High precision perturbative QCD predictions for Higgs boson production at the LHC

Jesús Urtasun Elizari

Milan, December 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.

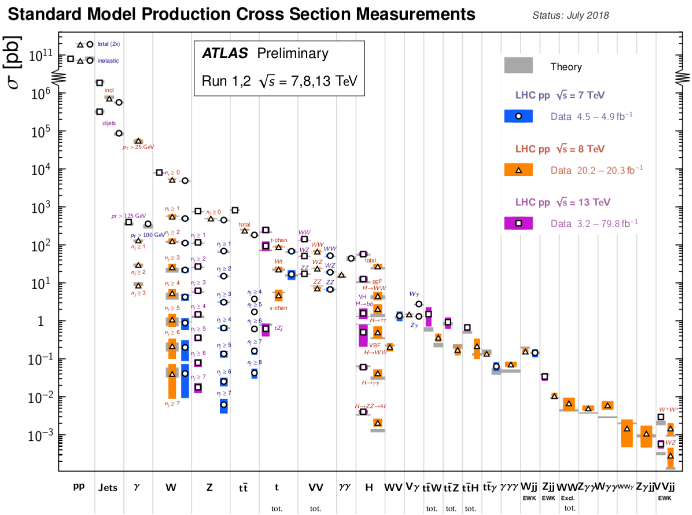
Outline

1. QCD and collider physics
    - QCD Factorization
    - Partonic cross section and perturbative QCD
2. The N3PDF project
    - Parton Distribution Functions
    - Machine Learning for PDFs
3. All order perturbative resummation
    - Higher orders radiative corrections
    - Resummation of large logarithmic corrections
4. Precise and fast predictions for Higgs boson physics
    - Higgs production at the LHC
    - HTurbo numerical code
    - Preliminary results & Conclusions

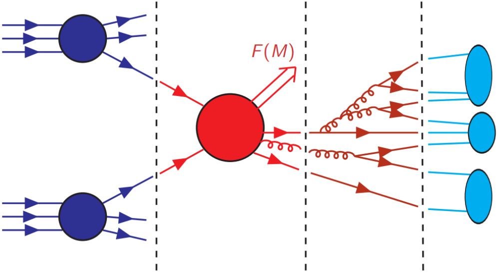
QCD and collider physics

QCD

LHC physics



QCD
Factorization theorem

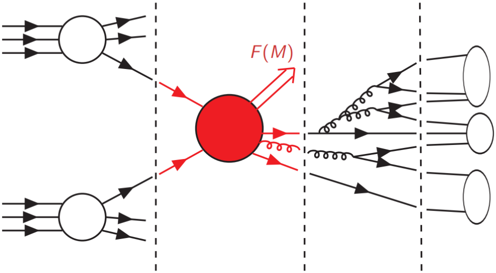


Compute hadronic cross sections is a hard problem $\longrightarrow$ QCD Factorization

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

QCD

Partonic cross section

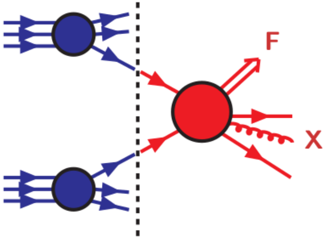


- Parton densities (PDFs) $f_\alpha(x_i, \mu_F^2)$: non perturbative but universal
- Partonic cross section $\hat{\sigma}^{\mathrm{F}}_{\alpha\beta}$: process dependent but computable as perturbative series in α_s

QCD

Perturbative QCD

- Born cross section is the leading-order (LO) term of the perturbative series
- $\sigma^{(1)}, \sigma^{(2)}, \sigma^{(3)}$ are the NLO, NNLO, N3LO corrections



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

Lower order predictions strongly depend on the auxiliary and unphysical renormalization and factorization scales $\longrightarrow$ Need higher order corrections to increase theoretical accuracy!

