NLO QCD and other recents results in POWHEG-BOX-ew

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This talk

- Recent results from Eur. Phys. J. C 84 (2024) 5, 539

  most recent report on Z_ew-BMNNPV with comparison of different input schemes

- Results including NLO QCD

Main features of POWHEG Z_ew-BMNNPV

- Possibility to select among different EW input and renormalization schemes:

$$(\alpha_0 \,/\, \alpha(M_Z^2) \,/\, G_\mu, M_W, M_Z) \qquad (\alpha, G_\mu, M_Z)$$

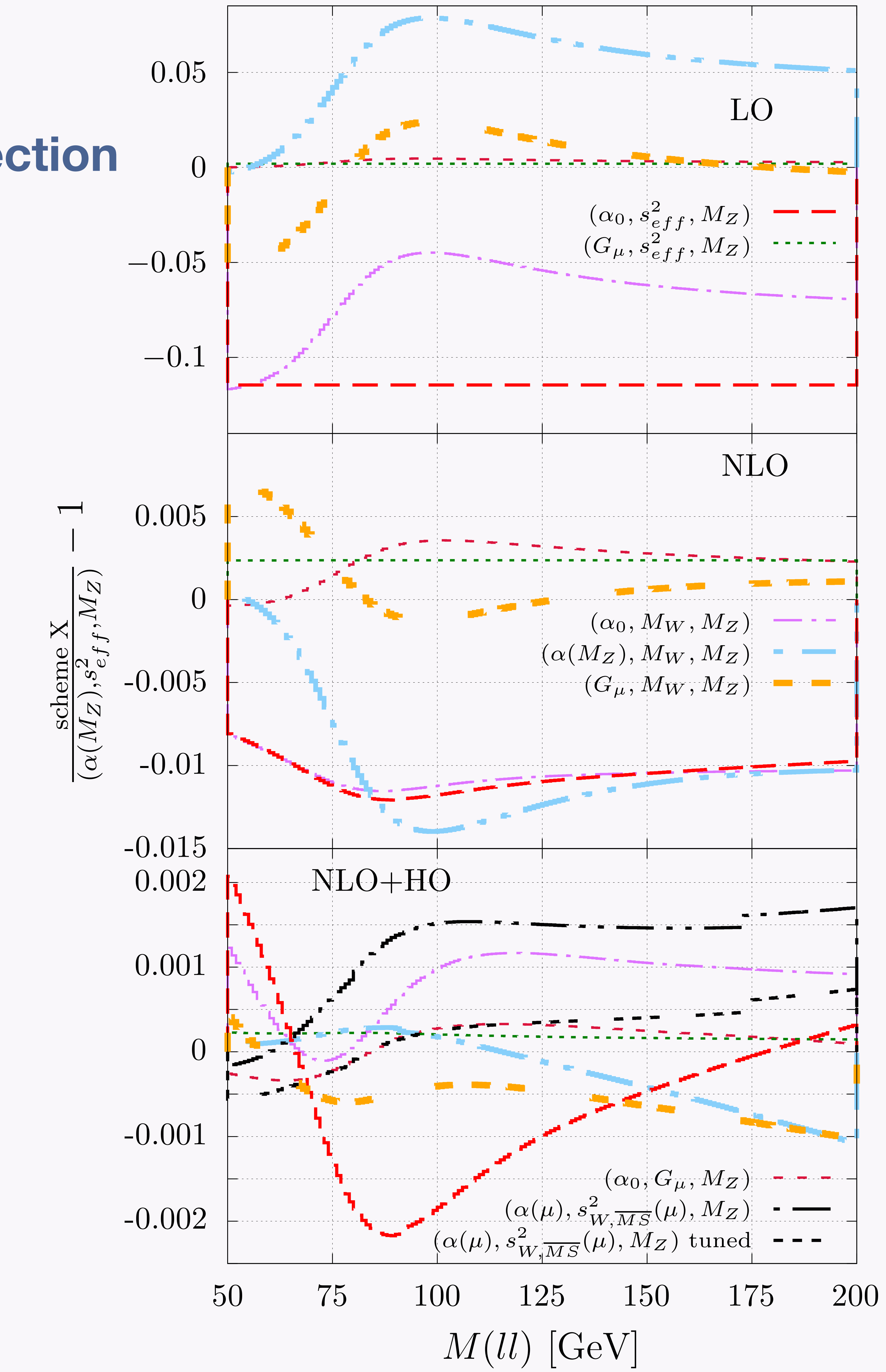
$$(\alpha_0 \,/\, \alpha(M_Z^2) \,/\, G_\mu, s_{eff}^2, M_Z) \qquad (\alpha(\mu^2), s_w^2(\mu^2), M_Z)$$

- Different options for resonance treatment: complex-mass scheme, pole scheme, factorization scheme

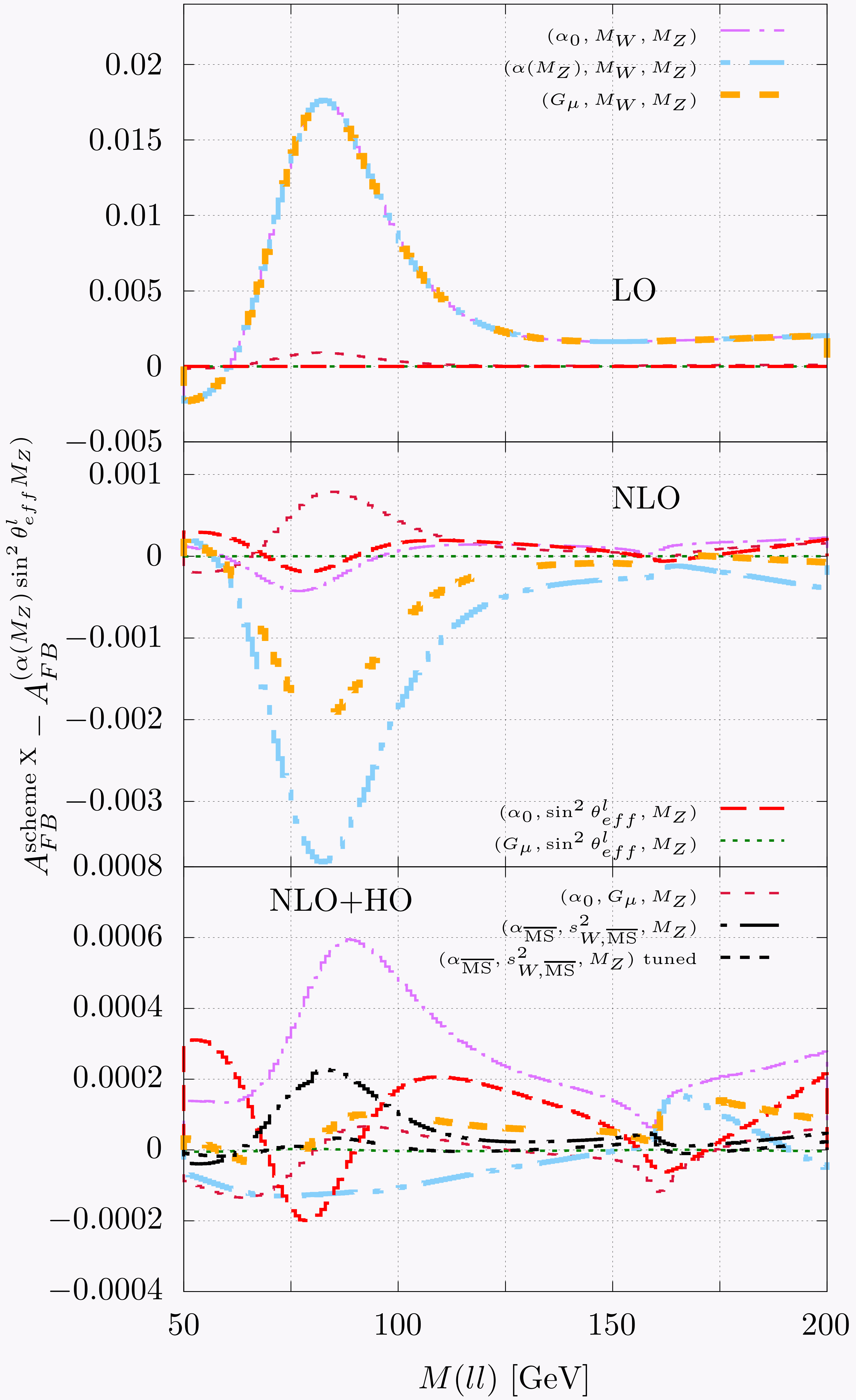
- Results for weak corrections are presented in the Z-peak region and high energy region (Sudakov regime)

