Electroweak corrections for LHC physics

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Michigan State University, Nov 01 2016

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FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

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

1. Next-to-leading order electroweak corrections
   - Tools and setup
   - Selected results
2. Electroweak effects in multijet merging
   - QCD multijet merging
   - Inclusion of electroweak corrections
3. Real boson radiation
   - Resummation via EW parton showers
   - Case study: Finding W bosons inside jets
4. Conclusions

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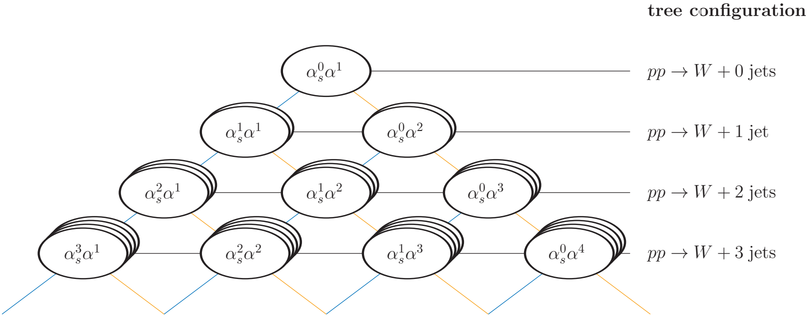
Consistent setup: counting orders and defining signatures



- 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 $\mathcal{O}(g_s^{n\pm1} e^{m\mp1})$ diagrams, resonances

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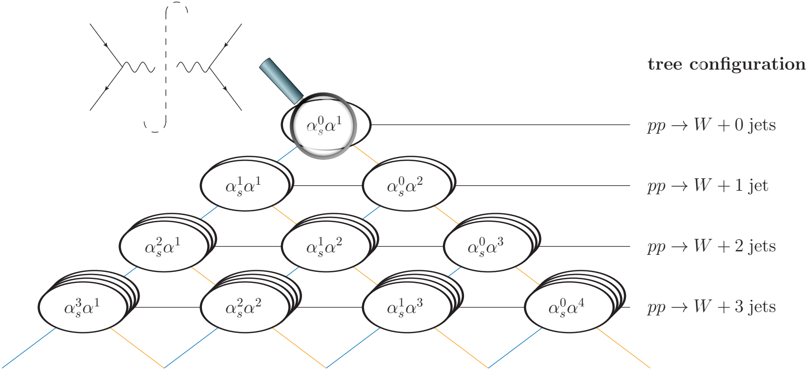

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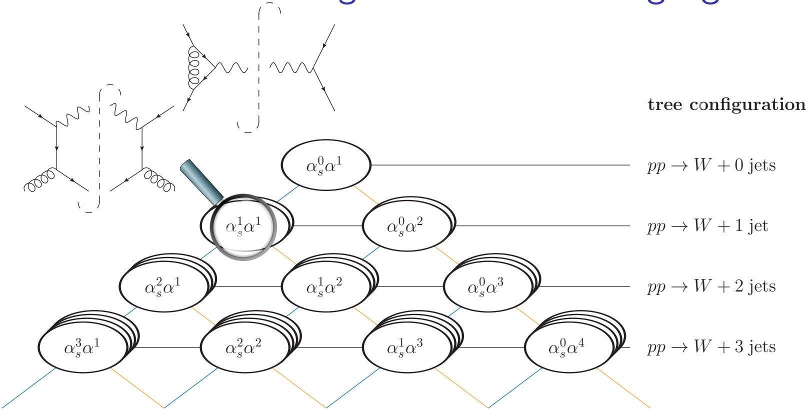

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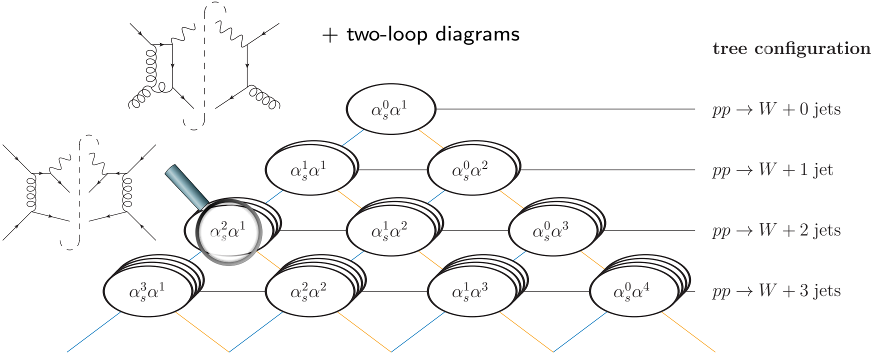

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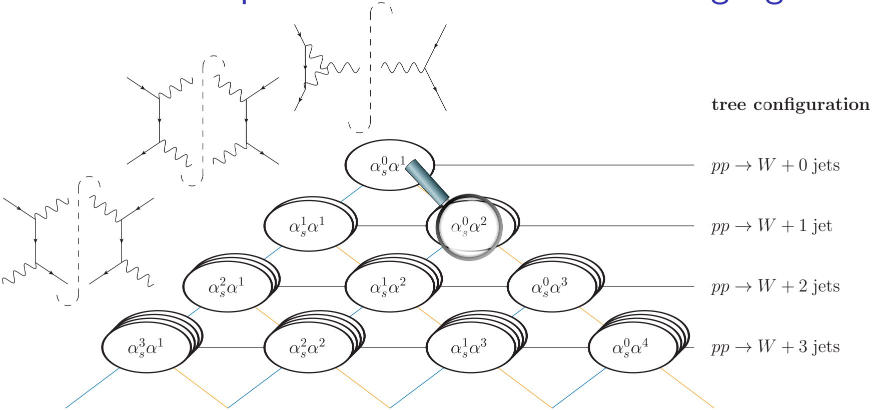

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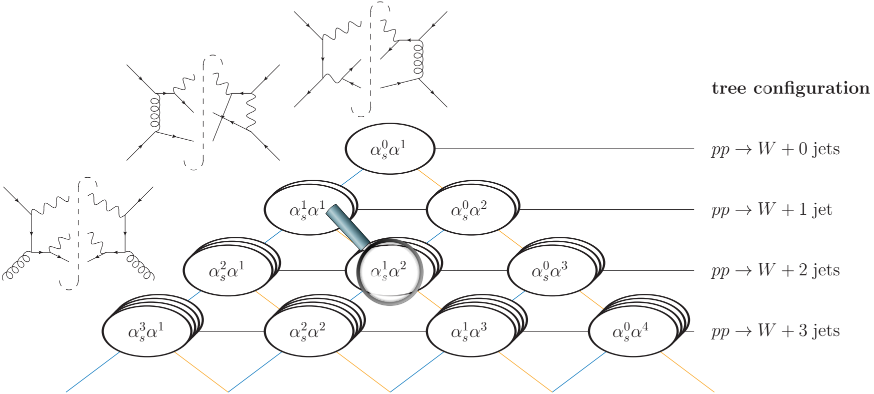

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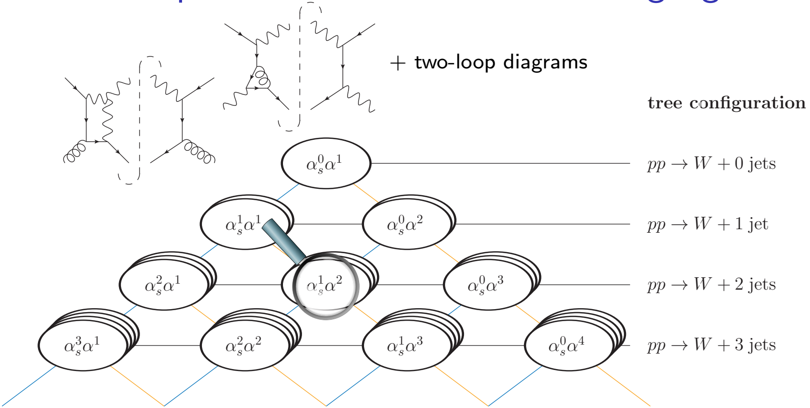

