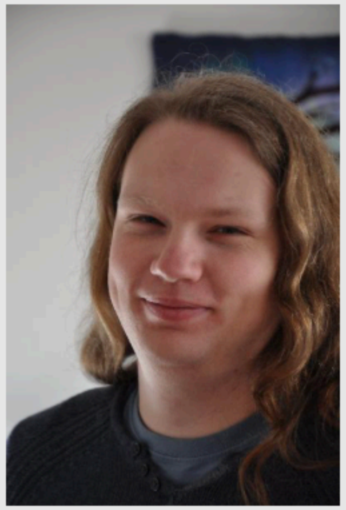
Göttingen report

SHERPA Annual Meeting
Milan, 7 January 2020

Enrico Bothmann

The Göttingen group these days ...


@Email
Prof. Dr. Steffen Schumann


@Email
Dr. Vincent Michel Theeuwes


@Ema
Dr. Enrico Bothmann

PhD students:

Stephan Bräuer

Daniel Reichelt


Timo Janssen

@E
Simon Luca Villani

MCnet short-term student from ALICE


Suman Deb

Topics 2019 and ongoing

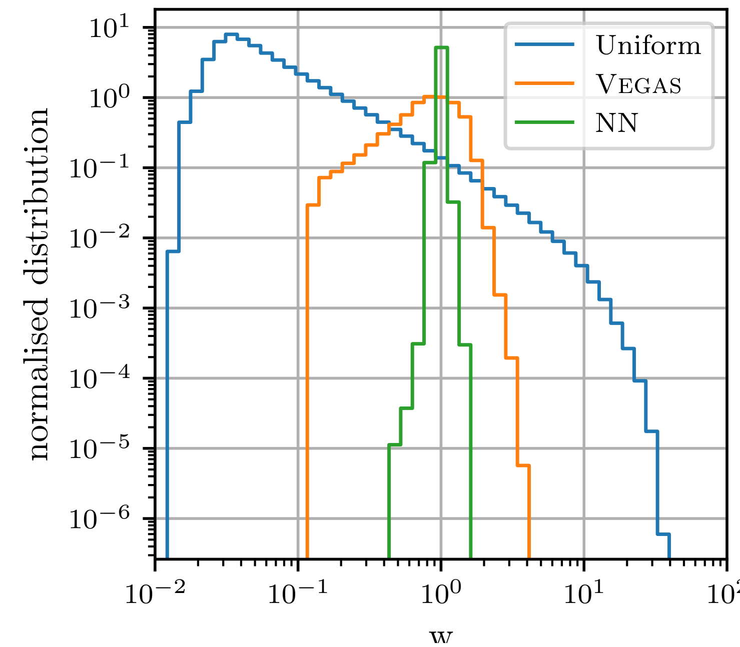
- explore phase space with Neural Importance Sampling
  Steffen, Enrico, → **Timo**
- resummation & automated CAESAR plug-in
  Steffen, → **Daniel**, Vincent
  - ee soft-drop Thrust @ NLO+NLL → apply to α_s fit
  - ee Durham jet resolutions @ NLO+NLL' → $N_{\text{jets}} \leq 6$
- loop-induced processes
  Steffen, Enrico, → **Simon**
  - use EXTAMP ME interface to calculate LI $gg \to VV$ @ NLO+PS
- electro-weak corrections
  Steffen, Enrico, Stephan
  - calculation of QCD+EW NLO 3-jet production → apply to R_{32}
  - WW(j) @ MEPS@NLO+EWvirt
  - ongoing development of EW Sudakov corrections

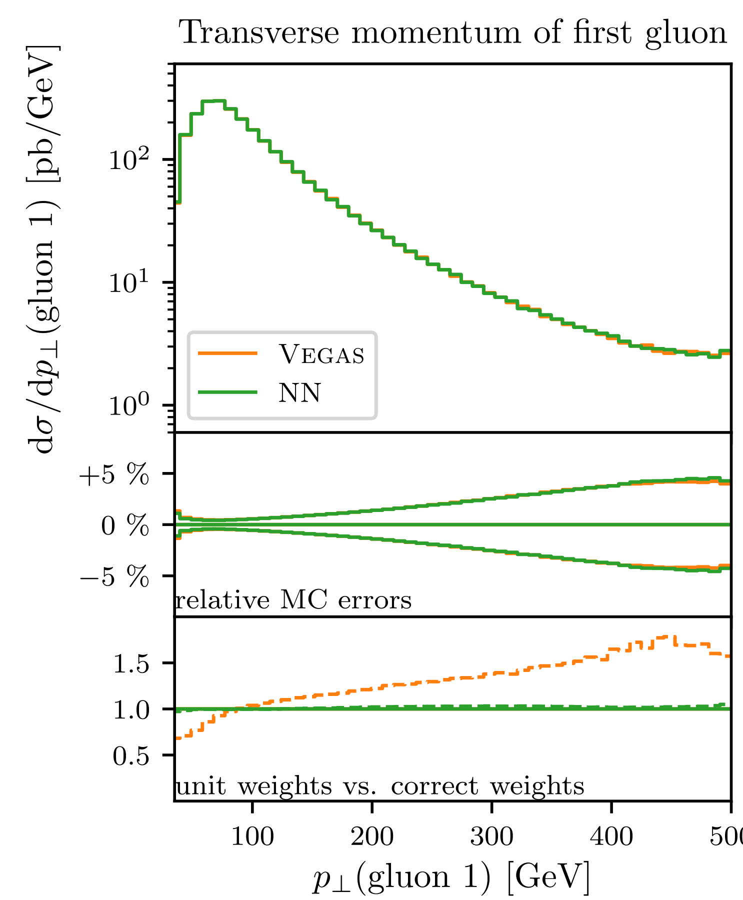
Neural importance sampling

[EB, Timo Janßen, Max Knobbe, Tobias Schmale, Steffen Schumann, TBP]

- train a NN to propose points
  - replace VEGAS as channel optimiser
- NN architecture guarantees ...
  - full phase-space coverage
  - cheap weight calculation (Jacobians $\mathcal{O}(D)$)
- inspired by methods developed for light transport simulation (3D rendering)
  [Müller et al., Disney Research, 1808.03856]
- proof-of-principle study for:
  - top decays & leptonic $t\bar{t}$ production
  - $gg \to 3g/4g$
- coordinated with complementary study focusing on scaling behaviour in $pp \to W + n\,\text{jets}$
  [Stefan Höche et al., TBP]

→ Timo





Resummation I: soft-drop Thrust for α_s fits

[Simone Marzani, Daniel Reichelt, Steffen Schumann, Gregory Soyez, Vincent Theeuwes, 1906.10504]

- use soft-drop to reduce hadronisation effects in Thrust at LEP to improve α_s fit
- MEPS@NLO SHERPA+OPENLOOPS simulated data (there is no experimental analysis)
- NLO+NLL prediction
  [Baron, Marzani, Theeuwes, 1803.04719]
- validated by automated CAESAR-based SHERPA plug-in
  [Gerwick, Höche, Marzani, Schumann, 1411.7325]

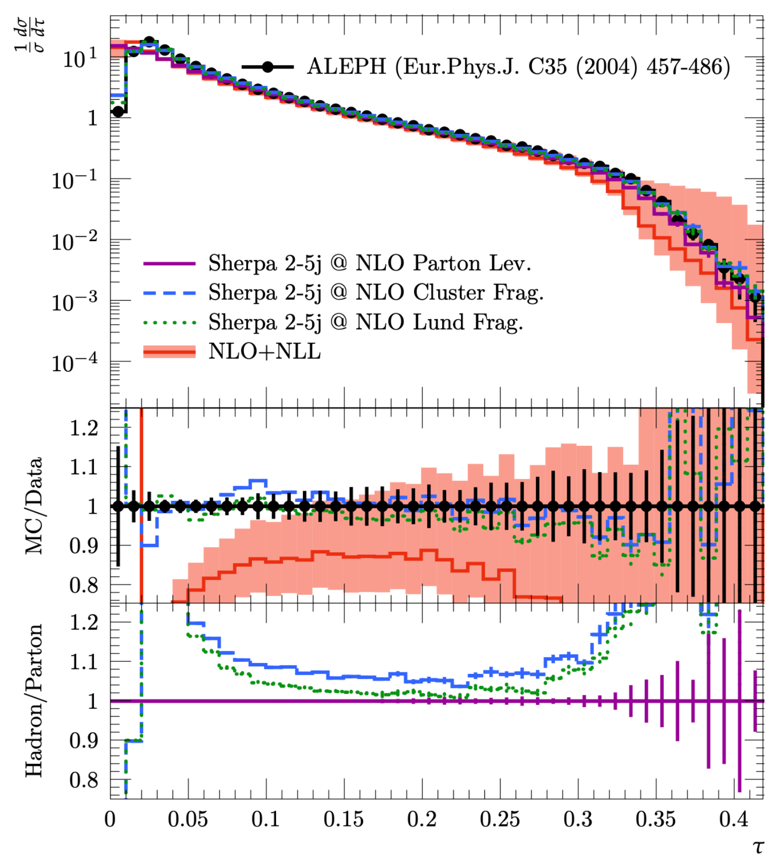
➡ reduced shift by hadronisation (very broadly speaking $\sim 20\,\% \rightarrow \lesssim 10\,\%$, flatter shape)

