Generalised resummation of final-state observables

Gavin Salam
LPTHE — Univ. Paris VI & VII and CNRS

work done with Andrea Banfi & Giulia Zanderighi

Manchester University
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Collider QCD

QCD is *the* theory of hadronic physics

Constraining it

- measuring fundamental unknowns (α_s, quark masses)
- measuring quantities which could be predicted if only we had the right theoretical tools (structure functions, fragmentation functions)
- understanding, improving and verifying accuracy of QCD (NNLO, MC+NLO)

$\Downarrow$

providing a reference
(search for 'new physics')

$\Longleftrightarrow$

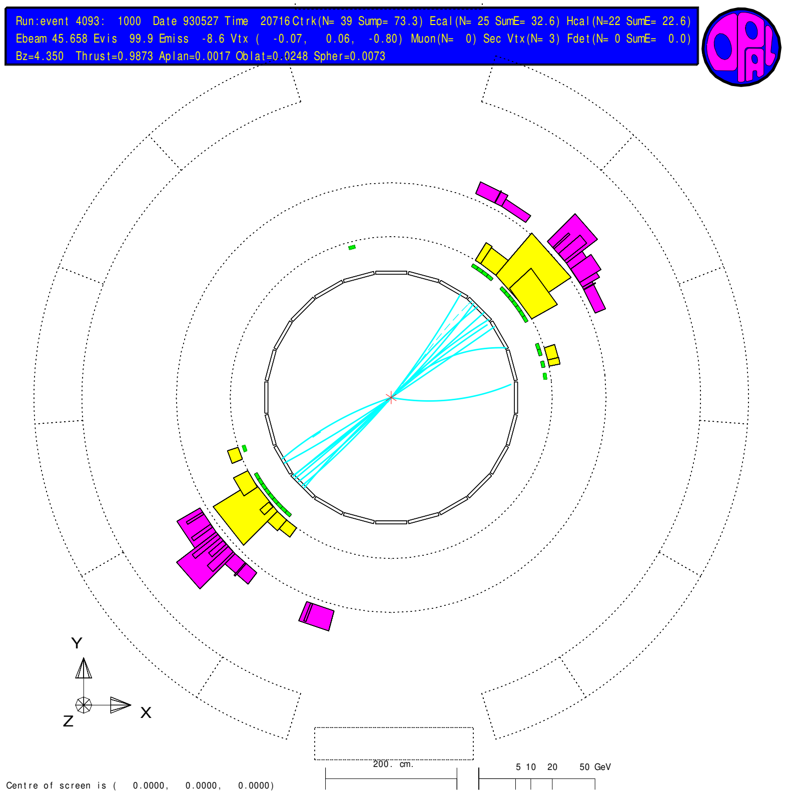
Exploring it

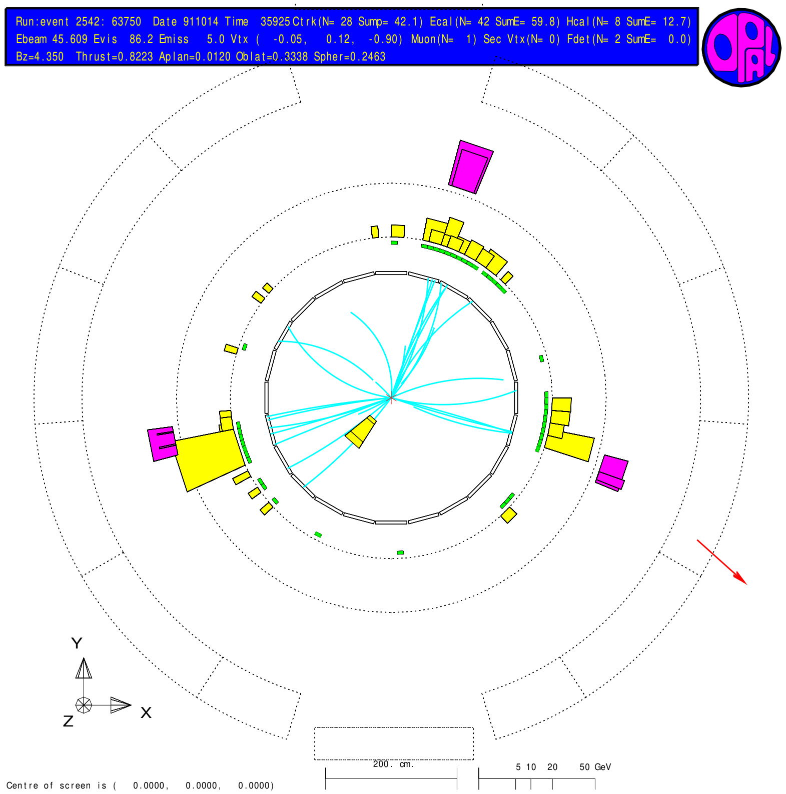
- developing an understanding of non-perturbative phenomena (hadronization, diffraction)
- pushing it to new limits (small-x, saturation)
- new phenomena and phases (instantons, quark-gluon plasma, colour superconductor)

$\Downarrow$

mining the wealth
of QCD

A wealth of information about QCD lies in its final states. Problem is how to extract it.





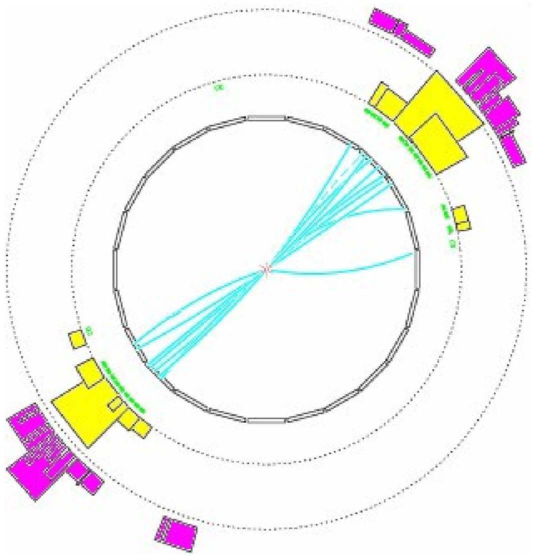
One option is to use a jet-algorithm and *classify* events – 2 jets, 3 jets,. . .

But this does not capture *continuous nature* of variability of events.

