FCC physics: importance for HEP and challenges in theory and phenomenology

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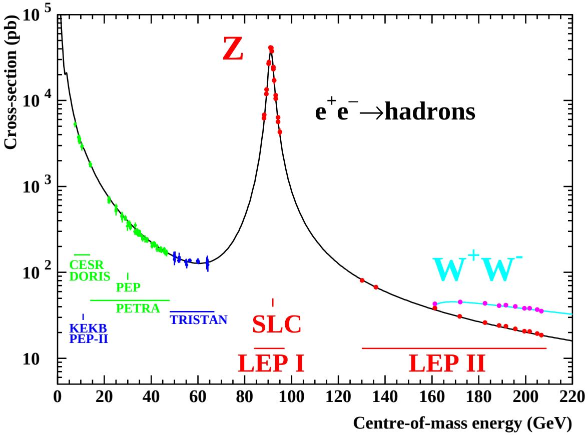
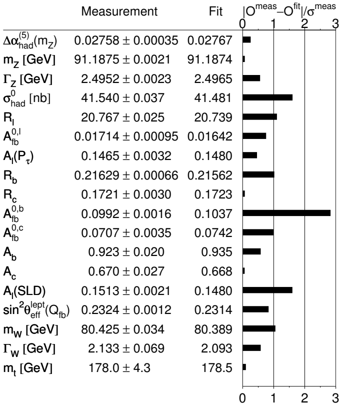
First FCC-Italy Workshop 2022, Roma, 21 – 22 March 2022

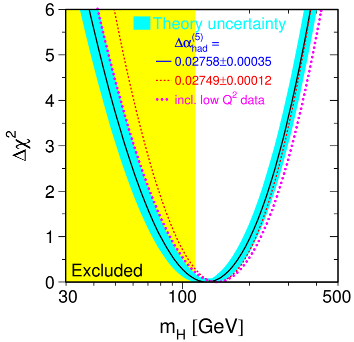
SM tested up to ~ 200 GeV with e^+e^- colliders



LEP EWWG, SLD WG, ALEPH, DELPHI, L3, OPAL, Phys. Rept. 427 (2006) 257

- precision $\mathcal{O}(0.1\%)$ measurements of the processes $e^+e^- \to f\bar{f}$
- $\mathcal{O}(1\%)$ for the processes $e^+e^- \to WW/ZZ \to 4$ fermions





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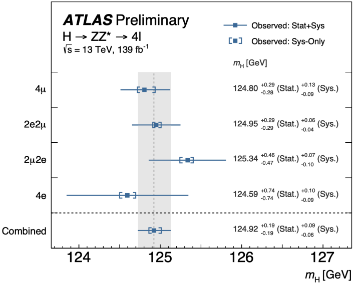
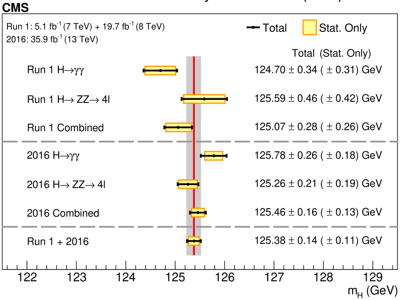
2012 $\rightarrow$ Higgs boson @LHC: mass and width

ATLAS-CONF-2020-005



$m(H)=124.92\pm0.19^{+0.09}_{-0.06}$ GeV

Phys. Lett. B 805 (2020) 135425



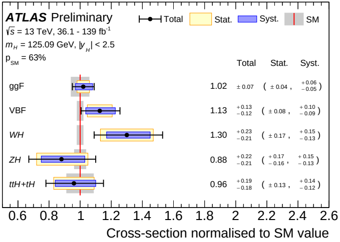
$m(H)=125.38\pm0.14$ (0.11) GeV

T.B. Ta, La Thuile 2022

- $\sim 0.1\%$ precision on Higgs mass
- Width (SM ~ 4 MeV)
  - $\Gamma < 14.4$ MeV (ATLAS 36 fb^{-1})
  - $\Gamma < 3.2^{+2.4}_{-1.7}$ MeV (CMS)

2012 → Higgs boson @LHC

- production (and decay) measured in several channels
- agreement with th. predictions
- for some channel th. uncertainties main systematics



