Final-state observables in QCD

Resummation vs MC simulations

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Resummation and exponentiation

- Any short distance cross section can be written as a power series in $\alpha_s(Q)$

$$d\sigma = \underbrace{d\sigma_0}_{\text{LO}} + \alpha_s \times \underbrace{d\sigma_1}_{\text{NLO}} + \alpha_s^2 \times \underbrace{d\sigma_2}_{\text{NNLO}} + \dots$$

$Q \gg \Lambda_{QCD} \Rightarrow \alpha_s(Q) \ll 1$, the above expansion is justified

- Coefficients may be large: two physical scales Q and Q_0
Large logarithms $L = \ln Q/Q_0$ from incomplete IRC real-virtual cancellations

- Resummation = reorganisation of the perturbative expansion

$$d\sigma =$$

Soft and collinear $\Rightarrow$ double logarithms $\alpha_s L^2$

Hard collinear or soft large angle $\Rightarrow$ single logarithms $\alpha_s L$

Finite virtual and exact SC phase space $\Rightarrow$ constant $C(\alpha_s)$

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$$d\sigma = 1 + \alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \dots$$

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$$d\sigma = \exp(\underbrace{L g_1(\alpha_s L)}_{\text{LL}} + \underbrace{g_2(\alpha_s L)}_{\text{NLL}} + \underbrace{\alpha_s g_3(\alpha_s L)}_{\text{NNLL}} + \dots) \times C(\alpha_s) + \text{suppressed terms}$$

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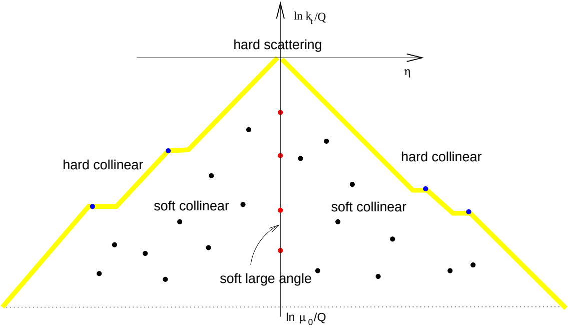
Inclusive and fi nal-state observables

Example: real and virtual corrections to DY pair production

[Collins, Soper, Sterman]



- virtual corrections are universal ⇒ exponentiation
- observable ⇔ veto on real emissions

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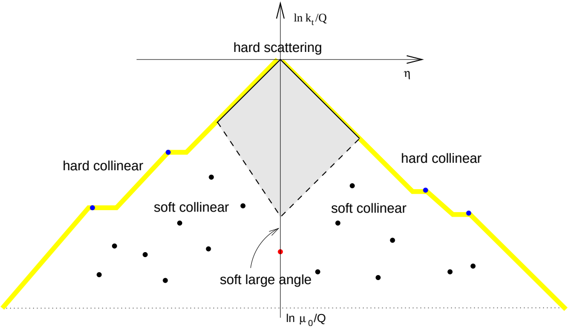

- virtual corrections are universal $\Rightarrow$ exponentiation
- observable $\Leftrightarrow$ veto on real emissions

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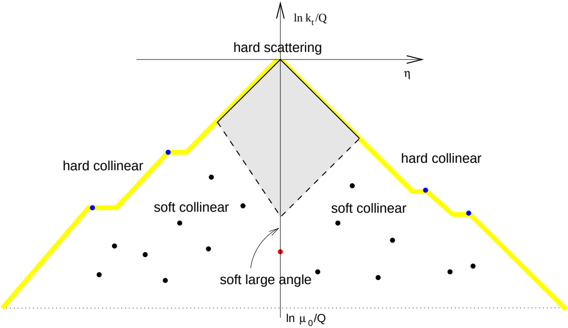

