Global status of EW precision calculations

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Disclaimer: I will not review recent EW calculations so much.

Selected topical results highlighted in talks by A. Freytas, A. Vicini, C. Schwan, M. Bonetti, and M. Pellen.

Focus on the **global view** in this talk.
Address a few common open issues and questions.

Overview

Global status

1. Global status
2. Scheme uncertainties
3. Observable and object definition
4. Conclusions

Recent advances

NLO EW corrections are fully automated

- Monte-Carlo frameworks (Born and real emission matrix elements, infrared subtraction, phase space generation, process coordination)
  - SHERPA — MS '17
  - MADGRAPH — Frederix et.al. '18
- virtual corrections (EW one-loop matrix elements, renormalisation)
  - MADLOOP — Frixione et.al. '14
  - OPENLOOPS — Kallweit et.al. '14
  - RECOLA — Actis et.al. '12
- a number of dedicated calculations and private codes

NNLO QCD-EW mixed corrections available for $q\bar{q} \to \ell^+\ell^-$, $gg \to h(j)$

see talks by A. Vicini, M. Bonetti

NLO EW off-shell triboson production

Besides off-shell top-pair production, VBS and VVV are technically most challenging due to complexity of the phase space and number of contributing channels/diagrams. see talk by M. Pellen

VVV **off-shell NLO EW** corrections among the most involved involved, up to $2 \to 6$ (like VBS, just with more and competing resonances)

- $pp \to \gamma\gamma\gamma$ — Greiner, MS '17
- $pp \to \gamma\gamma\ell\nu\,/\,\gamma\gamma\ell\ell$ — Greiner, MS '17
- $pp \to \gamma 2\ell 2\nu$ ($\ell = e^\pm, \mu^\pm$, 0,1 SFOS channels, incl. γWW and γZZ topologies) — Ju, Lindert, MS in prep.
- $pp \to 3\ell 3\nu$ ($\ell = e^\pm, \mu^\pm$, 0/1/2 SFOS channels, incl. WWW and WZZ topologies) — MS '18

$pp \to e^\mp \nu_e\, \mu^\pm \nu_\mu\, \tau^\pm \nu_\tau$ (WWW only) — Dittmaier, Knippen, Schwan '19

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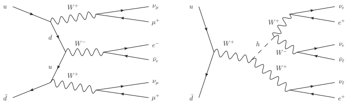
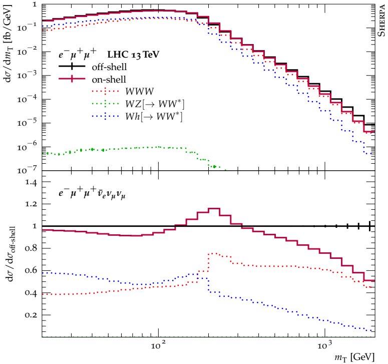
Necessity of off-shell calculations

Example *WWW*:
Typically $3\ell + \text{MET}$ with $\ell = e, \mu$, thus 0/1/2 SFOS lepton pairs.

This means that 0 SFOS channel contains interference of WWW, $Wh[\to WW^*]$, $WZ[\to WW^*]$ at Born level, more at NLO EW.



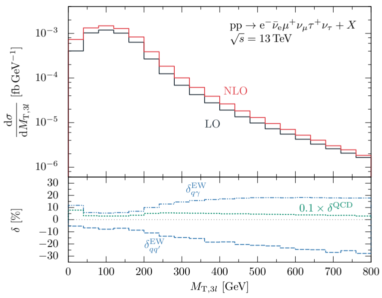


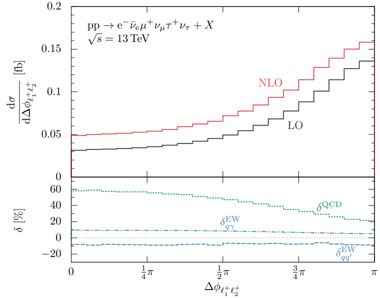
1/2 SFOS additionally contain WZZ, $Wh[\to ZZ^*]$, etc.

off-shell effects of $\mathcal{O}(20\%)$ or larger

Differential distributions

Example distributions for $3\ell +$ MET: Dittmaier, Knippen, Schwan '19





- large photon-induced corrections, can be controlled through jet veto, or $\Delta\phi(\ell\ell\ell, \not{E}_{\rm T})$ veto (no jet-related uncertainties, better for theory)

Resummed corrections in Sudakov limit

NLL Sudakov logarithms (exponentiable) — Denner, Pozzorini '01

- universal corrections in limit all invariants $s_{ik} \gg m_W$
- automated implementations — Bothmann, Napoletano '20; Pagani, Zaro '21

Match to NLO EW

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

Lindert et.al. '17
Bothmann, Napoletano, MS, Schumann, Villani '21

Can be used to resum dominant EW corrections to all orders in Sudakov region while maintaining the inclusive NLO EW accuracy. Needed when $\mathcal{O}(\alpha)$ corrections are large.