ATLAS-CONF-2021-053

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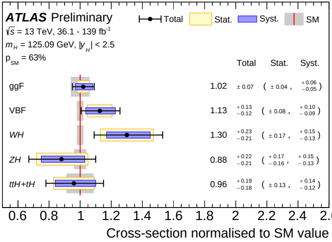
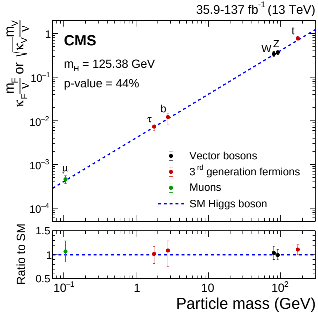


ATLAS-CONF-2021-053

- coupling strengths in the "k" framework

$$k_i = \frac{g_{Hi}}{g_{Hi}^{SM}}$$

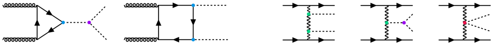


CMS, JHEP 01 (2021) 148

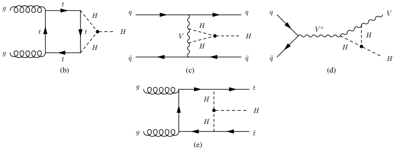
Higgs self-coupling: sensitivity through

- double Higgs production (at NLO or LO in associated production)

Borowka et al., arXiv:1604.06447; Grazzini et al., arXiv:1803.02463

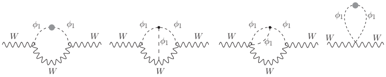


- single Higgs production (at NNLO or NLO in associated production) and decay (at NLO or NNLO for $H \to \gamma\gamma$)



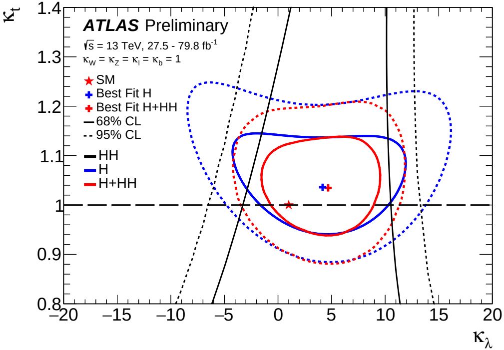
- EW precision observables at two loops

Degrassi et al., arXiv:1702.01737; Kribs et al., arXiv:1702.07678



Present sensitivity to k_λ

- $k_\lambda = \lambda_{HHH}/\lambda_{HHH}^{SM}$



ATLAS-CONF-2019-049

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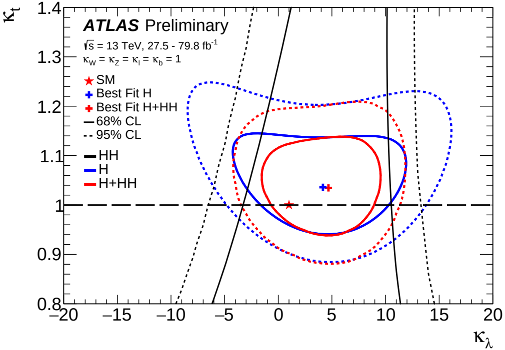

ATLAS-CONF-2019-049

- relevant constraining power also from EWPO M_W and $\sin^2\vartheta^\ell_{eff}$

Degrassi et al., arXiv:2102.0765

Summarizing the present status

- SM gauge sector tested with $\mathcal{O}(0.1\%)$ precision

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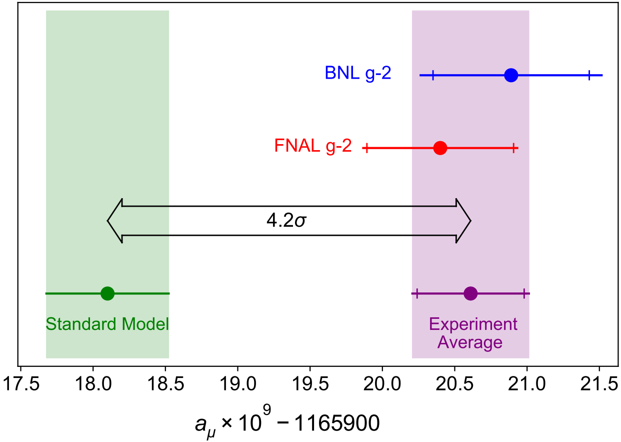
- negative searches of New Physics at high energy

