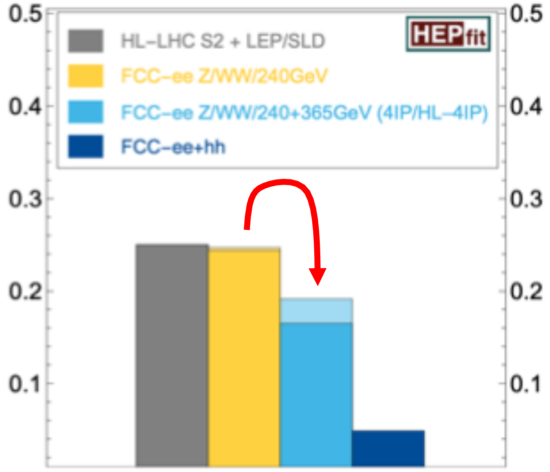
- At lower energies, no di-Higgs production
- But loops including Higgs self coupling contribute to Higgs production



- Effect on σ_{ZH} and $\sigma_{\nu\nu H}$ of Higgs self coupling (λ_3 and hence $\kappa_\lambda=\lambda_3/\lambda_3^{SM}$) depends on √s

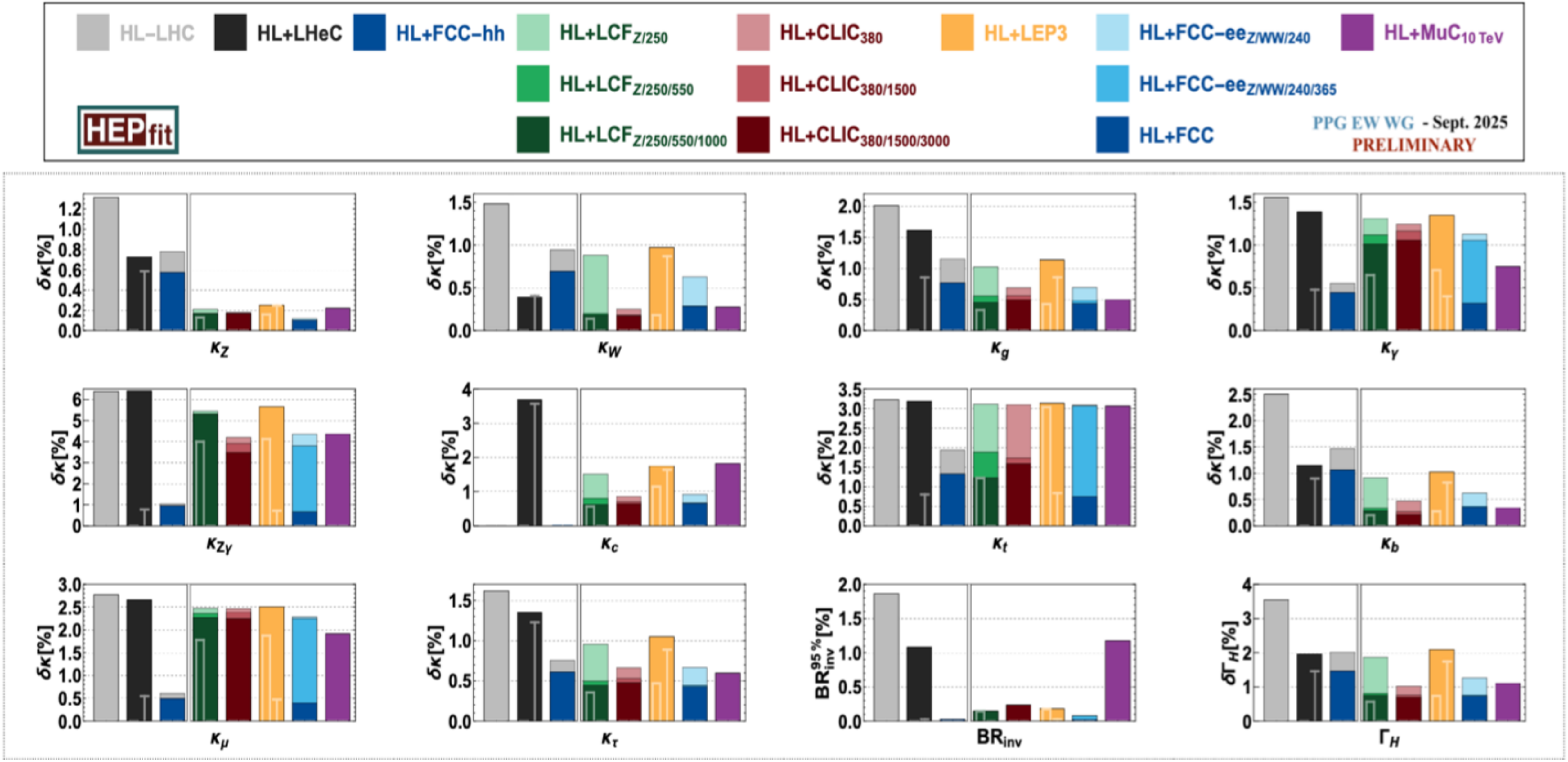




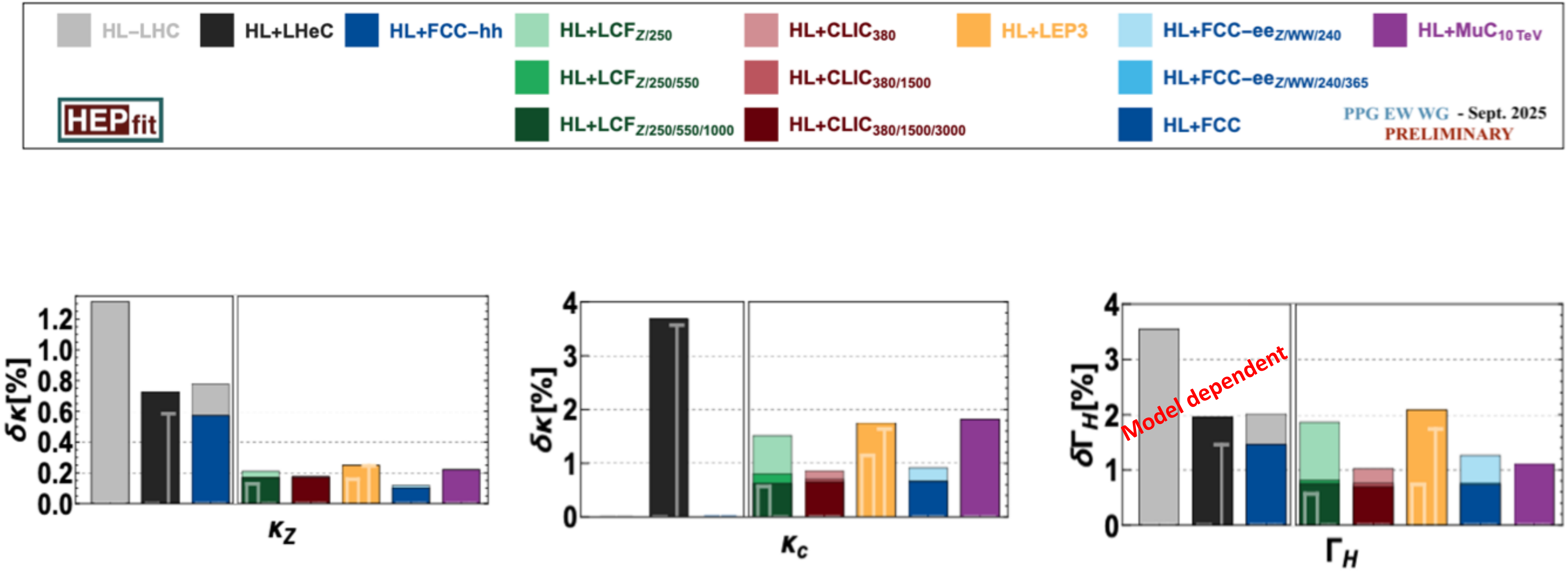


- Two energy points (240 and 365 GeV) lift the degeneracy between $\delta\kappa_Z$ and $\delta\kappa_\lambda$

Complete Overview of Higgs Coupling Prospects



A few highlights



Very precise measurement of HZZ coupling from $e^+e^- \rightarrow$ HZ channel

Charm tagging at lepton colliders

Model independent measurement of Higgs width at e^+e^- colliders

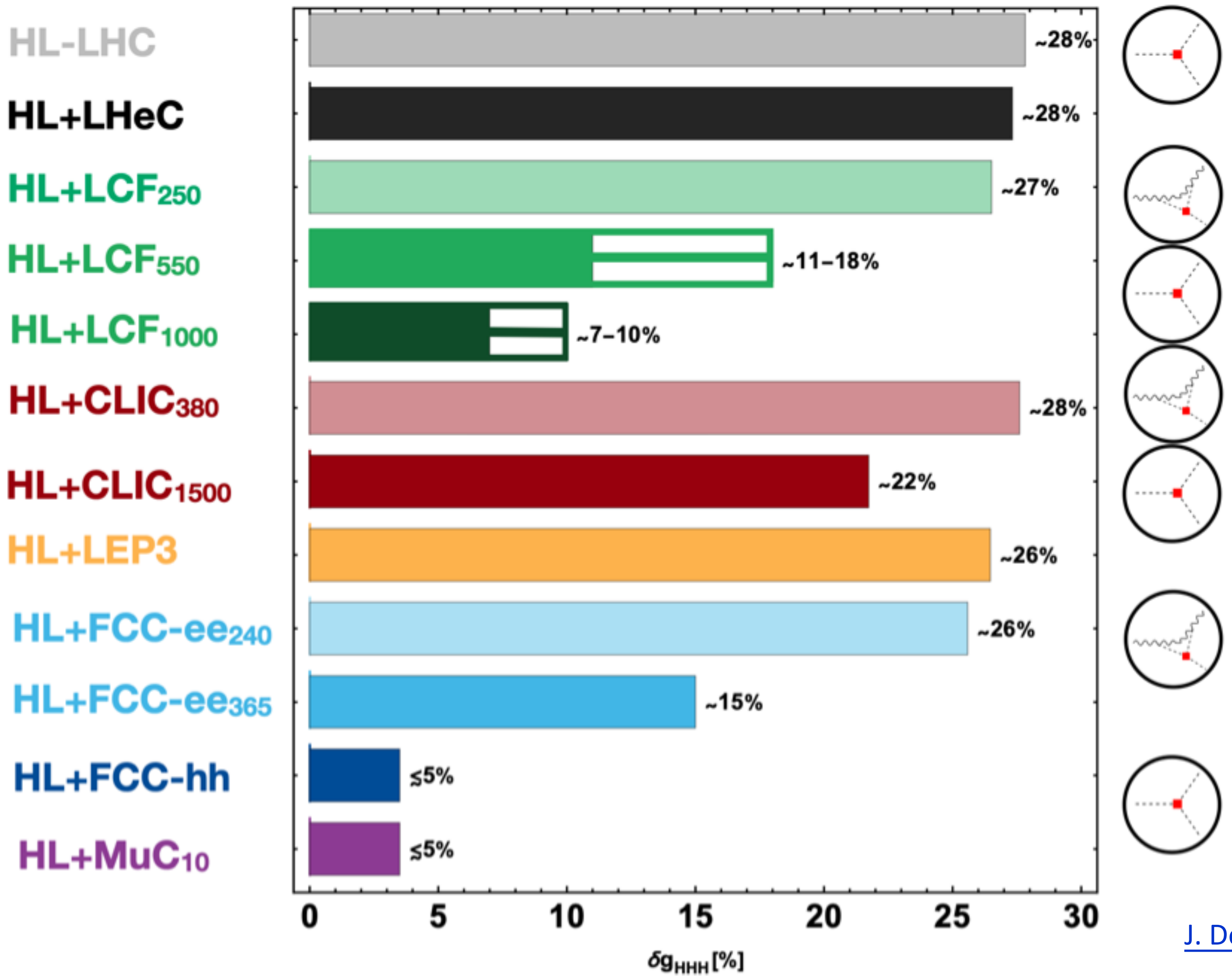
FCC-ee Higgs Precisions in Numbers

Coupling	HL-LHC	FCC-ee
κ_Z (%)	1.3*	0.10
κ_W (%)	1.5*	0.29
κ_b (%)	2.5*	0.38 / 0.49
κ_g (%)	2*	0.49 / 0.54
κ_τ (%)	1.6*	0.46
κ_c (%)	–	0.70 / 0.87
κ_γ (%)	1.6*	1.1
$\kappa_{Z\gamma}$ (%)	10*	4.3
κ_t (%)	3.2*	3.1
κ_μ (%)	4.4*	3.3
$\lvert\kappa_s\rvert$ (%)	–	$^{+29}_{-67}$
Γ_H (%)	–	0.78
$\mathcal{B}_{inv}$ (<, 95% CL)	1.9×10^{-2} *	5×10^{-4}
$\mathcal{B}_{unt}$ (<, 95% CL)	4×10^{-2} *	6.8×10^{-3}

Generally, a factor of 2–10 better than HL-LHC.
Plus, Model Independence

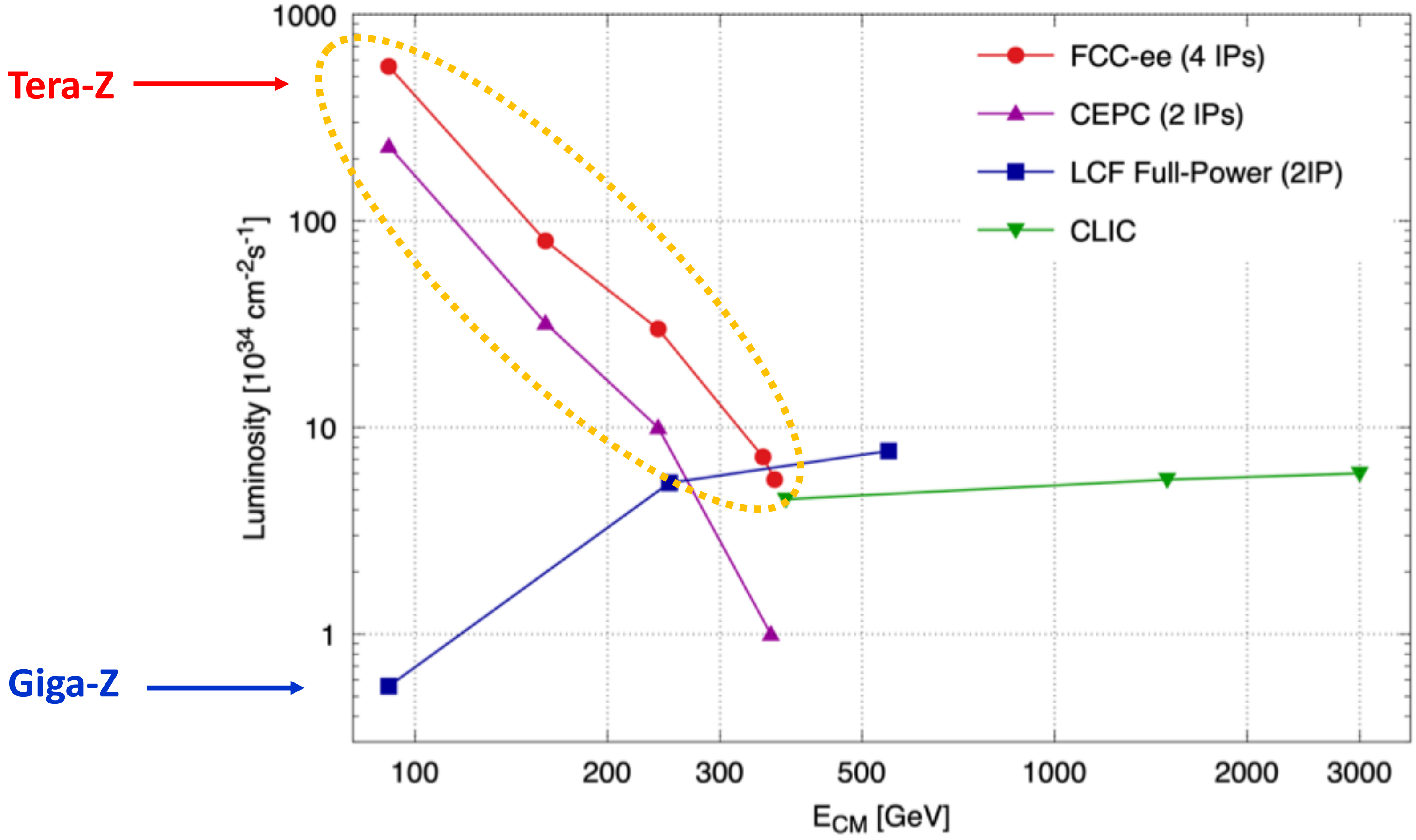
* LHC numbers model dependent, since Γ_H not know; $|\kappa_V| \leq 1$ assumed

