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

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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

Part I
QCD and collider physics

QCD and the strong interactions

- The parton model
- QCD is the theory of the strong interactions
- Predictions in QFTs are done by computing cross sections
- Experiments for high energy physics are done at the LHC

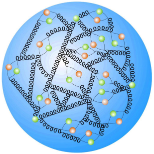
How to explore proton's inner structure?

- Point-like projectile on the object $\longrightarrow$ DIS
- Smash the two objects $\longrightarrow$ LHC physics

"A way to analyze high energy collisions is to consider any hadron as a composition of point-like constituents $\longrightarrow$ **partons"** R.Feynman, 1969

QCD and collider physics

Asymptotic freedom and pQCD



- QCD and QFTs, coupling strength changes with energy
- Charge a particle feels depends on the scale
- QED

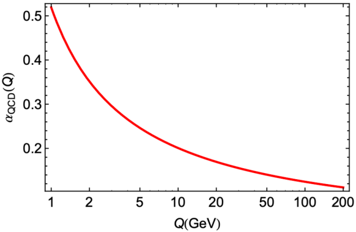
QCD is strongly coupled at short scales $\longrightarrow$ confinement

Non-perturbative physics

- Running coupling given by Renormalization Group Equation (RGE)

$$\mu \frac{d\alpha_s(\mu)}{d\mu} = \beta(\alpha_s(\mu)) = -\sum_{n=0}^{\infty} \beta_n \left(\frac{\alpha_s}{\pi}\right)^{n+1}$$

- Coupling α_s evolves with scale μ as given by RGE $\rightarrow$ LO behavior driven by β_0
- $\beta_0^{\mathrm{QED}} < 0 \implies$ strongly coupled at large energies, UV divergent
- $\beta_0^{\mathrm{QCD}} > 0 \implies$ weakly coupled at large energies, IR divergent



- Running coupling given by Renormalization Group Equation (RGE)

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

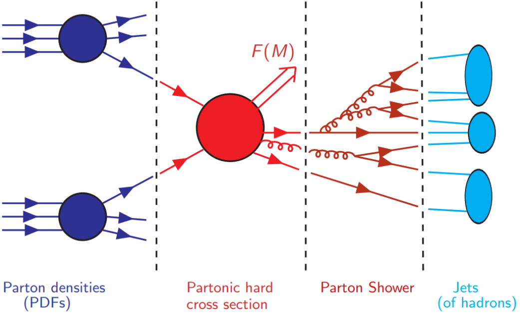
- β_0 LO of the β function, is > 0
- Λ_{QCD}, parameter that defines value of the coupling at large scales

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

Perturbative Quantum Chromodynamics (pQCD)

QCD and collider physics

Hadronic processes and factorization

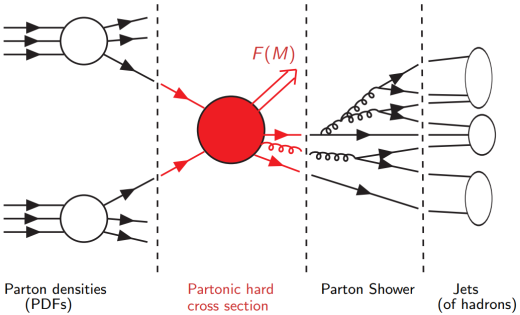


Compute hadronic cross sections is a hard problem $\longrightarrow$ QCD Factorization

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

QCD and collider physics

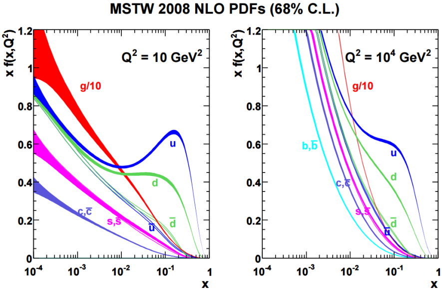
Hadronic processes and factorization



- 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 and collider physics

Parton densities

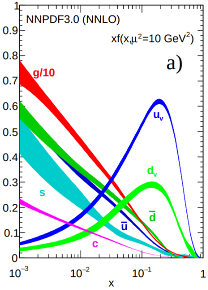


- Hadrons made of partonic objects $\longrightarrow$ non perturbative physics
- Interactions take place only at partonic level

Parton Distribution Functions: probability distribution of finding a particular parton (u, d, ..., g) carrying a fraction x of the proton's momentum

