Phenomenology studies of Mueller-Tang and Mueller-Navelet jets

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The high-energy limit is defined by $\hat{s} \gg -\hat{t} \gg \Lambda^2_{\mathrm{QCD}}$, where $\hat{s}$, $\hat{t}$ are the Mandelstam variables at parton-level, **the fixed-order pQCD approach breaks down**.

The perturbative expansion should be rearranged (symbolically) as,

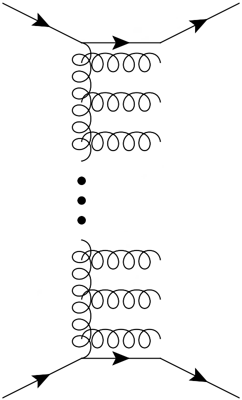
$$\mathrm{d}\hat{\sigma} \simeq \alpha_s^2 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \alpha_s^3 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \alpha_s^4 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \dots$$

such that $\alpha_s^n \ln^n (\hat{s}/|\hat{t}) \lesssim 1$.

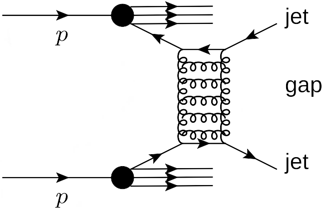
Resummation of large logarithms of $\hat{s}$ to all orders in α_s via **Balitsky-Fadin-Kuraev-Lipatov (BFKL)** evolution equations of pQCD.

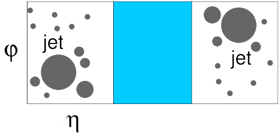
Resummation known at leading-logarithmic (LL) and next-to-LL accuracy.

Very important test of QCD; very challenging to isolate experimentally



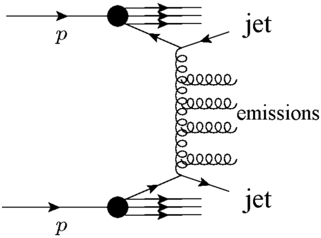
Multi-gluon ladder diagrams contribute significantly in the high-energy limit



gap


Mueller–Tang jets:
Events with two jets separated by a rapidity gap (hard color-singlet exchange).

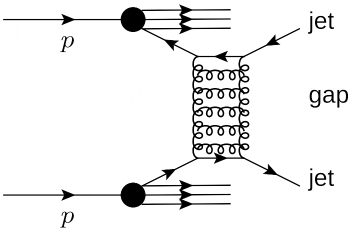
In $\Delta y \equiv |y_{\text{jet1}} - y_{\text{jet2}}| \gg 1$, it is expected to be described by perturbative pomeron exchange.

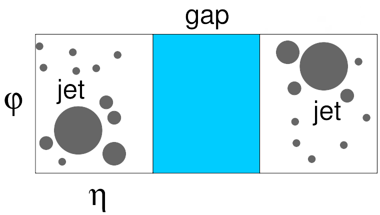


Mueller–Navelet jets:
Events where the two outermost jets are largely separated by a large interval in $\Delta y \equiv |y_{\text{jet1}} - y_{\text{jet2}}| \gg 1$.

At large Δy, the $\Delta\phi$ decorrelations between MN jets are stronger due to increased parton emission with the available phase-space.

$\Delta\phi$ decorrelations are expected to be strong in the BFKL picture.





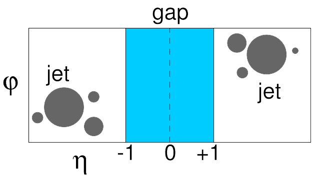
t-channel color-singlet exchange between partons (two-gluon exchange)
→ η **interval void of particles between jets (pseudorapidity gap)**.

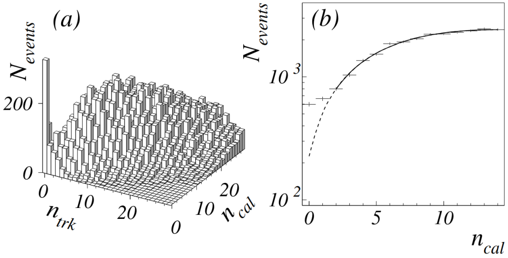
In the high-energy limit of QCD, process is expected to be described by **Balitsky–Fadin–Kuraev–Lipatov pomeron exchange**.
A. Mueller and W-K. Tang, PLB 284 (1992) 123.

