

# Electroweak parton showers in SHERPA

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THE  
ROYAL  
SOCIETY

# Overview

- 1 QED parton showers and soft-photon resummation
- 2 Electroweak parton showers
- 3 EW corrections in event generation
- 4 Conclusions

# QED parton showers and soft-photon resummation

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## QED parton showers

Well-understood abelian limit of QCD parton showers which suffer from non-existing  $N_c \rightarrow \infty$  limit. QED is  $U(1)$ , and  $\frac{1}{1}$  is not so small.  
 $\Rightarrow$  all charge partners of equal importance, but contrib. with diff. signs.

### Parton showers:

coll. emission pattern trivial, soft coherence tricky

### Dipole showers:

without inclusion of neg. dipoles get both soft and coll. limits wrong

Additional complication: QED result of a broken gauge group

$$SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{QED}}$$

in addition to massive fermions

$\Rightarrow$  resonances everywhere

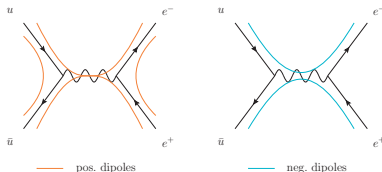
## QED dipoles

**Main issue:** QED is U(1)

equivalent of large- $N_c$  expansion not very meaningful

need full multipole picture for soft-photon coherence

**Example:**  $u\bar{u} \rightarrow e^+e^-$ , 6 dipoles (4 opposite sign, 2 same sign)



need all dipoles for correct soft-collinear structure,

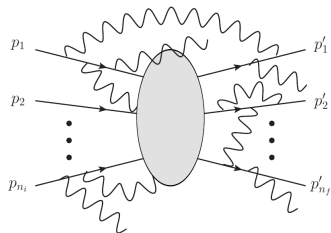
all dipoles contribute on equal footing

can be handled like full colour MC@NLO matching using  
weighted shower

Höche, Krauss, MS, Siegert '11

## Soft-photon resummation

- universal soft-photon limit of all-order QED amplitudes  
(Abelian nature and fermion masses/absence of divergent photon splittings essential) Yennie, Frautschi, Suura '61



$$d\sigma^{\text{YFS}} = \sum_{n_\gamma} \frac{1}{n_\gamma!} d\Phi e^Y \prod_{i=1}^{n_\gamma} [d\Phi_{k_i} \cdot \alpha \tilde{S}(k_i)] \left[ \tilde{\beta}_0 + \sum_{i=1}^{n_\gamma} \frac{\tilde{\beta}_1(k_i)}{\tilde{S}(k_i)} + \dots \right]$$

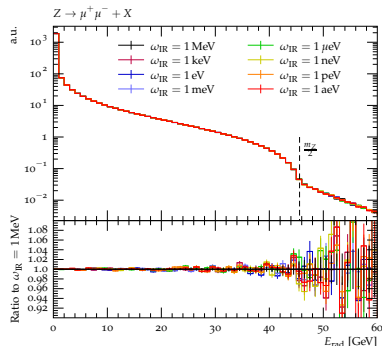
- coherent multiple soft-photon emission from Eikonals  $\tilde{S}$
- re-orders perturbative series in terms of hard-remainders  $\tilde{\beta}_i$  defined on reduced phase spaces in multiphoton configurations

# Soft-photon resummation

MS, Krauss '08

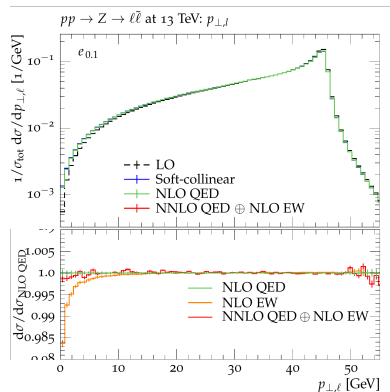
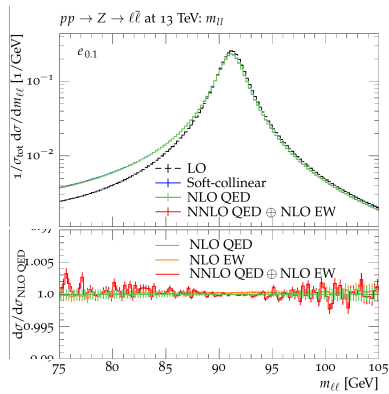
## Numerical stability

