Diboson production including NLO QCD and electroweak corrections

Presenter:
Simon Luca Villani

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Online
Helmholtz Alliance Workshop

Overview

Corrections to $pp \to e^+e^-\mu^+\mu^- + jets$

- Approximated EW corrections (EWvirt, EWsud)
- Fixed-order EW NLO
- Multi-jet merged with EW corrections
  - Structural analysis
  - Phenomenological results

Contributors list:
Enrico Bothmann
Davide Napolitano
Marek Schrönherr
Steffen Schumann
SLV

GEORG-AUGUST-UNIVERSITÄT
GÖTTINGEN

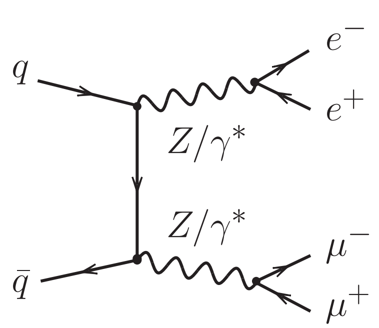
Approximated EW corrections - **EWvirt**

EW virtual corrections have Sudakov-like enhancement: $\frac{\alpha}{4\pi \sin^2\theta_W}\log^2\left(\frac{Q^2}{M_V^2}\right),\quad \frac{\alpha}{4\pi \sin^2\theta_W}\log\left(\frac{Q^2}{M_V^2}\right)$

Enhanced for high energies

$$\sigma^{NLO\ EW} = B(\Phi) + V(\Phi) + \int \mathrm{d}\Phi_1\, R(\Phi\cdot\Phi_1) \simeq B(\Phi) + V(\Phi) + I(\Phi)$$

B V I



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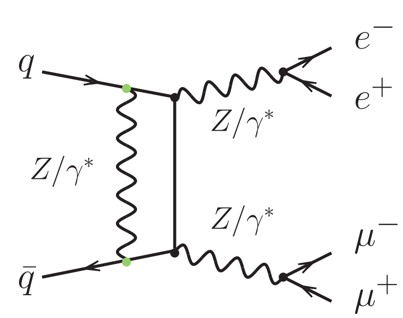
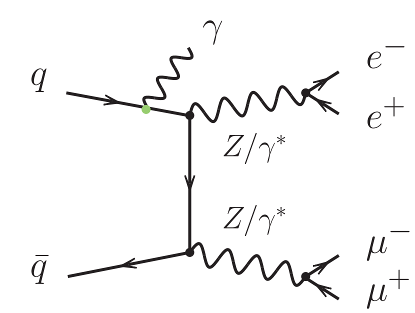


$+ \ldots + \int \mathrm{d}\Phi_1$



$+ \ldots$

soft-collinear approximation

S. Bräuer, et al. [arXiv:2005.12128 [hep-ph]]

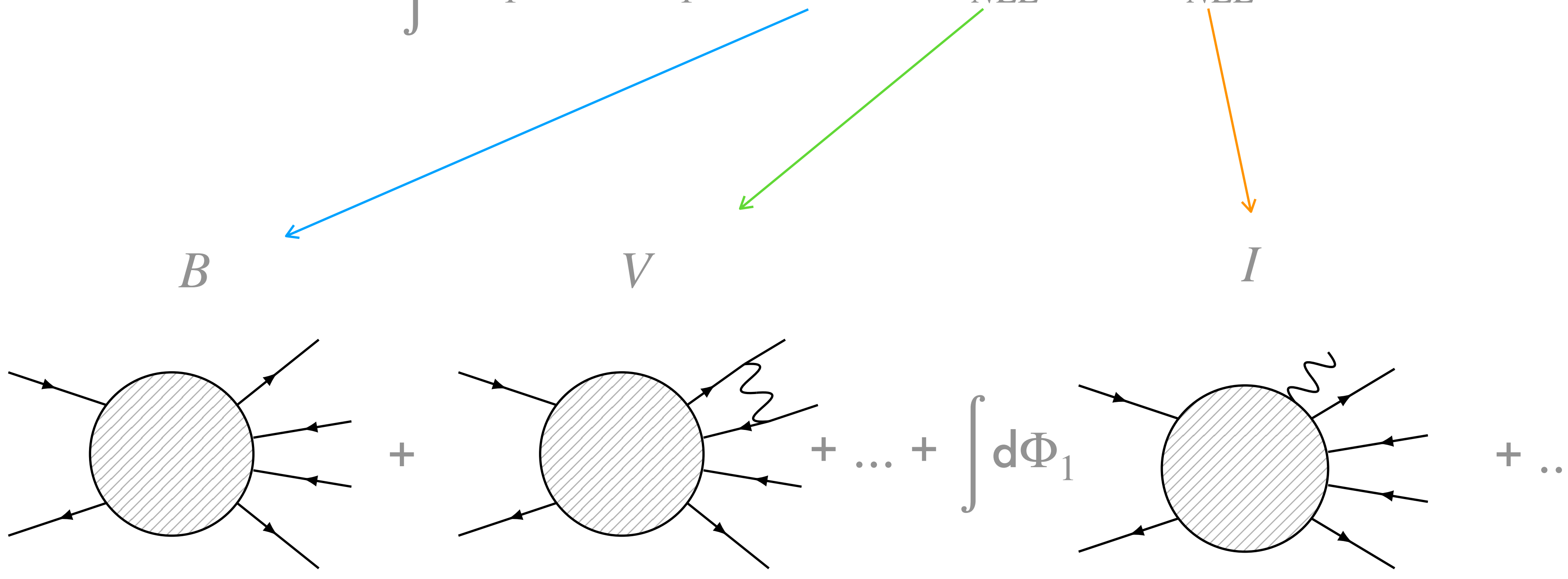
- Has all the EW NLL of the high energy limit
- Important finite corrections
- Non-trivial EW scheme dependence
- Needs actual virtual ME, i.e. costly for high multiplicity

Approximated EW corrections - **EWsud**

EW virtual corrections have Sudakov-like enhancement: $\frac{\alpha}{4\pi \sin^2\theta_W}\log^2\left(\frac{Q^2}{M_V^2}\right), \quad \frac{\alpha}{4\pi \sin^2\theta_W}\log\left(\frac{Q^2}{M_V^2}\right)$

Enhanced for high energies

$$\sigma^{NLO\ EW} = B(\Phi) + V(\Phi) + \int d\Phi_1\, R(\Phi\cdot\Phi_1) \simeq B(\Phi) + V_{NLL}(\Phi) + I_{NLL}(\Phi)$$



soft-collinear approximation | soft-collinear approximation

E. Bothmann, D. Napolitano [arXiv:2006.14635 [hep-ph]]

- Has all the EW NLL of the high energy limit
- Sudakov logs can be factorized and then exponentiated
- Applicable to any final state multiplicity
- Lacking of non-trivial scheme dependence and finite terms

Fixed-order EW NLO

Generators/Tools
Sherpa + OpenLoops/Recola

ZZ

$pp \to e^+e^-\mu^+\mu^-$		fiducial cross section	corrections to LO				
Scheme	Region	LO	NLO EW	LO+EW$_{\text{virt}}$+YFS	LO+EW$_{\text{sud}}$+YFS	LO+EW$^{\text{exp}}_{\text{sud}}$+YFS	NLO EW + NLL EW$^{\text{exp}}_{\text{sud}}$
G_μ	inclusive	**9.8189(2) fb**	−6.8 %	−7.9 %	−7.3 %	−7.2 %	−6.7 %
$\alpha(M_Z^2)$		10.928 fb	−19.4 %	−20.2 %	−7.7 %	−7.6 %	−19.3 %
$\delta_{G_\mu}^{\alpha(M_Z^2)}$		11.3 %	−3.8 %	−3.6 %	10.8 %	10.8 %	−3.7 %
G_μ	high energy	**$4.27 \cdot 10^{-3}$ fb**	−42 %	−45 %	−39 %	−33 %	−36 %

