QCD resummation of jet mass distributions

Simone Marzani
IPPP / Durham University

XX International Workshop on Deep Inelastic Scattering and Related Subjects
26th - 30th March 2012, Bonn Germany

in collaboration with

A . Banfi, M.Dasgupta, K.Khelifa-Kerfa and M. Spannowsky

JHEP 1008 (2010) 064
arXiv:12xx.xxxx

Jet sub-structure

- Understanding the substructure of jets is crucial for LHC phenomenology
- It is important for new physics searches
  - we need tools to distinguish jets coming from decays of boosted resonances from QCD jets
- It has also interest on its own as a test of pQCD
- Jet shapes enable us to look at energy distributions inside a jet
- Grooming techniques enable us to improve our ability of distinguishing signal from background by getting rid of soft radiation
- e.g. Butterworth et al (2008), Ellis et al. (2009), Krohn et al. (2010) and several others

The Jet Mass

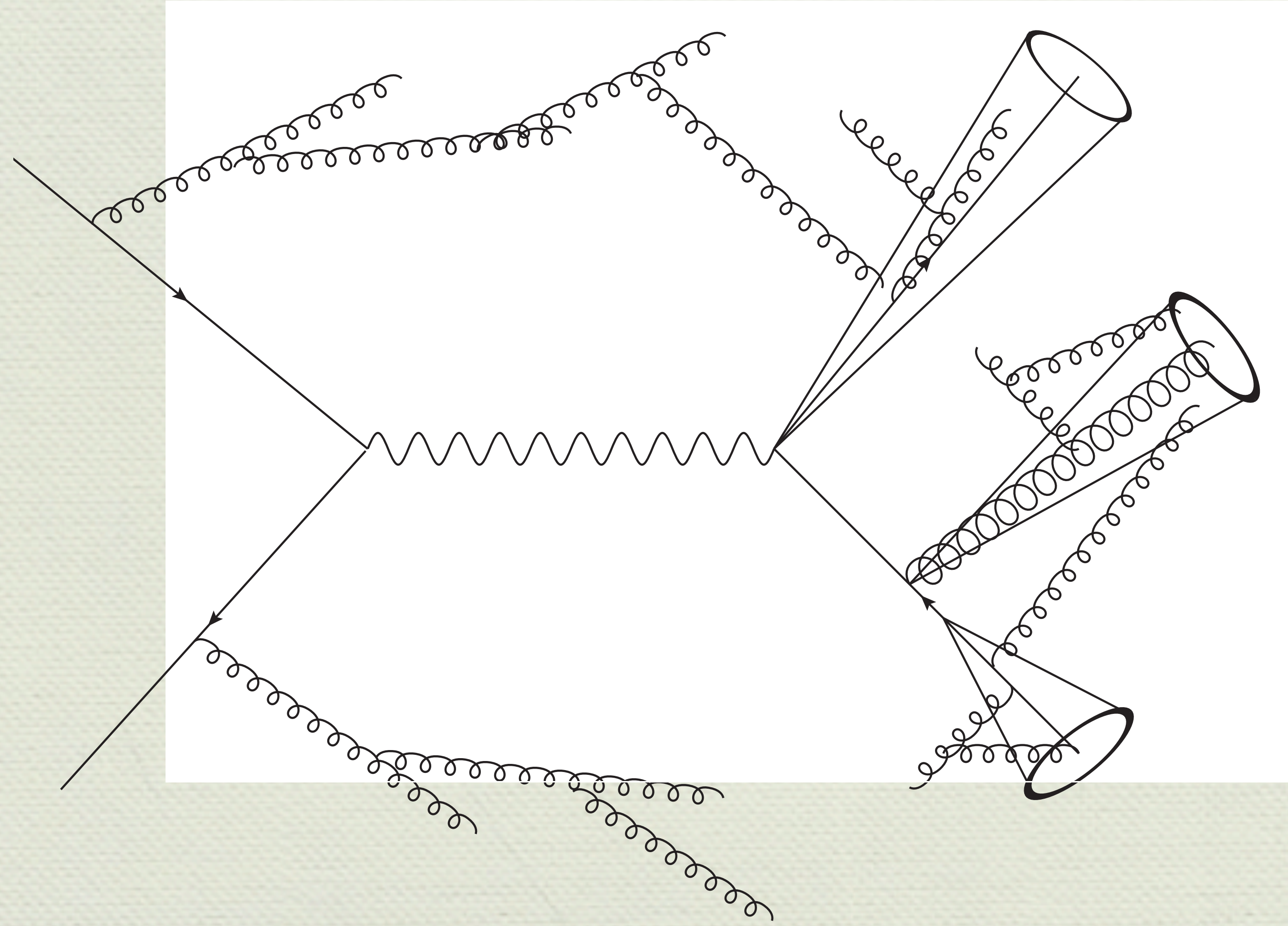
- In our studies we concentrate on the jet-mass as an example of a jet shape
- Jet mass distributions are affected by large logarithms

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}m_J^2} = \frac{1}{m_J^2}\left[\alpha_s A_1 \ln\frac{m_J^2}{p_T^2} + \alpha_s^2 A_2 \ln^3\frac{m_J^2}{p_T^2} + \ldots\right]$$

- Reliable calculations in pQCD require resummation
- In e^+e^- resummation exists CTTW (1993), Burby and Glover (2001)
- Can we extend this to hadron colliders ?

