Mueller-Navelet jets at LHC: matching NLL BFKL with fixed NLO calculations

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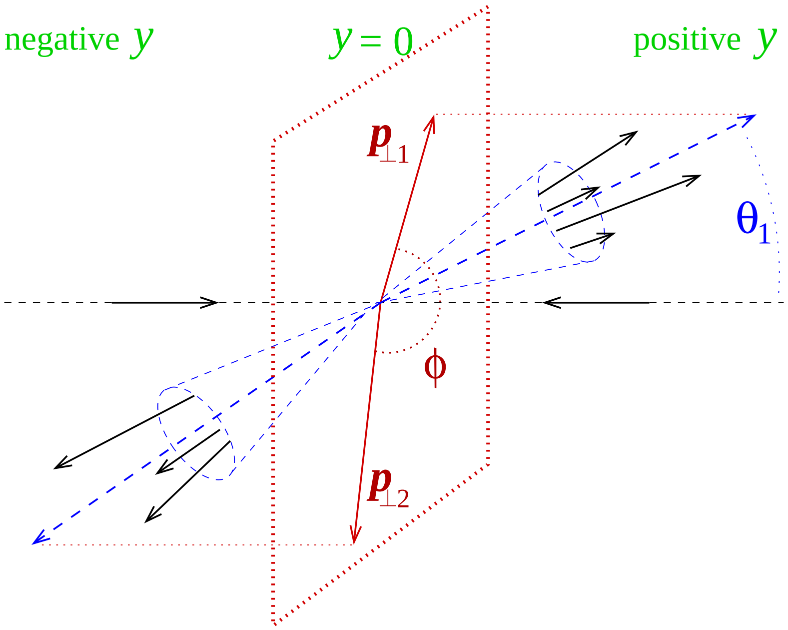
Motivation and Outline

- 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 $s \gg -t \gg \Lambda^2_{\rm QCD}$, P.Th still applicable with all-order resummation of logarithmic coefficients $(\alpha_{\rm s} \log s)^n$
- 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 fixed-order based MC
  - Improvement by matching fixed NLO with resummed BFKL:
    method and preliminary results

Mueller-Navelet jets

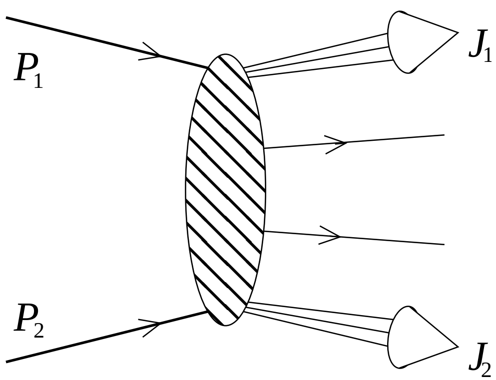
One of most famous testing processes for studying PT high-energy QCD at hadron colliders *[Mueller Navelet 1987]*



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

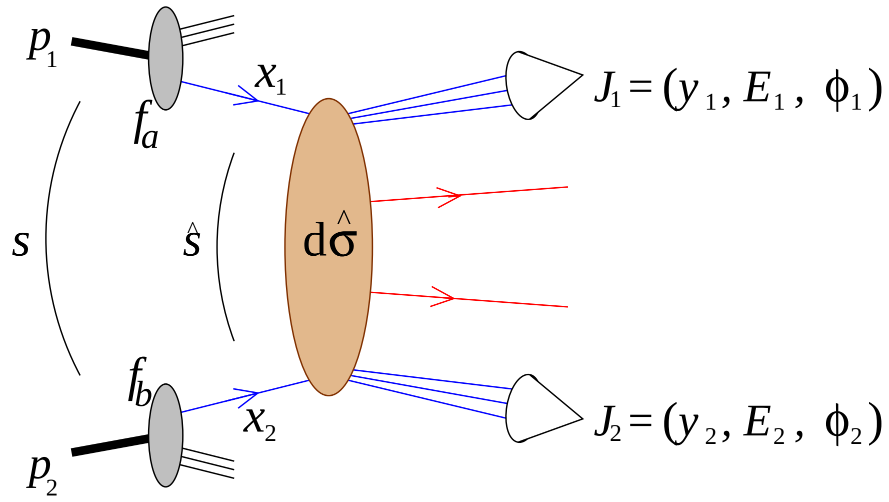
Rapidity: $y = \log(\cot(\theta/2))$

- Comparable hard scales (jet energies) limit the logarithms of collinear type $\log(E_1/E_2)$
- Big separation in rapidity $Y \equiv y_1 - y_2 \quad \Rightarrow \quad$ large $\log(s/E_J^2) \sim Y$



Anything can be emitted between the jets

Factorization of NP effects



MN propose use of factorization theorem:

$$\frac{\mathrm{d}\sigma}{(\mathrm{d}y_1\mathrm{d}E_1\mathrm{d}\phi_1)(\mathrm{d}y_2\mathrm{d}E_2\mathrm{d}\phi_2)} =$$

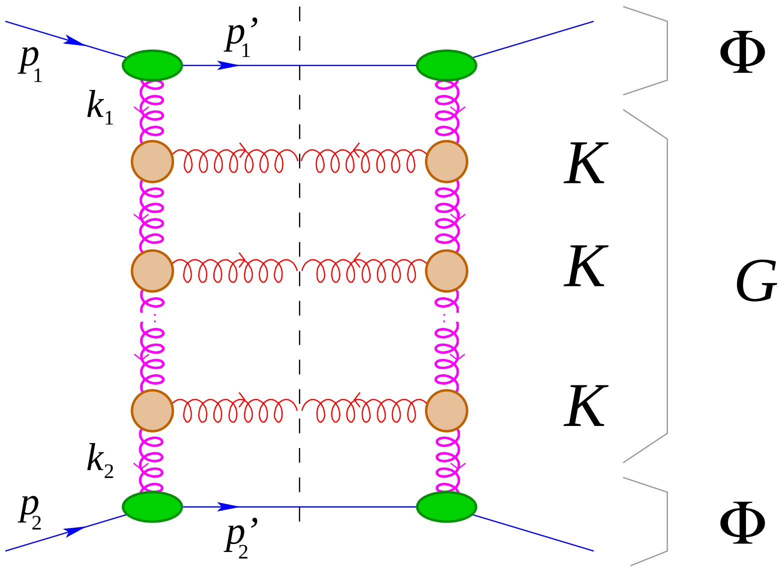
$$\frac{\mathrm{d}\sigma}{\mathrm{d}J_1\mathrm{d}J_2} = \sum_{a,b=g,q,\bar{q}} \int_0^1 \mathrm{d}x_1\mathrm{d}x_2 \; f_a(x_1, E_{J1}^2) f_b(x_2, E_{J2}^2) \frac{\mathrm{d}\hat{\sigma}(x_1, x_2)}{\mathrm{d}J_1\mathrm{d}J_2}$$

Factorization formula justified because:

- semi-inclusive observable (jets + anything)
- large transferred momenta ($E_J \gg \Lambda_{\mathrm{QCD}}$)

High energy factorization and BFKL

At high energy, partonic cross section is factorized in $\boldsymbol{k}_\perp$-dependent factors



Impact factors describe coupling of external particles with (reggeized) gluons

All energy dependence in universal Gluon Green's function is the sum of all ladder diagrams

$$\sigma_{12}(s) = \int \mathrm{d}\boldsymbol{k}_1 \mathrm{d}\boldsymbol{k}_2\ \Phi_1(\boldsymbol{k}_1) G(s, \boldsymbol{k}_1, \boldsymbol{k}_2) \Phi_2(\boldsymbol{k}_2)$$

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

$$K = \alpha_\mathrm{s} K_0 + \alpha_\mathrm{s}^2 K_1 + \dots$$

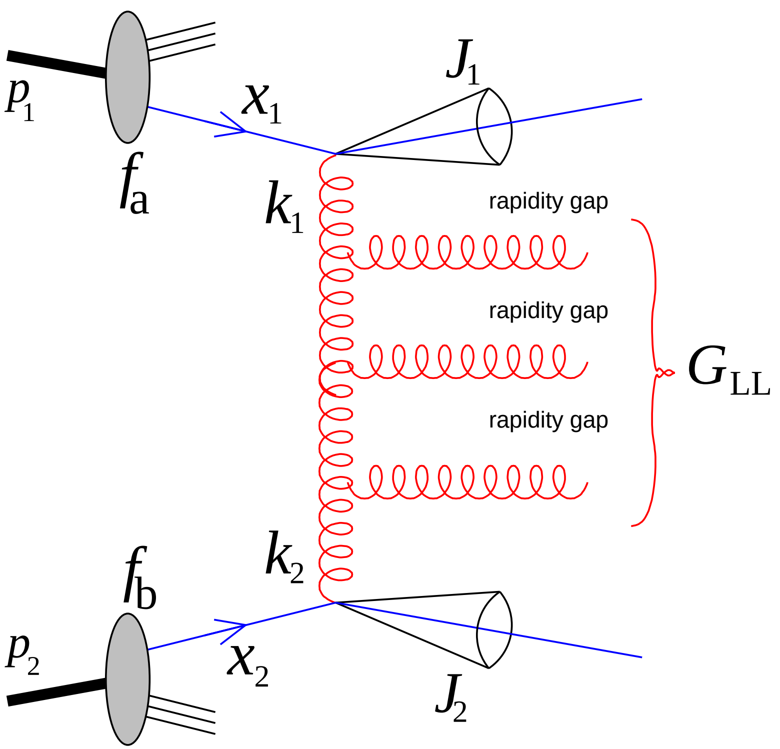
LL resums $\alpha_\mathrm{s}^n \log^n s$ *[Balitski-Fadin -Kuraev-Lipatov '78]*

NLL resums $\alpha_\mathrm{s}^n \log^{n-1} s$ *[Fadin-Lipatov, Camici-Ciafaloni '98]*

MN Jets in LL approximation

MN jet factorization formula is a convolution of 5 objects

Starting from LL factorization formula



$$\frac{\mathrm{d}\sigma(s)}{\mathrm{d}J_1\mathrm{d}J_2} = \sum_{a,b}\int_0^1 \mathrm{d}x_1\mathrm{d}x_2 \int \mathrm{d}\boldsymbol{k}_1\mathrm{d}\boldsymbol{k}_2$$
$$\times\; f_a(x_1)$$
$$\times\; V_a^{(0)}(x_1,\boldsymbol{k}_1;J_1)$$
$$\times\; G_{\rm LL}(x_1x_2s,\boldsymbol{k}_1,\boldsymbol{k}_2)$$
$$\times\; V_b^{(0)}(x_2,\boldsymbol{k}_2;J_2)$$
$$\times\; f_b(x_2)$$

where $V_a^{(0)}(x,\boldsymbol{k};J) = \alpha_{\rm s}C_a\delta(\boldsymbol{k}-\boldsymbol{p}_J)\delta(x-x_J)$ and $x_J = |\boldsymbol{p}_J|\mathrm{e}^{y_J}/\sqrt{s}$

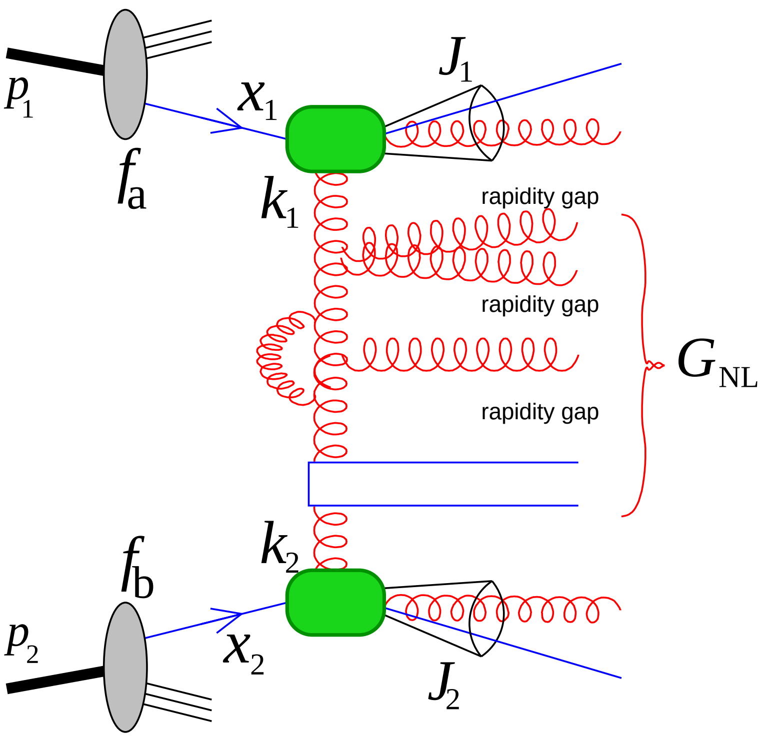
- Kinematics characterized by large rapidity gaps among particles
- At LL level the jet vertex condition is trivial (only 1 parton)

MN Jets in NLL approximation

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

Proved NLL factorization formula

$$\frac{\mathrm{d}\sigma(s)}{\mathrm{d}J_1\mathrm{d}J_2} = \sum_{a,b}\int_0^1 \mathrm{d}x_1\mathrm{d}x_2 \int \mathrm{d}\boldsymbol{k}_1\mathrm{d}\boldsymbol{k}_2$$
$$\times\ f_a(x_1)$$
$$\times\ \boldsymbol{V_a^{(1)}}(x_1,\boldsymbol{k}_1;J_1)$$
$$\times\ G_{\mathrm{NL}}(x_1x_2s,\boldsymbol{k}_1,\boldsymbol{k}_2)$$
$$\times\ \boldsymbol{V_b^{(1)}}(x_2,\boldsymbol{k}_2;J_2)$$
$$\times\ f_b(x_2)$$



where $V_a^{(0)}(x,\boldsymbol{k};J) = \alpha_s C_a \delta(\boldsymbol{k}-\boldsymbol{p}_J)\delta(x-x_J)$ and $x_J = |\boldsymbol{p}_J|\mathrm{e}^{y_J}/\sqrt{s}$

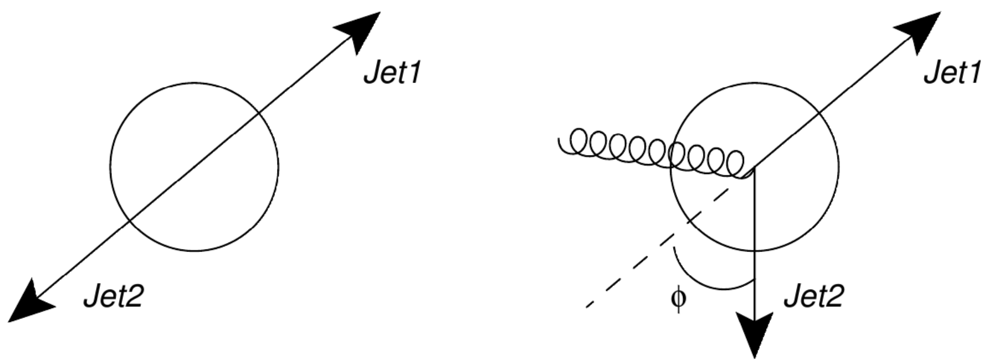
- Pairs of particles can be emitted without rapidity gaps
- At NL level the jet vertex condition is non-trivial (e.g. depends on jet radius R and algorithm)

CMS analysis of MN jets at 7 TeV

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

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

- 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: $E_{T1,2} > 35\text{GeV}$, $|y_i| < 4.7$

