Introduction: EW precision as a probe to scenarios of new physics

Brief introduction to the section devoted to EW interactions

Fulvio Piccinini

INFN, Sezione di Pavia

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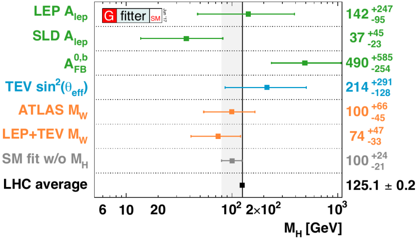
- All particles and interactions of the (minimal) SM discovered
  $\Longrightarrow$ every observable can be computed
- electroweak interactions tested at $\sim$0.1% level at LEP/SLC
- Higgs signal rates at the LHC in agreement with SM within $\sim$10%
- hadron colliders provide important electroweak measurements
  - M_W
  - $\sin^2\vartheta^l_{eff}$
  - self-interactions in the gauge sector
- all these data can be used to check the internal SM consistency/signal hints of BSM effects

overall good agreement with EWPO

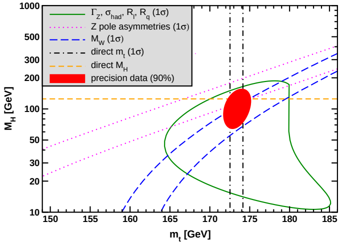
	Measurement	Posterior	Prediction	Pull
$\alpha_s(M_Z)$	0.1180 ± 0.0010	0.1180 ± 0.0009	0.1184 ± 0.0028	-0.1
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.02750 ± 0.00033	0.02743 ± 0.00025	0.02734 ± 0.00037	0.3
M_Z [GeV]	91.1875 ± 0.0021	91.1880 ± 0.0021	91.198 ± 0.010	-1.0
m_t [GeV]	$173.1 \pm 0.6 \pm 0.5$	173.43 ± 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

Looking in more detail at subsets of observables

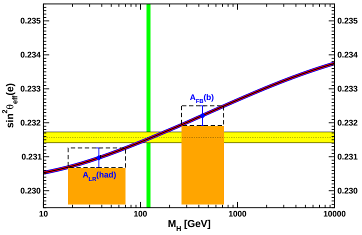


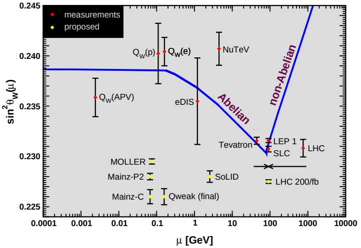
T. Pfeiffer, EPS2017



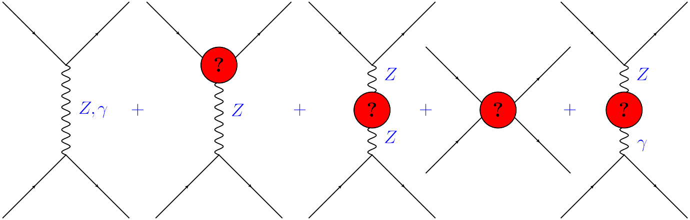
J. Erler, A. Freitas, PDG2017

- small tensions between different observables, the largest one in the asymmetry sector $\Longrightarrow \sin^2\vartheta^l_{eff}$



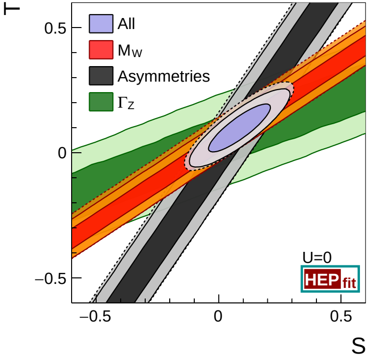


J. Erler, arXiv:1710.06503

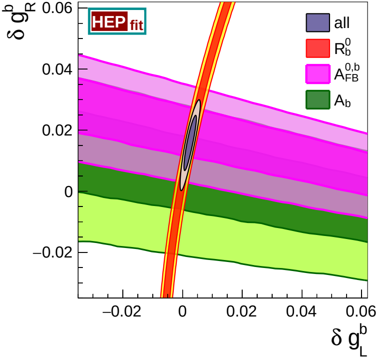


parameterizing possible New Physics

- oblique corrections with S, T U parameters
- $Zb\bar{b}$ couplings with $\delta g^b_{L/R}$



