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QCD issues at TeV colliders

Les Houches, 27/5/2003

Where we stand

QCD has been/is being tested thoroughly, and works beautifully: there is no doubt that it is the correct theory of strong interactions. However, there are cases in which the comparison between theory and data is not satisfactory

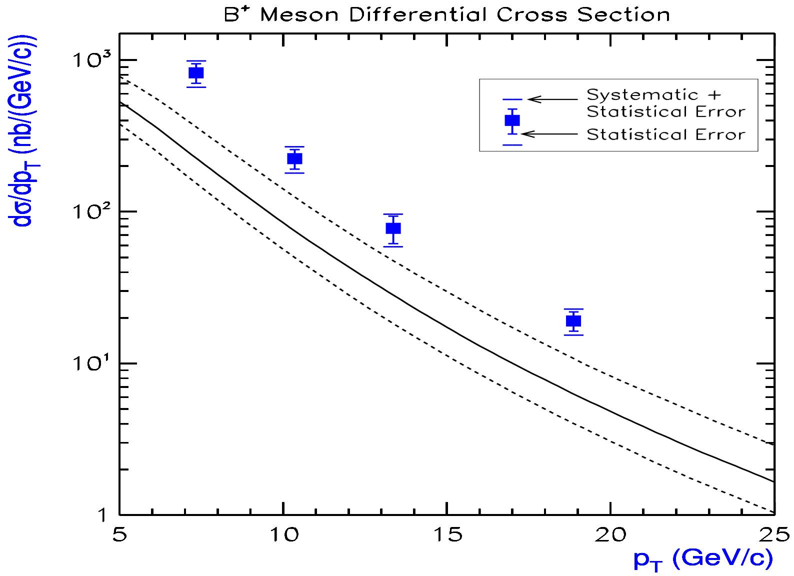
Claim: the present discrepancies are not the signal that something dramatic is happening. However, failure to understand them will most likely result into very serious problems at TeV colliders (especially LHC)

Proof: unfortunately, only a very few (real) proofs of QCD theorems exist, so I'll rather argue that the claim is true using the following examples:

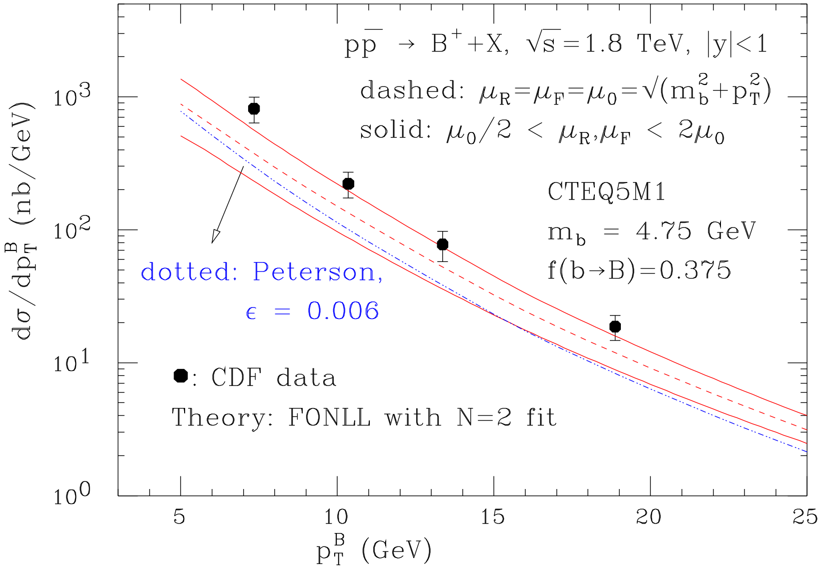
- Bottom physics
- High-p_T jet production
- Ratios of jet cross sections
- Prompt-photon production

