# Mueller-Navelet, Mueller-Tang and forward jets

Christophe Royon
University of Kansas, Lawrence, USA
ECT* workshop, Trento, Italy

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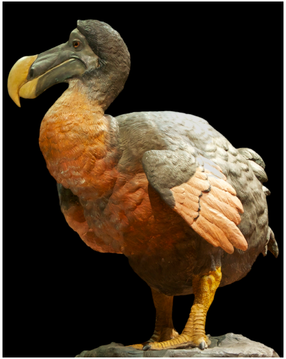
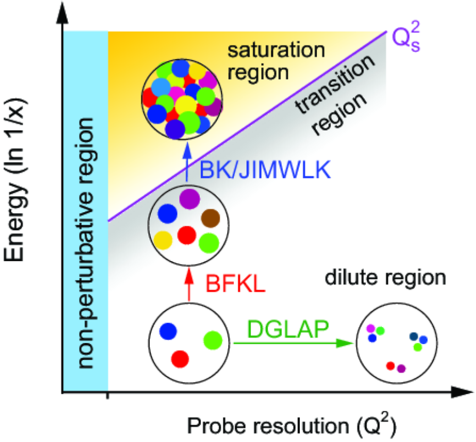
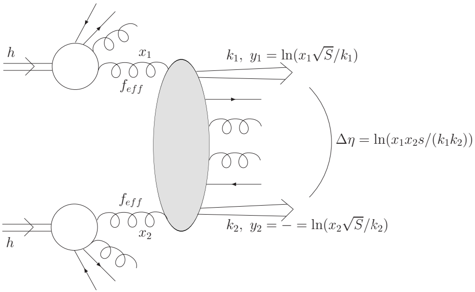


- Mueller-Navelet processes at the LHC and mini-jet production
- Mueller-Tang processes at the Tevatron and the LHC
- Jet production in the very forward direction

# Looking for BFKL resummation /saturation effects



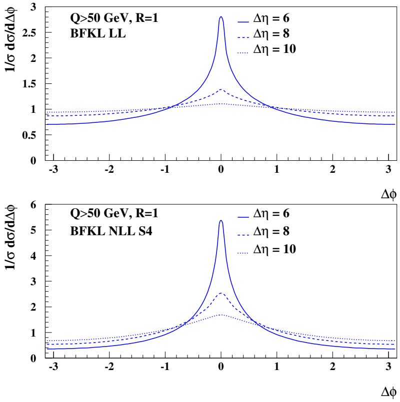

- DGLAP (Dokshitzer Gribov Lipatov Altarelli Parisi): Evolution in resolution $Q^2$, resums terms in $\alpha_S \log Q^2 \rightarrow$ resolving "smaller" partons at high $Q$
- BFKL (Balitski Fadin Kuraev Lipatov (BFKL): Evolution in energy $x$, resums terms in $\alpha_S \log 1/x \rightarrow$ Large parton densities at small $x$
- Saturation region at very small $x$
- Important to understand QCD evolution, parton densities
- EIC: look for saturation effects using HIN



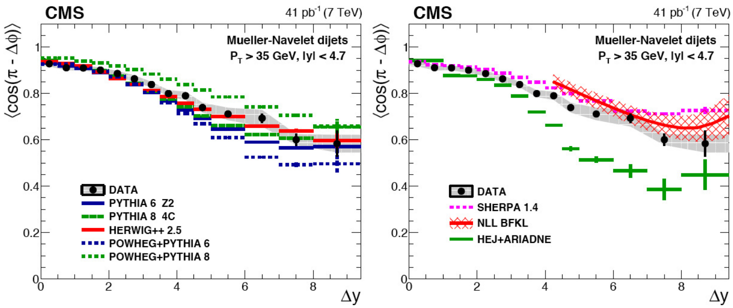

- Mueller Navelet jets: Look for dijet events separated by a large interval in rapidity
- If jets have similar $p_T$, DGLAP cross section suppressed because of the $k_T$ ordering of the gluons emitted between the two jets
- BFKL cross section enhanced: gluon emissions possible because of large rapidity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

