Ununtegrated NLO evolution in the MC modelling of the QCD initial state radiation for LHC The KRKMC Project

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QUESTION 1

Can we think about new scheme/technique of the pQCD calculations for LHC which is substantially better/different from the ones based on the 1978-85 standards?

HAVING IN MIND:

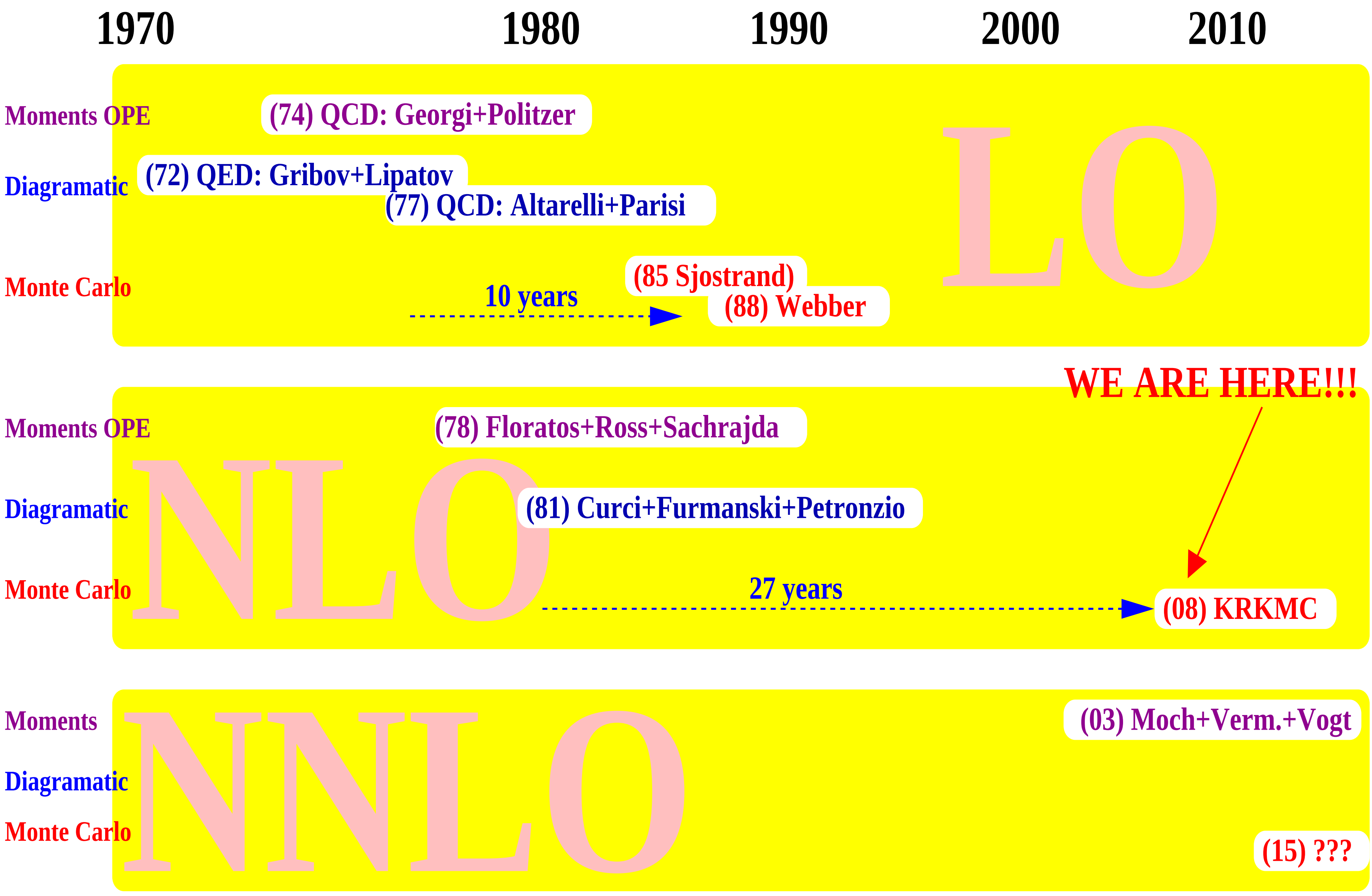
(1) more precise pQCD predictions within MC event generators,

(2) better treatment of heavy quark masses (thresholds),

(3) new method of transferring parton distributions HERA$\longrightarrow$LHC,

(4) better control of parton luminosity and kT, and more... **YES!**

Time evolution of the Collinear QCD Evolution



QUESTION 2

What is the most promissing, desirable and difficult type of the MC event generator for pQCD/QED/EW/BM, for data analysis at LHC and other colliders?