These topics motivate the study of the hottest issues in QCD to date

b at the Tevatron



Cacciari & Nason



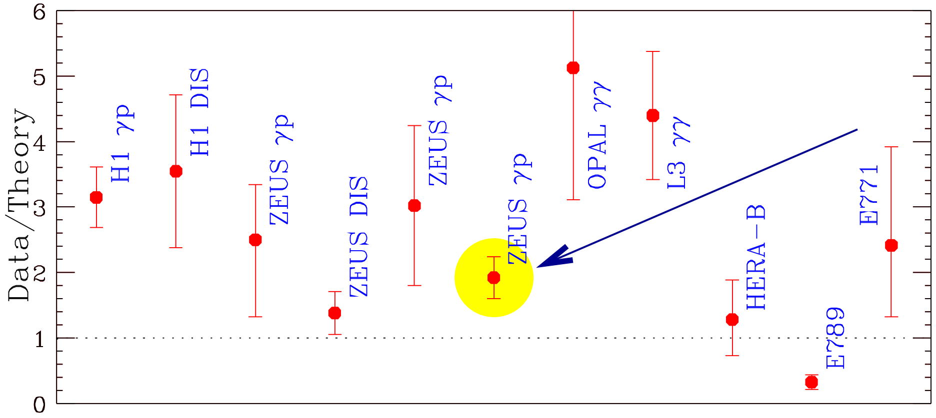
Data/Theory$=2.9 \pm 0.2 \pm 0.4$

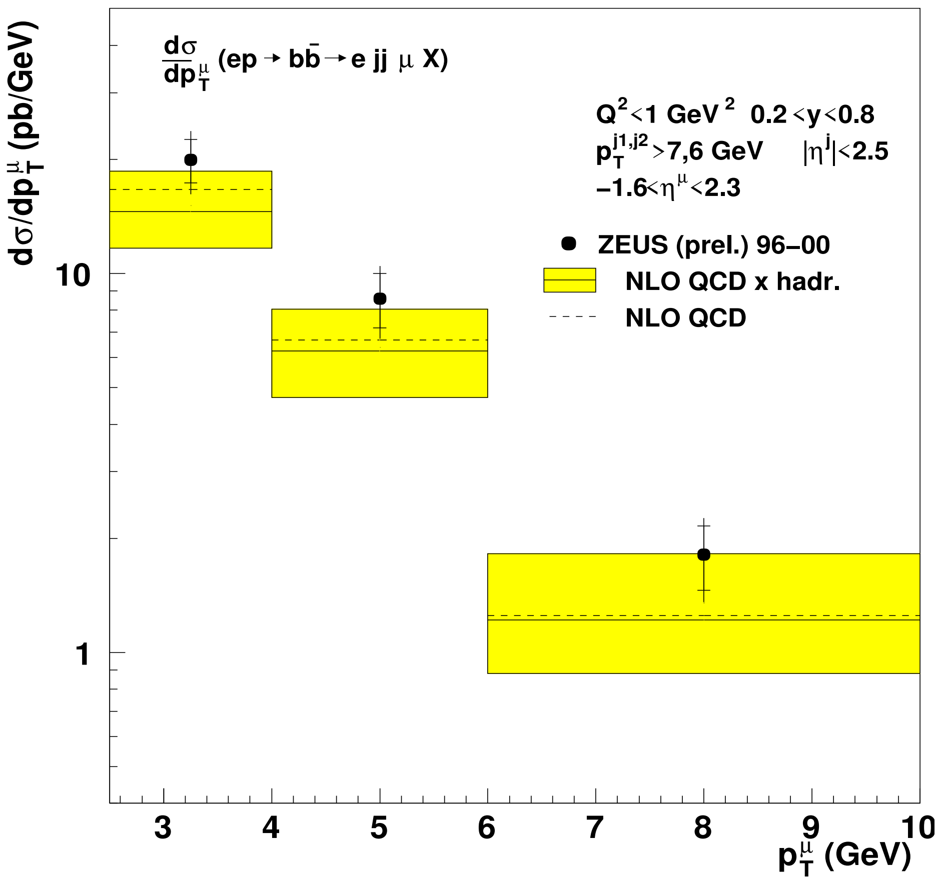
Data/Theory$=1.7 \pm 0.5 \pm 0.5$

- Improvement due to FO $\rightarrow$ FONLL (20%), and to the correct treatment of the fragmentation (45%). Data are consistent with the upper end of the QCD band
- QCD does also well for b-jets (Mangano&SF). It is wise to reconsider former $B \rightarrow b$ deconvolutions
- Further improvements: small-x and threshold resummation (a ∼20% each?)

■ What we need: NNLO computations (the K factor is large)

So is the problem gone?





Perhaps not quite gone: ep, γp and $\gamma\gamma$ data are off by large factors (2–5!). However, most recent HERA data are closer to theory

And, there are oddities:

a) Charm is better than bottom

b) In the context of the same analysis:
Data/Theory=1.9 [total rate]
Data/Theory=1.4 [distributions]

a) can't be understood in perturbation theory. b) relies on small-p_T *extrapolations*

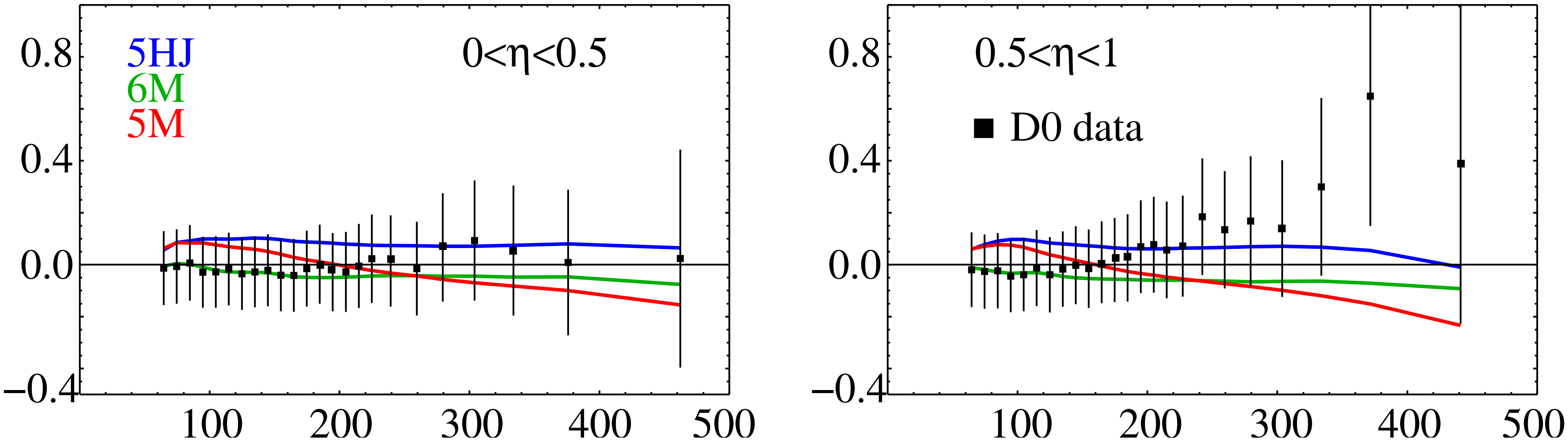
■ What we need: better Monte Carlos (at best, present ones cannot be trusted at small p_T's in heavy-quark physics)

Jets at the Tevatron I

An excess of data over theory has been reported by CDF (PRL77(96)438) for $p_T > 250$ GeV in the single-inclusive jet spectrum. This region, with the highest momentum transfer probed so far, is the most sensitive to new physics

