Phenomenological studies of jet-gap-jet

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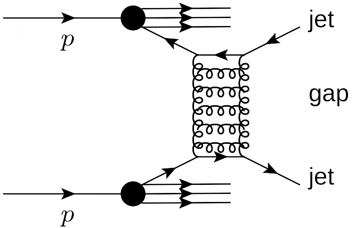
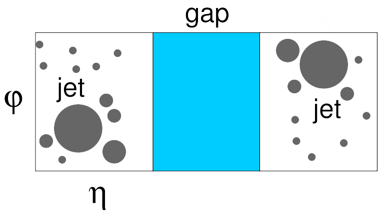
Snowmass EF06 working group





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 **BFKL pomeron exchange**.
A. Mueller and W-K. Tang, PLB 284 (1992) 123.

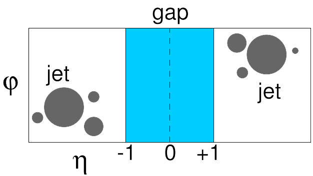
DGLAP dynamics are strongly suppressed in events with pseudorapidity gaps (Sudakov form factor to suppress radiation in the gap).

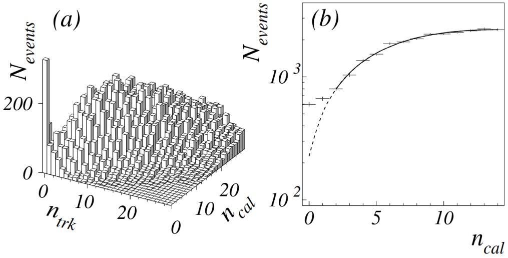
We see this fitting in the Snowmass White Paper together with other BFKL probes.

Pseudorapidity gap definitions

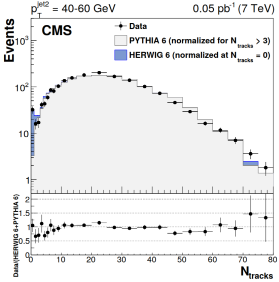
HERA, Tevatron, & LHC gap: **absence of particles with $p_T > 200 - 300$ MeV between the jets**.

Theory-like gap: **absence of particles between the jets.**





D0, PRL 72, 2332 (1994)



CMS, EPJC 78,242 (2018)

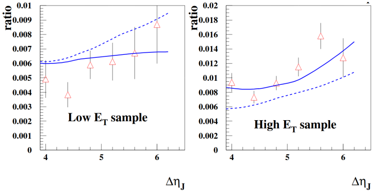
Fraction of color-singlet exchange dijet events (f_{CSE})

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

$$f_{\text{CSE}} \equiv \frac{d\sigma_{\text{CSE jets}}}{d\sigma_{\text{inclusive dijet}}} \quad (1)$$

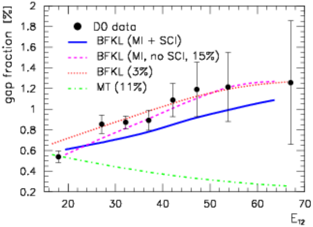
- Color-singlet exchange dijet cross section calculated at LL or NLL in BFKL.
- Inclusive dijet cross section is calculated with fixed-order LO or NLO + PS.
- Yields description of color-singlet exchange relative to color-octet exchange in a way such that theoretical and experimental uncertainties approximately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

Pre-LHC studies with BFKL calculations at NLL



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

- NLL resummation with LO impact factor.
- Sum over even conformal spin terms.
- Implementation in HERWIG6.
- K-factor for NLO corrections to inclusive dijets with `NLOJet++` package.



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

- 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.

