Event shapes for hadron colliders

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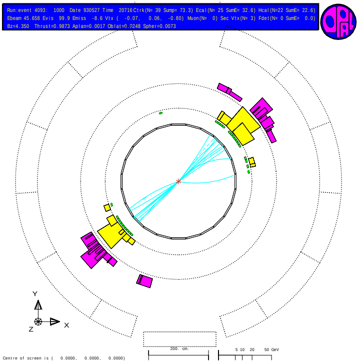
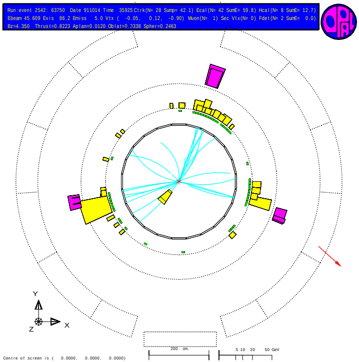
Max Planck Institut für Physik
Munich, July 2007

Final states

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





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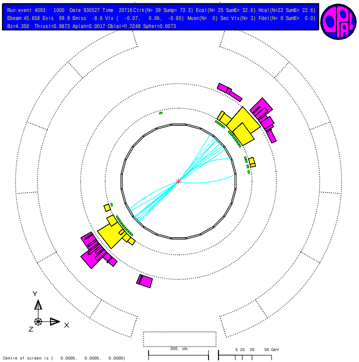

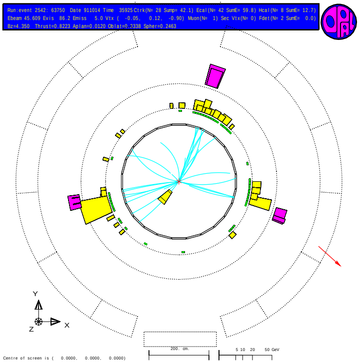

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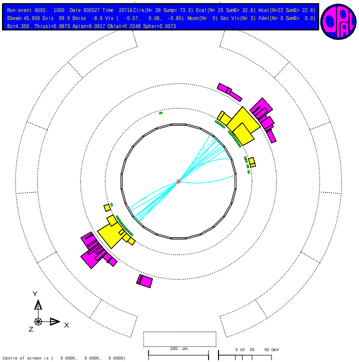

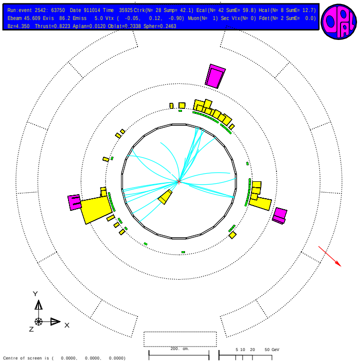

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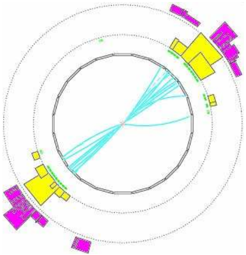
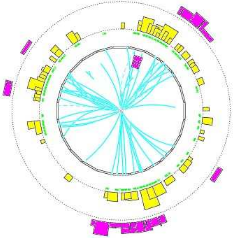
$$T = \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_i . \vec{n}_T|}{\sum_i |\vec{p}_i|} \,,$$



2-jet event: $T \simeq 1$



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

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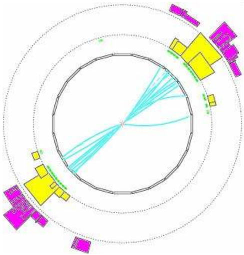

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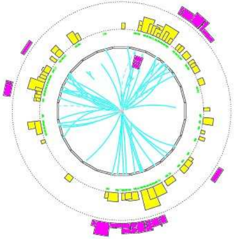

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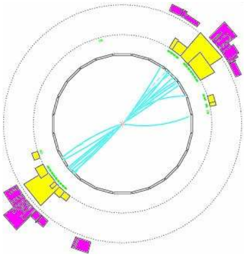

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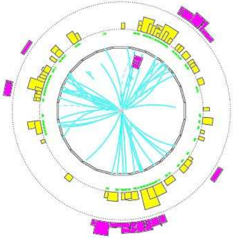

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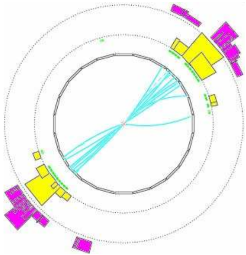

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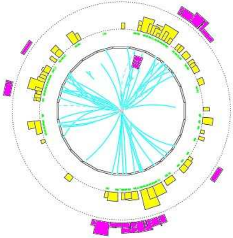

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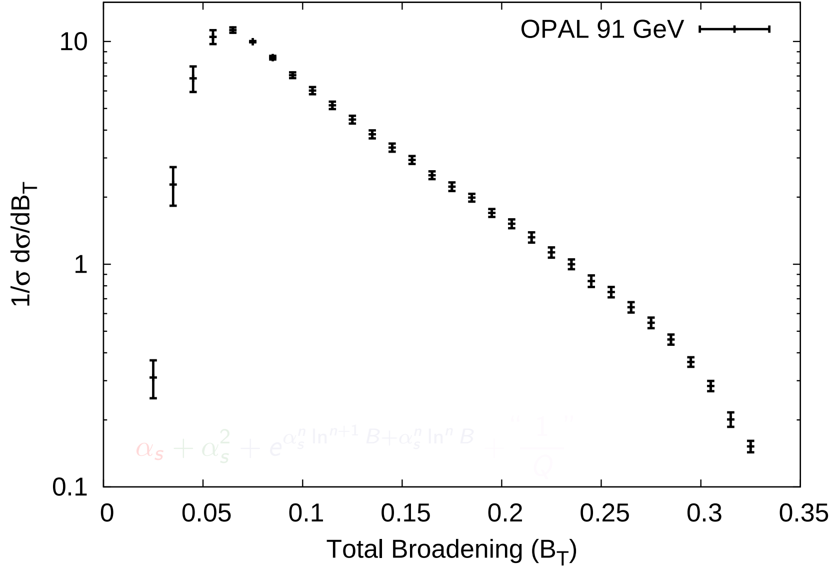

