NLO QCD with Massive Quarks

An extension of the NSC subtraction scheme

Bachelor Degree in Physics

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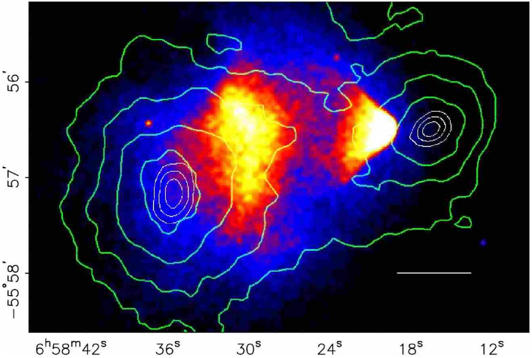
Precision estimates at the LHC

Evidence for Beyond-Standard-Model physics



Main BSM evidence

- dark matter and dark energy
- matter-antimatter asymmetry
- neutrino masses

Figure from Clowe et al. 2006.
Offset between the observed baryonic mass distribution and the gravitational potential in the Bullet Cluster (1E 0657-56).

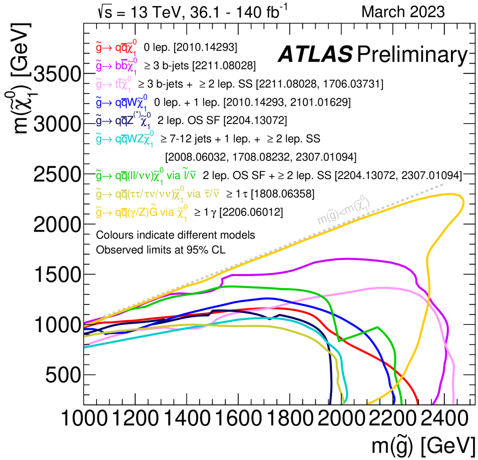
Precision estimates at the LHC

BSM constraints and shift in research paradigm

Main BSM proposals

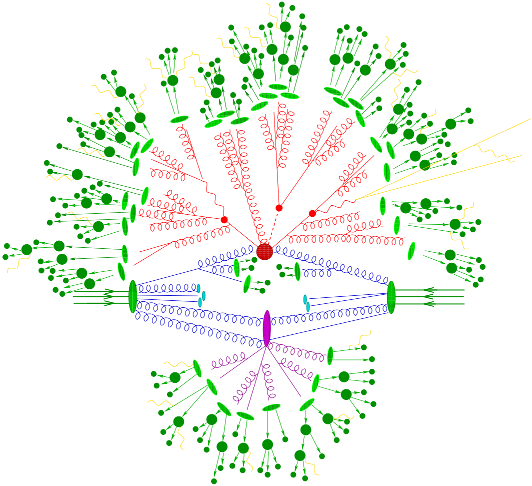
- supersymmetric models (MSSM, ...)
- dark matter models (WIMPs, axions, ...)
- extended gauge sectors ($SO(10)$, ...)
- SM Effective Field Theory (SMEFT)

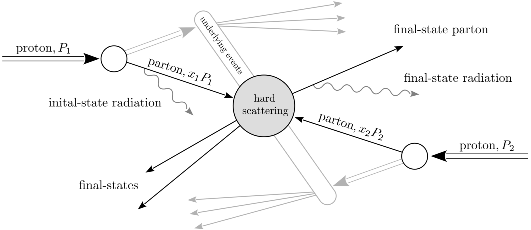
Figure from ATLAS PUB Note 2023-025. Exclusion limits in the $\tilde{g} - \tilde{\chi}_1^0$ mass plane for various models for the decay of the gluino to the lightest supersymmetric particle.



Precision estimates at the LHC

Factorization theorem and perturbative QCD





Figures from Höche 2015 (left) and Asteriadis 2021 (right).
Hadronization of jets produced in hadronic scattering and detail of the underlying hard partonic scattering.

