Electroweak corrections for LHC physics

Marek Schönherr

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Introduction

Electroweak correction come in two variants: virtual corrections and real emission correction.

Virtual electroweak corrections often studied in the context of gauge boson and jet production at large transverse momentum (EW-Sudakov suppression). Usually negative and increasing with $p_\perp$.

Real electroweak corrections usually constitute a separate process. However, largest BR of W/Z bosons is hadronic, thus (almost) indistinguishable in jet production. Nonetheless may constitute signal in itself.

When large scale differences occur resummation is needed in either case. Practically at LHC13/14 these scale differences are moderate.

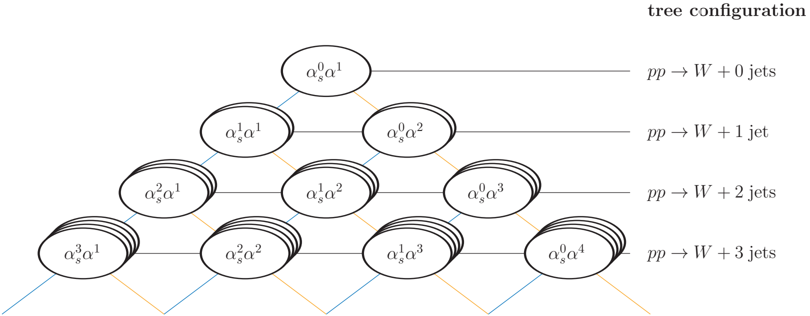
Beware of subleading orders.

Outline

1. Next-to-leading order electroweak corrections
   - Setup and subtleties
   - Selected results
2. Electroweak corrections in MCs
   - Approximate inclusion in NLO QCD multijet merging
   - Selected results
3. Real boson radiation
   - Resummation via EW parton showers
   - Case study: Finding W bosons inside jets
4. Conclusions

Electroweak corrections for LHC physics

Consistent setup: counting orders and defining signatures



- NLO QCD: $\alpha_s^1 = 1$ parton, only MEs from squared diagrams
- NLO EW: $\alpha^1 = 1$ photon or 1 parton
  also MEs from interfering $\mathcal{O}(\alpha_s^{n+1}\alpha^{m-1})$ diagrams, resonances

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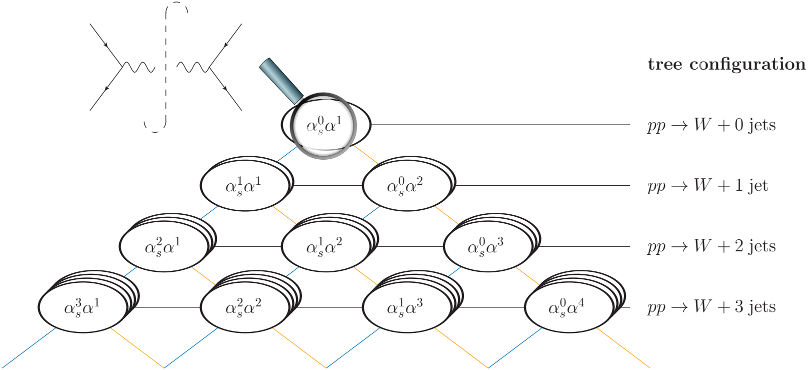

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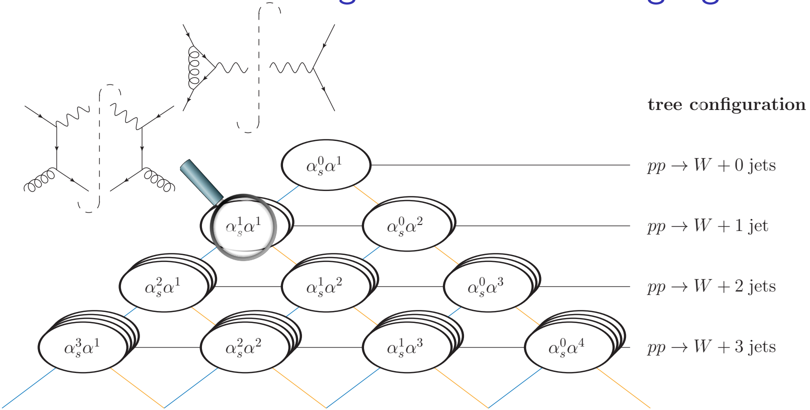

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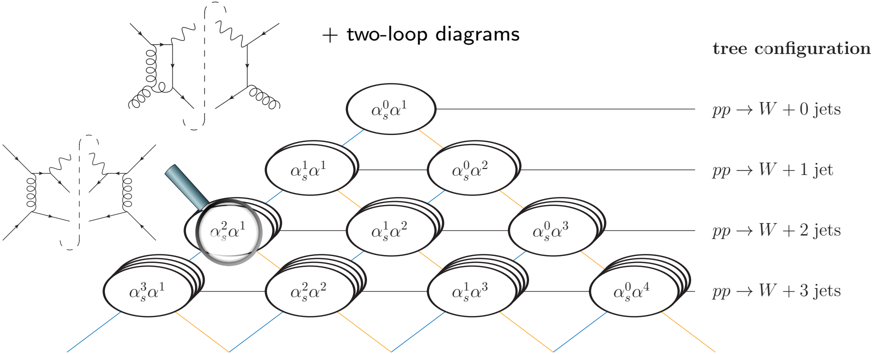

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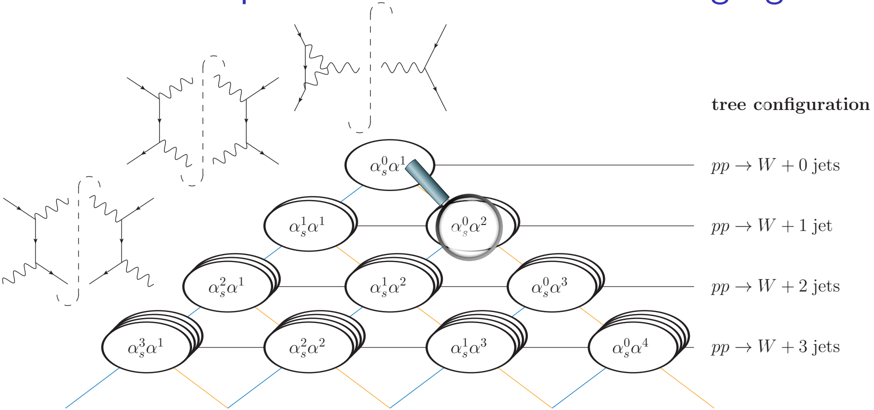

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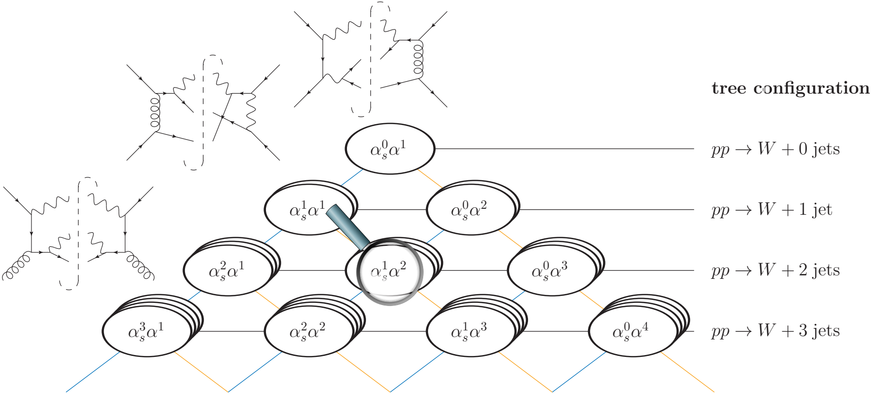

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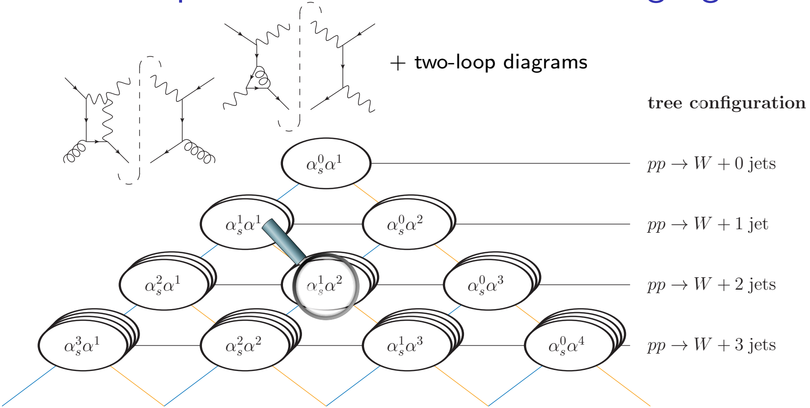

