High-precision EW and QCD physics at FCC-ee

65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders (eeFACT2022)

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The SM after the Higgs boson discovery and gravitational waves observation

Einstein-Hilbert action

$$S = \int \left[\frac{1}{2} M_{\rm pl}^2 R + \mathcal{L} \right] d^4x \sqrt{-g}$$

gravity

matter and gauge force fields

gravity

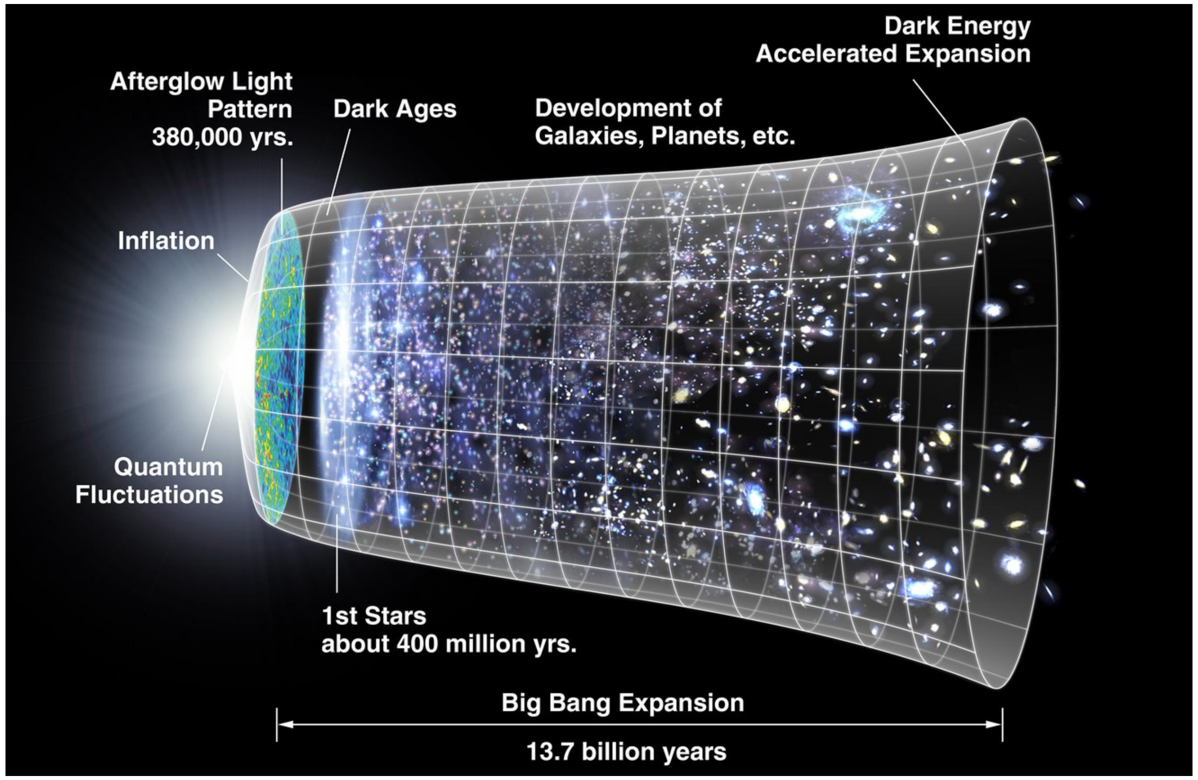
$$\begin{aligned}\mathcal{L} = \\ & -\frac{1}{4g'^4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} W^a_{\mu\nu} W^{\mu\nu a} - \frac{1}{4g_s^2} G^a_{\mu\nu} G^{\mu\nu a} \\ & + \bar{Q}_i i \not{D} Q_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{L}_i i \not{D} L_i + \bar{\ell}_i i \not{D} \ell_i \\ & + \left(Y_u^{ij} \bar{Q}_i u_j \tilde{H} + Y_d^{ij} \bar{Q}_i d_j H + Y_l^{ij} \bar{L}_i \ell_j H + c.c. \right) \\ & - \lambda (H^\dagger H)^2 + \lambda v^2 H^\dagger H - (D^\mu H)^\dagger D_\mu H\end{aligned}$$

not observed in: e, μ, c, u, d, s

still not observed

Higgs boson couplings to ordinary matter still need to be observed !!

The Higgs boson and the inflation

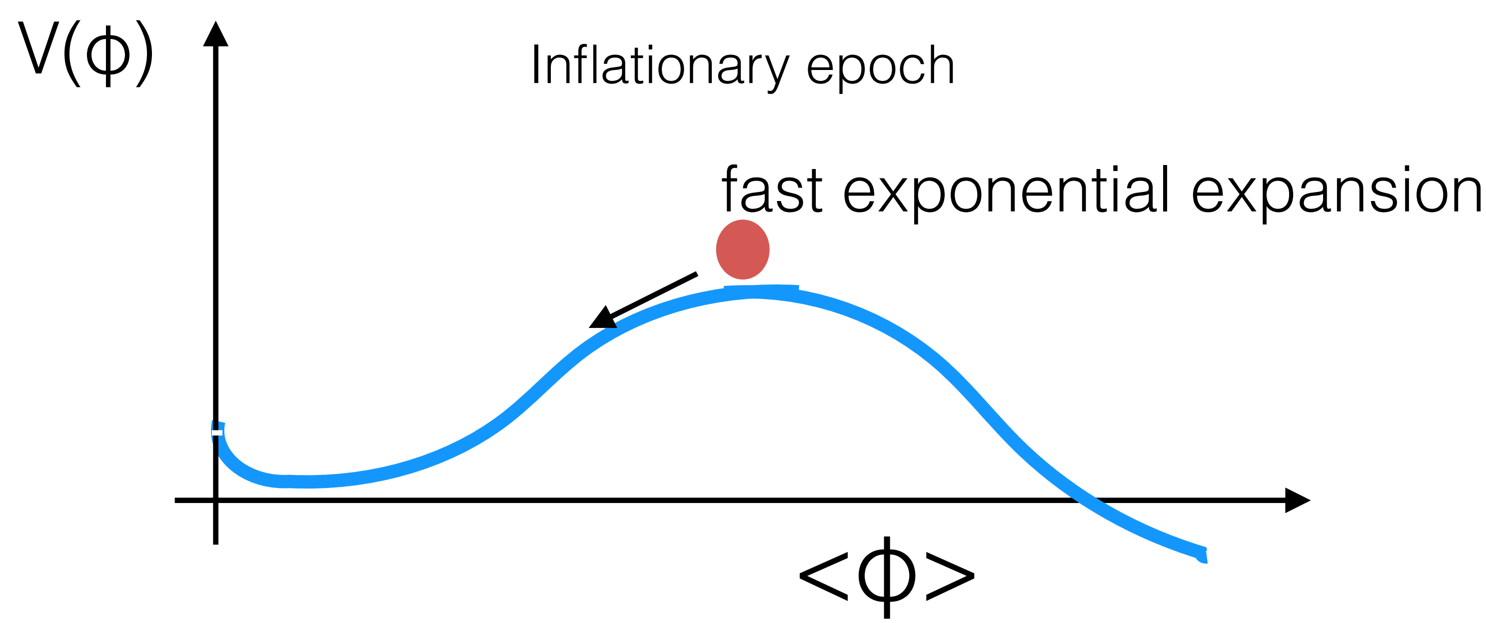


- **Exponential expansion of the universe at the starting age, it involves one scalar ϕ with a properly shaped energy potential $V(\phi)$. This energy behaves like dark-energy inducing universe acceleration (inflaton field)**

- **The Higgs potential could have such role if its potential is properly shaped**

$$V(\phi) >> \frac{1}{2}\dot{\phi}^2 \longrightarrow H^2 = \frac{8\pi G}{3} V(\phi) \simeq const. \longrightarrow a(t) \simeq e^{Ht} \quad \left(H(t) = \frac{\dot{a}}{a} \right)$$

a(t) universe expansion parameter



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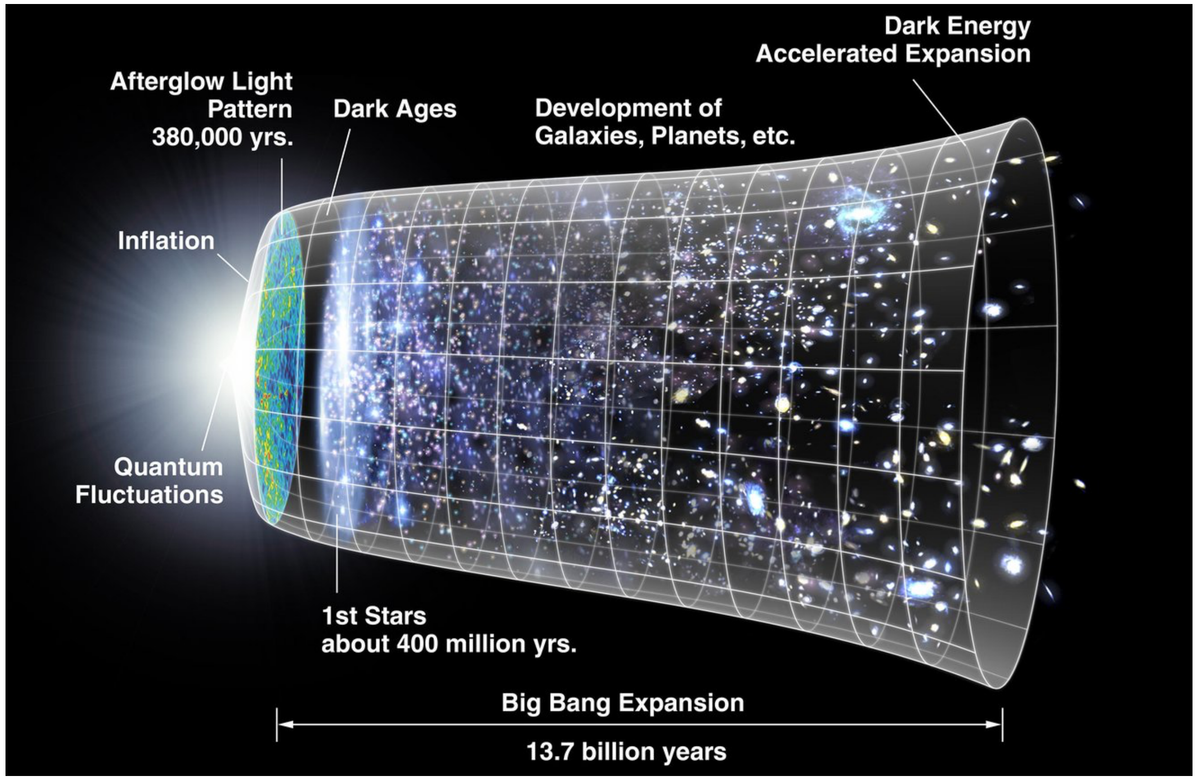

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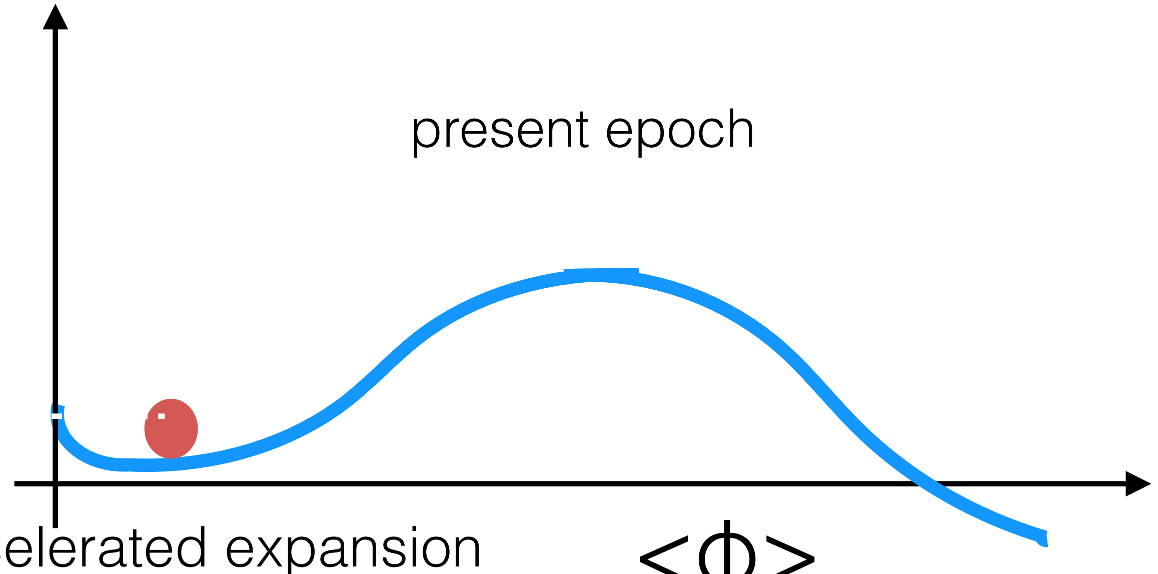

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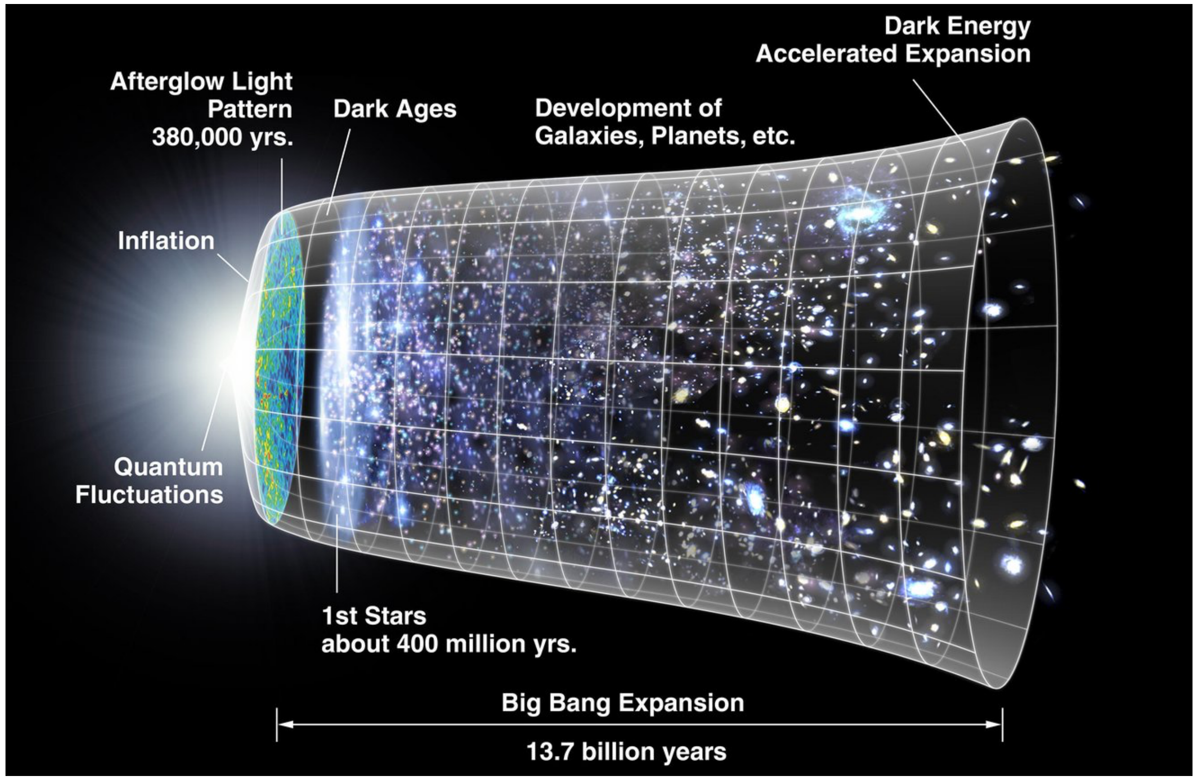

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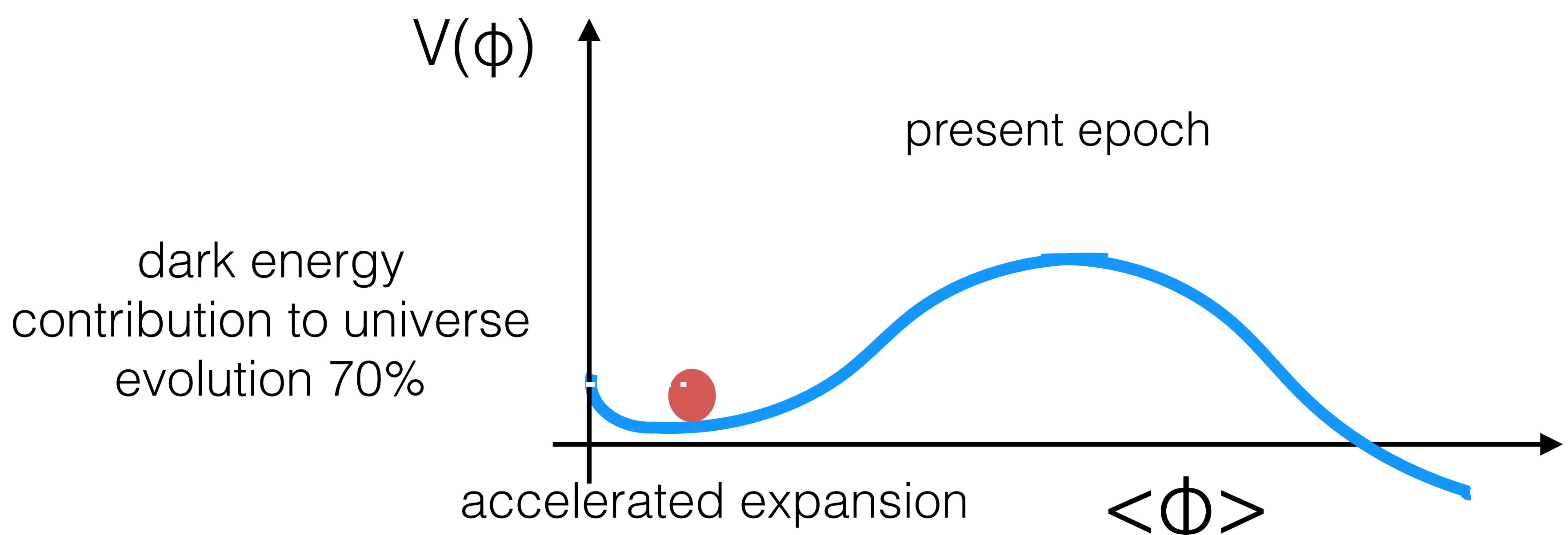
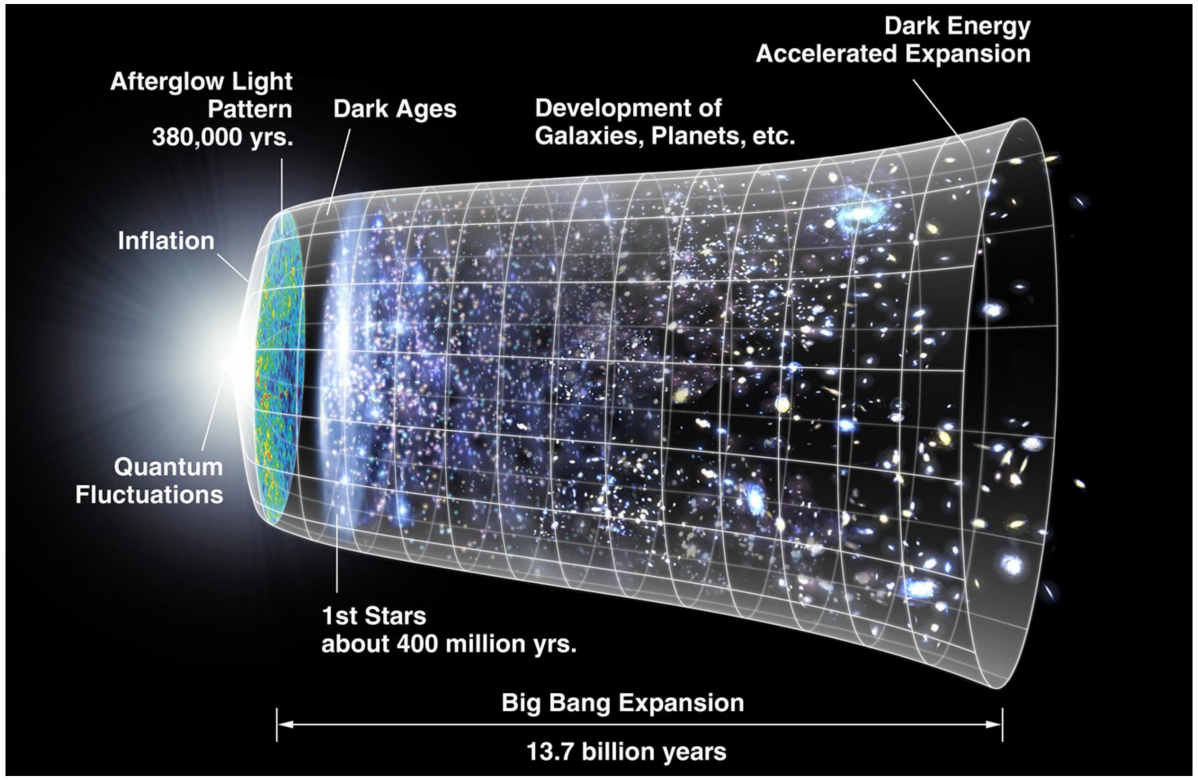


