Automated NLO QCD+EW corrections for the LHC

Universität Zürich UZH

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work in collaboration with:

S. Kallweit, P. Maierhöfer, S. Pozzorini, M. Schönherr

[arXiv:1412.5157 , arXiv:1505.05704]

DESY Theory Workshop 2015

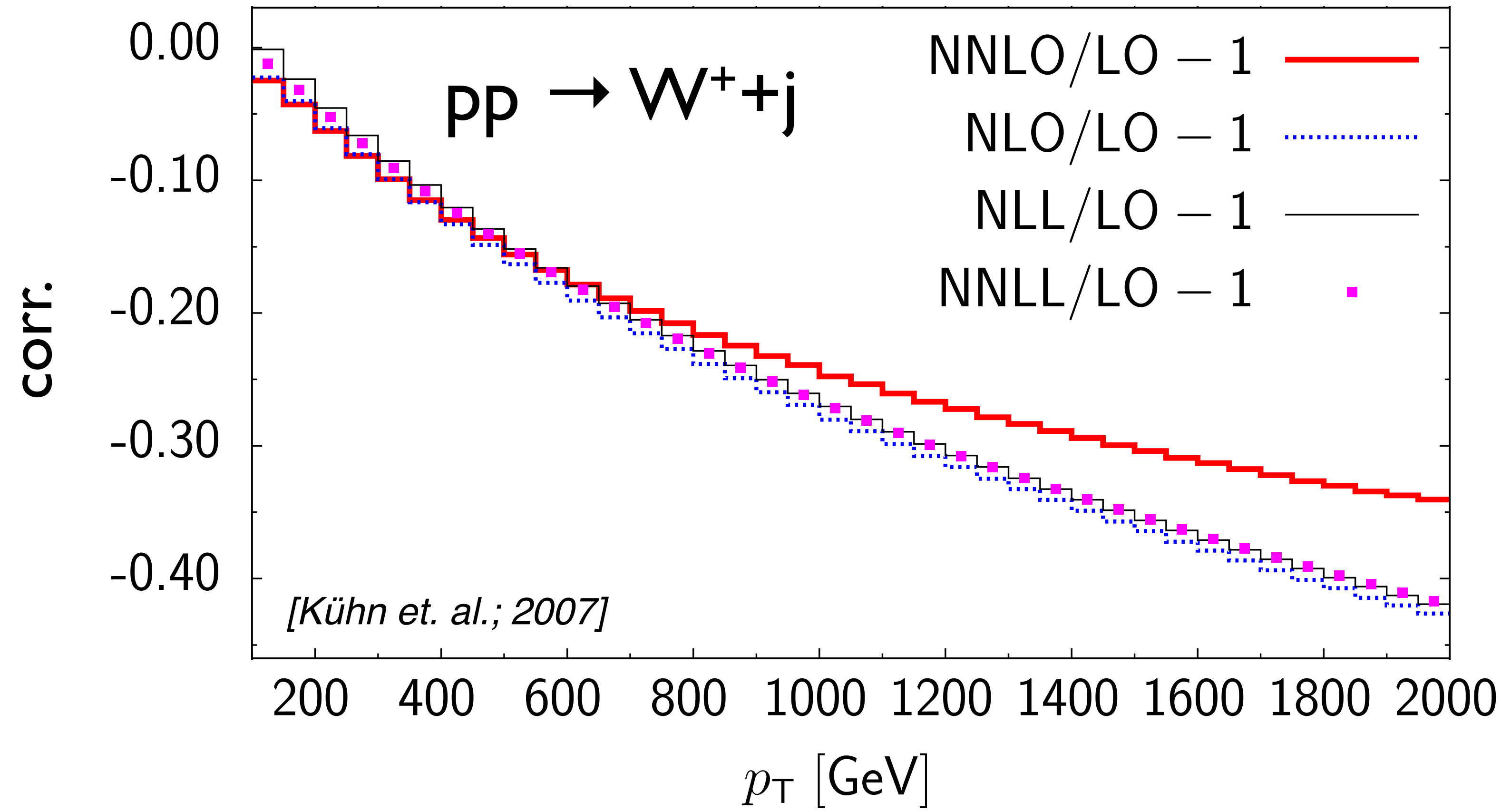
DESY, Hamburg, 30th of September 2015

Why EW corrections?

- Formally suppressed by α/α_s with respect to QCD and numerically $\mathcal{O}(\alpha) \sim \mathcal{O}(\alpha_s^2) \Rightarrow$ NLO EW ~ NNLO QCD

- Possible large (negative) enhancement due to universal virtual Sudakov logs at high energies (i.e. in the tails of the distributions): NLO EW $\sim -\alpha \log^2\left(\frac{M_V^2}{\hat{s}}\right)$

[Ciafaloni, Comelli,'98; Lipatov, Fadin, Martin, Melles, '99; Kuehen, Penin, Smirnov, '99; Denner, Pozzorini, '00]



What are EW corrections?

Perturbative power counting

LO subleading Born contributions

$$d\sigma = d\sigma(\alpha_s^n \alpha^m) + d\sigma(\alpha_s^{n-1}\alpha^{m+1}) + \sigma(\alpha_s^{n-2}\alpha^{m+2}) + \dots$$

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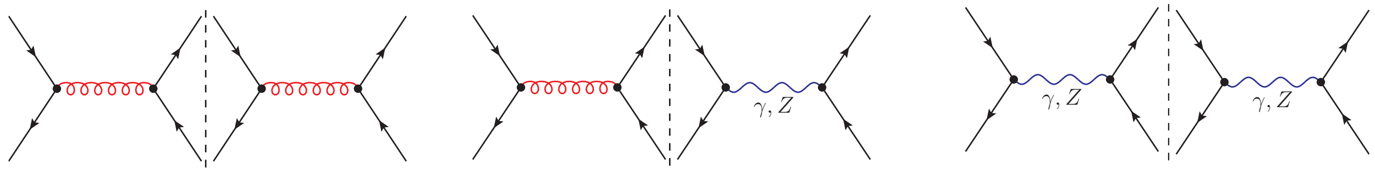

Illustrative example: $q\bar{q} \rightarrow q\bar{q}$

Perturbative power counting

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$$\dots + \sigma(\alpha_s^{n+1}\alpha^m) + d\sigma(\alpha_s^n \alpha^{m+1}) + \sigma(\alpha_s^{n-1}\alpha^{m+2}) + \sigma(\alpha_s^{n-2}\alpha^{m+3}) + \dots$$

"NLO QCD" "NLO EW"

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$\mathcal{O}(\alpha_s)$ $\mathcal{O}(\alpha)$

$$\cdots + \sigma(\alpha_s^{n+1}\alpha^m) + d\sigma(\alpha_s^n\alpha^{m+1}) + \sigma(\alpha_s^{n-1}\alpha^{m+2}) + \sigma(\alpha_s^{n-2}\alpha^{m+3}) + \ldots$$

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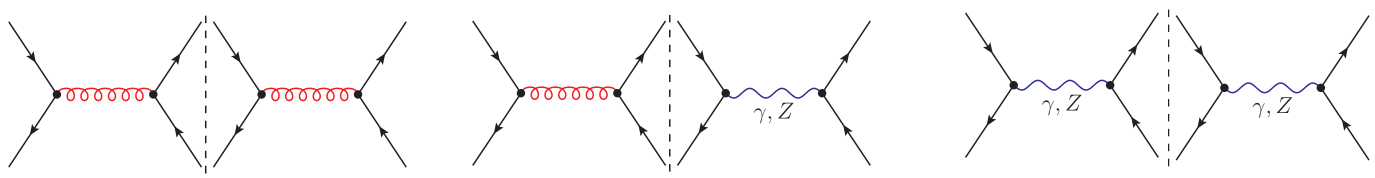

Illustrative example: $\mathbf{q\bar{q} \to q\bar{q}}$

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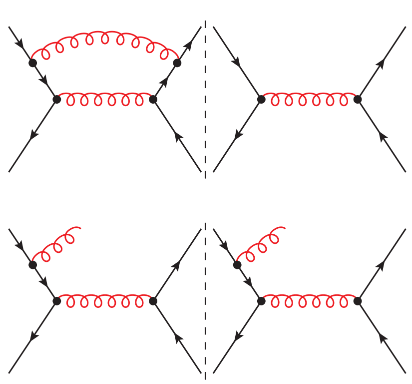
"NLO QCD"



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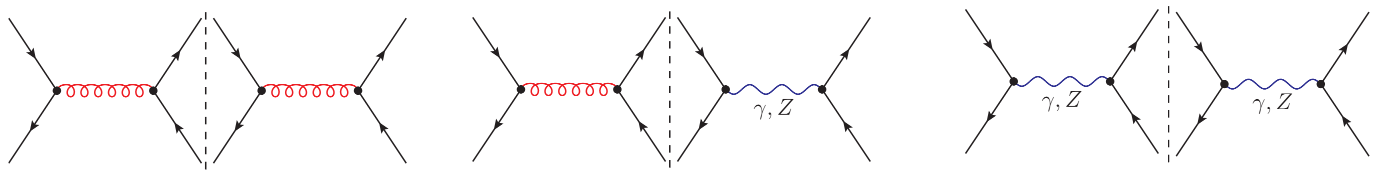

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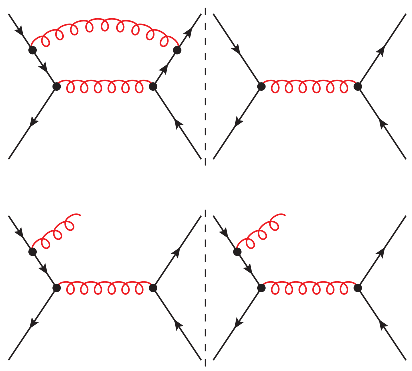

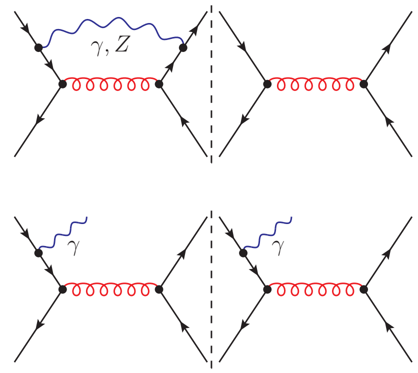

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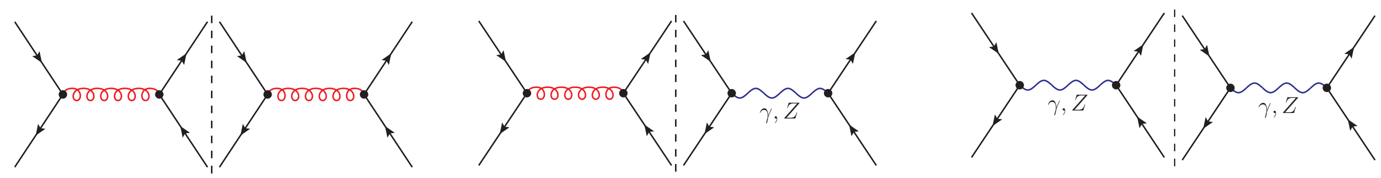

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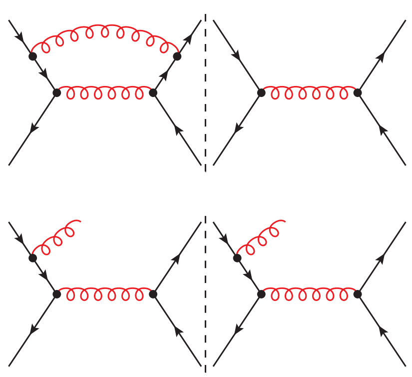

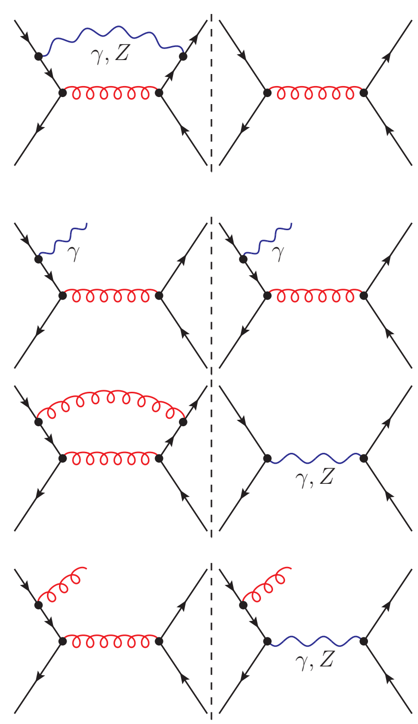

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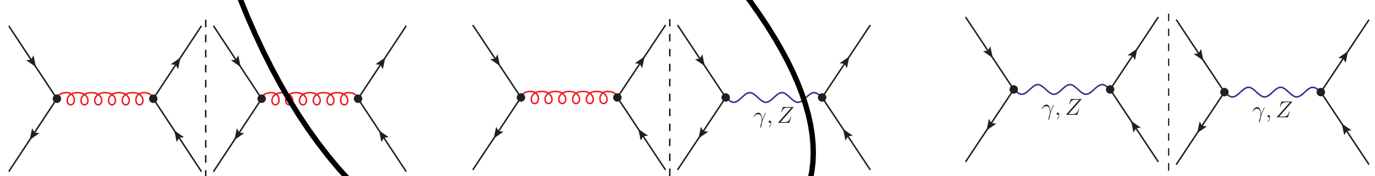

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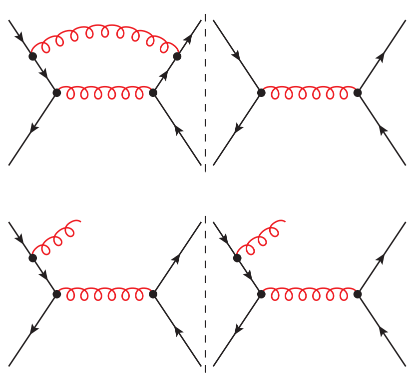
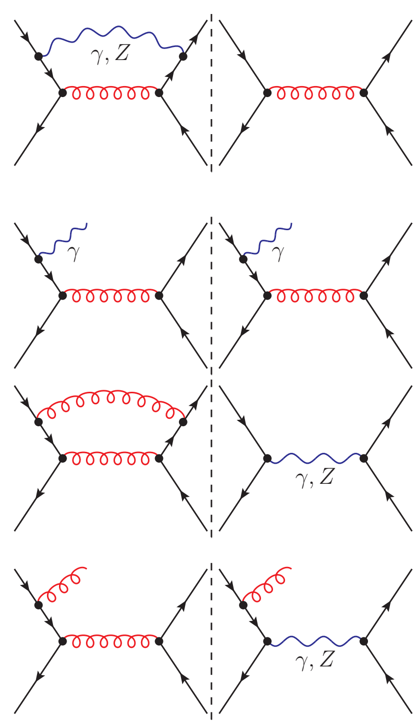
"NLO QCD" "NLO EW" "subleading one-loop contributions"





Note:

- No diagrammatic separation in NLO QCD and EW
- An IR finite & gauge invariant result is only obtained including all virtual and real contributions of a given perturbative order.

Perturbative power counting

LO subleading Born contributions

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"NLO QCD" "NLO EW" "subleading one-loop contributions"

✓ ***Automation*** requires universal power counting and bookkeeping in α and α_s including different interference effects for all contributions: virtual, real, subtraction.

Input:

1. Born process and desired order $\alpha_s^n \alpha^m$
2. type of correction, i.e. "NLO QCD" $\equiv \alpha_s^{n+1}\alpha^m$ or "NLO EW" $\equiv \alpha_s^n \alpha^{m+1}$

Automation of NLO QCD

$$\sigma^{\rm NLO} = \int d\Phi_B \,(B + V + I) + \int d\Phi_R \,(R - S)$$

OpenLoops

[JML, Maierhöfer, Pozzorini]

Monte-Carlo-Framework:

Sherpa

[Gleisberg, Höche, Krauss, Schönherr, Schumann, Siegert, Winter et. al.]