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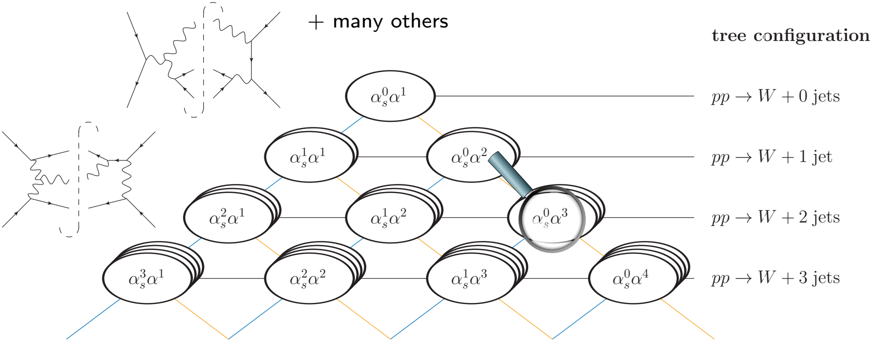

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Subtleties: photons in initial state

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

NLO EW for photon initiated processes

- initial state photons are not resolved,
  should be treated as any other parton
- multiple sources: elastic (proton remains intact)
  inelastic (proton broken up)
- both elastic and inelastic photons evolve according to DGLAP
  $\rightarrow$ splittings $\gamma \rightarrow \gamma$, $\gamma \rightarrow q\bar{q}$, $q \rightarrow q\gamma$
  $\rightarrow$ can be combined into a single PDF as long as one is not concerned with what happens to the proton
- 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, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...)

Subtleties: photons in final state

What is a jet?

- photons must be part of a jet, but to what extent?
- **democratic:**
  - \+ straight forward, close to experiment for many procs
  - − more subtractions (Born configs with FS photons)
  - → single photons constitute a jet
- **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)
  - − ill-defined at lower order NLO correction (w/ $\gamma \to q\bar{q}$ splittings)
  - → single photons do not constitute a jet

  general anti-tagging must proceed through fragmentation functions

Subtleties: photons in final state

What is a photon?

- differentiate: short-distance photon (photon as parton),
  long-distance photon (identified, measurable photon)

a) treat as identified particle, renormalise on-shell ($\alpha(0)$), no $\gamma \to ff$
$\to$ renormalisation contains IR poles
$\to$ problematic if both identified and unresolved photons in Born

b) treat 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
$\to$ if needed, identify photon through frag. function $D_\gamma^p(z,\mu)$

$$\text{i.e. } D_\gamma^\gamma(z,\mu) = \frac{\alpha(0)}{\alpha_{\text{sd}}}\,\delta(1-z) + \mathcal{O}(\alpha^2)$$

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

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

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Subtleties: photons in final state

What is a lepton?

- in principle, again differentiate between short-distance parton and long-distance identified and measurable object
- simplified as leptons not gauge bosons, thus

  $D_\ell^\ell(z,\mu) = \delta(1-z)$+QED bremsstrahlung

  $D_\ell^\gamma(z,\mu) = \mathcal{O}(\alpha)$ problematic in processes with ℓ and unresolved photons in Born

  all other $D_\ell^q(z,\mu) = \mathcal{O}(\alpha^2)$, $D_\ell^g(z,\mu) = \mathcal{O}(\alpha_s\alpha^2)$
- dressed lepton: masseless leptons must be dressed for IR safety
- bare lepton: massive leptons may be measured bare
- Born lepton: not an infrared-safe concept

Combination of NLO QCD and EW correction

- additive – strict fixed order expansion

$$\mathrm{d}\sigma^{\text{NLO}}_{\text{QCD+EW}} = \mathrm{d}\sigma^{\text{LO}}\left(1+\delta_{\text{QCD}}+\delta_{\text{EW}}\right)$$

- multiplicative – contains terms of $\mathcal{O}(\alpha_s\alpha)$

$$\mathrm{d}\sigma^{\text{NLO}}_{\text{QCD}\times\text{EW}} = \mathrm{d}\sigma^{\text{LO}}\left(1+\delta_{\text{QCD}}\right)\left(1+\delta_{\text{EW}}\right)$$

this construction is expected to well approximate the true $\mathcal{O}(\alpha_s\alpha)$ in the Sudakov limit where QCD and EW corrections factorise

$\Rightarrow$ in general, difference between additive and multiplicative combination can be used to assign higher-order uncertainty

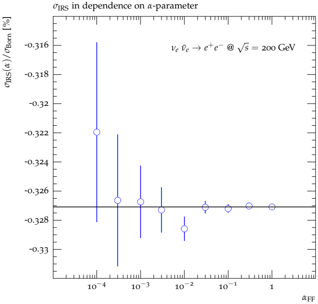
NLO EW subtraction in SHERPA

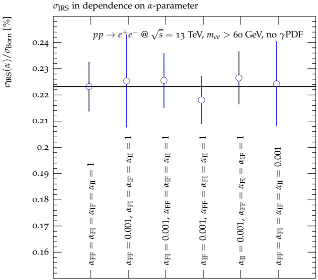
MS arXiv:1712.07975

- adapt QCD subtraction (spl. fns. and colour-/spin-correlated MEs)

Catani, Dittmaier, Seymour, Trocsanyi Nucl.Phys.B627(2002)189-265

- replacements: $\alpha_s \to \alpha,\ C_F \to Q_f^2,\ C_A \to 0,$
$$T_R \to N_{c,f}\, Q_f^2,\ n_f\, T_R \to \textstyle\sum_f N_{c,f}\, Q_f^2,$$
$$\frac{\mathbf{T}_{ij}\cdot\mathbf{T}_k}{\mathbf{T}_{ij}^2} \to \frac{Q_{ij}Q_k}{Q_{ij}^2}$$





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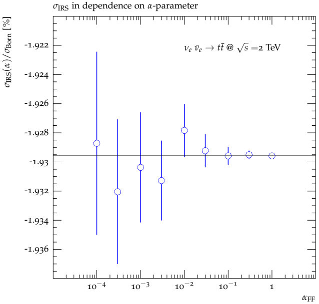

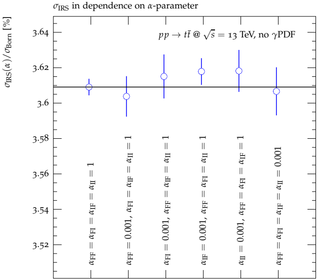

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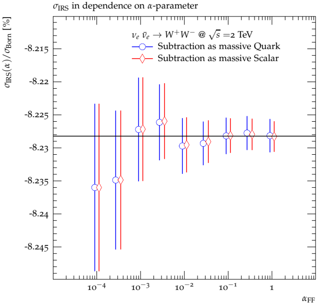

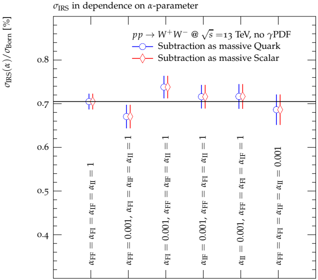

NLO EW calculations with SHERPA

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  - $pp \to Zj/pp \to \gamma j$ ratio — LH'15 arXiv:1605.04692; Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1505.05704
  - $pp \to \gamma/\ell\ell/\ell\nu/\nu\nu + j$ — Lindert et.al arXiv:1705.04664
  - $pp \to Vh$ — FCC report arXiv:1607.01831
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  - $pp \to t\bar{t}/t\bar{t}j$ — Gütschow, Lindert, MS arXiv:1803.00950
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  - $pp \to \gamma\gamma\gamma\ /\ \gamma\gamma\ell\nu\ /\ \gamma\gamma\ell\ell$ — Greiner, MS arXiv:1710.11514
  - $pp \to \gamma\gamma b\bar{b}$ — Greiner, MS in prep.
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Diboson production – $2\ell 2\nu$ – DF and SF