QCD and collider physics

Parton densities

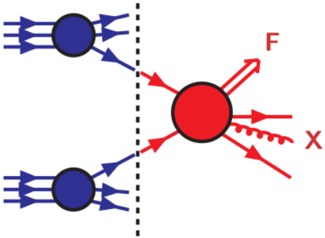


- Each parton has a different PDF $\longrightarrow$ $u(x), d(x), \ldots, g(x)$
- PDFs can not predicted and yet can not measured $\longrightarrow$ extracted from data
- The N^{3}PDF project: ML for PDFs determination

QCD and collider physics

Partonic cross section and pQCD

- 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

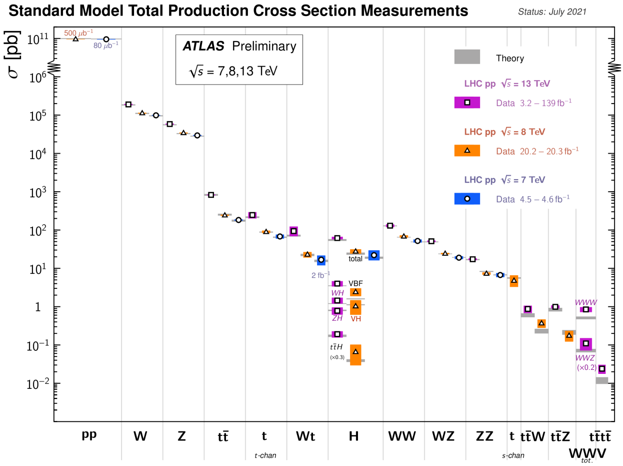


$$\hat{\sigma} = \sigma^{\mathtt{Born}}\left(1 + \alpha_s \sigma^{(1)} + \alpha_s^2 \sigma^{(2)} + \alpha_s^3 \sigma^{(3)} + \ldots\right)$$

Lower order predictions strongly depend on the auxiliary / unphysical scales
Need higher order corrections to increase theoretical accuracy!

Predictions made by the Standard Model

- Eight gluons and three generations of quarks, described by the SU(3) gauge group, mixing angles described by CKM matrix
- Three generations of charged leptons and three generations of massive neutrinos mixing angles described by PMNS matrix
- The photon and the massive $W^{\pm}$ and Z bosons
- A scalar Higgs boson, responsible for the electroweak symmetry breaking


Standard Model Total Production Cross Section Measurements
Status: July 2021
ATLAS Preliminary
$\sqrt{s}$ = 7,8,13 TeV
Theory
LHC pp $\sqrt{s}$ = 13 TeV
Data 3.2 – 139 fb^{-1}
LHC pp $\sqrt{s}$ = 8 TeV
Data 20.2 – 20.3 fb^{-1}
LHC pp $\sqrt{s}$ = 7 TeV
Data 4.5 – 4.6 fb^{-1}
σ [pb]
500 μb^{-1}
80 μb^{-1}
2 fb^{-1}
total
VBF
WH
ZH
VH
$t\bar{t}H$
(×0.3)
WWW
WWZ
(×0.2)
pp
W
Z
$t\bar{t}$
t
t-chan
Wt
H
WW
WZ
ZZ
t
s-chan
$t\bar{t}W$
$t\bar{t}Z$
$t\bar{t}t\bar{t}$
WWV
tot.

Main processes studied at the LHC

- Deep inelastic scattering
- Drell-Yan lepton pair production
- Higgs boson production through gluon fusion

Part II

All order resummation

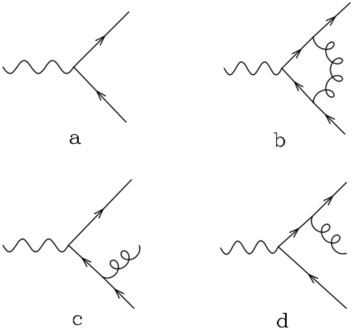
Resummation in QCD

The need for resummation

Resummation in QCD

Higher order corrections

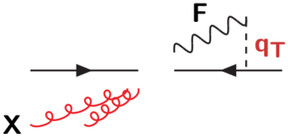
1. Calculation of higher order corrections is not an easy task due to infrared (IR) soft and collinear singularities
2. Final state singularities cancel by combining real and virtual contributions
3. Initial state collinear singularities factorized inside the PDFs



Resummation in QCD

$q_\perp$ resummation

- Cancellation only works in completely inclusive final states
- Study the differential $q_\perp$ distribution
  $h_1(p_1) + h_2(p_2) \longrightarrow F(M, q_\perp) + X$



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

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

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

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

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

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

Resumption in QCD

$q_\perp$ resummation

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

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

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

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

Each term $g^{(i)}$ and $\mathcal{H}^{(i)}$ in the series becomes increasingly complicated

Current codes able to produce only up to NNLL predictions!