Precision estimates at the LHC

Factorization theorem and perturbative QCD

Hadronic and partonic physics decouple in hard scattering processes, and we can formulate a factorization theorem:

$$\mathrm{d}\sigma_{h_1,h_2}(P_1,P_2) = \sum_{a,b}\int_{[0,1]^2}\frac{\mathrm{d}\xi_1}{\xi_1}\frac{\mathrm{d}\xi_2}{\xi_2} f_a^{(h_1)}(\xi_1,\mu_\mathsf{F}^2) f_b^{(h_2)}(\xi_2,\mu_\mathsf{F}^2)\times$$

$$\times\, \mathrm{d}\hat{\sigma}_{a,b}(\xi_1 P_1,\xi_2 P_2,\alpha_\mathsf{s},\mu_\mathsf{R}^2,\mu_\mathsf{F}^2)\left[1 + o\left(\frac{\Lambda_\mathsf{QCD}^n}{Q^n}\right)\right]$$

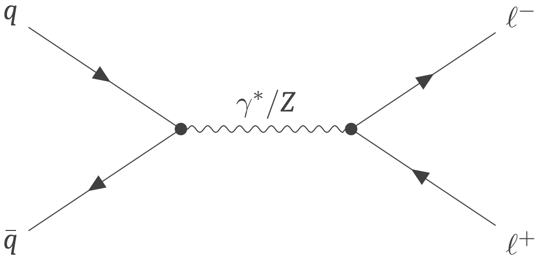
Asymptotic freedom allows for a perturbative analysis of the hard partonic scattering:

$$\mathrm{d}\hat{\sigma}_{a,b}(p_1,p_2) = \sum_{n\in\mathbb{N}_0}\mathrm{d}\hat{\sigma}_{a,b}^{(n)}(p_1,p_2)$$

$n \geq 1$ are denoted by N^{n}LO QCD corrections.

IR-pole structure of QCD
Radiative corrections to partonic processes

Our focus is on NLO QCD corrections. Consider e.g. the Drell-Yan process:



LO process

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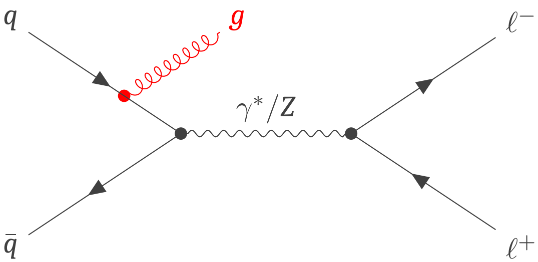

Real correction

IR-pole structure of QCD

Radiative corrections to partonic processes

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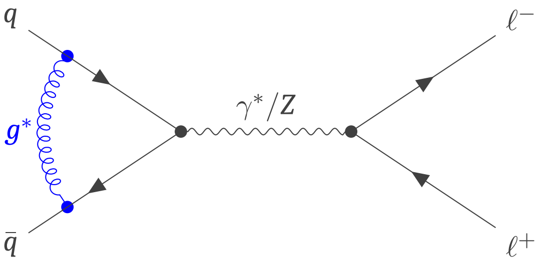


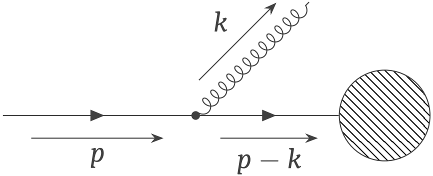
Virtual correction

IR-pole structure of QCD

Infrared singularities of scattering amplitudes

Main difficulty: infrared singularities in particular kinematic regimes.

Example in real corrections:



$$\sim \quad \frac{1}{(p-k)^2} = -\frac{1}{2E_p E_k(1-\cos\theta)}$$

IR-pole structure of QCD

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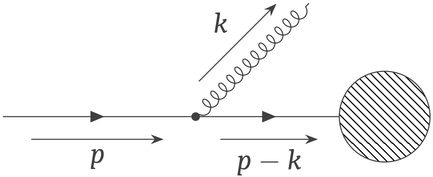

$$\sim \quad \frac{1}{(p-k)^2} = -\frac{1}{2E_p \textcolor{red}{E_k}(1-\cos\theta)}$$

