

QCD for the LHC

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Preface

Why Do We Need the LHC?

Crucial Step Toward Resolving Fundamental Outstanding Issues:

- Big and Little Hierarchy Problems
- Number of Families
- Fermion Masses
- Baryon Stability
- Union of QM & Gravity



- Origin of CP Violation
- Origin of Lambda
- Dark Matter,

Much Theory Effort: **New Physics**

*String Theory: Solves Everything in Principle but Trouble in Practice –
> 10^{500} candidate “solutions”!



- *String Inspired Theory:
 - Large Extra Dimensions
 - KK Excitations, ...
- * MSSM
- * ANTHROPICTY
- * NEW PARADIGMS:
arXiv:1005.3394, 1008.1046,....

* NEW PARADIGMS:

1005.3394 -- 3 or more New Heavy

Families w SM quarks-New

Leptons, SM leptons-New Quarks:

$M_{\text{GUT}} \sim 100\text{TeV}$, proton stable,

coupling unification,...

1008.1046 -- RQG w Asymptotic

Safety $\Rightarrow \rho_{\Lambda} \cong (2.400 \times 10^{-3} \text{eV})^4$

1010.1415 -- Classicalons....



** NEW PHYSICS AT LHC

Must Distinguish from Higher
Order SM Processes AND Must
Probe Precisely to Specify Uniquely

⇒ Precision QCD for the LHC



Goals in Today's Talk

- QCD at High Energies
- Applications of QCD for LHC Physics
 1. Normalization
 2. SM Processes
 3. BSM Processes
- Future

QCD at High Energies

$$d\sigma = \sum_{i,j} \int dx_1 dx_2 F_i(x_1) F_j(x_2) d\hat{\sigma}_{res}$$

\Rightarrow

Hadron-Hadron: $\Delta\sigma_{th} = \Delta F_i \oplus \Delta\hat{\sigma}_{res}$,

(QCD \otimes QED corrections)

($e^+ e^-$ Annhln : $\Delta\sigma_{th} = 0 \oplus \Delta\hat{\sigma}_{res}$)

The precision $\Delta\sigma_{th}$ validates

- **Backgrounds, SM and BSM**
- **Signals, SM and BSM**
- **Normalization**

Components of $\Delta\sigma_{\text{th}}$

- **Technical, $\Delta\sigma_{\text{tech}}$** : bugs, numerical rounding errors, convergence issues,
- **Physical, $\Delta\sigma_{\text{phys}}$** : missing graphs, approximations to graphs, truncations,
- $\Delta\sigma_{\text{th}} = \Delta\sigma_{\text{phys}} \oplus \Delta\sigma_{\text{tech}}$

Examples for $\Delta\sigma_{\text{th}}$

- **Tevatron: 6-7% $\cong \Delta\sigma_{\text{norm(expt)}}$**
 $\Rightarrow \Delta\sigma_{\text{th}} \sim 10\%$ OK , generically
- **LEP1 : 20M Z's $\Rightarrow \Delta\sigma_{\text{th}} (\text{norm}) = 0.061\%$ **
.....
- **What do we need for LHC?**

Applications of QCD for LHC Physics

- **Goals for $\Delta\sigma_{\text{th}}$**

Standard Candle Processes:

Single Z, W prod. -- $\Delta\sigma_{\text{th}} \approx 1\%$

$t\bar{t}$ prod. – $\Delta\sigma_{\text{th}} \approx 1\%$

Les Houches List:

$2 \rightarrow n$ to $O(\alpha_s)$, $n \geq 3$ -- $\Delta\sigma_{\text{th}} \cong 10\%$

- **Exactness – Key**



SOTA[†] for $\Delta\sigma_{\text{th}}$ for LHC Physics

- Single Z, W prod.: (Adam et al., JHEP11 (2010)074)

Z prod. -- $\Delta\sigma_{\text{th}} = (4.91 \pm 0.38)\% =$
 $(2.45 \pm 0.73)\%(\text{QCD+EW}) \oplus 4.11\%(\text{PDF}) \oplus$
 $1.10 \pm 0.44)\%(\text{QCD Scale}),$

[W⁺, W⁻] prod. -- $\Delta\sigma_{\text{th}} = [(5.05 \pm 0.58)\%,$
 $(5.24 \pm 0)\%]$

[†] State of the art.



