GENEVA: Colour singlet + 1jet Event Generation

Davide Napoletano, QCD@LHC ’24, Freiburg 08/10/24

Intro

- GENEVA: fully differential event generator at NNLO + PS accuracy

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In principle completely agnostic on the final state!

- In practice, many ingredients are required and many possible technical difficulties may arise in doing so

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- GENEVA: fully differential event generator at NNLO + PS accuracy

In principle completely agnostic on the final state!

- In practice, many ingredients are required and many possible technical difficulties may arise in doing so

Which comprises the work of many more people than just a single speaker!

GENEVA: Towards colour singlet + 1jet Event Generation

Davide Napoletano, QCD@LHC ’24, Freiburg 08/10/24

Ministero dell’Università e della Ricerca

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN Istituto Nazionale di Fisica Nucleare

Intro: Geneva

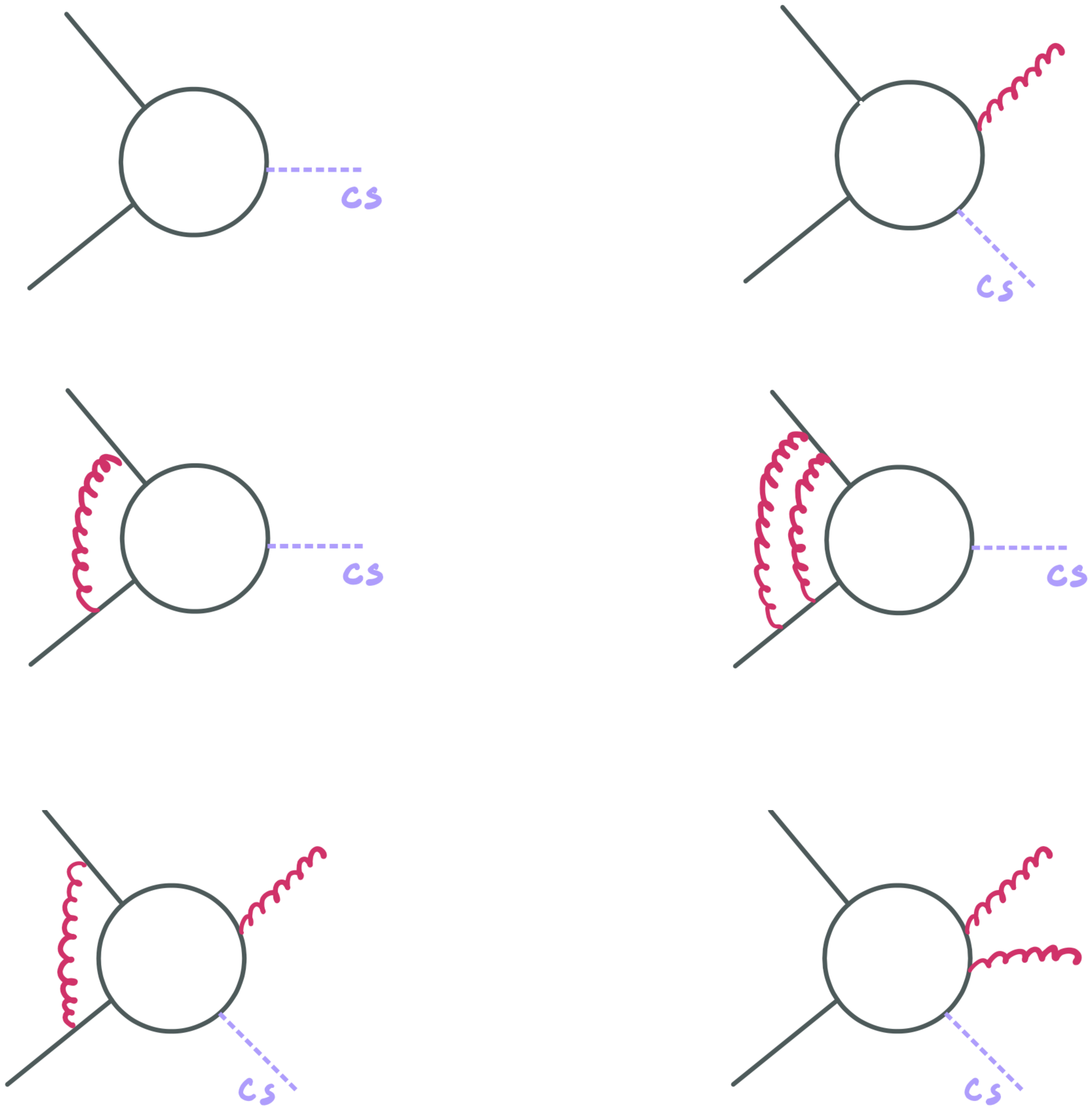
$$\sigma(X) = \int \mathrm{d}\Phi_0 \frac{\mathrm{d}\sigma_0^{\mathrm{MC}}}{\mathrm{d}\Phi_0}\left(r_0^{\mathrm{cut}}\right) M_X\left(\Phi_0\right) + \int \mathrm{d}\Phi_1 \frac{\mathrm{d}\sigma_1^{\mathrm{MC}}}{\mathrm{d}\Phi_1}\left(r_0 > r_0^{\mathrm{cut}}; r_1^{\mathrm{cut}}\right) M_X\left(\Phi_1\right) + \int \mathrm{d}\Phi_2 \frac{\mathrm{d}\sigma_{\geq 2}^{\mathrm{MC}}}{\mathrm{d}\Phi_2}\left(r_0 > r_0^{\mathrm{cut}}, r_1 > r_1^{\mathrm{cut}}\right) M_X\left(\Phi_2\right)$$

- **Split NNLO observables into contributions you can compute**

- **Better if you know the resummation of r_i to high accuracy!**

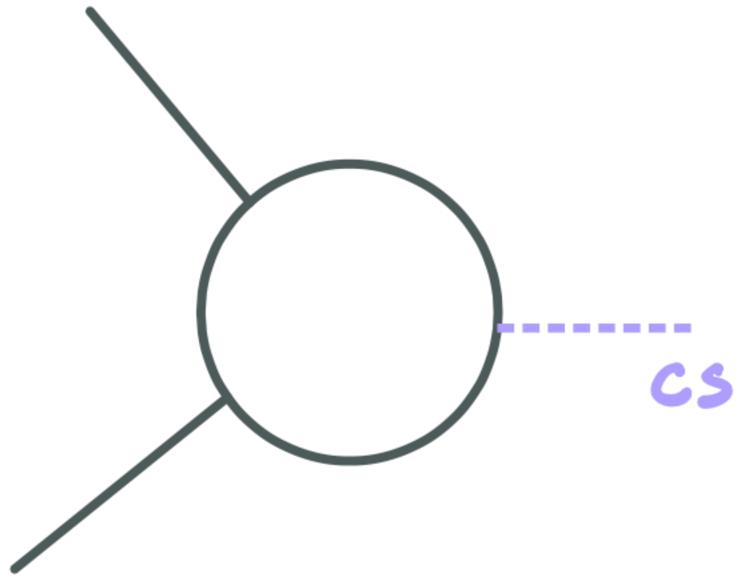
Introduction

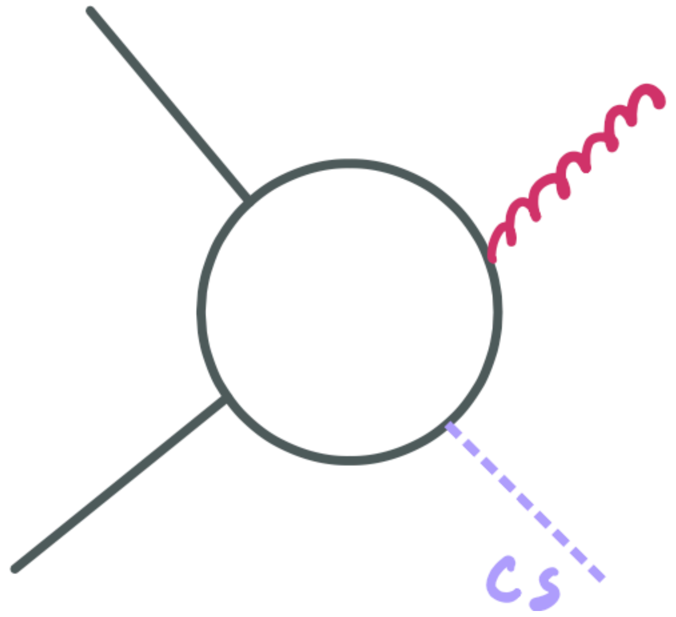
$$\sigma(X) = \int \mathrm{d}\Phi_0 \frac{\mathrm{d}\sigma_0^{\mathrm{MC}}}{\mathrm{d}\Phi_0}\left(r_0^{\mathrm{cut}}\right) M_X\left(\Phi_0\right)$$
$$+ \int \mathrm{d}\Phi_1 \frac{\mathrm{d}\sigma_1^{\mathrm{MC}}}{\mathrm{d}\Phi_1}\left(r_0 > r_0^{\mathrm{cut}}; r_1^{\mathrm{cut}}\right) M_X\left(\Phi_1\right)$$
$$+ \int \mathrm{d}\Phi_2 \frac{\mathrm{d}\sigma_{\geq 2}^{\mathrm{MC}}}{\mathrm{d}\Phi_2}\left(r_0 > r_0^{\mathrm{cut}}, r_1 > r_1^{\mathrm{cut}}\right) M_X\left(\Phi_2\right)$$



Introduction

Φ_0 **Event**





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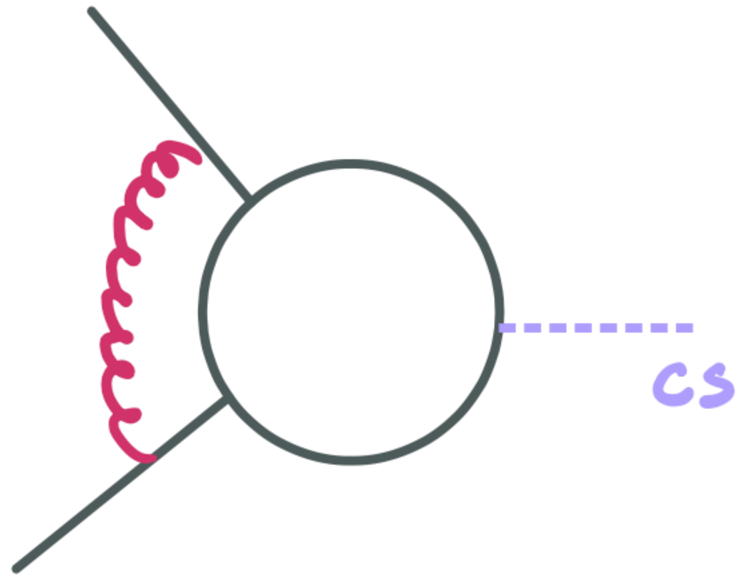

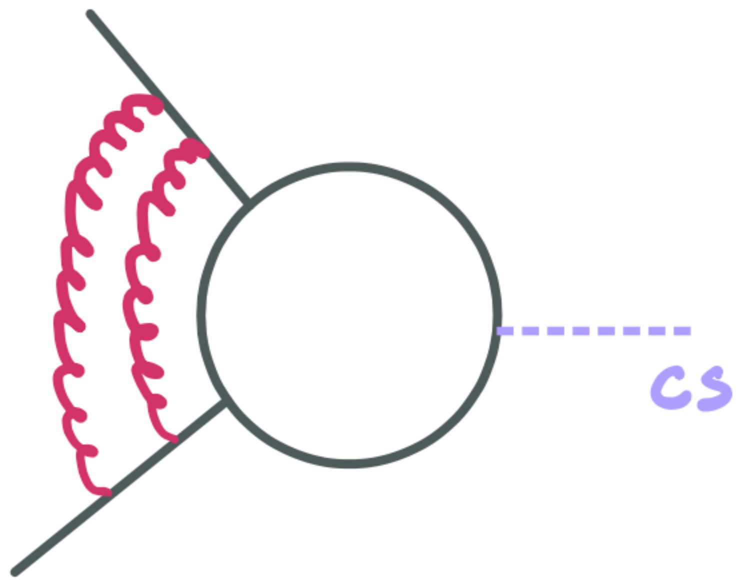

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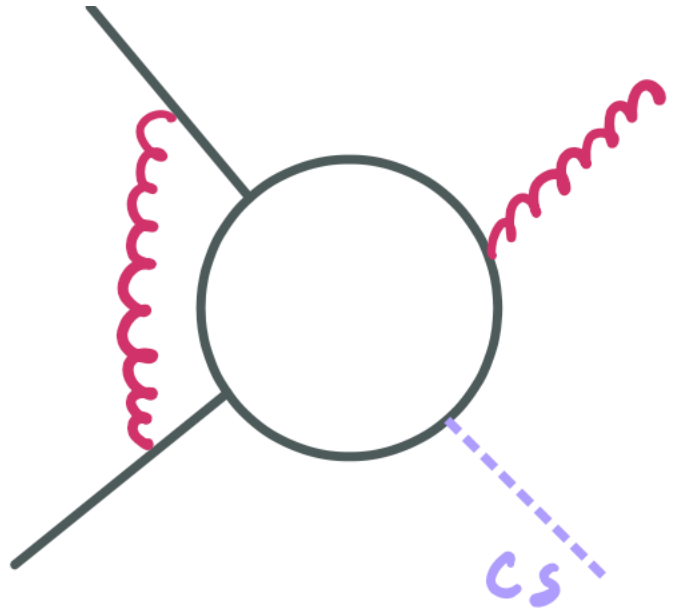

