Event shapes and jet rates in hadronic dijet production

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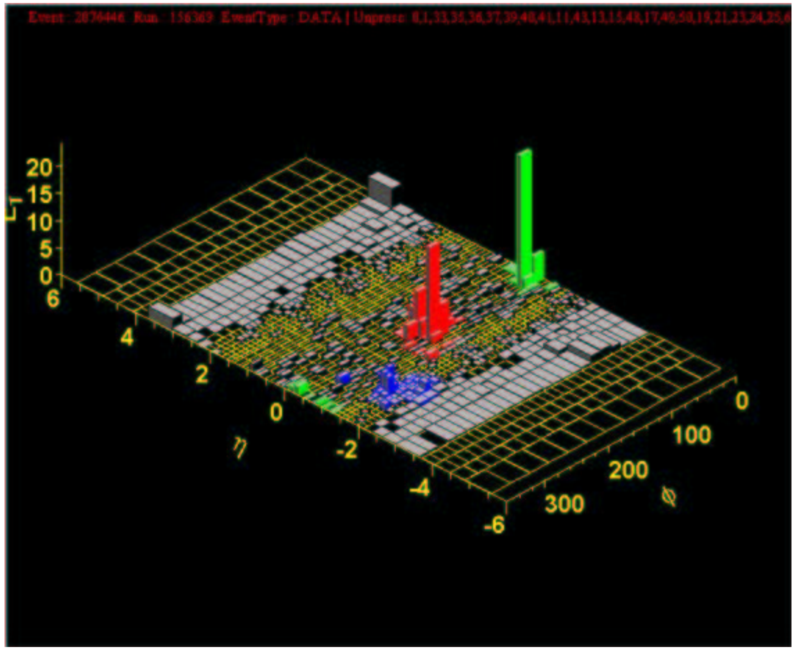

- Physical motivations
- Event shapes in hh collisions
- Master formula for resummation
- First results obtained with CAESAR
- Conclusions and outlook

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Physical motivations

Hadronic collider experiments

- constitute the ideal environment for the search of new physics
- are incredibly rich from the point of view of QCD

In particular jet observables at hadronic colliders

- allow 'traditional' measures of α_s and of colour factors
- require investigation of non-perturbative effects
  ➥ insight into hadronisation mechanism and soft collisions (underlying event)
- test our knowledge of strong interaction dynamics in a very involved environment
- constitute the QCD background for the search of new physics

Event shape variables in hadronic dijet production

Event shape variables (V) describe the geometry of the final state in high energy hadronic processes

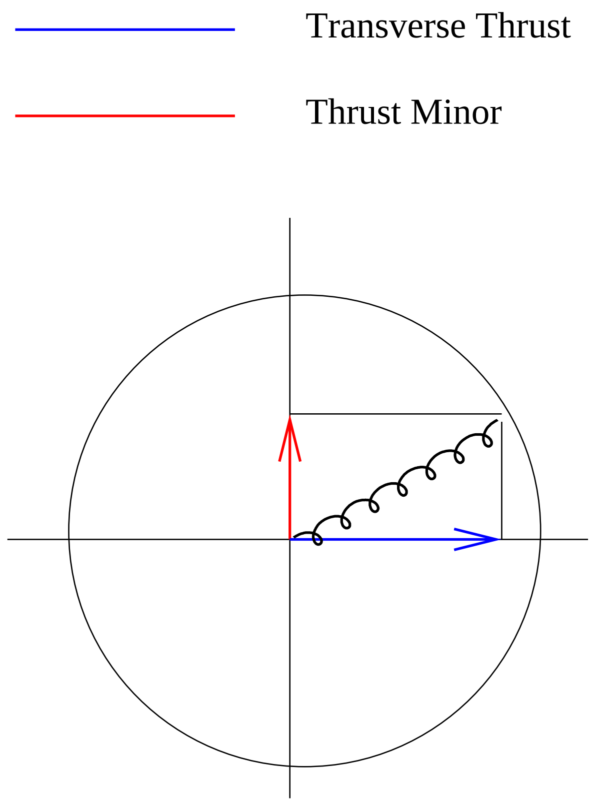
Event shapes in hh collisions can be constructed in analogy with e^+e^- and DIS

Transverse Thrust: particle alignment in the transverse plane

$$T_T \equiv \frac{\max_{\vec{n}_T} \sum_i |\vec{p}_i \cdot \vec{n}_T|}{\sum_i |p_{ti}|}$$

