Improved theoretical description of Mueller-Navelet jets at LHC

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+ to appear

In collaboration with A. Niccoli and F. Deganutti (Univ. Florence)

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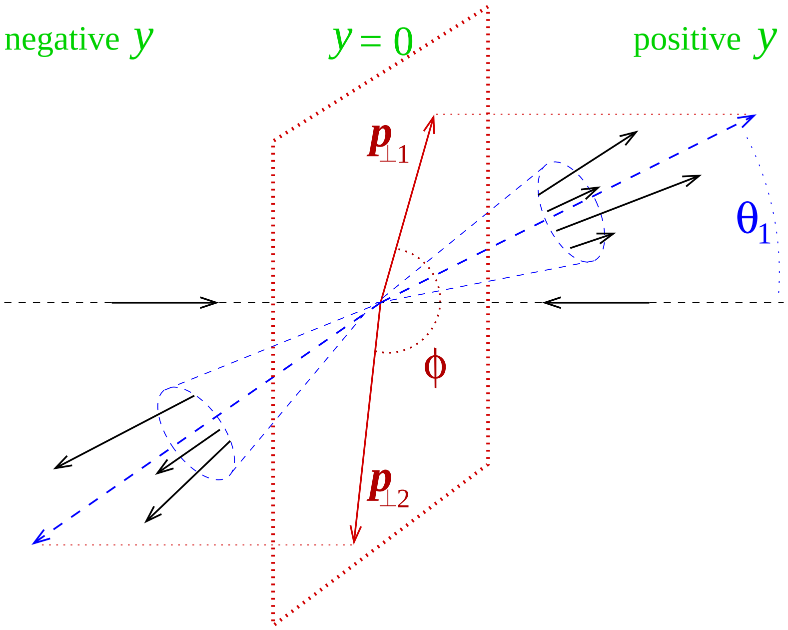
Motivations and Outline

- 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, with amplitudes and cross section governed by 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 logarithmic coefficients $(\alpha_{\mathrm{s}} \log s)^n$
- 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) $\to$ comparison with BFKL and with MonteCarlo
  - Unsatisfactory descriptions $\rightsquigarrow$ ask for improvements
    - Need of theoretical description consistent with experimental analysis
    - matching BFKL with fixed NLO: method and preliminary results

Mueller-Navelet jets

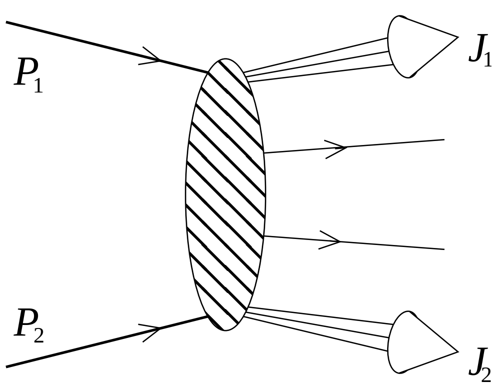
One of most famous testing processes for studying PT high-energy QCD at hadron colliders *[Mueller Navelet 1987]*



Final states with two jets with similar p_T and large rapidity separation

Rapidity: $y = \log(\cot(\theta/2))$

- Comparable hard scales (jet energies) limit the logarithms of collinear type $\log(p_{T1}/p_{T2})$
- Big separation in rapidity $Y \equiv y_1 - y_2 \quad \Rightarrow \quad$ large $\log(s/p_T^2) \sim Y$



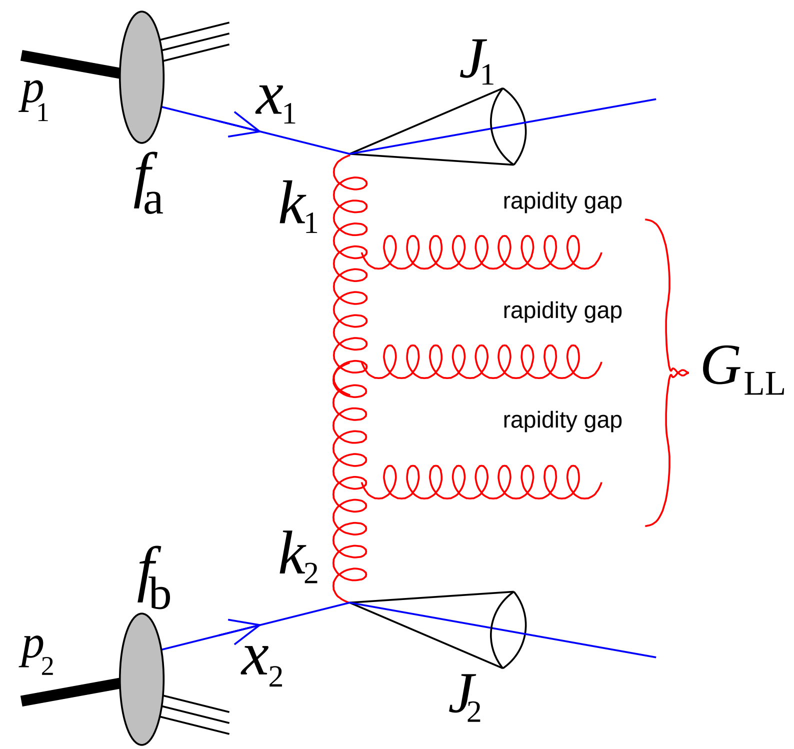
Anything can be emitted between the jets

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

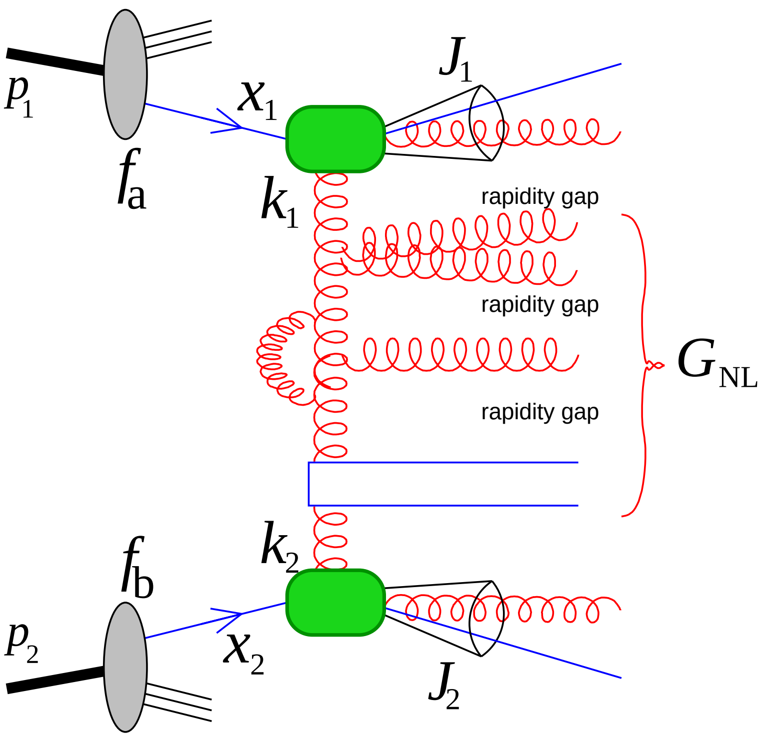
- Kinematics characterized by large rapidity gaps among particles
- At LL level the jet vertex condition is trivial (only 1 parton)

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!

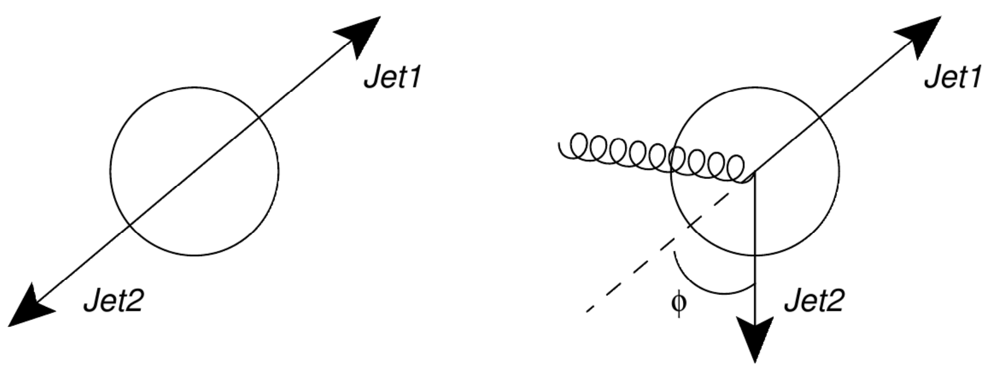
- First NLL analysis for 14 TeV *[DC,Schwensenn,Szymanowski,Wallon '10]* showed sizeable corrections from both GGF and Jet vertices
- NLL prediction definitely different from MC ones
- Mueller-Navelet jets looked promising for finding signals of BFKL dynamics

CMS analysis of MN jets at 7 TeV

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

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

- 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

Angular distribution $\dfrac{1}{\sigma}\dfrac{\mathrm{d}\sigma}{\mathrm{d}\phi}$ with $\phi \equiv |\pi - \phi_1 - \phi_2|$

Data selection: $p_{T1,2} > 35\mathrm{GeV}$, $|y_i| < 4.7$

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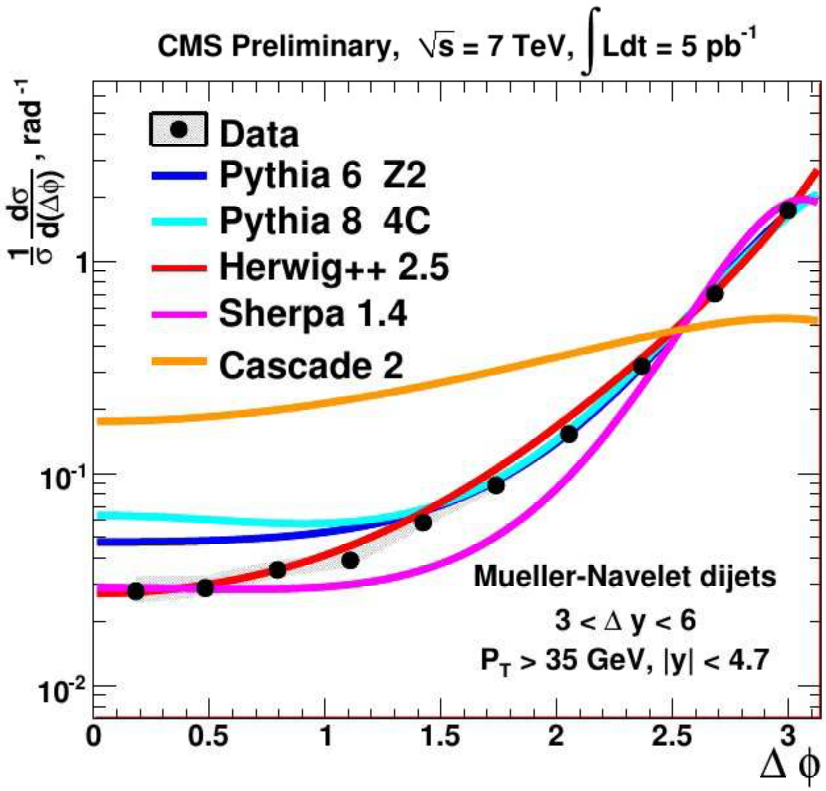

