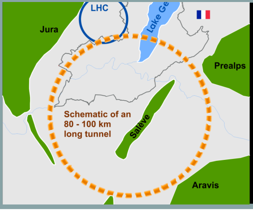


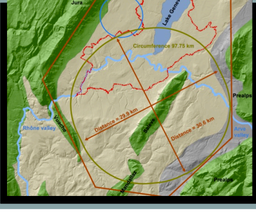
Theory Challenges at lepton colliders

Stanisław Jadach

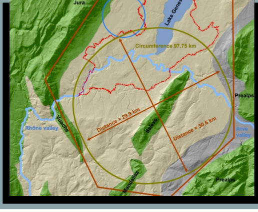
in collaboration with M. Skrzypek

September 2-6, 2019 Matter To The Deepest 2019, Chorzów

*This work is partly supported by the Polish National Science Center grant 2016/23/B/ST2/03927 and the CERN FCC Design Study Programme.



Future accelerator projects



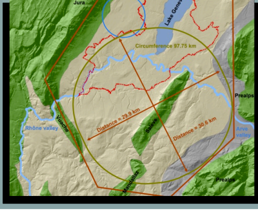
More future colliders worldwide

Japan

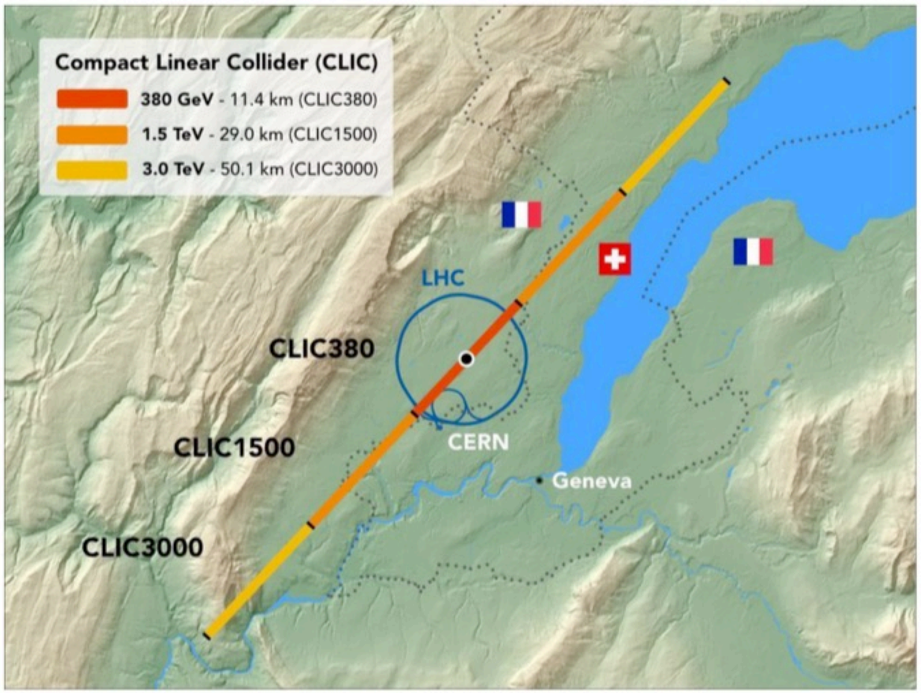
China

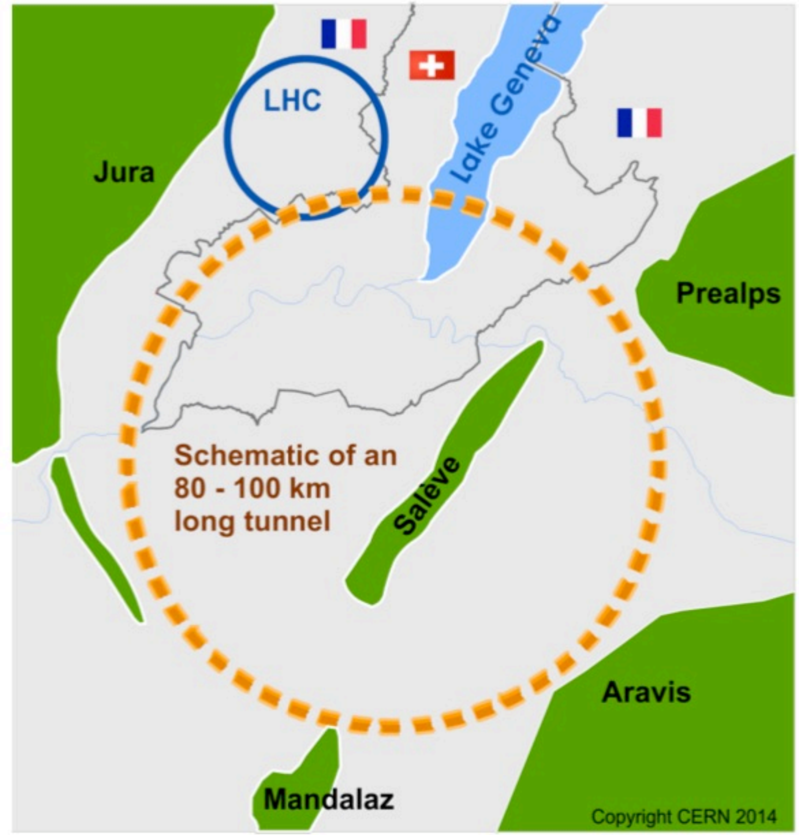
CERN

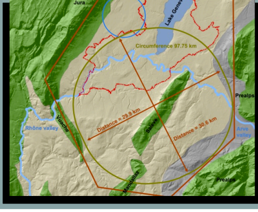
Project	Type	Energy [TeV]	Int. Lumi. [a^{-1}]	Oper. Time [y]	Power [MW]	Cost
ILC	ee	0.25	2	11	129 (upgr. 150-200)	4.8-5.3 GILCU + upgrade
		0.5	4	10	163 (204)	7.98 GILCU
		1.0			300	?
CLIC	ee	0.38	1	8	168	5.9 GCHF
		1.5	2.5	7	(370)	+5.1 GCHF
		3	5	8	(590)	+7.3 GCHF
CEPC	ee	0.091+0.16	16+2.6		149	5 G$
		0.24	5.6	7	266	
FCC-ee	ee	0.091+0.16	150+10	4+1	259	10.5 GCHF
		0.24	5	3	282	
		0.365 (+0.35)	1.5 (+0.2)	4 (+1)	340	+1.1 GCHF
LHeC	ep	60 / 7000	1	12	(+100)	1.75 GCHF
FCC-hh	pp	100	30	25	580 (550)	17 GCHF (+7 GCHF)
HE-LHC	pp	27	20	20		7.2 GCHF



Two competing e^+e^- projects in CERN







FCC: Most ambitious plan for CERN

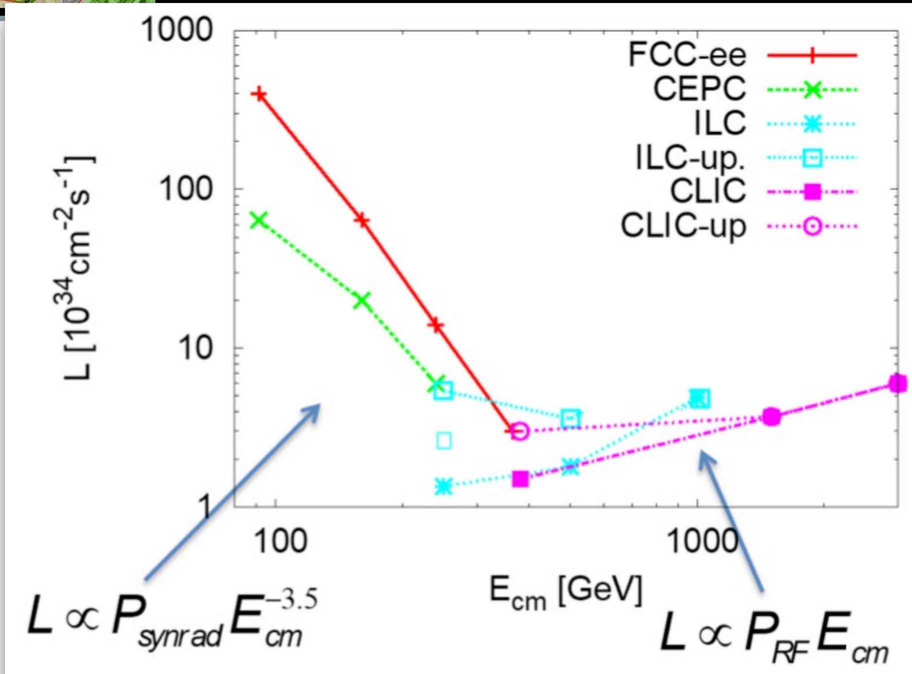
This is essentially an ultimate plan for the next ~70 years in CERN:

- **In the new 100km tunnel:**
- **FCC-ee 80-380GeV for 10-15 years,**
- **FCC-hh 100TeV for 25 years in the same tunel,**
- **FCC-eh in parasitic mode in parallel with FCC-hh,**

- **Something for our grandchildren: Muon collider 10-30TeV afterwards:)**

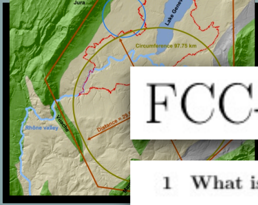
(Unfortunately CLIC does not fit into the above plan:)

Energy and luminosity for e^+e^- colliders



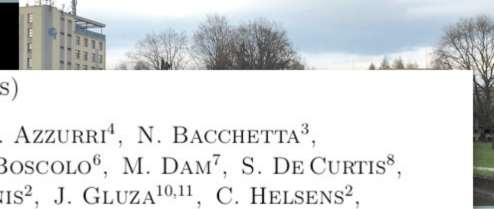
Fantastic luminosity 10^5xLEP of FCC-ee collider !!!

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340-350	365
Lumi/IP ($10^{34}\,cm^{-2}s^{-1}$)	115	230	28	8.5	0.95	1.55
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34
Physics Goal (ab^{-1})	150		10	5	0.2	1.5
Run time (year)	2	2	2	3	1	4
Number of events	5×10^{12} Z		10^8 WW	10^6 HZ + 25k WW $\to$ H	$10^6 t\bar{t}$ +200k HZ +50k WW $\to$ H	



arXiv:1906.02693

FCC-ee: Your Questions Answered



A. Blondel[1,2], P. Janot[2] (Editors)

N. Alipour Tehrani[2], P. Azzi[3], P. Azzurri[4], N. Bacchetta[3], M. Benedikt[2], F. Blekman[5], M. Boscolo[6], M. Dam[7], S. De Curtis[8], D. d'Enterria[2], J. Ellis[9], G. Ganis[2], J. Gluza[10,11], C. Helsens[2], S. Jadach[12], M. Koratzinos[13], M. Klute[13], C. Leonidopoulos[14], E. Locci[15], M. Mangano[2], S. Monteil[16], K. Oide[2], V. A. Okorokov[17], E. Perez[2], T. Riemann[10,18], R. Tenchini[4], M. Selvaggi[2], G. Voutsinas[2], J. Wenninger[2], F. Zimmermann[2].

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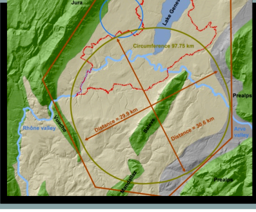
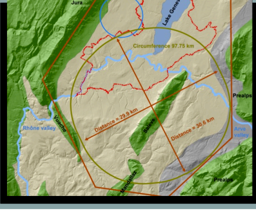


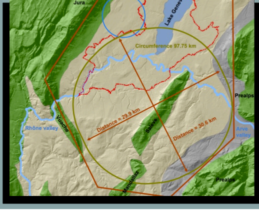
THEORY: Where are we?



THEORY: Where are we?

The important questions

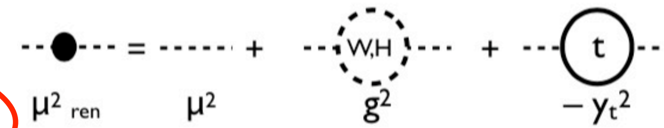
- **Data driven:**
  - DM
  - Neutrino masses
  - Matter vs antimatter asymmetry
  - Dark energy
  - …
- **Theory driven:**
  - The hierarchy problem and naturalness
  - The flavour problem (origin of fermion families, mass/mixing pattern)
  - Quantum gravity
  - Origin of inflation
  - …



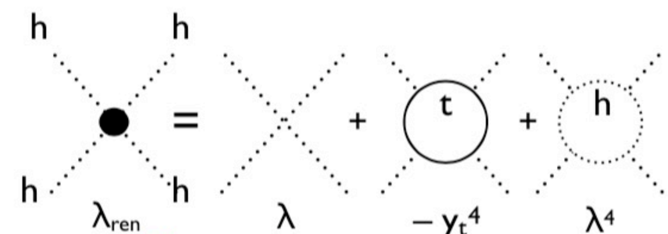
THEORY: Where are we?