Thrust minor: out of event plane energy flow

$$T_m \equiv \frac{\sum_i |p_i^{\text{out}}|}{\sum_i |p_{ti}|}$$



Transverse plane

Ideal testing ground for an automated resummation

- complicated phase space cuts
- non-trivial flavour and colour structure

➥ analytical resummation cumbersome

Resummation master formula

NLL resummation in the N-jet limit for $\Sigma(v)$ (fraction of events with $V < v$)

[AB, Salam, Zanderighi hep-ph/0304148]

$$V(k) \simeq d_\ell \left(\frac{k_t}{Q}\right)^a e^{-b_\ell \eta} g_\ell(\phi)$$

$$\Downarrow$$

$$\Sigma(v) = \prod_{\ell=1}^{n_{in}} \underbrace{f_\ell(v^{\frac{2}{a+b_\ell}} \mu_F^2)}_{\alpha_s^n L^n} \otimes \prod_{\ell=1}^{N} \underbrace{J_\ell(L, a, b_\ell)}_{\alpha_s^n L^{n+1}} \cdot \underbrace{S\left(T(L/a)\right) \cdot \mathcal{F}(R')}_{\alpha_s^n L^n}$$

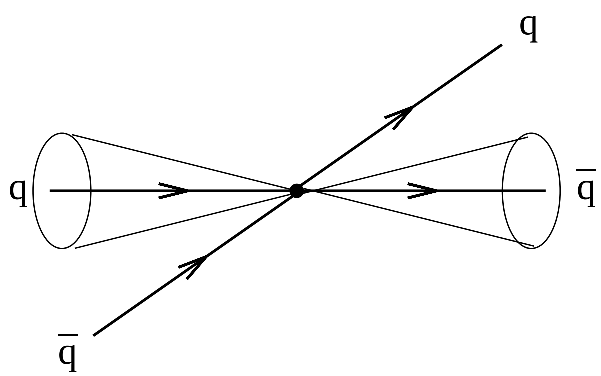
- collinear emissions $\Rightarrow$ LL jet function $J_\ell(L, a, b_\ell)$ with $L \equiv \ln 1/v$
- initial state hard collinear splitting $\Rightarrow$ evolution of the pdf's
- QCD coherence $\Rightarrow$ geometry dependence through the NLL function $S(T)$

  [Botts, Sterman NPB 352 (1989) 62]
- multiple emission effects $V(k_1, \ldots, k_n) \neq V(k_1) \Rightarrow$ NLL function $\mathcal{F}(R')$

Computed automatically by the numerical program CAESAR. The program needs only a routine that computes the observable given a set of four-momenta

Theoretical problems in hadronic collisions

Experiments in hadronic collisions involve necessarily measures only in a part of the phase space, namely one imposes a rapidity cut around the beam



☹ emission in the beam region does not affect the observable
➥ non global logarithms arise, CAESAR stops warning the user that the observable is non-global

Non global logarithms are problematic for two reasons

- non-trivial geometry $\Rightarrow$ only numerical resummation
- complicated colour structure $\Rightarrow$ only large N_c limit

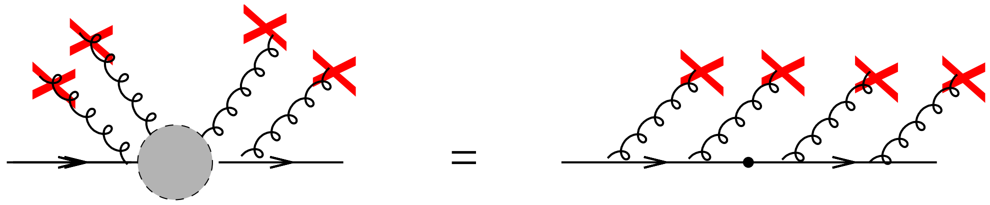
☹ emission in the beam region affects the observable through recoil
➥ CAESAR proceeds but the function $\mathcal{F}(R')$ has divergences for $R' = R'_c$

One needs to introduce observables that are computable at the current accuracy

Independent soft gluon emission

The basic assumption of the master formula is the independent emission picture of soft radiation (QED)