# Mueller Navelet jets: $\Delta\Phi$ dependence

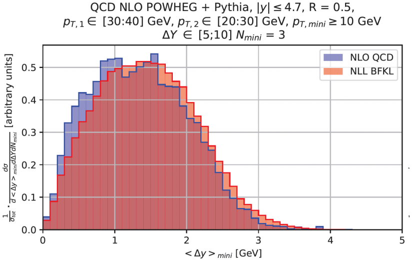
- $1/\sigma d\sigma/d\Delta\Phi$ spectrum for BFKL NLL as a function of $\Delta\Phi$ for different values of $\Delta\eta$, (scale dependence: $\sim$20%)
- Stronger decorrelation for BFKL prediction than for DGLAP
- C. Marquet, C.Royon, Phys. Rev. D79 (2009) 034028
- Implementation of NLL BFKL predictions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

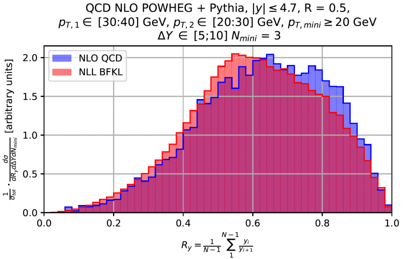


# Mueller Navelet jets: ΔΦ dependence: CMS measurements



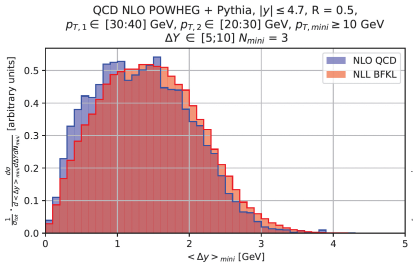

- CMS collaboration: Azimuthal decorrelation between jets at 7 TeV: J. High Energy Phys. 08 (2016) 139
- BFKL NLL leads to a good description of data but also PYTHIA/HERWIG after MPI tuning...
- More differential observables needed or completely new ones

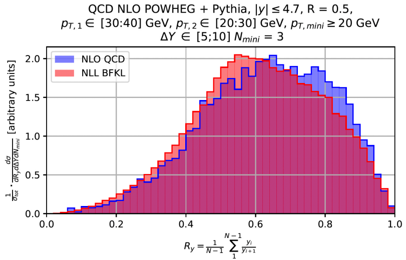



- Looking for multi-gluon emission along ladder, characteristic of BFKL NLL/DGLAP NLO
- Comparison between BFKL-ex MC and usual QCD NLO MC to compare both approaches (M. Kampshoff, A. Sabio Vera, G. Chachamis, C. Baldenegro, CR in preparation)
- We first require two forward jets with $5 < |\Delta Y|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

# Mueller Navelet processes: Looking for less inclusive variables



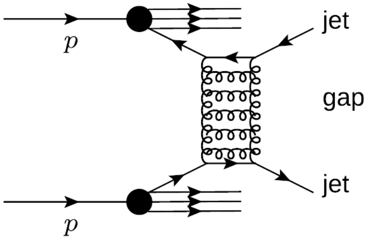



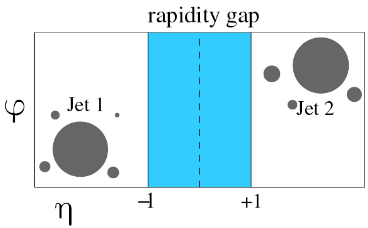

- We define as $y = 0$ the rapidity of the mini-jet closest to the MN jet and $N$ is the number of mini-jets above 20 GeV (or 10 GeV) emitted between the two MN jets
- Rapidity of emitted mini-jets