SOTA for $\Delta\sigma_{th}$ in LHC Physics

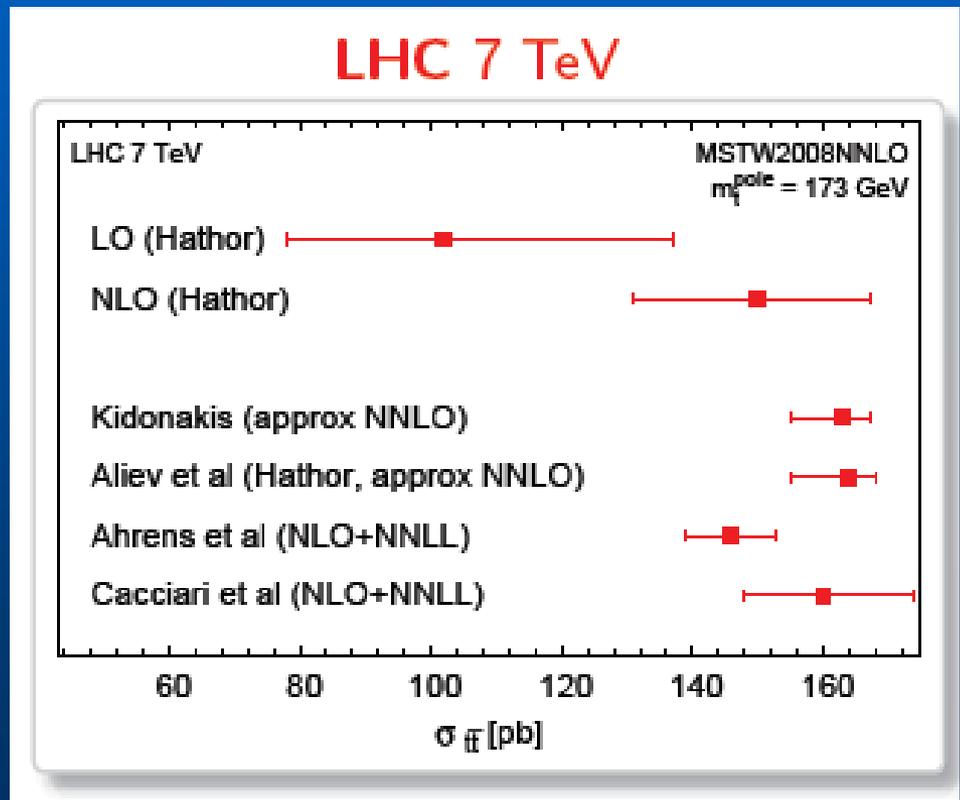
- $t\bar{t}$ prod. – $\Delta\sigma_{th} = \Delta\sigma_{PDF} \oplus \Delta\sigma_{rest}$

Salam (ICHEP10)

