Physics at future e^+e^- colliders

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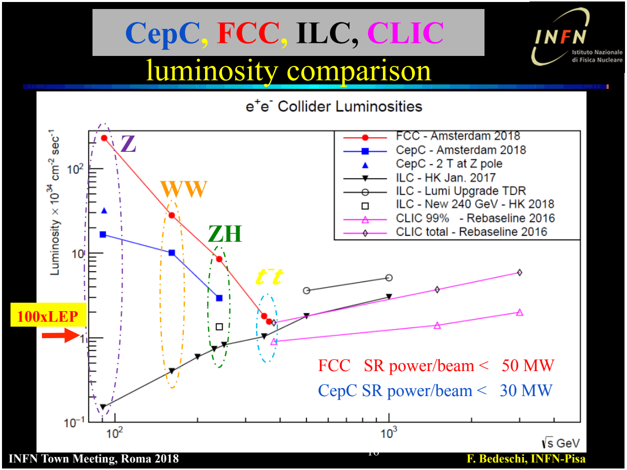
Pisa School on future colliders, Pisa

Pisa, 17-21 September 2018

luminosity comparison among lepton colliders



CepC, FCC, ILC, CLIC

luminosity comparison

FCC SR power/beam < 50 MW

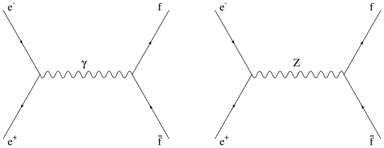
CepC SR power/beam < 30 MW

INFN Town Meeting, Roma 2018

F. Bedeschi, INFN-Pisa

F. Bedeschi, INFN EU Strategy Meeting, 6-7 September 2018, Roma, Italy

e^+e^- collisions @ $\sqrt{s} \simeq M_Z$



Primary observables

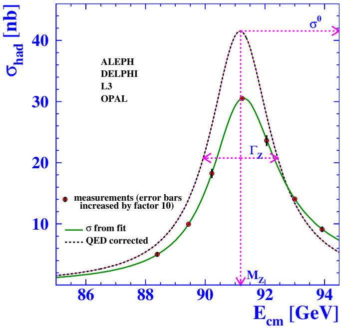
- absolute cross sections for different species of fermions $\sigma_f(s)$
- Forward-backward asymmetries $A_{FB}(s)$ (sensitive to parity violation)

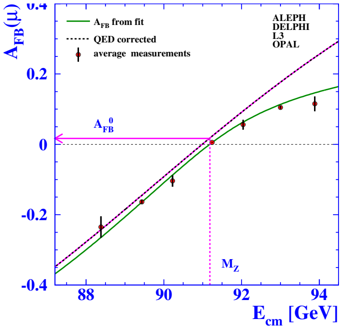
$$\sigma = \sigma_F + \sigma_B$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\sigma_F = 2\pi \int_0^1 d\cos\vartheta \, \frac{d\sigma}{d\Omega}, \qquad \sigma_B = 2\pi \int_{-1}^0 d\cos\vartheta \, \frac{d\sigma}{d\Omega}$$

measurements @ Z peak at LEP





Large differences due to QED initial state radiation

$$\sigma_{\rm T}(s) = \int_{z_0}^{1} dz H(z;s) \hat\sigma_{\rm T}(zs) \qquad A_{FB}(s) = \frac{\pi\alpha^2 Q_e^2 Q_f^2}{\sigma_{\rm tot}} \int_{z_0}^{1} dz \frac{1}{(1+z)^2} H_{\rm FB}(z;s)\, \hat\sigma_{\rm FB}(zs)$$

Pseudo-observables

- Idea: extract as much as possible information on the Z properties *independently* of the event selection details