J. De Blas et al., arXiv:1710.05402

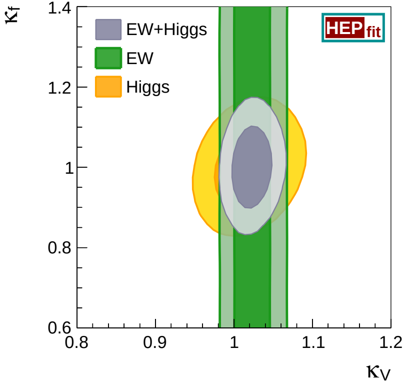


J. De Blas et al., arXiv:1611.05354

- dashed limits: excluding last Tevatron/LHC measurements of m_t, M_W and $\sin^2\vartheta^l_{eff}$

with an EFT approach for the Higgs sector

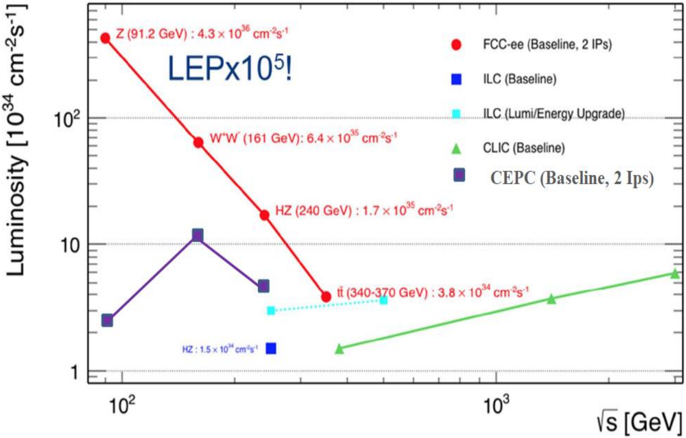
$$\mathcal{L}_{eff} = \frac{v^2}{4} \mathrm{tr} \left(D_\mu \Sigma^\dagger D^\mu \Sigma \right) \left(1 + 2\mathcal{K}_V \frac{H}{v} + \ldots \right) - m_i \bar{f}_L^i \left(1 + 2\mathcal{K}_f \frac{H}{v} + \ldots \right) f_R^i + \ldots$$



J. De Blas et al., arXiv:1710.05402

- on $\mathcal{K}_V$ EW precision data still dominate over LHC data

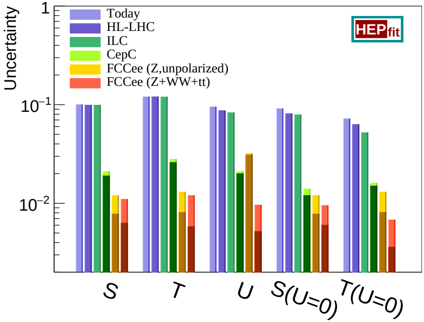
Future e^+e^- machine projects

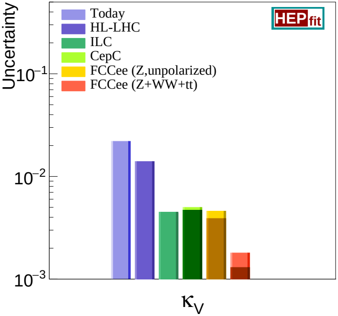


by talk of A. Blondel at Mini workshop on Precision Calculations for FCC, 12/01/2018

- $\sqrt{s} \simeq M_Z$ and $\sqrt{s} \simeq WW$ threshold already investigated at LEP luminosities lower by several orders of magnitude ($\sim 10^{31}$ cm^{-2}s^{-1})
- HZ and $t\bar{t}$ thresholds never investigated at a leptonic collider

Which gain with EWPO





J. De Blas et al., arXiv:1611.05354

- light shaded colours consider the effect of theoretical uncertainties
- for very high lumi runs, **reduction of th. uncertainty crucial**

Th. uncertainties: main systematics at future colliders

- intrinsic uncertainties (unknown higher orders)
- parametric uncertainties (input parameters: G_μ, $\alpha(M_Z)$, $\alpha_s(M_Z)$, M_Z, M_H, m_t)

- classes of processes/observables which need high precision radiative corrections (one or two orders of magnitude w.r.t. present knowledge!)