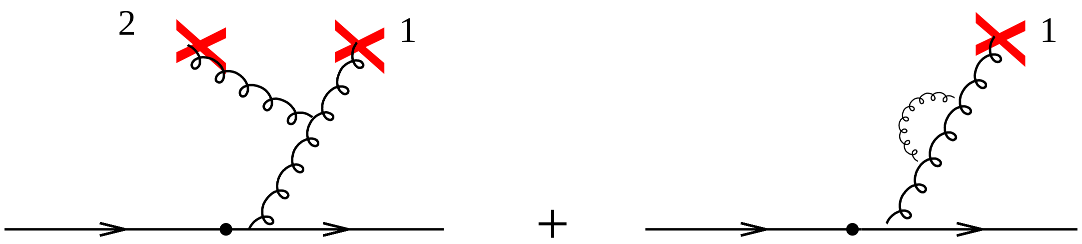
$$w(k_1,\ldots,k_n) = \prod_i w(k_i)$$



The basis of independent emission is that secondary gluon branching can be neglected within NLL accuracy

Consider for instance the Transverse Thrust

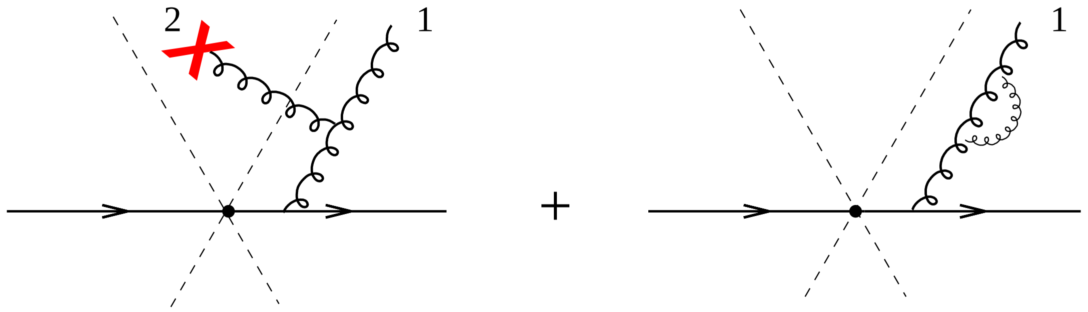
$$\tau \equiv 1 - T_T \simeq \sum_i \omega_i/Q \qquad \text{(large angles)}$$



$$= \alpha_s^2 \int_{\tau Q}^{\tau Q} \frac{d\omega_1}{\omega_1} \int_{\tau Q}^{\omega_1} \frac{d\omega_2}{\omega_2} = \mathcal{O}\left(\alpha_s^2 L\right)$$

Non-global logarithms

In the case of a non-global observable such a real-virtual cancellation does not work any more



$$= \alpha_s^2 \int_{\tau Q}^{Q} \frac{d\omega_1}{\omega_1} \int_{\tau Q}^{\omega_1} \frac{d\omega_2}{\omega_2} = \mathcal{O}\left(\alpha_s^2 L^2\right)$$

SL contributions arise when only the softest gluon is emitted in the measure region

$$\Sigma(\tau) = \underbrace{\Sigma_g(\tau)}_{\text{independent}} \cdot \underbrace{S_{ng}(t)}_{\text{non-global}} \qquad t = \int_{\tau Q}^{Q} \frac{d\omega}{\omega} \alpha_s(\omega)$$

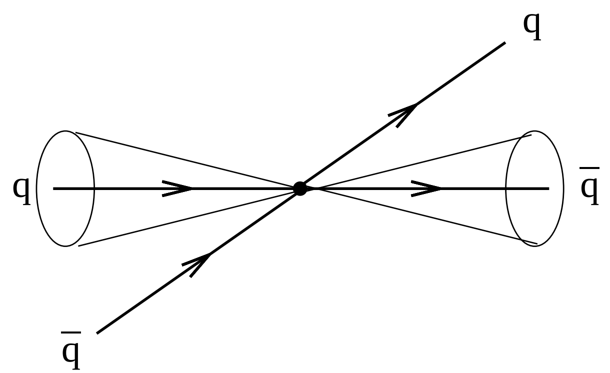
Two main approaches to resum non global logarithms in the large N_c limit

- Monte Carlo simulation [Dasgupta, Salam JHEP 0203(2002)017]
- Non-linear evolution equation [AB, Marchesini, Smye JHEP 0208(2002)006]