The picture at the LHC

- Can we deal with a more complicated environment ?
- Complex colour structure and geometry ?
- Does the choice of the jet algorithm play a role ?
- How do we treat ISR ?
- Can we reduce the underlying event ?



MC vs Analytical Approach

- MC simulations using parton showers
  - they are powerful general purpose tools
  - they are often interfaced with hadronisation and UE models to give a realistic description
  - they are formally LL (although they contain many sub-leading terms)
- Analytical resummations
  - well defined and improvable accuracy (LL, NLL, etc)
  - the dependence on various parameters is manifest
- The two approaches are complementary

One gluon calculation

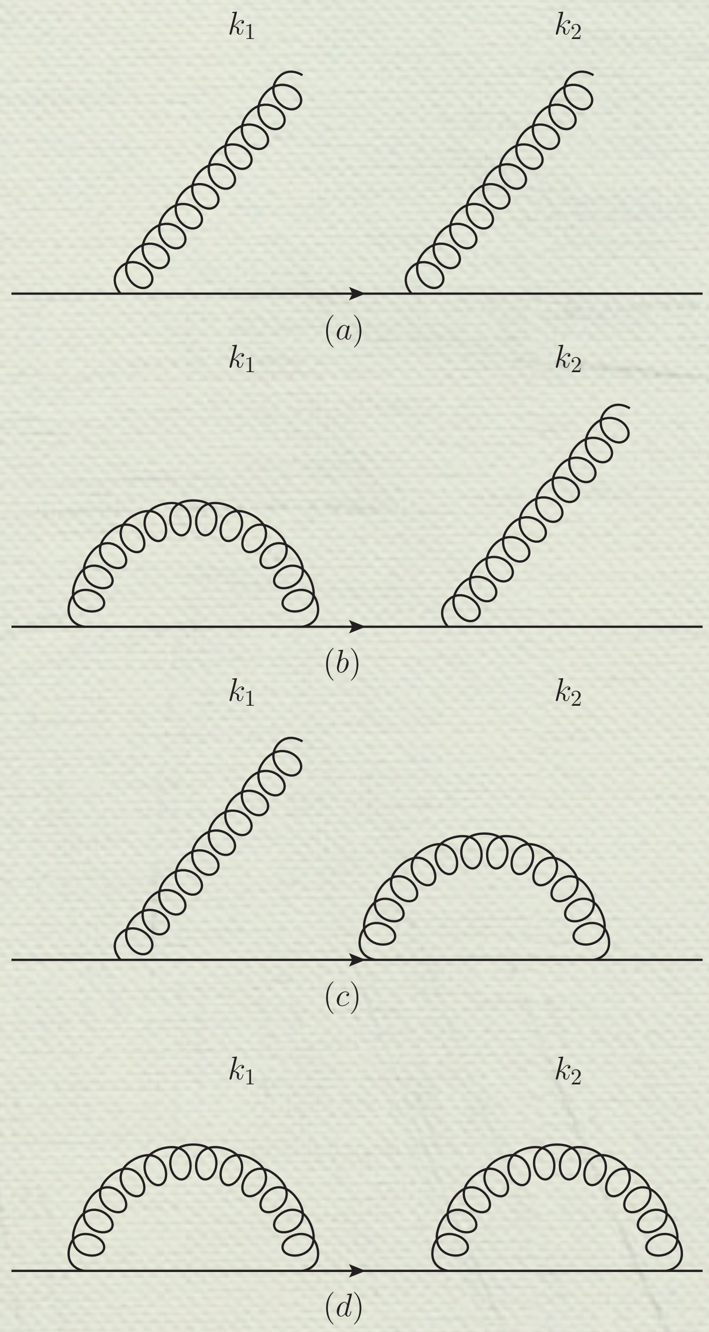
- We wish to study the mass of one or more high-p_T jets
- We follow a traditional approach to QCD resummation
- There are many results also from SCET (e.g. Horning, Lee, Stewart, Walsh and Zuberi; Schwartz et al.)
- We consider the emission of one soft gluon off a quark-antiquark dipole (as in e^+e^-)
- At this level all IRC jet algorithm will give the same answer

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma^{(1)}}{\mathrm{d}\rho} = \frac{\mathrm{d}}{\mathrm{d}\rho}\left[\frac{\alpha_s}{2\pi}C_F \ln^2\frac{R^2}{\rho}\right], \quad \rho = \frac{m_J^2}{p_T^2}$$

- The naïve expectation is that the resummed result is obtained by exponentiation of the 1-loop contribution

Two gluons ... *n* gluons (?)

