NLO corrections to WZA production in SM and tree-level effects of dim-8 operators in SMEFT at the LHC

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Phenomenology Symposium
May 26th, 2021

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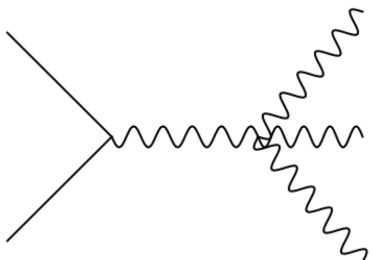
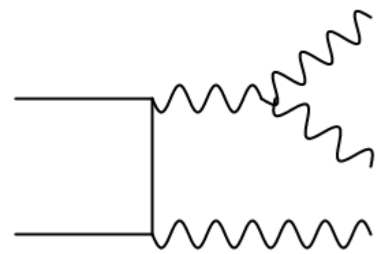
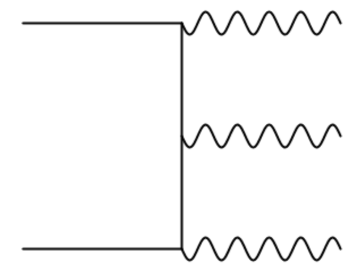
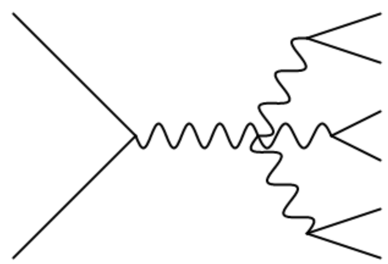
Triple gauge boson production - Features

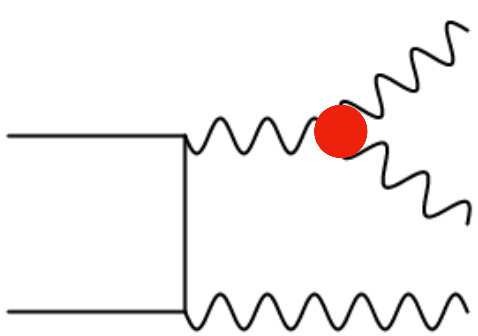
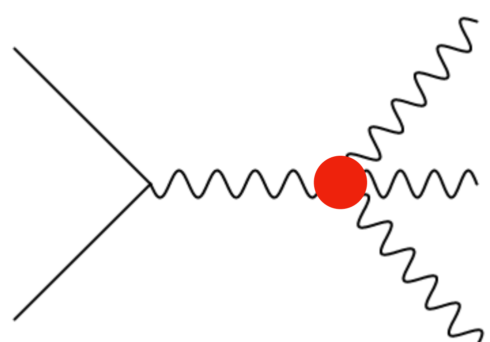
- One of the least tested processes
  - WWA and ZAA measured at LEP 2 [OPAL Collaboration (1999)] [L3 Collaboration (2002)]
  - Massive triple gauge boson search since LHC Run2

- Rich decay products as backgrounds of other SM processes/BSM searches



- Manifest triple/quartic gauge boson couplings
  - Verify the non-Abelian gauge structure predicted by the SM
  - Induce potentially non-standard gauge couplings —> small deviations?

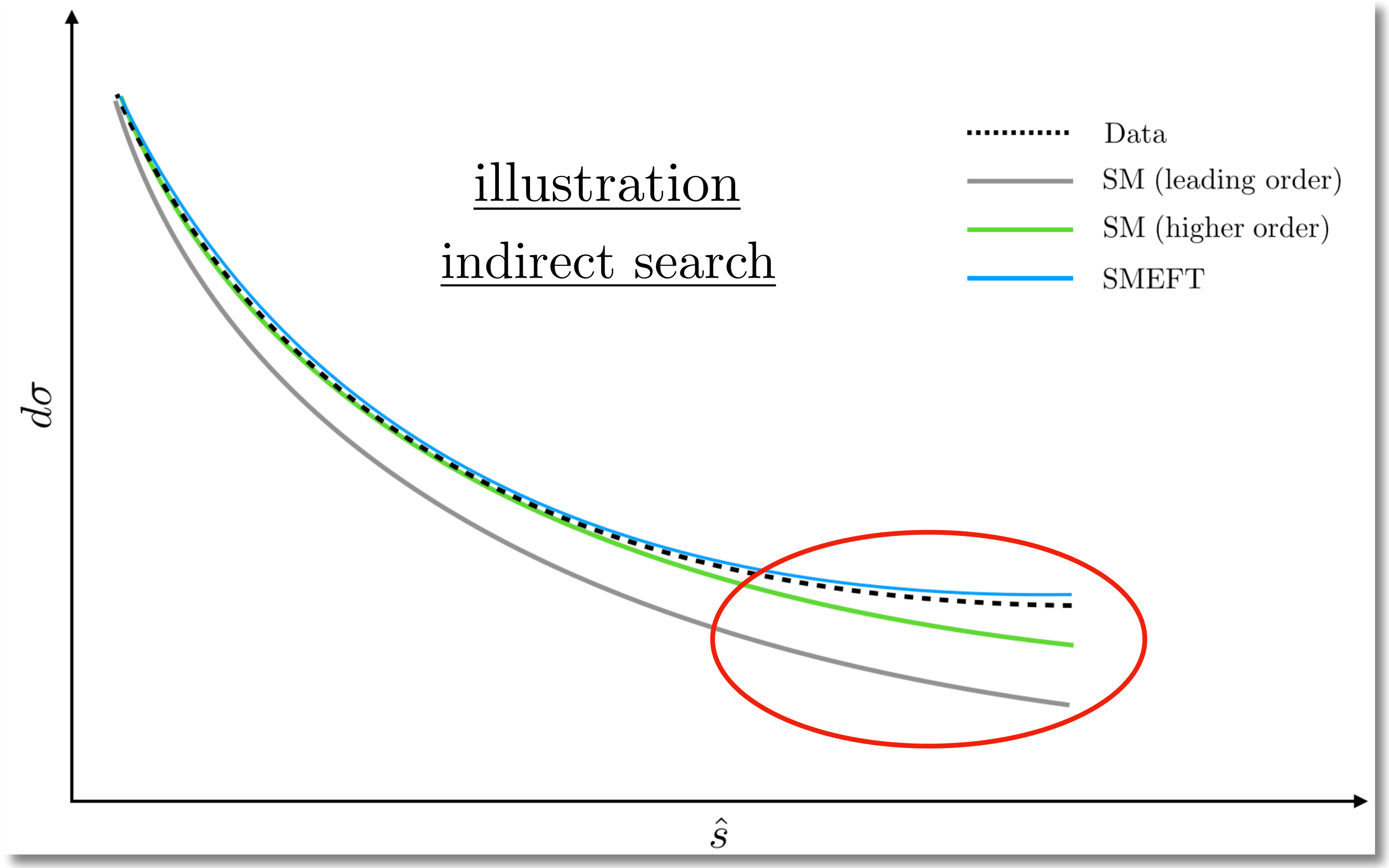

Standard Model effective field theory

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}}^{(4)} + \sum_{d>4} \sum_i \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

SMEFT (bottom-up)

$\Downarrow$

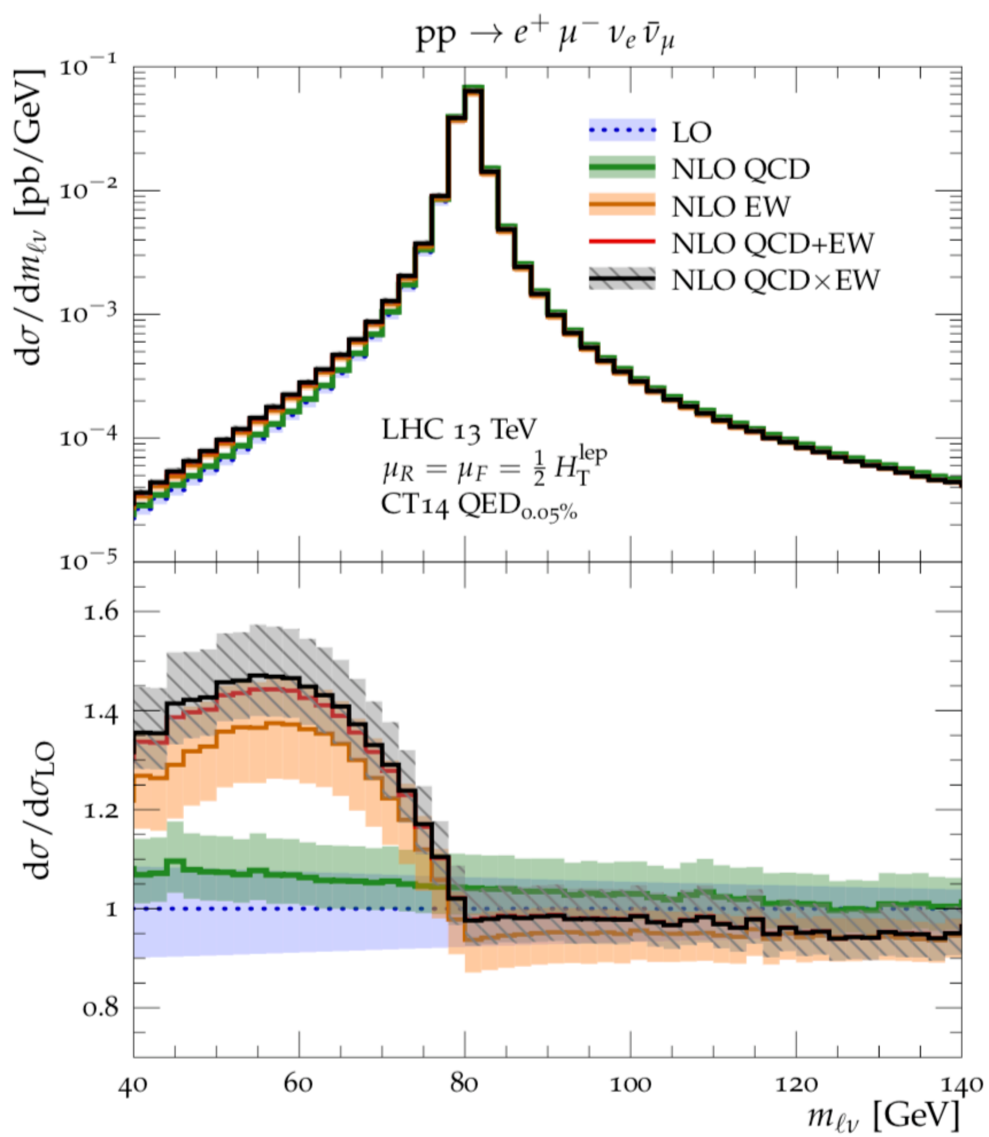
precision required
to tell if "small deviation" is true