➡ possibility of extending fit range to smaller values of $\tau = 1 - T$, while retaining perturbativity

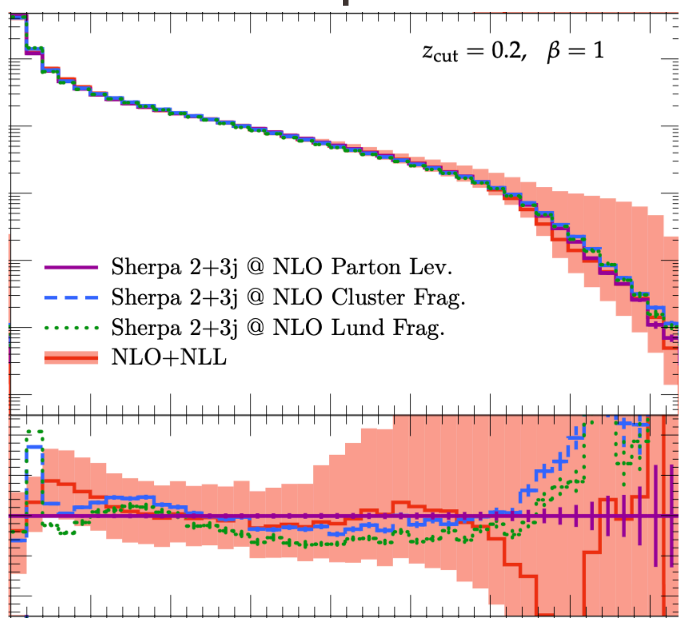
- proof-of-principle study, precision extraction would require NNLO+NNLL (and experimental analysis)
- ongoing study for hadronic event shapes with soft-drop, where also UE comes into play

→ Daniel

normal Thrust



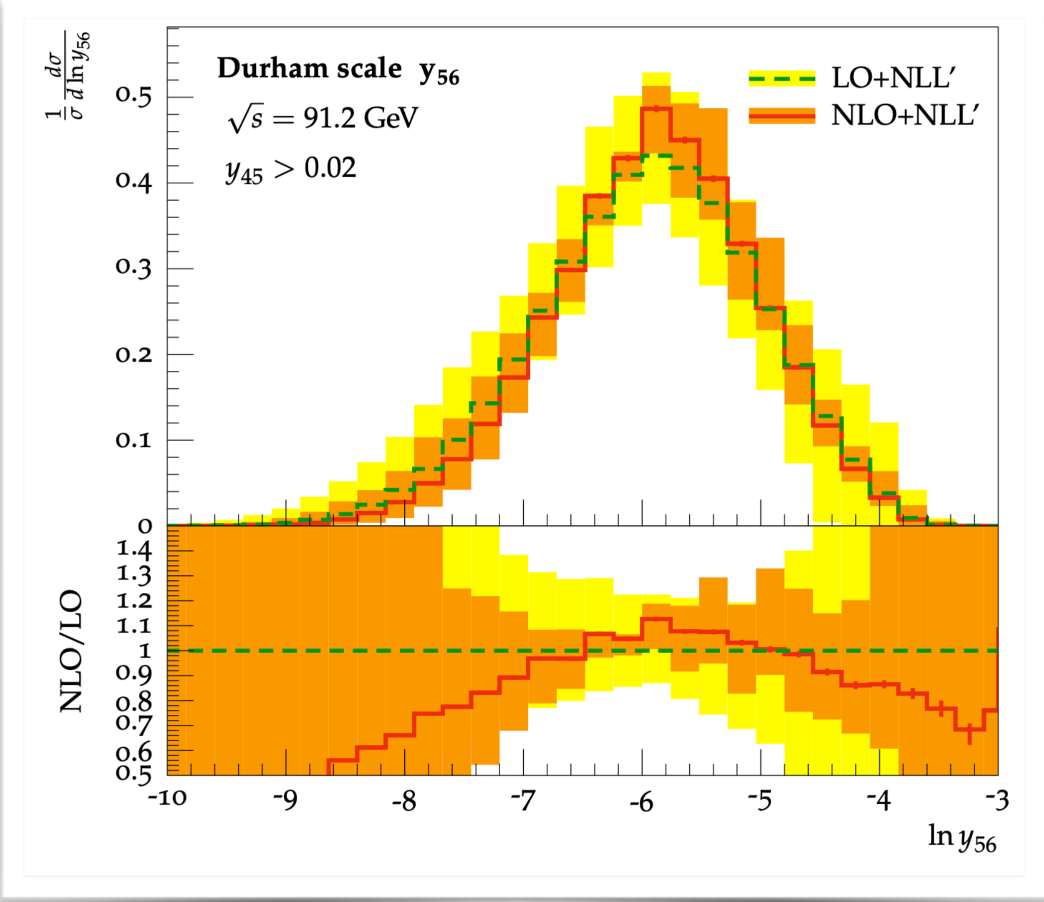
soft-drop Thrust



Resummation II: Durham jet resolutions

[Nick Baberuxki, Christian T Preuss, Daniel Reichelt, Steffen Schumann, 1912.09396]

- Jet resolution scales at NLO+NLL' for ee
- first time up to $N_{\text{Jets}} = 6$
- resummation by CAESAR plug-in (virtuals from OPENLOOPS & RECOLA)
- multi-emission contribution numerically challenging
- comparison between LC, improved LC (shower-like) and full colour
  ➡ improved LC very good approximation



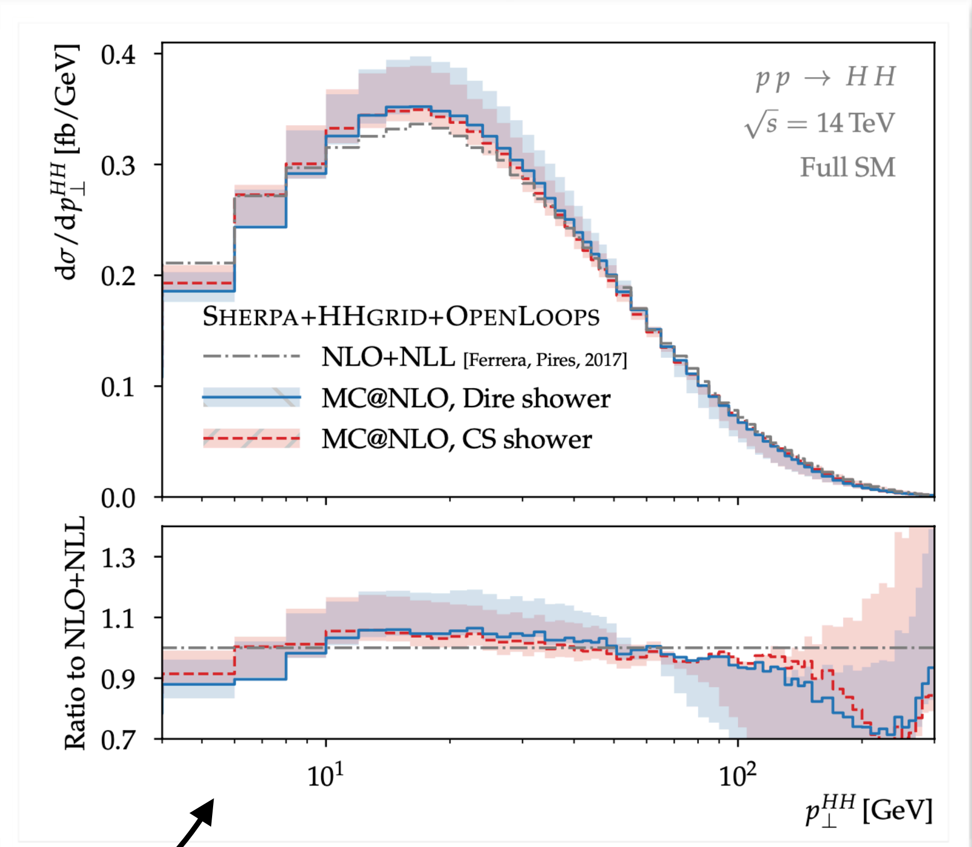
- sub-leading colour contributions smaller than differences observed when comparing resummation and parton-shower results
  ➡ other ambiguities must be more important:
  recoil scheme, phase-space constraints, sub-leading α_s running …
- comparison to data not possible due to $y_{\text{cut}} = 0.02$ requirement, would require re-evaluation by LEP

