Electroweak corrections and theoretical uncertainties in the weak mixing angle determination at the LHC and HL-LHC

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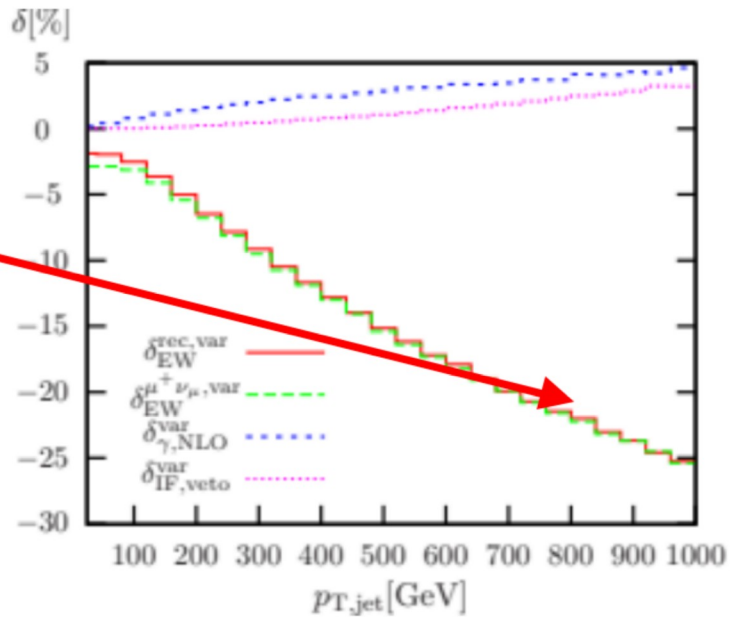
Italiadomani

NLO EW corrections

- Common wisdom: $\delta_{EW}^{NLO} \sim$ some%
- But…

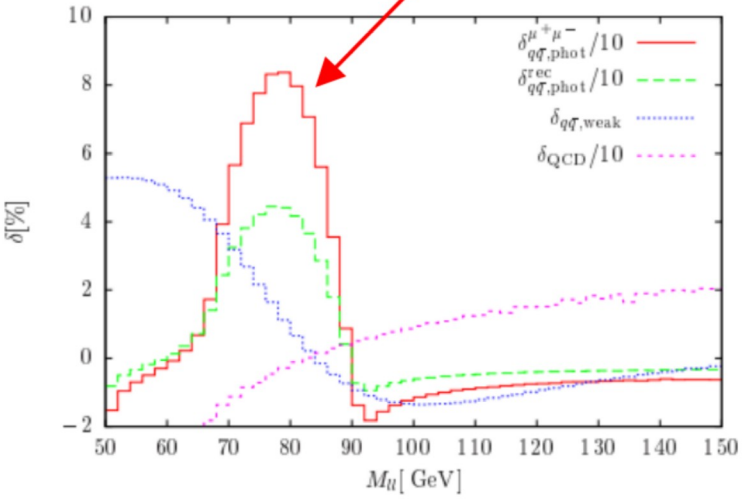
Weak Sudakov corrs.

(V+j, from 0906.1656)



QED radiative return

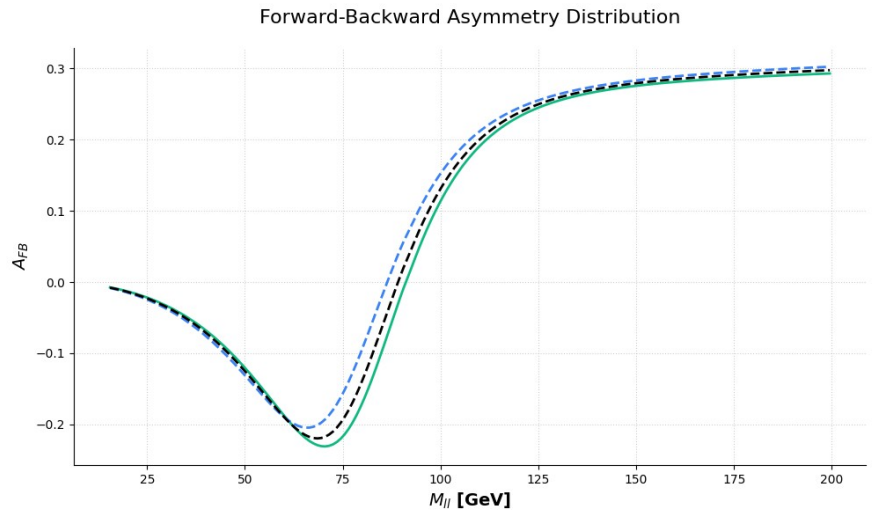
(NC DY from 0911.2329)



In one way or another NLO EW effects included or accounted for in many LHC measurements

Theory predictions and precision physics

In general, high-precision theoretical predictions are essential to fully exploit the physics potential of the LHC and the HL-LHC.



Artificially large (non-physical) $\sin^2\theta^{lept}_{W,eff}$ variations to enhance plot readability

Precise predictions are crucial in the context of template fits:

- Theory predictions enter the measurement via the Monte Carlo Templates
- Theory uncertainties on the templates become part of the total error budget

NLO EW calculations

Huge progress over the last ~ 10 years

Development of automated one-loop providers: GoSam, Recola, OpenLoops

1111.2034, 1111.5206, 1404.7096, 1412.5157, 1605.01090

OLPs and IR-subtraction algorithms implemented in general purpose tools:
Madgraph, MocaNLO, Sherpa, …

1111.1220, 1405.0301, 1804.10017,1905.09127, 2602.19842

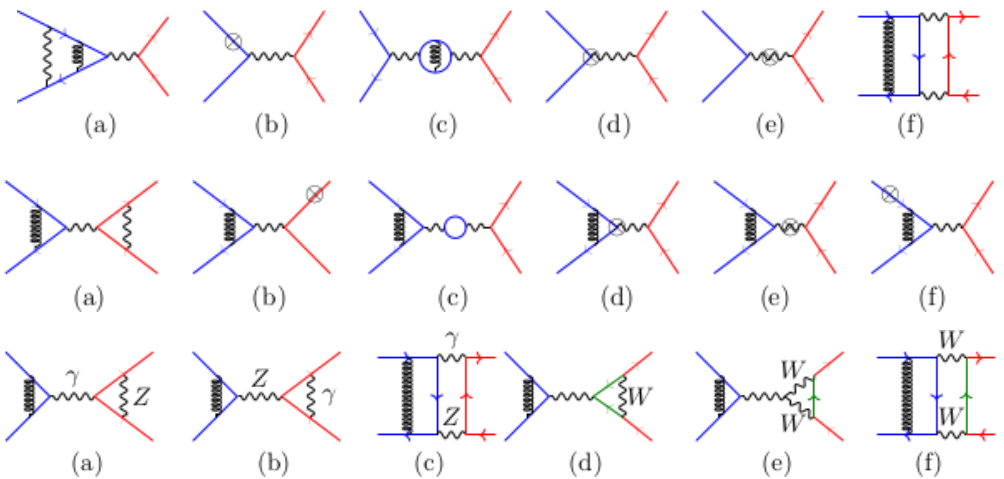
Plus many (more or less) dedicated tools