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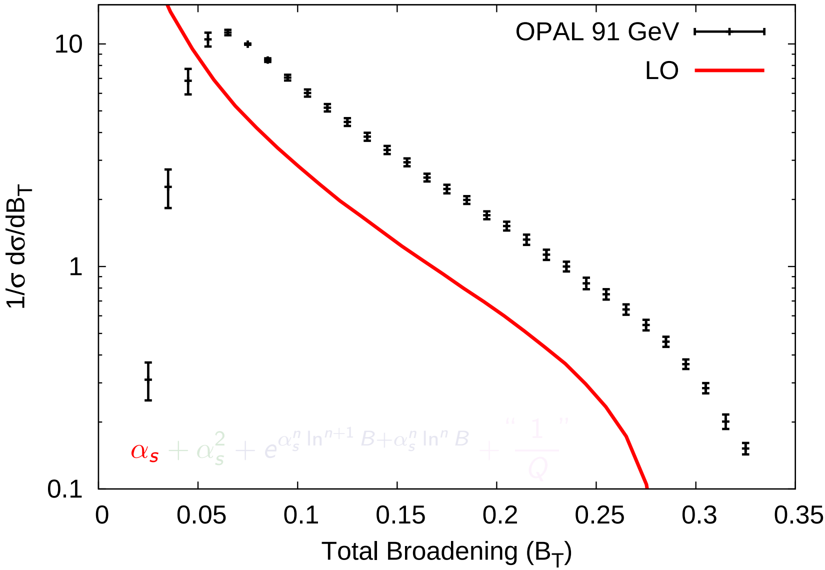

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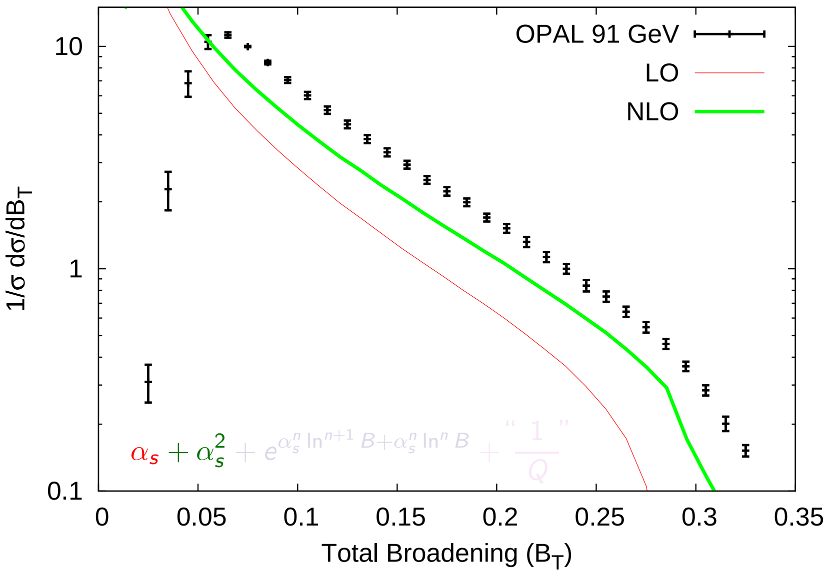

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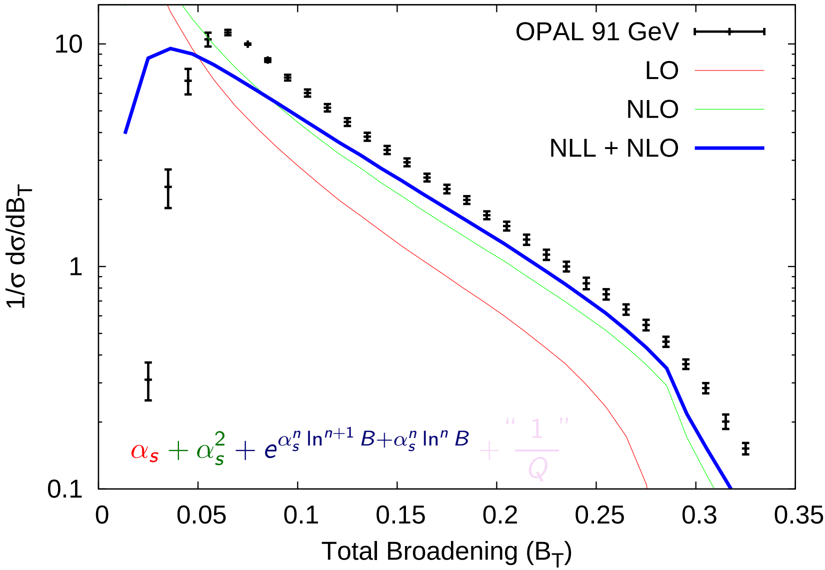

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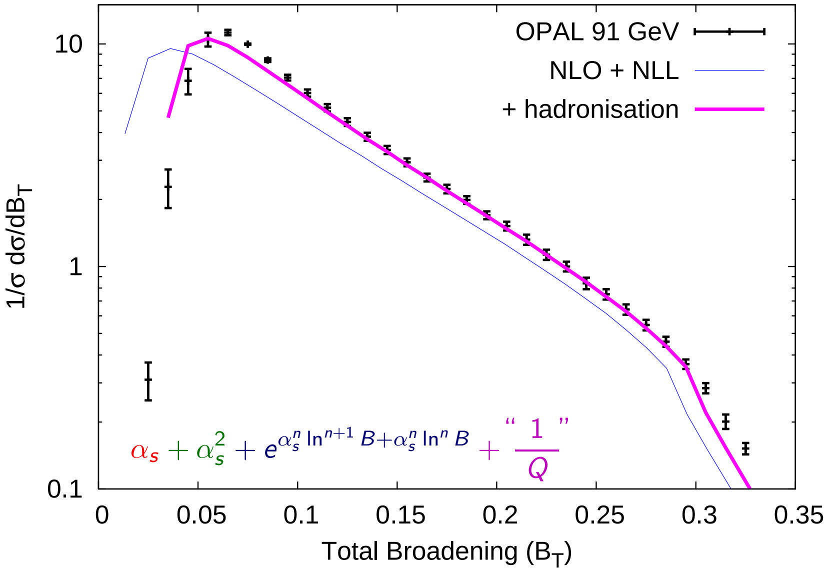

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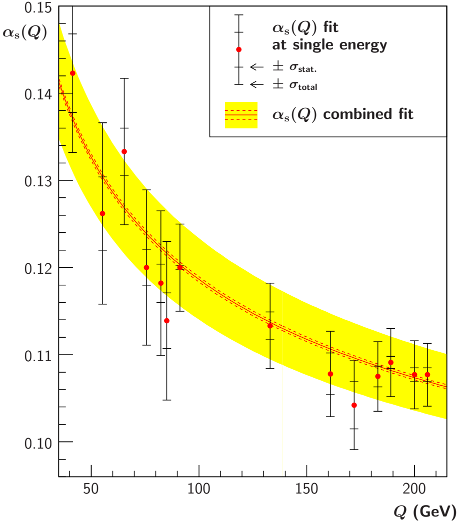