- To predict the properties of EM at large scales, we don't need to know what happens at short scales
- The Higgs dynamics is sensitive to all that happens at any scale larger than the Higgs mass !!! A very unnatural **fine tuning** is required to protect the Higgs dynamics from the dynamics at high energy
- This issue goes under the name of **hierarchy problem**

$$V_{SM}(H) = -\mu^2 |H|^2 + \lambda |H|^4$$



$$\Delta\mu^2 \sim (c_B m_B^2 - c_F m_F^2) \times (\Lambda / v)^2$$



$$\Rightarrow \frac{d\lambda}{d \log \mu} \propto \lambda^4 - y_t^4 \propto a\, m_H^4 - b\, m_t^4$$

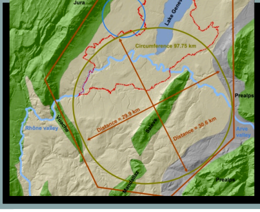
high-energy modes can change size and sign of both μ^2 and λ, dramatically altering the stability and dynamics

Lack of experimental evidence so far for a straightforward answer to naturalness, forces us to review our biases, and to take a closer look even at the most basic assumptions about Higgs properties

- again, "who ordered that?"
- in this perspective, even innocent questions like whether the Higgs gives mass also to 1st and 2nd generation fermions call for experimental verification, nothing of the Higgs boson can be given for granted
- what we've experimentally proven so far are basic properties, which, from the perspective of EFT and at the current level of precision of the measurements, could hold in a vast range of BSM EWSB scenarios

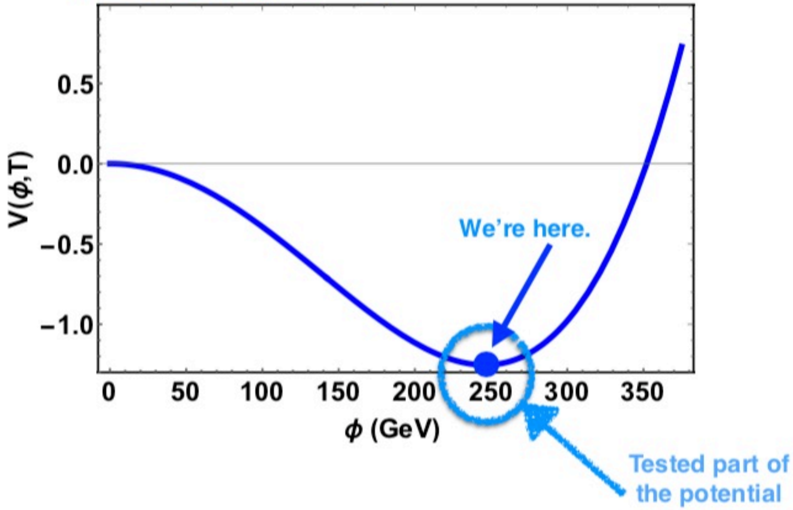
➡ *the Higgs discovery does not close the book, it opens a whole new chapter of exploration, based on precise measurements of its properties, and relying on a future generation of colliders*

Michelangelo Mangano, CERN, March 2019, FCC-ee big meeting.



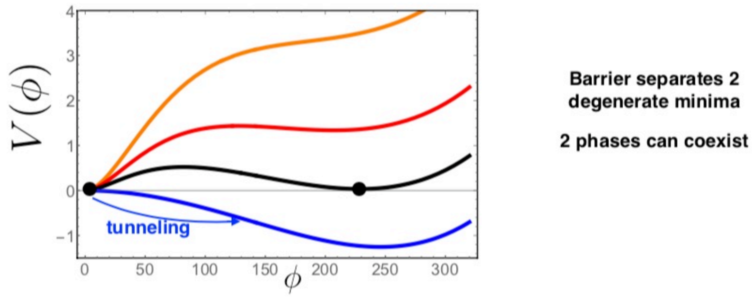
Higgs is there! So what?

TODAY, T=0



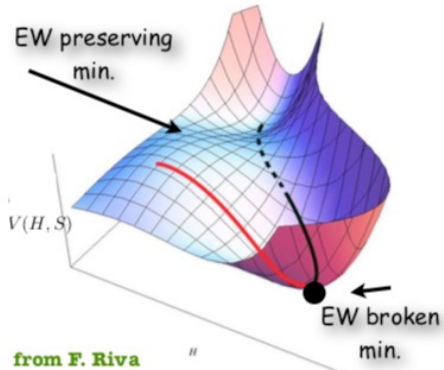
How have we got there?
At the end of inflation….

First-order EW phase transition



Nucleation, expansion and collision of Higgs bubbles

May be like that?

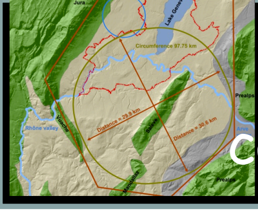


> Framework for EW baryogenesis !

Géraldine SERVANT
DESY/U.Hamburg

Astrophysics begs for 1% measurement of the Higgs potential parameters!

Can we ever measure Higgs potential with 1% precision?

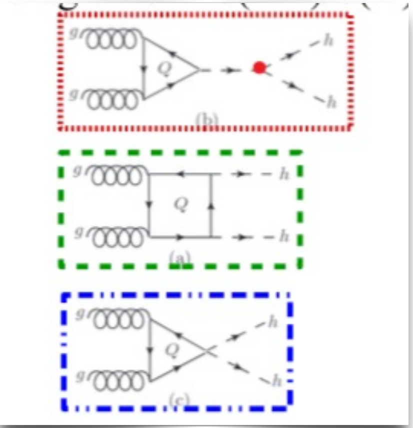


How well Higgs self couplings H^3 and H^4 can be measured? Can we ever get to 1%?

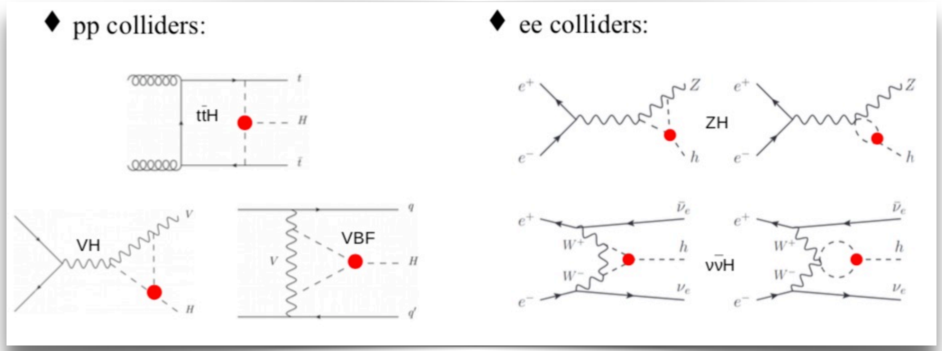
♦ Approximation around the v.e.v.:

$$V(\Phi)\approx \underbrace{\lambda v^2 h^2}_{\text{mass term}} + \underbrace{\lambda v h^3 + \frac{1}{4}\lambda h^4}_{\text{self-coupling terms}}$$

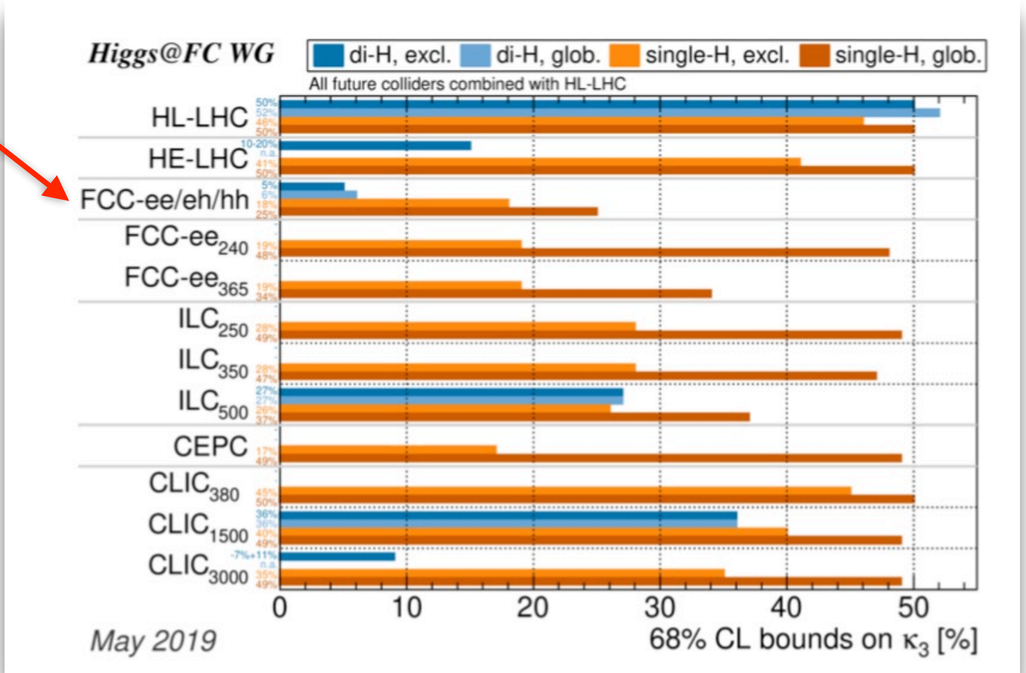
H^*->2H at HL-LHC



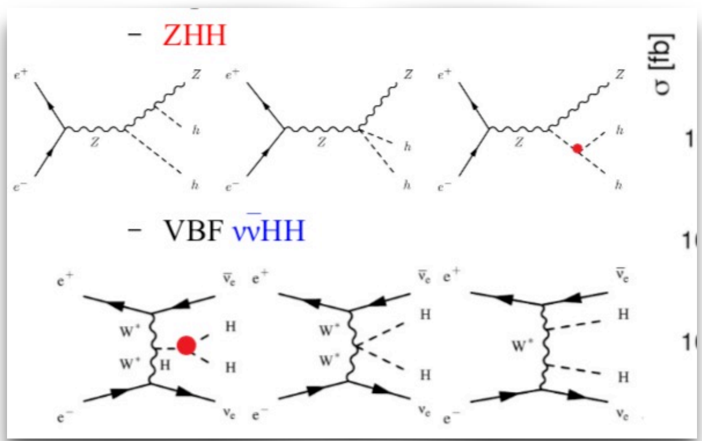
From virtual loop to 1H



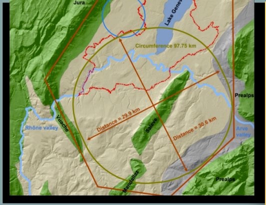
FCC wins at ~5%



CLIC



Only muon collider at 30TeV can provide 1% for H^3 and 30-50% for H^4 !!!

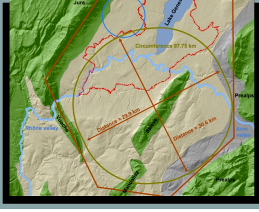


Precision Electroweak Calculations for Z, WW, Higgs @ e^+e^- colliders

- Full line-shape prediction to NNLO EW + leading effects beyond
  - technical progress in 2- and multi-loop amplitudes/integrals
  - conceptual progress in NNLO EW corrections (unstable particles!)
  - improvements on leading ISR corrections beyond NNLO
  - leading EW corrections beyond NNLO
- Validity of pseudo-observable approach
  - better field-theoretical foundation of Z-pole pseudo-observables (complex pole definition, absorptive parts, continuum subtraction)
  - Improved Born Approximation (IBA) to parametrize line-shape via pseudo-obs. (+ precise concept to treat non-resonant parts)
  - careful validation of IBA against full $e^+e^- \to Z/\gamma \to f\bar{f}$ prediction

$\hookrightarrow$ Impact on experimental analysis possible

Stefan Dittmaier
Albert-Ludwigs-Universität Freiburg



#125 input to ESPP

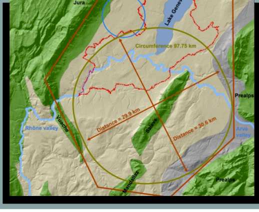
Improved precision equates discovery potential.
significant deviation from the Standard Model predictions will definitely be a discovery.

EWPO	Exp. direct error	Param. error	Main source	Theory uncert.
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$	0.07
R_b $[10^{-5}]$	6	1	$\delta\alpha_s$	3
R_ℓ $[10^{-3}]$	1	1.3	$\delta\alpha_s$	0.7
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	0.5	1	$\delta(\Delta\alpha)$	0.7
M_W [MeV]	0.5	0.6	$\delta(\Delta\alpha)$	0.3

Table 3: Estimated experimental precision for the direct measurement of several important EWPOs at FCC-ee [2] (column two) and experimental parametric error (column three), with the main source shown in the forth column. Important input parameter errors are $\delta(\Delta\alpha) = 3 \cdot 10^{-5}$, $\delta\alpha_s = 0.00015$ see FCC CDR, vol. 2 [1]. Last column shows anticipated theory uncertainties at start of FCC-ee.

https://arxiv.org/abs/1901.02648

Janusz Gluza (University of Silesia)
Alain Blondel (Universite de Geneve...)
Patrick Janot (CERN)
Staszek Jadach (Polish Academy of S...)
Tord Riemann
Sven Heinemeyer (CSIC (Madrid, ES))
Ayres Freitas (University of Pittsbur...)



Tera-Z: will need Factor 10-100 more precise SM EW/QED/QCD calculations !!!

