QCD Corrections to BSM Signal Processes

Anna Kulesza
University of Münster

QCD@LHC 2018, TU Dresden, 27.08.2018
But there is **no** BSM physics at the LHC!!
But there is **no** BSM physics at the LHC!!

(* shakes head, opens up laptop, checks emails *)
At this point in the LHC history BSM precision calculations are needed more than ever.
At this point in the LHC history BSM precision calculations are needed more than ever.

The question is not if BSM exists but if it is at reach at the LHC.
As in real life...

- **Dumb luck**
  - teeny-tiny resonance hiding somewhere in the data

- need to characterize new physics
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POSSIBLE SCENARIOS

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- **Hard work**
  - need to search for BSM effects in the “boring SM physics”
  - focus on determination of SM couplings and kinematical distributions of SM particles, search for deviations from the SM predictions

[credit: U.Haisch]
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*loops & legs equally important: N^nLO (+NNLL / to a parton shower)*

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**loops & legs equally important:** $N^n\text{LO} (+\text{NNLL} / \text{to a parton shower})$

backgrounds to BSM searches: see previous talk by P. Gunnelini and J. Lindert
Connecting Higgs measurements with UV physics

**Kappa Framework**
- NP models simple rescaling of couplings
- No new Lorentz structures or kinematics

**EFT**
- SM degrees of freedom and symmetries
- New kinematics/Lorentz structures

**Simplified Models**
- New low-energy degrees of freedom
- Subset of states of full models, reflective at scale of measurement

**Full (UV) Model**
- Very complex and often high-dimensional parameter space
- Allows to correlate high-scale and low-scale physics

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A. Kulesza, QCD corrections to BSM signals at the LHC  
QCD@LHC18, TU Dresden
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**Complexity/Flexibility**

**Ignorance/Generality**
Theoretical Approaches

Connecting Higgs measurements with UV physics

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- Simplified

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In what follows a selection of recent activities / progress

Obviously, the literature is much richer -- apologies if some specific work has not been mentioned!
HIGGS & FRIENDS
Higgs sector extensions attract a lot of interest:
- the least explored sector
- many BSM models modify or extend the scalar sector of EW breaking
- can either be constructed as complete models or simplified models

Typical examples
- Singlet (under SM gauge symmetry) extension: two CP-even neutral scalars $h, H$
- Two Higgs Doublet Model (2HDM) / Minimal Supersymmetric Standard Model (MSSM): two CP-even neutral scalars $h, H$, CP-odd neutral scalar $A$ and two charged $H^+, H^-$ scalars
\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_S - \frac{1}{4v} C_S S G_{\mu\nu}^a G_a^{\mu\nu} \]

Gluon fusion: SM N^3LO results can be recast to calculate cross section for a CP-even scalar directly coupling to gluons in an effective theory approach

- Exact N^3LO available in iHixs2 [Dulat, Lazopoulos, Mistlberger’18]

- N^3LO from threshold expansion implemented also in SusHi Bento [Harlander, Liebler, Mantler’16]

[Anastasiou et al.’16]
For pseudoscalars $N^3\text{LO}$ not fully known, $N^3\text{LO}_A$ approximation proposed

$$
\sigma(t, m_A^2) = \tau \sigma_0 \sum_{i,j} \int_0^1 \frac{dz}{z} \mathcal{L}_{ij}(\frac{t}{z}, \mu_F^2) C_{ij}(z, \alpha_s, \mu_F^2)
$$

where

$$
C_{ij}(z, \alpha_s) = \frac{g_0(\alpha_s)}{g_0^H(\alpha_s)} \left[ C^H_{ij}(z, \alpha_s) + \delta C_{ij}(z, \alpha_s) \right]
$$

Resummation added at $N^3\text{LL}'$ accuracy (hard function known at three loops [Ahmed, Gehrmann, Mathews, Rana, Ravindran'15])

see also [Schmidt, Spira’15] for NNLO+$N^3\text{LL}$ for $h, H$ and $A$ results
MSSM Higgs $p_T$