Comparison among input schemes

Cross section



Asymmetry



Tuning (LEP inspired) I

Tuning from reference scheme (α_0, G_μ, M_Z)

$$\alpha(M_Z^2) = \frac{\alpha_0}{1-\Delta\alpha}$$

$(\alpha_0, s^2_{eff}, M_Z)$

$$s^2_{eff}|_{G_\mu} = \frac{1}{2} - \sqrt{\frac{1}{4} - \frac{\pi}{\sqrt{2}G_\mu M_Z^2}\alpha(M_Z^2)\left(1+\Delta\tilde{r}_{HO}\right)}$$

$$\Delta\tilde{r}_{rem} = \Delta\tilde{r}^{(1)} - \Delta\alpha + \Delta\rho^{(1)}$$

$$\Delta\tilde{r}_{HO} = \Delta\tilde{r}_{rem} - \Delta\rho$$

$$\Delta\rho = \Delta\rho^{(1)} + \Delta\rho^{(2)}$$

(α_0, M_W, M_Z)

$$M_W|_{G_\mu} = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi}{G_\mu M_Z^2}\alpha(M_Z^2)\frac{1+\Delta r^{(1)}-\Delta\alpha+\frac{c_W^2}{s_W^2}\Delta\rho^{(1,X)}}{1+\frac{c_W^2}{s_W^2}\Delta\rho^{(X)}}}\right)$$

$$\Delta\rho^{(1,X)} = \frac{\Sigma_T^{ZZ}(M_Z)}{M_Z^2} - \frac{\Sigma_T^{W}(M_W)}{M_W^2}\Bigg|_{fin,\,\mu_{dim}=M_Z}$$

$$\Delta\rho^{(X)} = \Delta\rho^{(1,X)} + \Delta\rho^{(2,X)}$$

Tuning (LEP inspired) II

Higher orders in Born Improved Approximation with $\alpha(M_Z^2)$ and s_{eff}^2

(α_0, G_μ, M_Z)

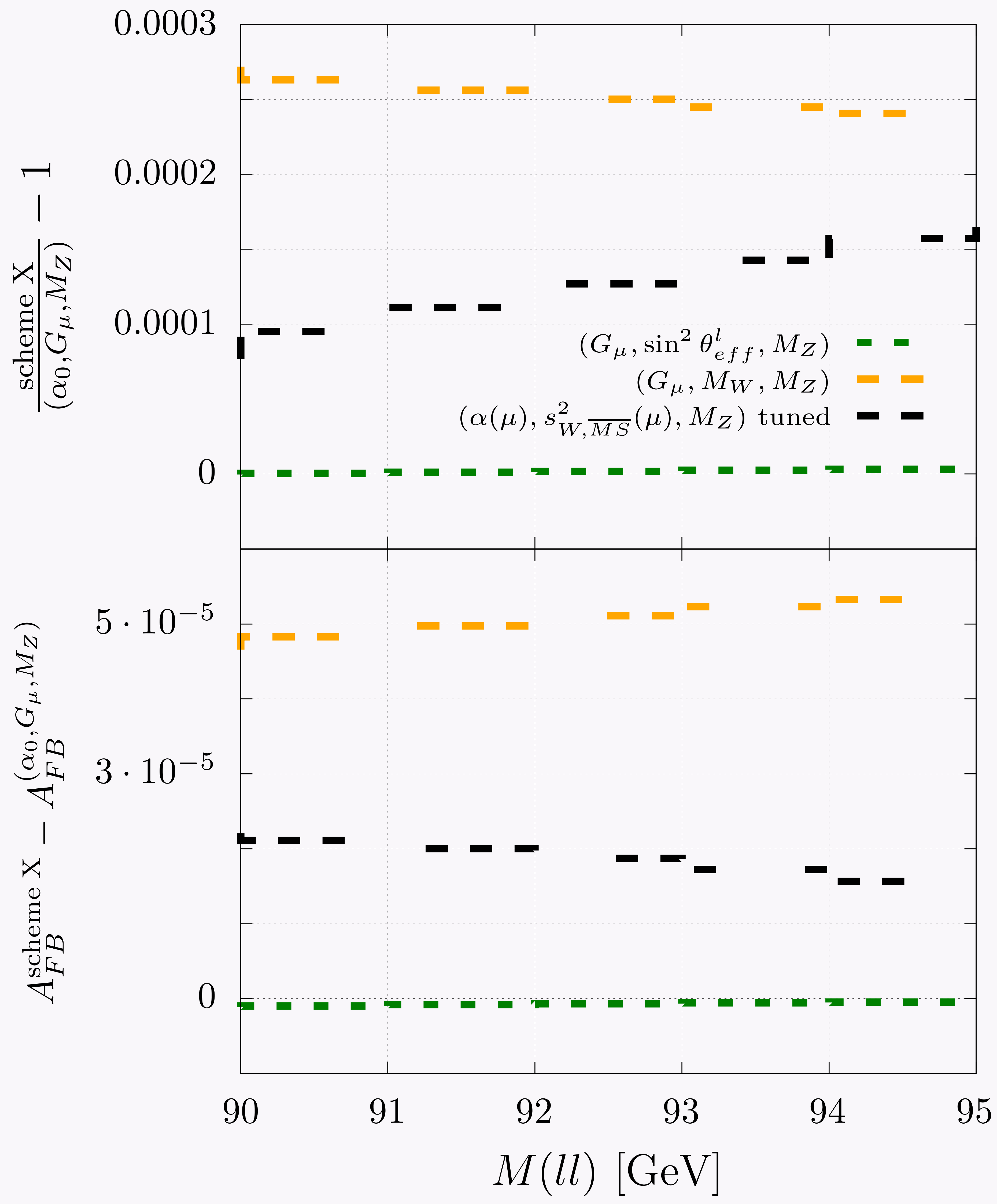
$$\tilde{s}^2_{w,\,\mathrm{NLO+HO}} = \frac{1}{2} - \sqrt{\frac{1}{4} - \frac{\pi\alpha}{\sqrt{2}G_\mu M_Z^2}(1 + \Delta\tilde{r}|_{s_w^2})}$$

(α_0, M_W, M_Z)

$$\tilde{s}^2_{w,\,\mathrm{NLO+HO}} = s_w^2\left(1 + \frac{c_w^2}{s_w^2}\Delta\rho^{(X)}\right)\left[1 - \frac{c_w^2}{s_w^2}\Delta\rho^{(1,X)} + \frac{1}{s_w^2}\frac{1}{2}\frac{g_L g_R}{(g_L - g_R)^2}\mathrm{Re}\left(\frac{\delta g_L}{g_L} - \frac{\delta g_R}{g_R}\right)\right]$$

$(\alpha_0, s_{eff}^2, M_Z)$ already ok

Results of tuning



How can this impact on our uncertainty estimation?