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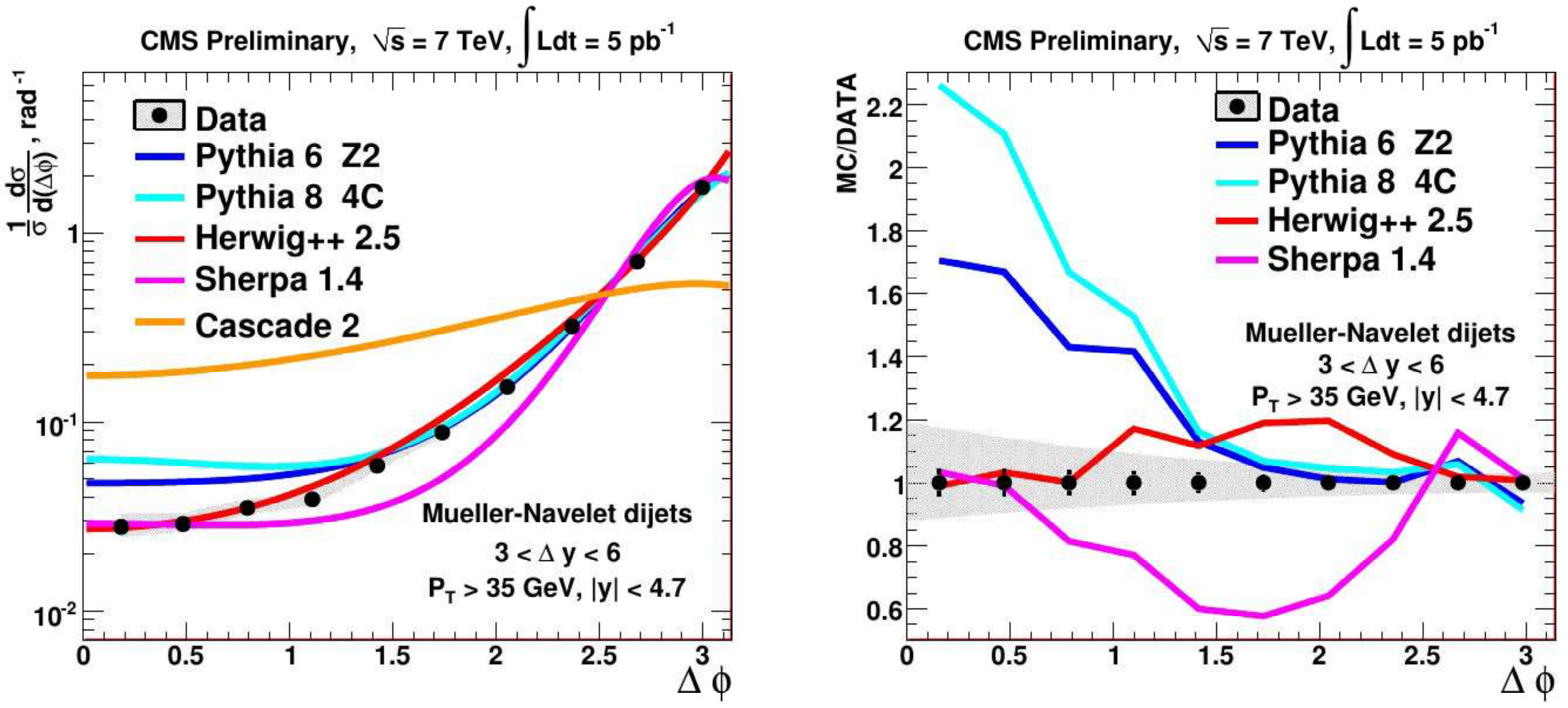

Some MC are close to data somewhere in ϕ

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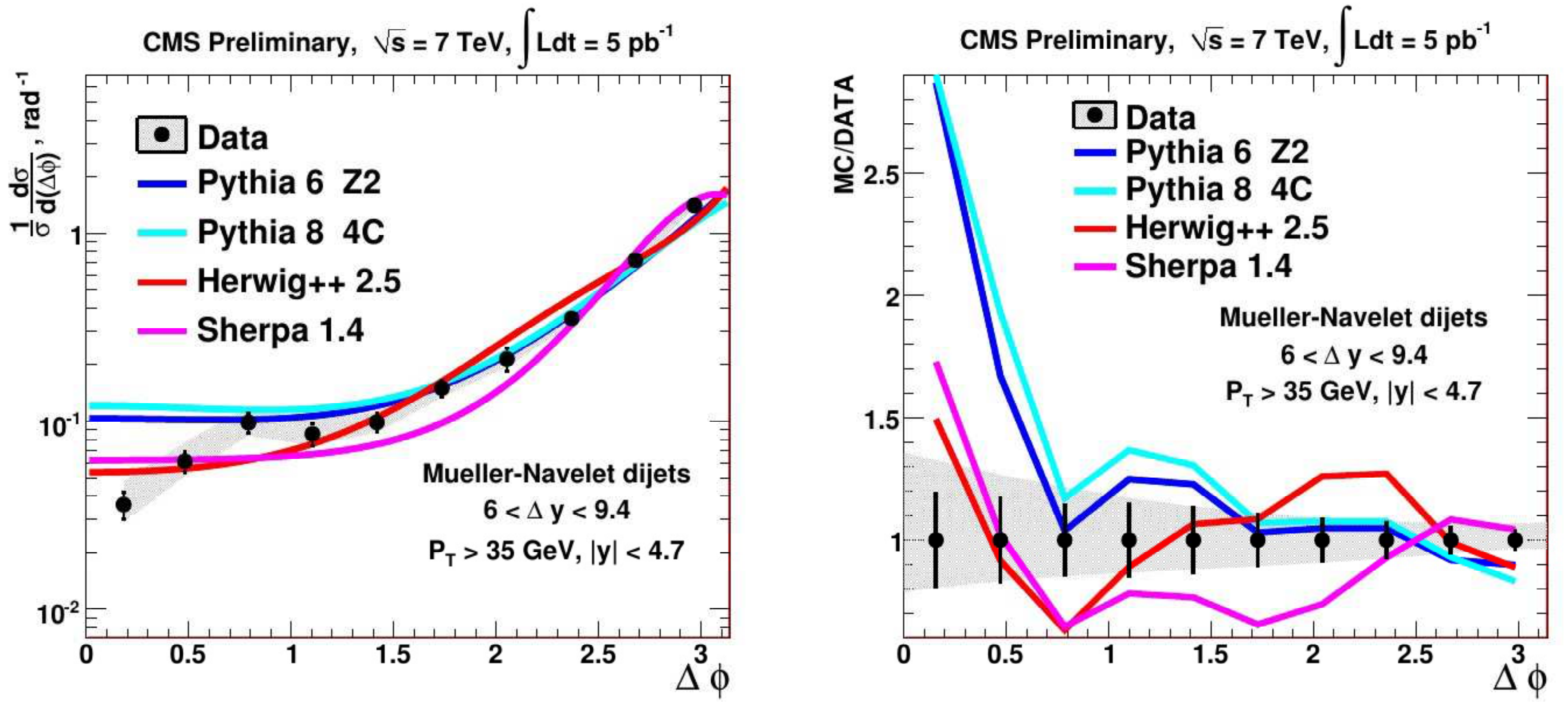

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Overall description is not very good

CMS analysis of MN jets at 7 TeV

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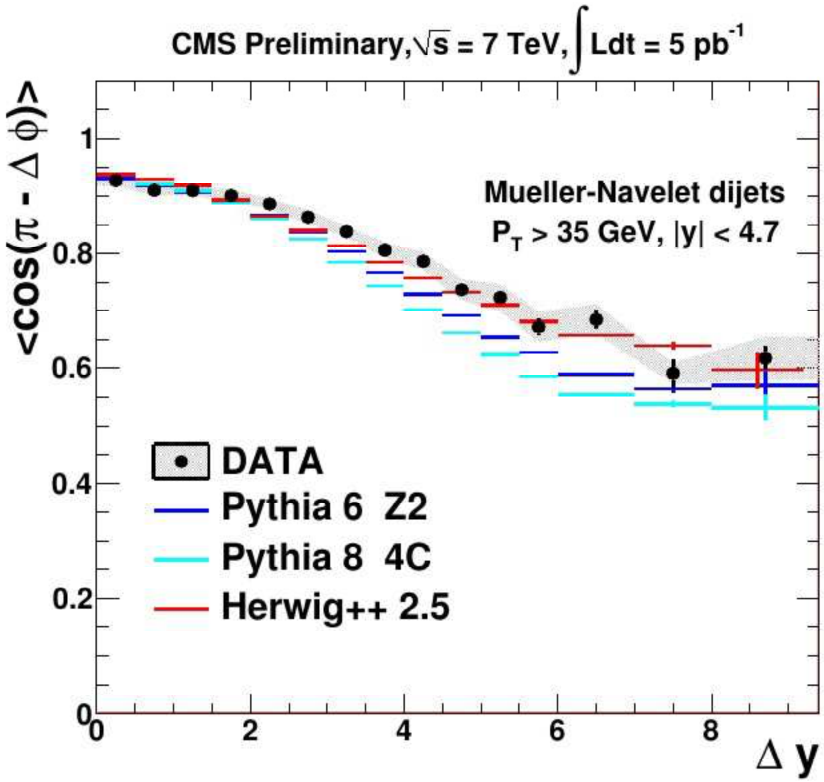
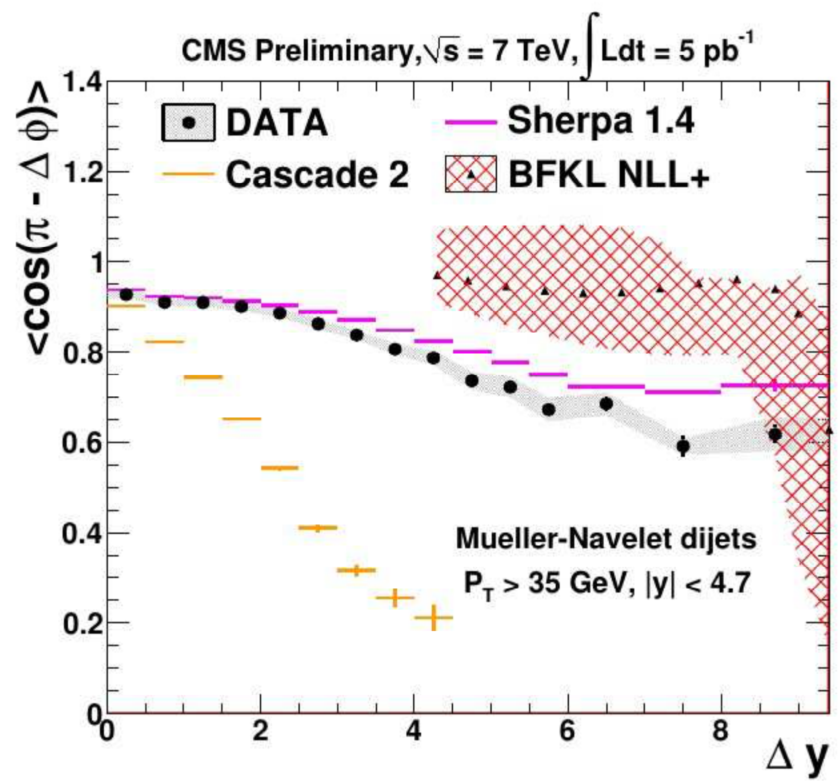
$$\langle \cos(m\phi) \rangle = \frac{C_m(Y)}{C_0(Y)} \equiv \frac{\int \mathrm{d}\phi \, \frac{\mathrm{d}^2(\sigma \cos(m\phi))}{\mathrm{d}\phi \mathrm{d}Y}}{\mathrm{d}\sigma/\mathrm{d}Y}$$

CMS analysis of MN jets at 7 TeV

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





The larger Y, the more radiation and decorrelation

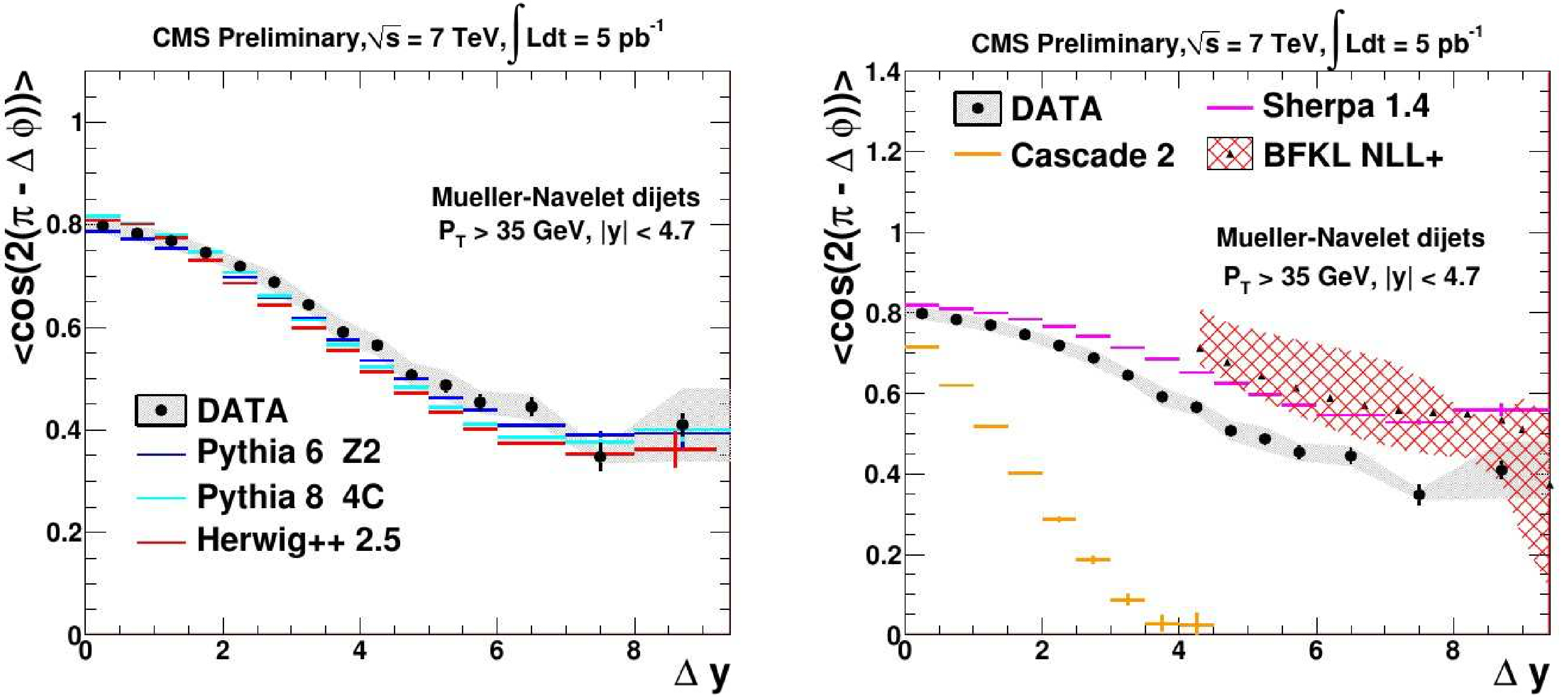
BFKL was expected to predict more radiation than fixed order $\Rightarrow$ more decorrelation

Some MC agree with data

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

CMS analysis of MN jets at 7 TeV

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



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NLL BFKL still unable to reproduce data

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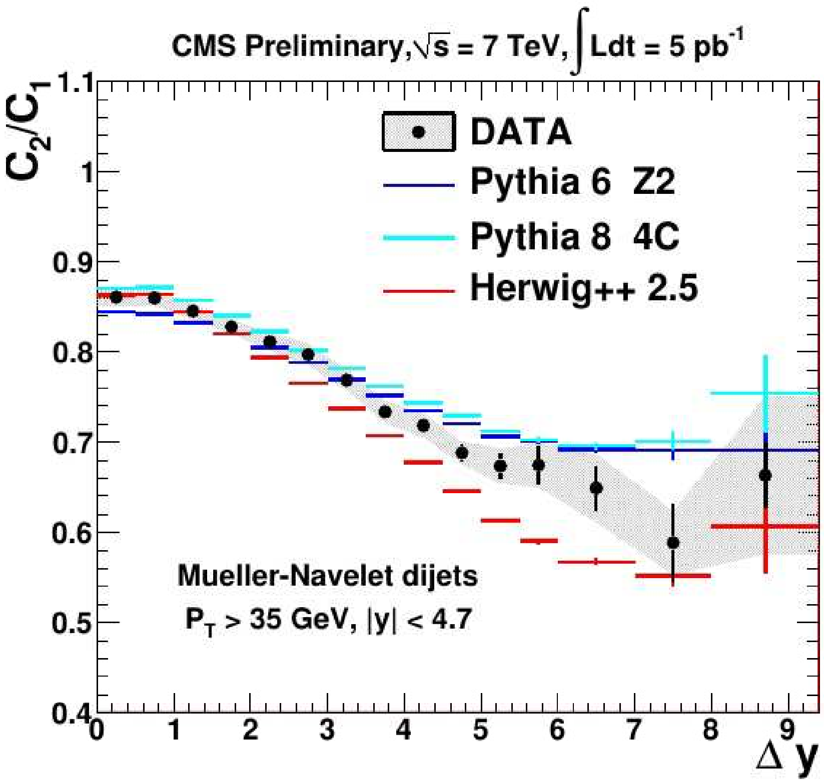

