

SHERPA for $V+jets$

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Outline

- 1 Overview
- 2 Recent results
- 3 V+jets
- 4 Reweighting
- 5 Conclusions

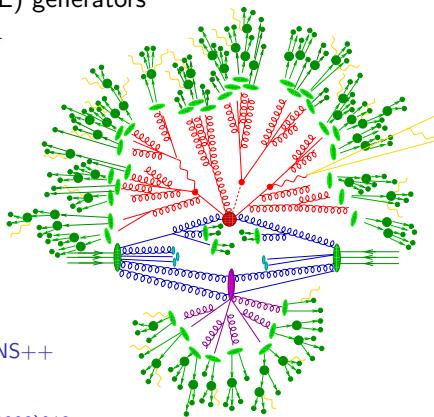
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The SHERPA event generator framework

JHEP02(2009)007

- Two multi-purpose Matrix Element (ME) generators
 AMEGIC++ JHEP02(2002)044, EPJC53(2008)501
 COMIX JHEP12(2008)039, PRL109(2012)042001
- Two Parton Shower (PS) generators
 CSSHOWER JHEP03(2008)038
 DIRE EPJC75(2015)461
- A multiple interaction simulation
 à la PYTHIA AMISIC++ hep-ph/0601012
- A cluster fragmentation module
 AHADIC++ EPJC36(2004)381
- A hadron and τ decay package HADRONS++
- A higher order QED generator using
 YFS-resummation PHOTONS++ JHEP12(2008)018



Sherpa's traditional strength is the perturbative part of the event
 LO, NLO, NNLO, LoPs, NLOPs, **NNLOs**, MEPS, MENLOs, **MEPS@NLO**

Acronyms and nomenclature

Fixed order calculations

- matrix elements only, implies fixed multiplicities
- no parton shower, no non-perturbative physics, no particle level

⇒ LO, NLO, NNLO

Parton shower matched calculations

- combination of fixed order calculation and parton shower for one multiplicity
- particle level predictions, no multijet observables

⇒ LOPs, NLOPs, **NNLOPs**

Multijet merged calculations

- combination of parton shower matched calculations for increasing final state multiplicities (mostly jets)
- particle level predictions, multijet observables

⇒ MEPS(@LO), **MEPS@NLO** (special case MENLOPs)

SHERPA-2.2.3

- SHERPA-2.2.3 released Apr '17
- contains bugfixes for all known bugs up to SHERPA-2.2.2
- UFO support for BSM physics
- new parton shower DIRE in addition to CSSHOWER
- on-the-fly scale and PDF variations for ME part in
 - LO, NLO
 - LOPs, NLOPs (S-MC@NLO)
 - MEPS, MENLOPs, MEPS@NLO
- use named weights in HEPMC (av. since HEPMC-2.06)
- full scale & PDF variations including parton shower and for NNLO/NNLOPs in SHERPA-2.3.0
- allow to force HEPMC event record into pure tree structure, lost information available through disconnected vertices
- new default PDF: NNPDF30_nnlo_as_0118 → new tune

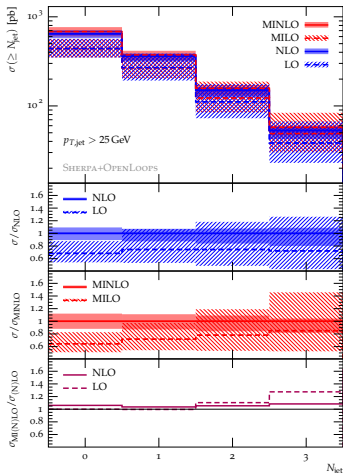
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NLO QCD calculations – $pp \rightarrow t\bar{t} + 3\text{jets}$

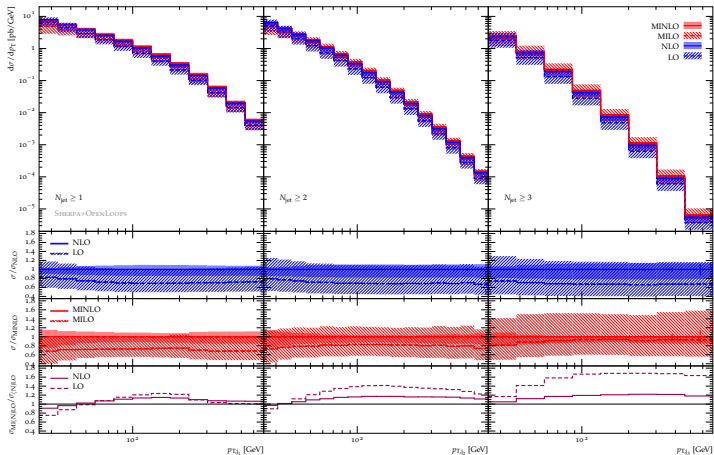
Höche, Maierhöfer, Moretti, Pozzorini, Siebert arXiv:1607.06934

