Improved theoretical description of Mueller-Navelet jets at LHC

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LOW X MEETING

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Motivations and Outline

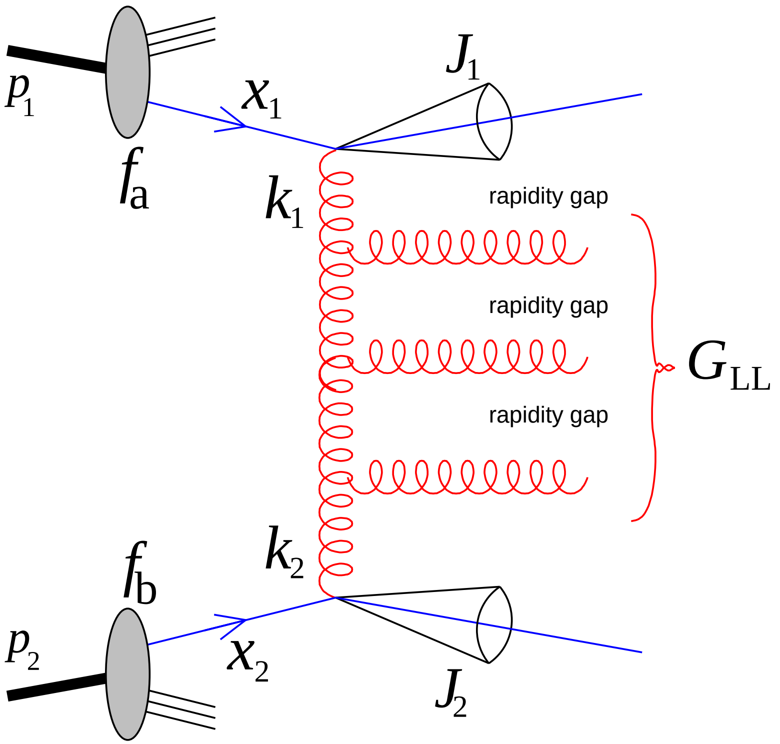
- Motivations
  - One of the important longstanding theoretical questions: the behaviour of QCD in the high-energy (Regge) limit $s \gg -t$
  - We expect a new kind of dynamics (BFKL dynamics)
    - beyond fixed order perturbative predictions
    - amplitudes with power-like behaviour s^ω
  - For (semi-)hard processes $s \gg -t \gg \Lambda^2_{\mathrm{QCD}}$
    P.Th still applicable with all-order resummation of $(\alpha_{\mathrm{s}} \log s)^n$
- Outline
  - Process suited for study of high energy QCD: Mueller-Navelet dijets
  - Review the theoretical description of MN jets within the BFKL approach
  - CMS analysis (2012) $\rightarrow$ comparison with BFKL and with MonteCarlo
  - Unsatisfactory descriptions $\rightsquigarrow$ ask for improvements
    - jet identification consistent with exp. analysis
    - matching BFKL with fixed NLO: method and preliminary results

MN Jets in LL approximation

MN jet factorization formula is a convolution of 5 objects

Starting from LL factorization formula $[J \equiv (y, p_T, \phi)]$

$$\frac{\mathrm{d}\sigma(s)}{\mathrm{d}J_1 \mathrm{d}J_2} = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}\boldsymbol{k}_1 \mathrm{d}\boldsymbol{k}_2$$
$$\times\ f_a(x_1)$$
$$\times\ V_a^{(0)}(x_1, \boldsymbol{k}_1; J_1)$$
$$\times\ G_{\mathrm{LL}}(x_1 x_2 s, \boldsymbol{k}_1, \boldsymbol{k}_2)$$
$$\times\ V_b^{(0)}(x_2, \boldsymbol{k}_2; J_2)$$
$$\times\ f_b(x_2)$$



where $\frac{\partial}{\partial \log s} G(s, \boldsymbol{k}_1, \boldsymbol{k}_2) = \int \mathrm{d}\boldsymbol{k}\ K(\boldsymbol{k}_1, \boldsymbol{k}) G(s, \boldsymbol{k}, \boldsymbol{k}_2)$, $\qquad K = \alpha_{\mathrm{s}} K_0$

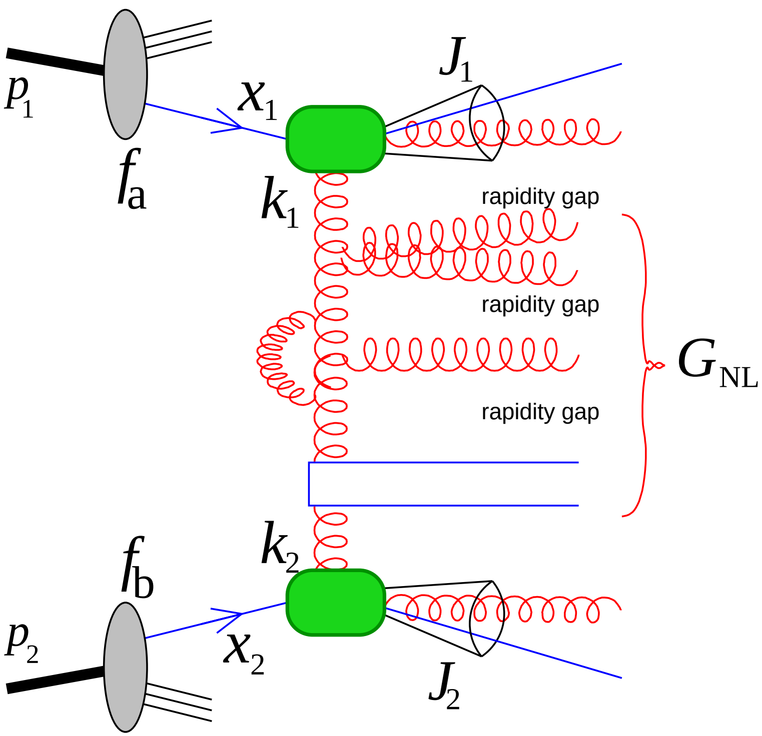
- Kinematics characterized by large rapidity gaps among particles
- At LL level the jet vertex condition is trivial (only 1 parton)

MN Jets in NLL approximation

[Bartels, DC, Vacca '02] computed NLL calculations of impact factors for Mueller-Navelet jets

Proved NLL factorization formula $[J \equiv (y, p_T, \phi)]$

$$\frac{\mathrm{d}\sigma(s)}{\mathrm{d}J_1 \mathrm{d}J_2} = \sum_{a,b} \int_0^1 \mathrm{d}x_1 \mathrm{d}x_2 \int \mathrm{d}\boldsymbol{k}_1 \mathrm{d}\boldsymbol{k}_2$$
$$\times\ f_a(x_1)$$
$$\times\ \boldsymbol{V_a^{(1)}}(x_1, \boldsymbol{k}_1; J_1)$$
$$\times\ G_{\mathrm{NL}}(x_1 x_2 s, \boldsymbol{k}_1, \boldsymbol{k}_2)$$
$$\times\ \boldsymbol{V_b^{(1)}}(x_2, \boldsymbol{k}_2; J_2)$$
$$\times\ f_b(x_2)$$



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- Pairs of particles can be emitted without rapidity gaps
- At NL level the jet vertex condition is non-trivial (e.g. depends on jet radius R and algorithm)

With LHC we can test these ideas!

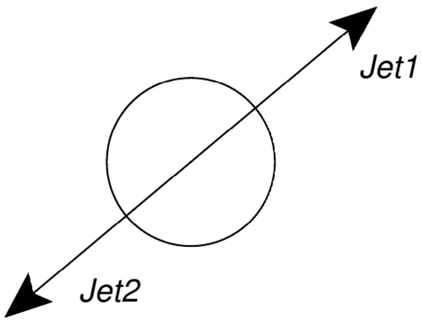
- First NLL analysis for 14 TeV *[DC,Schwensenn,Szymanowski,Wallon '10]* showed sizeable corrections from both GGF and Jet vertices
- NLL prediction definitely different from MC ones
- Mueller-Navelet jets looked promising for finding signals of BFKL dynamics

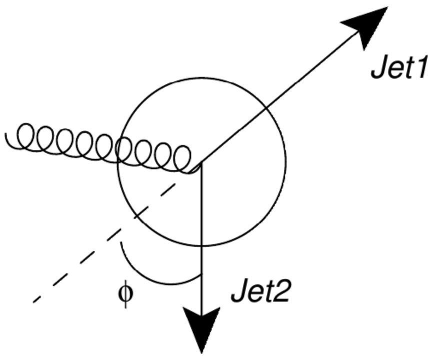
CMS analysis of MN jets at 7 TeV

Analysis of the azimuthal decorrelation of the two jets *[CMS: FSQ-12-002-pas]*

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\phi} \qquad \Big\| \qquad \langle\cos(m\phi)\rangle = \frac{C_m(Y)}{C_0(Y)} \equiv \frac{\int \mathrm{d}\phi\, \frac{\mathrm{d}^2\sigma}{\mathrm{d}\phi\mathrm{d}Y}\cos(m\phi)}{\mathrm{d}\sigma/\mathrm{d}Y}$$

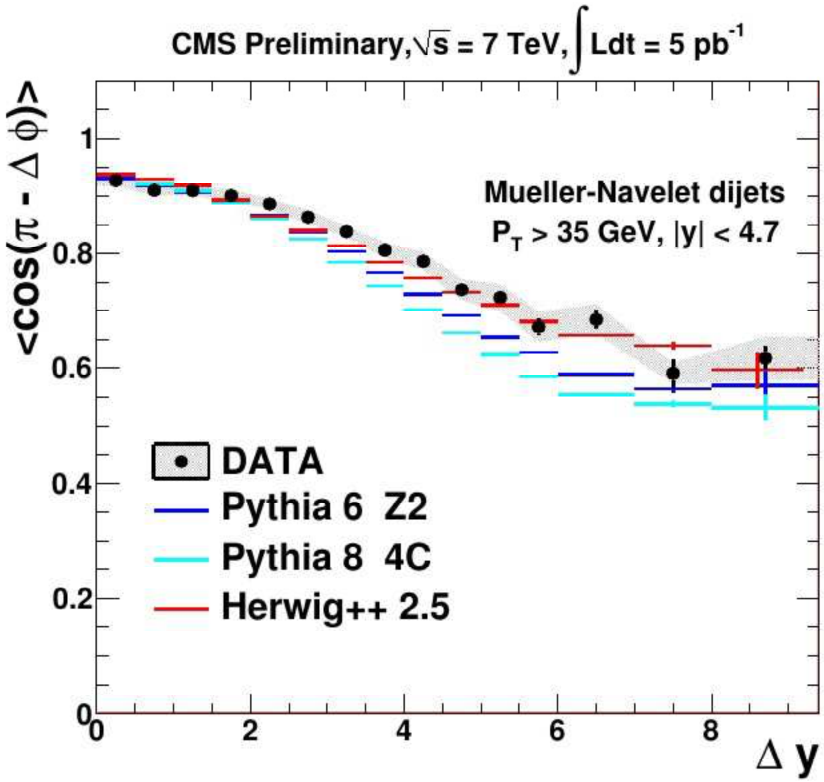
- Distinguishes BFKL dynamics from fixed order one: they provide different amount of particle emissions between jets, which is responsible for their decorrelation
- $\langle\cos(m\phi)\rangle$ has reduced theoretical scale uncertainties being a ratio of differential cross sections

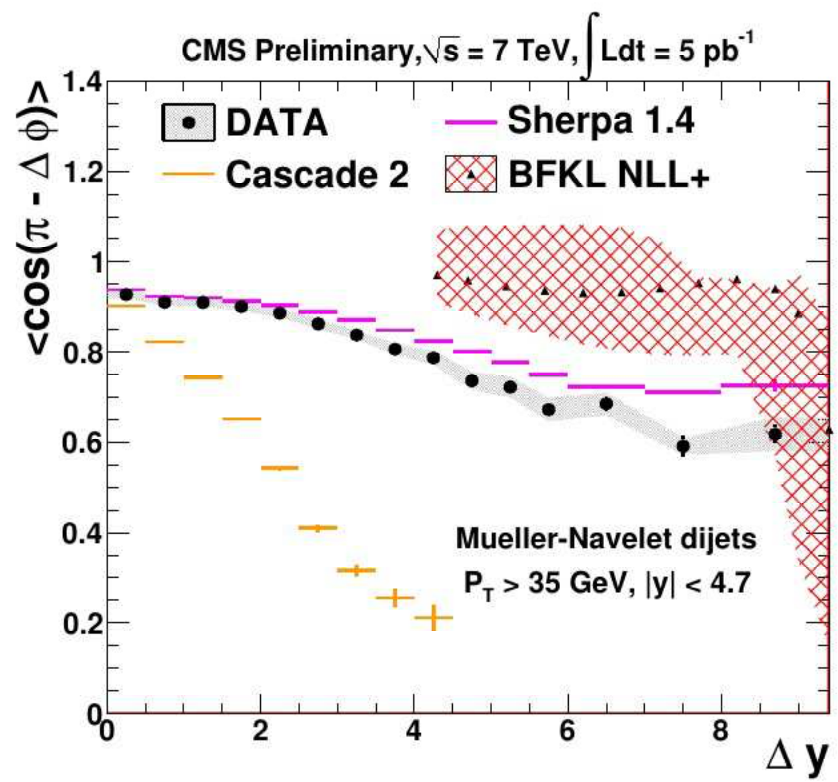




CMS analysis of MN jets at 7 TeV

Data: $p_{T1,2} > 35\text{GeV}$, $|y_i| < 4.7$ $\Delta y \equiv Y \equiv |y_1 - y_2| < 9.4$ $m = 1$





