

# Stato lavoro fisica EWK

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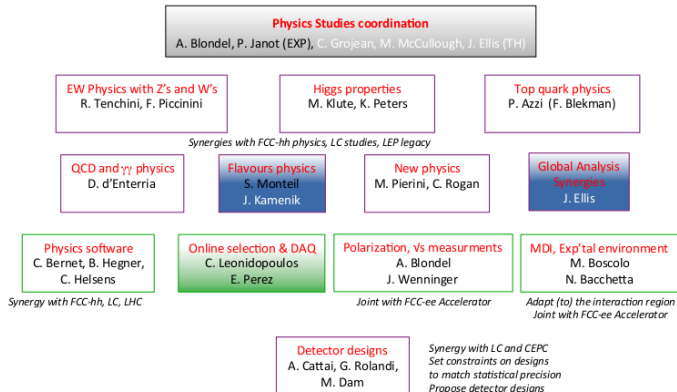
INFN, Sezione di Pavia

July 4, 2017

Reference slides from talks in Berlin

RD\_FA meeting, Bologna, 3-4 July 2017

## Physics and Experiments Studies Coordination

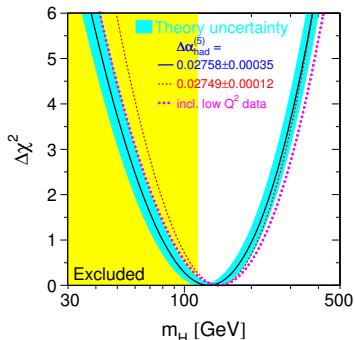
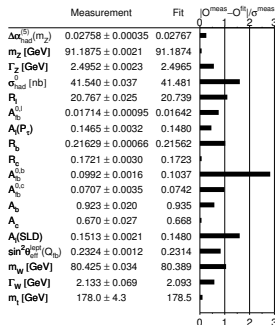


# FCC-ee CDR outline

- **WG1: Electroweak physics at the  $Z$  pole**
  - The  $Z$  line-shape
  - Experimental categorisation of  $Z$  decays
  - Luminosity measurement
  - Measurement of the number of neutrino species
  - Measurements of  $R_b$  and  $R_c$
  - Measurement of forward-backward asymmetries
- **WG2: Dibosons**
  - Measurement of the  $W$  mass
  - Measurement of  $W$  decay branching fractions
  - Measurement of gauge couplings
  - Measurement of  $ZZ$  and  $Z\gamma$  cross sections
  - Measurement of neutral gauge self-couplings
  - $Z$  radiative return events

- revisit LEP physics with much larger statistics
  - at  $Z$  pole ( $\sim 0.1\%$  at LEP1)
  - at  $WW$  threshold ( $\sim 1\%$  at LEP2)
- explore for the first time at a leptonic collider
  - $ZH$  and  $t\bar{t}$  thresholds
- Given the immense available statistics, uncertainties in theoretical calculations risk to be a dangerous source of systematics
- in this talk brief overview on theoretical uncertainties in SM electroweak calculations
  - **intrinsic uncertainties** (unknown higher orders)
  - **parametric uncertainties** (input parameters:  $G_\mu, \alpha(M_Z), \alpha_s(M_Z), M_Z, M_H, m_t$ )

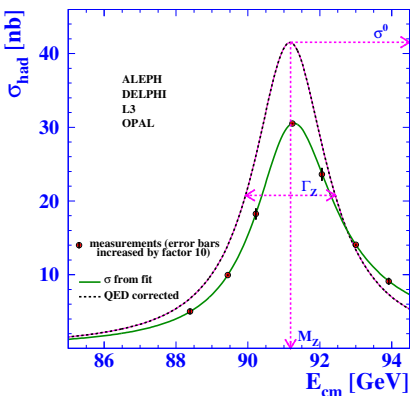
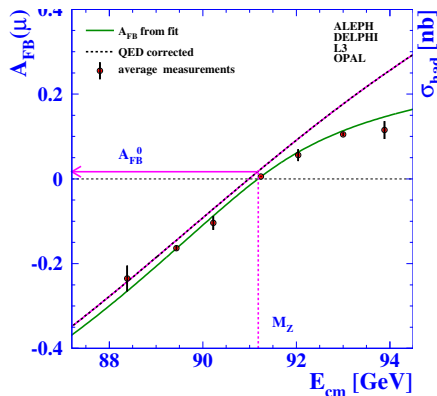
# LEP/SLC legacy at the Z pole