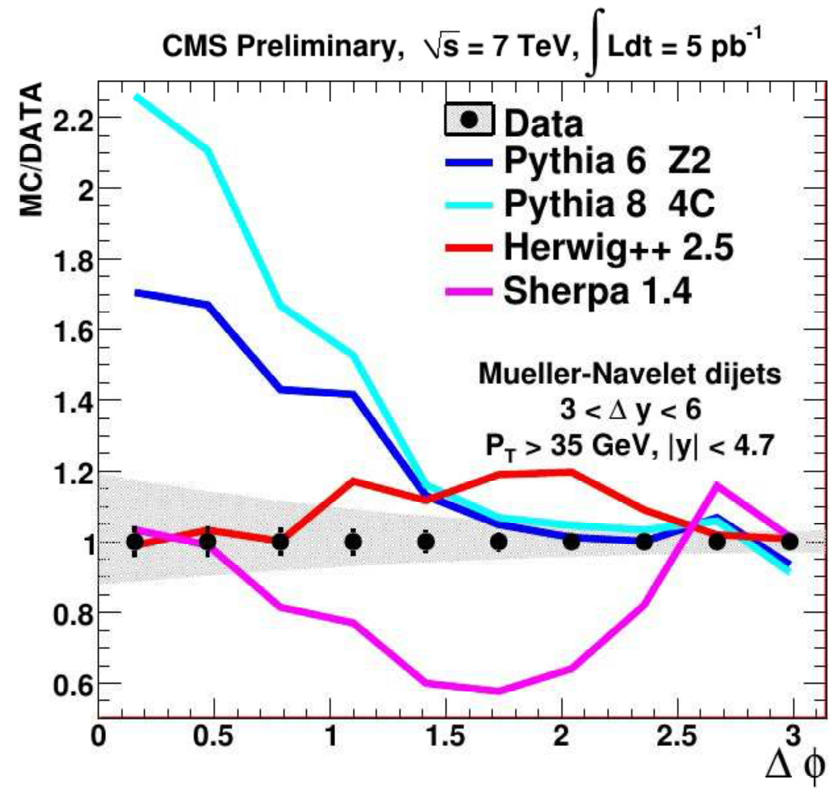

Some MC are close to data somewhere in ϕ

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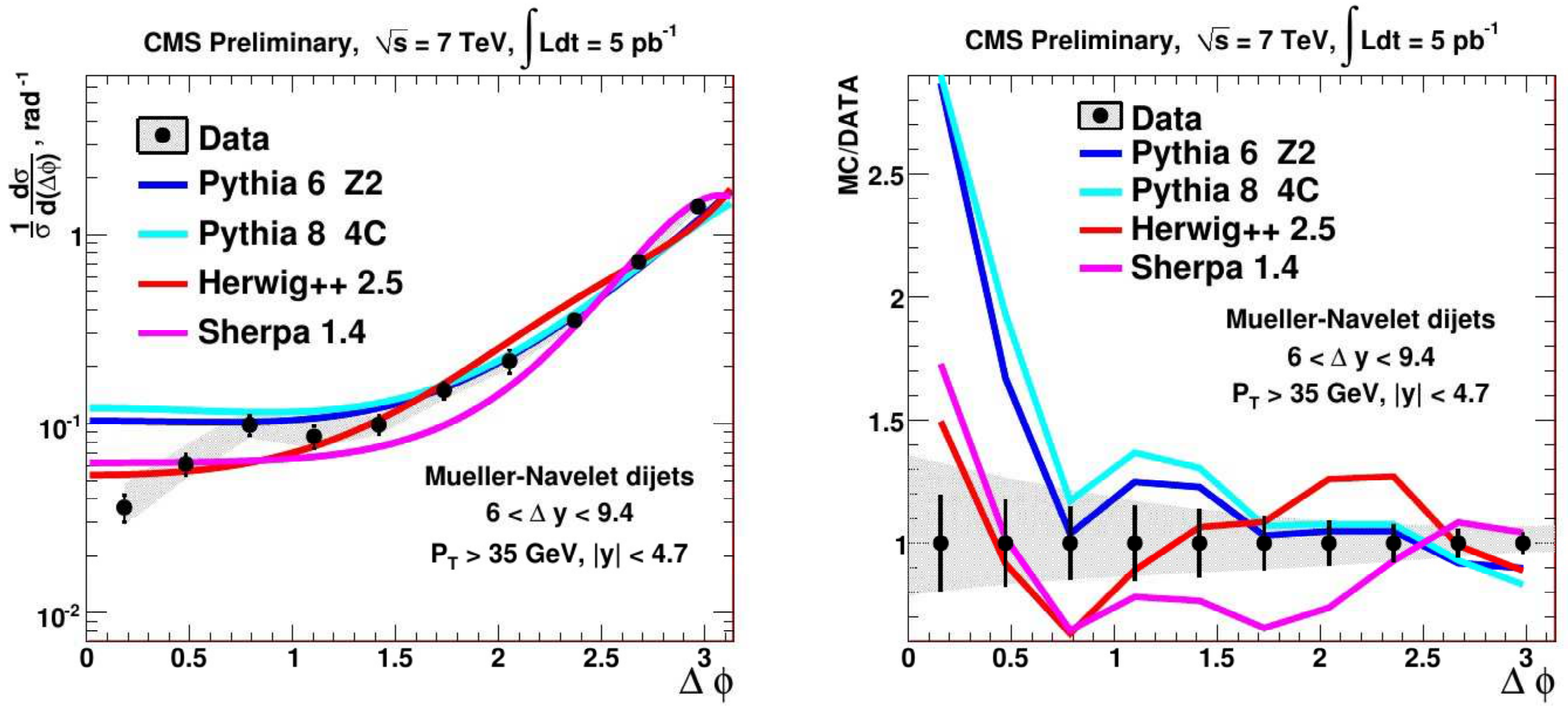
Data selection: $p_{T1,2} > 35\text{GeV}, |y_i| < 4.7$ $6 < \Delta y \equiv Y < 9.4$



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Overall description is not very good

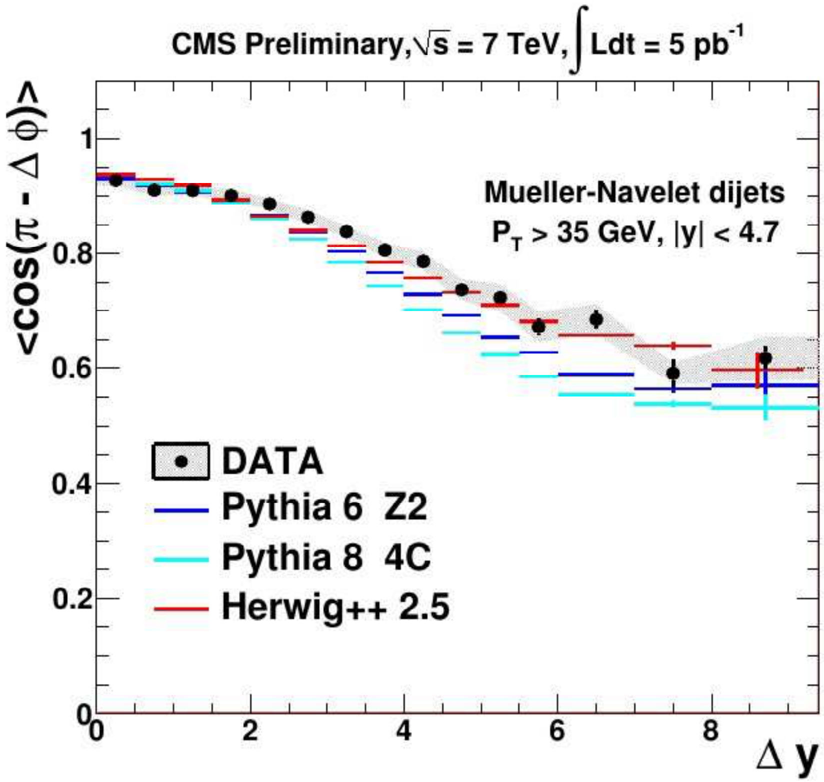
CMS analysis of MN jets at 7 TeV

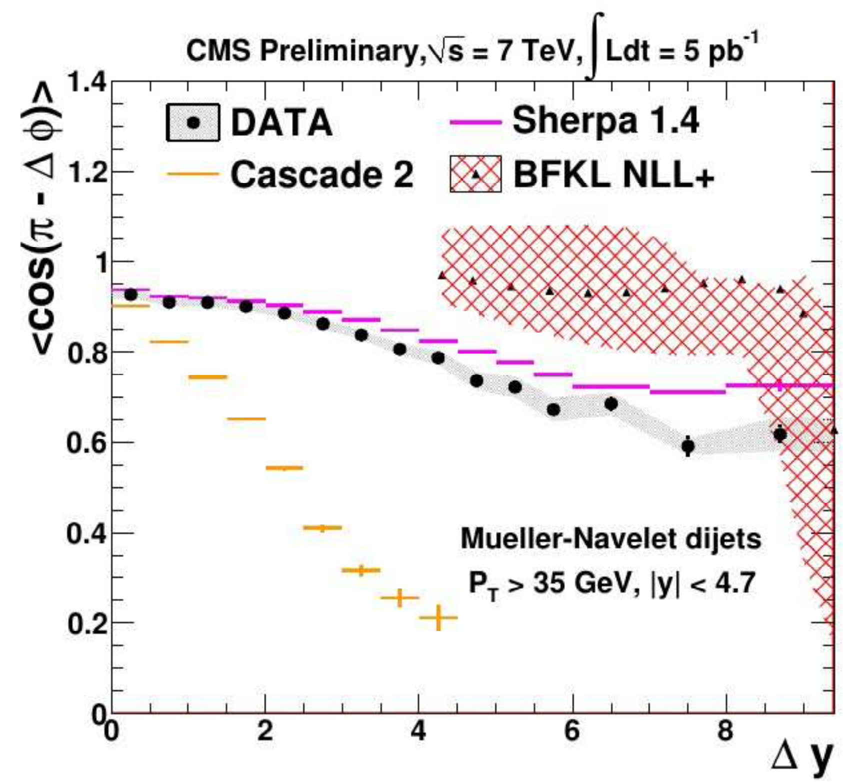
Data: $p_{T1,2} > 35\text{GeV}$, $|y_i| < 4.7$ $\Delta y \equiv Y \equiv |y_1 - y_2| < 9.4$

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

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

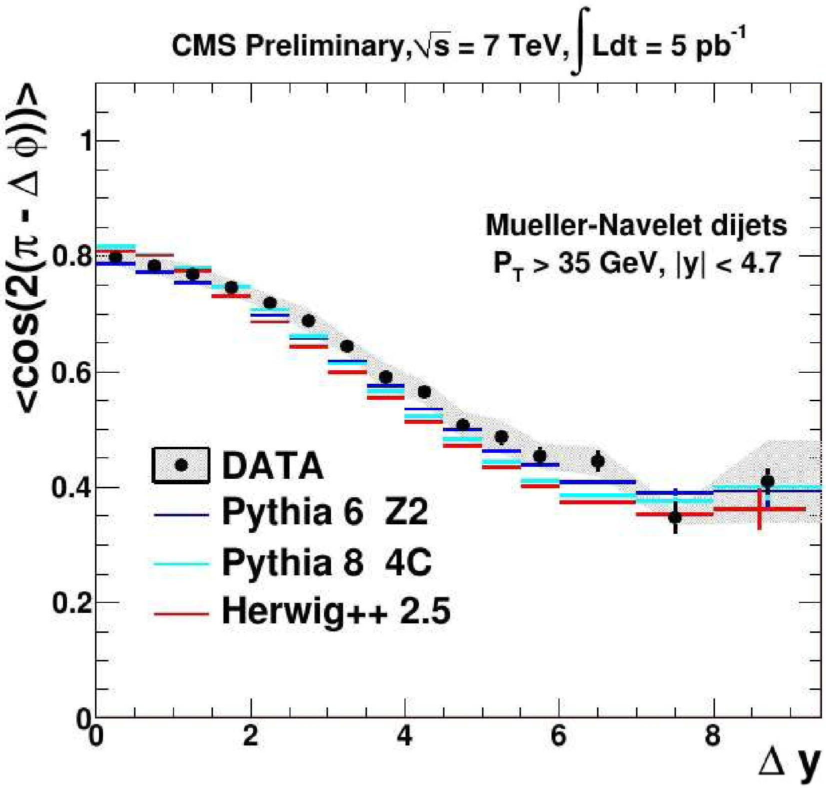
BFKL was expected to predict more radiation than fixed order $\Rightarrow$ more decorrelation

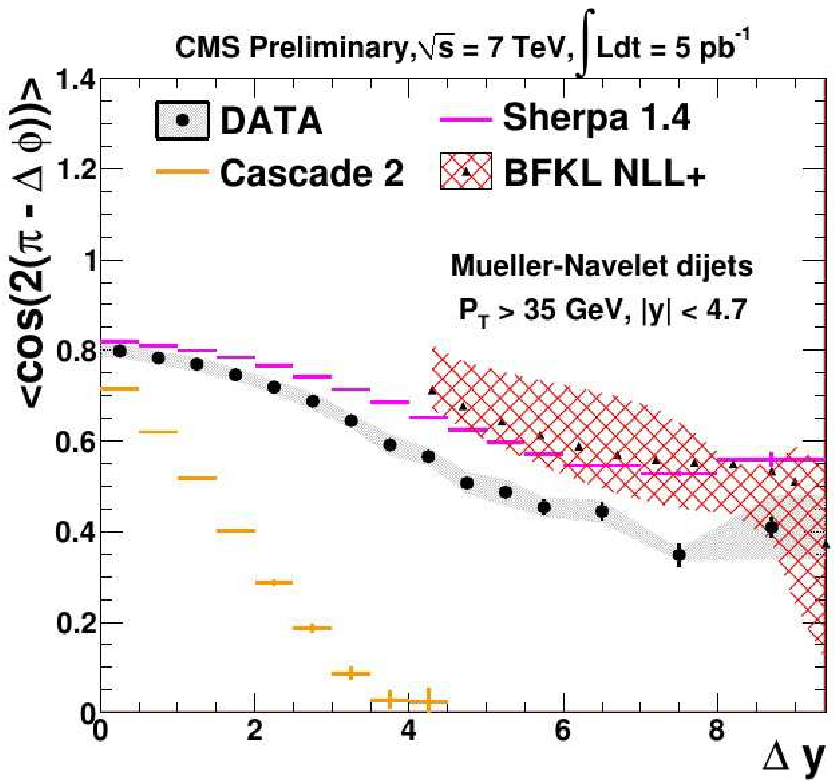
Some MC agree with data

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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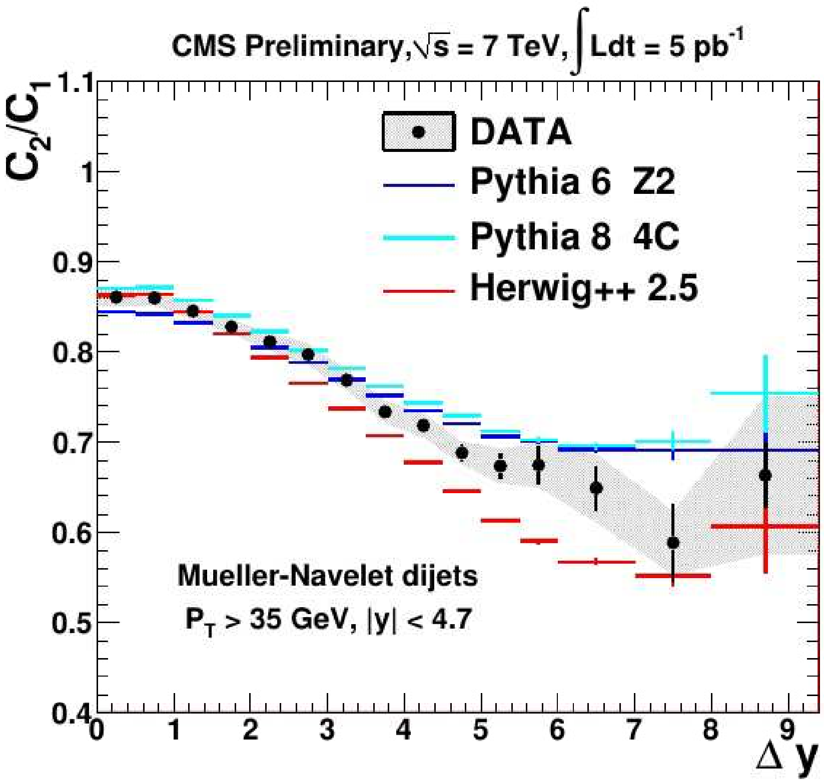

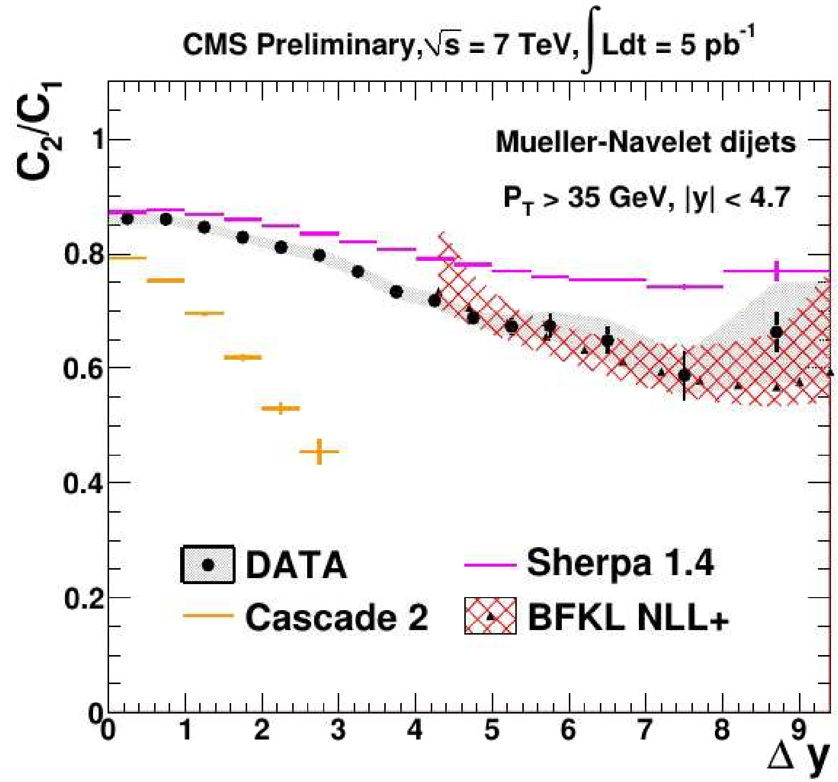

Ratio $\dfrac{C_2}{C_1} = \dfrac{\langle \cos(2\phi) \rangle}{\langle \cos \phi \rangle}$