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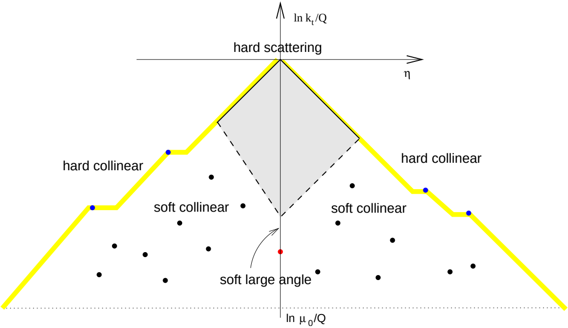

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Final-state observables

- real veto from direct measurement
- need approximated multi-parton ME

Event-shape variables

- Event-shape variables $V(p_1, \ldots, p_n)$ are continuous measures of the geometrical properties of hadron energy-momentum flow.
- Thrust: longitudinal particle alignment

$$T \equiv \frac{\max_{\vec{n}_T} \sum_i |\vec{p}_i \cdot \vec{n}_T|}{\sum_i |\vec{p}_i|} \qquad \underbrace{\Sigma(1-T)}_{\mathrm{th}} = \int_{1-T}^{1} dT \underbrace{\frac{1}{\sigma}\frac{d\sigma}{dT}}_{\mathrm{exp}} =$$

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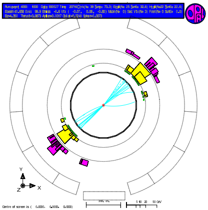
Pencil-like event: $1 - T \gtrsim 0$



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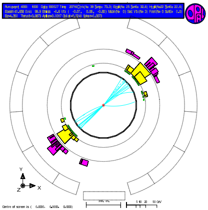
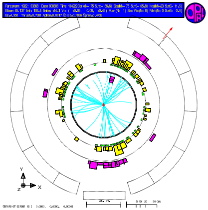


Planar event: $1 - T \simeq 1/3$



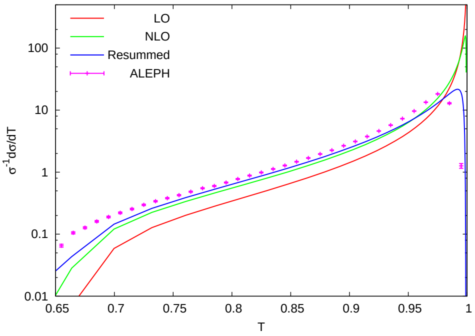
Physics of event shapes

Sensitive to QCD radiation ⇒ measure α_s

Large non-perturbative contributions

- $1/Q$ power corrections ⇒ α_s-α_0 fits
  [Dokshitzer, Dasgupta, Marchesini, Lucenti, Salam, Webber]
- MC work very well ⇒ use MC hadronisation

Useful for discovery? ⇒ No investigation yet



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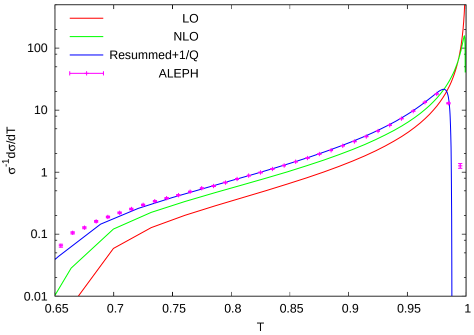

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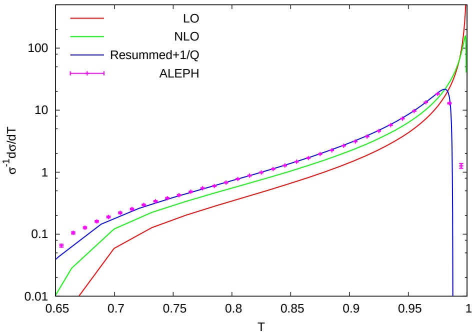

