

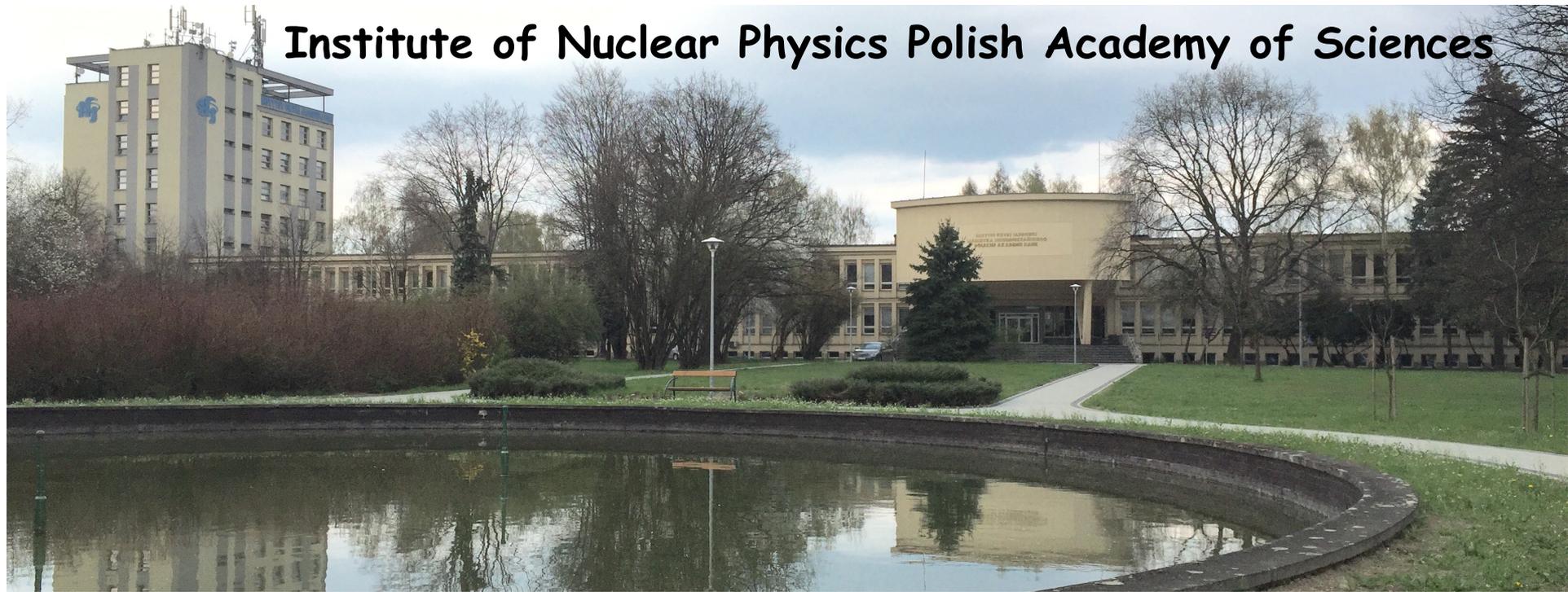
EWPOs: Looking backward and forward



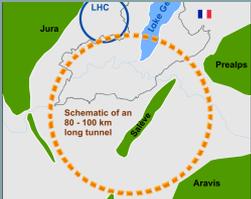
Stanisław Jadach

In collaboration with J. Gluza and A. Freitas and feedback from T. Riemann

Institute of Nuclear Physics Polish Academy of Sciences



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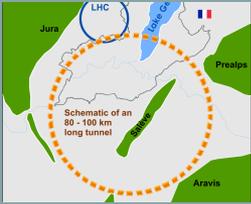


Outline



1. EWPOs at LEP
2. More on precision QED at FCCee
3. EWPOs (EWPPs) at FCC-ee

New scheme of EWPO's better suited for the FCCee high precision was outlined in chapter C.3 in [arXiv:1809.01830](https://arxiv.org/abs/1809.01830).



EWPOs at LEP



Electroweak pseudo-observables, EWPOs, were instrumental at LEP in:

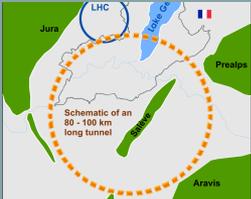
- combining data from four LEP collaboration and SLD experiments and
- organising conveniently the procedure of fitting the Standard Model to experimental data.

The effects of QED in data, even if large, are in principle perfectly calculable with arbitrary precision (QED “deconvolution”).

Once removed, the remaining EWPOs include smaller non-QED pure electroweak corrections and possibly signals of a New Physics beyond the SM.

The EWPOs used in the final ADLO analysis [arXiv:hep-ex/0509008](https://arxiv.org/abs/hep-ex/0509008) of LEP1 data near Z resonance were defined and thoroughly tested in the fundamental paper [arXiv:hep-ph/9902452](https://arxiv.org/abs/hep-ph/9902452) by Bardin, Grunewald and Passarino.

Some solutions/procedures advocated in the following are already present in some form in [arXiv:hep-ph/9902452](https://arxiv.org/abs/hep-ph/9902452)



Example of LEP1 EWPOs from [arXiv:hep-ex/0509008](https://arxiv.org/abs/hep-ex/0509008) ADLO 2005



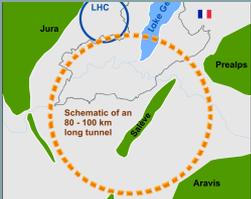
Correlation matrix

$\chi^2/\text{dof} = 155/194$		OPAL								
m_Z [GeV]	91.1858 ± 0.0030	1.000								
Γ_Z [GeV]	2.4948 ± 0.0041	0.049	1.000							
σ_{had}^0 [nb]	41.501 ± 0.055	0.031	-0.352	1.000						
R_e^0	20.901 ± 0.084	0.108	0.011	0.155	1.000					
R_μ^0	20.811 ± 0.058	0.001	0.020	0.222	0.093	1.000				
R_τ^0	20.832 ± 0.091	0.001	0.013	0.137	0.039	0.051	1.000			
$A_{\text{FB}}^{0,e}$	0.0089 ± 0.0045	-0.053	-0.005	0.011	-0.222	-0.001	0.005	1.000		
$A_{\text{FB}}^{0,\mu}$	0.0159 ± 0.0023	0.077	-0.002	0.011	0.031	0.018	0.004	-0.012	1.000	
$A_{\text{FB}}^{0,\tau}$	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

QED uncertainties in EW observables LEP and FCCee

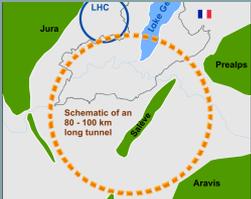


EWPOs are by construction “model independent” representation of data, but small residual dependence on QED remains and is added to *exper. error*, except of luminosity where it dominates. The table below shows this QED error in EWPOs at LEP and at FCCee. (From IFJPAN-IV-2018-2 to appear).