Resonance treatment

Complex-mass scheme

Denner, Dittmaier, Roth, Wackeroth, Nucl. Phys. B 560 no. 1-3, 33–65, 1999
Denner, Dittmaier, Roth, Wieders, Nucl. Phys. B 724 no. 1-2, 247–294, 2005
Denner, Dittmaier, Nucl. Phys. B - Proceedings Supplements 160, 22–26, 2006

$$\mu_Z = M_Z - i\Gamma_Z M_Z \qquad \mu_W = M_W - i\Gamma_W M_W$$

Pole scheme

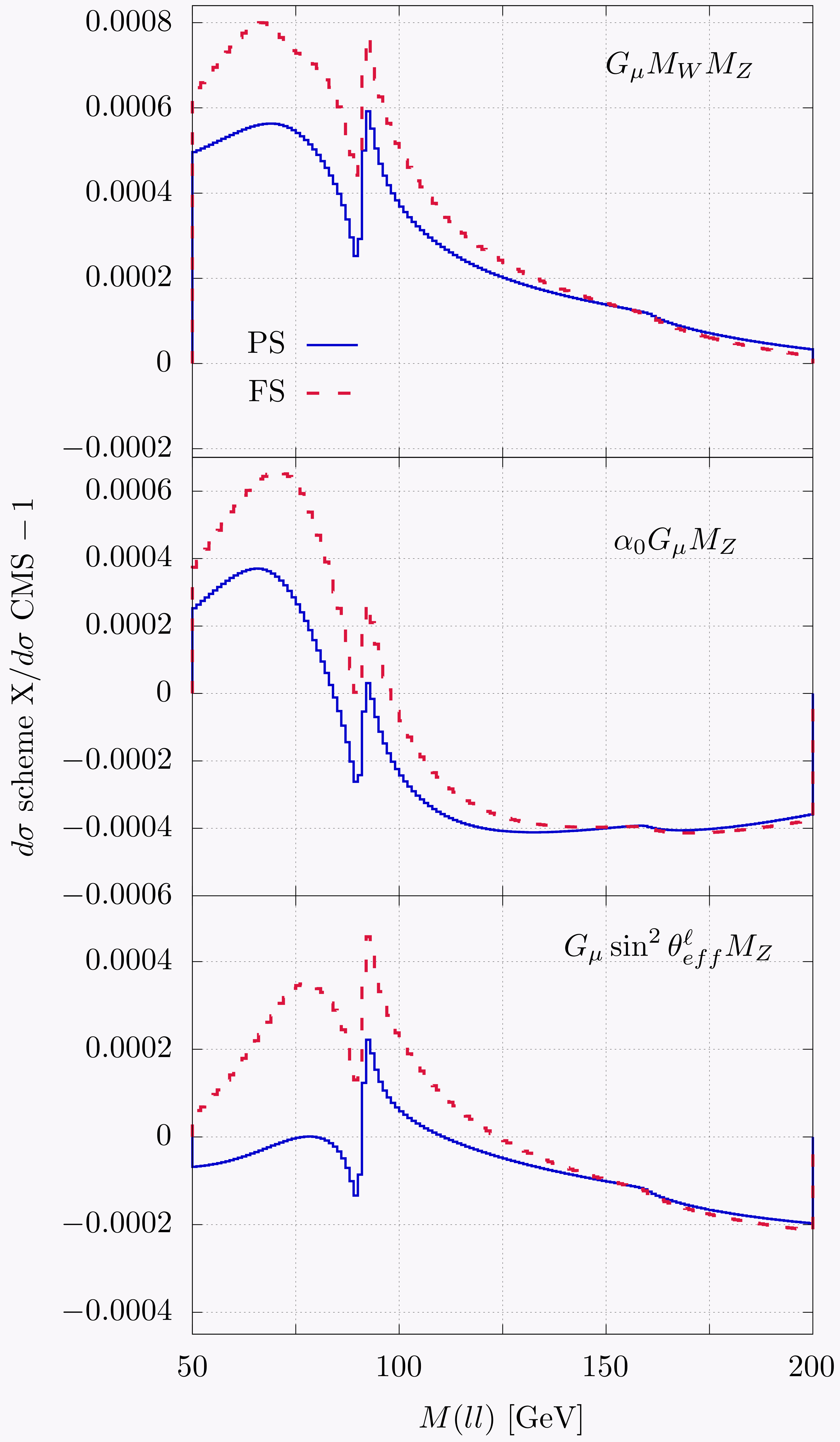
Stuart, Phys. Lett. B 262 no. 1, 113–119, 1991 - Sirlin, Phys. Lett. B 267 no. 2, 240–242, 1991
Gambino, Grassi, Phys. Rev. D 62 no. 7, 2000 - Grassi, Kniehl, Sirlin, Phys. Rev. D 65 no. 8, 2002
Stuart, Phys. Rev. Lett. 70, 3193–3196, 1993 - Dittmaier, Huber, JHEP 2010 no. 1, 2010)

$$\mathscr{M} = \frac{\tilde{R}(\mu_P^2)}{p^2 - \mu_P^2} + \frac{R(p^2) - R(M_P^2)}{p^2 - M_P^2} + \tilde{N}(p^2)$$

Factorization scheme

Argyres et al., Phys. Lett. B 358 no. 3-4, 339–346, 1995
Kurihara, Perret-Gallix, Shimizu, Phys. Lett. B 349 no. 3, 367–374, 1995
S. Dittmaier and M. Krämer, Phys. Rev. D 65 no. 7, 2002

$$f_P(p^2) = \frac{p^2 - M_P^2}{p^2 - \mu_P^2}$$



Sudakov regime

Channel with d-quarks only: no PDFs dependence
→ no large unphysical distortions at high energies

