



Gaps between jets at the LHC

Simone Marzani
University of Manchester

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In collaboration with Jeff Forshaw and James Keates
arXiv:0905.1350 [hep-ph]

Outline

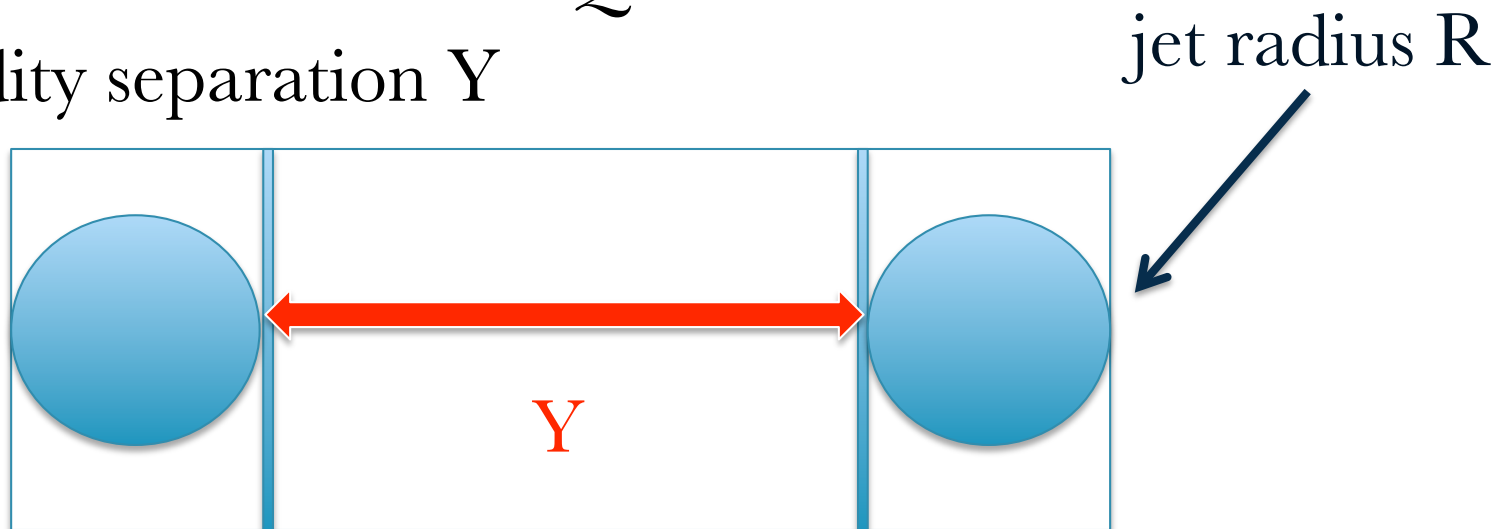
- Jet vetoing: Gaps between jets
 - Global and non-global logarithms
 - Discovery of super-leading logarithms
- Some LHC phenomenology
 - Global logarithms
 - Super-leading logarithms
- Conclusions and Outlook

Jet vetoing:
Gaps between jets

The observable

Production of two jets with

- transverse momentum Q
- rapidity separation Y



- Emission with $k_T > Q_0$
forbidden in the inter-jet region

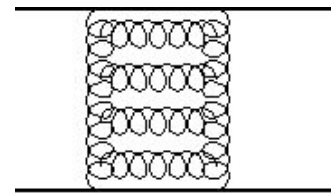
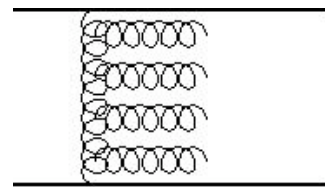
Plenty of QCD effects

“wider” gaps

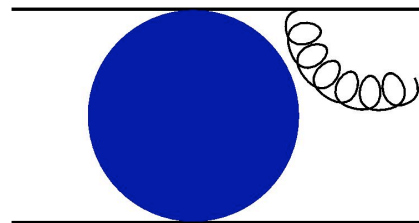
Y

Forward BFKL
(Mueller-Navelet jets)

Non-forward BFKL
(Mueller-Tang jets)



