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High Energy Resummation of Transverse Momentum Distributions

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Università di Milano

Physics Workshop 12 October 2015

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LHC Phenomenology



I will present a new method to increase the precision of the theoretical predictions at LHC.

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LHC Phenomenology

Particle Physics Phenomenology is a part of the Theoretical Physics, with a crucial role in collider physics experiments.

- Its task is to calculate detailed prediction for the collider experiments, with high precision.
- These predictions, built in the Standard Model, are fundamental in discovering any trace of New Physics.

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Discovering New Physics

New Physics at LHC appears as a significant discrepancy between the theoretical prediction and the experimental data.

 "significant" means a discrepancy greater than the uncertainties, both theoretical and experimental.

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In order to find traces of New Physics, we measure at LHC:

- Inclusive observables
- Exclusive observables

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-

Discovering New Physics

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Inclusive observables
 Example in Particle Physics:
 Number of Higgs in unit time and area

$$\sigma = 100 \cdot 10^{-36} cm^{-2} \tag{1}$$

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Exclusive observables

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Discovering New Physics

In order to find traces of New Physics, we measure at LHC:

Inclusive observables
 Example in real life:
 Number of Marios today in Milan

$$\sigma_{\rm MARIO} = 274 \tag{1}$$

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Exclusive observables

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Discovering New Physics

In order to find traces of New Physics, we measure at LHC:

- Inclusive observables
- Exclusive observables

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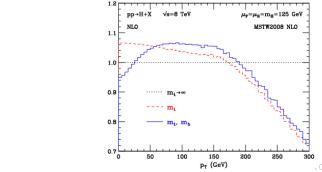
Discovering New Physics

In order to find traces of New Physics, we measure at LHC:

- Inclusive observables
- Exclusive observables

Example in Particle Physics:

Number of Higgs in unit time and area with a certain angle



$rac{d\sigma}{dp_{\mathrm{T}}^2}$

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Discovering New Physics

In order to find traces of New Physics, we measure at LHC:

- Inclusive observables
- Exclusive observables
 - Example in **real** life:

Number of Marios today in Milan in a certain neighbourhood

 $\frac{d\sigma_{MARIO}}{dp_{NEIGHBOURHOOD}^2}$



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Discovering New Physics

In order to find traces of New Physics, we measure at LHC:

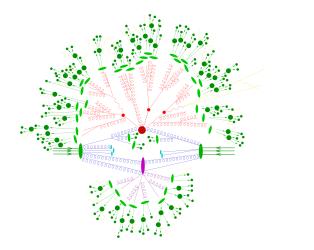
- Inclusive observables
- Exclusive observables

 $\mathsf{Exclusive} \to \mathsf{More} \ \mathsf{Information} \to \mathsf{More} \ \mathsf{complexity}$

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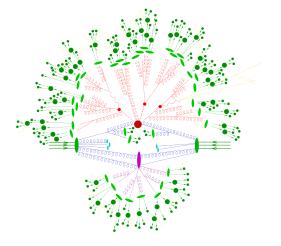
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What do we see at LHC??



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What do we see at LHC??



What we want to predict is this mess!!!

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What do we see at LHC??

Let's inspect more carefully...

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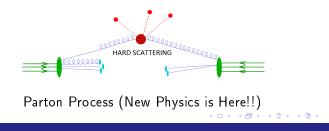
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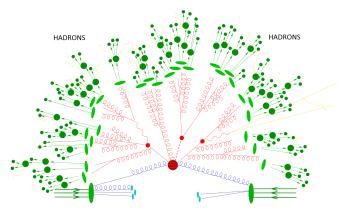
Parton Shower Tools (PYTHIA or POWEG)

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What do we see at LHC??

Let's inspect more carefully...



Hadronization Models

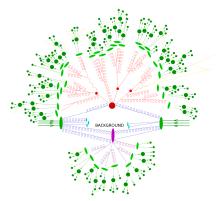
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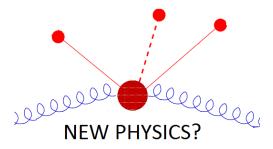
Then there are Experimental Problems (BACKGROUND)!

