# Electroweak corrections for LHC physics

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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.

# Outline

# Electroweak corrections for LHC physics

# Construction of a parton shower

- approximate higher orders in (soft-)collinear limit

$$\mathrm{d}\sigma_{n+1}(t,z,\phi) \approx \mathrm{d}\sigma_n \sum_{\widetilde{\imath\jmath}} \sum_{s}^{n_\text{spec}} \mathrm{d}t\,\mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}\,\frac{1}{n_\text{spec}}\,J(t,z)\,\mathcal{K}_{\widetilde{\imath\jmath}(s)\to ij(s)}(t,z)$$

- using universal splitting kernels $\mathcal{K}(t,z) \propto \frac{\alpha_s}{2\pi t}\,P(z)$
- phase space $\mathrm{d}\Phi_1 = \mathrm{d}t\,\mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}\,J(t,z)$
  emission variable $t$, splitting variable $z$, azimuthal angle $\phi$
- spectators needed for local recoil,
  also ensure colour coherence in non-angular ordered showers
- construct emission probability at scale $t$

$$\mathrm{d}\mathcal{P}_\text{em}(t) = \frac{\mathrm{d}\sigma_{n+1}(t)}{\mathrm{d}\sigma_n} = \sum_{\widetilde{\imath\jmath}} \sum_{s}^{n_\text{spec}} \mathrm{d}t \int \mathrm{d}z\,\frac{\mathrm{d}\phi}{2\pi}\,\frac{1}{n_\text{spec}}\,J(t,z)\,\mathcal{K}_{\widetilde{\imath\jmath}(s)\to ij(s)}(t,z)$$

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- Poisson statistics leads to no-emission probability

$$\mathcal{P}_{\text{no-em}}(t,t') = \exp\left\{ -\sum_{\widetilde{\imath\jmath}} \sum_{s}^{n_{\mathrm{spec}}} \int_t^{t'} \mathrm{d}\bar{t} \int \mathrm{d}z \, \frac{\mathrm{d}\phi}{2\pi} \, \frac{1}{n_{\mathrm{spec}}} \, J(\bar{t},z) \, \mathcal{K}_{\widetilde{\imath\jmath}(s)\to ij(s)}(\bar{t},z) \right\}$$

$\to$ Sudakov form factor $\Delta(t,t') = \mathcal{P}_{\text{no-em}}(t,t')$

$\Rightarrow$ probability of a parton produced at $t'$ to radiate/resolve another parton at $t$

$$\mathrm{d}\mathcal{P}(t) = \mathrm{d}\mathcal{P}_{\mathrm{em}}(t)\, \mathrm{d}\mathcal{P}_{\text{no-em}}(t,t') = \mathrm{d}t \, \frac{\mathrm{d}\Delta(t,t')}{\mathrm{d}t}$$

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# Construction of a parton shower

General form

$$\mathrm{d}\sigma^{\text{LOPS}} = \mathrm{d}\sigma_n^{\text{LO}} \left[\Delta(t_c, t_{\max}) + \int_{t_c}^{t_{\max}} \mathrm{d}t' \, \mathcal{K}_n(t') \, \Delta_n(t', t_{\max})\right]$$

- first term: probability of resolving no additional parton in $[t_{\max}, t_c]$
- second term: probability and distribution of resolving another parton at scale $t'$ (but not above)
- iterate:
  - approximate $n+2$ parton matrix element by showering the $n+1$ parton expression, now $t'$ being the upper limit (strong ordering)

- Sudakov form factor: (soft-)collinear LL all-orders virtual correction emission term: (soft-)collinear approximated real correction
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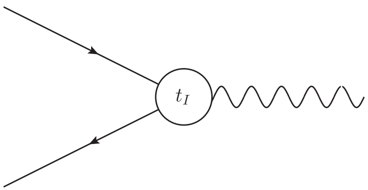
# Resummation properties of parton showers

**Example: Drell-Yan production**




- core process: arbitrary scale $\mu_R = \mu_{\text{core}}$
- define initial conditions: set $t_{\max} = t_I$
- first emission at $t_1$ with $\alpha_s(t_1)$
- second emission at $t_2$ with $\alpha_s(t_2)$
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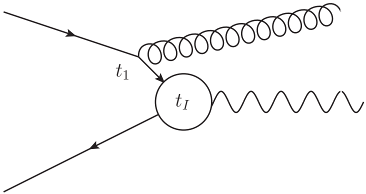


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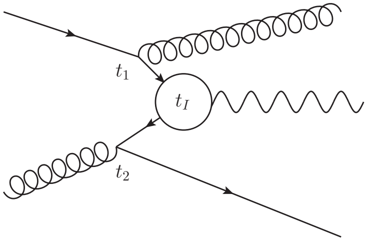