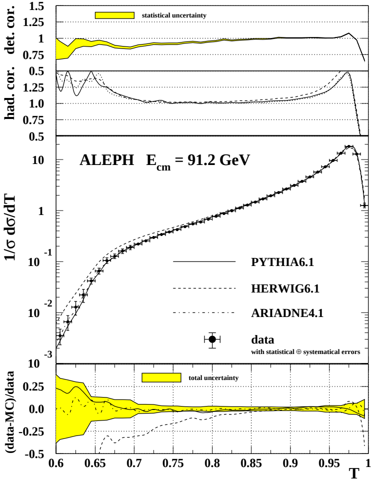

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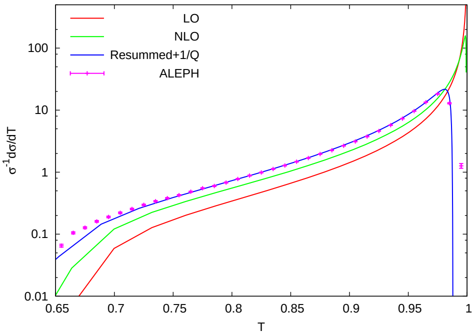

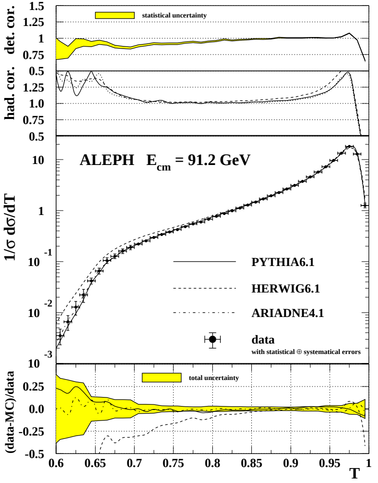

Recursive IRC safety

Exponentiation at NLL holds only for variables satisfying rIRC safety conditions

Consider $V(k_1, \ldots, k_n)$ and $V(k_i) = \zeta_i v \Rightarrow k_i$ is a function of v and ζ_i

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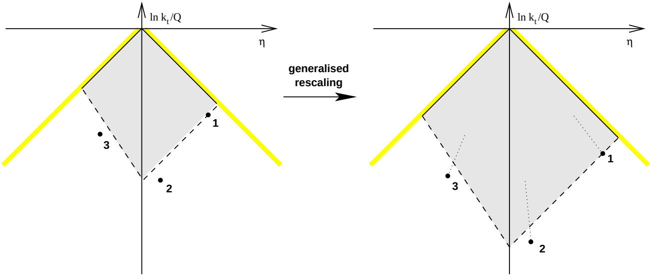

1. Observable scaling properties are the same with any number of emissions

$$\lim_{v\to 0}\frac{V(k_1,\dots,k_n)}{V(k_1)} = \text{constant} \neq 0$$

2. Addition of a soft and/or collinear particle does not modify observable scaling

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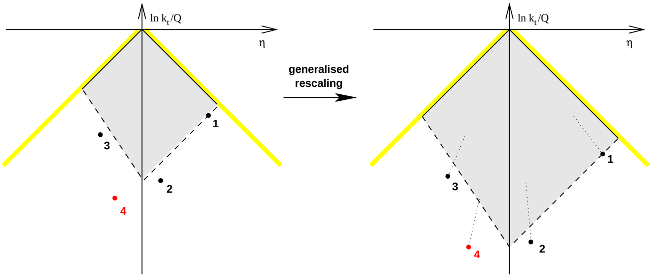

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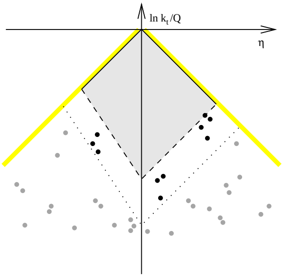
NLL resummations vs MC simulations



Event generators

- Angular ordering from hard legs
  ⇒ LL and NLL
- Secondary emissions
  ⇒ more subleading logarithm, but no control over accuracy
- Colour exact only in large N_c limit
- Missing pure virtual corrections
  ⇒ no Coulomb phases

Analytical NLL resummations

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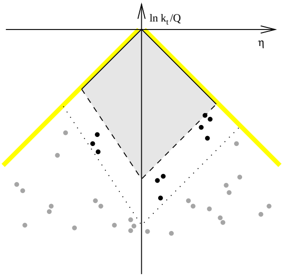