- With dedicated PDF fits (4HJ and 5HJ) the excess is basically absent. The explanation is so simple since, at these x's, the gluon is not constrained
- Thanks to recent D0 measurements (p_T spectrum in 5 slices of η) the central PDF set (6M, 6.1M) is HJ-like, and good agreement is found

Stump *et al* (CTEQ), `hep-ph/0303013`



■ What we need: better PDFs

Jets at the Tevatron II

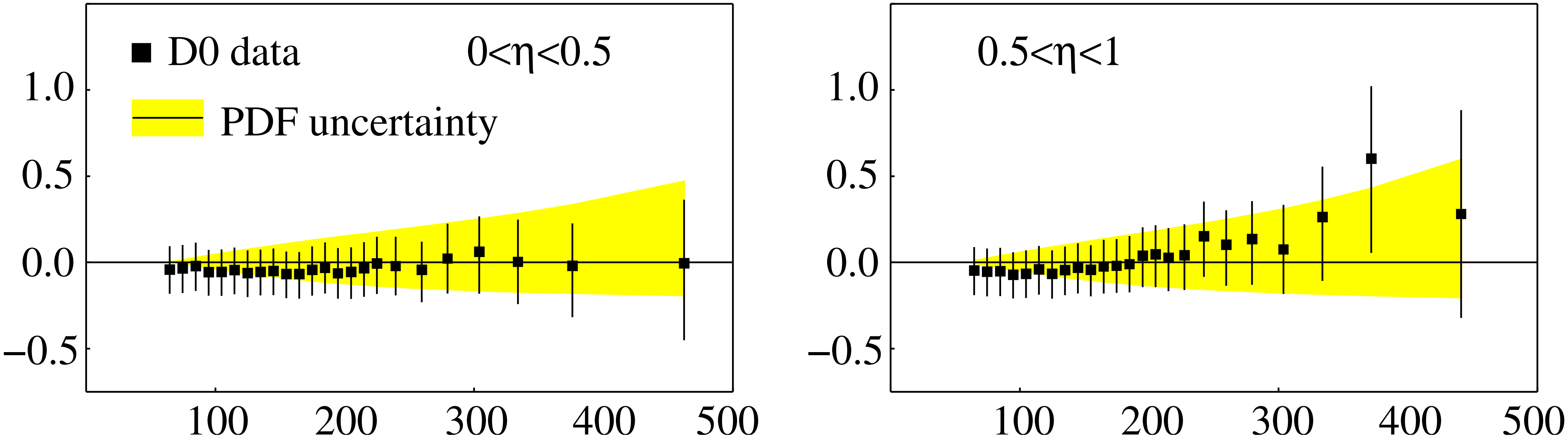
Does the use of jet data to predict jet cross sections signal a lack of predictive power?

Only marginally: large x $\Leftrightarrow$ large p_T OR large y

$$x_1 = \frac{1}{\sqrt{S}} \sum_{i=1}^{n} p_{Ti} \exp(y_i) \qquad x_2 = \frac{1}{\sqrt{S}} \sum_{i=1}^{n} p_{Ti} \exp(-y_i)$$

Actually, another test of evolution equations. Still, PDFs (gluon) are underconstrained