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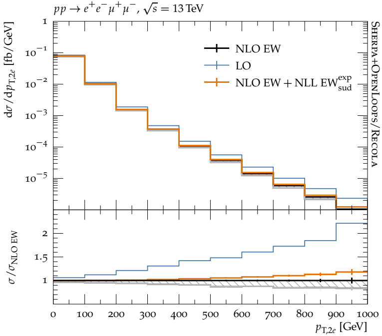


Bothmann, Napoletano, MS, Schumann, Villani '21

Example: $pp \to e^+e^-\mu^+\mu^-$

- NLO EW corrections reach -50% at 1 TeV
- resum universal Sudakov logs $\Rightarrow -40\%$ corrections

Uncertainties:

- here by varying the EW renormalisation scheme, too conservative?

Scheme uncertainties

Scheme uncertainties

The EW sector is overconstrained, choose input parameters, determine derived parameters.

Renormalisation schemes tie physical parameters to measurements.
Popular EW renormalisation schemes: $\alpha(0)$, $\alpha(m_Z)$, G_μ, $\sin\theta_w$

By construction,

- $\alpha(0)$ offers optimal description of real photon production
- $\alpha(m_Z)$ evolves $\alpha(0)$ to the typical hard scale m_Z, thus absorbs leading logarithm corrections
- G_μ absorbs universal corrections to $\sin\theta_w$ into derived coupling α_{G_μ}, which minimises higher-order corrections in W-mediated processes
- ...

For details see Denner, Dittmaier '20

Scheme uncertainties

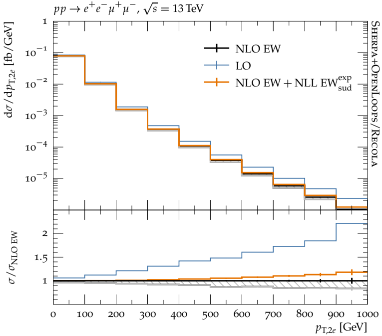
EW scheme uncertainty to some extent plays the role of the renormalisation scale uncertainty in QCD and can in principle be used to gauge missing higher order corrections as the scheme dependence must vanish when including all orders.

However, EW renormalisation schemes are discrete choices, and some are more appropriate for a given situation than others. Changing to a less appropriate scheme reduces the quality of the calculation and likely severely overestimates the uncertainty from missing higher orders.

Also, as scheme variations are discrete, it is even less obvious how to derive a statistical interpretation from them.

Scheme uncertainties

Bothmann, Napoletano, MS, Schumann, Villani '21



Example: $pp \to e^+e^-\mu^+\mu^-$

Scheme	LO	δ_{EW}^{NLO}
G_μ	**9.819 fb**	−6.8 %
$\alpha(m_Z)$	10.928 fb	−19.4 %
$\delta_{G_\mu}^{\alpha(m_Z)}$	11.3 %	−3.8 %

NNLO QCD: $\sim 3\%$ uncertainty

- $\alpha(m_Z)$ has much worse convergence than G_μ in this process
- may not be ideal choice for scheme uncertainty, but what else to do $\to$ possibly have G_μ-like scheme with a free parameter

Observable and object definition

Infrared safety

IR safety: any observable must be insensitive to soft or coll. splitting

	gluon	quark	photon	lepton
at NLO:	$g \to gg$	$q \to qg$	$\gamma \to q\bar{q}$	$\ell \to \ell\gamma$
	$g \to q\bar{q}$	$q \to q\gamma$	$\gamma \to \ell^+\ell^-$	

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	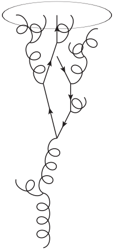			
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	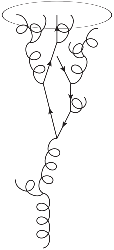	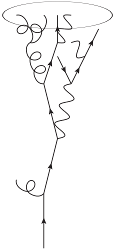		
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	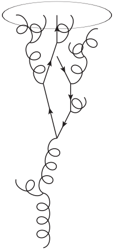	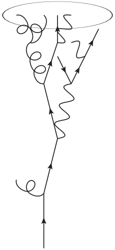		
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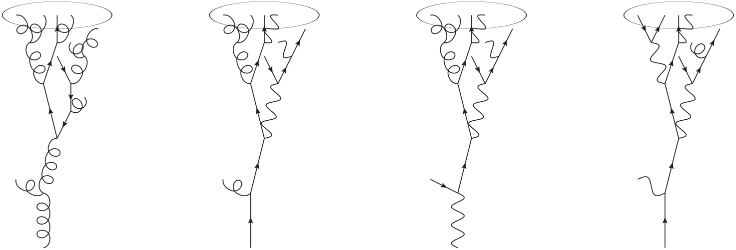

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Definition of physical objects

Same problem as in QCD: there are soft-collinear singularities between pairs of particles

Solution: differentiate between short-distance objects (partons) and long-distance objects (observable particles).