FUTURE CIRCULAR COLLIDER

The Higgs boson and the inflation



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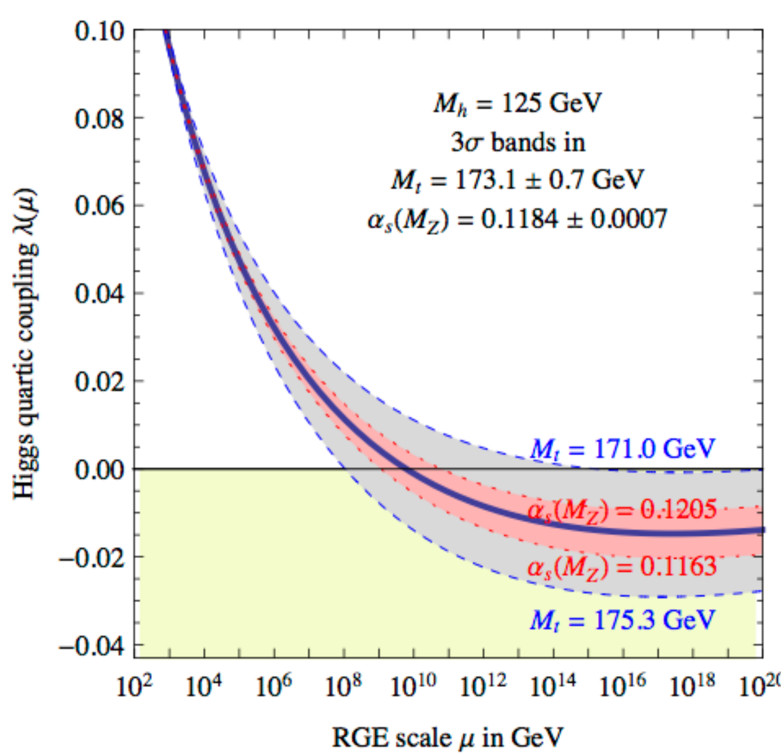
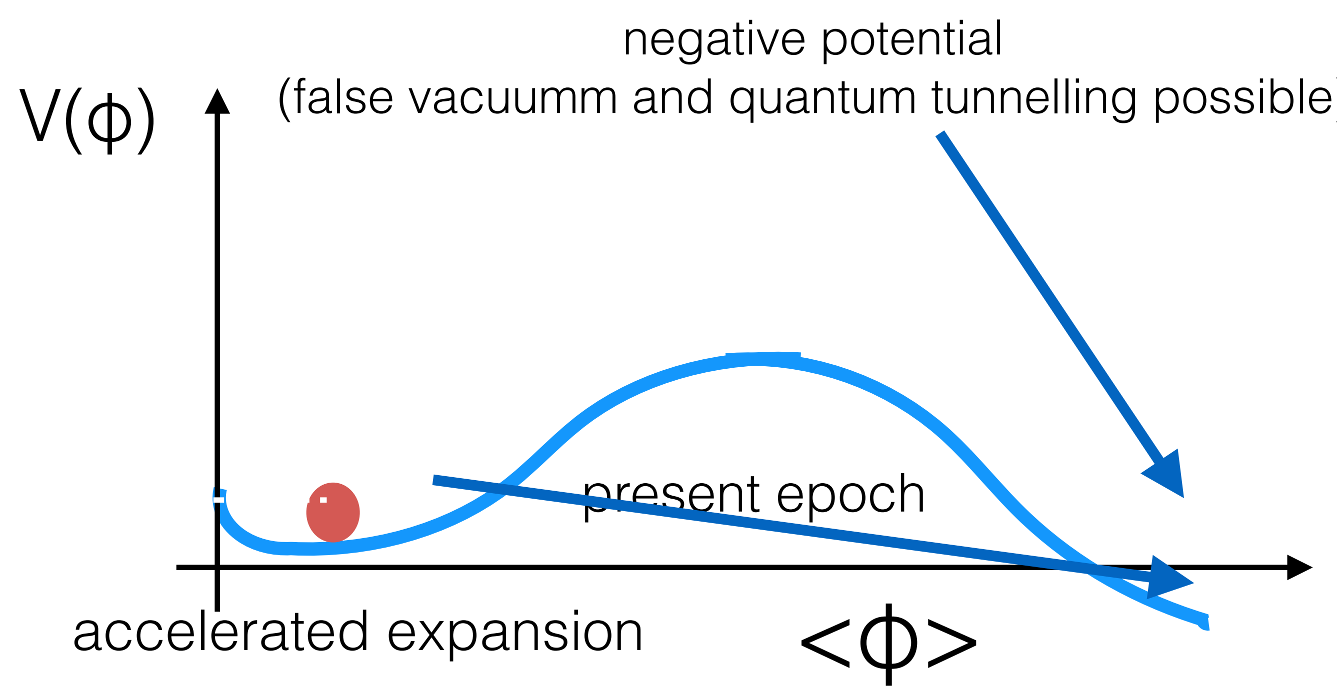
$$V(\phi) \sim \lambda\phi^4$$

λ energy scale dependence is function of M_h, M_t and the strong coupling constant at Mz





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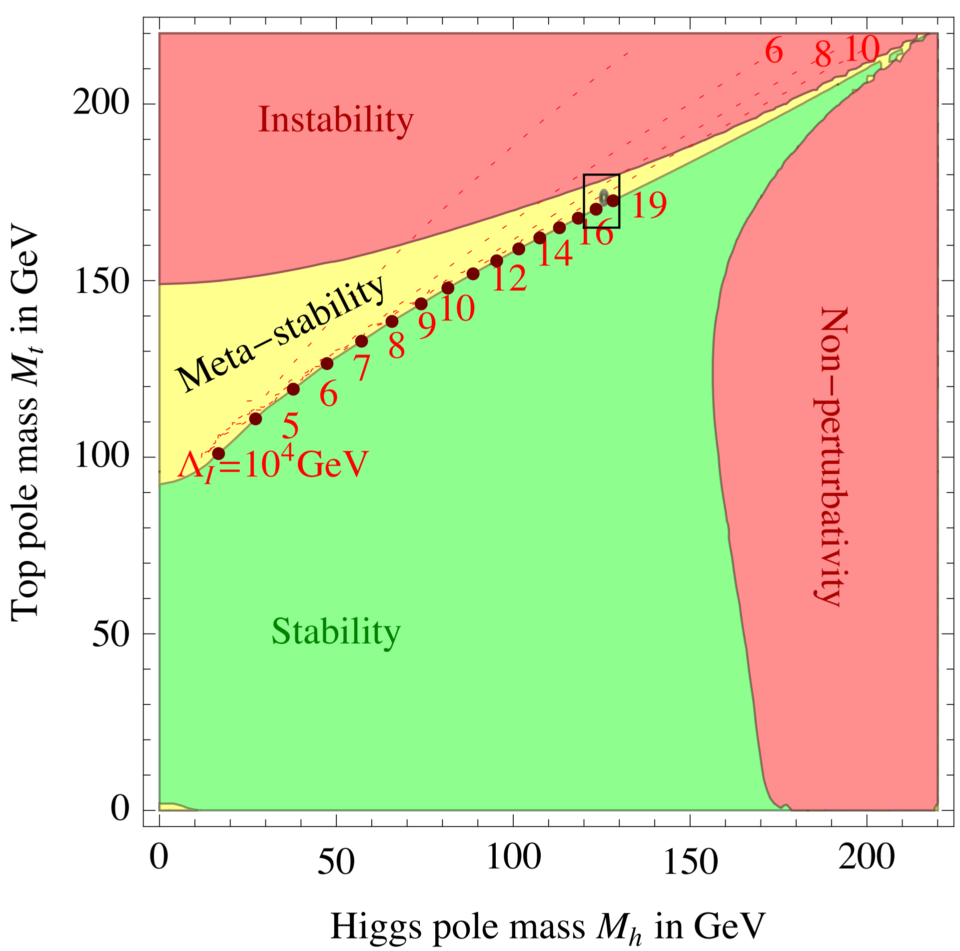
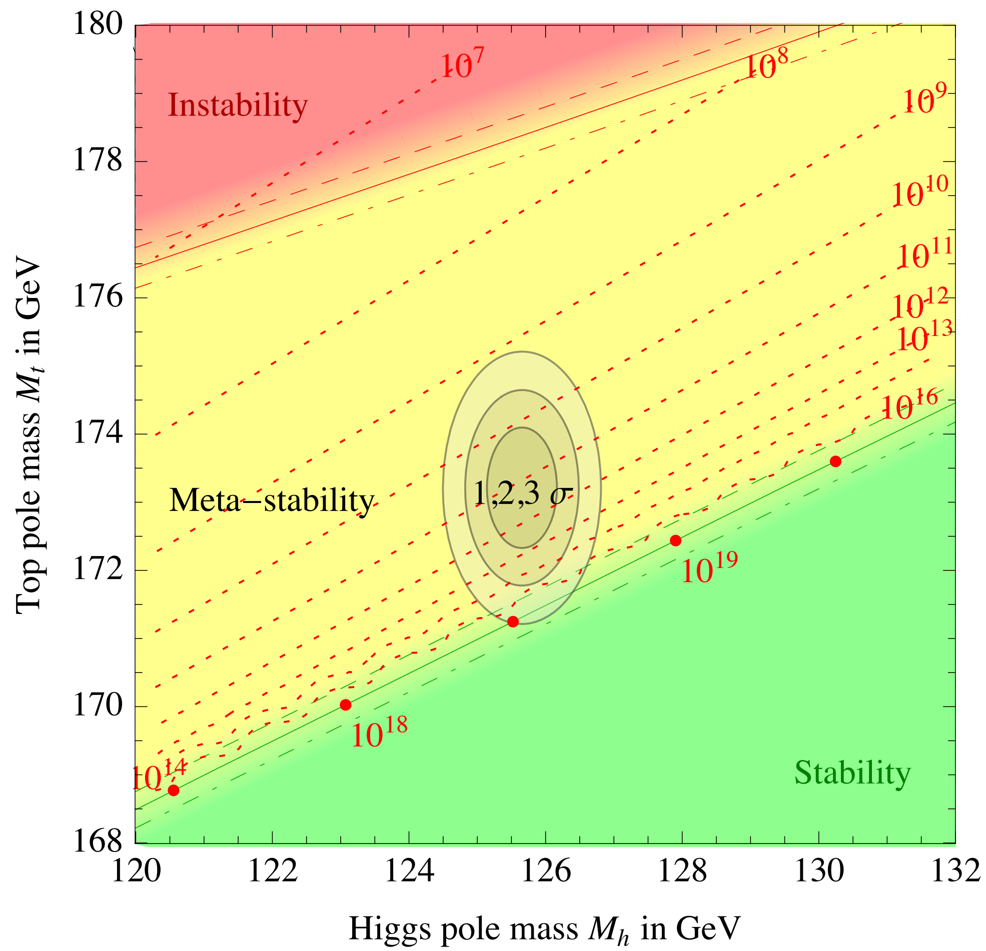
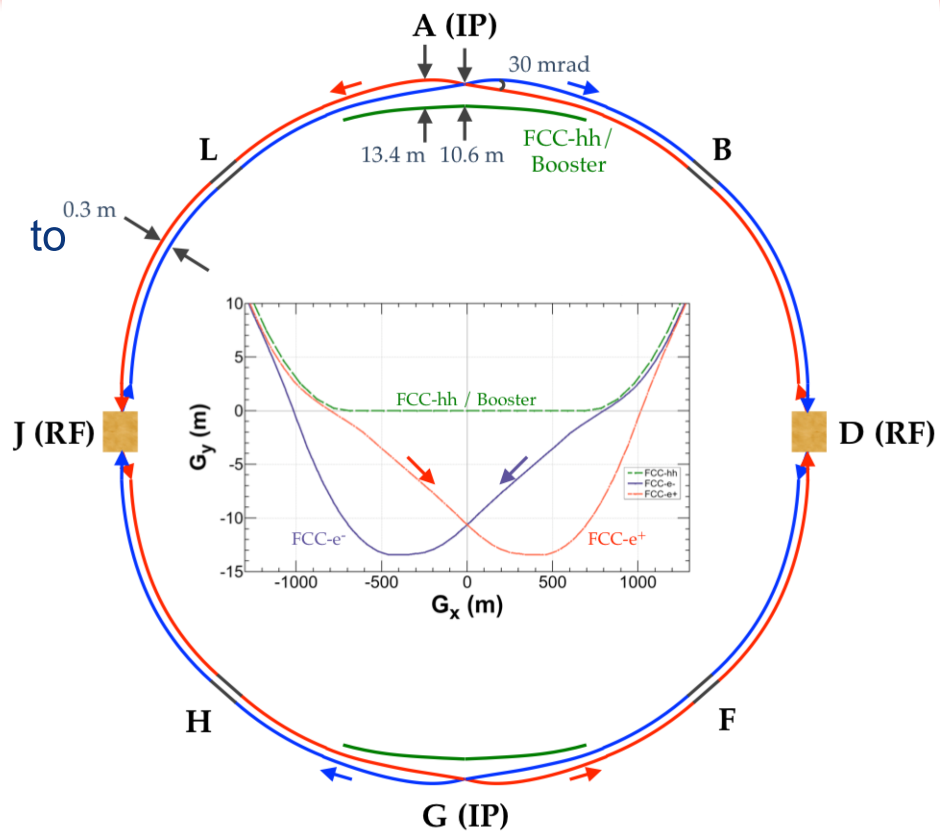
Vacuum stability

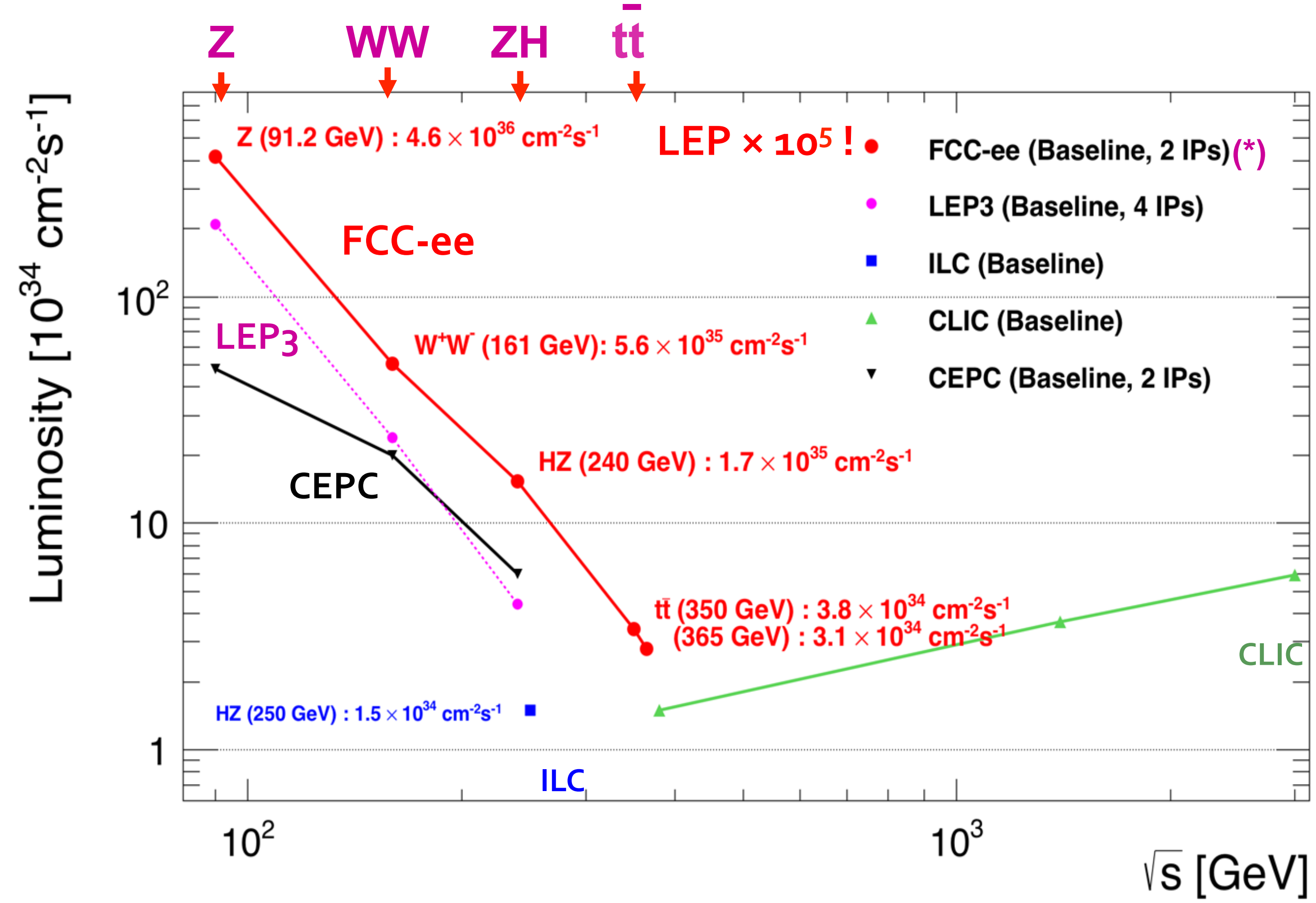
It is critical for our understanding of universe evolution to measure the Higgs boson self-coupling, the Higgs, the W and the top mass with the highest possible accuracy





FCC-ee: Machine scheme and luminosity





collider properties

- double accumulator ring, energy booster for acceleration, continuous injection, crossing angle (30 mrad), crab-waist techinque for luminosity optimisation

- minimal setup 2IP, optimal one with 4 IP

proposed timeline , energies and luminosity

Working point	Z, years 1-2	Z, later	WW	HZ	tt threshold...	...and above
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340 – 350	365
Lumi/IP (10^{34} cm^{-2}s^{-1})	100	200	25	7	0.8	1.4
Lumi/year (2 IP)	24 ab^{-1}	48 ab^{-1}	6 ab^{-1}	1.7 ab^{-1}	0.2 ab^{-1}	0.34 ab^{-1}
Physics goal	150 ab^{-1}		10 ab^{-1}	5 ab^{-1}	0.2 ab^{-1}	1.5 ab^{-1}
Run time (year)	2	2	2	3	1	4

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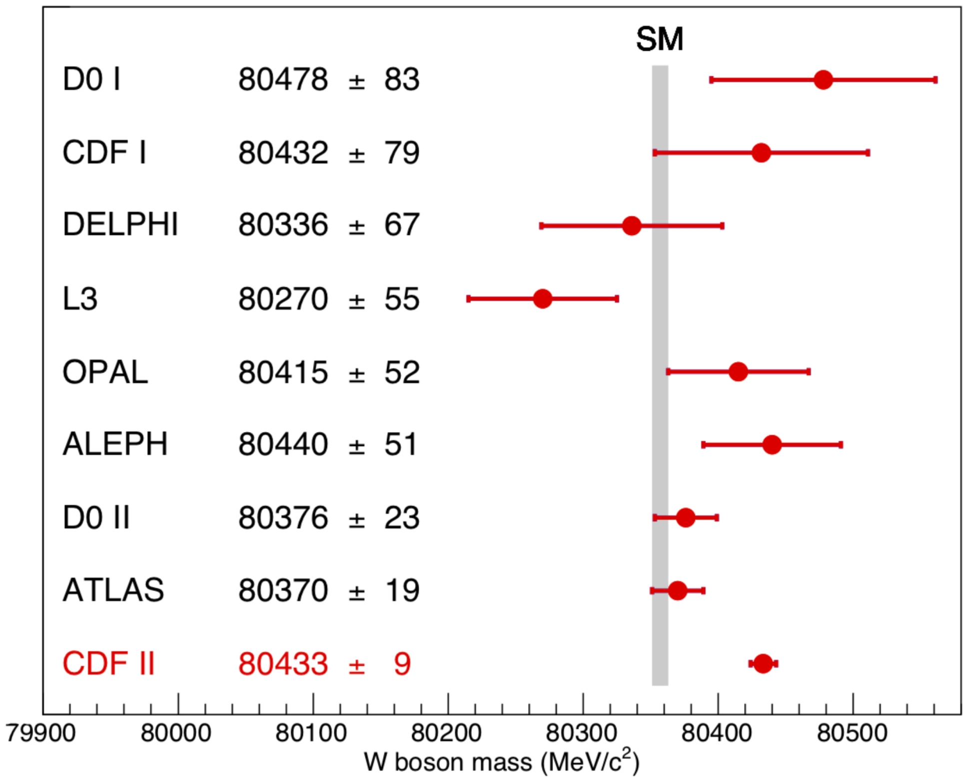
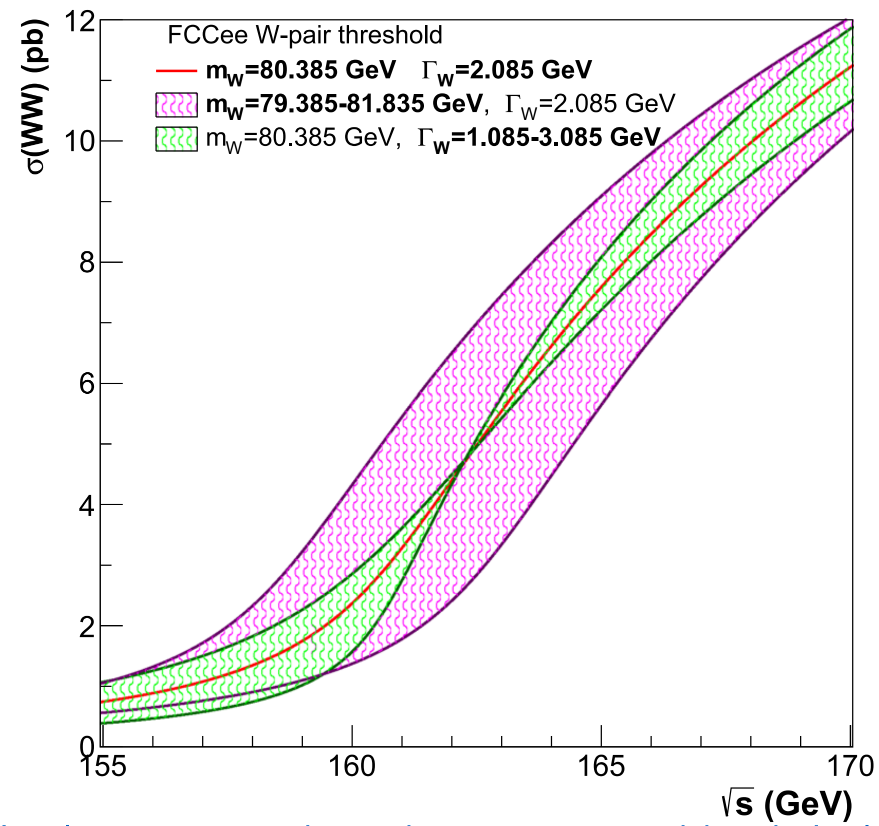
Measurement of m_W

present status



- Large number of measurements from LEP, Tevatron, LHC
- Recent CDF RunII results greatly reduce the error keeping the previous central value
- compatibility among the measurements at the 0.2% level