→ **Daniel**

Loop-induced processes

[Jones, Kuttimalai, 1711.03319]

- in principle, (fully generic) support for LI processes at MC@NLO in SHERPA by EXTAMP module which …
  - interfaces external libs for double-virtual ME
  - implements Catani–Seymour NLO subtraction
  - performs MC@NLO parton-shower matching
- proof-of-principle study for $gg \to HH$



- manual steps to add more processes: make sure conventions agree (schemes, prefactors, …), slow double-virtual potentially requires interpolation, validation
- first attempt after reproduction of $gg \to HH$: $gg \to VV$ with double virtuals from VVAMP code [Manteuffel, Tancredi, 1503.08835]

→ Simon

[EB, Simon Luca Villani, Steffen Schumann]

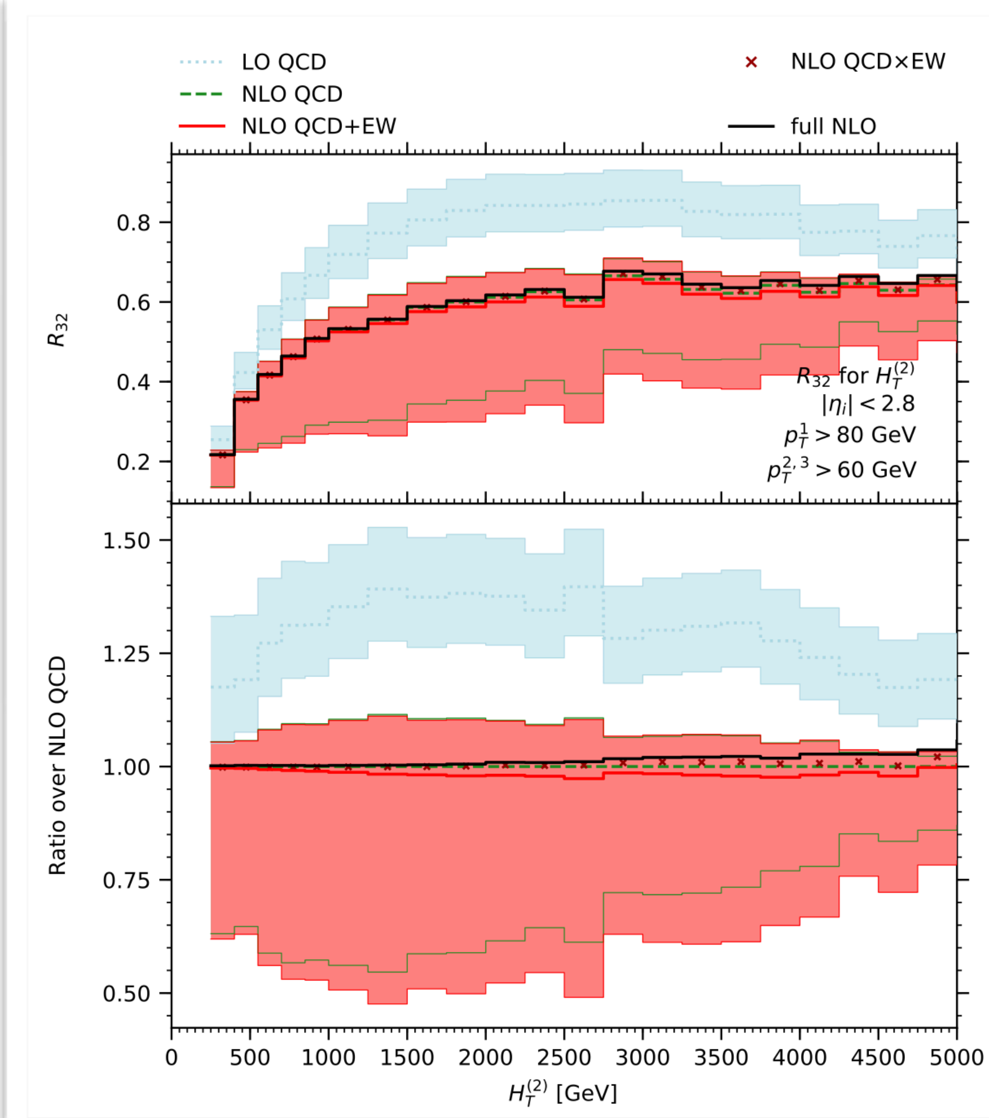
EW corrections I: fixed-order

- corrections to (differential) 3-jet production @ QCD+EW NLO
  [Max Reyer, Marek Schönherr, Steffen Schumann, 1902.01763]
  - observe compensations between Sudakov-type suppression and sub-leading contributions

    ➡ accidental, but illustrates importance of including all contributions

  - application: 3-to-2 jet ratio R_{23}
    - found to be stable against EW corrections: $\leq 5\,\%$ even for large p_T

    ➡ "confirms particular usefulness of R_{23} for determination of the strong coupling"



- WW(j) @ MEPS@NLO+EWvirt → study EWvirt validation/applicability
  [Bräuer, Pellen, Schönherr, Schumann]

→ **Marek (?)**

EW corrections II: Sudakov logs

[EB, Davide Napoletano]

- Implement Sudakov logs in high-energy (HE) limit within SHERPA
  - approximate EW corrections, capturing dominant contributions
  - as universal ME-level corrections: directly applicable to full machinery
- Fully general calculation for physical fields [Denner, Pozzorini (2001) hep-ph/0010201]
  - checked exact reproduction of their explicit log coefficients in HE limit (only PR missing)

Double/Single logs:

$$\mathrm{DL} \sim \frac{\alpha}{4\pi s_\mathrm{W}^2} \log^2 \frac{s}{M_\mathrm{W}^2}$$

$$\mathrm{SL} \sim \frac{\alpha}{4\pi s_\mathrm{W}^2} \log \frac{s}{M_\mathrm{W}^2}$$

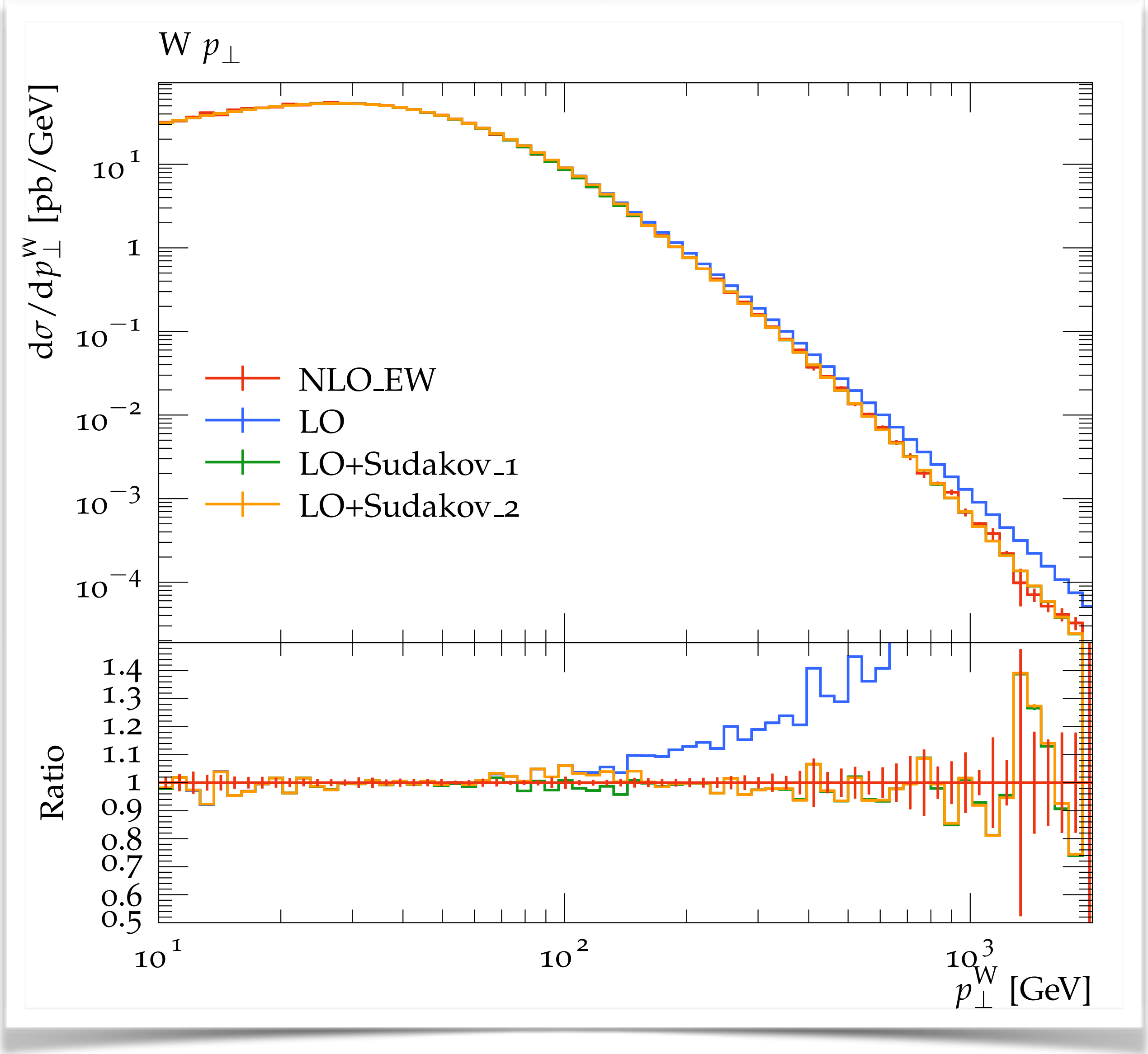
$$K = \frac{\sum_s \sum_j (1 + 2\mathrm{Re}\,\delta_s^j) \, |\mathcal{M}_s|^2}{\sum_i |\mathcal{M}_s|^2}$$