It is the MC implementing the Resummed and Fixed-Order perturbative Matrix Element with the COMPLETE NLO in both!

NLO Parton Shower MC $\otimes$ NLO ME for hard process

QUESTION 3

What is missing on the way to the ”new brave world”?

Parton Shower Monte Carlo featuring complete NLO (collinear) Evolution does not exists yet!

WHY?

Two bottlenecks, see next slide....

Two most important bottlenecks

MC technique:

The addict use of Markovian MC algorithm, ”Backward Evolution” (Sjostrand 1985), narrowing options for phase space integration and the use of integrated/collidear PDFs.

Theory:

The existing collinear factorization theorems in QCD (Collins etal. 1985) are not very well suited for the Monte Carlo.

State of art: recent partial solutions, in the right direction

- New better MC parton showers in PYTHIA and HERWIG in the improved LL approximation. ISR “backward evolution" + integrated PDFs.
- MC@NLO, NLO matrix element for the hard process + LL parton shower MC (piggyback). By Frixione, Webber and Nason.
- Constrained MC algorithm for the initial parton shower by Krakow group. An alternative to backward evolution. **Bottleneck No. 1 removed!**
- GR@PPA Monte Carlo project (GRACE@KEK) with a NLL parton shower.
- Nagy and Soper: General PS scheme LL class with many emitters, better phase space treatment and colour interferences.
- Collins, Rogers, Stasto: Redoing factorization theorem from the scratch (in Feynman gauge) in for suitable for the Monte Carlo!
- The other LL-class PS based MCs: CASCADE with CCFM low-x resummation, ARIADNE LL with improved soft limit, SHERPA implementing the CKKW, tree-level QCD matrix elements + LL PS MC.
- SANC project for QCD, QED and electroweak one loop fixed order corrections, to be used in KRKMC projects.

The name of the game for today

Can we construct Parton Shower Monte Carlo

for QCD Initial State Radiation:

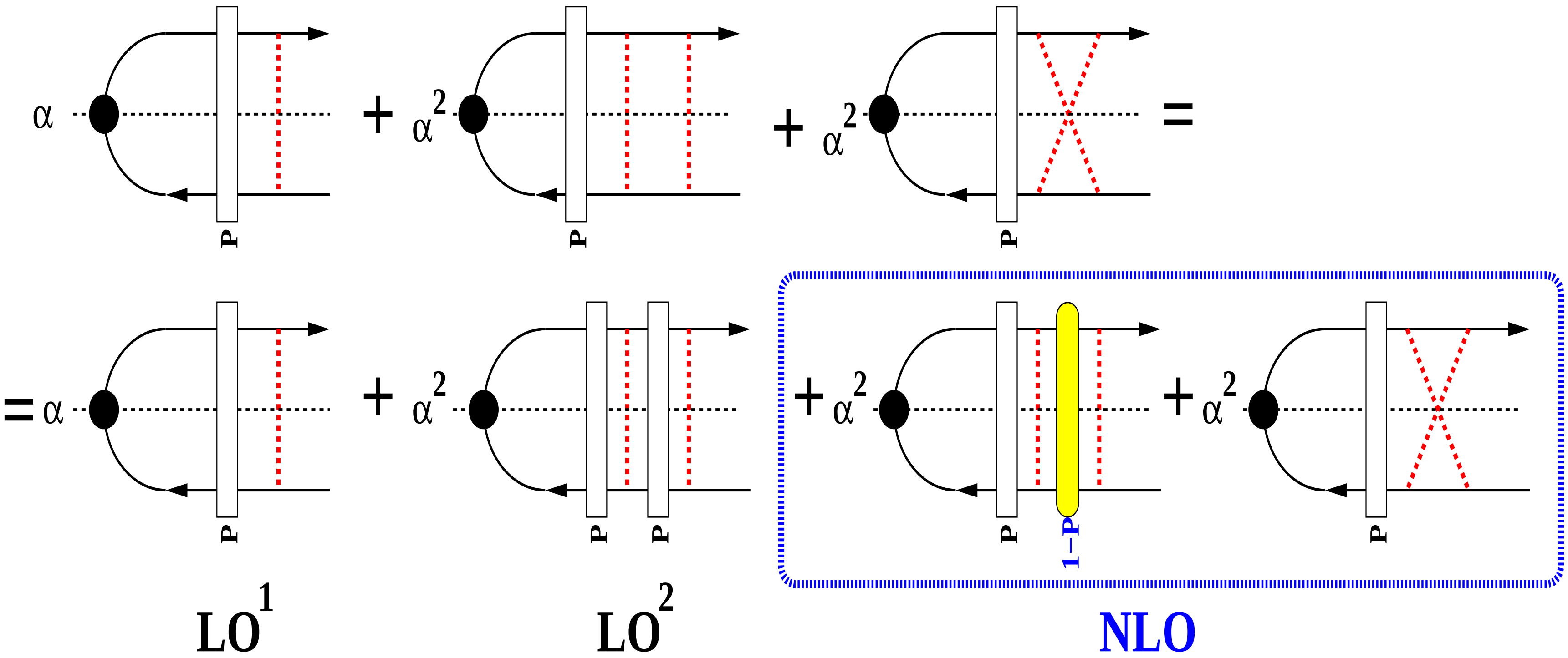
- based firmly on Feynman Diagrams (ME) and LIPS,
- based rigorously on the collinear factorization (EGMPR, CSS),
- implementing exactly NLO $\overline{MS}$ DGLAP evolution **?**
- implementing fully unintegrated PDFs (FunPDF);

