

Higgs boson production at the Large Hadron Collider: accurate theoretical predictions at higher orders in QCD

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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

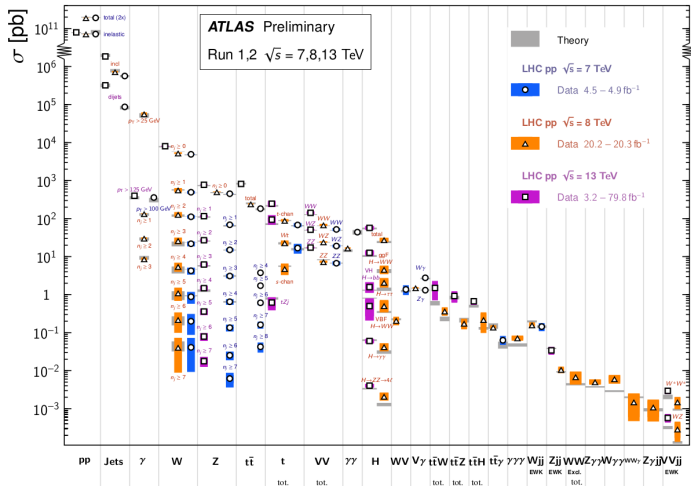
QCD and collider physics

QCD and collider physics

LHC physics

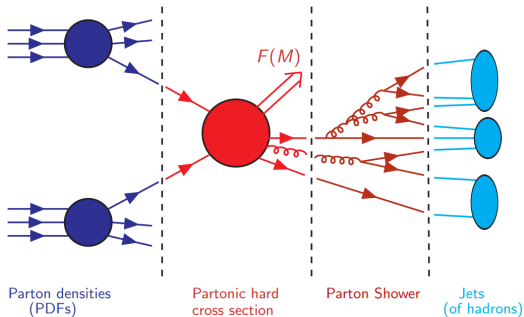
Standard Model Production Cross Section Measurements

Status: July 2018



QCD and collider physics

Factorization theorem

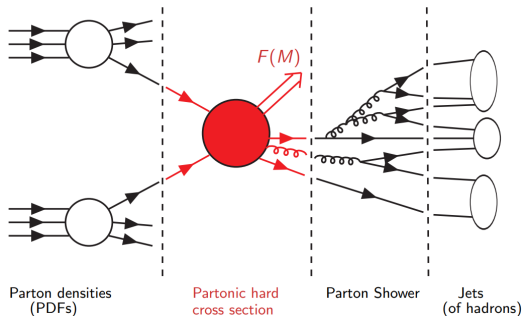


Compute hadronic cross sections is a **hard problem** \rightarrow QCD Factorization

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

QCD and collider physics

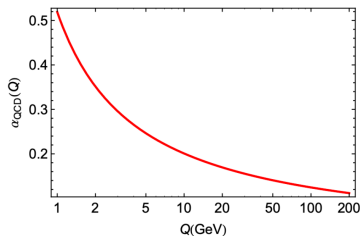
Partonic cross section



- 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 α_s

QCD and collider physics

QCD coupling



- Running coupling given by Renormalization Group Equation (RGE)

$$\alpha_s(\mu) = \frac{1}{\beta_0 \log\left(\frac{\mu^2}{\Lambda_{\text{QCD}}^2}\right)}$$

- β_0 LO of the β function, is > 0
- Λ_{QCD} , parameter that defines value of the coupling at large scales

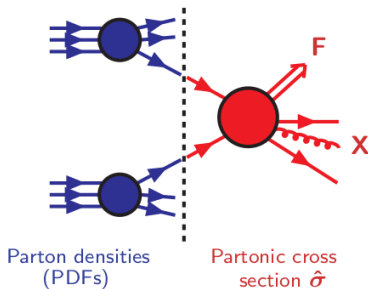
QCD is weakly coupled for $\mu \gg \Lambda_{\text{QCD}} \rightarrow$ asymptotically free

Perturbative Quantum Chromodynamics (pQCD)