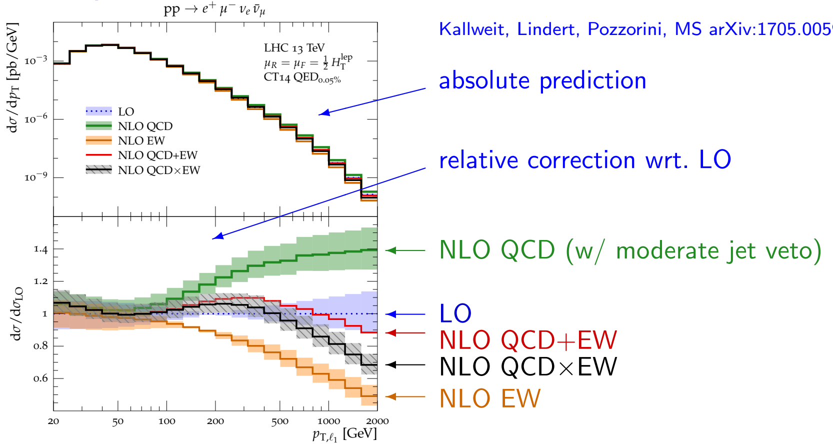
Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

- study $e^+\mu^-\nu\bar{\nu}$ (DF) and $e^+e^-\nu\bar{\nu}$ (SF) production

DF	$e^+\mu^-\nu_e\bar{\nu}_\mu$	WW
SF	$e^+e^-\nu_e\bar{\nu}_e$	$WW + ZZ$
	$e^+e^-\nu_{\mu/\tau}\bar{\nu}_{\mu/\tau}$	ZZ

- SHERPA for Born, real em., subtraction and phase space integration, MUNICH (MEs from OPENLOOPS) for subtraction and p. s. int.
- OPENLOOPS for virtual corrections using COLLIER for tensor integrals
- dress quarks and leptons in $\Delta R = 0.1$, incl. event selection w/ standard lepton acceptance cuts, $n_f = 4$ and mild jet veto to suppress large NLO QCD corr.

Diboson production – $2\ell 2\nu$ – DF

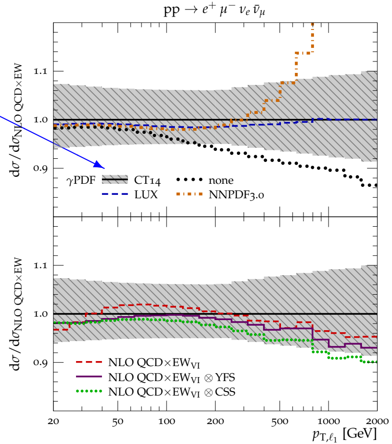


- large pos. NLO QCD, large neg. NLO EW
  $\rightarrow$ NLO QCD+EW and NLO QCD$\otimes$EW differ significantly

Diboson production – $2\ell 2\nu$ – DF

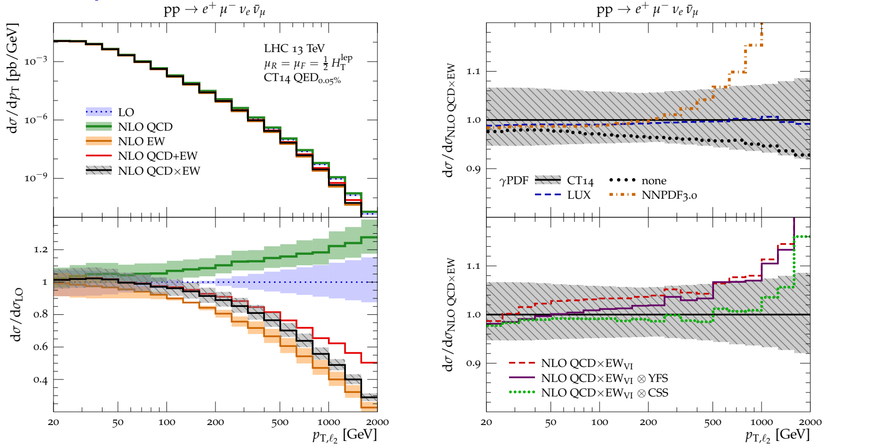
relative importance of γ-induced channels wrt. NLO QCD×EW

CT14qed (baseline)	no γPDF
LUXqed	NNPDF3.0qed



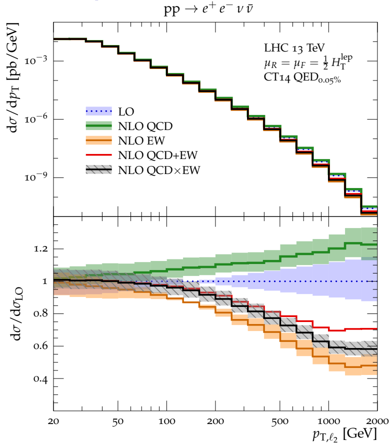
- all γPDF agree that γ-ind. $> 10\%$ for $p_T > 500\,\text{GeV}$
  very good agreement between CT14qed and LUXqed

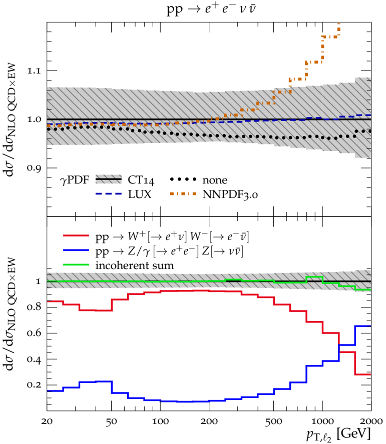
Diboson production – $2\ell 2\nu$ – DF



- ZZ dominant at very large p_T
  → different EW corrections, take care when extrapolating

Diboson production – $2\ell2\nu$ – SF





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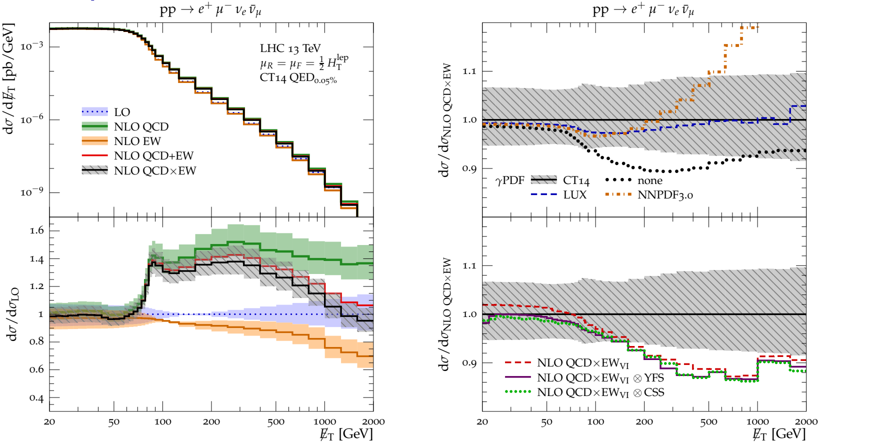
Diboson production – $2\ell 2\nu$ – DF



- kinematic suppression for $p_\mathrm{T}^{\nu\nu}$ at LO, unlocked at NLO QCD not present in γ-induced $\Rightarrow$ large contrib

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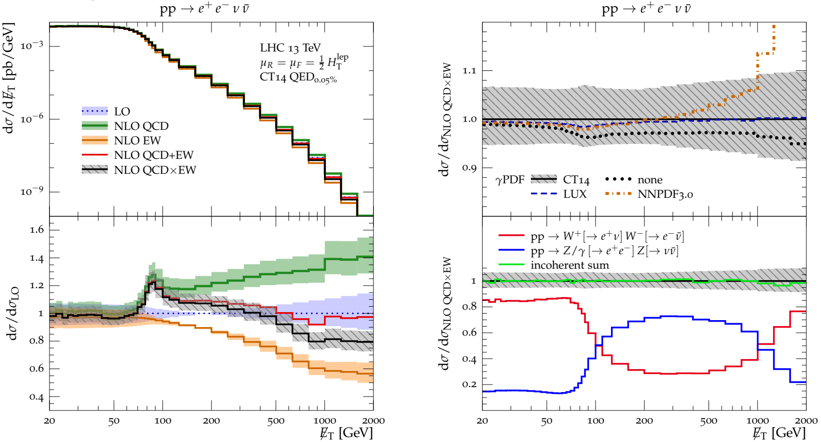

- kinematic suppression for $p_T^{\nu\nu}$ for WW, but not ZZ
  ZZ dominates for MET $> 100\,$GeV with large EW corr.