Transition between partons and observable particles mediated by fragmentation function / parton shower + hadronisation.

Familiar in QCD, unfamiliar in EW sector as in many cases no non-perturbative component involved.

Additional complication: want to identify different flavours, e, μ, γ, etc.

Definition of physical objects

What is a jet?

- photons and leptons must be part of a jet, but to what extent?
- **democratic:**
  - + straight forward, always well defined
  - − many contributions
  - → single photons constitute a jet
  - → single leptons constitute a jet
- **anti-tagging jets with certain flavour content:**
  - + fewer contributions
  - − needs a lot of care to be well-defined at all contributing orders
  - → anti-tag jets with too large photon content
  - → anti-tag jets with net lepton content
- which approach is closer to experiment depends on analysis, general anti-tagging must proceed through fragmentation functions

Definition of physical objects

What is a photon?

- differentiate: short-distance photon (photon as parton),
  long-distance photon (identified, measurable photon)
- identify through fragmentation function

$$D_\gamma^\gamma(z,\mu) = \frac{\alpha(0)}{\alpha_{\text{sd}}}\,\delta(1-z) + \mathcal{O}(\alpha^2)$$

$\Rightarrow$ leads to $\alpha(0)$-scheme for identified photons

- identified photons do not split further (IR poles absorbed in $\alpha(0)$)
- need to be isolated from other particles using smooth or hybrid cone

Definition of physical objects

What is a lepton?

- in principle, again differentiate between short-distance parton and long-distance identified and measurable object
- simplified as leptons not gauge bosons, thus

  $D_\ell^\ell(z,\mu) = \delta(1-z)+$QED bremsstrahlung

  $D_\ell^\gamma(z,\mu) = \mathcal{O}(\alpha)$ problematic in processes with ℓ and unresolved photons in Born

  all other $D_\ell^q(z,\mu) = \mathcal{O}(\alpha^2)$, $D_\ell^g(z,\mu) = \mathcal{O}(\alpha_s\alpha^2)$
- dressed lepton: masseless leptons must be dressed for IR safety
- bare lepton: massive leptons may be measured bare
- Born lepton: not an infrared-safe concept

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Example: Dijet production at $\mathcal{O}(\alpha_s^2, \alpha_s\alpha, \alpha^2)$

- **define jets completely democratically**,
  incl. all massless visible particles of the SM (q, g, γ, ℓ)

- **anti-tag jets against leptons**
  exclude jets with net lepton number within lepton acceptance
  care: jet acceptance and lepton acceptance may differ

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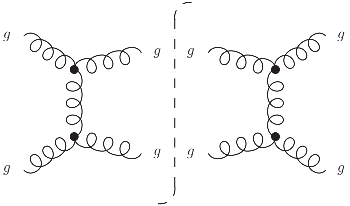

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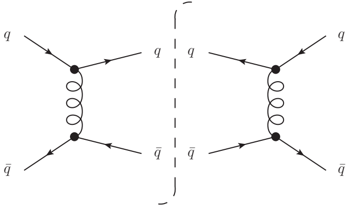

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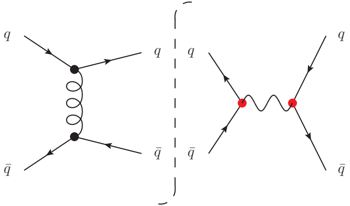

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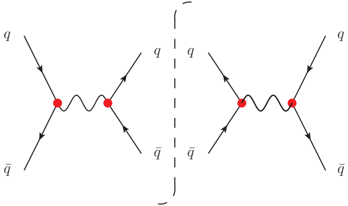

hadronic DY

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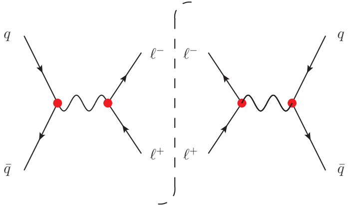

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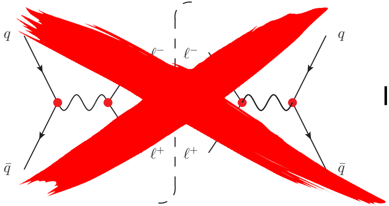

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Conclusions

Fixed-order

- NLO EW automated, but many subtleties that need expert steering (renormalisation scheme, object & observable definitions, etc.)
- resonances everywhere
- object & observable definitions need careful coordination with experimental analysis strategy
  (analoguous to QCD jet definition, just more complex)

Event generators

- QED resummation, solved 60 years ago, EW parton showers recently
- NLO+PS available for selected processes
- approximate corrections in Sudakov limit universally available

Thank you!