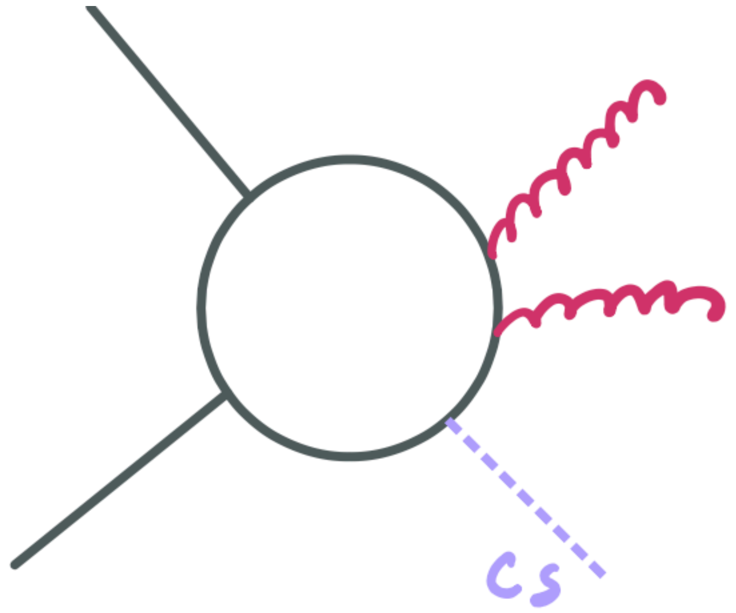

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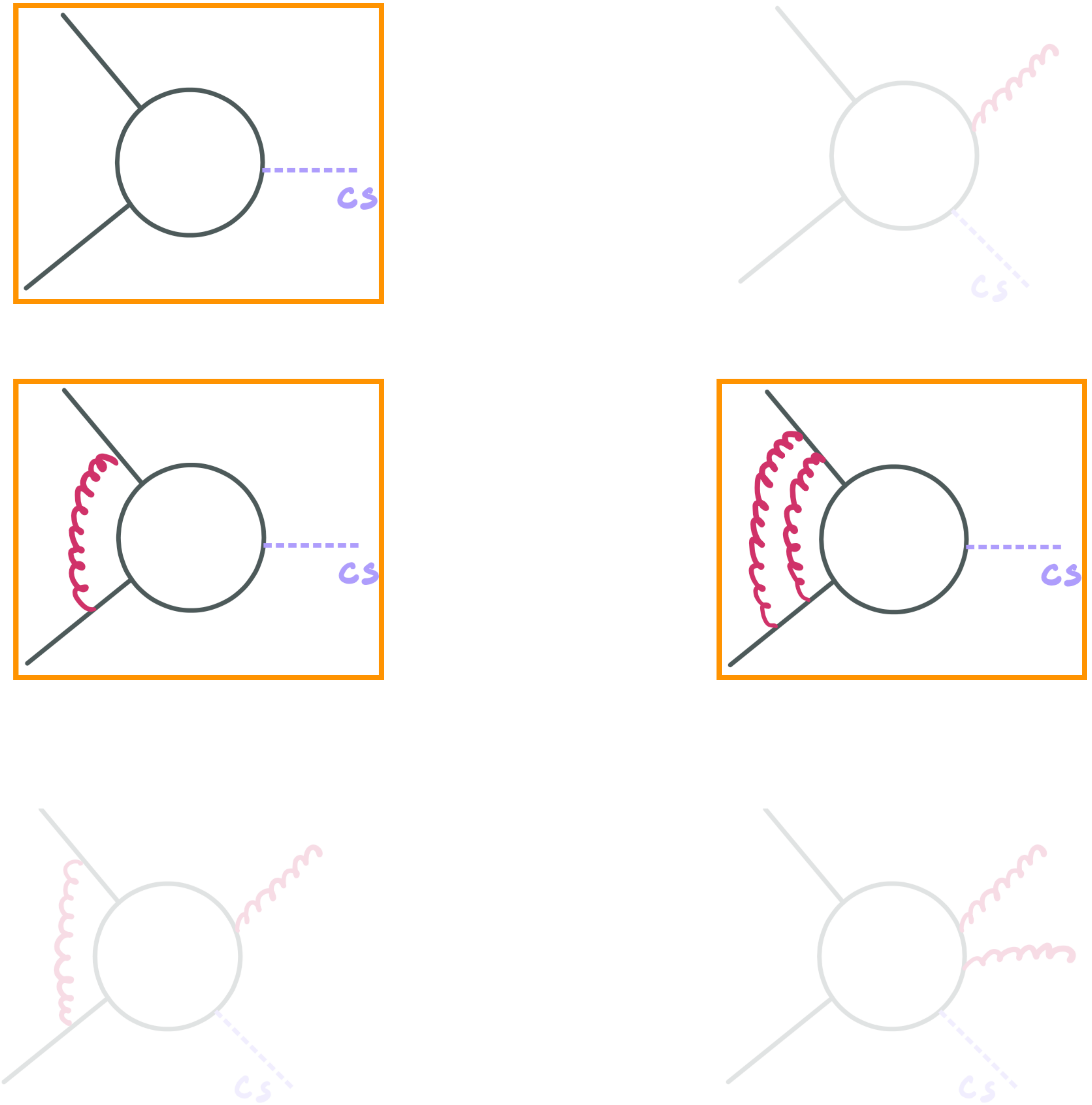
Φ_2 **Event**



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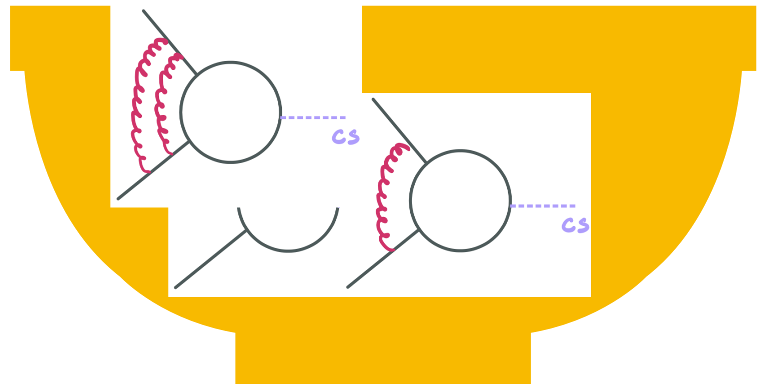

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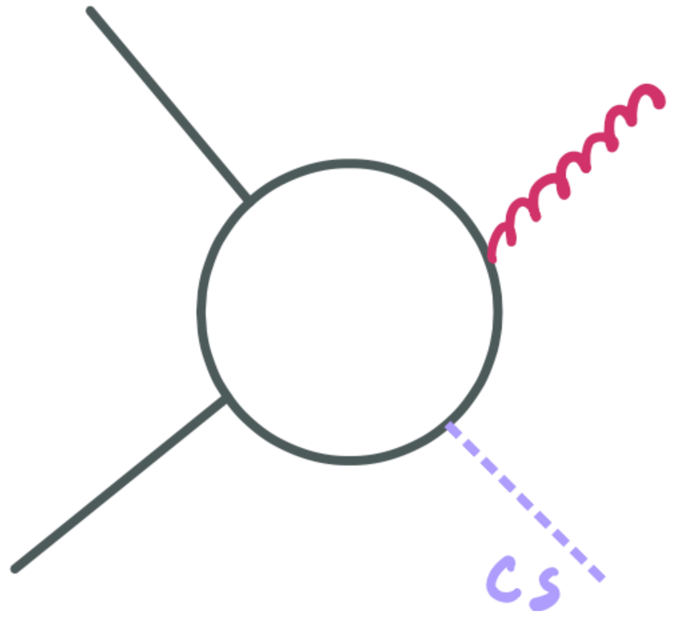

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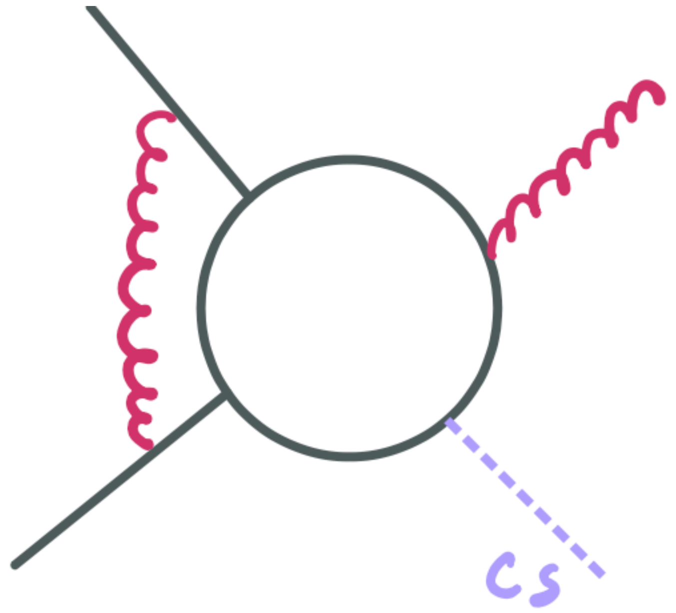

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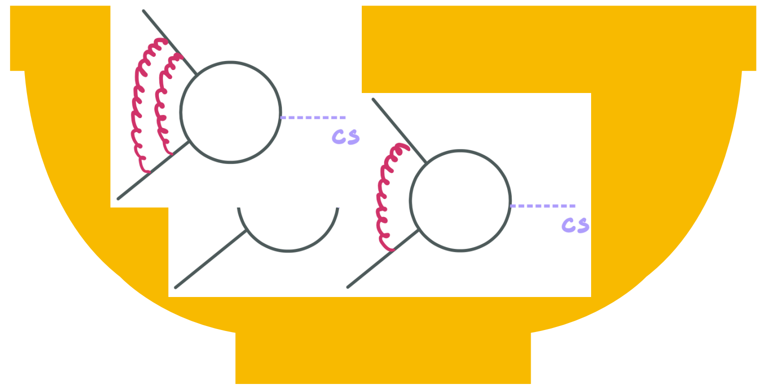

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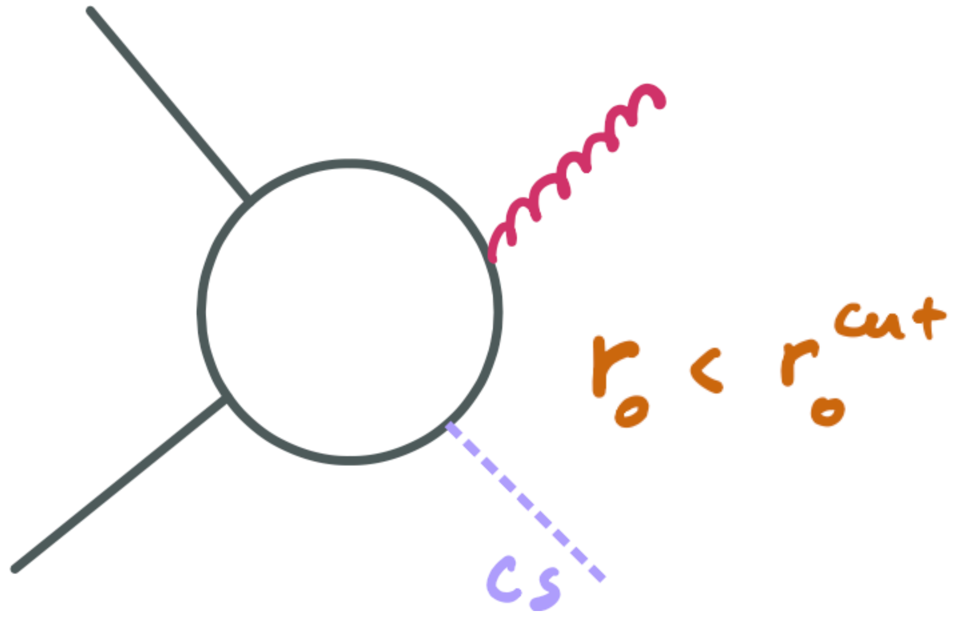

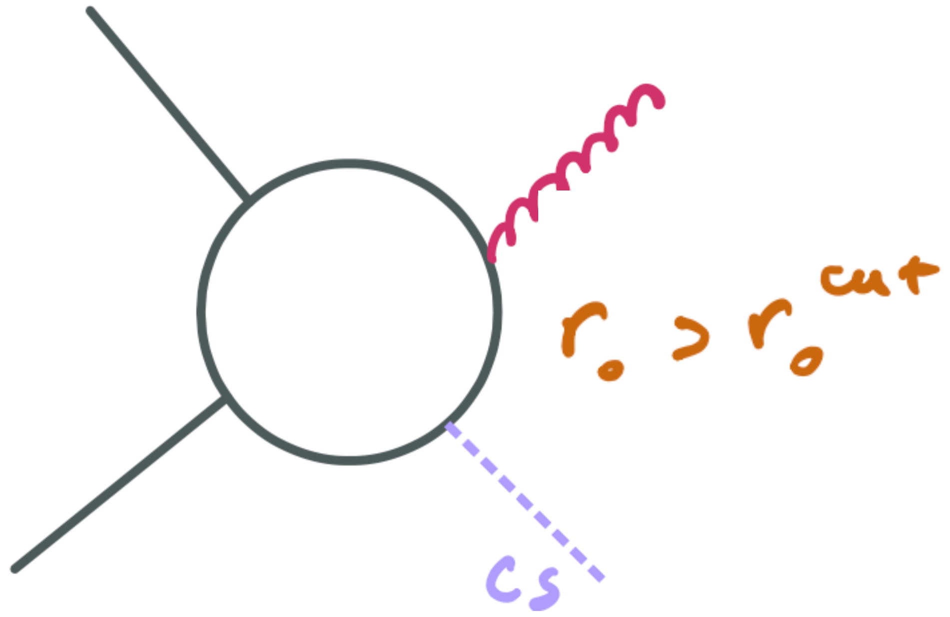

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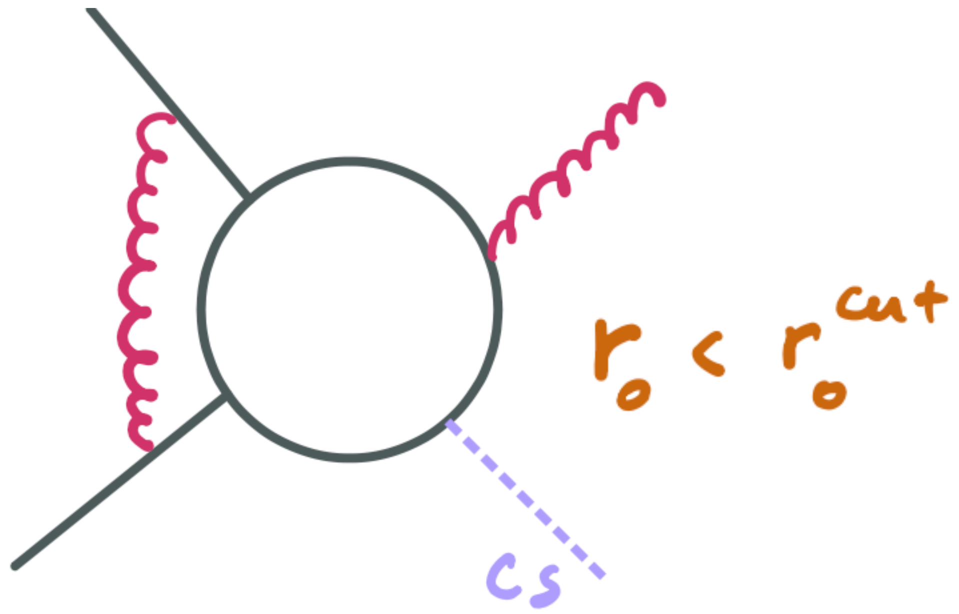

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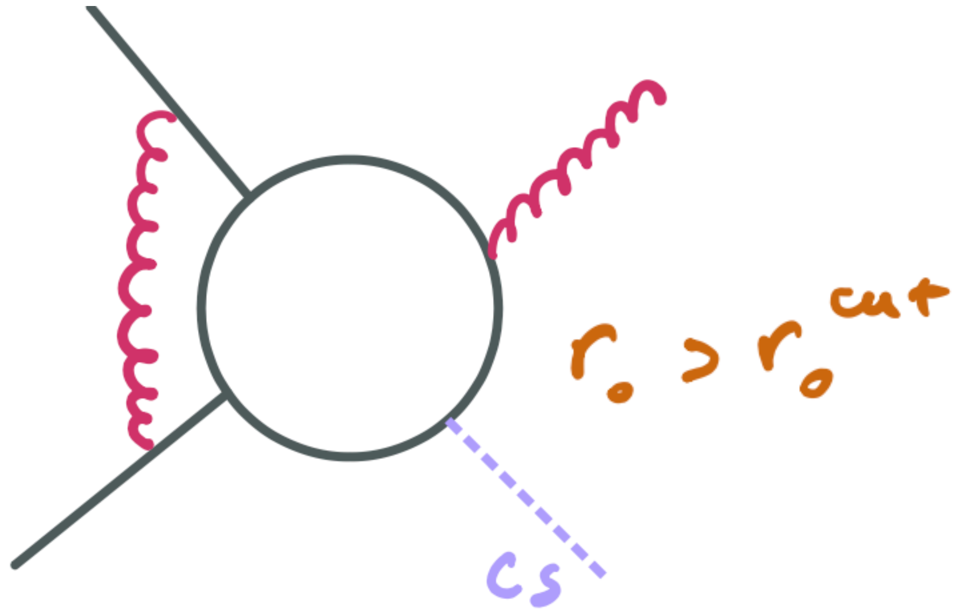