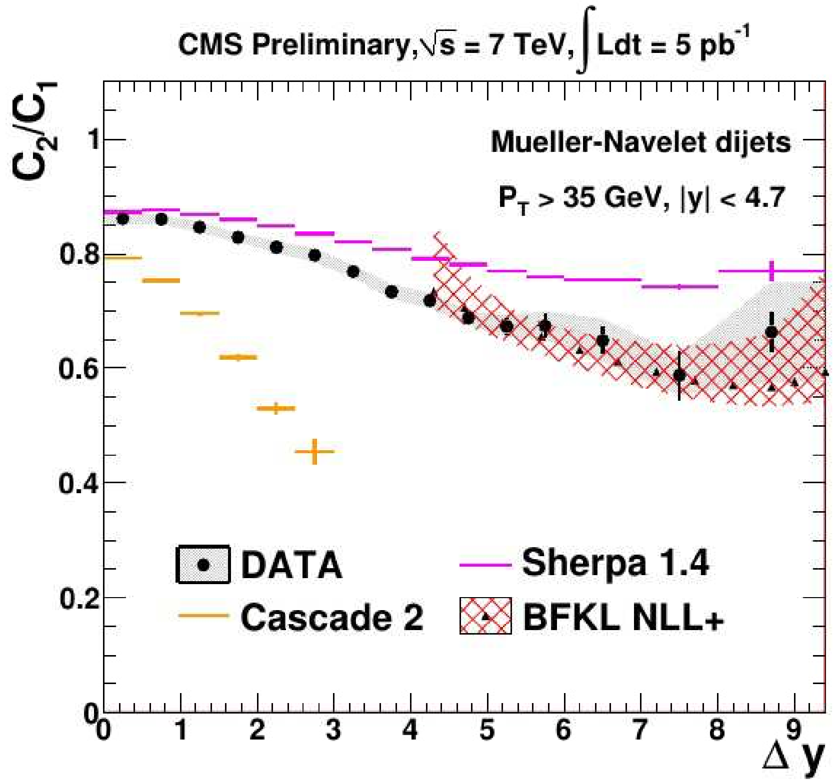

Ratio $\dfrac{C_2}{C_1} = \dfrac{\langle\cos(2\phi)\rangle}{\langle\cos\phi\rangle}$

MC 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 still 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

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

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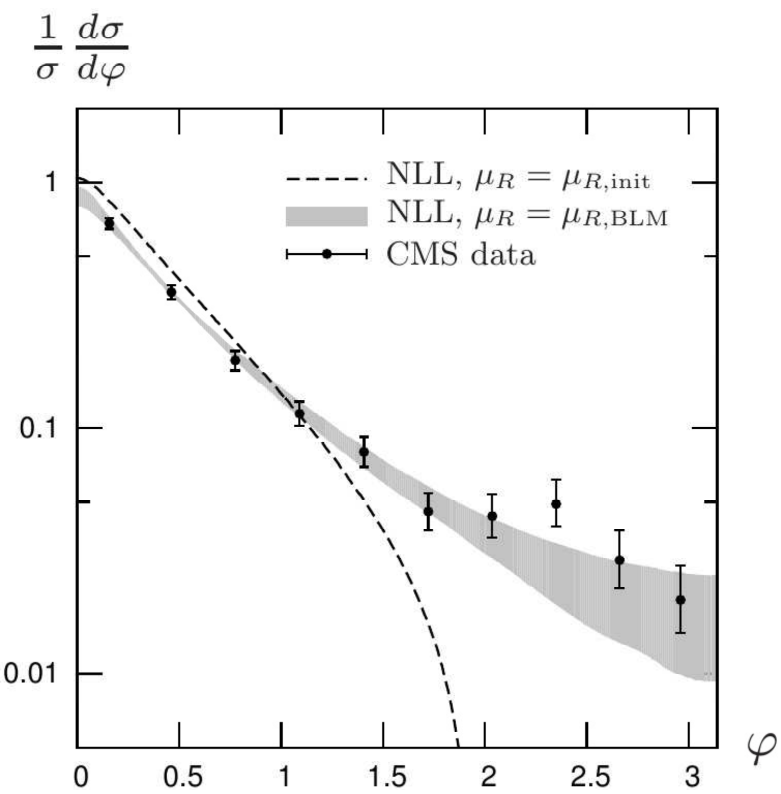

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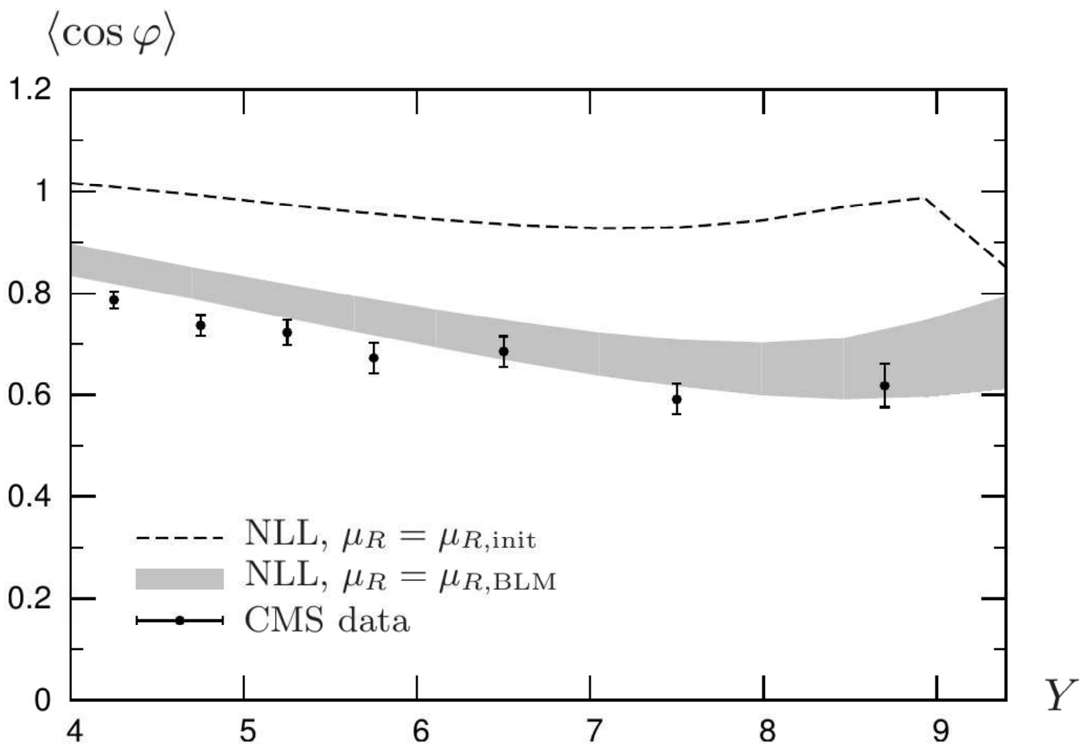

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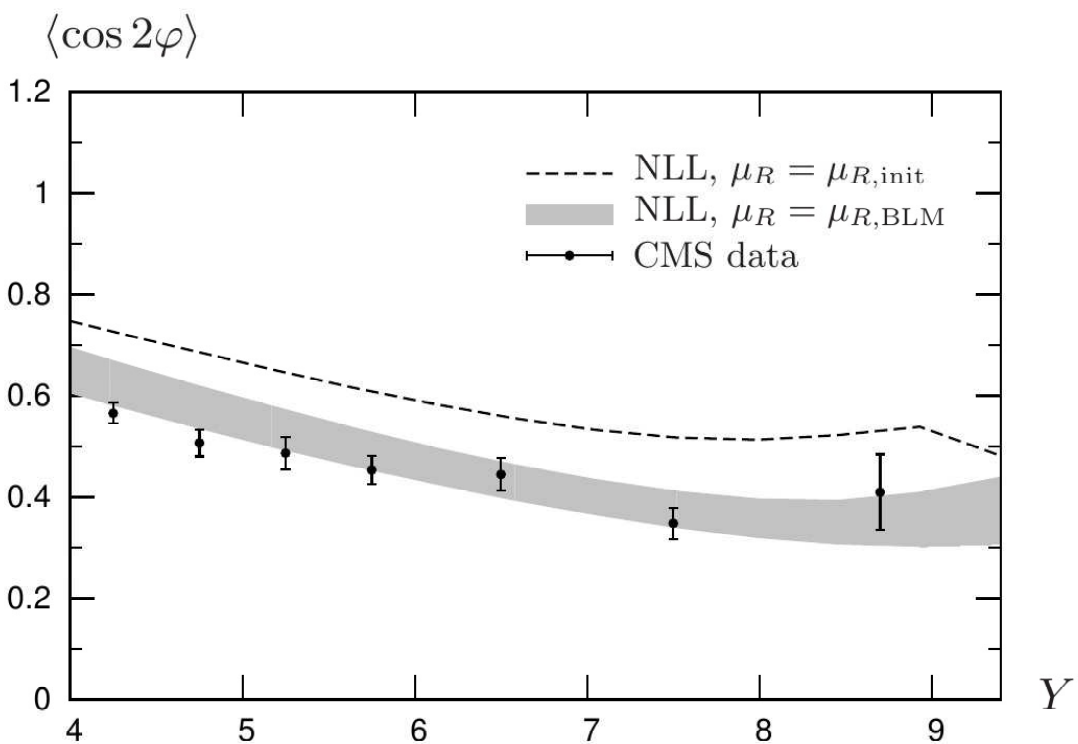

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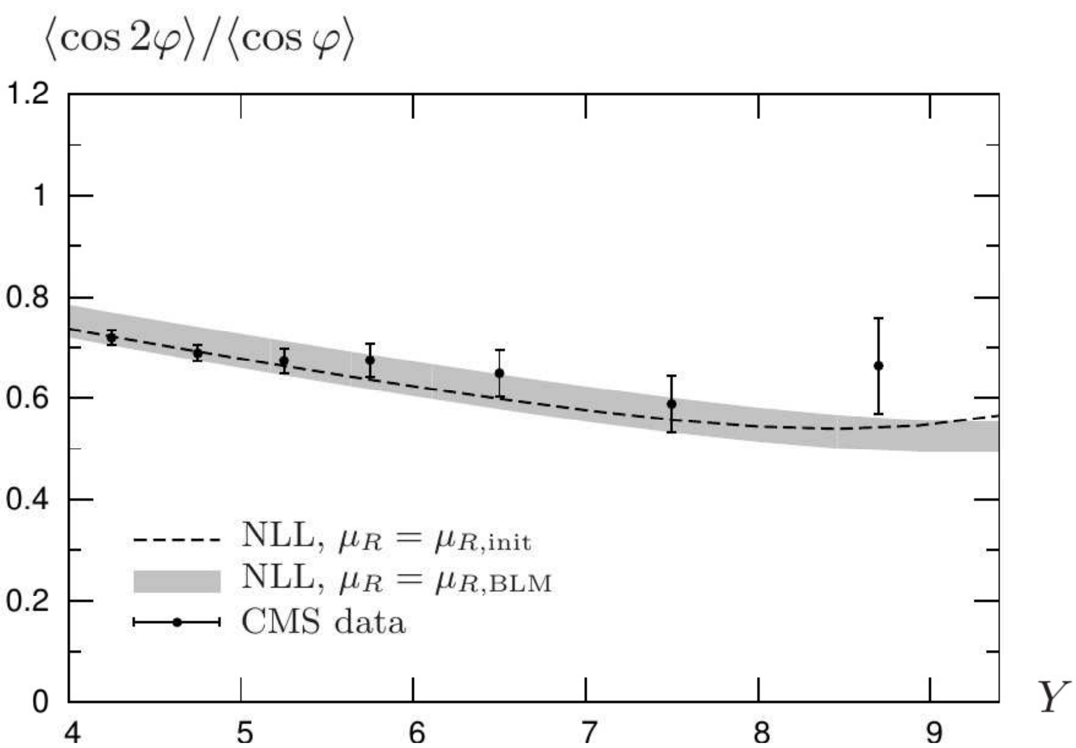
$$\mu_R^2 = \exp\left[\frac{1}{2}\chi_0 - \frac{5}{3} + 2\left(1 + \frac{2}{3}I\right)\right] E_{T1}\, E_{T2} \sim 20^2\, E_{T1}\, E_{T2}$$



Very large renorm. scale

NLL BFKL + BLM provides good description of data

Matching BFKL with Fixed NLO

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

- improve description of data
- correctly reproduce not only ratios but absolute values

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Standard matching procedure:

- add to BFKL the full perturbative NLO result $\mathcal{O}\left(\alpha_s^3\right)$
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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)

Matching (sym. jets $E_1, E_2 > 35\mathrm{GeV}$)

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

$$\frac{\mathrm{d}\sigma(s)}{\mathrm{d}J_1\mathrm{d}J_2} = \sum_{a,b}\int_0^1 \mathrm{d}x_1\mathrm{d}x_2\; f_a(x_1)f_b(x_2)\Big\{$$

$$\int \mathrm{d}\boldsymbol{k}_1\mathrm{d}\boldsymbol{k}_2\Big[V_a^{(0+1)}(x_1,\boldsymbol{k}_1;J_1)\,G_{\mathrm{NLL}}(x_1x_2s,\boldsymbol{k}_1,\boldsymbol{k}_2)\,V_b^{(0+1)}(x_2,\boldsymbol{k}_2;J_2)\Big]$$