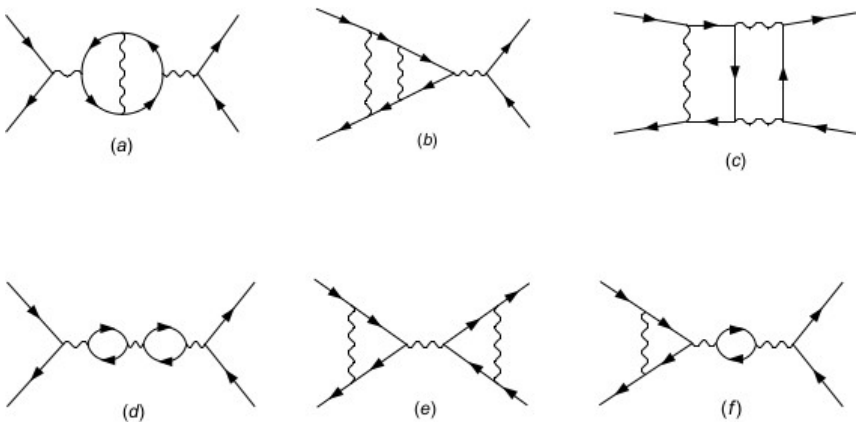
At NLO, EW corrections ***virtually*** available for any process

EW corrections for Drell-Yan

NLO EW corrections known since quite a while

Current frontier of EW corrections for DY @ 2 loop





Mixed α α_S corrections

ArXiv:1403.3216, 1511.08016, 1611.00645, 1805.12214, 1909.08428, 1911.06200, 2005.01315, 2005.10221, 2007.06518, 2009.10386, 2009.02229, 2102.12539, 2103.02671, 2106.11953, 2111.12694, 2203.11237, 2201.01754, 2401.15682, 2405.00612

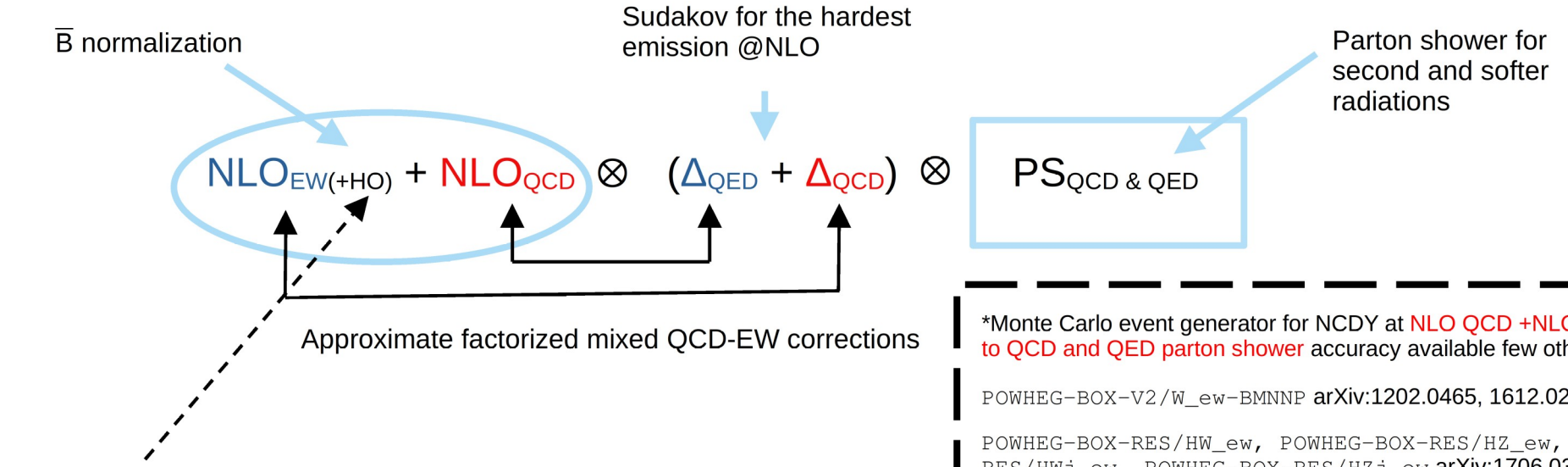
2-loop EW corrections

2211.16272, 2511.20365, 2512.15700

EW corrections @ NLO+PS in POWHEG

git clone https://gitlab.com/POWHEG-BOX/V2/User-Processes/Z_ew-BMNNPV.git

arXiv:2402.14659, 2302.10782, 1906.11569, 1612.02841, 1302.4606



*Monte Carlo event generator for NCDY at NLO QCD +NLO EW matched to QCD and QED parton shower accuracy available few other generators:

