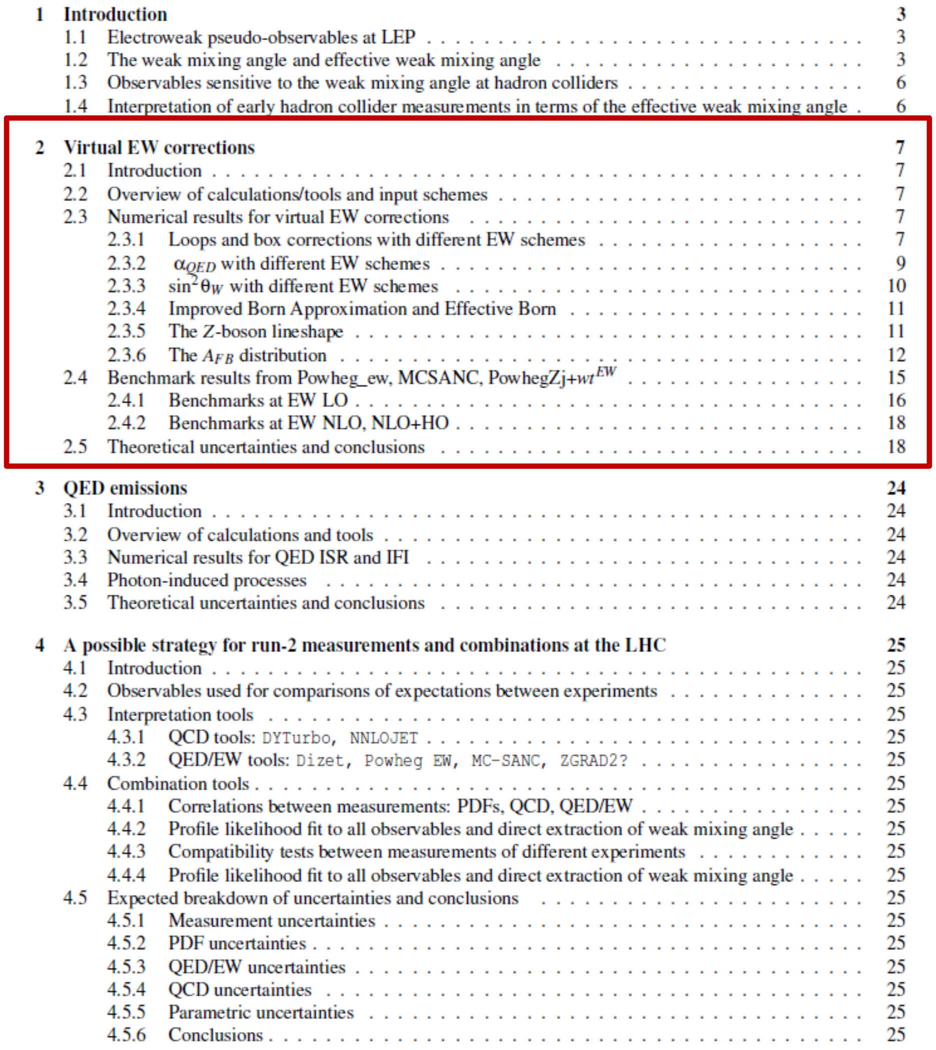
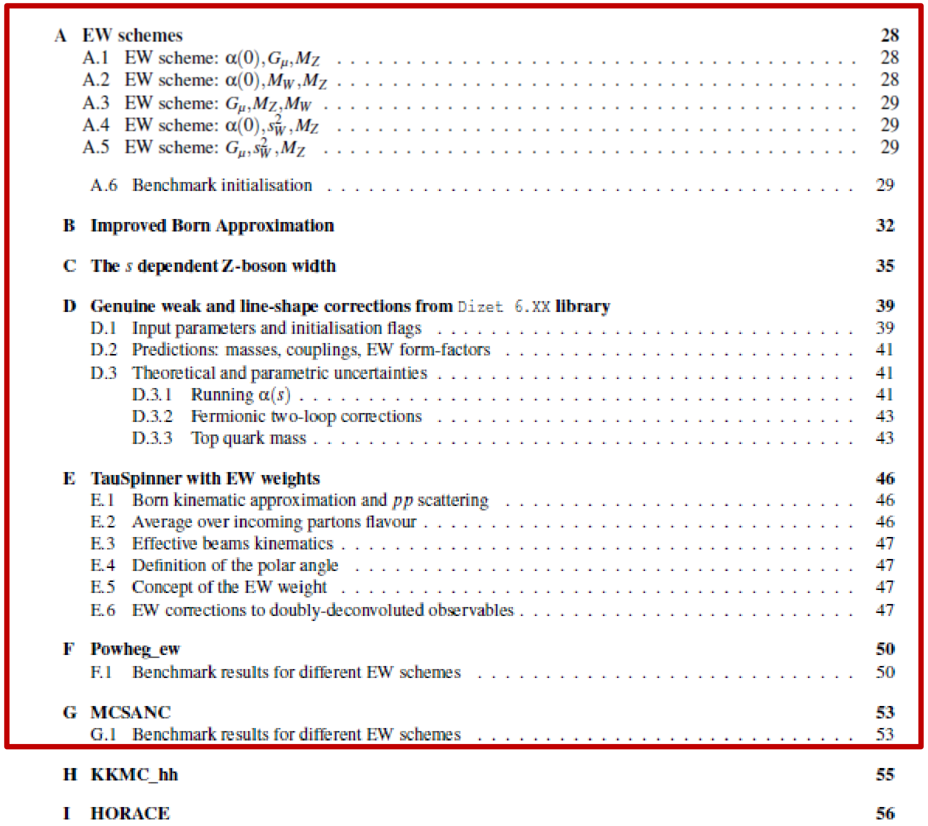
Wrap-up from discussion on freezing choices for calculations: virtual corrections and QED emissions

E. Richter-Was, IF UJ, Kraków

- Genuine weak and lineshape corrections
- Z-boson propagator
- Scan for $\sin^2\theta_{eff}$
- QED FSR/ISR/IFI

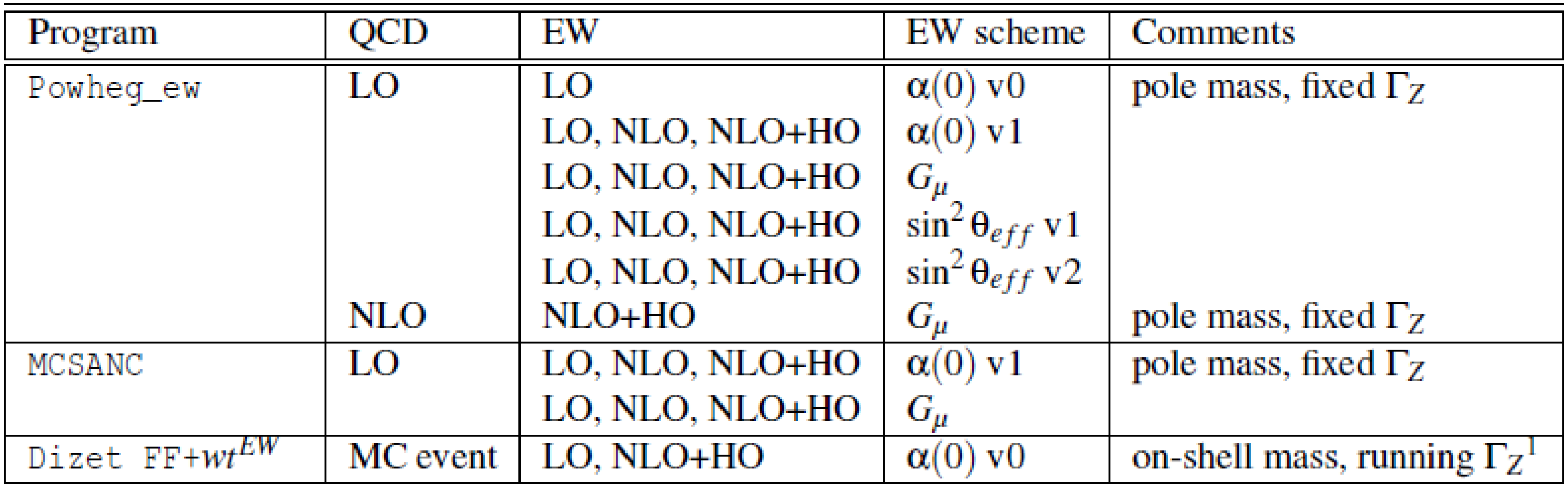
Draft of YR: Section 2 & Appendixes A-G





Genuine weak and lineshape corrections

- **Defined five benchmark points i.e. EW schemes which differ by input parameters and/or formalisms for calculating corrections.**
- **Compared are three different codes:**
  - **Powheg_ew,**
  - **MCSANC,**
  - **Dizet FF + wt^{EW} (TauSpinner)**
- **Plans to have also QCD NLO for the final tables.**



