Higher order QCD corrections to the gluon-induced associated production of an Higgs and a Z boson at the LHC

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Milan Christmas Meeting 2023

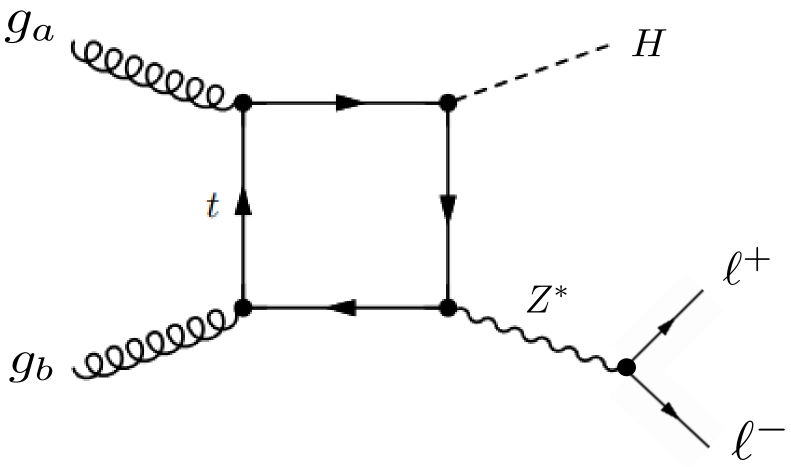
gg → HZ

$$g_a(q_a)g_b(q_b) \longrightarrow H(p_H)Z^*(p_Z)$$

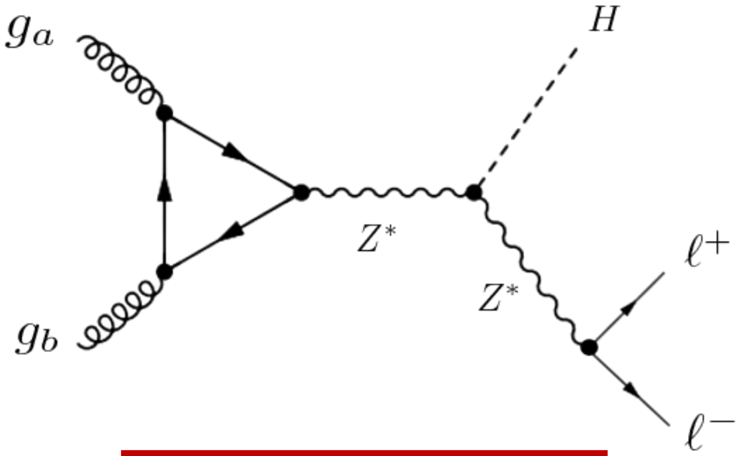
$$Z^*(p_Z) \longrightarrow \ell^+(p_{\ell^+})\ell^-(p_{\ell^-})$$

