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

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UNIVERSITÀ DEGLI STUDI DI MILANO

N3PDF
Machine Learning • PDFs • QCD

European Research Council

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Outline

1. QCD and collider physics
   - The strong interactions
   - Asymptotic freedom and pQCD
   - Factorization in QCD
   - Phenomenology at the LHC
2. All order perturbative resummation
   - Higher order radiative corrections
   - Resummation of large logarithmic corrections
   - Resummed component, asymptotic and fixed-order
3. HTurbo numerical implementation
   - Higgs production at the LHC
   - HTurbo numerical implementation
   - N^3LL implementation
4. Results & Conclusions

Part I
QCD and collider physics

Introduction

QCD and the strong interactions

- The Standard Model describes fundamental interactions at the TeV scale
- Fundamental objects described as irreducible representations of Lorentz group
- Particles as local excitations of fields with quantum mechanical behavior

$$\mathcal{L} = \bar{\psi}_q^i (i\gamma^\mu)(D_\mu)_{ij}\psi_q^j - m_q \bar{\psi}_q^i \psi_{qi} - \frac{1}{4} F_{\mu\nu}^a F^{a\mu\nu}$$

QCD is the theory of the strong interactions $\longrightarrow$ interactions between quarks and gluons

Introduction
QCD and the strong interactions

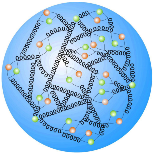
How to explore proton's inner structure?

- At different scales, hadrons show different behavior
- From point-like to complex internal dynamics
- Scattering experiments (DIS) and hadronic physics (LHC)

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

QCD and collider physics

Asymptotic freedom and pQCD



- Parton model as LO approximation to QCD
- Real QCD coupling strength changes with energy
- At high energies the hadron involves extremely complex internal dynamics

QCD is strongly coupled at large distances / low energies $\longrightarrow$ confinement

Non-perturbative physics

QCD and collider physics

Asymptotic freedom and pQCD

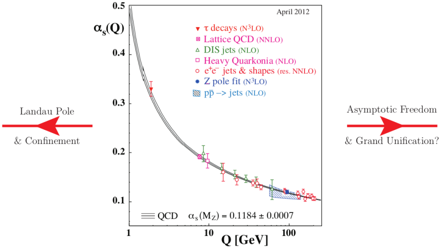
- Running coupling given by Renormalization Group Equation (RGE)

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

- 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

QCD and collider physics

Asymptotic freedom and pQCD



- Running coupling given by Renormalization Group Equation (RGE)

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

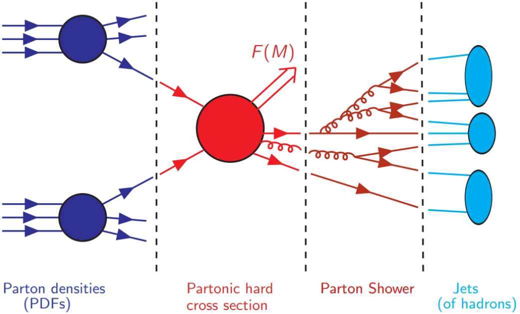
- β_0 LO of the β function, is > 0
- Λ_{QCD}, parameter that defines value of the coupling at large scales

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

Perturbative Quantum Chromodynamics (pQCD)

QCD and collider physics

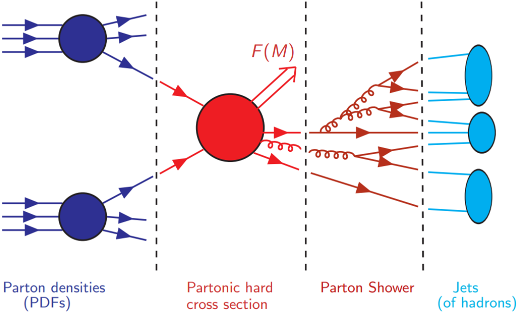
Hadronic processes and factorization



- LHC physic rely on hadronic collisions $\longrightarrow$ pQCD
- Compute **cross section** σ^F $\longrightarrow$ probability for a given process

QCD and collider physics

Hadronic processes and factorization

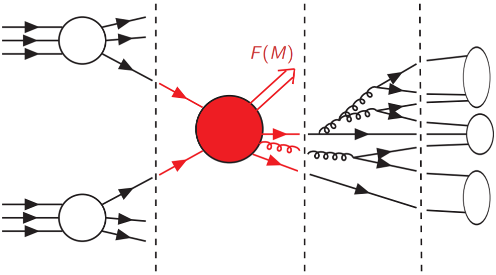


Compute hadronic cross sections is a hard problem $\longrightarrow$ QCD Factorization