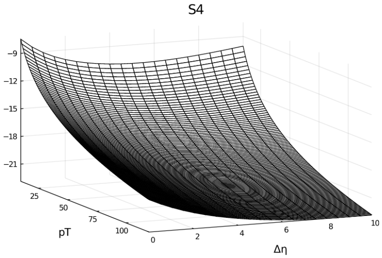
New implementation of BFKL pomeron exchange in PYTHIA8

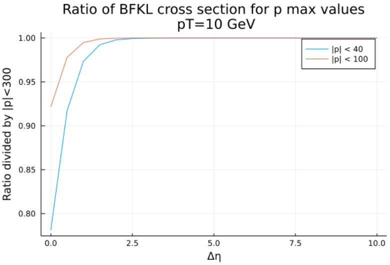
- New PYTHIA8 subroutine for $qq \to qq$, $qg \to qg$, and $gg \to gg$ color-singlet exchange scattering with NLL resummation in BFKL framework.
- PYTHIA8 tuned to Run-1 and Run-2 LHC data, in principle better description of ISR, FSR, and UE.
- Parton-level BFKL NLL cross section calculated numerically and fit with empirical formula for implementation in PYTHIA8.
- We simulate inclusive dijet events with fixed-order LO QCD + PS (**PYTHIA8**). and NLO QCD + PS (**POWHEG+PYTHIA8**).

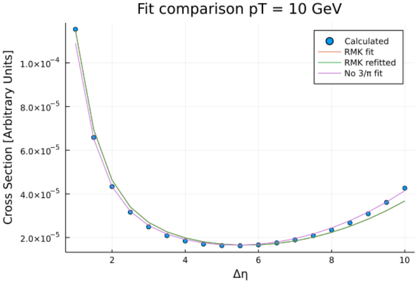
Following Kepka, Marquet, Royon, PRD 83.034036 (2011), the scattering amplitude for $qq \to qq$ is calculated as

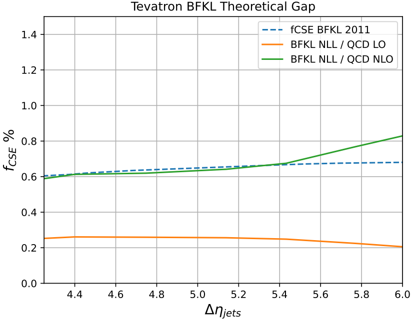
$$\mathcal{A}^{qq}(\Delta y, p_T^2) = \frac{16\pi\alpha_s^2(p_T^2)}{p_T^2} \sum_{p=-\infty}^{\infty} \int \frac{d\gamma}{2\pi i} \frac{[p^2 - (\gamma - 1/2)^2] \exp\left\{\bar{\alpha}(p_T^2)\chi_{\text{eff}}[2p, \gamma, \bar{\alpha}(p_T^2)]\Delta y\right\}}{[(\gamma - 1/2)^2 - (p - 1/2)^2][(\gamma -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

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







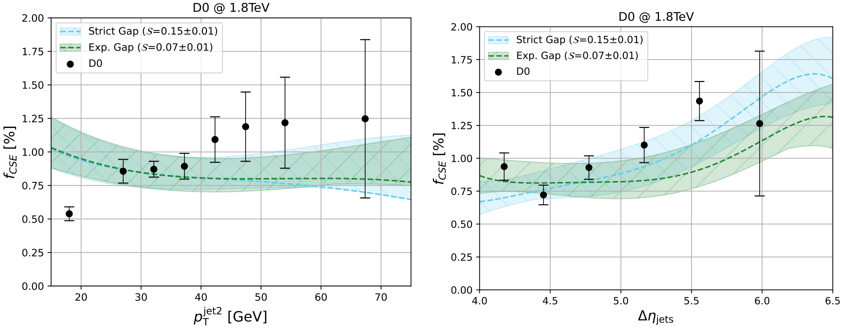


Left: numerical calculation (blue markers). Red curve represents the previous fit, the magenta line represents the new fit.