Program	QCD	EW	EW scheme	Comments
`Powheg_ew`	LO	LO	$\alpha(0)$ v0	pole mass, fixed Γ_Z
		LO, NLO, NLO+HO	$\alpha(0)$ v1	
		LO, NLO, NLO+HO	G_μ	
		LO, NLO, NLO+HO	$\sin^2\theta_{eff}$ v1	
		LO, NLO, NLO+HO	$\sin^2\theta_{eff}$ v2	
	NLO	NLO+HO	G_μ	pole mass, fixed Γ_Z
`MCSANC`	LO	LO, NLO, NLO+HO	$\alpha(0)$ v1	pole mass, fixed Γ_Z
		LO, NLO, NLO+HO	G_μ	
`Dizet FF+`wt^{EW}	MC event	LO, NLO+HO	$\alpha(0)$ v0	on-shell mass, running Γ_Z[1]

EW schemes: input parameters

SM fundamental relation used to calculate EW LO parameters for different schemes (on-shell mass).

Completed since last meeting!

Parameter	$(\alpha(0), G_\mu, M_Z)$ $\alpha(0)$ v0	$(\alpha(0), M_W, M_Z)$ $\alpha(0)$ v1	(G_μ, M_Z, M_W) G_μ	$(\alpha(0), s_W^2, M_Z)$ $\sin^2_{eff}$ v1	(G_μ, s_W^2, M_Z) sin^2_{eff} v2
M_Z (GeV)	91.1876	91.1876	91.1876	91.1876	91.1876
Γ_Z (GeV)	2.4952	2.4952	2.4952	2.4952	2.4952
Γ_W (GeV)	2.085	2.085	2.085	2.085	2.085
$1/\alpha$	137.035999139	137.035999139	132.23323	137.035999139	128.744939484
α	0.007297353	0.007297353	0.007562396	0.007297353	0.007767296
G_μ (GeV^{-2})	$1.1663787 \cdot 10^{-5}$	$1.1254734 \cdot 10^{-5}$	$1.1663787 \cdot 10^{-5}$	$1.09580954 \cdot 10^{-5}$	$1.1663787 \cdot 10^{-5}$
M_W (GeV)	80.93886	80.385	80.385	79.93886984	79.93886984
s_W^2	0.2121517	0.2228972	0.2228972	0.231499	0.231499
$\frac{G_\mu \cdot M_Z^2 \cdot 16 c_W^2 s_W^2}{\sqrt{2} \cdot 8\pi \cdot \alpha} = 1.0$ $s_W^2 = 1 - m_W^2 / m_Z^2$	$\rightarrow s_W^2, M_W$	$\rightarrow G_\mu, s_W^2$	$\rightarrow \alpha, s_W^2$	$\rightarrow G_\mu, m_W$	$\rightarrow \alpha, m_W$
$\alpha_s(M_Z)$	0.120178900000	0.120178900000	0.120178900000	0.120178900000	0.120178900000

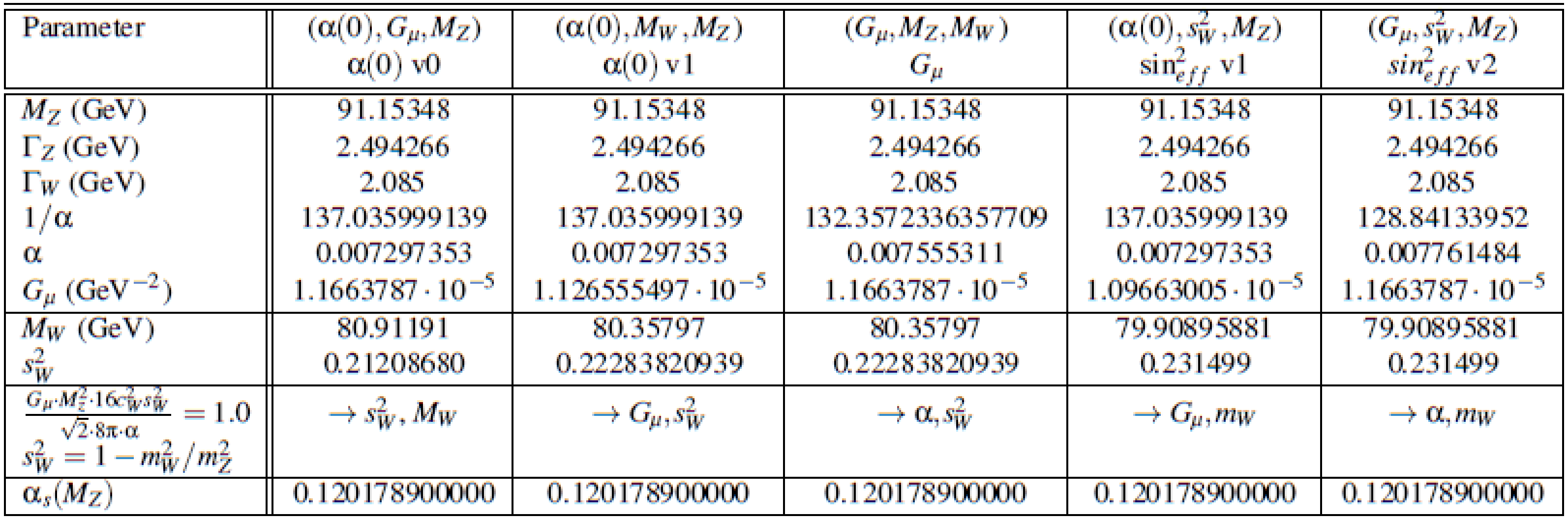
$$\boxed{s_W^2 = 1 - m_W^2 / m_Z^2}$$

$$\boxed{G_\mu = \frac{\pi\alpha}{\sqrt{2} M_W^2 s_W^2}}$$

EW schemes: input parameters

SM fundamental relation used to calculate EW LO parameters for different schemes (pole mass).

Completed since last meeting!



Parameter	$(\alpha(0), G_\mu, M_Z)$ $\alpha(0)$ v0	$(\alpha(0), M_W, M_Z)$ $\alpha(0)$ v1	(G_μ, M_Z, M_W) G_μ	$(\alpha(0), s_W^2, M_Z)$ $\sin^2_{eff}$ v1	(G_μ, s_W^2, M_Z) sin^2_{eff} v2
M_Z (GeV)	91.15348	91.15348	91.15348	91.15348	91.15348
Γ_Z (GeV)	2.494266	2.494266	2.494266	2.494266	2.494266
Γ_W (GeV)	2.085	2.085	2.085	2.085	2.085
$1/\alpha$	137.035999139	137.035999139	132.3572336357709	137.035999139	128.84133952
α	0.007297353	0.007297353	0.007555311	0.007297353	0.007761484
G_μ (GeV^{-2})	$1.1663787 \cdot 10^{-5}$	$1.126555497 \cdot 10^{-5}$	$1.1663787 \cdot 10^{-5}$	$1.09663005 \cdot 10^{-5}$	$1.1663787 \cdot 10^{-5}$
M_W (GeV)	80.91191	80.35797	80.35797	79.90895881	79.90895881
s_W^2	0.21208680	0.22283820939	0.22283820939	0.231499	0.231499
$\frac{G_\mu \cdot M_Z^2 \cdot 16 c_W^2 s_W^2}{\sqrt{2} \cdot 8\pi \cdot \alpha} = 1.0$ $s_W^2 = 1 - m_W^2/m_Z^2$	$\to s_W^2, M_W$	$\to G_\mu, s_W^2$	$\to \alpha, s_W^2$	$\to G_\mu, m_W$	$\to \alpha, m_W$
$\alpha_s(M_Z)$	0.120178900000	0.120178900000	0.120178900000	0.120178900000	0.120178900000