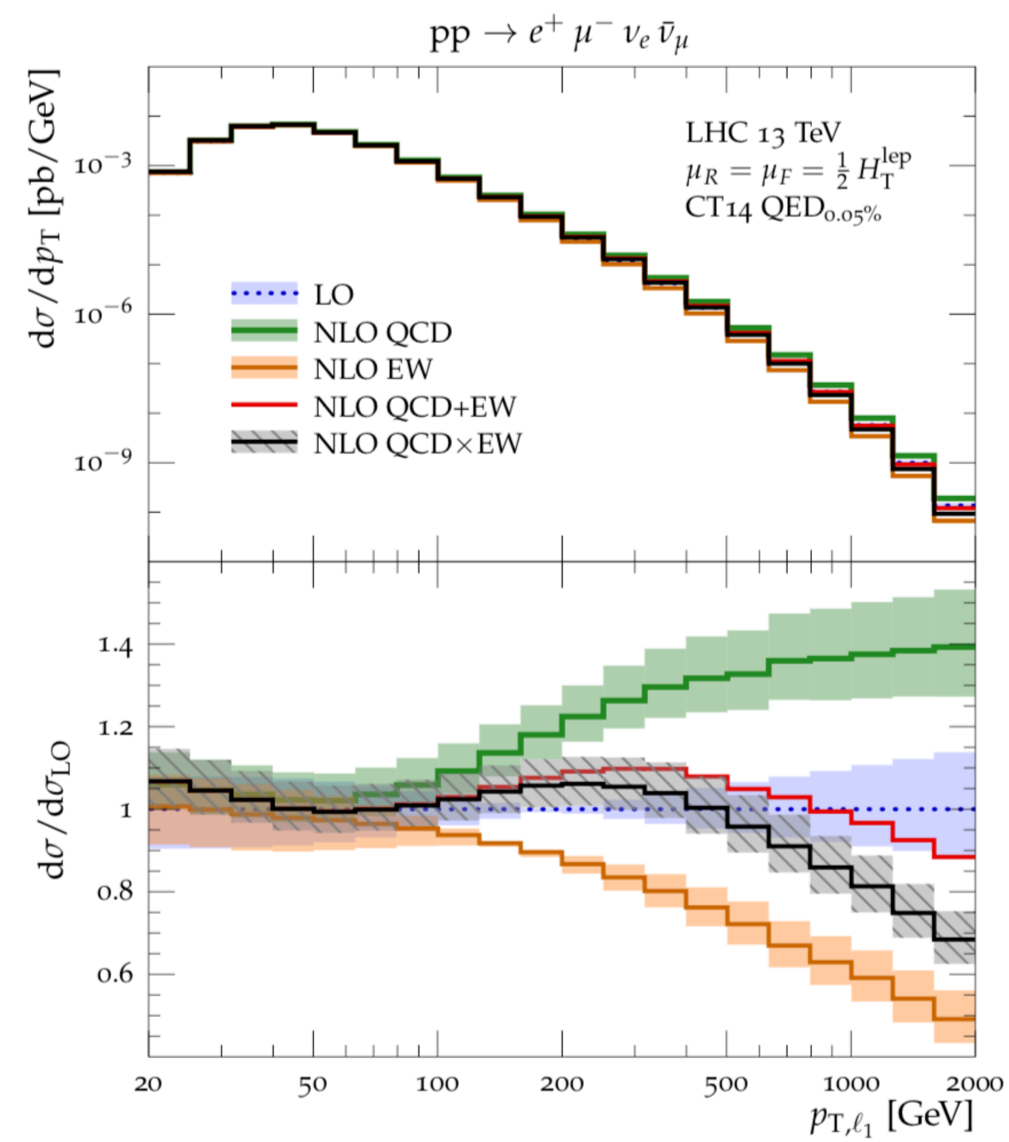
Next-to-leading order EW corrections

- Total cross section: $\alpha_s^2 \sim \alpha \Rightarrow$ if $\mathrm{NNLO_{QCD}}$ reached, then $\mathrm{NLO_{EW}}$ needed.
- Differential cross section: shape of distributions significantly changed.

Example: NLO EW corrections to W^+W^- production with leptonic decays [Kallweit, Lindert, Pozzorini, Schönherr (2017)]



$\rightarrow$ QED (real photon radiation)

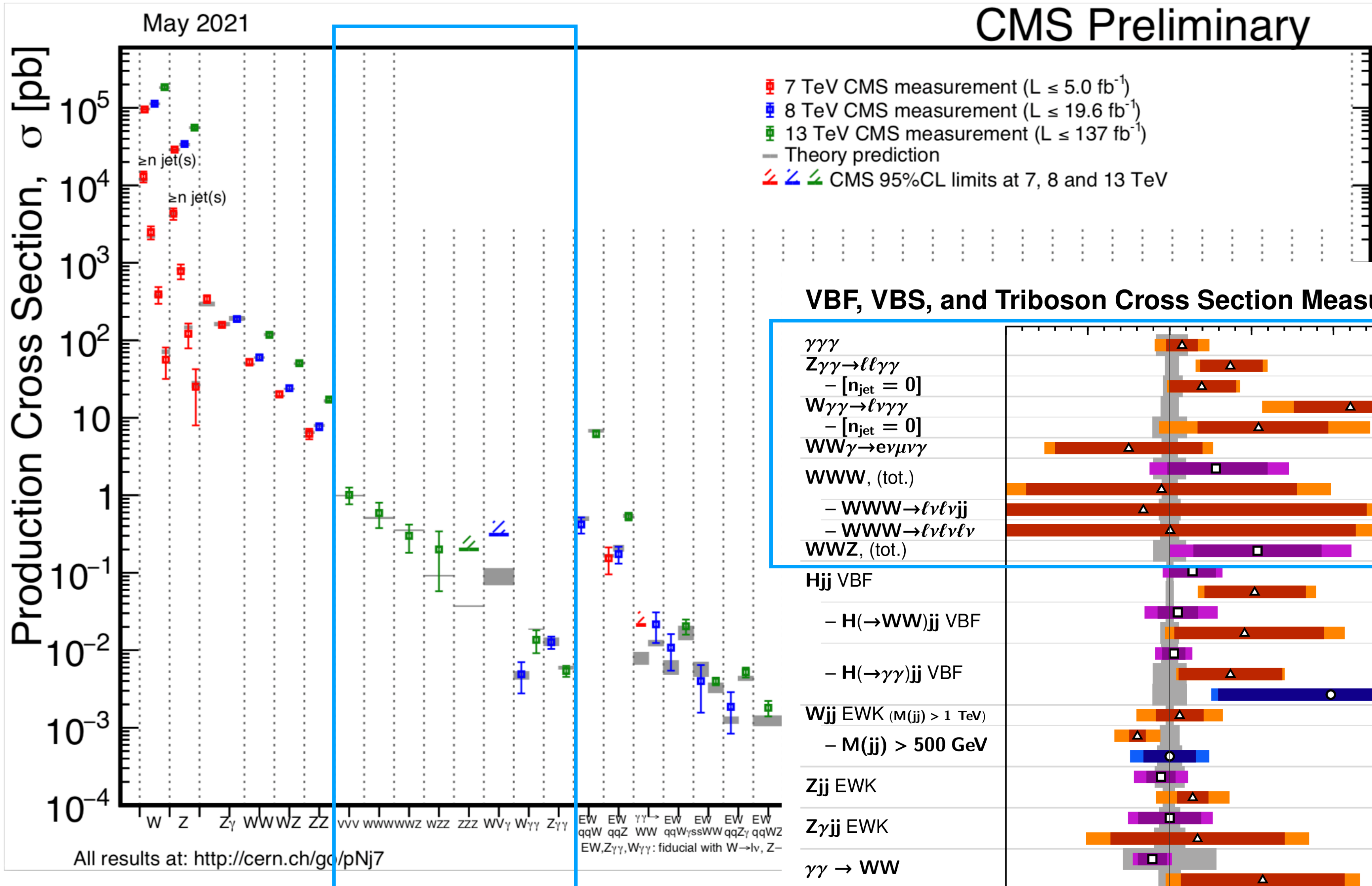


$\rightarrow$ Weak (Sudakov logarithm)

