Gaps between jets at the LHC

Simone Marzani
University of Manchester

SM discoveries with early LHC data
UCL 30th March 2009

In collaboration with Jeff Forshaw and James Keates

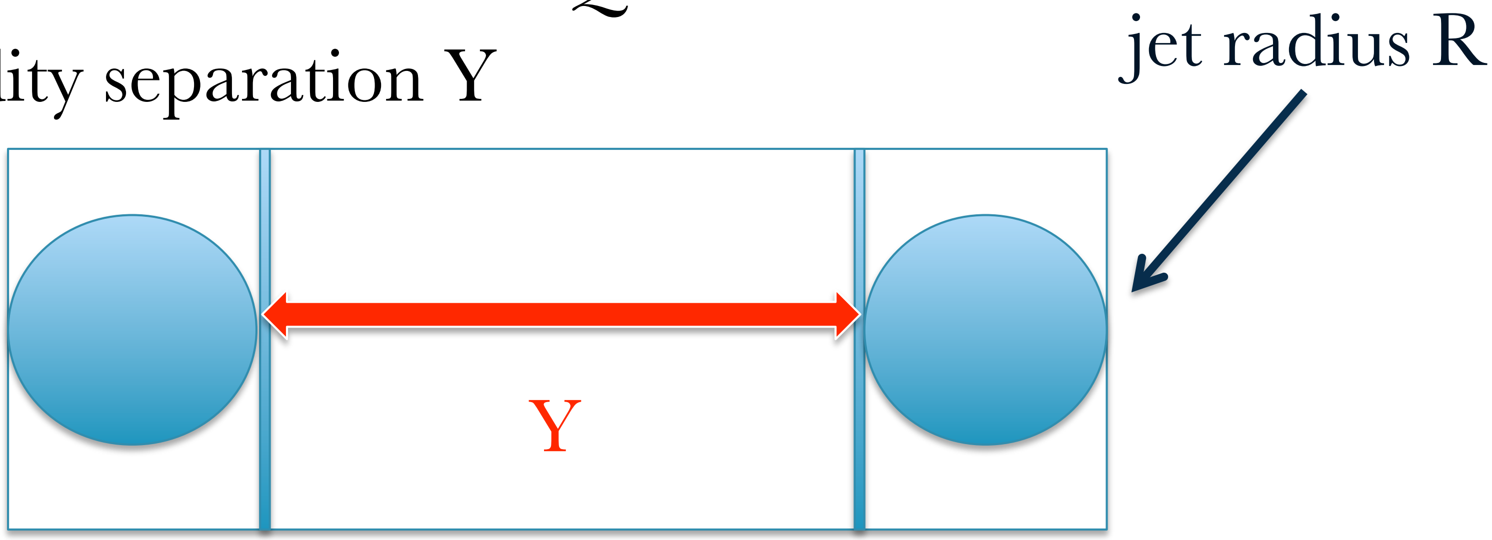
Outline

- Importance of rapidity gaps for LHC physics
- Soft gluons
- Discovery of super-leading logarithms
- Some phenomenological studies
- Conclusions and Outlook