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 $\sim 10 \div 15\%$

NLL with BLM scale fixing

[Ducloué,Szymanowski,Wallon '13] proposed to tame large scale dependence of BFKL by fixing μ_R with BLM procedure

$$\mu_R^2 = \exp\left[\frac{1}{2}\chi_0 - \frac{5}{3} + 2\left(1 + \frac{2}{3}I\right)\right] p_{T1}\, p_{T2}$$

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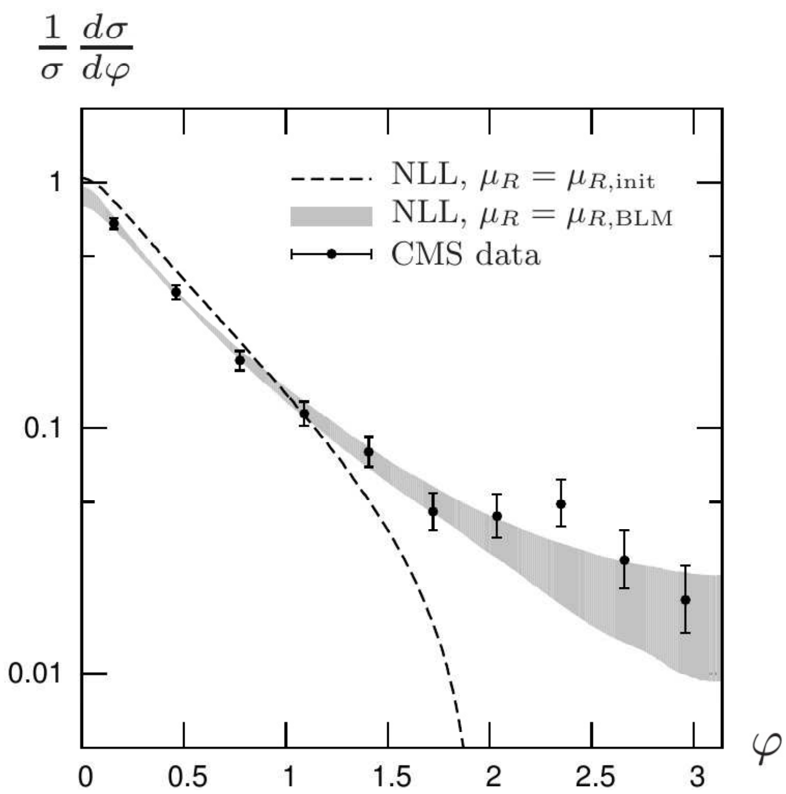

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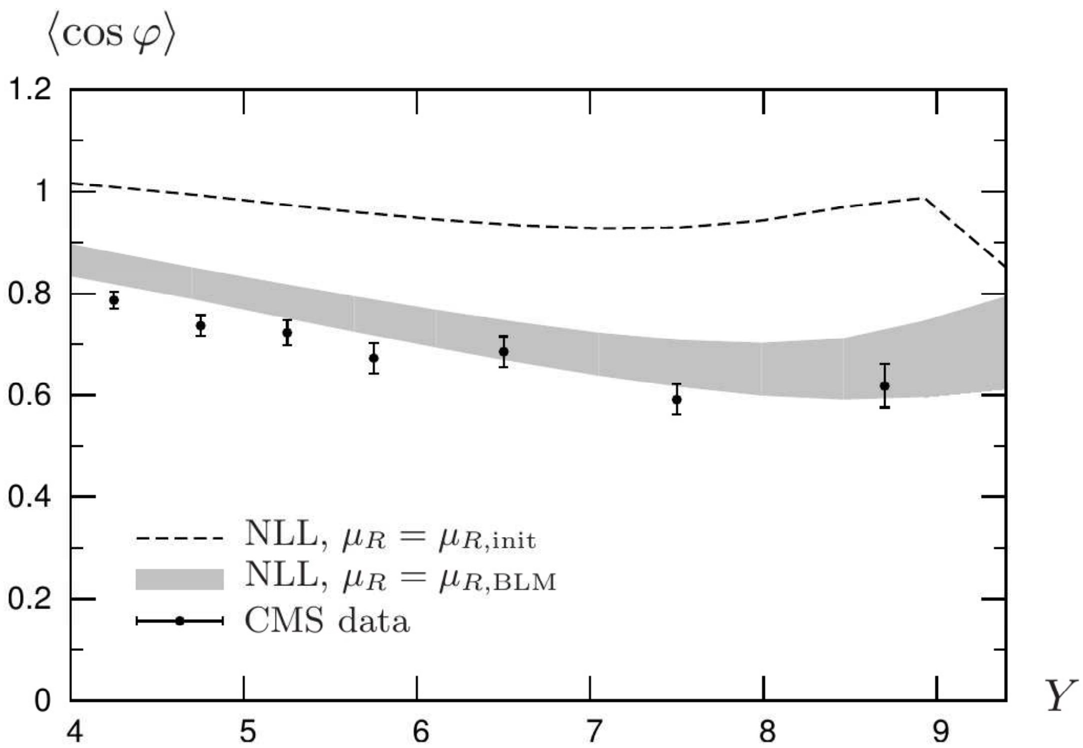

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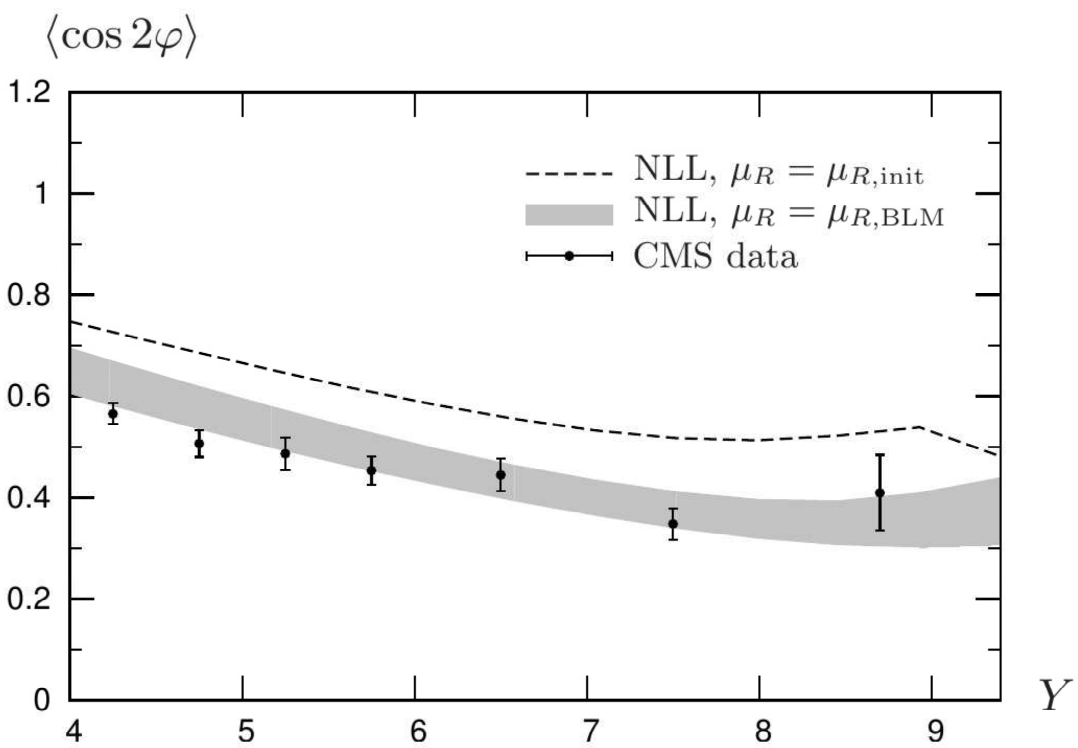

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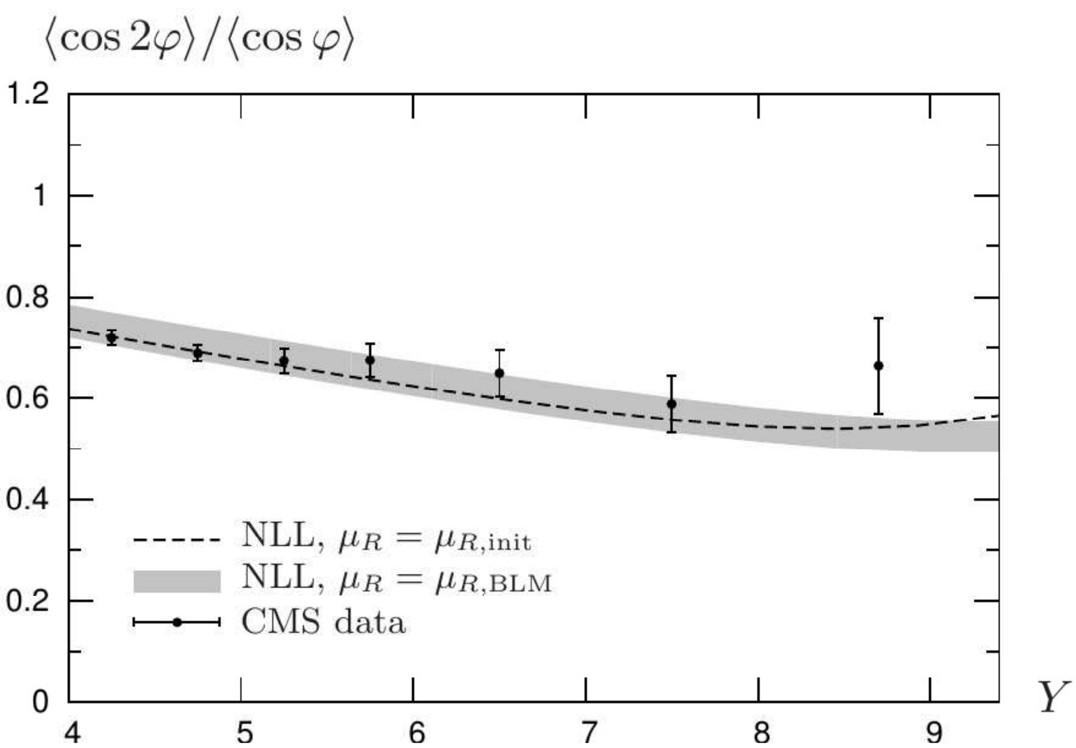
$$\mu_R^2 = \exp\left[\frac{1}{2}\chi_0 - \frac{5}{3} + 2\left(1 + \frac{2}{3}I\right)\right] p_{T1}\, p_{T2} \sim (10 \div 20)^2\, p_{T1}\, p_{T2}$$



Very large renorm. scale

NLL BFKL + BLM provides good description of data

Other methods

- *[Ducloué,Szymanowski,Wallon '14]*

  try to take into account energy-momentum conservation

  by using an effective rapidity Y_{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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Underlying idea: to effectively include higher-orders

- 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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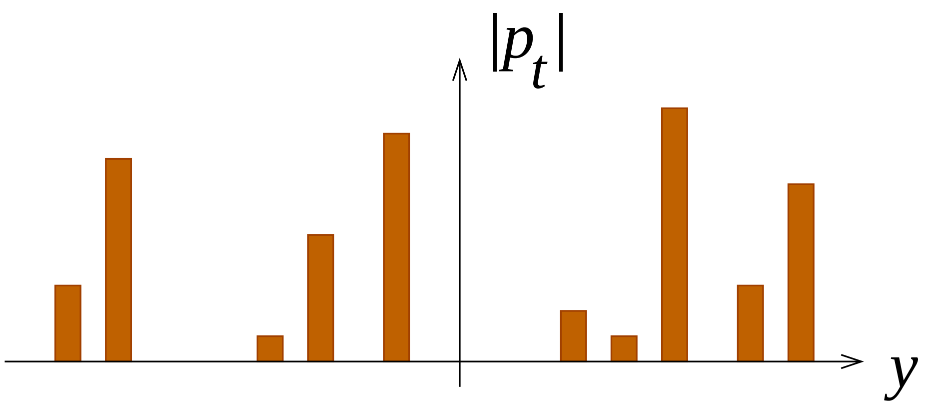

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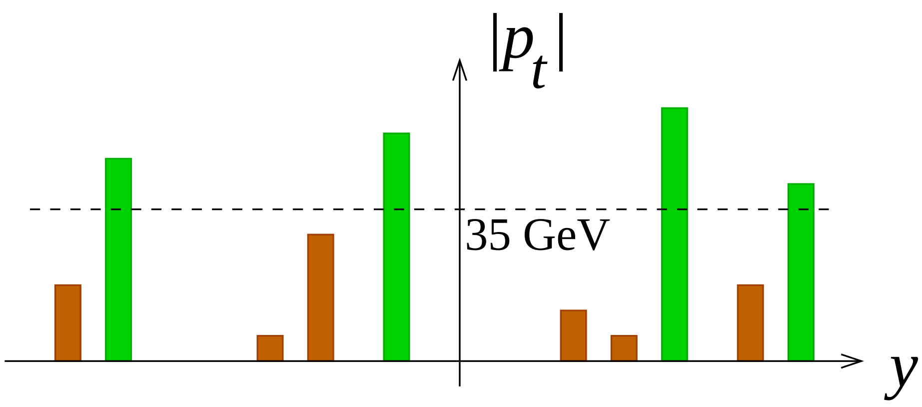

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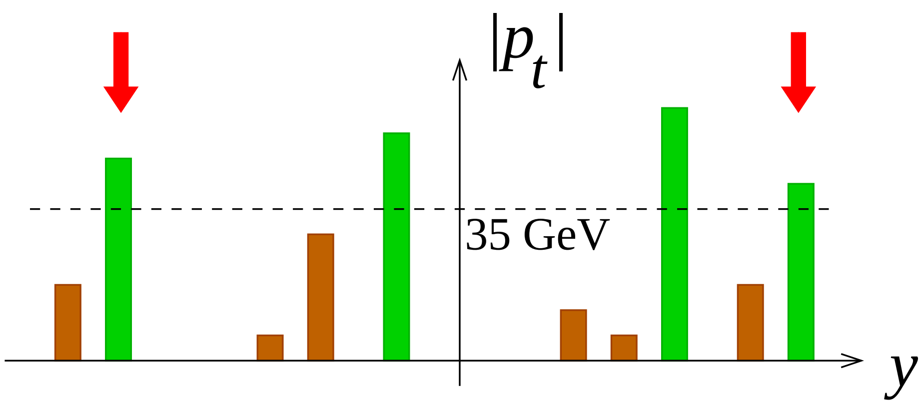
- Tag jets with largest rapidity difference (MN jets)