$$+\frac{\mathrm{d}\hat{\sigma}^{(NLO)}(x_1,x_2)}{\mathrm{d}J_1\mathrm{d}J_2}$$

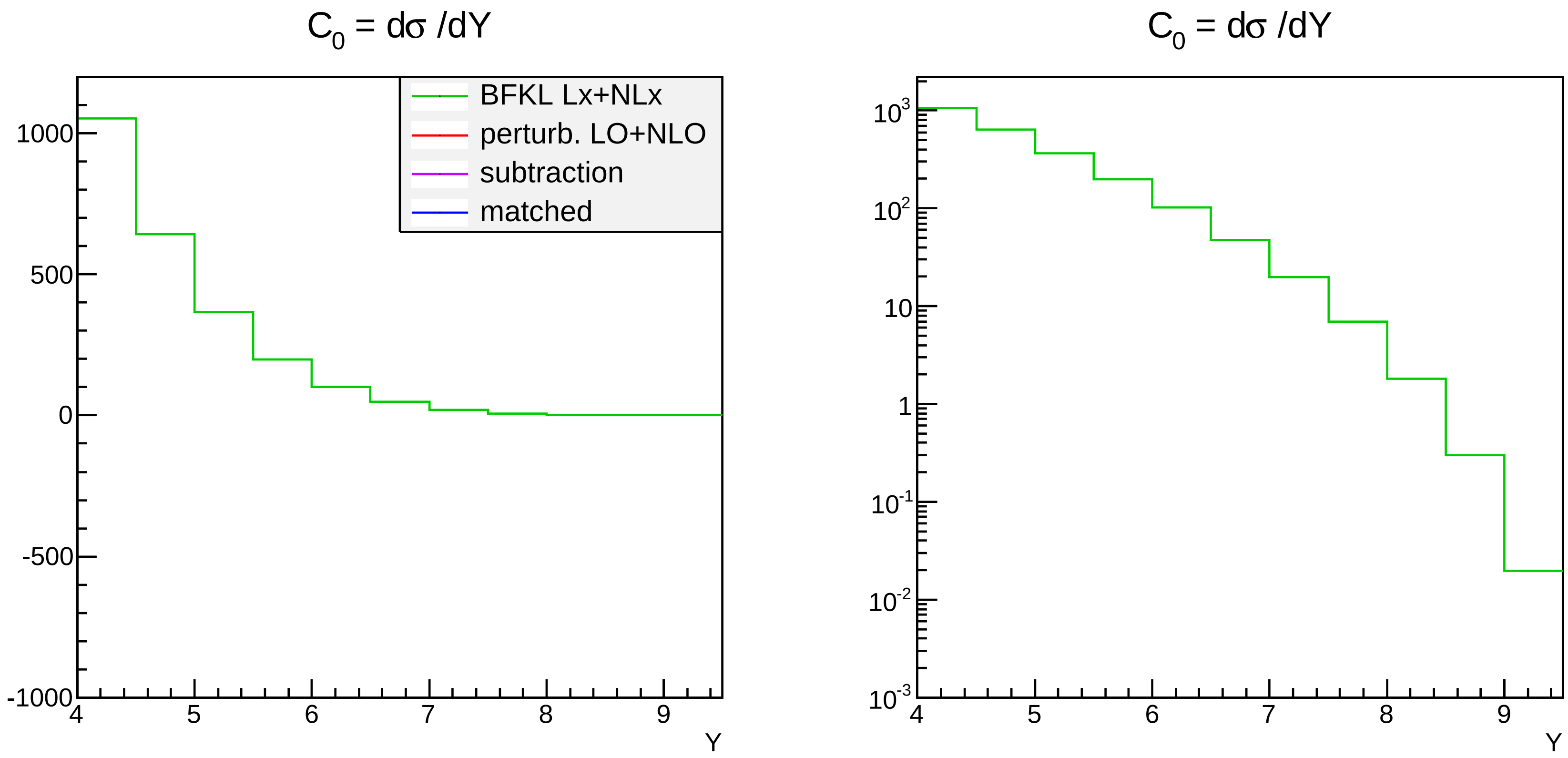
$$-\int \mathrm{d}\boldsymbol{k}_1\mathrm{d}\boldsymbol{k}_2\Big[V_a^{(0)}(x_1,\boldsymbol{k}_1;J_1)\,\delta^2(\boldsymbol{k}_1-\boldsymbol{k}_2)\,V_b^{(0)}(x_2,\boldsymbol{k}_2;J_2)\Big]$$

$$-\int \mathrm{d}\boldsymbol{k}_1\mathrm{d}\boldsymbol{k}_2\Big[V_a^{(1)}(x_1,\boldsymbol{k}_1;J_1)\,\delta^2(\boldsymbol{k}_1-\boldsymbol{k}_2)\,V_b^{(0)}(x_2,\boldsymbol{k}_2;J_2)\Big]$$

$$-\int \mathrm{d}\boldsymbol{k}_1\mathrm{d}\boldsymbol{k}_2\Big[V_a^{(0)}(x_1,\boldsymbol{k}_1;J_1)\,\delta^2(\boldsymbol{k}_1-\boldsymbol{k}_2)\,V_b^{(1)}(x_2,\boldsymbol{k}_2;J_2)\Big]$$

$$-\int \mathrm{d}\boldsymbol{k}_1\mathrm{d}\boldsymbol{k}_2\Big[V_a^{(0)}(x_1,\boldsymbol{k}_1;J_1)\,\alpha_s\log\frac{\hat{s}}{s_0}K_0(\boldsymbol{k}_1,\boldsymbol{k}_2)\,V_b^{(0)}(x_2,\boldsymbol{k}_2;J_2)\Big]\Big\}$$

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



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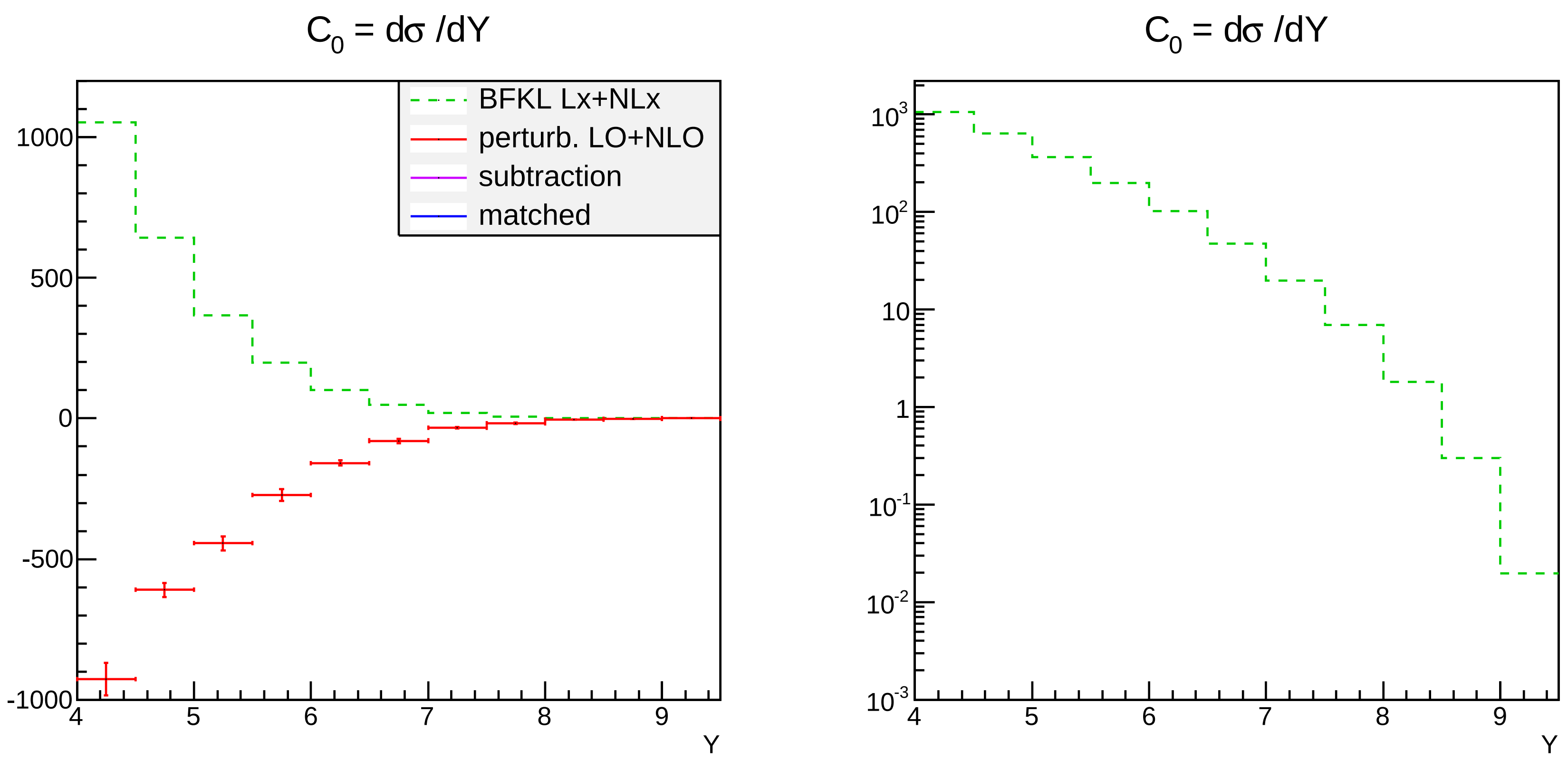

LO+NLO cross section obtained with NLOJET++ *[Nagy]* is negative!

Large errors due to very slow convergence in MC integration

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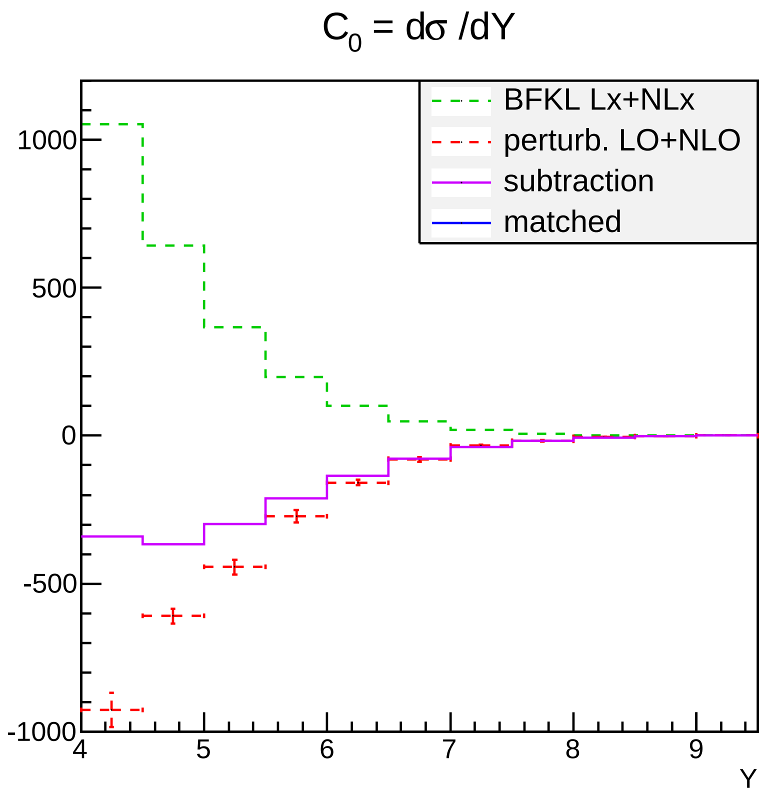

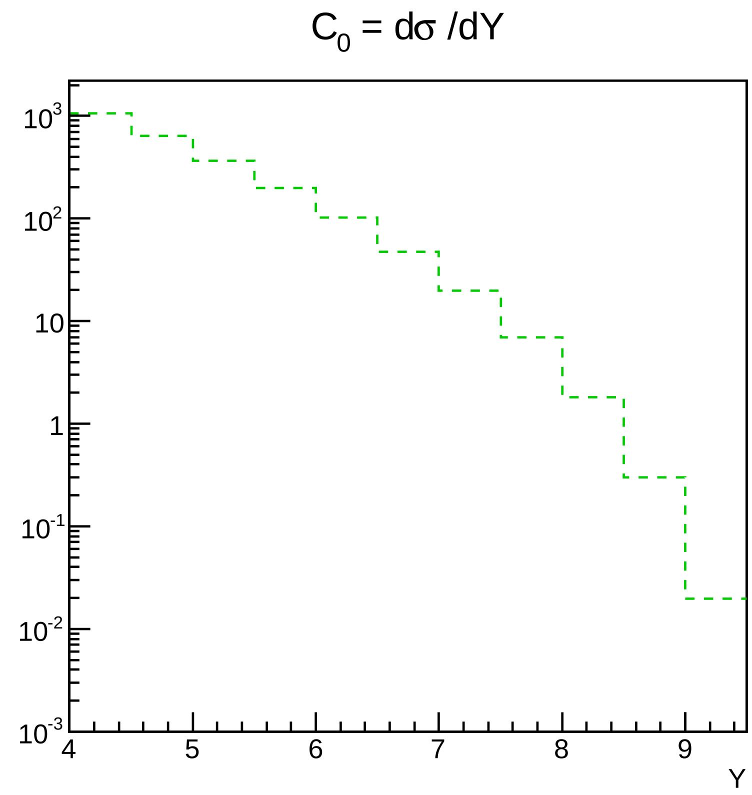

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However, also the subtraction is negative

Their difference is moderate

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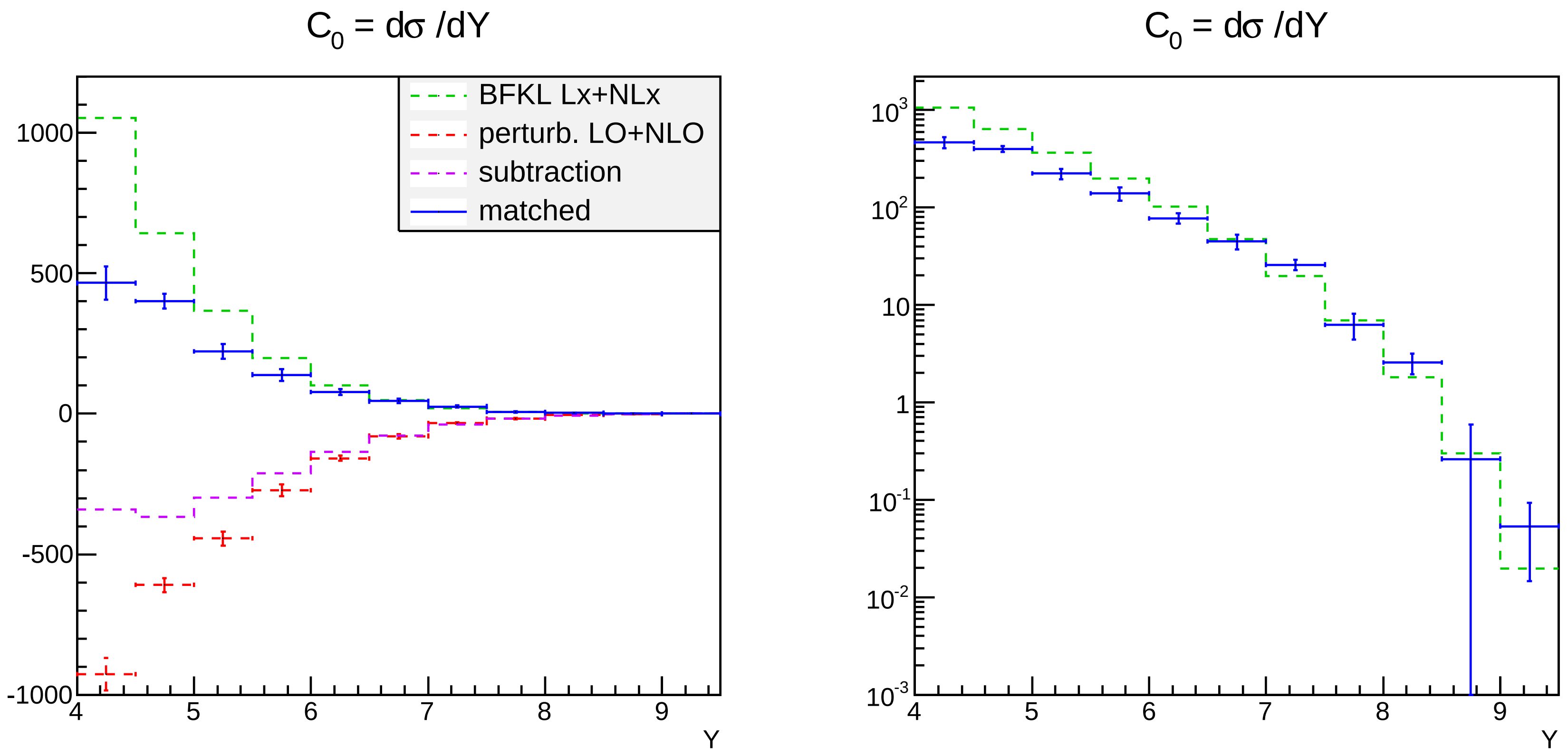