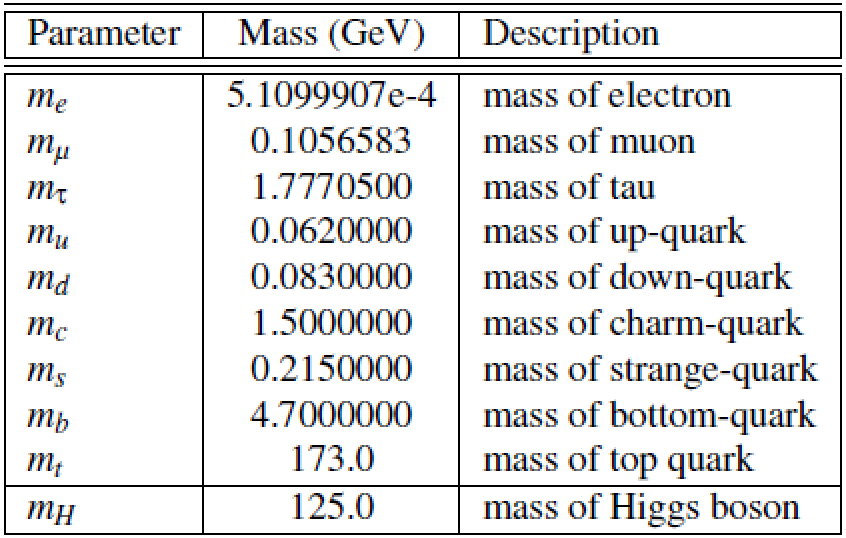
$$\boxed{s_W^2 = 1 - m_W^2/m_Z^2}$$

$$\boxed{G_\mu = \frac{\pi\alpha}{\sqrt{2} M_W^2 s_W^2}}$$

EW schemes: input parameters

To complete, we defined also masses for fermions which are used in all codes.

Table 12: Values of fermions and Higgs boson massed used for calculating EW corrections.



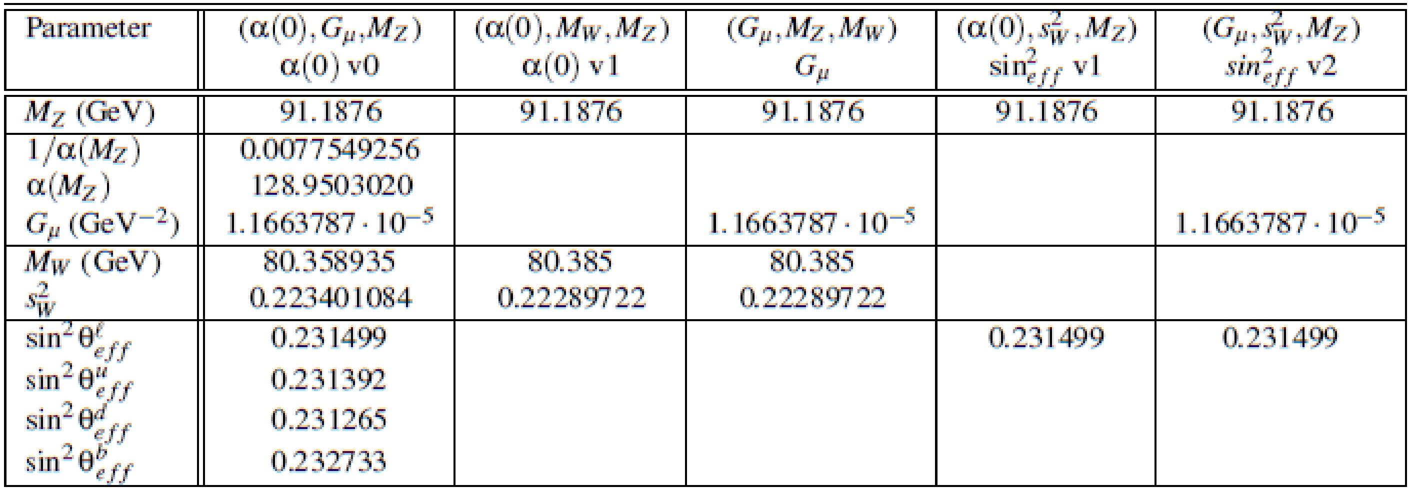
Parameter	Mass (GeV)	Description
m_e	5.1099907e-4	mass of electron
m_μ	0.1056583	mass of muon
m_τ	1.7770500	mass of tau
m_u	0.0620000	mass of up-quark
m_d	0.0830000	mass of down-quark
m_c	1.5000000	mass of charm-quark
m_s	0.2150000	mass of strange-quark
m_b	4.7000000	mass of bottom-quark
m_t	173.0	mass of top quark
m_H	125.0	mass of Higgs boson

Pseudo-observables at Z-pole

Table to go into Section 2, started working on it.

New since last meeting!

„Best predictions” in each EW scheme, i.e. EW NLO+HO



Parameter	$(\alpha(0), G_\mu, M_Z)$ $\alpha(0)$ v0	$(\alpha(0), M_W, M_Z)$ $\alpha(0)$ v1	(G_μ, M_Z, M_W) G_μ	$(\alpha(0), s^2_W, M_Z)$ $\sin^2_{eff}$ v1	(G_μ, s^2_W, M_Z) sin^2_{eff} v2
M_Z (GeV)	91.1876	91.1876	91.1876	91.1876	91.1876
$1/\alpha(M_Z)$	0.0077549256				
$\alpha(M_Z)$	128.9503020				
G_μ (GeV^{-2})	$1.1663787 \cdot 10^{-5}$		$1.1663787 \cdot 10^{-5}$		$1.1663787 \cdot 10^{-5}$
M_W (GeV)	80.358935	80.385	80.385		
s^2_W	0.223401084	0.22289722	0.22289722		
$\sin^2\theta^\ell_{eff}$	0.231499			0.231499	0.231499
$\sin^2\theta^u_{eff}$	0.231392				
$\sin^2\theta^d_{eff}$	0.231265				
$\sin^2\theta^b_{eff}$	0.232733				

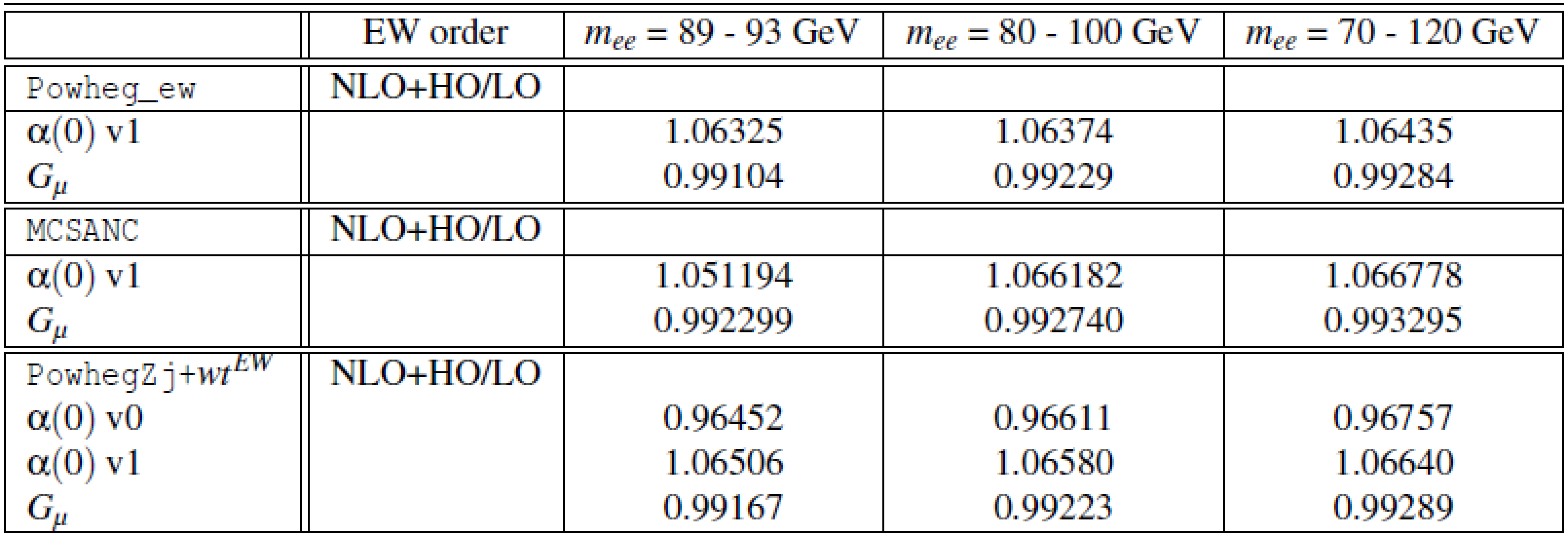
Dizet v6.45

$$\boxed{s^2_W = 1 - m^2_W / m^2_Z}$$

Observables (distributions): Tables and plots

What used so far:

Example



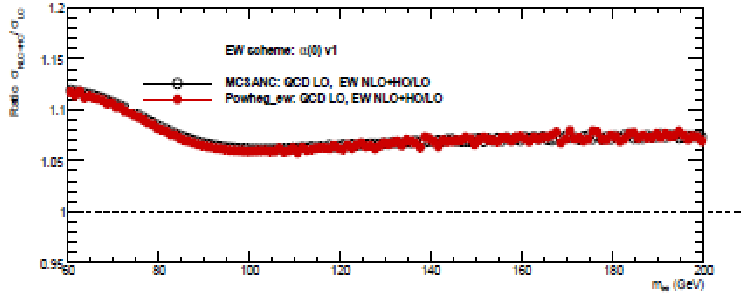
	EW order	m_{ee} = 89 - 93 GeV	m_{ee} = 80 - 100 GeV	m_{ee} = 70 - 120 GeV
`Powheg_ew`	NLO+HO/LO			
$\alpha(0)$ v1		1.06325	1.06374	1.06435
G_μ		0.99104	0.99229	0.99284
`MCSANC`	NLO+HO/LO			
$\alpha(0)$ v1		1.051194	1.066182	1.066778
G_μ		0.992299	0.992740	0.993295
`PowhegZj+`wt^{EW}	NLO+HO/LO			
$\alpha(0)$ v0		0.96452	0.96611	0.96757
$\alpha(0)$ v1		1.06506	1.06580	1.06640
G_μ		0.99167	0.99223	0.99289

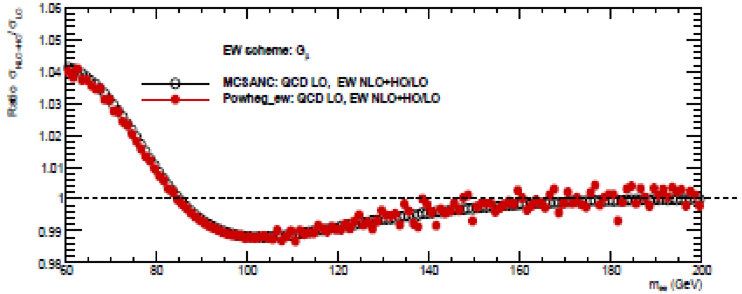
We stay with this format for a now, **no decision made to change !**
However, as **everybody will provide also results in form of histograms**, they can be
Produced in desired bins later.

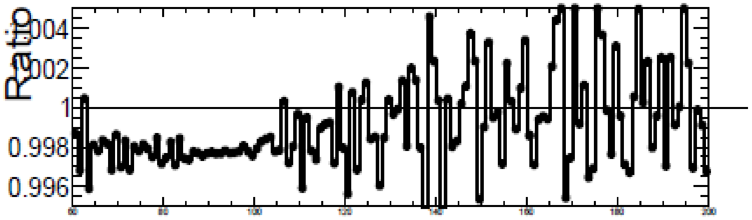
Tables and plots

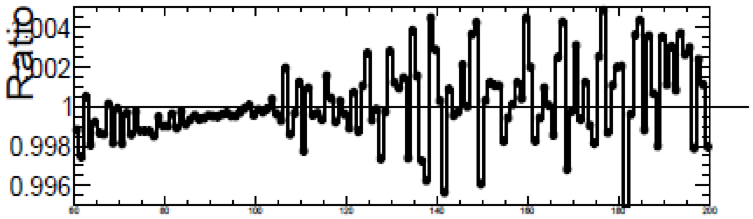
What used so far: range 60-200 GeV with 1 GeV binning.
Histograms: total cross-sections, forward - backward cross-sections,
and for convenience also A_{FB}

Example









Status of the draft: Section 2 & Appendix: A-G

- Completed setup for bechmark configurations
- Updated several tables to Dizet v6.45 + benchmark points specifications. Will continue on it during next weeks.
- Started receiving updates from MCSANC: synchronizing with benchmarks specifications.
- We should try to
  - Conclude discussion on the Z-boson propagator
  - Add at least 2 more points to validate scan in $\sin^2_{\mathrm{eff}}$

Z-boson propagator

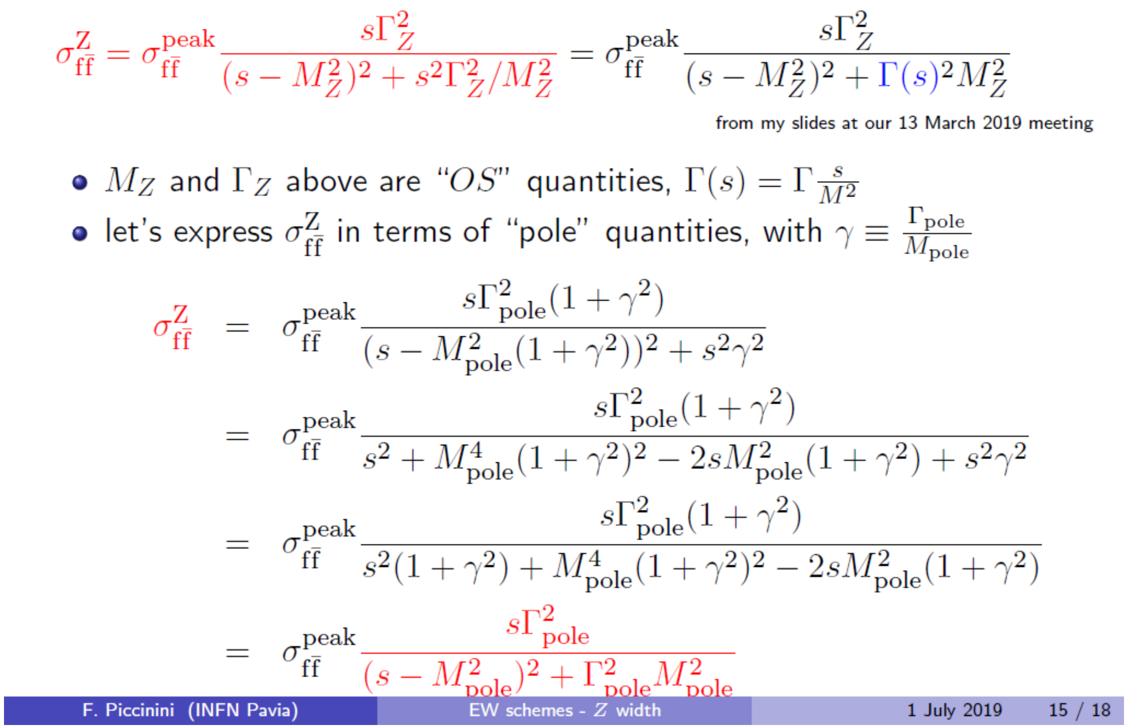
- Discussed since fall last year, problem in nutshell
  - LEP1 legacy (Dizet+Zfitter, experiments):
    - use running width in the Born propagator
    - form-factors calculated with pole-mass/fixed width (internally converted), applied to Born with on-shell mass/running width
    - see references: hep-ex/0509008, hep-ph/9908433
  - LEP2, LHC standard
    - use complex-mass scheme, pole masses, fixed width propagator
  - Zfitter+Dizet v6.42, v6.45, FCCee standard
    - stayed with LEP1 convention

Is that a concern for $\sin^2\theta_{eff}$ measurement at LHC ?