Higgs Self-coupling Precisions

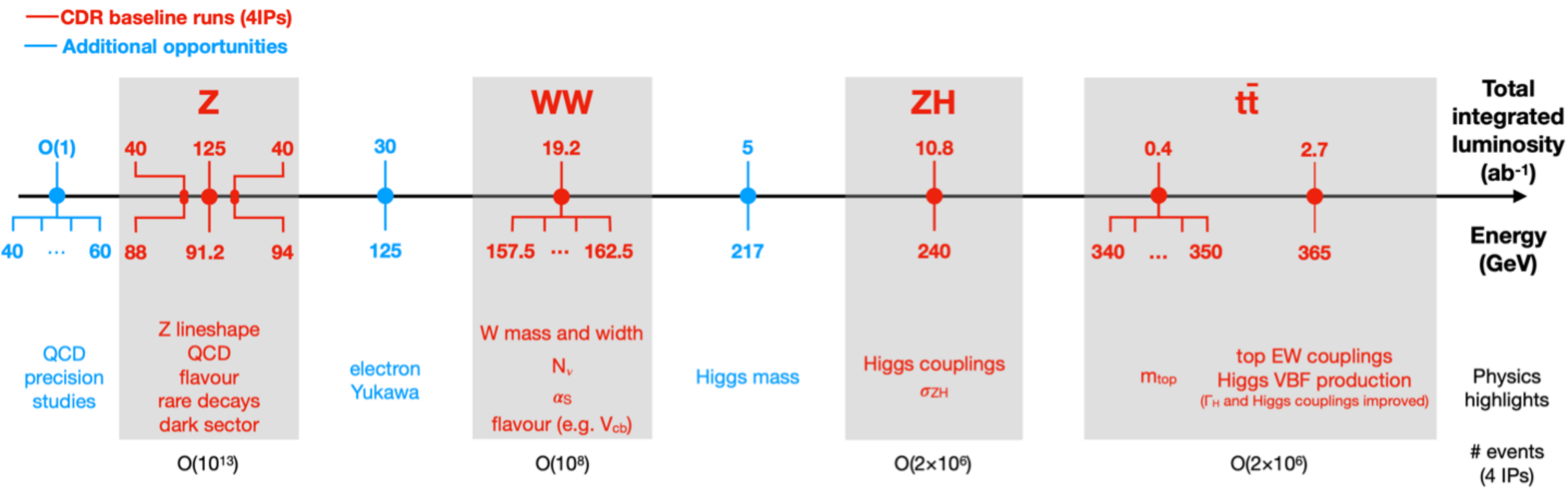


J. De Blas, June 2025

Electroweak precision Physics
Tera-Z



FCC-ee Programme



TeraZ: $\times10^5$ more than LEP1

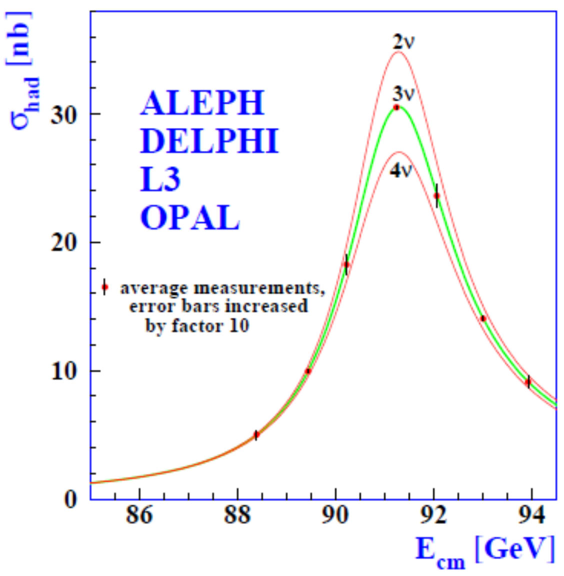
$\times10^3$ more than LEP1

Never done before

FCC-ee is the ultimate Z, W, Higgs and top factory

FCC-ee Electroweak Programme at a Glance

Tera-Z: Z resonance



Lineshape

- ❑ Exquisite E_{beam} (unique to circular colliders)
- ❑ m_Z (Γ_Z) to 100 (12) keV (2.2 MeV)

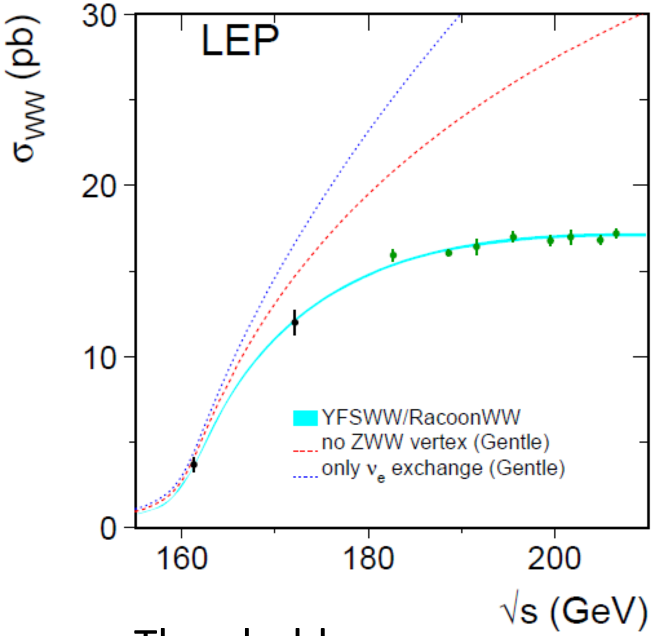
Asymmetries

- ❑ $\sin^2\theta_W$ to 1.2×10^{-6} (1.6×10^{-4})
- ❑ $\alpha_{QED}(m_Z)$ to 1×10^{-5} (1.1×10^{-4})

Branching ratios R_l, R_b

- ❑ $\alpha_S(m_Z)$ to 0.0001 (0.003)

WW threshold scan



Threshold scan

- ❑ m_W to 0.2 MeV (10 MeV)

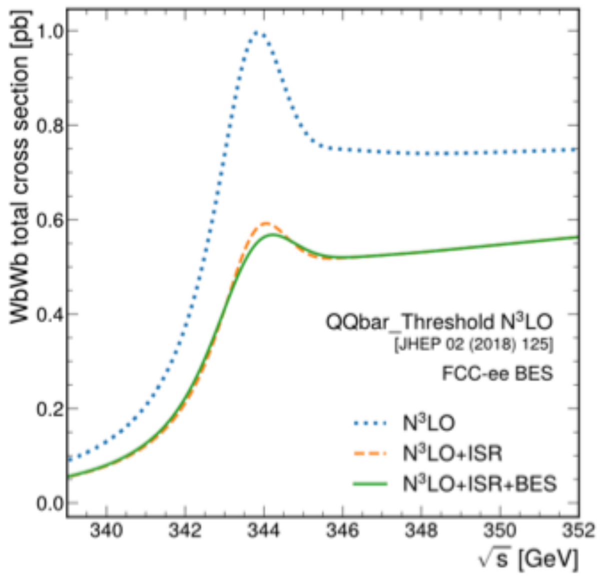
Branching ratios R_l, R_b

- ❑ $\alpha_S(m_W)$ to 0.0002

Radiative return $e^+e^- \rightarrow Z\gamma$

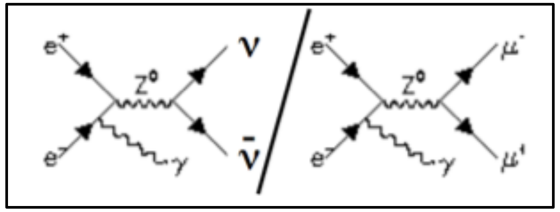
- ❑ N_ν to 0.0005

$t\bar{t}$ threshold scan



Threshold scan

- ❑ m_{top} to 5 MeV (300 MeV)
- ❑ λ_{top} to 1.5%
- ❑ ttZ coupling to ~1%



FCC-ee Electroweak Programme

- The Tera-Z programme (and beyond) provides an unparalleled data-sample size
  - Lineshape scan of the Z resonance; threshold scans of the WW and tt production thresholds
  - 2-3 orders of magnitude improvement w.r.t current knowledge
- Several challenges to keep systematic uncertainties under control
  - Beam energy calibration by resonant spin depolarization to ~ 100 keV
  - Detectors: acceptance, efficiencies, resolutions, hermeticity
  - Luminosity measurement: using QED processes (Bhabha, $\gamma\gamma$)
  - Calibration: in situ using enormous samples of collected data
  - Theory: need to cope with orders of magnitude improvement of theoretical calculations and Monte Carlo generator accuracies

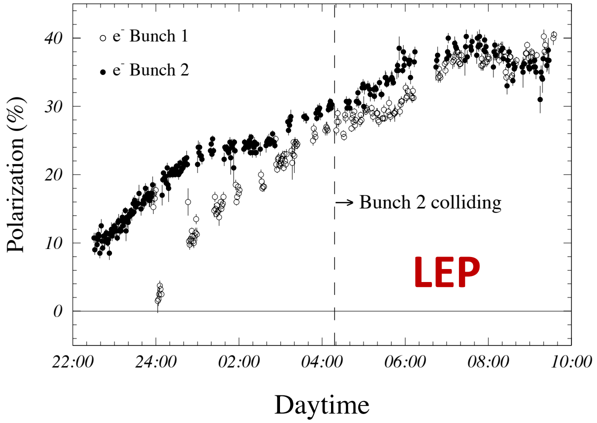
Uncertainty	m_Z (keV)	Γ_Z (keV)	$\sin^2\theta_W^{\rm eff}$ $(\times 10^{-6})$*	$\frac{\Delta\alpha_{\rm QED}(m_Z^2)}{\alpha_{\rm QED}(m_Z^2)}$ $(\times 10^{-5})$	$A_{\rm FB}^{{\rm pol},\tau}$ $(\times 10^{-4})$
LEP	2000	2300	40	/	49
FCC-ee statistical	4	4	2	3	0.15
$\sqrt{s}$ systematic	101	12	1.2	0.5	/

Improvements in precision of $\mathcal{O}(10^2)$ available

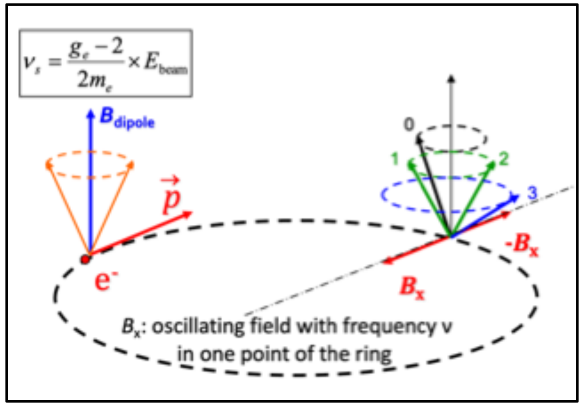
- Keep in mind that often systematic uncertainties also scale down with increased statistics

Example Challenge: 1 ppm measurement of collision energy

- Transverse polarisation builds up in the circulating beams via the Sokolov-Ternov effect
  - Experience from LEP
  - Will be slower at FCC-ee (weaker dipole field)
    - need for wigglers

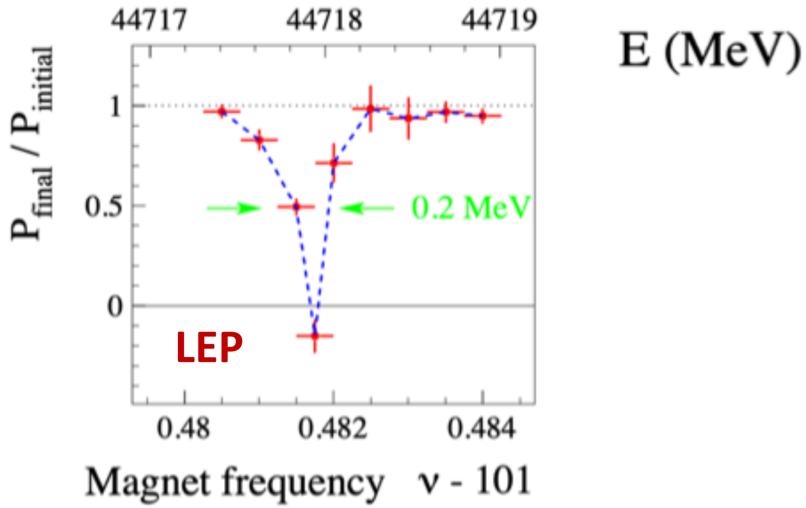


- Spin precesses around B-field (Larmor precession) with a frequency, ν_s , proportional to E_{BEAM}



  - Determine E_{BEAM} by measuring ν_s

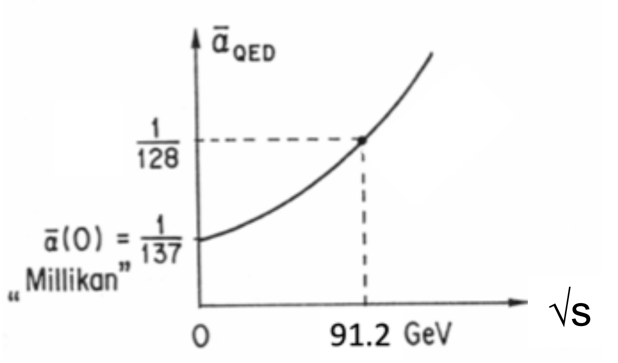
- Resonant depolarisation:
  - By exciting the beam with a transverse oscillating magnetic field, the transverse polarization can be destroyed when the excitation frequency matches the spin precession frequency

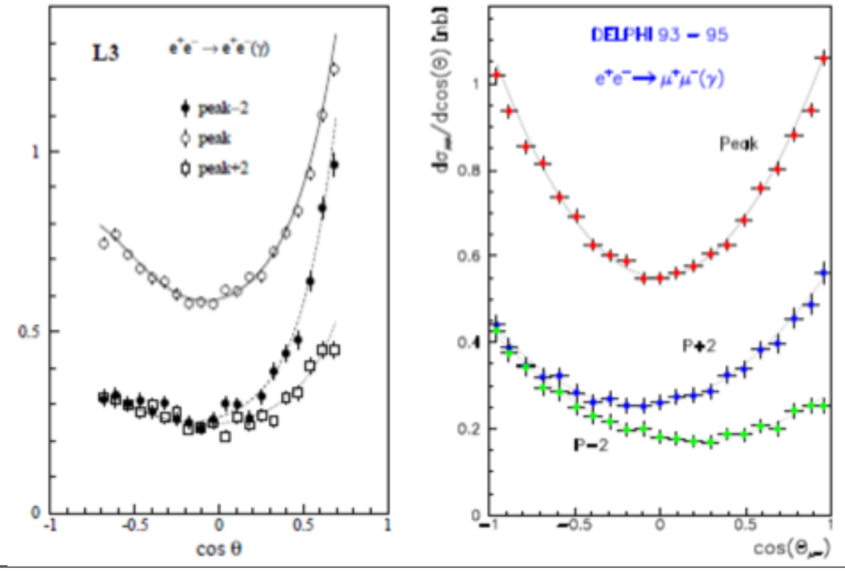


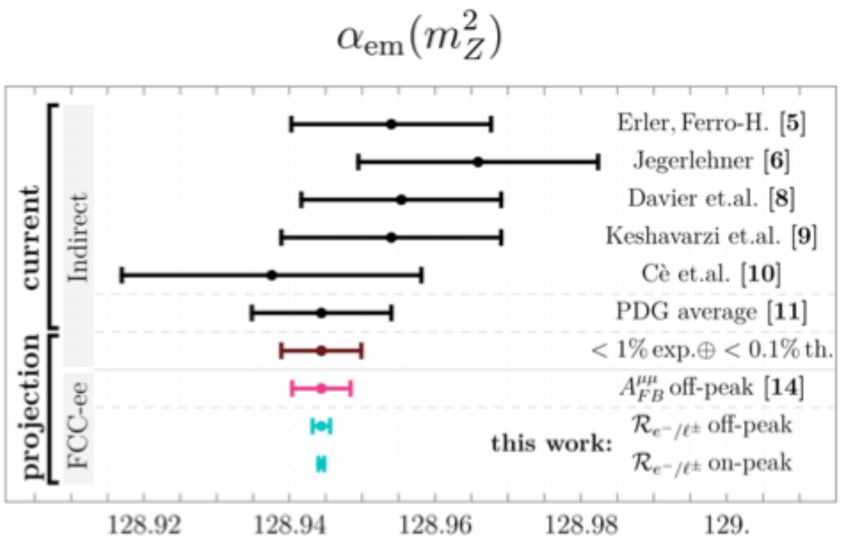
- E_{BEAM} measurement to ~100 keV
  - LEP: extrapolation from dedicated runs to physics runs
    - Factor 20: $\delta\sqrt{s} \simeq 2$ MeV
  - FCC-ee: Use dedicated bunches in physics runs
    - No extrapolation: $\delta\sqrt{s} \simeq 100$ keV

Example challenge: $\alpha_{QED}(m_Z)$

- Magnitude of electron electric charge (expressed via α_{QED}) increases with √s
- For extration of physics results from ee → Z, value that matters is $\boldsymbol{\alpha_{QED}(m_Z)}$
- Currently, determined from extrapolation of low energy data
  - Relative uncertainty, $\delta\alpha_{QED}(m_Z) / \alpha_{QED}(m_Z) \simeq 10^{-4}$; Limiting factor to many BSM searches
- With Tera-Z statistics, access to direct $\alpha_{QED}(m_Z)$ measurement
  - **Off-pole** (Janot, 2015): determined from slope of $A_{FB}^{\mu\mu}$ vs. √s (interference of Z and γ channels) **→ ±3 × 10^{-5}**
  - **On-pole** (Riembau, 2025)**:** both s- and t-channel $e^+e^- \to e^+e^-$ and $e^+e^- \to \mu^+\mu^-$ at the Z pole; sizeable photon contribution for e^- only, not for μ^- **→ ±0.6 × 10^{-5}**
    - Experimental systematics ?