ZZ+1jet

$pp \to e^+e^-\mu^+\mu^- j$		fiducial cross section	corrections to LO				
Scheme	Region	LO	NLO EW	LO + EW$_{\text{virt}}$ + YFS	LO + EW$_{\text{sud}}$ + YFS	LO + EW$^{\text{exp}}_{\text{sud}}$ + YFS	NLO EW + NLL EW$^{\text{exp}}_{\text{sud}}$
G_μ	inclusive	**5.1698(1) fb**	−6.6 %	−8 %	−6.9 %	−6.7 %	−6.4 %
$\alpha(M_Z^2)$		5.754 fb	−19.2 %	−21 %	−6.9 %	−6.7 %	−19.0 %
$\delta_{G_\mu}^{\alpha(M_Z^2)}$		11.29 %	−3.7 %	−3 %	11.3 %	11.3 %	−3.7 %
G_μ	high energy	**$6.64 \cdot 10^{-3}$ fb**	−33 %	−37 %	−30 %	−25 %	−29 %

Fiducial cuts

$p_{T,l} > 20$ GeV	$p_{T,j} > 30$ GeV
$\lvert y_l \rvert < 2.5$	$\lvert y_j \rvert < 4.5$
$\Delta R_{ll'} > 0.1$	$\Delta R_{lj} > 0.4$

Preliminary

Fixed-order EW NLO - Scheme variation

Generators/Tools
Sherpa + OpenLoops/Recola

ZZ

$pp \to e^+e^-\mu^+\mu^-$		fiducial cross section	corrections to LO				
Scheme	Region	LO	NLO EW	LO+EW$_{\text{virt}}$+YFS	LO+EW$_{\text{sud}}$+YFS	LO+EW$_{\text{sud}}^{\text{exp}}$+YFS	NLO EW + NLL EW$_{\text{sud}}^{\text{exp}}$
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ZZ+1jet

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G_μ	high energy	**$6.64 \cdot 10^{-3}$ fb**	−33 %	−37 %	−30 %	−25 %	−29 %

EWvirt captures very well the scheme dependence

EWsud has a LO-like scheme dependence → worse agreement

Fiducial cuts

$p_{T,l} > 20$ GeV	$p_{T,j} > 30$ GeV
$\lvert y_l \rvert < 2.5$	$\lvert y_j \rvert < 4.5$
$\Delta R_{ll'} > 0.1$	$\Delta R_{lj} > 0.4$

Preliminary

Fixed-order EW NLO - Correction impact

Generators/Tools
Sherpa + OpenLoops/Recola

ZZ

$pp \to e^+e^-\mu^+\mu^-$		fiducial cross section	corrections to LO				
Scheme	Region	LO	NLO EW	LO+EW$_{\text{virt}}$+YFS	LO+EW$_{\text{sud}}$+YFS	LO+EW$_{\text{sud}}^{\text{exp}}$+YFS	NLO EW + NLL EW$_{\text{sud}}^{\text{exp}}$
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ZZ+1jet

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EWvirt captures very well the scheme dependence

EWsud has a LO-like scheme dependence → worse agreement

G_μ is a more adequate scheme for this study

All the approximations reproduce quite well the NLO EW result

Magnitude EW corrections similar between 0 and 1 jet → extra jet doesn't affect charge distribution

Fiducial cuts

$p_{\mathrm{T},l} > 20\,\mathrm{GeV}$ $\quad p_{\mathrm{T},j} > 30\,\mathrm{GeV}$

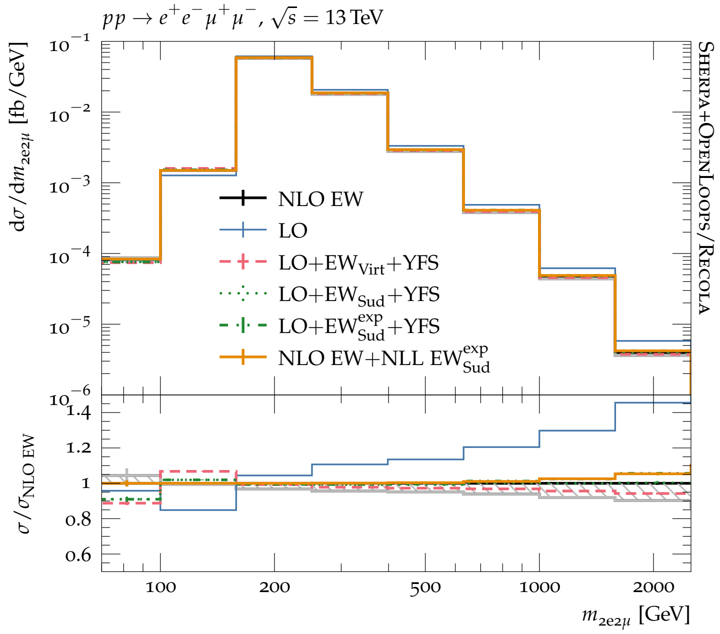
$|y_l| < 2.5$ $\quad |y_j| < 4.5$

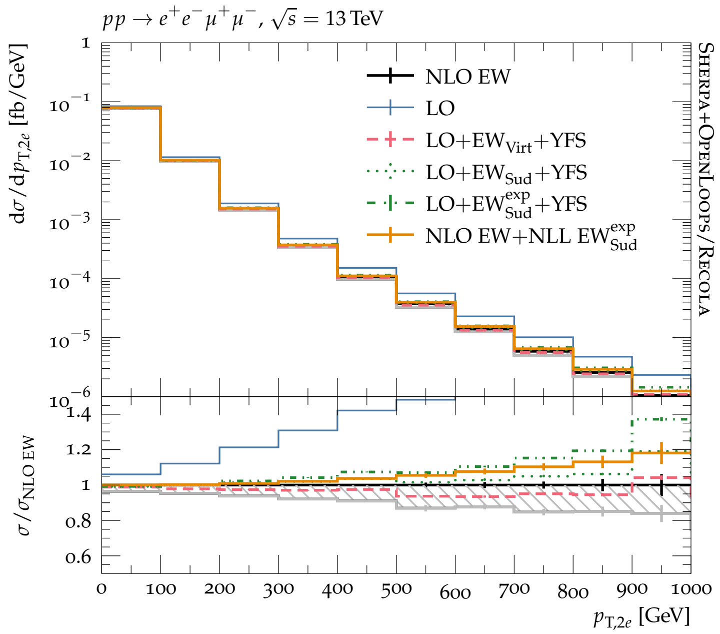
$\Delta R_{ll'} > 0.1$ $\quad \Delta R_{lj} > 0.4$

