Mueller Navelet and Mueller Tang processes at the LHC

Christophe Royon
University of Kansas, Lawrence, USA
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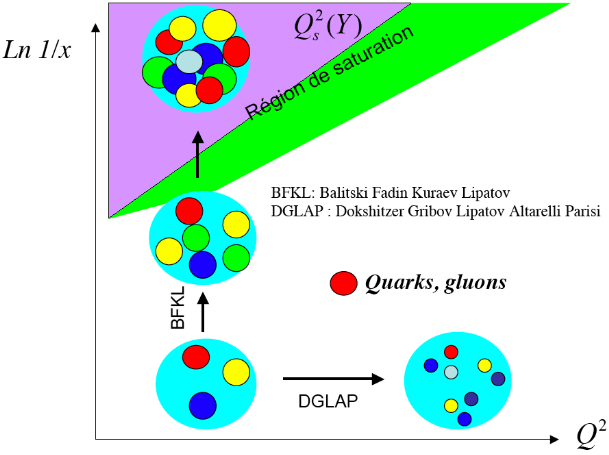
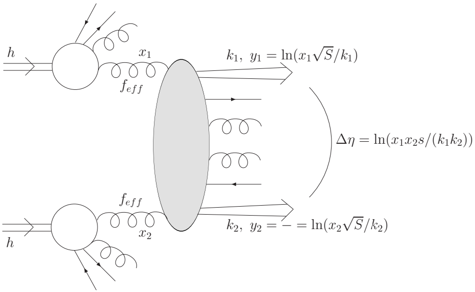
Looking for BFKL/CGC effects at LHC/EIC in dedicated final states



Looking for BFKL resummation effects at hadron colliders



- Mueller Navelet jets: Look for dijet events separated by a large interval in rapidity
- If jets have similar p_T, DGLAP cross section suppressed because of the k_T ordering of the gluons emitted between the two jets
- BFKL cross section enhanced: gluon emissions possible because of large rapidity interval
- Study the $\Delta\Phi$ between jets dependence of the cross section as an example

Mueller Navelet jets: $\Delta\Phi$ dependence

- Study the $\Delta\Phi$ dependence of the relative cross section using BFKL NLL formalism
- Relevant variables:

$$\Delta\eta = y_1 - y_2 \qquad y = (y_1 + y_2)/2$$
$$Q = \sqrt{k_1 k_2} \qquad R = k_2/k_1$$

- Azimuthal correlation of dijets:

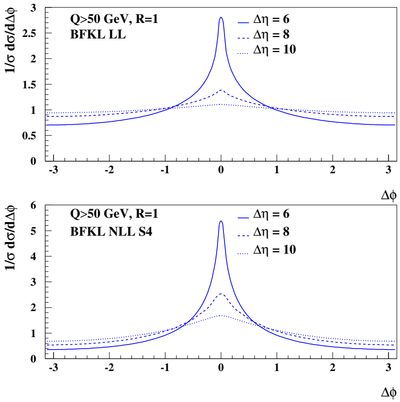
$$2\pi \frac{d\sigma}{d\Delta\eta dR d\Delta\Phi} \Big/ \frac{d\sigma}{d\Delta\eta dR} = 1 + \frac{2}{\sigma_0(\Delta\eta, R)} \sum_{p=1}^{\infty} \sigma_p(\Delta\eta, R) \cos(p\Delta\Phi)$$

where

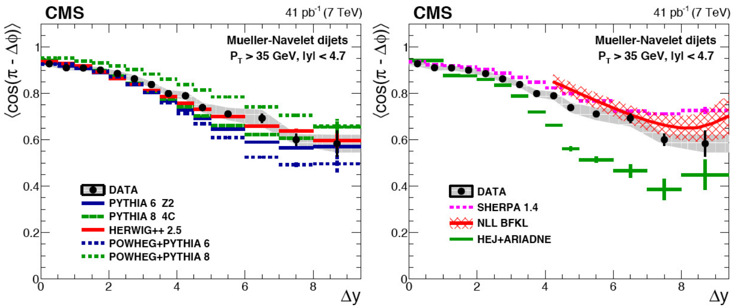
$$\sigma_p = \int_{E_T}^{\infty} \frac{dQ}{Q^3} \alpha_s(Q^2/R)\alpha_s(Q^2 R) \left(\int_{y_<}^{y_>} dy x_1 f_{eff}(x_1, Q^2/R) x_2 f_{eff}(x_2, Q^2 R) \right)$$
$$\int_{1/2-\infty}^{1/2+\infty} \frac{d\gamma}{2i\pi} R^{-2\gamma} \; e^{\bar{\alpha}(Q^2)\chi_{eff}(p)\Delta\eta}$$