- independence of resolution criterion (IR cut-off)  $\omega_{\text{IR}}$
- inclusion of ME corrections  $\tilde{\beta}_1, \tilde{\beta}_2, \dots$ , reduces numerical stability somewhat



# Soft-photon resummation

MS, Krauss '08; Krauss, Lindert, Linten, MS '18



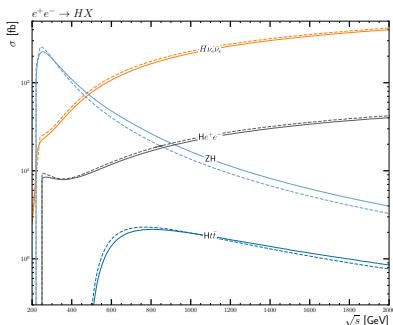
- implementation in SHERPA: matched to NNLO QED + NLO EW
- permille accuracy in the description of the  $Z \rightarrow \ell\bar{\ell}$  kinematics

# Soft-photon resummation for initial states

Price, Krauss, MS to appear

## Lepton colliders:

- in the absence of QCD YFS soft-photon resummation is a method of choice to also resum QED ISR
- coherent ISR and FSR
- LEP: KKMC, YFSWW, YFSZZ, ...



# Electroweak parton showers

- ① QED parton showers and soft-photon resummation
- ② Electroweak parton showers**
- ③ EW corrections in event generation
- ④ Conclusions

## Weak showers: Collinear limit with $E \gg m$

Krauss, Petrov, MS, Spannowsky '14

- 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  $x, Q, \text{flavour}$ )
- immediately decay freshly produced boson
- similar ansatz with diff. kernels in
- many new developments

Christiansen, Sjöstrand '14

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

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

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

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

# Case study: Finding $W$ bosons inside jets

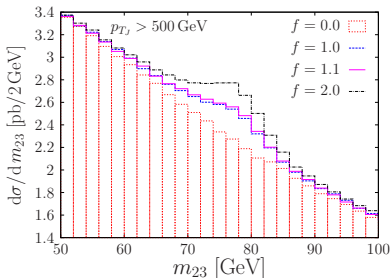
## Boosted analysis:

- high- $p_{\perp}$  fat jet, recluster into C/A microjets
- discard leading microjet as likely from leading quark
- use  $m_{23}$  as gluon em. tends to be softer than decay prod. of  $W$  em.
- 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

Krauss, Petrov, MS, Spannowsky '14

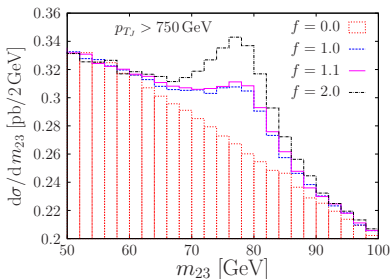


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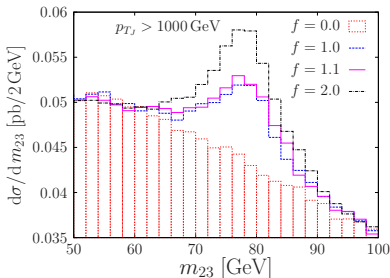


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## Weak showers

### What is missing?

- 1) spin-correlations  
 $O(1)$  effect in EW splittings,  
in principle no different than colour-correlations in QCD PS
- 2) secondary splittings  
 $W \rightarrow W\gamma$ ,  $W \rightarrow WZ$ ,  $W \rightarrow Wh$ ,  $Z \rightarrow WW$ , ...
- 3) simultaneous treatment of secondary scattering and decays  
 $W \rightarrow q\bar{q}'$ ,  $Z \rightarrow q\bar{q}$ ,  $h \rightarrow 4f$ , ...

### Conclusions (for the time being):

- do not enable in actual showering,  
but important in CKKW clustering (will return to it later)
- default: QCD evolution via parton-shower  
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EW corrections at fixed-order

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## EW clustering

In the interpretation of a  $Z + \text{jets}$  configuration allow for the possibility that this signature was produced by dijet configuration radiating a  $Z$  boson.

