Automated NLO EW corrections with OpenLoops

and

precise predictions for vector boson plus multijet production

Jonas M. Lindert

work in collaboration with:

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

[arXiv:1412.5157 , arXiv:1505.05704]

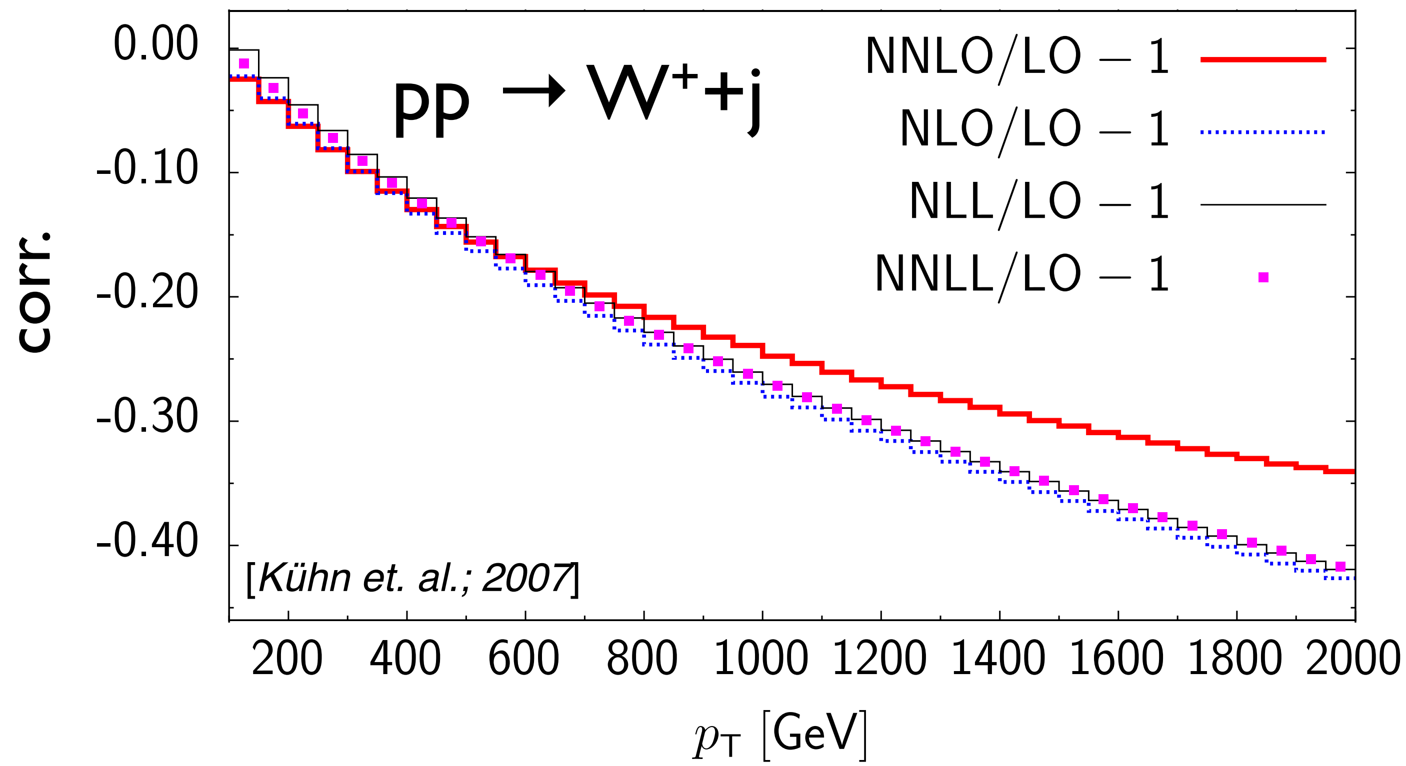
Radcor-Loopfest 2015

UCLA, LA, 16th June 2015

Why NLO EW automation?

- 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 (reflected in 2013 Les Houches Wishlist)

- 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]

- NLO EW known for most (some) 2→2(3) processes
- …missing for a multitude of 2→3(4) processes (and with decays and/or PS matching)

Automation of NLO QCD

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

OpenLoops

[JML, Maierhöfer, Pozzorini]

Sherpa

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

MUNICH

[Kallweit]

POWHEG-BOX

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

Herwig++/Matchbox

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

Whizard

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Automation of NLO QCD+EW

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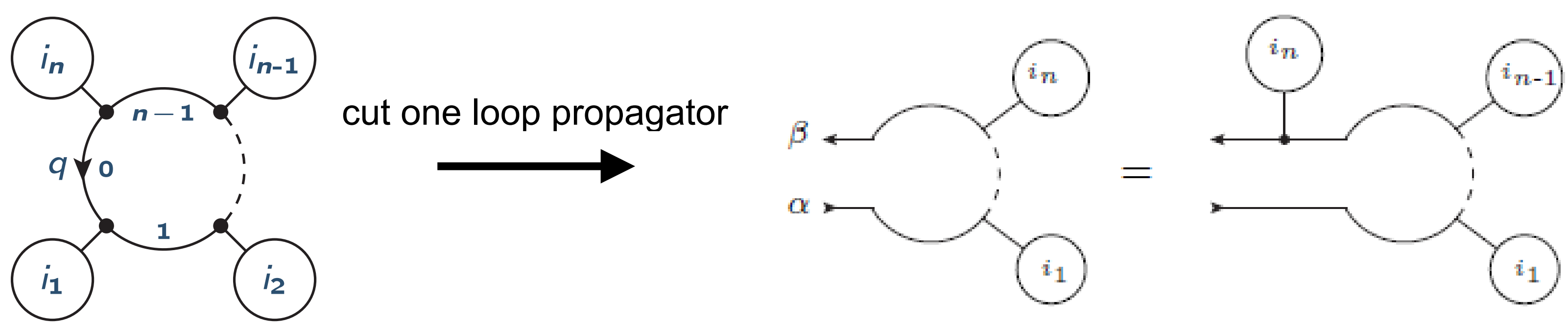
The OpenLoops program

