Electroweak corrections for LHC physics

Marek Schönherr

CERN

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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 jet production at large transverse momentum (EW-Sudakov suppression). Usually negative and rising 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. Real boson radiation
   - Resummation via EW parton showers
   - Case study: Finding W bosons inside jets
3. Conclusions

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   - Resummation via EW parton showers
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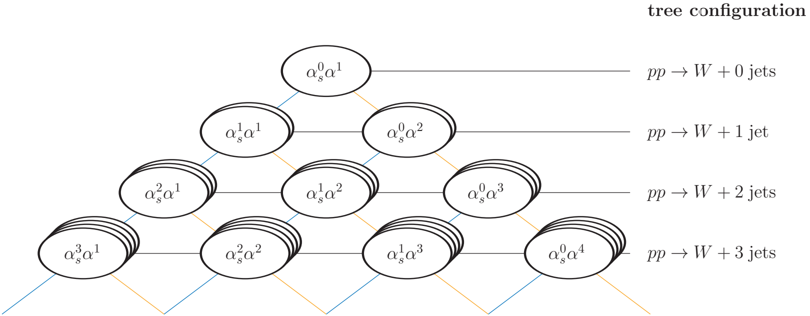
Consistent setup: counting orders and defining signatures



- 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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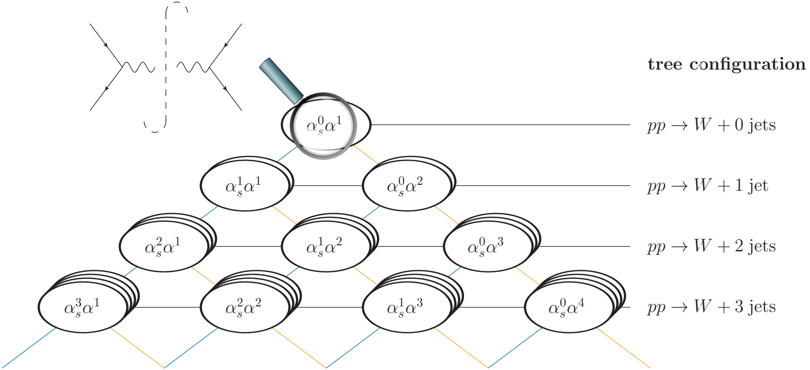

tree configuration

$pp \to W + 0$ jets

$pp \to W + 1$ jet

$pp \to W + 2$ jets

$pp \to W + 3$ jets

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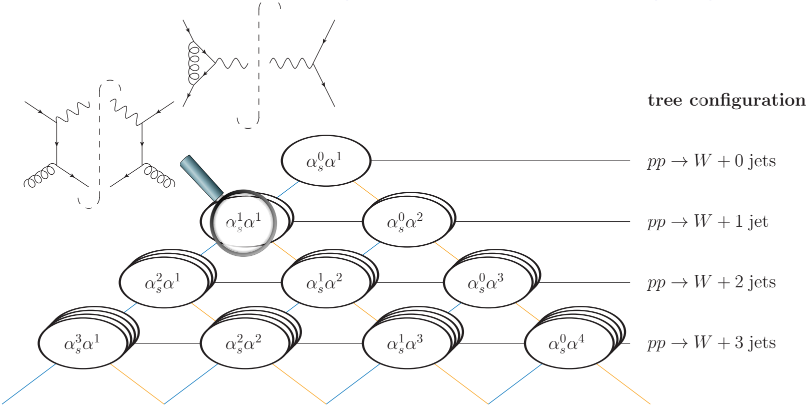

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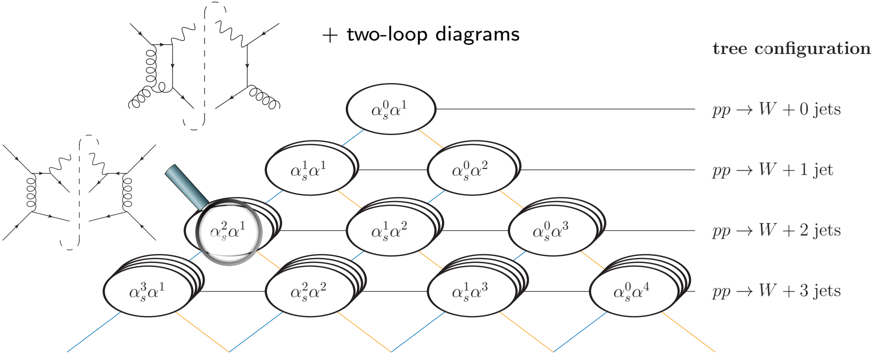

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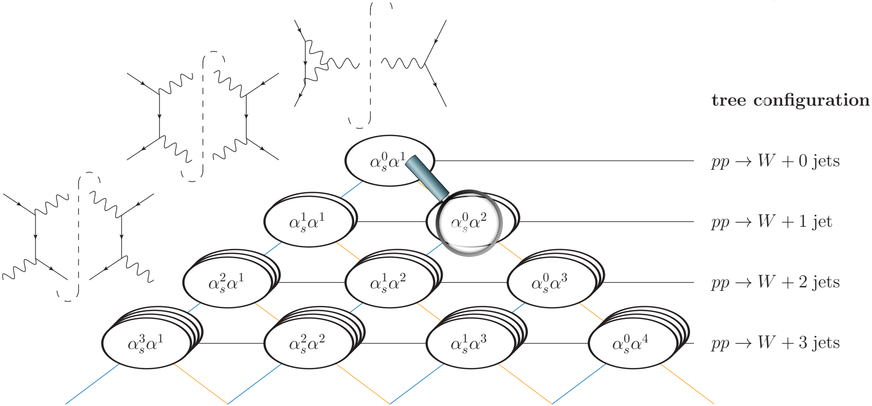

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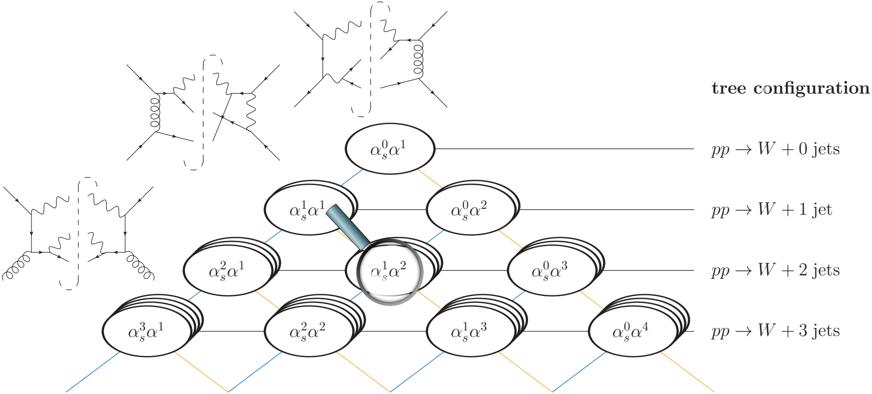

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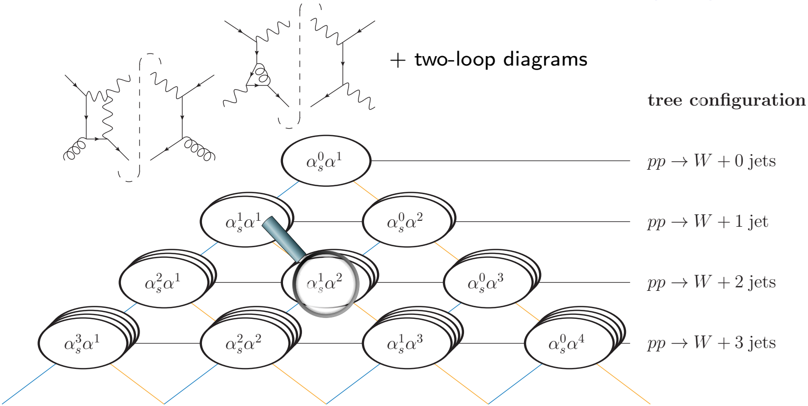

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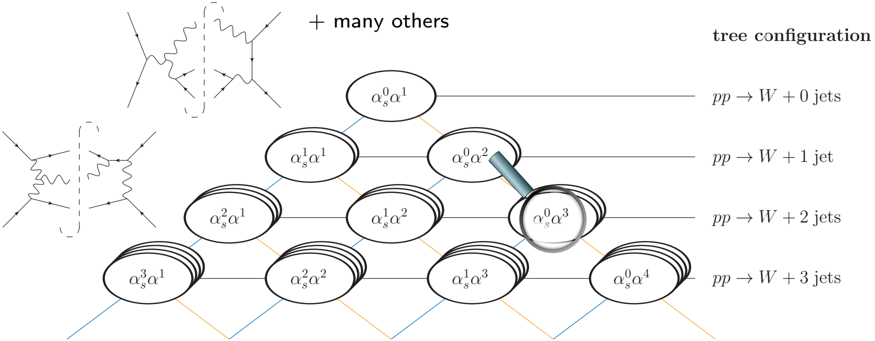

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NLO EW subtraction in SHERPA

MS in preparation

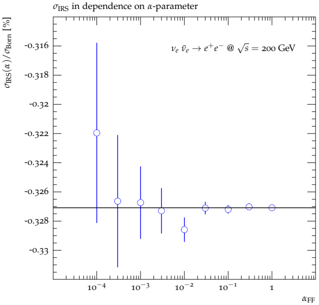
- adapt QCD subtraction (spl. fns. and colour-/spin-correlated MEs)