Preliminary

Fixed-order EW NLO - Differential XS

ZZ





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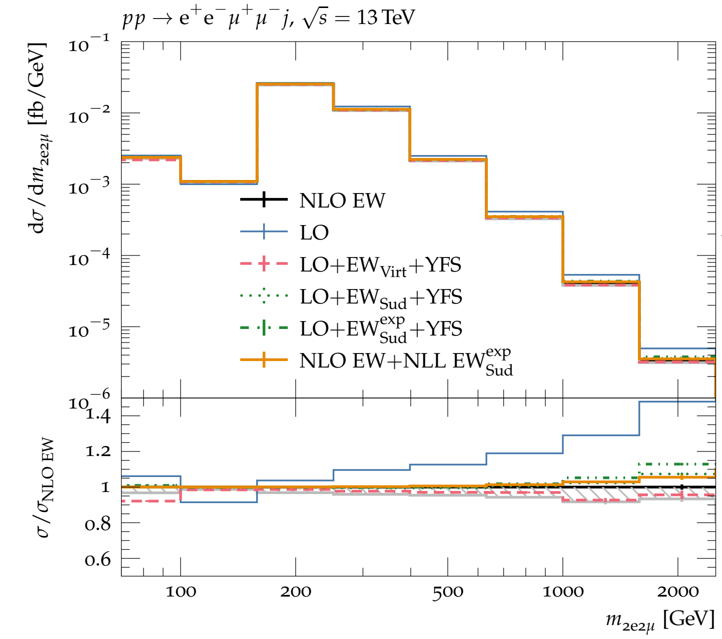
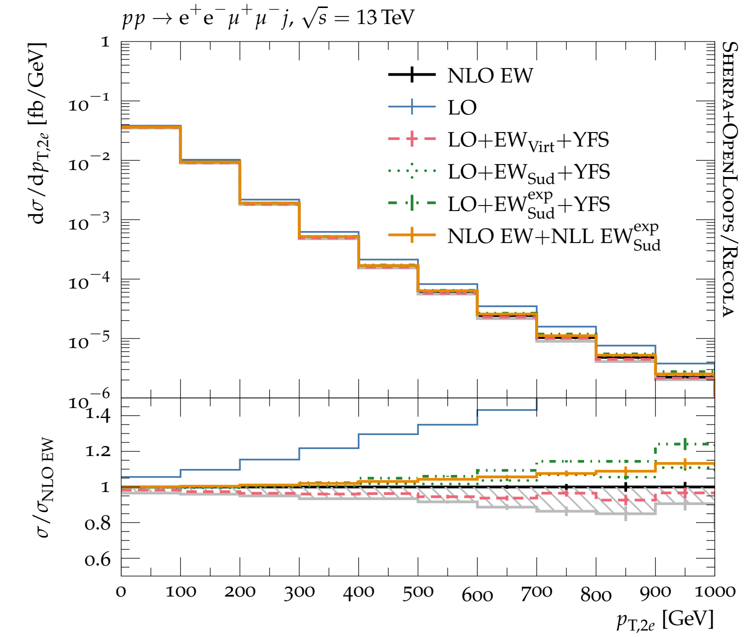




- The effect of the EW logs are more visible in energy scaling observables
- Similar correction between 0 and 1 jet
- Large impact of Sud. logs resummation in high energy region
- EW$_{\rm sud}$ has harder spectrum

	Scheme	Region	LO	NLO EW	LO+EW$_{\rm virt}$+YFS	LO+EW$_{\rm sud}$+YFS	LO+EW$^{\rm exp}_{\rm sud}$+YFS	NLO EW + NLL EW$^{\rm exp}_{\rm sud}$
0 jet	G_μ	high energy	**$4.27 \cdot 10^{-3}$ fb**	$-42\,\%$	$-45\,\%$	$-39\,\%$	$-33\,\%$	$-37\,\%$
1 jet	G_μ	high energy	**$6.64 \cdot 10^{-3}$ fb**	$-33\,\%$	$-37\,\%$	$-30\,\%$	$-25\,\%$	$-29\,\%$

