NLO Calculation for aGCs in VBFNLO

Matthias Kerner

LHC EWK Multiboson Working Group

3 July 2017

MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

arXiv:1704.01921
$Z\gamma$ production in vector-boson scattering at NLO QCD
Francisco Campanario, MK, Dieter Zeppenfeld

Overview

- VBFNLO
  - Processes and features
  - Implementation of NLO corrections

- Zγjj Production
  - Production mechanisms
  - EW production:
    uncertainties & differential results
  - Anomalous gauge couplings

VBFNLO

A parton level Monte Carlo for processes with electroweak bosons

New in VBFNLO-3-beta

Features

- processes implemented at NLO
- fully differential (cuts&histograms)
- including leptonic decays with all off-shell effects, semi-leptonic decay for selected processes
- fast
- BSM effects for many processes: aGC, 2HDM, KK, spin-2
- K-matrix unitarisation for $\mathcal{O}_{S,0}$ $\mathcal{O}_{S,1}$
- BLHA interface for VBF processes
- MPI parallelization

Processes:

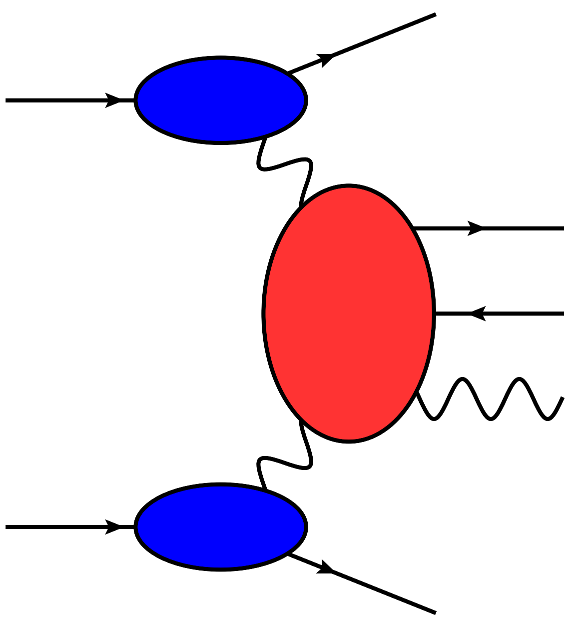
- VBF Hjj, Hjjj, HHjj, Hγjj
- Gluon Fusion Hjj (@LO)
- Higgs-Strahlung: HW, HWj

- VBF Vjj, VVjj (new: Zγjj)
- QCD-induced Vjj, VVjj

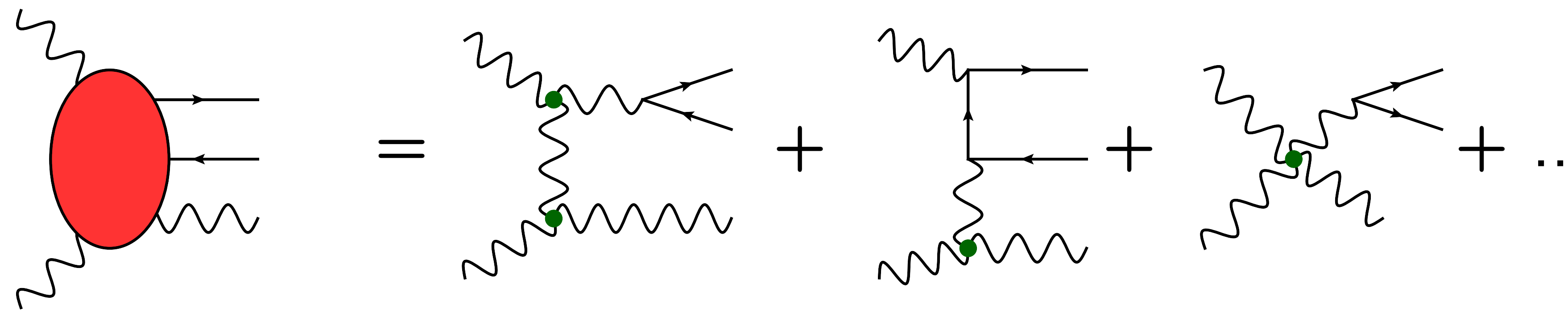
- di/tri-boson: VV, VVV
- Bosons + 1j: Wj, VVj (new: WWj, ZZj), W$\gamma\gamma$j
- Gluon Fusion (@LO): VV, VVj

NLO implementation

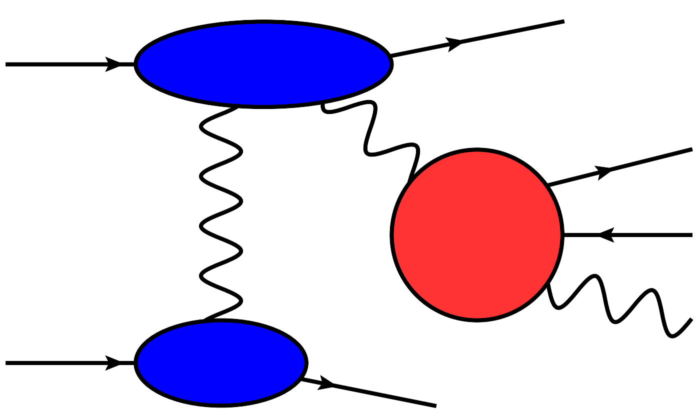
factorize amplitude into EW part (leptonic tensor) and parts involving partons



leptonic tensors

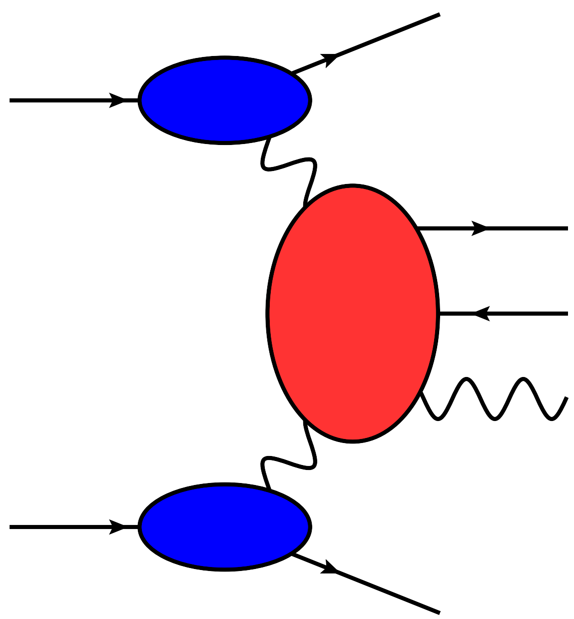


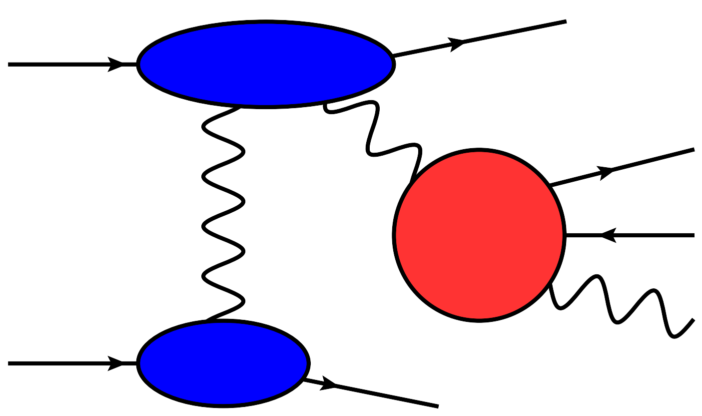
- possibly involving anomalous gauge couplings
- evaluated once per phase-space point
  used for all subprocesses → speedup



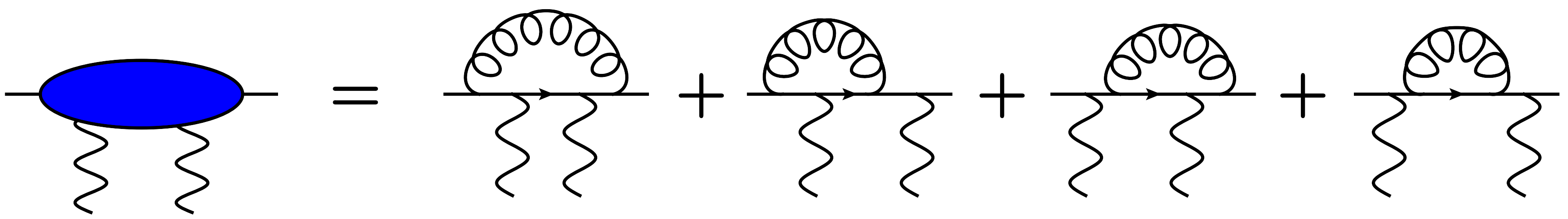
NLO implementation

factorize amplitude into EW part (leptonic tensor) and parts involving partons





QCD part — virtual corrections



grouped into building blocks with fixed order of bosons

- universal, can be used for many processes
- VBF processes: up to pentagon diagrams
  $W\gamma\gamma j$, QCD-induced VVjj: up to hexagons
- tensor reduction: [Passarino, Veltman; Denner, Dittmaier]
- ward identities $\rightarrow$ test of stability, if fails:
  discard point, expand in small Gram determinant,
  or reevaluate in quadruple precision (process dep.)
- implementation: [Campanario `11]

real radiation: Dipole subtraction [Catani, Seymour `96]