Much knowledge has been extracted from event-shapes in e^+e^- and DIS:

- α_s fits
- Tuning of Monte Carlos
- Colour factor fits ($C_A, C_F, \ldots$)
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But mostly neglected so far at hadron colliders

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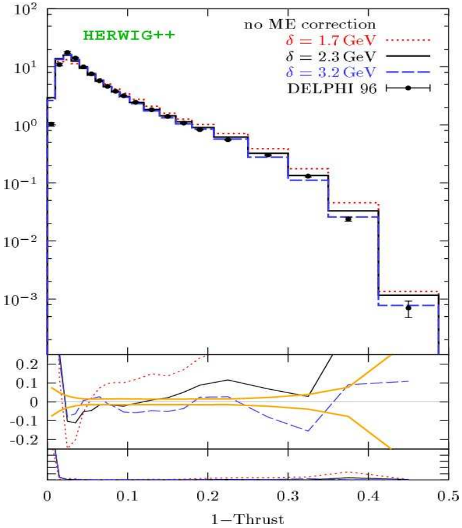

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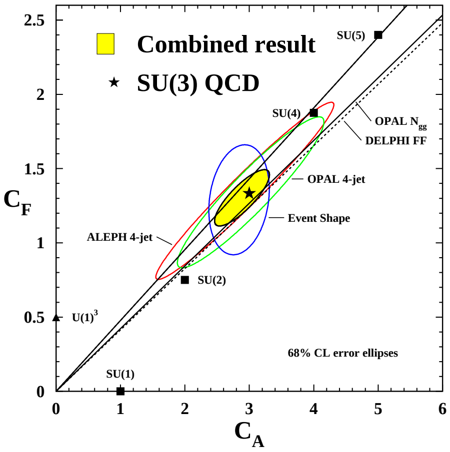

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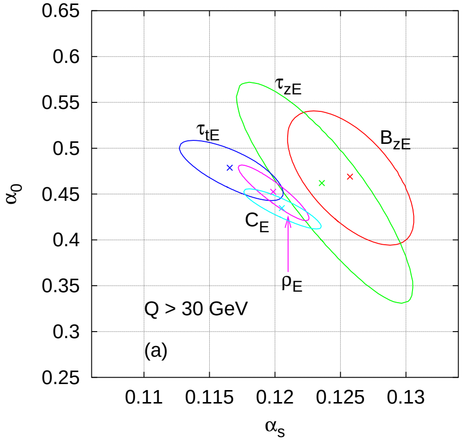

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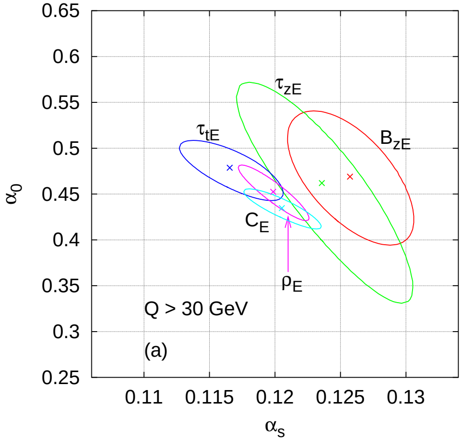

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Interest of hadronic colliders?

Various processes:

- $pp \to$ W/Z/H boson + jet — Banfi Marchesini Smye Zanderighi '01
- $pp \to$ 2 jets — Main subject of this talk

Standard applications (*e.g.*)

- Measure α_s
- As for 3-jet/2-jet ratio in $p\bar{p}$, reduce dependence on PDFs
- But for event-shapes → *distribution*
- Far more information than 3-jet/2-jet ratio

New territory

- 4-jet $(2+2)$ topology → novel perturbative structures
  soft colour evln matrices
- 3 & 4-jet topologies (& g-jets) → rich environment for analytical non-pert. studies
- Underlying event — test models (analytical & MC).

Variety of event-shape observables → complementary information → disentangle the different physics issues.

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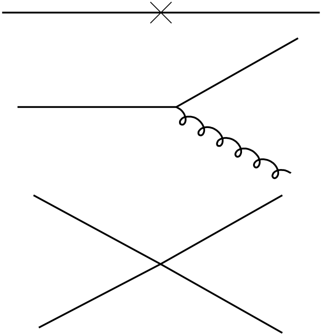
Soft colour evolution

Multi-jet final states: relative colour of pairs of hard partons determines soft large-angle radiation.



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3 jets: colour state of any pair *fixed by third parton* (colour conservation).

4 jets: a given pair can be in various colour states. Soft virtual corrections mix colour states.

Resummation leads to *matrix evolution equation for colour state of amplitudes* ('soft anomalous dimenions')

Developed at Stony Brook: Botts, Kidonakis, Oderda & Sterman '89–99

Interesting to test it (NB: used also for top threshold corrections).

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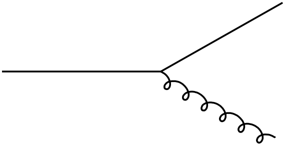

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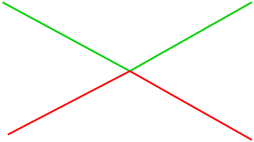

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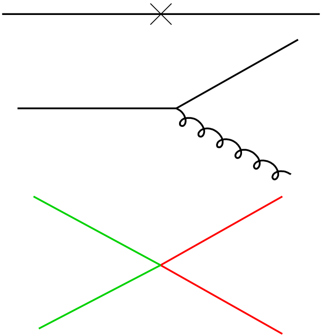

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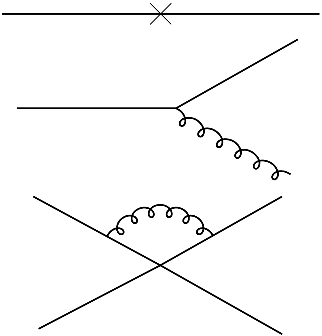

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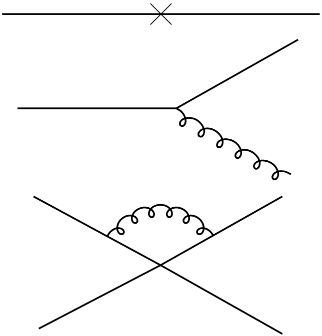

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Fixed order

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- First non-trivial order (LO) is Born + 1 parton, *i.e.* $p\bar{p} \to 3$ jets
- For NLO, need a program like NLOJET++ ($p\bar{p} \to 3$ jets @ NLO)
  Nagy, '01 & '03
- Also:
  - Kilgore-Giele code ($p\bar{p} \to 3$ jets @ NLO),
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Resummation

- In e^+e^- it was always done by hand, one observable at a time.
- *Next-to-leading logs* (NLL) are tedious, complicated, error-prone.
- Recently automated: Computer-Automated Expert Semi-Analytical Resummer (CAESAR). Banfi, GPS & Zanderighi '01–'04
- For $p\bar{p} \to$ 2jets, uses 'Stony Brook' soft-colour evolution matrices.
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Manual resummation (up to '04)

$e^+e^- \to 2$ 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 paper

Automated resummation

Analytical work (done once and for all)

A1. derive a master formula for a generic observable in terms of simple properties of the observable

A2. formulate the exact applicability conditions for the master formula

Numerical work (to be repeated for each observable)

N1. let an "expert system" investigate the applicability conditions

N2. it also determines the inputs for the master formula

N3. straightforward evaluation of the master formula, including phase space integration etc.