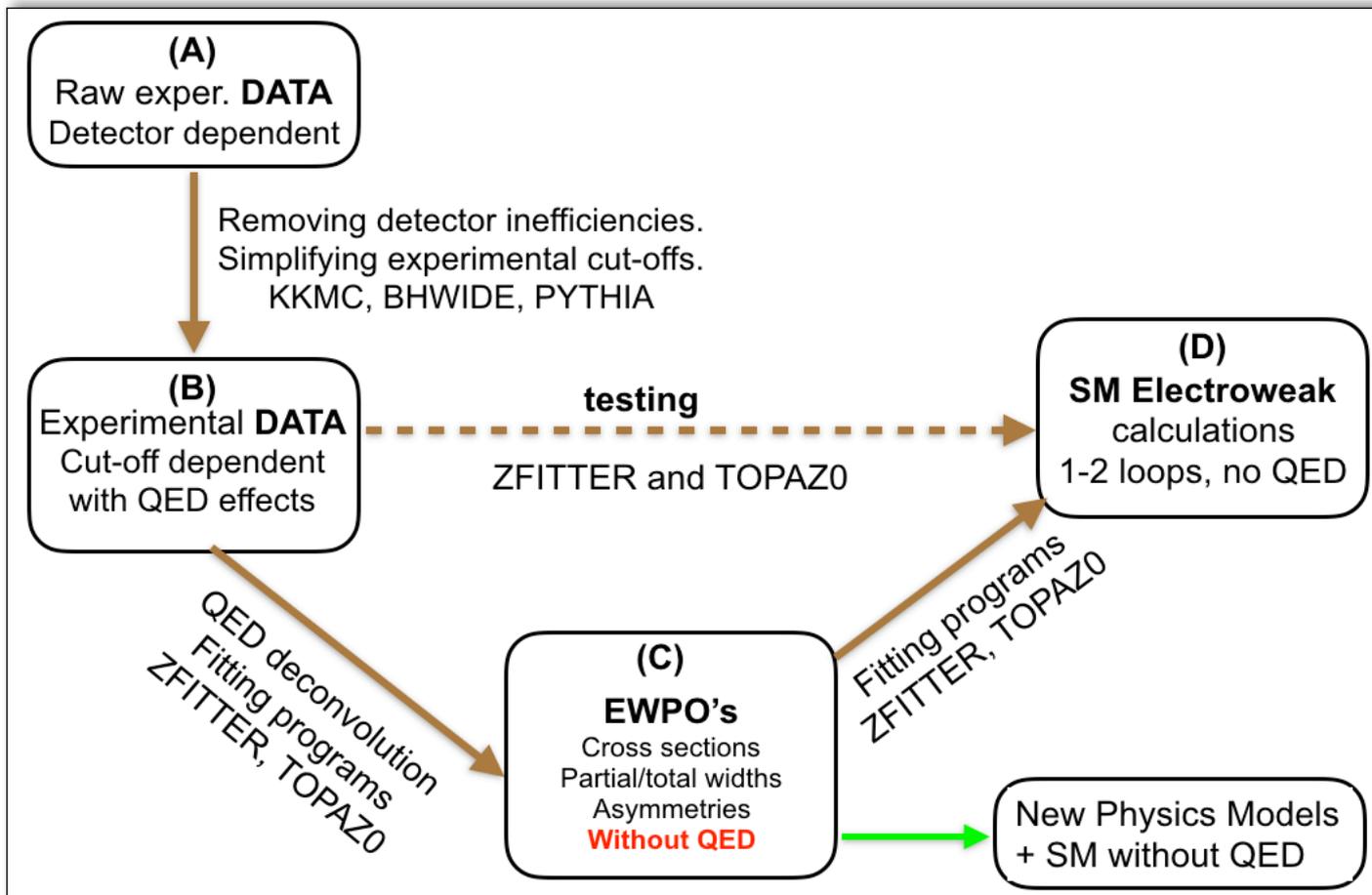
Observable	Where from	Present	FCCee stat.	FCCee syst	$\frac{\text{Now}}{\text{FCCee}}$
M_Z [MeV]	Z linesh. [2]	$91187.5 \pm 2.1\{0.3\}$	0.005	0.1	3
Γ_Z [MeV]	Z linesh. [2]	$2495.2 \pm 2.1\{0.2\}$	0.008	0.1	2
$R_l^Z = \Gamma_h/\Gamma_l$	$\sigma(M_Z)$ [3]	$20.767 \pm 0.025\{0.012\}$	$6 \cdot 10^{-5}$	$1 \cdot 10^{-3}$	12
σ_{had}^0	σ_{had}^0 [2]	$41.541 \pm 0.037\{25\}$ nb	$0.1 \cdot 10^{-3}$	$4.0 \cdot 10^{-3}$	6
N_ν	$\sigma(M_Z)$ [2]	$2.984 \pm 0.008\{0.006\}$	$5 \cdot 10^{-6}$	$1 \cdot 10^{-3}$	6
N_ν	$Z\gamma$ [4]	$2.69 \pm 0.15\{0.06\}$	$0.8 \cdot 10^{-3}$	$< 10^{-3}$	60
$\sin^2 \theta_W^{\text{eff}}$	$A_{FB}^{\text{lept.}}$ [3]	$0.23099 \pm 0.00053\{06\}$	$3 \cdot 10^{-6}$	$5 \cdot 10^{-6}$	10
$\sin^2 \theta_W^{\text{eff}}$	$A_{\text{pol.}}^\tau$ [2,3]	$0.23159 \pm 0.00041\{12\}$	$0.6 \cdot 10^{-5}$	$< 10^{-5}$	20
M_W [MeV]	ADLO [5]	$80376 \pm 33\{7\}$	0.6	0.3	12
$A_{FB,\mu}^{M_Z \pm 3.5\text{GeV}}$	$\frac{d\sigma}{d\cos\theta}$ [2]	$\pm 0.020\{0.001\}$	$1.0 \cdot 10^{-5}$	$0.3 \cdot 10^{-5}$	100

extreme case

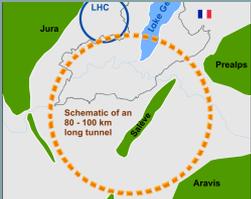
Table 1: Table of present experimental precision of electroweak observables, which are most sensitive to QED effects. The numbers in the braces {...} in the 3-rd column are component of the systematic error components due to QED calculation uncertainty. The necessary improvement factor of QED calculations for FCCee experiments is shown in the last column. FCCee systematic is without QED component.