FCC-ee can measure m_W and Γ_W using a scan of $\sigma(e^+e^- \to W^+W^-)$ as a function of $\sqrt{s}$

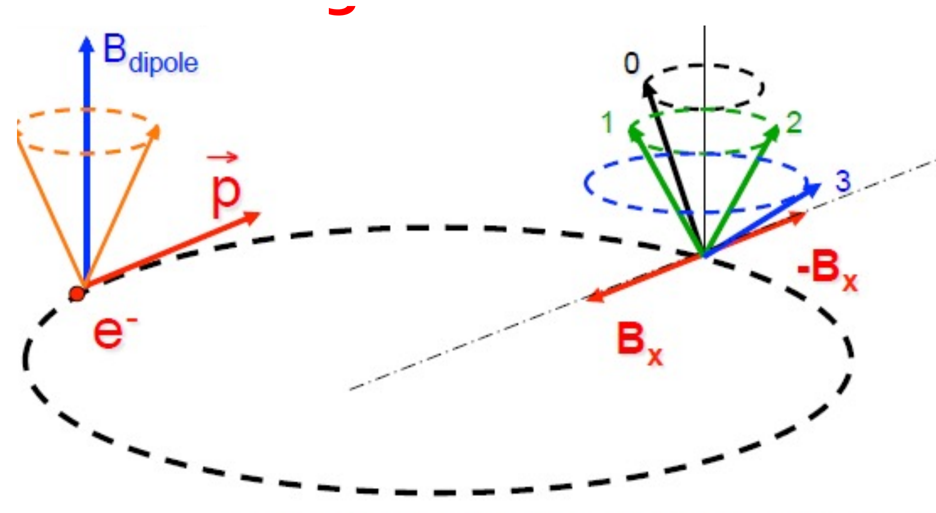


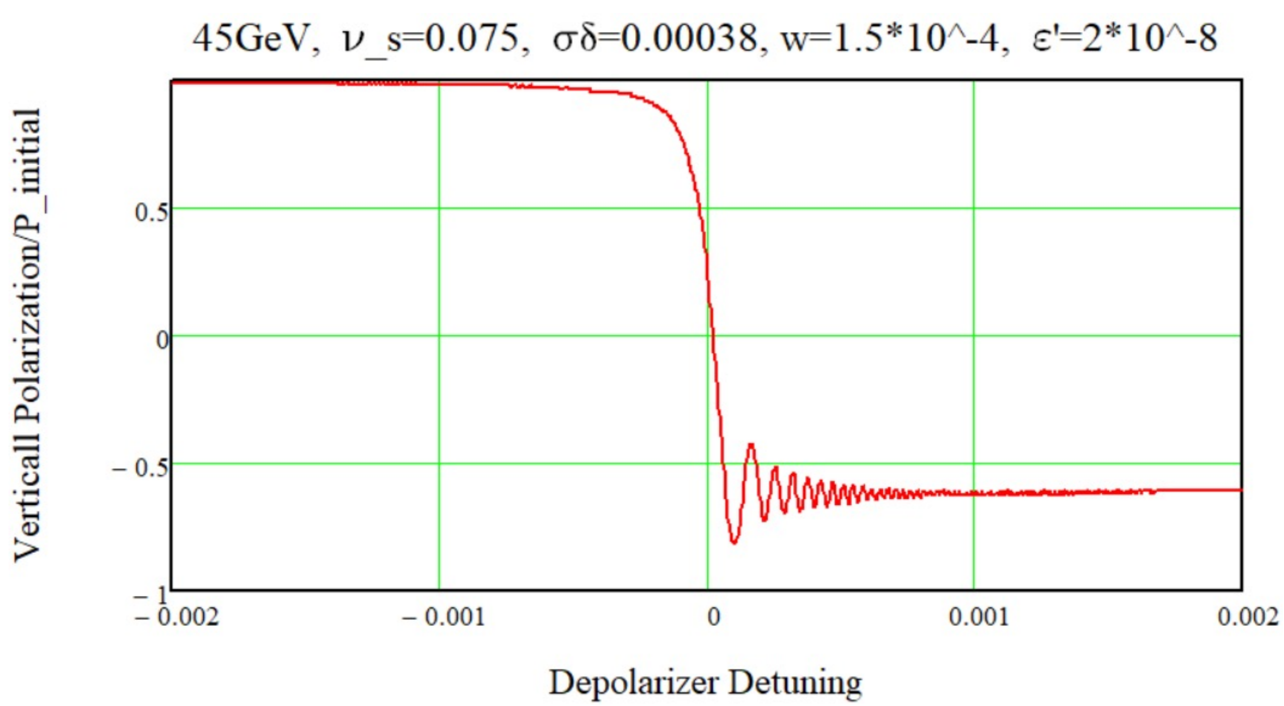
- the WW final state needs to be measured both in leptonic and hadronic channels to maximise statistics
- measuring the XS at a single energy point a statistical precision of 0.3 MeV on m_W can be obtained with 12 ab^{-1} of data, beam energy spread ΔE_{beam} < 0.35 MeV is needed;
- using 2 energy points E_1 = 157.1 GeV, E_2 = 162.3 GeV, L_{int} = 12 ab^{-1}, 40% of the luminosity at E_2 : Δm_W = 0.5 MeV , $\Delta\Gamma_W$ = 1.2 MeV (stat. only.)
- It is crucial to have low beam-energy spread and accurate absolute beam energy measurement

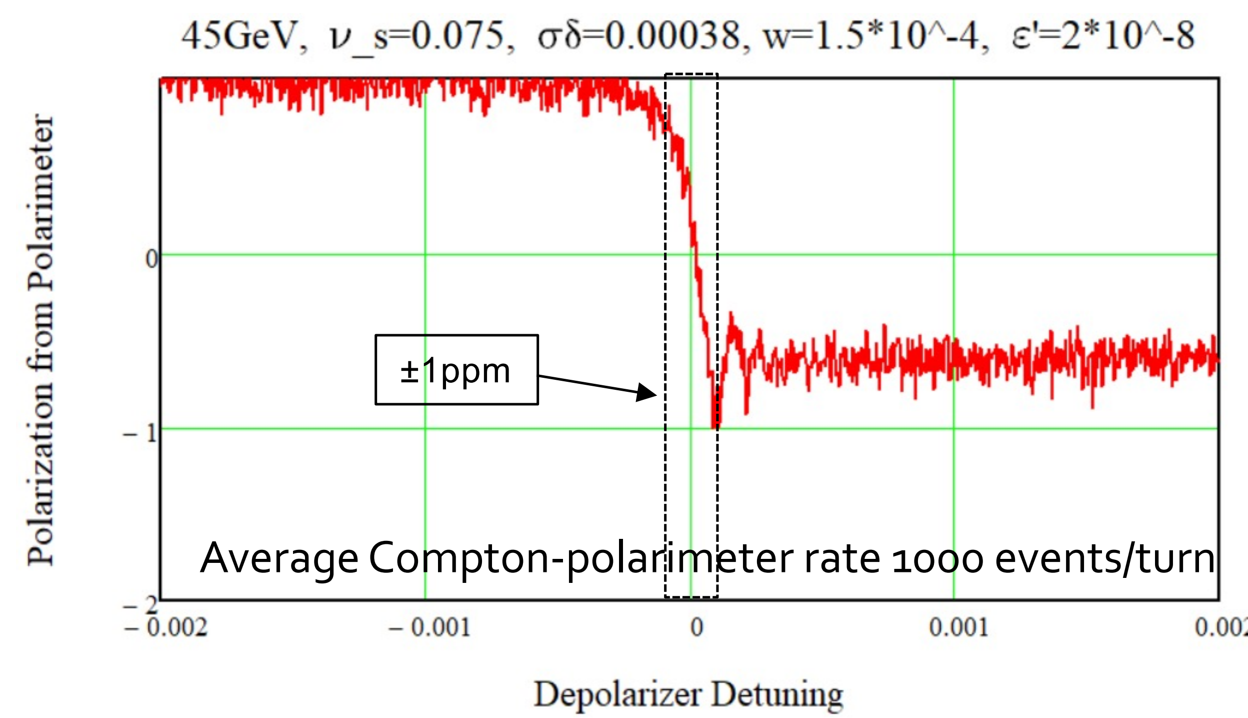
Absolute determination of $\sqrt{s}$

Continuous resonant depolarisation to measure the beam energies

- electrons are transverse-polarised using Wigglers
- spin precession frequency $\nu_0 \sim E_{beam}$
- beams are depolarised by a kicker at frequency ν_0
- polarisation measurement through Compton backscattering







1 ppm accuracy on beam energy is feasible
accuracy at level of 100 keV at the Z pole

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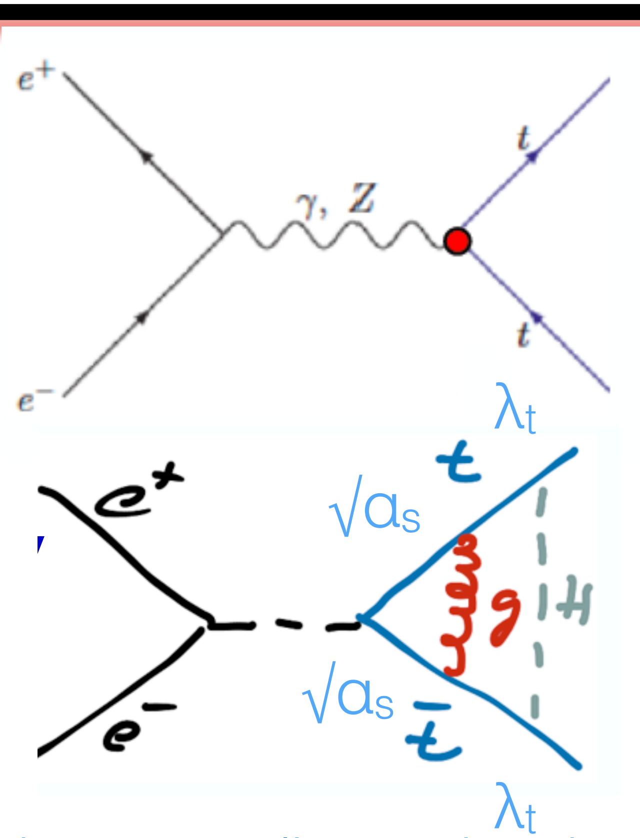
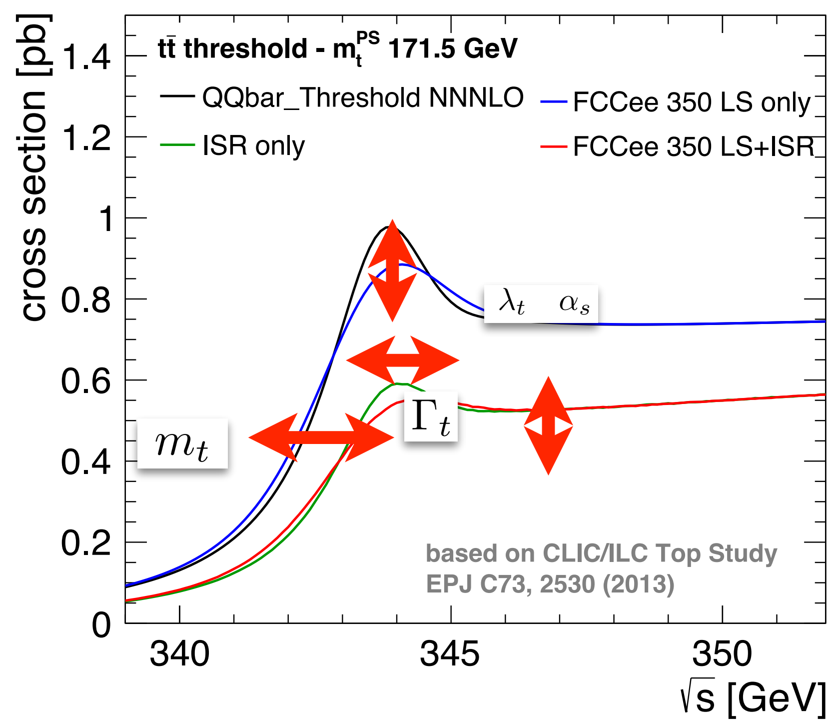
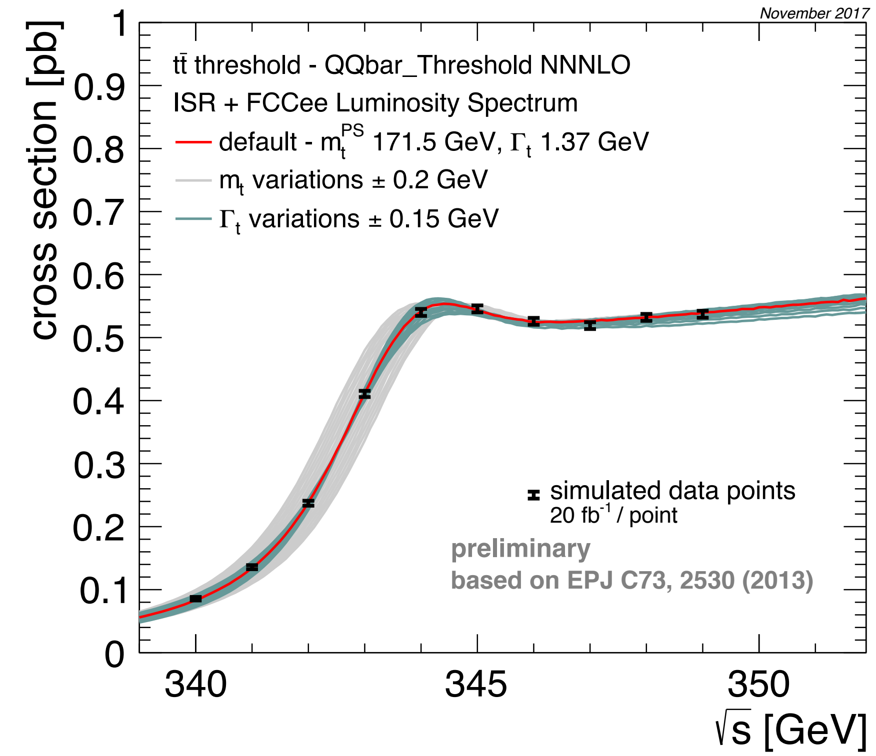
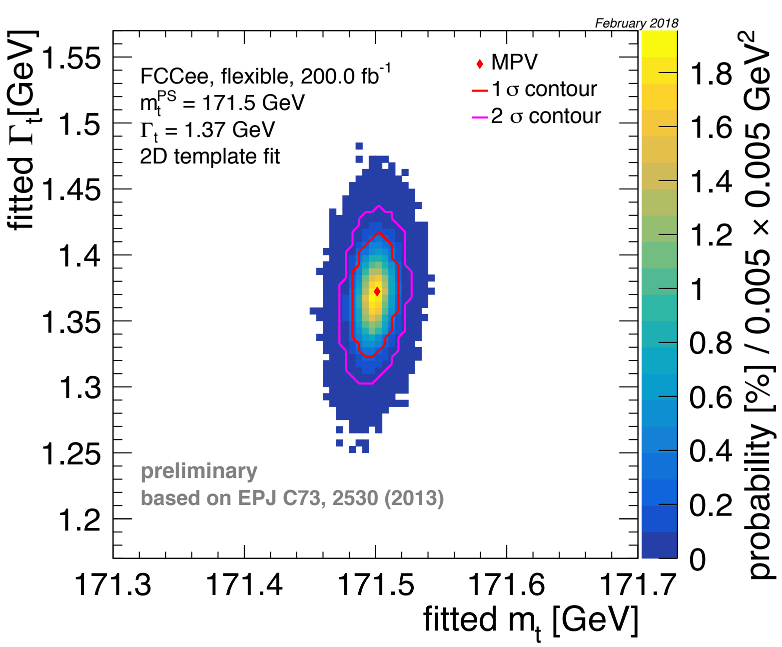
Measurement of the top mass

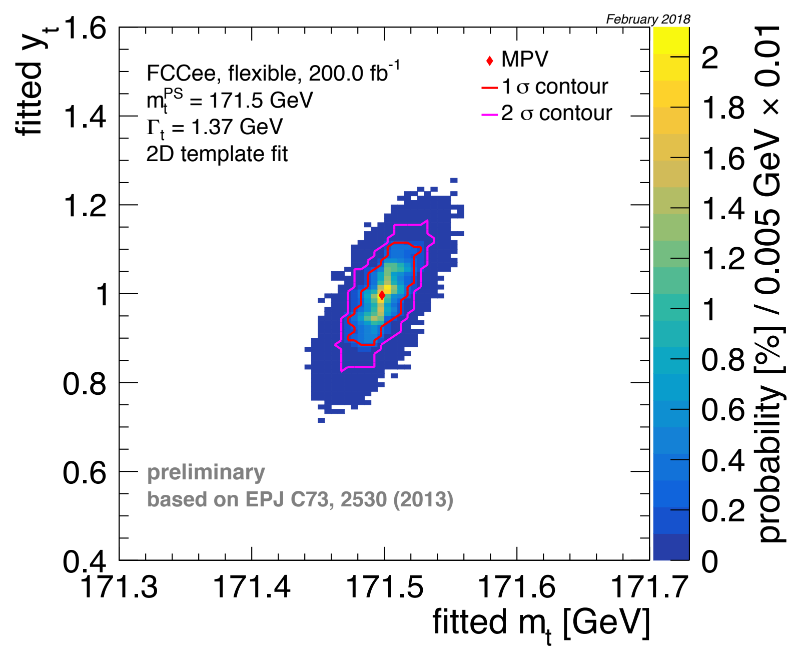


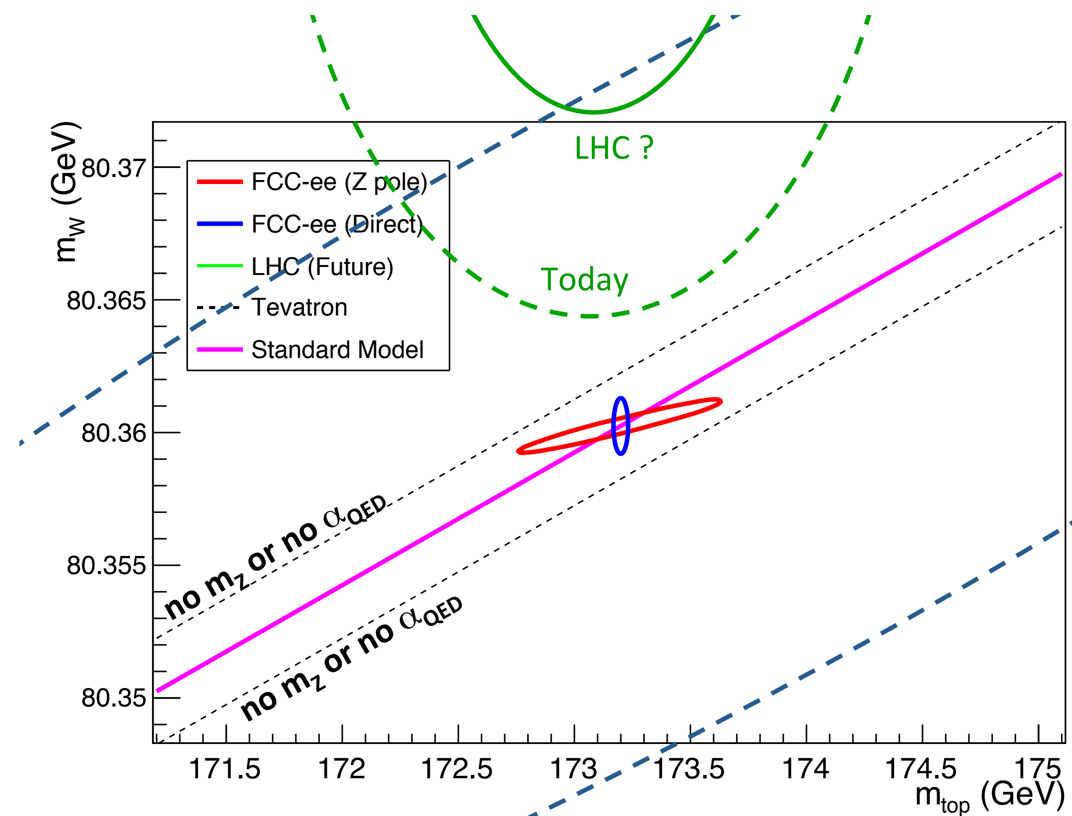




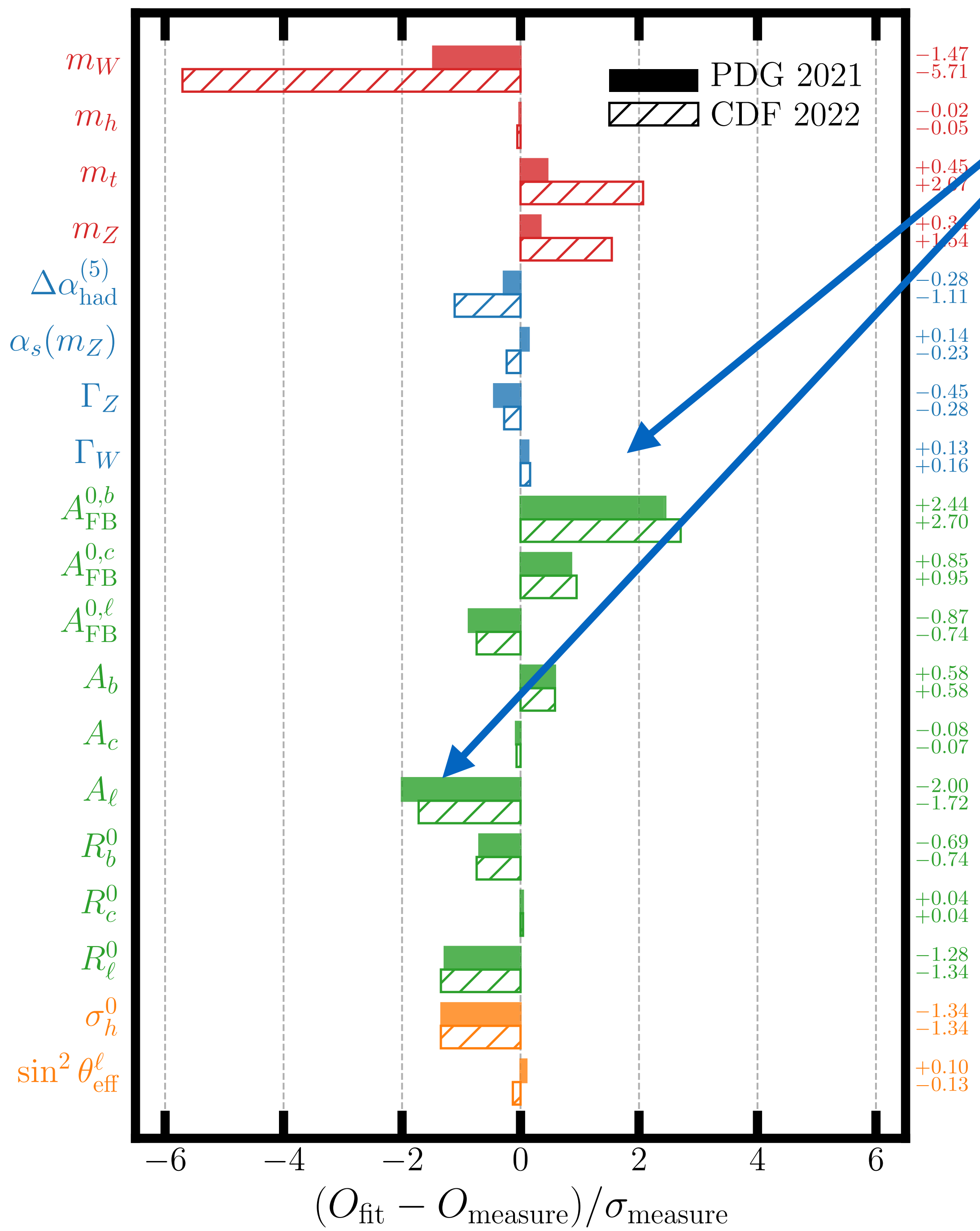
Yukawa coupling and α_S through loop higher orfer corrections