From low energy...: Muon $g - 2$ recent result



B. Abi et al., Phys. Rev. Lett. 126 (2021) 14, 141801 [arXiv:2104.03281[hep-ex]]

Increased experimental precision expected soon

Tensions in measurements involving the transitions

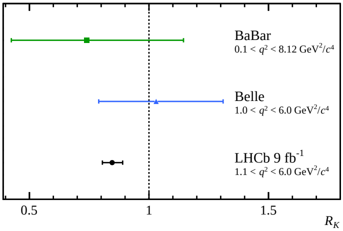
- $\bar{\mathbf{b}} \to \bar{\mathbf{s}}\ell^+\ell^-$ $(\ell = \mu, e)$
- $\bar{\mathbf{b}} \to \bar{\mathbf{c}}\ell^+\nu_\ell$

e.g.

$$R_K = \frac{\frac{\mathcal{B}(B^+ \to K^+\mu^+\mu^-)}{\mathcal{B}(B^+ \to J/\psi(\to\mu^+\mu^-)K^+\mu^+\mu^-)}}{\frac{\mathcal{B}(B^+ \to K^+e^+e^-)}{\mathcal{B}(B^+ \to J/\psi(\to e^+e^-)K^+e^+e^-)}}$$

$$R_{K^*} = \ldots$$

$$R_{K_S^0} = \ldots$$



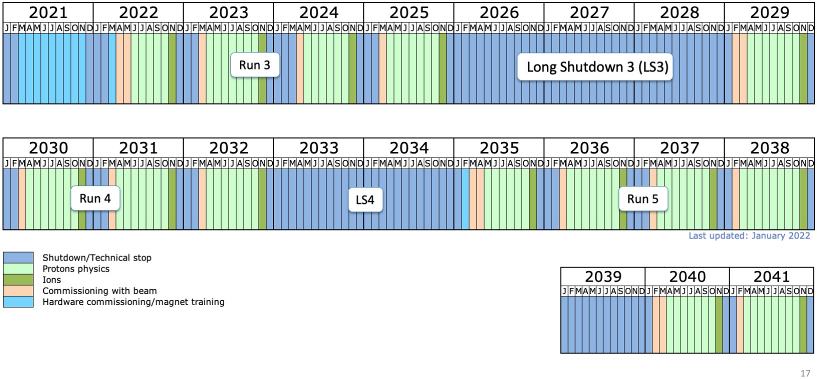
R. Aaij et al. (LHCb Coll.), arXiv:2103.11769

$> 3\ \sigma$

In addition to unanswered questions, e.g.

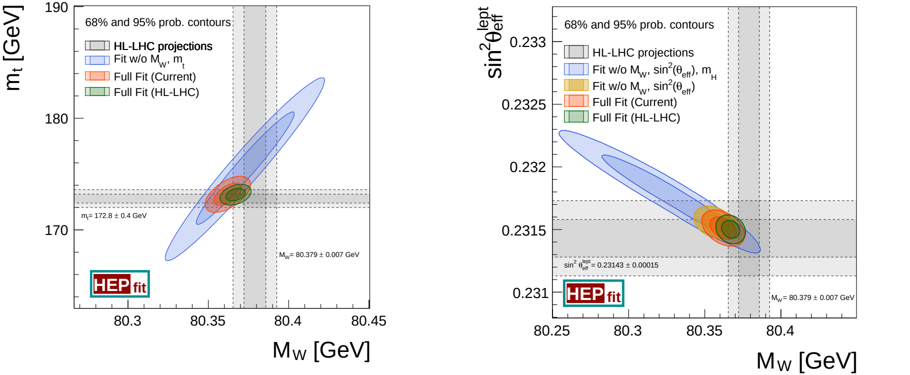
- Nature of EWSB
- Neutrino masses
- Connection of the Higgs with Flavour
- Dark Matter
- Baryon asymmetry in the Universe
- Gravity
- ...

