Summary of working group on

Multi-jet final states and energy flows

Part II

Giulia Zanderighi

Many talks in common sessions with MC tools Underlying Events, PDFs and diffraction working groups. Most of those talks not covered here.

Many talks in common sessions with MC tools Underlying Events, PDFs and diffraction working groups. Most of those talks not covered here.

Talks summarized here – PART I (Leif Lonnblad)

- ✗ The Underlying Event at the LHC [Fano]
- ✗ The Underlying Event at ZEUS [Namsoo]
- ✗ How to subtract the underlying event from jets? [Starovoitov]
- ✗ Sensitivity of μ isolation cut efficiency to UE uncertainty [Drozdetskiy]
- ✗ Low x physics studies using the hadronic final state from H1 [Traynor]
- ✗ New results from jet physics at HERA [Gwenlan]
- ✗ Prompt Photons at HERA [Mueller]

Many talks in common sessions with MC tools Underlying Events, PDFs and diffraction working groups. Most of those talks not covered here.

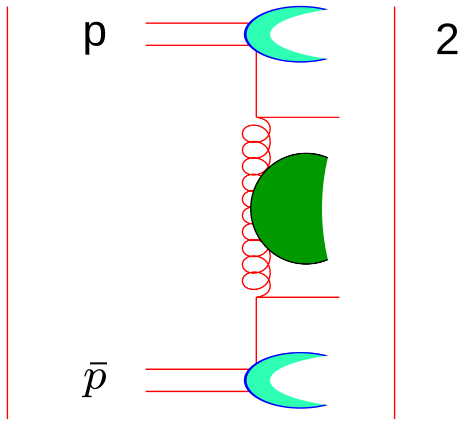
Talks summarized here – PART II

- ✗ Angular decorrelations of Mueller-Navelet Jets at NLO [Sabio-Vera]
- ✗ Towards the fully exclusive NLL BFKL evolution [Anderson]
- ✗ New fits to uPDFs [Jung]
- ✗ Jet algorithms & energy flows - log surprises [Dasgupta]
- ✗ IR safe determination of jet flavour at parton level [Banfi]
- ✗ Super-leading logs in energy-flow observables [Kyrieleis]

Consider inclusive dijet production in the limit

$$s \gg p_{t1}^2 \sim p_{t2}^2 \sim p_t$$

$$Y \sim \ln \frac{x_1 x_2 s}{p_t^2} \ll 1$$

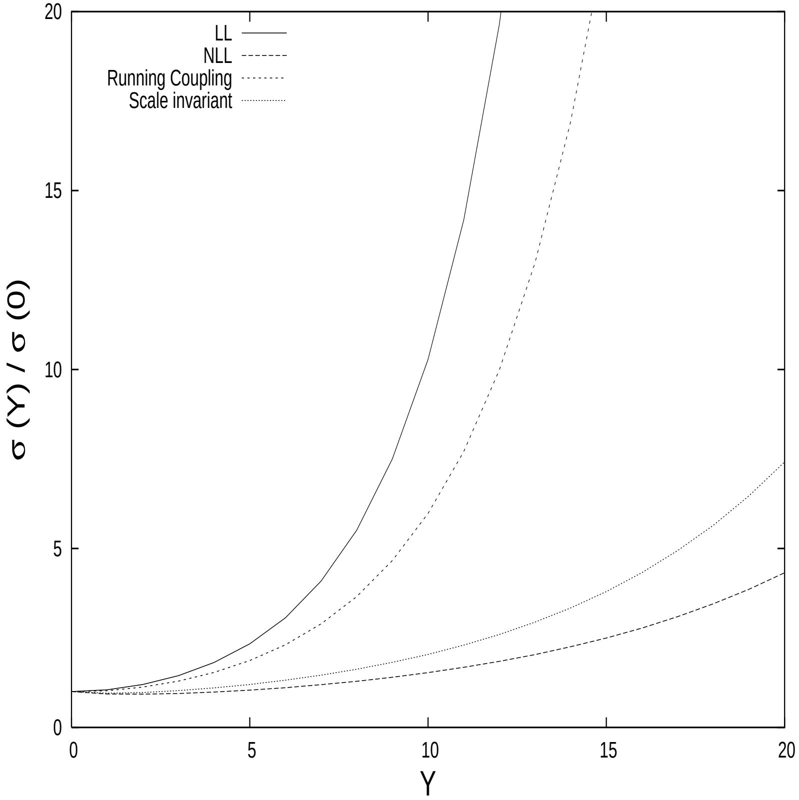


Analytical study of angle decorrelation between most forward and most backward jets the with next–to–leading corrections to the BFKL kernel [while keeping the jet vertices at leading order]

[Sabio-Vera]

Angular decorrelations of Mueller-Navelet Jets at NLO

Evolution of the partonic cross section with the rapidity separation of dijets

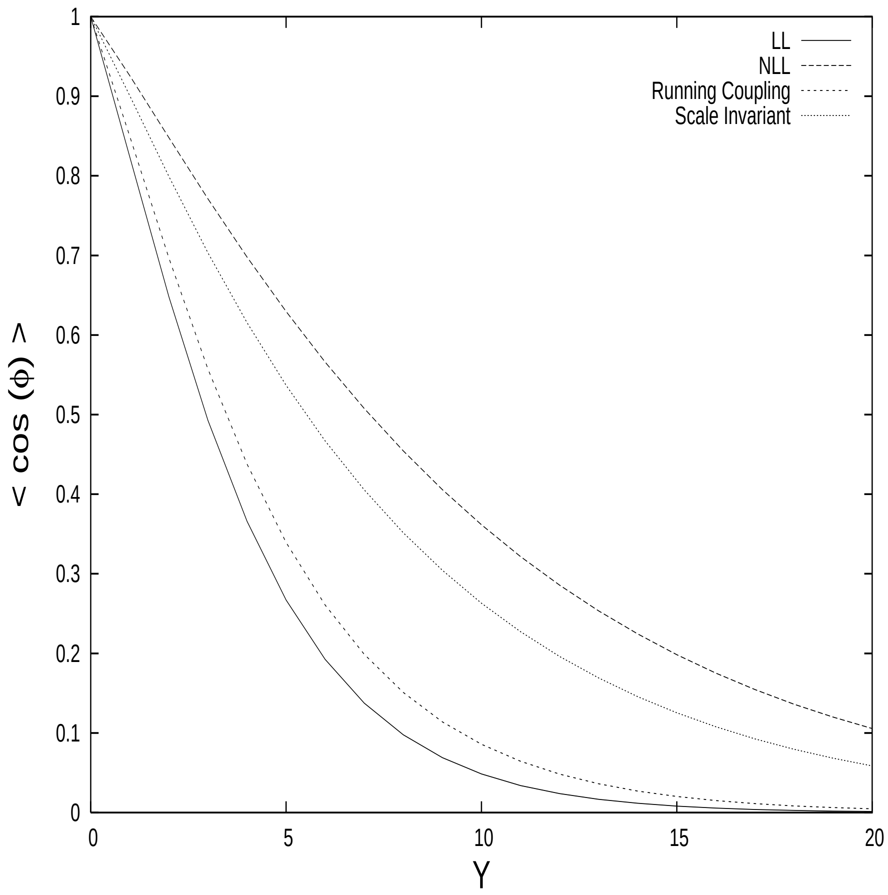


⇒ rise of cross section with rapidity distance

⇒ NLL intercept much reduced compared to LL case

[Sabio-Vera]