- **Loop induced process of order:** $\mathcal{O}(\alpha_s^2)$

High gluon luminosity

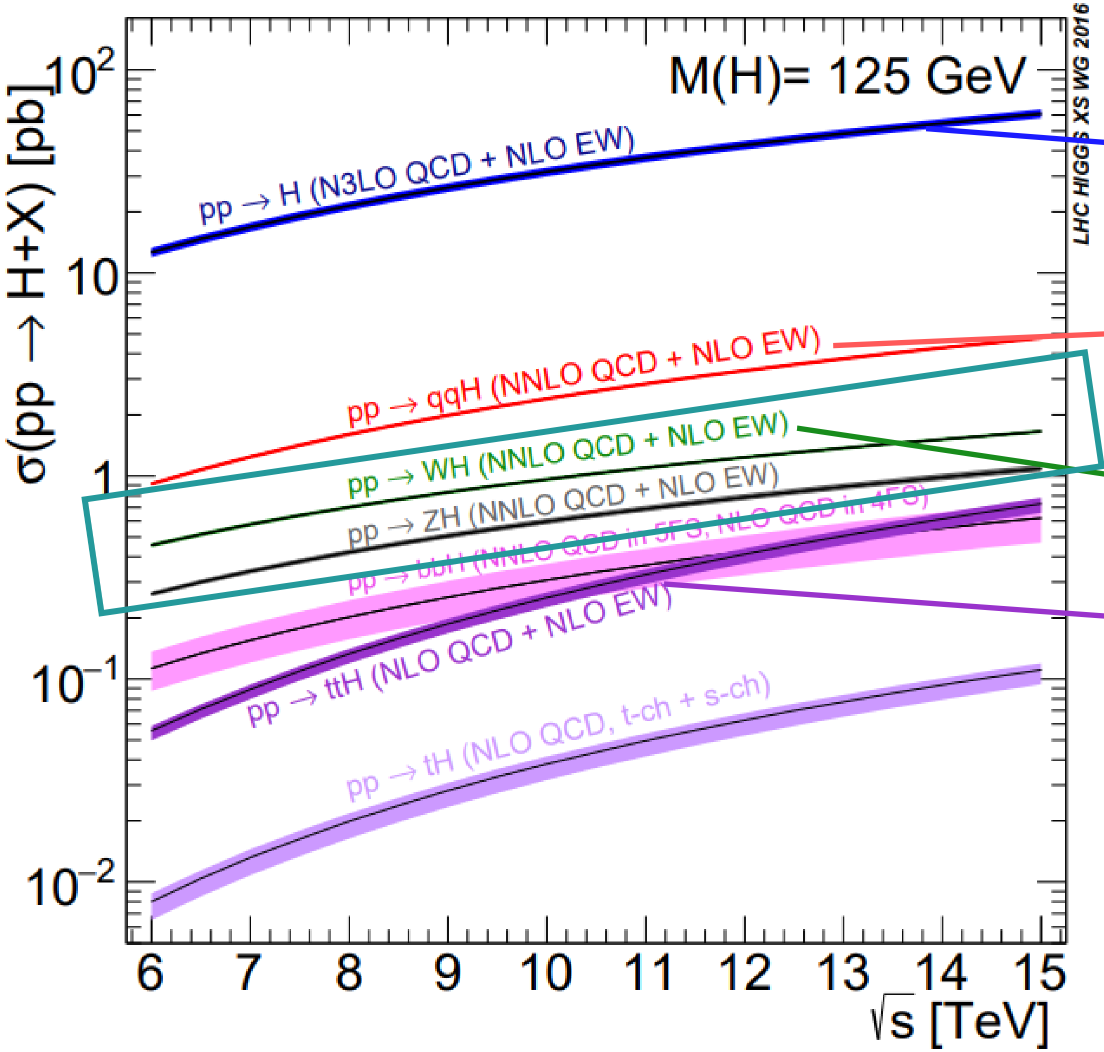


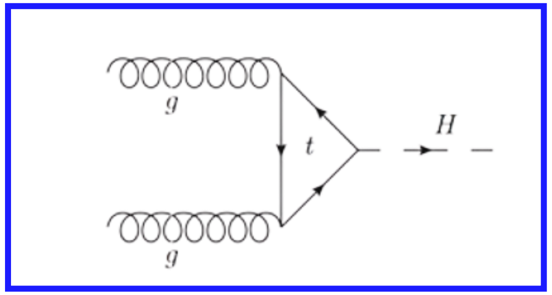
Topology: $\square$

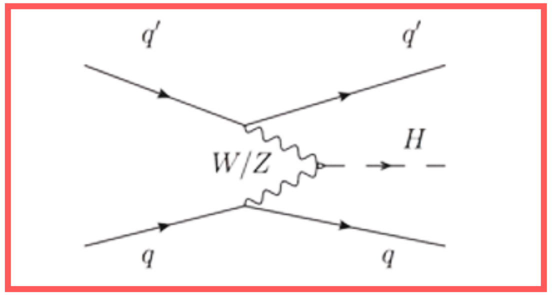


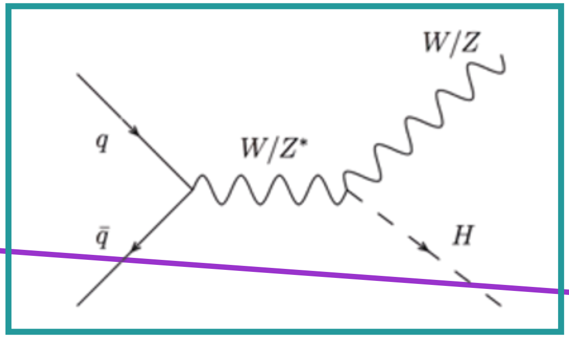
Topology: $\triangle$

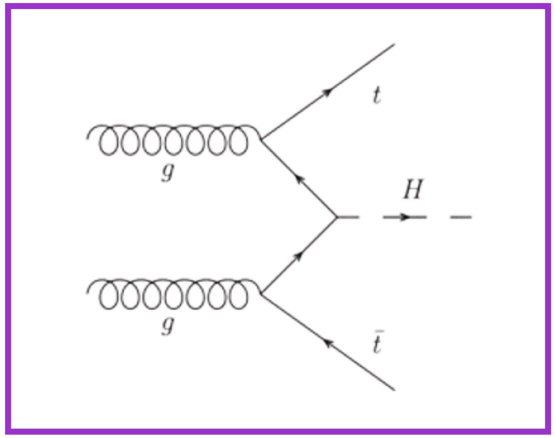
Higgsstrahulung











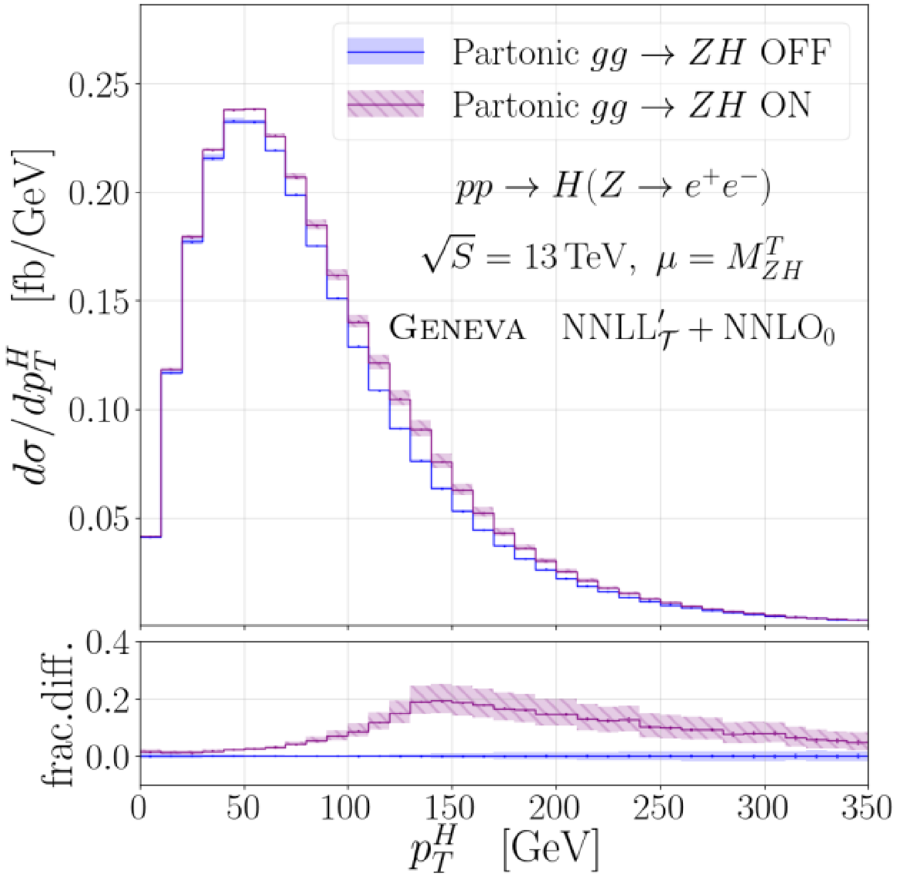
$$pp \to HV, \;\; V \in \{Z, W^{\pm}\}$$

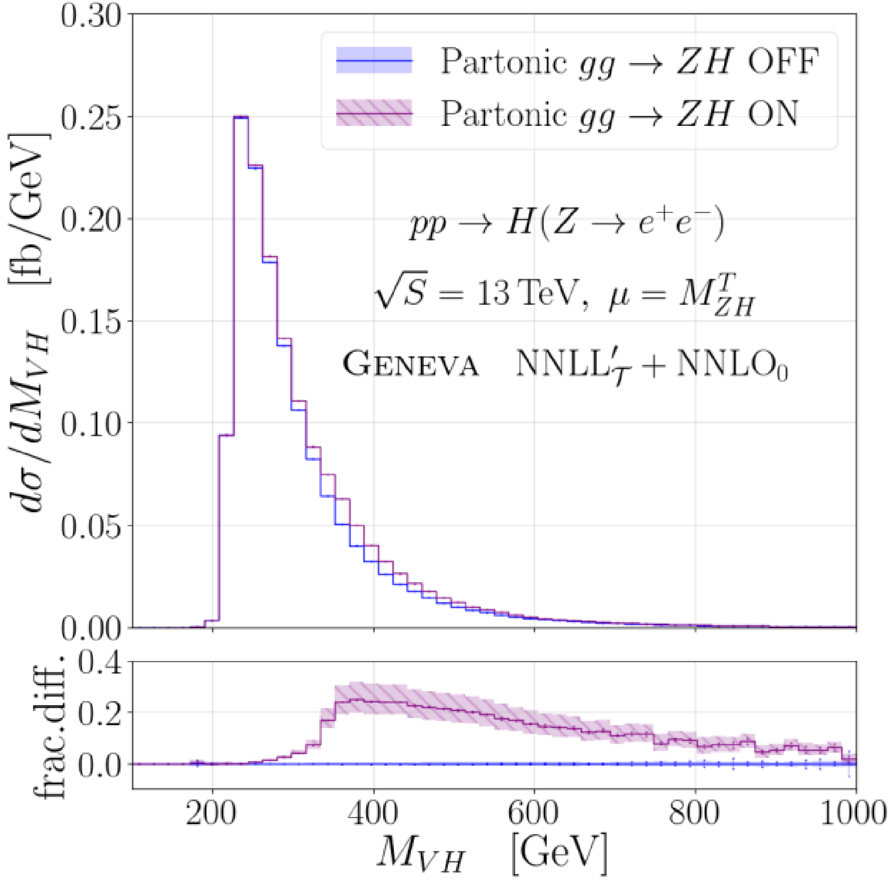
Higgsstrahulung

- Easy to detect (leptonic signature)
- Test for the HV coupling
- Test for the Yukawa coupling
- Test for perturbative QCD
  - Corrections for the total cross section known up to the order N3LO in the qq channel
- Starting from NNLO the gg $\rightarrow$ HZ channel starts contributing

Higgsstrahulung

"Higgsstrahlung at NNLL0+NNLO Matched to Parton Showers in GENEVA"
arXiv:1909.02026v2 [hep-ph] 1 Oct 2019
Simone Alioli, Alessandro Broggio, Stefan Kallweit, Matthew A. Lim, and Luca Rottoli

