EWK corrections to non-VBF processes

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work in collaboration with:

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Future of VBF measurements
IPPP Durham, 21st Sepetember 2016

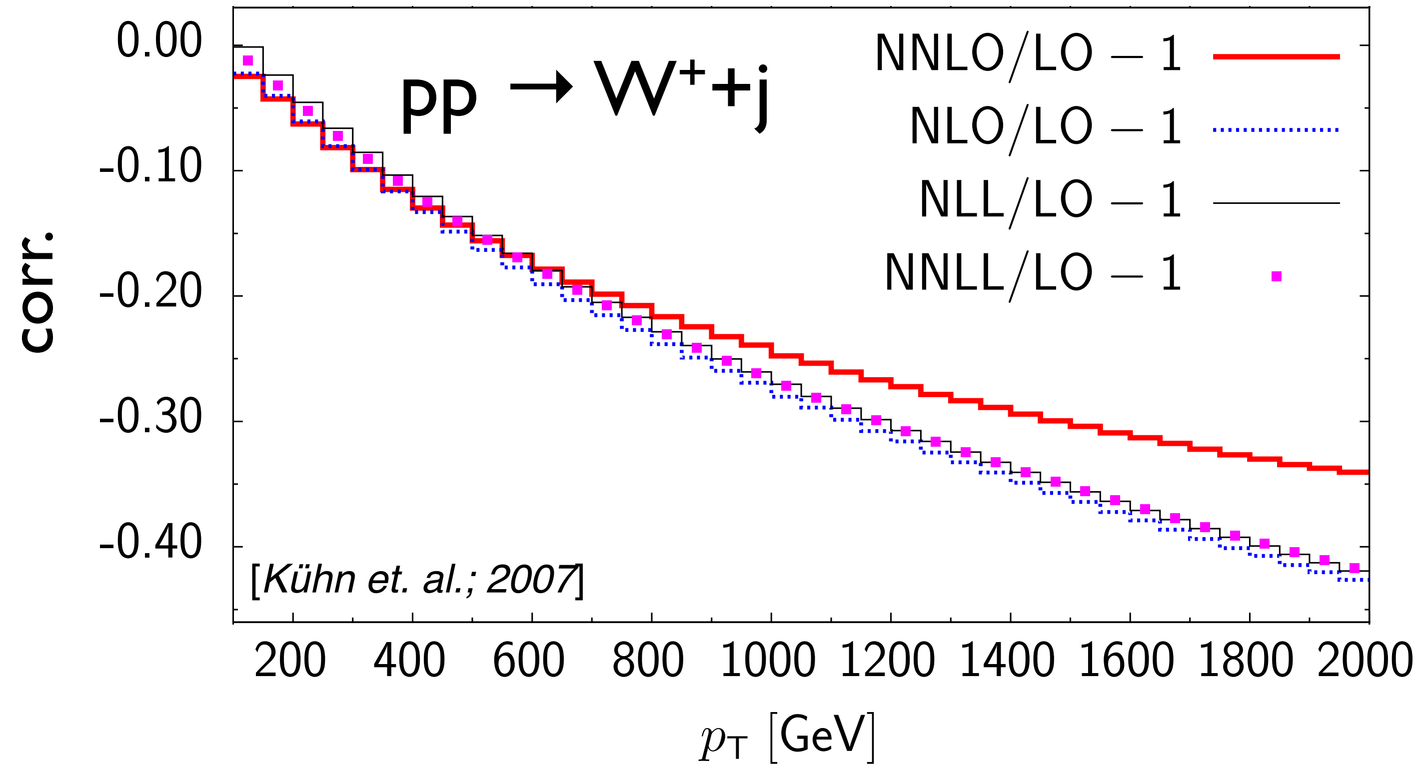
Why EW automation?

- 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

- Possible large (negative) enhancement due to universal virtual Sudakov logs at high energies (i.e. in the tails of the distributions):

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

$$\text{NLO EW} \sim -\alpha \log^2\left(\frac{M_V^2}{\hat{s}}\right)$$



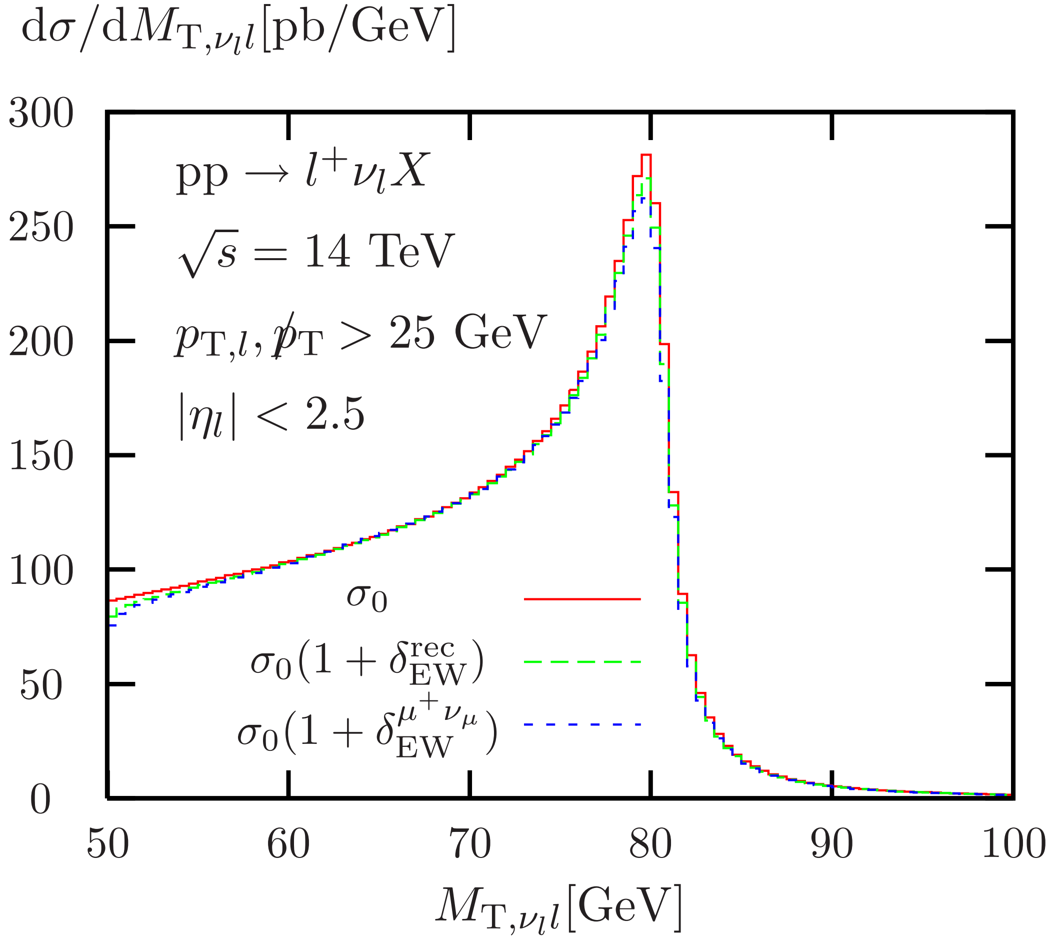
- NLO EW known for most (some) 2→2(3) processes

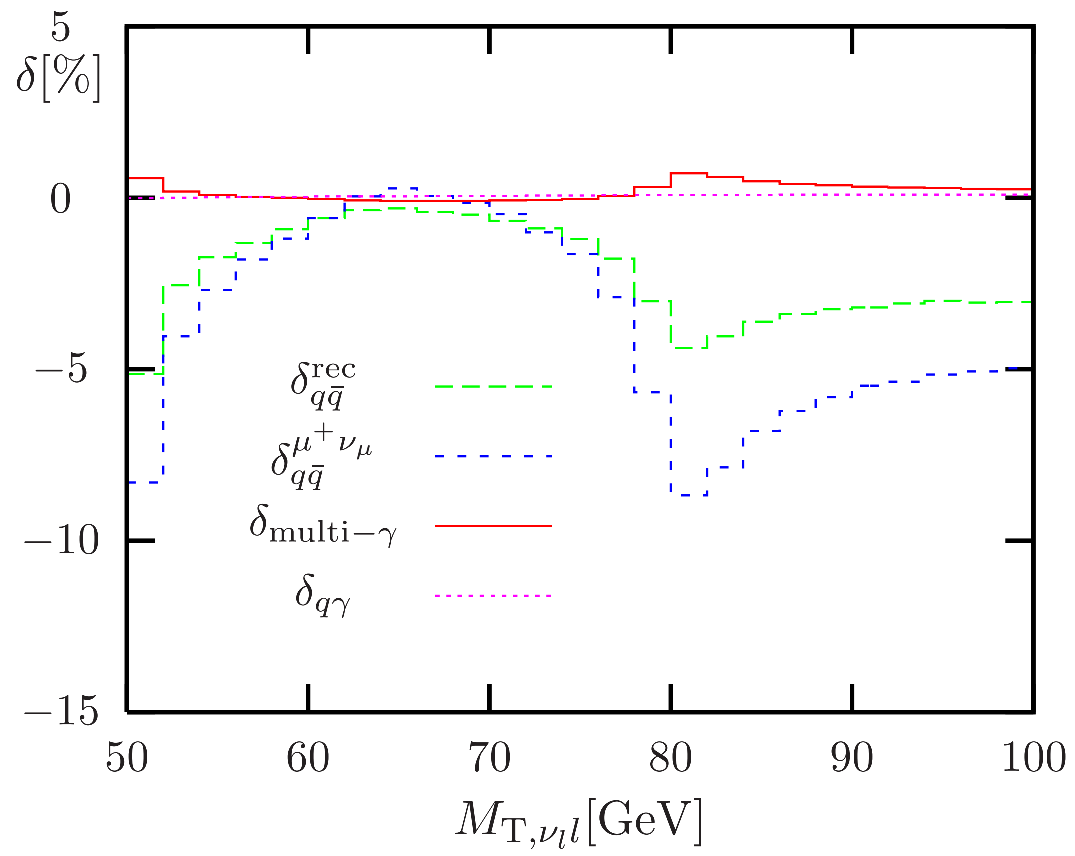
- …missing for a multitude of 2→3(4) processes (and with decays and/or PS matching)

Why EW automation?

- Photon bremsstrahlung known to be important for various precision observables, e.g. for determination of M_W.
- Origin: soft/collinear photon radiation $\sim \alpha \log\left(\frac{m_f^2}{Q^2}\right)$
- Possible important corrections in sufficiently exclusive observables.

[Brensing, Dittmaier, Krämer, Mück; '08]





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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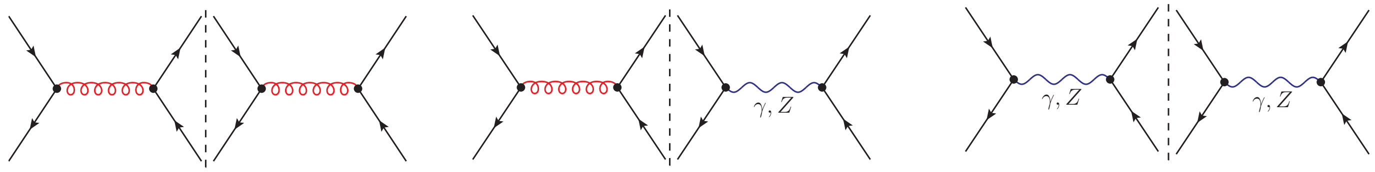

Illustrative example: $q\bar{q} \rightarrow q\bar{q}$

[Dittmaier, Huss, Speckner ; '12]

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

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

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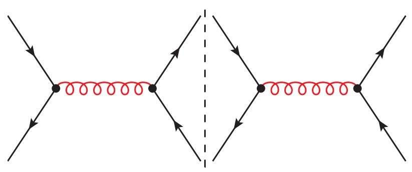

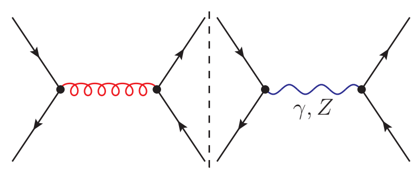

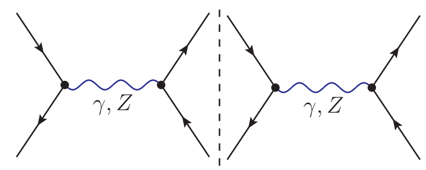

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[Dittmaier, Huss, Speckner ; '12]

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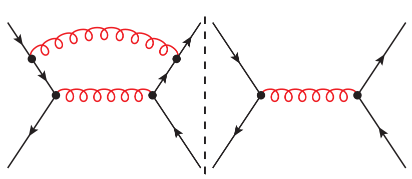
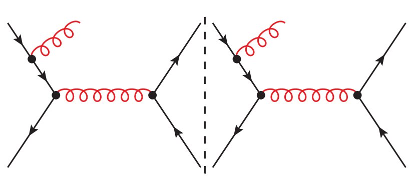
"NLO QCD"





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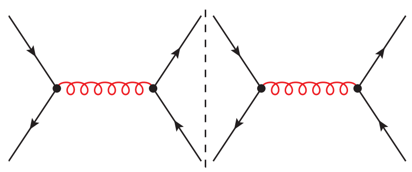

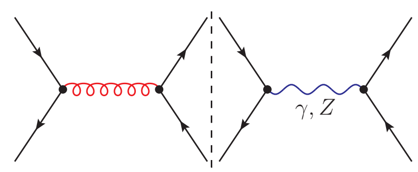

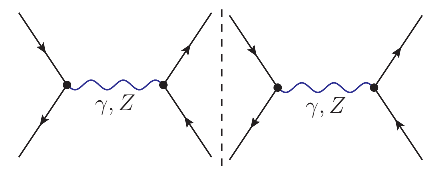

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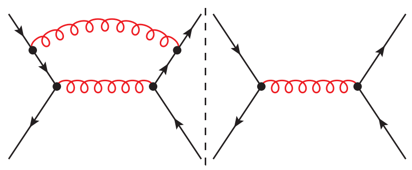

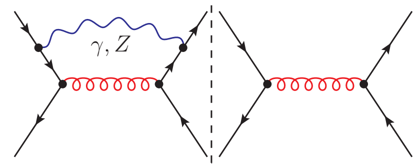

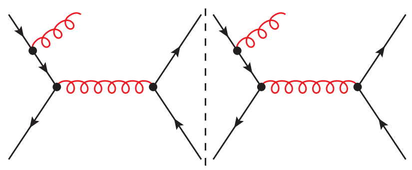

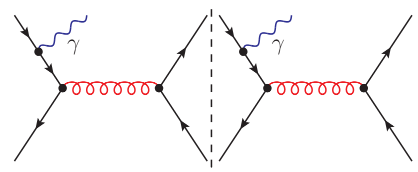

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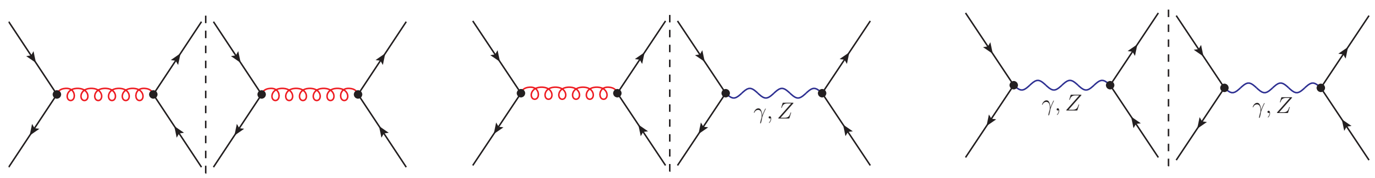

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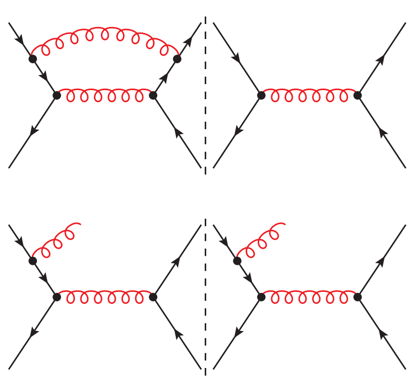

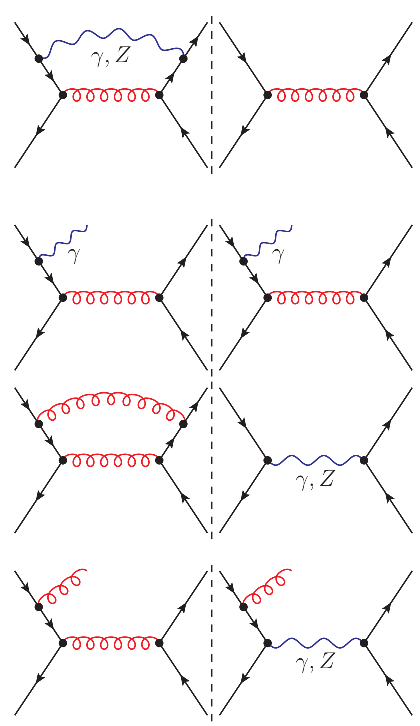

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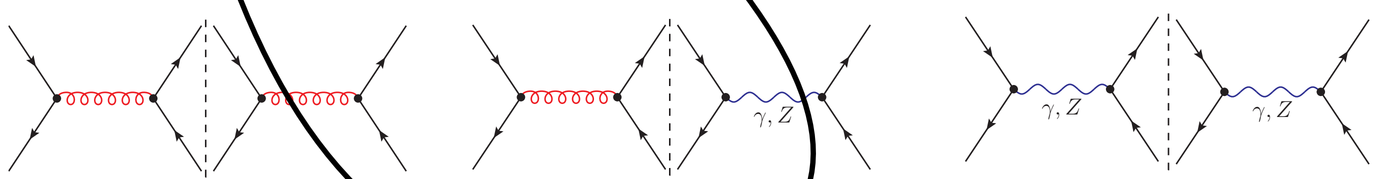

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$\mathcal{O}(\alpha)$ $\mathcal{O}(\alpha_s)$

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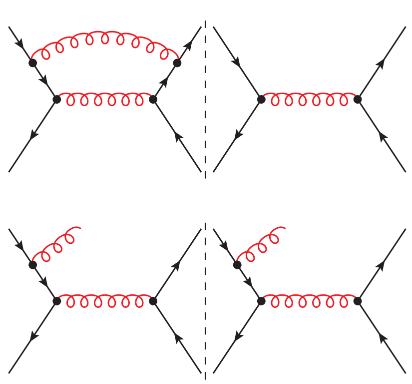
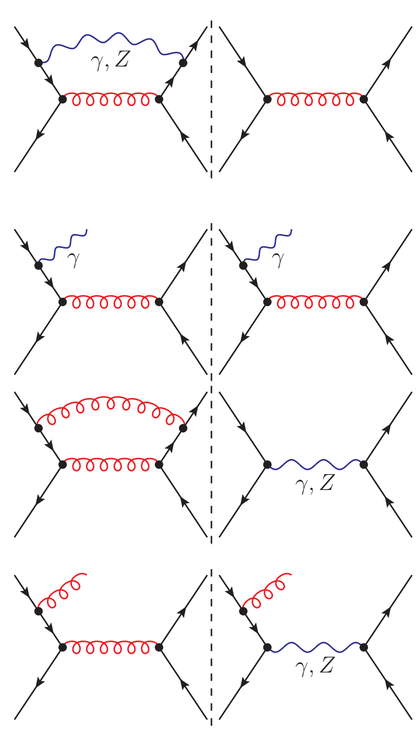
"NLO QCD" "NLO EW" "subleading one-loop contributions"





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

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

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

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

"NLO QCD"　　"NLO EW"　　"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.