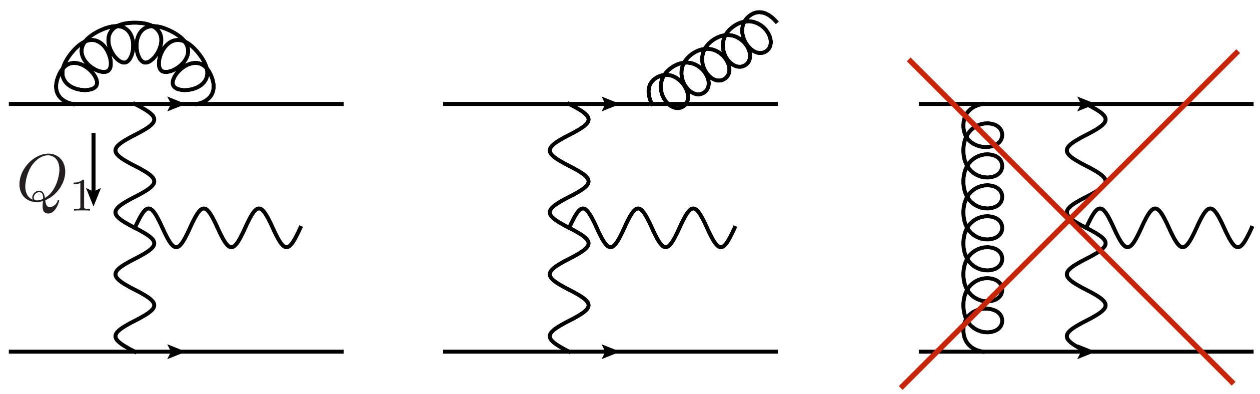
VBF approximation

VBF processes peak at large m_{jj}

$\rightarrow$ t- and u-channels are dominant

$\rightarrow$ s-channel and t-/u-channel interferences are suppressed

$\rightarrow$ QCD corrections to both quark lines can be treated separately

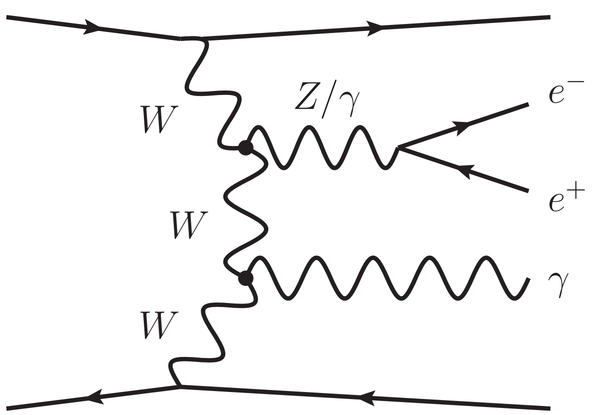


only contributes to
t-/u-channel interference

+ corrections to lower quark line with momentum transfer Q_2

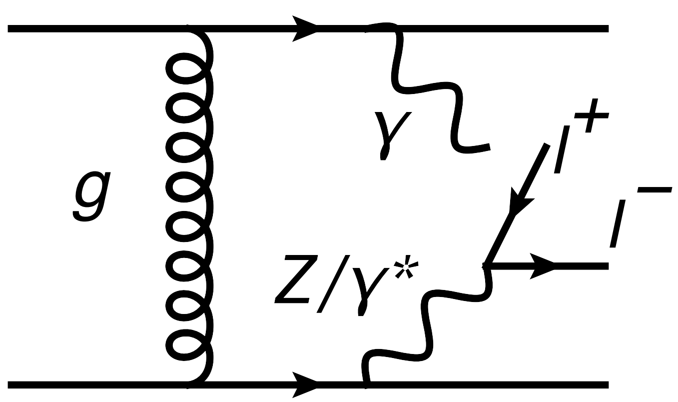
$Z\gamma$jj Production Channels

Vector Boson Scattering [Campanario, MK, Zeppenfeld `17]



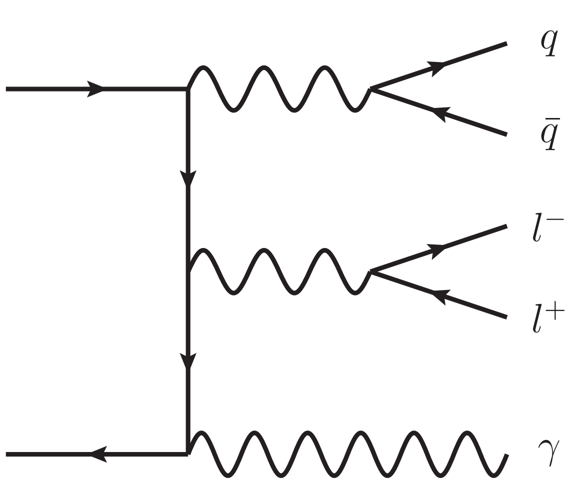
- typically high m_{jj}, large Δy_{jj}
- small scale uncertainty
- quartic gauge couplings

QCD-induced [Campanario, MK, Ninh, Zeppenfeld `14]



- gluon-induced subprocesses
  $\rightarrow$ relatively soft events
- relatively large scale uncertainty

Triboson production [Bozzi, Campanario, Hankele, Zeppenfeld `09] [Bozzi, Campanario, Rauch, Rzehak, Zeppenfeld `11], [Feigl `13]



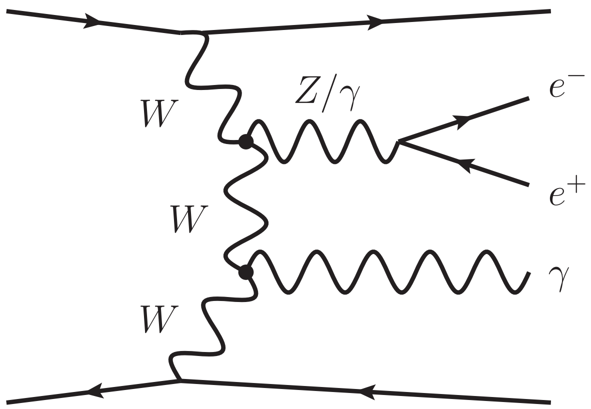
- s-channel decay V$\rightarrow$jj peaks at $m_{jj} \approx m_V$
  $\rightarrow$ small contribution at high m_{jj}

  contributes $\mathcal{O}(1‰)$ to $Z\gamma$jj

  contributes $\mathcal{O}(1\%)$ to $Z\gamma$jjj

$Z\gamma jj$ Production Channels

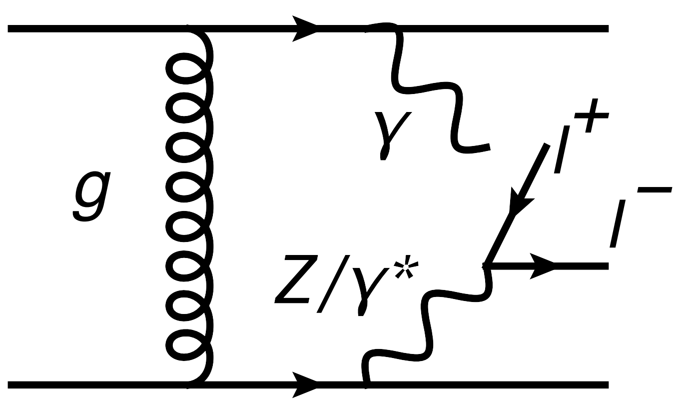
Vector Boson Scattering [Campanario, MK, Zeppenfeld `17]



- typically high m_{jj}, large Δy_{jj}
- small scale uncertainty
- quartic gauge couplings

QCD-induced

[Campanario, MK, Ninh, Zeppenfeld `14]



- gluon-induced subprocesses
  $\rightarrow$ relatively soft events
- relatively large scale uncertainty

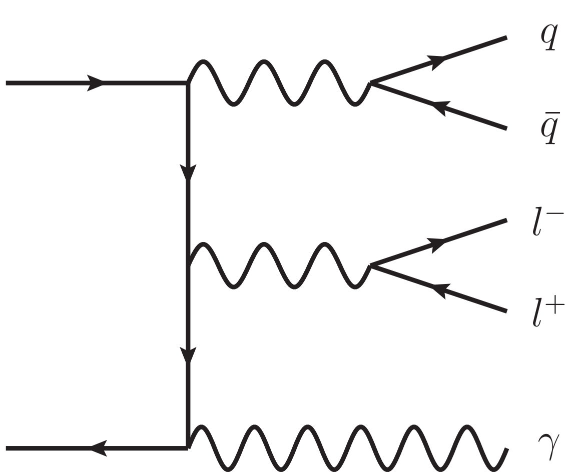
Interferences:

Expected to be largest for W^+W^+jj

~1% in W^+W^+jj with VBF cuts [Campanario, MK, Ninh, Zeppenfeld 13]

Triboson production

[Bozzi, Campanario, Hankele, Zeppenfeld `09]
[Bozzi, Campanario, Rauch, Rzehak, Zeppenfeld `11], [Feigl `13]



- s-channel decay $V \rightarrow jj$ peaks at $m_{jj} \approx m_V$
  $\rightarrow$ small contribution at high m_{jj}

contributes $\mathcal{O}(1‰)$ to $Z\gamma jj$

contributes $\mathcal{O}(1\%)$ to $Z\gamma jjj$

Cuts

Jets: anti-k_T, $R = 0.4$

$$p_{T,j} > 30\,\mathrm{GeV}, \qquad |y_j| < 4.5$$

Leptons:

$$\begin{aligned} p_{T,\ell(\gamma)} &> 20(30)\,\mathrm{GeV}, & |y_{\ell(\gamma)}| &< 2.5, \\ R_{j\ell} &> 0.4, & R_{\ell\gamma} &> 0.4, \\ R_{j\gamma} &> 0.4, & R_{\ell\ell} &> 0.0, \\ m_{\ell\ell\gamma} &> 120\,\mathrm{GeV}, & m_{\ell\ell} &> 15\,\mathrm{GeV} \end{aligned}$$

reduces $Z \to l^+ l^- \gamma$ contributions

VBF-cuts:

$$m_{j_1 j_2} > 600\,\mathrm{GeV}, \quad |\eta_{j_1} - \eta_{j_2}| > 4 \quad \eta_{j_1} \times \eta_{j_2} < 0$$

Smooth photon isolation [Frixione `98]

$$\sum_{i \in \text{partons}} p_{T,i}\,\theta(R - R_{\gamma i}) \le \epsilon\, p_{T,\gamma} \frac{1 - \cos R}{1 - \cos \delta_0} \quad \forall R < \delta_0 \qquad \text{with} \quad \begin{aligned} \delta_0 &= 0.4 \\ \epsilon &= 0.05 \end{aligned}$$