Note: N1 and N2 are core of automation

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A1. derive a master formula for a generic observable in terms of simple properties of the observable

A2. formulate the exact applicability conditions for the master formula

Numerical work (to be repeated for each observable)

N1. let an "expert system" investigate the applicability conditions

N2. it also determines the inputs for the master formula

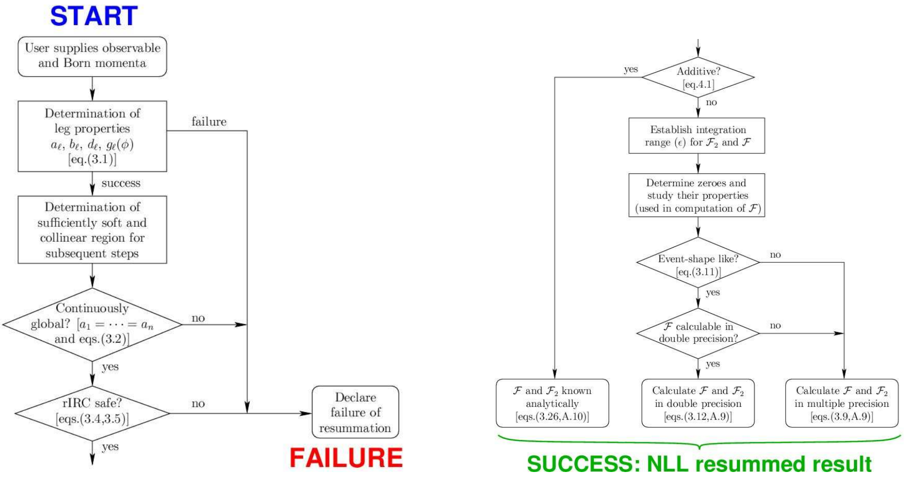
N3. straightforward evaluation of the master formula, including phase space integration etc.

Note: N1 and N2 are core of automation

a) they require high precision arithmetic to take asymptotic (soft & collinear) limits

b) validatation of hypotheses uses methods inspired by "Experimental Mathematics"

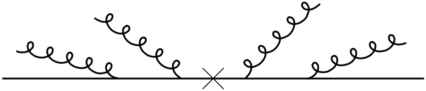
CAESAR flow chart



Requirement: globalness

Global observable:

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



making $B \ll 1$ restricts emissions everywhere.

Coherence + globalness:

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

Answers guaranteed to NLL accuracy

Non-Global observable:

Right-hemisphere Broadening, B_R

making $B_R \ll 1$ restricts emissions in right-hand hemisphere ($\mathcal{H_R}$).

Tempting to *assume* one can:

- ignore left hemisphere ($\mathcal{H_L}$)
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WRONG AT NLL ACCURACY

Dasgupta & GPS '01

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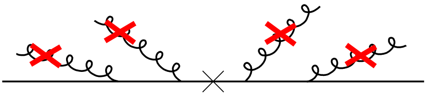

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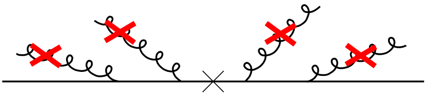

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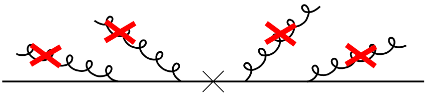

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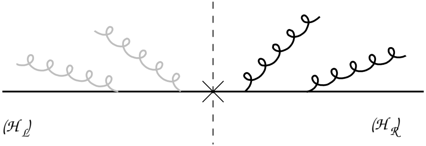

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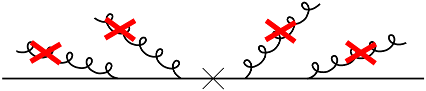

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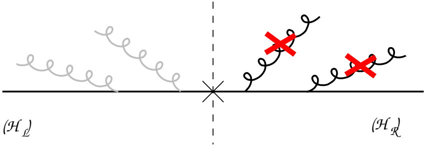

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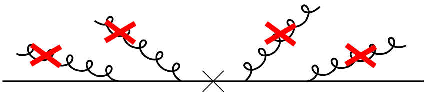

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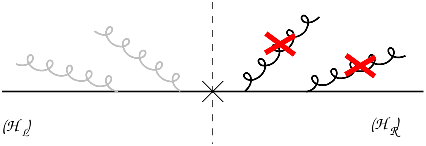

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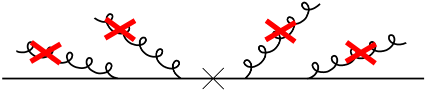

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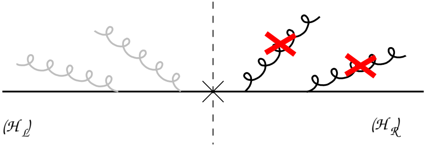

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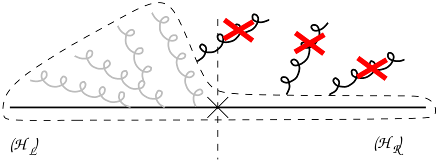
Resummation of NG observables

All-orders:

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



➥ $\alpha_s^n \ln^n B_R$

Difficulties:

- Logarithms resummed so far only in large-N_c limit
- In general, boundary between the two regions may have arbitrary shape.
- It may depend on the pattern of emissions (*e.g.* with jet algorithm).

Appleby & Seymour '02, '03
Banfi & Dasgupta '05
Delenda, A, B & D '06

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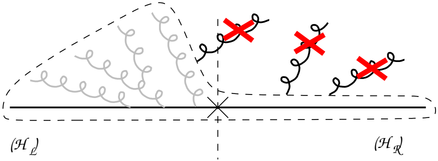

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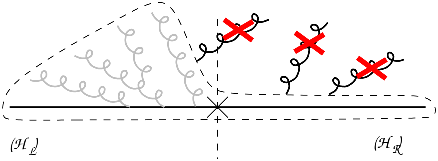

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Contradiction?