  NLO evolution done by MC itself using EXClusive NLO kernels.

We are going to show that YES, we can!

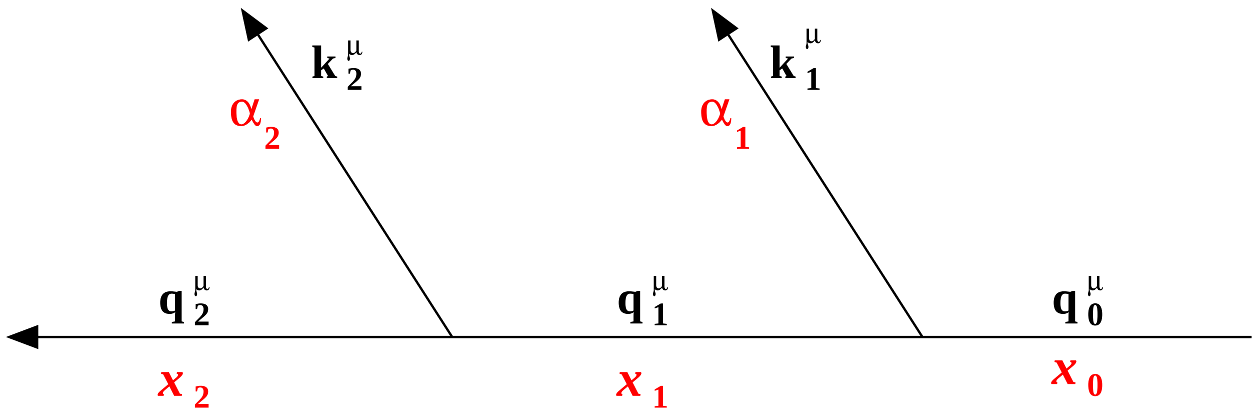
And to show first numerical implementation – proof of the concept.

CFP: Extraction of NLO kernel from Feynman diags.



- CFP = Curci-Furmanski-Petronzio (1980-82)
- Double gluonstrahlung, only 2 diagrams, $C_F C_A$ part only.
- Axial gauge, projection operator $P = P_{spin} P_{kin.} P_{pole}$.
- LO: $\mathcal{P}(z) = \frac{1+z^2}{2(1-z)}$
- NLO: $\mathcal{P}^N(z) = \frac{1+3x^2}{16(1-x)} \ln^2(x) + \frac{2-x}{4} \ln(x) + \frac{3}{8}(1-x)$.

