# Modern Techniques for Multi-loop Amplitudes

**Vasily Sotnikov**

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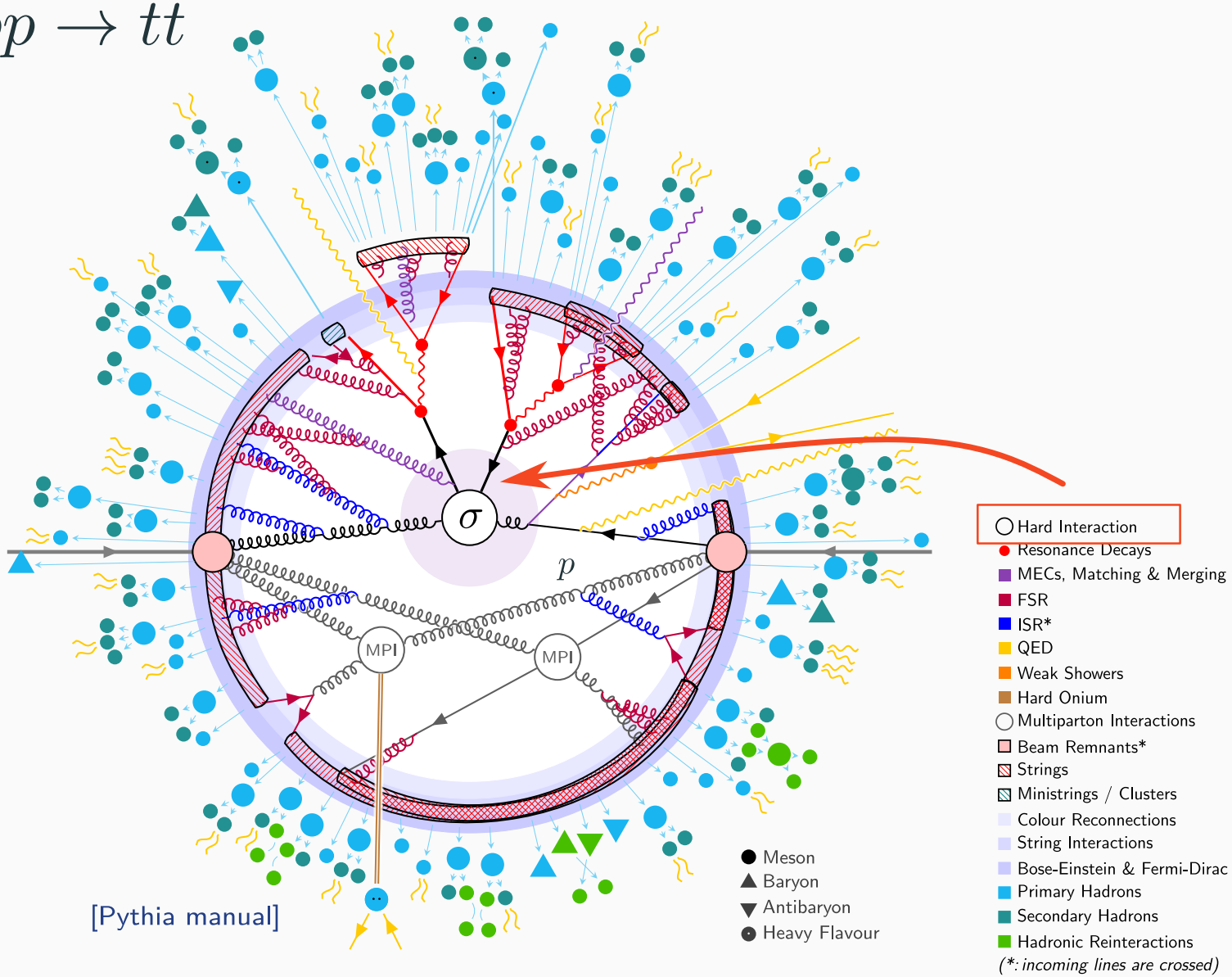
Universität Zürich[UZH]

# Theoretical description of particle collisions

$pp \to t\bar{t}$




[Pythia manual]

# Hard scattering

Collinear factorization:

$$d\sigma_{h_1 h_2 \to X}(p_1, p_2) = \sum_{i,j} \int \mathrm{d}x_1 \, \mathrm{d}x_2 \, f_i(x_1, \mu) f_j(x_2, \mu) \, \mathrm{d}\hat{\sigma}_{ij \to X}(x_1 p_1, x_2 p_2, \mu) + \mathcal{O}(\Lambda_{\mathrm{QCD}}/Q)$$

Parton channels

Parton distribution functions

e.g. $pp \to t\bar{t} + X$ :
$q\bar{q} \to t\bar{t}$
$gg \to t\bar{t}$
$qg \to qt\bar{t}$
$\ldots$

# Perturbation theory

- Properties of fundamental interactions are encoded in patterns of scattered particles.
- Scattering amplitudes are theoretical building blocks for these observable quantities, computable from first principles of QFT.
- Cannot compute amplitudes exactly $\implies$ calculation via perturbative expansion in the coupling constants.