Dokshitzer–Gribov–Lipatov–Altarelli–Parisi dynamics are strongly suppressed in events with pseudorapidity gaps (Sudakov form factor to suppress radiation in the gap).

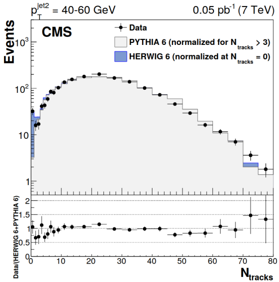
HERA, Tevatron, & LHC gap: **absence of particles with $p_T > 200 - 300$ MeV between the jets**.

Theory-like gap: **absence of particles between the jets with $p_T > \mathcal{O}(5)$ MeV.**





D0, PRL 72, 2332 (1994)



CMS, EPJC 78,242 (2018)

Previous experimental measurements on CSE process

We have over 20+ years of jet-gap-jet data in ep, p$\bar{\text{p}}$, and pp collisions:

HERA:

ZEUS: PLB 369 (1996)

H1: EPJC 24, 517 (2002)

Tevatron:

D0: $\sqrt{s} = 1.8$ TeV PRL 72, 2332 (1994), $\sqrt{s} = 1.8$ TeV PRL 76, 734 (1996), $\sqrt{s} = 0.63$ &1.8 TeV PLB 440 189 (1998)

CDF: $\sqrt{s} = 1.8$ TeV PRL 74, 855 (1995), $\sqrt{s} = 1.8$ TeV PRL 80, 1156 (1998), $\sqrt{s} = 0.63$ TeV PRL 81, 5278 (1998).

LHC:

CMS: 7 TeV EPJC 78,242 (2018), 13 TeV PRD 104, 032009 (2021)

BFKL at LL and NLL with LO impact factors: A. Ekstedt, R. Enberg, G. Ingelman arXiv:1703.10919, C. Marquet, C. Royon, M. Trzebinski, R. Zlebcik, PRD 87 (2013) 034010, O. Kepka, C. Marquet, C. Royon PRD 83.034036 (2011), R. Enberg, G. Ingelman, L. Motyka PLB 524,273 (2002), L. Motyka, A.D. Martin, M.G. Ryskin PLB 524 107 (2002), B. Cox, J. Forshaw, L. Lönnblad JHEP9910, 023 (1999)

Survival probability for jet-gap-jet events estimated with MPI (I. Babiarz, R. Staszewski, A. Szczurek PLB 771,532 (2017)), also MPI supplemented with soft color interactions (R. Enberg, G. Ingelman, L. Motyka PLB 524,273 (2002), A. Ekstedt, R. Enberg, G. Ingelman, arXiv:1703.10919).

Mueller–Tang NLO impact factors calculated by M. Hentschinski, Madrigal-Martínez, B. Murdaca, A. Sabio Vera: Nucl. Phys. B887, 309 (2014), Nucl.Phys. B889, 549 (2014), PLB 735,168 (2014).

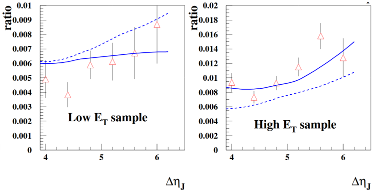
NLO impact factors have yet to be implemented for phenomenology studies to complete the NLO calculation (BFKL@NLL + impact factors@NLO).
See talks by D. Colferai and F. Deganutti this week at Low-x on this subject!

Fraction of color-singlet exchange dijet events (f_{CSE})

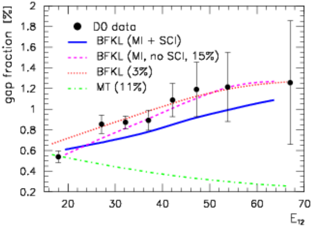
- Experiments have reported the fraction of CSE dijet events present in the inclusive dijet sample (suggested in Mueller–Tang original paper):

$$f_{\text{CSE}} \equiv \frac{d\sigma_{\text{CSE jets}}}{d\sigma_{\text{inclusive dijet}}} \tag{1}$$

- Color-singlet exchange dijet cross section calculated at LL or NLL in BFKL.
- Inclusive dijet cross section can be calculated with fixed-order LO or NLO QCD + PS.
- Yields description of color-singlet exchange relative to color-octet exchange in a way such that theoretical and experimental uncertainties approximately cancel in the ratio.