Where are we going: LHC schedule



LHC Performance Workshop, Chamonix 2022

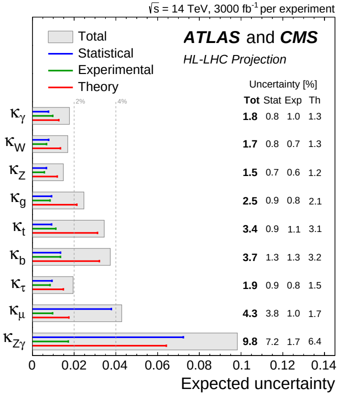
Prospects for HL-LHC: SM EW fit



J. de Blas et al., (Azzi, Farry, Nason, Tricoli, Zeppenfeld Eds.)

CERN-LPCC-2018-03, arXiv:1902.04070

Prospects for HL-LHC: Higgs and global analysis



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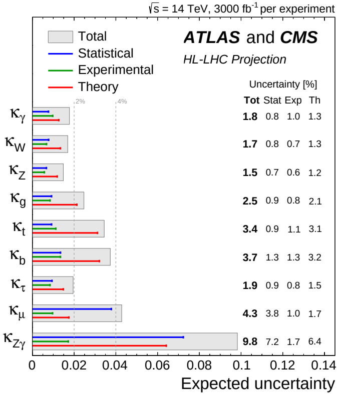

- few % uncertainty for signal strengths
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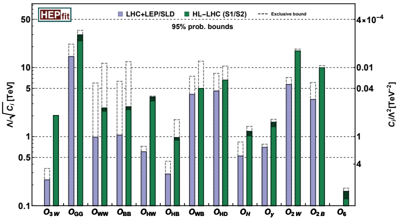
- in the SMEFT approach

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{d>4} \frac{1}{\Lambda^{d-4}} \mathcal{L}_d$$

$$\mathcal{L}_d = \sum_i C_i \mathcal{O}_i^{(d)}$$



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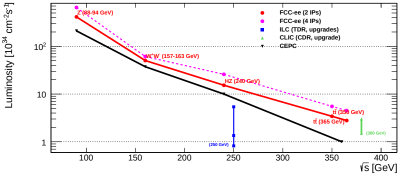
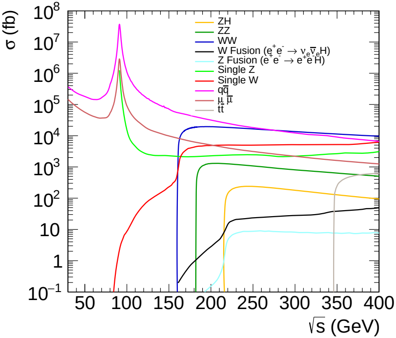
in the following some considerations on the first stage, FCC-ee

FCC-ee will

- revisit LEP physics with much larger statistics
  - at Z pole (~ 0.1% at LEP1)
  - at WW threshold (~ 1% at LEP2)
- explore for the first time at a leptonic collider
  - ZH threshold
  - $t\bar{t}$ threshold

Cross sections and event numbers





G. Bernardi et al., arXiv:2203.06520[hep-ex]

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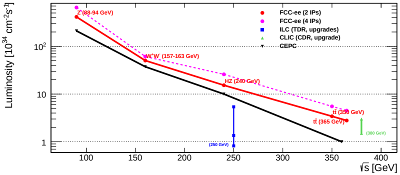

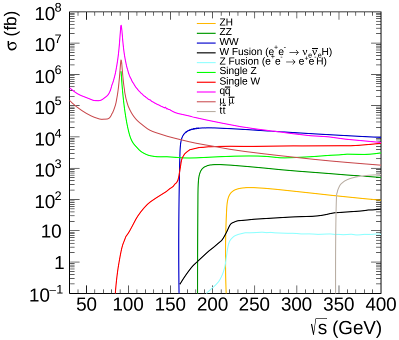

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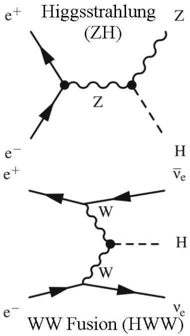
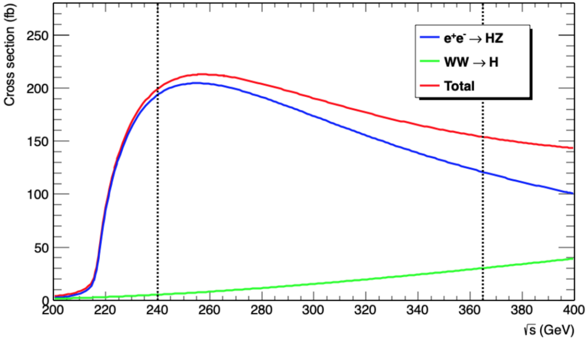
- Z-pole, 3 points: $5 \times 10^{12}\ Z$
- WW threshold, 2 points: $10^8\ W$ pairs
- HZ threshold: $10^6\ HZ$ $+\,2.5 \times 10^4\ WW \to H$
- $t\bar{t}$ threshold, 3 points: $10^6\ t\bar{t}$ + $2 \times 10^5\ HZ$ $+5 \times 10^4\ WW \to H$