Observable	Symbol
hadronic peak cross-section	σ_h
partial leptonic and hadronic widths	$\Gamma_l \ (l = e, \mu, \tau), \Gamma_c, \Gamma_b$
total width	Γ_Z
hadronic width	Γ_h
invisible width	Γ_{inv}
ratios	R_l, R_b, R_c
forward-backward asymmetries	$A^l_{FB}, A^b_{FB}, A^c_{FB}$
polarization asymmetries	P^τ, P^b
left-right asymmetry (SLC)	A^e_{LR}
effective sine	$\sin^2\vartheta^l_{eff}, \sin^2\vartheta^b_{eff}$

$$\Gamma_f = 4N_c\Gamma_0[(g^f_V)^2 R^f_V + (g^f_A)^2 R^f_A]$$

$$\Gamma_{inv} = \Gamma_Z - \Gamma_e - \Gamma_\mu - \Gamma_\tau - \Gamma_h$$

$$R_l = \frac{\Gamma_h}{\Gamma_l}$$

$$R_{b,c} = \frac{\Gamma_{b,c}}{\Gamma_h}$$

$$\sigma^0_{had} = 12\pi \frac{\Gamma_e\Gamma_h}{M_Z^2\Gamma_Z^2}$$

$$A_f = \frac{2g^f_V g^f_A}{(g^f_V)^2 + (g^f_A)^2}$$

$$A^f_{FB} = \frac{3}{4}A_e A_f$$

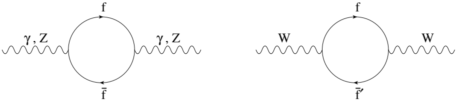
$$A^e_{LR} = A_e$$

$$P^f = -A_f$$

$$4\,|Q_f|\sin^2\vartheta^f_{eff} = 1 - \frac{g^f_V}{g^f_A}$$

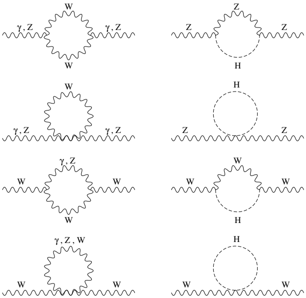
High exp. precision and th. precision

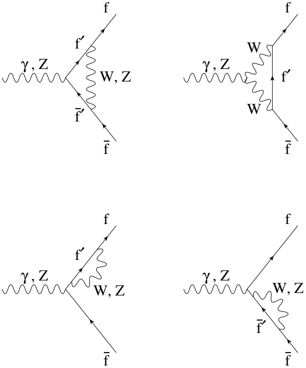
- Exp. precision at the level of 0.01% or better
- How accurate are theoretical predictions? The one-loop example
  - we have to rely on perturbation theory
  - the "theoretical accuracy" is given by the size of the next (not calculated) perturbative order
  - the tree-level approximation has an uncertainty of the order of several %, as proved by the calculated effects at one-loop approximation $\Longrightarrow$ we need to include higher order effects



- in the loop we have to sum over all possible (also heavy) particles which couple to γ and/or Z

Not only fermions but also bosons...

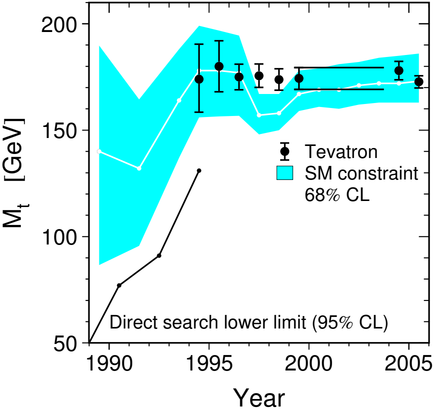




- Theoretical predictions become sensitive to all the spectrum and structure of the theory: m_t, number of light neutrinos, m_H, non abelian γWW and ZWW vertices
- m_t experimental uncertainty becomes a source of th. uncertainty $\Longrightarrow$ **very important the run at the $t\bar{t}$ threshold**