- $p_T$ spectra available in specific models, e.g. 2HDM/ MSSM
  - [Bagnaschi, Degrassi, Slavich, Vicini’11] [Mantler, Wiesemann’15] (NLO +PS)
  - [Harlander, Mantler, Wiesemann’14] (NLO+NLL), NMSSM
- Results for the light Higgs very SM-like
- For heavy or pseudoscalar Higgs exact results dependent on a particular scenario but $p_T$ spectra generally softer than in the SM
- Contributions involving $b$-quark loops very important

Shape ratios:

$$N_S(p_T) = \frac{d\sigma_S/dp_T}{d\sigma_{SM}/dp_T},$$

MoRe–SusHi [Harlander, Mantler, Wiesemann’14]

- Pseudoscalar $p_T$ distributions at NNLO$_A$+NNNL recently obtained in [Agarwal et al.’18]
Higgs' $p_T$ in the EFT

$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$

- $\frac{c_1}{\Lambda^2} \mathcal{O}_1 \to \frac{\alpha_s}{\pi v} c_g h G^{\mu\nu} G^{\alpha,\mu\nu}$,
- $\frac{c_2}{\Lambda^2} \mathcal{O}_2 \to \frac{m_t}{v} c_b h t$,
- $\frac{c_3}{\Lambda^2} \mathcal{O}_3 \to \frac{m_b}{v} c_b h b$

Modifications introduced by different operators affect mostly different $p_T$ regions

$\left( \frac{d\sigma}{dp_T} \right)^{SMEFT}_{NNLL+NNLO} (p_T) = \left( \frac{d\sigma}{dp_T} \right)^{SMEFT}_{NLL+NLO} (p_T) \cdot \left( \frac{d\sigma}{dp_T} \right)^{SM}_{NNLL+NNLO} (p_T)$

A. Kulesza, QCD corrections to BSM signals at the LHC

QCD@LHC18, TU Dresden
Gluon Fusion @ NLO in SMEFT

- Yukawa
- gluon-Higgs (same as in heavy top limit)
- Chromomagnetic dipole moment (new @NLO)

At the inclusive level, contributions from effective operators have K-factors similar to the SM one.

Chromomagnetic and gluon-Higgs contact interaction operators modify high $p_T$ tails, see also [Grazzini, Ilnicka, Spira'18]

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<thead>
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<th>13 TeV</th>
<th>$\sigma$ LO</th>
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<td>$\sigma_3$</td>
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Gluon Fusion @ NLO in SMEFT

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- Chromomagnetic dipole moment (new @NLO)

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See also a talk on Higgs @ large $p_T$ by K. Kudashkin (Monday afternoon).
**Higgs-Pair with Full $m_T$ Dependence @NLO QCD**

\[ \mathcal{L} = -m_t \left( c_t \frac{h}{v} + c_{tt} \frac{h^2}{v^2} \right) \bar{t} t - c_{hhh} \frac{m_h^2}{2v} h^3 + \frac{\alpha_s}{8\pi} \left( c_{ggh} \frac{h}{v} + c_{gghh} \frac{h^2}{v^2} \right) G^a_{\mu\nu} G^{a,\mu\nu} \]

- NLO [Gröber, Mühlleitner, Spira, Streicher'15] [Gröber, Mühlleitner, Spira'17] and NNLO [de Florian, Fabre, Mazzitelli'17] calculations in the EFT framework in the $m_T \rightarrow \infty$ limit show rather flat K-factors w.r.t. variation of the coupling.

- K-factors calculated with full mass dependence can be large and non-uniform as couplings varied [Buchalla et al.'18].

- $m_{hh}$ and $p_T$ distributions highly discriminative.
NLO \cite{Grober:2015, Muhlleitner:2015} and NNLO \cite{deFlorian:2017} calculations in the EFT framework in the $m_t \to \infty$ limit show rather flat K-factors w.r.t. variation of the coupling.

K-factors calculated with full mass dependence can be large and non-uniform as couplings varied \cite{Buchalla:2018}.

$m_{hh}$ and $p_T$ distributions highly discriminative.
**Higgs Strahlung for BSM**

\[ \sigma_{VH} = \sigma_{DY}^{VH} + \sigma_{\text{non-DY}}^{VH} \]

**SM:**

- Diagrams for SM processes involving Higgs production.

**BSM:**

- **2HDM/MSSM**
  - Diagrams involving anomalous Higgs boson production.
- **MSSM**
  - Diagrams involving MSSM-like Higgs boson production.