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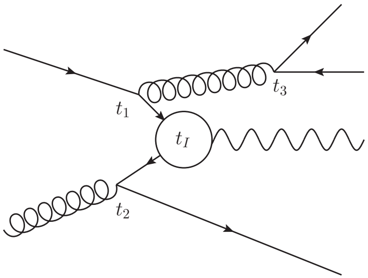


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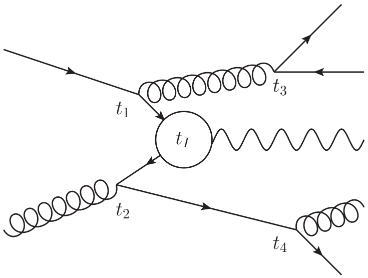


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# Improvements through merging

- higher order real emission corrections in (soft-)collinear limit
  → identify hard region, replace kernel with LO matrix element

$$\mathrm{d}\sigma^{\text{MEPS}} = \mathrm{d}\sigma_n^{\text{LO}}\left[\Delta(t_c,t_{\max}) + \int_{t_c}^{t_{\max}} \mathrm{d}t'\,\mathcal{K}_n(t')\,\Delta_n(t',t_{\max})\,\Theta(Q_{\text{cut}}-Q)\right]$$

$$+\,\mathrm{d}\sigma_{n+1}^{\text{LO}}\,\Delta_n(t',t_{\max})\,\Theta(Q-Q_{\text{cut}})$$

$$= \mathrm{d}\sigma_n^{\text{LO}}\left[\Delta(t_c,t_{\max}) + \int_{t_c}^{t_{\max}} \mathrm{d}t'\,\mathcal{K}_n(t')\,\Delta_n(t',t_{\max})\,\Theta(Q_{\text{cut}}-Q) + \int_{t_c}^{t_{\max}} \mathrm{d}t'\,\frac{\mathrm{d}\sigma_{n+1}^{\text{LO}}}{\mathrm{d}\sigma_n^{\text{LO}}}\,\Delta_n(t',t_{\max})\,\Theta(Q-Q_{\text{cut}})\right]$$

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- need to identify scales $t_i$ in $n+k$ matrix element to set scales in $\alpha_s$
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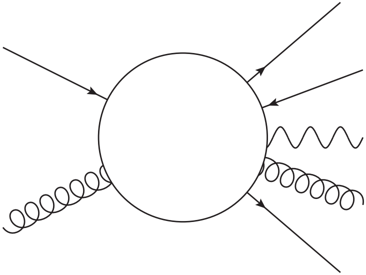

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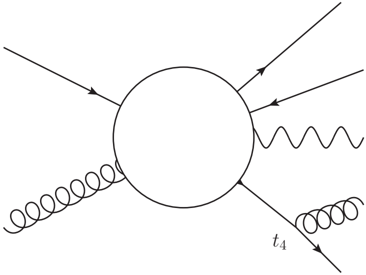


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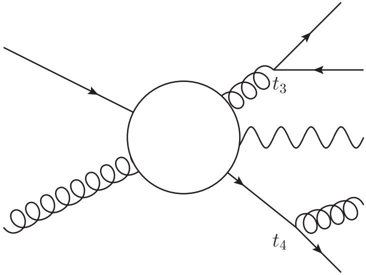


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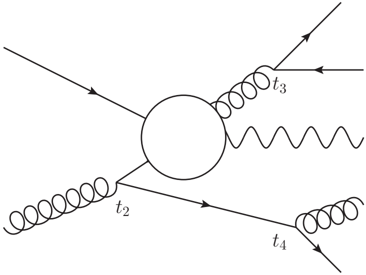


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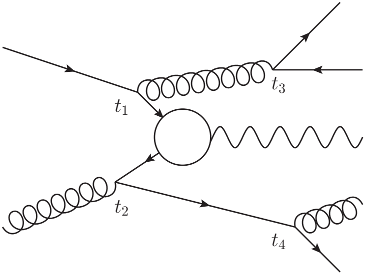
$$\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\text{core}}^2) \prod_{i=1}^{n} \alpha_s(t_i)$$

# Improvements through merging

**Example: Drell-Yan production in association with jets**

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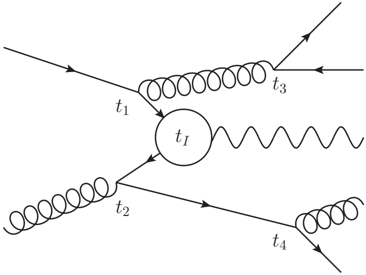