Sudakov logs

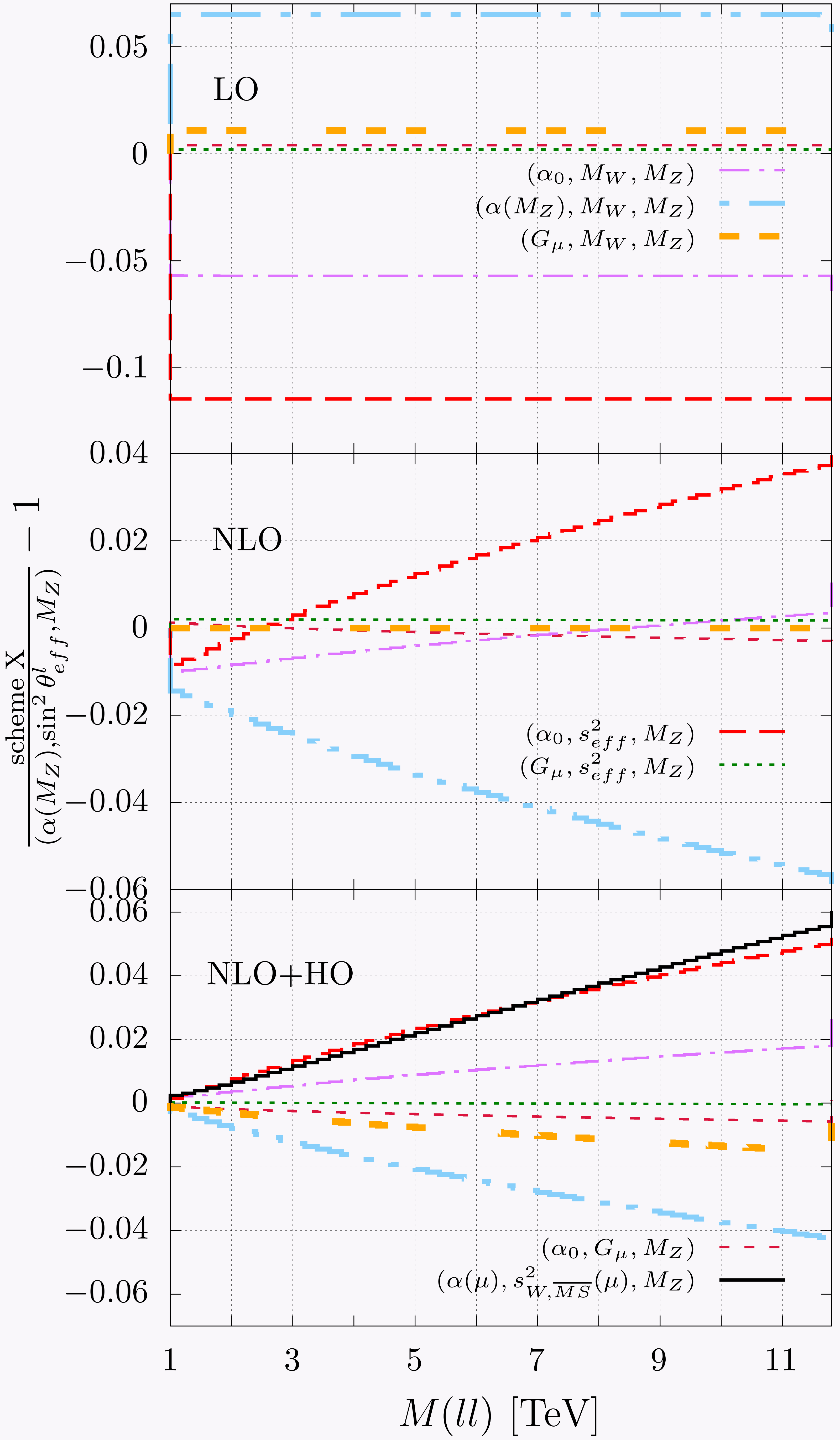
$$A(\alpha, s_w^2)\ \ln^2 \frac{s}{M_Z^2} + B(\alpha, s_w^2)\ \ln \frac{s}{M_Z^2}$$

Parameter renormalization logs

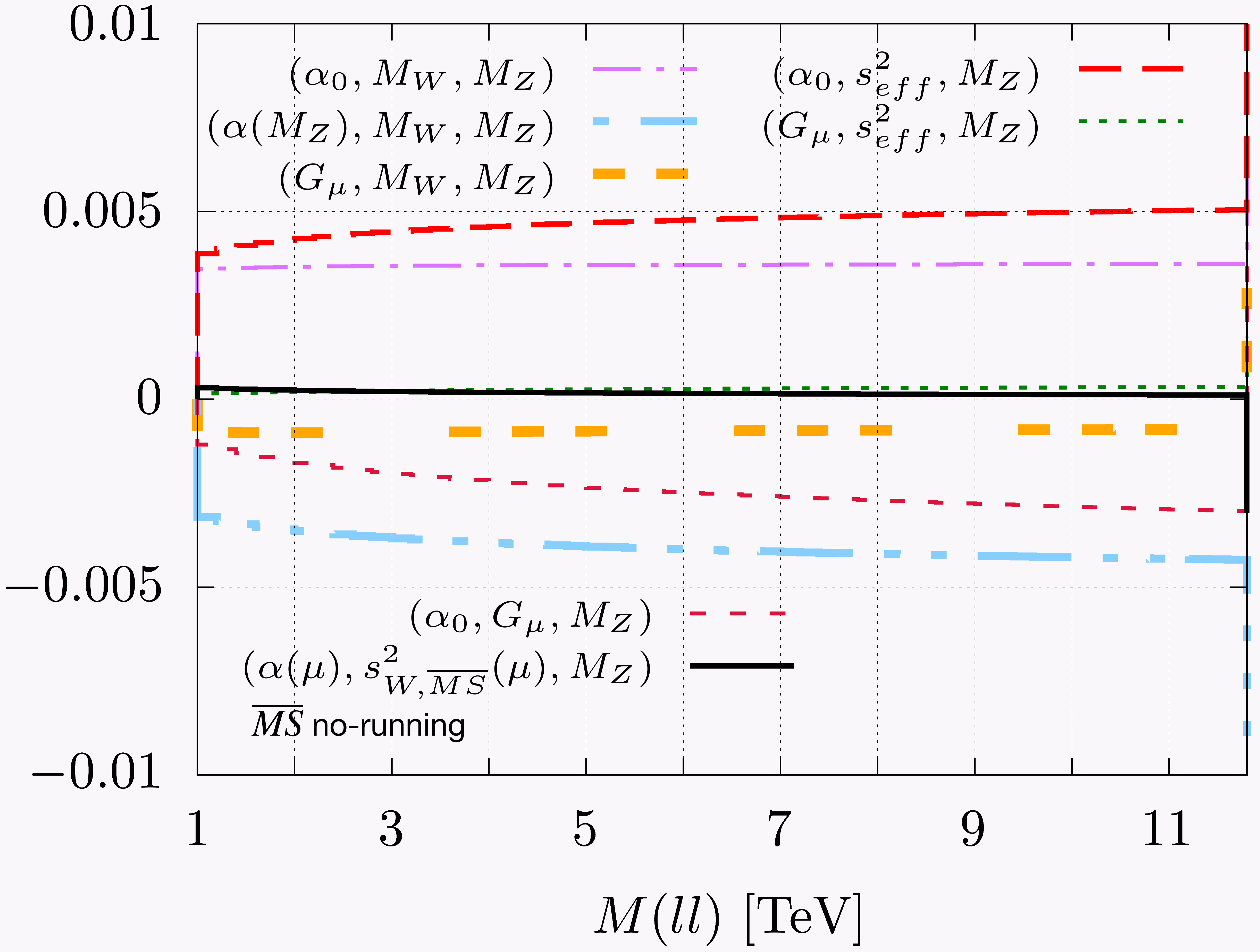
$$\frac{1}{\epsilon} - \ln \frac{r_{ct}^2}{\mu_{dim}^2} - \frac{1}{\epsilon} + \ln \frac{r_{bare}^2}{\mu_{dim}^2} = \ln \frac{r_{bare}^2}{r_{ct}^2} \sim \ln \frac{M_{ll}^2}{m^2}$$

Counterterms from parameter renorm.