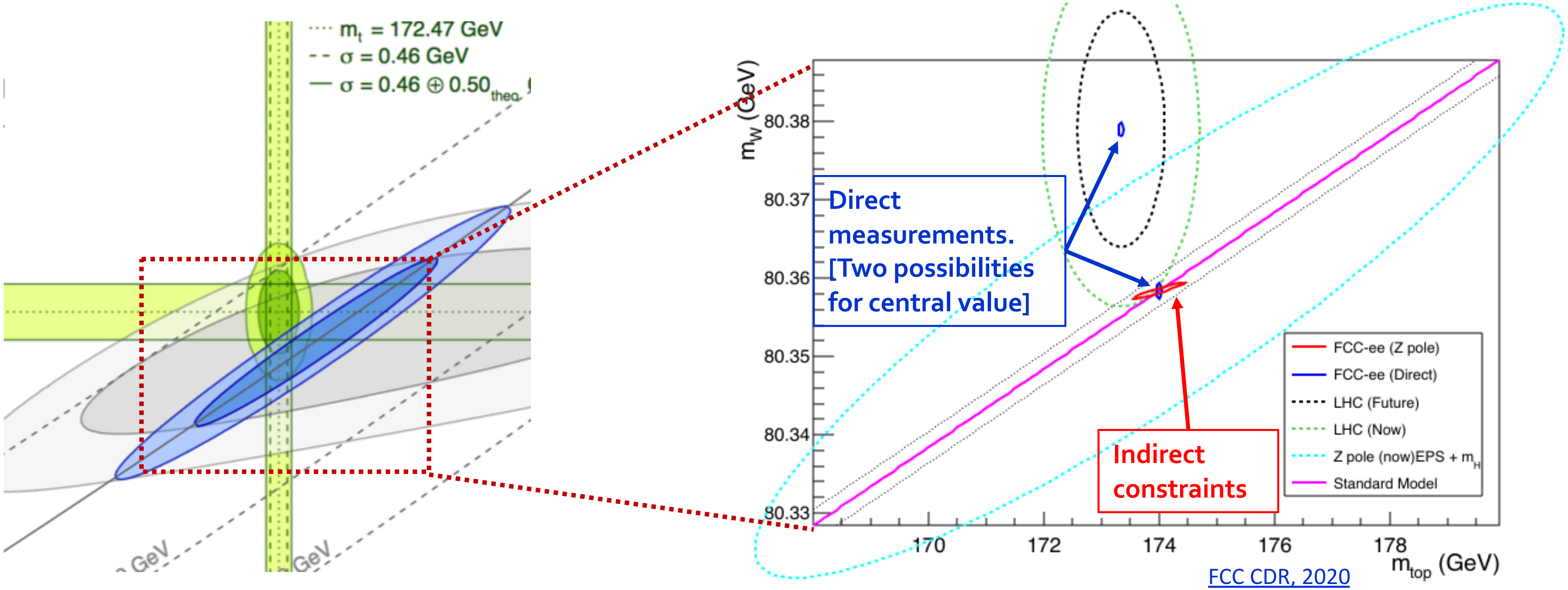
EW Precision Measurements

Observable	present value	±	uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty	improvement factor w.r.t. now
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration	20
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration	200
$\sin^2\theta_W^{\rm eff}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration	130
$1/\alpha_{\rm QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate	
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons	500
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, $\Gamma_{\rm tot}^Z$, $\sigma_{\rm had}^0$ fit	
$\sigma_{\rm had}^0$ ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement	
N_ν ($\times 10^3$)	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement	
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons	2000
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge	
$A_{FB}^{{\rm pol},\tau}$ ($\times 10^4$)	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics	
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass	
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR	
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency	
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration	50
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration	
$\alpha_S(m_W^2)$ ($\times 10^4$)	1 010	±	270	**2**	2	Combined R_ℓ^W, $\Gamma_{\rm tot}^W$ fit	
N_ν ($\times 10^3$)	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns	
$m_{\rm top}$ (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate	60
$\Gamma_{\rm top}$ (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate	
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate	

Experimental (statistical and systematic) precision of a selection of measurements accessible at FCC-ee, compared to the present world-average precision. FCC-ee systematics scaled down from LEP estimates. Room for improvement with dedicated studies.

Ultra Precise EW Consistency Checks

- Combination of all precision electroweak measurements
  - FCC-ee precision allows m_{top}, m_W, $\sin^2\theta_W$ to be predicted within the SM
    - … and to be compared to the direct measurements



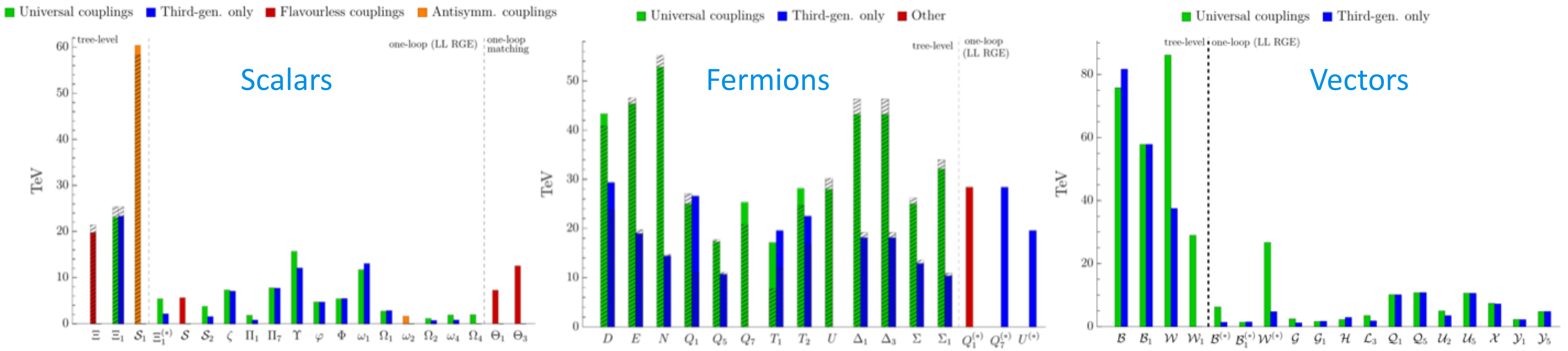
FCC CDR, 2020

  - New Physics ?
    - Direct measurement (tiny blue ellipse) and indirect constraints (tiny red ellipse) may or may not overlap

New-Physics Reach from FCC-ee

- There are 48 different types of particles that can have tree-level linear interactions to SM
  - They are not all affecting EW observables at tree-level
  - However, all, but a few, have leading-log running into EW observables

Projected bounds (95% CL) on the masses of new scalar fields

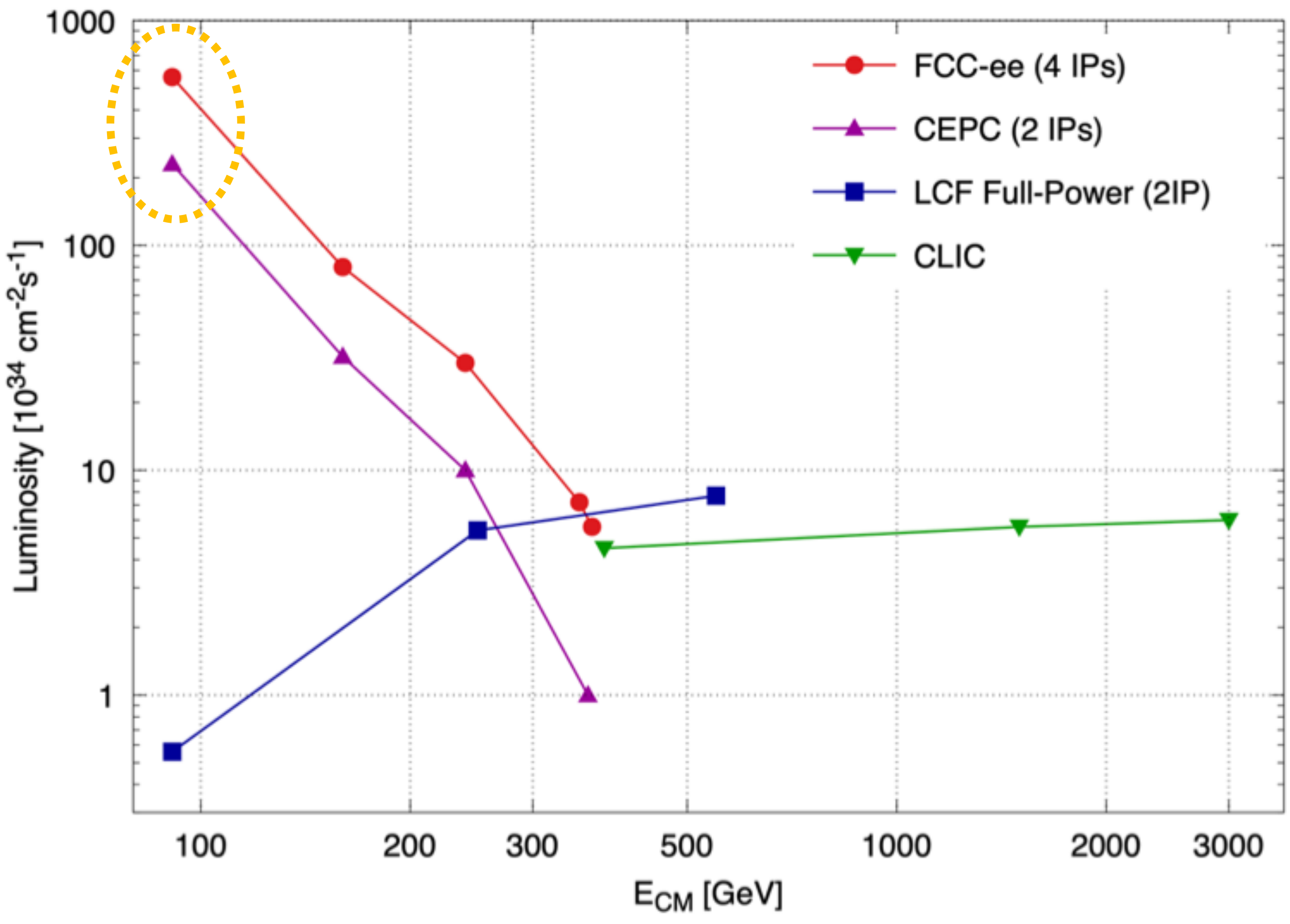


W- and Z- observables (not Higgs)

Allwicher, McCullough, Renner, arXiv:2408.03992

- Tera-Z programme gives comprehensive coverage of new physics coupled to SM
  - Takes advantage of the quantum nature of particle physics to maximise sensitivity to New Physics

Tera-Z : Flavour Physics and Direct Discoveries

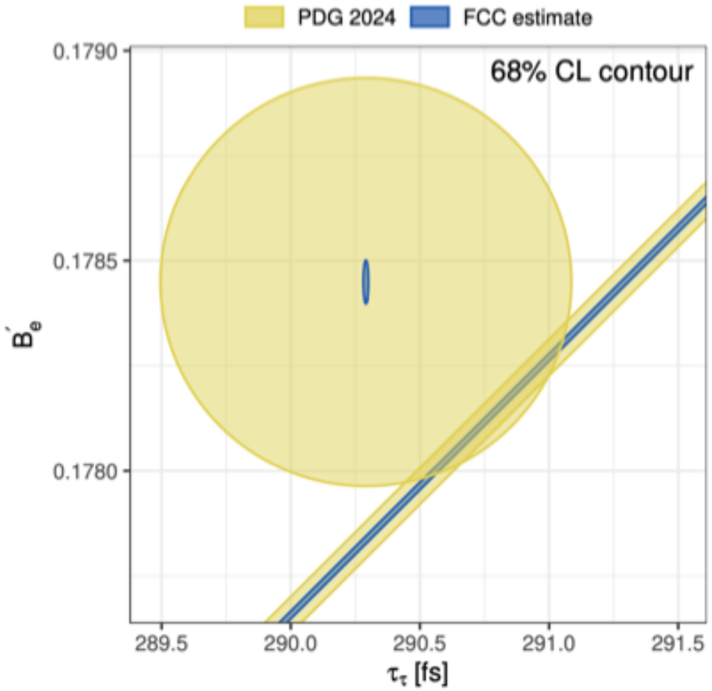


FCC-ee as a flavour factory

- Tera-Z will produce a huge number of beauty hadrons in a very clean environment
  - Many measurement opportunities that are highly complementary to LHCb Upgrade II
- Tera-Z will also provide world's largest sample of "background free" tau decays.

Particle species	B^0	B^-	B^0_s	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield (10^9)	740	740	180	160	3.6	720	200

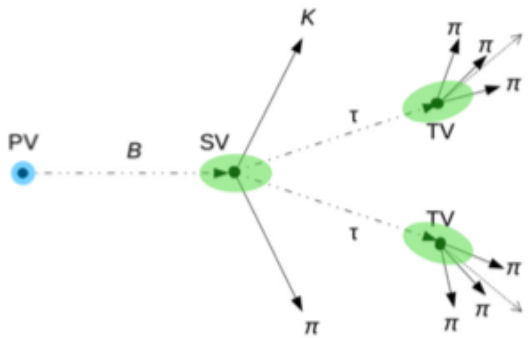
Example: lepton universality test with taus



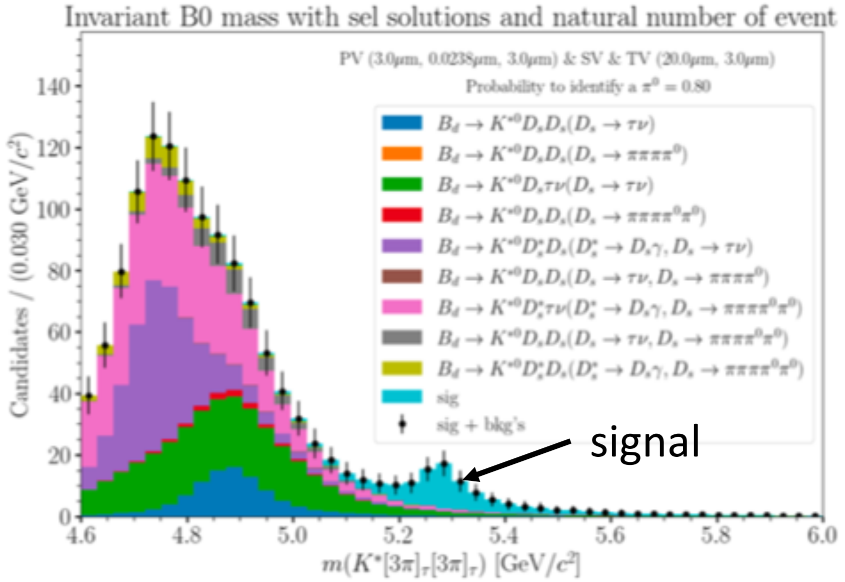
link

Example: B decays with taus

e.g. $B^0 \to K^{*0}\tau\tau$ channel



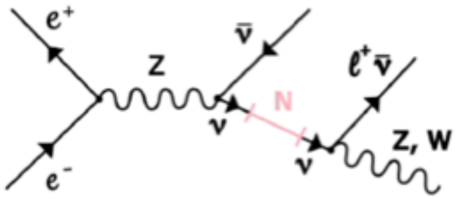
Strong requirements on vertexing
- 1 primary vertex
- 1 secondary vertex
- 2 tertiary vertices



Ambitious – possible feasible: sets detector requirements

Direct Searches for Elusive New Physics

- LLP searches with displaced vertices
  - e.g. Neutral Heavy Leptons, a.k.a. righthanded neutrinos

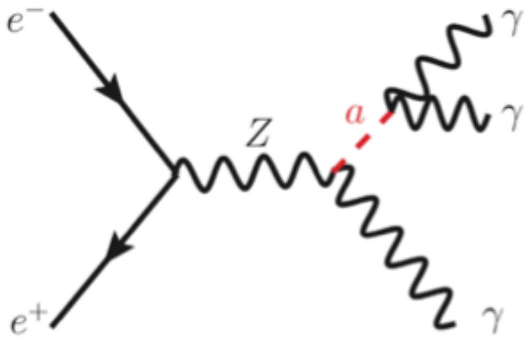


- Rare decays
  - e.g. ALP mixing w/ SM mesons:

$$K_L \to \pi^0 a \to \pi^0 \gamma\gamma \text{ (KOTO)}$$
$$K^+ \to \pi^+ a \to \pi^+ \gamma\gamma \text{ (NA62)}$$