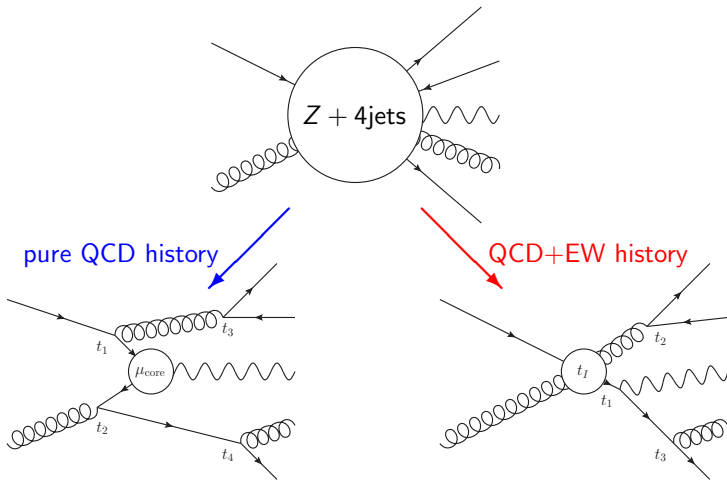
- identify parton shower history to determine CKKW scales and calculate intermediate Sudakov factors

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

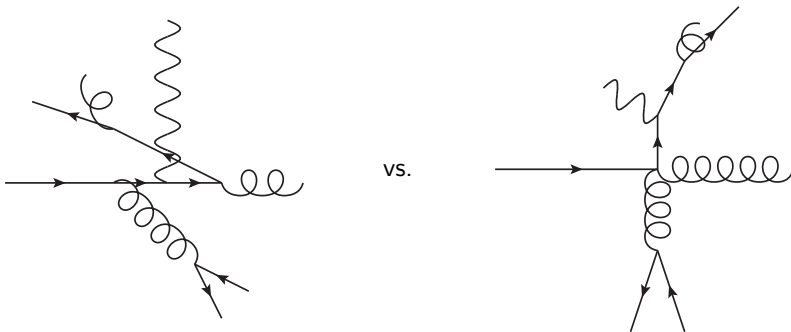
- identifying an EW splitting will “simply skip a step”,  $\alpha$  taken as constant (as in ME), no EW Sudakov applied
- use spin averaged EW splitting functions in  $E \gg m$  limit

**This affects scale choices, no higher-order EW corrs. introduced.**

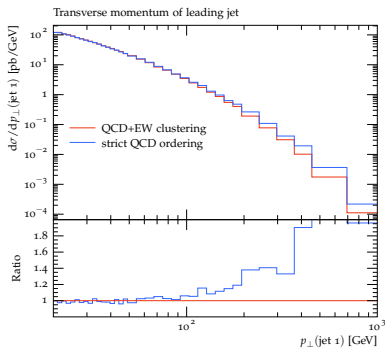
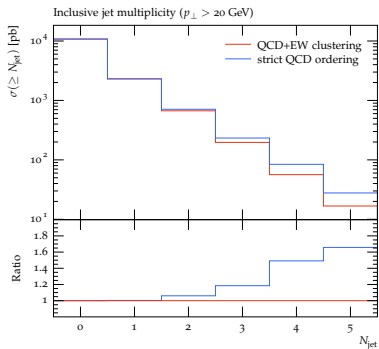
# Multijet merging – identifying a history



# QCD multijet merging – identifying a history

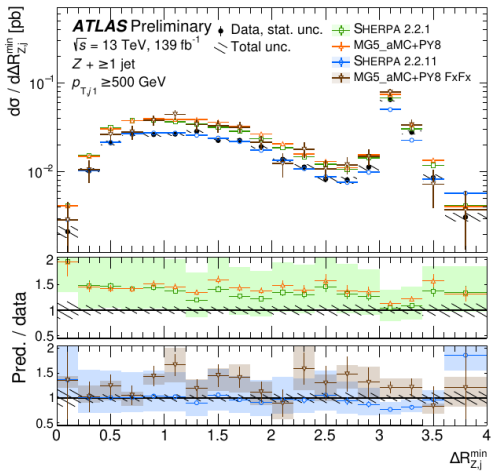


# Importance of electroweak clustering



⇒ large impact at high  $p_{\perp}$  and multiplicity

ATLAS '21 (ATLAS-CONF-2021-033)