Triboson production – $3\ell 3\nu$ – 0, 1, 2 SFOS

MS arXiv:1806.00307

- contribs from 0 SFOS ($e^-\mu^+\mu^+\bar{\nu}\nu\nu$), 1 SFOS ($e^-e^+\mu^+\bar{\nu}\nu\nu$) and 2 SFOS ($e^-e^+e^+\bar{\nu}\nu\nu$) processes, and $e \leftrightarrow \mu$

0 SFOS	$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	WWW
1 SFOS	$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	$WWW + WZZ$
	$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	WZZ
	$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	WZZ
2 SFOS	$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	$WWW + WZZ$
	$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	WZZ

- Sherpa for Born, real em., subtraction and phase space integration
- Recola for virtual corrections using Collier for tensor integrals
- dress quarks and leptons in $\Delta R = 0.1$, cuts idealised from ATLAS arXiv:1610.05088

Triboson production – $3\ell 3\nu$ – 0, 1, 2 SFOS

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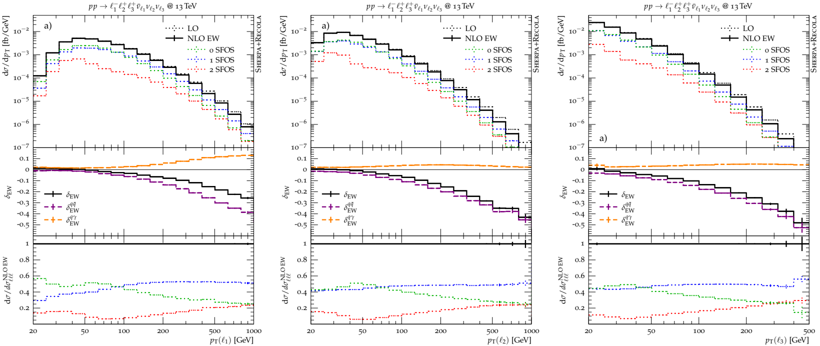
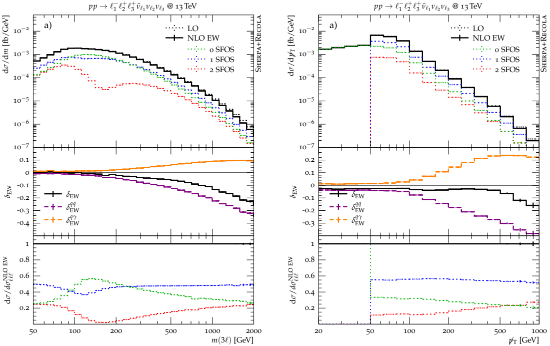


- includes 0, 1, 2 SFOS processes (WWW and WZZ structures)
- EW correction (incl. γ-induced) important

Triboson production – $3\ell3\nu$ – 0, 1, 2 SFOS

MS arXiv:1806.00307



- includes 0, 1, 2 SFOS processes (*WWW* and *WZZ* structures)
- large cancellations of EW correction in $q\bar{q}$ and $q\gamma$ channels

Triboson production – $\gamma\gamma\gamma$, $\gamma\gamma\ell\nu$, $\gamma\gamma\ell\ell$

Greiner, MS arXiv:1710.11514

- $\gamma\gamma\gamma$ and off-shell $\gamma\gamma W$, $\gamma\gamma Z$
- SHERPA for Born, real em., subtraction and phase space integration
- GOSAM for virtual corrections
- dress quarks and leptons in $\Delta R = 0.1$,
  optional jet veto

Triboson production – $\gamma\gamma\gamma$, $\gamma\gamma\ell\nu$, $\gamma\gamma\ell\ell$

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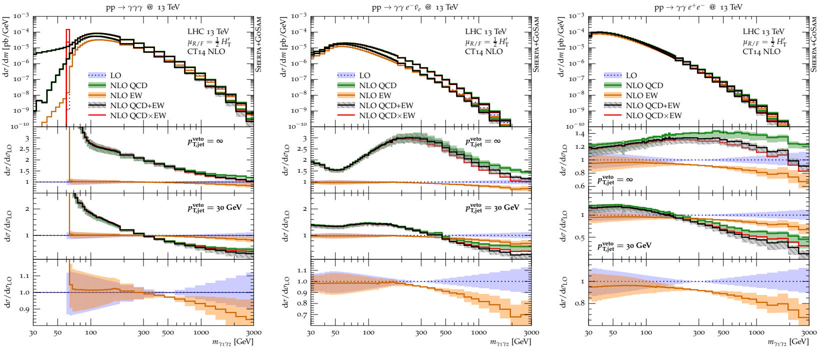

- NLO QCD$\times$EW breaks down at LO kinematic limit
- huge NLO QCD, moderate NLO EW, largest for $\gamma\gamma\ell\ell$

Electroweak corrections for LHC physics

Electroweak corrections in particle-level event generation

- 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

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

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging
  $\rightarrow$ validated at fixed order, found to be reliable,
  diff. $\lesssim 5\%$ for observables not driven by real radiation

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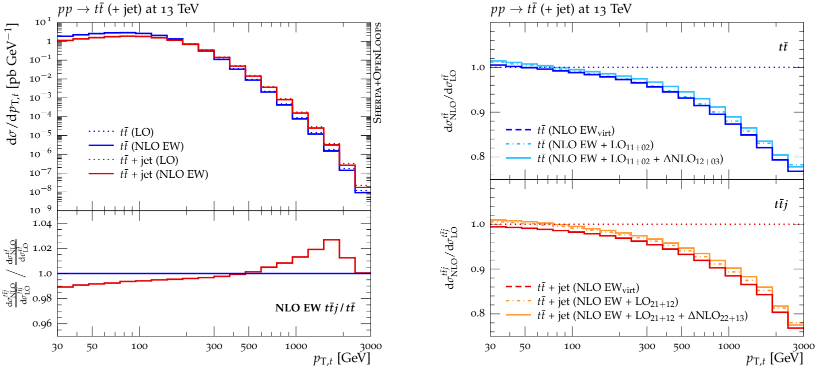
Top pair production in association with jets

Gütschow, Lindert, MS in arXiv:1803.00950



Observation: NLO EW factorises from additional jet activity when rather inclusive on jet definition

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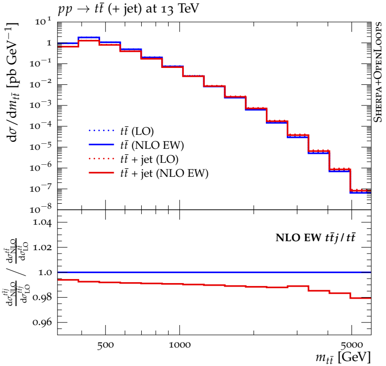
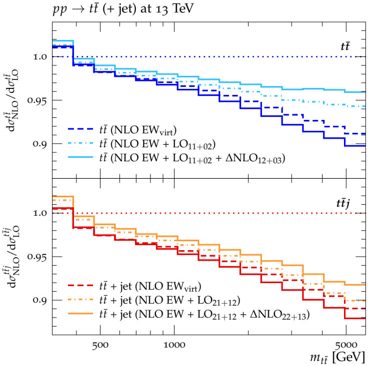
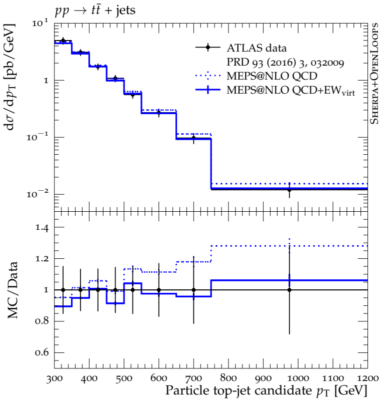




Observation: subleading orders important

Results: $pp \to t\bar{t} + \text{jets}$



Gütschow, Lindert, MS in arXiv:1803.00950

- $pp \to t\bar{t} + 0, 1j$@NLO $+ 2, 3, 4j$@LO
- additional LO multiplicities inherit electroweak corrections through MENLOPS differential K-factor

  Höche, Krauss, MS, Siegert arXiv:1009.1127
- improved description of data

Electroweak corrections for LHC physics

Collinear limit with $E \gg m$

- QED parton showers well known and available in every major shower
- approximation to collinear (vector) boson emission in limit $E \gg m$, in dipole language (splitter-spectator pairs): $f(s) \to f^{(\prime)}V(s)$

$$\mathrm{d}\sigma_{n+V} = \mathrm{d}\sigma_n \sum_f \sum_s^{n_\text{spec}} \mathrm{d}t\,\mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}\,\frac{1}{n_\text{spec}}\,J(t,z)\,\mathcal{K}_{f(s)\to f^{(\prime)}V(s)}(t,z)$$