MUNICH:

MUlti-chaNnel Integrator at swiss (CH) precision

[Kallweit]

POWHEG-BOX

[Alioli, Nason, Oleari, Re, et. al.]

Herwig++/Matchbox

[Bellm, Gieseke, Grellscheid, Papaefstathiou, Plätzer, Richardson, Seymour, Siodmok, et al.]

Whizard

[Kilian, Ohl, Reuter, Bach, Chokoufe Nejad,, Weiss, et.al.]

OpenLoops with NLO QCD is publicly available at

`http://openloops.hepforge.org`

Automation of NLO QCD+EW

$$\sigma^{\mathrm{NLO}} = \int d\Phi_B \,(B + V + I) + \int d\Phi_R \,(R - S)$$

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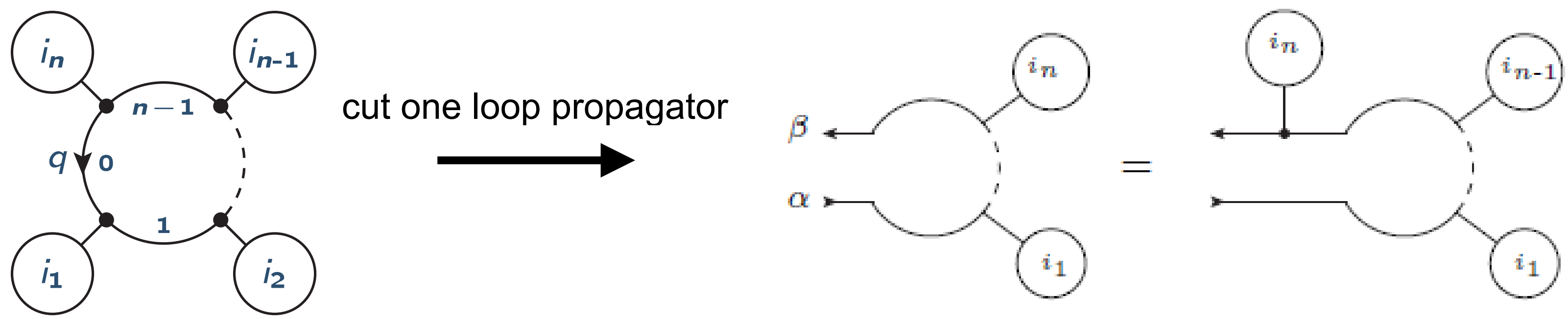
- NLO corrections in the full SM (QCD & EW) are implemented in OpenLoops together with Sherpa and MUNICH (will be included in upcoming public releases)
- missing: PS matching & merging (work in progress)

The OpenLoops program

[F. Cascioli, JML, P. Maierhöfer, S. Pozzorini, '14]

- FAST and flexible implementation of the Open Loops algorithm *[F. Cascioli, P. Maierhöfer, S. Pozzorini, '12]:* a process- and model-independent numerical recursion for the calculation of one-loop amplitudes



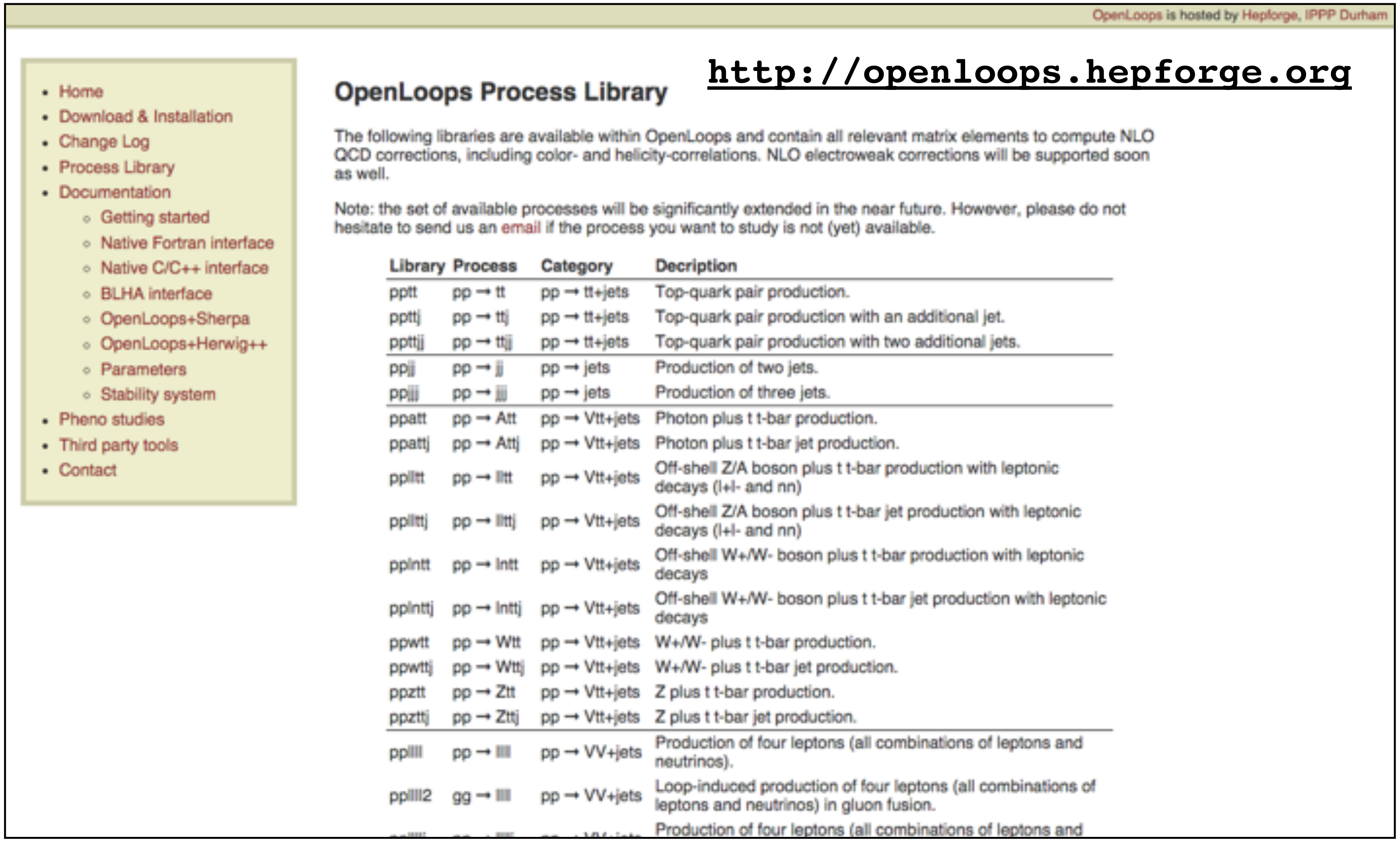
- Publicly available at **`http://openloops.hepforge.org`**
- Amplitudes for any 2 → 4(5) NLO QCD process in the SM available: tree & (renormalized) virtual amplitudes, color correlations, spin correlations
- Installation (Requirements: gfortran ≥ 4.6, Python 2.x, x ≥ 4):

```
$ cd ./OpenLoops && ./scons
```

- Interfaces to reduction/scalar integral libraries:
  - CutTools [Ossola, Papadopolous, Pittau; '07] + OneLOop [van Hameren], COLLIER [Denner, Dittmaier, Hofer], Samurai [Mastrolia, Ossola, Reiter, Tramontano; '10]

The OpenLoops NLO QCD process library

- Public library includes > 100 LHC processes including $t\bar{t}$+0,1,2 j, $t\bar{t}V$+0,1 j, $t\bar{t}h$+0,1 j, H+0,1,2,3 j …
- List of available process will grow continuously


OpenLoops is hosted by Hepforge, IPPP Durham

- Home
- Download & Installation
- Change Log
- Process Library
- Documentation
  - Getting started
  - Native Fortran interface
  - Native C/C++ interface
  - BLHA interface
  - OpenLoops+Sherpa
  - OpenLoops+Herwig++
  - Parameters
  - Stability system
- Pheno studies
- Third party tools
- Contact

http://openloops.hepforge.org

OpenLoops Process Library

The following libraries are available within OpenLoops and contain all relevant matrix elements to compute NLO QCD corrections, including color- and helicity-correlations. NLO electroweak corrections will be supported soon as well.

Note: the set of available processes will be significantly extended in the near future. However, please do not hesitate to send us an email if the process you want to study is not (yet) available.

Library	Process	Category	Decription
pptt	pp → tt	pp → tt+jets	Top-quark pair production.
ppttj	pp → ttj	pp → tt+jets	Top-quark pair production with an additional jet.
ppttjj	pp → ttjj	pp → tt+jets	Top-quark pair production with two additional jets.
ppjj	pp → jj	pp → jets	Production of two jets.
ppjjj	pp → jjj	pp → jets	Production of three jets.
ppatt	pp → Att	pp → Vtt+jets	Photon plus t t-bar production.
ppattj	pp → Attj	pp → Vtt+jets	Photon plus t t-bar jet production.
pplltt	pp → lltt	pp → Vtt+jets	Off-shell Z/A boson plus t t-bar production with leptonic decays (l+l- and nn)
ppllttj	pp → llttj	pp → Vtt+jets	Off-shell Z/A boson plus t t-bar jet production with leptonic decays (l+l- and nn)
pplntt	pp → lntt	pp → Vtt+jets	Off-shell W+/W- boson plus t t-bar production with leptonic decays
pplnttj	pp → lnttj	pp → Vtt+jets	Off-shell W+/W- boson plus t t-bar jet production with leptonic decays
ppwtt	pp → Wtt	pp → Vtt+jets	W+/W- plus t t-bar production.
ppwttj	pp → Wttj	pp → Vtt+jets	W+/W- plus t t-bar jet production.
ppztt	pp → Ztt	pp → Vtt+jets	Z plus t t-bar production.
ppzttj	pp → Zttj	pp → Vtt+jets	Z plus t t-bar jet production.
ppllll	pp → llll	pp → VV+jets	Production of four leptons (all combinations of leptons and neutrinos).
ppllll2	gg → llll	pp → VV+jets	Loop-induced production of four leptons (all combinations of leptons and neutrinos) in gluon fusion.
			Production of four leptons (all combinations of leptons and

- Install (for example for Z+1,2,3 production) :

```
./openloops libinstall ppzj ppzjj ppzjjj
```

Technical implementation of NLO EW

✓ Virtuals with **OpenLoops**:

- Fast numerical routines for all tree+loop vertices in the full SM
- $\mathcal{O}(\alpha)$ renormalization [Denner, '92] + R_2 rational terms
- Treatment of unstable particles: complex-mass-scheme / narrow-width approximations

✓ Real radiation, subtraction, subprocess bookkeeping

✓ **Sherpa** [Höche, Schönherr, in preperation]

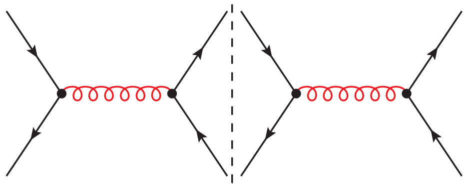
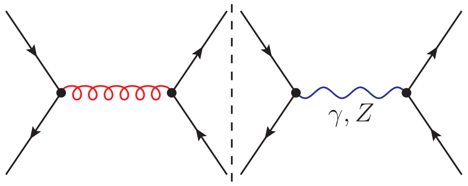
✓ **MUNICH**: MUlti-chaNnel Integrator at swiss (CH) precision
[Kallweit, in preparation]

- Based on the well established NLO QCD dipole subtraction frameworks with replacements for QCD → QED

$$\alpha_s \longrightarrow \alpha, \qquad C_F \longrightarrow Q_f^2, \qquad T_R \longrightarrow N_{c,f} Q_f^2, \qquad T_R N_f \longrightarrow \sum_f N_{c,f} Q_f^2, \qquad C_A \longrightarrow 0$$

$$\frac{\mathbf{T}_{ij}\cdot\mathbf{T}_k}{\mathbf{T}_{ij}^2} \longrightarrow \begin{cases} \frac{Q_{ij}Q_k}{Q_{ij}^2} & \text{if the emitter } ij \text{ is a (anti)fermion} \\ \kappa_{ij,k} & \text{if the emitter } ij \text{ is a photon}, \end{cases}$$

- Mixed QCD-QED I-operator requires a non-trivial interplay between different Born orders

$$I \propto \sum \int_1 V_{\mathrm{QED}} \otimes$$  $$+ \int_1 V_{\mathrm{QCD}} \otimes$$ 

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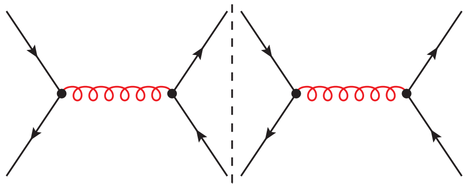
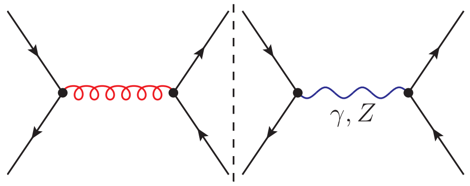
$$I \propto \sum \int_1 V_{\mathrm{QED}} \otimes$$  $$+ \int_1 V_{\mathrm{QCD}} \otimes$$ 

All ingredients carefully validated:

✓ OpenLoops vs. private code by S. Pozzorini

✓ MUNICH vs. Sherpa

Combination of NLO QCD and EW & Setup

Two alternatives:

$$\sigma^{\rm NLO}_{\rm QCD+EW} = \sigma^{\rm LO} + \delta\sigma^{\rm NLO}_{\rm QCD} + \delta\sigma^{\rm NLO}_{\rm EW}$$

$$\sigma^{\rm NLO}_{\rm QCD\times EW} = \sigma^{\rm NLO}_{\rm QCD}\left(1+\frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm LO}}\right) = \sigma^{\rm NLO}_{\rm EW}\left(1+\frac{\delta\sigma^{\rm NLO}_{\rm QCD}}{\sigma^{\rm LO}}\right)$$

Difference between the two approaches indicates uncertainties due to missing two-loop EW-QCD corrections of $\mathcal{O}(\alpha\alpha_s)$