see talk by P. Maierhöfer

[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



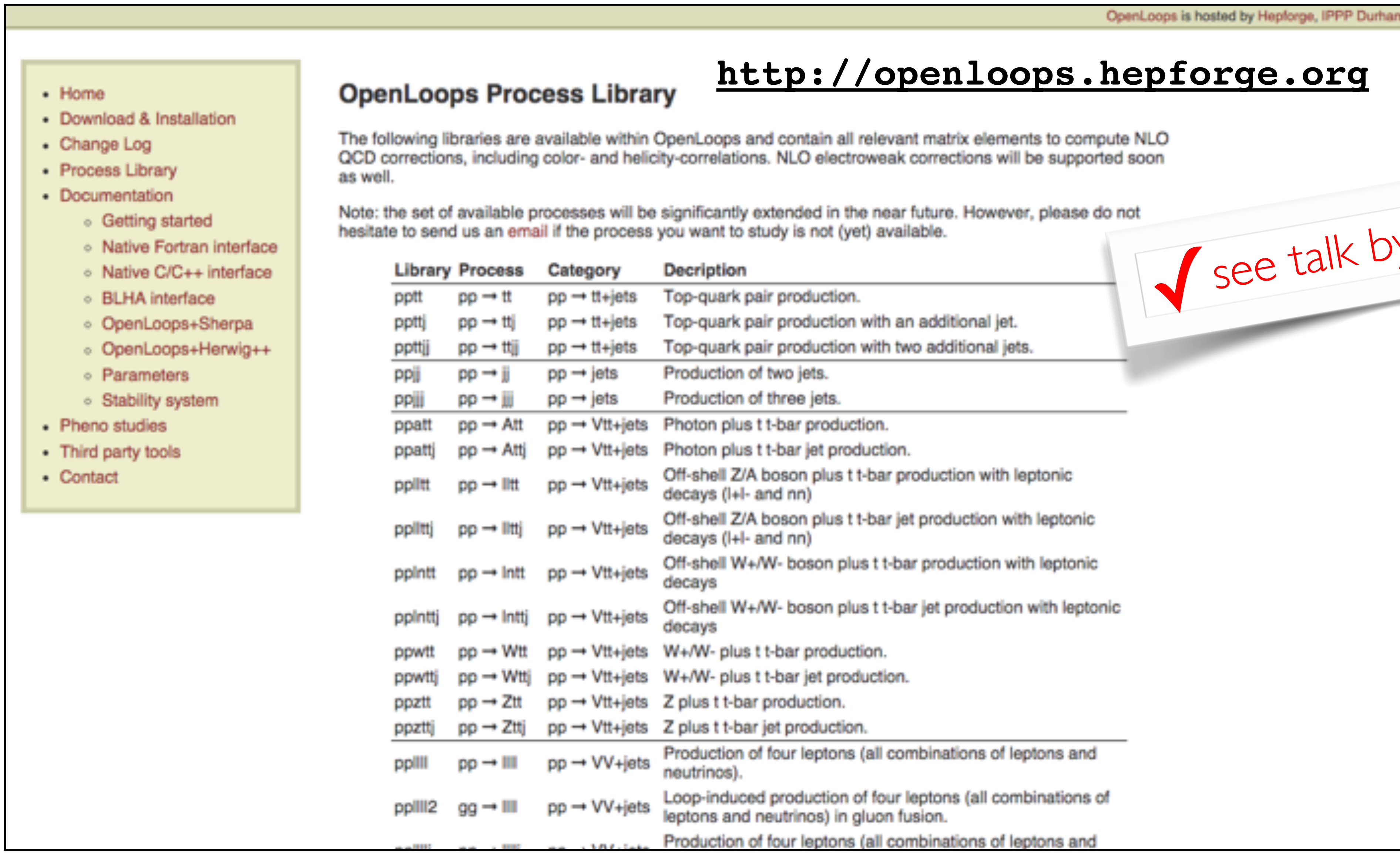
- Publicly available at **`http://openloops.hepforge.org`**
- Amplitudes for any $2 \to 4(5)$ NLO QCD process in the SM available:
  tree & (renormalized) virtual amplitudes, color correlations, spin correlations
- Installation (Requirements: gfortran ≥ 4.6, Python 2.x, x ≥ 4):

```
$ 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 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, HV+0,1,2 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

OpenLoops Process Library

http://openloops.hepforge.org

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

✓ see talk by P. Maierhöfer

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

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

Perturbative power counting

LO subleading Born contributions

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

Perturbative power counting

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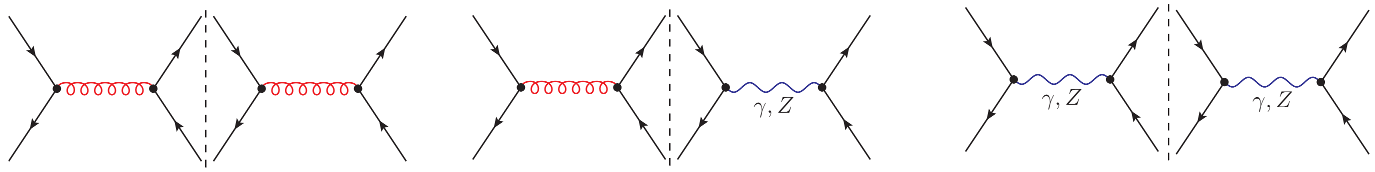

Illustrative example: $q\overline{q} \rightarrow q\overline{q}$

Perturbative power counting

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

"NLO QCD" "NLO EW"

Perturbative power counting

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

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

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

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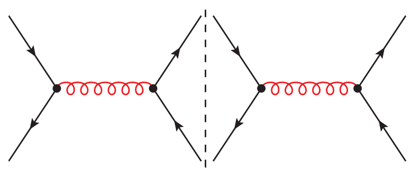
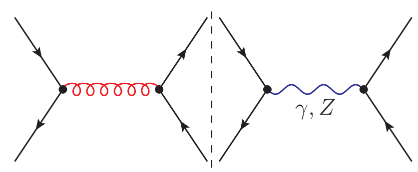
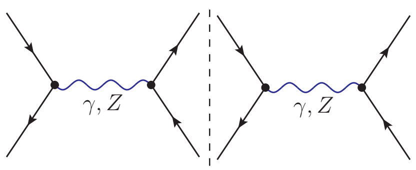
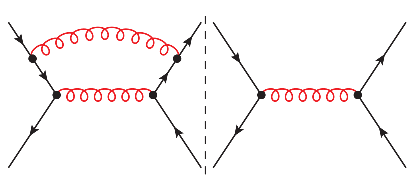
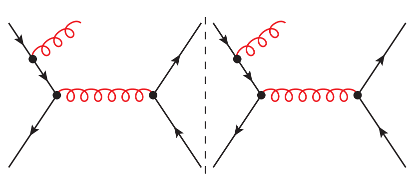





Illustrative example: **q$\overline{\mathbf{q}}$** $\rightarrow$ **q$\overline{\mathbf{q}}$**

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

"NLO QCD"

Perturbative power counting

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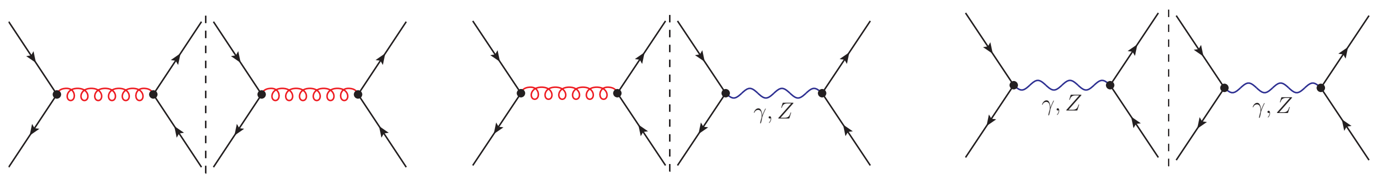
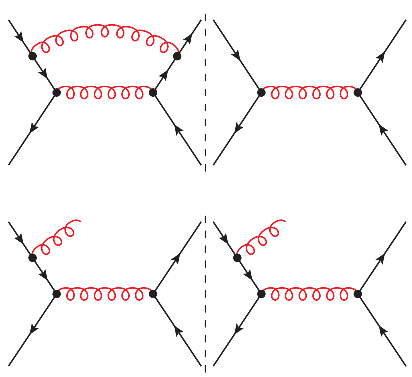
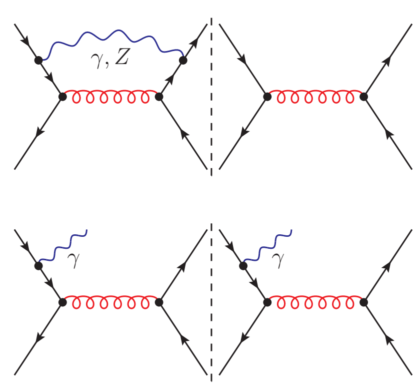


Illustrative example: $\mathbf{q\bar{q} \to q\bar{q}}$

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

"NLO QCD" "NLO EW"





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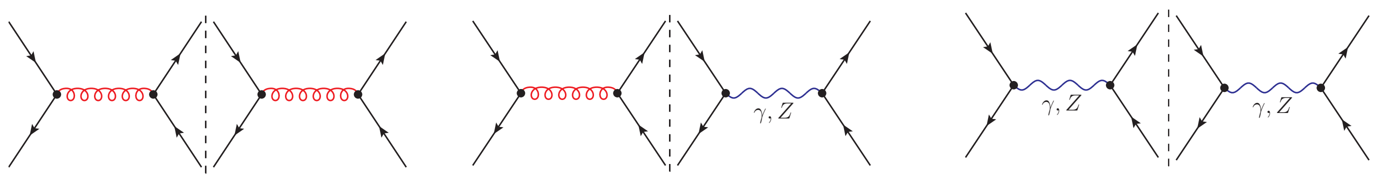

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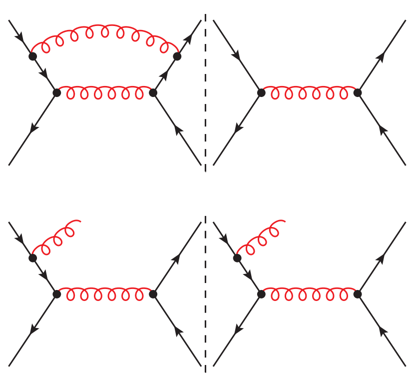

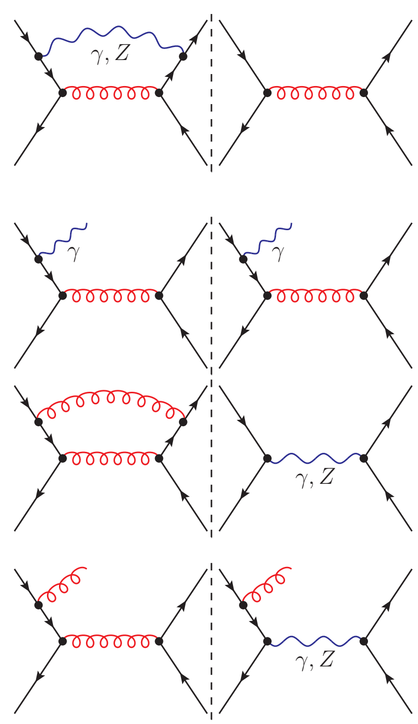

Perturbative power counting

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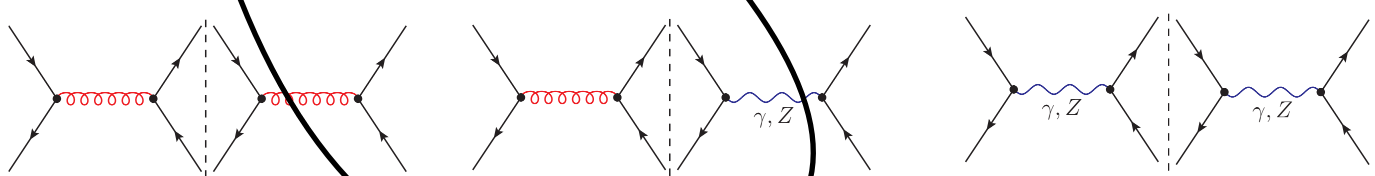
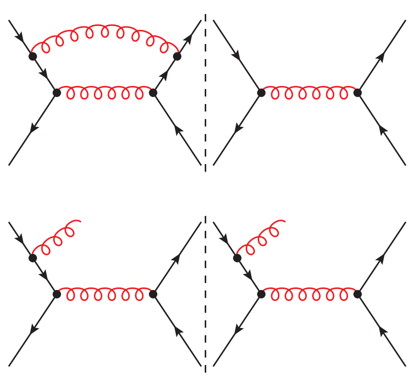


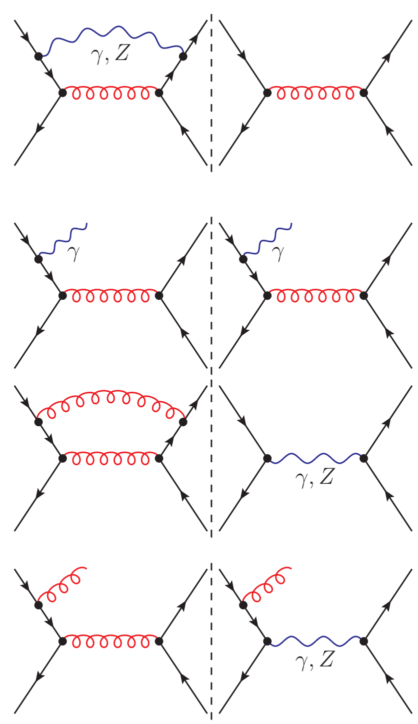
Illustrative example: $\mathbf{q\bar{q} \to q\bar{q}}$

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

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

"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

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

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

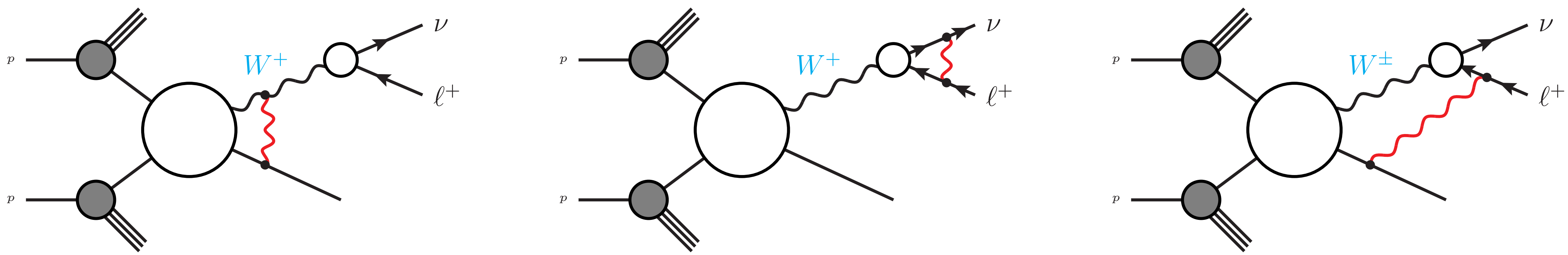
✓ ***Automation*** requires universal power counting and bookkeeping in α and α_s including different interference effects for all contributions: virtual, real, subtraction.

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" $\equiv \alpha_s^n \alpha^{m+1}$

Decays of heavy particles

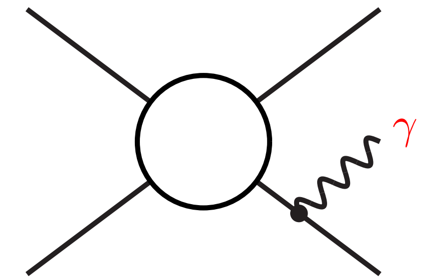
- Leptonic decays of gauge bosons are trivial at NLO QCD. At NLO EW corrections in production, decay and non-factorizable contributions have to be considered.