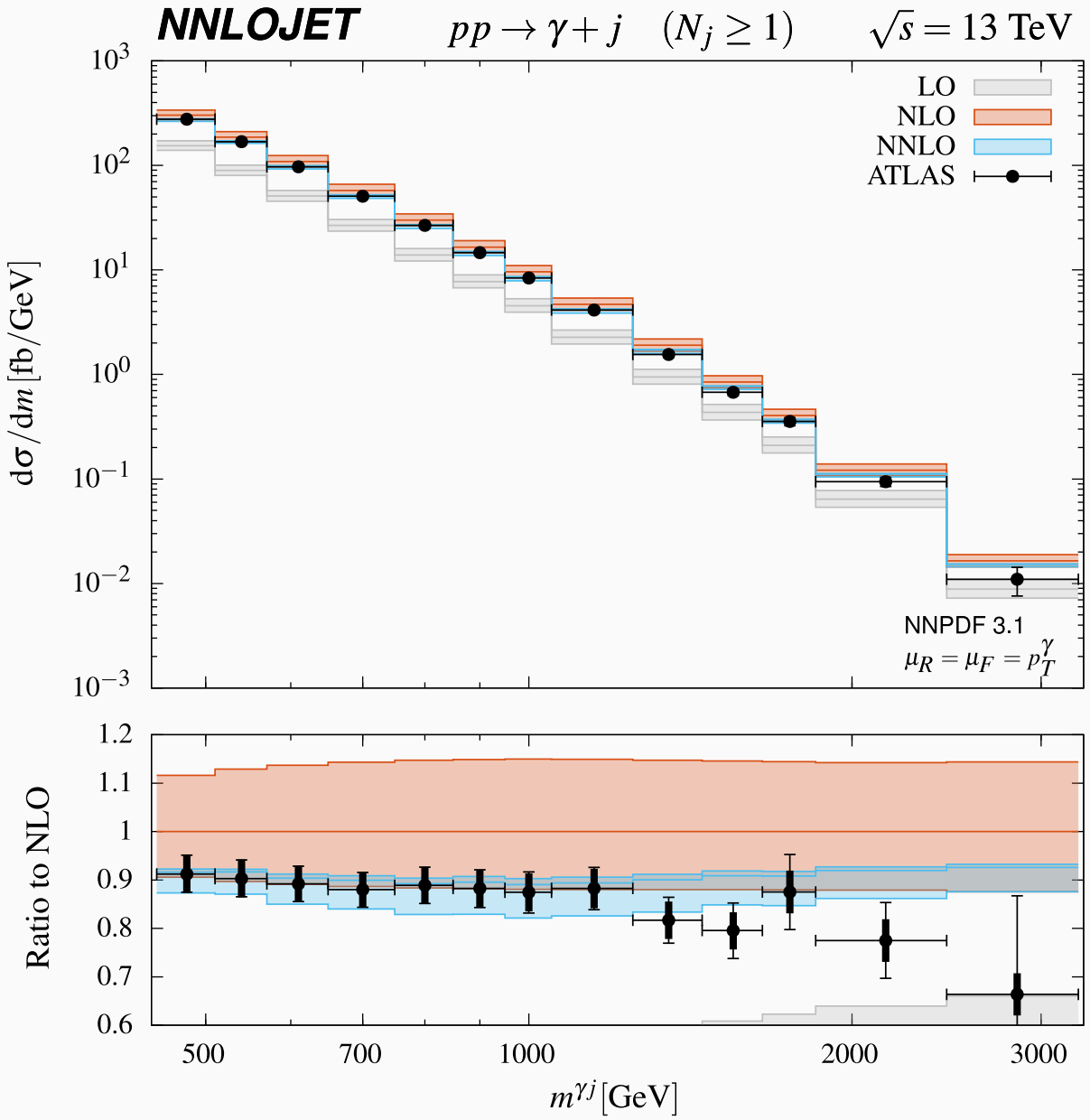
$$\alpha_s(M_Z) \sim 0.1$$
$$\alpha(M_Z) \sim 0.01$$

$$\mathrm{SM} = \mathrm{QCD} \otimes \mathrm{EW}$$

$$\sigma = \sigma_0 \left(1 + \alpha_s \sigma^{(1,0)} + \alpha \sigma^{(0,1)} + \alpha_s^2 \sigma^{(2,0)} + \alpha \alpha_s \sigma^{(1,1)} + \alpha_s^3 \sigma^{(3,0)} + \alpha_s^2 \alpha \sigma^{(2,1)} + \dots\right)$$