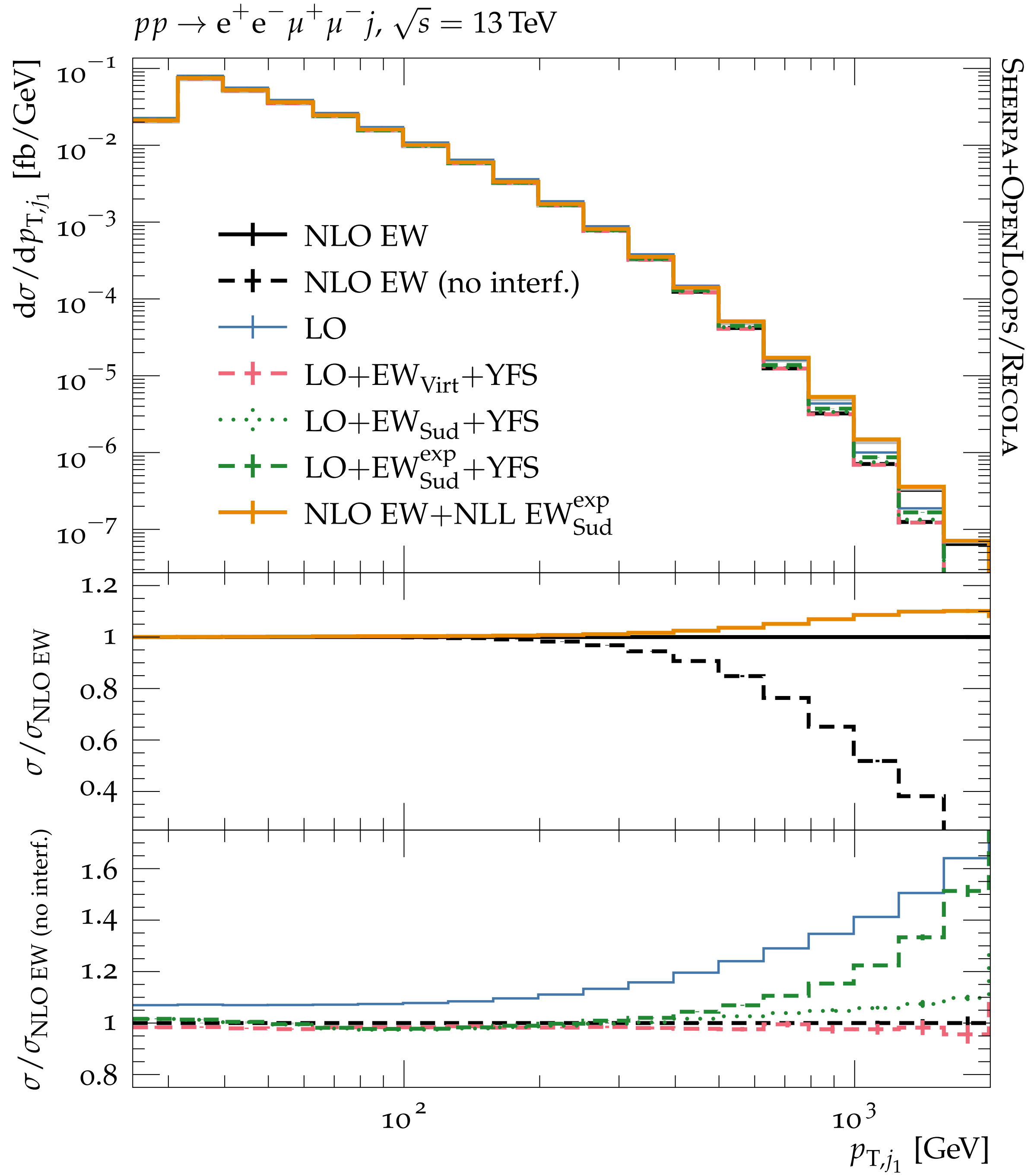
High energy cut: $p_{T,2e} > 600$ GeV

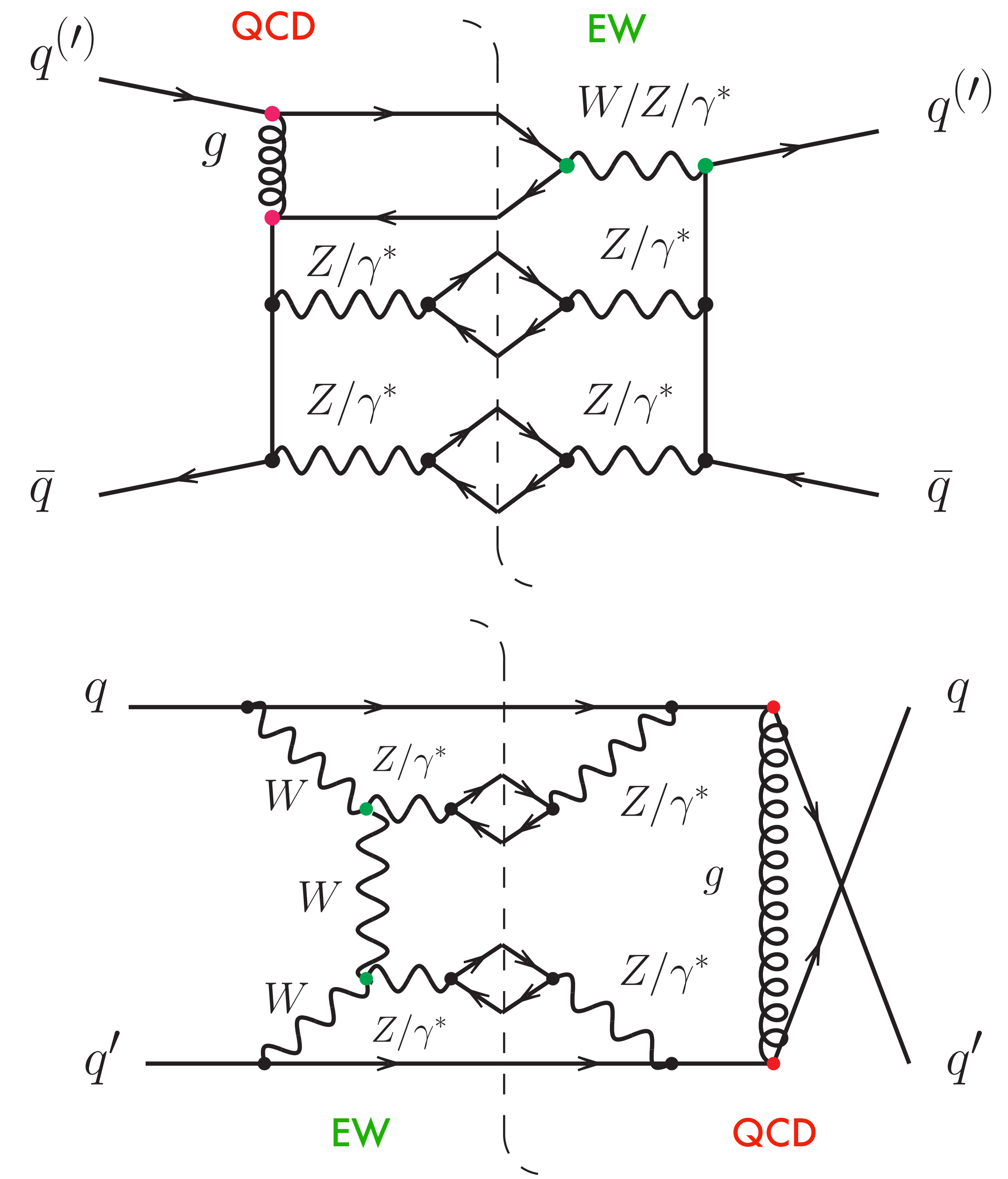
Preliminary

Fixed-order EW NLO - Differential XS

ZZ+1jet

Finite real contribution





Adding a jet veto to reduce the activity of this 4 quarks process would allow the approximations to be even closer to the fixed order

S. Bräuer, et al. [arXiv:2005.12128 [hep-ph]]

Preliminary

Multi-jet merged - Structural analysis

How are the EW approximations taken into account ?

Example case **MEPS@NLO**:

$\bar{B} = B + V + I$ — Real subtracted

$$d\sigma_n^{MEPS@NLO} = d\Phi_n \bar{B}_n\left(\Phi_n\right) \Theta_n(Q_c)\, \bar{F}_n\left(\mu_Q^2; Q_c\right) + d\Phi_{n+1} H_n\left(\Phi_{n+1}\right) \Theta_n(Q_c)\, \Theta\left(Q_c - Q_{n+1}\right) F_{n+1}\left(\mu_Q^2; Q_c\right)$$

$$\bar{B}_n \to \bar{B}_n\left(1 + \delta_{n,\mathbb{S}}^{EW}\right) \qquad H_n \to H_n\left(1 + \delta_{n,\mathbb{H}}^{EW}\right)$$

$$\delta_n^{EW} = \frac{V_n + I_n}{B_n}$$ Multiplicative

$$\delta_n^{EW} = \frac{V_n + I_n}{\bar{B}_n}$$ Additive

EWvirt is applied only to $\delta_{n,\mathbb{S}}^{EW}$, i.e. to lower multiplicity configurations → practical/technical choice

S. Bräuer, et al. [arXiv:2005.12128 [hep-ph]]

For this reason we need to check what is the impact of the $\mathbb{H}$ events

Actually EWvirt is applied also to higher multiplicity LO events through a k-factor strategy… see back-up slides

EWsud is applied to $\delta_{n,\mathbb{S}}^{EW}$, $\delta_{n,\mathbb{H}}^{EW}$, $\delta_{n,B}^{EW}$, where $\delta_{n,B}^{EW}$ is applied to LO events

EWsud exponentiated applied similarly: $1 + \delta_n^{EW} \to \exp\left(\delta_n^{EW}\right)$

Multi-jet merged - Structural analysis

How are the EW approximations taken into account ?

Example case **MEPS@NLO**:

$\bar{B} = B + V + I$ — Real subtracted

$$d\sigma_n^{MEPS@NLO} = d\Phi_n \bar{B}_n\left(\Phi_n\right) \Theta_n(Q_c)\, \bar{F}_n\left(\mu_Q^2; Q_c\right) + d\Phi_{n+1} H_n\left(\Phi_{n+1}\right) \Theta_n(Q_c) \Theta\left(Q_c - Q_{n+1}\right) F_{n+1}\left(\mu_Q^2; Q_c\right)$$

$$\bar{B}_n \to \bar{B}_n\left(1 + \delta_{n,\mathbb{S}}^{EW}\right) \qquad H_n \to H_n\left(1 + \delta_{n,\mathbb{H}}^{EW}\right)$$

$$\delta_n^{EW} = \frac{V_n + I_n}{B_n} \quad \text{Multiplicative}$$

$$\delta_n^{EW} = \frac{V_n + I_n}{\bar{B}_n} \quad \text{Additive}$$

Expected to be small due to p.s. constraints

EWvirt is applied only to $\delta_{n,\mathbb{S}}^{EW}$, i.e. to lower multiplicity configurations → practical/technical choice

S. Bräuer, et al. [arXiv:2005.12128 [hep-ph]]

For this reason we need to check what is the impact of the $\mathbb{H}$ events

Actually EWvirt is applied also to higher multiplicity LO events through a k-factor strategy... see back-up slides

EWsud is applied to $\delta_{n,\mathbb{S}}^{EW}$, $\delta_{n,\mathbb{H}}^{EW}$, $\delta_{n,B}^{EW}$, where $\delta_{n,B}^{EW}$ is applied to LO events

EWsud exponentiated applied similarly: $1 + \delta_n^{EW} \to \exp\left(\delta_n^{EW}\right)$

Multi-jet merged

Generators/Tools
Sherpa + OpenLoops/Recola

$pp \to e^+e^-\mu^+\mu^-$	NLO
$pp \to e^+e^-\mu^+\mu^- j$	NLO
$pp \to e^+e^-\mu^+\mu^- jj$	LO
$pp \to e^+e^-\mu^+\mu^- jjj$	LO

Merge cut of $Q_c = 30$ GeV

$pp \to e^+e^-\mu^+\mu^-$	LI
$pp \to e^+e^-\mu^+\mu^- j$	LI

Fiducial cuts

$p_{\mathrm{T},l} > 20$ GeV	$p_{\mathrm{T},j} > 30$ GeV
$\lvert y_l \rvert < 2.5$	$\lvert y_j \rvert < 4.5$
$\Delta R_{ll'} > 0.1$	$\Delta R_{lj} > 0.4$

	$pp \to e^+e^-\mu^+\mu^-$ + jets fiducial cross section [fb]		corrections to MePs@Nlo		
Scheme	MePs@Lo	MePs@Nlo	$\times\mathrm{EW}_{\mathrm{virt}}$+YFS	$\times\mathrm{EW}_{\mathrm{sud}}$+YFS	$\times\mathrm{EW}^{\mathrm{exp}}_{\mathrm{sud}}$+YFS
G_μ	11.101(13)	**13.342(7)**	−4 %	−4 %	−3 %
ZZ fixed-order case:			– 7.9%	– 7.3%	– 7.2%

Ratio taken with respect of the fixed order LO for which YFS was not enabled. It alone would bring a 4% correction making up for the difference

Preliminary

Multi-jet merged - Invariant mass

Generators/Tools
Sherpa + OpenLoops/Recola

$pp \to e^+e^-\mu^+\mu^-$ $pp \to e^+e^-\mu^+\mu^- j$	NLO
$pp \to e^+e^-\mu^+\mu^- jj$ $pp \to e^+e^-\mu^+\mu^- jjj$	LO