Kinematics of double gluonstrahlung



- Initial parton $q_0^\mu = (E, 0, 0, E)$
- Emitted gluons: $k_i^\mu = (k_i^0, \mathbf{k}_i, k_i^3)$, $k_{Ti} = |\mathbf{k}_i|$.
- Lightcone plus variables: $x_i = \frac{q_i \cdot \zeta}{q_0 \cdot \zeta}$, $\alpha_i = \frac{k_i \cdot \zeta}{q_0 \cdot \zeta}$, $\zeta = (1, 0, 0, -1)$.

Unintegrated (exclusive) NLO kernel

$$\alpha'^2 \mathcal{P}^N(x) = \frac{1}{2!} \int \frac{d^3k_2}{2k_2^0} \int \frac{d^3k_1}{2k_1^0}\; \delta_{1=\max(|\mathbf{k}_1|,|\mathbf{k}_2|)/Q}\; \delta_{1-x=\alpha_1+\alpha_2}\; b_2^N(k_1,k_2)$$

UNINTEGRATED exclusive NLO kernel directly from FEYNMAN DIAGRAMS

$$b_2^N(k_1,k_2) = \frac{(\alpha')^2}{16(2\pi)^2}\left[b^{Ladd.}(k_1,k_2) + b^{Ladd.}(k_2,k_1) + b^{XLad.}(k_1,k_2) - b^{Count.}(k_1,k_2)\right],$$

$$b^{Ladd.}(k_1,k_2) = \frac{1}{q^4(k_1,k_2)}\left\{\frac{T_1(\alpha_1,\alpha_2)}{\alpha_1\alpha_2} + \frac{T_2(\alpha_1,\alpha_2,0)}{\alpha_2^2}\frac{\mathbf{k}_2^2}{\mathbf{k}_1^2} + \frac{T_3(\alpha_1,\alpha_2)}{\alpha_2}\frac{2\mathbf{k}_1\cdot\mathbf{k}_2}{\mathbf{k}_1^2}\right\},$$

$$b^{Xlad.}(k_1,k_2) = \frac{1}{q^4(k_1,k_2)}$$

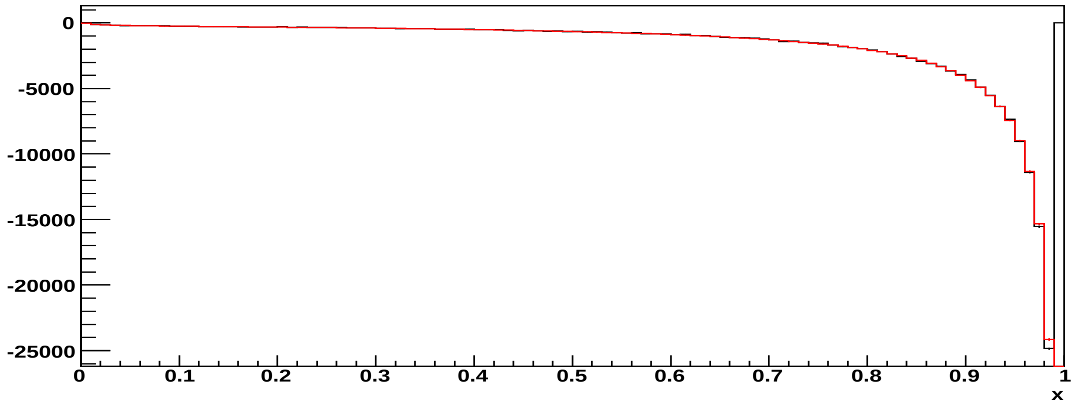
$$\times\left\{\frac{2T_1^x(\alpha_1,\alpha_2)}{\alpha_1\alpha_2} - T_{2a}^x(\alpha_1,\alpha_2)\frac{2\mathbf{k}_1\cdot\mathbf{k}_2}{\alpha_1\mathbf{k}_2^2} - T_{2b}^x(\alpha_1,\alpha_2)\frac{2\mathbf{k}_1\cdot\mathbf{k}_2}{\alpha_2\mathbf{k}_1^2} + T_3^x(\alpha_1,\alpha_2)\frac{(\mathbf{k}_1\cdot\mathbf{k}_2)^2}{\mathbf{k}_1^2\mathbf{k}_2^2}\right\},$$