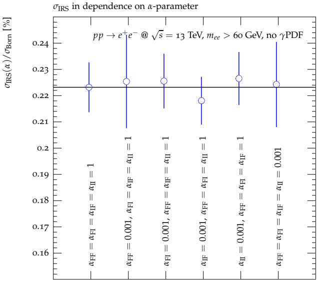
  Catani, Dittmaier, Seymour, Trocsanyi Nucl.Phys.B627(2002)189-265

- replacements: $\alpha_s \to \alpha,\ C_F \to Q_f^2,\ C_A \to 0,$

  $T_R \to N_{c,f}\, Q_f^2,\ n_f\, T_R \to \sum_f N_{c,f}\, Q_f^2,$

$$\frac{\mathbf{T}_{ij}\cdot\mathbf{T}_k}{\mathbf{T}_{ij}^2} \to \frac{Q_{ij}Q_k}{Q_{ij}^2}$$


σ_{IRS} in dependence on α-parameter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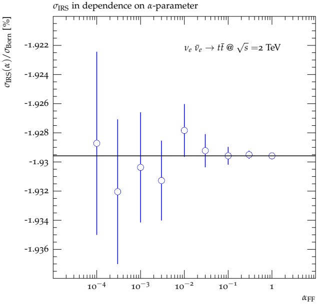

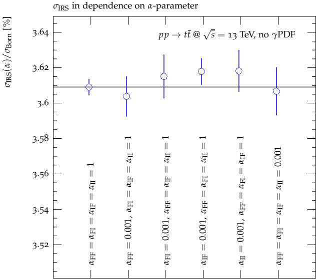

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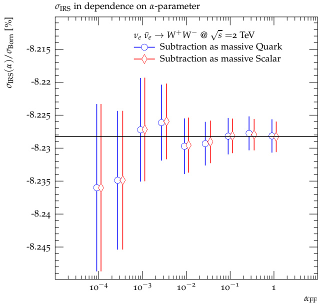
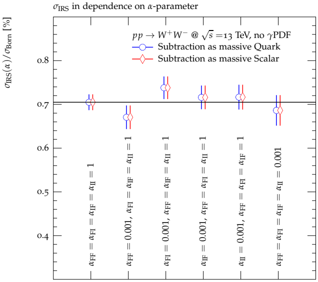

$\sigma_{\rm IRS}$ in dependence on α-parameter


$\sigma_{\rm IRS}$ in dependence on α-parameter

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
  → splittings $\gamma \to \gamma$, $\gamma \to q\bar{q}$, $q \to q\gamma$
- the photon PDF (at NLO QED) contains renormalisation factors that must be cancelled by the partonic cross section

⇒ 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

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

⇒ 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 $D_\gamma^p(z,\mu)$

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

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)

n_f schemes and limited PDF availability

- all available QED PDFs are either 5F (CT14, LUX, NNPDF3.0) or 6F (NNPDF2.3)
- need scheme conversion terms Cacciari, Greco, Nason hep-ph/9803400

$$
\begin{aligned}
&\sigma^{(n_{lf})}_{\text{NLO}}(\mu_R^2,\mu_R^2)\\
&\quad=\sigma^{(n_f)}_{\text{NLO}}(\mu_R^2,\mu_R^2)\\
&\qquad+\frac{\alpha_s}{3\pi}\sum_{i=n_{lf}}^{n_f}\sum_{\{j_1j_2\}}T_R\left[p\,\log\frac{m_i^2}{\mu_R^2}\,\Theta\left(\mu_R^2-m_i^2\right)-\Delta^{gg}_{j_1j_2}\log\frac{m_i^2}{\mu_F^2}\,\Theta\left(\mu_F^2-m_i^2\right)\right]\sigma^{(n_f)}_{\text{LO};j_1j_2}(\mu_R^2,\mu_F^2)\\
&\qquad-\frac{\alpha}{3\pi}\sum_{i=n_{lf}}^{n_f}\sum_{\{j_1j_2\}}N_{C,i}\,Q_i^2\,\Delta^{\gamma\gamma}_{j_1j_2}\log\frac{m_i^2}{\mu_F^2}\,\Theta\left(\mu_F^2-m_i^2\right)\;\sigma^{(n_f)}_{\text{LO};j_1j_2}(\mu_R^2,\mu_F^2)\;.
\end{aligned}
$$

- emergence of NLO QED PDFs good for consistency
- is there even a point of still having QCD-only PDFs?

NLO EW calculations

- MUNICH/SHERPA+OPENLOOPS:
  - $pp \to V + 0, 1, 2(, 3)$ jets Lindert et.al. arXiv:1705.04664
    FCC report, arXiv:1607.01831
    EW report arXiv:1606.02330
    LH'15 arXiv:1605.04692
    Kallweit,Lindert,Maierhöfer,Pozzorini,MS JHEP04(2015)012, JHEP04(2016)021
  - $pp \to Zj/pp \to \gamma j$ 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
  - $pp \to 2\ell 2\nu$ Kallweit,Lindert,Pozzorini,MS, arXiv:1705.00598
  - $pp \to t\bar{t}h$ LH'15 arXiv:1605.04692
- SHERPA+GOSAM
  - $pp \to \gamma\gamma + 0, 1, 2$ jets Chiesa et.al. arXiv:1706.09022
  - $pp \to \gamma\gamma\gamma\ /\ \gamma\gamma\ell\nu\ /\ \gamma\gamma\ell\ell$ Greiner, MS arXiv:1710.11514
- SHERPA+RECOLA
  - $pp \to V + 0, 1, 2$ j, $pp \to 4\ell$, $pp \to t\bar{t}h$ Biedermann et.al. arXiv:1704.05783

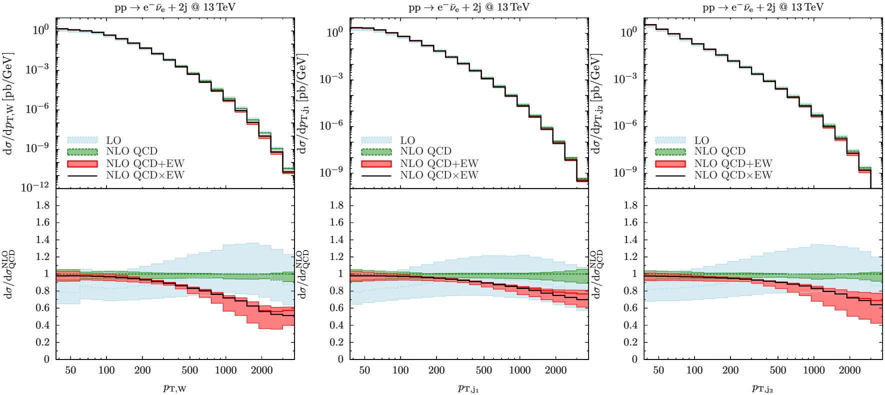
Tools and setup

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

- OpenLoops for virtual corrections using Collier for tensor integrals
- Sherpa for Born, real em., subtraction and phase space integration, Munich (MEs from OpenLoops) for subtraction and p. s. int.
- combine QCD and EW corrections as:
  QCD+EW: $\sigma_{\text{NLO QCD+EW}} = \sigma_{\text{LO}}\left(1 + \delta_{\text{QCD}} + \delta_{\text{EW}}\right)$
  QCD×EW: $\sigma_{\text{NLO QCD}\times\text{EW}} = \sigma_{\text{LO}}\left(1 + \delta_{\text{QCD}}\right)\left(1 + \delta_{\text{EW}}\right)$
  $\Rightarrow$ use difference as indication of potential size of $\mathcal{O}(\alpha_s\alpha)$ corrs.
- dress quarks and leptons in $\Delta R = 0.1$,
  if γ in jet, $E_\gamma < \frac{1}{2}E_{\text{jet}}$, discard jet otherwise

$pp \to Wjj$ @ 13 TeV

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



$pp \to Zjj$ @ 13 TeV

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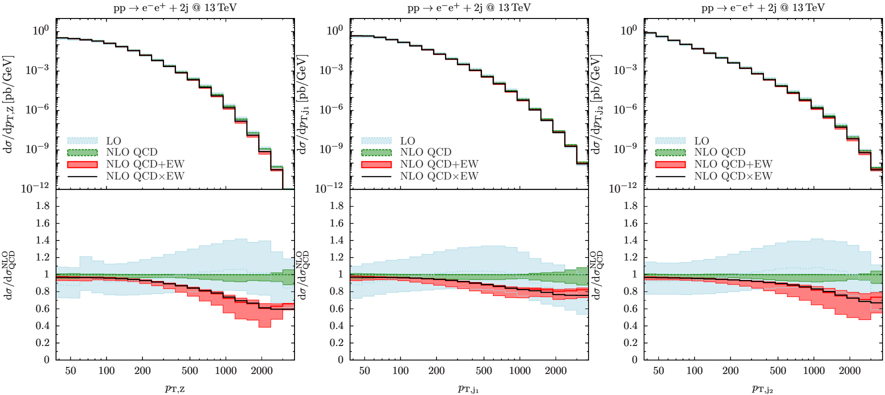