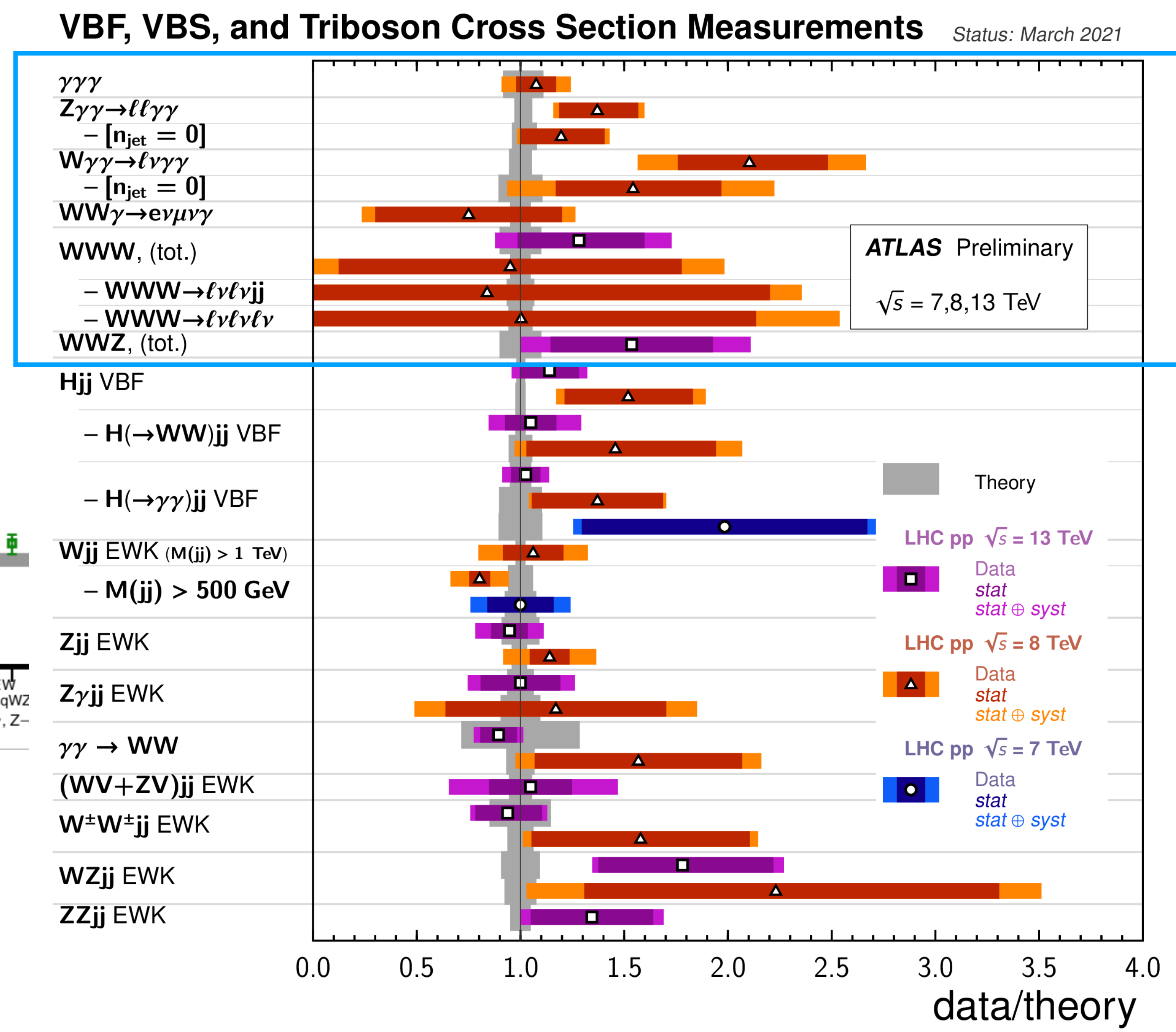
- Photon induced channel: photon parton distribution functions (γPDFs)

[Manohar, Nason, Salam, Zanderighi (2016)]

Measurements of triboson production at the LHC



[CMS Collaboration, May 2021]



[ATLAS Collaboration (2019)]

[CMS Collaboration (2020)]

three massive gauge bosons production

[ATLAS Collaboration, March 2021]

Calculations of NLO EW corrections to triboson production

$\mathrm{p\,p} \to W\ W\ Z$

1st NLO EW, on-shell production
[Nhung, Ninh, Weber (2013)]

$\mathrm{p\,p} \to W\ Z\ Z$

$\mathrm{p\,p} \to Z\ Z\ Z$

$\mathrm{p\,p} \to Z\ Z\ \gamma$

narrow width approximation
- **MadSpin** [Artoisenet, Frederix, Mattelaer, Rietkerk (2012)]
[Shen, Zhang, Ma, Li, Zhang, Guo (2015)]
[H.Wang, Zhang, Ma, Guo, Li, S.Wang (2016)]
[Y.Wang, Zhang, Ma, Li, S.Wang, Bi (2017)]

$\mathrm{p\,p} \to W\ \gamma\ \gamma$

$\mathrm{p\,p} \to Z\ \gamma\ \gamma$

$\mathrm{p\,p} \to \gamma\ \gamma\ \gamma$

leptonic decays for W/Z boson
- **Sherpa-3.0**
[Greiner, Schönherr (2017)]

$\mathrm{p\,p} \to W\ W\ W$

narrow width approximation
- **MadSpin**
[Shen, Zhang, Ma, Li, Guo (2017)]

scale and PDF uncertainties
[Dittmaier, Huss, Knippen (2017)]

leptonic decays for W boson
[Schönherr (2018)]
[Dittmaier, Knippen, Schwan (2019)]

$\mathrm{p\,p} \to W\ W\ \gamma$

Narrow width approximation, @ILC
[C.Chen, Ma, R.Zhang, Y.Zhang, L.Chen, Guo (2014)]

$\mathrm{p\,p} \to W\ Z\ \gamma$

NLO QCD with leptonic decays - **VBFNLO**
[Bozzi, Campanario, Rauch, Rzehak, Zeppenfeld (2010)]

$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ with leptonic decays
✓ ? ?
[Les Houches 2019 Precision wishlist]

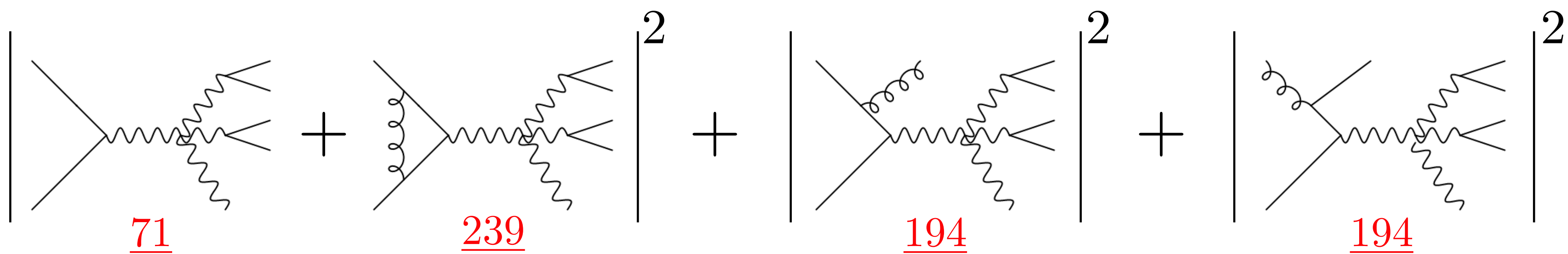
Hadronic cross section of $\mathrm{p}\,\mathrm{p} \to e^+\,\nu_e\,\mu^+\,\mu^-\,\gamma$

$$\sigma_{2\to n}(p_1,p_2) = \sum_{a,b}\int_0^1 dx_1 dx_2\; f_a(x_1,\mu_F) f_b(x_2,\mu_F)\; \hat{\sigma}_{ab}(p_a,p_b)$$

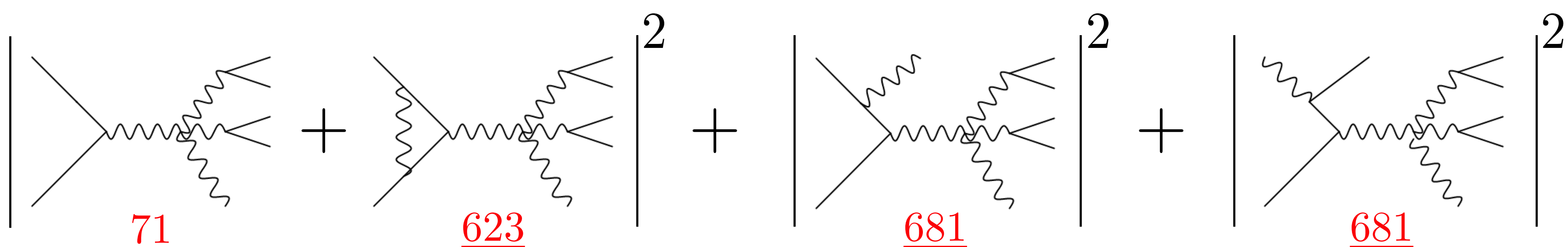
LO: $\mathcal{O}\left(\alpha^5\right)$

$$\begin{aligned}\hat{\sigma}_{ab} &= \hat{\sigma}_{ab}^{\mathrm{LO}} + \hat{\sigma}_{ab}^{\mathrm{NLO}} \\ &= \int_n d\sigma_{ab}^{\mathrm{B}} + \int_n d\sigma_{ab}^{\mathrm{V}} + \int_{n+1} d\sigma_{ab}^{\mathrm{R}} + \int_n d\sigma_{ab}^{\mathrm{C}}\end{aligned}$$