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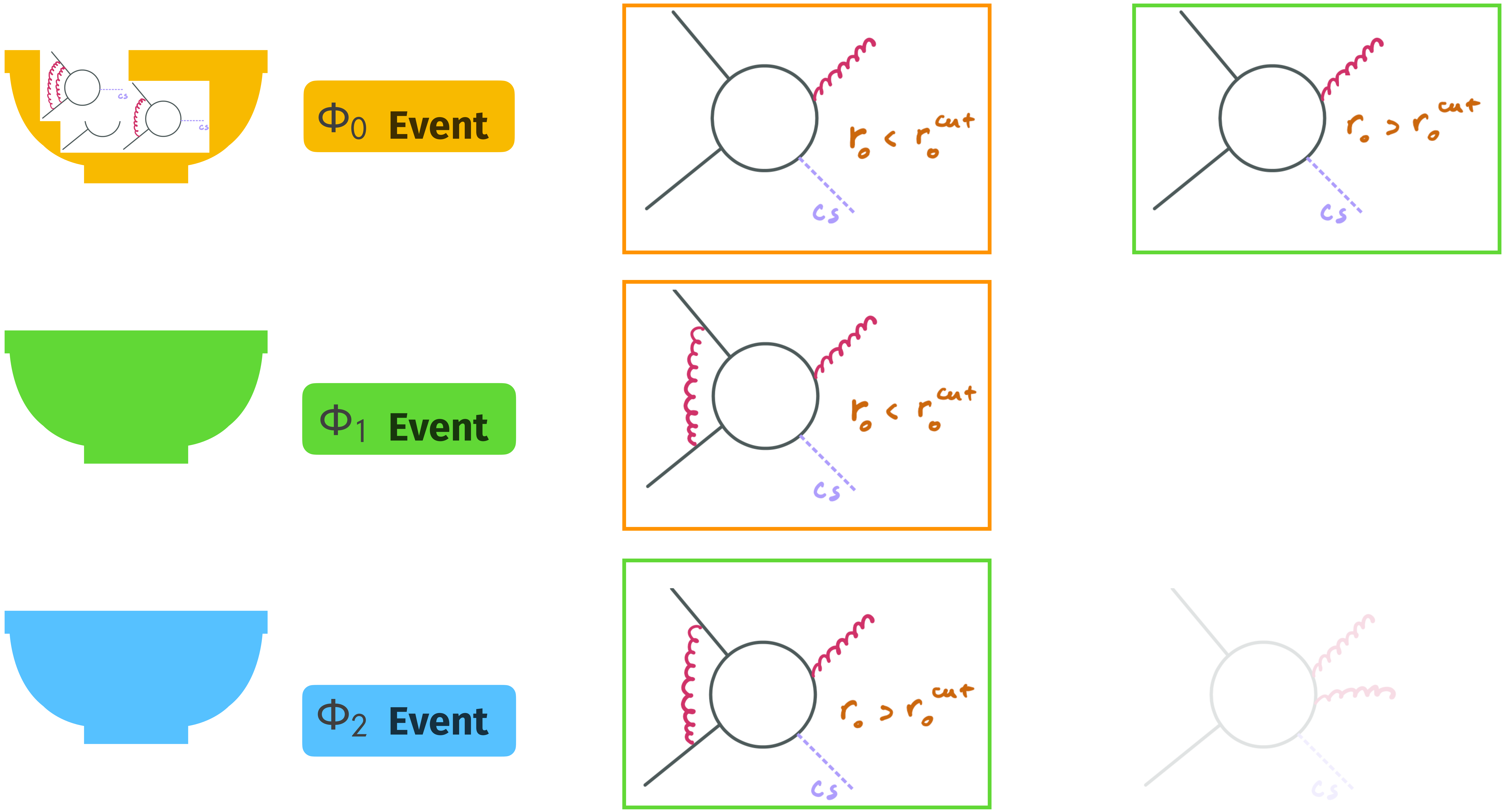

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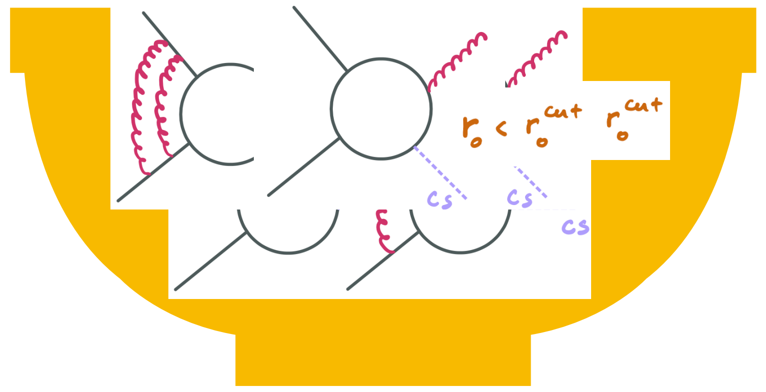

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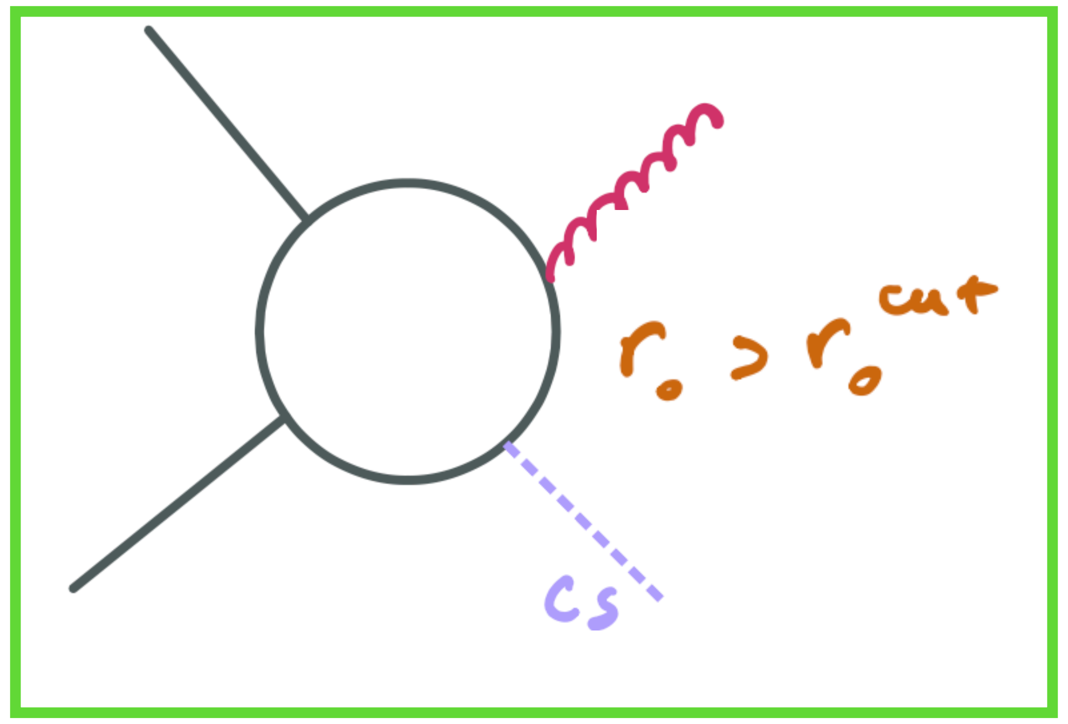

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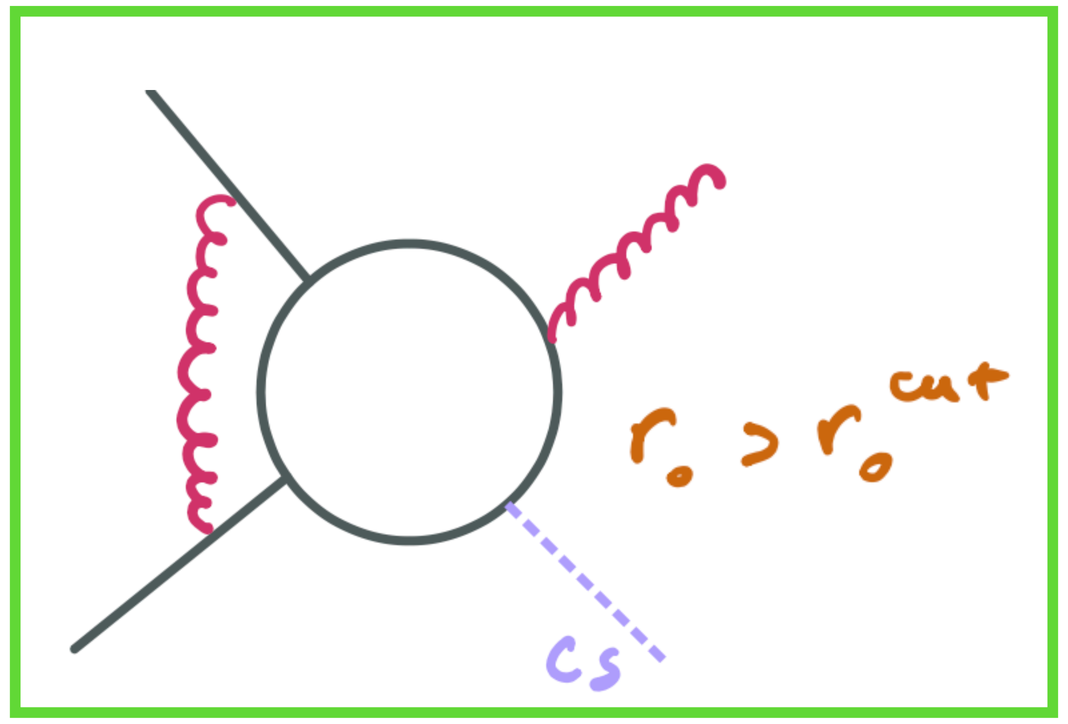

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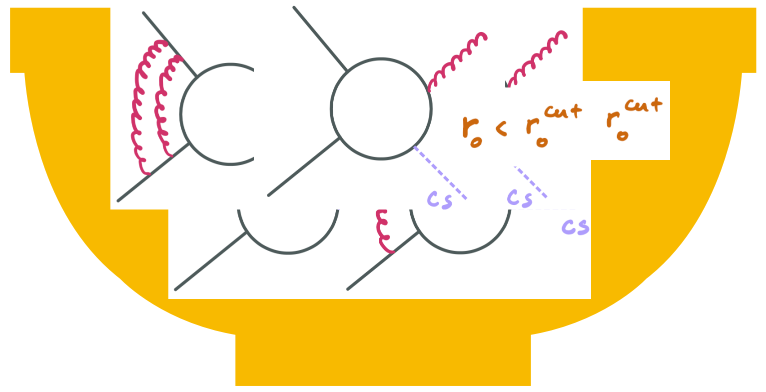

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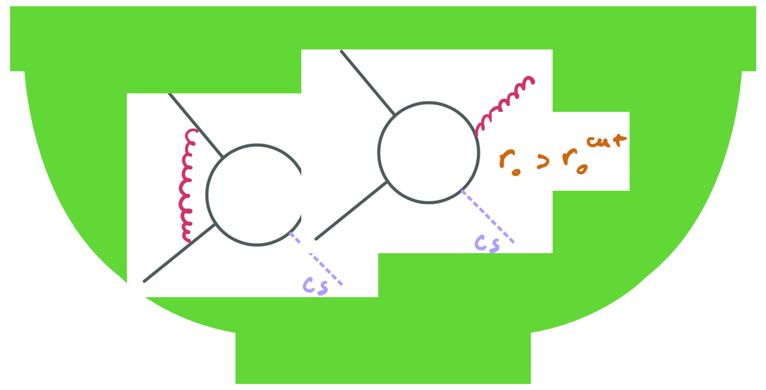

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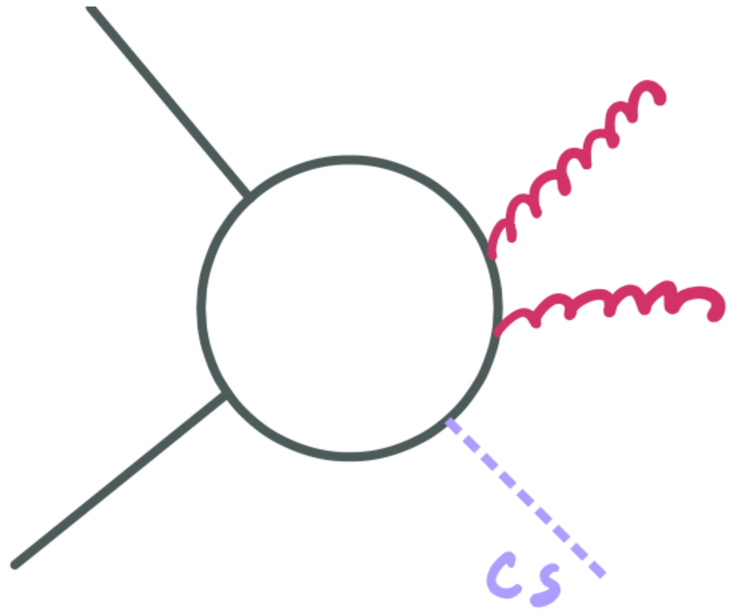

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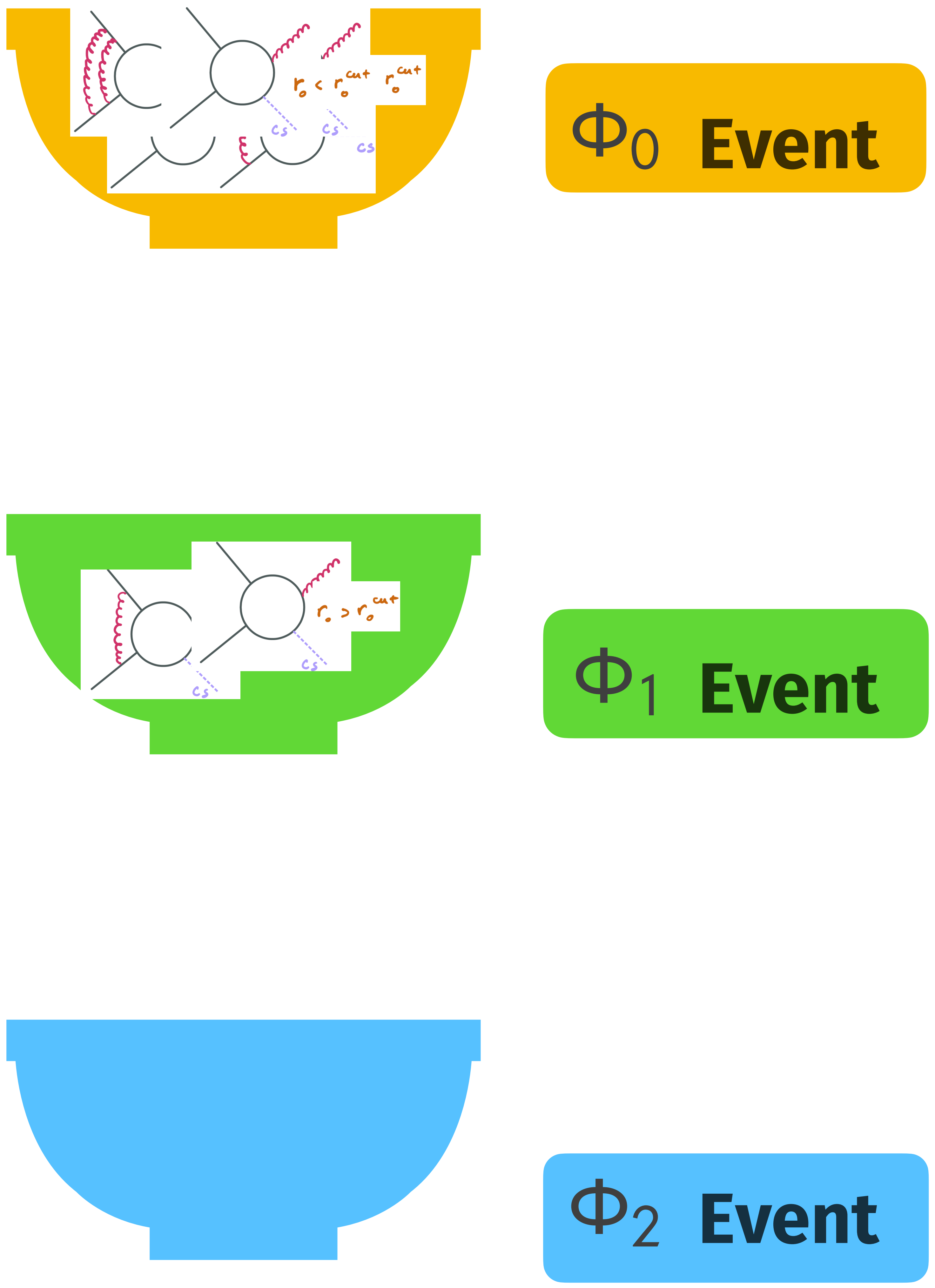