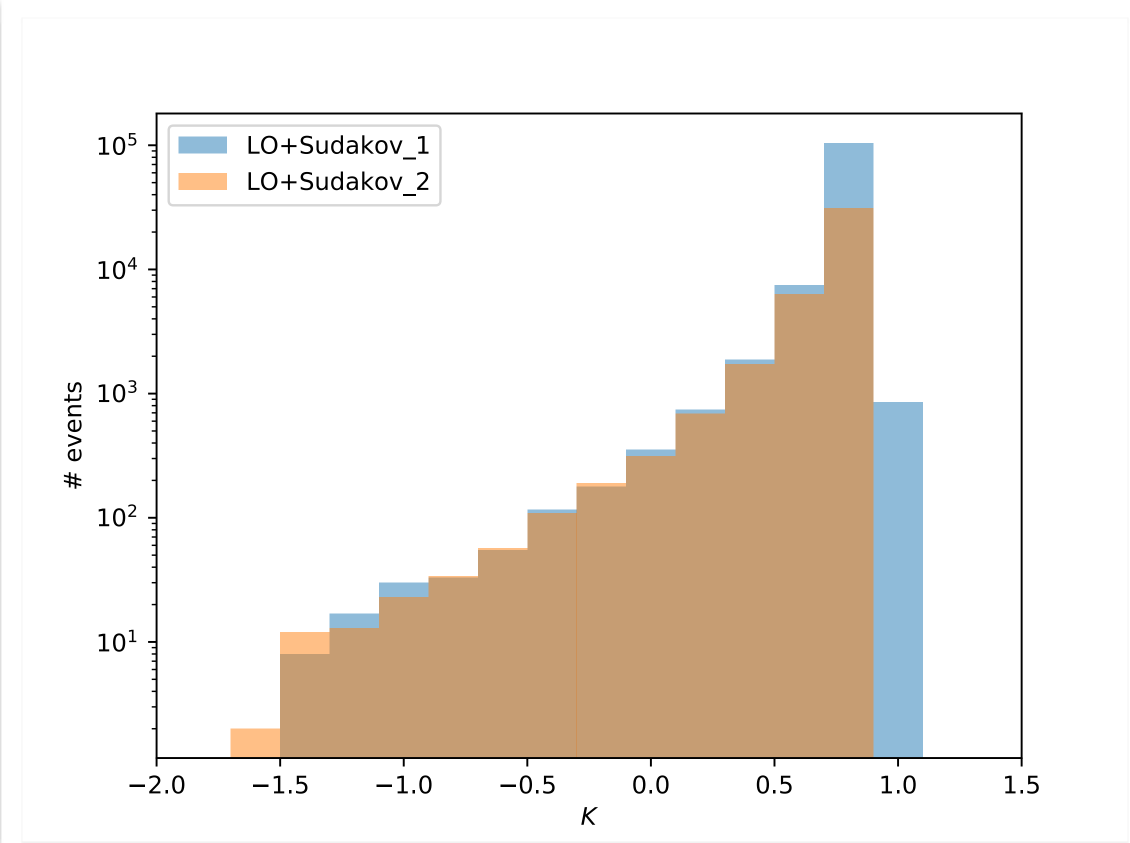
E.g. VBS WZ: "The corrections [to σ] reach −16% in the chosen fiducial region and are driven by Sudakov logarithms [...]" [Denner et al. (2019) 1904.00882]

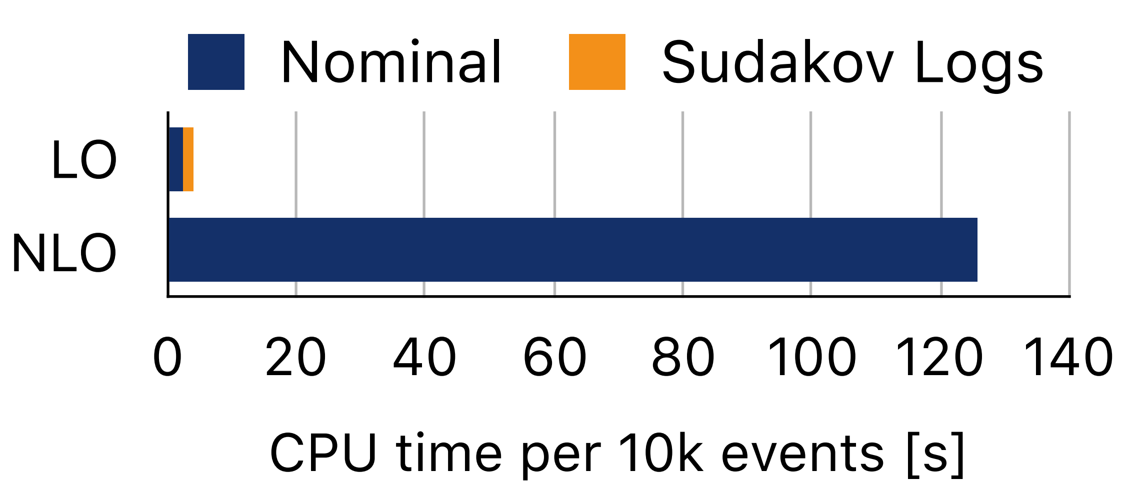
EW corrections II: Sudakov logs

[EB, Davide Napoletano]

- Example: $pp \to W^+W^-$ (on-shell)
  - FCC-pp: $\sqrt{s} = 100\,\mathrm{TeV}$
  - no PR, no SSC (numerical issues!)
  - HE threshold: $1,2\,m_W$







- **phase-space:**
  neural importance sampling
- **resummation / CAESAR plug-in:**
  soft-drop applications & jet resolutions
- **Loop-induced processes:**
  $gg \to VV$ at MC@NLO
- **EW corrections:**
  3-jet calculation, WW(j) & Sudakov logs

Thanks

Backup

Motivation: EW Sudakovs

- ALPGEN implementation
  - → [Chiesa et al. (2013) 1305.6837]
  - → proof-of-principle for Z[vv]+1,2,3jets
  - → fully general, BUT missing longitudinal V corrections
  - → "two is one and one is none"

Why not use NLO EW?:

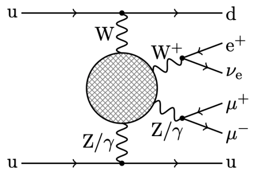
NLO (QCD+)EW is ...

... not available for arbitrary procs / multiplicities

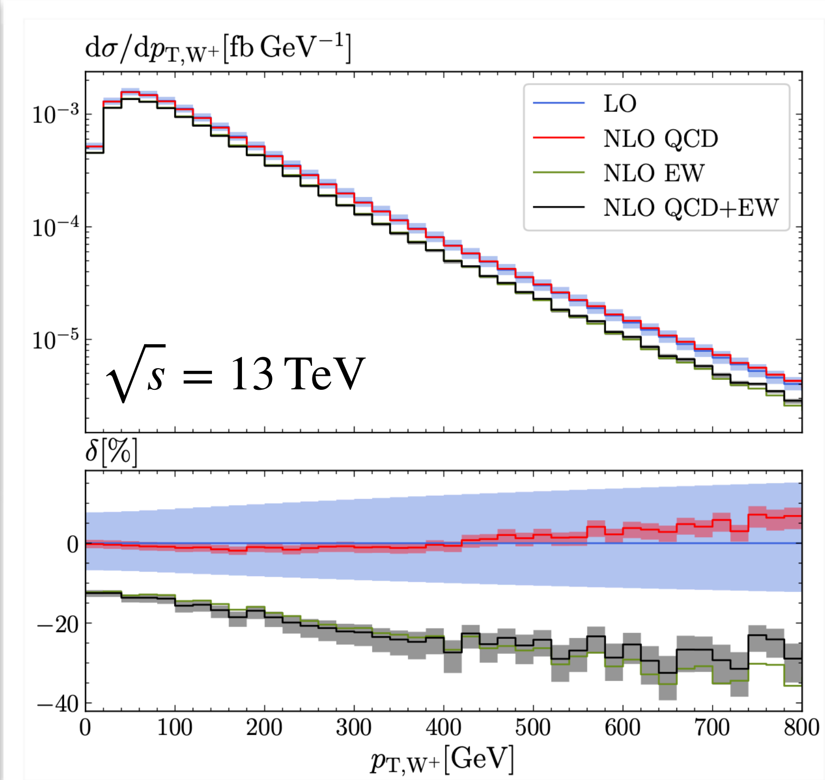
... not yet automated for precision event samples (→matching/merging)