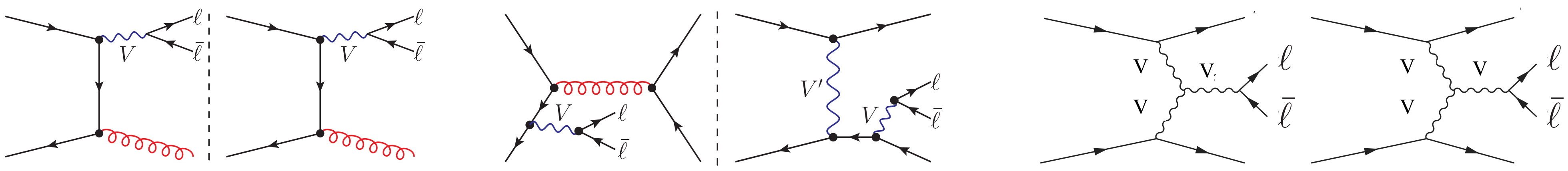
Input:

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

Perturbative power counting for V+jets/VBF

QCD interference VBF

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



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

NLO QCD
V+jets

NLO EW
V+jets

NLO QCD
VBF

NLO EW
VBF

Perturbative power counting for V+2 jets/VBF-V

QCD interference VBF

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

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

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

NLO QCD V+jets	NLO EW V+jets	NLO QCD VBF	NLO EW VBF
[Campbell, R. K. Ellis, '03]	*[S. Kallweit, JML, P. Maierhöfer, S. Pozzorini, M. Schönherr; '14, '15]*	*[Oleari, Zeppenfeld, '03]* in VBF approx.	*[unknown]*

Automation of NLO QCD+EW

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

OpenLoops

[JML, Maierhöfer, Pozzorini]

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.]

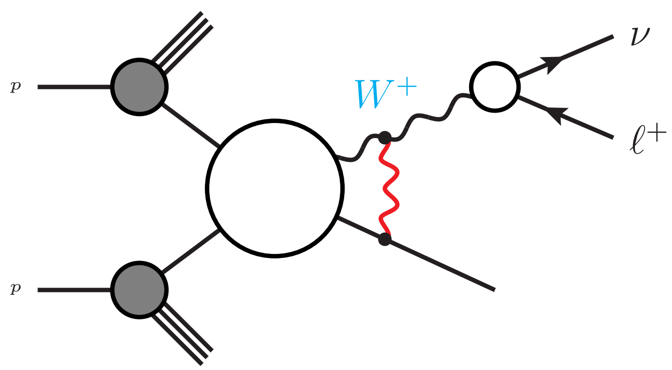
Whizard

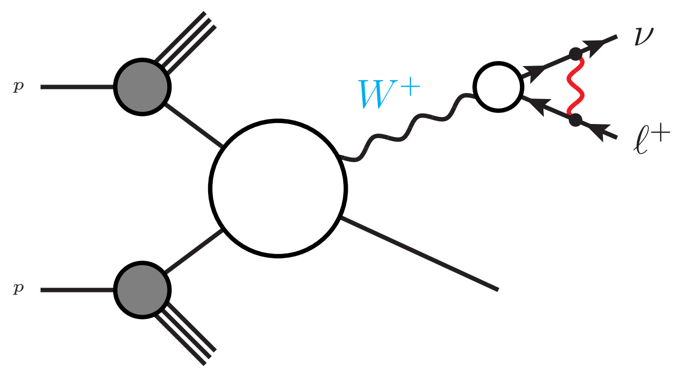
[Kilian, Ohl, Reuter et. al.]

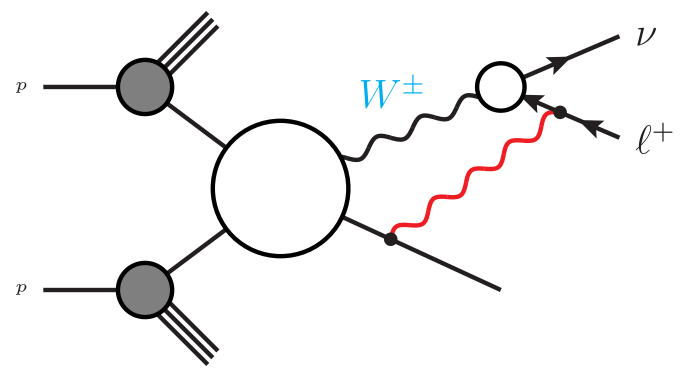
- NLO corrections in the full SM (QCD & EW) are implemented in OpenLoops together with Sherpa and MUNICH (will be included in upcoming public releases)
- missing: NLO EW + PS matching & merging (work in progress, approximation available!)

Decays of heavy particles @ NLO EW

- 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.





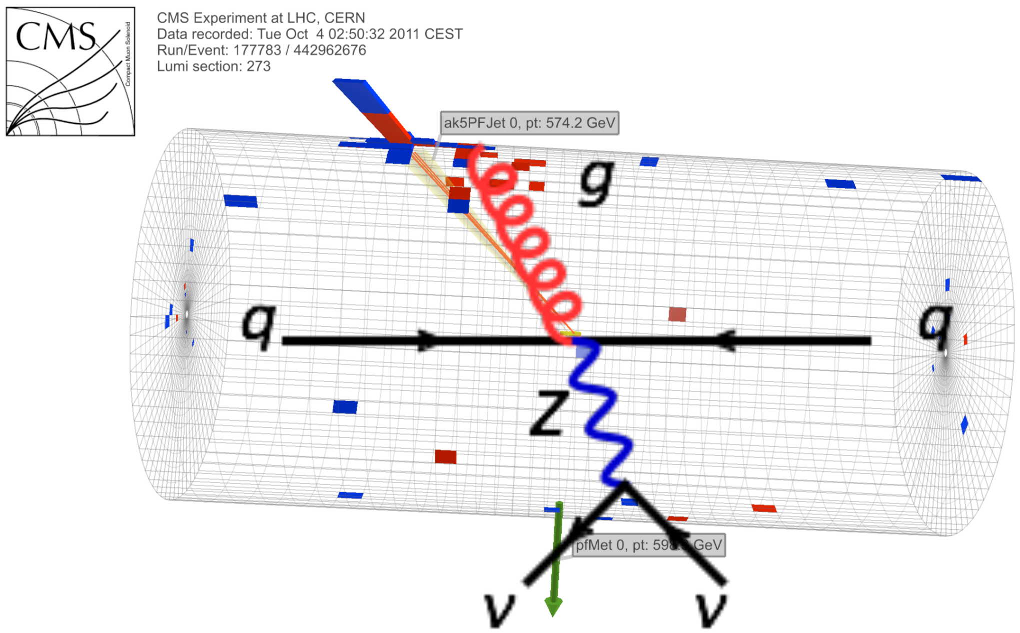


- Scheme of choice: complex-mass-scheme *[Denner, Dittmaier]*
  - gauge invariant and exact NLO
  - **computationally very expensive**: one extra leg per two-body decay

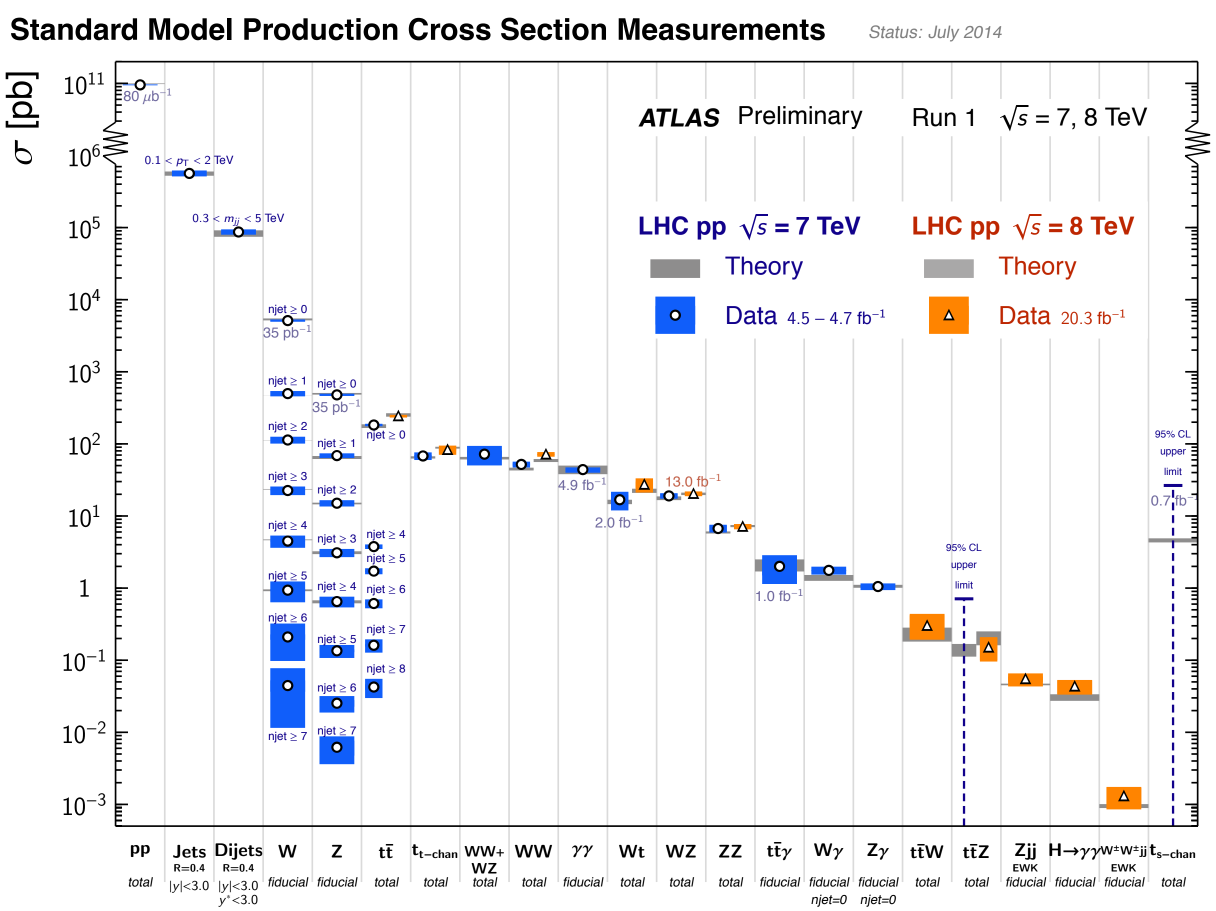
- Pragmatic choice: Narrow-width-approximation (NWA)
  - gauge invariant in strict on-shell limit of NWA
  - **allows to capture all Sudakov effects** (not present in decay)
  - **allows to go to higher jet multiplicities**
  - not applicable to all processes at all perturbative orders

V + multijet @ NLO QCD+EW

[S. Kallweit, JML, P. Maierhöfer, S. Pozzorini, M. Schönherr; '14, arXiv:1412.5157; '15; arXiv:1511.08692]



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



- 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,…)
- **Show all technical challenges of NLO EW!**

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 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

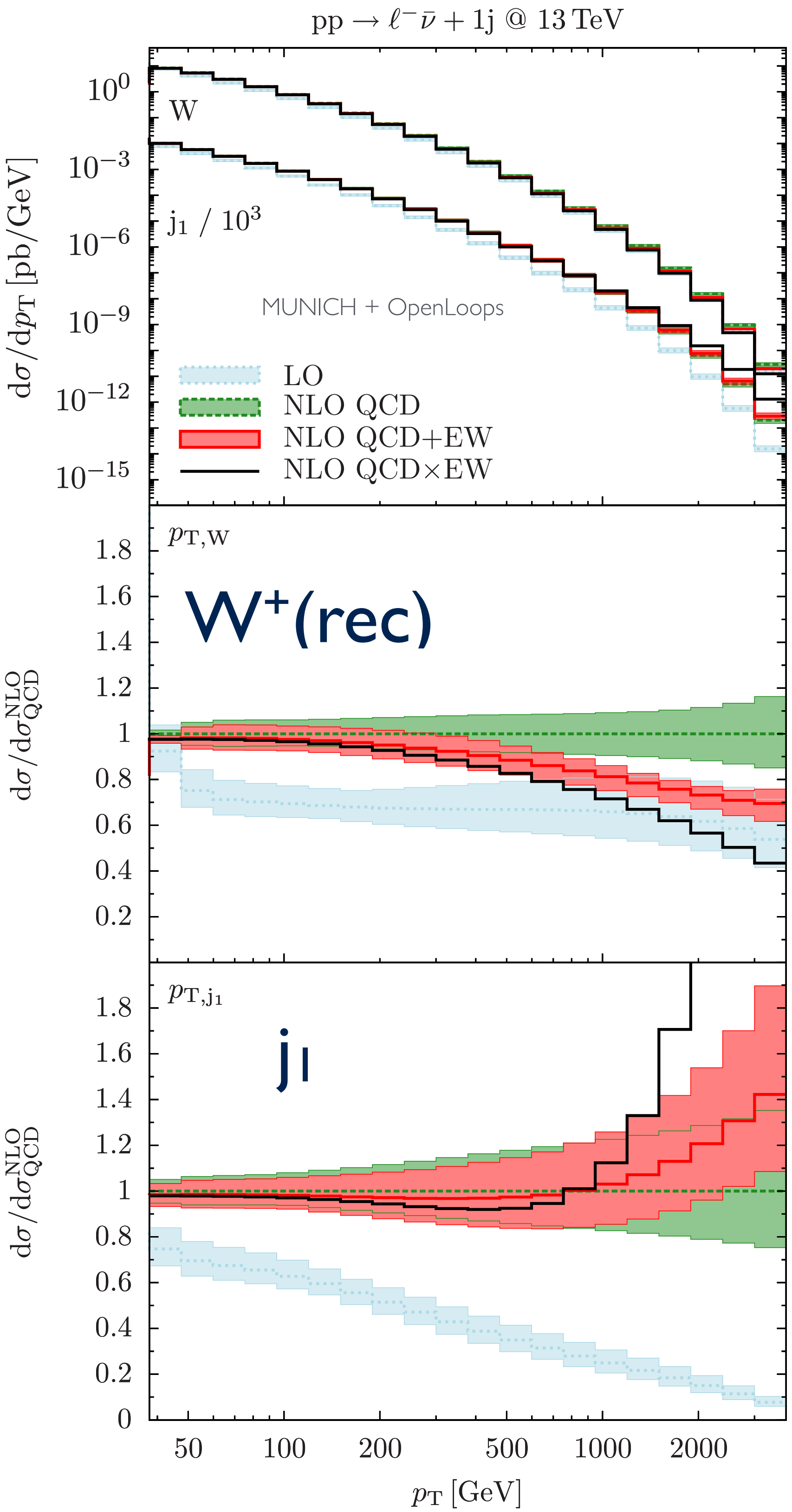
$$\frac{\sigma^{\rm NLO}_{\rm QCD\times EW}}{\sigma^{\rm NLO}_{\rm QCD}} = \left(1+\frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm LO}}\right)$$

"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 $G_\mu = 1.16637\times10^{-5}\ {\rm GeV}^{-2}$
- PDFs: NNPDF 2.3QED with $\alpha_{\rm S}(M_{\rm Z}) = 0.118$ for LO and NLO QCD/EW
- $\mu_0 = \hat{H}_T/2\ (+\ \text{7-pt. variation})$

V + 1 jet

$l^{-}\nu$ + 1 jet: inclusive



Setup:

$\sqrt{S} = 13$ TeV

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

$p_{\mathrm{T,l}} > 20$ GeV, $|\eta_{\mathrm{l}}| < 2.5$, $E_T^{\mathrm{miss}} > 25$

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

inclusive

≲ 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

- "giant QCD K-factors" in the tail *[Rubin, Salam, Sapeta '10]*
- dominated by **dijet configurations** (effectively LO, no EW)
- positive 10-50% EW corrections from quark bremsstrahlung

NNLO QCD: *[Boughezal, Focke, Liu, Petriello '15,'16]*

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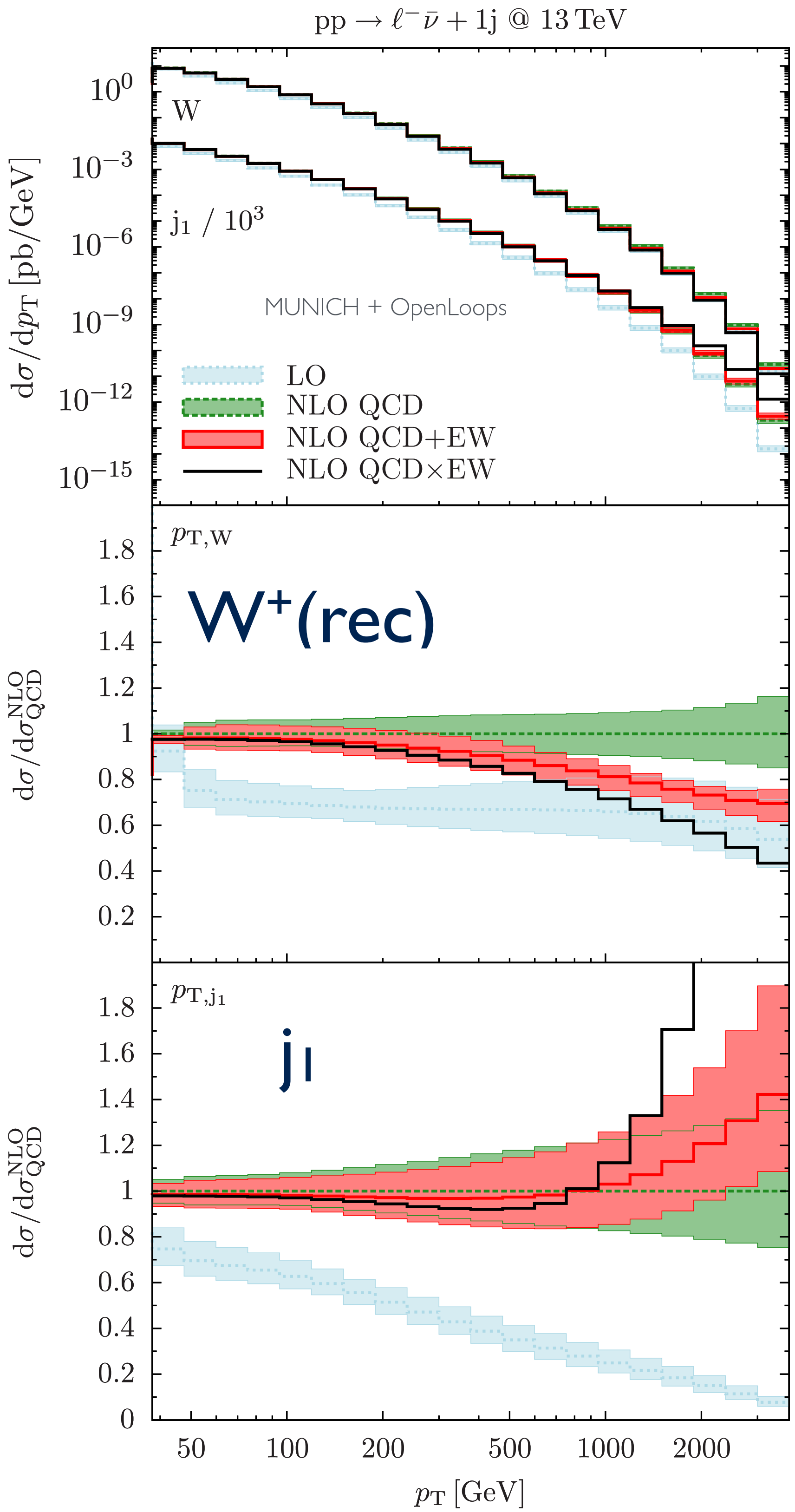