Slightly more pessimistic table of Stefan Dittmaier from Granada talk:

Central EW precision (pseudo-)observables at the Z pole

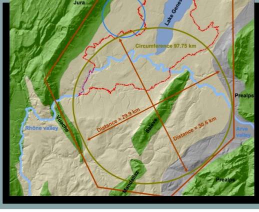
FCC-ee: update of Blondel et al., 1901.02648 (in prep.); ILC: Moortgat-Pick et al., 1504.01726

	experimental accuracy			intrinsic th. unc.		parametric unc.	
	current	ILC	FCC-ee	current	prospect	prospect	source
ΔM_Z[MeV]	2.1	–	0.1				
$\Delta \Gamma_Z$[MeV]	2.3	1	0.1	0.4	0.15	0.1	α_s
$\Delta \sin^2\theta^\ell_{eff}[10^{-5}]$	23	1.3	0.6	4.5	1.5	2(1)	$\Delta\alpha_{had}$
$\Delta R_b[10^{-5}]$	66	14	6	11	5	1	α_s
$\Delta R_\ell[10^{-3}]$	25	3	1	6	1.5	1.3	α_s

Parametric uncertainties of EW pseudo-observables:

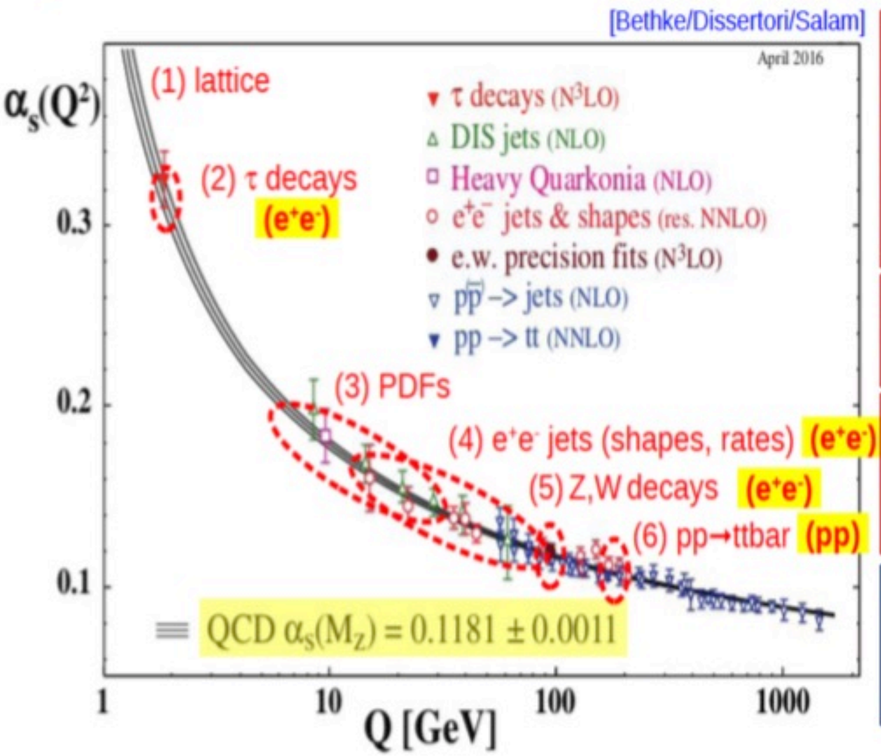
- QCD: (talk by F.Caola)
  - ◇ most important: $\delta\alpha_s \sim 0.00015$ @ FCC-ee?
    $\hookrightarrow \alpha_s$ from EW POs competitive $\Rightarrow$ cross-check with other results!
  - ◇ quark masses m_t, m_b, m_c
- $\Delta\alpha_{had}$: $\delta(\Delta\alpha_{had}) \sim 5(3) \times 10^{-5}$ for/from FCC-ee?

Stefan Dittmaier
Albert-Ludwigs-Universität Freiburg



QCD coupling constant at 0.1% precision!

$\alpha_S(M_Z)$ from today's $\delta\alpha_S/\alpha_S \simeq 1\,\%$ down to $0.1\,\%$ at FCC-ee



FCC-ee

from hadronic Z decays	$\delta\alpha_s$ <0.15%	*(today 2.5%)*
from hadronic W decays	$\delta\alpha_s$ < 0.2%	*(today 35%)*
from hadronic τ decays	$\delta\alpha_s$ < 1%	*(today 1.5%)*
event shapes	$\delta\alpha_s$ < 1%	*(today 2.9%)*

FCC-eh or LHeC

with DIS would be able to reach $\delta\alpha_s \sim$ 0.1-0.2%

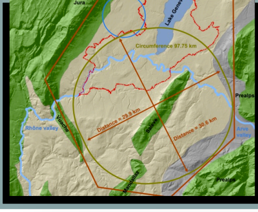
FCC-hh

from top quark pair production

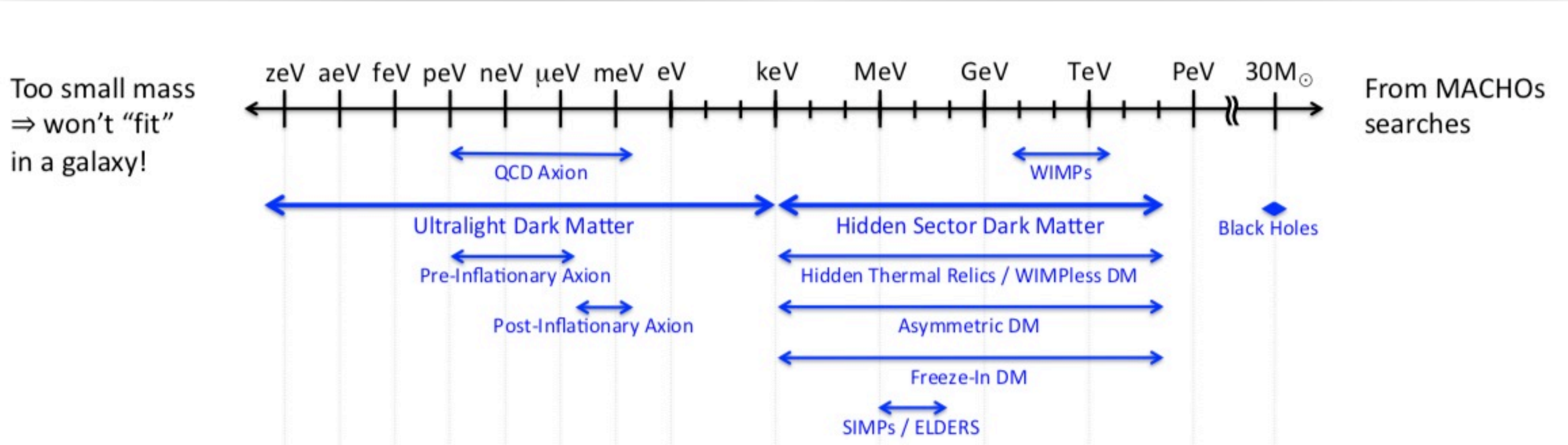
test the running of α_s up to 25 TeV (jet cross sections)

Lattice QCD

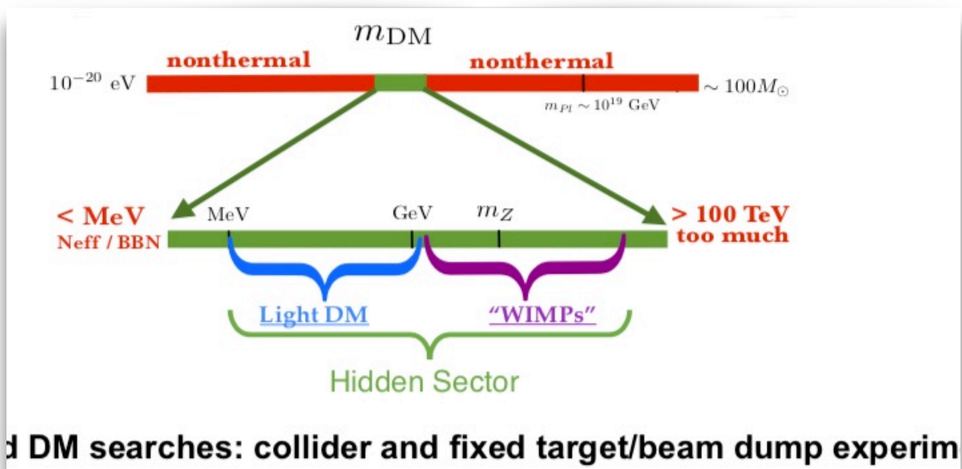
with adequate R&D on computing a robust calculation up to 0.3% precision might be within reach



Dark Matter: vast energy scale possible
We are completely in the dark!!!



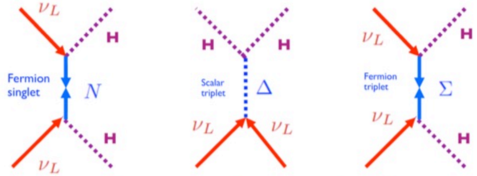
What accelerator experiments may probe:



Accelerator experiments may eliminate VIMPS from the menu

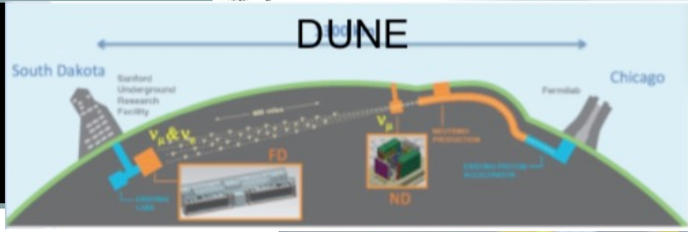
Neutrino as a window to new physics

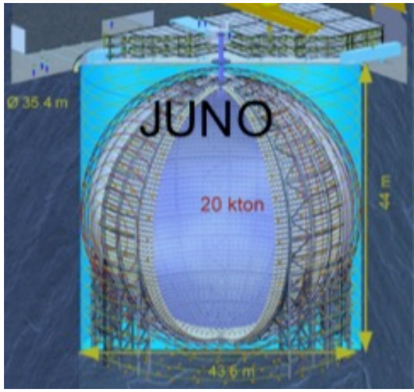
- The minimal extension is to have new elementary neutral fermions
- Neutrinos could have new interactions



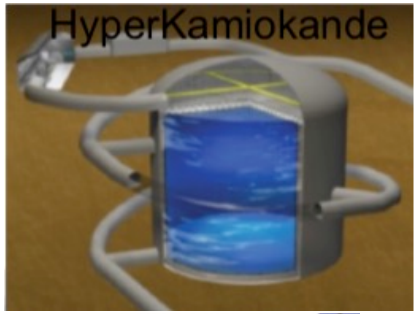
- A strong physics case for precisely measuring the mass and mixing parameters
- Determining the nature (Dirac or Majorana) of the neutrino is a crucial step
- The (possible) CP violation in the mixing could be related to the baryon asymmetry in the Universe
- We shoud also look for new states or new interactions (neutrino portal) : could be a ground-breaking discovery !

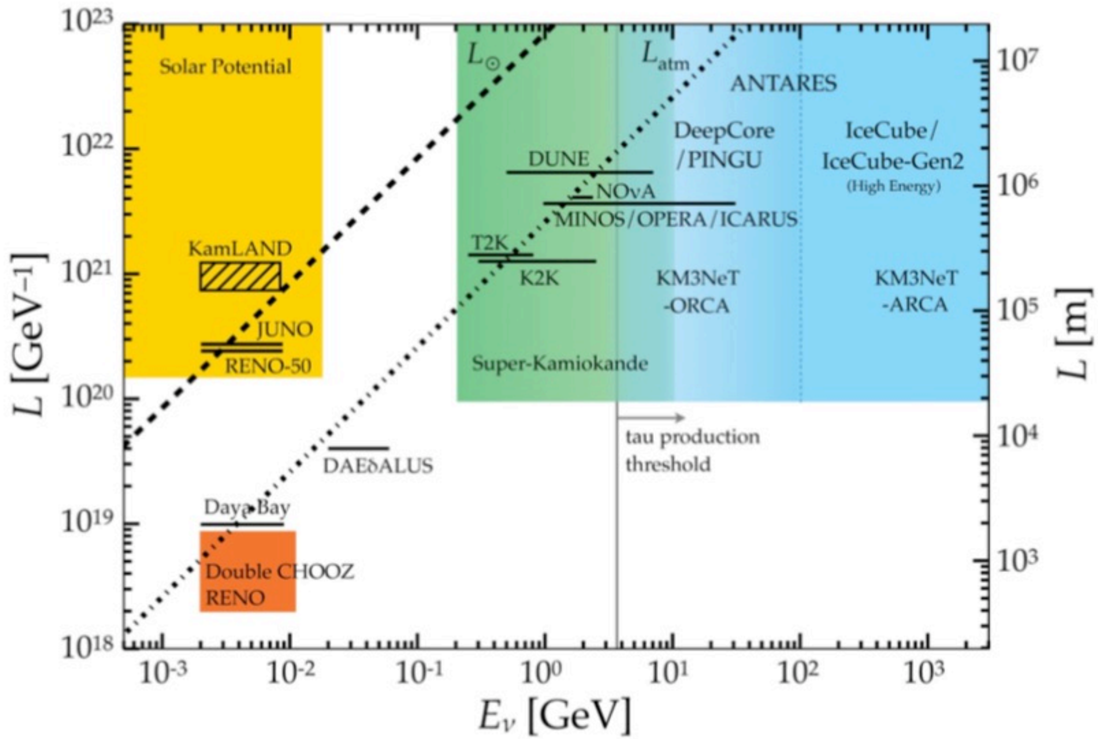
Neutrino Physics

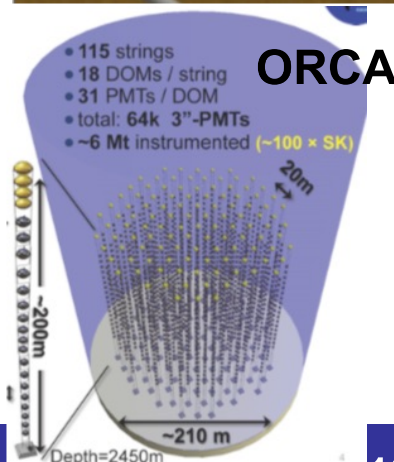


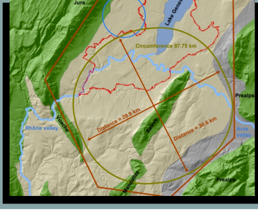


Is Europe lagging behind?









SM/EW calc. improvements mandatory for FCCe EWPO's
Complete 2-loops EW are there… 3-4 loop needed…

Almost complete 2-loop corrections available since 2006, see for example:
Hollik,Meier,Uccirati, Nucl.Phys. B765(2007)154 or Awramik,Czakon,Freitas,JHEP 11(2006)048.