Theoretical calculations are for global observables.
But experiments only have detectors in limited rapidity range.
(Strictly: series of sub-detectors, of worsening quality as rapidity increases)

Model by cut around beam $|\eta| < \eta_{\max}$
➥ Problems with globalness

Take cut as being edge of most forward detector with momentum or energy resolution:

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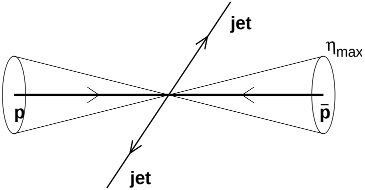

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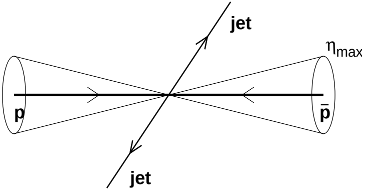

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Sidestepping non-globalness

Select events with central, hard jets (x_1, x_2 not too small), with transverse momentum $P_\perp$.

From kinematics, emissions (k) near forward detector edges typically have small transverse momentum:

$$k_\perp \sim P_\perp e^{-\eta_0} \ll P_\perp$$

If event-shape value is always sufficiently large that such an emission contributes negligibly, then:

we can ignore rapidity cut & pretend measurement is global

Proceed as follows:

- Calculate distribution without any rapidity cutoff
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Event selection cuts

Results that follow based on this (illustrative) event selection:

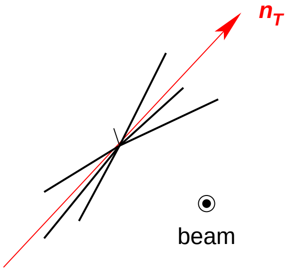
- Run longitudinally invariant inclusive k_t jet algorithm (could also use Cambridge/Aachen or SISCone)
- Require hardest jet to have $P_{\perp,1} > P_{\perp,\text{min}} = 50$ GeV
- Require two hardest jets to be central $|\eta_1|, |\eta_2| < \eta_c = 0.7$

Pure resummed results
no matching to NLO (or even LO)
Shown for Tevatron run II

Transverse thrust & minor

Some observables are naturally defined in terms of all particles in the event, *e.g.* *Global Transverse Thrust*

$$T_{\perp,g} \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{q}_{\perp i} \cdot \vec{n}_T|}{\sum_i q_{\perp i}}\,, \qquad \tau_{\perp,g} = 1 - T_{\perp,g}\,,$$



and *Global Thrust Minor*

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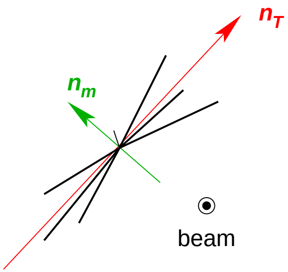


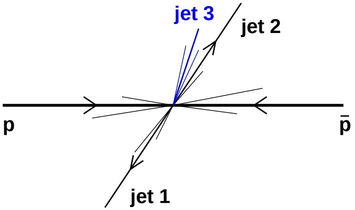
3-jet resolution threshold

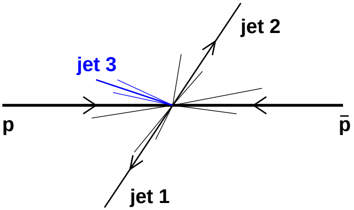
Use *exclusive* long. inv. k_t algorithm: successive recombination of pair with smallest closeness measure d_{kl}, d_{kB}:

$$d_{kB} = q_{\perp k}^2 \,, \qquad d_{kl} = \min\{q_{\perp k}^2, q_{\perp l}^2\} \left((\eta_k - \eta_l)^2 + (\phi_k - \phi_l)^2\right) \,.$$

Define $d^{(n)}$ as smallest d_{kl}, d_{kB} when only n pseudo-jets left. Examine (normalised) 3-jet resolution threshold

$$y_{23} = \frac{1}{(E_{\perp,1} + E_{\perp,2})^2} d^{(3)}$$





Generalisation of 3-jet cross section

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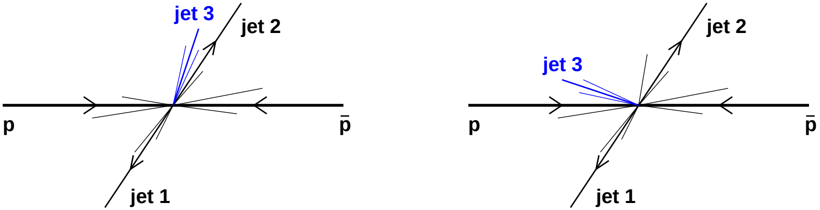

Generalisation of 3-jet cross section

Results

Probability $P(v)$ that event shape is smaller than some value v:

$$P(v) = \exp\left[-G_{12}\frac{\alpha_s L^2}{2\pi} + \cdots\right], \quad L = \ln\frac{1}{v}$$

Ev.Shp.	G_{12}
$\tau_{\perp,g}$	$2C_B + C_J$
$T_{m,g}$	$2C_B + 2C_J$
y_{23}	$\frac{1}{2}C_B + \frac{1}{2}C_J$

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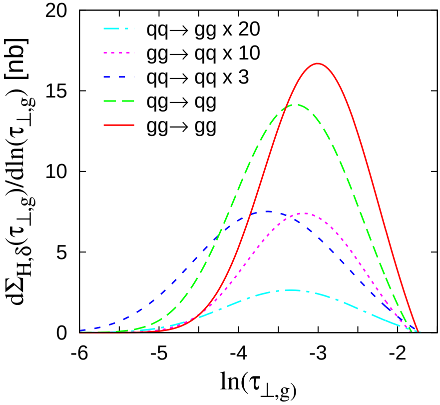

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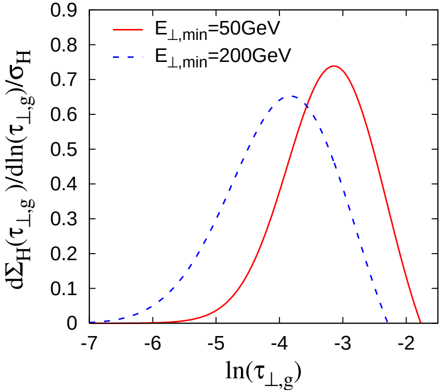