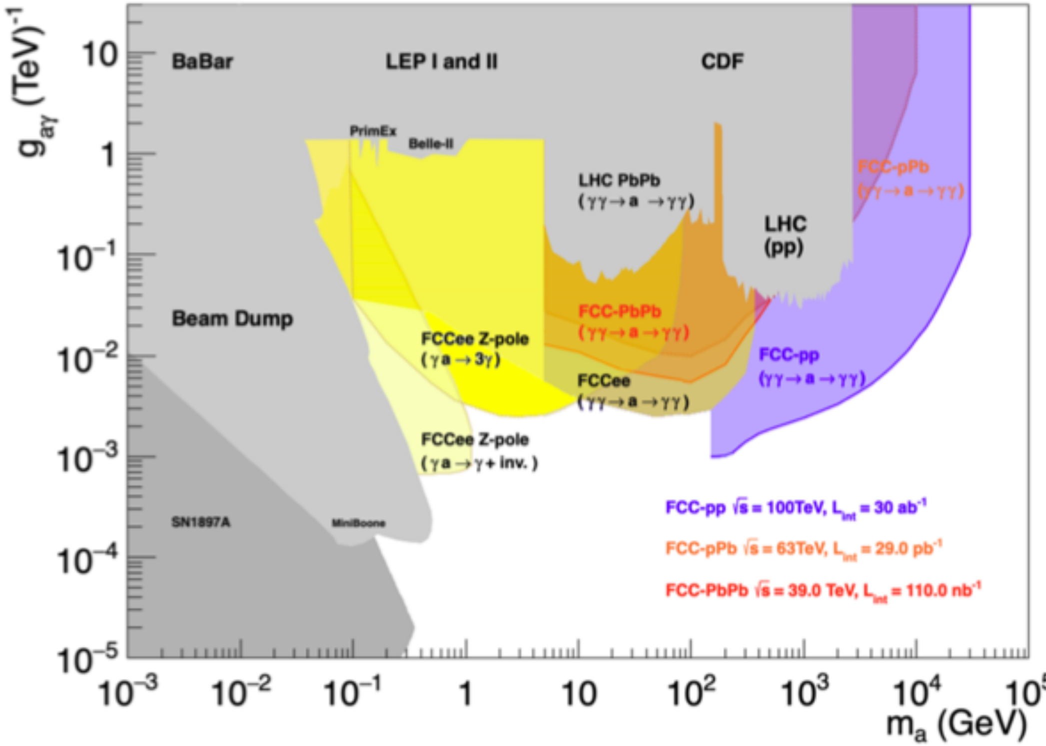
- ALPs @ colliders
  - e.g.

$$e^+e^- \to \gamma a$$
$$e^+e^- \to ha$$



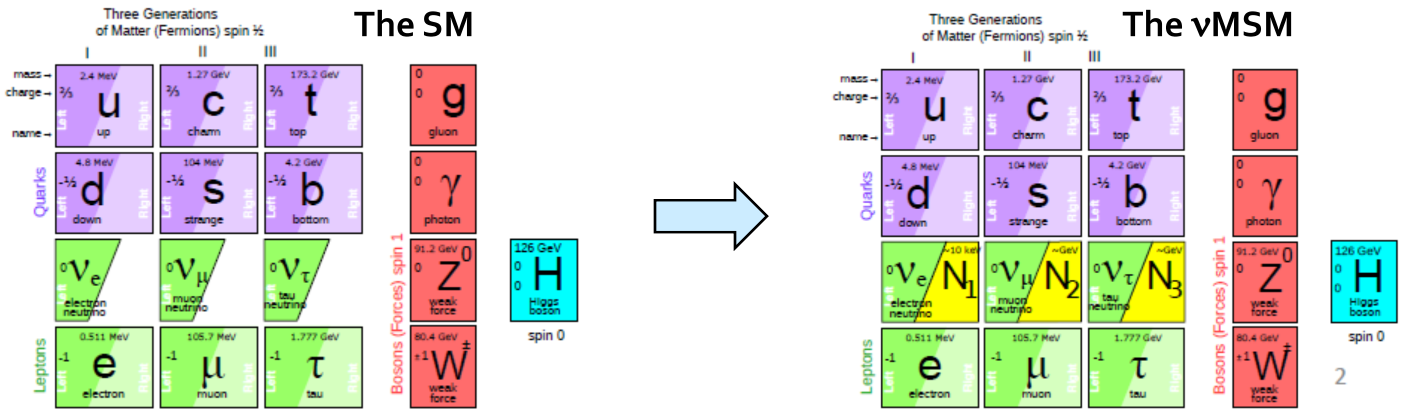
Direct searches for ALPs

[link]

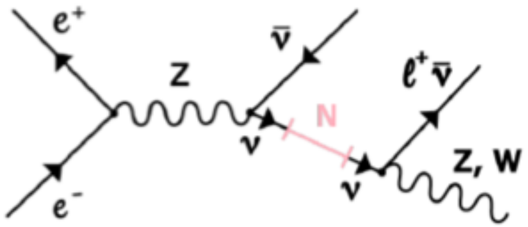


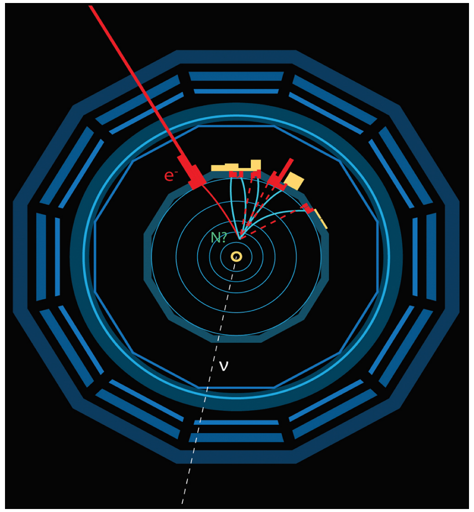
Heavy Neutral Leptons

- νMSM model: Complete Standard Model with addition of right-handed neutrinos
  - Could explain "everything":
    - Dark matter (N_1)
    - Baryon asymmetry
    - Neutrino masses

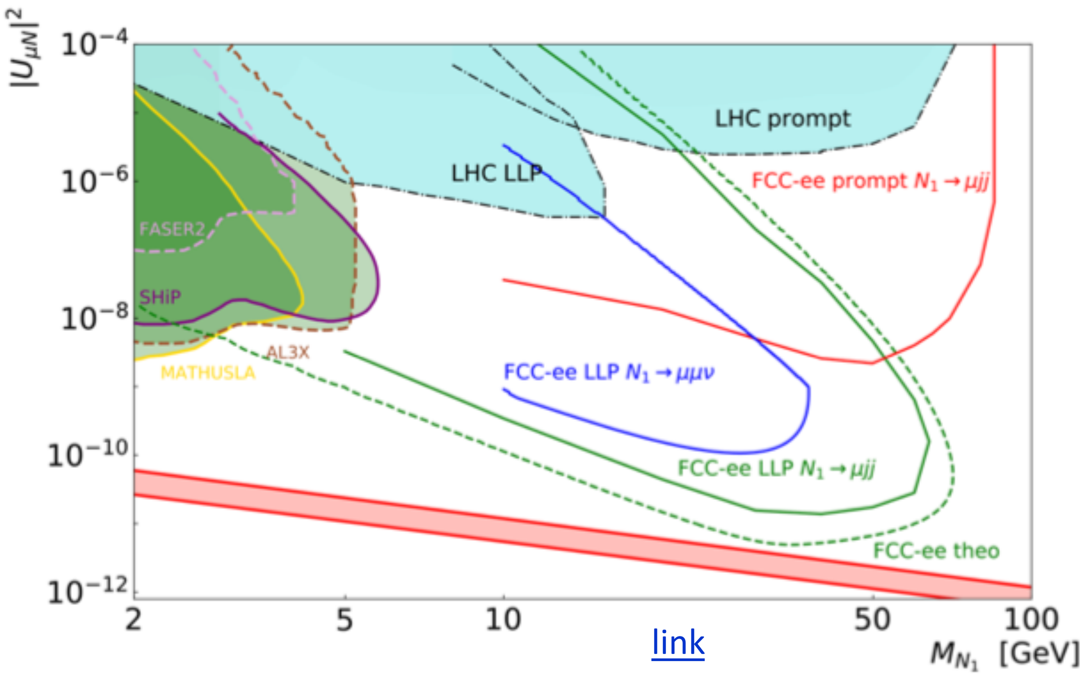


- Searched for in rare Z decays





Signature:
- monojet + detached vertex



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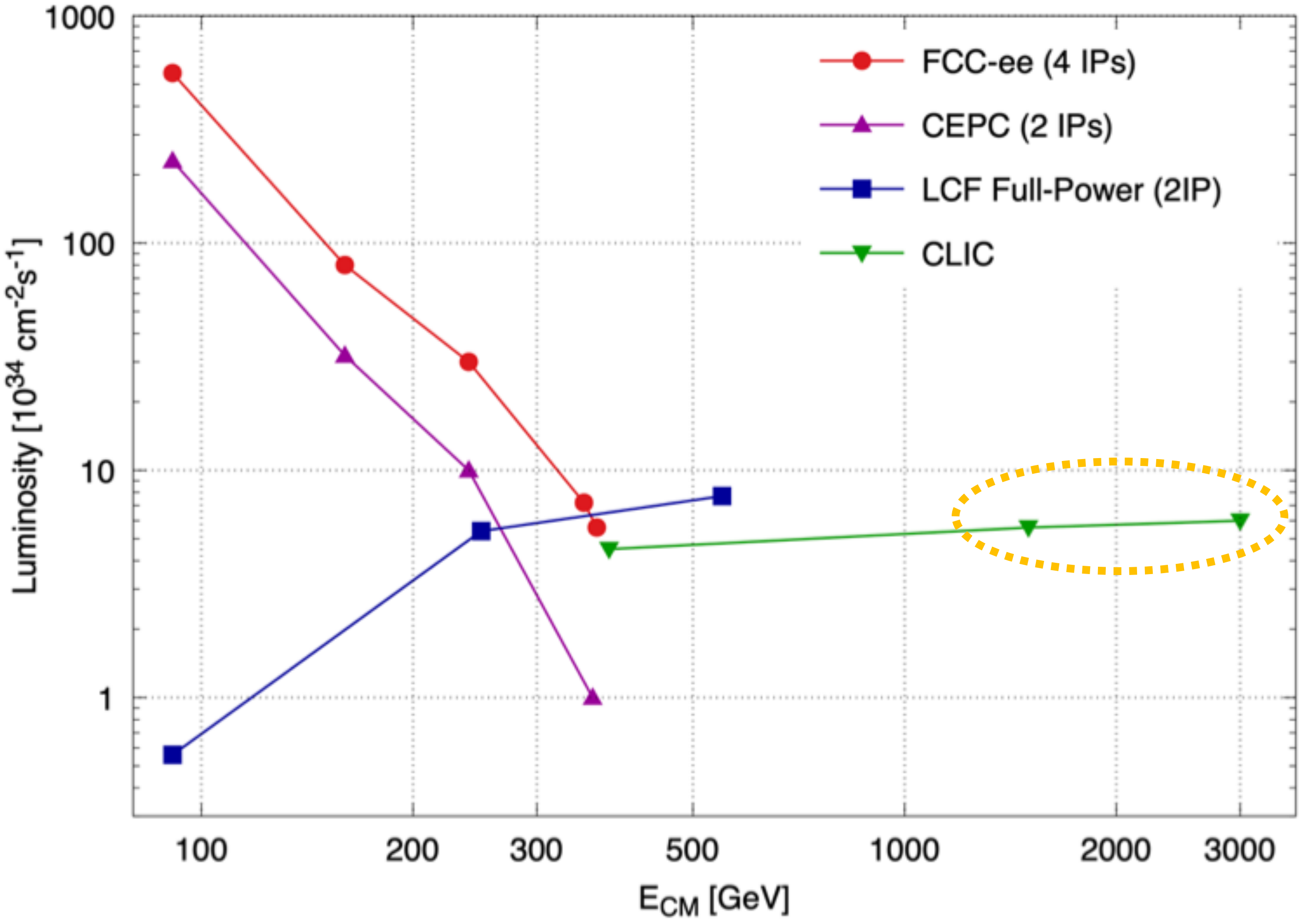
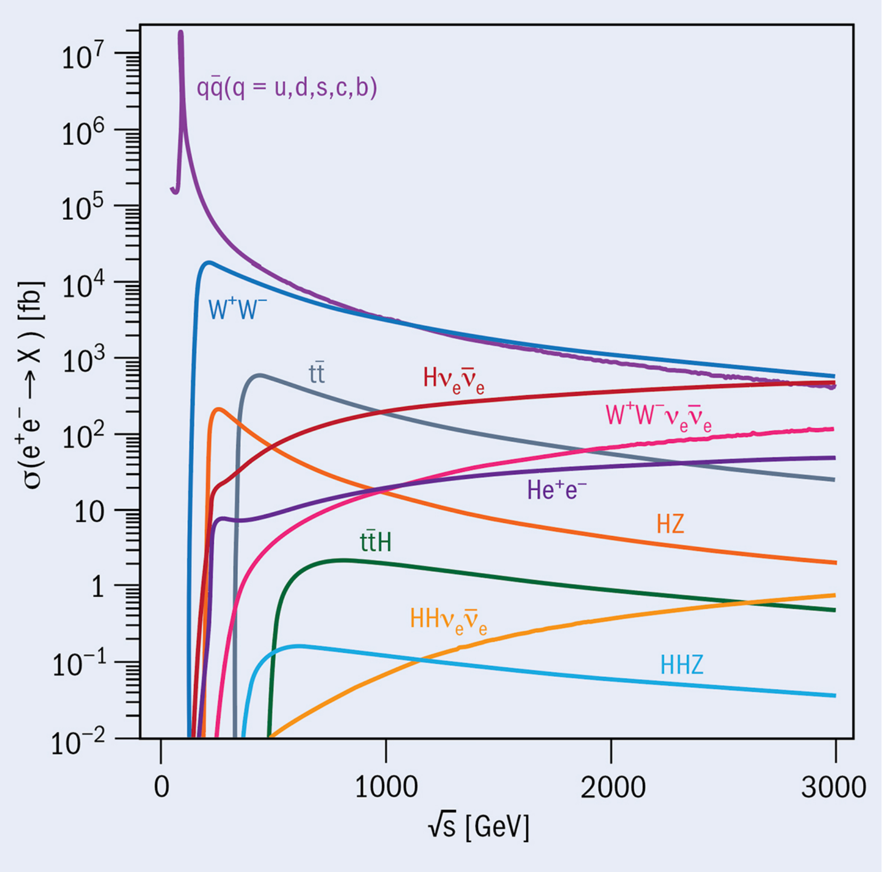
Huge statistics: explore large parameter space

CLIC : High Energy e^+e^- Physics

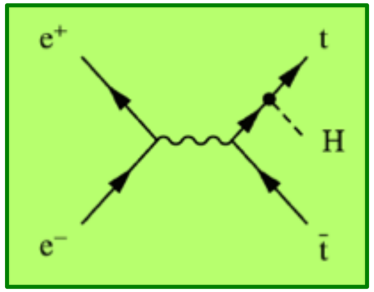


Higgs Poperties at higher energies

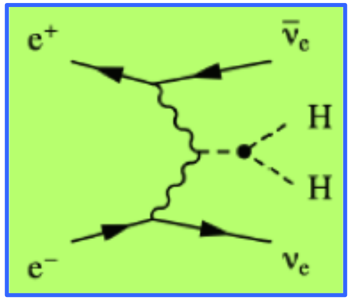
- Why do precision Higgs physics at high √s ?
  - Precision achieved with e^+e^- colliders at √s=240-500 GeV : 0.1% - 1%
    - Superior to what can be done at higher energy
      - σ_{HZ} decreases, kinematics less favourable, backgrounds increase, …
- However, …
  - Some production processes are not directly accessible at low-energy e^+e^- colliders
    - Hence more couplings become measurable at larger energy
      - Htt, HHH, HHHH, …



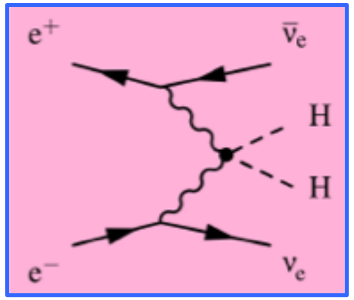
Htt



HHH (for λ_3 determination)

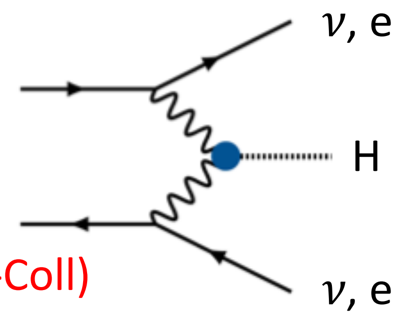


Signal



Background

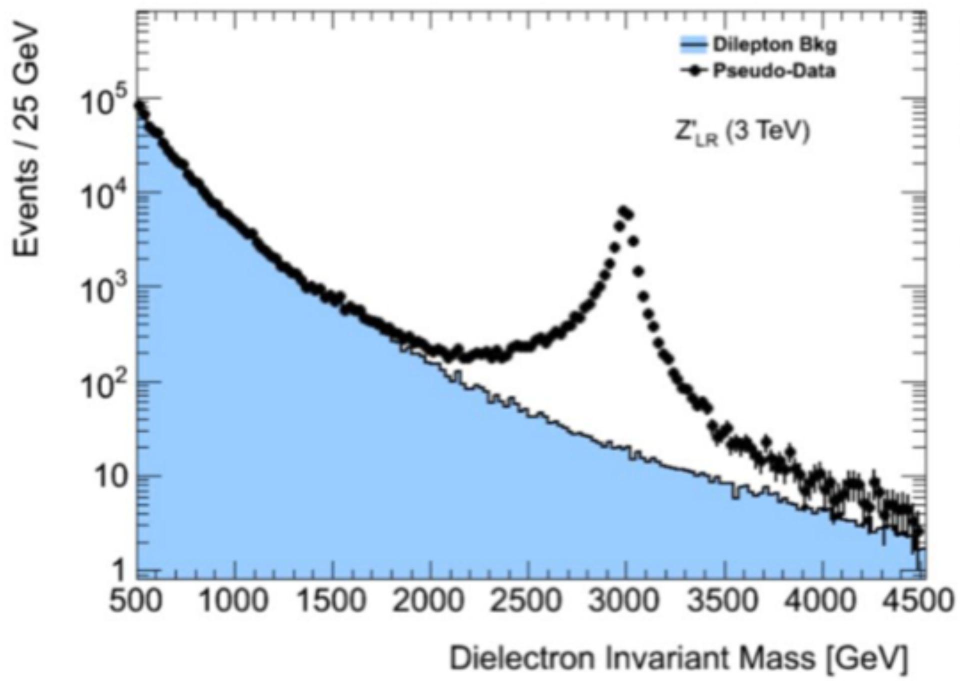
Note: Vector Boson Fusion diagrams increase with energy. Motivation to go to even higher energies (μ-Coll)