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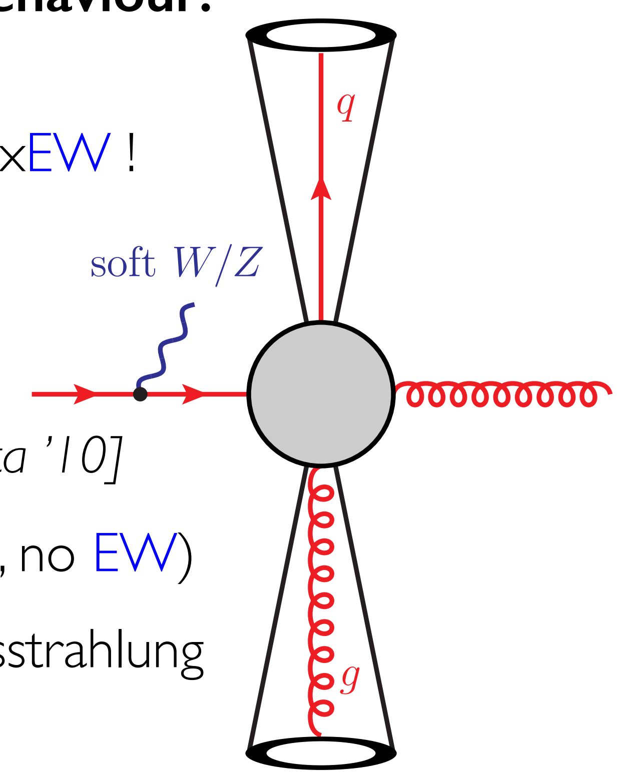

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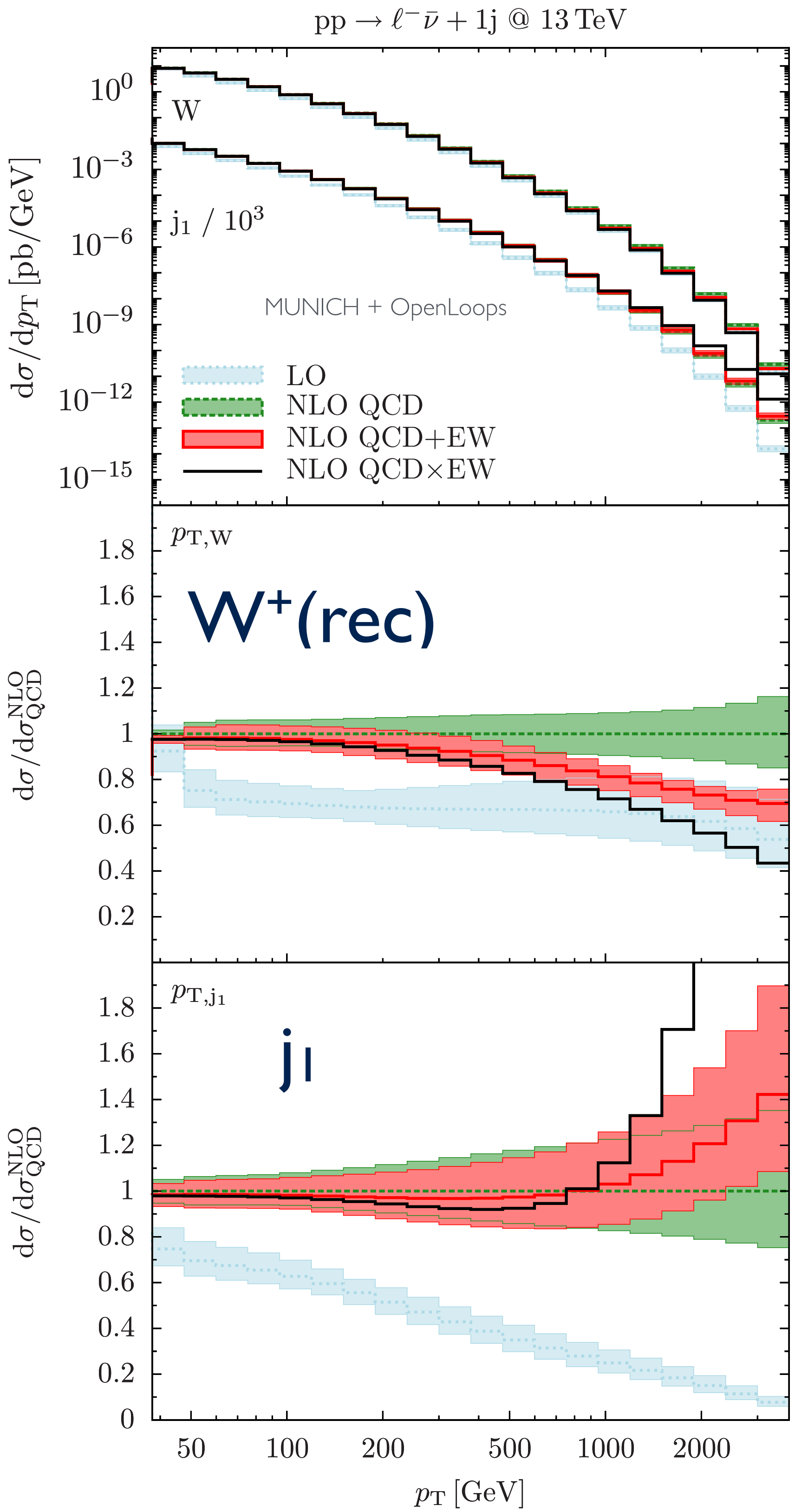

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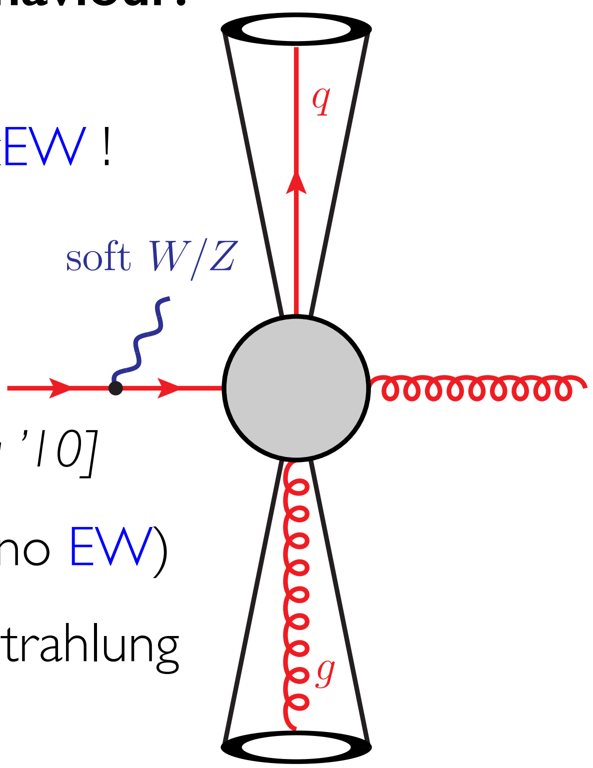
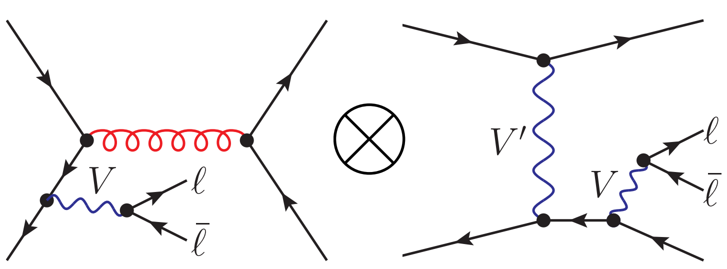
- large negative EW corrections due to **Sudakov behaviour:** -20–35% corrections at 1-4 TeV
- sizeable difference between QCD+EW and QCDxEW !



p_T of jet

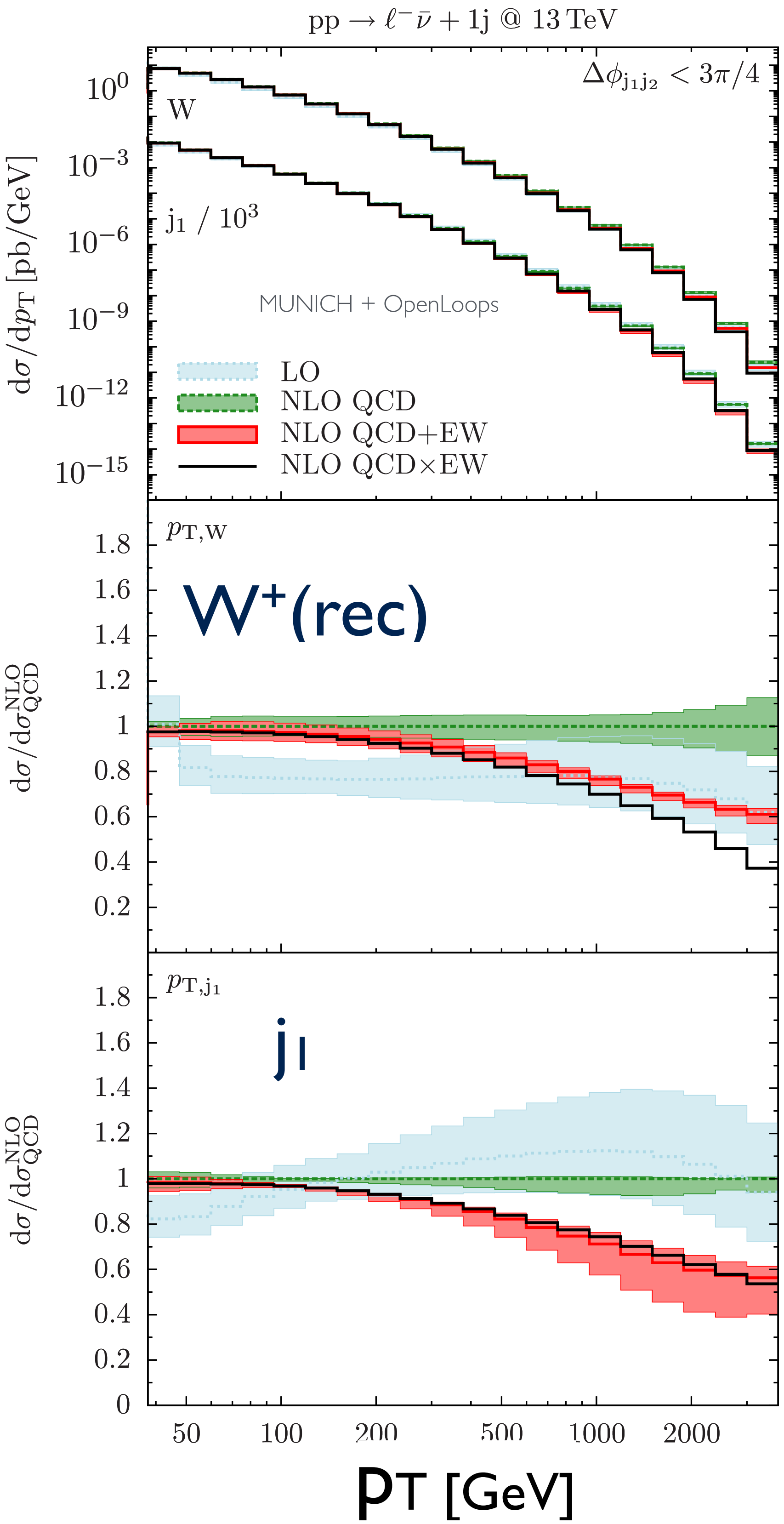
- "giant QCD K-factors" in the tail *[Rubin, Salam, Sapeta '10]*
- dominated by **dijet configurations** (effectively LO, no EW)
- positive 10-50% EW corrections from quark bremsstrahlung



⟹ pathologic with large uncertainties!

NNLO QCD: *[Boughezal, Focke, Liu, Petriello '15,'16]*

$l^-\nu$ + 1 jet: exclusive



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

(veto on dijet configurations)

QCD corrections

- mostly moderate and stable QCD corrections

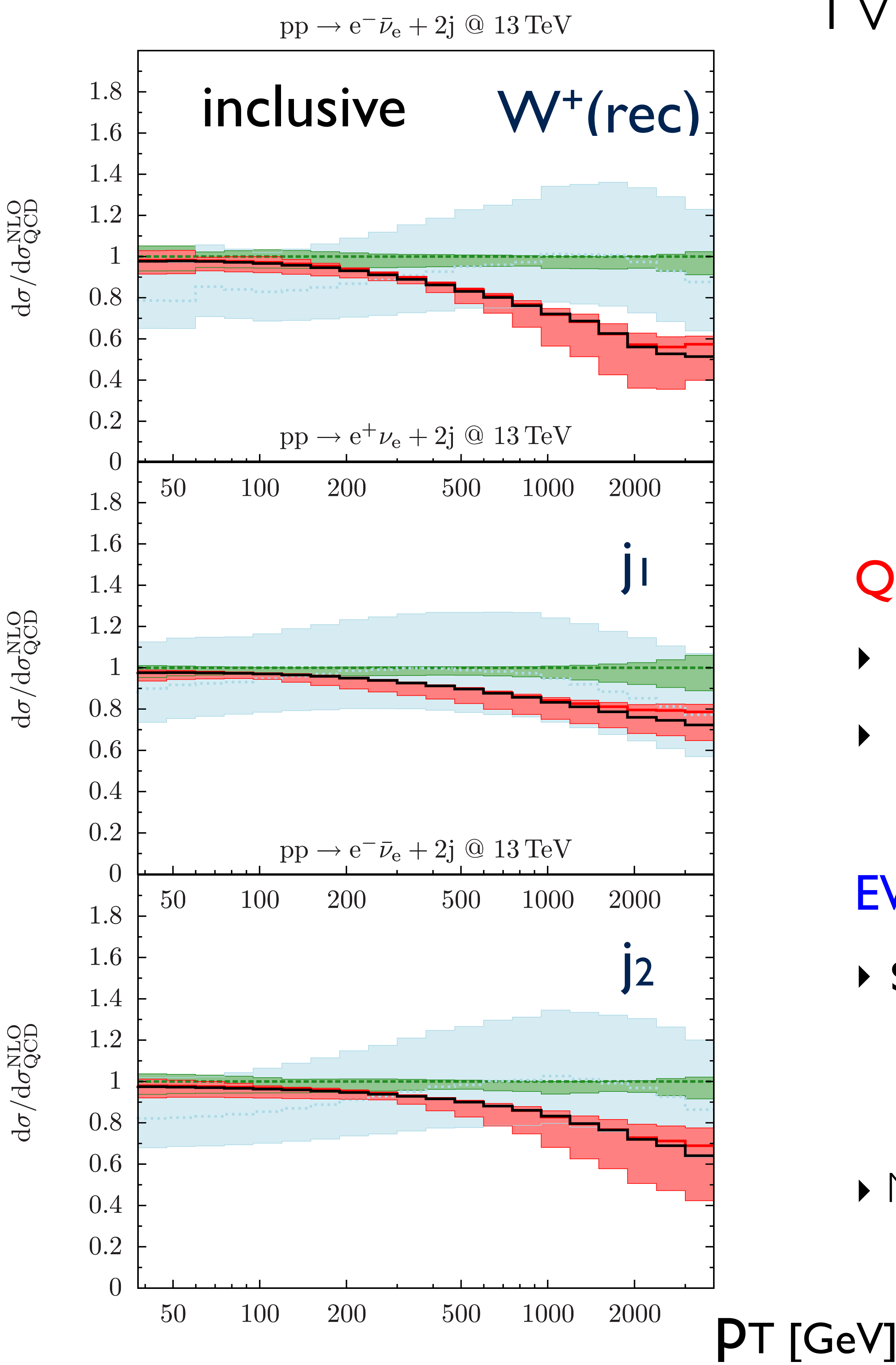
EW corrections

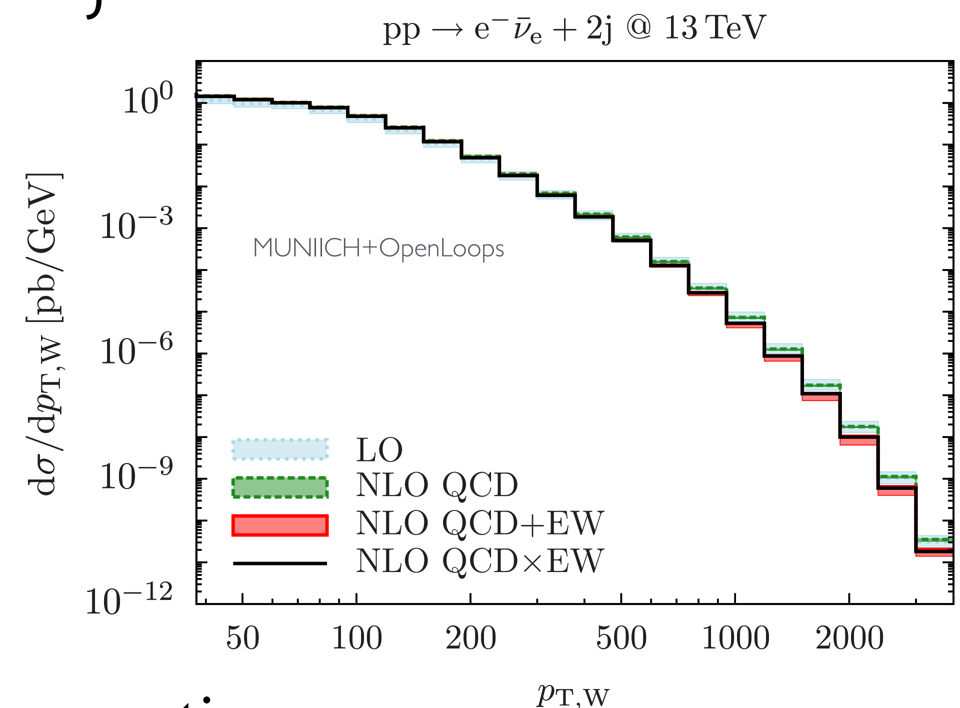
- **Sudakov behaviour** in both tails: -20–50% EW corrections at 1-4 TeV
- EW corrections larger than QCD uncertainties for $p_{T,W+}$ > 300 GeV

⇒ *exclusive* W+1jet ok!

⇒ *inclusive* W+1jet requires merging with W+2 jets at NLO QCD+EW!