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Parton Process Calculation

We study this process in Perturbative QCD:



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Conclusion

Parton Process Calculation

We study this process in Perturbative QCD:

$$\frac{d\sigma}{dp_{\rm T}^2} = C_0 \left(1 + C_1 \alpha_s + C_2 \alpha_s^2 + \ldots \right) \tag{1}$$

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$$\frac{d\sigma}{dp_{\rm T}^2} = C_0 \left(1 + C_1 \alpha_s + C_2 \alpha_s^2 + \ldots \right) \tag{1}$$

• C_0 is called Leading order (LO).

- C₁ is called Next-to-Leading order (NLO).
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- And so on...

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Parton Process Calculation

$$\frac{d\sigma}{dp_{\rm T}^2} = C_0 \left(1 + C_1 \alpha_s + C_2 \alpha_s^2 + \dots \right) \tag{1}$$

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The tool to evaluate them is the Feynman Diagram Technique

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The tool to evaluate them is the Feynman Diagram Technique

- Leading Order
- Next-to-Leading Order
- Next-to-Next-to-Leading-Order More than a hundred diagrams!!!

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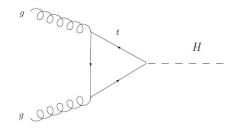
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The tool to evaluate them is the **Feynman Diagram Technique**Leading Order



- Next-to-Leading Order
- Next-to-Next-to-Leading-Order

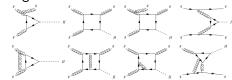
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Next-to-Next-to-Leading-Order More than a hundred diagrams!!

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Feynman Diagram Evaluation is not enough!!

There are cases where the usual Fixed Order Evaluation does not permit us to reach the desired accuracy!

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Conclusion

A Simple Example: Higgs Boson Production

At LHC, the Higgs Boson is produced mainly by gluon fusion:

C. Muselli High Energy Resummation of Transverse Momentum Distributions UniMi

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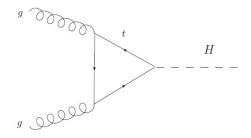
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Conclusion

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A Simple Example: Higgs Boson Production

At LHC, the Higgs Boson is produced mainly by gluon fusion:

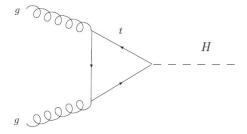


Conclusion

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A Simple Example: Higgs Boson Production

At LHC, the Higgs Boson is produced mainly by gluon fusion:



Too difficult!

The presence of a loop and the huge number of diagrams in the next orders prevent us from reaching the desired accuracy.

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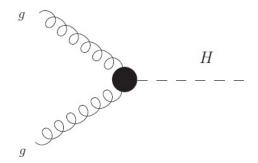
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Conclusion

A Simple Example: Higgs Boson Production

At LHC, the Higgs Boson is produced mainly by gluon fusion:



So...

...normally we use a approximation called heavy top approximation

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Conclusion

How good is this approximation?

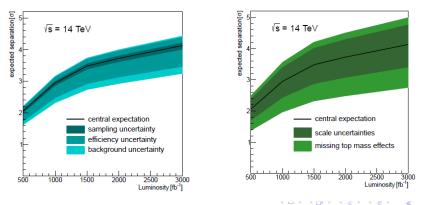
Correct answer: We don't know!! This is now our biggest uncertainty in the final result

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How good is this approximation?

Correct answer: We don't know!! [Langenegger *et al* '15] This is now our biggest uncertainty in the final result Experimental Theoretical



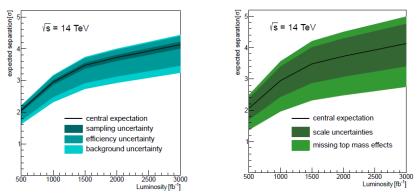
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How good is this approximation?

