# HO QCD and HO EW calculations for NC Drell-Yan production

**Uta Klein**
**for the ATLAS Collaboration**

**University of Liverpool**
**and**
**CERN-RFBR Scientific-Cooperation 12-02-91526-CERN_a**

**LPCC EW WG Meeting, 9.10.2012**

# NNLO QCD and HO EW corrections - so far

**ATLAS strategy since 2010 for calculations of theory predictions: a "wise" choice of the EW parameter schema may minimise the missing pure weak effects, e.g. like the $G_\mu$ schema for W and Z production : input W and Z masses and $G_\mu$**

$$\frac{1}{\alpha_G} = \frac{\sqrt{2} G_\mu M_W^2}{\pi} \left(1 - \frac{M_W^2}{M_Z^2}\right); \quad \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

**see e.g. QED FSR corrected 2010 W and Z data, ATLAS Phys. Rev. D85, 072004 (2012)**

- ➔ **apply to HO QCD predictions remaining missing HO EW corrections (pure weak, QED ISR and ISR+FSR interferences) for the differential Z and W distributions**
- ➔ **estimated using the SANC program** A. Andonov, A. Arbuzov, D. Bardin, S. Bondarenko,P. Christova, et al., Comput.Phys.Commun., 181, 305 (2010), arXiv:0812.4207 [physics.comp-ph].
- ➔ **The interference effects are below 0.1% for all considered channels.**
- ➔ **Pure weak effects may change the predicted cross sections by about 0.5%. Shape modifications due to the pure weak corrections are calculated to be at most 10 % of the quoted correction values.**

# NNLO QCD and HO EW corrections - now

**New calculations based on FEWZ 3.1 (3.1.a3 and 3.1.b2) :**

**"Combining QCD and electroweak corrections to dilepton production in FEWZ", Ye Li, Frank Petriello, arXiv:1208.5967 (August 2012)**

**and**

**"SANC integrator in the progress: QCD and EW contributions", D. Bardin et al., arXiv:1207.4400.**

**Aim: Combine HO QCD and HO EW corrections for precision analysis of NC and CC DY production.**

**Focus : Currently ongoing high and low mass Drell-Yan analysis → crucial to evaluate impact of EW corrections for NNLO QCD fits**

**Issues : Benchmarking of results obtained with FEWZ 3.1.X versions (pre-releases used since several months in close discussion with Frank P. and Ye Li) w.r.t. SANC**

- **Understand predictions for 2 different EW parameter schemata**
- **Understand cut and PDF sensitivity of EW corrections**
- **NEW since Durham workshop : estimate photon-photon induced contributions**

arXiv:0911.2329v2

# EW parameter schema

- $\alpha(0)$-*scheme:* The fine-structure constant $\alpha(0)$ and all particle masses define the complete input. In this scheme, the relative corrections to the $q\bar{q} \to \gamma/\mathrm{Z} \to l^- l^+$ cross sections sensitively depend on the light-quark masses via $\alpha \ln m_q$ terms that enter the charge renormalization. ➔ has to be used for photon induced processes

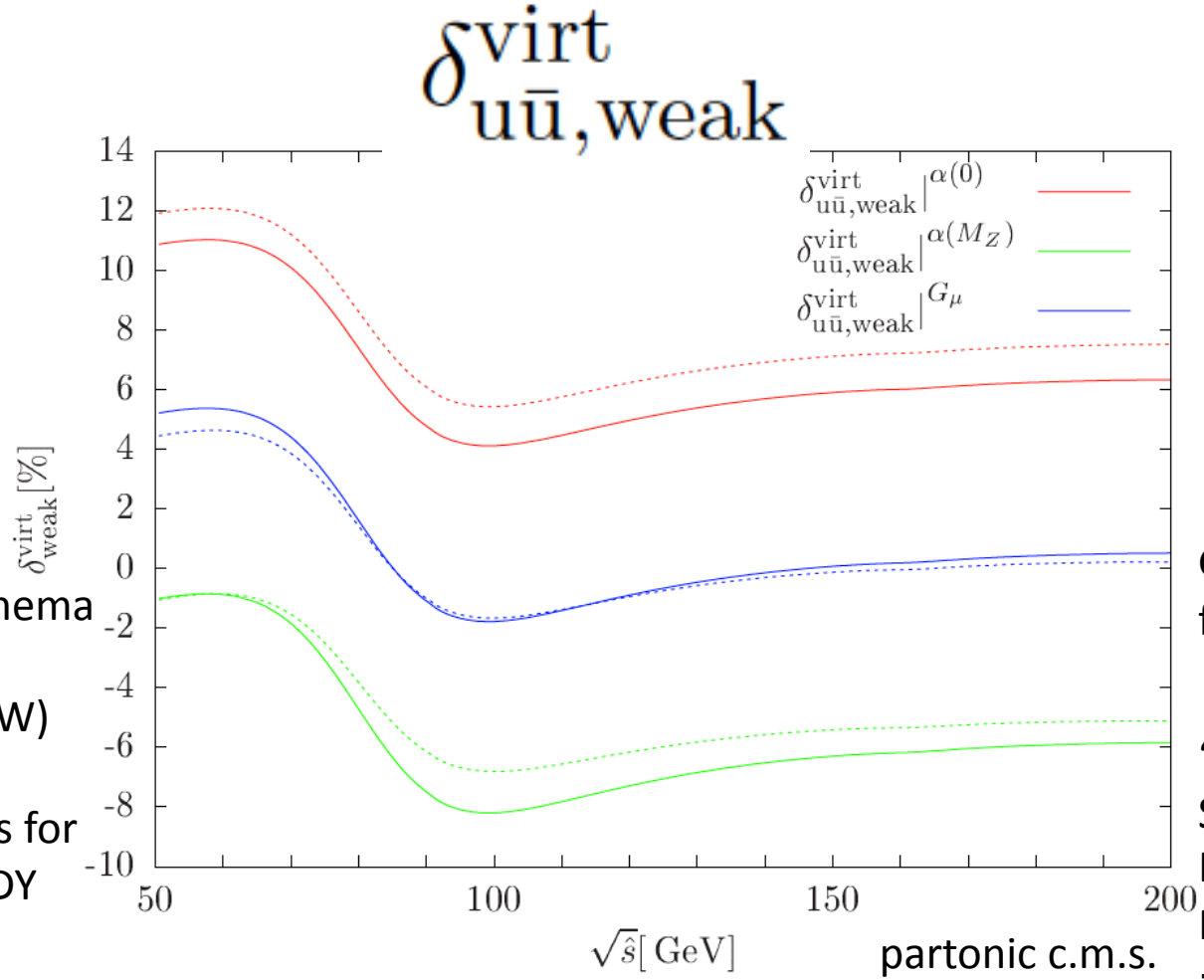
- $\alpha(M_\mathrm{Z})$-*scheme:* The effective electromagnetic coupling $\alpha(M_\mathrm{Z})$ and all particle masses define the basic input. Tree-level couplings are derived from $\alpha(M_\mathrm{Z})$, and the relative corrections receive contributions from the quantity $\Delta\alpha(M_\mathrm{Z})$, which accounts for the running of the electromagnetic coupling from scale $Q = 0$ to $Q = M_\mathrm{Z}$ (induced by light fermions) and cancels the corresponding $\alpha \ln m_q$ terms that appear in the corrections to the $q\bar{q}$ channels in the $\alpha(0)$-scheme. ➔ default schema in FEWZ 2.0, 2.1, e.g. used by CMS for PAS EWK-11-007
  ➔ **we use it as a cross check**

