Mueller-Navelet Jets at LHC:
Complete NLL calculation

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In collaboration with

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- S. Wallon (Orsay)

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Motivation and Outline

- Motivations
  - One of the important longstanding theoretical questions raised by QCD is its behaviour in the high-energy (Regge) limit $s \gg -t$
  - E.g., to establish the Regge behaviour of QCD, predict the Regge trajectories (growth exponents of particular amplitudes)
- Outline
  - Identify processes suited for study of high energy QCD dynamics (among which Mueller-Navelet jets);
  - Review the most important aspects of PT QCD at high energies (BFKL approach);
  - Describe details of the factorization formula for MN jets and the factors for a complete NLL study;
  - Numerical results: predictions for LHC phenomenology of MN jets;
  - Unexpected conclusions stemming from our results.

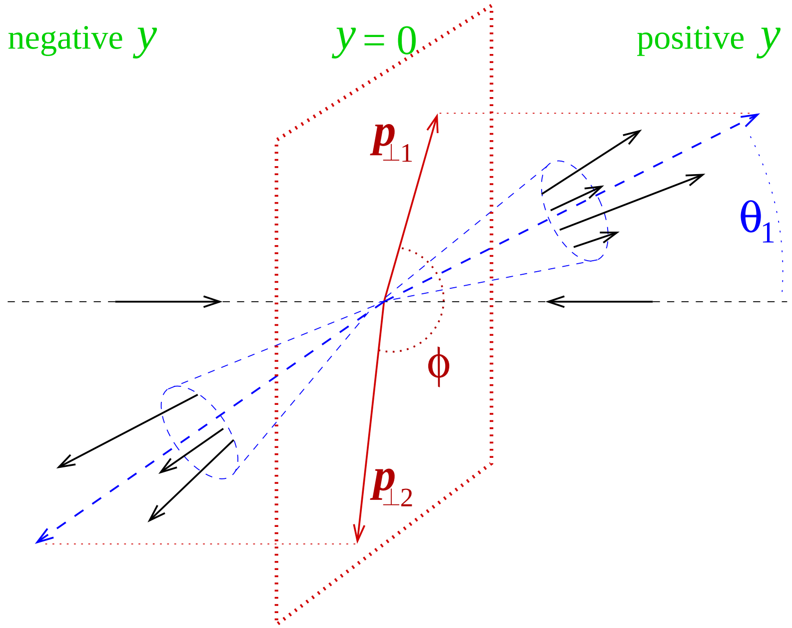
How to test QCD in the Regge limit?

Look for high-energy observables

- accessible at present and (near) future colliders (Tevatron, LHC, ...)
- calculable within perturbative QCD (large scales: hard γ^*, heavy mesons (J/ψ, Υ), energetic [forward] jets)
- insensitive to partonic content of hadrons, to hadronization, and to standard collinear evolution (DGLAP)

Criteria met by semi-hard processes with $s \gg \boldsymbol{k}_i^2 \gg \Lambda_{\rm QCD}^2$,
where $\boldsymbol{k}_i^2$ are typical transverse scales, all of the same order

Mueller-Navelet jets

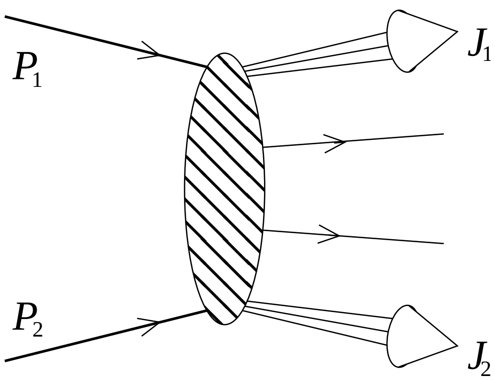


One of most famous testing processes for studying PT high-energy QCD at hadron colliders *[Mueller Navelet 1987]*

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

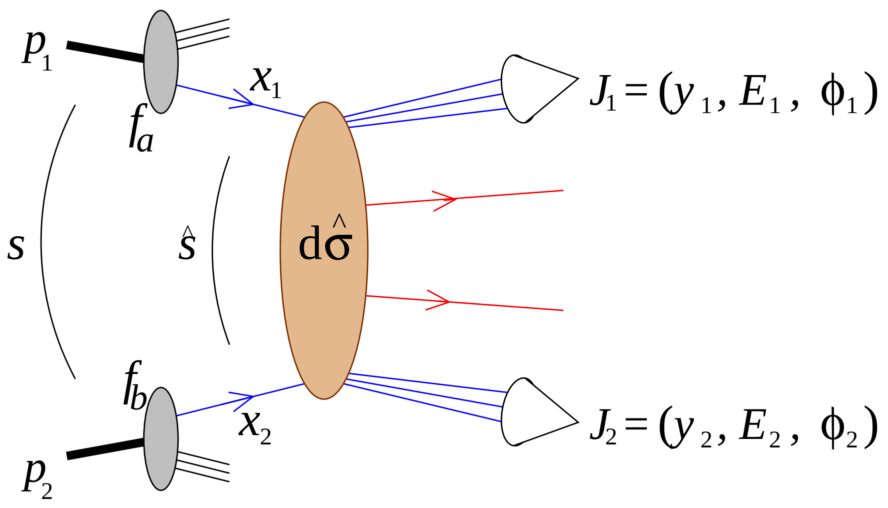
Rapidity: $y = \log(\cot(\theta/2))$

- 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:

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

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

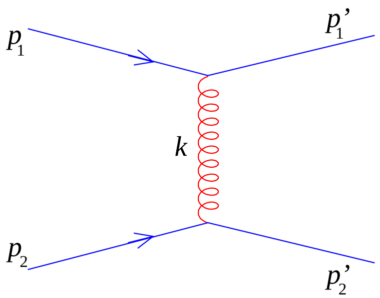
Factorization formula justified because:

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

QCD at large s

Factorization theorem ⇒ perturbatively compute partonic cross sections

At high energy, gluon exchanges dominate



Lowest order:

constant (in s) cross section

QCD at large s

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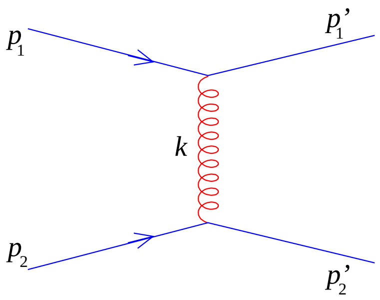

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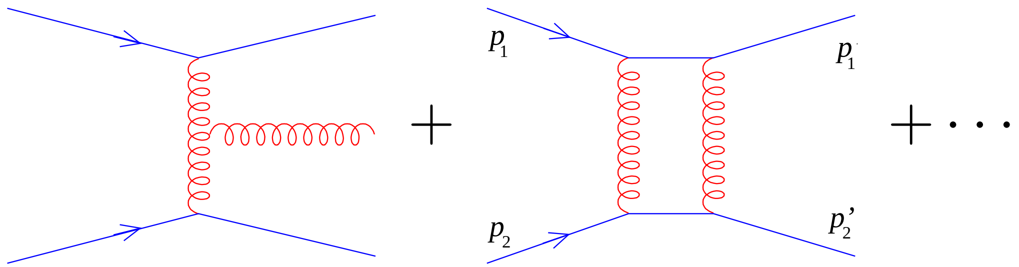

First order corrections show

increasing cross section $\sim \alpha_s \log s$

QCD at large s

Factorization theorem $\Rightarrow$ perturbatively compute partonic cross sections

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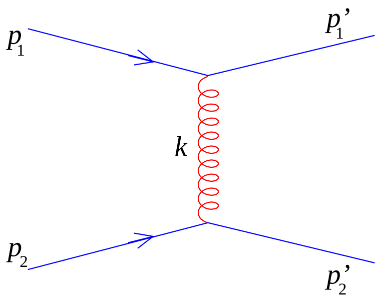

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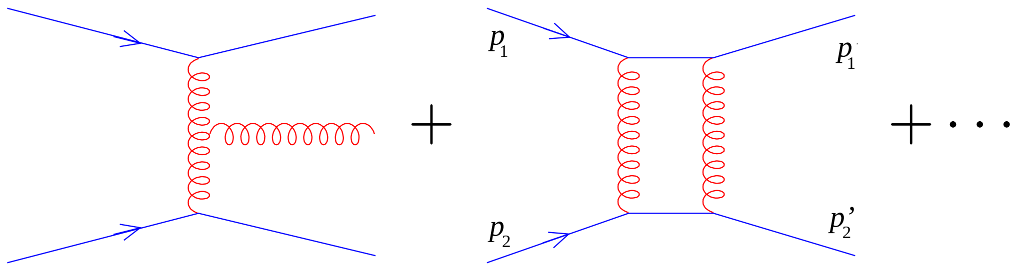