`POWHEG-BOX-V2/W_ew-BMNNP` arXiv:1202.0465, 1612.02841

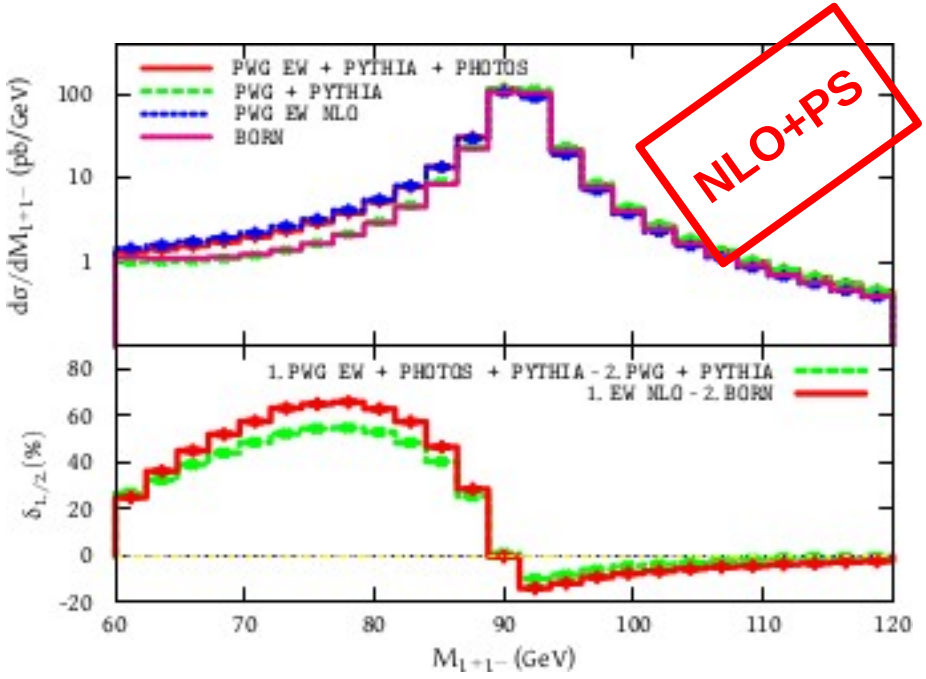
`POWHEG-BOX-RES/HW_ew`, `POWHEG-BOX-RES/HZ_ew`, `POWHEG-BOX-RES/HWj_ew`, `POWHEG-BOX-RES/HZj_ew` arXiv:1706.03522

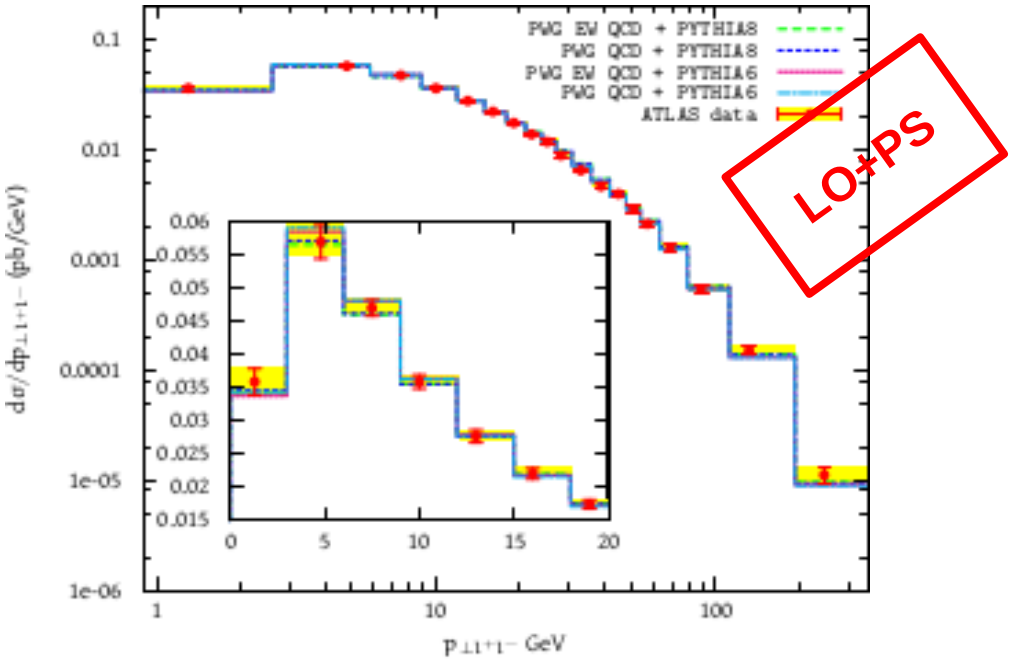
`POWHEG-BOX-RES/VV_dec_ew` arXiv:2005.12146

`POWHEG-BOX-RES/vbs-ssww-nloew` (*) arXiv:1906.01863

`POWHEG-BOX-RES/Hjj_ew` (*) arXiv:2208.00013

POWHEG-BOX-V2/Z_ew-BMNNPV is NLO+PS accurate for DY (inclusive over radiation)



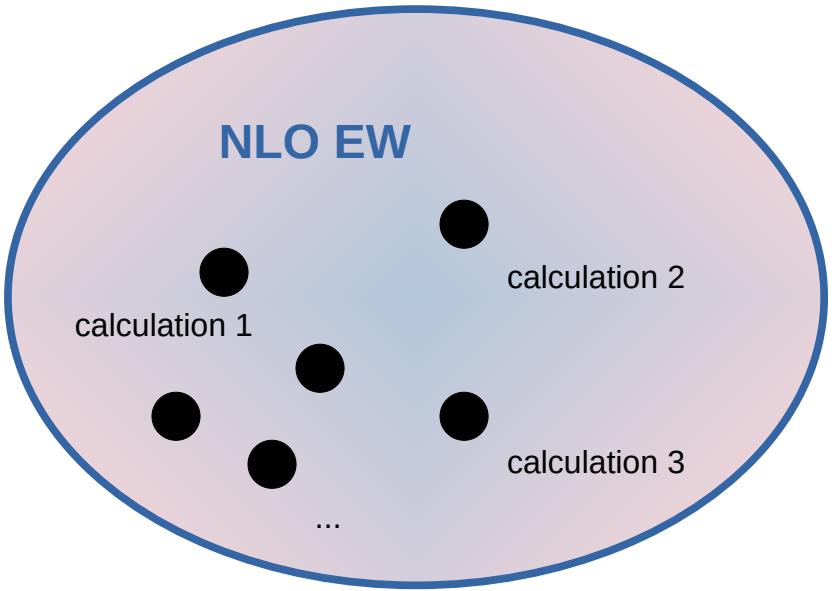


Ongoing work in reaching NLO (EW+QCD) +PS(QED,QCD) accuracy for V+jet and consistent merging with inclusive Drell-Yan:

Very first steps in EPJC86(2026)4, but other groups working on this topic

Accurate description of p_T^Z in the context of resummation of mixed QCD-EW effects provided in JHEP 07 (2024) 193

Weak corrections & theory uncertainties



What is the relation between these choices and the theory error?

Can we use the spread of the results as an estimate of the th. uncertainties?