Electroweak precision measurements



- **new CDFII measurement increases tension in the fit**
- **usual border-line measurements are still there**

C.T. Lu et al., Phys. Rev. D 106, 035034 (2022)

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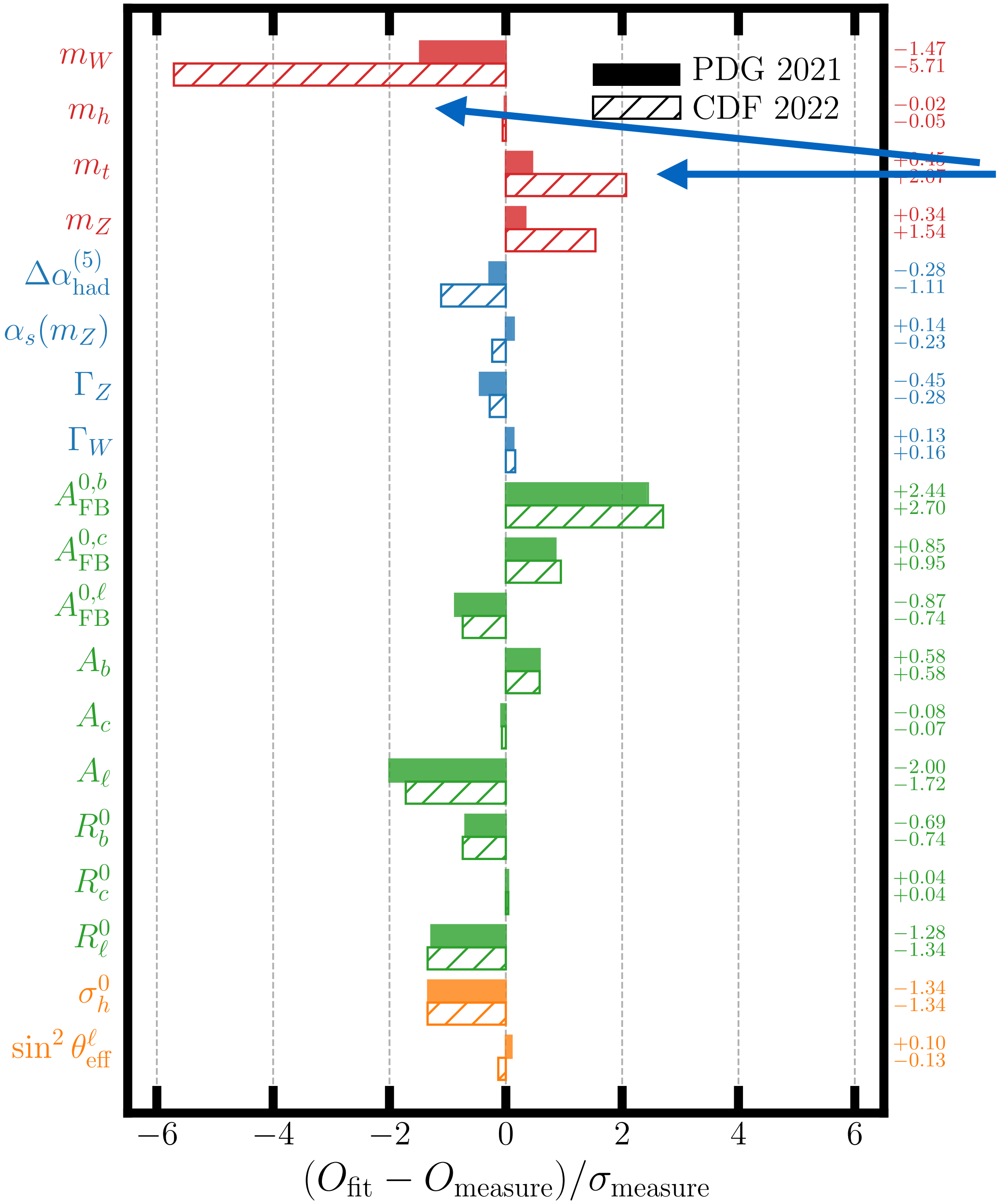

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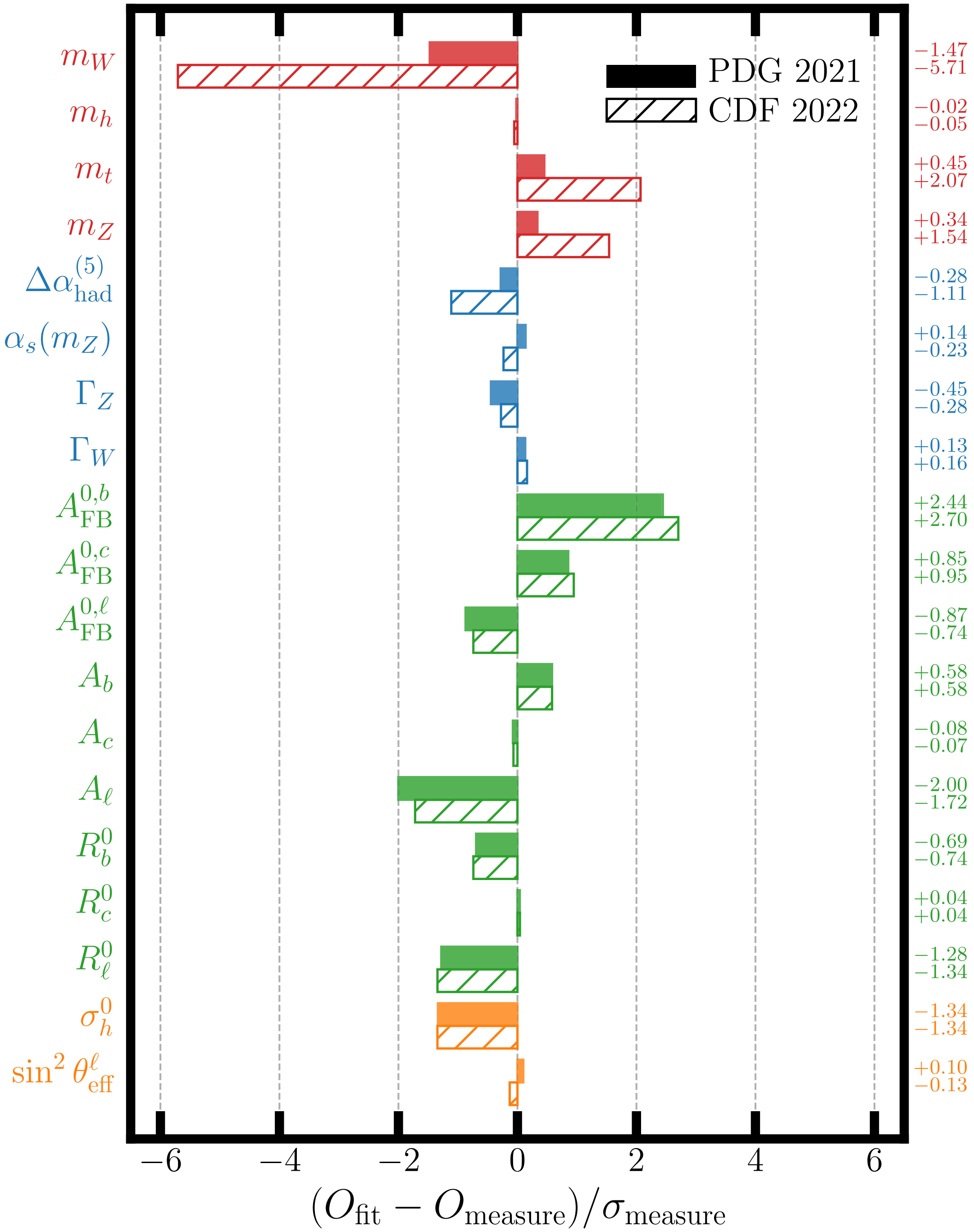

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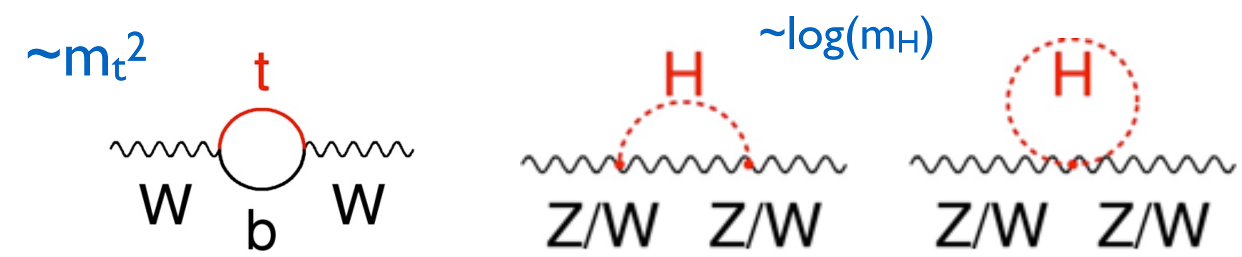
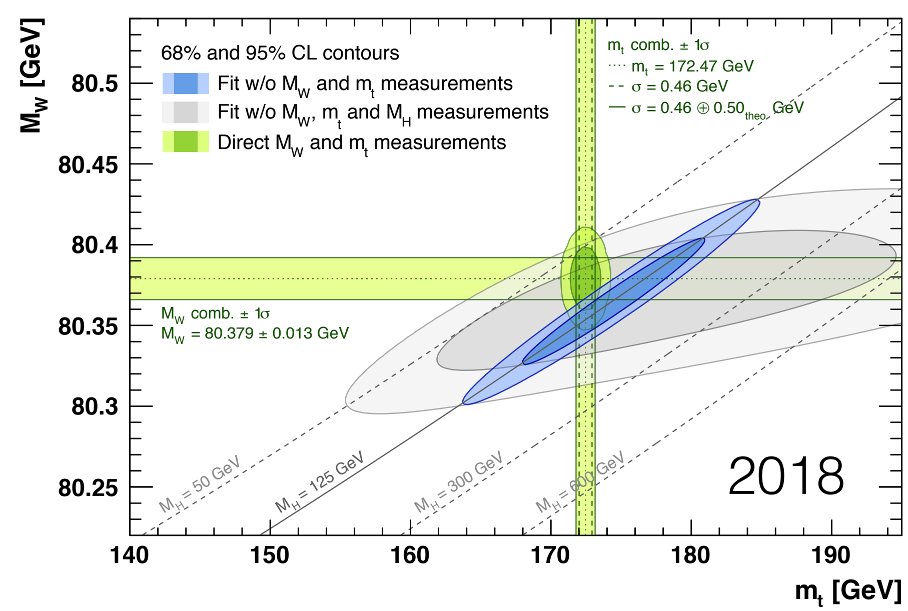
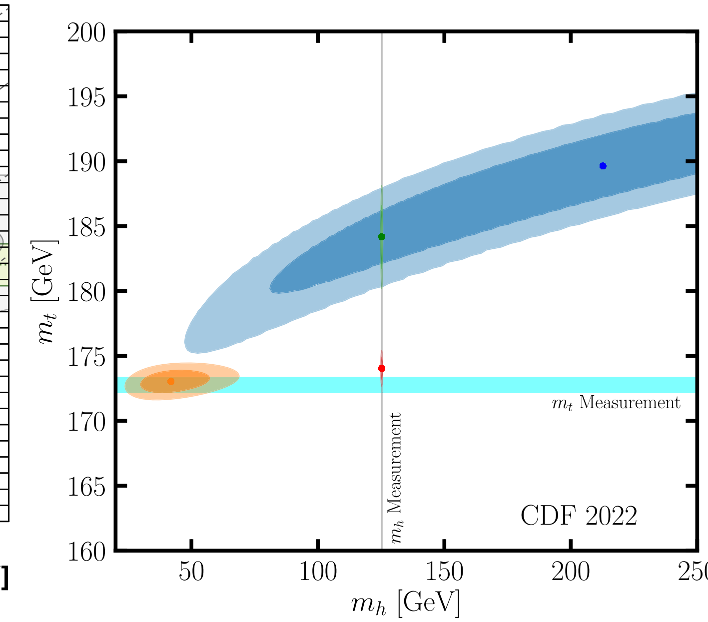
- **new CDFII measurement increases tension in the fit**
- **usual border-line measurements are still there**
- **new incompatibilities show up :-)**
- **hopefully LHC will clarify (or add confusion) to the m_W puzzle**
- **other tensions will remain, will it be the next e^+e^- collider to address this issue (and find new ones ?)**

W mass gets top and Higgs mass correction through loops







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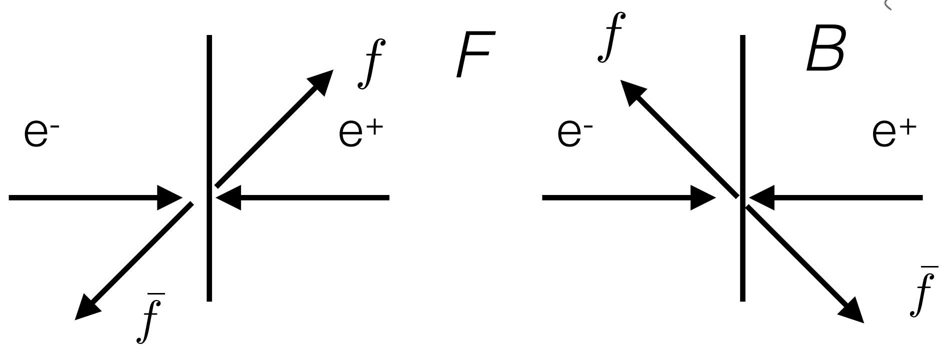
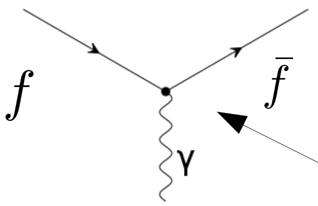
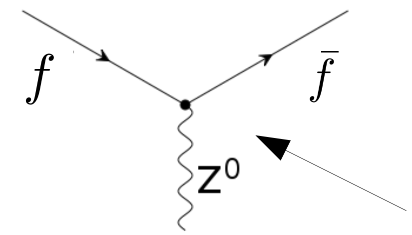
Fermionic asymmetries measurements

$$A^f_{FB} = \frac{N_F - N_B}{N_F + N_B}$$





$$-ieQ^f\gamma^\mu$$



$$\frac{-ig}{cos\theta_W}\gamma^\mu\frac{g_{Vf} - g_{Af}\gamma_5}{2}$$

$$\mathcal{A}_f = \frac{2g_{Vf}g_{Af}}{1 + (g_{Vf}/g_{Ae})^2}$$

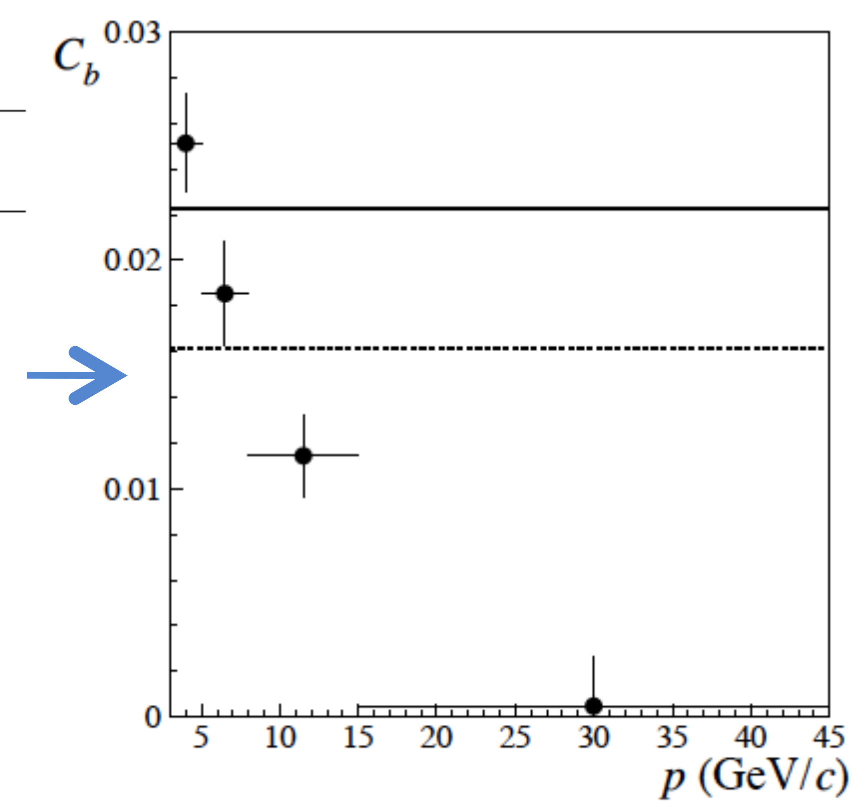
$$A^f_{\rm FB}(\sqrt{s} = m_Z) = A^{0,f}_{\rm FB} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

	Statistical uncertainty	Systematic uncertainty	improvement w.r.t. LEP
$\mathcal{A}_e$	$5. \times 10^{-5}$	$1. \times 10^{-4}$	50
$\mathcal{A}_\mu$	2.5×10^{-5}	1.5×10^{-4}	30
$\mathcal{A}_\tau$	$4. \times 10^{-5}$	$3. \times 10^{-4}$	15
$\mathcal{A}_b$	2×10^{-4}	30×10^{-4}	5
$\mathcal{A}_c$	3×10^{-4}	80×10^{-4}	4
$\sin^2\theta_{W,eff}$ (from muon FB)	10^{-7}	$5. \times 10^{-6}$	100
$\sin^2\theta_{W,eff}$ (from tau pol)	10^{-7}	6.6×10^{-6}	75

Profiting of the high available statistics hard cuts can be used to reduce the impact of systematic errors

	LEP	FCC-ee
statistics	0.00156	0.00002
unc. sys.	0.00061	orig. stat.
QCD corr	0.00030	tagli su p_T^l

impact of QCD correction



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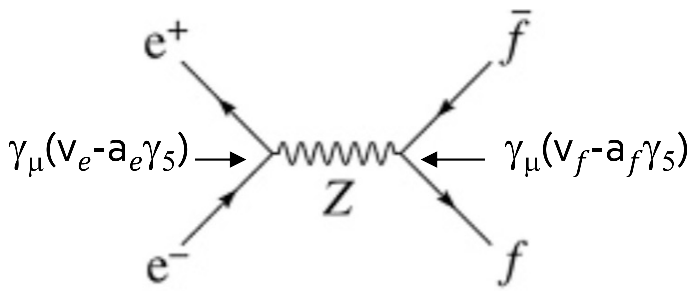
$\sin^2\theta_{eff}$ from τ polarisation

Parity-violating (L ≠ R) weak couplings at the Z pole



$a_f = \pm 1/2$

$v_f = a_f(1 - 4|Q_f|\, \sin^2\theta^\ell_{eff})$

Asymmetry parameter

$$A_f = \frac{2a_f v_f}{v_f^2 + a_f^2}$$

- At linear colliders it is possible to increase the sensitivity using longitudinally polarised beams

$$P = \frac{P_{e^-} - P_{e^+}}{(1 - P_{e^-}P_{e^+})}$$

$$A_{LR} = \frac{\sigma_{tot}(P) - \sigma_{tot}(-P)}{\sigma_{tot}(P) + \sigma_{tot}(-P)} = PA_e$$

$$A_{FB}^{polf} = \frac{\sigma_{Ff}(P) - \sigma_{Ff}(-P) - [\sigma_{Bf}(P) - \sigma_{Bf}(-P)]}{\sigma_{totf}(P) + \sigma_{totf}(-P)} = \frac{3}{4}PA_f$$

- Polarisation is present also in the final state fermions, it can be measured in the τ case using the angular distribution of the decay products