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

- electroweak fit based on *derived (pseudo-)observables* (allow easy combination among experiments and easy comparison data/theory within and beyond SM)
- primary measured observables: cross section and asymmetries

# Z pole: primary observables



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

## Deconvolution performed at LEP by means of

- TOPAZ0

G. Montagna, O. Nicosini, G. Passarino, F.P., R. Pittau, 1993, 1996, 1999

- ZFITTER

D. Bardin et al., 1989, 1991, 1992, 1994, 2001

# From measured observables to pseudo-observables

$$\sigma_T(s) = \int_{z_0}^1 dz H(z; s) \hat{\sigma}_T(zs) \quad A_{FB}(s) = \frac{\pi \alpha^2 Q_e^2 Q_f^2}{\sigma_{\text{tot}}} \int_{z_0}^1 dz \frac{1}{(1+z)^2} H_{FB}(z; s) \hat{\sigma}_{FB}(zs)$$

- Radiator  $H$  (including exact  $\mathcal{O}(\alpha)$ ,  $\mathcal{O}(\alpha^2)$ ) up to  $\mathcal{O}(\alpha^3 L^3)$

① additive form

G. Montagna, O. Nicosini, F.P., PLB 406, (1997) 243; D. Bardin et al., CPC 133 (2001) 229

② factorized form

S. Jadach, M. Skrzypek, B.F.L. Ward, PLB257 (1991) 173, M. Skrzypek, APPB23 (1992) 135

- $H_{FB}$  known up to  $\mathcal{O}(\alpha) + \mathcal{O}(\alpha^2 L^2)$
- kernel cross section known with  $\mathcal{O}(\alpha)$  corrections plus  $\mathcal{O}(\alpha^2)$  enhanced contributions (running couplings)

Remaining intrinsic th. uncertainty estimated below the 0.01% level by comparing TOPAZ0 and ZFITTER

D.Y. Bardin, M. Grünewald, G. Passarino, hep-ph/9902452

- FCC-ee will require pushing this uncertainty down by a factor of 10 on cross sections and even more on  $A_{FB}$



# prospects and issues for FCC-ee

- $\implies$  full NNLO calculations for  $e^+e^- \rightarrow f\bar{f}$  required
- $\implies$  radiator function  $H$  up to  $\mathcal{O}(\alpha^3 L^2)$
- the QED unfolding process itself should be critically reassessed

Dubovyk et al., PoS LL2016 (2016) 075

- QED corrections to  $A_{FB}$  off  $Z$ -peak require particular consideration, in connection with the proposal of a direct measurement of  $\Delta\alpha(M_Z)$ @FCC-ee: the present theoretical precision of  $\sim 2.5 \times 10^{-3}$  should be improved by more than a factor of 100!

P. Janot, JHEP 1602 (2016) 053; see talk by R. Tenchini yesterday

- effects of QED initial-final state interference effects in  $A_{FB}$  slightly off peak are important

talk by S. Jadach at FCC week in Rome, 12 April 2016

- effects at the few % level; resummation needed
- formalism of QED resummation around a resonance developed in  
M. Greco, G. Panzeri and Y. Srivastava, Nucl.Phys. B101 (1975) 234; NPB171 (1980) 118
- such resummation is implemented in the  $\text{KKMC}$  Monte Carlo with additional matching to NLO (and NNLO, QED ISR+FSR) corrections  
S. Jadach, B.F.L. Ward and Z. Was, CPC 130 (2000) 260
- work is in progress to quantify the remaining theoretical uncertainty