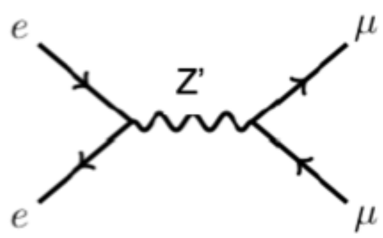


High Energy Searches, Peak vs. mass tails

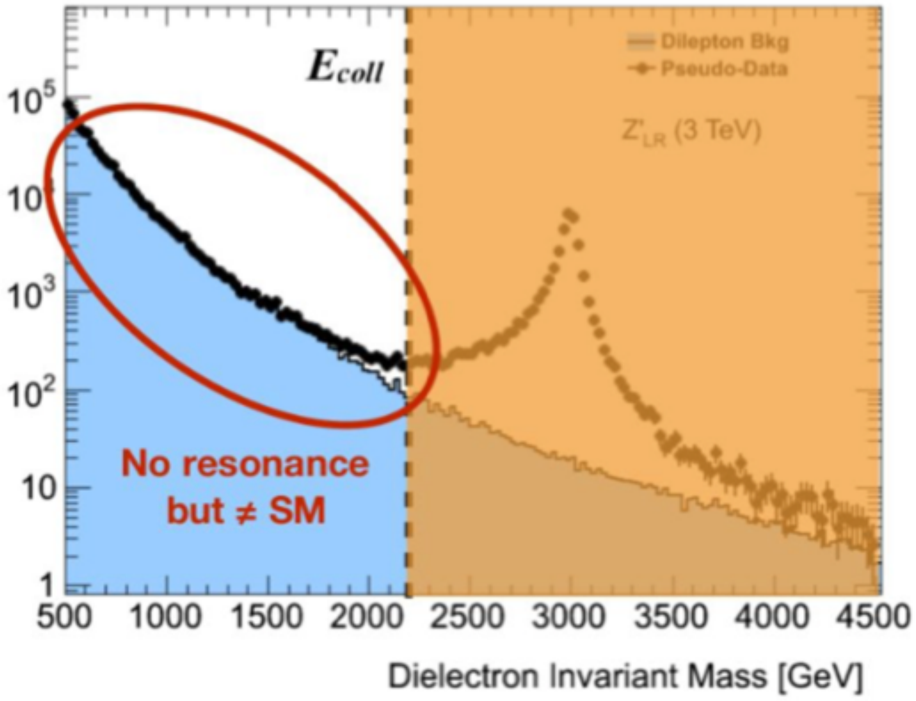
Example:

Z' at 3 TeV





accelerator only goes to √s = 2.2 TeV

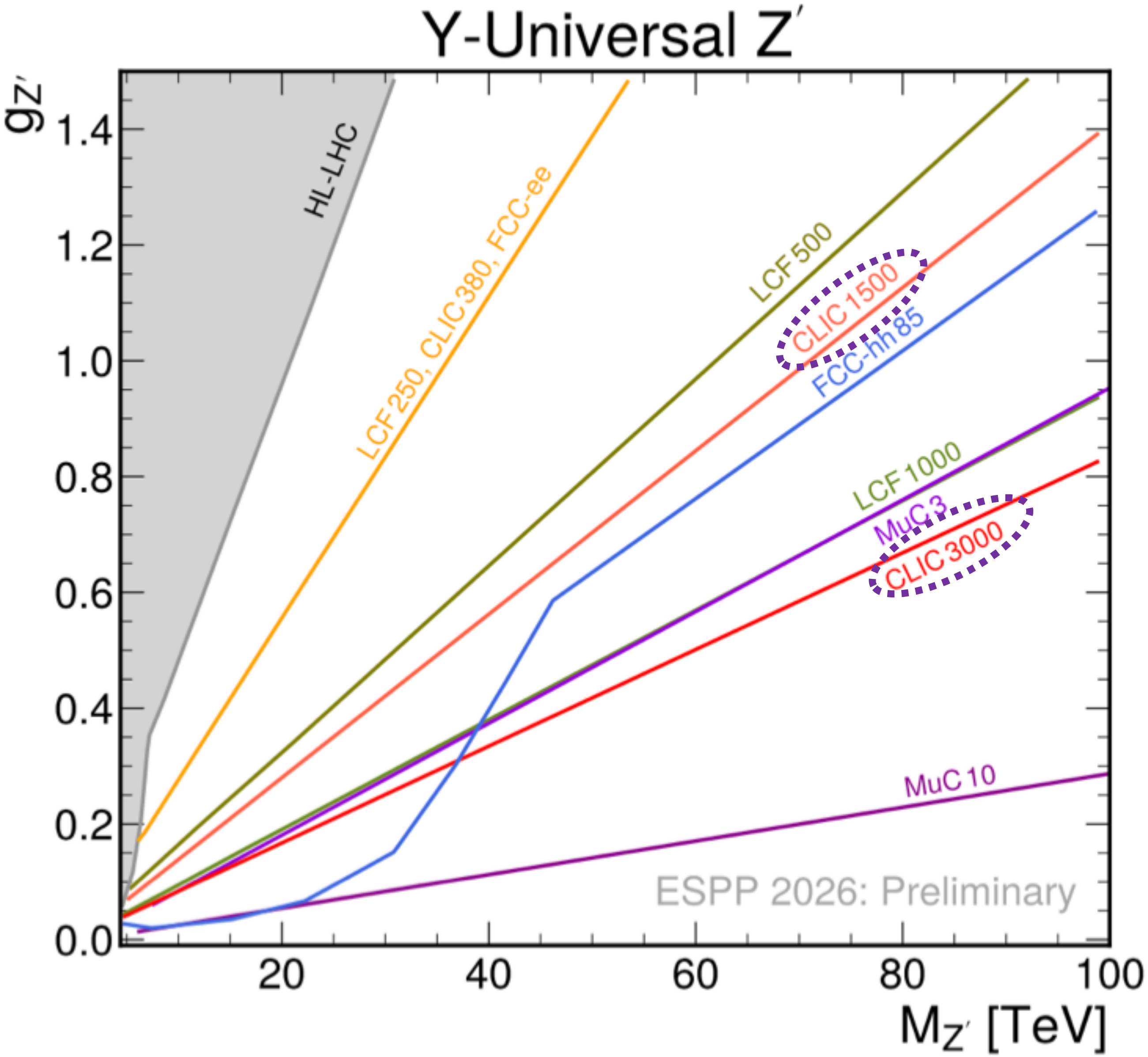


- Seeing the ”peak”. Mass reach:
  - mass < √s for lepton colliders
  - mass ≲ 0.3−0.5 √s at hadron for couplings ~ weak couplings

- Deviations in high-mass tails:
  - Very well suited for lepton colliders; sentitive to [mass/couplings] ≫ √s

High Energy Searches, Peak vs. mass tails

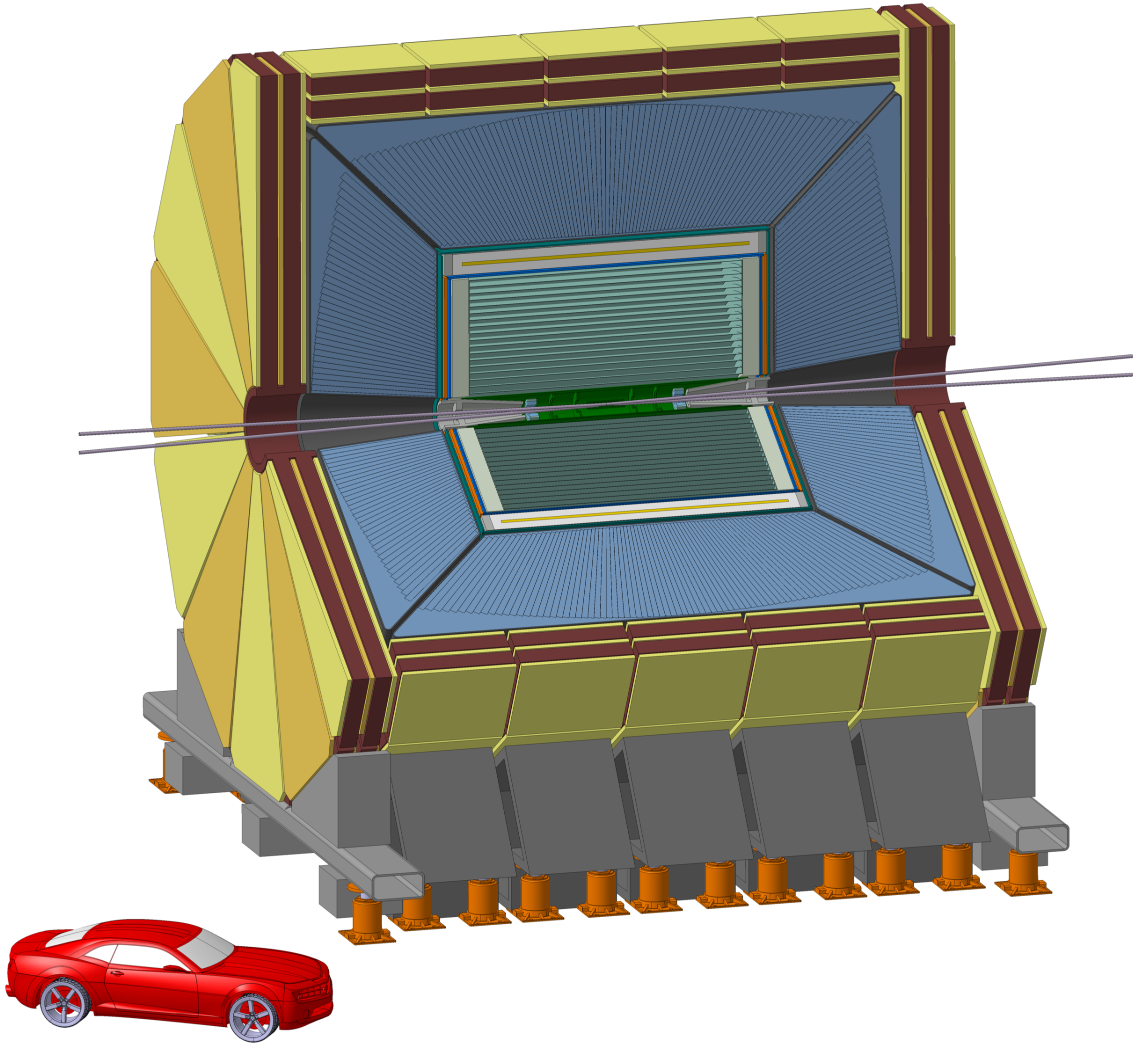
Example: **CLIC se** … oes to √s = 2.2 TeV



- Seeing the "pea … -mass tails:
  - mass < √s for l … d for lepton colliders;
  - mass ≲ 0.3–0. … ass/couplings] ≫ √s
    couplings ~ w

[ESPPU2026 presentation]

Detectors for e^+e^- colliders



Requirements (case FCC-ee including Tera-Z programme)

Higgs Factory Programme

- At $\sqrt{s}$=240 and $\sqrt{s}$=365 GeV collect 2.6M HZ and 150k WW→ H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: s-channel e^+e^- → H at 125 GeV

→

- **Momentum resolution $\sigma(p_T)/p_T \simeq 10^{-3}$ @ $p_T \sim 50$ GeV**
  - σ(p)/p limited by multiple scattering → minimise material
- **Jet σ(E)/E ≃ 3-4% in multijet events for Z/W/H separation**
- **Superior impact parameter resolution for b, c tagging**
- **Hadron PID for s tagging**

Precision EW and QCD Programme

- 6×10^{12} Z and 2×10^8 WW events
- × 500 improvement of statistical precision on EWPO:
  m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W$, R_b, m_W, Γ_W, …
- 2×10^8 tt events: m_{top}, Γ_{top}, EW couplings
- Indirect sensitivity to new physics up to tens of TeV

→

- **Absolute normalisation of luminosity to 10^{-4}**
- **Relative normalisation to ≤ 10^{-5} (e.g. Γ_{had}/Γ_ℓ)**
  - Acceptance definition to $\mathcal{O}$(10 μm)
- **Track angular resolution < 0.1 mrad**
- **Stability of B field to 10^{-6}**

Heavy Flavour Programme

- 10^{12} bb, cc, 2×10^{12} ττ (clean and boosted): 10 × Belle II
- CKM matrix, CP measurements
- rare decays, CLFV searches, lepton universality

→

- **Superior impact parameter resolution**
- **Precise identification and measurement of secondary vertices**
- **ECAL resolution at few %/$\sqrt{E}$**
- **Excellent π^0/γ separation for τ decay-mode identification**
- **PID: K/π separation over wide p range** → dN/dx, RICH, timing

Feebly coupled particles Beyond SM

- Opportunity to directly observe new feebly interacting particles with masses below m_Z
- Axion-like particles, dark photons, Heavy Neutral Leptons
- Long-lifetime LLPs

→

- **Sensitivity to (significantly) detached vertices (mm → m)**
  - tracking: more layers, "continous" tracking
  - calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

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- **Absol… …osity to 10^{-4}**
- **…e.g. $\Gamma_{had}/\Gamma_{\ell}$)**
- **…(10 µm)**
- **…ution < 0.1 mrad**
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Paris Sphicas, ECFA Chair :
"Super Detectors for super Physics"

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  - tracking: more layers, "continous" tracking
  - calorimetry: granularity, tracking capabilities
- **Precise timing**
- **Hermeticity**

Options for subdetector technology

Muon System:
- instrumented return yoke

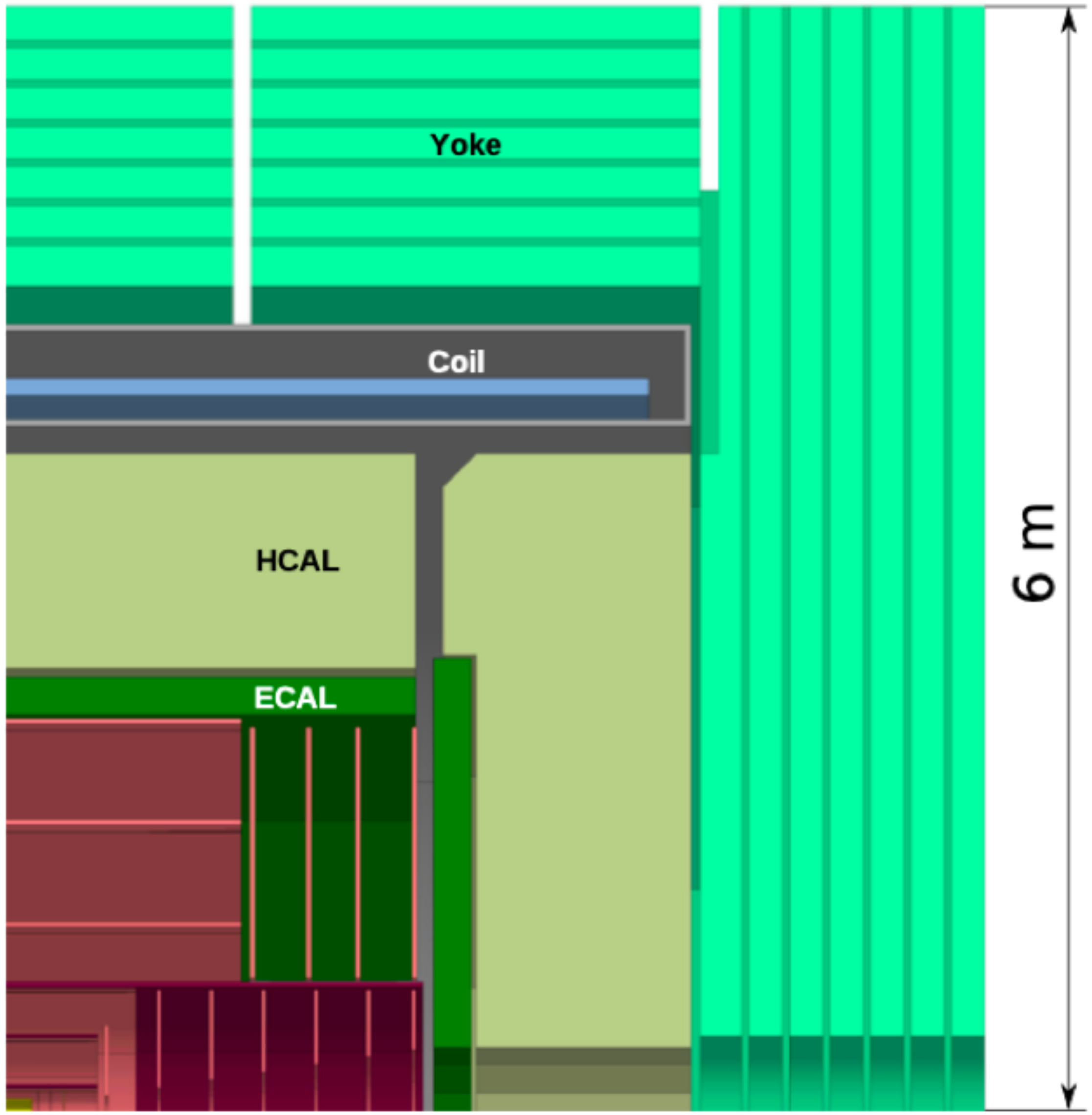
Superconducting Coil:
- Limited to 2 T by beam emittance considerations
- Inside / outside calorimeter system