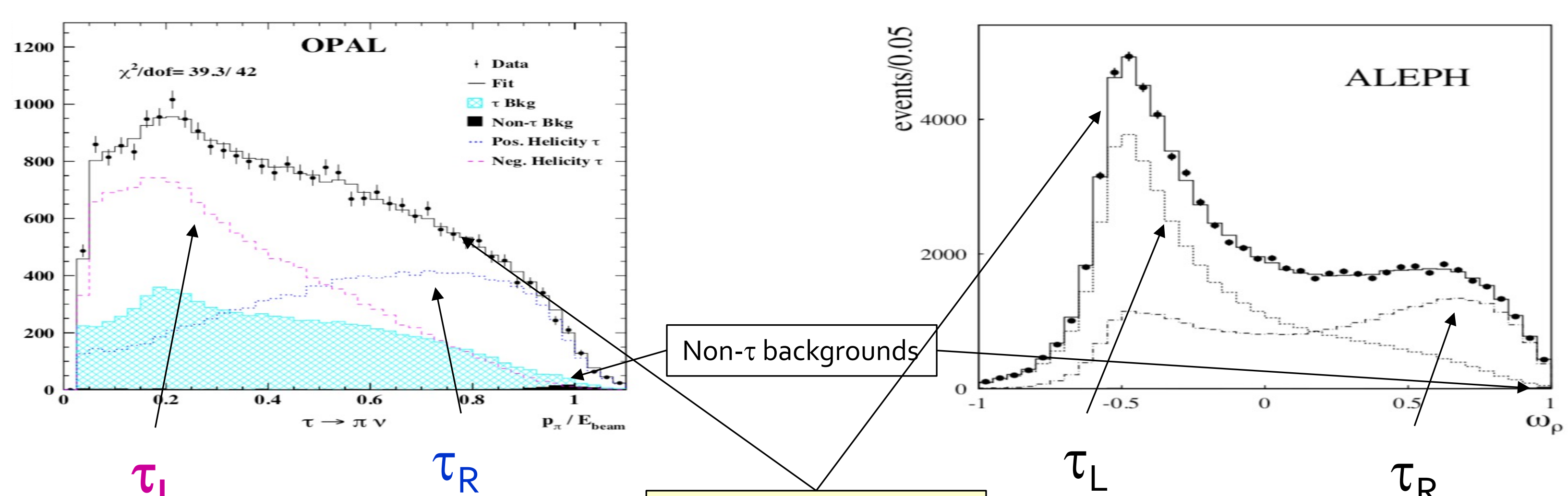
$$\langle P_\tau \rangle = \frac{\sigma_{R\tau} - \sigma_{L\tau}}{\sigma_{R\tau} + \sigma_{L\tau}} = -A_\tau$$

$$A_{FB}^{pol\tau} = \frac{\sigma_{RF\tau} - \sigma_{LF\tau} - [\sigma_{RB\tau} - \sigma_{LB\tau}]}{\sigma_{R\tau} + \sigma_{L\tau}} = -\frac{3}{4}A_e$$

$$A_{FB}^{f} = \frac{\sigma_{Ff} - \sigma_{Bf}}{\sigma_{Ff} + \sigma_{Bf}} = \frac{3}{4}A_e\, A_f$$

- $\tau \to \pi\nu_\tau$: pion energy

$\tau \to \rho\nu_\tau$: optimal observable ω_ρ



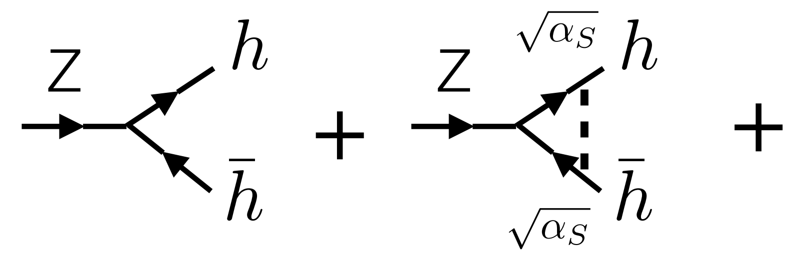
example from LEP

Slide from P. Janot, Precision Calculations for future e+ e- colliders

R_ℓ measurement and α_S

$$R_\ell = \frac{\Gamma_{\text{had}}}{\Gamma_\ell}$$

Γ_{had} is sensitive to α_S through QCD loop corrections on final state hadrons: h



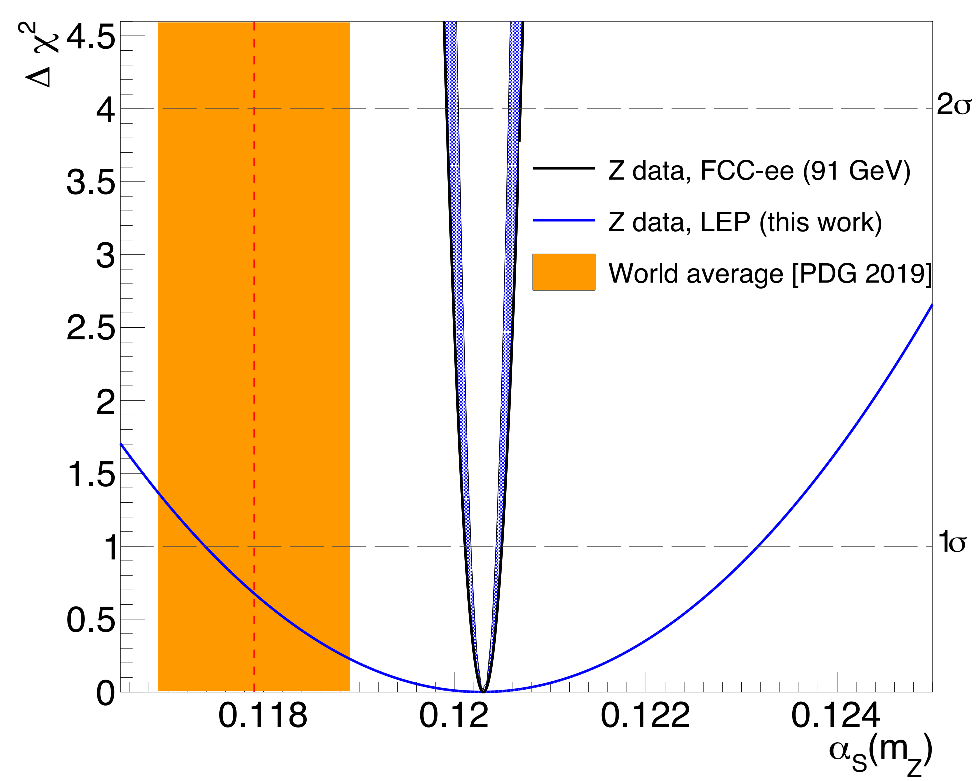
R_ℓ statistical precision at 3×10^{-6} level

- allows a test of lepton universality and quark-lepton universality
- allows the extraction of α_S at m_Z

Main systematics at LEP from detector acceptance

- can be reduced increasing the fiducial volume $|\cos(\theta)| < 0.95 \rightarrow |\cos(\theta)| < 0.995$;
- providing a clean and simple design of the forward region

Z boson observable	$\alpha_S(m_Z)$ extraction	uncertainties exp.	param.	theor.
Γ_Z^{tot}	0.1192 ± 0.0047	±0.0046	±0.0005	±0.0008
R_Z	0.1207 ± 0.0041	±0.0041	±0.0001	±0.0009
σ_Z^{had}	0.1206 ± 0.0068	±0.0067	±0.0004	±0.0012
All combined	0.1203 ± 0.0029	±0.0029	±0.0002	±0.0008
Global SM fit	0.1202 ± 0.0028	±0.0028	±0.0002	±0.0008
All combined (FCC-ee)	0.12030 ± 0.00026	±0.00013	±0.00005	±0.00022
Global SM fit (FCC-ee)	0.12020 ± 0.00026	±0.00013	±0.00005	±0.00022



α_S from W decays

- QCD coupling extracted from new N³LO fit of combined Γ_W, R_W pseudo-observ.:

W boson observables	$\alpha_S(m_Z)$ extraction	uncertainties exp.	param.	theor.
Γ_W^{tot}, R_W (exp. CKM)	0.044 ± 0.052	± 0.024	± 0.047	(± 0.0014)
Γ_W^{tot}, R_W (CKM unit.)	0.101 ± 0.027	± 0.027	(± 0.0002)	(± 0.0016)
Γ_W^{tot}, R_W (FCC-ee, CKM unit.)	0.11790 ± 0.00023	± 0.00012	± 0.00004	± 0.00019

Slide from D. d'Entreria
LFC '21 Trento

- FCC-ee extraction:

– Huge W pole stats. ($\times 10^4$ LEP-2).

– Exquisite syst./parametric precision:

$$\Gamma_W^{tot} = 2088.0 \pm 1.2 \text{ MeV}$$

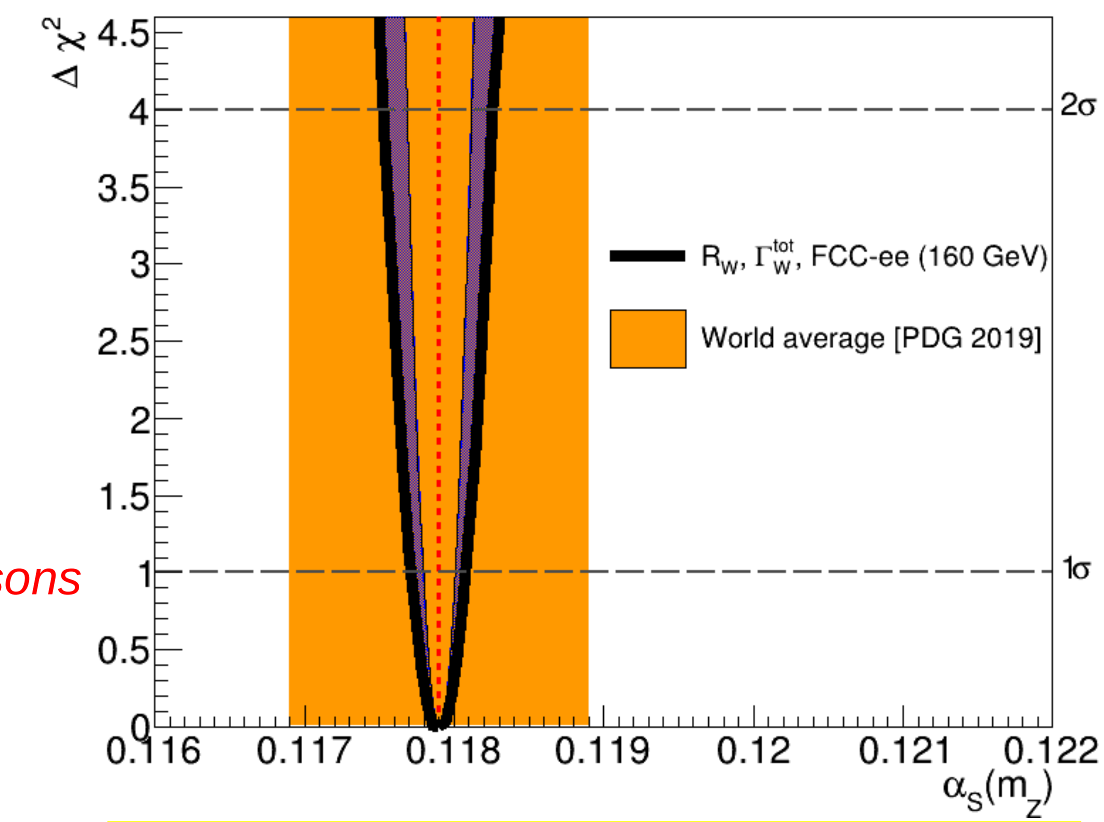
$$R_W = 2.08000 \pm 0.00008$$

$$m_W = 80.3800 \pm 0.0005 \text{ GeV}$$

$$|V_{cs}| = 0.97359 \pm 0.00010$$ ← $O(10^{12})$ D mesons

– TH uncertainty reduced by $\times 10$ after computing missing α_s^5, α^2, α^3, $\alpha\alpha_s^2$, $\alpha\alpha_s^2$, $\alpha^2\alpha_s$ terms

DdE, Jacobsen: arXiv:2005.04545 [hep-ph]

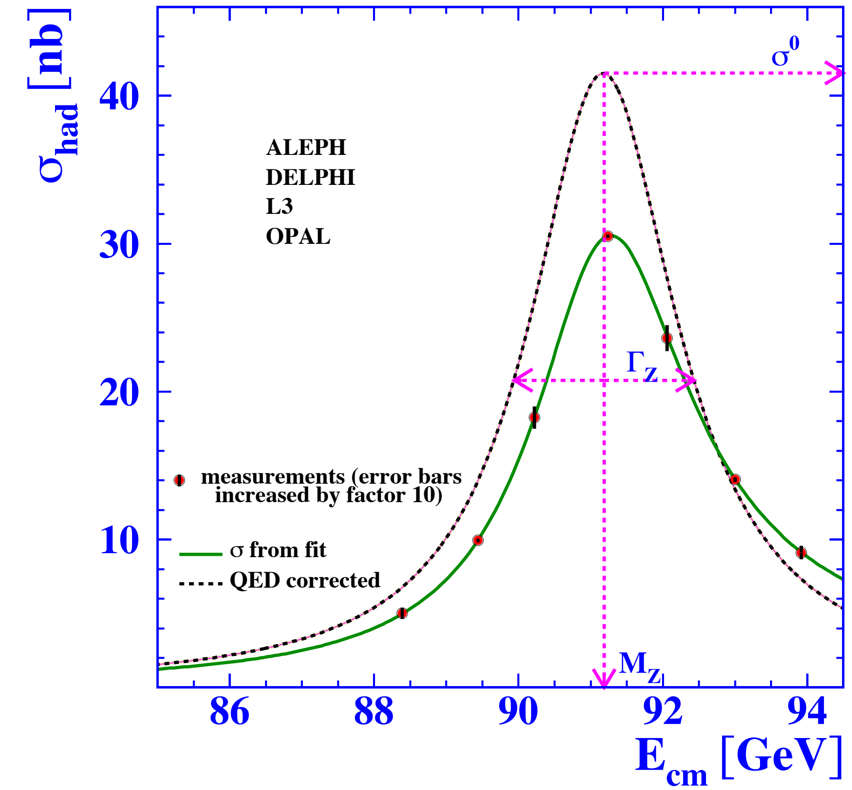


$\alpha_s(m_Z) = 0.11790 \pm 0.00023$ ($\pm 0.2\%$)

Measurement of the Z mass and width

10^{12} expected Z bosons

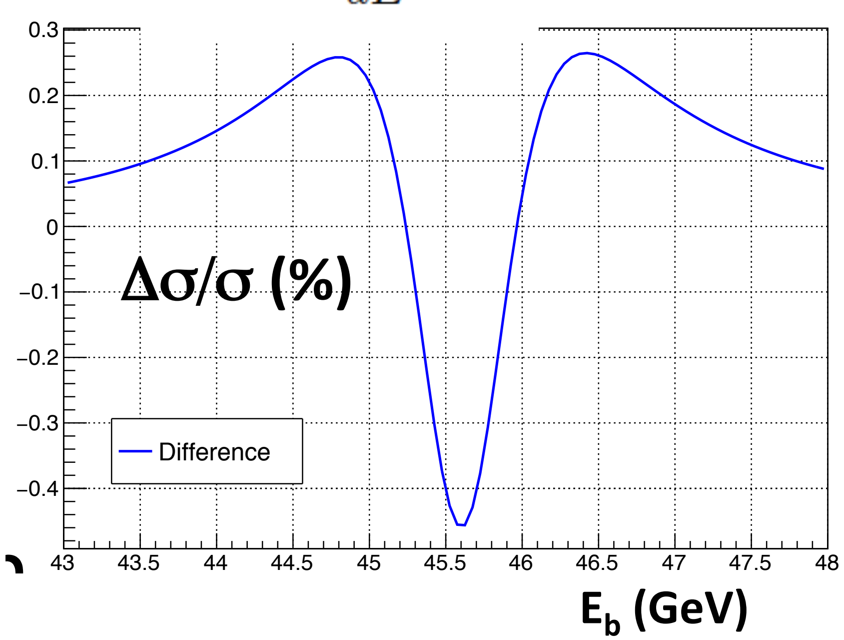
- mass and width are measured using the hadronic cross section as a function of E_{cm}
- statistics error is negligible, main systematics from beam energy calibration ΔE_{cm} = 10 keV (stat.) + 100 keV (syst)
- beam energy calibration from resonant depolarisation technique



Γ_Z measurement

- dominant uncertainty from the beam energy spread

$$\delta\sigma \simeq 0.5 \frac{d^2\sigma}{dE^2}\epsilon^2_{CMS}$$

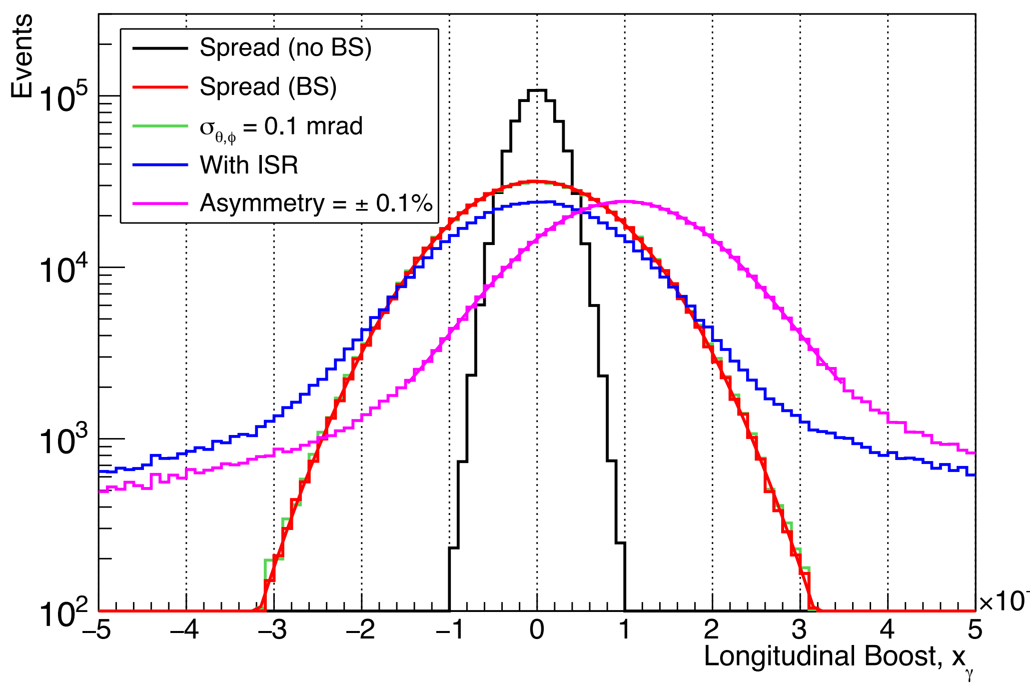


- the beam energy spread is measured using $e^+e^- \to \mu^+\mu^-(\gamma)$

$$x_\gamma = -\frac{x_+ \cos\theta^+ + x_- \cos\theta^-}{\cos(\alpha/2) + |x_+\cos\theta^+ + x_-\cos\theta^-|}$$

- 4 min 10^6 muons, energy spread measured at 0.1%
- $\Delta\Gamma_Z$ < 30 keV

One million dimuon events



Electroweak observables

Table 3 Measurement of selected precision measurements at FCC-ee, compared with present precision. Statistical errors are indicated in boed phase. The systematic uncertainties are initial estimates, aim is to improve down to statistical errors. This set of measurements, together with those of the Higgs properties, achieves indirect sensitivity to new physics up to a scale Λ of 70 TeV in a description with dim 6 operators, and possibly much higher in specific new physics (non-decoupling) models

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and leading exp. error
m_Z (keV)	91186700 ± 2200	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	**4**	25	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{\rm eff} (\times 10^6)$	231480 ± 160	**2**	2.4	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)(\times 10^3)$	128952 ± 14	**3**	Small	From $A_{FB}^{\mu\mu}$ off peak QED&EW errors dominate
R_ℓ^Z $(\times 10^3)$	20767 ± 25	**0.06**	0.2–1	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_s(m_Z^2)$ $(\times 10^4)$	1196 ± 30	**0.1**	0.4–1.6	From R_ℓ^Z above
$\sigma_{\rm had}^0$ $(\times 10^3)$ (nb)	41541 ± 37	**0.1**	4	Peak hadronic cross section Luminosity measurement
$N_\nu (\times 10^3)$	2996 ± 7	**0.005**	1	Z peak cross sections Luminosity measurement
R_b $(\times 10^6)$	216290 ± 660	**0.3**	< 60	Ratio of $b\bar{b}$ to hadrons

Observable	Present value ± error	FCC-ee stat.	FCC-ee syst.	Comment and leading exp. error
$A_{FB}^b, 0$ $(\times 10^4)$	992 ± 16	**0.02**	1–3	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{{\rm pol},\tau}$ $(\times 10^4)$	1498 ± 49	**0.15**	<2	τ polarization asymmetry τ decay physics
τ lifetime (fs)	290.3 ± 0.5	**0.001**	0.04	Radial alignment
τ mass (MeV)	1776.86 ± 0.12	**0.004**	0.04	Momentum scale
τ leptonic $(\mu\nu_\mu\nu_\tau)$ B.R. (%)	17.38 ± 0.04	**0.0001**	0.003	e/μ/hadron separation
m_W (MeV)	80350 ± 15	**0.25**	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	**1.2**	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W^2)(\times 10^4)$	1170 ± 420	**3**	Small	from R_ℓ^W
$N_\nu (\times 10^3)$	2920 ± 50	**0.8**	Small	Ratio of invis. to leptonic in radiative Z returns
$m_{\rm top}$ (MeV/c^2)	172740 ± 500	**17**	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\Gamma_{\rm top}$ (MeV/c^2)	1410 ± 190	**45**	Small	From $t\bar{t}$ threshold scan QCD errors dominate
$\lambda_{\rm top}/\lambda_{\rm top}^{\rm SM}$	1.2 ± 0.3	**0.10**	Small	From $t\bar{t}$ threshold scan QCD errors dominate
ttZ couplings	$\pm$ 30%	**0.5–1.5%**	Small	From $\sqrt{s} = 365$ GeV run

