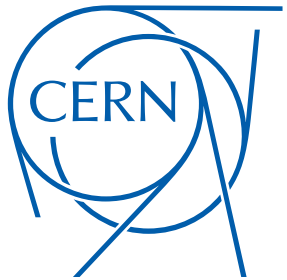
Jet and V+jet production
–
theory overview

Marek Schönherr

CERN

LHC EW Working Group Meeting



Outline

Inclusive jet and dijet production

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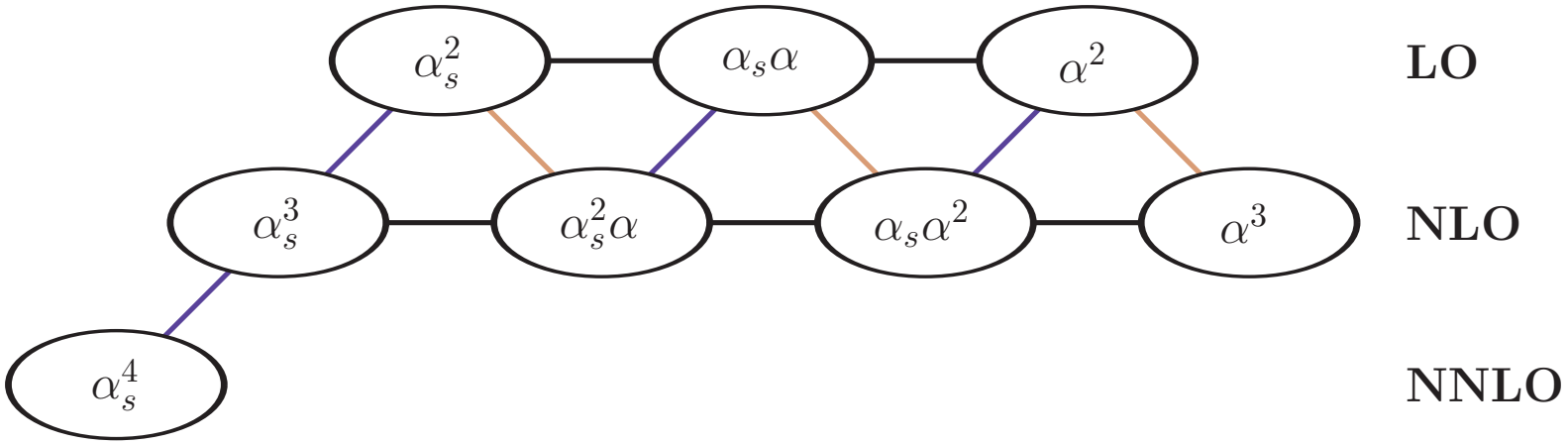

- LO processes (QCD production, EW production, interference)
- NLO QCD corrections Ellis, Kunszt, Soper Phys.Rev.Lett.64(1990)2121
  - → available as POWHEG, aMC@NLO, MCFM, ...
- NLO weak corrections Dittmaier, Huss, Speckner arXiv:1210.0438
- all NLO corrections Frederix et.al. arXiv:1612:06548
- (LC) NNLO QCD corrections Currie, Glover, Pires arXiv:1611.01460

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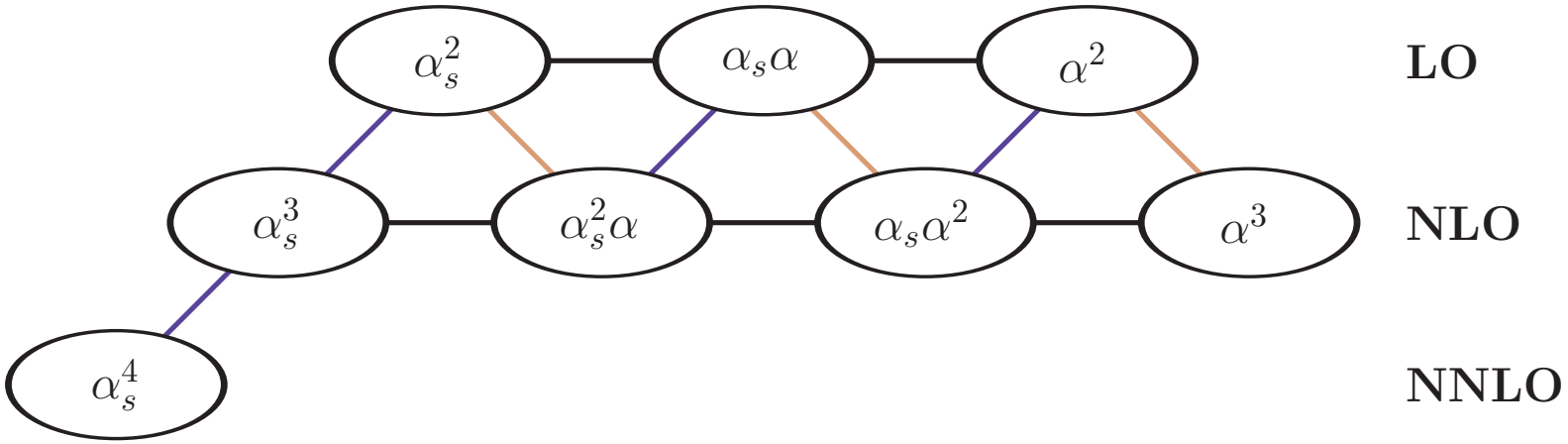

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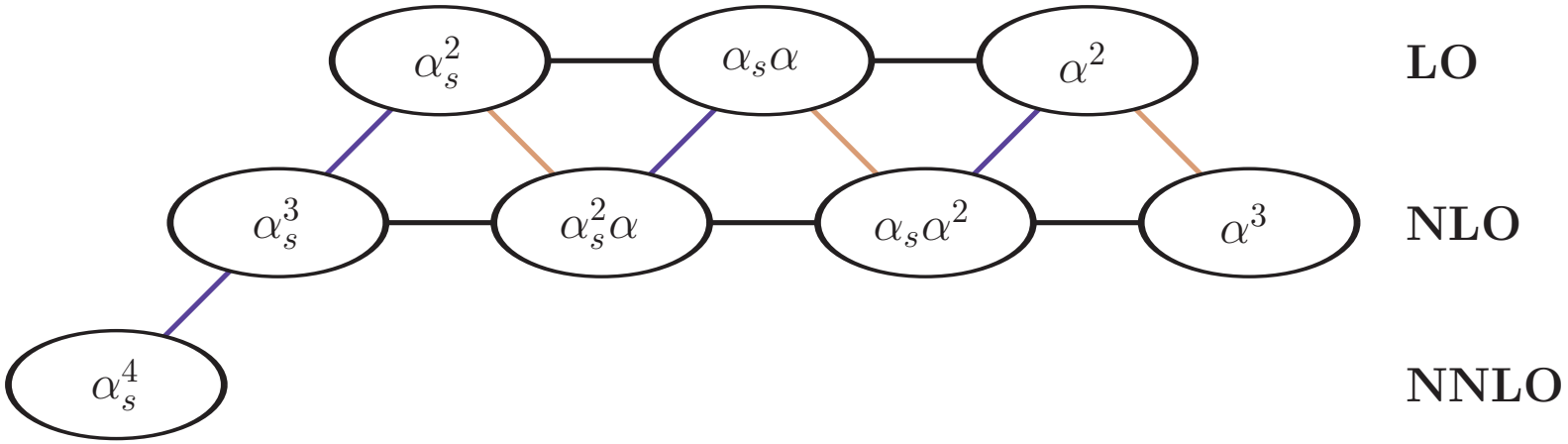

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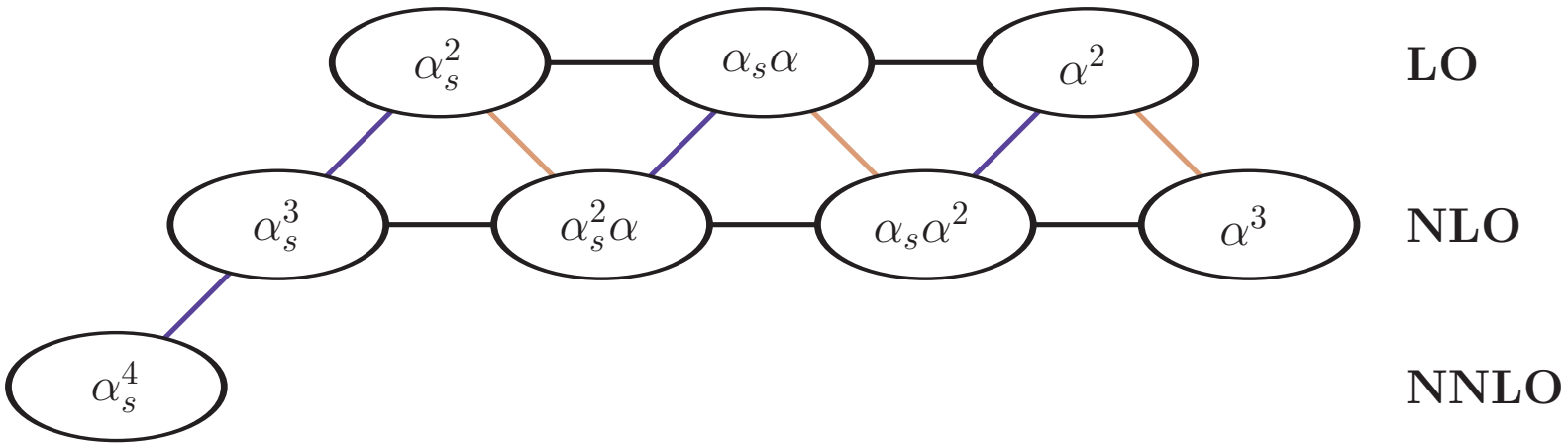