Error due to series truncation

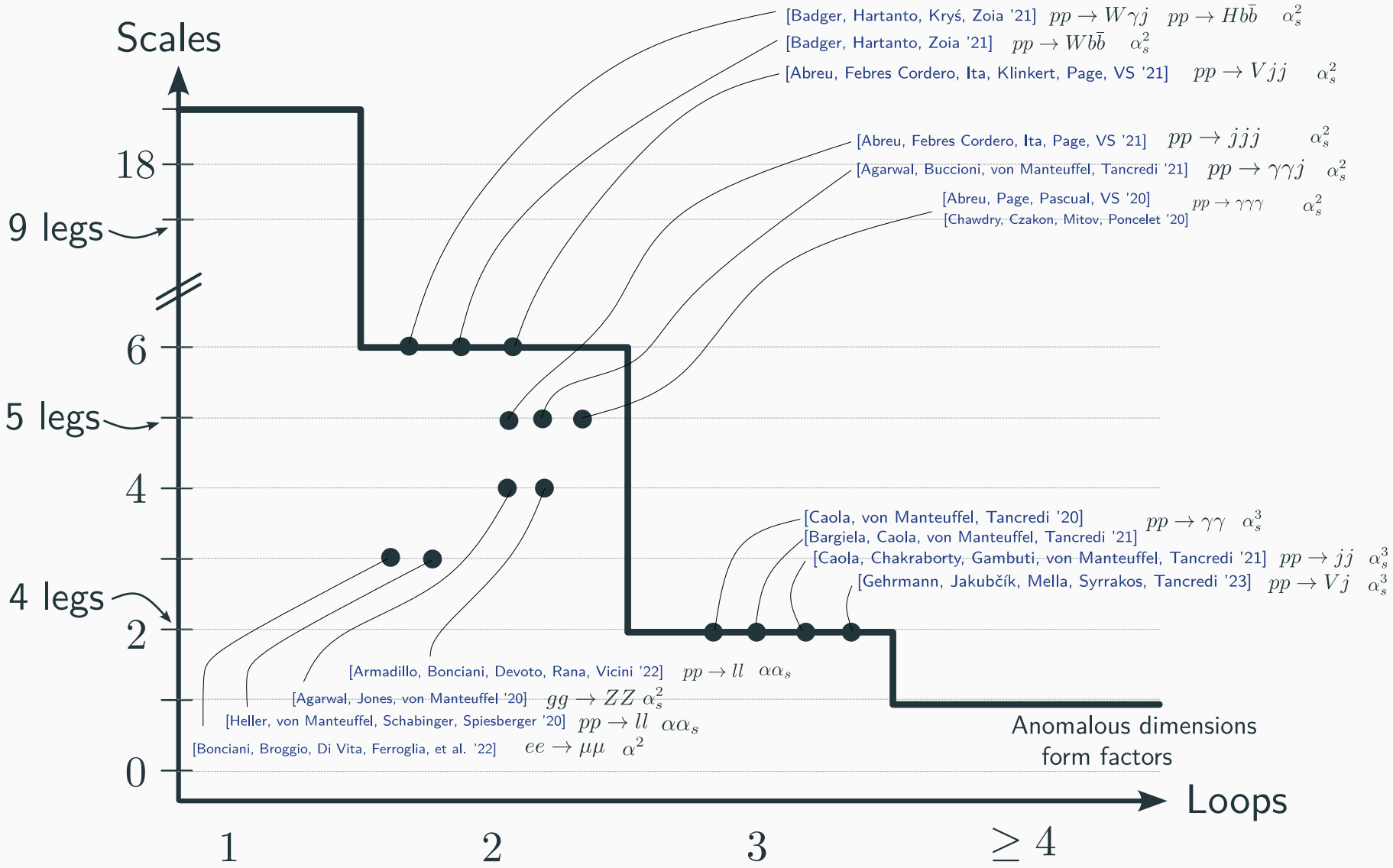
# Example: NNLO predictions vs experimental data




[arXiv:1904.01044]

data from [1801.00112]

# Loop amplitudes in SM: state of the art




Warning: a biased selection of references!