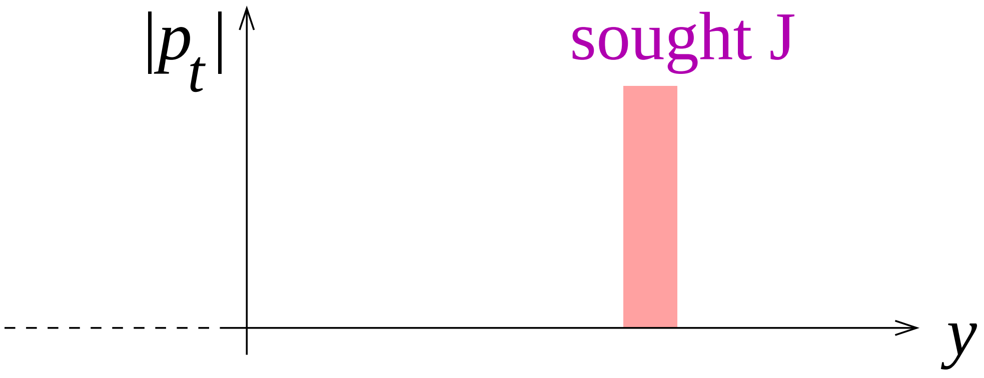


On the definition of MN Jets

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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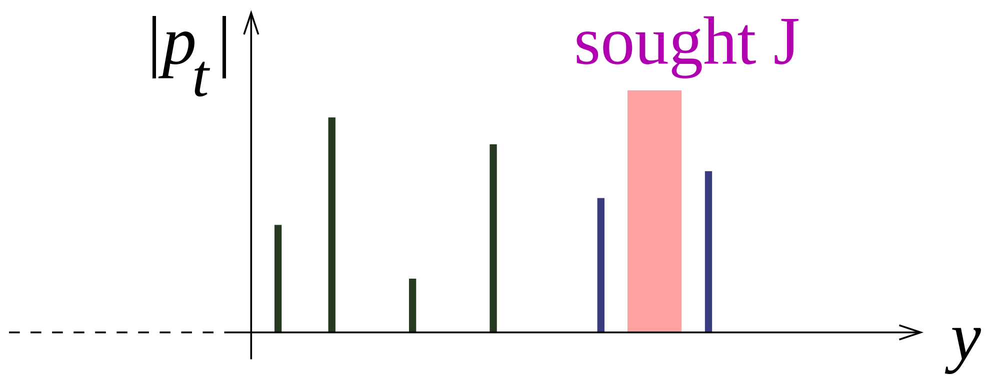

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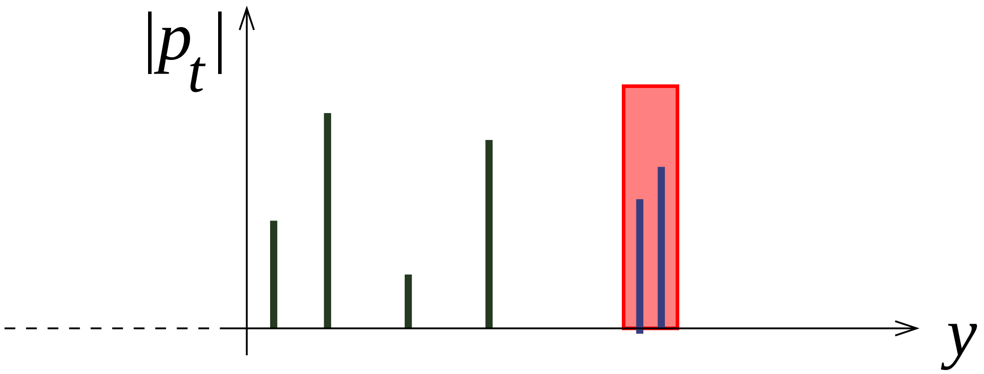

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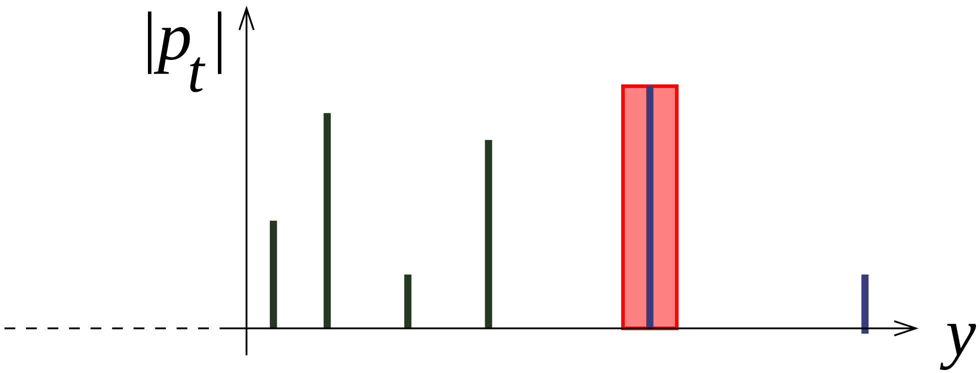

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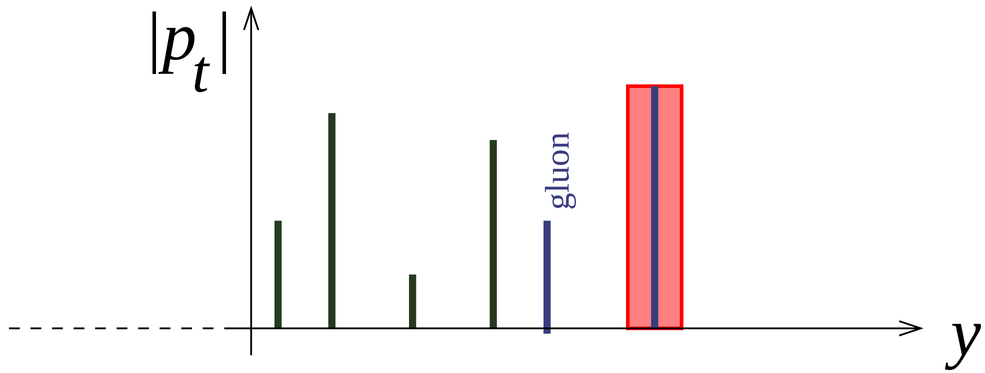

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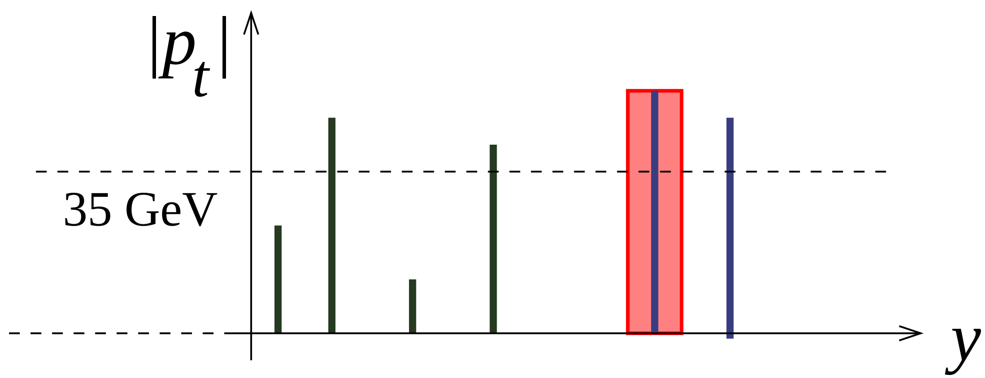

A hard parton ($\to$ jet at hadron level)
can be emitted at rapidity $y > y_J$

On the definition of MN Jets

- Conceptually, the 2 prescriptions are very 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 $y < y_{J2}$

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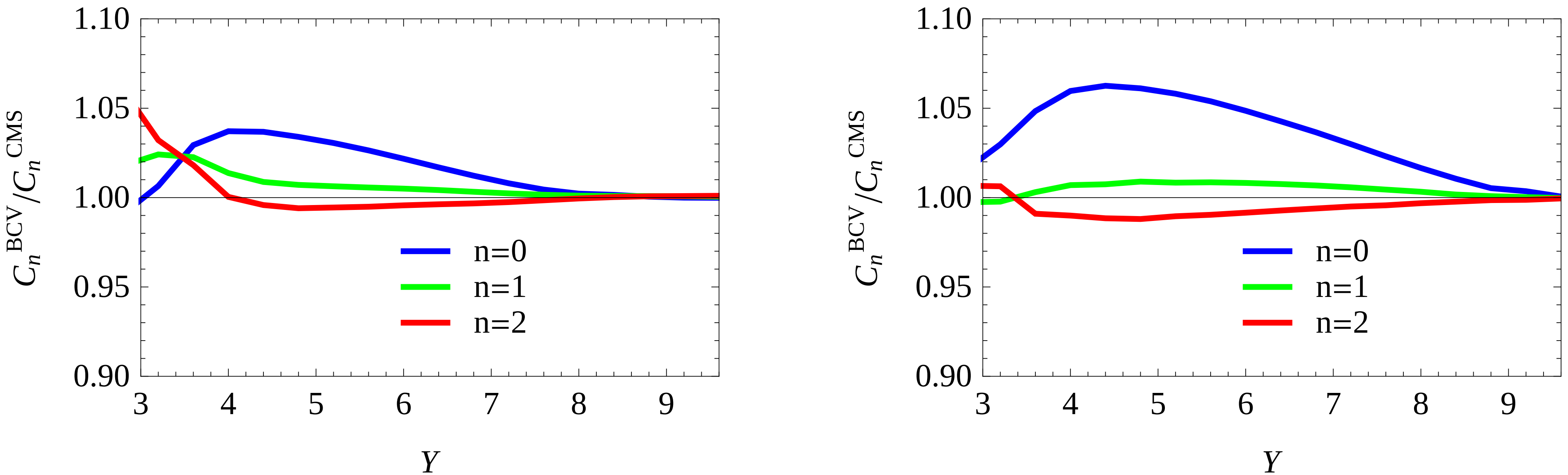
- Conceptually, the 2 prescriptions are very different
- In practice, since $Y \equiv y_{J1} - y_{J2} \gg 1$, it is rather unlikely to emit additional partons with $y > y_{J1}$ or $y < y_{J2}$
- Largest difference at $\sqrt{s} = 7$ TeV is $\simeq 4\%$ at $Y \simeq 4$; at 13 TeV $\simeq 7\%$



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

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- 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

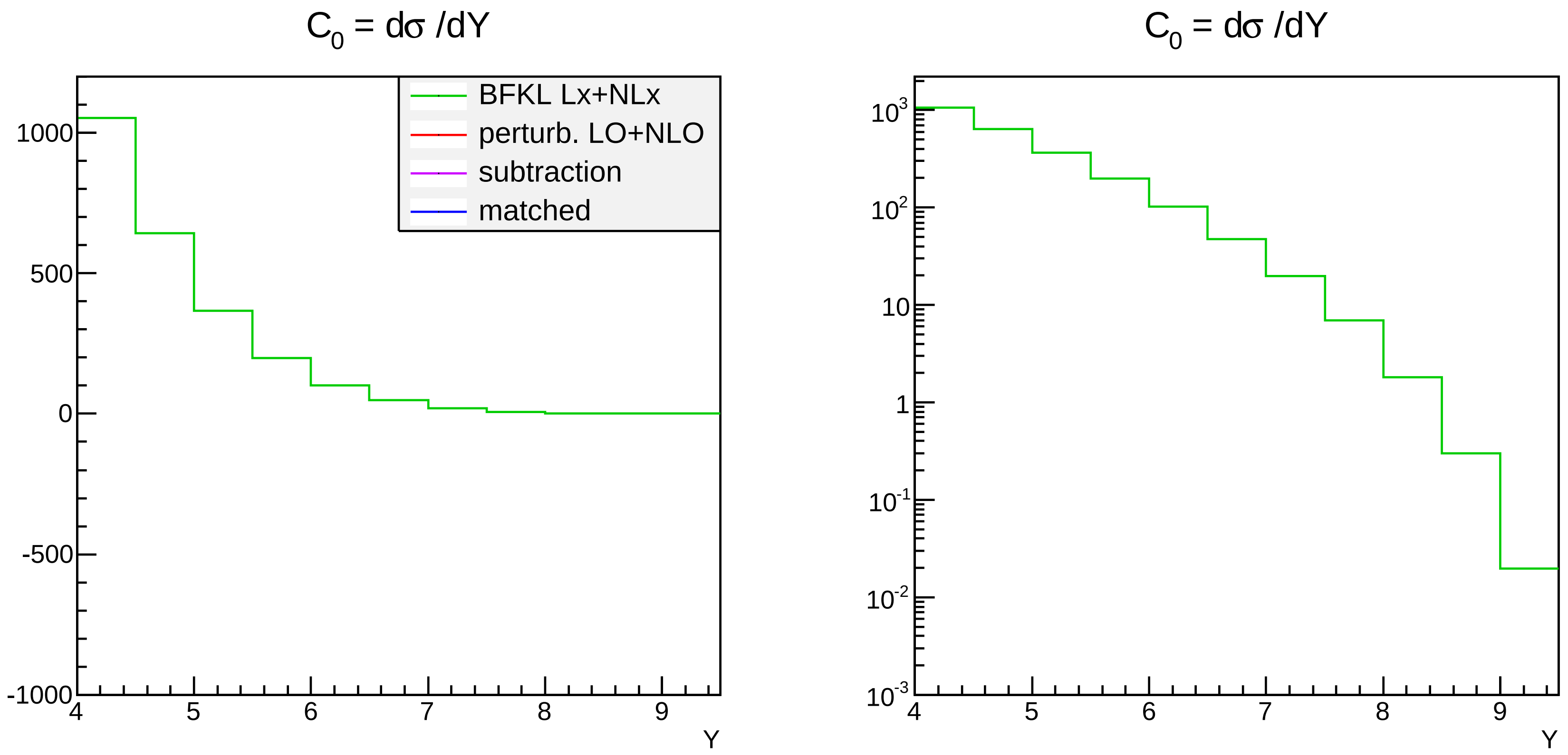
Matching (sym. jets $p_{T1}, p_{T2} > 35\mathrm{GeV}$)

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

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

(same colours in plots)