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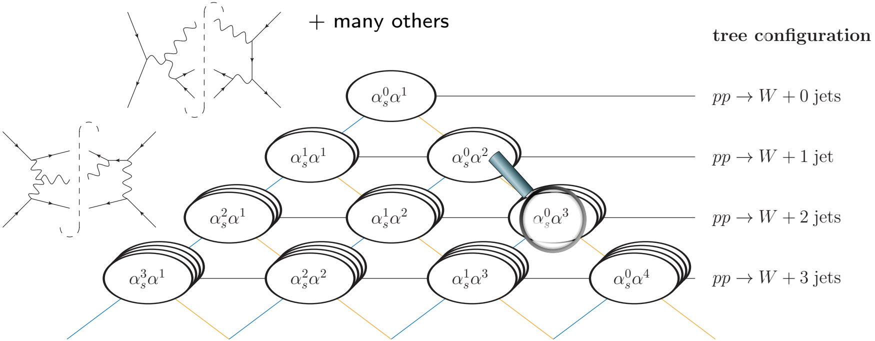

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Tools and setup

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: $\sigma_{\text{NLO QCD+EW}} = \sigma_{\text{LO}}\,(1 + \delta_{\text{QCD}} + \delta_{\text{EW}})$
  QCD×EW: $\sigma_{\text{NLO QCD}\times\text{EW}} = \sigma_{\text{LO}}\,(1 + \delta_{\text{QCD}})\,(1 + \delta_{\text{EW}})$
  $\Rightarrow$ 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
- so far use NNPDF2.3QED with LO QED PDF ideally would need NLO QED PDF

NLO EW subtraction in SHERPA

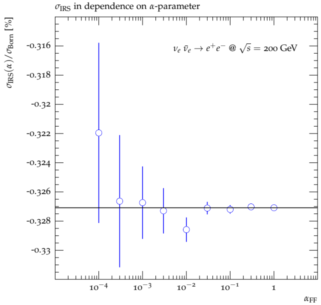
MS in preparation

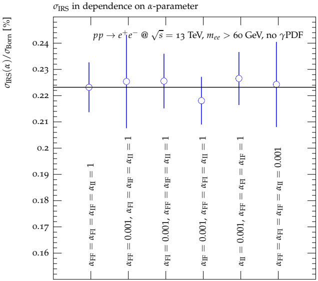
- adapt QCD subtraction (spl. fns. and colour-/spin-correlated MEs)

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

- replacements: $\alpha_s \to \alpha,\ C_F \to Q_f^2,\ C_A \to 0,$
  $T_R \to N_{c,f}\, Q_f^2,\ n_f\, T_R \to \sum_f N_{c,f}\, Q_f^2,$

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





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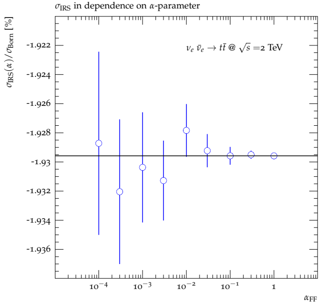

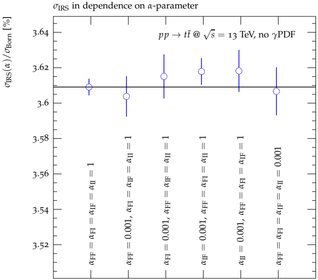

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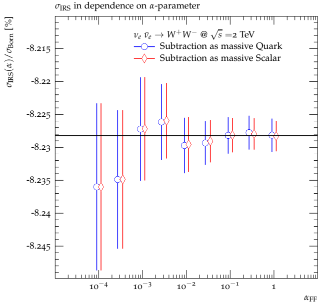
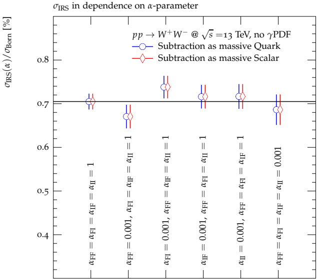


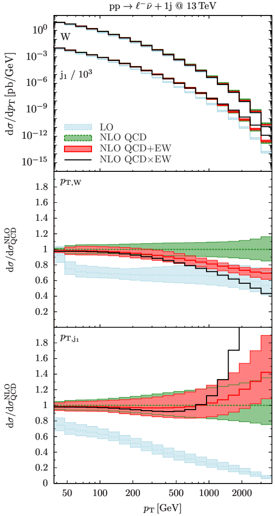


Next-to-leading order electroweak corrections

- generally `NNPDF23_nlo_as_0118_qed`
  (6 fl., important in α_s-running, neglect tiny top PDF)
- already studied a range of processes:
  - $pp \to V + 0, 1, 2(, 3)$ jets
    Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2015)012, JHEP04(2016)021
    EW report arXiv:1606.02330
  - $pp \to t\bar{t}h$
    LH'15 arXiv:1605.04692
  - $pp \to Zj/pp \to \gamma j$ ratio
    Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1505.05704
    LH'15 arXiv:1605.04692
  - $pp \to Vh$
    FCC report, arXiv:1607.01831
  - $pp \to 2\ell 2\nu$
    Kallweit, Lindert, Maierhöfer, Pozzorini, MS to appear
- dedicated comparisons in LH'15 against RECOLA ($Z + 2j$) and MADGRAPH (tth) showed agreement

$pp \to Wj$ @ 13 TeV

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



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

  Rubin, Salam, Sapeta JHEP09(2010)084

  $\to$ need merging
- remove dijet configs through $\Delta\phi_{j_1 j_2} < \frac{3}{4}\pi$
  $\to$ EW Sudakov recovered

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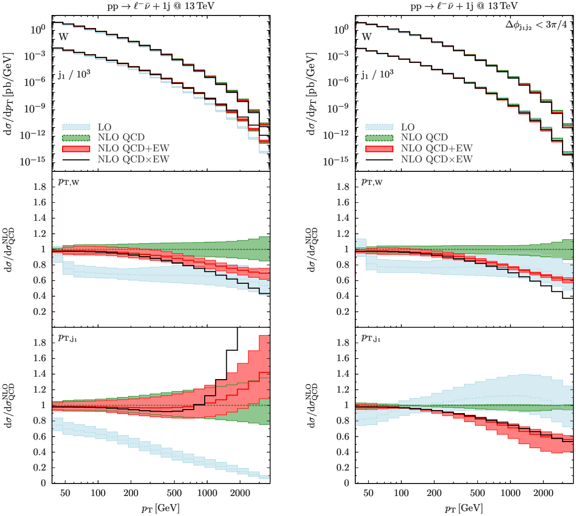

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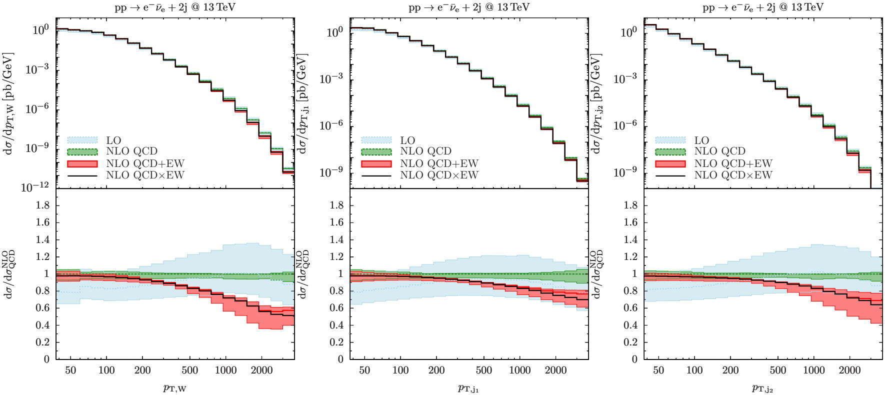

