The exclusive NLO DGLAP kernels for Non Singlet evolution

A prototype of NLO Parton Shower for the Initial-State QCD

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Can one imagine a new scheme/technique of the pQCD calculations in the Monte Carlo 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$\rightarrow$LHC,
4. better control of parton luminosity and kT, and more...

The ultimate MC ?

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

It is the MC combining both “Resummed” evolution and “Fixed-Order” perturbative Matrix Element, featuring complete NLO in both of them.

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

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

State of the art: recent partial solutions

in the right direction

- New better MC parton showers in PYTHIA and HERWIG in the improved LL approx. ISR “backward evolution"+integr.PDFs
- MC@NLO, NLO matrix element for the hard process + LL parton shower MC. By Frixione, Webber and Nason.
- Constrained MC algorithm for ISR parton shower by Krakow group. An alternative to backward evolution.
- GR@PPA Monte Carlo project (GRACE@KEK), NLL parton sh.
- 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 form 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 with 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 aim of our KRKMC project

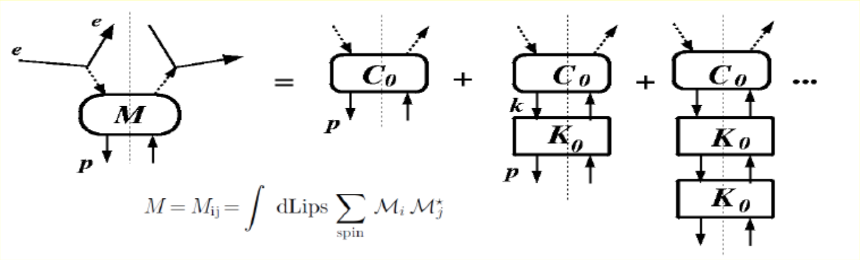
Can we construct Parton Shower Monte Carlo for QCD Initial State Radiation:

- 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); with NLO evolution done by MC itself, using EXClusive NLO kernels**???**

We are going to show that YES, we can do it**!**
And show first numerical implementation
– the proof of the concept.

EGMPR scheme of collinear factorization (1978)

"Raw" factorization of the IR collinear singularities



$$M = M_{ij} = \int \mathrm{dLips} \sum_{\mathrm{spin}} \mathcal{M}_i \mathcal{M}_j^*$$

- Cut vertex M: spin sums and Lips integrations over all lines cut across
- C_0 and K_0 and are 2-particle irreducible (2PI)
- C_0 is IR finite, while K_0 encapsulates all IR collinear singularities
- Use of the axial gauge essential for the proof
- Formal proof given in EGMPR NP B152 (1979) 285
- Notation next slide

$$M = C_0\left(1 + K_0 + K_0^2 + \cdots\right) = C_0 \frac{1}{1 - K_0} \equiv C_0 \Gamma_0$$

Factorization of EGMPR improved by Furmanski and Petronzio (80):

$$F = C_0 \cdot \frac{1}{1 - K_0} = C\left(\alpha, \frac{Q^2}{\mu^2}\right) \otimes \Gamma\left(\alpha, \frac{1}{\epsilon}\right),$$

$$= \left\{ C_0 \cdot \frac{1}{1 - (1 - \mathbf{P}) \cdot K_0} \right\} \otimes \left\{ \frac{1}{1 - \left(\mathbf{P}K_0 \cdot \frac{1}{1-(1-\mathbf{P})\cdot K_0}\right)} \right\}_{\otimes},$$

$$\Gamma\left(\alpha, \frac{1}{\epsilon}\right) \equiv \left(\frac{1}{1 - K}\right)_{\otimes} = 1 + K + K \otimes K + K \otimes K \otimes K + ...,$$