The larger Y, the more radiation and decorrelation

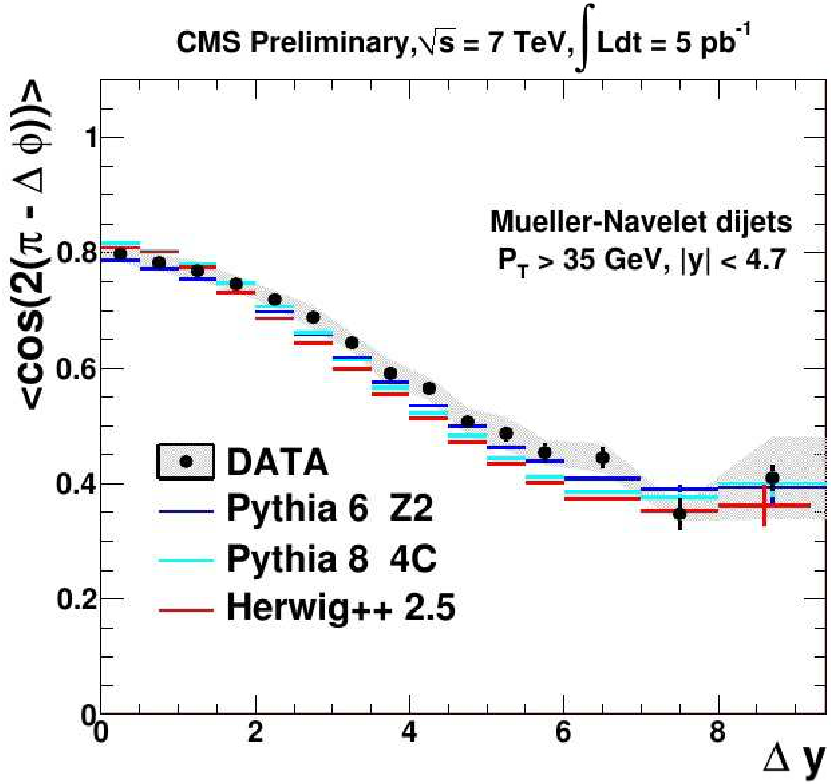
BFKL was expected to predict more radiation than fixed order $\Rightarrow$ more decorrelation

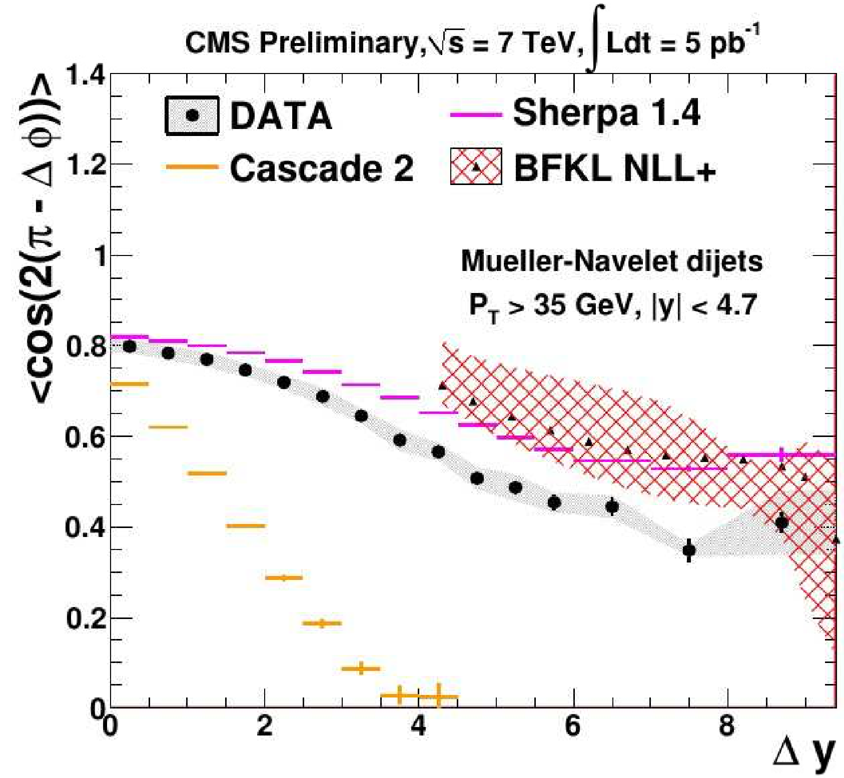
Some MC agree with data

NLL BFKL estimate has problems $\langle\cos\phi\rangle > 1$ for $\mu_R = \mu_F = p_T/2$

CMS analysis of MN jets at 7 TeV

Data: $p_{T1,2} > 35\text{GeV}$, $|y_i| < 4.7$ $\Delta y \equiv Y \equiv |y_1 - y_2| < 9.4$ $m = 2$





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NLL BFKL still unable to reproduce data

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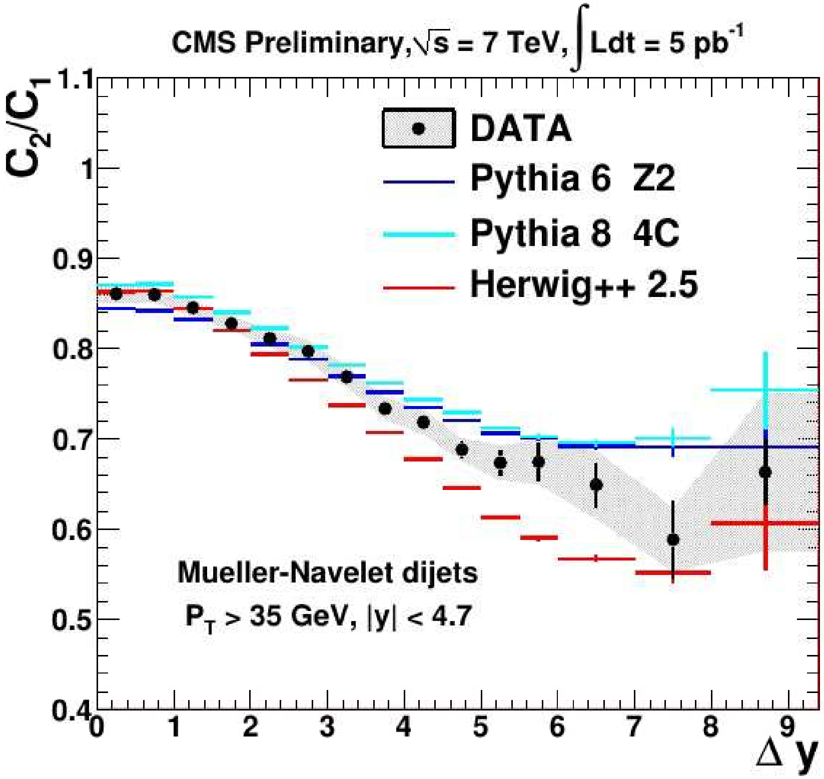

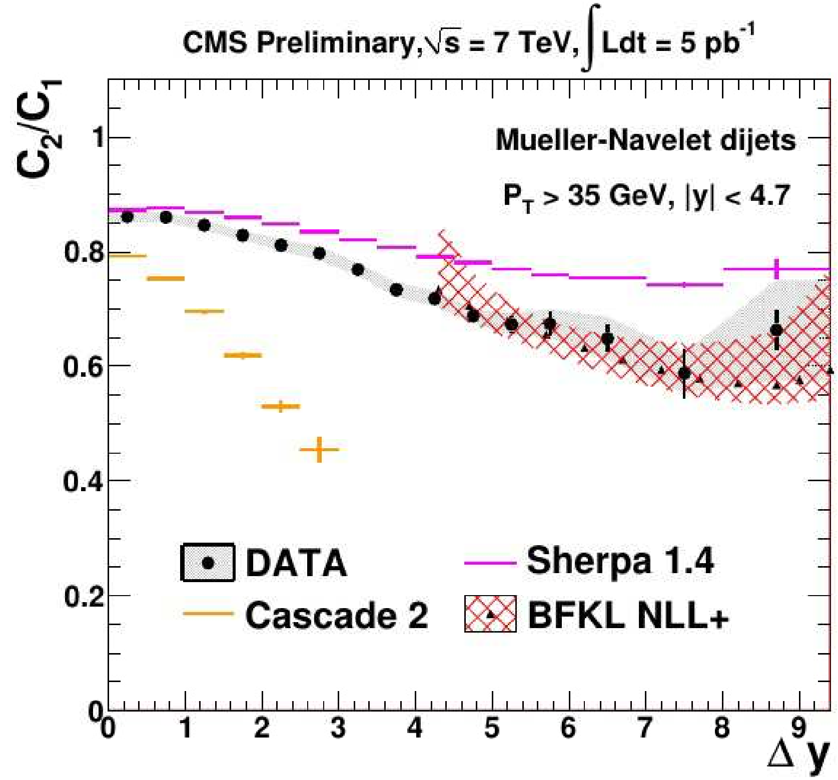

Ratio $\frac{C_2}{C_1} = \frac{\langle \cos(2\phi) \rangle}{\langle \cos \phi \rangle}$

MCs don't agree well with data

NLL BFKL in perfect agreement with data

- Neither BFKL NLL nor fixed order MC give a satisfactory description of data yet

- BFKL NLL suffers from large scale uncertainties $\sim 10 \div 15\%$

BFKL improvements

- *[Ducloué,Szymanowski,Wallon '13]*

  proposed to tame large scale dependence of BFKL

  by fixing μ_R with BLM procedure

- *[Ducloué,Szymanowski,Wallon '14]*

  try to take into account energy-momentum conservation

  by using an effective rapidity $Y_{\rm eff}$, as suggested by *[Del Duca, Schmidt]*

- *[Caporale, Ivanov, Murdaca, Papa '14]*

  consider various representations of the NLL cross section

  by fixing energy scales with PMS, FAC, BLM

Underlying idea: to effectively include higher-orders

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- Why not to include known NLO (+NNLO) calculations?

On the definition of MN Jets

Mismatch between

- theoretical MN jet definition at NLO of *[Bartels, DC, Vacca '02]* (checked by *[Caporale, Ivanov et al '11]*)
- event selection of experimental CMS analysis

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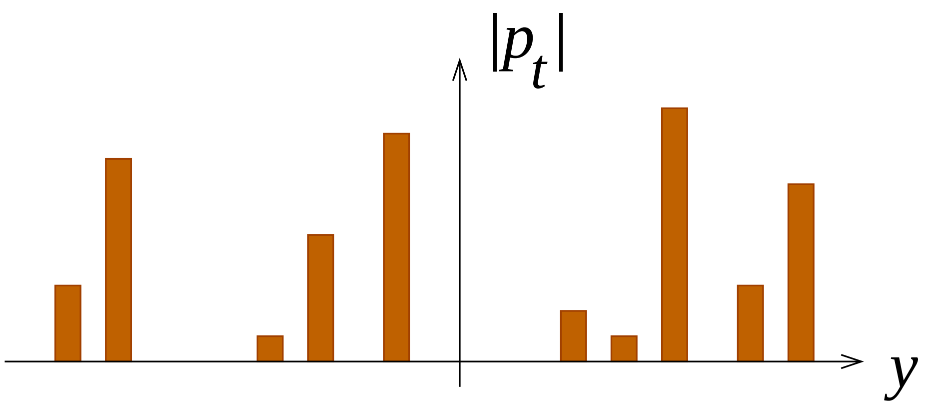

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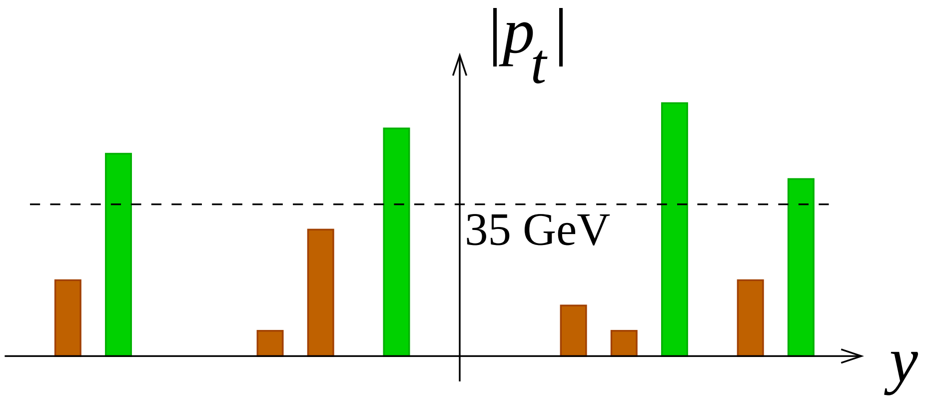