Missing bosonic 2-loop cor. to b-quark observables added recently:
Dubovyk,Freitas,Gluza,Riemann,Usovitsch, Phys.Lett.B762(2016)184
and poster at FCCee Week Amsterdam 2018

Completing 2-loops: bosonic corrections [2,3]

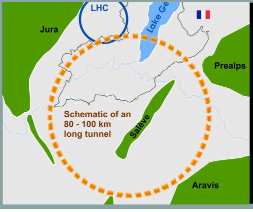
Γ_i [MeV]	$\Gamma_e, \Gamma_\mu, \Gamma_\tau$	$\Gamma_{\nu_e}, \Gamma_{\nu_\mu}, \Gamma_{\nu_\tau}$	Γ_d, Γ_s	Γ_u, Γ_c	Γ_b	Γ_Z
$\mathcal{O}(\alpha)$	2.273	6.174	9.717	5.799	3.857	60.22
$\mathcal{O}(\alpha\alpha_s)$	0.288	0.458	1.276	1.156	2.006	9.11
$\mathcal{O}(N_f^2\alpha^2)$	0.244	0.416	0.698	0.528	0.694	5.13
$\mathcal{O}(N_f\alpha^2)$	0.120	0.185	0.493	0.494	0.144	3.04
$\mathcal{O}(\alpha_{\rm bos}^2)$	**0.017**	**0.019**	**0.058**	**0.057**	**0.167**	**0.505**
$\mathcal{O}(\alpha_t\alpha_s^2, \alpha_t\alpha_s^3, \alpha_t^2\alpha_s, \alpha_t^3)$	0.038	0.059	0.191	0.170	**0.190**	1.20

Table 1: Weak 2-loop and QCD 3-loop corrections for various Γ_f
Red entries are preliminary, unpublished (March 2018) [3].

- New corrections substantially bigger than expectation
- They are of the order of the estimated leading 3-loop effects
- Not crucial for the present precision tests but mandatory for FCCee, see next slide
- Obtained numerically using Melin-Barnes and sectorization methods with 8 digits!
- The same methods are considered as promising candidates for the future 3-loop calculations
- Preliminary/unpublished

Precision calculations for the Z line shape at the FCC-ee

I. Dubovyk[a], A. Freitas[b], J. Gluza[c], K. Grzanka[c], S. Jadach[d], T. Riemann[c], J. Usovitsch[e]



QED at the Z pole: Challenges

Master Table of https://arxiv.org/abs/1903.09895

What are PSEUDO-OBSERVABLEs (POs)?

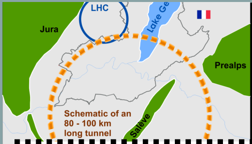
Desired improvement factor for QED!

What is QED-induced uncertainty in PO?

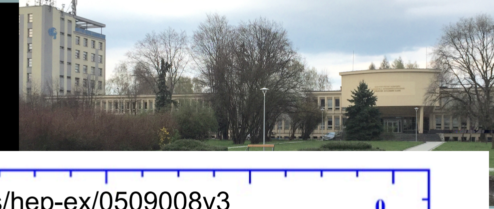
Observable	Where from	Present (LEP)	FCC stat.	FCC syst	$\frac{\text{Now}}{\text{FCC}}$
M_Z [MeV]	Z linesh. [29]	$91187.5 \pm 2.1\{0.3\}$	0.005	0.1	3
Γ_Z [MeV]	Z linesh. [29]	$2495.2 \pm 2.1\{0.2\}$	0.008	0.1	2
$R_l^Z = \Gamma_h/\Gamma_l$	$\sigma(M_Z)$ [34]	$20.767 \pm 0.025\{0.012\}$	$6 \cdot 10^{-5}$	$1 \cdot 10^{-3}$	12
$\sigma^0_{\rm had}$[nb]	$\sigma^0_{\rm had}$ [29]	$41.541 \pm 0.037\{0.025\}$	$0.1 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	6
N_ν	$\sigma(M_Z)$ [29]	$2.984 \pm 0.008\{0.006\}$	$5 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	6
N_ν	$Z\gamma$ [35]	$2.69 \pm 0.15\{0.06\}$	$0.8 \cdot 10^{-3}$	$< 10^{-3}$	60
$\sin^2\theta_W^{eff} \times 10^5$	$A_{FB}^{lept.}$ [34]	$23099 \pm 53\{28\}$	0.3	0.5	55
$\sin^2\theta_W^{eff} \times 10^5$	$\langle\mathcal{P}_\tau\rangle, A_{\rm FB}^{pol,\tau}$ [29]	$23159 \pm 41\{12\}$	0.6	< 0.6	20
M_W [MeV]	ADLO [36]	$80376 \pm 33\{6\}$	0.5	0.3	12
$A_{FB,\mu}^{M_Z \pm 3.5\rm GeV}$	$\frac{d\sigma}{d\cos\theta}$ [29]	$\pm 0.020\{0.001\}$	$1.0 \cdot 10^{-5}$	$0.3 \cdot 10^{-5}$	100

Go to page 36

How LEP and FCC-ee exp. precisions do compare?



What are EW pseudo-observables (EWPOs)?

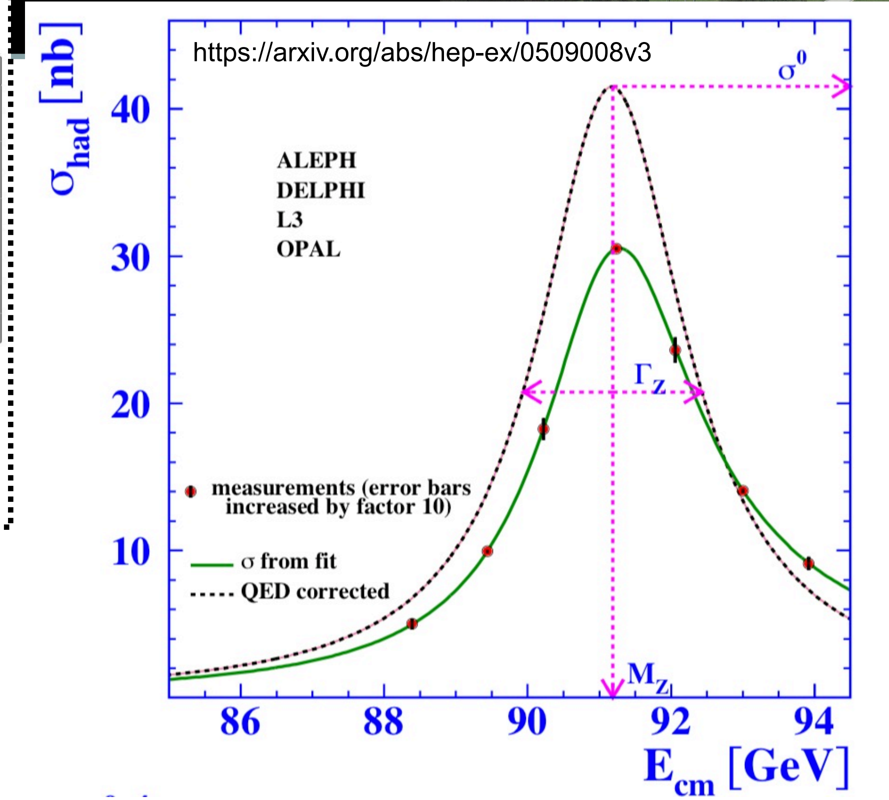


Correlation matrix

$\chi^2/\mathrm{dof} = 155/194$		OPAL								
m_Z [GeV]	91.1858 ± 0.0030	1.000								
Γ_Z [GeV]	2.4948 ± 0.0041	0.049	1.000							
σ^0_{had} [nb]	41.501 ± 0.055	0.031	−0.352	1.000						
R^0_e	20.901 ± 0.084	0.108	0.011	0.155	1.000					
R^0_μ	20.811 ± 0.058	0.001	0.020	0.222	0.093	1.000				
R^0_τ	20.832 ± 0.091	0.001	0.013	0.137	0.039	0.051	1.000			
$A^{0,e}_{\mathrm{FB}}$	0.0089 ± 0.0045	−0.053	−0.005	0.011	−0.222	−0.001	0.005	1.000		
$A^{0,\mu}_{\mathrm{FB}}$	0.0159 ± 0.0023	0.077	−0.002	0.011	0.031	0.018	0.004	−0.012	1.000	
$A^{0,\tau}_{\mathrm{FB}}$	0.0145 ± 0.0030	0.059	−0.003	0.003	0.015	−0.010	0.007	−0.010	0.013	1.000

Table 2.4: Individual results on Z parameters and their correlation coefficients from the four experiments. Systematic errors are included here except those summarised in Table 2.9.

Example of basic 9 EWPO's at LEP1, without lepton universality



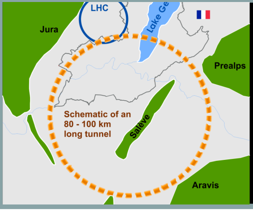
Example of EWPO: σ^0_{had}

Experimental $\sigma_{\mathrm{had}}(s_i)$ measured at 7 energies $E^{(i)}_{\mathrm{cm}} = s_i^{1/2}$

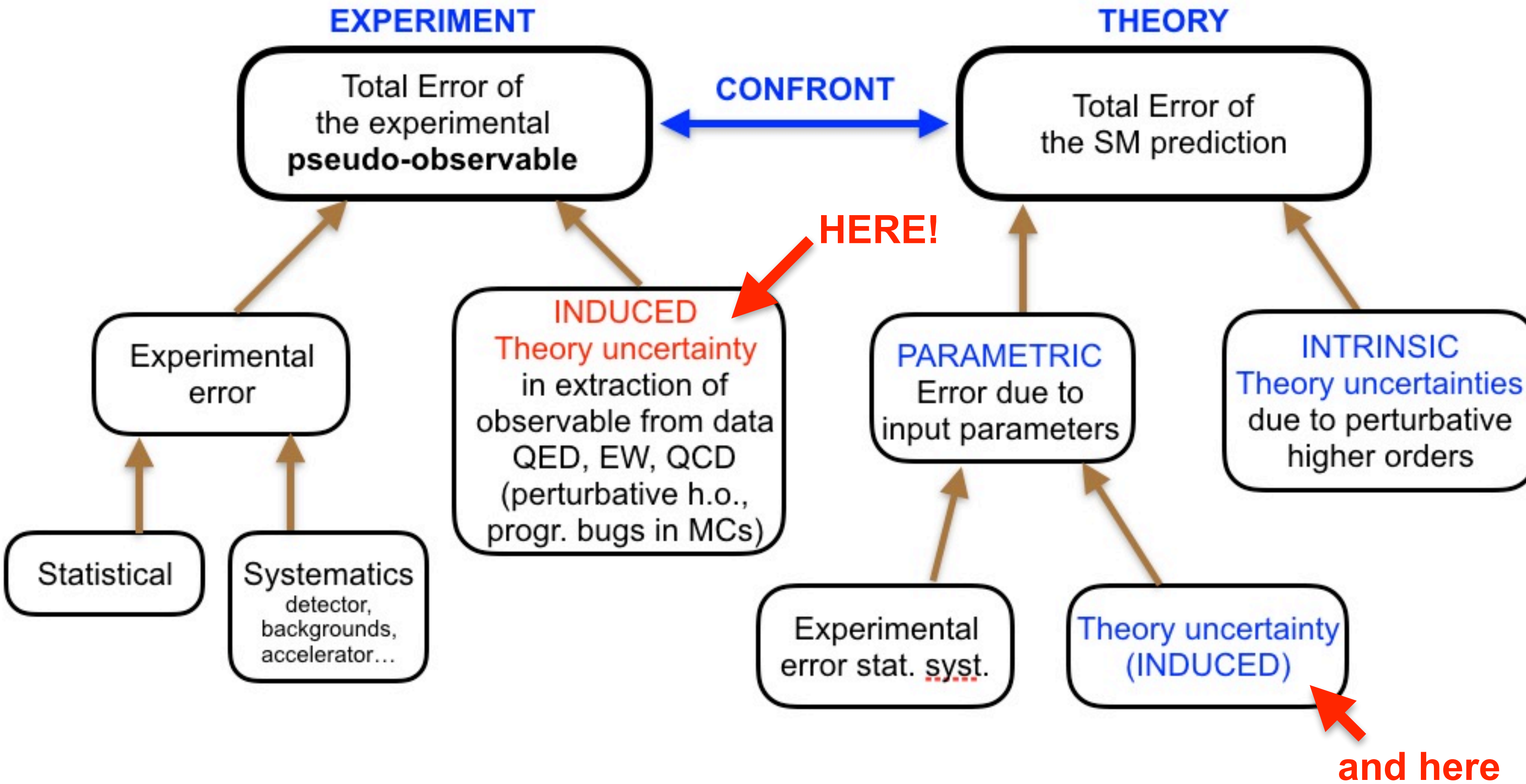
are fit using 1-D convolution formula $\sigma(s) = \int_0^1 dz\, \sigma^{Born}(zs)\, \rho_{QED}(z)$

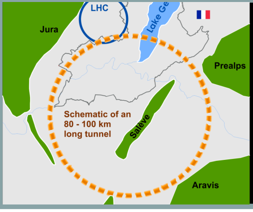
and $\sigma^0_{\mathrm{had}} = \sigma^{Born}_{\mathrm{had}}(M_Z)$ is calculated afterwards! Z Mass and width from the same fit.

Induced QED uncertainty (next slide) enters through ρ_{QED}



Where is QED-induced uncertainty of PO in the landscape of theory and exp. errors?



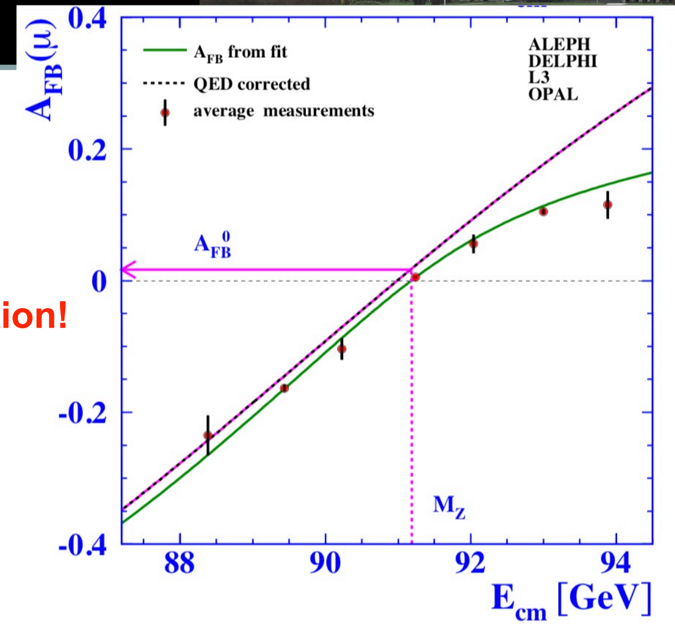


What are EW pseudo-observables (EWPOs)?