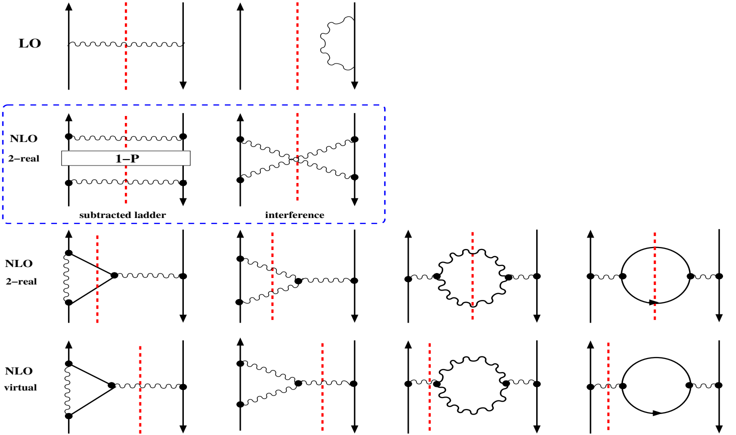
$$K = \mathbf{P}K_0 \cdot \frac{1}{1 - (1 - \mathbf{P}) \cdot K_0}, \quad C = C_0 \cdot \frac{1}{1 - (1 - \mathbf{P}) \cdot K_0}.$$

Ladder part Γ corresponds to MC parton shower
C is the hard process part

$\mathbf{P}$ is the projection operator: $\mathbf{P} = P_{spin}\, P_{kin}\, PP$

The KRKMC project

Step 1. Re-do the CFP calculation of the NLO kernels in the exclusive way, for various types of evolution time (virtuality, $k_\perp$, rapidity ...). Use $\overline{MS}$. For now only the C_F^2 part - blue frame



Step 2. Get rid of dimensional regularisation, go back to 4-dimensions. Include cut-off Δ instead

$$\frac{1}{\epsilon} \to \int_0^{Q^2} d\left(\frac{q^2}{Q^2}\right)\left(\frac{Q^2}{q^2}\right)^{1-\epsilon} \to \int_{\Delta^2}^{Q^2} d\left(\frac{q^2}{Q^2}\right)\frac{Q^2}{q^2}$$

Calculate appropriate Sudakov form-factor to keep the momentum sum rule !

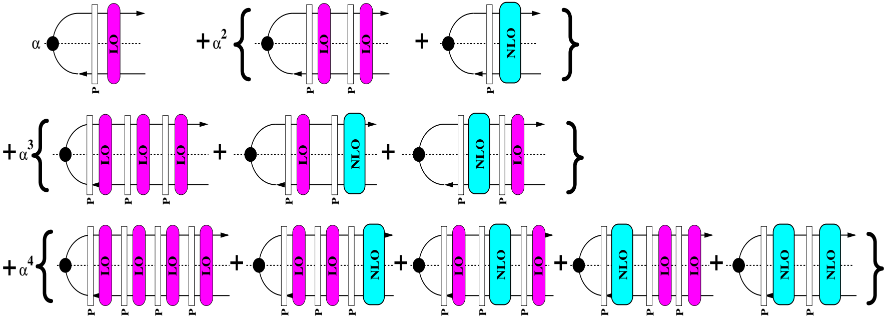
In full agreement with the $\overline{MS}$ scheme.

Step 3. Re-formulate the factorization formula:

⇒ DGLAP mixes orders of pert. expansion:

$$P = \alpha P^{LO} + \alpha^2 P^{NLO}$$

⇒we want order-by-order expansion (e.g. to avoid negative weights)



Step 4. Do the explicit Bose-Einstein symmetrisation:
⇒ In inclusive DGLAP one uses ordering: $|k_n| > |k_{n-1}| > \cdots > |k_0|$
⇒ In exclusive MC Bose-Einstein symmetric form is better because NLO contribution allows both $|k_i| > |k_{i-1}|$ and $|k_{i-1}| > |k_i|$

$$D_3^{L+N}(t,x) \sim \frac{1}{3!} \int_{k_{\min}}^{k_{\max}} \left(\prod_{i=1}^{3} \frac{d^3 k_i}{2k_i^0} \right) \delta_{x_0 - x = \alpha_1 + \alpha_2 + \alpha_3} \rho_3^{L+N}(k_3, k_2, k_1),$$