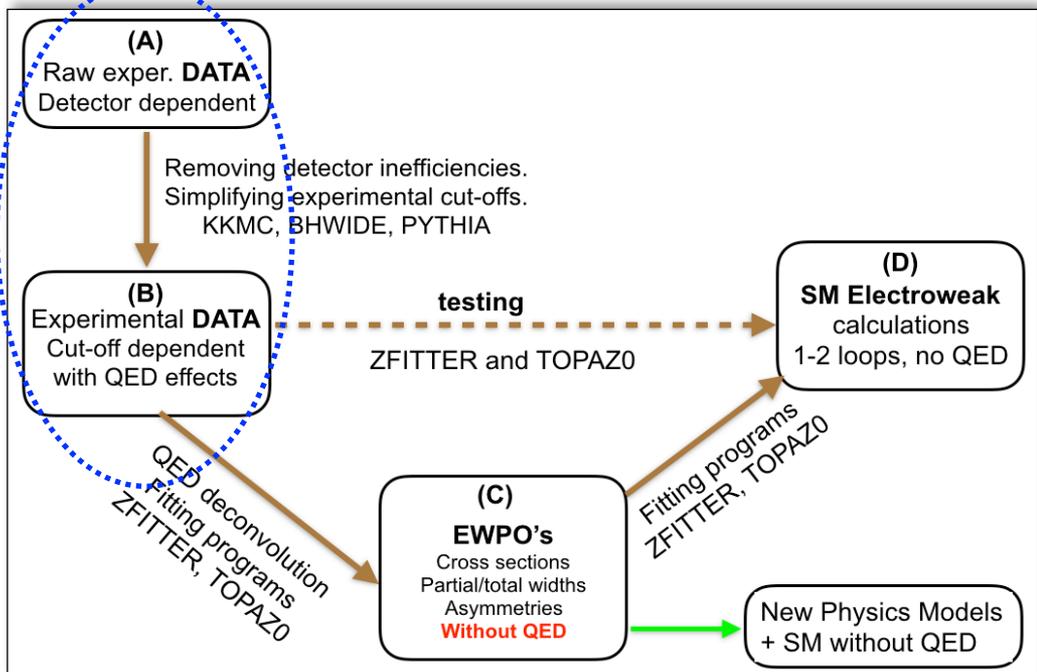
Electroweak Pseudo-Observables, EWPO's, at LEP - the meeting point between data and theory



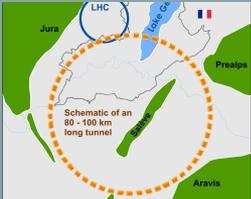
- EWPO's are in the center of the ADLO+SLD scheme in analysing/fiting LEP1 data as implemented in [arXiv:hep-ex/0509008](https://arxiv.org/abs/hep-ex/0509008)



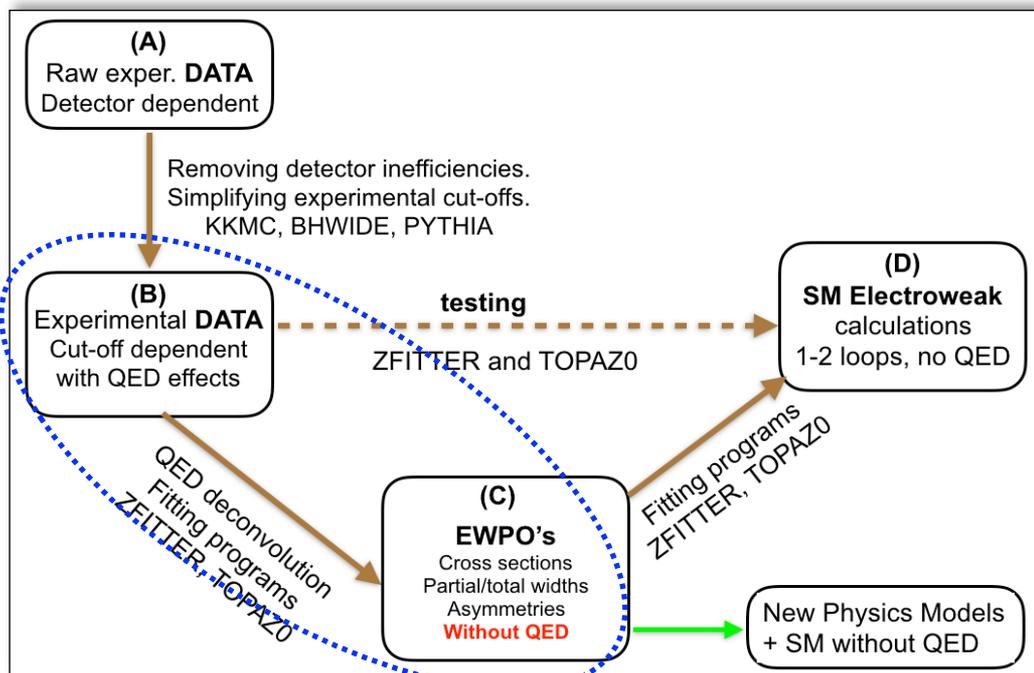
Electroweak Pseudo-Observables, EWPO's, at LEP



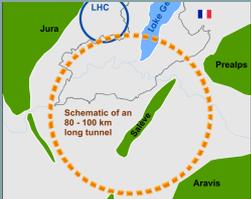
1. In the first step, from (A) to (B) raw data are corrected for inefficiencies of the detector and kinematic cut-offs were rounded up to a simpler shape, which could be dealt with non-MC “fitter” programs ZFITTER and TOPAZ0.
2. The transition (A) to (B) was done with sophisticated Monte Carlo event generators like KORALZ, KKMC, BHWIDE, PYTHIA etc.
3. Data at stage (B) were obtained separately for each LEP collaboration.
(For the same type of experimental cuts the values of the cut-off parameters could be different among experiments)