Angular decorrelations of Mueller-Navelet Jets at NLO

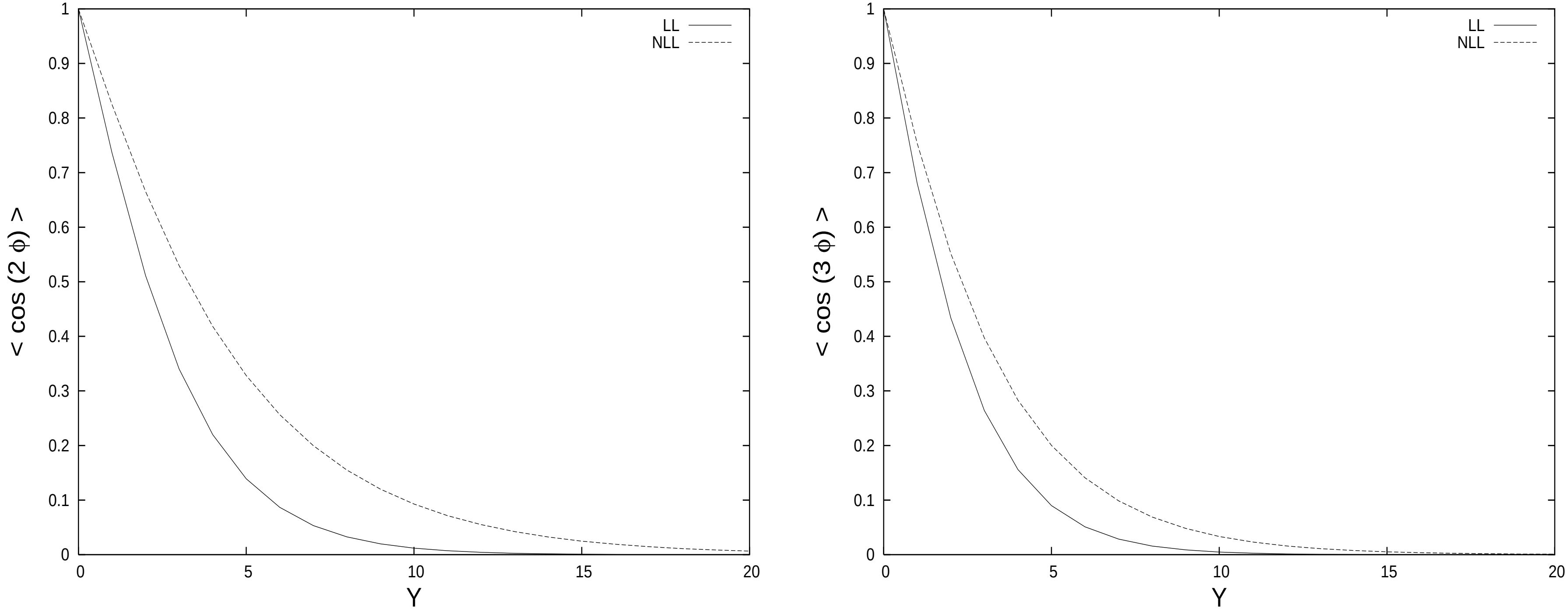


⇒ computed analytically

⇒ NLL decrease dramatically decorrelations

[Sabio-Vera]

Angular decorrelations of Mueller-Navelet Jets at NLO



➥ possible to study ratios which have reduced uncertainties

$$R_{m,n} = \frac{\langle \cos(m\phi) \rangle}{\langle \cos(n\phi) \rangle}$$

[Sabio-Vera]

[Sabio-Vera]

General features: NLL have less decorrelation compared to LL, much better description of Tevatron data with just $\langle \cos(m\phi) \rangle$ by hand $+$ simple assumptions (waiting to see the plots!)

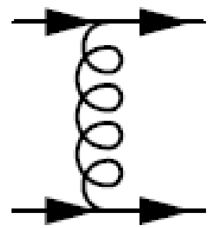
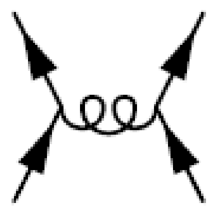
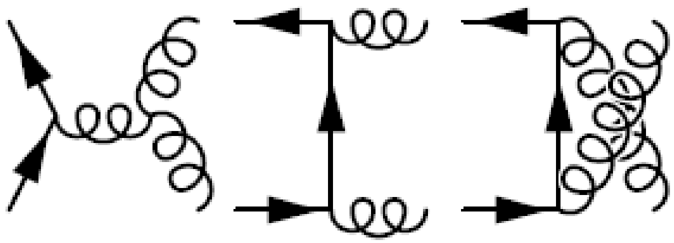
Room for improvement:

energy/momentum conservation?

higher order jet vertices?

. . .

The High Energy Limit of Fixed Order Matrix Elements

Process	Diagrams	$\overline{\sum} \lvert\mathcal{M}\rvert^2/g^4$
$qq' \to qq'$		$\frac{4}{9}\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}$
$q\bar{q} \to q'\bar{q}'$		$\frac{4}{9}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$
$q\bar{q} \to gg$		$\frac{32}{27}\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}} - \frac{8}{3}\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}$

High Energy Limit: $\lvert\hat{t}\rvert$ fixed, $\hat{s} \to \infty$

Observations

- In the limit of large rapidity spans, the fixed order matrix elements are dominated by contributions from diagrams with a t-channel gluon exchange
- This limit will be called The High Energy Limit and is generally characterised by the following phase space configuration of the final state particles

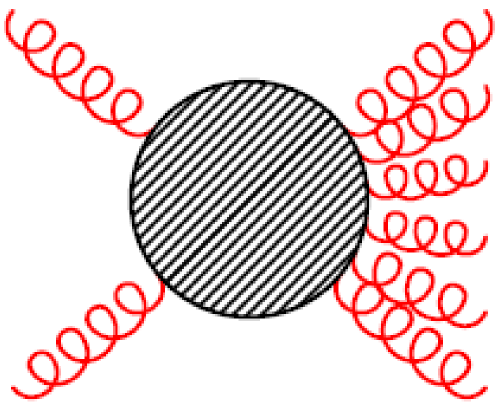
$$y_0 > y_1 > \cdots > y_n > y_{n+1}, \quad |k_0| \sim |k_i| \sim |k_{n+1}|$$

i.e. multiple, isolated, hard parton production (multiple jets)

- Good agreement ($\sim$ 10%) with the full, fixed order result in the relevant limit

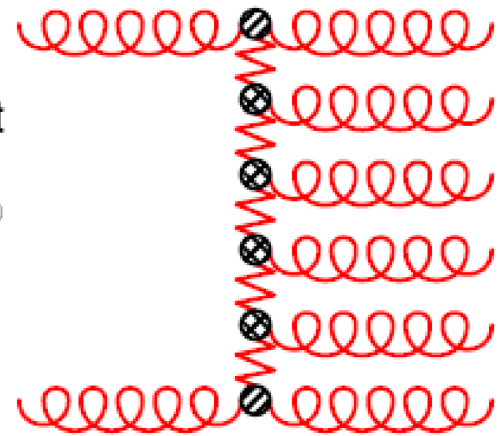
The Possibility for Prediction of *n*-jet Rates

The Power of Reggeisation



High Energy Limit

$$|\hat{t}| \quad \text{fixed}, \quad \hat{s} \to \infty$$



$$\mathcal{A}^R_{2\to 2+n} = \Gamma_{A'A} \left(\prod_{i=1}^{n} \frac{e^{\omega(q_i)(y_{i-1}-y_i)}}{q_i^2} V^{J_i}(q_i, q_{i+1}) \right) \frac{e^{\omega(q_{n+1})(y_n - y_{n+1})}}{q_{n+1}^2} \Gamma_{B'B}$$

$$\mathbf{q}_i = \mathbf{k}_a + \sum_{l=1}^{i-1} \mathbf{k}_l$$

At LL only gluon production; at NLL also quark–anti-quark pairs produced.

Prediction of any-jet rate possible.

Reggeisation and the BFKL Equation

The **evolution of the reggeised gluon** is described by the BFKL equation

$$\omega f_\omega\left(\mathbf{k}_a,\mathbf{k}_b\right)=\delta^{(2+2\epsilon)}\left(\mathbf{k}_a-\mathbf{k}_b\right)+\int d^{2+2\epsilon}\mathbf{k}'\mathcal{K}_\epsilon\left(\mathbf{k}_a,\mathbf{k}'\right)f_\omega\left(\mathbf{k}',\mathbf{k}_b\right)$$

ω: Mellin conjugated variable to the rapidity y along the evolution.

- The kernel $\mathcal{K}_\epsilon$ consists of the **virtual** corrections of the trajectory and the **real** corrections from the Lipatov vertices.
- The BFKL equation provides a very convenient framework for organising the divergences in the factorised form of the $|\mathcal{M}|^2$ on the previous slide.

Direct BFKL Evolution, 3

1. Choose a random number of vertices for the evolution, $n \geq 0$
2. Generate a set $\{\mathbf{k}_i\}_{i=1,\ldots,n}$ of transverse momenta (the outgoing momenta are $\{-\mathbf{k}_i\}_{i=1,\ldots,n}$)
3. Calculate the corresponding set of trajectories $\{\omega(\mathbf{q}_i)\}_{i=1,\ldots,n+1}$, and vertex factors $\{V(\mathbf{q}_i,\mathbf{q}_{i+1})\}_{i=1,\ldots,n}$, $\mathbf{q}_i = k_a + \sum_{l=1}^{i-1} \mathbf{k}_l$
4. Generate the inter-vertex rapidity separations $\{\delta y_i\}$ according to the distributions $e^{\omega(\mathbf{q}_i)\delta y_i}$
5. Calculate the corresponding $\Delta = \sum_{i=1}^{n+1} \delta y_i$ and return $\prod_{i=1}^{n} V(\mathbf{q}_i,\mathbf{q}_{i+1})$

Can construct full final state[2]! Trivial to impose energy and momentum conservation and do **proper jet studies**.

