

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

Jesús Urtasun Elizari

PhD seminar - Milan, September 2020



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

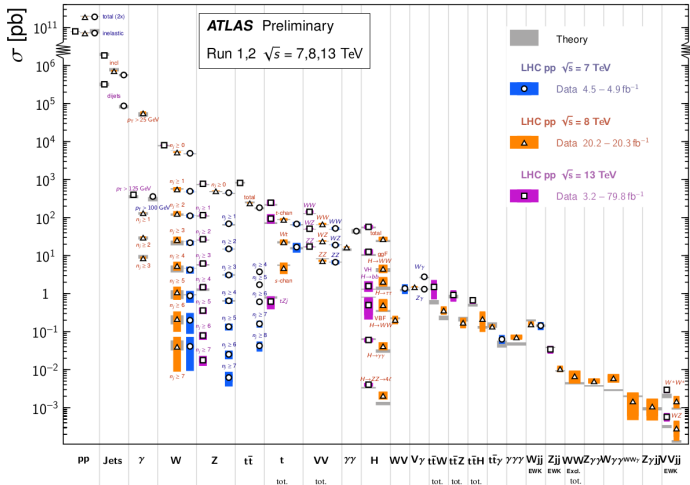
# Outline

- ① QCD and collider physics
  - QCD Factorization
  - Partonic cross section and perturbative QCD
- ② All order perturbative resummation
  - Higher order radiative corrections
  - Resummation of large logarithmic corrections
- ③ Precise and fast predictions for Higgs boson physics
  - Higgs production at the LHC
  - HTurbo numerical code
  - Preliminary results & Conclusions

## QCD and collider physics

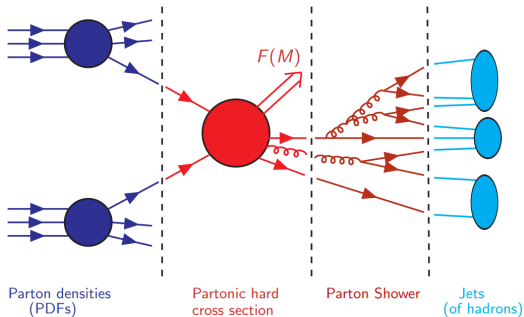
## Standard Model Production Cross Section Measurements

Status: July 2018



# QCD

## Factorization theorem

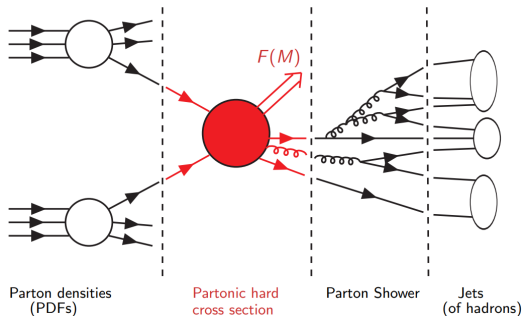


Compute hadronic cross sections is a **hard problem**  $\rightarrow$  **QCD Factorization**

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

# QCD

## Partonic cross section

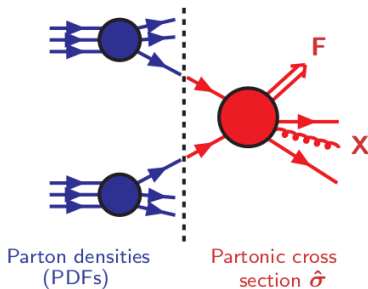


- Parton densities (PDFs)  $f_\alpha(x_i, \mu_F^2)$ : non perturbative but universal
- Partonic cross section  $\hat{\sigma}_{\alpha\beta}^F$ : process dependent but computable as perturbative series in  $\alpha_s$