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



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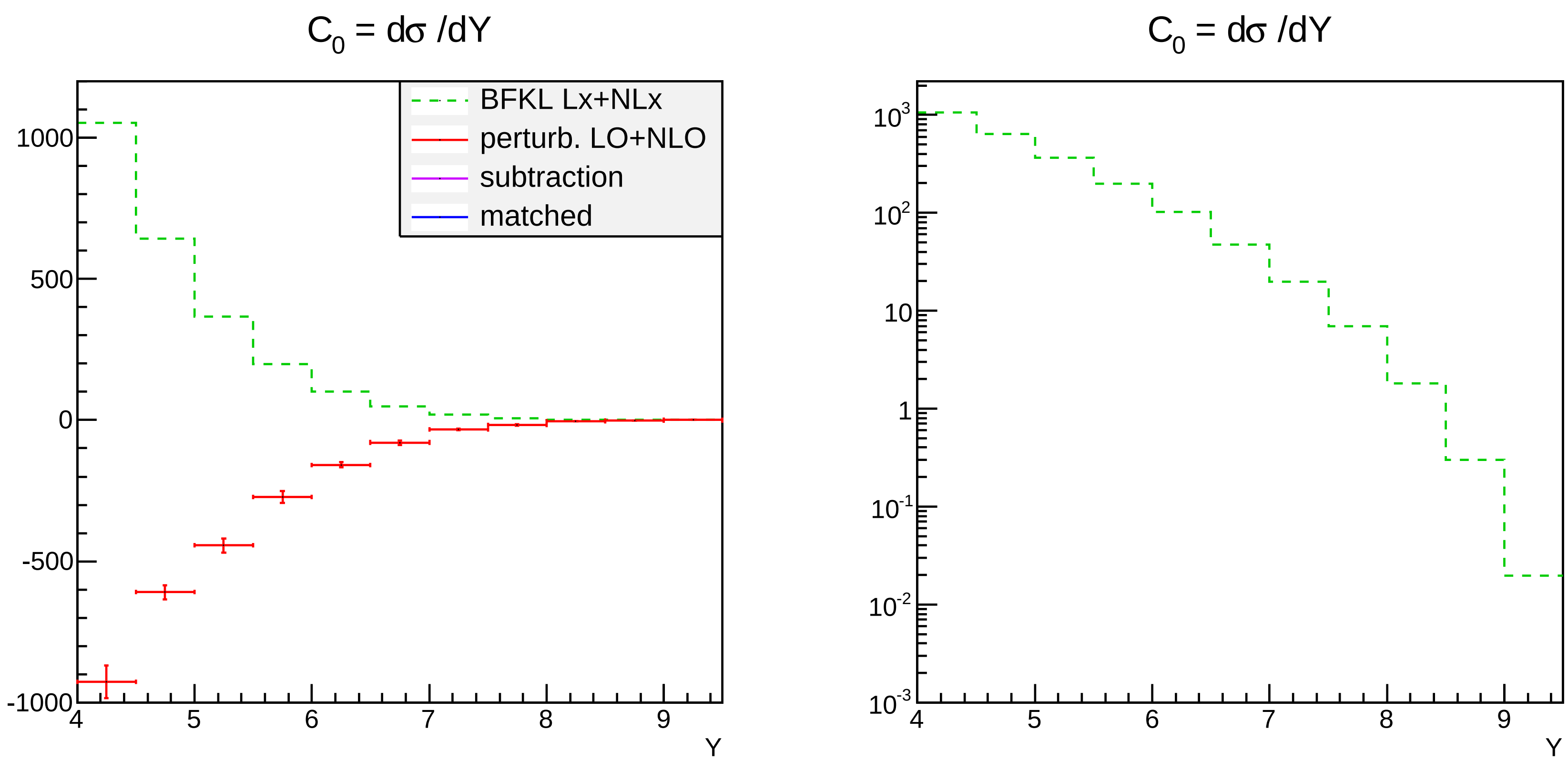

LO+NLO cross section obtained with NLOJET++ *[Nagy]* is negative!

Large errors due to very slow convergence in MC integration

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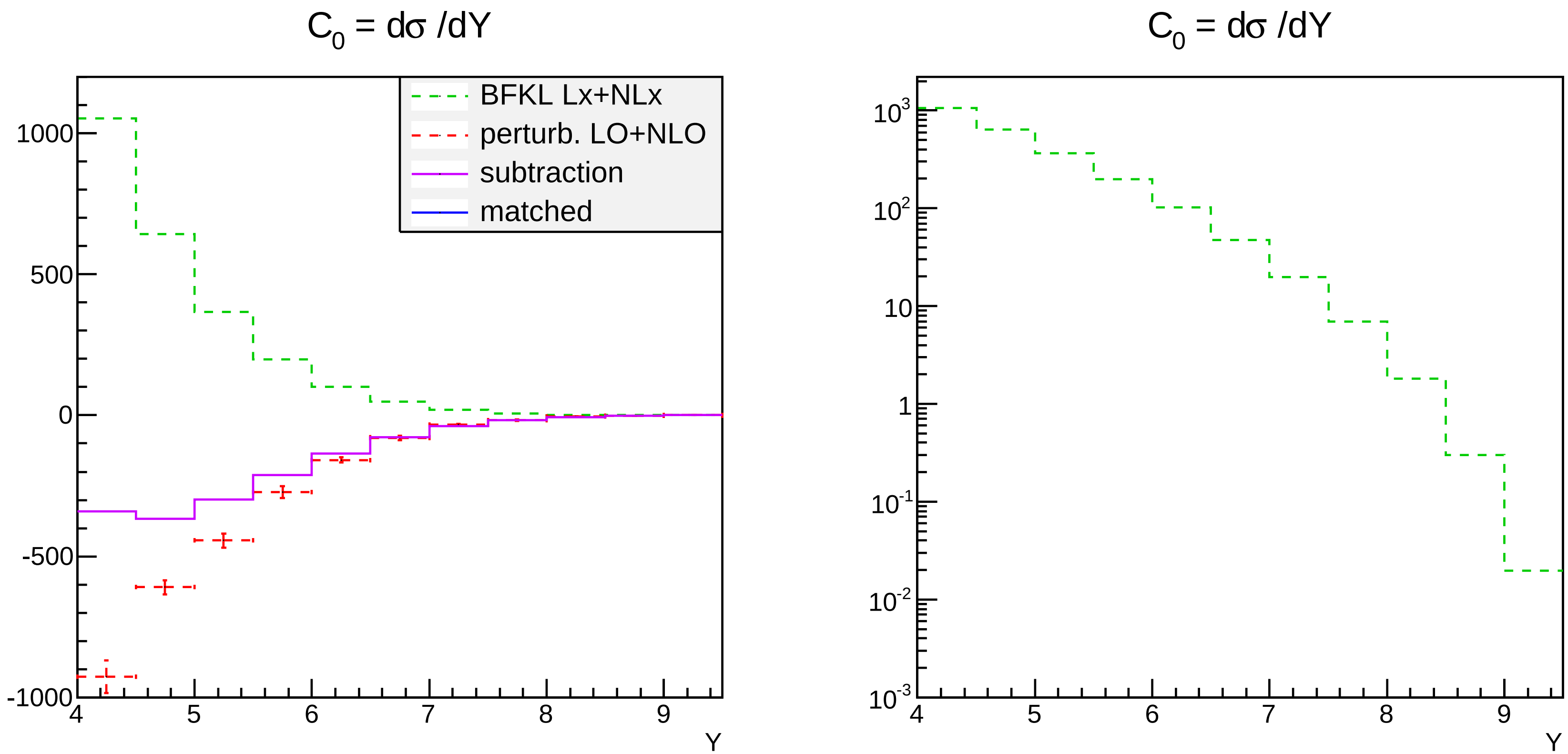

LO+NLO cross section obtained with NLOJET++ *[Nagy]* is negative!

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However, also the subtraction is negative

Their difference is moderate

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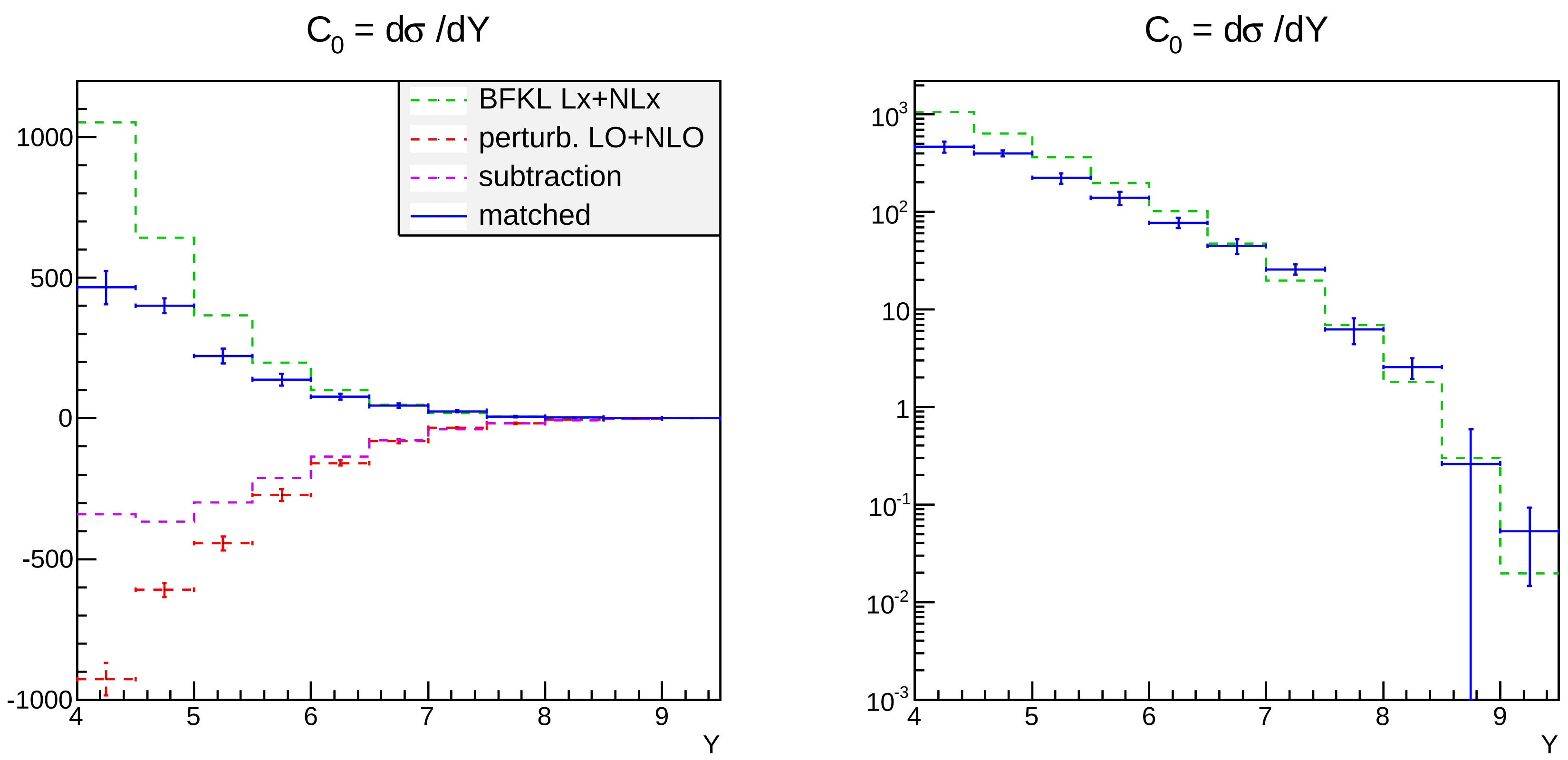


LO+NLO cross section obtained with NLOJET++ *[Nagy]* is negative!

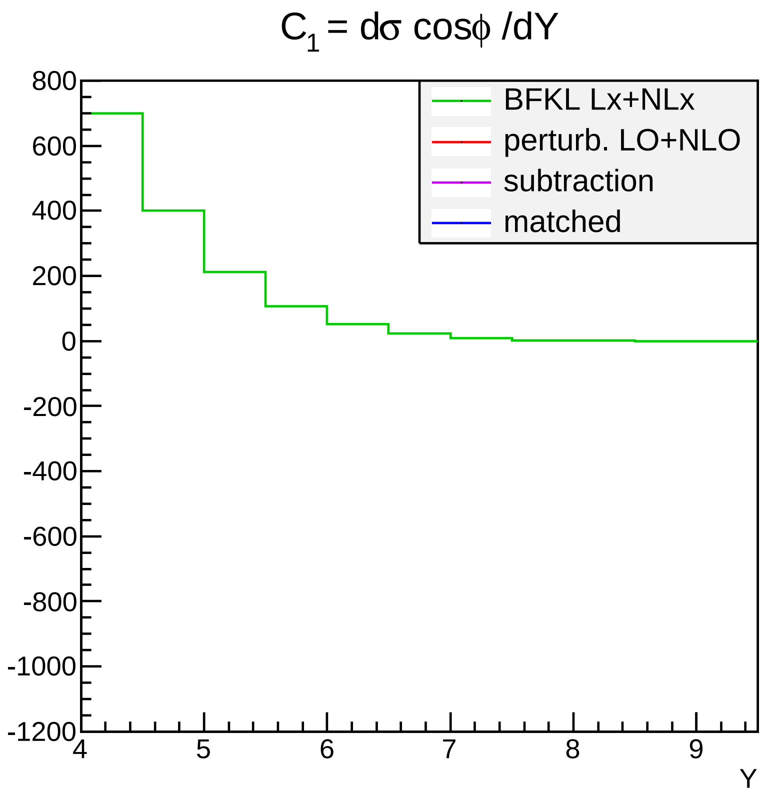
Large errors due to very slow convergence in MC integration

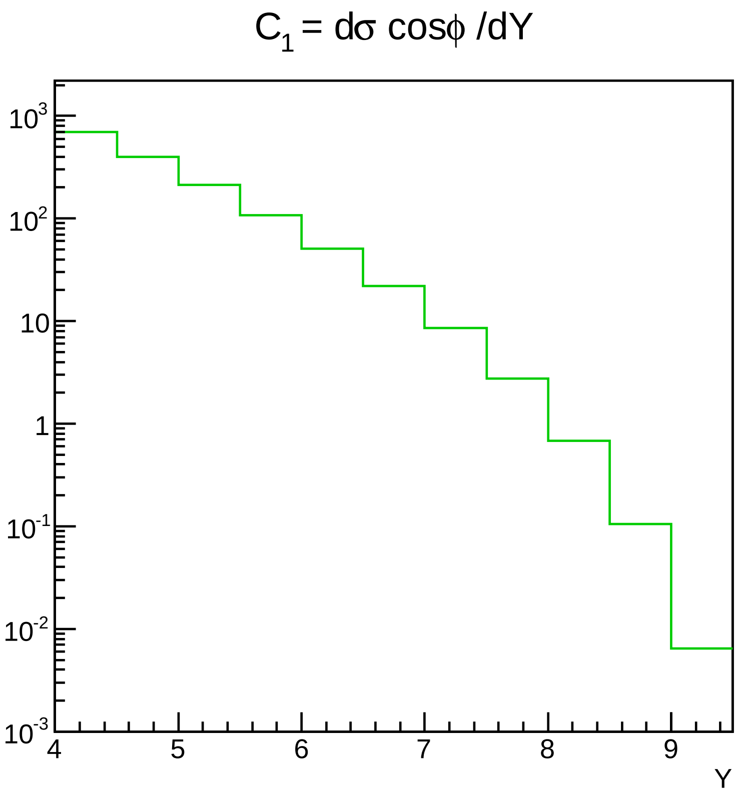
However, also the subtraction is negative