All calculations are formally equivalent, but they give different results

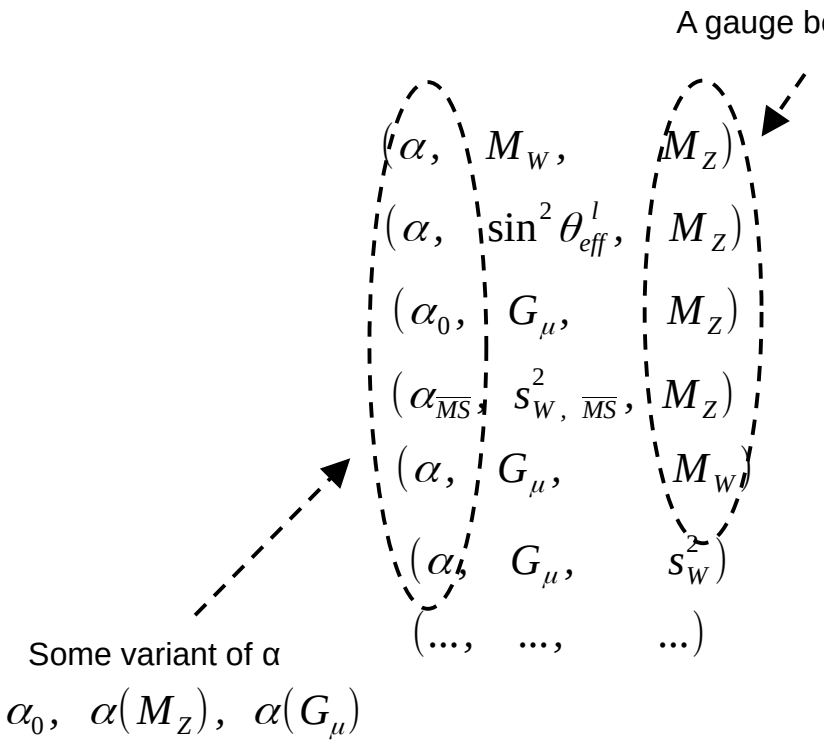
Different calculations are based on different (in principle arbitrary) choices:

- EW input scheme
- Renormalization strategy
- Treatment of unstable particles
- Treatment of possible non pert. contributions

- Focus on weak corrections to NCDY (weak mixing angle measurement)
- Accuracy NLO weak w/w-o leading fermionic corrections ($\Delta\alpha$,$\Delta\rho$) up to
- Calculation implemented/results obtained with `POWHEG-BOX-V2/Z_ew-BMNNPV`

EW input parameters choice

There are 3 independent parameters (beside fermion and Higgs masses)



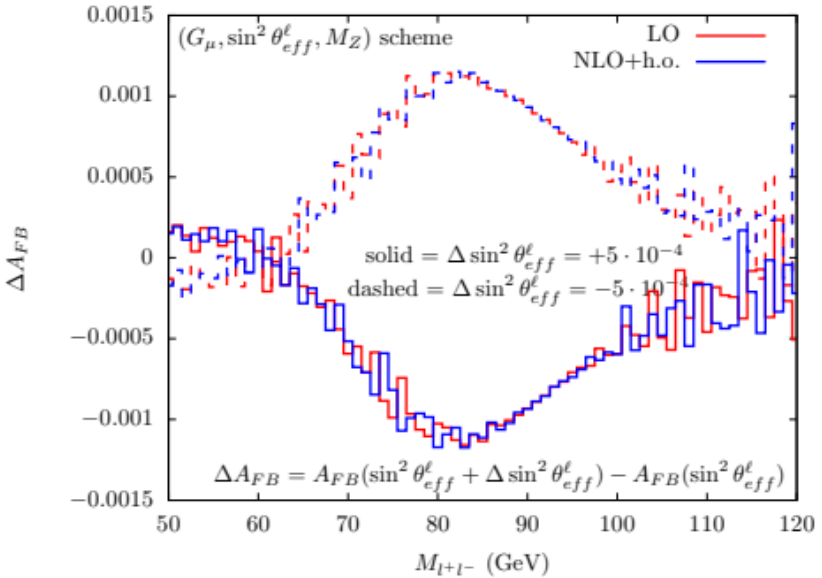
On top, each parameter can be renormalized on-shell, MS, ...

Possible criteria

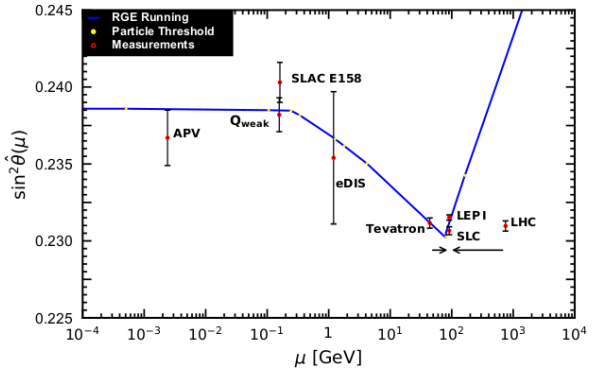
- Size of radiative corrections/convergence of perturbative expansion/missing higher-order effects
- Experimental precision on inputs/parametric uncertainties on predictions
- Need of having a specific free parameter to perform fits (see M_W and s^2_w measurements)

Template fits & independent parameters beyond LO

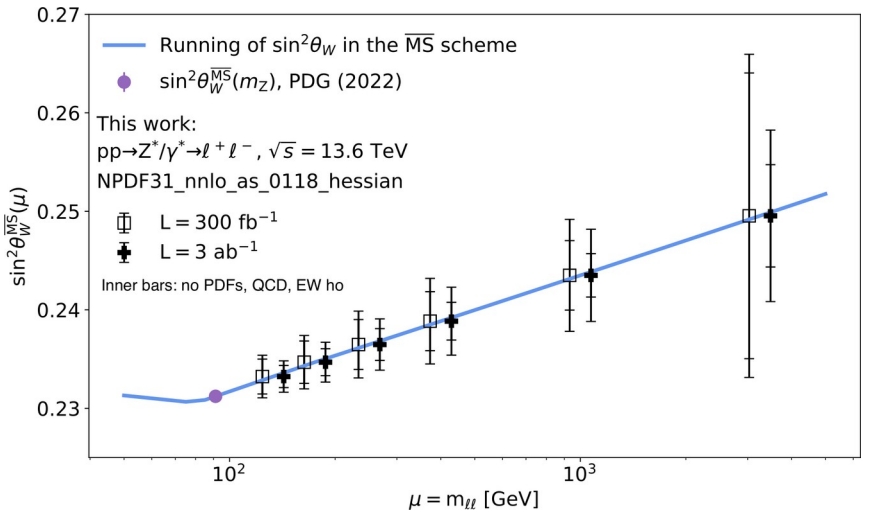
Using $\sin^2\theta^{lept}_{W,eff}$ as input parameter beyond LO requires a consistent renormalization scheme PRD 100(2019)