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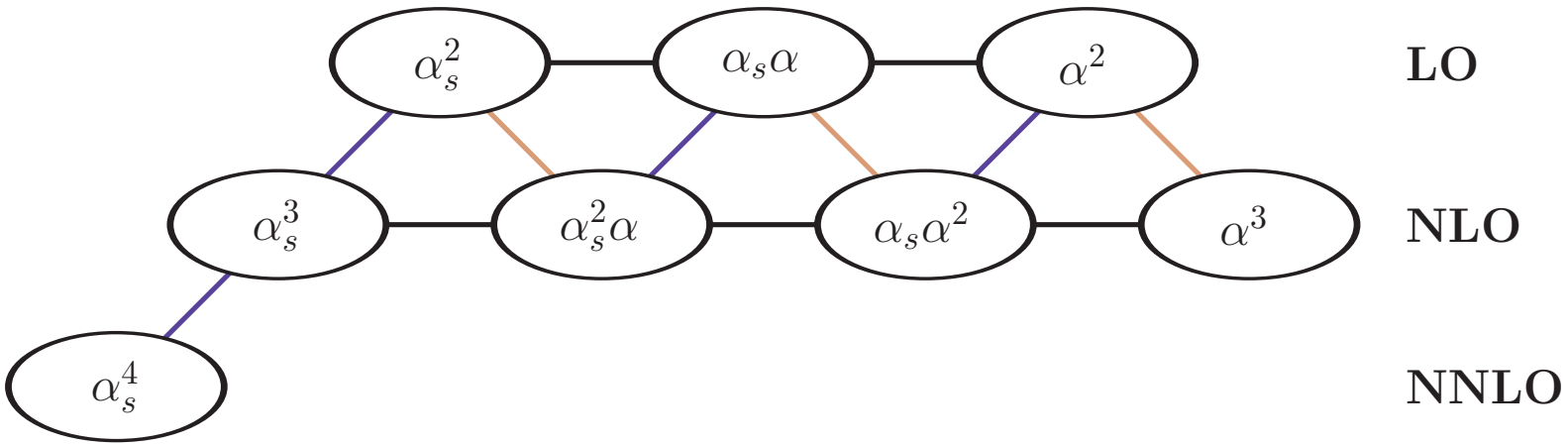

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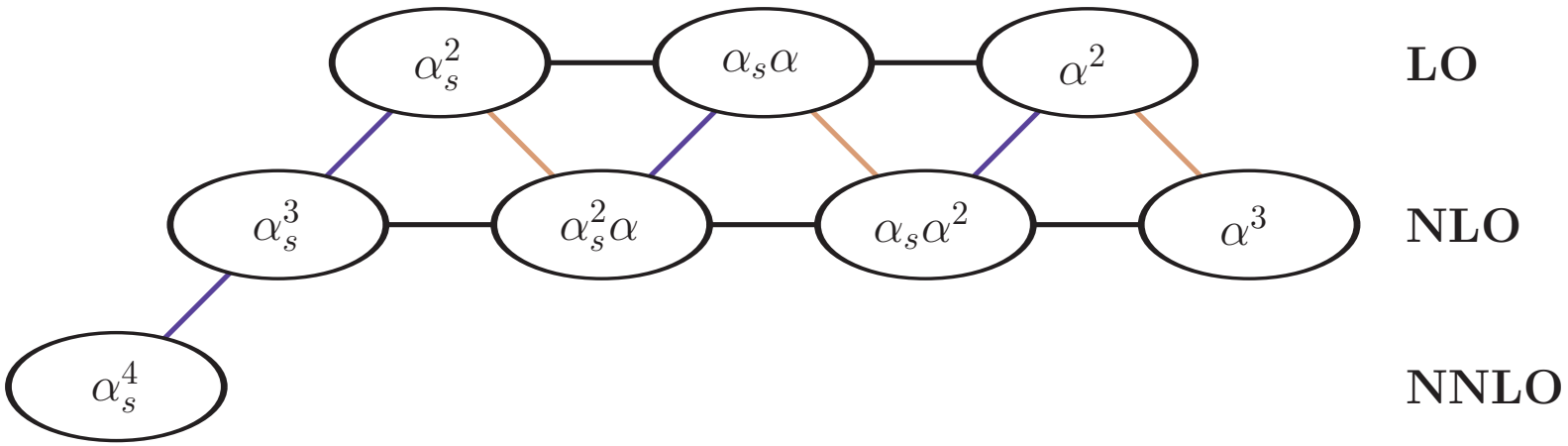

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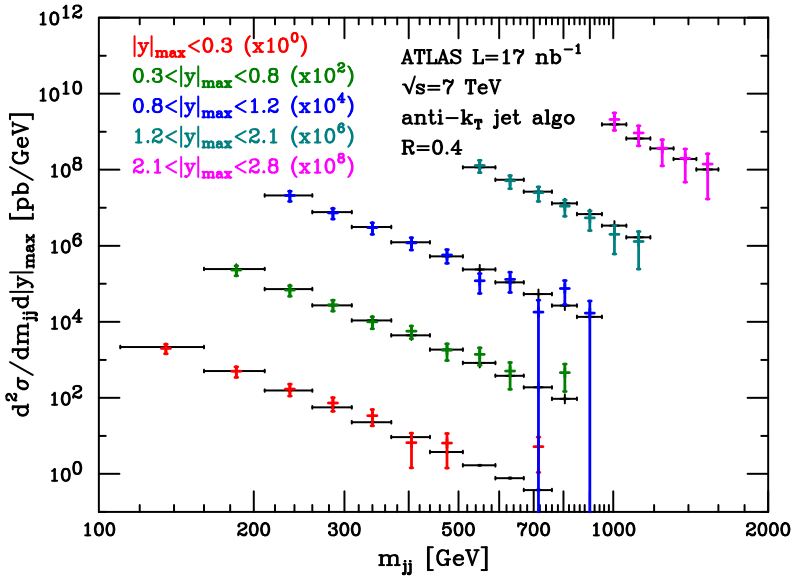

POWHEG

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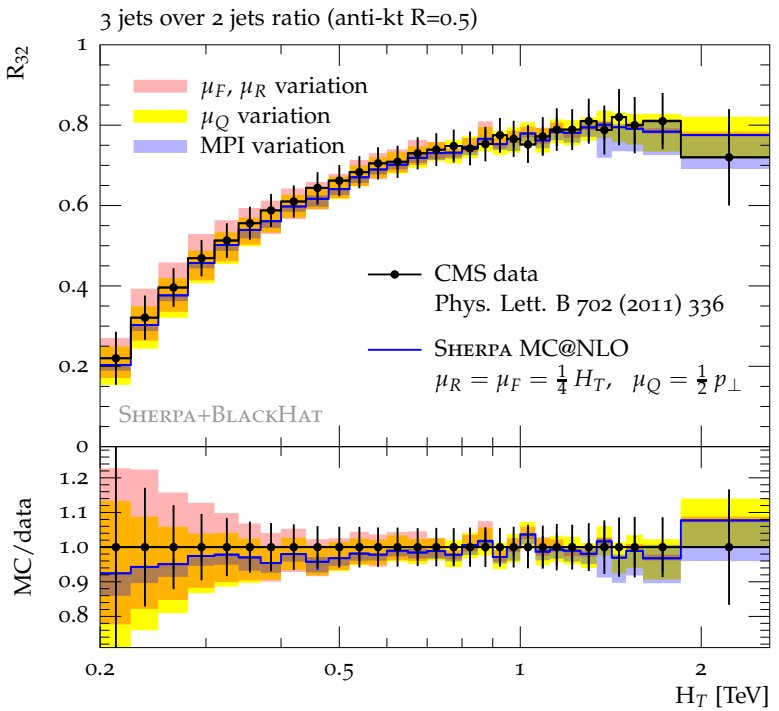
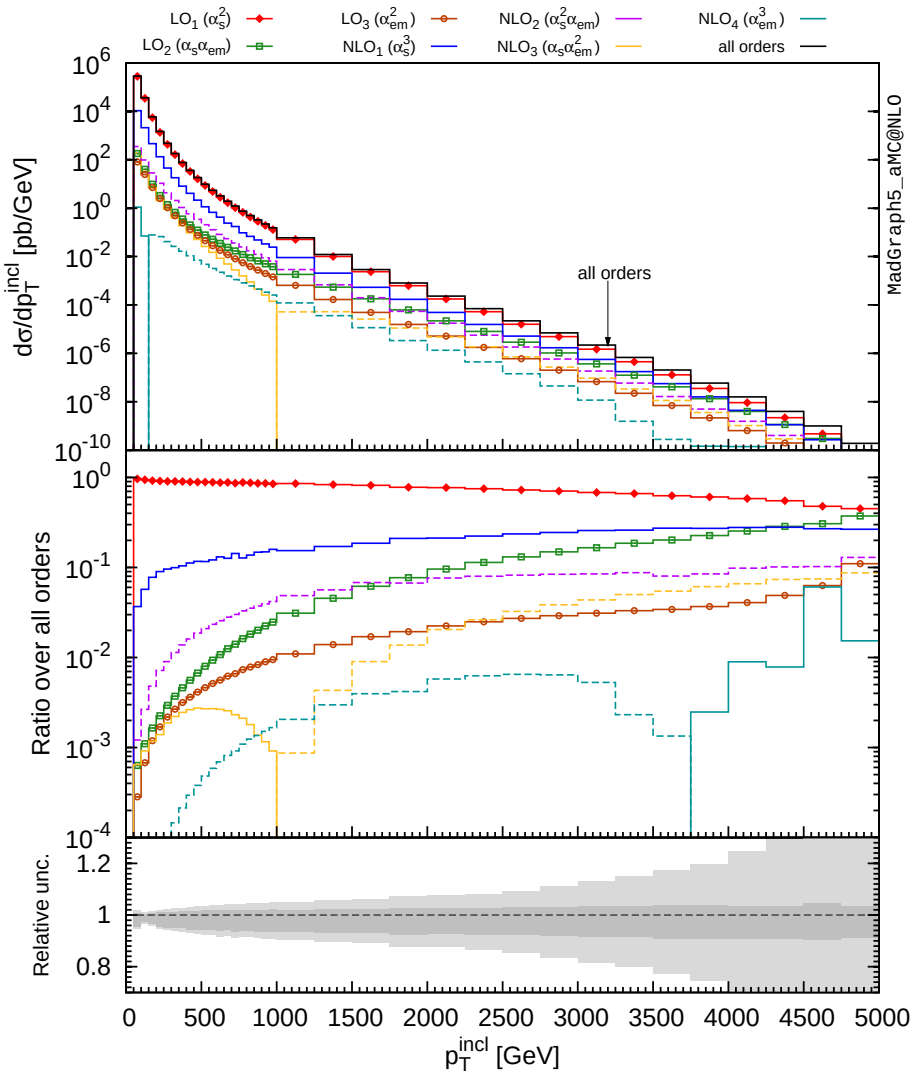