Soft singularity: $E_k \to 0$

IR-pole structure of QCD

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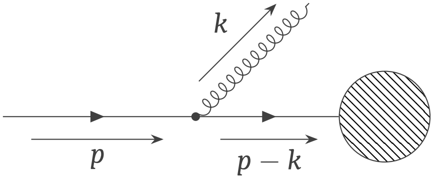
Example in real corrections:



$$\sim \quad \frac{1}{(p-k)^2} = -\frac{1}{2E_pE_k(1-\cos\theta)}$$

Collinear singularity: $\theta \to 0$

IR-pole structure of QCD

Dimensional regularization

The key idea to regularize IR divergences is dimensional regularization:

$$d = 4 - 2\epsilon \quad , \quad \epsilon \in \mathbb{C} : \Re\epsilon < 0$$

Then, soft and collinear singularities are expressed as poles in ϵ:

$$\int \frac{\mathrm{d}^{d-1}k}{(2\pi)^{d-1}2E_k} \left|\mathcal{A}(p_k)\right|^2 \sim \int_0^{\mathcal{E}} \frac{\mathrm{d}E_k}{E_k^{5-d}} \int_0^{\pi} \mathrm{d}\theta \frac{\sin^{d-3}\theta}{1-\cos\theta} \left|\mathcal{A}_0\right|^2$$

IR-pole structure of QCD

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soft singularity $= -\dfrac{\mathcal{E}^{-2\epsilon}}{2\epsilon}$

IR-pole structure of QCD

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soft singularity $= -\dfrac{\mathcal{E}^{-2\epsilon}}{2\epsilon}$

collinear singularity $= -\dfrac{2^{-2+\epsilon}}{\epsilon}$

IR-pole structure of QCD

Subtraction schemes

ϵ-poles can be extracted from partonic cross-sections via subtraction methods.
General idea using a regular function $f(x)$:

$$I = \int_0^1 \frac{\mathrm{d}x}{x^{1+\epsilon}} f(x) = \int_0^1 \frac{\mathrm{d}x}{x^{1+\epsilon}} \left[f(x) - f(0)\right] + f(0) \int_0^1 \frac{\mathrm{d}x}{x^{1+\epsilon}}$$

- $\dfrac{f(x) - f(0)}{x^{1+\epsilon}}$ regular at $x = 0$, so it can be numerically integrated with $\epsilon \to 0$;
- $f(0) \displaystyle\int_0^1 \frac{\mathrm{d}x}{x^{1+\epsilon}} = -\frac{f(0)}{\epsilon}$ contains the explicit ϵ-pole.

Our aim is finding the most general subtraction terms $f(0)$ for partonic scattering.

NSC subtraction scheme

Sequential extraction of singularities

The Nested Soft-Collinear (NSC) Subtraction Scheme (SS) at NLO is modular and local:

- singular limits extracted by operators: S_i soft limit $E_i \to 0$, C_{ij} collinear limit $\theta_{ij} \to 0$;

NSC subtraction scheme

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- first soft singularities removed applying $\overline{\mathsf{S}}_{\mathfrak{m}} \equiv \mathrm{id} - \mathsf{S}_{\mathfrak{m}}$, then collinear ones removed using $\overline{\mathsf{C}}_{i\mathfrak{m}} \equiv \mathrm{id} - \mathsf{C}_{i\mathfrak{m}}$, with $\mathfrak{m}$ unresolved parton;

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- IR-safe part of cross-section extracted by:

$$\mathrm{O}^{\mathfrak{m}}_{\mathrm{NLO}} := \sum_{i \in \mathcal{H}^n_{m,0}} \overline{\mathrm{S}}_{\mathfrak{m}} \overline{\mathrm{C}}_{i\mathfrak{m}} \omega^{\mathfrak{m}i}$$

NSC subtraction scheme
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- counterterms contain the IR divergences.

NSC subtraction scheme

IR-safe cross-section

The total ϵ-finite NLO cross-section can be written as:

$$\mathrm{d}\hat{\sigma}^{(1)}_{a,b} = \mathrm{d}\hat{\sigma}^{\text{NLO,reg}}_{a,b} + \frac{1}{2\hat{s}} \sum_{n \in \mathcal{G}_m} \left[\frac{\alpha_{\mathrm{s}}(\mu_{\mathrm{R}}^2)}{2\pi} \left\langle I_{\mathrm{T}}^{(0)} \mathcal{F}_{a,b}[\mathcal{X}_m^n] \right\rangle + \left\langle \mathcal{F}^{\text{fin}}_{a,b}[\mathcal{X}_m^n] \right\rangle \right]$$

$$+ \frac{\alpha_{\mathrm{s}}(\mu_{\mathrm{R}}^2)}{2\pi} \sum_c \left[P^{\text{gen}}_{f_c,f_a} \otimes \mathrm{d}\hat{\sigma}^{(0)}_{c,b} + P^{\text{gen}}_{f_c,f_b} \otimes \mathrm{d}\hat{\sigma}^{(0)}_{a,c} \right]$$