Experimental





The inclusion of the mass quark effects is of primary importance in this context

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Changing point of view

Since technical difficulties does not allow us to evaluate higher orders in the full theory, we follow a new road

Changing point of view

Since technical difficulties does not allow us to evaluate higher orders in the full theory, we follow a new road



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Changing point of view



Resummation

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$$x = \frac{m_{\rm H}^2}{s}$$

$rac{d\sigma}{dp_{\mathrm{T}}^2}\left(x,p_{\mathrm{T}}^2 ight)$	${f Threshold} \ x o 1$	$\begin{array}{c} Collinear \\ \boldsymbol{p}_{\scriptscriptstyle \mathrm{T}}^{2} \to \boldsymbol{0} \end{array}$	$\begin{array}{c} H E \\ x \to 0 \end{array}$	Other
LO α_s	$\bar{c}_0\left(\frac{ \mathfrak{n}(1-x) }{1-x}\right)_+$	$ ilde{C}_0 rac{1}{ ho_{ m T}^2}$	$C_0 \frac{1}{x}$	$C_0^{\mathrm{reg}}\left(x, p_{\mathrm{T}}^2\right)$
NLO α_s^2	$\overline{c}_1\left(\frac{\ln^2(1-x)}{1-x}\right)_+$	$\widetilde{c}_1 rac{\ln p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$c_1 \frac{\ln x}{x}$	$C_{1}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$
NNLO α_s^3	$\overline{c}_2\left(\frac{\ln^3(1-x)}{1-x}\right)_+$	$\widetilde{C}_2 \frac{ \mathbf{n}^2 \ \rho_{\mathrm{T}}^2}{\rho_{\mathrm{T}}^2}$	$C_2 \frac{ \mathbf{n}^2 x }{x}$	$C_{2}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$

High Energy Resummation of Transverse Momentum Distributions

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Resummation in QCD

Fixed Order Evaluation

$rac{d\sigma}{dp_{\mathrm{T}}^2}\left(x,p_{\mathrm{T}}^2 ight)$	${f Threshold} \ x o 1$	$egin{array}{c} {\sf Collinear}\ {m ho}_{ m T}^2 o 0 \end{array}$	H. E. $x \rightarrow 0$	Other
LO α_s	$\bar{c}_0\left(\frac{\ln(1-x)}{1-x}\right)_+$	$ ilde{C}_0rac{1}{ ho_{ m T}^2}$	$C_0 \frac{1}{x}$	$C_0^{ m reg}\left(x, p_{ m T}^2 ight)$
NLO α_s^2	$\bar{c}_1\left(\frac{\ln^2(1-x)}{1-x}\right)_+$	$\widetilde{c}_1 rac{\ln p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$C_1 \frac{\ln x}{x}$	$C_{1}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$
NNLO α_s^3	$\bar{c}_2\left(\frac{\ln^3(1-x)}{1-x}\right)_+$	$ ilde{C}_2 rac{\ln^2 p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$C_2 \frac{ \mathbf{n}^2 \times \mathbf{x} }{\mathbf{x}}$	$C_{2}^{\mathrm{reg}}\left(x, p_{\mathrm{T}}^{2}\right)$

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Resummation in QCD

Fixed Order Evaluation

$rac{d\sigma}{d p_{\mathrm{T}}^2}\left(x, p_{\mathrm{T}}^2\right)$	${\sf Threshold} \ x o 1$	${f Collinear}\ {m ho}_{ m T}^2 o 0$	H. E. $x \rightarrow 0$	Other
LO α_s	$\bar{c}_0\left(\frac{\ln(1-x)}{1-x}\right)_+$	$\widetilde{C}_0 rac{1}{ ho_{ m T}^2}$	$C_0 \frac{1}{x}$	$C_0^{\mathrm{reg}}\left(x, p_{\mathrm{T}}^2\right)$
NLO α_s^2	$\bar{c}_1\left(\frac{\ln^2(1-x)}{1-x}\right)_+$	$ ilde{C}_1 rac{\ln p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$C_1 \frac{\ln x}{x}$	$C_{1}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$
NNLO α_s^3	$\bar{c}_2\left(\frac{\ln^3(1-x)}{1-x}\right)_+$	$ ilde{C}_2 rac{\ln^2 p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$C_2 \frac{ \mathbf{n}^2 \times \mathbf{x} }{\mathbf{x}}$	$C_{2}^{\mathrm{reg}}\left(x, p_{\mathrm{T}}^{2}\right)$