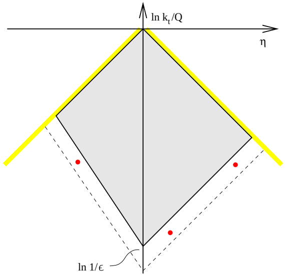

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General resummation of rIRC safe final-state observables

- Master Formula for NLL resummation of $\Sigma(v) = \mathrm{Prob}(V(k_1,\dots,k_n) < v)$

[AB, Salam, Zanderighi]

$$\Sigma(v) = e^{-R(v)}\mathcal{F}(R') \qquad R' = -v\frac{dR}{dv}$$

- Virtual corrections up to scale v in $R(v)$ $\Rightarrow$ exponentiation of LL (and part of NLL)

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

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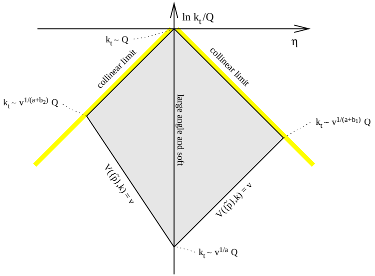

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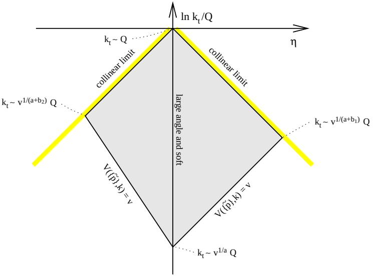

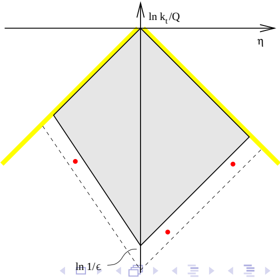

Computer Automated Expert Semi-Analytical Resummer

1. For each hard leg ℓ determine single emission parameterisation

$$V(k) \simeq d_\ell \left(\frac{k_t}{Q}\right)^a e^{-b_\ell \eta} g_\ell(\phi) \qquad 1 - T = \frac{k_t}{Q} e^{-\eta}$$

2. Perform tests of applicability, in particular rIRC safety
3. Generate emissions ordered in $V(k_i) = v\zeta_i$ with the constraint $V(k_1) = v$

$$dP(k_i(\zeta_i, \eta_i, \ell_i)) = R'_\ell \frac{d\eta_i}{\Delta\eta_i} \frac{d\phi_i}{2\pi} \frac{d\zeta_i}{\zeta_i} \left(\frac{\zeta_i}{\zeta_{i-1}}\right)^{R'}, \qquad \sum_\ell R'_\ell = R'$$

   and compute $\mathcal{F}(R')$ as the following mean value

$$\mathcal{F}(R') = \lim_{v \to 0} \left\langle \left(\frac{V(k_1, \ldots, k_n)}{V(k_1)}\right)^{-R'} \right\rangle$$

4. Evaluate the master formula, and integrate over Born configurations

Important notes:

- No need of integral transform but NLL accuracy guaranteed
- The user needs simply to provide a routine to compute $V(k_1, \ldots, k_n)$

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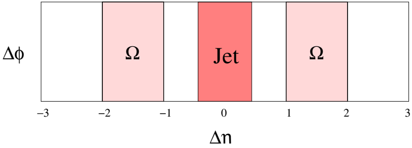
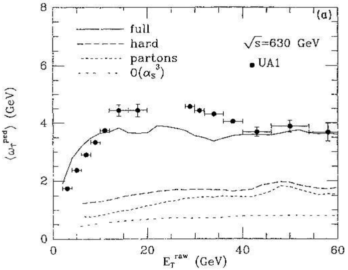
Away-from-jet E_t flow

The energy flow away from the jet region has been a subject of study for many years



$$E_t = \sum_{i \in \Omega} E_{ti} \quad i \in \text{hadrons}$$

$$\Sigma(Q_\Omega) = \int_0^{Q_\Omega} dE_t \frac{1}{\sigma} \frac{d\sigma}{dE_t}$$



- Soft underlying event in hadronic collisions
- Dijet rapidity gaps in photoproduction
- Current-hemisphere jet-shapes in DIS