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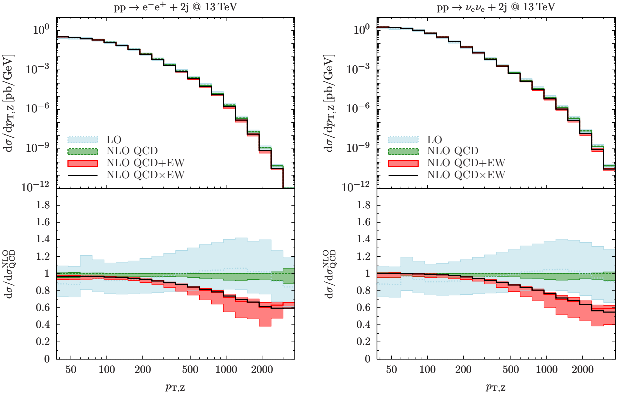
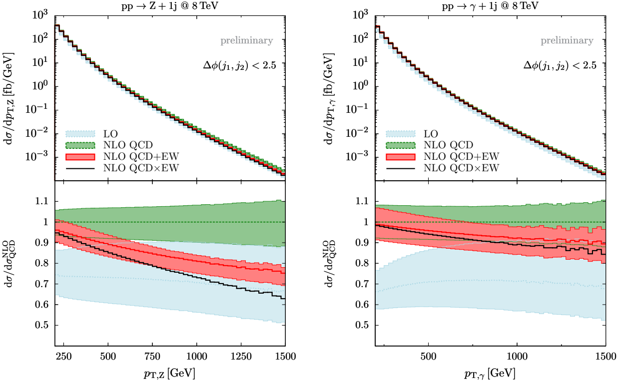


→ EW corrections independent of the decay mode

Z/γ ratio @ 8 TeV

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



→ EW corrections different for Z and γ

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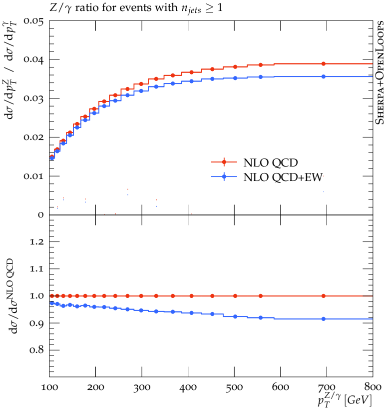

Kallweit, Lindert, Pozzorini, MS for LH'15

- 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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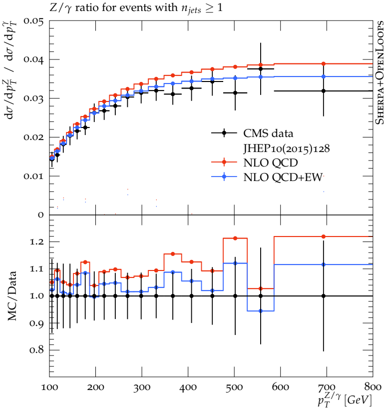

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⇒ NLO EW improves data description

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
  → validated at fixed order, found to be reliable,
  diff. $\lesssim 5\%$ for observables not driven by real radiation

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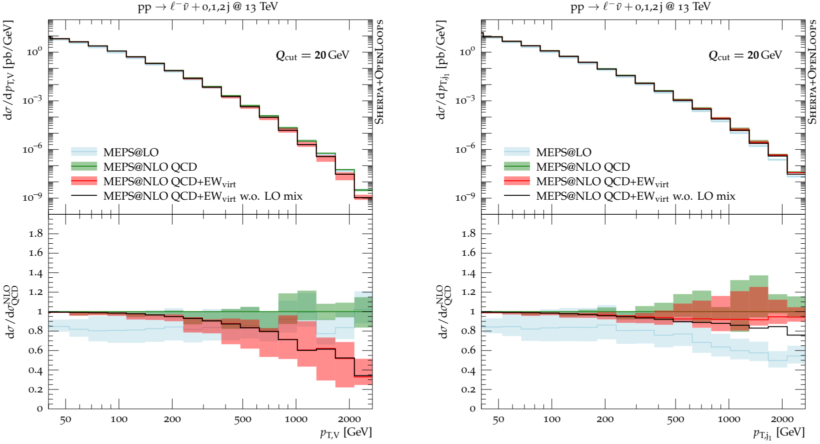
Results: $pp \to \ell^- \bar{\nu}$ + jets

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



⇒ particle level events including dominant EW corrections

Diboson production – DF and SF

Combination of QCD and EW correction

- additive – strict fixed order expansion

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

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

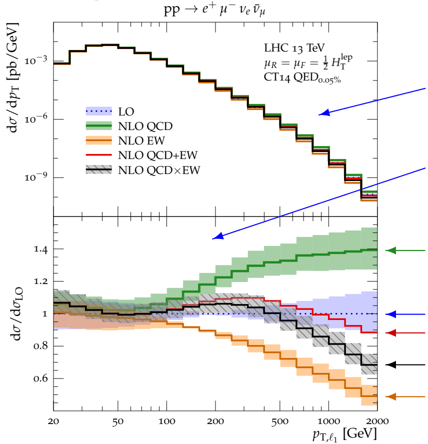
$$\mathrm{d}\sigma^{\mathsf{NLO}}_{\mathsf{QCD\times EW}} = \mathrm{d}\sigma^{\mathsf{LO}}\left(1+\delta_{\mathsf{QCD}}\right)\left(1+\delta_{\mathsf{EW}}\right)$$

NLO EW for photon initiated processes

- resolved final state photons should be renormalised on-shell ($\alpha(0)$)
  → absorbs IR divergences from $\gamma \to f\bar{f}$ splittings not included
- initial state (and unresolved final state) photons should be renormalised at the hard scale ($\alpha(m_Z)$, G_μ, $\overline{\mathsf{MS}}$, etc.)
  → match IR divergences in PDF evolution and collinear counter term

Harland-Lang, Khoze, Ryskin Phys.Lett.B761(2016)20-24
Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

Diboson production – DF



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absolute prediction

relative correction wrt. LO

NLO QCD (w/ moderate jet veto)

LO

NLO QCD+EW

NLO QCD×EW

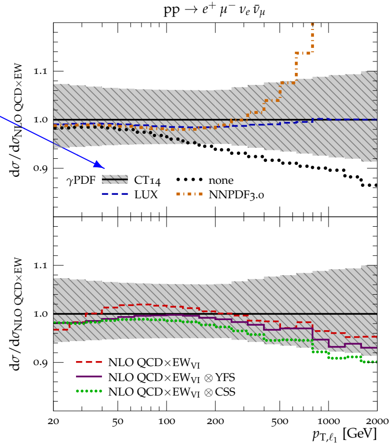
NLO EW

- large pos. NLO QCD, large neg. NLO EW
  → NLO QCD+EW and NLO QCD⊗EW differ significantly

Diboson production – DF

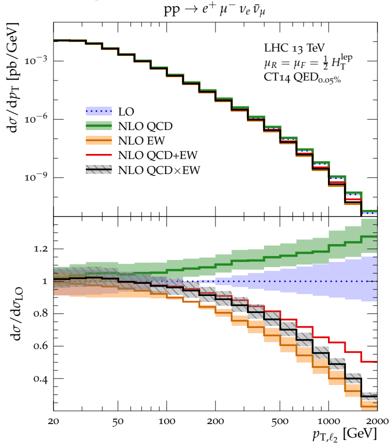
relative importance of γ-induced channels wrt. NLO QCD$\times$EW

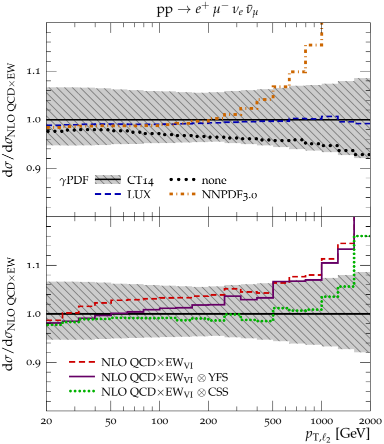
CT14qed (baseline)	no γPDF
LUXqed	NNPDF3.0qed