Z-boson propagator

Topic discused in Fulvio's talks at EW meetings on 13.03, 7.05 and 1.07

How to model „resonance"
Is the Breit-Wigner form good enough?



$$\sigma^{Z}_{f\bar{f}} = \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} = \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + \Gamma(s)^2 M_Z^2}$$

from my slides at our 13 March 2019 meeting

- M_Z and Γ_Z above are "OS" quantities, $\Gamma(s) = \Gamma\frac{s}{M^2}$
- let's express $\sigma^Z_{f\bar{f}}$ in terms of "pole" quantities, with $\gamma \equiv \frac{\Gamma_{\rm pole}}{M_{\rm pole}}$

$$\begin{aligned}
\sigma^{Z}_{f\bar{f}} &= \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma^2_{\rm pole}(1+\gamma^2)}{(s-M^2_{\rm pole}(1+\gamma^2))^2 + s^2\gamma^2} \\
&= \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma^2_{\rm pole}(1+\gamma^2)}{s^2 + M^4_{\rm pole}(1+\gamma^2)^2 - 2sM^2_{\rm pole}(1+\gamma^2) + s^2\gamma^2} \\
&= \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma^2_{\rm pole}(1+\gamma^2)}{s^2(1+\gamma^2) + M^4_{\rm pole}(1+\gamma^2)^2 - 2sM^2_{\rm pole}(1+\gamma^2)} \\
&= \sigma^{\rm peak}_{f\bar{f}} \frac{s\Gamma^2_{\rm pole}}{(s-M^2_{\rm pole})^2 + \Gamma^2_{\rm pole}M^2_{\rm pole}}
\end{aligned}$$

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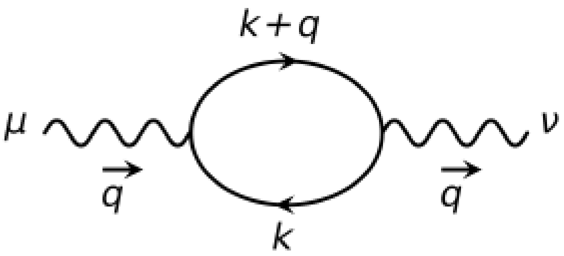
idea behind running width



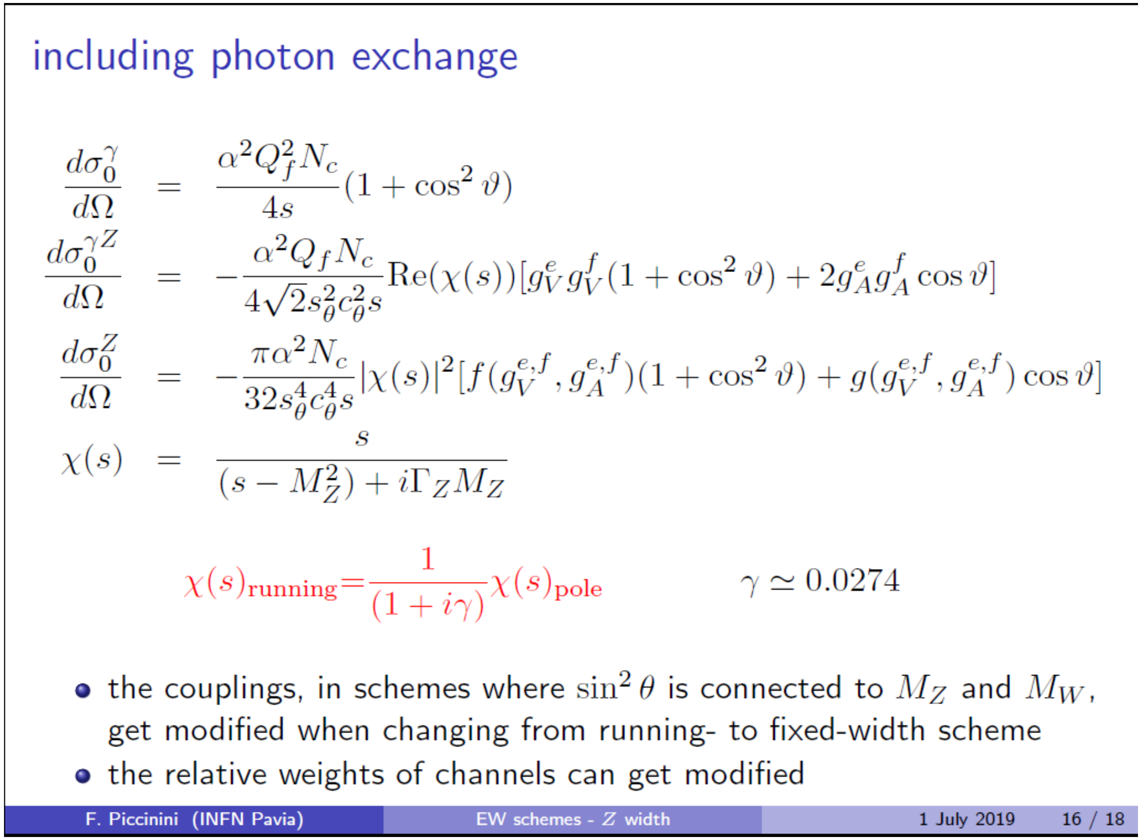
$$\begin{aligned}
M^2_{OS} &= M^2_{\rm pole}\left(1 + \frac{\Gamma^2_{\rm pole}}{M^2_{\rm pole}}\right) \\
\Gamma^2_{OS} &= \Gamma^2_{\rm pole}\left(1 + \frac{\Gamma^2_{\rm pole}}{M^2_{\rm pole}}\right)
\end{aligned}$$

But the propagator in ME is of the form

$$\chi_Z(s) = \frac{1}{s - M_Z^2 + i\cdot\Gamma_Z\cdot s/M_Z}$$

Z-boson propagator

Topic discused in Fuvio talks at EW meetings on 13.03, 7.05 and 1.07



including photon exchange

$$
\begin{aligned}
\frac{d\sigma_0^{\gamma}}{d\Omega} &= \frac{\alpha^2 Q_f^2 N_c}{4s}(1+\cos^2\vartheta)\\
\frac{d\sigma_0^{\gamma Z}}{d\Omega} &= -\frac{\alpha^2 Q_f N_c}{4\sqrt{2} s_\theta^2 c_\theta^2 s}\mathrm{Re}(\chi(s))[g_V^e g_V^f(1+\cos^2\vartheta)+2g_A^e g_A^f\cos\vartheta]\\
\frac{d\sigma_0^{Z}}{d\Omega} &= -\frac{\pi\alpha^2 N_c}{32 s_\theta^4 c_\theta^4 s}|\chi(s)|^2[f(g_V^{e,f},g_A^{e,f})(1+\cos^2\vartheta)+g(g_V^{e,f},g_A^{e,f})\cos\vartheta]\\
\chi(s) &= \frac{s}{(s-M_Z^2)+i\Gamma_Z M_Z}
\end{aligned}
$$

$$\chi(s)_{\mathrm{running}}=\frac{1}{(1+i\gamma)}\chi(s)_{\mathrm{pole}} \qquad \gamma \simeq 0.0274$$

- the couplings, in schemes where $\sin^2\theta$ is connected to M_Z and M_W, get modified when changing from running- to fixed-width scheme
- the relative weights of channels can get modified

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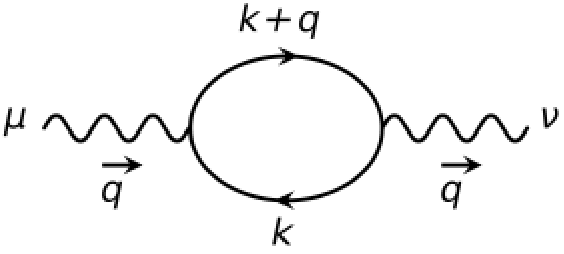
idea behind running width



$$
\begin{aligned}
M_{OS}^2 &= M_{\mathrm{pole}}^2\left(1+\frac{\Gamma_{\mathrm{pole}}^2}{M_{\mathrm{pole}}^2}\right)\\
\Gamma_{OS}^2 &= \Gamma_{\mathrm{pole}}^2\left(1+\frac{\Gamma_{\mathrm{pole}}^2}{M_{\mathrm{pole}}^2}\right)
\end{aligned}
$$

Z-boson propagator

Mathematically formulas for $\chi(s)$ are equivalent, ones M_Z, Γ_Z, N_Z are properly implemented.

At the Z-pole both formulas should lead to same calculated cross-section.