- First computation of $t\bar{t}+3$ jets at NLO / MiNLO accuracy
- Sherpa NLO MC framework using Comix [Gleisberg, Höche arXiv:0808.3674](#) combined with OpenLoops [Casoli, Maierhöfer, Pozzorini arXiv:1111.5206](#)
- Public results in NTuple format à la [BlackHat collaboration arXiv:1310.7439](#) for easy analysis & recycling available at NERSC (login req'd)
- Scale dependence studied using $H_{T,m} = \sum m_{\perp}$ and MiNLO [Hamilton, Nason, Zanderighi arXiv:1206.3572](#) extended to massive partons



NLO QCD calculations – $pp \rightarrow t\bar{t} + 3\text{jets}$

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- Inclusive jet- p_T spectra

Parton showers – DIRE

Höhe, Prestel EPJC75(2015)461

- combination of parton and dipole shower picture
 → partial fractioning soft eikonal [Catani, Seymour Nucl.Phys.B485\(1997\)291](#)

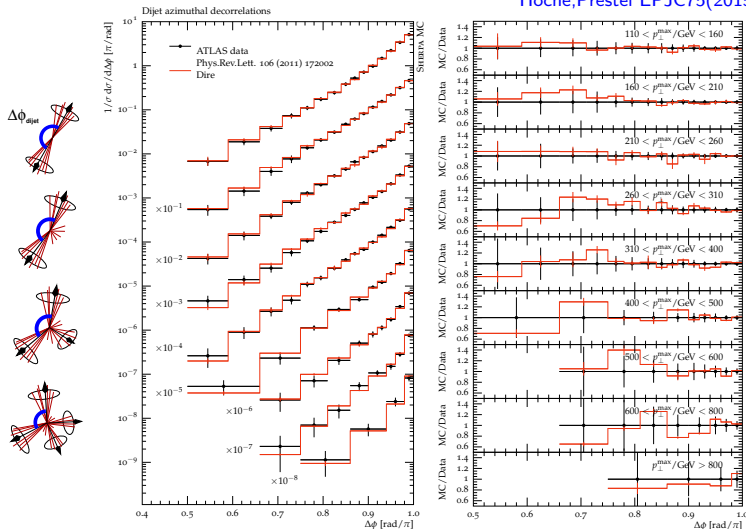
$$\frac{p_i p_k}{(p_i p_j)(p_j p_k)} \rightarrow \frac{1}{p_i p_j} \frac{p_i p_k}{(p_i + p_k) p_j} + \frac{1}{p_k p_j} \frac{p_i p_k}{(p_i + p_k) p_j}$$

⇒ disentangles soft and coll. limits, allows for systematic improv.

- analytically integrable ⇒ allows comparison to dedicated calcs.
 - recovers momentum and flavour sum rules
 - recovers anomalous dimensions
- ⇒ cannot be used in NLO matching and merging yet
- ⇒ base design towards higher precision parton showering

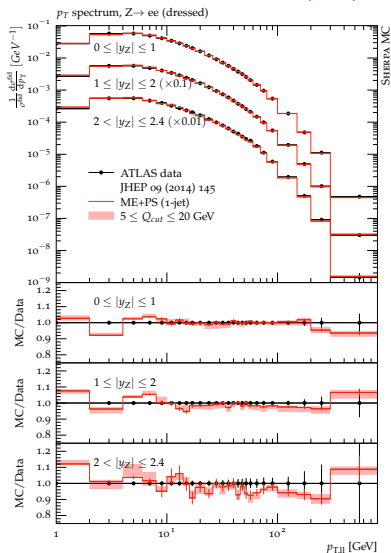
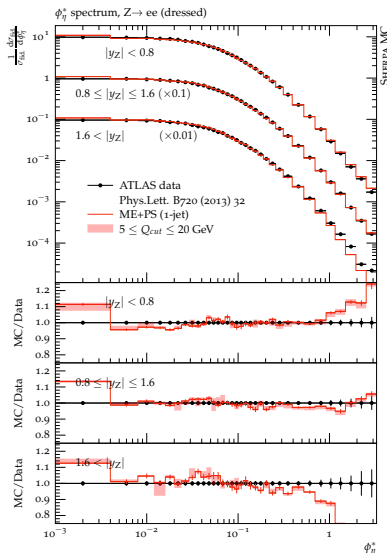
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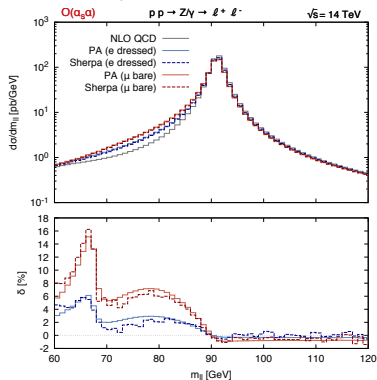
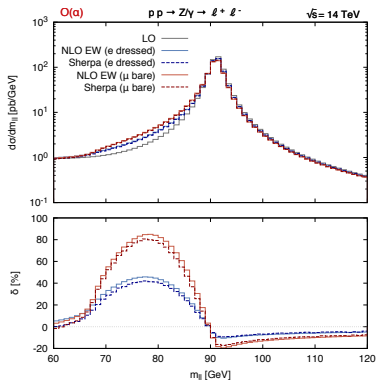
Parton showers – DIRE