$l^-\nu$ + 2 jets





QCD corrections

- small and very stable
- ≲ 10% scale uncertainties

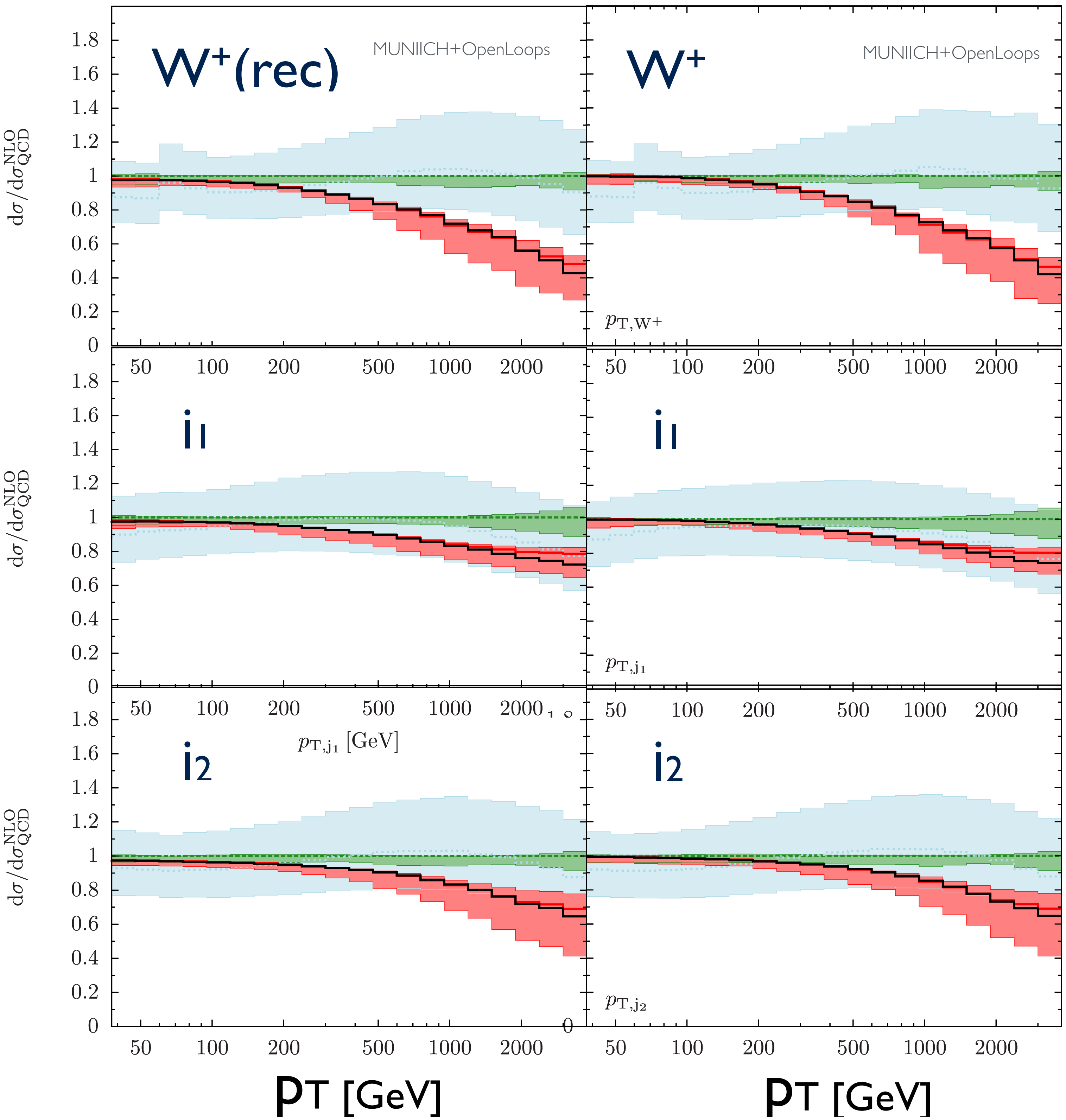
EW corrections

- **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

off-shell vs. on-shell production

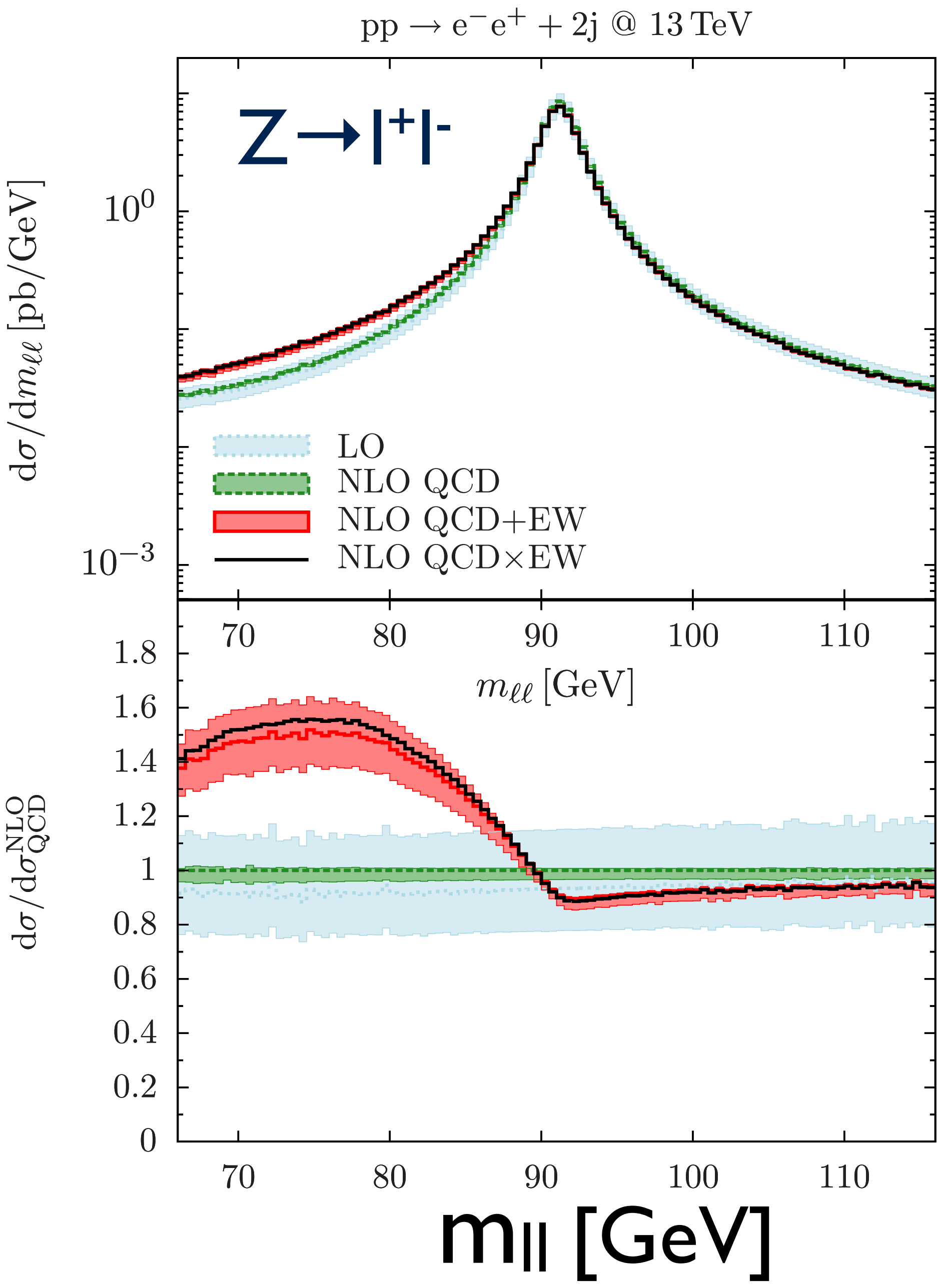
l⁺v + 2 jets vs. W⁺+2 jets

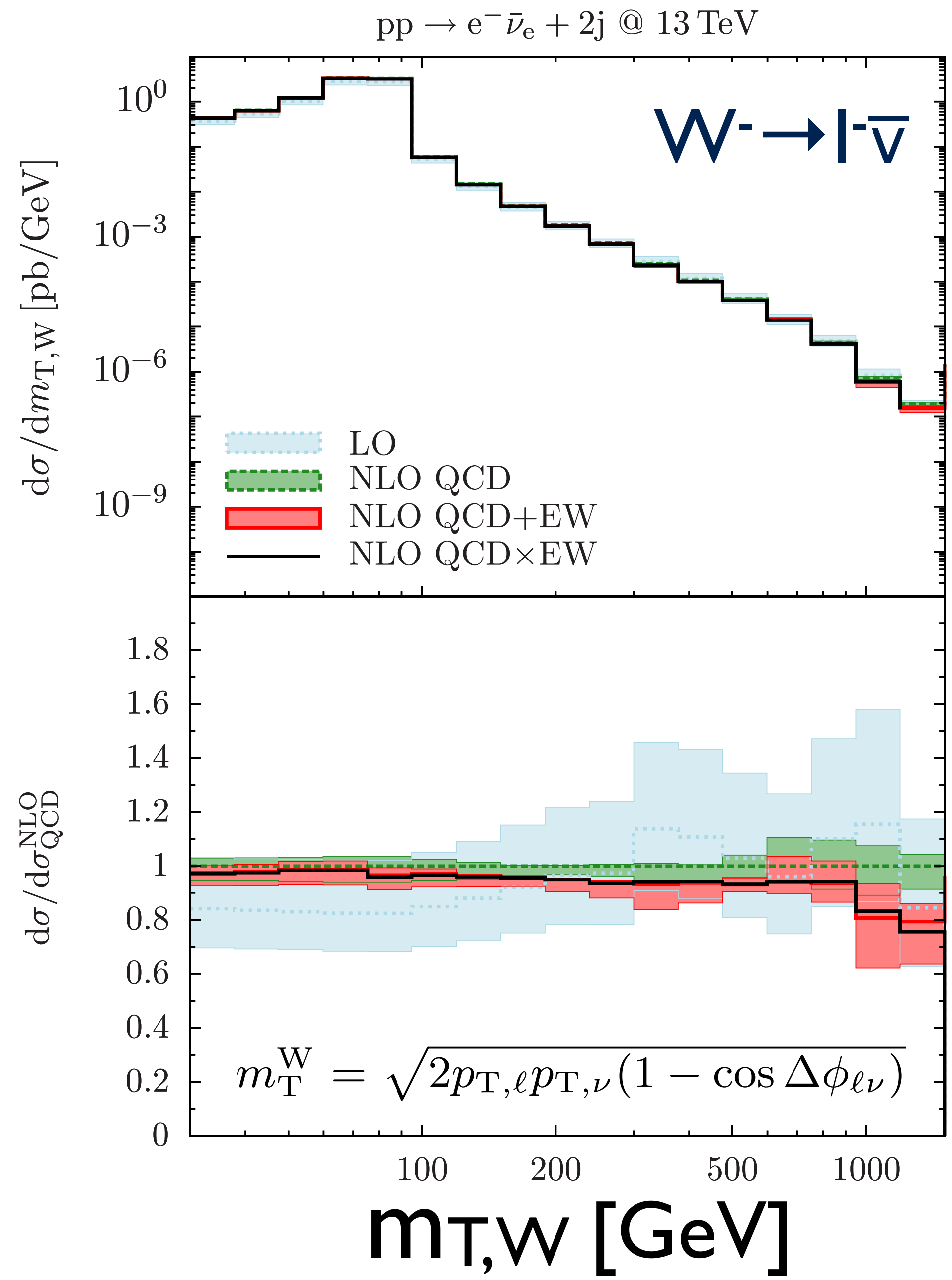


Effect of decays:

- **Large Sudakov corrections unaffected**
- However: needed for realistic experimental cuts

Leptonic observables: only in off-shell calculation

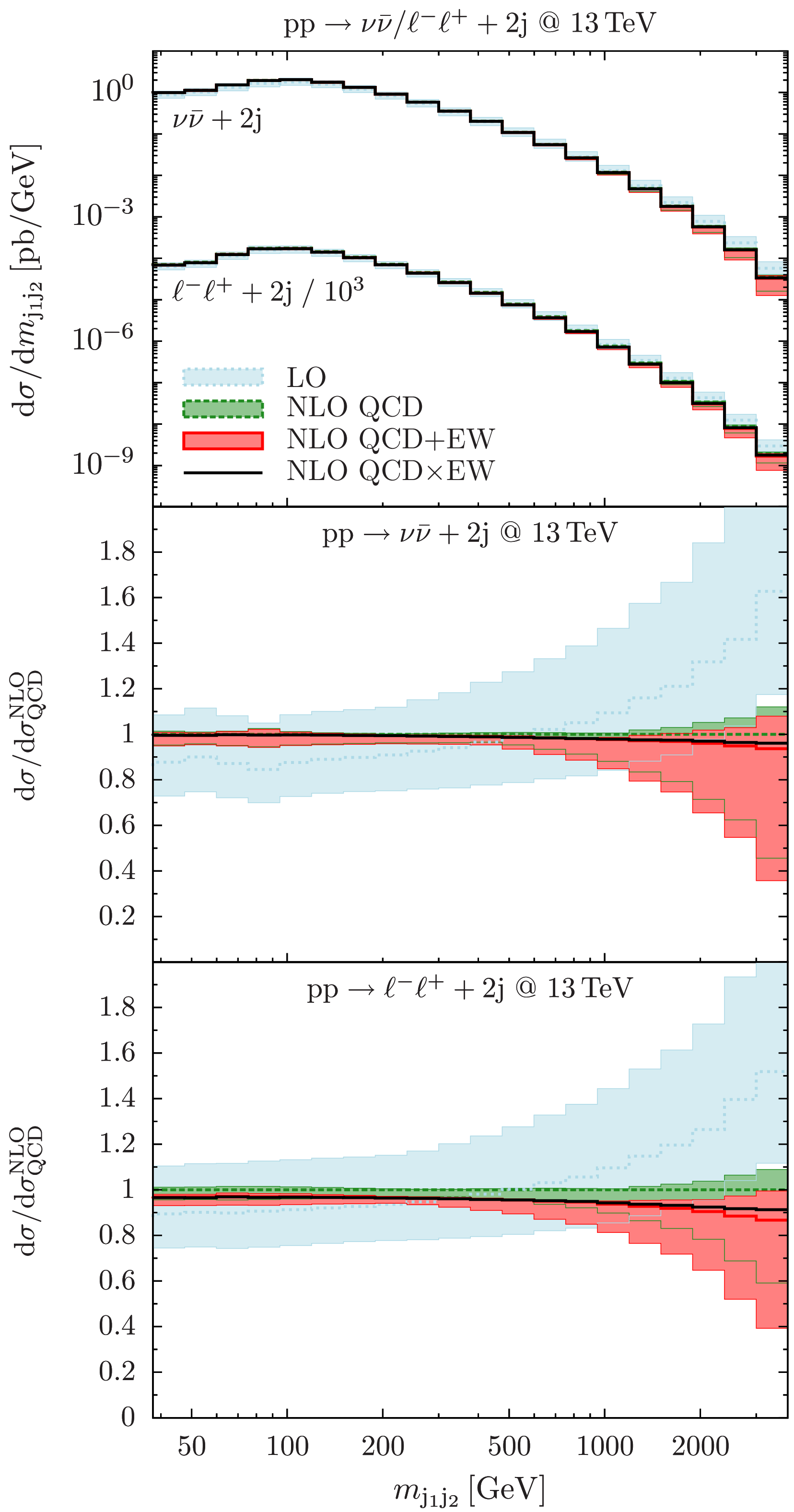




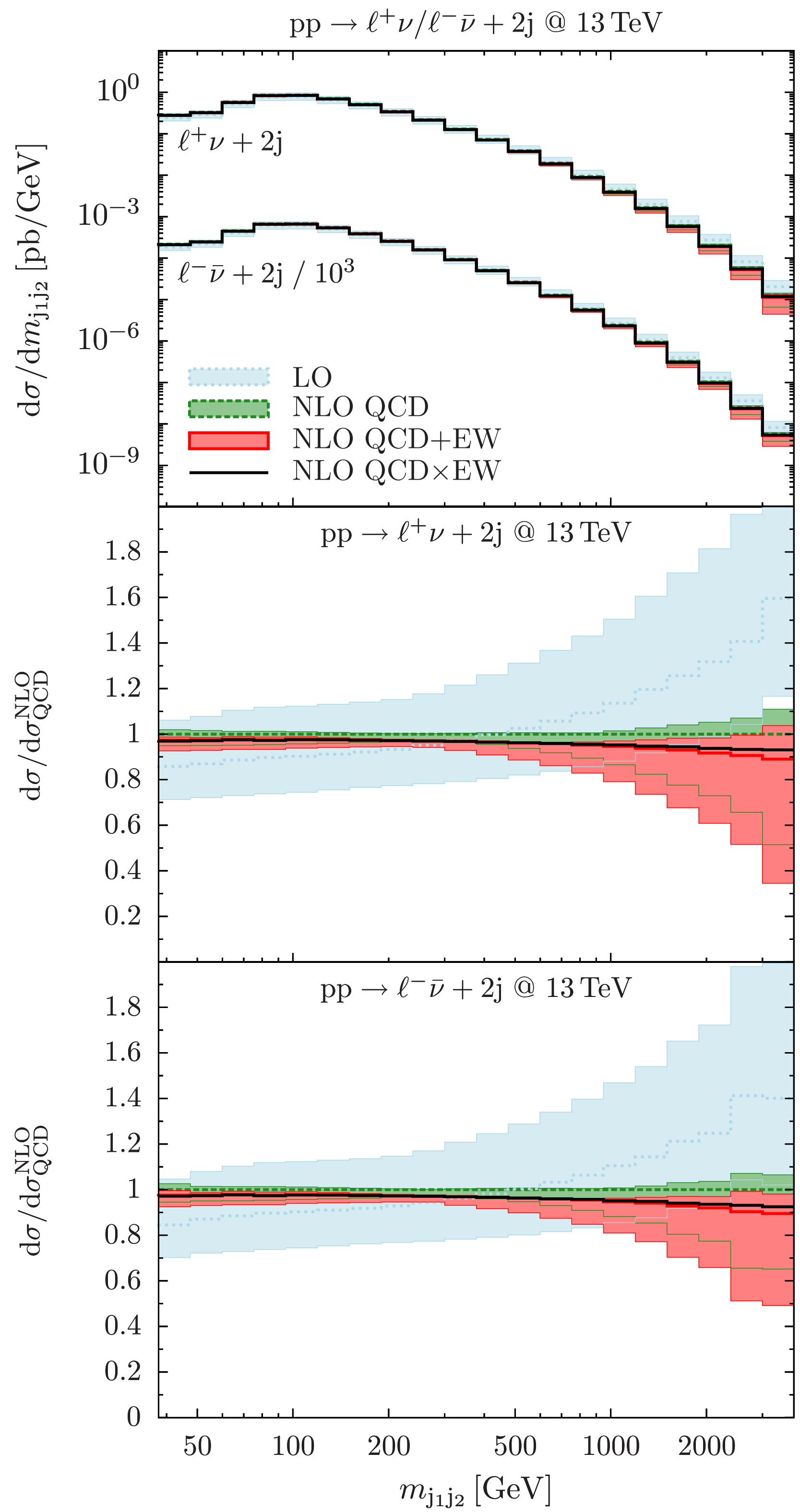
- up to 50% from QED Bremsstrahlung.
- Similar shape as for NC DY
- moderate EW corrections at large $m_{T,W}$
- no (strong) Sudakov enhancement

dijet invariant mass

$Z \to l^+l^-$



$W^- \to l^-\bar{\nu}$



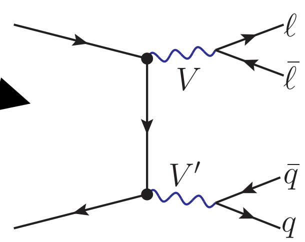
- EW corrections <10 % up to the multi TeV in m_{j1j2}
- only moderate Sudakov enhancement! ($\hat{s}_{ij} \not\gg M_W$)

$$\text{V + 1 jet} \otimes \text{V + 2 jets}$$

MEPS@NLO QCD+EW$_{\text{virt}}$

- Incorporate approximate EW corrections into MEPS@NLO framework *[Höche, Krauss, Schönherr, Siegert; '13]*
- Idea: integrate out real photon corrections (typical at the percent level for high-energy observables)

$$\tilde{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) \longrightarrow \tilde{\mathrm{B}}_{n,\mathrm{QCD+EW}}(\Phi_n) = \tilde{\mathrm{B}}_n(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$



$$d\sigma = d\sigma(\alpha_S^2\alpha) + d\sigma(\alpha_S\alpha^2) + d\sigma(\alpha^3)$$