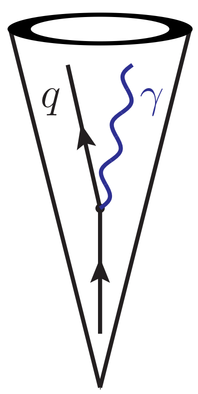
- Scheme of choice: complex-mass-scheme *[Denner, Dittmaier]*
  - gauge invariant and exact NLO
  - **computationally very expensive**: one extra leg per two-body decay

- 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

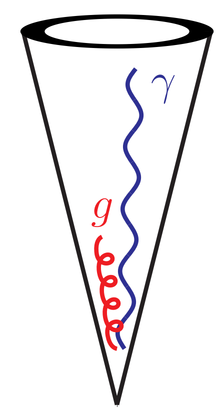
Treatment of Photons



- 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

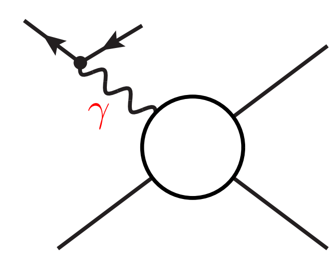


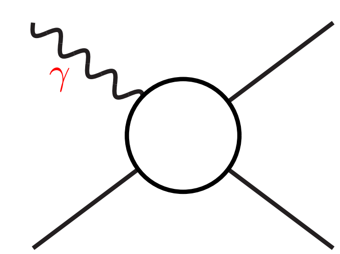
soft gluon singularities ↔ hard photons inside jets: cancelled in jet-production (NLO EW) + γ-production (NLO QCD)

  - 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!)





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]. Available schemes: on-shell, G_μ and $\alpha(mZ)$
  - R_2 rational terms
  - Treatment of unstable particles: complex-mass-scheme

- ✓ Real radiation, subtraction, subprocess bookkeeping

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

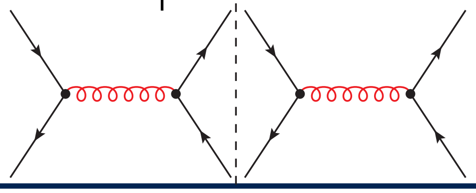
  - Based on the well established NLO QCD dipole subtraction frameworks with replacements for QCD → QED

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

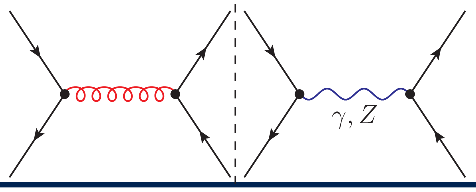
$$\frac{\mathbf{T}_{ij}\cdot\mathbf{T}_k}{\mathbf{T}_{ij}^2} \longrightarrow \begin{cases} \frac{Q_{ij}Q_k}{Q_{ij}^2} & \text{if the emitter } ij \text{ is a (anti)fermion} \\ \kappa_{ij,k} & \text{if the emitter } ij \text{ is a photon}\,, \end{cases}$$

  - 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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- Fast numerical routines for all tree+loop vertic...
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- Treatmen...

...grator at swiss (CH) precision

...ablished NLO QCD dipole subtraction frameworks with replacements for ...QED

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

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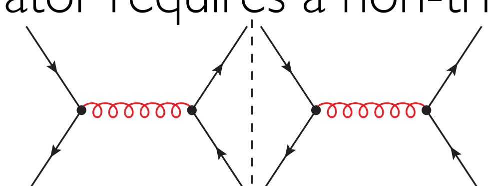
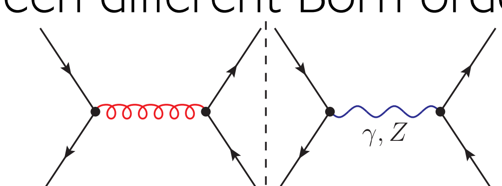
$$I \;\propto\; \sum \int_1 V_{\text{QED}} \otimes$$  $$+ \int_1 V_{\text{QCD}} \otimes$$ 

All ingredients carefully validated:

✓ OpenLoops vs. private code by S. Pozzorini

✓ MUNICH vs. Sherpa

Performance of NLO EW OpenLoops amplitudes

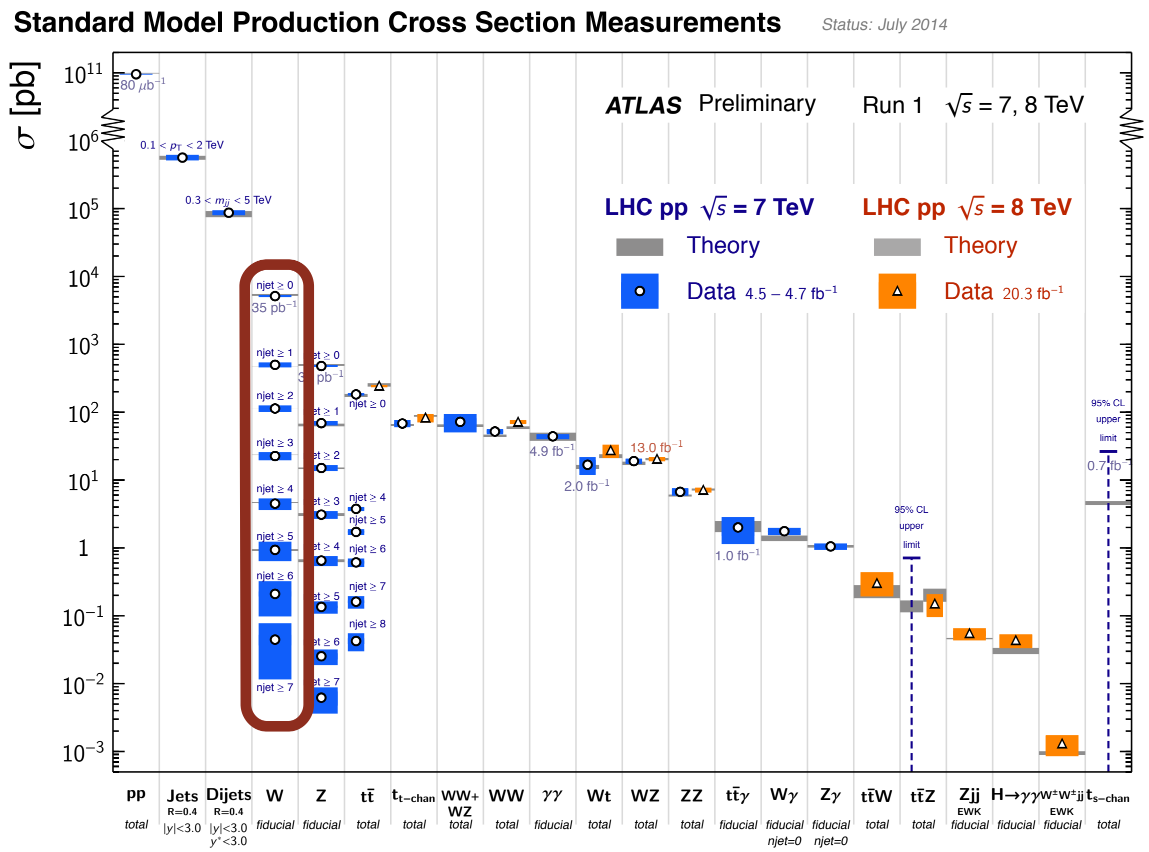
- Performance study for pp → $t\bar{t}$ + n jets with n=0,1,2

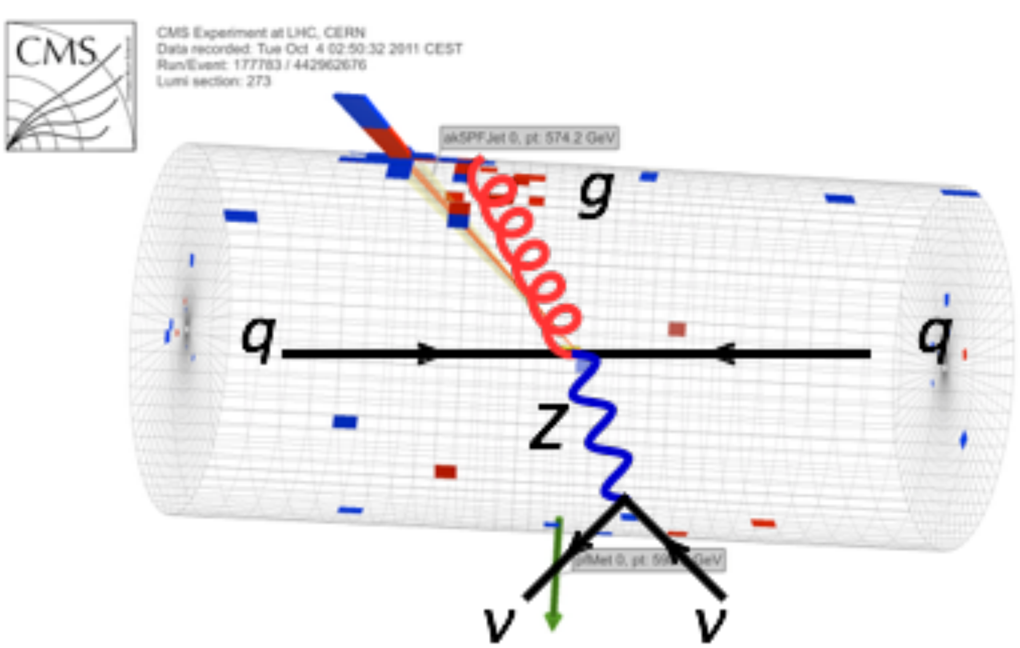
$t\bar{t}+0,1,2\,\mathrm{j}$	$n_{\mathrm{loop\ diag}}$ QCD	EW	t_{compile} [s] QCD	EW	size [MB] QCD	EW	t_{run} [ms/point] QCD	EW
$d\bar{d} \to t\bar{t}$	11	33	2.1	3.5	0.1	0.2	0.27	0.69
$gg \to t\bar{t}$	44	70	3.6	3.7	0.2	0.3	1.6	2.8
$d\bar{d} \to t\bar{t}g$	114	360	3.5	5.9	0.4	0.9	4.8	13
$gg \to t\bar{t}g$	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!

Motivation: V + multijet production



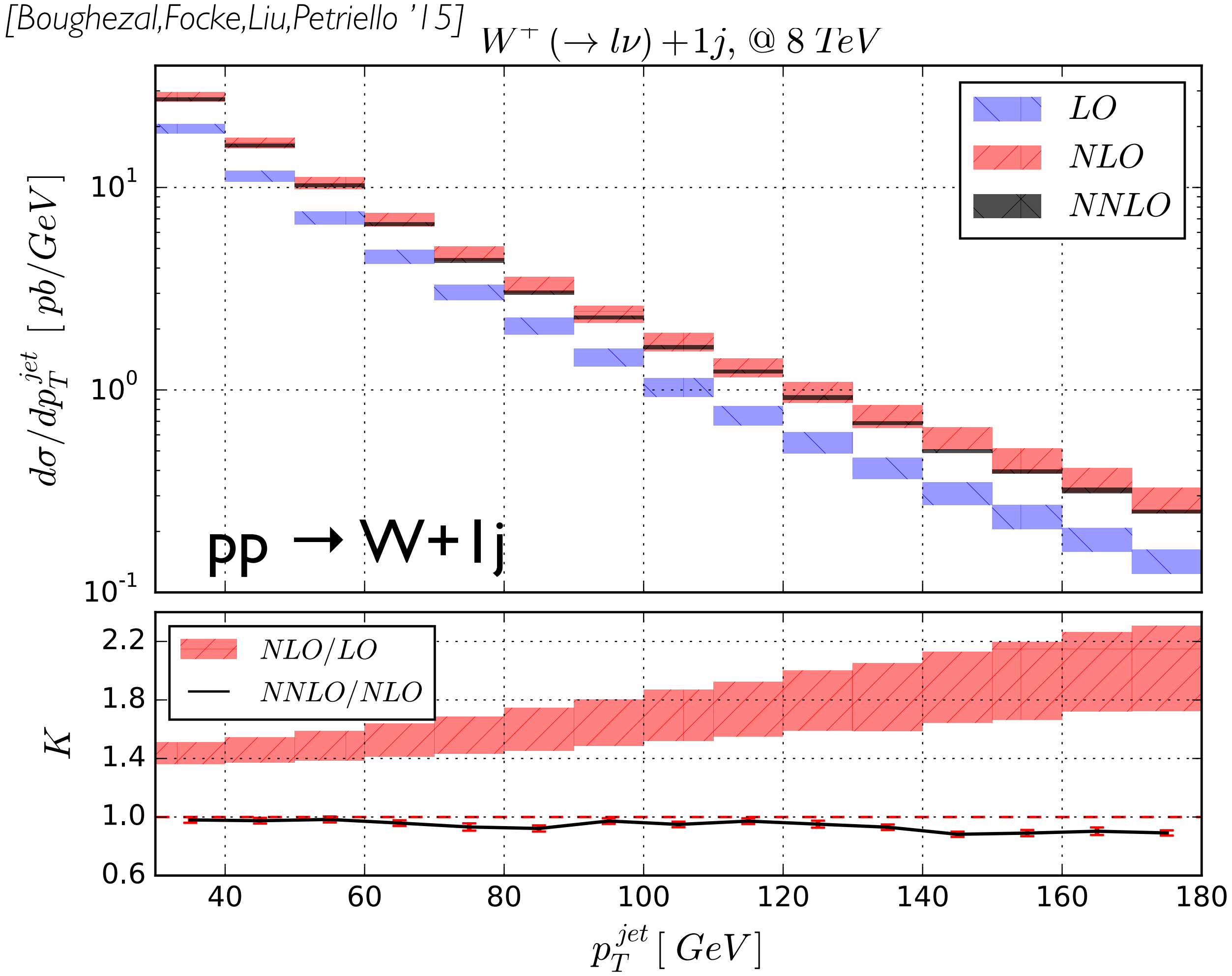


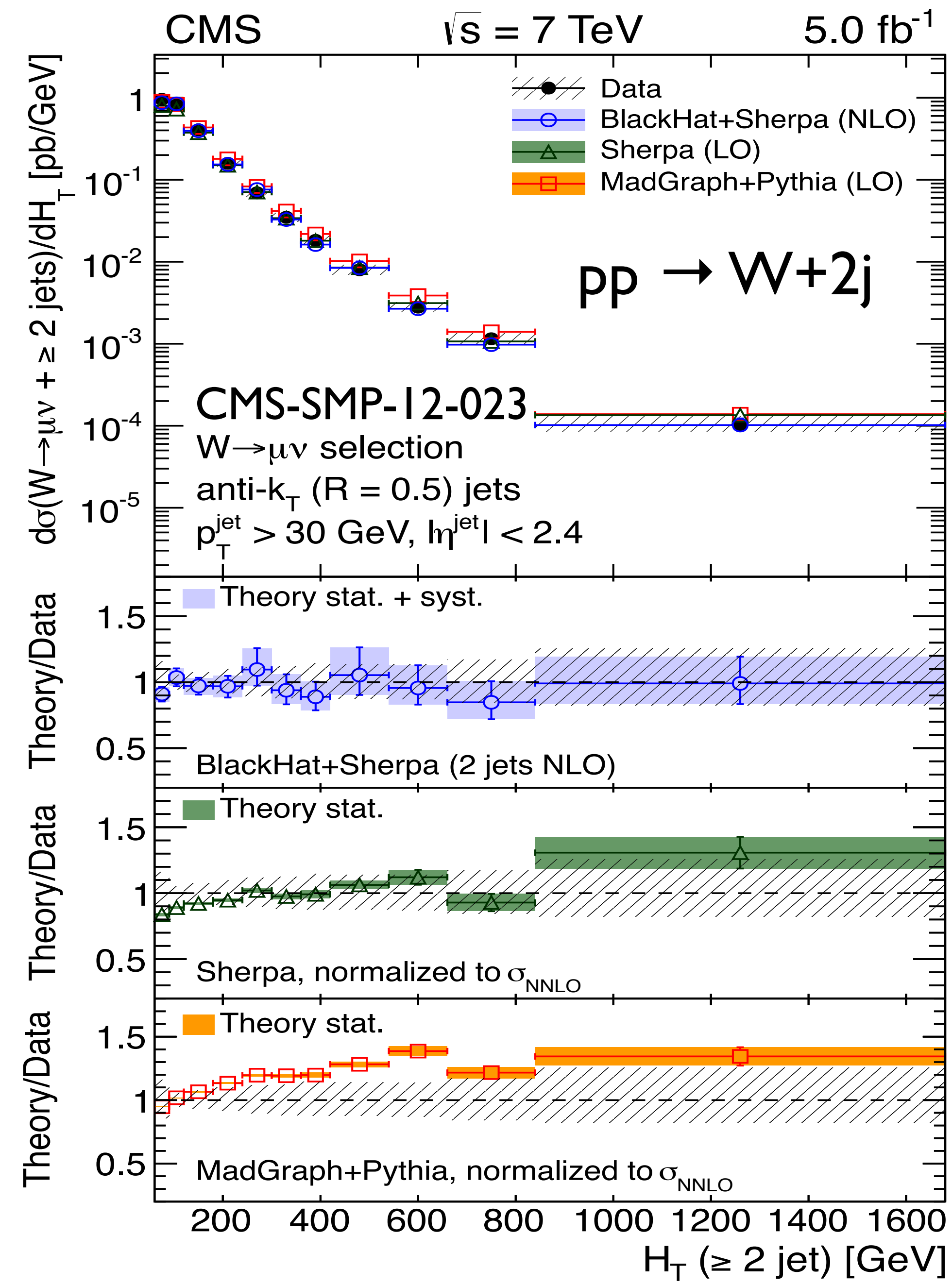
- Large cross-sections and clean leptonic signatures
- Precision QCD at LHC
- Playground to probe different aspects of higher-order calculations
  (LO+PS, NLO+PS, NLO-Merging, NLO EW,…)

- 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 + multijet production

[Boughezal,Focke,Liu,Petriello '15]





- p_T (jet) @ NNLO QCD has tiny uncertainties (~1 %)

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

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:

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

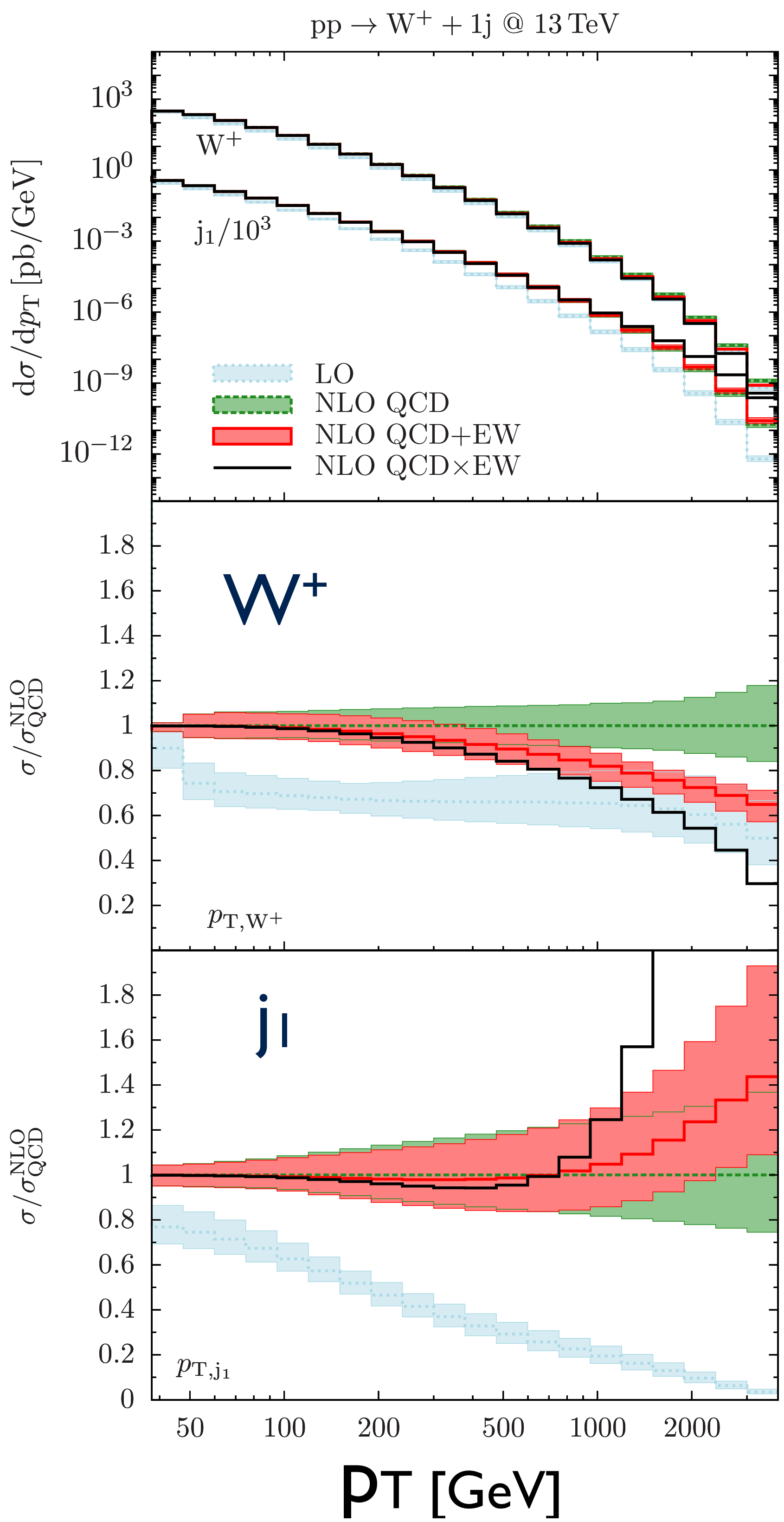