Example of charge asymmetry is more complicated:

$$A_{FB}^{\mu,0} = \left.\frac{\int_F d\sigma^{Born} - \int_B d\sigma^{Born}}{\int_F d\sigma^{Born} + \int_B d\sigma^{Born}}\right|_{s=M_Z^2}$$

calculated using $\dfrac{d\sigma^{Born}(s)}{d\cos\theta}[g_V^\mu, g_A^\mu]$



Eff. Born is central in EWPO construction!

$$\frac{2s}{\pi}\frac{1}{N_c^f}\frac{d\sigma_{ew}}{d\cos\theta}(e^+e^- \to f\bar{f}) = \underbrace{|\alpha(s)Q_f|^2(1+\cos^2\theta)}_{\sigma^\gamma}$$
$$\underbrace{-8\Re\left\{\alpha^*(s)Q_f\chi(s)\left[\mathcal{G}_{Ve}\mathcal{G}_{Vf}(1+\cos^2\theta) + 2\mathcal{G}_{Ae}\mathcal{G}_{Af}\cos\theta\right]\right\}}_{\gamma\text{–Z interference}} \tag{1.34}$$
$$\underbrace{\begin{array}{c}+16|\chi(s)|^2\left[(|\mathcal{G}_{Ve}|^2+|\mathcal{G}_{Ae}|^2)(|\mathcal{G}_{Vf}|^2+|\mathcal{G}_{Af}|^2)(1+\cos^2\theta)\right. \\ \left.+8\Re\{\mathcal{G}_{Ve}\mathcal{G}_{Ae}{}^*\}\Re\{\mathcal{G}_{Vf}\mathcal{G}_{Af}{}^*\}\cos\theta\right]\end{array}}_{\sigma^Z}$$

with:

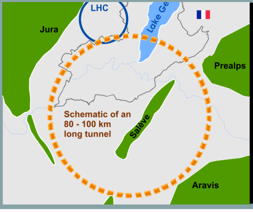
$$\chi(s) = \frac{G_F m_Z^2}{8\pi\sqrt{2}}\frac{s}{s - m_Z^2 + is\Gamma_Z/m_Z}, \tag{1.35}$$

https://arxiv.org/abs/hep-ex/0509008v3

Z coupling constants in the <u>effective Born</u> $g_{V,A}^f = \Re(\mathcal{G}_{Vf,Af})$

are fit to $A_{FB}^\mu(s_i), \sigma(s_i)$ at several s_i using convolution formula

$$\frac{d\sigma^\mu}{d\cos\theta^*}(s,\theta^*) = \mathbf{CONV}\left\{\frac{d\sigma_\mu^{Born}(s)}{d\cos\theta}, \rho_{QED}\right\}, \qquad \theta^* \neq \theta$$



What are EW pseudo-observables (EWPOs)?

From experimental **DATA to EWPO —** effective Born is central object!

$$A_{FB}^{e,\mu,\tau}(s_i),\ \sigma^{h,e,\mu,\tau}(s_i),\ P_\tau(s_i)\ldots$$

Fit (MINUIT) using eff. Born

$$g_{V,A}^f = \Re(\mathscr{G}_{Vf,Af})$$

pocket calculator

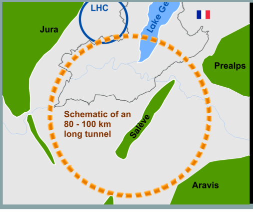
$$
\begin{aligned}
A_{FB}^{0,f} &= \frac{3}{4}\mathcal{A}_e\mathcal{A}_f & \mathcal{A}_f &= \frac{g_{Lf}^2 - g_{Rf}^2}{g_{Lf}^2 + g_{Rf}^2} = \frac{2g_{Vf}g_{Af}}{g_{Vf}^2 + g_{Af}^2}\\
A_{LR}^0 &= \mathcal{A}_e & &\\
A_{LRFB}^0 &= \frac{3}{4}\mathcal{A}_f & \frac{g_{Vf}}{g_{Af}} &= 1 - \frac{2Q_f}{T_3^f}\sin^2\theta_{eff}^f\\
\langle\mathcal{P}_\tau^0\rangle &= -\mathcal{A}_\tau & &\\
A_{FB}^{pol,0} &= -\frac{3}{4}\mathcal{A}_e\,. & \sigma_{f\bar{f}}^0 &= \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}.
\end{aligned}
$$

$$\Gamma_{f\bar{f}} = N_c^f\frac{G_F m_Z^3}{6\sqrt{2}\pi}\left(|\mathcal{G}_{Af}|^2 R_{Af} + |\mathcal{G}_{Vf}|^2 R_{Vf}\right) + \Delta_{ew/QCD}.$$

Two key points:

1. The convolution formula approximates QED, including (at LEP) $\mathcal{O}(\alpha^1), \mathcal{O}(L_e^2\alpha^2), \mathcal{O}(L_e^3\alpha^3), \mathcal{O}(L_e^2\alpha^1)$, etc. (It may include 1-st order IFI.) Most likely <u>will be replaced by the Monte Carlo</u> to attain FCC-ee precision.

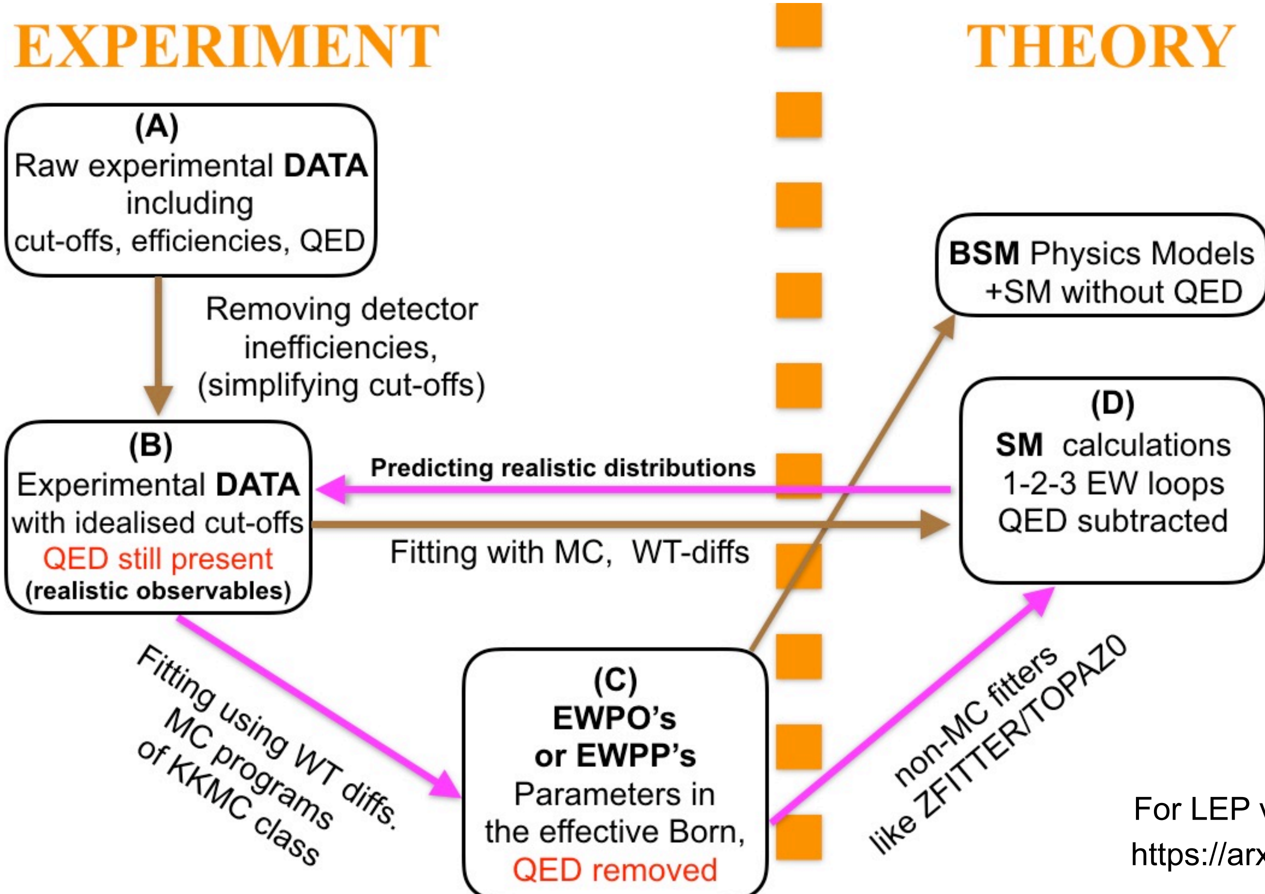
2. The role of the effective Born is to encapsulate/represent data within exp. precision in the (SM) Model independent way. At FCC-ee precision it may necessarily <u>include more of h.o. SM</u> (EW boxes?), then just only imaginary parts of g_V, g_A !!!



Validating/testing Pseudo-Observables at FCC-ee

https://arxiv.org/abs/1903.09895

Basic circular test (B)->(C)->(D)->(B) will be at FCC-ee the same as in LEP

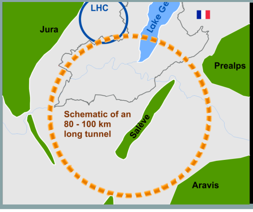


For LEP version see:

https://arxiv.org/abs/hep-ph/9902452

https://arxiv.org/abs/hep-ex/0509008v3

Main difference with LEP is Monte Carlo use in steps (B)->(C) and (B)->(D) instead of progs like ZFITTER/TOPAZ0



QED at the Z pole: Challenges

Coming back to Master Table of https://arxiv.org/abs/1903.09895

Desired improvement factor for QED!

Observable	Where from	Present (LEP)	FCC stat.	FCC syst	Now / FCC
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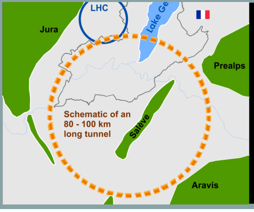
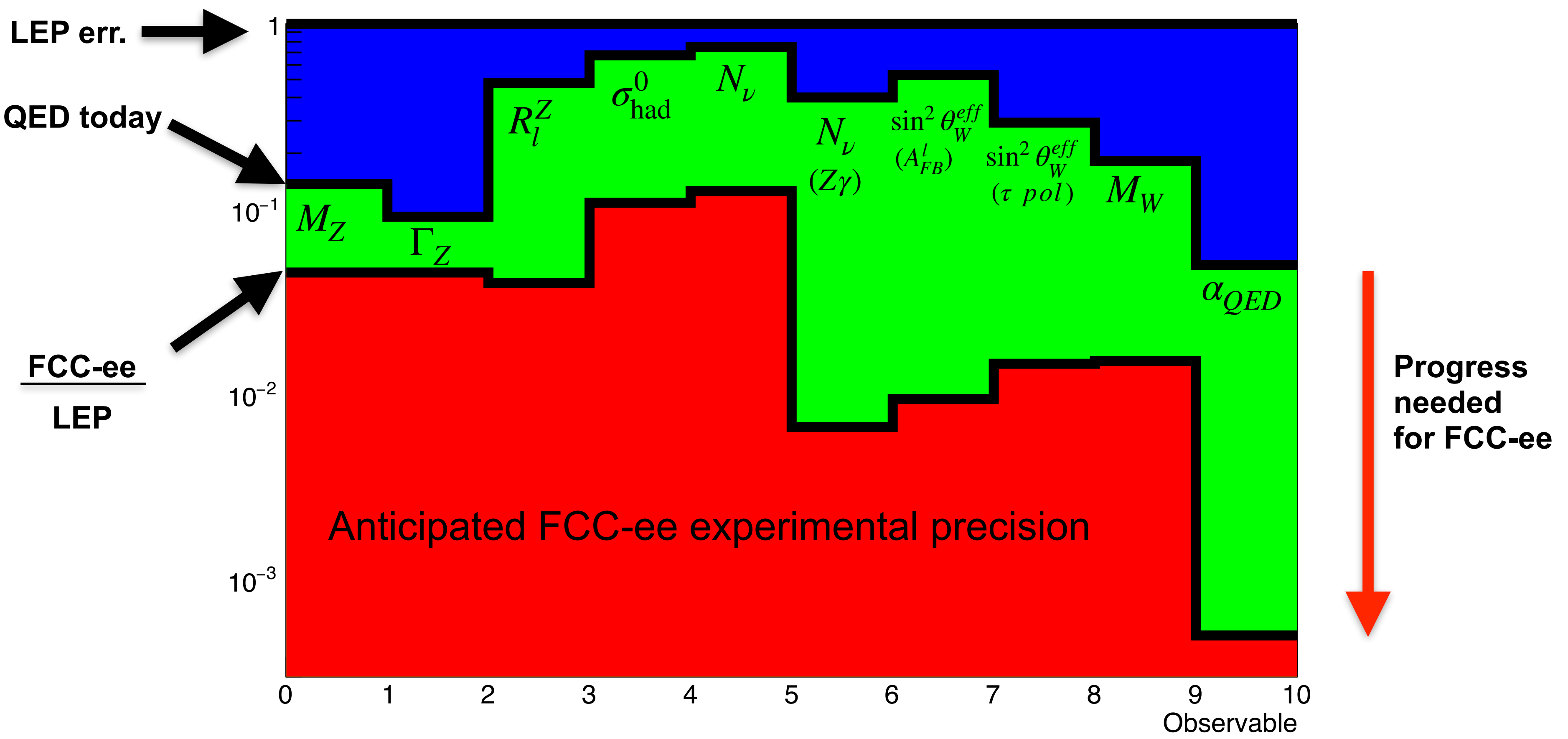
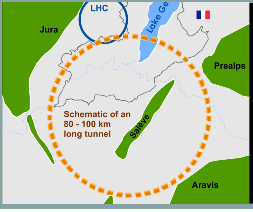
How LEP and FCC-ee exp. precisions do compare?