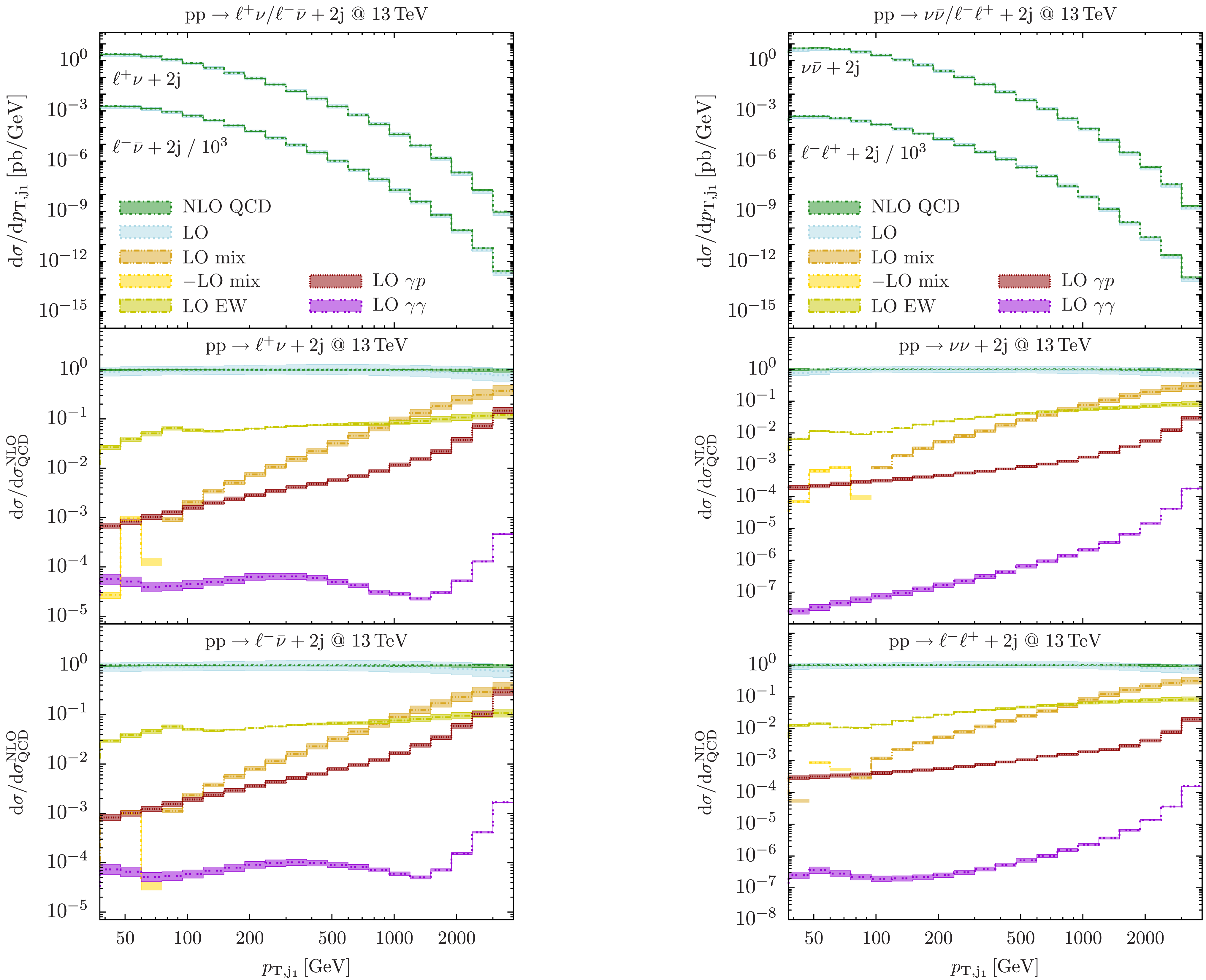
QCD EW QCD EW QCD EW

$$+\, d\sigma(\alpha_S^3\alpha) + d\sigma(\alpha_S^2\alpha^2) + d\sigma(\alpha_S\alpha^3) + d\sigma(\alpha^4)$$

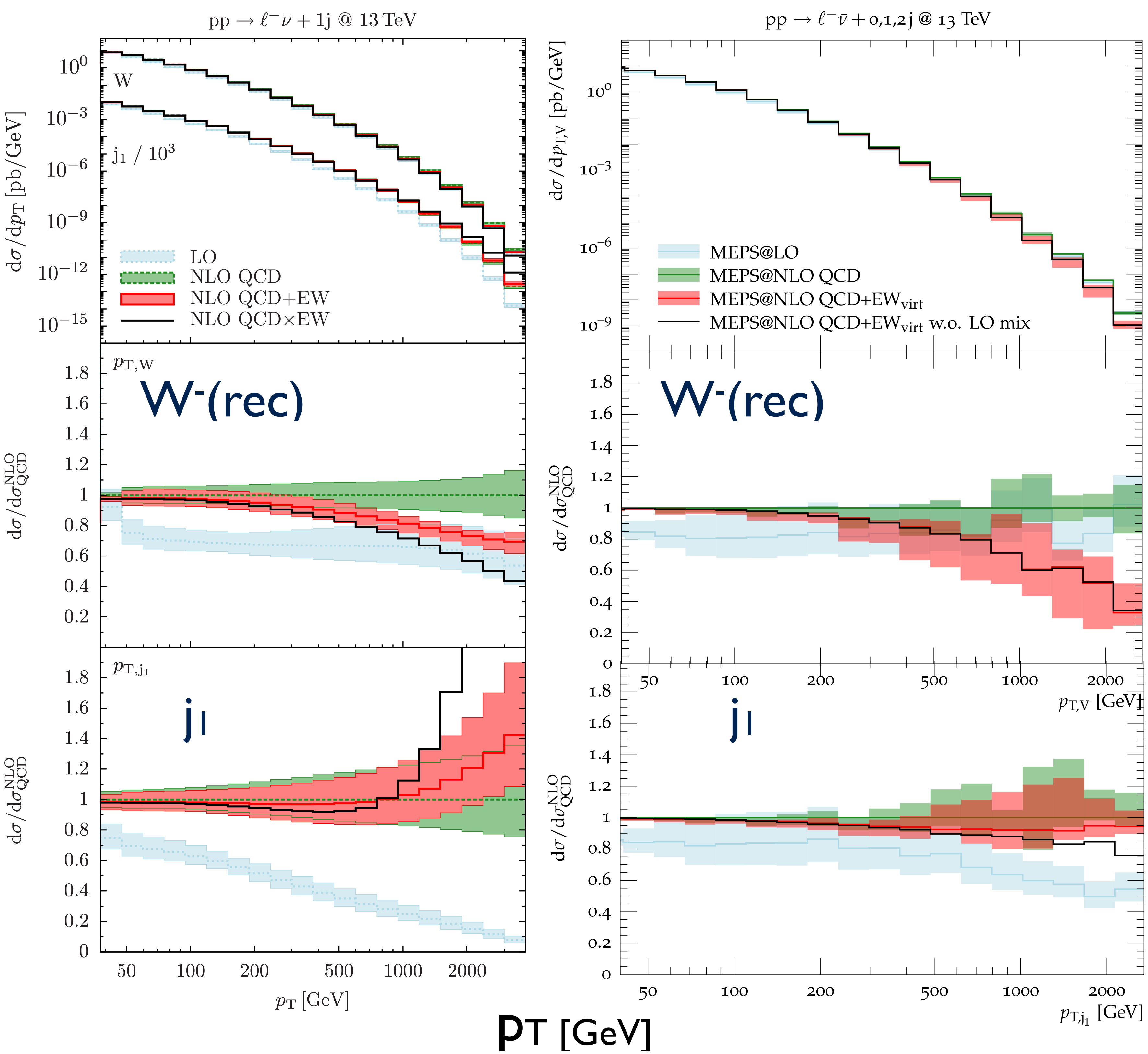
- Validated at fixed-order level (using exclusive sums for merging): percent-level agreement
- exlusive QED corrections could be readded via the parton shower
- use CKKW scale setting $\alpha_S^N(\mu_{\mathrm{CKKW}}^2) = \alpha_S^{N-M}(\mu_{\mathrm{core}}^2)\,\alpha_S(t_1)\ldots\alpha_S(t_M)$ with EW clustering and

$$\mu_{\mathrm{core},\ell\ell} = m_{\ell\ell}, \qquad \mu_{\mathrm{core},Vj} = \frac{1}{2}E_{T,V} = \frac{1}{2}\sqrt{M_V^2 + p_{T,V}^2}, \qquad \mu_{\mathrm{core},jj} = \frac{1}{2}\left(\frac{1}{\hat{s}} - \frac{1}{\hat{t}} - \frac{1}{\hat{u}}\right)^{-\frac{1}{2}}$$

Subleading Born: $p_{T,j1}$



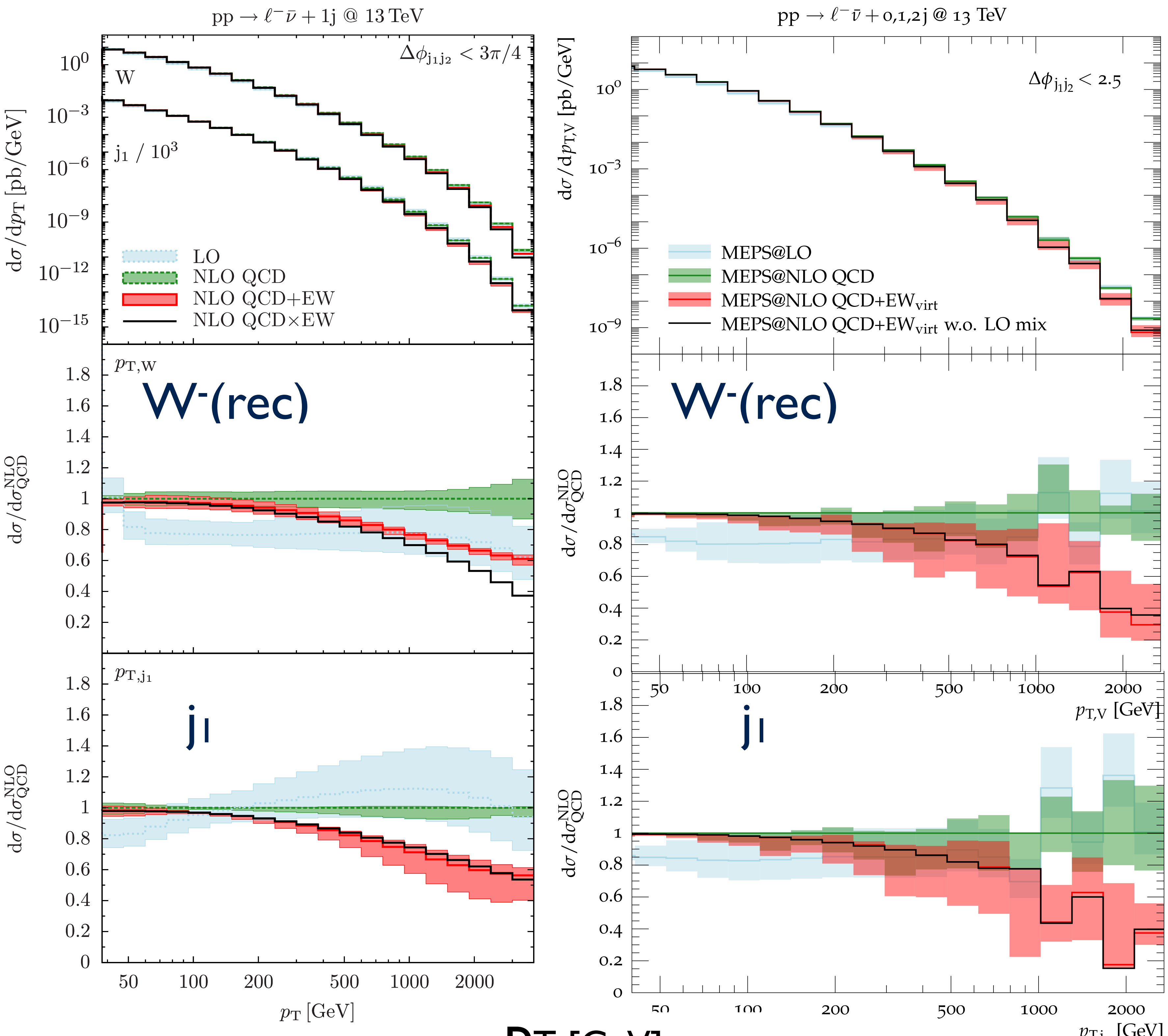
inclusive V+1 jet: MEPS@NLO QCD+EW$_{virt}$



- Stable NLO QCD+EW predictions in all of the phase-space…
- …including Parton-Shower effects.
- Can directly be used by the experimental collaborations

- $p_{T,V}$: MEPS@NLO QCD+EW in agreement with QCDxEW (fixed-order)
- $p_{T,j1}$: compensation between negative Sudakov and LO mix

exclusive V+1jet: MEPS@NLO QCD+EW



pT [GeV]

- Stable NLO QCD+EW predictions in all of the phase-space…
- …including Parton-Shower effects.
- Can directly be used by the experimental collaborations
- $p_{T,j1}$: recover large EW corrections (as in fixed-order)

Conclusions

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

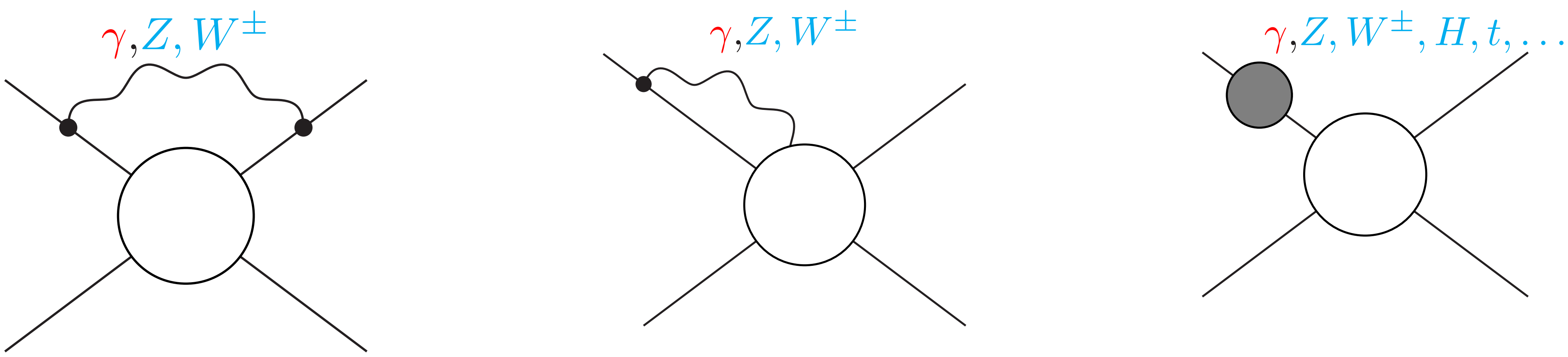
- V + multijets / VV in NLO QCD+EW:
  - inclusion of EW corrections *crucial* at the TeV scale
  - non-trivial interplay between QCD and EW
  - multi-jet final states genuinely different from V+1jet, merging essential for inclusive V+1 jet

- Outlook:
  - Full NLO QCD + EW PS matching & multi-jet merging
  - more processes…
  - ….including VBF processes @ NLO QCD + EW

Backup slides

Virtual EW Sudakov logarithms

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



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

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

- process-independent, simple structure, independent of $\sqrt{S}$
- 2-loop extension and resummation partially available
- typical size at $\sqrt{\hat{s}} = 1, 5, 10$ TeV:

$$\delta_{\text{LL}} \sim -\frac{\alpha}{\pi s_W^2} \log^2 \frac{\hat{s}}{M_W^2} \simeq -28, -76, -104\%,$$

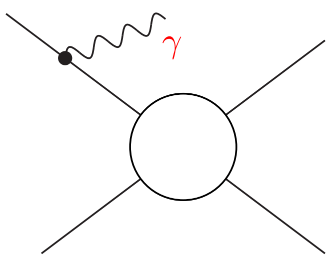
$$\delta_{\text{NLL}} \sim +\frac{3\alpha}{\pi s_W^4} \log \frac{\hat{s}}{M_W^2} \simeq +16, +28, +32\%$$

➡ overall very large effect in the tail of distributions (relevant for BSM searches)

➡ large cancellations possible

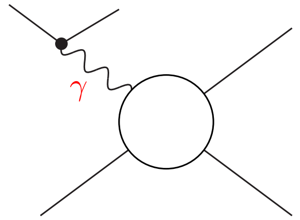
Real EW logarithms

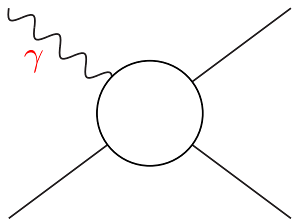
Real photon radiation



- soft/coll. photon unresolved
- needed to cancel QED singularities

Photon initial states

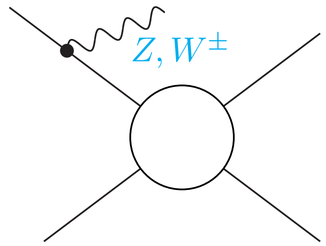




- QED factorisation needed to absorb IS photon singularities
- possible strong enhancement, e.g. for VV *[Baglio, Ninh, Weber; '13]*
  (however huge uncertainties!)

Real W,Z,h radiation (HBR) *[Baur '06, Bell et. al. '10]*

- partial cancellation with virtual Sudakov logs (Bloch-Nordsick theorem not applicable)
  (strongly dependent on experimental selection)
- free from singularities $\Longrightarrow$ trivial LO calculation
- themselves receive large virtual EW corrections
  $\Longrightarrow$ inclusion requires care (double-counting issues)



Performance of NLO EW OpenLoops amplitudes

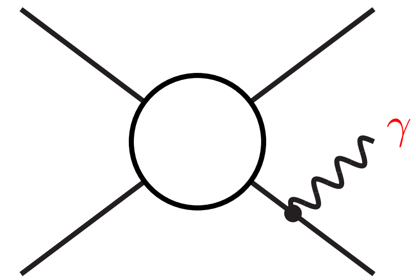
- Performance study for pp → $t\bar{t}$ + n jets with n=0,1,2

$t\bar{t}+0,1,2\,\mathrm{j}$	$n_{\mathrm{loop\ diag}}$ 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

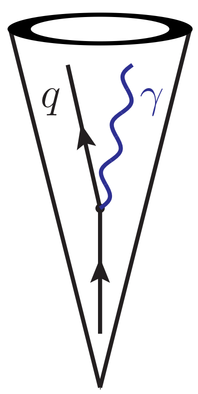
Timings on i7-3770K with gcc 4.8 –O0 dynamic and unpolarised $t\bar{t}$ (significantly faster with decays!) using **COLLIER** for reduction

- 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!