Mueller Navelet jets: $\Delta\Phi$ dependence

- Implementation of NLL BFKL predictions in BFKL-Ex (A. Sabio Vera, G. Chachamis), allow to obtain gluon emission along the ladder, also to compare with NLO QCD (POWHEG+PYTHIA)
- $1/\sigma d\sigma/d\Delta\Phi$ spectrum for BFKL NLL as a function of $\Delta\Phi$ for different values of $\Delta\eta$, scale dependence: $\sim$20%
- Stronger decorrelation for BFKL prediction than for DGLAP
- C. Marquet, C.Royon, Phys. Rev. D79 (2009) 034028

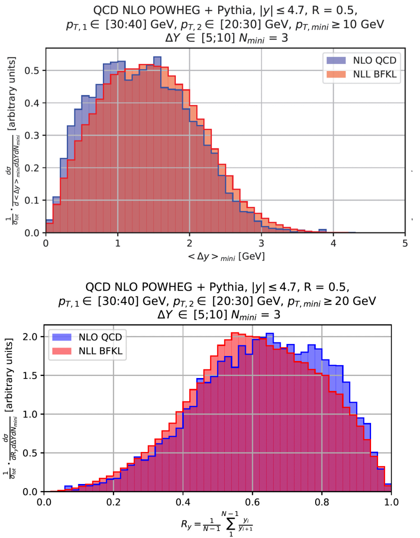


Mueller Navelet jets: ΔΦ dependence: CMS measurements



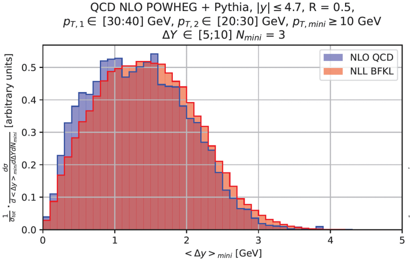
- CMS collaboration: Azimuthal decorrelation between jets at 7 TeV: J. High Energy Phys. 08 (2016) 139
- BFKL NLL leads to a good description of data but also PYTHIA/HERWIG after MPI tuning...
- More differential observables needed or completely new ones

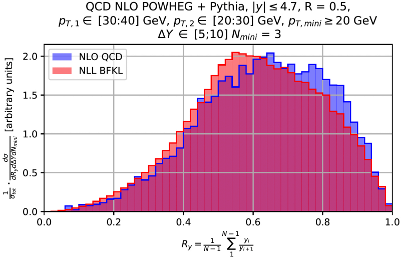
Mueller Navelet processes: Looking for less inclusive variables



- Looking for multi-gluon emission along ladder, characteristic of BFKL NLL/DGLAP NLO
- Comparison between BFKL-ex MC and usual QCD NLO MC to compare both approaches (M. Kampshoff, A. Sabio Vera, G. Chachamis, C. Baldenegro, CR in preparation)
- We first require two forward jets with $5 < |\Delta Y| < 10$, $30 < p_{T_1} < 40$ GeV, $20 < P_{T_2} < 30$ GeV

Mueller Navelet processes: Looking for less inclusive variables



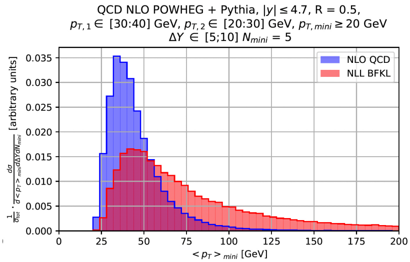


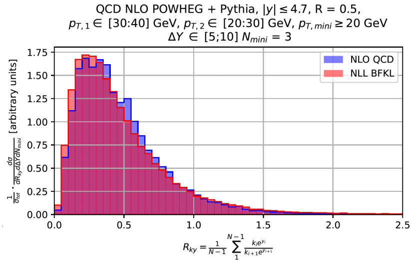
- We define as $y = 0$ the rapidity of the mini-jet closest to the MN jet and N is the number of mini-jets above 20 GeV (or 10 GeV) emitted between the two MN jets
- Rapidity of emitted mini-jets

$$< \Delta y_{mini} > = \frac{1}{N-1}(y_N - y_1)$$

$$< R_y > = \frac{1}{N-1} \Sigma_1^{N-1} \frac{y_i}{y_{i+1}}$$

- Similar distributions for both approaches (R_y slightly higher for NLO QCD): test of gluon emission as predicted by QCD





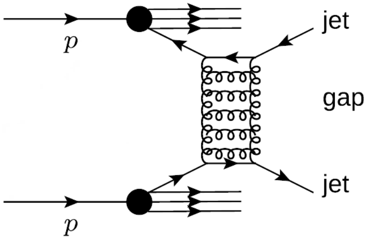
- We look for the average p_T of the emitted jets, as well as p_T weighted rapidity distrbutions