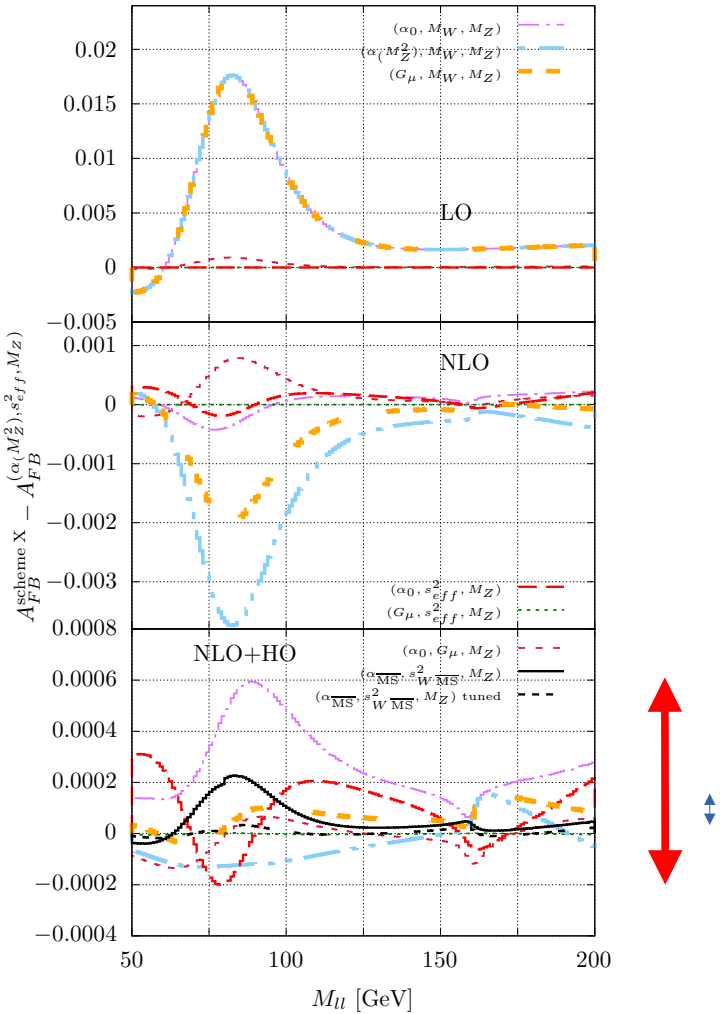
HUGE plus: sensitivity to $\sin^2\theta^{lept}_{W,eff}$ basically unaffected by EW corrections in this scheme



Away from the resonance, one can use the $\overline{\text{MS}}$ definition/renormalization of s^2_W [PLB 844 '23]



Predictions from different EW input schemes



All schemes actually independent: input pars taken from data, no tuning attempt whatsoever

Spread of the predictions measurement of theory uncertainties ~some 10^{-4} (relevant for s^2_W measurement)

But…

1) might be an overestimate: schemes with coupling effectively defined at MZ have smaller corrections and thus smaller missing h.o. effects (compared to the schemes using α_0, that give the larger spread). Resulting spread ~10^{-5}

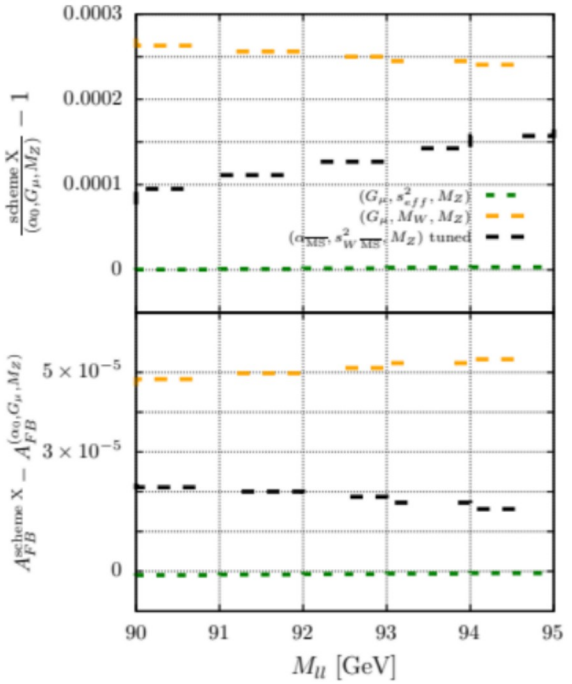
2) different approach at LEP1: comparison of schemes with TUNED input parameters as a function of (α, G_μ, M_Z)

Predictions for LEP1-like tuning to (α, G_μ, M_Z)

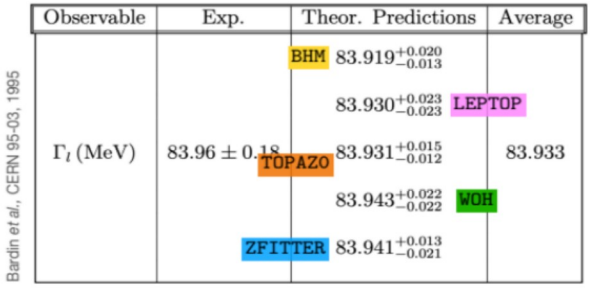
Start from (α, G_μ, M_Z)

Compute $\Delta r_X(X)$, X being $M_W, s^2_{W,eff}, s^2_{W,\overline{MS}}(M_Z)$

Derive X from the relation between $\Delta r_X(X)$ and the parameters (α, G_μ, M_Z)