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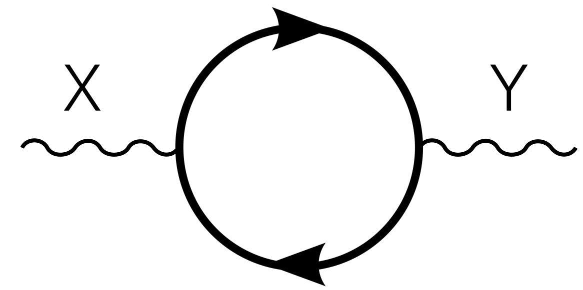
S,T relations

$$\widehat{\alpha}(M_Z)T \equiv \frac{\Pi^{\rm new}_{WW}(0)}{M_W^2} - \frac{\Pi^{\rm new}_{ZZ}(0)}{M_Z^2} ,$$

$$\frac{\widehat{\alpha}(M_Z)}{4\,\widehat{s}_Z^2\widehat{c}_Z^2} S \equiv \frac{\Pi^{\rm new}_{ZZ}(M_Z^2) - \Pi^{\rm new}_{ZZ}(0)}{M_Z^2} - \frac{\widehat{c}_Z^2 - \widehat{s}_Z^2}{\widehat{c}_Z\widehat{s}_Z}\frac{\Pi^{\rm new}_{Z\gamma}(M_Z^2)}{M_Z^2} - \frac{\Pi^{\rm new}_{\gamma\gamma}(M_Z^2)}{M_Z^2}$$

Π_{XY}



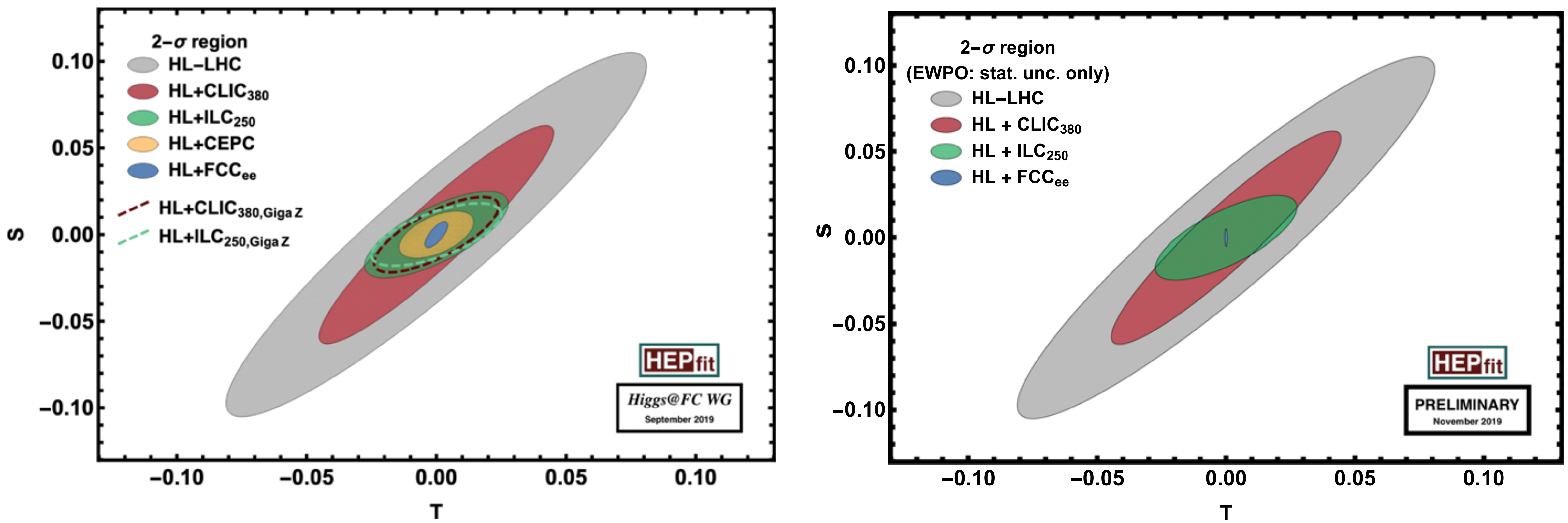
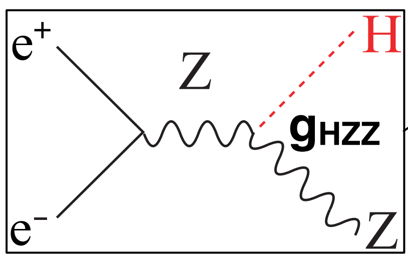
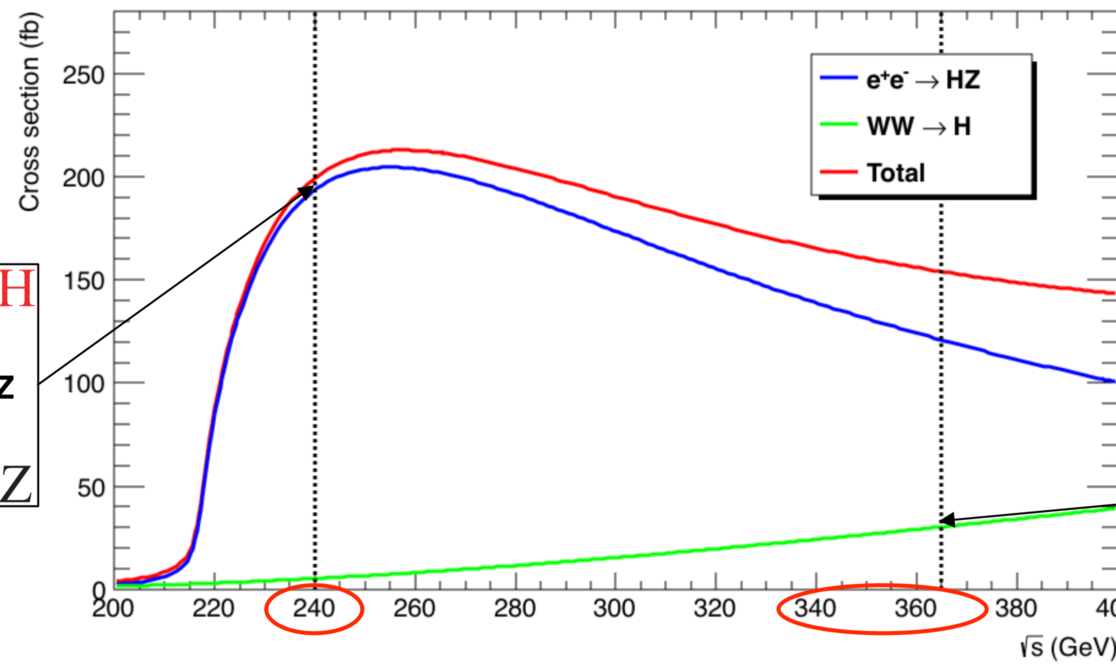


Fig. 4 Expected uncertainty contour for the S and T parameters for various colliders in their first energy stage. For ILC and CLIC, the projections are shown with and without dedicated running at the Z pole, with the current (somewhat arbitrary) estimate of future experimental and theoretical systematic uncertainty (left, from Ref. [36]); and with only statistical and parametric uncertainties (right, from Ref. [48])

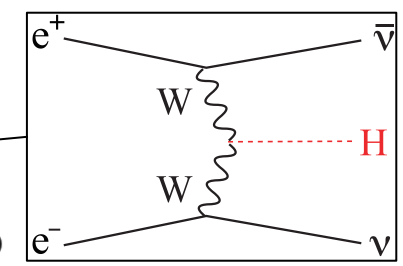
Higgs physics

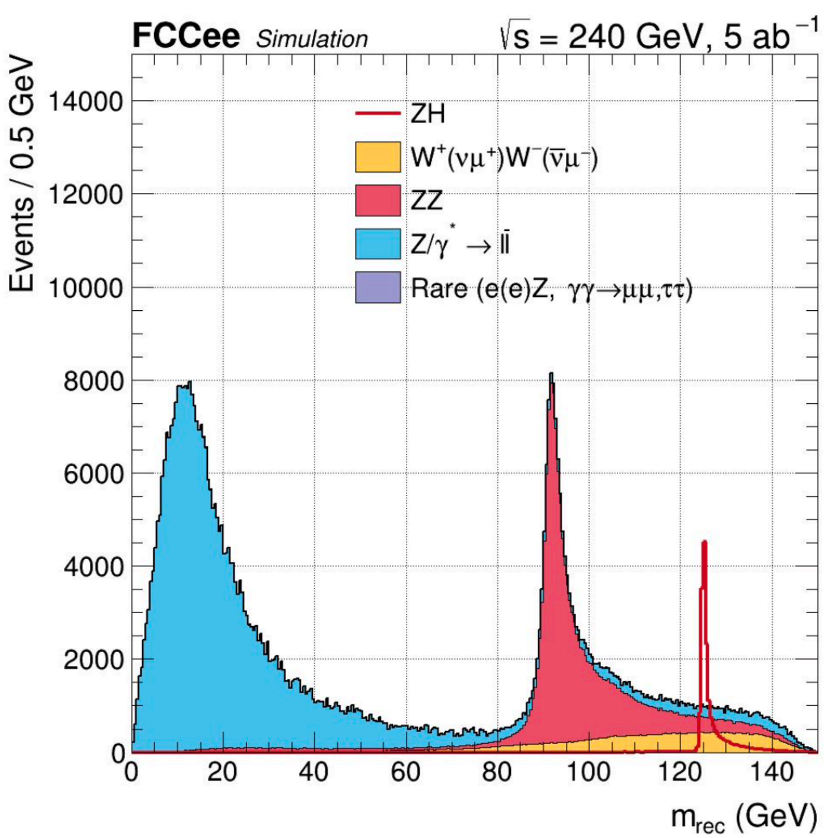




- maximum cross section √s = 250 GeV, luminosity decreases with √s: maximum event production at √s = 240 GeV
- Higgs mass from lepton missing mass

$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$





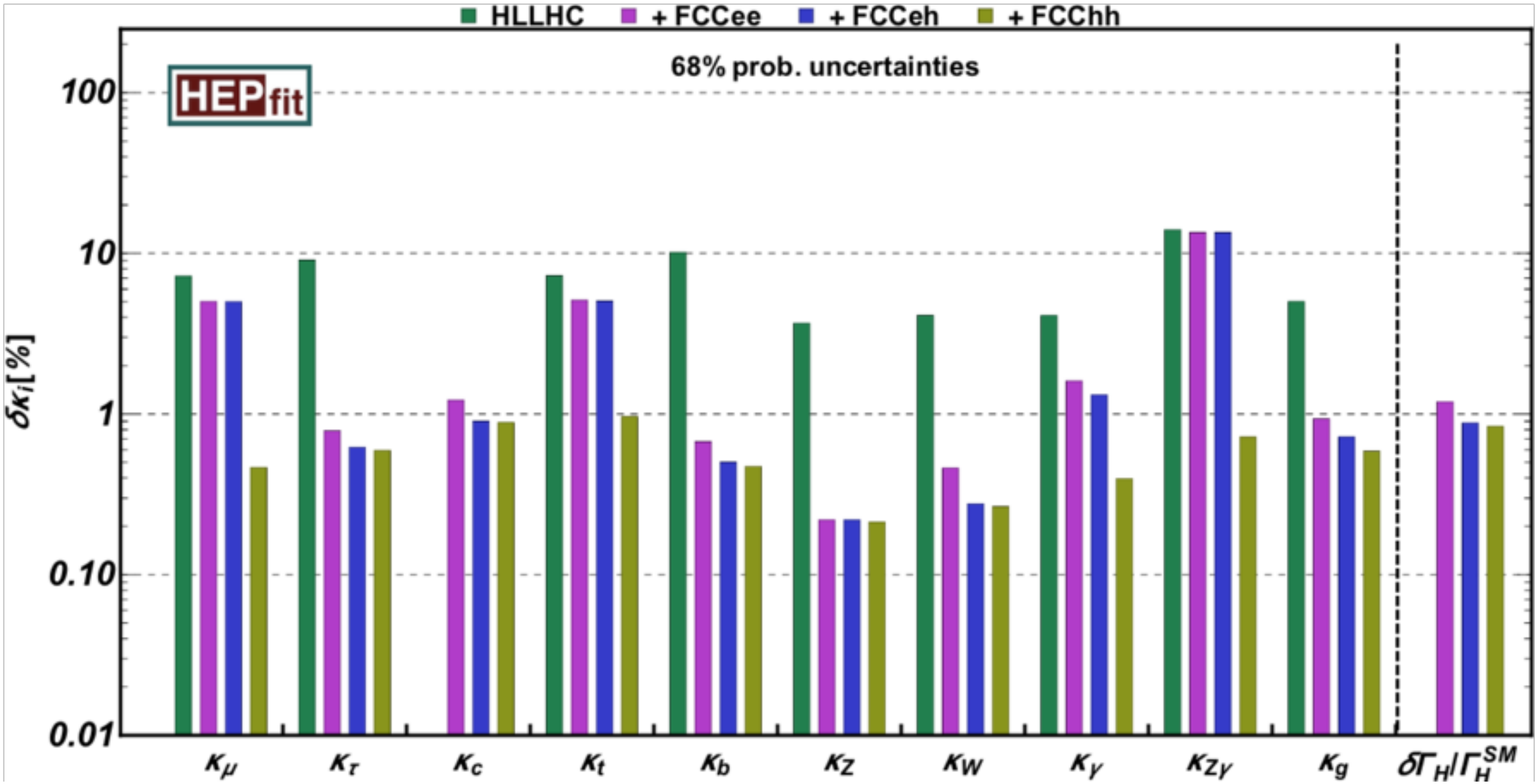
total cross section ~g_{HZZ}^2, g_{HZZ} ~ 0.2%

- ZH → ZZZ ~$g_{HZZ}^2 Br(H\rightarrow ZZ) = g_{HZZ}^4/\Gamma_H$, Γ_H ~ 2%
- ZH → ZXX ~$g_{HZZ}^2 Br(H\rightarrow XX) = g_{HZZ}^2 g_{HXX}^2/\Gamma_H$, g_{HXX} ~ 2%
- invisible decays (h → DM), unexpected decays (BSM9

adding e^+e^- → Hνν

- σ(Hνν,H→bb)/[σ(ZH,H→bb)σ(ZH,H→WW)] ~ Γ_H/g_{HZZ}^4, Γ_H ~ 1%
- σ(Hνν,H→WW)/[σ(ZH,H→bb)σ(ZH,H→WW) ~ g_{HWW}^4/Γ_H, g_{HWW} ~0.3%

Higgs boson couplings



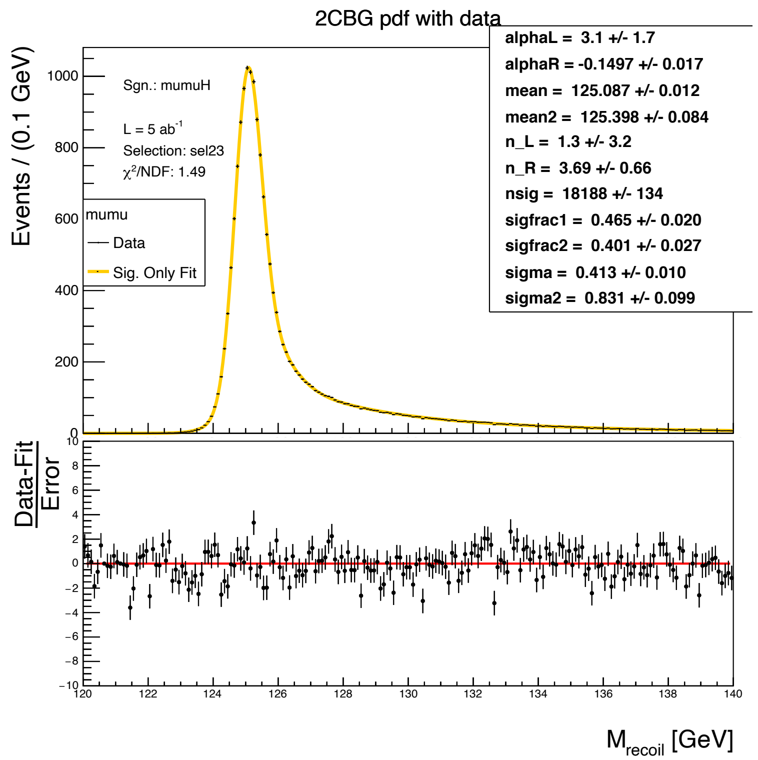
Higgs mass measurement

Higgs mass from the lepton recoil mass distribution

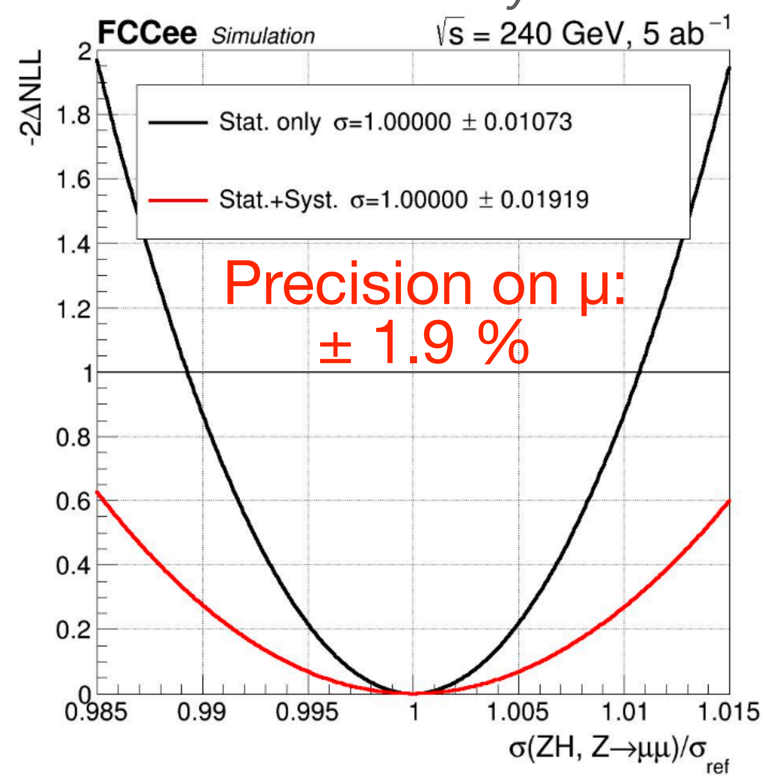
$$m_H^2 = s + m_Z^2 - 2\sqrt{s}(E_+ + E_-)$$