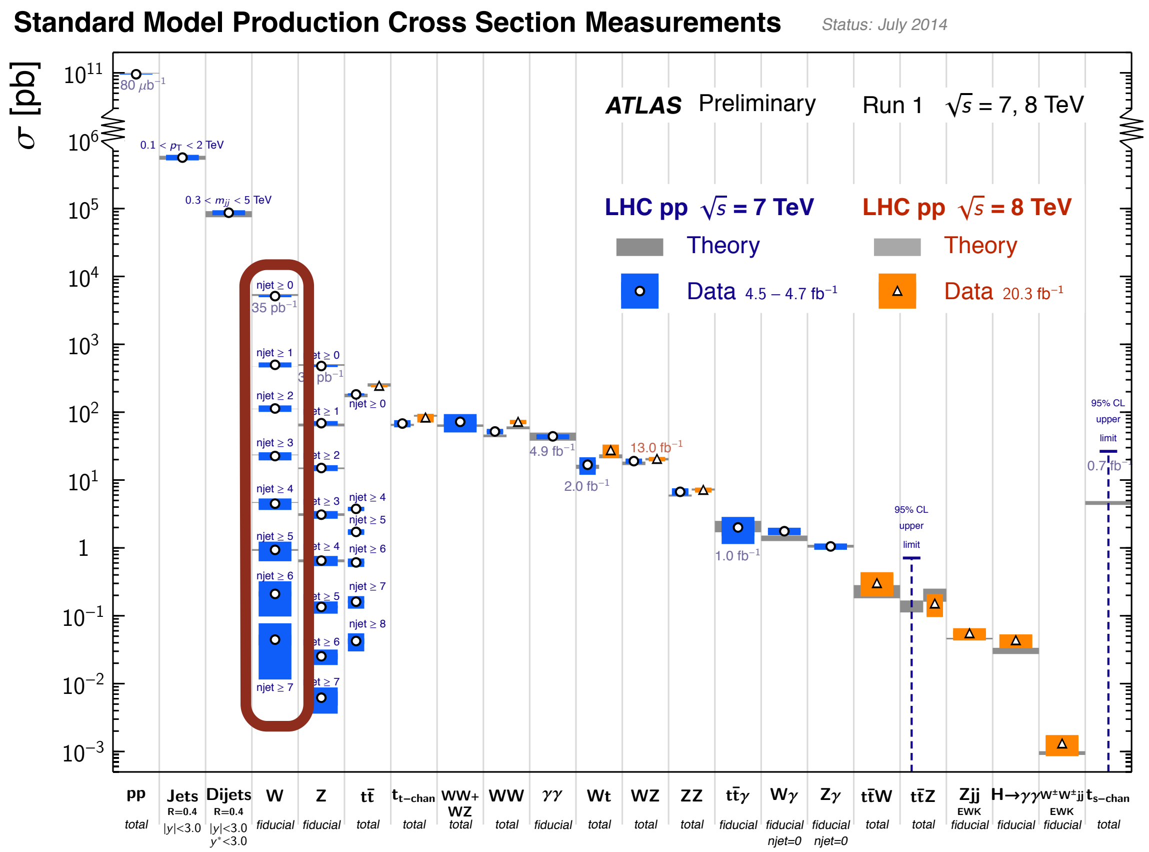
Relative corrections w.r.t. NLO QCD:

$$\frac{\sigma^{\rm NLO}_{\rm QCD+EW}}{\sigma^{\rm NLO}_{\rm QCD}} = \left(1+\frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm NLO}_{\rm QCD}}\right)$$ suppressed by large NLO QCD corrections

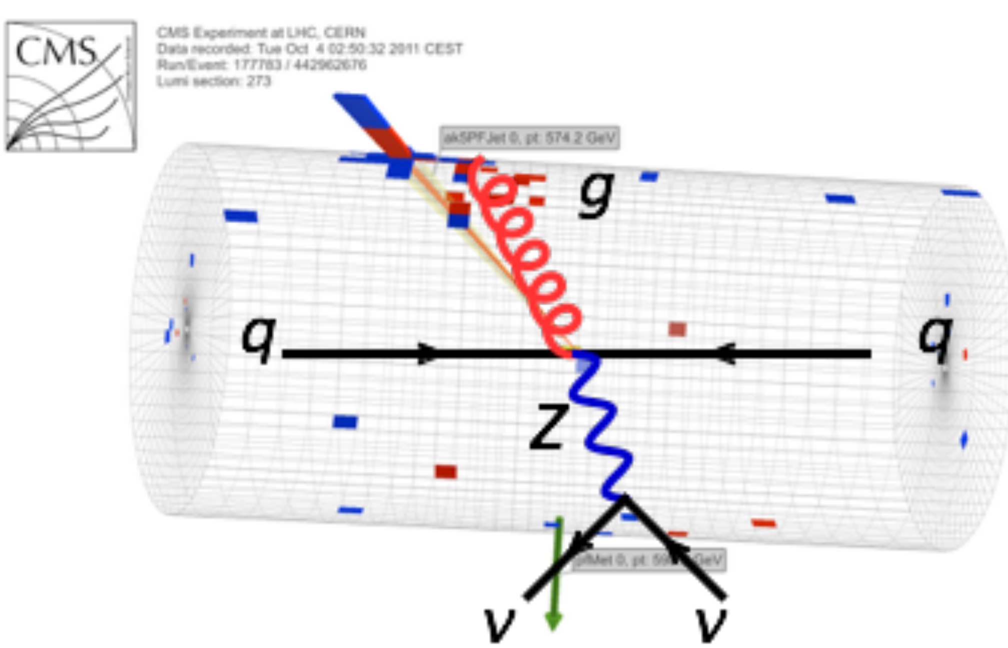
$$\frac{\sigma^{\rm NLO}_{\rm QCD\times EW}}{\sigma^{\rm NLO}_{\rm QCD}} = \left(1+\frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm LO}}\right)$$ "usual" NLO EW w.r.t. LO

- $\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_{\rm W}^2 \left(1-\frac{M_{\rm W}^2}{M_{\rm Z}^2}\right)$ in G_μ-scheme with $G_\mu = 1.16637\times 10^{-5}\ {\rm GeV}^{-2}$
- or: $\alpha(0) = 1/137.036$ in on-shell-scheme
- PDFs: NNPDF 2.3QED with $\alpha_{\rm S}(M_{\rm Z}) = 0.118$ for LO and NLO QCD/EW

Motivation: V + multijet production



- Large cross-sections and clean leptonic signatures
- Precision QCD at LHC
- Playground to probe different aspects of higher-order calculations (LO+PS, NLO+PS, NLO-Merging, NLO EW,…)



- Important/dominant background for various **BSM searches** (lepton + jets + missing E_T)
- Dominant background for monojet **DM searches**
- Dominant background for **top physics**
- Important background for **Higgs physics**, e.g. VH(→bb)

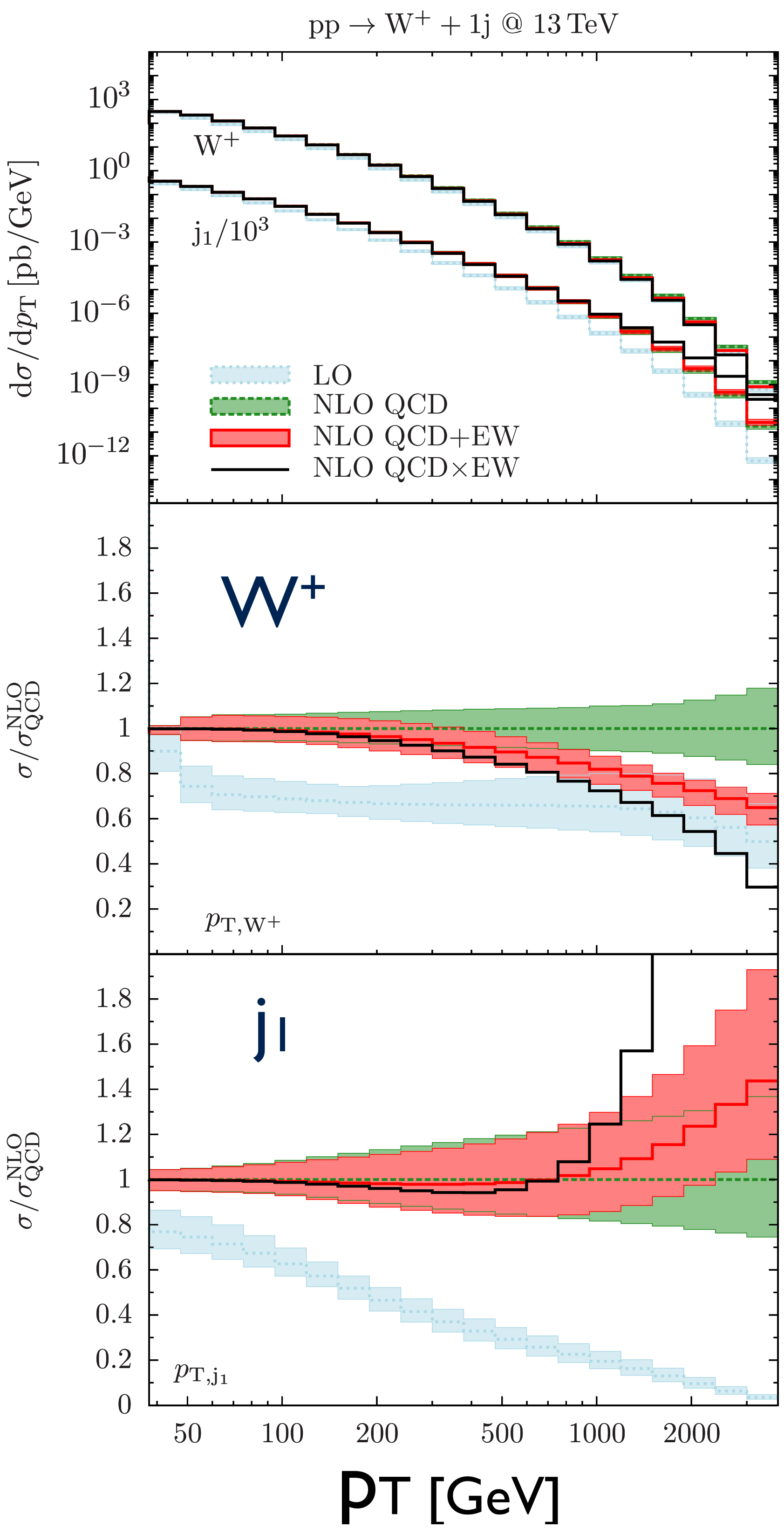
W^+ + 1 jet: inclusive

Setup:

$\sqrt{S} = 13$ TeV

$p_{T,j} > 30$ GeV, $|\eta_j| < 4.5$

$\mu_0 = \hat{H}_T/2$ (+ 7-pt. variation)



inclusive

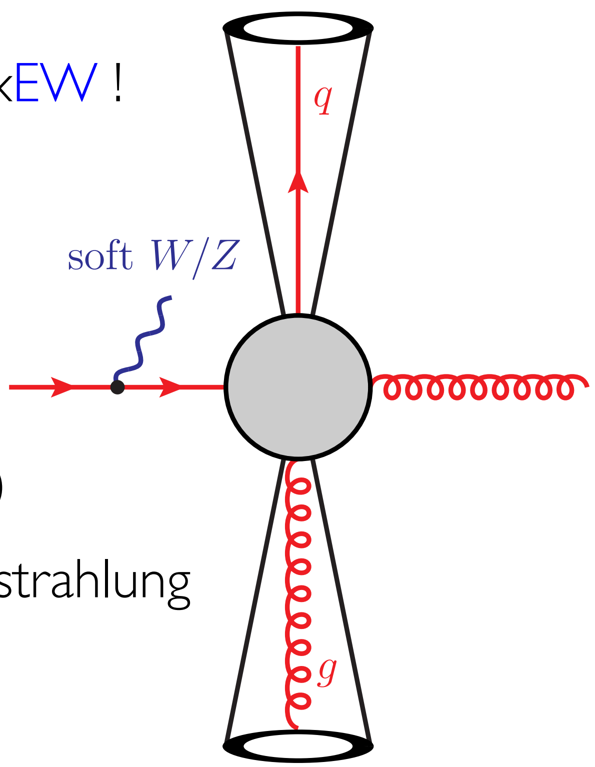
$\lesssim$ 1% EW corrections

p_T of W-boson

- +100 % QCD corrections in the tail
- large negative EW corrections due to **Sudakov behaviour:** -20–35% corrections at 1-4 TeV
- sizeable difference between QCD+EW and QCDxEW !

p_T of jet

- factor-10 NLO QCD corrections in the tail!
- dominated by **dijet configurations** (effectively LO)
- positive 10-50% EW corrections from quark bremsstrahlung



NNLO QCD: *[Boughezal, Focke, Liu, Petriello '15]*

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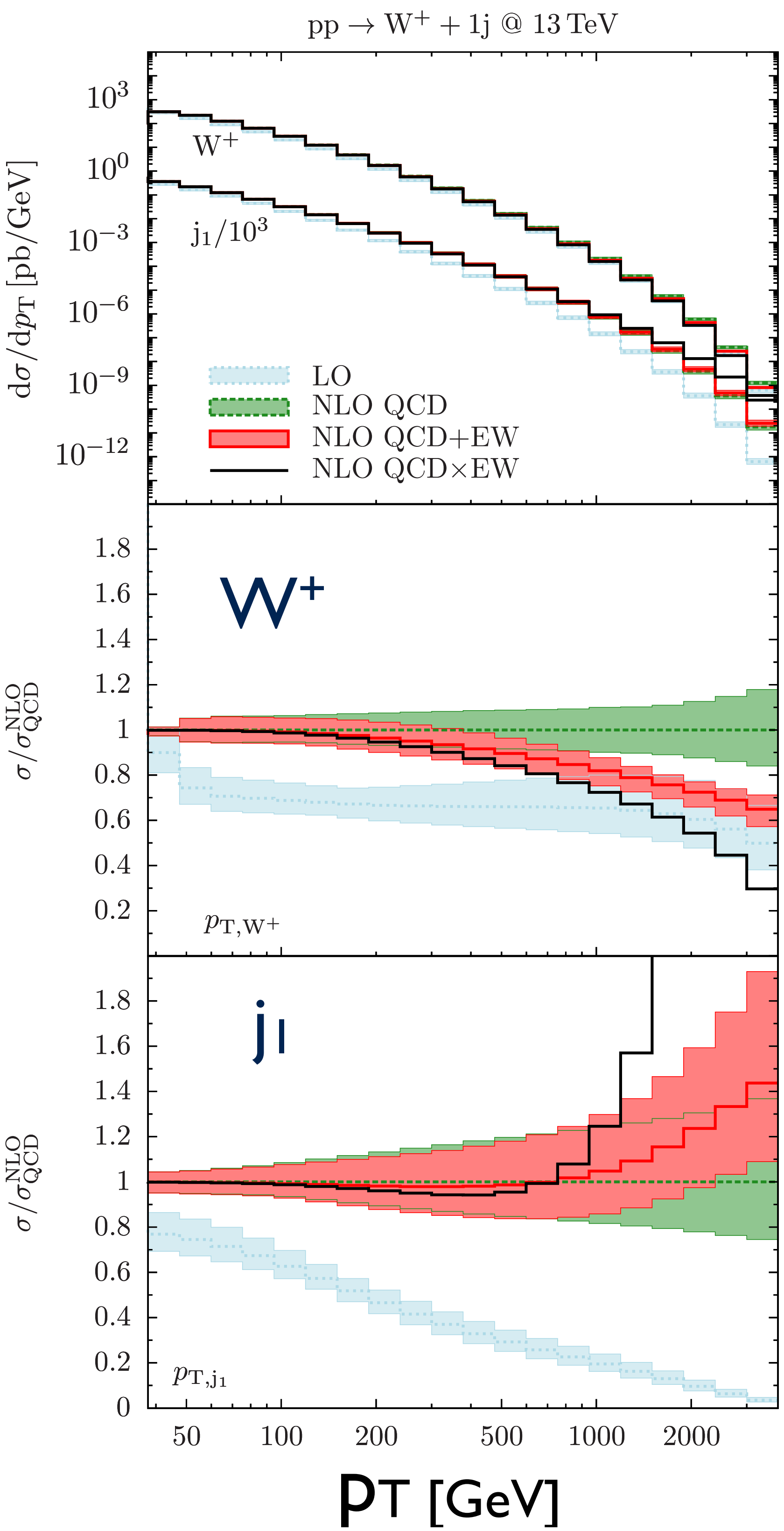