HCAL options:
- Fe / Scintillating tiles
- Dual readout radial fibres

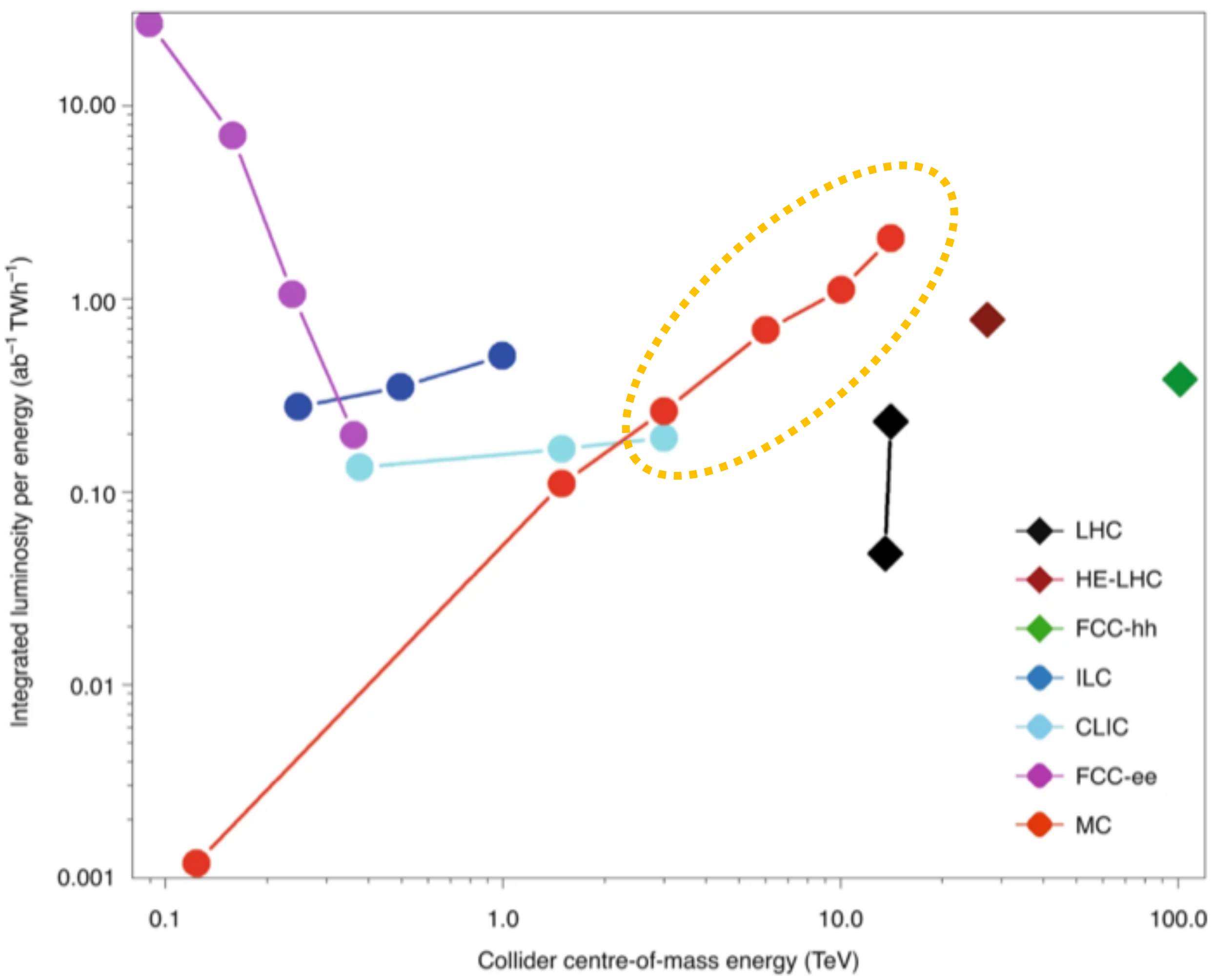
ECAL options:
- W/Si sandwich
- Pb / LAr (or alternatively W / LKr)
- Crystal
- Granita: Crystal gains in heavy liquid

Main tracker options:
- Full silicon
- Drift chamber or straw chamber
- Time Projection Chamber (TPC)

Vertex detector
- Thin 50 µm MAPS silicon pixels sensors, 3x3 µm^2 resolution



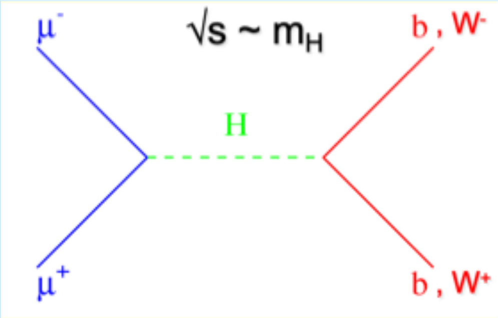
Muon Colliders



Why muon colliders ?

- Like electrons, muons are elementary
  - Collisions at the full energy, small physics background, (E,**p**) conservation
    - Muons can *a priori* do all what electrons can do
- Muons are heavy (107 times electron mass)
  - Negligible synchrotron radiation and beamstrahlung
    - Small circular colliders, up to large $\sqrt{s}$
    - Excellent energy definition (up to a few 10^{-5})
  - Sizeable direct coupling to the Higgs boson
    - Unique *s*-channel Higgs factory at $\sqrt{s}$ = 125.11 GeV
- Muons are naturally longitudinally polarized (100%)
  - Because arising from $\pi^\pm$ decays to $\mu^\pm\nu_\mu$
    - Ultra-precise beam energy and beam energy spread measurement
- Muons eventually decay (τ= 2.2 μs; $c\tau$ = 660 m) to $e\nu_\mu\nu_e$
  - Outstanding neutrino physics programme
    - Muon colliders could be the natural successors of neutrino factories ?

Few years back there was talk of an *s*-channel Higgs factory

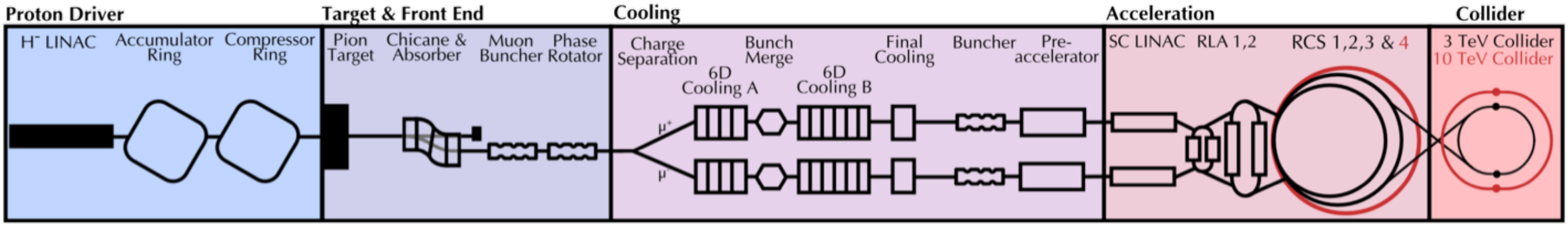


Problematic to get sufficient luminosity at such low energies. Projeced event counts only at $\mathcal{O}(10^4)$ after years of operation.

Here, concentrate on High Energy Muon Collliders

Muon Collider Concept

Muons decay, $\tau = \gamma \times 2.2\ \mu s$: Produce, Collect, Cool, Accelerate, and Collide them fast !



Short, intense proton bunch

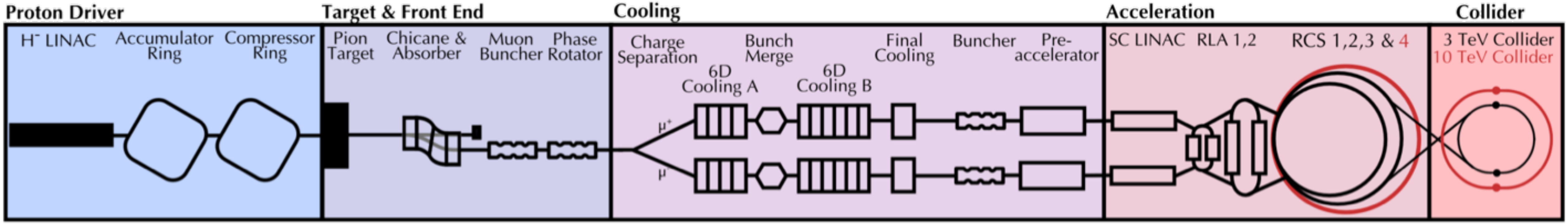
Protons produce pions which decay into muons which are captured

Ionisation cooling of muon in matter

Fast acceleration to collision energy

Collision

Muon Collider Challenges



- Intense proton driver to get adequate number of muons
  - 2-4 MW for the desired luminosities
- Robust target to not evaporate at the first proton bunch
  - Re-circulated liquid metal (mercury) or possibly graphite
- Efficient muon collecor from pion decays
  - Focussing by solenoidal magnets of up to 40-55 Tesla strength
- Unique 6D muon cooling to reduce beam sizes and energy spread
  - Alternating multiple-scattering energy loss and re-acceleration
- Fast acceleration and injection into circular ring
  - Multiple acceleration rings of increasing size (RCS = Rapid Cycling Synchrotrons)
- Background from decaying beam muons
  - In detectors and environmental

All these aspects are at the level of intense R&D. Time is needed to demonstrate feasibility

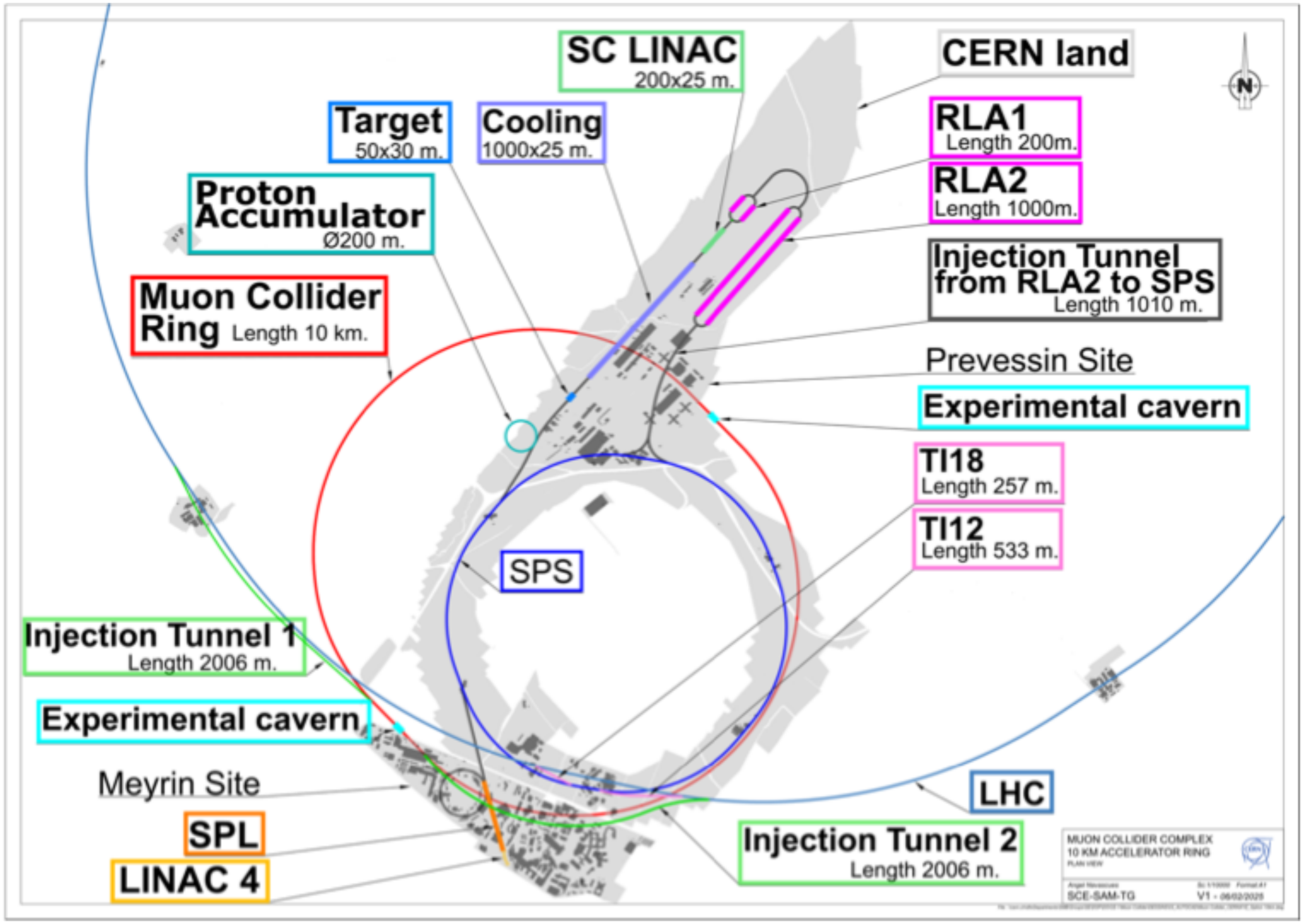
ESPP Comparative Evaluation Working Group, May 2025:
"While progress is being made, the MC has not yet reached a matyrity level that gives sufficient confidence in its feasibility"

CERN specific placement studies

First studies:

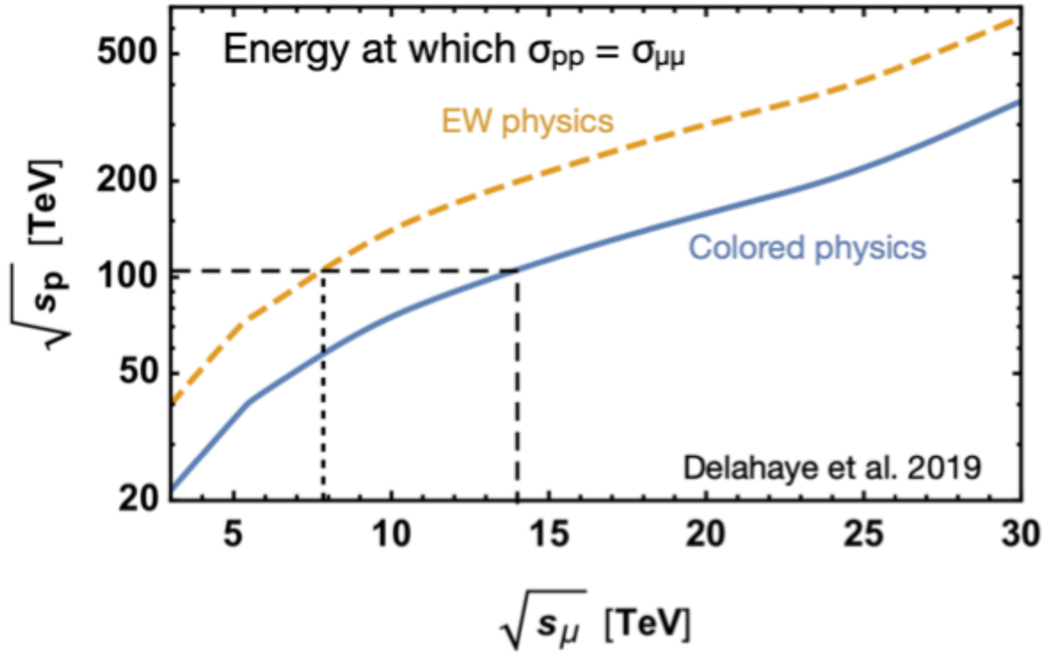
- Facility constructed entirely on CERN site except tunnels
- Three RCS accelerator rings
  - One in SPS, two in LHC tunnels
- New 10 km collider ring
  - Two experimental sites
- Collision energy considered
  - Stages of 3.2 and 7.6 TeV
  - 10 TeV maybe possible with better technology
    - e.g. 16 T dipoles