- emitter fermion f, suitable spectator s
- flavour change $f \to f'$ in case of W emissions
- IS kernels contain ratio of PDFs (change in x,Q,flavour)
- similar ansatz with diff. kernels in Christiansen, Sjöstrand JHEP04(2014)115
- new developments Chen, Han, Tweedie arXiv:1611.00788; Bauer, Ferland, Webber JHEP08(2017)036

Splitting kernels

Denner, Hebenstreit unpublished

- use Denner-Hebenstreit expressions modified into CDST form

$$\mathcal{K}_{f(s)\to f'W(s)}(t,z) = \frac{\alpha}{2\pi t}\left[f_W\, c_\perp^W\, \tilde{\mathrm{V}}^{\mathrm{CDST}}_{f(s)\to f'b(s)}(t,z) + f_h\, c_L^W\, \tfrac{1}{2}\,(1-z)\right]$$
$$\mathcal{K}_{f(s)\to fZ(s)}(t,z) = \frac{\alpha}{2\pi t}\left[f_Z\, c_\perp^Z\, \tilde{\mathrm{V}}^{\mathrm{CDST}}_{f(s)\to fb(s)}(t,z) + f_h\, c_L^Z\, \tfrac{1}{2}\,(1-z)\right]$$

with

$$c_\perp^W = s_{\mathrm{eff}}\,\tfrac{1}{2s_W^2}\,|V_{ff'}|^2\,, \qquad c_\perp^Z = s_{\mathrm{eff}}\,\tfrac{s_W^2}{c_W^2}\,Q_f^2 + (1-s_{\mathrm{eff}})\,\tfrac{(I_f^3-s_W^2Q_f)^2}{s_W^2c_W^2}\,,$$
$$c_L^W = \tfrac{1}{2s_W^2}\,|V_{ff'}|^2\left[s_{\mathrm{eff}}\,\tfrac{m_{f'}^2}{m_W^2} + (1-s_{\mathrm{eff}})\,\tfrac{m_f^2}{m_W^2}\right]\,, \qquad c_L^Z = \tfrac{I_f^3}{s_W^2}\,\tfrac{m_f^2}{m_W^2}\,,$$

- couplings $ff^{(\prime)}V$ depend on spin of f, but standard parton showers are spin avaraged (no spin information)
- process dependent avarage spin of fermion line s_{eff}
  $\Rightarrow pp\to jj$: $s_{\mathrm{eff}}=\frac{1}{2}$, $pp\to W$: $s_{\mathrm{eff}}=1$, undefined in general
- factors f_W, f_Z, f_h modify couplings to test sensitivity

Krauss, Petrov, MS, Spannowsky Phys.Rev.D89(2014)114006

Can we see radiated W bosons inside jets at the LHC (14 TeV)?

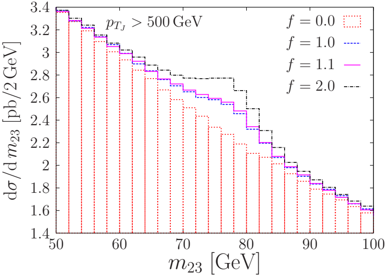
- need high-$p_\perp$ jets to produce real W bosons at sufficient rate
- need high-$p_\perp$ jets to satisfy assumption $E \gg m$

Boosted analysis:

- find jets (anti-$k_\perp$, $R = 1.5$, $p_\perp > 200$ GeV)
- no isolated leptons ($p_\perp > 25$ GeV, $|\eta| < 2.5$, $E_\text{had} < 0.1\, E_\ell$ in $\Delta R = 0.2$)
- require further two jets with $p_\perp > 500, 750, 1000$ GeV to drive W radiation into collinear region

Hadronic analysis

- recluster fat jets into C/A ($R = 0.3$, $p_\perp > 20$ GeV) microjets
- discard leading microjet as likely from leading quark
- use m_{23} as gluon em. tends to be softer then decay prod. of W em.
- accept candidate if $m_{23} \in [70, 86]$ GeV



$\Rightarrow$ large, but continuous QCD background, clear signal shape

$\Rightarrow$ more W emissions with hight $p_\perp$, but peak shifts

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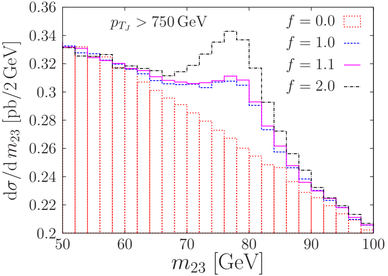

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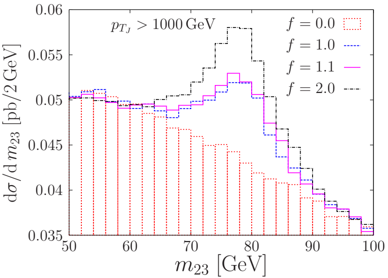

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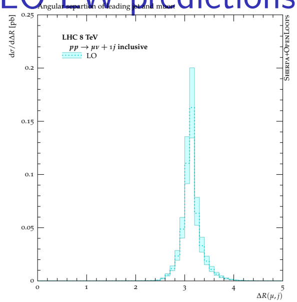
NLO EW predictions for $\Delta R(\mu, j_1)$



Measure coll. W emissions, simplified from
Krauss, Petrov, MS, Spannowsky PRD89(2014)114006

LHC@8TeV, $p_\perp^{j_1} > 500\,\mathrm{GeV}$, central μ and jet

- LO $pp \to Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
  large $pp \to Wjj$ component opening PS
- subleading Born (γPDF) imp. at large ΔR
- restrict to exactly $1j$, no $p_\perp^{j_2} > 100$ GeV
- describe $pp \to Wjj$ @ NLO, $p_\perp^{j_2} > 100$ GeV
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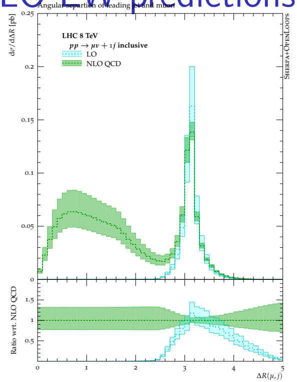

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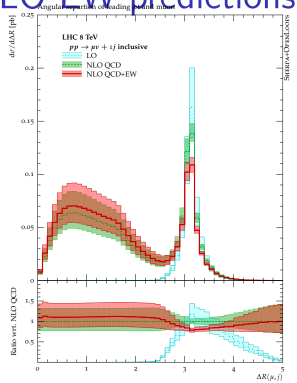

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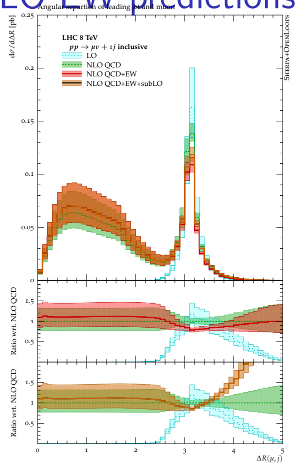

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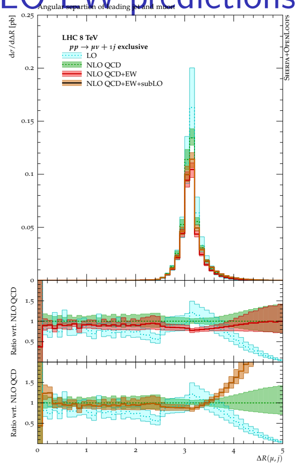

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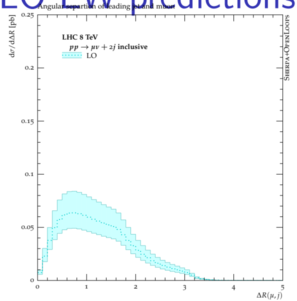

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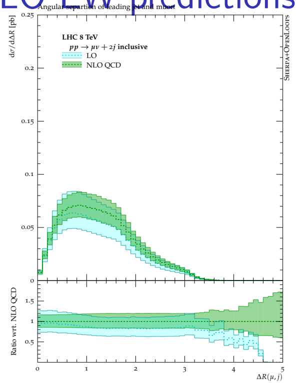

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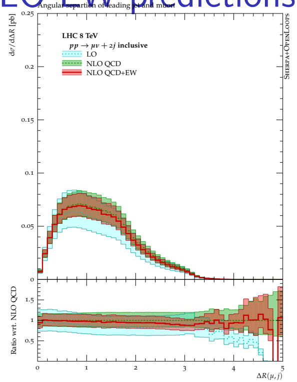

