Overview of Theory / deliverables for the FCC Feasibility Study

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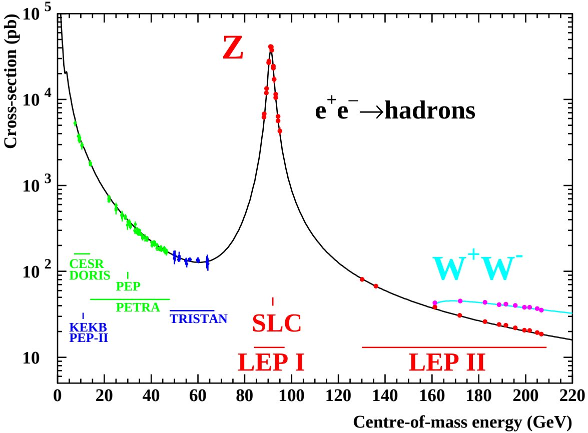
Joint FCC-France & Italy 2022 Workshop in Lyon, Lyon, 21 – 22 November 2022

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

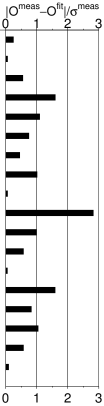


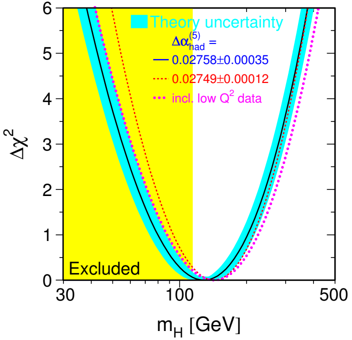
LEP EWWG, SLD WG, ALEPH, DELPHI, L3, OPAL, Phys. Rept. 427 (2006) 257

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

LEP/SLC legacy at the Z pole

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5

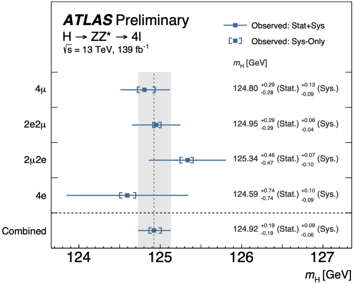




LEP EWWG, SLD WG, ALEPH, DELPHI, L3, OPAL, Phys. Rept. 427 (2006) 257

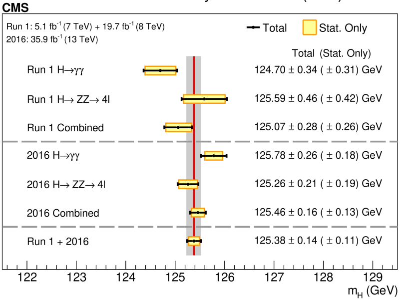
2012 → Higgs boson @LHC: mass and width

ATLAS-CONF-2020-005



$m(H)=124.92 \pm 0.19^{+0.09}_{-0.06}$ GeV

Phys. Lett. B 805 (2020) 135425



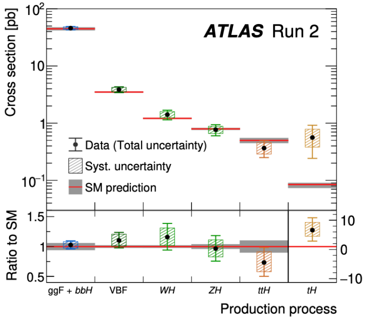
$m(H)=125.38 \pm 0.14$ (0.11) GeV

T.B. Ta, La Thuile 2022

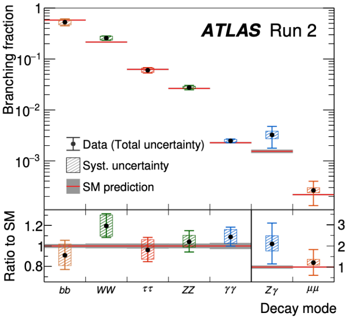
- $\sim 0.1\%$ precision on Higgs mass
- Width (SM ~ 4 MeV)
    - $\Gamma < 14.4$ MeV (ATLAS 36 fb^{-1})
    - $\Gamma < 3.2^{+2.4}_{-1.7}$ MeV (CMS)

- **production (and decay) measured in several channels**
- for some channel th. uncertainties of same order of exp systematics