Wide-angle soft
radiation



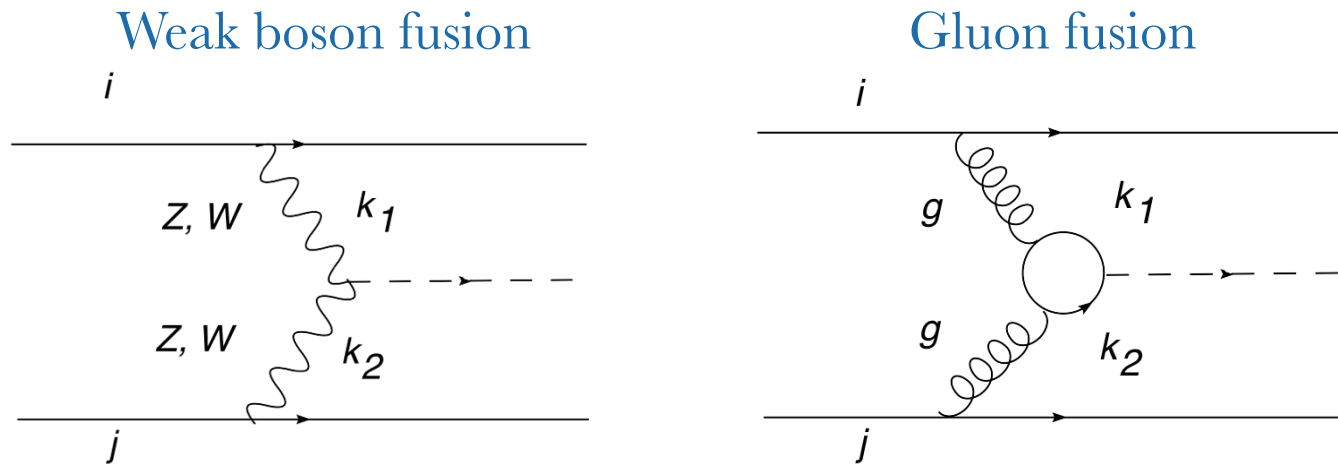
Fixed order

Super-leading
logs

$$L = \ln \frac{Q}{Q_0}$$

“emptier” gaps

Higgs + 2 jets

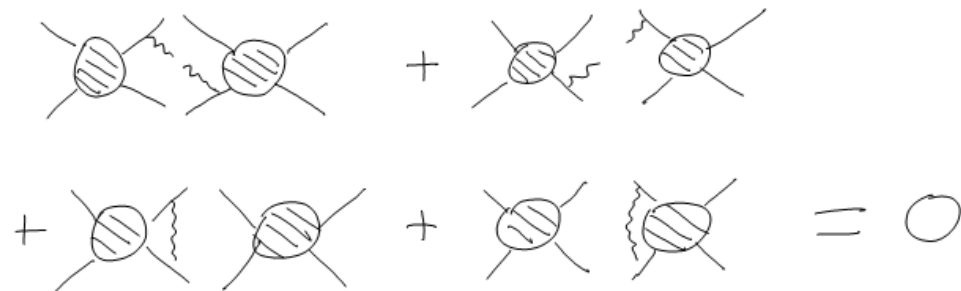


- Different QCD radiation in the inter-jet region
- To enhance the WBF channel, one can make a veto Q_0 on additional radiation between the tagged jets
- QCD radiation as in dijet production
- Important in order to extract the VVH coupling

Forshaw and Sjödal
arXiv:0705.1504 [hep-ph]

Soft gluons in QCD

- What happens if we dress a hard scattering with soft gluons?
- Sufficiently inclusive observables are not affected: real and virtual cancel via Bloch-Nordsieck theorem



- Soft gluon corrections are important if the real radiation is constrained into a small region of phase-space
- In such cases BN fails and miscancellation between real and virtual induces large logarithms

$$-\alpha_s \int_0^{Q_0} \frac{dE}{E} \Big|_{\text{real}} + \alpha_s \int_0^Q \frac{dE}{E} \Big|_{\text{virtual}} = \alpha_s \int_{Q_0}^Q \frac{dE}{E} \Big|_{\text{virtual}} = \alpha_s \ln \frac{Q}{Q_0}$$

Soft gluons in gaps between jets

- Naive application of BN:
real and virtual contributions cancel everywhere
except within the gap region for $k_T > Q_0$
- One only needs to consider **virtual corrections** with
 $Q_0 < k_T < Q$
- Leading logs (LL) are resummed by iterating the one-loop result:

$$\mathcal{M} = e^{-\alpha_s L \Gamma} \mathcal{M}_0$$

soft anomalous dimension

Born

Oderda and Sterman
hep-ph/9806530

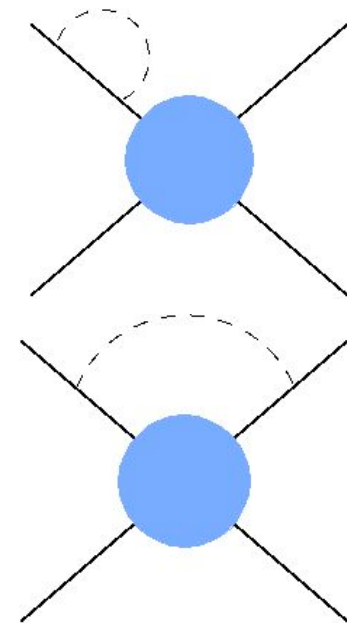
Colour evolution (I)