Estimate of $\Delta\sigma_{th}$:
Standard Methods

$$\hat{\sigma}^2 = \frac{1}{N-1} \sum_{i=1}^N (x_i - \hat{\mu})^2$$

⇒ 4.8%

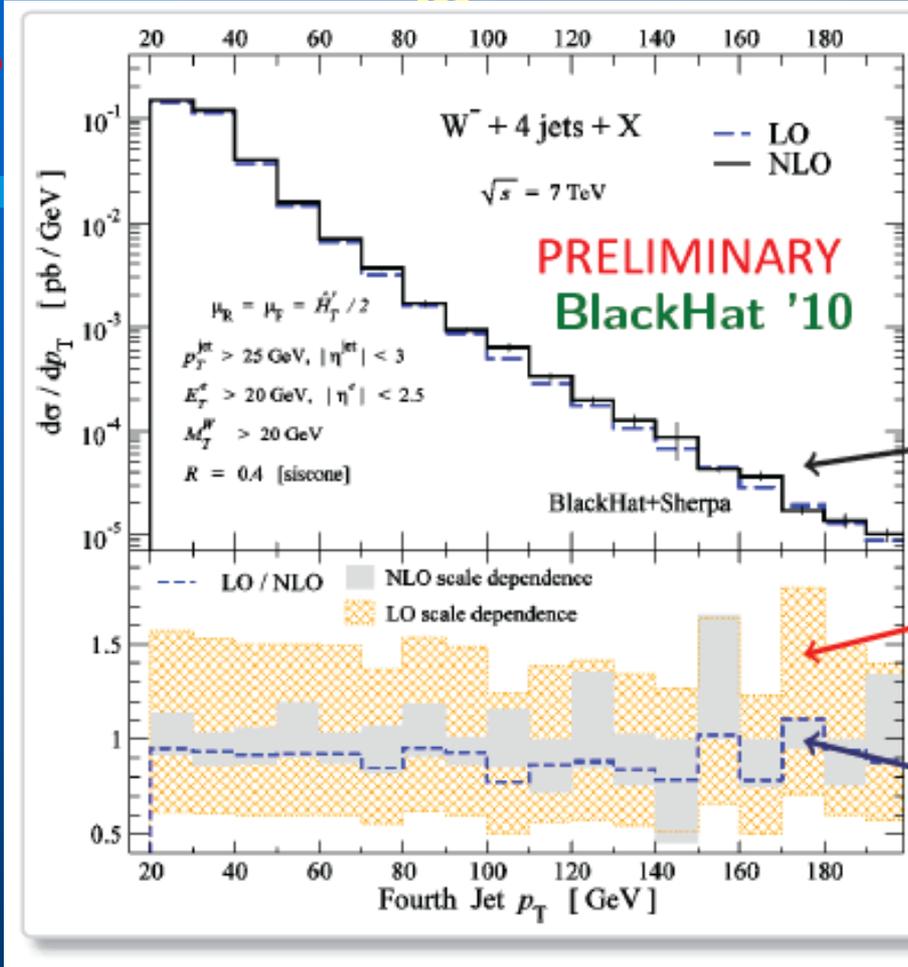


SOTA for $\Delta\sigma_{\text{th}}$ in LHC Physics

- **2 → n : Background to New Physics, susy, extra dim., etc. ⇒ $O(\alpha_s)$ Corr. Essential**
- **Great Progress:**
 - 2 → 5, BlackHat Group, almost done
 - 2 → 4, many results, automation too - see review by Salam (ICHEP2010), PoS ICHEP 2010 (2010) 135,....
- **QUESTION : What is the $\Delta\sigma_{\text{th}}$?**

SOTA for $\Delta\sigma_{th}$ in LHC Physics

GS



First (nearly) complete
 $2 \rightarrow 5$ computation
 (as needed in our
 SUSY example)

NLO spectrum
 of 4th jet!

LO uncertainty

NLO uncertainty

[Currently, leading colour
 & missing $W+6q$ diags]

$\Rightarrow \sim 10-30\%$

$\Delta\sigma_{\text{th}}$ in LHC Physics

- **Basic Paradigm:**

MC \cup NLO \cup NNLO/NNLL

\Rightarrow EW and **MIXED** EWXQCD ALSO (See Dittmaier, Denner, Glosser et al.,)

$\Rightarrow m_q \neq 0, \text{ISR}, O(\alpha_s^n), n \geq 2$ (PRD78(2008)056001)

- **Standard Tools:**

MC's(parton shower)