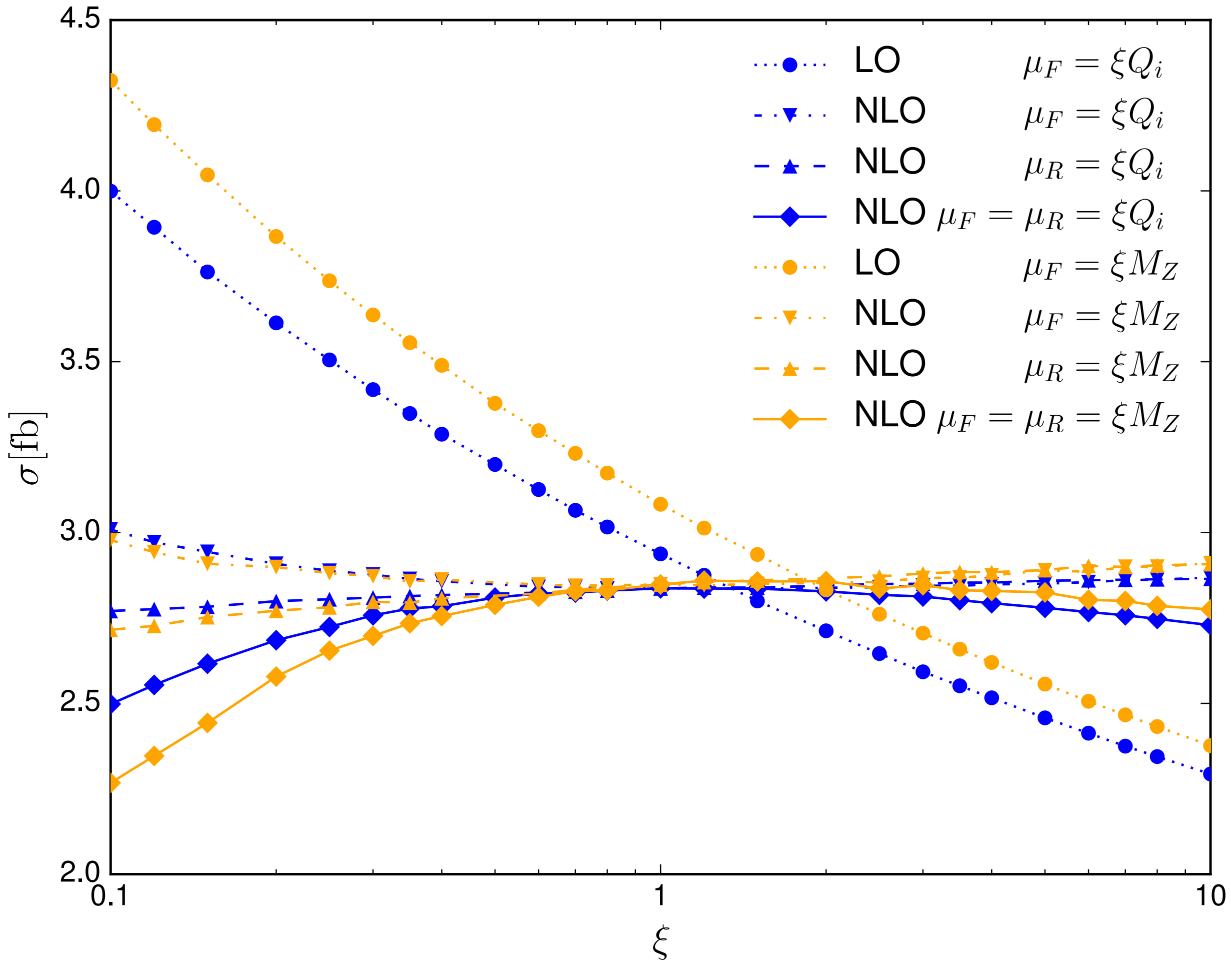
VBF Zγjj — Scale Dependence

$$H_T = \frac{1}{2}\left(\sum_{\text{partons}} p_{T,i} + \sum_{V_i}\sqrt{p_{T,V_i}^2 + m_{V_i}^2}\right)$$

$$H_{T^*} = \frac{1}{2}\left(\sum_{\text{jets}} p_{T,i} \exp|y_i - y_{12}| + \sum_{V_i}\sqrt{p_{T,V_i}^2 + m_{V_i}^2}\right)$$

$$E_T = \frac{1}{2}\left[E_T(jj) + E_T(VV)\right]$$

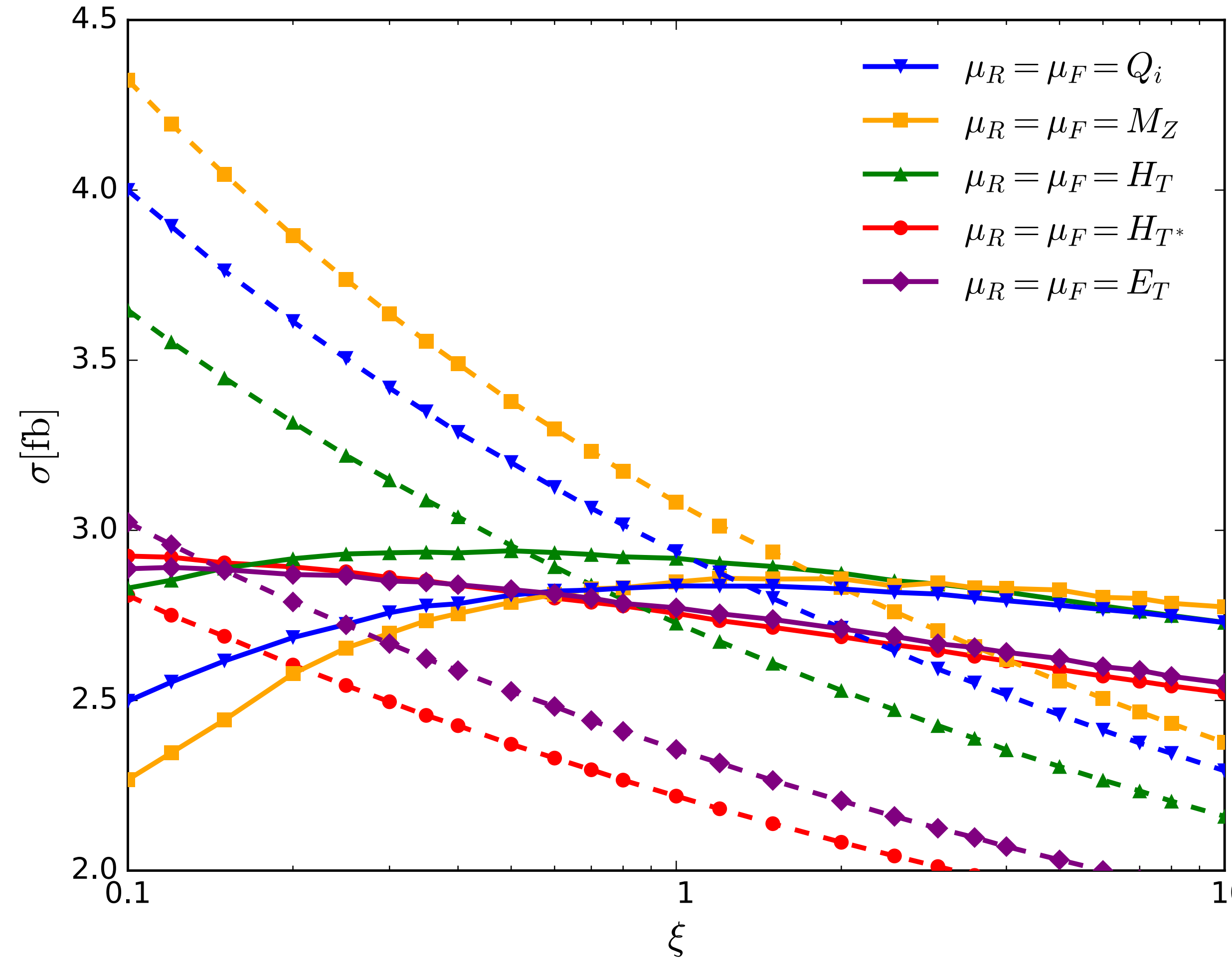
Dependence on μ_F and μ_R



No μ_F dependence at LO

NLO scale dependence: ~1%

Various central scales

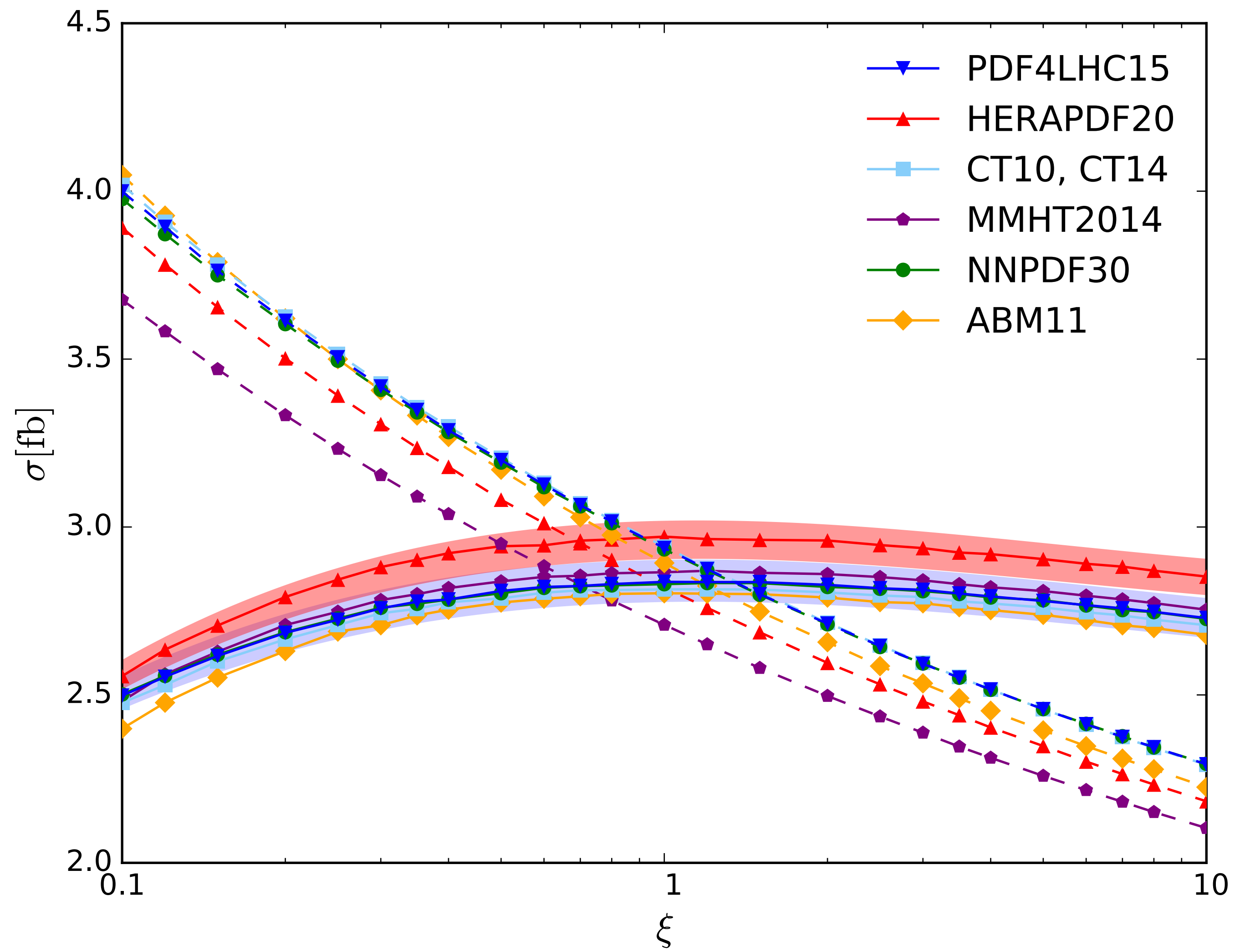


Stable results at NLO:

Differences of 5% at $\xi = 1$ (40% @LO)