S-MC@NLO

Inclusive jet and dijet production

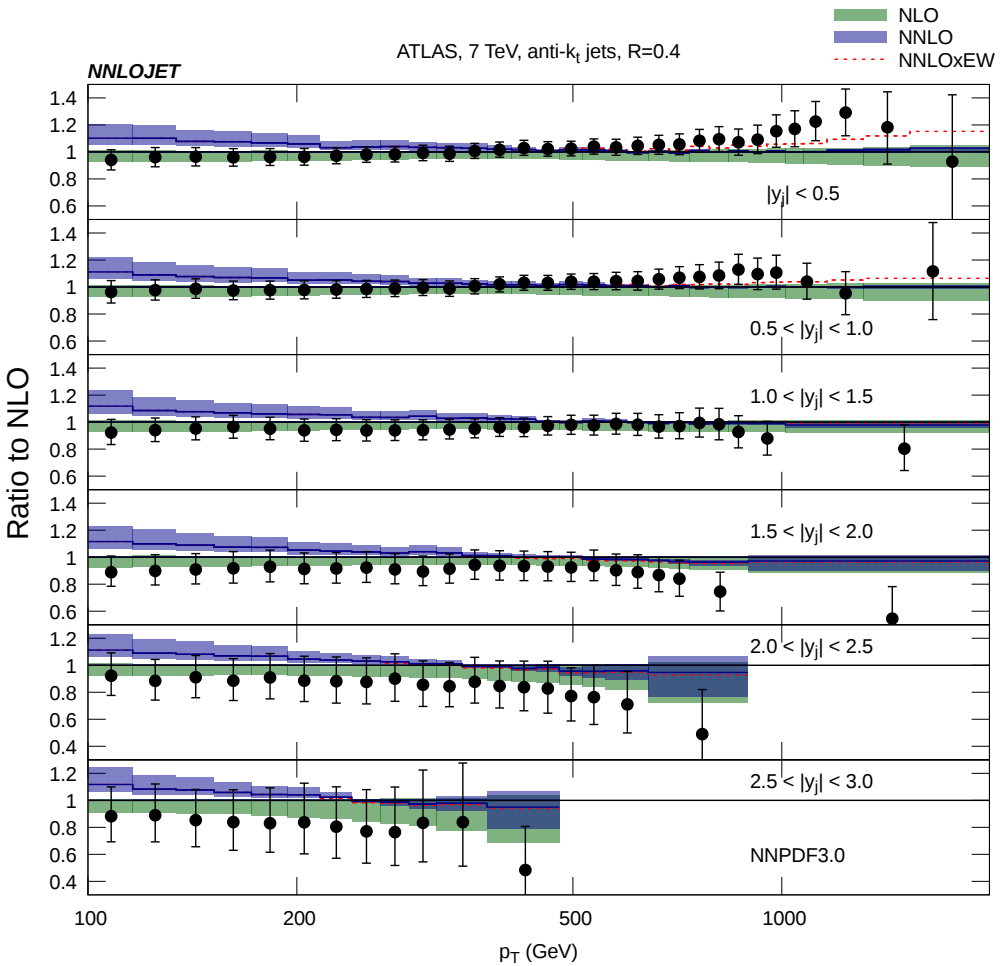
Frederix et.al. arXiv:1612:06548

- calculate all LO & NLO contribs to incl. jet and dijet production
- dominated by leading $\mathcal{O}(\alpha_S{}^2)$ and $\mathcal{O}(\alpha_S{}^3)$ contribs over large parts of the spectrum
- subleading contribs important at high p_{T}
- final state partons: g, q, γ, ℓ
- in some of the orders jets are photon-anti-tagged

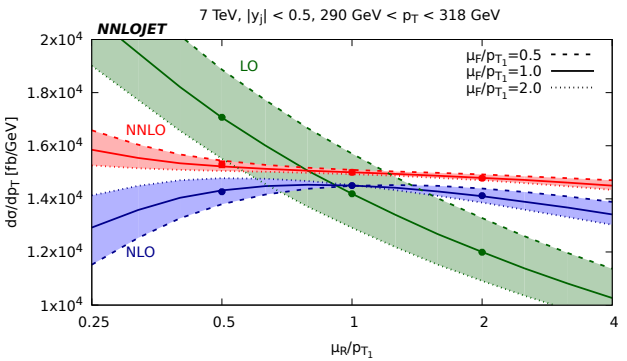


Inclusive jet production @ NNLO

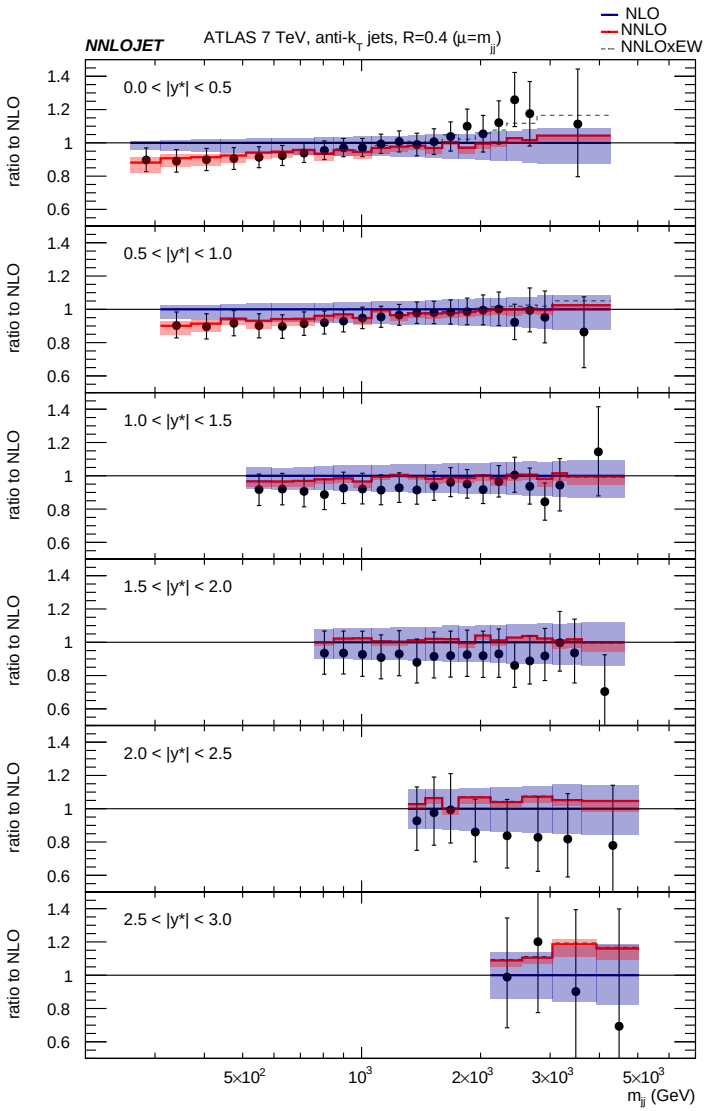
Currie, Glover, Pires arXiv:1611.01460



- $\mu_R = \mu_F = p_{\mathrm{T}}^{\mathrm{lead}}$
- no sign. reduction in scales found for this scale
- $\mu_R = \mu_F = p_{\mathrm{T}}$ works better



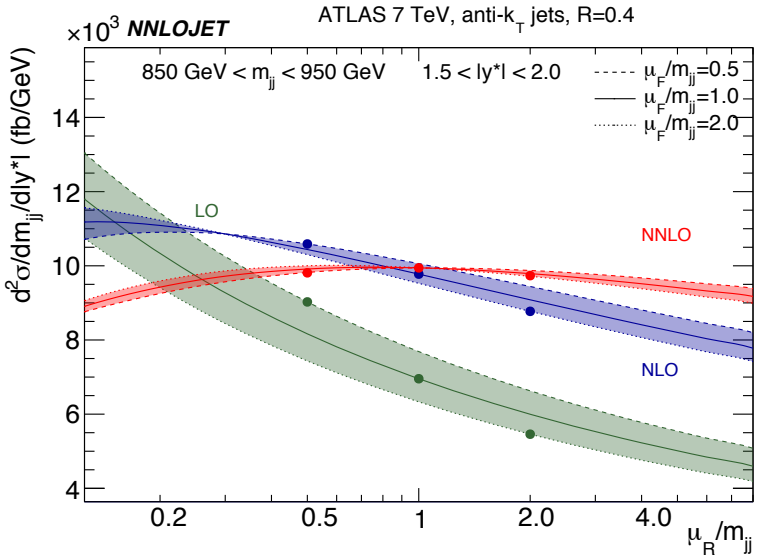
Dijet production @ NNLO



Currie et.al. arXiv:1705.10271

- $\mu_R = \mu_F = m_{jj}$
- classic improvements at NNLO, but in data description and theoretical uncertainty
- EW corrections needed at large m_{jj}

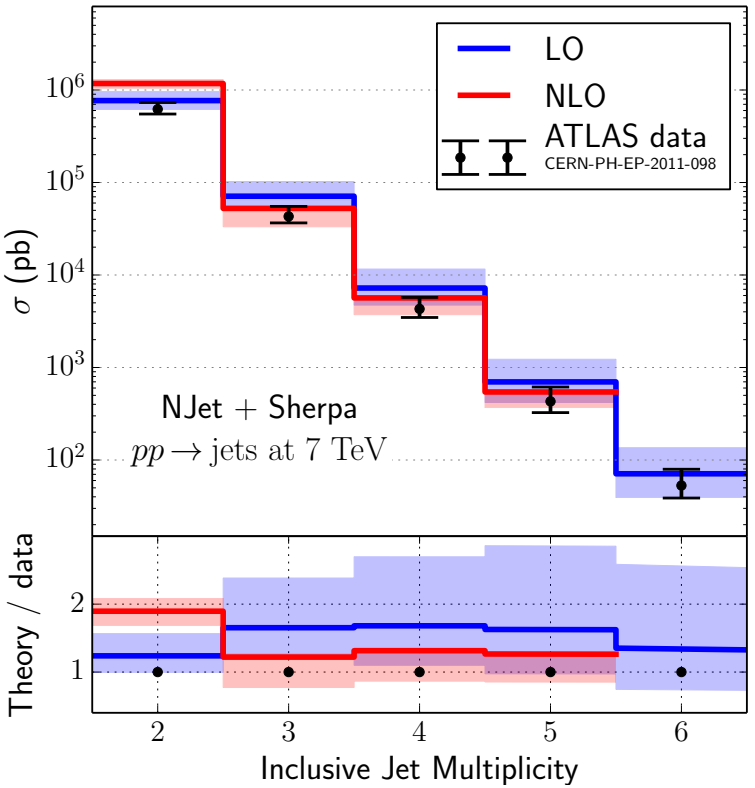
Dittmaier, Huss, Speckner arXiv:1210.0438



Multijet production

Badger et.al. arXiv:1309.6585

- NLO QCD corrections $\mathcal{O}(\alpha_S{}^{n+1})$ known for up to 5j production