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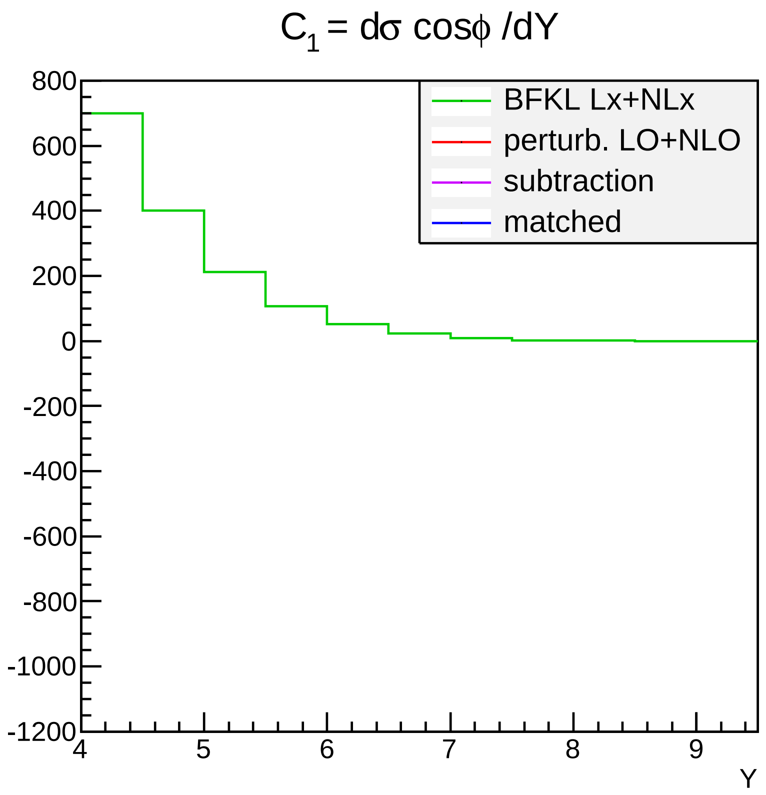
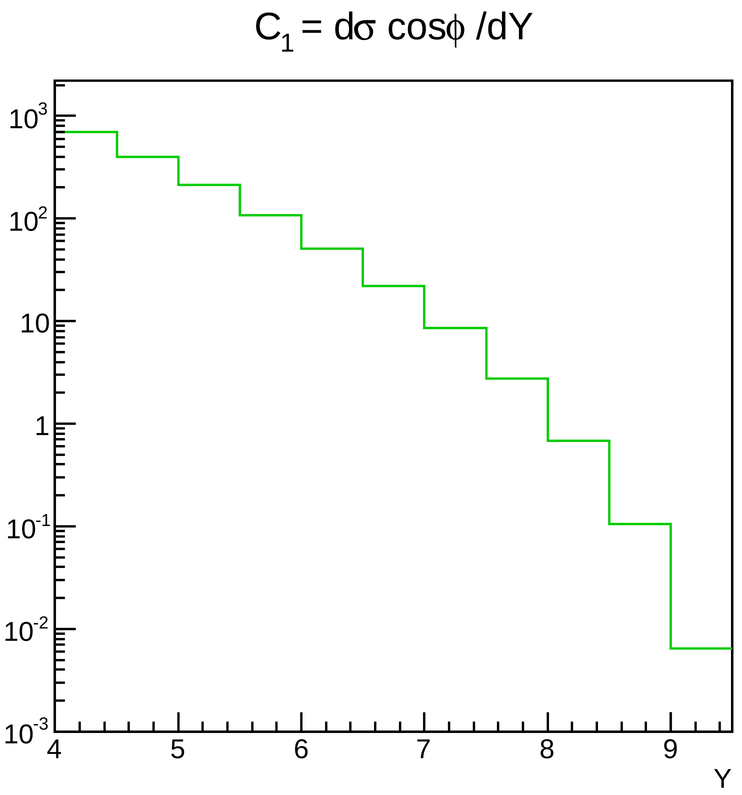
Matched cross section is positive, of the same magnitude of NLL BFKL prediction

Matching (azimuthal coeff. C_1)





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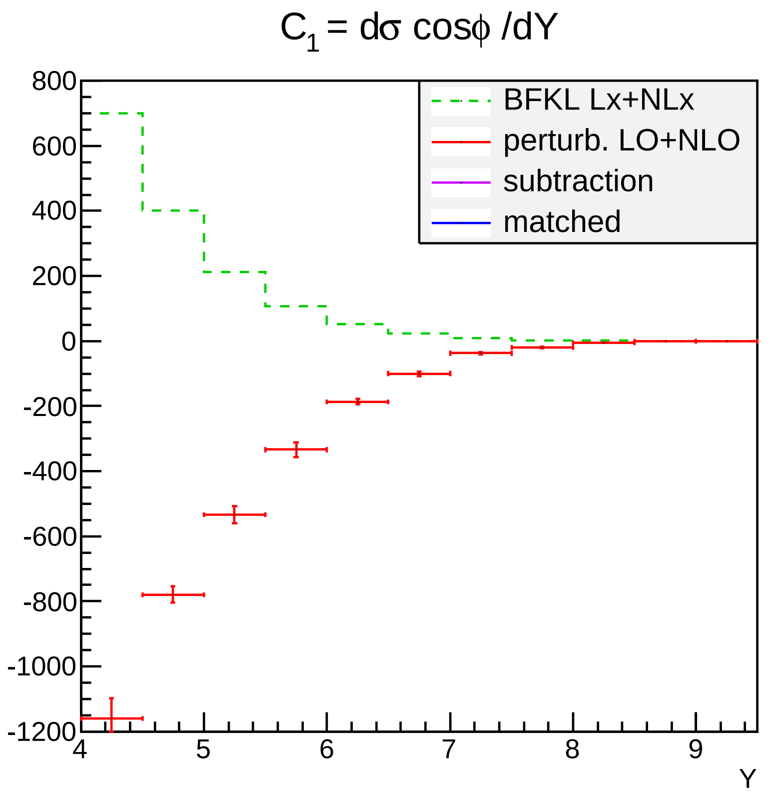

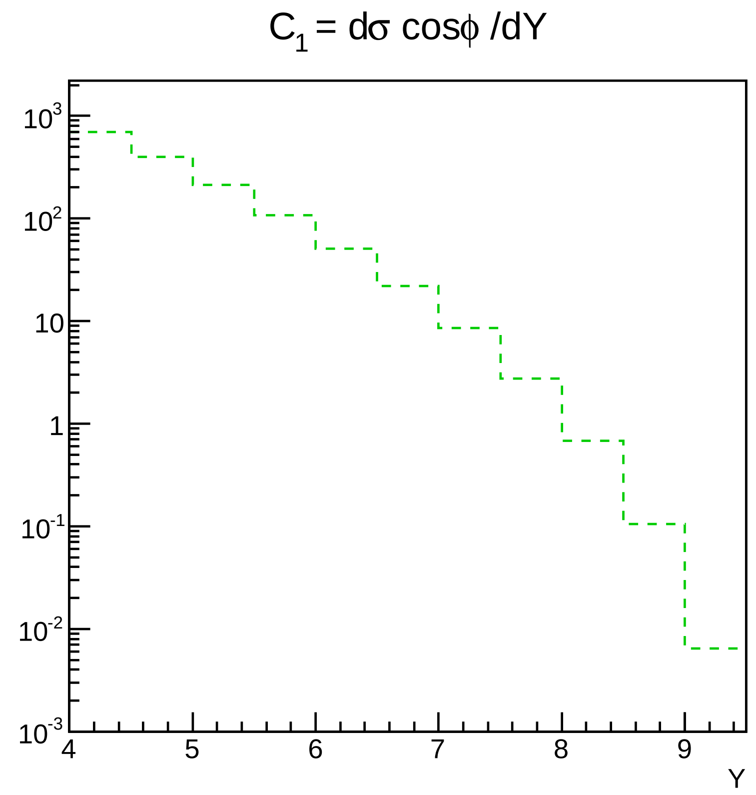

Large errors of NLO calculation due to very slow convergence in MC integration

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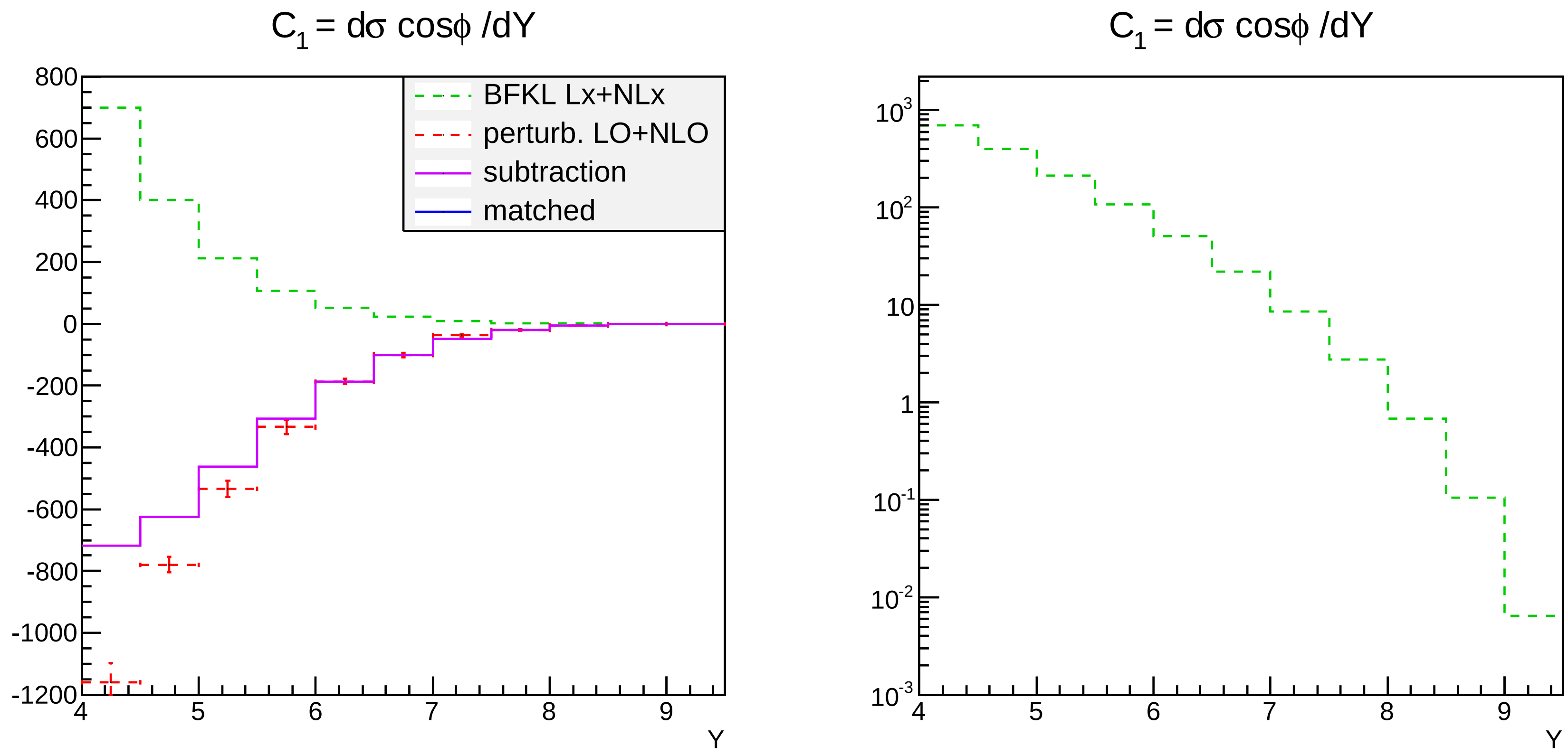

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Moderate difference between NLO and subtraction

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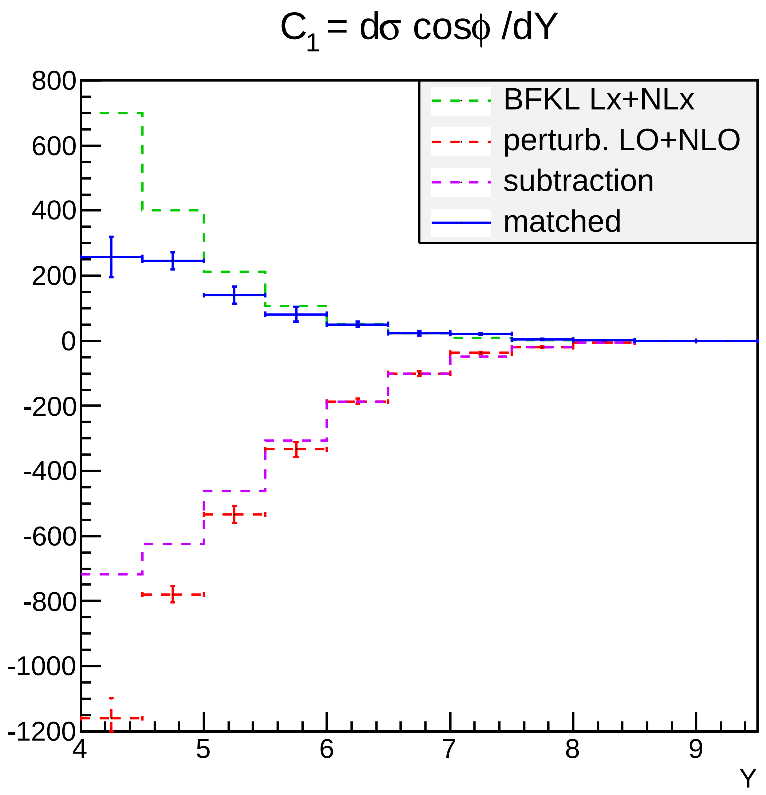

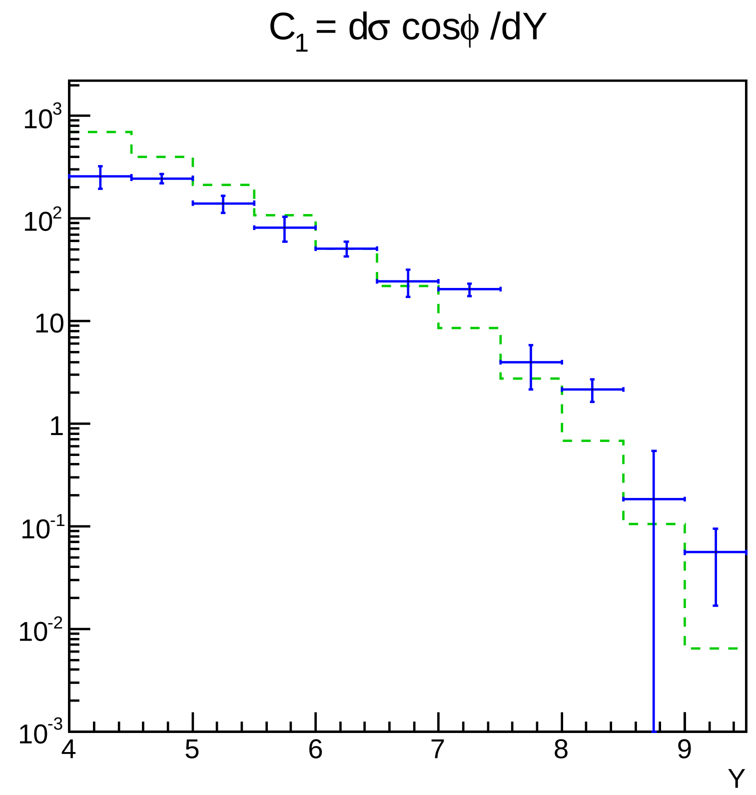

Large errors of NLO calculation due to very slow convergence in MC integration

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 $\Delta = E_{T1} - E_{T2}$ *[Frixione,Ridolfi '97]*

The leading collinear singularity for real emission is given by

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

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

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It is well known that cross section of jets at NLO is very sensitive to the asymmetry parameter $\Delta = E_{T1} - E_{T2}$ *[Frixione,Ridolfi '97]*