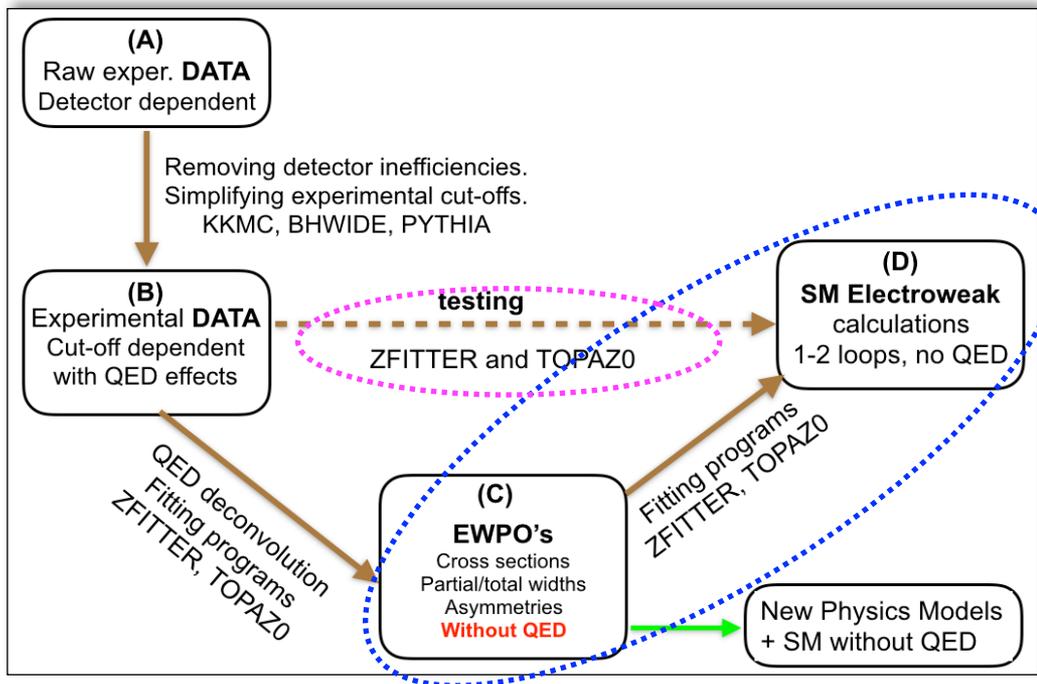
Electroweak Pseudo-Observables, EWPO's, at LEP



1. The most important transformation of data from (B) to (C), using **fitter programs based on ZFITTER and TOPAZ0**, was removing QED effects and cut-off dependence, such that resulting EWPOs did not depend on specific details of the individual experiments and were not "polluted" by the QED.
2. This step is introducing certain loss of the data precision (QED origin), tolerable at LEP precision, but will require nontrivial effort to master them at FCC-ee. Negligible dependence on the SM parameters was at LEP.
3. **An effective Born spin amplitudes** were used in the fitter programs instead of complete EW corrections.
4. The differential distribution were from spin amplitudes of the $ee \rightarrow ff$ process, with adjustable parameters being mass and width of Z, QED coupling at M_Z and two real couplings a_f and v_f of Z to each fermion type f .
Let's call them **EW pseudo-parameters, EWPPs**.



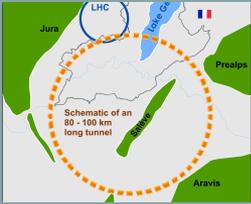
Electroweak Pseudo-Observables, EWPO's, at LEP



1. In the (C) -> (D) step the fitting of the SM Lagrangian parameters to EWPOs was done at LEP, with QED eliminated. The EWPOs at stage (C) represent data and in principle know nothing about parameters in the SM Lagrangian.
2. Combining data from all four LEP experiments and SLD was done at the stage (C).
3. For a given LEP experiment, one may also fit the SM directly to data from stage (B), see (B) - - - -> (D) in the figure.

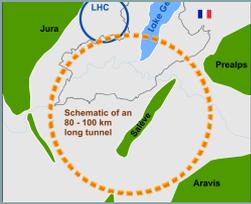
In this way one avoids an additional bias present in the two step fitting (A) -> (C) -> (D). This important crosscheck was done for each LEP experiment.

QED challenges at FCCee



QED challenges at FCCee are 2-fold:

- A. More higher (fixed) orders, better resummation, more sophisticated Monte Carlo programs
- B. Possibly (completely) new methodology of the QED "deconvolution" and the related new definition of the EW pseudo-observables (EWPO's)



Towards new QED "deconvolution" at FCCee

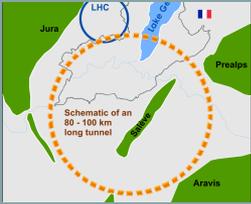


- QED deconvolution at LEP era was removing ISR, neglecting IFI:

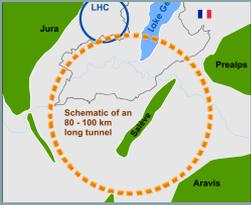
$$\sigma_T(s) = \int_{z_0}^1 dz H(z; s) \hat{\sigma}_T(zs) \quad A_{FB}(s) = \frac{\pi\alpha^2 Q_e^2 Q_f^2}{\sigma_{\text{tot}}} \int_{z_0}^1 dz \frac{1}{(1+z)^2} H_{FB}(z; s) \hat{\sigma}_{FB}(zs)$$

- Unfortunately **IFI cannot be cast into such a simple 1-dim convolution** form!!!
- At LEP times IFI was either put into error budget or subtracted at $\mathcal{O}(\alpha^1)$
- At FCCee higher precision this can be continued for EWPO's related to hadronic total x-section but NOT for EWPO's from angular distribution, asymmetries.
- **Luckily, QED factorises perfectly at the amplitude level, and QED can be factored (deconvoluted) at the amplitude level.**
- Hence the solution is to define **EWPO's in form of parameters in the spin amplitudes of effective Born**, EWPP's, before squaring and spin summing.
- Removing QED from exp. data is then done using MC of the KKMC class, with QED factorisation done at the amplitude level and **resummation done numerically** in MC.
- **Getting 5 digit result numerically from MC takes 50h on 100 processors, but this is done only once and the variation of EWPOs to be calculated quite quickly (<1min on a farm) using MC weight differences (ratios), provided MC's are enabled to provide correction weights due to SM parameter variation.**

Electroweak Pseudo-Observables, EWPO's (or EWPP's), at FCCee



- ❖ New scheme of EWPO's better suited for the FCCee high precision was outlined in chapter C.3 in [arXiv:1809.01830](https://arxiv.org/abs/1809.01830).
- ❖ Before going into details, the following should be kept in mind:
 - ➔ Data analysis at FCCee will evolve with the increase of statistic. The proposed scenario aims at the statistic/precision close to the final one.
 - ➔ More prominent role of the MC event generators than at LEP is foreseen.
 - ➔ Improved systematic separation/factorisation of:
 - (i) the resummed QED and
 - (ii) pure EW corrections beyond the first order, at the amplitude level, will be the key point in the next round of the SM calculations for the FCCee data analysis.
 - ➔ New scheme is aimed mainly for FCCee-Z and FCCee-WW stages?