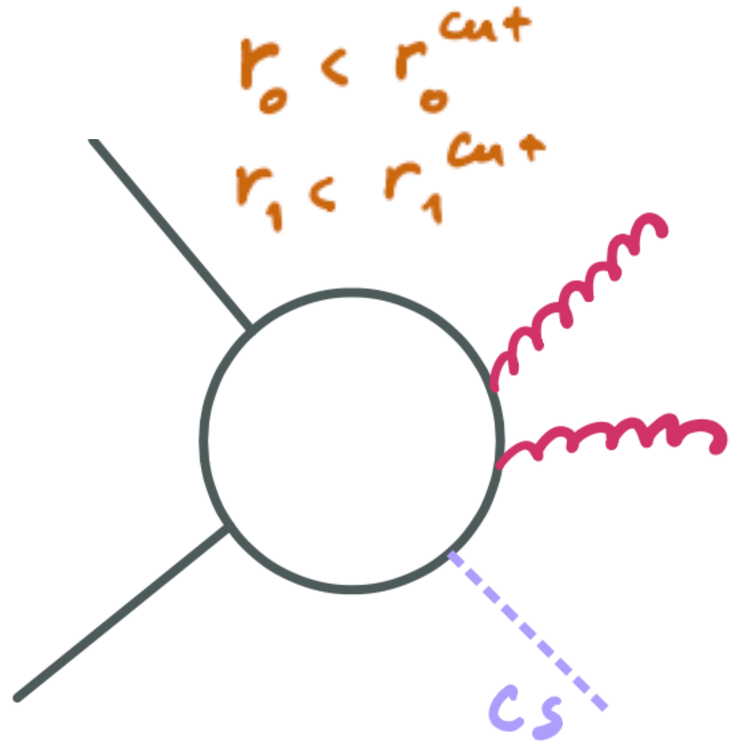

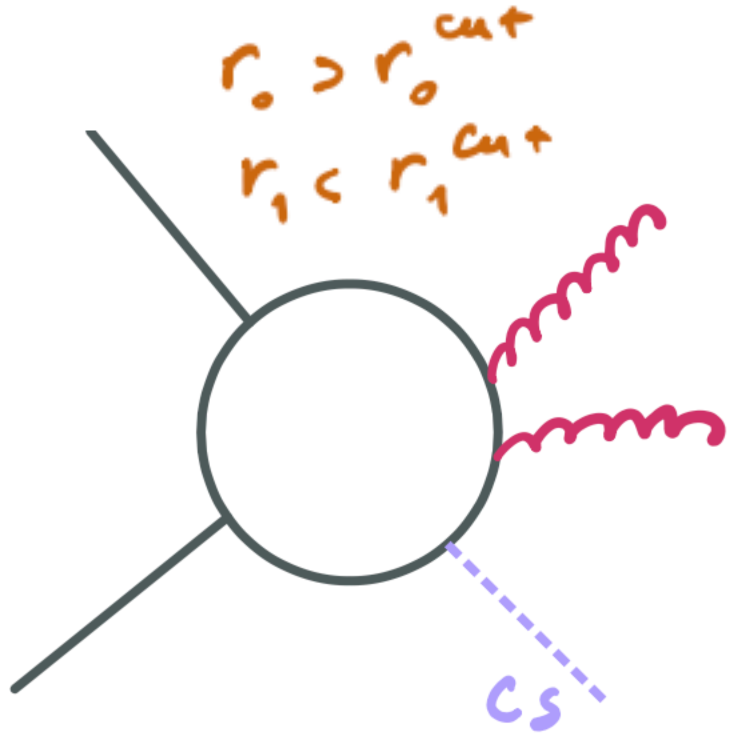

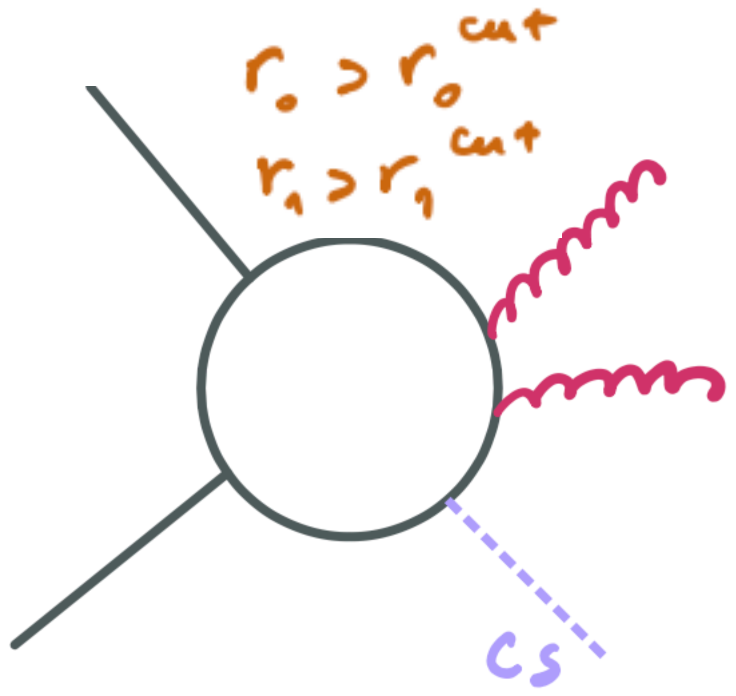

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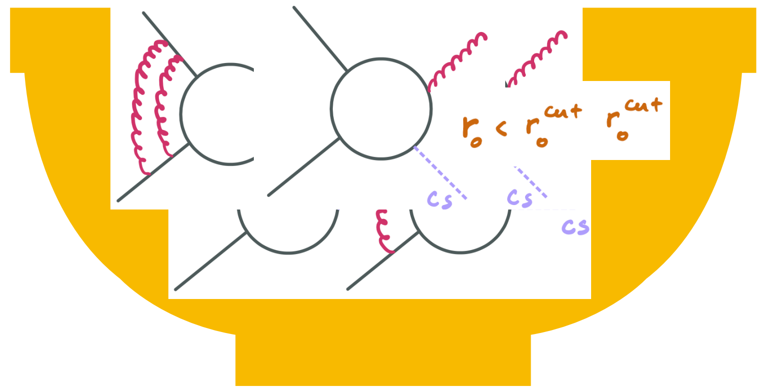

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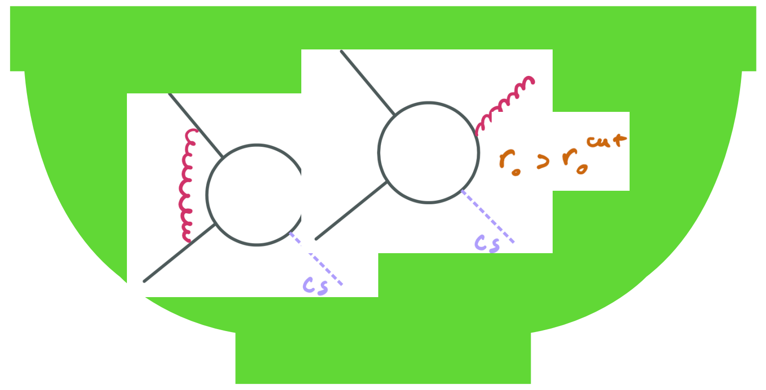

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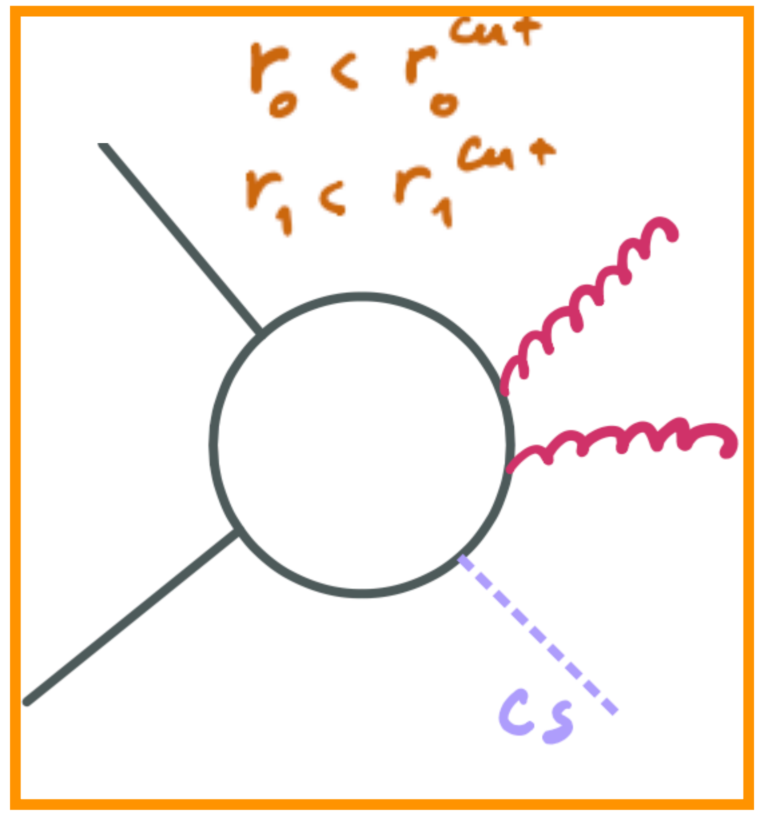

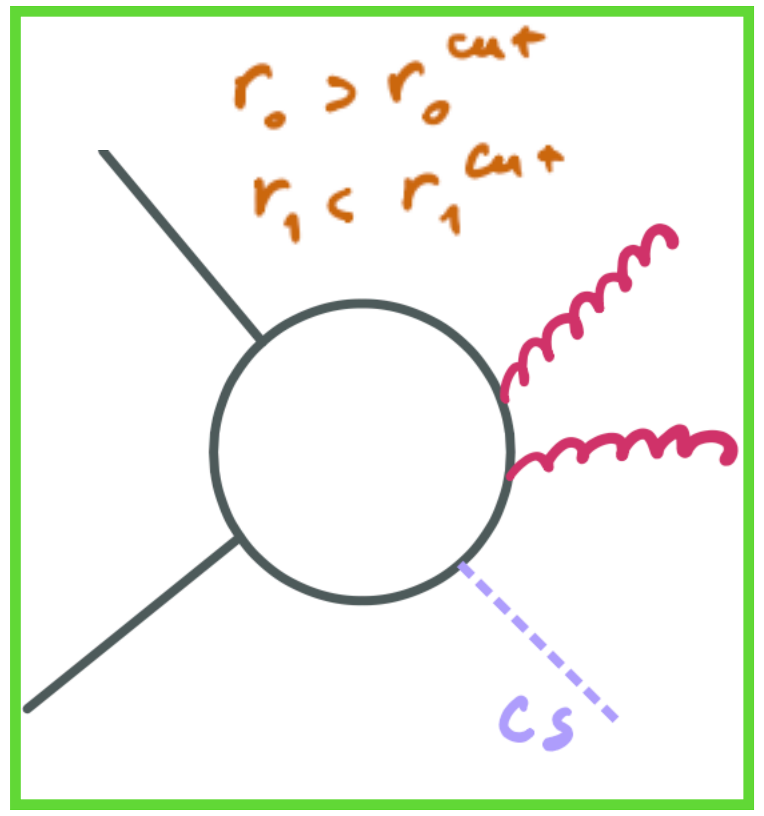

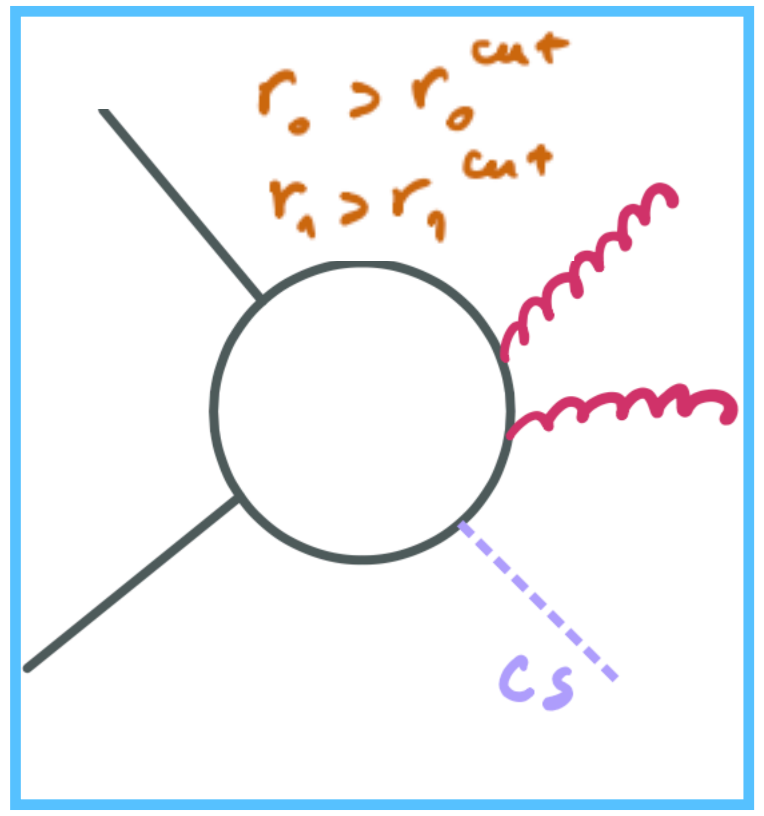

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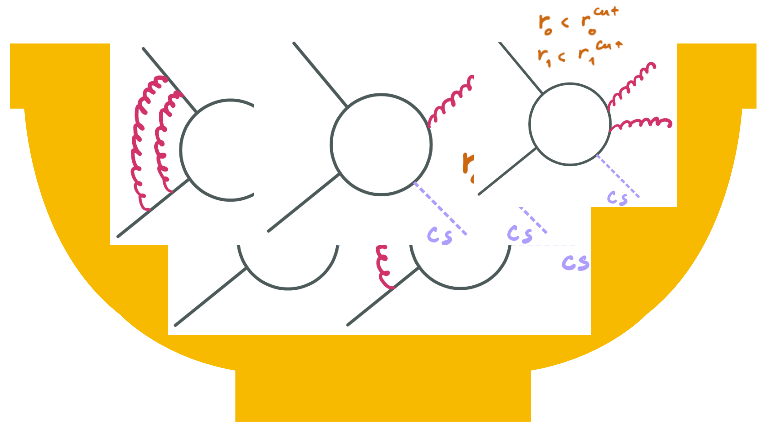

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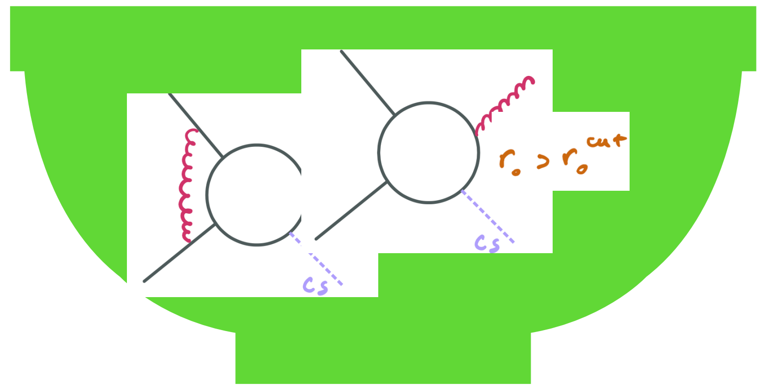