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

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

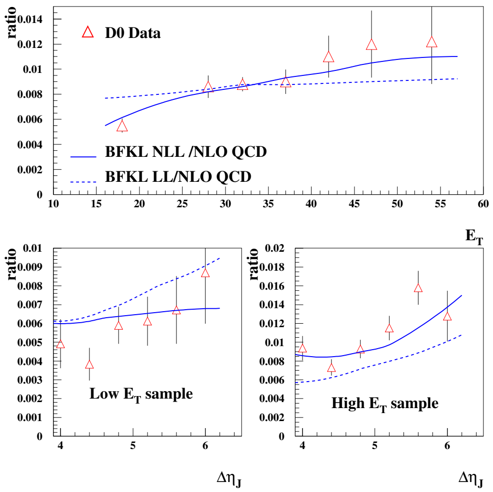
- Similar distributions for both approaches ($R_y$ slightly higher for NLO QCD): test of gluon emission as predicted by QCD




- 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

# Tevatron: Comparison with D0 data

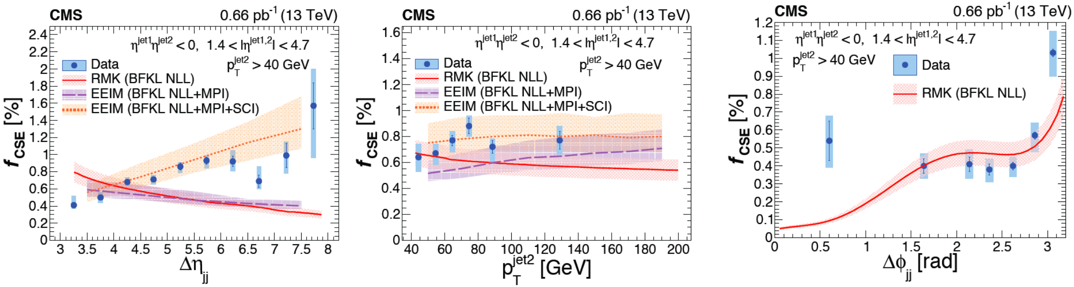



- D0 measurement: Jet gap jet cross section ratios, gap between jets being between -1 and 1 in rapidity
- Comparison with BFKL formalism:

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

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

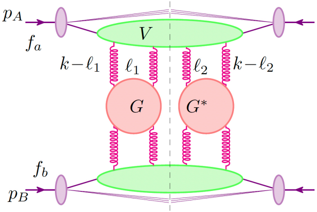
# LHC: Measurement of jet gap jet fraction (CMS)



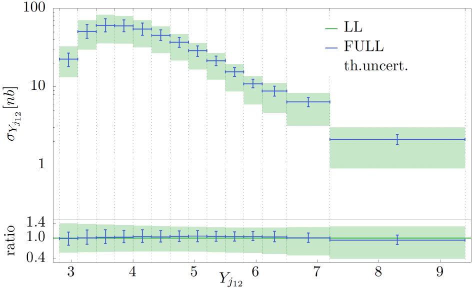

- Measurement of fraction of jet gap jet events as a function of jet $\Delta\eta$, $p_T$, $\Delta\Phi$ (Phys.Rev.D 104 (2021) 032009)
- Comparison with NLL BFKL (with LO impact factors) as implemented in PYTHIA, and soft color interaction based models (Ingelman et al.)
- Disagreement between BFKL and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

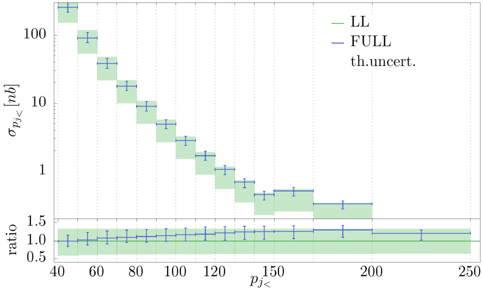
# Jet gap jet: Full NLO BFKL calculation including NLO impact factor