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

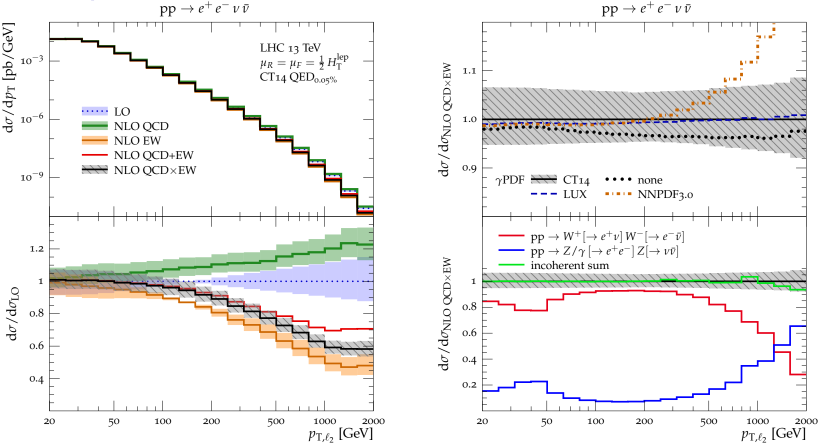
Diboson production – DF





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

Diboson production – SF



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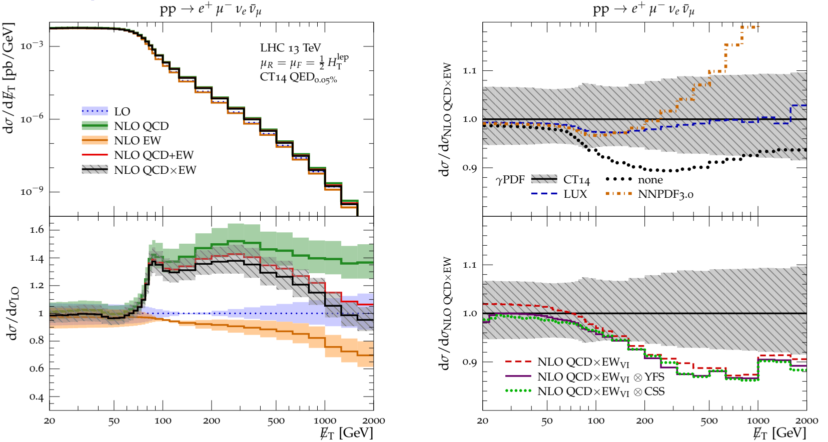
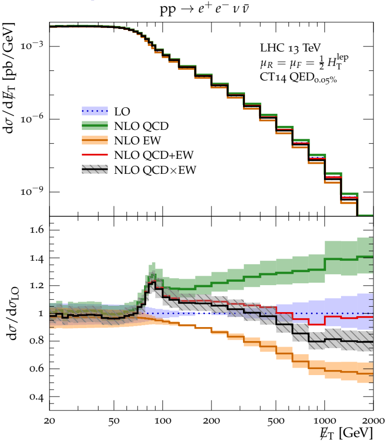
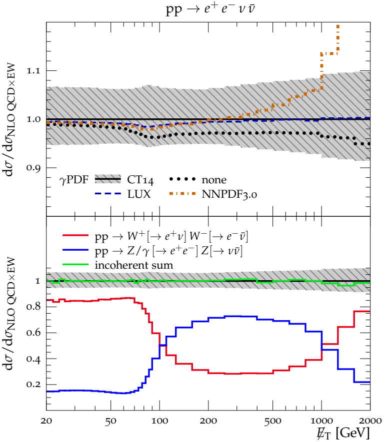


- kinematic suppression for $p_T^{\nu\nu}$ at LO, unlocked at NLO QCD
  not present in γ-induced ⇒ large contrib

Diboson production – SF

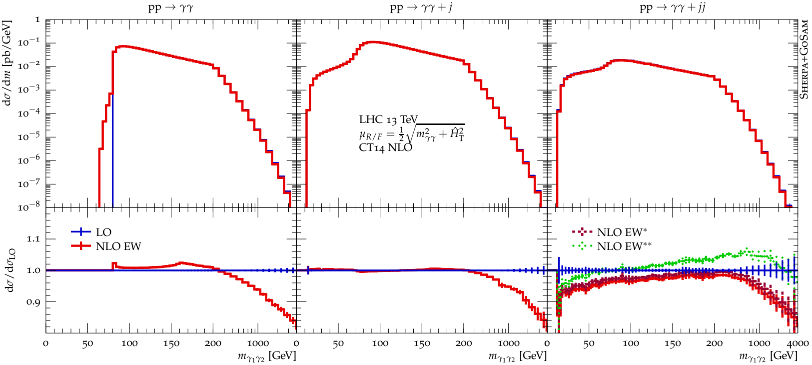




- kinematic suppression for $p_T^{\nu\nu}$ for WW, but not ZZ
  ZZ dominates for MET > 100 GeV with large EW corr.

Diphoton production in association with jets

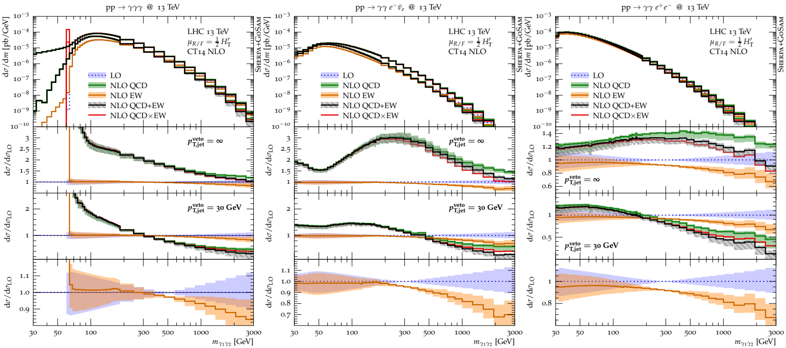
Chiesa, Greiner, MS, Tramontano arXiv:1706.09022



- EW corrections vary with jet multiplicity
- sizeable subleading orders, though partly resonant $\gamma\gamma V$

Diphoton production in association with a vector boson

Greiner, MS arXiv:1710.11514



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

Electroweak corrections for LHC physics

1. Next-to-leading order electroweak corrections
    - Setup and subtleties
    - Selected results

2. Real boson radiation
    - Resummation via EW parton showers
    - Case study: Finding W bosons inside jets

3. Conclusions

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

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

- 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)?

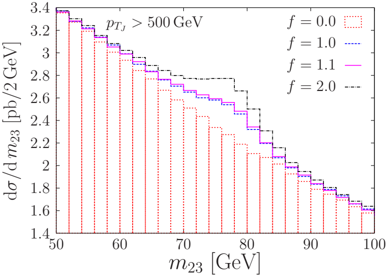
- need high-$p_\perp$ jets to produce real W bosons at sufficient rate
- need high-$p_\perp$ jets to satisfy assumption $E \gg m$

Boosted analysis:

- isolated leptons ($p_\perp > 25$ GeV, $|\eta| < 2.5$, max. 10% in $\Delta R = 0.2$)
- find jets (anti-$k_\perp$, $R = 1.5$, $p_\perp > 200$ GeV) on remainder
- two cases: no isolated leptons ⇒ hadronic analysis
  one isolated lepton ⇒ leptonic analysis
- 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 em. gluons tend to be softer then decay prod. of em. W
- accept candidate if $m_{23} \in [70, 86]$ GeV



⇒ large, but continuous QCD background, clear signal shape

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

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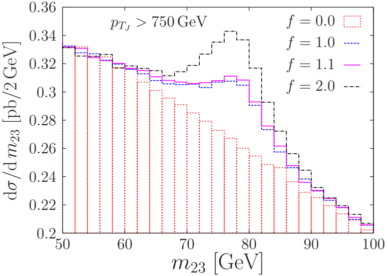

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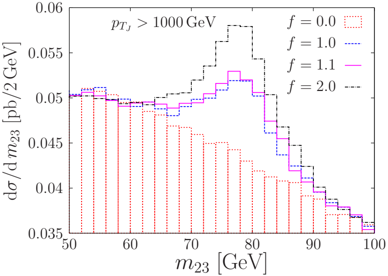

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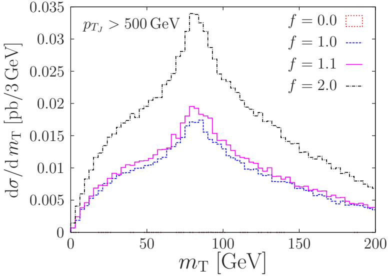
Leptonic analysis

- exactly one isolated lepton
- require $\not{E}_T > 50$ GeV
- reconstruct

$$m_\mathrm{T} = \sqrt{2E_{T_l}\not{E}_T\,(1-\cos\theta)}$$

- accept candidate if $m_\mathrm{T} \in [60, 100]$ GeV



$\Rightarrow$ provides good background rejection

$\Rightarrow$ loose some sensitivity for higher fat jet $p_\perp$ as isolation is compromised for more collinear W emissions

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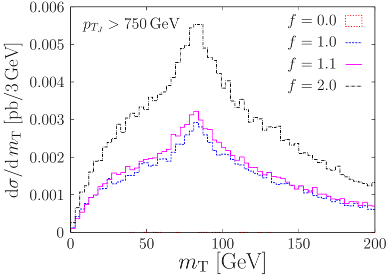

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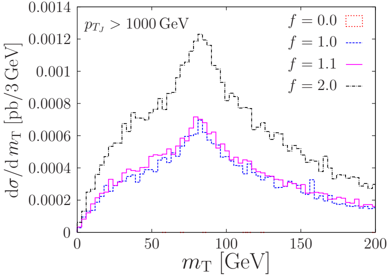

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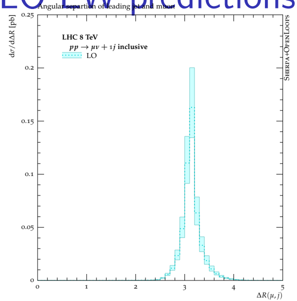
NLO EW predictions for $\Delta R(\mu, j_1)$



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 $p_\perp^{j_2} > 100\,\mathrm{GeV}$
- describe $pp \to Wjj$ @ NLO, $p_\perp^{j_2} > 100\,\mathrm{GeV}$
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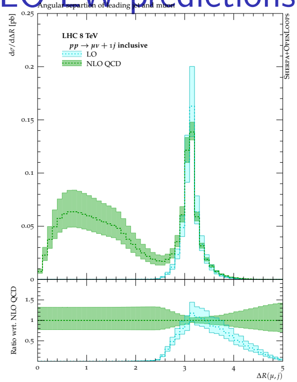

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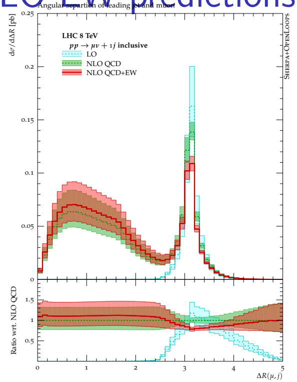