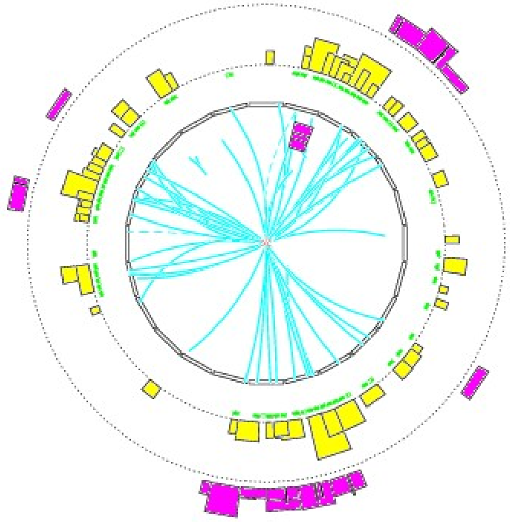
Event Shapes

First discussion goes back to 1964. Serious work got going in late '70s. Various proposals to measure *shape* of events. Most famous example is Thrust:

$$T = \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_i . \vec{n}_T|}{\sum_i |\vec{p}_i|},$$



2-jet event: $T \simeq 1$



3-jet event: $T \simeq 2/3$

There exist many other measures of aspects of the shape: Thrust-Major, C-parameter, broadening, heavy-jet mass, jet-resolution parameters,. . .

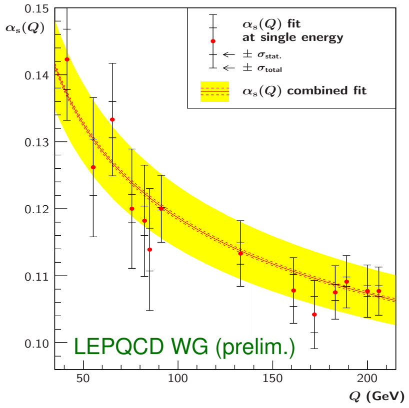
Event shapes (cont.)

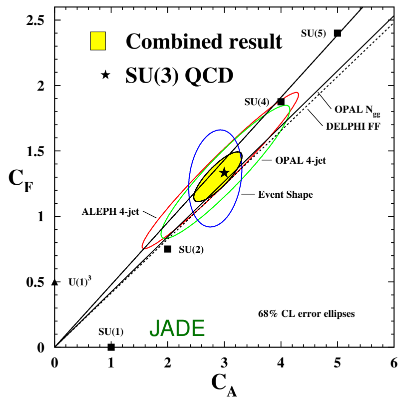
Event shapes are a good compromise between

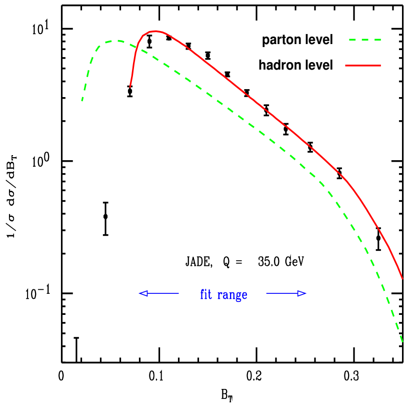
- simplicity (it is feasible to make theoretical predictions about them)
- sensitivity to properties of QCD

Provide a wealth of information, e.g.:

- Measurements of the coupling α_s and its renormalization group running
- Measurements/cross checks of the values of the colour factors of QCD
- Studies of connection between parton-level (QCD calculations of quarks and gluons) and (the real) hadron-level







Perturbative QCD ingredients for study of event-shapes

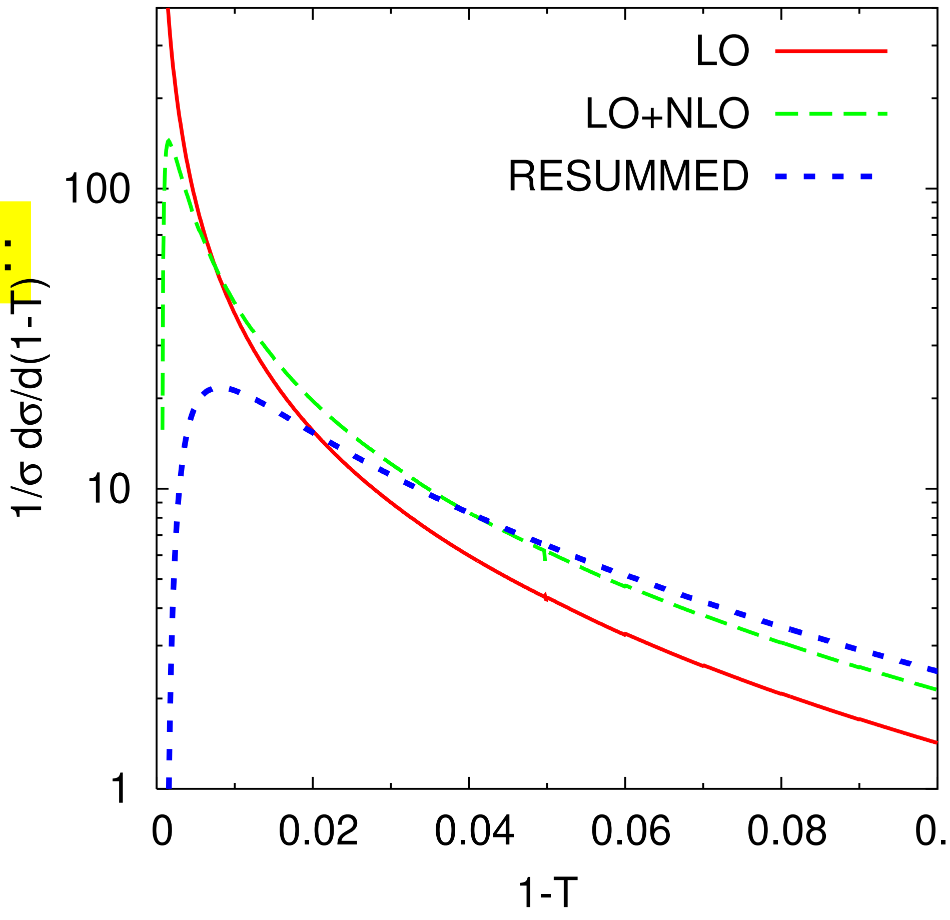
At the base of all these studies lie perturbative predictions for the distribution of the event shape.

Leading order (LO) $\equiv \mathcal{O}(\alpha_s)$:

- By hand or numerically

Next-to-Leading order (NLO) $\equiv \mathcal{O}(\alpha_s^2)$:

- Usually only done numerically.
  EERAD, Event, Event2



LO, NLO, ... all *diverge* in two-jet region, *i.e.* for $1 - T \to 0$.

Subject of this seminar is

FINAL-STATE RESUMMATION

i.e. techniques for an *all-orders* understanding of what happens in this "exclusive" 2-jet limit.