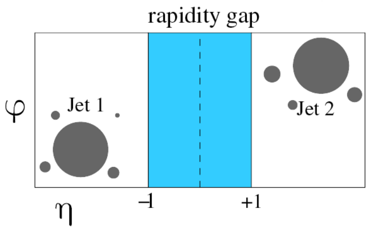
$$< p_T > \; = \; \frac{1}{N+} \Sigma_1^{N-1} p_{T_i}$$

$$< R_{ky} > \; = \; \frac{1}{N-1} \Sigma_1^{N-1} \frac{p_{T_i} e^{y_i}}{p_{T_{i+1}} e^{y_{i+1}}}$$

- Small differences, NLO QCD giving slightly higher values for R_{ky}
- $< p_T >$ is quite different but probably an artefact due to the fact there is no showering in BFKL-Ex and only conservation of transverse energy in the BFKL equation

Mueller Tang: Gap between jets at the Tevatron and the LHC





- Looking for a gap between two jets: Region in rapidity devoid of any particle production, energy in detector
- Exchange of a BFKL Pomeron between the two jets: two-gluon exchange in order to neutralize color flow
- Method to test BFKL resummation: Implementation of BFKL NLL formalism in HERWIG/PYTHIA Monte Carlo

BFKL formalism

- BFKL jet gap jet cross section: integration over ξ, p_T performed in Herwig event generation

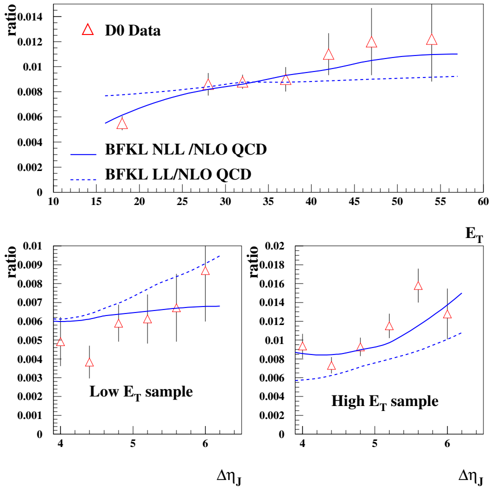
$$\frac{d\sigma^{pp\to XJJY}}{dx_1 dx_2 dp_T^2} = \mathcal{S}\frac{f_{eff}(x_1, p_T^2) f_{eff}(x_2, p_T^2)}{16\pi} \left|A(\Delta\eta, p_T^2)\right|^2$$

where S is the survival probability (0.1 at Tevatron, 0.03 at LHC)

$$A = \frac{16 N_c \pi \alpha_s^2}{C_F p_T^2} \sum_{p=-\infty}^{\infty} \int \frac{d\gamma}{2i\pi} \frac{[p^2 - (\gamma - 1/2)^2]}{[(\gamma - 1/2)^2 - (p - 1/2)^2]} \frac{\exp\left\{\frac{\alpha_S N_C}{\pi} \chi_{eff} \Delta\eta\right\}}{[(\gamma - 1/2)^2 - (p + 1/2)^2]}$$

- α_S: 0.17 at LL (constant), running using RGE at NLL
- BFKL effective kernel χ_{eff}: determined numerically, solving the implicit equation: $\chi_{eff} = \chi_{NLL}(\gamma, \bar{\alpha}\ \chi_{eff})$
- S4 resummation scheme used to remove spurious singularities in BFKL NLL kernel
- Implementation in Monte Carlo: needed to take into account: jet size and gap size smaller than $\Delta\eta$ between jets

Comparison with D0 data

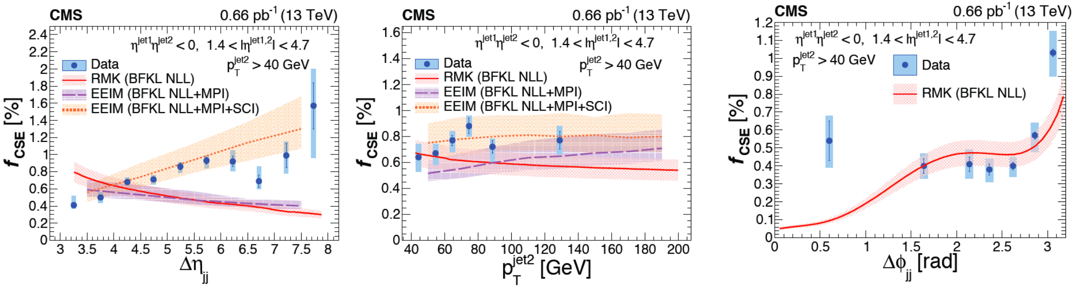


- D0 measurement: Jet gap jet cross section ratios, gap between jets being between -1 and 1 in rapidity
- Comparison with BFKL formalism:

$$Ratio = \frac{BFKL\ NLL\ Herwig}{Dijet\ Herwig} \times \frac{LO\ QCD\ NLOJet++}{NLO\ QCD\ NLOJet++}$$