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

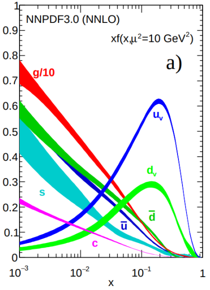
QCD and collider physics

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

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



- Each parton has a different PDF $\longrightarrow$ $u(x), d(x), ..., g(x)$
- PDFs can not predicted and yet can not measured $\longrightarrow$ extracted from data (MSTW, CTEQ, NNPDF collaborations)
- The N3PDF project: Machine Learning for PDFs determination [Urtasun-Elizari et al.] ref. at 1910.07049

QCD and collider physics

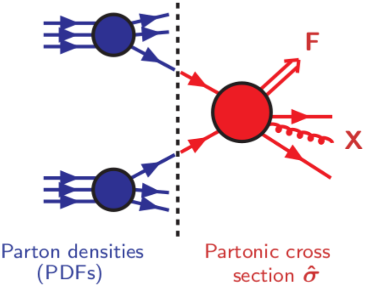
The N3PDF project

- Use `TensorFlow` and `Keras` to determine the PDFs with ML fitting models
- See paper by S.Carraza - J.Cruz-Martinez
  "Towards a new generation of parton densities with deep learning models", Carrazza et al., https://arxiv.org/abs/1907.05075
- TensorFlow operator implementation $\longrightarrow$ optimize PDF fitting
  "Towards hardware acceleration for parton densities estimation", Urtasun-Elizari et al., https://arxiv.org/abs/1909.10547

QCD and collider physics

Partonic cross section and pQCD

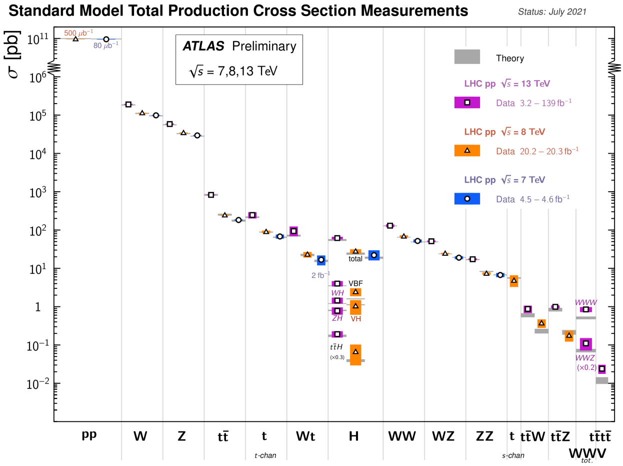
- Born cross section is the leading-order (LO) term of the perturbative series
- $\sigma^{(1)}, \sigma^{(2)}, \sigma^{(3)}$ are the NLO, NNLO, $\mathrm{N^3LO}$ corrections



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

Lower order predictions strongly depend on the auxiliary / unphysical scales

Need higher order corrections to increase theoretical accuracy!



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.

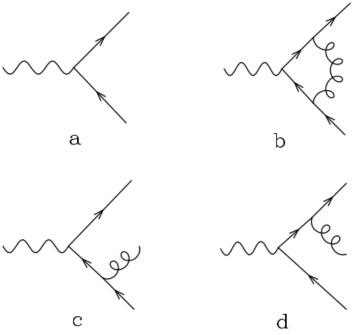
Part II

All order resummation

Resummation in QCD

Higher order corrections - need for resummation

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 $\longrightarrow$ KLN theorem
3. Initial state collinear singularities factorized inside the PDFs

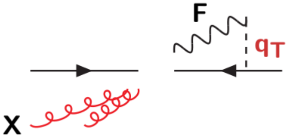


Cancellation only works in completely inclusive final states!