QCD and collider physics

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



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

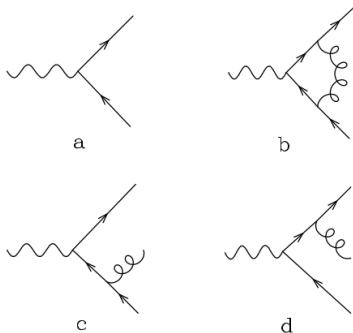
Lower order predictions strongly depend on the auxiliary and unphysical renormalization and factorization scales \rightarrow **Need higher order corrections to increase theoretical accuracy!**

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

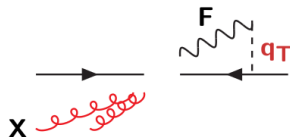


Resummation in QCD

q_\perp resummation

Study the differential q_\perp distribution

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



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

$\alpha_S L^2$	$\alpha_S L$	\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 $z = M^2/\hat{s}$)

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

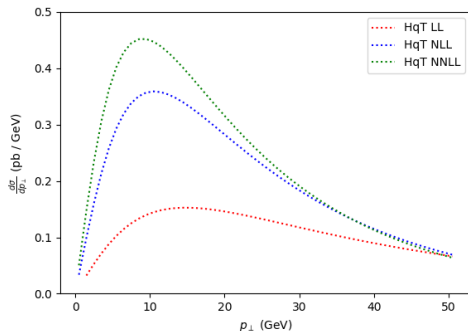
- Large logarithms exponentiated in the universal Sudakov form factor $\mathcal{G}_N(\alpha_s, L)$
- Constant (b -independent) terms factorized in the process dependent hard factor $\mathcal{H}_N(\alpha_s)$

Accurate predictions for Higgs boson at the LHC

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 $N^3\text{LL}+N^3\text{LO}$

HTurbo

Starting point DYTurbo

Both Sudakov factor \mathcal{G}_N and hard coefficient \mathcal{H}_N can be expanded as perturbative series in α_s

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

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

For each new order implement a factor of \mathcal{G}_N and Hard \mathcal{H}_N

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

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

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

Start by building predictions up to NNLO+NNLL, then add
N³LO+N³LL

Reimplementation of **HqT** and **HRes** for q_T -resummation

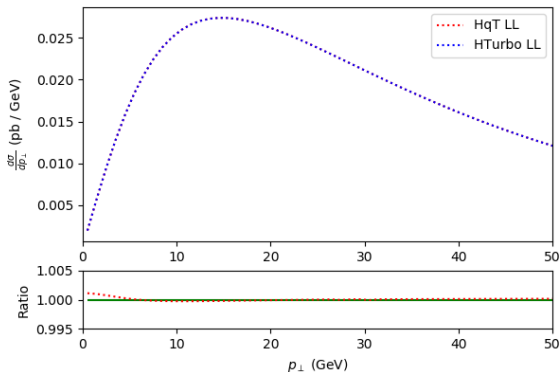
- **C++** structure with **Fortran** interfaces → Multi-threading
- Optimization in the integration routines / integral transforms
 - Factorize boson and decay kinematics
 - Gauss-Legendre quadrature rules (1-dim.)
 - Vegas/Cuhre through **Cuba** (multi-dim.)