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Fixed Order Evaluation

$rac{d\sigma}{dp_{\mathrm{T}}^2}\left(x,p_{\mathrm{T}}^2 ight)$	${\sf Threshold} \ x o 1$	${f Collinear}\ {m ho}_{ m T}^2 o 0$	H. E. $x \rightarrow 0$	Other
LO α_s	$\bar{c}_0\left(\frac{\ln(1-x)}{1-x}\right)_+$	$\tilde{c}_0 rac{1}{ ho_{ m T}^2}$	$C_0 \frac{1}{x}$	$C_0^{\mathrm{reg}}\left(x, p_{\mathrm{T}}^2\right)$
NLO α_s^2	$\overline{c}_1\left(\frac{\ln^2(1-x)}{1-x}\right)_+$	$\widetilde{c}_1 rac{\ln \rho_{\mathrm{T}}^2}{\rho_{\mathrm{T}}^2}$	$C_1 \frac{\ln x}{x}$	$C_{1}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$
NNLO α_s^3	$\bar{c}_2\left(\frac{\ln^3(1-x)}{1-x}\right)_+$	$ ilde{C}_2 rac{\ln^2 p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$C_2 \frac{\ln^2 x}{x}$	$C_{2}^{\mathrm{reg}}\left(x, p_{\mathrm{T}}^{2} ight)$

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High Energy Resummation of Transverse Momentum Distributions

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Resummation



$rac{d\sigma}{dp_{\mathrm{T}}^2}\left(x,p_{\mathrm{T}}^2 ight)$	${f Threshold} \ x o 1$	${f Collinear}\ {m ho}_{ m T}^2 o 0$	H. E. $x \rightarrow 0$	Other
LO α_s	$\bar{c}_0\left(rac{\ln(1-x)}{1-x} ight)_+$	$\tilde{C}_0 \frac{1}{p_{\mathrm{T}}^2}$	$C_0 \frac{1}{x}$	$C_0^{\mathrm{reg}}\left(x, p_{\mathrm{T}}^2\right)$
NLO α_s^2	$\bar{c}_1\left(\frac{\ln^2(1-x)}{1-x}\right)_+$	$\widetilde{c}_1 rac{\ln p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$c_1 \frac{\ln x}{x}$	$C_{1}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$
NNLO α_s^3	$\bar{c}_2\left(rac{\ln^3(1-x)}{1-x} ight)_+$	$\widetilde{C}_2 \frac{ \mathbf{n}^2 \ p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$C_2 \frac{ \mathbf{n}^2 \times \mathbf{x} }{\mathbf{x}}$	$C_{2}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$

High Energy Resummation of Transverse Momentum Distributions

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Resummation

$d\sigma$ (x p^2)	Threshold	Collinear	H. E.	Other
$rac{d\sigma}{dp_{\mathrm{T}}^2}\left(x,p_{\mathrm{T}}^2 ight)$	x ightarrow 1	$p_{ m T}^2 ightarrow 0$	$x \rightarrow 0$	Other
LO α_s	$\bar{c}_0\left(\frac{ \mathfrak{n}(1-x) }{1-x}\right)_+$	$ ilde{C}_0rac{1}{ ho_{ m T}^2}$	$C_0 \frac{1}{x}$	$C_0^{\mathrm{reg}}\left(x, p_{\mathrm{T}}^2\right)$
NLO α_s^2	$\overline{c}_1\left(\frac{\ln^2(1-x)}{1-x}\right)_+$	$\widetilde{c}_1 rac{\ln ho_{ m T}^2}{ ho_{ m T}^2}$	$c_1 \frac{\ln x}{x}$	$C_{1}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2}\right)$
NNLO α_s^3	$\overline{c}_2\left(\frac{\ln^3(1-x)}{1-x}\right)_+$	$ ilde{C}_2 rac{\ln^2 p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$C_2 \frac{ \mathbf{n}^2 \times \mathbf{x} }{\mathbf{x}}$	$C_{2}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$

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High Energy Resummation of Transverse Momentum Distributions