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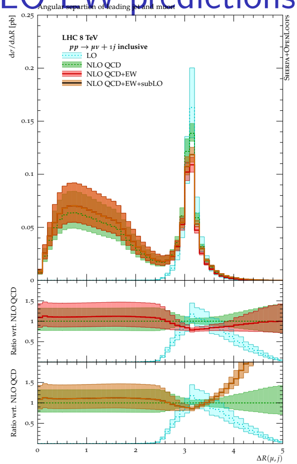

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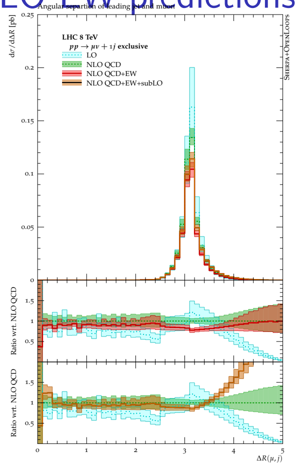

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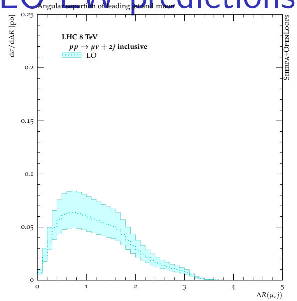

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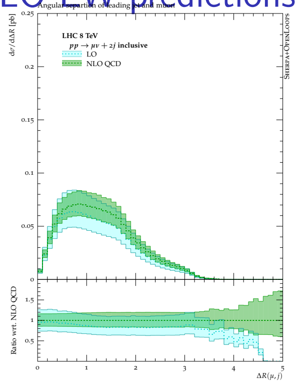

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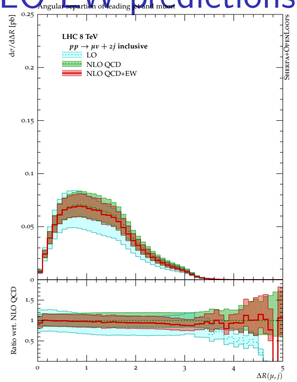

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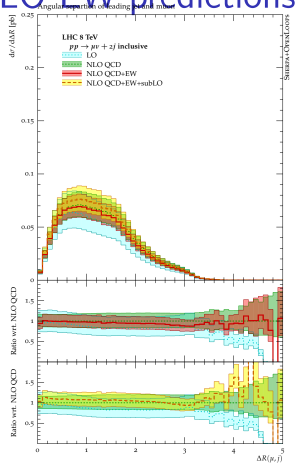

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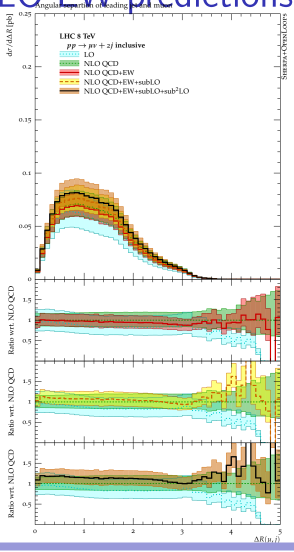

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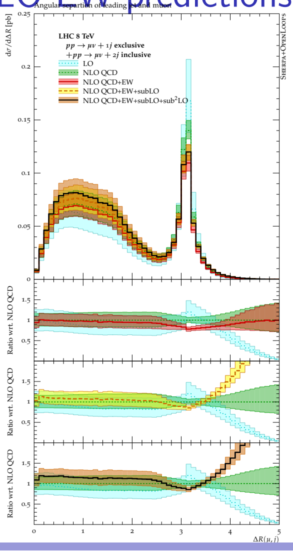

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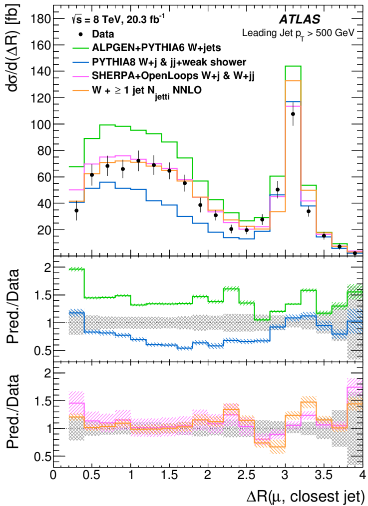
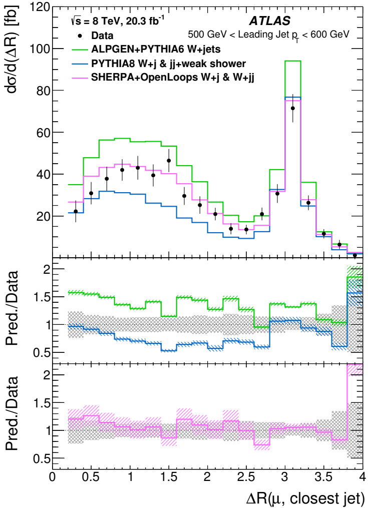


Data comparison

M. Wu ICHEP'16, ATLAS arXiv:1609.07045

- ALPGEN+PYTHIA
  $pp \to W +$ 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
- SHERPA+OPENLOOPS
  NLO QCD+EW+subLO
  $pp \to Wj/Wjj$ excl. sum
  Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021
- NNLO QCD $pp \to Wj$
  Boughezal, Liu, Petriello arXiv:1602.06965

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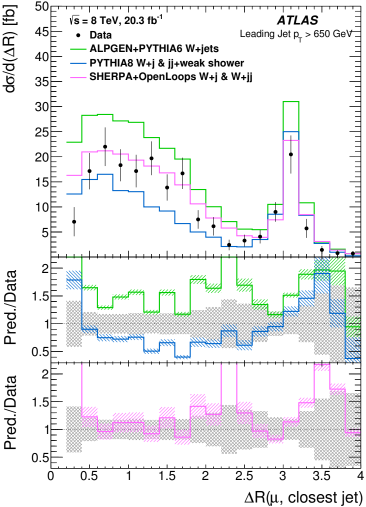

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Conclusions

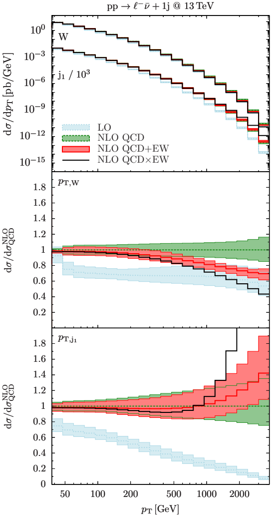
- electroweak effects are important at LHC, HE–LHC, FCC, etc.
- become large whenever the scale is large compared the EW scale
- can be incorporated in multijet merging to improve description in those regions
  ⇒ included since SHERPA-2.2.1 (now SHERPA-2.2.4)
- automation of NLO EW follows on the heels of NLO QCD
  → much more care with consistent schemes and order counting
  → very rich phenomenology
  → includes many more pitfalls than NLO QCD
  ⇒ 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
  ⇒ not included in SHERPA puclic release

Thank you for your attention!

Backup

$pp \rightarrow Wj$ @ 13 TeV

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



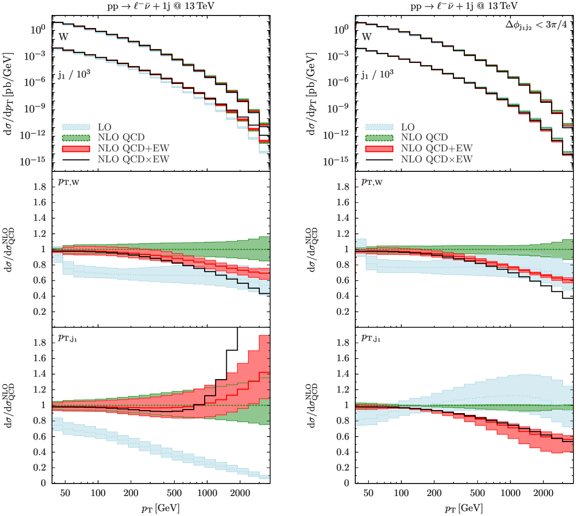
- NLO QCD to $p_T^{j_1}$ dominated by hard dijet topologies
  → LO, no EW corr.

  Rubin, Salam, Sapeta JHEP09(2010)084

  → need merging
- remove dijet configs through $\Delta\phi_{j_1j_2} < \frac{3}{4}\pi$
  → EW Sudakov recovered

$pp \to Wj$ @ 13 TeV

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



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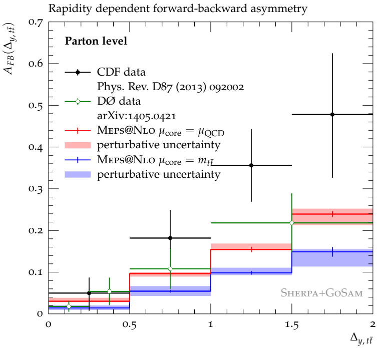
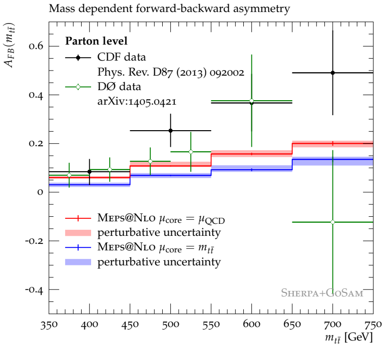
Example: Forward-backward asymetry @ Tevatron

Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)1,014040



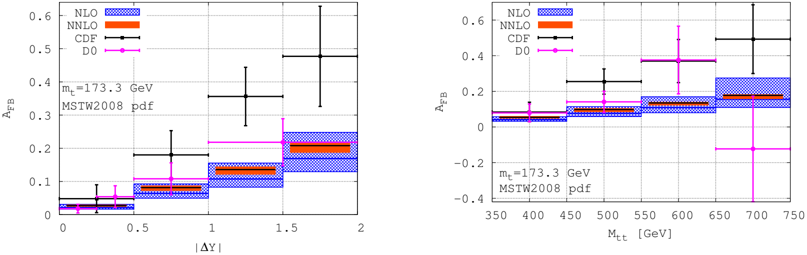


Chose two different μ_{core} → largest impact

Electroweak histories not an issue, but merging works nicely

Recent NNLO+NNLL results: Forward-backward asymetry @ Tevatron

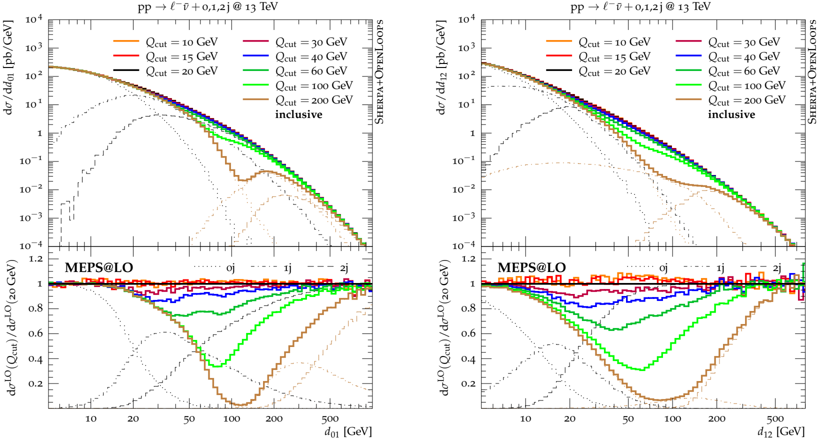
Czakon, Fiedler, Mitov arXiv:1411.3007



MEPS@NLO result very well reproduced by higher order calculation

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

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



⇒ dead zones in incl. obs. if Q_{cut} too high

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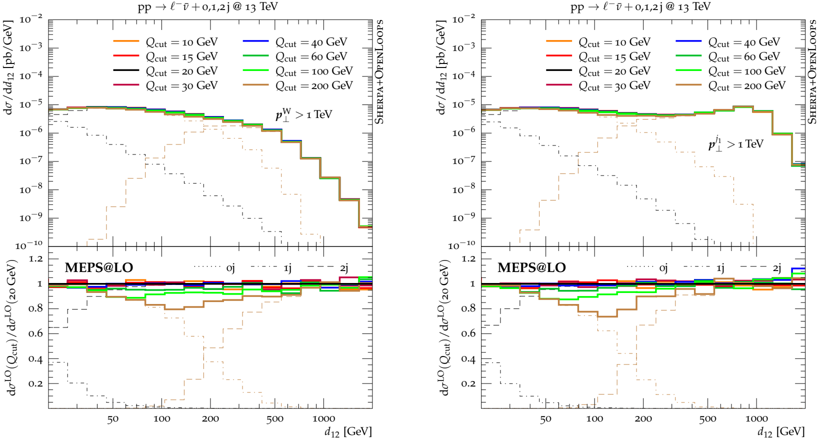

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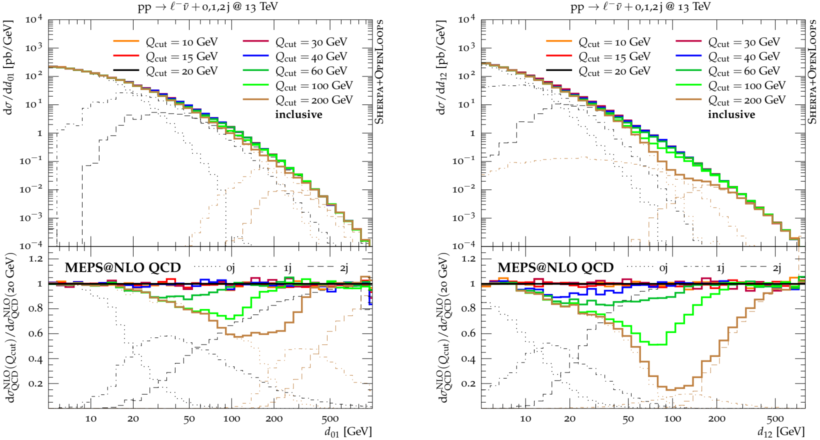

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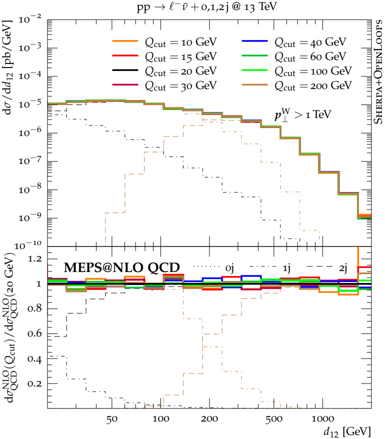

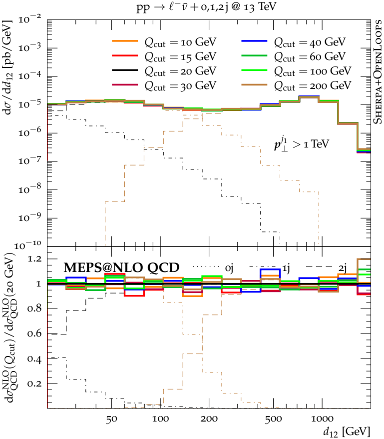

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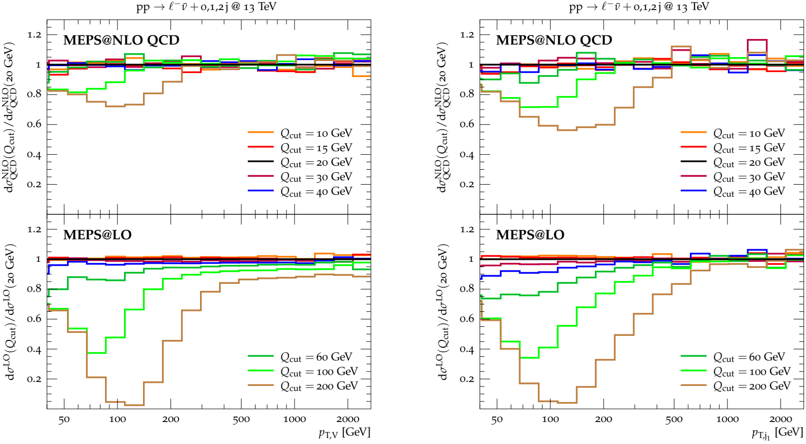
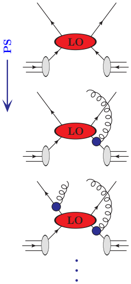


$\Rightarrow$ TeV region stable ($\lesssim 5\%$), $Q_{\text{cut}} = 20\,\text{GeV}$ suitable for whole range

QCD multijet merging – LO case

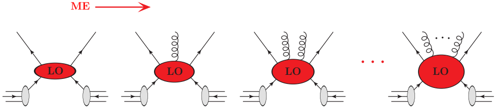


Parton showers

resummation of (soft-)collinear limit
→ intrajet evolution

- matrix elements (ME) and parton showers (PS) are approximations in different regions of phase space
- MEPS combines multiple LOPS – keeping either accuracy
- NLOPS elevate LOPS to NLO accuracy
- MENLOPS supplements core NLOPS with higher multiplicities LOPS

QCD multijet merging – LO case



Matrix elements

fixed-order in α_s
$\rightarrow$ hard wide-angle emissions
$\rightarrow$ interference terms

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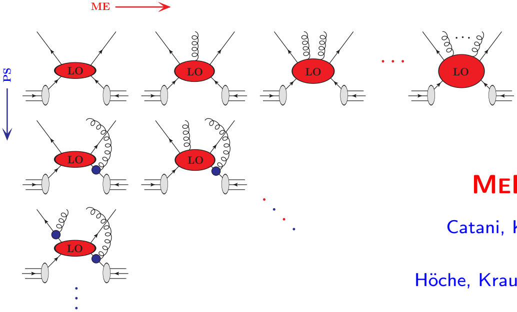

MEPS (CKKW,MLM)

Catani, Krauss, Kuhn, Webber JHEP11(2001)063
Lönnblad JHEP05(2002)046
Höche, Krauss, Schumann, Siegert JHEP05(2009)053

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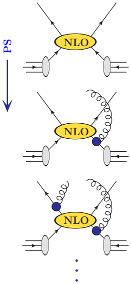

NLOPS (MC@NLO,POWHEG)

Frixione, Webber JHEP06(2002)029
Nason JHEP11(2004)040, Frixione et.al. JHEP11(2007)070
Höche, Krauss, MS, Siegert JHEP09(2012)049

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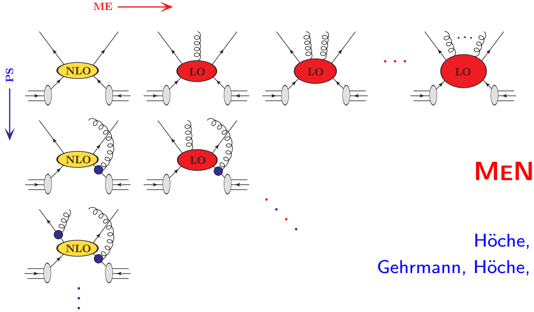