suppressed by large NLO QCD corrections

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

"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 $G_\mu = 1.16637\times 10^{-5}\ {\rm GeV}^{-2}$
- PDFs: NNPDF 2.3QED with $\alpha_{\rm S}(M_{\rm Z}) = 0.118$ for LO and NLO QCD/EW

W^+ + 1 jet: inclusive



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

$\lesssim$ 1% EW corrections

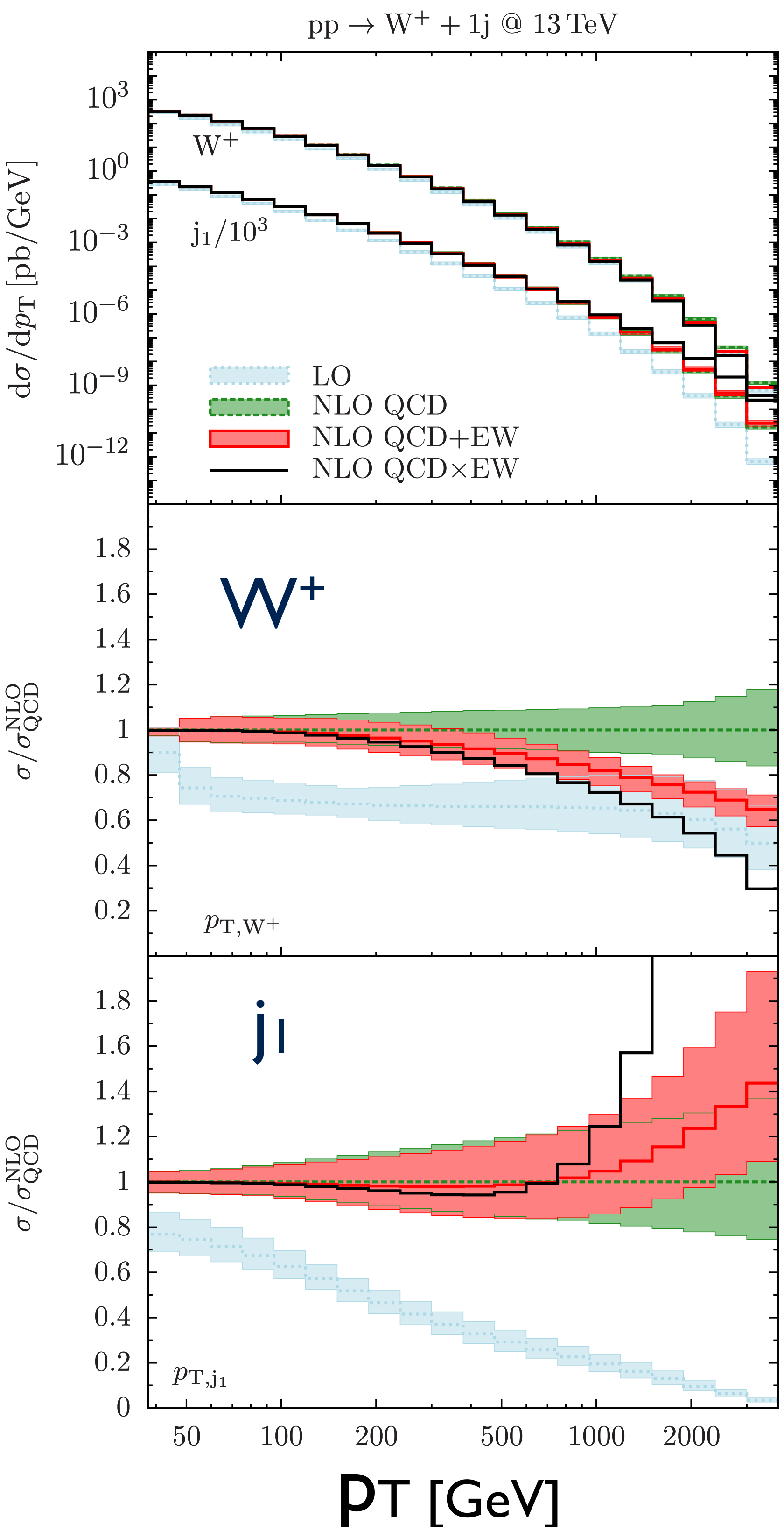
p_T of W-boson

- +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

W^+ + 1 jet: inclusive



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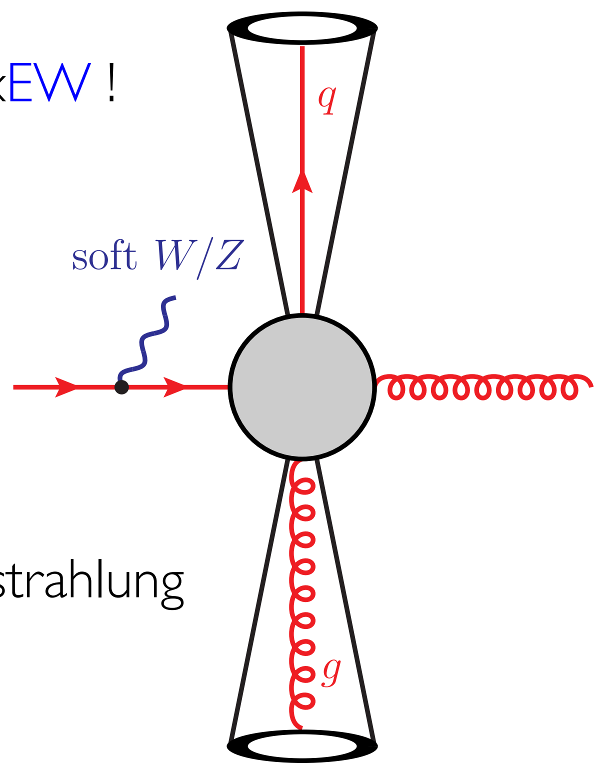
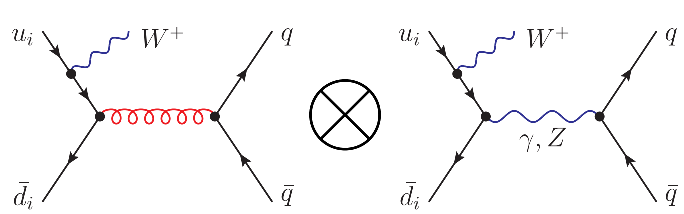


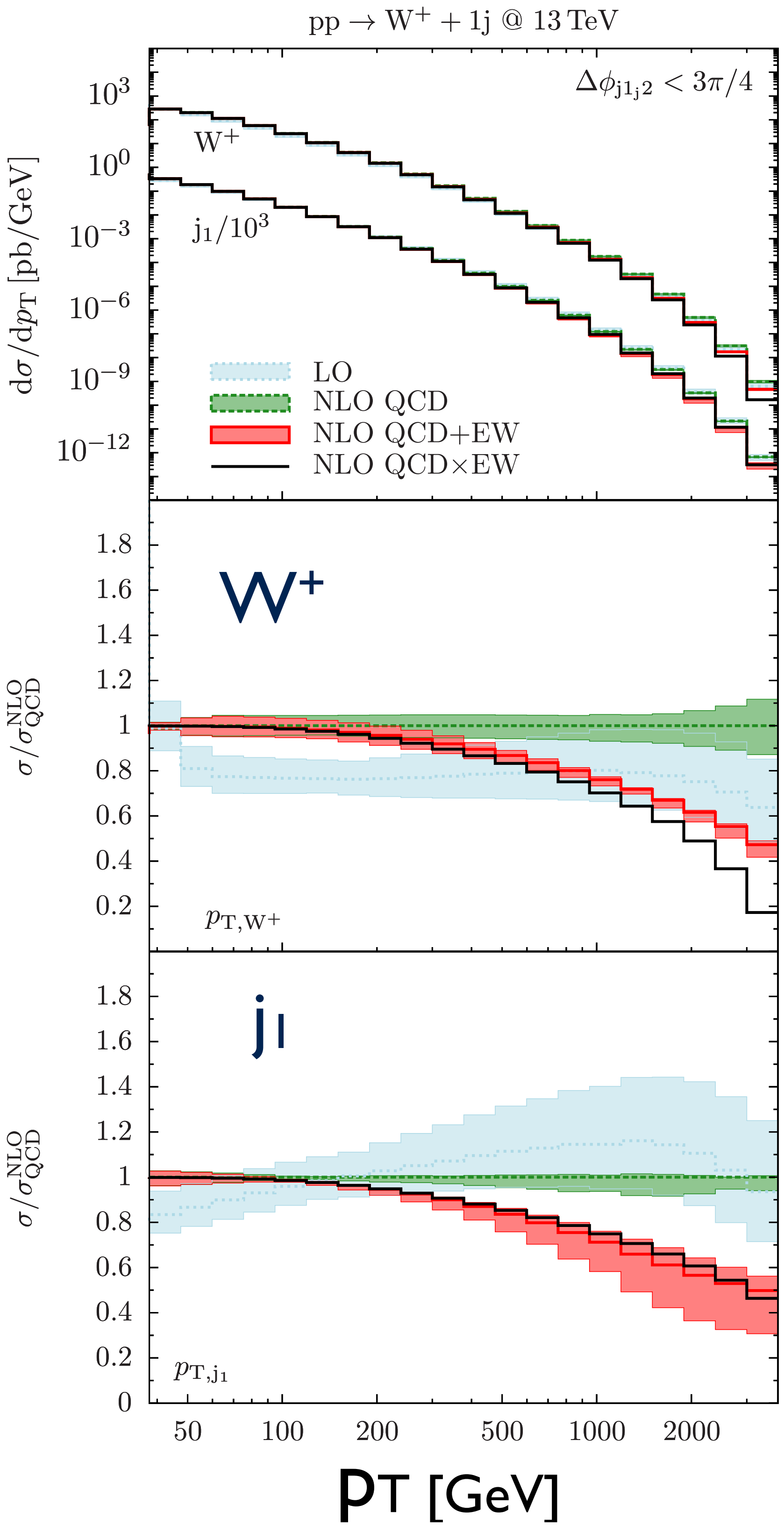


$\Longrightarrow$ pathologic with large uncertainties!

W^+ + 1 jet: exclusive

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

(veto on dijet configurations)



Setup:

$\sqrt{S} = 13$ TeV

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

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

QCD corrections

- mostly moderate and stable QCD corrections

EW corrections

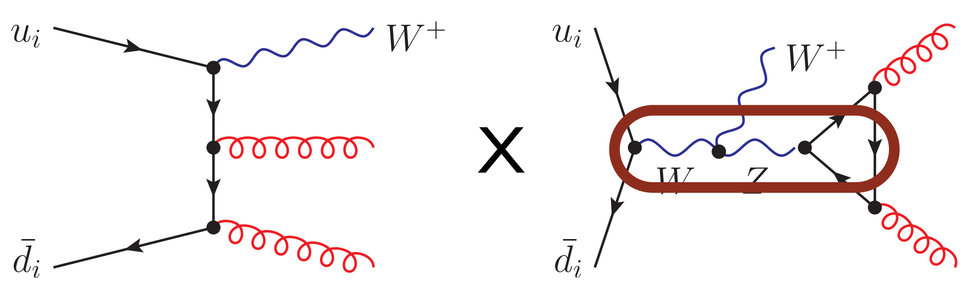
- **Sudakov behaviour** in both tails: -20–50% EW corrections at 1-4 TeV
- EW corrections larger than QCD uncertainties for $p_{\mathrm{T,W+}} > 300$ GeV

⟹ *exclusive* W+1jet ok!

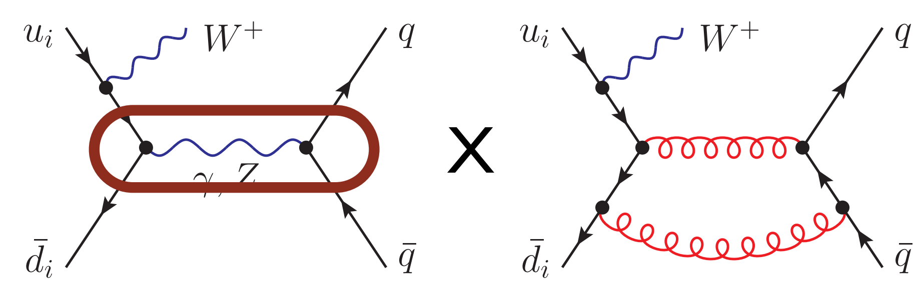
⟹ *inclusive* W+1jet requires W+2 jets at NLO QCD+EW!

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

gluonic channels



fermionic channels



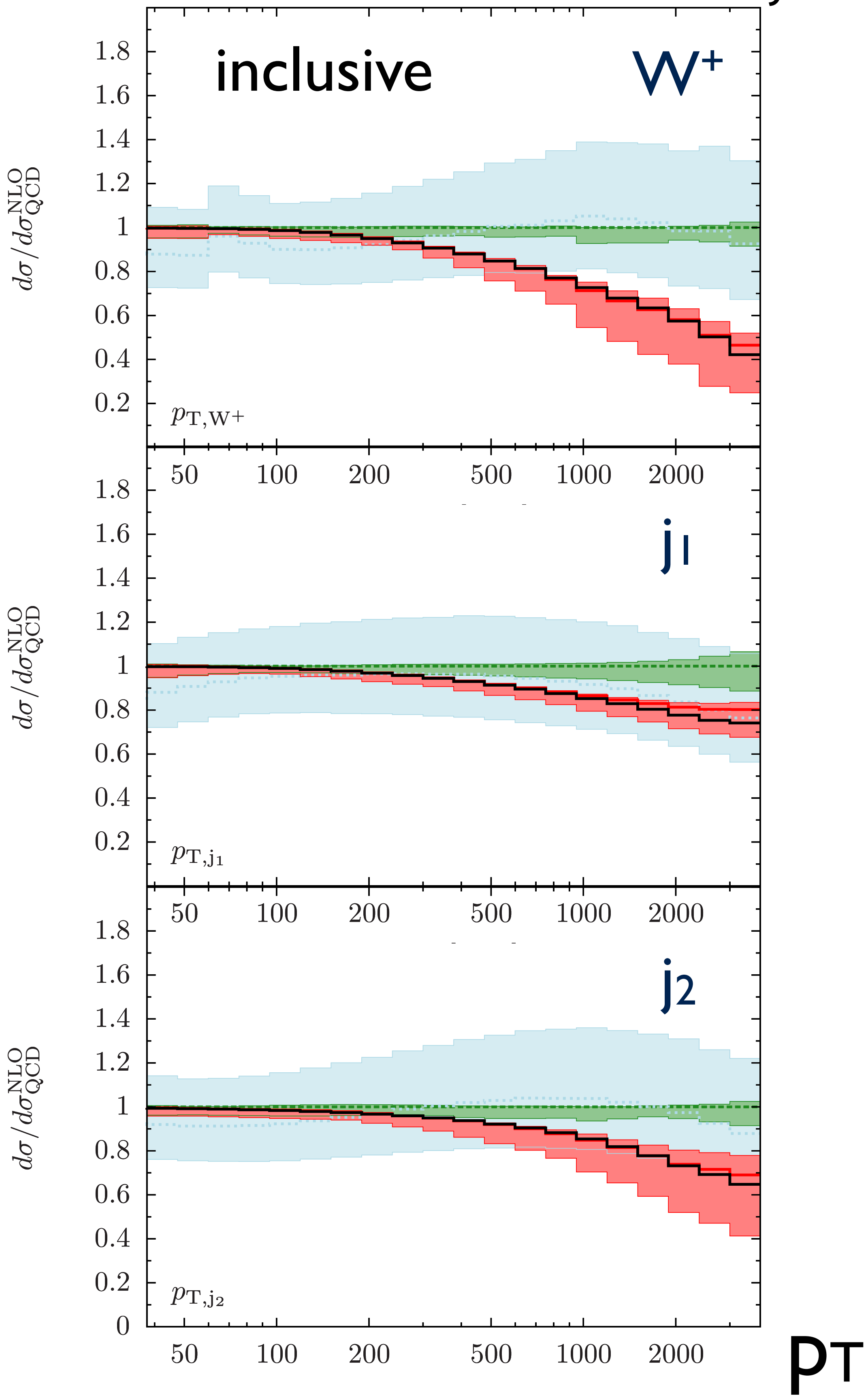
- At the considered order **only effects QCD-EW interferences**
- Complex-mass-scheme can not be used with on-shell/stable W's
- NWA: finite width $\Gamma_{\mathrm{reg.}}$ in potentially s-channel propagators for W, Z ,t ,H
- Smooth **gauge-invariant limit** and negligible numerical dependence for $\Gamma_{\mathrm{reg.}}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

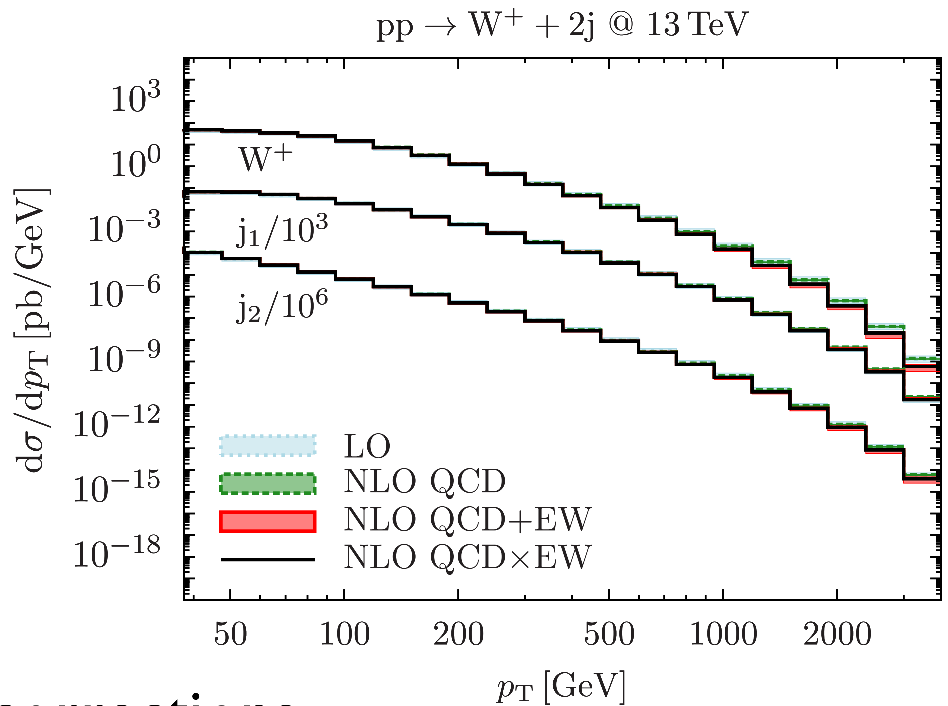
$$\Rightarrow \frac{Q^2 - M^2}{(Q^2 - M^2)^2 + \Gamma_{\mathrm{reg}}^2 M^2}$$

Goal:

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

W$^+$ + 2 jets: large EW corrections





QCD corrections

- small and very stable
- ≲ 10% scale uncertainties

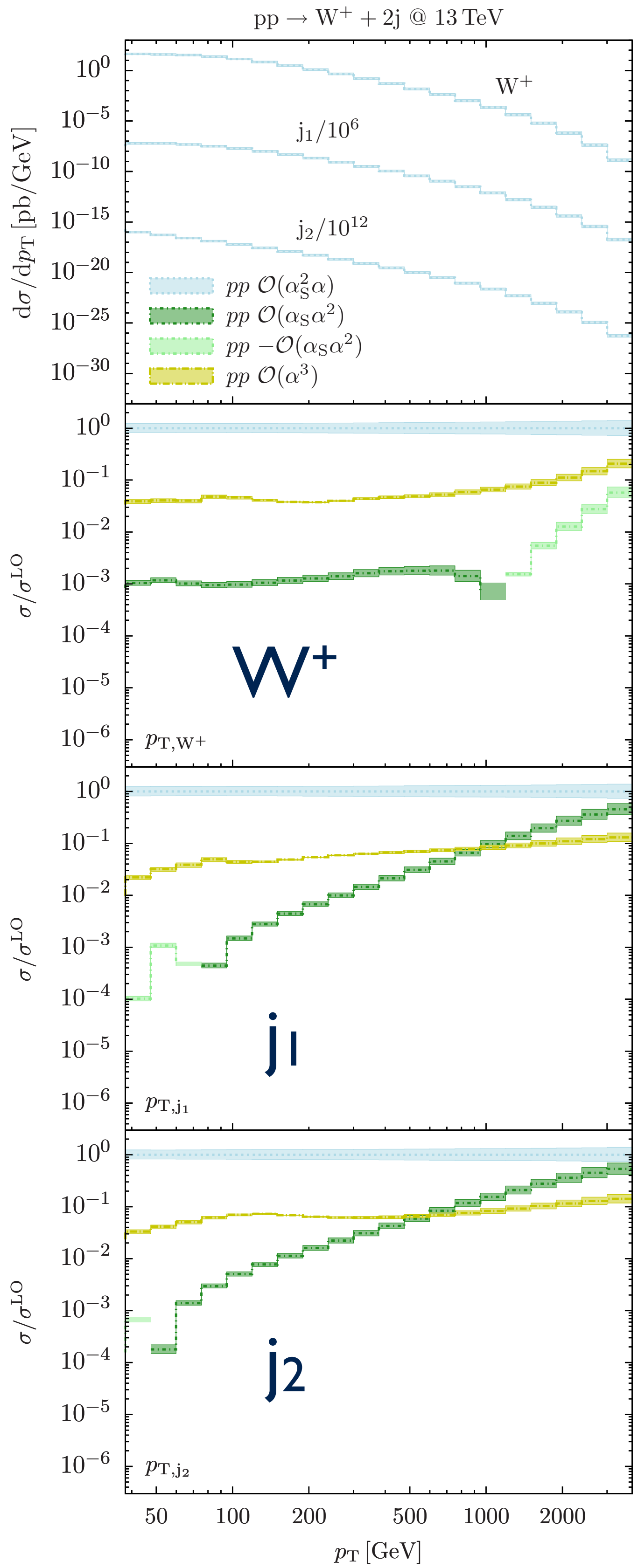
EW corrections

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



Setup:

$\sqrt{S} = 13$ TeV

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

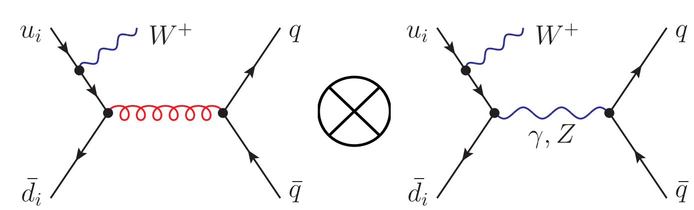
$\mu_0 = \hat{H}_T/2$ (+ 7-pt. variation)

Inclusive

- Subleading contributions highly suppressed

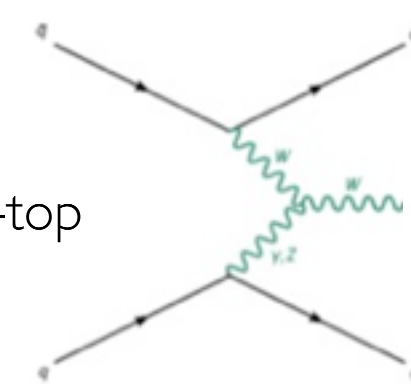
$O(\alpha_S\alpha^2)$ mixed QCD-EW contribution

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



$O(a^3)$ pure EW contribution

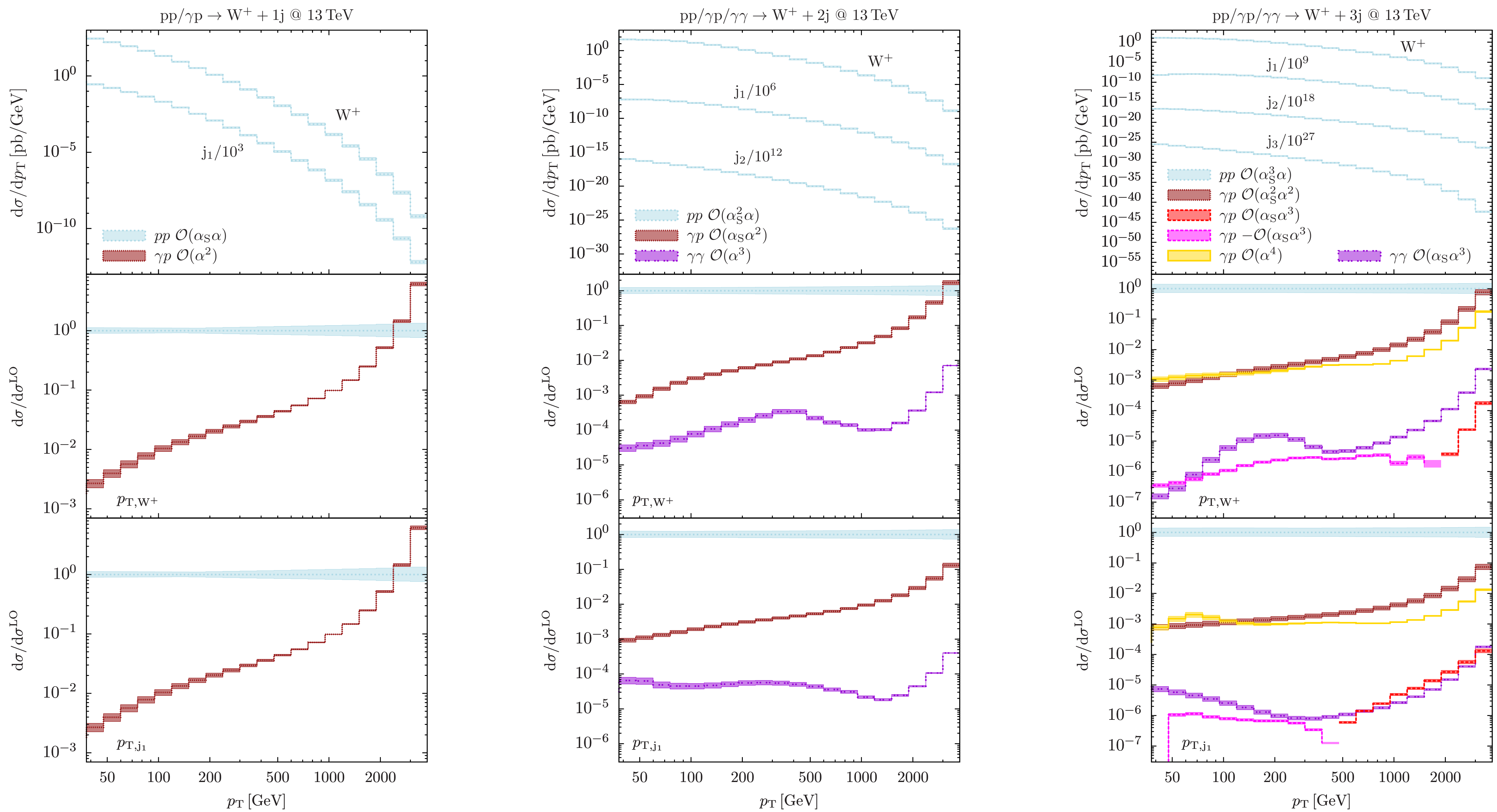
- includes contributions from WW, WZ, VBF, single-top
- 10-20% at 1-4 TeV



LO γ-induced W+1,2,3 jet production

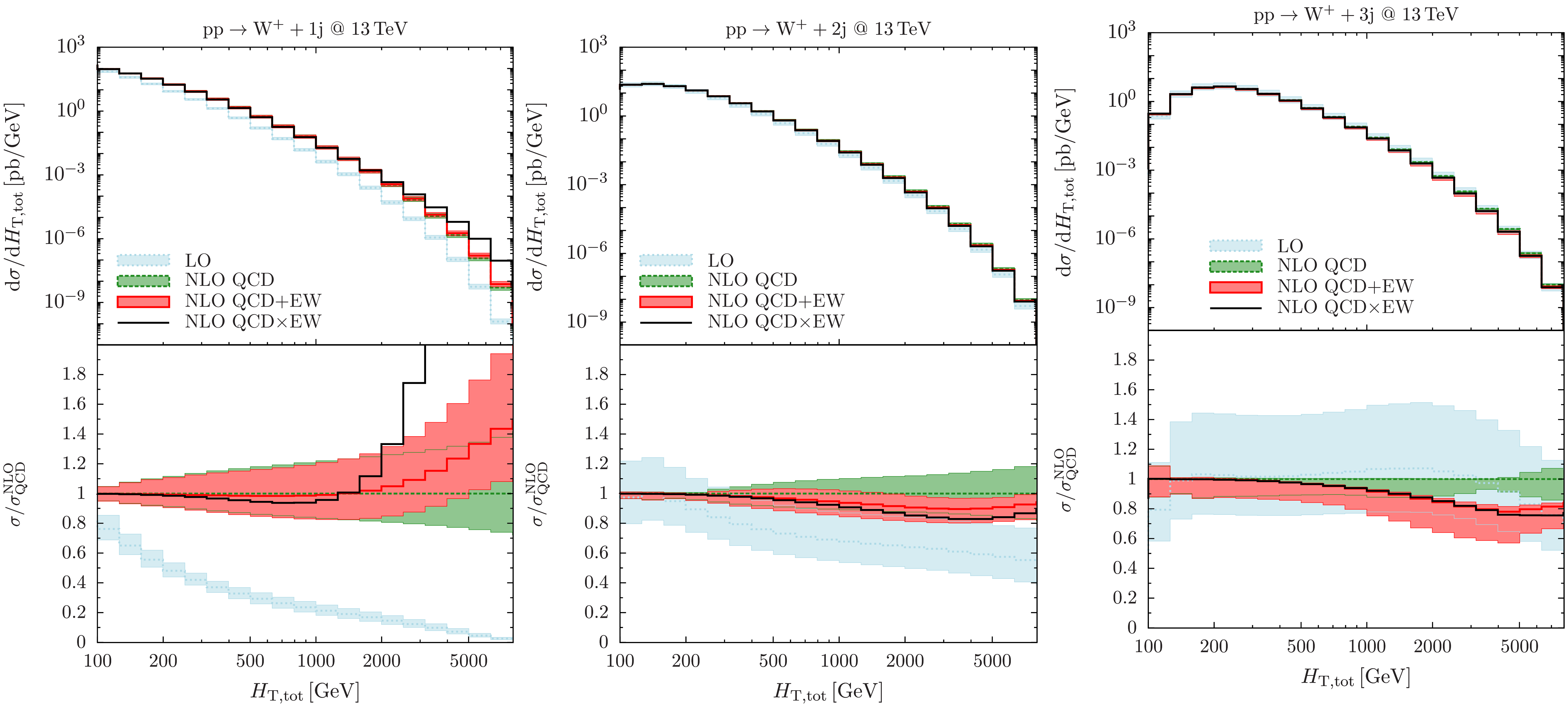
W+

j1



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

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



QCD corrections

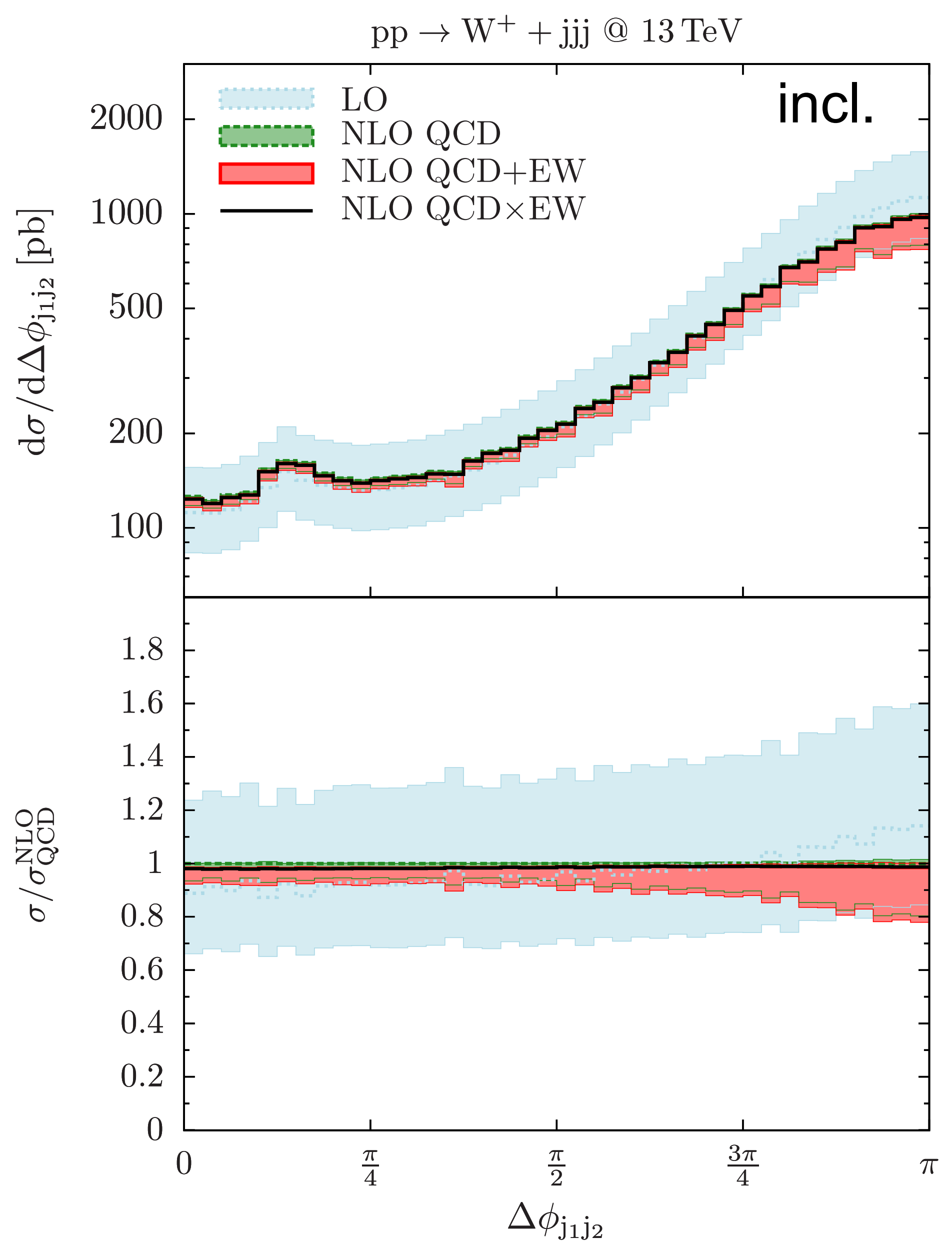
- for W+2j: large QCD corrections (80-100%)
- starting to be stable only for W+3 jets

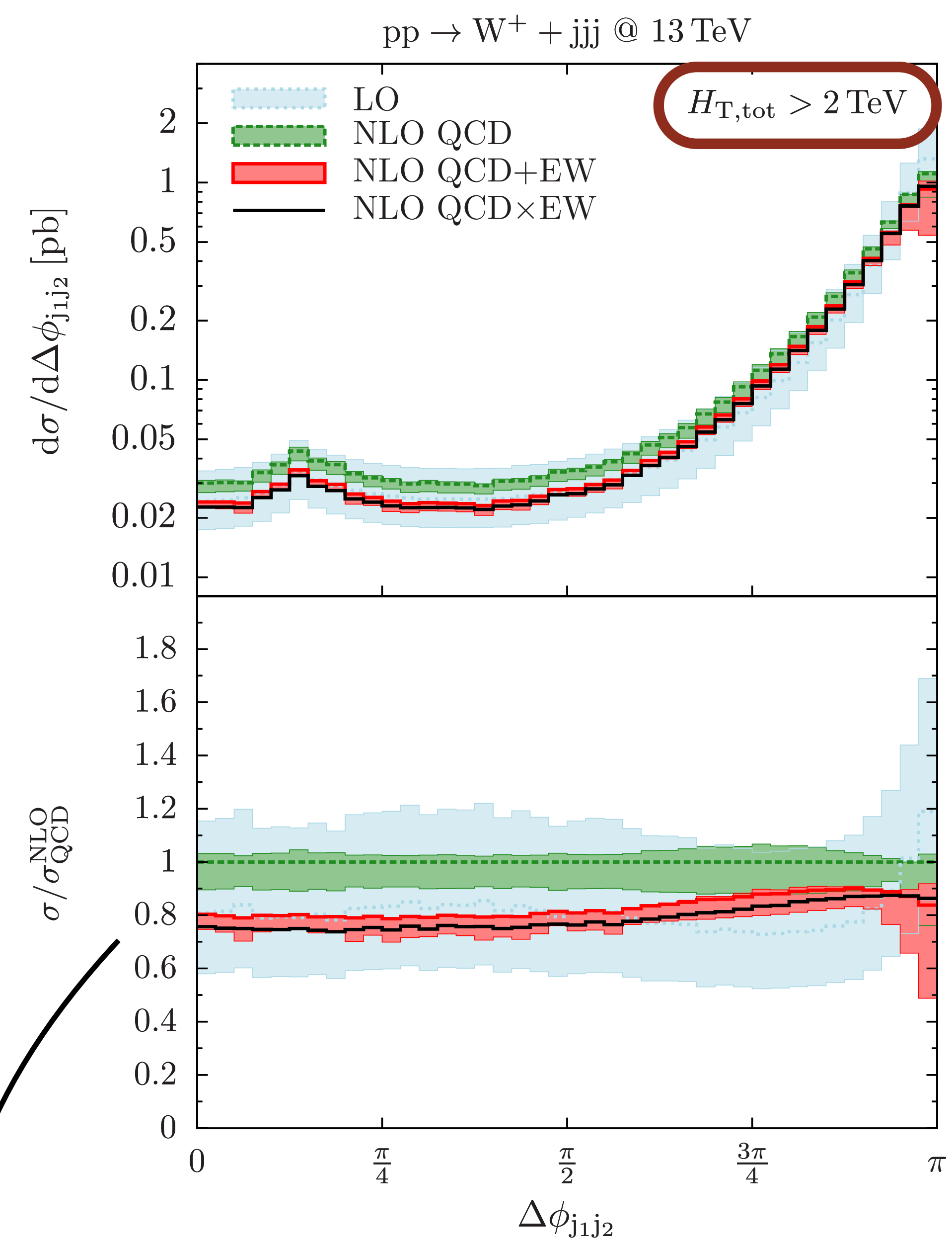
EW corrections

- moderate EW corrections: -20 % in the tail

$\Longrightarrow$ *calls for NLO QCD+EW multi-jet merging!*

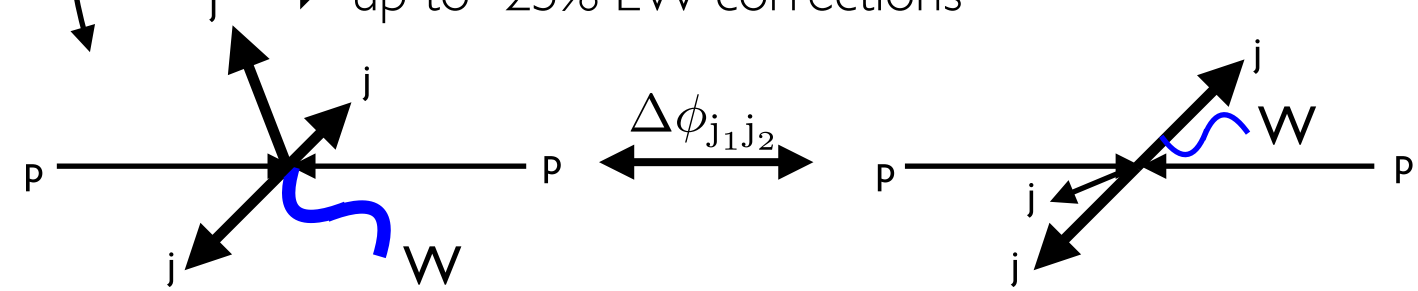
W^+ + 3 jets: topology of EW corrections



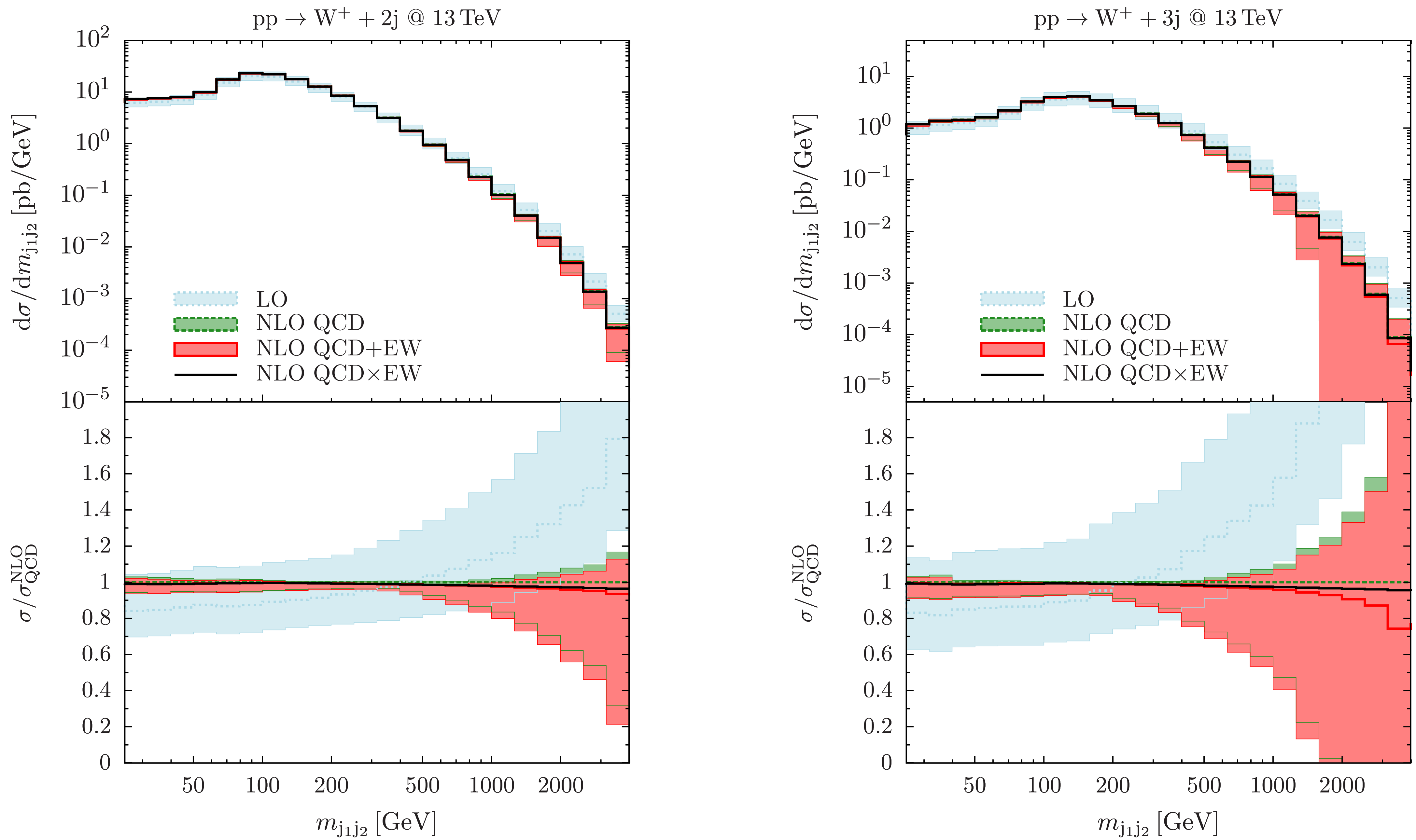