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Resummation in QCD

Resummation

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$d\sigma (x, p^2)$	Threshold	Collinear	H. E.	Other
$rac{d\sigma}{dp_{\mathrm{T}}^2}\left(x,p_{\mathrm{T}}^2 ight)$	x ightarrow 1	$p_{\scriptscriptstyle m T}^2 ightarrow 0$	x ightarrow 0	Other
LO α_s	$\bar{c}_0\left(\frac{ n(1-x) }{1-x}\right)_+$	$\widetilde{c}_0 rac{1}{ ho_{ m T}^2}$	$C_0 \frac{1}{x}$	$C_{0}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$
NLO α_s^2	$\overline{c}_1\left(\frac{\ln^2(1-x)}{1-x}\right)_+$	$ ilde{C}_1 rac{\ln p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$c_1 \frac{\ln x}{x}$	$C_{1}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$
NNLO α_s^3	$\overline{c}_2\left(\frac{\ln^3(1-x)}{1-x}\right)_+$	$ ilde{C}_2 rac{\ln^2 p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$C_2 \frac{\ln^2 x}{x}$	$C_2^{\mathrm{reg}}\left(x, p_{\mathrm{T}}^2\right)$

Resummation

$rac{d\sigma}{dp_{\mathrm{T}}^2}\left(x,p_{\mathrm{T}}^2 ight)$	$\begin{array}{c} Threshold \\ x \to 1 \end{array}$	${f Collinear}\ {m ho}_{ m T}^2 o 0$	H. E. $x \rightarrow 0$	Other
LO α_s	$\bar{c}_0\left(\frac{ \mathfrak{n}(1-x) }{1-x}\right)_+$	$\widetilde{c}_0 rac{1}{ ho_{ m T}^2}$	$C_0 \frac{1}{x}$	$C_0^{\mathrm{reg}}\left(x, p_{\mathrm{T}}^2\right)$
NLO α_s^2	$\overline{c}_1\left(\frac{\ln^2(1-x)}{1-x}\right)_+$	$\widetilde{c}_1 rac{\ln p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$c_1 \frac{\ln x}{x}$	$C_{1}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$
NNLO α_s^3	$\bar{c}_2\left(\frac{\ln^3(1-x)}{1-x}\right)_+$	$ ilde{C}_2 rac{\ln^2 p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$C_2 \frac{ \mathbf{n}^2 x }{x}$	$C_2^{ m reg}\left(x,p_{ m T}^2 ight)$

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High Energy Resummation of Transverse Momentum Distributions

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Resummation in QCD

Fixed Order+Resummation

$rac{d\sigma}{dp_{\mathrm{T}}^{2}}\left(x, p_{\mathrm{T}}^{2} ight)$	${\sf Threshold} \ x o 1$	${f Collinear}\ {m ho}_{ m T}^2 o 0$	H. E. $x \rightarrow 0$	Other
LO α₅	$\bar{c}_0\left(rac{\ln(1-x)}{1-x} ight)_+$	$ ilde{C}_0rac{1}{ ho_{ m T}^2}$	$C_0 \frac{1}{x}$	$C_0^{ m reg}\left(x, p_{ m T}^2 ight)$
NLO α_s^2	$\bar{c}_1\left(\frac{\ln^2(1-x)}{1-x}\right)_+$	$\widetilde{c}_1 rac{\ln p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$C_1 \frac{\ln x}{x}$	$C_{1}^{\mathrm{reg}}\left(x,p_{\mathrm{T}}^{2} ight)$
NNLO α_s^3	$\bar{c}_2\left(\frac{\ln^3(1-x)}{1-x}\right)_+$	$\widetilde{c}_2 rac{\ln^2 p_{\mathrm{T}}^2}{p_{\mathrm{T}}^2}$	$C_2 \frac{ \mathbf{n}^2 _X}{x}$	$C_2^{\mathrm{reg}}\left(x, p_{\mathrm{T}}^2\right)$