Höche, Prestel EPJC75(2015)461



YFS – comparison against dedicated calculations

Huss,MS for LH'15 arXiv:1605.04692



- compare against pole approximation NNLO $\mathcal{O}(\alpha_s\alpha)$
Dittmaier,Huss,Schwinn Nucl.Phys.B904(2016)216
- very good reproduction of $\mathcal{O}(\alpha)$ and $\mathcal{O}(\alpha_s\alpha)$
- major differences traced to multi-photon emissions in YFS

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NLO EW corrections

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

- fixed-order next-to-leading order electroweak corrections
- use one-loop matrix element from OPENLOOPS
- already studied a range of processes:
 - $pp \rightarrow V + 0, 1, 2(, 3) \text{ jets}$

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

EW report arXiv:1606.02330

- $pp \rightarrow t\bar{t}h$

LH'15 arXiv:1605.04692

- $pp \rightarrow Zj/pp \rightarrow \gamma j$ ratio

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

LH'15 arXiv:1605.04692

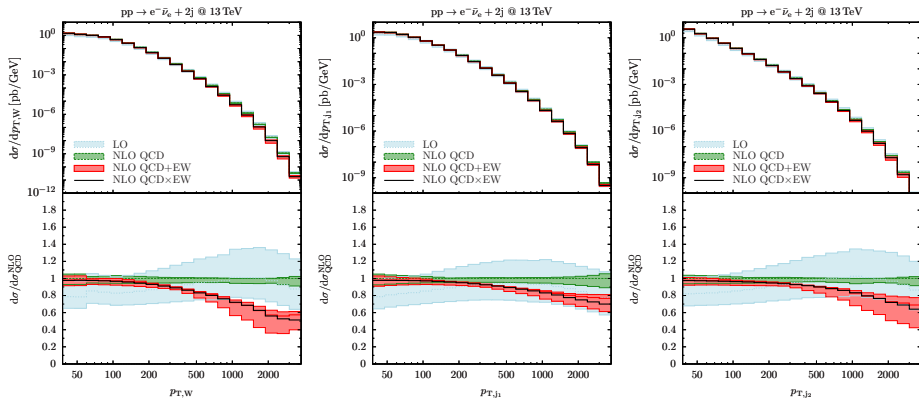
- $pp \rightarrow Vh$

FCC report, arXiv:1607.01831

- dedicated comparisons in LH'15 against RECOLA ($Z + 2j$) and MADGRAPH (tth) showed agreement

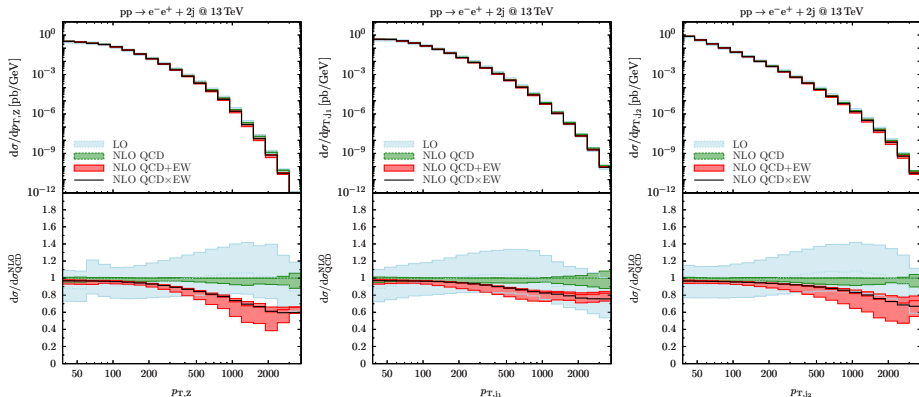
$pp \rightarrow Wjj @ 13 \text{ TeV}$

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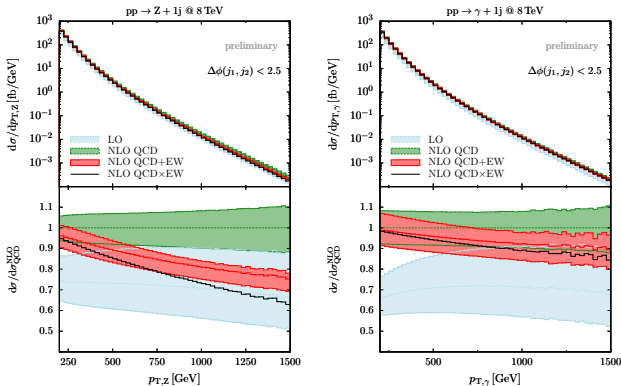
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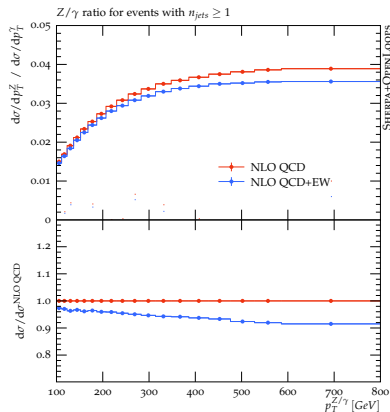
Z/ γ ratio @ 8 TeV