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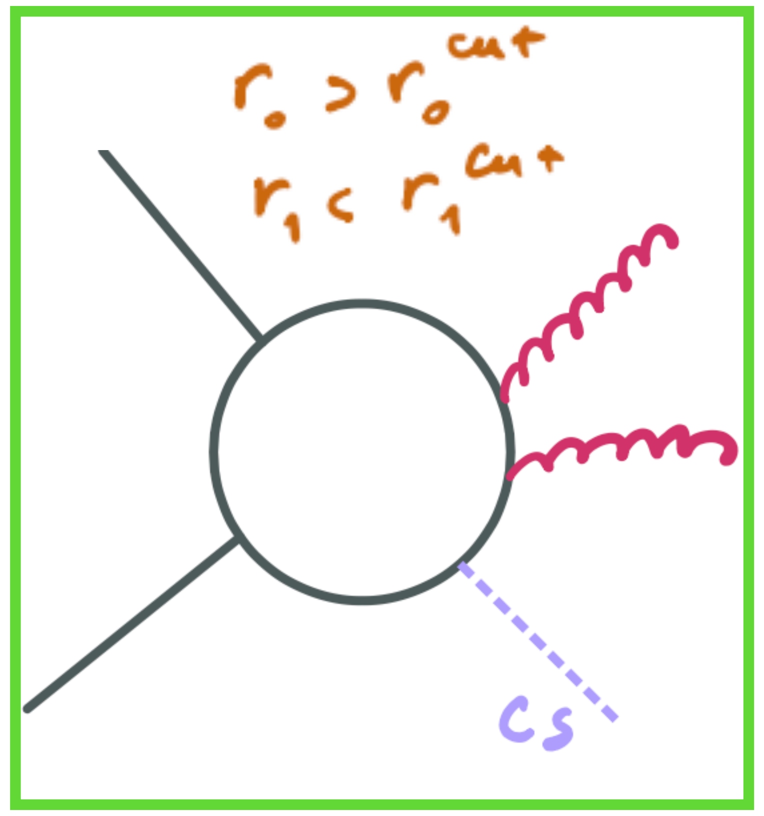

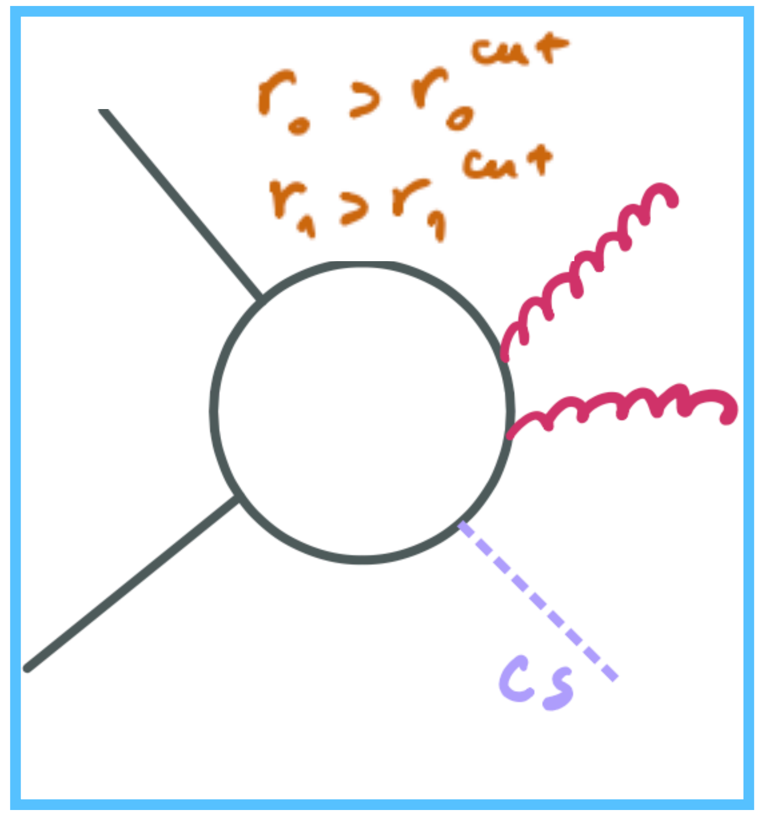

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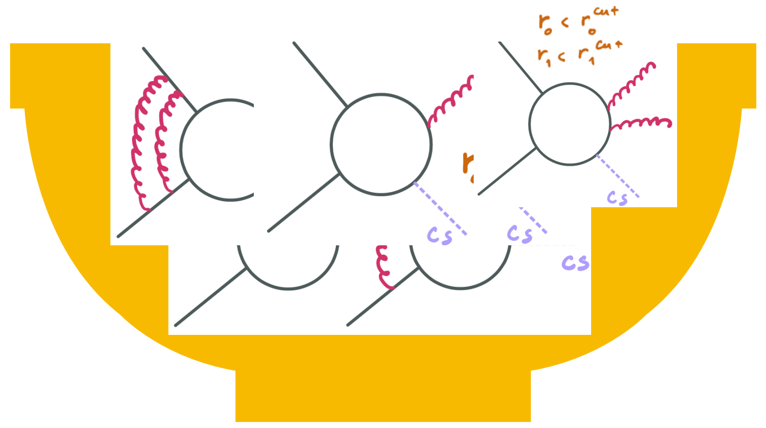

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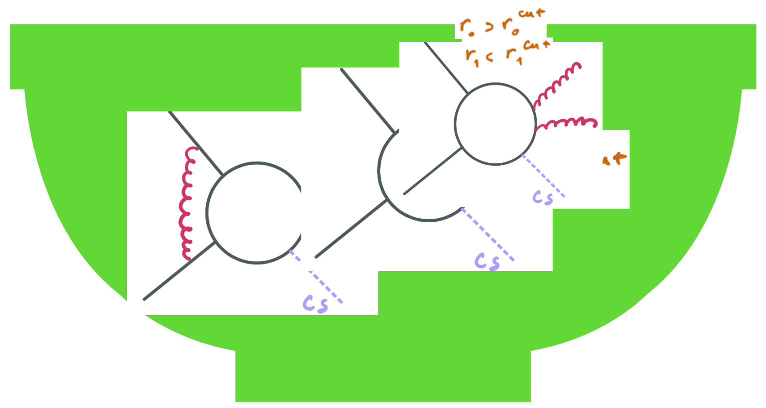

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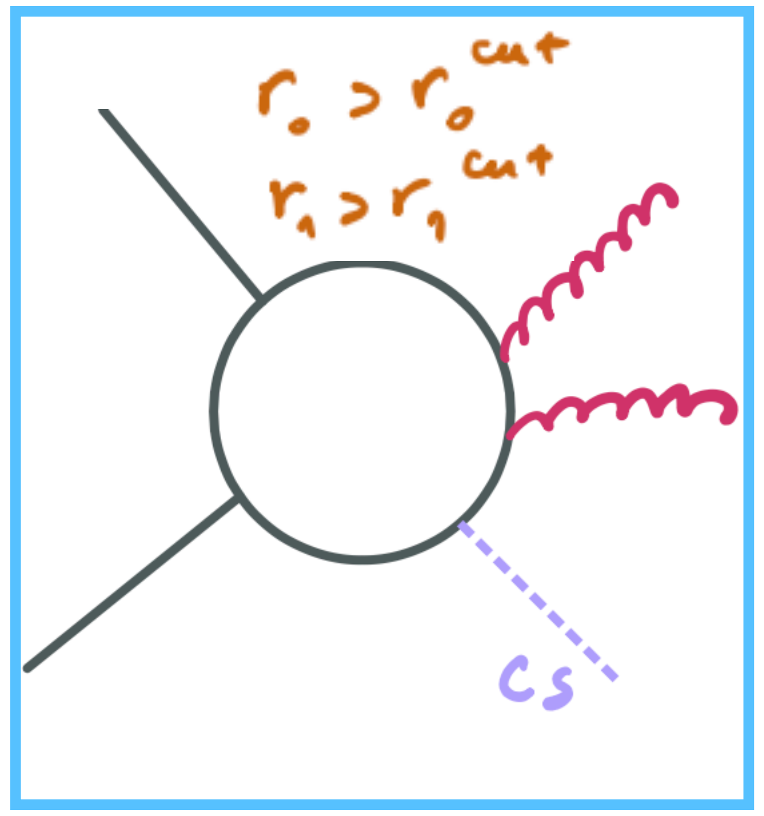

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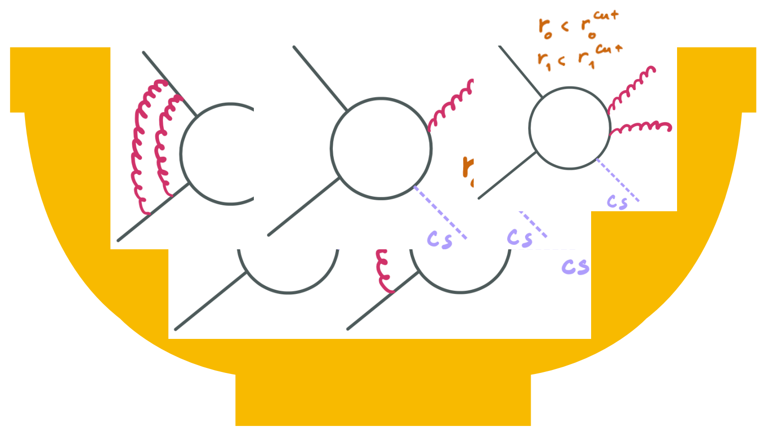

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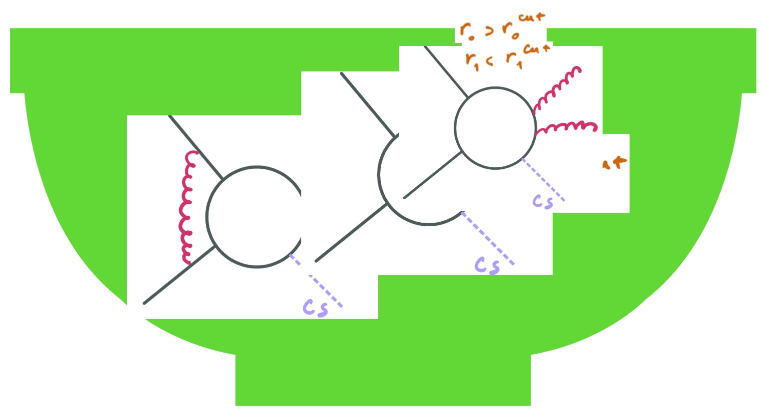

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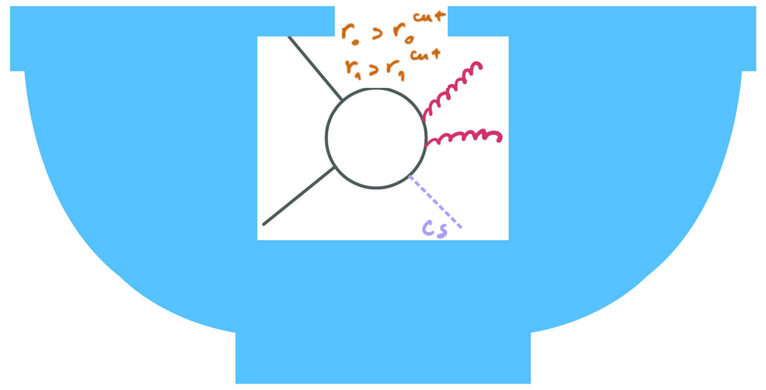
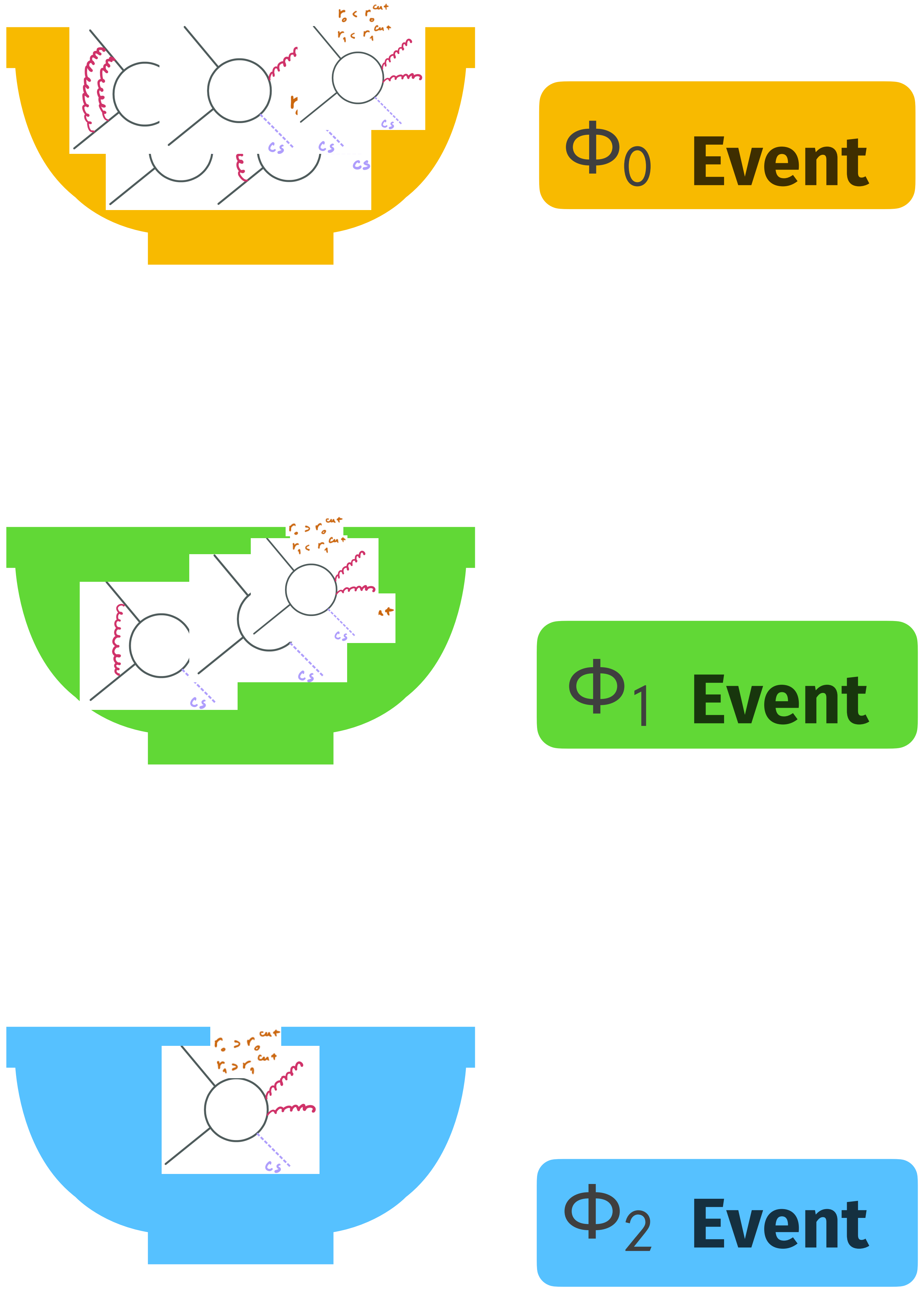
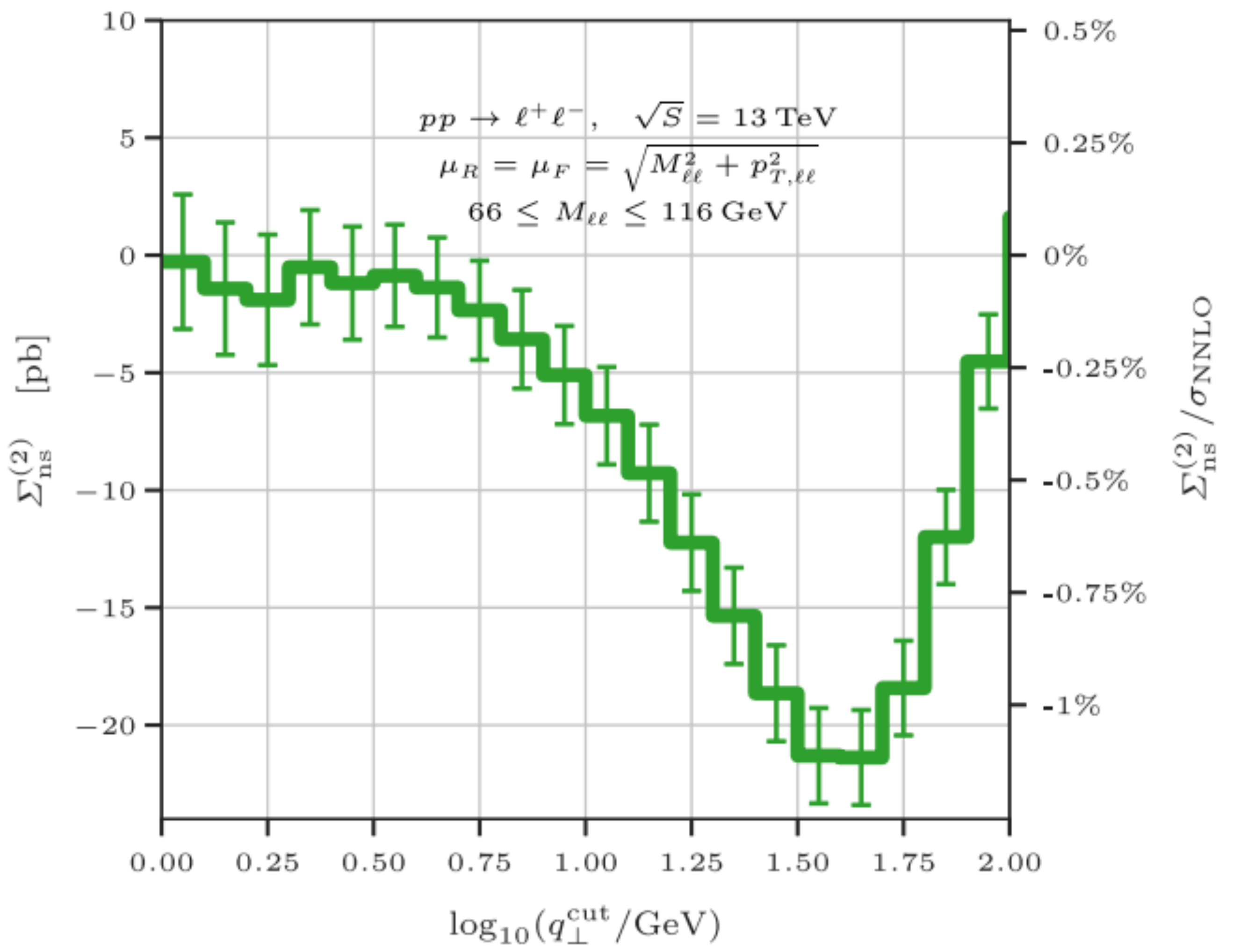


