

NLO corrections in the initial state parton shower Monte Carlo

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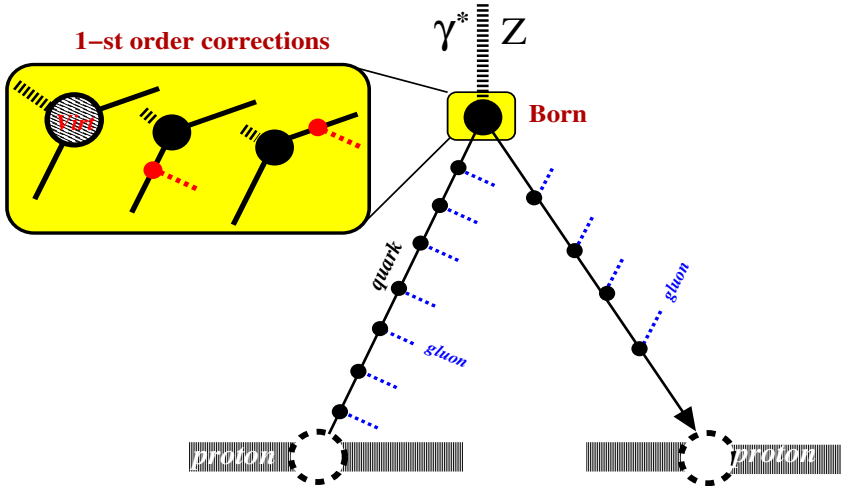
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- ▶ NLO corrections to hard process
(an alternative to MCatNLO and/or POWHEG)
- ▶ NLO corrections in the ladder
(for NLO parton shower MC + NNLO hard process)

NLO correcting HARD process



The essence of our NLO methodology:



$$\sum_{m=0}^{\infty} \left\{ \left| \begin{array}{c} \vdots \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \vdots \end{array} \right|^2 + \sum_{j=1}^{n-1} \left| \begin{array}{c} \vdots \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \vdots \end{array} \right|^2 + \sum_{r=1}^m \left| \begin{array}{c} \vdots \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \vdots \end{array} \right|^2 \right\}$$

The diagram shows a series of Feynman diagrams for a process with \$n\$ external lines. The first term is a sum over \$m\$ real emissions, represented by a vertical chain of vertices with \$m\$ horizontal lines extending to the right. The second term is a sum over \$j\$ virtual corrections, represented by a vertical chain of vertices with \$j\$ horizontal lines extending to the right and a loop structure. The third term is a sum over \$r\$ real emissions, represented by a vertical chain of vertices with \$r\$ horizontal lines extending to the right. The diagrams are grouped by large curly braces.

NLO real/virtual distributions (subtracted) from Feynman diags

$$\left| \begin{array}{c} \vdots \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \vdots \end{array} \right|^2 = \left| \begin{array}{c} \vdots \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \vdots \end{array} \right|^2 + \left| \begin{array}{c} \vdots \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \vdots \end{array} \right|^2 - \left| \begin{array}{c} \vdots \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \vdots \end{array} \right|^2 - \left| \begin{array}{c} \vdots \\ \text{---} \\ \text{---} \\ \text{---} \\ \text{---} \\ \vdots \end{array} \right|^2$$

The diagram shows the subtraction of NLO real/virtual distributions from Feynman diagrams. The left side is a square of a Feynman diagram with a red square vertex and a red dashed line labeled \$g\$. The right side is a sum of four Feynman diagrams: a tree-level diagram with a black circle vertex and a red dashed line labeled \$g\$; a diagram with a black circle vertex and a red dashed line labeled \$g\$ and a red dot; a diagram with a black circle vertex and a red dashed line labeled \$g\$ and a red dot; and a diagram with a black circle vertex and a red dashed line labeled \$g\$ and a red dot.

free of any double/single collinear/soft singularities.

MC weight with NLO corrs. to DY hard proc.

NLO correction introduced using simple **positive MC weight**:

$$W_{MC}^{NLO} = 1 + \Delta_{S+V} + \sum_{j \in F} \frac{\tilde{\beta}_1(\hat{s}, \hat{p}_F, \hat{p}_B; a_j, z_{Fj})}{\bar{P}(z_{Fj})} \frac{d\sigma_B(\hat{s}, \hat{\theta})}{d\Omega} + \sum_{j \in B} \frac{\tilde{\beta}_1(\hat{s}, \hat{p}_F, \hat{p}_B; a_j, z_{Bj})}{\bar{P}(z_{Bj})} \frac{d\sigma_B(\hat{s}, \hat{\theta})}{d\Omega},$$