The observable

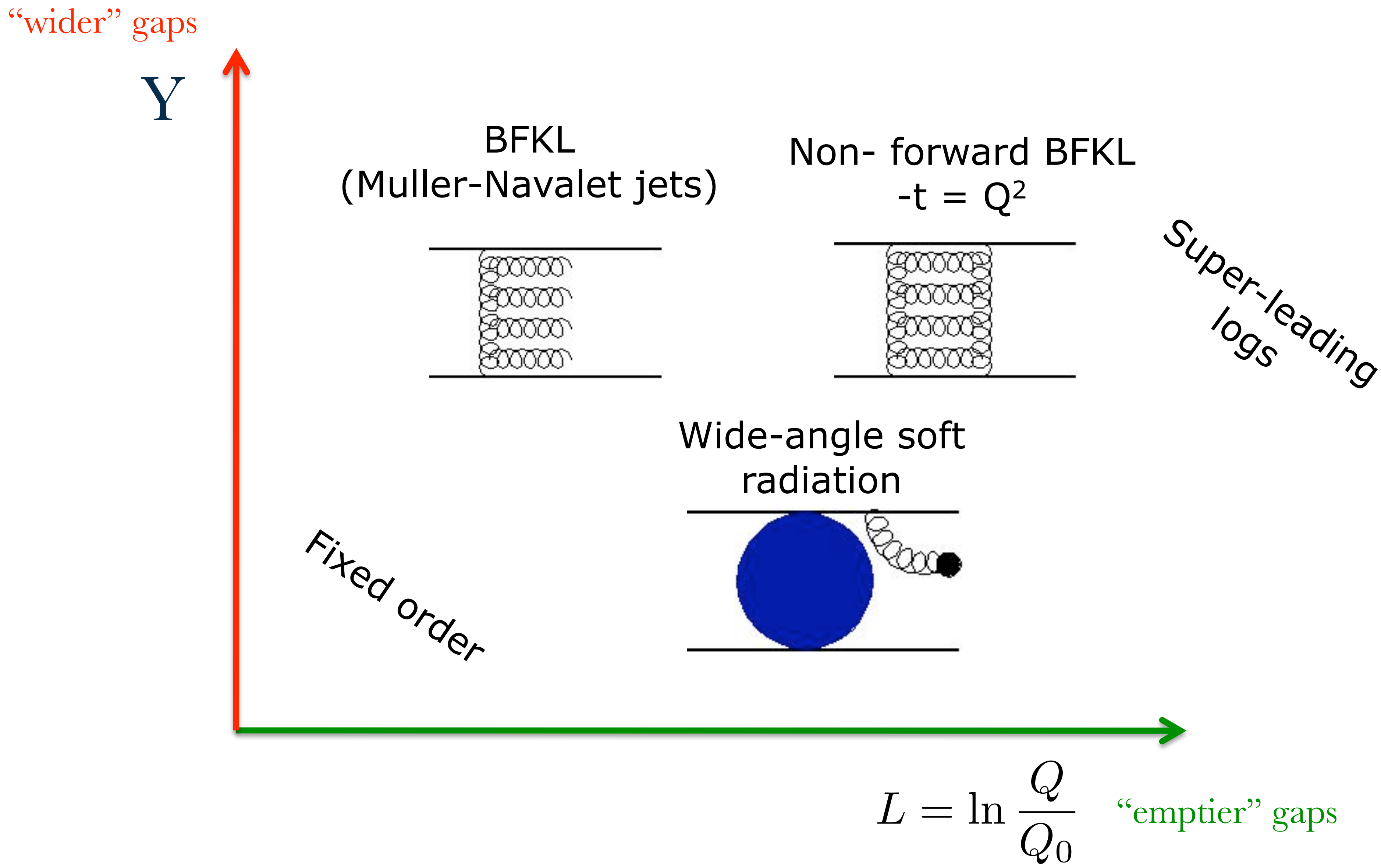
Production of two jets with

- transverse momentum Q
- rapidity separation Y



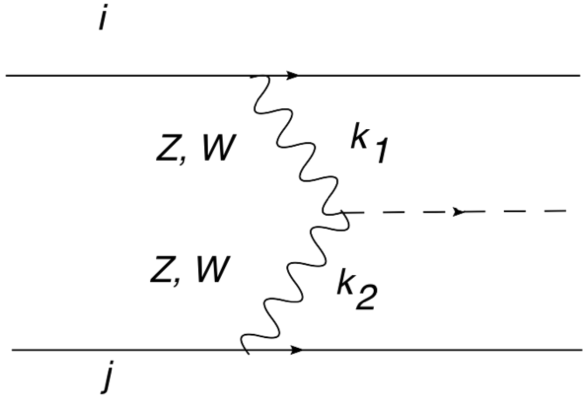
- Emission with $k_T > Q_0$
  forbidden in the inter-jet region