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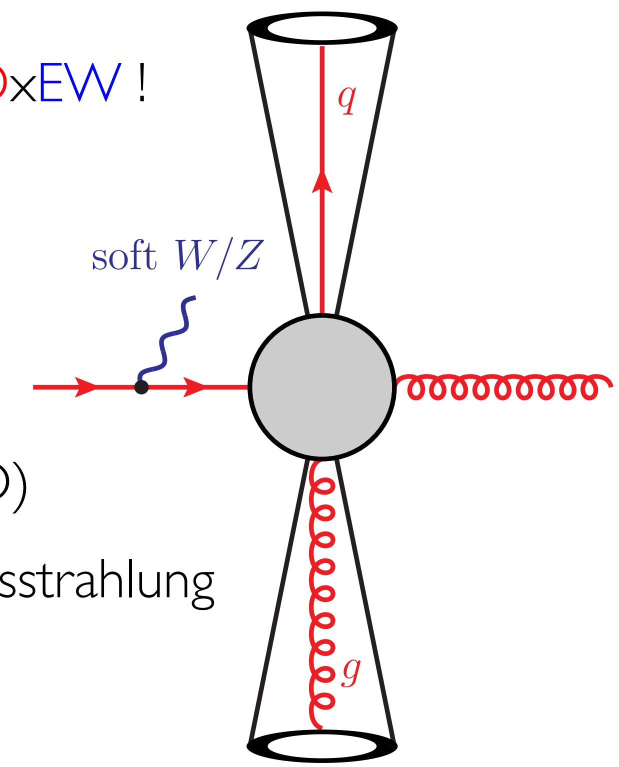
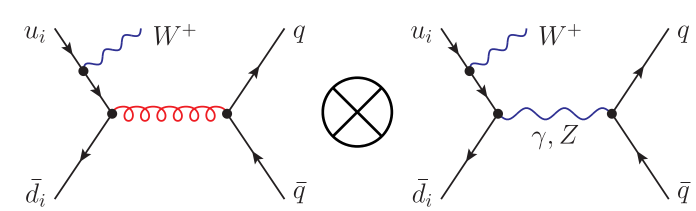
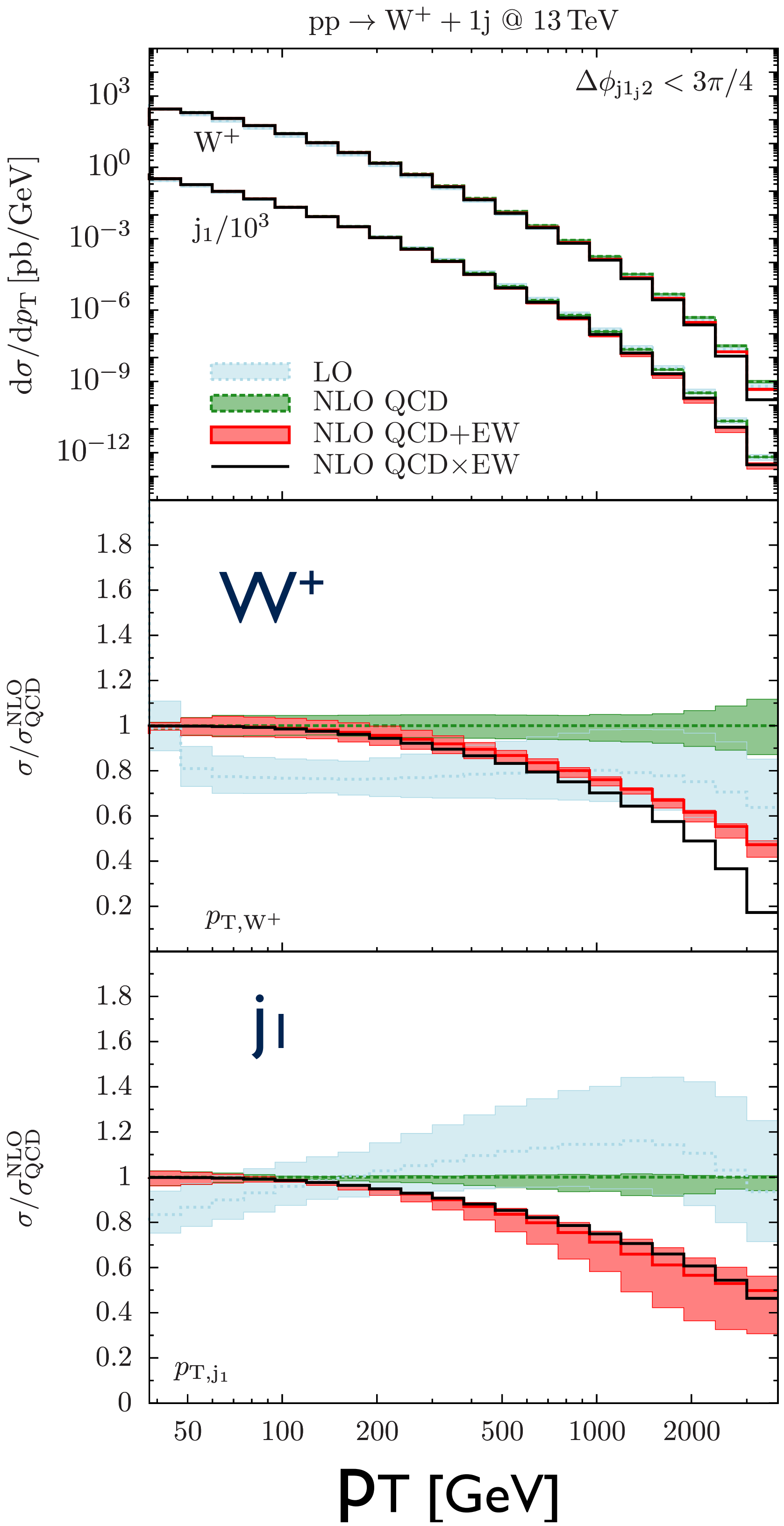
- positive 10-50% EW corrections from quark bremsstrahlung





$\Longrightarrow$ pathologic with large uncertainties!

W$^+$ + 1 jet: exclusive



$\Delta\phi_{j1j2} < 3\pi/4$

(veto on dijet configurations)

Setup:

$\sqrt{S} = 13$ TeV

$p_{T,j} > 30$ GeV, $|\eta_j| < 4.5$

$\mu_0 = \hat{H}_T/2$ (+ 7-pt. variation)

QCD corrections

- mostly moderate and stable QCD corrections

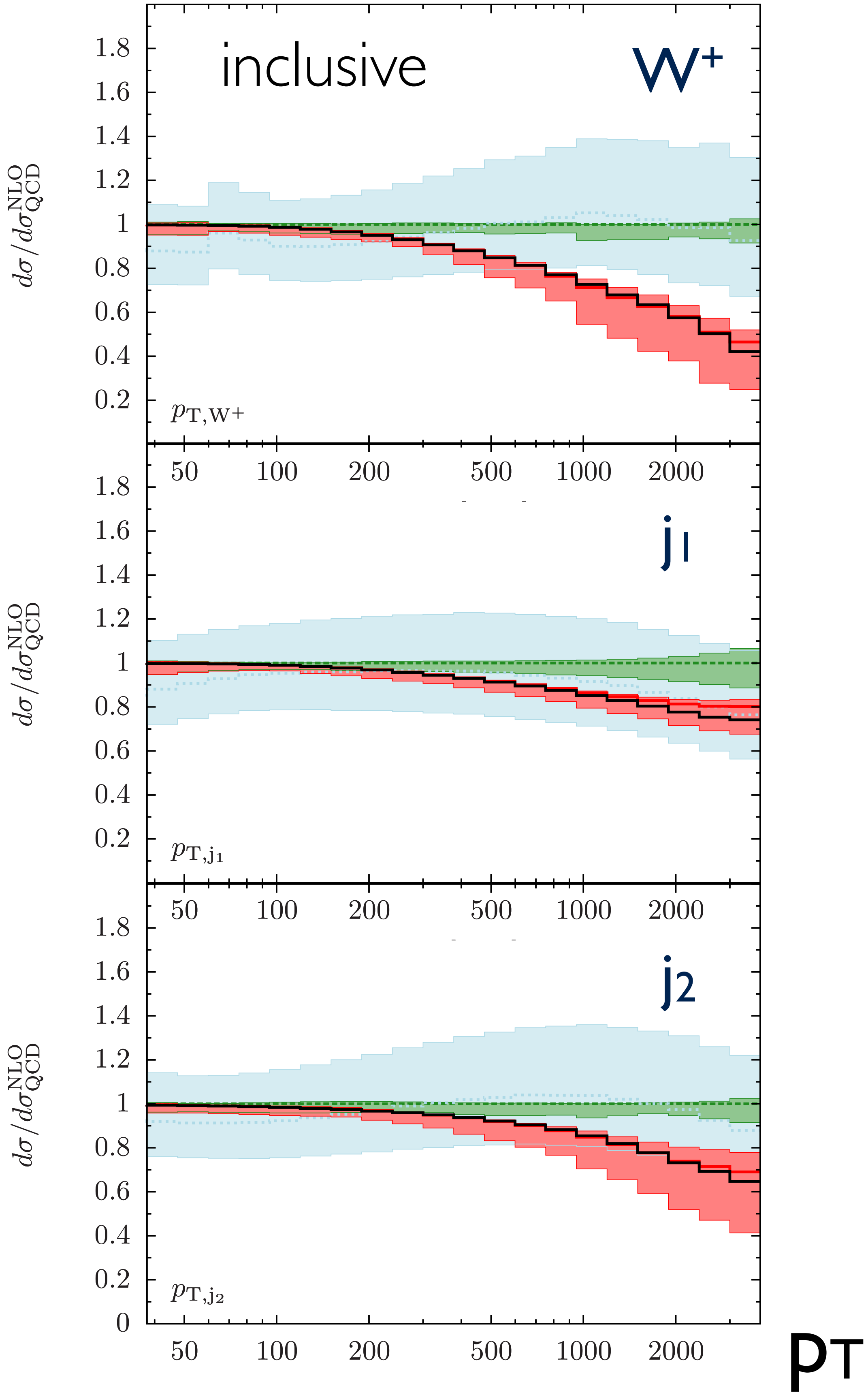
EW corrections

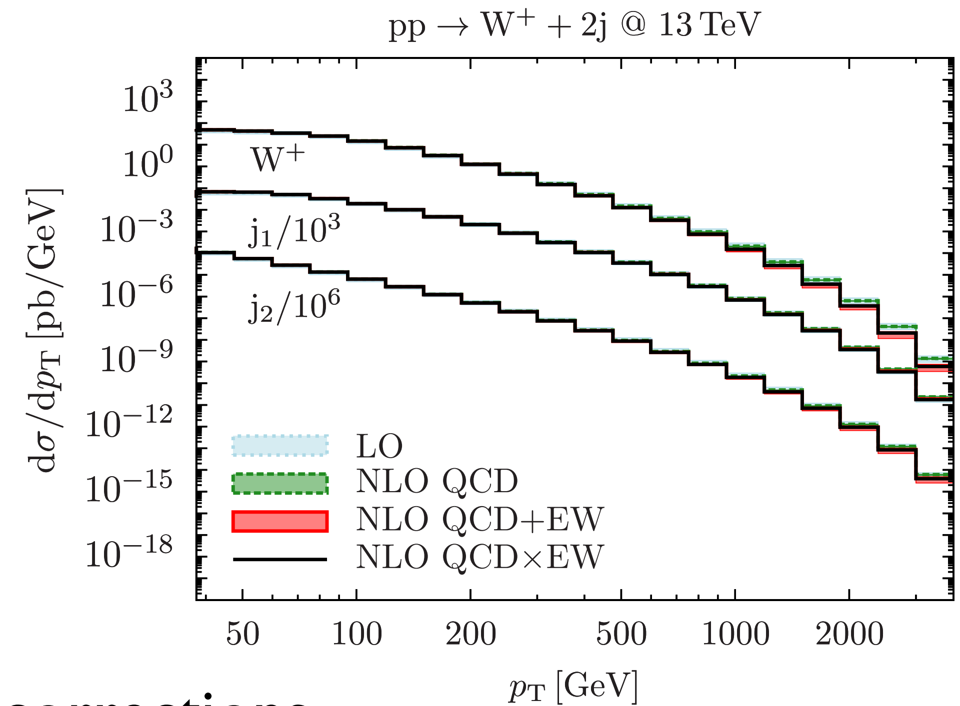
- **Sudakov behaviour** in both tails:
  -20–50% EW corrections at 1-4 TeV
- EW corrections larger than QCD uncertainties for $p_{T,W+}$ > 300 GeV

⟹ *exclusive* W+1jet ok!

⟹ *inclusive* W+1jet requires W+2 jets at NLO QCD+EW!

W+ + 2 jets: NLO EW





QCD corrections

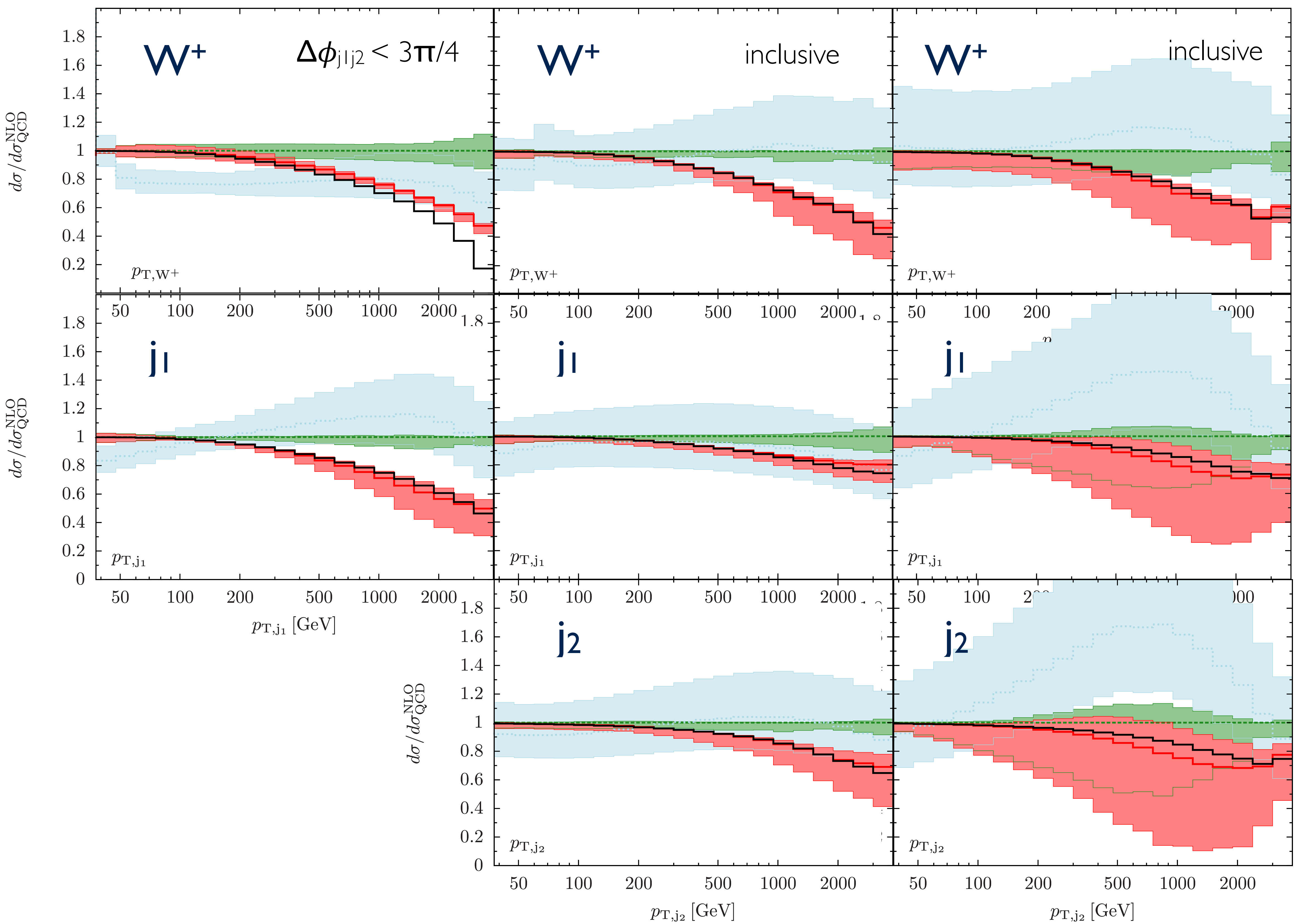
- small and very stable
- ≲ 10% scale uncertainties