Higgs@FCCee





P. Azzurri et al., arXiv:2106.15438

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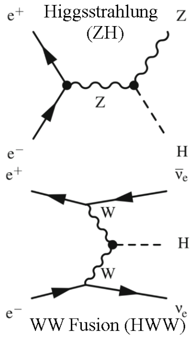

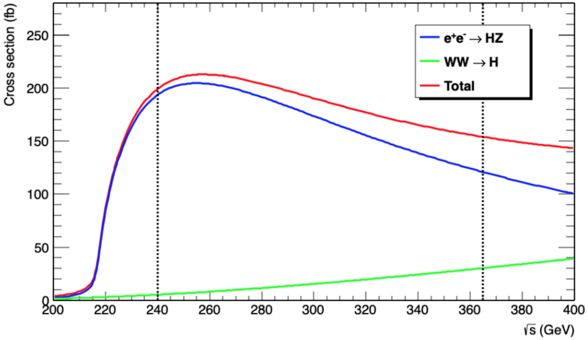

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- key feature: model-independent measurement of g_{HZZ}

Higgs@FCCee

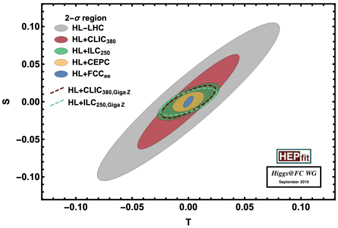
Collider	HL-LHC	$\text{FCC-ee}_{240\to365}$	FCC-ee + HL-LHC	FCC-INT	FCC-INT + HL-LHC
Int. Lumi (ab^{-1})	3	5 + 0.2 + 1.5	–	30	–
Years	10	3 + 1 + 4	–	25	–
g_{HZZ} (%)	1.5	0.18	0.17	0.17	0.16
g_{HWW} (%)	1.7	0.44	0.41	0.20	0.19
g_{Hbb} (%)	5.1	0.69	0.64	0.48	0.48
g_{Hcc} (%)	SM	1.3	1.3	0.96	0.96
g_{Hgg} (%)	2.5	1.0	0.89	0.52	0.5
$g_{\text{H}\tau\tau}$ (%)	1.9	0.74	0.66	0.49	0.46
$g_{\text{H}\mu\mu}$ (%)	4.4	8.9	3.9	0.43	0.43
$g_{\text{H}\gamma\gamma}$ (%)	1.8	3.9	1.3	0.32	0.32
$g_{\text{HZ}\gamma}$ (%)	11.	–	10.	0.71	0.7
g_{Htt} (%)	3.4	–	3.1	1.0	0.95
g_{HHH} (%)	50.	44.	33.	3–4	3–4
Γ_{H} (%)	SM	1.1	1.1	0.91	0.91