Stump *et al* (CTEQ), `hep-ph/0303013`

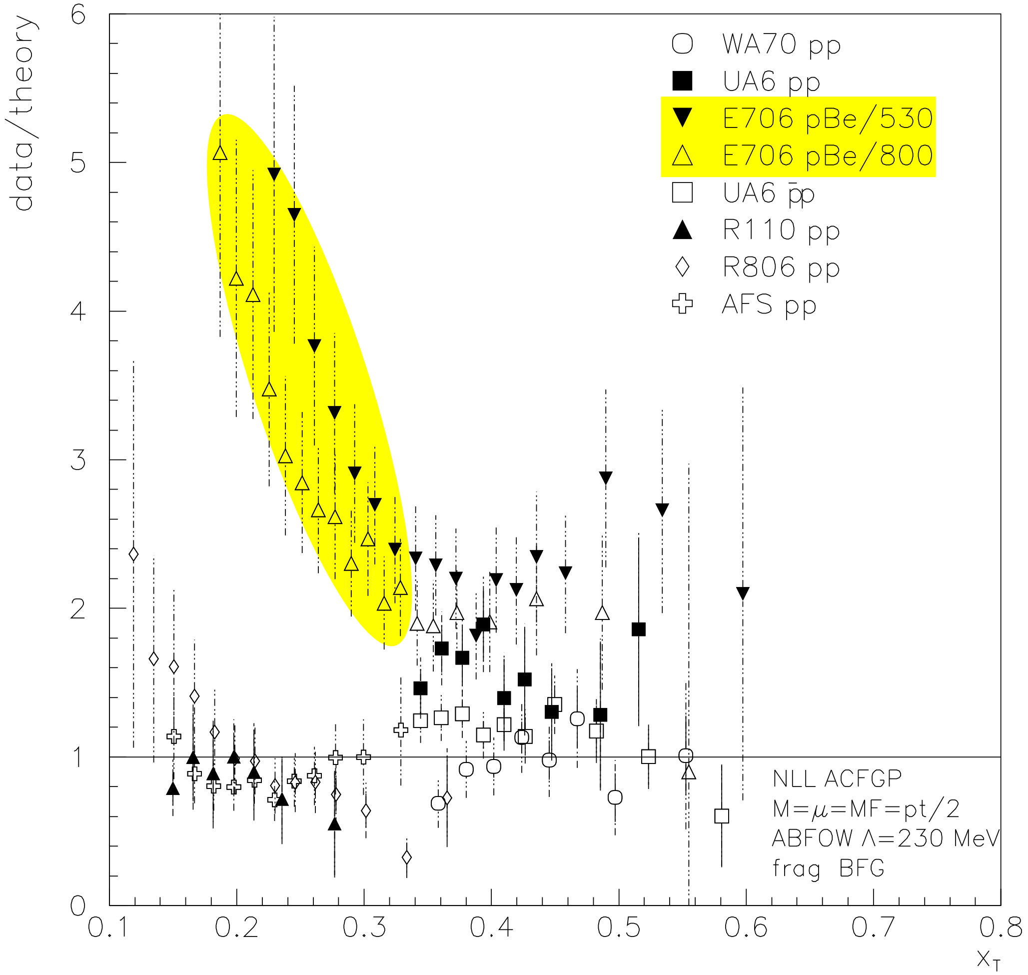


- What we need: PDFs with uncertainties

  More constraints (i.e. other processes)

Photons at fixed-target experiments

Aurenche *et al*, `hep-ph/9811382`



Fixed-target inclusive photon data are sensitive to the gluon exactly where it is relevant:

$$x_T = 0.2 \Longrightarrow p_T(\text{jet@1800}) = 180 \text{ GeV}$$

$$x_T = 0.5 \Longrightarrow p_T(\text{jet@1800}) = 450 \text{ GeV}$$

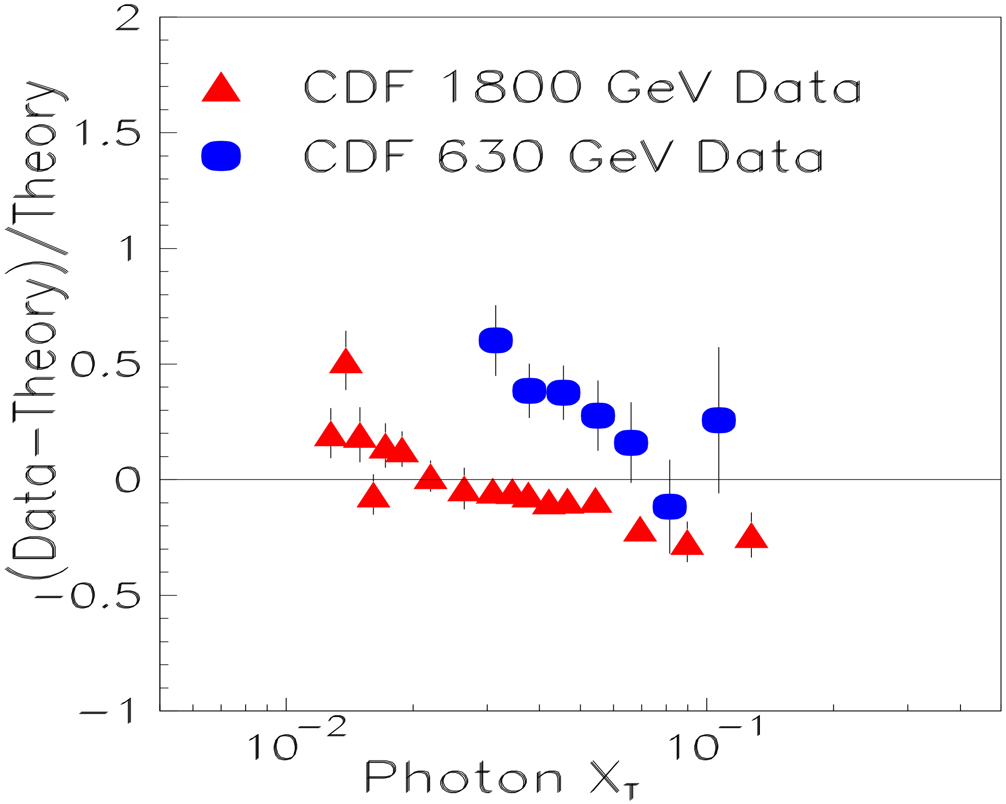
Unfortunately, data are no consistent with each other: it is not possible to fit all the data with an unique parameter setting

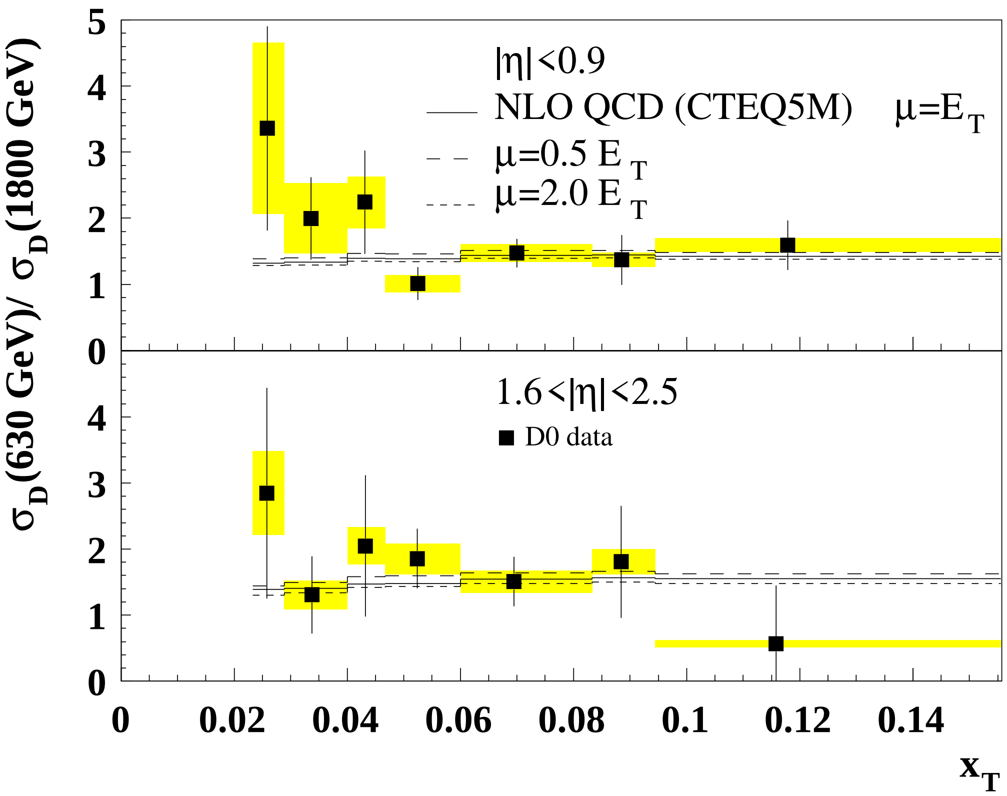
- Drop some low-p_T data?
- Reconsider corrections for isolation?