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- NLO final reminder, defined using $\mathrm{O}^{\mathfrak{m}}_{\mathrm{NLO}}$;

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NSC subtraction scheme

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- NLO final reminder, defined using $\mathrm{O}^{\mathfrak{m}}_{\text{NLO}}$;
- finite counterterm from virtual corrections;
- finite counterterm from PDF renormalization;

NSC subtraction scheme

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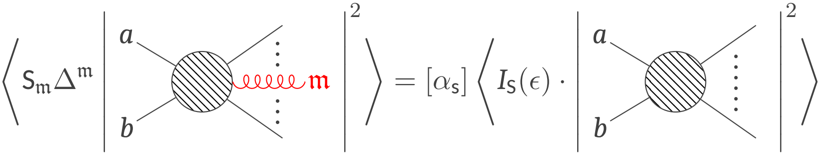
- NLO final reminder, defined using $\mathrm{O}^{\mathfrak{m}}_{\text{NLO}}$;
- finite counterterm from virtual corrections;
- finite counterterm from PDF renormalization;
- counterterm we are interested in.

NSC subtraction scheme

Pole extraction through operators

Soft singularities



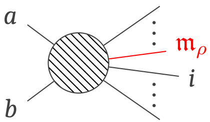
$$I_S(\epsilon) := -\frac{1}{\epsilon^2}\left(\frac{2\mathcal{E}}{\mu}\right)^{-2\epsilon}\frac{\Gamma^2(1-\epsilon)}{\Gamma(1-2\epsilon)}\sum_{i\neq j\in\mathcal{X}^n_{m,0}}\eta_{ij}\left(\mathbf{T}_i\cdot\mathbf{T}_j\right){}_2F_1(1,1,1-\epsilon,1-\eta_{ij})$$

NSC subtraction scheme

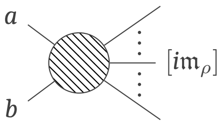
Pole extraction through operators

Hard-collinear singularities

$$\sum_{\rho=1}^{2n_f+1}\ \sum_{i\in\mathcal{H}^n_{m,0}(\mathfrak{m}_\rho)} \Bigg\langle \bar{\mathsf{S}}_{\mathfrak{m}}\mathsf{C}_{i\mathfrak{m}_\rho}\Delta^{\mathfrak{m}_\rho} \Bigg|$$



$$\Bigg|^2 \Bigg\rangle \sim [\alpha_s] \Bigg\langle I_{\mathsf{C}}(\epsilon)\cdot \Bigg|$$



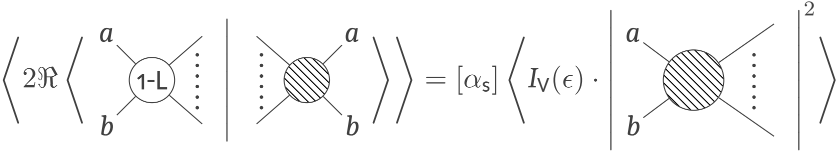
$$\Bigg|^2 \Bigg\rangle$$

$$I_{\mathsf{C}}(\epsilon) := \sum_{i\in\mathcal{H}^n_{m,0}} \frac{\Gamma_{i,f_i}}{\epsilon} = \frac{1}{\epsilon}\sum_{i\in\mathcal{H}^n_{m,0}}\left[\gamma_i + 2\mathbf{T}_i^2\log\frac{\mathcal{E}}{E_i}\right] + o(\epsilon^0)$$

NSC subtraction scheme

Pole extraction through operators

Virtual singularities



$$I_{\mathsf{V}}(\epsilon) \equiv \sum_{i \neq j \in \mathcal{X}^n_{m,0}} (\mathbf{T}_i \cdot \mathbf{T}_j) \left(\frac{\mu^2}{2 p_i \cdot p_j} \right)^{\epsilon} \cos\left(\lambda_{ij} \pi \epsilon\right) \left[\frac{1}{\epsilon^2} + \frac{1}{\mathbf{T}_i^2} \frac{\gamma_i}{\epsilon} \right]$$