NLO QCD: $\mathcal{O}\left(\alpha^5\alpha_s\right)$



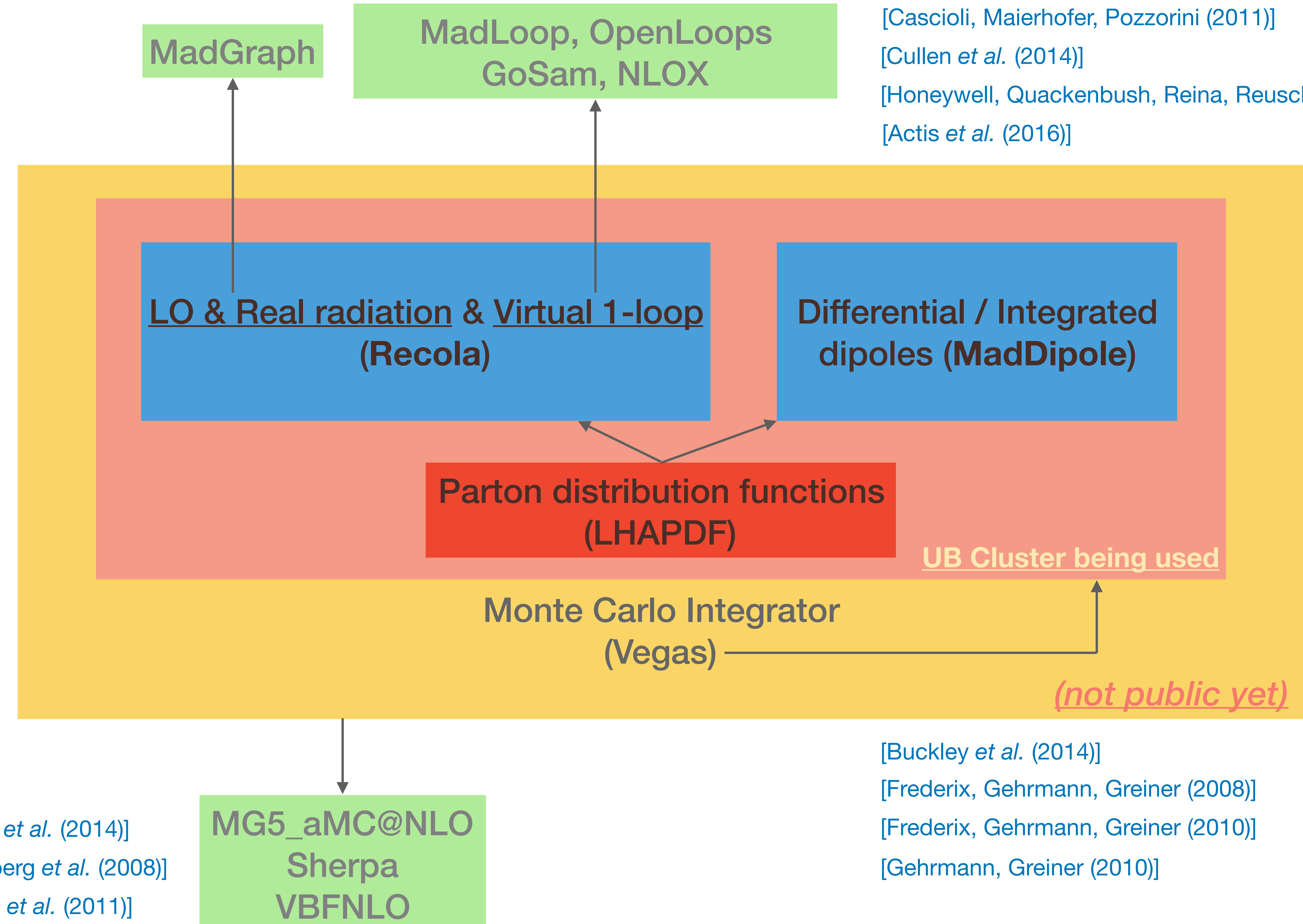
NLO EW: $\mathcal{O}\left(\alpha^6\right)$



$$\begin{aligned}\hat{\sigma}_{ab}^{\mathrm{NLO}} &= \int_n d\sigma_{ab}^{\mathrm{V}} + \int_{n+1} d\sigma_{ab}^{\mathrm{S}} + \int_{n+1}\left[d\sigma_{ab}^{\mathrm{R}} - d\sigma_{ab}^{\mathrm{S}}\right] + \int_n d\sigma_{ab}^{\mathrm{C}} \\ &= \int_n \left[d\sigma_{ab}^{\mathrm{V}} + d\sigma_{ab}^{\mathrm{I}} + d\sigma_{ab}^{\mathrm{C}}\right]_{\epsilon=0} + \int_{n+1}\left[d\sigma_{ab}^{\mathrm{R}} - d\sigma_{ab}^{\mathrm{S}}\right]\end{aligned}$$

dipole subtraction method [Catani, Seymour (1996)]

Our Monte Carlo framework



[Cascioli, Maierhofer, Pozzorini (2011)]
[Cullen *et al.* (2014)]
[Honeywell, Quackenbush, Reina, Reuschle (2018)]
[Actis *et al.* (2016)]

[Buckley *et al.* (2014)]
[Frederix, Gehrmann, Greiner (2008)]
[Frederix, Gehrmann, Greiner (2010)]
[Gehrmann, Greiner (2010)]

[Alwall *et al.* (2014)]
[Gleisberg *et al.* (2008)]
[Baglio *et al.* (2011)]

Input parameters & Total cross sections

$\sqrt{s} = 13$ TeV

Mass/Width [GeV]	M_W	M_Z	M_H	Γ_W	Γ_Z	Γ_H
	80.379	91.1876	125.0	2.085	2.4952	0

[Particle Data Group (2020)]

G_μ-scheme $\quad (G_\mu = 1.16637 \times 10^{-5})$

NNPDF31_nlo_as_0118_luxqed

$$\mu_\mathrm{R} = \mu_\mathrm{F} = m_{WZ\gamma} \equiv \sqrt{(p_{e^+} + p_{\nu_e} + p_{\mu^+} + p_{\mu^-} + p_\gamma)^2}$$

recombine photon and charged lepton if $R_{l\gamma} < 0.1$

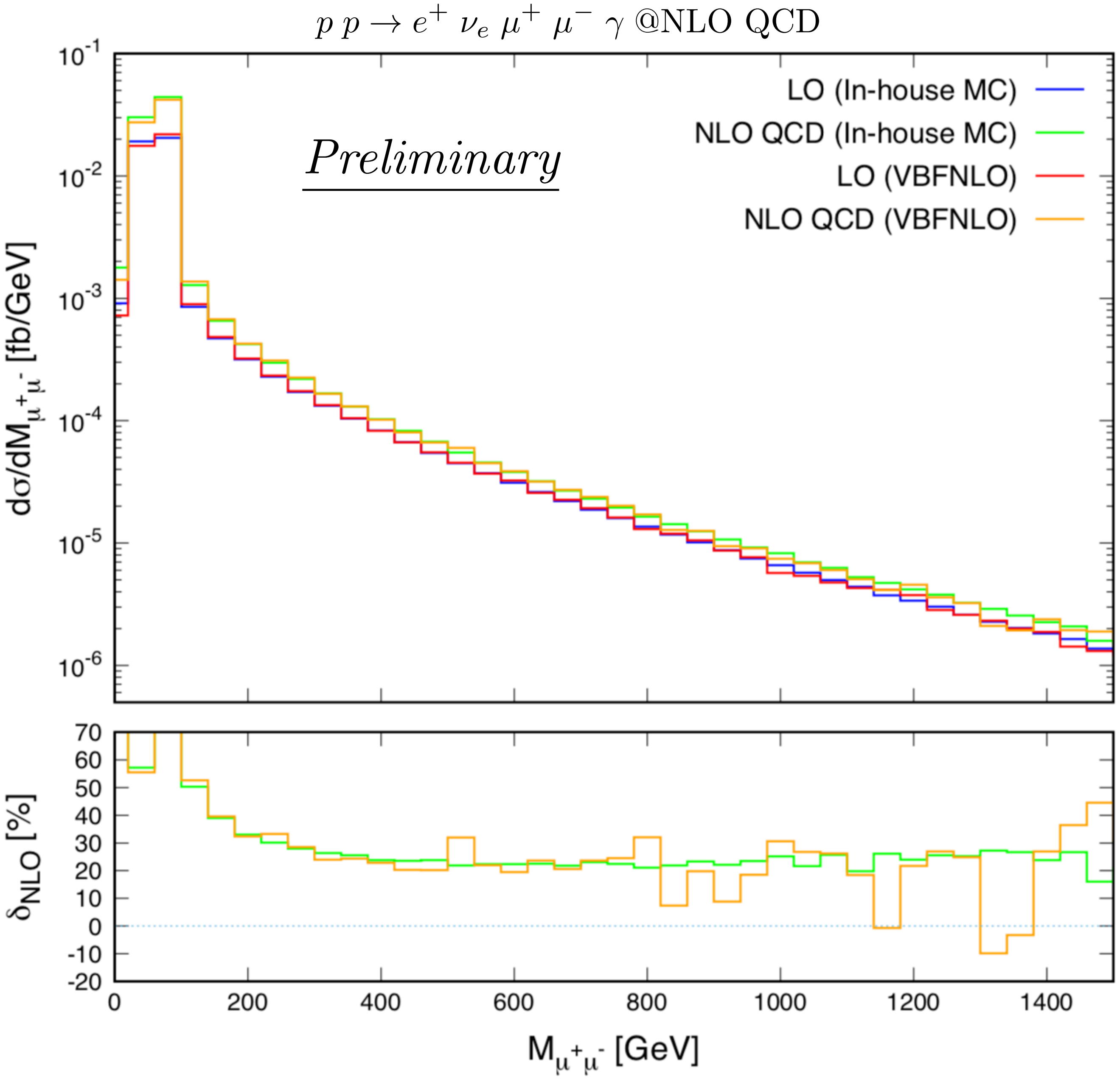
accept if $\quad R_{\gamma j} > R_0 = 0.7 \quad$ or $\quad p_{\mathrm{T},j} < p_{\mathrm{T},\gamma}\left(\frac{1-\cos(R_{\gamma j})}{1-\cos(R_0)}\right)$ [Frixione (1998)]