- Vector-like quarks
- Dim.-6 operators

- Implemented in \( v \hbar@n\hbar@o-v2 \) [Harlander, Klappert, Liebler, Simon’18]

- Ratio sensitive to non-DY component -> probe of BSM [Harlander, Klappert, Pandini, Papaefstathiou’18]

A. Kulesza, QCD corrections to BSM signals at the LHC

QCD@LHC18, TU Dresden
Looking for possible deviations from the SM

- model-independent theoretical framework of effective field theories
- SMEFT: Standard Model with higher dimensional operators

\[ \mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i + O(\Lambda^{-4}) + h.c., \]

same operators also probed in $H$, $Hj$ and $HH$ production $\leftrightarrow$ cross-talk
Total cross sections:

\[ \sigma = \sigma_{SM} + \sum_i \frac{1}{\Lambda^2} C_i \sigma_i + \sum_{i \leq j} \frac{1}{\Lambda^4} C_i C_j \sigma_{ij}. \]

K-factors depend on the eff. operator, corrections up to 60%.

Renormalization and factorization scale variation dominant uncertainty, substantially reduced @NLO

\( \mu_0^{R,F}/2 < \mu_F = \mu_R < 2 \mu_0^{R,F} \)

\( \mu_0^{EFT}/2 < \mu^{EFT} < 2 \mu_0^{EFT} \)

pdf uncertainty
NLO QCD to TTH in the EFT

\[ \sigma = \sigma_{SM} + \sum_i \frac{1}{\Lambda^2} T_i \sigma_i + \sum_{i \leq j} \frac{1}{\Lambda^4} C_i C_j \sigma_{ij}. \]

Total cross sections:

\[
\begin{align*}
\mu_0^{R,F} &= m_t + m_H/2 \\
\mu_0^{EFT} &= m_t
\end{align*}
\]

[Maltoni, Vryniidou, Zhang’16]

\( \mu_0^{R,F}/2 < \mu_F = \mu \)

A. Kulesza, QCD corrections to BSM signals at the LHC
COLOURED SECTOR
SUSY @ the LHC

MSSM: minimal content of SUSY particles + R-parity

Hadron colliders: coloured sparticles most copiously produced

High rates for pair-production of squarks and gluinos

\[ p \bar{p} \rightarrow \tilde{t}_k \bar{t}_k, \tilde{q} \bar{q}, \tilde{q} \bar{q}, \tilde{g} \tilde{g}, \tilde{g} \tilde{g} \]

Key discovery processes in SUSY searches
**Problem:** at higher orders in QCD, large corrections of the form \( \alpha_s^n \log^m \left( 1 - 4m^2 / \hat{s} \right) \) with \( m \leq 2n \)

\[
\begin{align*}
\sigma_{\text{tot}}[\text{pb}]: \text{pp} \to \text{SUSY} \\
\sqrt{s} = 13 \text{ TeV} \\
\text{NLO+NLL}
\end{align*}
\]

- standard tool to evaluate total cross section in SUSY, used in 100+ experimental analysis of Run 1 and Run 2

[AK and L. Motyka, Phys. Rev. Lett. 102, 111802 (2009)]
[M. Krämer, AK, R. van der Leeuw, M. Mangano, S. Padhi, T. Plehn, X. Portell’12]
[C. Borschensky, M. Krämer, AK, M. Mangano, S. Padhi, T. Plehn, X. Portell’14]
Squarks and Gluinos at NNLL

- NNLL resummation of soft gluon corrections combined with Coulomb resummation (NRQCD approach with NLO potential) and LO bound states corrections below threshold.

- Significant increase of the total cross section for almost all processes of squark and gluino production.

- Scale variation error decreases due to including NNLL terms down to 5-10%.