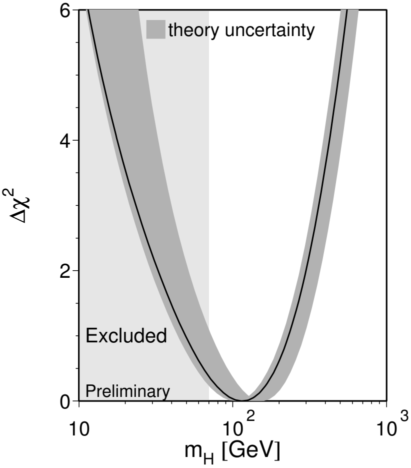
The “indirect” discovery of the quark top at LEP

- before 1995 the dependence on m_t could be used to “measure” m_t from a best-fit to Z-peak data (χ^2 depends quadratically on $G_F(m_t^2 - m_b^2)$ in a gauge theory with SSB)

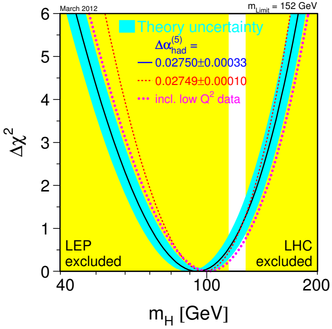


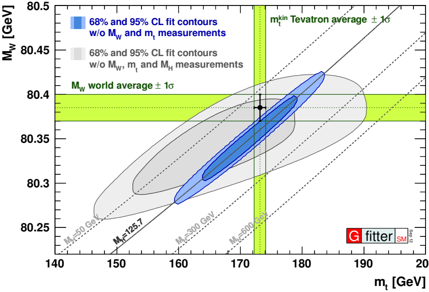
the same could be said about m_H

- however, dependence on m_H is only logarithmic
- at the end of LEP1

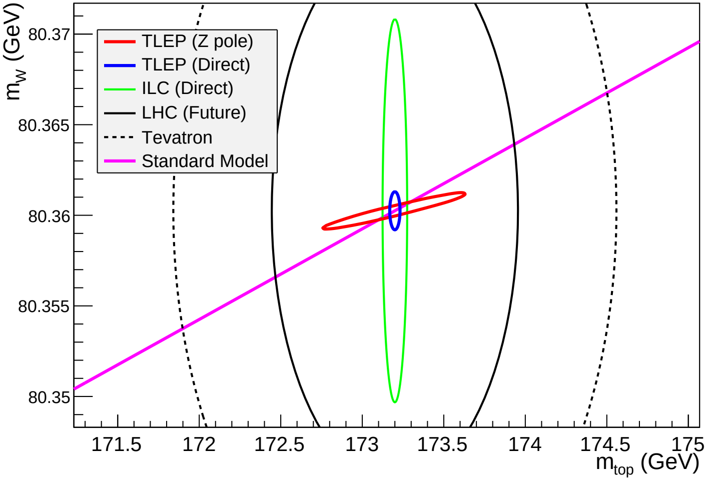


some years later, after switching on LHC





possible contour 68% plot after FCC-ee running



M. Bicer et al., arXiv:1308.6176

N_ν from Z invisible width

$$R^0_{\rm inv} = \frac{\Gamma_{\rm inv}}{\Gamma_{ll}} = \sqrt{\frac{12\pi R^0_l}{\sigma^0_{\rm had} m_Z^2}} - R^0_l - (3+\delta_\tau)$$

- assuming lepton universality

$$\left(R^0_{\rm inv}\right)_{\rm exp} = N_\nu \left(\frac{\Gamma_{\nu\bar\nu}}{\Gamma_{ll}}\right)_{\rm SM}$$

- from LEP Z-peak measurements

$$\begin{aligned} N_\nu &= 2.9840 \pm 0.0082 \\ \delta N_\nu &\simeq 10.5\frac{\delta n_{\rm had}}{n_{\rm had}} \oplus 3.0\frac{\delta n_{\rm lept}}{n_{\rm lept}} \oplus 7.5\frac{\delta\mathcal{L}}{\mathcal{L}} \\ \frac{\delta\mathcal{L}}{\mathcal{L}} &= 0.061\% \Longrightarrow \delta N_\nu = 0.0046 \end{aligned}$$