At the FCC-ee exp. precisions present QED uncertainty is unacceptable!

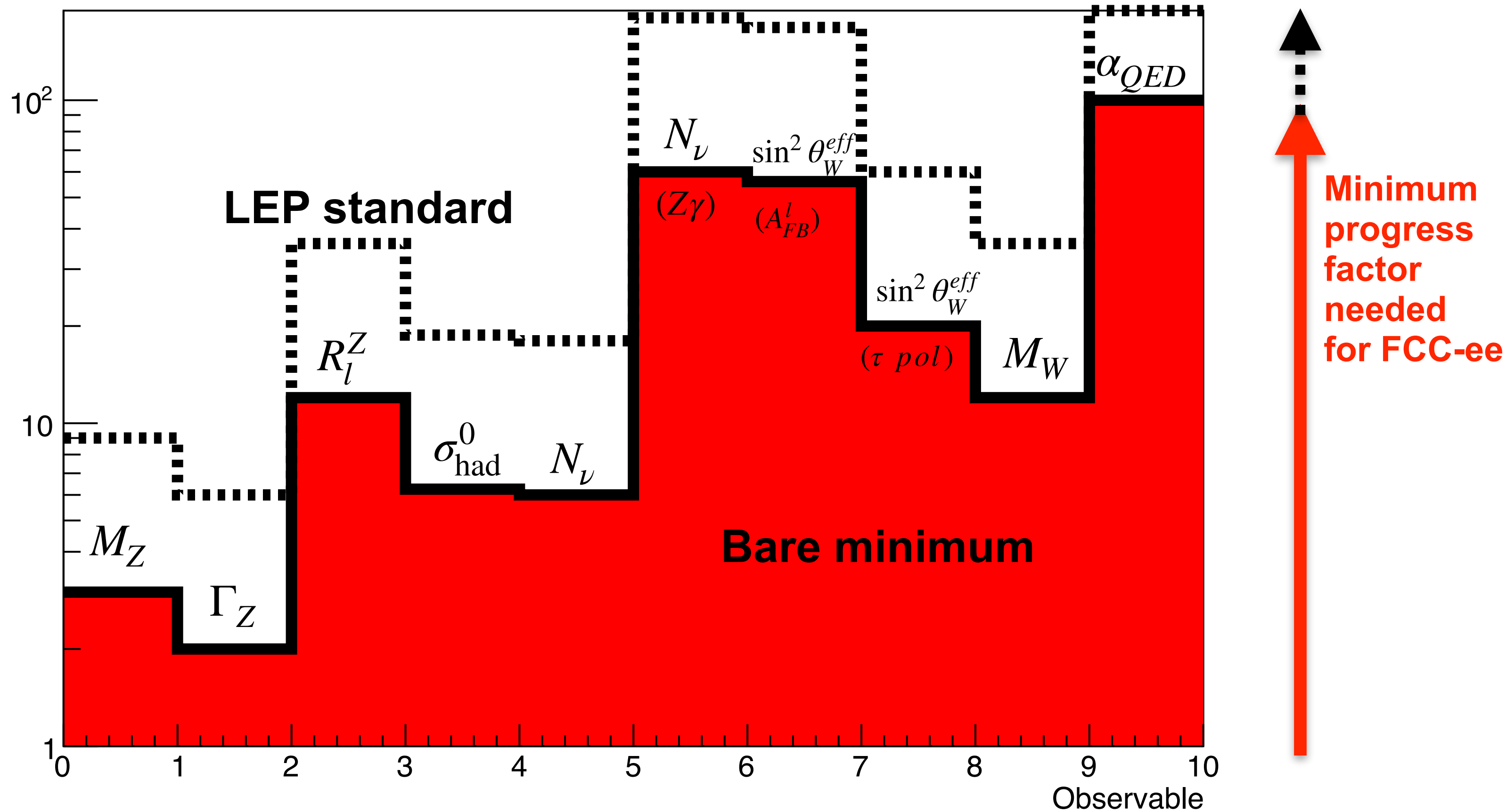
Current QED precision vs. FCCee exp. error



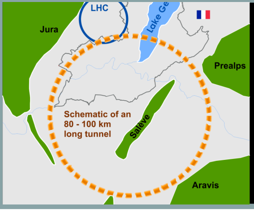


Desired improvement factor for QED uncertainty at FCC-ee

Needed improvement for QED precision at FCCee



Depending on the observable factor 6-200 improvements needed!



More details for selected observables

QED in Z line-shape: $\sigma_{tot}(s), M_Z, \Gamma_Z, R_l$

Present (LEP)

No cut-offs (except on $\sum E_\gamma$)

QED err. according to ADLO 2005: $\delta M_Z, \delta\Gamma_Z \simeq 0.2 - 0.3$ MeV

σ_{had} ISR: $\mathcal{O}(\alpha^1 L_e^1, \alpha^1, \alpha^2 L_e^2, \alpha^2 L_e^1, \alpha^3 L_e^3)_\gamma$ $\mathcal{O}(\alpha^2 L^2, \alpha^2 L^1, \alpha^3 L^3)_{pairs}$

Phys.Lett. B456 (1999) 77

σ_{lept} ISR+FSR

Non-MC implementation, 1-d or 2-d convolution
Initial-final interference (IFI) neglected

Simplified idealised cut-offs

ZFITTER and TOPAZ0 non-MC programs

AND

MC event generators: KORALZ, KKMC, BHWIDE

Arbitrary realistic cut-offs

MC event generators: KORALZ, KKMC, BHWIDE

FCC-ee

No cut-offs

exp. $\delta M_Z, \delta\Gamma_Z \leq 0.1$ MeV, QED ≤ 0.03 MeV

Factor ~10 improvement in QED is needed!

LEP simplistic convolution may survive only for σ_{had} provided pairs improved, $\mathcal{O}(\alpha^2 L_e^0, \alpha^3 L_e^2, \alpha^4 L_e^4)_\gamma$ are added and mixed QCD-QED corrections are improved.

For leptons MCs will *take over* due to IFI and pairs

Simplified idealised cut-offs

Only MC event generators of the KKMC class or better will be able to match FCC-ee precision

Arbitrary realistic cut-offs

Only MC event generators of the KKMC class or better:

Upgrades of the matrix element:
$\mathcal{O}(\alpha^2 L_e^1)$ penta-boxes, $\mathcal{O}(\alpha^3 L_e^3)$ in CEEX m.e.

Inventing new MC approach for light fermion pairs.

Provisions for SM parameter fitting
and extracting new EWPOs from data

For luminosity uncertainty see next…

Charge and spin asymmetries at mZ

Present (LEP) | **FCC-ee**

Charge asymmetry

QED err. at LEP: $\delta A^{\mu}_{FB}(M_Z) \simeq 50 \cdot 10^{-5}$

translates into $\delta \sin^2 \theta^{eff}_W \simeq 28 \cdot 10^{-5}$

[Conservative estimate based on comparisons of KKMC, ZFITTER, KORALZ, Phys. Ref. D63 (2001) 113009]

However, the effects due to h.o. ISR, IFI, EW boxes, imaginary parts of Z couplings, gamma exch. background are genuinely of order $\delta A^{\mu}_{FB}(M_Z) \simeq 10 \cdot 10^{-5}$

FCC-ee exp. error $\delta A^{\mu}_{FB}(M_Z) \simeq 1 \cdot 10^{-5}$, $\delta \sin^2 \theta^{eff}_W \simeq 0.5 \cdot 10^{-5}$

Factor ~ 50-150 improvement in QED is needed!

Once they are mastered with 10% precision, the way to $\delta A^{\mu}_{FB}(M_Z) \simeq 1 \cdot 10^{-5}$ is open!

KKMC with complete $\mathcal{O}(\alpha^2)$ matrix element, soft photon resummation including IFI, EW corrections is already there. One needs the same for Bhabha!

The biggest challenge is, may be, the consistent definition of $\sin^2 \theta^{eff}_W$ at the FCC-ee precision!

Spin asymmetries

$\langle \mathcal{P}_\tau \rangle$ and $A^{pol,\tau}_{FB}$ at LEP were worth $\delta \sin^2 \theta^{eff}_W \simeq 41 \cdot 10^{-5}$

including QED induced uncertainty due to photon emissions in tau decays $\delta \sin^2 \theta^{eff}_W \simeq 12 \cdot 10^{-5}$

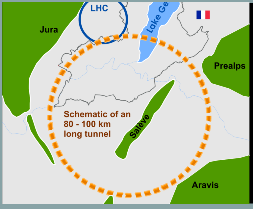
QED err. is small due to weak dependence on CMS energy.

Expected FCC-ee exp. error $\delta \sin^2 \theta^{eff}_W \simeq 0.6 \cdot 10^{-5}$

Factor ~ 20-60 improvement in QED is needed!

To be studied:

- polarimeter biases due to decay chanel cross-talk and photon emission in tau decays
- QED effects in tau-pair production
- exploiting super-Belle tau decay data in order to calibrate tau decay MC simulation



$\alpha_{QED}(M_Z)$ from $A_{FB}(M_Z \pm 3.5GeV)$

- Determination of $\alpha_{QED}(M_Z) = \alpha(0)/(1-\Delta\alpha)$ with precision ~3x10-5 critical for SM fits.
- Table of **parametric uncertainty** with

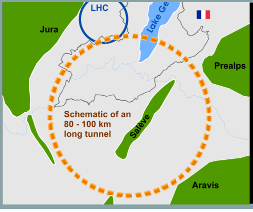
$$\delta M_Z \simeq 0.1 MeV, \quad \delta m_t \simeq 50 MeV$$
$$\delta\alpha_s \simeq 2\cdot 10^{-4}, \quad \delta(\Delta\alpha) \simeq 5\cdot 10^{-5}$$

http://arxiv.org/abs/arXiv:1901.02648

EWPO	Exp. direct error	Param. error	Main source	Theory uncert.
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$	0.07
R_b [10^{-5}]	6	1	$\delta\alpha_s$	3
R_ℓ [10^{-3}]	1	1.3	$\delta\alpha_s$	0.7
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	0.5	1	$\delta(\Delta\alpha)$	0.7
M_W [MeV]	0.5	0.6	$\delta(\Delta\alpha)$	0.3

Table 3: Estimated experimental precision for the direct measurement of several important EWPOs at FCC-ee [2] (column two) and experimental parametric error (column three), with the main source shown in the forth column. Important input parameter errors are $\delta(\Delta\alpha) = 3\cdot 10^{-5}$, $\delta\alpha_s = 0.00015$ see FCC CDR, vol. 2 [1]. Last column shows anticipated theory uncertainties at start of FCC-ee.

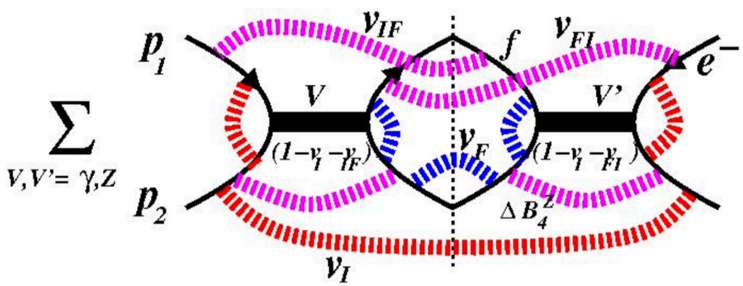
- Measuring $A_{FB}(M_Z \pm 3.5GeV)$ with precision 3x10-5 , **factor 200 more precisely** than at LEP was proposed in order to get $\alpha_{QED}(M_Z)$ with the needed precision ~10-5.
  P. Janot, JHEP11,164 (2017) arXiv:1512.05544
- QED Initial-Final state interference **IFI** is the main obstacle!
- IFI cancels partly in the difference $A_{FB}(M_Z \pm 3.5GeV)$, but ~1% effect remains.
  Can one control IFI in A_{FB} with the precision 3x10-5 ???
- In arXiv:1801.08611 Phys. Rev. D (S.J. and S.Yost)
  it was shown using **KKMC** and new **KKfoam** programs one may get precision $\leq 10^{-4}$



5-dim convolution formula including IFI

NEW analytical exponentiation formula for ISR+FSR+IFI

Eq.(90) in [JWW2001] and in older Frascati works, implemented recently in **KKfoam**



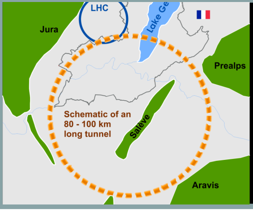
$$\frac{d\sigma}{d\Omega}(s,\theta,v_{\max}) = \sum_{V,V'=\gamma,Z} \int d\theta\; dv_I\; dv_F\; dv_{IF}\; dv_{FI}\; \theta(v_I - v_F - v_{IF} - v_{FI} < v_{\max})$$

$$\times\, F(\gamma_I)\gamma_I v_I^{\gamma_I-1}\; F(\gamma_F)\gamma_I v_F^{\gamma_F-1}\;\; F(\gamma_{IF})\gamma_{IF} v_{IF}^{\gamma_{IF}-1}\; F(\gamma_{FI})\gamma_{FI} v_{IF}^{\gamma_{FI}-1}$$

$$\times\, e^{2\alpha\Delta B_4^V}\mathcal{M}_V^{(0)}(s(1-v_I-v_{IF}),\theta)\; [e^{2\alpha\Delta B_4^{V'}}\mathcal{M}_{V'}^{(0)}(s(1-v_I-v_{FI}),\theta)]^*\; \left[1+\mathrm{NIR}(v_I,v_F)\right],$$

- Convolution of **four** radiator functions (instead of two)!
- Extra virtual formfactor ΔB_4^Z due to IFI for resonant contrib.
- $\gamma_I = Q_e^2\frac{\alpha}{\pi}[\frac{s}{m_e^2}-1],\quad \gamma_{IF}=\gamma_{FI}=Q_eQ_f\frac{\alpha}{\pi}\ln\frac{1-\cos\theta}{1+\cos\theta},\quad F(\gamma)=\frac{e^{-C_E\gamma}}{\Gamma(1+\gamma)}$

arXiv:1801.08611 [hep-ph] Phys. Rev. D



Low angle Bhabha (luminosity) at FCCee

arXiv:1902.05912

- LEP legacy, lumi TH error budget

	LEP1		LEP2	
Type of correction/error	1996	1999	1996	1999
(a) Missing photonic $O(\alpha^2)$ [4,5]	0.10%	0.027%	0.20%	0.04%
(b) Missing photonic $O(\alpha^3 L^3)$ [6]	0.015%	0.015%	0.03%	0.03%
(c) Vacuum polarization [7,8]	0.04%	0.04%	0.10%	0.10%
(d) Light pairs [9,10]	0.03%	0.03%	0.05%	0.05%
(e) Z-exchange [11,12]	0.015%	0.015%	0.0%	0.0%
Total	0.11% [12]	0.061% [13]	0.25% [12]	0.12% [13]

Table 1: Summary of the total (physical+technical) theoretical uncertainty for a typical calorimetric detector. For LEP1, the above estimate is valid for a generic angular range within 1°-3° (18-52 mrads), and for LEP2 energies up to 176 GeV and an angular range within 3°-6°. Total uncertainty is taken in quadrature. Technical precision included in (a).