MENLOPS

Hamilton, Nason JHEP06(2010)039
Höche, Krauss, MS, Siegert JHEP08(2011)123
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144

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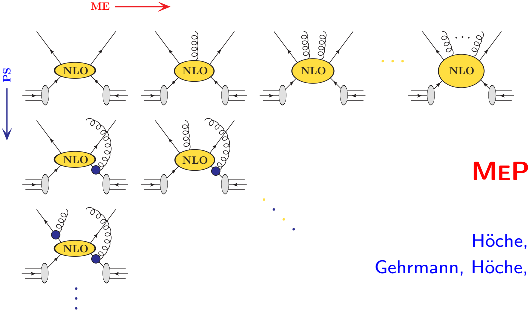

MEPS@NLO

Lavesson, Lönnblad JHEP12(2008)070
Höche, Krauss, MS, Siegert JHEP04(2013)027
Gehrmann, Höche, Krauss, MS, Siegert JHEP01(2013)144
Lönnblad, Prestel JHEP03(2013)166
Plätzer JHEP08(2013)114

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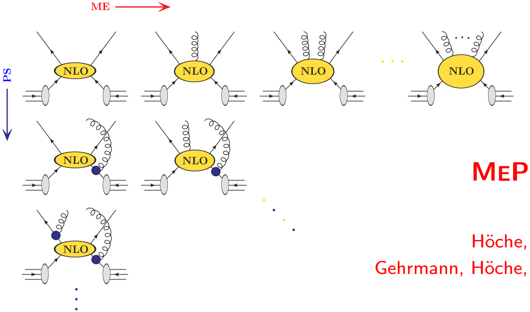

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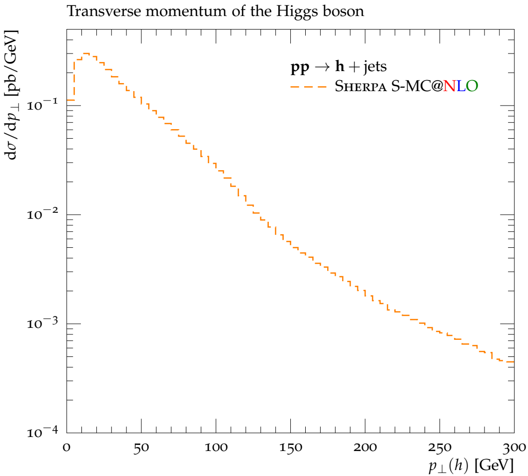

- first emission by NLOPS, restrict to $Q_1 < Q_\text{cut}$
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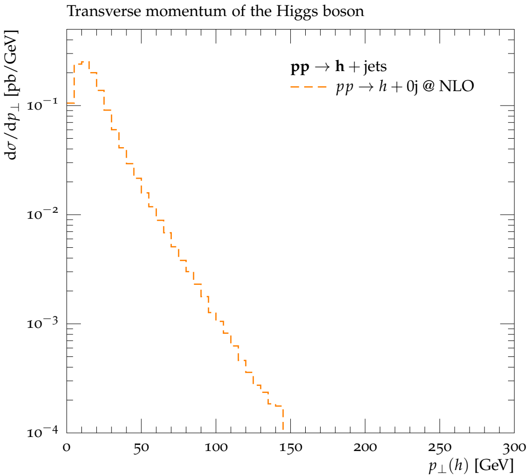
- iterate
- sum all contribs

MEPS@NLO



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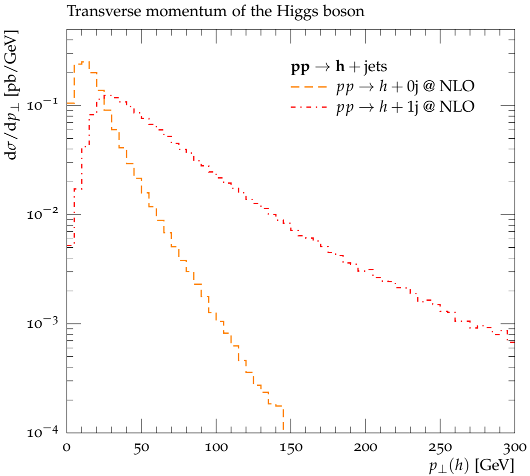

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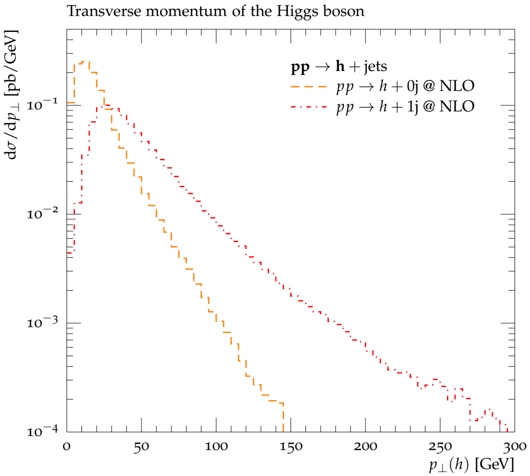

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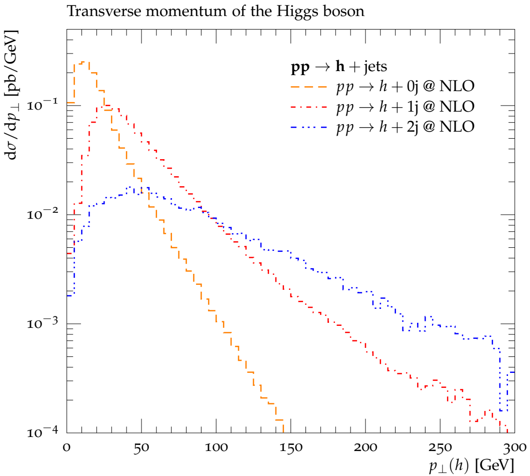

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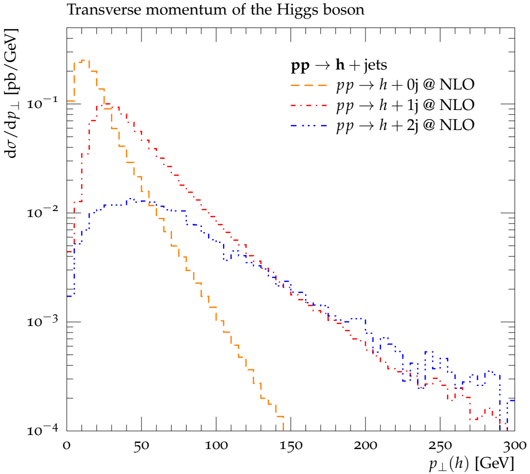

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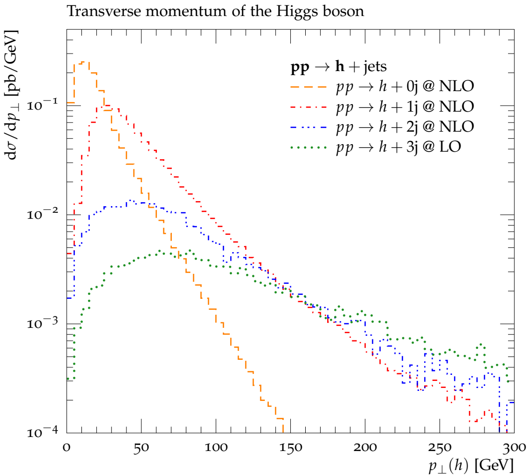

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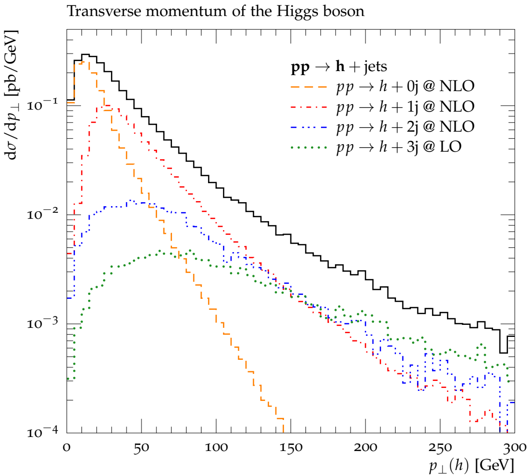

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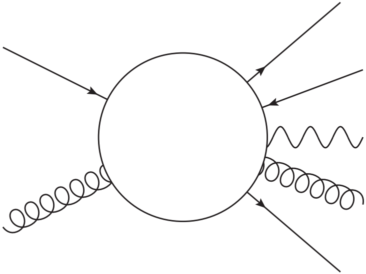
QCD multijet merging – identifying a history

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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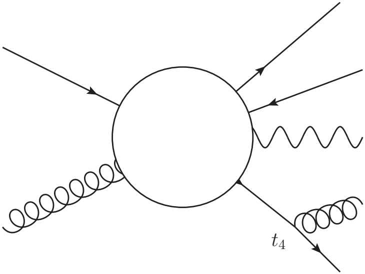

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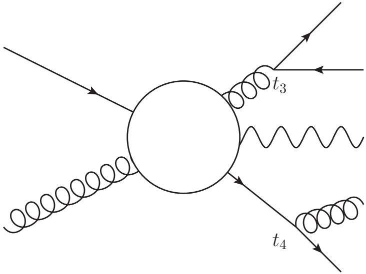