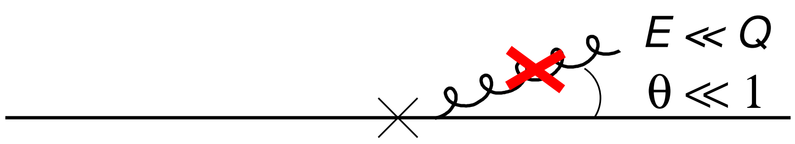
Large Logarithms

Going to the 2-jet limit $\equiv$ forbidding gluon radiation.

This has an *unequal effect* on real and virtual contributions to Feynman diagrams:

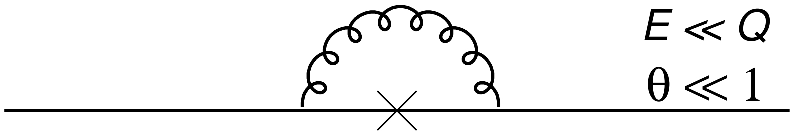
- hard emissions forbidden (no 3-jet like configurations)
- *soft and collinear* real emissions are almost all forbidden

$$\cancel{\frac{dE}{E}\frac{d\theta}{\theta}\alpha_s(\theta E)}$$



- virtual corrections are unaffected

$$-\frac{dE}{E}\frac{d\theta}{\theta}\alpha_s(\theta E)$$



Imbalance leads to large logarithms in distribution of event shape:

$$\boxed{\mathrm{Prob}(1 - T < \tau) \simeq 1 - \frac{\alpha_s C_F}{2\pi} \ln^2 \tau + \ldots} \qquad (\tau \ll 1)$$

Large Logarithms at all orders

There is a soft and a collinear divergence ($\mapsto$ logs) for each emitted gluon.

At all orders, probability of event being two-jet like is has *divergent perturbation series:*

$$P(1 - T < \tau) \equiv \Sigma(\tau) = 1 + \sum_{n=1} R_{n,2n}\, \alpha_s^n \ln^{2n} \tau + \dots$$

Resummation involves determining the whole set of dominant terms (and summing them).

Today's state of the art involves *exponentiation* and resummation of *Leading Logs* (LL) and *Next-to-Leading Logs* (NLL):

$$\Sigma(\tau) \simeq \exp\left[\sum_{n=1} \Big(\underbrace{G_{n,n+1}\, \alpha_s^n \ln^{n+1} \tau}_{\text{LL}} + \underbrace{G_{n,n}\, \alpha_s^n \ln^{n} \tau}_{\text{NLL}} + \cdots \Big)\right]$$

NB: $\alpha_s^n \ln^{2n} \tau$ in Σ, but only $\alpha_s^n \ln^{n+1} \tau$ in exponent.

Basics of resummation: factorization

First half of story:

In most resummations, phase-space & matrix-element for multiple (soft, collinear) gluon emission can be *factorized* into *independent gluon emission:*

$$\sum_{n=0}^{\infty} \frac{1}{n!} \prod_{i=1}^{n} \frac{d\theta_i}{\theta_i} \frac{dE_i}{E_i} \alpha_{\mathsf{s}}(E_i \theta_i) \quad + \quad \text{virtual corrections}$$

Second half of story:

Analyse the observable:

$$1 - T \simeq \frac{1}{Q} \sum_{i=1}^{n} \frac{E_i \theta_i^2}{2}$$

Factorize the observable:

$$\Theta(1 - T < \tau) = \int \frac{d\nu}{2\pi i \nu} e^{\nu\tau} \prod_{i=1}^{n} e^{-\nu \frac{E_i \theta_i^2}{2Q}}$$

ANSWER:

$$\boxed{\Sigma(\tau) = \int \frac{d\nu}{2\pi i \nu} e^{\nu\tau} \exp\left[\int \frac{d\theta}{\theta} \frac{dE}{E} \alpha_{\mathsf{s}}(E\theta) \left(e^{-\nu \frac{E_i \theta_i^2}{2Q}} - 1\right)\right]}$$

So simple? A good thing referees haven't caught on. . .

$e^+e^- \longrightarrow$ 2 jets

S. Catani, G. Turnock, B. R. Webber and L. Trentadue, *Thrust distribution in e^+e^- annihilation,* Phys. Lett. B **263** (1991) 491.

S. Catani, G. Turnock and B. R. Webber, *Heavy jet mass distribution in e^+e^- annihilation,* Phys. Lett. B **272** (1991) 368.

S. Catani, Yu. L. Dokshitzer, M. Olsson, G. Turnock and B. R. Webber, *New clustering algorithm for multi-jet cross-sections in e^+e^- annihilation,* Phys. Lett. B **269** (1991) 432.

S. Catani, L. Trentadue, G. Turnock and B. R. Webber, *Resummation of large logarithms in e^+e^- event shape distributions,* Nucl. Phys. B **407** (1993) 3.

S. Catani, G. Turnock and B. R. Webber, *Jet broadening measures in e^+e^- annihilation,* Phys. Lett. B **295** (1992) 269.

G. Dissertori and M. Schmelling, *An Improved theoretical prediction for the two jet rate in e^+e^- annihilation,* Phys. Lett. B **361** (1995) 167.

Y. L. Dokshitzer, A. Lucenti, G. Marchesini and GPS, *On the QCD analysis of jet broadening,* JHEP **9801** (1998) 011

S. Catani and B. R. Webber, *Resummed C-parameter distribution in e^+e^- annihilation,* Phys. Lett. B **427** (1998) 377

S. J. Burby and E. W. Glover, *Resumming the light hemisphere mass and narrow jet broadening distributions in e^+e^- annihilation,* JHEP **0104** (2001) 029

M. Dasgupta and GPS, *Resummation of non-global QCD observables,* Phys. Lett. B **512** (2001) 323

C. F. Berger, T. Kucs and G. Sterman, *Event shape / energy flow correlations,* Phys. Rev. D **68** (2003) 014012

DIS 1+1 jet

V. Antonelli, M. Dasgupta and GPS, *Resummation of thrust distributions in DIS,* JHEP **0002** (2000) 001

M. Dasgupta and GPS, *Resummation of the jet broadening in DIS,* Eur. Phys. J. C **24** (2002) 213

M. Dasgupta and GPS, *Resummed event-shape variables in DIS,* JHEP **0208** (2002) 032

e^+e^-, DY, DIS 3 jets

A. Banfi, G. Marchesini, Y. L. Dokshitzer and G. Zanderighi, *QCD analysis of near-to-planar 3-jet events,* JHEP **0007** (2000) 002

A. Banfi, Y. L. Dokshitzer, G. Marchesini and G. Zanderighi, *Near-to-planar 3-jet events in and beyond QCD perturbation theory,* Phys. Lett. B **508** (2001) 269

A. Banfi, Y. L. Dokshitzer, G. Marchesini and G. Zanderighi, *QCD analysis of D-parameter in near-to-planar three-jet events,* JHEP **0105** (2001) 040

A. Banfi, G. Marchesini, G. Smye and G. Zanderighi, *Out-of-plane QCD radiation in hadronic Z0 production,* JHEP **0108** (2001) 047

A. Banfi, G. Marchesini, G. Smye and G. Zanderighi, *Out-of-plane QCD radiation in DIS with high p(t) jets,* JHEP **0111** (2001) 066

A. Banfi, G. Marchesini and G. Smye, *Azimuthal correlation in DIS,* JHEP **0204** (2002) 024

Average: 1 observable per article

Why is it not so simple?