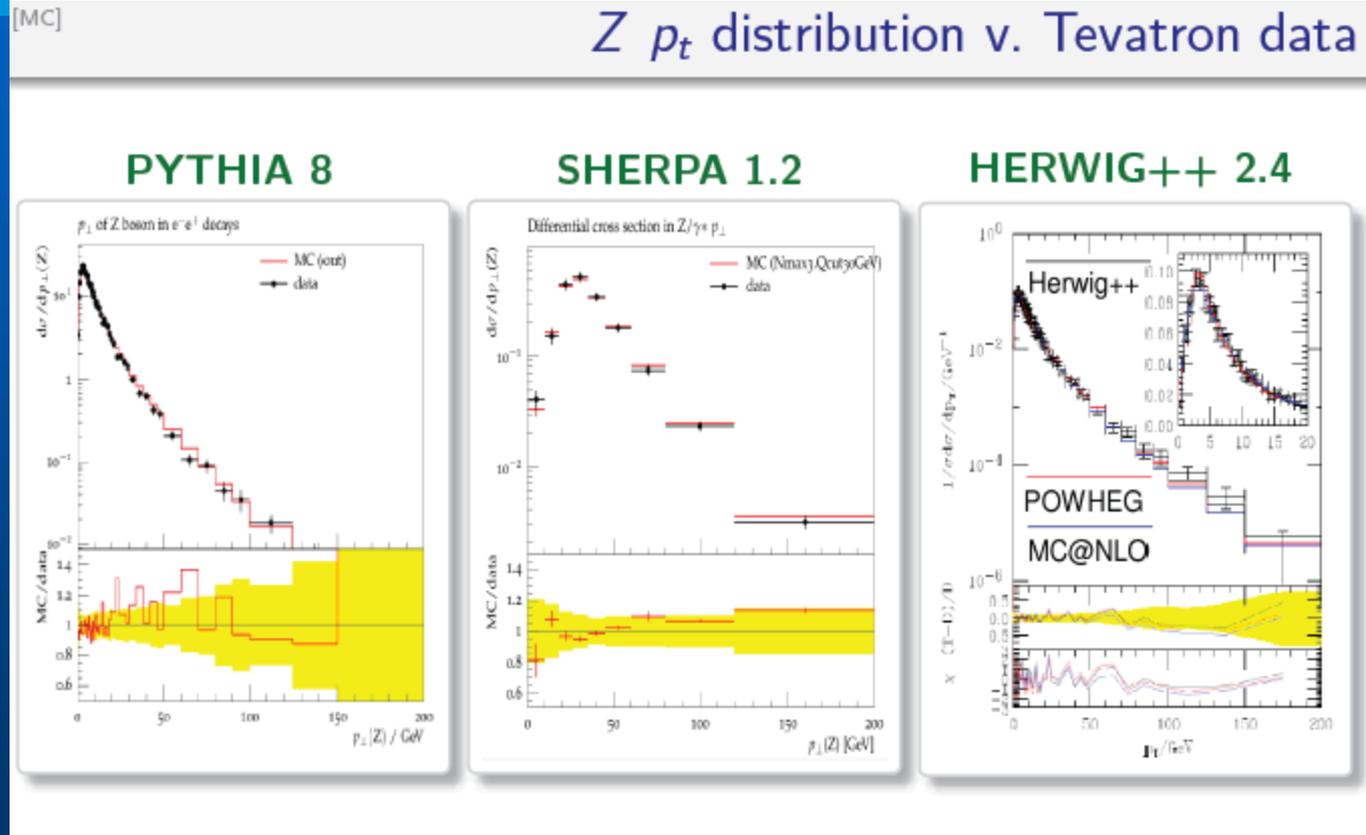
Fortran: HERWIG6.510, Pythia6.4

C++('New'): SHERPA, HERWIG++, Pythia 8

$\Delta\sigma_{th}$ in LHC Physics

G.S.(ICHEP10)

- $\Delta\sigma_{th}$,
low P_t ?
high P_t ?



$\Delta\sigma_{\text{th}}$ in LHC Physics

- **New Jet Algorithms: IR safe anti- k_T (Cacciari et al.) (in FASTJET) – cones without cones!**
[repeatedly recombine pair
of objects with smallest $d_{ij} = R^2_{ij}/\max(k^2_{ti}; k^2_{tj})$]
- **MC@NLO, POWHEG, POWHEG/HERWIG++**
Parton Shower MC's with Exact $O(\alpha_s)$ Normalization,
Different $O(\alpha_s^n)$ Corrections, $n \geq 2$: what is $\Delta\sigma_{\text{th}}$?
- **MENLOPS, ...**
NLO Z; LO Z+ n jets w Parton Shower, Hamilton& Nason;
Sherpa group
NLO Z; NLO Z+ n jets w Parton Shower, Alioli et al., in
progress

What is $\Delta\sigma_{\text{th}}$?