# Intrinsic th. uncertainties on EWPO

- from the CDR draft contribution

WG 2 write-up

“Theoretical uncertainties for electroweak and Higgs-boson precision measurements at the FCC-ee”

Conveners: A. Freitas and S. Heinemeyer; Contributors: M. Beneke et al.  
see talk by S. Heinemeyer

Quantity	FCC-ee	Current intrinsic error	Projected intrinsic error
$M_W$ [MeV]	1–1.5 <sup>‡</sup>	4 ( $\alpha^3, \alpha^2\alpha_s$ )	1
$\sin^2 \theta_{\text{eff}}^\ell$ [ $10^{-5}$ ]	0.6	4.5 ( $\alpha^3, \alpha^2\alpha_s$ )	1.5
$\Gamma_Z$ [MeV]	0.1	0.5 ( $\alpha_{\text{bos}}^2, \alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2$ )	0.2
$R_b$ [ $10^{-5}$ ]	6	15 ( $\alpha_{\text{bos}}^2, \alpha^3, \alpha^2\alpha_s$ )	7
$R_l$ [ $10^{-3}$ ]	1	5 ( $\alpha_{\text{bos}}^2, \alpha^3, \alpha^2\alpha_s$ )	1.5

<sup>‡</sup>The pure experimental precision on  $M_W$  is  $\sim 0.5$  MeV [3].

- with present and conceivable loop technology, the intrinsic th. uncertainties will be at the same level of the experimental errors
- new calculation methods should be introduced

see talk by J. Gluza

see e.g. the recent review on multi-loop integrals, A. Freitas, Prog. Part. Nucl. Phys. 90 (2016) 201

# Parametric uncertainties on EWPO assuming

- $\delta M_Z \sim 0.1 \text{ MeV}$  from FCC-ee scan around the  $Z$ -peak
- $\delta m_t \sim 50 \text{ MeV}$  from the  $t\bar{t}$  FCC-ee scan, using recent NNNLO QCD predictions  
M. Beneke et al., Phys. Rev. Lett. **115** (2015) 192001
  - and assuming  $\delta\alpha_s \sim 10^{-4}$  for the mass translation
- $\delta\alpha_s(M_Z) \sim 2 \times 10^{-4}$  induced by the intrinsic  $\delta R_\ell = 1.5 \times 10^{-3}$
- $\delta(\Delta\alpha) \sim 5 \times 10^{-5}$ 
  - from the present  $\delta(\Delta\alpha) \sim 1 \times 10^{-4}$  (F. Jegerlehner, Davier et al., T. Teubner et al.) conceivable with dispersion relation techniques with new data from BESIII and Belle II
  - considering the possibility of direct measurement at FCC-ee using two off-peak points for  $A_{FB}(\mu^+\mu^-)$

P. Janot, JHEP **1602** (2016) 053

Quantity	FCC-ee	future parametric unc.	Main source
$M_W$ [MeV]	1 – 1.5	1 (0.6)	$\delta(\Delta\alpha)$
$\sin^2 \theta_{\text{eff}}^\ell$ [ $10^{-5}$ ]	0.6	2 (1)	$\delta(\Delta\alpha)$
$\Gamma_Z$ [MeV]	0.1	0.1	$\delta\alpha_s$
$R_b$ [ $10^{-5}$ ]	6	< 1	$\delta\alpha_s$
$R_\ell$ [ $10^{-3}$ ]	1	1.3	$\delta\alpha_s$

WG 2 write-up

- **Th. uncertainties dominated by  $\delta\alpha_s$  and  $\delta(\Delta\alpha)$**
- $\delta(\Delta\alpha)$  also the main source for  $N_\nu$  determination  $\implies$