Divergences in the function $\mathcal{F}(R')$

Thrust minor as an example

$$T_m = \frac{1}{E_T}\left\{\sum_{|\eta_i|<\Delta} |p_i^{\text{out}}| + \left|\sum_{i\in U} p_i^{\text{out}}\right| + \left|\sum_{i\in D} p_i^{\text{out}}\right|\right\}$$



Consider an emission from the incoming legs: there are two main mechanisms that make the out-of-plane momentum p_{out} small

- Real radiation suppression $\Rightarrow$ probability $\sim p_{\text{out}}^{-R'_{in}}$
- Transverse momentum cancellation $\Rightarrow$ probability $\sim p_{\text{out}}$

Transverse momentum cancellation dominant for $R'_{in} \geq 1 \Rightarrow$ no LL jet function

➥ divergence in the function $\mathcal{F}(R')$ for $R'_{in} = 1$

The intuitive position of the divergence should be taken with care: complications may arise due to kinematics

Directly and indirectly global observables

Directly global observables:

Δ as large as possible

- Transverse thrust

$$T_T = \frac{1}{E_T} \max_{\vec{n}_T} \sum_i |\vec{p}_{ti} \cdot \vec{n}_T|$$

- Thrust minor

$$T_m = \frac{1}{E_T} \sum_i |p_i^{out}|$$

Predictions valid as long as

$|\log v| \lesssim (a + b_\ell)|\Delta|$

Indirectly global observables:

$\Delta = \mathcal{O}(1) \Rightarrow$ recoil term added

- Transverse thrust

$$T_T = \frac{1}{E_{T,\Delta}} \left(\max_{\vec{n}_T} \sum_{|\eta_i|<\Delta} |\vec{p}_{ti} \cdot \vec{n}_T| - \left| \sum_{|\eta_i|<\Delta} \vec{p}_{ti} \right| \right)$$

- Thrust minor

$$T_m = \frac{1}{E_{T,\Delta}} \left(\sum_{|\eta_i|<\Delta} |p_i^{out}| + \left| \sum_{|\eta_i|<\Delta} \vec{p}_{ti} \right| \right)$$

Predictions valid everywhere but

divergence for $R_c' = 2$

Directly global two-jet rate

For Δ large we can define a directly global jet rate

1. One chooses a particular frame (two-jet c.o.m. frame)

$$\sum_i p_{ti}\eta_i = 0$$

2. For each pair of hadrons and for each combination of particle i and beam direction b one defines

$$y_{ij} \equiv \frac{2\min\{E_i^2, E_j^2\}}{E_T^2}(1 - \cos\theta_{ij}) \qquad y_{ib} \equiv \frac{2E_i^2}{E_T^2}(1 - \cos\theta_{ib})$$

3. One finds $y_{\min} = \min\{y_{ij}, y_{ib}\}$ and if $y_{\min} < y_c$ either recombines particles i and j or include particle i in the beam jet

4. If all $\{y_{ij}, y_{ib}\} > y_c$ one stops, otherwise goes back to 2

We study the 3-jet resolution y_{23}, the maximum value of y_c for which the event is clustered as a 3-jet event

This algorithm is the generalisation of the Durham algorithm in DIS in the Breit frame

Other indirectly global observables

- Jet invariant mass: total mass of the U hemisphere and the D hemisphere

$$\rho = \frac{1}{E_T^2}\left[\left(\sum_{i\in U} p_i\right)^2 + \left(\sum_{i\in D} p_i\right)^2\right] + \left|\sum_{|\eta_i|<\Delta} \vec{p}_{ti}\right|$$

- Two-jet rate: one computes $y_{23,\Delta}$ restricted to particles with $|\eta| < \Delta$ and adds the recoil term

$$y_{23} = y_{23,\Delta} + \left|\sum_{|\eta_i|<\Delta} \vec{p}_{ti}\right|^2$$

The two recoil terms have different powers to make the observables continuously global

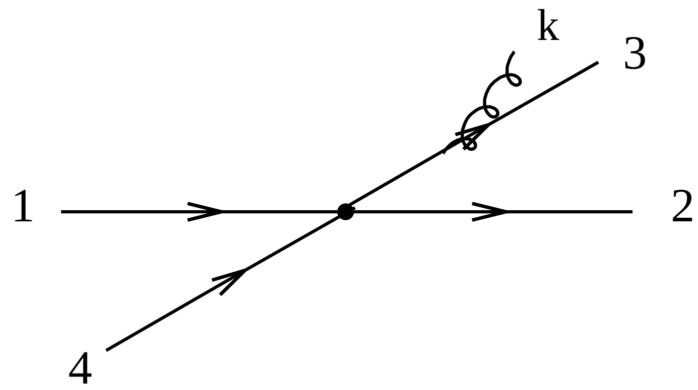
Analysis of the indirectly global thrust minor