$\Gamma_{Z\ell\bar{\ell}}$



Agreement within 10^{-4}

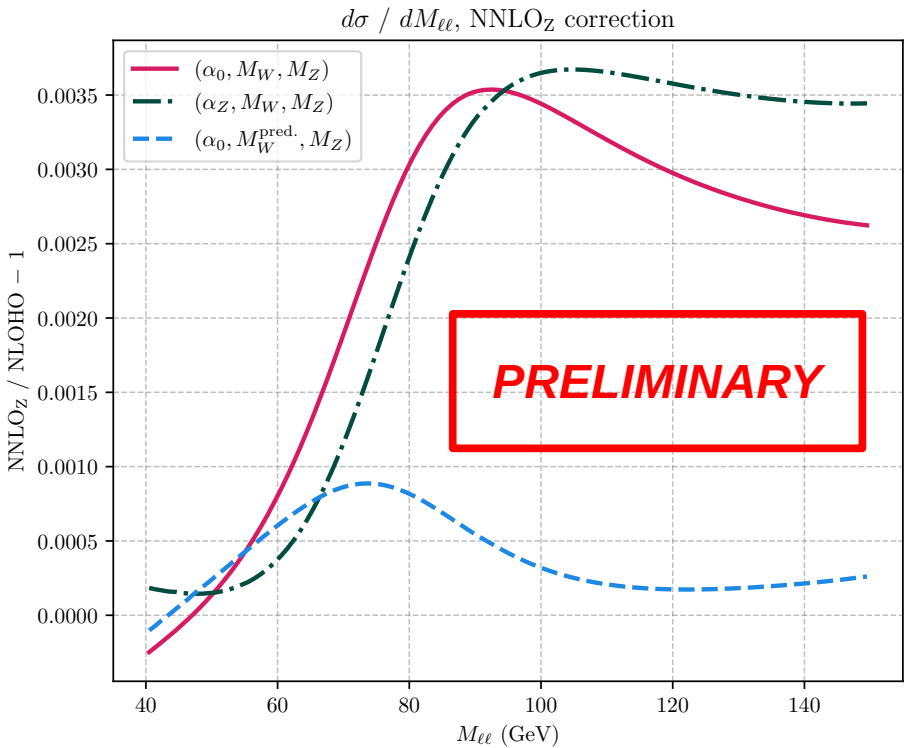
	$(\alpha(M_Z^2), M_W\|_{G_\mu}, M_Z)$	$(\alpha(M_Z^2), s^2_{eff}\|_{G_\mu}, M_Z)$	$(\alpha(M_Z^2), G_\mu, M_Z)$
$\tilde{s}^2_{w,\text{NLO+HO}}$	0.2316749	0.2315919	0.2315965
Γ_e LO	$8.58920545 \cdot 10^{-2}$	$8.3203418 \cdot 10^{-2}$	$8.3315838 \cdot 10^{-2}$
Γ_e NLO+HO	$8.3697741 \cdot 10^{-2}$	$8.3717562 \cdot 10^{-2}$	$8.3717744 \cdot 10^{-2}$

2-loop weak corrections at the Z resonance

Griffin [SciPost Phys. Codeb. 18 ‘23]

C++ library for the calculation of form factors at two loop EW accuracy

PWG+Griffin/PWG



Griffin – POWHEG-BOX-V2/Z-ew-BMNNPV can be used to reach 2 loop weak corrections in pole scheme on the resonance

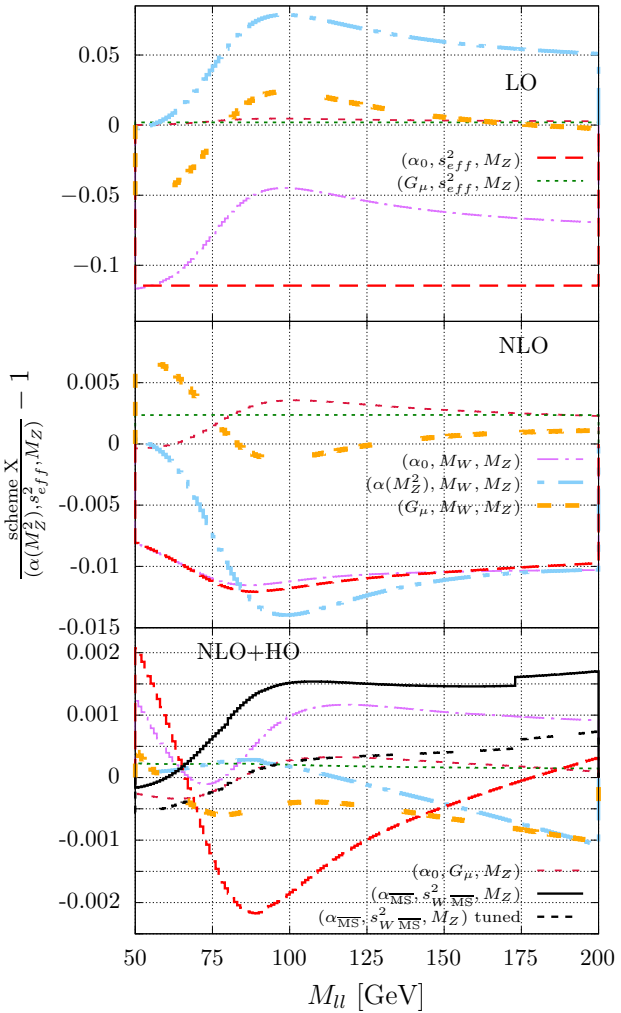
Conclusions

- At a given order in perturbation theory, details of the calculation (EW input parameter/renormalization choice, ...) are connected to the accuracy of theory predictions/theory uncertainties

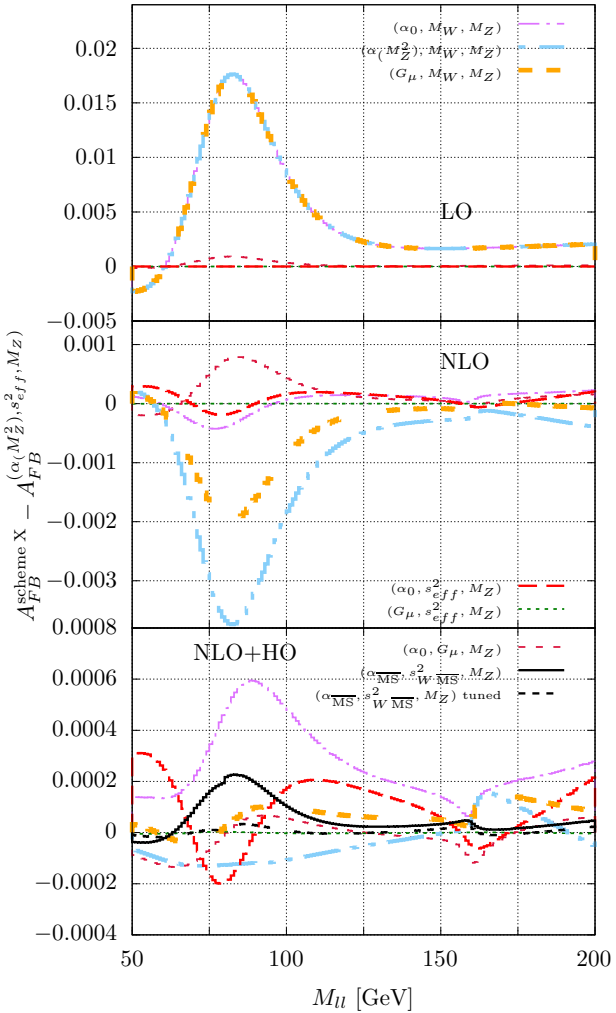
- Update on new Z_ew-BMNNPV: new calculation schemes implemented, in particular the ones designed for the weak mixing angle measurement