Φ_2 **Event**

Introduction



- Exchange IR singularities with logs of resolution variable
- However, need to lower cut as much as possible



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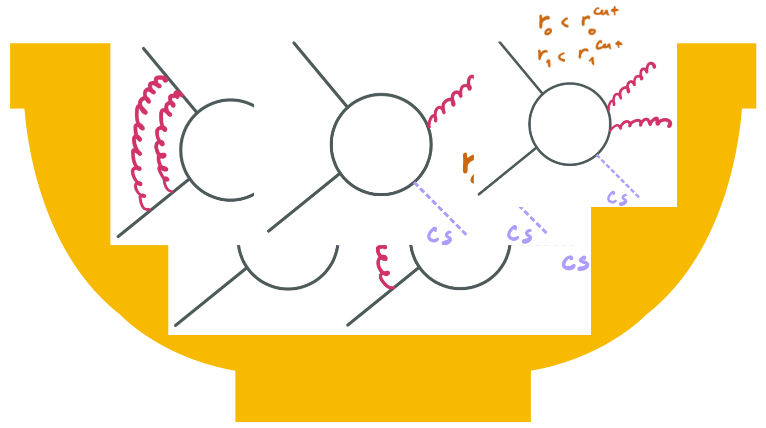

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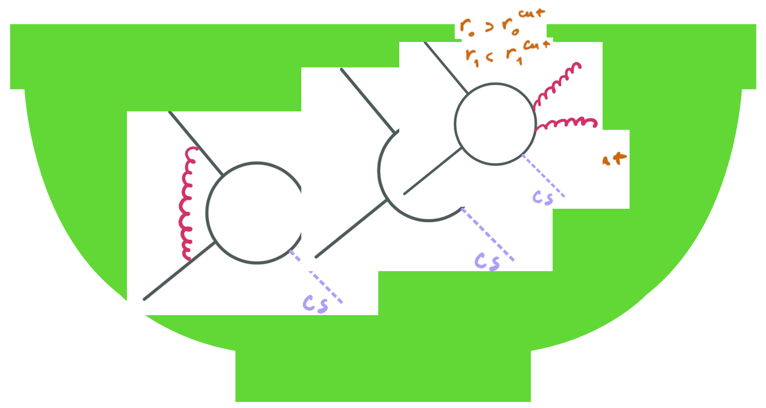

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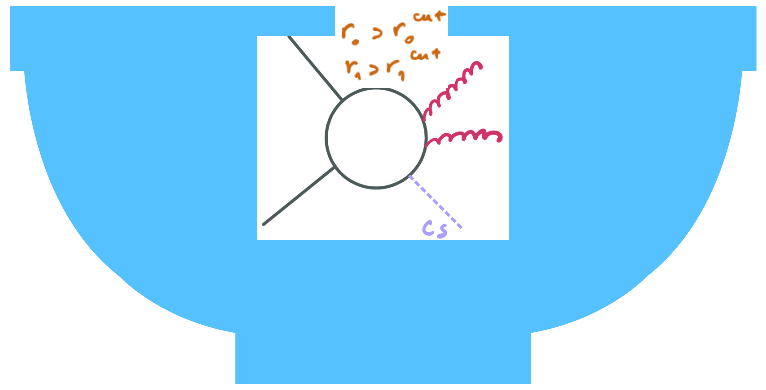


Φ_2 **Event**

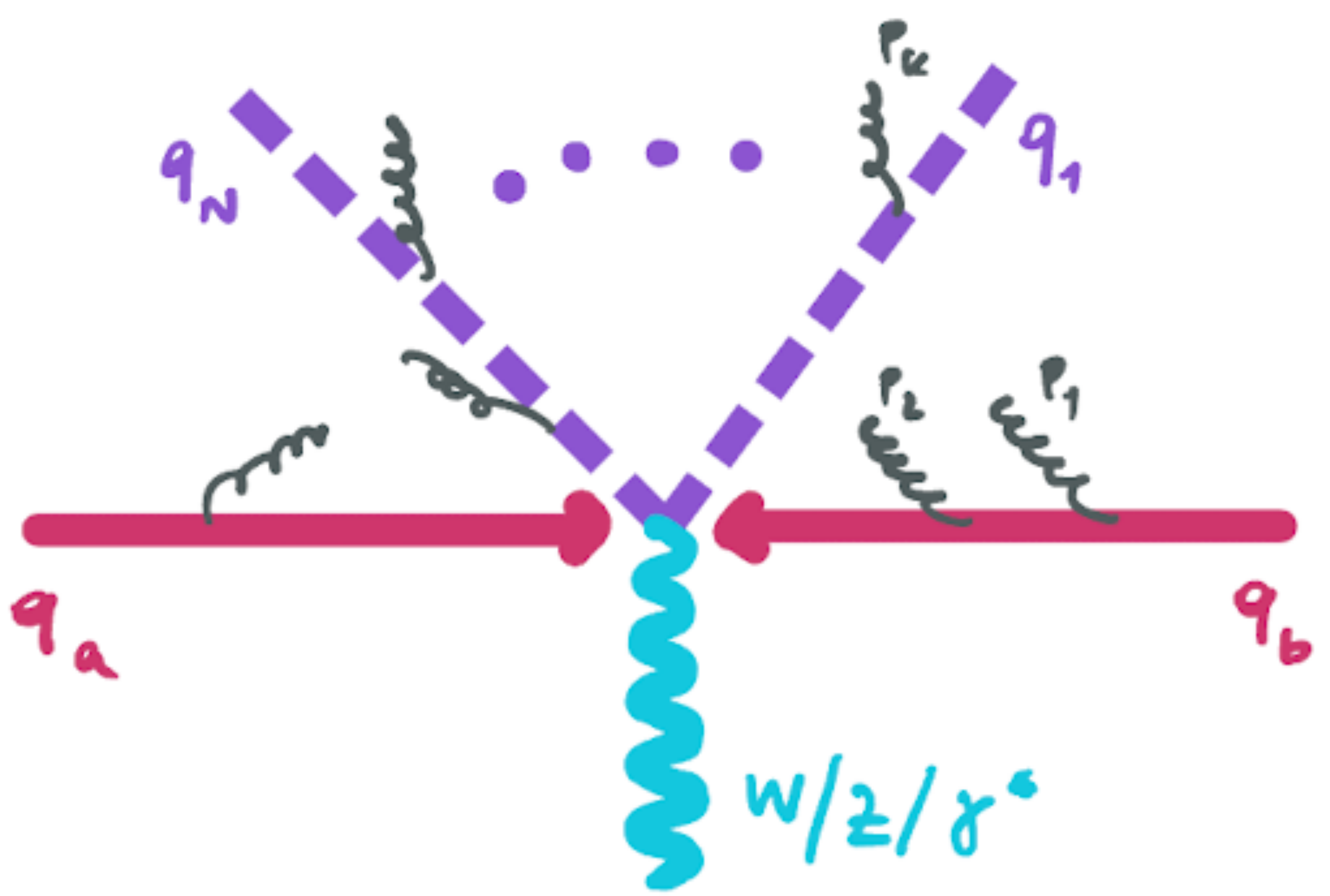
=> Resummation to the rescue!

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Phi\mathrm{d}r} = \frac{\mathrm{d}\sigma^{\mathrm{NNLL}'}}{\mathrm{d}\Phi\mathrm{d}r} - \frac{\mathrm{d}\sigma^{\mathrm{resExp}}}{\mathrm{d}\Phi\mathrm{d}r} + \frac{\mathrm{d}\sigma^{\mathrm{FO}}}{\mathrm{d}\Phi\mathrm{d}r}$$

Intro: N-Jettiness

- **Historically only variable used in GENEVA (now also pT)**

- **Geometric measure to tell how N-Jett like an event is:**



$$\tau_N = \sum_{k=1} \min\left(2p_k \cdot \hat{q}_a,\ 2p_k \cdot \hat{q}_b,\ 2p_k \cdot \hat{q}_1,\ \dots,\ 2p_k \cdot \hat{q}_N\right)$$

Introduction

- Ingredients:

  * NNLO FO events for V+j

  * NNLL' resummation formula for $\mathcal{T}_1$ with three coloured partons

  * (optional) NNL resummation for $\mathcal{T}_2$

  * A suitable matching procedure to the shower

NNLO Validation

- $\mathscr{T}_1$ - **slicing:**

$$\Theta^{\delta NNLO_1}(\phi_1) = \frac{d\sigma^{N^3LL}}{d\phi_1}(\tau_1^{cut})\Big|_{\mathcal{O}(\alpha_s^3)} \Theta(\phi_1) + \int_{\tau_1^{cut}}^{\tau_1^{max}} \frac{d\Phi_2}{d\Phi_1} \frac{d\sigma^{\delta NLO_2}}{d\Phi_2} \Theta(\Phi_{2,3})$$

NNLO Validation

- $\mathscr{T}_1$ - slicing:

$$\theta^{SNNLO_1}(\phi_1) = \left.\frac{d\sigma^{N^3LL}}{d\phi_1}(\tau_1^{cut})\right|_{O(\alpha_s^3)} \Theta(\phi_1) + \int_{\tau_1^{cut}}^{\tau_1^{max}} \frac{d\Phi_2}{d\Phi_1} \frac{d\sigma^{SNLO_2}}{d\Phi_2} \Theta(\Phi_{2,3})$$