- The anomalous dimension can be written as

$$\Gamma = \frac{1}{2} Y T_t^2 + i\pi T_1 \cdot T_2 + \frac{1}{4} \rho (T_3^2 + T_4^2)$$

- T_i is the colour charge of parton i
- T_i^2 is a Casimir

- $T_t^2 = (T_1^2 + T_3^2 + 2T_1 \cdot T_3)$
is the colour exchange in the t -channel



Coulomb gluons

- The $i\pi$ term is due to Coulomb (Glauber) gluon exchange

$$i\pi T_1 \cdot T_2 \mathcal{M} = \text{Diagram}$$

- It doesn't play any role for processes with less than 4 coloured particles (e.g. DIS or DY)

$$T_1 + T_2 + T_3 = 0 \Rightarrow T_1 \cdot T_2 = \frac{1}{2}(T_3^2 - T_1^2 - T_2^2)$$

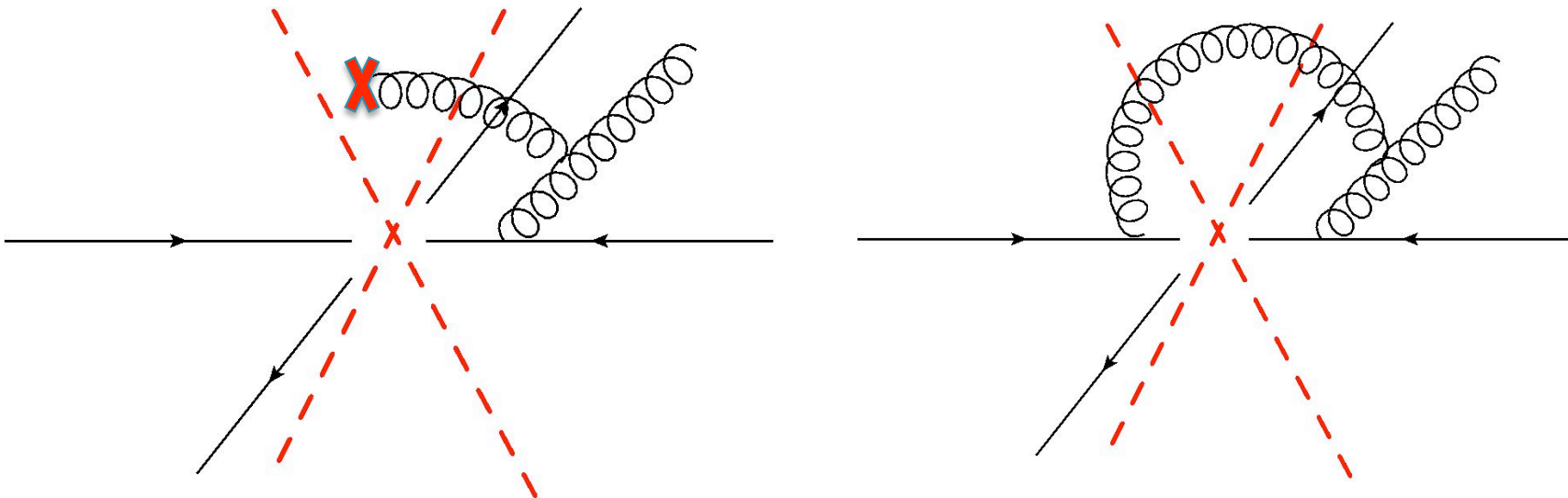
leading to an unimportant overall phase

- Coulomb gluon contributions are *not* implemented in parton showers

Non-global effects

Dasgupta and Salam
hep-ph/0104277

- However this approach completely **ignores a whole tower of LL**
- Virtual contributions are not the whole story because real emissions out of the gap are forbidden to remit back into the gap