$pp \to Zjj$ @ 13 TeV

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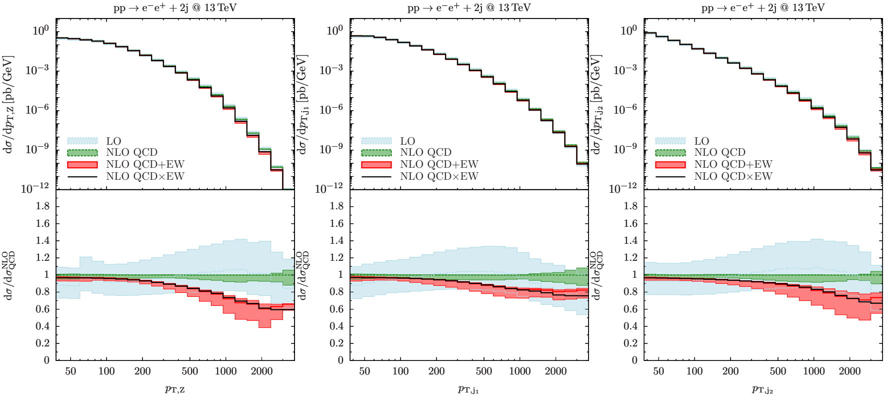

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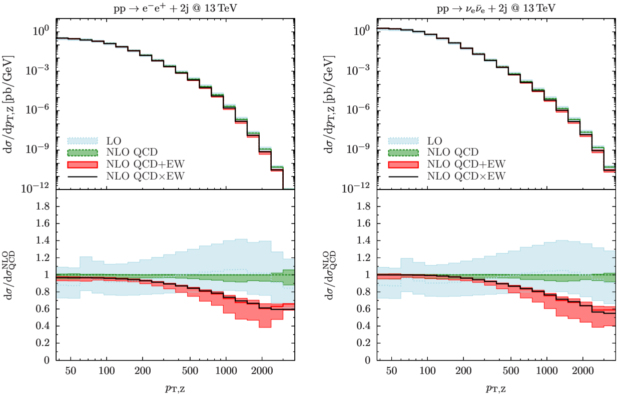
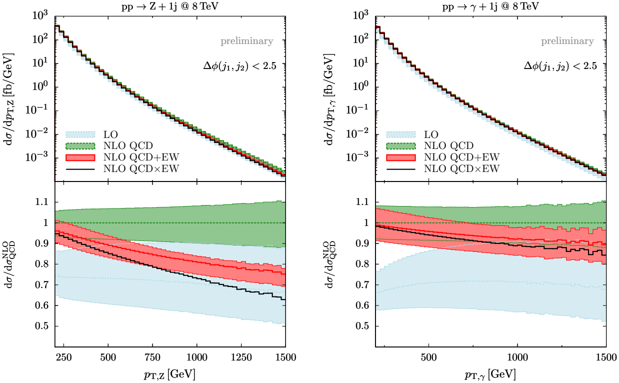


→ EW corrections independent of the decay mode

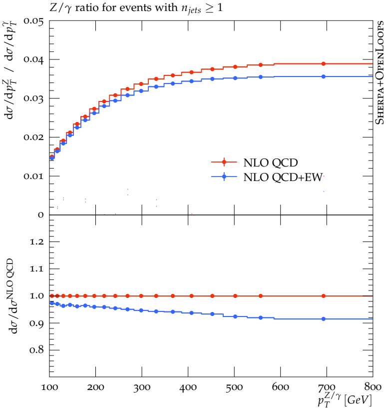
Z/γ ratio @ 8 TeV

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



→ EW corrections different for Z and γ

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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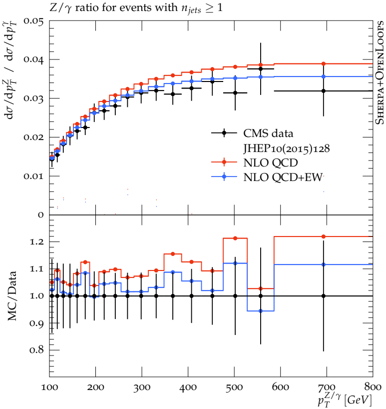

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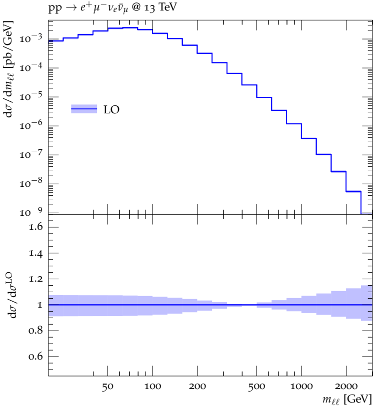
$pp \to 2\ell 2\nu$ @ 13 TeV



Kallweit, Lindert, Pozzorini, MS in prep.

$pp \to e^+\mu^-\nu_e\bar{\nu}_\mu$ @ 13 TeV

- $\mu = H_T^{\mathrm{lep}} = \sum_{i\in\{e,\mu\}} p_{\perp,i} + \not{E}_T$
- analyses impose jet veto to control $t\bar{t}$-background
  → also reduces QCD corr.
- usual behaviour of NLO EW
- γ-induced LO large at high-x
- γPDF depedence huge
  similar in all obs.
  → ideal to measure γPDF

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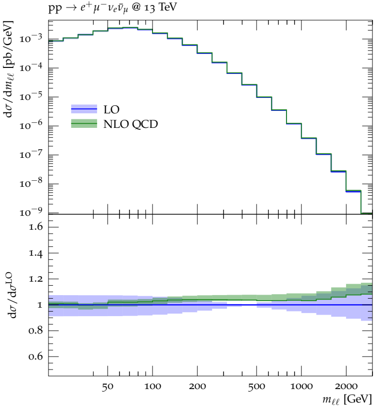

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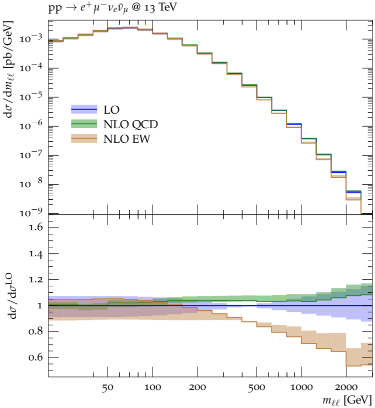

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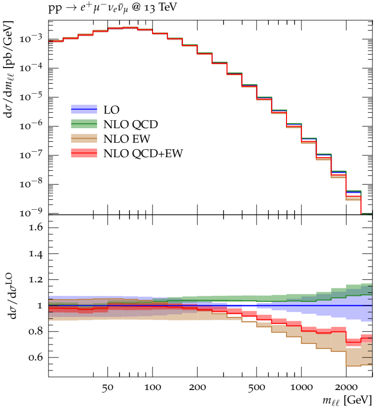

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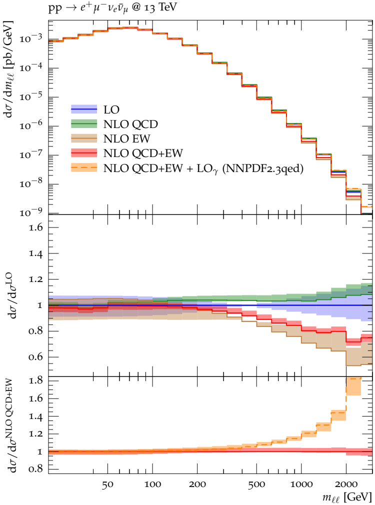

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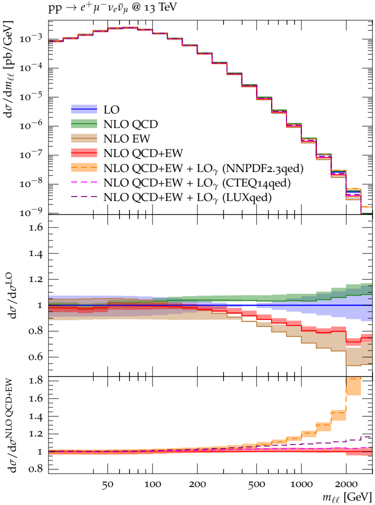