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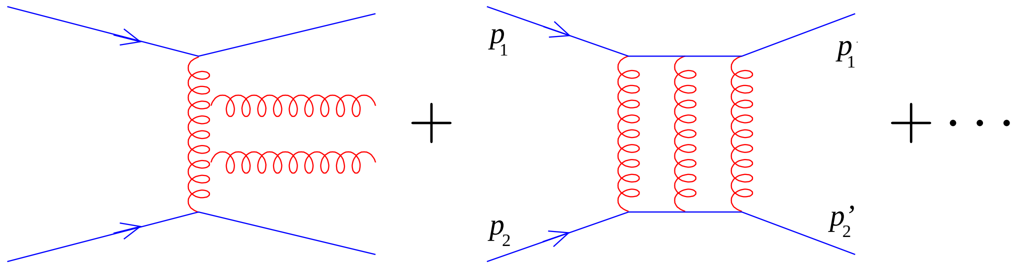


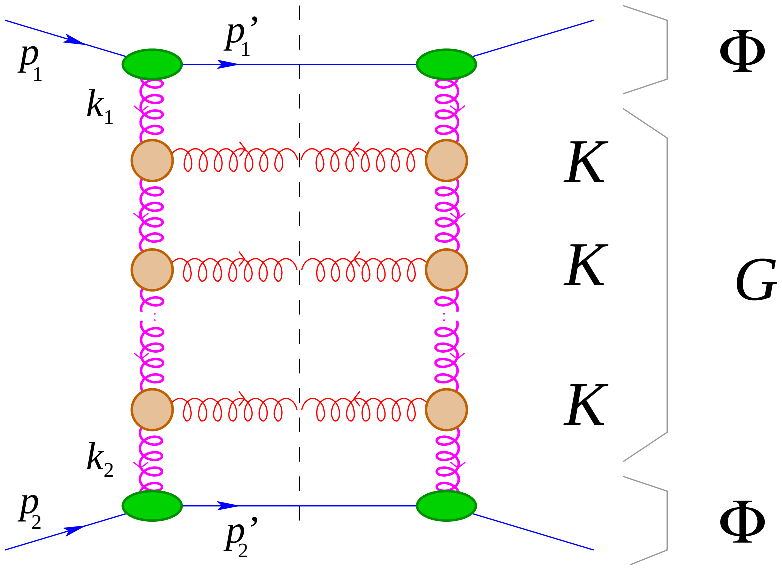
Second order corrections

yield $\sim (\alpha_s \log s)^2$ contributions

and so on

BFKL theory

[BFKL '78] QCD amplitudes have $\sim (\alpha_s \log s)^n$ enhancements to all perturbative orders (LL approx)



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

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

$$K = \alpha_s K_0 + \alpha_s^2 K_1 + \dots$$

$$G(s, \boldsymbol{k}, \boldsymbol{k}) = G(s_0, \boldsymbol{k}, \boldsymbol{k}) \left(\frac{s}{s_0} \right)^{\omega_{\mathbb{P}}}$$

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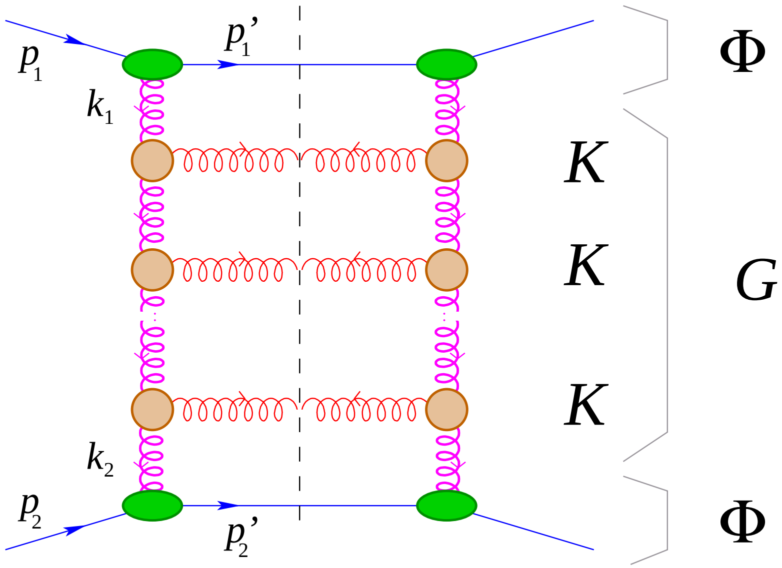

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The Pomeron (?) shows up as a colour-singlet state of two (Reggeized) gluons.

But: $\omega_{\mathbb{P}} = 4 \log(2) N_c \alpha_s / \pi \simeq 0.5 \gg 0.08$ (for $\alpha_s \simeq 0.2$)

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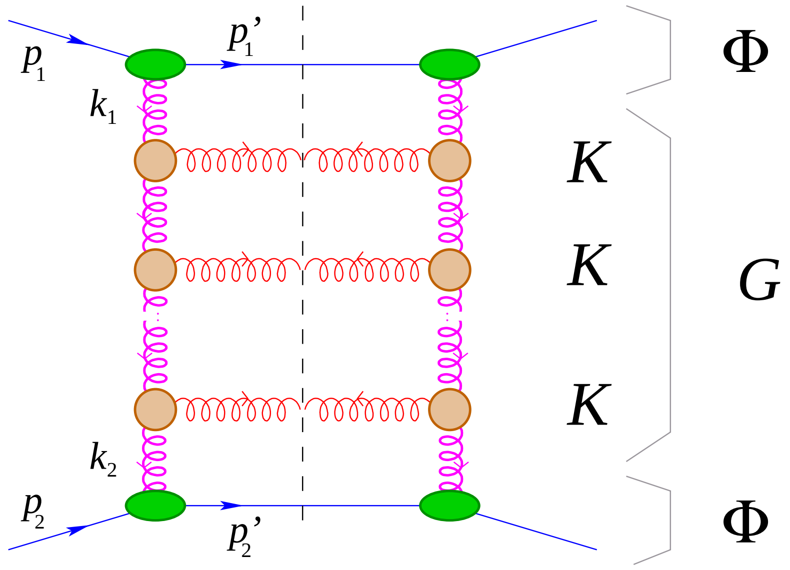

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NLL approx resums $\alpha_s^n \log^{n-1} s$ *[Fadin-Lipatov, Camici-Ciafaloni '98]*
Even worse: $\omega_{\mathbb{P}} = 4 \log(2) N_c \alpha_s / \pi (1 - 6.7 \alpha_s) \simeq -0.15$ (for $\alpha_s \simeq 0.2$)
Possible issues:

- $s^{\omega_{\mathbb{P}}}$ is asymptotic behaviour. At present energies preasymptotic behaviour, exact kinematics and RG improvements are important
- need full NL treatment of impact factors (also for estimate of errors)

Known NLL impact factors

Impact factors are known in some cases at NLL

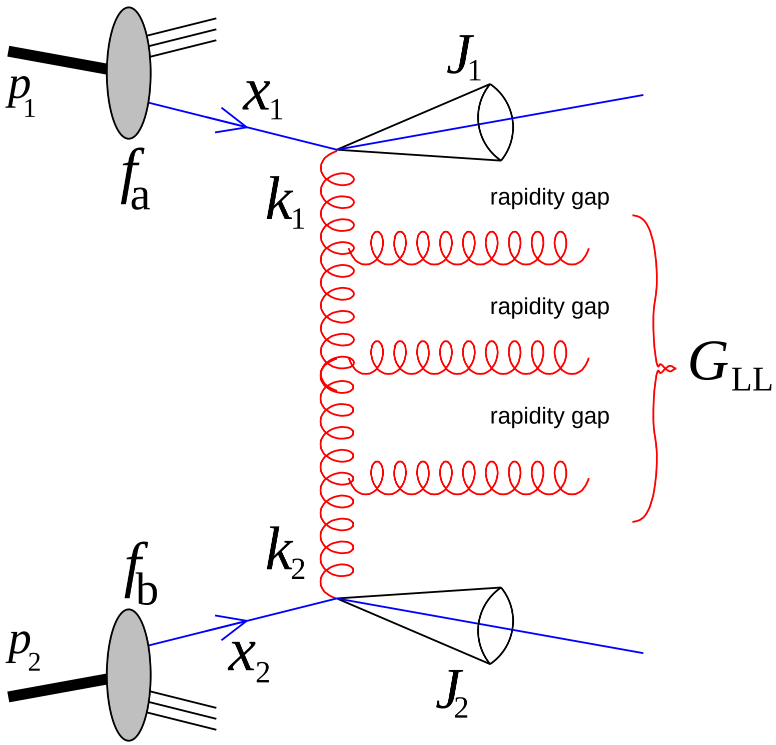
- $\gamma^* \to$ anything *[Bartels, Colferai, Gieseke, Kyrieleis, Qiao]*
- $\gamma^* \to \rho$ in forward limit *[Ivanov, Kotsky, Papa]*
- forward jet production *[Bartels, Colferai, Vacca]*