$\bar{P}(z) \equiv \frac{1+z^2}{2}$. The **IR/Col.-finite real** emission part is

$$\begin{aligned} \tilde{\beta}_1(\hat{p}_F, \hat{p}_B; q_1, q_2, k) = & \left[\frac{(1-\alpha)^2}{2} \frac{d\sigma_B}{d\Omega_q}(\hat{s}, \theta_{F1}) + \frac{(1-\beta)^2}{2} \frac{d\sigma_B}{d\Omega_q}(\hat{s}, \theta_{B2}) \right] \\ & - \theta_{\alpha > \beta} \frac{1 + (1-\alpha-\beta)^2}{2} \frac{d\sigma_B}{d\Omega_q}(\hat{s}, \hat{\theta}) - \theta_{\alpha < \beta} \frac{1 + (1-\alpha-\beta)^2}{2} \frac{d\sigma_B}{d\Omega_q}(\hat{s}, \hat{\theta}), \end{aligned}$$

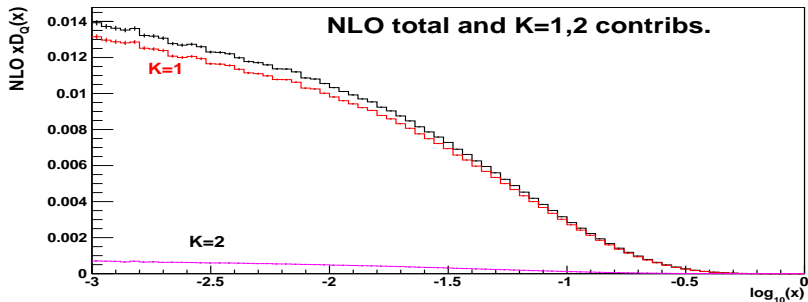
the **kinematics independent virtual+soft** correction is

$$\Delta_{V+S} = \frac{C_F \alpha_s}{\pi} \left(\frac{1}{3} \pi^2 - 4 \right) + \frac{C_F \alpha_s}{\pi} \frac{1}{2}$$

Terms like $\left(\frac{f(z)}{1-z} \right)_+$ in virt. corrs completely **absent!**

Thanks to transforming MS-bar PDFs to MC Fact scheme,
(see also Martin+Ryskin 2013)

Only one single term dominates sum in W_{MC}^{NLO}



The (-)NLO contributions from $K = 1, 2$ single gluons, the one with maximum and another one with next-to-max. k_T , in the x -distribution of quark entering W boson.

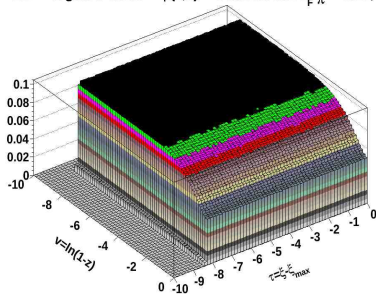
POWHEG exploits the above. We do it differently, without vetoed/truncated gluons, see next slides...

Location and size of the (real) NLO correction on the Sudakov plane (rapidity, $\ln(1-z)$)



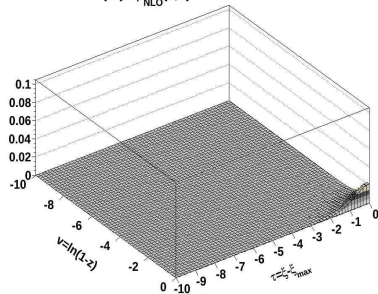
LO inclusive

LO 1-gluon distr. $\rho(\tau, v)$ Plateau at $2C_F \frac{\alpha}{\pi} = 0.10$;



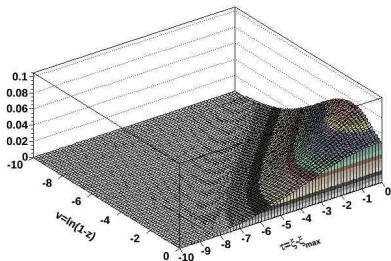
pure NLO

$(-1) \Delta \rho_{\text{NLO}}(\tau, v)$

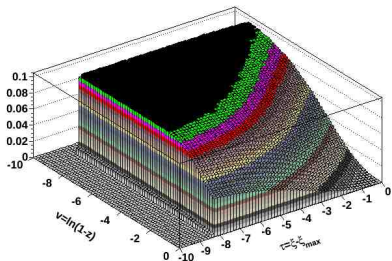


Gluons generated in angular ordering and re-ordered in kT

LO gluon $K=1$



LO gluon $K>1$



Sudakov suppression for the highest kT gluon ($K=1$)!

Our NLO weight with summation is ignorant about the above kT (re-)ordering.