Spares

Predictions from different EW input schemes

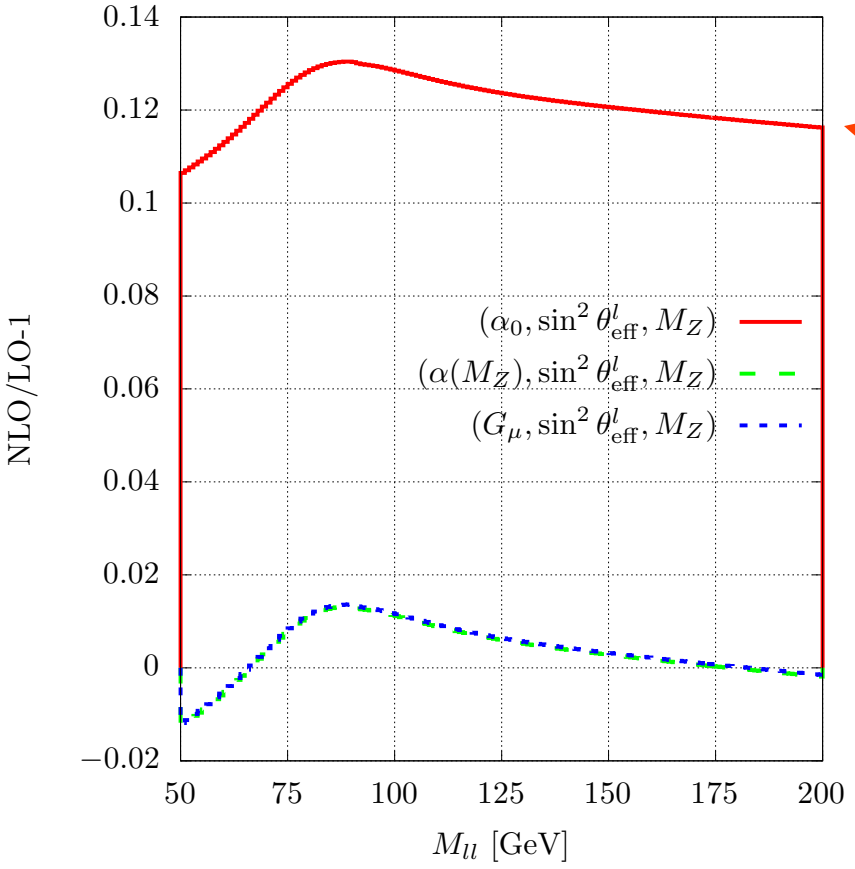


Spread reduced when including NLO and NLO+universal fermionic corrs.