## EW virtual approximation

Kallweit, Lindert, Maierhöfer, Pozzorini, MS '15

- ultimate goal: incorporate EW corrections in standard/established parton showered event generation
- construct approximation that only reweights a Born configuration

$$\delta_{\text{virt}}^{\text{EW}}(\Phi_n) = \frac{V_n^{\text{EW}}(\Phi_n) + I_n^{\text{EW}}(\Phi_n)}{B_n(\Phi_n)}$$

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)

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exact virtual contribution (incl. ren. terms)

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$$\delta_{\text{virt}}^{\text{EW}}(\Phi_n) = \frac{V_n^{\text{EW}}(\Phi_n) + I_n^{\text{EW}}(\Phi_n)}{B_n(\Phi_n)}$$

exact virtual contribution

approximate integrated real contribution

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$$\delta_{\text{virt}}^{\text{EW}}(\Phi_n) = \frac{V_n^{\text{EW}}(\Phi_n) + I_n^{\text{EW}}(\Phi_n)}{B_n(\Phi_n)}$$

$$\delta_{\text{sud}}^{\text{EW}}(\Phi_n) = \frac{2\text{Re} \{ [(\delta^{\text{LL,NLL}})\mathcal{M}] \mathcal{M}^* \}}{|\mathcal{M}|^2}$$

Denner, Pozzorini '01  
Bothmann, Napoletano '20

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)

## EW virtual approximation in multijet merging

- incorporate approximate electroweak corrections in MEPS@NLO
- modify MC@NLO  $\bar{B}$ -function to include NLO EW virtual corrections and integrated approx. real corrections

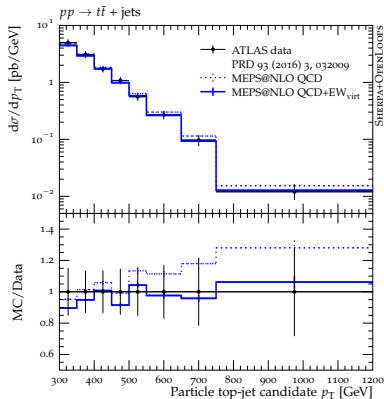
$$\bar{B}_{n,\text{QCD}+\text{EW}_{\text{approx}}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) + B_n(\Phi_n) \delta_{\text{EW}}^{\text{approx}} + B_{n,\text{mix}}(\Phi_n)$$

$$\bar{B}_{n,\text{QCD}\times\text{EW}_{\text{approx}}}(\Phi_n) = \bar{B}_{n,\text{QCD}}(\Phi_n) (1 + \delta_{\text{EW}}^{\text{approx}}) + B_{n,\text{mix}}(\Phi_n)$$

- $\delta_{\text{virt}}^{\text{EW}}$  can be calculated also for  $\mathbb{H}$ -events and LO higher-multis,  $\delta_{\text{sud}}^{\text{EW}}$  in general not  $\implies$  use MENLOPS  $K$ -factor or hybrid schemes
- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging

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

Gütschow, Lindert, MS in '18



- $pp \rightarrow t\bar{t} + 0, 1j@NLO$   
+ 2, 3, 4j@LO
- additional LO multiplicities inherit electroweak corrections through MENLOPS differential  $K$ -factor  
Höhe, Krauss, MS, Siegert '10
- improved description of data

## EW virtual approximation in $4\ell$ production

Gütschow, MS '20

- investigate quality of approximation in  $4\ell$  production, using exact NLO EW as reference ( $G_\mu$  vs.  $\alpha(m_Z)$  as uncertainty estimate)
- use fiducial phase space of ATLAS analysis ATLAS '19
  - $p_T(\ell_1, \ell_2, \ell_3, \ell_4) > (20, 15, 10, 7)$  GeV
  - sliding window for subleading  $m_{\ell\ell}$  in dependence on  $m_{4\ell}$
- investigate different systematic uncertainty
  - dependence on  $\Delta R_{\text{dress}}$ : [0.005, 0.02, 0.1, 0.2]
  - resonance identification  $\Delta_{\text{thr}}$ : [1, 10] for  $\frac{|m_{\ell\ell} - m_V|}{\Gamma_V} < \Delta_{\text{thr}}$
  - QED FSR resummation: [YFS, PHOTOS]