- $G_\mu$-*scheme:* The Fermi constant $G_\mu$ and all particle masses define the basic input. Tree-level couplings are derived from the effective coupling $\alpha_{G_\mu} = \sqrt{2} G_\mu M_\mathrm{W}^2 (1 - M_\mathrm{W}^2/M_\mathrm{Z}^2)/\pi$, and the relative corrections receive contributions from the quantity $\Delta r$ [40], which describes the radiative corrections to muon decay. Since $\Delta\alpha(M_\mathrm{Z})$ is contained in $\Delta r$, there is no large effect on the $q\bar{q}$ channels induced by the running of the electromagnetic coupling in the $G_\mu$-scheme either. ➔ we used it in our W,Z publication
  ➔ **our nominal EW parameter schema**

arXiv:0911.2329v2

# Scheme dependence of weak corrections

- **Full lines** : includes **leading** two-loop terms
- Dashed lines : include leading higher order corrections




Default schema FEWZ 2.0 (w/o HO EW) → smaller corrections for low mass DY

partonic c.m.s.

Gμ : smallest corrections for Z exchange

"offset" = $(\alpha_G/\alpha(m_Z))^2 - 1$
SANC : 5.74 %
FEWZ 3.1.a3 : 5.44%
FEWZ 2.0 : 6.9%
→ choice of $\alpha(m_Z)$

# Methodology

- Use FEWZ 3.1.a3 / FEWZ 3.1.b2
- Baseline : as given in the plots, e.g. NLO QCD
- default : cuts applied (not indicated), but mentioned if "no cuts" applied
- default : $G_\mu$ schema or EW schema as indicated in the plots
- scales set individually per bin, or use of dynamic scales with FEWZ 3.1.b2
  ➔ each bin calculated separately to avoid integration bias
  ➔ statistical precision <0.01% for LO, ~0.02% for NLO, for NNLO ~0.2% (with cuts)
- To get MISS (Weak, ISR*FSR, ISR on; FSR off) : use FEWZ flag
  Ewflag = 1

**➔ to compare with QED FSR corrected Atlas data**

Comparisons done to

➢ FEWZ 2.1.1 vs FEWZ 3.1.X

→ agreement better than 0.2% found

➢ NLO MCFM for all mass ranges

→ trend : MCFM lower by about -0.8% (but not a fully tuned comparison yet)

➢ LO QCD and MISS SANC for all mass ranges, no cuts

➢ NLO QCD and MISS SANC low mass with cuts

→ very new and work in progress!

➔ Selected examples shown in the following

# High mass Drell Yan (1)

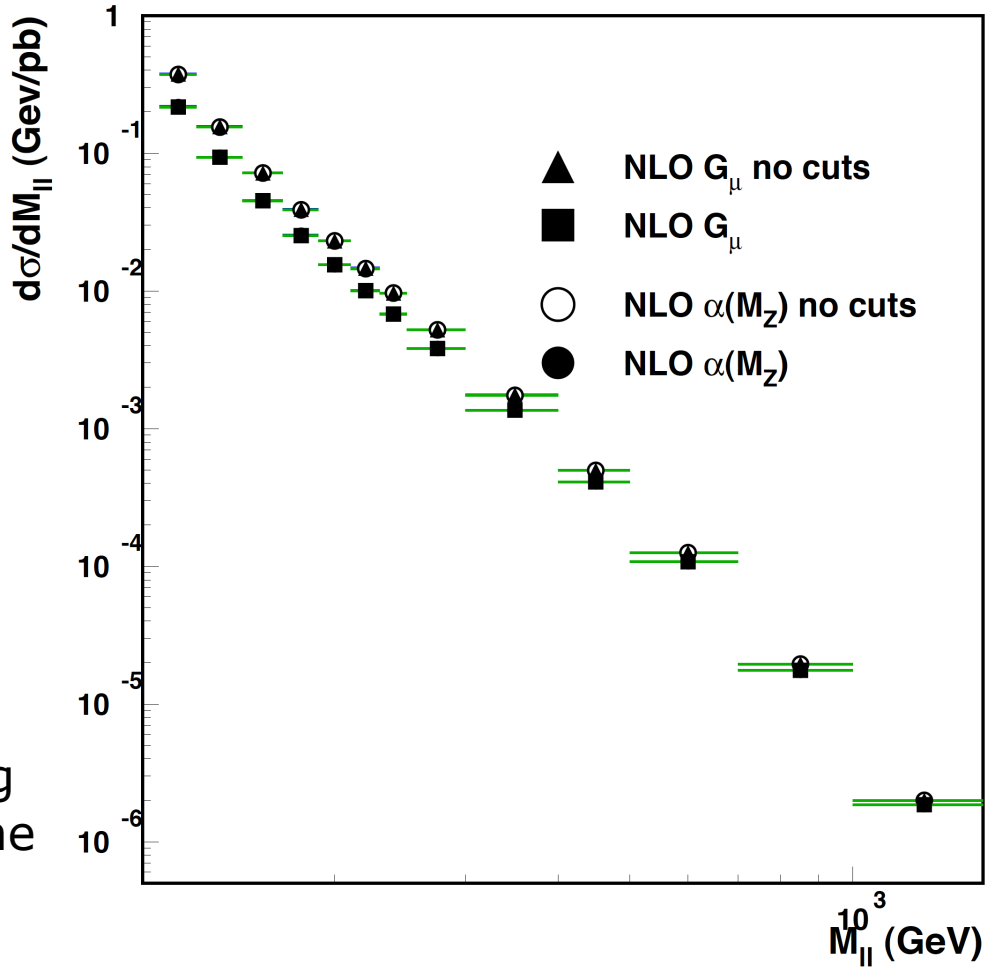
Kinematic requirements

- 116 GeV<$M_{ll}$<1500 GeV
- $P_T^l$>25 GeV
- $|\eta_l|$<2.5

➔ focus in understanding HO EW corrections for NNLO QCD and HO EW corrections mainly for fiducial cuts