Production



Decay



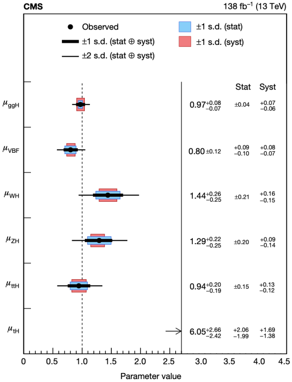
ATLAS Coll., Nature 607 (2022) 7917

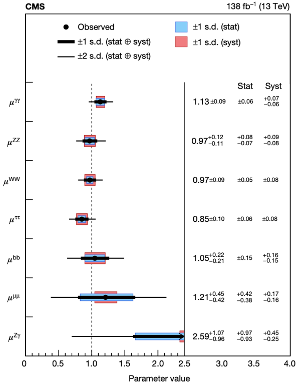
- **agreement with th. predictions**

- **coupling strengths in the “k” framework**

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

Production **Decay**

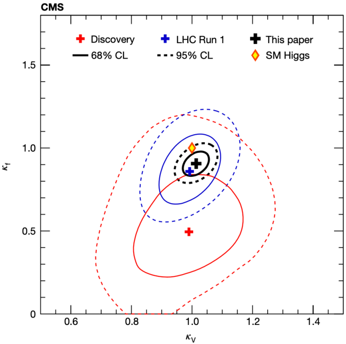




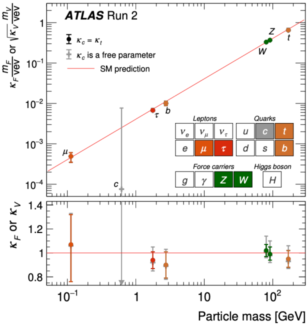
CMS Coll., Nature 607 (2022) 7917

- **agreement with th. predictions**

2022: Higgs @LHC



CMS Coll., Nature 607 (2022) 7917

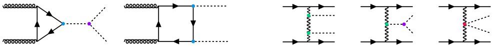


ATLAS Coll., Nature 607 (2022) 7917

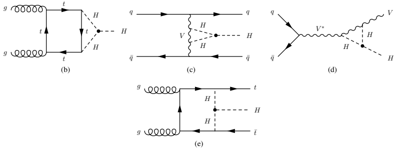
Higgs self-coupling: sensitivity through

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

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

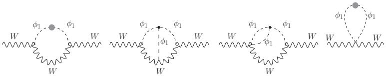


- **single Higgs production** (at NNLO or NLO in associated production) and decay (at NLO or NNLO for $H \to \gamma\gamma$)

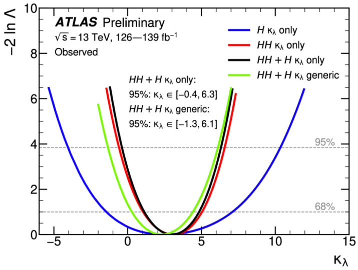


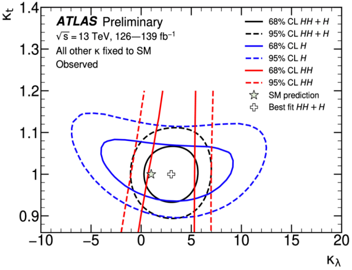
- **EW precision observables at two loops**

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



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



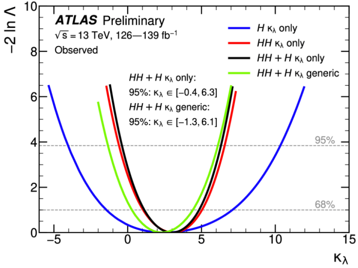


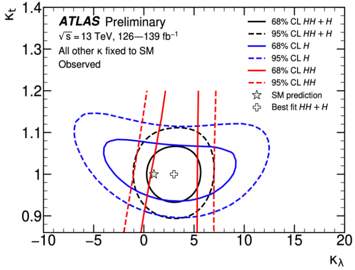
ATLAS, arXiv:2211.01216

- HH driven constraining power
- $-1.4 < k_\lambda < 6.1$ @95% CL

Present sensitivity to k_λ

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





ATLAS, arXiv:2211.01216

- HH driven constraining power
- $-1.4 < k_\lambda < 6.1$ @95% CL
- additional constraining power also from EWPO M_W and $\sin^2 \vartheta^\ell_{eff}$, in particular in view of future FCC precision