MN Jets in NL approximation

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

Starting from LL factorization formula

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



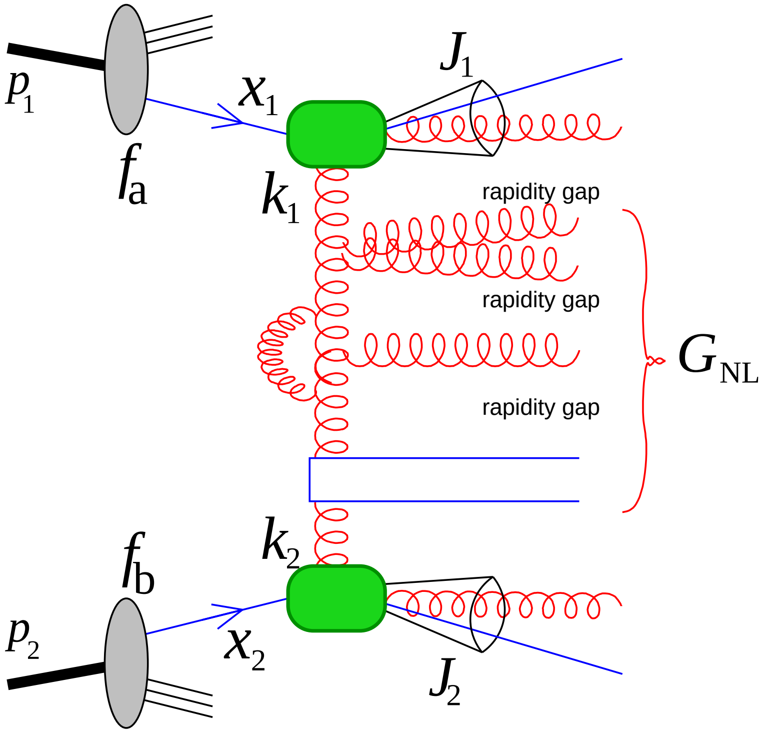
where $V_a^{(0)}(x,\boldsymbol{k};J) = \alpha_{\mathrm{s}}C_a\delta(\boldsymbol{k}-\boldsymbol{p}_J)\delta(x-x_J)$ and $x_J = |\boldsymbol{p}_J|\mathrm{e}^{y_J}/\sqrt{s}$

MN Jets in NL approximation

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

Assume NLL factorization formula

$$\frac{d\sigma(s)}{dJ_1 dJ_2} = \sum_{a,b} \int_0^1 dx_1 dx_2 \int d\boldsymbol{k}_1 d\boldsymbol{k}_2 \times f_a(x_1) \times \boldsymbol{V_a^{(1)}}(x_1, \boldsymbol{k}_1; J_1) \times G_{\mathrm{NL}}(x_1 x_2 s, \boldsymbol{k}_1, \boldsymbol{k}_2) \times \boldsymbol{V_b^{(1)}}(x_2, \boldsymbol{k}_2; J_2) \times f_b(x_2)$$

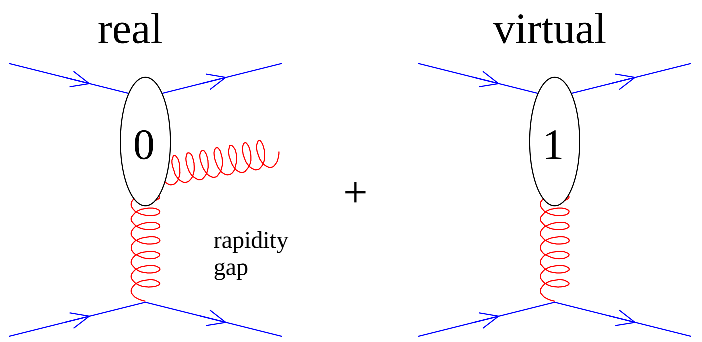


where $V_a^{(0)}(x, \boldsymbol{k}; J) = \alpha_s C_a \delta(\boldsymbol{k} - \boldsymbol{p}_J)\delta(x - x_J)$ and $x_J = |\boldsymbol{p}_J| e^{y_J}/\sqrt{s}$

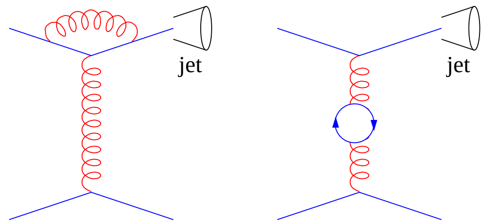
- At NL level the jet vertex condition is non-trivial (e.g. depends on jet radius R)
- Factorization formula must be proven *[Bartels, DC, Vacca '02]*

NL jet vertex

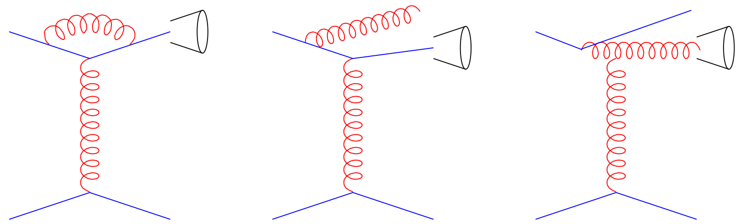
Proof of NL factorization formula require disentangling various structures from 1-loop diagrams:



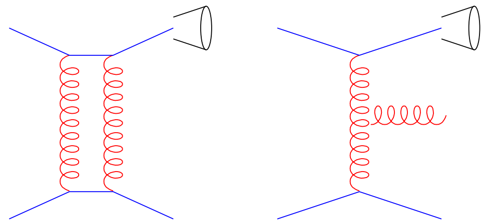
- UV divergencies (absorbed by running coupling)



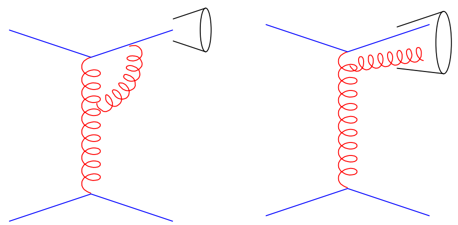
- IR collinear divergencies (absorbed by PDFs)



- $\log(s)$ enhanced contributions (to build GGF)

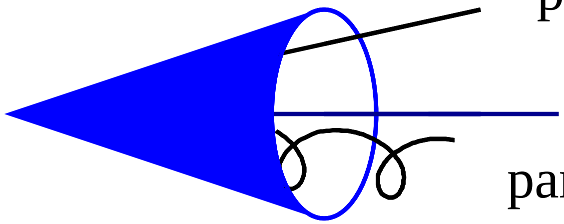


- all remaining IR singularities must cancel,
  to yield finite (in ε) and constant (in s) terms
  to be identified with $V^{(1)}$



Cone jet algorithm

- Should partons $(|\boldsymbol{k}_1|, \phi_1, y_1)$ and $(|\boldsymbol{k}_2|, \phi_2, y_2)$ combined in a single jet?
  $|\boldsymbol{k}_i|$ =transverse energy deposit in the calorimeter cell i of parameter $\Omega = (y_i, \phi_i)$ in (y, ϕ) plane
- define transverse energy of the jet: $E_J = |\boldsymbol{k}_1| + |\boldsymbol{k}_2|$
- jet axis: $$\Omega_c \begin{cases} y_J = \dfrac{|\boldsymbol{k}_1|\, y_1 + |\boldsymbol{k}_2|\, y_2}{E_J} \\[2ex] \phi_J = \dfrac{|\boldsymbol{k}_1|\, \phi_1 + |\boldsymbol{k}_2|\, \phi_2}{E_J} \end{cases}$$



$\Omega = (y_i, \phi_i)$ in (y, ϕ) plane

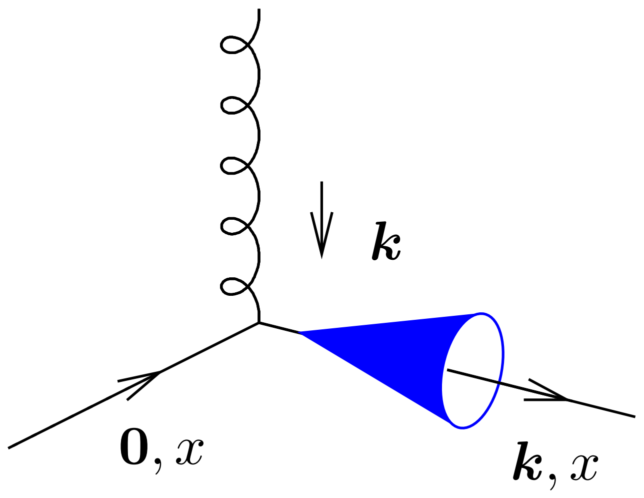
If distances $|\Omega_i - \Omega_c|^2 \equiv (y_i - y_c)^2 + (\phi_i - \phi_c)^2 < R^2$ $(i = 1$ and $i = 2)$