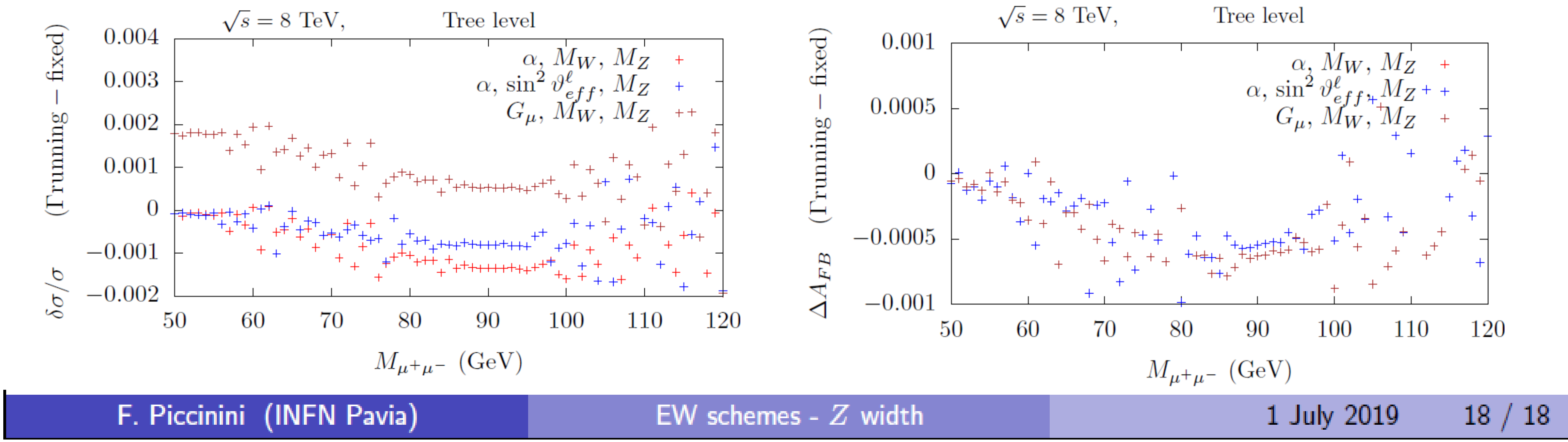
$$
\begin{aligned}
\chi'_Z(s) &= \frac{1}{s(1+i\cdot\Gamma_Z/M_Z)-M_Z^2} \\
&= \frac{(1-i\cdot\Gamma_Z/M_Z)}{s(1+\Gamma_Z^2/M_Z^2)-M_Z^2(1-i\cdot\Gamma_Z/M_Z)} \\
&= \frac{(1-i\cdot\Gamma_Z/M_Z)}{(1+\Gamma_Z^2/M_Z^2)}\,\frac{1}{s-\frac{M_Z^2}{1+\Gamma_Z^2/M_Z^2}+i\cdot\frac{\Gamma_Z M_Z}{1+\Gamma_Z^2/M_Z^2}} \\
&= N_Z\frac{1}{s-{M'_Z}^2+i\Gamma'_Z M'_Z} \\
M'_Z &= \frac{M_Z}{\sqrt{1+\Gamma_Z^2/M_Z^2}} \\
\Gamma'_Z &= \frac{\Gamma_Z}{\sqrt{1+\Gamma_Z^2/M_Z^2}} \\
N_Z &= \frac{(1-i\cdot\Gamma_Z/M_Z)}{(1+\Gamma_Z^2/M_Z^2)} = \frac{(1-i\cdot\Gamma'_Z/M'_Z)}{(1+{\Gamma'_Z}^2/{M'_Z}^2)}
\end{aligned}
$$

Z-boson propagator

Topic discused in Fulvio’s talks at EW meetings on 13.03, 7.05 and 1.07

PRELIMINARY

PRELIMINARY



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At Z-pole, predictions for σ and A_{FB} are not the same, difference of 0.15% for ratio of cross-sections and 5 10^{-4} for ΔA_{FB}. Looks like residuum scaling factor 1/(1+iγ) is missing, was it intentional?

Some differences for cross-sections between both formulas for χ(s), for observables outside the Z-pole were indeed discussed already at LEP1 times, considered not relevant for the precision of the measurements there. The „running width” model was observed as agreeing better with measured Z lineshape.

The effect was much smaller than what shown on plots above.

Z-boson propagator

For now we took pragmatic approach: use defaults of each code:

- Powheg_ew and MCSANC: pole-mass and fixed width propagator
- wt^{EW} : calculated with on-shell masses and running width propagator, as it is standard used by Zfitter+Dizet

We should keep it in mind, that ones we reach precision of the comparisons which might be sensitive to the effect of $\chi(s)$ implementation.

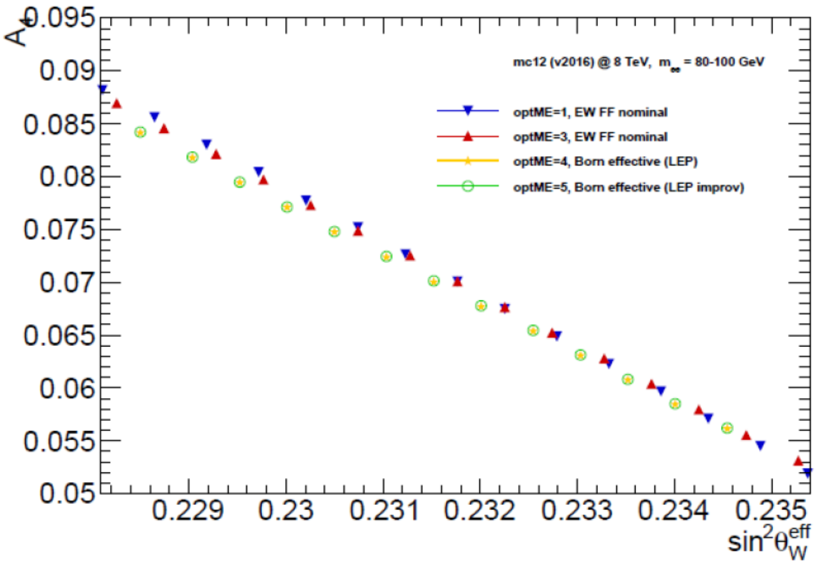
It should be discussed as component of theoretical uncertainties of the predictions.

$\sin^2\theta_{eff}$ scan for A_{FB} and/or A4

Can be done with codes predicting this pseudo-observable explicitly

- **It is available with (Dizet FF +wt^{EW})**
- **Main motivation for Powheg_ew to devellop new EW schemes was to have it available as well.**
- **We should complete this comparison benchmark. Needs at least two additional $\sin^2\theta_{eff}$ points, eg. $\sin^2\theta_{eff}$ = 0.231499 +- 0.00050 and then predicted slope of the A_{FB}.**