$\Longrightarrow$ talk by J. Gluza

  - reference process(es) for luminosity (Bhabha scattering/$\gamma\gamma$)
  - $e^+e^- \to f\bar{f}$ (σ and A_{FB})

$\Longrightarrow$ talk by S. Jadach

  - $e^+e^- \to V^{(*)}V^{(*)} \to (4\,\mathrm{fermions})$

$\Longrightarrow$ talk by M. Skrzypek

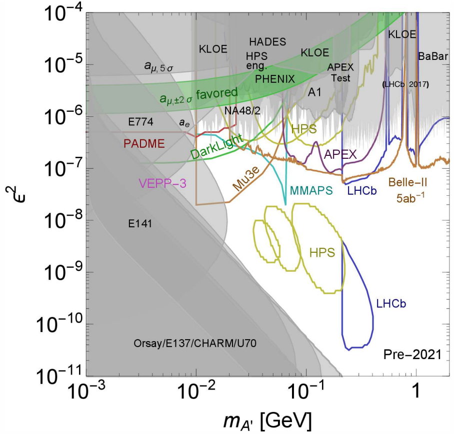
  - $e^+e^- \to Z^{(*)}H \to (4\,\mathrm{fermions})$
  - $e^+e^- \to t^{(*)}\bar{t}^{(*)} \to (6\,\mathrm{fermions})$
  - Z partial decay widths
  - H partial decay widths

Which kind of NP? E.g. light dark-photon/scalars

- vector mixing $\sim \epsilon_Y F^Y_{\mu\nu} F'^{\mu\nu}$

talk by Schuster at PBC Workshop, CERN 2017

- scalar mixing $\sim \epsilon_h |h|^2 |\phi|^2$



arXiv:1707.04591

- for dark-photon reach at FCC-ee $\Longrightarrow$ talk by B. Mele in Exotica session

- If NP threshold above electroweak scale, a complete and model independent tool to study departures from the SM is given by **SMEFT**

$$\mathcal{L} = \mathcal{L}^{(4)}_{SM} + \frac{1}{\Lambda^2}\sum_k c_k^{(6)} Q_k^{(6)} + \frac{1}{\Lambda^4}\sum_k c_k^{(6)} Q_k^{(8)} + \dots$$

- usually analysis performed at the leading dimension 6 order
- by fitting projected data we get constraints on the scale probed (actually $\Lambda/\sqrt{c_i}$) by the various operators
- the over-optimistic way is to fit one operator at a time
  - but every particular model switches on more operators for each observable $\Longrightarrow$ **correlations among Wilson coefficients**
- a conservative estimate of the correlated sensitivity is obtained by fitting all c_i at the same time
- vast literature on EFT applications to collider data; in the following one recent example

A recent analysis as an example

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

- observables
  - cross sections
    - $e^+e^- \to ZH$
    - $e^+e^- \to \nu_e \bar{\nu}_e H$
    - $e^+e^- \to ZH$
    - $e^+e^- \to W^+W^-$
  - angular observables in $e^+e^- \to HZ(\to \ell^+\ell^-)$
  - EWPO at the Z peak
    - N_ν
    - A_b
    - R_b, R_μ, R_τ
    - $\sin^2 \vartheta^l_{eff}$
    - Γ_Z
    - M_W
- operators

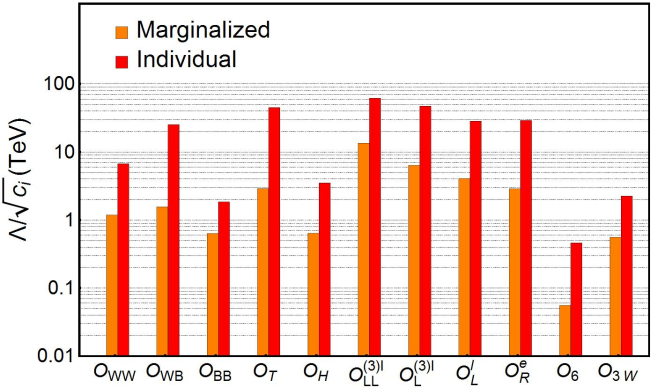
$\mathcal{O}_{WW} = g^2 \|H\|^2 W^a_{\mu\nu} W^{a,\mu\nu}$	$\mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2$	$\mathcal{O}^{(3)l}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}_{WB} = g g' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_H = \frac{1}{2}(\partial_\mu \|H\|^2)^2$	$\mathcal{O}^{(3)l}_{LL} = (\bar{L}_L \gamma_\mu \sigma^a L_L)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}_{BB} = g'^2 \|H\|^2 B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_6 = \lambda \|H^\dagger H\|^3$	$\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}_{3W} = g \frac{\varepsilon_{abc}}{3!} W^{a\nu}_\mu W^{b\rho}_\nu W^{a\mu}_\rho$		$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}_R \gamma^\mu l_R)$