- Public tool to calculate NNLL+NNLO approx cross sections at 13 TeV: **NNLL-fast**

---

[Beenakker, S. Brensing, M. Krämer, AK, E. Laenen, L. Motyka and I. Niessen'11] [Beenakker, Borschensky, Krämer, AK, Laenen, Thewes, Theeuwes’14] [Beenakker, Borschensky, Heger, Krämer, AK, Laenen’16][Beenakker, Borschensky, Krämer, AK, Laenen’16]
THE ULTIMATE NNLL

**NNLO\textsubscript{Approx}+NNLL calculations also performed in the SCET framework** [Beneke, Piclum, Schwinn, Wever’16]

![Graph showing K_X (pp \rightarrow \bar{q}g + X) results.]

\[ K_X (pp \rightarrow \bar{q}g + X) \]
\[ \sqrt{S} = 8 \text{ TeV} \]

- **NNLO\textsubscript{Approx}+NNLL+Coul+BS**
- **NNLO\textsubscript{Approx}+NNLL+Coul**
- **NNLO\textsubscript{Approx}+NNLL**
- **NNLL (SCET)**
- **NNLL\textsubscript{fixed-c} (SCET)**

- Work in progress: comparison of the results with the predictions obtained in the SCET framework

[Beneke, Borschensky, Krämer, AK, Piclum, Schwinn, Wever, in prep.]
NNLO_{Approx}+NNLL calculations also performed in the SCET framework \cite{Beneke-Piclum-Schwinn-Wever16}

\[ K_X(pp \to \tilde{q}\tilde{g} + X) \]
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\begin{align*}
\text{NNLO}_{\text{Approx}}+\text{NNLL} & + \text{Coul} + \text{BS} \\
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\text{NNLL} (\text{SCET}) & \\
\text{NNLL}_{\text{fixed} - c} (\text{SCET}) &
\end{align*}

Work in progress: comparison of the results with the predictions obtained in the SCET framework

Gluino-gaugino production known at NLO+NLL \cite{Fuks-Klasen-Rothering16}, squark-gaugino only at NLO \cite{Plehn04}
In search of DM @ the LHC

In MSSM with R-parity, neutralino (mixture of superpartners of Higgs and Z bosons) is a DM candidate

Direct pair production difficult to observe $\rightarrow$ need a visible particle to recoil against $\rightarrow$ “mono-X” searches ($X=$ jet, Z, photon,...)

NLO SUSY-QCD corrections to $pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 j$
first considered in [Cullen, Greiner, Heinrich’13]

NLO SUSY QCD matched to PS (in POWHEG-BOX)
$pp \rightarrow \tilde{\chi}_i \tilde{\chi}_j j$, result including a scheme to remove on-shell single and double resonances in [Baglio, Jäger, Kesenheimer’17]

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MRSSM model [Kribs, Poppitz, Werner’07]:
unbroken, continuous R-symmetry (additional symmetry allowed by SUSY algebra)

solves the SUSY flavour problem, consistent with EW precision observables, Higgs mass
and and LHC EW searches [Diessner, Kalinowski, Kotlarski, Stöckinger’15-16],
provides a candidate for a DM particle, viable parameter space

MRSSM phenomenology different from
MSSM: R-charge conservation imposes
constraints on the allowed chiralities of SUSY final states

MRSSM: \( u \rightarrow \bar{u}_L \) vs MSSM: \( u \rightarrow \bar{u}_L \bar{u}_L \bar{u}_R \)
squark production rates lower in MRSSM

MRSSM K-factors?
SUSY QCD corrections to squark-squark and squark-antisquark pair production

The 10-20% difference in K-factors generally does not compensate the decrease in the LO rates at large squark masses -> avoids detection
Sgluons: coloured scalar partners of the gluons in the adjoint representation of the QCD gauge group

- Appear in the non-minimal versions (e.g. hybrid N=1/N=2, R-symmetric) SUSY, extra dimensions, ...

- Ongoing searches at the LHC

- Studies of sgluon pair production @NLO QCD in simplified models [Goncalves Netto et al.’12] [Degrande et al.’14] [Beck et al.’15] [Kotlarski’16] [Darme, Fuks, Goodsell’18]

For NLO results on massive colour octet vector (coloron) production see [Sekhar Chivukula et al. ‘11-Freytas, Wieland’17]

A. Kulesza, QCD corrections to BSM signals at the LHC
Vector-like quarks: fermions with LH and RH components in the same representation of the EW symmetry group

- Appears e.g. in extra dimension models, composite/little Higgs models
- Single and pair production modes studied