- Similar studies also for Fermilab site

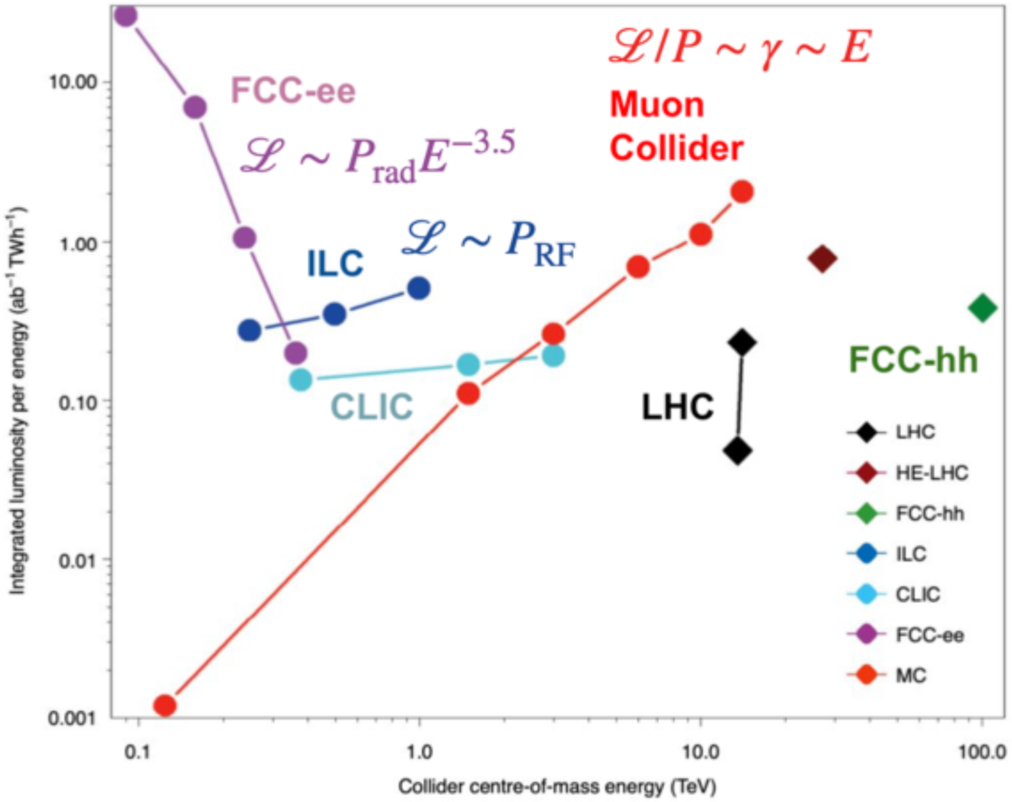


Muon Colliders at the energy frontier

- Muons are elementary
  - No energy lost in PDFs, full beam energy available for hard scattering
  - From comparison of pp and μμ cross sections
    - Coloured particles: 100 TeV pp ~ 14 TeV μμ
    - EW particles: 100 TeV pp ~ 8 TeV μμ



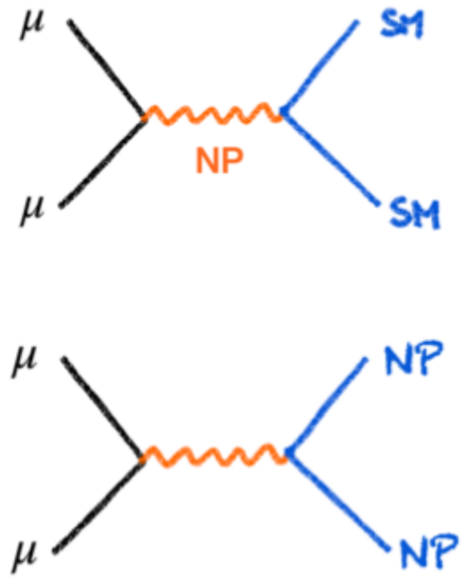
- Very attractive luminosity performance at highest energies
  - Luminosity scales with square of energy
    - Muon lifetime increases
    - Transverse beam emmitance decreases



Muon Collider Physics brief Overview

Direct Searches

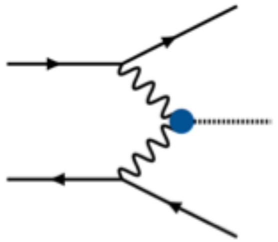
high energy to search for heavy new particles

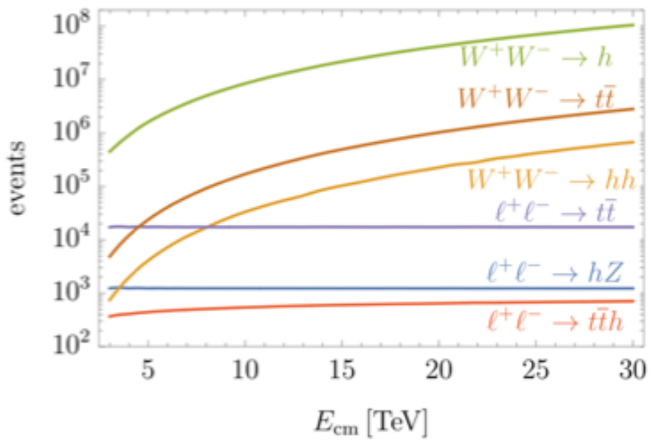


High-rate SM measurements

high statistics for precise measurements

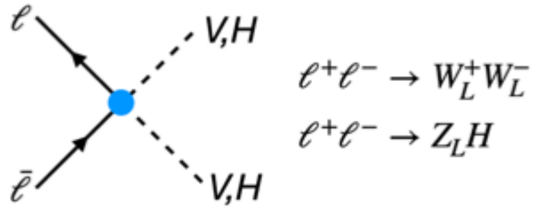
large rates for VBF

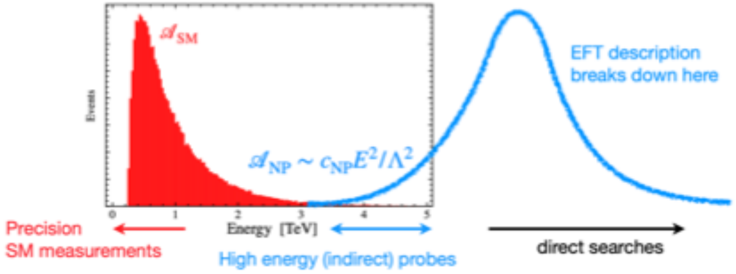




High-energy SM measurements

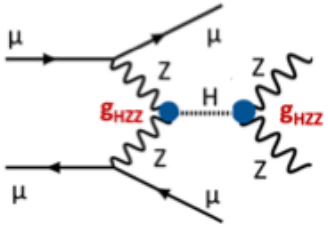
high energy to look for NP in SM processes



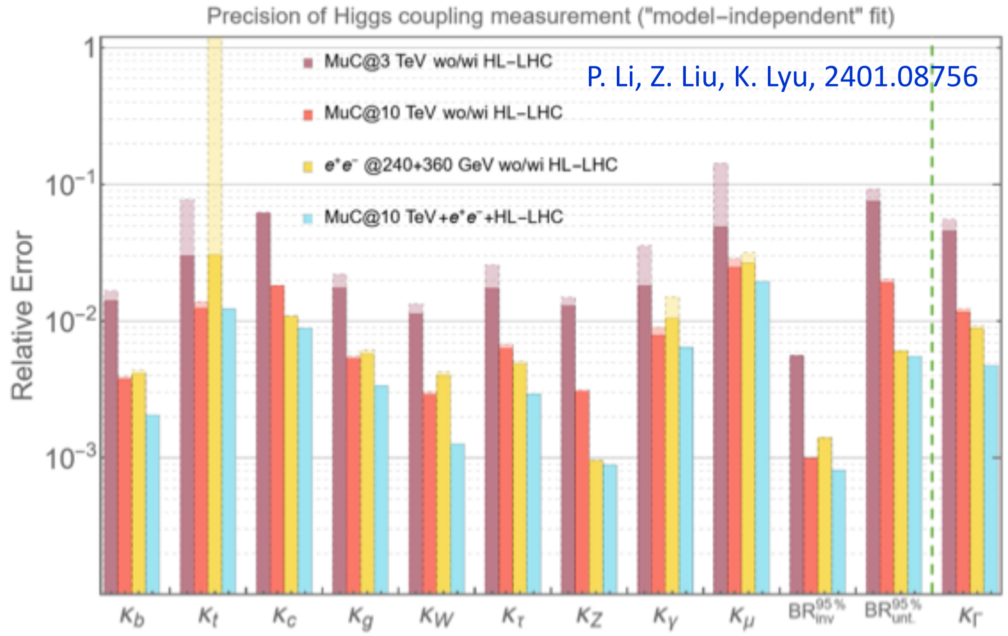


Higgs Physics at Muon Colliders

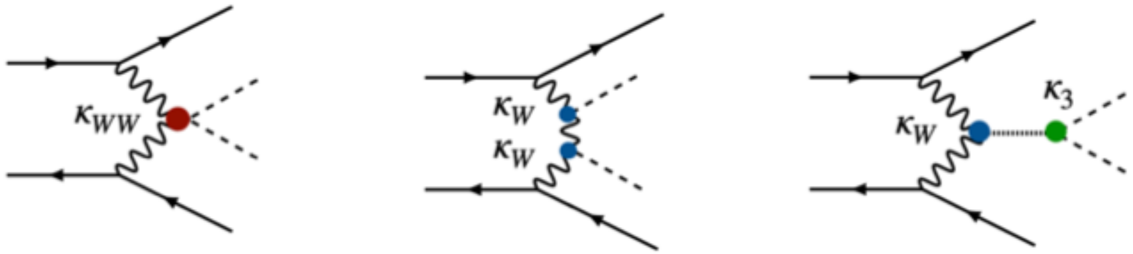
- Comprehensive Higgs programme
  - With forward muon tagging, can determine Higgs width and hence absolute couplings

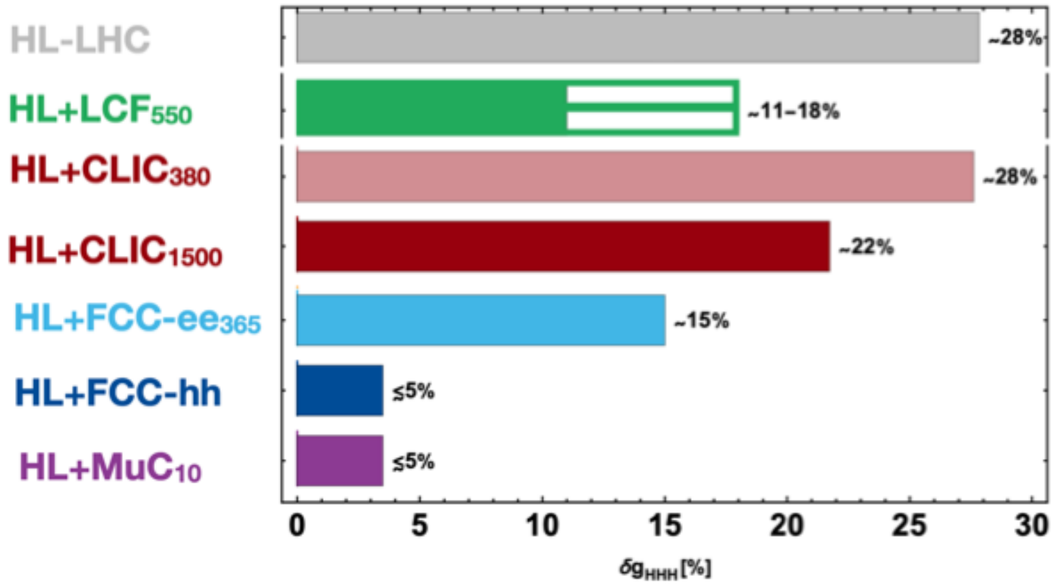


  - Precisions: approaching but not beating FCC-ee…



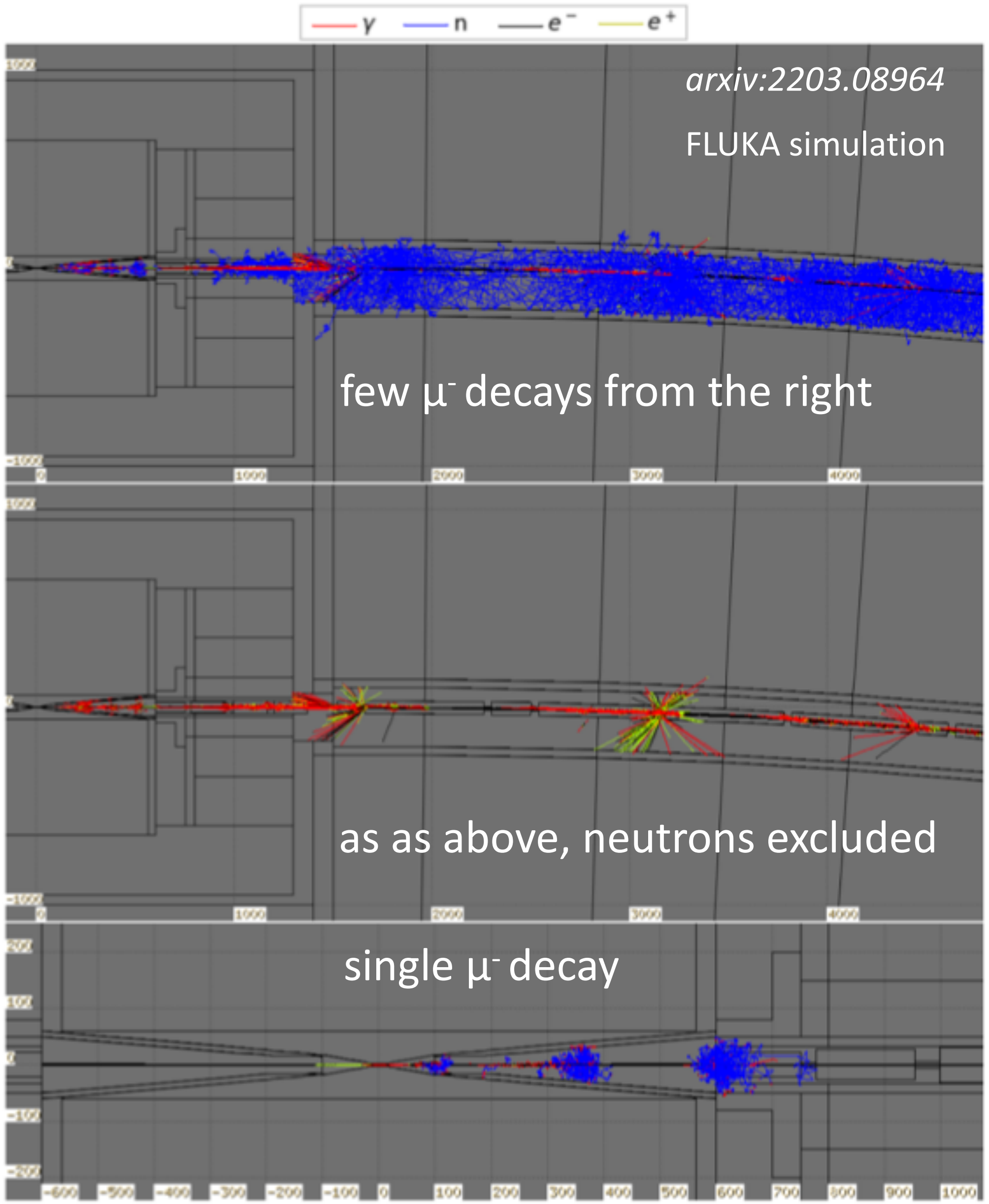
- Very competitive measurement of Higgs self-coupling via di-Higgs production





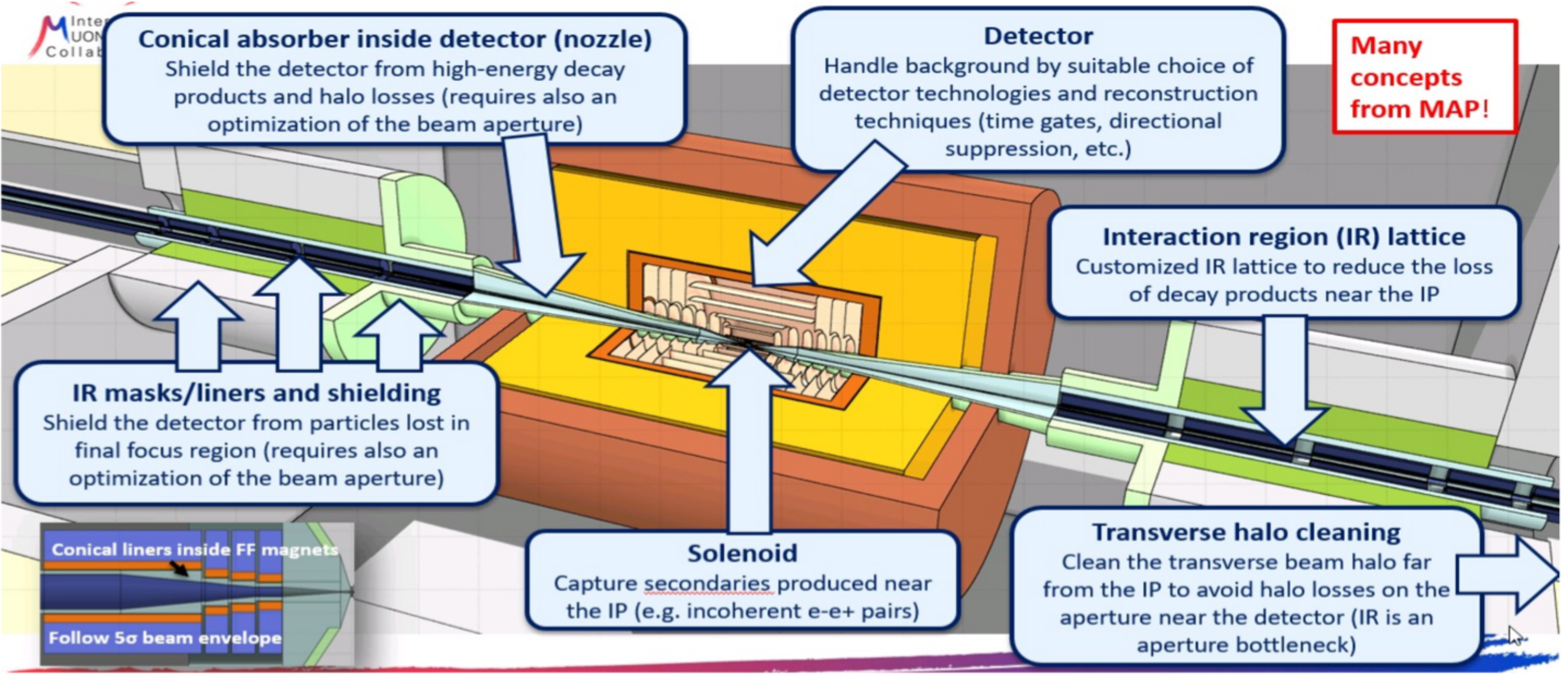
Muon Collider Experimental Challenge

- Beam population of 2×10^{12} per bunch
- Huge number, $\mathcal{O}(10^5)$, muon decays per meter of lattice
- Decay electrons carry enormous energy (>10^4 TeV/meter)
- Secondary / tertiary particles interact with lattice creating "Beam induced Background" (BIB)
- Layout of Machine Detector Interface (MDI) crucial for absorbing as much of BIB as possible and keep it away from detector volume
- Design for 0.75 TeV beam
  - Conical nozzles with 10° opening angle
    - limiting forward acceptance; potential conflicting with desire to tag forward muons from ZZ-fusion process
- Designs being development also for 1.5 TeV and 5 TeV beams