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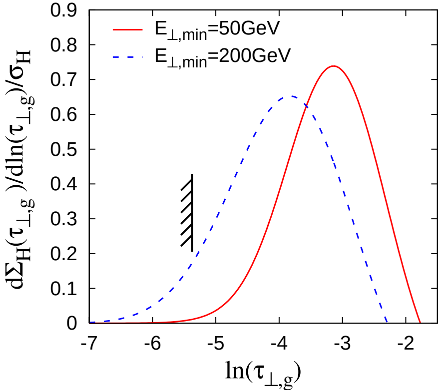

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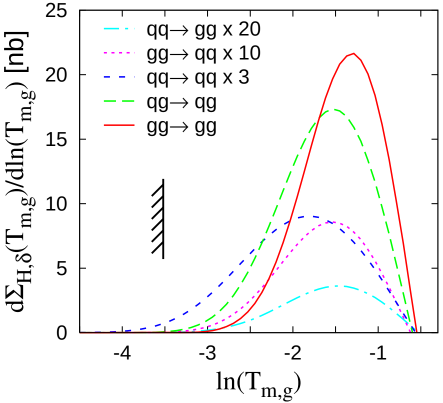

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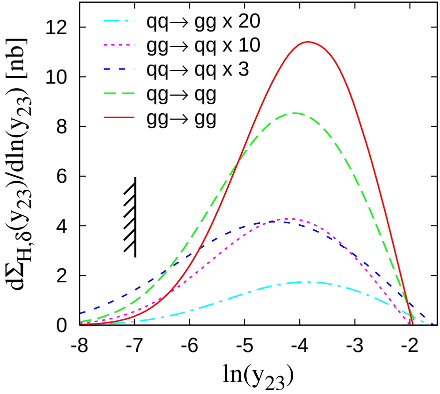


Beam cut: $y_{23} \gtrsim e^{-2\eta_{\max}}$ [because $y_{23} \sim k_t^2$]

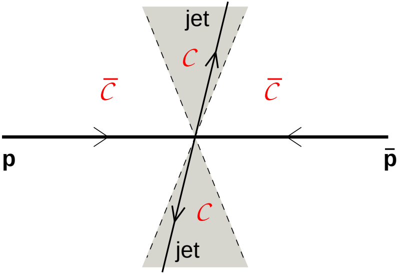
Forward-suppressed observables

Divide event into central region ($\mathcal{C}$, say $|\eta| < 1.1$) and rest of event ($\bar{\mathcal{C}}$).

[NB: $\exists$ considerable freedom in definition of $\mathcal{C}$: *e.g.* can also be two hardest jets]

Define central $\perp$ mom., and rapidity:

$$Q_{\perp,\mathcal{C}} = \sum_{i \in \mathcal{C}} q_{\perp i}\,, \quad \eta_{\mathcal{C}} = \frac{1}{Q_{\perp,\mathcal{C}}} \sum_{i \in \mathcal{C}} \eta_i \, q_{\perp i}$$



and an *exponentially suppressed forward term,*

$$\mathcal{E}_{\bar{\mathcal{C}}} = \frac{1}{Q_{\perp,\mathcal{C}}} \sum_{i \notin \mathcal{C}} q_{\perp i} \, e^{-|\eta_i - \eta_{\mathcal{C}}|}\,.$$

Define a non-global event-shape in $\mathcal{C}$. Then add on $\mathcal{E}_{\bar{\mathcal{C}}}$.

Result is a global event shape, with suppressed sensitivity to forward region.

Forward-suppressed observables

Divide event into central region ($\mathcal{C}$, say $|\eta| < 1.1$) and rest of event ($\bar{\mathcal{C}}$).

[NB: $\exists$ considerable freedom in definition of $\mathcal{C}$: *e.g.* can also be two hardest jets]

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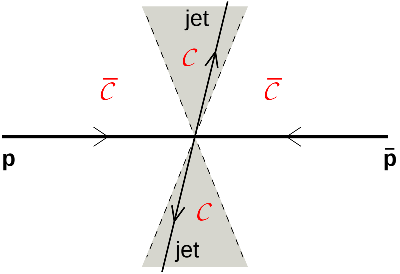

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Examples

- Split $\mathcal{C}$ into two pieces: *Up, Down*
- Define *jet masses* for each

$$\rho_{X,\mathcal{C}} \equiv \frac{1}{Q_{\perp,\mathcal{C}}^2}\Big(\sum_{i\in\mathcal{C}_X} q_i\Big)^2\,, \qquad X = U, D\,,$$

Define sum and heavy-jet masses

$$\rho_{S,\mathcal{C}} \equiv \rho_{U,\mathcal{C}} + \rho_{D,\mathcal{C}}\,, \qquad \rho_{H,\mathcal{C}} \equiv \max\{\rho_{U,\mathcal{C}}, \rho_{D,\mathcal{C}}\}\,,$$

Define global extension, with extra forward-suppressed term

$$\rho_{S,\mathcal{E}} \equiv \rho_{S,\mathcal{C}} + \mathcal{E}_{\bar{\mathcal{C}}}\,, \qquad \rho_{H,\mathcal{E}} \equiv \rho_{H,\mathcal{C}} + \mathcal{E}_{\bar{\mathcal{C}}}\,.$$

- Similarly: *total and wide jet-broadenings*

$$B_{T,\mathcal{E}} \equiv B_{T,\mathcal{C}} + \mathcal{E}_{\bar{\mathcal{C}}}\,, \qquad B_{W,\mathcal{E}} \equiv B_{W,\mathcal{C}} + \mathcal{E}_{\bar{\mathcal{C}}}\,.$$

Results

$$P(v) = \exp\left[-G_{12}\frac{\alpha_s L^2}{2\pi} + \cdots\right], \quad L = \ln\frac{1}{v}$$

Ev.Shp.	G_{12}
$\rho_{S,\mathcal{E}}$	$C_B + C_J$
$\rho_{H,\mathcal{E}}$	$C_B + C_J$
$B_{T,\mathcal{E}}$	$C_B + 2C_J$
$B_{W,\mathcal{E}}$	$C_B + 2C_J$
$\vdots$	$\vdots$

C_B = total colour of Beam partons
C_J = total colour of Jet partons

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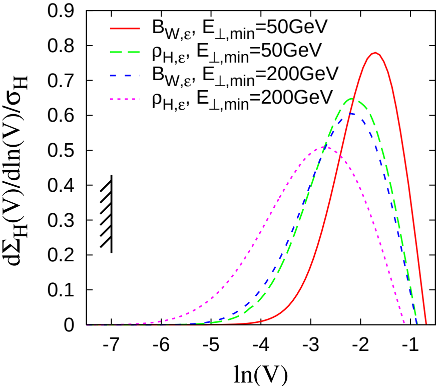