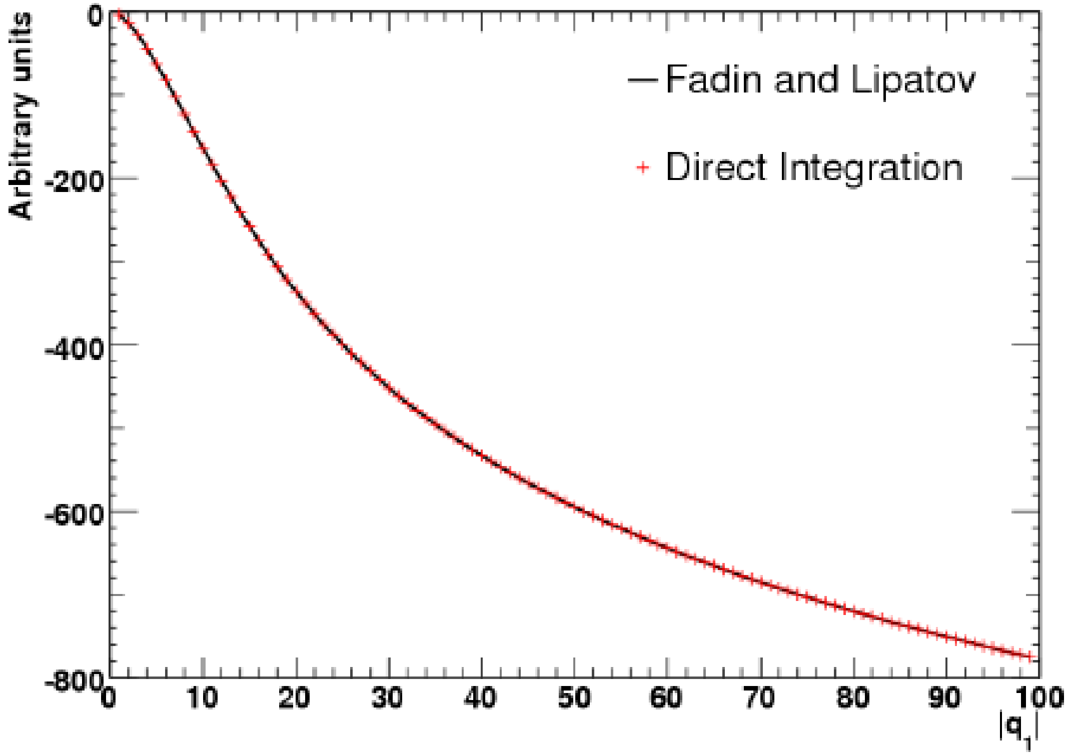
[2] See later

Observation

1. Imposing Energy and Momentum conservation (i.e. restricting phase space integral to that accessible at a given energy) is completely unrelated to the NLL corrections to the evolution.
2. To calculate an observable to full NLL accuracy, three ingredients are necessary:
   - NLL Impact Factors
   - NLL Evolution
   - Energy and Momentum Conservation

First Check. . .

Check of finite part



$1/N_c^2$ suppressed terms: 100% agreement.
Calculation under control.

Summary and Conclusions

- Have constructed a **very efficient** method for obtaining the BFKL evolution as an approximation to multi-leg processes
  Also applicable to small-x studies etc.
- Have started the program to obtain **fully exclusive final state information** of the NLL BFKL Evolution **necessary for** energy and momentum conservation and thus **full NLL accuracy**
- Conclusion from the study of the exclusive NLL quark–anti-quark vertex:
  Exclusive information absolutely **crucial for realistic phenomenology**, since the $q\bar{q}$-vertex gets contributions from relatively large invariant masses of the $q\bar{q}$-pair.
  Cannot assign a single rapidity to the quark and the anti-quark.
- `http://www.hep.phy.cam.ac.uk/~andersen/BFKL`

New fits to uPDFs

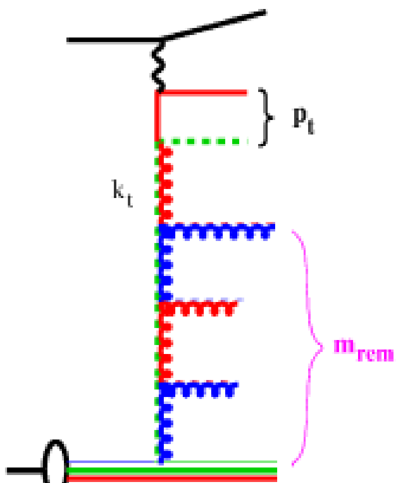
H. Jung (DESY)

- Motivation: why full event information is needed for PDF fits
- Fit method
  - full event simulation and parton evolution
  - FULLFIT instead of FASTNLO
- Example application to uPDF
  - using CCFM to fit F_2, F_2^c and charm photoproduction
- Apologies...
  - talk more about intentions rather than results...
  - results will come for proceedings ...

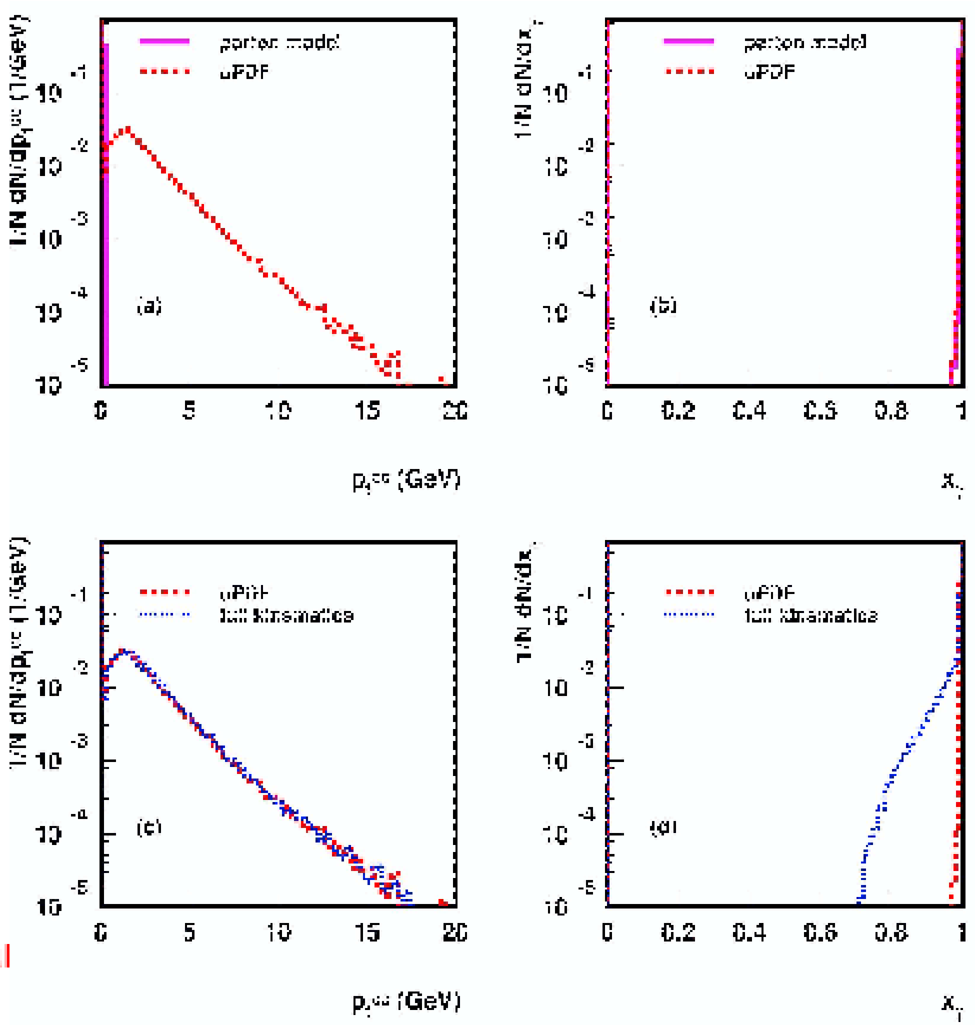
Need for uPDFs

Define:

- $p_{T\,q\bar{q}}$
- $x_\gamma = \frac{\sum_{i=q,\bar{q}}(E_i - p_{z\ i})}{2yE_e} = \frac{p^-_{q\bar{q}}}{q^-}$