$$\rho_3^{L+N}(k_3,k_2,k_1) = \sum_{\pi} \left(\rho_3^L(k_{\pi_3}, k_{\pi_2}, k_{\pi_1}) + \rho_{3a}^N(k_{\pi_3}, k_{\pi_2}, k_{\pi_1}) + \rho_{3b}^N(k_{\pi_3}, k_{\pi_2}, k_{\pi_1}) \right),$$

$$\rho_3^L(k_3,k_2,k_1) = \rho^L(k_3|x_2)\, \rho^L(k_2|x_1)\, \rho^L(k_1|x_0)\, \theta_{|\mathbf{k}_3|>|\mathbf{k}_2|>|\mathbf{k}_1|},$$

$$\rho_{3a}^N(k_3,k_2,k_1) = \rho^L(k_3|x_2)\, b_2^{\theta N}(k_2,k_1|x_0)\, \theta_{|\mathbf{k}_3|>|\mathbf{k}_2|},$$

$$\rho_{3b}^N(k_3,k_2,k_1) = b_2^{\theta N}(k_3,k_2|x_1)\, \rho^L(k_1|x_0)\, \theta_{|\mathbf{k}_3|>|\mathbf{k}_1|}.$$

Step 5. Construct the NLO weight to be applied on top of the regular LO MC (Markovian or Constrained Markovian). For 3 emissions:

$$w = 1 + w^N_{3a} + w^N_{3b}$$

$$w^N_{3a} = \frac{b_2^{\theta N}(\tilde{k}_2, \tilde{k}_1|x_0)}{\rho^L(\tilde{k}_2|x_1)\; \rho^L(\tilde{k}_1|x_0)} \theta_{\tilde{t}_2 > t_M},$$

$$w^N_{3b} = \frac{b_2^{\theta N}(\tilde{k}_3, \tilde{k}_2|x_1)}{\rho^L(\tilde{k}_3|x_2)\; \rho^L(\tilde{k}_2|x_1)} \theta_{\tilde{t}_3 > t_M} + \frac{b_2^{\theta N}(\tilde{k}_3, \tilde{k}_1|x_1^{\pi^\bullet_b})}{\rho^L(\tilde{k}_3|x_2)\; \rho^L(\tilde{k}_1|x_0)} \; \frac{\rho^L(\tilde{k}_2|x_0)}{\rho^L(\tilde{k}_2|x_1)} \theta_{\tilde{t}_3 > t_M}.$$

Step 6. Solve problem of “lower limit of internal NLO phase space”. NLO kernels contain “internal emission”:

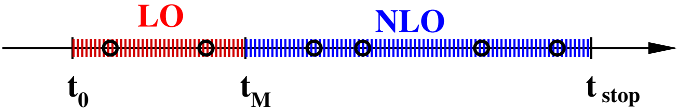
$$\text{Inclusive NLO: } \int_0^{Q^2} dq^2_{\rm internal} \quad \Leftrightarrow \quad \text{Exclusive MC: } \int_{Q^2_{\rm min}}^{Q^2} dq^2_{\rm internal}$$

Two solutions:

⇒ Difference has to be calculated analytically

⇒ Use “pre-evolution” of pure LO type with VERY low t_0.

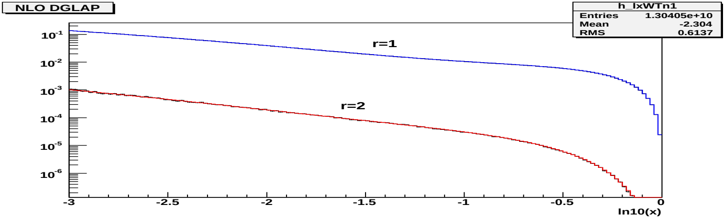
NLO corrections start at intermediate $t = t_M$.