NSC subtraction scheme

Pole cancellation: $I_{\mathrm{S}}(\epsilon) + I_{\mathrm{V}}(\epsilon)$

$$I_{\mathrm{S+V}} = \sum_{i \neq j \in \mathcal{X}^n_{m,0}} (\mathbf{T}_i \cdot \mathbf{T}_j) \left[-\frac{1}{\epsilon^2} \left(\frac{2\mathcal{E}}{\mu} \right)^{-2\epsilon} K_{ij} + \left(\frac{\mu^2}{2p_i \cdot p_j} \right)^{\epsilon} \cos\left(\lambda_{ij}\pi\epsilon\right) \left(\frac{1}{\epsilon^2} + \frac{1}{\mathbf{T}_i^2} \frac{\gamma_i}{\epsilon} \right) \right]$$

$$\equiv \frac{\Gamma^2(1-\epsilon)}{\Gamma(1-2\epsilon)} \eta_{ij}\, {}_2F_1(1,1,1-\epsilon,1-\eta_{ij}) = 1 - \epsilon \log \eta_{ij} + o(\epsilon^2)$$

$$= \sum_{i \neq j \in \mathcal{X}^n_{m,0}} (\mathbf{T}_i \cdot \mathbf{T}_j) \frac{1}{\epsilon^2} \left(\frac{2\mathcal{E}}{\mu} \right)^{-2\epsilon} \left[-1 + \epsilon \log \eta_{ij} + \left(\frac{\mathcal{E}^2}{E_i E_j} \right)^{\epsilon} \eta_{ij}^{-\epsilon} \cos\left(\lambda_{ij}\pi\epsilon\right) \left(1 + \epsilon \frac{\gamma_i}{\mathbf{T}_i^2} \right) \right] + o(\epsilon^0)$$

$$= \frac{1}{\epsilon} \sum_{i \neq j \in \mathcal{X}^n_{m,0}} (\mathbf{T}_i \cdot \mathbf{T}_j) \left(L_i + L_j + \frac{\gamma_i}{\mathbf{T}_i^2} \right) + o(\epsilon^0) = -\frac{1}{\epsilon} \sum_{i \in \mathcal{H}^n_{m,0}} \left(\gamma_i + 2\mathbf{T}_i^2 L_i \right) + o(\epsilon^0)$$

NSC subtraction scheme

Pole cancellation: $I_{\mathsf{T}}(\epsilon)$

Compare:

$$I_{\mathsf{S+V}}(\epsilon) = -\frac{1}{\epsilon} \sum_{i \in \mathcal{H}^n_{m,0}} \left(\gamma_i + 2\mathbf{T}_i^2 L_i\right) + I^{(0)}_{\mathsf{S+V}} + o(\epsilon)$$

$$I_{\mathsf{C}}(\epsilon) = +\frac{1}{\epsilon} \sum_{i \in \mathcal{H}^n_{m,0}} \left(\gamma_i + 2\mathbf{T}_i^2 L_i\right) + I^{(0)}_{\mathsf{C}} + o(\epsilon)$$

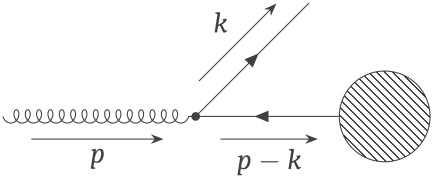
Hence:

$$I_{\mathsf{T}}(\epsilon) \equiv I_{\mathsf{S}}(\epsilon) + I_{\mathsf{C}}(\epsilon) + I_{\mathsf{V}}(\epsilon) = I^{(0)}_{\mathsf{T}} + o(\epsilon)$$

NSC SS with massive quarks

Mass-regualtion of soft and collinear limits

Massive partons do not determine soft or collinear singularities:



$$\sim \quad \frac{1}{(p-k)^2 - m^2} = -\frac{1}{2E_p\left(E_k - |\mathbf{k}|\cos\theta\right)}$$

Clearly, no more collinear singularities as $E_k \neq |\mathbf{k}|$ for $m \neq 0$.
The soft limit is non-singular even in the massless case.