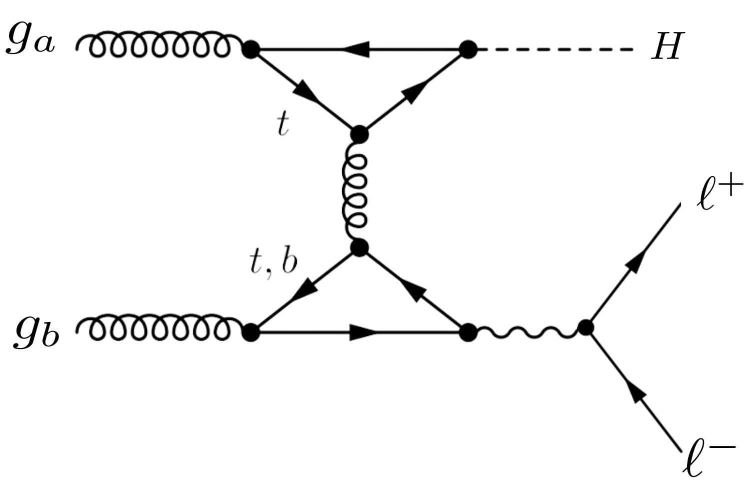


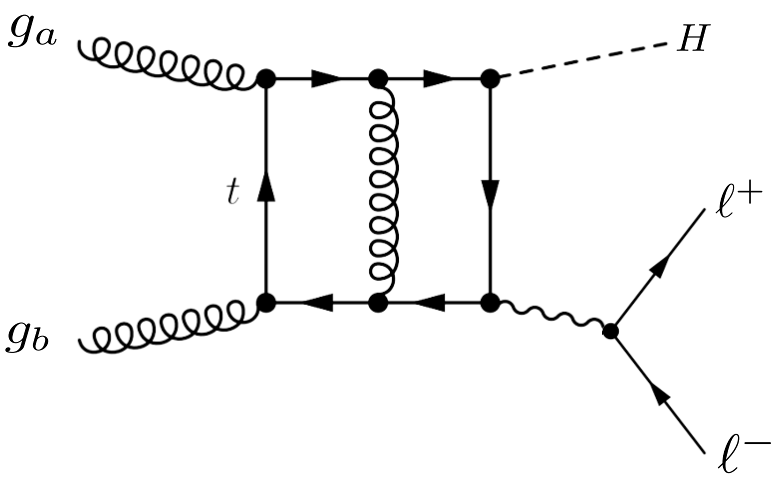


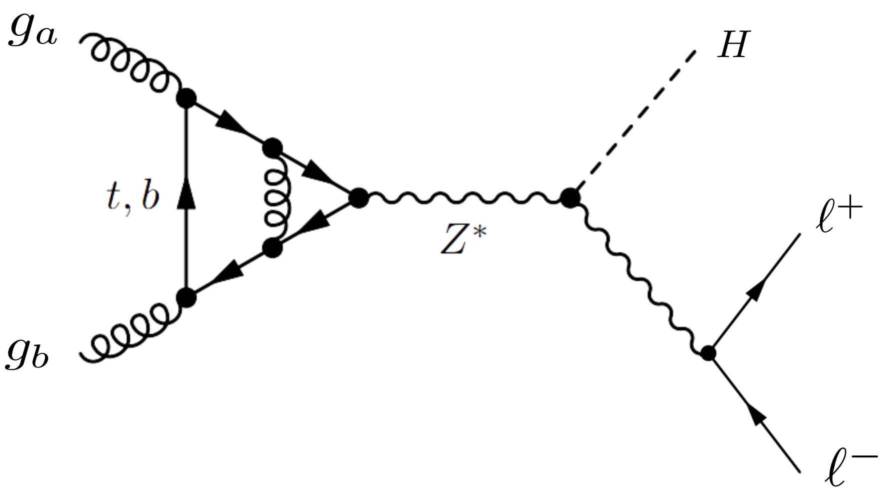
Ingredients for the NLO predictions

- **Virtual corrections:**

''ZH-production at NLO in QCD''
arXiv:2204.05225v1 [hep-ph] 11 Apr 2022
Long Chen,a,i Joshua Davies,b Gudrun Heinrich,c Stephen P. Jones,d Matthias Kerner,c,e Go Mishima,f Johannes Schlenkg and Matthias Steinhauserh