Merge cut of $Q_c = 30$ GeV

$pp \to e^+e^-\mu^+\mu^-$ $pp \to e^+e^-\mu^+\mu^- j$	LI

Fiducial cuts

$p_{T,l} > 20$ GeV $p_{T,j} > 30$ GeV

$|y_l| < 2.5$ $|y_j| < 4.5$

$\Delta R_{ll'} > 0.1$ $\Delta R_{lj} > 0.4$

	$pp \to e^+e^-\mu^+\mu^- +$ jets fiducial cross section [fb]		corrections to MEPS@NLO		
Scheme	MEPS@LO	MEPS@NLO	$\times$EW$_{\text{virt}}$+YFS	$\times$EW$_{\text{sud}}$+YFS	$\times$EW$^{\text{exp}}_{\text{sud}}$+YFS
G_μ	11.101(13)	**13.342(7)**	$-4\,\%$	$-4\,\%$	$-3\,\%$
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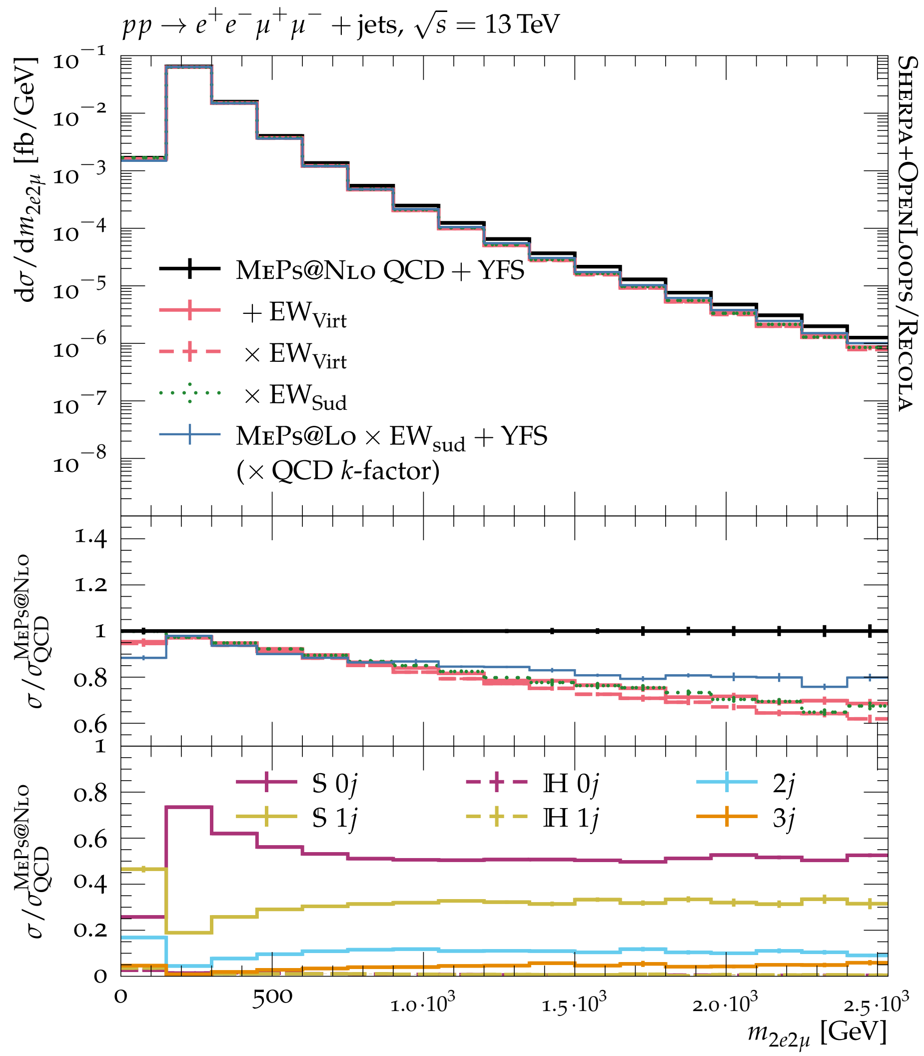
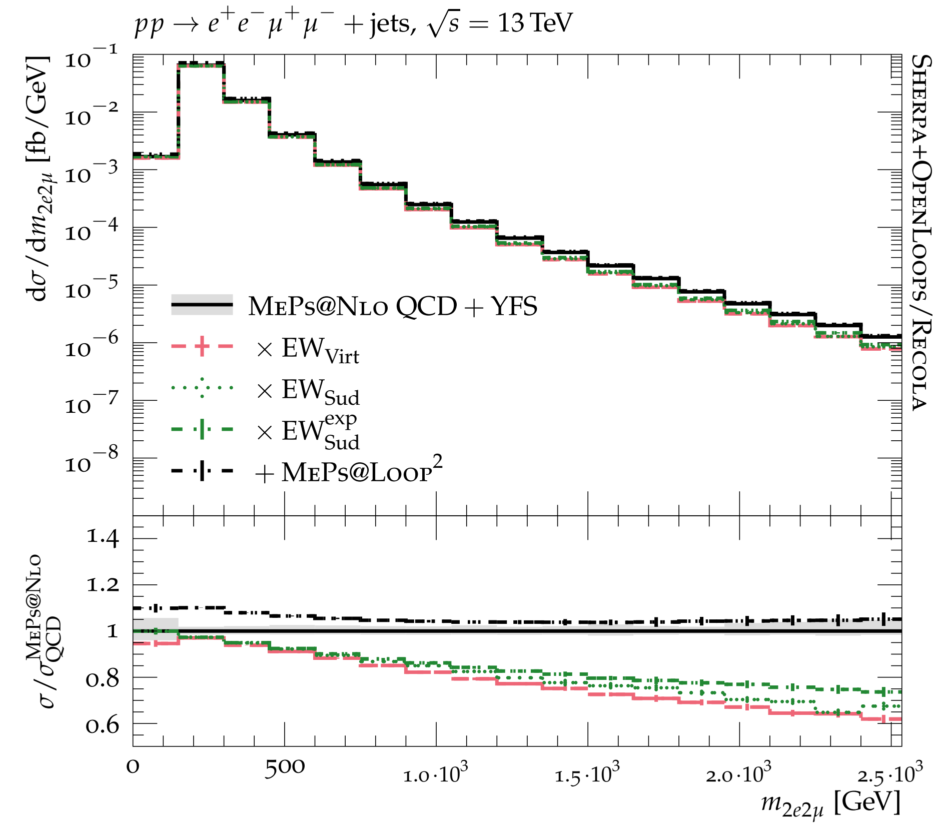
Structure of MEPS@NLO



Pheno



Preliminary

Multi-jet merged - 4-lepton transverse momentum

Generators/Tools
Sherpa + OpenLoops/Recola

	$pp \to e^+e^-\mu^+\mu^-$ + jets fiducial cross section [fb]		corrections to MEPS@NLO		
Scheme	MEPS@LO	MEPS@NLO	$\times \mathrm{EW_{virt}}$+YFS	$\times \mathrm{EW_{sud}}$+YFS	$\times \mathrm{EW^{exp}_{sud}}$+YFS
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NLO