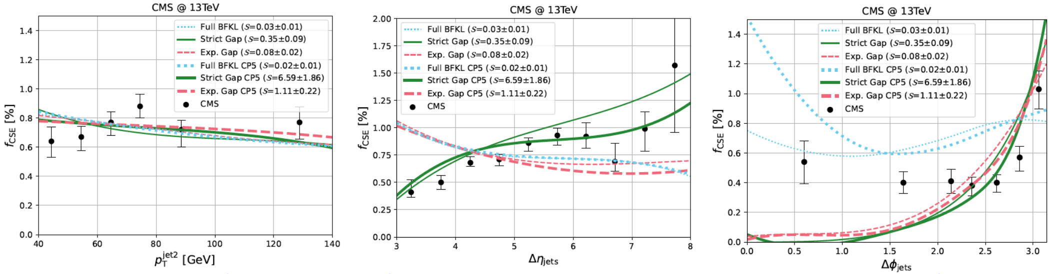
- Reasonable description using BFKL NLL formalism
- O. Kepka, C. Marquet, C. Royon, Phys. Rev. D 83 (2011) 034036

LHC: Measurement of jet gap jet fraction (CMS)



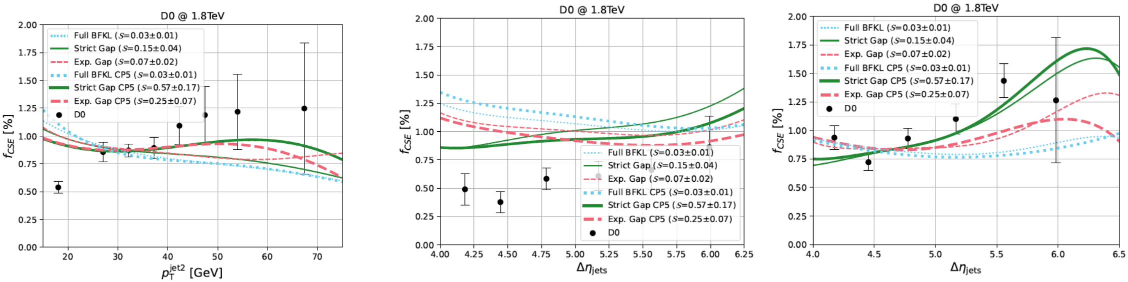
- Measurement of fraction of jet gap jet events as a function of jet $\Delta\eta$, p_T, $\Delta\Phi$ (Phys.Rev.D 104 (2021) 032009)
- Comparison with NLL BFKL (with LO impact factors) as implemented in PYTHIA, and soft color interaction based models (Ingelman et al.)
- Disagreement between BFKL and measurements ($\Delta\eta$ dependence): What is going on?

Jet gap jet measurements at the LHC (CMS@13 TeV)



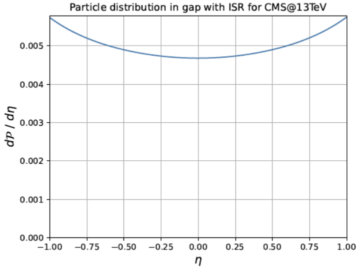
- Implementation of BFKL NLL formalism in Pythia and compute jet gap jet fraction
- Dijet cross section computed using POWHEG and PYTHIA8
- Three definitions of gap: theory (pure BFKL), experimental (no charged particle above 200 MeV in the gap $-1 < \eta < 1$) and strict gap (no particle above 1 MeV in the gap region) (C. Baldenegro, P. Gonzalez Duran, M. Klasen, C. Royon, J. Salomon, JHEP 08 (2022) 250)
- Two different CMS tunes: CP1 without MPI, CP5 with MPI

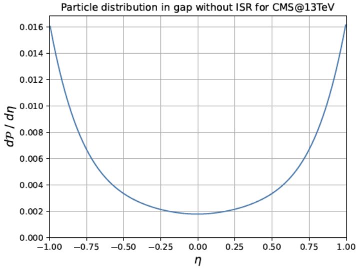
Jet gap jet measurements at the Tevatron (D0)



- Better agreement with the strict gap definition
- Fair agreement with the experimental gap definition since the differences between strict and experimental predictions are now that large compared to results at LHC energies
- Why such a large difference at the LHC?