History of High Energy Resummation

Periodo	Risultati	Autori
Fine '70	P_{gg} - BFKL equation	Balitsky, Fadin, Kuraev, Lipatov
'80	Amplitude Factorization	Catani, Ciafaloni e collab.
'90-'00	DIS,Heavy flavour production	Catani, Ciafaloni, Hartmann - Ellis, Ball
'00	Parton Evolution at small-x	Ciafaloni, Colferai, Salam, Stasto (CCSS) Altarelli, Ball, Forte (ABS)
2008	Higgs in gluon fusion	Marzani, Ball, Forte, Vicini, Del Duca
2007-2010	Rapidity Distribution	Caola, Forte, Marzani
2014-2015	Transverse Momentum Distribution	Forte, Muselli

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Building a Resummation Theory

- Select the limit and the observable High Energy $x \to 0$ Transverse momentum distribution $\frac{de}{dp}$
- Factorization In the limit, a generic dominant diagram is wirtten as $\longrightarrow D_n = F(E_1, \dots, E_m)$ with E_i some simple ingredients or subdiagrams



Sum all the $D_n \longrightarrow$ Exponentiation $R = \sum_i D_n = H$ exp K

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Building a Resummation Theory

Select the limit and the observable High Energy $x \rightarrow 0$ Transverse momentum distribution $\frac{d\sigma}{d\rho_x^2}$

2 Factorization In the limit, a generic dominant diagram is wirtten as → D_n = F (E₁,..., E_m) with E_i some simple ingredients or subdiagrams



3 Sum all the $D_n \longrightarrow \mathbf{Exponentiation} \ R = \sum_n D_n = H \exp K$

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Building a Resummation Theory

- Select the limit and the observable High Energy $x \rightarrow 0$ Transverse momentum distribution $\frac{d\sigma}{dp_{a}^{2}}$
- **2** Factorization In the limit, a generic dominant diagram is wirtten as $\longrightarrow D_n = F(E_1, \ldots, E_m)$ with E_i some simple ingredients or subdiagrams

$$D_n = \frac{1}{n!} K^n H$$

3 Sum all the $D_n \longrightarrow \mathbf{Exponentiation} \ R = \sum_n D_n = H \exp K$

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Building a Resummation Theory

- Select the limit and the observable High Energy $x \rightarrow 0$ Transverse momentum distribution $\frac{d\sigma}{dp_{a}^{2}}$
- **2** Factorization In the limit, a generic dominant diagram is wirtten as $\longrightarrow D_n = F(E_1, \ldots, E_m)$ with E_i some simple ingredients or subdiagrams

$$D_n = \frac{1}{n!} K^n H$$

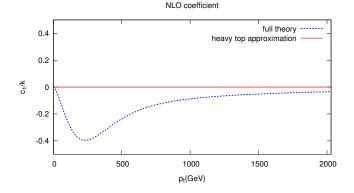
3 Sum all the $D_n \longrightarrow \text{Exponentiation } R = \sum_n D_n = H \exp K$

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Preliminary Results

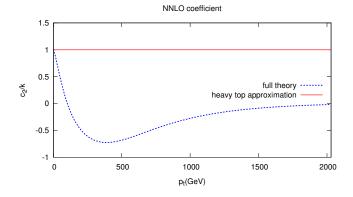


Sizeable difference also at relative small value of ρ_Γ.
 Inclusion of these terms may reduce the uncertainty due to the

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Preliminary Results

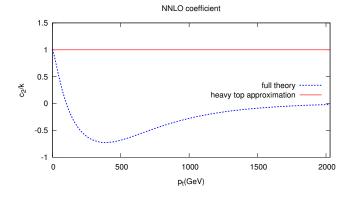


- Sizeable difference also at relative small value of $p_{\rm T}$.
- Inclusion of these terms may reduce the uncertainty due to the effective approximation.

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Conclusion

Conclusion and Outlook

In conclusion:

- QCD Phenomenology is of primary importance in collider physics.
- The usual perturbative approach in some cases fail to reach the desired accuracy
- To increase the precision, it's possible to follow new roads: → Resummation Theories.

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Possible outlook:

- We want to apply all the machinery to other process (DY, Heavy quark production, jets...)
- We want to join two resummation theories (High Energy with small p_T) to gain the benefits of both.
- Many other things...

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