$\Longrightarrow$ partons 1 and 2 are in the same cone Ω_c *[Ellis, Kunszt, Soper]*

combined condition: $|\Omega_1 - \Omega_2| < \dfrac{|\boldsymbol{k}_1| + |\boldsymbol{k}_2|}{\max(|\boldsymbol{k}_1|, |\boldsymbol{k}_2|)} R$

Jet algorithm: LL

$\boldsymbol{k}, \boldsymbol{k}'$ = Euclidian two dimensional vectors

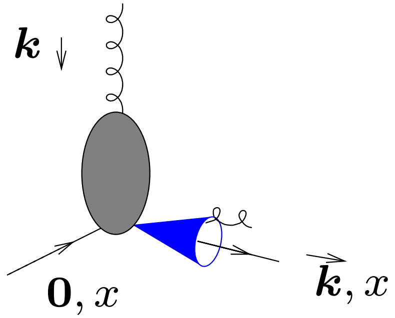


$$S_J^{(2)}(\boldsymbol{k}; x) = x_J\, \delta(x - x_J)\, |\boldsymbol{k}|\, \delta^{(2)}(\boldsymbol{k} - \boldsymbol{k}_J)$$

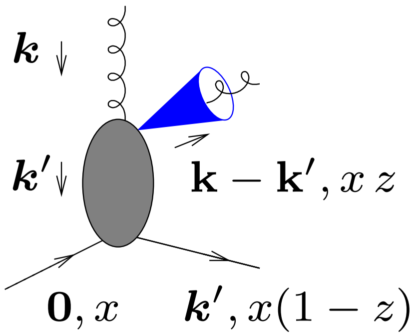
Jet algorithm: NLL

$\boldsymbol{k}, \boldsymbol{k}' =$ Euclidian two dimensional vectors

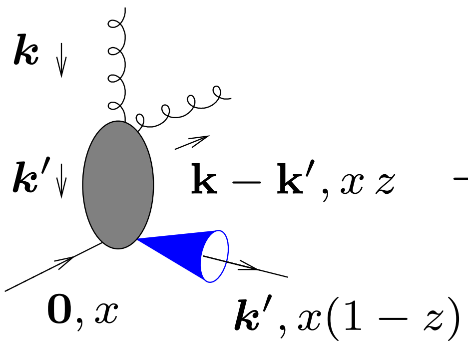
$$S_J^{(3,\mathrm{cone})}(\boldsymbol{k}', \mathbf{k}-\mathbf{k}', xz; x) =$$



$$S_J^{(2)}(\boldsymbol{k}, x)\,\Theta\left(\left[\frac{|\mathbf{k}-\mathbf{k}'|+|\boldsymbol{k}'|}{\max(|\mathbf{k}-\mathbf{k}'|,|\boldsymbol{k}'|)}R_{\mathrm{cone}}\right]^2 - \left[\Delta y^2 + \Delta\phi^2\right]\right)$$



$$+\,S_J^{(2)}(\mathbf{k}-\mathbf{k}', xz)\,\Theta\left(\left[\Delta y^2 + \Delta\phi^2\right] - \left[\frac{|\mathbf{k}-\mathbf{k}'|+|\boldsymbol{k}'|}{\max(|\mathbf{k}-\mathbf{k}'|,|\boldsymbol{k}'|)}R_{\mathrm{cone}}\right]^2\right)$$



$$+\,S_J^{(2)}(\boldsymbol{k}', x(1-z))\,\Theta\left(\left[\Delta y^2 + \Delta\phi^2\right] - \left[\frac{|\mathbf{k}-\mathbf{k}'|+|\boldsymbol{k}'|}{\max(|\mathbf{k}-\mathbf{k}'|,|\boldsymbol{k}'|)}R_{\mathrm{cone}}\right]^2\right),$$

NL (quark-initiated) jet vertex

$$V_q^{(1)}(\boldsymbol{k},x) = \left[\left(\frac{3}{2}\log\frac{\boldsymbol{k}^2}{\mu_F^2} - 2\right)\frac{C_F}{\pi} + \left(\frac{85}{36} + \frac{\pi^2}{4}\right)\frac{C_A}{\pi} - \frac{5}{18}\frac{N_f}{\pi} - b_0 \log\frac{\boldsymbol{k}^2}{\mu_R^2}\right] V_q^{(0)}(\boldsymbol{k},x)$$

$$+ \int \mathrm{d}z\, V_q^{(0)}(\boldsymbol{k},xz)\left\{\frac{C_F}{\pi}\left[\frac{1-z}{2} + \left(\frac{\log(1-z)}{1-z}\right)_+ (1+z^2)\right] + \frac{C_A}{\pi}\frac{z}{2}\right\}$$

$$+ \frac{C_A}{\pi}\int\frac{\mathrm{d}\boldsymbol{k}'}{\pi}\int \mathrm{d}z\left[\frac{1}{2}P_{qq}(z)\left((1-z)\frac{\boldsymbol{q}\cdot(\boldsymbol{q}-\boldsymbol{k})}{\boldsymbol{q}^2(\boldsymbol{q}-\boldsymbol{k})^2} h_q^{(0)}(\boldsymbol{k}')\mathcal{S}_J^{(3)}(\boldsymbol{k}',\boldsymbol{q},xz;x) + \right.\right.$$

$$\left.\left. - \frac{1}{\boldsymbol{k}'^2}\Theta({\mu_F}^2 - \boldsymbol{k}'^2) V_q^{(0)}(\boldsymbol{k},xz)\right) - \frac{1}{z\boldsymbol{q}^2}\Theta(|\boldsymbol{q}| - z(|\boldsymbol{q}| + |\boldsymbol{k}'|)) V_q^{(0)}(\boldsymbol{k}',x)\right]$$

$$+ \frac{C_F}{2\pi}\int \mathrm{d}z\, \frac{1}{(1-z)_+}(1+z^2)\int\frac{\mathrm{d}\boldsymbol{l}}{\pi \boldsymbol{l}^2}\left[\frac{\mathcal{N}C_F}{\boldsymbol{l}^2 + (\boldsymbol{l}-\boldsymbol{k})^2}\right.$$

$$\times \Big(\mathcal{S}_J^{(3)}(z\boldsymbol{k} + (1-z)\boldsymbol{l}, (1-z)(\boldsymbol{k}-\boldsymbol{l}), x(1-z); x)$$

$$+ \mathcal{S}_J^{(3)}(\boldsymbol{k} - (1-z)\boldsymbol{l}, (1-z)\boldsymbol{l}, x(1-z); x)\Big)$$

$$\left. - \Theta(\mu_F^2 - \boldsymbol{l}^2)\left(V_q^{(0)}(\boldsymbol{k},xz) + V_q^{(0)}(\boldsymbol{k},x)\right)\right]$$

Implementation

[DC,Schwennsen,Szymanowski,Wallon '09] used:

- MSTW 2008 PDFs (available as Mathematica packages)
- $\mu_R = \mu_F$ (this is imposed by the MSTW 2008 PDFs)
- two-loop running coupling $\alpha_s(\mu_R^2)$
- all numerical calculations are done in Mathematica
- we use Cuba integration routines (in practice Vegas):
  precision 10^{-2} for 500.000 max points per integration