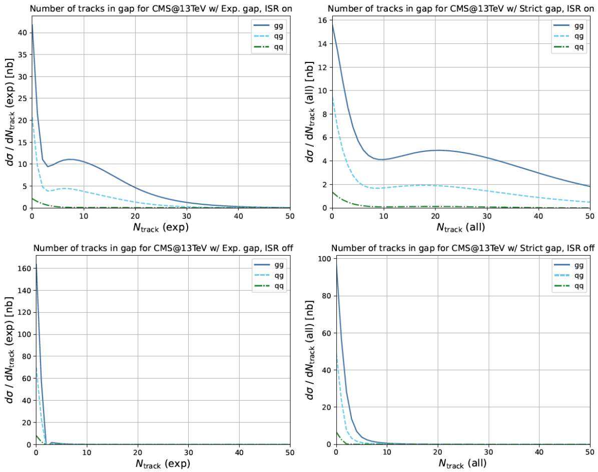
Charged particle distribution





- Disitribution of charged particles from PYTHIA in the gap region $-1 < \eta < 1$ with ISR ON (left) and OFF (right)
- Particles emitted at large angle with $p_T > 200$ MeV from initial state radiation have large influence on the gap presence or not, and this on the gap definition (experimental or strict)

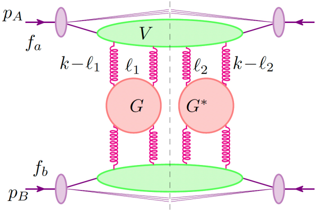
$N_{particle}$



- Number of particles emitted in the gap region $-1 < \eta < 1$ with $p_T > 200$ MeV from PYTHIA with ISR ON (top) and OFF (bottom)
- Number of particles much larger for *gg* processes, gluons radiate more
- Tevatron/LHC energies: mainly quark gluon/gluon gluon induced processes, so more radiation at LHC
- ISR emission from PYTHIA too large at high angle and must be further tuned for jet gap jet events: Use for instance J/Ψ-gap-J/Ψ events which is a *gg* dominated process

Jet gap jet: Full NLO BFKL calculation incuding NLO impact factor

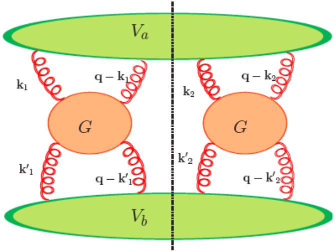
- Combine NLL kernel with NLO impact factors (Hentschinski, Madrigal, Murdaca, Sabio Vera 2014)



- Gluon Green functions in red
- Impact factors in green
- Will lead to an improved parametrisation to be implemented in HERWIG/PYTHIA
- D. Colferai, F. Deganutti, T. Raben, C. Royon, ArXiv 2304.09073

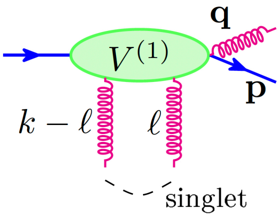
NLO BFKL jet gap jet cross section

$$\frac{d\hat{\sigma}}{dJ_1 dJ_2 d^2\mathbf{q}} = \int d^2k_1 d^2k_2 V^1(\mathbf{k}_1, \mathbf{k}_2, \mathbf{q}; J_1) \times \underbrace{\int d^2k'_1 G(\mathbf{k}_1, \mathbf{k}'_1, \mathbf{q}, Y)}_{\overline{G}(\mathbf{k}_1, \mathbf{q}, Y)} \underbrace{\int d^2k'_2 G(\mathbf{k}_2, \mathbf{k}'_2, \mathbf{q}, Y)}_{\overline{G}(\mathbf{k}_2, \mathbf{q}, Y)} V^0(J_2, \mathbf{q})$$



- Full NLL BFKL calculation: NLO impact factors have been computed
- Cross section given as a multiple convolution between the jet vertices (impact factors, green blobs) and the gluon Green functions in red

NLL BFKL jet gap jet cross section: Gluon Green function

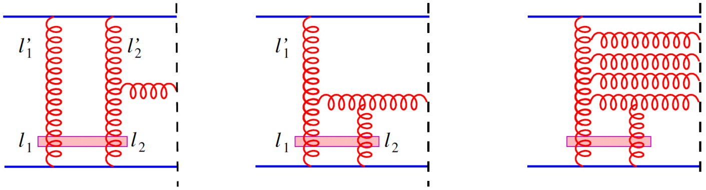


- Difficulty arises when the emitted gluon/quark, because of the impact factor, is in the gap region
- Constrain the rapidity of the gluon to stay outside the gap

$$\bar{G}(x_1 x_2, q, \Delta\theta, k) = \propto \left[k^{*\,\bar{h}-2} k'^{*\,h-2} \;\, {}_2F_1(1-h, 2-h; 2, -\frac{k}{k'}) \;\, {}_2F_1(1-\bar{h}, 2-\bar{h}; 2, -\frac{k'^*}{k_1^*}) + \{1 \to 2\} \right]$$