O. Kepka, C. Marquet, C. Royon
PRD 83.034036 (2011)



R. Enberg, G. Ingelman, L. Motyka
PLB 524 (2002) 273

- NLL resummation with LO impact factor.
- Sum over even conformal spin terms.
- Implementation in HERWIG6.
- fixed-order NLO QCD jets cross section calculated with `NLOJet++` package.

- NLL resummation with LO impact factor.
- Δy dependence from asymptotic effects of higher conformal spins.
- Implementation in PYTHIA6 with soft color interaction model.
- PYTHIA6 for QCD inclusive dijet.

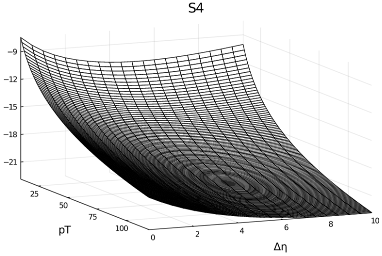
- New PYTHIA8 subroutine for $qq \to qq$, $qg \to qg$, and $gg \to gg$ color-singlet exchange scattering with NLL resummation in BFKL framework.
- PYTHIA8 tuned to Run-1 and Run-2 LHC data (hadron production, initial- and final-state parton showers, and underlying event activity).
- Parton-level BFKL NLL cross section calculated numerically and fit with empirical formula for implementation in a MC generator.
- Similar implementation for LL BFKL in PYTHIA8 by I. Babiarz, R. Staszewski, A. Szczurek PLB 771,532 (2017) used to study MPI effects.
- We simulate inclusive dijet events with fixed-order LO QCD + PS (**PYTHIA8**) and NLO QCD + PS (**POWHEG+PYTHIA8**).

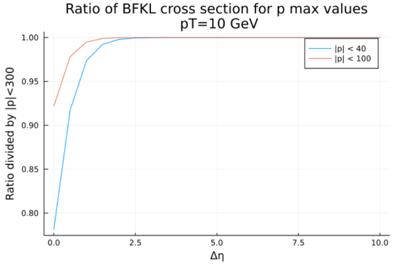
Numerical calculation of Mueller-Tang parton-level cross section

Following Kepka, Marquet, Royon, PRD 83.034036 (2011), the scattering amplitude for $qq \to qq$ is given by,

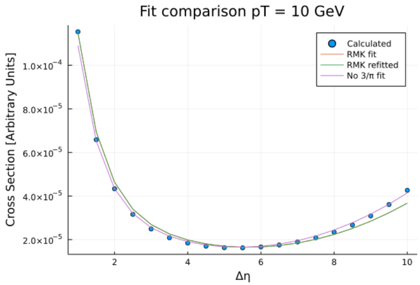
$$\mathcal{A}^{qq}(\Delta y, p_T^2) = \frac{16\pi\alpha_s^2(p_T^2)}{p_T^2} \sum_{p=-\infty}^{\infty} \int \frac{d\gamma}{2\pi i} \frac{[p^2 - (\gamma - 1/2)^2] \exp\{\bar{\alpha}(p_T^2)\chi_{\text{eff}}[2p, \gamma, \bar{\alpha}(p_T^2)]\Delta y\}}{[(\gamma - 1/2)^2 - (p - 1/2)^2][(\gamma - 1/2)^2 - (p + 1/2)^2]}$$

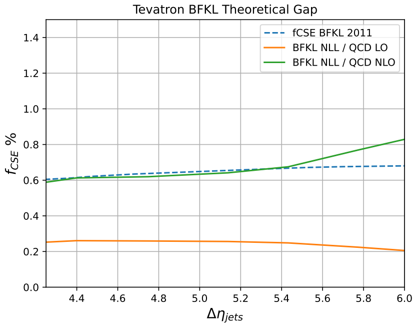
χ_{eff} is obtained numerically by solving $\chi_{\text{eff}} = \chi_{\text{NLL}}(\gamma, \bar{\alpha}\chi_{\text{eff}})$





S4 resummation scheme used to remove spurious singularities in BFKL NLL kernel, following approach described in C. Marquet, C. Royon arXiv:0903.4598.