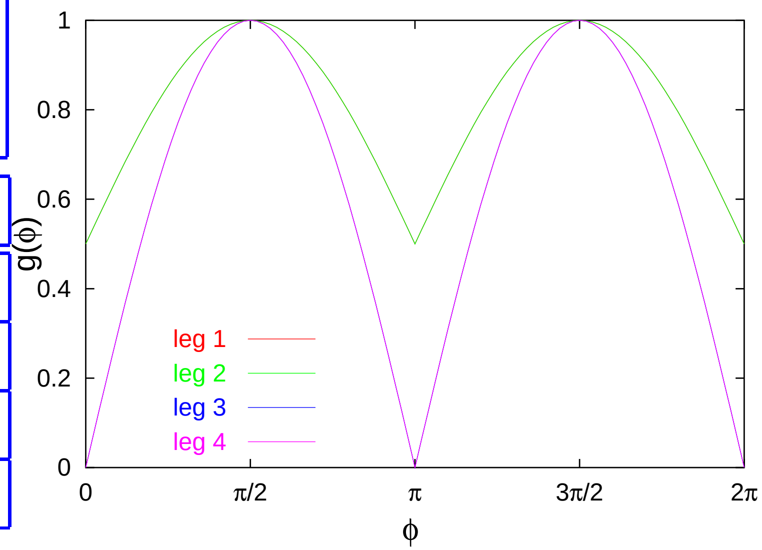
Soft/collinear emission from 2+2 partons at an angle $\cos\theta = 0.2$ in their c.o.m. frame

Tables and plots generated automatically by CAESAR, picture generated by AB

Test	performed	result
check number of jets	YES	T
all legs positive	YES	T
globalness	YES	T
continuously global	YES	T
additivity	YES	F
exponentiation (preliminary)	YES	T
eliminate subleading effects	YES	T
opt. probe region exists	YES	T

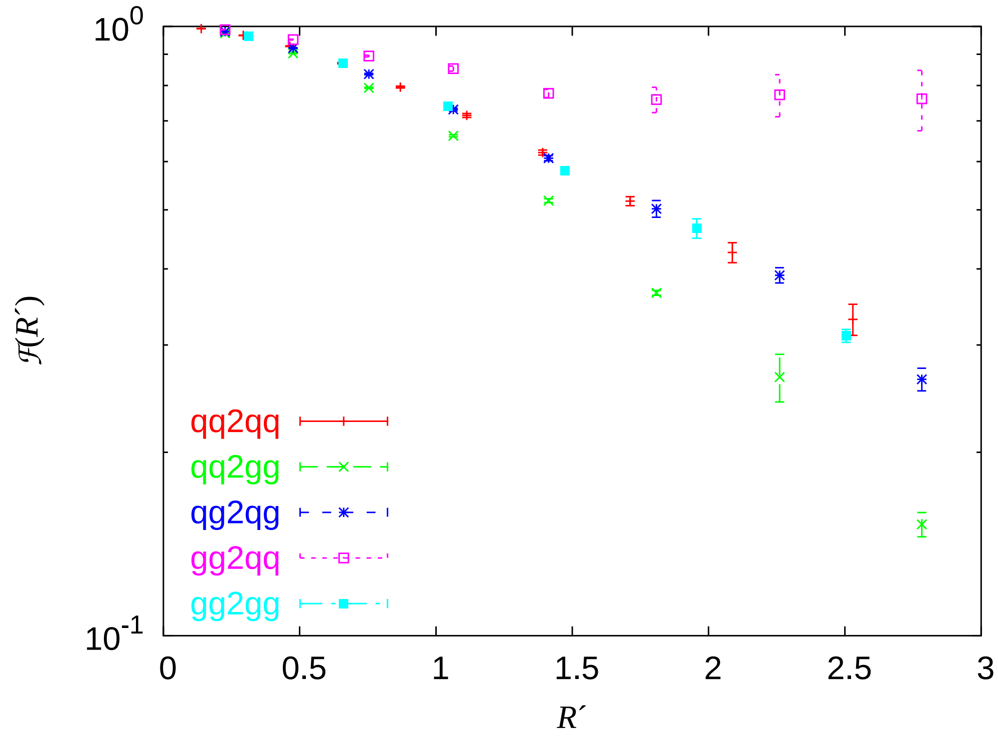
leg ℓ	a_ℓ	b_ℓ	$g_\ell(\phi)$	d_ℓ	$\langle \ln g_\ell(\phi) \rangle$
1	1	0	tabulated	2.04124	-0.22005
2	1	0	tabulated	2.04124	-0.22005
3	1	0	$\|\sin(\phi)\|$	2.04124	$-\ln(2)$
4	1	0	$\|\sin(\phi)\|$	2.04124	$-\ln(2)$