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



\rightarrow EW corrections different for Z and γ

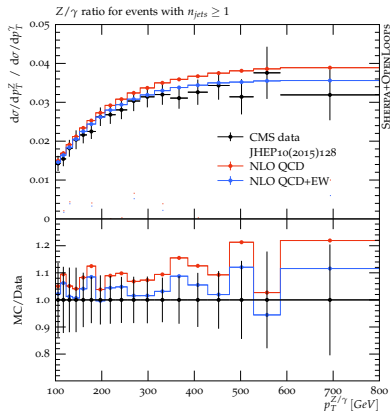
Z/ γ ratio @ 8 TeV



Kallweit, Lindert, Pozzorini, MS for LH'15

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

Z/ γ ratio @ 8 TeV



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Electroweak corrections in particle-level event generation

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

$$\bar{B}_{n,\text{QCD}+\text{EW}_{\text{virt}}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) + V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n) + B_{n,\text{mix}}(\Phi_n)$$

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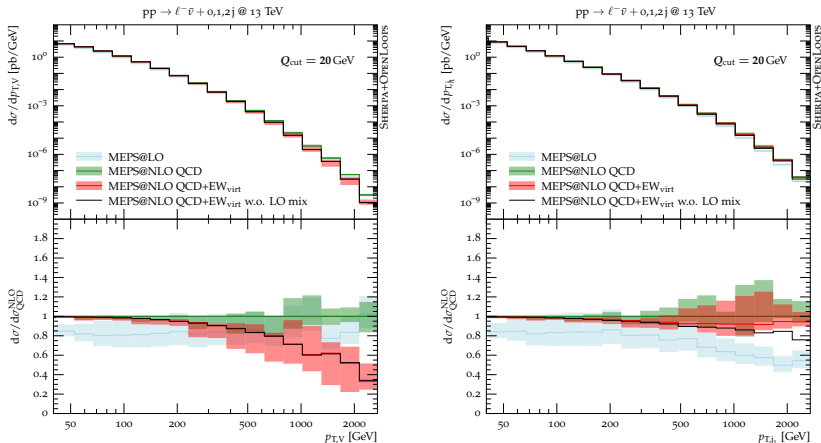
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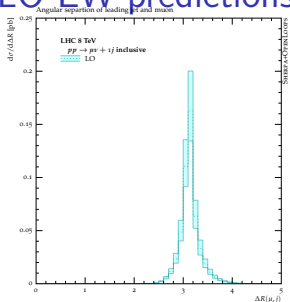
Results: $pp \rightarrow \ell^- \bar{\nu} + \text{jets}$

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



⇒ particle level events including dominant EW corrections

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

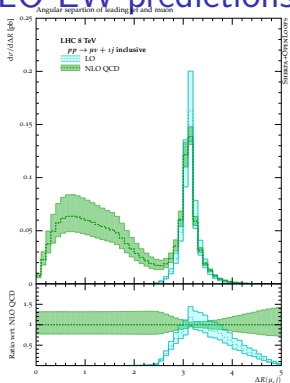


Measure coll. W emissions, simplified from Krauss, Petrov, MS, Spannowsky PRD89(2014)114006

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

- LO $pp \rightarrow Wj$ with $\Delta\phi(\mu, j) \approx \pi$
 - NLO corrections neg. in peak
 - large $pp \rightarrow Wjj$ component opening PS
 - subleading Born (γ PDF) imp. at large ΔR
 - restrict to exactly $1j$, no $p_{\perp}^j > 100$ GeV
 - describe $pp \rightarrow Wjj$ @ NLO, $p_{\perp}^j > 100$ GeV
 - pos. NLO QCD, ΔR NLO \sim flat
 - subleading Born contribs positive
 - sub²leading Born (diboson etc) conts. pos. \rightarrow possible double counting with BG
 - merge using exclusive sums

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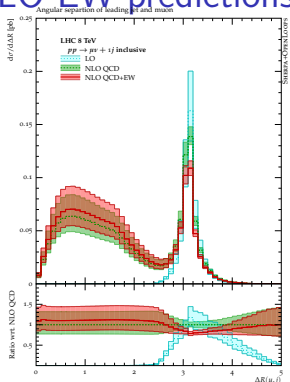