EW corrections

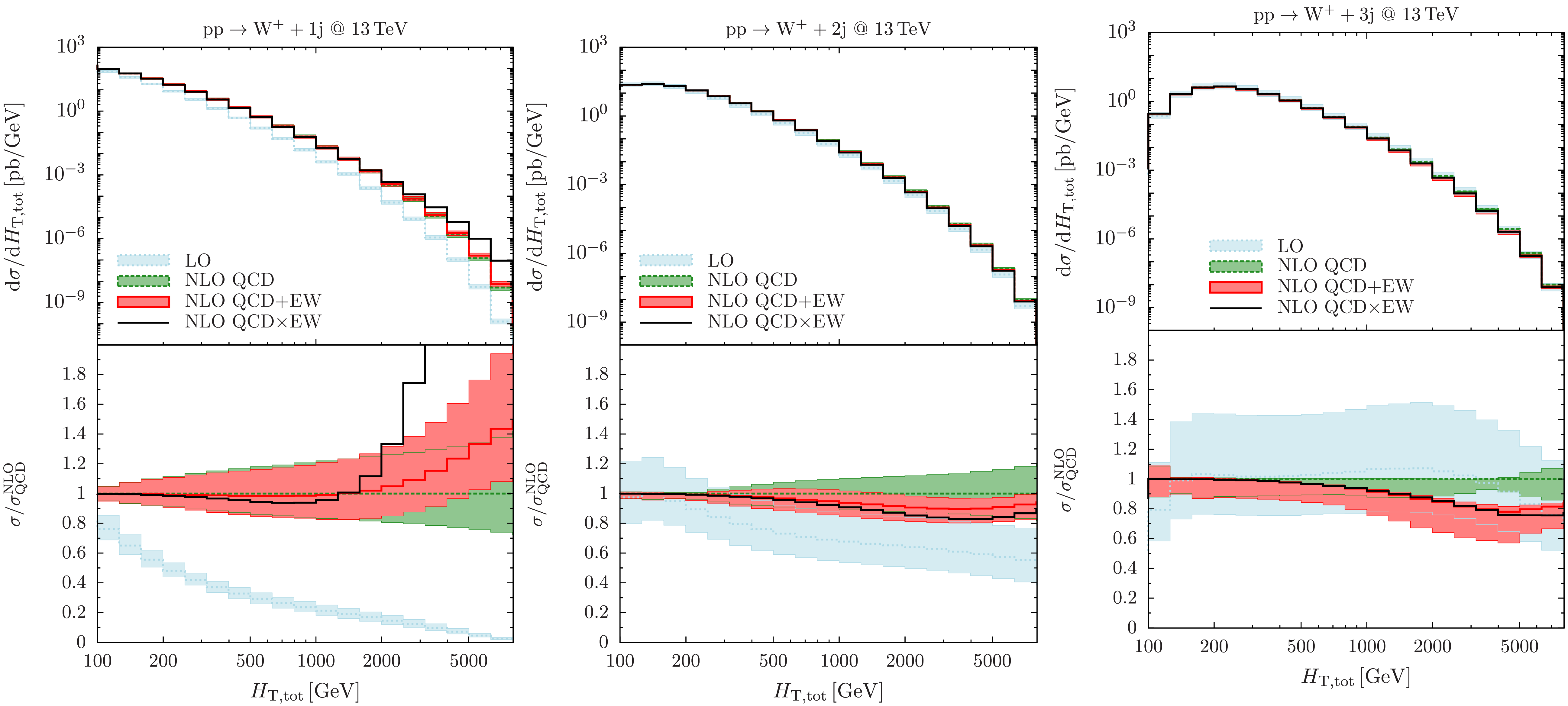
- **Sudakov behaviour** in all p_T tails:
  - -30–60% for W-boson at 1-4 TeV
  - -15–25% for 1st and 2nd jet at 1-4 TeV

  different!
- Might need resummation of leading EW Sudakov logs

W+ + 1 jets   W+ + 2 jets   W+ + 3 jets



$H_{T,tot}$ for W^+ + 1, 2,3 jets



QCD corrections

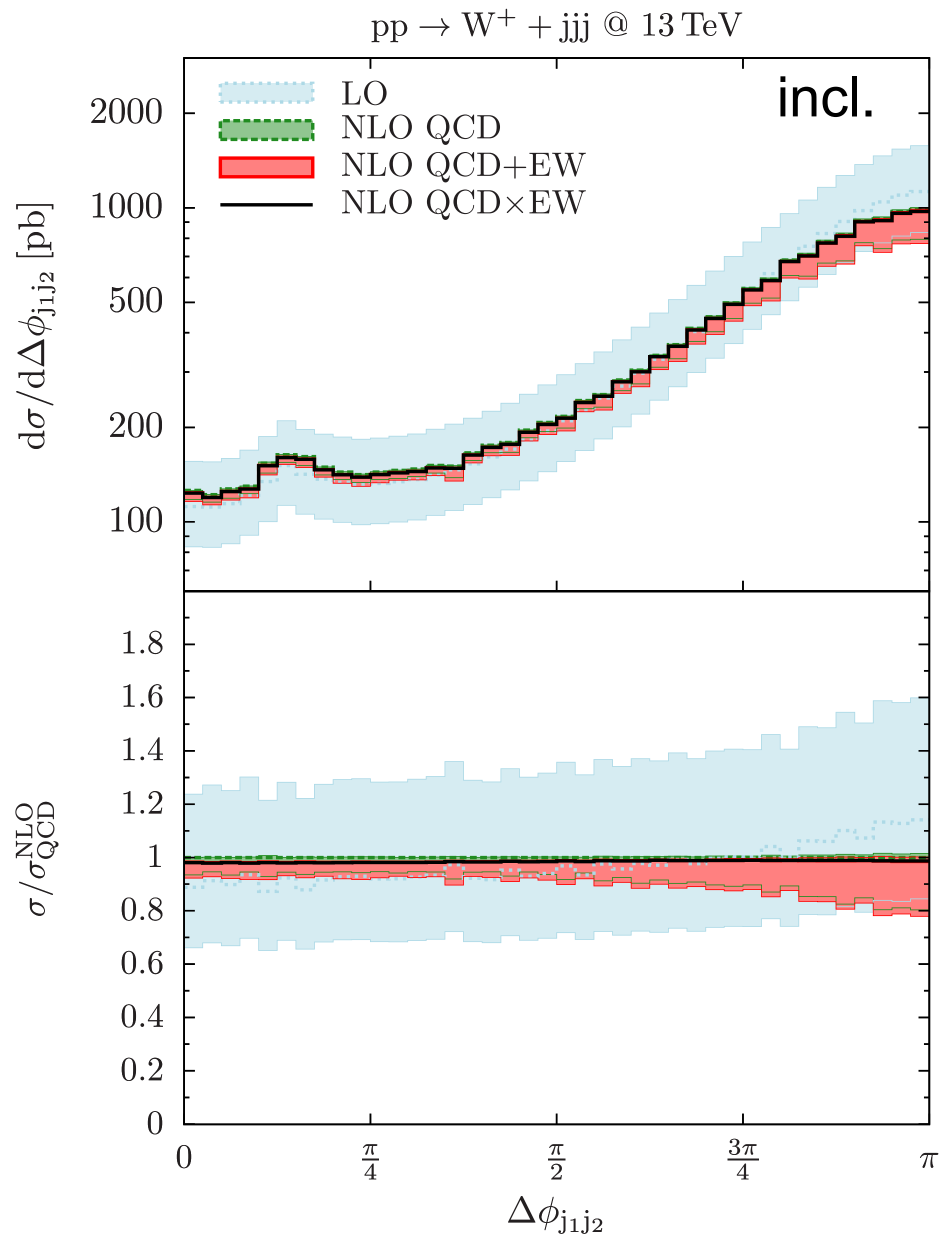
- for W+2j: large QCD corrections (80-100%)
- starting to be stable only for W+3 jets

EW corrections

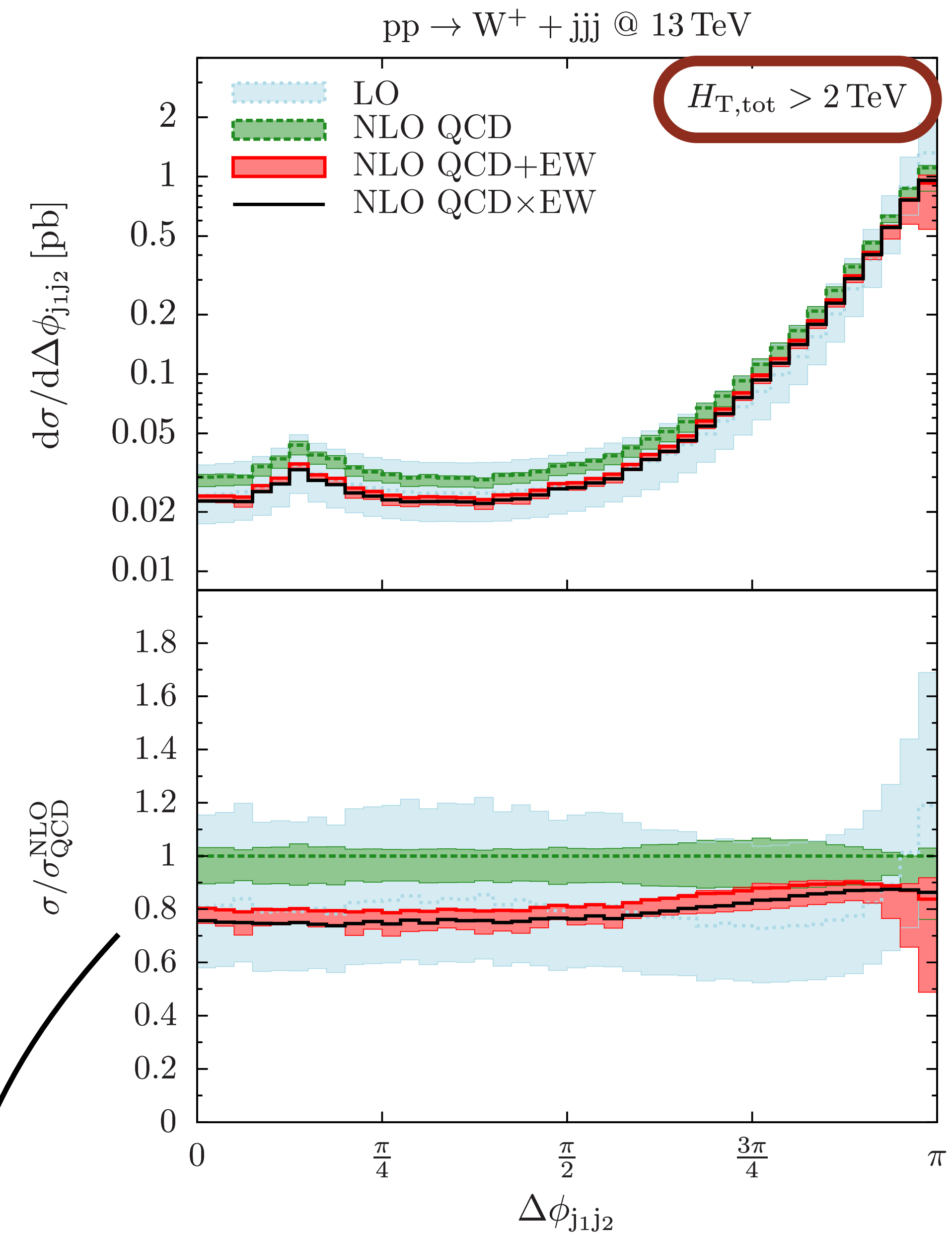
- moderate EW corrections: -20-30 % in the tail

⟹ calls for NLO QCD+EW multi-jet merging!

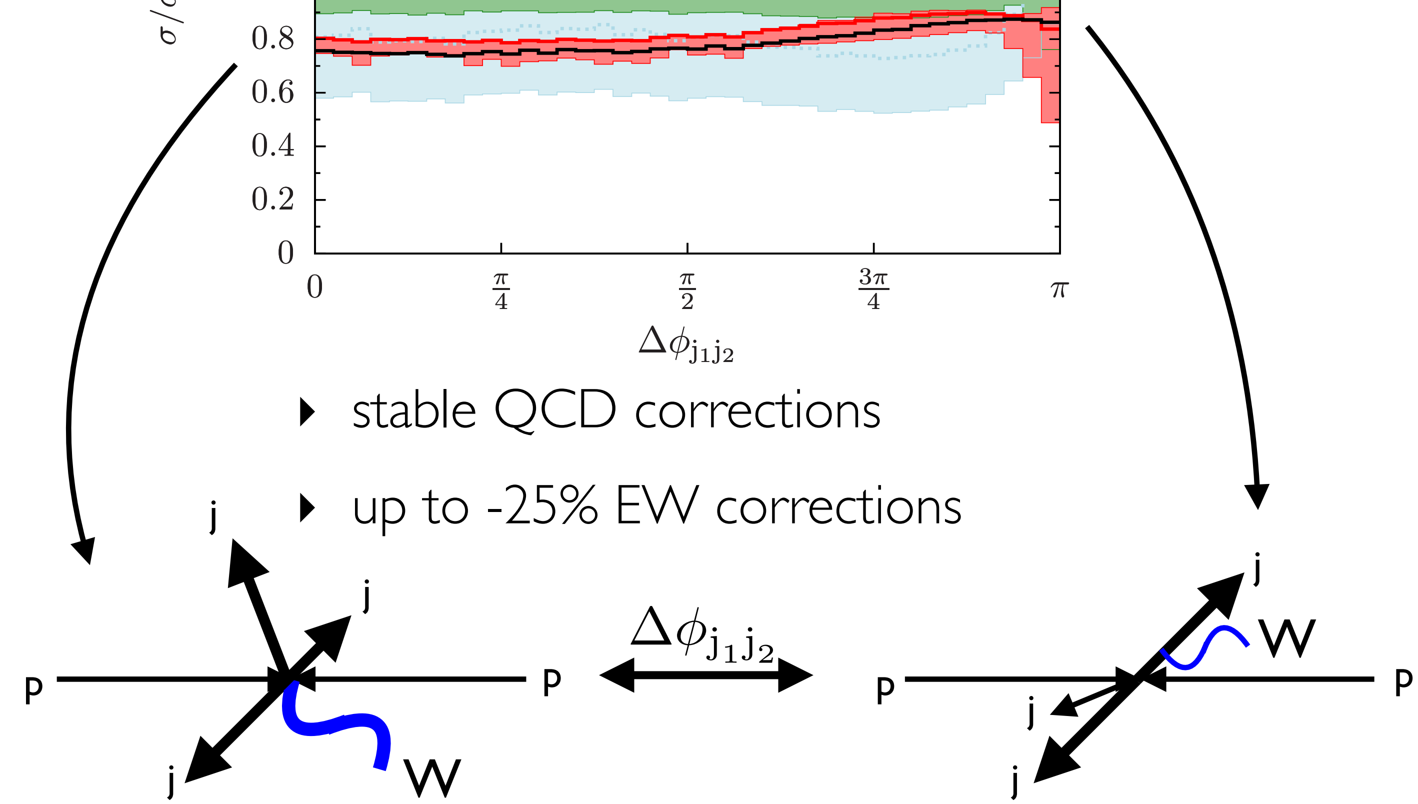
W^+ + 3 jets: topology of EW corrections