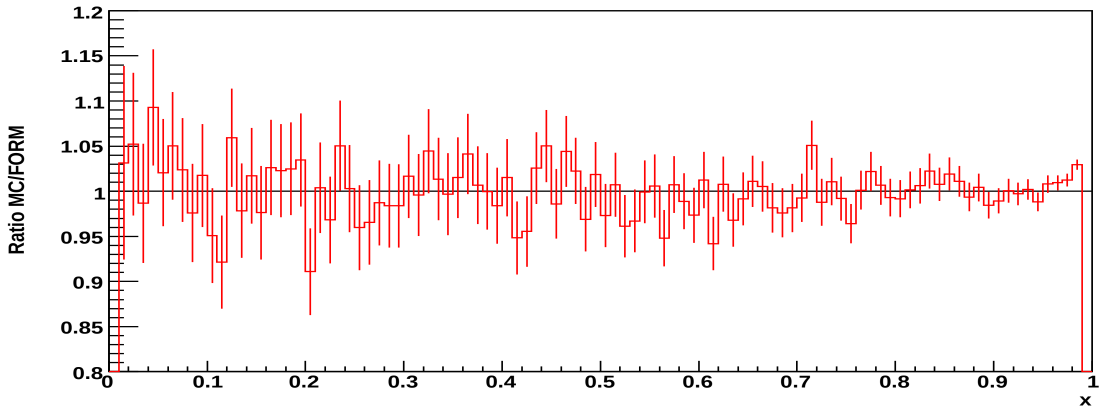
$$b^{Count.}(k_1,k_2) = \frac{\mathbf{k}_2^2}{q^4(0,k_2)}\frac{T_2(\alpha_1,\alpha_2,0)}{\alpha_2^2}\frac{1}{\mathbf{k}_1^2} = \frac{T_2(\alpha_1,\alpha_2,0)}{(1-\alpha_1)^2\mathbf{k}_1^2\mathbf{k}_2^2}.$$

$$-q^2(k_1,k_2) = \frac{1-\alpha_2}{\alpha_1}\mathbf{k}_1^2 + \frac{1-\alpha_1}{\alpha_2}\mathbf{k}_2^2 + 2\mathbf{k}_1\cdot\mathbf{k}_2.$$

For simplicity we omitted terms due to ϵ part in in the γ-trace T^2.