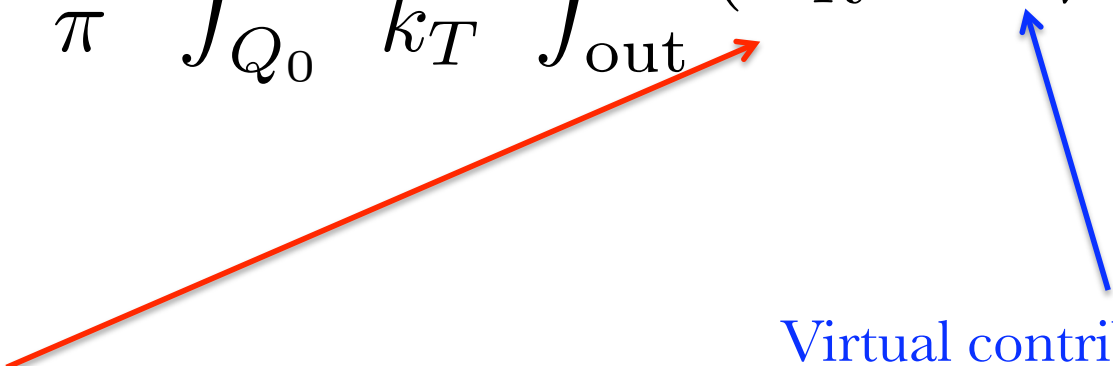
Resummation of non-global logarithms

- The full LL result is obtained by dressing the $2 \rightarrow n$ (i.e. $n-2$ out of gap gluons) scattering with virtual gluons (and not just $2 \rightarrow 2$)
- The colour structure soon become intractable
- Resummation can be done (so far) only in the large N_c limit
 - Numerically [Dasgupta and Salam](#)
[hep-ph/0104277](#)
 - By solving a non-linear evolution equation

[Banfi, Marchesini and Smye](#)
[hep-ph/0206076](#)

One gluon outside the gap

- As a first step we compute the tower of logs coming from only one out-of-gap gluon but keeping finite N_c :

$$\sigma^{(1)} = -\frac{2\alpha_s}{\pi} \int_{Q_0}^Q \frac{dk_T}{k_T} \int_{\text{out}} (\Omega_R + \Omega_V)$$


Real contribution:

- real emission vertex D^u
- 5 - parton anomalous dimension Λ

Sjödahl
arXiv:0807.0555 [hep-ph]

Virtual contribution:

- virtual eikonal emission γ
- 4-parton anomalous dimension Γ

A big surprise

Conventional wisdom (“plus prescription” of DGLAP)

when the out-of-gap gluon becomes collinear with one of the external partons the real and virtual contributions should cancel

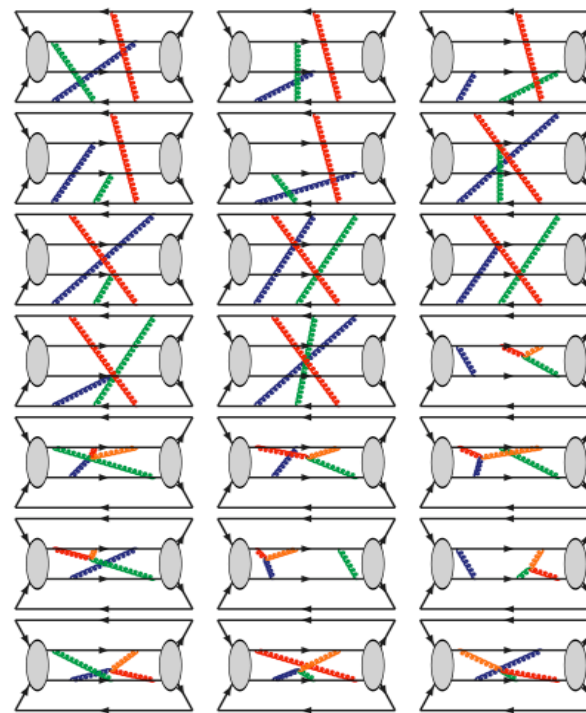
- It works when the out-of-gap gluon is collinear to one of the outgoing partons ✓
- But it fails for **initial state collinear emission** ✗
- Cancellation *does* occur for up to 3rd order relative to the Born, but fails at 4th order
- The problem is entirely due to the emission of Coulomb gluons
- As result we are left with **super-leading logarithms** (SLL):

$$\sigma^{(1)} \sim -\alpha_s^4 L^5 \pi^2 + \dots$$

Forshaw Kyrielleis Seymour
hep-ph/0604094

Fixed order calculation

- Gluons are added in all possible ways to trace diagrams and colour factors calculated using COLOUR
- Diagrams are then cut in all ways consistent with strong ordering
- At fourth order there are 10,529 diagrams and 1,746,272 after cutting.
- SLL terms are confirmed at fourth order and **computed for the first time at 5th order**