$E_1 \gg E_2$



- Let's look at the two-gluon calculation
- Double virtual (d) never contributes
- k_1 in, k_2 out: (a) and (c) cancel; (b) is zero
- k_1 out, k_2 in: (a) and (b) cancel; (c) is zero
- Non-vanishing contributions only when both gluons are inside the jet:

$$\frac{1}{\sigma}\frac{d\sigma^{(2)}}{d\rho} = \frac{d}{d\rho}\left[\frac{1}{2}\left(\frac{\alpha_s}{2\pi}\right)^2 C_F^2 \ln^4 \frac{R^2}{\rho}\right]$$

- Consistent with exponentiation
- Is this result the same with any jet algorithm ?

The role of the jet algorithm

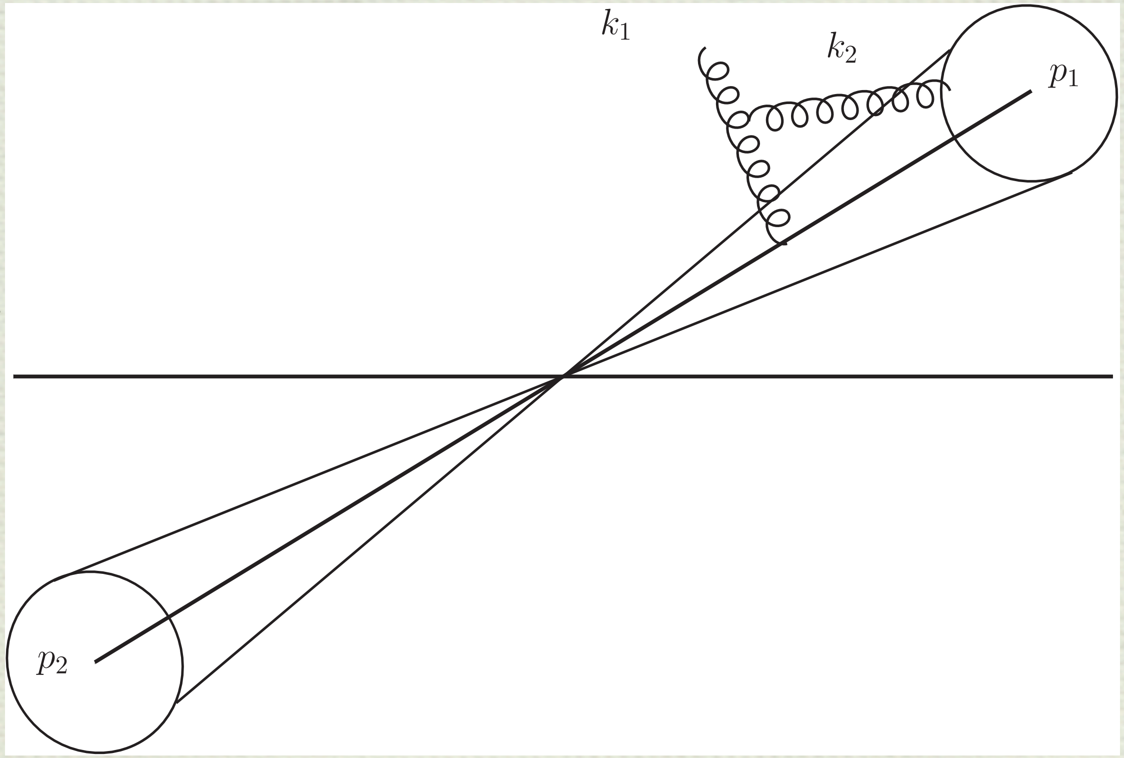
- NO! Because of soft gluon self-clustering
- Two gluons are recombined with each other is their distance is smaller than R
- The recombined momentum essentially lies along the harder one
- As a result a hard gluon can pull a softer one out of the jet
- This does not happen if we use anti-k_t algorithm: two soft gluons are always far apart with this measure
- The anti-k_t algorithm in the soft limit works as a perfect cone
- Exponentiation of the independent emission is OK in this case, but what happens with different algorithms ?

C/A and k_t algorithm

- With C/A or k_t algorithm two soft gluons can be recombined together
- If k_1 is outside the jet, it can pull k_2 outside (if they are close enough)
- This spoils the cancellation between diagrams (a) and (b) (virtual gluons are unaffected by clustering)
- This results into a new single-log contribution wrt to the anti-k_t case
- Resummation possible for gaps between jets — Delenda, Appleby, Banfi, Dasgupta (2006)
- These effects received recently a lot of attention — Kelley, Walsh and Zuberi (2012)
- From now on we work with the anti-k_t algorithm

Non-global logarithms

- BUT, even if we use anti-k_t, exponentiation of the independent emission is not the whole story
- The jet-mass is a non-global observable: it receives single log corrections from correlated emission
- This is a $C_F C_A$ term and it's missed by single gluon exponentiation
- In principle we need to consider any number of gluons outside the jet
- Colour structure becomes intractable, so the resummation is performed in the large N_c limit



Dasgupta and Salam (2001)

From e$^+$e$^-$ to pp collisions

- So far we have discussed the resummation for a quark-antiquark dipole (appropriate for e$^+$e$^-$)