Meaningless to ask whether this is a problem of QCD, if a consistent picture is not emerging from the data. These data are not used any longer in PDF fits. Need new data (RHIC? News on π^0 are encouraging – hep-ex/0304038)

The problem is not peculiar to fixed-target experiments $\longrightarrow$

Photons at the Tevatron



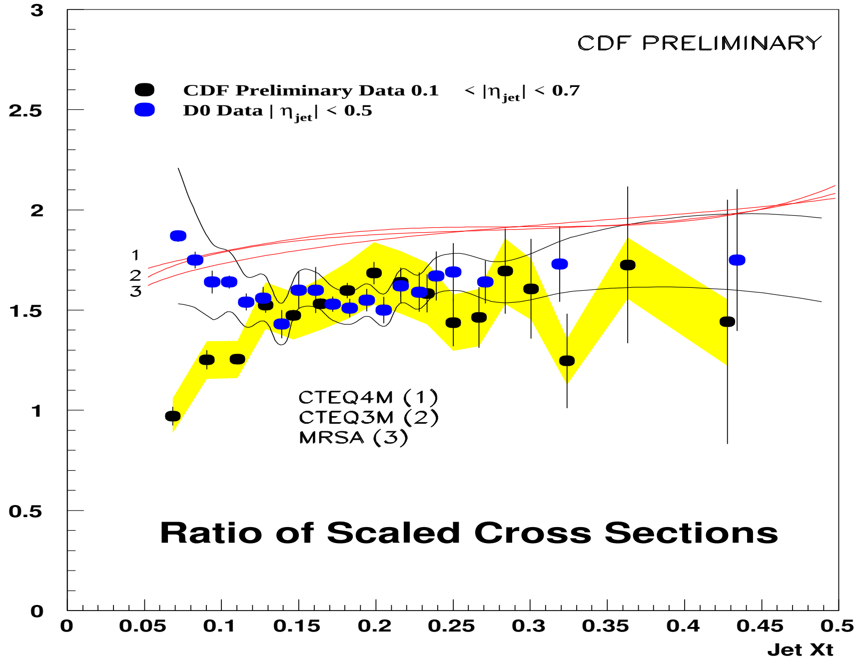


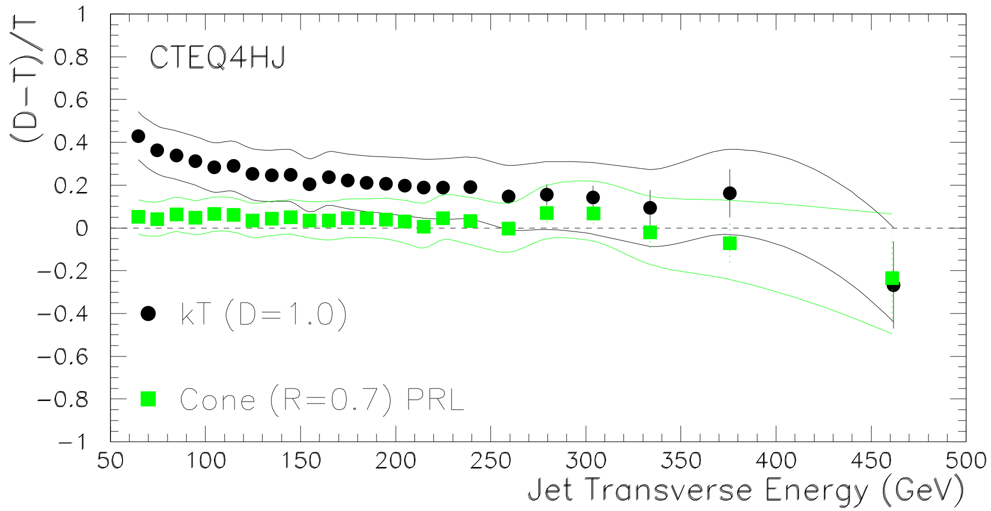
$\sqrt{S} = 1.8$ TeV and $\sqrt{S} = 0.63$ TeV CDF data cannot be simultaneously described by pQCD. The situation is considerably better for D0

- Mismatch between theoretical and experimental isolation criteria?
- Can joint resummation (Laenen, Sterman & Vogelsang) help?