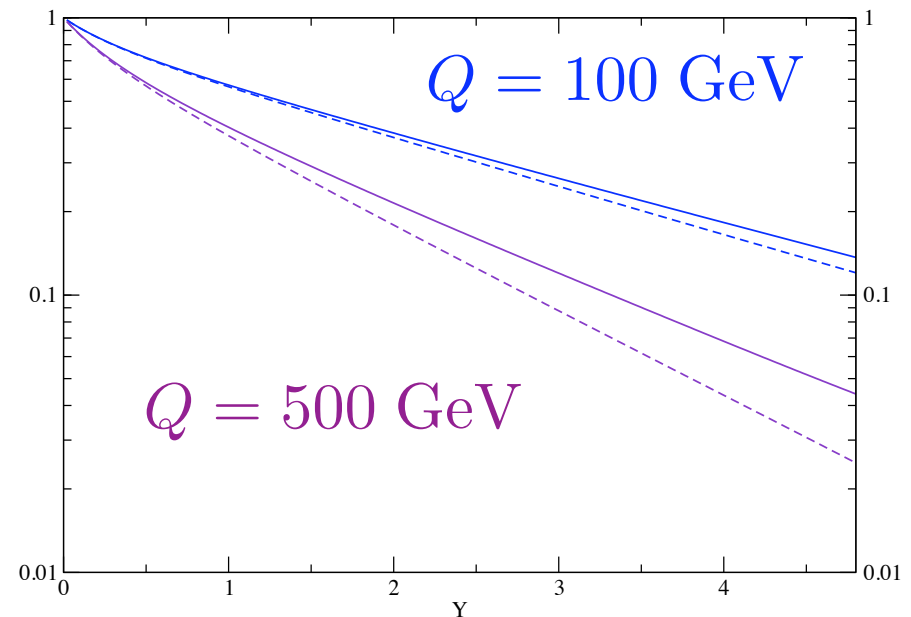
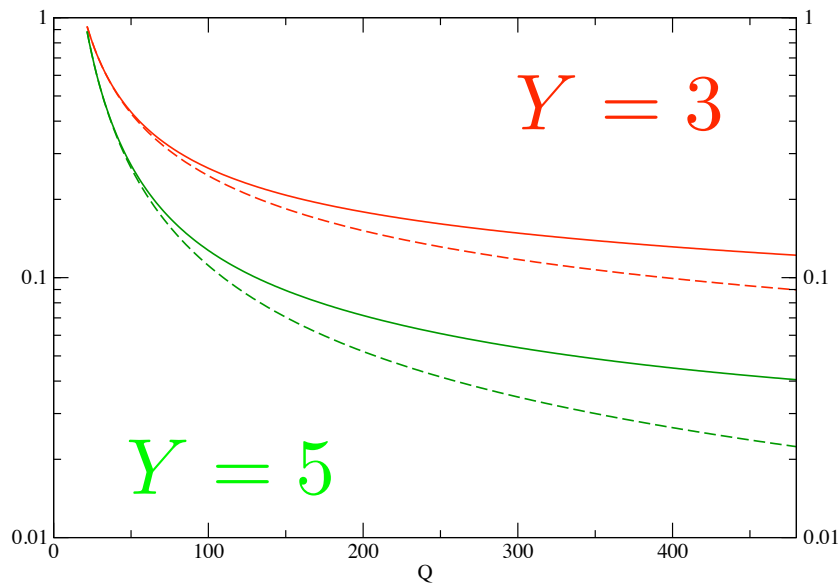
Keates and Seymour
arXiv:0902.0477 [hep-ph]

Some LHC phenomenology

Global logs and Coulomb gluons (no gluon outside the gap)

$$f^{(0)} = \sigma^{(0)} / \sigma^{\text{born}}$$

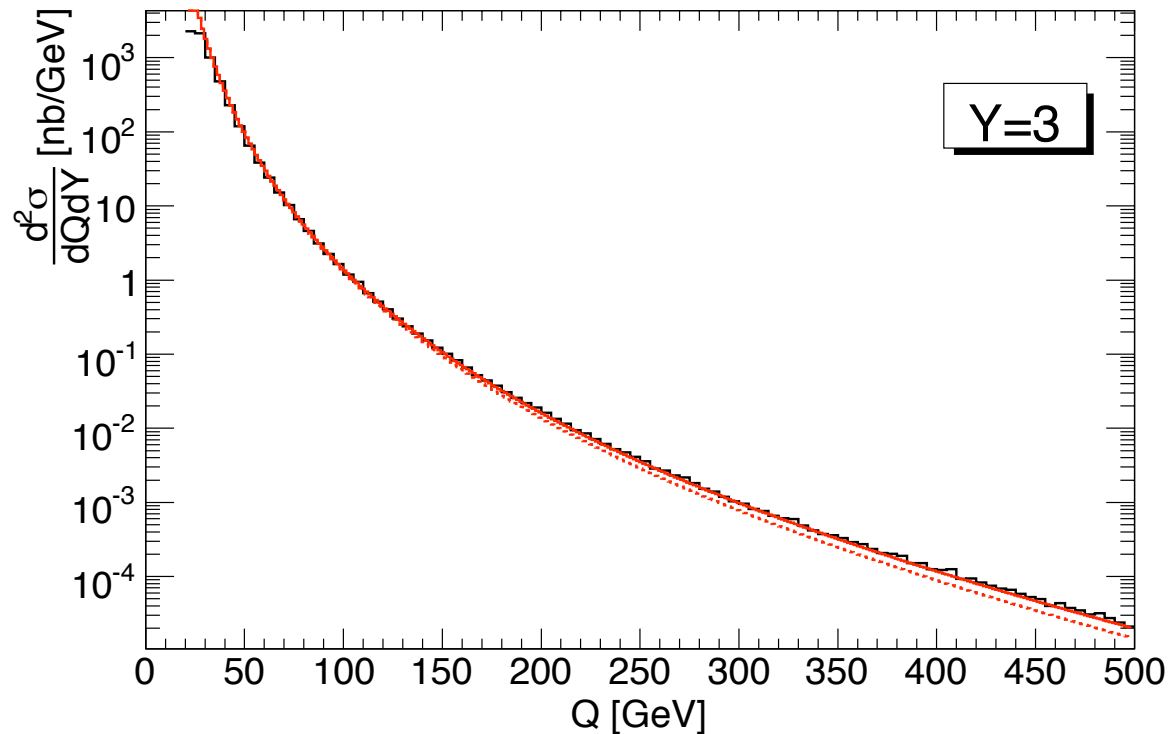
$$\begin{aligned} \sqrt{S} &= 14 \text{ TeV} \\ Q_0 &= 20 \text{ GeV} \\ R &= 0.4 \\ \eta_{\text{cut}} &= 4.5 \end{aligned}$$