Their difference is moderate

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

Matching (azimuthal coeff. C_1)





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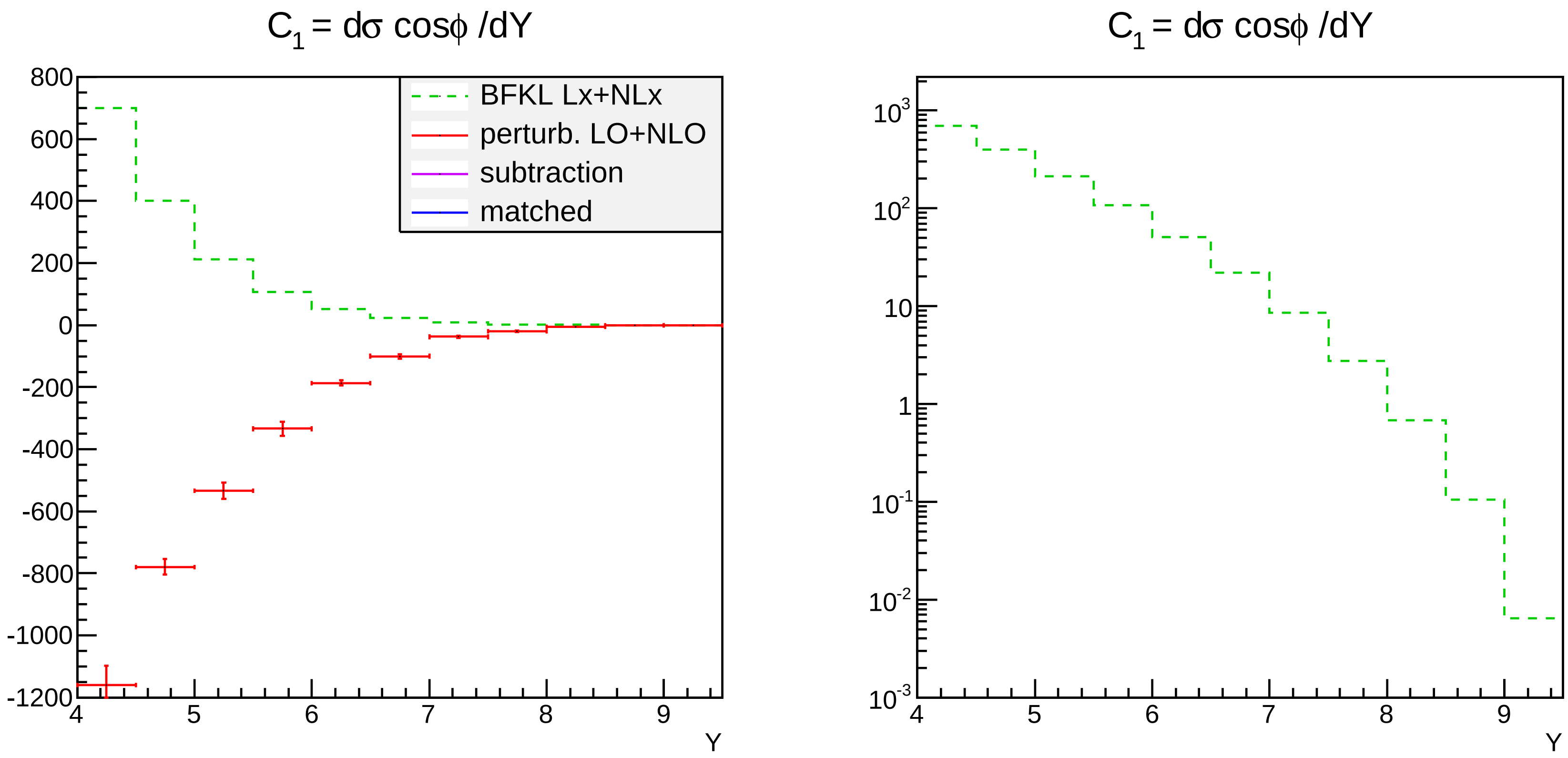

Large errors of NLO calculation due to very slow convergence in MC integration

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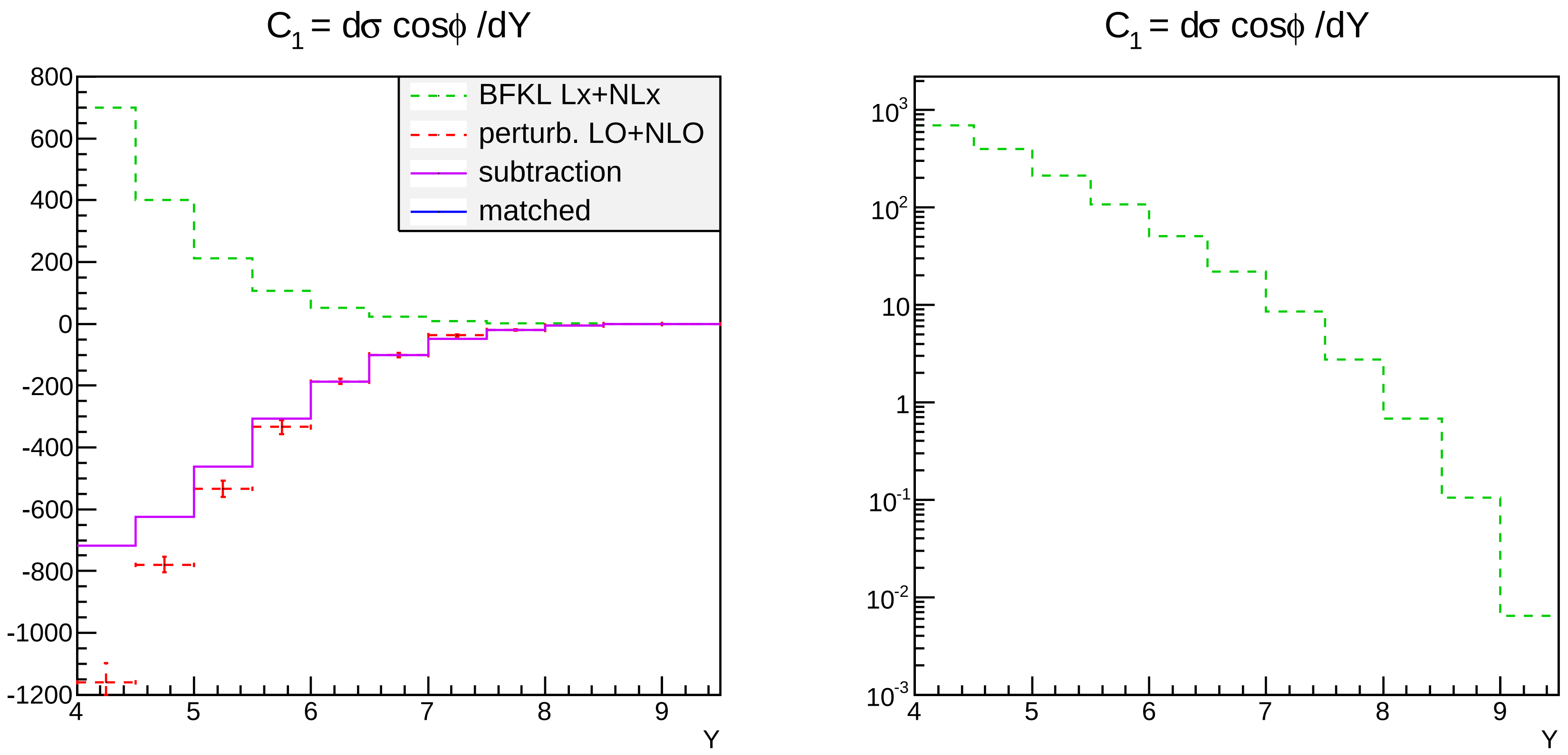

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Moderate difference between NLO and subtraction

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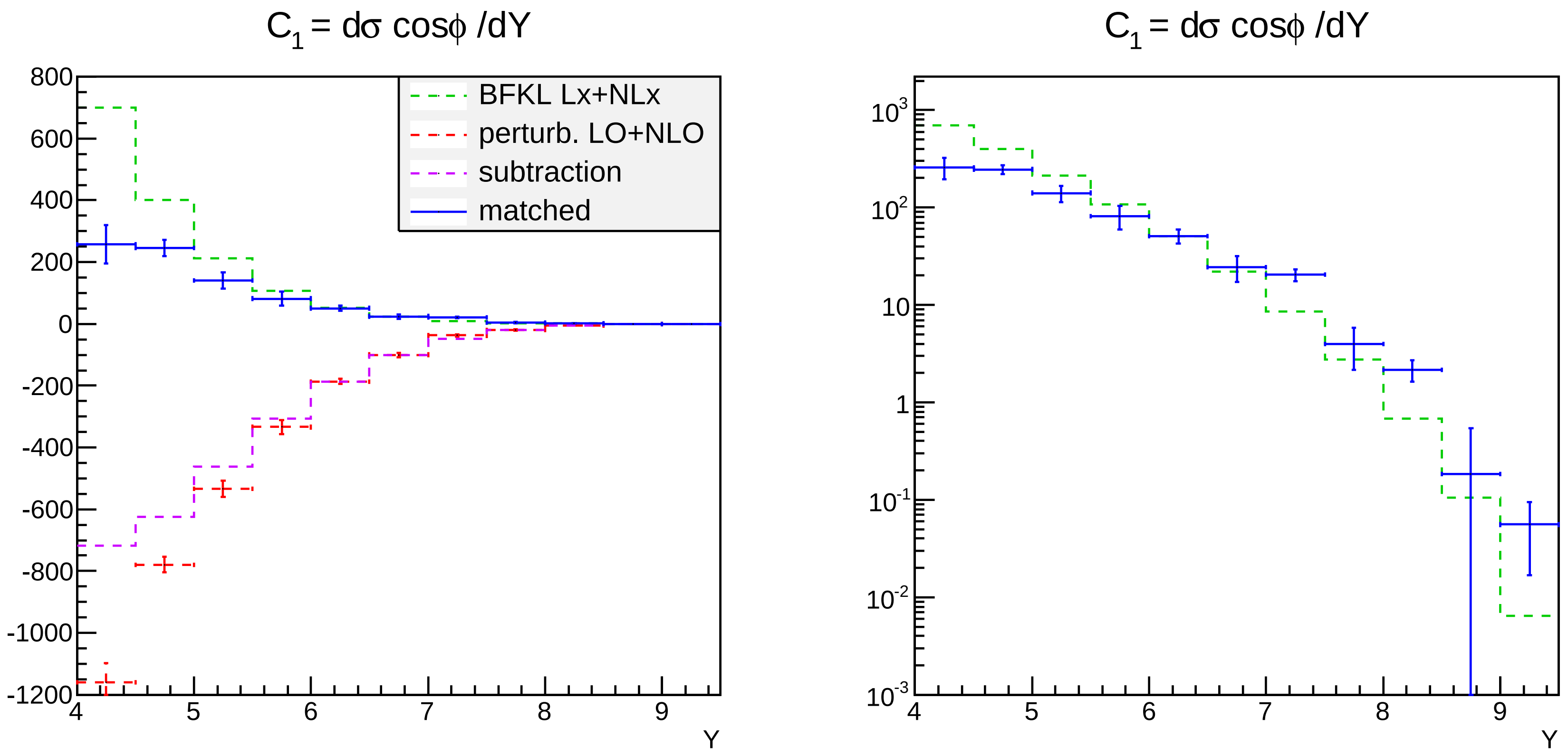

Large errors of NLO calculation due to very slow convergence in MC integration

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

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

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

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$$= A(\Delta, \epsilon) + B \log(\epsilon) - C\,(\Delta + \epsilon) \log(\Delta + \epsilon)$$

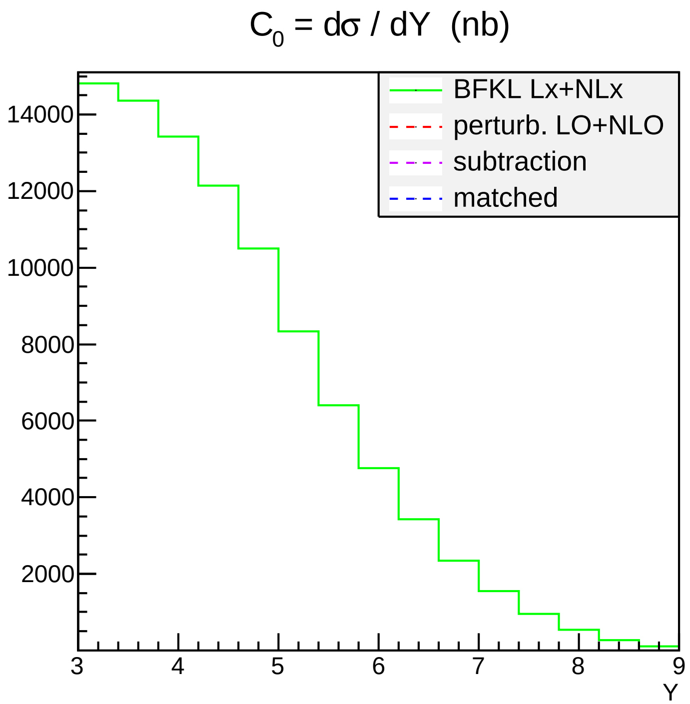
thus fixed order PTh is not reliable in this case (finite, but infinite deriv at $\Delta = 0$)

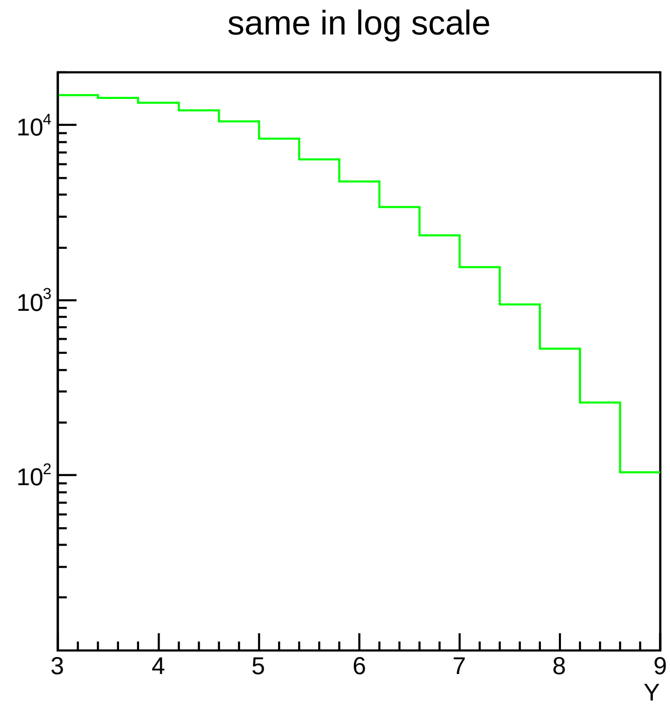
An analogous singularity occurs in the PT expansion of LL BFKL *[Andersen, Del Duca et al. '01]*