Example for A_4 with wt^{EW}

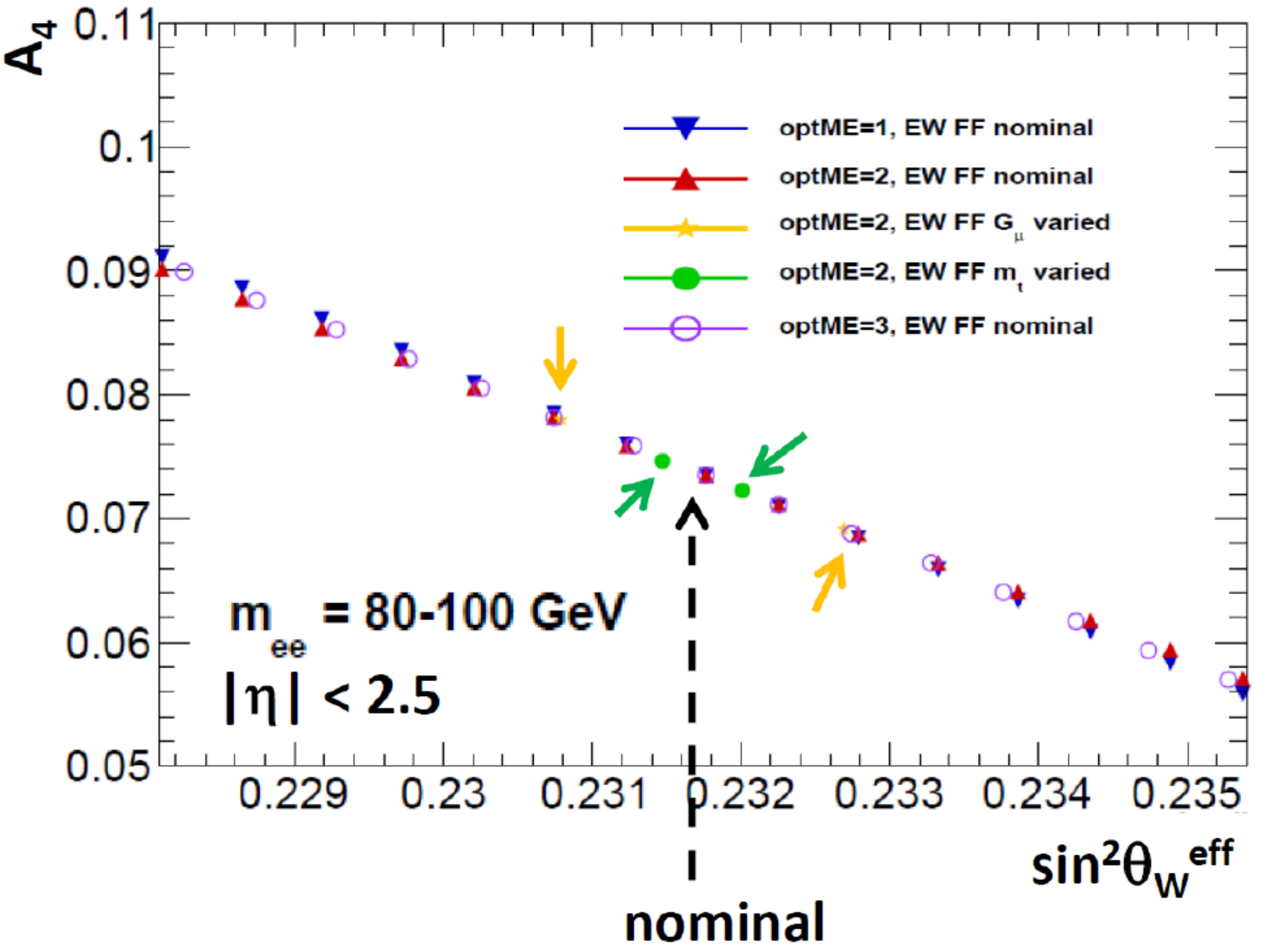


Formulas used for this plot, varied δV

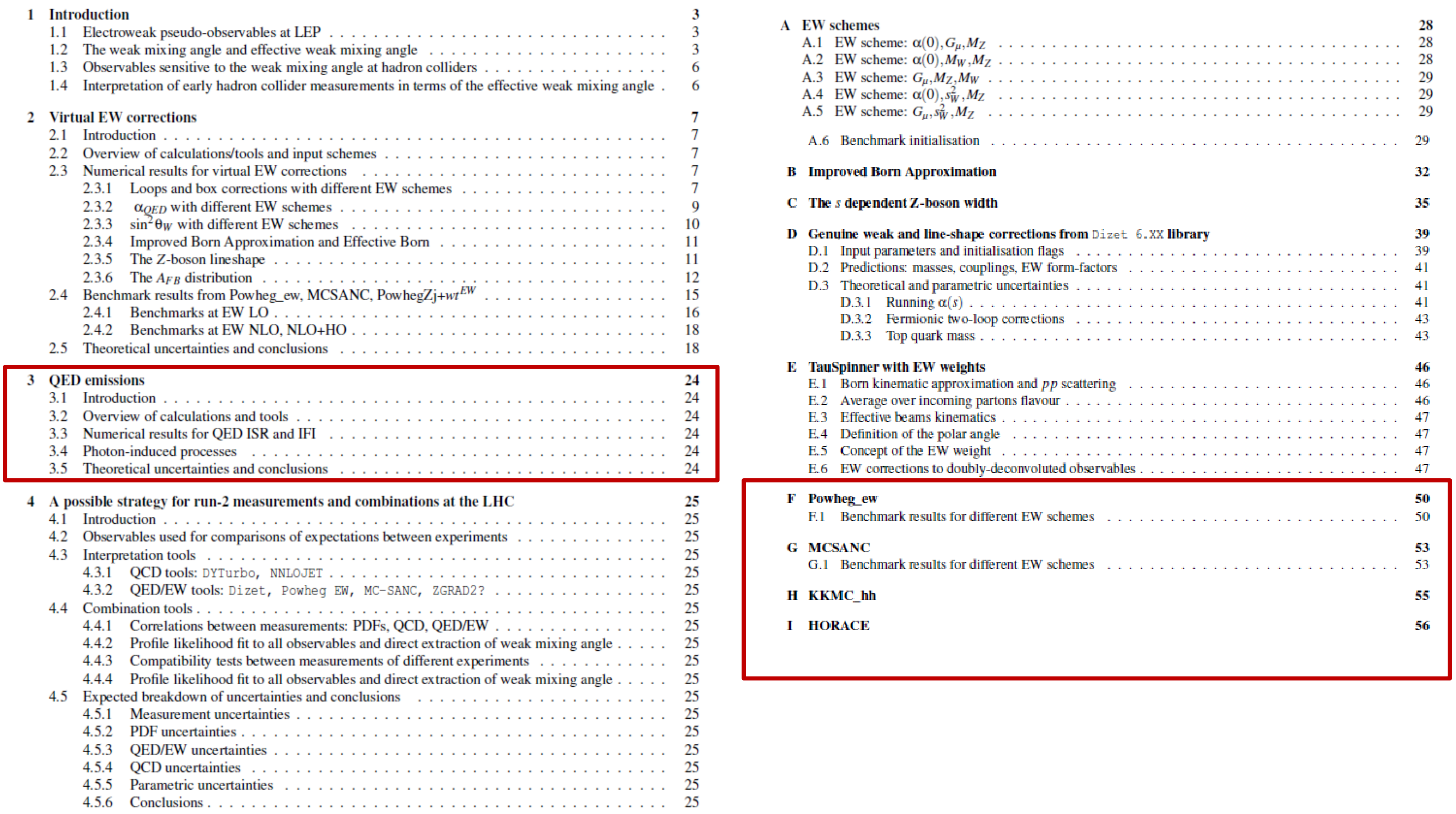
$$
\begin{aligned}
v_\ell = \quad & (2 \cdot T_3^\ell - 4 \cdot q_\ell \cdot (s_W^2 \cdot K_\ell(s,t) + \delta_V))/\Delta \\
v_f = \quad & (2 \cdot T_3^f - 4 \cdot q_f \cdot (s_W^2 \cdot K_f(s,t) + \delta_V))/\Delta \\
vv_{\ell f} = \quad & \frac{1}{v_\ell \cdot v_f}[(2 \cdot T_3^\ell)(2 \cdot T_3^f) \\
& -4 \cdot q_\ell \cdot (s_W^2 + \cdot K_f(s,t) + \delta_V)(2 \cdot T_3^\ell) \\
& -4 \cdot q_f \cdot (s_W^2 \cdot K_\ell(s,t) + \delta_V)(2 \cdot T_3^f) \\
& +(4 \cdot q_\ell \cdot s_W^2)(4 \cdot q_f \cdot s_W^2) K_{\ell f}(s,t) \\
& +2 \cdot (4 \cdot q_\ell))(4 \cdot q_f \cdot) \cdot s_W^2 \cdot K_{\ell f}(s,t) \cdot \delta_V]\,\frac{1}{\Delta^2}
\end{aligned}
$$