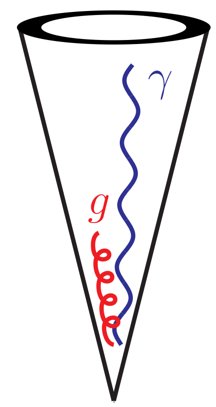
Treatment of Photons



- 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

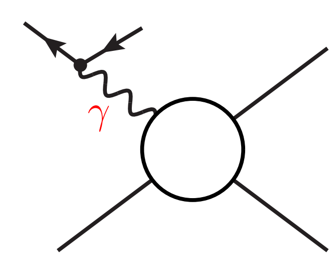


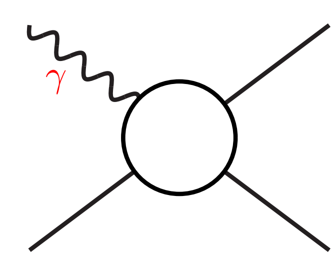
soft gluon singularities ↔ hard photons inside jets: cancelled in jet-production (NLO EW) + γ-production (NLO QCD)

  - Separation of jets from photons through $E_\gamma/E_{jet} < z_{thr}$ 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}!

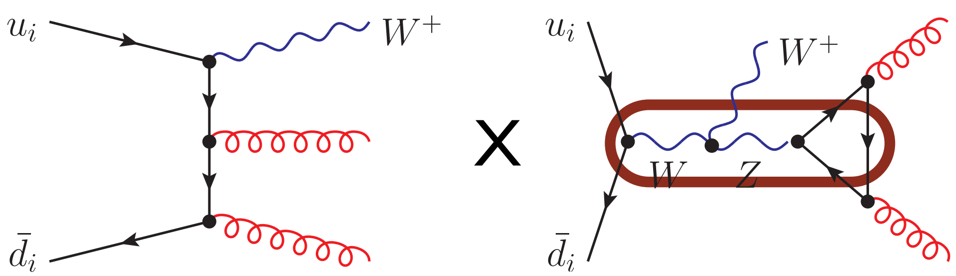
- QED factorisation for IS photons and PDF evolution *[MRST2004, NNPDF2.3]*
- γ-induced processes → possible TeV scale enhancements (However large uncertainties!)



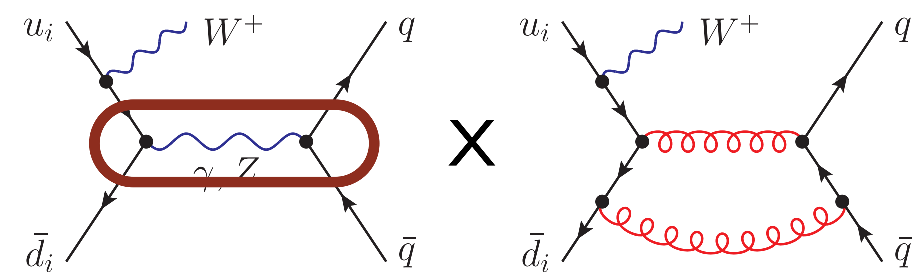


Technical note: pseudo-singularities for W+2,3 jets

gluonic channels



fermionic channels



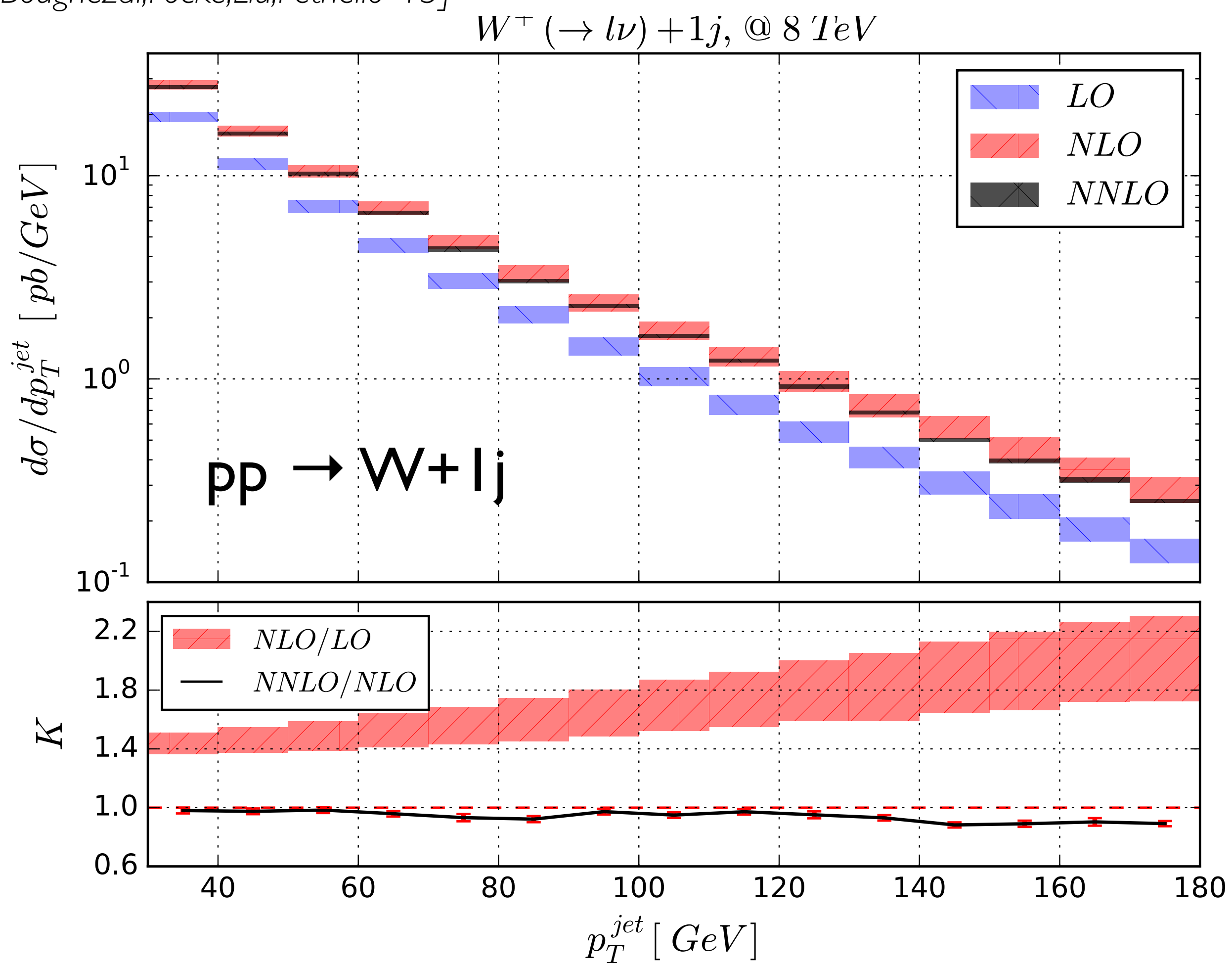
- At the considered order **only effects QCD-EW interferences**
- Complex-mass-scheme can not be used with on-shell/stable W's
- NWA: finite width $\Gamma_{\mathrm{reg.}}$ in potentially s-channel propagators for W, Z ,t ,H
- Smooth **gauge-invariant limit** and negligible numerical dependence for $\Gamma_{\mathrm{reg.}}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

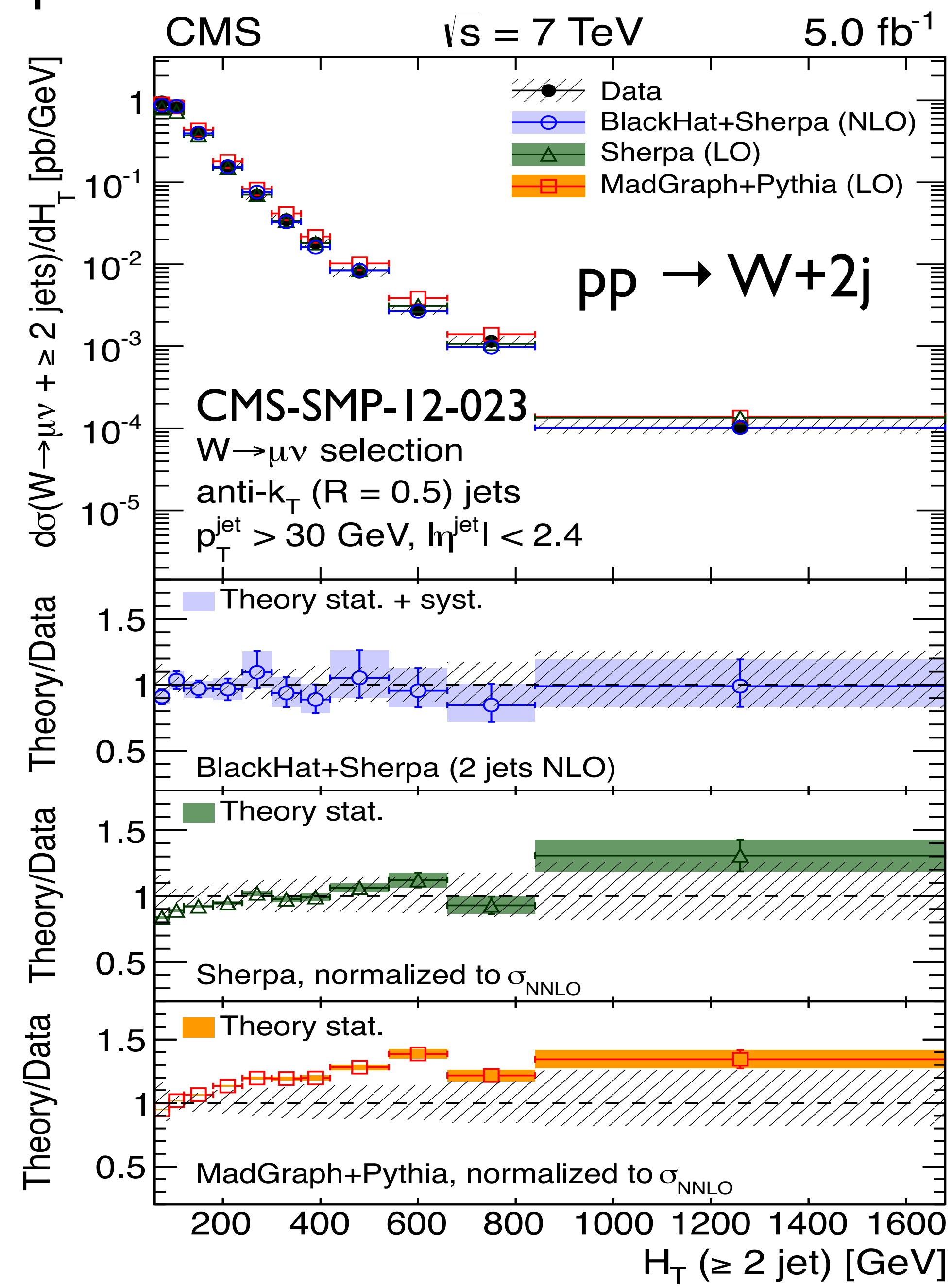
Goal:

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

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 %)

References: W + multijet production

NLO QCD:

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

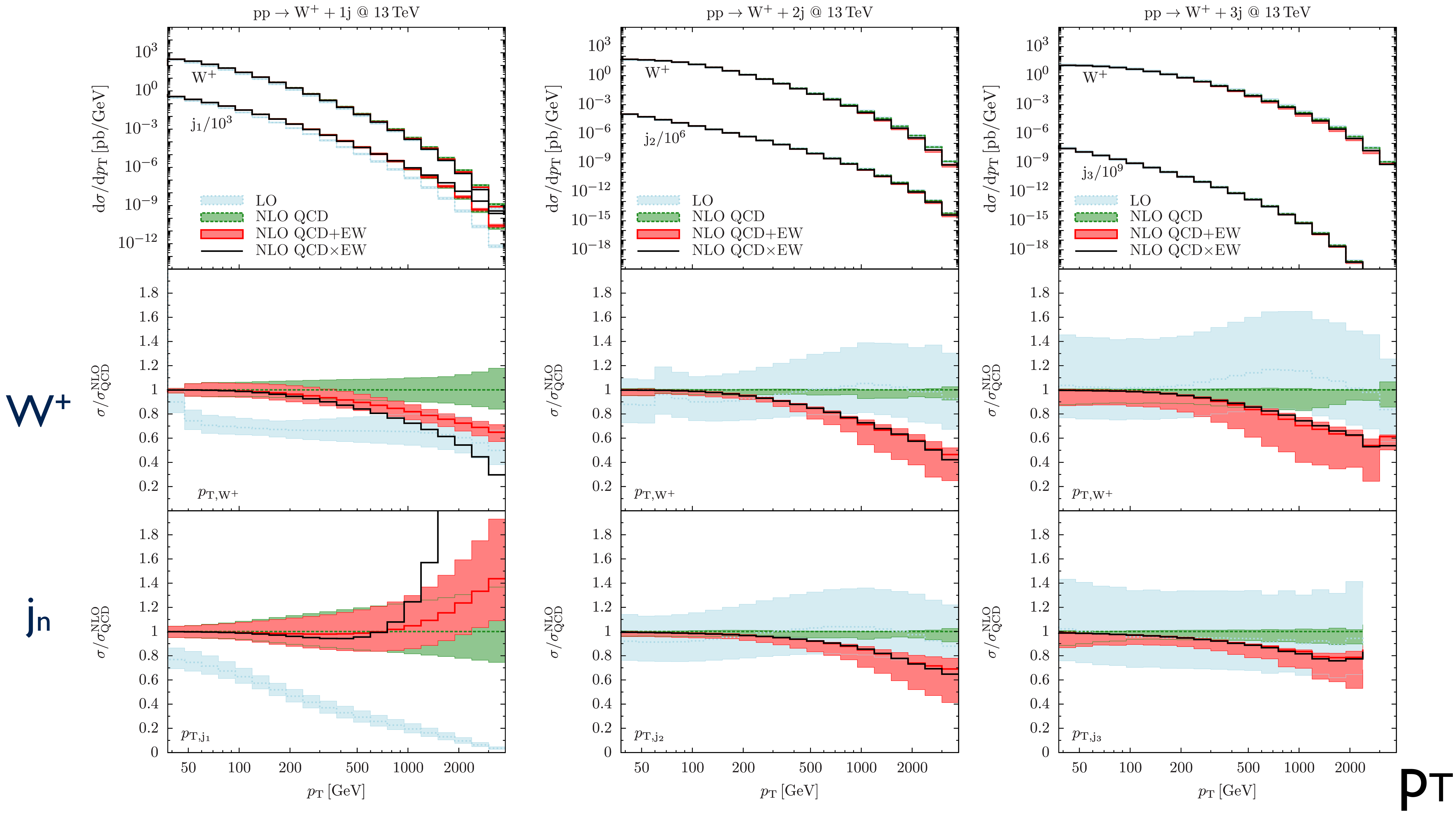
NNLO QCD:

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

NLO EW:

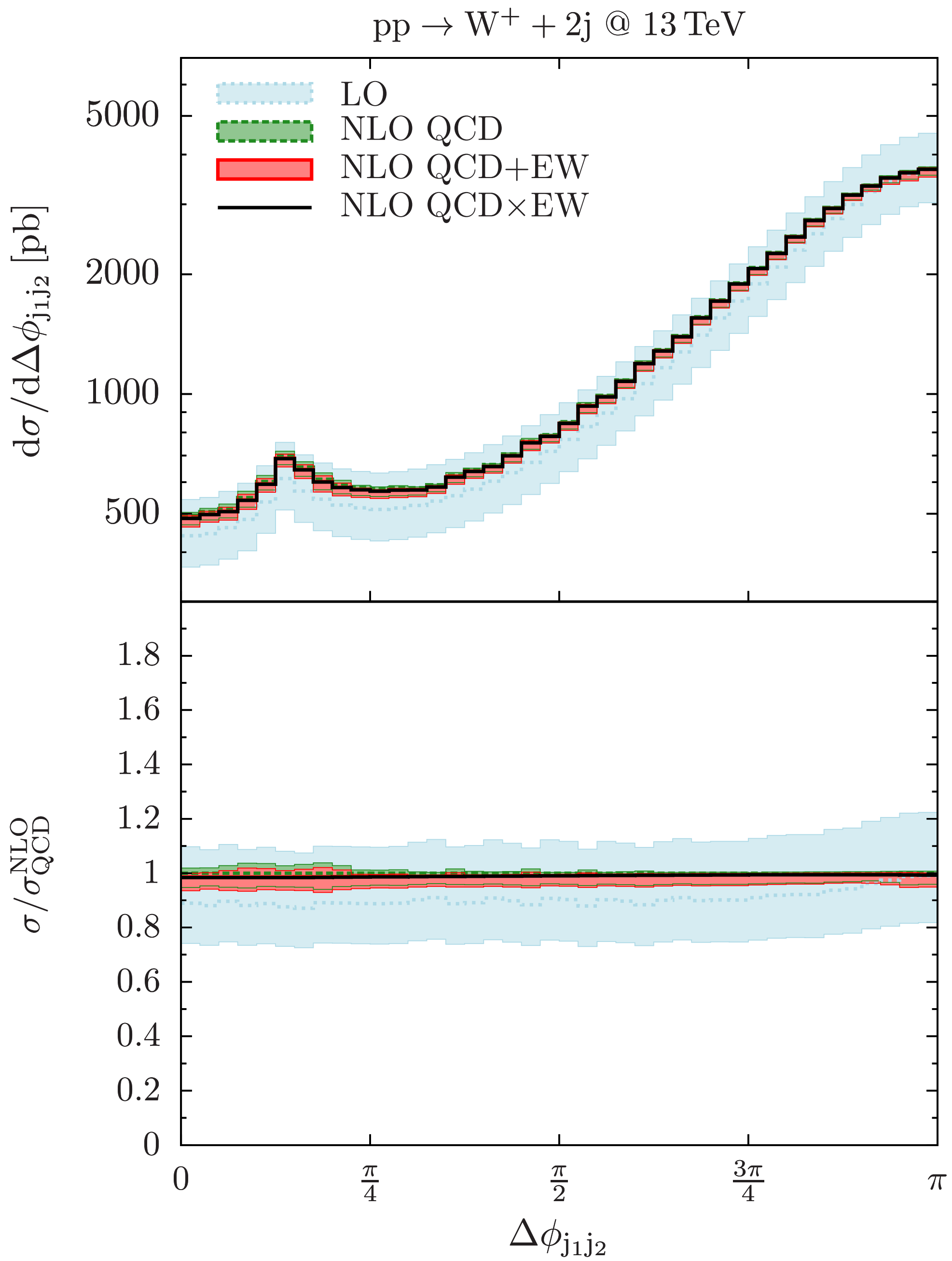
- W + 1 jet *[Kühn, Kulesza, Pozzorini, Schulze, '07; Hollik, Kasprzik, Kniehl, '07; Kühn, Kulesza, Pozzorini, Schulze, '09]* **[this talk!]**
- W(→lν) + 1 jet *[Denner, Dittmaier, Kasprzik, Mück, '09]* **[this talk!]**
- W + 2,3 jets ***[this talk!]***
- W(→lν) + 2 jets ***[this talk!]***