... time-consuming

- E.g. VBS WZ



  - → "The corrections [to σ] reach −16% in the chosen fiducial region and are driven by Sudakov logarithms that are large and negative and grow in size in the high-energy limit." [Denner et al. (2019) 1904.00882]
  - → VBS same-sign WW [Biedermann, Denner, Pellen (2017) 1708.00268]



EW Sudakov Theory: Overview

- DL
  - → soft+coll. V loops between pairs of ext. legs
- SL
  - → purely coll. virtual V emission from ext. leg
  - → field renormalisation constants
- Parameter renormalisation
  - → charge and weak mixing angle, Yukawa and scalar self couplings
  - → SL from UV region
- All shown to factorise from ME as a matrix:
  - → $\delta\mathcal{M}^{i_1\ldots i_n}(p_1,\ldots,p_n) = \mathcal{M}_0^{i'_1\ldots i'_n}(p_1,\ldots,p_n)\,\delta_{i'_1 i_1 \ldots i'_n i_n}$

High-energy limit (HE):

All invariants much larger than V masses:

$$r_{kl} = (p_k + p_l)^2 \sim 2 p_k p_l \gg M_\mathrm{W}^2$$

i.e. $\mathrm{d}\sigma$ better not dominated by resonances

Write logs in terms of:

$$L\left(\left|r_{kl}\right|, M^2\right) := \frac{\alpha}{4\pi}\log^2\frac{r_{kl}}{M^2}$$

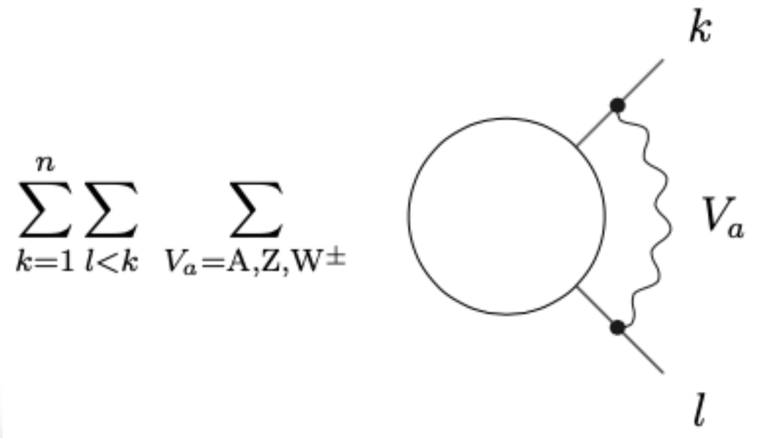
$$l\left(r_{kl}, M^2\right) := \frac{\alpha}{4\pi}\log\frac{r_{kl}}{M^2}$$

$$L(s) := L\left(s, M_\mathrm{W}^2\right), \qquad l(s) := l\left(s, M_\mathrm{W}^2\right)$$

log. approximation:

omit terms $\propto \log(\mathcal{O}(1))$

EW Sudakov Theory: DL corrections I



gauge bosons/couplings:

$$V_a = A, Z, W^{\pm}, \quad ieI^{V_a}_{i_k i'_k}(k)$$

eikonal approx:
set masses in numerator = 0

$$\delta\mathcal{M}^{i_1\dots i_n} = \sum_{k=1}^{n}\sum_{l<k}\sum_{V_a=A,Z,W^\pm}\int\frac{d^4q}{(2\pi)^4}\frac{-4ie^2 p_k p_l I^{V_a}_{i'_k i_k}(k) I^{V_a}_{i'_l i_l}(l)\mathcal{M}_0^{i_1\dots i'_k\dots i'_l\dots i_n}}{\left(q^2 - M^2_{V_a}\right)\left[(p_k+q)^2 - m^2_{k'}\right]\left[(p_l-q)^2 - m^2_{l'}\right]}$$

logarithmic approx:
region where V_a both soft and collinear to one leg

$$\delta\mathcal{M}^{i_1\dots i_n} = \frac{1}{2}\sum_{k=1}^{n}\sum_{l\neq k}\sum_{V_a=A,Z,W^\pm} I^{V_a}_{i'_k i_k}(k) I^{\bar{V}_a}_{i'_l i_l}(l)\mathcal{M}_0^{i_1\dots i'_k\dots i'_l\dots i_n}\left[\boxed{L\left(|r_{kl}|, M^2_{V_a}\right)} - \delta_{V_a A} L\left(m_k^2, \lambda^2\right)\right]$$

$$L\left(|r_{kl}|, M^2\right) = \underbrace{\boxed{L\left(s, M^2\right)}}_{\text{LSC}} + \underbrace{\boxed{2l\left(s, M^2\right)\log\frac{|r_{kl}|}{s}}}_{\text{"angular" SSC}} + \cancel{L\left(|r_{kl}|, s\right)}$$

EW Sudakov Theory: DL corrections II: LSC

$$\delta^{\mathrm{LSC}}\mathcal{M}^{i_1\ldots i_n} = \frac{1}{2}\sum_{k=1}^{n}\sum_{l\neq k}\sum_{V_a=A,Z,W^\pm} I^{V_a}_{i'_k i_k}(k) I^{\bar{V}_a}_{i'_l i_l}(l)\mathcal{M}_0^{i_1\ldots i'_k\ldots i'_l\ldots i_n} L\left(s,M^2\right)$$

use invariance under global $\mathrm{SU(2)\times U(1)}$ transformations:

$$0 = \delta_{V_a}\mathcal{M}^{i_1\ldots i_n} = \mathrm{i}e\sum_{l} I^{V_a}_{i'_l i_l}(l)\mathcal{M}_0^{i_1\ldots i'_l\ldots i_n}$$

$$= \sum_{k=1}^{n} \boxed{\delta^{\mathrm{LSC}}_{i'_k i_k}(k)}\,\mathcal{M}_0^{i_1\ldots i'_k\ldots i_n}$$

→ factorise as a matrix for each leg!

W/Z mass gap

$$\delta^{\mathrm{LSC}}_{i'_k i_k}(k) = -\frac{1}{2}\left[\boxed{C^{\mathrm{ew}}_{i'_k i_k}(k)L(s)} - \boxed{2\left(I^Z(k)\right)^2_{i'_k i_k}\log\frac{M_Z^2}{M_W^2}l(s)} + \boxed{\delta_{i'_k i_k}Q_k^2 L^{\mathrm{em}}\left(s,\lambda^2,m_k^2\right)}\right]$$

(nearly) symmetric ew part

$$C^{\mathrm{ew}} := \sum_{V_a=A,Z,W^\pm} I^{V_a} I^{\bar{V}_a}$$

purely em part:
not meaningful w/o
adding real radiation!

EW Sudakov Theory: DL corrections III: SSC

- also factorise as a matrix, for each leg pair:

$$\delta^{\mathrm{SSC}}\mathcal{M}^{i_1\ldots i_n} = \sum_{k=1}^{n}\sum_{l<k}\sum_{V_a=A,Z,W^\pm} \boxed{\delta^{V_a,\mathrm{SSC}}_{i'_k i_k i'_l i_l}(k,l)}\,\mathcal{M}_0^{i_1\ldots i'_k\ldots i'_l\ldots i_n}$$

A loops:

purely em

$$\delta^{A,\mathrm{SSC}}_{i'_k i_k i'_l i_l}(k,l) = 2\left[l(s) + \boxed{l\left(M_\mathrm{W}^2,\lambda^2\right)}\right]\log\frac{|r_{kl}|}{s} I^A_{i'_k i_k}(k) I^A_{i'_l i_l}(l)$$

Z loops:
non-diagonal in neutral sector ($h_0 ZZ$)

$$\delta^{Z,\mathrm{SSC}}_{i'_k i_k i'_l i_l}(k,l) = 2l(s)\log\frac{|r_{kl}|}{s} I^Z_{i'_k i_k}(k) I^Z_{i'_l i_l}(l)$$

W loops:
non-diagonal everywhere

$$\delta^{\pm,\mathrm{SSC}}_{i'_k i_k i'_l i_l}(k,l) = 2l(s)\log\frac{|r_{kl}|}{s} I^{\pm}_{i'_k i_k}(k) I^{\mp}_{i'_l i_l}(l)$$