$\Delta\sigma_{\text{th}}$ in LHC Physics

- **NNLO w (Resummed) Parton Shower MC's: Needed for Complete Realization of LHC Discovery Potential**
 - * Resummation of all large collinear effects:
 1. DGLAP evolution, p_T integrated out
 2. Evolutions with p_T alive
 - * Resummation of all large soft effects (Regge too!)
 1. In collinear regime
 2. In non-collinear regime
 - * Exact treatment of **DIFFERENTIAL** distributions through **NNLO**, with exact phase space and no miss-counting of effects, including m_q .
- **GOAL: Event-by-event realization with exclusive NNLO w PS,**



proof of $\Delta\sigma_{\text{th}}$.

$\Delta\sigma_{\text{th}}$ in LHC Physics

- **PROGRESS: IN**

$$d\sigma = \sum_{i,j} \int dx_1 dx_2 F_i(x_1) F_j(x_2) d\hat{\sigma}_{\text{res}}$$

Resummed Collinear Evolution $\Leftrightarrow \{F_i\}$

Soft Resummation (non-coll.) $\Leftrightarrow d\hat{\sigma}_{\text{res}}$

$\Delta\sigma_{\text{th}}$ in LHC Physics

- FOR EXAMPLE

$$\begin{aligned}
 d\hat{\sigma}_{\text{res}} &= \sum_n d\hat{\sigma}_n \\
 &= e^{\text{SUM}_{\text{IR}}(\text{QCD})} \sum_{m,n=0}^{\infty} \frac{1}{m!n!} \int \prod_{j_1=1}^m \frac{d^3 k_{j_1}}{k_{j_1}} \prod_{j_2=1}^n \frac{d^3 k_{j_2}}{k_{j_2}} \int \frac{d^4 y}{(2\pi)^4} e^{iy(p_1+q_1-p_2-q_2-\sum_{j_1} k_{j_1}-\sum_{j_2} k'_{j_2})+D_{\text{QCD}}} \\
 &\quad * \tilde{\beta}_{m,n}(k_1, \dots, k_m; k'_1, \dots, k'_n) \frac{d^3 p_2}{p_2^0} \frac{d^3 q_2}{q_2^0}
 \end{aligned}$$

$\Delta\sigma_{\text{th}}$ in LHC Physics

- **Shower/ME Matching:**

$$\tilde{\beta}_{m,n} \rightarrow \hat{\tilde{\beta}}_{m,n}, \text{ shower - subtracted residuals}$$

