High precision perturbative QCD predictions for Higgs production at the LHC

Jesús Urtasun Elizari

PhD seminar - Milan, September 2020

UNIVERSITÀ DEGLI STUDI DI MILANO

N3PDF Machine Learning • PDFs • QCD

European Research Council

This project has received funding from the European Union′s Horizon 2020 research and innovation program under grant agreement No 740006.

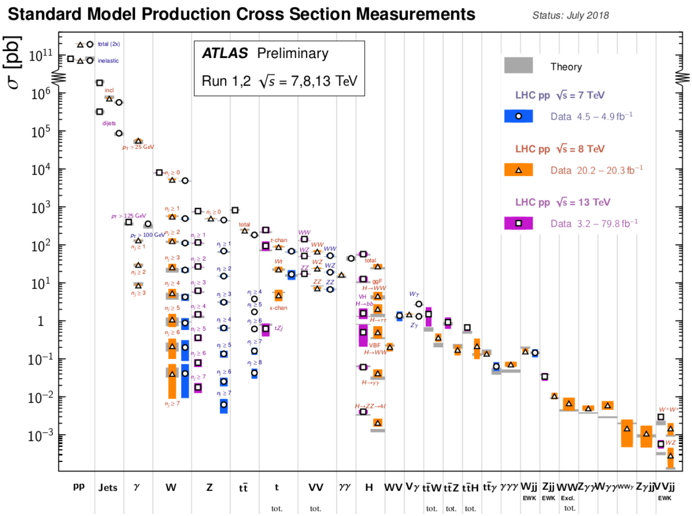
Outline

1. QCD in a nutshell
    - Factorization in QCD
    - Partonic cross section
    - Perturbative QCD
2. Resummation in QCD
    - Higher order corrections
    - Resummation of $q_\perp$
3. HTurbo
    - Higgs production at the LHC: HRes and HqT
    - HTurbo: Fast predictions for Higgs production
    - Results & Conclusions

QCD in a nutshell

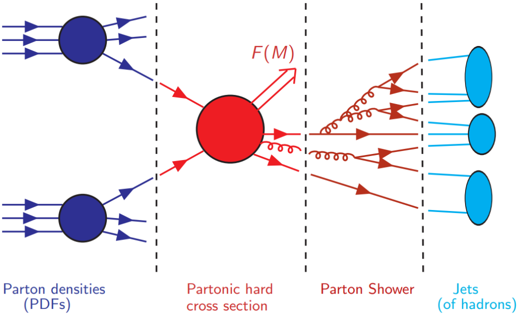
QCD in a nutshell

LHC physics



QCD in a nutshell

Factorization theorem

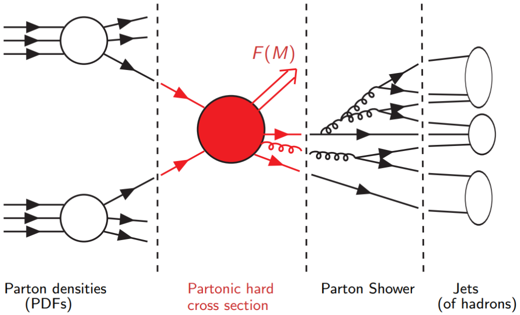


Compute cross sections is a Hard problem $\longrightarrow$ QCD Factorization

$$\sigma^{\mathrm{F}}(p_1, p_2) = \int_0^1 dx_1 dx_2 \; f_\alpha(x_1, \mu_F^2) * f_\beta(x_2, \mu_F^2) * \hat{\sigma}^{\mathrm{F}}_{\alpha\beta}(x_1 p_1, x_2 p_2, \alpha_s(\mu_R^2), \mu_F^2)$$

QCD in a nutshell

Partonic cross section

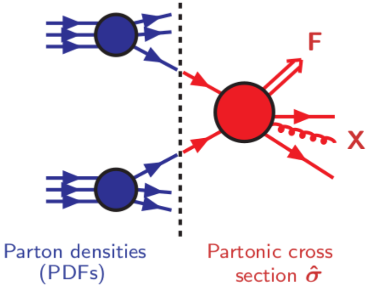


- PDFs $f_\alpha(x_i, \mu_F^2)$ absorb the non perturbative effects, evaluated at μ_F
- Partonic $\hat{\sigma}^{\mathrm{F}}_{\alpha\beta}$ can be computed as perturbative series in α_s

QCD in a nutshell

Perturbative QCD

- Born cross section as LO value of a perturbative series
- $\sigma^{(1)}, \sigma^{(2)}, \sigma^{(3)}$ are the NLO, NNLO, N3LO corrections



$$\hat{\sigma} = \sigma^{\mathrm{Born}} \left(1 + \frac{\alpha_s}{2\pi} \sigma^{(1)} + \left(\frac{\alpha_s}{2\pi}\right)^2 \sigma^{(2)} + \left(\frac{\alpha_s}{2\pi}\right)^3 \sigma^{(3)} + \ldots \right)$$

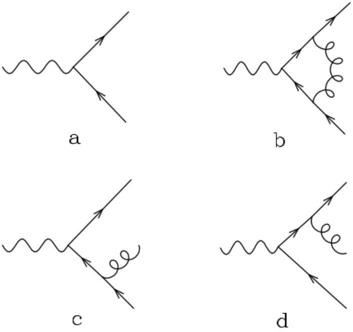
Leading order predictions can strongly depend on the renormalization and factorization scales $\rightarrow$ Need higher order corrections!