EW virtual approximation in  $4\ell$  production

Gütschow, MS '20

$\mu^+ \mu^- \mu^+ \mu^-$	fiducial cross-section [fb]					
	LO	NLO EW	NLO EW <sub>approx</sub> × YFS		NLO EW <sub>approx</sub> × PHOTOS	
			$\Delta_{\text{thr}} = 1$	$\Delta_{\text{thr}} = 10$	$\Delta_{\text{thr}} = 1$	$\Delta_{\text{thr}} = 10$
$\alpha_{G\mu}^4 \cdot \alpha(0)$	8.99	8.56	8.54	8.54	8.55	8.55
$\alpha^4(m_Z) \cdot \alpha(0)$	8.11	8.33	8.34	8.34	8.36	8.36

$\mu^+ \nu_\mu e^- \bar{\nu}_e$	fiducial cross-section [fb]		
	LO	NLO EW	NLO EW <sub>approx</sub> × YFS
$\alpha_{G\mu}^5$	319.7	310.8	313.3

- good agreement for inclusive cross section accidental, approximation not constructed for this limit

EW virtual approximation in  $4\ell$  production

Gütschow, MS '20

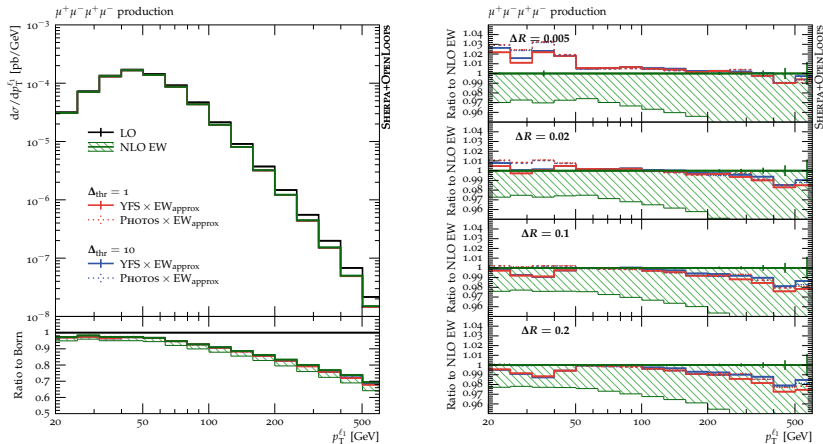
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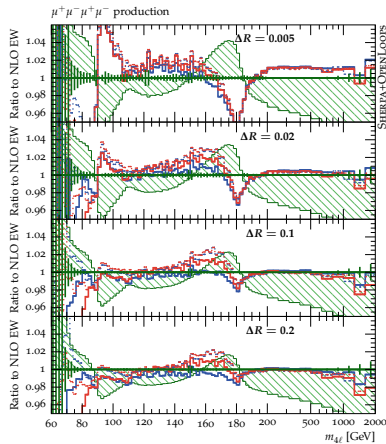
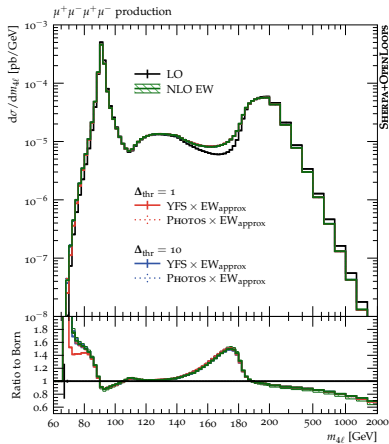
EW virtual approximation in  $4\ell$  production

Gütschow, MS '20



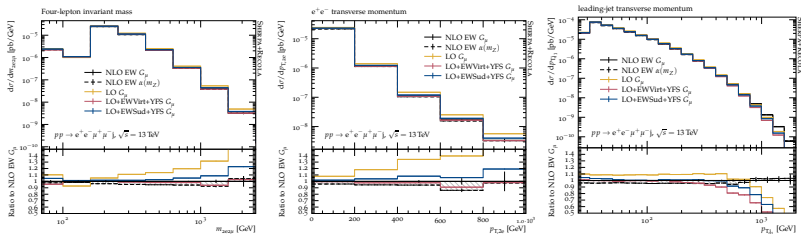
# EW virtual approximation in $4\ell$ production