J. Eysermans - talk at the FCC week - June 2021

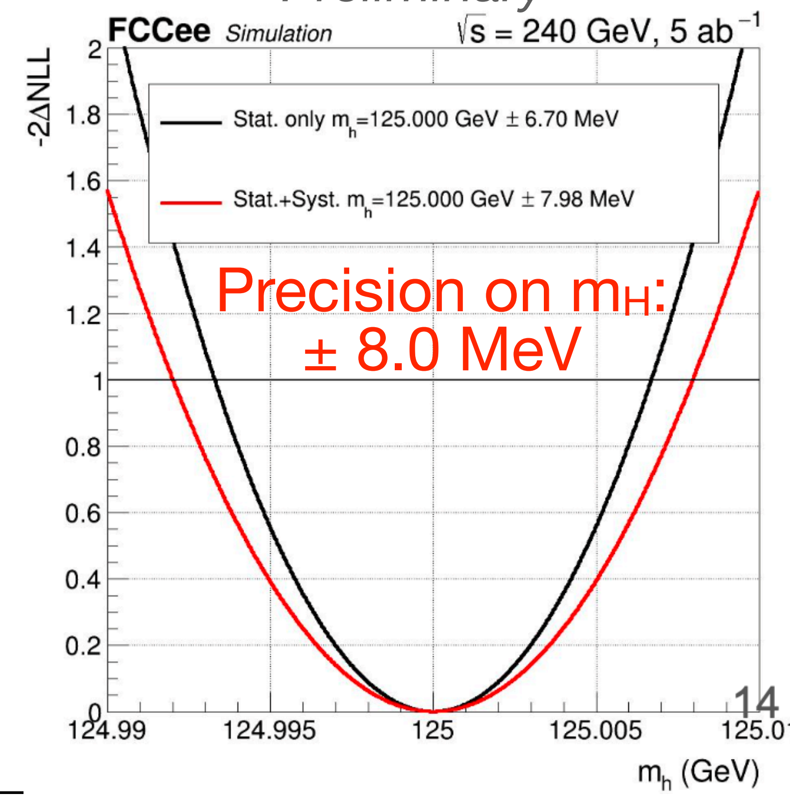
Preliminary



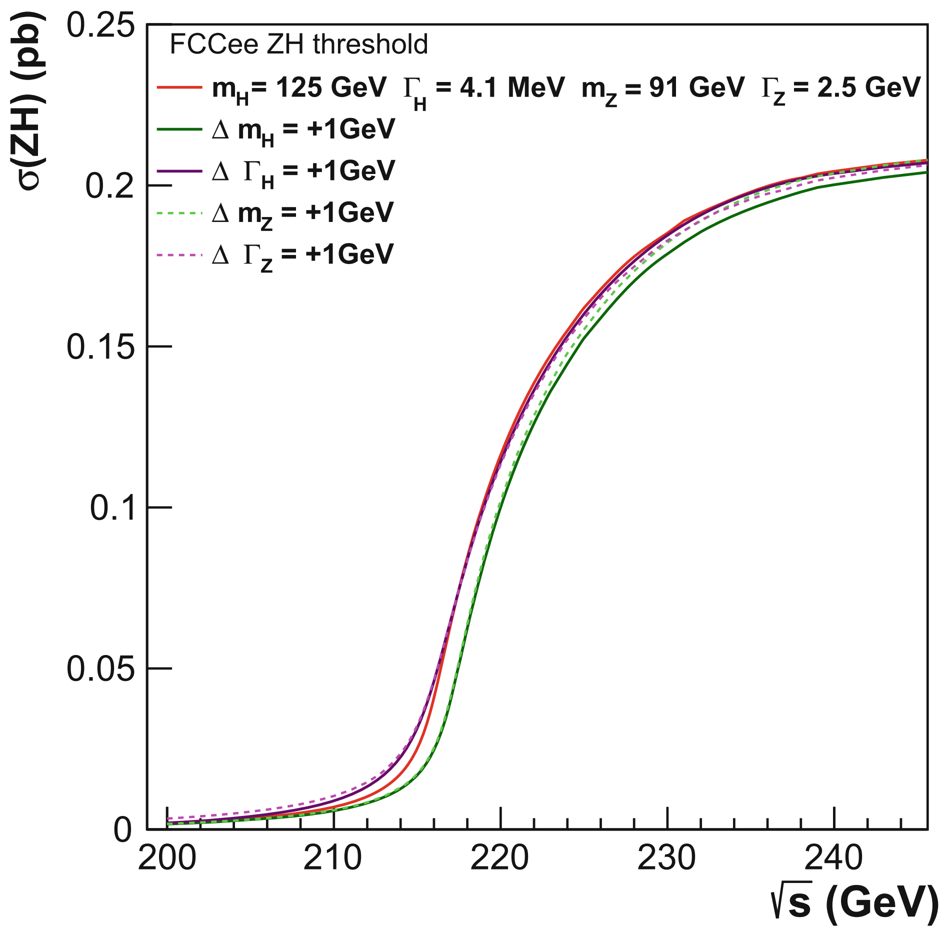
Preliminary



Preliminary



Higgs mass from ZH threshold scan



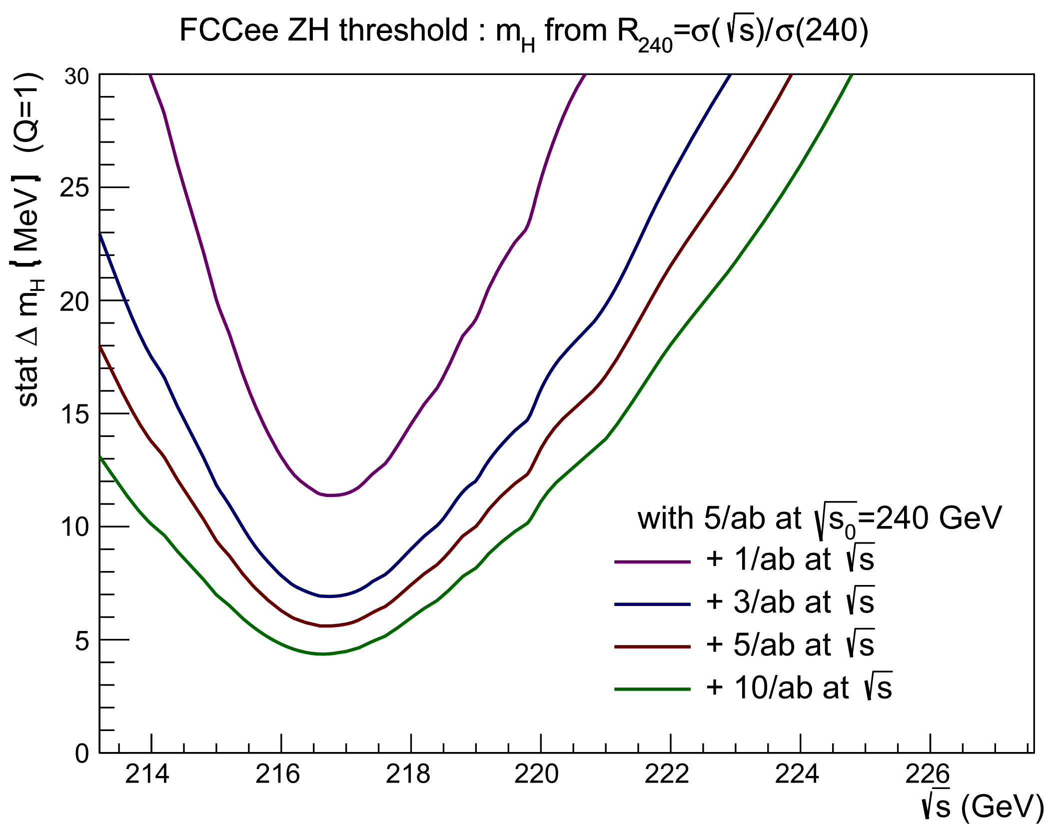


Fig. 6 Expected ideal statistical uncertainties on the Higgs boson mass from the threshold cross section ratio R (Eq. 4) assuming an integrated luminosity of 5 ab^{-1} at $\sqrt{s}$ = 240 GeV and different integrated luminosities accumulated at lower centre-of-mass energies around the ZH production threshold

Uncertainties on the Higgs mass of 6 MeV (stat.) can be obtained with 3 ab^{-1} at √s = 217 GeV

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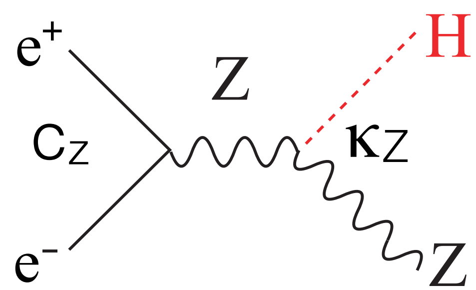
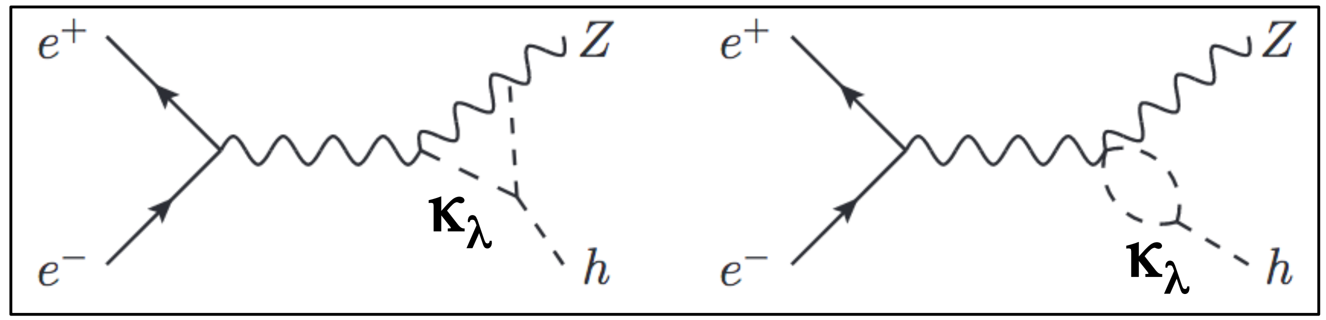
Higgs boson self-coupling determination

σ_{HZ}

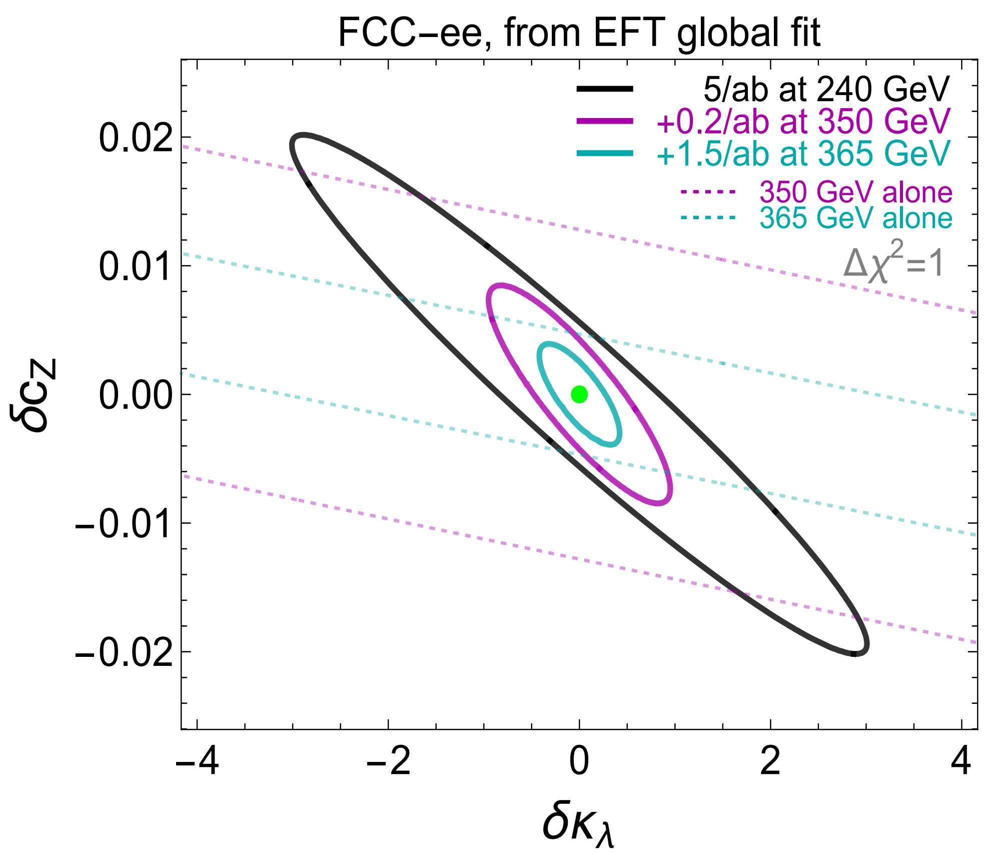


+

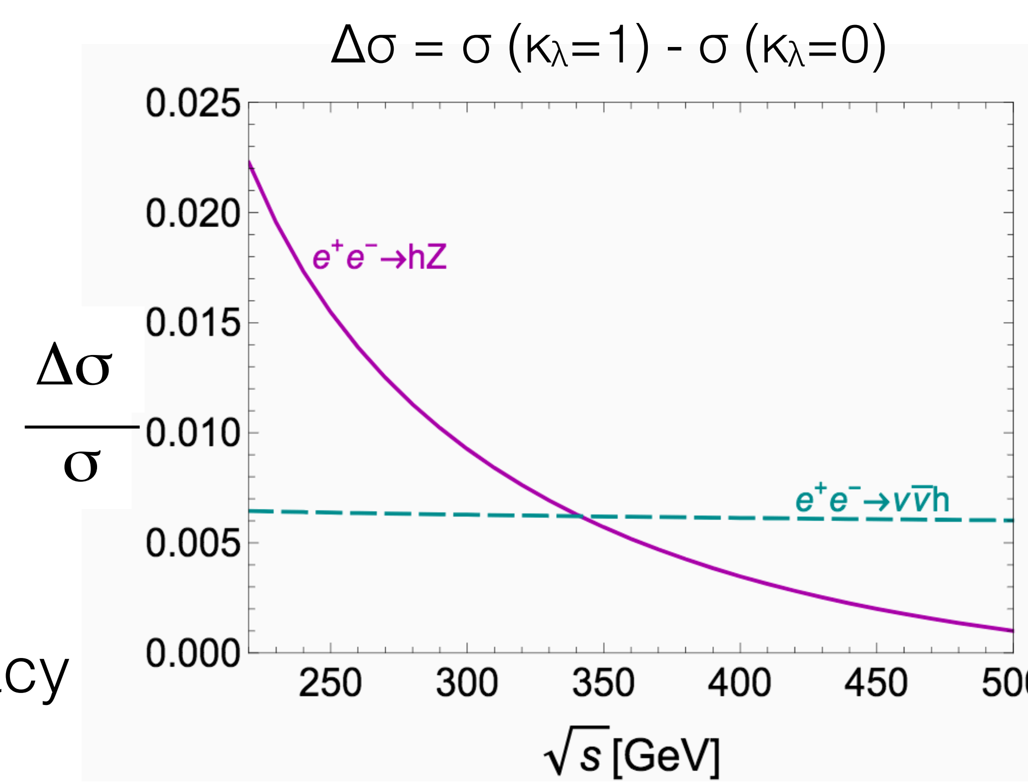


$\kappa = g/g_{\mathrm{SM}}$

M. McCullough
arXiv:1312.3322



- setting all other SM paramters to the SM, $\Delta\kappa_\lambda/\kappa_\lambda$ ~ 9%
- using a global EFT fit $\Delta\kappa_\lambda/\kappa_\lambda$ ~ 25% with 4 IP.



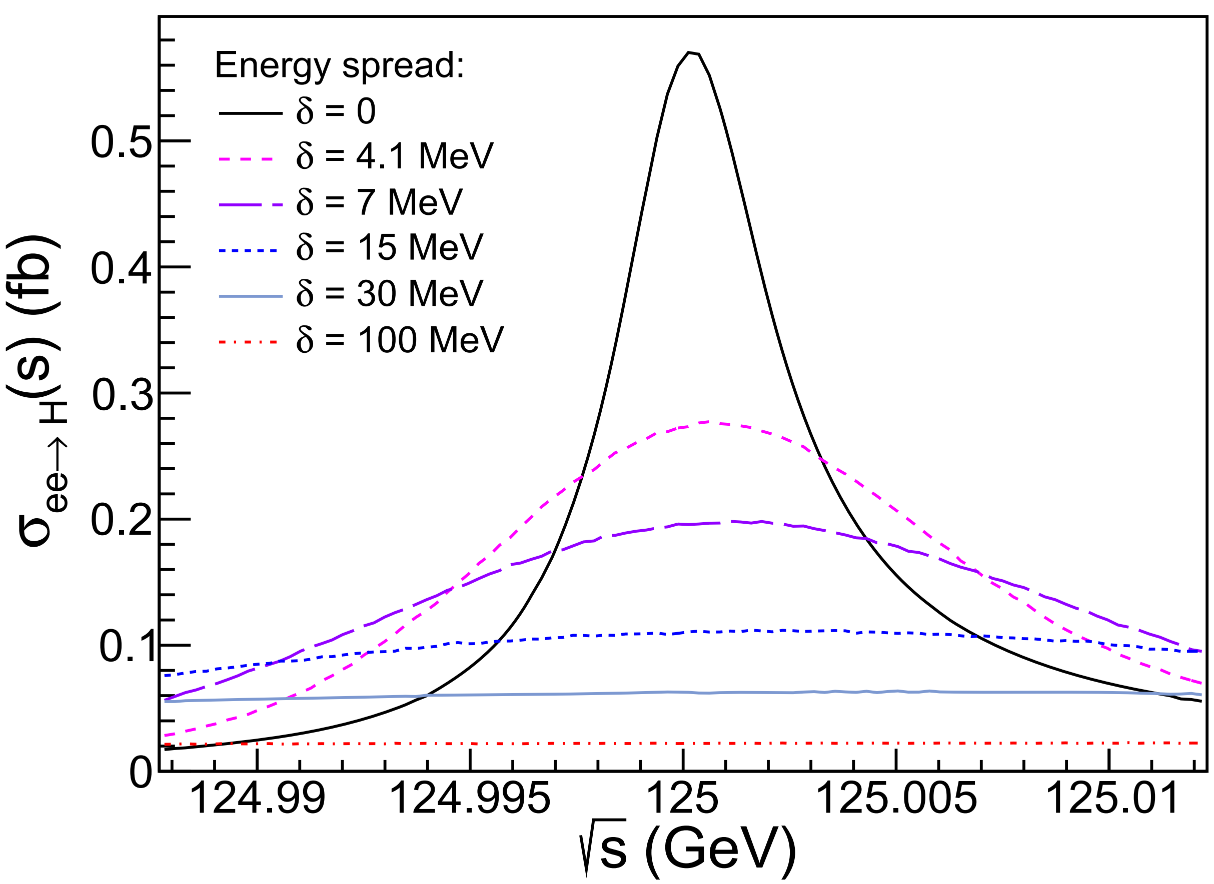
varying $\sqrt{s}$ removes partially cZ, κ_λ degeneracy

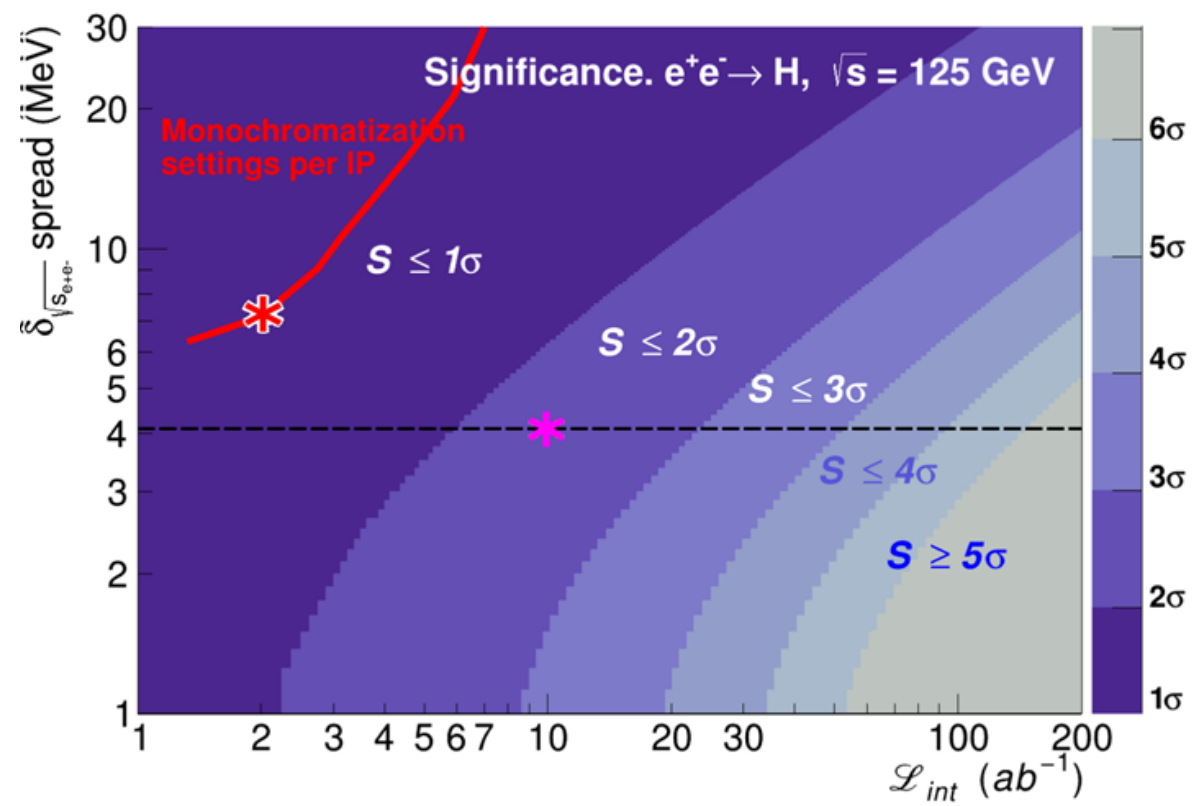
FUTURE CIRCULAR COLLIDER

Electron Yukawa coupling

- Electron Yukawa coupling can be measured using $e^+e^- \to H \to$ all, Γ_H = 4.1 MeV, knowledge of Higgs mass at MeV level is needed before starting the run;
- Event yield extremely low due to the low value of the electron coupling; $\sigma_{\mathrm{ee}\to\mathrm{H}} = 4\pi\mathcal{B}(\mathrm{H}\to\mathrm{e}^+\mathrm{e}^-)/m_\mathrm{H}^2 = 1.64$ fb
- the beam energy spread strongly affects the cross section peak value
- initial state radiation increases the line-shape width and reduces the peak value to 0.57 fb, the beam energy spread further reduces the xs value

Target Higgs decay	Final state definition	Signal presel. efficiency (%)
$\mathrm{H}\to b\bar{b}$	2 (excl.) jets, 1 b-tagged jet, no τ_{had}	80
$\mathrm{H}\to gg$	2 (excl.) gluon-tagged jets, 0 isolated $\ell^\pm$	50
$\mathrm{H}\to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$	Exactly 2 τ_{had}, 0 isolated $\ell^\pm$	65
$\mathrm{H}\to c\bar{c}$	2 (excl.) jets, 1 c-tagged jet, no τ_{had}	70
$\mathrm{H}\to \mathrm{WW}^*\to \ell\nu 2j$	1 isolated $\ell^\pm$, $E_{\mathrm{miss}} > 2$ GeV, 2 (excl.) jets	~100
$\mathrm{H}\to \mathrm{WW}^*\to 2\ell 2\nu$	2 isolated opp.-charge $\ell^\pm$, $E_{\mathrm{miss}} > 2$ GeV, 0 non-isol. $\ell^\pm$, 0 charged hadrons	~100
$\mathrm{H}\to \mathrm{WW}^*\to 4j$	4 (excl.) jets, $\geq$ 1 c-tag jets, 0 b-,g-tag jets; jets with $m_{j1j2}\approx m_\mathrm{W}$ not both c-tagged, 0 τ_{had}, 0 isolated $\ell^\pm$	70
$\mathrm{H}\to \mathrm{ZZ}^*\to 2j2\nu$	2 (excl.) jets, $E_{\mathrm{miss}} > 30$ GeV, 0 isolated $\ell^\pm$, 0 τ_{had}	~100
$\mathrm{H}\to \mathrm{ZZ}^*\to 2\ell 2j$	2 isolated opposite-charge $\ell^\pm$, 2 (excl.) jets, 0 τ_{had}	~100
$\mathrm{H}\to \mathrm{ZZ}^*\to 2\ell 2\nu$	2 isolated opp.-charge $\ell^\pm$, $E_{\mathrm{miss}} > 2$ GeV, 0 non-isol. $\ell^\pm$, 0 charged hadrons	~100
$\mathrm{H}\to \gamma\gamma$	2 (excl.) isolated photons	~100