Assumed luminosities and exp/th errors on observables

Observables	ILC		FCC-ee		CEPC	
$\sigma(Zh)$	2.0% [22]	250GeV,2ab^{-1}	0.5% [31]	240GeV,5ab^{-1}	0.5% [6]	240GeV,5ab^{-1}
	4.2% [22]	500GeV,4ab^{-1}	-	-	-	-
$\sigma(\nu\bar{\nu}h)$	3.89% [5]	250GeV,2ab^{-1}	0.97% [19]	350GeV,1.5ab^{-1}	2.86% [19]	240GeV,5ab^{-1}
	1.45% [5]	500GeV,4ab^{-1}	-	-	-	-
$\sigma(Zhh)$	15.0% [5]	500GeV,4ab^{-1}	-	-	-	-
$\sigma(W^+W^-)$	0.0200%[36]	250GeV,2ab^{-1}	0.0136% [36]	240GeV,5ab^{-1}	0.0136% [36]	240GeV,5ab^{-1}
	0.0191% [36]	500GeV,4ab^{-1}	-	-	-	-
N_ν	0.0013 [4]	Z lineshape,100fb^{-1}	1.58×10^{-3} [31]	Z pole,150ab^{-1}	0.0018 [19]	240 GeV, 100fb^{-1}
A^b_{FB}	-	-	-	-	$(\pm 15 \pm 2_{\rm in}) \times 10^{-4}$ [6]	Z pole, 150fb^{-1}
A^μ_{FB}	-	-	7.1×10^{-4} [31, 37]	Z pole,150ab^{-1}	-	-
A_b	0.001 [4]	Z pole,100fb^{-1}	-	-	-	-
R_b	6.5×10^{-4} [4]	Z pole,100fb^{-1}	3.6×10^{-4} [31, 37]	Z pole,150ab^{-1}	8×10^{-4} [6]	Z pole, 100fb^{-1}
R_μ	2×10^{-4} [32]	Z pole,100fb^{-1}	6.1×10^{-5} [31, 37]	Z pole,150ab^{-1}	5×10^{-4} [6]	Z pole, 100fb^{-1}
R_τ	2×10^{-4} [32]	Z pole,100fb^{-1}	6.1×10^{-5} [31, 37]	Z pole,150ab^{-1}	5×10^{-4} [6]	Z pole, 100fb^{-1}
Γ_Z(MeV)	$\pm 1 \pm 0.21_{\rm in}$ [4, 35]	Z pole,100fb^{-1}	$\pm 0.1 \pm 0.08_{\rm th} \pm 0.065_{\rm in}$ [35, 37]	Z pole,150ab^{-1}	$\pm 0.1 \pm 0.08_{\rm th} \pm 0.13_{\rm in}$ [6, 35]	Z pole, 150fb^{-1}
$\sin^2\theta^{\rm lep}_{\rm eff}(10^{-5})$	$\pm 1.3 \pm 1.5_{\rm th} \pm 2.2_{\rm in}$ [4, 35]	Z pole,100fb^{-1}	$\pm 0.3 \pm 1.5_{\rm th} \pm 1.6_{\rm in}$ [35, 37]	Z pole,150ab^{-1}	$\pm 2.3 \pm 1.5_{\rm th} \pm 2.5_{\rm in}$ [6, 35]	Z pole, 150fb^{-1}
m_W (MeV)	$\pm 2.5 \pm 1_{\rm th} \pm 2.8_{\rm in}$ [35, 38]	250GeV, 2ab^{-1}	$\pm 1.2 \pm 1_{\rm th} \pm 0.91_{\rm in}$ [31, 35]	WW threshold,10ab^{-1}	$\pm 3 \pm 1_{\rm th} \pm 3.8_{\rm in}$ [6, 35]	240GeV,5ab^{-1}
$\mathcal{A}_{\theta_1}$	0.0083 [29]	250GeV,2ab^{-1}	0.0060 [29]	240GeV,5ab^{-1}	0.0060 [29]	240GeV,5ab^{-1}
$\mathcal{A}_{c\theta_1,c\theta_2}$	0.0092 [29]	250GeV,2ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}
$\mathcal{A}^{(3)}_\phi$	0.0092 [29]	250GeV,2ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}
$\mathcal{A}^{(4)}_\phi$	0.0092 [29]	250GeV,2ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}	0.0067 [29]	240GeV,5ab^{-1}