Coherent Exclusive Exponentiation (CEEX) scheme of separating multi-loop EW corrections and QED



In the CEEX *factorization scheme* cross section for the process

$$e^-(p_a) + e^+(p_b) \rightarrow f(p_c) + \bar{f}(p_d) + \gamma(k_1), \dots, \gamma(k_n)$$

with complete perturbative corrections up to $\mathcal{O}(\alpha^r)$ and soft photon resummation reads as follows:

$$\sigma^{(r)} = \sum_{n=0}^{\infty} \frac{1}{n!} \int d\tau_n(p_1 + p_2; p_3, p_4, k_1, \dots, k_n) e^{2\alpha\Re B_4(p_a, \dots, p_d)} \frac{1}{4} \sum_{\text{spin}} \left| \mathfrak{M}_n^{(r)}(p, k_1, k_2, \dots, k_n) \right|^2, \quad (\text{C.120})$$

where the virtual formfactor B_4 is factorized (exponentiated) and real emission factors \mathfrak{s} are also factorized out^[7]:

$$\mathfrak{M}_n^{(r)}(p, k_1, k_2, k_3, \dots, k_n) = \prod_{s=1}^n \mathfrak{s}(k_s) \left\{ \hat{\beta}_0^{(r)}(p) + \sum_{j=1}^n \frac{\hat{\beta}_1^{(r)}(p, k_j)}{\mathfrak{s}(k_j)} + \sum_{j_1 < j_2} \frac{\hat{\beta}_2^{(r)}(p, k_{j_1}, k_{j_2})}{\mathfrak{s}(k_{j_1})\mathfrak{s}(k_{j_2})} + \dots \right\}, \quad (\text{C.121})$$

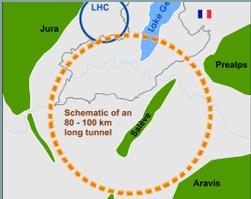
such that the subtracted amplitudes $\hat{\beta}_j^{(r)}$ are IR-finite. Resummation, that is spin summing/averaging of the squared amplitudes and the phase space integration $\int d\tau_n$ is performed numerically in a separate Monte Carlo module of the KKMC, independent from the other part of KKMC where spin amplitudes $\mathfrak{M}_n^{(r)}(p, k_1, k_2, k_3, \dots, k_n)$ are constructed and evaluated. The S-matrix methodology of eqs. (C.111)-(C.116) is relevant for the $2 \rightarrow 2$ Born like object $\hat{\beta}_0^{(r)}$. In the $\mathcal{O}(\alpha^2)$ ($r = 2$) implementation of KKMC, this object reads:

$$\hat{\beta}_0^{(2)}(p) = \mathfrak{M}_0^{(2)}(p) = \left[e^{-\alpha B_4(p)} \mathcal{M}_0^{(2)}(p) \right] \Big|_{\mathcal{O}(\alpha^2)}, \quad (\text{C.122})$$

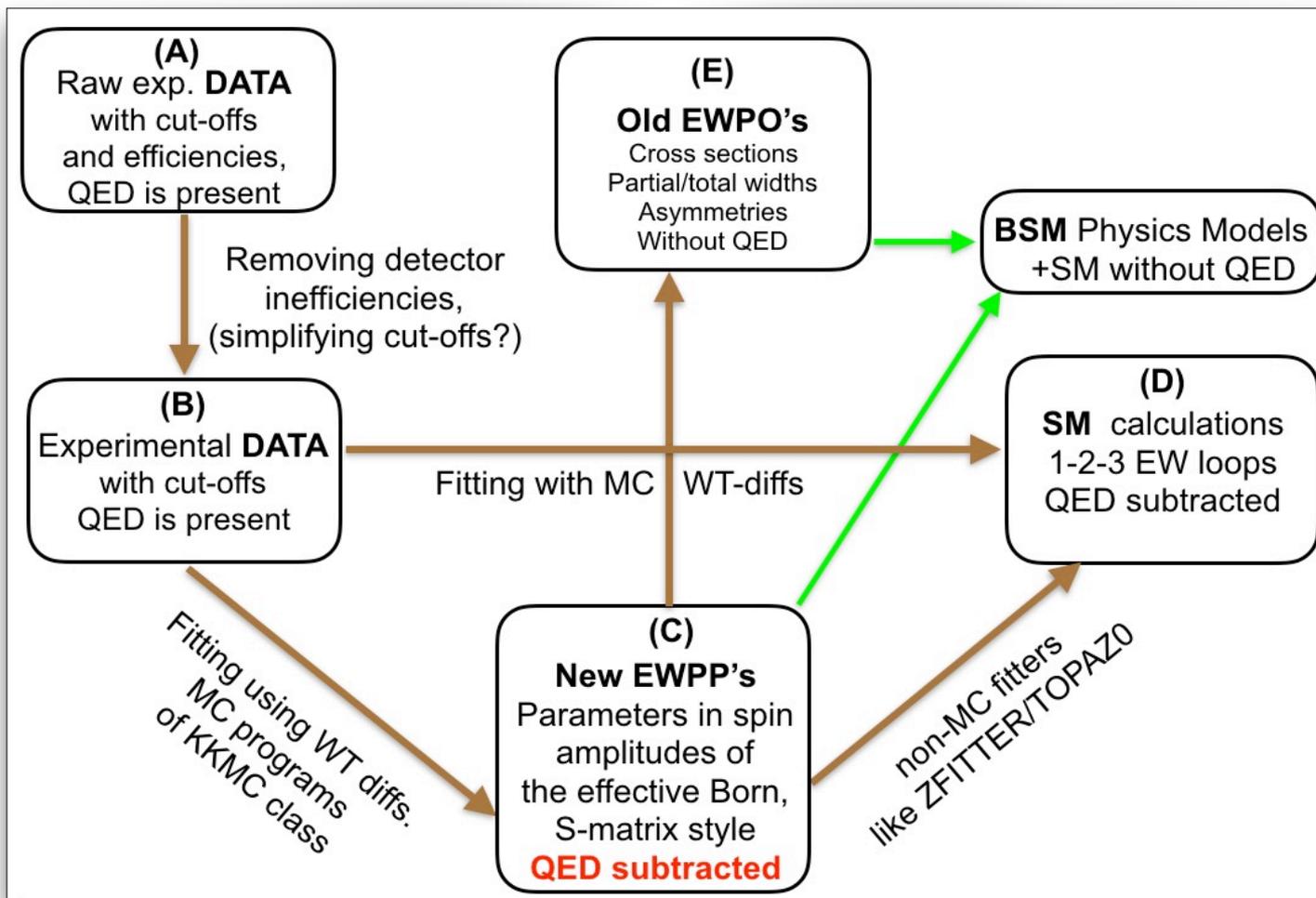
where $\mathcal{M}_0^{(2)}(p)$ represents Born spin amplitudes corrected up to 2-loops, derived directly from Feynman diagrams. In practice, the non-soft parts of the QED corrections are complete in $\hat{\beta}_0^{(2)}(p)$ up to 2-loops, while the EW corrections are taken from DIZET 6.21 [27] (i.e. they are at 1+1/2 loops), exactly according to the prescription shown in eqs. (C.124); see also eqs. (21-24) in ref. [29]. This implementation of the EW corrections in KKMC can be easily modified to be compatible with the S-matrix approach, following the prescription of eqs. (C.125)-(C.129).