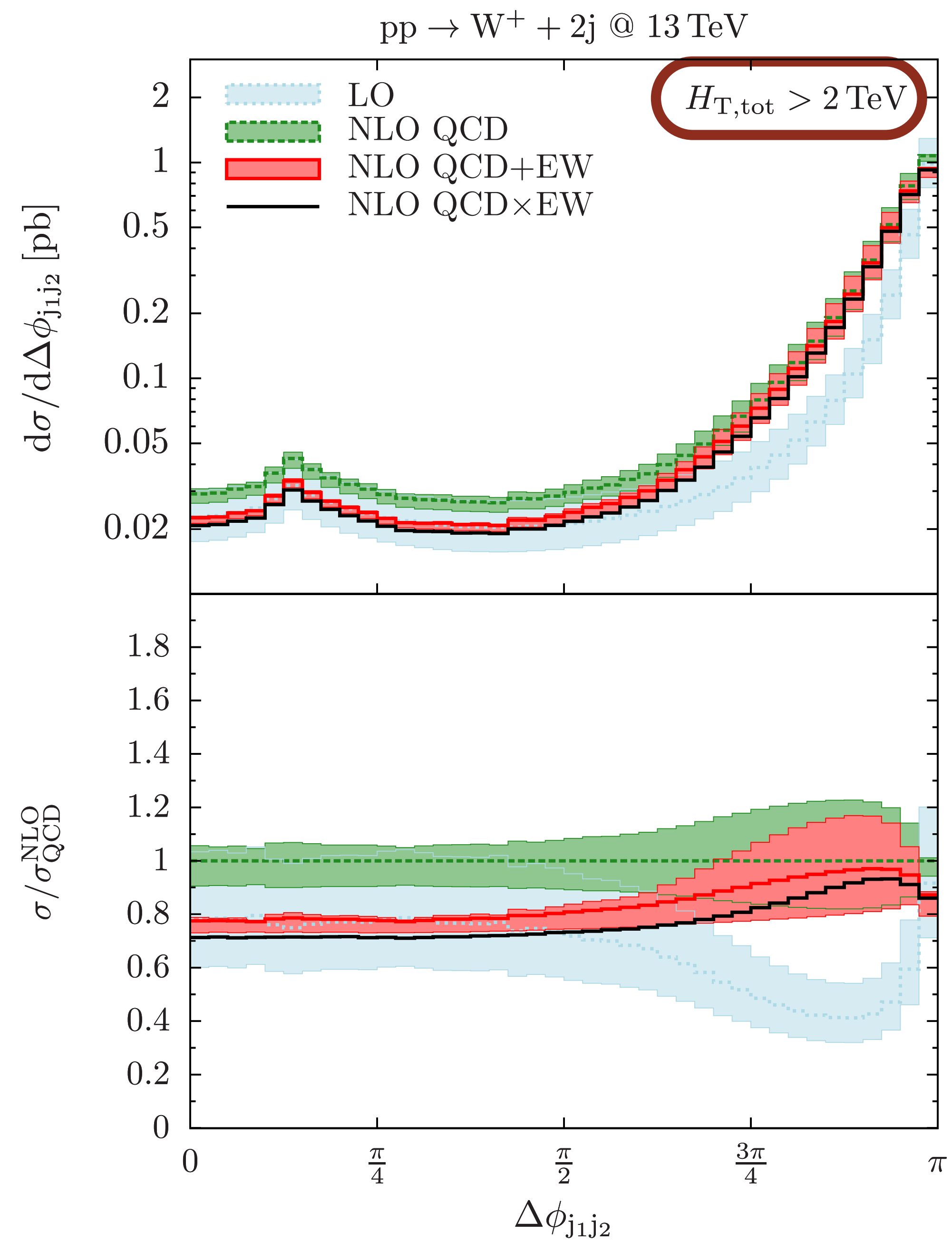
W⁺ + 1,2,3 jets: large EW corrections



- 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

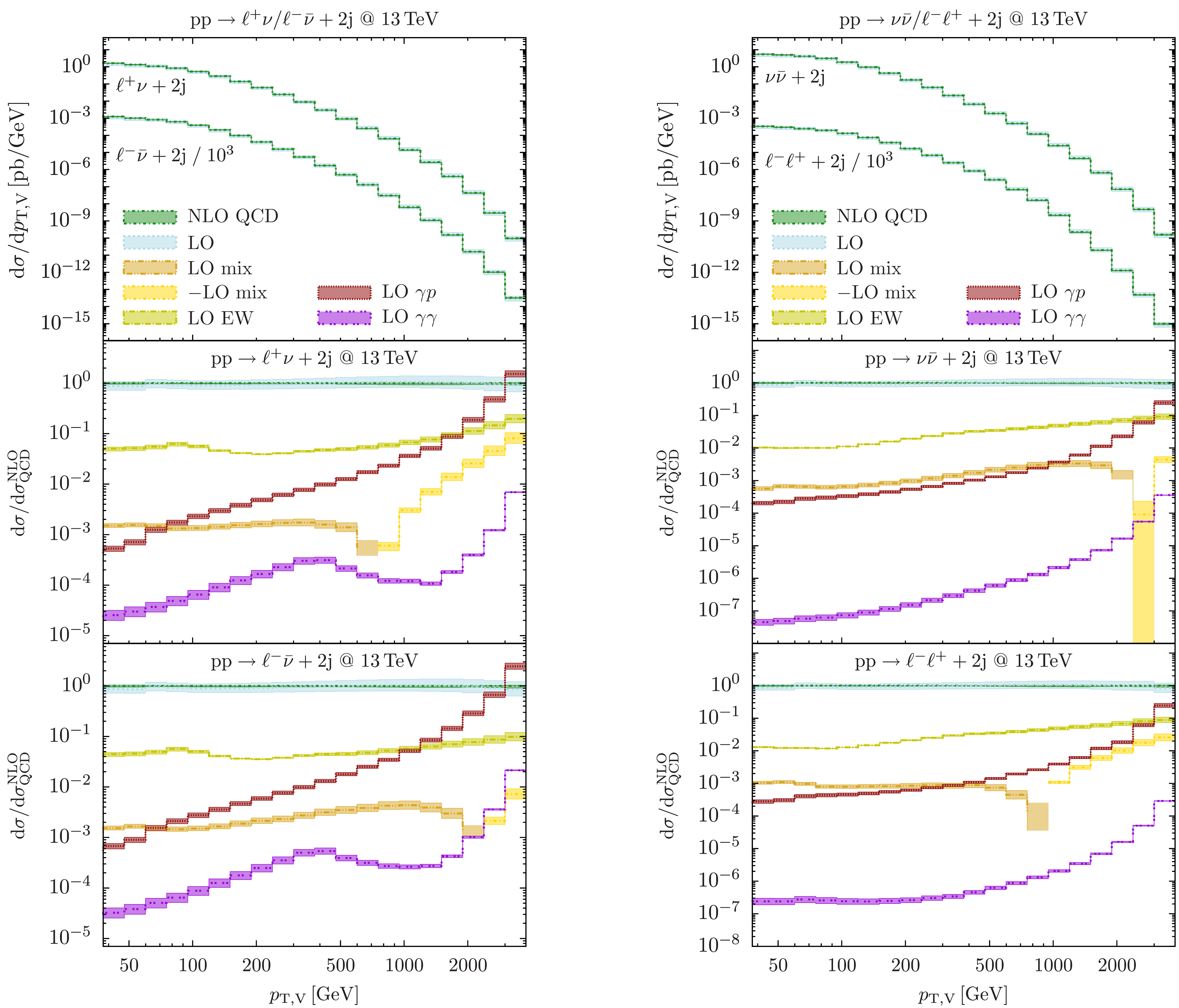




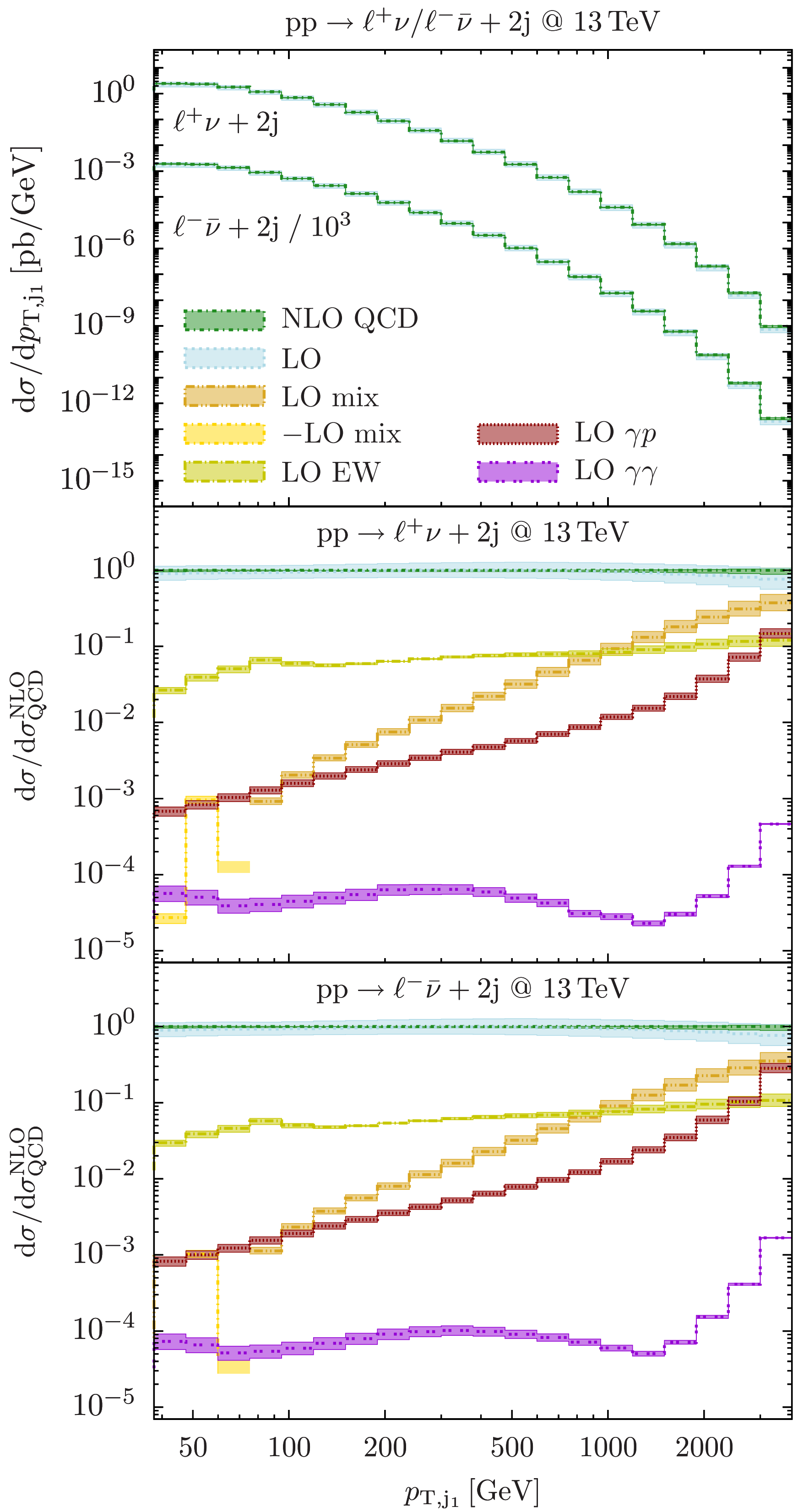
- QCD corrections vanish for $\Delta\phi_{j_1j_2} = \pi$
- small EW corrections

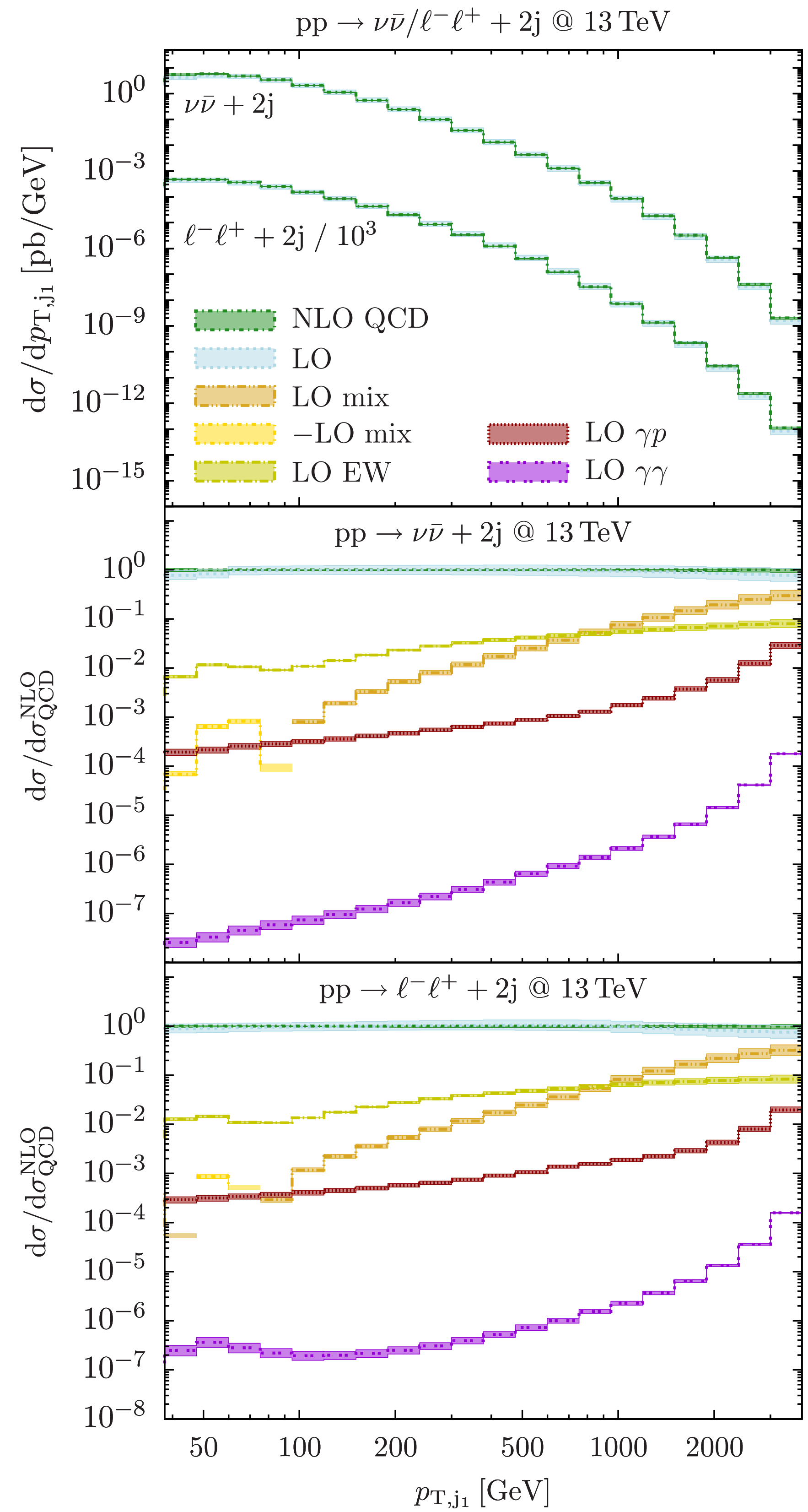
- QCD corrections strongly increase for $3\pi/4 < \Delta\phi_{j_1j_2} < \pi$
- sizeable difference between QCD+EW and QCDxEW
- up to -25% EW corrections

