
CAESAR: Computer automated resumptions

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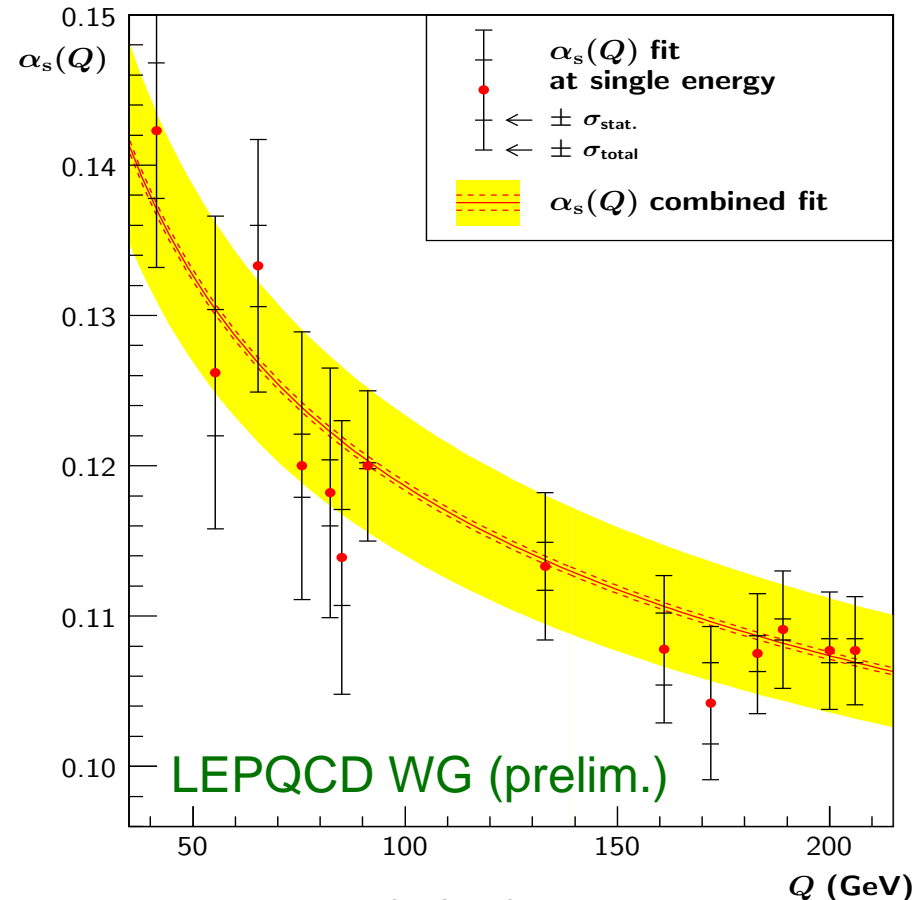
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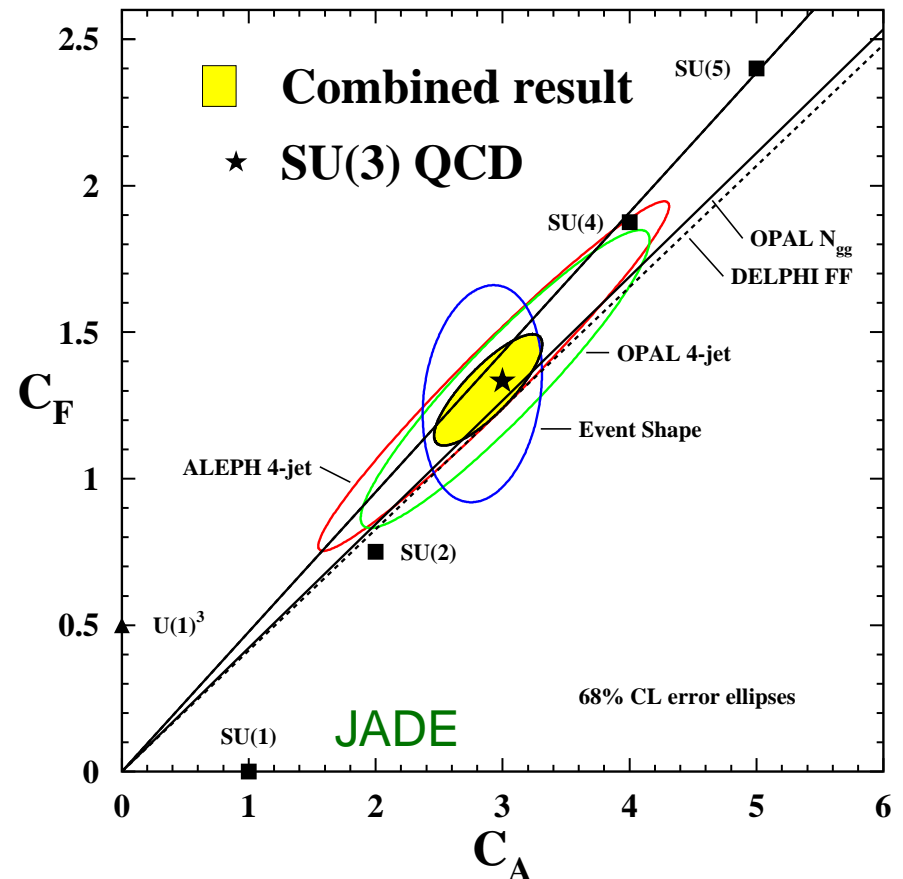