■ Not worrisome as a test of QCD, but may cause problems in those analyses/for those techniques that make use of photons

Jets at the Tevatron III





These results are very difficult to understand in the context of perturbation theory

A) The ratio of jet cross sections is predicted with high accuracy

B) k_T algorithm is theoretically cleaner than cone (besides working well at HERA)

- Power-suppressed effects can account for the discrepancies in A) (Mangano)
- Final-state hadronization effects (HERWIG) improve the agreement in B) (D0)

■ What we need: improved understanding of perturbative/non-perturbative interplay

- in MC (inclusion of higher orders; underlying event simulation)
- in pQCD (DMW-like, $\langle \alpha_S, \alpha_0 \rangle$ plane $\Longleftarrow$ resummations in jet physics)

A quick summary

A few discrepancies in the comparisons between experiments and theory remain. They'd likely disappear with a deeper understanding of the following topics

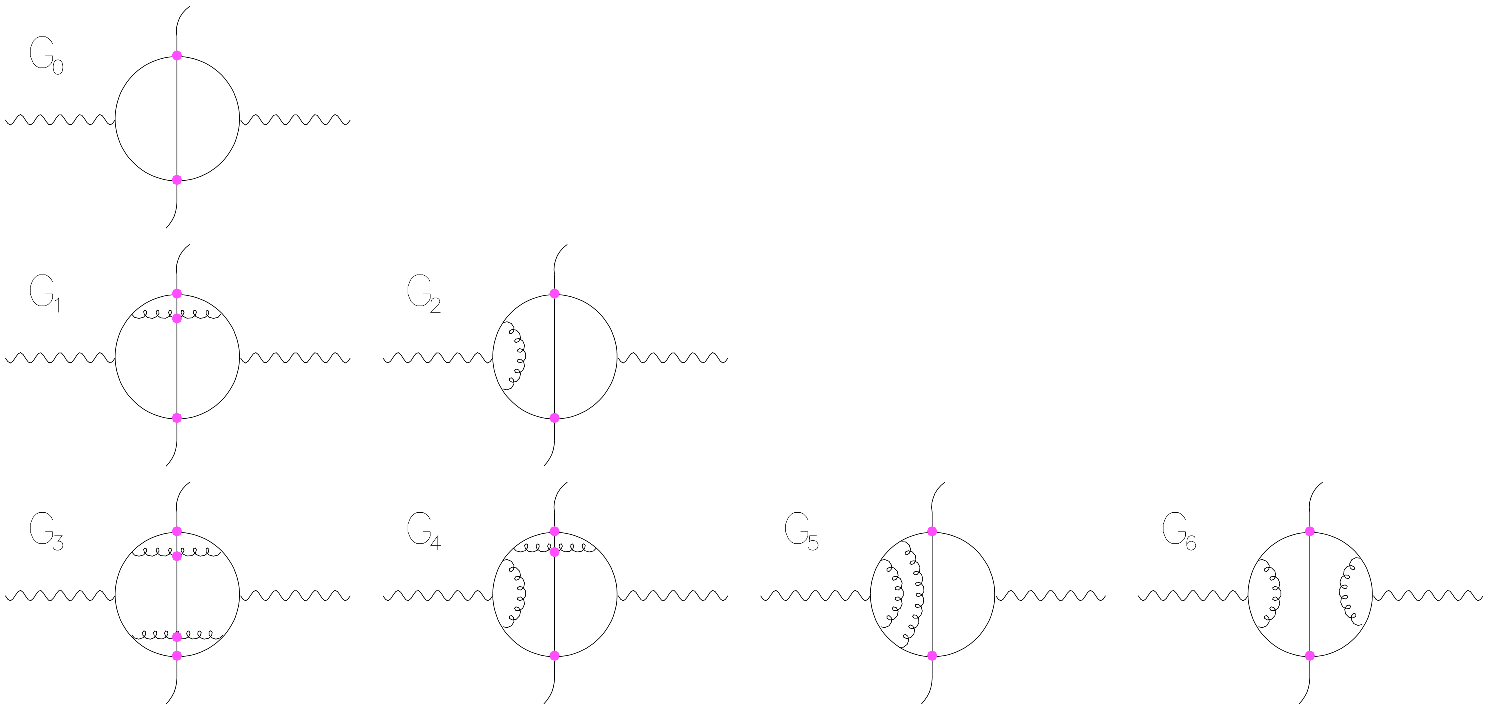
- NNLO computations
- Improved MC's
- Perturbative/non-perturbative interplay (resummations and power corrections)
- Better constraints on PDFs (with errors)

These are tough problems, and the current phenomenological implications are perhaps too marginal for providing us with strong motivations

However, in a very complicated environment, such as the one resulting from hadronic collisions at very high energy and luminosity ($\Longrightarrow$ large K-factors, large number of hard jets, larger impact of the accompanying non-hard events), the solutions of these problems are necessary for a variety of crucial issues (signal significance and analysis design, computation of acceptances, luminosity monitors)

Tevatron and LHC demand the development of new tools

NNLO computations



$\mathcal{O}(\alpha_S^0)$ LO

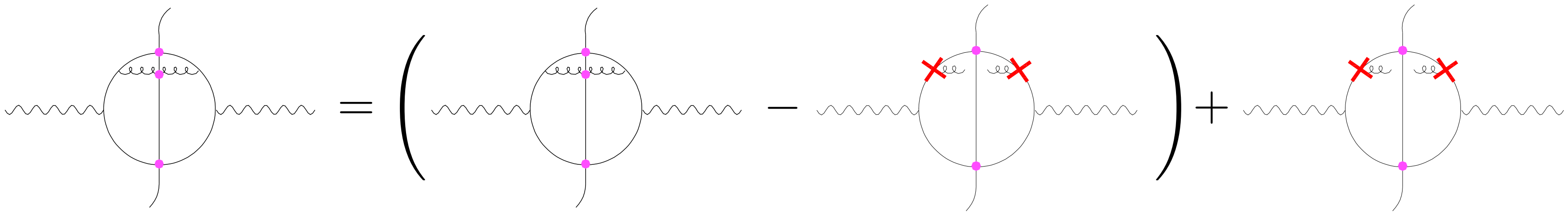
$\mathcal{O}(\alpha_S^1)$ NLO

$\mathcal{O}(\alpha_S^2)$ NNLO

- At the NLO, the extra parton can be: G_1) real; G_2) virtual
- At the NNLO, the two extra partons can be: G_3) both real; G_4) one real and one virtual; G_5+G_6) both virtual
- *The problem* is the same: how to cancel analytically the divergences without performing a complete analytical computation, which is impossible in general
- A notable exception: fully-inclusive quantities. With simple kinematics, analytical integrations possible (but tough): DY K-factor, DIS CF, Higgs

