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

Jesús Urtasun Elizari

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erc European Research Council

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Outline

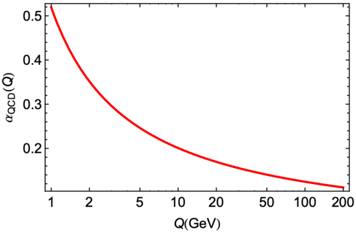
1. Introduction to QCD
    - A historical approach
    - Asymptotic freedom and pQCD
2. QCD and collider physics
    - QCD Factorization
    - Partonic cross section and perturbative QCD
3. All order perturbative resummation
    - Higher order radiative corrections
    - Resummation of large logarithmic corrections
    - Resummed, asymptotic and fixed-order
4. Precise and fast predictions for Higgs boson physics
    - Higgs production at the LHC
    - HTurbo numerical code
    - Preliminary results & Conclusions

Introduction

- The Standard Model
- QCD and the strong interactions
- Higgs boson physics and the LHC

Part I
QCD and collider physics

- The Standard Model
- QCD and the strong interactions
- Higgs boson physics and the LHC



- Running coupling given by Renormalization Group Equation (RGE)

$$\alpha_s(\mu) = \frac{1}{\beta_0 \log\left(\frac{\mu^2}{\Lambda^2_{\mathrm{QCD}}}\right)}$$

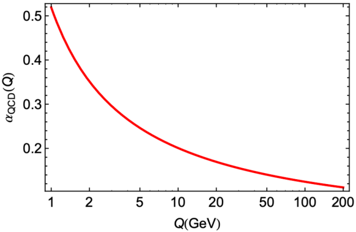
- β_0 LO of the β function, is > 0
- Λ_{QCD}, parameter that defines value of the coupling at large scales

QCD is weakly coupled for $\mu >> \Lambda_{\mathrm{QCD}} \longrightarrow$ asymptotically free

Perturbative Quantum Chromodynamics (pQCD)

QCD and collider physics

Asymptotic freedom and pQCD



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Perturbative Quantum Chromodynamics (pQCD)

- Hadronic processes and factorization

- The parton model

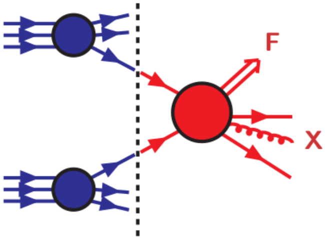
- Parton densities

- Fixed-order QCD

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



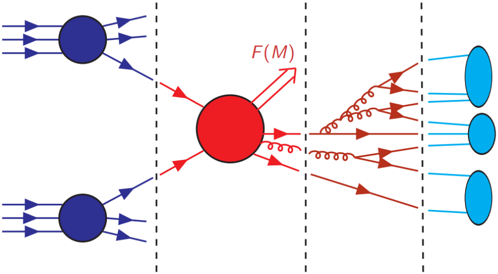
$$\hat{\sigma} = \sigma^{\mathtt{Born}}\left(1 + \alpha_s \sigma^{(1)} + \alpha_s^2 \sigma^{(2)} + \alpha_s^3 \sigma^{(3)} + \dots\right)$$

Lower order predictions strongly depend on the auxiliary / unphysical scales

Need higher order corrections to increase theoretical accuracy!

QCD and collider physics

Factorization theorem

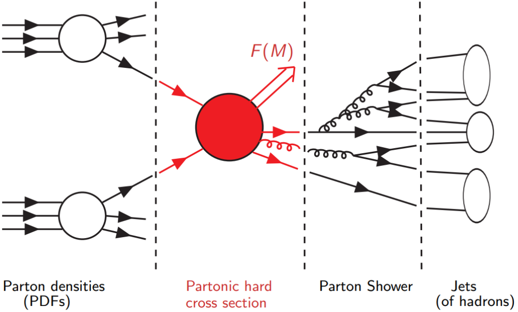


Compute hadronic cross sections is a hard problem $\longrightarrow$ QCD Factorization