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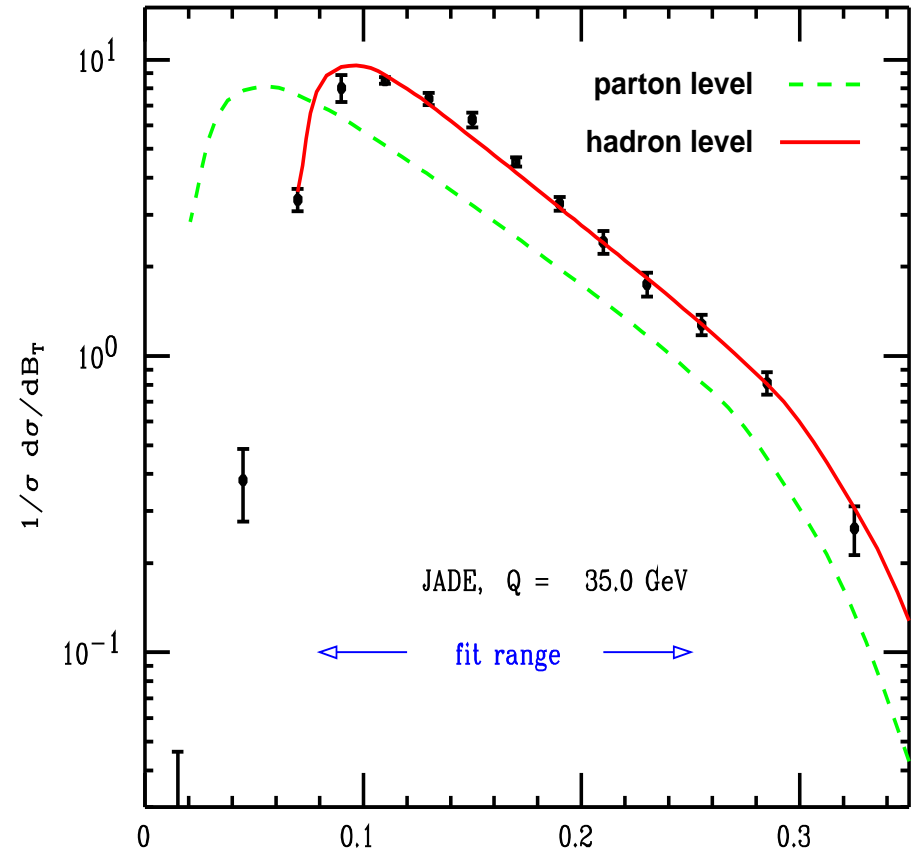


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Provide a wealth of information, e.g.:

- 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



Extending scope of these studies

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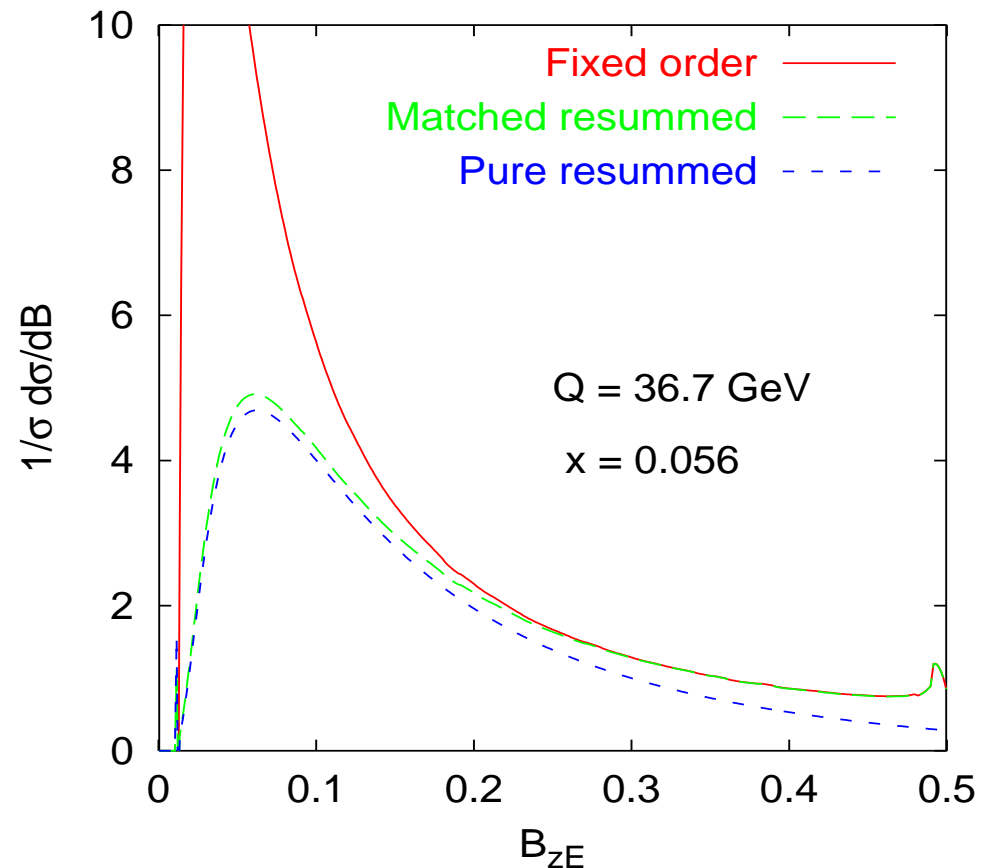
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- Studies of event-shapes for three (2+1) jet events is vital for testing non-perturbative (NP) models
 - success of $1/Q$ hadronisation corrections is ‘almost trivial’ in 2-jet events (follows from boost invariance)
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- A wide range of studies are possible in hadron-hadron colliders (dijet events, $W, Z + \text{jet}$)
 - analogous studies to those in e^+e^- and DIS
 - purely analytical studies of underlying event and minimum bias properties

Need the theoretical tools

- Account for hard gluon/quark radiation (fixed order)
 - ✓ Programs calculate NLO predictions given subroutine for observable
 - ✓ Many processes: Event2, Disent, Disaster++, NLOJET++, MCFM, ...
 - ✗ distributions diverge in soft/collinear region
- Account for multiple soft/collinear radiation (NLL resummation)
 - ✓ Ensures sensible distribution
 - ✗ Has to be done by hand for each observable & process



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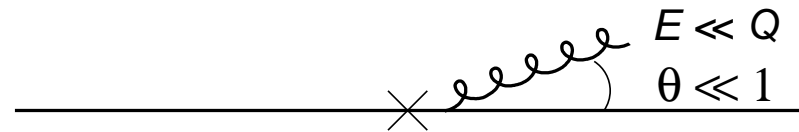
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$$\frac{dE}{E} \frac{d\theta}{\theta} \alpha_s(\theta E)$$

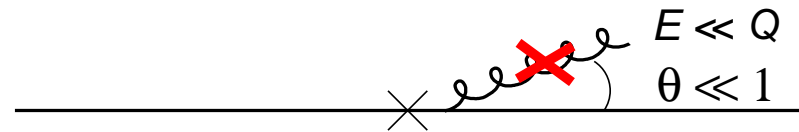


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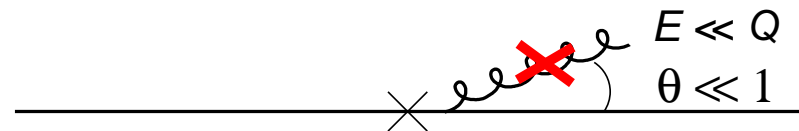