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



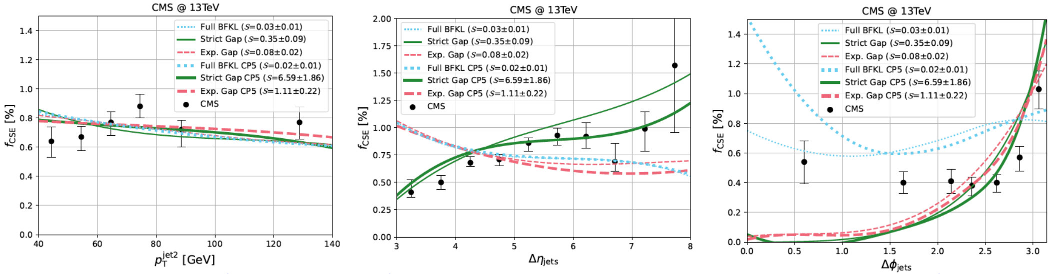

- Gluon Green functions in red
- Impact factors in green
- Will lead to an improved parametrisation to be implemented in HERWIG/PYTHIA
- D. Colferai, F. Deganutti, T. Raben, C. Royon, JHEP 06 (2023) 091



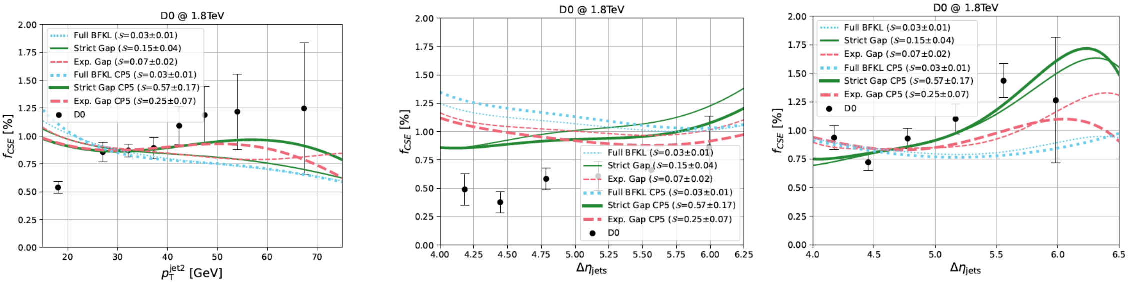

- Higher cross section by 20% at high $p_T$ and small effect on the $y$ dependence
- Total uncertainties are much smaller at NLO: 15-20%

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



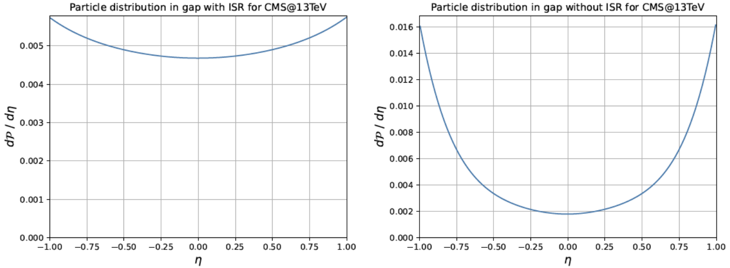

- Implementation of BFKL NLL formalism in Pythia and compute jet gap jet fraction
- Dijet cross section computed using POWHEG and PYTHIA8
- Three definitions of gap: theory (pure BFKL), experimental (no charged particle above 200 MeV in the gap $-1 < \eta < 1$) and strict gap (no particle above 1 MeV 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)