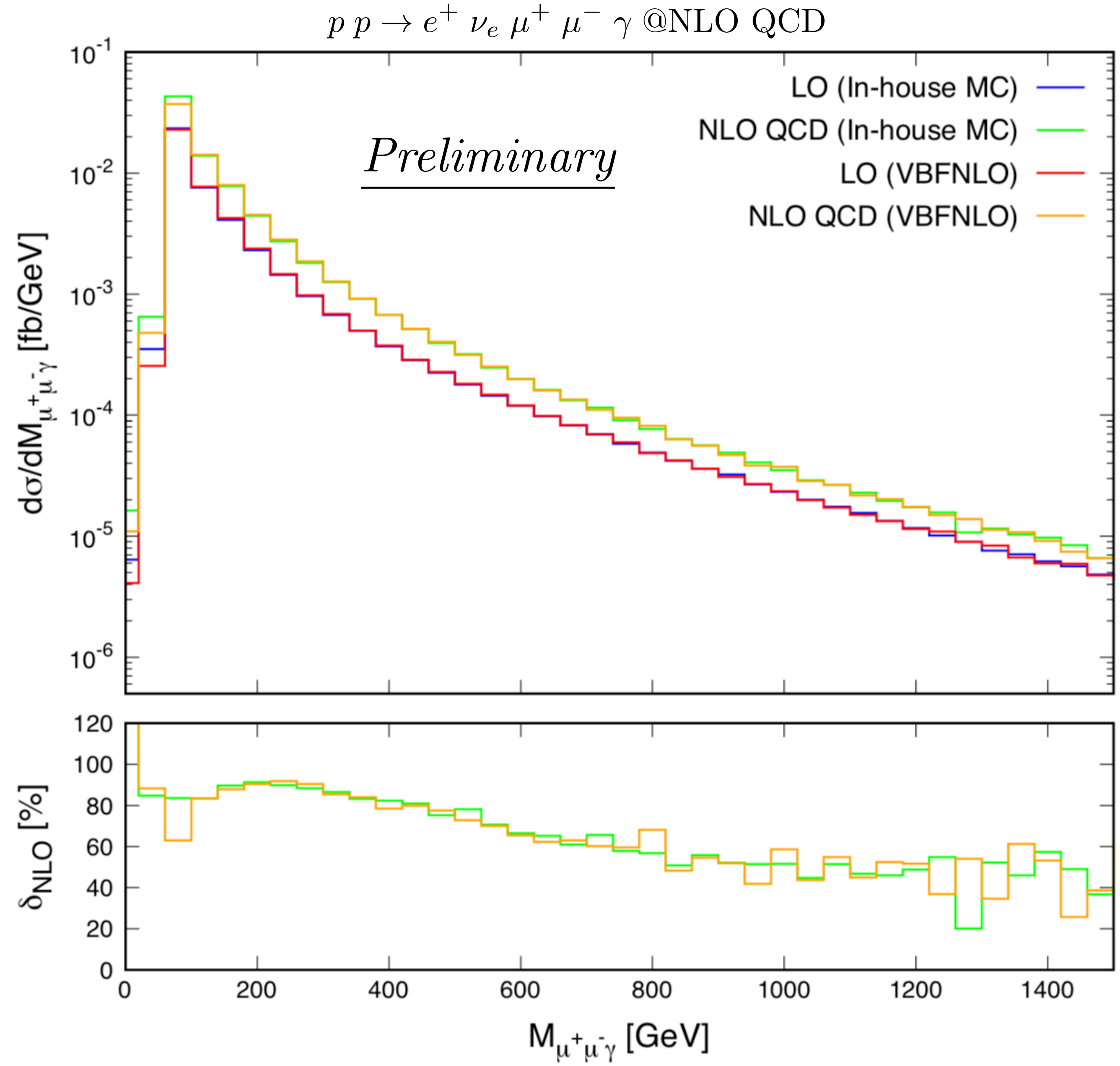
$$p_{T,l} > 20 \text{ GeV}, \quad |\eta_l| < 2.5, \quad p_{T,\gamma} > 15 \text{ GeV}, \quad |\eta_\gamma| < 2.5$$
$$E_{T,\mathrm{miss}} > 15 \text{ GeV}, \quad R_{l\gamma} > 0.4, \quad m_{\mu^+\mu^-} > 20 \text{ GeV}$$

	σ_LO [fb]	$\sigma_\mathrm{NLO\ QCD}$ [fb]	K-factor
in-house MC	0.2155(1)	0.3709(2)	1.721(1)
VBFNLO-2.7.1	0.2157(1)	0.3734(6)	1.731(3)

	$\sigma_\mathrm{NLO\ EW}$ [fb]	$\delta_\mathrm{NLO\ EW}$ [%]	$\delta_{\mathrm{EW},q\bar{q}}$ [%]	$\delta_{\mathrm{EW},\gamma q(\bar{q})}$ [%]
in-house MC	0.2176(1)	0.97(1)	-3.99(4)	+4.96(1)