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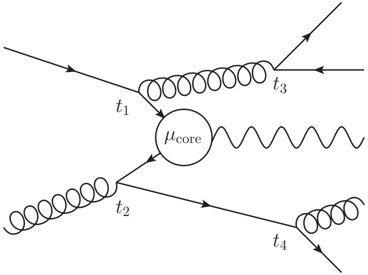


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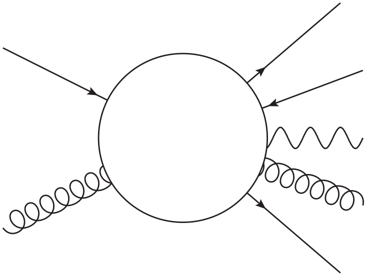
# Multijet merging beyond improving parton shower kernels

ME also provides expression beyond $t_{\mathrm{max}}$
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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- necessitates EW splitting kernels to calculate splitting probability
  → see next part
- leads to different scale choices

Electroweak clustering

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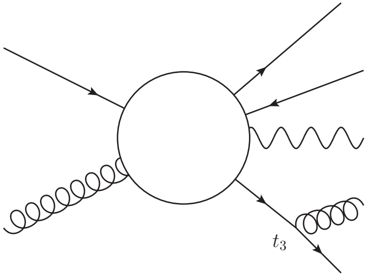


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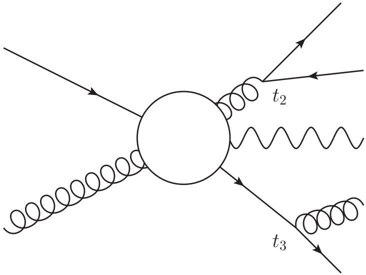


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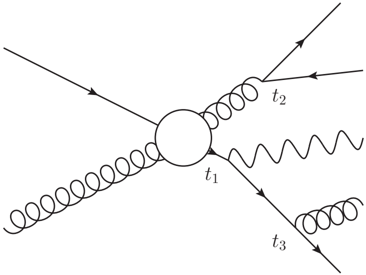


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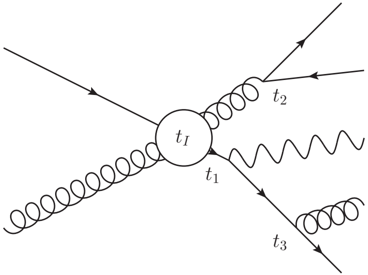


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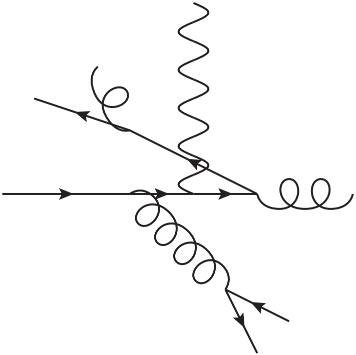
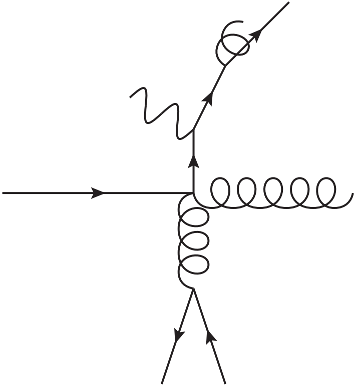
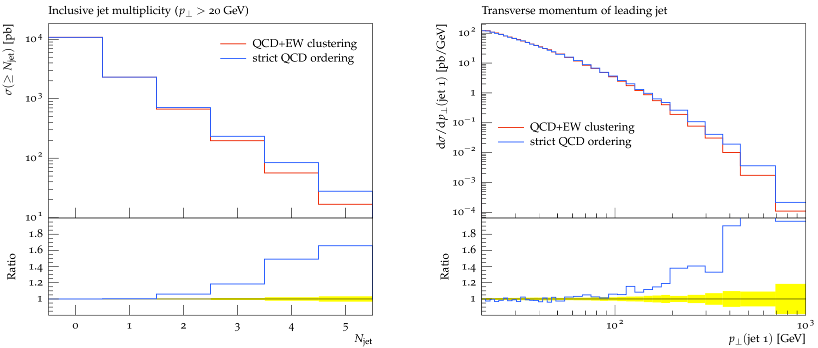


vs.