# $N_\nu$ from $Z$ invisible width

$$R_{\text{inv}}^0 = \frac{\Gamma_{\text{inv}}}{\Gamma_{ll}} = \sqrt{\frac{12\pi R_l^0}{\sigma_{\text{had}}^0 m_Z^2}} - R_l^0 - (3 + \delta_\tau)$$

- assuming lepton universality

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

- from LEP  $Z$ -peak measurements

$$N_\nu = 2.9840 \pm 0.0082$$
$$\delta N_\nu \simeq 10.5 \frac{\delta n_{\text{had}}}{n_{\text{had}}} \oplus 3.0 \frac{\delta n_{\text{lept}}}{n_{\text{lept}}} \oplus 7.5 \frac{\delta \mathcal{L}}{\mathcal{L}}$$
$$\frac{\delta \mathcal{L}}{\mathcal{L}} = 0.061\% \implies \delta N_\nu = 0.0046$$

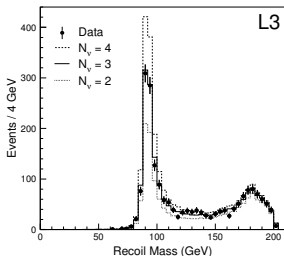
ADLO, SLD and LEPEWWG, Phys. Rept. 427 (2006) 257, hep-ex/0509008

- $\delta N_\nu$  severely affected by luminosity uncertainty through  $\sigma_0$

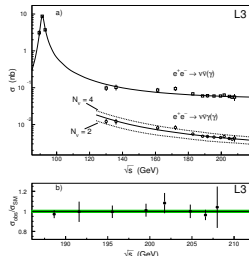
# Independent way for $\nu$ count: $\nu\bar{\nu}\gamma$ and LEP2

- radiative return to the  $Z$  peak through emission of a hard photon
- provided large enough luminosity is available to be competitive with  $\Gamma_{\text{inv}}$  method (not a problem at FCC-ee!)

$$190 \text{ GeV} \leq \sqrt{s} \leq 208 \text{ GeV}, \mathcal{L} \sim 600 \text{ pb}^{-1}$$



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

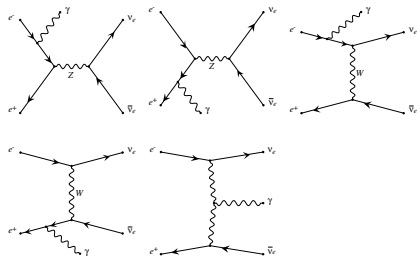


- agreement of data with SM predictions at % level
- $N_\nu = 2.98 \pm 0.05 \pm 0.04$  (L3) (important but not competitive with the  $\Gamma_{\text{inv}}$  method)
- similar results for ALEPH, DELPHI and OPAL

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

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

in order to cancel common systematics (such as luminosity)



- $\mu^+\mu^-$  only  $s$ -channel but ISR and FSR
- $\nu_\mu$  and  $\nu_\tau$  f.s.: only  $s$ -channel ISR
- $\nu_e$  f.s.: ISR with  $t$ -channel
- $\nu_e$  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

- the technology for full 2  $\rightarrow$  3 EW one-loop calculations is available

# Luminosity: theoretical systematics on $\sigma$ normalization

- theoretical error in small angle Bhabha process at LEP1

Type of correction/error	(%)	(%)	updated (%)
missing photonic $O(\alpha^2 L)$	0.100	0.027	0.027
missing photonic $O(\alpha^3 L^3)$	0.015	0.015	0.015
vacuum polarization	0.040	0.040	0.040
light pairs	0.030	0.030	0.010
Z-exchange	0.015	0.015	0.015
total	0.110	0.061	0.054

I column: Jadach, Nicosini et al. Physics at LEP2 YR 96-01, Vol. 2; Arbuzov et al., Phys. Lett. B389 (1996) 129

II column: Ward, Jadach, Melles, Yost, hep-ph/9811245; III column: Montagna et al., Nucl. Phys. B547 (1999) 39