$pp \to e^+e^-\mu^+\mu^- jj$
$pp \to e^+e^-\mu^+\mu^- jjj$
LO

Merge cut of $Q_c = 30$ GeV

$pp \to e^+e^-\mu^+\mu^-$
$pp \to e^+e^-\mu^+\mu^- j$
LI

Fiducial cuts

$p_{T,l} > 20$ GeV $p_{T,j} > 30$ GeV
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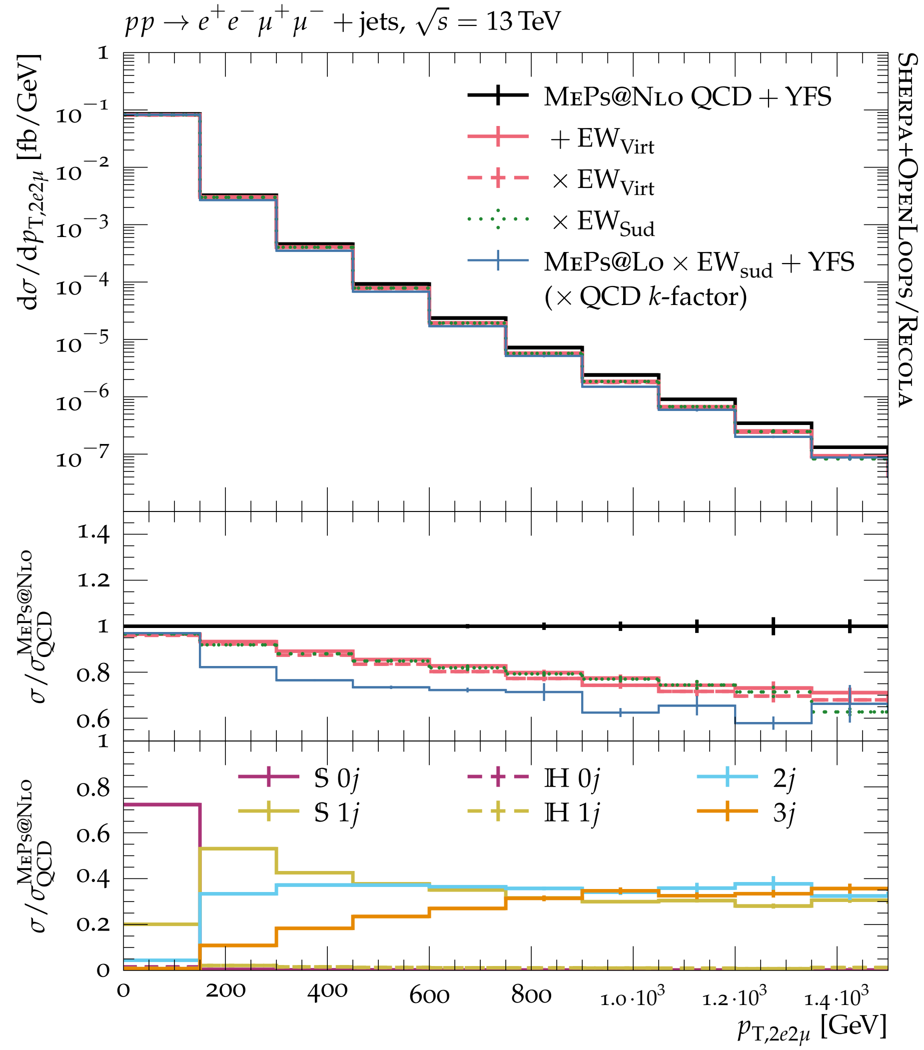
Structure of MEPS@NLO



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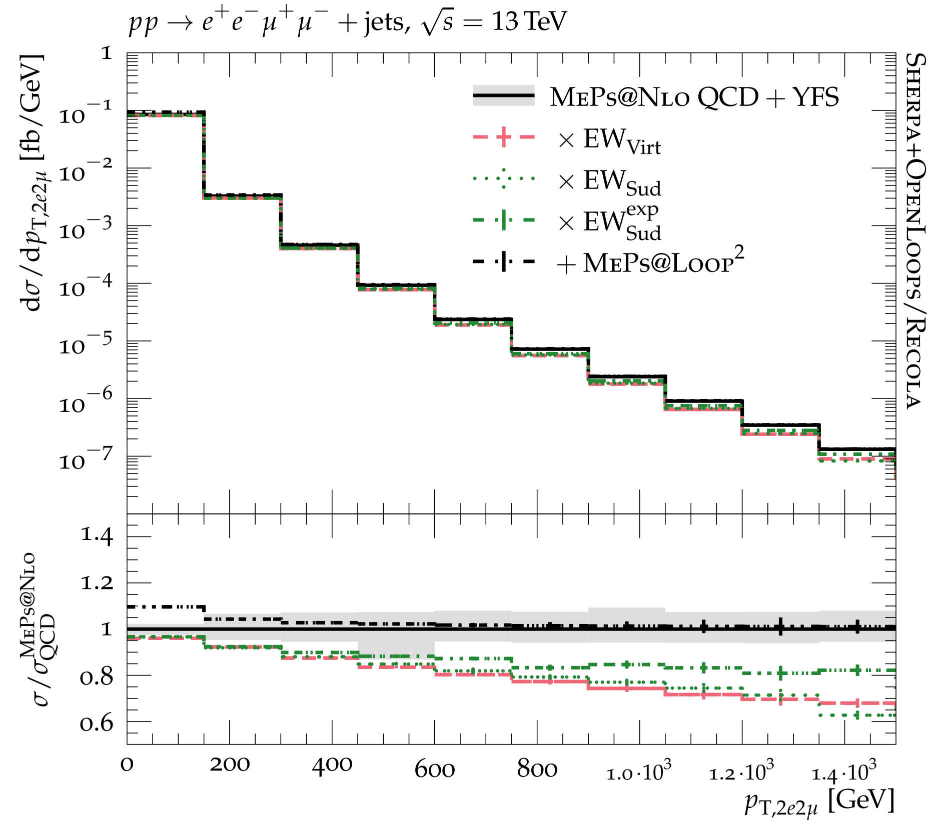

Preliminary

Multi-jet merged - Jet’s number

Generators/Tools
Sherpa + OpenLoops/Recola

	$pp \to e^+e^-\mu^+\mu^-$ + jets fiducial cross section [fb]		corrections to MEPS@NLO		
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$pp \to e^+e^-\mu^+\mu^-$
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$pp \to e^+e^-\mu^+\mu^- jj$
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Merge cut of $Q_c = 30$ GeV

$pp \to e^+e^-\mu^+\mu^-$
$pp \to e^+e^-\mu^+\mu^- j$ — LI

Fiducial cuts

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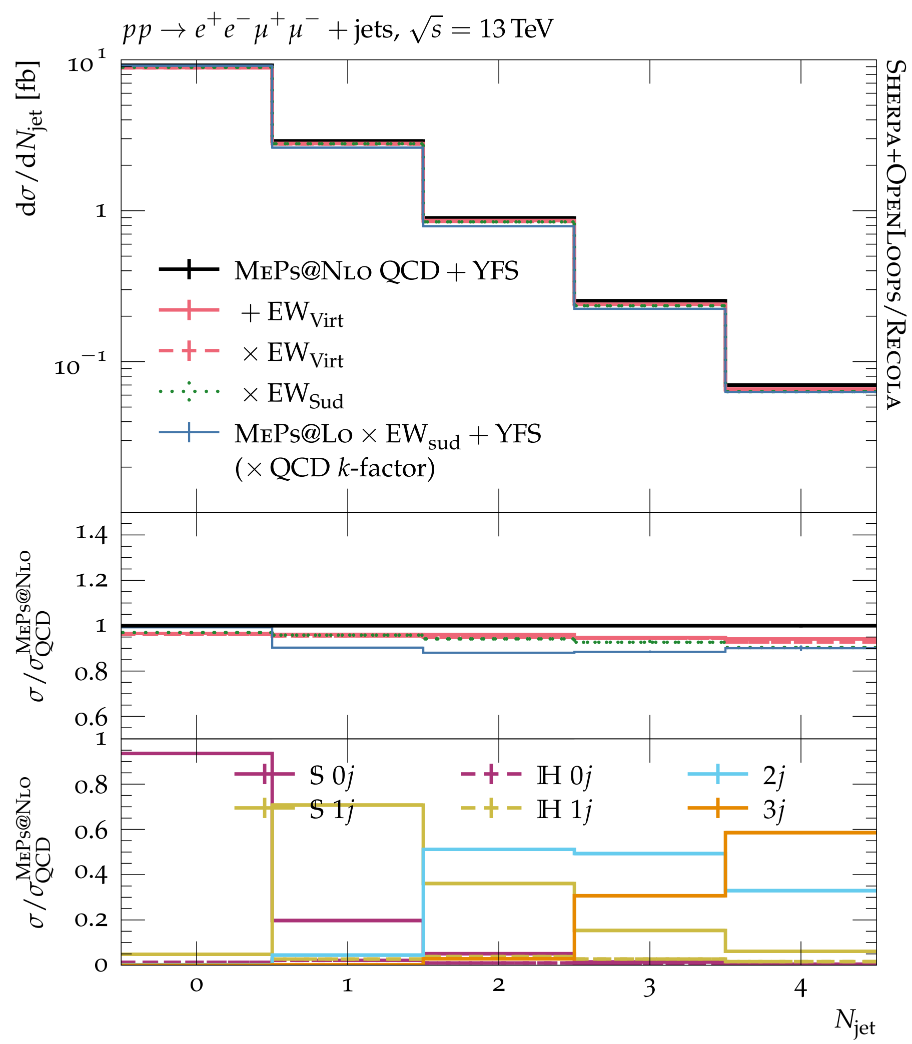
Structure of MEPS@NLO