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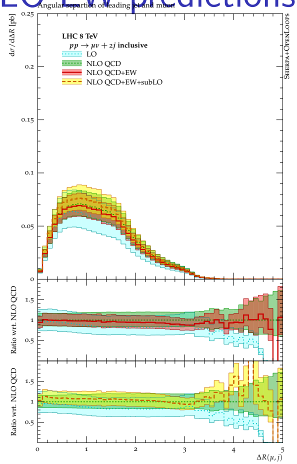

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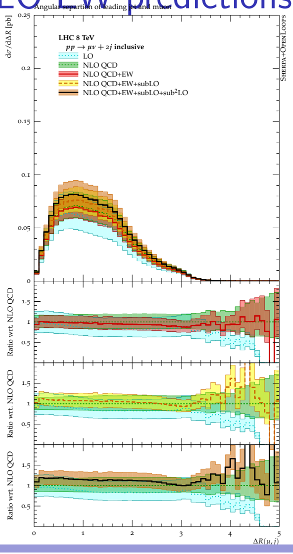

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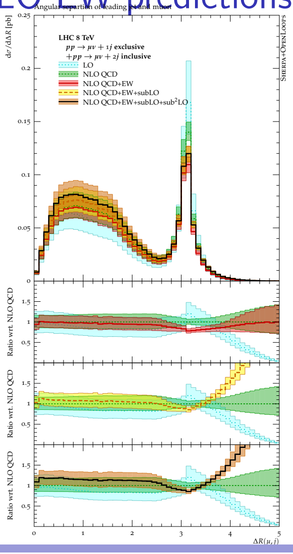

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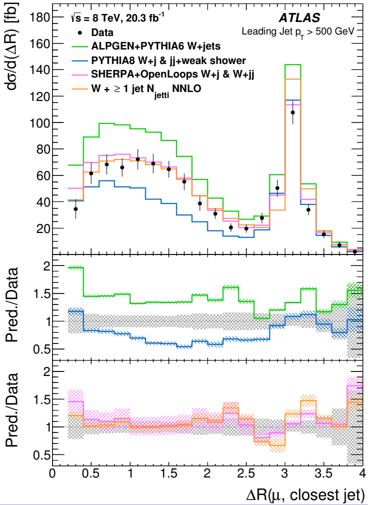

Data comparison
M. Wu ICHEP'16, ATLAS arXiv:1609.07045

- ALPGEN+PYTHIA
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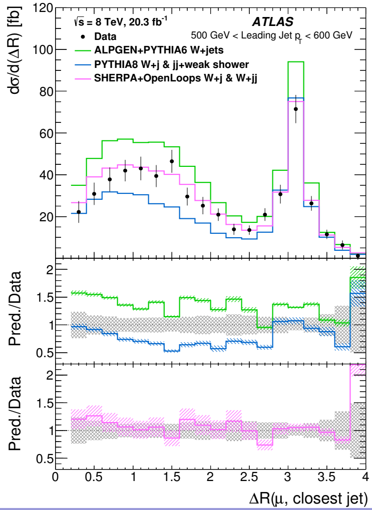

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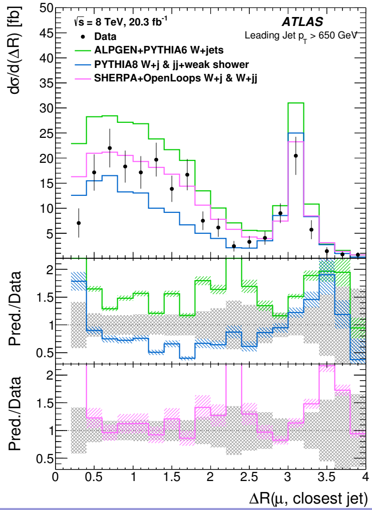

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Conclusions

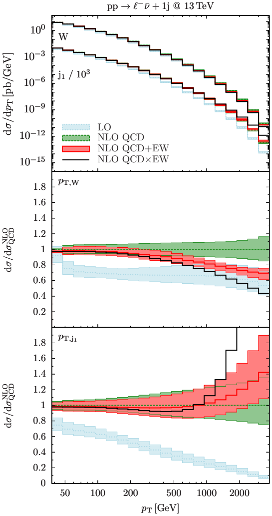
- electroweak effects are important at LHC, HE–LHC, FCC, etc.
- become large whenever the scale is large compared the EW scale
- can be incorporated in multijet merging to improve description in those regions
  $\Rightarrow$ included since SHERPA-2.2.1 (now SHERPA-2.2.5)
- automation of NLO EW follows on the heels of NLO QCD
  $\rightarrow$ much more care with consistent schemes and order counting
  $\rightarrow$ very rich phenomenology
  $\rightarrow$ includes many more pitfalls than NLO QCD
  $\Rightarrow$ included in next major SHERPA release
- EW parton showers suffer from strong spin depedence of W/Z emission as parton showers are usually do not have spin information
  $\Rightarrow$ not included in SHERPA puclic release

Thank you for your attention!

Backup

$pp \to Wj$ @ 13 TeV

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



- NLO QCD to $p_T^{j_1}$ dominated by hard dijet topologies
  $\to$ LO, no EW corr.

  Rubin, Salam, Sapeta JHEP09(2010)084

  $\to$ need merging
- remove dijet configs through $\Delta\phi_{j_1 j_2} < \frac{3}{4}\pi$
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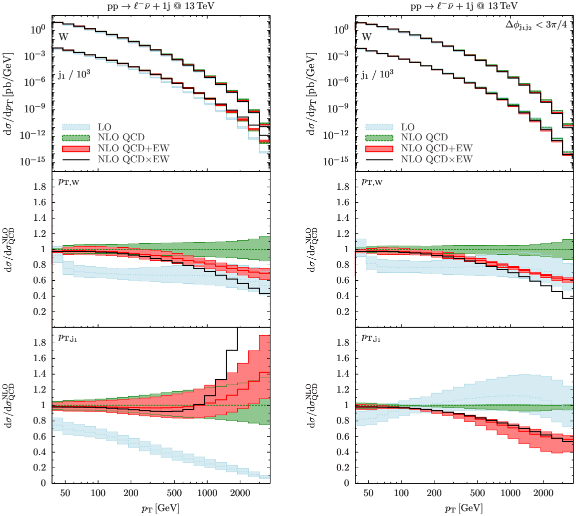
$pp \to Wj$ @ 13 TeV

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



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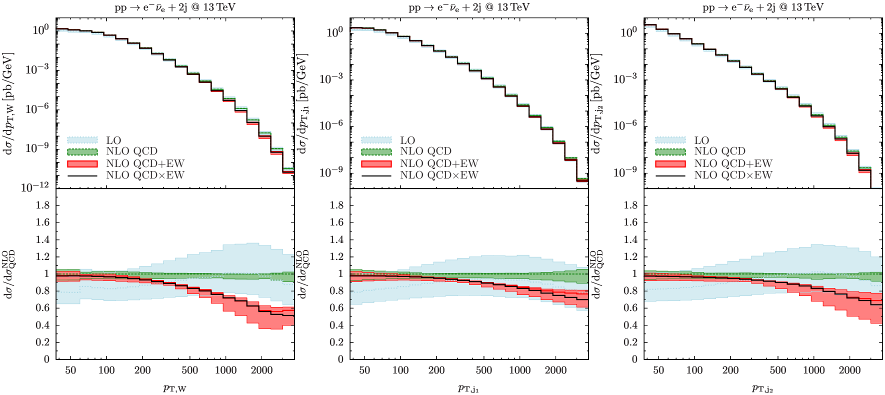
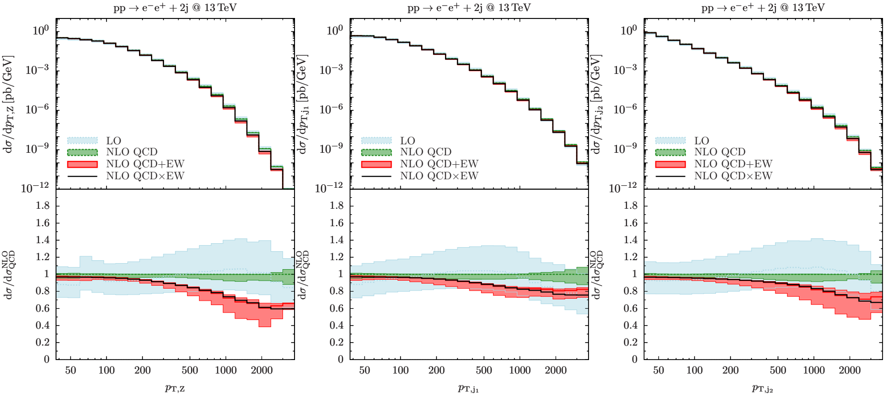
Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021