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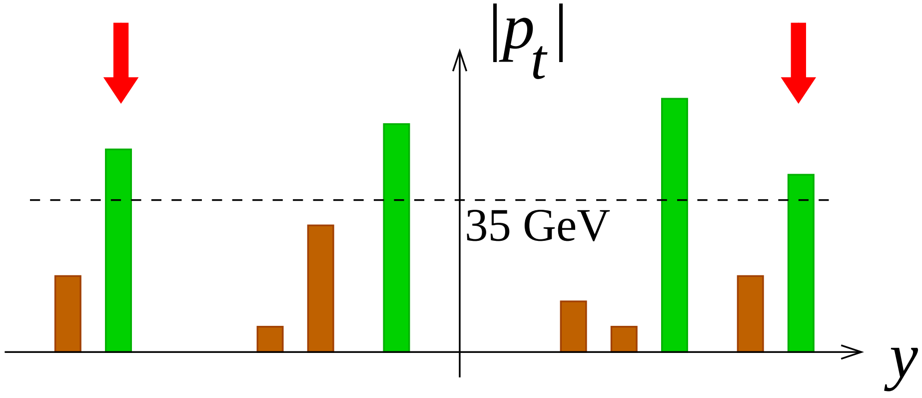
Experimental analysis:

- Cluster particles into jets
- Consider jets with $p_t > 35\text{GeV}$
- Tag jets with largest rapidity difference (MN jets)

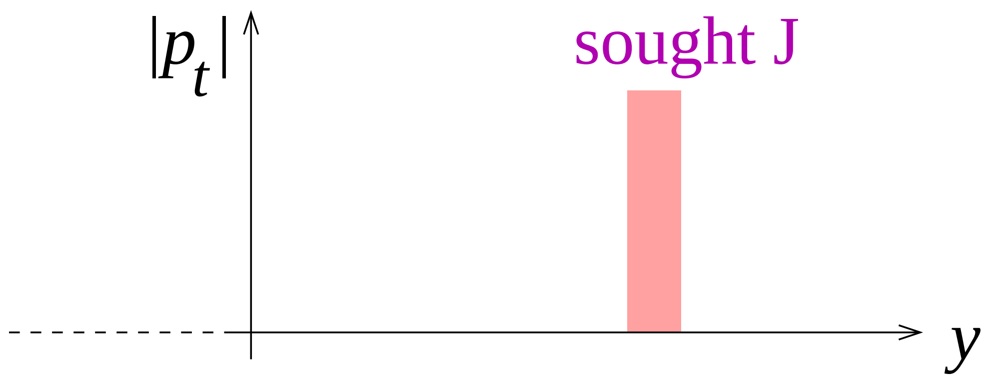


On the definition of MN Jets

Theoretical prescription

A different definition of jet vertices was adopted in NL BFKL approximation

$$\frac{\mathrm{d}\sigma}{\mathrm{d}J_1\mathrm{d}J_2} = f_b \otimes V_b \otimes G \otimes \left(V_a^{(0)} + \alpha_\mathrm{s} V_a^{(1)}\right) \otimes \left(f_a^{(0)} + \frac{\alpha_\mathrm{s}}{\varepsilon} f_a^{(1)}\right)$$



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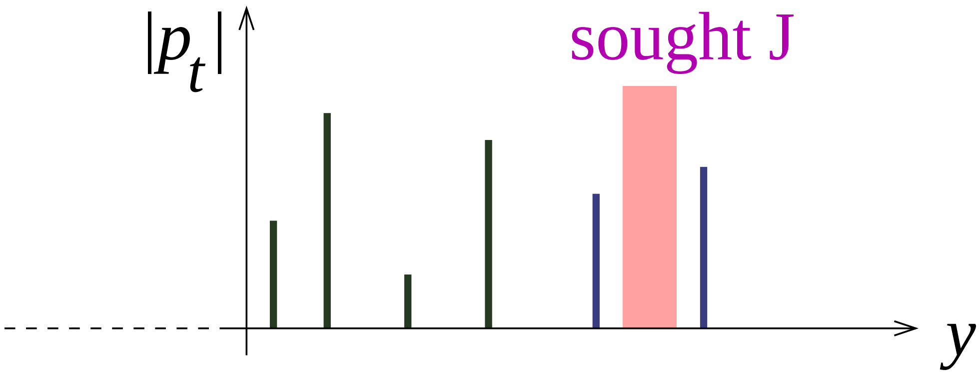

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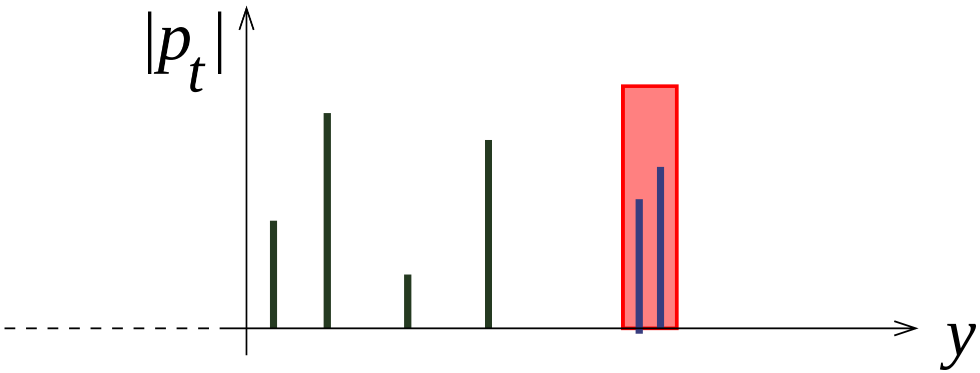

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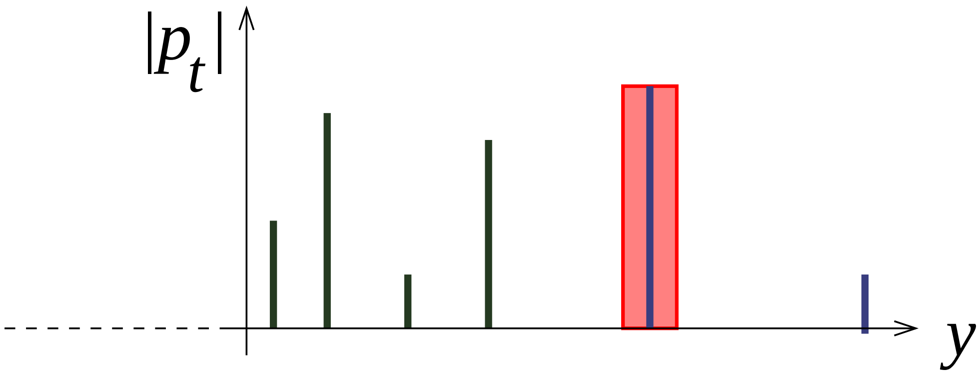

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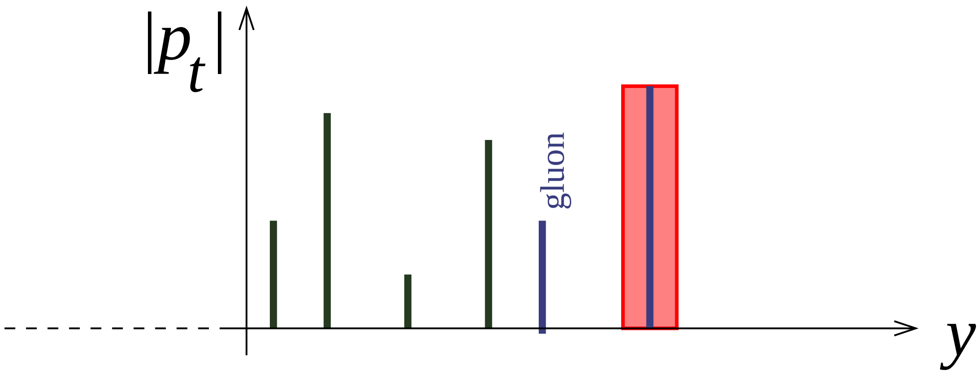

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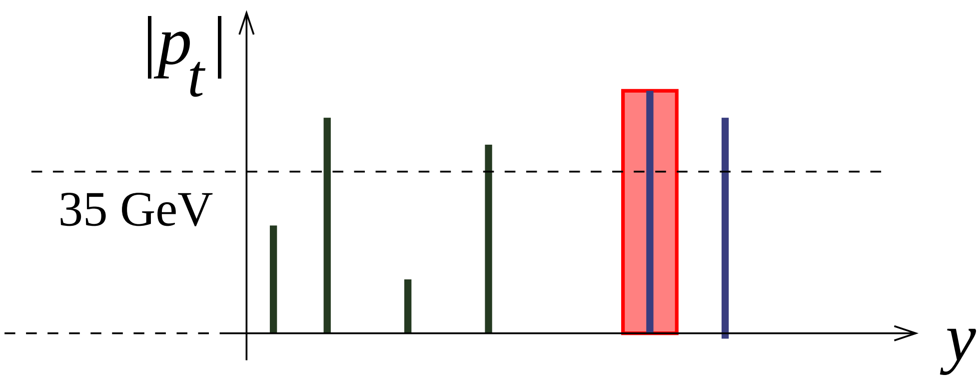


A hard parton ($\to$ jet at hadron level)
can be emitted at rapidity $y > y_J$

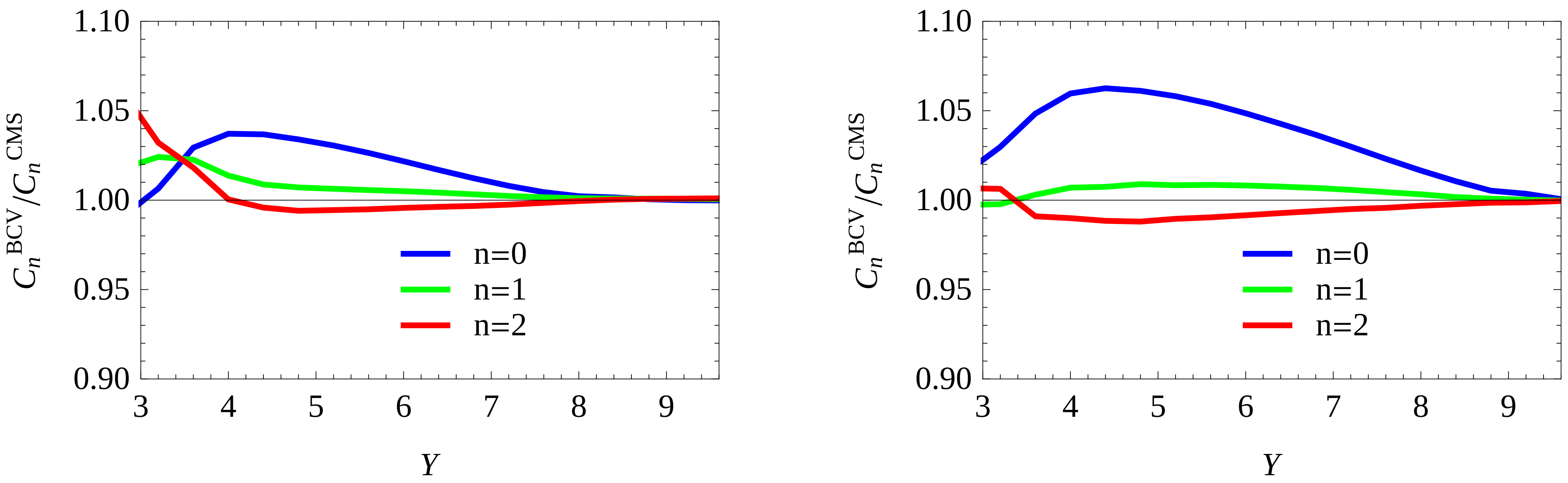
On the definition of MN Jets

- Conceptually, the 2 prescriptions are quite different
- In practice, since $Y \equiv y_{J1} - y_{J2} \gg 1$, it is rather unlikely to emit additional partons with $y > y_{J1}$ or $y < y_{J2}$

On the definition of MN Jets

- Conceptually, the 2 prescriptions are quite different
- In practice, since $Y \equiv y_{J1} - y_{J2} \gg 1$, it is rather unlikely to emit additional partons with $y > y_{J1}$ or $y < y_{J2}$
- Largest difference at $\sqrt{s} = 7$ TeV is $\simeq 4\%$ at $Y \simeq 4$; at 13 TeV $\simeq 7\%$

[DC, Deganutti '16]



Better (and easy) to modify the theoretical prescription for $V^{(1)}$ by requiring the absence of partons/jets with $p_t > p_{t,\min}$ and $y > y_J$

Matching BFKL with Fixed NLO

Our aim is to merge fixed NL order and NLL BFKL resummation

- more reliable results $\Rightarrow$ improve description of data
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Results for cross section and C_m coefficients

- The implementation is still work in progess
- Preliminary results of central values (no error estimate yet)
  $\rightsquigarrow$ important lesson for future analyses

Matching (sym. jets $p_{T1}, p_{T2} > 35\text{GeV}$)