Numerical Results

$$\sqrt{s} = 14 \text{ TeV}$$

$$E_J = 35, 50 \text{ GeV}$$

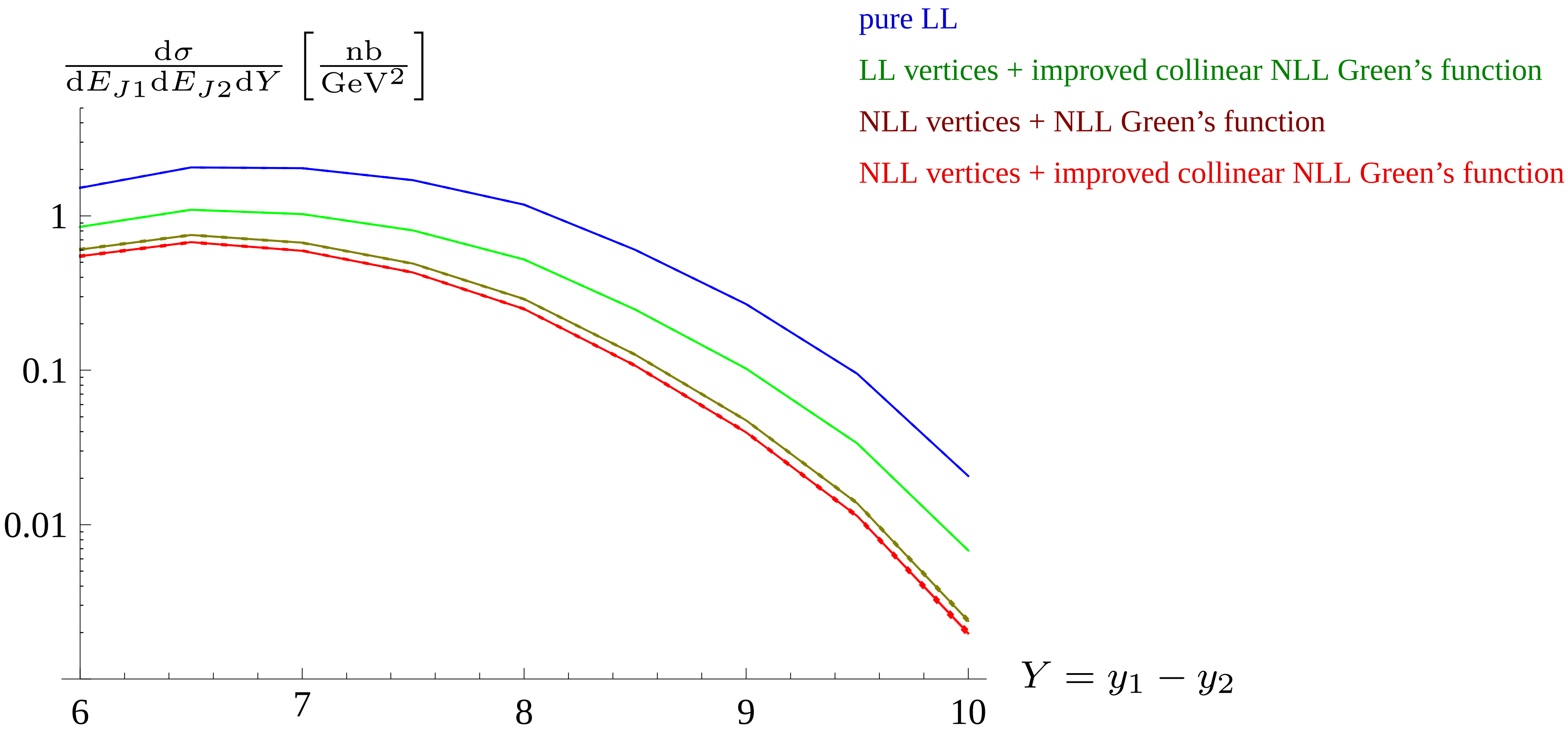
$$3 \leq y_J \leq 5$$

$$Y \equiv y_1 - y_2$$

$$6 \leq Y \leq 10$$

Symmetric configuration ($E_{J1} = E_{J2} = 35\,\mathrm{GeV}$)

Cross-section



Differential cross section in dependence on Y for $E_{J1} = E_{J2} = 35\,\mathrm{GeV}$.
error bands = errors due to the Monte Carlo integration (2% to 5%)

The effect of NLL vertex correction is very sizeable, comparable with NLL Green's function effects

Symmetric configuration ($E_{J1} = E_{J2} = 35\,\mathrm{GeV}$)

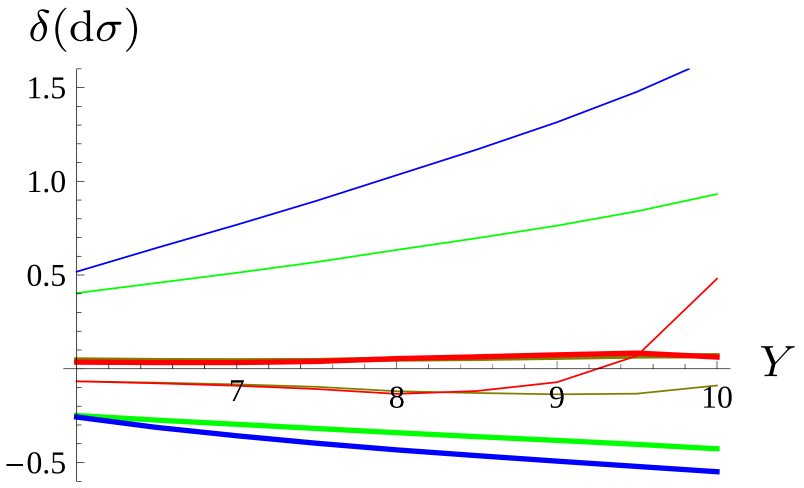
Cross-section: stability with respect to $\mu_R = \mu_F$ and s_0 changes

pure LL

LL vertices + improved collinear NLL Green's function

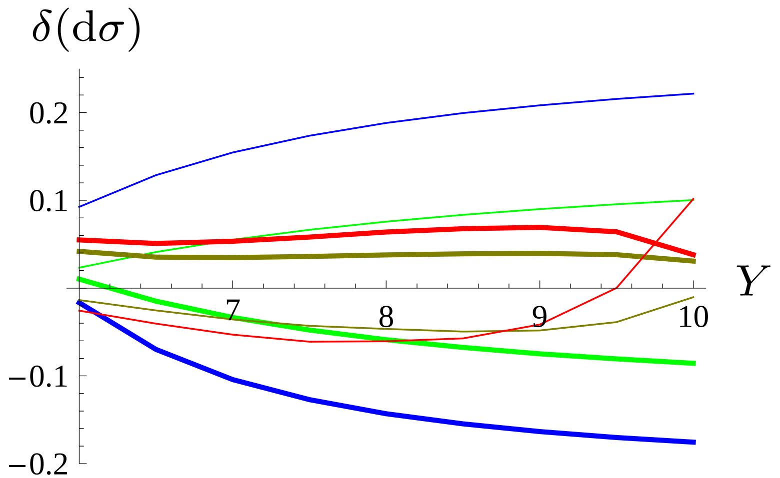
NLL vertices + NLL Green's function

NLL vertices + improved collinear NLL Green's function



Relative effect of changing $\mu_R = \mu_F$

by factors 2 (thick) and $1/2$ (thin)



Relative effect of changing $\sqrt{s_0}$ (in $\log(\frac{s}{s_0})$)

by factors 2 (thick) and $1/2$ (thin)

Symmetric configuration ($E_{J1} = E_{J2} = 35\,\mathrm{GeV}$)

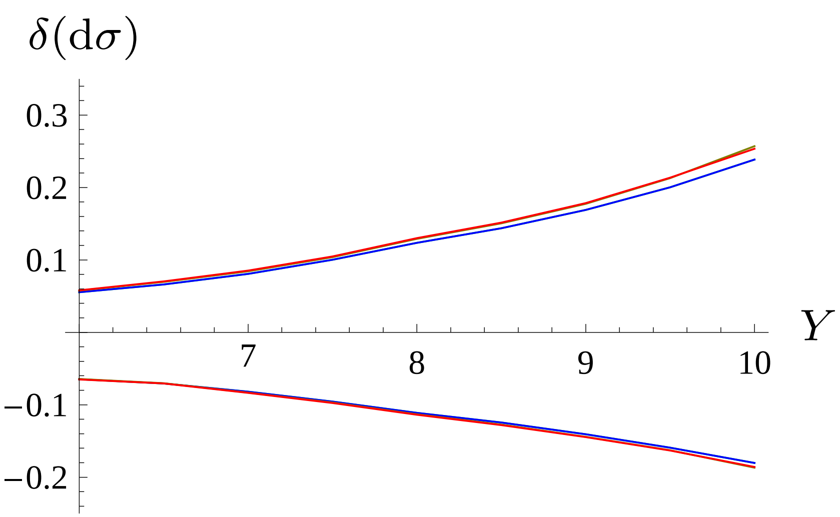
Cross-section: PDF and Monte Carlo errors

pure LL

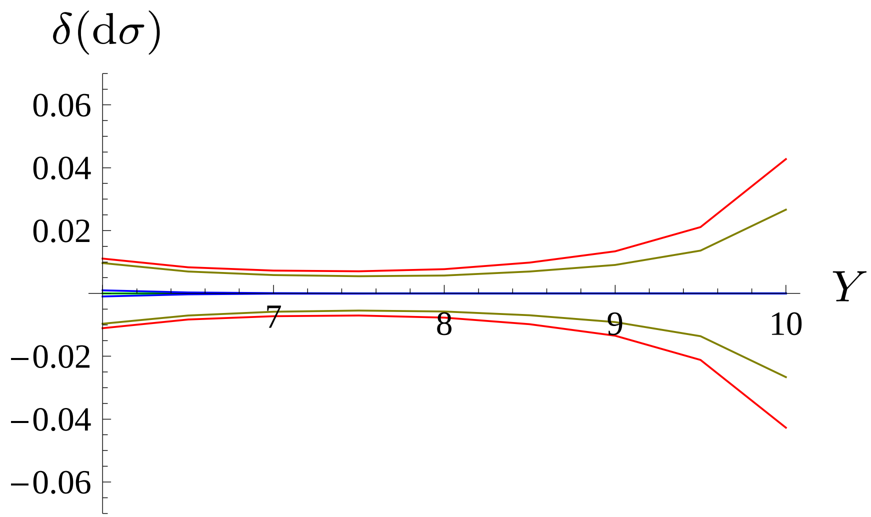
LL vertices + improved collinear NLL Green's function