- **IR-Improved DGLAP-CS Theory:**

New resummed scheme for P_{AB} , reduced cross section --

$$F_j, \hat{\sigma} \rightarrow F'_j, \hat{\sigma}' \text{ for}$$

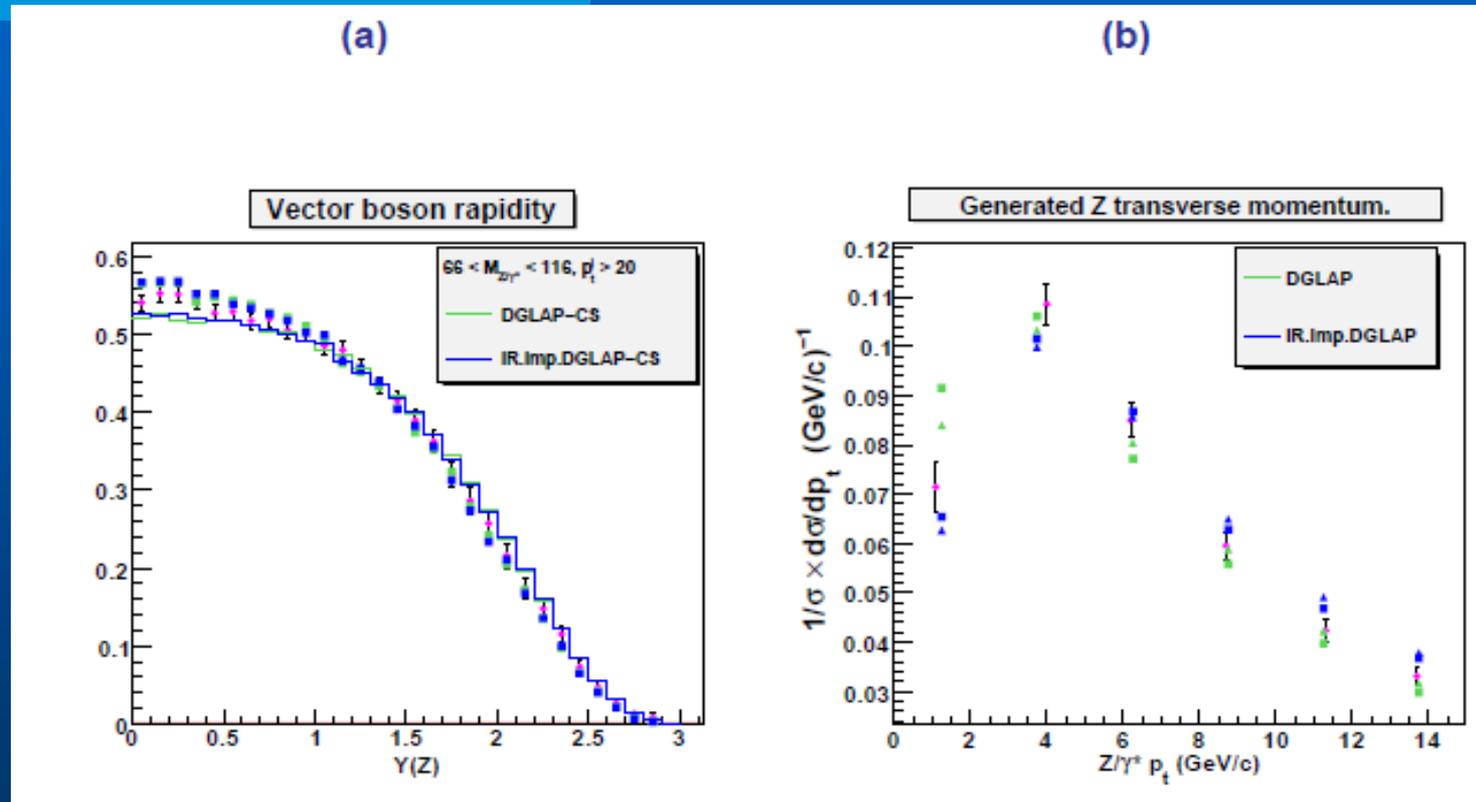
$$P_{qq} \rightarrow P_{qq}^{\text{exp}} = C_F F_{YFS}(\gamma_q) e^{\frac{1}{2}\delta_q} \frac{1+z^2}{1-z} (1-z)^{\gamma_q}, \text{ etc.,}$$

giving the same value for σ , with improved MC stability.

$\Delta\sigma_{\text{th}}$ in LHC Physics

- **HERWIRI1.031: First Realization in HERWIG6.5 Environment--PRD81 (2010) 076008:**

$\chi^2 \downarrow$



$\Delta\sigma_{\text{th}}$ in LHC Physics

- **HERWIRI1.031: First Realization in HERWIG6.5 Environment--PRD81 (2010) 076008:**

- For the CDF rapidity data, HERWIRI1.031 is closer to the data than is HERWIG6.510 (1.54 vs 1.77 for $\chi^2/\text{d.o.f.}$ resp.);
for MC@NLO/HERWIRI1.031 and MC@NLO/HERWIG6.510 the $\chi^2/\text{d.o.f.}$ are 1.42 and 1.40 resp., both are within 10% of the data
 \Rightarrow Need NNLO level, in progress.
- For the D0 p_T data, HERWIRI1.031 gives a better fit to the data compared to HERWIG6.5 for low p_T ,
for $p_T < 12.5\text{GeV}$, the $\chi^2/\text{d.o.f.}$ are ~ 2.5 and 3.3 respectively
- we add the statistical and systematic errors,
showing that the IR-improvement makes a better representation of QCD in the soft regime for a given fixed order in perturbation theory.