Resummation in QCD

$q_\perp$ resummation

- Describing exclusive 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

- Formalism developed by Catani-Bozzi (*)
  "Transverse-momentum resummation and the spectrum of the Higgs boson at the LHC",
  Bozzi, Catani et al., https://arxiv.org/abs/hep-ph/0508068
- Separate partonic $q_\perp$ distribution as follows:

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

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

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

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

Resummed component

Resummation holds in impact parameter space b

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

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

Resummation in QCD

Extend formalism to N^{3}LL

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

$$\mathcal{G}_N(\alpha_s, L) = L\, g^{(1)}(\alpha_s L) + g^{(2)}(\alpha_s L) + \frac{\alpha_s}{\pi} g^{(3)}(\alpha_s L) + \left(\frac{\alpha_s}{\pi}\right)^2 g^{(4)}(\alpha_s L) + \ldots$$

$$\mathcal{H}_N(\alpha_s) = 1 + \alpha_s \mathcal{H}^{(1)} + \alpha_s^2 \mathcal{H}^{(2)} + \alpha_s^2 \mathcal{H}^{(3)} + \ldots$$

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

$$\mathrm{LL}(\sim \alpha_s^n L^{n+1}) : g^{(1)}, \hat{\sigma}^{(0)}$$
$$\mathrm{NLL}(\sim \alpha_s^n L^{n}) : g^{(2)}, \mathcal{H}^{(1)}$$
$$\mathrm{NNLL}(\sim \alpha_s^n L^{n-1}) : g^{(3)}, \mathcal{H}^{(2)}$$
$$\mathrm{N^3LL}(\sim \alpha_s^n L^{n-2}) : g^{(4)}, \mathcal{H}^{(3)}$$

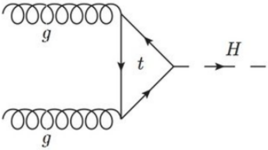
- Implement Catani-Bozzi resummation up to C++ implementation
- Extend the formalism up to N^{3}LO+N^{3}LL accuracy!

Part III

HTurbo numerical implementation

- Fast and accurate predictions for Higgs boson production cross section
- Predictions for differential cross section $d\sigma^{\mathrm{H}}/dq_{\perp}^{2}$
- Numerical implementation of resummed and finite components

$$
\begin{aligned}
d\sigma^{\mathrm{H}}_{\mathrm{(N)NLL+(N)LO}} &= d\sigma^{\mathrm{(res.)}}_{\mathrm{(N)NLL}} - d\sigma^{\mathrm{(asy.)}}_{\mathrm{(N)LO}} + d\sigma^{\mathrm{(f.o.)}}_{\mathrm{(N)LO}} \\
d\sigma^{\mathrm{(res.)}}_{\mathrm{(N)NLL}} &= \hat{\sigma}^{\mathrm{H}}_{\mathrm{LO}} \times \mathcal{H}_{\mathrm{(N)LO}} \times \exp \mathcal{G}_{\mathrm{(N)NLL}} \\
d\sigma^{\mathrm{(asy.)}}_{\mathrm{(N)LO}} &= \hat{\sigma}^{\mathrm{H}}_{\mathrm{LO}} \times \Sigma_{\mathrm{(N)LO}}
\end{aligned}
$$

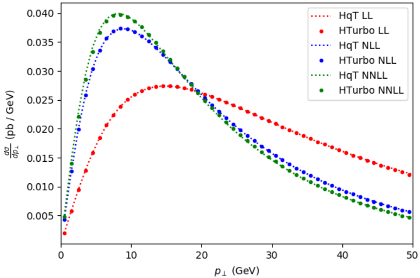


- LO process is just gg $\rightarrow$ H, but NLO and beyond require gg $\rightarrow$ H + jet!

HTurbo

Predictions for Higgs $q_\perp$ distribution

- $q_\perp$ resummation implemented in numerical codes **HqT**, **HRes**, **HNNLO** [Catani, de Florian, Ferrera, Grazzini, Tommasini]
- Higher order accuracy require high computation times
- NNLL predictions can take more than 48h $\longrightarrow$ need for fast numerical implementations



Codes producing fast and accurate predictions are needed for precision era of the LHC (High Luminosity LHC, from 80 - 140 fb^{-1} to **2000 fb^{-1}** !)

HTurbo

Starting point: DYTurbo

Numerical code **DYTurbo** [Camarda et al., https://arxiv.org/abs/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 resummed component
- Set Σ coefficients for asymptotic term
- Implement MC producing the LO and NLO H+jet cross sections
- Compare with **HRes** and **HqT**

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

HTurbo

Code optimization

Optimized reimplementation of **HqT**, **HRes** and **HNNLO** for q_T-resummation