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

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

Comparison to D0 1.8 TeV data (preliminary results)

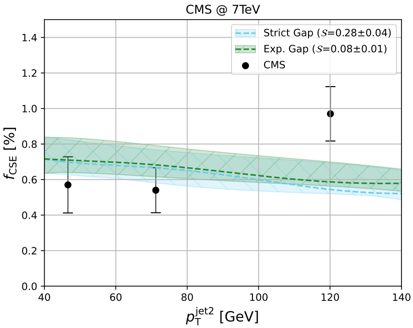


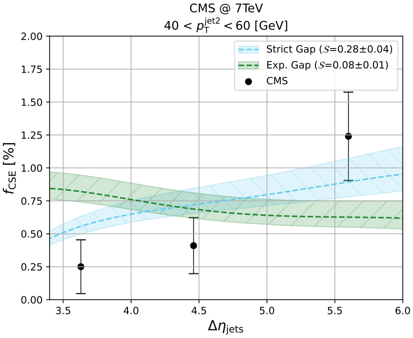
data from D0, PLB 440 (1998) 189

$p_T^{jet1,2} > 12$ GeV, $1.9 < |\eta^{jet1,2}| < 4.1$, $\eta^{jet1}\eta^{jet2} < 0$. 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.
- cyan curve: predictions based on theory-like gap definition. ($N_{part} = 0$ in $|\eta| < 1$).
- green curve: predictions based on D0 gap definition. ($N_{part} < 2$ in $|\eta| < 1$ with $p_T > 300$ MeV).
- Both gap definitions are able to describe general trend in data (modulo global scale factor).

Comparison to CMS 7 TeV data (preliminary results)

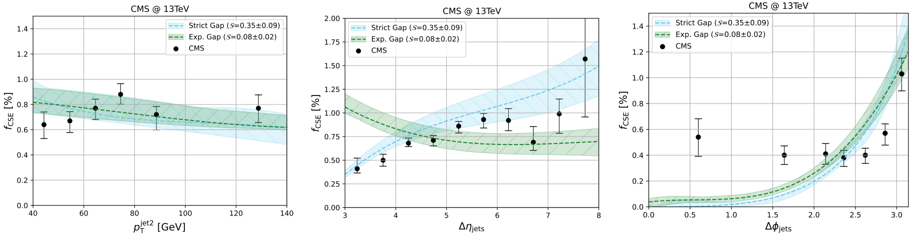




Data from CMS, EPJC 78,242 (2018)

$p_T^{\text{jet1,2}} > 40$ 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
- cyan curve: predictions based on theory-like gap definition.($N_{part} = 0$ in $|\eta| < 1$).
- green 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 production modeling.**

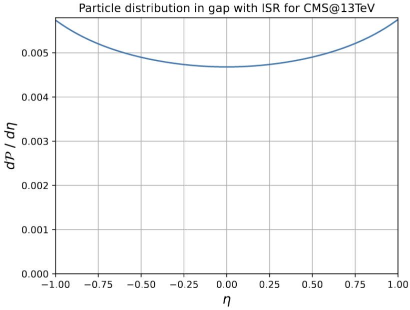


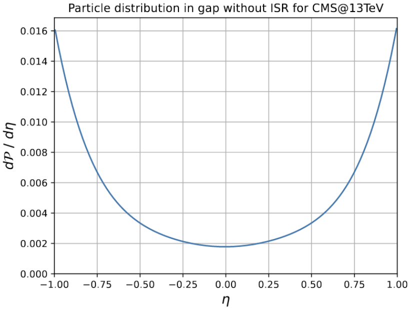
Data from CMS, 13 TeV PRD 104, 032009 (2021)

$p_T^{\text{jet1,2}} > 40$ 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
- cyan curve: predictions based on theory-like gap definition ($N_{part} = 0$ in $|\eta| < 1$).
- green 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. → **Sensitivity to low p_T particle production modeling.**