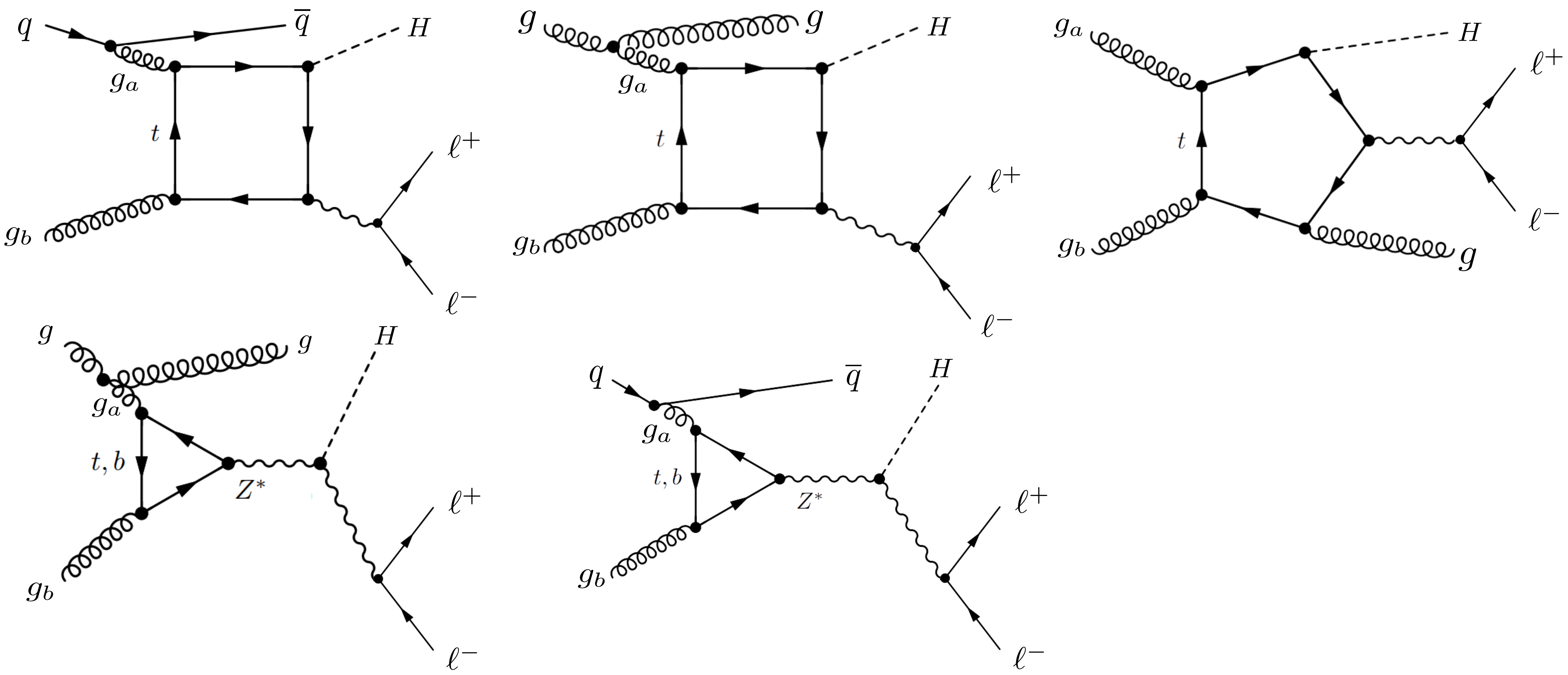
Topology: ⋈

Topology: □

Topology: △

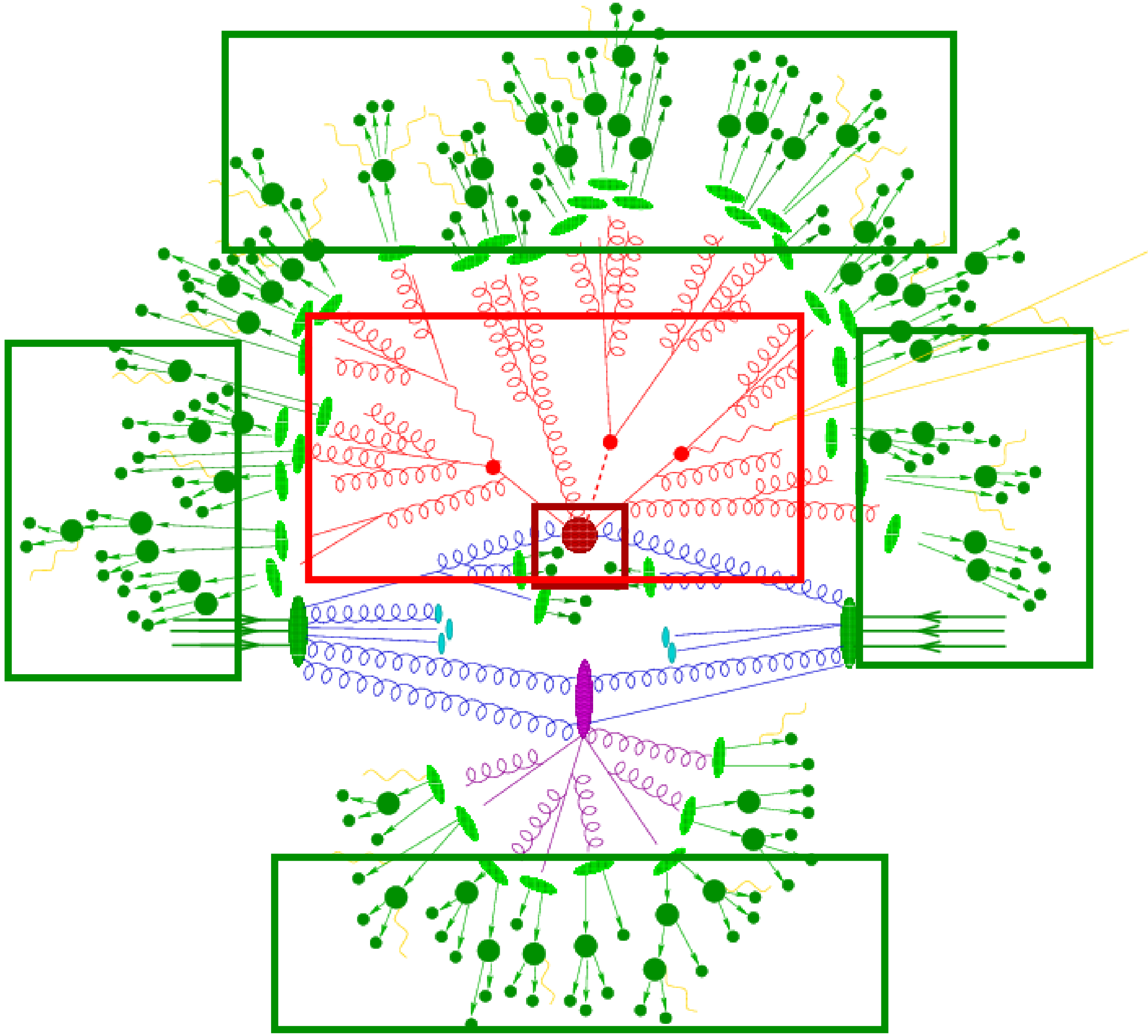
Ingredients for the NLO predictions

- **Real corrections:**



Event generator

- **Physical predictions at the LHC can be obtained combining three different approaches:**
  - **FO perturbative expansion**
  - **Resummation and parton shower**
  - **Underlying event and Hadronization**



GENEVA

- **Generation of IR-safe events**

- **Each M-partonic event shall correspond to an IR-safe N-jet event**

- $\Phi_M \longrightarrow \Phi_N$ → $\dfrac{d\sigma_N^{(\mathrm{MC})}}{d\Phi_N}$ **IR-safe Monte Carlo Cross section**

- Φ_M **Gets partitioned in different regions with different numbers of resolved emissions**

GENEVA – General Aspects

- Resolution variable $\mathcal{T}_N$
  - Sensitive to the extra emission
  - IR-safe

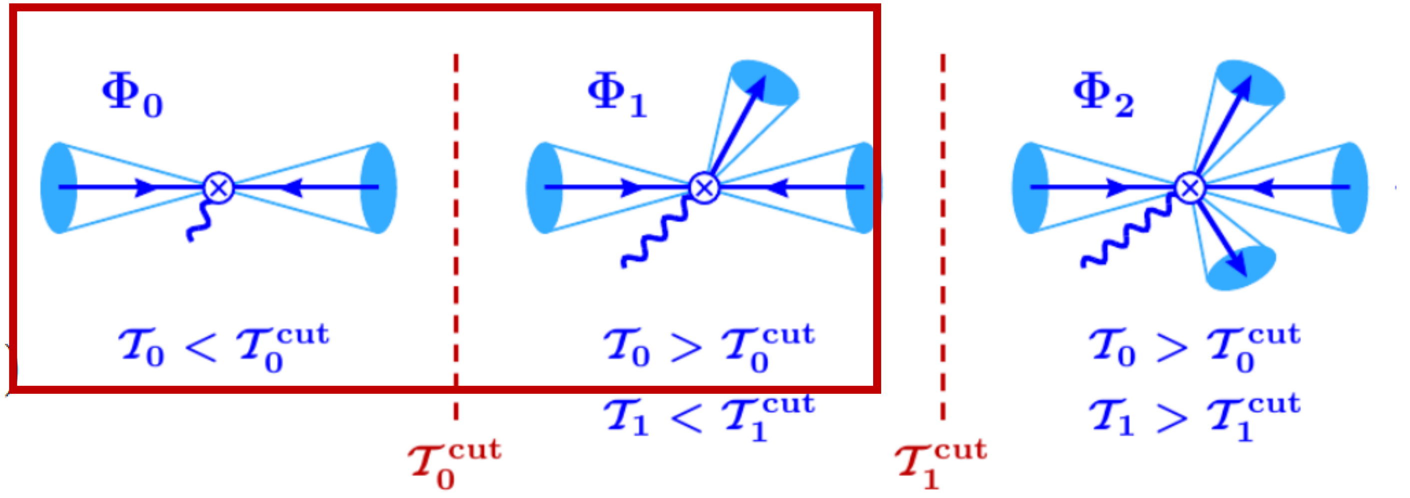