Resummation in QCD

Resummation in QCD

Higher order corrections

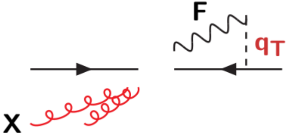
1. Higher order corrections are not an easy task due to infrared (IR) singularities
2. Final state radiations cancel by combining real and virtual contributions
3. Initial state radiations factorized inside the PDFs, then IR-free, finite $\hat{\sigma}$



Study the differential $q_\perp$ distribution

$$h_1(p_1) + h_2(p_2) \longrightarrow F(M, q_\perp) + X$$

$\alpha_S L^2$	$\alpha_S L$	$\cdots$	$\mathcal{O}(\alpha_S)$
$\alpha_S^2 L^4$	$\alpha_S^2 L^3$	$\cdots$	$\mathcal{O}(\alpha_S^2)$
$\cdots$	$\cdots$	$\cdots$	$\cdots$
$\alpha_S^n L^{2n}$	$\alpha_S^n L^{2n-1}$	$\cdots$	$\mathcal{O}(\alpha_S^n)$
dominant logs	$\cdots$	$\cdots$	$\cdots$



Truncated fixed order predictions $\rightarrow$ divergent $\alpha_s^n \ln^m(M^2/q_\perp^2)$ appear

Replace partonic $q_\perp$ distribution as follows

$$\frac{d\hat{\sigma}_{ab}}{dq_\perp^2} \to \left[\frac{d\hat{\sigma}_{ab}^{(\text{res.})}}{dq_\perp^2}\right]_{\text{l.a.}} + \left[\frac{d\hat{\sigma}_{ab}^{(\text{fin.})}}{dq_\perp^2}\right]_{\text{f.o.}} \quad \text{, such that}$$

$$\int dq_\perp^2 \frac{d\hat{\sigma}_{ab}^{(\text{res.})}}{dq_\perp^2} \sim \sum \alpha_s^n \log^m \frac{M^2}{Q_\perp^2} \quad \text{for} \quad q_\perp \to 0$$

$$\int dq_\perp^2 \frac{d\hat{\sigma}_{ab}^{(\text{fin.})}}{dq_\perp^2} \sim 0 \quad \text{for} \quad q_\perp \to 0$$

Resummed and finite components need to be matched at some logarithmic accuracy (LL, NLL, NNLL, ...)

Resummation holds in impact parameter space b

$$\frac{d\hat{\sigma}_{ab}^{(\mathrm{res.})}}{dq_\perp^2} = \frac{M^2}{\hat{s}} \int db \, \frac{b}{2} \, J_0(bq_\perp) \, \mathcal{W}_{ab}(b, M)$$

Which is expressed in Mellin space (with respect to $z = M^2/\hat{s}$)

$$\mathcal{W}_N(b, M) = \mathcal{H}_N(\alpha_s) \times \exp\{\mathcal{G}_N(\alpha_s, L)\} \quad \text{being} \quad L \equiv \log(M^2 b^2)$$

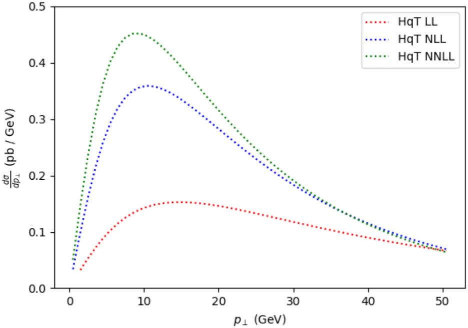
- Resummed effects exponentiated in the Sudakov factor $\mathcal{G}_N(\alpha_s, L)$
- Process-dependence factorized in the hard factor $\mathcal{H}_N(\alpha_s)$

HTurbo: Fast predictions for Higgs production

HqT and HRes

Predictions for Higgs $q_\perp$ distribution

- HqT and HRes [de Florian, G.F., Grazzini, Tommasini] produce $q_\perp$ distributions
- Higher order corrections require high computation times
- Codes producing fast predictions are needed for precision era of the LHC



HTurbo

Starting point DYTurbo

- Start from **DYTurbo** [Camarda et al.] ref. at 1910.07049, producing $q_\perp$ distribution fro Drell-Yan ($q\bar{q} \to l^+ l^-$)

C++ interface rather that Fortran of **HRes** or **HqT**

- Set LO amplitude $gg \to H$
- Set Sudakov and Hard coefficients for Higgs production
- Implement PDF evolution
- Compare with **HRes** and **HqT**

State of the art is just up to NNLL!