➔ NLO QCD is usually used as the standard baseline : best compromise between incorporating HO QCD effects and precision of the calculation

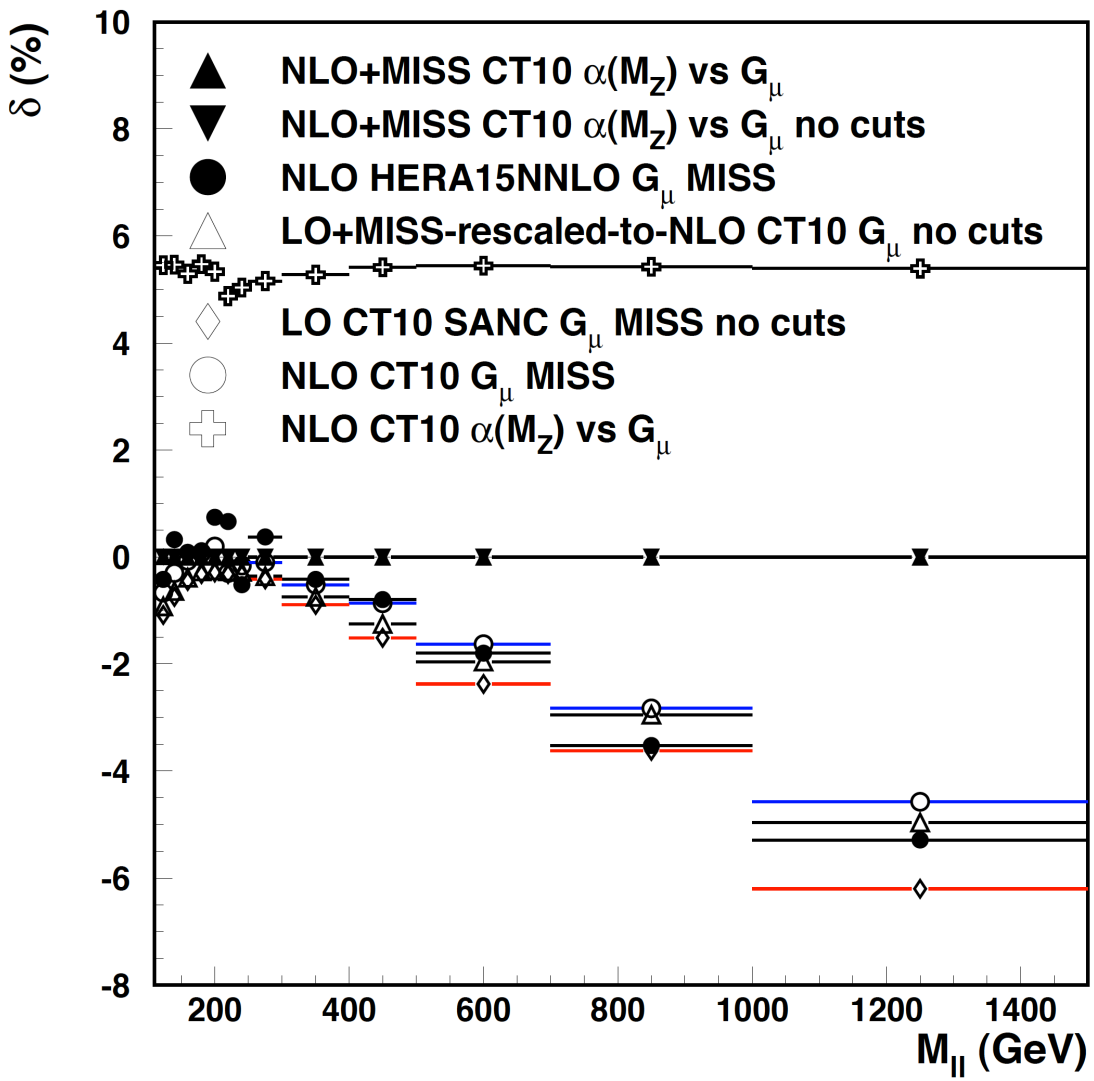
NLO QCD : CT10



# High mass Drell Yan (2)

Observations:

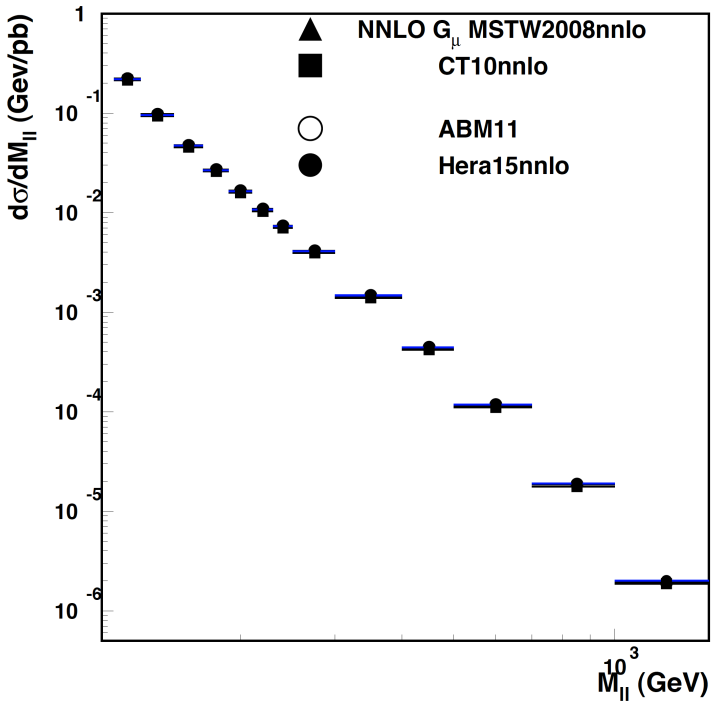
- ratio of 2 EW schemata shows expected offset, but not strictly flat
- But very good convergence (max dev. 0.4% for lowest mass bin with cuts) for EW corrected predictions
- Good agreement with SANC MISS values versus FEWZ MISS values within 0.2% (no cuts) and 0.5% with cuts
- approximately rescaling for MISS corrections derived based on LO QCD to N(N)LO QCD works