Numerical cross-check on unintegrated kernel using FOAM



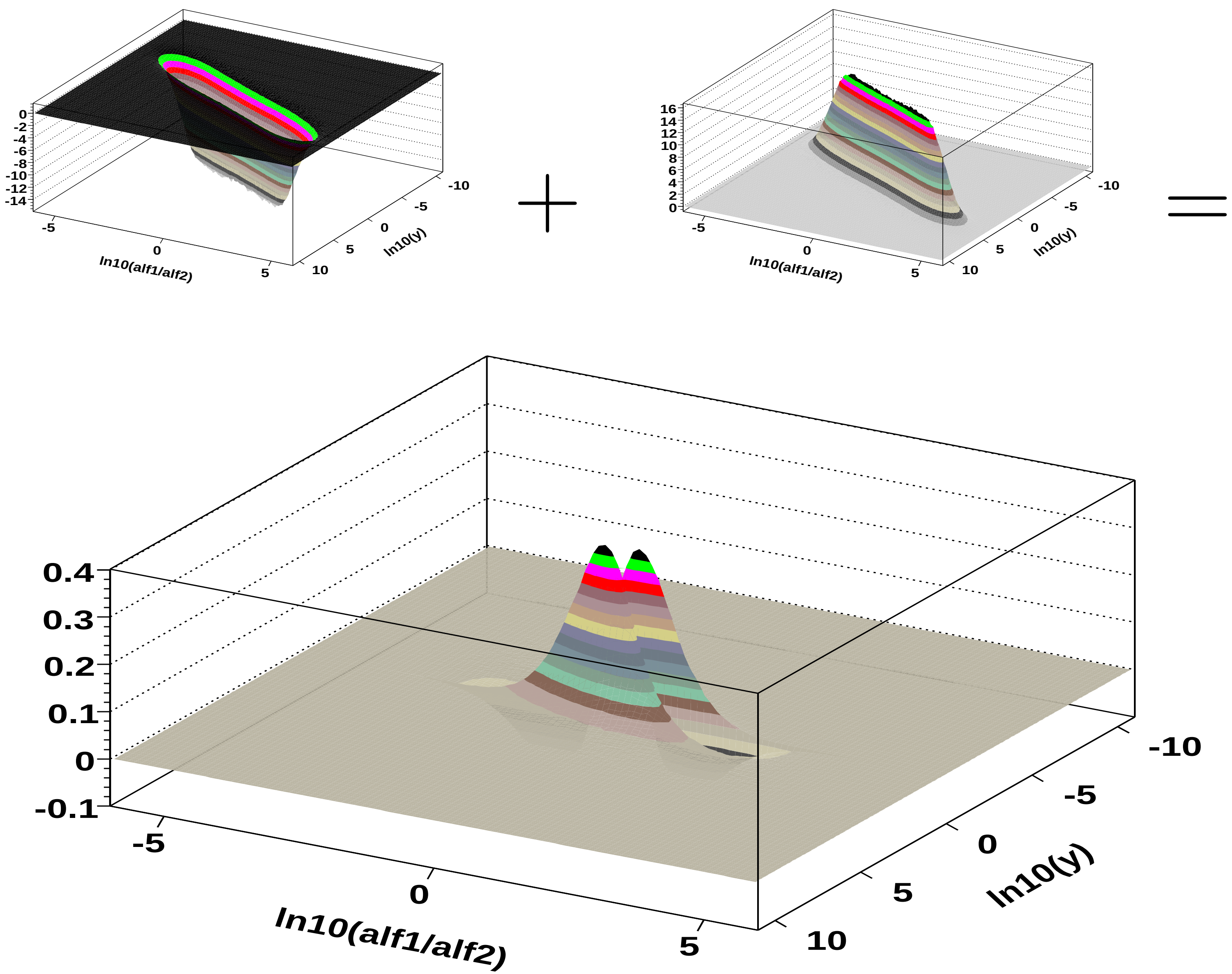


Xchecking Monte Carlo (FOAM) with the formula (Furmanski-Petronzio):

$$\alpha'^2 \mathcal{P}^N(z) = \frac{1}{2!} \int \frac{d^3k_2}{2k_2^0} \int \frac{d^3k_1}{2k_1^0} \; \delta_{1=\max(|\mathbf{k}_1|,|\mathbf{k}_2|)/Q} \; \delta_{1-x=\alpha_1+\alpha_2} \; b_2^N(k_1, k_2)$$

$$= \alpha'^2 \left(\frac{1+3x^2}{16(1-x)} \ln^2(x) + \frac{2-x}{4} \ln(x) + \frac{3}{8}(1-x) \right)$$

Unintegr. NLO kernel on the $(\ln k_{Ti},\ \ln \alpha_i)$ plane



$1 - x = \alpha_1 + \alpha_2$, $y = \frac{k_{T1}}{k_{T2}}$. Bose-symmetrized. **Short-range correlat.!**

Implanting NLO UNintegrated kernel into parton shower MC

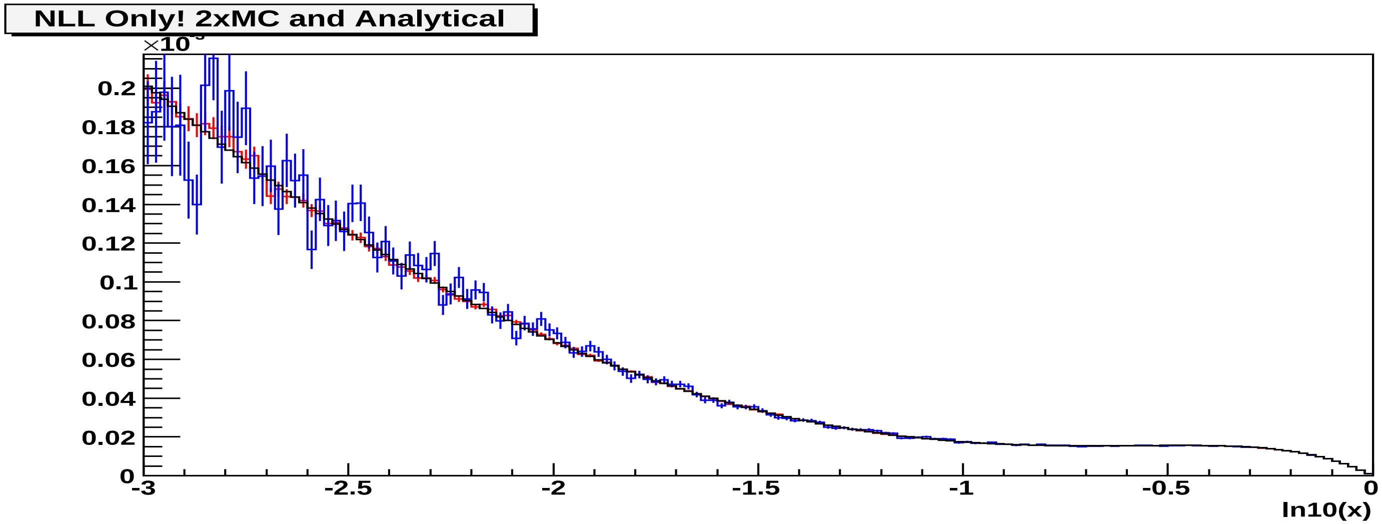
THE FRAMEWORK:

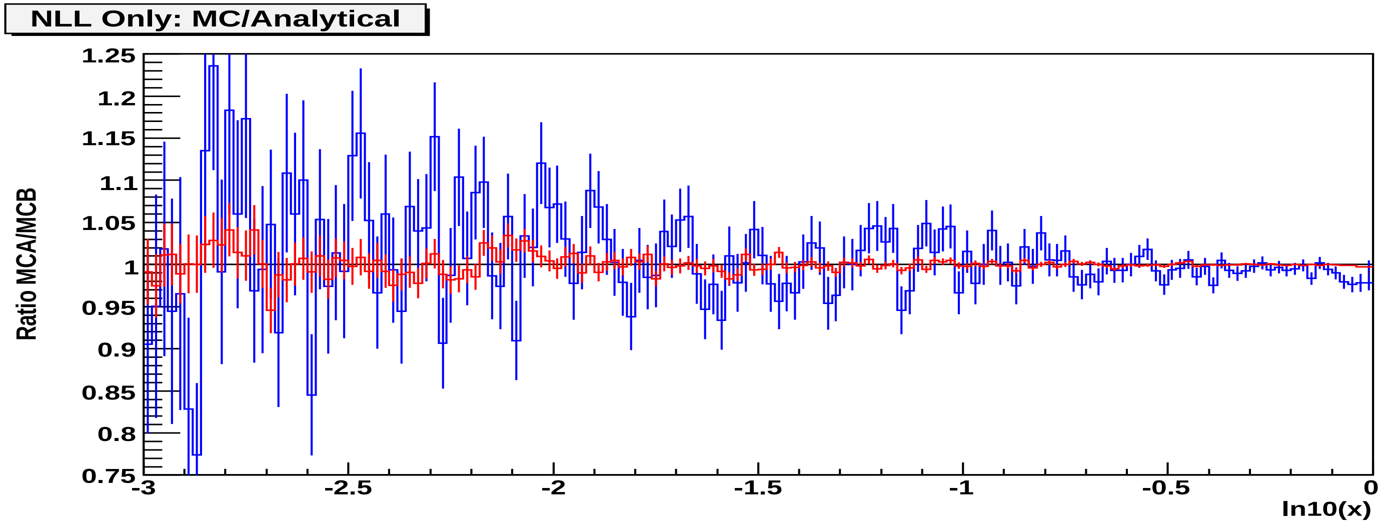
- Markovian MC with standard integrated LO+NLO DGLAP kernel (gluonstrahlung part)
- Markovian MC with UNINTEGRATED LO+NLO DGLAP kernel. NEW!!!
- Analytical integration leading to NLO DGLAP kernel following Curci-Furmanski-Petronzio (1980); Feynman diagrams $\times$ LIPS, see HERA-LHC, May 2008:

  http://jadach.web.cern.ch/jadach/public/skrzypek-CERN08.pdf

  http://jadach.web.cern.ch/jadach/public/HELHC08.pdf

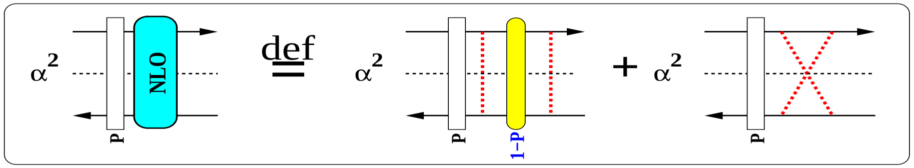
Benchmark comparison of 2 MCs and Analytical integration