NSC SS with massive quarks

Generalized soft operator

- In presence of final-state massive partons, $I_{\mathrm{S}}(\epsilon)$ becomes:

$$I_{\mathrm{S}}(\epsilon) = \frac{1}{2\epsilon}\left(\frac{2\mathcal{E}}{\mu}\right)^{-2\epsilon}\frac{\Gamma^2(1-\epsilon)}{\Gamma(1-2\epsilon)}\sum_{i,j\in\mathcal{X}^n_{m,0}}(\mathbf{T}_i\cdot\mathbf{T}_j)I_{i,j}(\epsilon)$$

NSC SS with massive quarks

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- $I_{i,j}(\epsilon)$ depends on the nature (massive or massless) of partons i and j;

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- $I_{i,j}(\epsilon)$ depends on the nature (massive or massless) of partons i and j;
- $I_{i,j}(\epsilon)$ is singular as $\sim\epsilon^{-1}$ if at least one parton is massless, otherwise it is ϵ-finite;
- ϵ^{-2}-poles of $I_{\mathrm{S}}(\epsilon)$ are determined only by massless partons.

NSC SS with massive quarks

Generalized virtual operator

- In presence of final-state massive partons, $I_{\mathsf{S}}(\epsilon)$ becomes:

$$I_{\mathsf{V}}(\epsilon) := \Re I_1(\epsilon) = \sum_{i \neq j \in \mathcal{X}^n_{m,0}} (\mathbf{T}_i \cdot \mathbf{T}_j) \left(\frac{\mu^2}{|s_{ij}|} \right)^{\epsilon} \left[\mathcal{V}_{i,j}(\epsilon) - \frac{1}{v_{ij}} \frac{\pi^2}{2} \theta(s_{ij}) \right] - \sum_{i \in \mathcal{X}^n_{m,0}} \Gamma_i(\epsilon)$$

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- $\Gamma_i(\epsilon)$ is ϵ^{-1}-singular;
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Pole cancellation: generalized pole terms in $I_{\mathrm{S}}(\epsilon) + I_{\mathrm{V}}(\epsilon)$

It is convenient to group summations as follows:

$$
\begin{aligned}
I_{\mathrm{S+V}}(\epsilon) &= \sum_{i,j \in \mathcal{X}^n_{m,0}} I^{i,j}_{\mathrm{S}}(\epsilon) + \sum_{i \neq j \in \mathcal{X}^n_{m,0}} \tilde{I}^{i,j}_{\mathrm{V}}(\epsilon) - \sum_{i \in \mathcal{X}^n_{m,0}} \Gamma_i(\epsilon) \\
&= \sum_{i \neq j \in \mathcal{X}^n_{m,0}} \left[I^{i,j}_{\mathrm{S}}(\epsilon) + \tilde{I}^{i,j}_{\mathrm{V}}(\epsilon) \right] + \sum_{i \in \mathcal{X}^n_{m,\mathrm{m}}} \left[I^{i,i}_{\mathrm{S}}(\epsilon) - \Gamma_i(\epsilon) \right] - \sum_{i \in \mathcal{H}^n_{m,0}} \Gamma_i(\epsilon)
\end{aligned}
$$

Then, ϵ^{-2}-singularities are only present in the first sum:

$$
I^{i,j}_{\mathrm{S}}(\epsilon) + \tilde{I}^{i,j}_{\mathrm{V}}(\epsilon) = \chi_{i,j} + \text{Ж}_{i,j} + o(\epsilon)
$$

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Laurent expansion: pole terms and ϵ-finite finite reminder.

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Pole cancellation: quadratic pole terms

Quadratic pole terms have a complex general form:

$$\chi_{i,j} \equiv \frac{1}{\epsilon^2}\left(\frac{1}{2}I_{i,j}^{(-1)} + \mathcal{V}_{i,j}^{(-2)}\right) + \frac{1}{\epsilon}\left(\frac{1}{2}I_{i,j}^{(0)} + \mathcal{V}_{i,j}^{(-1)} - \mathscr{L}_{\mathrm{m}} I_{i,j}^{(-1)} + \mathcal{V}_{i,j}^{(-2)} \log\frac{\mu^2}{|s_{ij}|}\right)$$

However, with further manipulation, the explicit structure is simple:

$$\chi_{i,j} = \begin{cases} 0 & i,j \text{ massive} \\ \frac{1}{\epsilon}L_j & i \text{ massive}, j \text{ massless} \\ \frac{1}{\epsilon}L_i & i \text{ massless}, j \text{ massive} \\ \frac{1}{\epsilon}\left(L_i + L_j\right) & i,j \text{ massless} \end{cases} \qquad L_k \equiv \log\frac{\mathcal{E}}{E_k}$$