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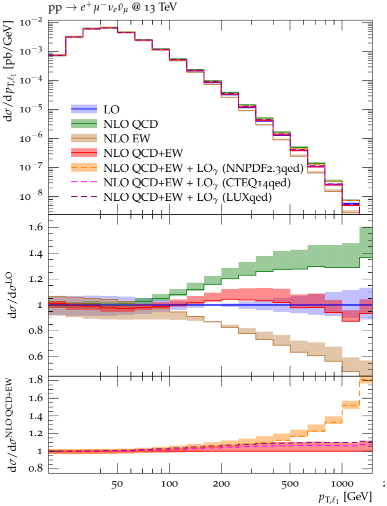

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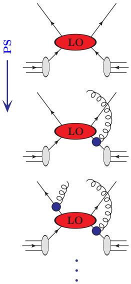
QCD multijet merging – LO case

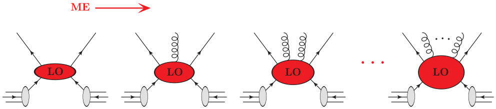


Parton showers

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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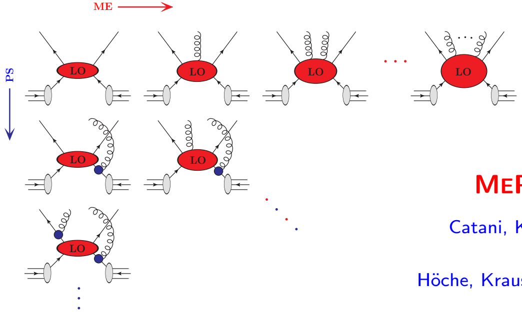

MePs (CKKW,MLM)

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

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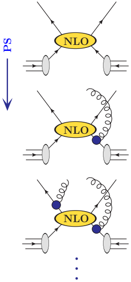
QCD multijet merging – NLO case



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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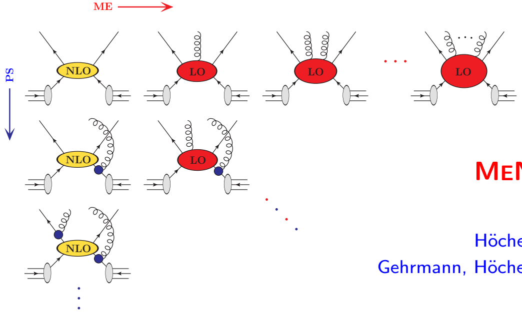
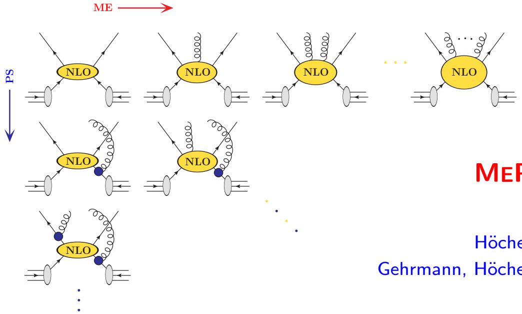


MENLOPS

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

- 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 – NLO case



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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- MePs@Nlo combines multiple NloPs – keeping either accuracy

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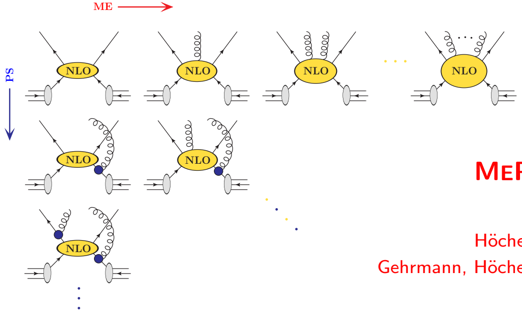

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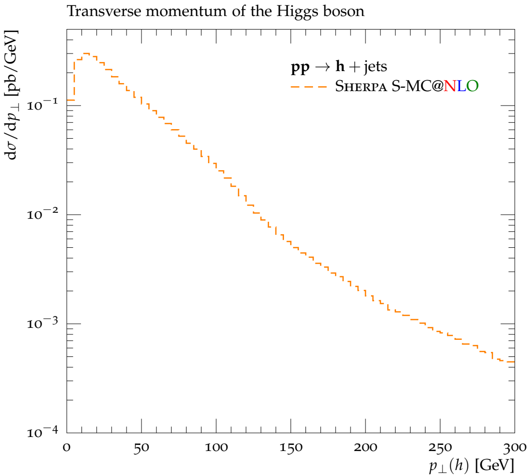

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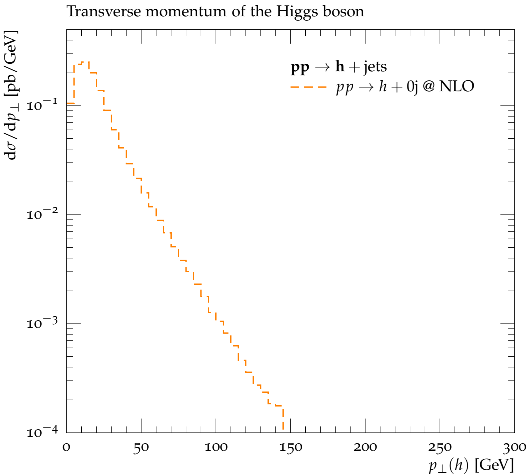

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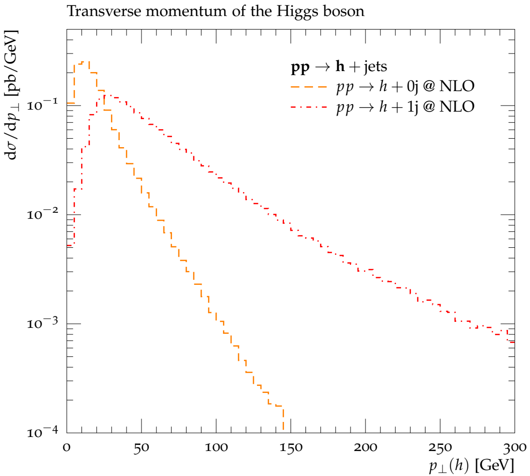

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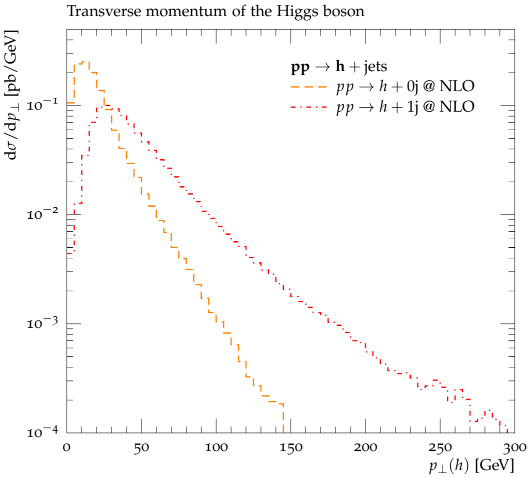

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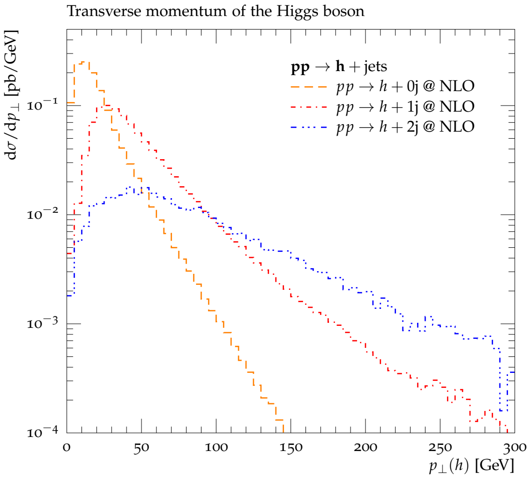

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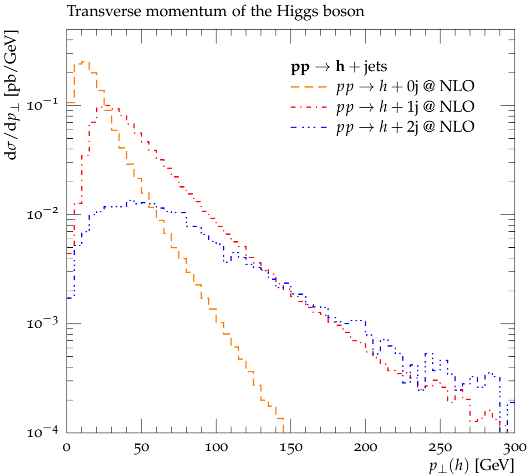