Less-inclusive cross sections

At the NLO, add and subtract the most singular part of the real matrix element, using a reduced kinematics to compute the observable (Ellis, Ross & Terrano)



If we use the same strategy at the NNLO, we have to:

A: Compute 2-loop integrals (many $2 \to 2$ and $1^* \to 3$ now available)

B: Compute the most singular terms of double-real and real-virtual diagrams (done!)

C: Use the result of B to construct the IR counterterms, avoiding overlapping divergences. Integrate the counterterms analytically, factoring out the phase space of hard partons (to be integrated numerically)

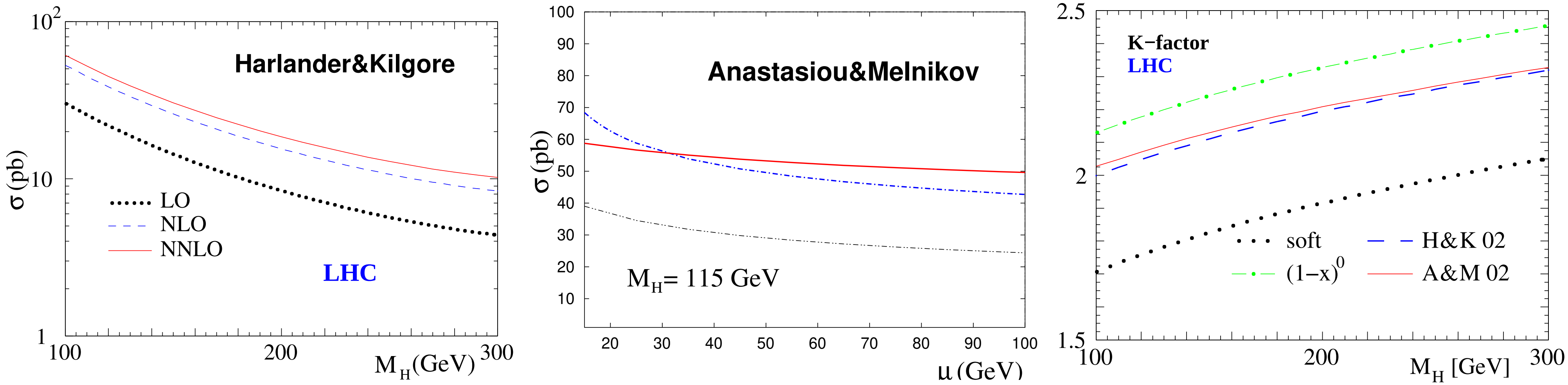
At variance with B and C, A has to be carried out for each and every new process

BUT ONLY WHEN C WILL BE ACHIEVED

Techniques are becoming available to tackle C numerically (Binoth&Heinrich). First attempts to build IR counterterms with no overlapping divergences (Kosower, Weinzierl)

SM Higgs at the NNLO

A) gg channel dominates; B) the top is very heavy: use $m_t \to \infty$; C) the effective ggH interaction is known to $\mathcal{O}(\alpha_s^4)$ (Chetyrkin, Kniehl & Steinhauser)



0) The computation of $gg \to H$ to 2 loops (Harlander)

1) 2-loop+SC (Catani, deFlorian & Grazzini) or 2-loop+S+SL (Harlander&Kilgore) approximation of double-real ME's (most singular terms for $x_H \equiv M_H^2/\hat{s} \to 1$)

2) Double-real ME's expanded for $x_H \to 1$, up to $(1 - x_H)^{16}$, the rest exact (H&K)

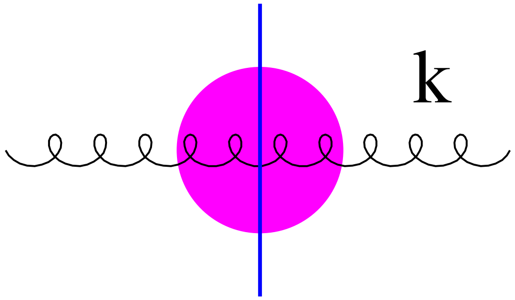
3) Double-real ME's computed exactly (Anastasiou&Melnikov). Result cross-checked by Ravindran, Smith & van Neerven without any $x_H \to 1$ expansion

Associated $H(b\bar{b})$ production computed at NNLO (H&K). However, b-triangle contribution is beyond current capabilities. SUSY has to wait...