Degrassi et al., arXiv:2102.07651

Summarizing the present status

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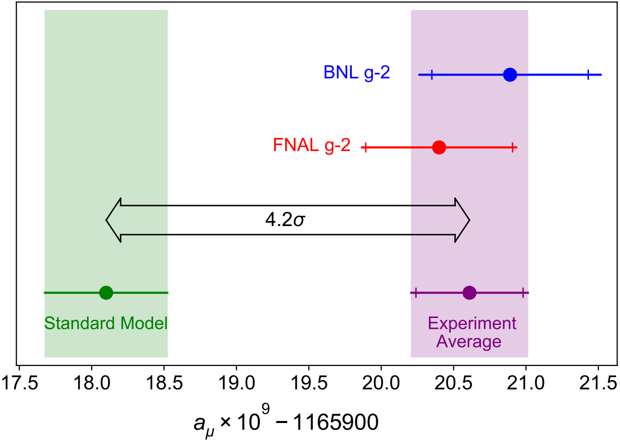
- negative searches of New Physics at high energy

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



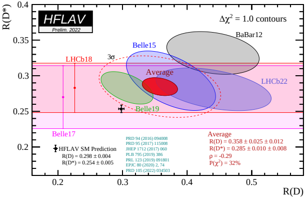
B. Abi et al., Phys. Rev. Lett. 126 (2021) 14, 141801 [arXiv:2104.03281[hep-ex]]

- Increased experimental precision expected soon
- puzzle of SM prediction based on LQCD

Tensions in measurements involving the transitions

- $\bar{\mathbf{b}} \to \bar{\mathbf{c}}\ell^+\nu_\ell$ (R_D, R_{D^*})
- $\bar{\mathbf{b}} \to \bar{\mathbf{s}}\ell^+\ell^-$

  $(\ell = \mu, e)$



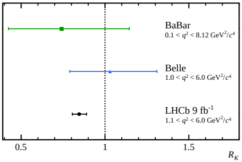
G.M. Ciezarek, LHC Seminar, CERN 18/10/2022

e.g.

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

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

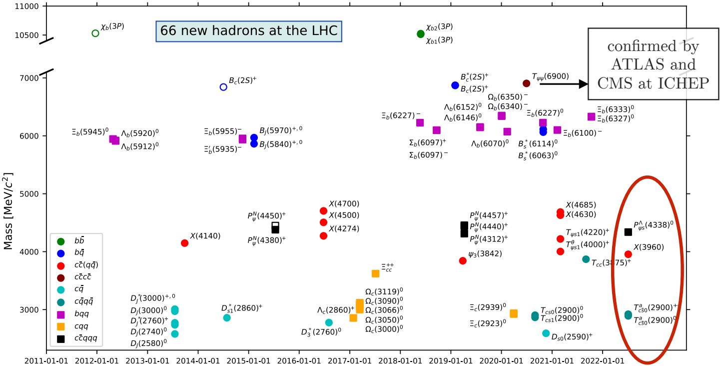
$$R_{K^0_S} = \ldots$$



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

$\sim 3\ \sigma$

Exotic hadron spectroscopy



F. Blanc (LHCb Coll.), ICHEP 2022

Challenge for QCD in the non-perturbative regime

In addition to unanswered questions, e.g.

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

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connections with Higgs in the following picture

What is the origin of the early-universe inflation?

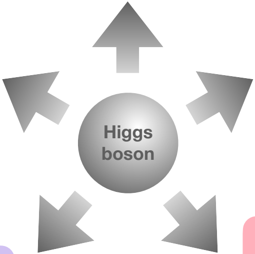
- Is the Higgs connected to the mechanism that drives inflation?
- Are there any imprints in cosmological observations?

Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs with the W and Z?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs decay into pairs of quarks and leptons with distinct flavours (for example, $H \to \mu^+\tau^-$)?



What is dark matter?

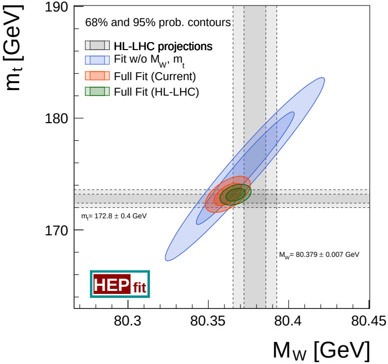
- Can the Higgs provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs?