J. Collins, H. Jung



- parton kinematics
- uPDFs
- full kinematics

➔ history is needed for long. and trai components

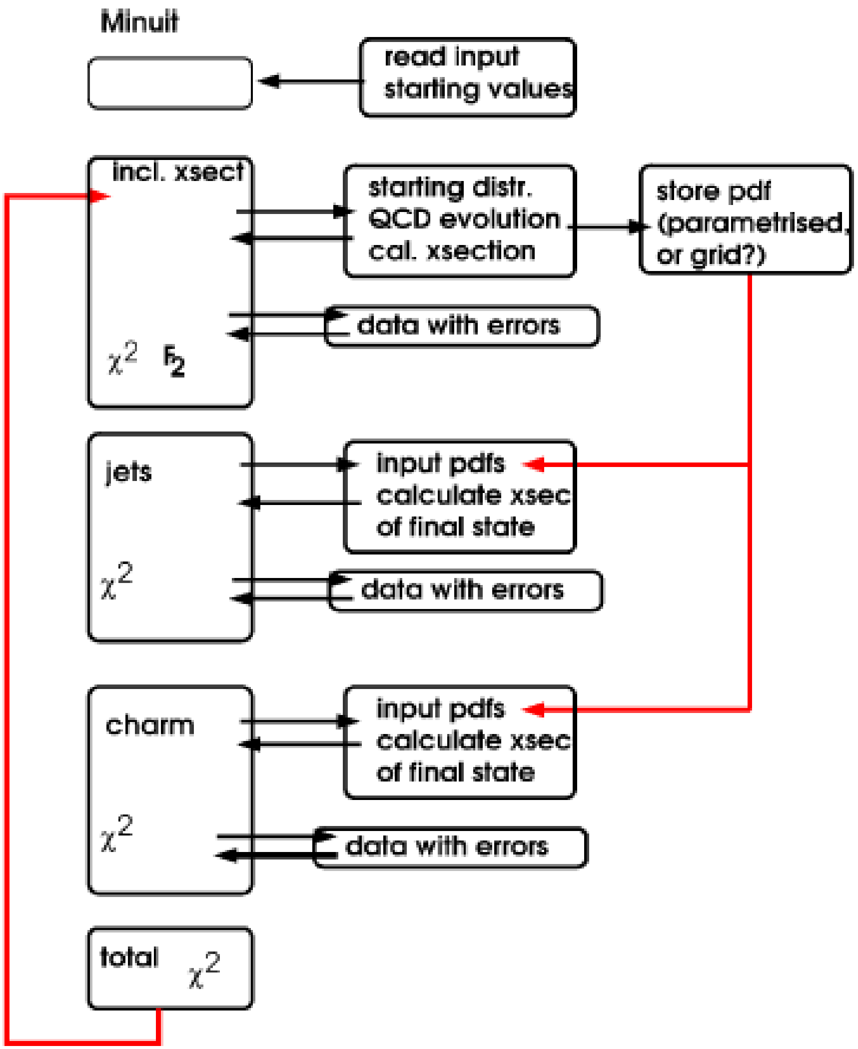
Need for fully uPDFs

- full kinematics can only be described by fully (double) uPDFs
- dependence on k_t^2 and k^2
- reformulate pQCD methods in terms of fully uPDFs
- extension of $k_{t\ factorization}$
- Advantages:
  - kinematics correct already at LO
  - NLO corrections much smaller (BFKL example: 70 % from kinematics)
  - no need for separate methods (resummation or the CCS (Collins Soper Sterman))
  - unified treatment of ME calcs and MC generators

Different steps of approximations

- fully uPDFs
- uPDFs ($k_{t\ factorization}$)
- integrated PDFs + parton showers
- integrated PDFs + fixed order calculations in LO and NLO

PDF fit - program



Goals for PDF fits:

- fit inclusive and exclusive measurements
- using as many measurements as possible ... which can constrain the PDFs
- → HZTool
- using full information of final states
- → MC@NLO or similar
- → CASCADE
- consistent treatment of experimental and theoretical errors

Method to fit incl. and final states

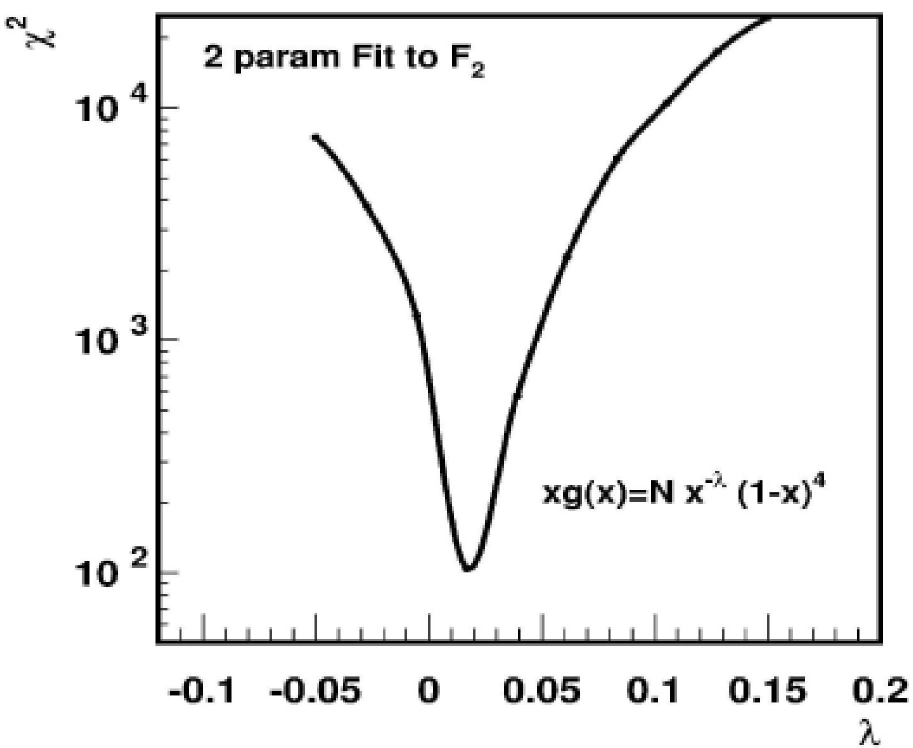
- Use full information of inclusive and final state measurements (using HZTOOL – histograms of predictions and measurements)
- Use full event simulation including parton showering and hadronization
- Method for uPDF a la CCFM:
  - generate grid file for $\tilde{\mathcal{A}}(x, k_\perp, \bar{q})$
  - use convolution with starting distribution $\mathcal{A}_0(x_0)$ to obtain full PDF:

$$x\mathcal{A}(x, k_\perp, \bar{q}) = \int dx_0 \mathcal{A}_0(x_0) \cdot \frac{x}{x_0} \tilde{\mathcal{A}}\left(\frac{x}{x_0}, k_\perp, \bar{q}\right)$$

  - simulate for many events
  - calculate chi**2 for different processes
- General purpose fitting procedure, can be applied also to DGLAP type fits and in collinear factorization
- Does not rely on any approximation or pre-calculation !!!

Fit to F_2 data

- Define $$\chi^2 = \sum_i \left(\frac{\left(T - D - \sum_j \alpha_j \Delta_j^{sys}\right)^2}{\sigma_i^{2\ stat} + \sigma_i^{2\ uncor} + \sigma^{2\ T}} \right) + \sum_j \alpha_j^2$$
- using offset method:
  - set $\alpha_j = 0$ for calculation of central value
  - later use $\alpha_j = \pm 1$ for calculation of uncertainty
- fit parameters of starting distribution
  $$xg(x, \mu_0^2) = N x^{-\lambda} \cdot (1-x)^4$$
- using F_2 data H1 (H1 Eur. Phys. J. C21 (2001) 33-61, DESY 00-181)
  - $x < 0.005 \ Q^2 > 5 \ \mathrm{GeV}^2$
- Fit result: $\lambda = 0.018 \pm 0.003$



Fit results

Fit details:

- using full splitting function in CCFM including non-singular terms
- using proper
  - still only one-loop $\alpha_s(M_Z)$

Results so far:

- no dependence on (1-x) parameters observed (fit only $x<0.005$) fix to $\sim(1-x)^4$
- using stat and uncorr syst errors for fit
- $\chi^2/ndf \sim 1$ much better than before ....
- with different $\alpha_s(M_Z)$, k_t dependence of uPDF also different

NEW:

- fit of initial parameters $xg(x,\mu_0^2) = Nx^{-\lambda} \cdot (1-x)^4$

TO DO

- study of experimental uncertainties
- systematic study of theory parameters

Conclusion

- Full treatment of kinematics in fits to PDFs necessary
  - at least if less inclusive quantities are investigated
- Fit method including full evolution and event generation works !
  - although slow and needs improvements
- Method applicable for all kinds of QCD evolution and measurements implemented in HZTOOL - package
- Example application - reasonable results for inclusive quantities:
  - F_2, F_2^c, photoproduction of charm

→ **Making full use of all relevant experimental measurements !**

→ **Consistent set of uPDFs from inclusive and final states** (with proper kinematics) **!**

Quark and gluon jets

- In the literature 376 papers with ‘quark/gluon jet’ in title
- Physically a quark/gluon jet = a jet initiated by a quark/gluon
- Experimentalists try determination of jet flavour
  - Discriminate quark/gluon jets using kinematical properties [jet profile, subjet multiplicity]
  - Jet charge = weighted charge of particles in a jet

$$Q_{\rm jet} = \sum_{i \in {\rm jet}} q_{ti} Q_i / \sum_{i \in {\rm jet}} q_{ti}$$

All experimental definitions are practical but IR unsafe

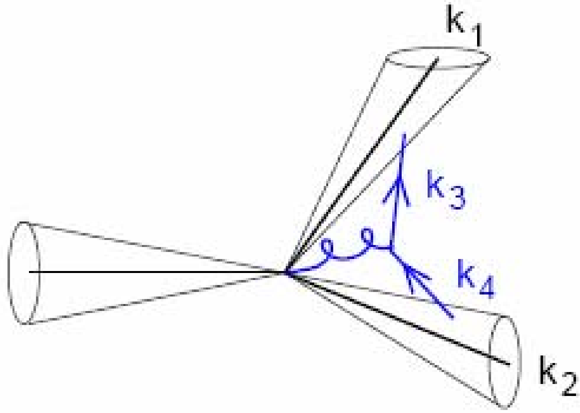
- Hints of theoretical problems in IR safety and flavour
  - Feynman is alleged to have said “impossible”
  - Flavour insensitive definition of observable suggested [Nagy, Soper]

Jet flavour and infrared safety

At NLO any IR safe jet algorithm is also an IR safe flavour algorithm

- Soft/collinear gluons do not change the flavour
- Collinear $q\bar{q}$ pairs are always recombined together

Beyond NLO soft large angle $q\bar{q}$ pairs can be clustered into different jets thus spoiling the reconstruction of jet flavour



IR safety $\Leftrightarrow$ soft quarks and hard partons never recombined

Jet flavour algorithms in e^+e^-

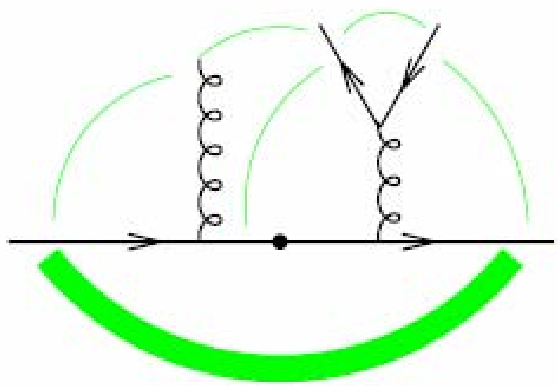
Durham algorithm

- Soft gluon emission $g \to g_i g_j$

$$[dk_j]|M^2(k_j)| \sim \frac{dE_j}{\min(E_i, E_j)} \frac{d\theta_{ij}^2}{\theta_{ij}^2}$$

- $d_{ij}^{(D)} \to 0$ for $\theta_{ij} \to 0$ and $E_j \to 0$

$$d_{ij}^{(D)} = 2(1 - \cos\theta_{ij}) \times \min(E_i^2, E_j^2)$$



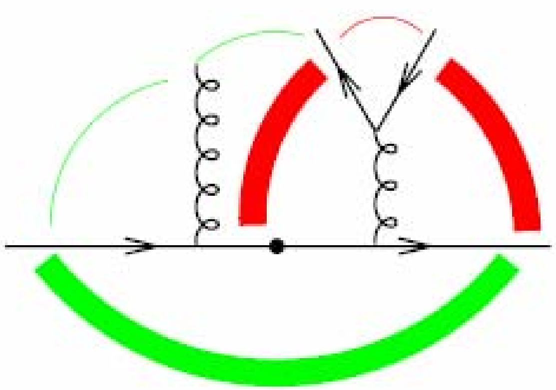
Flavour algorithm

- $q\bar{q}$ splitting $g \to q_i q_j$

$$[dk_j]|M^2(k_j)| \sim \frac{dE_j}{\max(E_i, E_j)} \frac{d\theta_{ij}^2}{\theta_{ij}^2}$$

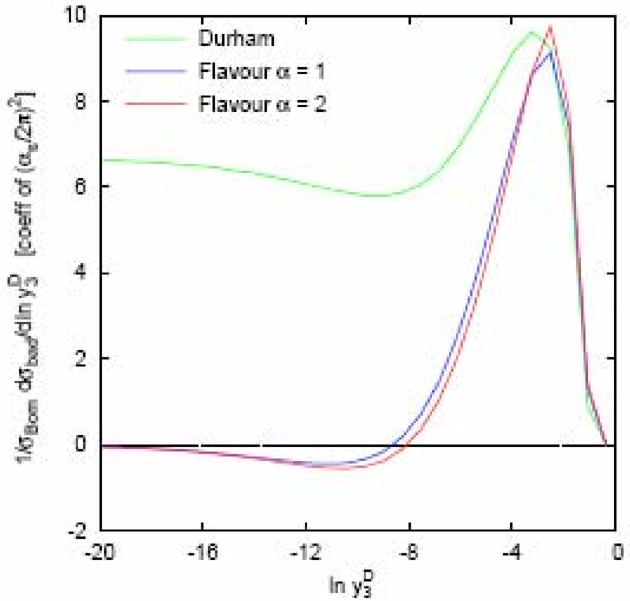
- $d_{ij}^{(F)} \to 0$ for $\theta_{ij} \to 0$ only

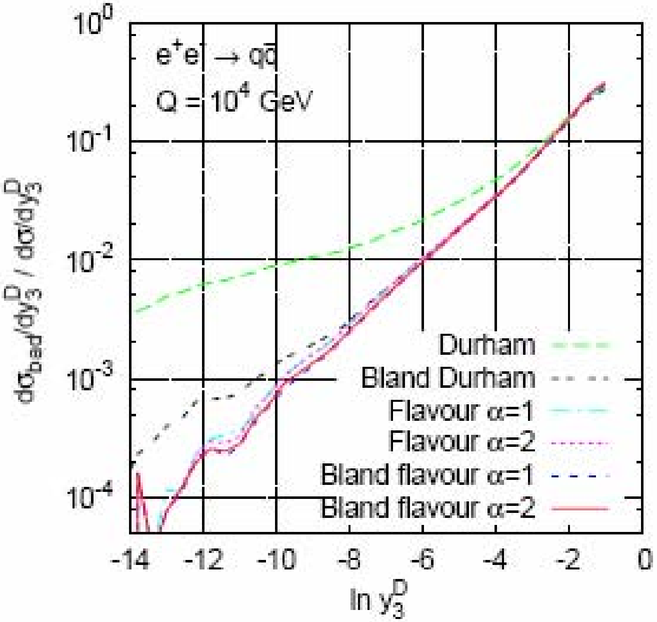
$$d_{ij}^{(F)} = 2(1 - \cos\theta_{ij}) \times \max(E_i^2, E_j^2)$$



Tests of IR safety in e^+e^- annihilation

- Generate multi-parton configurations in e^+e^- and cluster to 2 jets
- Compute fraction of misidentified events $\sigma_{\rm bad}$ as a function of y_3^D
- IR safety at fixed order (EVENT2) $\Leftrightarrow$ $\sigma_{\rm bad}$ vanishes for $y_3 \to 0$
- IR safety at all orders (HERWIG) $\Leftrightarrow$ different scalings for $y_3 \to 0$