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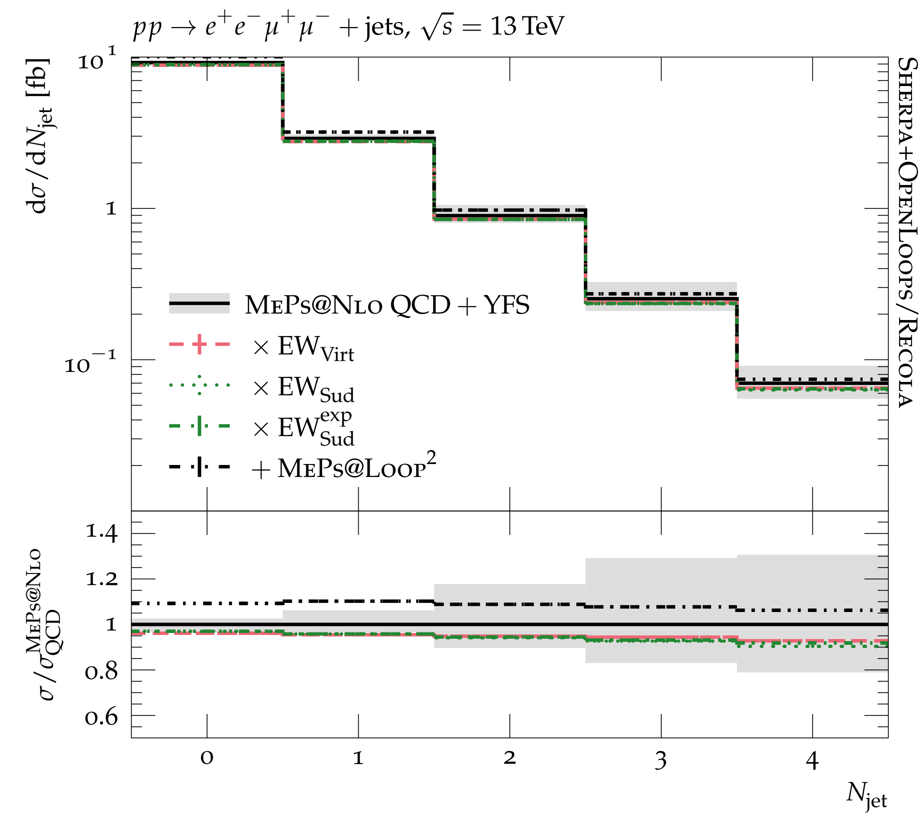

Preliminary

Conclusions

Fixed order

- EW corrections for $e^+e^-\mu^+\mu^-$ production at high energy is dominated by Sudakov logs, well visible in differential and total XS
- EWvirt and EWsud can replicate very well the NLO result
- We have studied for the first time the NLO EW for $e^+e^-\mu^+\mu^-j$ showing that the addition of extra QCD radiation does not affect the EW charge distribution
- Possibility to match the resummed Sudakov logarithms to the fixed order calculation.
  Effect $\rightarrow$ harder spectrum

Phenomenological study

- Shown how to implement EW corrections in a general simulation (MEPS@NLO)
- Structural analysis of the samples have shown that the way the EWvirt is applied is not spoiled by H-events
- Also in this setup the EW corrections are very sizeable for observable with an energy scaling
- Resummation of Sudakov logarithms
- Loop induced corrections up to 1 jet do not affect the magnitude of the EW corrections
- EW corrections largely exceeds theoretical uncertainty $\rightarrow$ they need to be taken into account in a general simulation