$\Delta\sigma_{th}$ in LHC Physics

- NLO P_{AB} Exclusively (Jadach et al.):**

Proof of the concept for non-singlet NLO

DGLAP --

NLO-corrected middle-of-the-ladder kernel, $\sim C_F^2$

Position of the NLO correction/insertion p can be anywhere in the ladder and we sum over p :

$$\bar{D}_B^{[1]}(x, Q) = e^{-S_{ISR}} \sum_{n=0}^{\infty} \left\{ \begin{array}{c} \text{Diagram 1: Ladder with } n \text{ rungs, } x \text{ at top, } t \text{ at bottom.} \\ \text{Diagram 2: Ladder with } n \text{ rungs, } x \text{ at top, } t \text{ at bottom, } p \text{ at } p \text{th rung.} \\ \text{Diagram 3: Ladder with } n \text{ rungs, } x \text{ at top, } t \text{ at bottom, } p \text{ at } p \text{th rung, } j \text{ at } j \text{th rung.} \end{array} \right\} = e^{-S_{ISR}} \left\{ \delta_{x=1} + \right.$$

$$\left. + \sum_{n=1}^{\infty} \left(\prod_{i=1}^n \int_{Q > a_i > a_{i-1}} d^3 \eta_i \rho_{1B}^{(1)}(k_i) \right) \left[\sum_{p=1}^n \beta_0^{(1)}(z_p) + \sum_{p=1}^n \sum_{j=1}^{p-1} W(\vec{k}_p, \vec{k}_j) \right] \delta_{x=\prod_{j=1}^n x_j} \right\},$$

Next step is to add more "NLO insertions" 2, 3 and so on...

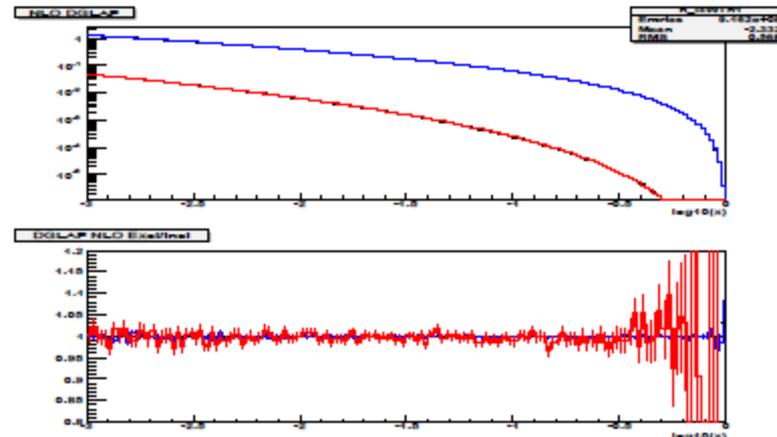


$\Delta\sigma_{th}$ in LHC Physics

- **NLO P_{AB} Exclusively (Jadach et al.):**
Proof of the concept for non-singlet NLO
DGLAP –

Similar Results
for FSR. Next,
more insertions,
.....
Very promising

Numerical test of ISR pure C_F^2 NLO MC



Numerical results for $D(x, Q)$ from **two** Monte Carlos inclusive and exclusive. **Blue curve** is single NLO insertion, **red curve** is double insertion component. Evolution $10\text{GeV} \rightarrow 1\text{TeV}$ starting from $\delta(1-x)$. The ratio demonstrates 3-digit agreement, in units of LO.

Future

- **Exact Amplitude-Based Resummation with NNLO Hard Corrections ($O(\alpha_s^2, \alpha\alpha_s, \alpha^2)$) on Event-by-Event Basis:**
 - *MC Methods – IR&Coll. Improved Parton Showers
 - *Exact Phase Space
 - *Complete Mass Effects
- **Provable Control of $\Delta\sigma_{\text{th}}$ in LHC Physics**