- negligible EW corrections

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



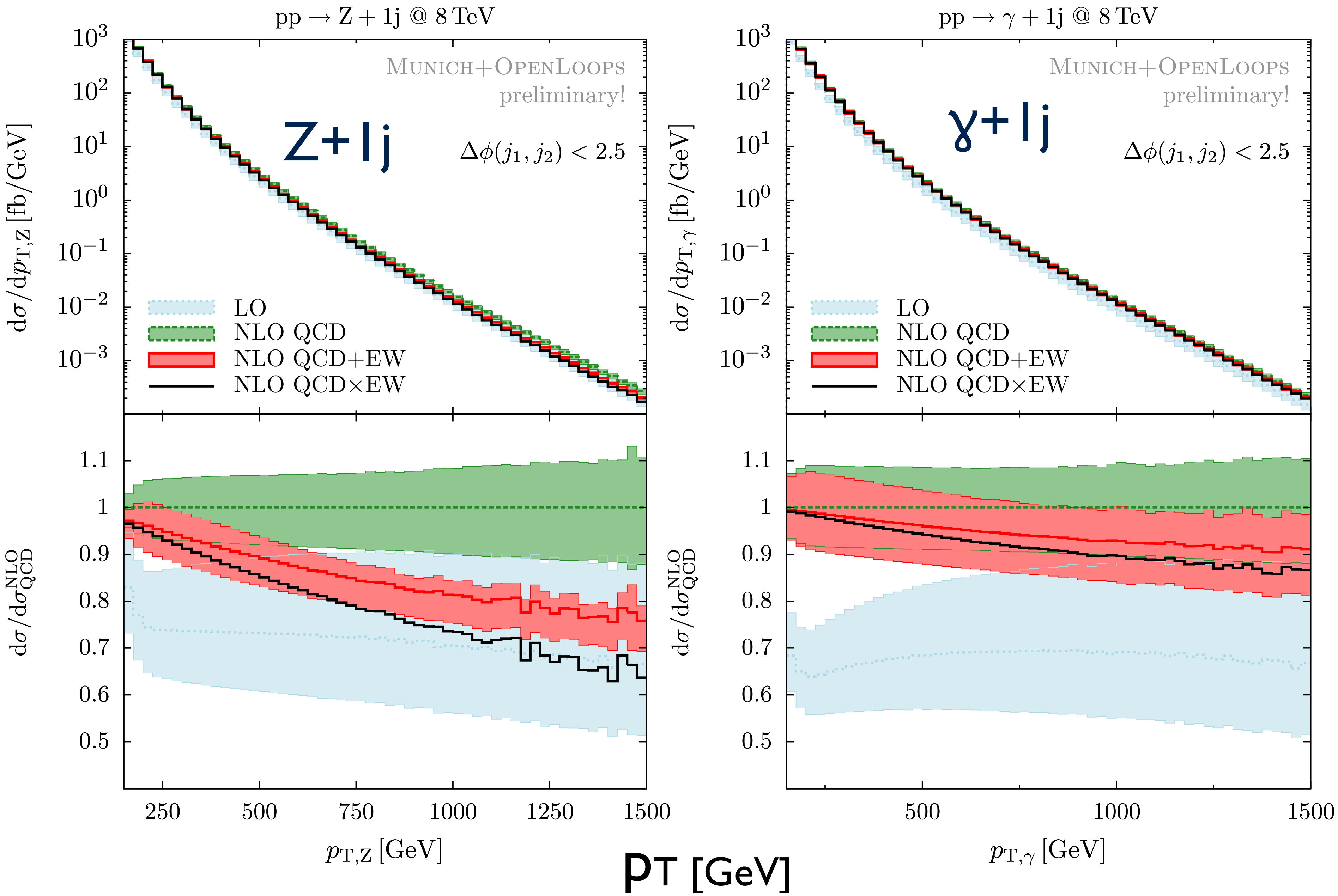
jet invariant mass in $W^+ + 2,3$ jets



m_{j1j2}

- large negative QCD corrections in the tail with huge uncertainties (⟹ resummation needed)
- negligible EW corrections

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

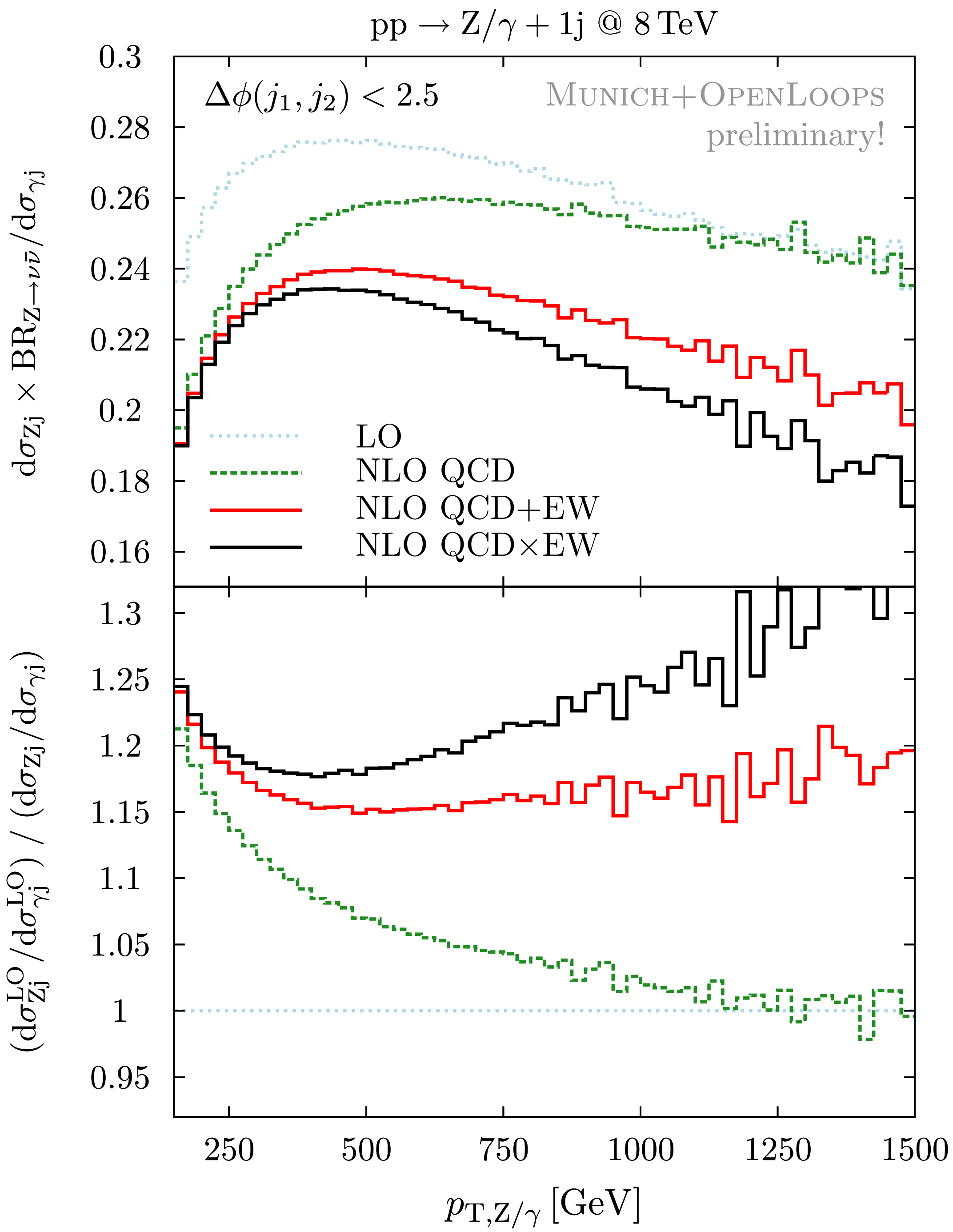
QCD corrections

- 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

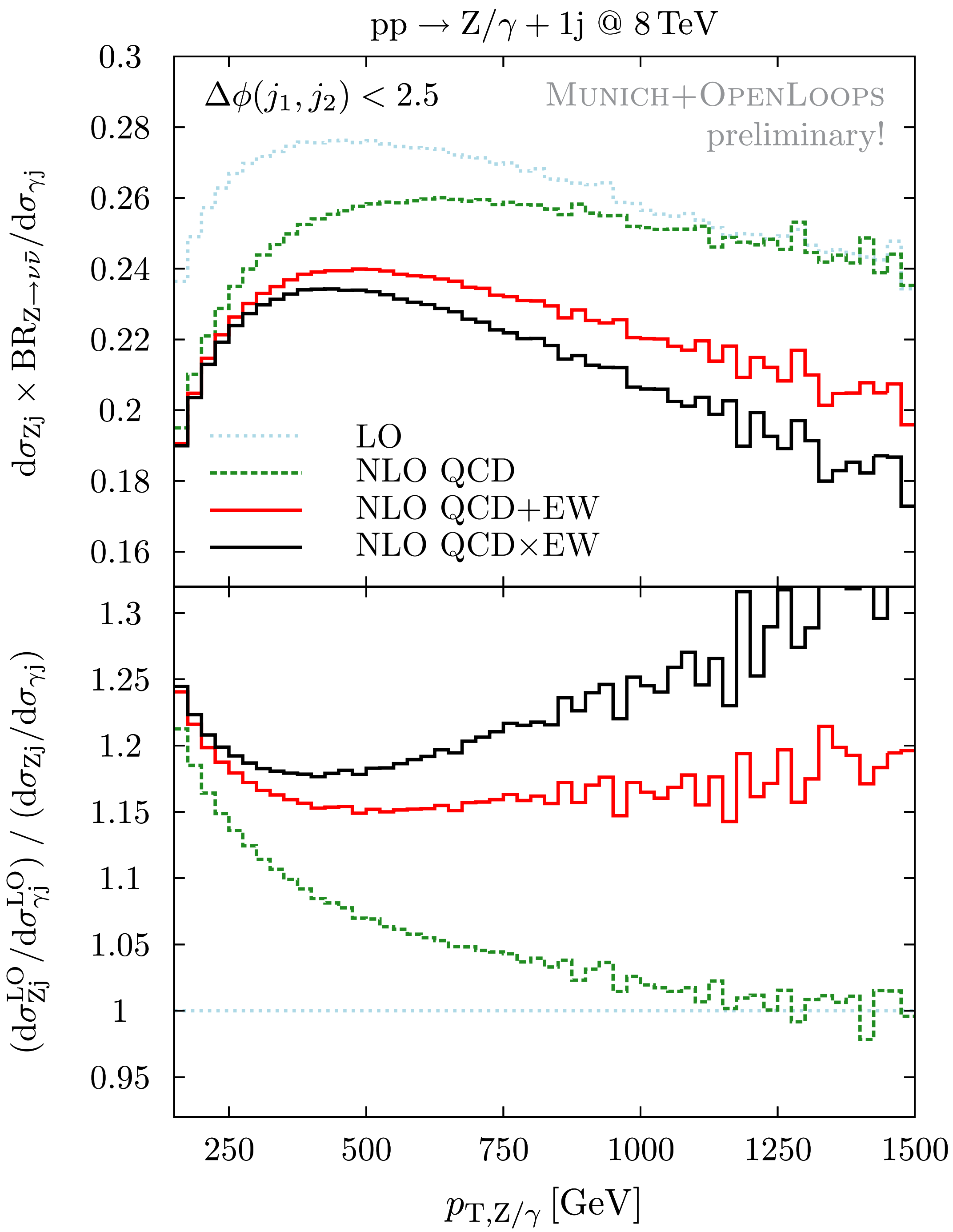
- ≲ 10% above 300 GeV

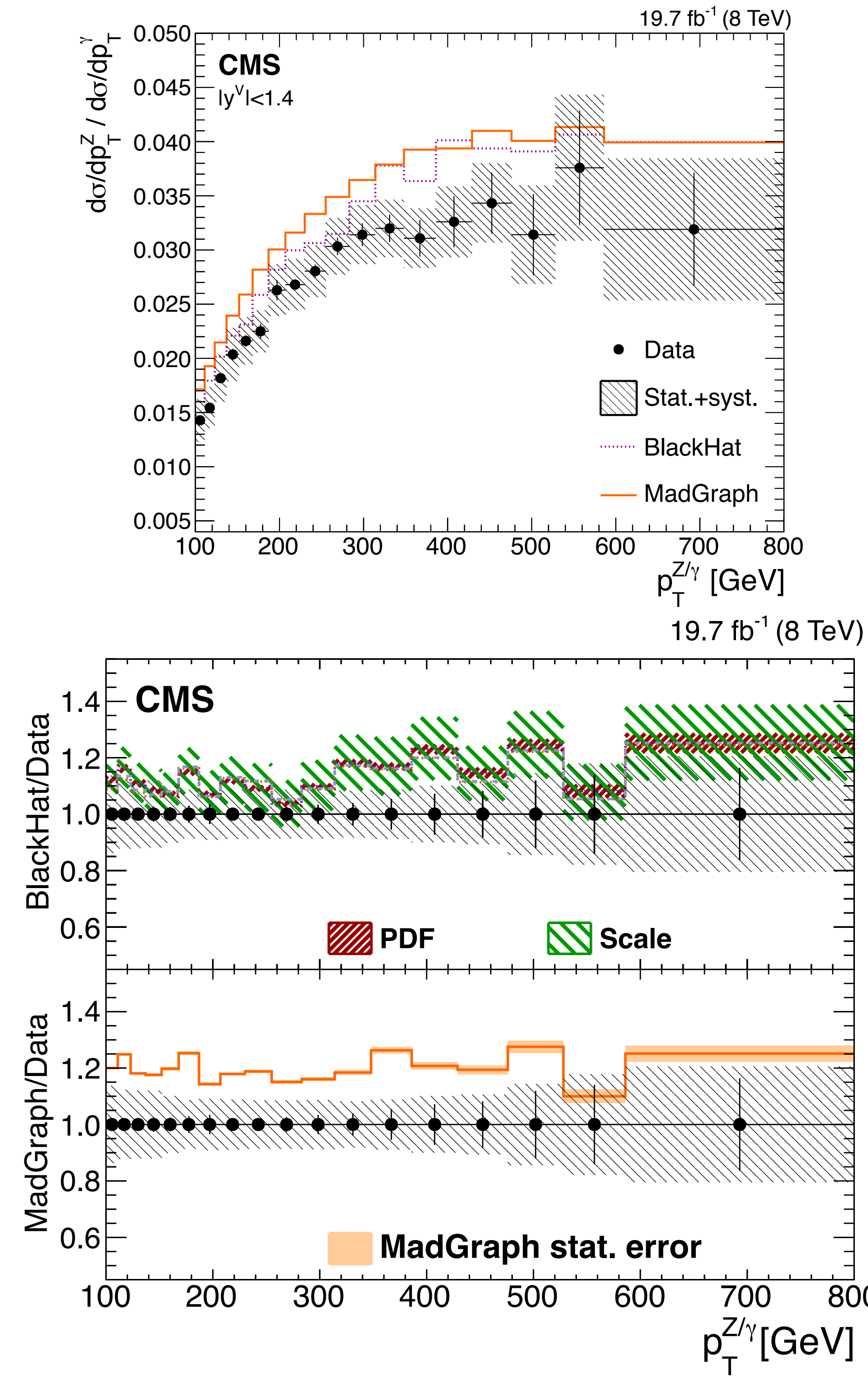
EW corrections

- 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

- Automation of NLO QCD+EW:
  - OpenLoops with NLO QCD publicly available at

    `http://openloops.hepforge.org`

  - NLO corrections in the full SM (QCD & EW) are implemented in OpenLoops together with Sherpa and MUNICH (will be included in upcoming public releases)

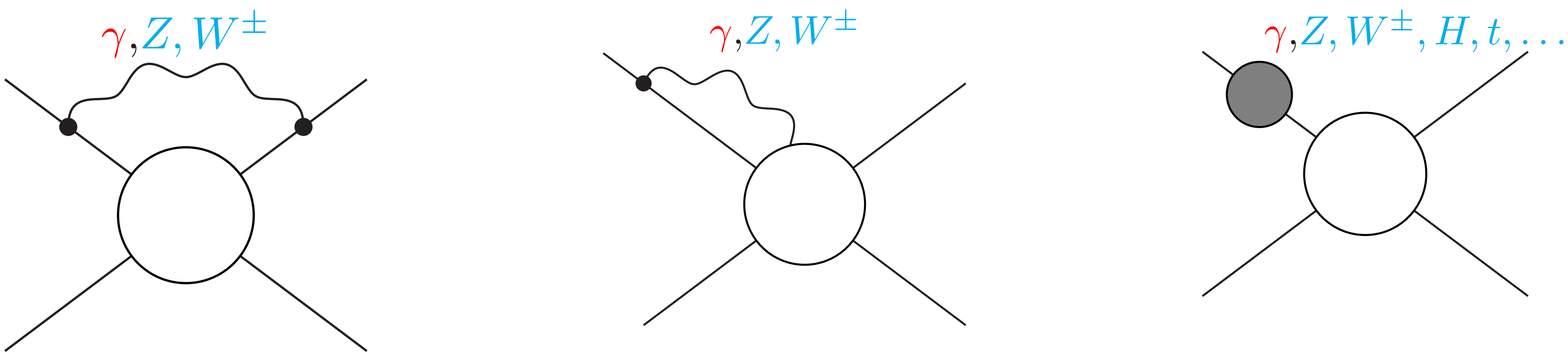
- V + multijets at QCD+EW :
  - 2 → 4 NLO EW feasible!
  - inclusion of EW corrections *crucial* at the TeV scale (up to 50%)
  - multi-jet final states genuinely different from W+1jet
  - non-trivial interplay between QCD and EW

- Outlook:
  - many more phenomenology & processes
  - PS matching & multi-jet merging

Backup slides

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]*

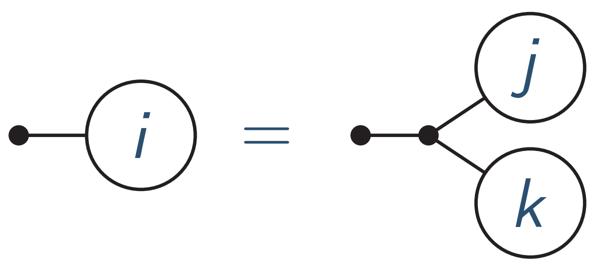
$$\delta^{1-\mathrm{loop}}_{\mathrm{LL+NLL}} = \frac{\alpha}{4\pi} \sum_{k=1}^{n} \left\{ \frac{1}{2} \sum_{l \neq k} \sum_{a=\gamma, Z, W^{\pm}} I^{a}(k) I^{\bar{a}}(l) \ln^2 \frac{s_{kl}}{M^2} + \gamma^{\mathrm{ew}}(k) \ln \frac{s}{M^2} \right\}$$

- 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

The Open Loops algorithm: From tree recursion to loop diagrams

[F. Cascioli, P. Maierhöfer, S. Pozzorini; '12]

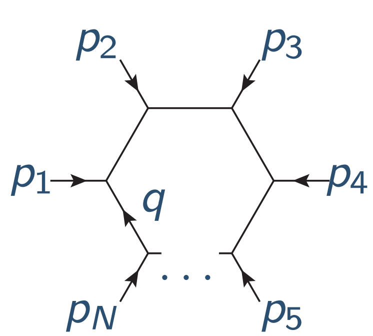
- Recursive construction of tree wave functions
  - start from wave functions w^{α} of external legs.
  - connect wave functions with vertices $X^{\beta}_{\gamma\delta}$ and propagators to recursively build "sub-trees".
  - recycle identical structures
  - wave functions of sub-trees are 4-tuples of complex numbers (for the spinor/Lorentz index).



(external lines not shown)

$$w^{\beta}(i) = \frac{X^{\beta}_{\gamma\delta}}{p_i^2 - m_i^2}\, w^{\gamma}(j)\, w^{\delta}(k)$$

- Factorize one-loop amplitude into colour factors, tensor coefficients and tensor integrals



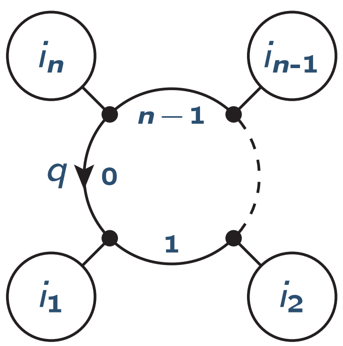
$$= \mathcal{C} \cdot \sum_{r=0}^{R} \mathcal{N}_r^{\mu_1\dots\mu_r} \cdot \int d^d q \, \frac{q_{\mu_1}\dots q_{\mu_r}}{D_0\, D_1\, \dots\, D_{N-1}}$$

$$D_i = (q + \sum_{\ell=0}^{i} p_\ell)^2 - m_i^2$$

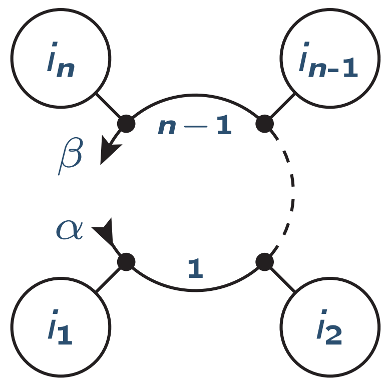
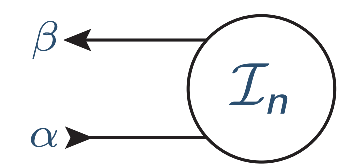
The Open Loops algorithm:
From tree recursion to loop diagrams

[F. Cascioli, P. Maierhöfer, S. Pozzorini; '12]

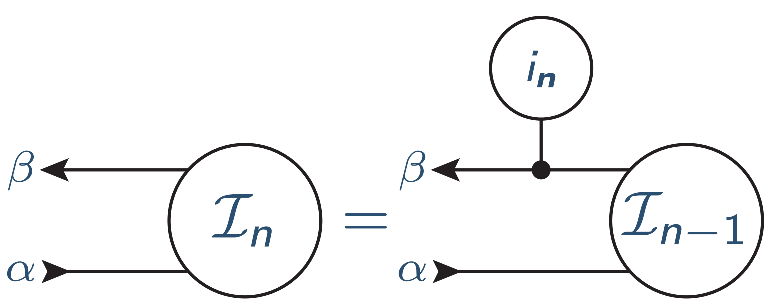
- Treat one-loop diagram as ordered set of sub-trees $\mathcal{I}_n = \{i_1, \ldots, i_n\}$ connected by propagators



cut one loop propagator

$\mathcal{N}^{\beta}_{\alpha}(\mathcal{I}_n; q) =$  $\equiv$ 

- Build numerator connecting subtrees along the loop



$$\mathcal{N}^{\beta}_{\alpha}(\mathcal{I}_n; q) = X^{\beta}_{\gamma\delta}(q)\ \mathcal{N}^{\gamma}_{\alpha}(\mathcal{I}_{n-1}; q)\ w^{\delta}(i_n)$$

The Open Loops algorithm: one-loop recursion

[F. Cascioli, P. Maierhöfer, S. Pozzorini; '12]