Concerning the EW corrections to the $2 \rightarrow 3$ process, they would enter into

$$\hat{\beta}_1^{(2)}(p, k_1) = \mathfrak{M}_1^{(2)}(p, k_1) - \hat{\beta}_0^{(1)}(p) \mathfrak{s}(p, k_1), \quad \mathfrak{M}_1^{(2)}(p, k_1) = \left[e^{-\alpha B_4(p)} \mathcal{M}_1^{(2)}(p, k_1) \right] \Big|_{\mathcal{O}(\alpha^2)}. \quad (\text{C.123})$$

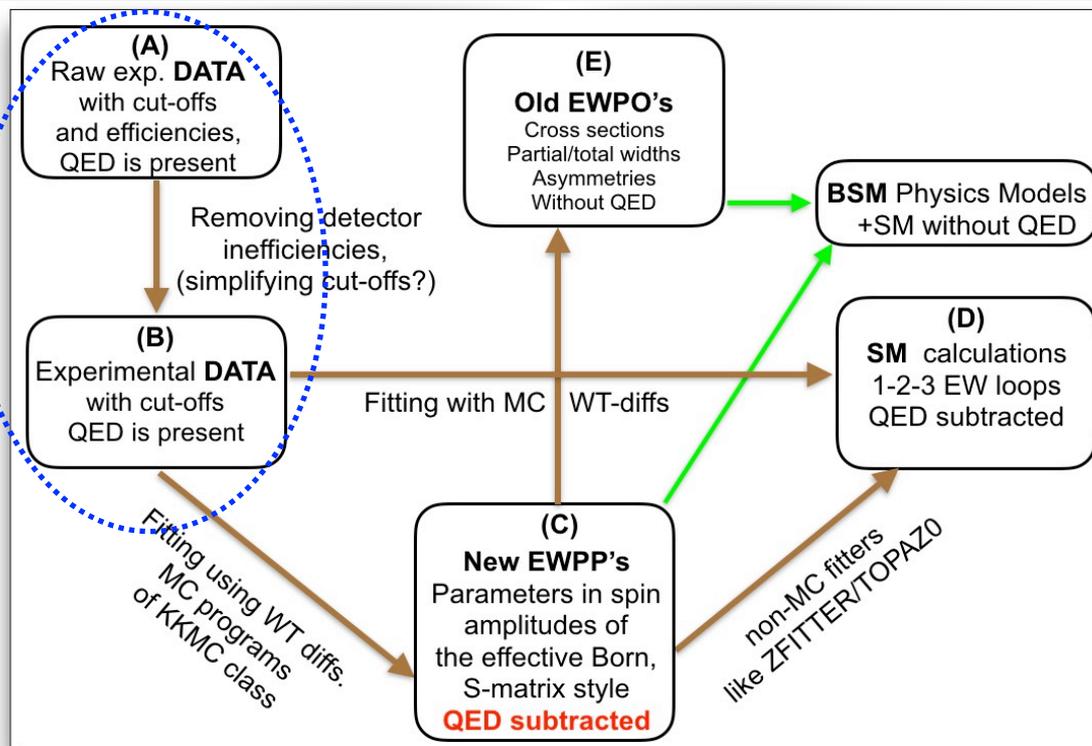
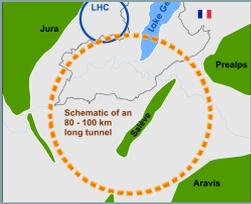


Electroweak Pseudo-Observables, EWPO's (or EWPP's), at FCCee



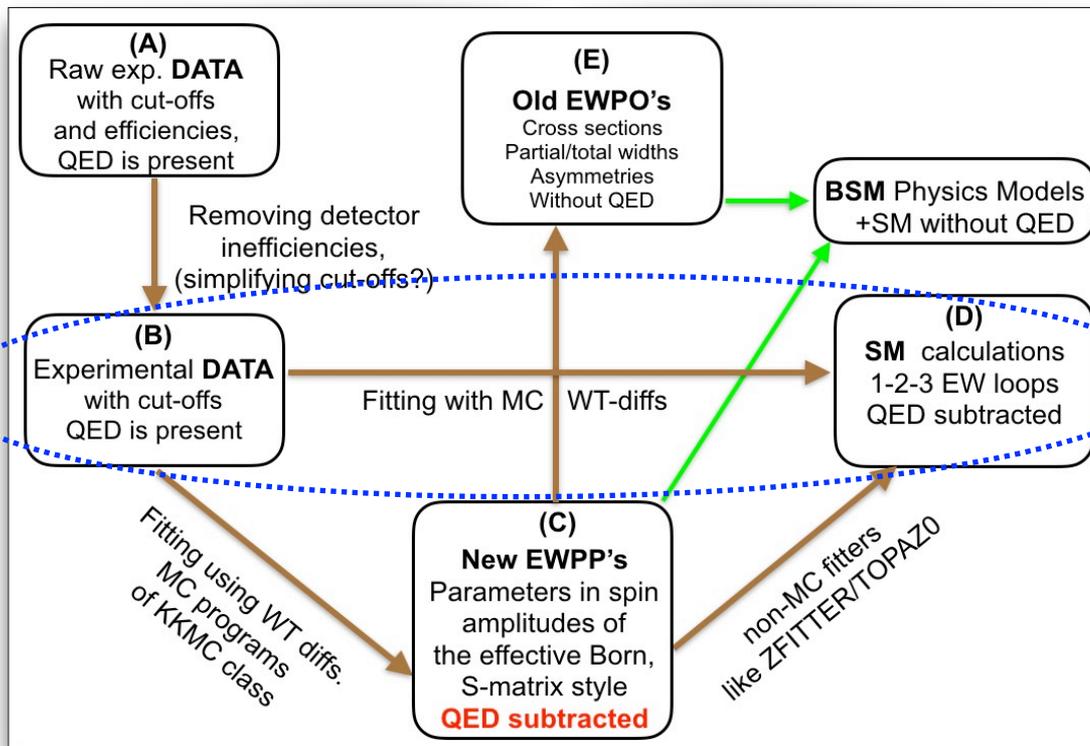
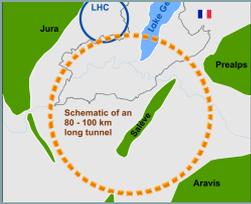
New scheme for FCCee of the QED "deconvolution" with new EWPP's defined at the amplitude level. Old style EWPO's can still play a role but take back seat... Monte Carlo role gets expanded.