$$\mathcal{T}_0 = \frac{2}{Q}\sum_k \min\{\hat{q}_a \cdot p_k, \hat{q}_b \cdot p_k\}$$

- Phase space partition

$$\Phi_0 \text{ events:} \quad \frac{d\sigma_0^{MC}}{d\Phi_0}(\mathcal{T}_0^{cut}),$$

$$\Phi_1 \text{ events:} \quad \frac{d\sigma_1^{MC}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{cut}; \mathcal{T}_1^{cut}),$$

$$\Phi_2 \text{ events:} \quad \frac{d\sigma_{\geq 2}^{MC}}{d\Phi_2}(\mathcal{T}_0 > \mathcal{T}_0^{cut}, \mathcal{T}_1 > \mathcal{T}_1^{cut})$$



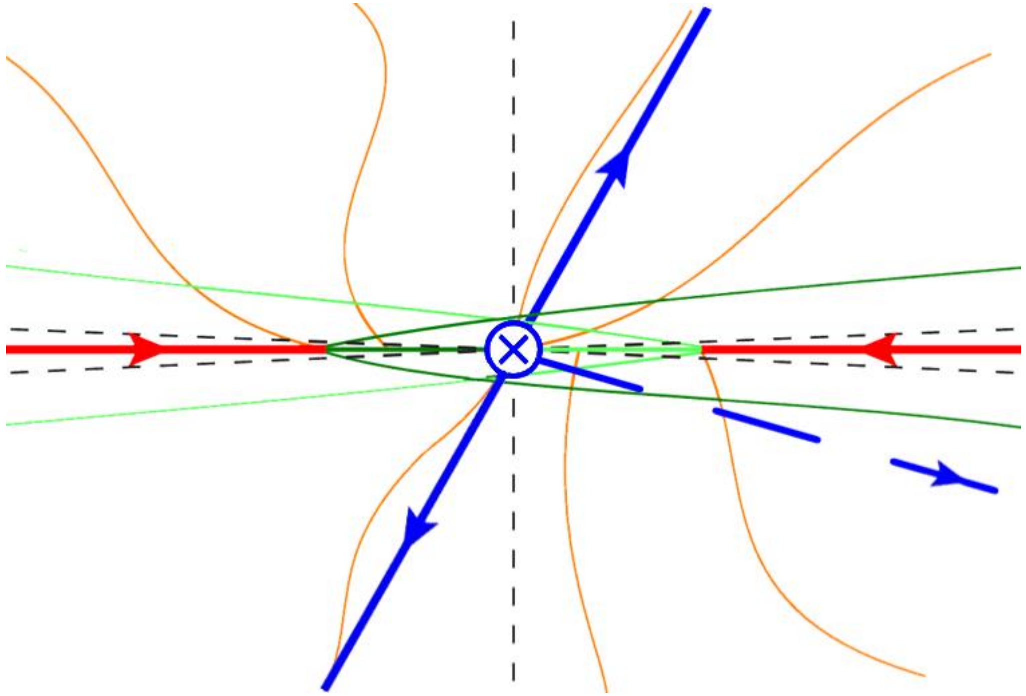
Resummation: SCET

- Describes the propagation of the soft and collinear modes in the presence of an hard (effective) interaction
- The lagrangian is expanded in the soft and collinear limit
- The hard modes are integrated out
- Factorization at the cross section level
  - Many scales problem ⟶ Sequence of single scale problem
- Systematic resummation