Validating NLO QCD against VBFNLO



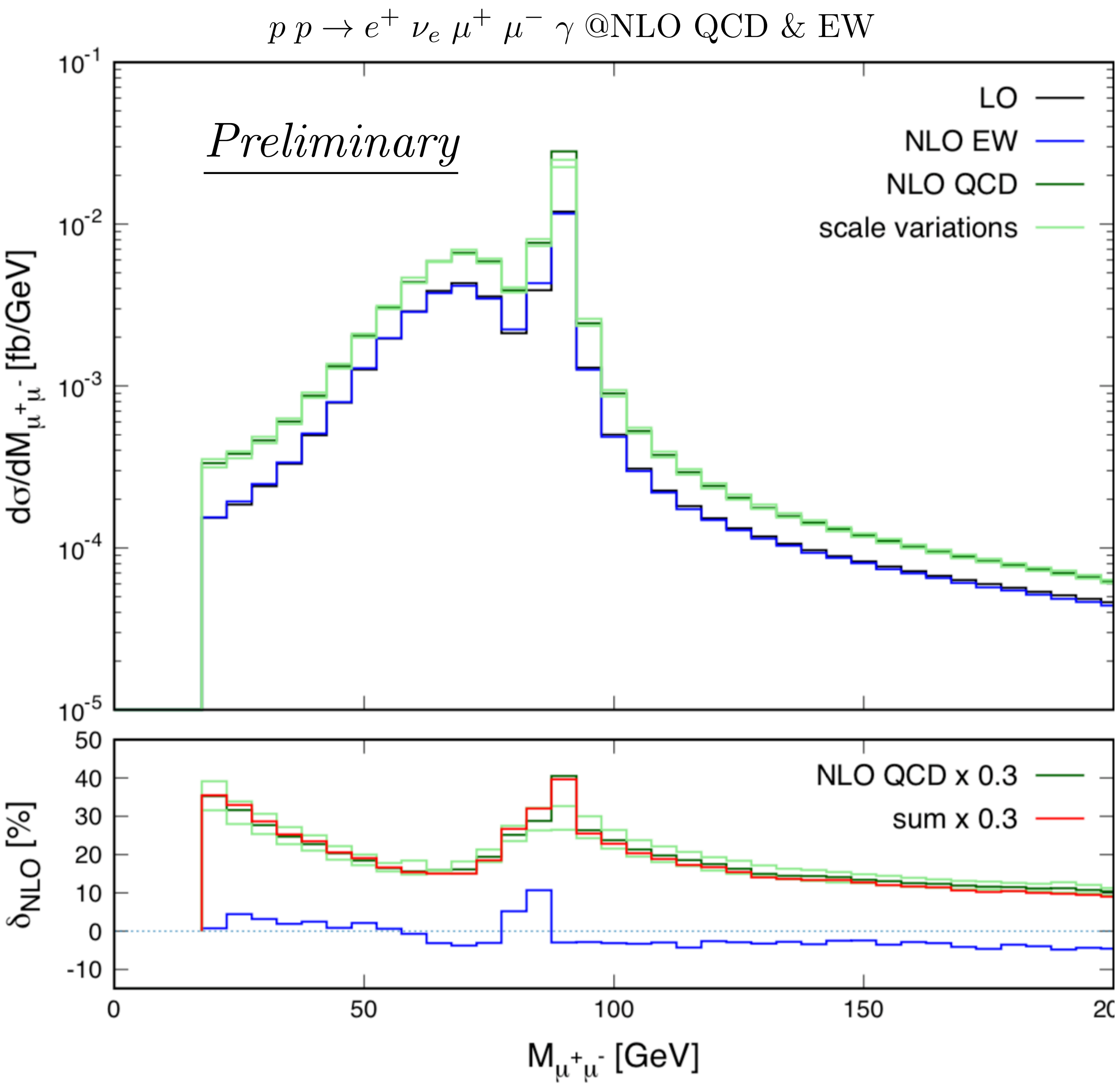


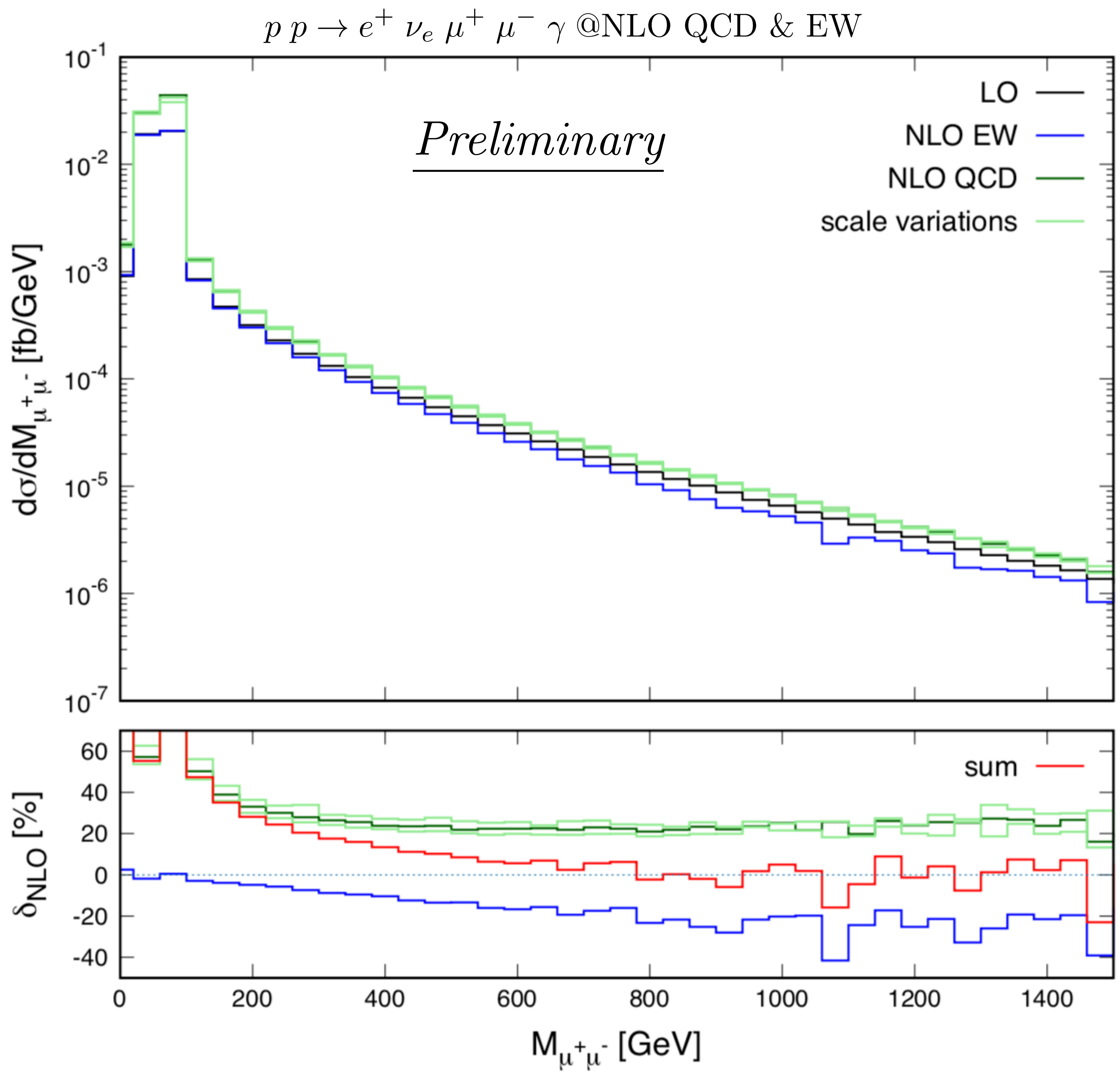
Other validations done at total cross section level:

NLO QCD to on-shell WWZ production [Nhung, Ninh, Weber (2013)]
NLO EW to Drell-Yan e+e- production [Dittmaier, Huber (2009)]
NLO EW to ZA production with leptonic decays [Denner, Dittmaier, Hecht, Pasold (2015)]
NLO QCD to WZA production with leptonic decays [Bozzi, Campanario, Rauch, Rzehak, Zeppenfeld (2010)]

$M_{\mu^+\mu^-}$

scale variations: '2-point' - varying μ_R and μ_F simultaneously up and down by a factor of 2

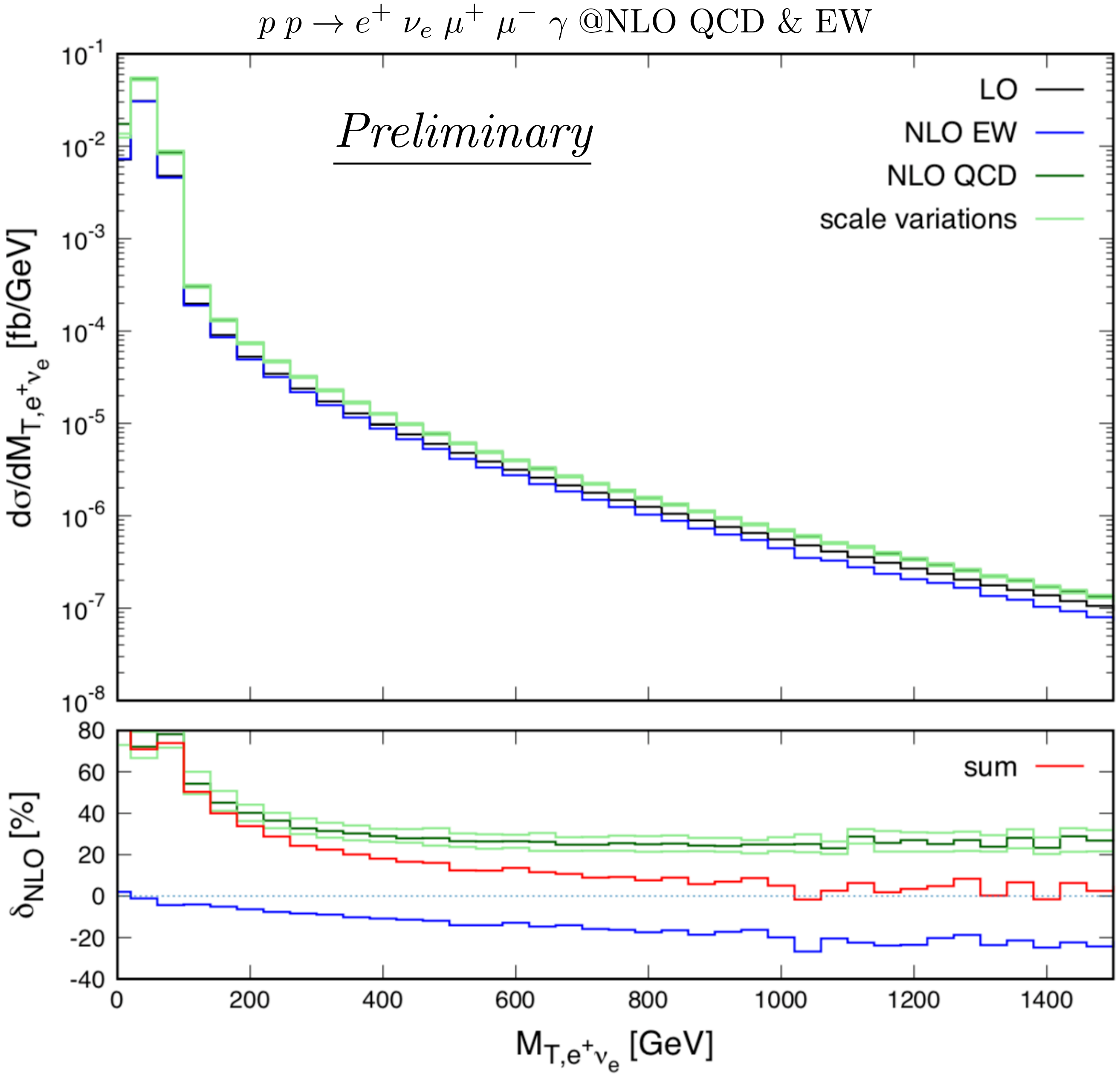


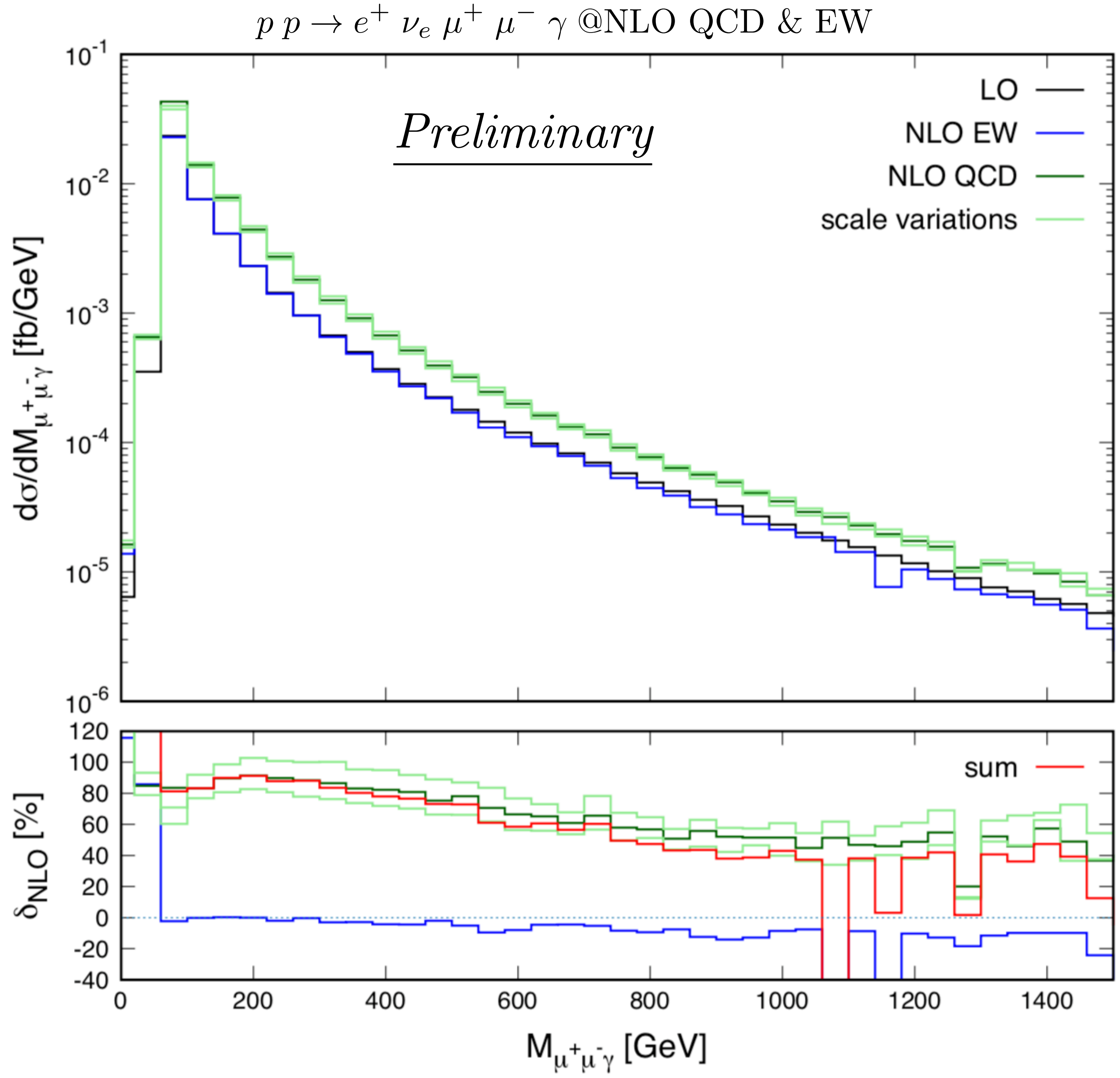


resonance region: QED effects
QCD corrections are dominant

tail region: EW and QCD corrections are comparable
→ large cancellations

$M_{\mathrm{T},e^+\nu_e}$ & $M_{\mu^+\mu^-\gamma}$





similar with $M_{\mu^+\mu^-}$ at tail region

NLO EW corrections become relevant at the tail (beyond 1 TeV)

NLO corrections in SM vs. tree-level effects of single dim-8

Questions: [Grzadkowski, Iskrzynski, Misiak, Rosiek (2010)]

1. Which operators (effects) should be included? (SM * Dim-6, Dim-6 ^2, SM * Dim-8 ?)
   - **A:** including NLO EW corrections in SM should be the bottom line.