- Matrix-element is not quite as simple as was written (hard gluons, large-angle gluons, gluon splitting, ...)
- Observable analysis requires care
- Observable factorization can be quite non trivial, *e.g.* jet broadening:

$$B_T \simeq \frac{1}{2Q}\left(\sum_i |\vec{k}_{ti}| + \left|\sum_i \vec{k}_{ti}\Theta(k_{zi})\right| + \left|\sum_i \vec{k}_{ti}\Theta(-k_{zi})\right|\right)$$

  or impossible (*e.g.* thrust major).
- Doing all the integrals at the end can be scary (3-jet limit of thrust minor involves 5 integral transforms)
- There are observables for which the *matrix-element* may not be factorized (non-global observables) or which do not exponentiate (JADE jet resolution)
- Phenomenology, combining NLL & NLO, is technically quite involved

Help wanted

Typical life-cycle of a resummer:

- Writes a paper to learn the methods
- Takes advantage of the expertise learnt to write another couple of 'easy' papers
- Gets bored and goes off to do other things

It's a very error-prone business

On earlier page of resummation articles, *only three authors* can say that all their final resummed results were correct to the accuracy claimed.

But there are many phenomenological applications

Would like some way of *automating the job*

Possible approaches (1)

- It's an analytical calculation: how about getting a *symbolic manipulation program* to do it (just as is done on Feynman graphs)?

  Problem is getting Mathematica/Maple/. . . to make sense of observable definition

  $$T = \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_i . \vec{n}_T|}{\sum_i |\vec{p}_i|} \Longrightarrow 1 - \frac{1}{Q} \sum_{i=1}^{n} \frac{E_i \theta_i^2}{2} \,,$$

  and then to find a way of factorizing it

  $$\Theta(1 - T < \tau) = \int \frac{d\nu}{2\pi i \nu} e^{\nu\tau} \prod_{i=1}^{n} e^{-\nu \frac{E_i \theta_i^2}{2Q}}$$

  Latter step may not even be possible. Resulting integrals may be difficult to evaluate.

- At best Mathematica/. . . would have to be extensively guided through the problem.

Possible approaches (2)

- Monte Carlo event generators (*e.g.* Herwig) already embody many resummation ingredients (parton showering).
- <u>But</u> difficult to get 'clean' answer:
  - 'resummation' part is mixed up with much other physics (*e.g.* non-perturbative cutoffs)
  - Uncertainties are hard to gauge (*e.g.* renormalization scale)
  - Matching with 3-jets at NLO is beyond state of the art
  - Impossible to get analytical form for the answer
- Could imagine a pared-down Monte Carlo, with just the basics needed for resummation (+ any extras to get it right at NLL)

> But, how can we be sure that physics ingredients are the right ones for the observable in question? Different degrees of sophistication are needed for different observables.

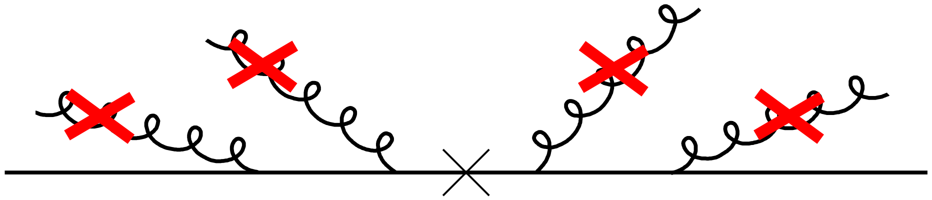
This is a *fundamental problem* of any approach that just averages the observable's value over many configurations.

Global v. Non-Global observables?

<u>Global observable:</u>

e.g. total e^+e^- Broadening, B

making $B \ll 1$ restricts emissions everywhere:



Coherence + globalness:

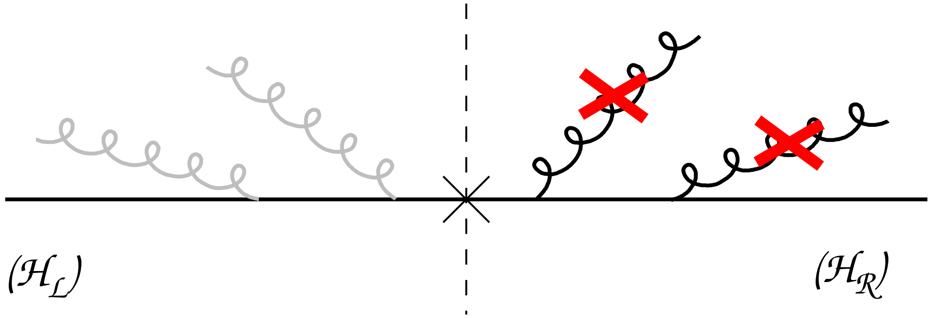
➥ emissions can be resummed as if they were independent *(proved)*

Answers guaranteed to NLL accuracy

<u>NG observable:</u>

Right-hemisphere Broadening, B_R

making $B_R \ll 1$ restricts emissions in right-hand hemisphere ($\mathcal{H}_\mathcal{R}$):



Tempting to *assume* one can:

- ignore left hemisphere ($\mathcal{H}_\mathcal{L}$)
- use independent emission approximation in $\mathcal{H}_\mathcal{R}$.