G. Bernardi et al., arXiv:2203.06520[hep-ex]

Observable	Present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	$91,186,700 \pm 2200$	4	100	From Z lineshape scan; beam energy calibration
Γ_Z (keV)	$2,495,200 \pm 2300$	4	25	From Z lineshape scan; beam energy calibration
R_ℓ^Z ($\times 10^3$)	$20,767 \pm 25$	0.06	$0.2 - 1.0$	Ratio of hadrons to leptons; acceptance for letpons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	$1,196 \pm 30$	0.1	$0.4 - 1.6$	From R_ℓ^Z above
R_b ($\times 10^6$)	$216,290 \pm 660$	0.3	< 60	Ratio of $b\bar{b}$ to hadrons; stat. extrapol. from SLD
$\sigma^0_{\rm had}$ ($\times 10^3$) (nb)	$41,541 \pm 37$	0.1	4	Peak hadronic cross section; luminosity measurement
N_ν ($\times 10^3$)	$2,996 \pm 7$	0.005	1	Z peak cross sections; luminosity measurement
$\sin^2\theta_W^{\rm eff}$ ($\times 10^6$)	$231,480 \pm 160$	1.4	1.4	From $A_{FB}^{\mu\mu}$ at Z peak; beam energy calibration
$1/\alpha_{\rm QED}(m_Z^2)$ ($\times 10^3$)	$128,952 \pm 14$	3.8	1.2	From $A_{FB}^{\mu\mu}$ off peak
$A_{FB}^{b,0}$ ($\times 10^4$)	992 ± 16	0.02	1.3	b-quark asymmetry at Z pole; from jet charge
A_e ($\times 10^4$)	$1,498 \pm 49$	0.07	0.2	from $A_{FB}^{{\rm pol},\tau}$; systematics from non-τ backgrounds
m_W (MeV)	$80,350 \pm 15$	0.25	0.3	From WW threshold scan; beam energy calibration
Γ_W (MeV)	$2,085 \pm 42$	1.2	0.3	From WW threshold scan; beam energy calibration
N_ν ($\times 10^3$)	$2,920 \pm 50$	0.8	Small	Ratio of invis. to leptonic in radiative Z returns
$\alpha_S(m_W^2)$ ($\times 10^4$)	$1,170 \pm 420$	3	Small	From R_ℓ^W

G. Bernardi et al., arXiv:2203.06520[hep-ex]

- through oblique S, T, U parameters



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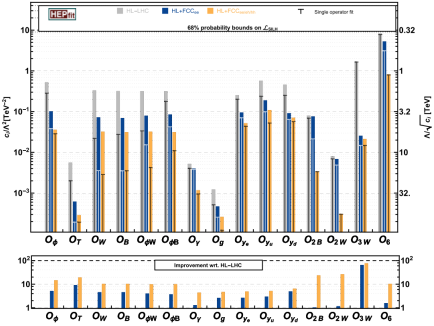

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Challenges for theory: an example, Z pole

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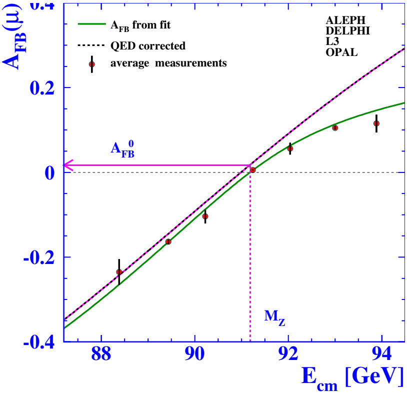

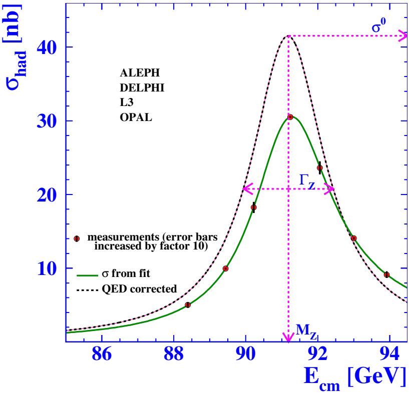

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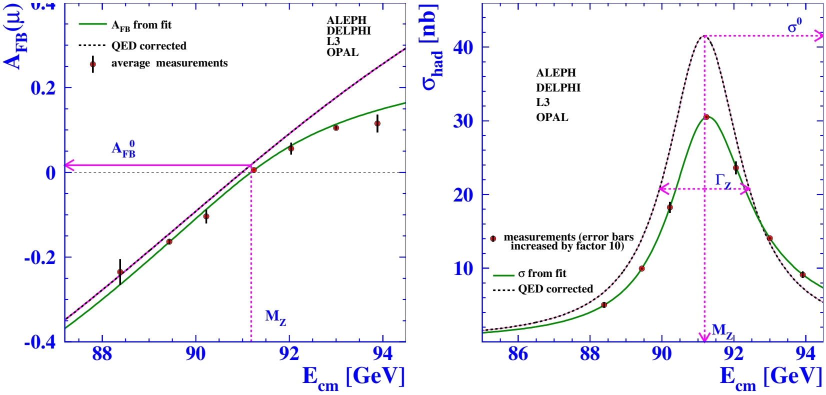