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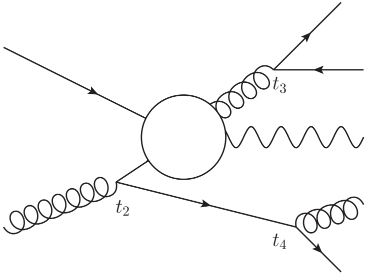

- cluster external particles using inverse parton shower $\rightarrow$ flavour conscious, initial state aware, probability determined through splitting kernels
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QCD multijet merging – identifying a history

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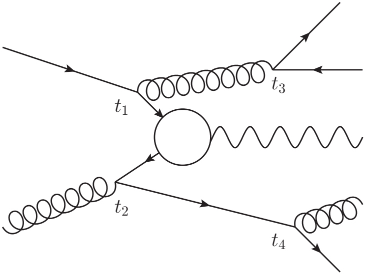

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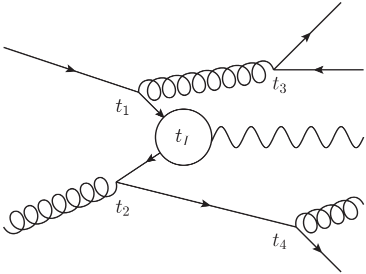

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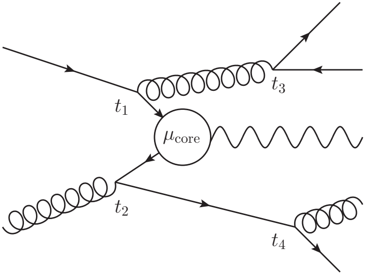

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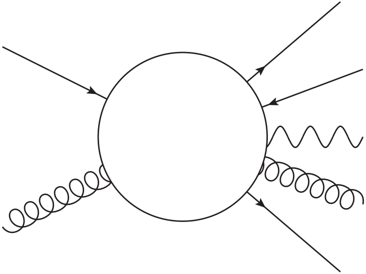
QCD multijet merging – identifying a history

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
- configuration that would have arisen from dijets plus QCD+EW showering
- necessitates EW splitting kernels to calculate splitting probability
- leads to different scale choices and Sudakov factors

QCD multijet merging – identifying a history

ME also provides expression beyond t_I
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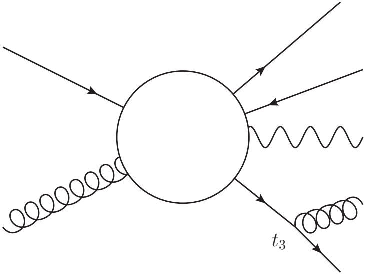

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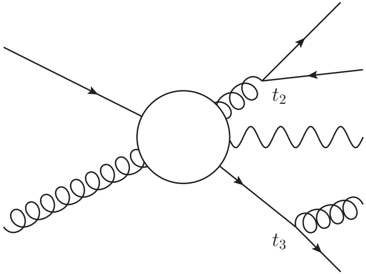

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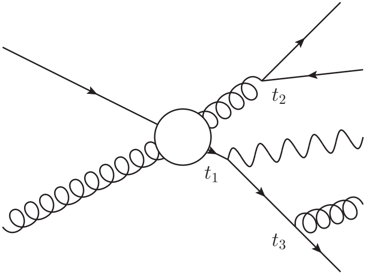

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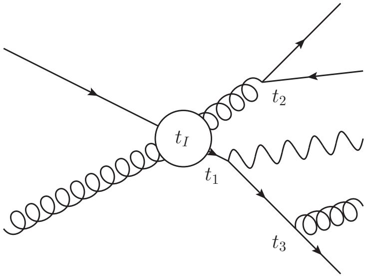

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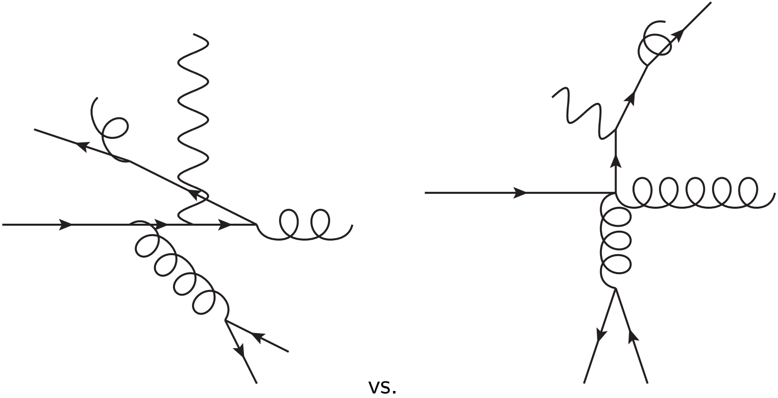
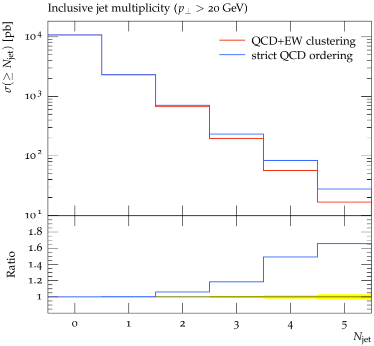
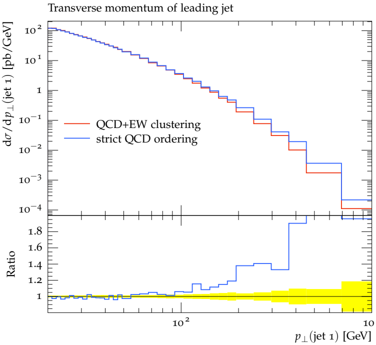


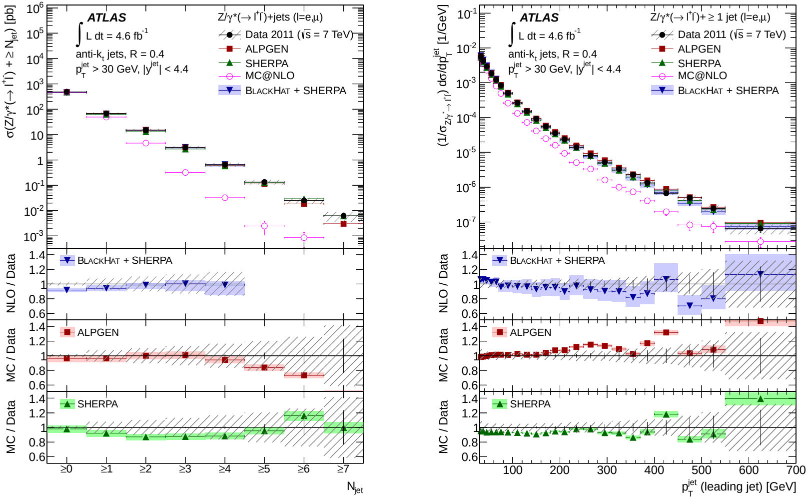
Importance of electroweak clustering


Inclusive jet multiplicity ($p_\perp > 20$ GeV)


Transverse momentum of leading jet

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

Importance of electroweak clustering



Hadronic analysis

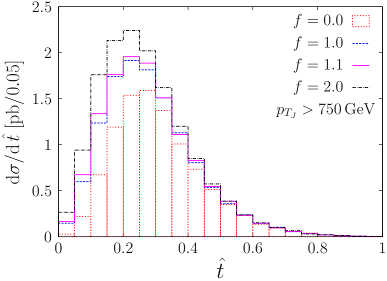
- use event shape variables on microjets of reconstructed W candidate to enhance S/B, e.g. ellipticity

$$\hat{t} = \frac{T_{\mathrm{min}}}{T_{\mathrm{maj}}}$$

→ small when radiation pattern is 1D ($W \to q\bar{q}$)

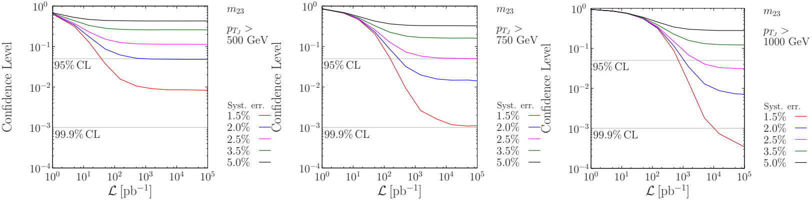
- fat jet $p_\perp > 750$ GeV optimal best balance between cross section and emission rate

⇒ additional discrimination



Hadronic analysis

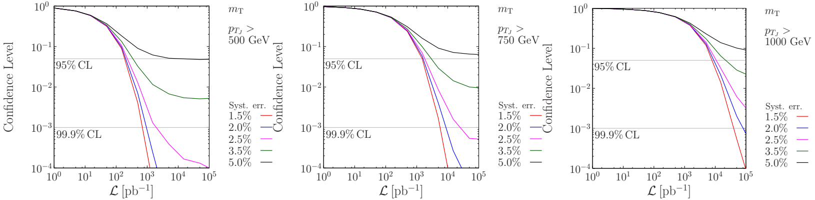
Can we distinguish between $f = 1$ and $f = 2$?
(simplified version of: How accurate can we measure the coupling?)



- signal: $f = 2$, background: $f = 1$ (SM)
- moderate sensitivity even under ideal conditions
  benefits from larger emission at large $p_\perp$ despite smaller cross section

Leptonic analysis

Can we distinguish between $f = 1$ and $f = 1.1$?
(simplified version of: How accurate can we measure the coupling?)



- signal: $f = 1.1$, background: $f = 1.0$ (SM)
- improved sensitivity, despite small cross sections, benefits from ideal background rejection