Smaller effects: overall Δα, Δρ largely cancel in Asymmetry

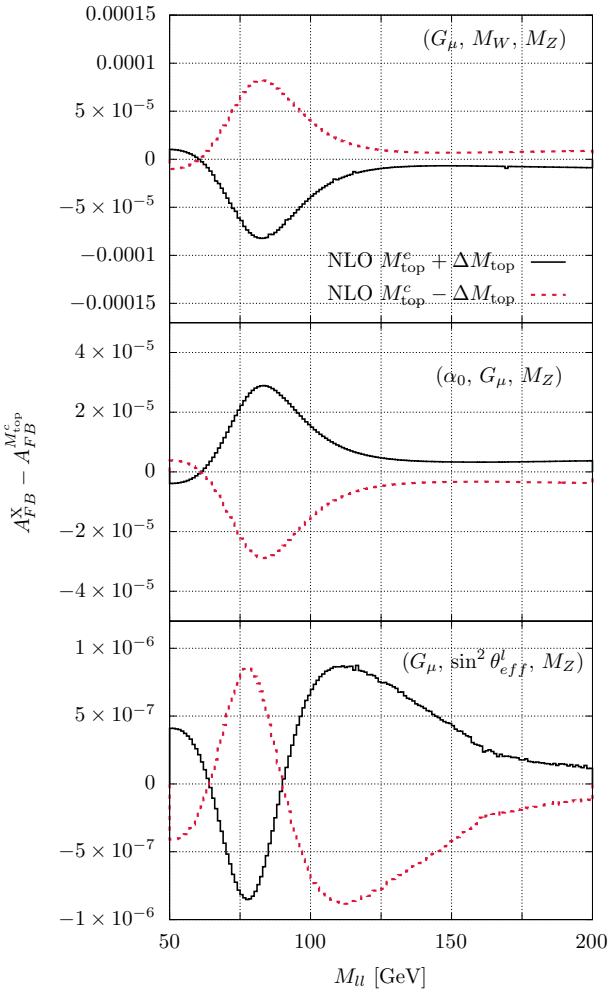
Size of radiative corrections: example

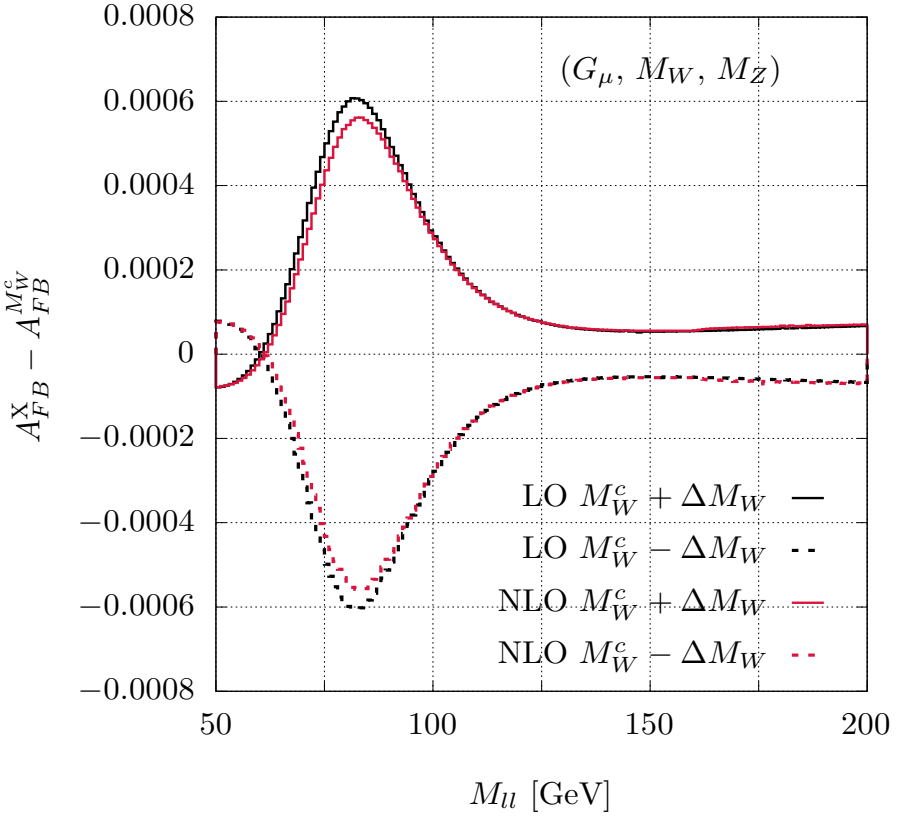


α(0) scheme:
large corrections ~ 2 Δα

Besides, sensitive to the non-perturbative hadronic running of α at low scales

Parametric uncertainties: examples

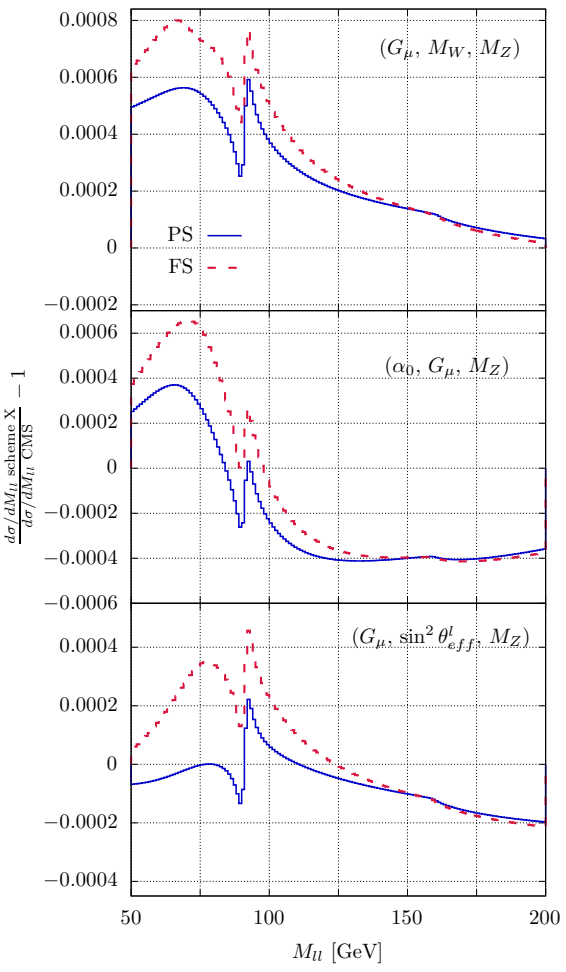


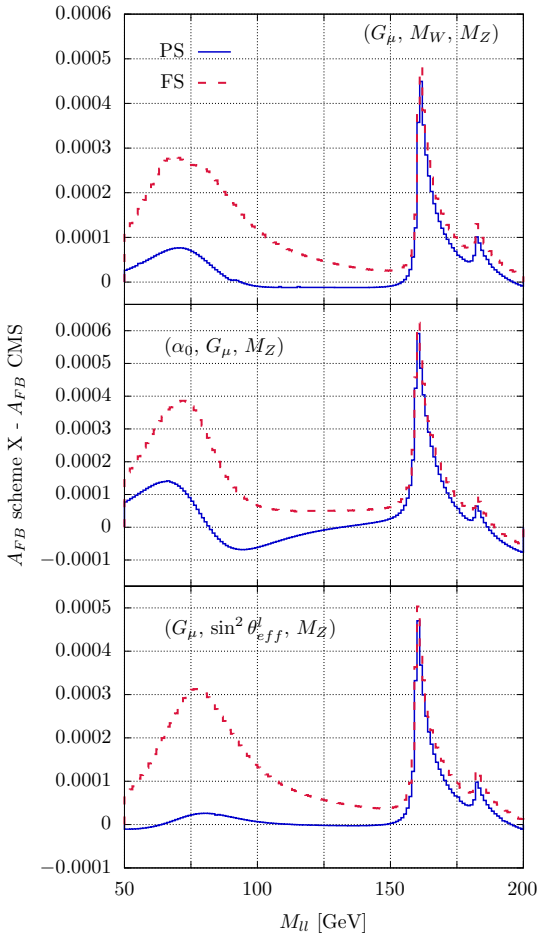


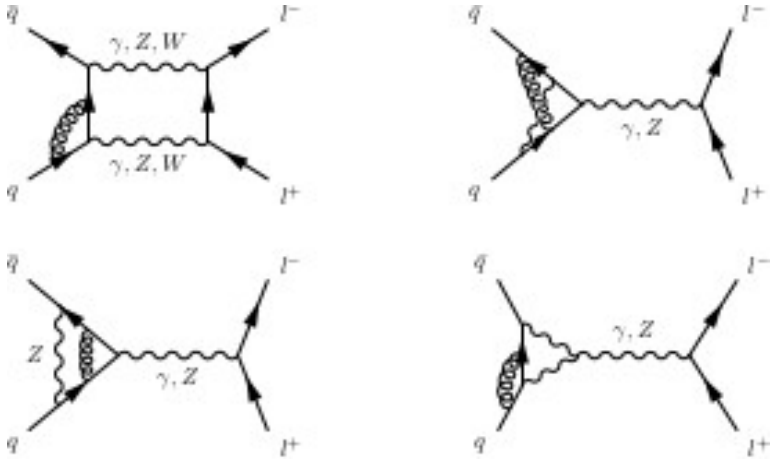
$M_{top} = 173.0 \pm 0.4\, GeV$

$M_W = 80.385 \pm 0.015\, GeV$

Th. uncertainties from other details of the calculation



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