2. Adding on single dim-8 operator, if we can approach up to eg. 1.5 TeV, what would be the max allowed Wilson coefficient not to violate the unitarity?

One guidance: [Almeida, Eboli, Gonzalez-Garcia (2020)]

Derive partial-wave unitarity bounds on dim-8 operators from 2->2 scattering.

- applied by CMS on ZZjj VBS and ZAjj VBS [CMS Collaboration: ZZjj (2020)] [CMS Collaboration: ZAjj (2021)]

-> apply this guidance to WZA production

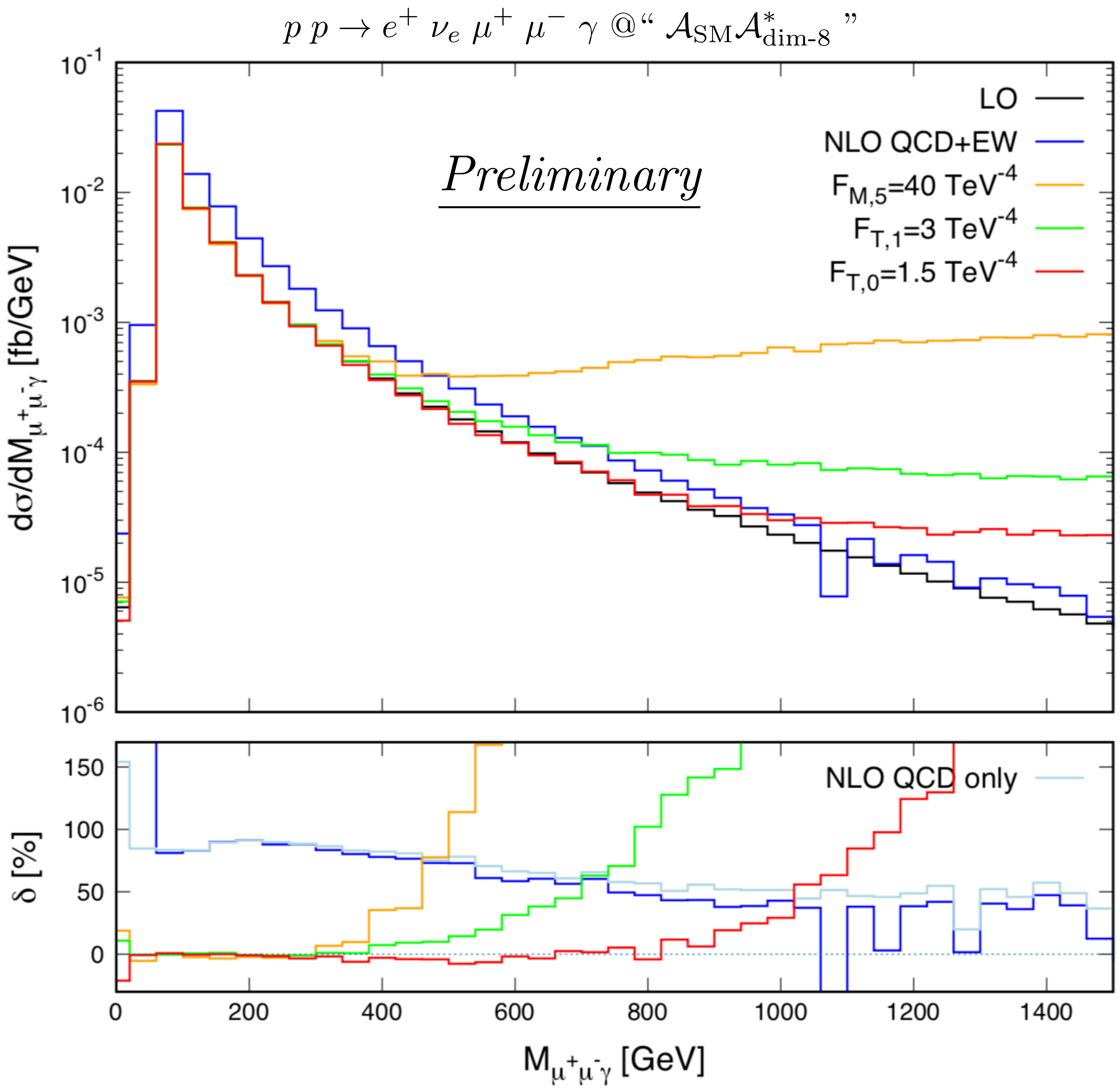
	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0}$, $\mathcal{O}_{S,1}$	X	X	X						
$\mathcal{O}_{M,0}$, $\mathcal{O}_{M,1}$, $\mathcal{O}_{M,6}$, $\mathcal{O}_{M,7}$	X	X	X	X	X	X	X		
$\mathcal{O}_{M,2}$, $\mathcal{O}_{M,3}$, $\mathcal{O}_{M,4}$, $\mathcal{O}_{M,5}$		X	X	X	X	X	X		
$\mathcal{O}_{T,0}$, $\mathcal{O}_{T,1}$, $\mathcal{O}_{T,2}$	X	X	X	X	X	X	X	X	X
$\mathcal{O}_{T,5}$, $\mathcal{O}_{T,6}$, $\mathcal{O}_{T,7}$		X	X	X	X	X	X	X	X
$\mathcal{O}_{T,8}$, $\mathcal{O}_{T,9}$			X			X	X	X	X

↓ affect quartic gauge couplings without touching the triple ones

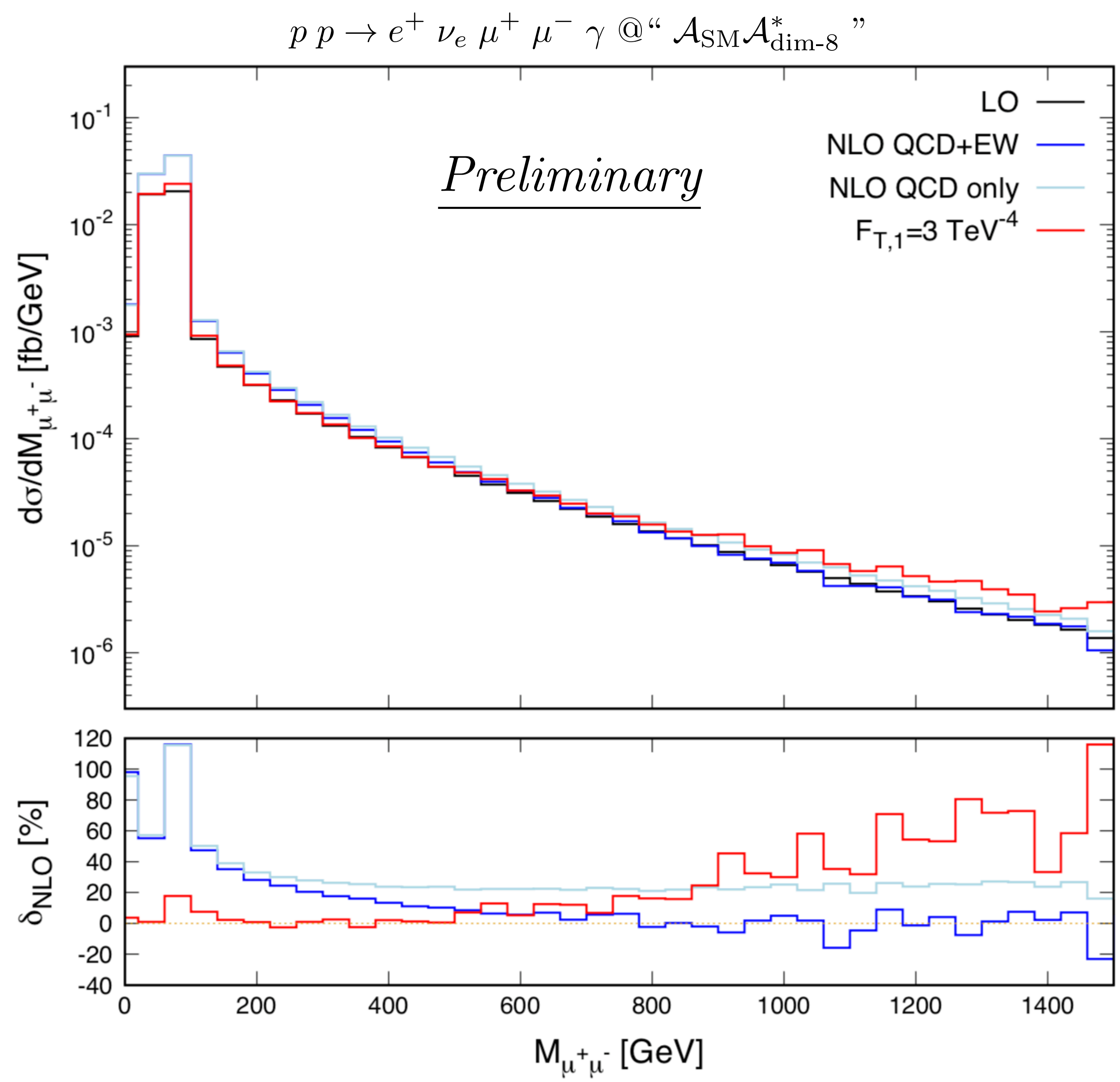
[Snowmass White Paper (2013)]
[Eboli, Gonzalez-Garcia, Mizukosh (2006)]
[Eboli, Gonzalez-Garcia (2016)]

NLO corrections in SM vs. tree-level effects of single dim-8

The coefficients of each dim-8 operators are taken as the maximum allowed values not to violate the unitarity for $\sqrt{\hat{s}} < 1.5$ TeV. All realistic effects should stay below the bounds.