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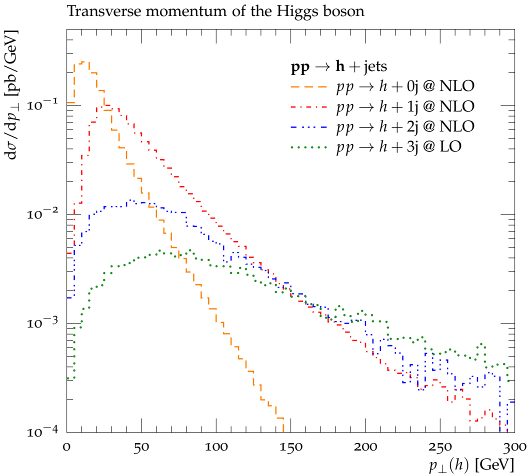

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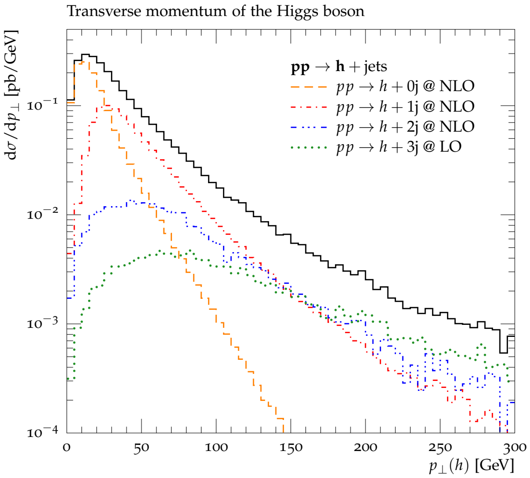

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QCD multijet merging – identifying a history

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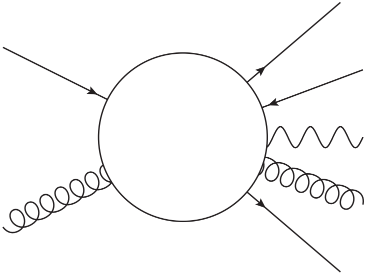

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- identify a shower history (probabilistically), determine scale t_i up to predefined t_I
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$$\alpha_s^{n+k}(\mu_R^2) = \alpha_s^k(\mu_{\text{core}}^2) \prod_{i=1}^{n} \alpha_s(t_i)$$

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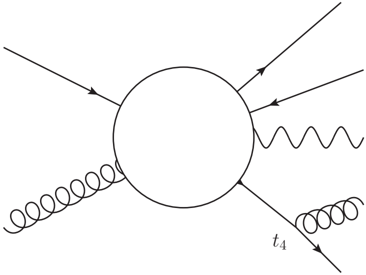

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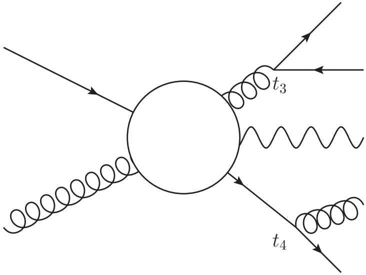

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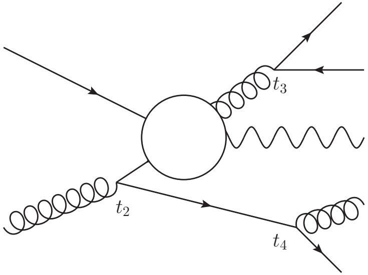

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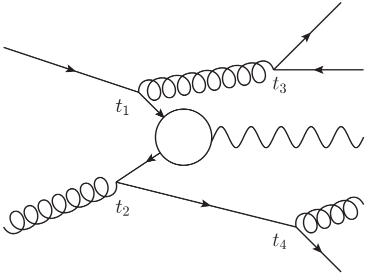

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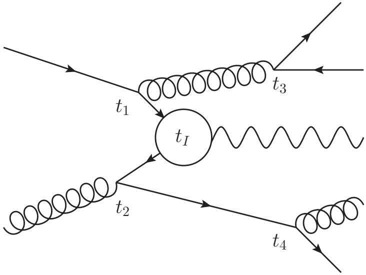

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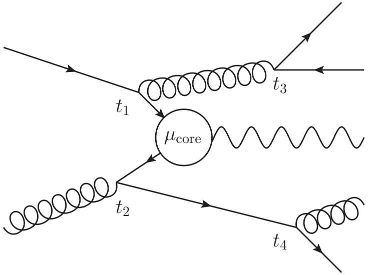

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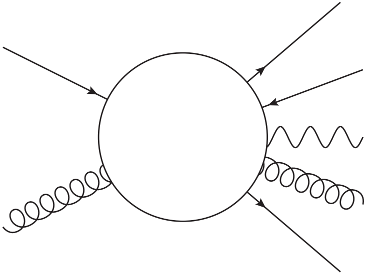
QCD multijet merging – identifying a history

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



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- configuration that would have arisen from dijets plus QCD+EW showering
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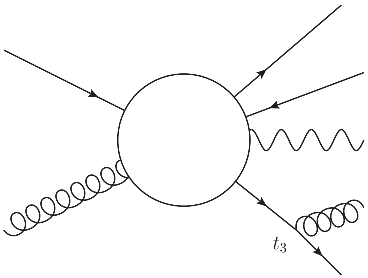

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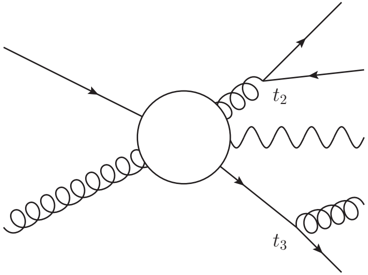

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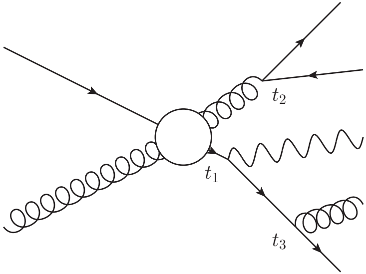

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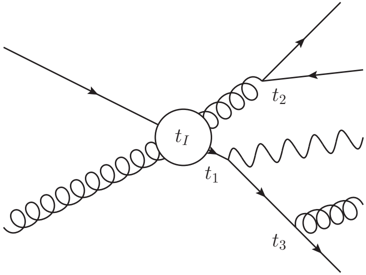

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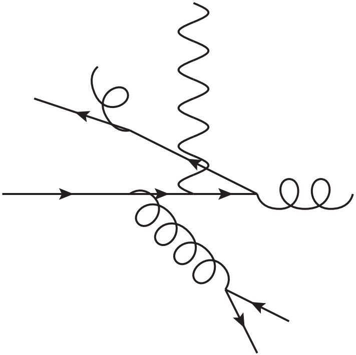