VBF Zγjj — Dependence on PDF set

Scale dependence using different PDF sets $\mu_F = \mu_r = \xi Q_i$



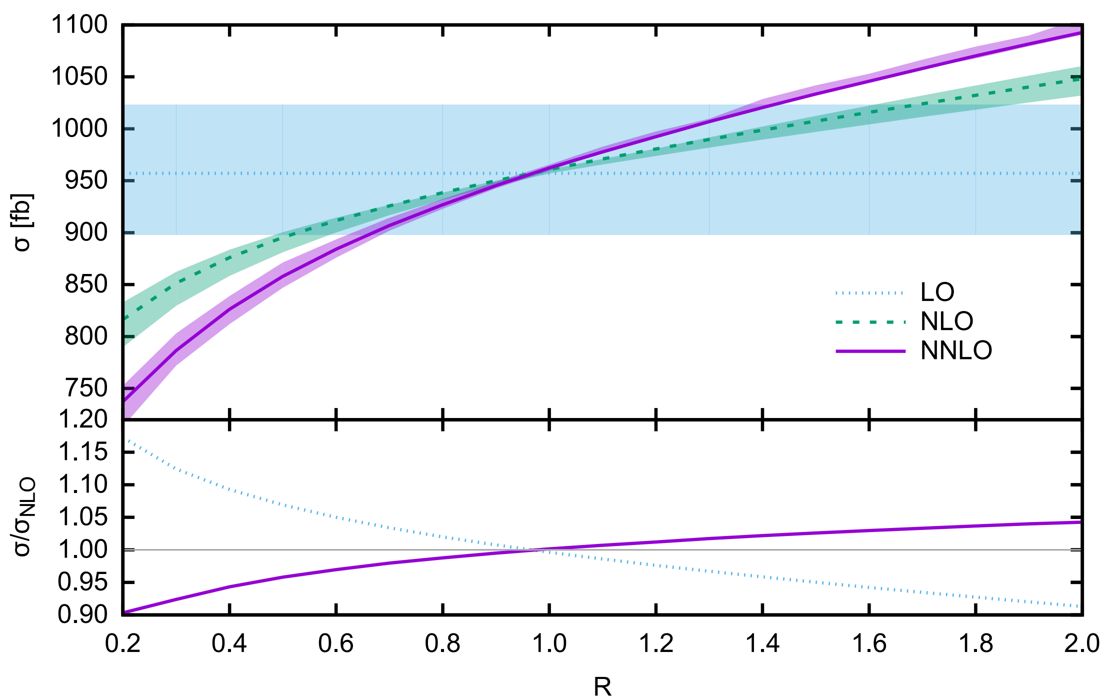
differences/uncertainties of PDF sets ~2%

Estimation of NNLO QCD and NLO EW effects

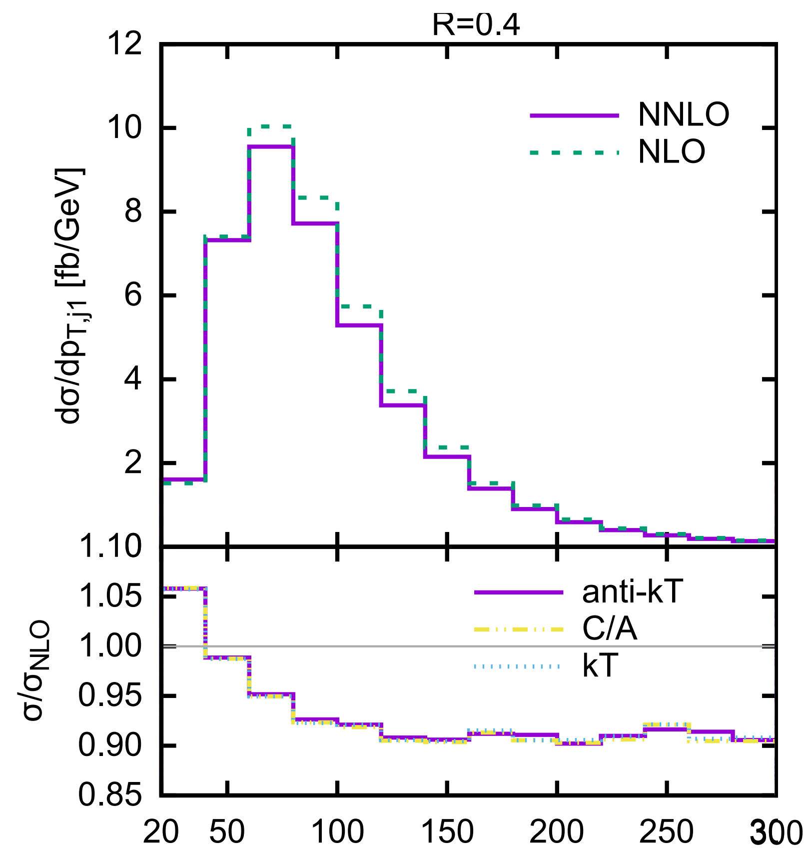
- NNLO and N^3LO corrections known for Hjj
  [Bolzoni, Maltoni, Moch, Zaro `10] [Dreyer, Karlberg `16]

  Effects of similar size expected for VVjj production

  Higher order correction introduce dependence on jet radius (no jet shape @LO)



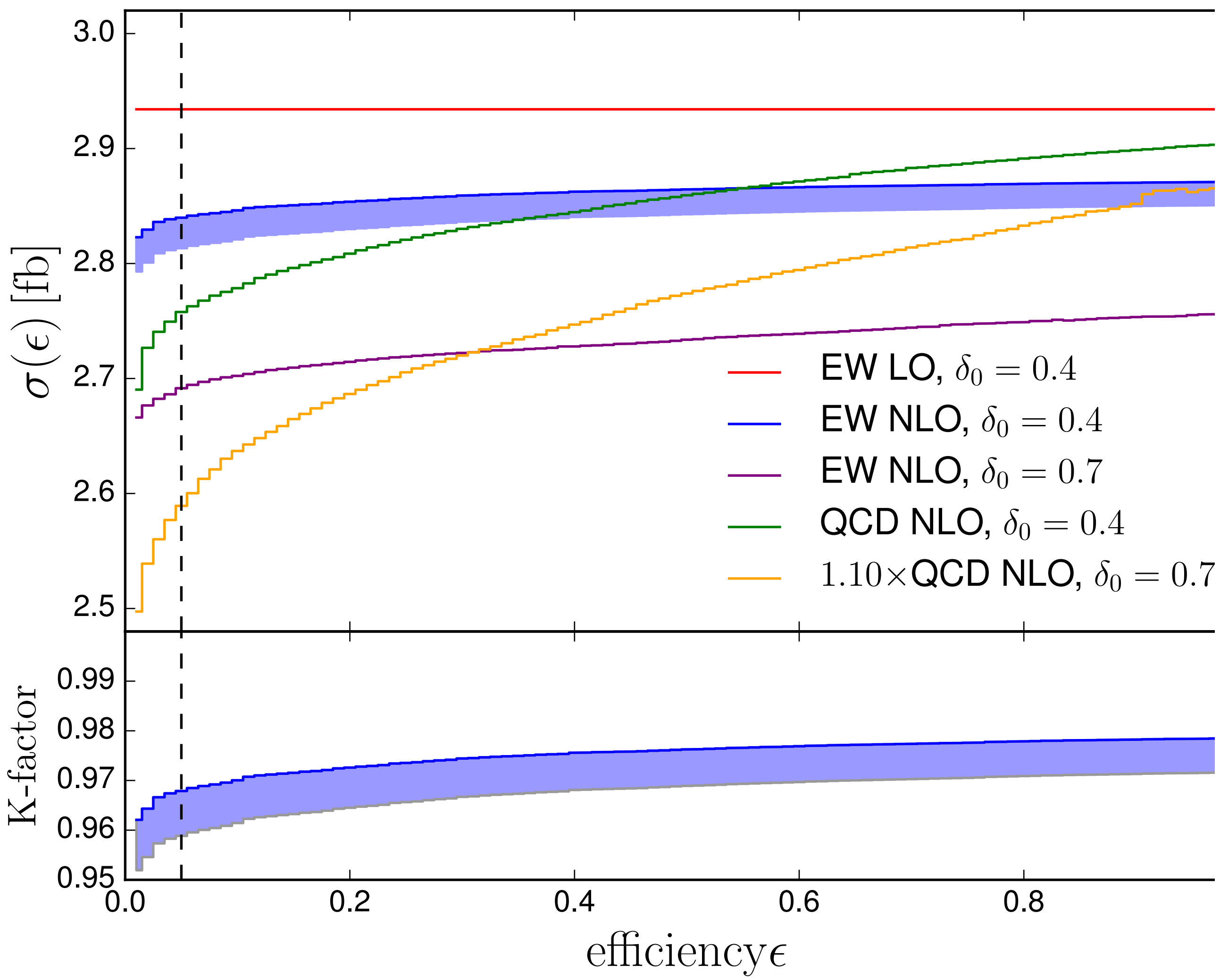
[Rauch, Zeppenfeld]

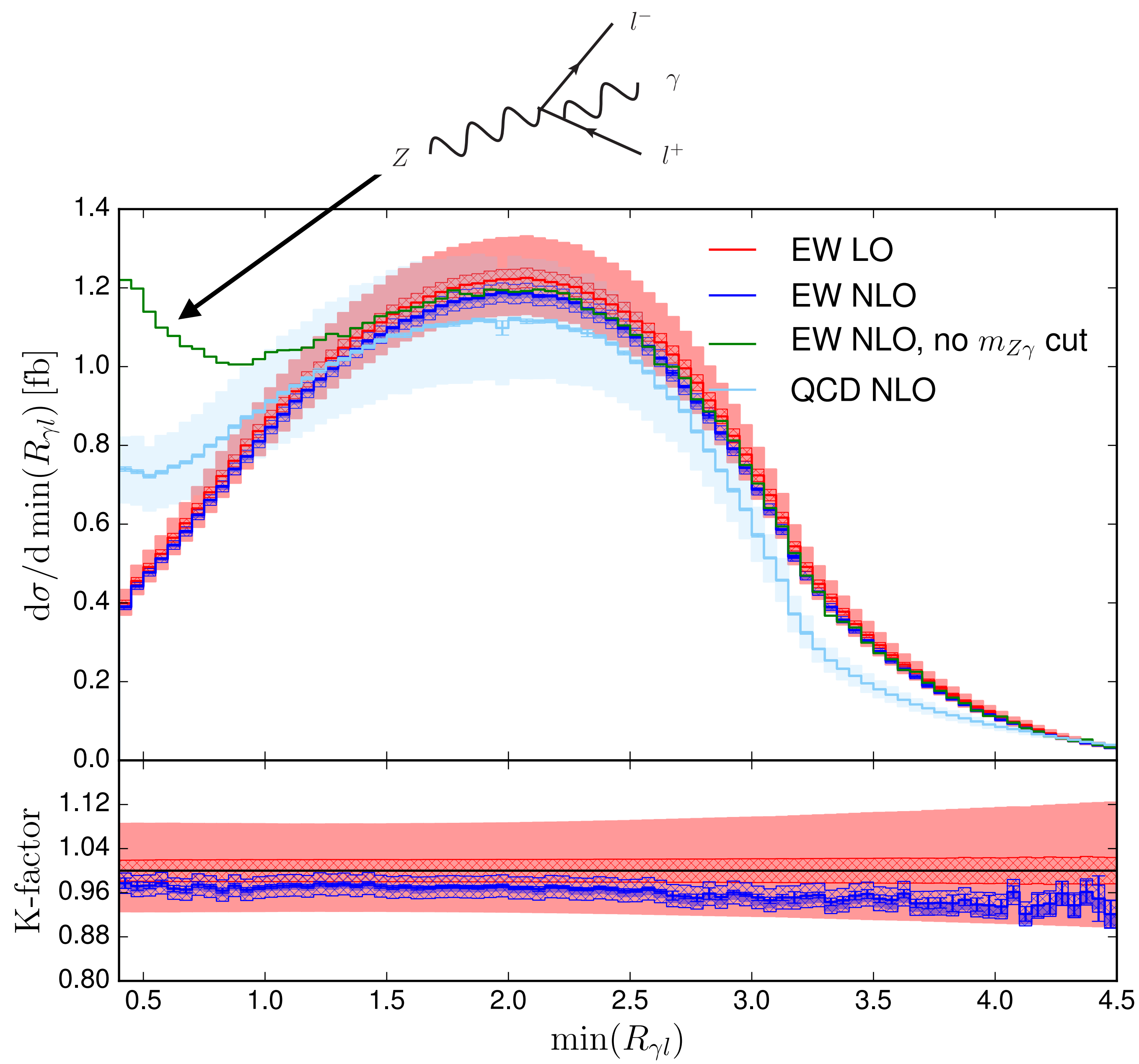


→ 5-10% effect

- NLO EW corrections for Hjj: $\mathcal{O}(10\%)$
  [Ciccolini, Denner, Dittmaier `07]
  [Figy, Palmer, Weiglein `10]