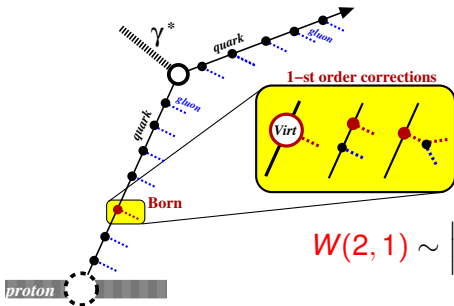
The summation (or max. kT-selection) takes care of picking up correctly the hardest gluon, for NLO-completeness.

No need of truncated/vetoed gluon showers.



Exclusive NLO-corrections to the middle-of-the-ladder kernels for NLO Monte Carlo parton shower

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

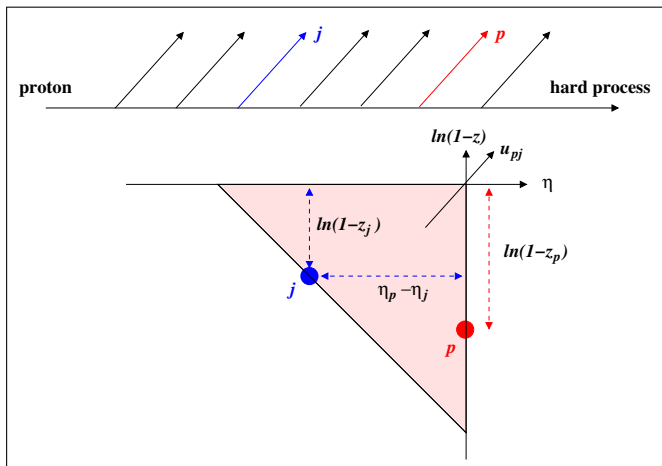


$$W(2,1) \sim \left| \begin{array}{c} 2 \\ | \\ j \end{array} \right|^2 = \left| \begin{array}{c} 2 \\ | \\ j \end{array} \right|^2 + \left| \begin{array}{c} 2 \\ | \\ j \end{array} \right|^2 - \left| \begin{array}{c} 2 \\ | \\ j \end{array} \right|^2$$

$$\bar{D}_B^{[1]}(x, Q) = e^{-S_{ISR}} \sum_{n=0}^{\infty} \left\{ \begin{array}{c} x \\ | \\ n \\ | \\ n-1 \\ | \\ \vdots \\ | \\ 2 \\ | \\ 1 \end{array} \right|^2 + \sum_{p=1}^n \begin{array}{c} | \\ | \\ n \\ | \\ n-1 \\ | \\ \vdots \\ | \\ p \\ | \\ \vdots \\ | \\ 2 \\ | \\ 1 \end{array} + \sum_{p=1}^n \sum_{j=1}^{p-1} \begin{array}{c} | \\ | \\ n \\ | \\ p \\ | \\ \vdots \\ | \\ j \\ | \\ \vdots \\ | \\ 1 \end{array} \right\} = e^{-S_{ISR}} \left\{ \delta_{x=1} + \right.$$

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

Define variable u_{pj} for “u-ordering” in the middle of the ladder

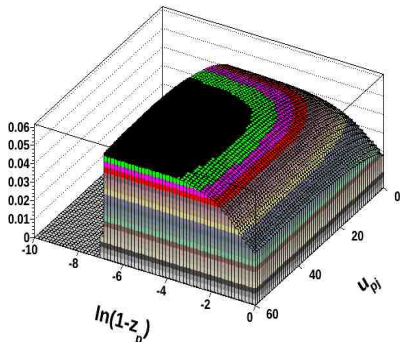


$$u_{pj} = |\eta_p - \eta_j| + \lambda \ln(1 - z_j), \quad \lambda \sim 1 - 2.$$

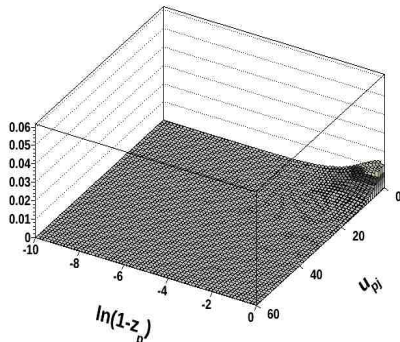
Variable η is rapidity, z is conventional lightcone variable.

Location and size of the (real) NLO correction in the ladder on the Sudakov log space

LO, all spect. gluons



pure NLO, all spect. gluons



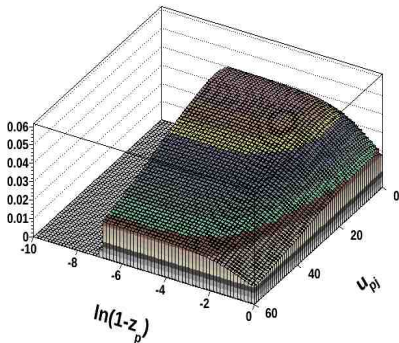
LO inclusive distribution features triple-log IR/coll. singularity, seen as a plateau in 2-dim. projection.