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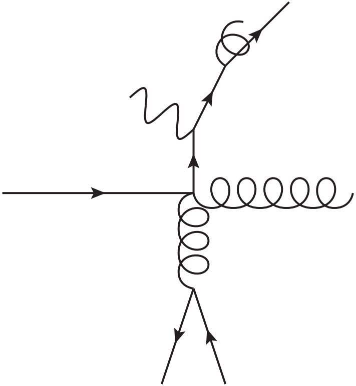
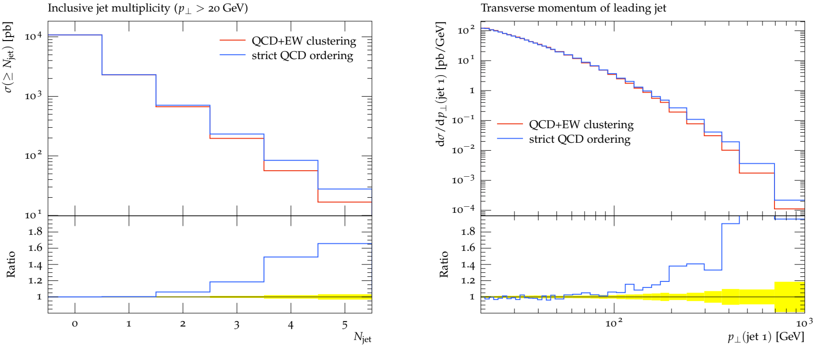
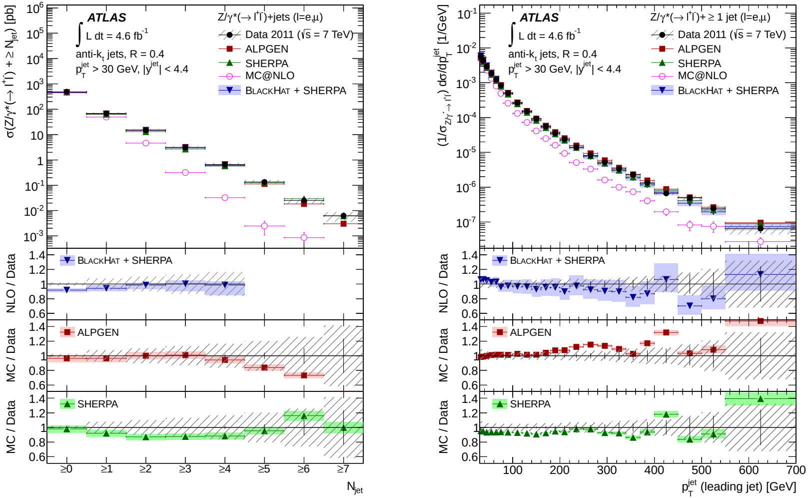


Importance of electroweak clustering



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

Importance of electroweak clustering



Inclusion of electroweak corrections

- incorporate approximate electroweak corrections in MEPS@NLO

1) using electroweak Sudakov factors

$$\tilde{\mathrm{B}}_{n,\mathsf{QCD}\times\mathsf{EW}_{\mathrm{sud}}}(\Phi_n) = \tilde{\mathrm{B}}_n(\Phi_n)\,\Delta_{\mathsf{EW}}(\Phi_n)$$

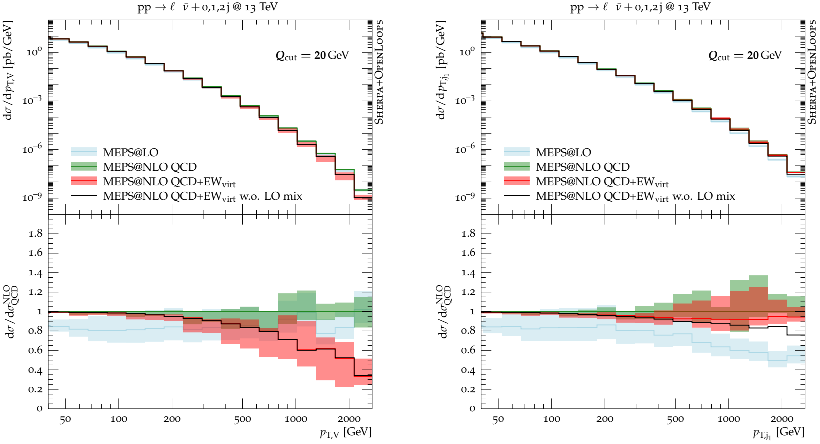
2) using virtual corrections and approx. integrated real corrections

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

- 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, difference $\lesssim 5\%$ for observables not driven by real radiation

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

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



$\Rightarrow$ particle level events including dominant EW corrections

Electroweak corrections for LHC physics

1. Next-to-leading order electroweak corrections
   - Tools and setup
   - Selected results
2. Electroweak effects in multijet merging
   - QCD multijet merging
   - Inclusion of electroweak corrections
3. Real boson radiation
   - Resummation via EW parton showers
   - Case study: Finding W bosons inside jets
4. 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
- same ansatz as used for clustering in multijet merging

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

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

- 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_{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)?

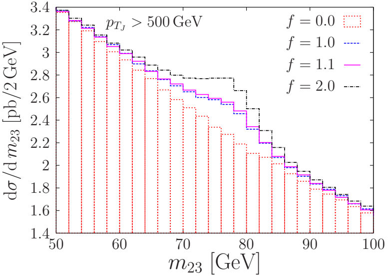
- need high-$p_\perp$ jets to produce real W bosons at sufficient rate
- need high-$p_\perp$ jets to satisfy assumption $E \gg m$

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 $\Rightarrow$ 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

- 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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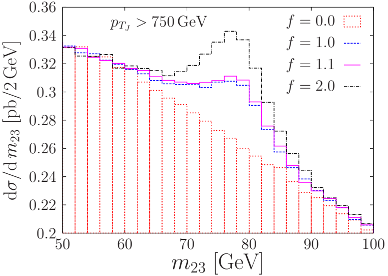

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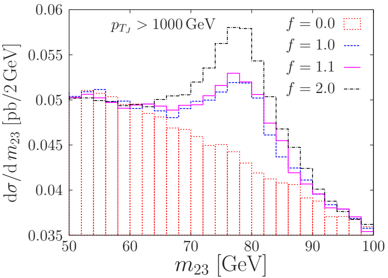

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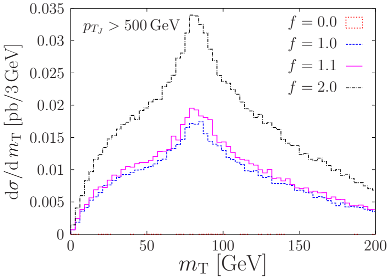
Leptonic analysis

- 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



⇒ provides good background rejection

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

Leptonic analysis

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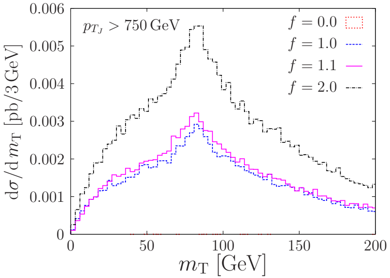
- require $\not{E}_T > 50$ GeV
- reconstruct

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

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



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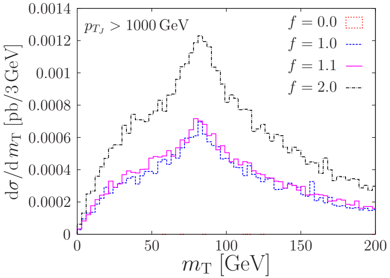

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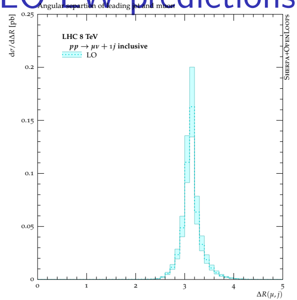
NLO EW predictions for $\Delta R(\mu, j_1)$



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

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

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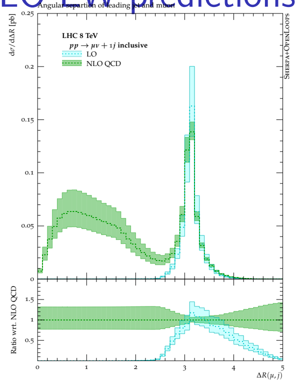

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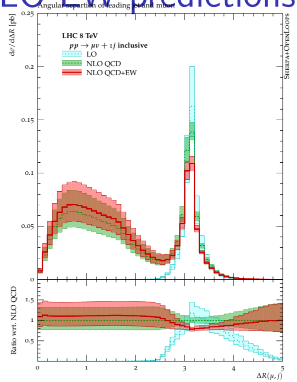

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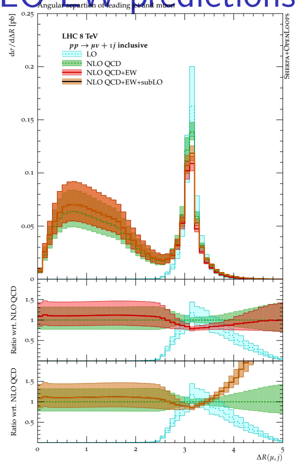