LEP lumi update 2018

Type of correction / Error	1999	Update 2018
(a) Photonic $O(L_e\alpha^2)$	0.027% [5]	0.027%
(b) Photonic $O(L_e^3\alpha^3)$	0.015% [6]	0.015%
(c) Vacuum polariz.	0.040% [7,8]	0.013% [25]
(d) Light pairs	0.030% [10]	0.010% [18,19]
(e) s-channel Z-exchange	0.015% [11,12]	0.015%
(f) Up-down interference	0.0014% [27]	0.0014%
(f) Technical Precision	–	(0.027)%
Total	0.061% [13]	0.038%

- By the time of FCC-ee VP contribution will be merely 0.006%
- QED corrections and Z contrib. come back to front!
- Z contr. easy to master, even if rises at FCC-ee, because (28-58)->(64-86) mrad.
- Our FCC-ee forecast is 0.01% provided QED m.e. and VP are improved.

Type of correction / Error	Update 2018	FCCee forecast
(a) Photonic $O(L_e^4\alpha^4)$	0.027%	0.6×10^{-5}
(b) Photonic $O(L_e^2\alpha^3)$	0.015%	0.1×10^{-4}
(c) Vacuum polariz.	0.014% [25]	0.6×10^{-4}
(d) Light pairs	0.010% [18,19]	0.5×10^{-4}
(e) Z and s-channel γ exchange	0.090% [11]	0.1×10^{-4}
(f) Up-down interference	0.009% [27]	0.1×10^{-4}
(f) Technical Precision	(0.027)%	0.1×10^{-4}
Total	0.097%	1.0×10^{-4}

Z invisible width from peak cross section and radiative return

Present (LEP) | **FCC-ee**

Peak cross section

Present (LEP)

QED err. of luminosity $\frac{\delta\mathcal{L}}{\mathcal{L}} = \frac{\delta\sigma^0_{had}}{\sigma^0_{had}} \simeq 0.06\,\%$

dominates LEP exp. error $N_\nu \simeq 2.984 \pm 0.008\ \{\pm 0.006\}_{QED}$

$$R^0_{\rm inv} = \left(\frac{12\pi R^0_\ell}{\sigma^0_{\rm had} m^2_{\rm Z}}\right)^{\frac{1}{2}} - R^0_\ell - (3+\delta_\tau)\,, \qquad R^0_{\rm inv} = N_\nu \left(\frac{\Gamma_{\nu\bar\nu}}{\Gamma_{\ell\ell}}\right)_{\rm SM}.$$

FCC-ee

FCC-ee exp. error (syst.) $\delta N_\nu \simeq 0.001$

Factor ~10 improvement in luminosity is needed!

$\frac{\delta\mathcal{L}}{\mathcal{L}} \simeq 10^{-4} \rightarrow \delta N_\nu \simeq 8\cdot 10^{-4}$ seems achievable.

Radiative return I

Present (LEP)

$$e^+e^- \rightarrow \nu\bar\nu\gamma$$

$N_\nu \simeq 2.69 \pm 0.15\ \{\pm 0.06\}_{QED}$

Limited by poor LEP statistics at 161GeV

FCC-ee

Expected FCC-ee exp. error of $\sigma_{\nu\bar\nu\gamma}$ not yet established,
most likely: $\delta\sigma/\sigma \simeq 0.03\,\% \rightarrow \delta N_\nu \simeq 0.001$

Future luminosity error 0.01% looks ok.

Estimate of h.o. QED effects using KKMC
is merely 0.02% (unpublished).

Altogether $\delta N_\nu \simeq 0.001$ seems achievable:)
(Factor ~60 improvement in QED rather easy.)

Radiative return II

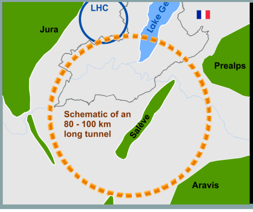
FCC-ee

Measuring ratio $R = \frac{\sigma_{\nu\bar\nu\gamma}}{\sigma_{\mu^+\mu^-\gamma}}$

Luminosity error drops out!

QED uncertainty due to FSR in $\sigma_{\mu^+\mu^-\gamma}$ rated at 0.03%
(unpublished study using KKMC).

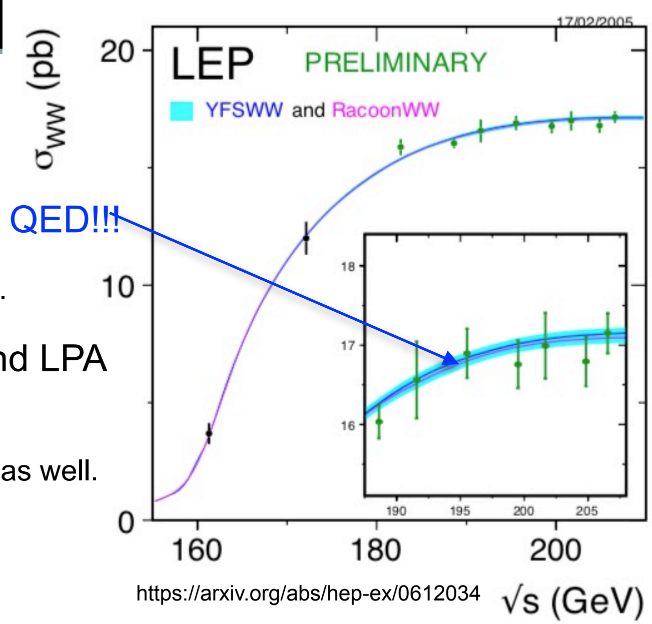
Again $\delta N_\nu \simeq 0.001$



A few comments on WW production

LEP:

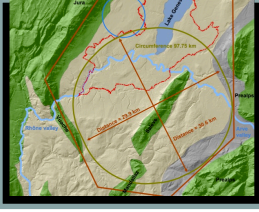
- 0.5% difference between YFSWW and RacoonWW was entirely due to QED!!!
  It was checked that O(alpha¹) genuine EW correction in both programs for on-shell W's were numerically identical within 3 digits. Leading pole approximation (LPA) was the same.
- The difference ~0.5% between O(alpha¹) calculation for $e^+e^- \to 4f$ and LPA is also dominated by QED component. (Denner et.al., arXiv:hep-ph/0502063).
- QED effects dominated W mass measurement at LEP from final state mass reconstruction as well.



https://arxiv.org/abs/hep-ex/0612034

FCC-ee:

- 0.5MeV precision of W mass from threshold cross section will require clever resummation of QED effects using Effective Field Theory, soft photon technique etc. (Actis at.al. arXiv:0807.0102).
- Solution of long standing QED problem of resummation of soft photons emitted from instable W's was recently proposed by S.J. and M. Skrzypek, arxiv.org/abs/arXiv:1906.09071
- Above WW threshold FCC-ee measurement of total cross section and W mass (~0.5MeV) will require:
  (i) O(alpha²) calculation of EW corrections for double-resonant (on-shell) $e^+e^- \to W^+W^-, W^\pm \to X$
  non-trivial but feasible, to be done,
  (ii) O(alpha¹) calculation for single-resonant component (partly done in arXiv:hep-ph/0502063),
  (iii) tree-level for non-resonant part (available),
  (iv) and consistent scheme of combining all that in the Monte Carlo event generator!
- QED component will be again most sizeable and equally important as pure EW corrections.

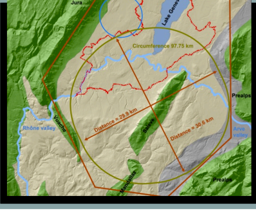


Summary

- A lot of BIG intriguing questions!
- No clear hint from theory where to look for answer
- Hence one should explore all possible fronts:
- -highest possible energies
- -very weak and rare processes (neutrinos)
- -astrophysics

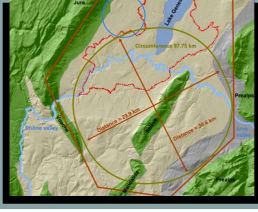
European Strategy for Particle Physics shall recommend for CERN next big project to answer some of the above burning questions. FCCee + FCChh seems to be the leading candidate…

- Major effort is needed to improve SM/QED predictions for FCC-ee observables by factor 10-200
- In particular QED corrections for asymmetries near Z has to be improved by factor up to 200
- New algorithms of extracting EW pseudo-observables from experimental data has to be worked out and cross-checked
- Increased role of MC event generators is anticipated

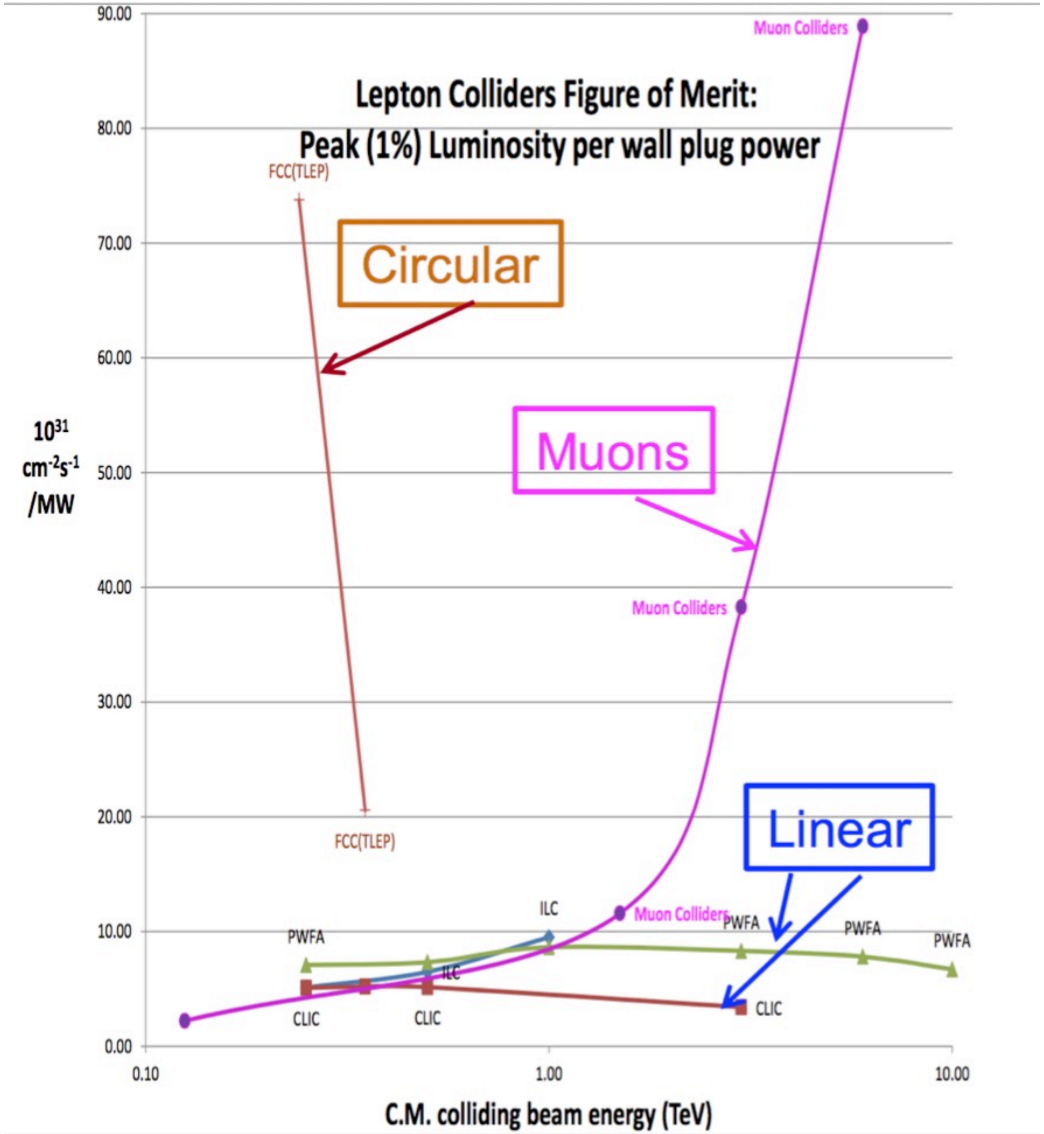


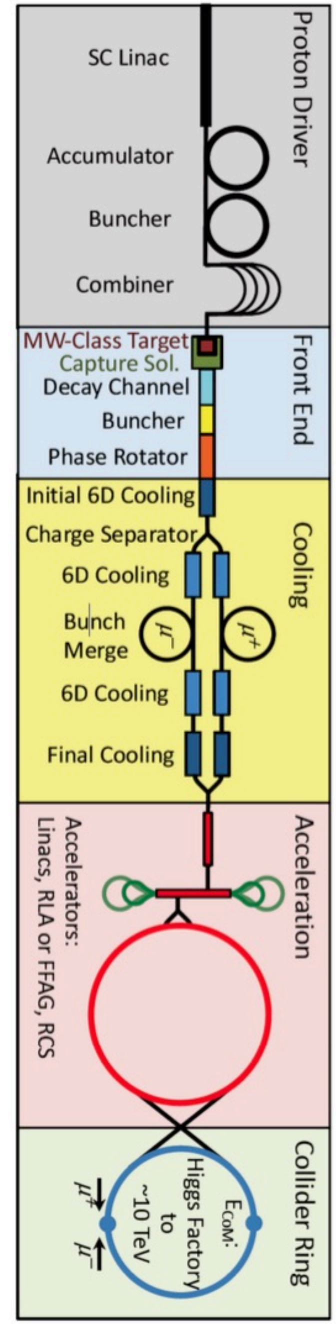
Reserve

Reserve



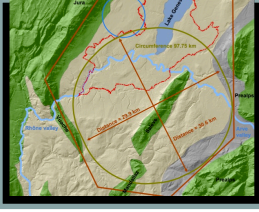
Why H.E. muon collider?
Superior Lumi/El.Power





Muon-based technology represents a unique opportunity for the future of high energy physics research: the multi-TeV energy domain exploration.