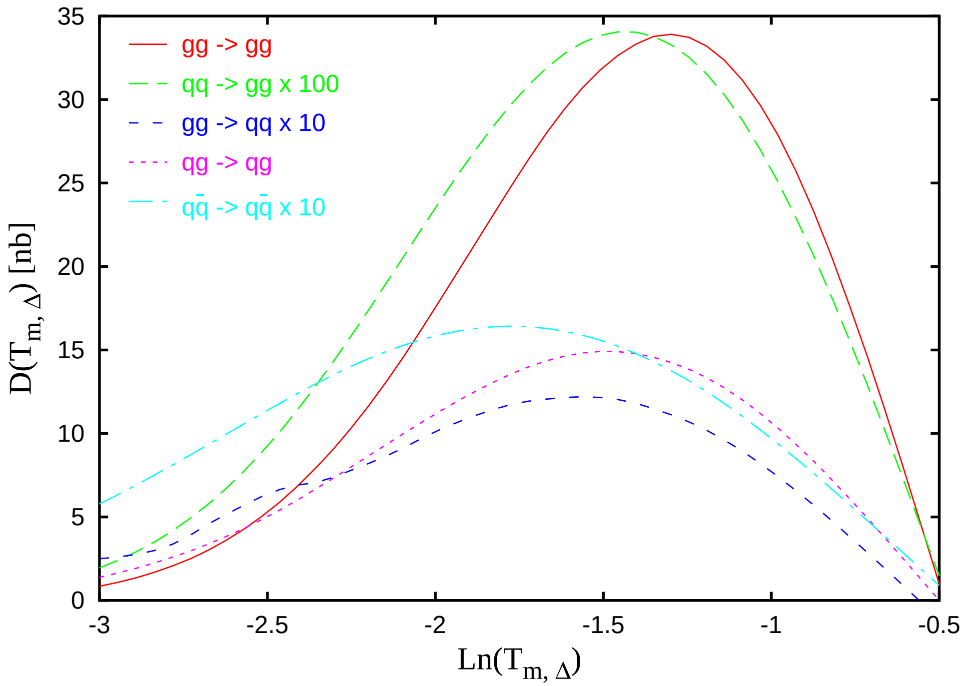




Resummation of the indirectly global thrust minor

Dijet events at Tevatron run II $\sqrt{s} = 1.96\text{TeV}$ with $E_T > 50\text{GeV}$ and $\Delta = 1$





- The divergences in $\mathcal{F}(R')$ occur at the left of the peak
  ➥ NLL resummation still sensible

- Clean separation of the different incoming channels
  ➥ useful information for fits of parton distributions

Only hadronic collisions? Of course not!

y_3 in DIS with 1+1 jets

Test	result
check number of jets	T
all legs positive	T
globalness	T
continuously global	T
additivity	F
exponentiation (preliminary)	T
eliminate subleading effects	F
opt. probe region exists	F