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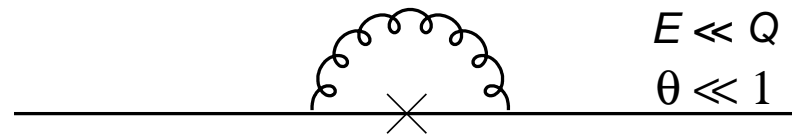
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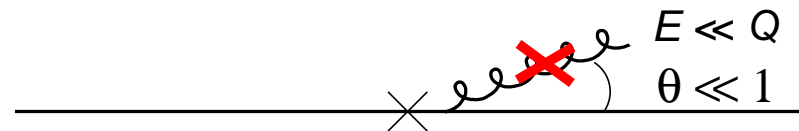


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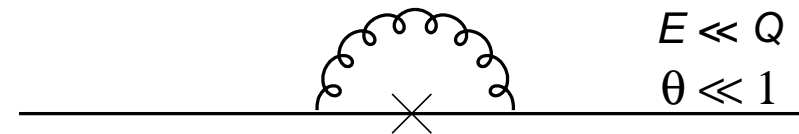
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Imbalance leads to large logarithms in distribution of event shape:

$$\text{Prob}(1 - T < \tau) \simeq 1 - \frac{\alpha_s C_F}{2\pi} \ln^2 \tau + \dots \quad (\tau \ll 1)$$

Resummation: 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 has *poorly convergent perturbation series*:

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

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

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

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

The analytical resummation industry...

$e^+e^- \rightarrow 2 \text{ jets}$

- 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 et al., *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 [...]*, 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.
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- S. Catani and B. R. Webber, *Resummed C-parameter distribution in e^+e^- annihilation*, Phys. Lett. B **427** (1998) 377
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- 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
- E. Gardi and J. Rathsman, *Renormalon resummation and exponentiation of soft and collinear gluon radiation in the thrust distribution*, Nucl. Phys. B **609** (2001) 123
- E. Gardi and J. Rathsman, *The thrust and heavy-jet mass distributions in the two-jet region*, Nucl. Phys. B **638** (2002) 243

E. Gardi and L. Magnea, *The C parameter distribution in e^+e^- annihilation*, JHEP **0308** (2003) 030

F. Krauss and G. Rodrigo, *Resummed jet rates for e^+e^- annihilation into massive quarks*, Phys. Lett. B **576** (2003) 135

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

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 - Matching with fixed order (LO, NLO, NNLO) is complex

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*Computer Automated Expert Semi-Analytical Resummation
(CAESAR)*

Single emission properties

- Observable must have standard functional form for soft & collinear gluon emission

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

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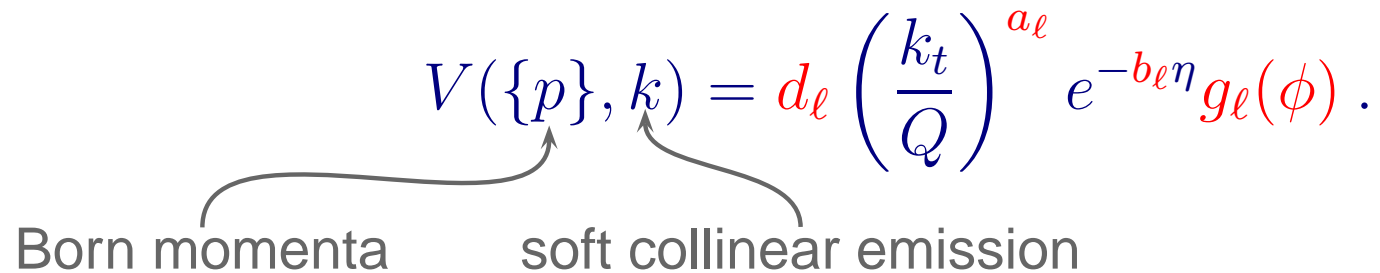
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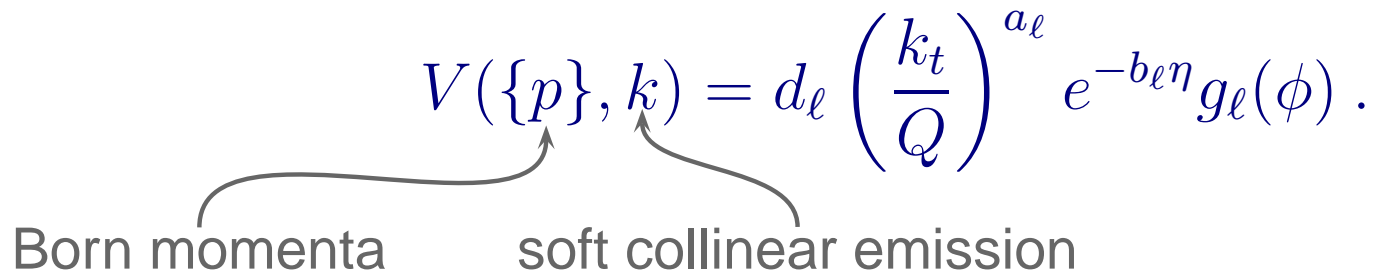
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- **Determine coefficients** a_ℓ , b_ℓ , d_ℓ and $g_\ell(\phi)$ for emissions close to each hard Born parton (leg) ℓ .
- Require **continuous globalness**, i.e. uniform dependence on k_t independently of emission direction ($a_1 = a_2 = \dots = a$)