- Recursively build "open loops" polynomials $\mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}$
  - disentangle loop momentum q from the coefficients

$$\mathcal{N}^{\beta}_{\alpha}(\mathcal{I}_n;q) = \sum_{r=0}^{n} \mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_n)\, q^{\mu_1}\ldots q^{\mu_r} \qquad X^{\beta}_{\gamma\delta} = Y^{\beta}_{\gamma\delta} + q^{\nu} Z^{\beta}_{\nu;\gamma\delta}$$

  - recursion in d=4

$$\boxed{\mathcal{N}^{\beta}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_n) = \left[Y^{\beta}_{\gamma\delta}\,\mathcal{N}^{\gamma}_{\mu_1\ldots\mu_r;\alpha}(\mathcal{I}_{n-1}) + Z^{\beta}_{\mu_1;\gamma\delta}\,\mathcal{N}^{\gamma}_{\mu_2\ldots\mu_r;\alpha}(\mathcal{I}_{n-1})\right] w^{\delta}(i_n)}$$

  - model and process independent algorithm
  - numerical implementation requires only universal building blocks, derived from the Feynma rules of the theory (full SM implemented; also HEFT; more BSM/EFT to come)

- **ε**-dimensional part of the numerator x poles of the tensor integrals yield R_2 rational terms

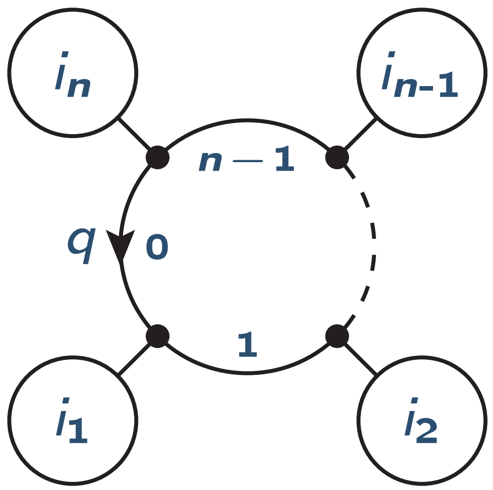
$$R_2 = ([\mathcal{N}]_{d=4-2\epsilon} - [\mathcal{N}]_{d=4}) \cdot [TI]_{UV}$$

  - numerical recursion in D=4 ➞ restore R_2 via process independent counter terms

[Draggiotis, Garzelli, Malamos, Papadopoulos, Pittau '09, '10; Shao, Zhang, Chao '11]

The Open Loops algorithm: one loop amplitudes

[F. Cascioli, P. Maierhöfer, S. Pozzorini; '12]

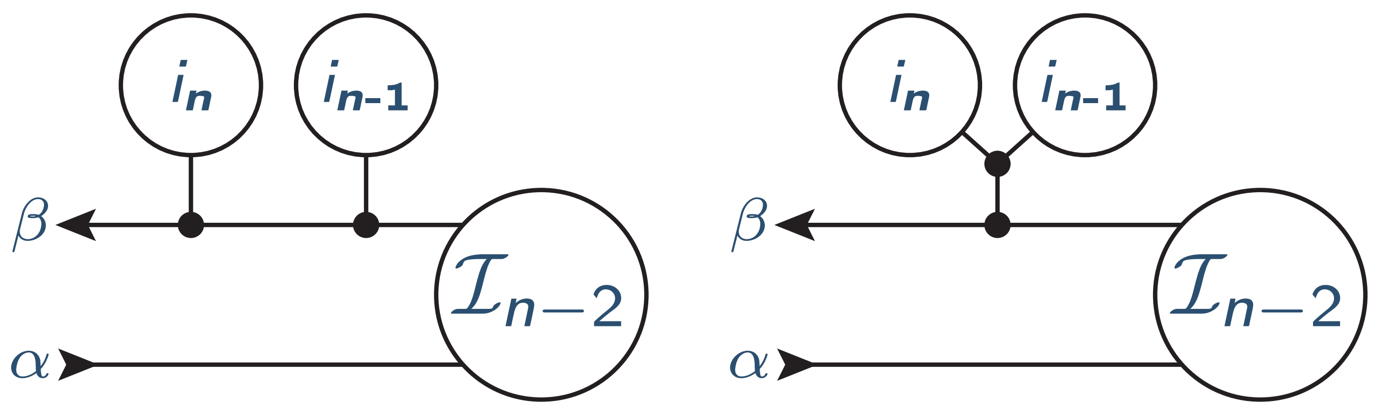


$$= \int \frac{d^D \mathcal{N}(q)}{D_0 D_1 \ldots D_{n-1}} = \sum_{r=0}^{R} \mathcal{N}_{\mu_1 \ldots \mu_r} \underbrace{\int \frac{q^{\mu_1} \ldots q^{\mu_r}}{D_0 D_1 \ldots D_{n-1}}}_{\text{tensor integral}}$$

- Tensorial coefficients $\mathcal{N}^{\alpha}_{\mu_1 \ldots \mu_r;\alpha}$ can directly be used with tensor integral libraries avoiding numerical instabilities (Gram-determinant expansion) [Denner, Dittmaier; '05]
- Fast evaluation of $\mathcal{N}(q) = \sum \mathcal{N}_{\mu_1 \ldots \mu_r} q^{\mu_1} \ldots q^{\mu_r}$ at multiple q-values, required in OPP reduction methods *[Ossola, Papadopolous, Pittau; '07]*

The Open Loops algorithm: recycle loop structures

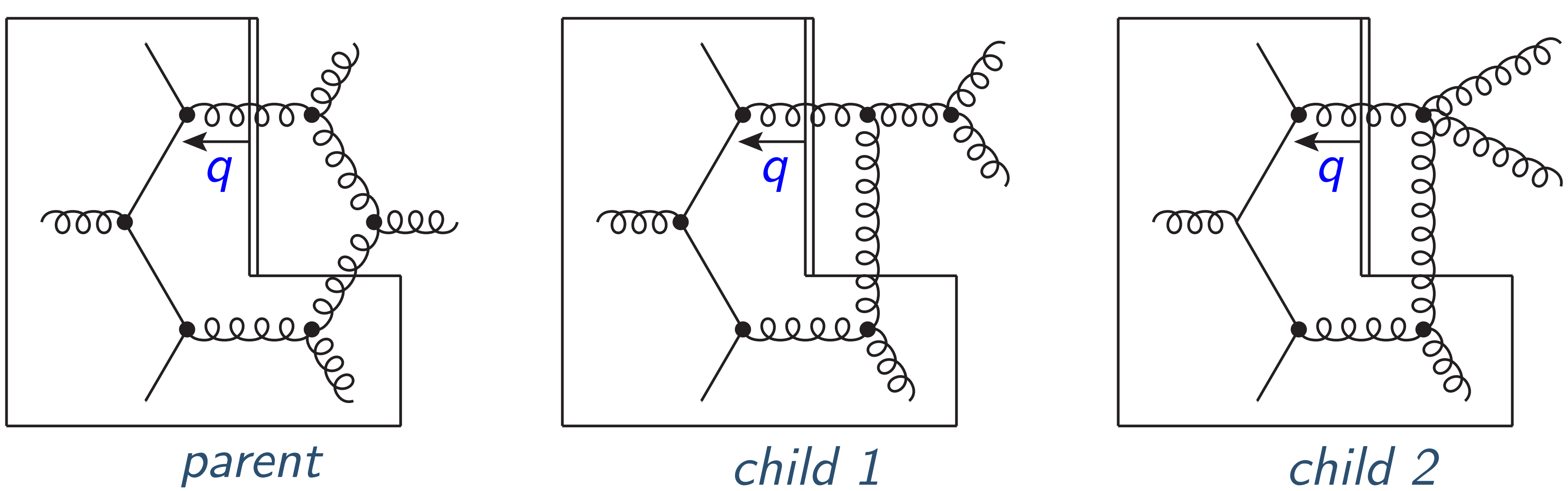
OpenLoops recycling:



Lower-point open-loops can be shared between diagram if

- cut is put appropriately
- direction chosen to maximise recyclability

Illustration:



Complicated diagrams require only "last missing piece"

Recent applications of OpenLoops

- Include challenging NLO QCD, S-MC@NLO, MEPS@NLO, NNLO QCD and NLO QCD+EW calculations

NLO QCD for pp → $W^+W^-b\bar{b}$ with $m_b > 0$, *[arXiv:1312.0546]*

S–MC@NLO for pp → $t\bar{t}b\bar{b}$ with mb > 0, *[arXiv:1309.5912]*

MEPS@NLO for llvv+0,1 jets, *[arXiv:1309.0500]*

NLO merging for pp → HH+0,1 jets, *[arXiv:1401.0007]*

MEPS@NLO for $t\bar{t}$ + 0,1,2 jets, *[arXiv:1402.6293]*

MEPS@NLO for WWW+0,1 jets, *[arXiv:1403.7516]*

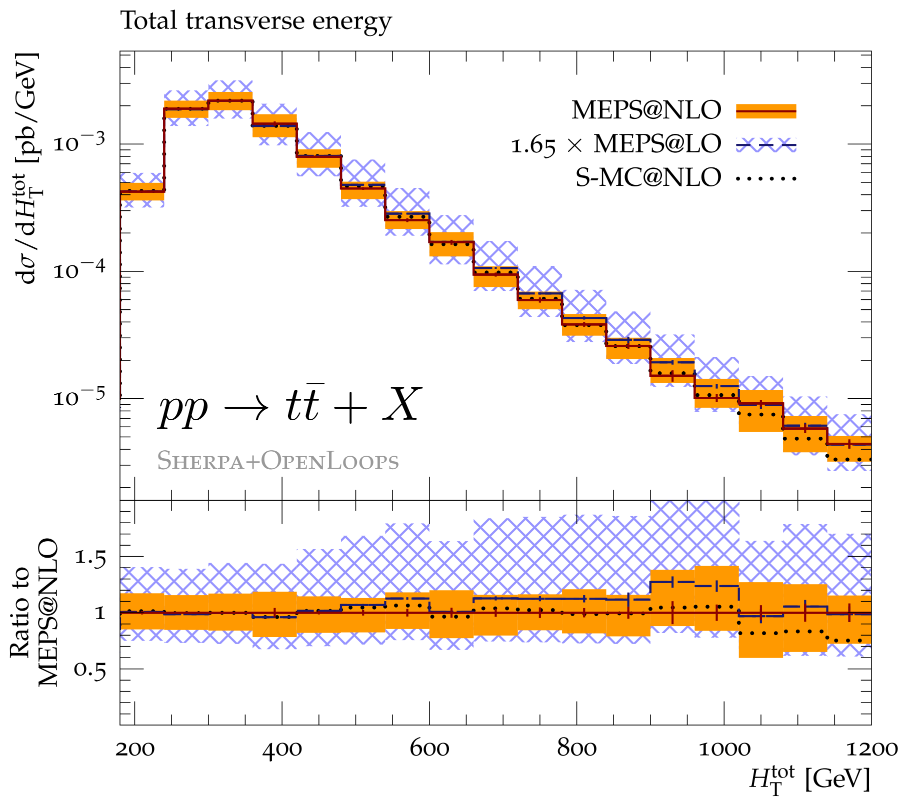
NNLO for pp → γZ, *[arXiv:1309.7000]*

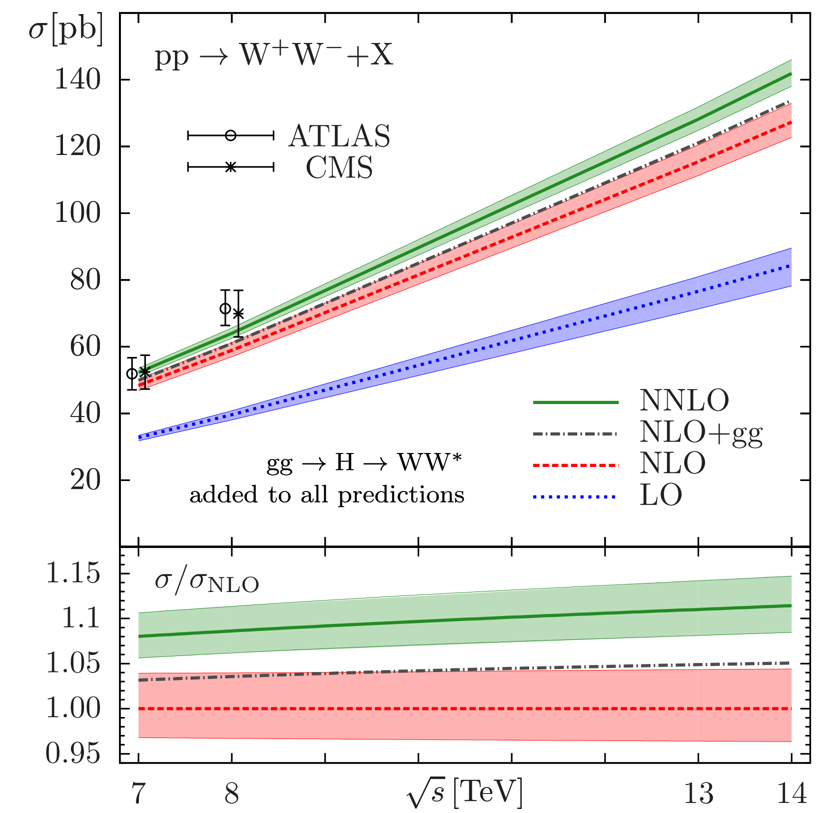
NNLO for $q\bar{q}$ → $t\bar{t}$, *[arXiv:1404.6493]*

NNLO for pp → ZZ, *[arXiv:1405.2219]*

NNLO for pp → W^+W^-, *[arXiv:1408.524]*

NLO QCD+EW for pp → W^++1,2,3 jet, *[arXiv:1412.5157]*





The Open Loops program: performance

process	diags	size/MB	time/ms
$u\bar{u} \to t\bar{t}$	11	0.1	0.27(0.16)
$u\bar{u} \to W^+W^-$	12	0.1	0.14
$u\bar{d} \to W^+g$	11	0.1	0.24
$u\bar{u} \to Zg$	34		0.75
$gg \to t\bar{t}$	44	0.2	1.6(0.7)
$u\bar{u} \to t\bar{t}g$	114	0.4	4.8(2.4)
$u\bar{u} \to W^+W^-g$	198	0.4	3.4