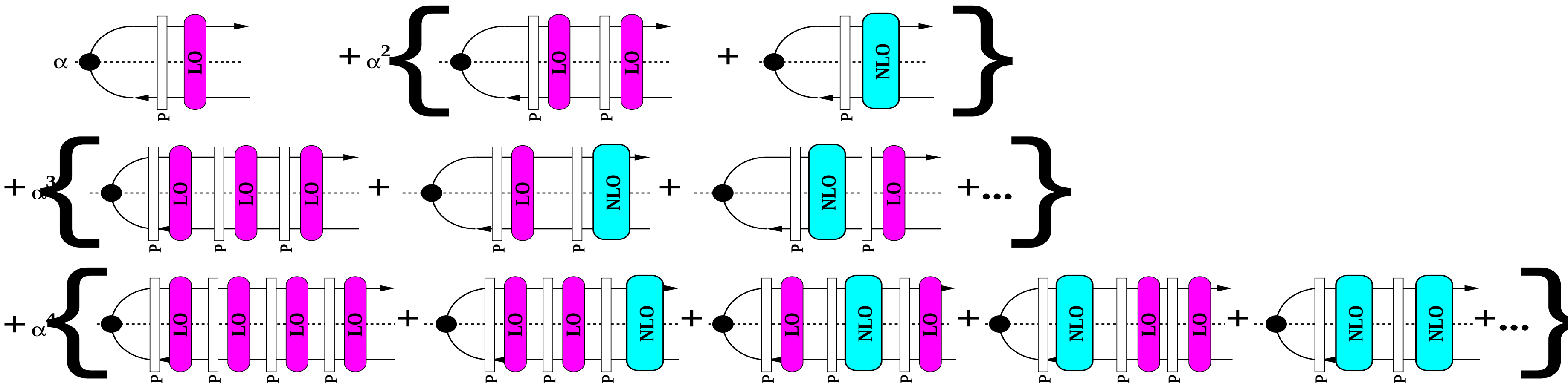




- **BLACK** Analytical formula from Curci-Furmanski-Petronzio (table 1)
- **RED** Integrated kernel in Markovian MC (iEVMC), n=1!
- **BLUE** UNINTEGRATED kernel in Markovian MC (eEVMC), n=2!

What next? NLO insertion for $n = 3, 4, ..\infty$





NLO decomposition in powers of α in factorization theorems. Example $n = 4$:

$$D_4^{L+N}(t,x) = e^{-S} \left(\prod_{i=1}^{4} \int \frac{d^3k_i}{2k_i^0} \theta_{t_{i+1}>t_i} \right) \delta_{1-x=\sum_{i=1}^{3} \alpha_i} \; \rho_4^{L+N}(k_4,k_3,k_2,k_1),$$

$$\rho_4^{L+N}(k_4,k_3,k_2,k_1) = \rho^L(k_4|x_3)\; \rho^L(k_3|x_2)\; \rho^L(k_2|x_1)\; \rho^L(k_1|x_0)$$

$$+ \rho^L(k_4|x_3)\; \rho^L(k_3|x_2)\; b_2^N(k_2,k_1|x_0) + \rho^L(k_4|x_3)\; b_2^N(k_3,k_2|x_1)\; \rho^L(k_1|x_0)$$

$$+ b_2^N(k_4,k_3|x_2)\; \rho^L(k_2|x_1)\; \rho^L(k_1|x_0)$$

$$+ b_2^N(k_4,k_3|x_2)\; b_2^N(k_2,k_1|x_0)$$

Discussion, Conclusions

- Unintegrated NLO kernel within full 2-particle LIPS in the MC can be constructed. (Dimensional regularization "removed".)
- The integrand of the NLO kernel features nice IR cancellations, such that only **short range correlation** remain for large y_i and α_i. No IR cancellations between distant regions in the LIPS!
- Re-insertion of the NLO unintegrated kernel into LO MC model representing LO+NLO (DGLAP) evolution done for $n = 2$ and is perfectly feasible for $n > 2$.
- Monte Carlo weight looks regular/positive.
- **A decisive/critical milestone towards NLO parton shower MC has been reached.**
- Once completed, will be used as a building block in MC simulating W/Z production at LHC and DIS at HERA up to complete NLO level both in parton shower and hard process.