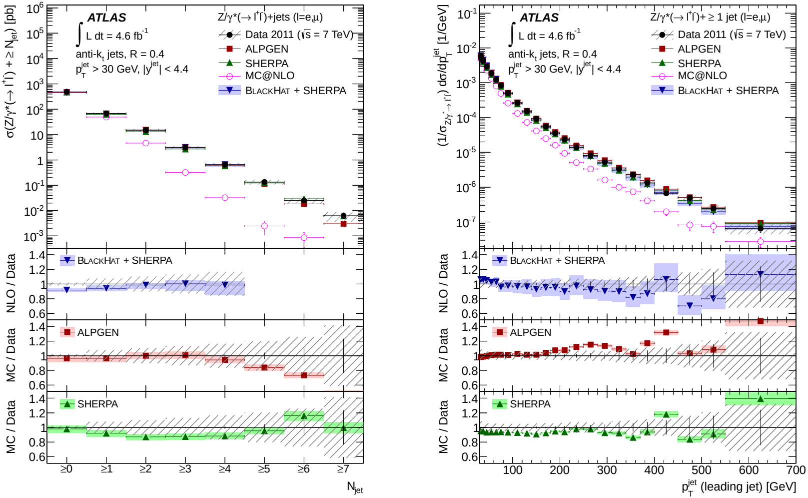


# Importance of electroweak clustering



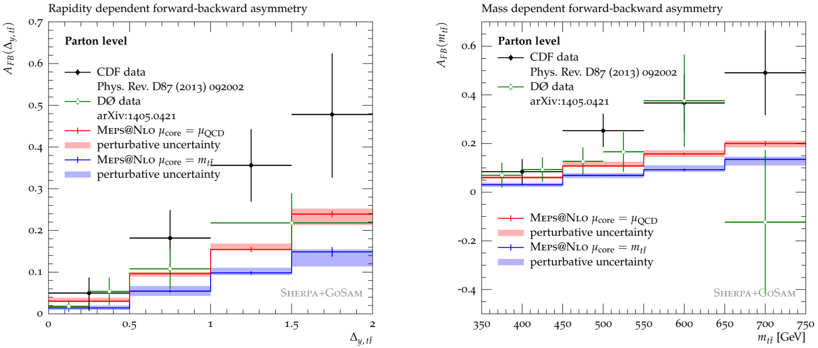

$\Rightarrow$ large impact at high $p_\perp$ and multiplicity

# Importance of electroweak clustering



# Example: Forward-backward asymetry @ Tevatron

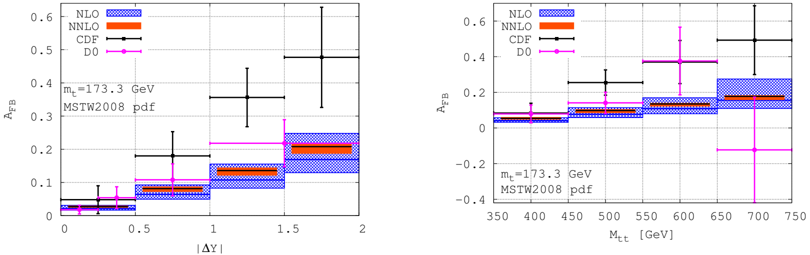
Höche, Huang, Luisoni, MS, Winter Phys.Rev.D88(2013)1,014040




Chose two different $\mu_{\text{core}} \to$ 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

# Electroweak corrections for LHC physics

# Collinear limit with $E \gg m$

- 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
- same ansatz as used for clustering in multijet merging

# Choice of spectator

**Role of the spectator:**

- needed for momentum conservation in splitting $1(s) \to 2(s)$
- ~~colour~~ coherence for soft emissions

**Which particles are allowed as spectators?**

- kernels are derived in collinear limit
  $\to$ collinear emissions exhibit no coherence, any spectator would do for momentum conservation
- to fit into dipole shower picture choose any other electroweak particle, in particular any fermion

# Splitting kernels

Denner, Hebenstreit unpublished

- use Denner-Hebenstreit expressions modified into CDST form

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

$$\mathcal{K}_{f(s)\to fZ(s)}(t,z) = \frac{\alpha}{2\pi t}\left[f_Z\, c_\perp^Z\, \tilde{\mathrm{V}}^{\mathrm{CDST}}_{f(s)\to fb(s)}(t,z) + f_h\, c_L^Z\, \tfrac{1}{2}\,(1-z)\right]$$

- contain a transverse component as standard splitting functions
  $\to$ in limit $E \gg m$ revert to CDST splitting functions for emission of a massless gauge boson

  Catani, Dittmaier, Seymour, Trocsanyi Nucl.Phys.B627(2002)189-265
- contain a longitudinal component
  $\to$ in limit $E \gg m$ this is the emission of the corresponding scalar Higgs component/Goldstone boson
- construct phase space with massive bosons (fully differential)
  $\to$ emulates some mass effects à la ACOT