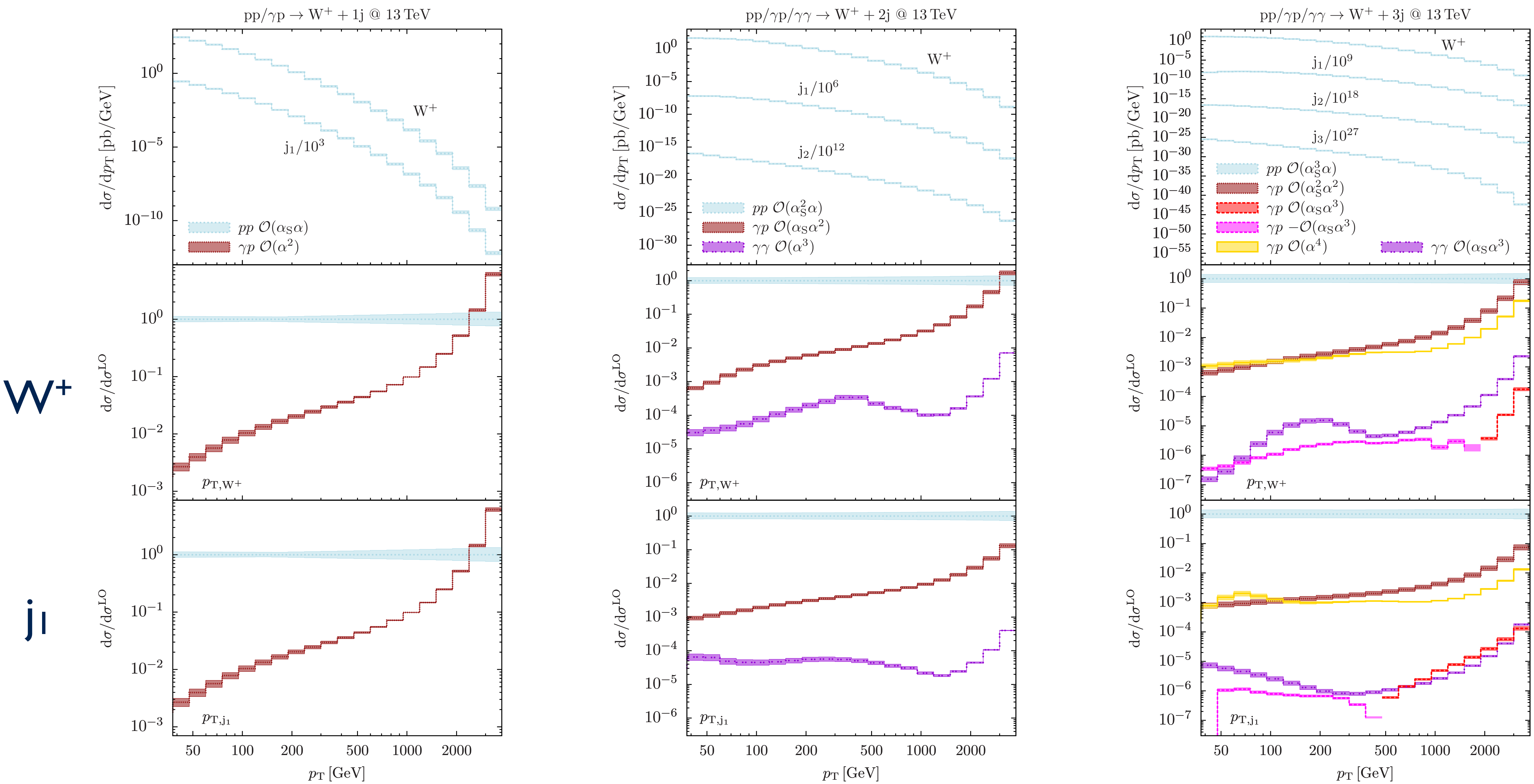
- negligible EW corrections



- stable QCD corrections
- up to -25% EW corrections

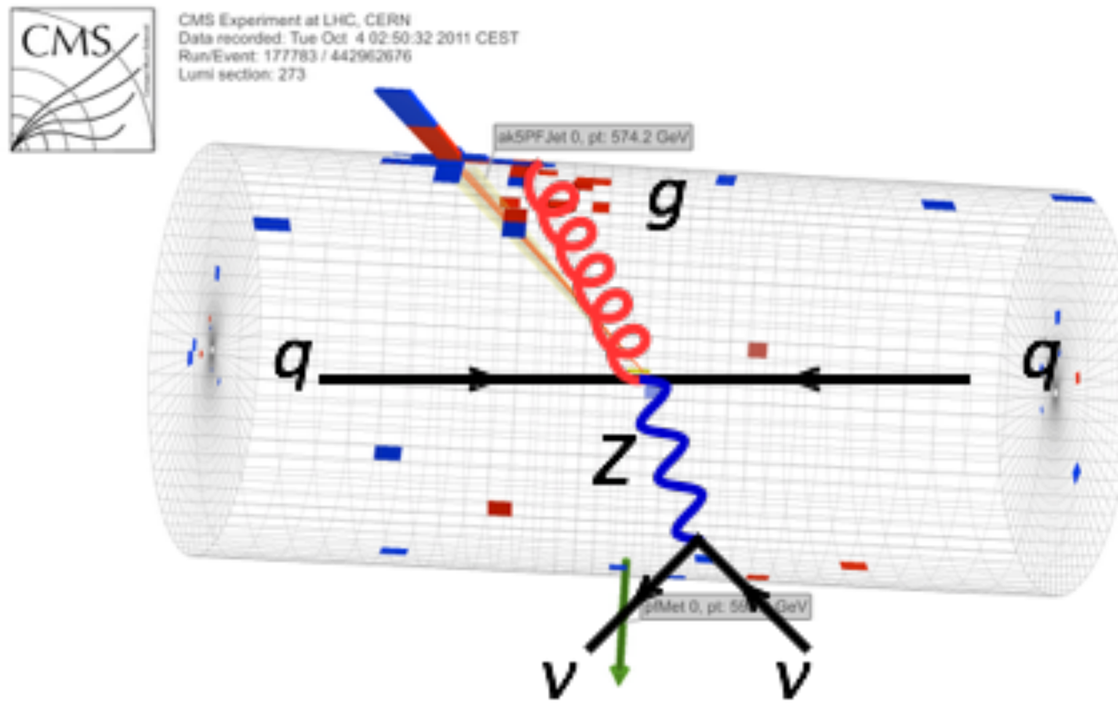


W + 1,2,3 jets @ sub-LO: γ-induced



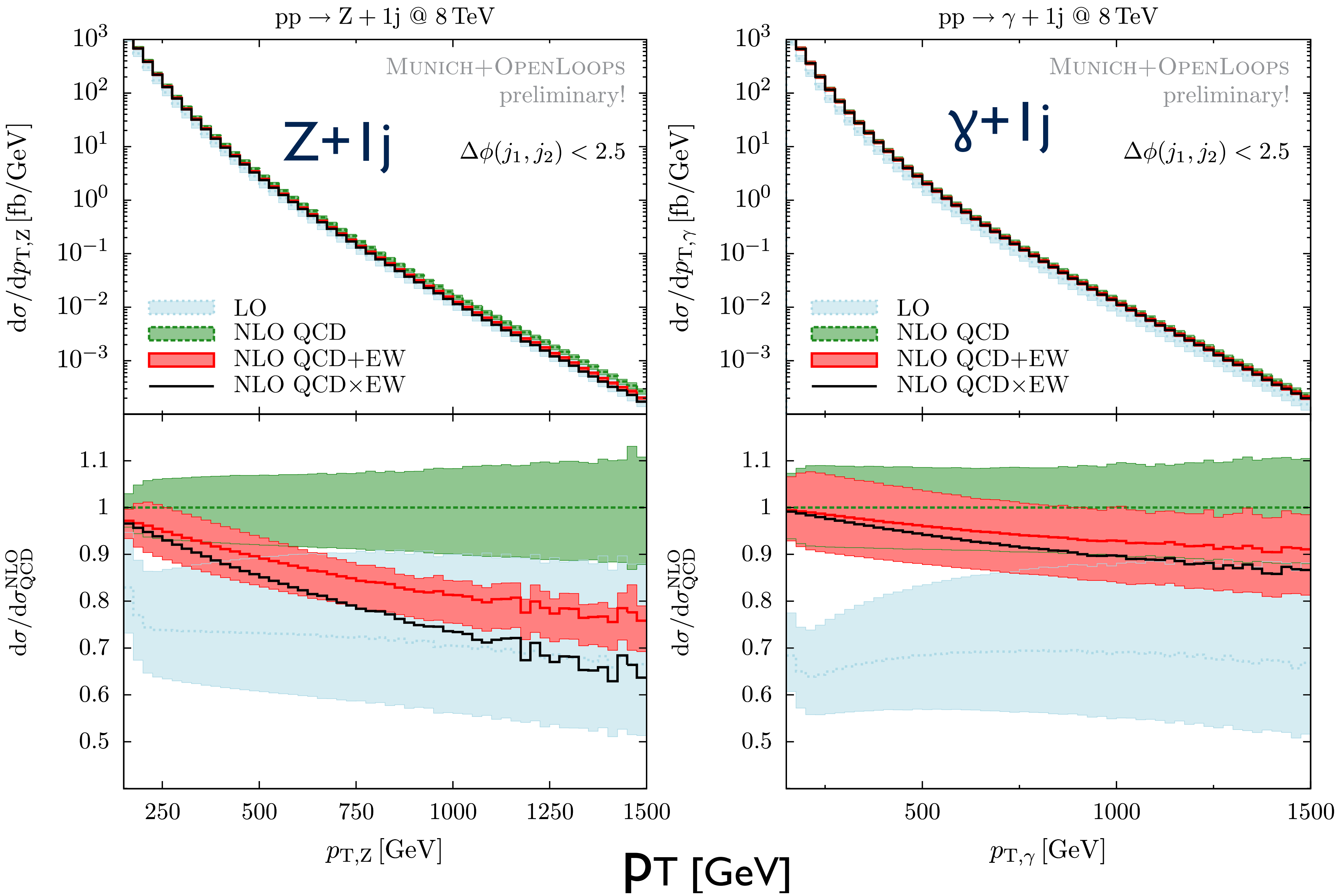
- As large as 5 - 100% at $p_{T,W+}$=1-4 TeV
- However: giant γ-PDF uncertainties at large x!

Motivation: V + multijet production



- Z(→$\nu\bar{\nu}$)+jets irreducible background for monojet/multijet **Dark Matter searches**
- can be determined from γ+jets and/or W+jets measurements together with *theoretical predictions* for Z+jets/γ+jets and Z+jets/W+jets ratios

Z/γ + 1 jet: exclusive



Setup:

$\sqrt{S} = 8$ TeV

$p_{T,j} > 110$ GeV, $|\eta_j| < 2.4$

$\mu_0 = \hat{H}_T/2$ (+ 7-pt. variation)

$\Delta\phi_{j1j2} < 2.5$

Frixione-Isolation with dR=0.3

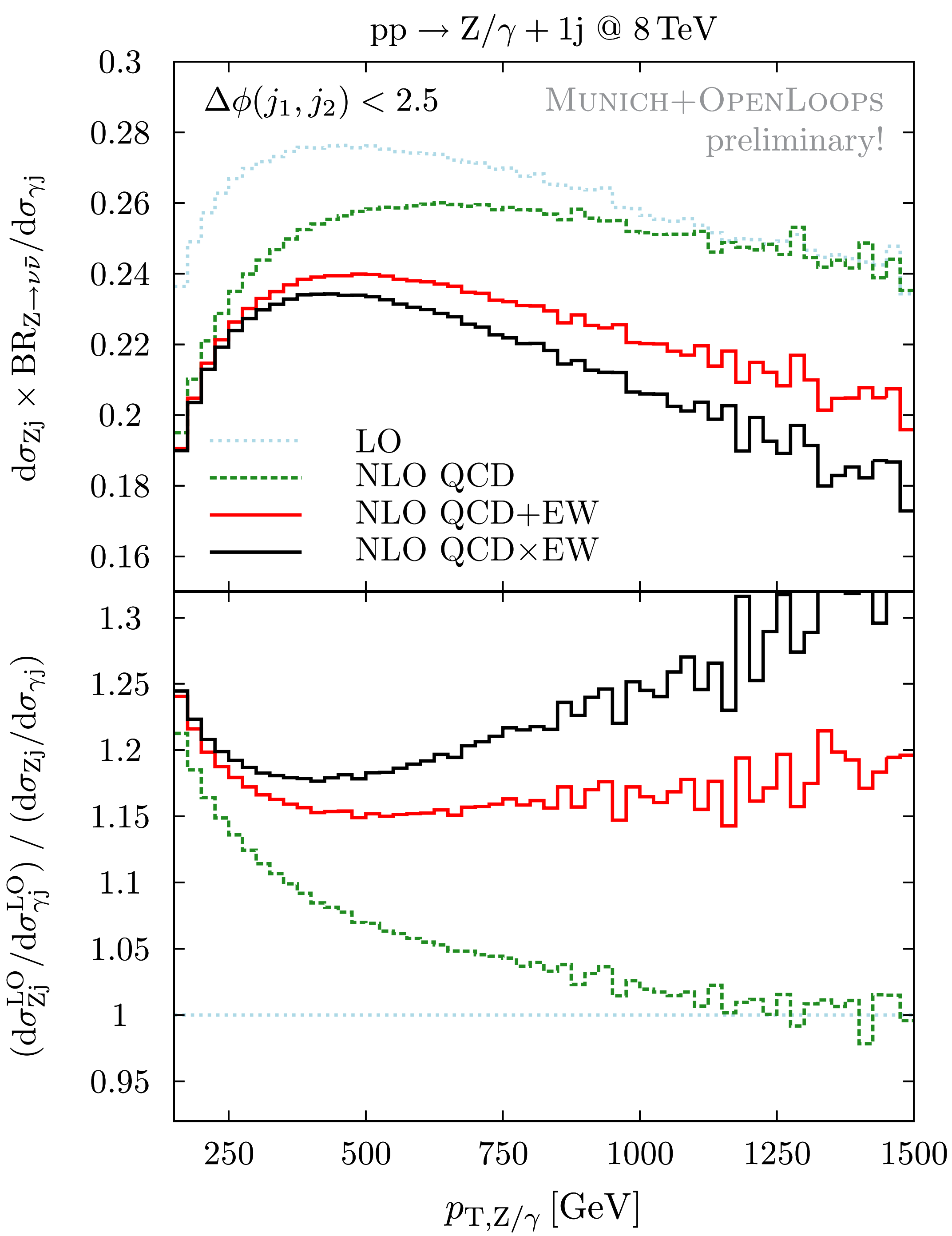
QCD corrections

- mostly moderate and stable QCD corrections
- (almost) identical QCD corrections in the tail, sizeable differences for small pT

EW corrections

- correction in pT(Z) > correction in pT(γ)
- **-20/-8% EW for Z/γ at 1 TeV**
- EW corrections > QCD uncertainties for $p_{T,Z}$ > 350 GeV