- In the soft limit, the emission probability for a gluon off an ensemble of hard partons can be written as

$$|\mathcal{M}|^2 = \mathcal{M}_0^\dagger \exp\left[\frac{\alpha_s}{2\pi}\left(-2\sum_{i<j} W_{ij}\, t_i \cdot t_j\right)\right]\mathcal{M}_0$$

- The sum runs over all the possible dipoles in the hard scattering

- Dipoles involving the measured jet(s) will produce double logs (soft and collinear gluons), while the other ones only single logs (soft gluons at large angle)

The NLL resummed result

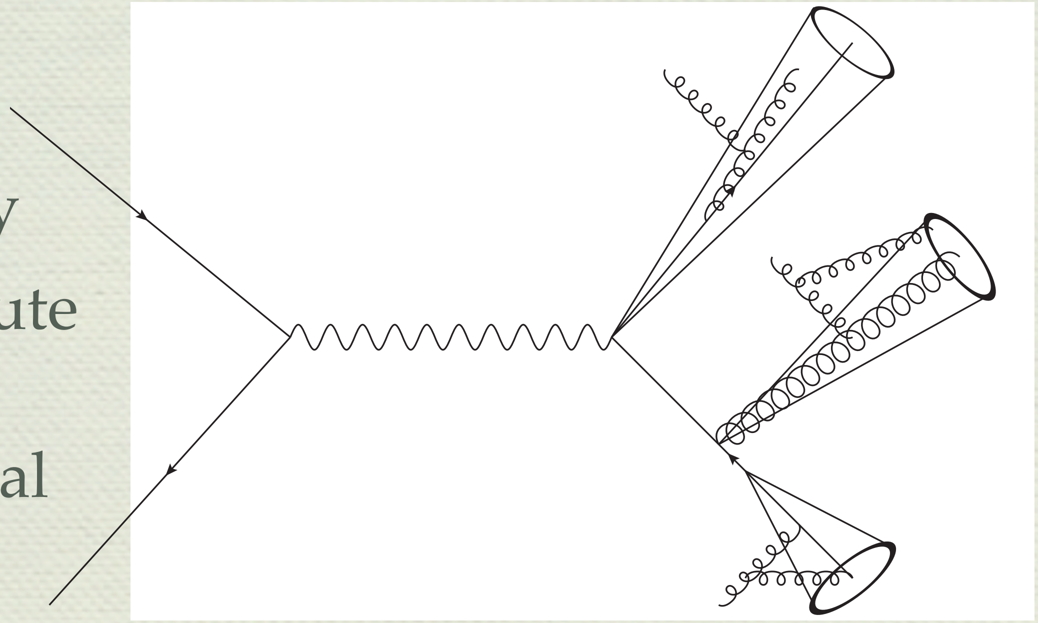
- For each partonic sub-process we can write a NLL resummed expression
- Once a basis is specified the colour factors are represented by matrices

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\rho} = \frac{\mathrm{d}}{\mathrm{d}\rho}\mathrm{tr}\left[H\left(1+\frac{\alpha_s}{2\pi}\mathcal{C}_1\right)e^{-\mathcal{R}^\dagger}Se^{-\mathcal{R}}\right]$$

- H contains the Born contributions and S = 1 for our choice of bases
- The radiator is also a matrix in colour space. To NLL it contains
  - soft and/or collinear radiation
  - two-loop running coupling
  - non-global logs in the large N_c limit

Small R and beyond

- In the small-R limit a simpler picture emerges
- Large-angle emissions are R-suppressed and only the dipoles involving the measured jet(s) contribute
- Each jet evolves independently and the non-global part is the same as in the hemisphere case
- Finite R-corrections are at the percent level if R < 0.4, but they reach $O(40\%)$ for R=1.0
- It turns out that they are dominated by $O(R^2)$ terms, while $O(R^4)$ are below 1% (even at R=1.0)