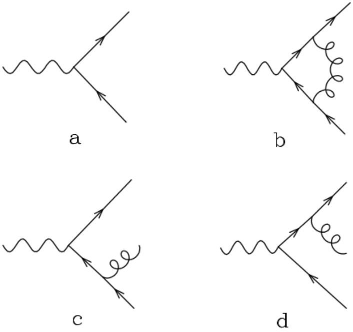
The N3PDF project

All orders perturbative resummation

Resummation in QCD

Higher order corrections

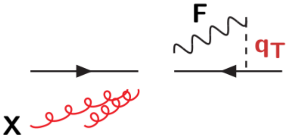
1. Calculation of higher order corrections is not an easy task due to infrared (IR) soft and collinear singularities
2. Final state singularities cancel by combining real and virtual contributions
3. Initial state collinear singularities factorized inside the PDFs



Resummation in QCD

$q_\perp$ resummation

Study the differential $q_\perp$ distribution



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

$$\int_0^{Q_\perp^2} dq_\perp^2 \frac{d\hat{\sigma}}{dq_\perp^2} \sim c_0 + \alpha_s(c_{12}L^2 + c_{11}L + c_{10}) + \ldots, \quad \text{where} \quad L = \ln(q_\perp/M^2)$$

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

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

Resummation in QCD

$q_\perp$ resummation

Separate partonic $q_\perp$ distribution as follows

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

$$\int_0^{q_\perp^2} dq_\perp^2 \frac{d\hat{\sigma}_{ab}^{(\text{res.})}}{dq_\perp^2} \sim \sum \alpha_s^n \log^m \frac{M^2}{q_\perp^2} \quad \text{for} \quad q_\perp \to 0$$

$$\lim_{q_\perp \to 0} \int_0^{q_\perp^2} dq_\perp^2 \frac{d\hat{\sigma}_{ab}^{(\text{fin.})}}{dq_\perp^2} = 0$$

Resummed and finite components can be matched (LL+LO, NLL+NLO, NNLO+NNLL, ...) to have uniform accuracy in a wide range of $q_\perp$

Resummation holds in impact parameter space b

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

with $\mathcal{W}_{ab}$ also expressed in Mellin space (with respect to $z = M^2/\hat{s}$)

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

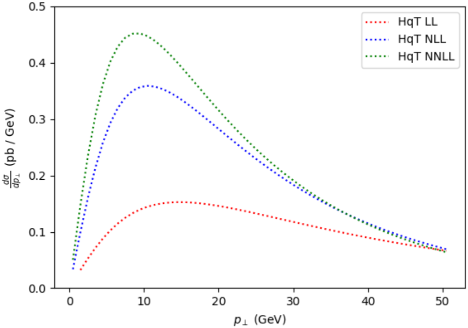
- Large logarithms exponentiated in the universal Sudakov form factor $\mathcal{G}_N(\alpha_s, L)$
- Constant (b-independent) terms factorized in the process dependent hard factor $\mathcal{H}_N(\alpha_s)$

Precise and fast predictions for Higgs boson physics

HqT and HRes

Predictions for Higgs $q_\perp$ distribution

- $q_\perp$ resummation implemented in numerical codes HqT and HRes [Catani, de Florian, Ferrera, Grazzini, Tommasini]
- Higher order accuracy require high computation times
- Codes producing fast and accurate predictions are needed for precision era of the LHC



HTurbo

Starting point DYTurbo

Numerical code **DYTurbo** [Camarda et al.] ref. at 1910.07049, fast and precise $q_\perp$ resummation and several improvements for Drell-Yan ($h_1 h_2 \to V + X \to l^+ l^- + X$)

- First goal: set up a numerical code for Higgs boson production starting from **DYTurbo**
- Set LO amplitude $gg \to H$
- Set Sudakov and Hard coefficients for Higgs production
- Compare with **HRes** and **HqT**