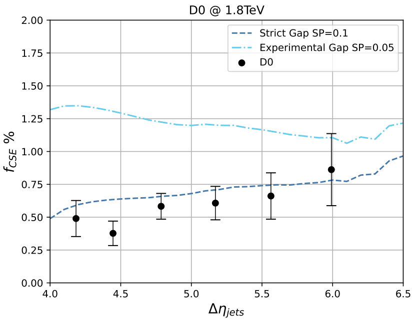


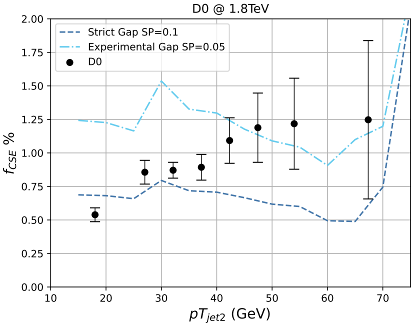


Left: numerical calculation (blue markers). Red curve represents the previous fit, the magenta line represents the new fit.

Right:
The green curve is based on PYTHIA8 for jet-gap-jet divided by POWHEG+PYTHIA8 for inclusive dijets.

It agrees with previous calculation based on HERWIG6 jet-gap-jet/`NLOJet++` inclusive dijets.
The orange is for PYTHIA8 (LO+PS) for inclusive dijet. **Important to include NLO corrections for QCD jets.**

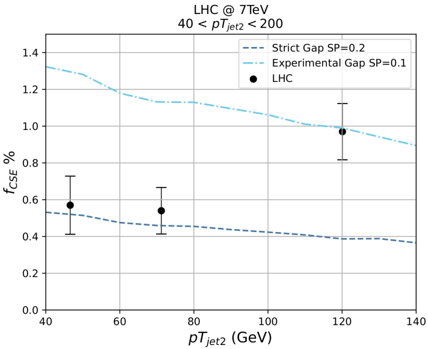


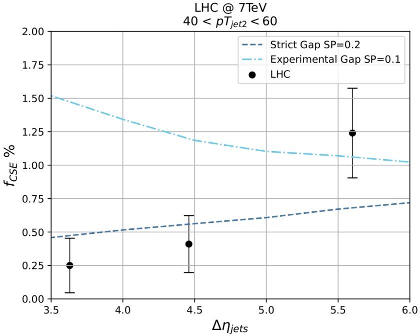


data from D0, PLB 440 (1998) 189

$p_T^{\text{jet1,2}} > 12$ GeV, $1.9 < |\eta^{\text{jet1,2}}| < 4.1$, $\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$. Jets with $R = 0.7$.

- BFKL pomeron exchange in PYTHIA8 (`ISR = on`, `MPI = off`). Inclusive dijet events with POWHEG+PYTHIA8 (`ISR = on`, `MPI = on`). CTEQ6L1.
- Dark blue-dashed curve: predictions based on theory-like gap definition. ($N_{particles} = 0$ in $|\eta| < 1$ with $p_T > 5$ MeV).
- Cyan dash-dotted curve: predictions based on D0 gap definition. ($N_{ch} < 2$ in $|\eta| < 1$ with $p_T > 200$ MeV).
- Theory-like gap definition able to describe general trend in the data. → **Sensitivity to low p_T particle emission.**

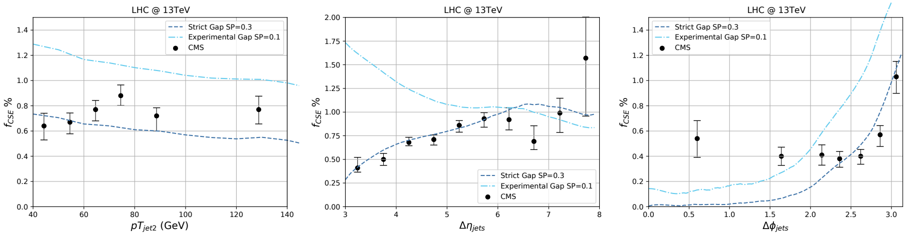




Data from CMS, EPJC 78,242 (2018)

$p_T^{\text{jet1,2}} > 40$ GeV, $1.5 < |\eta^{\text{jet1,2}}| < 5.2$, $\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$. Anti-$k_t$ jets with $R = 0.5$.