Comparison **HRes** and **HTurbo** - speed performance

Predictions	HRes	HTurbo
resummed NNLL	10h	10'
combined NNLO+NNLL	20h	1h

Results

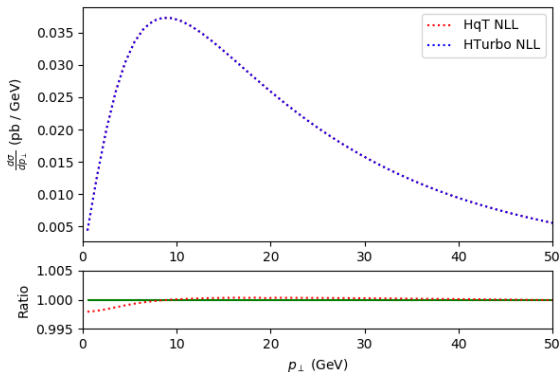
Comparison HTurbo and HqT - LL



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

Results

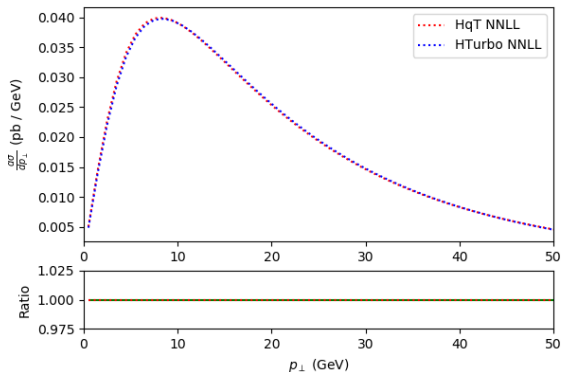
Comparison HTurbo and HqT - NLL



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

Results

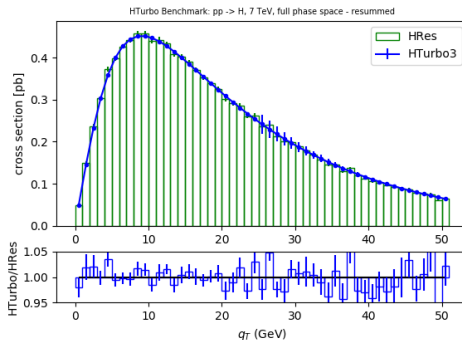
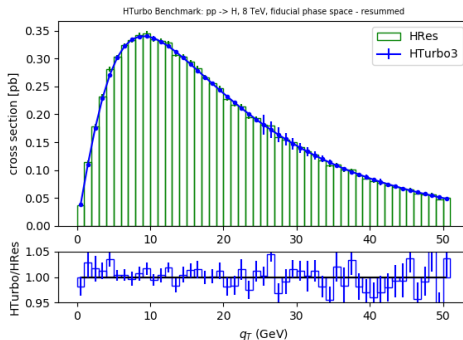
Comparison HTurbo and HqT - NNLL



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

Results

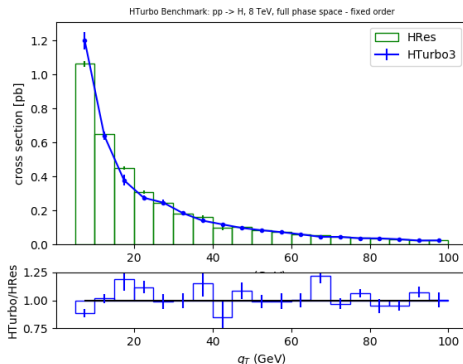
Comparison HTurbo and HRes - resummed



- Represent full (LHS) and fiducial (RHS) phase space ✓
- Agreement up to resummed NNLL \rightarrow ready for N^3 LL

Results

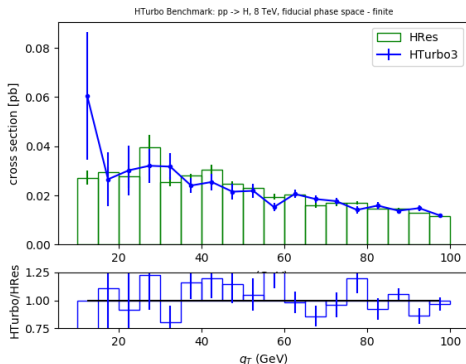
Comparison HTurbo and HRes - fixed order



- Represent fiducial (RHS) phase space - HRes vs HTurbo ✓
- Agreement up to fixed order NLO \rightarrow ready for N³LL

Results

Comparison HTurbo and HRes - finite



- Represent fiducial phase space - HRes vs HTurbo ✓
- Agreement up to finite NNLL+NLO \rightarrow ready for N^3 LL

Summary & Conclusions

- ① Fast and accurate predictions are needed 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 Outlook of thesis work:
 - Add $N^3\text{LO}+N^3\text{LL}$ prediction
 - Perform phenomenological studies comparing with LHC data

Thank you!



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