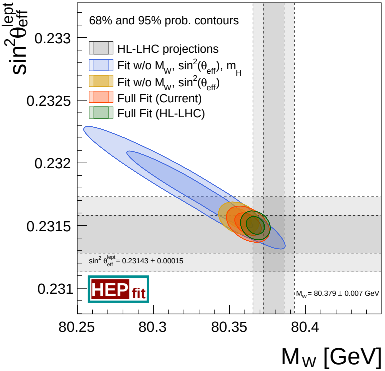
Why is there more matter than antimatter in the universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-universe electroweak phase transition?
- Are there multiple Higgs sectors?

G.P. Salam, L.-T. Wang, G. Zanderighi, Nature 607 (2022) 7917

Prospects for HL-LHC: SM EW fit



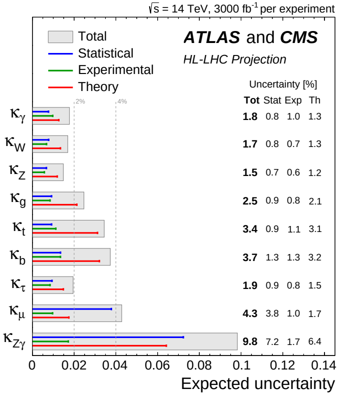


J. de Blas et al., (Azzi, Farry, Nason, Tricoli, Zeppenfeld Eds.)

CERN-LPCC-2018-03, arXiv:1902.04070

not including the latest CDF M_W measurement

Prospects for HL-LHC: Higgs and global analysis

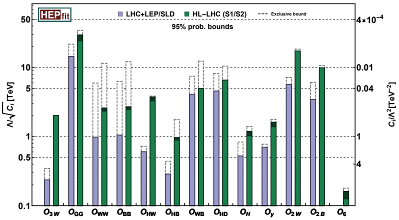


- few % uncertainty for signal strengths
- foreseen th. uncertainty dominant

- in the SMEFT approach

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

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



J. de Blas et al., (Azzi, Farry, Nason, Tricoli, Zeppenfeld Eds.) arXiv:1902.04070

With no clearcut compelling direction for an extension of the SM, a future machine with very broad physics potential is necessary to advance our knowledge

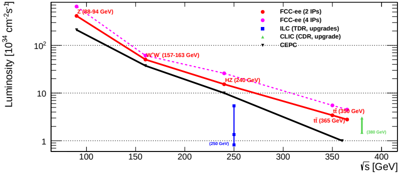
FCC is an ideal machine allowing to investigate at a never explored level both the intensity and the energy frontier

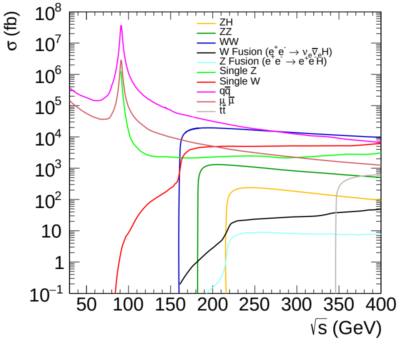
in the following some considerations on the first stage, FCC-ee

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

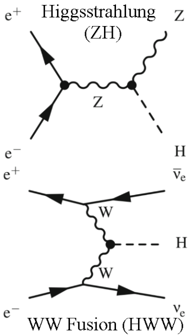


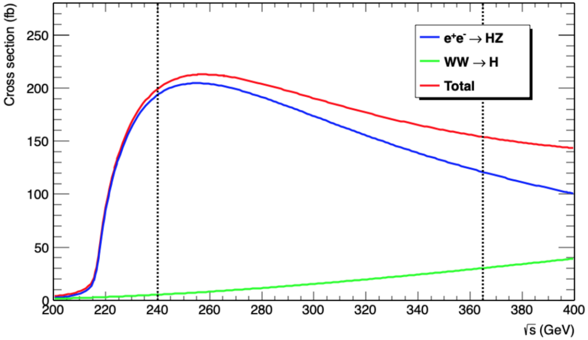


G. Bernardi et al., arXiv:2203.06520[hep-ex]

- 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

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

Higgs@FCCee

Collider	HL-LHC	FCC-ee$_{240\to 365}$	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
$g_{\mathrm{H}\tau\tau}$ (%)	1.9	0.74	0.66	0.49	0.46
$g_{\mathrm{H}\mu\mu}$ (%)	4.4	8.9	3.9	0.43	0.43
$g_{\mathrm{H}\gamma\gamma}$ (%)	1.8	3.9	1.3	0.32	0.32
$g_{\mathrm{HZ}\gamma}$ (%)	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]