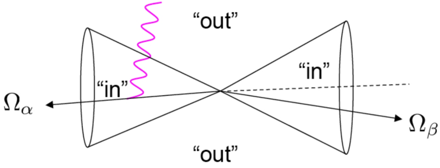
- BFKL pomeron exchange in PYTHIA8 (`ISR = on, MPI = off`). Inclusive dijet events with POWHEG+PYTHIA8 (`ISR = on, MPI = on`). NNPDF31_nlo_as_0118
- Dark blue-dashed curve: predictions based on theory-like gap definition.($N_{ch} = 0$ in $|\eta| < 1$ with $p_T > 5$ MeV).
- Light blue-dashdotted curve: predictions based on CMS gap definition. ($N_{ch} < 3$ with $|\eta| < 1$ with $p_T > 200$ MeV)
- Theory-like gap definition able to describe general trend in the data. $\rightarrow$ **Sensitivity to low p_T particle emission.**



Data from CMS, 13 TeV PRD 104, 032009 (2021)

$p_T^{\text{jet1,2}} > 40$ GeV, $1.4 < |\eta^{\text{jet1,2}}| < 5.2$, $\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$. Anti-$k_t$ jets with $R = 0.4$.

- BFKL pomeron exchange in PYTHIA8 (`ISR = on, MPI = off`). Inclusive dijet events with POWHEG+PYTHIA8 (`ISR = on, MPI = on`). NNPDF31_nlo_as_0118
- Dark blue-dashed curve: predictions based on theory-like gap definition ($N_{part} = 0$ in $|\eta| < 1$ with $p_T > 5$ MeV).
- Light blue-dashdotted curve: predictions based on CMS gap definition ($N_{ch} < 3$ with $|\eta| < 1$ with $p_T > 200$ MeV).
- Theory-like gap definition able to describe general trend in the data. $\rightarrow$ **Sensitivity to low p_T particle emission.**



Resummation of soft-gluon emissions at large angles is not taken into account in parton showers or in BFKL calculation.

When $p_T^{\text{jet}} \gg E_{\text{out}}$, resummation of $\alpha_s^n \log(p_T^{\text{jet}}/E_{\text{out}})^n$ becomes important.

The probability P_τ that the E_{total} emitted outside the jets boundaries is $E_{\text{total}} < E_{\text{out}}$ satisfies the Banfi–Marchesini–Smye (BMS) equation:

$$\partial_\tau P_\tau(\Omega_\alpha,\Omega_\beta) = -\int_{\mathcal{C}_{out}} \frac{d^2\Omega_\gamma}{4\pi} \frac{1-\cos\theta_{\alpha\beta}}{(1-\cos\theta_{\alpha\gamma})(1-\cos\theta_{\gamma\beta})} P_\tau(\Omega_\alpha,\Omega_\beta)$$
$$+\int_{\mathcal{C}_{in}} \frac{d^2\Omega_\gamma}{4\pi} \frac{1-\cos\theta_{\alpha\beta}}{(1-\cos\theta_{\alpha\gamma})(1-\cos\theta_{\gamma\beta})} \Big(P_\tau(\Omega_\alpha,\Omega_\gamma)P_\tau(\Omega_\gamma,\Omega_\beta) - P_\tau(\Omega_\alpha,\Omega_\beta)\Big),$$

soft-gluon emission

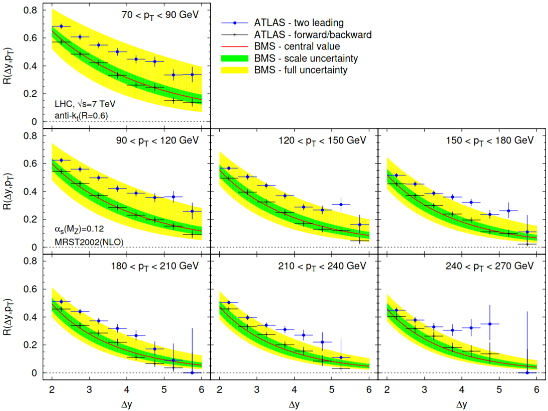
Events with at least two high-p_T jets separated by Δy.

Measure the ratio,

$$R(p_T, \Delta y) = \frac{d\sigma^{\text{veto}}/dp_T d(\Delta y)}{d\sigma^{\text{inc}}/dp_T d(\Delta y)}$$

where jets with $p_T > Q_0 = 20$ GeV are vetoed between the highest p_T jets in the numerator.

Soft-gluon resummation with BMS equation for jet-veto configuration.