Jet flavour in hadron-hadron collisions

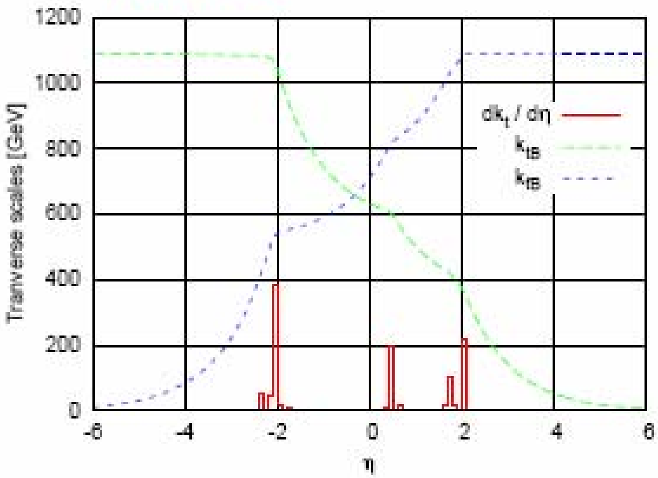
- Distance d_{ij} is modified to have boost invariance

$$d_{ij}^{(F)} = (\Delta\eta_{ij}^2 + \Delta\phi_{ij}^2) \times \begin{cases} \max(k_{ti}, k_{tj})^{\alpha} \min(k_{ti}, k_{tj})^{2-\alpha} & \text{softer of } i, j \text{ flavoured} \\ \min(k_{ti}^2, k_{tj}^2) & \text{softer of } i, j \text{ flavourless} \end{cases}$$

- Need a distance wrt B $(\eta \to \infty)$ and $\bar{B}$ $(\eta \to -\infty)$

$$d_{iB}^{(F)} = \begin{cases} \max(k_{ti}, k_{tB}(\eta_i))^{\alpha} \min(k_{ti}, k_{tB}(\eta_i))^{2-\alpha} & i \text{ flavoured} \\ \min(k_{ti}^2, k_{tB}^2(\eta_i)) & i \text{ flavourless} \end{cases}$$

- $k_{tB}(\eta)$ and $k_{tB}(\eta)$ monotonic functions of η that saturate at the typical hardness of the event

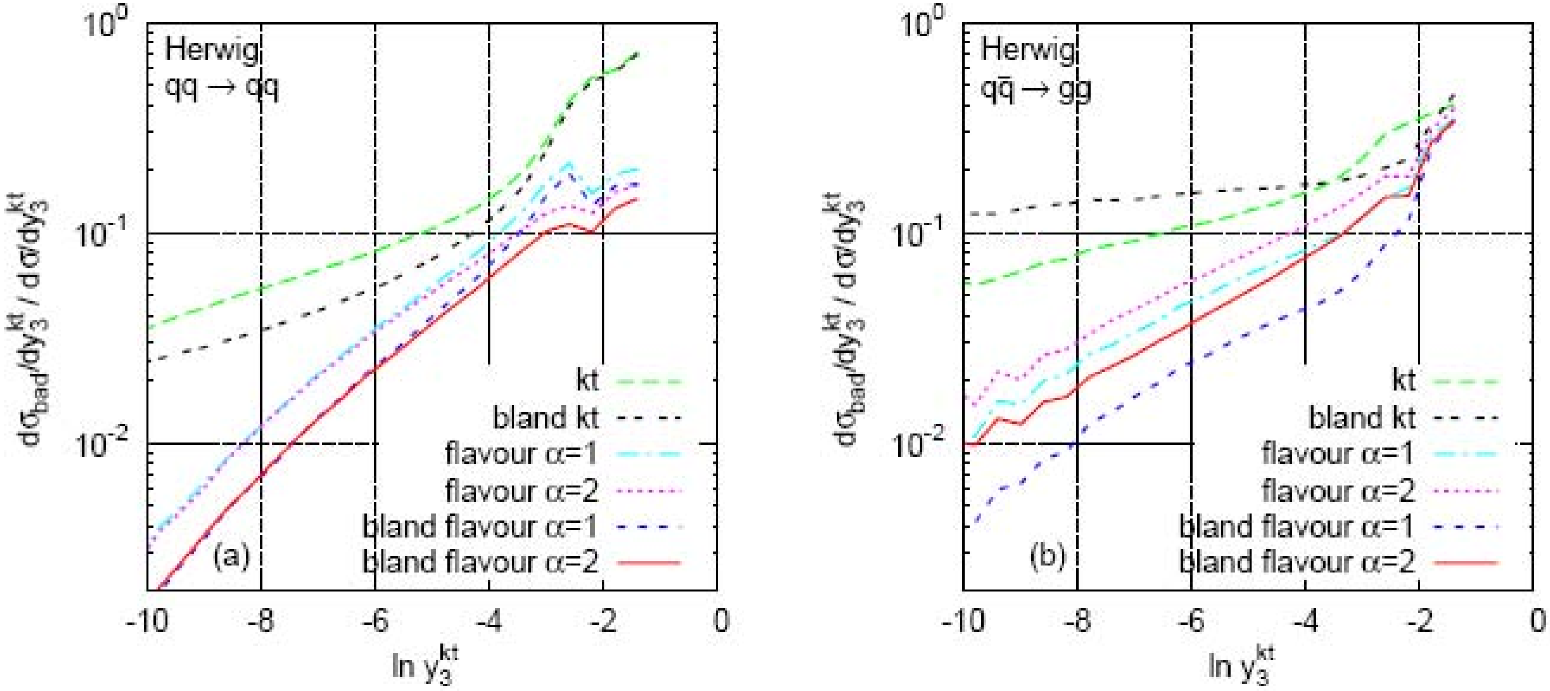


$$k_{tB} = \sum_i k_{ti}(\Theta(\eta_i - \eta) + \Theta(\eta - \eta_i) e^{\eta_i - \eta})$$

$$k_{tB} = \sum_i k_{ti}(\Theta(\eta - \eta_i) + \Theta(\eta_i - \eta) e^{\eta - \eta_i})$$

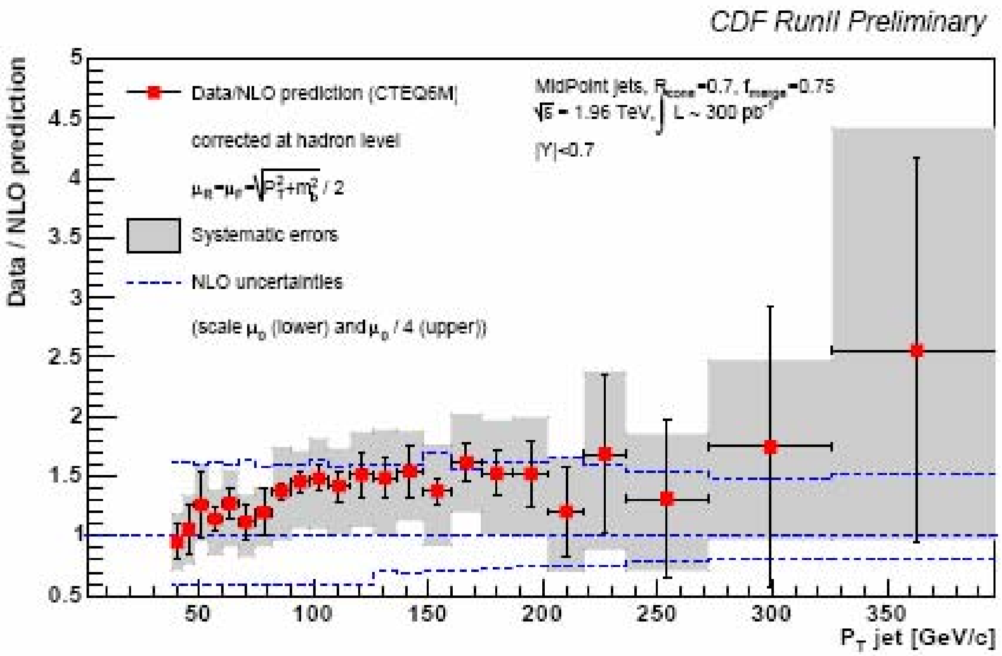
Tests of IR safety in hadron-hadron collisions

- IR safety tests impossible at fixed order at the moment
  - Missing flavour information in fixed order programs
  - Missing two-loop virtual correction to each subprocess
- Tests with HERWIG ⇒ Importance of flavour blandness



Heavy-flavour jets

- The algorithm has been designed to work at parton level
- At hadron level the algorithm can be used for heavy flavour jets
- Experimental definition of b-jet = jet containing b-flavour
- Comparisons to NLO of inclusive p_T spectra have large renormalisation scale uncertainties ($\sim 40-50\%$)



Definitions

One way of quantitatively describing gaps between hard jets is in terms of E_t flow into the gap. Thus we study the differential distribution

$$\frac{1}{\sigma}\frac{d\sigma}{dQ_\Omega}.$$

Q_Ω is sum over E_t of emissions inside the gap :