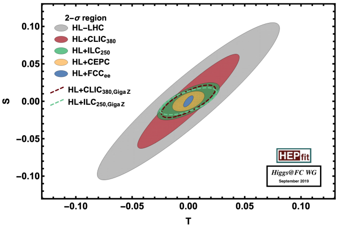
EWPO@FCCee

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
$\sigma_{\rm had}^0$ ($\times 10^3$) (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

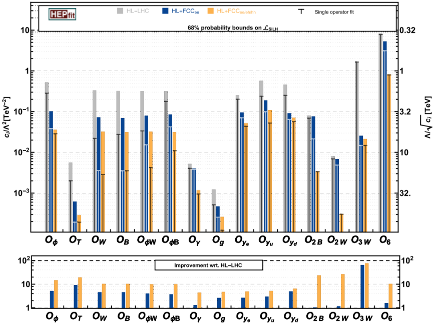
G. Bernardi et al., arXiv:2203.06520[hep-ex]

Global EW fit@FCC-ee

- through oblique S, T, U parameters



- in the SMEFT approach



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

Two directions for theoretical studies towards FCC

- **analysis of presently conceivable and/or new scenarios of BSM physics**
    - study of potential FCC sensitivity to new heavy degrees of freedom through EFT approaches
    - investigation of light new degrees of freedom through classes of models

$\Longrightarrow$ this will be discussed within the Theory session of tomorrow

Theory session

(many thanks to Giacomo Cacciapaglia)

Models of Composite Higgs at FCC
Aldo Deandrea et al.
Room 2 09:15 - 09:40

Dark Matter: status and prospect at FCC
Dario Buttazzo.

Status and prospects of SUSY
Mark Goodsell
Room 2 10:15 - 10:40

Flavour anomalies *Aoife Bharucha*
Room 2 11:15 - 11:40

Axion-like particles at FCC
Dr Jérémie Quevillon
Room 2 11:40 - 12:05

Light composite scalars at FCC-ee and FCC-hh
Leonard Schwarze et al.

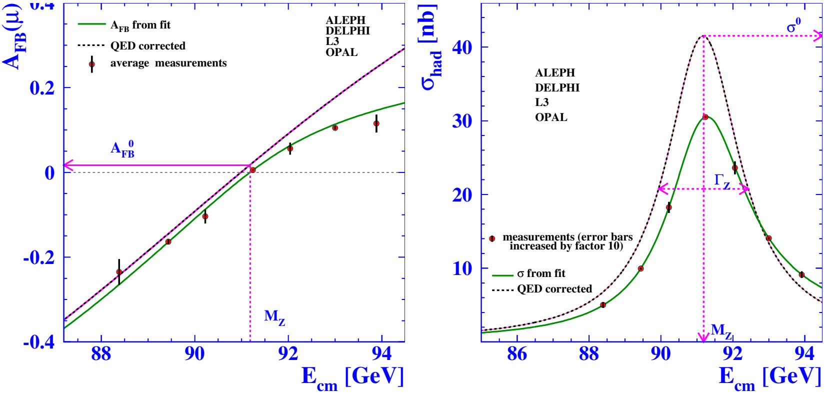
Discussion / potential synergies

Two directions for theoretical studies towards FCC

- **development of theoretical calculations necessary to satisfy the unprecedented precision requirements of FCC**

$\Longrightarrow$ some example concerning FCC-ee in the following slides

Challenges for theory: an example, Z pole



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

FCC-ee will require pushing th. uncertainty down by at least a factor of 10 on cross sections and even more on A_{FB} w.r.t LEP

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

Impressive development during LHC era

Impressive development during LHC era

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

Impressive development during LHC era

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

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not enough for FCC-ee

- Workshop "Precision calculations for future e^+e^- colliders: targets and tools", CERN, 7-17 June 2022

https://indico.cern.ch/event/1140580/

- **Need at FCC-ee around Z pole**
  - improved description of ISR QED radiation and IF interference (non-factorizable effects larger than the required precision, contrary to LEP precision), together with a sensible procedure for extracting EWPO in presence of higher order corrections (beyond one loop)
  - some progress already achieved and future paths identified