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<td>EM charge</td>
<td>5/3</td>
<td>2/3</td>
<td>-2/3</td>
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</tr>
<tr>
<td>QCD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NLO QCD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K-factor</td>
<td>~1.5</td>
<td></td>
<td></td>
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<tr>
<td>Scale error</td>
<td>~10%</td>
<td></td>
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Total cross section for $pp \rightarrow T\bar{T}, TT, T\bar{T}$ (TH scenarios)

pure QCD @NNLO+NNLL [Cacciari et al.’11]

EW mode

NLO QCD K-factor ~ 1.5, scale error ~10%

A. Kulesza, QCD corrections to BSM signals at the LHC

QCD@LHC18, TU Dresden
Vector-like quarks: fermions with LH and RH components in the same representation of the EW symmetry group

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Credit: A. Modak

Large K-factors, new qg channel opens up
Meanwhile...

... in the land of flavour...

\[ R(D^*) = \frac{B(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{B(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)} \]

\[ R_{K(*)} = \frac{\Gamma(\bar{B} \to K^{(*)}\mu^+\mu^-)}{\Gamma(\bar{B} \to K^{(*)}e^+e^-)} \]

A. Kulesza, QCD corrections to BSM signals at the LHC

QCD@LHC18, TU Dresden
MEANWHILE...

... in the land of flavour...

\[ \mathcal{R}(D^*) = \frac{\mathcal{B}(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^* \ell^- \bar{\nu}_\ell)} \]

\[ R_{K(*)} = \frac{\Gamma(\bar{B} \to K^{(*)} \mu^+ \mu^-)}{\Gamma(\bar{B} \to K^{(*)} e^+ e^-)} \]

see talk on Thursday afternoon by Ch. Langenbruch
Meanwhile...

... in the land of flavour...

\[ \mathcal{R}(D^*) = \frac{B(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)}{B(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)} \]
Meanwhile...

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R(D^*) = \frac{B(\bar{B} \to D^* \tau^- \bar{\nu}_\tau)}{B(\bar{B} \to D^* \ell^- \bar{\nu}_\ell)}
\]

BSM ?
† Leptoquarks (LQ): colour-triplet bosons simultaneously coupling to leptons and quarks at tree level

† Naturally arising in GUT models, also appear in composite Higgs models, R-parity violating SUSY, ...

† Under SM gauge group, six scalar and six vector multiplets -- singlets, doublets or triplets of SU(2)

† Many analyses attempting to explain flavour anomalies with LQs [...] ; not a clear-cut case [Buttazzo, Greljo, Isidori, Marzocca’17]

† LQs can be produced directly at the LHC through pair- or single production -> complementarity!
NLO corrections to scalar LQ pair-production [Krämer, Plehn, Spira, Zerwas’04] return substantial K-factors

K-factors for differential distributions only moderately vary [Mandal, Mitra, Seth’15]

Single scalar production [Dorsner, Greljo’18] and single vector production [Hammett, Ross’15] known at NLO

When LQ decay added, important effects from the non-factorizable contribution and q{bar}q channel opening up, NWA cannot be trusted!
Ideally, need to cover the widest possible range of parameter space.

Separate calculations for each model/observable very inefficient.
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BSM predictions with QCD corrections.

BSM Lagrangian

Nuts and bolts:

*) Lagrangian translator into a model

*) Automated NLO technology (based on SM version)

*) Renormalization
Ideally, need to cover the widest possible range of parameter space

Separate calculations for each model/observable very inefficient

In short: very quick and promising progress!

*) Beyond NLO and resummation need a dedicated implementation: SusHi, vh@nnlo, NNLL-fast, ...

BSM Lagrangian

Nuts and bolts:

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*) Automated NLO technology (based on SM version)

*) Renormalization

BSM predictions with QCD corrections

FeynRules, SARAH, ...

MadGraph5_aMC@NLO, Recola2, OpenLoops, Gosam, ...