ISR effects in jet-gap-jet simulation



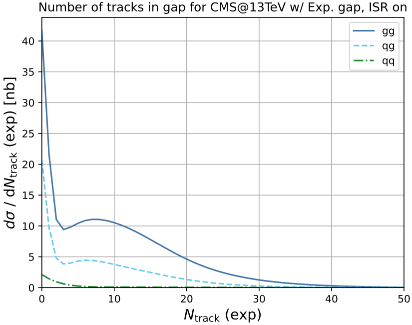


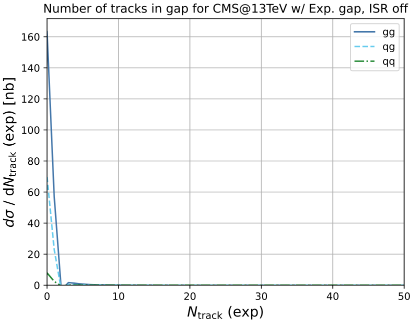
`ISR = on` $\rightarrow$ more particles between the jets.

`ISR = off` $\rightarrow$ fewer particles between the jets (unclustered wide-angle hadrons).

ISR produces additional color charges in the forward-backward region $\rightarrow$ **net color-flow is reestablished.**

Particle multiplicity in $|\eta| < 1$ between the Mueller–Tang jets



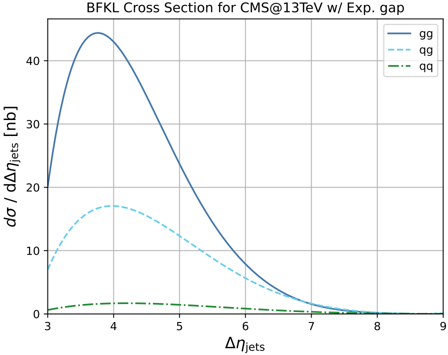


`ISR = on` $\rightarrow$ more particles between the jets.

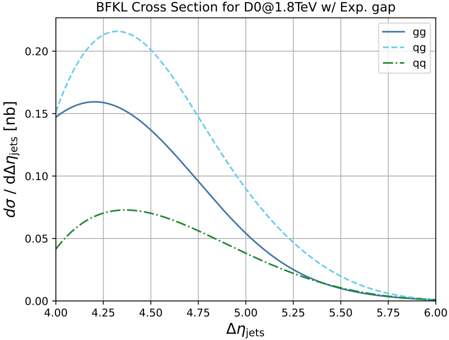
`ISR = off` $\rightarrow$ fewer particles between the jets (unclustered wide-angle hadrons).

ISR produces additional color charges in the forward-backward region $\rightarrow$ **net color-flow is reestablished.**

Effect is more prominent for $gg \rightarrow gg$ scatterings.



13 TeV



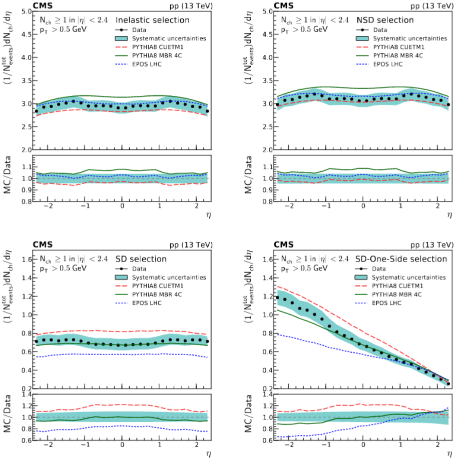
1.8 TeV

At 13 TeV, $gg \to gg$ dominates over $qg \to qg$ and $qq \to qq$.

At 1.8 TeV, $qg \to qg$ dominates over $gg \to gg$ and $qq \to qq$.

At 13 TeV, we are more sensitive to ISR effects for gluon-gluon processes.

No central gap topologies for MC tuning



It would be useful to have future measurements of minimum-bias events with central gap topologies using similar p_T thresholds in order to tune ISR and fragmentation effects independently of the jet-gap-jet measurement.