Multiple emission properties

- Require *recursive infrared & collinear safety* (schematic)

$$\left[\lim_{\epsilon \rightarrow 0}, \lim_{\epsilon' \rightarrow 0} \right] \frac{1}{\epsilon} V(\{p\}, \epsilon k_1, \epsilon' k_2, \dots) = 0$$

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

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$$\mathcal{F} = \lim_{\epsilon' \rightarrow 0} \frac{\epsilon'^{R'}}{R'} \sum_{m=0}^{\infty} \frac{1}{m!} \left(\prod_{i=1}^{m+1} \sum_{\ell_i=1}^n C_{\ell_i}^{r'_{\ell_i}} \int_{\epsilon'}^1 \frac{d\zeta_i}{\zeta_i} \int_0^{2\pi} \frac{d\phi_i}{2\pi} \right) \delta(\ln \zeta_1) \times$$

$$\times \exp \left(-R' \ln \lim_{\epsilon \rightarrow 0} \frac{V(\{\tilde{p}\}, \kappa_1(\zeta_1 \epsilon), \dots, \kappa_{m+1}(\zeta_{m+1} \epsilon))}{\epsilon} \right).$$

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General Result (e^+e^- , DIS, hh; 2, 3, 4 jets)

Given info from previous pages, *answer is analytical*:

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

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C_ℓ = colour factor (C_F or C_A), $f_\ell(x_\ell, \mu_f^2)$ = 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)

...

Example: global thrust in hadronic dijet production

$$1 - T_{t,g} \equiv 1 - \max_{\vec{n}_t} \frac{\sum_i |\vec{p}_{ti} \cdot \vec{n}_t|}{\sum_i p_{ti}},$$