Resummation: SCET

- **Factorization theorem**

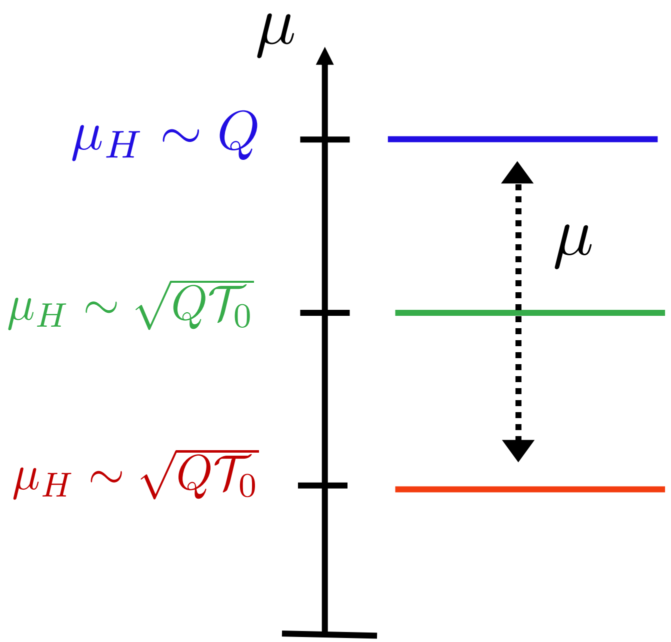
$$\frac{d\sigma}{d\Phi_0 d\mathcal{T}_0} = \boxed{\frac{d\sigma^{\rm B}}{d\Phi_0} H(Q^2,\mu)} \int dt_a dt_b \boxed{B_a(t_a,x_a,\mu)} \boxed{B_b(t_b,x_b,\mu)} \boxed{S\left(\mathcal{T}_0 - \frac{t_a+t_b}{Q},\mu\right)}$$



- **Perturbative expansion**
- **Logarithmic dependence from the scales**
- $\mu_H = Q,\ \mu_B = \sqrt{Q\mathcal{T}},\quad \mu_S = \mathcal{T}_0$

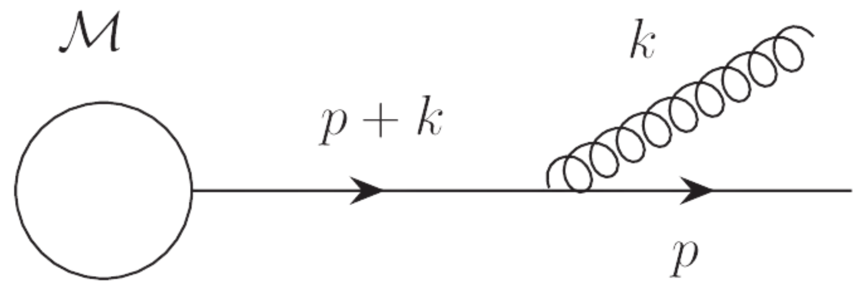
Resummation: SCET

$$
\frac{d\sigma^{\text{res}}}{d\Phi_0 d\mathcal{T}_0} = \frac{d\sigma^{\text{B}}}{d\Phi_0} H(Q^2, \mu_H) U_H(\mu_H, \mu) \int dt_a dt_b
$$
$$
\times \left[B_a(t_a, x_a, \mu_B) \otimes U_B(\mu_B, \mu)\right]
$$
$$
\times \left[B_b(t_b, x_b, \mu) \otimes U_B(\mu_B, \mu)\right]
$$
$$
\times \left[S\left(\mathcal{T}_0 - \frac{t_a + t_b}{Q}, \mu_S\right) \otimes U_S(\mu_S, \mu)\right]
$$



GENEVA – Implementation

- **Phase space Φ_0**
  - $$\frac{d\sigma_0^{\rm MC}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) = \frac{d\sigma_0^{\rm res}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) + \frac{d\sigma_0^{\rm nons}}{d\Phi_0}(\mathcal{T}_0^{\rm cut})$$
  - $$\frac{d\sigma_0^{\rm nons}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) = \frac{d\sigma_0^{\rm FO}}{d\Phi_0}(\mathcal{T}_0^{\rm cut}) - \left[\frac{d\sigma_0^{\rm res}}{d\Phi_0}(\mathcal{T}_0^{\rm cut})\right]_{FO}$$



- **Phase space Φ_1**
  - $$\frac{d\sigma_{\geq 1}^{\rm MC}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) = \frac{d\sigma_{\geq 1}^{\rm res}}{d\Phi_0 d\mathcal{T}_0}\mathcal{P}(\Phi_1)\theta(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut}) + \frac{d\sigma_{\geq 1}^{\rm nons}}{d\Phi_1}(\mathcal{T}_0 > \mathcal{T}_0^{\rm cut})$$
    - **Built using Altarelli Parisi splitting function**
    - **Normalised in such a way that the spectrum is not spoiled**

GENEVA – Implementation

- **RES expansion** $\xrightarrow{\mathcal{T}_0 >> Q}$ **FO expansion**

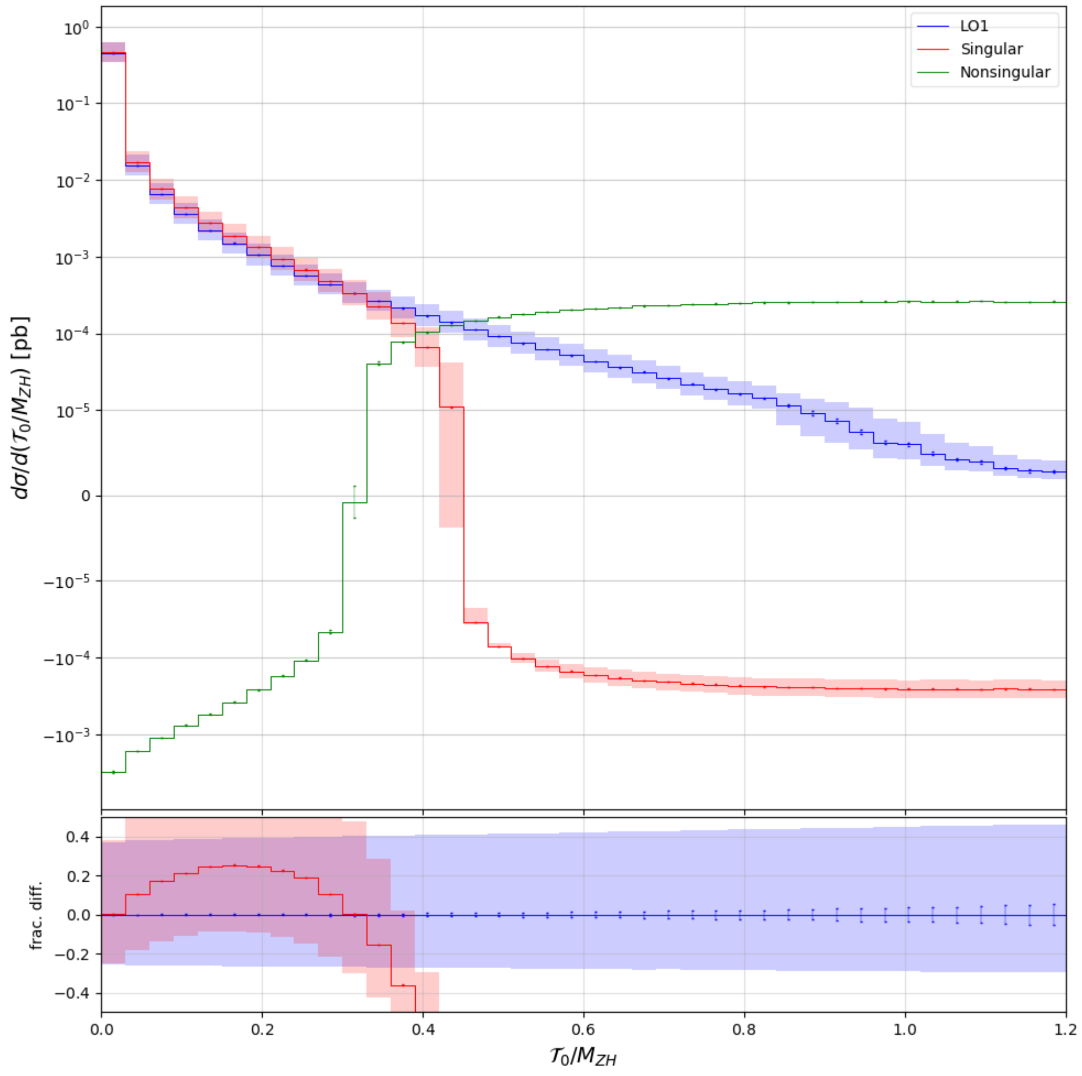
- **The resummation is switched off using the RG to evolve all scales at a common non singular scale μ_{NS}**