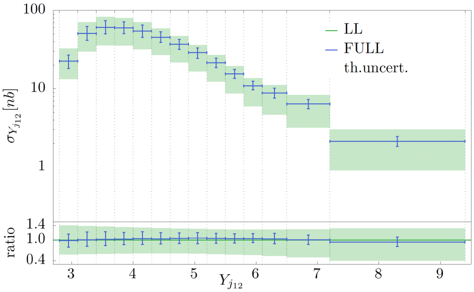
- We keep only NLO terms in the calculation (avoid NLL GGF and NLO IF together)
- Complex integrals are computed numerically and sum over many conformal spins
- Hypergeometric functions appear in the calculation and are hard to compute (recent mathematical developments in 2015

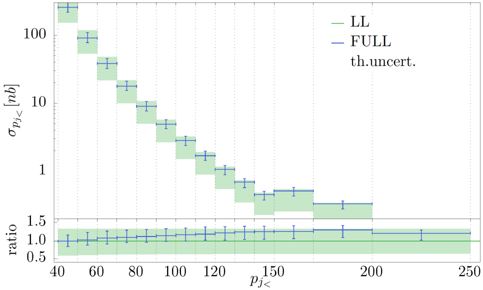
NLL BFKL jet gap jet cross section: violation of BFKL factorization



- Constrain the rapidity of the gluon (and of any parton stemming from the incoming forward quark) to stay outside gap region unless its energy is so small that it remains undetected
- For such gluons below threshold, there is a $\log s/s_0$ term in the cross section and the BFKL factorization in the NLLA is violated for MT jet processes
- This effect depends on the energy in the gap and the gap size
- However, practically, the BFKL factorization violating term is small (negligible for large / dynamic gaps)

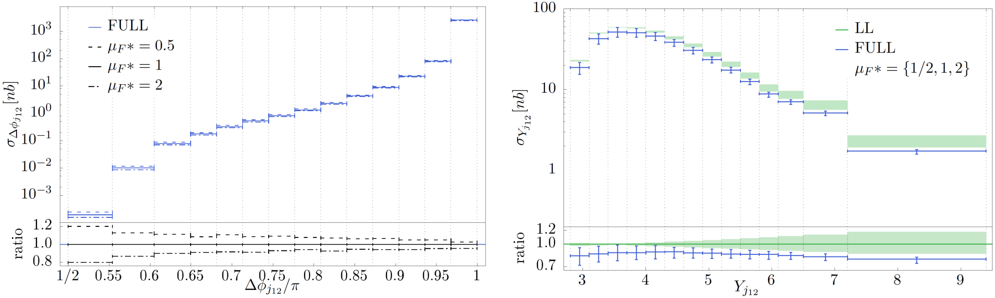
Effect of NLO impact factor on jet gap jet cross section: final results





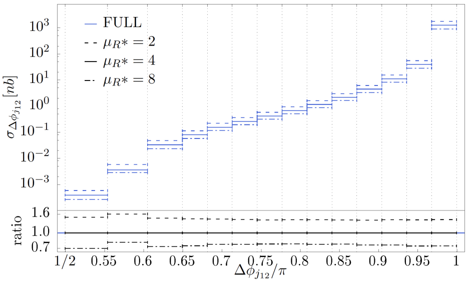
- Higher cross section by 20% at high p_T and small effect on the y dependence
- Total uncertainties are much smaller at NLO: 15-20%

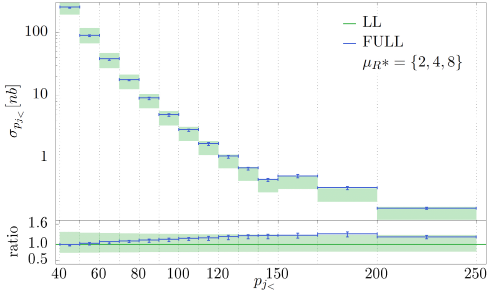
Effect of NLO impact factor on jet gap jet cross section: μ_F dependence



- Variation of the factorization scale (the sum of the jets p_T) leads to a systematic between 5 and 20% on the $\Delta\Phi$, y dependence

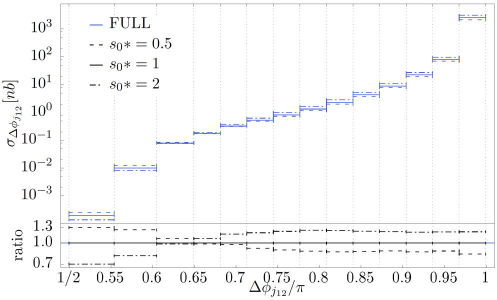
Effect of NLO impact factor on jet gap jet cross section: μ_R dependence

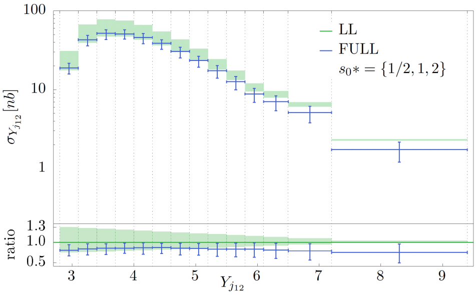




- Sensitivity to renomalization scale μ_R ($\mu_R = 4(p_{T_{j1}} p_{T_{j2}})$)
- Small uncertainties at NLO