The leading collinear singularity for real emission is given by

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

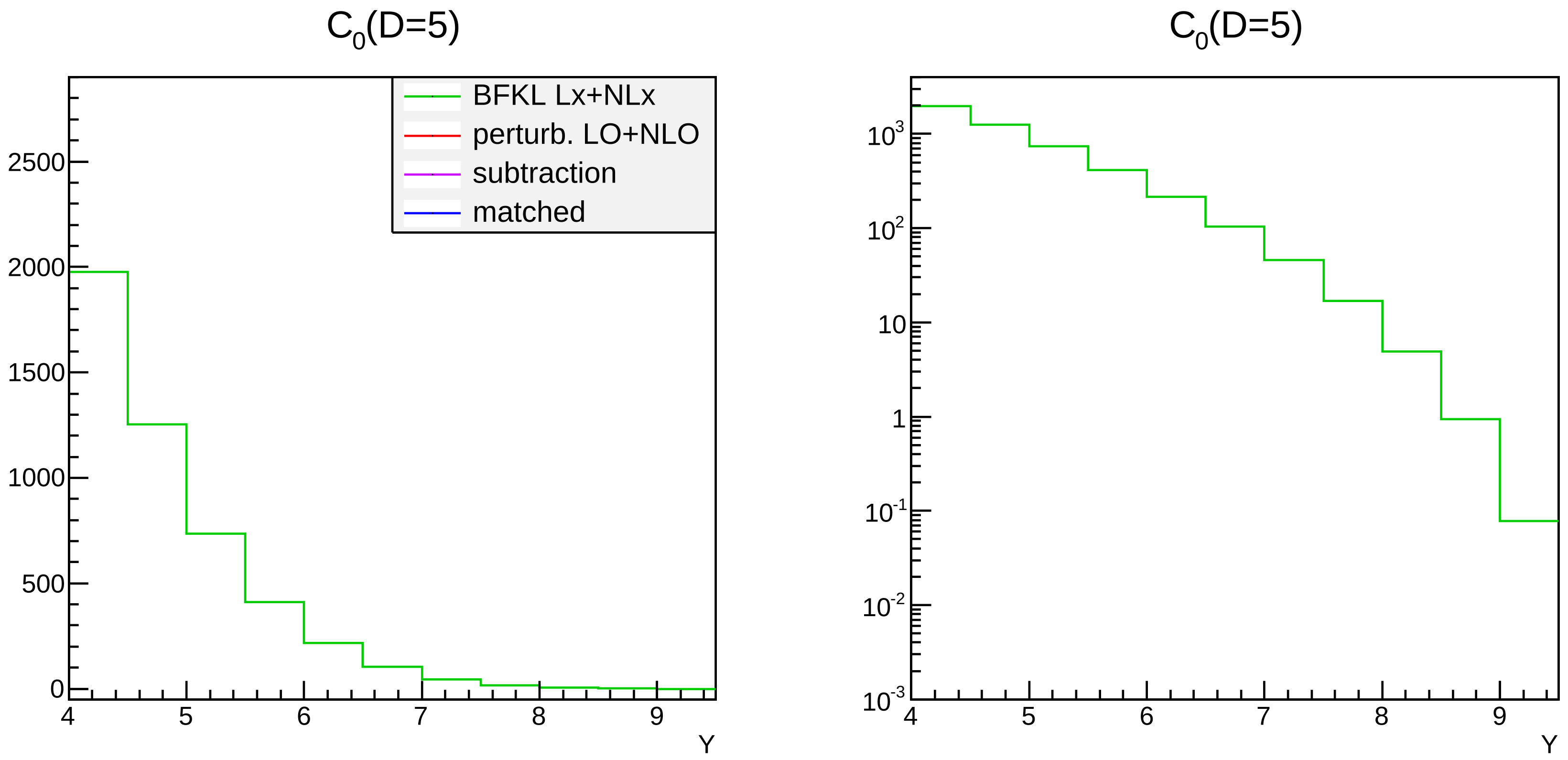
thus fixed order PTh is not reliable in this case (finite, but infinite deriv at $\Delta = 0$)

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

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

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

Asymmetric jets $E_{T1} > 30\ , E_{T2} > 35$ GeV



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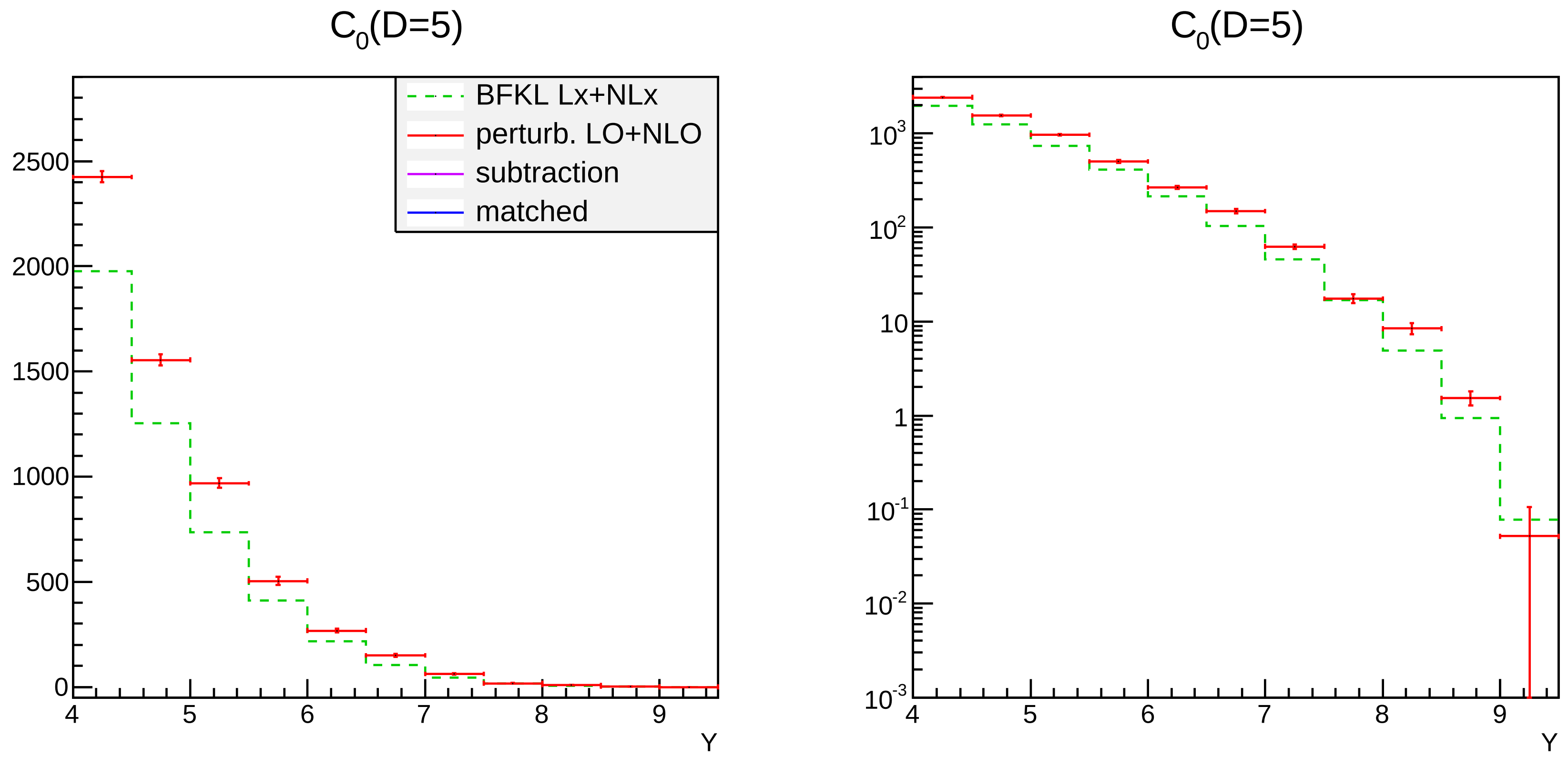

LO+NLO cross section obtained with NLOJET++ *[Nagy]* now is positive

Still large errors due to slow convergence in MC integration (will improve)

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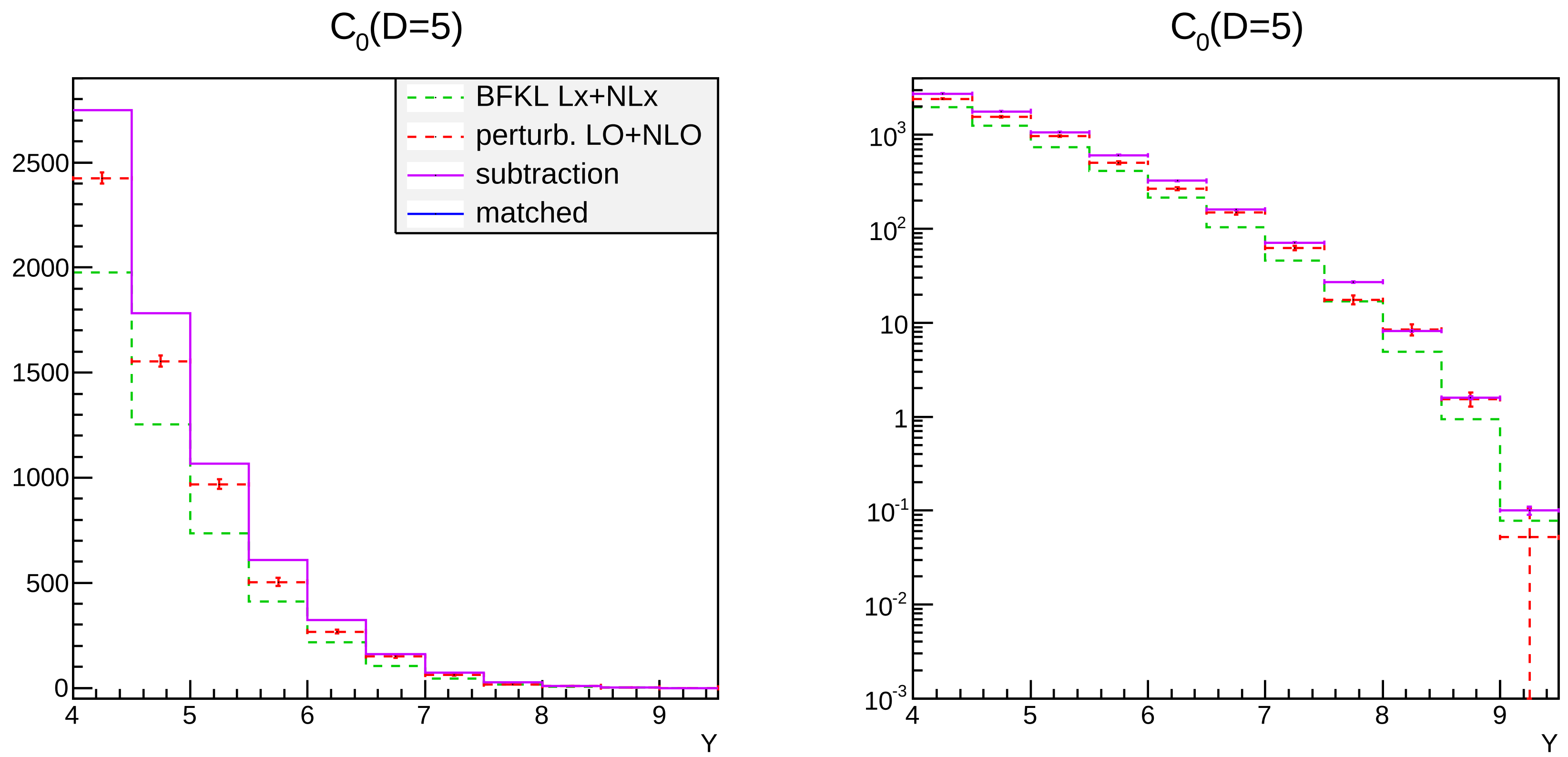

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Their difference is moderate,

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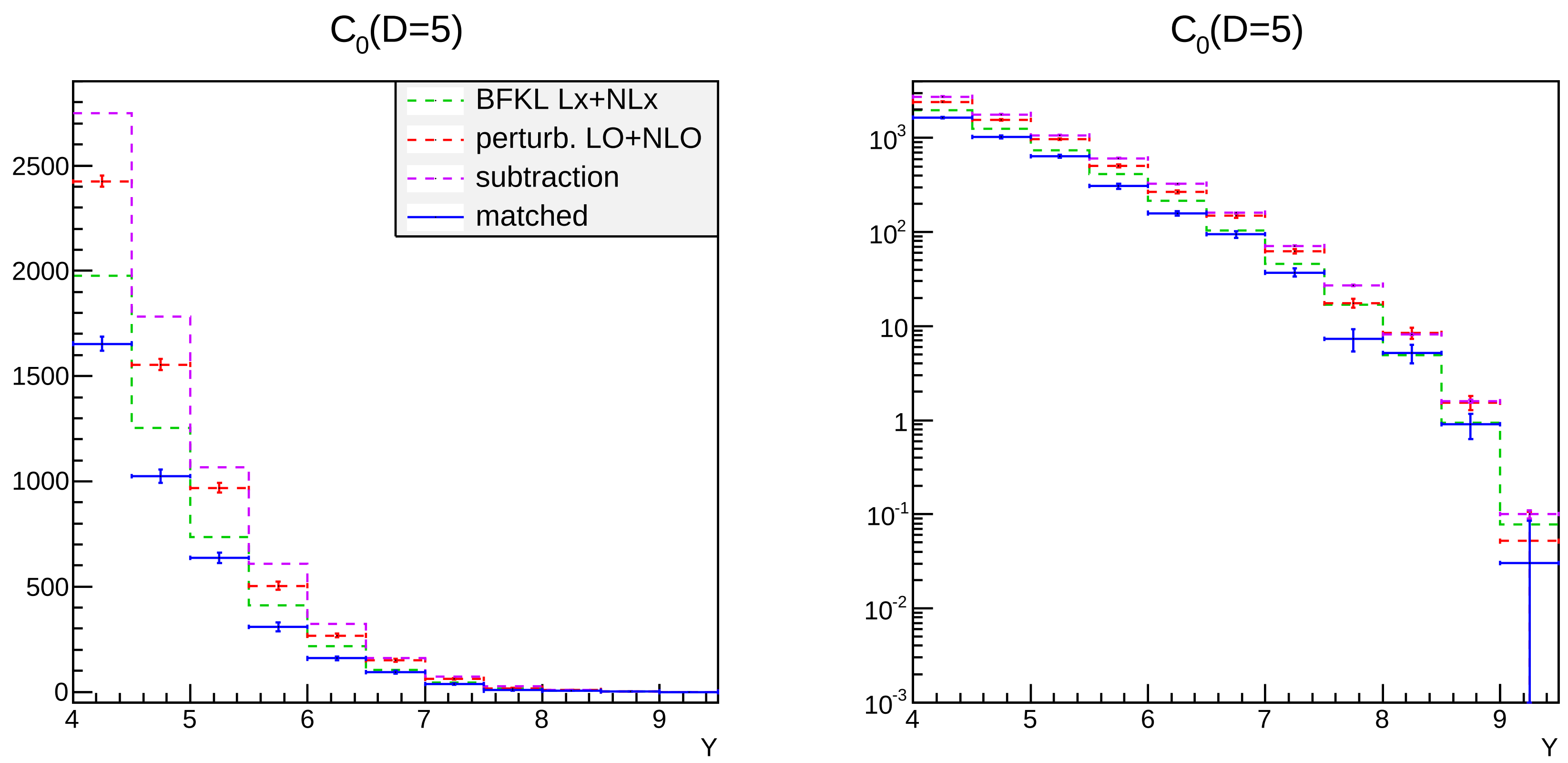