Electroweak Pseudo-Observables, EWPO's (or EWPP's), at FCCee

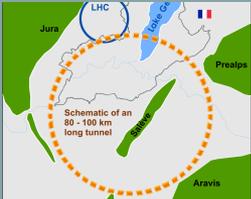


- ❖ In the 1st step (A) -> (B) detector inefficiencies are removed. Also kinematic boundaries of the detectors are replaced by simpler ones in terms of some kinematic cuts, without a minimum loss of the precision, using MC event generators with sophisticated QED matrix element and full phase space coverage, interfaced with the detector simulation programs.
- ❖ Contrary to LEP procedure, we are not constrained by the limited choice of the semi-realistic cut-offs of the non-MC programs like ZFITTER/TOPAZ0, which may be too far away from the true experimental cut-offs. This is thanks to the use of the Monte Carlo programs in the next step (B) -> (D) or (B)->(C).

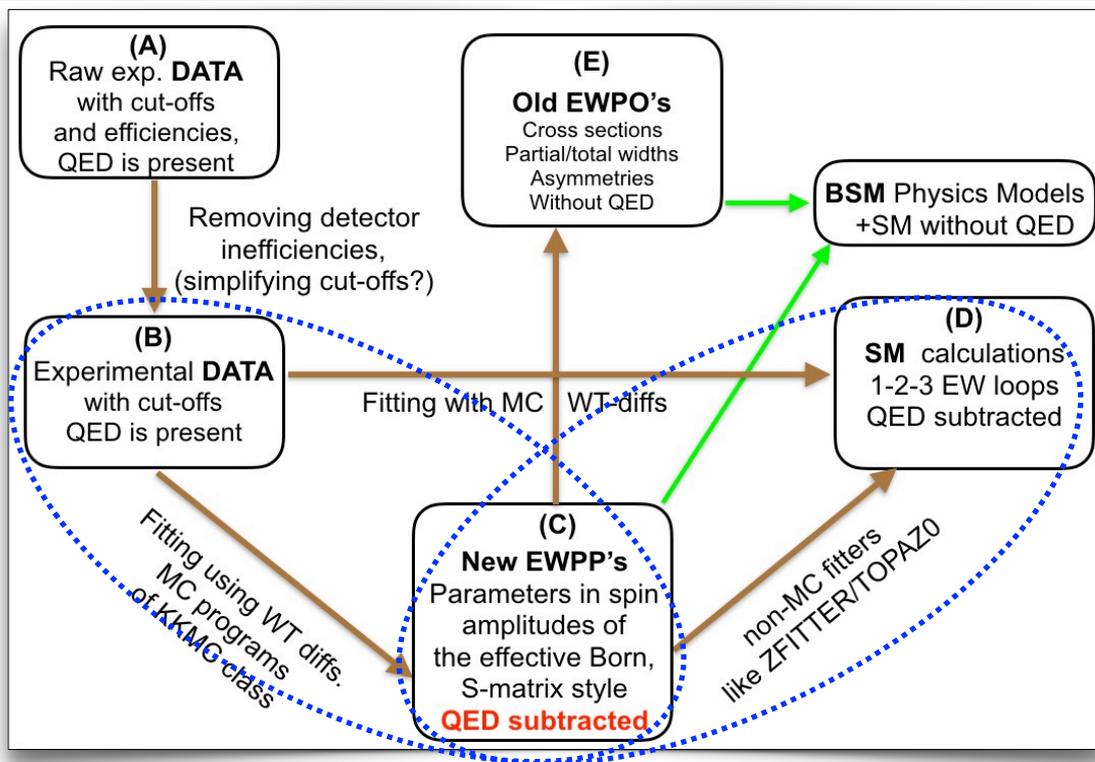
Electroweak Pseudo-Observables, EWPO's (or EWPP's), at FCCee



- ❖ The role of the direct fitting of the SM internal parameters in single step (B) -> (D) will grow. Contrary to former LEP scenario, this step is now implemented using sophisticated Monte Carlo programs, because only this kind of tool is capable to calculate QED effects for arbitrary cut-offs and properly combine IR-resummed QED with 2-3 loop EW corrections with arbitrary precision (following KKMC example).
- ❖ The use of MC programs in the fitting cannot be done in a straightforward way due to slowness of the MC event generators (even without detector simulation). It will be possible using weight-differences methodology, provided MC generators are designed to include provisions for this technique (like KORALW+YFSWW).

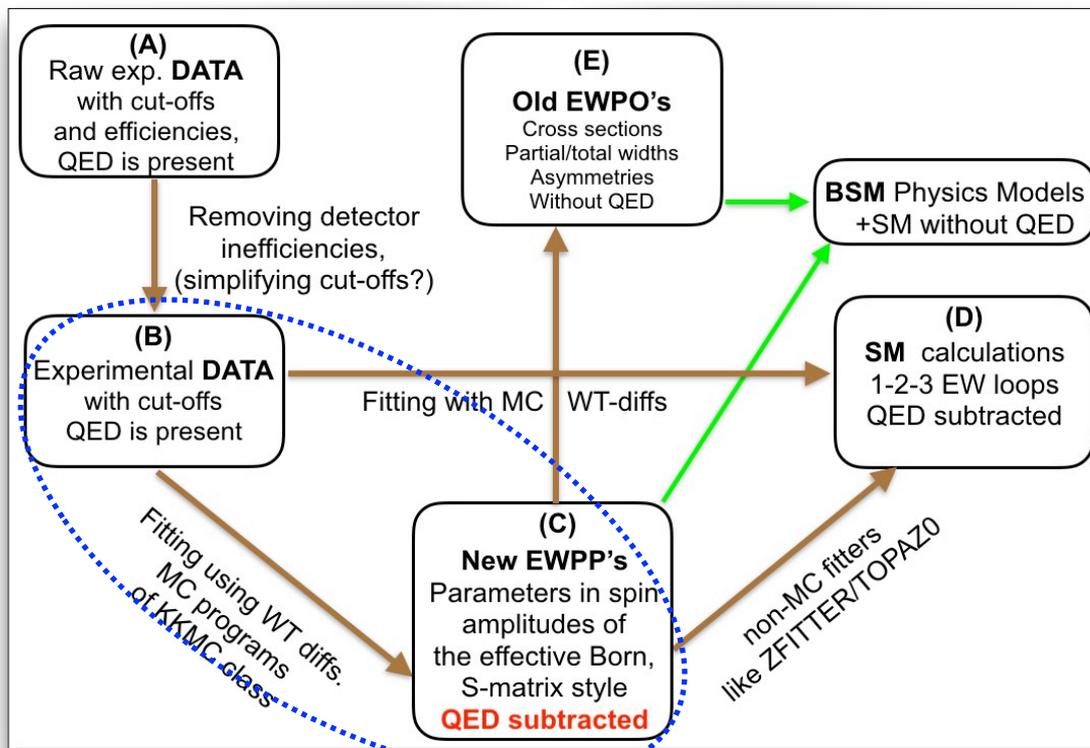
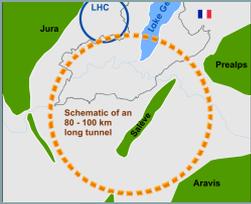


Electroweak Pseudo-Observables, EWPO's (or EWPP's), at FCCee

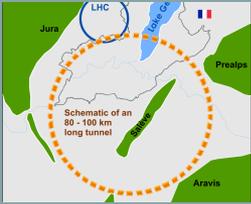


- ❖ The two-step scenario (B)->(C)->(D) with some kind of EW pseudo-observables at the intermediate stage (C) **will be preferred**. However, as in the LEP scheme, the single step (B)->(D) will be more precise and will be used to crosscheck biases introduced in the two-step scenario.
- ❖ If these biases are acceptable in view of the FCC-ee experimental precision then (B)->(C)->(D) then will be preferred, otherwise (B)->(D) will be the principal one and pseudo-observables of the intermediate stage (C) will lose a lot of its attractiveness, (unless an idea on the next slide helps ?)