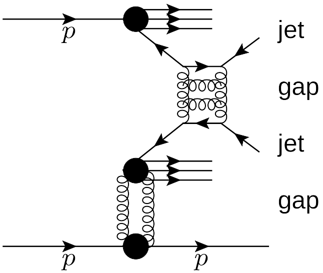
Effect of NLO impact factor on jet gap jet cross section: s_0 dependence

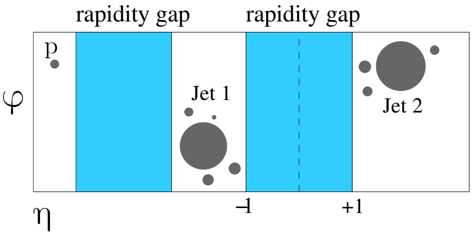




- Sensitivity of the $\log s$ term responsible for the violation of the BFKL factorization to the gap definition
- Variation of the BFKL scale (the product of the jets p_T) leads to a systematic between 5 and 20% on the $\Delta\Phi$, y dependence

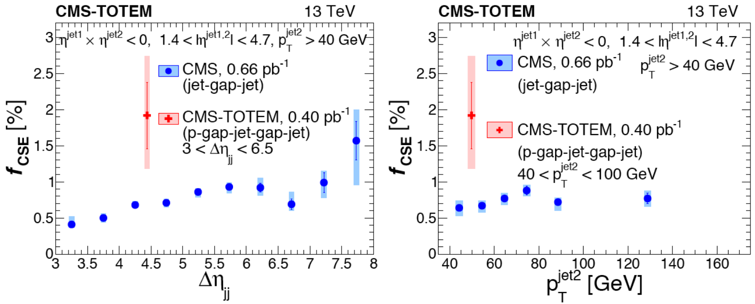
Another kind of events: Jet gap jet events in diffraction (CMS/TOTEM)





- Jet gap jet events: powerful test of BFKL resummation C. Marquet, C. Royon, M. Trzebinski, R. Zlebcík, Phys. Rev. D 87 (2013) 3, 034010
- Subsample of gap between jets events requesting in addition at least one intact proton on either side of CMS
- **Jet gap jet events were observed for the 1st time by CMS!** (Phys.Rev.D 104 (2021) 032009)

First observation of jet gap jet events in diffraction (CMS/TOTEM)

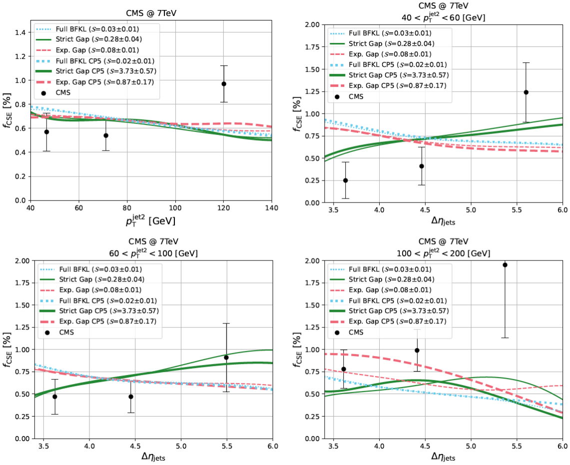


- First observation: 11 events observed with a gap between jets and at least one proton tagged with ~ 0.7 pb^{-1}
- Leads to very clean events for jet gap jets since MPI are suppressed and might be the "ideal" way to probe BFKL
- Would benefit from more stats $>$10 pb^{-1} needed, 100 for DPE

Conclusion

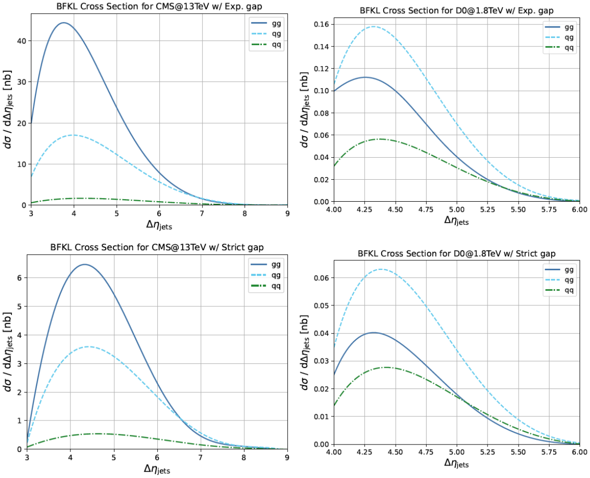
- New variables to probe QCD dynamics: mini-jets emission between Mueller Navelet jets
- Measurement of jet gap jet fraction at Tevatron and LHC: Agreement of BFKL calculation and measurement at the Tevatron, but apparent disagreement at 13 TeV
- BFKL predictions very sensitive to Initial State Radiation as described in PYTHIA especially for gg interaction processes: Too much ISR at high angle predicted by PYTHIA, should be tuned further using for instance J/Ψ-gap-J/Ψ events
- First calculation of Mueller Tang processes including NLO impact factors: Higher cross section by 20% at high p_T and small effect on the y dependence