Cross section: NLL BFKL + NLO pert. $\mathcal{O}(\alpha_s)^3$ − BFKL $\mathcal{O}(\alpha_s^3)$

$$
\begin{aligned}
\frac{\mathrm{d}\sigma(s)}{\mathrm{d}J_1\mathrm{d}J_2} = \sum_{a,b}\int_0^1 \mathrm{d}x_1\mathrm{d}x_2\; f_a(x_1)f_b(x_2)\Big\{ \\
&\int \mathrm{d}\boldsymbol{k}_1\mathrm{d}\boldsymbol{k}_2\Big[V_a^{(0+1)}(x_1,\boldsymbol{k}_1;J_1)\,G_{\mathrm{NLL}}(x_1x_2s,\boldsymbol{k}_1,\boldsymbol{k}_2)\,V_b^{(0+1)}(x_2,\boldsymbol{k}_2;J_2)\Big] \\
&+\frac{\mathrm{d}\hat{\sigma}^{(NLO)}(x_1,x_2)}{\mathrm{d}J_1\mathrm{d}J_2} \\
&-\int \mathrm{d}\boldsymbol{k}_1\mathrm{d}\boldsymbol{k}_2\Big[V_a^{(0)}(x_1,\boldsymbol{k}_1;J_1)\,\delta^2(\boldsymbol{k}_1-\boldsymbol{k}_2)\,V_b^{(0)}(x_2,\boldsymbol{k}_2;J_2)\Big] \\
&-\int \mathrm{d}\boldsymbol{k}_1\mathrm{d}\boldsymbol{k}_2\Big[V_a^{(1)}(x_1,\boldsymbol{k}_1;J_1)\,\delta^2(\boldsymbol{k}_1-\boldsymbol{k}_2)\,V_b^{(0)}(x_2,\boldsymbol{k}_2;J_2)\Big] \\
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&-\int \mathrm{d}\boldsymbol{k}_1\mathrm{d}\boldsymbol{k}_2\Big[V_a^{(0)}(x_1,\boldsymbol{k}_1;J_1)\,\alpha_s\log\frac{\hat{s}}{s_0}K_0(\boldsymbol{k}_1,\boldsymbol{k}_2)\,V_b^{(0)}(x_2,\boldsymbol{k}_2;J_2)\Big]\Big\}
\end{aligned}
$$

(same colours in plots)

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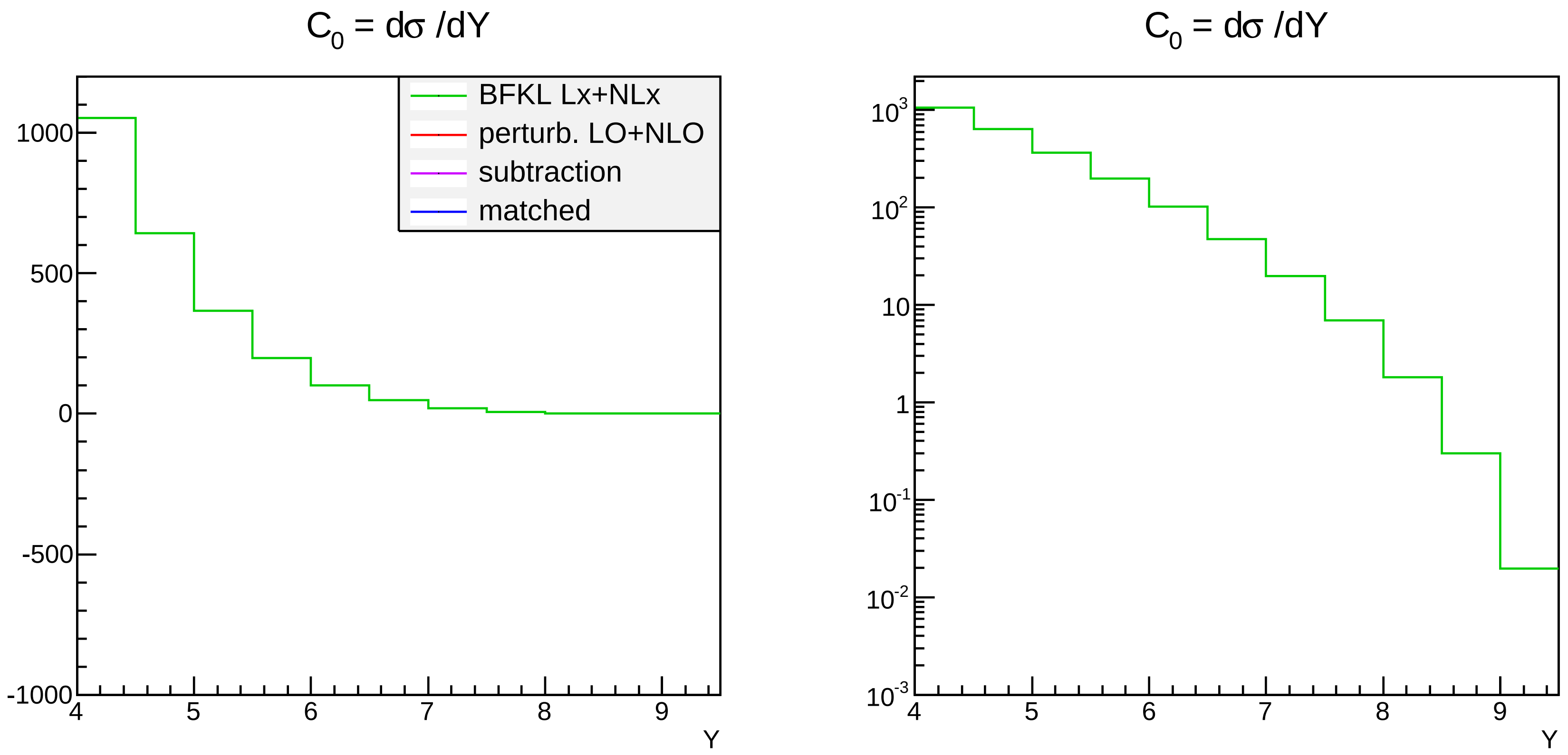

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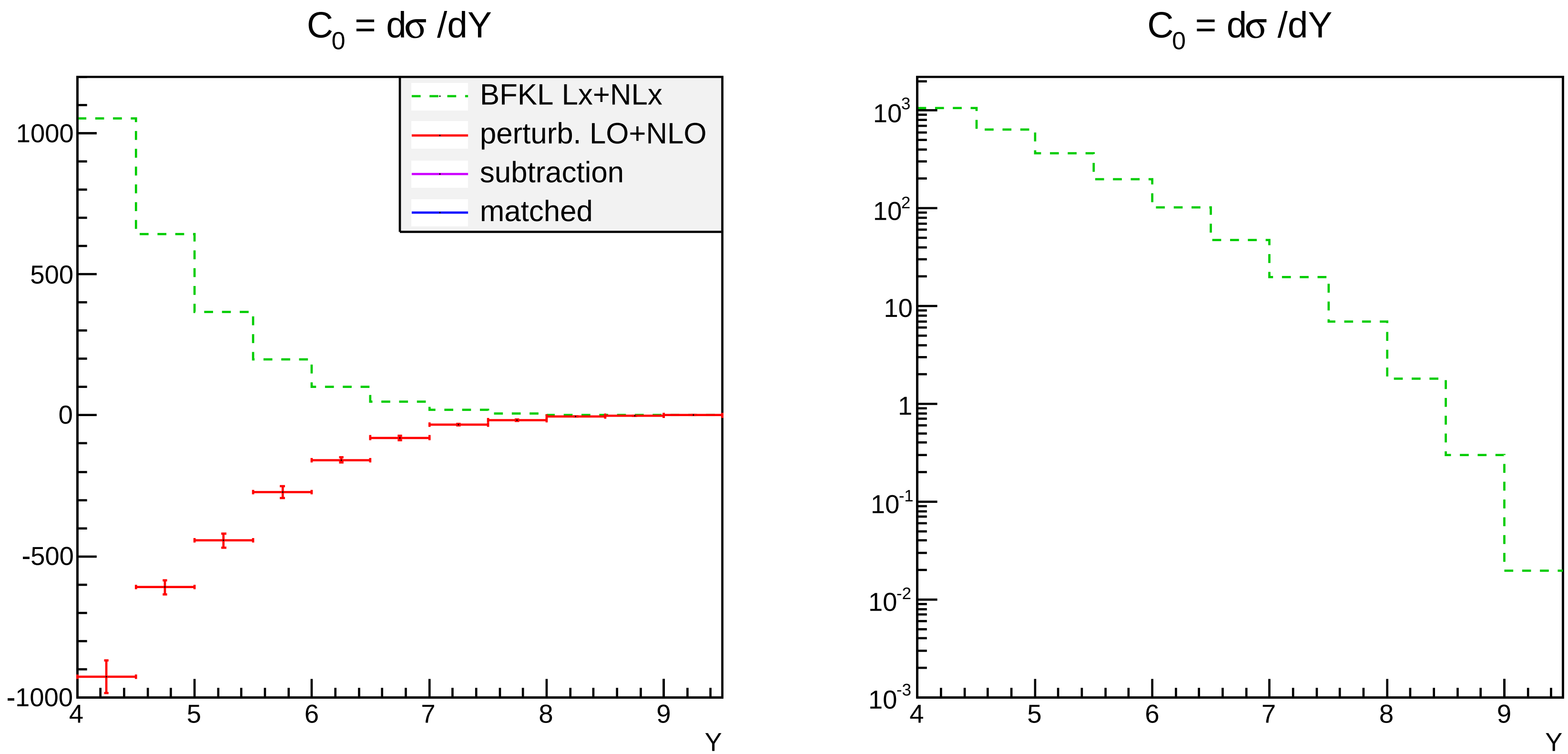

LO+NLO cross section obtained with NLOJET++ *[Nagy]* is negative!

Large errors due to very slow convergence in MC integration

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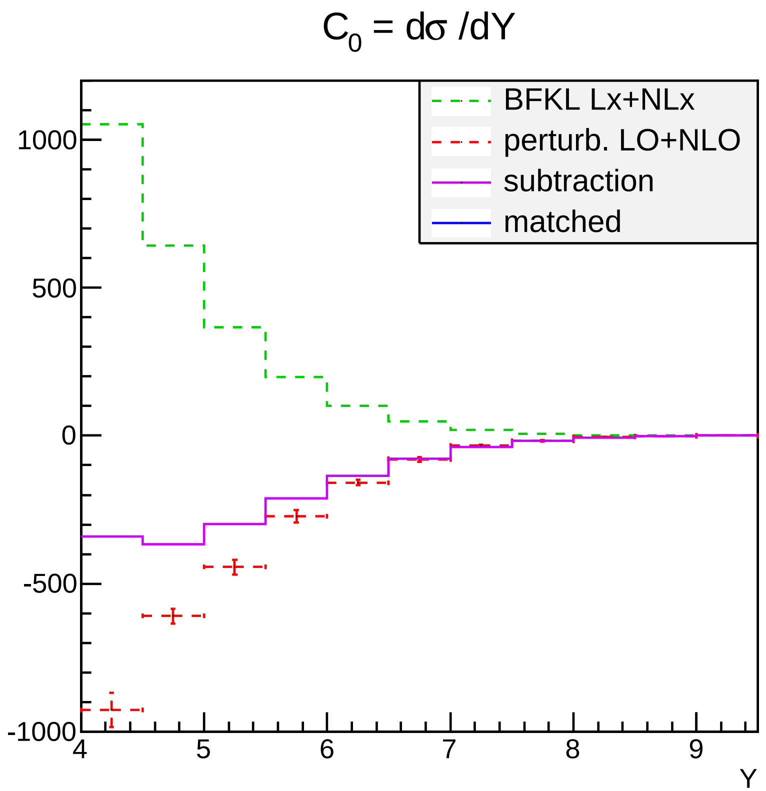

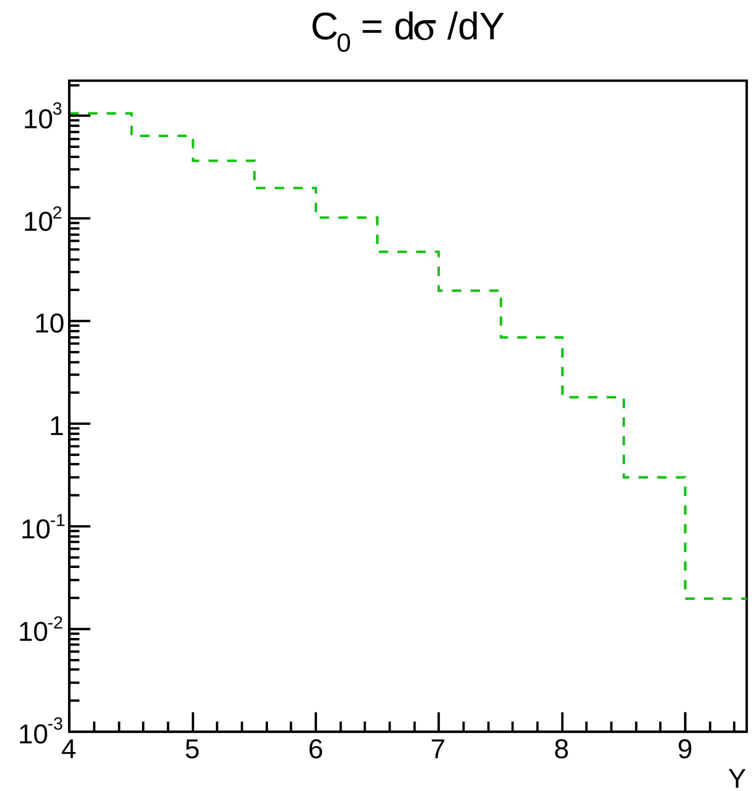

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However, also the subtraction is negative