$pp \to Zjj$ @ 13 TeV

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



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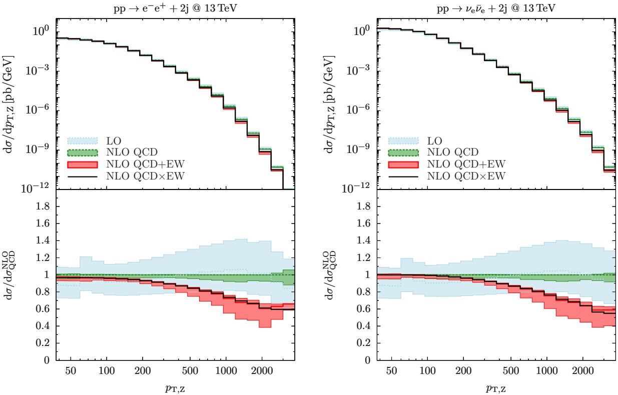
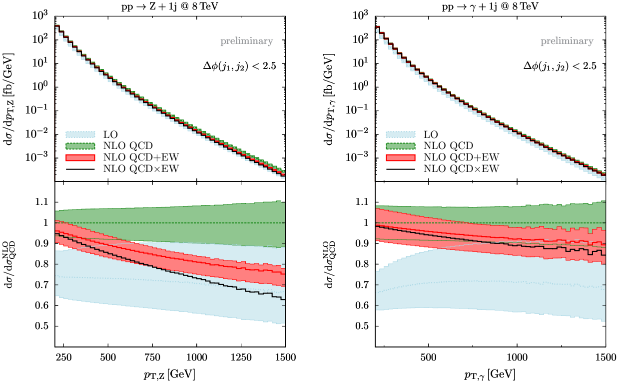
Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021



→ EW corrections independent of the decay mode

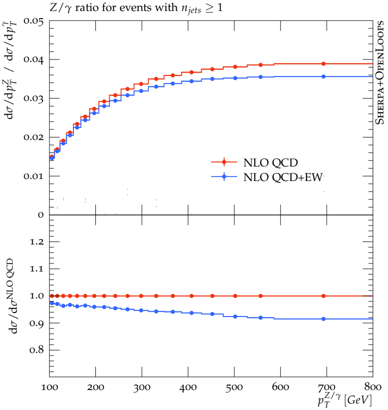
Z/γ ratio @ 8 TeV

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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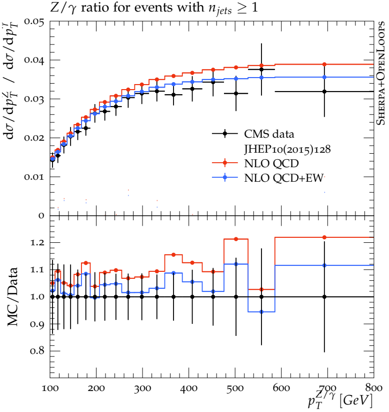

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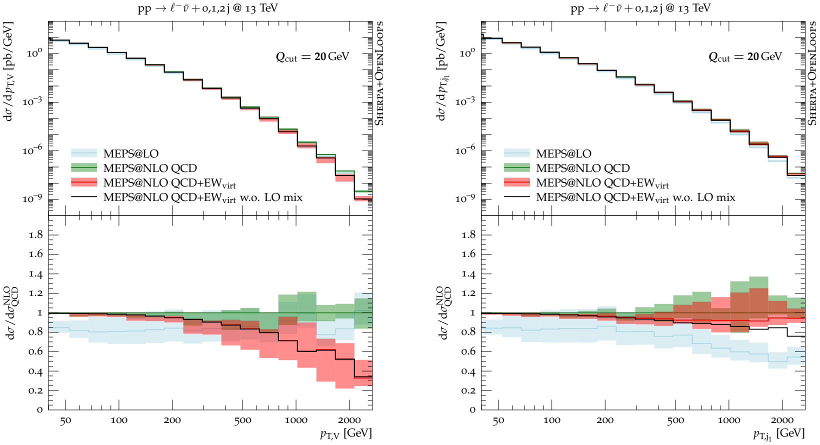
Results: $pp \to \ell^- \bar{\nu} + \text{jets}$

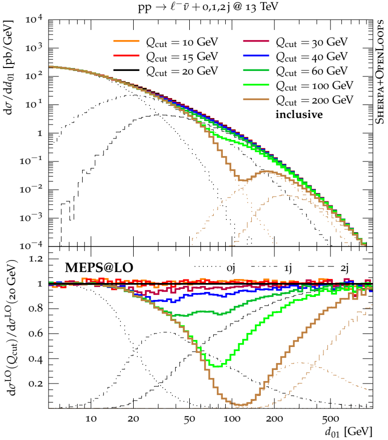
Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021

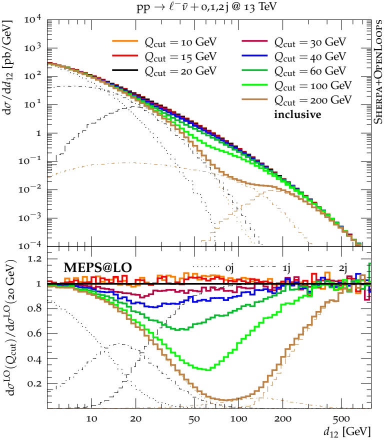


$\Rightarrow$ particle level events including dominant EW corrections

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

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





$\Rightarrow$ dead zones in incl. obs. if Q_{cut} too high

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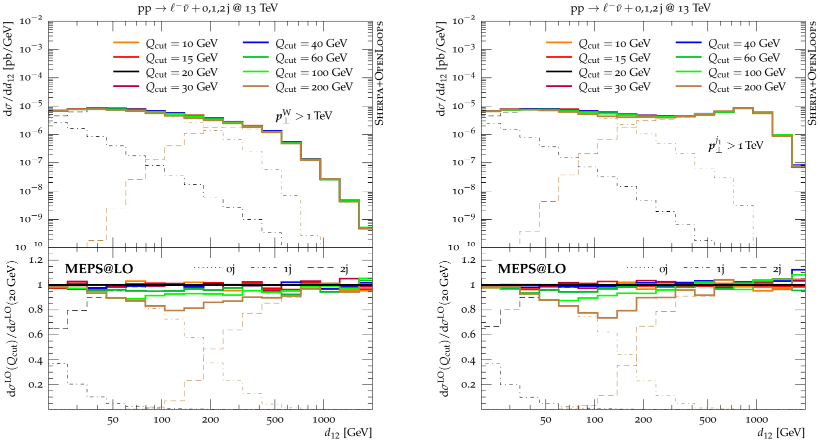

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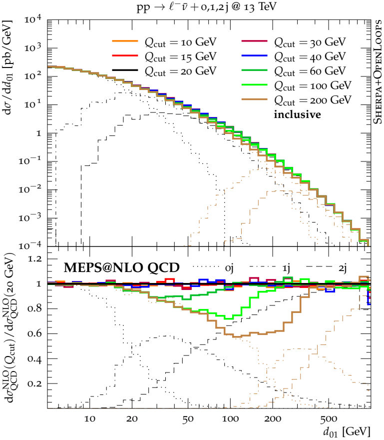

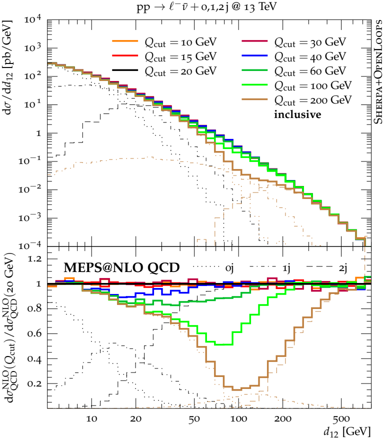

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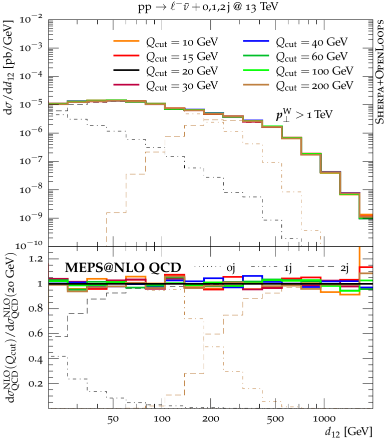