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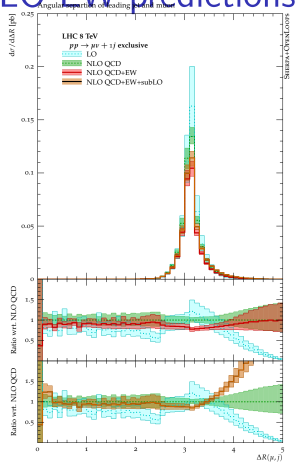

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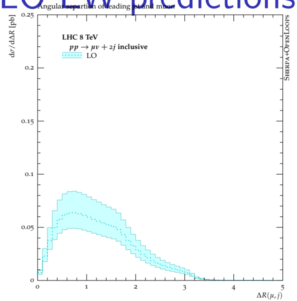

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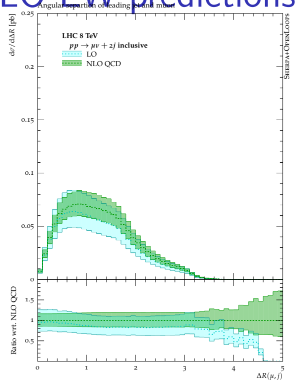

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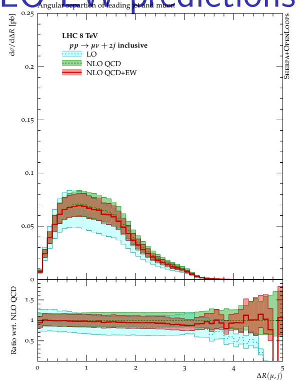

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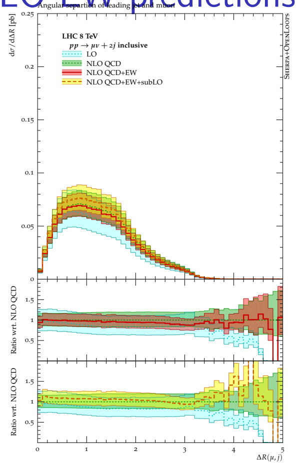

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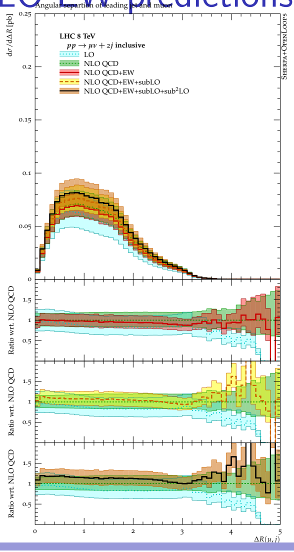

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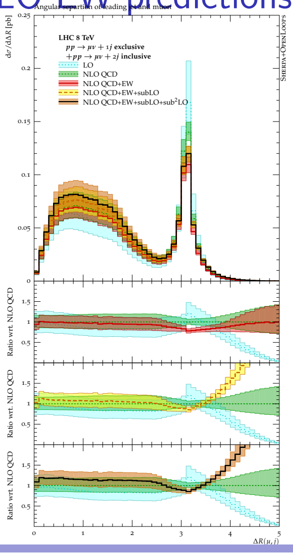

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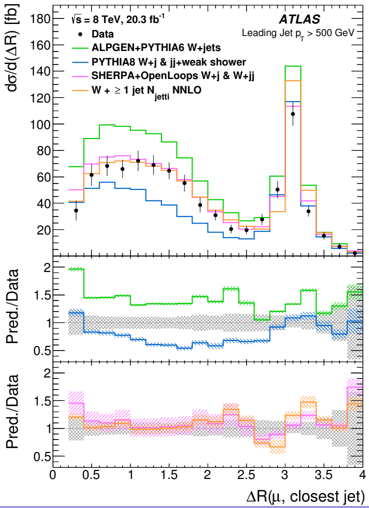

Data comparison

M. Wu ICHEP'16, ATLAS arXiv:1609.07045

- ALPGEN+PYTHIA
  $pp \to W +$ jets MLM merged
  Mangano et.al. JHEP07(2003)001
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  $pp \to Wj$ + QCD shower
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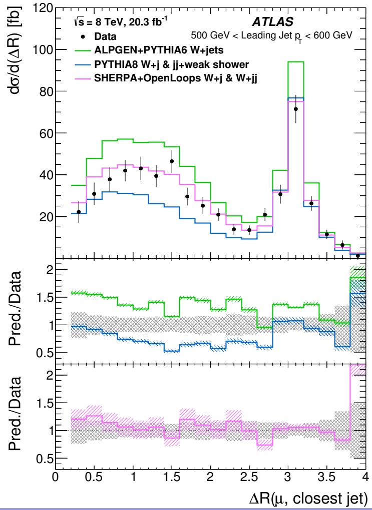

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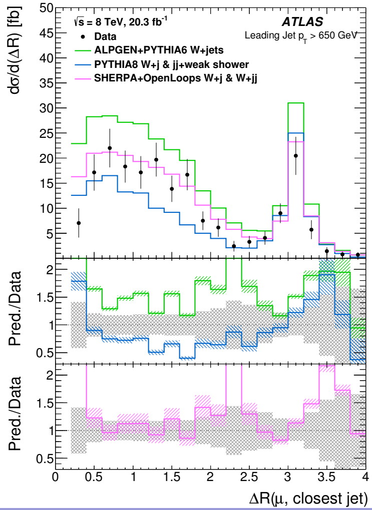

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Conclusions

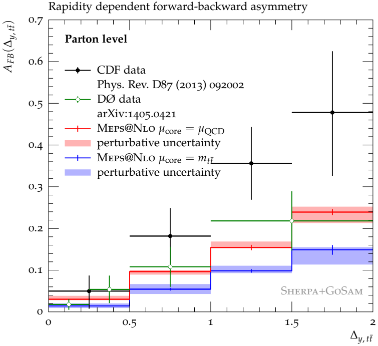
- electroweak effects are important at LHC at 13 TeV, FCC etc.
- become large whenever the scale is large compared the EW scale
- can be incorporated in multijet merging to improve description in those regions
  $\Rightarrow$ included in Sherpa-2.2.1
- proper QCD+EW merging methods still needs to be defined
- automation of NLO EW follows on the heels of NLO QCD
  $\rightarrow$ much more care with consistent schemes and order counting
  $\rightarrow$ automated in Sherpa/Munich +OpenLoops
  $\Rightarrow$ 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

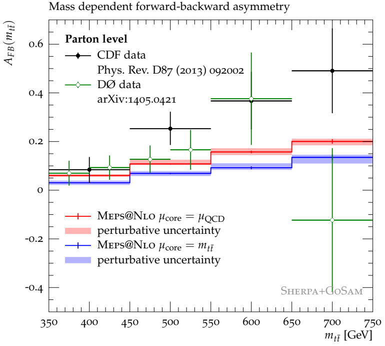
Thank you for your attention!