ADLO, SLD and LEPEWWG, Phys. Rept. 427 (2006) 257, hep-ex/0509008

- δN_ν severely affected by luminosity uncertainty through σ_0

QED processes: candles for $\mathrm{e}^+\mathrm{e}^-$ collider luminosity

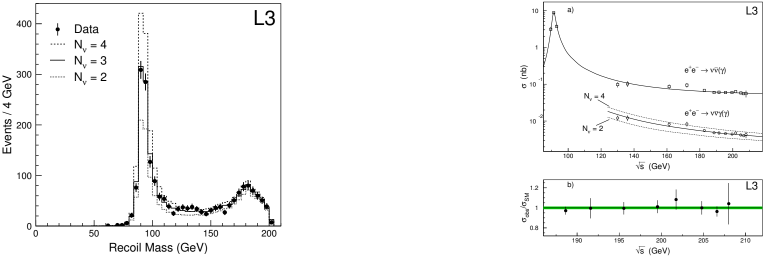
- Luminosity is a machine (process independent) parameter entering every experimental cross-section

$$\frac{N_{obs}}{\mathcal{L}} = \sigma \quad \rightarrow \quad \mathcal{L} = \frac{N_{obs}^X}{\sigma_{theory}^X}$$

- in order to minimize $\delta\mathcal{L}$, the reference process X has to have large statistics, be well calculable theoretically, be cleanly detectable (small systematics)
- the best choice are QED processes, in particular Bhabha
  - ⋆ at small angles
  - huge statistics, by far dominated by photon t-channel contribution (only QED, no "Z contamination")
- to reduce the theoretical error on σ all the relevant radiative corrections (RC) must be included
- at present the theoretical ingredients to reach 0.01% are available

Independent way for ν count: $\nu\bar{\nu}\gamma$ at higher energies

- radiative return to the Z peak through emission of a hard photon
- provided large enough luminosity is available to be competitive with Γ_{inv} method (not a problem at future e^+e^- colliders!)
  at LEP2, 190 GeV $\leq \sqrt{s} \leq 208$ GeV, $\mathcal{L} \sim 600$ pb^{-1}



L3 Collab., P. Achard et al., CERN-EP/2003-068 (2003)

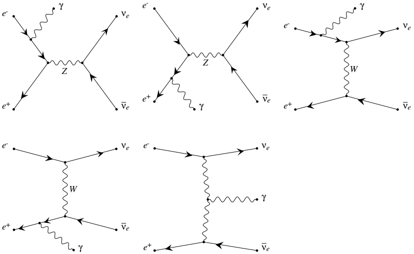
- agreement of data with SM predictions at % level
- $N_\nu = 2.98 \pm 0.05 \pm 0.04$ (L3) (important but not competitive with the Γ_{inv} method)
- similar results for ALEPH, DELPHI and OPAL

$\nu\bar{\nu}\gamma$@FCC-ee: ratio measurements

- a factor $10^3/10^4$ of improvement in luminosity w.r.t. LEP allows to exploit the ratios

$$\frac{d\sigma(e^+e^- \to \nu\bar{\nu}\gamma)}{d\sigma(e^+e^- \to \mu^+\mu^-\gamma)}$$

in order to cancel common systematics (such as luminosity)

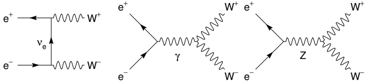


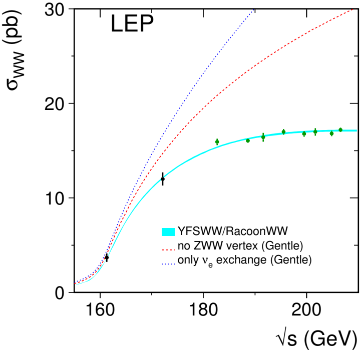
- $\mu^+\mu^-$ only $s-$channel but ISR and FSR
- ν_μ and ν_τ f.s.: only $s-$channel ISR
- ν_e f.s.: ISR with $t-$channel
- ν_e f.s.: also W radiation