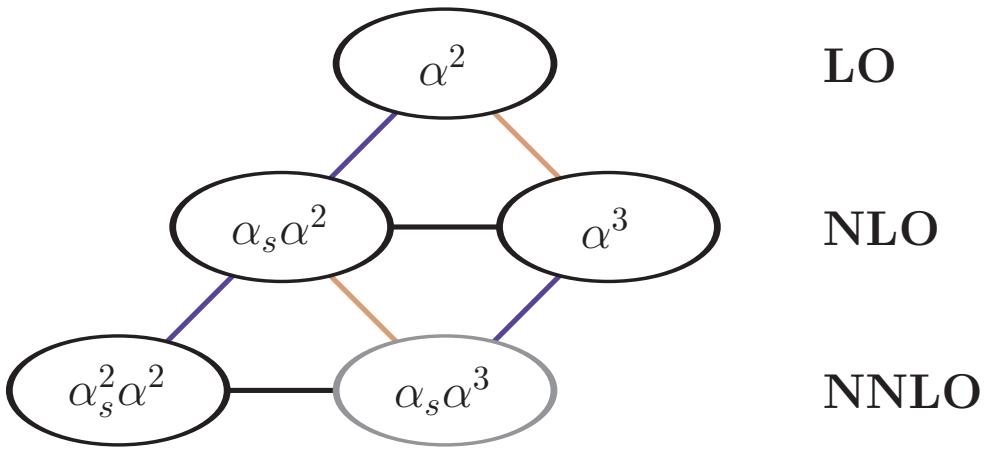


Bern et.al. arXiv:1112.3940

no. jets	ATLAS	LO	ME+PS	NLO	NP factor	NLO+NP
≥ 2	$620 \pm 1.3^{+110}_{-66} \pm 24$	$958(1)^{+316}_{-221}$	559(5)	$1193(3)^{+130}_{-135}$	0.95(0.02)	$1130(19)^{+124}_{-129}$
≥ 3	$43 \pm 0.13^{+12}_{-6.2} \pm 1.7$	$93.4(0.1)^{+50.4}_{-30.3}$	39.7(0.9)	$54.5(0.5)^{+2.2}_{-19.9}$	0.92(0.04)	$50.2(2.1)^{+2.0}_{-18.3}$
≥ 4	$4.3 \pm 0.04^{+1.4}_{-0.79} \pm 0.24$	$9.98(0.01)^{+7.40}_{-3.95}$	3.97(0.08)	$5.54(0.12)^{+0.08}_{-2.44}$	0.92(0.05)	$5.11(0.29)^{+0.08}_{-2.32}$

Vector boson plus jets production

Vector boson plus jets production



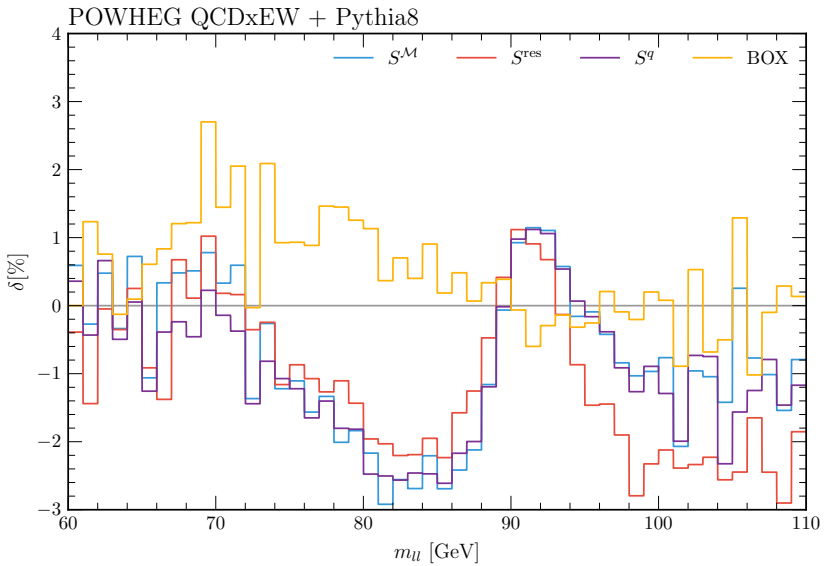
- no interferences at LO
  $\rightarrow$ need $4q$, start at $V + 2j$, NLO EW $V + j$, NNLO QCD-EW V
- if NLO EW to be included, then include also LO $\gamma\gamma$ channels
- NNLO QCD-EW mixed correction known in pole approximation

Inclusive W/Z production

- NNLO QCD and NLO EW known and available at fixed-order
- approximate NNLO QCD-EW-mixed ($\mathcal{O}(\alpha_S\alpha)$) corrections known

  Dittmaier, Huss, Schwinn

  arXiv:1403.3216



- NNLOPS in two schemes

  UN^{2}LOPS Höche, Li, Prestel arXiv:1405.3607

  MiNLO Karlberg, Re, Zanderighi arXiv:1407.2940
- NLOPS for QCD+EW available in

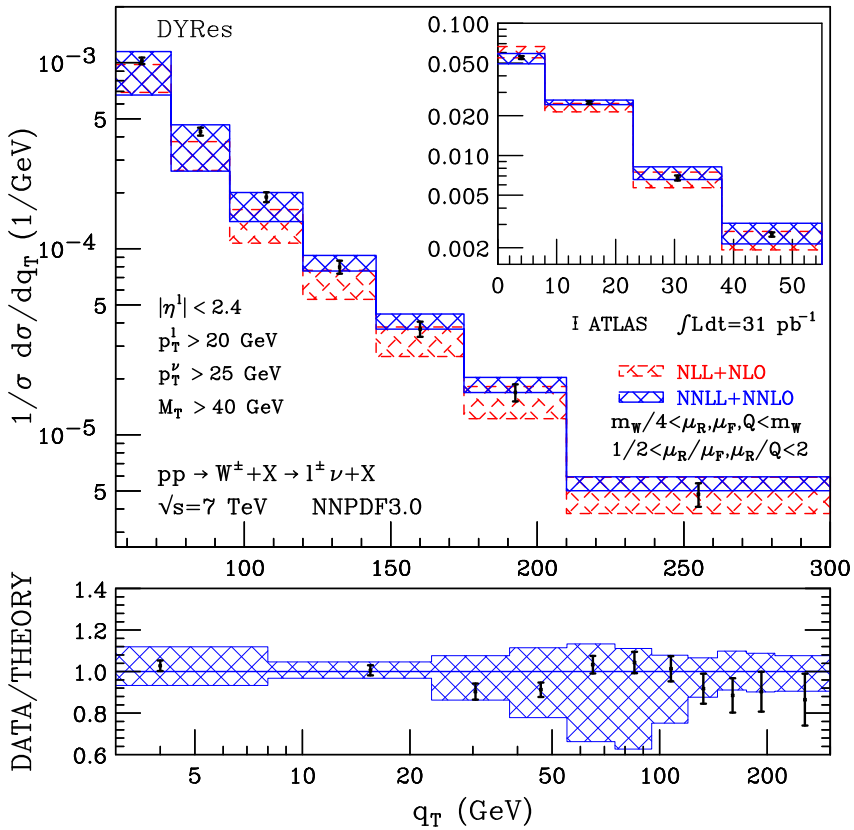
  POWHEGBernaciak, Wackeroth arXiv:1201.4804

  Barze et.al. arXiv:arXiv:1202.0465

  Mück, Oymanns arXiv:1612.04292

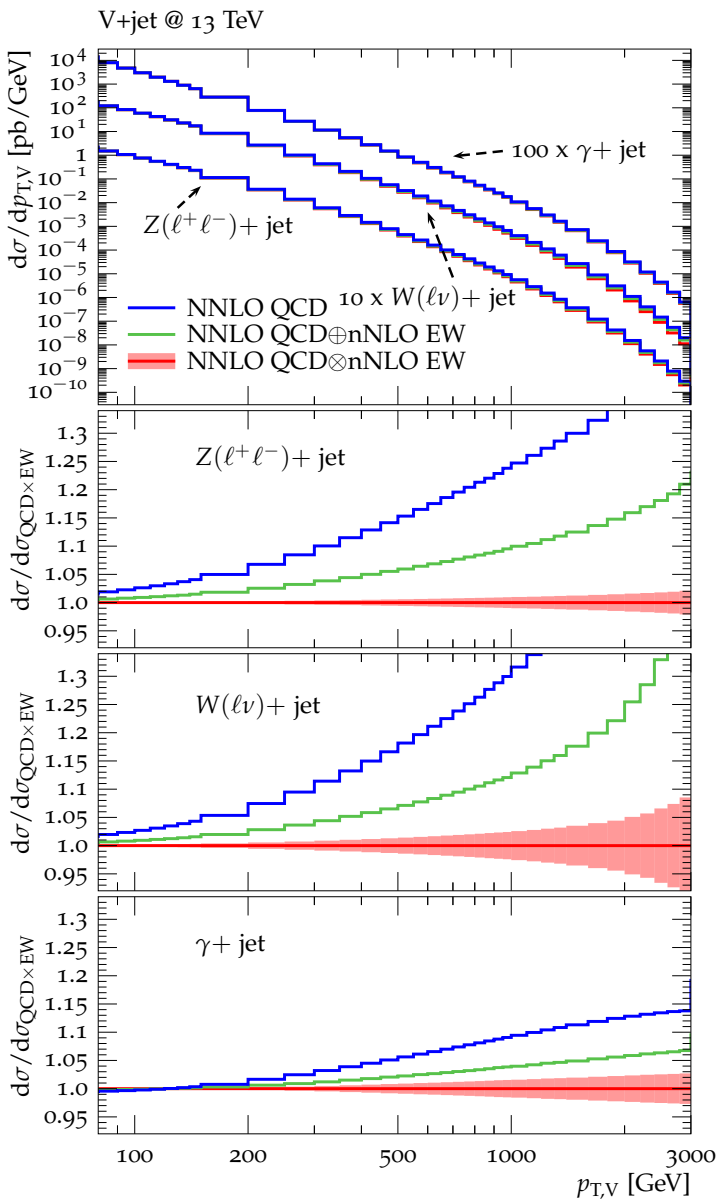
V transverse momentum

- q_{T} resummation in DYqT
  Catani et.al. arXiv:1507.06937
  and RESBOS Balazs et.al.
  hep-ph/9505203
- dedicated resummations for related variables ϕ^* Banfi, Dasgupta, Marzani arXiv:1102.3594
- EW effects should be subleading at small q_{T}