Backup

Example: Forward-backward asymetry @ Tevatron

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

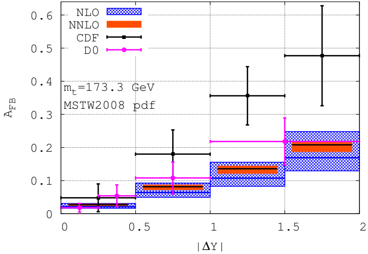


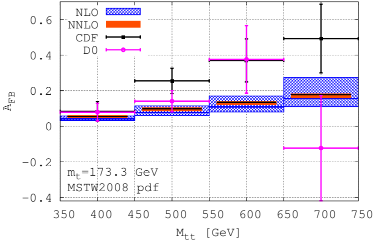


Chose two different $\mu_{\text{core}} \to$ largest impact
Electroweak histories not an issue, but merging works nicely

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

Czakon, Fiedler, Mitov arXiv:1411.3007

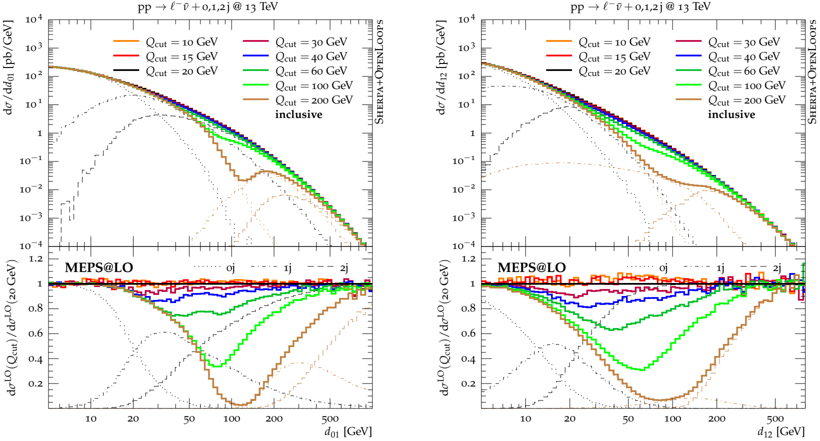




MEPS@NLO result very well reproduced by higher order calculation

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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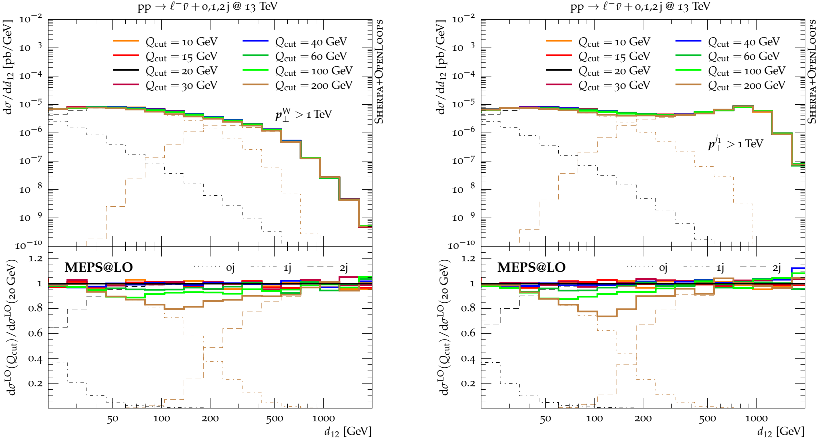

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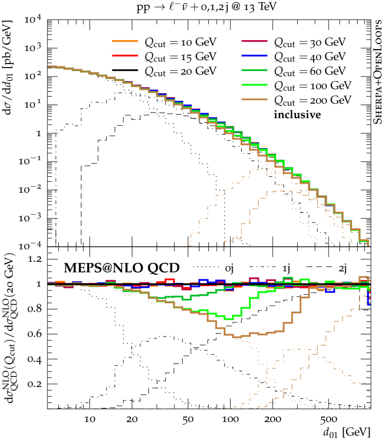

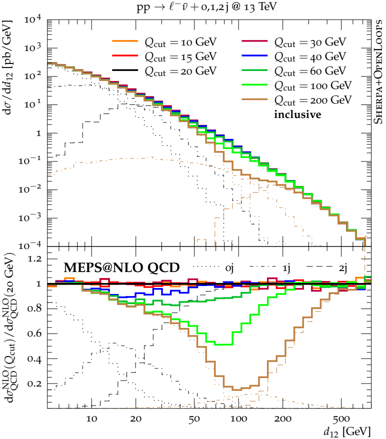

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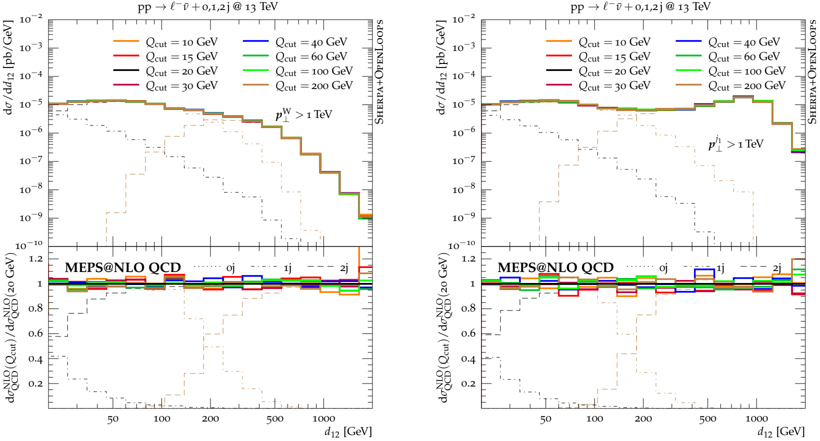

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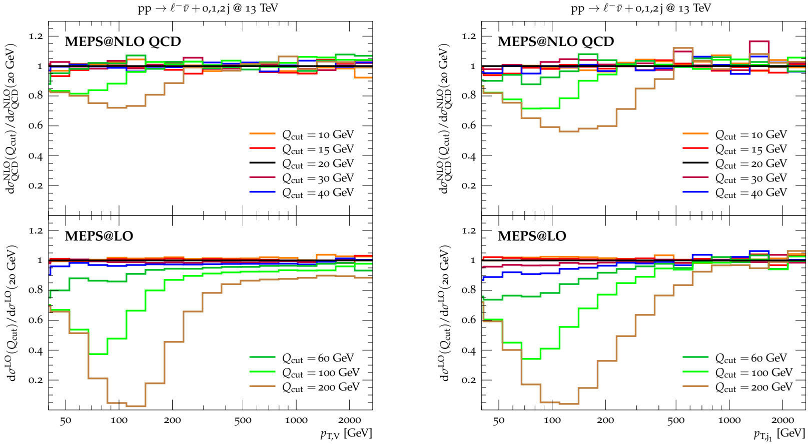


$\Rightarrow$ TeV region stable ($\lesssim 5\%$), $Q_{cut} = 20\,\text{GeV}$ suitable for whole range

Hadronic analysis

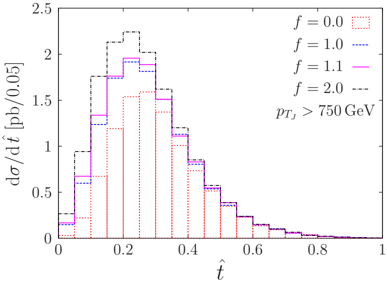
- use event shape variables on microjets of reconstructed W candidate to enhance S/B, e.g. ellipticity

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

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

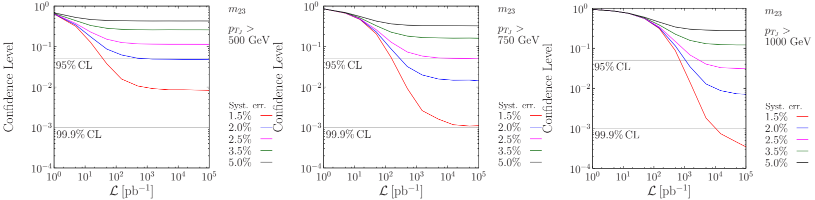
- fat jet $p_\perp > 750$ GeV optimal best balance between cross section and emission rate

$\Rightarrow$ additional discrimination



Hadronic analysis

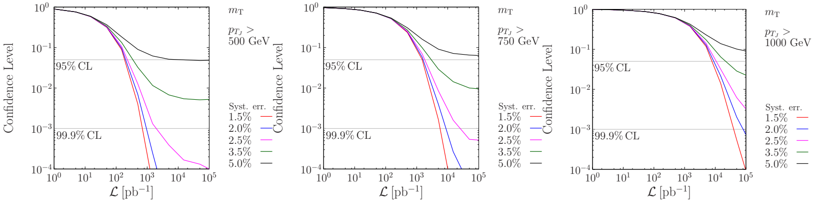
Can we distinguish between $f = 1$ and $f = 2$?
(simplified version of: How accurate can we measure the coupling?)



- 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

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