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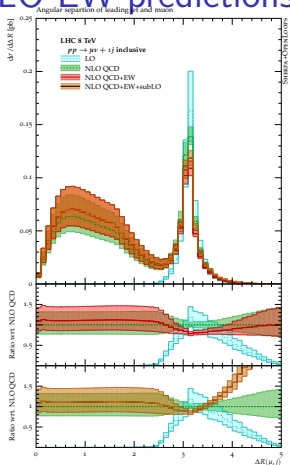


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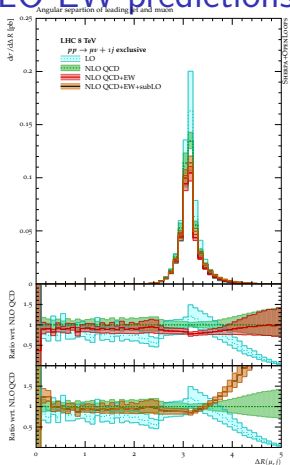


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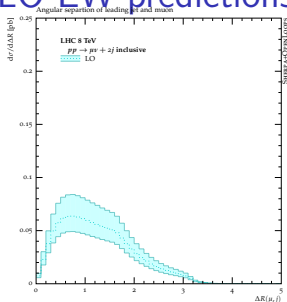


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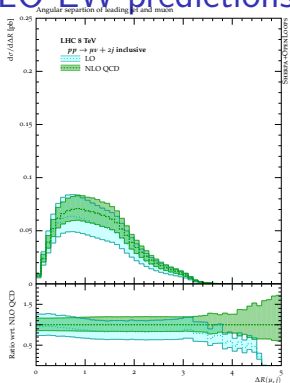


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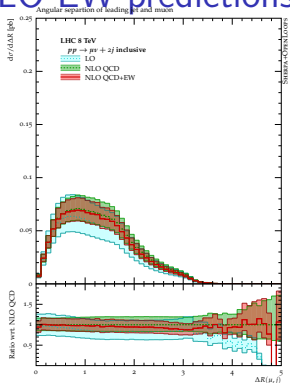


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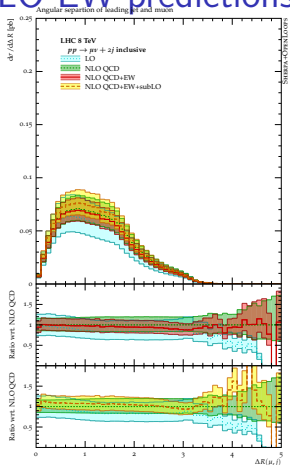


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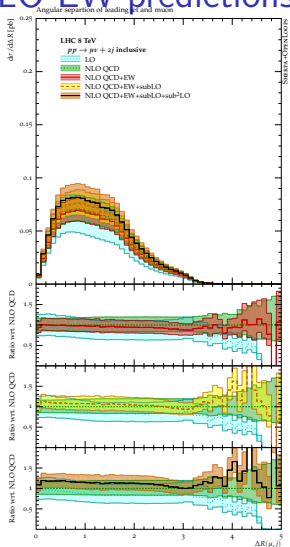


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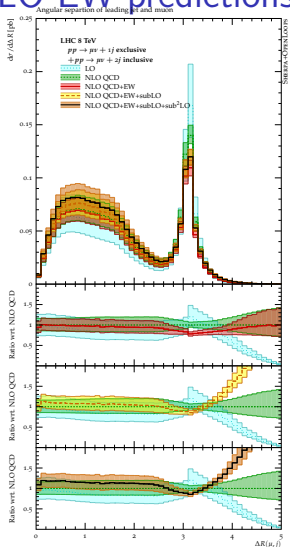


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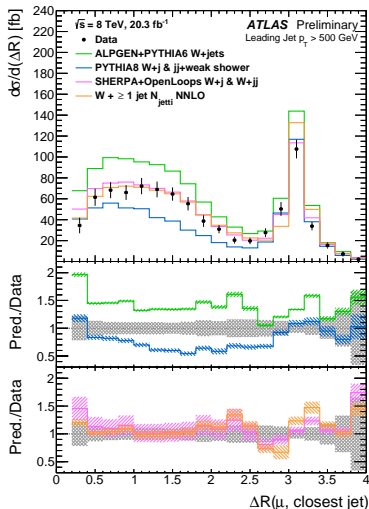


Measure coll. W emissions, simplified from
 Krauss, Petrov, MS, Spannowsky PRD89(2014)114006

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

- LO $pp \rightarrow Wj$ with $\Delta\phi(\mu, j) \approx \pi$
- NLO corrections neg. in peak
 large $pp \rightarrow Wjj$ component opening PS
- subleading Born (γ PDF) imp. at large ΔR
- restrict to exactly $1j$, no $p_{\perp}^j > 100$ GeV
- describe $pp \rightarrow Wjj$ @ NLO, $p_{\perp}^j > 100$ GeV
- pos. NLO QCD, neg. NLO EW, \sim flat
- subleading Born contribs positive
- sub²leading Born (diboson etc) conts. pos.
 \rightarrow possible double counting with BG
- merge using exclusive sums