Bare diagrams



Sudakov regime

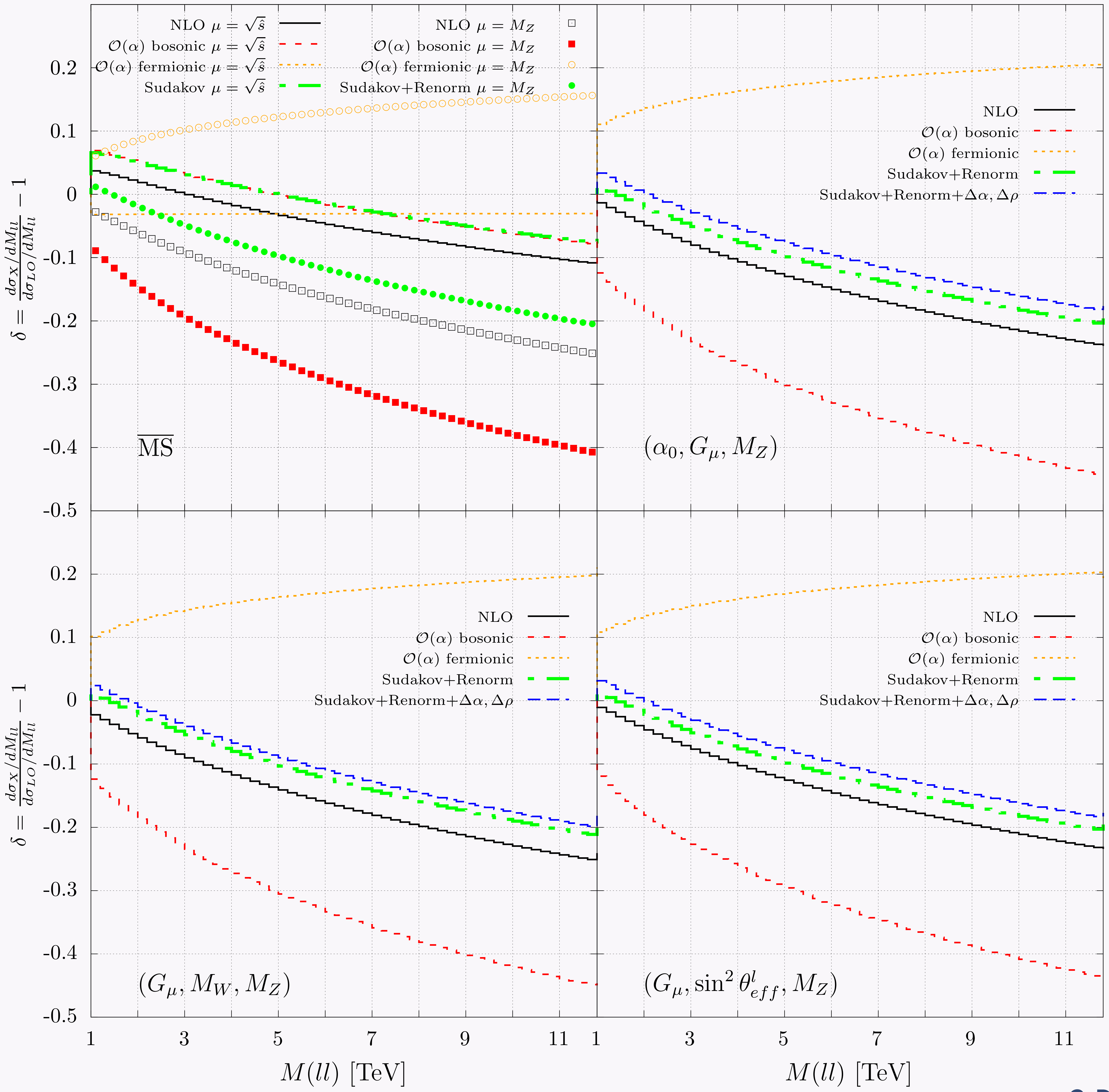


Cross section at NLO+ho - (Sudakov + param. renorm. logs)

$$\frac{scheme\ X}{(\alpha(M_Z^2), s^2_{eff}, M_Z)} - 1$$

Sudakov regime

True NLO - approx. $\sim 5\,\%$



NLO QCD effects

Code inputs and definitions

- EW scheme: (α, M_Z, M_W)
- CMS scheme
- $\sqrt{s} = 8\ \mathrm{TeV}$
- PDF: MSTW2008nlo68cl (LHA 21100)
- factorisation scheme: $\overline{MS}$

  $\mu_F = \mu_R = M_{\ell\bar{\ell}}$

Parameter	Value
α	$7.297353 \cdot 10^{-3}$
G_μ	$1.166389 \cdot 10^{-5}$
M_Z*	91.1876
Γ_Z*	2.4952
M_W*	80.385
Γ_W*	2.085
M_H	125
m_e	$0.51099907 \cdot 10^{-3}$
m_μ	0.1056583
m_τ	1.77705
m_b	4.7
m_t	173

Parameter	Value
m_u	0.06983
m_d	0.06984
m_s	0.15
m_c	1.2

* Automatically translated to pole values

QED corrections

$A_4 = 8/3 A_{FB}$

Code:		$89 < M_{\ell\bar{\ell}}[\text{GeV}] < 93$	$60 < M_{\ell\bar{\ell}}[\text{GeV}] < 81$	$81 < M_{\ell\bar{\ell}}[\text{GeV}] < 101$	$101 < M_{\ell\bar{\ell}}[\text{GeV}] < 150$
$8/3 \cdot [A_{FB}\text{ (NLO QED ISR)} - A_{FB}\text{ (LO)}]/10^{-4}$					
MCSANC		0.2(3)	−5(2)	0.2(3)	5(2)
WZGRAD2		0.2(5)	−5(3)	0.3(5)	6(4)
KKMC-hh		−1.0(6)	0(1)	−0.5(5)	−8(2)
KKMC-hh (NISR)		−1(2)	0(4)	0(1)	6(8)
RADY (CMS)		0.16(4)	−4.05(3)	0.12(3)	4.90(3)
A. Huss		0.17(1)	−4.07(1)	0.11(1)	4.94(4)
POWHEG_{ew}		0.1(1)	−4.0(4)	0.1(1)	4.5(7)
$8/3 \cdot [A_{FB}\text{ (NLO QED IFI)} - A_{FB}\text{ (LO)}]/10^{-4}$					
MCSANC		−2.8(5)	−34(2)	−4.0(4)	−60(3)
WZGRAD2		−1.1(5)	−37(3)	−2.3(5)	−51(4)
KKMC-hh		−3.8(6)	−25(1)	−2.1(1)	−53(1)
KKMC-hh (NISR)		−3.1(6)	−17(1)	−3.2(5)	−60(3)
RADY (CMS)		−1.5(1)	−33.6(4)	−2.49(7)	−59.5(1)
A. Huss		−1.42(6)	−33.9(6)	−2.57(7)	−58.7(3)
POWHEG_{ew}	$\mu_F = M_{\ell\bar{\ell}\gamma}$	−1.2(3)	−62(1)	−2.5(4)	−59(2)
	$\mu_F = M_{\ell\bar{\ell}}$	−1.3(6)	−34(2)	−2.6(7)	−59(3)

- POWHEG_{ew} $\mu_F(1) \Longrightarrow M_{ll}$ for real rad calculated with underlying Born momenta
- POWHEG_{ew} $\mu_F(2) \Longrightarrow M_{ll}$ for real rad calculated with radiative event momenta
- differences between $\mu_F(1)$ and (2) expected to decrease when including also QCD corrections

F. Piccinini (INFN Pavia) QED/EW subgroup 11 July 2024 25 / 31

From last General Meeting July 2024

Overall agreement of the codes

QED corrections

$A_4 = 4\langle \cos\vartheta \rangle$

Code:	$89 < M_{\ell\bar{\ell}}$[GeV] < 93	$60 < M_{\ell\bar{\ell}}$[GeV] < 81	$81 < M_{\ell\bar{\ell}}$[GeV] < 101	$101 < M_{\ell\bar{\ell}}$[GeV] < 150
$[A_4\,(\text{NLO QED ISR}) - A_4\,(\text{LO})]/10^{-4}$				
RADY (CMS)	0.15(3)	−4.05(3)	0.10(2)	4.89(2)
A. Huss	0.16(1)	−4.07(1)	0.11(1)	4.87(2)
POWHEG$_{ew}$	0.07(9)	−4.0(3)	0.10(7)	4.8(4)
$[A_4\,(\text{NLO QED IFI}) - A_4\,(\text{LO})]/10^{-4}$				
RADY (CMS)	−1.7(1)	−42.3(4)	−2.97(6)	−71.6(2)
A. Huss	−1.68(6)	−42.4(6)	−3.05(8)	−71.2(3)
POWHEG$_{ew}$ $\mu_F = M_{\ell\bar{\ell}\gamma}$	−1.5(5)	−70(1)	−3.0(4)	−71(3)
POWHEG$_{ew}$ $\mu_F = M_{\ell\bar{\ell}}$	−1.5(5)	−43(1)	−3.0(4)	−71(3)

- POWHEG$_{ew}$ $\mu_F(1) \Longrightarrow M_{ll}$ for real rad calculated with underlying Born momenta
- POWHEG$_{ew}$ $\mu_F(2) \Longrightarrow M_{ll}$ for real rad calculated with radiative event momenta
- at low and high M_{ll} virtual QED boxes and I-F real radiation interference break factorization assumption for angular coefficients and the LO equality between the two A_4 def's
- differences between $\mu_F(1)$ and (2) expected to decrease when including also QCD corrections

From last General Meeting July 2024

Overall agreement of the codes

NLO QED and QCD corrections - how to combine them?