Electroweak Pseudo-Observables, EWPO's (or EWPP's), at FCCee



- ❖ Back to most important step (B)->(C) defining EWPP's at (C): the strategic question is whether this transformation removes only all QED effects, as in LEP, or we also courageously remove also significant part of pure EW corrections ?!
- ❖ In any case, all of available SM corrections will be included in the entire chain (B)->(C)->(D). The decision is only how pure EW effects are distributed cleverly along (B)->(C) and (C)->(D) chain, such that most of the convenient features of the LEP EWPOs are preserved.
- ❖ The above issue requires separate dedicated study.



Important!!!



QED part of the SM calculations are not done order-by-order!

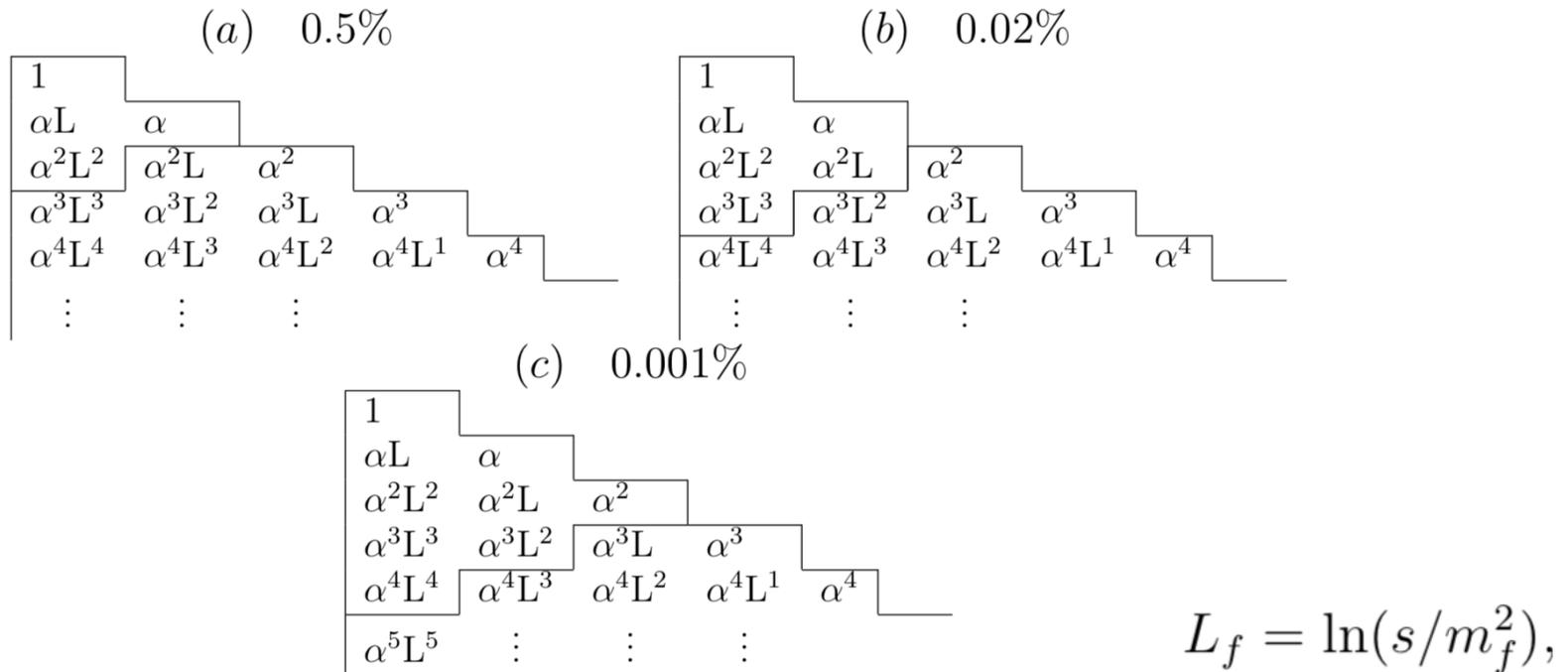
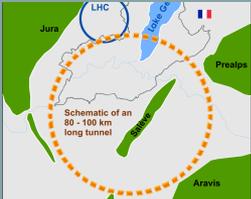


Figure 2: QED perturbative leading and subleading corrections. Rows represent corrections in consecutive perturbative orders – the first row is the Born contribution. The first column represents the leading logarithmic (LO) approximation and the second column depicts the next-to-leading (NLO) approximation. In the figure, terms selected for the same precision level (a) $5 \cdot 10^{-2}$ (b) $2 \cdot 10^{-3}$ and (c) $1 \cdot 10^{-5}$ are limited with the help of an additional line.

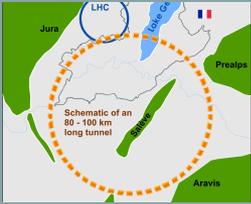


More details omitted here can be found in chapter C of [arXiv:1809.01830](https://arxiv.org/abs/1809.01830)



- * Review of CEEX methodology of factorising QED and EW parts at the amplitude level, including examples at the 2-3 loop level.
- * Methodology of fitting SM parameters using MC event generators.
- * Construction of the effective Born spin amplitudes with adjustable parameters (EWPP's) and their relation to S -matrix pole scheme.
- * Comments on non-factorisable QED and QCD corrections.
- * Arguing “never ever use Bloch-Nordsieck method” to cancel IR divergences — subtract them instead.

Summary



- **FCC-ee is an attractive project — thanks to high luminosity it would probe New Physics up to 20 TeV scales**
- **Major effort is needed to improve SM/QED predictions for FCC-ee observables by factor 10-200**
- **QED corrections for certain observables has to be improved by factor up to 200**
- **New algorithms of “QED deconvolution” leading to new type of EW pseudo-observables is proposed, has to be worked out.**

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