THIS IS WRONG AT NLL ACCURACY

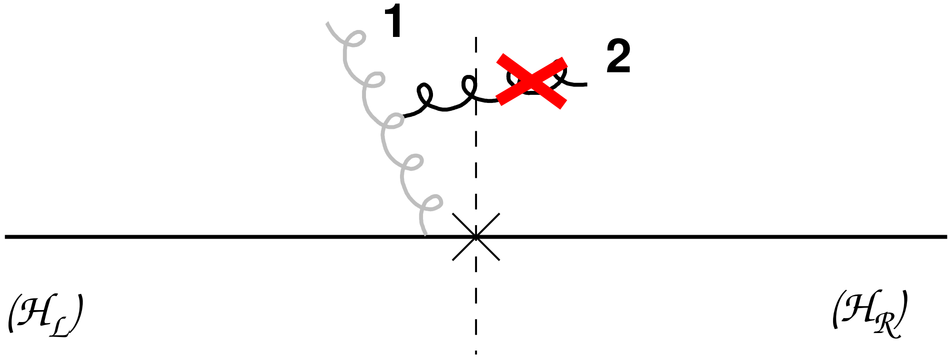
Dasgupta & GPS ’01

Extra ingredient for NG observables

Order α_s^2:

suppress energy-ordered large-angle secondary emissions:

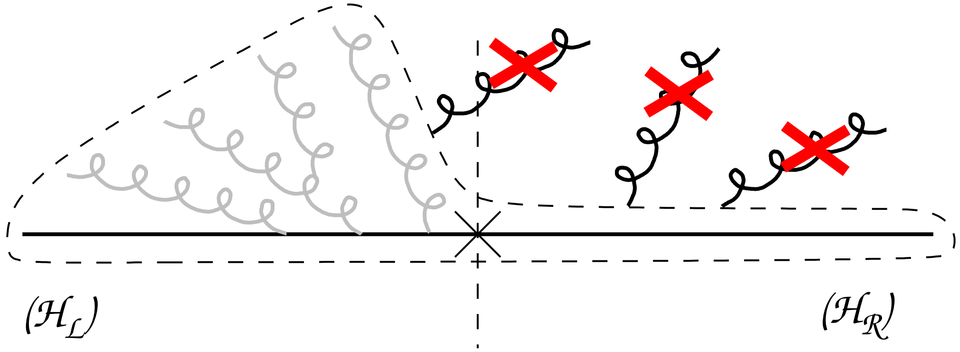
$$Q \gg E_1 \gg E_2 \gg B_R Q$$



➥ $\alpha_s^2 \ln^2 B_R$

All-orders:

Forbid coherent radiation from energy-ordered ensembles of large-angle gluons



➥ $\alpha_s^n \ln^n B_R$

Non-global observables need a much more sophisticated resummation treatment than global ones. . .

Exponentiation

Some observables have exponentiating double logs, others do not, *e.g.* Jade-algorithm jet rates:

$$P_{\text{Jade 2-jet}}(y_{cut}) = 1 - \frac{\alpha_{\mathsf{s}} C_F}{\pi} \ln^2 y_{cut} + \frac{1}{2!} \left(\frac{\alpha_{\mathsf{s}} C_F}{\pi} \ln^2 y_{cut} \right)^2 \cdot \frac{5}{6} + \cdots$$

Brown & Stirling 1990

No one knows how to resum Leading Logs for Jade jet rates, let alone what 'matrix-element ingredients' are needed to get NLL accuracy.

Any automated approach to NLL resummation had better be able to establish whether an observable exponentiates.

Physical basis of exponentiation

Consider first a single emission, 1:

A condition on observable, *e.g.* $1 - T < \tau$, translates to some restriction on the emission, $E_1\theta_1^2/2 < \tau$.

Now suppose we have many emissions $1 \dots n$:

The condition on the observable should translate, approximately, to a similar restriction on each and every emission, $\forall_i : E_i\theta_i^2/2 \lesssim \tau$.

Formal requirement for exponentiation of Leading Logs:

recursive infrared and collinear safety

Recursive infrared and collinear (IRC) safety

Define $k_i(\lambda)$ to be an emission (inserted into Born event) which is made soft and/or collinear as $\lambda \to 0$, such that $V(k_i(\lambda)) = \lambda$.

Normal IRC safety tells us that

$$\lim_{\epsilon \to 0} V\left[k_1(\lambda_1), \ldots, k_n(\lambda_n), k_{n+1}(\epsilon\lambda_{n+1})\right] = V\left[k_1(\lambda_1), \ldots, k_n(\lambda_n)\right]$$

Recursive IRC safety adds two extra conditions

$$\lim_{\epsilon' \to 0} \frac{1}{\epsilon'} V\left[k_1(\epsilon'\lambda_1), \ldots, k_n(\epsilon'\lambda_n)\right] = \text{constant (not } 0\text{)}$$

$$\lim_{\epsilon \to 0} \lim_{\epsilon' \to 0} \frac{1}{\epsilon'} V\left[k_1(\epsilon'\lambda_1), \ldots, k_n(\epsilon'\lambda_n), k_{n+1}(\epsilon'\epsilon\lambda_{n+1})\right] = \text{same const.}$$

Schematically: addition of a relatively softer or more collinear emission (strictly: smaller $V(k)$) should not change value of observable, no matter how soft/collinear the other emissions are.

Examples of non rIRC safe observables

- JADE jet rates / jet-resolution parameters
- Certain combinations of rIRC observables
  - $B_T(1-T)$
  - $C^3/y_{23,Durham}$
  - $\ldots$

So how does one automate resummation?

Proposal for resummation is based in large part on *automated numerical analysis* of observable, provided in the form of a computer subroutine.

- For each leg ℓ, probe observable with a single emission, k, collinear to leg ℓ and soft. Specify k by its transverse mom. k_t, rapidity η and azimuth ϕ. Verify that functional dependence on momentum is of form

$$V(k) = d_\ell \left(\frac{k_t}{Q}\right)^{a_\ell} e^{-b_\ell \eta} g_\ell(\phi)\,.$$

  and determine coefficients d_ℓ, a_ℓ and b_ℓ and function $g_\ell(\phi)$. Make sure it's (continuously) global, $a_1 = a_2 = \ldots = a_n$ (for n hard 'legs').
- Use ensembles of soft and collinear emissions to test properties such as rIRC safety.
- Do it all in multiple precision so as to be able to safely take limits.

Used Bailey's MPFUN90 package

This is enough for Leading Logs and most NLL terms

So how does one automate resummation? (cont.)

Given coefficients from previous page, *answer is almost entirely analytical:*

$$\ln \Sigma(v) = -\sum_{\ell=1}^{n} C_\ell \left[r_\ell(v) + r'_\ell(v) \left(\ln \bar{d}_\ell - b_\ell \ln \frac{2E_\ell}{Q} \right) \right.$$
$$\left. + B_\ell \, T\left(\frac{\ln 1/v}{a + b_\ell} \right) \right] + \sum_{\ell=1}^{n_i} \ln \frac{f_\ell(x_\ell, v^{\frac{2}{a+b_\ell}} \mu_f^2)}{f_\ell(x_\ell, \mu_f^2)}$$
$$+ \ln S\left(T\left(\frac{\ln 1/v}{a} \right) \right) + \ln \mathcal{F}(C_1 r'_1, \ldots, C_n r'_n) \,,$$

$C_\ell =$ colour factor (C_F or C_A), $\qquad f_\ell(x_\ell, \mu_f^2) =$ parton distributions

$r_\ell(L) = \int_{v^{\frac{2}{a}} Q^2}^{v^{\frac{2}{a+b_\ell}} Q^2} \frac{dk_t^2}{k_t^2} \frac{\alpha_s(k_t)}{\pi} \ln \left(\frac{k_t}{v^{1/a} Q} \right)^{a/b_\ell} + \int_{v^{\frac{2}{a+b_\ell}} Q^2}^{Q^2} \frac{dk_t^2}{k_t^2} \frac{\alpha_s(k_t)}{\pi} \ln \frac{Q}{k_t} \,,$

$S(T(\frac{1}{a} \ln 1/v)) =$ large-angle logarithms (process dependence)

...