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

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





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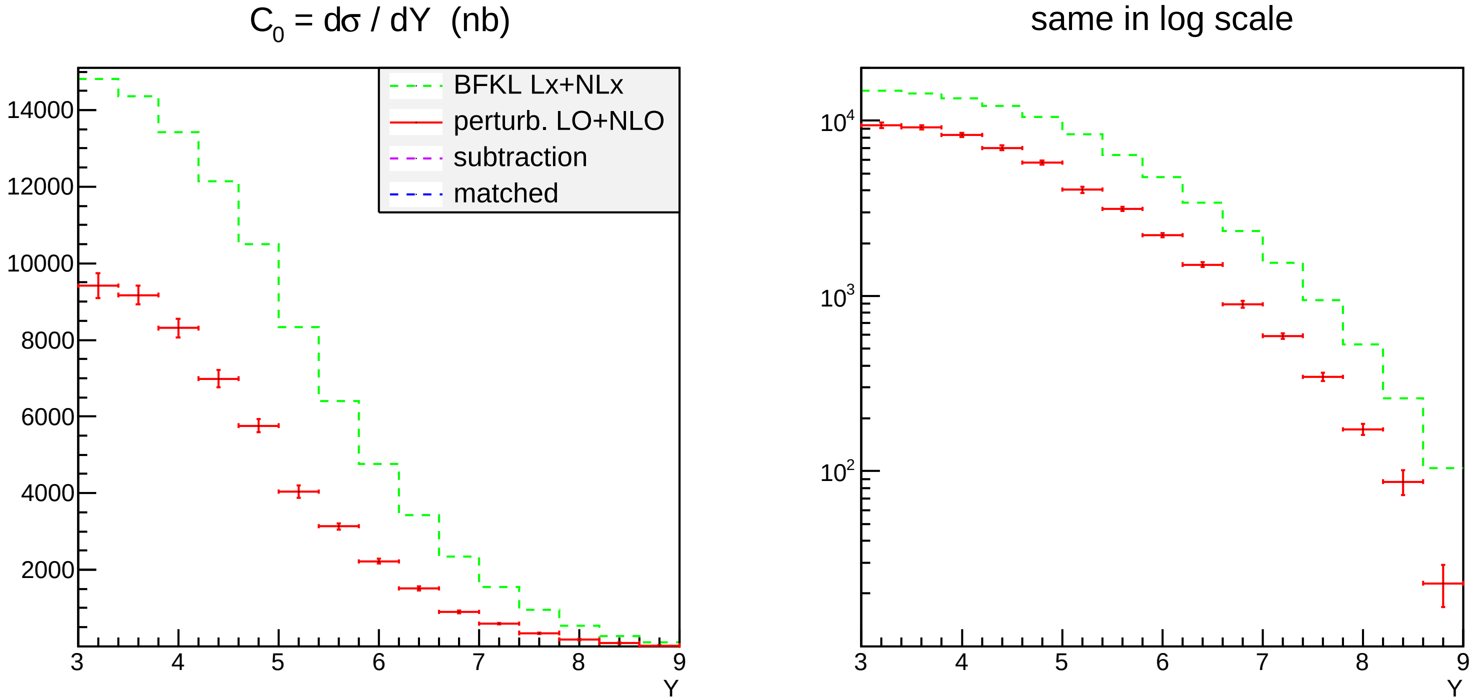

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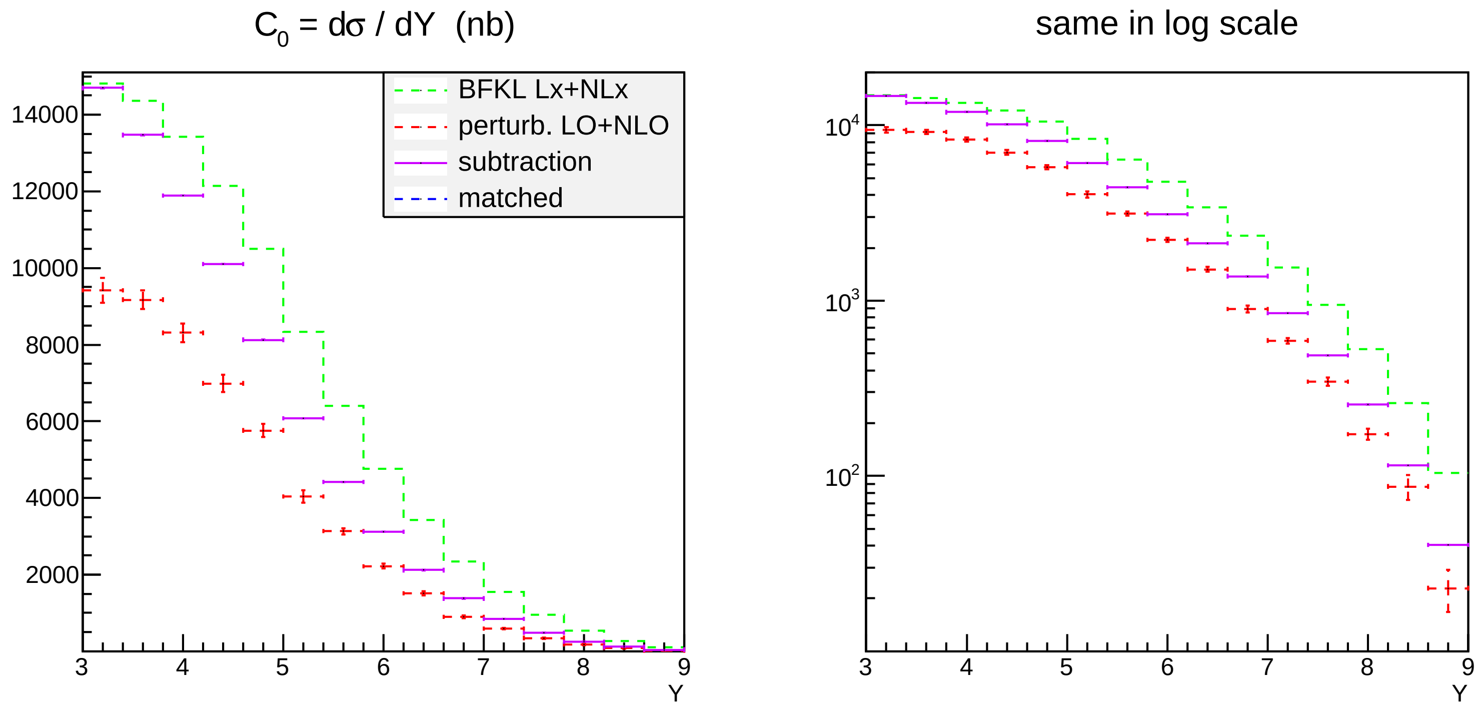

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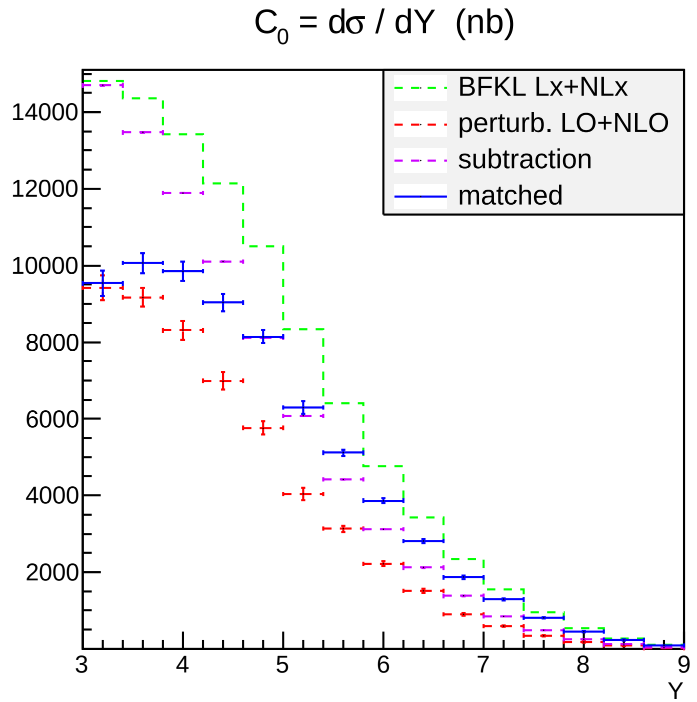
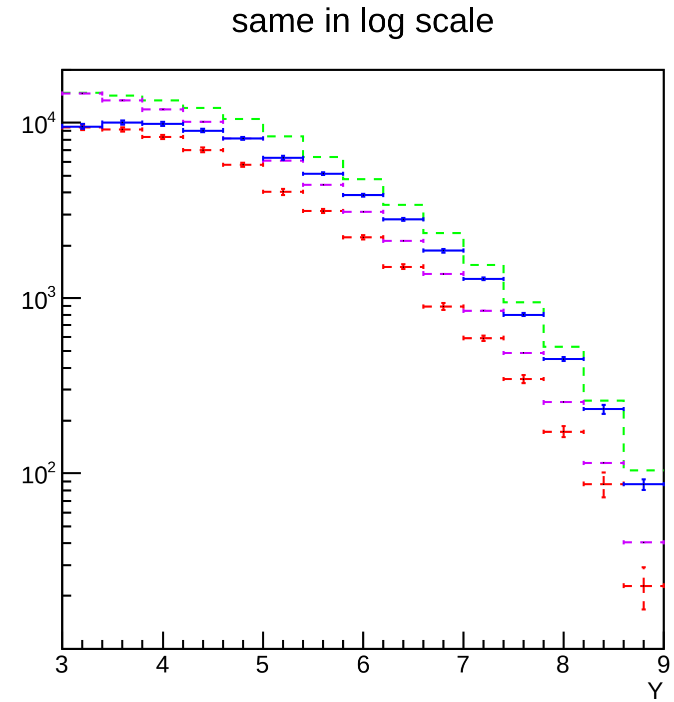
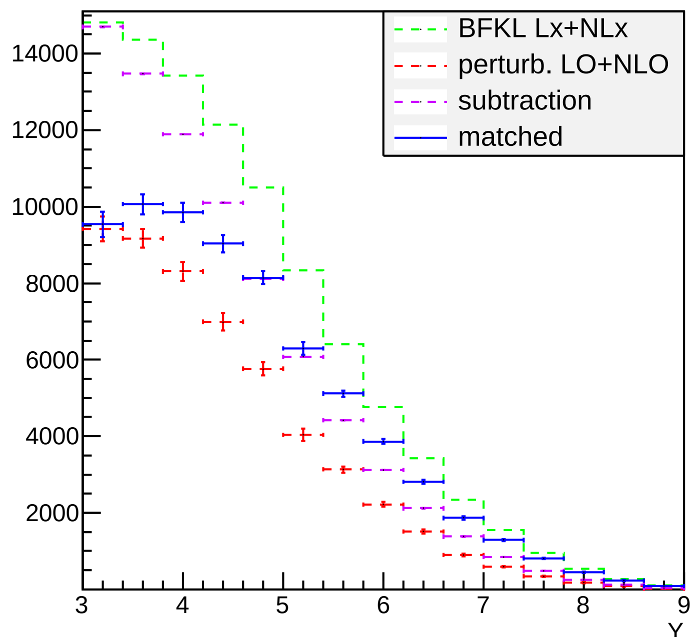




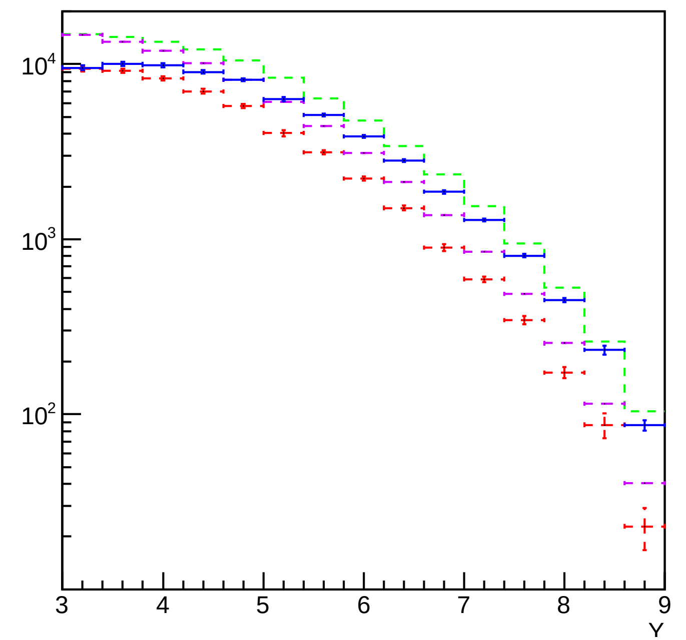
Procedure is more stable than the previous one

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

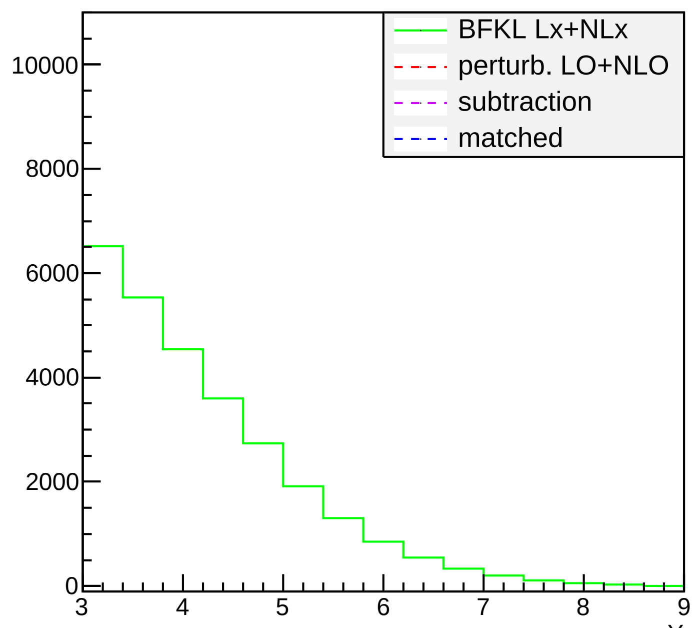
$C_0 = d\sigma / dY$ (nb)



same in log scale



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



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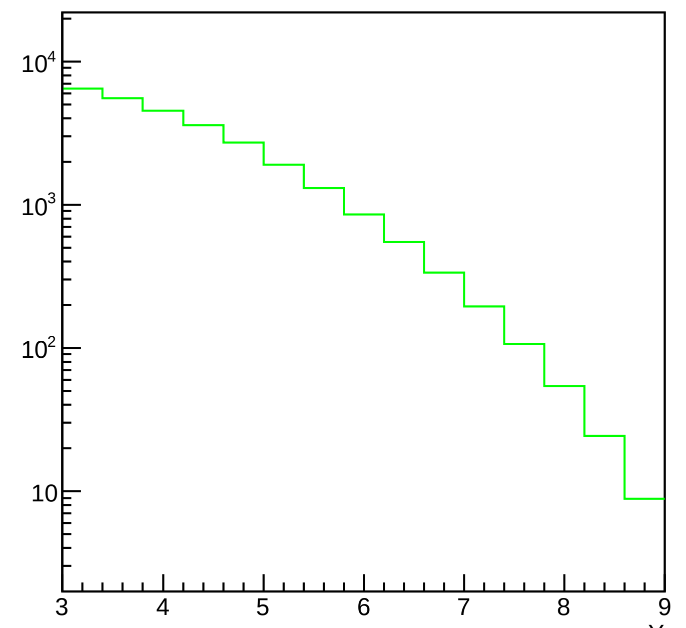