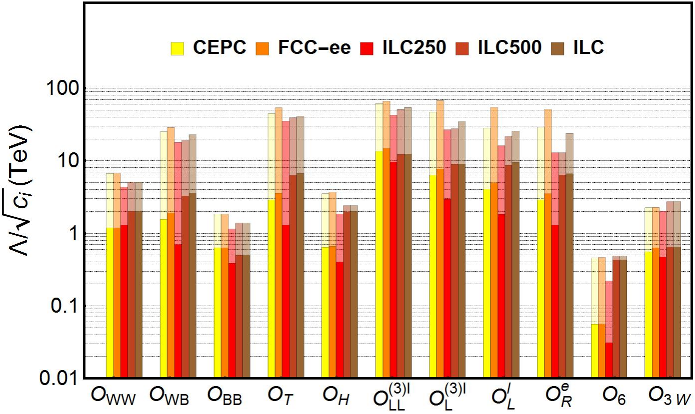
W.H. Chiu et al., arXiv:1711.04046

Sensitivity projections



- analysis available for CEPC
- **Very important redoing the study for FCC-ee**

Comparison on sensitivities for different colliders



- light colours: individual operator contributing
- Large impact of correlations in decreasing the sensitivity. This could be partially removed by adding other exp. data
- **to be checked with more realistic parameters for FCC-ee**

Role of the EWPD: the case of M_W

- in the scheme of switching on one operator at a time
- consider $\sigma(Zh)$

S.-F. Ge, H.-J. He, R.-Q. Xiao, arXiv:1603.03385

- and then add the observable M_W with an error of 3 MeV

$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{LL}^{(3)}$	$\mathcal{O}_L^{(3)}$	$\mathcal{O}_L$	$\mathcal{O}_R$
2.48	2.01	4.83	0.89	1.86	2.09	0.567	5.38	11.6	10.2	8.78
2.48	10.6	4.83	0.89	5.16	2.09	0.567	8.22	12.1	10.2	8.78
2.48	10.6	4.83	0.875	5.12	2.09	0.567	8.15	12.1	10.2	8.78

- large jump in the 95% exclusion limit
- $\Longrightarrow$ best attainable exp. precision for M_W is relevant to probe higher scales

$\Longrightarrow$ talk by P. Azzurri

Adding (one after the other) additional EWPO

Observables	Relative Error
N_ν	1.8×10^{-3}
$A_{FB}(b)$	1.5×10^{-3}
R_b	8×10^{-4}
R_μ	5×10^{-4}
R_τ	5×10^{-4}
$\sin^2 \theta_W$	1×10^{-4}

- $\sigma(Zh)$ at plus EWPO
- in the scheme of switching on one operator at a time
- from projected precision for M_Z (0.5-1) MeV and M_W (3-5) MeV
- and then the observables of the above Table

S.-F. Ge, H.-J. He, R.-Q. Xiao, arXiv:1603.03385

$\mathcal{O}_H$	$\mathcal{O}_T$	$\mathcal{O}_{WW}$	$\mathcal{O}_{BB}$	$\mathcal{O}_{WB}$	$\mathcal{O}_{HW}$	$\mathcal{O}_{HB}$	$\mathcal{O}_{LL}^{(3)}$	$\mathcal{O}_{L}^{(3)}$	$\mathcal{O}_L$	$\mathcal{O}_R$	$\mathcal{O}_{L,q}^{(3)}$	$\mathcal{O}_{L,q}$	$\mathcal{O}_{R,u}$	$\mathcal{O}_{R,d}$	$\mathcal{O}_g$
2.74	23.7	6.38	5.78	11.6	2.16	0.604	17.4	18.1	10.2	8.78	2.06	0.568	0.393	0.339	43.8
2.74	23.7	6.38	5.78	11.6	2.16	0.604	17.5	18.3	10.5	8.78	2.06	0.568	0.393	0.339	43.8
2.74	24.0	8.32	5.80	12.2	2.16	0.604	20.7	23.0	12.5	13.0	2.23	1.62	0.393	3.97	43.8
2.74	24.0	8.33	5.80	12.2	2.16	0.604	20.7	23.0	12.5	13.0	7.90	7.89	3.55	4.05	43.8
2.74	24.0	8.54	5.80	12.2	2.16	0.604	20.7	23.4	14.4	14.0	8.63	8.62	4.88	4.71	43.8
2.74	24.0	8.75	5.81	12.3	2.16	0.604	20.7	23.7	15.8	14.9	9.21	9.21	5.59	5.17	43.8
2.74	26.3	12.6	5.93	15.3	2.16	0.604	30.2	35.2	19.8	21.6	9.21	9.21	5.59	5.17	43.8

- **great benefit from all EWPO at the Z peak**
- study available for CEPC; FCC-ee reach foreseen even better!