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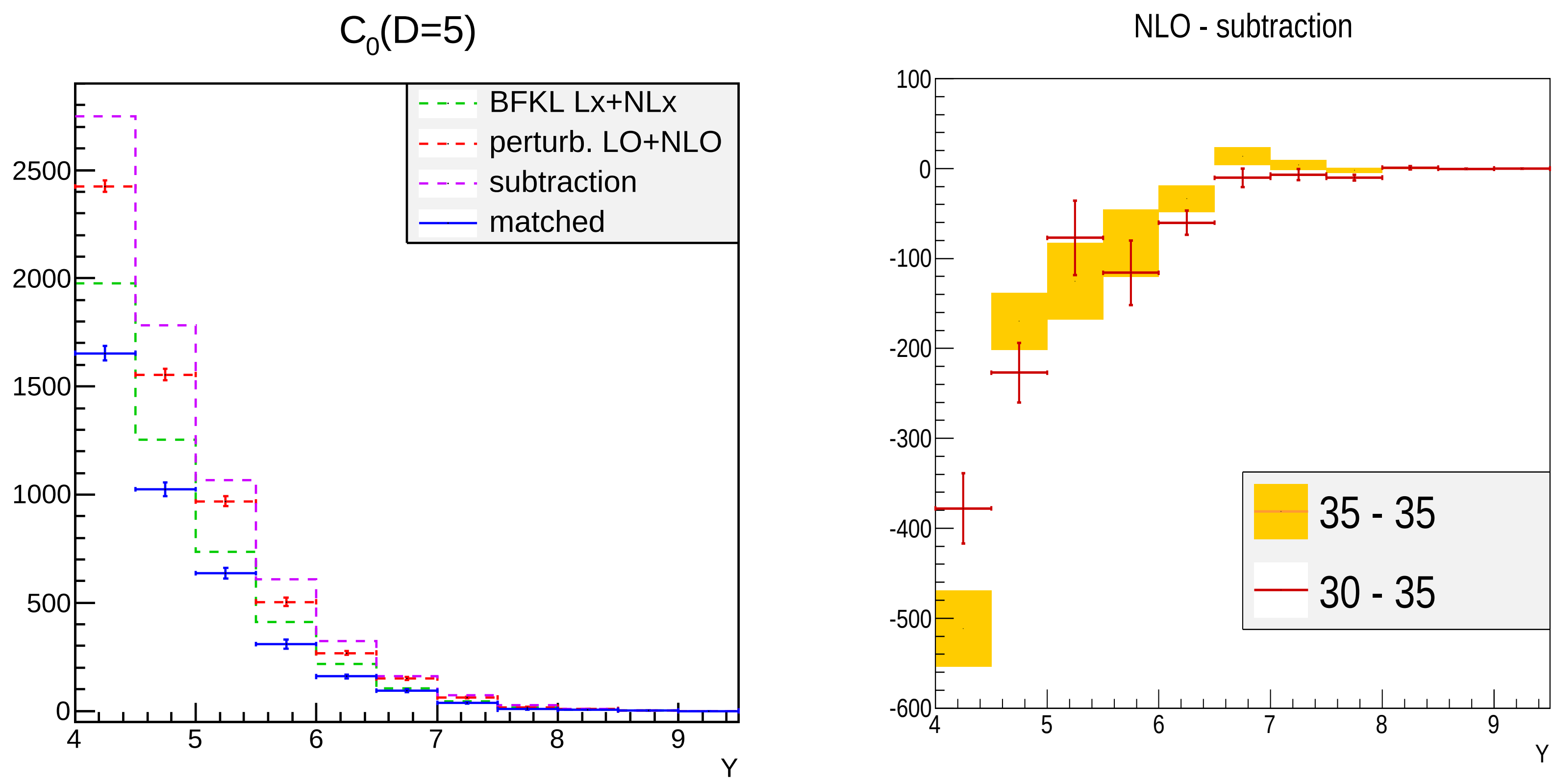

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Still large errors due to slow convergence in MC integration (will improve)

Also the subtraction is positive

Their difference is moderate, similar to the symmetric case

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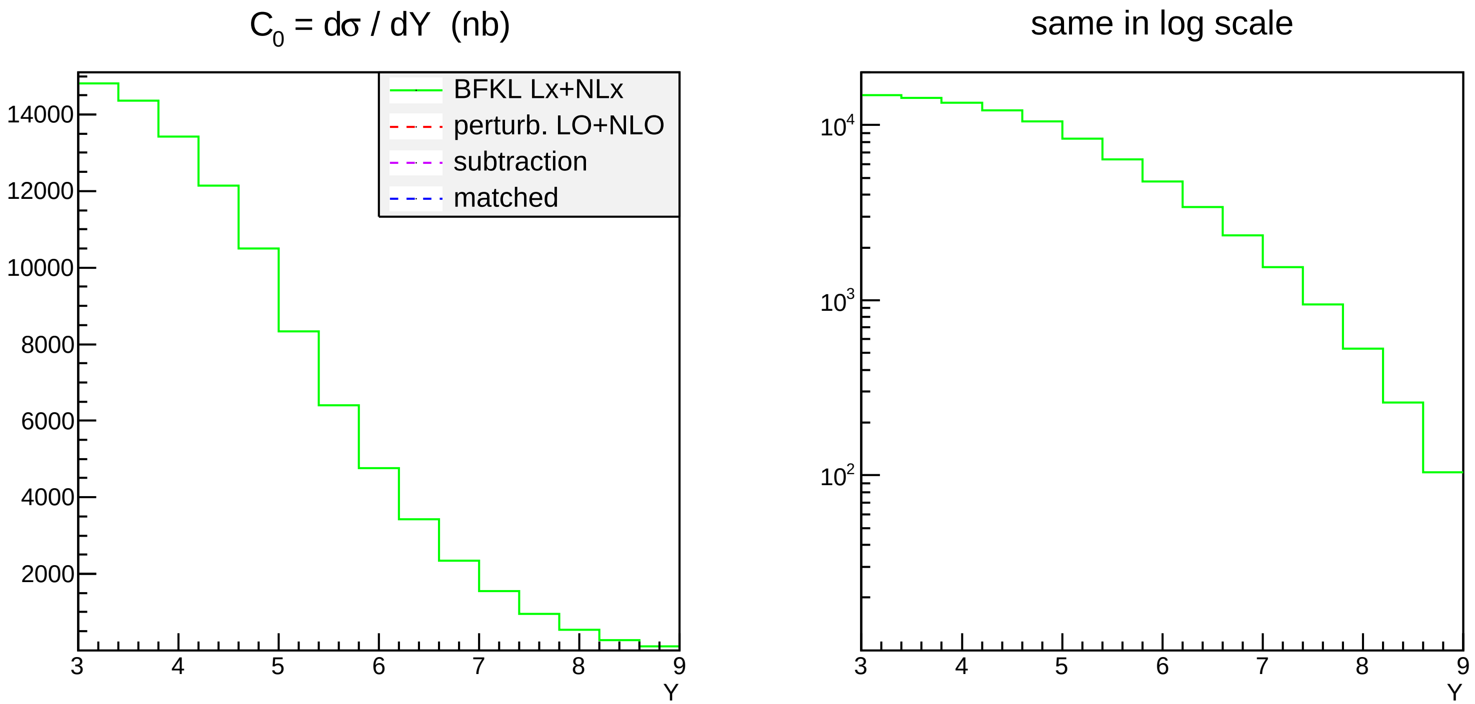
Half-sum cut: $\frac{1}{2}(E_{T1} + E_{T2}) > 35\text{GeV}$



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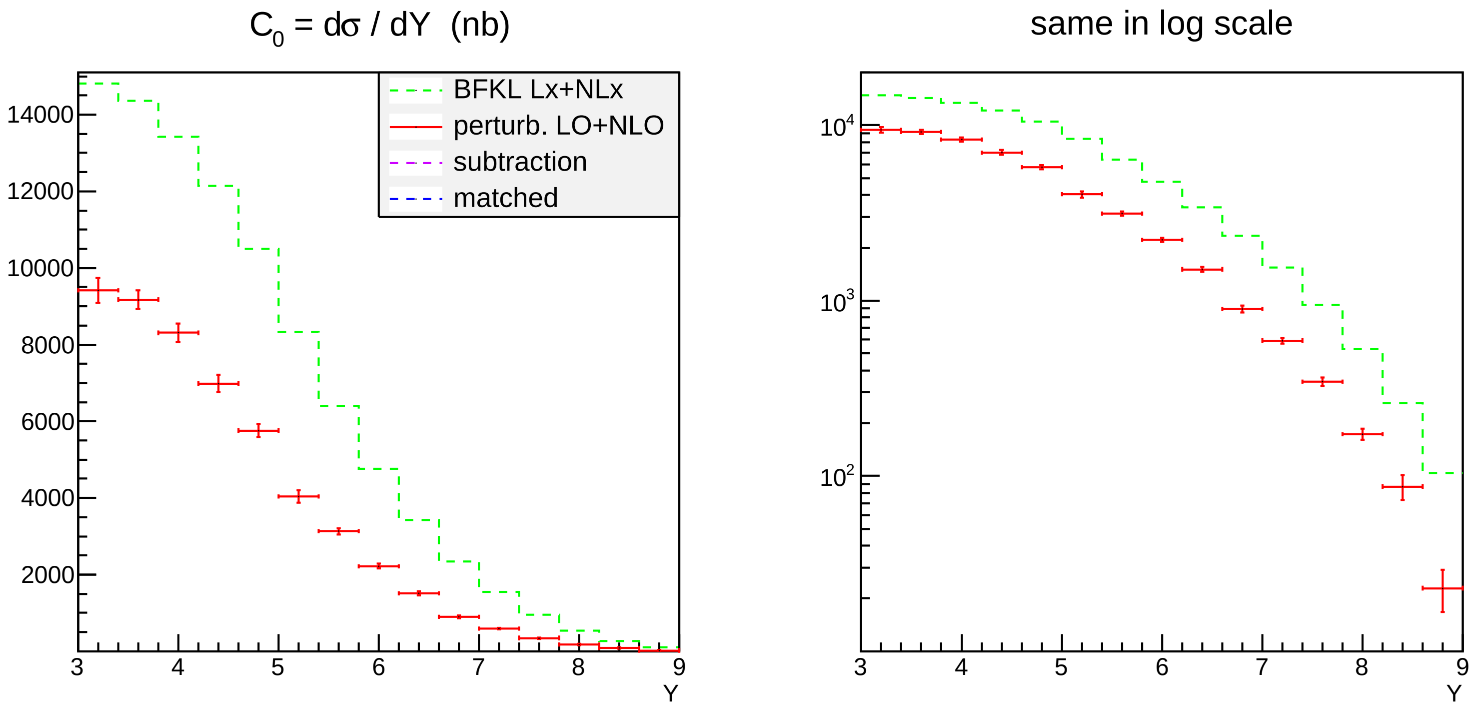

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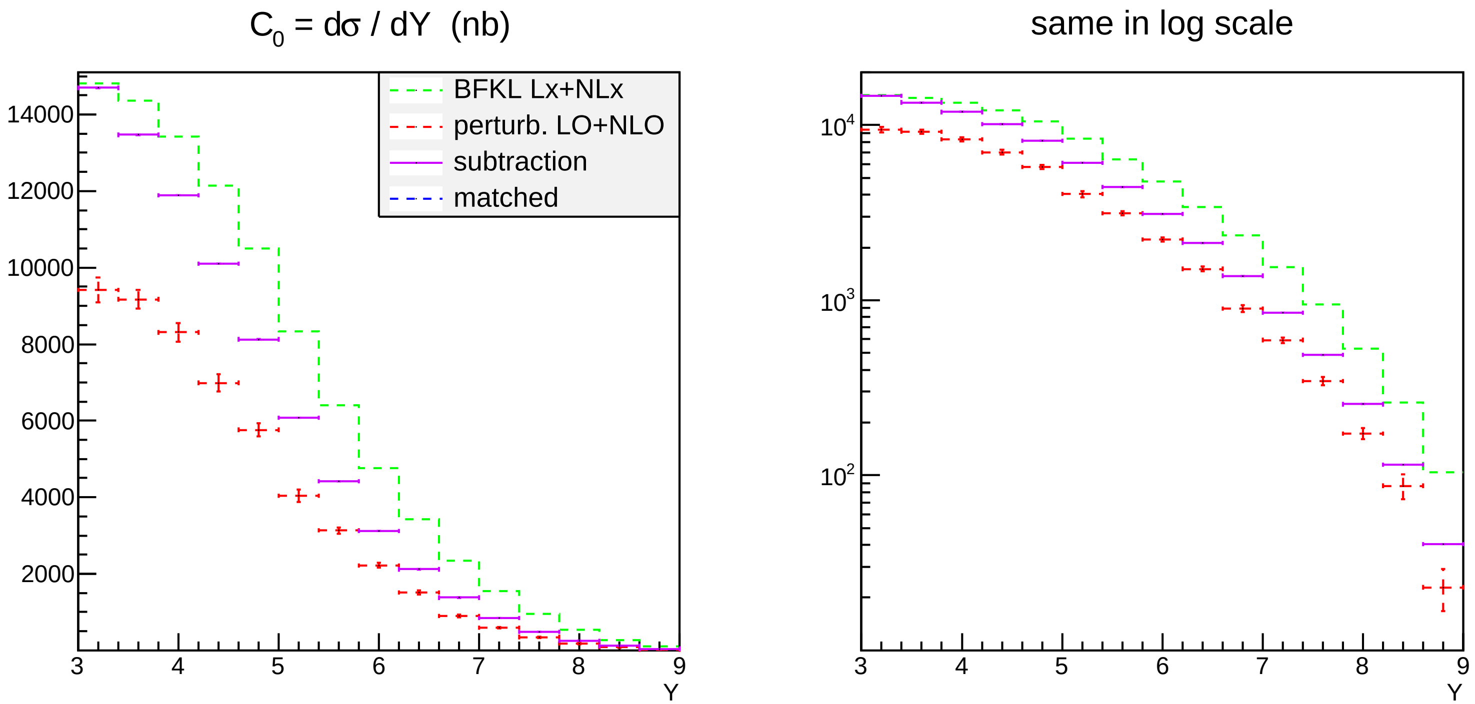

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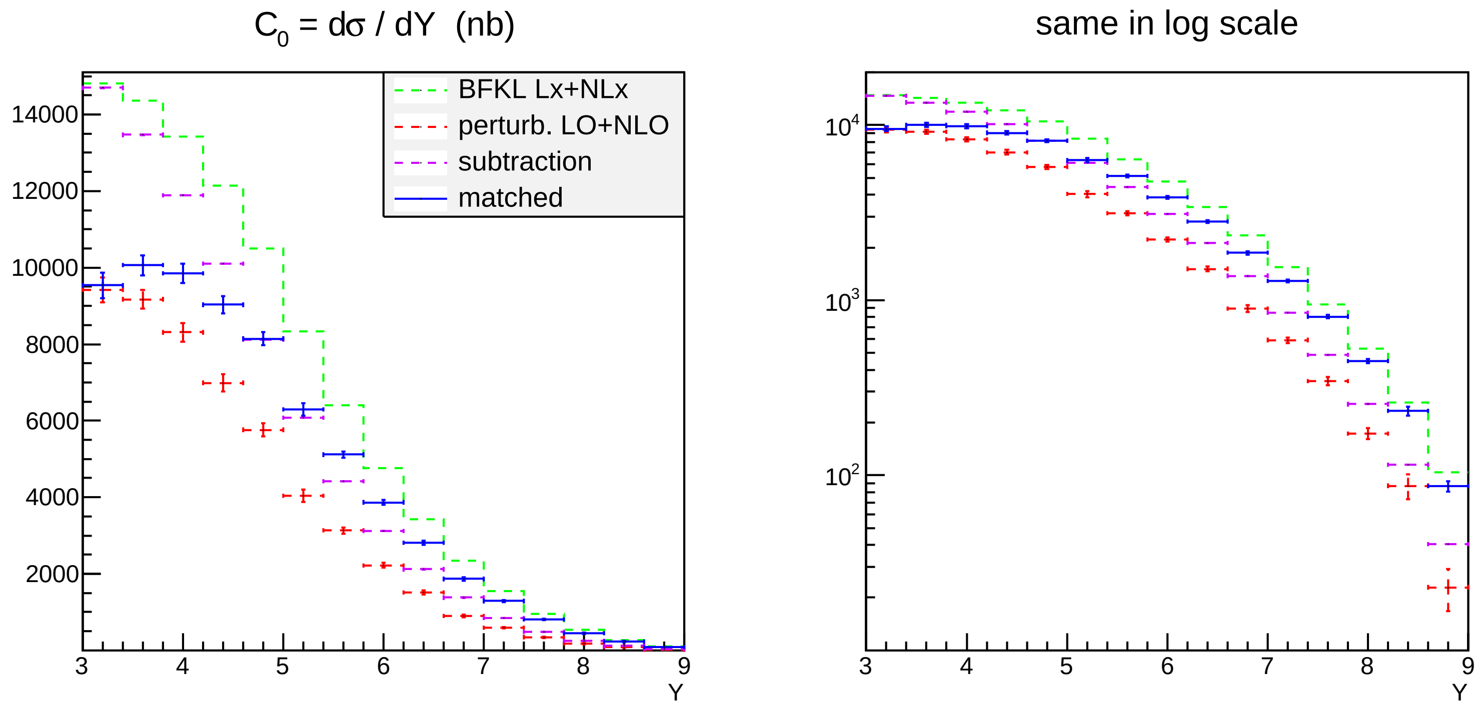