Thanks for the attention

Back up - Scale-less observable

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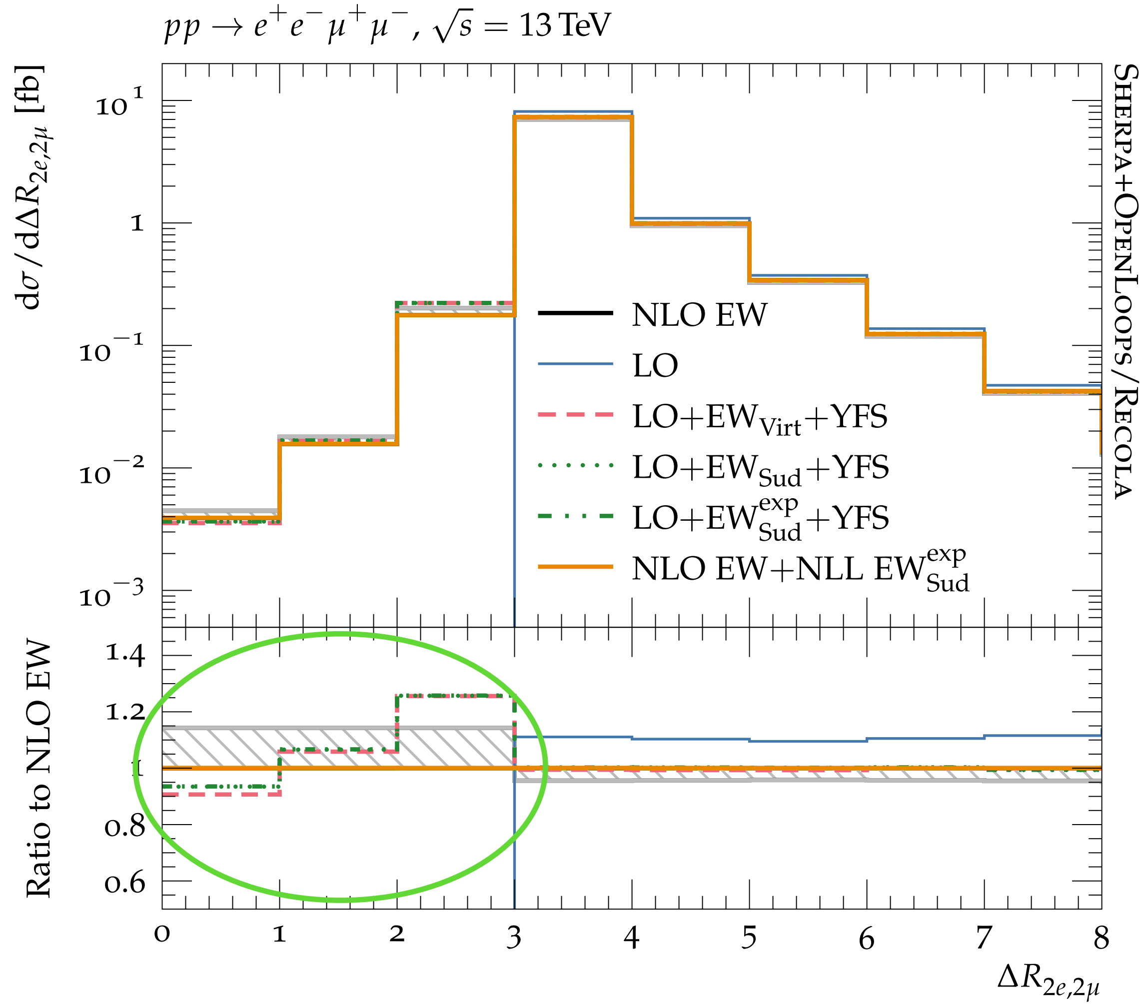
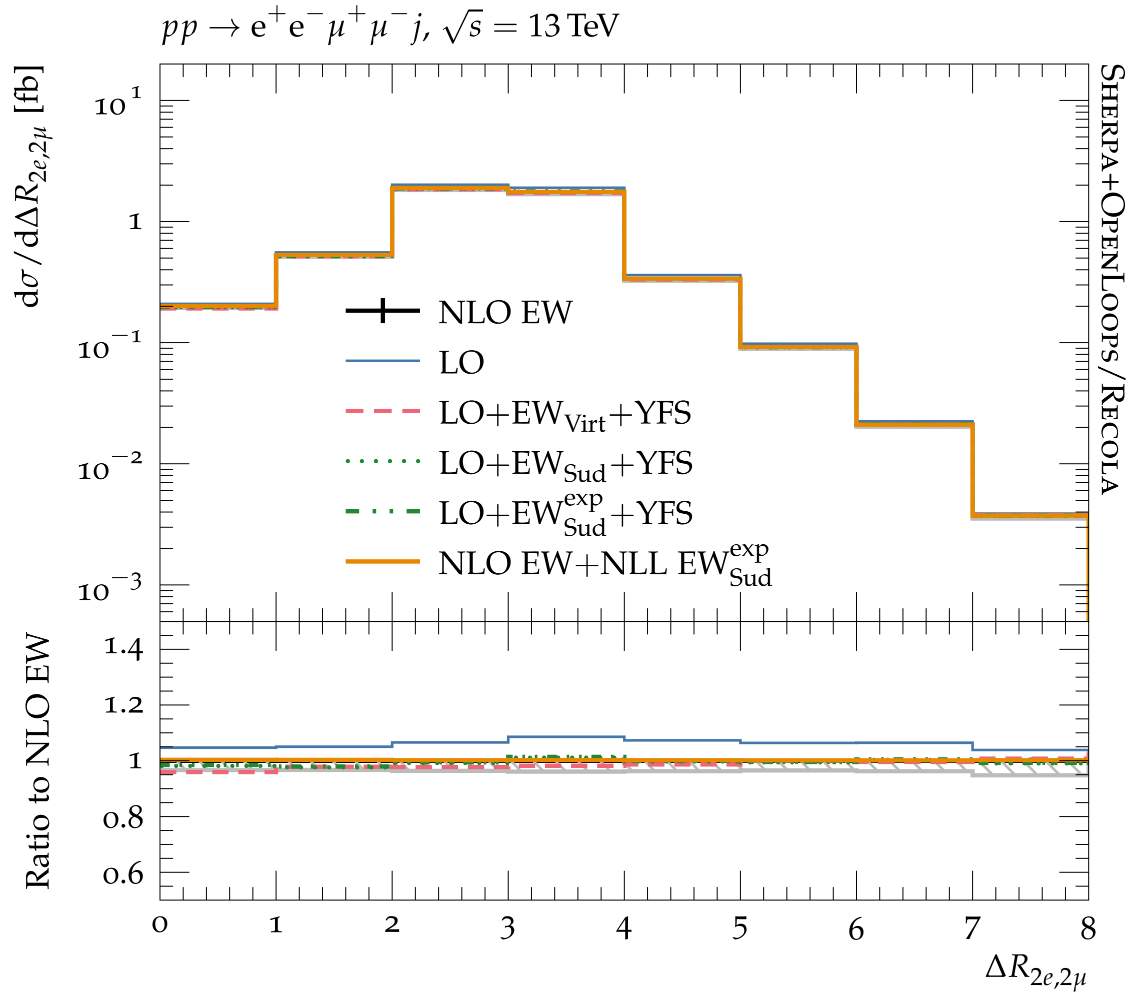


YFS captures rather well the real emission correction

ZZ+1jet



The entire region is already populated at LO

Preliminary

MEPS k-factor

$$\mathrm{d}\sigma^{\text{excl,}\textsc{MePs@Nlo}}_{n>n^{\text{NLO}}_{\text{max}}} = \mathrm{d}\Phi_n \boxed{k_{n^{\text{NLO}}_{\text{max}}}\left(\Phi_{n^{\text{NLO}}_{\text{max}}}\left(\Phi_n\right), \Phi_{n^{\text{NLO}}_{\text{max}}+1}\left(\Phi_n\right)\right)} \; \mathrm{B}_n\left(\Phi_n\right) \; \Theta_n(Q_{\text{cut}}) \, \mathcal{F}_n\left(\mu_Q^2; Q_{\text{cut}}\right)$$

$$k_m\left(\Phi_m, \Phi_{m+1}\right) = \frac{\boxed{\overline{\mathrm{B}}_m\left(\Phi_m\right)}}{\mathrm{B}_m\left(\Phi_m\right)}\left(1 - \frac{\mathrm{H}_m\left(\Phi_{m+1}\right)}{\mathrm{B}_{m+1}\left(\Phi_{m+1}\right)}\right) + \frac{\mathrm{H}_m\left(\Phi_{m+1}\right)}{\mathrm{B}_{m+1}\left(\Phi_{m+1}\right)}$$

Improved resummation by EWvirt

$$k^{\text{EW}}_{\text{matched},n}\left(\Phi_n, \Phi_{n+1}\right) = \frac{\overline{\mathrm{B}}_n\left(\Phi_n\right)\left[\exp\left(\delta^{\text{EW}}_{\text{sud},n}(\Phi_n)\right) - \delta^{\text{EW}}_{\text{sud},n}(\Phi_n) + \delta^{\text{EW}}_{\text{virt},n,\mathbb{S}}(\Phi_n)\right]}{\mathrm{B}_n\left(\Phi_n\right)\exp\left(\delta^{\text{EW}}_{\text{sud},n}(\Phi_n)\right)}\left(1 - \frac{\mathrm{H}_n\left(\Phi_{n+1}\right)}{\mathrm{B}_{n+1}\left(\Phi_{n+1}\right)}\right) + \frac{\mathrm{H}_n\left(\Phi_{n+1}\right)}{\mathrm{B}_{n+1}\left(\Phi_{n+1}\right)}$$

Matching Sud. logs resummation to NLO EW

Fixed order

$$\mathrm{d}\sigma^{\mathrm{NLO\ EW\ +\ NLL\ Sud}} = \mathrm{d}\Phi\ \mathrm{B}(\Phi)\ \left[\exp\left(\delta^{\mathrm{EW}}_{\mathrm{sud}}(\Phi)\right) - \delta^{\mathrm{EW}}_{\mathrm{sud}}(\Phi) + \delta^{\mathrm{EW}}(\Phi)\right]$$

Multi-jet merged

$$\overline{\mathrm{B}}_n \to \overline{\mathrm{B}}_n\ \left[\exp\left(\delta^{\mathrm{EW}}_{\mathrm{sud},n,\mathbb{S}}\right) - \delta^{\mathrm{EW}}_{\mathrm{sud},n,\mathbb{S}} + \delta^{\mathrm{EW}}_{\mathrm{virt},n,\mathbb{S}}\right] \quad \text{and} \quad \mathrm{H}_n \to \mathrm{H}_n\ \exp\left(\delta^{\mathrm{EW}}_{\mathrm{sud},n,\mathbb{H}}\right)$$

YFS

$$\mathrm{d}\Gamma^{\mathrm{YFS}} = \mathrm{d}\Gamma_0 \cdot e^{\alpha Y(\omega_{\mathrm{cut}})} \cdot \sum_{n_\gamma} \frac{1}{n_\gamma!} \left[\prod_{i=1}^{n_\gamma} \mathrm{d}\Phi_{k_i} \cdot \alpha\, \tilde{S}(k_i)\, \Theta(k_i^0 - \omega_{\mathrm{cut}}) \right] \cdot \mathcal{C}$$