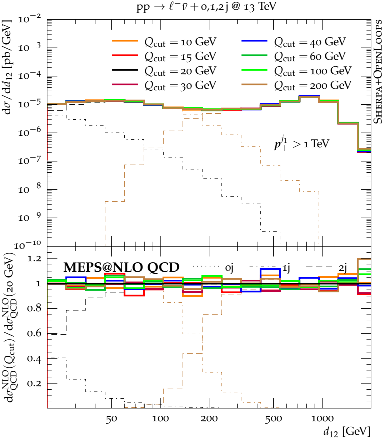

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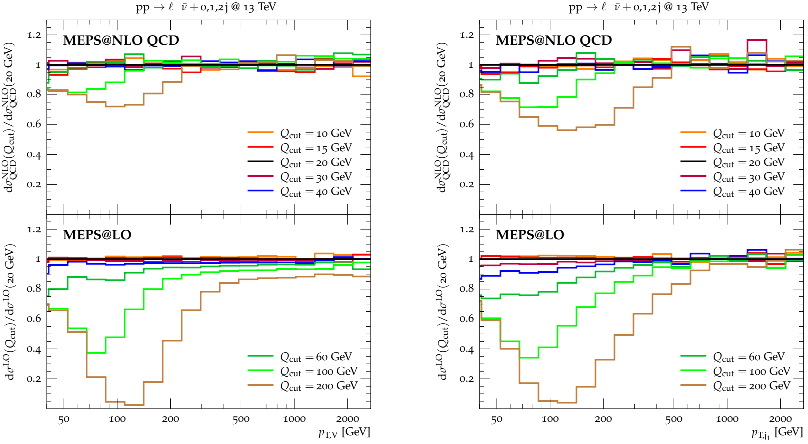
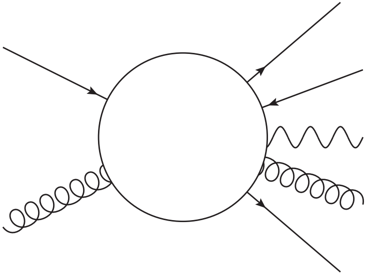


$\Rightarrow$ TeV region stable ($\lesssim 5\%$), $Q_{\text{cut}} = 20\,\text{GeV}$ suitable for whole range

QCD multijet merging – identifying a history

Example: Drell-Yan production in association with jets



- cluster external particles using inverse parton shower → flavour conscious, initial state aware, probability determined through splitting kernels
- identify a shower history (probabilistically), determine scale t_i up to predefined t_I
- choose

$$\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\text{core}}^2) \prod_{i=1}^{n} \alpha_s(t_i)$$

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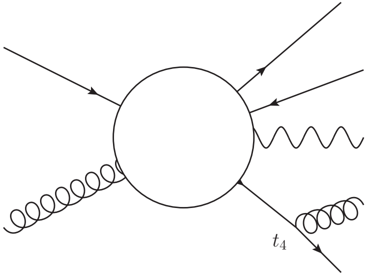

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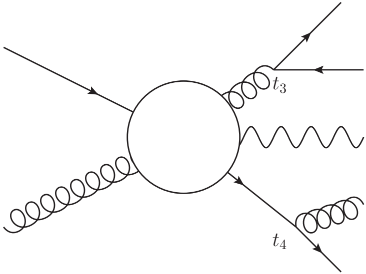

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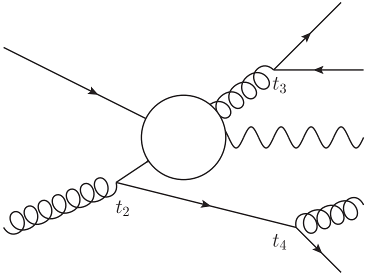

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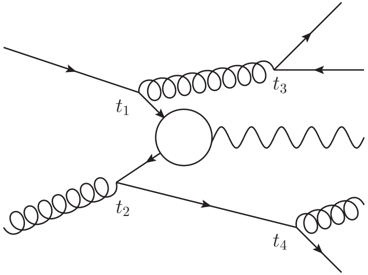

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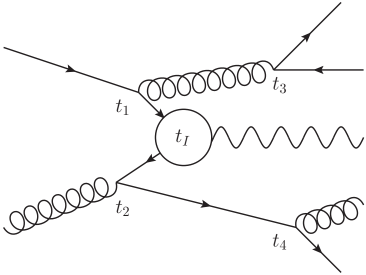

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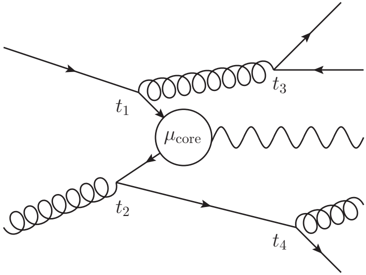

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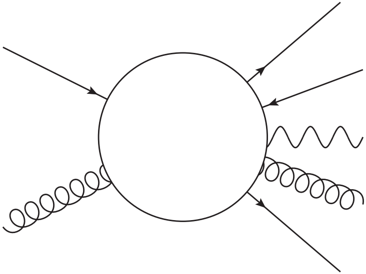
QCD multijet merging – identifying a history

ME also provides expression beyond t_I
two types of configuration: $pp \to Z$+jets and $pp \to$jets$+Z$



- different core process, naïvely not part of $pp \to Z$+jets but indistinguishable
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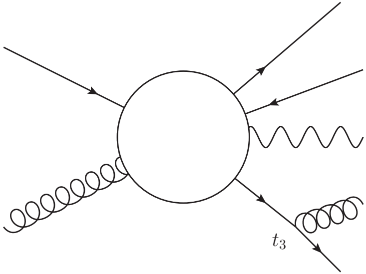

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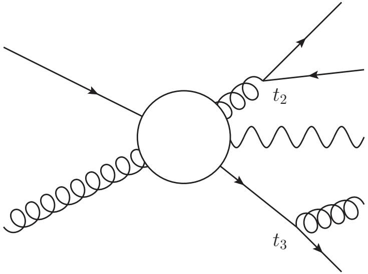

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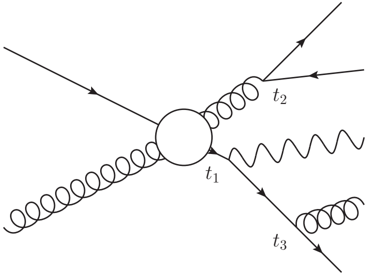

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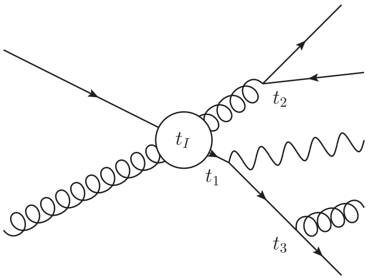

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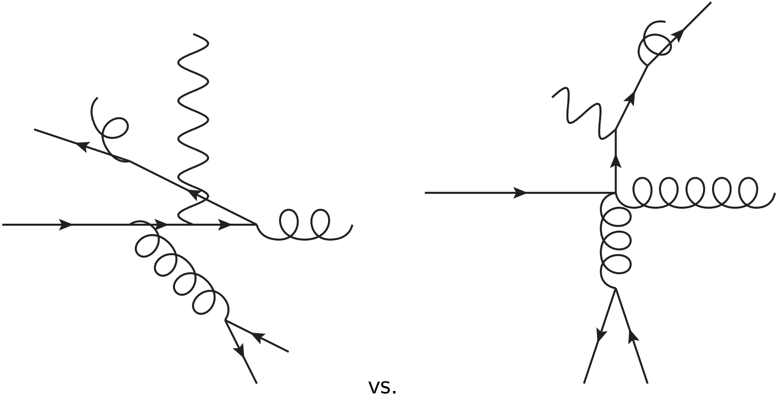
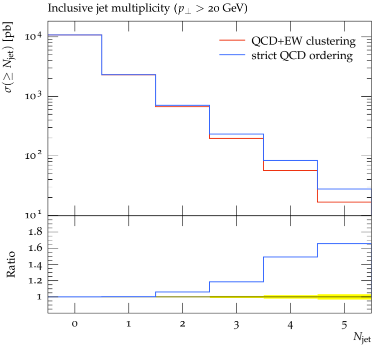
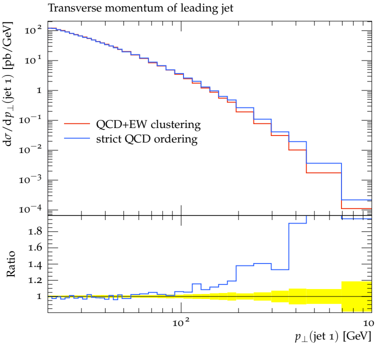


Importance of electroweak clustering





$\Rightarrow$ large impact at high $p_\perp$ and multiplicity