Their difference is moderate

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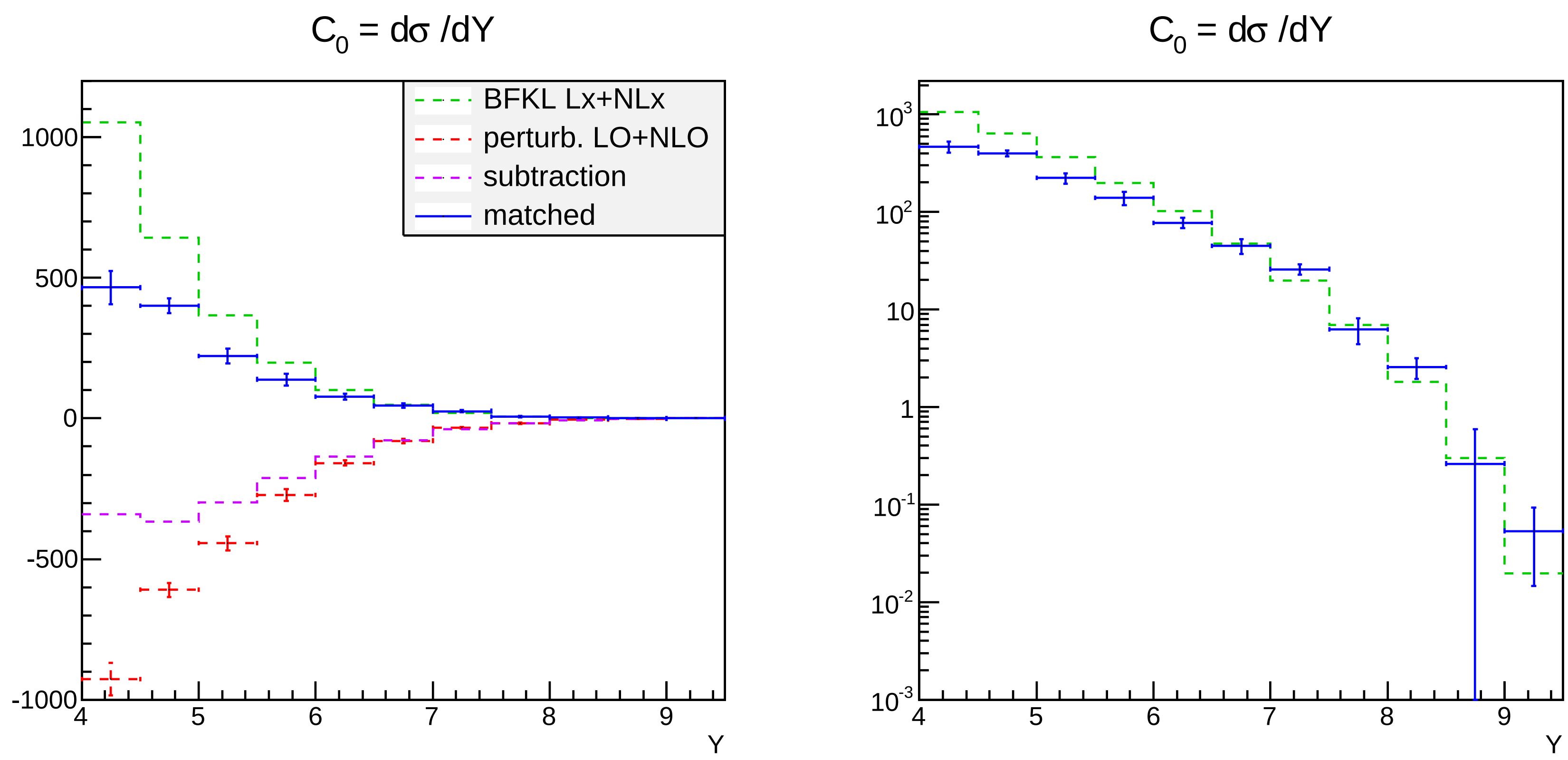

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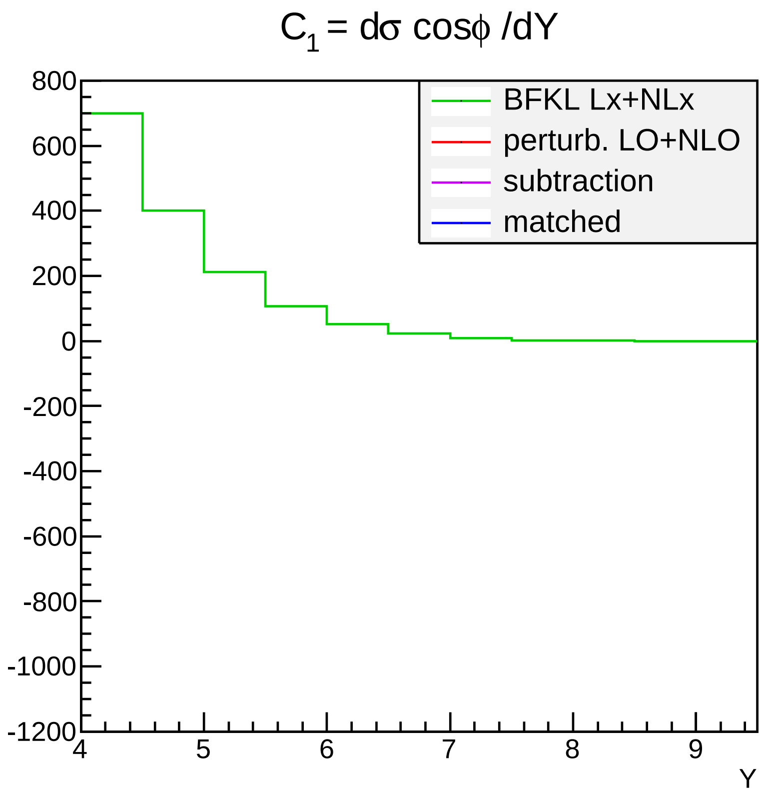
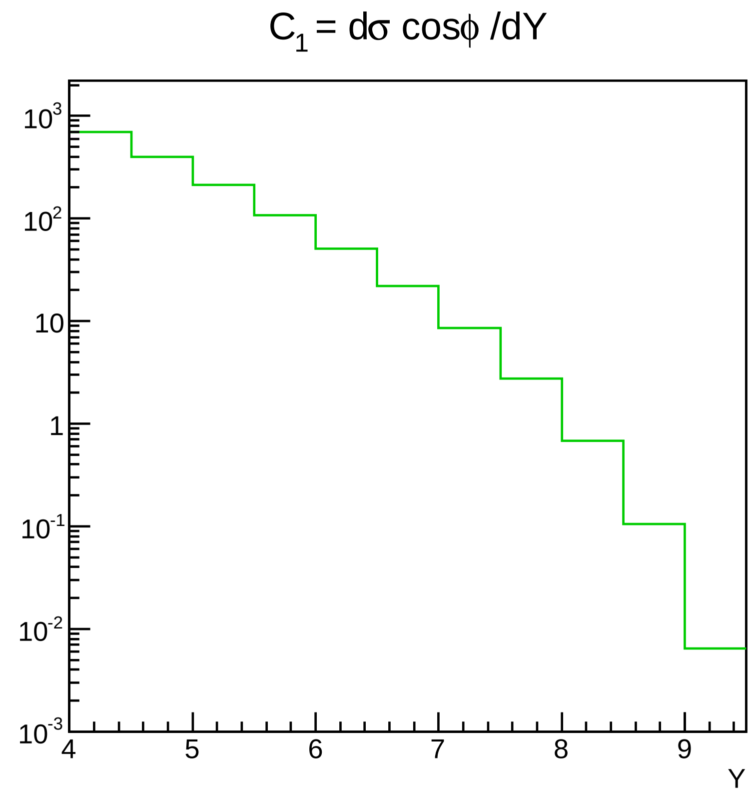
Matched cross section is positive, of the same magnitude of NLL BFKL prediction

Matching (azimuthal coeff. C_1)





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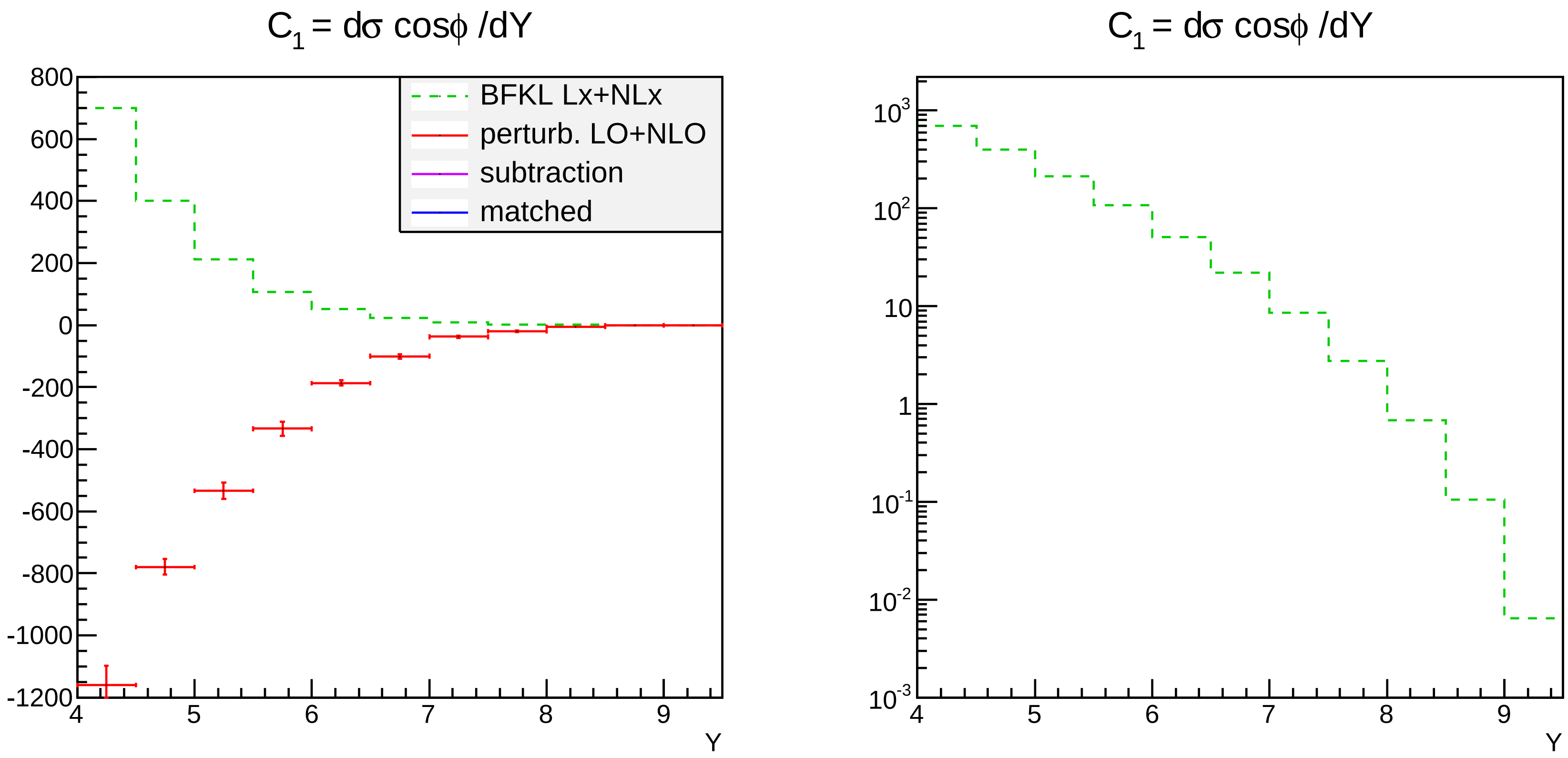

Large errors of NLO calculation due to very slow convergence in MC integration

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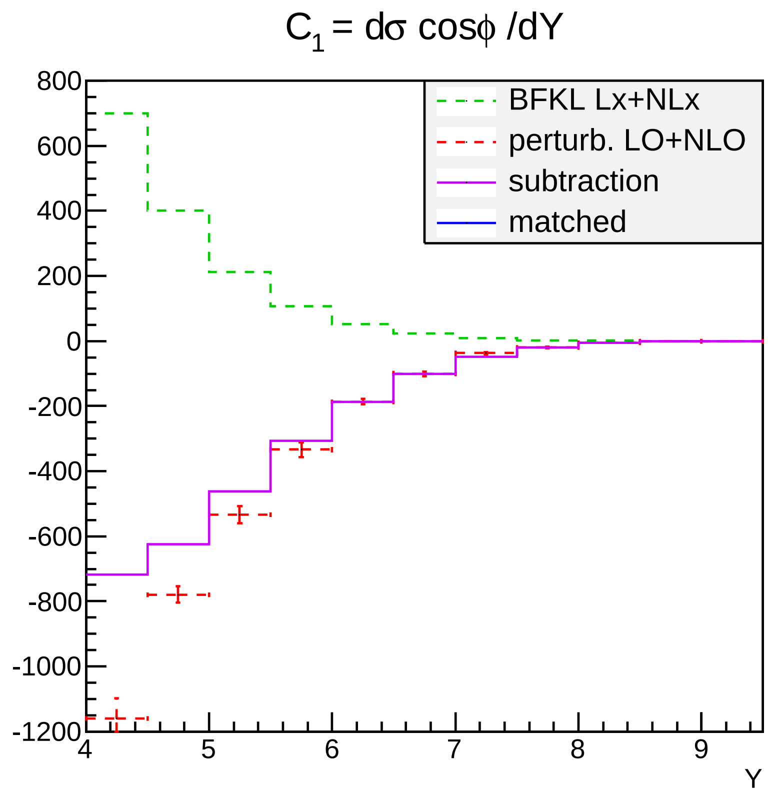