NLOCT, Rept1l, ..
• Precision BSM predictions needed more than ever

• QCD corrections a very active field, many new results

• Need for precision in the EFT results very well recognized

• Analyses in EFTs, simplified models and complete-UV models are complementary – all avenues need to be explored

• Trickle down effect: advancements in the SM calculations get transferred to the BSM sector

• Recent progress in the NLO automation will allow to test a large range of BSM models / observables

• Exciting times for QCD experts!
SUMMARY

- Precision BSM predictions needed more than ever
- QCD corrections a very active field, many new results
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A. Kulesza, QCD corrections to BSM signals at the LHC
**SOFT GLUON RESUMMATION**

Systematic reorganization of perturbative series

\( \hat{\sigma} \sim c_{00} + \)

\[ + \alpha_s \left( \begin{array}{c}
\alpha_s \log^2 (\beta^2) \\
\alpha_s^2 \log^4 (\beta^2) \\
\ldots
\end{array} \right) + \]

\[ + c_{11} \log (\beta^2) + \]

\[ + c_{12} \log^2 (\beta^2) + \]

\[ + c_{10} \log (\beta^2) + \ldots \]  

\( \xrightarrow{NLO} \)

\[ + c_{23} \log^3 (\beta^2) + \]

\[ + c_{24} \log^4 (\beta^2) + \]

\[ + c_{22} \log^2 (\beta^2) + \ldots \]  

\( \xrightarrow{NNLO} \)

\[ \alpha_s^n \log^{2n}(\beta^2) \]

\[ \alpha_s^n \log^{2n-1}(\beta^2) \]

Factorization at threshold: space of Melin moments \( N \), taken wrt. \( M^2/S \) or \( Q^2/S \)

\[ \hat{\sigma}^{(N)} \sim C(\alpha_s) \exp \left[ L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots \right] \]

sums up

LL: \( \alpha_s^n \log^{n+1}(N) \)

NLL: \( \alpha_s^n \log^n(N) \)
Higher Orders at Threshold

Large masses of SUSY particles ⇒ production close to threshold

\[ \hat{s} \sim 4m^2 \]

General structure of the NLO correction in the threshold limit

\[ \Delta \hat{\sigma}_i^{NLO} \sim \alpha_s \hat{\sigma}_i^{LO} \left\{ A^{(i)} \log^2 (\beta^2) + B^{(i)} \log (\beta^2) + C^{(i)} \frac{1}{\beta} + D^{(i)} \right\} \]

Soft/collinear gluon emission

Coulomb gluons
Large masses of SUSY particles ⇒ production close to threshold

General structure of the NLO correction in the threshold limit

\[ \Delta \hat{\sigma}_i^{\text{NLO}} \sim \alpha_s \hat{\sigma}_i^{\text{LO}} \left\{ A(i) \log^2(\beta^2) + B(i) \log(\beta^2) + C(i) \frac{1}{\beta} + D(i) \right\} \]

- Soft/collinear gluon emission
- Coulomb gluons

At higher orders:

\[ \sim \alpha_s^n \log^{2n}(\beta) \quad \text{and} \quad \sim \alpha_s^n / \beta^n \]

Both types of corrections can be resummed to all orders
REACHING HIGHER: NNLL

Long-term project, started in 2011...

\[ \sigma_{\text{res}} \sim \sigma_0 \otimes \mathcal{C}(\alpha_s) \otimes \exp \left[ Lg_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots \right] \]

\[ L = L(\text{threshold variable}) \]

LL: \[ \sim \sum_n \alpha_s^n L^{n+1} \]

NLL: \[ \sim \sum_n \alpha_s^n L^n \]

NNLL: \[ \sim \sum_n \alpha_s^n L^{n-1} \]

known at NNLL

\[ C(\alpha_s) = C^{\text{Coul}}(\alpha_s) \otimes C^{\text{hard}}(\alpha_s) = 1 + \alpha_s C^{\text{Coul}}_{(1)} + \alpha_s C^{\text{hard}}_{(1)} + \ldots \]

- For NNLL, hard matching coefficients \( C^{\text{hard}} \) need to be known up to \( O(\alpha_s) \) ->
  - [Beenakker, Janssen, Lepoeter, Krämer, AK, Laenen, Niessen, Thewes, Van Dal'13]
  - [Broggio, Ferroglia, Neubert, Vernazza, Yang'13]

- Coulomb corrections \( C^{\text{Coul}} \) at least up to \( O(\alpha_s) \), better: \( O(\alpha_s^2) \), even better: resummed to all orders

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