- For phenomenological studies we then keep $O(R^2)$

An example: Z + jet

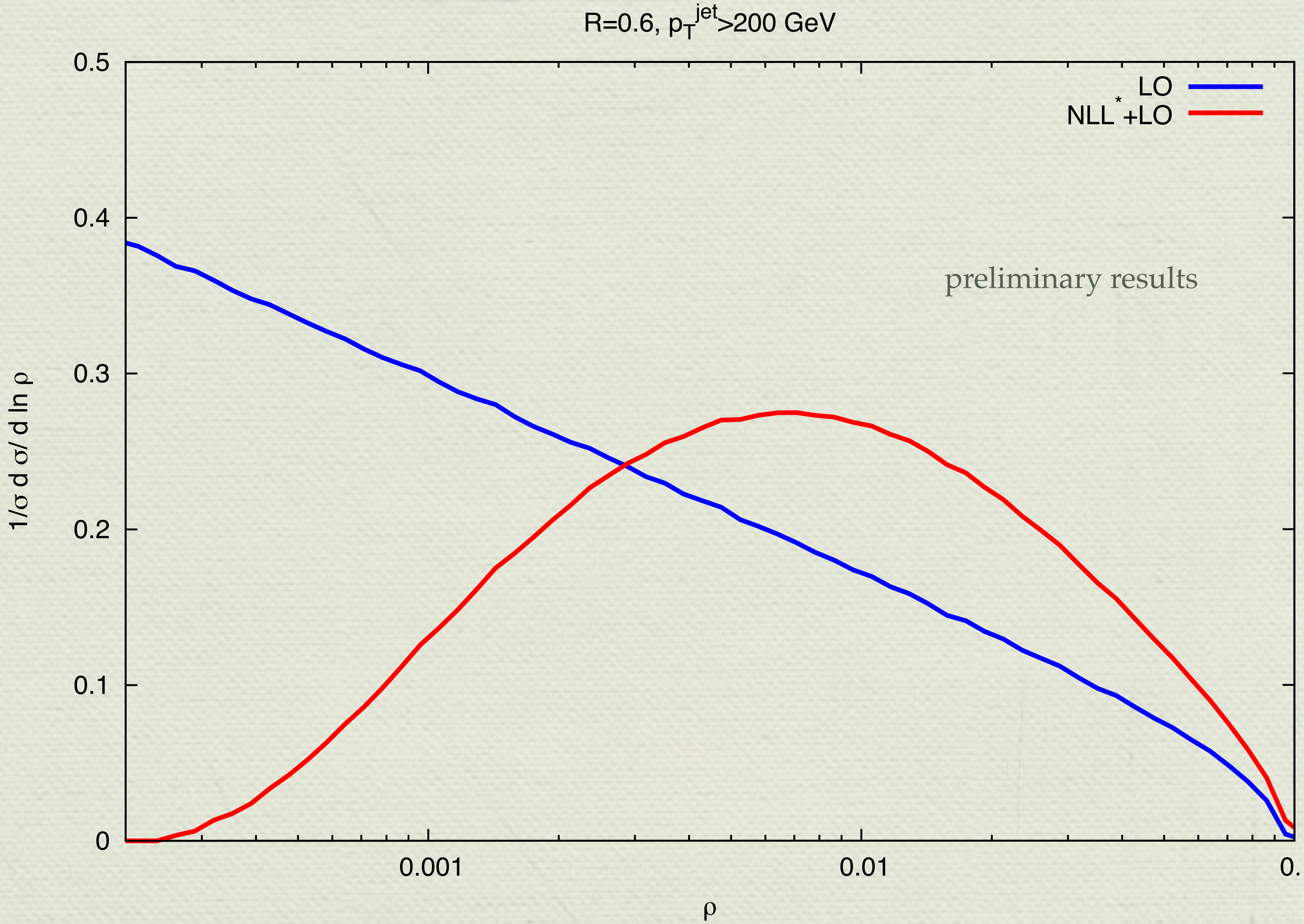
- We study in detail the mass distribution of a QCD jet produced in association with a Z boson
- Background to associated Higgs production with a Z
- If the Higgs is boosted its decay products are likely to end up in a fat jet

  Butterworth et al. (2008)
- Interesting correlations between grooming techniques found in this channel

  Soper and Spannowsky (2010)
- QCD resummation
  - colour structure is relative simple because only 3 partons in the Born
  - we are differential in the jet (or Z boson) kinematics