Y. Hatta, C. Marquet, C. Royon, G. Soyez, T. Ueda, D. Werder, Phys.Rev. D87 (2013) 054016

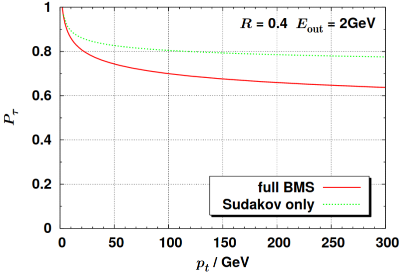
Soft-gluon, large-angle resummation for jet-gap-jet?

$$\frac{d\sigma}{d\Delta\eta d\bar{\eta} dt} = x_a x_b \tilde{f}_{eff}(x_a,t)\tilde{f}_{eff}(x_b,t)\frac{d\sigma^{q\bar{q}\to q\bar{q}}}{dt}\mathcal{S}P_\tau(\Omega_1,\Omega_a)P_\tau(\Omega_2,\Omega_b),$$

$$\tilde{f}_{eff}(x_a,t) = q(x_a,t)+\bar{q}(x_a,t)+\frac{N_c^2}{C_F^2}g(x_a,t)P_\tau(\Omega_1,\Omega_a)$$

$$\tilde{f}_{eff}(x_b,t) = q(x_b,t)+\bar{q}(x_b,t)+\frac{N_c^2}{C_F^2}g(x_b,t)P_\tau(\Omega_2,\Omega_b)\,.$$

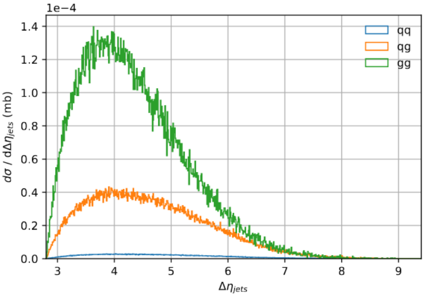
Expressions valid in large-N_c limit



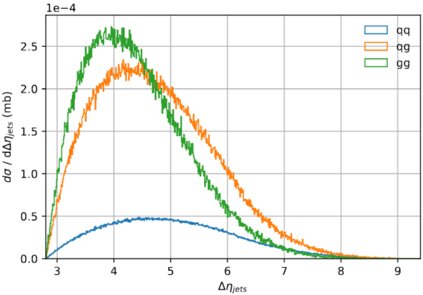
Y. Hatta, T. Ueda PRD 80 (2009) 074018

- Soft-gluon resummation is not included in BFKL calculation, although prescriptions for how these could be implemented have been presented e.g. by Y. Hatta, T. Ueda PRD 80 (2009) 074018.
- $gg \to gg$ contributions are more strongly suppressed after taking these effects into account (expressions valid in large N_c limit).

Parton flavor composition at $\sqrt{s} = 13$ TeV



Color-singlet exchange dijets



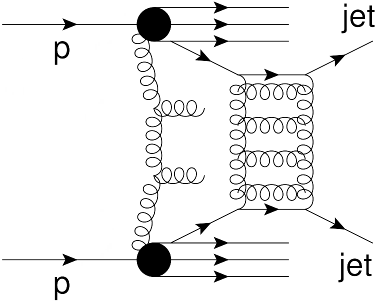
Inclusive dijets

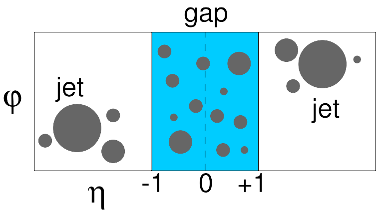
Stronger hierarchy of $gg \to gg$, $qg \to qg$, and $qq \to qq$ in color-singlet exchange than in inclusive dijet events simulated by PYTHIA8 (consequence of CSE color structure & PDFs of the proton).

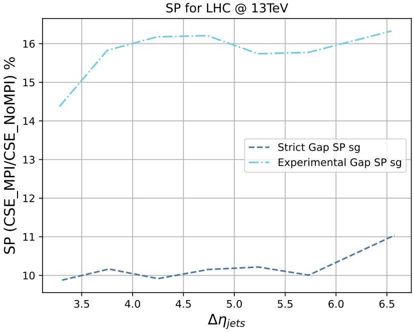
Is it possible that there's an unaccounted $gg \to gg$ suppression coming from missing resummation of soft-gluon large-angle emissions?