Remaining non-trivial piece: $\mathcal{F}(\ldots)$

Formula from previous page contains one non-trivial, purely NLL piece:

$$\mathcal{F}(C_1 r'_1, \ldots, C_n r'_n)$$

This encodes the information on how, precisely, the observable depends on multiple emissions, *e.g.*

- $V(k_1, k_2, \ldots k_m) = \max\{V(k_1), V(k_1), \ldots, V(k_m)\}$

  $$\Rightarrow \mathcal{F}(C_1 r'_1, \ldots, C_n r'_n) = 1$$

- $V(k_1, k_2, \ldots k_m) = V(k_1) + V(k_2) + \cdots + V(k_m)$

  $$\Rightarrow \mathcal{F}(C_1 r'_1, \ldots, C_n r'_n) = \frac{e^{-\gamma_E R'}}{\Gamma(1+R')}$$

  $$R' = C_1 r'_1 + \cdots + C_n r'_n$$

- In general, use a Monte Carlo event sample *targeted to observable*

$$\mathcal{F}(C_1 r'_1, \ldots, C_n r'_n) = \left\langle \exp\left\{ -R' \ln \frac{V(k_1, \ldots, k_m)}{\max\{V(k_1), \ldots, V(k_m)\}} \right\} \right\rangle$$

(Divergent for non rIRC observables)

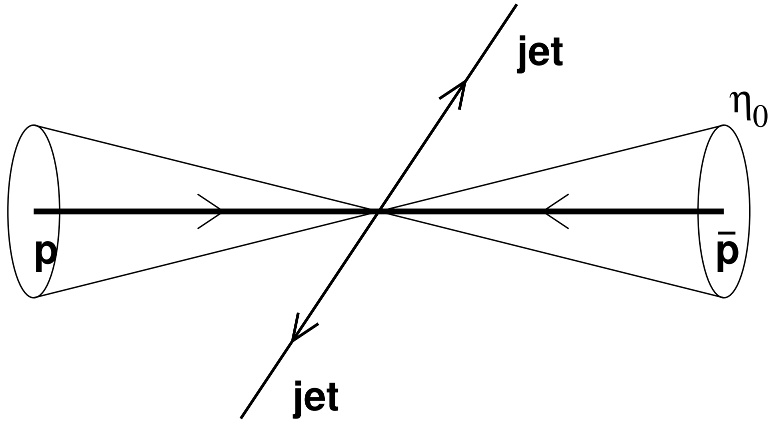
Putting it together: CAESAR

Computer Automated Expert Semi-Analytical Resummation

- Currently limited to global observables
- Tested against all known global, exponentiable event-shape resummations.
- Results from early version (numsum, partially manual) are being used by the LEP experiments for the Durham two-jet rate in e^+e^-.
- Can be applied to a range of new observables in the following processes
  - 2 & 3 jets in e^+e^-
  - $1+1$ and $2+1$ jets in DIS
  - Drell-Yan + jet
  - hadron-hadron dijet production

Observables in hadronic dijet production

Cut around the beam $|\eta| < \eta_0$
➥ Problems with globalness



Directly global observables: $\eta_0 \gg 1$

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
$\log 1/v < (a + b_\ell)|\eta_0|$

Indirectly global observables: $\eta_0 = \mathcal{O}(1)$

Transverse thrust

$$T_T = \frac{1}{E_{T,\eta_0}} \left(\max_{\vec{n}_T} \sum_{|\eta_i|<\eta_0} |\vec{p}_{ti} \cdot \vec{n}_T| - \Big| \sum_{|\eta_i|<\eta_0} \vec{p}_{ti} \Big| \right)$$

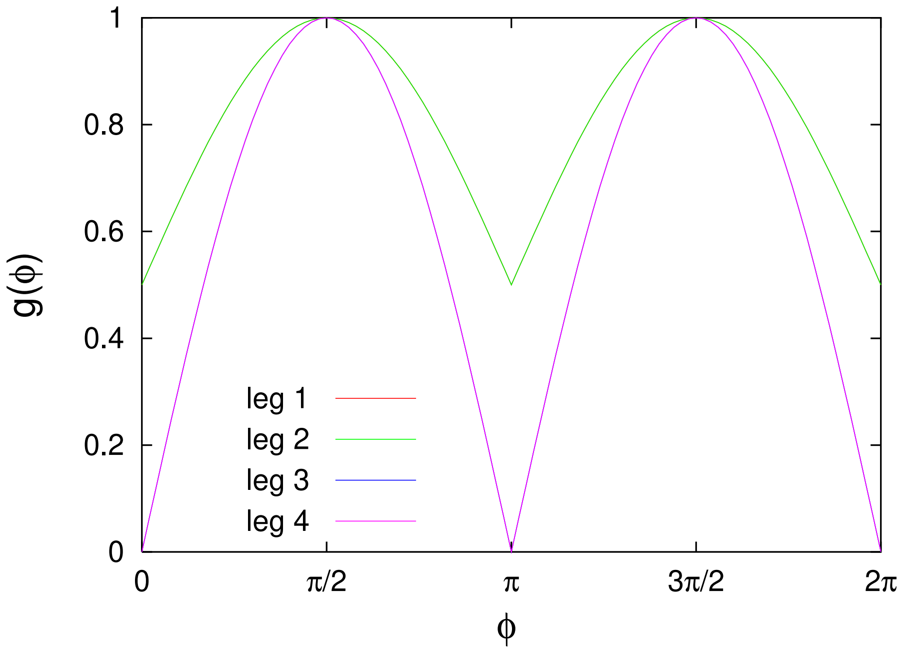
Thrust minor

$$T_m = \frac{1}{E_{T,\eta_0}} \left(\sum_{|\eta_i|<\eta_0} |p_i^{out}| + \Big| \sum_{|\eta_i|<\eta_0} \vec{p}_{ti} \Big| \right)$$

Predictions valid as usual
but $\mathcal{F}$ diverges for $R' = R'_c$

Results from Caesar (generated automatically)