$\sin^2\theta_{eff}$ scan for $A_{FB\ and/or}$ A4

Example for A_4 with wt^{EW}

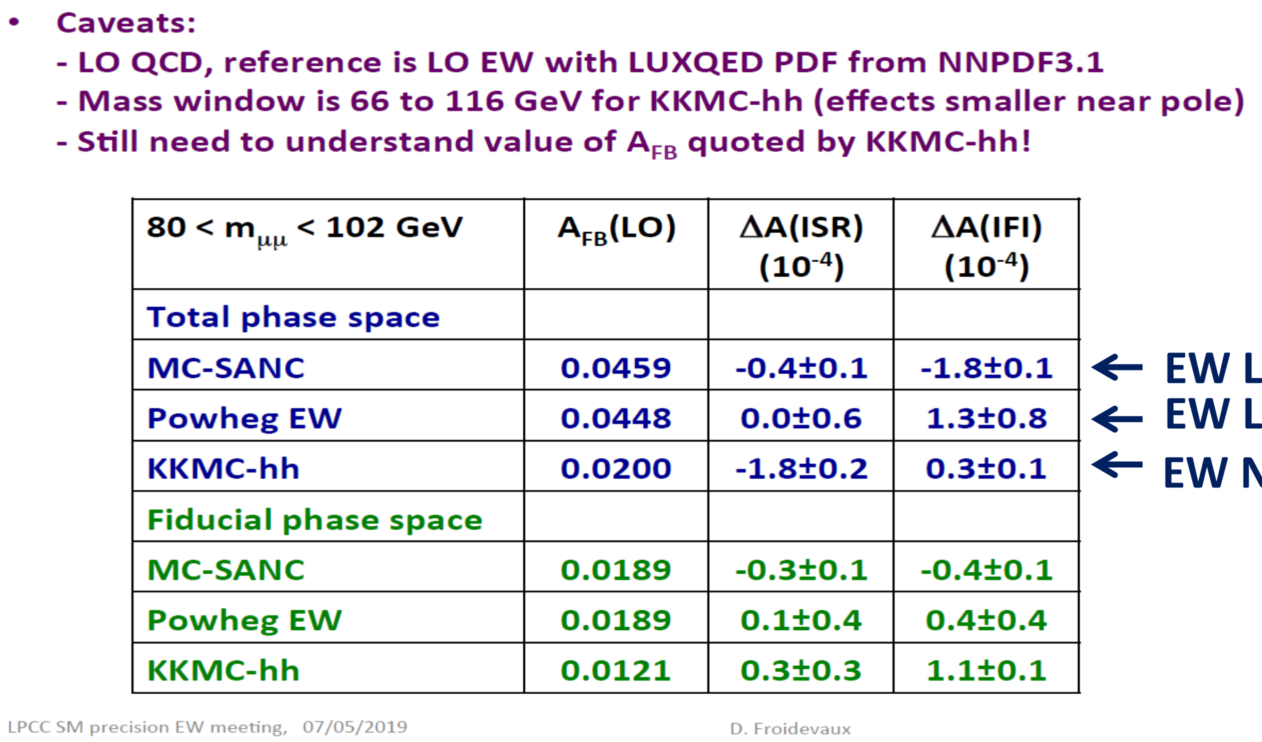


Draft of YR: Section 3 & Appendixes F,G,H,I



QED emission

- **Problem with consistency of Afb because not calculated in the EW schemes.**
- **Proposal to normalise to „best predictions" of the EW scheme used. It will make Section 3 consistent with Section 2.**
- **We could also show only ΔA and ratio of cross-sections with different EW schemes, not the central values.**



- **Caveats:**
  - LO QCD, reference is LO EW with LUXQED PDF from NNPDF3.1
  - Mass window is 66 to 116 GeV for KKMC-hh (effects smaller near pole)
  - Still need to understand value of A_{FB} quoted by KKMC-hh!

$80 < m_{\mu\mu} < 102$ GeV	A_{FB}(LO)	ΔA(ISR) (10^{-4})	ΔA(IFI) (10^{-4})
Total phase space			
MC-SANC	0.0459	-0.4±0.1	-1.8±0.1
Powheg EW	0.0448	0.0±0.6	1.3±0.8
KKMC-hh	0.0200	-1.8±0.2	0.3±0.1
Fiducial phase space			
MC-SANC	0.0189	-0.3±0.1	-0.4±0.1
Powheg EW	0.0189	0.1±0.4	0.4±0.4
KKMC-hh	0.0121	0.3±0.3	1.1±0.1

LPCC SM precision EW meeting, 07/05/2019 D. Froidevaux

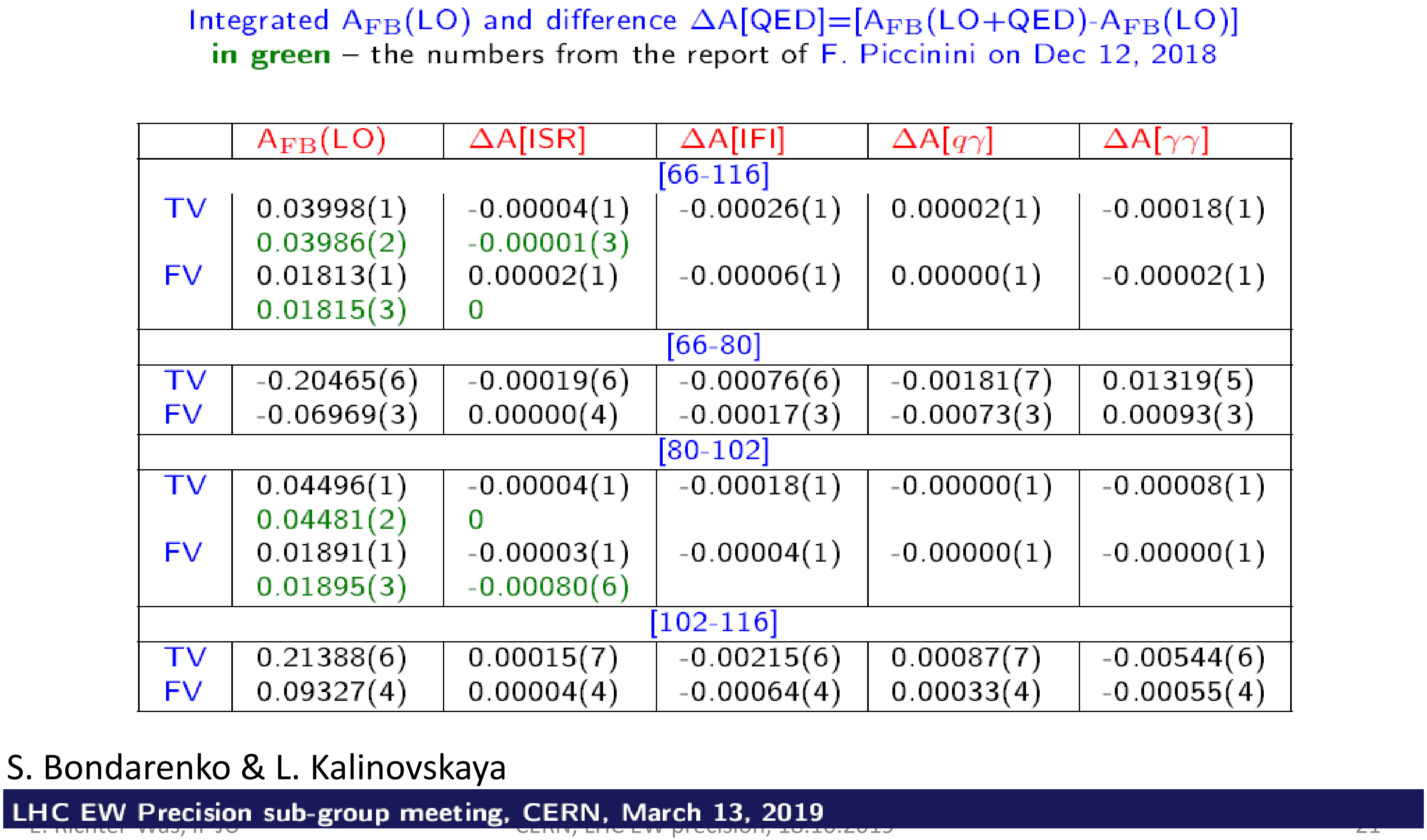
← EW LO G_μ

← EW LO G_μ

← EW NLO+HO $\alpha(0)$ v1

QED emission

Snapshot of existing comparison results.



Integrated A_{FB}(LO) and difference ΔA[QED]=[A_{FB}(LO+QED)-A_{FB}(LO)]

in green – the numbers from the report of F. Piccinini on Dec 12, 2018

	A_{FB}(LO)	ΔA[ISR]	ΔA[IFI]	ΔA[$q\gamma$]	ΔA[$\gamma\gamma$]
			[66-116]		
TV	0.03998(1)	-0.00004(1)	-0.00026(1)	0.00002(1)	-0.00018(1)
	0.03986(2)	-0.00001(3)			
FV	0.01813(1)	0.00002(1)	-0.00006(1)	0.00000(1)	-0.00002(1)
	0.01815(3)	0			
			[66-80]		
TV	-0.20465(6)	-0.00019(6)	-0.00076(6)	-0.00181(7)	0.01319(5)
FV	-0.06969(3)	0.00000(4)	-0.00017(3)	-0.00073(3)	0.00093(3)
			[80-102]		
TV	0.04496(1)	-0.00004(1)	-0.00018(1)	-0.00000(1)	-0.00008(1)
	0.04481(2)	0			
FV	0.01891(1)	-0.00003(1)	-0.00004(1)	-0.00000(1)	-0.00000(1)
	0.01895(3)	-0.00080(6)			
			[102-116]		
TV	0.21388(6)	0.00015(7)	-0.00215(6)	0.00087(7)	-0.00544(6)
FV	0.09327(4)	0.00004(4)	-0.00064(4)	0.00033(4)	-0.00055(4)

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LHC EW Precision sub-group meeting, CERN, March 13, 2019

Status of the draft: Section 3 & Appendix: H, I

- Nothing there yet.
- Got collection of plots from KKMC_hh which could go to Appendix H.
- Nice results exist on ISR/FSR/IFI from Powheg_ew and MCSANC in presentions of previous meetings.
- I would like to start putting it into draft, so all is collected in one place. Please send me text/tables/plots as .tex and .eps files.
  Even if there are not final ones, will help converging.