- after LEP, progress in complete NNLO contributions to QED Bhabha scattering:

- NNLO photonic corrections A. Penin, PRL **95** (2005) 010408 & NPB**734** (2006) 185
- fermionic loop corrections

R. Bonciani *et al.*, Nucl. Phys. **B701** (2004) 121 & Nucl. Phys. **B716** (2005) 280  
S. Actis, M. Czakon, J. Gluza and T. Riemann, Nucl. Phys. **B786** (2007) 26 R. Bonciani, A. Ferroglia and A. Penin, PRL **100** (2008) 131601

S. Actis, M. Czakon, J. Gluza and T. Riemann, PRL **100** (2008) 131602  
J.H. Kühn and S. Uccirati, Nucl. Phys. **B806** (2009) 300

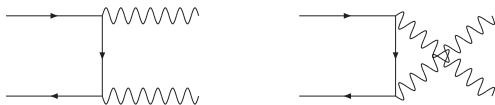
- one-loop soft+virtual corrections to single hard bremsstrahlung

S. Actis, P. Mastrolia and G. Ossola, Phys. Lett. **B682** (2010) 419

- VP present at NLO, recent estimate: 0.040%  $\rightarrow$  0.021%

C.M. Carloni Calame, 9th FCC-ee Workshop, Pisa, February 2015

# possible alternative to Bhabha scattering: $e^+e^- \rightarrow \gamma\gamma$



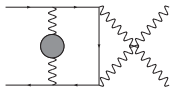
- $e^+e^- \rightarrow \gamma\gamma$  could be used to **cross-check independently**  $\mathcal{L}$

- ★ present theoretical accuracy: QEDPS NLO  $\sim 0.1\%$

G. Balossini et al., Phys.Lett. B663 (2008) 209

- ★ **Advantages**

- no Z exchange diagrams (at LO)
- **no photon VP corrections (up to NNLO)**



- ★ **Disadvantages**

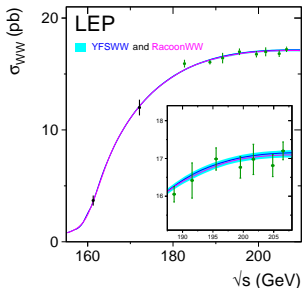
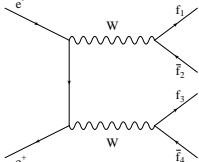
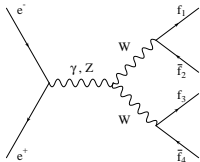
- lower x-section by  $\sim$  three order of magnitude
- efficiency in detecting  $\gamma\gamma$  events



It is worth investigating the potential of  $e^+e^- \rightarrow \gamma\gamma$  for precision luminosity measurement

- CepC members willing to start a fast detector simulation on  $\gamma\gamma$
- next week “CepC Theory Group Workshop” will host a session on “Z-pole EWK precision measurements”

# WW threshold: $e^+e^- \rightarrow 4$ fermions



- first NLO exact calculation completed in 2005 for  $WW \rightarrow 4f$ 
  - th. accuracy  $\lesssim 1\%$  A. Denner et al., PLB612 (2005) 223; NPB 724 (2005) 247
- the same accuracy can be extended to other  $e^+e^- \rightarrow 4f$  f.s., with recent automated tools for LHC (e.g. GoSam, MadLoop, OpenLoops, RECOLA, etc.)
- NNLO enhanced contributions because of Coulomb photon effects calculated by means of EFT methods

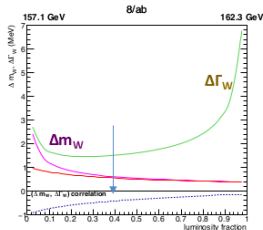
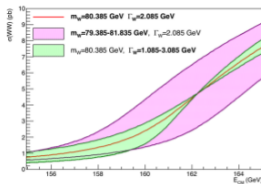
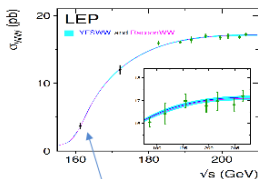
M. Beneke et al., NPB 792 (2008) 89; S. Actis et al., NPB807 (2009) 1