- solid lines: full resummation
- dashed lines: ignoring $i\pi$'s

Large Coulomb gluon
contributions !

Comparison to HERWIG++ (gap cross-section)

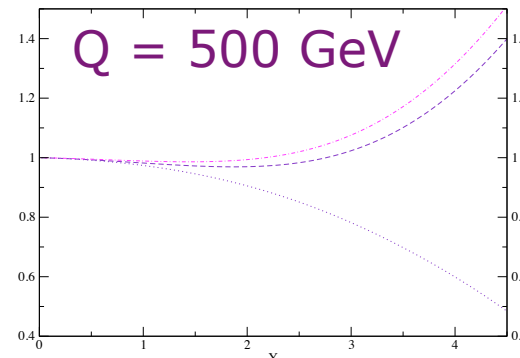
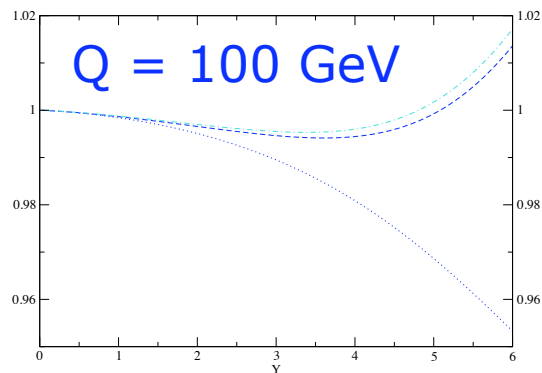
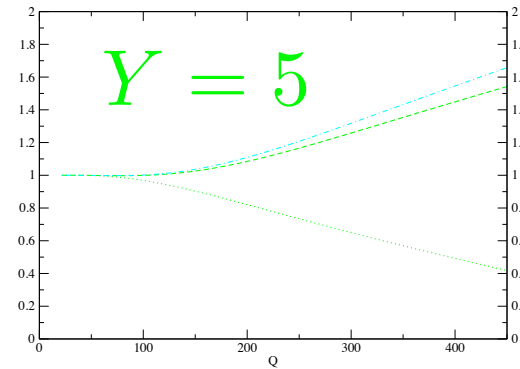
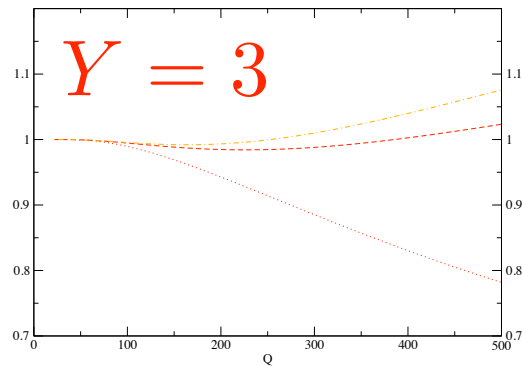


- We compare our results to HERWIG++
- LO scattering + parton shower (no hadronisation)
- Q is the mean p_T of the leading jets
- Jet algorithm SIScone

- The overall agreement is encouraging
- One should compare the histogram to the dotted curve (no Coulomb gluons)
- Energy-momentum conservation plays a role: we need matching to NLO
- Other differences: large N_c limit and non-global effects