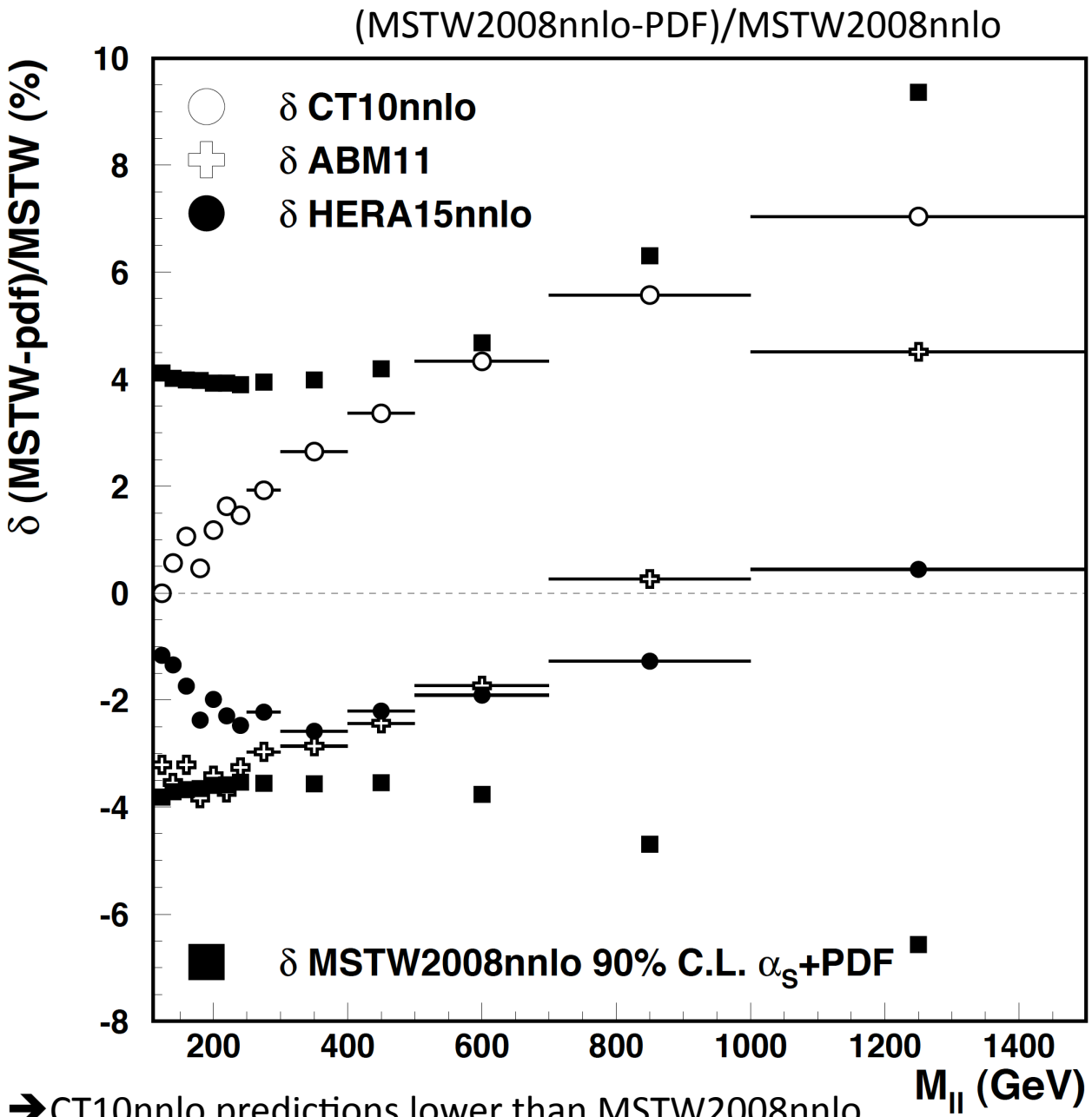



$$\sigma_{(HO\_QCD+EW)} = \sigma_{HO\_QCD}\left(1+\delta_{MISS}\frac{\sigma_{LO\_QCD}}{\sigma_{HO\_QCD}}\right)$$

# High mass Drell Yan (3)

➔ NNLO QCD fiducial cross section predictions including HO EW MISS contributions




➔CT10nnlo predictions lower than MSTW2008nnlo, while HERA15nnlo and ABM11 tend to be higher

# Low $M_{ll}$ (1)

Atlas extended binning:

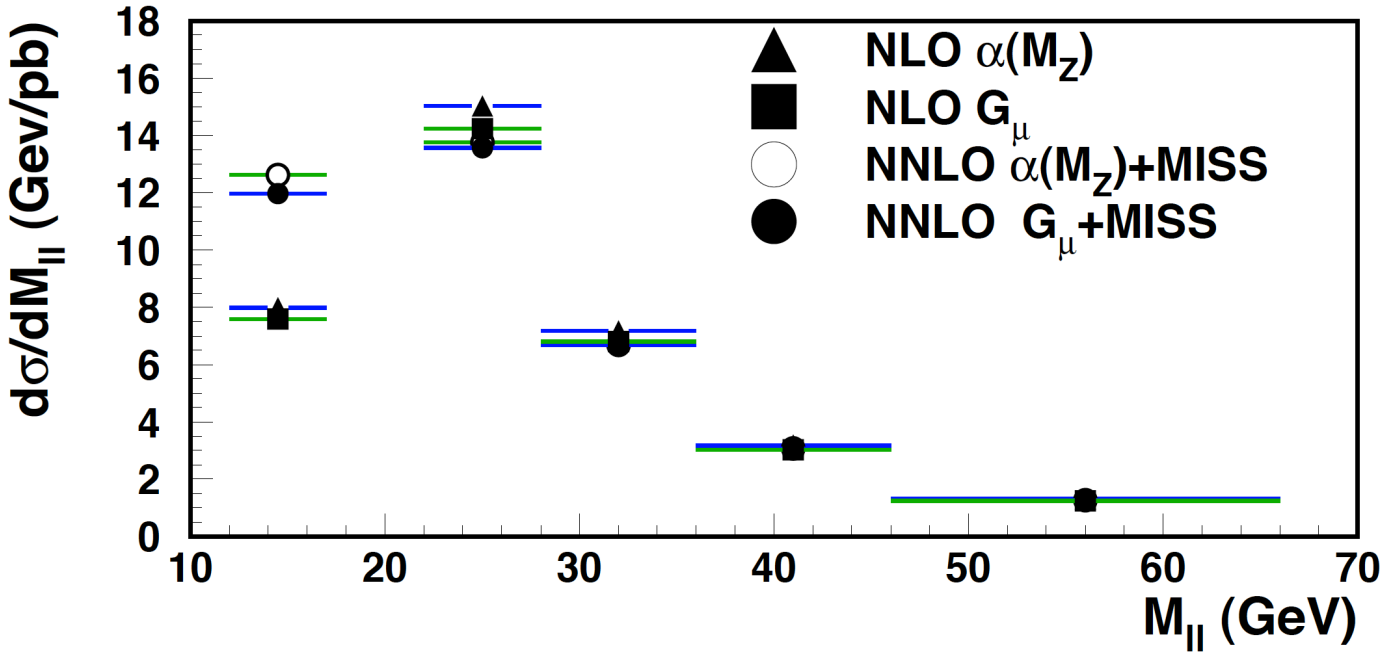
- 12 GeV<$M_{ll}$<66 GeV
- $P_T^1(^2)$>9(6) GeV
- $|\eta_l|$<2.4