Gütschow, MS '20



# EW virtual approximation in $4\ell + j$ production

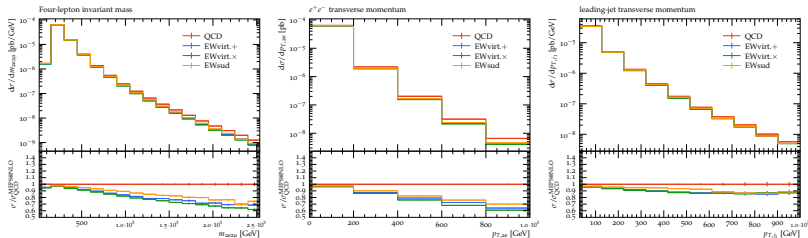
Bothmann, Napoletano, MS, Schumann, Villani to appear



- exact NLO EW also well reproduced in the presence of an add. jet
- exception: jet at large  $p_T$  dominated by  $qq \rightarrow 4\ell + qq @ \mathcal{O}(\alpha_s\alpha^5)$ , overwhelmed by NLO QCD in full calculation

$pp \rightarrow 4\ell + 0, 1j @ \text{NLO} + 2, 3j @ \text{LO}$ 

Bothmann, Napoletano, MS, Schumann, Villani to appear



- small differences between approximations

# 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 (and beyond)
  - ⇒ included since SHERPA-2.2.1  
(since SHERPA-2.2.9 both in add. and mult. scheme)
- default: QCD evolution via parton-shower  
QED correction through YFS  
EW corrections at fixed-order
- new results available with SHERPA-3.0  
(QED ISR through YFS, EW Sudakovs, hybrid schemes)

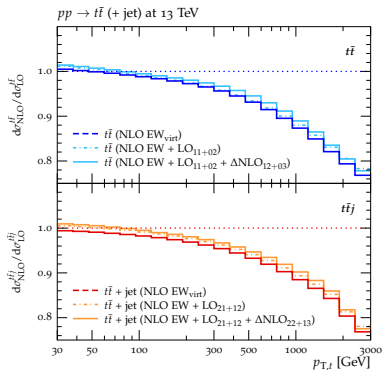
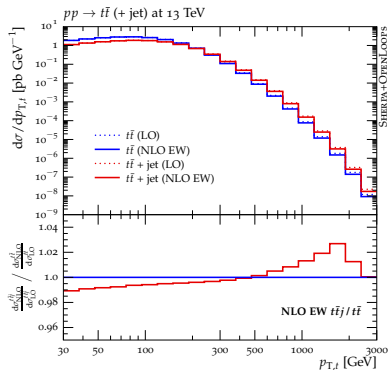
<http://sherpa.hepforge.org>

Thank you!

# Backup

# Top pair production in association with jets

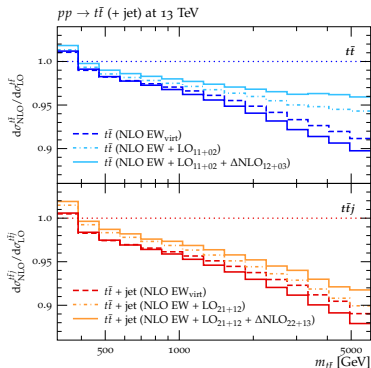
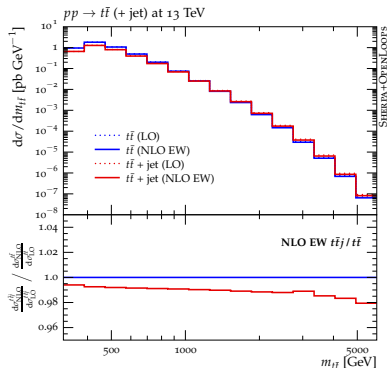
Gütschow, Lindert, MS in '18