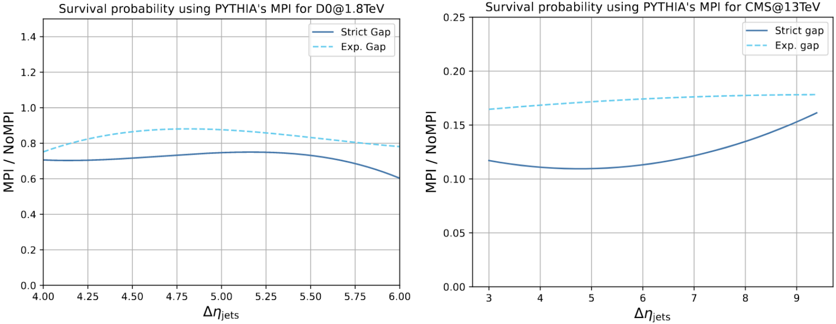
Preliminary results of Mueller-Tang jet study:

- We have data at the Tevatron and the LHC of jet-gap-jet events. In principle, this could be used to test predictions based on BFKL calculations.
- dijet production by BFKL pomeron exchange process has been implemented in PYTHIA8 as a new subprocess (NLL resummation + LO impact factors).
- ISR with up-to-date PYTHIA8 tunes might not be adecuate for central rapidity gap signatures. Our proposal is to consider topologies with central gaps in future minimum-bias event measurements.
- For future measurements, it might be useful to do the analysis considering different p_T thresholds used to define the pseudorapidity gaps, as well as double-differential f_{CSE} fractions to better understand this process.
- **Contribution to Snowmass White Paper in progress.**

Crucial for future phenomenological developments to understand this process in BFKL framework:

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). **Not yet included in full phenomenological analyses.**

Implementation in other MCs with different treatment of ISR (HERWIG7, Sherpa).



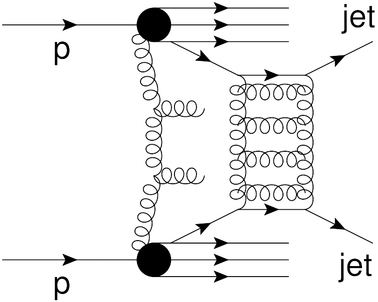
Proxy for the survival probability $\mathcal{S}$ calculated with MPI,

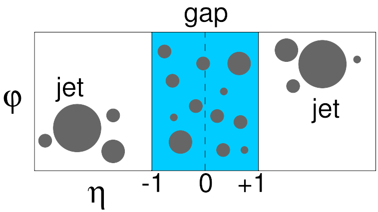
$$\mathcal{S} \equiv f_{\mathsf{CSE}}(\texttt{MPI = on})/f_{\mathsf{CSE}}(\texttt{MPI = off})$$

$\mathcal{S}$ from MPI is a factor of ≈ 10 (2) off w.r.t. fitted $\mathcal{S}$ values.

$\mathcal{S}$ is mostly flat as a function of $\Delta\eta_{\text{jets}}$, consistent with typical assumptions that $\mathcal{S}$ decouples from kinematics.

The central η gap signature can be destroyed by MPI.





Previous phenomenological studies

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 phenomenological studies to complete the NLO calculation (BFKL@NLL + impact factors@NLO).

Previous experimental measurements on CSE process

We have over 20+ years of jet-gap-jet data in ep, $p\bar{p}$, 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)

The high-energy limit is defined by $\hat{s} \gg -\hat{t} \gg \Lambda^2_{\text{QCD}}$, 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,

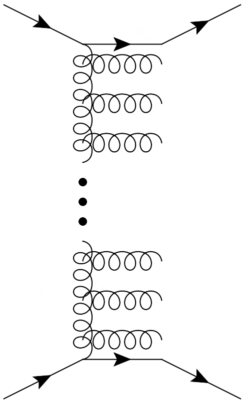
$$d\hat{\sigma} \simeq \alpha_s^2 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \alpha_s^3 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \alpha_s^4 \sum_{n=0}^{\infty} \alpha_s^n \ln^n \left(\frac{\hat{s}}{|\hat{t}|}\right) + \ldots$$

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.