Subleading Born: $p_{T,V}$



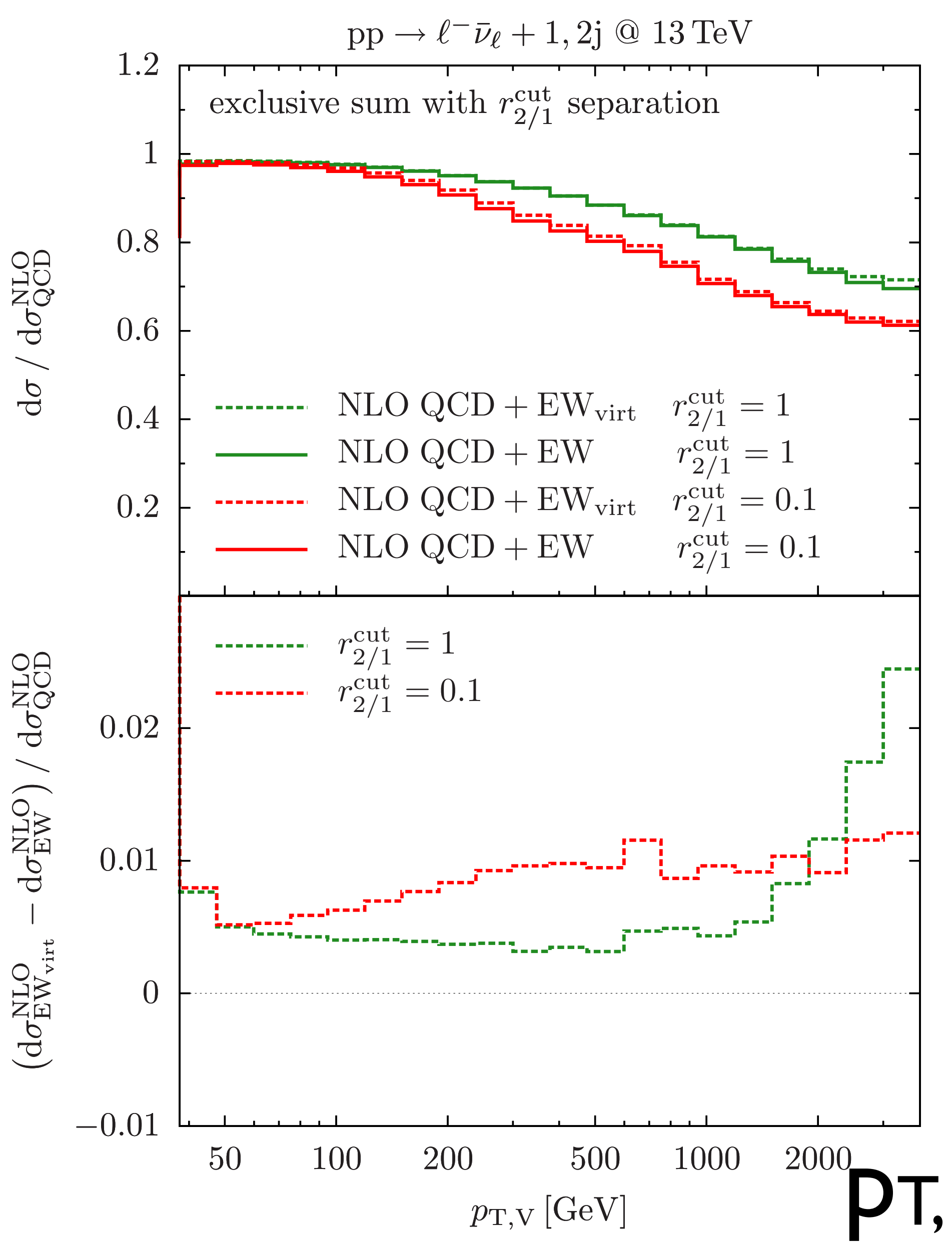
Subleading Born: $p_{T,j1}$



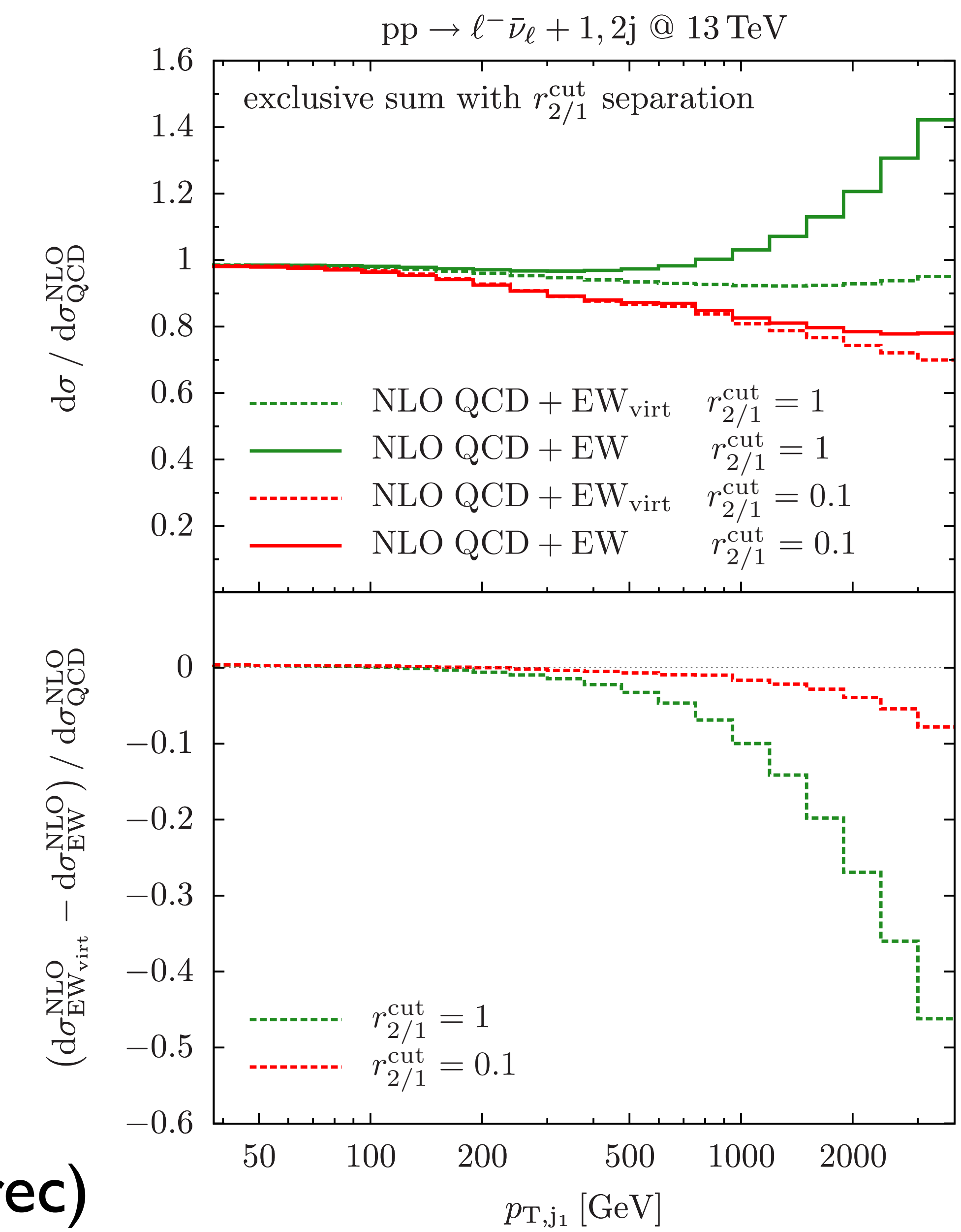


NLO EW$_{\mathrm{virt}}$ Approximation

- Goal: include dominant (Sudakov) corrections into PS Monte-Carlo & apply multi-jet merging (MEPS@NLO)
- Idea: $\mathrm{d}\sigma_{n,\mathrm{NLO\,EW_{virt}}} = \Big[\mathrm{B}_n(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n)\Big]\,\mathrm{d}\Phi_n.$
- Check: agreement within few percent (with $r_{2/1}^{\mathrm{cut}} = 0.1$):

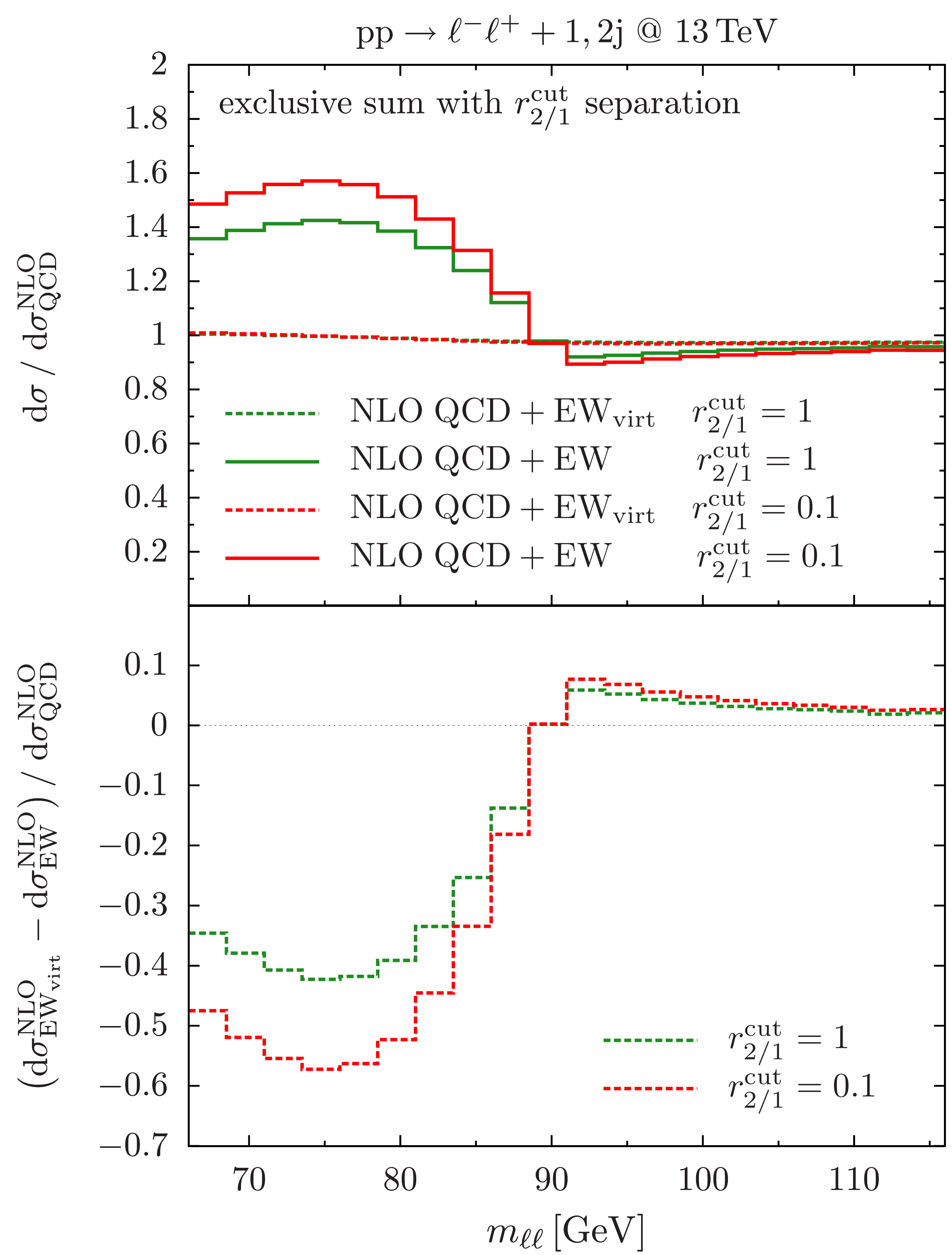


$p_{\mathrm{T,V(rec)}}$



$p_{\mathrm{T,j1}}$

NLO EW_{virt} Approximation: Fail



MEPS@NLO QCD+EW$_{\text{virt}}$ (in a nutshell)

- partition phase-space: n-jet regions for $0 \le n < n_{\max}$ with
$$Q_1 > \cdots > Q_n > Q_{\text{cut}} > Q_{n+1} > \ldots\ .$$

Sudakov

- MEPS@LO: $\mathrm{d}\sigma_n^{(\text{MEPS@LO})} = \mathrm{d}\Phi_n\,\mathrm{B}_n(\Phi_n)\,\Theta(Q_n - Q_{\text{cut}})\,\mathcal{F}_n(\mu_Q^2\,;<Q_{\text{cut}})$,
- Scale setting: $\alpha_S^N(\mu_{\text{CKKW}}^2) = \alpha_S^{N-M}(\mu_{\text{core}}^2)\,\alpha_S(t_1)\ldots\alpha_S(t_M)$ with

$$\mu_{\text{core},\ell\ell} = m_{\ell\ell}, \qquad \mu_{\text{core},Vj} = \frac{1}{2}E_{T,V} = \frac{1}{2}\sqrt{M_V^2 + p_{T,V}^2}, \qquad \mu_{\text{core},jj} = \frac{1}{2}\left(\frac{1}{\hat{s}} - \frac{1}{\hat{t}} - \frac{1}{\hat{u}}\right)^{-\frac{1}{2}}$$

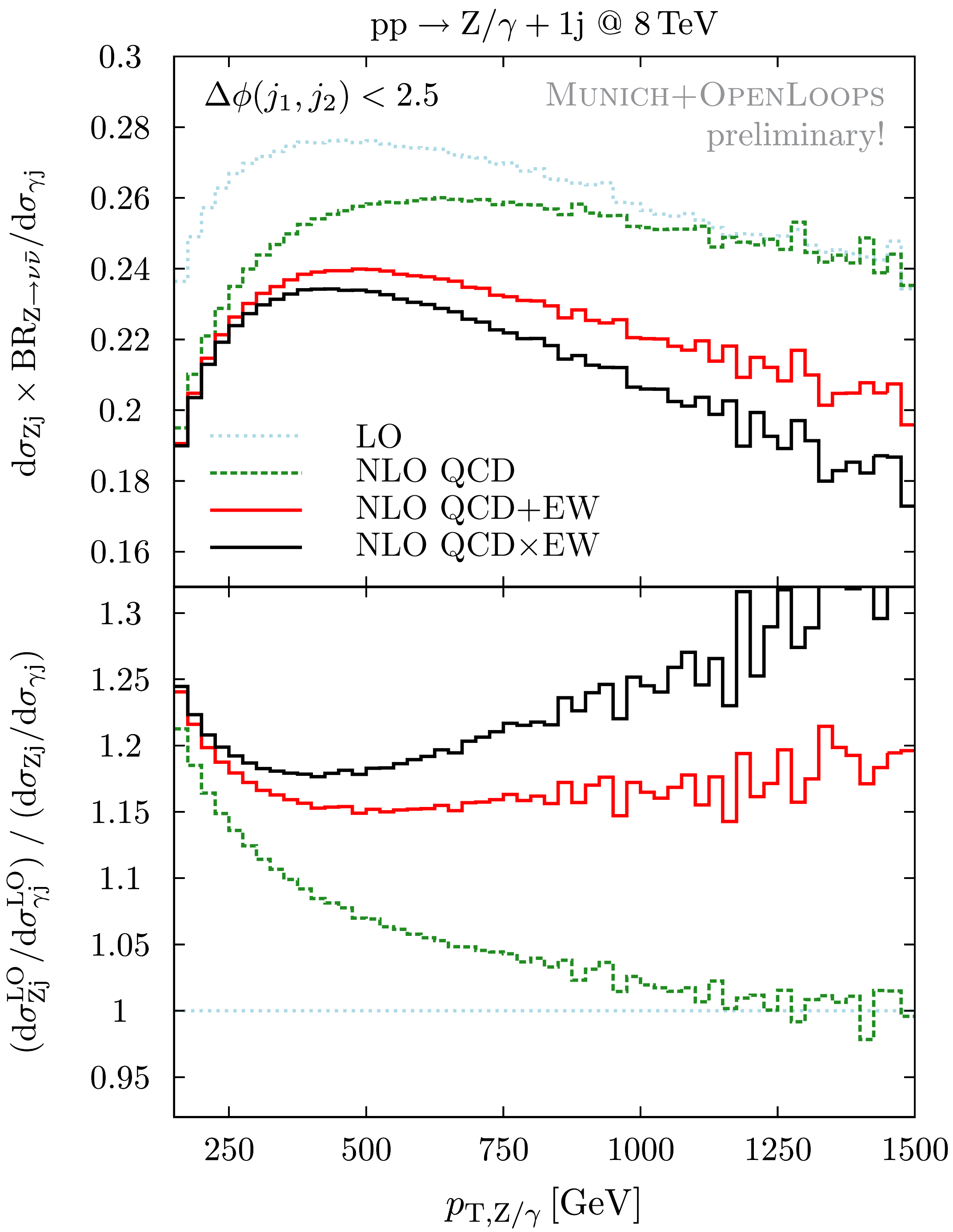
- MEPS@NLO: $$\mathrm{d}\sigma_n^{(\text{MEPS@NLO})} = \Big[\mathrm{d}\Phi_n\,\tilde{\mathrm{B}}_n(\Phi_n)\,\bar{\mathcal{F}}_n(\mu_Q^2\,;<Q_{\text{cut}}) + \mathrm{d}\Phi_{n+1}\,\tilde{\mathrm{H}}_n(\Phi_{n+1})\,\Theta(Q_{\text{cut}} - Q_{n+1})\,\mathcal{F}_{n+1}(\mu_Q^2\,;<Q_{\text{cut}})\Big]\,\Theta(Q_n - Q_{\text{cut}})$$

$$\tilde{\mathrm{B}}_n(\Phi_n) = \mathrm{B}_n(\Phi_n) + \tilde{\mathrm{V}}_n(\Phi_n) + \int \mathrm{d}\Phi_1\,\tilde{\mathrm{D}}_n(\Phi_n,\Phi_1)\,\Theta(\mu_Q^2 - t_{n+1})$$

$\tilde{H}_n$ = "hard function" , $\tilde{D}_n$ = kernel of first emission

- MEPS@NLO QCD+EW: $\tilde{\mathrm{B}}_{n,\text{QCD+EW}}(\Phi_n) = \tilde{\mathrm{B}}_n(\Phi_n) + \mathrm{V}_{n,\text{EW}}(\Phi_n) + \mathrm{I}_{n,\text{EW}}(\Phi_n) + \mathrm{B}_{n,\text{mix}}(\Phi_n)$

Z/γ + 1 jet: pT-ratio



Overall

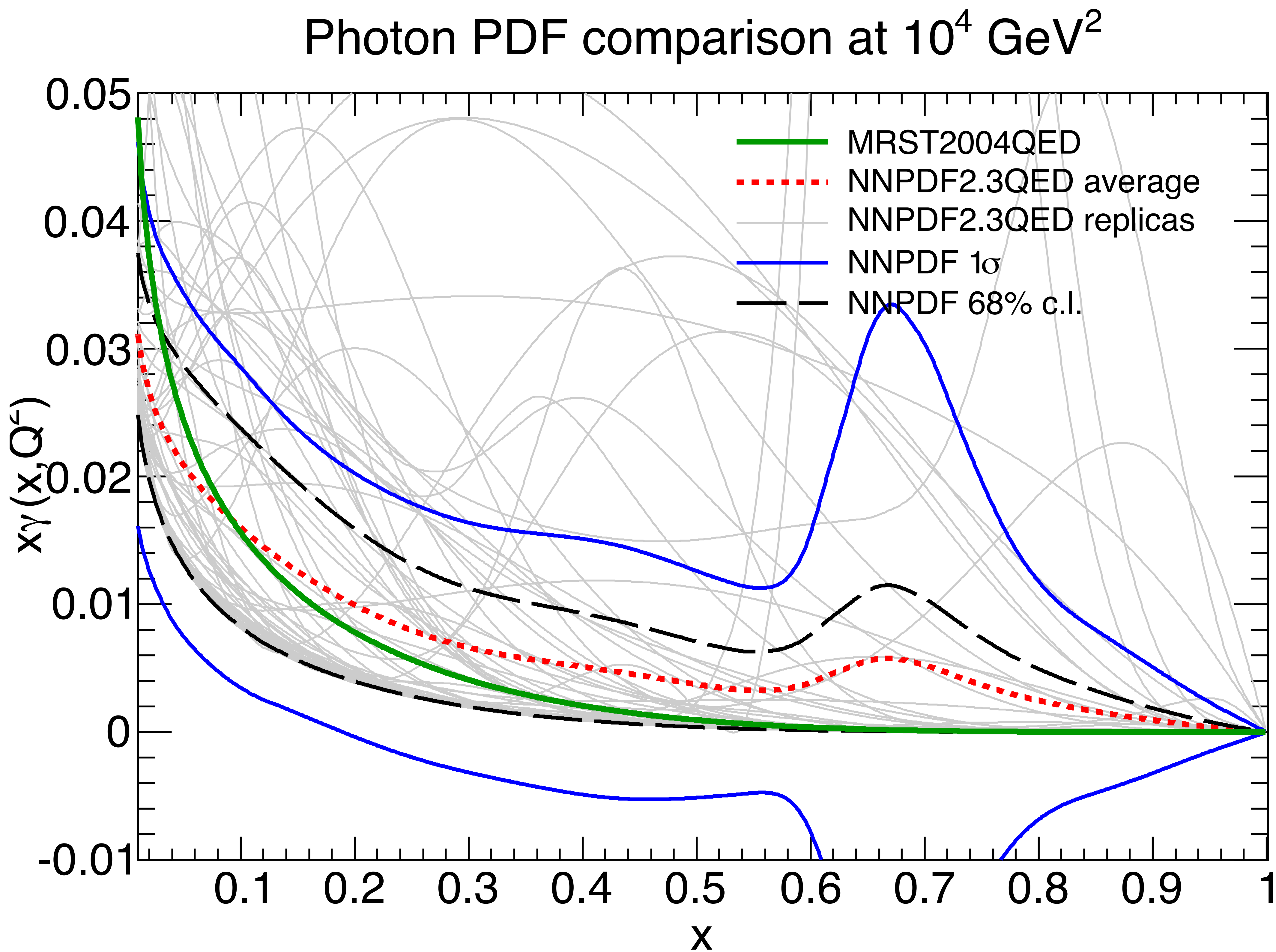
- mild dependence on the boson pT

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



Photon PDF comparison at 10^4 GeV^2
MRST2004QED
NNPDF2.3QED average
NNPDF2.3QED replicas
NNPDF 1σ
NNPDF 68% c.l.
$x\gamma(x,Q^2)$
x
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