- preliminary investigations show that QED effects are very small

talk by S. Jadach at FCC-ee physics Workshop, Paris, 27-29 October 2014

Direct M_W measurement at WW threshold



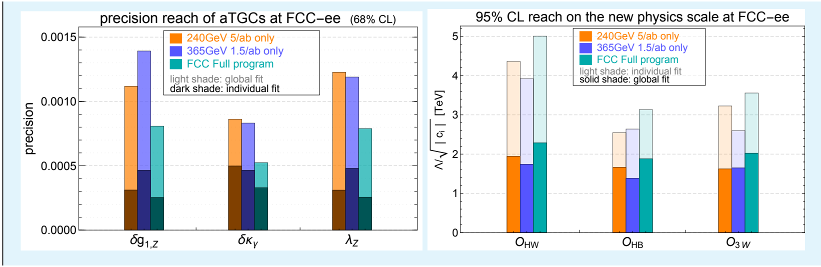


- by using the lineshape dependence on M_W at threshold
  $\Longrightarrow$ M_W measurement with uncertainty $\Delta M_W \sim 0.6$ MeV
  (precision 200 times higher than the best present M_W direct measurement)

talk by P. Azzurri at FCC Week 2018, Amsterdam

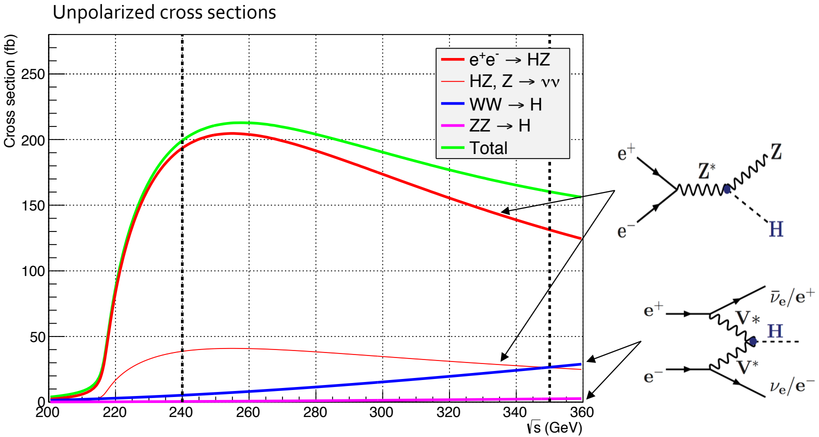
Anomalous triple gauge couplings

$\sqrt{s}$	Luminosity	# of events
161 GeV	$10\,\mathrm{ab}^{-1}$	$\sim 3 \times 10^7$
240 GeV	$5\,\mathrm{ab}^{-1}$	$\sim 8 \times 10^7$
350 GeV	$0.2\,\mathrm{ab}^{-1}$	$\sim 0.2 \times 10^7$
365 GeV	$1.5\,\mathrm{ab}^{-1}$	$\sim 1.5 \times 10^7$