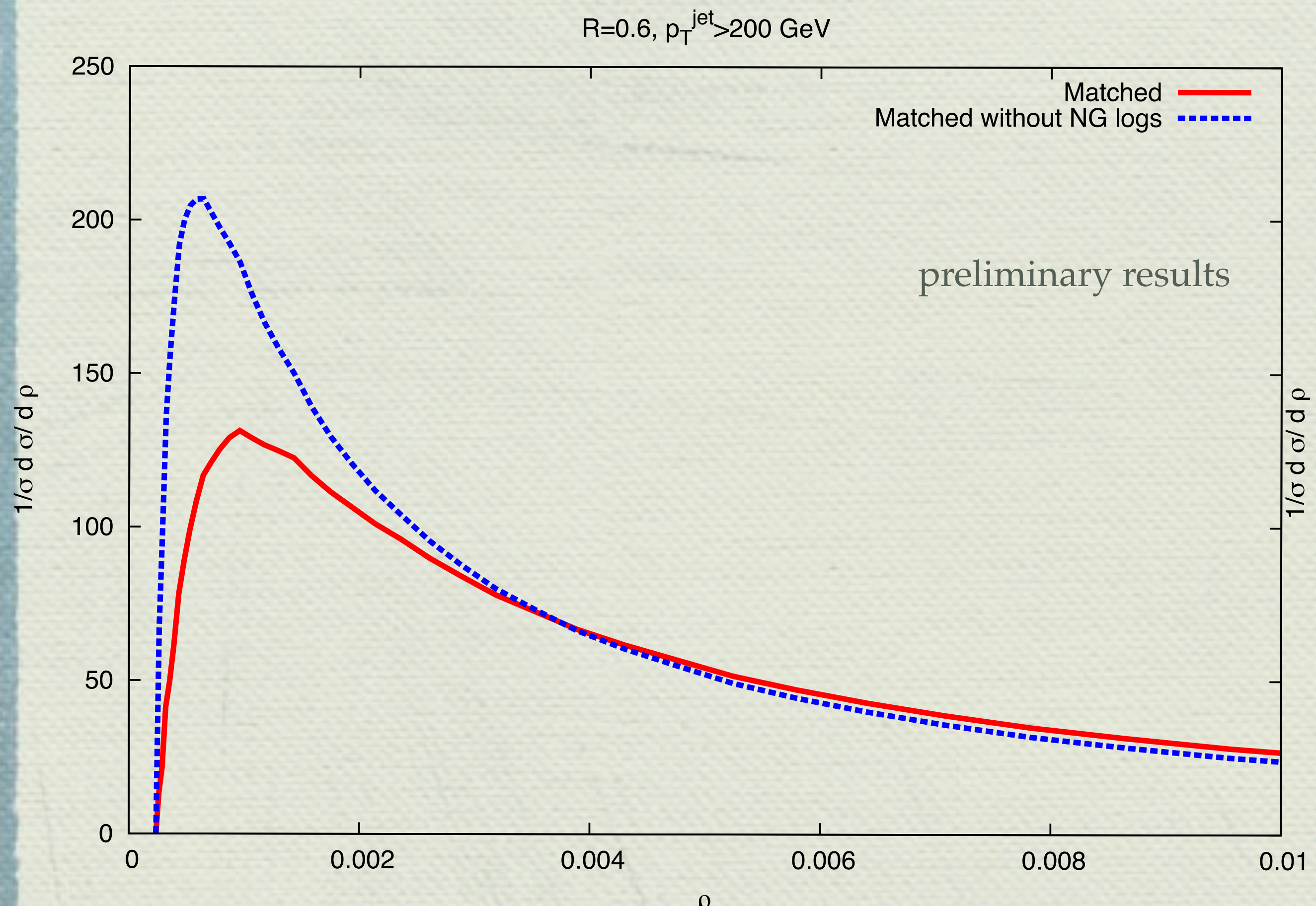
Matching: NLL* + LO

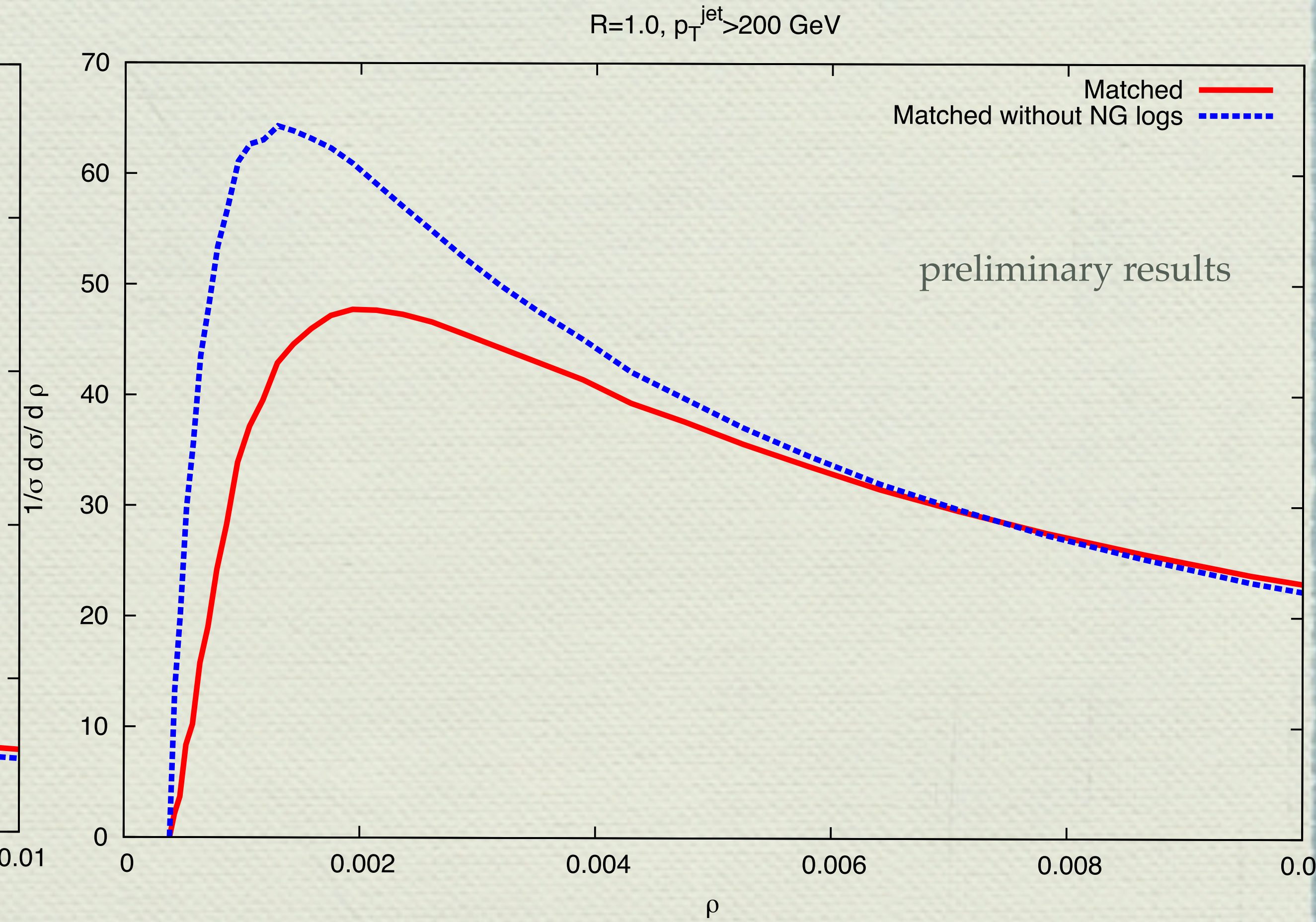
- We perform an (almost) NLL resummation (without the coefficient C_1)
- We match it a fixed-order computation of the mass distribution (at LO)
- A complete pheno study will require C_1 and NLO matching together with a faithful estimate of the perturbative uncertainties