Plenty of QCD effects

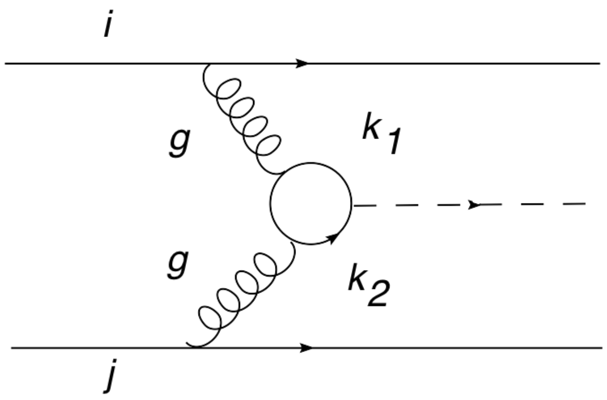


Higgs +2 jets

Weak boson fusion



Gluon fusion



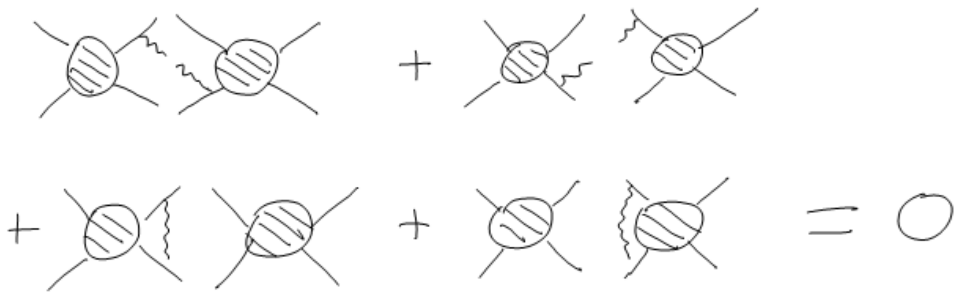
- Different QCD radiation in the inter-jet region
- To enhance the WBF channel, one can make a veto Q_0 on additional radiation between the tagged jets
- QCD radiation as in dijet production

Forshaw and Sjödahl

- Important in order to extract the VVH coupling

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

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

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:

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

Oderda and Sterman

soft anomalous dimension

Born

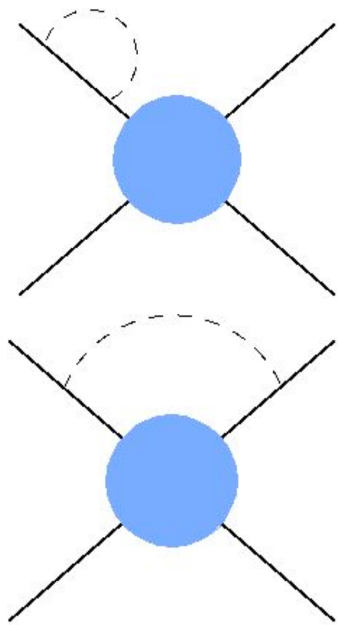
Colour evolution (I)

- The anomalous dimension can be written as

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

Forshaw Kyrieleis Seymour

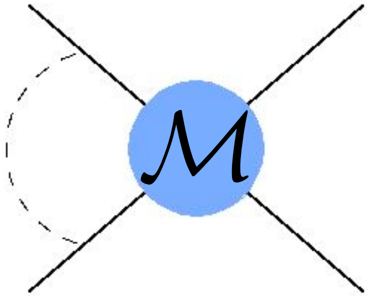
- T_i is the colour charge of parton i
- T_i^2 is a Casimir
- $T_t^2 = (T_1^2 + T_3^2 + 2T_1 \cdot T_3)$
 is the colour exchange in the t-channel



Colour evolution (II)

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

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



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

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

leading to an unimportant overall phase

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

Non-global effects

- However this naive 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
- The full LL result is obtained by dressing the $2 \to n$ (i.e. n-2 out of gap gluons) scattering with virtual gluons (and not just $2 \to 2$)
- Resummation can be done (so far) only in the large N_c limit

Dasgupta and Salam

One gluon outside the gap

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

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

Real contribution:
- real emission vertex D^μ
- 5 - parton anomalous dimension Λ

Sjödahl

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)