• th. accuracy  $\sim 0.5\%$

$\Delta M_W \sim 3$  MeV

- 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  $e^+e^- \rightarrow WW$  in NWA
    - NNLO accuracy in the  $W$  decay
  - improved treatment of subleading effects in ISR
- full NNLO  $e^+e^- \rightarrow 4$  fermions out of reach with present methods
  - new ideas necessary

## W mass (and width) from WW cross section



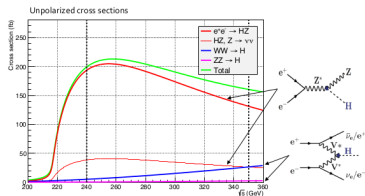
At LEP2  $\sqrt{s}=161$  GeV  $\sigma=4$ pb  
 $\epsilon=0.75$ ,  $\sigma_B=300$  fb  
 $p=0.9$  :  $\epsilon_p \approx 0.68$  (@161)  
 $\rightarrow m_W=80.40 \pm 0.21$  GeV  
 with 11/pb @  $E_{CM}=161$  GeV

Sensitivity to mass and width is different at different  $E_{CM}$ : can optimize measurement mass AND width choosing carefully two energy points. Same concept can be used to minimize systematics (e.g. due to backgrounds)

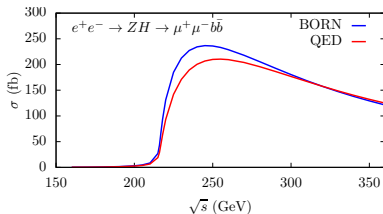
with  $E_1=157.1$  GeV  $E_2=162.3$  GeV  $f=0.4$   
 $\Delta m_W=0.62$   $\Delta \Gamma_W=1.5$  (MeV)

Goal: control acceptance and systematics at  $10^{-4}$  level !

# Higgs production at ZH threshold



Bicer et al., 2014



M. Greco et al., in progress

- **ISR QED corr. large,  $\sim 35\%$  at threshold;  $\sim 15\%$  @ 240 GeV**
- **NLO corrections available for  $e^+e^- \rightarrow ZH$  and to  $e^+e^- \rightarrow \nu\bar{\nu}H$** 
  - J. Fleischer and F. Jegerlehner, NPB216 (1983) 469; B.A. Kniehl, Z. Phys. C55 (1992) 605; A. Denner et al., Z. Phys. C56 (1992) 261; G. Belanger et al., Nucl. Phys. Proc. Suppl. 116 (2003) 353
  - weak corrections at the  $\sim 5\%$  level
- **recently calculated dominant contributions to NNLO corrections**
  - $\mathcal{O}(\alpha_s\alpha) \gtrsim 1\%$
  - Y. Gong et al., Phys Rev. D95 (2017) 093003; Q.F. Sung et al., arXiv:1609.03995
- **for the future, to match the 0.4% experimental accuracy**
  - full NNLO to  $e^+e^- \rightarrow ZH$  and maybe  $\mathcal{O}(\alpha\alpha_s^2)$  needed
  - complete calculation of  $e^+e^- \rightarrow ZH \rightarrow f\bar{f}H$