HTurbo

Starting point DYTurbo

- Set LO amplitude to be $gg \to H$
- Set Sudakov and Hard coefficients for Higgs production
- Compare with **HRes** and **HqT**

$$\mathcal{G}_N(\alpha_s, L) = L\, g^{(1)}(\alpha_s L) + g^{(2)}(\alpha_s L) + \frac{\alpha_s}{\pi} g^{(3)}(\alpha_s L) + \ldots$$

$$\mathcal{H}_N(\alpha_s) = 1 + \frac{\alpha_s}{\pi}\mathcal{H}^{(1)} + \left(\frac{\alpha_s}{\pi}\right)^2 \mathcal{H}^{(2)} + \ldots$$

$$\mathrm{LL}(\sim \alpha_s^n L^{n+1}) : g^{(1)}, \hat{\sigma}^{(0)}$$

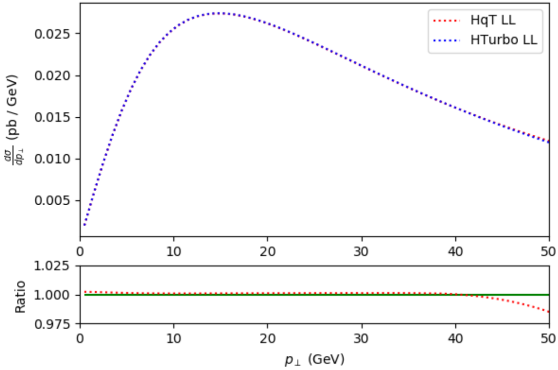
$$\mathrm{NLL}(\sim \alpha_s^n L^{n}) : g^{(2)}, \mathcal{H}^{(1)}$$

$$\mathrm{NNLL}(\sim \alpha_s^n L^{n-1}) : g^{(3)}, \mathcal{H}^{(2)}$$

Start by building predictions up to NNLO, then add $\mathrm{N}^3\mathrm{LL}$

Results

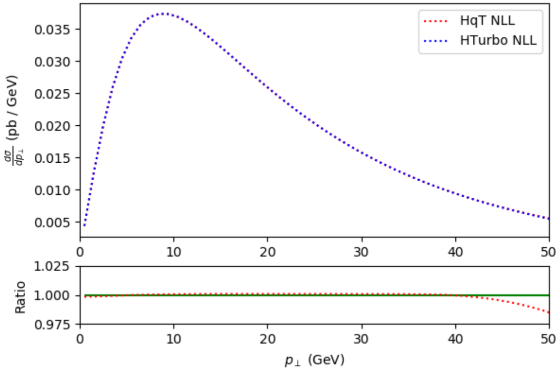
Comparison HTurbo and HqT - LL



- HTurbo $q_\perp$ distribution matches HRes and HqT at LL
- Excellent numerical agreement up to the $1/1000$ level

Results

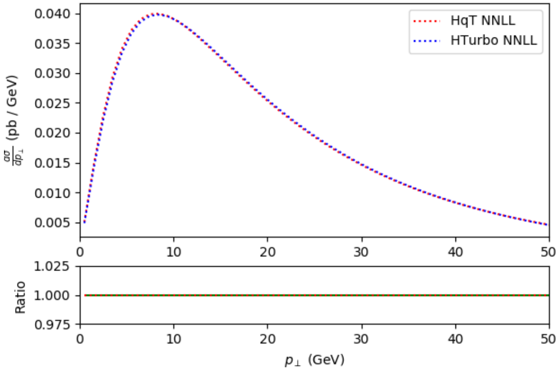
Comparison HTurbo and HqT - NLL



- HTurbo $q_\perp$ distribution matches HRes and HqT at NLL
- Agreement obtained by switching off PDF evolution

Results

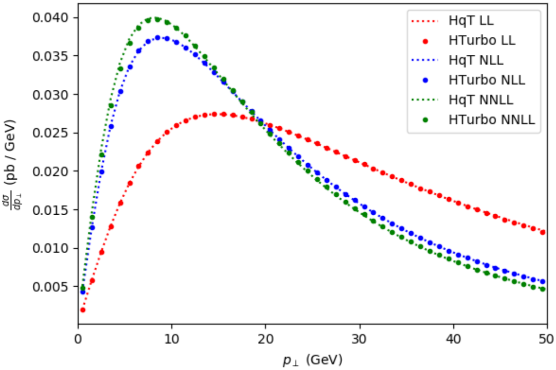
Comparison HTurbo and HqT - NNLL



- HTurbo $q_\perp$ distribution matches HRes and HqT at NNLL
- Agreement obtained by switching off PDF evolution

Results

Comparison HTurbo and HqT - all orders



- Higher orders lead to more reliable predictions ✓
- Agreement up to NNLL $\longrightarrow$ ready for N^{3}LL

Summary & Conclusions

1. Fast predictions are required towards the precision era of the LHC
2. $q_\perp$ distributions from HTurbo match HRes and HqT up to NNLL
3. HTurbo is much faster than any of the existing Higgs codes
4. Next steps: Implement PDF evolution and N^3LO distributions

Thank you!

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 740006.