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Beam cuts: $B_{X,\mathcal{E}}, \rho_{X,\mathcal{E}} \gtrsim e^{-2\eta_{\max}}$ [because $\mathcal{E}_{\bar{\mathcal{C}}} \sim k_t e^{-|\eta|}$]

Recoil observables

By momentum conservation

$$\sum_{i\in\mathcal{C}} \vec{q}_{\perp i} = -\sum_{i\notin\mathcal{C}} \vec{q}_{\perp i}$$

Use central particles to define *recoil term*, which is *indirectly sensitive* to non-central emissions

$$\mathcal{R}_{\perp,\mathcal{C}} \equiv \frac{1}{Q_{\perp,\mathcal{C}}} \left| \sum_{i\in\mathcal{C}} \vec{q}_{\perp i} \right| ,$$

Define event shapes exclusively in terms of *central particles:*

$$\rho_{X,\mathcal{R}} \equiv \rho_{X,\mathcal{C}} + \mathcal{R}_{\perp,\mathcal{C}} , \qquad B_{X,\mathcal{R}} \equiv B_{X,\mathcal{C}} + \mathcal{R}_{\perp,\mathcal{C}} , \ldots$$

These observables are *indirectly global*

First studied at HERA (B_{zE} broadening)

Results

CAESAR resummation works for observables having *direct exponentiation*:

$$P(v) = e^{Lg_1(\alpha_s L)+g_2(\alpha_s L)+\dots}$$

For recoil observables, exponentiation holds fully only after Fourier & other integral transforms (generalised *b*-space resummation).

Manifestation: NLLs ($g_2(\alpha_s L)$) diverge at some $\alpha_s L \sim 1$.

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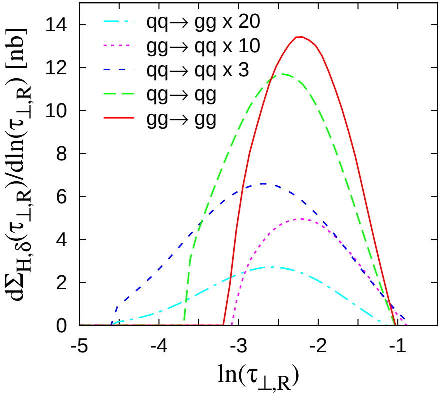
recoil transverse thrust



Quite large effect: $\sim$ 15% of X-sct is beyond cutoff

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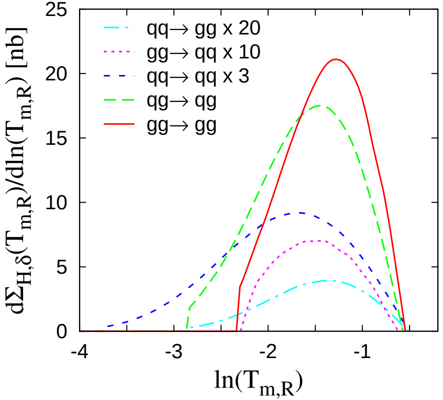
recoil thrust minor



Moderate effect: few % of X-sct is beyond cutoff

Summary of observables

Event-shape	Impact of $\eta_{\max}$	Resummation breakdown	Underlying Event	Jet hadronisation
$\tau_{\perp,g}$	tolerable	none	$\sim \eta_{\max}/Q$	$\sim 1/Q$
$T_{m,g}$	tolerable	none	$\sim \eta_{\max}/Q$	$\sim 1/(\sqrt{\alpha_s}Q)$
y_{23}	tolerable	none	$\sim \sqrt{y_{23}}/Q$	$\sim \sqrt{y_{23}}/Q$
$\tau_{\perp,\mathcal{E}}$, $\rho_{X,\mathcal{E}}$	negligible	none	$\sim 1/Q$	$\sim 1/Q$
$B_{X,\mathcal{E}}$	negligible	none	$\sim 1/Q$	$\sim 1/(\sqrt{\alpha_s}Q)$
$T_{m,\mathcal{E}}$	negligible	serious	$\sim 1/Q$	$\sim 1/(\sqrt{\alpha_s}Q)$
$y_{23,\mathcal{E}}$	negligible	none	$\sim 1/Q$	$\sim \sqrt{y_{23}}/Q$
$\tau_{\perp,\mathcal{R}}$, $\rho_{X,\mathcal{R}}$	none	serious	$\sim 1/Q$	$\sim 1/Q$
$T_{m,\mathcal{R}}$, $B_{X,\mathcal{R}}$	none	tolerable	$\sim 1/Q$	$\sim 1/(\sqrt{\alpha_s}Q)$
$y_{23,\mathcal{R}}$	none	intermediate	$\sim \sqrt{y_{23}}/Q$	$\sim \sqrt{y_{23}}/Q$

NB: there may be surprises after more detailed study, *e.g.* matching to NLO...

Grey entries are definitely subject to uncertainty

Note complementarity between observables

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News since '05

First NLO+NLL+$1/Q$ matching for multi-jet ev. shapes

Banfi & Zanderighi prelim.

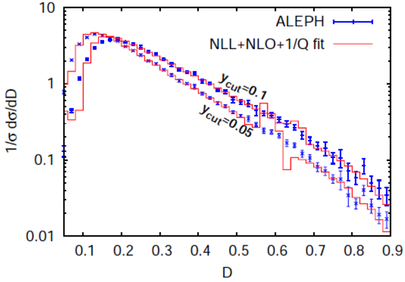
e^+e^- D-parameter and thrust minor

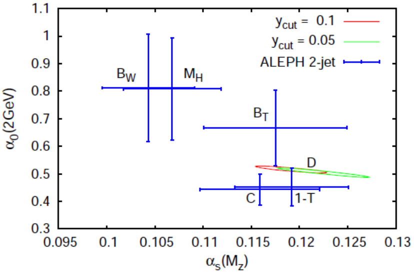
- confirms that framework can work in multi-jet context
- progress on road to full matching in pp

Tests of power corrections for D and T_m

- Select 3-jet events with $y_3 > y_{\rm cut}$
- Differential distributions obtained with CAESAR at $Q = 91.2\,{\rm GeV}$

[AB, G. Salam, G. Zanderighi hep-ph/0407286]





- D-parameter: first ever α_s-α_0 fits in a three-jet event shapes!
- Good fits only for $D > 0.2$: $\chi^2/{\rm d.o.f.}(y_{\rm cut} = 0.1) = 12/20$
  $\Rightarrow$ Small-D region: shape function or large subleading logs?