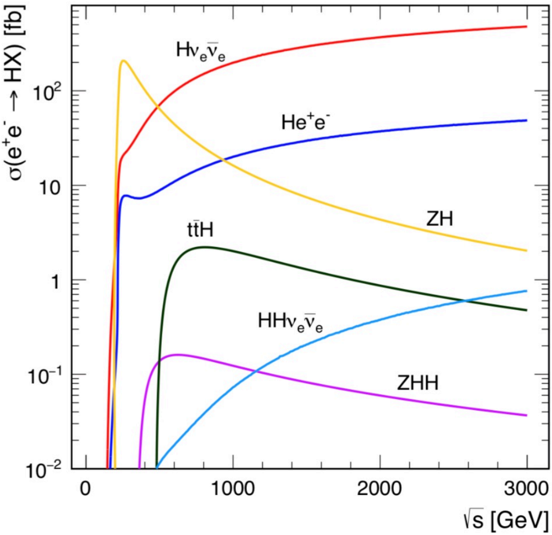
poster by J. Gu at FCC Week 2018, Amsterdam

Higgs production at circular e^+e^- colliders

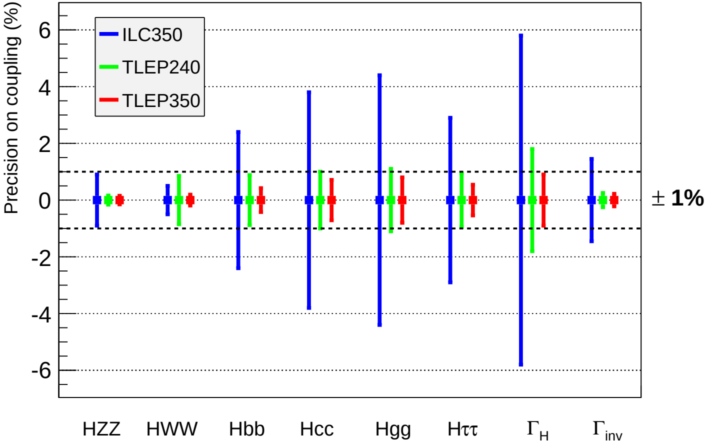


M. Bicer et al., arXiv:1308.6176

Higgs production at e^+e^- linear colliders

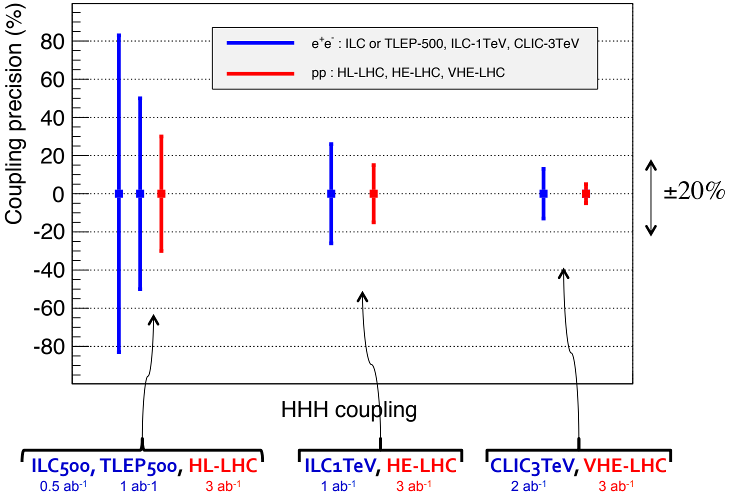


after five years of running FCC-ee



M. Bicer et al., arXiv:1308.6176

Comparison on λ_{HHH} between linear e^+e^- and pp



±20%

ILC500, TLEP500, HL-LHC
0.5 ab^{-1} 1 ab-1 3 ab^{-1}

ILC1TeV, HE-LHC
1 ab^{-1} 3 ab^{-1}

CLIC3TeV, VHE-LHC
2 ab^{-1} 3 ab^{-1}

M. Bicer et al., arXiv:1308.6176

Summary

- rich physics potential of e^+e^- colliders
- very high precision measurements at Z peak give the strongest internal consistency checks of the SM
- challenge for precision in theory calculations
- direct measurements of M_W and m_t at the respective thresholds give strong input to the internal consistency checks
- Higgs couplings can be measured at the % level
  - except for Htt, λ_{HHH} where pp colliders display more sensitivity, as well as rare channels like $HZ\gamma$