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

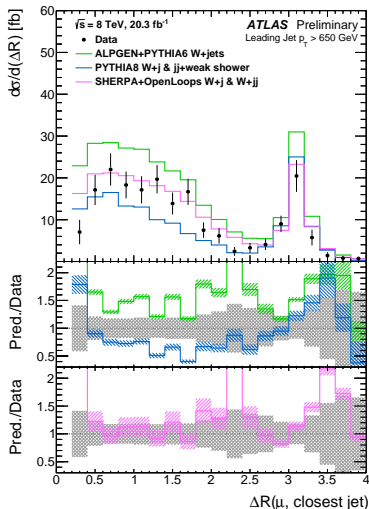


Data comparison

M. Wu ICHEP'16, ATLAS arXiv:1609.07045

- ALPGEN+PYTHIA
 $pp \rightarrow W + \text{jets}$ MLM merged
[Mangano et.al. JHEP07\(2003\)001](#)
- PYTHIA 8
 $pp \rightarrow Wj + \text{QCD shower}$
 $pp \rightarrow jj + \text{QCD+EW shower}$
[Christiansen, Prestel EPJC76\(2016\)39](#)
- SHERPA+OPENLOOPS
 NLO QCD+EW+subLO
 $pp \rightarrow Wj/Wjj$ excl. sum
[Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04\(2016\)021](#)
- NNLO QCD $pp \rightarrow Wj$
[Boughezal, Liu, Petriello arXiv:1602.06965](#)

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



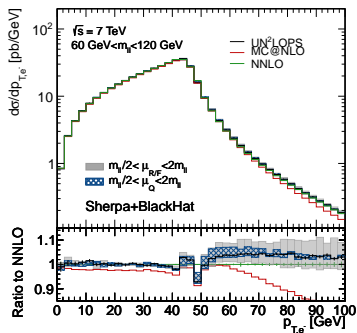
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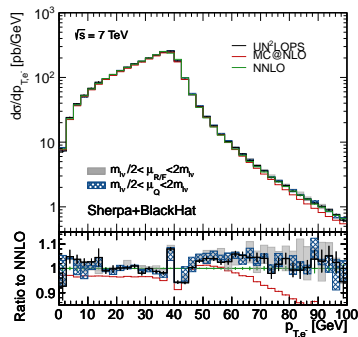
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NNLOs for $pp \rightarrow W/Z$

Höche, Li, Prestel arXiv:1405.3607, arXiv:1407.3773



$pp \rightarrow ll$



$pp \rightarrow lv$

SHERPA for V +jets

- 1 Overview
- 2 Recent results
- 3 V +jets
- 4 Reweighting**
- 5 Conclusions

Reweighting

Parameters

parametric e.g. $\alpha_s(m_Z)$, m_t , PDF

perturbative e.g. NLO, NLL, leading- $N_c \rightarrow \mu_R, \mu_F$

algorithmic e.g. evolution variable, recoil schemes, matching scheme

Explicit variations

- can be done for any scale or PDF dependence
- functional form can be changed
- separate run (independent calculation) for every variation

On-the-fly variations

[Bothmann,MS,Schumann arXiv:1606.08753](#)

- can be done for μ_R, μ_F, α_s & PDF dependence of ME & PS
- functional form can currently not be changed
- full syntax, cf. Manual

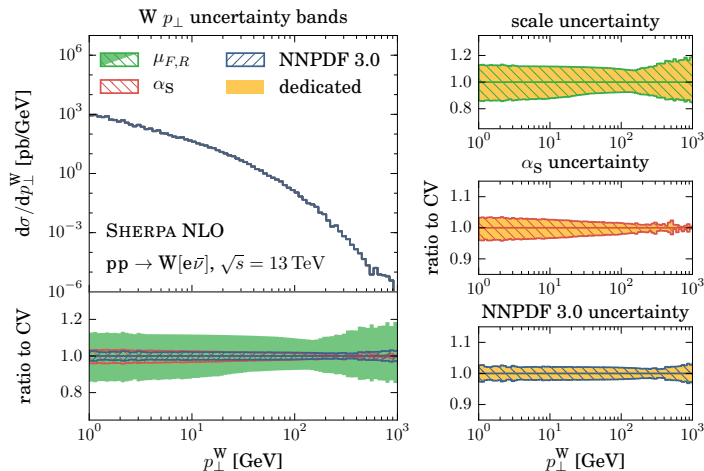
```
SCALE_VARIATIONS 0.25,0.25 4.,4.
```

```
PDF_VARIATIONS NNP30_nnlo_as_0118[a11]
```