NLL vertices + NLL Green's function

NLL vertices + improved collinear NLL Green's function



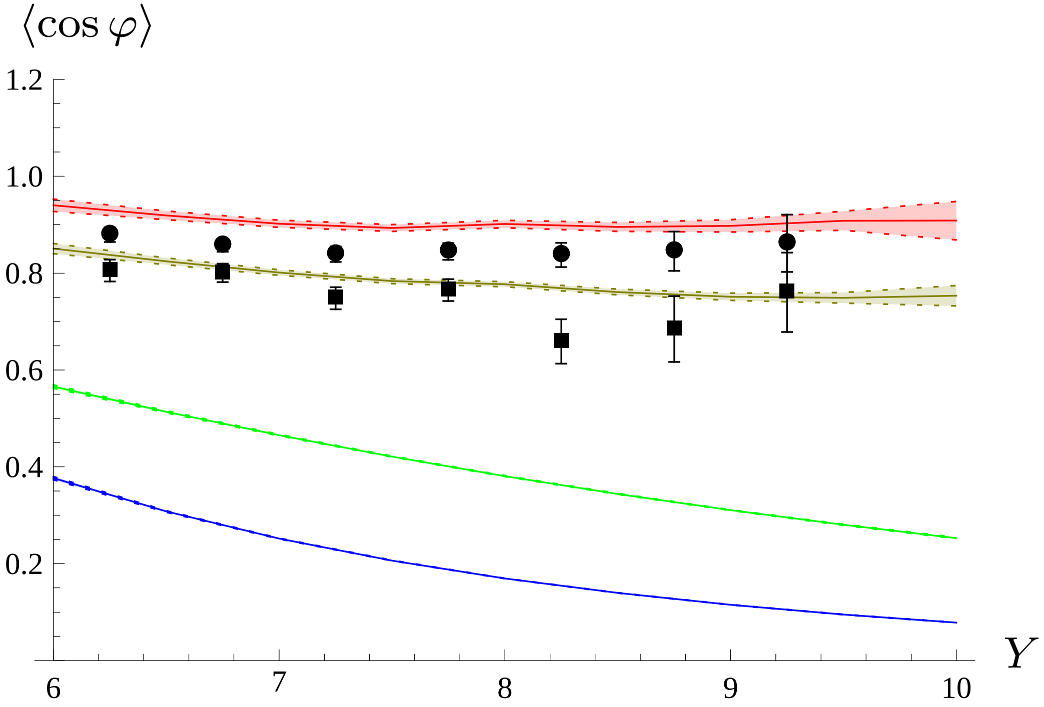
Relative effect of the PDF errors



Relative effect of the Monte Carlo errors

Symmetric configuration ($E_{J1} = E_{J2} = 35\,\mathrm{GeV}$)

Azimuthal correlation: $\phi \equiv \phi_1 - \phi_2 - \pi$



pure LL

LL vertices + improved collinear NLL Green's function

NLL vertices + NLL Green's function

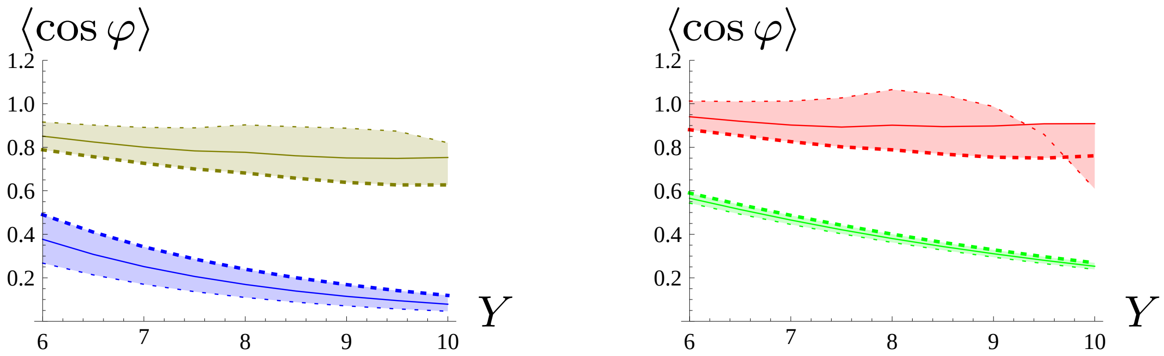
NLL vertices + improved collinear NLL Green's function

error bands	=	errors due to the Monte Carlo integration
dots	=	results obtained with PYTHIA (DGLAP LO MC)
squares	=	results obtained with HERWIG (DGLAP LO MC)

- NLL $\rightarrow$ LL vertices change results dramatically
- At NLL, the decorrelation is very flat and close to LO DGLAP type of Monte Carlo

Symmetric configuration ($E_{J1} = E_{J2} = 35\,\mathrm{GeV}$)

Azimuthal correlation: dependency with respect to $\mu_R = \mu_F$ and s_0 changes



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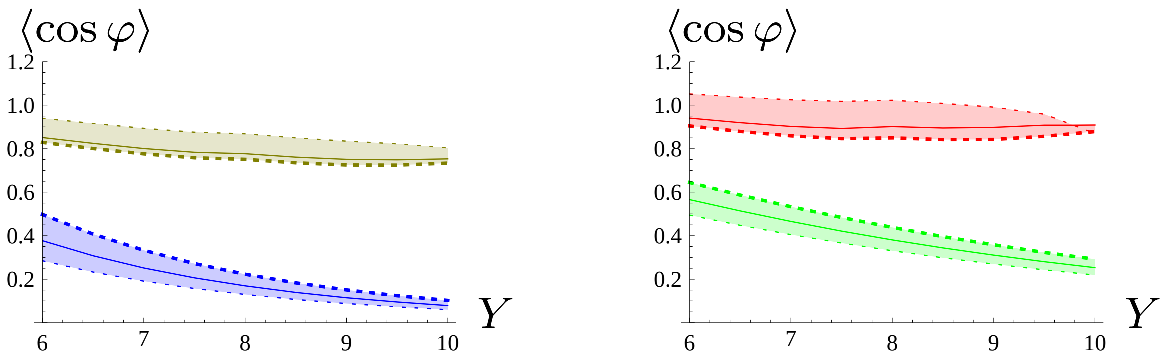
Effect of changing $\mu_R = \mu_F$ by factors 2 (thick) and $1/2$ (thin)

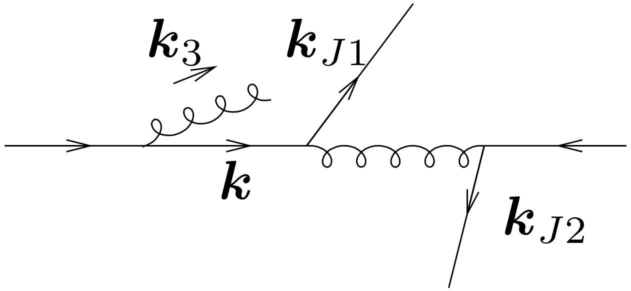


Effect of changing $\sqrt{s_0}$ by factors 2 (thick) and $1/2$ (thin)

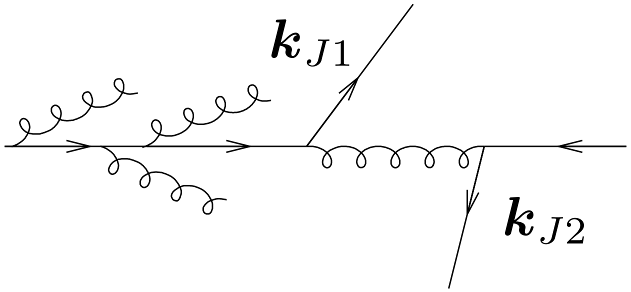
- $\langle\cos\varphi\rangle$ is still rather $\mu_R = \mu_F$ and s_0 dependent
- collinear resummation can lead to $\langle\cos\varphi\rangle > 1(!)$ for small $\mu_R = \mu_F$
- based on NLL double-ρ production *[Ivanov, Papa]* one can expect that small scales is disfavored *[Caporale, Papa, Sabio Vera]*

Motivation for asymmetric configurations

- Initial state radiation (unseen) produces divergencies if one touches the collinear singularity $\boldsymbol{k} \to 0$

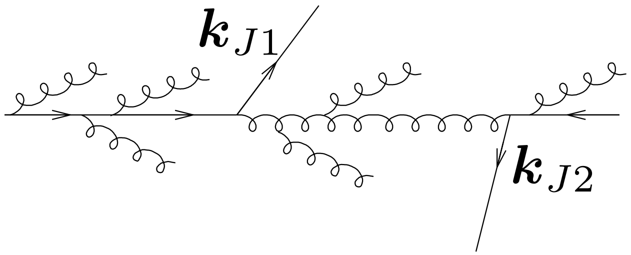


- they are compensated by virtual corrections
- this compensation is in practice difficult to implement when for some reason this additional emission is in a ”corner” of phase space (dip in the differential cross-section)
- this is the case when $\boldsymbol{k}_{J1} + \boldsymbol{k}_{J2} \to 0$ (at NLO, $\mathrm{d}\sigma$ is finite but has a $\log$ cusp)
- this calls for a Sudakov resummation of large logs