NLO correction IR/coll. finite, nonzero in the corner of the size ~ 1 .

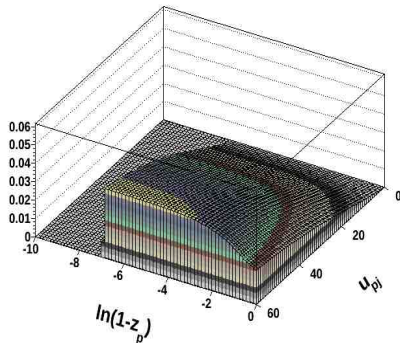
Split of inclusive LO distribution of gluons into contr. from the u-hardest one and the rest



LO, hardest spect. gluon $K=1$



LO, spect. gluons $K>1$



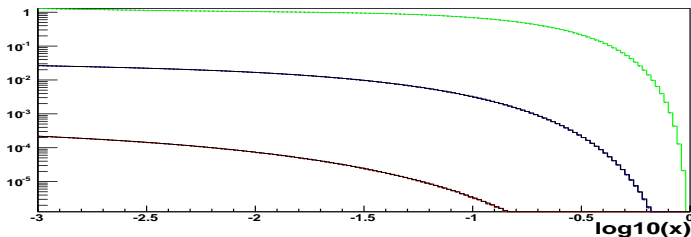
Distribution of the hardest (in u_{p_j}) LO spectator gluon approximates well the total distribution in small corner where NLO is non-zero.



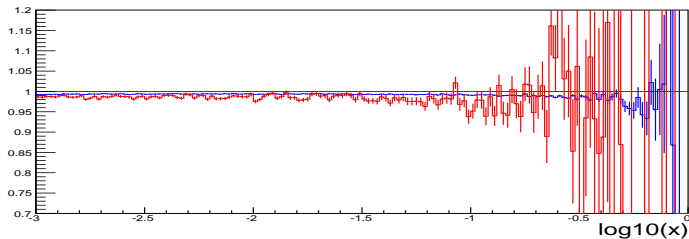
Repetition of test for NLO-corrected ladder

OLD: NLO MC vs. analyt. NLO kernels. Perfect agreement

LO+NLO (green), NLO for 1 (blue) and 2 (red) insertions



Ratios: (1 or 2 insertions)/exact

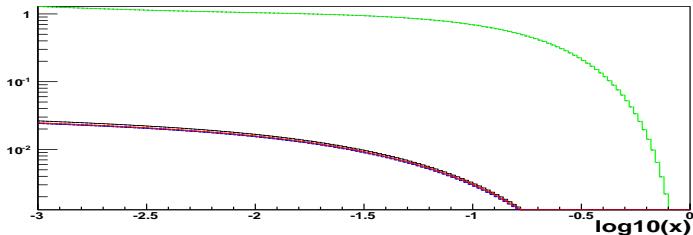


Single ladder, 1GeV-1TeV, 1 or 2 kernels NLO-corrected. (Slow in CPU time).

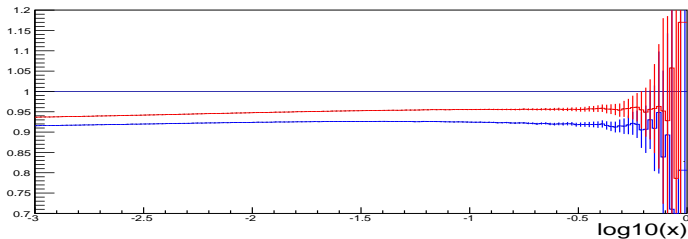
Repetition of test for NLO-corrected ladder

NEW: NLO contrib. to 1 kernel, 1 and 2 gluons with max. kT

LO+NLO (green), one insertions from 1 (blue) or 2 (red) hardest gluons



Ratios: (1 or 2 hardest gluons)/exact



This difference $\sim 15\%$ is formally the NNLO/NLO class. (Faster in CPU time).



- ▶ **An alternative (to MC@NLO or POWHEG) scenario for NLO-corrected hard proc. and LO PSMC is proposed.**
- ▶ **Parton shower MC implementing complete NLO DGLAP in the ladders in exclusive way is feasible.**
- ▶ Long term: NLO ladder + NNLO hard process, (but LO ladder + NLO hard proc. to be optimized first!)
- ▶ Most likely application: high quality QCD+EW+QED MC with hard process like $W/Z/H$ boson production.
- ▶ Potential gains from new QCD methods are:
 - reducing uncertainties due to PDFs
 - easier implementation of NLO and NNLO corrections to hard process.
Due to better treatment of “trivial” (albeit numerically sizeable) soft gluon corrections,
 - better environment for low x resumm. (BFKL, CCFM),
 - and more...