1: additive method

$$\sigma_{\mathrm{QED+QCD}} = \sigma_{\mathrm{NLOQCD}} + \sigma_{\mathrm{NLOQED}} - \sigma_{\mathrm{LO}} = \sigma_{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}} + \delta_{\mathrm{QED}}\right)$$

$$A_{\mathrm{FB}}^{\mathrm{QED+QCD}} = \frac{\left(\sigma_F - \sigma_B\right)^{\mathrm{NLOQED}} + \left(\sigma_F - \sigma_B\right)^{\mathrm{NLOQCD}} - \left(\sigma_F - \sigma_B\right)^{\mathrm{LO}}}{\left(\sigma_F + \sigma_B\right)^{\mathrm{NLOQED}} + \left(\sigma_F + \sigma_B\right)^{\mathrm{NLOQCD}} - \left(\sigma_F + \sigma_B\right)^{\mathrm{LO}}}$$

Equivalent at NLO
difference due to $\mathcal{O}(\alpha\alpha_S)$ terms

2: factorized method

$$\sigma_{\mathrm{QED+QCD}} = \sigma_{\mathrm{LO}}\left(1 + \delta_{\mathrm{QCD}}\right)\left(1 + \delta_{\mathrm{QED}}\right)$$

$A_{\mathrm{FB}}^{\mathrm{QED+QCD}}$ to be computed bin-by-bin from $d\sigma/d\cos\theta$ - has more complicated expression

starting point: $$\frac{d\sigma_{\mathrm{QED+QCD}}}{d\cos\theta} = \frac{d\sigma_{\mathrm{NLOQCD}}}{d\cos\theta}\left(\frac{d\sigma_{\mathrm{NLOQED}}}{d\cos\theta} \Big/ \frac{d\sigma_{\mathrm{LO}}}{d\cos\theta}\right)$$

QED and QCD corrections

Numbers obtained with additive method

$\mu_R = \mu_F = M_{\ell\bar{\ell}}$ $A_4 = 8/3 \cdot A_{FB}$

89 – 93 GeV	60 – 81 GeV	81 – 101 GeV	101 – 150 GeV
$8/3 \cdot A_{FB}(LO)$			
0.12414(1)	−0.54107(2)	0.119512(8)	0.60292(4)
$8/3 \cdot [A_{FB}(NLOQCD) - A_{FB}(LO)]/10^{-2}$			
−0.38(4)	2.10(2)	−0.36(3)	−1.86(3)
$8/3 \cdot [A_{FB}(NLOQCD + QED) - A_{FB}(LO)]/10^{-2}$			
−0.067(9)	27.24(1)	−0.152(6)	−1.79(4)

QED : $[A_{FB}(\text{NLO QED}) - A_{FB}(\text{LO})]/10^{-2}$

NLOQCD + QED : $[A_{FB}(\text{NLO QCD + QED}) - A_{FB}(\text{NLO QCD})]/10^{-2}$

	$89 < M_{\ell\bar{\ell}}[\text{GeV}] < 93$	$60 < M_{\ell\bar{\ell}}[\text{GeV}] < 81$	$81 < M_{\ell\bar{\ell}}[\text{GeV}] < 101$	$101 < M_{\ell\bar{\ell}}[\text{GeV}] < 150$
QED	0.423(2)	28.296(3)	0.262(2)	0.27(1)
NLO QCD + QED	0.32(1)	25.14(3)	0.209(9)	0.07(5)
QED FSR	0.439(2)	28.604(7)	0.289(1)	0.87(1)
NLO QCD + QED FSR	0.33(1)	25.42(3)	0.231(9)	0.58(5)
QED ISR	0.001(1)	−0.040(4)	0.001(1)	0.045(6)
NLO QCD + QED ISR	0.002(8)	−0.04(2)	0.002(7)	0.05(3)
QED IFI	−0.013(6)	−0.34(2)	−0.026(7)	−0.59(3)
NLO QCD + QED IFI	−0.01(1)	−0.30(4)	−0.02(1)	−0.52(5)

QED and QCD corrections

Numbers obtained with additive method

$\mu_R = \mu_F = M_{\ell\bar{\ell}}$ $A_4 = 4 < \cos\theta >$

89 – 93 GeV	60 – 81 GeV	81 – 101 GeV	101 – 150 GeV
$A_4 = 4 < \cos\theta >$ (LO)			
0.031034(1)	−0.135266(3)	0.029878(1)	0.150727(2)
$[A_4(\text{NLOQCD}) - A_4(\text{LO})]/10^{-2}$			
−0.384(4)	2.1(1)	−0.363(3)	−1.89(1)
$[A_4(\text{NLOQCD+QED}) - A_4(\text{LO})]/10^{-2}$			
−0.071(7)	27.154(6)	−0.160(5)	−1.94(3)

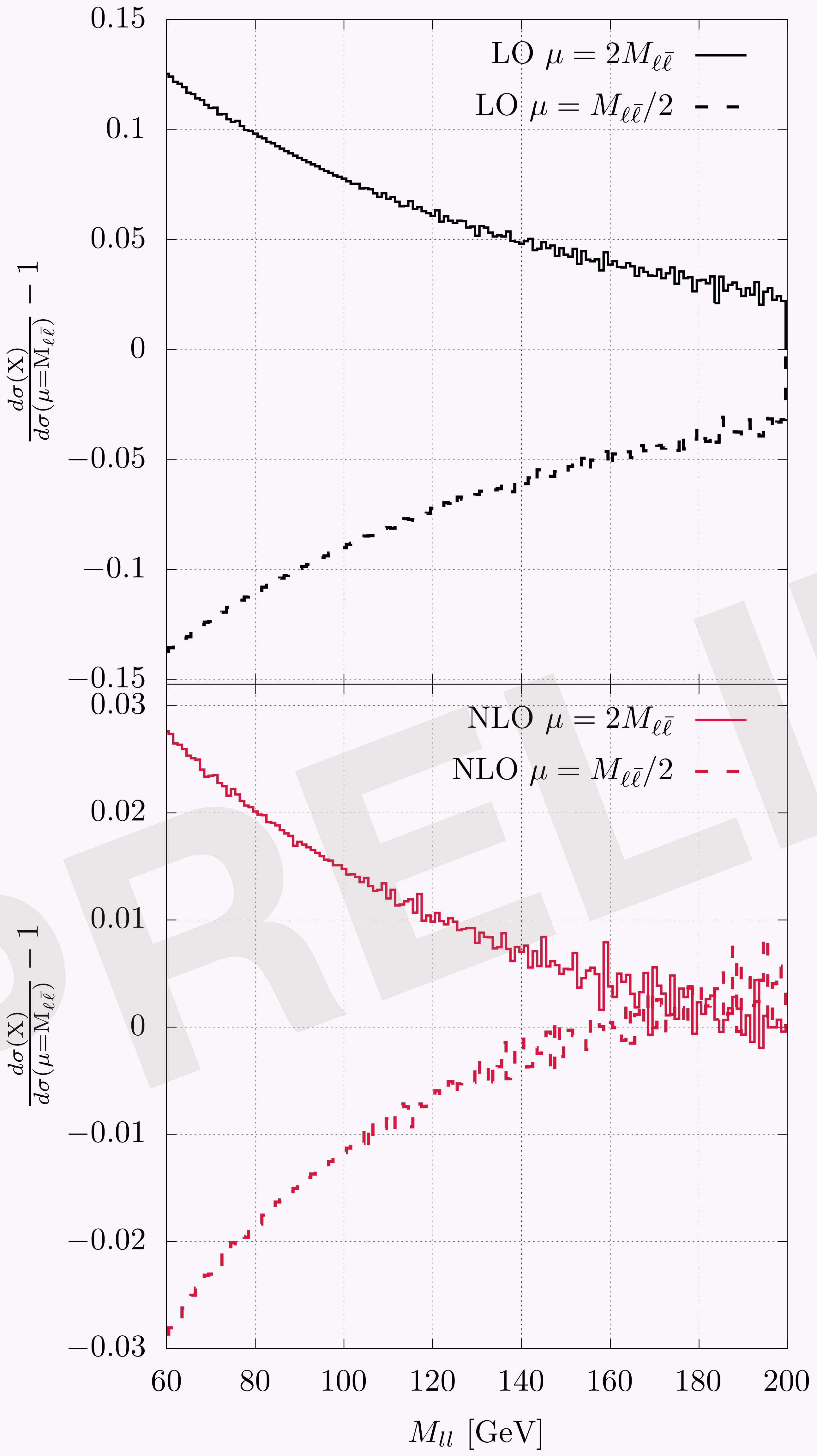
QED : $[A_4\,(\text{NLO QED}) - A_4\,(\text{LO})]/10^{-2}$