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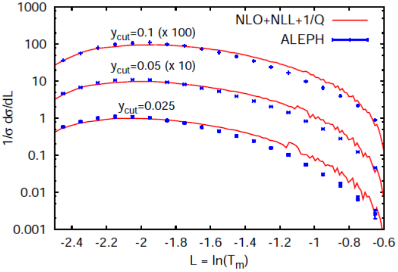

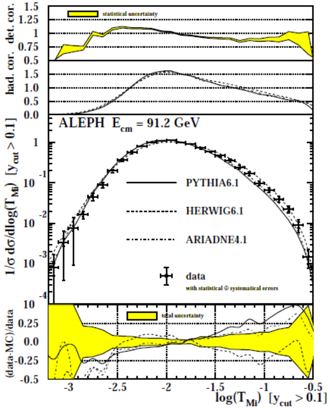

Thrust minor PC should be positive

MC say PC are negative at large T_m
$\Rightarrow$ PC from 4-jet configurations?

Super-leading logs?

Key ingredient in all resummations is **coherence**

Large-angle reals/virtuals not affected by small-angle emissions

Implies: interjet energy-flow type resummations involve single-logs, $\alpha_s^n L^n$

Calculation by Forshaw, Kyrieleis & Seymour '06 finds $\alpha_s^4 L^5 \times 1/N_c^2$

- If these terms exist they could affect resummations for $\tau_{\perp,\mathcal{E}}$, $\rho_{X,\mathcal{E}}$, $B_{X,\mathcal{E}}$, $y_{23,\mathcal{E}}$. $\equiv$ Observables with η dependence in forward regions
- FKS paper alone is not sufficient to prove existence — coefficient of result depends on (arbitrary) choice of ordering variable.
- FKS find they are numerically small (N_c suppressed phase interference) — perhaps not serious in practice even if conceptually important

One should keep an eye on this issue

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Progress towards pp matching

Main difficulty:

$$\sigma^{NLO}_{qq\to qq} e^{-2C_F\alpha_s L^2/2\pi} + \sigma^{NLO}_{gg\to gg} e^{-2C_A\alpha_s L^2/2\pi} + \dots$$
$$\neq \frac{\sigma^{NLO}}{\sigma^{LO}} \left[\sigma^{LO}_{qq\to qq} e^{-2C_F\alpha_s L^2/2\pi} + \sigma^{LO}_{gg\to gg} e^{-2C_A\alpha_s L^2/2\pi} + \dots\right]$$

In order to guarantee $\alpha_s^n L^{2n-2}$ (NNLL in expanded result), part at least of matching must be done channel by channel. Never an issue before

Problems:

- Flavour channel definition not IR safe with normal jet algs
  Use special *flavour-k_t* algorithm, Banfi, GPS & Zanderighi '06
- NLO Monte Carlos for *pp* do not provide information on flavour of partons. Can be disentangled in NLOJET++ (1 month of hard work)
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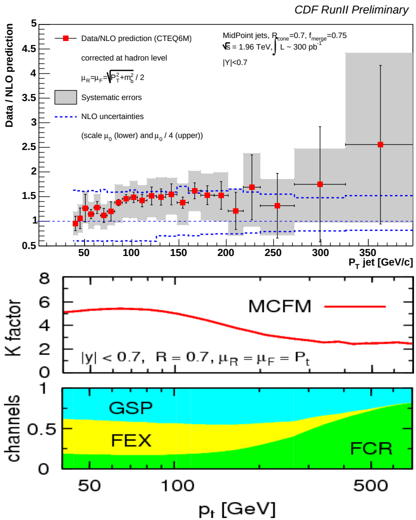

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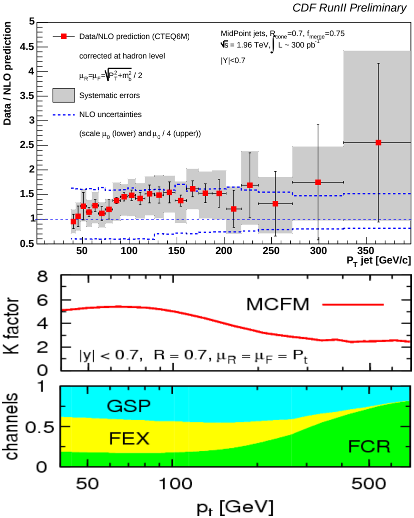

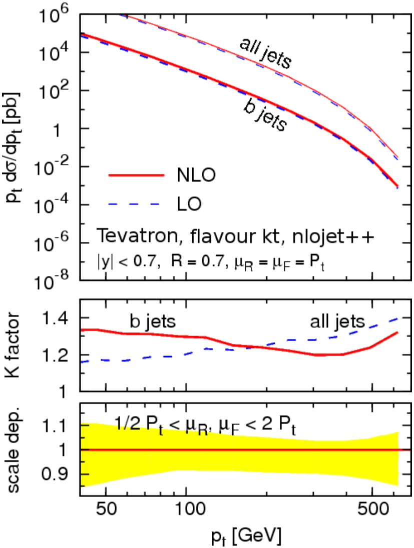

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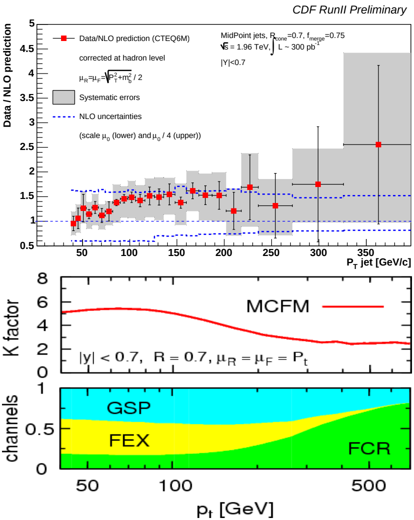

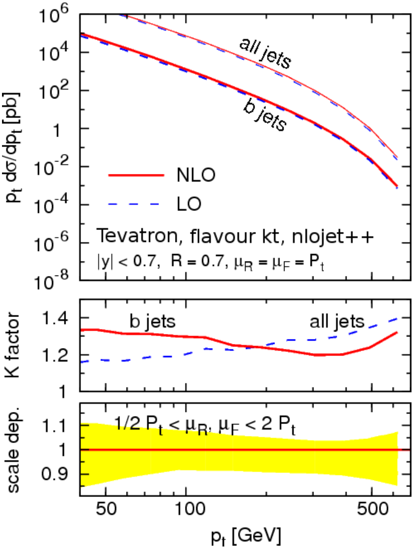

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Groundwork

- Important that multijet event shapes also be studied in DIS and e^+e^-.
  - Measurements available from LEP and HERA.
  - Theoretical comparisons now appearing — automation facilitates this.

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- New domain for "rigorous" QCD studies:
  - non-perturbative: underlying event
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Further info: hep-ph/0407287 and http://qcd-caesar.org

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