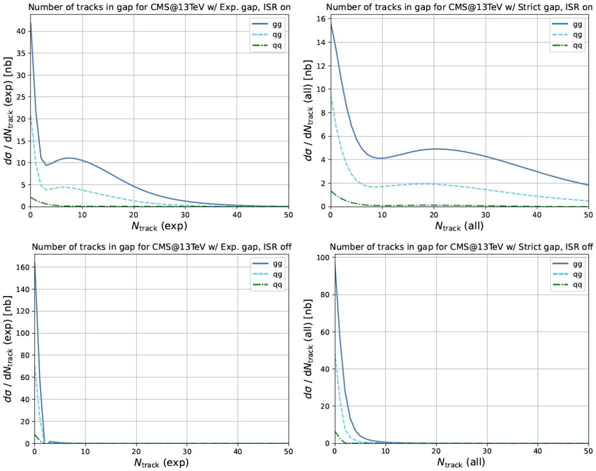

- Better agreement with the strict gap definition
- Fair agreement with the experimental gap definition since the differences between strict and experimental predictions are now that large compared to results at LHC energies
- Why such a large difference at the LHC?

# Charged particle distribution

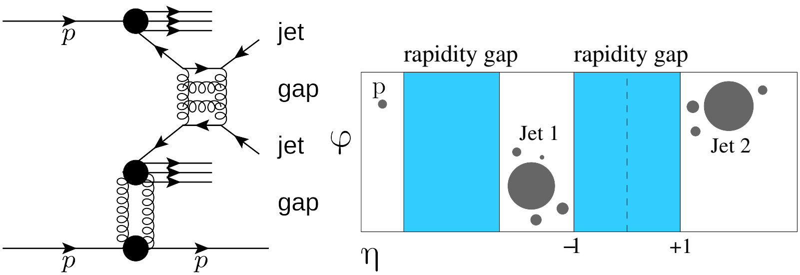



- Disitribution of charged particles from PYTHIA in the gap region $-1 < \eta < 1$ with ISR ON (left) and OFF (right)
- Particles emitted at large angle with $p_T > 200$ MeV from initial state radiation have large influence on the gap presence or not, and this on the gap definition (experimental or strict)

# $N_{particle}$

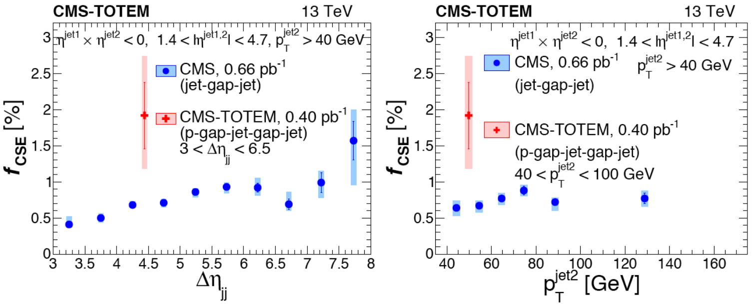



- Number of particles emitted in the gap region $-1 < \eta < 1$ with $p_T > 200$ MeV from PYTHIA with ISR ON (top) and OFF (bottom)
- Number of particles much larger for *gg* processes, gluons radiate more
- Tevatron/LHC energies: mainly quark gluon/gluon gluon induced processes, so more radiation at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



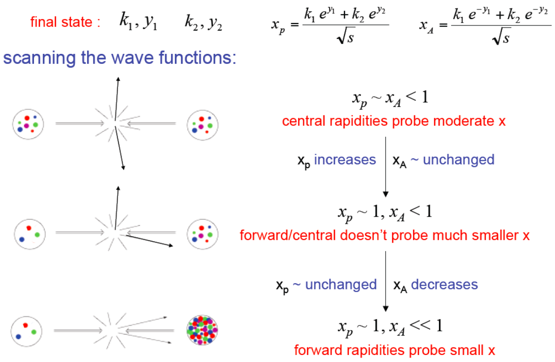

- Jet gap jet events: powerful test of BFKL resummation C. Marquet, C. Royon, M. Trzebinski, R. Zlebcík, Phys. Rev. D 87 (2013) 3, 034010
- Subsample of gap between jets events requesting in addition at least one intact proton on either side of CMS
- **Jet gap jet events were observed for the 1st time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