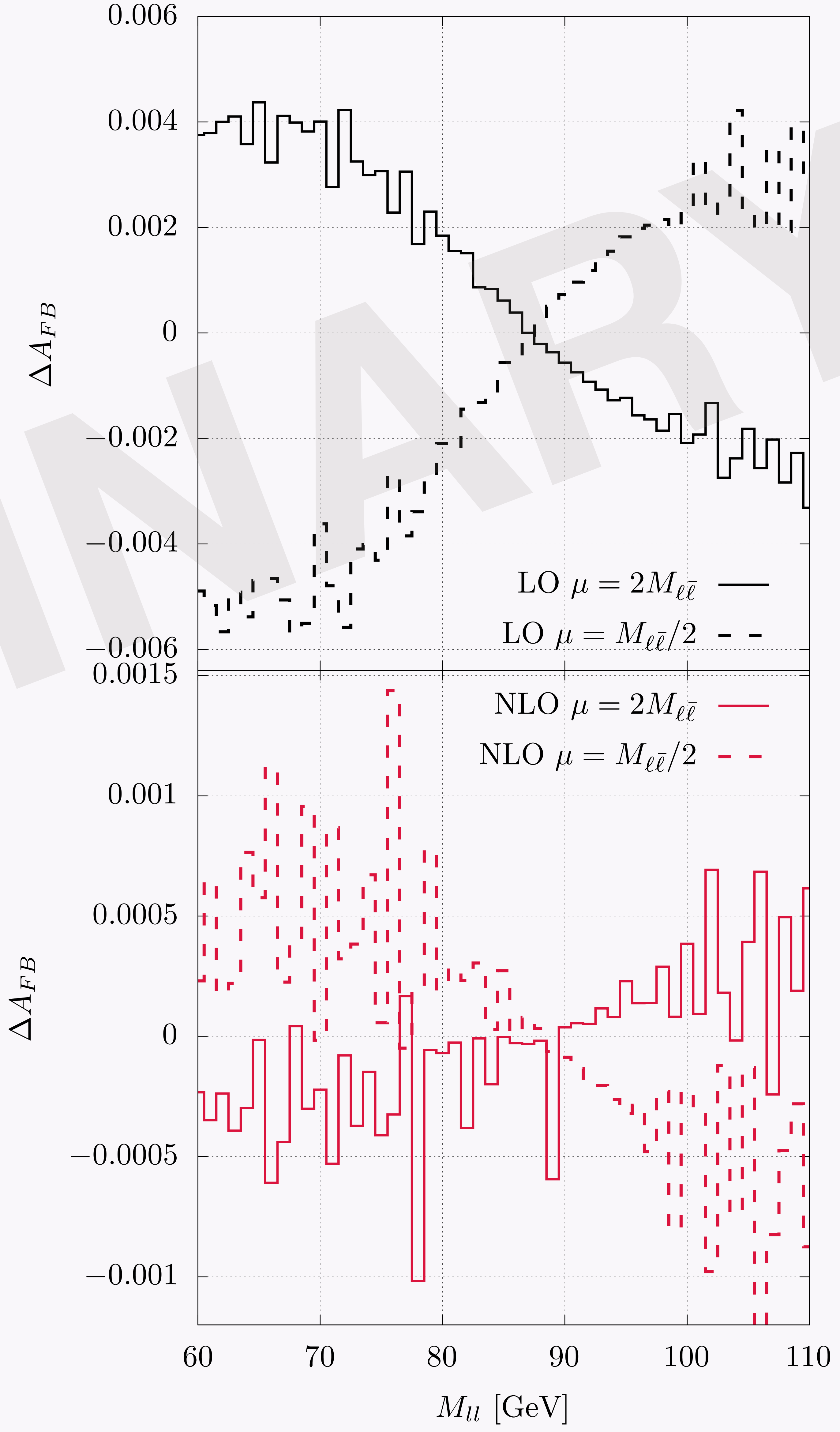
NLOQCD + QED : $[A_4\,(\text{NLO QCD + QED}) - A_4\,(\text{NLO QCD})]/10^{-2}$

	$89 < M_{\ell\bar{\ell}}[\text{GeV}] < 93$	$60 < M_{\ell\bar{\ell}}[\text{GeV}] < 81$	$81 < M_{\ell\bar{\ell}}[\text{GeV}] < 101$	$101 < M_{\ell\bar{\ell}}[\text{GeV}] < 150$
QED	0.420(2)	28.196(3)	0.256(1)	0.131(8)
NLO QCD + QED	0.313(9)	25.05(1)	0.203(7)	−0.05(4)
QED FSR	0.438(1)	28.553(6)	0.288(1)	0.862(9)
NLO QCD + QED FSR	0.327(9)	25.37(2)	0.229(7)	0.57(4)
QED ISR	0.0007(9)	−0.040(3)	0.0010(7)	0.048(4)
NLO QCD + QED ISR	0.002(6)	−0.04(1)	0.002(4)	0.05(3)
QED IFI	−0.015(5)	−0.43(1)	−0.030(4)	−0.72(3)
NLO QCD + QED IFI	−0.013(9)	−0.37(2)	−0.026(7)	−0.62(5)