Photon isolation





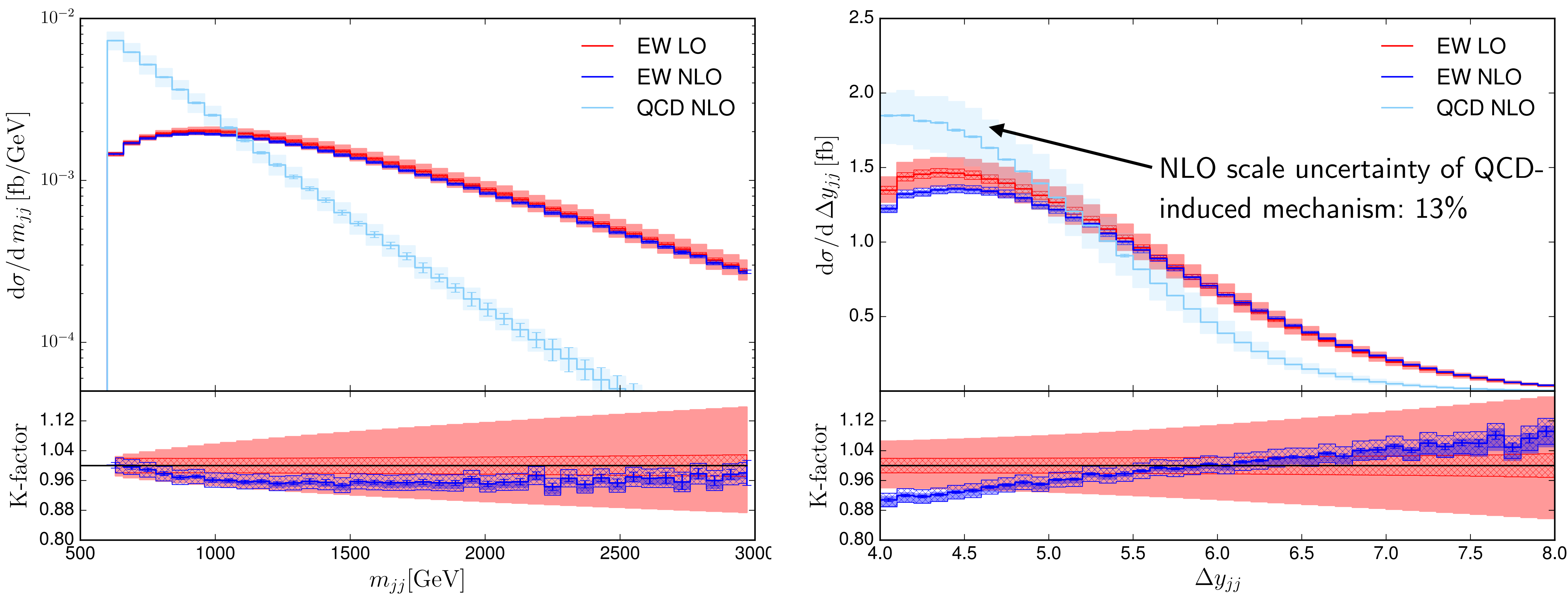
dependence on photon isolation efficiency:

- small for VBF $Z\gamma jj$ production (γ typically well isolated from jets)
- larger dependence for QCD-induces production

Differential results

solid bands: scale uncertainty

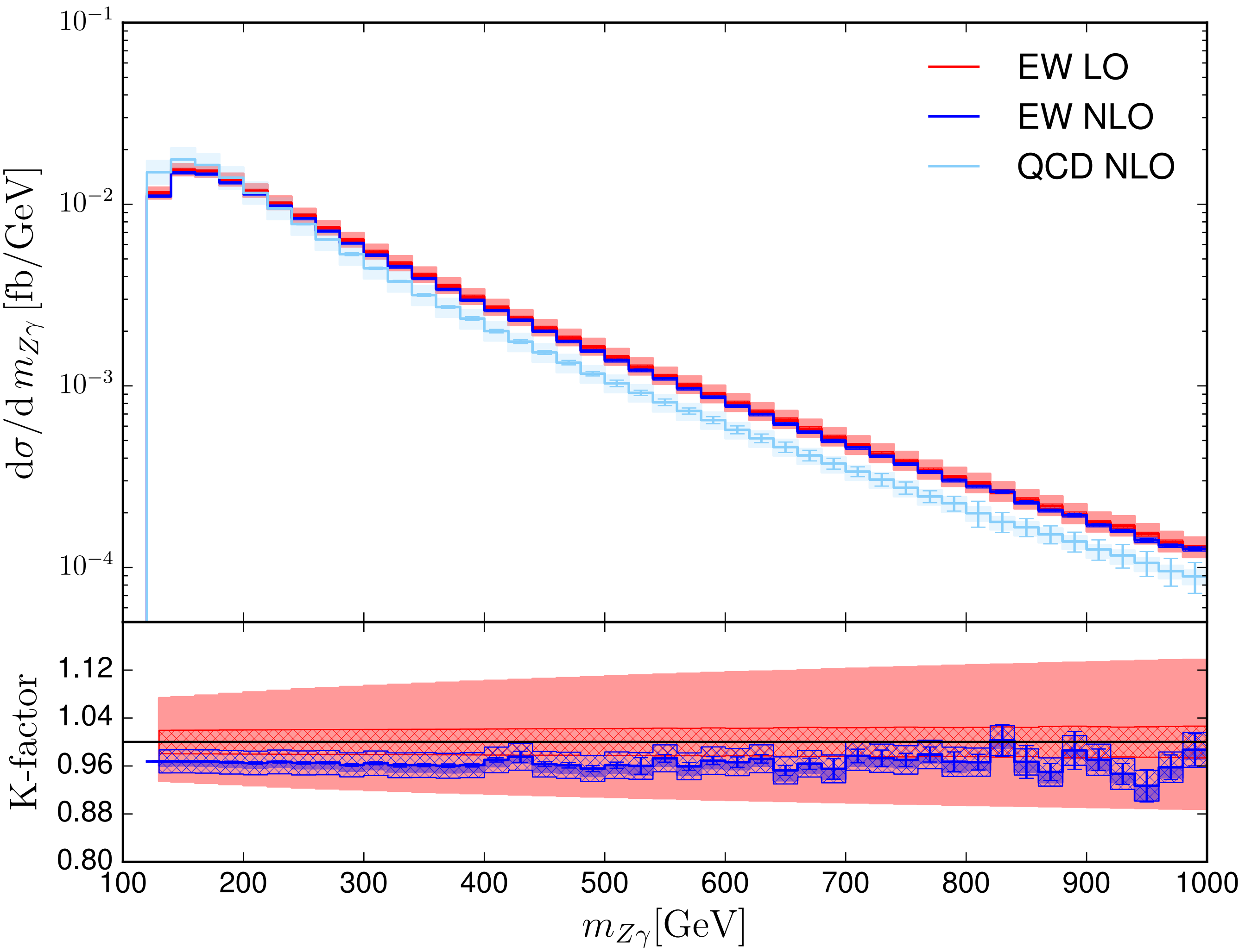
hatched bands: PDF uncertainty

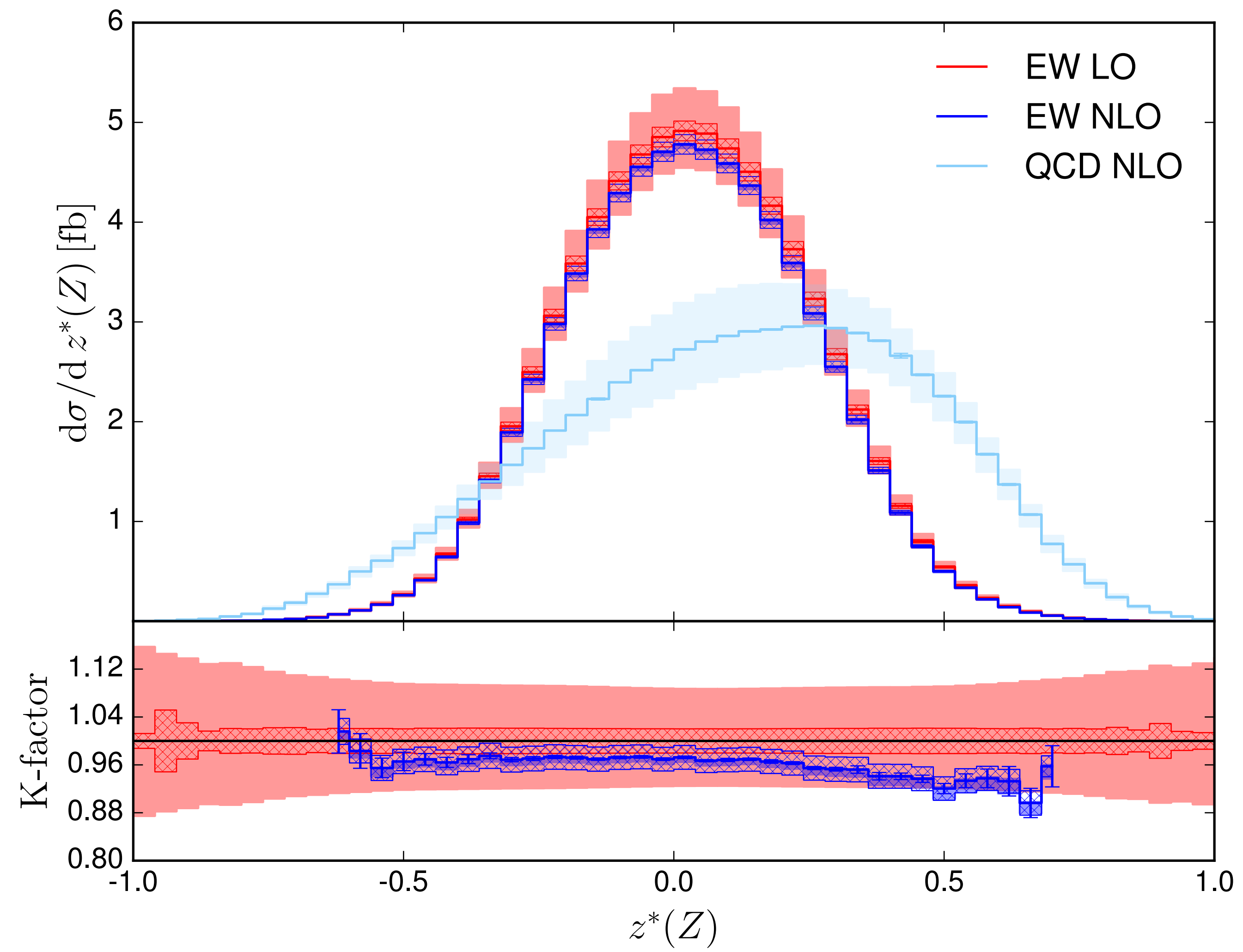


similar total cross sections for VBF and QCD-induced production, but different shape