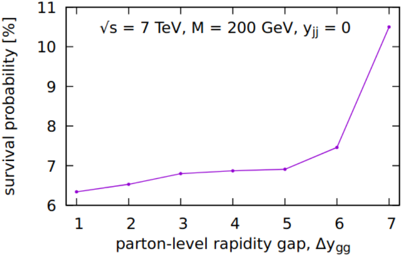
Plots created for anti-k_t $R = 0.4$ jets with $p_T^{\text{jet1,2}} > 40$ GeV and $1.4 < |\eta^{\text{jet1,2}}| < 4.7$ with $\eta^{\text{jet1}}\eta^{\text{jet2}} < 0$.

The central η gap signature can be destroyed by MPI.









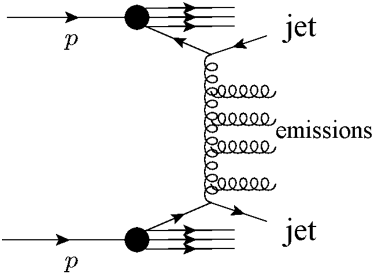
I. Babiarz, R. Staszewski, A. Szczurek, arXiv:1704.00546

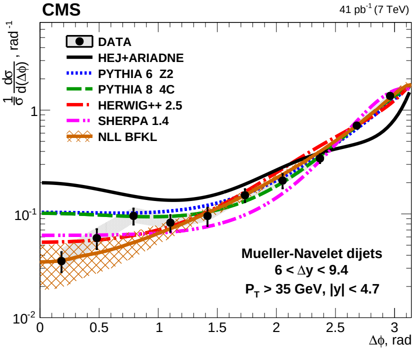
Survival probability *SP* calculated from MPI,

$$SP \equiv f_{\mathrm{CSE}}(\texttt{MPI = on})/f_{\mathrm{CSE}}(\texttt{MPI = off})$$

Mostly flat on jet kinematics (selection requirements *a la* CMS).

Other studies found some dependence at larger Δy_{gg}. Possibly difference due to different kinematic selection.





CMS, JHEP08(2016)139

Dijet events where the two outermost jets are largely separated by $\Delta y \gg 1$ can in principle be described in BFKL formalism. A. Mueller, H. Navelet, Nucl.Phys.B 282 (1987) 727.

$\Delta\phi$ decorrelations are expected to be strong in the BFKL picture due to available phase-space.

Lots of efforts in MN jets phenomenology with resummation at LL and NLL and LO and NLO impact factors:

V. T. Kim, G. B. Pivovarov, PhysRevD.53.6 (1995)

A. Sabio Vera, F. Schwennsen, Nucl.Phys.B776 (2007) 170,

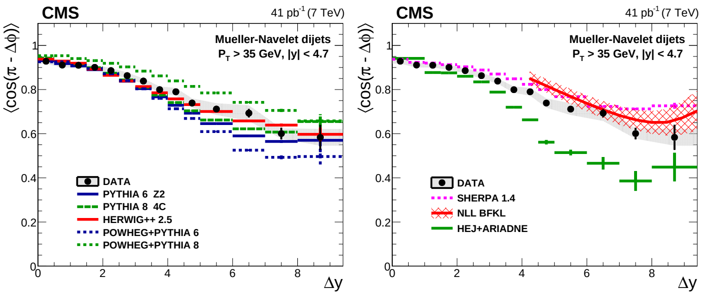
C. Marquet, C. Royon, PRD 79(2007)034028,

D. Colferai, F. Schwennsen, L. Szymanowski, S. Wallon, JHEP1012(2010)026,

F. Caporale, D. Yu. Ivanov, B. Murdaca, A. Papa, A. Perri, JHEP02(2012)101, EPJC74(2014)3084,

B. Ducloué, L. Szymanowski, S. Wallon, JHEP05(2013)096, PRL 112.082003 (2014),

F. G. Celiberto, D. Yu. Ivanov, B. Murdaca, A. Papa, EPJC 76 (2016) 4



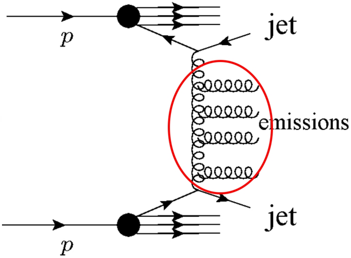
CMS, JHEP08(2016)139

$$\cos(\pi - \Delta\phi) = 1 \iff \text{back-to-back jets}$$
$$\cos(\pi - \Delta\phi) = 0 \iff \text{collinear jets}$$

- BFKL at NLL + NLO impact factor calculations describe data at large Δy within the uncertainties.
- Overall, fixed order LO or NLO QCD + PS predictions describe the data over wide Δy intervals within the uncertainties.