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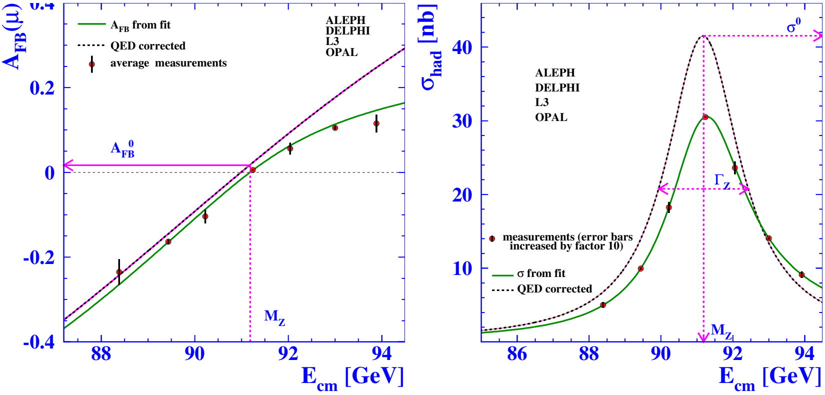

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What changed from LEP era in the field of theory predictions?

Impressive development during LHC era

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reality: automatic codes for event generation at NLO (QCD and EW) precision matched to all order resummation of logarithmic enhanced corrections

$2 \to 2$@NNLO QCD perturbative accuracy for all processes

$2 \to 3$@NNLO QCD accuracy becoming available for selected processes

N3LO QCD calculations for Higgs and DY production

different approaches for matching NNLO calculation and resummation of logs

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not enough for FCC-ee

Need at FCC-ee around Z pole

- improved description of ISR QED radiation and IF interference (factorizable effects larger than the required precision, contrary to LEP precision)
- complete NNLO accuracy in $e^+e^- \to f\bar{f}$
- EWPO extraction: $\to Zf\bar{f}$ vertex at N3LO and leading N4LO

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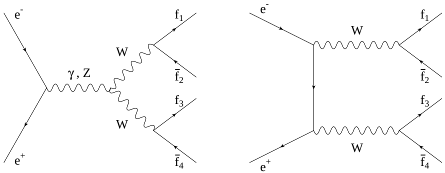
progress already achieved and future paths identified

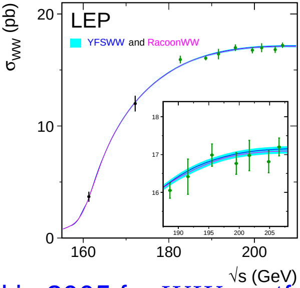
Blondel, Gluza, Jadach, Janot, Riemann (Eds), CERN-2019-003

progress needed on the study of the mathematical structure of scattering amplitudes

a seminumerical approach to Feynman diagram calculation could be the right way to progress with theory predictions

Another example, WW threshold: $\mathrm{e^+e^-} \to 4$ fermions





- first NLO exact calculation completed in 2005 for $WW \to 4f$
  - th. accuracy $\lesssim 1\%$

A. Denner et al., PLB612 (2005) 223; NPB 724 (2005) 247

- at present $e^+e^- \to 4f$ cross sections @NLO accuracy can be calculated with automated tools
- NNLO enhanced contributions because of Coulomb photon effects calculated by means of EFT methods

M. Beneke et al., NPB 792 (2008) 89; S. Actis et al., NPB807 (2009) 1

  - th. accuracy $\sim 0.5\%$ $\Delta M_W \sim 3$ MeV

WW threshold: future prospects

- Having in mind a target precision $\Delta M_W \sim 1$ MeV we would need
  - an improved treatment of EFT, which requires
    - NNLO corrections to $e^+e^- \to WW$ in NWA
    - NNLO accuracy in the W decay
  - improved treatment of subleading effects in ISR

Summary and outlook

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    - e.g. at LEP the theoretical uncertainty for Bhabha scattering has been of the same order than the experimental precision $(\sim 0.06\%)$
    - e.g. tiny effects as the beam-beam interactions give a shift which removes a tension in the number of light neutrinos

$$N_\nu = 2.9840 \pm 0.0082 \quad \Longrightarrow \quad N_\nu = 2.9963 \pm 0.0074$$

P. Janot and S. Jadach, arXiv:1912.02067; Voutsinas, Perez, Dam, Janot, arXiv:1908.01704