Z/γ + 1 jet: pT-ratio



Overall

- mild dependence on the boson pT

QCD corrections

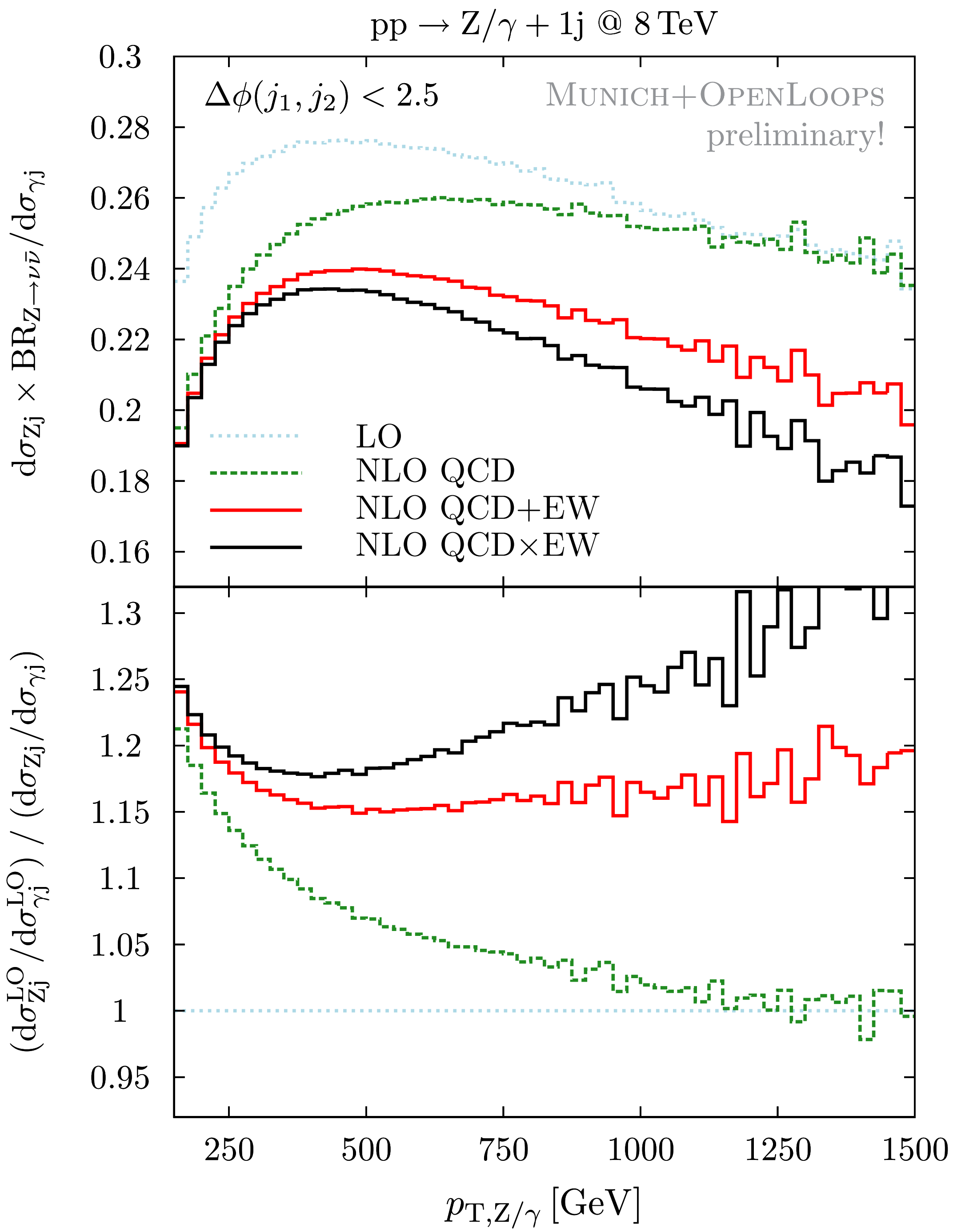
- ≲ 10% above 300 GeV

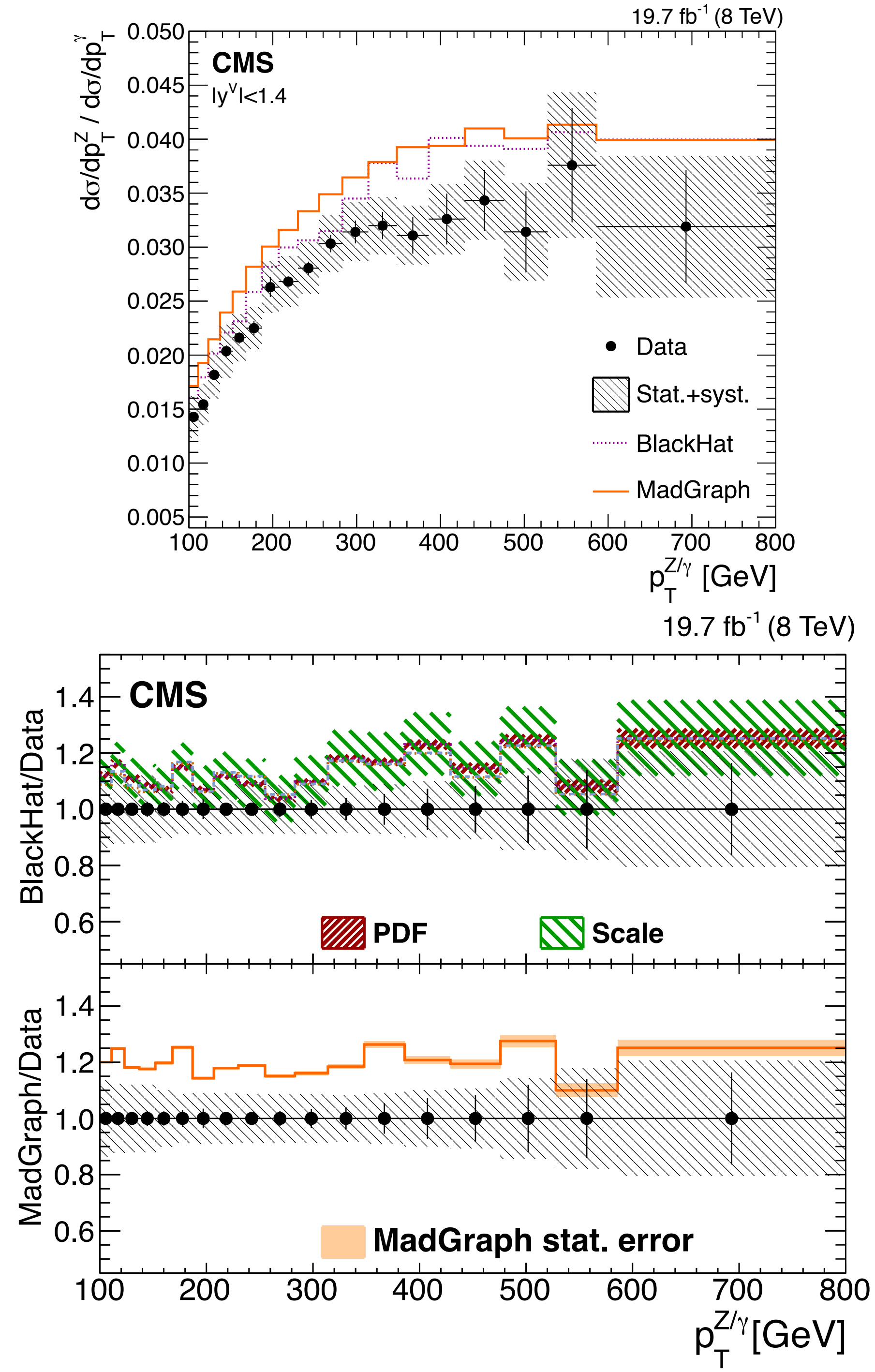
EW corrections

- result in an almost constant shift between LO and NLO QCD+EW of ~15%
- sizeable difference between QCD+EW & QCDxEW

Z/γ + 1 jet: pT-ratio

[CERN-PH-EP-2015-089]





Note: fiducial regions not identical!

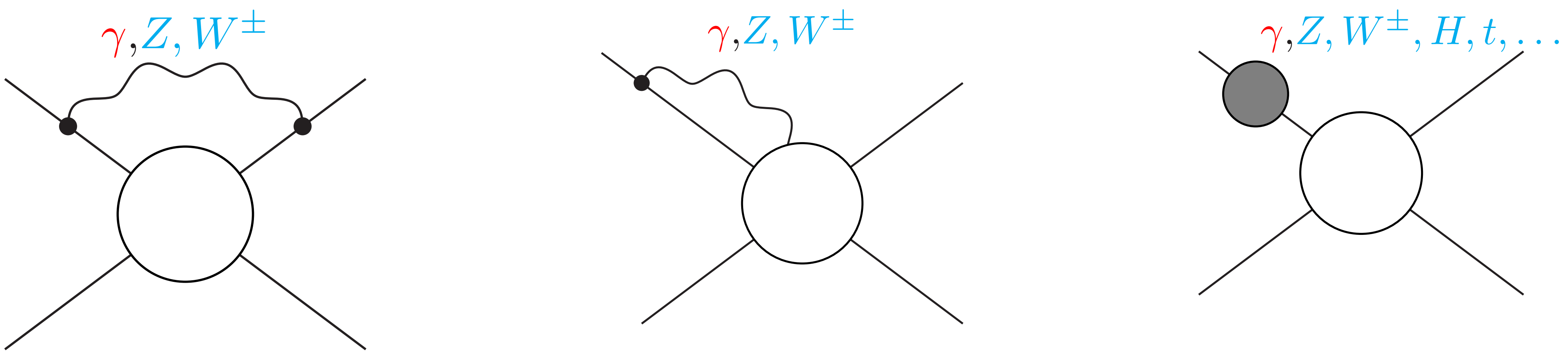
Conclusions

- V + multijets at QCD+EW:
  - 2 → 4 NLO EW feasible!
  - inclusion of EW corrections *crucial* at the TeV scale (up to 50%)
  - non-trivial interplay between QCD and EW
  - multi-jet final states genuinely different from V+1jet
  - Z+jets / ɣ+jets ratio sensitive to EW corrections *below* TeV scale

- Outlook:
  - **decays** of V's (ll+jets, ln+jets)
  - PS matching & **multi-jet merging**
  - NLO corrections in the full SM (QCD & EW) publicly available in OpenLoops+Sherpa

Origin of electroweak Sudakov logarithms

Originate from soft/collinear virtual EW bosons coupling to on-shell legs

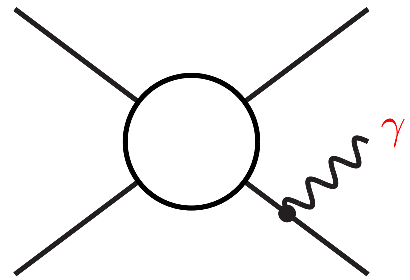


Universality and factorisation similar as in QCD *[Denner, Pozzorini; '01]*

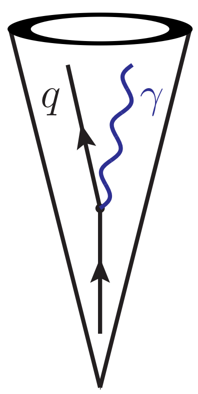
$$\delta^{1-\mathrm{loop}}_{\mathrm{LL+NLL}} = \frac{\alpha}{4\pi} \sum_{k=1}^{n} \left\{ \frac{1}{2} \sum_{l \neq k} \sum_{a=\gamma,Z,W^{\pm}} I^{a}(k) I^{\bar{a}}(l) \ln^2 \frac{s_{kl}}{M^2} + \gamma^{\mathrm{ew}}(k) \ln \frac{s}{M^2} \right\}$$

- process-independent and simple structure
- tedious implementation (ALPGEN [Chiesa et al. '13]) due to nontrivial $SU(2) \times U(1)$ features (P-violation, mixing, soft SU(2) correlations, Goldstone modes, . . .)
- 2-loop extension and resummation partially available

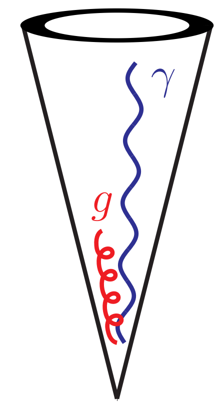
Treatment of Photons



- QED IR subtraction *[Catani,Dittmaier,Seymour,Trocsanyi; Frixione, Kunszt, Signer]*
- Problem of IR safeness in presence of FS QCD partons and photons:
  - Democratic jet-algorithm approach (jets ≡ photons)



collinear q → qγ singularities cancelled clustering q, g, γ on same footing

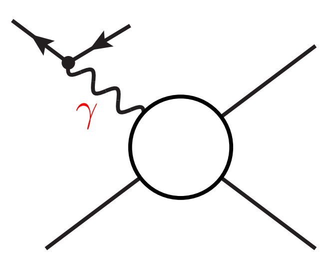


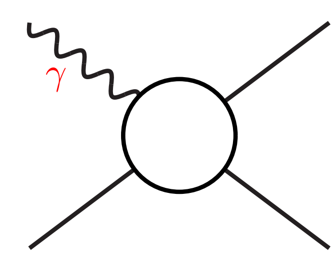
soft gluon singularities ↔ hard photons inside jets: cancelled in jet-production (NLO EW) + γ-production (NLO QCD)

  - Separation of jets from photons through Eγ/Ejet < z_{thr} inside jets
    - *rigorous approach*: absorb q → qγ singularity into fragmentation function
    - *approximation*: cancel singularity via qγ recombination in small cone $\Delta R_{q\gamma} < 0.1$

    difference < 1% for typical z_{thr}!

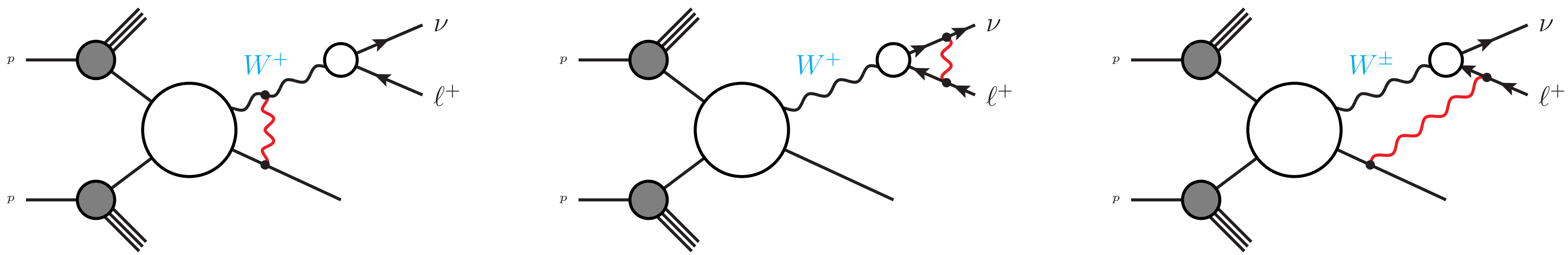
- QED factorisation for IS photons and PDF evolution *[MRST2004, NNPDF2.3]*
- γ-induced processes → possible TeV scale enhancements (However large uncertainties!)





Decays of heavy particles

- Leptonic decays of gauge bosons are trivial at NLO QCD. At NLO EW corrections in production, decay and non-factorizable contributions have to be considered.