Motivation for asymmetric configurations

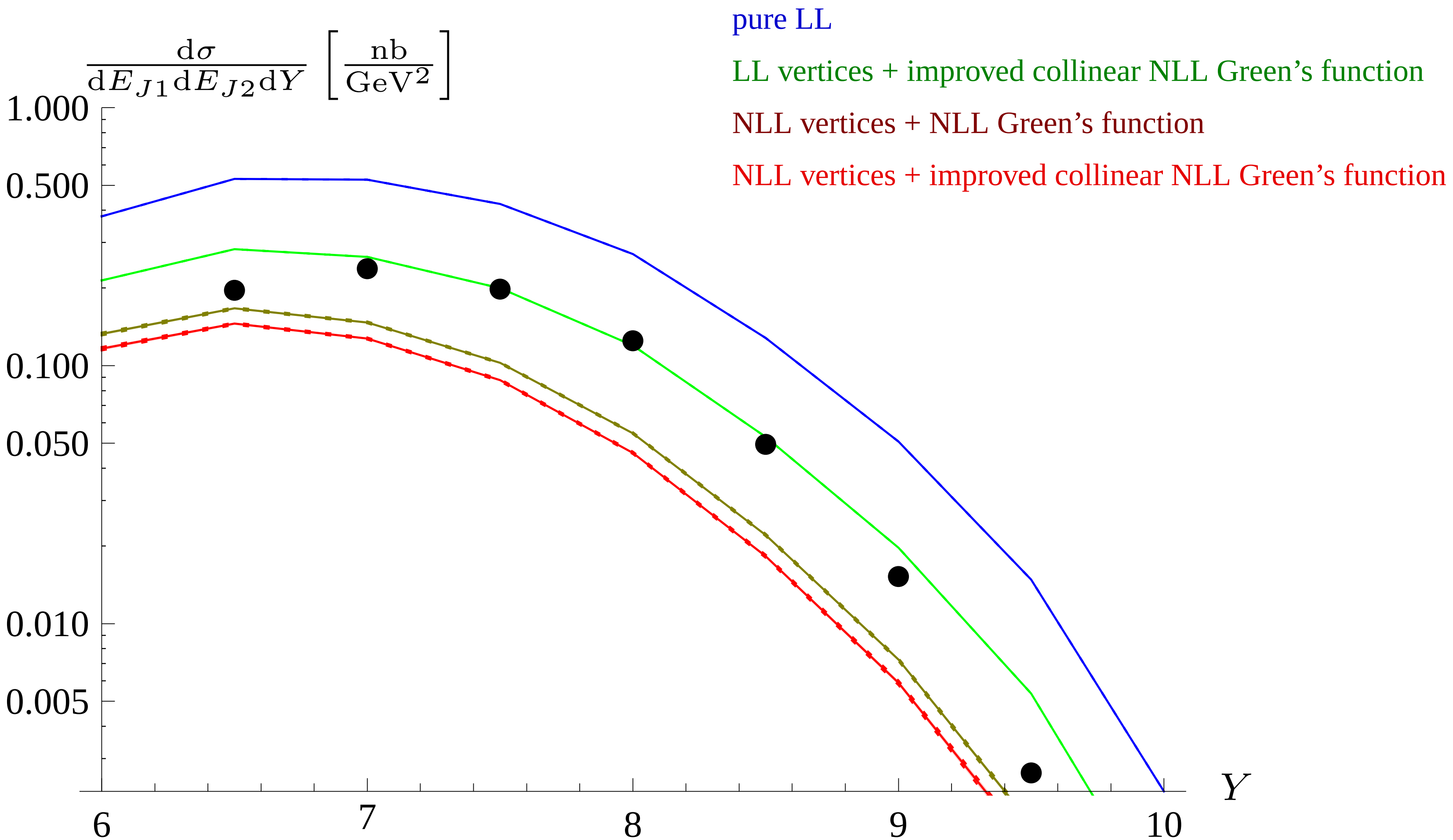
- since these resummation have never been investigated in this context, one should better avoid that region
- note that for BFKL, due to additional emission between the two jets, one may expect a less severe problem (at least a smearing in the dip region $|\boldsymbol{k}_{J1}| \sim |\boldsymbol{k}_{J2}|$)



- this may however not mean that the region $|\boldsymbol{k}_{J1}| \sim |\boldsymbol{k}_{J2}|$ is perfectly trustable even in a BFKL type of treatment
- we now investigate a region where NLL DGLAP is under control

Asymmetric configuration ($E_{J1} = 35\,\mathrm{GeV}$, $E_{J2} = 50\,\mathrm{GeV}$)

Cross-section

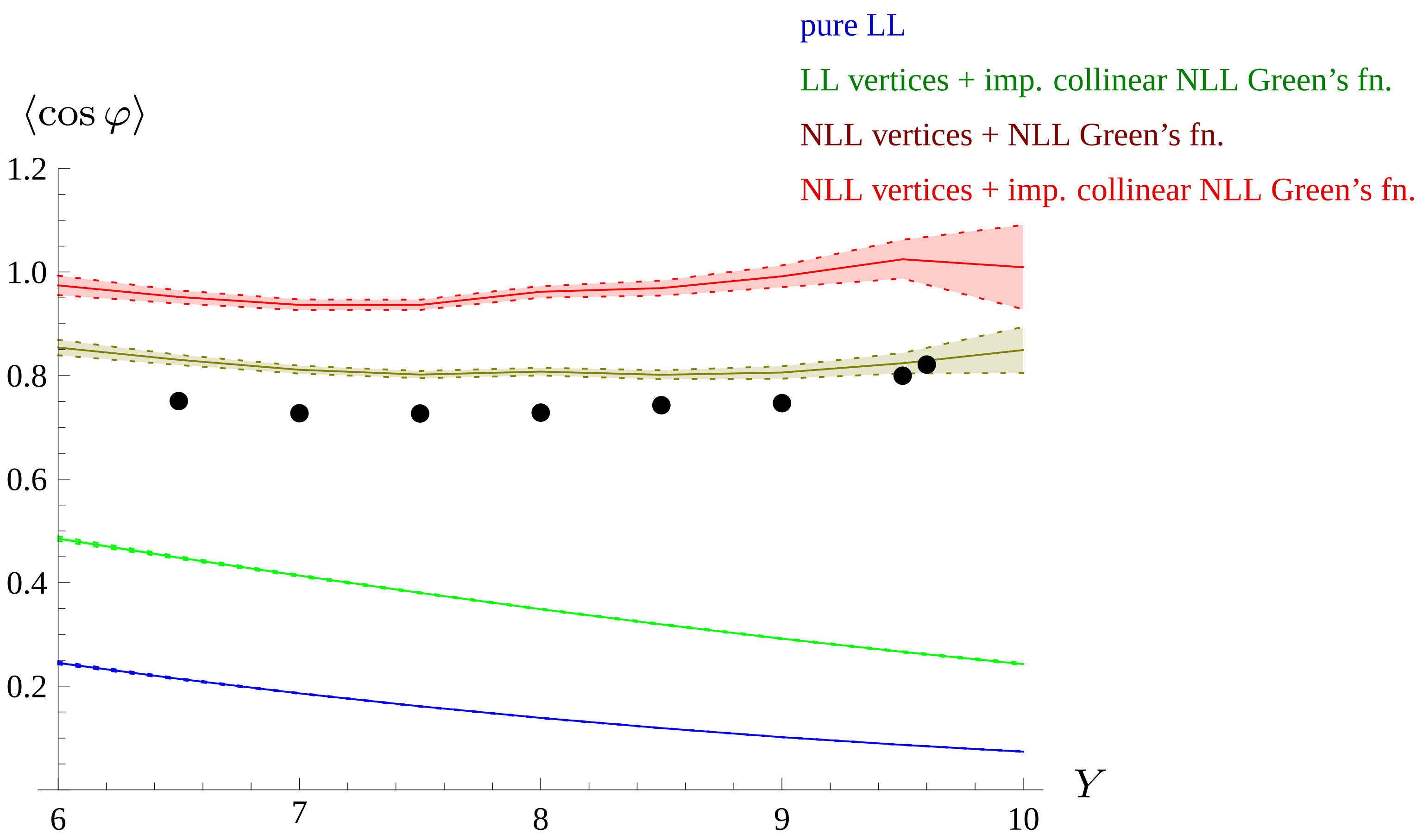


bands = errors due to the Monte Carlo integration

dots = based on the NLO DGLAP parton generator DIJET (thanks to *[Fontannaz]*)

Asymmetric configuration ($E_{J1} = 35\,\text{GeV}$, $E_{J2} = 50\,\text{GeV}$)