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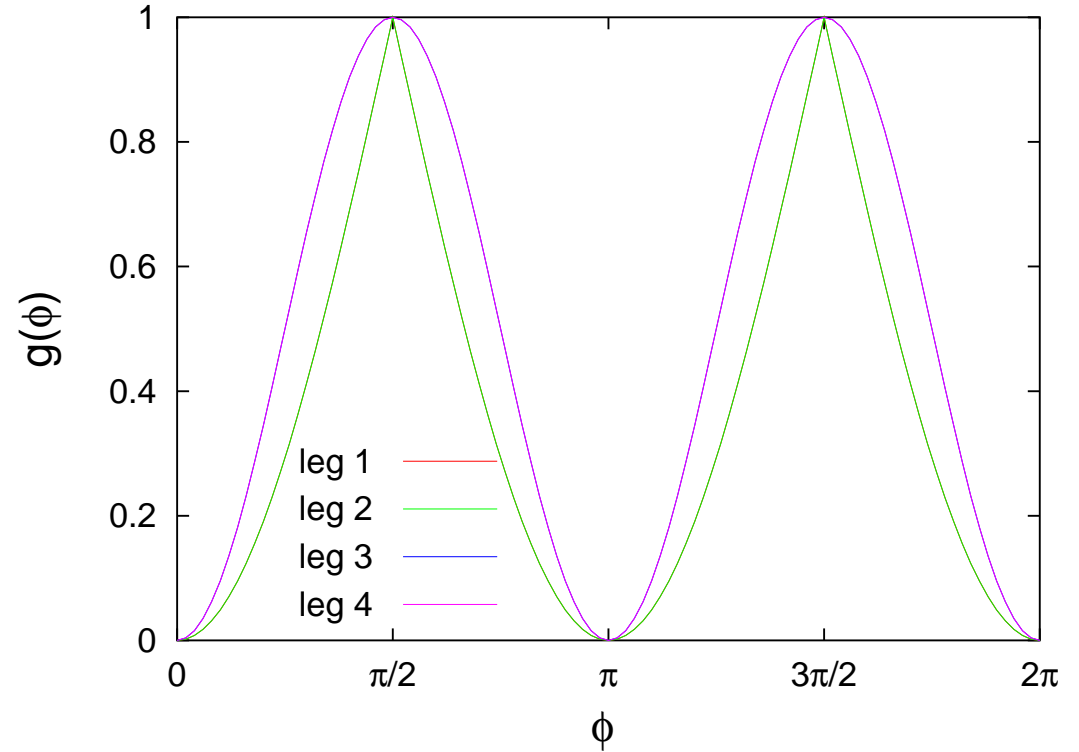
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leg ℓ	a_ℓ	b_ℓ	$g_\ell(\phi)$	d_ℓ	$\langle \ln g_\ell(\phi) \rangle$
1	1.000	0.000	tabulated	1.02062	-1.859
2	1.000	0.000	tabulated	1.02062	-1.859
3	1.000	1.000	$\sin^2 \phi$	1.042	$-2 \ln(2)$
4	1.000	1.000	$\sin^2 \phi$	1.042	$-2 \ln(2)$

Example: global thrust in hadronic dijet production

$$1 - T_{t,g} \equiv 1 - \max_{\vec{n}_t} \frac{\sum_i |\vec{p}_{ti} \cdot \vec{n}_t|}{\sum_i p_{ti}},$$

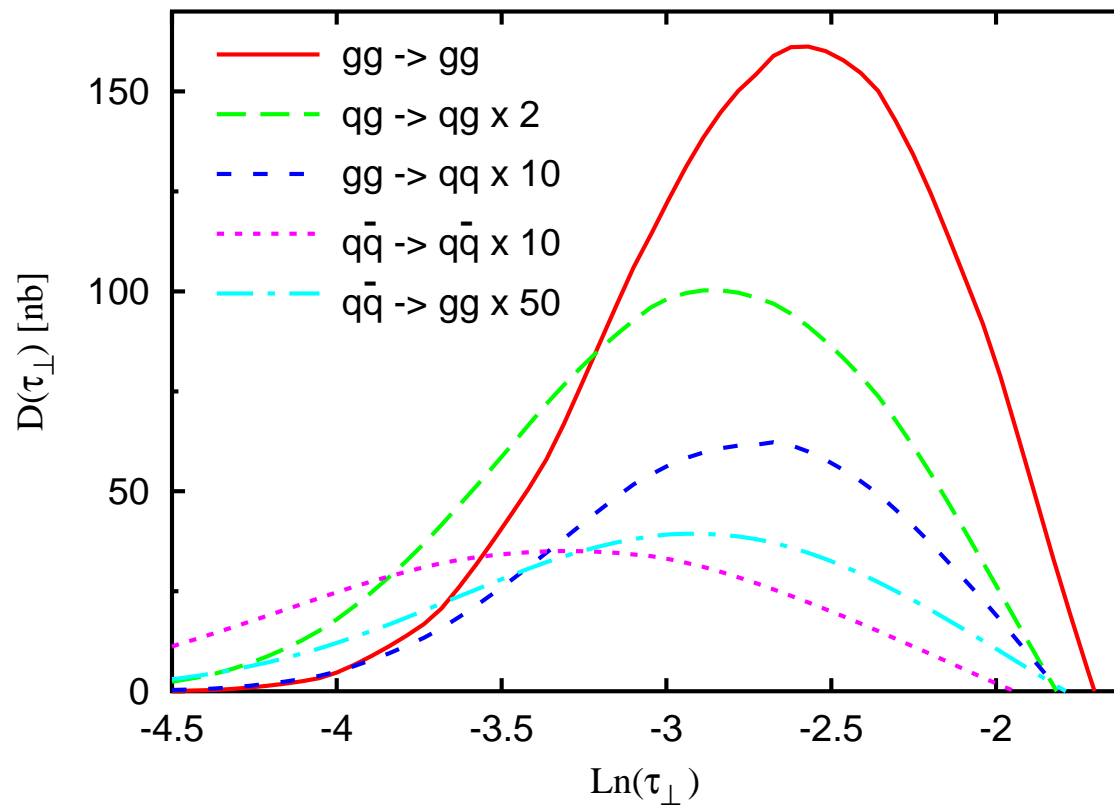
Test	result
continuously global	T
rec. IRC safe (cond. 1)	T
rec. IRC safe (cond. 2a)	T
rec. IRC safe (cond. 2b)	T
additivity	T