Differential results

$$z^*(V) = \frac{y_V - \frac{1}{2}(y_1 + y_2)}{y_1 - y_2}$$





- EW production: EW bosons produced in central region
- QCD production: EW bosons closer to hardest jet

Anomalous Couplings

Operator: $\mathcal{O}_{T,8} = \widehat{B}_{\mu\nu}\widehat{B}^{\mu\nu}\widehat{B}_{\alpha\beta}\widehat{B}^{\alpha\beta}$ $\longrightarrow$ only quartic couplings of neutral bosons

aGC lead to unitarity violation for large $s = m^2_{Z\gamma}$, because $\mathcal{M}(s) \propto s^2$

Unitarisation with

- dipole form factor (dotted lines)

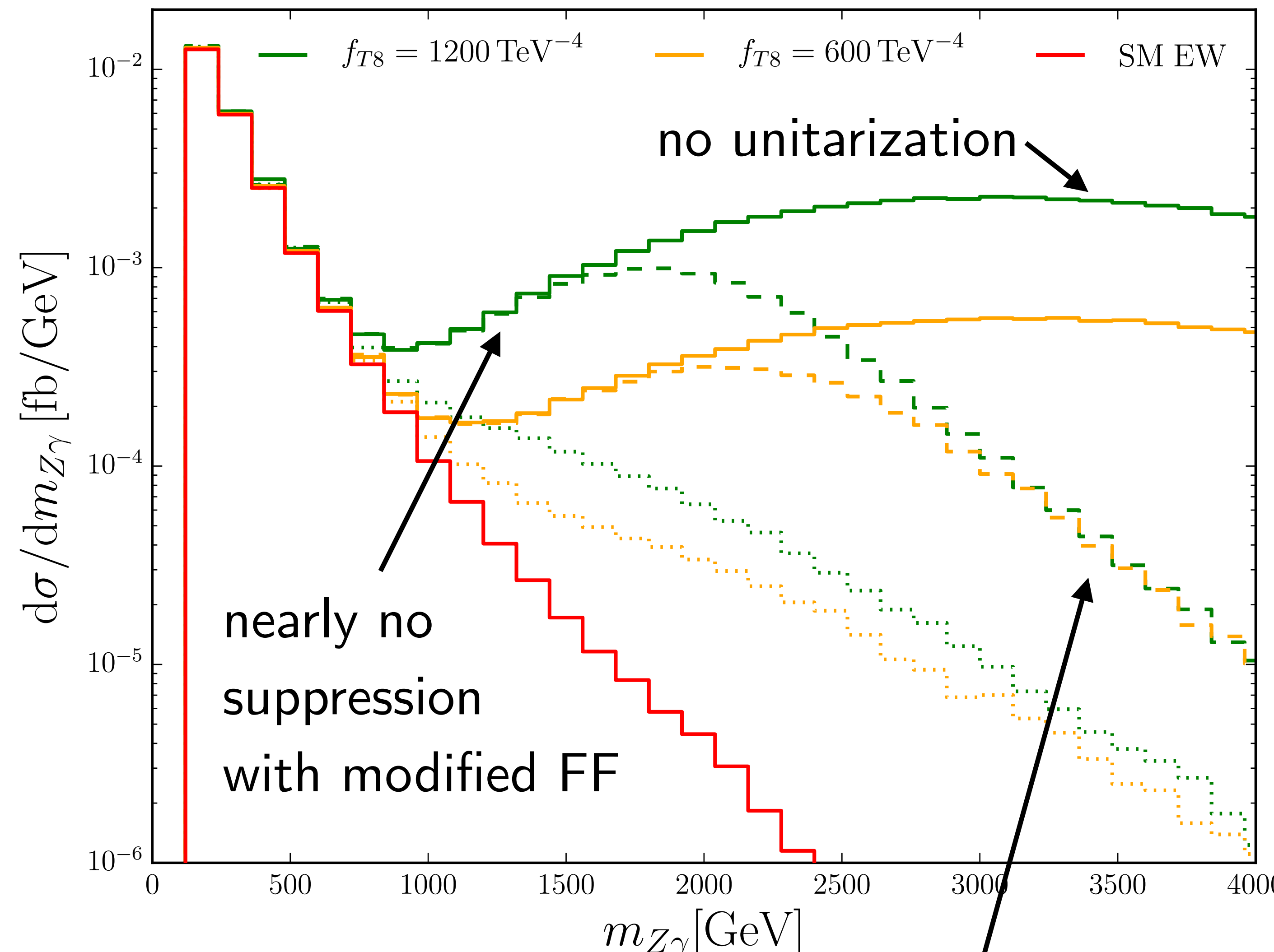
$$\mathcal{F}(s) = \left(1 + \frac{s}{\Lambda^2_{FF}}\right)^{-2}$$

- modified form factor (dashed lines)

$$\mathcal{F}^c(s) = \left(1 - i\frac{s^2}{{\Lambda^c_{FF}}^4}\right)^{-1}$$

inspired by K-matrix unitarisation, where partial waves are replaced by

$$a_{IJ} \rightarrow \frac{a_{IJ}}{1 - i a_{IJ}}$$



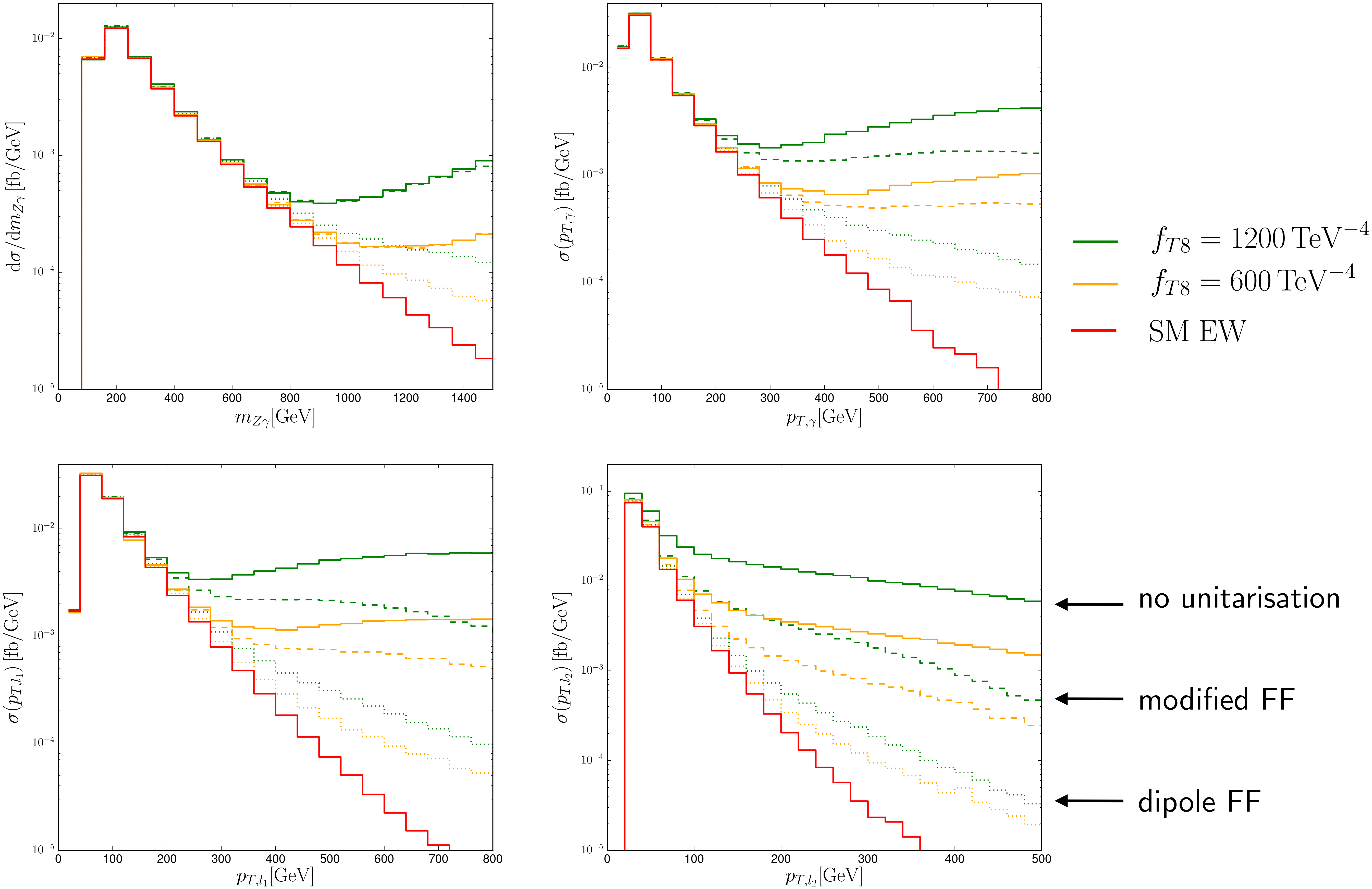
$\rightarrow$ modified form factor has same same high-s behavior as K-matrix unitarisation