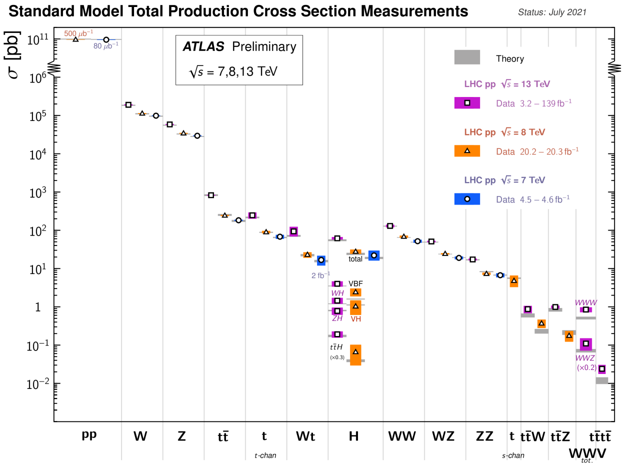
$$\sigma^{\mathrm{F}}(p_1, p_2) = \int_0^1 dx_1 dx_2 \; f_\alpha(x_1, \mu_F^2) * f_\beta(x_2, \mu_F^2) \; * \; \hat{\sigma}^{\mathrm{F}}_{\alpha\beta}(x_1 p_1, x_2 p_2, \alpha_s(\mu_R^2), \mu_F^2)$$

QCD and collider physics

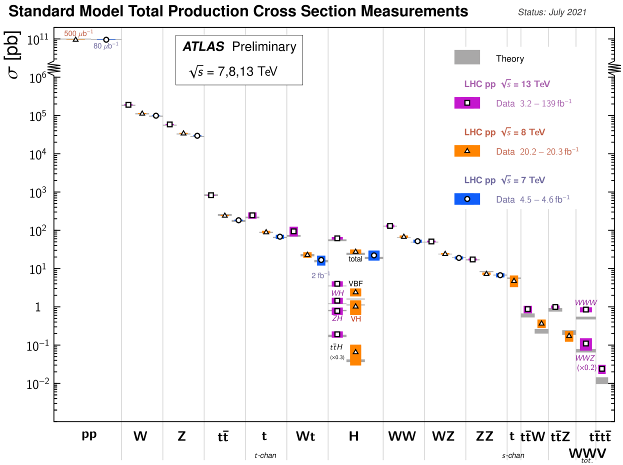
Partonic cross section



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



- Physics at the LHC



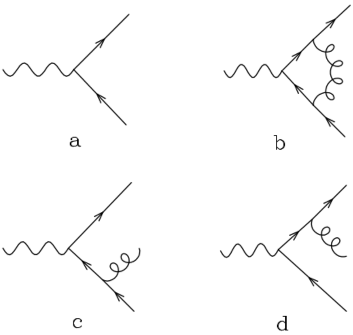
- Physics at the LHC

Part II
All order 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

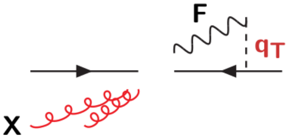


Resumation in QCD

$q_\perp$ 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

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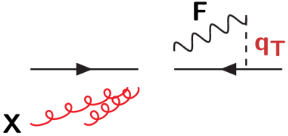

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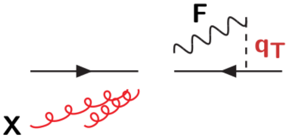

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Truncated fixed order predictions $\rightarrow$ enhanced $\alpha_s^n \ln^m(M^2/q_\perp^2)$ appear

Separate partonic $q_\perp$ distribution as follows

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

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

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

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

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

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 $\mathcal{H}_N(\alpha_s)$

Part III

HTurbo numerical implementation

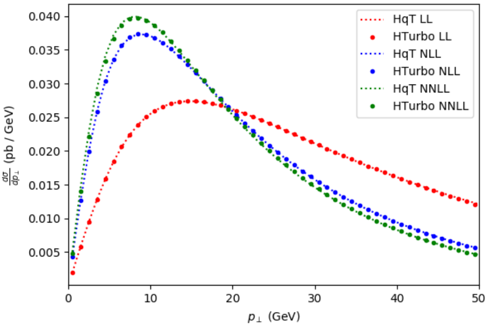
HqT and HRes

Need for fast numerical implementations

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



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

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 $\mathcal{H}_N$

$$\mathrm{LL}(\sim \alpha_s^n L^{n+1}) : g^{(1)}, \hat{\sigma}^{(0)}$$
$$\mathrm{NLL}(\sim \alpha_s^n L^{n}) : g^{(2)}, \mathcal{H}^{(1)}$$
$$\mathrm{NNLL}(\sim \alpha_s^n L^{n-1}) : g^{(3)}, \mathcal{H}^{(2)}$$