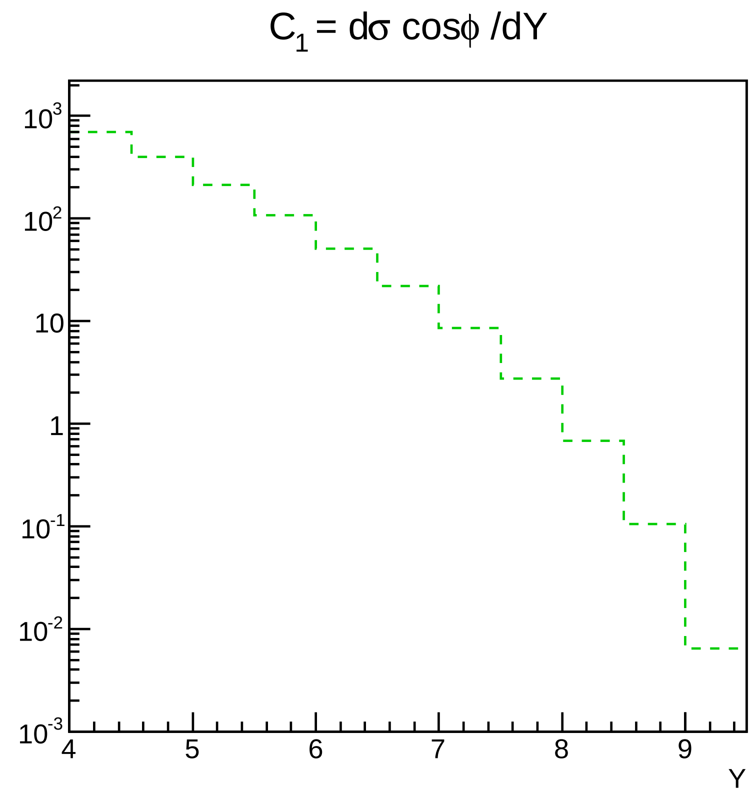

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Moderate difference between NLO and subtraction

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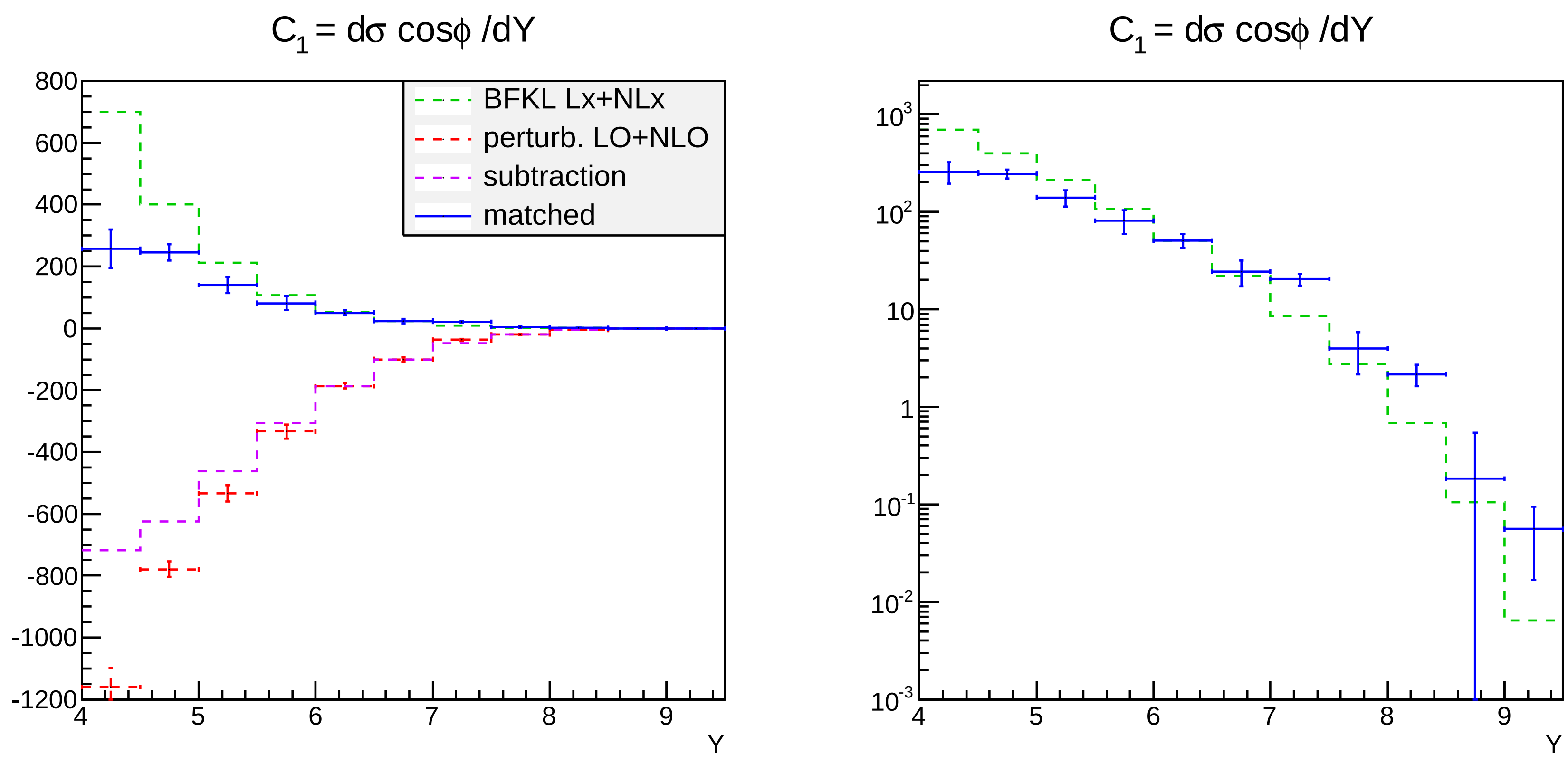

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Moderate difference between NLO and subtraction

Matched C_1 of the same magnitude of NLL BFKL prediction

but definitely different at intermediate $Y \simeq 4 \div 6$

PT instability of symmetric jets

It is well known that cross section of jets at NLO is very sensitive to the asymmetry parameter $\Delta = p_{T1} - p_{T2}$ *[Frixione,Ridolfi '97]*
The leading collinear singularity for real emission is given by

$$\sigma^{(r)} \propto \int \mathrm{d}\boldsymbol{k}_1 \mathrm{d}\boldsymbol{k}_2 \Theta(|\boldsymbol{k}_1| - p_T)\Theta(|\boldsymbol{k}_2| - (p_T + \Delta)) \frac{1}{(\boldsymbol{k}_1 + \boldsymbol{k}_2)^2 + \epsilon^2}$$
$$= A(\Delta, \epsilon) + B \log(\epsilon) - C\,(\Delta + \epsilon)\log(\Delta + \epsilon)$$

thus fixed order PTh is not reliable in this case (finite, but infinite deriv at $\Delta = 0$)

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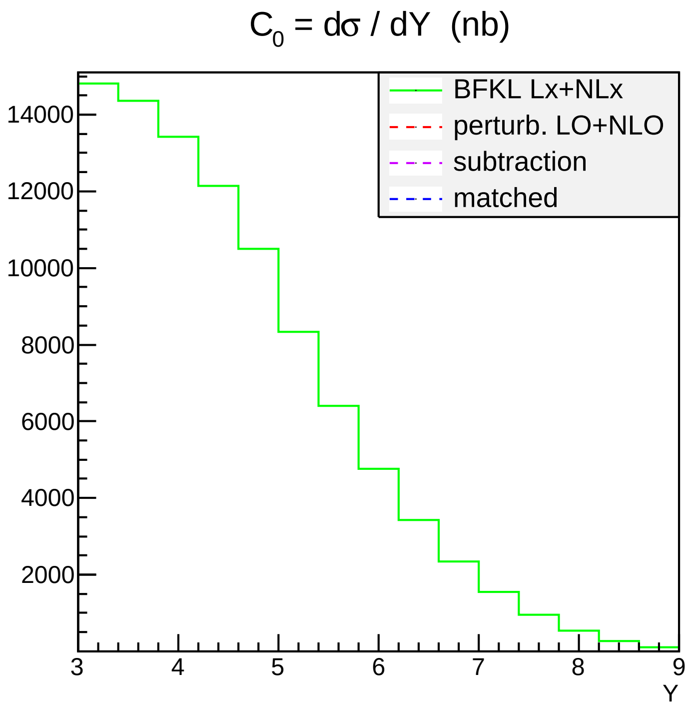
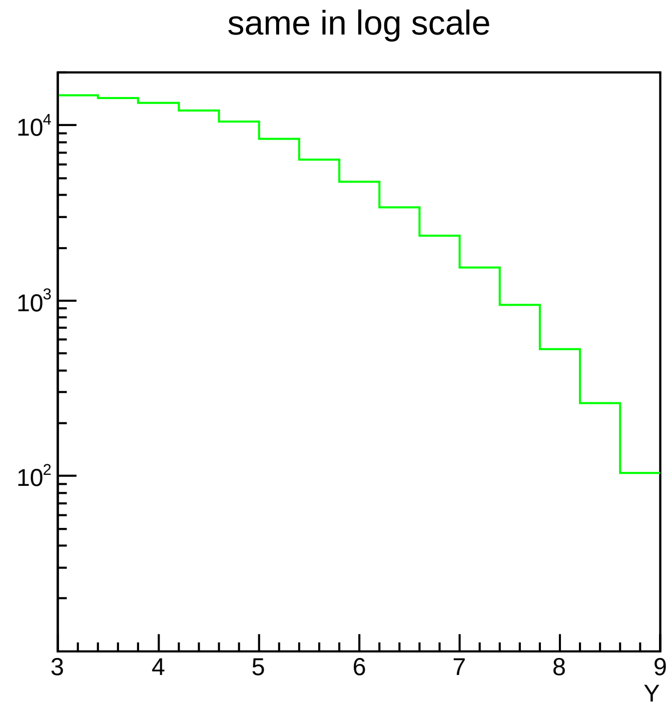
An analogous singularity occurs in the PT expansion of LL BFKL *[Andersen, Del Duca et al. '01]*

$$\sigma_{gg} \propto \frac{1}{(p_T + \Delta)^2}\left[1 - \alpha_s Y\left(\frac{2p_T\Delta + \Delta^2}{p_T^2}\log\frac{2p_T\Delta + \Delta^2}{(p_T + \Delta)^2} + 2\log\frac{p_T}{p_T + \Delta}\right)\right]$$

In the matching procedure such collinear $\Delta \log(\Delta)$ cancels out to a large extent, therefore the matching procedure should be safe

$\langle p_T \rangle$ cut: $\frac{1}{2}(p_{T1} + p_{T2}) > 35\text{GeV}$





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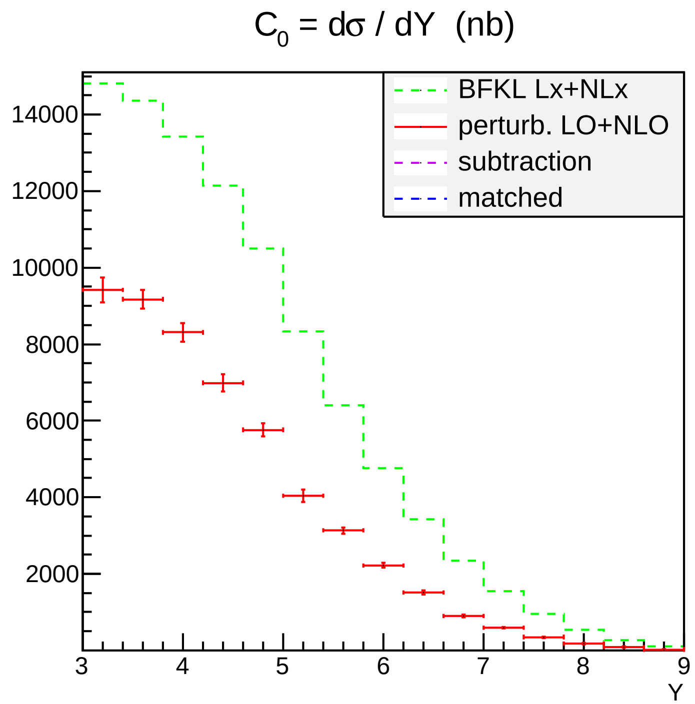