Azimuthal correlation: $\langle \cos \varphi \rangle$

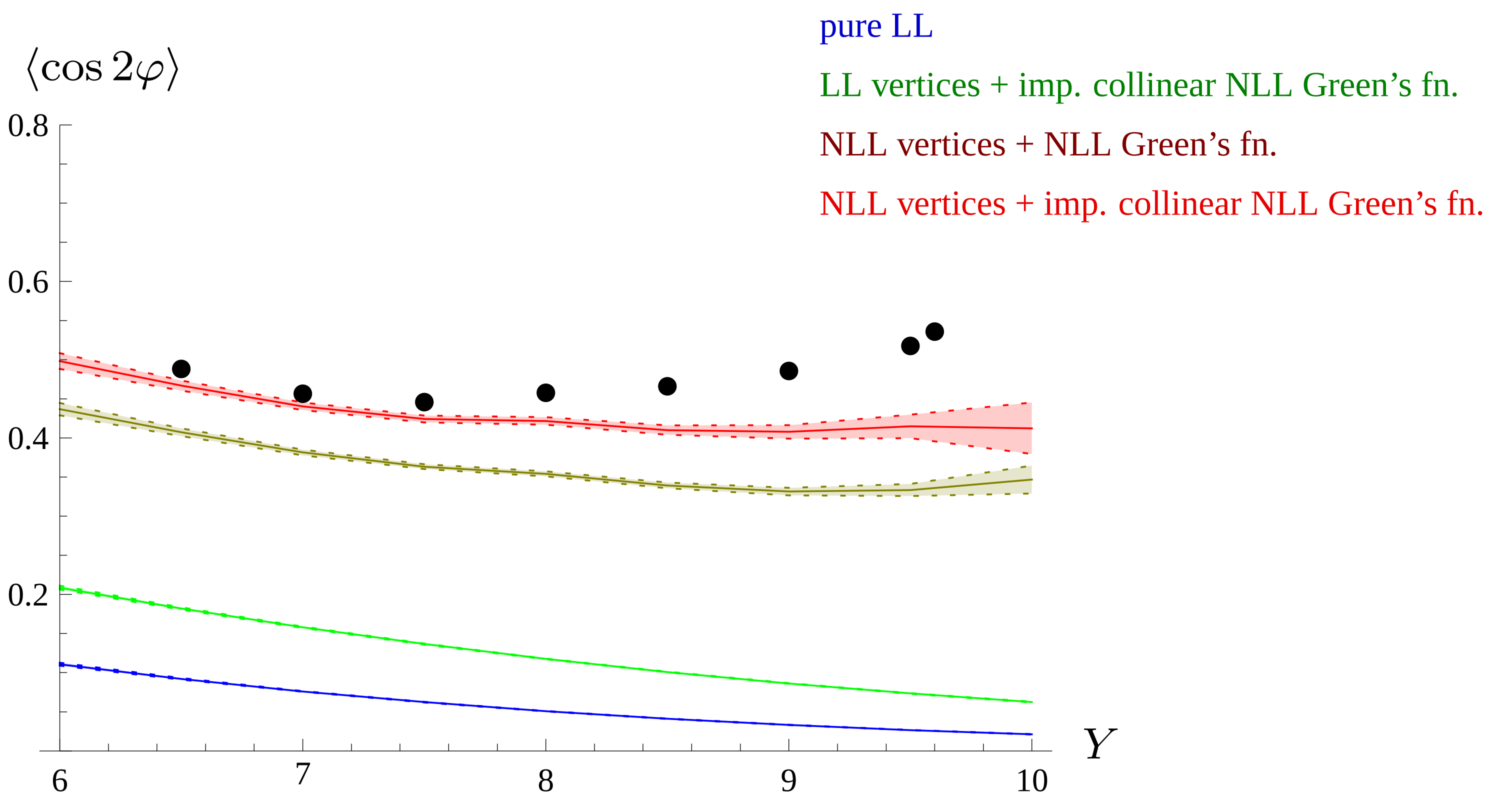


bands	=	errors due to the Monte Carlo integration
dots	=	based on the NLO DGLAP parton generator DIJET (thanks to *[Fontannaz]*)

- Both NLL and improved NLL results are almost flat in Y
- no significant difference between NLL BFKL and NLO DGLAP

Asymmetric configuration ($E_{J1} = 35\,\text{GeV}$, $E_{J2} = 50\,\text{GeV}$)

Azimuthal correlation: $\langle \cos 2\varphi \rangle$



bands = errors due to the Monte Carlo integration

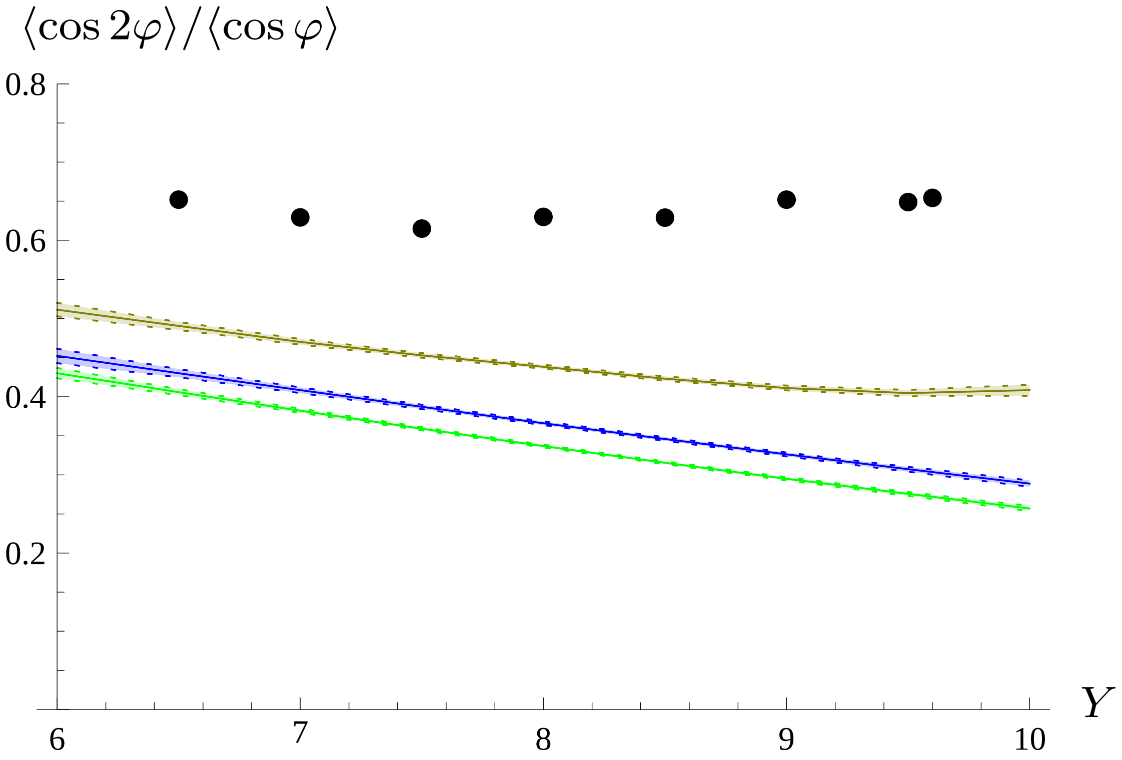
dots = based on the NLO DGLAP parton generator DIJET (thanks to *[Fontannaz]*)

Same conclusions:

- Both NLL and improved NLL results are almost flat in Y
- no significant difference between NLL BFKL and NLO DGLAP

Asymmetric configuration ($E_{J1} = 35\,\mathrm{GeV}$, $E_{J2} = 50\,\mathrm{GeV}$)

Ratio of azimuthal correlations $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$



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NLL vertices + imp. collinear NLL Green's fn.

bands	=	errors due to the Monte Carlo integration
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NB:		NLL collinear improved changed nothing wrt pure NLL

This is the only observable which might still differ between NLL BFKL and NLO DGLAP scenarii

Conclusions

- We have performed for the first time a complete NLL analysis of Mueller-Navelet jets
- Corrections due to NLL jet vertices corrections have a large effect, similar to the NLL Green function corrections
- for the cross-section:
  - it makes the prediction much more stable with respect to variation of parameters (factorization scale, scale s_0 entering the rapidity definition, Parton Distribution Functions)
  - it is close to DGLAP (although surprisingly a bit below!)
- the decorrelation effect is very small:
  - it is very close to DGLAP
  - it is very flat in rapidity Y
  - it is still rather dependent with respect to scale parameters
- pure NLL BFKL and collinear improved NLL BFKL lead to similar results
- collinear improved NLL BFKL faces some puzzling behaviour for the azimuthal correlation
- except for $\langle \cos 2\varphi \rangle / \langle \cos \varphi \rangle$, there is almost no difference between NLL BFKL and NLO DGLAP based observables
- Mueller Navelet jets are thus probably not such a conclusive observable to see the perturbative Regge effect of QCD

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- Mueller Navelet jets are thus probably not such a conclusive observable to see the perturbative Regge effect of QCD
- a serious study of Sudakov type of effects is still missing, both in DGLAP and BFKL approaches