- observable sensitive to the operators
- NLO EW corrections barely relevant



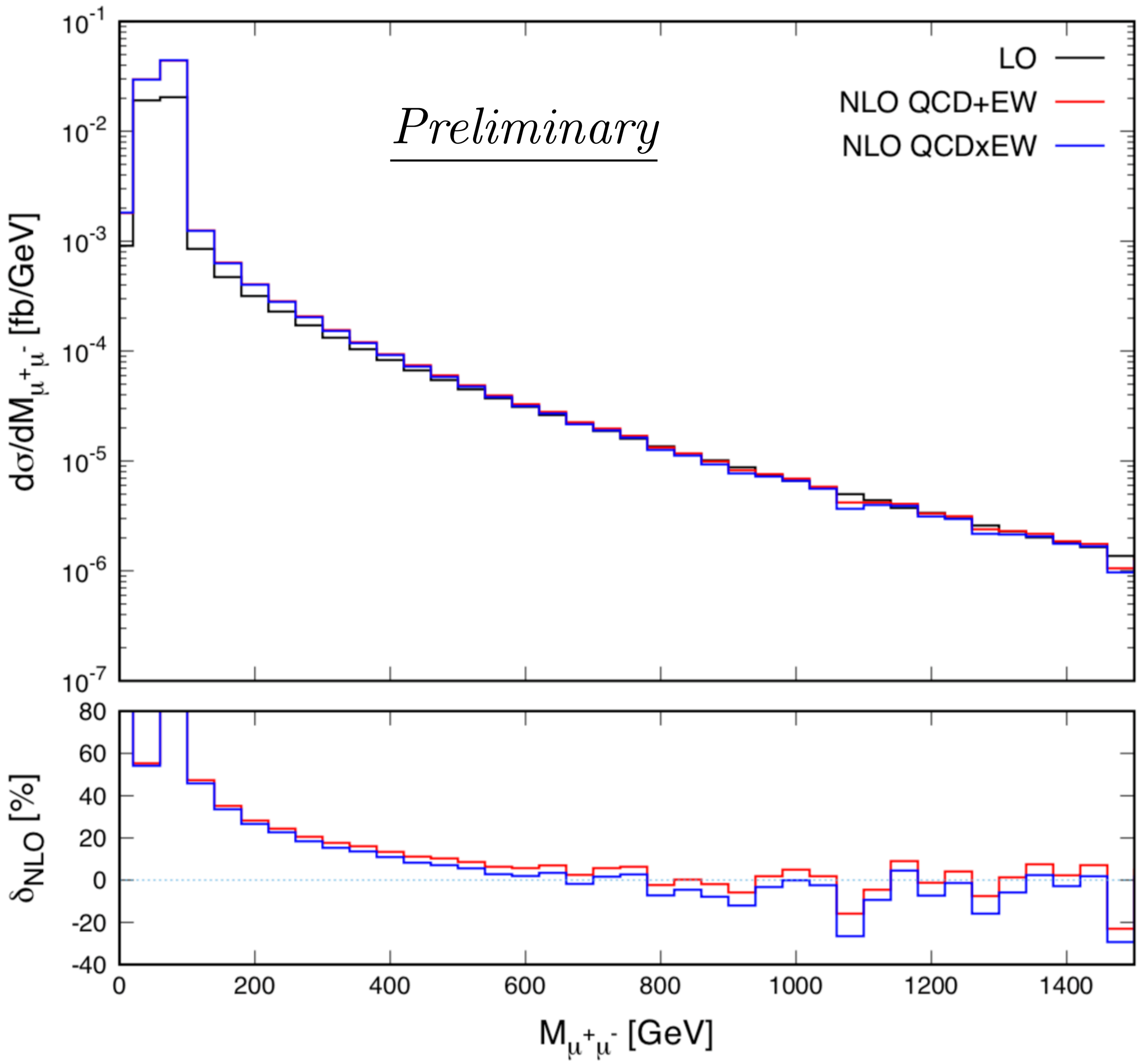
- observable less sensitive to the operators
- NLO EW corrections much more involved
- constraints not reliable without NLO EW corrections

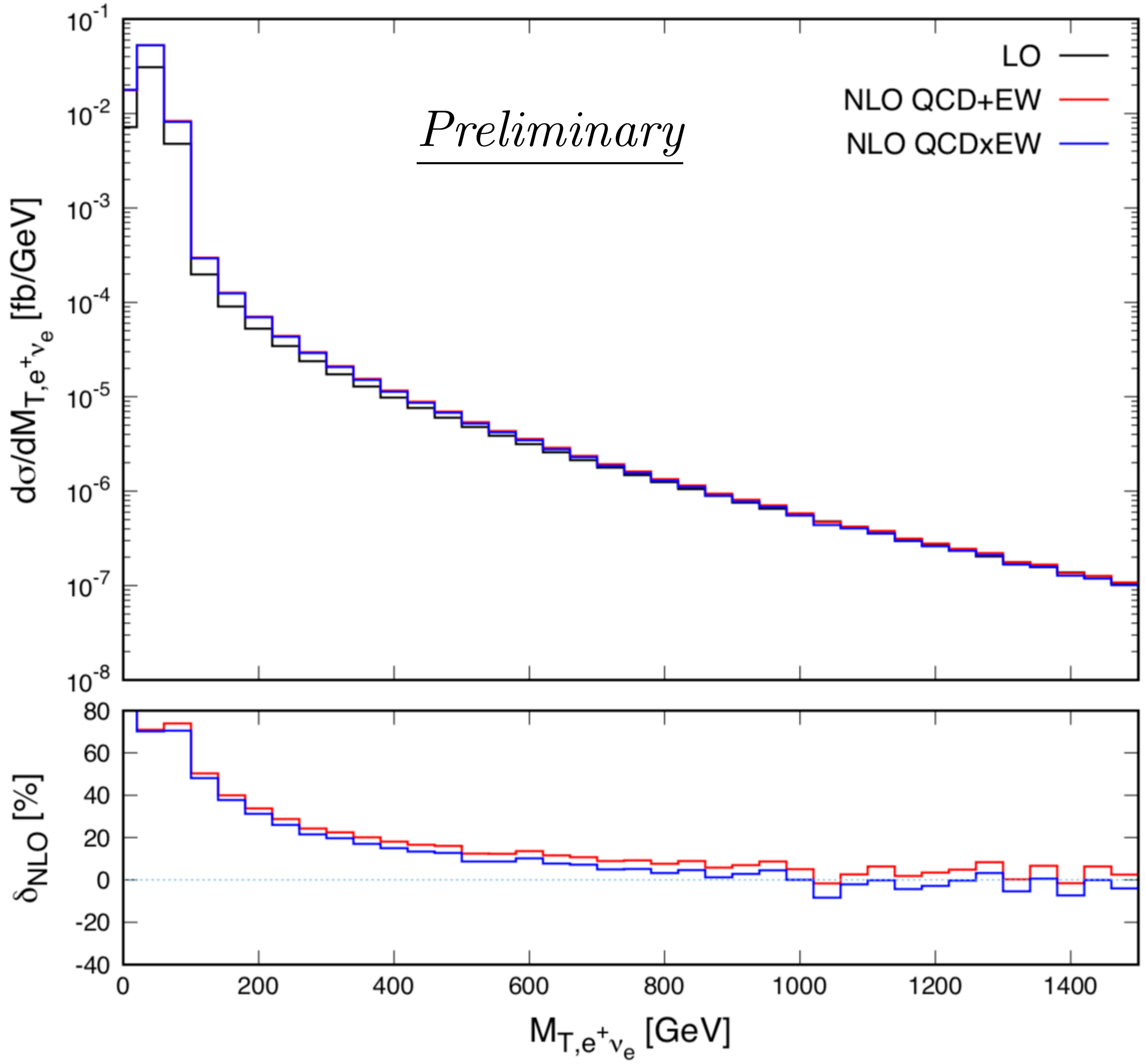
Summary

- We construct a Monte Carlo framework which can calculate any processes in SM at NLO QCD and EW accuracy automatically.
- We calculate the NLO EW corrections to WZA production with leptonic decays, including all off-shell effects.
- We study the tree-level effects of individual dimension-8 operator and its unitarity bound in various kinematic distributions.
- We conclude that NLO EW corrections are indispensable for the precision measurements in SM and set constraint on dimension-8 operators in SMEFT.

Back-ups

Back-up: Combining NLO QCD and NLO EW corrections





$$\delta_{\rm QCD} = \frac{\sigma_{\rm NLO\ QCD}}{\sigma_{\rm LO}} - 1 \qquad \sigma_{\rm NLO\ QCD+EW} = \sigma_{\rm LO} \cdot (1 + \delta_{\rm QCD} + \delta_{\rm EW})$$

$$\delta_{\rm EW} = \frac{\sigma_{\rm NLO\ EW}}{\sigma_{\rm LO}} - 1 \qquad \sigma_{\rm NLO\ QCD\times EW} = \sigma_{\rm LO} \cdot (1 + \delta_{\rm QCD}) \cdot (1 + \delta_{\rm EW})$$

Back-up: Some angular distributions