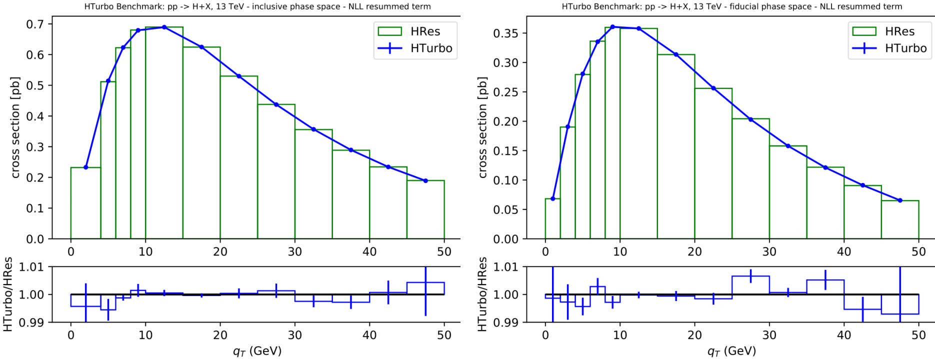
- **C++** structure with **Fortran** interfaces $\rightarrow$ Multi-threading
- Optimization in the integration routines / integral transforms
  - Factorize boson and decay kinematics
  - Gauss-Legendre quadrature rules (1-dim.)
  - Vegas/Cuhre through **Cuba** (multi-dim.)

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

Predictions	**HRes**	**HTurbo**
resummed NNLL	10h	10'
combined NNLO+NNLL	48h	2h

Results

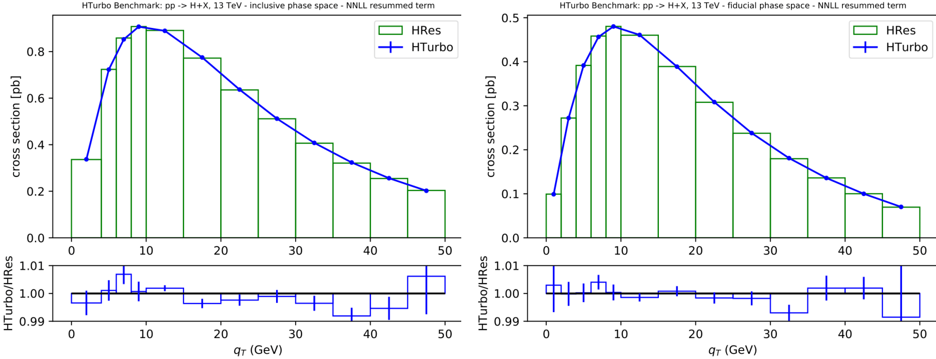
Comparison HTurbo and HRes - NLL resummed



- Cross section for fully inclusive (LHS) and fiducial (RHS) phase space ✓
- CM energy $\sqrt{s} = 13$ GeV and PDF set `NNPDF31_nlo_as_0118` PDF set

Results

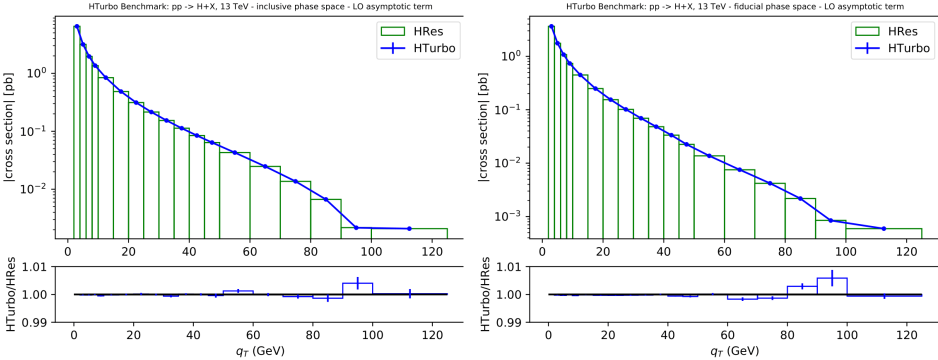
Comparison HTurbo and HRes - NNLL resummed



- 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

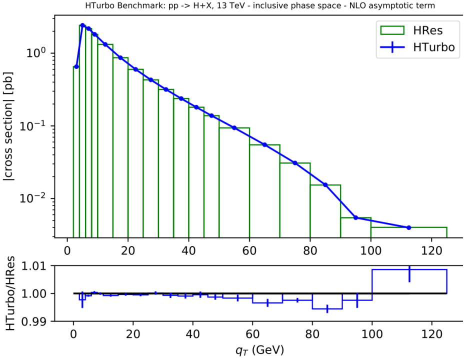
Comparison HTurbo and HRes - LO asymptotic