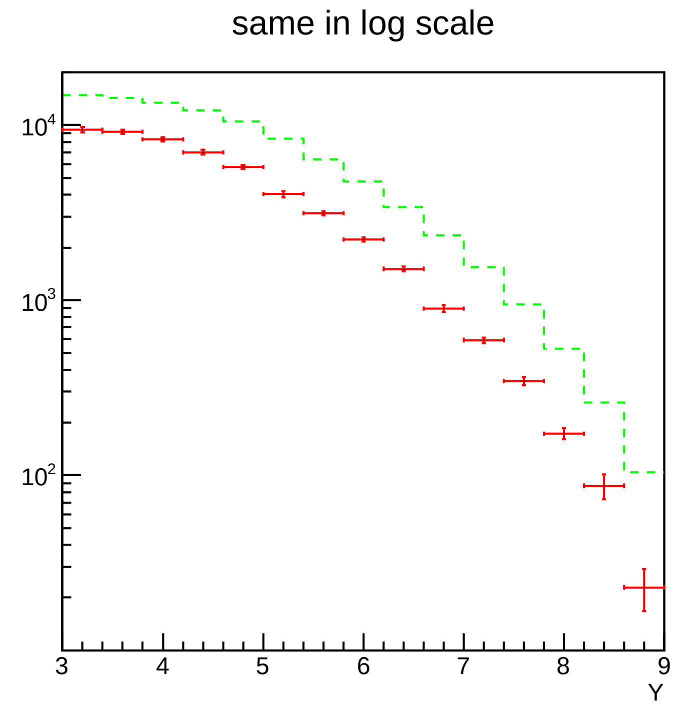

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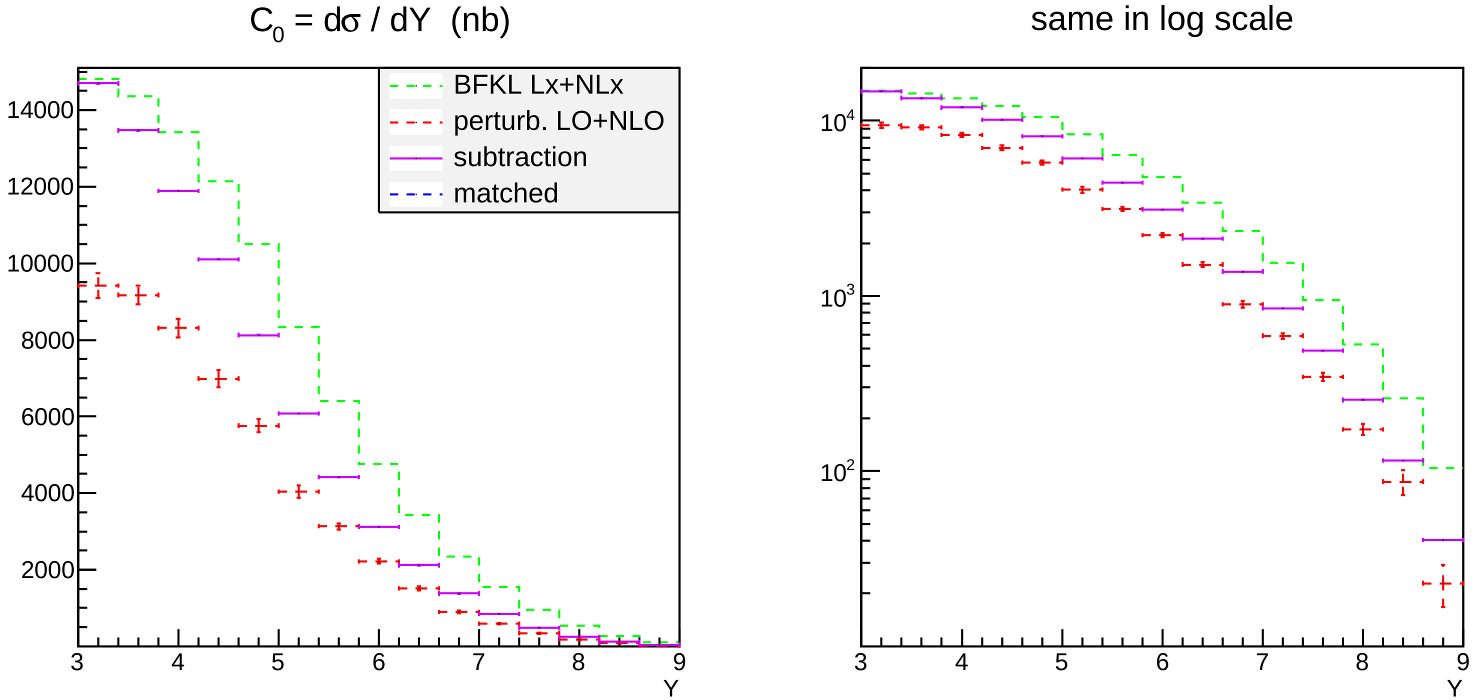

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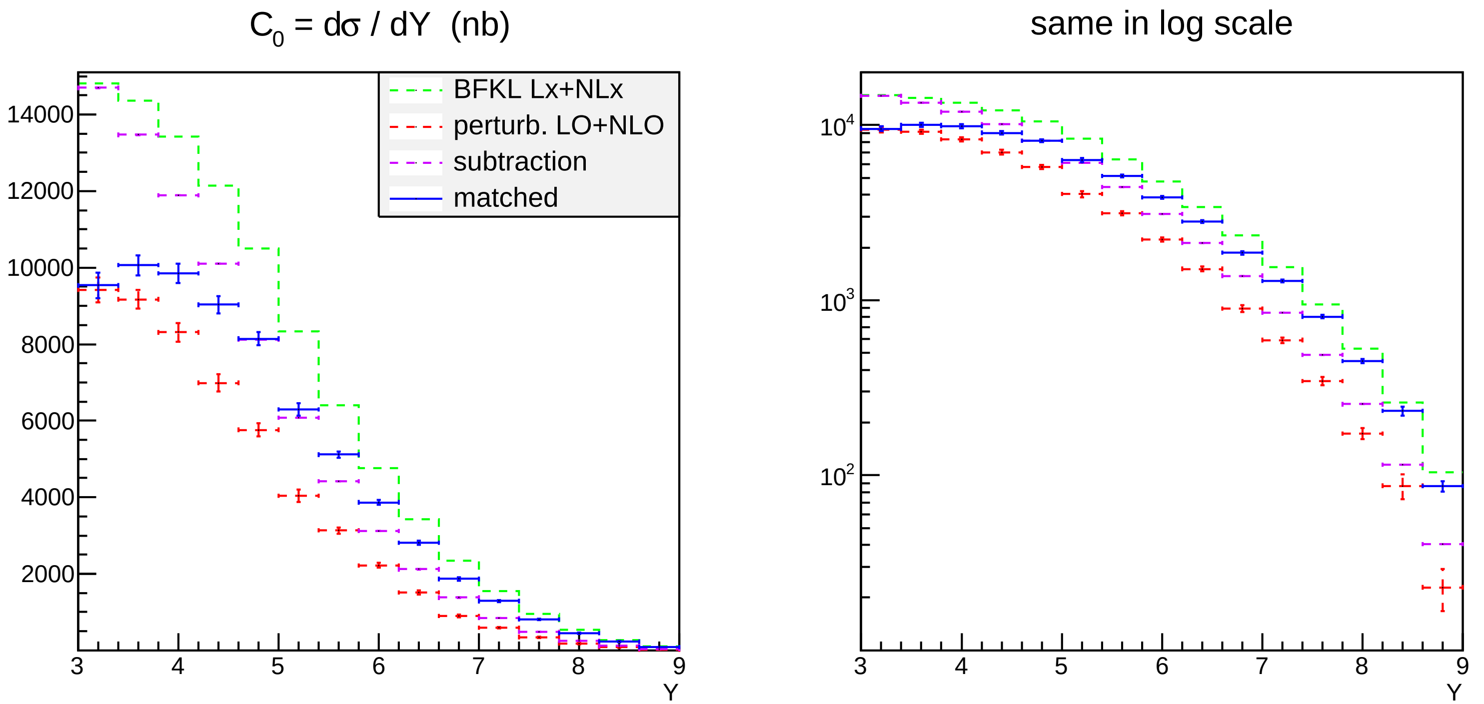
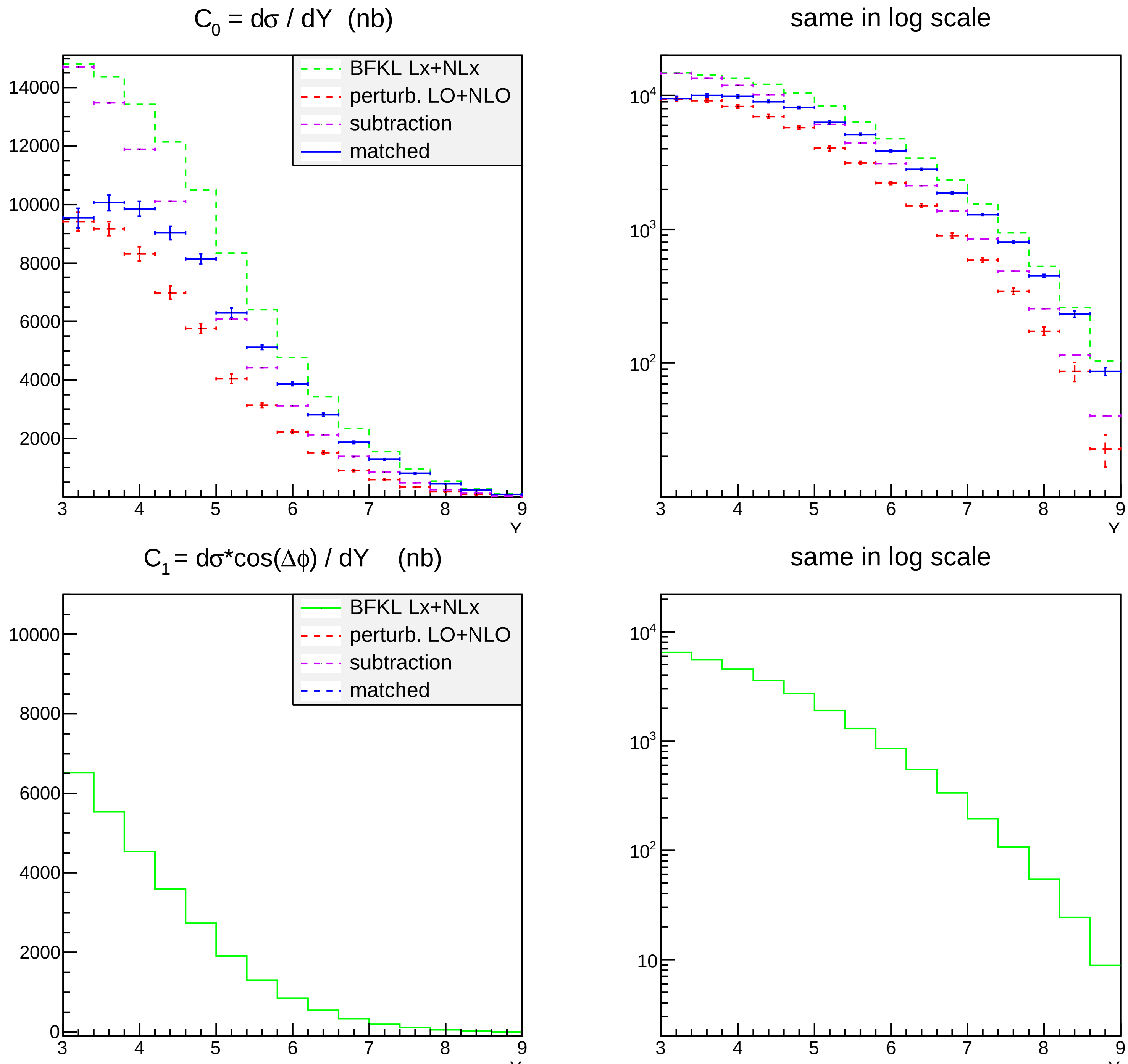