Scale variations at NLO QCD

Cross section



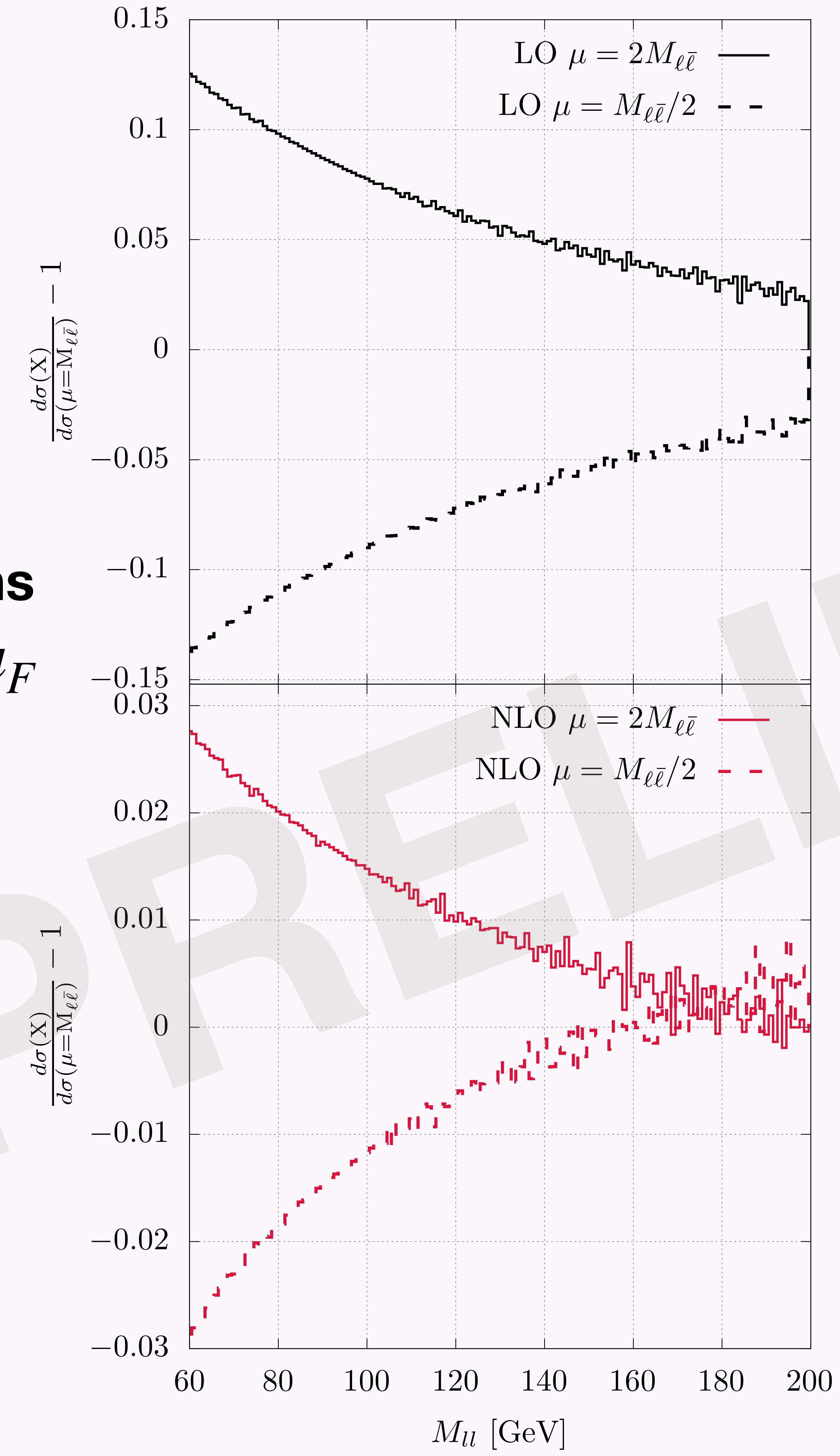


Asymmetry

Still low statistics

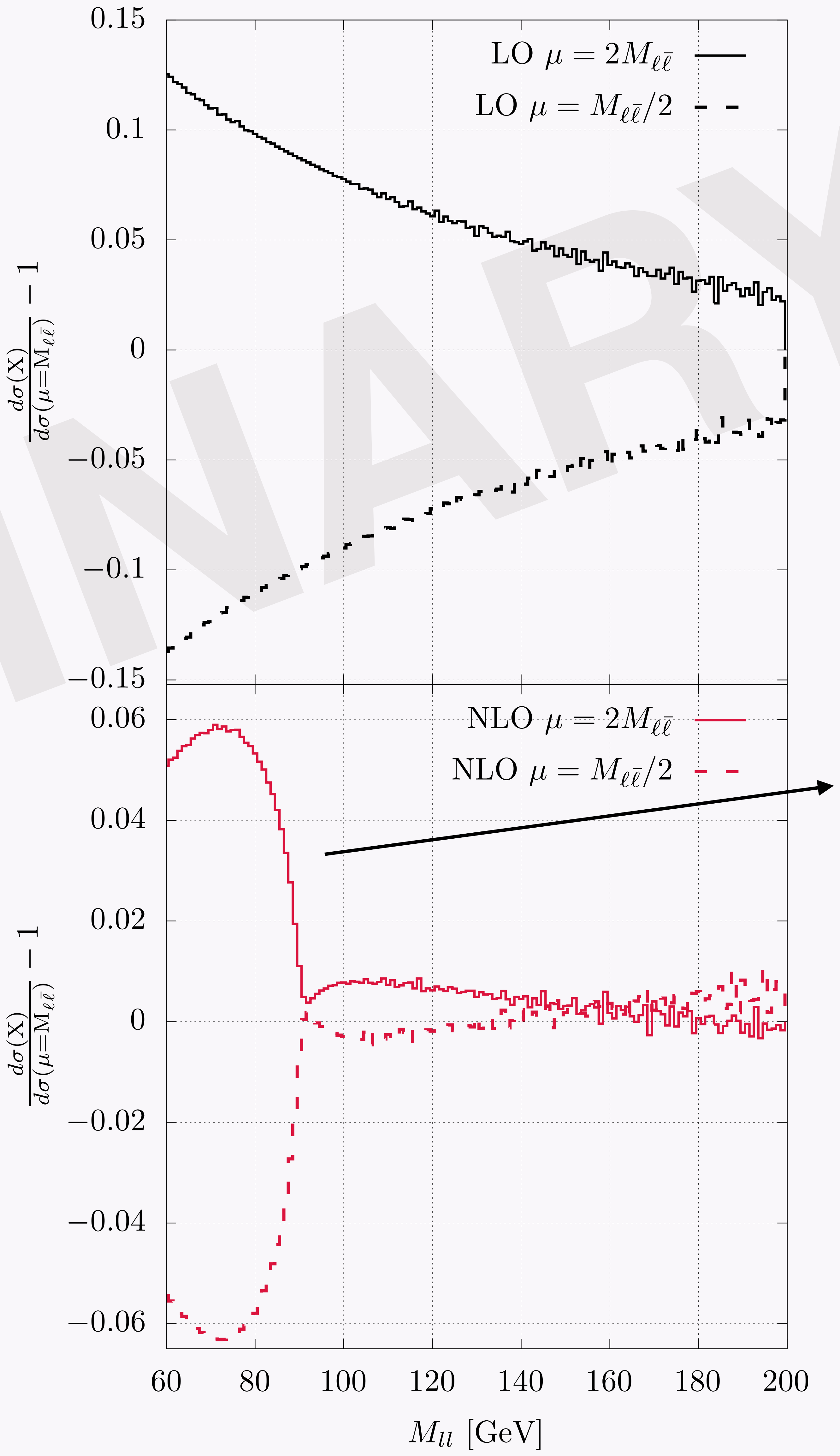
Scale variations at NLO QCD+QED

Cross section factorised method



Hp. QED corrections do not depend on μ_F

Cross section additive method



This bulk is due to NLO QED corrections: multi-photon emission would reduce the effect

Summary and roadmap

- Systematic study of different renormalization and input parameter schemes, as well as tuned realisations of some schemes, can be useful in our discussion on theoretical uncertainties
- Comparison of different schemes at high energy and effects of the Sudakov approximation for NC DY
- NLO QCD corrections with POWHEG and their combination with QED effects studied for A_4 and A_{FB} together with preliminary exploration of scale variations

To be done:

- plots for asymmetry with QCD+QED combination (higher stat will probably be needed)
- quantification of the impact of using $\mu_F = M_{\ell\bar{\ell}}$ or $\mu_F = M_{\ell\bar{\ell}\gamma}$ at NLO QCD+QED to follow-up previous discussions