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Pole cancellation: Catani's anomalous dimensions

The sum over $\mathcal{X}^n_{m,\mathrm{m}}$ in $I_{\mathrm{S+V}}(\epsilon)$ is manifestly ϵ-finite:

$$\sum_{i\in\mathcal{X}^n_{m,\mathrm{m}}}\left[I_{\mathrm{S}}^{i,i}(\epsilon)-\Gamma_i(\epsilon)\right]=\sum_{i\in\mathcal{X}^n_{m,\mathrm{m}}}\left[C_{\mathrm{F}}\left(\frac{1}{\epsilon}-\frac{1}{\kappa_i}\log\frac{1-\kappa_i}{1+\kappa_i}-2\mathscr{L}_{\mathrm{m}}\right)\right.$$

$$\left.-C_{\mathrm{F}}\left(\frac{1}{\epsilon}+\frac{1}{2}\log\frac{m^2_{Q_i}}{\mu^2}-2\right)\right]\equiv\sum_{i\in\mathcal{X}^n_{m,\mathrm{m}}}Д_i$$

Finally, the poles in Catani's generalized anomalous dimensions are isolated by definition:

$$\sum_{i\in\mathcal{H}^n_{m,0}}\Gamma_i(\epsilon)=\sum_{i\in\mathcal{H}^n_{m,0}}\left(\frac{1}{\epsilon}\gamma_i+Ц_i\right)\qquad\qquad Ц_i\equiv-\delta_{f_i,g}\frac{2}{3}T_{\mathrm{R}}\sum_{\rho=1}^{n_F}\log\frac{m^2_{Q_\rho}}{\mu^2}$$

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Pole cancellation: generalized integrated counterterms

Puttin geverything together, using colour-conservation we find:

$$I_{\mathsf{S+V}}(\epsilon) = -\frac{1}{\epsilon} \sum_{i \in \mathcal{H}^n_{m,0}} \left(\gamma_i + 2\mathbf{T}_i^2 L_i\right) + I^{(0)}_{\mathsf{S+V}} + o(\epsilon)$$

$$I_{\mathsf{C}}(\epsilon) = +\frac{1}{\epsilon} \sum_{i \in \mathcal{H}^n_{m,0}} \left(\gamma_i + 2\mathbf{T}_i^2 L_i\right) + I^{(0)}_{\mathsf{C}} + o(\epsilon)$$

The total operator $I_{\mathsf{T}} \equiv I_{\mathsf{S}} + I_{\mathsf{C}} + I_{\mathsf{V}}$ is the ϵ-finite, and the integrated counterterms read:

$$I^{(0)}_{\mathsf{T}} = \sum_{i \neq j \in \mathcal{X}^n_{m,0}} (\mathbf{T}_i \cdot \mathbf{T}_j)\text{Ж}_{i,j} + \sum_{i \in \mathcal{X}^n_{m,\mathrm{m}}} \text{Д}_i - \sum_{i \in \mathcal{H}^n_{m,0}} \text{Ц}_i - \sum_{i \in \mathcal{H}^n_{m,0}} \left[2\mathscr{L}_i \left(\gamma_i + 2\mathbf{T}_i^2 L_i\right) + 2\mathbf{T}_i^2 L_i^2\right]$$
$$+ (N_q + N_{\bar{q}}) \frac{C_{\mathtt{F}}}{6} \left(39 - 4\pi^2\right) + N_g \left[\frac{C_{\mathtt{A}}}{9} \left(67 - 6\pi^2\right) - \frac{23}{9} T_{\mathsf{R}} n_f\right]$$

Conclusions

Results and future developments

Main results

- proof of IR-poles cancellation even with generic massive final-state partons
- computation of generalized integrated counterterms

Future developments

- extension to NNLO in the NSC SS
- inclusion of initial-state massive partons
- resummation of massive logarithms
- application to heavy-quark processes

Figure from CMS Report CERN–EP 2025–025. Example Feynman diagram of non-resonant mono-t production at tree-level mediated by a spin-1 boson M, which decays directly into a dark-matter pair $\chi\bar{\chi}$.