$\Lambda,\ \Lambda^c$ set according to unitarity bound

high-s region determined by unitarisation procedure

Anomalous Couplings

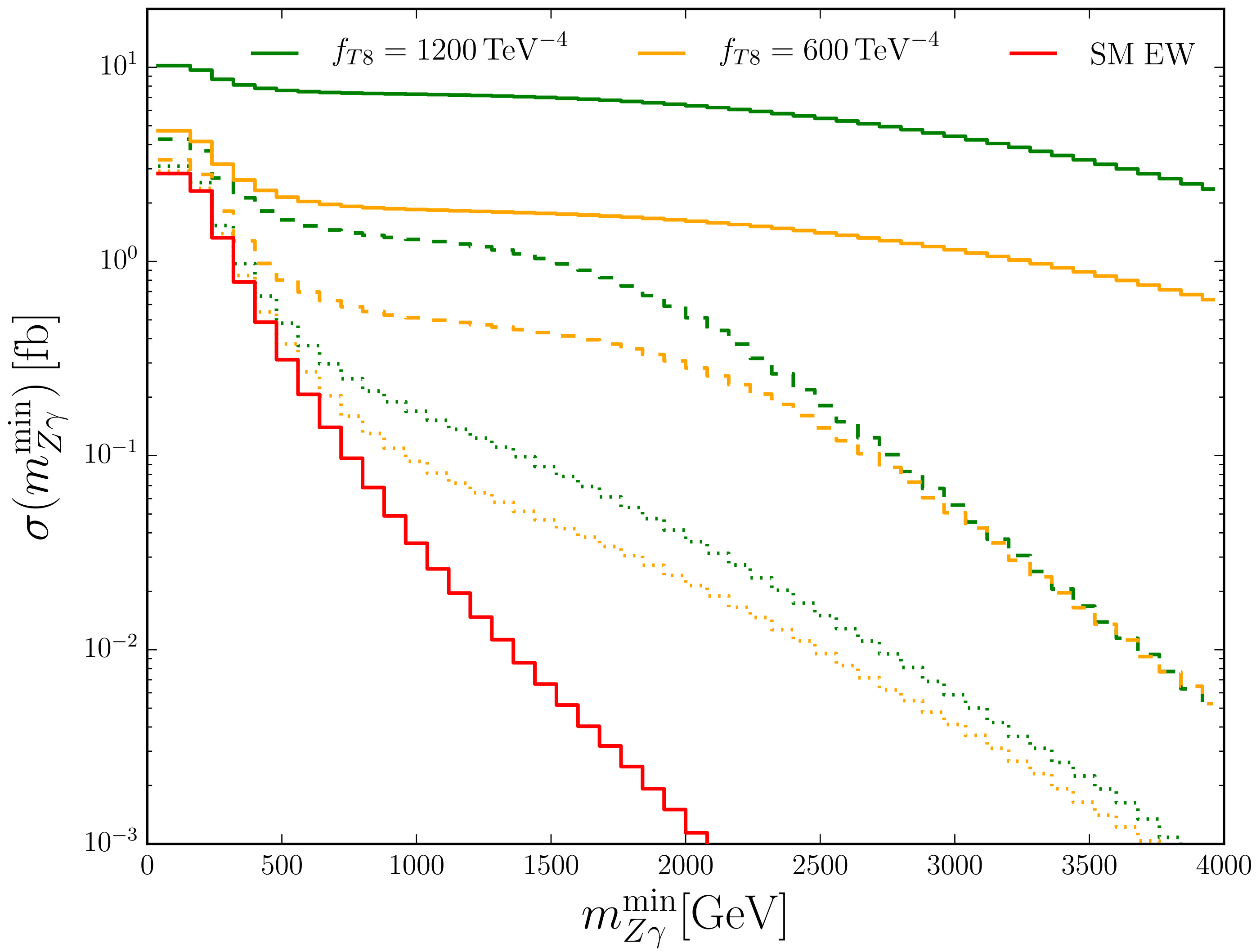
differential results



Anomalous Couplings — Integrated Results

experimental aGC limits usually set by $\sigma(m_{VV} > m_{VV}^{min})$

$\rightarrow$ consider $\sigma(m_{Z\gamma}^{\min}) = \int_{m_{Z\gamma}^{\min}}^{\infty} \mathrm{d}m_{Z\gamma} \frac{\mathrm{d}\sigma(m_{Z\gamma})}{\mathrm{d}m_{Z\gamma}}$



$\rightarrow$ significant contribution to xsec determined by unitarisation method

modified form factor:

- results closer to results without unitarisation $\rightarrow$ better description of aGC kinematics (?)
- large contribution from high-s region

$\rightarrow$ not clear which FF is preferable

Setting limits on aGC can be done using form factors.

Disentangling effects of different aGC best done on level of differential distributions in phase space regions below unitarity bound.

Conclusions

VBFNLO

- NLO predictions for various processes
  involving EW bosons
- Inclusion of BSM effects for many processes

Zγjj Production

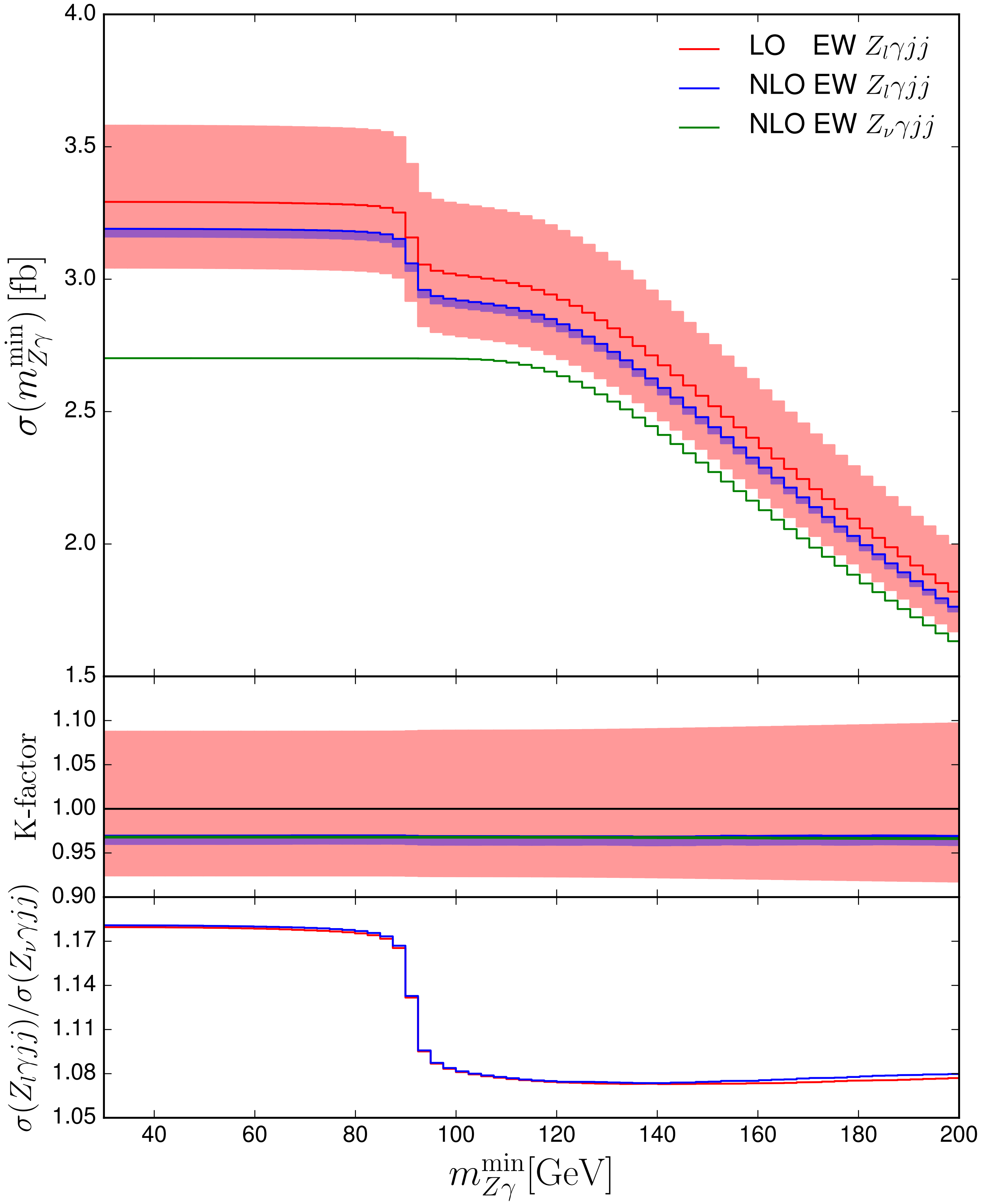
- Theory uncertainties:
  - scale variation: ~1-5%
  - PDF uncertainties: ~2%
  - higher order effects possibly relevant $\mathcal{O}(10\%)$
- Differential results
- Anomalous Gauge Couplings
  new unitarisation method inspired by K-matrix unitarisation

Thank you for your attention!

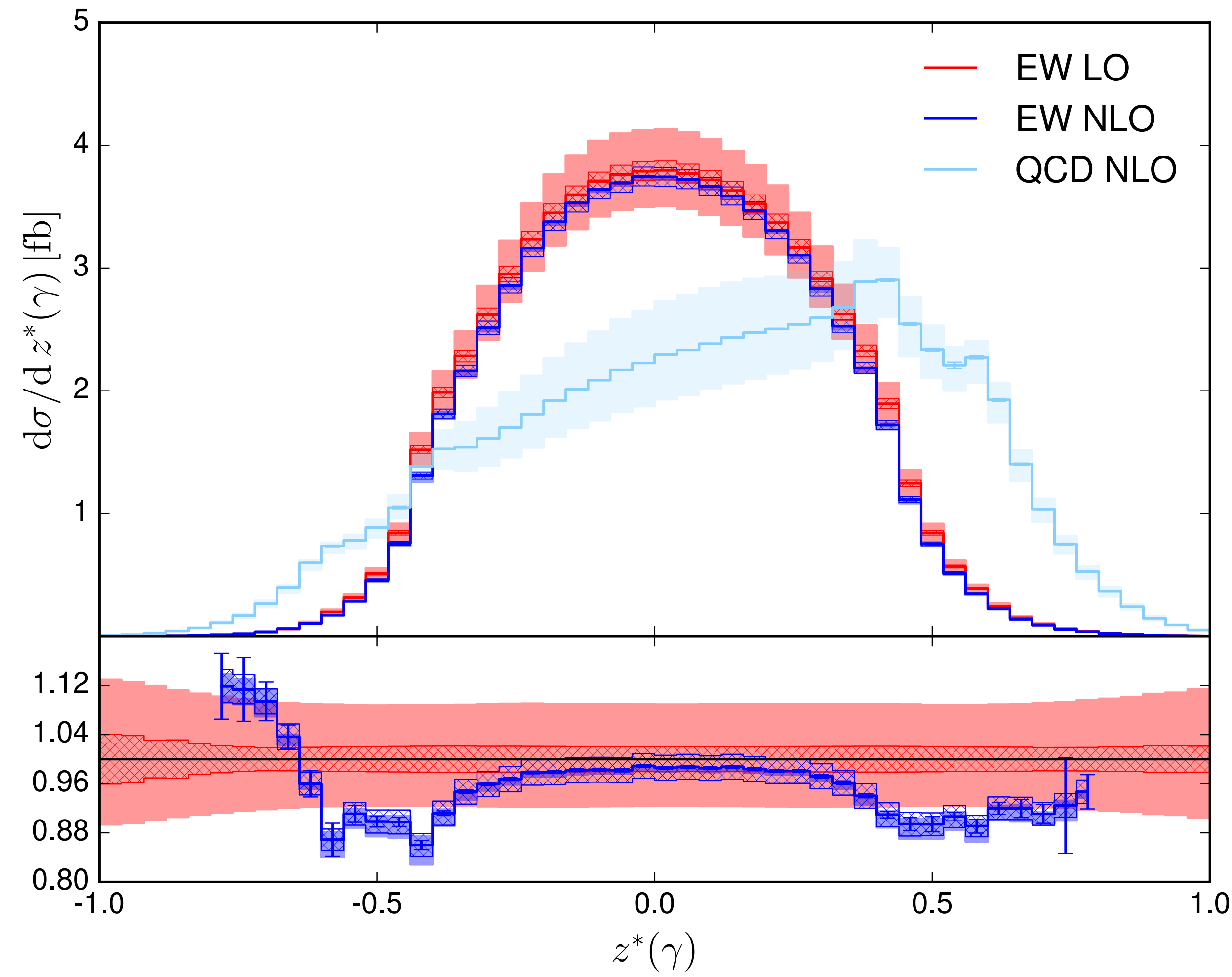
Backup

Total Cross Section

	EW	QCD
8 TeV	$0.808(1)^{-1\%}_{-0.9\%}$ fb	$0.735(6)^{-14\%}_{+15\%}$ fb
13 TeV	$2.837(1)^{-0.3\%}_{-1\%}$ fb	$2.764(2)^{-13\%}_{+13\%}$ fb
14 TeV	$3.359(6)^{-0.2\%}_{-0.9\%}$ fb	$3.31(2)^{-12\%}_{+13\%}$ fb