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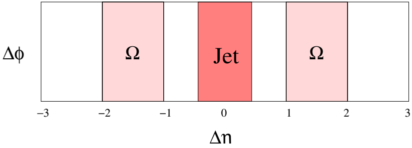

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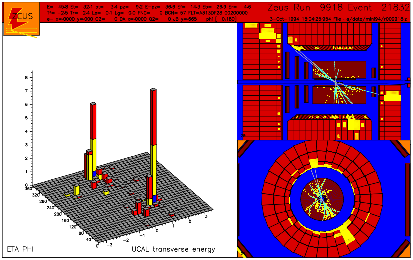

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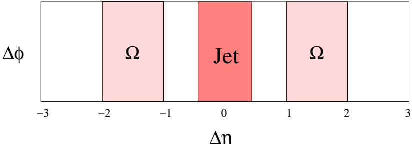

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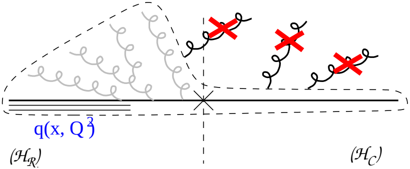

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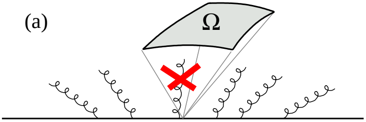
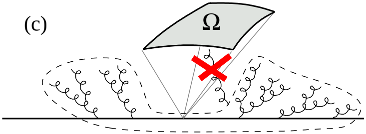
Non-global logarithms

The E_t flow is a non-global variable, measures particles in a restricted region Ω



Global variable $\Rightarrow$ Independent emission from primary partons!



Non-global variable $\Rightarrow$ Coherent emission from all partons!

- Evolution variable $t \sim \alpha_s \ln \frac{Q}{Q_\Omega}$

$$\Sigma_\Omega(t) = \Sigma_P(t) \times S(t)$$

Note: LL are single logarithms

- Primary emission

$$\Sigma_P(t) = \exp\{-4 \times \mathrm{Area}_\Omega \times t\}$$

- Non-global logarithms in $S(t)$

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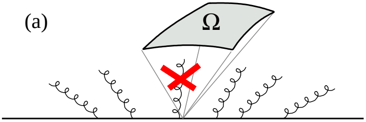

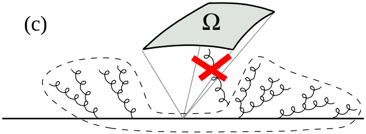

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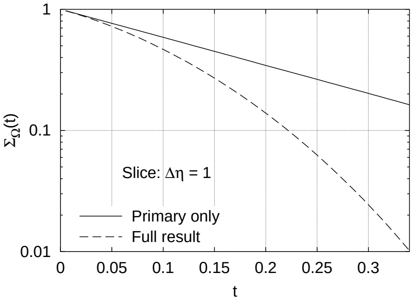

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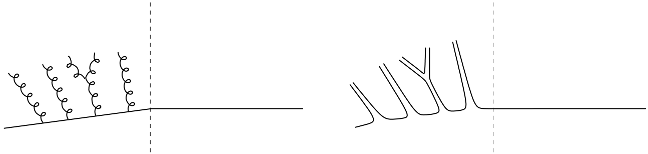
MC resummation of non-global logarithms

- Resummation of NG logs is performed in the large N_c limit via a dipole MC

[Dasgupta,Salam]



- Emissions are ordered in $t \sim \alpha_s \ln Q/k_t$, and a gluon k_i is emitted from a dipole j in the dipole back-to-back frame with a probability

$$dP(k_i(t_i,\eta_i,\phi_i)) = 2C_A\, d\eta_i \Theta\left(\frac{\Delta\eta_j}{2} - |\eta_i|\right) \frac{d\phi_i}{2\pi}\, dt_i \left(\frac{t_i}{t_{i-1}}\right)^{2C_A \Delta\eta_{\rm tot}}$$