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	$-\ln(2)$



Test	result
check number of jets	T
all legs positive	T
global	T
continuously global	T
additive	F
exponentiate	T
eliminate subleading effects	T
opt. probe region exists	T

Refined analysis

Find leg-pairs that could be source of divergence in $\mathcal{F}$

Leg pair	1 1	1 2	1 3	1 4	2 2	2 3	2 4	3 3	3 4	4 4
Zero type	gzf.	gzf.	nzf.	nzf.	gzf.	nzf	nzf.	nzf.	nzf.	nzf.

gzf. $\Rightarrow$ good zero found $\left(\frac{v}{v_s} \ll 1\right)$ nzf. $\Rightarrow$ no zero found $\left(\frac{v}{v_s} \gtrsim 1\right)$

Classify legs in sequences according to shared properties, identify the type of zero and establish position of the divergences

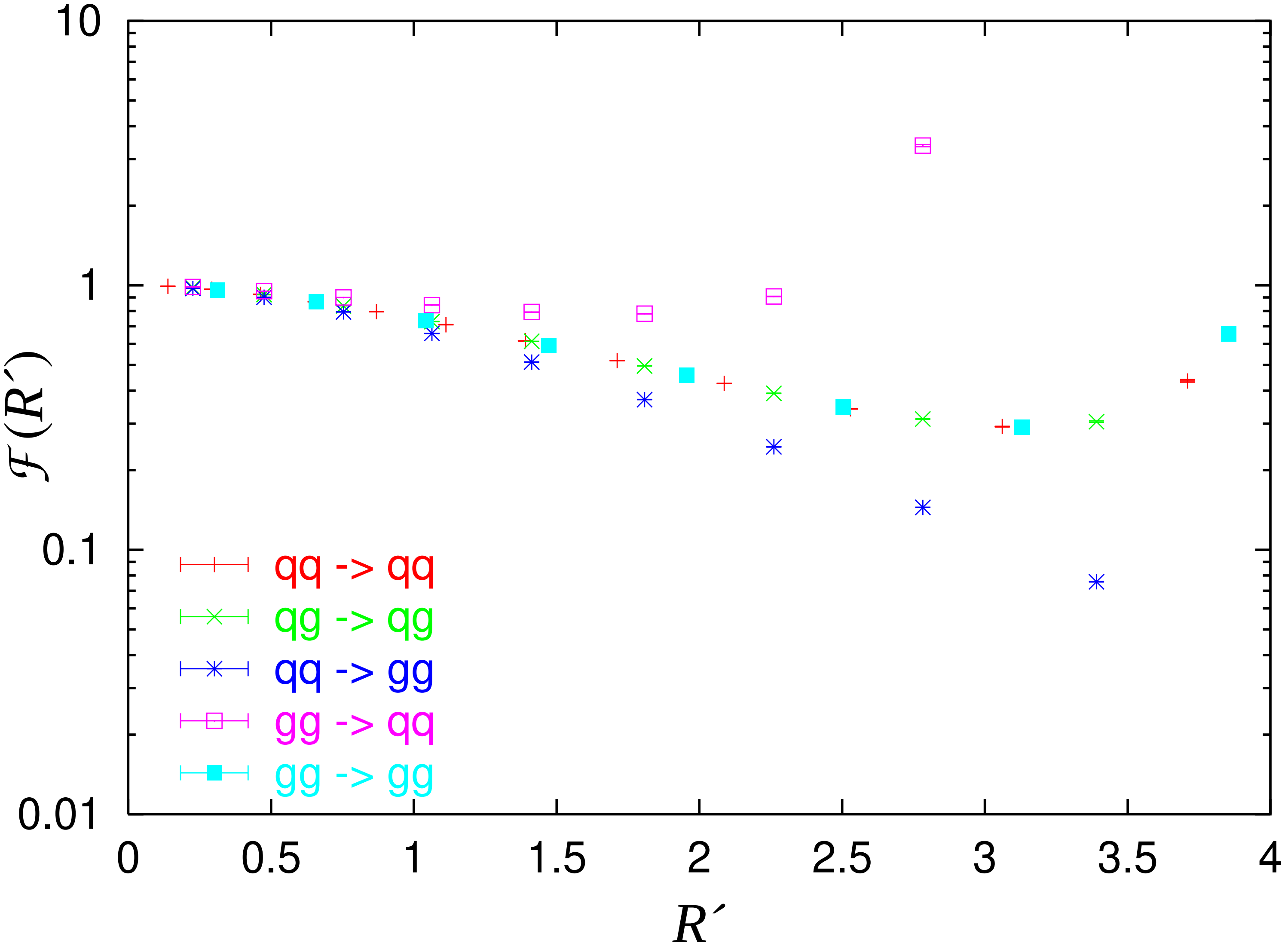
Leg sequence	(1 2)	(3 4)
Zero type	$\lvert\sum \vec{p}_t\rvert$	none
R'_c	2	none

classification allows better integration accuracy through good choice of MC Jacobian

MC-calculation of $\mathcal{F}$ exploits analytical distribution $\frac{d\sigma}{d\vec{p}_t}$ to generate $\vec{p}_t$

$\mathcal{F}(R')$ function (multiple-emissions)