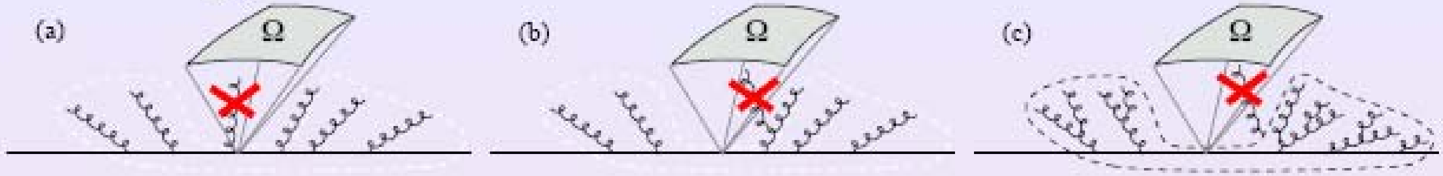
$$Q_\Omega = \sum_{i\in\Omega} E_{t,i}.$$

Here the sum can refer to either a sum over hadrons or a sum over minijets in the gap. Minijets are soft jets obtained after running a jet algorithm e.g k_t clustering. Commonly used definition experimentally (H1 ,ZEUS).

tu-logo

ur-logo

Since $Q_\Omega \ll Q$ one must resum large single-logarithms $\alpha_S(Q) \ln \frac{Q}{Q_\Omega}$ for reasonable theoretical description.



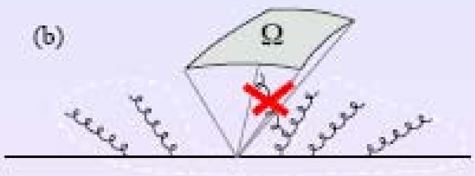
Problem with theoretical description of such observables uncovered some years ago. They are non-global in nature.

M. Dasgupta and G.P. Salam, 2002

If Q_Ω is defined in terms of the hadronic energies in the gap rather than minijet energies result is

$$\frac{d\sigma}{dQ_\Omega} = \frac{d}{dQ_\Omega}\left[e^{-R(Q/Q_\Omega)} S\left(Q/Q_\Omega\right)\right]$$

R independent-emission piece, exponentiates one gluon result. S represents effects of correlated soft emission, only numerical results for two/(1+1) jets, in large N_c limit exist.



- k_t clustering reduces the magnitude of the non-global component.

  R.B. Appleby and M.H. Seymour 2003

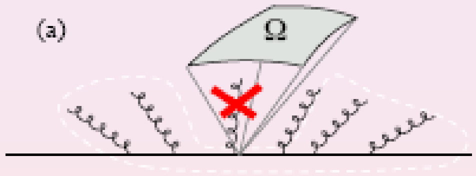
  Clustering algorithm pulls soft hadrons in the gap outside by clustering with harder emissions.
- Some configurations escape clustering , contribute to NG component. NG piece non-zero but significantly smaller. Appleby and Seymour's result : after k_t clustering the distribution takes the form $e^{-R}S$. S reduced by clustering and the independent emission e^{-R} is unchanged.
- Reduction of S shd reduce theoretical uncertainty.

- AS extended this ansatz to dijets in photoproduction. Computed just primary emission piece (analogous to e^{-R}) exactly. More complicated colour structure with colour anomalous dimension matrices.
- Approximated NG component, arguing that it's small. Agreement within theoretical uncertainty with HERA data.
- However there's more to the story !

A. Banfi and M. Dasgupta, 2005

New terms due to clustering

- There are algorithm dependent single-log pieces in addition to $e^{-R}S$.
- Discovered while studying jets e.g azimuthal correlations between dijets near $\phi = \pi$.
- Origin : Incomplete real-virtual cancellations outside the gap



Algorithm dependent corrections

Leading $\mathcal{O}\left(\alpha_s^2\right)$ correction thus obtained :

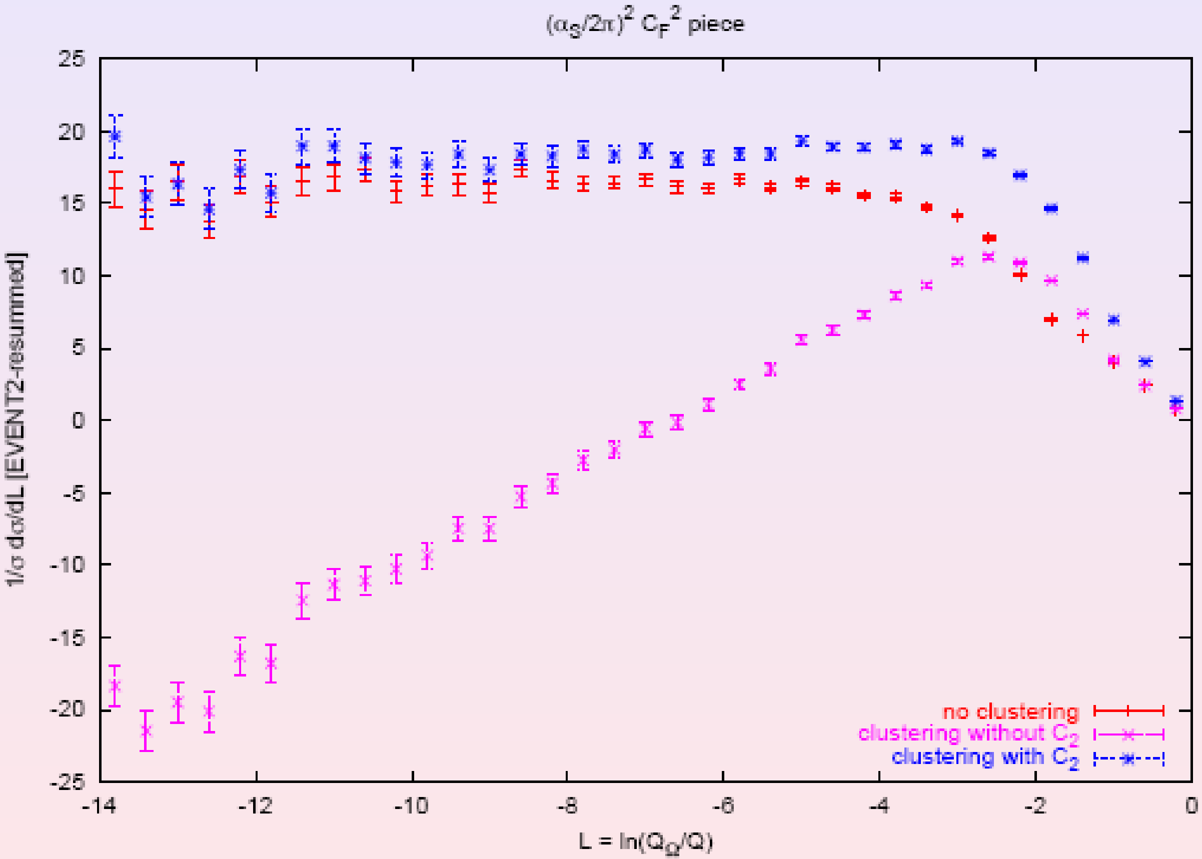
$$C_2^{\text{indep.}} = \frac{16}{3\pi} C_F^2 \left(\alpha_s^2 L^2\right) r^3, \, \Delta\eta \geq r.$$

Need to integrate the real-virtual piece over region where pure real emission are clustered away. Not accounted for by $e^{-R}S$ form.

tu-logo

ur-logo

Comparisons with EVENT2



Super Leading Logarithms in energy-flow observables

Albrecht Kyrieleis

in collaboration with M.Seymour and J. Forshaw

Gaps-between-jets

- pp $\to$ jet jet + soft gluons
- forbidden: real gluons with $k_\perp > Q_0$ in rapidity gap between jets