# QCD in a nutshell

## 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



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

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

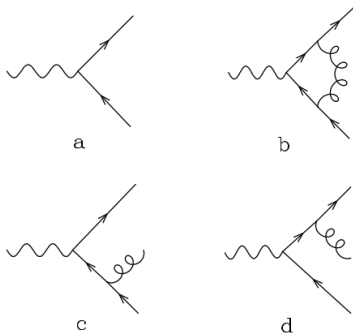
## All order perturbative resummation



# 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

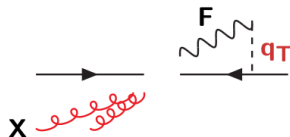


# Resummation in QCD

## $q_\perp$ resummation

Study the differential  $q_\perp$  distribution

$$h_1(p_1) + h_2(p_2) \longrightarrow F(M, \mathbf{q}_\perp) + X$$



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

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

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

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

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

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 in QCD

## $q_\perp$ resummation

Resummation holds in impact parameter space  $b$

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

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

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

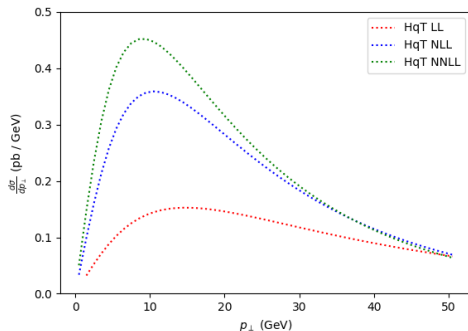
- Large logarithms exponentiated in the universal Sudakov form factor  $\mathcal{G}_N(\alpha_s, L)$
- Constante (b-independent) terms factorized in the process dependent hard factor  $\mathcal{H}_N(\alpha_s)$

## Precise and fast predictions for Higgs 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 ( $h_1 h_2 \rightarrow V + X \rightarrow l^+ l^- + X$ )

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

**Final goal**: extend theoretical accuracy up to N3LL+N<sup>3</sup>LO

# HTurbo

Starting point DYTurbo

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

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

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

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

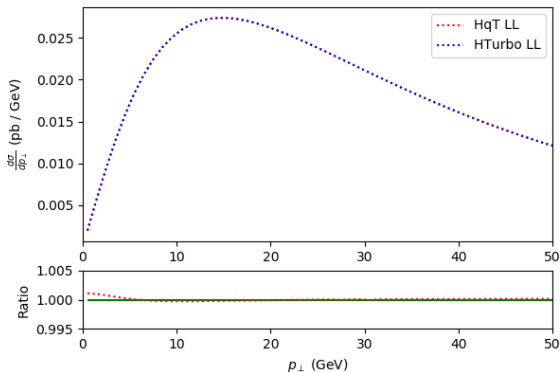
$$\text{NNLL}(\sim \alpha_s^n L^{n-1}) : g^{(3)}, \mathcal{H}^{(2)}$$

Start by building predictions up to NNLO, then add **N<sup>3</sup>LL**



# Results

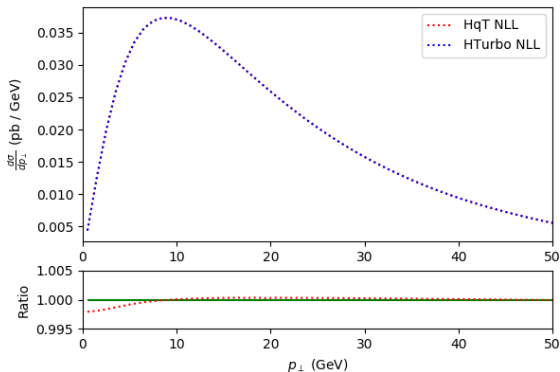
## Comparison HTurbo and HqT - LL



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

# Results

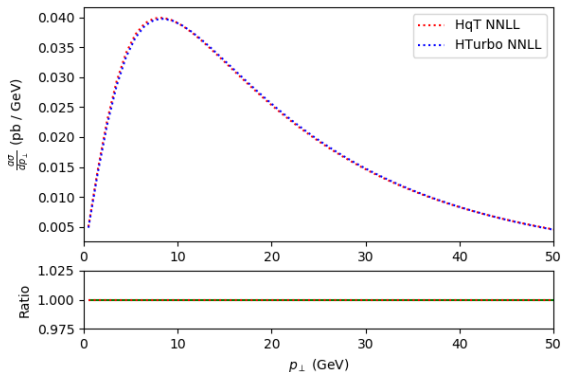
## Comparison HTurbo and HqT - NLL



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

# Results

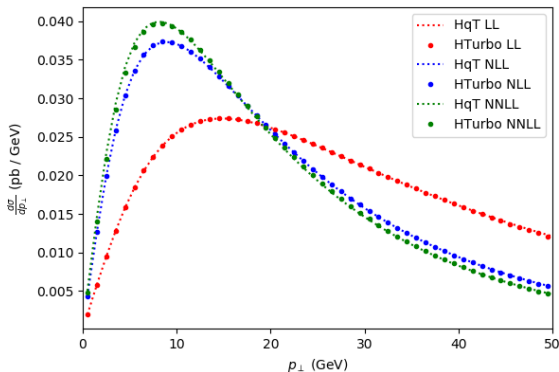
## Comparison HTurbo and HqT - NNLL



- 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 → ready for N<sup>3</sup>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  $N^3\text{LO}$
  - 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.