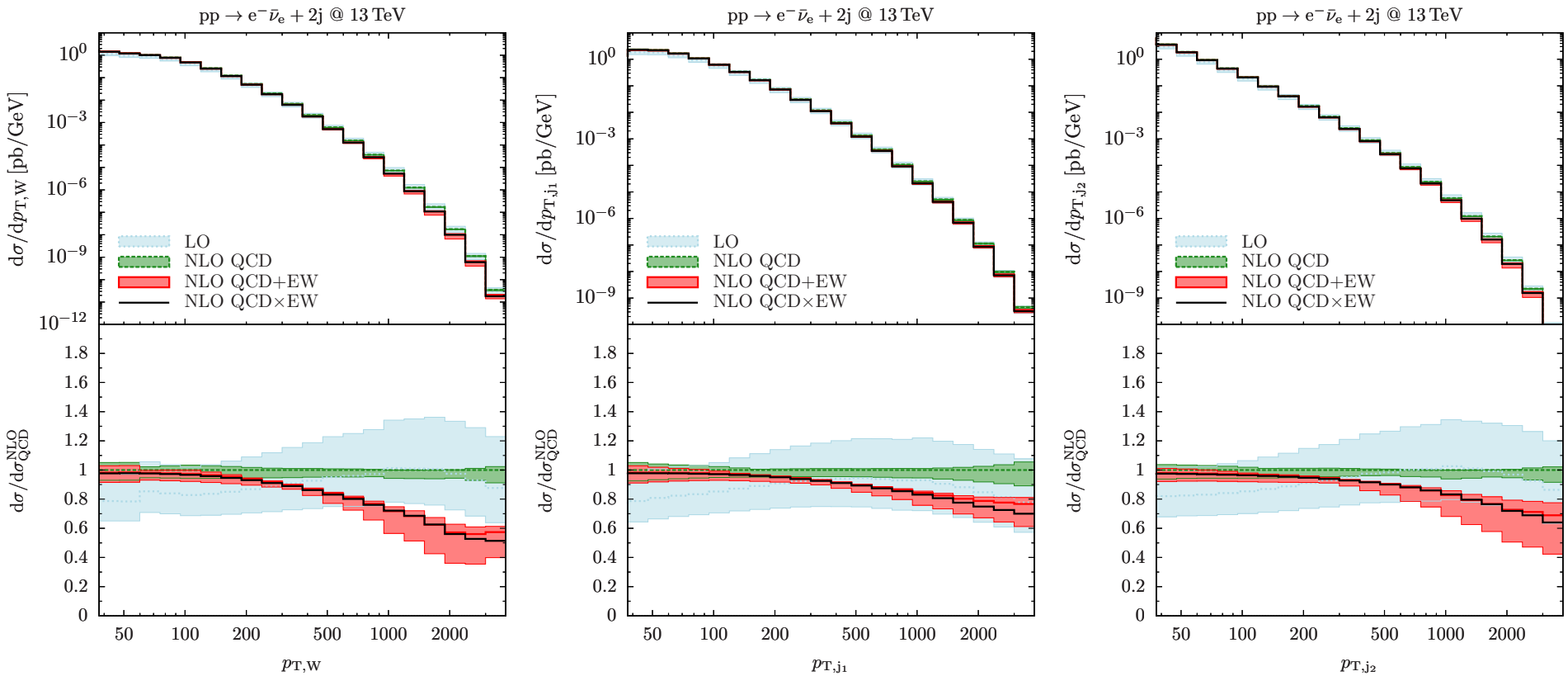
V+jet production

- NNLO QCD off-shell for $W/Z/\gamma + j$
  MCFM (NJetti), NNLOJET
- NLO QCD off-shell for $W + 2, 3, 4, 5j$, $Z/\gamma + 2, 3, 4j$
  BlackHat/NJet+Sherpa
- NLO EW for on-shell $W + 1, 2, 3j$
  Kallweit et.al. arXiv:1412.5157
- NLO EW for off-shell $W/Z + 1, 2j$
  Denner et.al. arXiv:1411.0916
  Kallweit et.al. arXiv:1511.08692
  Chiesa, Greiner, Tramontano
  arXiv:1507.08579
- NLO EW for $\gamma + j$



$pp \to Wjj$ @ 13 TeV

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2015)012, JHEP04(2016)021



$pp \to Zjj$ @ 13 TeV

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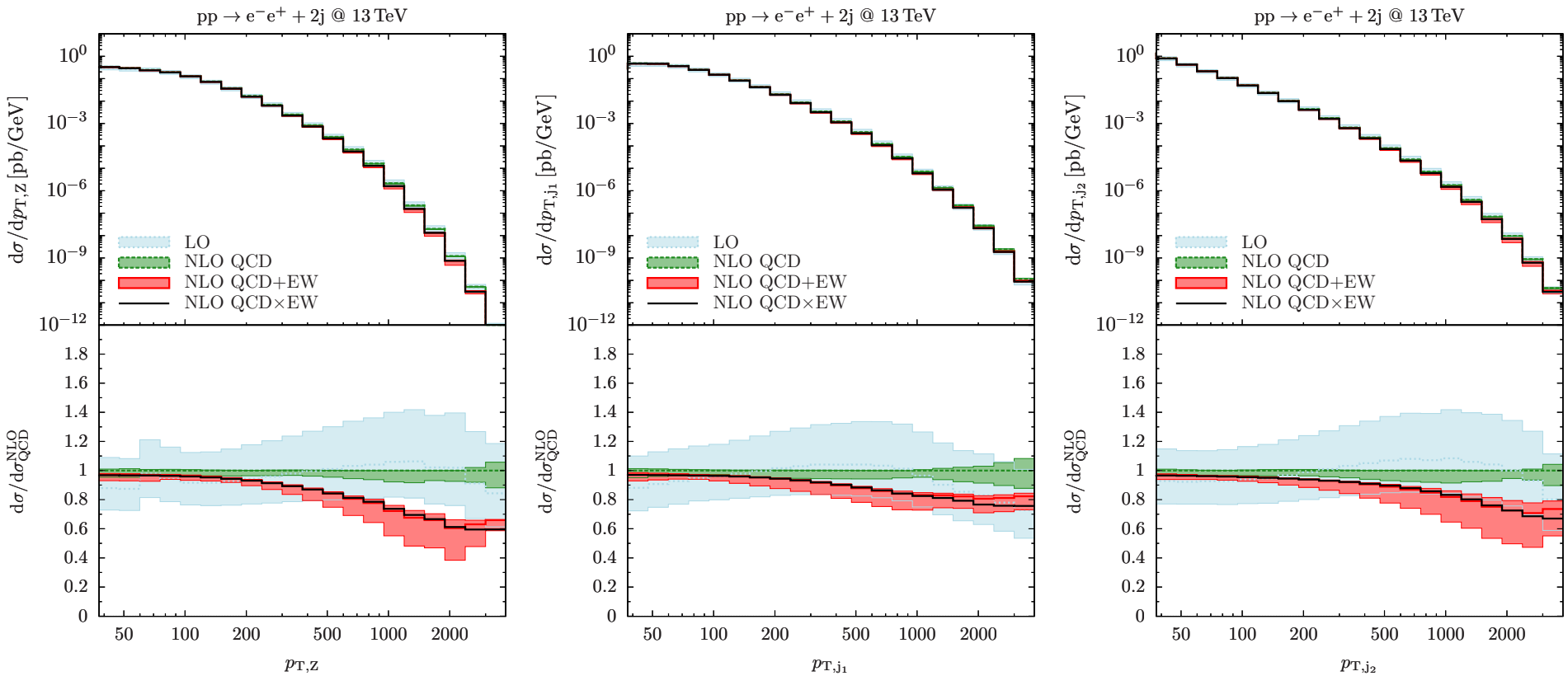
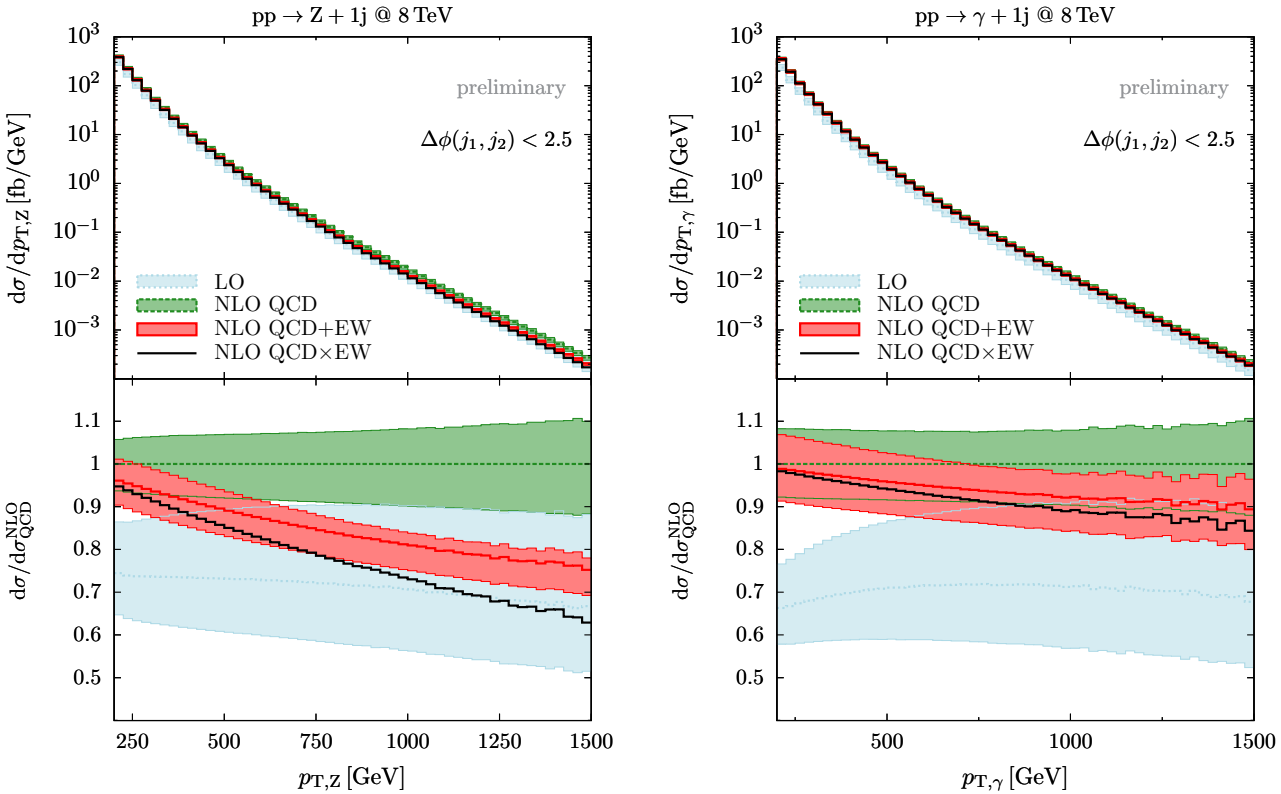