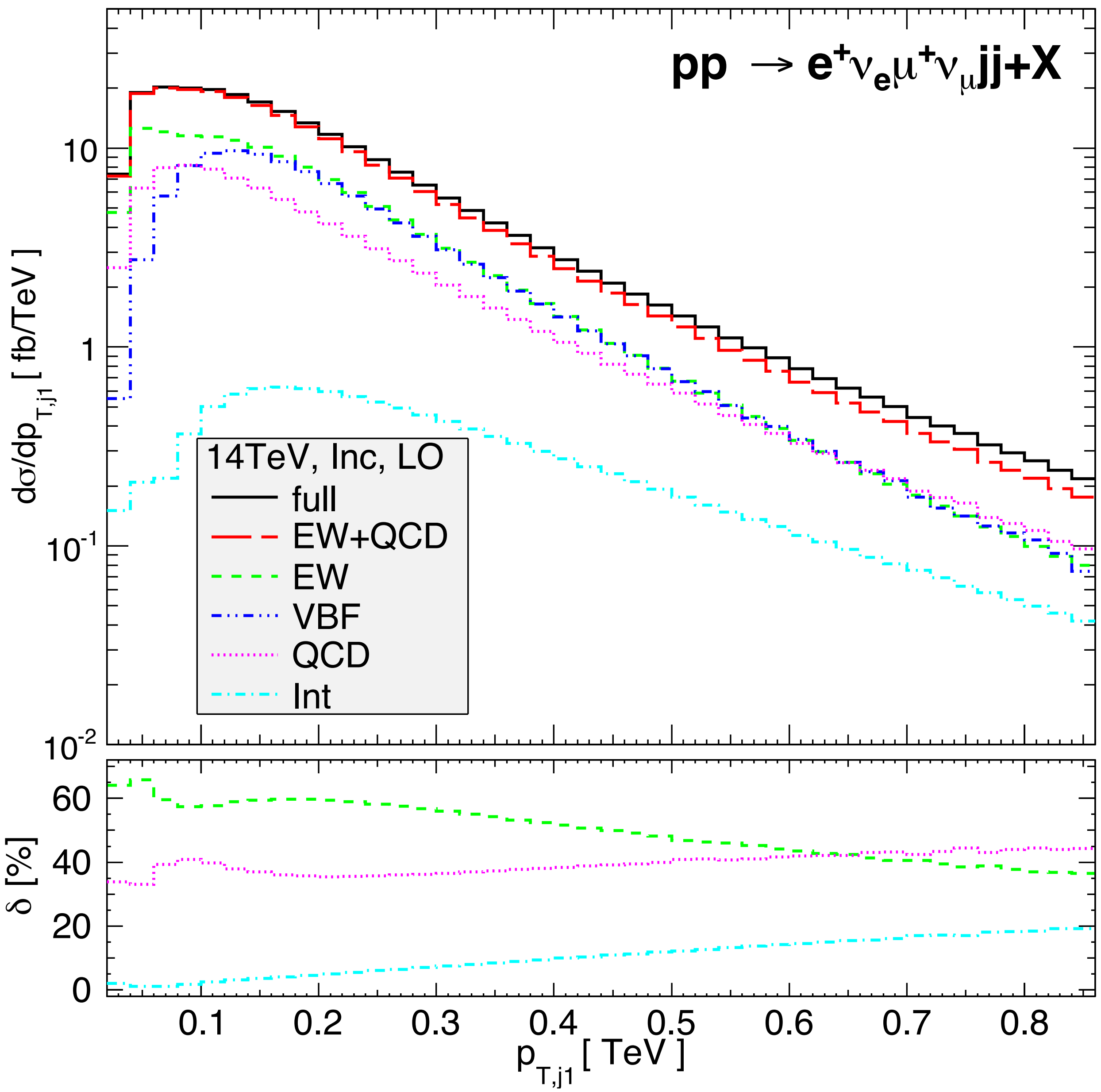


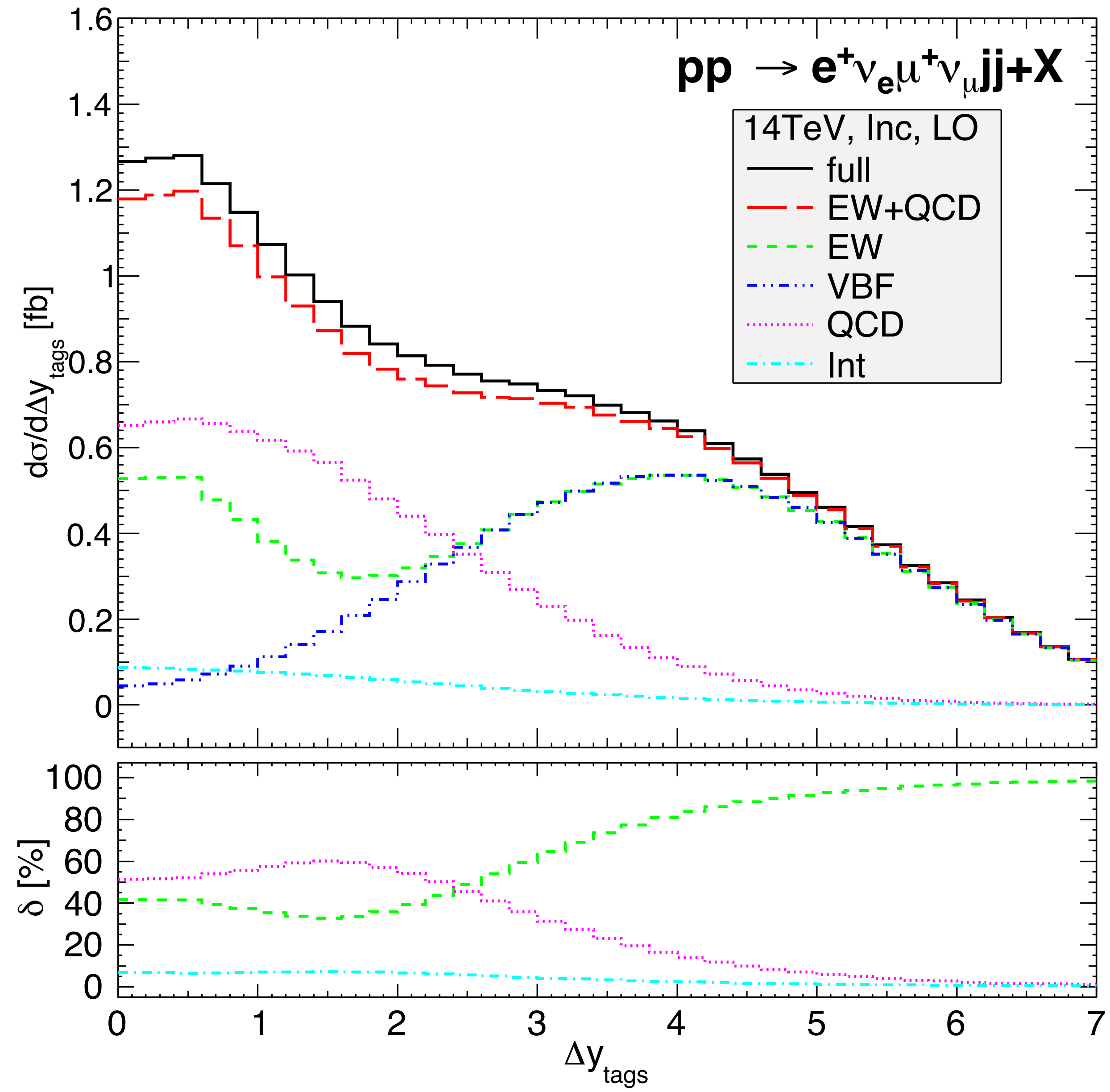
LO EW $Z_l\gamma jj$
NLO EW $Z_l\gamma jj$
NLO EW $Z_\nu\gamma jj$
$\sigma(m_{Z\gamma}^{\min})$ [fb]
K-factor
$\sigma(Z_l\gamma jj)/\sigma(Z_\nu\gamma jj)$
$m_{Z\gamma}^{\min}$[GeV]



EW LO
EW NLO
QCD NLO
$\mathrm{d}\sigma/\mathrm{d}\,z^*(\gamma)$ [fb]
$z^*(\gamma)$

same-sign WWjj





	VBF	EW	QCD	Int	Full
Inclusive	2.189	2.784	1.810	0.234	4.828
Loose VBF	1.784	1.783	0.362	0.058	2.203
Tight VBF	0.971	0.970	0.040	0.013	1.023

[Campanario, MK, Ninh, Zeppenfeld 13]

Form Factor Scales

$f_{T8} = 1200\,\mathrm{TeV}^{-4},\ \Lambda^{FF} = \infty$	$f_{T8} = 600\,\mathrm{TeV}^{-4},\ \Lambda^{FF} = \infty$
$f_{T8} = 1200\,\mathrm{TeV}^{-4},\ \Lambda_c^{FF} = 2.102\,\mathrm{TeV}$	$f_{T8} = 600\,\mathrm{TeV}^{-4},\ \Lambda_c^{FF} = 2.498\,\mathrm{TeV}$
$f_{T8} = 1200\,\mathrm{TeV}^{-4},\ \Lambda^{FF} = 1.782\,\mathrm{TeV}$	$f_{T8} = 600\,\mathrm{TeV}^{-4},\ \Lambda^{FF} = 2.127\,\mathrm{TeV}$
SM EW	