See talk by Salim Cerci for more details on these measurements.

ATLAS found similar results EPJC 74 (2014) 3117 (tagging highest p_T jets, rather than the outermost jets in y).



Target observables that are sensitive to the **high-energy limit radiation pattern between the MN jets.**

- A takeaway from Run-I LHC data: difficult to disentangle the onset of BFKL dynamics from other pQCD effects relying purely on $\Delta\phi$ in MN jets. *Situation might change with larger $\sqrt{s}$ and more data.*

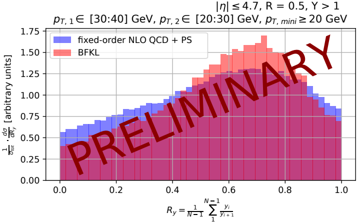
- A possibility for future measurements at the LHC *could be* a combination of $\Delta\phi$ analysis and minijet-based observables, now possible to study with `BFKLex` generator

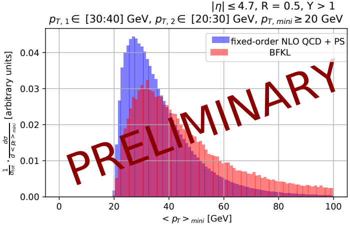
A. Sabio Vera, G. Chachamis, JHEP02 (2016) 064

Towards mini-jet based observables

Two examples of observables:

$$\langle R_{ky} \rangle = \frac{1}{N-1} \sum_{i=1}^{N} y_i / y_{i+1} \qquad \langle p_T \rangle = \frac{1}{N} \sum_{i=1}^{N} p_{T,i} \tag{2}$$





POWHEG+PYTHIA8 for fixed-order NLO QCD + PS calculation. BFKLex Monte Carlo generator for BFKL predictions.

In this plot, phase-space of the MN jets is integrated over $|\eta| < 4.7$ → use as validation region for fixed-order NLO QCD + PS and BFKL radiation patterns.

Next step: observables as a function of ΔY_{min} between the MN jets and $p_T^{\text{mini-jet}}$.

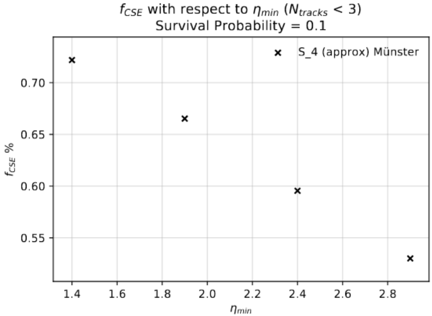
Preliminary results of Mueller-Tang jet study:

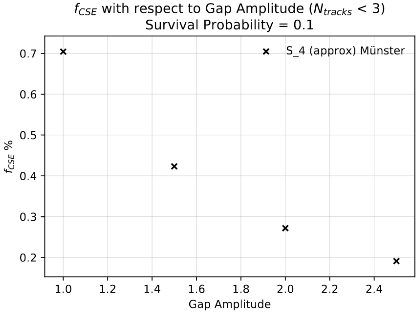
- Mueller-Tang process implemented in PYTHIA8 as a new subprocess.
- f_{CSE} ratios calculated with CSE dijets in PYTHIA8 divided by fixed-order NLO QCD + PS with POWHEG+PYTHIA8.
- Continue analyzing effects of initial-state radiation, MPI, and gap definitions and how they affect the f_{CSE} quantities.
- Important differences between theory and experimental gap definitions → sensitivity to mechanisms for low p_T particle production.
- Resummation of soft-, wide-angle gluon emissions might be important.

Preliminary results of Mueller-Navelet jet study:

- Comparison of mini-jet based observables computed with fixed-order NLO QCD + PS (POWHEG+PYTHIA8) and BFKL (BFKLex generator).
- Current exploration with additional observables and kinematic regimes of interest to distinguish the two approaches.

Respective articles are in preparation.





Left: f_{CSE} versus jet η_{min} for $|\eta| < 1$ for jet $p_T > 40$ GeV.

Right: f_{CSE} versus $|\eta| < \eta_{\text{gap amplitude}}$.

The larger the gap amplitude, the more f_{CSE} is