Interlude: GBET

Derivation of gauge invariance from high-energy unitarity bounds on the S matrix*

John M. Cornwall,† David N. Levin, and George Tiktopoulos
Department of Physics, University of California at Los Angeles, Los Angeles, California 90024
(Received 21 March 1974)

- Set masses to zero in loop integrand numerator
  - → Feynman rules should have no inverse powers of M_{V_a}
- BUUUT what about the HE limit of longitudinal polarisation vectors!?

$$\epsilon^{\mu}_{\mathrm{L}}(p) = \boxed{\frac{p^{\mu}}{M}} + \mathcal{O}\left(\frac{M}{p^0}\right)$$

  - → derivation so far not applicable!
- Use the Goldstone-Boson Equivalence Theorem (GBET)

$$\mathcal{M}_0^{\ldots \mathrm{W}^{\pm}_{\mathrm{L}}} = \mathcal{M}_0^{\ldots \phi^{\pm}}$$

$$\mathcal{M}_0^{\ldots Z_{\mathrm{L}} \ldots} = \mathrm{i}\mathcal{M}_0^{\ldots \chi \ldots}$$

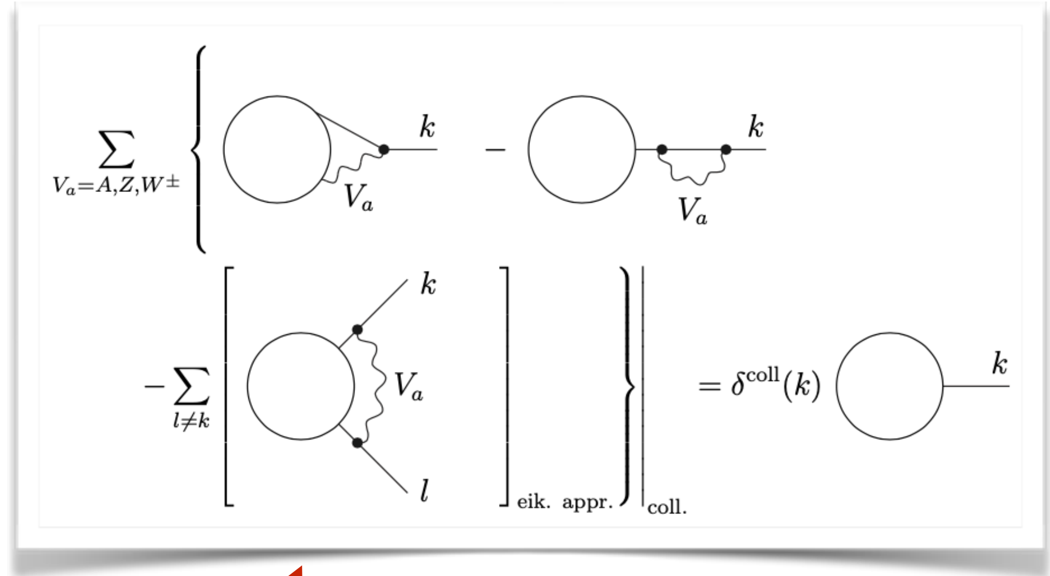
  - → ALPGEN does not support GB, hence no V_a^L corrections

one-loop corrections of the GBET:
- → do not contain DL
- → DL corrections can use Born approximation on the left

Tackling this w/o GB?:
- → [Cuomo, Vecchi, Wulzer (2019) 1911.12366]

EW Sudakov Theory: SL corrections

- Two sources of soft OR coll. logs
  - → field renormalisation constants give $\delta Z_\varphi/2$ for each leg, soft and coll. contribs
  - → coll. limit of loop diagrams where one leg splits into two internal lines (incl. one V_a)



$$\delta^{\mathrm{C}}\mathcal{M}^{i_1\ldots i_n} = \sum_{k=1}^{n} \delta^{\mathrm{C}}_{i'_k i_k}(k)\,\mathcal{M}_0^{i_1\ldots i'_k\ldots i_n}$$

$$\delta^{\mathrm{C}}_{i'_k i_k}(k) = \left.\boxed{\delta^{\mathrm{coll}}_{i'_k i_k}(k)} + \boxed{\frac{1}{2}\delta Z^{\varphi}_{i'_k i_k}}\right|_{\mu^2=s}$$

- Example result for chiral fermions:

$$\delta^{\mathrm{C}}_{f_\sigma f_{\sigma'}}\left(f^\kappa\right) = \delta_{\sigma\sigma'}\left\{\left[\frac{3}{2}C^{\mathrm{ew}}_{f^\kappa} - \boxed{\frac{1}{8s_{\mathrm{W}}^2}\left(\left(1+\delta_{\kappa\mathrm{R}}\right)\frac{m_{f_\sigma}^2}{M_{\mathrm{W}}^2} + \delta_{\kappa\mathrm{L}}\frac{m_{f_{-\sigma}}^2}{M_{\mathrm{W}}^2}\right)}\right] l(s) + Q_{f_\sigma}^2 l^{\mathrm{em}}\left(m_{f_\sigma}^2\right)\right\}$$

Yukawa terms:
large contribs for (t, b) doublet

EW Sudakov Theory: PR corrections

- From renomalisation of dimensionless parameters
  - → charge
  - → ew mixing angle $c_w = \cos\theta_w$
  - → Yukawa and Higgs self-couplings

- Logs are therefore related UV divergences

- Option 1: explicitly calculate logarithms:

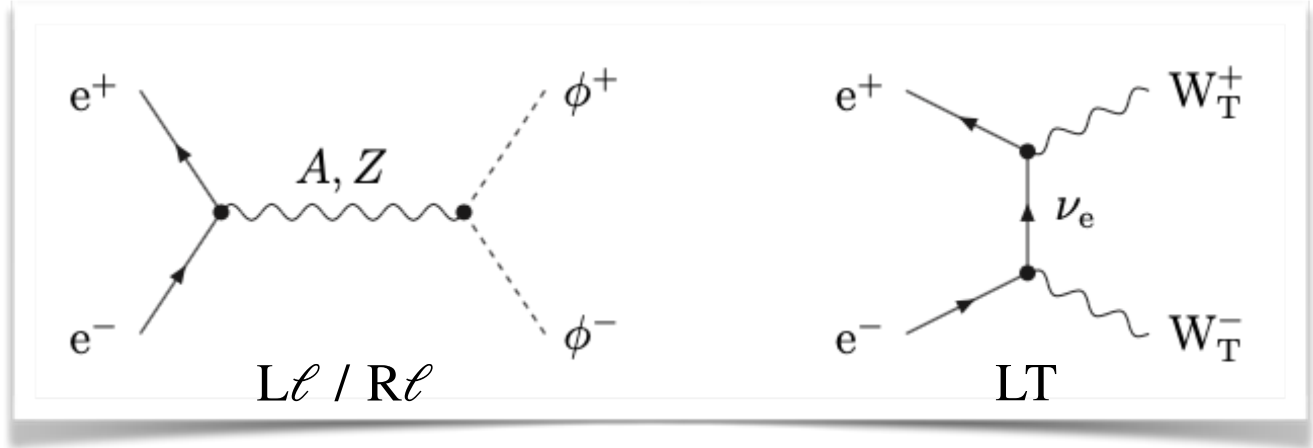
$$\delta^{\mathrm{PR}}\mathcal{M} = \frac{\delta\mathcal{M}_0}{\delta e}\delta e + \frac{\delta\mathcal{M}_0}{\delta c_{\mathrm{w}}}\delta c_{\mathrm{w}} + \frac{\delta\mathcal{M}_0}{\delta h_{\mathrm{t}}}\delta h_{\mathrm{t}} + \frac{\delta\mathcal{M}_0}{\delta h_{\mathrm{H}}}\delta h_{\mathrm{H}^2}^{\mathrm{eff}}\Bigg|_{\mu^2=s}$$

e.g. $\frac{\delta c_{\mathrm{w}}^2}{c_{\mathrm{w}}^2} = \frac{s_{\mathrm{w}}}{c_{\mathrm{w}}} b_{AZ}^{\mathrm{ew}} l\left(\mu^2\right)$