Final goal: extend theoretical accuracy up to N^{3}LL+N^{3}LO

HTurbo

Starting point DYTurbo

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

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

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

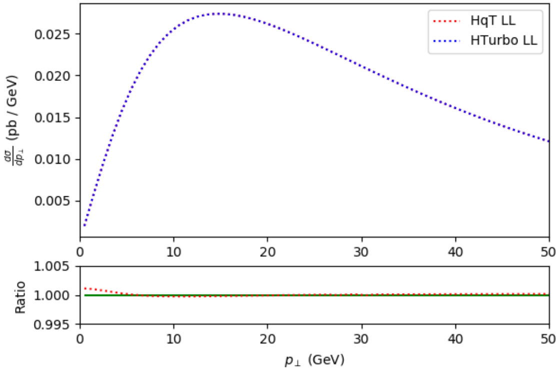
$\mathrm{NLL}(\sim \alpha_s^n L^n) : g^{(2)}, \mathcal{H}^{(1)}$

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

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

Results

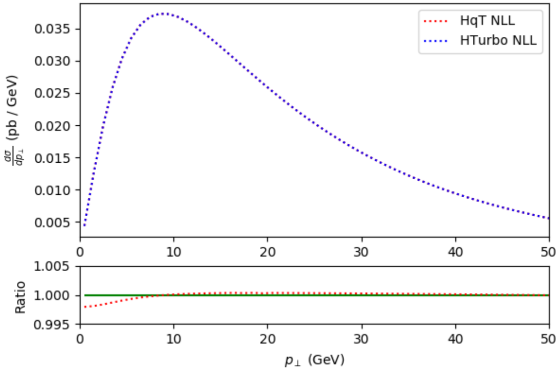
Comparison HTurbo and HqT - LL



- HTurbo $q_\perp$ distribution vs HRes and HqT at LL
- Excellent numerical agreement up to the 0.1% level

Results

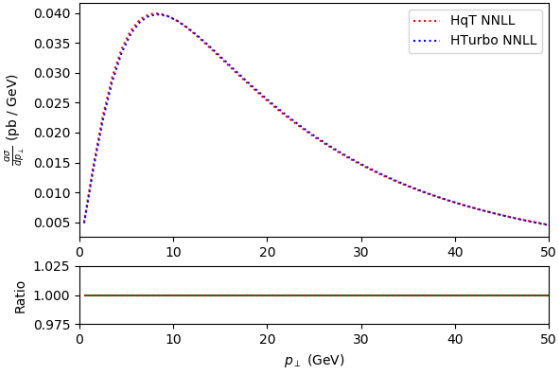
Comparison HTurbo and HqT - NLL



- HTurbo $q_\perp$ distribution vs HRes and HqT at NLL
- Excellent numerical agreement up to the 0.1% level

Results

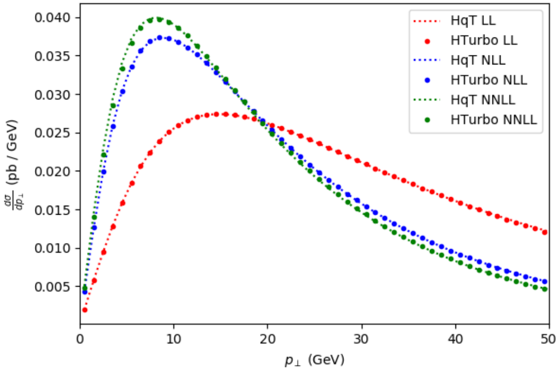
Comparison HTurbo and HqT - NNLL



- HTurbo $q_\perp$ distribution vs HRes and HqT at NNLL
- Excellent numerical agreement up to the 0.1% level

Results

Comparison HTurbo and HqT - all orders



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

Summary & Conclusions

1. Fast and accurate predictions are required towards the precision era of the LHC
2. Developing a novel numerical code, **HTurbo**, which implements $q_\perp$ resummation for Higgs boson production
3. HTurbo is faster than any of the existing codes
4. Next steps:
   - Validate results at NNLO
   - Add N^3LO prediction
   - Perform phenomenological studies comparing with LHC data

Thank you!

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