>10TeV Muon circular collider clear winner on the horizon!

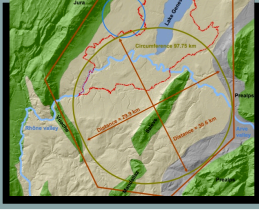


Fit of EWPO's to SM (2017)

	Measurement	Posterior	Prediction	Pull
$\alpha_s(M_Z)$	0.1180 ± 0.0010	0.1180 ± 0.0009	0.1184 ± 0.0028	-0.1
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.02750 ± 0.00033	0.02743 ± 0.00025	0.02734 ± 0.00037	0.3
M_Z [GeV]	91.1875 ± 0.0021	91.1880 ± 0.0021	91.198 ± 0.010	-1.0
m_t [GeV]	$173.1 \pm 0.6 \pm 0.5$	173.43 ± 0.74	176.1 ± 2.2	-1.3
m_H [GeV]	125.09 ± 0.24	125.09 ± 0.24	100.6 ± 23.6	1.0
M_W [GeV]	80.379 ± 0.012	80.3643 ± 0.0058	80.3597 ± 0.0067	1.4
Γ_W [GeV]	2.085 ± 0.042	2.08873 ± 0.00059	2.08873 ± 0.00059	-0.1
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012	0.231454 ± 0.000084	0.231449 ± 0.000085	0.8
$P^{\rm pol}_\tau = A_\ell$	0.1465 ± 0.0033	0.14756 ± 0.00066	0.14761 ± 0.00067	-0.3
Γ_Z [GeV]	2.4952 ± 0.0023	2.49424 ± 0.00056	2.49412 ± 0.00059	0.5
σ^0_h [nb]	41.540 ± 0.037	41.4898 ± 0.0050	41.4904 ± 0.0053	1.3
R^0_ℓ	20.767 ± 0.025	20.7492 ± 0.0060	20.7482 ± 0.0064	0.7
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	0.01633 ± 0.00015	0.01630 ± 0.00015	0.8
A_ℓ (SLD)	0.1513 ± 0.0021	0.14756 ± 0.00066	0.14774 ± 0.00074	1.6
R^0_b	0.21629 ± 0.00066	0.215795 ± 0.000027	0.215793 ± 0.000027	0.7
R^0_c	0.1721 ± 0.0030	0.172228 ± 0.000020	0.172229 ± 0.000021	-0.05
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	0.10345 ± 0.00047	0.10358 ± 0.00052	-2.6
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	0.07394 ± 0.00036	0.07404 ± 0.00040	-0.9
A_b	0.923 ± 0.020	0.934787 ± 0.000054	0.934802 ± 0.000061	-0.6
A_c	0.670 ± 0.027	0.66813 ± 0.00029	0.66821 ± 0.00032	0.1
$\sin^2\theta^{\rm lept}_{\rm eff}$(Tev/LHC)	0.23166 ± 0.00032	0.231454 ± 0.000084	0.231438 ± 0.000087	0.7

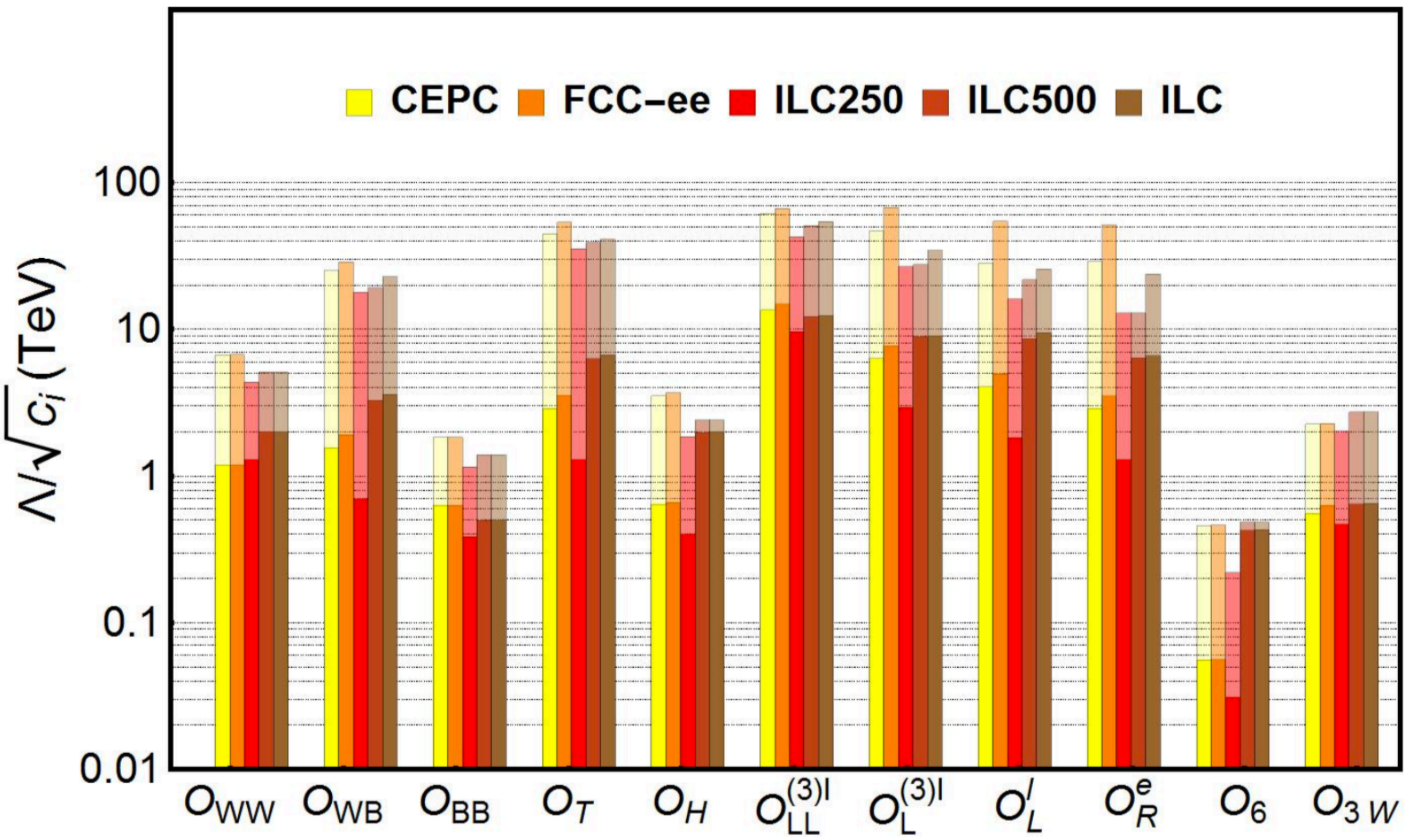
J. De Blas et al., arXiv:1710.05402

Recent results of hadron colliders are included

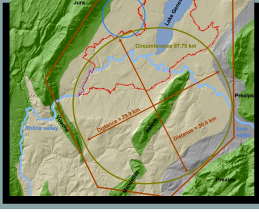


Comparative study of various proposed electron colliders

W.H. Chiu et al., arXiv:1711.04046



Thanks to higher luminosity FCC-ee competes quite efficiently with higher energy linear colliders in pinning down possible New Physics



SM + Effective Theory
Warsaw complete 59 operators basis (2010)

Effective Lagrangian Analysis of New Interactions and Flavor Conservation
W. Buchmuller (CERN), D. Wyler (Zurich, ETH). Aug 1985. 33 pp.
Published in **Nucl.Phys. B268 (1986) 621-653**

Dimension-six terms in the Standard Model Lagrangian[1]

B. Grzadkowski,[a] M. Iskrzyński,[a] M. Misiak[a,b] and J. Rosiek[a]

[a] *Institute of Theoretical Physics, University of Warsaw, Hoża 69, PL-00-681 Warsaw, Poland*

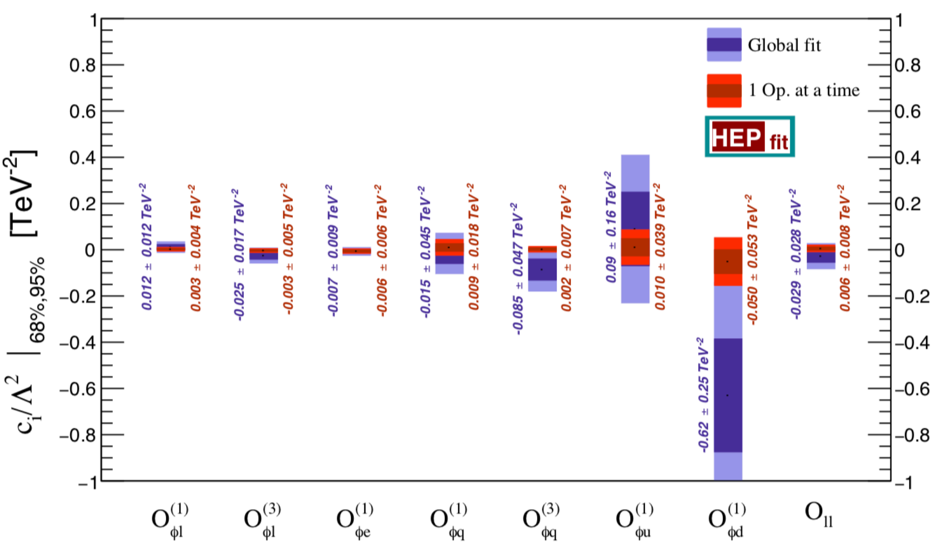
SM EFT

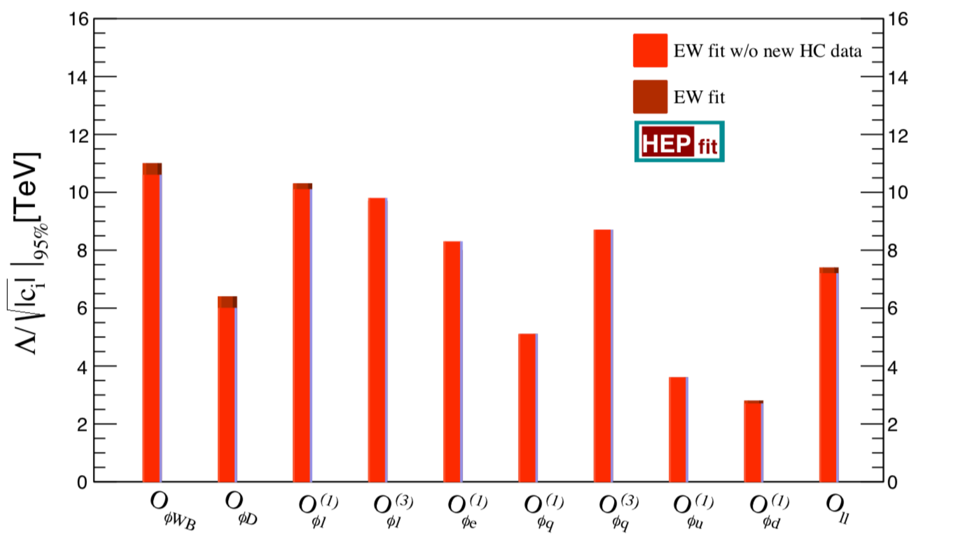
new operators

$$\mathcal{L}_{SM} + \sum_i c_i \frac{\mathcal{O}_i}{\Lambda^{d_i-4}}$$

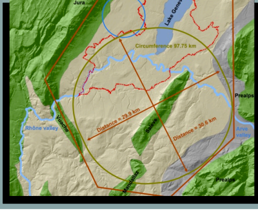
Standard Model

unknown coefficients





Fit of SM+EFT operator coefficients to present EWPO's, (J. de Blas et.al. 2017)



European Strategy for Particle Physics:
(May 2019, Granada Update)

Stanisław Jadach
Institute of Nuclear Physics Polish Academy of Sciences

https://indico.cern.ch/event/808335/timetable/

Talks of Granada conference provided full coverage of the state of particle physics:
1. Present experiments and future accelerator projects
2. Theory of particle physics and particle astrophysics
3. Non-accelerator experiments, rare and weak processes/interactions, neutrinos, etc.
4. Computing for big experiments
5. New acceleration techniques
6. Progress in detector techniques

About 500 participants, 15 plenary talks, 100 talks in parallel sessions.

Excellent quality of the talks!

The main aim of ESPP is to advice Cern Council about future big accelerator projects at CERN beyond LHC