BSM sensitivity

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$

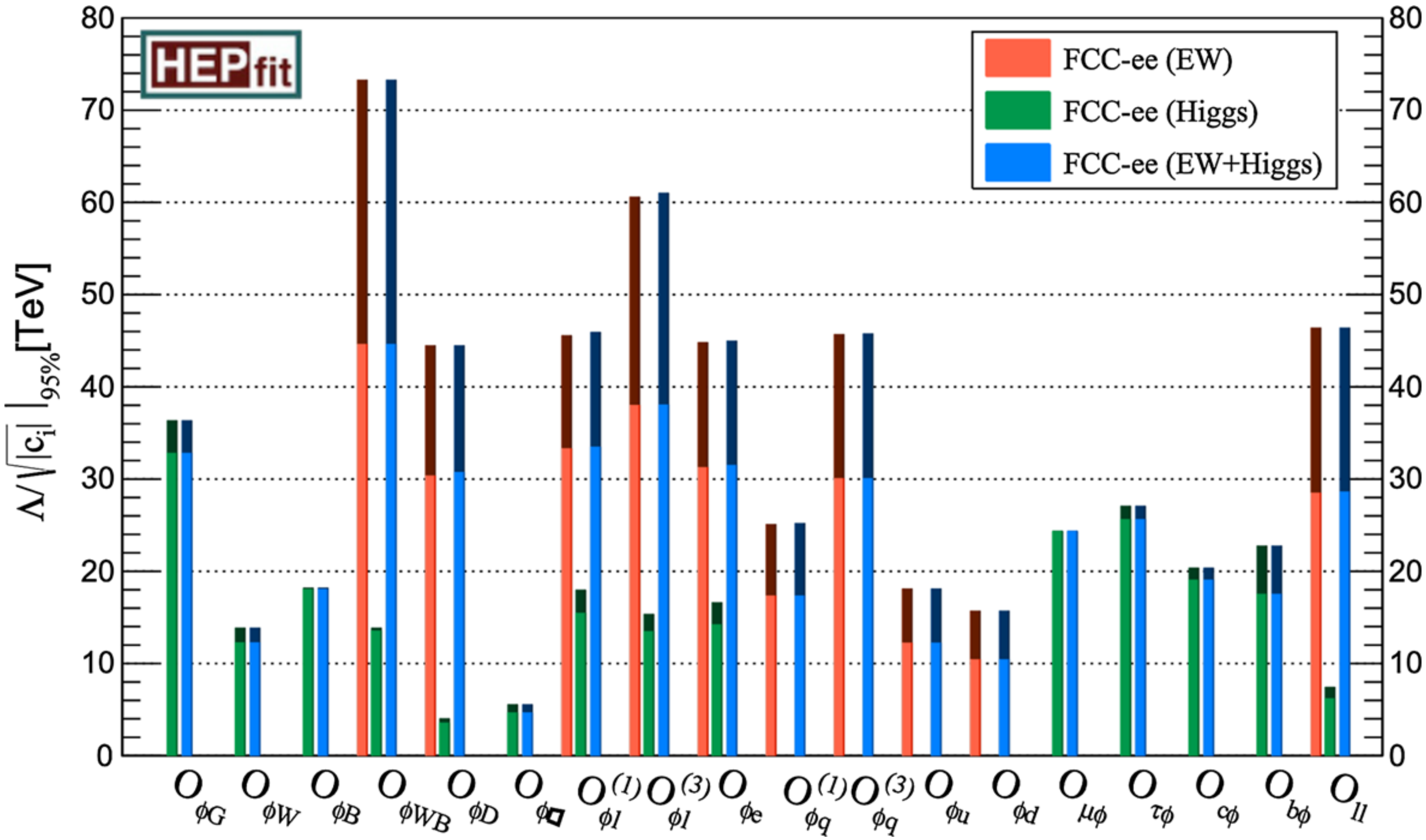


Fig. 5 Electroweak (red) and Higgs (green) constraints from FCC-ee, and their combination (blue) in a global EFT fit. The constraints are presented as the 95% probability bounds on the interaction scale, $\Lambda/\sqrt{c_i}$, associated to each EFT operator. Darker shades of each colour indicate the results when neglecting all SM theory uncertainties

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Flavour physics at FCC-ee

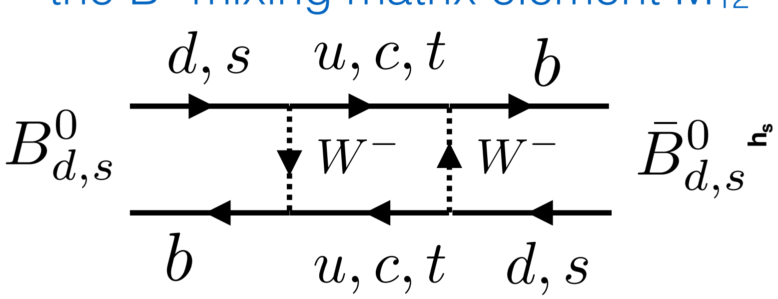
- FCC-ee is a Z^0 factories, a huge number of C, B mesons and τ mesons are produced through the decay of 10^{12} Z^0 bosons

- FCC-ee provides the richness and the statistics of hadronic final states of LHCb and the clean environment of e^+e^- colliders as Belle-2

Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

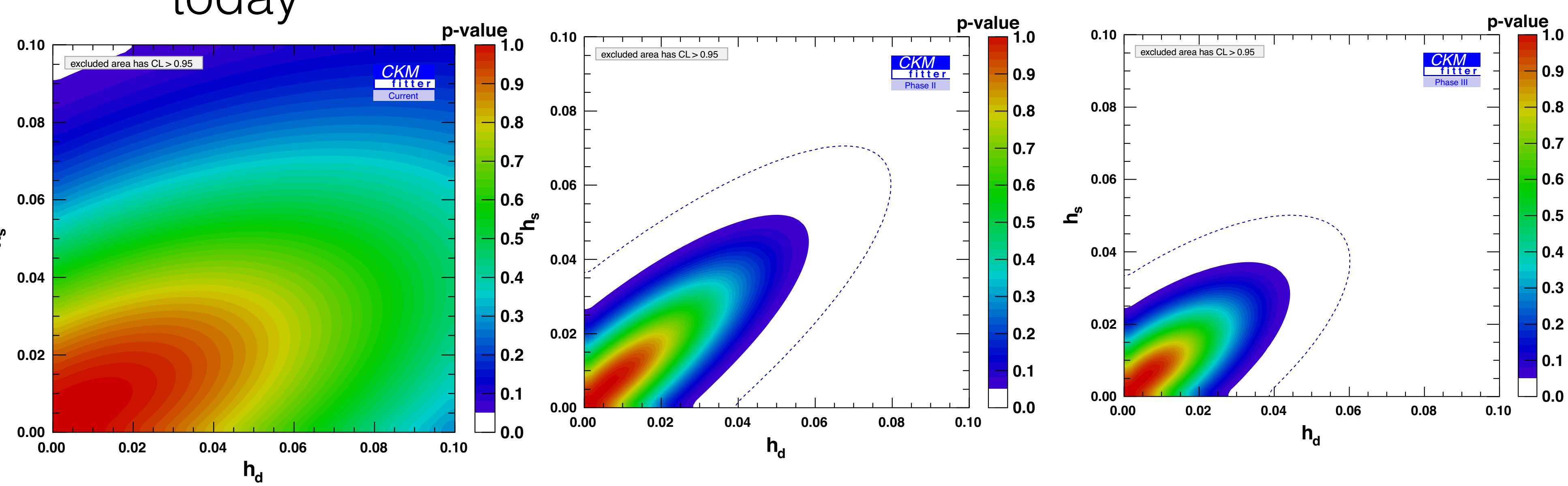
Particle species	B^0	B^+	B^0_s	Λ_b	B^+_c	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$)	310	310	75	65	1.5	600	170

- New physics can be parametrised as contribution to the B^0 mixing matrix element M_{12}



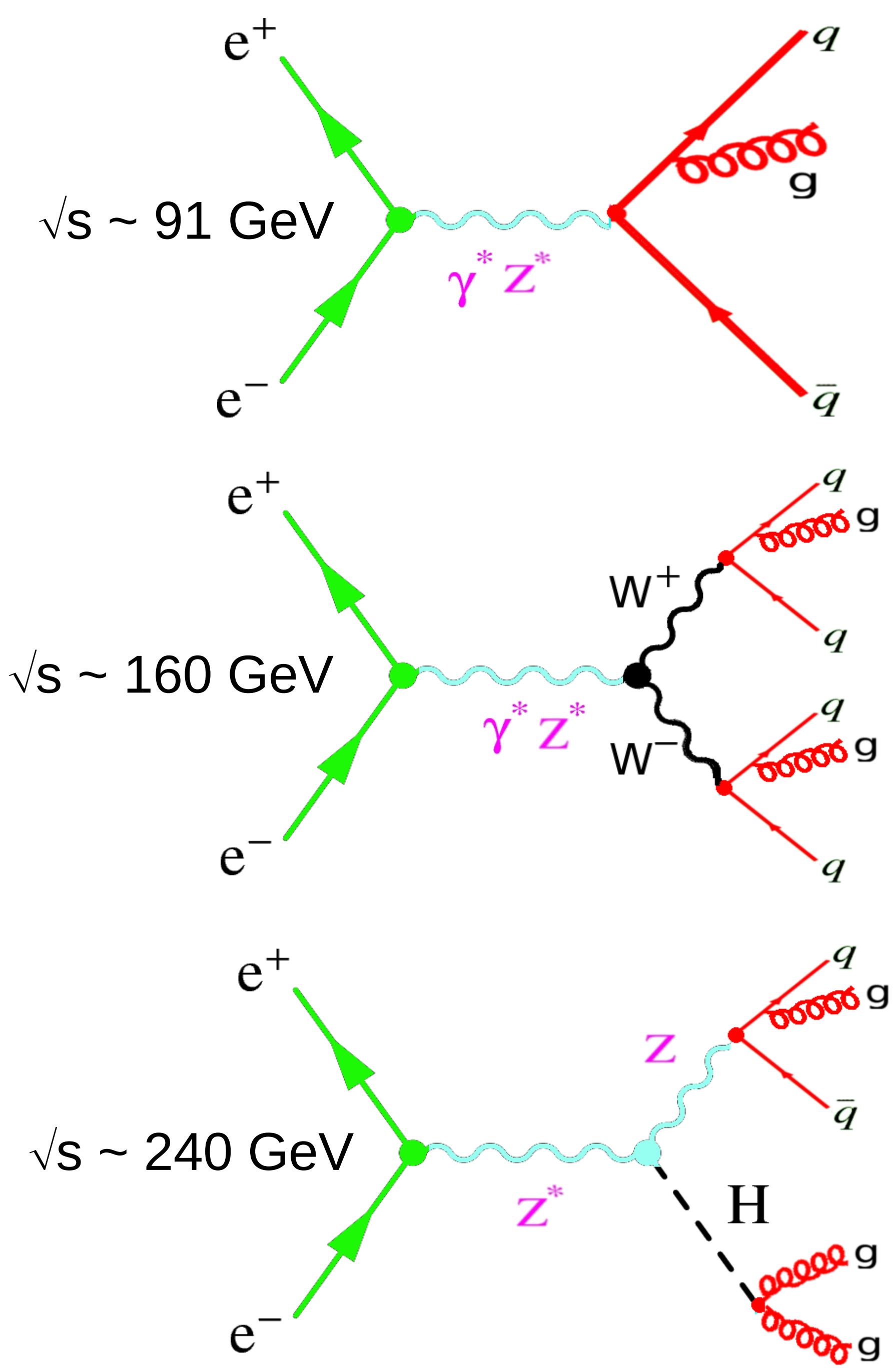
$$M_{12} = (M_{12})_{\rm SM} \times (1 + h e^{2i\sigma})$$

today | before FCC-ee | FCC-ee



QCD physics at e^+e^-

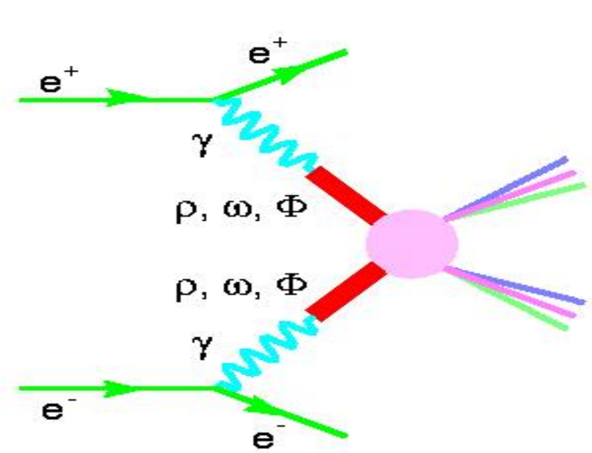
e^+e^- collisions provide a clean environment also for QCD measurements



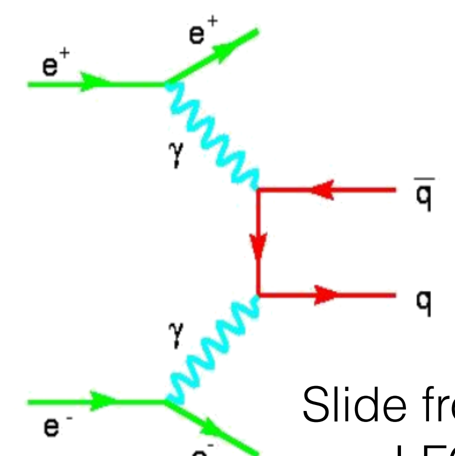
Advantages compared to p-p collisions:

- QED initial-state with known kinematics
- Controlled QCD radiation (only in final-state)
- Well-defined heavy-Q, quark, gluon jets
- Smaller non-pQCD uncertainties:
  no PDFs, no QCD "underlying event",…
  Direct clean parton fragmentation & hadroniz.

■ Plus QCD physics in $\gamma\gamma$ (EPA) collisions:



(soft, VDM)

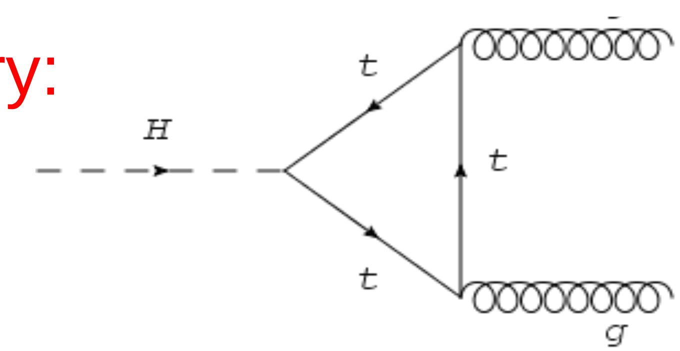


(direct)

Slide from D. d'Entreria
LFC '21 Trento

High precision gluon and jet studies

- Exploit FCC-ee H(gg) as a "pure gluon" factory: H→gg (BR~8% accurately known) provides O(100.000) extra-clean digluon events.

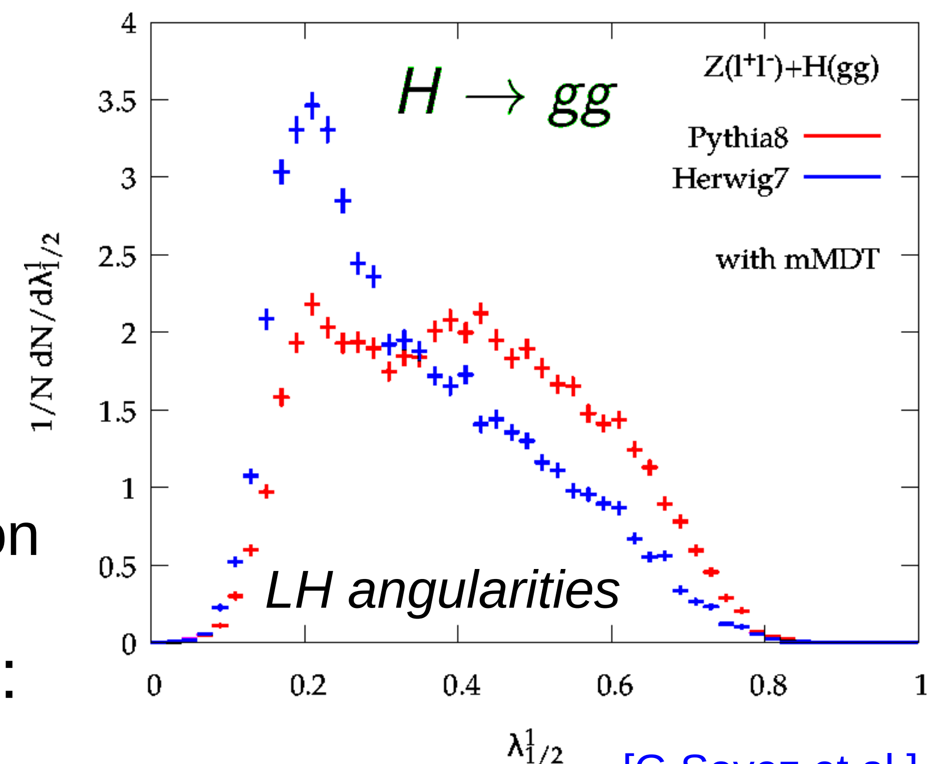


jet substructure

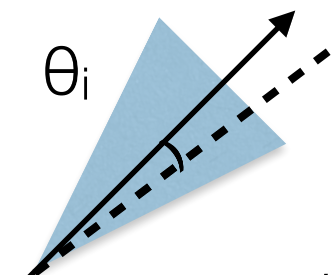
$$\lambda_\beta^\kappa = \sum_{i \in \mathrm{jet}} z_i^\kappa \theta_i^\beta ,$$

(normalized $E^n \times \theta^n$ products)

- Multiple handles to study gluon radiation & g-jet properties:
  - Gluon vs. quark via H→gg vs. Z→qq (Profit from excellent g,b separation)
  - Gluon vs. quark via Z→bbg vs. Z→qq(g) (g in one hemisphere recoiling against 2-b-jets in the other).
  - Vary E_{jet} range via ISR: $e^+e^- \to Z^*,\gamma^* \to jj(\gamma)$
  - Vary jet radius: small-R down to calo resolution



[G.Soyez et al.]



$Z_i = E_i/E_{jet}$

- Multiple high-precision analyses at hand:
  - BSM: Improve q/g/Q discrimination tools
  - pQCD: Check N^nLO antenna functions. High-precision QCD coupling.
  - non-pQCD: Gluon fragmentation: Octet neutralization? (zero-charge gluon jet with rap gaps). Colour reconnection? Glueballs ? Leading η's,baryons?

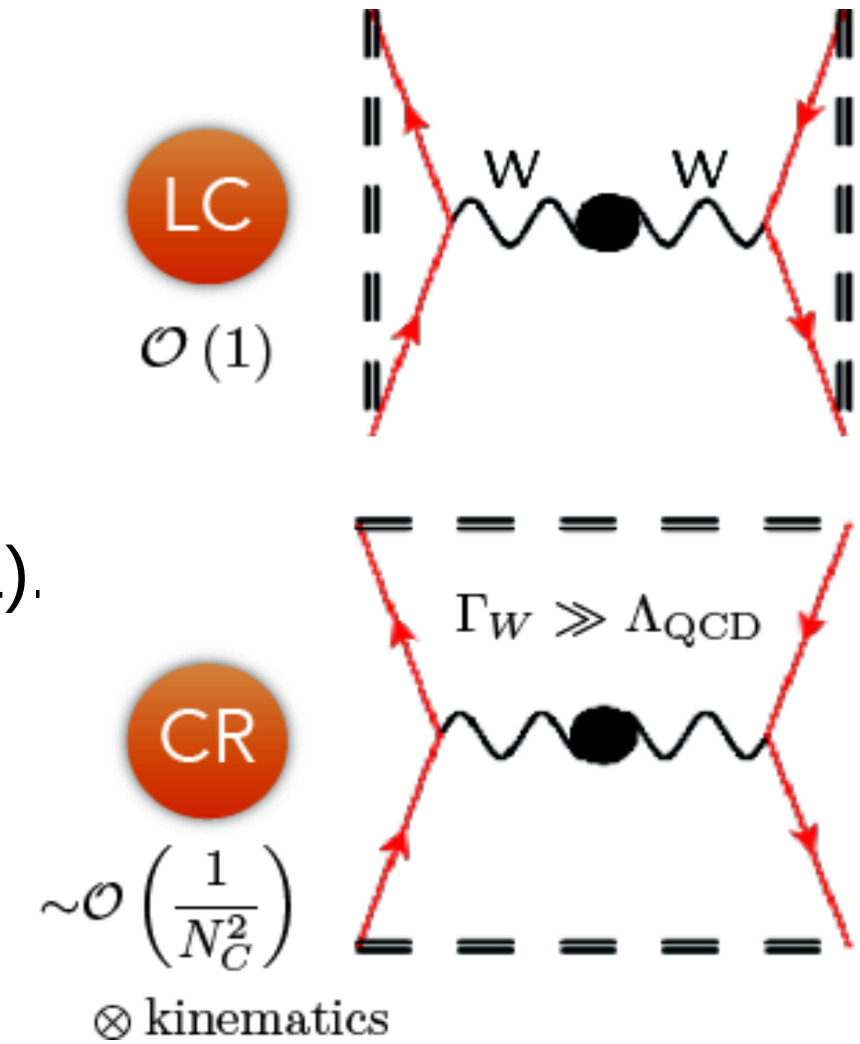
Slide from D. d'Entreria
LFC '21 Trento

Color reconnection

- Colour reconnection among partons is source of uncertainty in m_W, m_{top}, aGC extractions in multijet final-states. Especially in pp (MPI cross-talk).

  - CR impacts all FCC-ee multi-jet final-states (potentially shifted angular correlations):
    – $e^+e^- \to$ WW(4j), Z(4j), ttbar,
    – H(2j,4j) CP studies,…
    – String-drag effect on W mass
    (Hinted at LEP: No-CR excluded at 99% CL).

  - Exploit huge W stats ($\times 10^4$ LEP) to “turn the m_W measurement around”: Determine m_W leptonically and constrain CR in hadronic WW: Colour reconnection controlled to <1%



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Conclusions

- FCC-ee has a rich and striking physics goal
- improving accuracy of EWK measurement by factors 10-100
- constraints Higgs potential related parameters m_H, m_t, m_W, κ_λ
- providing the best measurement of the Higgs boson potential (check validity of the Higgs boson as inflation field, probe the vacuum instabilities, probe the nature of the Higgs boson)
- if you think that a 27 km muon collider could be a valuable option after HL-LHC, think what could be a 100 km muon collider if a working muon cooling mechanism will be available at the end of the FCC-ee running

FUTURE CIRCULAR COLLIDER

Higgs boson couplings

Table 2 Precision on the Higgs boson couplings from Ref. [37], in the κ framework without (first numbers) and with (second numbers) HL-LHC projections, for the FCC-ee and the complete FCC integrated programme (including both the FCC-hh and the FCC-ep option) [38]

Collider	HL-LHC	$\text{FCC-ee}_{240\rightarrow 365}$	FCC-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
$g_{H\tau\tau}$ (%)	1.9	0.74/0.66	0.49/0.46
$g_{H\mu\mu}$ (%)	4.4	8.9/3.9	0.43/0.43
$g_{H\gamma\gamma}$ (%)	1.8	3.9/1.2	0.32/0.32
$g_{HZ\gamma}$ (%)	11	–/10	0.71/0.7
g_{Htt} (%)	3.4	10./3.1	1.0/0.95
g_{HHH} (%)	50	44/33	3–4
		27/24	
Γ_H (%)	SM	1.1	0.91
BR_{inv} (%)	1.9	0.19	0.024
BR_{EXO} (%)	SM (0.0)	1.1	1