- store in HEPMC weight container using LH'13 naming convention

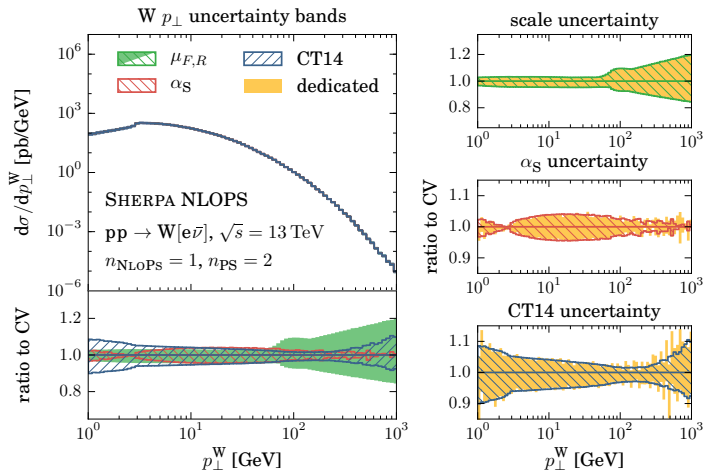
Reweighting – closure test – NLO

Bothmann,MS,Schumann arXiv:1606.08753



Reweighting – closure test – NLOs

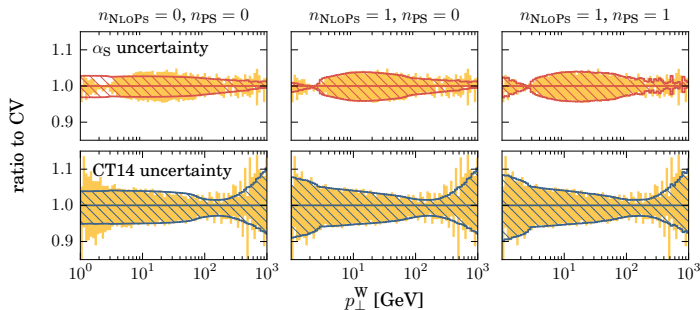
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Reweighting – closure test – NLOs

Bothmann,MS,Schumann arXiv:1606.08753

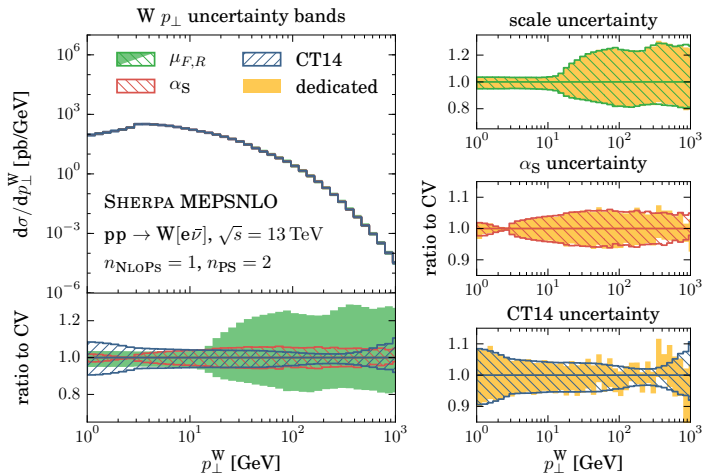
other maximum numbers of reweighted emissions $n_{\text{NLOs}}, n_{\text{PS}}$



→ reweighting two emission sufficient for this observable

Reweighting – closure test – MEPS@NLO

Bothmann,MS,Schumann arXiv:1606.08753



Timings in $pp \rightarrow \ell^+ \ell^- + \leq 4\text{jets}$ MEPs (LO)

weighted events

- low baseline per event timing (25s/1k)
- constant offset per computed variation

⇒ 217 vars. → factor 38

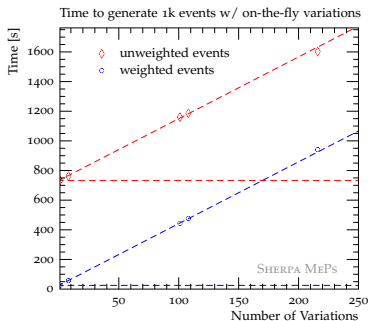
(partially) unweighted events

- high baseline per event timing (730s/1k)
- constant offset per computed variation

⇒ 217 vars. → factor 2.2

→ time to compute variations independent of event generation mode

⇒ **huge gain for standard (partially) unweighted events**



$\mu_{R F}$	→	7
PDF (NNPDF30)	→	100
$\mu_{R F} + \text{PDF}$	→	107
PDF4LHC (old)	→	217

SHERPA-2.2.3

- a new parton shower DIRE
- vastly extended support for UFO BSM format
- multijet merging for loop induced processes further tested, use as:
 - MEPS@LOOP²
 - reweight MEPS@NLO Higgs production in HEFT with top mass dependence (approximate in virtual corrections only)
- on-the-fly variations of μ_R , μ_F , α_s and PDF for
 - LO, NLO
 - LOPs, NLOPs (S-MC@NLO), NNLOPs through plugin
 - MEPS, MENLOPs, MEPS@NLO
- incorporation of approx. NLO EW corrs in existing NLO QCD MEPS@NLO
- default PDF: NNPDF30_nnlo_as_0118 including tune of non-perturbative parameters
- **coming in SHERPA-2.3.0:** PS reweighting, full NLO EW

<http://sherpa.hepforge.org>

Thank you for your attention!