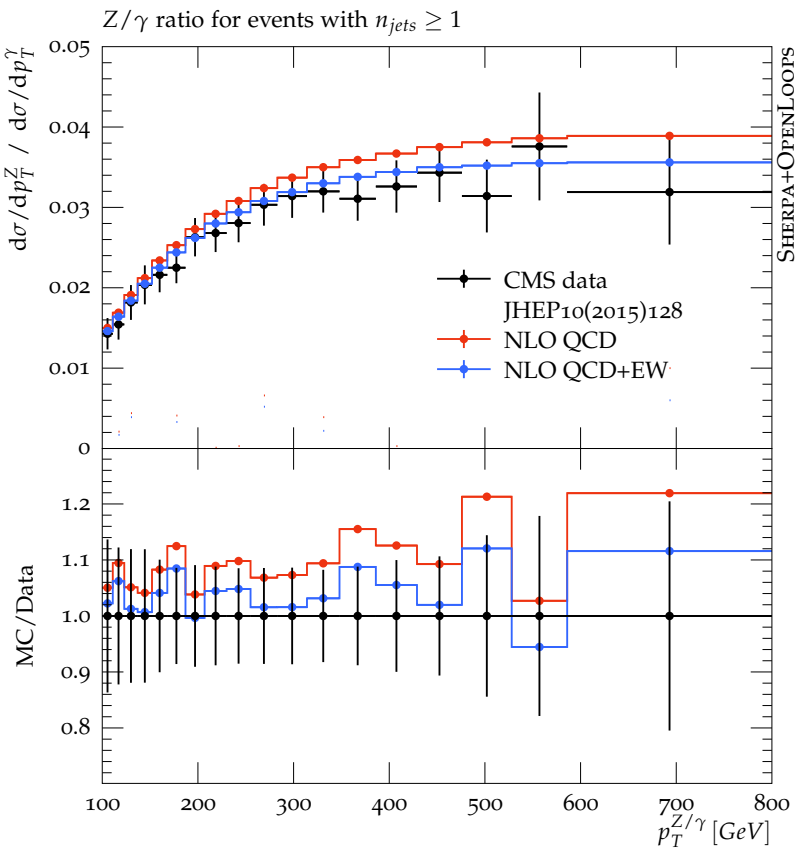
Z/γ ratio @ 8 TeV

Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1505.05704



→ EW corrections different for Z and γ

Z/γ ratio @ 8 TeV



Kallweit, Lindert, Pozzorini, MS for LH'15

- use this ratio to get handle on $p_\perp^Z$ in $Z \to \nu\bar{\nu}$ for NP searches
- test how well data is described in $Z \to \ell\ell$

$\Rightarrow$ NLO EW improves data description

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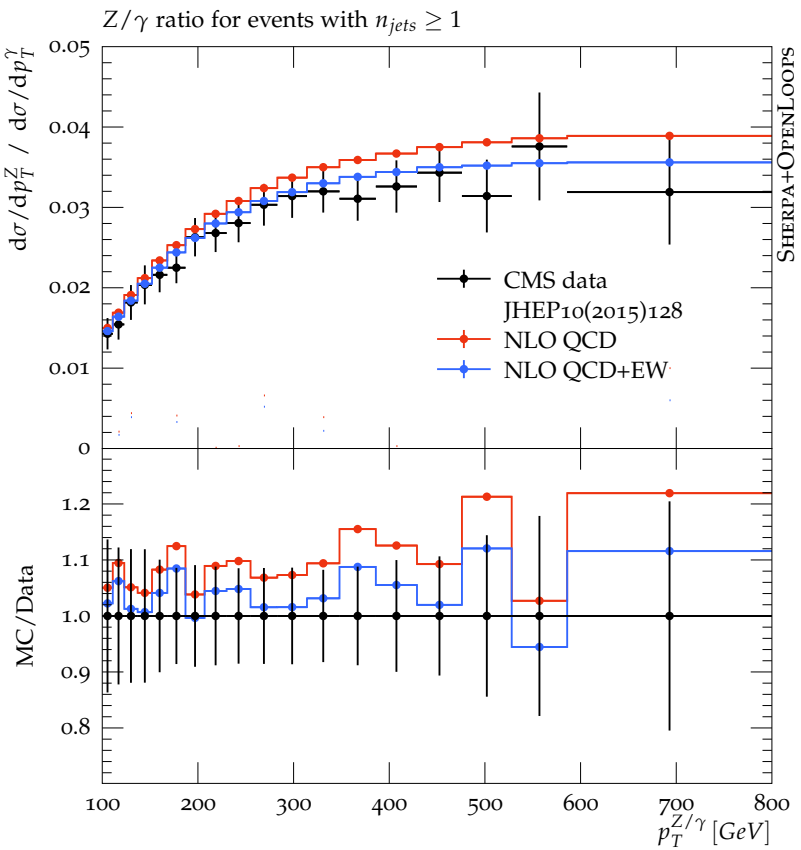

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Electroweak corrections in particle-level event generation

Kallweit,Lindert,Maierhöfer,Pozzorini,MS JHEP04(2016)021

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
- modify MC@NLO $\overline{\mathrm{B}}$-function to include NLO EW virtual corrections and integrated approx. real corrections

$$\overline{\mathrm{B}}_{n,\mathrm{QCD+EW_{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathrm{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{I}_{n,\mathrm{EW}}(\Phi_n) + \mathrm{B}_{n,\mathrm{mix}}(\Phi_n)$$

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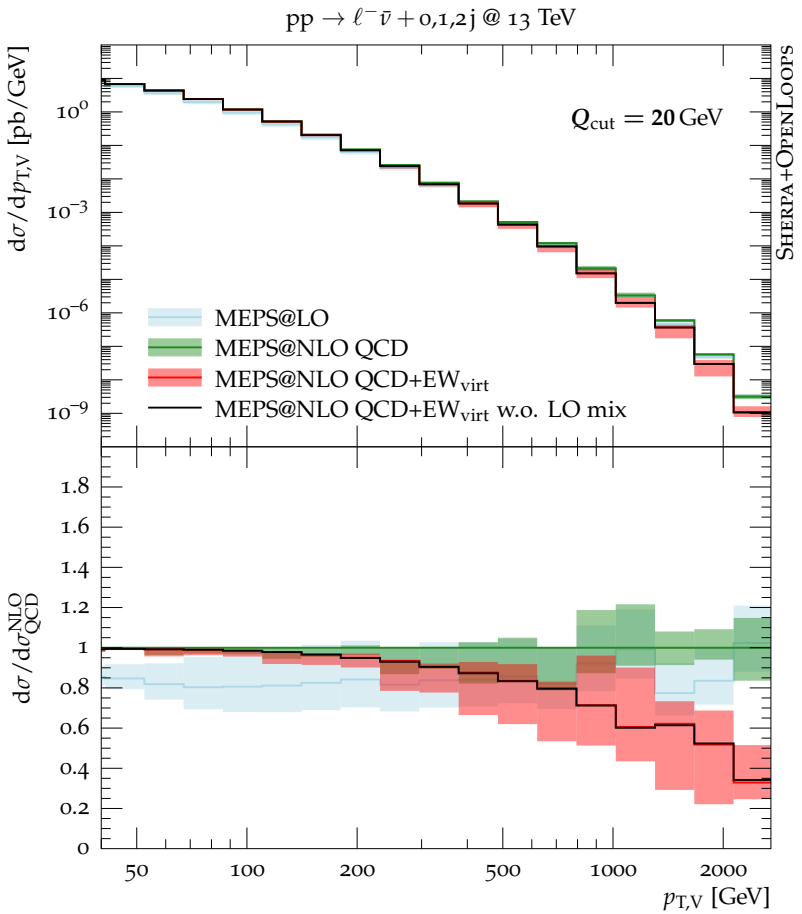
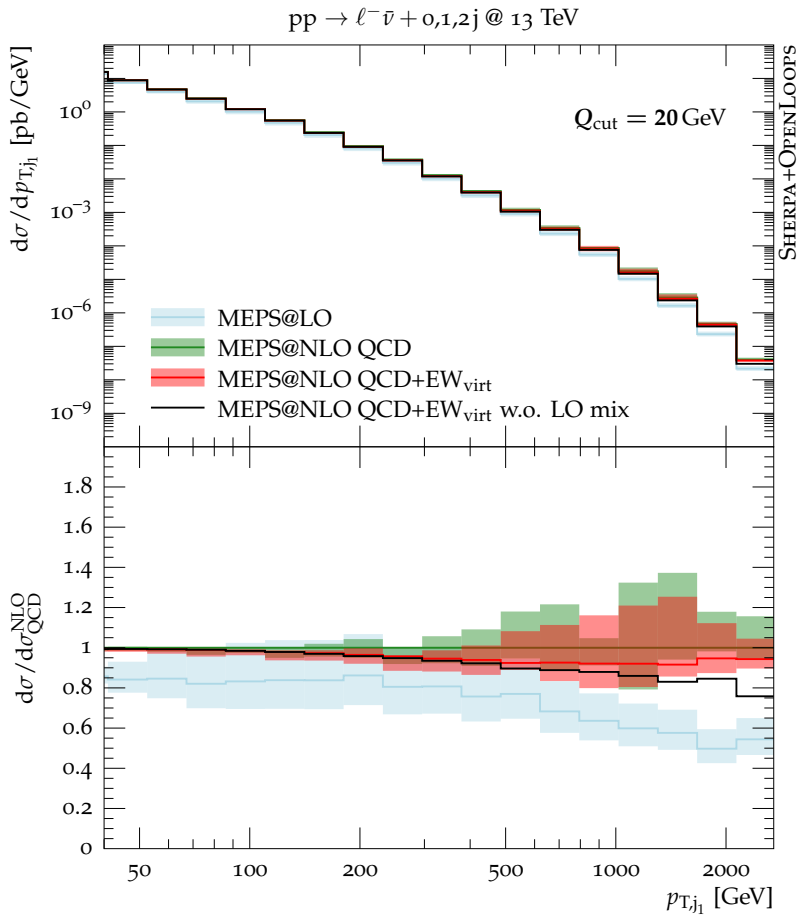
$pp \to \ell^- \bar{\nu} + \text{jets}$

Kallweit,Lindert,Maierhöfer,Pozzorini,MS JHEP04(2016)021





$\Rightarrow$ particle level events including dominant EW corrections

Conceptual problems

External photons – initial state

Harland-Lang et.al. arXiv:1605.04935, Kallweit et.al. arxiv:1705.00598

- **initial state photons** are not resolved, treat them identically to any other parton
- both elastic and inelastic photons evolve according to DGLAP
  $\rightarrow$ splittings $\gamma \rightarrow \gamma$, $\gamma \rightarrow q\bar{q}$, $q \rightarrow q\gamma$
  $\rightarrow$ γPDF at larger Q^2 driven by $q \rightarrow q\gamma$
- the photon PDF (at NLO QED) contains renormalisation factors that must be cancelled by the partonic cross section

$\Rightarrow$ renormalisation in short-distance scheme (G_μ, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...)