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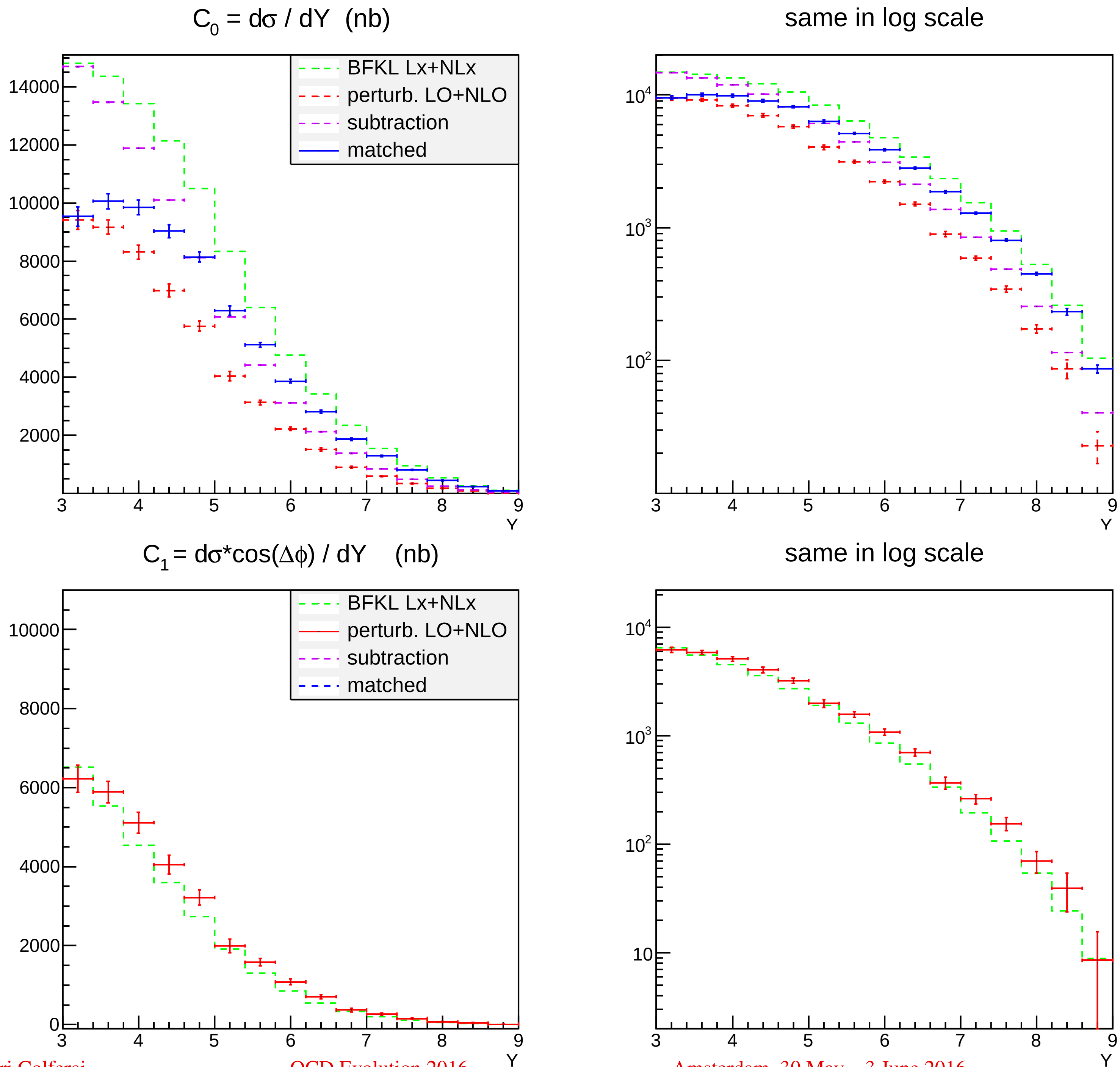

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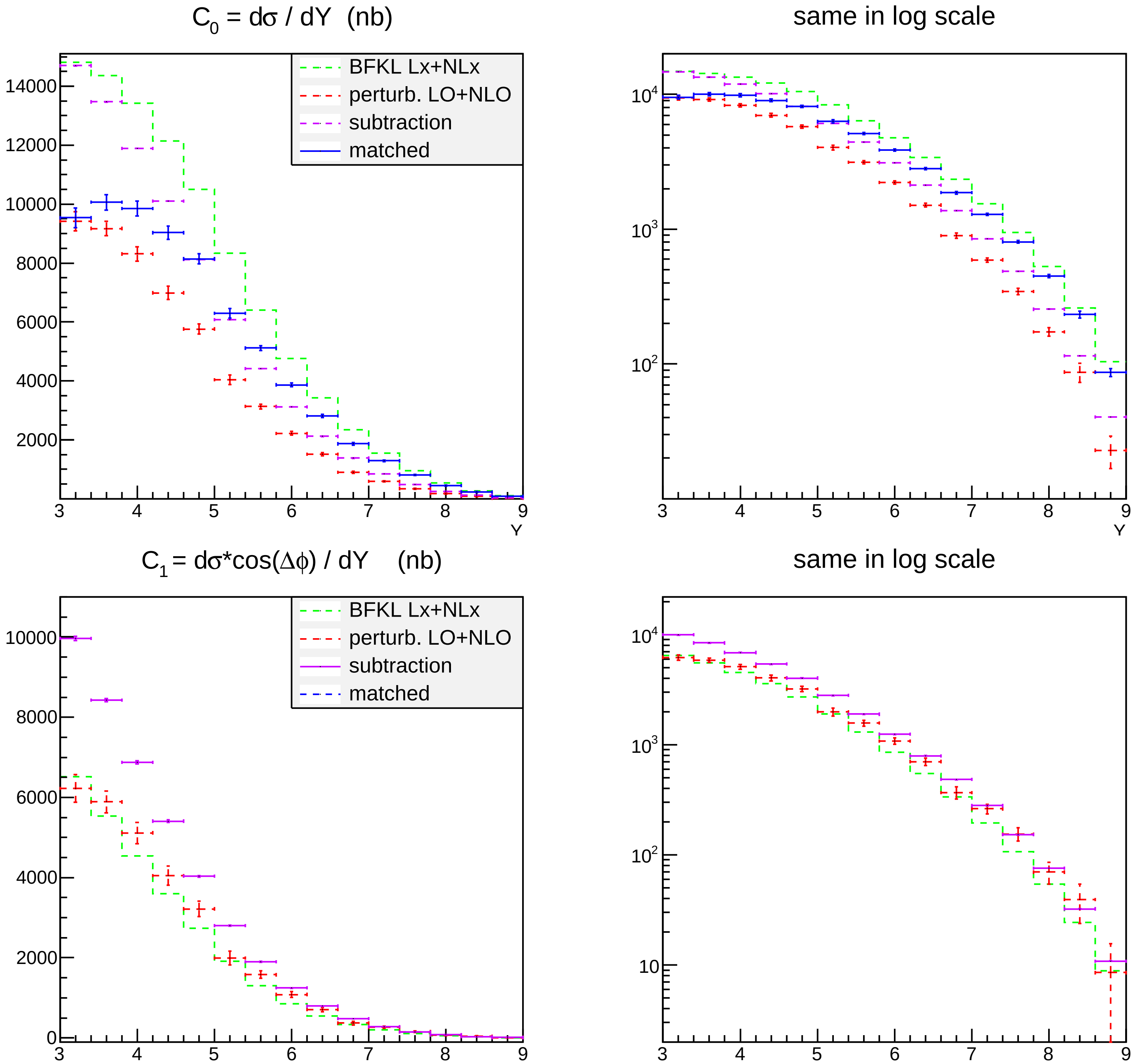

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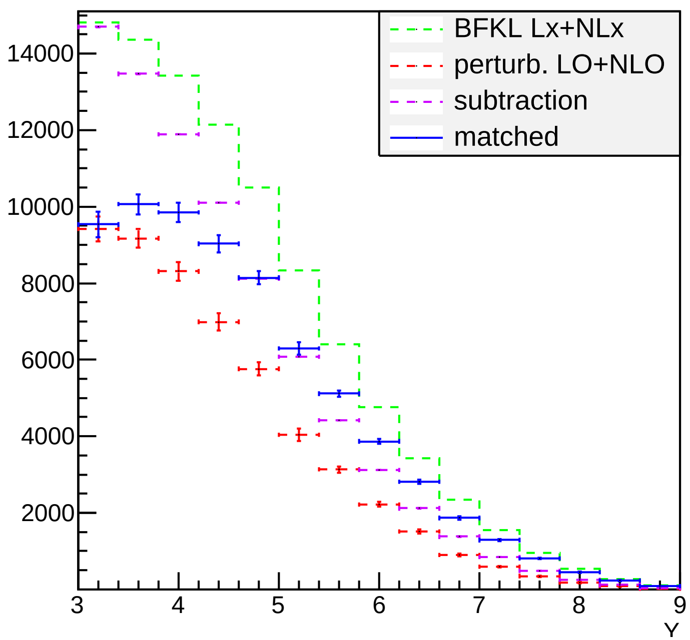

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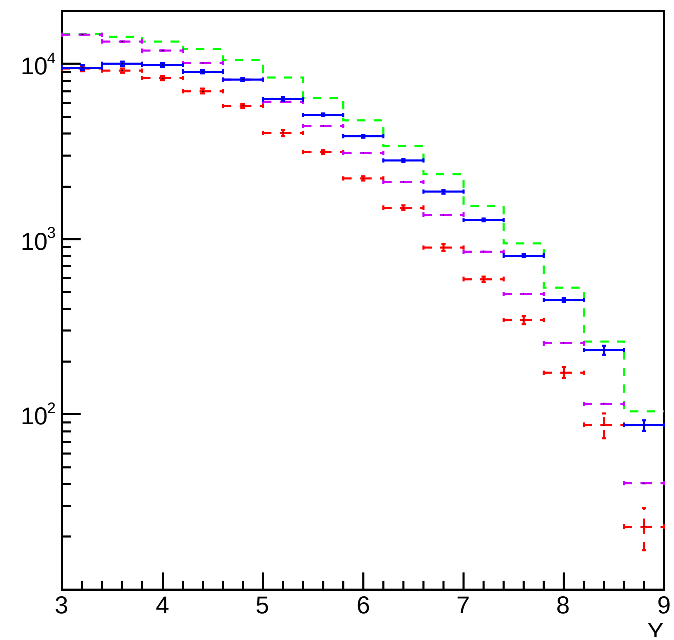

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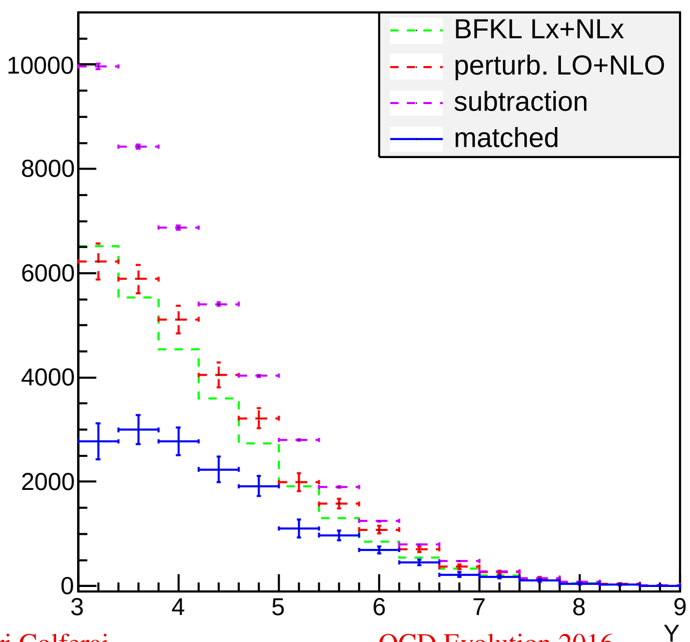

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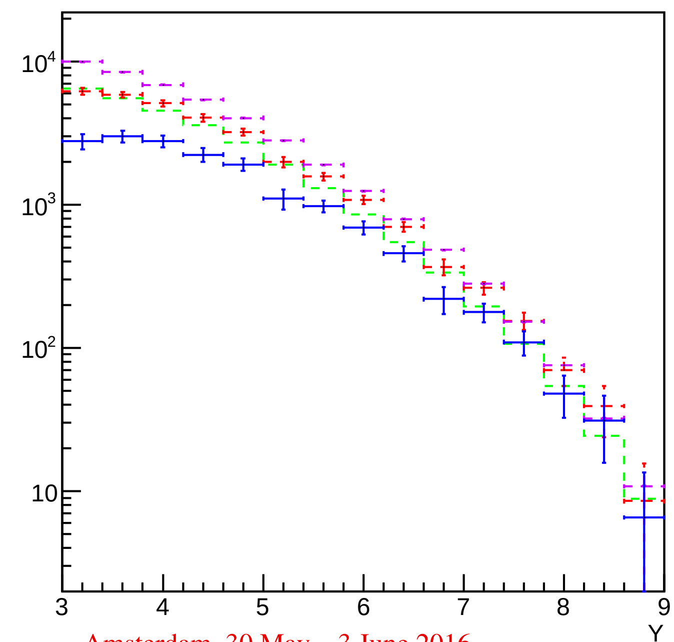

Advice for future analysis

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 open questions
- Fixed order MC and NLL BFKL quite different, in some cases close to data, but overall agreement is not good
- Jet vertices have to be modified in order to comply with experimental analysis (jets with largest rapidity separation)
- 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