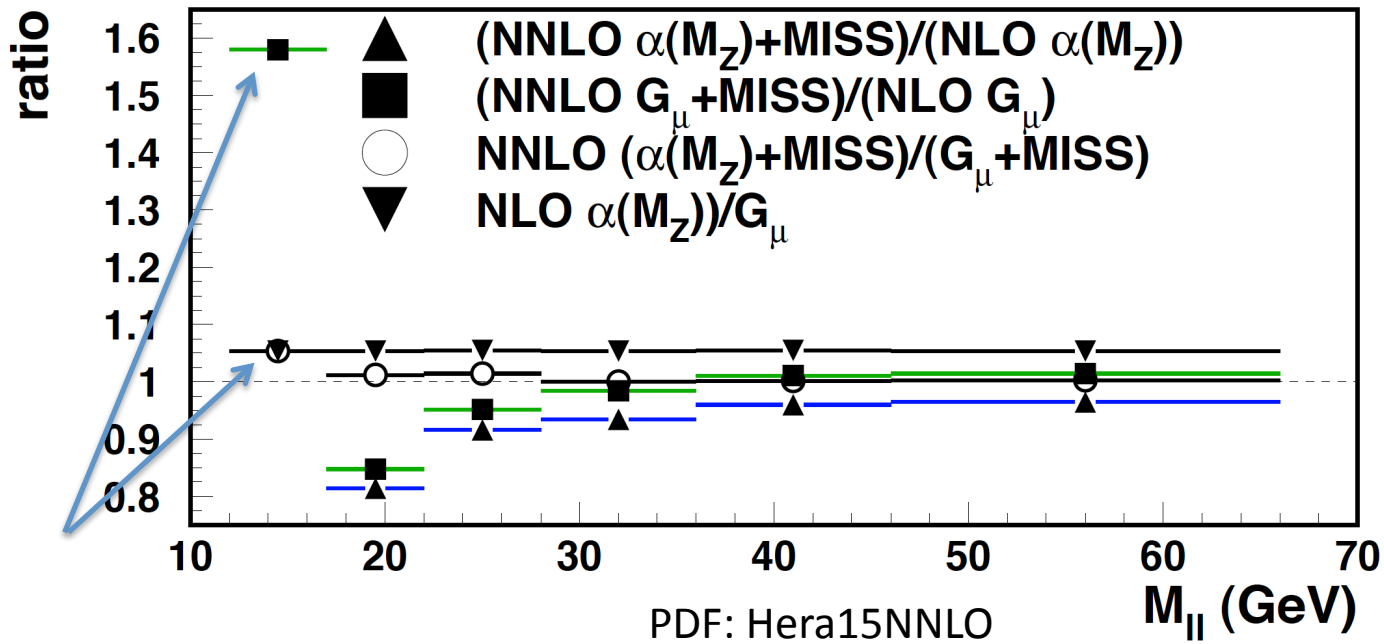
Checks:

✓ constant offset of 5.5% between the two EW schemata at NLO (NNLO) QCD

✓ MISS corrected predictions agree within 0.2% for $M_{ll}$>30 GeV and QCD NNLO/NLO factors including MISS are flat

➔ but strong effects for lower mass bins




PDF: Hera15NNLO

# Low $M_{ll}$ (2)

Atlas nominal binning:

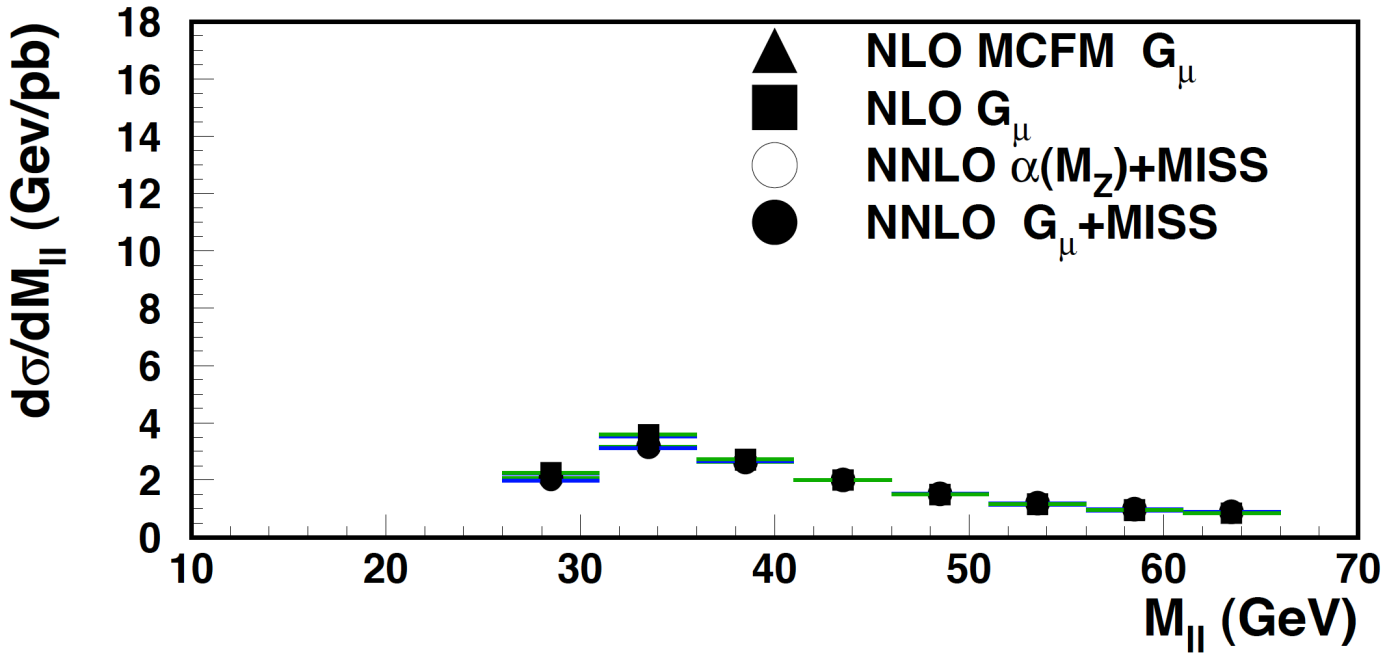
- 26 GeV<$M_{ll}$<66 GeV
- $P_T^1(^2)$>15(12) GeV
- $|\eta_l|$<2.4