Cumulant expanded

NLO with FKS

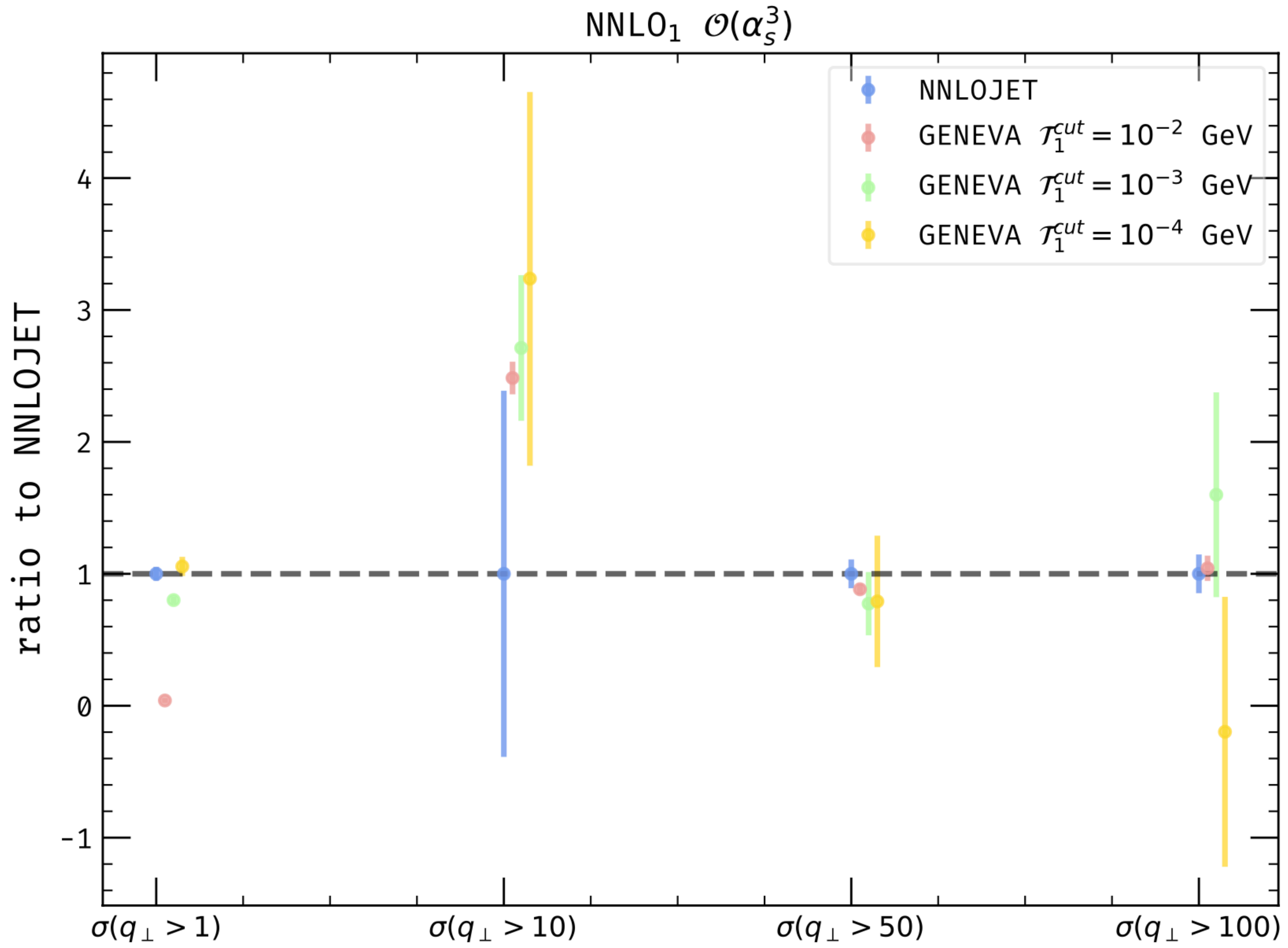
NNLO Validation

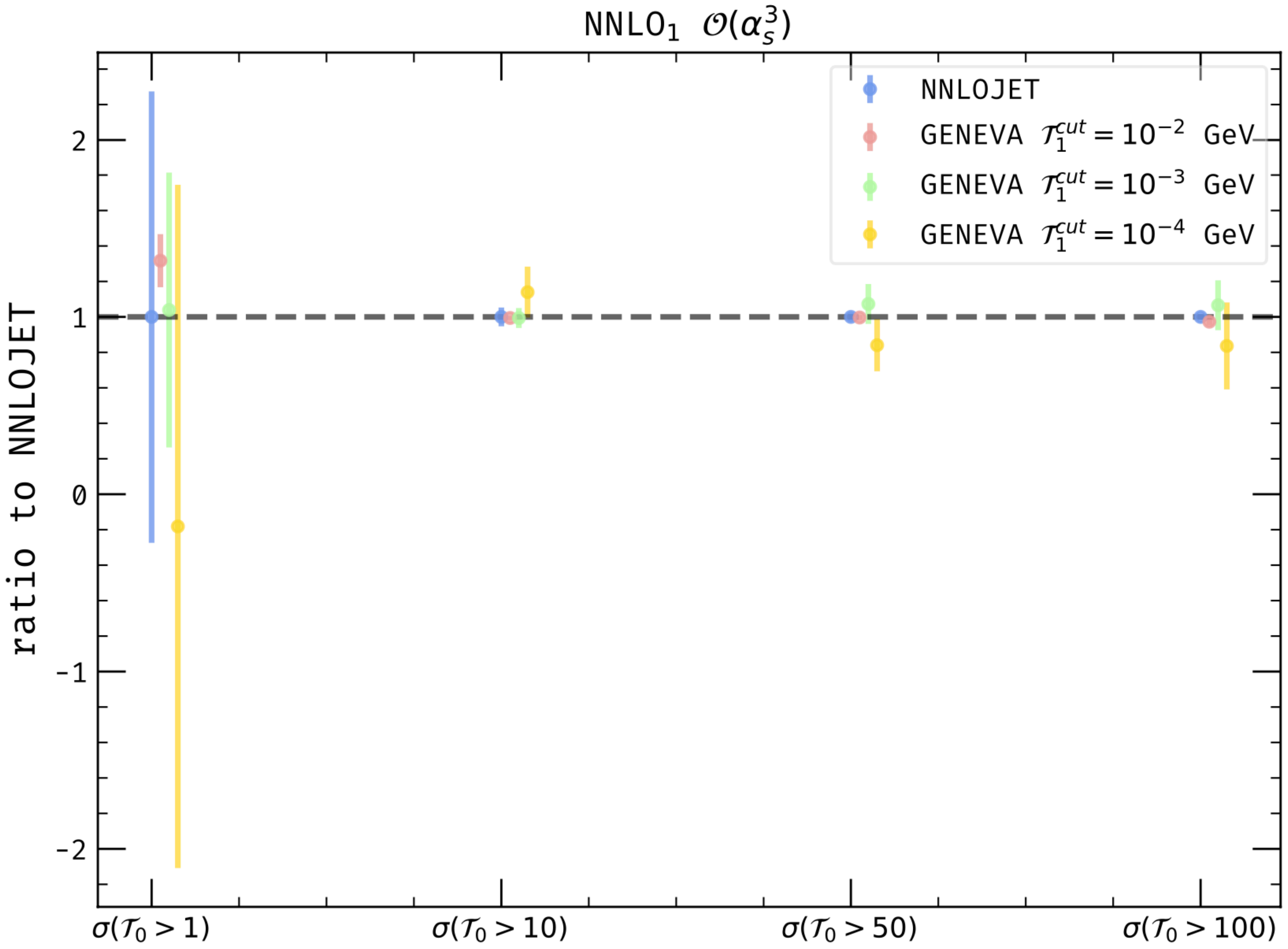
- $\mathscr{T}_1$ - slicing:

$$\Theta^{\delta NNLO_1}(\Phi_1) = \frac{d\sigma^{N^3LL}}{d\Phi_1}(\tau_1^{cut})\Big|_{\mathcal{O}(\alpha_s^3)} \theta(\Phi_1) + \int_{\tau_1^{cut}}^{\tau_1^{max}} \frac{d\Phi_2}{d\Phi_1}\frac{d\sigma^{\delta NLO_2}}{d\Phi_2}\,\theta(\Phi_{2,3})$$

cumulant expanded

NLO with FKS





NNLO Validation

- $\mathcal{T}_1$ - **Subtraction:**

$$\sigma^{SNNLO_1}(\phi_1) = \frac{d\sigma^{N^3LL}}{d\phi_1}(\tau_1^{cut})\Big|_{\mathcal{O}(\alpha_s^3)} \Theta(\phi_1) + \int_{\tau_1^{cut}}^{\tau_1^{max}} \frac{d\Phi_2}{d\Phi_1}\frac{d\sigma^{SNLO_2}}{d\Phi_2}\Theta(\Phi_{2,3}) + \int_{\tau_1^{\delta}}^{\tau_1^{cut}} \frac{d\Phi_2}{d\Phi_1}\left[\frac{d\sigma^{SNLO_2}}{d\Phi_2}\Theta(\Phi_{2,3}) - \frac{d\sigma^{N^3LL}}{d\phi_1 d\tau_1}\Big|_{\mathcal{O}(\alpha_s^3)}\Theta(\phi_1)\,P(\Phi_2)\right]$$

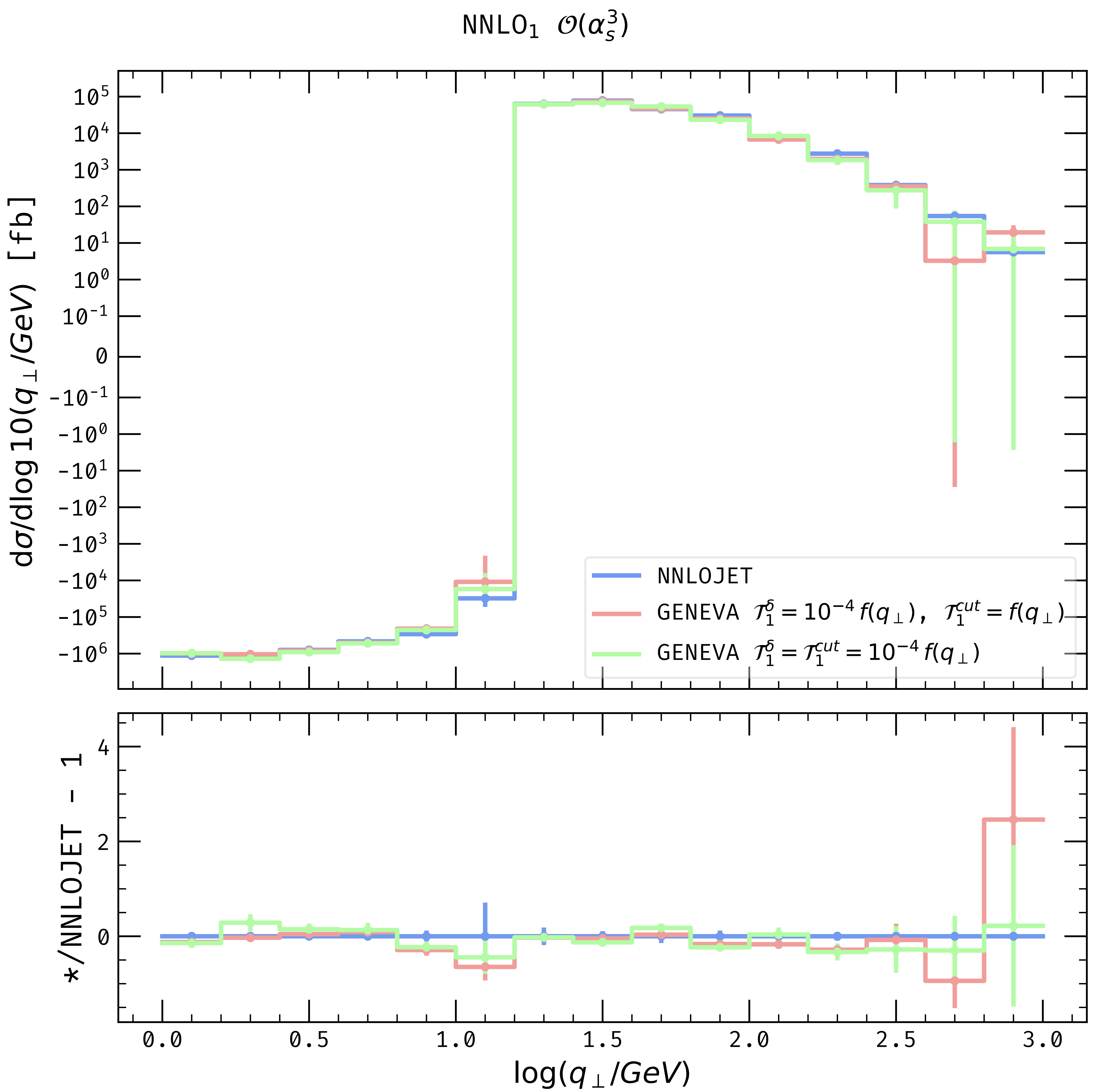
Non-singular

- $\mathcal{T}_1$ - **Dynamical Subtraction:**

$$\mathcal{T}_1^{cut} \equiv \mathcal{T}_1^{cut}(q_\perp)$$

NNLO Validation

- $\mathcal{T}_1$ - **Dynamical Subtraction:**



$$\Theta^{\delta NNLO_1}(\Phi_1) = \frac{d\sigma^{N^3LL}}{d\Phi_1}(\tau_1^{cut})\Big|_{\mathcal{O}(\alpha_s^3)} \Theta(\Phi_1) + \int_{\tau_1^{cut}}^{\tau_1^{max}} \frac{d\Phi_2}{d\Phi_1}\frac{d\sigma^{SNLO_2}}{d\Phi_2}\Theta(\Phi_{2,3})$$

Cumulant expanded — NLO with FKS

$$+ \int_{\tau_1^{\delta}}^{\tau_1^{cut}} \frac{d\Phi_2}{d\Phi_1}\left[\frac{d\sigma^{SNLO_2}}{d\Phi_2}\Theta(\Phi_{2,3}) - \frac{d\sigma^{N^3LL}}{d\Phi_1 d\tau_1}\Big|_{\mathcal{O}(\alpha_s^3)}\Theta(\Phi_1)\,\mathcal{P}(\Phi_2)\right]$$

Non-singular

Event Generation!

- Ingredients:

  * NNLO FO events for V+j ✓

  * NNLL' resummation formula for $\mathcal{T}_1$ with three coloured partons

  * (optional) NNL resummation for $\mathcal{T}_2$

  * A suitable matching procedure to the shower

$\mathcal{T}_1$ Resummation

[Phys.Rev.D 109 (2024) 9, 094009]

$$\frac{d\sigma^{N^3LL}}{d\Phi_1\, d\tau_1} = \sum_k H_k(\mu_H)\, B_k(x_a, \mu_B)\, B_k(x_b, \mu_B)\, J(\mu_J)\, S(\mu_S)$$

$\mathscr{T}_1$ Resummation

[Phys.Rev.D 109 (2024) 9, 094009]

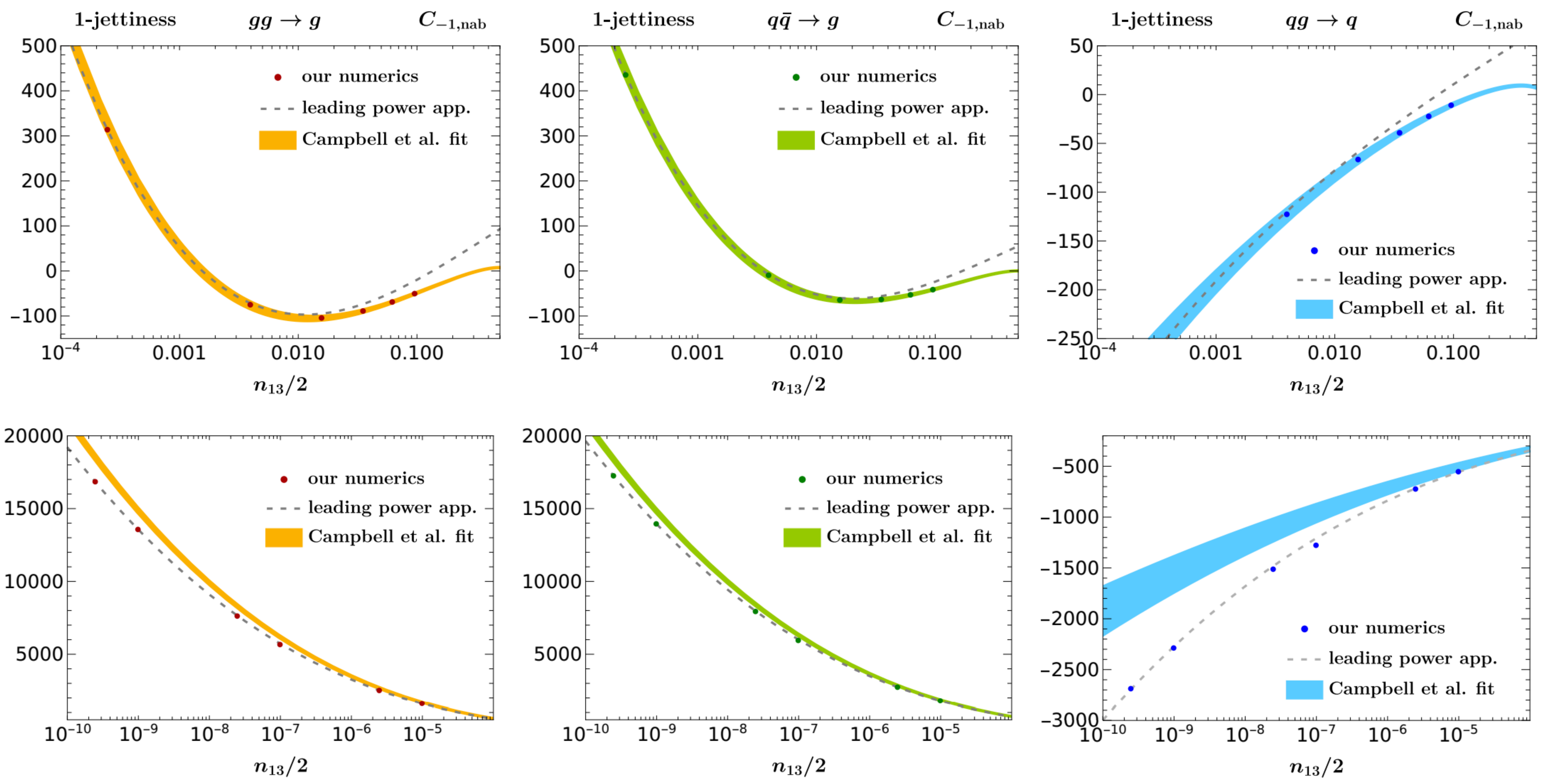
$$\frac{d\sigma^{N^3LL}}{d\Phi_1 \, d\tau_1} = \sum_k H_k(\mu_H) \, B_k(x_a, \mu_B) B_k(x_b, \mu_B) \, J(\mu_J) \, S(\mu_S)$$

- Hard Function and hard evolution [Gehrmann-Tancredi, Becher-Neubert]
- Beam Functions
- [Mistlberger et al, Becher-Bell, Gaunt et al]
- Jet Functions
- Soft Function and Evolution

$\mathcal{T}_1$ Resummation

$$\frac{d\sigma^{N^3LL}}{d\Phi_1\, d\tau_1} = \sum_k H_k(\mu_H)\, B_k(x_a,\mu_B) B_k(x_b,\mu_B)\, J(\mu_J)\, S(\mu_S)$$