Effect of NG logs

- Non-global logs have a significant impact on the peak of the distribution
- They lower the height of the peak by O(35%), depending on the jet radius



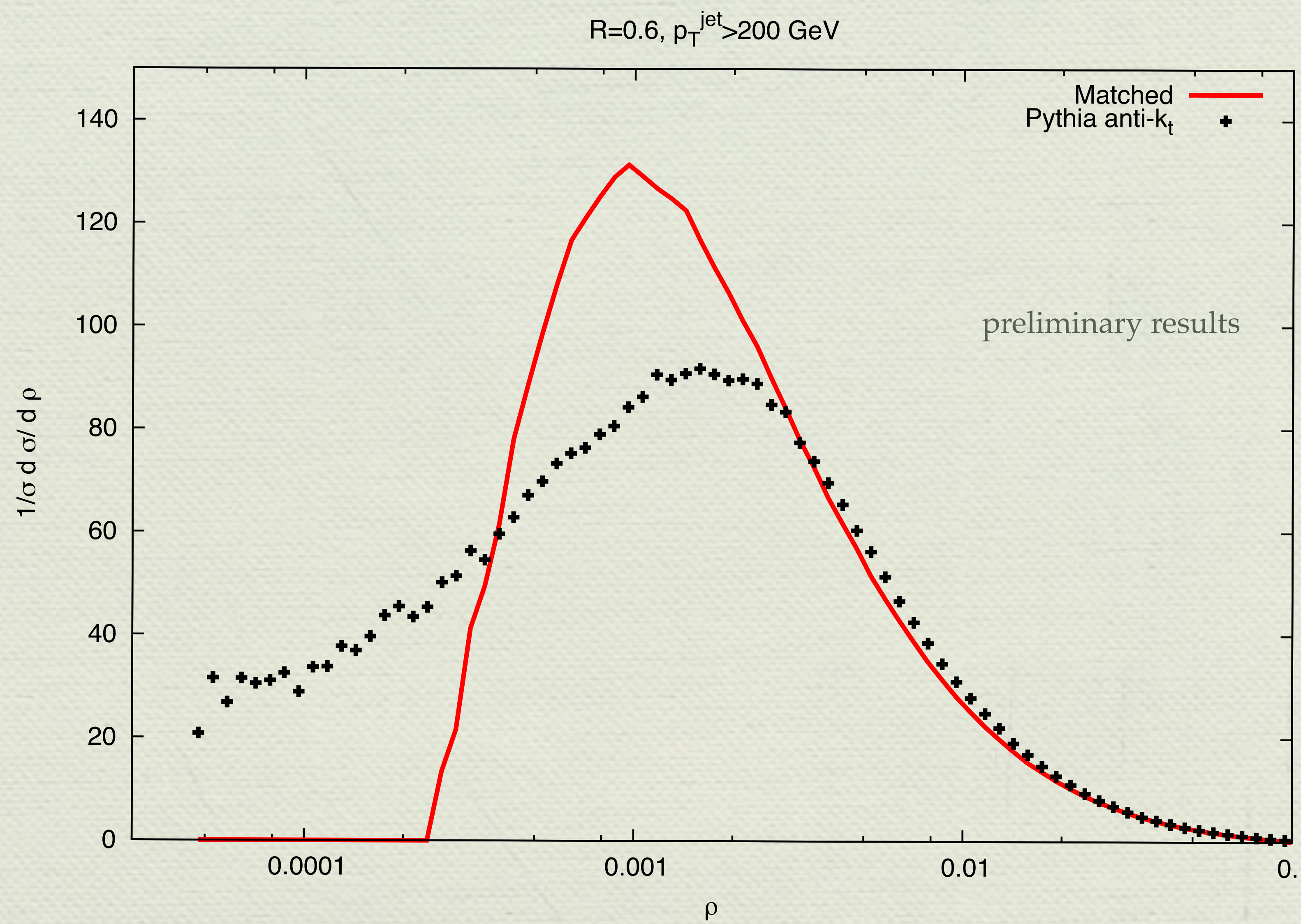


- These effects were not considered in previous studies and by fairly large NP effects were introduced

Hsiang-nan Li, Zhao Li, C.-P. Yuan (2011)