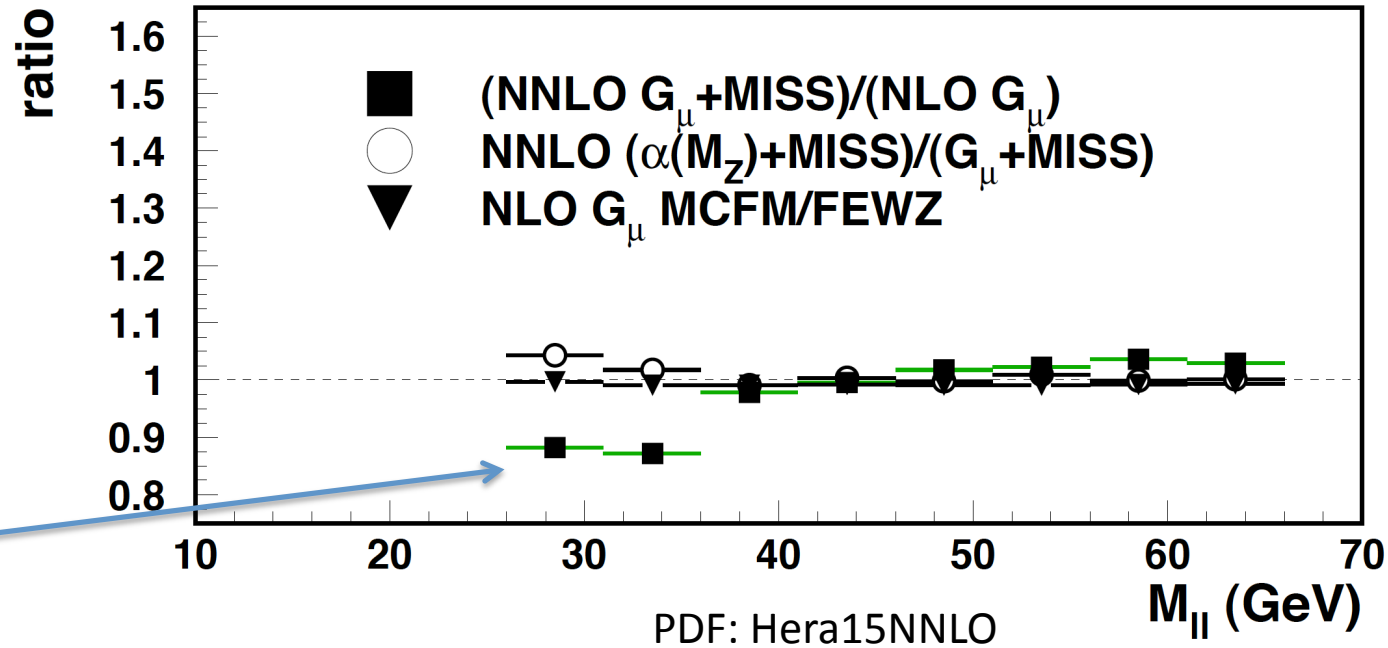
Checks:

✓ good agreement to MCFM (max. dev. -0.8%) at NLO QCD

✓ MISS corrected predictions agree within 0.2% for $M_{ll}$>36 GeV, QCD NNLO/NLO factors including MISS are flat

➔ strong effects for lower mass bins

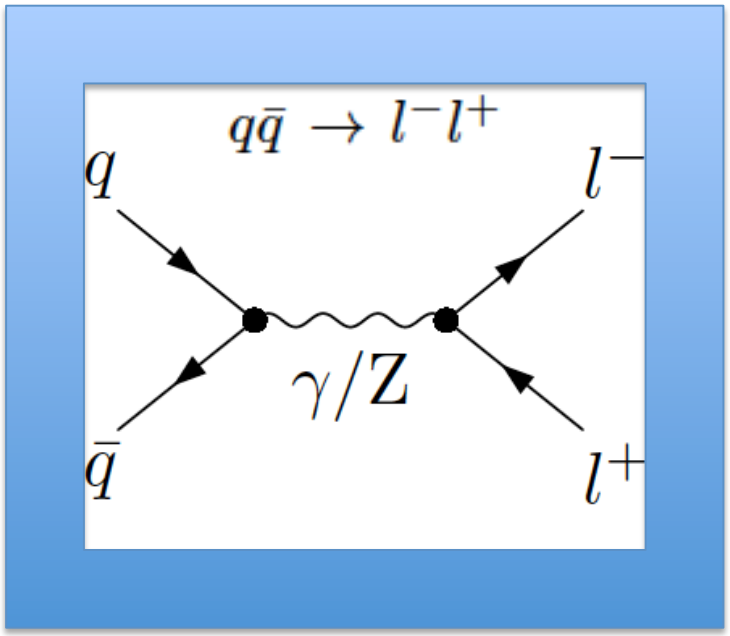


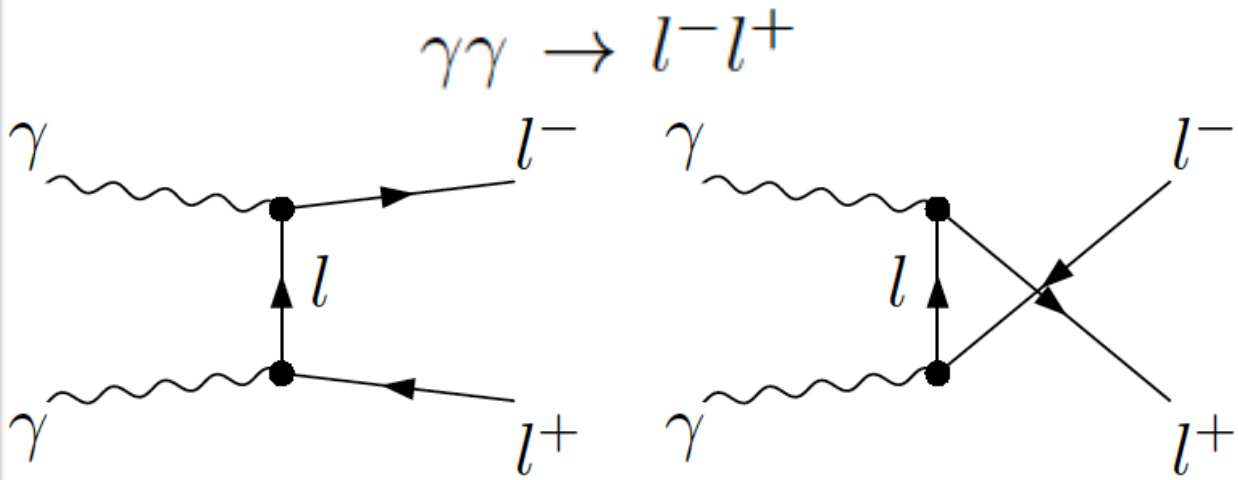




PDF: Hera15NNLO

arXiv:0911.2329v2

# Lowest order partonic cross section




**Neutral Current Drell Yan processes**

- qqbar induced processes : sensitive to structure of the **proton**

**Irreducible background**

- γγ (γq) induced processes : sensitive to QED and structure of the ***photon***

➔ *non-resonant; suppressed due to the smallness of the photon PDF*

➔ MRST 2004qed fit (NLO QCD):" Parton distributions incorporating QED contributions", A.Martin, R.Thorne, hep-ph/0411040