Reduction of Beam Induced Backgrounds

Nadia Pastrone

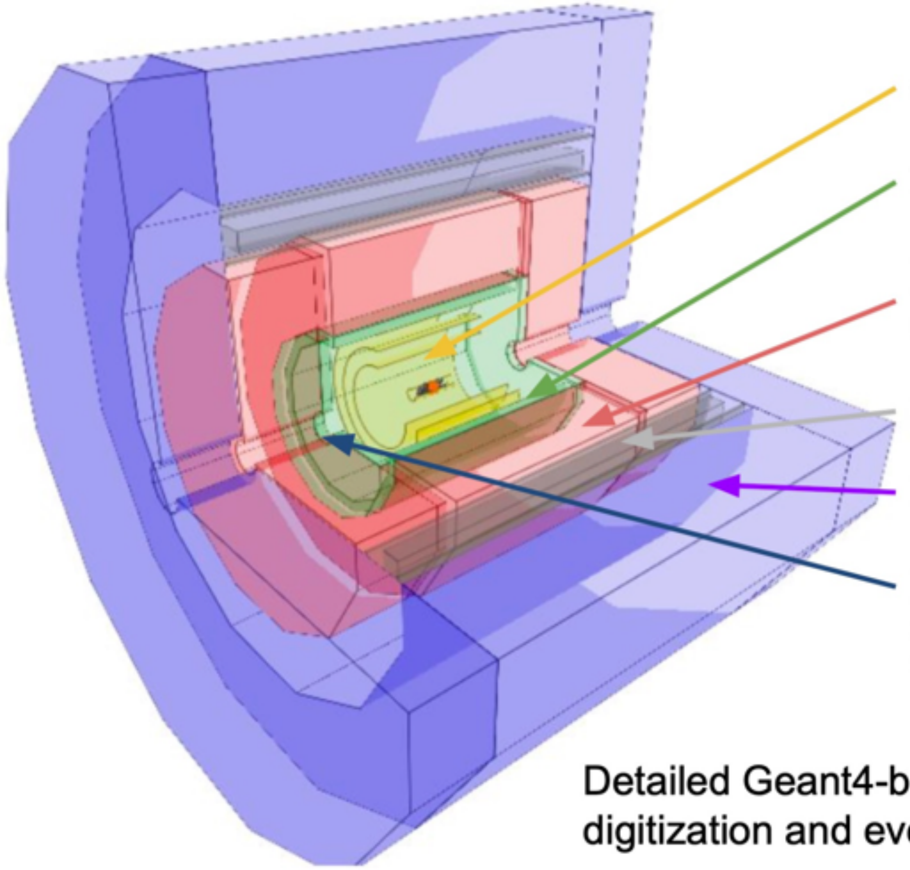


Detector Studies

Nadia Pastrone

Multi-purpose detector that targets very broad physics goals.

- many components still inherited from CLIC design and can be further optimized



Detailed Geant4-based simulation, dedicated digitization and event reconstruction software.

Vertex Detector (VXD)

- 4 double-sensor barrel layers 25x25μm^2
- 4+4 double-sensor disks 25x25μm^2

Inner Tracker (IT)

- 3 barrel layers 50x50μm^2
- 7+7 disks ”

Outer Tracker(OT)

- 3 barrel layers 50x50μm^2
- 4+4 disks ”

Electromagnetic Calorimeter (ECAL)

- 40 layers W absorber and silicon pad sensors, 5x5 mm^2

Hadron Calorimeter (HCAL)

- 60 layers steel absorber & plastic scintillating tiles, 30x30 mm^2

Rounding off

Key Points

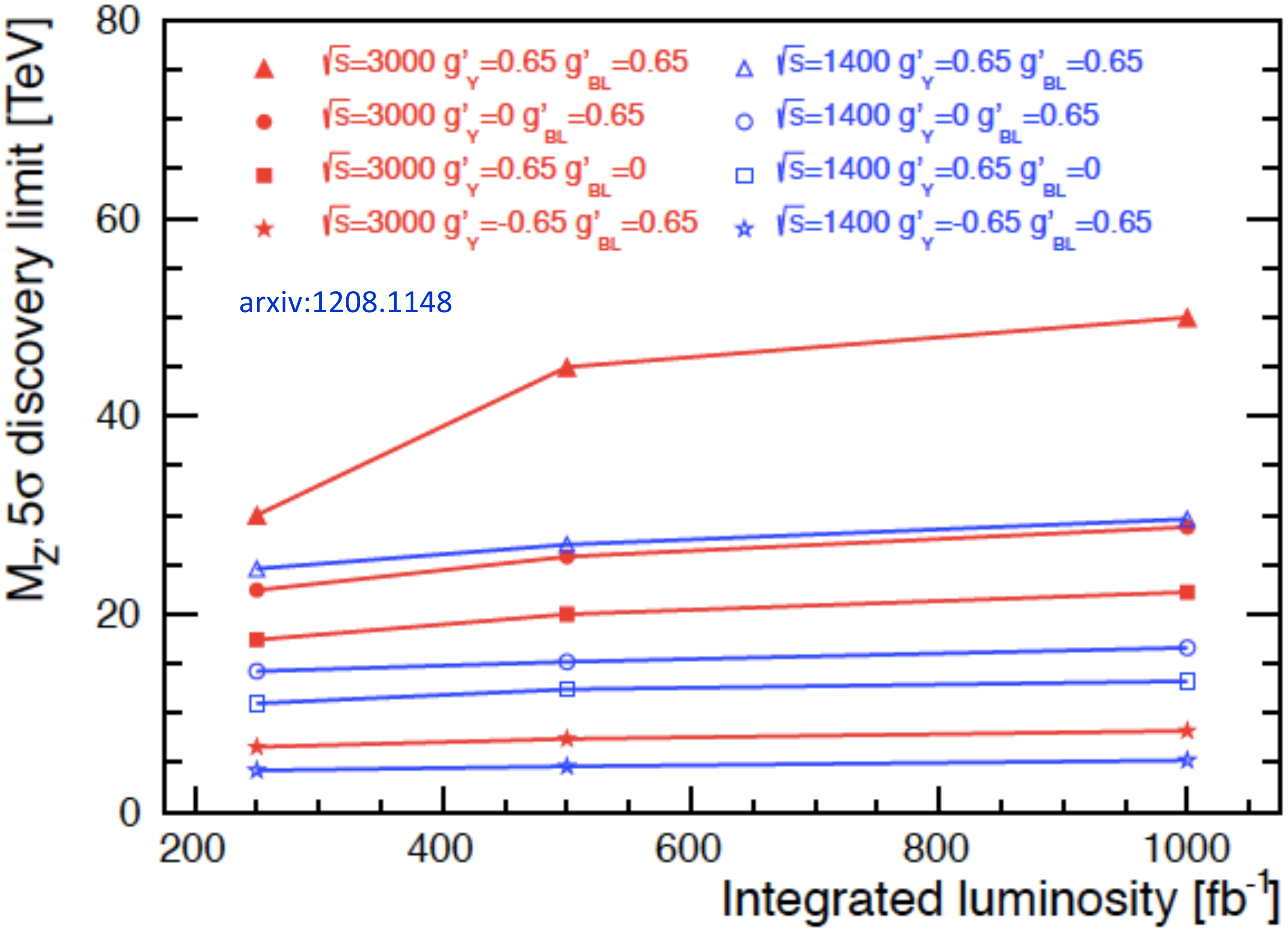
- Electron-positron colliders have played an important role in the development of particle physics research
- Since LEP, there has been a dramatic development in e^+e^- accelerator technology
  - Linear colliders: Energy reach up to $\sqrt{s}$ = 3 TeV
  - Circular colliders: Increase of instantaneous luminosity by 4-5 orders of magnitude
- With the discovery of a light Higgs boson and the non-discovery (so far) of new heavier states, e^+e^- communities have been sooming in on the $\sqrt{s}$ < 400 GeV region
  - LCF : Higgs factory at $\sqrt{s}$ = 250 GeV as first stage; $\sqrt{s}$ = 550 GeV in a later stage
  - CLIC : Higgs/top factory at $\sqrt{s}$ = 380 GeV; $\sqrt{s}$ = 1.5 TeV in a later stage
  - FCC-ee: Very high luminosity electroweak, Higgs, and top factory at $\sqrt{s}$ = 91, 160, 240, 365 GeV
- An e^+e^- Higgs factory with $\mathcal{O}(10^6)$ Higgs decays provides sub-% level measurement of (most) Higgs couplings
  - Strong New Physics reach!
- Electroweak precision measurements provide a strong test of SM
  - A circular e^+e^- collider with 90 < $\sqrt{s}$ < 400 GeV could improve precision of EW parameters by 1-2 orders of magnitude
  - Strong New Physics reach!
- CLIC programme at $\sqrt{s}$ = 1.5 TeV has access to complementary measurements
  - Higgs self-coupling, precise top studies, sensitivity to New Physics
- In a longer-term future, muon colliders may be the way to go for the energy frontier lepton colliders

Thank you !

High Energy Searches, Peak vs. mass tails

Example:

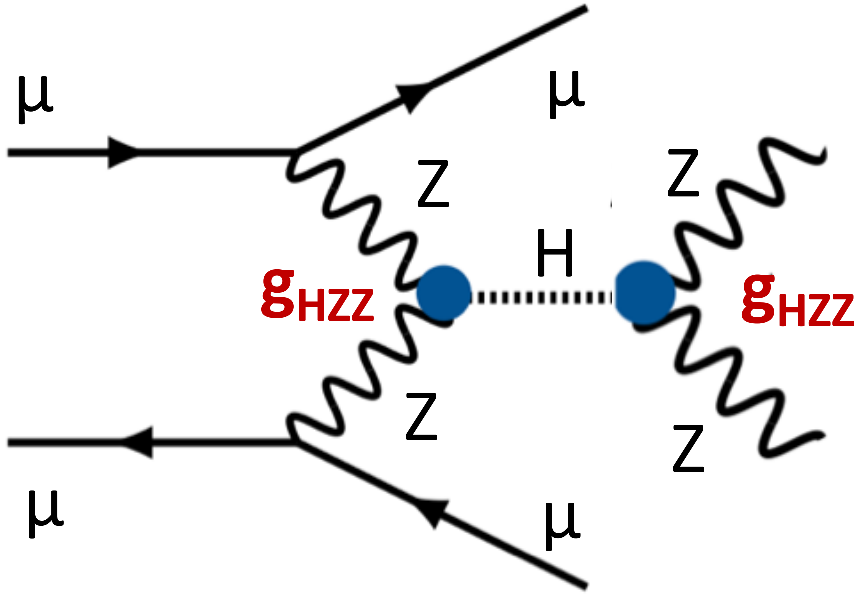
CLIC sensitive to Z' with masses up to several 10s of TeV

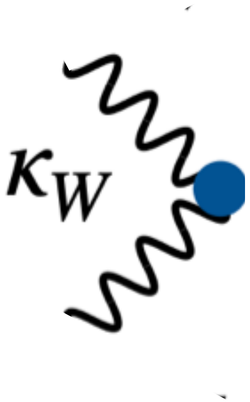


Observables:

- Total $e^+e^- \rightarrow \mu^+\mu^-$ cross section
- Forward-backward asymmetry
- Left-right asymmetry

(with ±80% e^- polarisation)


μ
μ
Z
Z
H
g_{HZZ}
g_{HZZ}
Z
Z
μ
μ

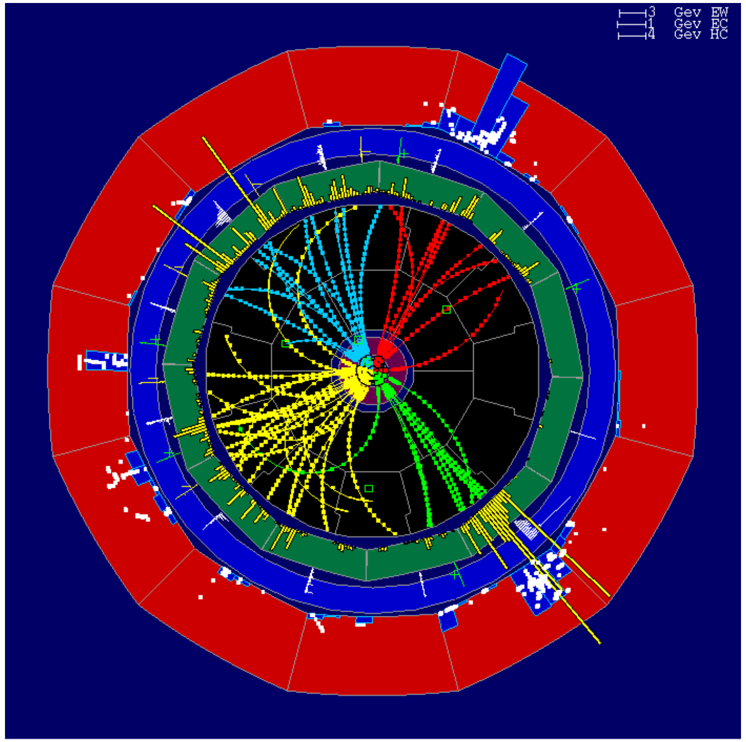

κ_W

e^+e^- collisions

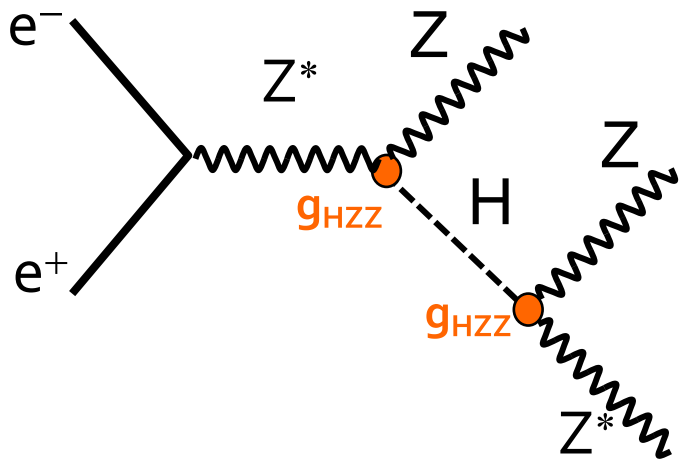
- Electrons are elementary particles: no underlying event
  - Final state has known energy and momentum: ($\sqrt{s}$, 0, 0, 0)

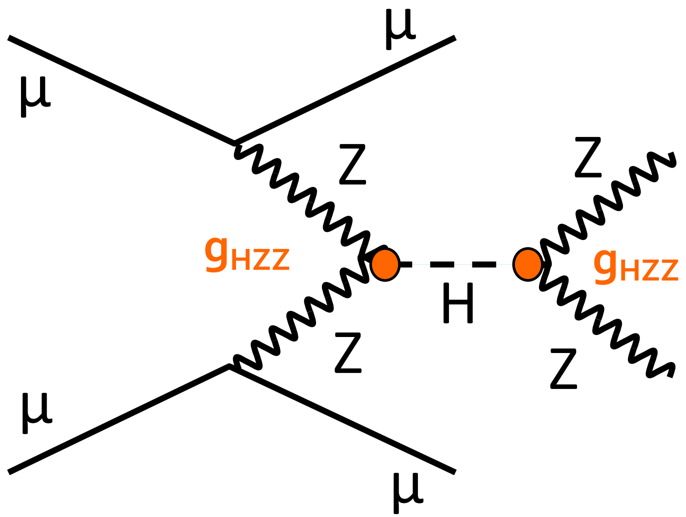
- Example: an $e^+e^- \rightarrow W^+W^-$ candidate
  - Four jets and nothing else
  - Total energy and momentum conserved
    - $E_1 + E_2 + E_3 + E_4 = \sqrt{s}$
    - $p_1^{x,y,z} + p_2^{x,y,z} + p_3^{x,y,z} + p_4^{x,y,z} = 0$

$$\begin{bmatrix} 1 & 1 & 1 & 1 \\ \beta_1^x & \beta_2^x & \beta_3^x & \beta_4^x \\ \beta_1^y & \beta_2^y & \beta_3^y & \beta_4^y \\ \beta_1^z & \beta_2^z & \beta_3^z & \beta_4^z \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \end{bmatrix} = \begin{bmatrix} \sqrt{s} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$



  - Jet energies (and di-jet masses, m_W) determined analytically by inverting the matrix
    - No systematic uncertainty related to jet energy calibration
      - A lot of Z are available anyway to calibrate and align everything


e⁻
e⁺
Z*
Z
Z
H
gHZZ
gHZZ
Z*


μ
μ
μ
μ
Z
Z
Z
Z
H
gHZZ
gHZZ