Procedure is more stable than that for symmetric jets

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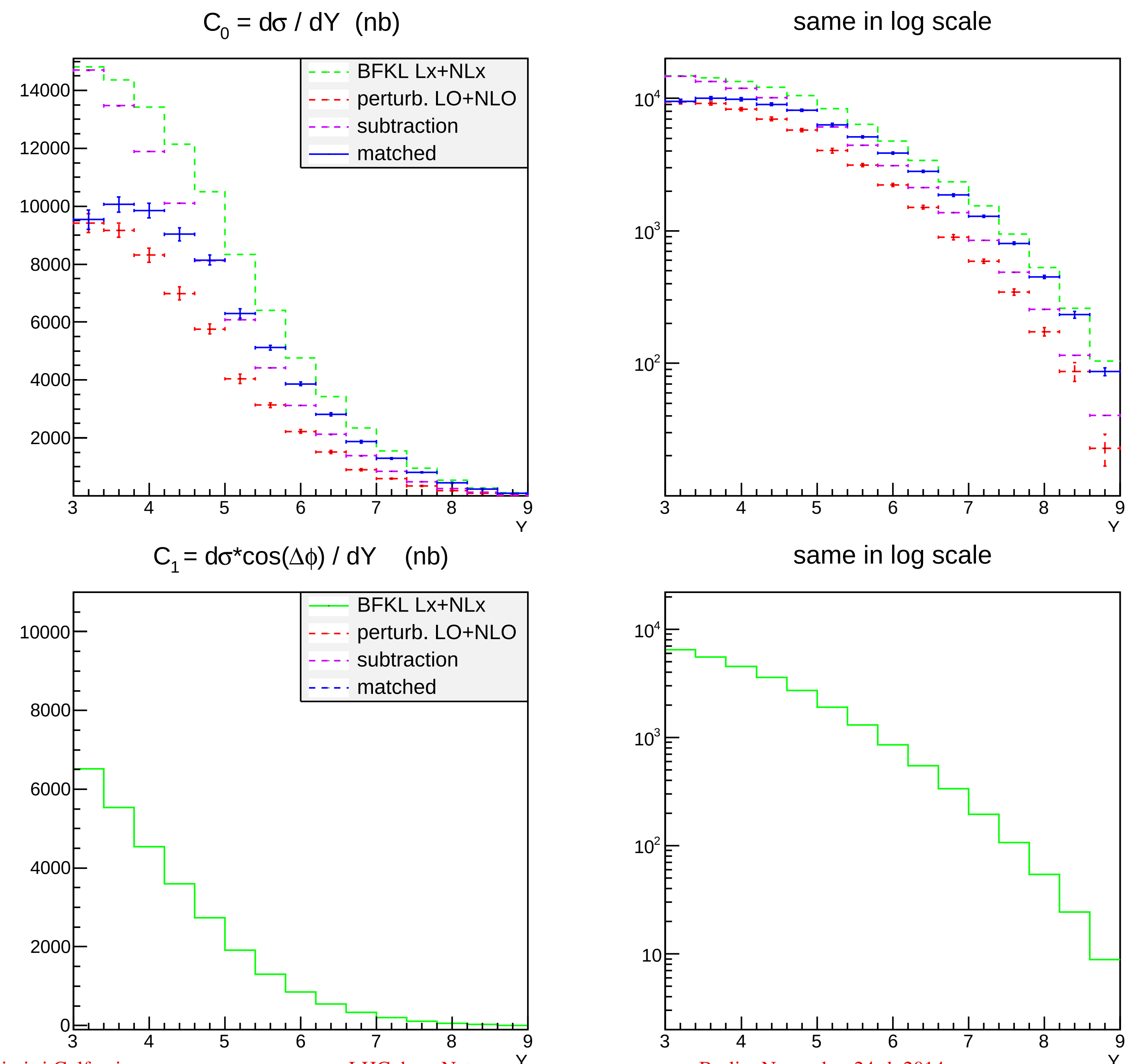

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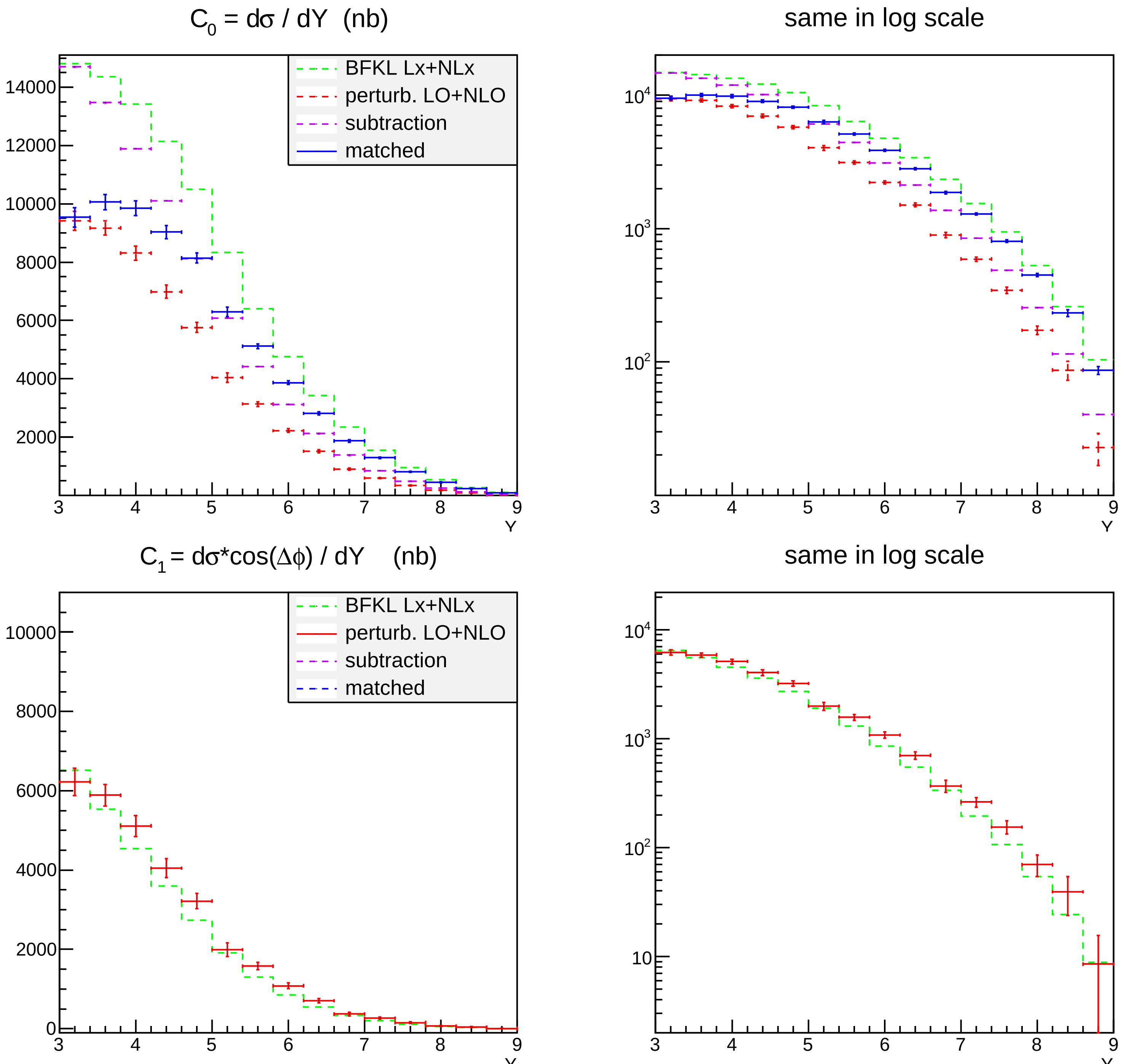

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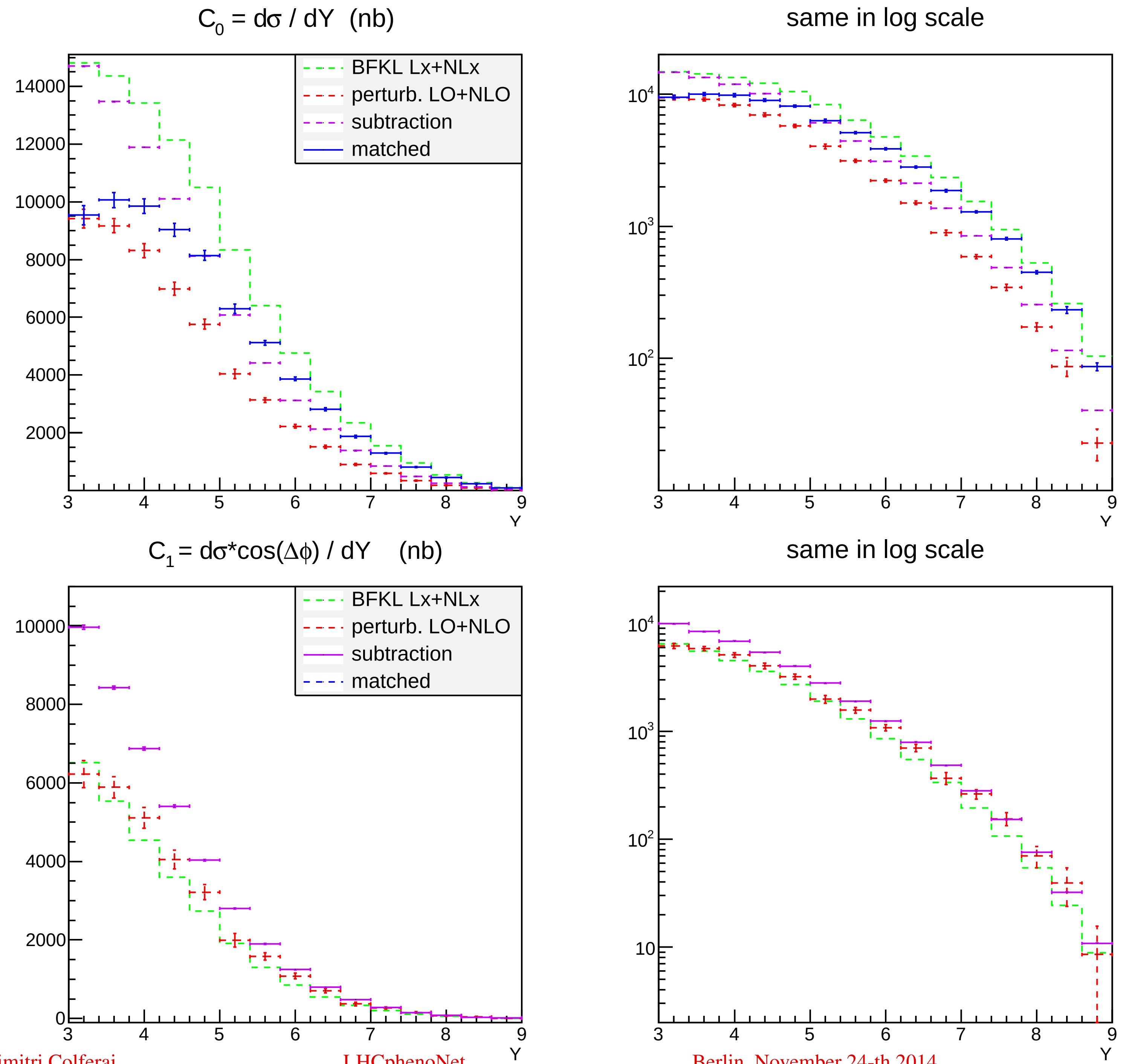

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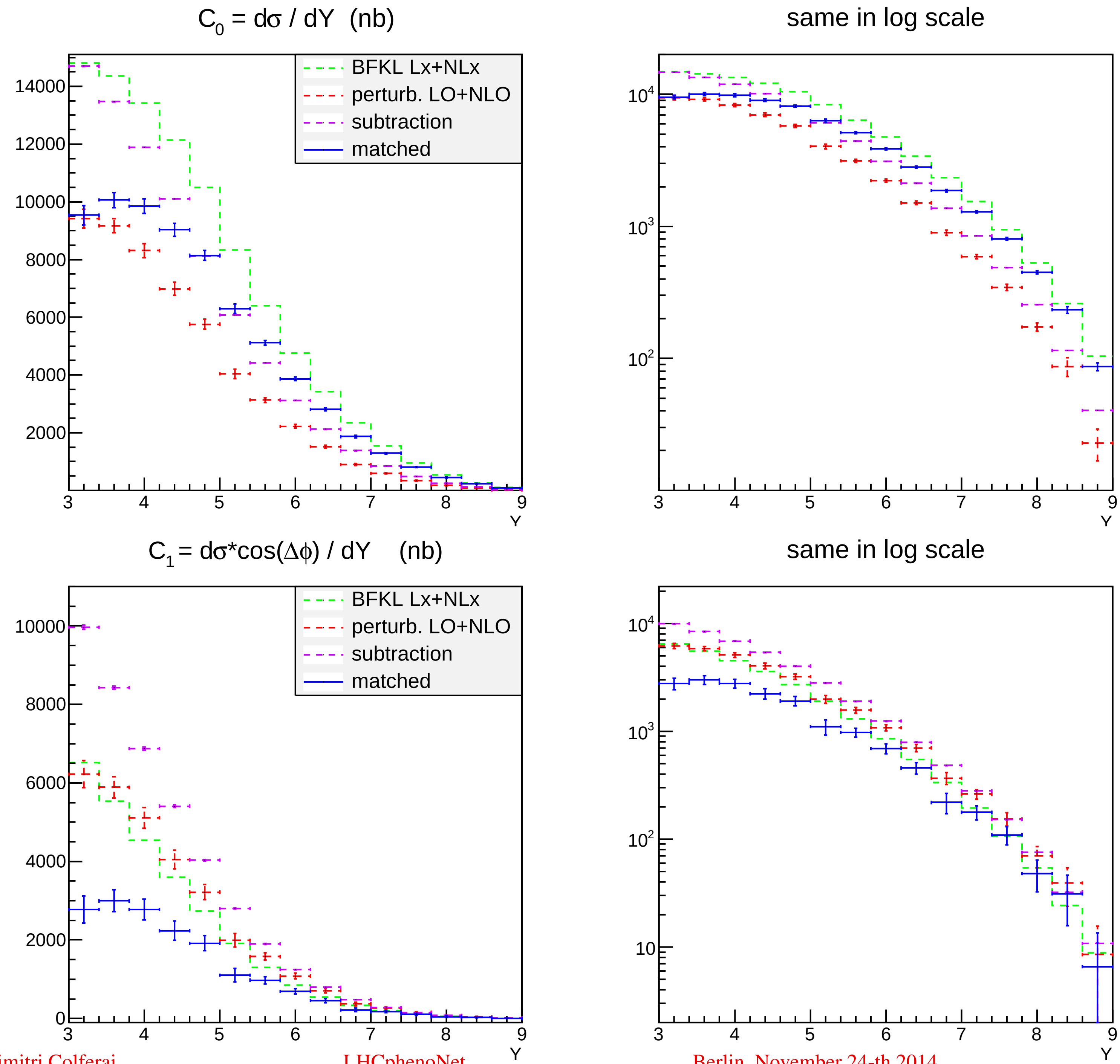

Future developments

- Increase "statistics" to reduce MC errors
- Estimate of errors due to variation of:
  - μ_R and μ_F scales
  - energy scale s_0
  - PDF uncertainties

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

  $\Longrightarrow$ smaller theoretical uncertainties

Conclusions and outlook

- Mueller-Navelet jets appear to be a good observable for demonstrating presence of BFKL dynamics at high energy
- Fixed order MC and NLL BFKL quite different,
  in some cases close to data, but overall agreement is not good
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