External photons – final state

- **final state photons** may be resolved or not
  strictly speaking: differentiate between short-distance photon and indentified, measurable photon

$\Rightarrow$ if treated as identified particle, renormalise on-shell ($\alpha(0)$),
no $\gamma \to ff$ splittings
$\to$ renormalisation contains IR poles

$\Rightarrow$ if treated democratically (just another parton), renormalise in short distance scheme (G_μ, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...), include $\gamma \to ff$ splittings
$\to$ pure UV renormalisation
$\to$ identify photon through fragmentation function $D_\gamma^p(z,\mu)$

i.e. $D_\gamma^\gamma(z,\mu) = \dfrac{\alpha(0)}{\alpha_{\text{sd}}}\,\delta(1-z) + \mathcal{O}(\alpha)$

all others $D_\gamma^q(z,\mu) = \mathcal{O}(\alpha)$, $D_\gamma^g(z,\mu) = \mathcal{O}(\alpha^2)$

- identical at NLO EW, if fragmentation D_γ^q on Born is negligible

External photons – final state

- **jet definition:** completely democratic vs. anti-tagging jets with too large photon content
- **democratic:**
  - \+ straight forward, close to experiment for many procs
  - – more subtractions (Born configs with FS photons)
- **anti-tagging jets with too large photon content:**
  dress quarks for collinear safety,
  discard jets if $E_\gamma > z_{\text{thr}} E_{\text{jet}}$ (e.g. $z_{\text{thr}} = 0.5$)
  - \+ fewer contributions
  - – difference to experimental jet definition (usually subpercent)
  - – only works when no $\gamma \to ff$ splittings in real,
    needs fragmentation function then
- **needs to be tailored to experimental analysis**

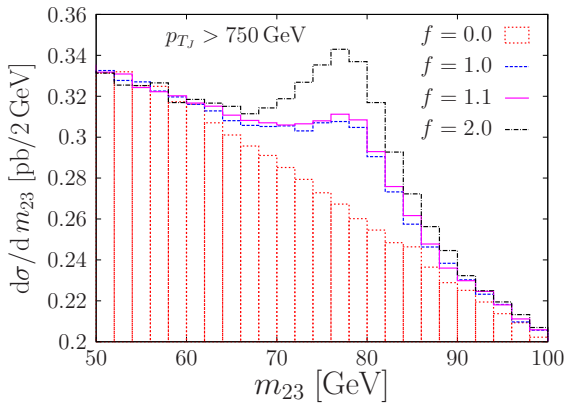
Real boson radiation

Fixed-order real emission

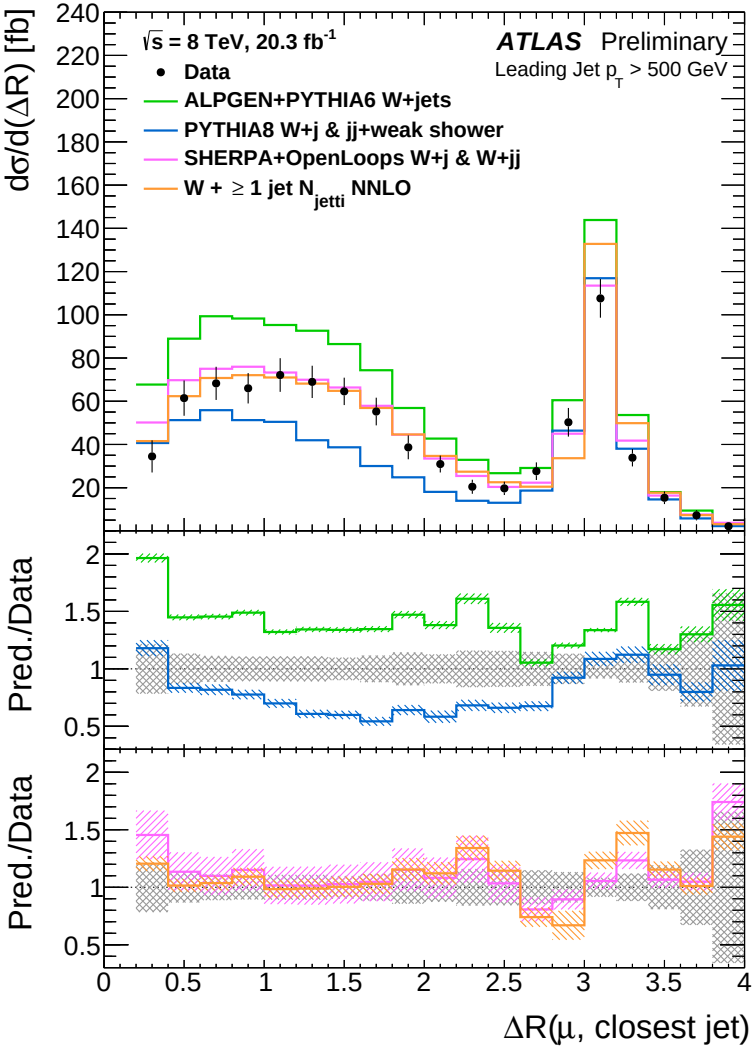
- finite additional processes
- contribution highly analysis dependent
  often partially included as backgrounds, no one number to be applied
- possible partial cancellation with large negative NLO EW corrections
  but often subleading LO contribs more important

Boson emissions in parton showers

- approximate implementations exist
  $\rightarrow$ proper implementation needs spin correlations
- resummation not needed at LHC
- embeds W/Z emissions in inclusive sample
  $\rightarrow$ important for substructure observables



NLO EW predictions for $\Delta R(\mu, j_1)$



Data comparison

M. Wu ICHEP'16, ATLAS arXiv:1609.07045

- ALPGEN+PYTHIA
  $pp \to W +$ jets MLM merged
  Mangano et.al. JHEP07(2003)001
- PYTHIA 8
  $pp \to Wj$ + QCD shower
  $pp \to jj$ + QCD+EW shower
  Christiansen, Prestel EPJC76(2016)39
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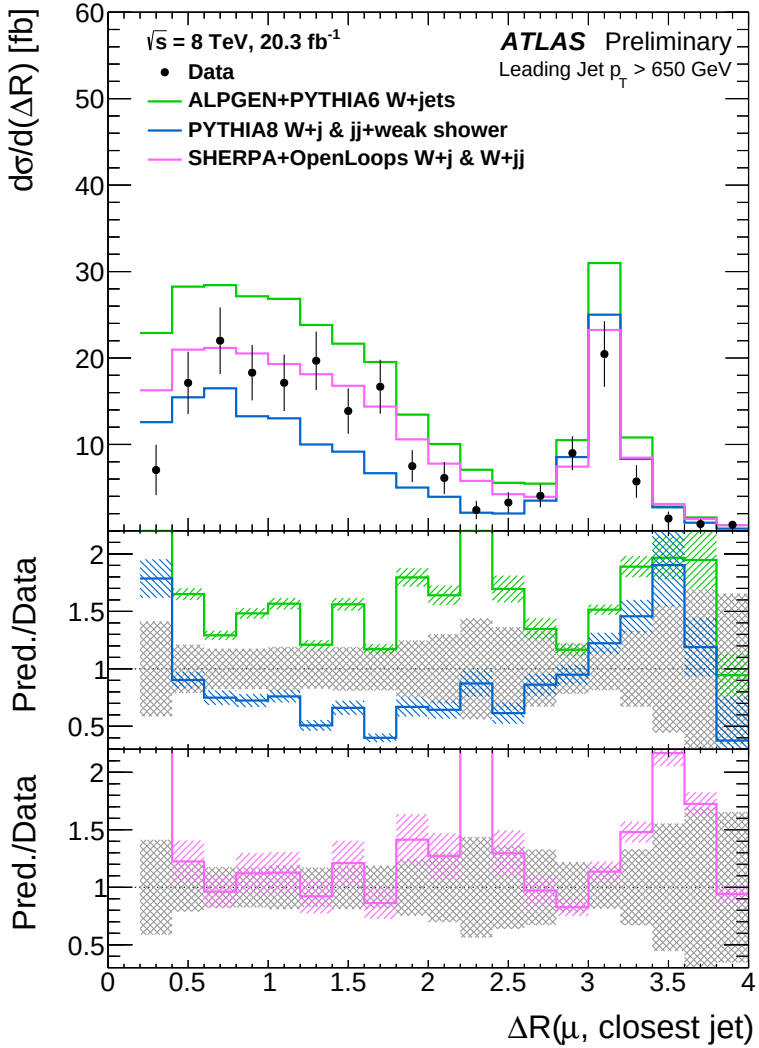

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Combination of QCD and EW corrections

- additive: QCD+EW, multiplicative: QCD×EW
  $\rightarrow$ assessment of potential size of NNLO QCD-EW mixed corrections
- in regions where QCD and EW corrections factorise,
  multiplicative combination well justified
  $\Rightarrow \delta_{\text{NNLO QCD-EW}} = \delta_{\text{NLO QCD}}\, \delta_{\text{NLO EW}}$
  example: high-p_{T} where EW Sudakov dominant
- once the definition of NLO QCD and NLO EW breaks down
  (e.g. dijets at NLO $\mathcal{O}(\alpha_S{}^n \alpha^{3-n})$, $n = 0..3$)
  multiplicative definition breaks downew

PDFs

PDFs for higher-order EW calculations

- NLO EW corrections contain NLO EW corrections to evolution of initial state partons
  $\rightarrow$ quarks dressed with (real and virtual) radiation of light EW gauge bosons
  $\rightarrow$ at the LHC this is only the photon

$\Rightarrow$ **need NLO QED PDF for NLO EW calculations**
$\rightarrow$ automatically adds photons as proton constituent

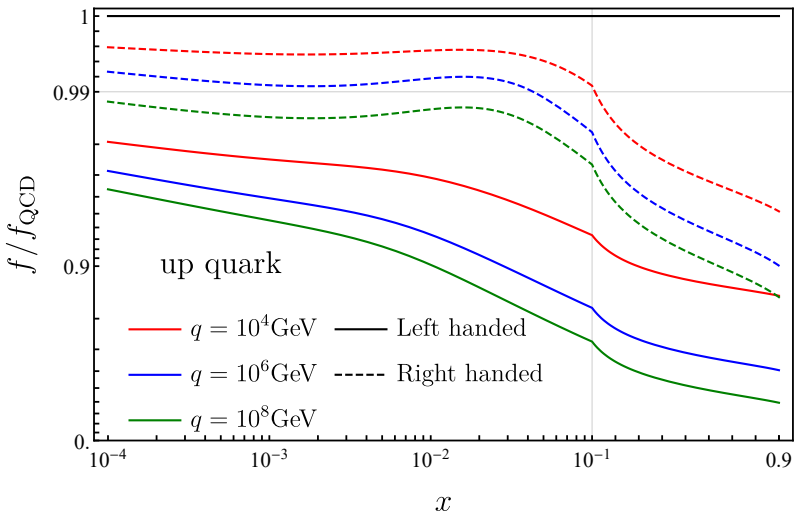
- evolution from MRST2004QED through NNPDF2.3QED to CT14QED Schmidt et.al. arXiv:1509.02905
  LUXQED Manohar, Nason, Salam, Zanderighi arXiv:1607.04266
  NNPDF3.1LUXQED NNPDF
- three modern PDF sets with very similar γPDF central values