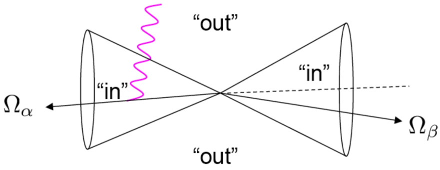
Resummation known at leading-logarithmic (LL) and next-to-LL accuracy.

Very important test of QCD; very challenging to isolate experimentally



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

Other possible QCD effects that may be at play



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:

$$
\begin{aligned}
\partial_\tau P_\tau(\Omega_\alpha, \Omega_\beta) &= -\int_{\mathcal{C}_{out}} \frac{d^2\Omega_\gamma}{4\pi} \frac{1-\cos\theta_{\alpha\beta}}{(1-\cos\theta_{\alpha\gamma})(1-\cos\theta_{\gamma\beta})} P_\tau(\Omega_\alpha, \Omega_\beta) \\
&\quad + \int_{\mathcal{C}_{in}} \frac{d^2\Omega_\gamma}{4\pi} \underbrace{\frac{1-\cos\theta_{\alpha\beta}}{(1-\cos\theta_{\alpha\gamma})(1-\cos\theta_{\gamma\beta})}}_{\text{soft-gluon emission}} \Big(P_\tau(\Omega_\alpha, \Omega_\gamma) P_\tau(\Omega_\gamma, \Omega_\beta) - P_\tau(\Omega_\alpha, \Omega_\beta) \Big) ,
\end{aligned}
$$

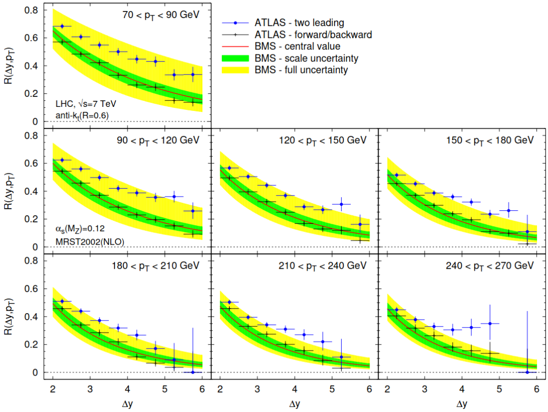
Events with at least two high-p_T jets separated by Δy.

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.



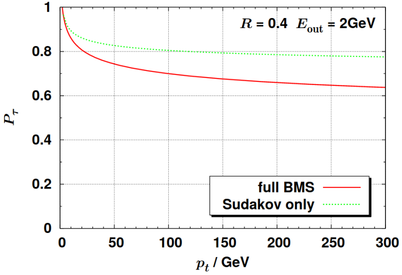
Y. Hatta, C. Marquet, C. Royon, G. Soyez, T. Ueda, D. Werder, Phys.Rev. D87 (2013) 054016

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

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

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

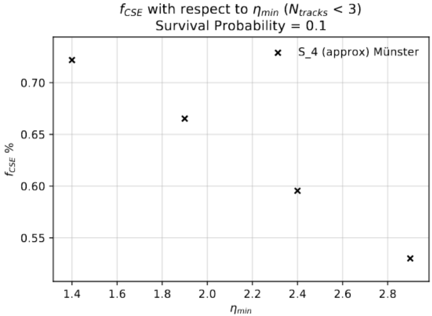
Expressions valid in large-N_c limit

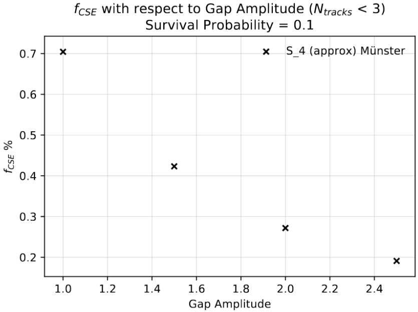


Y. Hatta, T. Ueda PRD 80 (2009) 074018

- 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).

Role of gap size and jet position at $\sqrt{s} = 13$ TeV





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

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

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