- Option 2: Just let the parameters run and evaluate ME at the HE scale

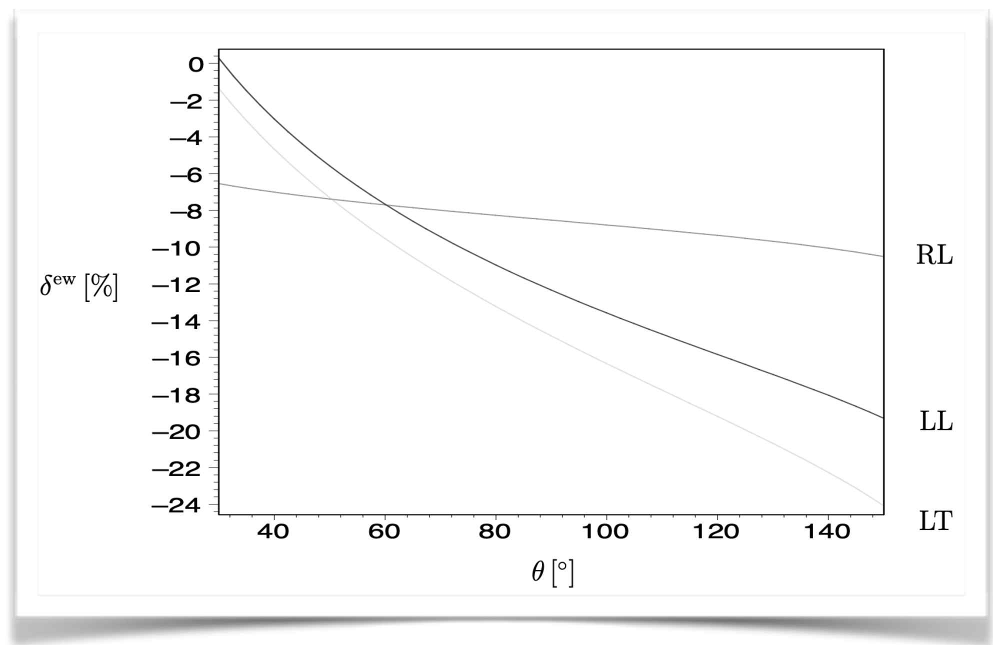
EW Sudakov Example: $e^+_\kappa e^-_\kappa \to W^+_{\lambda_+} W^-_{\lambda_-}$

- $\kappa = \mathrm{R}, \mathrm{L}$
- $\lambda_\pm = \ell, \pm$, but non-supressed in HE only: both ℓ (ℓ) or oppositely transverse (T)
- results independently verified



$\kappa\lambda_\pm$	DL: LSC	DL: LSC Z mass gap	DL: SSC (angular)	C	C: Yuk	PR
$\mathrm{L}\ell$	-7.35	0.45	$5.76 \log t/u + 13.9 \log \lvert t \rvert /s$	25.7	-31.8	-9.03
$\mathrm{R}\ell$	-4.96	0.37	$-2.58 \log t/u$	18.6	-31.8	8.80
LT	-12.6	1.98	$-8.95(\log t/u + (1 - t/u)\log \lvert t \rvert /s)$	25.2	—	-14.2
log	$L(s)$	$l(s)$	$l(s)$	$l(s)$	$l(s)$	$l(s)$

- left-handed fermion gives large negative DL and PR
- W_T: no Yukawa, but other coeffs larger
- however, for $\sqrt{s} = 1\,\mathrm{TeV}$, overall corrections similar for each helicity config



EW Sudakov: Implementation

- Implementation within the SHERPA 3.0 framework
- well-documented and follow closely notation in [Denner, Pozzorini (2001) hep-ph/0010201]
- Generalised Standard Model definition to include GB
  - → easy to calculate any ME value needed
- Calculate K-factor for each Monte-Carlo event
  - → check HE limit, e.g. $(p_i + p_j)^2 \geq x m_\mathrm{W}$
  - → put momenta on-shell for transformed MEs
  - → calculate contributions to K

```
Coeff_Value Sudakov::LsCoeff()
{
  Coeff_Value coeff{0.0};
  const auto& base_ampl = m_ampls.BaseAmplitude(m_current_spincombination);
  for (size_t i{0}; i < m_current_spincombination.size(); ++i) {
    const Flavour flav{base_ampl.Leg(i)->Flav()};
    const auto diagonal =
        -m_ewgroupconsts.DiagonalCew(flav, m_current_spincombination[i]) / 2.0;
    coeff += diagonal;
    if (flav.IsVector() && flav.Charge() == 0) {
      // special case of neutral transverse gauge bosons, they mix and hence
      // non-diagonal terms appear, cf. e.g. eq. (6.30);
      // assume they are are actually transverse, because we have already
      // replaced longitudinal ones with Goldstone bosons when calling
      // BaseAmplitude() above
      assert(m_current_spincombination[i] != 2);
      const kf_code newkf = (flav.Kfcode() == kf_Z) ? kf_photon : kf_Z;
      const auto prefactor = -m_ewgroupconsts.NondiagonalCew() / 2.0;
      // we can use amplitudes without replacing longitudinal gauge bosons
      // here, because of (i) eq. (3.4) and (ii) Goldstone boson correction
      // terms are diagonal (hence we only need to pass the right flavour above
      // when using DiagonalCew())
      const auto transformed =
          TransformedAmplitudeValue({{i, newkf}}, m_current_spincombination);
      auto amplratio = transformed / m_current_me_value;
      coeff += prefactor * amplratio;
    }
  }
  return coeff;
}
```

$$\frac{1}{L(s)}\delta_s^{\mathrm{LSC}} = \frac{1}{L(s)}\sum_{k'}\frac{\delta^{\mathrm{LSC}}_{i'_k i_k}(k)\mathcal{M}_s^{\ldots k \ldots}}{L(s)\mathcal{M}_s^{\ldots k \ldots}} = -\frac{1}{2}\left[\sum_{k'}\frac{C^{\mathrm{ew}}_{i'_k i_k}(k)\mathcal{M}_s^{\ldots k \ldots}}{\mathcal{M}_s^{\ldots k \ldots}}\right]$$

Sudakov log of type j for helicities i

$$K = \frac{\sum_s \sum_j (1 + 2\mathrm{Re}\,\delta_s^j)\,|\mathcal{M}_s|^2}{\sum_i |\mathcal{M}_s|^2}$$

EW Sudakov: Validation

$\kappa\lambda_\pm$	DL: LSC	DL: LSC Z mass gap	DL: SSC (angular)	C	C: Yuk	PR
$L\ell$	-7.35	0.45	$5.76 \log t/u + 13.9 \log \lvert t \rvert /s$	25.7	-31.8	-9.03
$R\ell$	-4.96	0.37	$-2.58 \log t/u$	18.6	-31.8	8.80
LT	-12.6	1.98	$-8.95(\log t/u + (1-t/u)\log \lvert t \rvert /s)$	25.2	—	-14.2
log	$L(s)$	$l(s)$	$l(s)$	$l(s)$	$l(s)$	$l(s)$

- Check *exact* reproduction of log coefficients for any HE kinematics (test-driven development)
  - → for all explicit results in [Denner, Pozzorini (2001)]:

$$ee \to \mathrm{W}^+\mathrm{W}^-, \mathrm{ZZ}, \mathrm{ZA}, \mathrm{AA}, \mu^+\mu^-, \mathrm{u\bar{u}}, \mathrm{d\bar{d}}, \mathrm{b\bar{b}}, \mathrm{t\bar{t}}$$

- TODO: Parameter Renormalisation implementation still missing

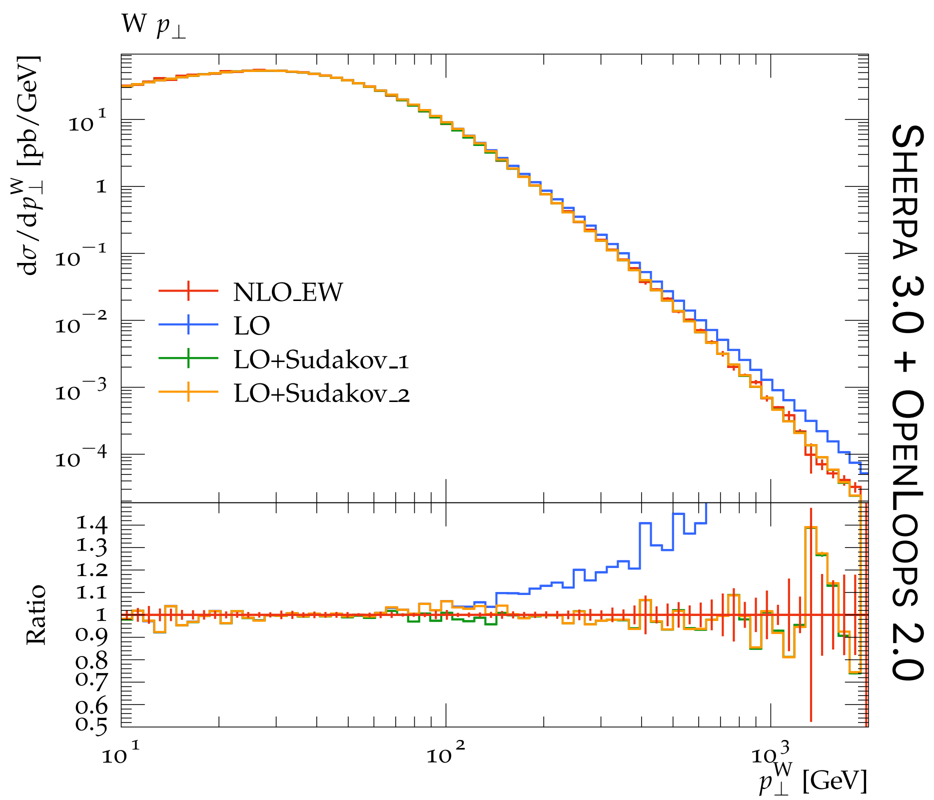
minus sign hunt due to different conventions:

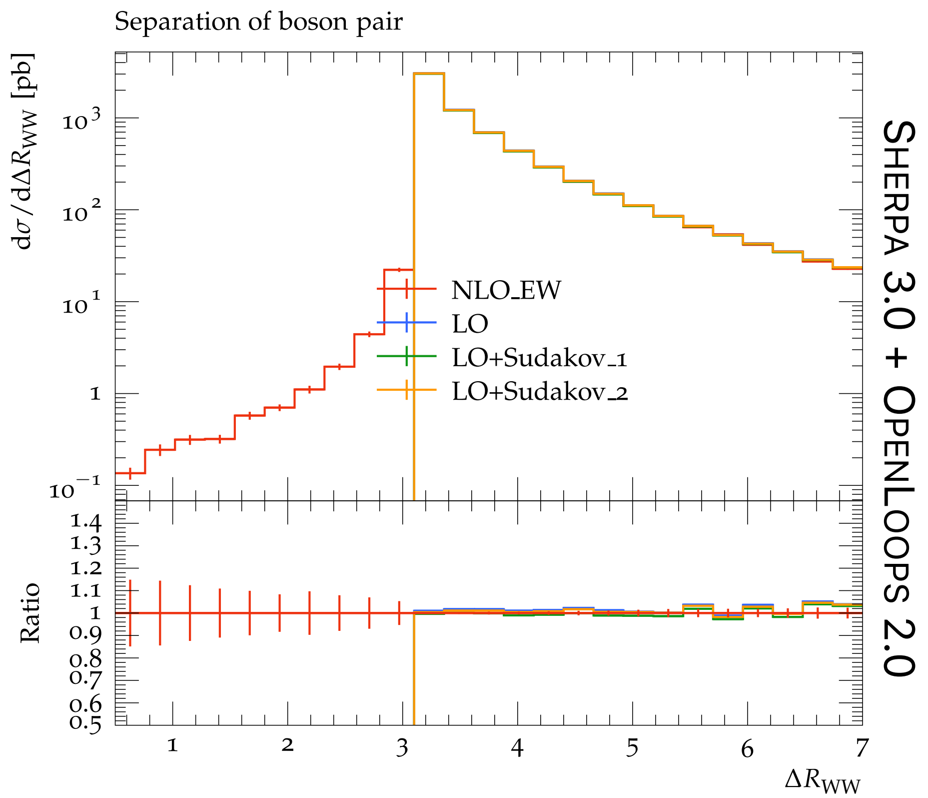
$$D_\mu = \partial_\mu - igA_\mu^a T^a - ig'YB_\mu \qquad \text{(Peskin/Schroeder, Sherpa)}$$

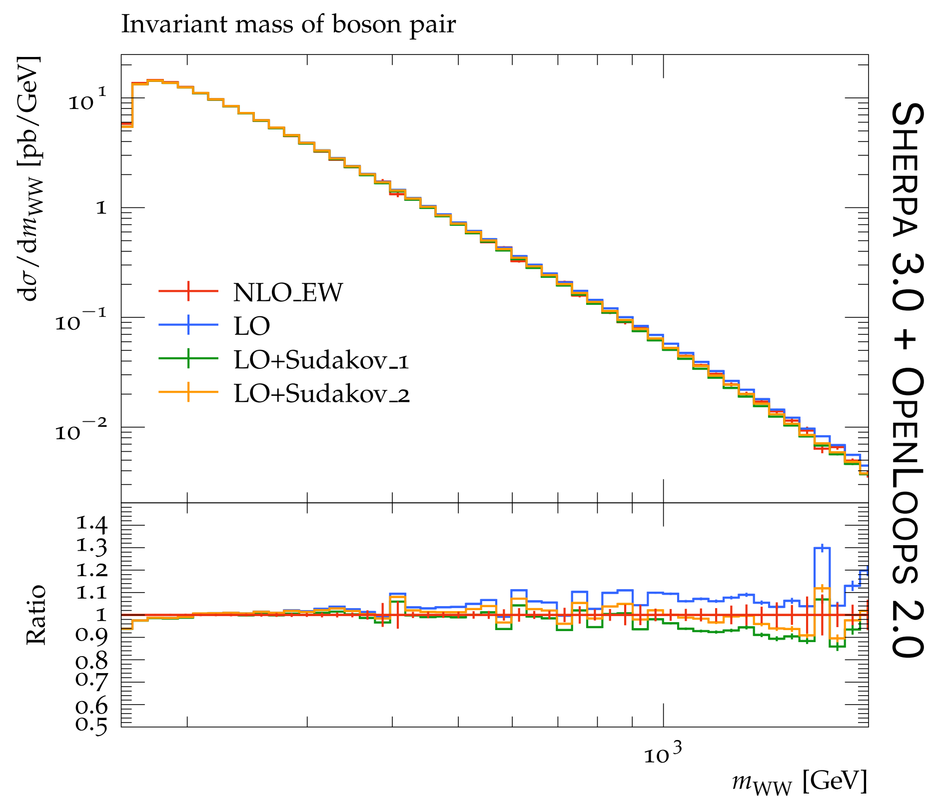
$$D_\mu = \partial_\mu - igA_\mu^a T^a + ig'YB_\mu \qquad \text{(Boehm/Denner, [Denner, Pozzorini(2001)])}$$

EW Sudakov Example: $pp \to W^+W^-$

- FCC-pp: $\sqrt{s} = 100\,\mathrm{TeV}$
- on-shell diboson production
- no PR, no SSC (numerical issues)
- HE threshold: $1{,}2\,m_W$

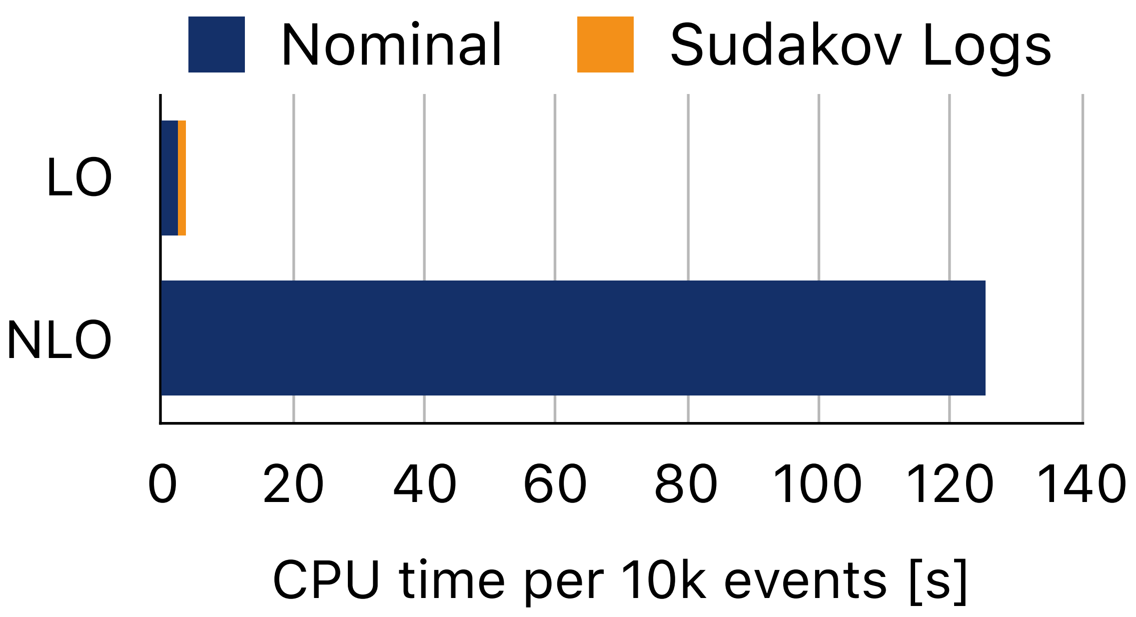






EW Sudakov Example: $pp \to W^+W^-$

- CPU time per 10k weighted events
  - → LO: 2.5 s
  - → LO+Sudakov: 3.4 s (+ 36 %)
  - → NLO: 125.5 s (× 50 / × 35) (NOTE: on top of that need 20 % more events for same total σ accuracy)



- Weights shifted to smaller values
  - → Sudakov suppression