Resummation in QCD

$q_\perp$ resummation

Resummation holds in impact parameter space b

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

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Part III

HTurbo numerical implementation

HqT and HRes

Resummation for Higgs differential distribution

- Meaningful description of exclusive final states requires resummed predictions
- Resummation is combined with the finite component

$$\sigma^{\textbf{(res.)}}_{N(NLL)} = \hat{\sigma}^{\mathbf{H}}_{\mathbf{LO}} \times \mathcal{H} \times \exp \mathcal{G}$$

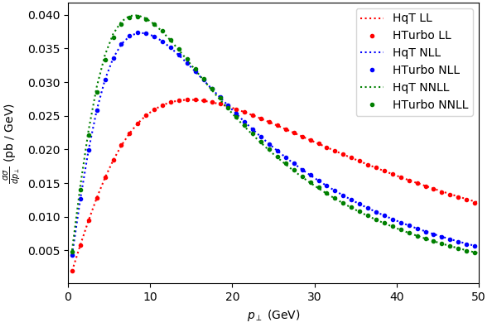
$$\sigma^{\textbf{(asy.)}}_{N(LO)} = \hat{\sigma}^{\mathbf{H}}_{\mathbf{LO}} \times \mathcal{H} \times \exp \mathcal{G}$$

NNLL predictions can take up to 24h $\longrightarrow$ 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



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

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

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

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

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

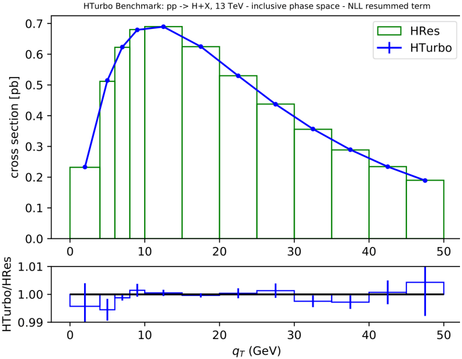
- **C++** structure with **Fortran** interfaces $\rightarrow$ Multi-threading
- Optimization in the integration routines / integral transforms
  - Factorize boson and decay kinematics
  - Gauss-Legendre quadrature rules (1-dim.)
  - Vegas/Cuhre through **Cuba** (multi-dim.)

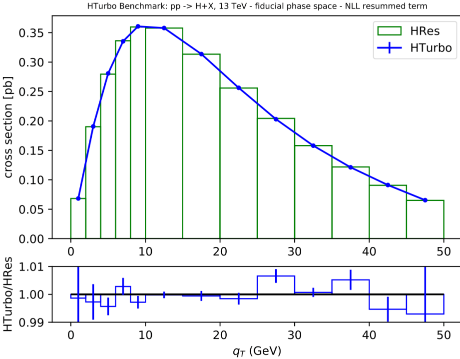
Comparison **HRes** and **HTurbo** - speed performance

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

Results

Comparison HTurbo and HRes - NLL resummed

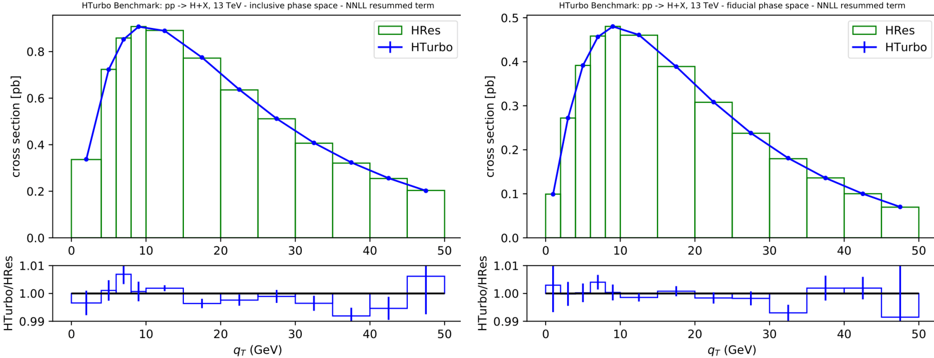




- Cross section for fully inclusive (LHS) and fiducial (RHS) phase space ✓

Results

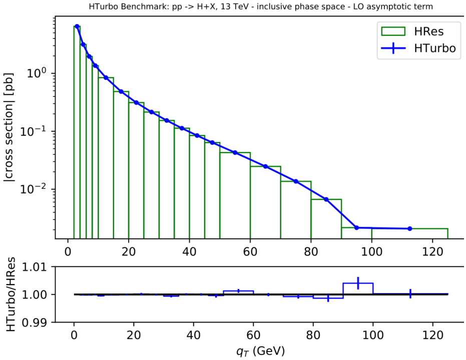
Comparison HTurbo and HRes - NNLL resummed