Jet gap jet measurements at the LHC (CMS@7 TeV)



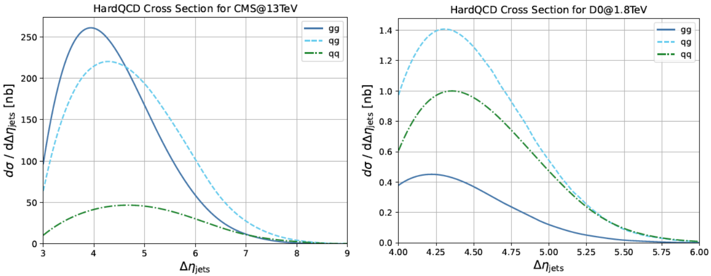
- Good agreement between CMS measurement at 7 TeV and experimental/strict gap definitions
- Slightly better agreement with strict gap definition for $\Delta\eta$ distribution
- Large uncertainties on measurements (mainly statistical)

BFKL cross sections: gg, qg or qq processes?



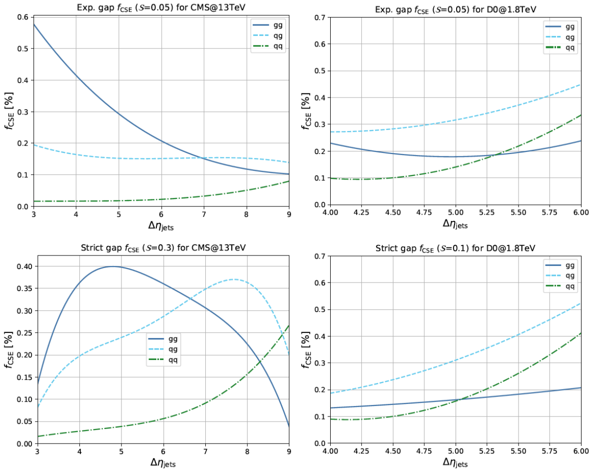
- Better understanding of BFKL and NLO QCD event production
- Events predicted by BFKL dynamics using the experimental and strict gap definitions: are they more gg, qg or qq events
- Tevatron energies: quark gluon induced process
- LHC energies: gluon gluon process

Hard QCD cross sections: gg, qg or qq processes?



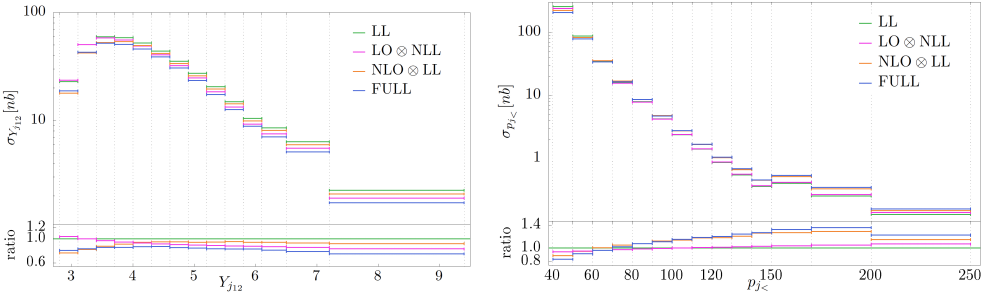
- Better understanding of BFKL and NLO QCD event production
- Events predicted by NLO QCD dynamics using the experimental and strict gap definitions: are they more gg, qg or qq events
- Tevatron energies: quark gluon induced process
- LHC energies: gluon gluon process except at large $\Delta\eta$, quark gluon

Jet gap jet fraction: *gg*, *qg* or *qq* processes?



- Jet gap jet ratios predicted by BFKL and NLO QCD dynamics using the experimental and strict gap definitions: are they more *gg*, *qg* or *qq* events
- Tevatron energies: quark gluon induced process
- LHC energies: gluon gluon process except at large $\Delta\eta$, quark gluon, but shapes very different for strict and experimental gap definitions

Effect of NLO impact factor on jet gap jet cross sections



- Comparison of LL, LO×NLL (NLL kernel+LO impact factor), NLO×LL (LL kernel+NLO impact factor (IF)), FULL NLO calculation
- Reduction of cross section from NLL kernel and NLO IF, the NLO IF have a strong impact at small rapidities
- NLO IF predict higher cross section at high p_T (the minimum p_T of the two jets)