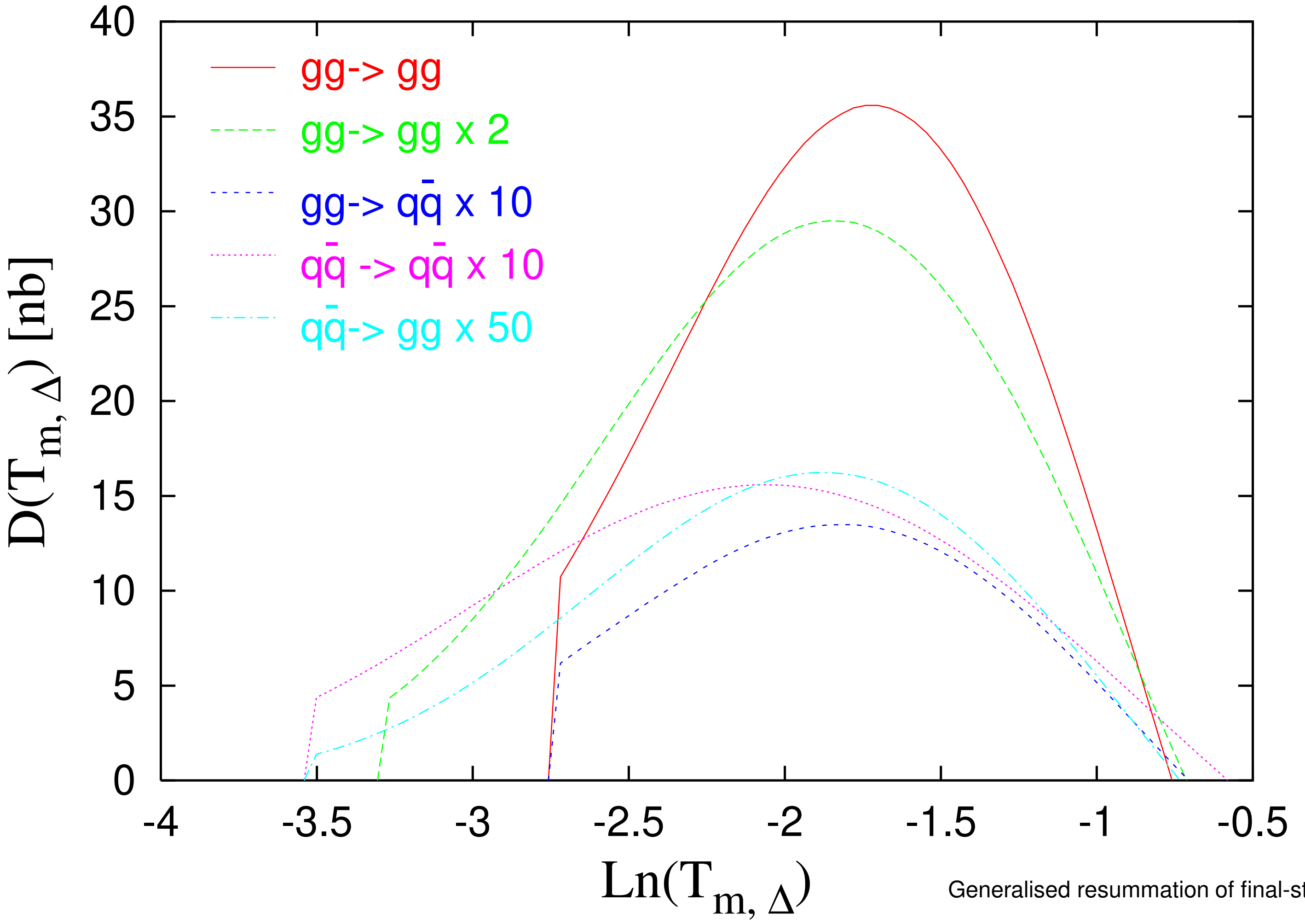
Different structure depending on colour factors of incoming and outgoing legs:



Example results: dijet events at Tevatron run II

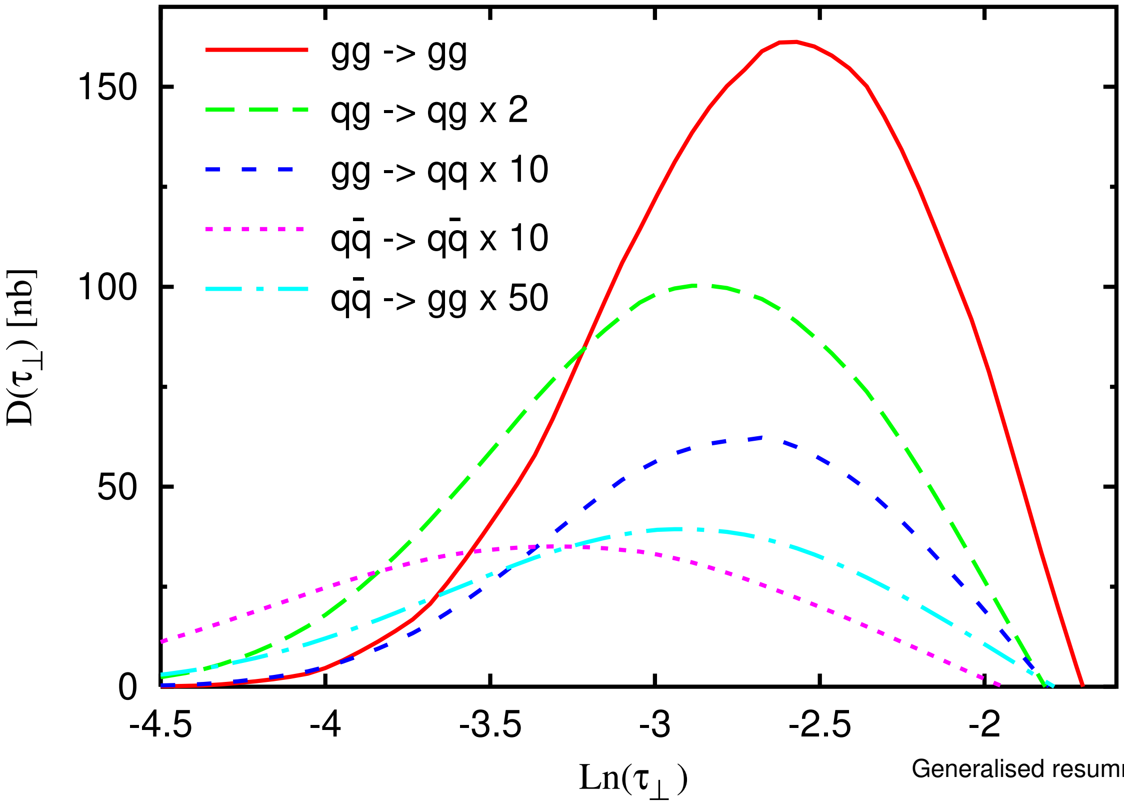
- run II regime $\sqrt{s} = 1.96$ TeV
- cut on rapidity $|\eta| < 1$
- cut on jet transverse energy $E_T > 50$GeV

The indirectly global thrust minor *(Preliminary!)*



Example 2: transverse thrust

leg ℓ	a_ℓ	b_ℓ	$g_\ell(\phi)$	d_ℓ	$\langle \ln g_\ell(\phi) \rangle$
1	1.000	0.000	tabulated	1.02062	-1.859
2	1.000	0.000	tabulated	1.02062	-1.859
3	1.000	1.000	$\sin^2\phi$	1.042	$-2\ln(2)$
4	1.000	1.000	$\sin^2\phi$	1.042	$-2\ln(2)$



Conclusions

- Systematic procedure to resum large class of final-state observables
- It can be implemented automatically, eliminating need for 'specialist'
  - Need just a computer subroutine for observable
  - Resummation becomes as easy as NLO calculations (with programs like EVENT2, NLOJET, . . .)
- Useful for
  - Experimentalists (many analyses no-longer 'theorist-limited')
  - Theorists (can get on with other things!)
  - Experimental-theorists (explore dozens of event-shapes & understand properties!)
- First resummation of hadronic dijet event-shapes.

Work in progress

- release of CAESAR v1.0
- matching with NLO(JET++)

Wish-list

- extension to non-global observables