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with

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

- 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 $s_{\mathrm{eff}}$
  $\Rightarrow pp\to jj$: $s_{\mathrm{eff}}=\frac{1}{2}$, $pp\to W$: $s_{\mathrm{eff}}=1$, undefined in general
- factors $f_W$, $f_Z$, $f_h$ modify couplings to test sensitivity

# Interaction with QCD shower

**Want to have simultaneous evolution of QCD+EW:**

$\rightarrow$ emissions compete for phase space

- combined evolution kernel

$$\mathcal{K}_{\text{tot}}(t,z) = \mathcal{K}_{\text{QCD}}(t,z) + \mathcal{K}_{\text{EW}}(t,z) + \mathcal{K}_{\text{QED}}(t,z)$$

$\Rightarrow$ emissions occur in correct proportions

$\Rightarrow$ splittings into heavy bosons are suppressed at small $t$

**How to embed decays into parton evolution?**

- decay bosons immediately
- ensures that evolution of singlet $q-\bar{q}$ pair is consistently embedded
- neglects secondary splittings of the type $W^\pm \to W^\pm\gamma$, $W^\pm \to W^\pm Z$ or $Z \to W^\pm W^\mp$

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

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

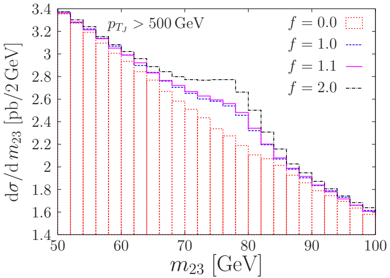
- need high-$p_\perp$ jets to produce real $W$ bosons at sufficient rate
- need high-$p_\perp$ jets to satisfy assumption $E \gg m$

**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 $\Rightarrow$ hadronic analysis
  one isolated lepton $\Rightarrow$ leptonic analysis
- require further two jets with $p_\perp > 500, 750, 1000$ GeV to drive $W$ radiation into collinear region

# Hadronic analysis

- proposed three analysis strategies, here method B
- 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




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

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

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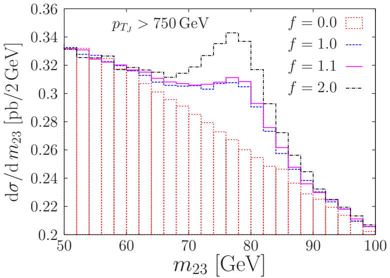


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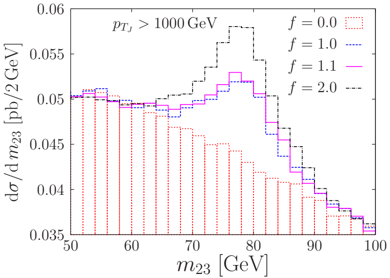


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# Hadronic analysis

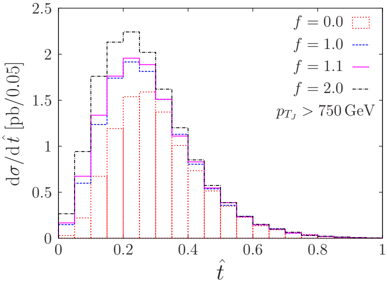
- use event shape variables on microjets of reconstructed $W$ candidate to enhance S/B, e.g. ellipticity

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

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

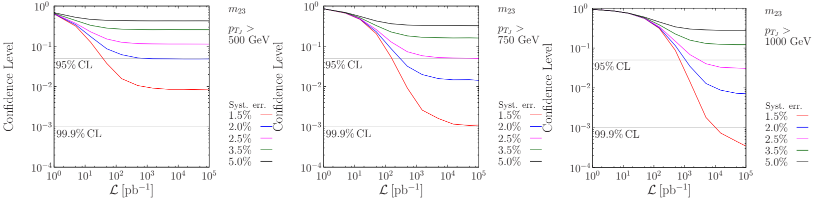
- fat jet $p_\perp > 750$ GeV optimal best balance between cross section and emission rate

$\Rightarrow$ additional discrimination



# Hadronic analysis

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



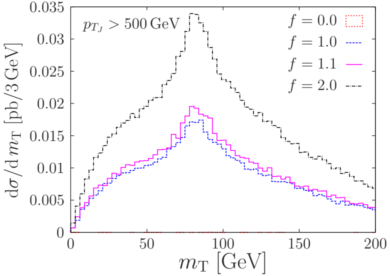

- signal: $f = 2$, background: $f = 1$ (SM)
- moderate sensitivity even under ideal conditions
  benefits from larger emission at large $p_\perp$ despite smaller cross section