$\Delta\eta_j$ is a collinear cutoff and $\Delta\eta_{\rm tot} = \sum_j \Delta\eta_j$

- After boost in the lab frame, if $k_i \in \Omega$, the bin $t = t_i$ is filled, and a new configuration is generated
- When the MC stops we have reconstructed the distribution $d\Sigma/dt$ at LL accuracy

Non-global logarithms: resummation vs HERWIG

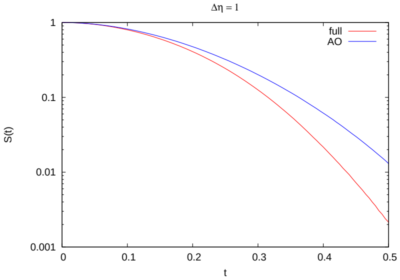
- Modify emission probability of gluon k with angular ordering

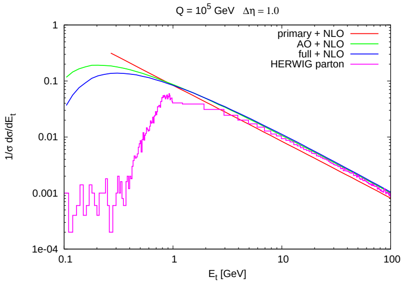
[AB, Corcella, Dasgupta]

$$\frac{1-\cos\theta_{ab}}{(1-\cos\theta_{ak})(1-\cos\theta_{kb})} \to \left[\frac{\Theta(\cos\theta_{ak}-\cos\theta_{ab})}{1-\cos\theta_{ak}} + \frac{\Theta(\cos\theta_{kb}-\cos\theta_{ab})}{1-\cos\theta_{kb}}\right]$$

The resummation MC remains the same, different Lorentz transform to the lab

- AO is close to full distribution and not to $\Sigma_P(t) \Rightarrow$ HERWIG describes well $d\sigma/dE_t$





- Radiation suppression is single-logarithmic $\Rightarrow$ sensitivity to shower cutoff

Super-leading logarithms

- Are leading logarithms for E_t flow are always single logarithms?
- The answer is NO: in hadron-hadron collisions super-leading logarithms
  [Forshaw, Kyrieleis, Seymour]
- k_1 incoming and collinear + k_2 in a gap Y + non-cancelling Coulomb phases

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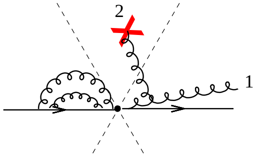

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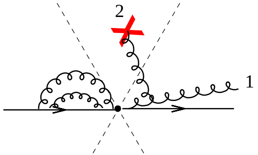

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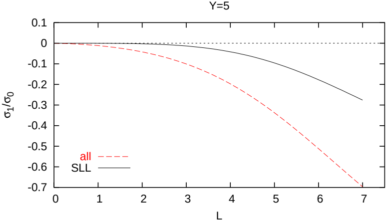

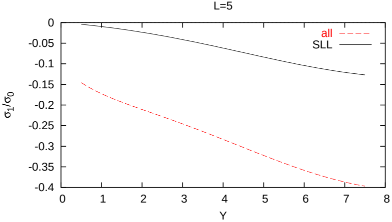

Conclusions and outlook

Conclusions

- rIRC safety is the condition that determines resummability
  [AB, Salam, Zanderighi]
- CAESAR is now a powerful tool to resum rIRC safe observables
- A lot of work is in progress to understand NG observables
  - Connection with small-x physics in saturation regime
    [AB, Marchesini, Smye]
    [Marchesini, Mueller]
    [Marchesini, Onofri]
  - Impact of k_t algorithm on non-global logs $\Rightarrow$ fundamental for jet cross sections
    [Appleby, Seymour]
    [Appleby, AB, Dasgupta, Delenda]
  - Superleading logarithms in hadronic collisions?
    [Forshaw, Kyrieleis, Seymour]

For coming year . . .

- NLL+NLO analysis of event shapes in hadron-hadron collisions (CAESAR v1.0)
- Resummation of dijet cross sections ($\Delta\phi_{JJ}$ near π)