Phenomenology of SLL (I)

$$(\sigma^{(0)} + \sigma^{(1)} + \sigma^{(2)}) / \sigma^{(0)}$$

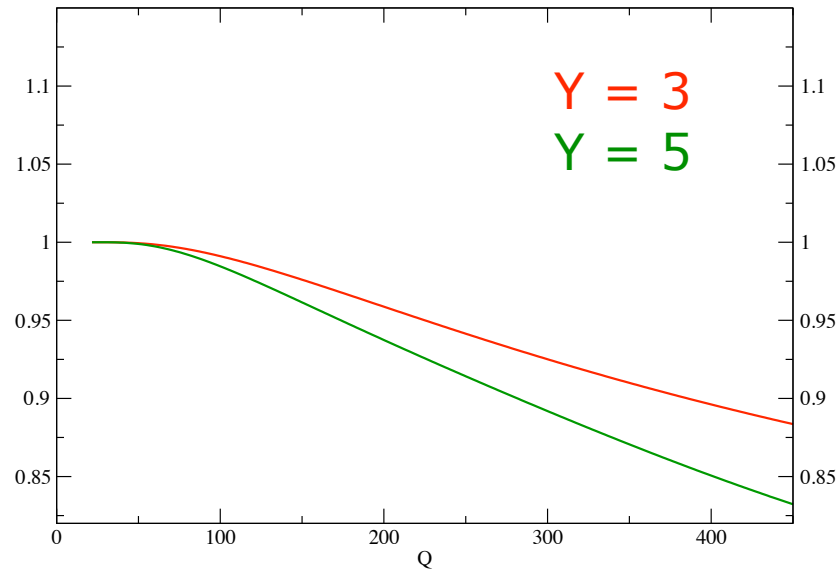


- dotted, one gluon, α_s^4
- dashed: one gluon, up to α_s^5
- dash-dotted: one+two gluons, up to α_s^5

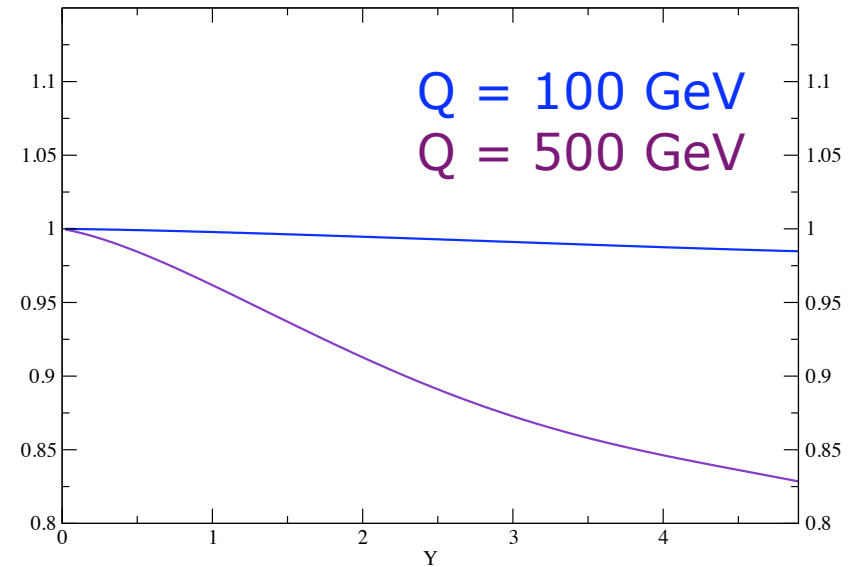
instability:
need of resummation

Phenomenology of SLL (II)

Resummed results (one out-of-gap gluon)



- $Y = 3$, $\sim 5\%$
- $Y = 5$, $\sim 10-15\%$



- $Q = 100 \text{ GeV}$, $\sim 2\%$
- $Q = 500$, $\sim 10-15\%$

- SLL could have an effect as big as 10-15 % in quite extreme dijet configurations
- There are no SLL effect on Higgs+ jj, unless $Q_0 < 10 \text{ GeV}$

Conclusions

- There is plenty of interesting QCD physics in gaps between jets
- Soft logs may be relevant for extracting the Higgs coupling to the weak bosons
- Coulomb gluons play an important role
- Dijet cross-section could be sensitive to SLL at large Y and L (e.g. 300 GeV and $Y = 5$, $\sim 15\%$)

Outlook (phenomenology)

- Compute the best theory prediction for gaps between jets at the LHC:
 - Matching to NLO
 - complete one gluon outside the gap
 - non-global (large N_c)
 - jet algorithm dependence
 - BFKL resummation

Outlook (theory)

- There is an interesting link between non-global logs and BK equation

Banfi, Marchesini and Smye
hep-ph/0206076

Avsar, Hatta and Matsuo
arXiv:0903.4285 [hep-ph]