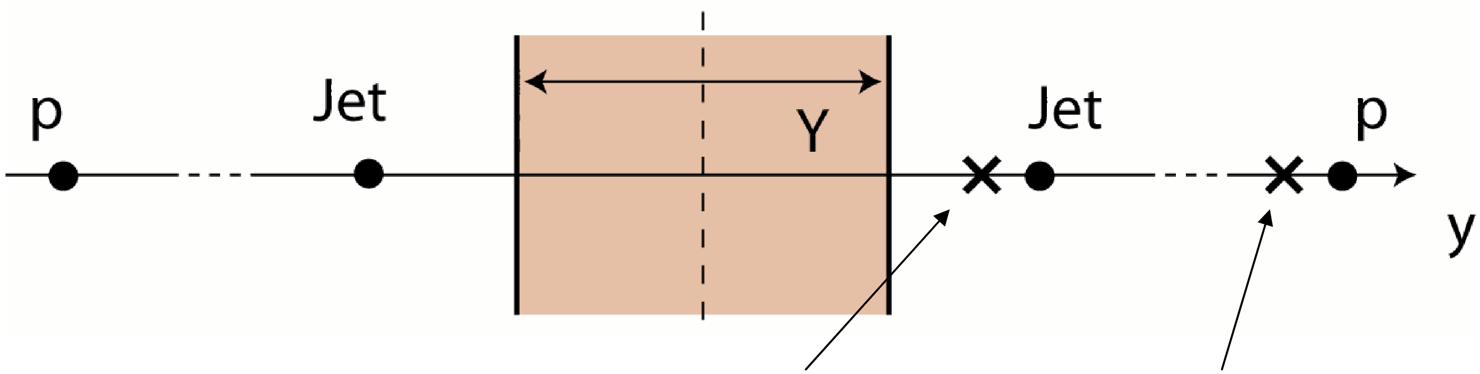
Resum: $$(\alpha_s L)^n, \quad L = Log\frac{Q^2}{Q_0^2}, \quad Q = p_{\perp,jet}$$

Independent emission (Sterman et al) calculated for:

- DIS at HERA ($k_\perp$ jet algorithm) [M.Seymour R.Appleby, 2003]
  + estimate of non-global piece
- Hadron collider [Oderda, Sterman, 1998]

Out-of-gap gluon in collinear limit: a surprise

$$\sigma_1 = \int_{Q_0}^{Q} \frac{dk_\perp}{k_\perp} \int_{Y/2}^{\infty} dy \; M^2$$



$M^2 = 0$

$M^2 \neq 0$!!

Non-zero contribution from initial state collinear limit

Super-leading logarithms (SLL)

Out-of-gap gluon :

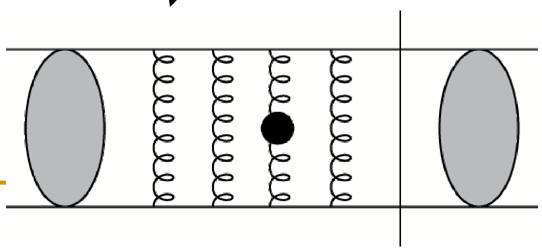
$$\alpha_s \int_{Q_0}^{Q} \frac{dk_\perp}{k_\perp} \, Log \frac{Q}{k_\perp} \sim \alpha_s L^2$$

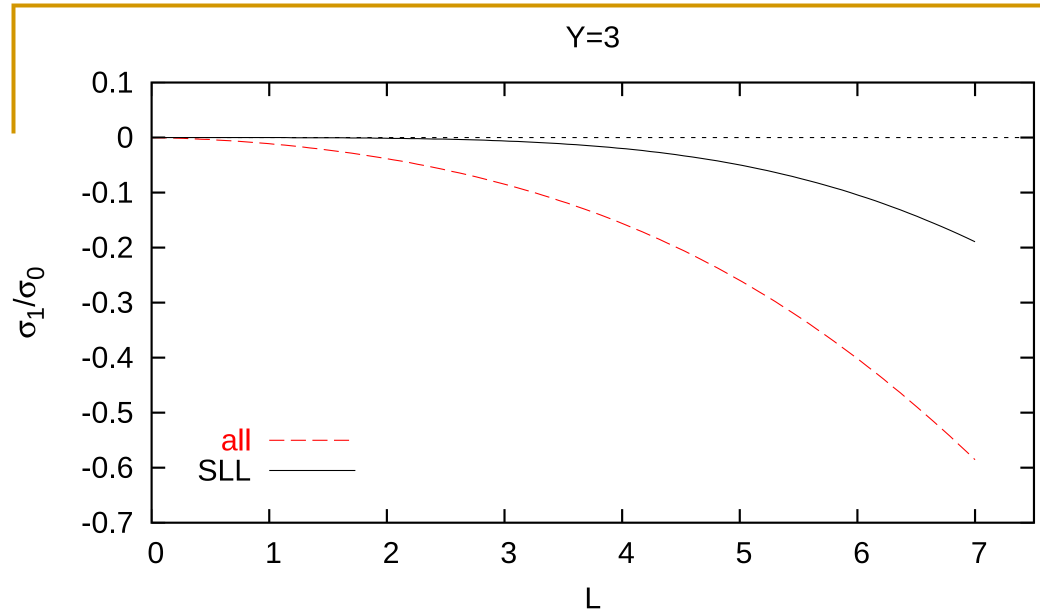
Each gluon in the gap:

$$\alpha_s \int_{Q_0}^{Q} \frac{dk_\perp}{k_\perp} \int_0^Y dy \sim \alpha_s L$$

$$\sigma_1 = \alpha_s^2 (c_1 \, \alpha_s L + c_2 \, \alpha_s^2 L^2 + c_3 \, \alpha_s^3 L^3 + c_4 \, \alpha_s^4 L^5 + \ldots)$$

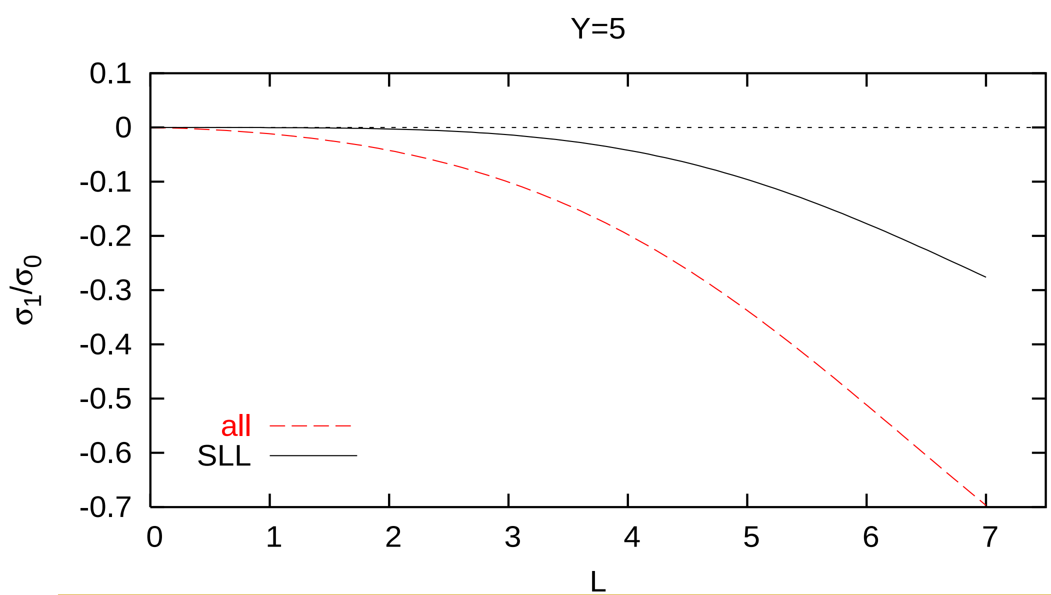
Failure of plus-prescription above $Q_0 \Rightarrow$ SLL
collinear gluons into pdf only below Q_0





σ_0: independent emission, all orders

σ_1: 1-outside-the-gap, all orders



SLL relatively small for L<4

But:
2,3,.. gluons outside the gap not yet included

Summary

We have found new super-leading logarithms in calculation of
$pp \to$ jet gap jet

- Stems from region where out-of-gap gluon becomes coll. to initial state particle, originates from Coulomb phase terms
- 'Breakdown of plus-prescription above Q_0' probably gives rise to double logs instead of single ones
- Formally more important than any LL result, numerically modest at LHC, but effect of n gluons outside the gap not yet included
- Saturation at large Y
  $\to$ deeper link between non-global observables and small-x physics

- ✗ Angular decorrelations of Mueller-Navelet Jets at NLO [Sabio-Vera]
  comparison with Tevatron data public very soon
- ✗ Towards the fully exclusive NLL BFKL evolution [Anderson]
  started program to obtain fully exclusive final state info
- ✗ New fits to uPDFs [Jung]
  first results presented, many more promised for the proceedings
- ✗ Jet algorithms & energy flows - log surprises [Dasgupta]
  in progress through dijet resummations in DIS and pp collisions
- ✗ IR safe determination of jet flavour at parton level [Banfi]
  next: application to b-jets
- ✗ Super-leading logs in energy-flow observables [Kyrieleis]
  breakthrough discovery??

Many new results presented, much more to come in the near future!