# Leptonic analysis

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

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

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




⇒ provides good background rejection

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

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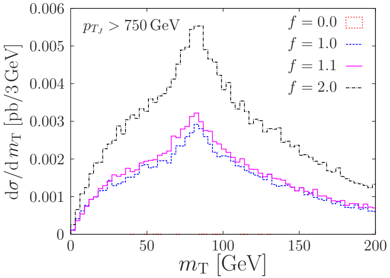


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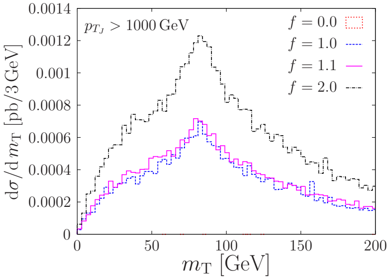


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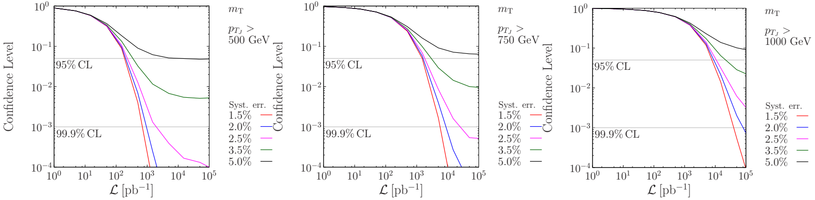
(simplified version of: How accurate can we measure the coupling?)




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

# Electroweak corrections for LHC physics

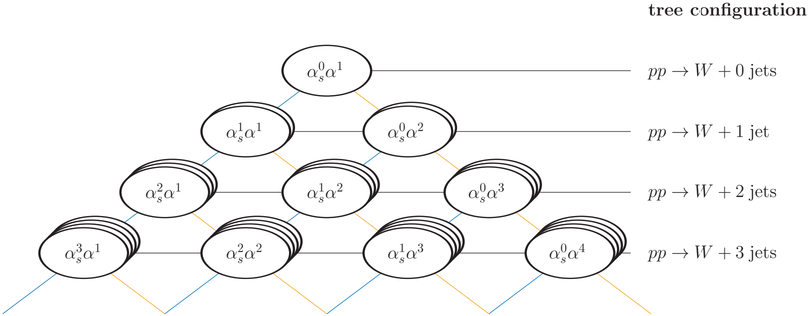
# Electroweak corrections at NLO

Kallweit, Lindert, Maierhöfer, Pozzorini, MS in preparation

- fixed-order next-to-leading order electroweak corrections to $pp \to W + 1, 2, 3$ jets production in on-shell approximation
- OpenLoops for virtual corrections using Collier for tensor integrals
  Denner, Dittmaier, Hofer PoS LL2014(2014)071
- Sherpa or private code by S. Kallweit for Born, real emission, subtraction and phase space integration
- combine QCD and EW to leading $pp \to W + 1, 2, 3$ process ($\mathcal{O}(\alpha_s^n \alpha)$) in two schemes
  QCD+EW: $\sigma_{\text{NLO QCD+EW}} = \sigma_{\text{LO}}\,(1 + \delta_{\text{QCD}} + \delta_{\text{EW}})$
  QCD×EW: $\sigma_{\text{NLO QCD}\times\text{EW}} = \sigma_{\text{LO}}\,(1 + \delta_{\text{QCD}})\,(1 + \delta_{\text{EW}})$
- use NNPDF2.3QED with LO QED PDF
  ideally would need NLO QED PDF

# Counting orders

- same problem as in e.g. Dittmaier, Huss, Speckner JHEP11(2012)095




- consistent definition of orders and signature to be calculated needed

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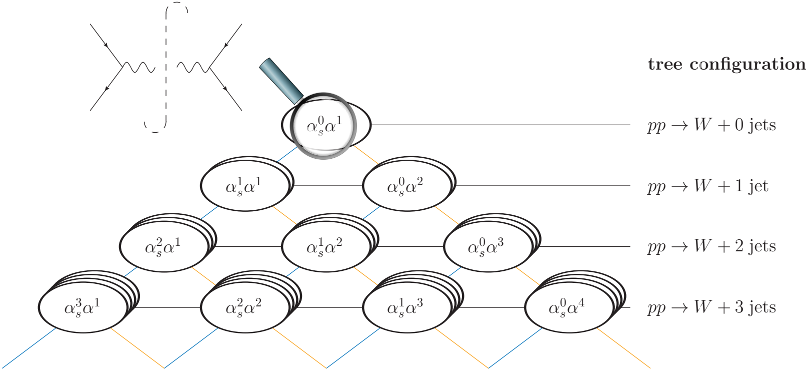