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

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  - at least complete NNLO accuracy in $e^+e^- \to f\bar{f}$
  - expansion of the amplitude for $e^+e^- \to f\bar{f}$ around the complex pole $s_0 = M_Z^2 - i\Gamma_Z M_Z$

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\begin{aligned}
\mathcal{M} &= \frac{R}{s - s_0} + S + S'(s - s_0) \\
R &\to \text{known@NNLO} + \text{leading higher orders} \\
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  - EWPO extraction: $\to Zf\bar{f}$ vertex at N3LO and leading N4LO

A. Freitas

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A. Freitas

  - The above two items are beyond present knowledge
  - progress needed on the study of the mathematical structure of scattering amplitudes
  - as well as seminumerical approaches to Feynman diagram calculation

- Also new MC generators will be necessary to keep under control the theoretical precision at the few 10^{-5} level
  - through matching between fixed order perturbative corrections and (exclusive) resummation
  - different groups already started, e.g. MG5_aMC@NLO, Whizard, Sherpa, Herwig7, Pythia8, KKmc, BhLumi, BabaYaga

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- Luminosity requires control of QED corrections (and had vacuum polarization) for Bhabha scattering with one order of magnitude better than for LEP $\sim 0.06\%$ (recently revisited at $\sim 0.04\%$)

P. Janot and S. Jadach, arXiv:1912.02067

- beam-beam interaction effects have to be considered
  - e.g. tiny shift on luminosity ($\sim 0.05\%$) which contributes to remove the LEP 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

- for hadronic final states ($\rightarrow A^0_{FB}$, $\alpha_s(Q^2)$ from event shape variables, $\tau^+\tau^-$)
    - parton shower precision, non perturbative QCD corrections
    - quark and gluon fragmentation
    - jet substructure

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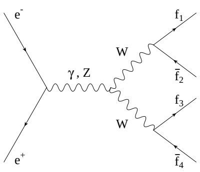
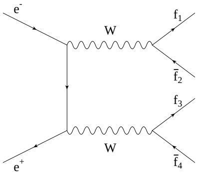
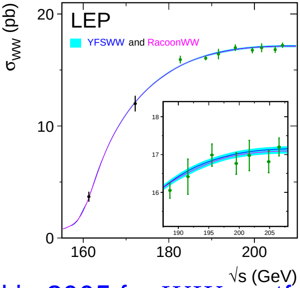
- Improvements in QED corrections crucial also for Flavour physics
  - two rare decays $B^0 \rightarrow K^*\tau^+\tau^-$ and $B^+ \rightarrow \pi\tau^+\nu_\tau$ (n.a. at LHC and BELLEII) will allow to perform strong checks of LFU
  - while QCD effects cancel in the ratio of BRs, QED do not (because of the different leptonic masses)
  - Workshop "FCC Flavour Physics Programme", CERN, 12-13 Sept. 2022

https://indico.cern.ch/event/1186057

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 ISR including the partonic structure of the electron up to NLL

S. Frixione, Bertone, Cacciari, Stagnitto, Zaro, Zhao

$t\bar{t}$ threshold (from M. Beneke)

I $e^+e^- \to t\bar{t}X$ cross section near threshold now computed at NNNLO in (PNR)QCD + top-Yukawa effects

- Sizeable 3rd order corrections and reduction of theoretical uncertainty to about $\pm 3\%$.

II Realistic predictions for $e^+e^- \to W^+W^-b\bar{b}$ near top-pair threshold

- NNLO available, including cuts invariant mass cuts.

III Parameter dependences $(m_t, \Gamma_t, y_t, \alpha_s)$ can be studied.

- (m_t, Γ_t) with unrivaled accuracy.
- y_t with 20% accuracy from threshold already challenging.

IV Further requirements:

- ISR / QED PDF's for $x \to 1$ with NLL evolution
- N4LO QCD would be reassuring, but appears prohibitive.

https://www.hepforge.org/downloads/qqbarthreshold/

M. Beneke (TU München) CERN, 08 June 2022 25 / 25

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  - **See Theory section tomorrow!**
- FCC-ee needs a very big jump in the accuracy of theoretical predictions
  - according to LEP and LHC experience, we had an enormous progress in the calculation techniques and development of new Monte Carlo generators, but
    progress requires coherent efforts in a long range in order to avoid as much as possible the systematics being dominated by theoretical uncertainty