## intrinsic uncertainties

Partial width	QCD	electroweak	total
$H \rightarrow bb/c\bar{c}$	$\sim 0.2\%$	$< 0.3\%$	$< 0.4\%$
$H \rightarrow \tau^+\tau^-/\mu^+\mu^-$	–	$< 0.3\%$	$< 0.3\%$
$H \rightarrow gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3.2\%$
$H \rightarrow \gamma\gamma$	$< 0.1\%$	$< 1\%$	$< 1\%$
$H \rightarrow Z\gamma$	$\lesssim 0.1\%$	$\sim 5\%$	$\sim 5\%$
$H \rightarrow WW/ZZ \rightarrow 4f$	$< 0.5\%$	$< 0.3\%$	$\sim 0.5\%$

decay	para. $m_q$	para. $\alpha_s$	para. $M_H$
$H \rightarrow b\bar{b}$	1.4%	0.4%	–
$H \rightarrow c\bar{c}$	4.0%	0.4%	–
$H \rightarrow \tau^+\tau^-$	–	–	–
$H \rightarrow \mu^+\mu^-$	–	–	–
$H \rightarrow gg$	$< 0.2\%$	3.7%	–
$H \rightarrow \gamma\gamma$	$< 0.2\%$	–	–
$H \rightarrow Z\gamma$	–	–	2.1%
$H \rightarrow WW$	–	–	2.6%
$H \rightarrow ZZ$	–	–	3.0%

- projected param. uncertainties

- $\delta\alpha_s = 0.0002$
- $\delta m_t = 50 \text{ MeV}$ ,  $\delta m_H = 10 \text{ MeV}$ ,  $\delta m_b = 13 \text{ MeV}$ ,  $\delta m_c = 7 \text{ MeV}$

decay	intrinsic	para. $m_q$	para. $\alpha_s$	para. $M_H$	FCC-ee prec. on $g_{HXX}^2$
$H \rightarrow b\bar{b}$	$\sim 0.2\%$	0.6%	$< 0.1\%$	–	$\sim 0.8\%$
$H \rightarrow c\bar{c}$	$\sim 0.2\%$	$\sim 1\%$	$< 0.1\%$	–	$\sim 1.4\%$
$H \rightarrow \tau^+\tau^-$	$< 0.1\%$	–	–	–	$\sim 1.1\%$
$H \rightarrow \mu^+\mu^-$	$< 0.1\%$	–	–	–	$\sim 12\%$
$H \rightarrow gg$	$\sim 1\%$	–	0.5%	–	$\sim 1.6\%$
$H \rightarrow \gamma\gamma$	$< 1\%$	–	–	–	$\sim 3.0\%$
$H \rightarrow Z\gamma$	$\sim 1\%$	–	–	$\sim 0.1\%$	–
$H \rightarrow WW$	$\lesssim 0.4\%$	–	–	$\sim 0.1\%$	$\sim 0.4\%$
$H \rightarrow ZZ$	$\lesssim 0.3\%^\dagger$	–	–	$\sim 0.1\%$	$\sim 0.3\%$
$\Gamma_{\text{tot}}$	$\sim 0.3\%$	$\sim 0.4\%$	$< 0.1\%$	$< 0.1\%$	$\sim 1\%$

<sup>†</sup> From  $e^+e^- \rightarrow HZ$  production

# Summary

- with present status, theoretical uncertainties would dominate systematics at FCC-ee in SM measurements
- recent advances in calculation methods will allow to increase the level of precision of th. predictions (intrinsic uncertainties)
  - new calculation methods will be necessary to reduce the intrinsic uncertainties for several observables
- a more accurate treatment of ISR will be necessary at all energies
- important role played by the parametric uncertainties, which should be kept under control by future precise measurements
- among the sources of parametric uncertainties, a big challenge will be posed by  $\alpha(M_Z)$ 
  - complementary strategies should be pursued
    - e.g., direct measurement of  $\alpha(M_Z)$ @FCC-ee  $\implies$  improvement required of two orders of magnitude in the calculation of  $A_{FB}$  off  $Z$ -peak  $\implies$  QED i.f.s. interference uncertainty key ingredient
    - for normalization, perform studies on  $e^+e^- \rightarrow \gamma\gamma$ , which is less exposed to  $\alpha(M_Z)$  uncertainties by one perturbative order w.r.t Bhabha scattering
- incredible amount of work ahead for theorists!