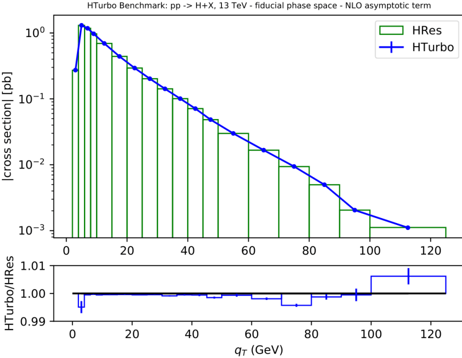


- Cross section for fully inclusive (LHS) and fiducial (RHS) phase space ✓
- CM energy $\sqrt{s} = 13$ GeV and PDF set `NNPDF31_nlo_as_0118` PDF set

Results

Comparison HTurbo and HRes - NLO asymptotic

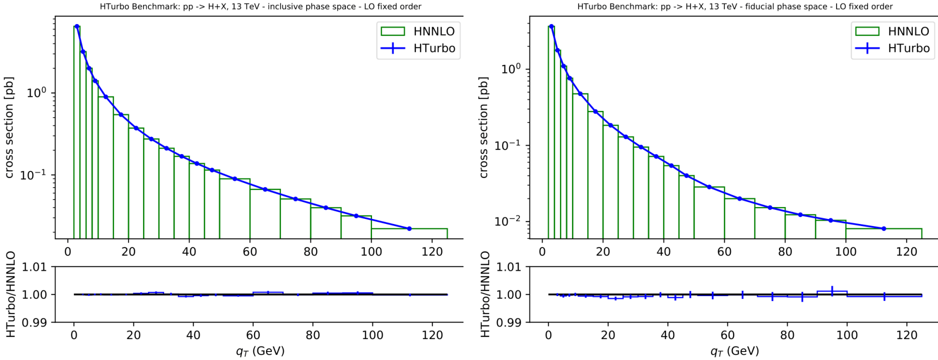




- Cross section for fully inclusive (LHS) and fiducial (RHS) phase space ✓
- CM energy $\sqrt{s} = 13$ GeV and PDF set `NNPDF31_nnlo_as_0118` PDF set

Results

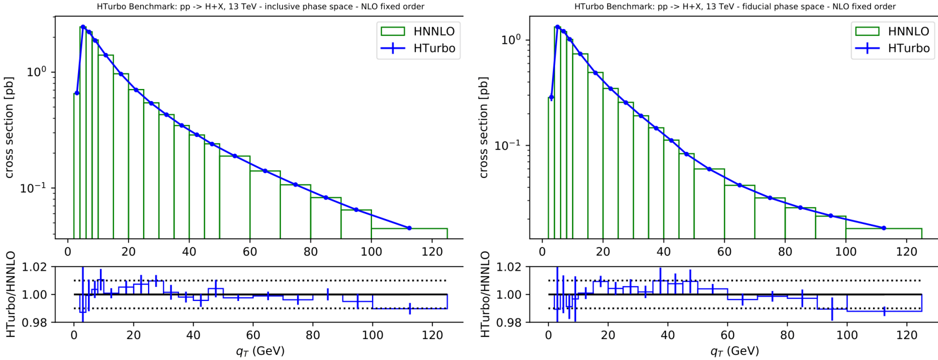
Comparison HTurbo and HRes - LO fixed-order



- Cross section for fully inclusive (LHS) and fiducial (RHS) phase space ✓
- CM energy $\sqrt{s} = 13$ GeV and PDF set `NNPDF31_nlo_as_0118` PDF set

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

Results

N^3LL implementation

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

$$\mathcal{G}_N(\alpha_s, L) = L\, g^{(1)}(\alpha_s L) + g^{(2)}(\alpha_s L) + \frac{\alpha_s}{\pi} g^{(3)}(\alpha_s L) + \left(\frac{\alpha_s}{\pi}\right)^2 g^{(4)}(\alpha_s L) + \dots$$

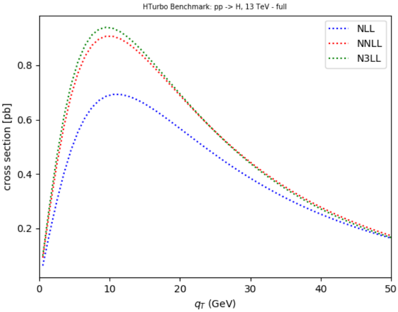
$$\mathcal{H}_N(\alpha_s) = 1 + \alpha_s \mathcal{H}^{(1)} + \alpha_s^2 \mathcal{H}^{(2)} + \alpha_s^2 \mathcal{H}^{(3)} + \dots$$