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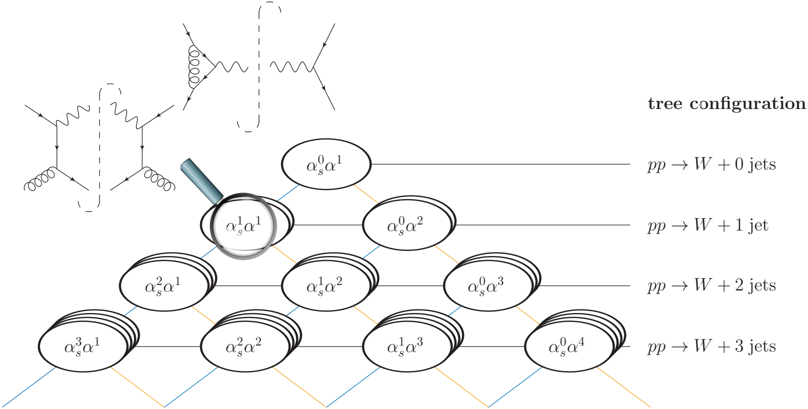


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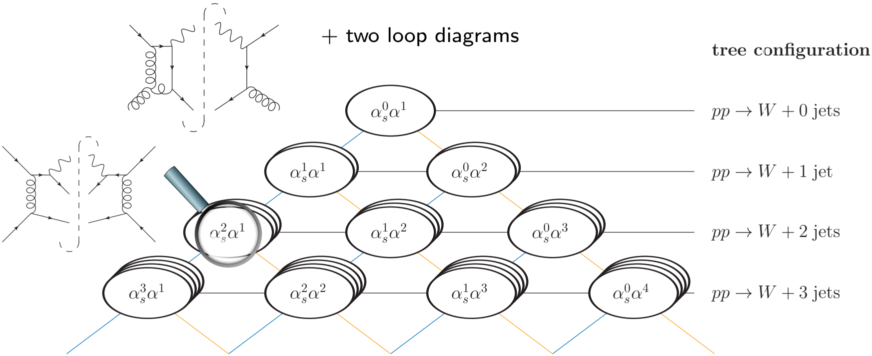


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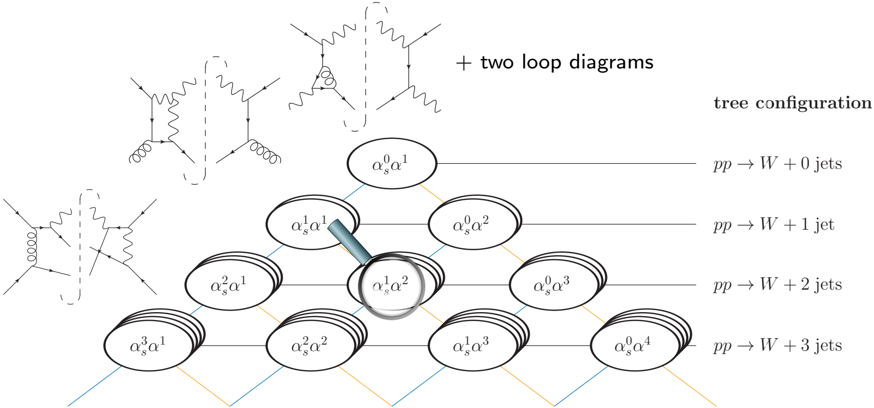


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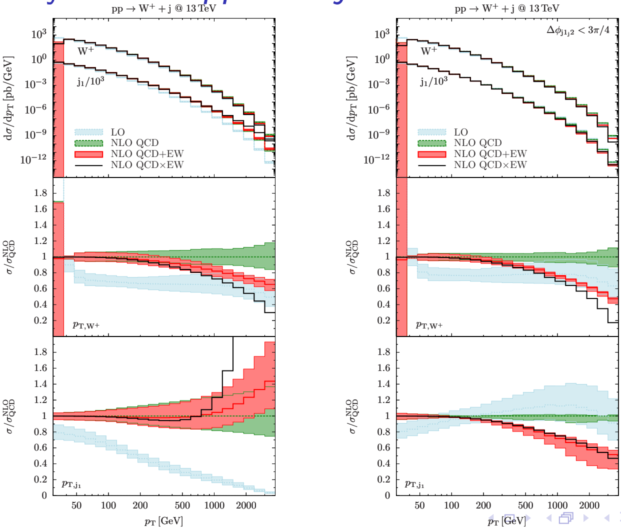
# Preliminary results: $pp \to Wj$