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



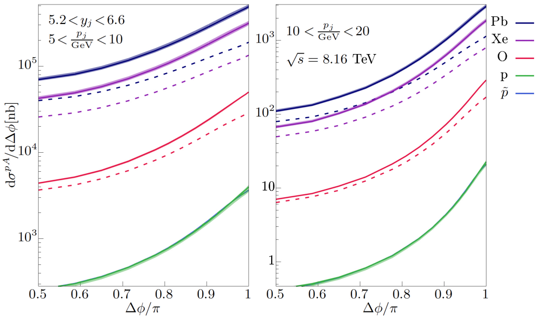

- First observation: 11 events observed with a gap between jets and at least one proton tagged with $\sim 0.7$ pb$^{-1}$
- Leads to very clean events for jet gap jets since MPI are suppressed and might be the "ideal" way to probe BFKL
- Would benefit from more stats $>$10 pb$^{-1}$ needed, 100 for DPE

# Saturation at the LHC: Use pA and AA data



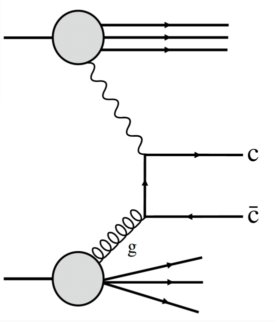

- If we want to see saturation effects, we need a dense object (Pb) and to go to very low $x$: measure jets in very forward direction
- Saturation effects: Measure two jets in very forward calorimeter (CASTOR in CMS, FOCAL project in ALICE)
- Compare pp and pA runs in order to remove many systematics
- Possibility to look for quark gluon plasma formation using $t\bar{t}$ production in PbPb

# Looking for saturation: very forward jet production




- Use dense objects to look for saturation: Pb instead of protons
- Dedicated observables to look for saturation: particle production in the forward region (F. Deganutti, C. Royon, S. Schlichting, JHEP 01 (2024) 159)
- Study effects of saturation for vector meson, *c*, *b* quark production (see talks by Jani/Heikki....)

# $J/\Psi$, $c$ and $b$ productions: ideal observables for saturation

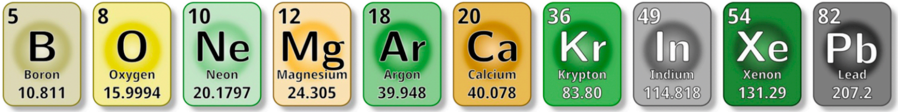



- What do we need to see saturation at the LHC?
- $\gamma Pb$ $c$, $b$, $J/\Psi$ are ideal probes for low-$x$ physics

$$x = \frac{m_{c\bar{c}}}{\sqrt{s_{NN}}} \exp(-y_c)$$

- We can reach low $x$ values of $10^{-4}$ or smaller
- We need a low scale (to be below $Q_S$), and this is why $c$ or $b$ where one can go to very low $p_T$ or $J/\Psi$ (low mass vector mesons) are ideal while still being in the perturbative region

# Using different heavy ions at the LHC?




- Possibility to use lighter heavy ions at the LHC beyond run 4
- This would mean starting around 2035, so in overlap with the EIC
- Is it potentially interesting to compare for instance very forward jets, $c$ and $b$ production, $J/\Psi$ and $\Upsilon$ production at higher energies of the LHC to see probably no saturation effects for light ions, and saturation for heavy ions?
- How much lumi would be needed?
- Can we measure $Q_s$ for different ions using these data (and compare to EIC)?

# Conclusion

- Measurement of Mueller-Navelet jets: emission of mini-jets characteristic of QCD emissions (similar predictions between BFKL and NLO QCD), small differences observed
- Mueller Tang processes: NLO BFKL corrections are small; very sensitive to ISR in PYTHIA
- Saturation at the LHC: use dedicated observables allowing to access low mass, low $x$ such as very forward jets, vector meson ($J/\Psi$), $c$ and $b$ production
- Complementarity between LHC and EIC: run the LHC with different ions?