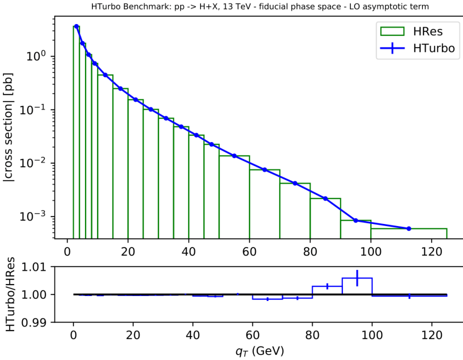


- Cross section for fully inclusive (LHS) and fiducial (RHS) phase space ✓
- CM energy $sqrt(s) = 13$ GeV and PDF set `NNPDF31_nnlo_as_0118` PDF set

Results

Comparison HTurbo and HRes - LO asymptotic





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Results

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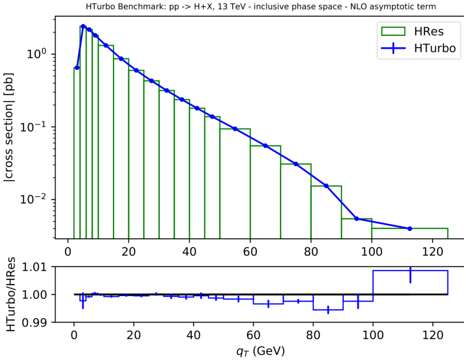

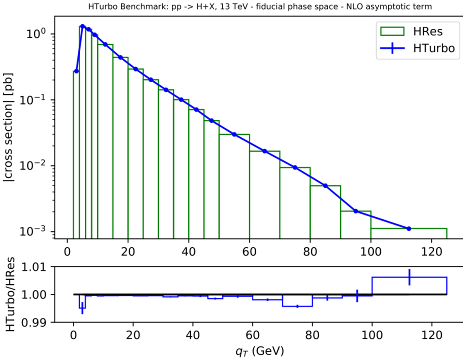

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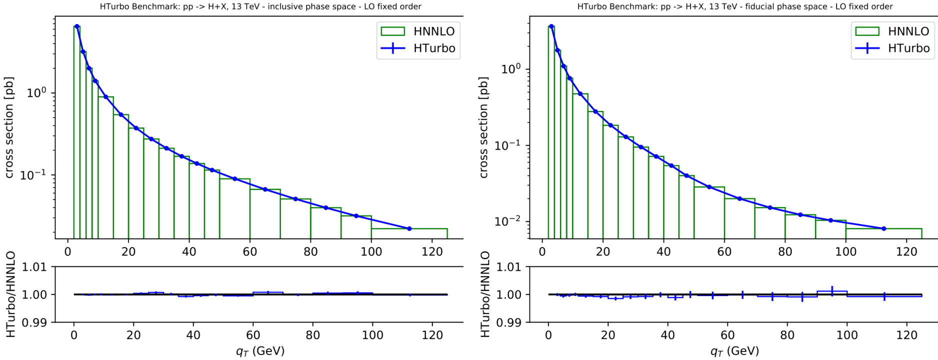
Results

Comparison HTurbo and HRes - LO fixed-order



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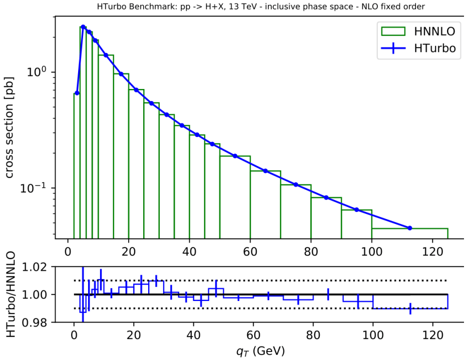
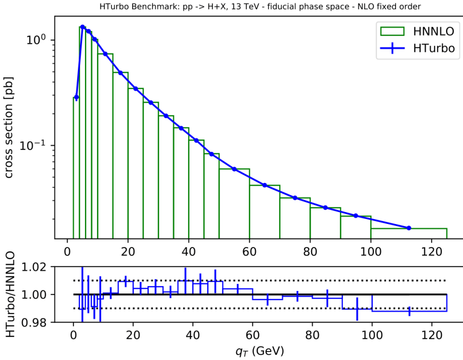
Results

Comparison HTurbo and HRes - NLO fixed-order





- Cross section for fully inclusive (LHS) and fiducial (RHS) phase space ✓
- CM energy $sqrt(s) = 13$ GeV and PDF set `NNPDF31_nnlo_as_0118` PDF set

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

Discussion & next steps

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
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Thank you!

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