- **Smooth transition from RES to FO expansion using profile scale**

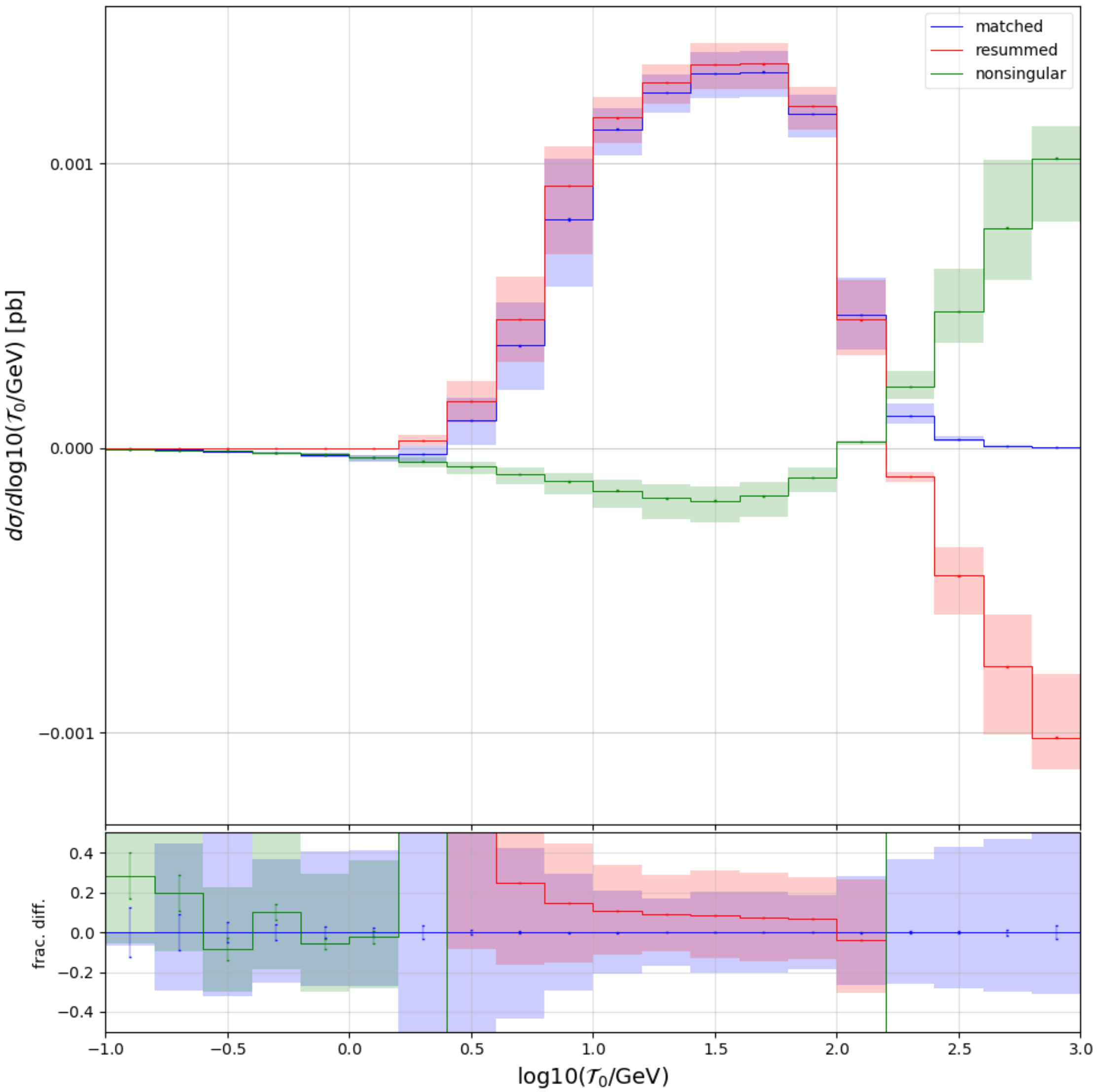
$$\mu_{\rm NS}(\mathcal{T}_0) = \mu_H$$

$$\mu_S(\mathcal{T}_0) = \mu_{NS} f_{\rm run}(\mathcal{T}_0/Q)$$

$$\mu_B(\mathcal{T}_0) = \mu_{NS} \sqrt{f_{\rm run}(\mathcal{T}_0/Q)}$$



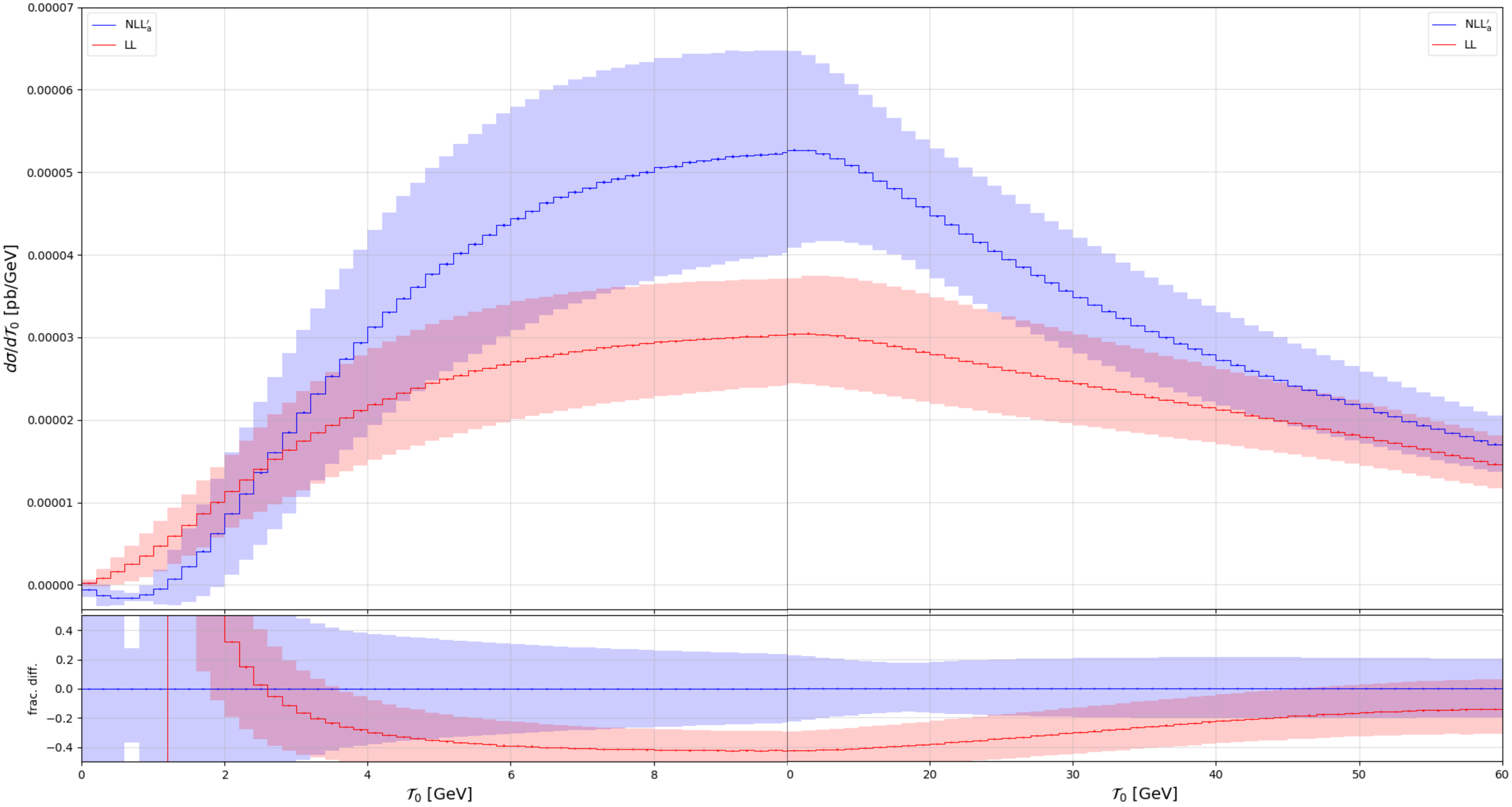
Preliminar results



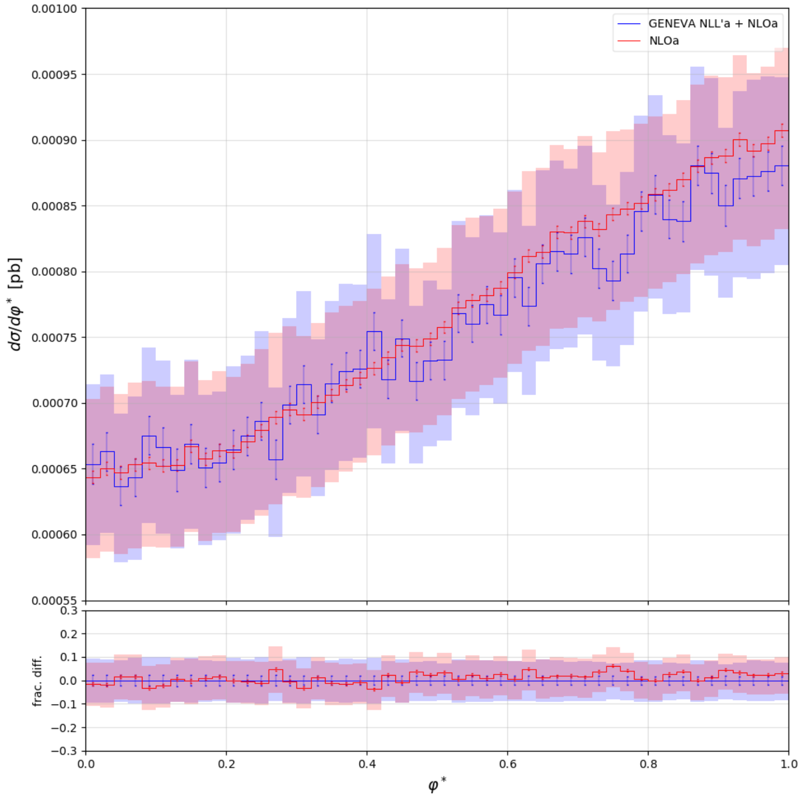
Agreement betweem Res and Matched for small value of $\mathcal{T}_0$

- **Matching between RES and FO $\mathcal{T}_0$**
- **Recovering of the FO results**
- **Linear beheavour of the non singular term**