# LO predictions

$M_{ll} > 50\,\mathrm{GeV}, \quad p_{\mathrm{T},l^\pm} > 25\,\mathrm{GeV}, \quad |y_{l^\pm}| < 2.5,$ arXiv:0911.2329v2

$\mathrm{pp} \to l^+l^- + X$ at $\sqrt{s} = 14\,\mathrm{TeV}$ Table 1

MRST2004QED

$G_\mu$ schema;

All scales set to $M_Z$

| $M_{ll}$/GeV | 50–∞ | 100–∞ | 200–∞ | 500–∞ | 1000–∞ | 2000–∞ |
|---|---|---|---|---|---|---|
| $\sigma_0$/pb | 738.733(6) | 32.7236(3) | 1.48479(1) | 0.0809420(6) | 0.00679953(3) | 0.000303744(1) |
| $\sigma_0\|_{\mathrm{FS/PS}}$/pb | 738.773(6) | 32.7268(3) | 1.48492(1) | 0.0809489(6) | 0.00680008(3) | 0.000303767(1) |
| $\delta_{\gamma\gamma,0}$/% | 0.17 | 1.15 | 4.30 | 4.92 | 5.21 | 6.17 |
| $\delta^{\mathrm{rec}}_{q\bar{q},\mathrm{phot}}$/% | −1.81 | −4.71 | −2.92 | −3.36 | −4.24 | −5.66 |
| $\delta^{\mu^+\mu^-}_{q\bar{q},\mathrm{phot}}$/% | −3.34 | −8.85 | −5.72 | −7.05 | −9.02 | −12.08 |
| $\delta^{\mu^+\mu^-}_{\mathrm{multi}-\gamma}$/% | $0.073^{+0.027}_{-0.024}$ | $0.49^{+0.18}_{-0.15}$ | $0.17^{+0.06}_{-0.05}$ | $0.23^{+0.07}_{-0.06}$ | $0.33^{+0.09}_{-0.08}$ | $0.54^{+0.13}_{-0.12}$ |
| $\delta_{q\bar{q},\mathrm{weak}}$/% | −0.71 | −1.02 | −0.14 | −2.38 | −5.87 | −11.12 |
| $\delta_{\mathrm{h.o.weak}}$/% | 0.030 | 0.012 | −0.23 | −0.29 | −0.31 | −0.32 |
| $\delta^{(2)}_{\mathrm{Sudakov}}$/% | −0.00046 | −0.0067 | −0.035 | 0.23 | 1.14 | 3.38 |
| $\delta_{q/\bar{q}\gamma,\mathrm{phot}}$/% | −0.11 | −0.21 | 0.38 | 1.53 | 1.91 | 2.34 |
| $\delta^{\mathrm{rec}}_{\gamma\gamma,\mathrm{phot}}$/% | −0.0060 | −0.032 | −0.11 | −0.14 | −0.16 | −0.23 |
| $\delta^{\mu^+\mu^-}_{\gamma\gamma,\mathrm{phot}}$/% | −0.011 | −0.058 | −0.22 | −0.30 | −0.39 | −0.59 |
| $\delta_{\gamma\gamma,\mathrm{weak}}$/% | 0.000045 | 0.00056 | −0.025 | −0.14 | −0.31 | −0.64 |
| $\delta_{\mathrm{QCD}}$/% | 4.0(1) | 13.90(6) | 26.10(3) | 21.29(2) | 8.65(1) | −11.93(1) |

photon induced

weak

to be added : NLO photon induced (photon-quark contribution, not in FEWZ)

'Benchmark' FEWZ 3.1.b2
→ I could reproduce exactly those (blue and red) numbers within 0.2% for photon-induced and weak contributions (c.f. also FEWZ 3.1 paper).
→ Perform calculations for Atlas cuts and bins