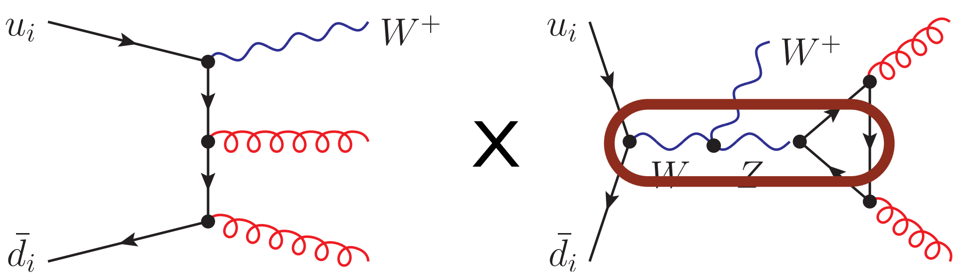


- Scheme of choice: complex-mass-scheme *[Denner, Dittmaier]*
  - gauge invariant and exact NLO
  - **computationally very expensive**: one extra leg per two-body decay

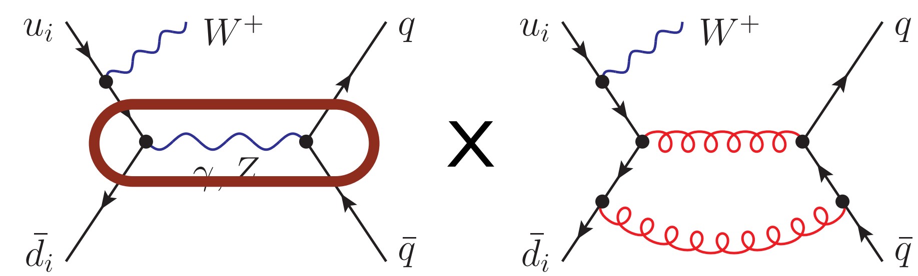
- Pragmatic choice: Narrow-width-approximation (NWA)
  - gauge invariant in strict on-shell limit of NWA
  - **allows to capture all Sudakov effects** (not present in decay)
  - **allows to go to higher jet multiplicities**
  - not applicable to all processes at all perturbative orders

Technical note: pseudo-singularities for W+2,3 jets

gluonic channels



fermionic channels



- At the considered order **only effects QCD-EW interferences**
- Complex-mass-scheme can not be used with on-shell/stable W's
- NWA: finite width $\Gamma_{\text{reg.}}$ in potentially s-channel propagators for W, Z ,t ,H
- Smooth **gauge-invariant limit** and negligible numerical dependence for $\Gamma_{\text{reg.}} \to 0$

$$\Rightarrow \frac{Q^2 - M^2}{(Q^2 - M^2)^2 + \Gamma^2_{\text{reg}} M^2}$$

Goal:

- Investigation of technical performance at highest possible jet multiplicity
- Investigate dependence of EW corrections on number of jets

Performance of NLO EW OpenLoops amplitudes

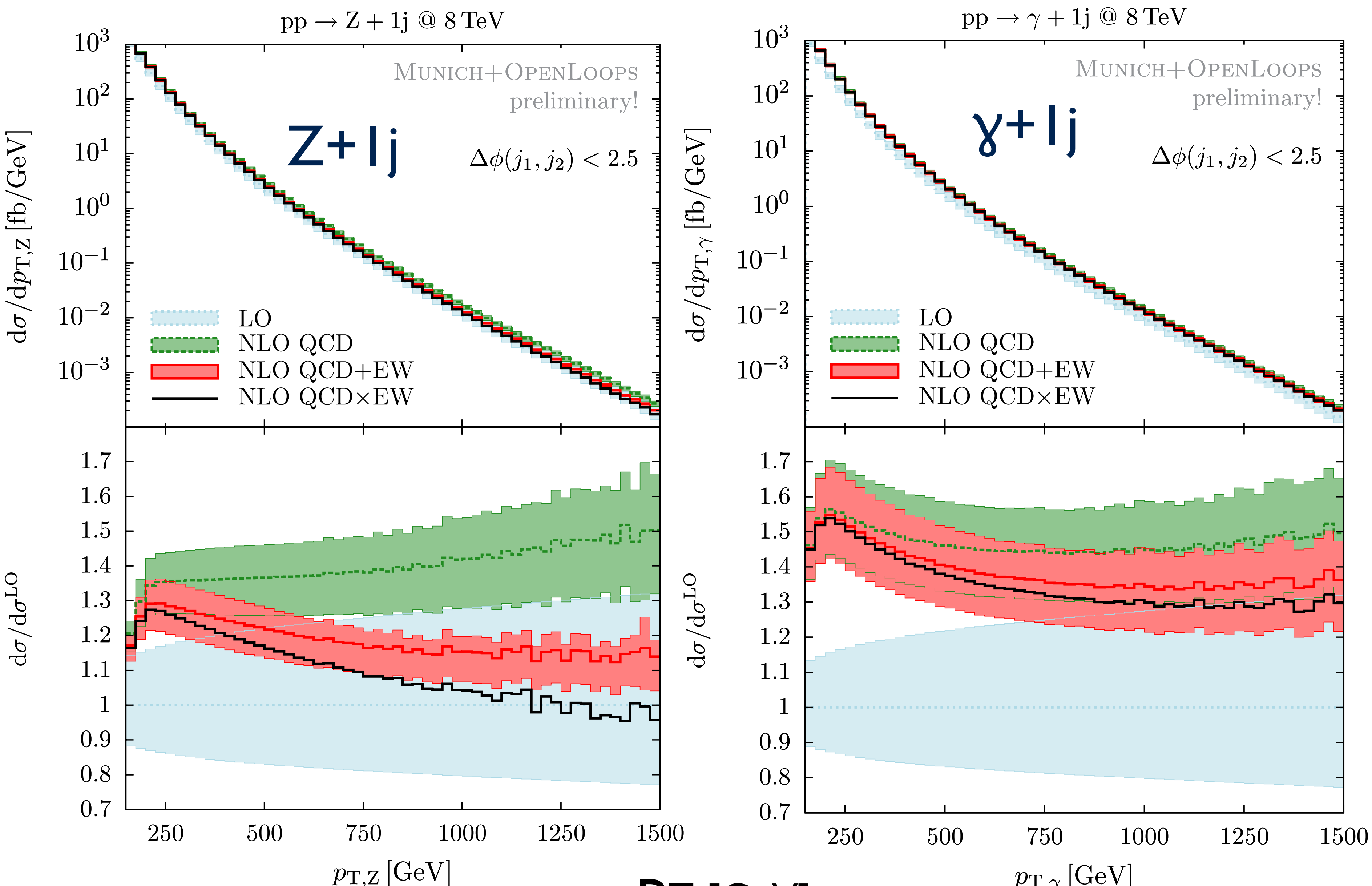
- Performance study for pp → $t\bar{t}$ + n jets with n=0,1,2

$t\bar{t}+0,1,2\,\mathrm{j}$	$n_{\mathrm{loop\ diag}}$ QCD	$n_{\mathrm{loop\ diag}}$ EW	t_{compile} [s] QCD	t_{compile} [s] EW	size [MB] QCD	size [MB] EW	t_{run} [ms/point] QCD	t_{run} [ms/point] EW
$d\bar{d}\to t\bar{t}$	11	33	2.1	3.5	0.1	0.2	0.27	0.69
$gg\to t\bar{t}$	44	70	3.6	3.7	0.2	0.3	1.6	2.8
$d\bar{d}\to t\bar{t}g$	114	360	3.5	5.9	0.4	0.9	4.8	13
$gg\to t\bar{t}g$	585	660	8.2	8.8	1.4	1.6	40	56
$d\bar{d}\to t\bar{t}u\bar{u}$	236	1274	5.3	16	0.8	2.8	12	48
$d\bar{d}\to t\bar{t}d\bar{d}$	472	2140	9.5	56	1.4	1.4	30	99
$d\bar{d}\to t\bar{t}gg$	1507	4487	20	47	3.5	8.2	133	327
$gg\to t\bar{t}gg$	8739	7614	105	79	18	16	1458	1557

Timings on i7-3770K with gcc 4.8 –O0 dynamic and unpolarised $t\bar{t}$ (significantly faster with decays!) using **COLLIER** for reduction

- 1-loop EW similarly fast as highly competitive 1-loop QCD timings up to $t\bar{t}$ + 2 jets
- code size, compilation- & runtime reflect a moderate increase of complexity w.r.t. QCD
- 2 → 4 NLO QCD+EW feasible!

Z/γ + 1 jet: exclusive



pT [GeV]

Setup:

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$\mu_0 = \hat{H}_T/2$ (+ 7-pt. variation)
$\Delta\phi_{j1j2} < 2.5$
Frixione-Isolation with dR=0.3

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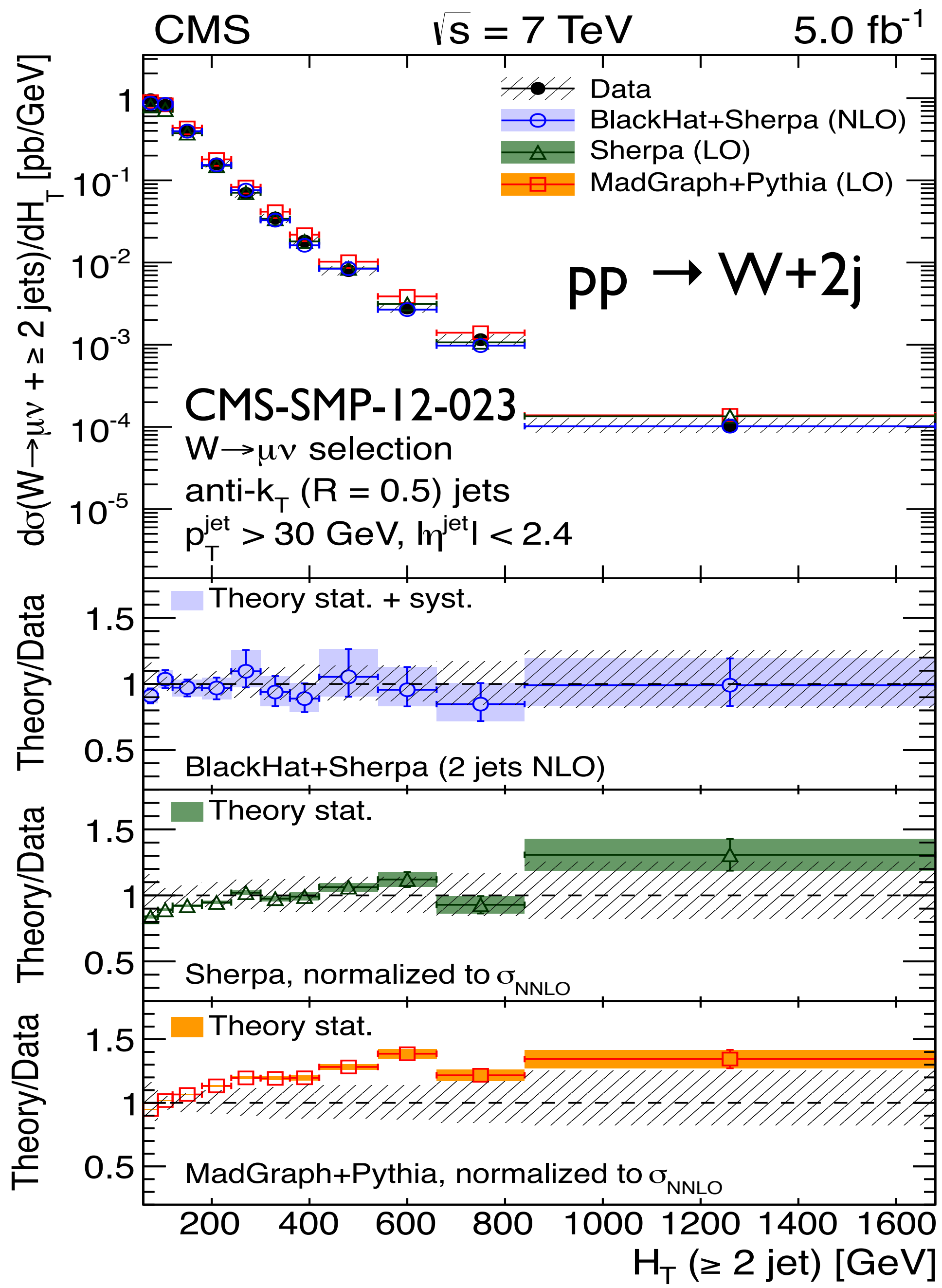
- mostly moderate and stable QCD corrections
- (almost) identical QCD corrections in the tail, sizeable differences for small pT

EW corrections

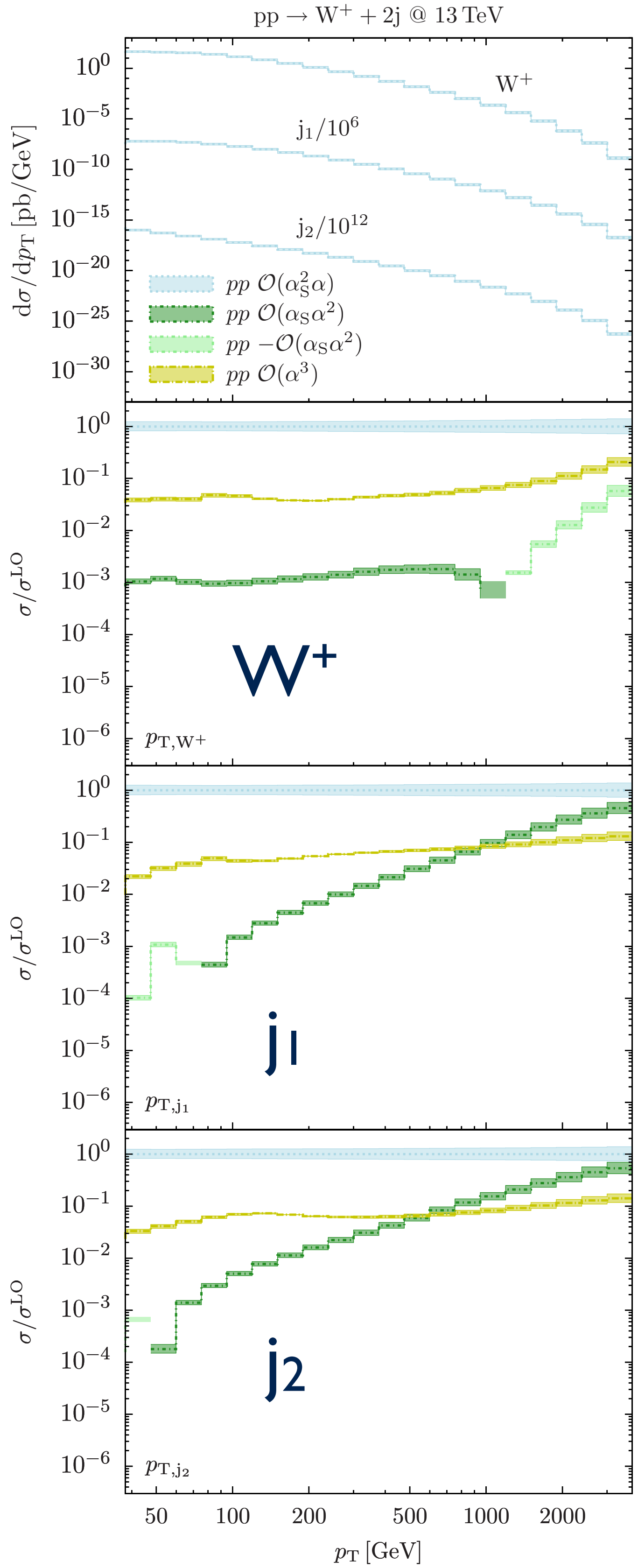
- correction in pT(Z) > correction in pT(γ)
- **-20/-8% EW for Z/γ at 1 TeV**
- EW corrections > QCD uncertainties for $p_{T,Z} > 350$ GeV

W + multijet production



- W+2j production badly described by LO+PS (merged)
- H_T @ NLO QCD small uncertainties (~10 %)

W + 2 jets @ sub-LO: QCD-EW interplay



Setup:

$\sqrt{S} = 13$ TeV

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

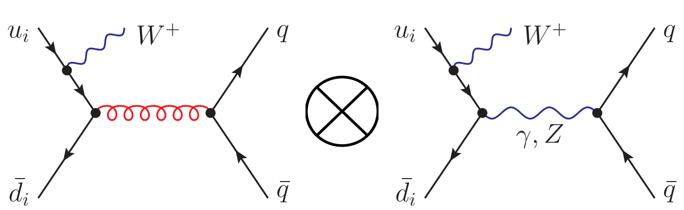
$\mu_0 = \hat{H}_T/2$ (+ 7-pt. variation)

Inclusive

- Subleading contributions highly suppressed

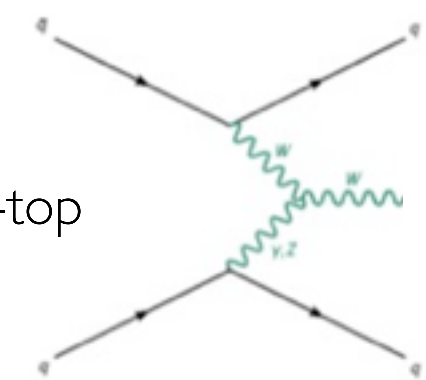
$O(\alpha_S \alpha^2)$ mixed QCD-EW contribution

- large impact at large jet-pT (10-50% at 1-4 TeV)!



$O(a^3)$ pure EW contribution

- includes contributions from WW, WZ, VBF, single-top
- 10-20% at 1-4 TeV



Photon PDF comparison at 10^4 GeV^2