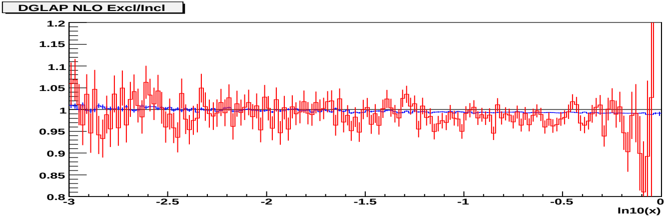


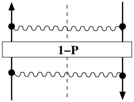
RESULTS

Exclusive NLO MC agrees with $\overline{MS}$ NLO DGLAP

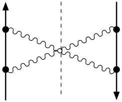
Comparison of new Exclusive NLO MC with $\overline{MS}$ NLO DGLAP







subtracted ladder



interference

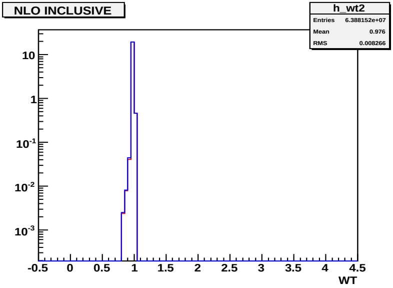
Both results agree!!

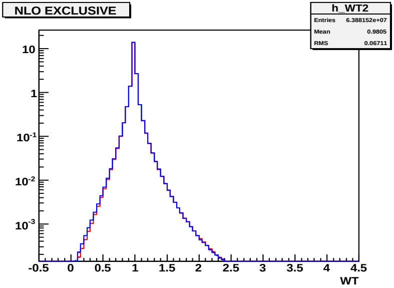
MC with Exclusive NLO kernels compared with standard DGLAP

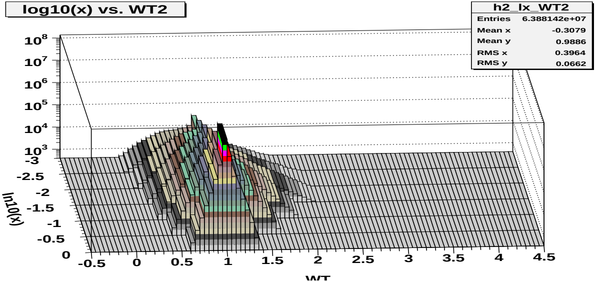
More on what is in these plots:

- Both evolutions on top of the same Markovian LO MC. (It can be put easily on top of non-Markovian CMC.)
- MC weights positive, weight distributions very reasonable, see next slide.
- Evolution range from 10GeV to 1TeV.
- LO pre-evolution staring from $\delta(1-x)$ at 1GeV to 10GeV provides initial x-distribution for the LO+NLO continuation.
- Only C_F^2 part of gluonstrahlung.
- Non-ruining α_S.
- Term due to ε part of γ-traces omitted. done.
- NLO virtual corrections omitted. partly done.

Excellent weight distribution!







Potential gains

While retaining exact NLO DGLAP evolution, excellent starting point for extensions:

- Possible extension towards CCFM, BFKL (low x limit)
- Correct soft limit and built-in colour coherence
- More realistic description of the quark thresholds
- The use of exact amplitudes for multigluon emission, the analog of Coherent Exclusive Exponentiation in QED (Jadach,Was,Ward)
- Better connection between hard process ME and the shower parts, as compared to MC@NLO and the likes
- In particular no negative weight events, no ambiguity of defining last emission before hard process, etc.
- Providing better tool for exploiting HERA DATA for LHC (fitting F_2 directly with MC)
- And more!!!

Summary and Prospects

- First serious feasibility study of the true NLO exclusive MC parton shower is under construction, well advanced...
- What next? Workplan well defined:
- Short range aim: Complete non-singlet.
- Middle range aim: Complete singlet.
- Speed up the MC weight calculation.
- Better documentation needed on what was done.
- NLO MC for W/Z production for LHC, including SANC electroweak library.
- NLO MC for DIS@HERA and an example of BSM processes at LHC