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

HTurbo

Code optimization

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

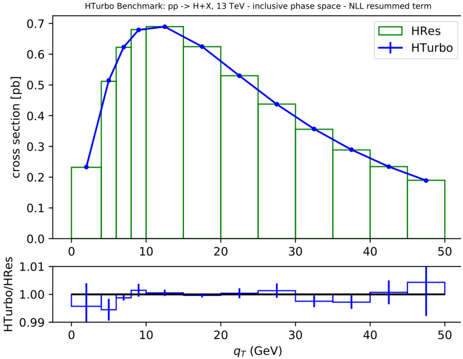
- **C++** structure with **Fortran** interfaces → Multi-threading
- Optimization in the integration routines / integral transforms
  - Factorize boson and decay kinematics
  - Gauss-Legendre quadrature rules (1-dim.)
  - Vegas/Cuhre through **Cuba** (multi-dim.)

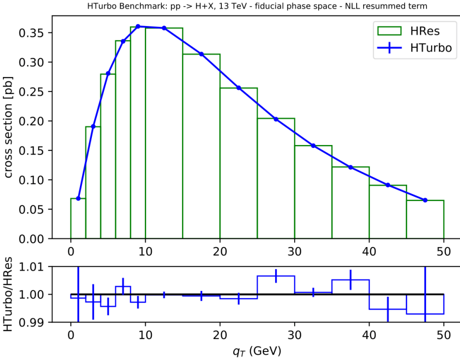
Comparison **HRes** and **HTurbo** - speed performance

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

Results

Comparison HTurbo and HRes - NLL resummed

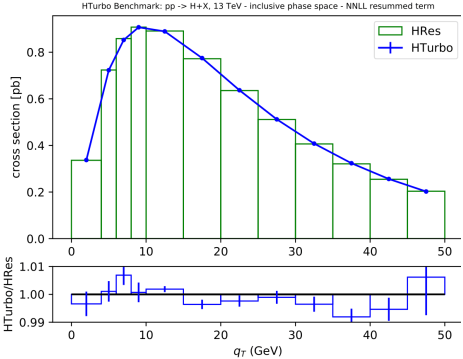


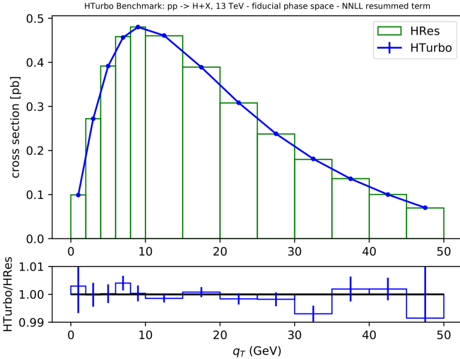


- Represent full (LHS) and fiducial (RHS) phase space ✓
- Excellent numerical agreement at NLL

Results

Comparison HTurbo and HRes - NNLL resumed

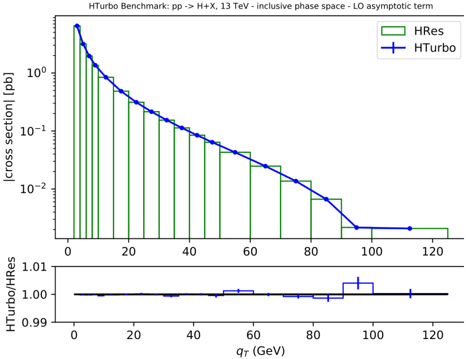


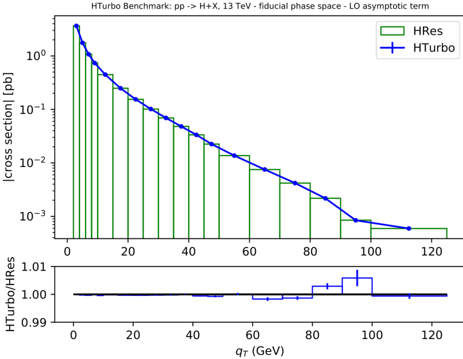


- Represent full (LHS) and fiducial (RHS) phase space ✓
- Excellent numerical agreement at NNLL