Soft Function and Evolution: Boundary conditions from SoftServe

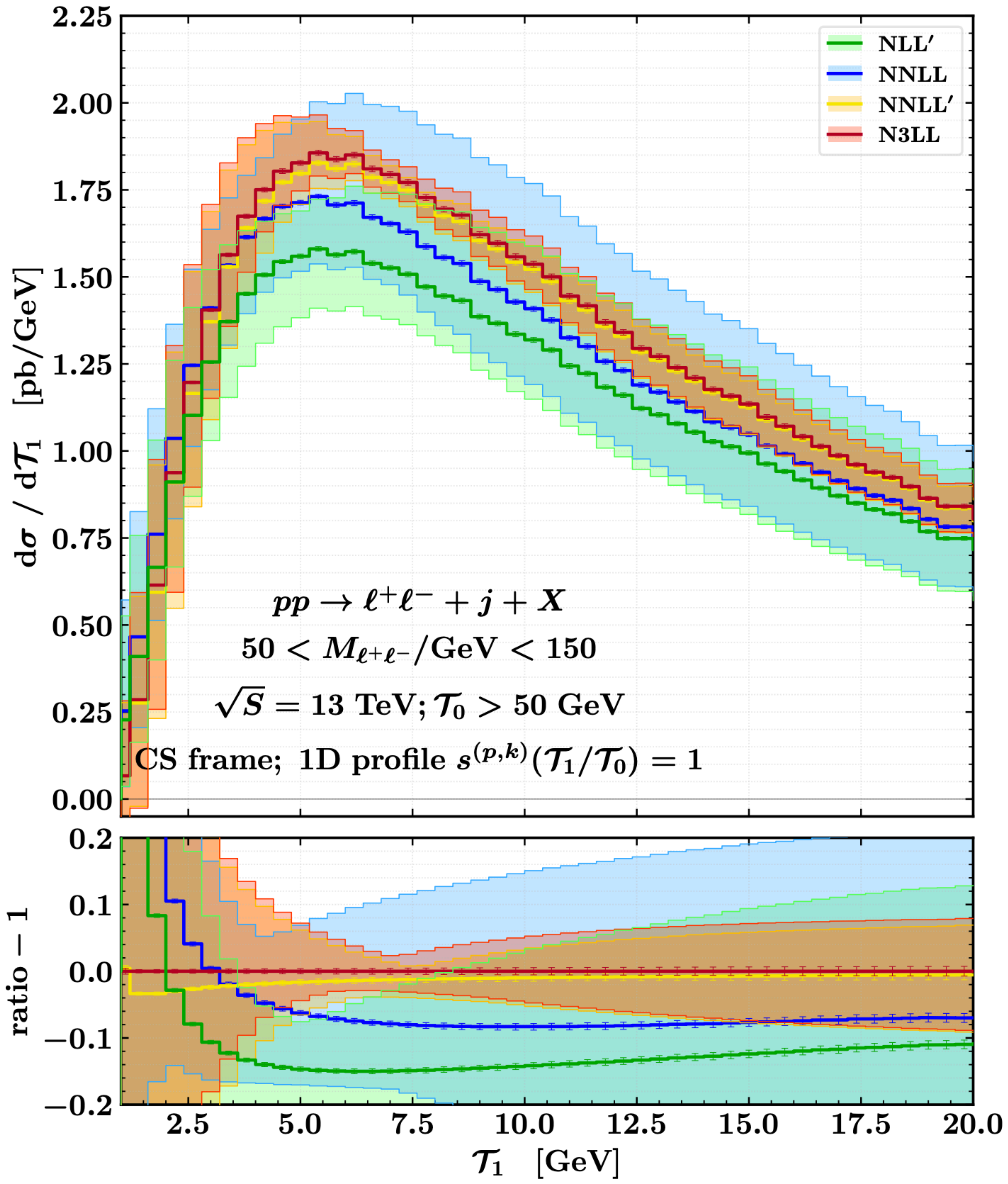


Non-trivial kinematical dependence/better control of small angles

$\mathcal{T}_1$ Resummation

[Phys.Rev.D 109 (2024) 9, 094009]

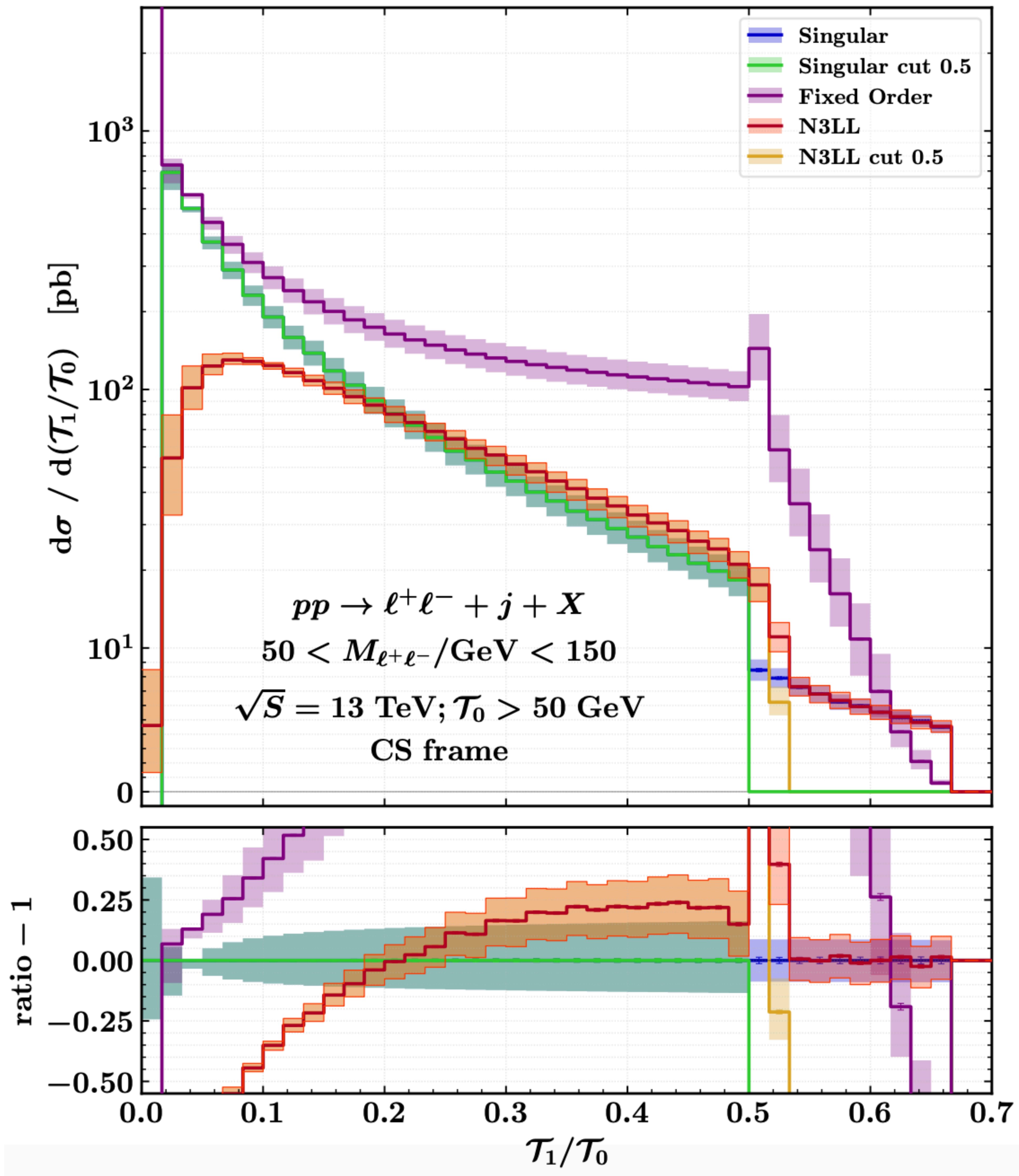
$$\frac{d\sigma^{N^3LL}}{d\Phi_1 d\mathcal{T}_1} = \sum_\kappa H_\kappa(\Phi_1,\mu_H)\, B_\kappa(x_a,\mathcal{T}_1,\mu_B)\, B_\kappa(x_b,\mathcal{T}_1,\mu_B)\, J_\kappa(\mathcal{T}_1,\mu_J)\, S_k(\mathcal{T}_1,\mu_S)$$



$\mathcal{T}_1$ Resummation

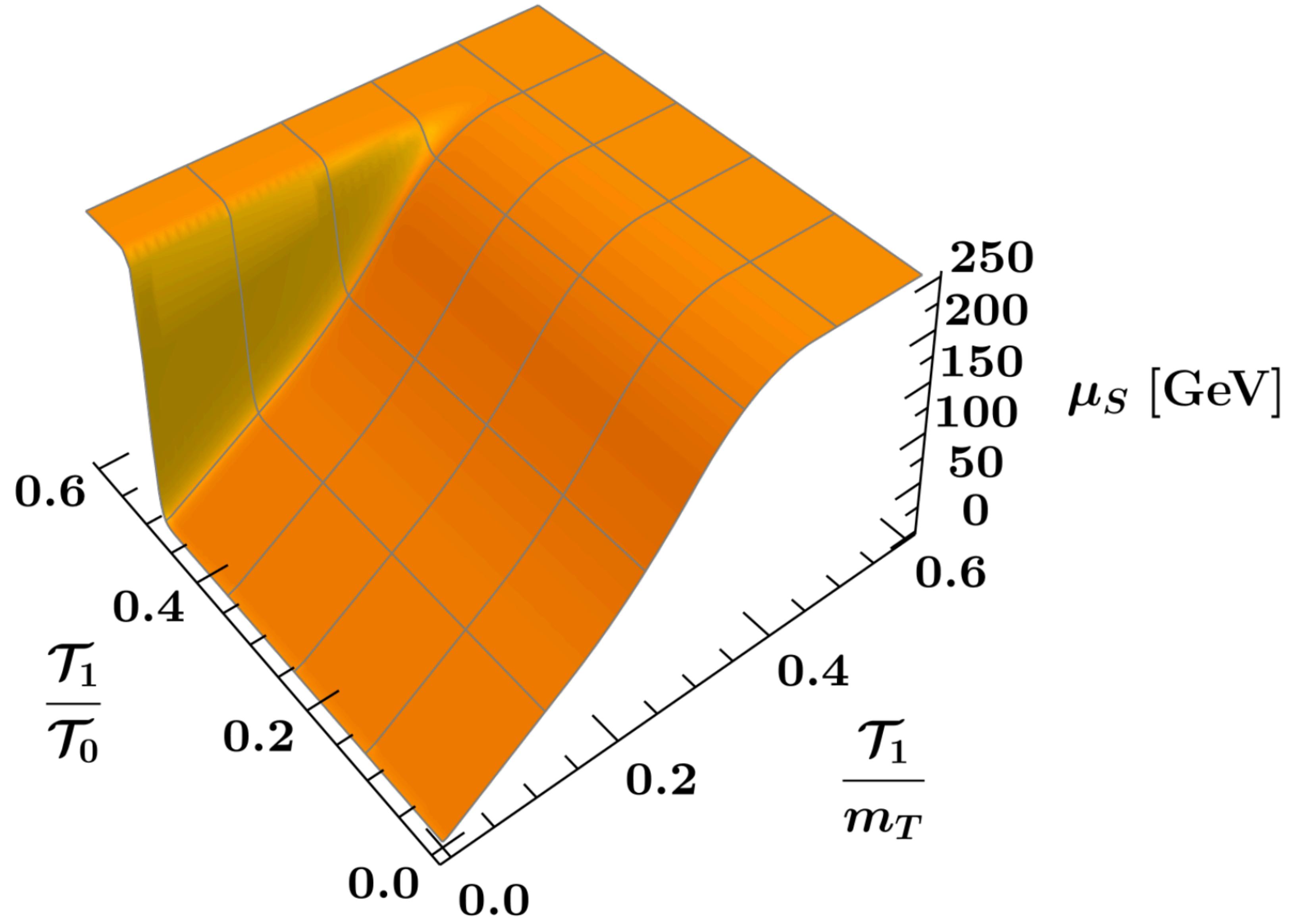
[Phys.Rev.D 109 (2024) 9, 094009]

$$\frac{d\sigma^{N^3LL}}{d\Phi_1 d\mathcal{T}_1} = \sum_\kappa H_\kappa(\Phi_1,\mu_H)\, B_\kappa(x_a,\mathcal{T}_1,\mu_B)\, B_\kappa(x_b,\mathcal{T}_1,\mu_B)\, J_\kappa(\mathcal{T}_1,\mu_J)\, S_k(\mathcal{T}_1,\mu_S)$$



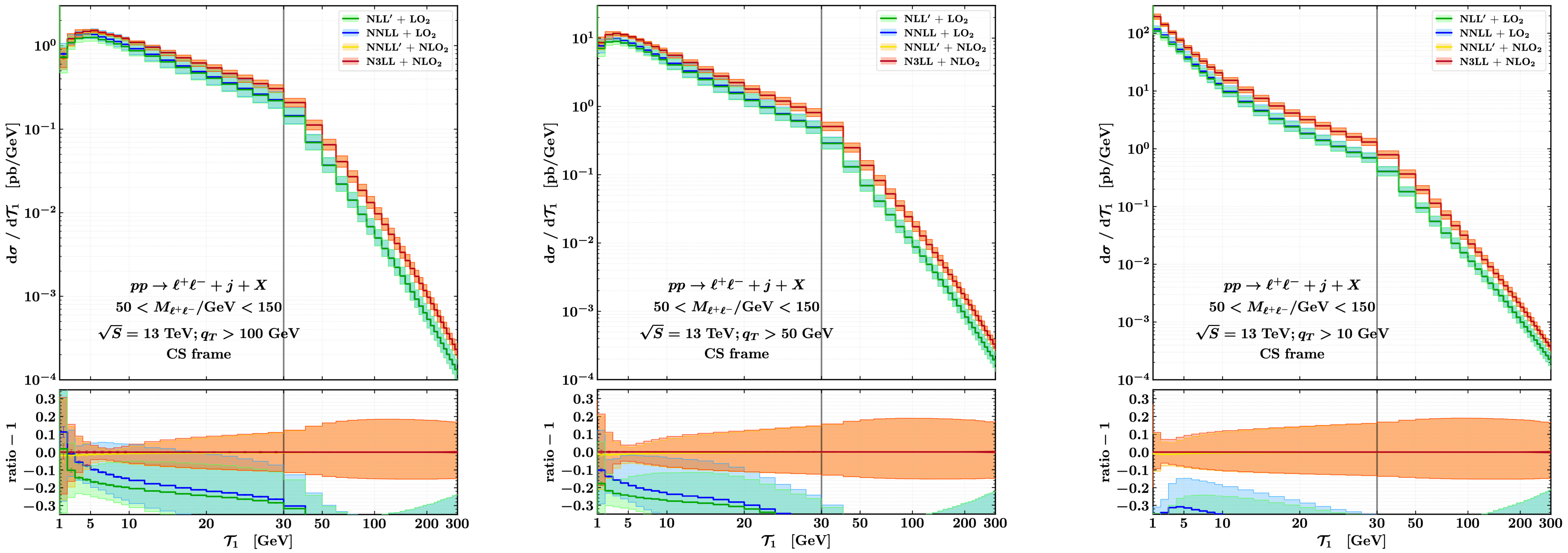
- **Need to impose kinematic constraint**

$$\frac{\mathcal{T}_1(\Phi_N)}{\mathcal{T}_0(\Phi_N)} \le \frac{N-1}{N} = \begin{cases} 1/2\,, & N=2 \\ 2/3\,, & N=3 \end{cases}$$



Matching FO and Resummation

$$\frac{d\sigma}{d\Phi dr} = \frac{d\sigma^{\text{resum}}}{d\Phi dr} - \frac{d\sigma^{\text{resExp}}}{d\Phi dr} + \frac{d\sigma^{\text{FO}}}{d\Phi dr}$$



- Sizeable contribution from non-singular for $q_\perp \to 0$

Resumption

- Ingredients:

  * NNLO FO events for V+j ✓
  * NNLL' resummation formula for $\mathscr{T}_1$ with three coloured partons ✓
  * (optional) NNL resummation for $\mathscr{T}_2$
  * A suitable matching procedure to the shower

Missing ingredients

* **Mapping for NLO_2 phase-space points:** $\Phi_2^{\mathcal{T}_1, q_\perp, \lambda_q} \to \Phi_3^{\mathcal{T}_1, q_\perp, \lambda_q}$

  (required for subtraction and spreading of resummation)

* **Sudakov suppression of $\Phi_2 \to \Phi_3$ events, $\mathcal{T}_2$ resummation**

  (required for shower matching)

Conclusions

- Ingredients:

  * NNLO FO events for V+j ✓
  * NNLL' resummation formula for $\mathscr{T}_1$ with three coloured partons ✓
  * (optional) NNL resummation for $\mathscr{T}_2$ ✗
  * A suitable matching procedure to the shower ✗