Backup

Resummation via EW parton showers

- 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): $f(s) \rightarrow f^{(\prime)}V(s)$

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

- emitter fermion f , suitable spectator s
- flavour change $f \rightarrow f'$ in case of W emissions
- IS kernels contain ratio of PDFs (change in $x, Q, \text{flavour}$)
- 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

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

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

with

$$c_{\perp}^W = s_{\text{eff}} \frac{1}{2s_W^2} |V_{ff'}|^2, \quad c_{\perp}^Z = s_{\text{eff}} \frac{s_W^2}{c_W^2} Q_f^2 + (1 - s_{\text{eff}}) \frac{(I_f^3 - s_W^2 Q_f)^2}{s_W^2 c_W^2},$$

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

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

Case study: Finding W bosons inside jets

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

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

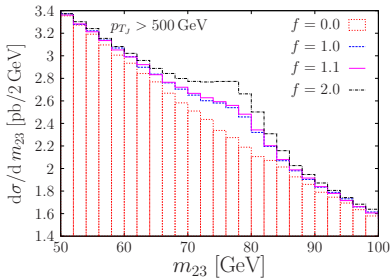
- need high- p_{\perp} jets to produce real W bosons at sufficient rate
- need high- p_{\perp} jets to satisfy assumption $E \gg m$

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

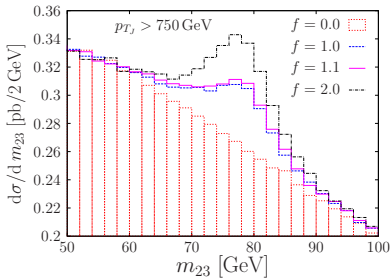
Hadronic analysis

- 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 than 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 high p_{\perp} , but peak shifts



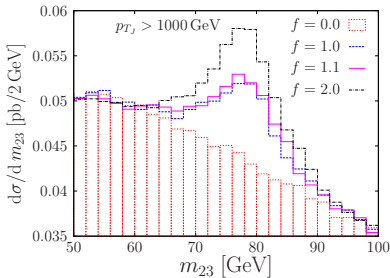
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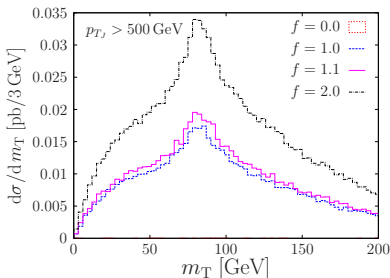
Leptonic analysis

- exactly one isolated lepton
- require $\cancel{E}_T > 50$ GeV
- reconstruct

$$m_T = \sqrt{2E_{T_l}\cancel{E}_T(1 - \cos\theta)}$$

- accept candidate if $m_T \in [60, 100]$ GeV

- ⇒ provides good background rejection
- ⇒ loose some sensitivity for higher fat jet p_\perp as isolation is compromised for more collinear W emissions



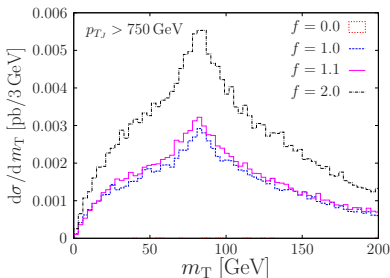
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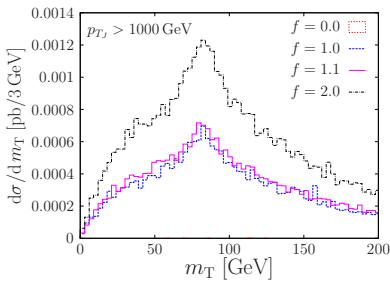
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Higgs physics I

Buschmann, Goncalves, Kuttimalai, MS, Krauss, Plehn JHEP02(2015)038
 Kuttimalai, Krauss, Maierhöfer, MS LH'15 arXiv:1605.04692
 Kuttimalai, Krauss, Maierhöfer, MS for YR4

$pp \rightarrow H + \text{jets}$ production (ggF)

- correction factor/weight

$$r_t^{(n)} = \frac{|\mathcal{M}^{(n)}(m_t)|^2}{|\mathcal{M}^{(n)}(m_t \rightarrow \infty)|^2}$$

- loops from OPENLOOPS
- construct MEPS@NLO from reweighted S-MC@NLO
- factorised approach for unknown top mass dependence in V_n , otherwise exact NLO mass dependence

$$d\sigma_n = d\Phi_n r_t^{(n)} \left[B_n + V_n + \int d\Phi_1 D_n \right] \widetilde{\text{PS}}_n + d\Phi_{n+1} \left[r_t^{(n+1)} R_n - r_t^{(n)} D_n \right]$$