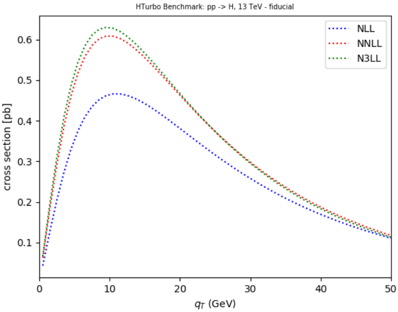
For each new order implement a new factor of $\mathcal{G}_N$ and Hard $\mathcal{H}_N$

- Extend the formalism up to $\mathrm{N}^3\mathrm{LO}+\mathrm{N}^3\mathrm{LL}$ accuracy!
- Implementation of N^3LL factors following
  - "Anomalous dimension for transverse-momentum resummation", Li - Zhu, https://arxiv.org/abs/1604.01404,
  - "Cusp and collinear anomalous dimensions in four-loop QCD", Von Manteuffel et al., https://arxiv.org/abs/2002.04617

Results

N^3LL implementation





- Cross section for fully inclusive (LHS) and fiducial (RHS) phase space ✓
- Implementation of N^3LL factors following [Li - Zhu, 1604.01404], [Von Manteuffel et al., 2002.04617]
- First implementation of resummation at N^3LL accuracy!

Summary & Conclusions

1. Accurate predictions are needed towards the precision era of the LHC
2. Resummation is needed for describing differential distributions
3. Fast numerical implementation are needed towards the precision era of the LHC
4. Developing a novel numerical code, **HTurbo**, which implements $q_\perp$ resummation for Higgs boson production
5. HTurbo is faster than any of the existing codes
6. HTurbo contains the first implementation of resummation at N^{3}LL accuracy!
7. Next steps:
   - Add full N^{3}LO+N^{3}LL prediction
   - Perform phenomenological studies comparing with LHC data

Thank you!

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Back up

Back up

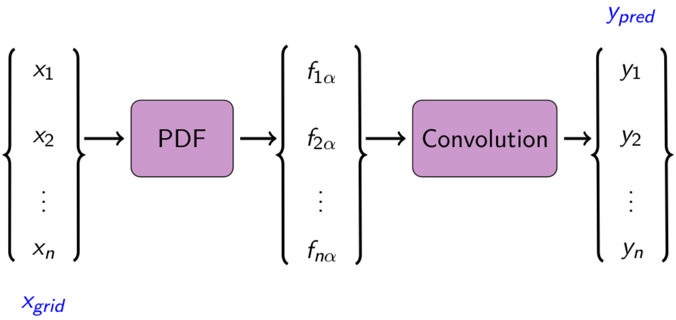
Back up

General structure of n3fit

- Use TensorFlow and Keras to determine the PDFs
- See paper by S.Carraza - J.Cruz-Martinez
  "Towards a new generation of parton densities with deep learning models",
  https://arxiv.org/abs/1907.05075

Back up

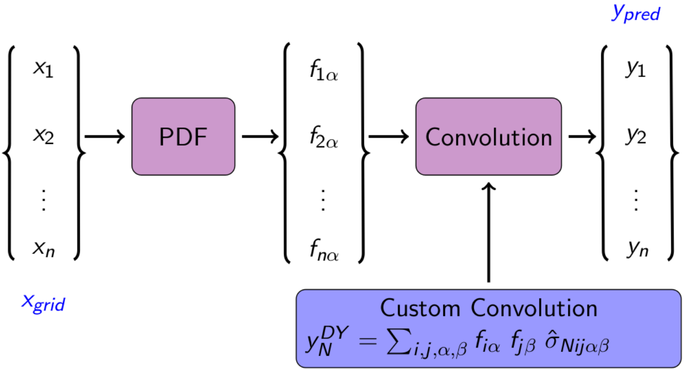
General structure of n3fit



1. Build a NN to compute y_{pred} observables from a grid of momentum fractions x_i
2. Compute loss function by comparing with LHC data
3. Update values of PDF $\longrightarrow$ Fit

Back up

Operator implementation



1. TF relies in symbolic computation $\longrightarrow$ High memory usage
2. Implement `C++` operator replacing the convolution

Back up

Back up