leg ℓ	a_ℓ	b_ℓ	$g_\ell(\phi)$	d_ℓ
1	2	0	1	0.00063
2	2	0	1	0.00063

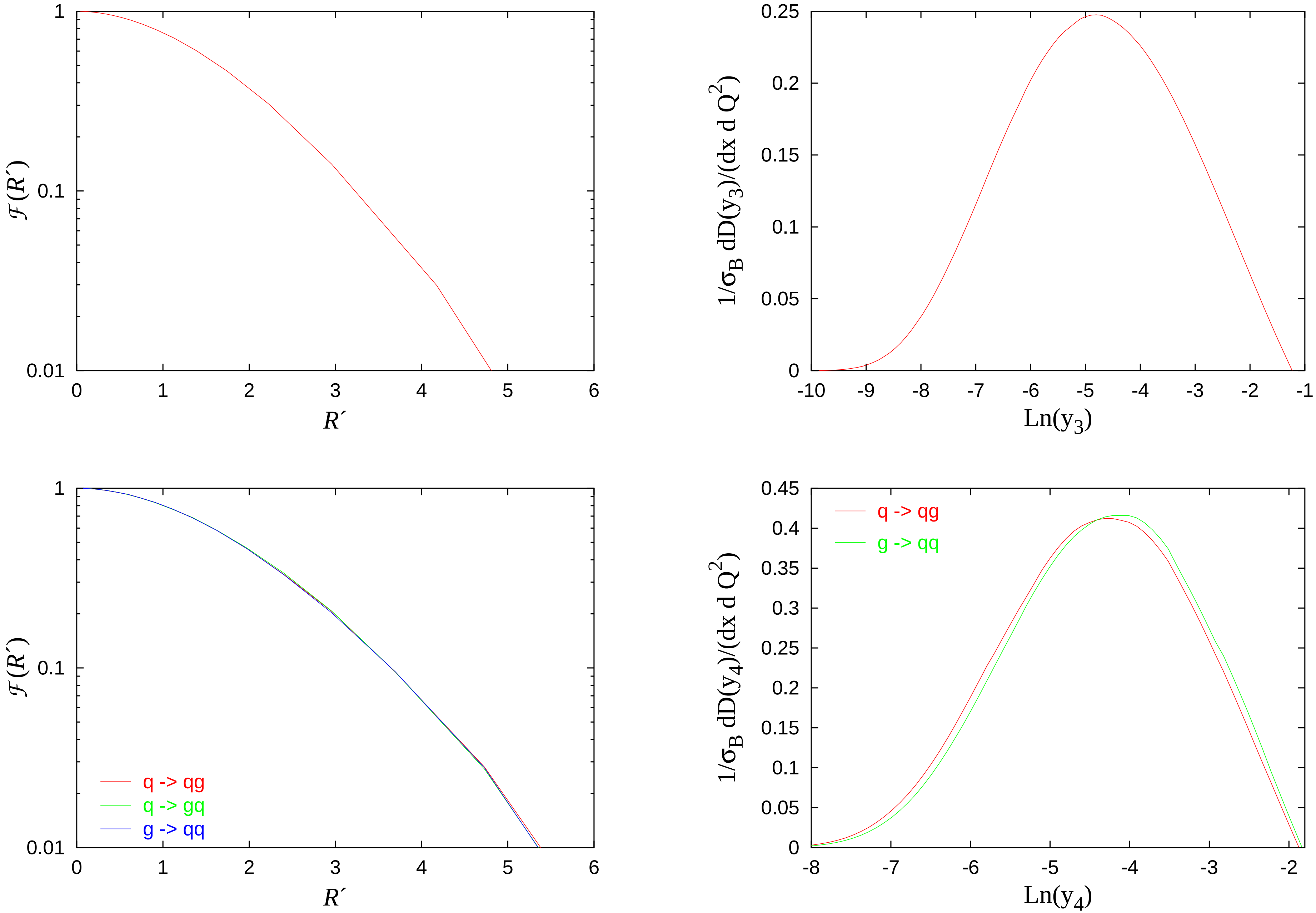
y_4 in DIS with 1+2 jets

Test	result
check number of jets	T
all legs positive	T
globalness	T
continuously global	T
additivity	F
exponentiation (preliminary)	T
eliminate subleading effects	F
opt. probe region exists	F

leg ℓ	a_ℓ	b_ℓ	$g_\ell(\phi)$	d_ℓ
1	2	0	1	0.00063
2	2	0	1	0.00063
3	2	0	1	0.00063

Resummation of jet rates in DIS

DIS jet events at HERA with $Q = 40\text{GeV}$ and $x_B = 0.039$ (dijets with $y_3 > 0.05$)



Conclusions and outlook

- We have a numerical program which fully automates the resummation of 'any'-jet suitable event shape in an arbitrary hard process

- First-ever prediction for event shapes in hh collisions
  - Soft radiation from four emitters, including colour interference
  - Multiple emission effects computed generally
  - Separation of different partonic channels

For the future . . .

- Extension to non-global observables

- Eventually include leading NP corrections (LAPPSE)

- Comparison with experimental data