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	$-2 \ln(2)$
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Resummed thrust for Tevatron

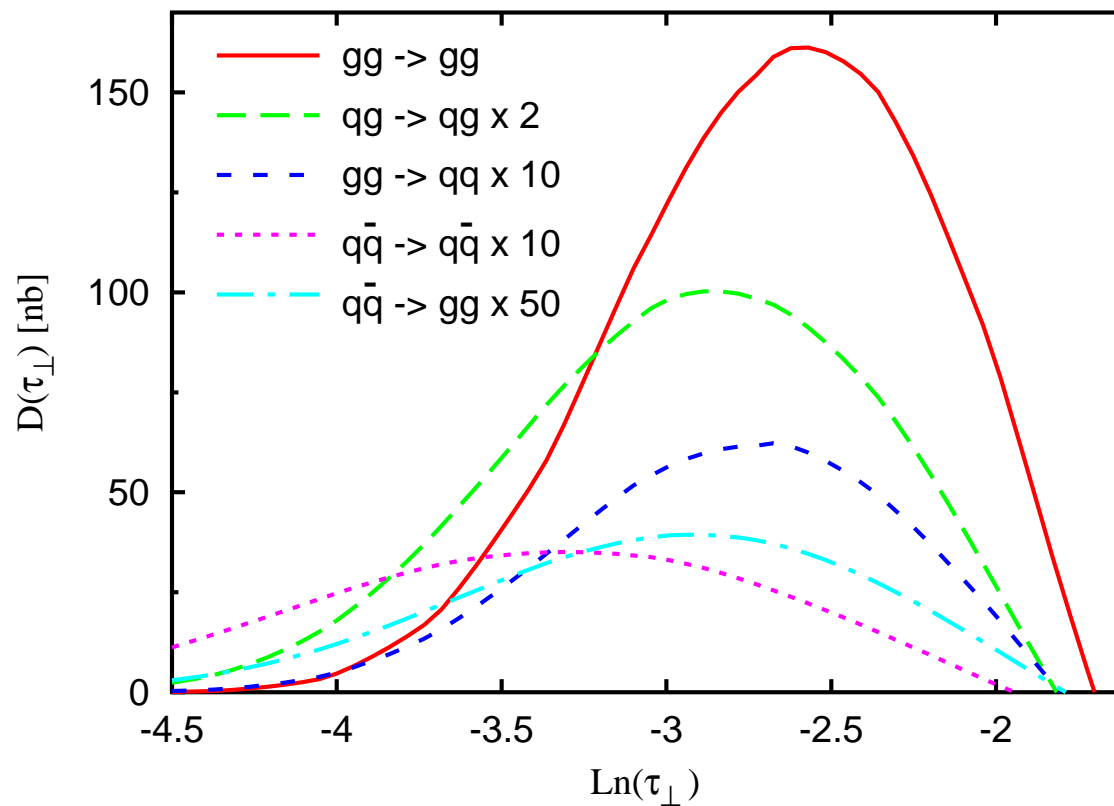
- run II regime $\sqrt{s} = 1.96$ TeV
- cut on rapidity $|\eta| < 1$
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PRELIMINARY!

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Longer-term Outlook

- Matching with fixed order (in progress) → Phenomenology
- Extending scope (e.g. non-global observables?)