$u\bar{d} \to W^+gg$	144	0.5	4.0
$u\bar{u} \to Zgg$	408		17
$gg \to t\bar{t}g$	585	1.2	40(14)
$u\bar{u} \to t\bar{t}gg$	1507	3.6	134(101)
$u\bar{u} \to W^+W^-gg$	2129	2.5	89
$u\bar{d} \to W^+ggg$	1935	4.2	120
$u\bar{u} \to Zggg$	5274		524
$gg \to t\bar{t}gg$	8739	16	1460(530)

Timings on i7-3770K with gfortran 4.8 –O0 dynamic (ifort static ~30% faster)

- timings for complete one-loop amplitude
- colour and helicity summed
- using COLLIER for reduction
- CutTools similarly fast for 2 ➞ 4
- W/Z production includes leptonic decays of gauge bosons and non-resonant contributions
- numbers for $t\bar{t}$ production for massless decays in brackets
- runtime can be significantly increased when quad-precision rescue is used

NLO EW Virtuals with OpenLoops

- Universal power counting in α and α_s including different interference contributions. 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" $\equiv \alpha_s^n \alpha^{m+1}$
- Fast numerical routines for all tree+loop vertices in the full SU(3)xSU(2)xU(1) SM
- On-shell NLO EW renormalization along the lines of [Denner,'92]
- Renormalization of α in on-shell or G_μ-scheme
- Complex-mass-scheme fully implemented [Denner, Dittmaier, Roth, '04]
- Fixed-width-scheme for on-shell massive particles
- NLO EW R_2 contributions via process independent counterterms (for all possible one-particle irreducible Green functions of the SM with up to four external legs) [Garzelli, Malamos, Pittau '10; Shao, Zhang, Chao, '11]

- All ingredients carefully validated against independent automated in-house tool based on algebraic techniques in D=4-2ε [Pozzorini]

Sherpa & MUNICH

- NLO EW subtraction based on the well established NLO QCD dipole subtraction [Catani, Seymour, '96] frameworks in Sherpa & MUNICH with replacements for QCD → QED
- Independent implementation in the two MC programs allows for powerful cross checks

- Sherpa [Gleisberg, Höche, Krauss, Schönherr, Schumann, Siegert, Winter et. al.]
  - ✦ widely used shower Monte-Carlo
  - ✦ used for pioneering $W + \leq 5$ jets NLO QCD calculations (in conjunction with BlackHat)
  - ✦ Advanced multi-jet merging available: MEPS@NLO

- MUNICH: MUlti-chaNnel Integrator at swiss (CH) precision [Kallweit, in preparation]
  - ✦ fast and flexible fixed-order multi-channel Monte-Carlo
  - ✦ used for example in $pp \to W^+W^-bb$ @ NLO QCD, $pp \to W^+W^-$ @ NNLO QCD

Bremsstrahlung and subtraction with Sherpa & MUNICH

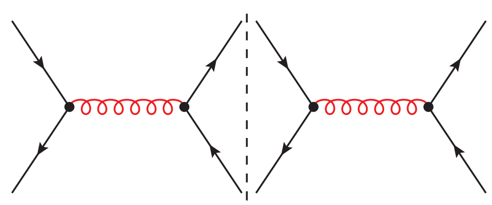
- Replacement QCD → QED

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

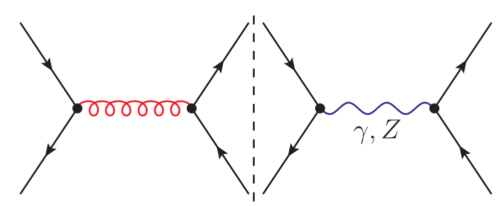
$$\frac{\mathbf{T}_{ij} \cdot \mathbf{T}_k}{\mathbf{T}_{ij}^2} \longrightarrow \begin{cases} \frac{Q_{ij} Q_k}{Q_{ij}^2} & \text{if the emitter } ij \text{ is a (anti)fermion} \\ \kappa_{ij,k} & \text{if the emitter } ij \text{ is a photon}, \end{cases}$$

- For external on-shell $W^\pm$ we use heavy fermion splitting functions *[Catani, Dittmaier, Seymour, Trocsanyi '02]*
- Mixed QCD-QED I-operator requires a non-trivial interplay between different Born orders

$$I \propto \sum \int_1 V_{\text{QED}} \otimes$$



$$+ \int_1 V_{\text{QCD}} \otimes$$



- Independent implementation in the two MC programs allows for powerful cross checks

References: W + multijet production

NLO QCD:

- W(→ ln) + 1 jet *[Arnold, Reno, '89; Arnold, Ellis, Reno, '89]*
- W(→ ln) + 2 jets *[Campbell, Ellis, '02; Febres Cordero, Reina, Wackeroth, '06; Campbell, Ellis, Febres Cordero, Maltoni, Reina, '09]*