Procedure is more stable than the previous one

$\langle p_T \rangle$ cut: $\frac{1}{2}(p_{T1} + p_{T2}) > 35\mathrm{GeV}$



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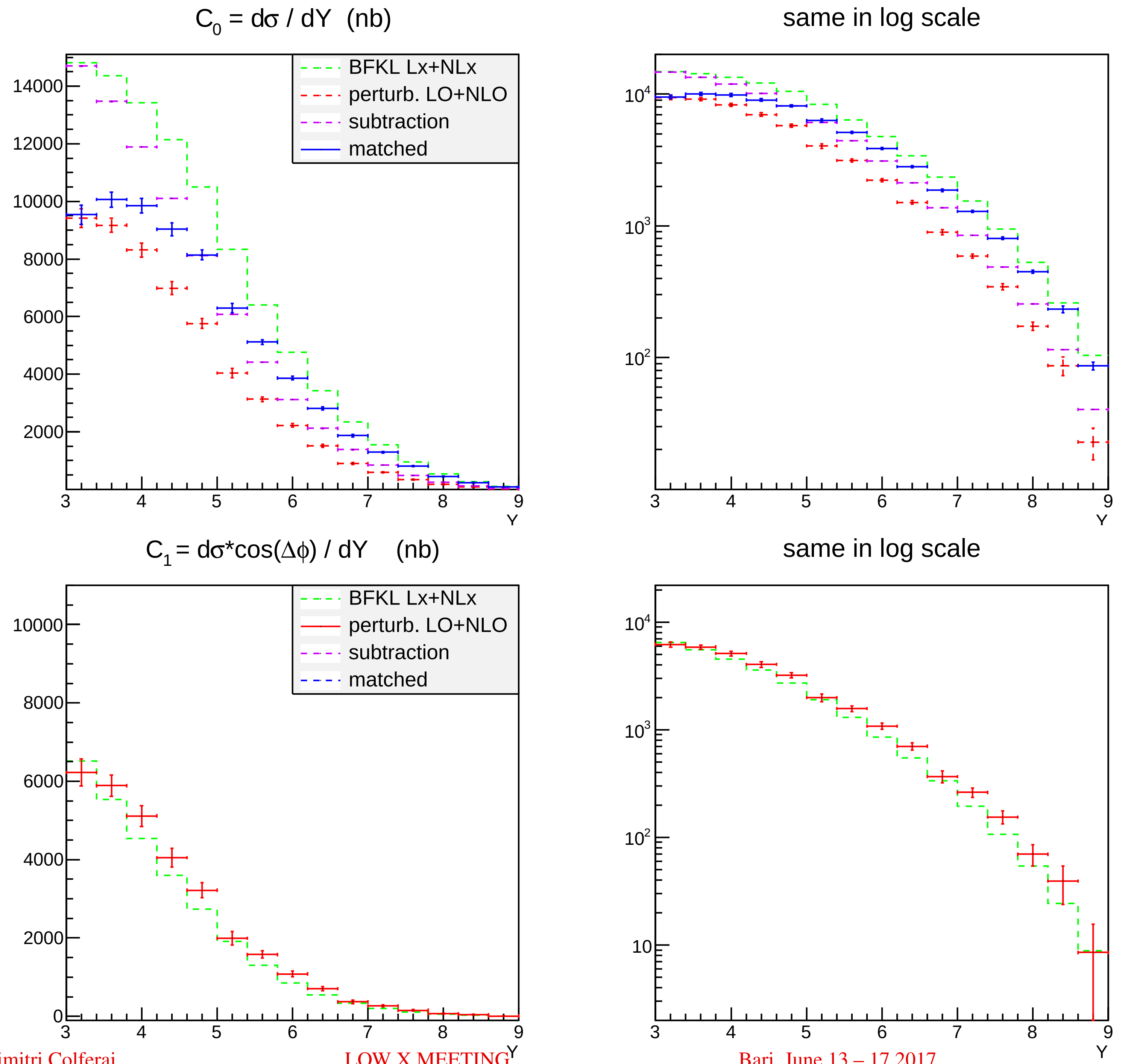
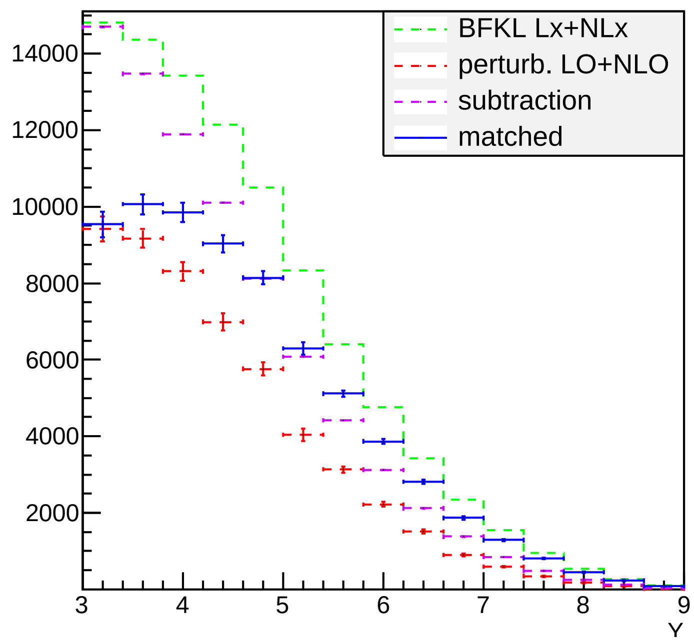
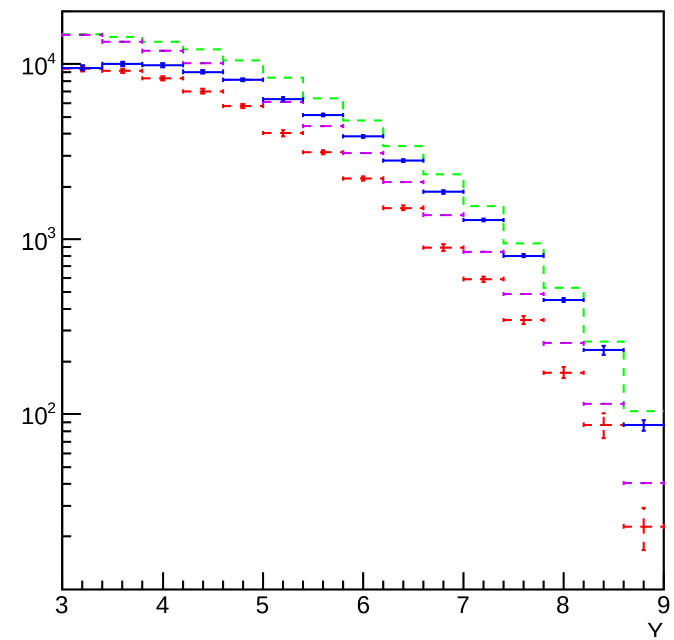


$\langle p_T \rangle$ cut: $\quad \frac{1}{2}(p_{T1} + p_{T2}) > 35\mathrm{GeV}$

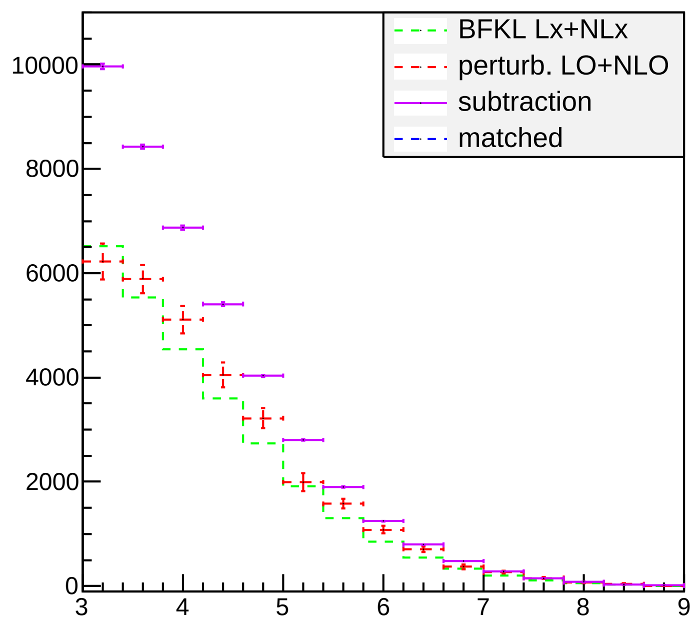
$C_0 = d\sigma / dY$ (nb)



same in log scale



$C_1 = d\sigma * \cos(\Delta\phi) / dY$ (nb)



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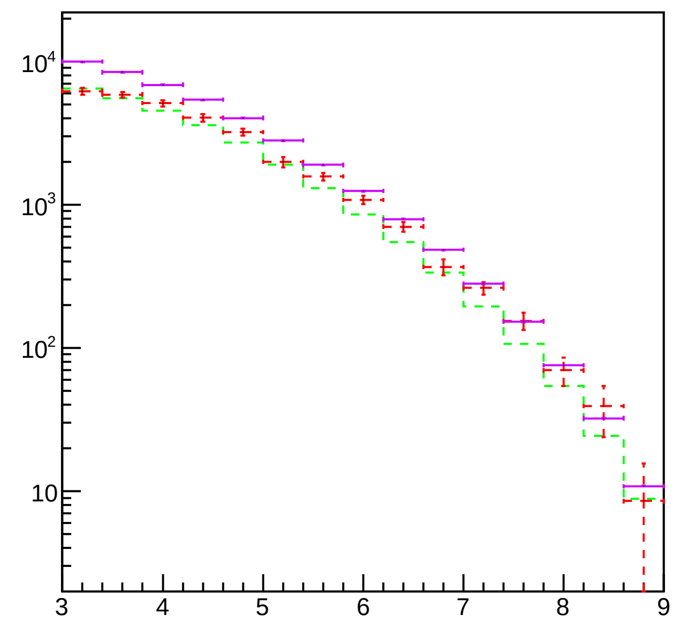
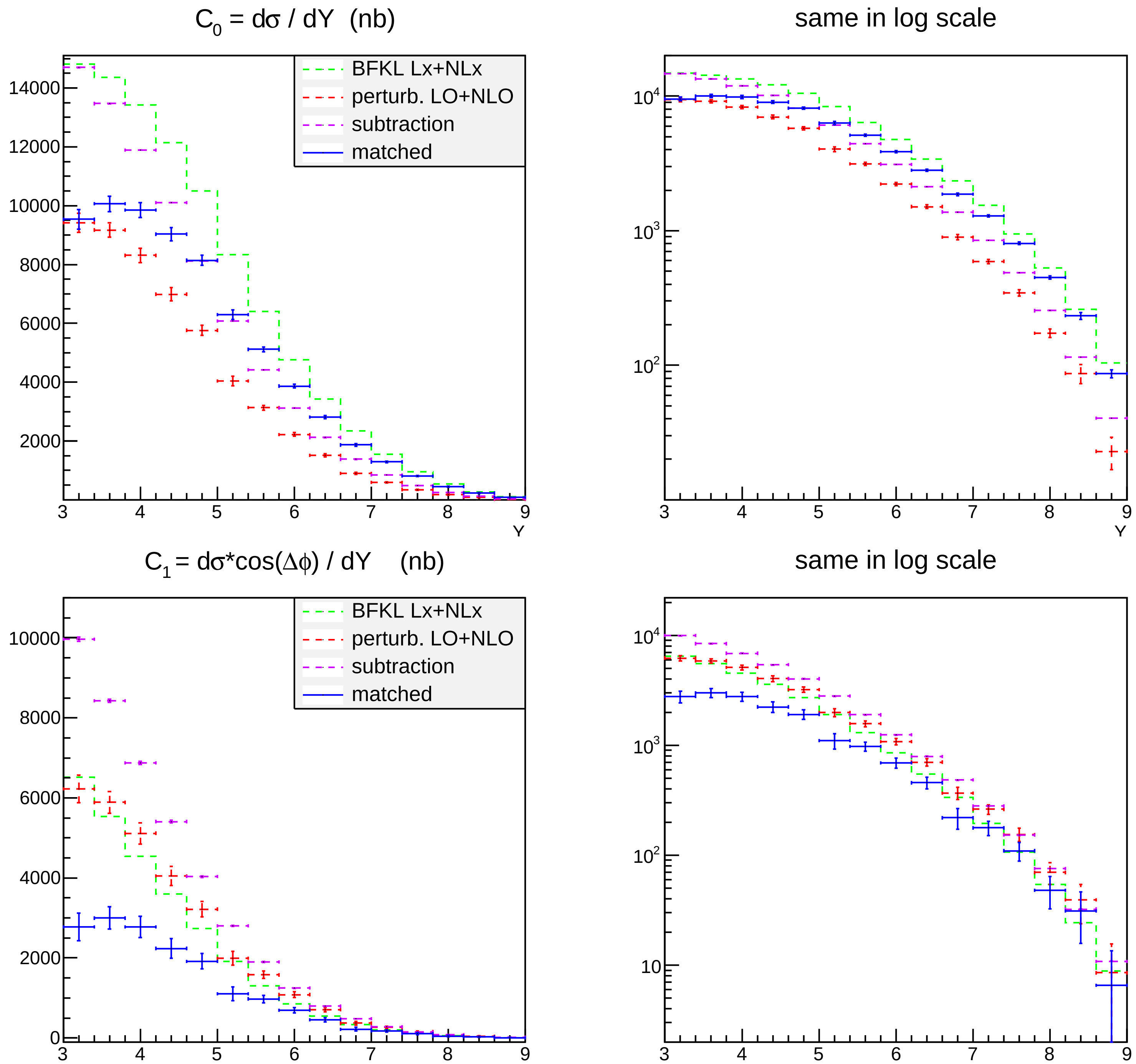


$\langle p_T \rangle$ cut: $\frac{1}{2}(p_{T1} + p_{T2}) > 35\text{GeV}$



Advice for future analysis

We *strongly suggest* experimentalists to perform MN jet analysis with average p_T cut: $\frac{1}{2}(p_{T1} + p_{T2}) > p_{\rm cut}$ in order to avoid perturbative sensitivity to phase space corner $p_{T1} = p_{T2} = p_{\rm cut}$

- Smaller theoretical uncertainties
- MNJ better tool for finding evidence of BFKL dynamics still competing with fixed-order contributions, even at LHC

Conclusions and outlook

- Mueller-Navelet jets are a good observable for demonstrating presence of BFKL dynamics at high energy. Yet there is room for improving theoretical description
- Original jet vertices have to be modified in order to comply with experimental analysis
- We propose an improved theoretical description by matching BFKL with NLO.
  - Preliminary results of various observables are encouraging
  - ... in particular with $\langle p_T \rangle$ cut
  - Full analysis with error is under way
- Experimental analysis of MNJ at 13 TeV very valuable