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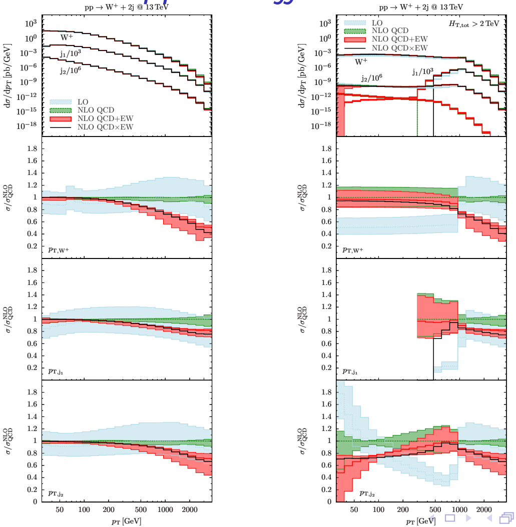

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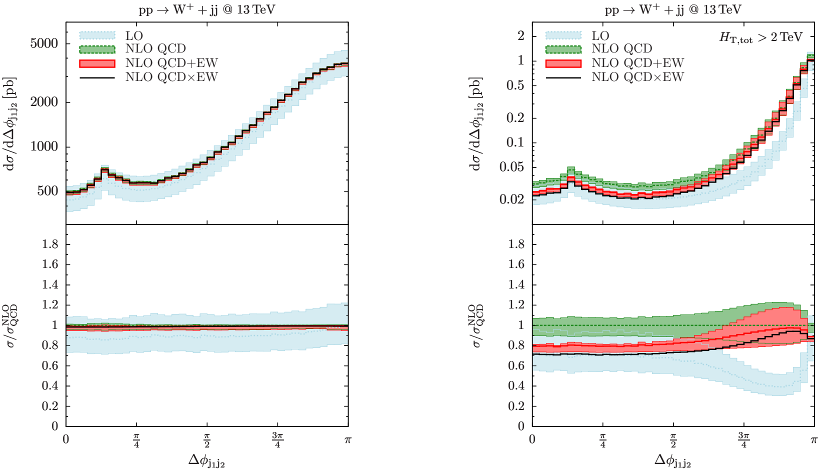

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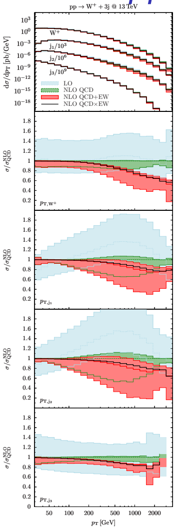
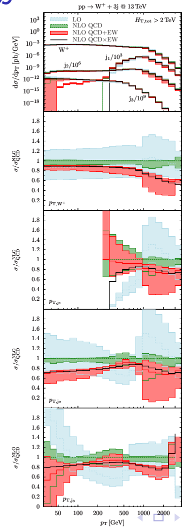
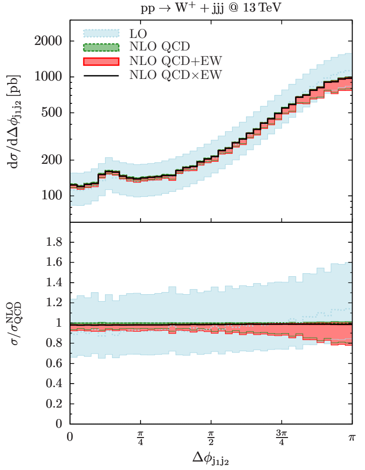
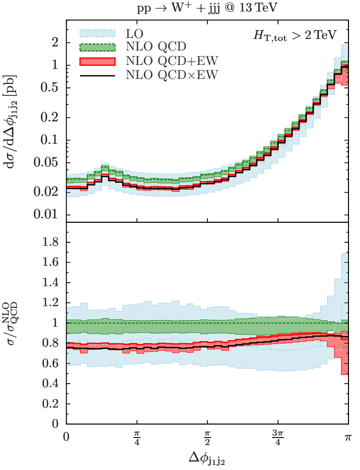


# Preliminary results: $pp \to Wjjj$



# Conclusions

- electroweak effects are important at LHC at 13/14 TeV
- become large whenever the scale is large compared the electroweak scale
- should be incorporated in multijet merging to correctly describe the regions where a given configuration is rather a electroweak correction to a QCD process than a QCD correction to an electroweak process ($pp \to W + jets$ vs. $pp \to jets + W$)
- QCD+QED combined merging methods exist
- proper QCD+EW merging methods need to be defined
- automation of NLO EW follows on the heels of NLO QCD
  $\to$ much more care with consistent schemes and order counting

# Thank you for your attention!

# Backup