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

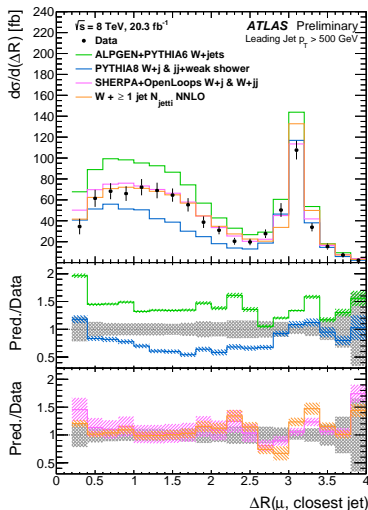
# Top pair production in association with jets

Gütschow, Lindert, MS in '18



Observation: subleading orders important

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



Measure coll. W em., simplified  
from [Krauss et.al. arXiv:1403.4788](#)

LHC@8TeV, central  $\mu$  and jet,  
 $p_{\perp}^{j_1} > 500 \text{ GeV}$  [ATLAS arXiv:1609.07045](#)

ALPGEN+PYTHIA

$pp \rightarrow W + \text{jets}$  MLM merged  
[Mangano et.al. hep-ph/0206293](#)

PYTHIA 8

$pp \rightarrow Wj + \text{QCD shower}$

$pp \rightarrow jj + \text{QCD+EW shower}$   
[Christiansen, Prestel arXiv:1510.01517](#)

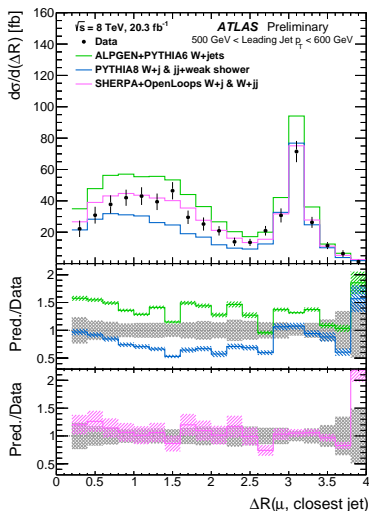
SHERPA+OPENLOOPS

NLO QCD+EW+subLO  
 $pp \rightarrow Wj/Wjj$  excl. sum  
[Kallweit, et.al. arXiv:1511.08692](#)

NNLO QCD  $pp \rightarrow Wj$

[Roughoul, Liu, Petriello arXiv:1602.06065](#)

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PYTHIA 8

$pp \rightarrow Wj + \text{QCD shower}$

$pp \rightarrow jj + \text{QCD+EW shower}$   
[Christiansen, Prestel arXiv:1510.01517](#)

SHERPA+OPENLOOPS

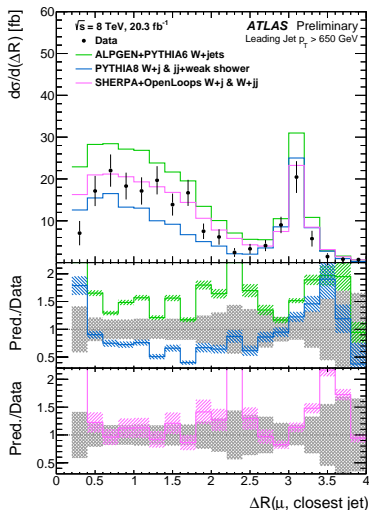
NLO QCD+EW+subLO

$pp \rightarrow Wj/Wjj$  excl. sum  
[Kallweit, et.al. arXiv:1511.08692](#)

NNLO QCD  $pp \rightarrow Wj$

[Roughoul, Liu, Petriello arXiv:1602.06065](#)

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



Measure coll. W em., simplified  
from [Krauss et.al. arXiv:1403.4788](#)

LHC@8TeV, central  $\mu$  and jet,  
 $p_{\perp}^{j_1} > 500$  GeV [ATLAS arXiv:1609.07045](#)

ALPGEN+PYTHIA

$pp \rightarrow W + \text{jets}$  MLM merged  
[Mangano et.al. hep-ph/0206293](#)

PYTHIA 8

$pp \rightarrow Wj + \text{QCD shower}$

$pp \rightarrow jj + \text{QCD+EW shower}$   
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SHERPA+OPENLOOPS

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[Bougheas, Liu, Petriello arXiv:1602.06065](#)