Results

Comparison HTurbo and HRes - LO asymptotic

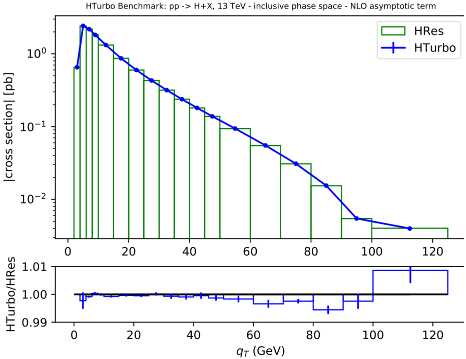


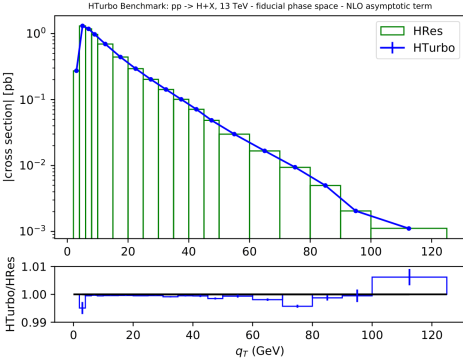


- Represent full (LHS) and fiducial (RHS) phase space ✓
- Excellent numerical agreement at LO

Results

Comparison HTurbo and HRes - NLO asymptotic





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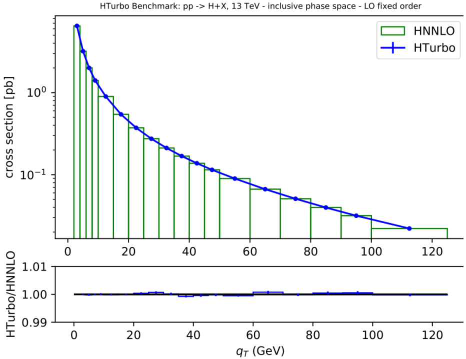
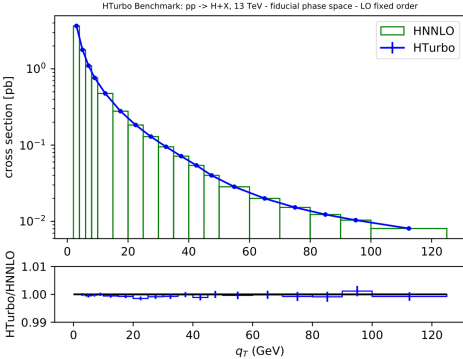
Results

Comparison HTurbo and HRes - LO fixed-order





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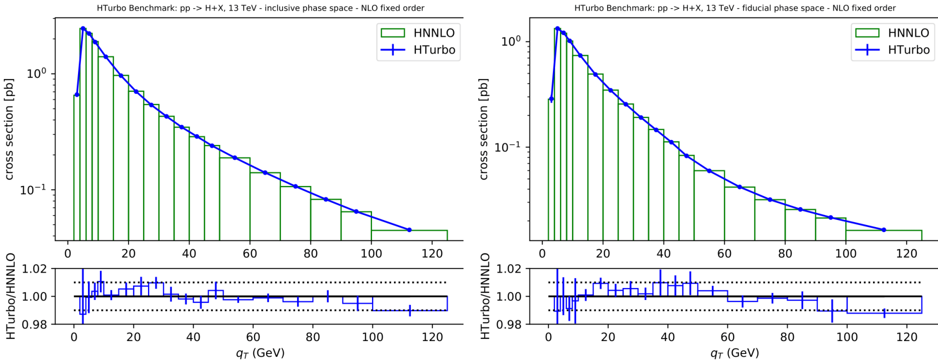
Results

Comparison HTurbo and HRes - NLO fixed-order



- Represent full (LHS) and fiducial (RHS) phase space ✓
- Excellent numerical agreement at NLO

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^3LO+N^3LL prediction
   - Perform phenomenological studies comparing with LHC data

Discussion & next steps

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