- Understanding the origin of super-leading logs
 - k_t ordering ?
 - interaction with the remnants ?

on-going projects in Manchester

BACKUP SLIDES

An interesting link to small- x

- The non-linear evolution equation which resums non-global logs resembles the BFKL/BK equations (in the dipole picture)

$$\frac{d^2 \Omega_c}{4\pi} \frac{1 - \cos \theta_{ab}}{(1 - \cos \theta_{ac})(1 - \cos \theta_{cb})} \rightarrow \frac{d^2 \mathbf{x}_c}{2\pi} \frac{\mathbf{x}_{ab}^2}{\mathbf{x}_{ac}^2 \mathbf{x}_{cb}^2}$$

- The two kernels can be mapped via a stereographic projection

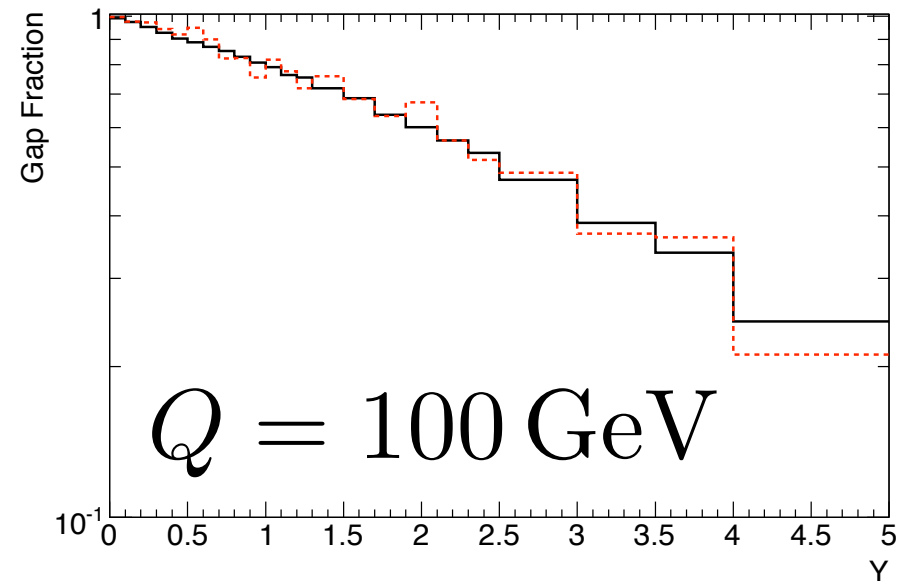
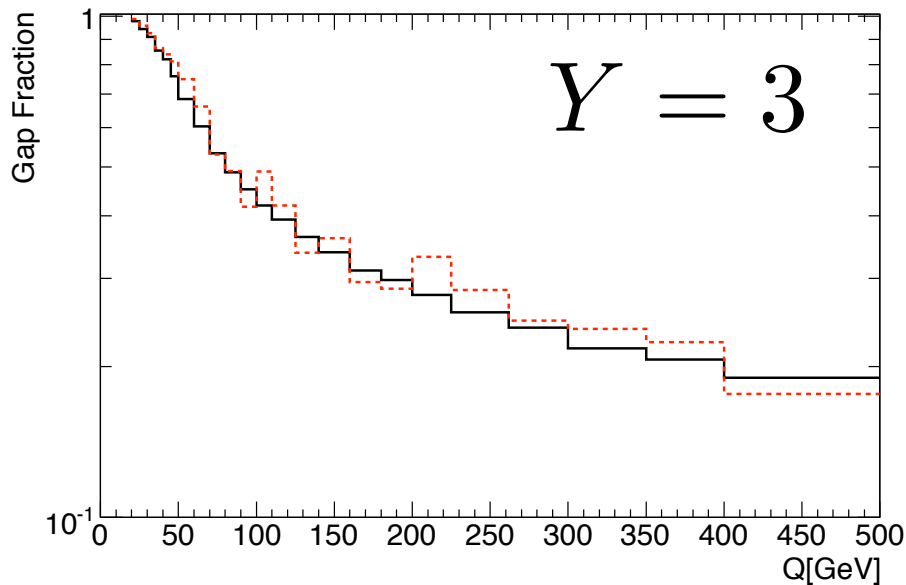
$$\Omega = (\theta, \phi) \rightarrow \mathbf{x} = (x^1, x^2)$$

Avsar, Hatta and Matsuo
arXiv:0903.4285 [hep-ph]

- Is there a fundamental connection between non-global (soft) evolution and small- x ?

Hadronisation effects

- Hadronisation is “gentle”
- It does not spoil the gap fraction



- black line: after parton shower
- red line: after hadronisation