- W(→ ln) + 3 jets *[Ellis, Melnikov, Zanderighi, '09]*
- W(→ ln) + 3,4,5 jets *[Blackhat Collaboration, '09, '11, '13]*

NNLO QCD:

- W+ 1 jet *[Boughezal, Focke, Liu, Petriello '15]*

NLO EW:

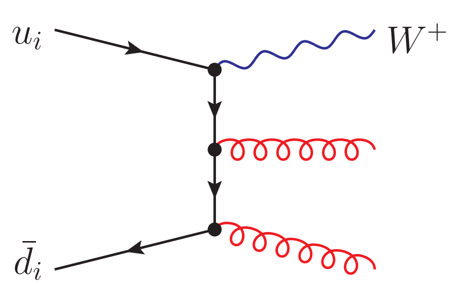
- W + 1 jet *[Kühn, Kulesza, Pozzorini, Schulze, '07; Hollik, Kasprzik, Kniehl, '07; Kühn, Kulesza, Pozzorini, Schulze, '09]* **[this talk]**
- W(→ln) + 1 jet *[Denner, Dittmaier, Kasprzik, Mück, '09]*
- W + 2,3 jets ***[this talk!]***

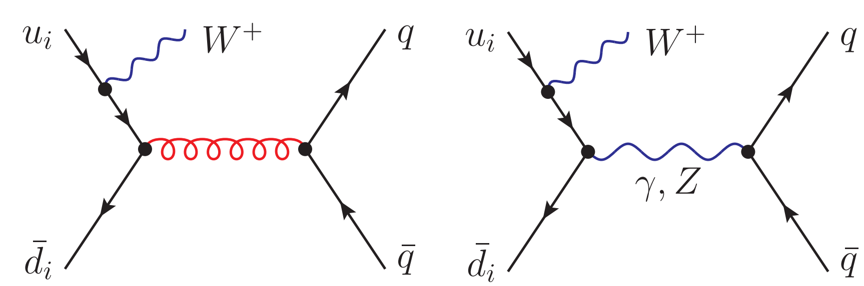
Contributing orders to W+n-jet production

	$pp \to W + n$ jets @LO				$pp \to W + n$ jets @NLO				
	$\alpha_s^n \alpha$	$\alpha_s^{n-1}\alpha^2$	$\alpha_s^{n-2}\alpha^3$	$\alpha_s^{n-3}\alpha^4$	$\alpha_s^{n+1}\alpha$	$\alpha_s^n\alpha^2$	$\alpha_s^{n-1}\alpha^3$	$\alpha_s^{n-2}\alpha^4$	$\alpha_s^{n-3}\alpha^5$
$u_i\bar{d}_i \to W + ng$	×	-	-	-	×	×	-	-	-
$u_i\bar{d}_i \to W + q\bar{q} + (n-2)g$	×	×	×	-	×	×	(×)	(×)	-
$\gamma u_i \to d_i W + (n-1)g$	-	×	-	-	-	-	-	-	-
$\gamma u_i \to d_i W + q\bar{q} + (n-3)g$	-	×	×	×	-	-	-	-	-
$\gamma\gamma \to \bar{u}_i d_i W + (n-2)g$	-	-	×	-	-	-	-	-	-
$u_i\bar{d}_i \to W + (n+1)g$	-	-	-	-	×	-	-	-	-
$u_i\bar{d}_i \to W + q\bar{q} + (n-1)g$	-	-	-	-	×	×	(×)	-	-
$u_i\bar{d}_i \to W + q\bar{q}q'\bar{q}' + (n-3)g$	-	-	-	-	×	×	(×)	(×)	(×)
$u_i\bar{d}_i \to W + ng + \gamma$	-	-	-	-	-	×	-	-	-
$u_i\bar{d}_i \to W + q\bar{q} + (n-2)g + \gamma$	-	-	-	-	-	×	(×)	(×)	(×)

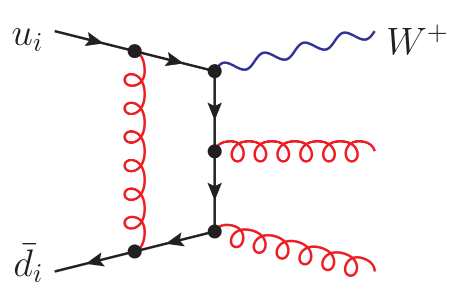
× (×) = (not) included in 1412.5156

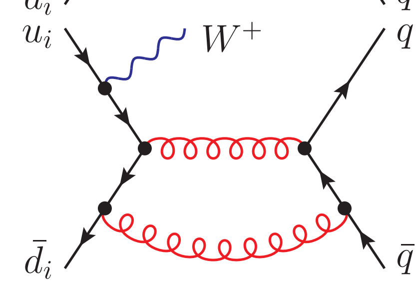
gluonic channels



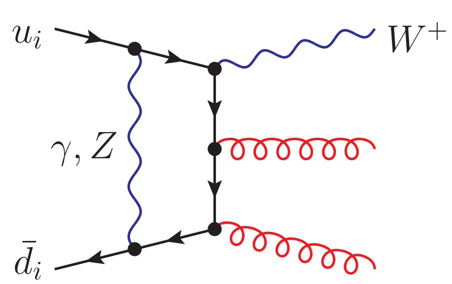


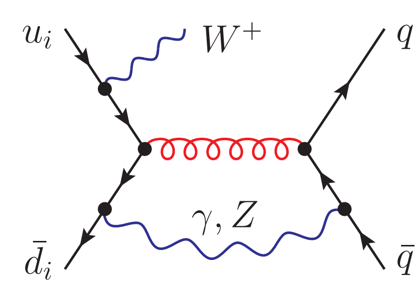
QCD dressing





EW dressing

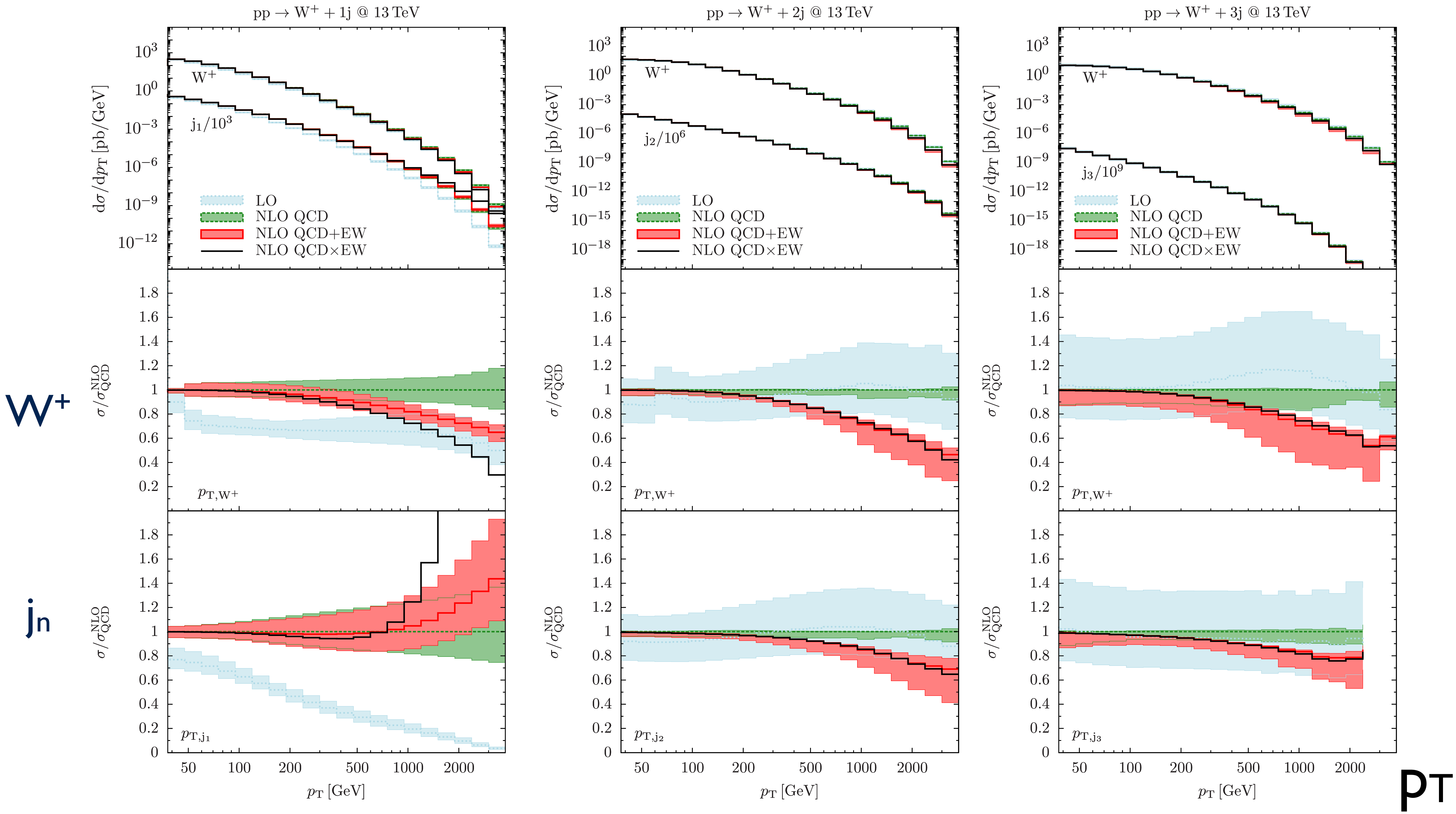




Setup and Observables

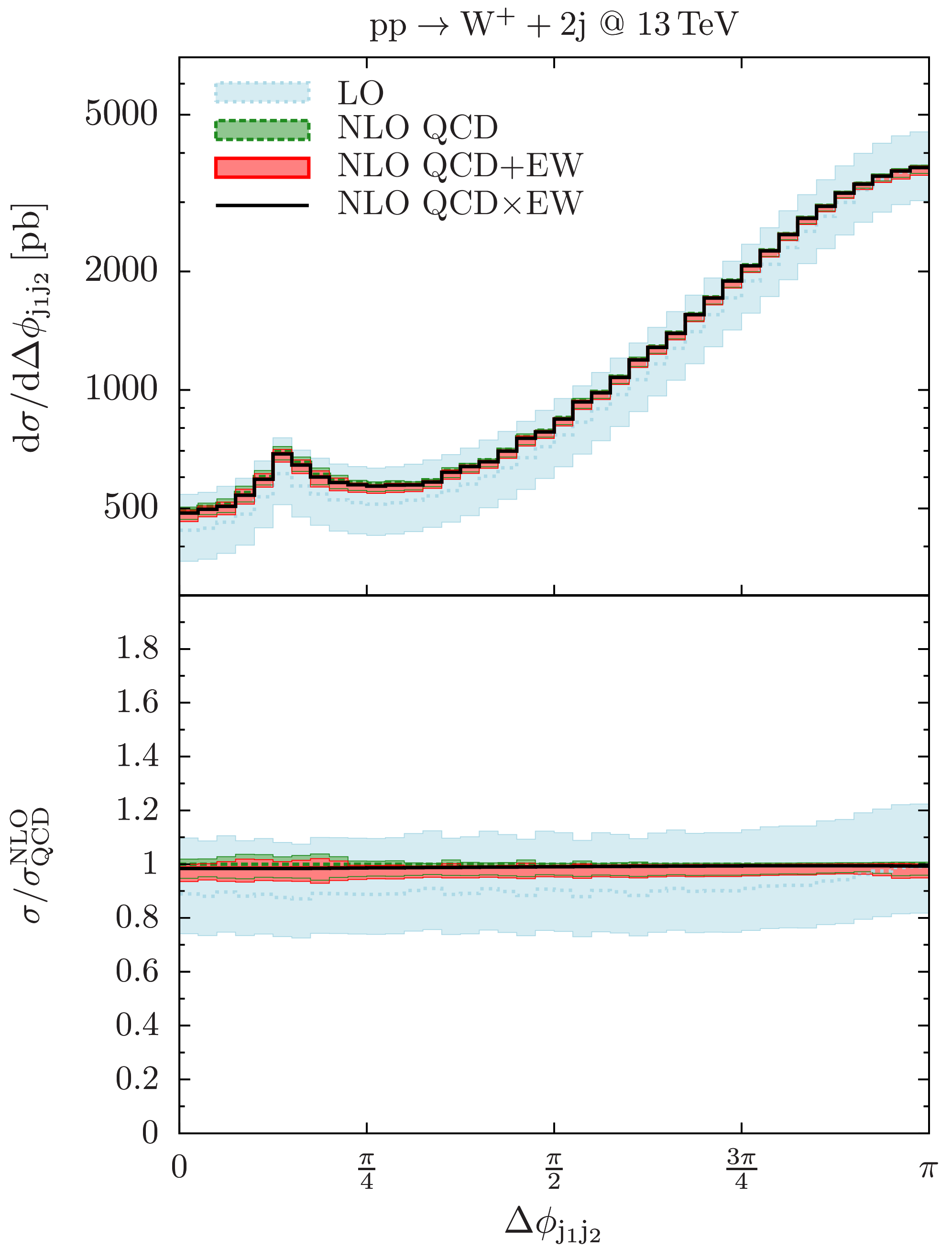
- $M_{\mathrm{Z}} = 91.1876\ \mathrm{GeV}, \quad M_{\mathrm{W}} = 80.385\ \mathrm{GeV}, \quad M_{\mathrm{H}} = 126\ \mathrm{GeV}, \quad m_{\mathrm{t}} = 173.2\ \mathrm{GeV}.$
- $\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_{\mathrm{W}}^2 \left(1 - \frac{M_{\mathrm{W}}^2}{M_{\mathrm{Z}}^2}\right)$ in G_μ-scheme with $G_\mu = 1.16637 \times 10^{-5}\ \mathrm{GeV}^{-2}$
- PDFs: NNPDF 2.3QED with $\alpha_{\mathrm{S}}(M_{\mathrm{Z}}) = 0.118$ for LO and NLO QCD/EW
- Jet definition: anti-k_T with $R = 0.4$, $p_{\mathrm{T,j}} > 30\,\mathrm{GeV}, \qquad |\eta_{\mathrm{j}}| < 4.5$
- Photon recombination for $R_{\gamma,q} < 0.1$ and democratic jet clustering with $E_\gamma / E_{\mathrm{j}} = 0.5$
- LHC with $\sqrt{S} = 13\ \mathrm{TeV}$
- Scale choice: $\mu_{\mathrm{R,F}} = \xi_{\mathrm{R,F}} \mu_0\,, \quad \mu_0 = \hat{H}_{\mathrm{T}}/2 = \frac{1}{2} \sum_{\mathrm{partons}} E_{\mathrm{T}}$ with 7-point variation

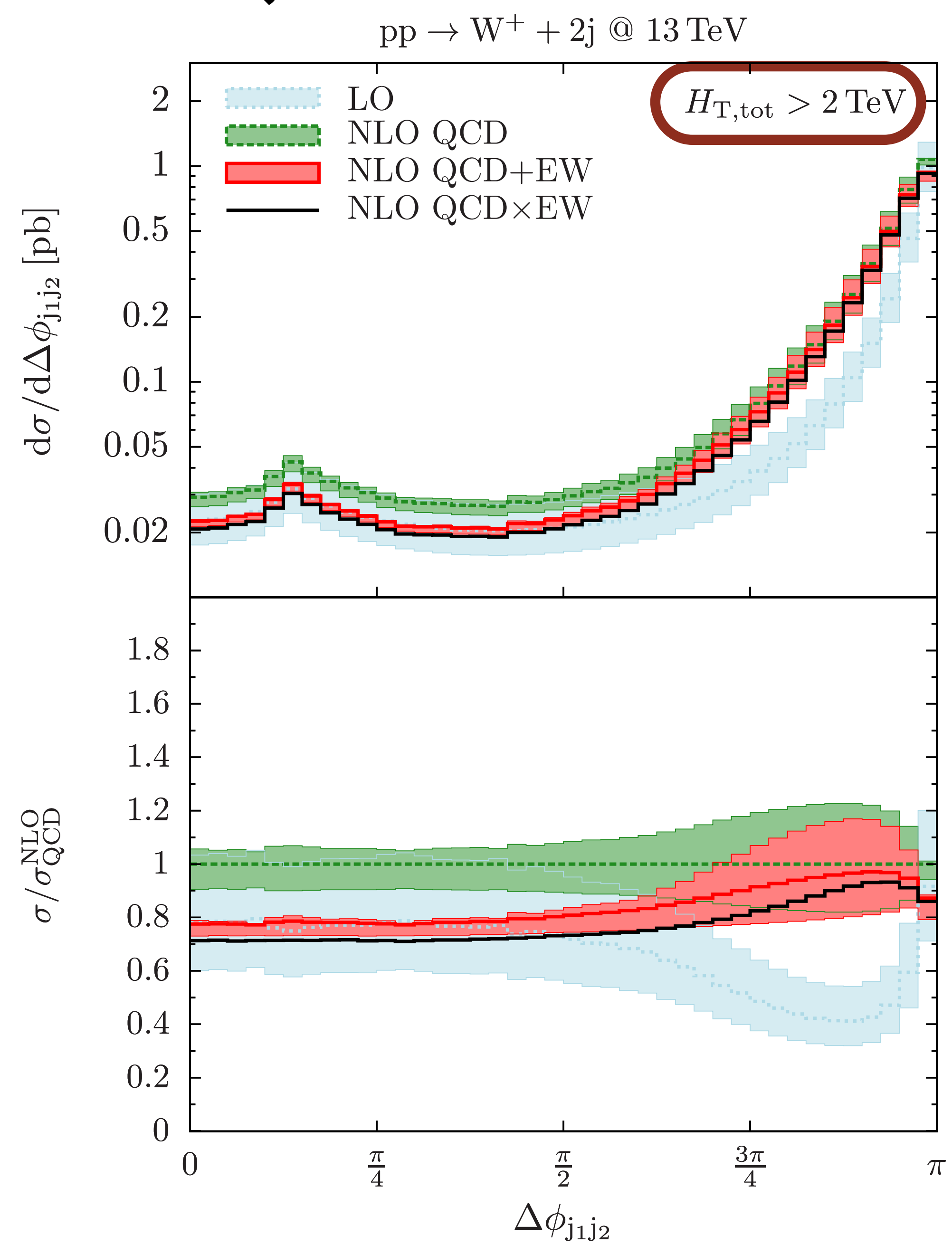
W$^+$ + 1,2,3 jets: large EW corrections



- up to 50% EW corrections in multi-TeV range due to Sudakov logs
- nontrivial dependence on number of jets and interplay with NLO QCD!

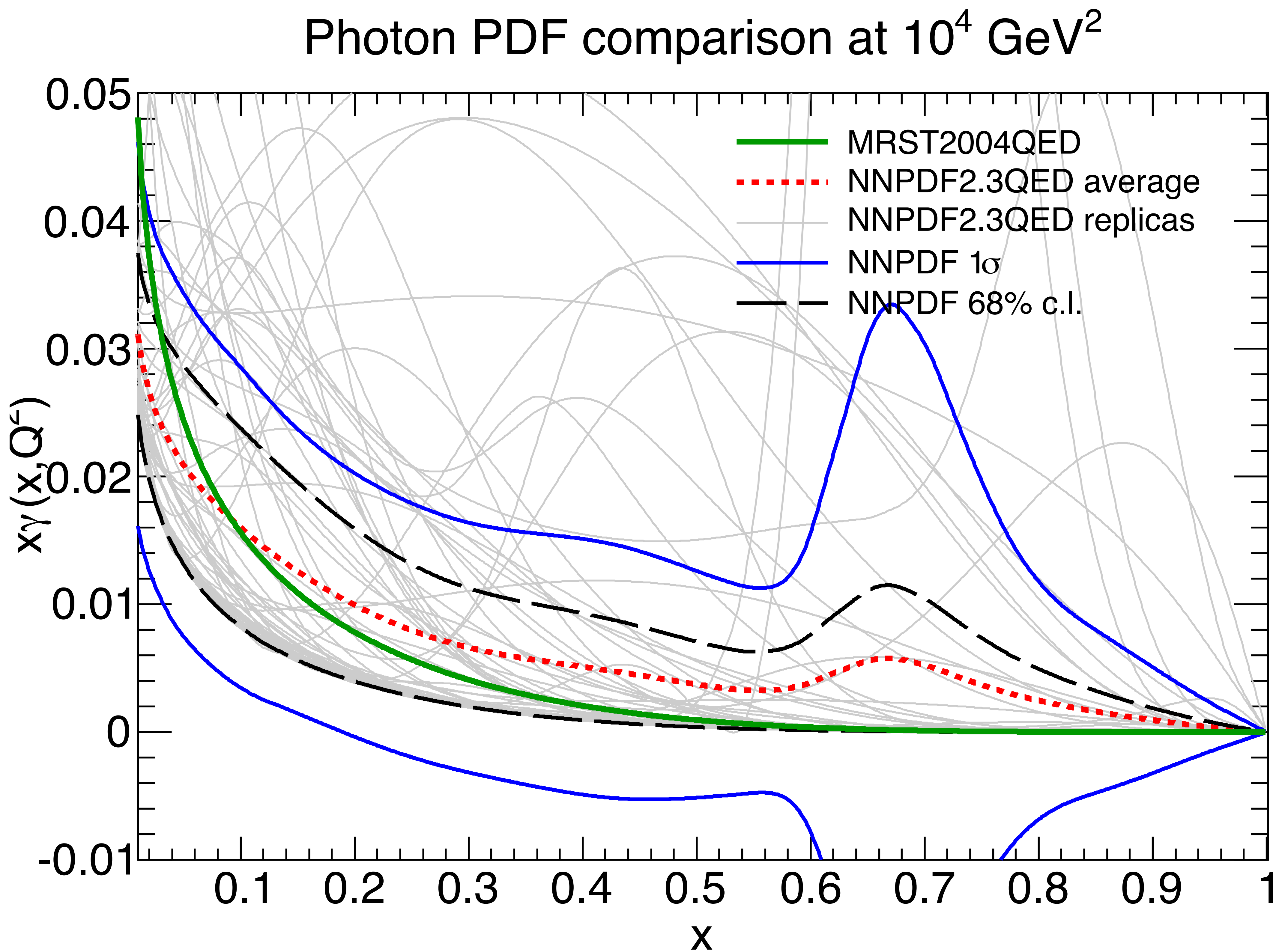
Results: W + 2 jets





- QCD corrections vanish for $\Delta\phi_{j_1 j_2} = \pi$
- small EW corrections

- QCD corrections strongly increase for $3\pi/4 < \Delta\phi_{j_1 j_2} < \pi$
- sizeable difference between QCD+EW and QCDxEW
- up to -25% EW corrections


Photon PDF comparison at 10^4 GeV^2
MRST2004QED
NNPDF2.3QED average
NNPDF2.3QED replicas
NNPDF 1σ
NNPDF 68% c.l.
0.05
0.04
0.03
0.02
0.01
0
-0.01
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x
$x\gamma(x,Q^2)$