Comparison to MC

- We compare our NLL* + LO result to Pythia8 (shower only)
- Still a difference in the peak height
- Actually the resummation and the shower populate the low mass region quite differently (peak ~ 6 GeV for p_T=200GeV)
- It would be interesting to go to higher p_T and move away from the NP region



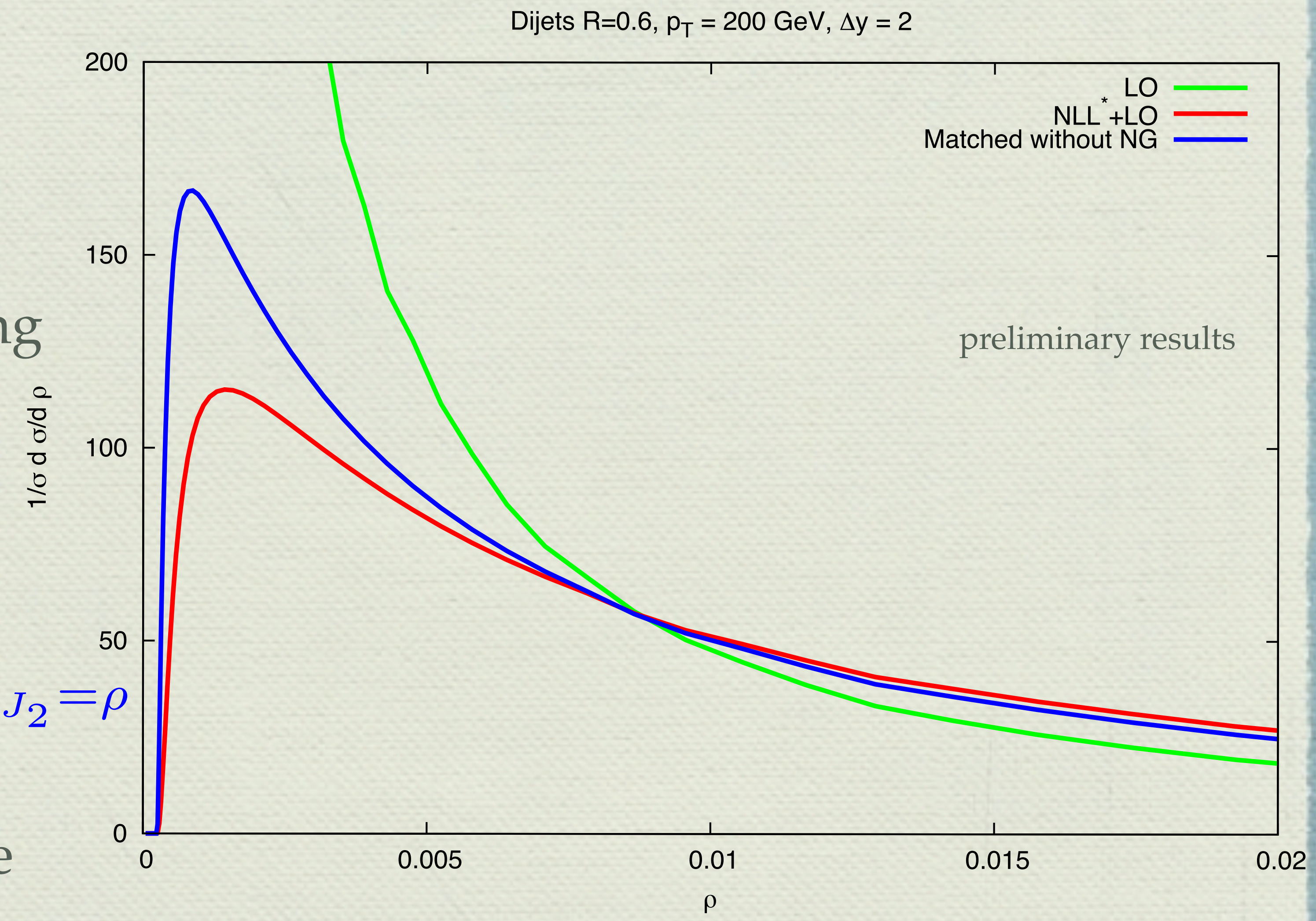
sharp cut-off because of Landau pole

Another example: dijets

- We also study the jet-mass distribution in dijets
- We measure the mass of the leading jets

$$\frac{d\sigma}{d\rho} = \left[\frac{d\sigma}{d\rho_{J_1}} + \frac{d\sigma}{d\rho_{J_2}}\right]_{\rho_{J_1}=\rho_{J_2}=\rho}$$

- More complicated colour structure



Analytic studies of grooming

- We are trying to better understand the discrepancy with MC
- Precise phenomenology will require full NLL+NLO to reduce perturbative uncertainties
- We are using analytic methods to study and compare different grooming techniques (filtering, pruning and trimming)
- This study will shed light on relations and differences between these procedures

Conclusions

- I have presented analytical predictions for jet mass distributions in hadron collisions
- I have discussed on the different effects one should consider to perform a NLL resummation, with particular emphasis on NG logs
- I have applied this formalism to two processes, Z+jet and dijets
- We are comparing our results to standard MC in different kinematical regions