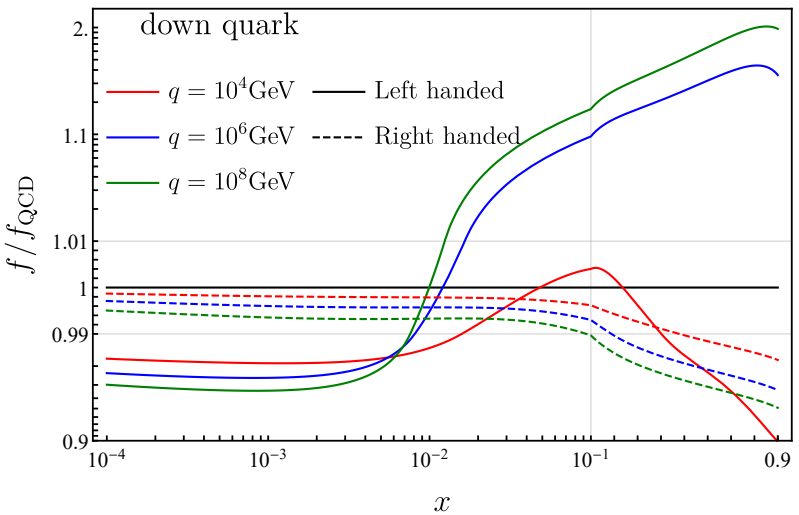
PDFs at high energies

Bauer, Ferland, Webber arXiv:1703.08562

- at higher energies EW gauge boson become light partons, include them in resummation (also t, h)
  $\rightarrow$ PDFs evolve with in full $SU(3) \times SU(2) \times U(1)$ (unbroken)
  $\rightarrow$ evolution of up and down quarks coupled

$\Rightarrow$ **left-handed and right-handed quark PDFs evolve differently**





PDFs at high energies

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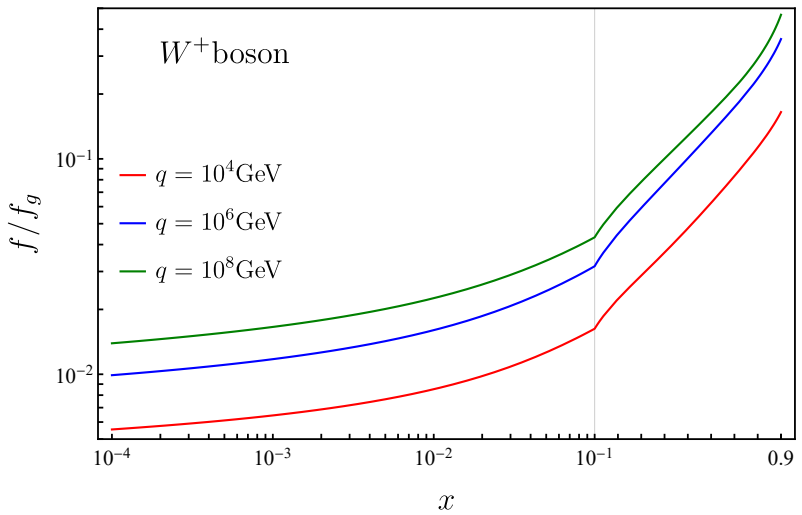

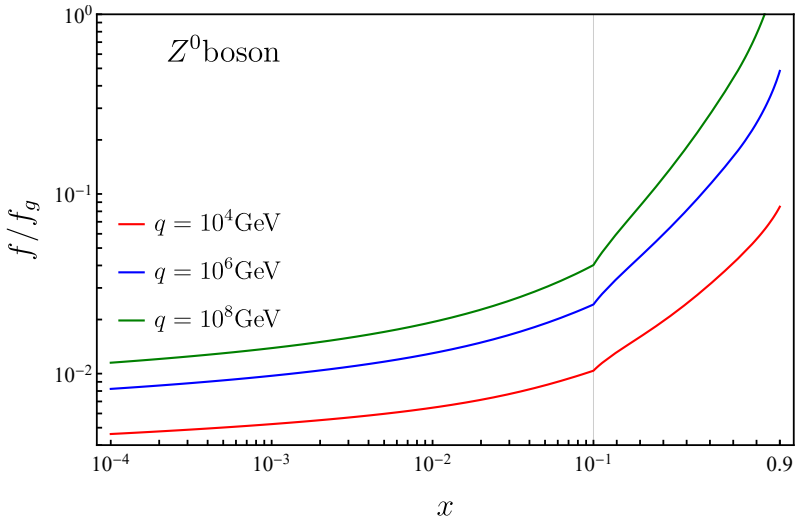

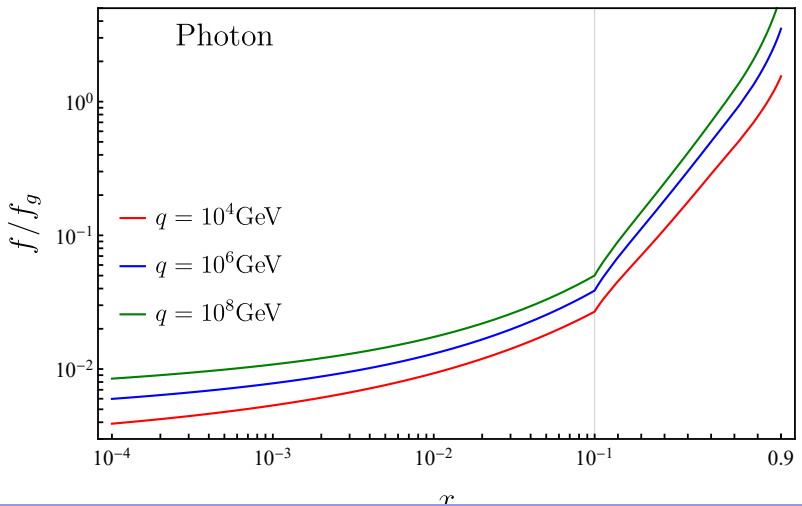

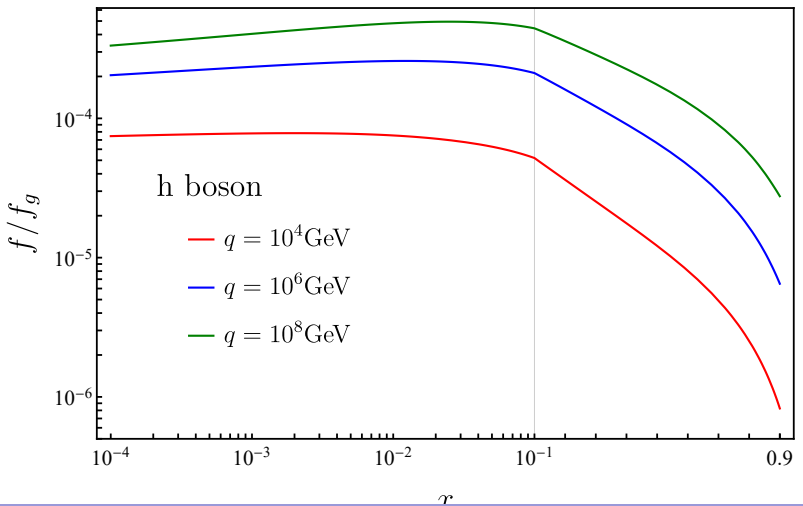

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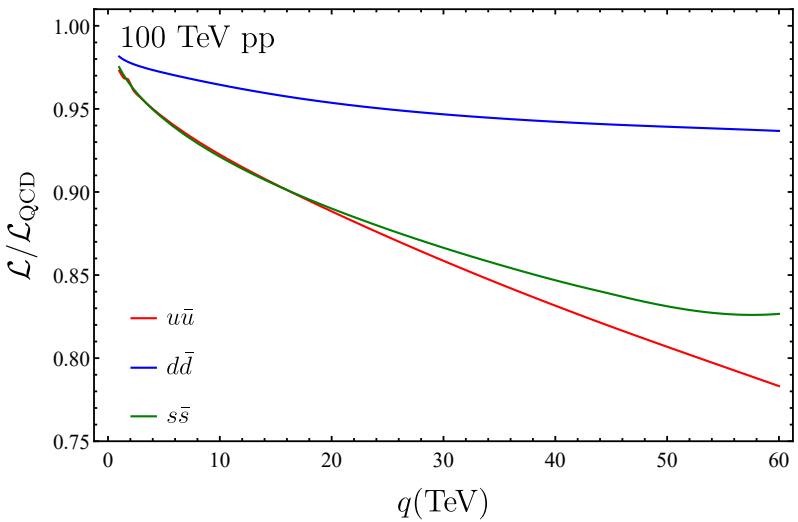

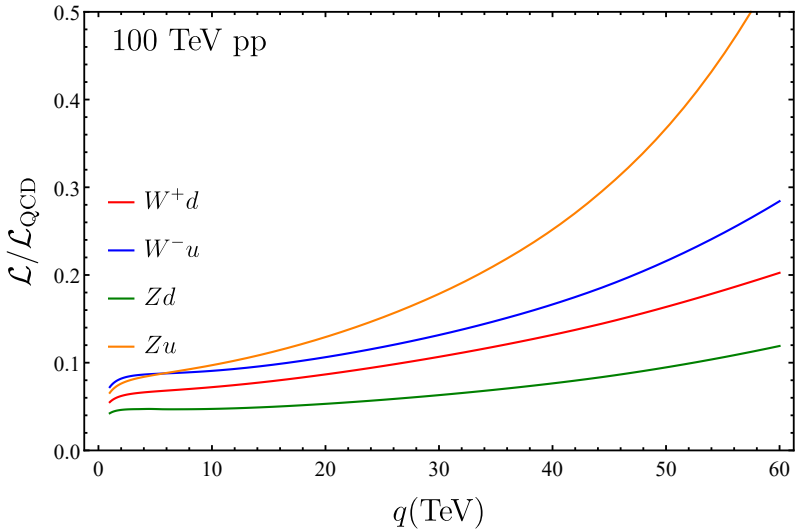

- typical Q^2 at the LHC: $\lesssim 5$ TeV, FCC: $\lesssim 40$ TeV
- appreciable corrections to parton fluxes, esp. at FCC energies
- Question: accuracy of calculation of unbroken SM at small Q^2 ?
- What are the compensating effects due to additional partonic channels for physical cross sections?

Conclusions

- NNLO QCD and NLO EW and subleading orders known for all inclusive processes
- NLO QCD and NLO EW for more exclusive ones
- conceptual problems remain, most of them are analysis specific and cannot be solved in general
- EW parton showers exist in some approximation
- NNLO QCD matched to parton showers exist for incl. W/Z production
- NLO QCD+EW matched to parton showers exist for incl. W/Z production

Thank you for your attention!