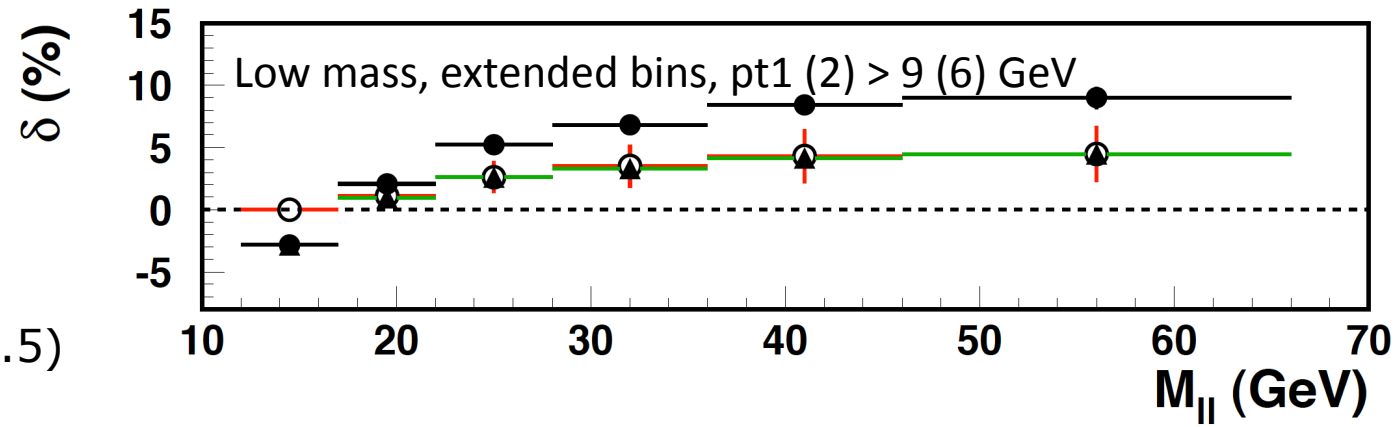
# Results

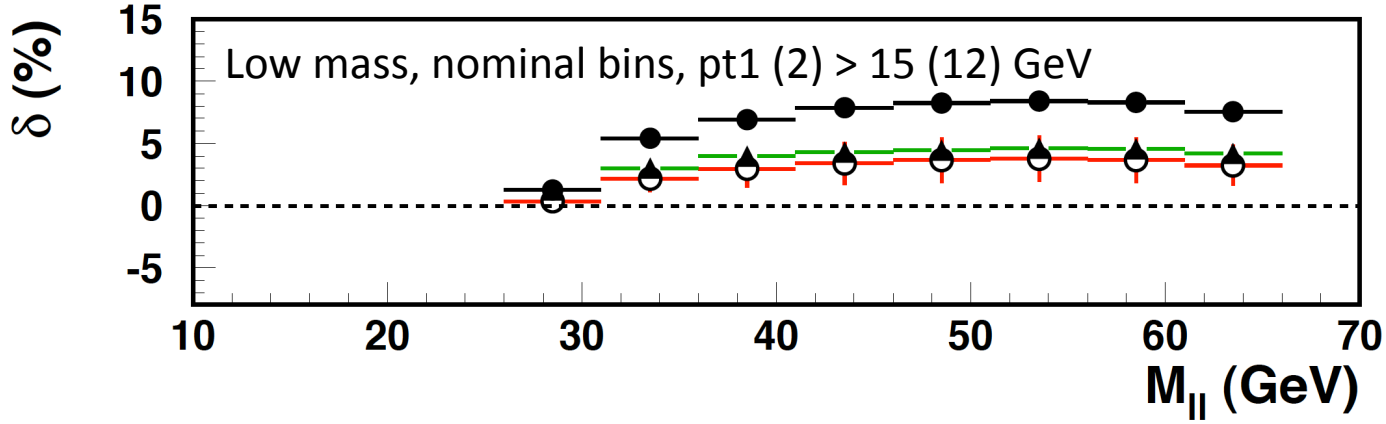
**[work in progress ]**

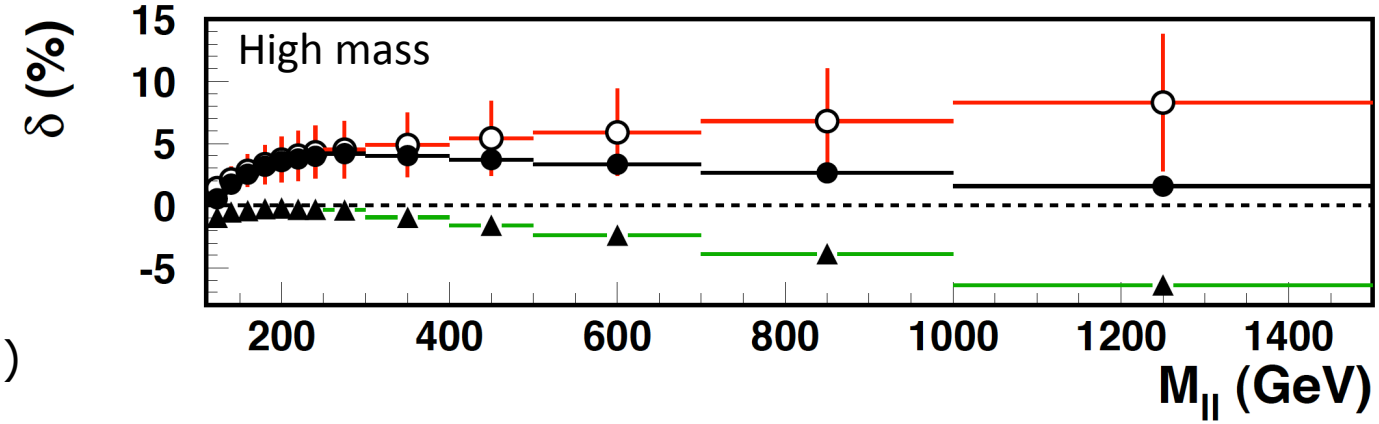
- MRST2004qed
- NLO QCD
- fiducial cuts : η <2.4 (2.5)

δ calculation:
denominator: NLO QCD w/o photon
numerator:
MISS=triangles (green)
LO γ induced=open (red) with ~50% error bar
QED FSR=triangles (blue)
MISS including γ induced =full (black)

➔ LO photon-photon induced contributions are as sizeable as the PW+ISR+IFI effects (MISS) and the PDF uncertainties



# Summary

Tools : FEWZ 3.1.a3 and FEWZ 3.1.b2 (pre-releases) and SANC

Baseline 1: LO QCD, CT10, $G_\mu$ schema, no cuts

Goal : Calculate HO EW MISS (pure weak, ISR, ISR+FSR interference)

- ✓ benchmark LO QCD cross sections
- ✓ MISS corrections between FEWZ and SANC within 0.2-0.5%

Baseline 2: (N)NLO QCD, various PDFs, $G_\mu$ and Mz schema, with and w/o cuts

Goal : Calculate HO EW MISS (pure weak, ISR, ISR+FSR interference)

- ✓ benchmark NLO MCFM versus FEWZ ($G_\mu$ – perhaps remaining small parameter mismatch which may cause a ~0.5-1% offset), started to benchmark NLO SANC versus FEWZ
- ✓ Confirm the expected constant offset between the 2 schemata w/o HO EW for high mass DY, but non-convergence for lowest DY bin for fiducial cross sections! offset remains also at NNLO QCD!
- ✓ Pdf sensitivity for MISS : found to be small (<0.5%)
- ✓ Cut sensitivity for MISS: small for high mass and low mass bins *well above cuts*
- ✓ NNLO/NLO k-factors for QCD fits using HERA15NNLO, but those k-factors are not flat anymore for the lowest and highest mass regions

# A working list

✧ Assign uncertainty for applying HO EW corrections (cut dependence, non-convergence between EW schemata etc.)

✧ Issue 1 : LO photon induced contribution based on NLO QCD calculated
➔ effects as large as PDF sensitivity observed

✧ Issue 2 : NLO photon induced contributions have to be added as well

✧ Issue 3 : Estimate remaining NNLO QCD scale uncertainties (CPU time)

✧ Issue 4 : Do we miss further EW corrections?
➔ EW corrections have to be matched with experimental procedures, e.g. we correct for QED FSR, we subtract diboson background with MC …
➔ MC modelling of photon induced contributions would be highly welcome

**ToDo : final combination of ALL effects and estimate uncertainties relevant for PDF fits**

**Mandatory : high precision calculations are crucial…**