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

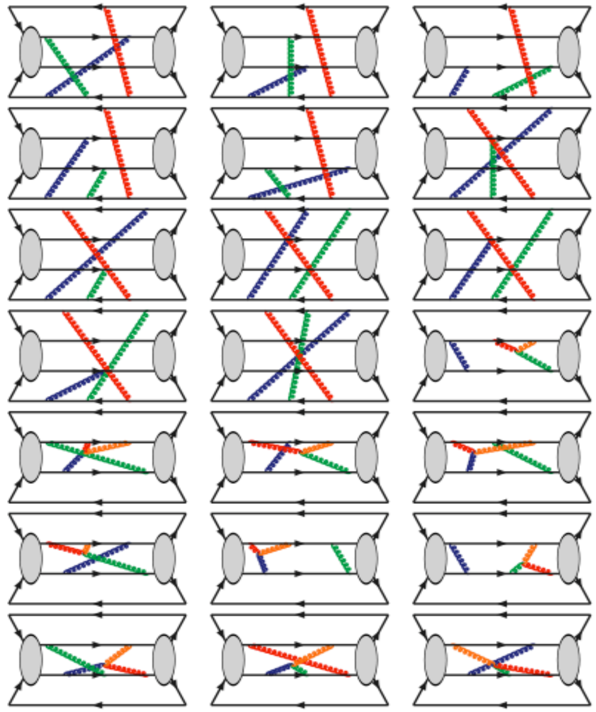
Fixed order calculation

- 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 5^{th} order

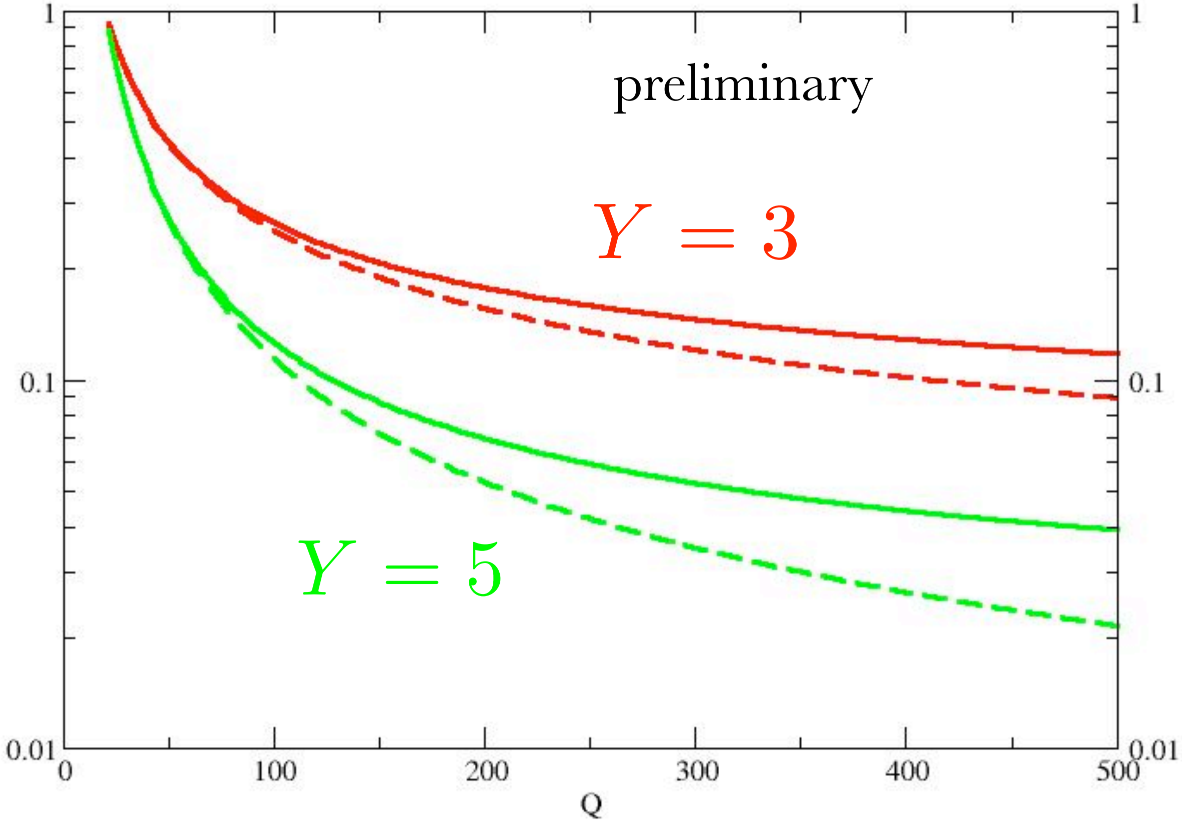


Keates and Seymour

LHC results:
no gluon outside the gap

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

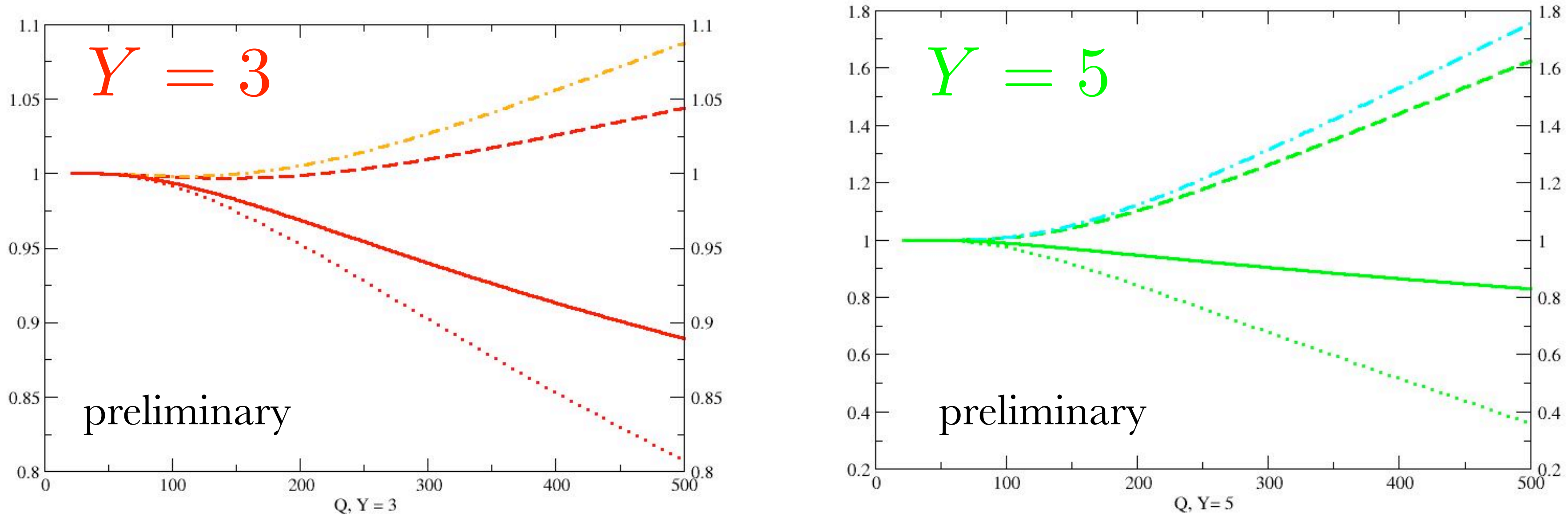
$\sqrt{S}$ = 14 TeV
Q_0 = 20 GeV
R = 0.4
η_{cut} = 4.5



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

Phenomenology of SLL

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



- dotted, one gluon, α_s^4
- dashed: one gluon, up to α_s^5
- solid: one gluon resummed
- dash-dotted: one+two gluons, up to α_s^5 (only fixed order)

- fixed order expansion unstable
- $\sigma^{(2)}$ less important than $\sigma^{(1)}$
- Y = 3, ~ 5 %
- Y = 5, ~10 %
- no effect for Higgs, unless Q_0 < 10 GeV

Conclusions

- Early data: there is plenty of interesting QCD physics in gaps between jets
- More data: Higgs coupling to 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, ~15%)
- There is an interesting link between non-global logs and BK equation

Banfi, Marchesini and Smye
Avsar, Hatta and Matsuo

Outlook (pheno)

Collect all the possible information and build up the best theory prediction for LHC:

- matching with NLO
- complete one gluon outside the gap
- non-global (large N_c)
- jet algorithm dependence
- BFKL resummation

Outlook (theory)

- Understanding the origin of SLL
- k_t ordering ?
- interactions with the remnants ?