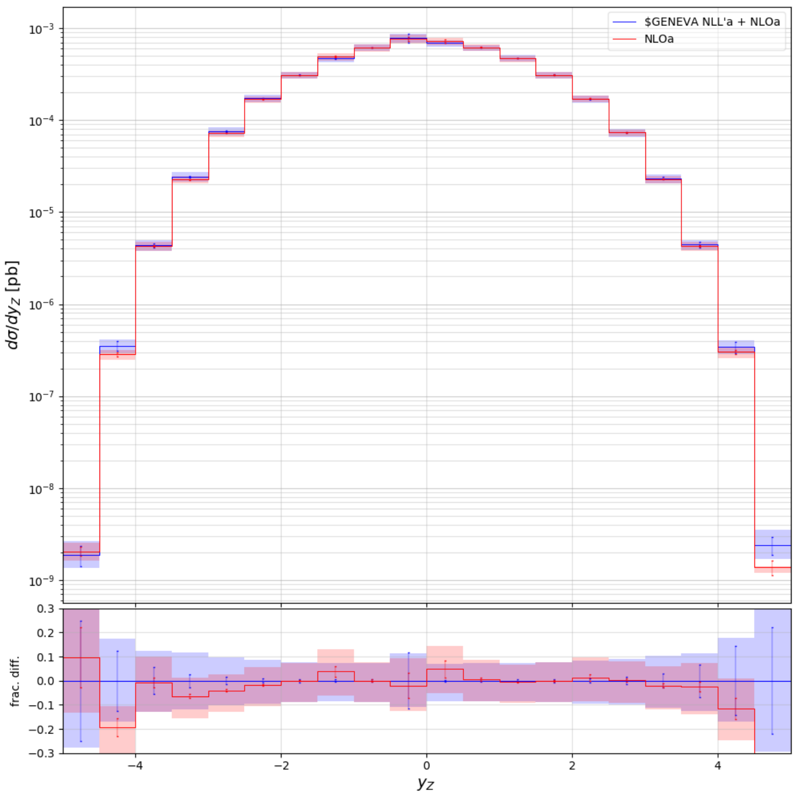
Preliminar results



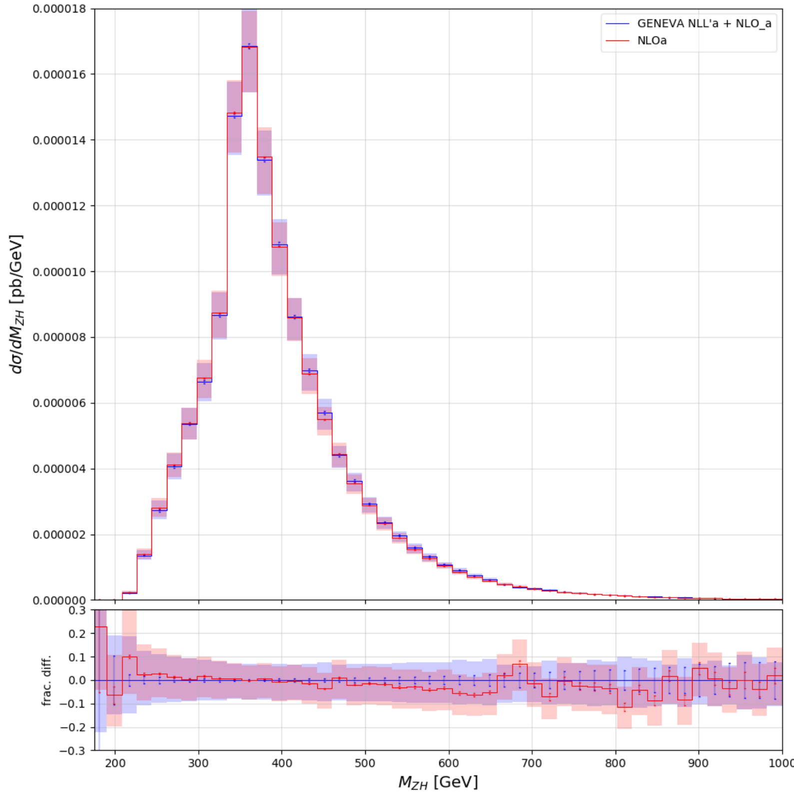
Preliminar results



φ^*

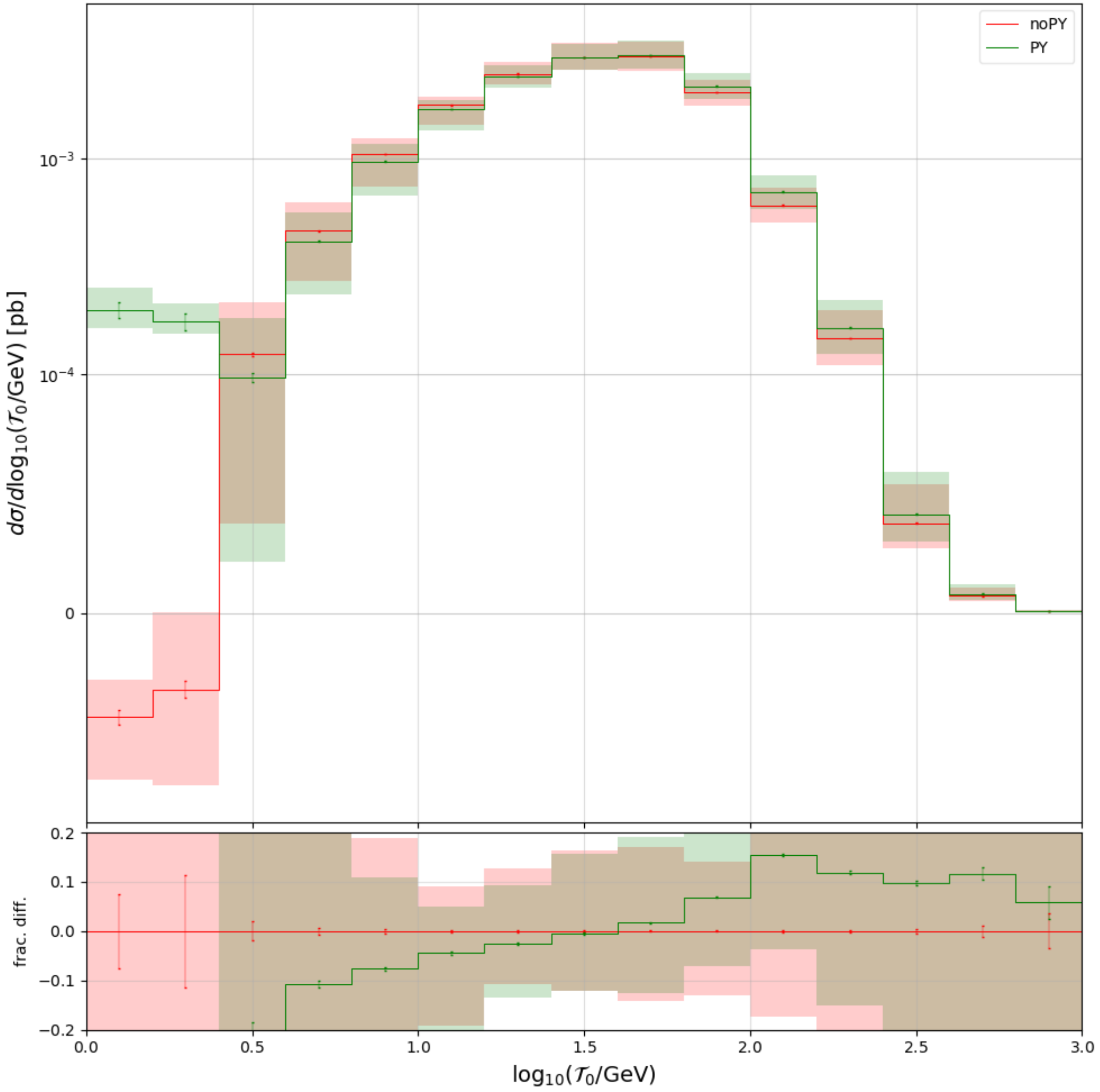


Y_Z **rapidity**



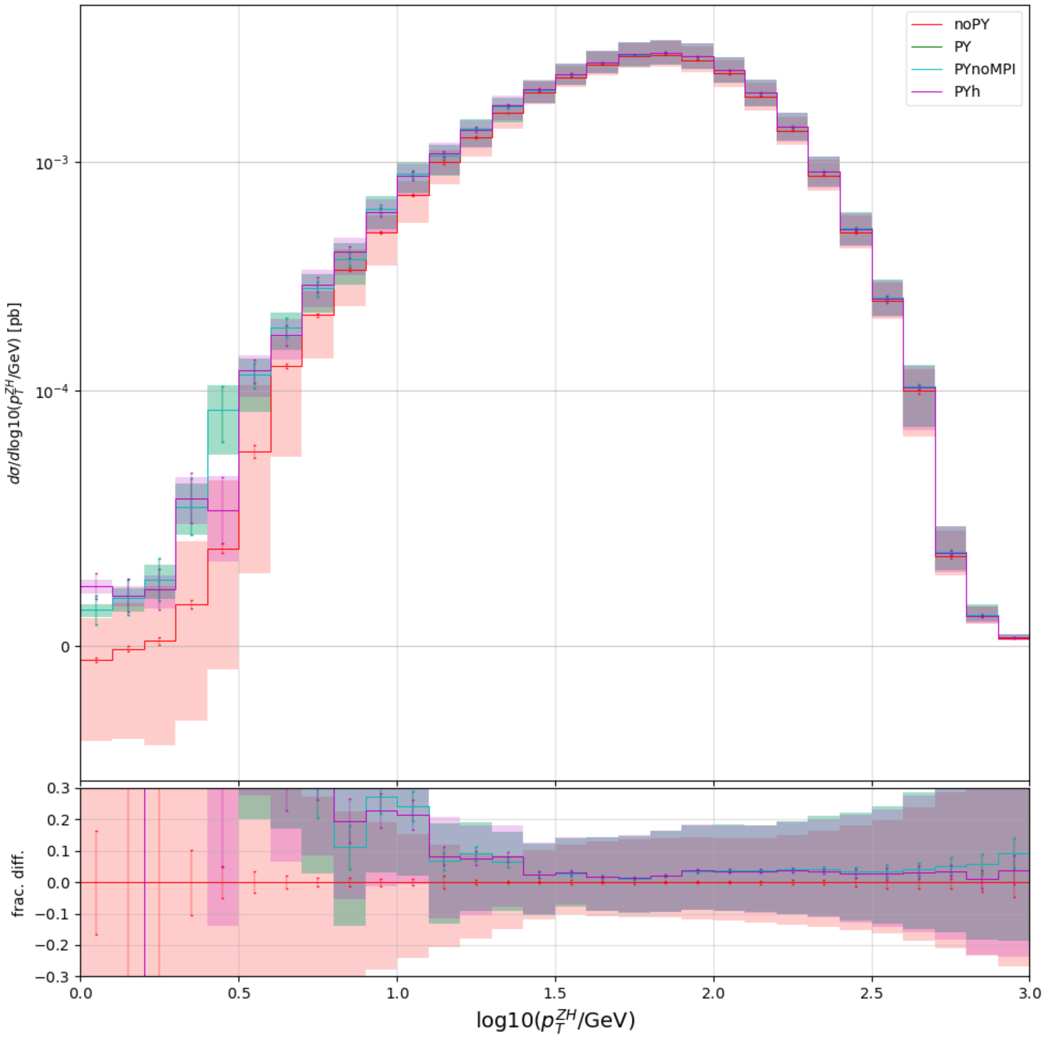
M_Z **mass**

Final result – Parton Shower



- **Sizable impact below** $\mathcal{T}_0 < 2\text{Gev}$
- **Almost unchanged above**

Final results – Hadronizatiom



- **Sizable effect only at low** P_T^{ZH}
- **No relevant deviation from between the cases with and without MPI**