Where the progress comes from

Reduction techniques are now established to reduce the (huge) number of loop integrals to a (small) set of scalar integrals (still highly non-trivial to compute)

A further step (A&M): $|\text{real diagrams}|^2 == $ loop diagrams, with cut rules



	Total rate	$d\sigma/d\mathcal{O}$
	$\delta(k^2 - m^2)$	$\delta(\mathcal{O} - \mathcal{O}(k))$

Then use

$$\delta(x) = \frac{1}{2\pi i}\left(\frac{1}{x - i\varepsilon} - \frac{1}{x + i\varepsilon}\right)$$

- Under integration by part, the sign in front of ε is irrelevant, so apply reduction techniques and reinstate the δ eventually
- Conditions on $\mathcal{O}$ must be met for this to work

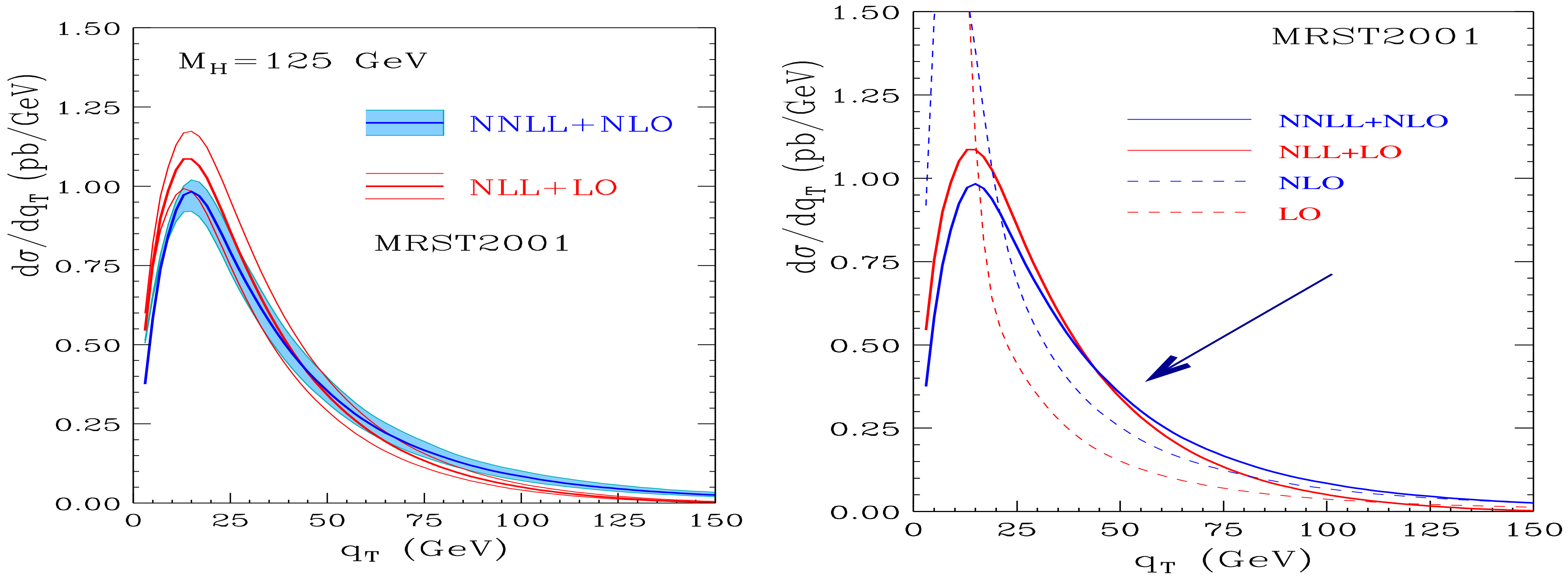
Higgs rapidity @NLO computed with this method (A&M&Dixon)

Drawback: probably not flexible enough (cuts?). Still, it will provide a very good check

SM Higgs: beyond fixed order

- Total rate: soft-gluon resummation in progress (Catani, deFlorian, Grazzini & Nason). Further enhancement of the fixed-order result: at the LHC/Tevatron $\mathrm{NLL+NLO} = \mathrm{NLO}\ (1 + 20\%/30\%)$, $\mathrm{NNLL+NNLO} = \mathrm{NNLO}\ (1 + 9\%/16\%)$

- q_T spectrum: resum in b-space, with $\log(M_H^2 b^2/b_0^2) \rightarrow \log(1 + M_H^2 b^2/b_0^2)$ (Bozzi& C&dF&G), as inspired by e^+e^- event shapes (Catani *et al*, 1993). Rate equal to the fixed-order one, which mainly affects the intermediate q_T's



■ Other matching prescriptions? Analogous work for backgrounds needed

NNLO computations: worth the effort?

1) Better estimates for total production rates 2) Reduced theoretical uncertainties (dependences on mass scales) 3) More realistic kinematic features (i.e. in jets)

In hadronic collisions, one needs NNLO-evolved PDFs. NNLO MRST set is only an approximation, since:

- AP kernels are only known at three loops (vNeerven&Vogt) through their lowest Mellin moments (Larin, Nogueira, Retey, Ritbergen, Vermaseren), and small-x behaviour; exact computation under way (Moch, Vermaseren, Vogt) – N_f-part of the non-singlet SF now available!
- The only genuine NNLO result used are DIS CFs (in DY, MRST use $x_F(NLO) \times \mathrm{K}_{NNLO}/\mathrm{K}_{NLO}$ $\leftarrow$ need for less-inclusive results)

PDFs uncertainties must be carefully considered: a lot of activity in the field recently (Giele&Keller&Kosower, Alekhin, Botje, CTEQ, MRST). Many issues to be settled: χ^2 definition, $\Delta\chi^2 = 1$ rule, bias from priors $\leftarrow$ neural net approach (Forte *et al*)?

$\Longrightarrow$ Yes, worth. However, *precision* physics requires a better understanding of the interplay between perturbative and non-perturbative/soft physics.

Processes with large K-factors must be high in the priority list

The major (perturbative) problems in MC's

$\mathcal{P}_1$: MC's cannot simulate the emissions of hard partons

$\mathcal{P}_2$: MC's cannot go beyond LO in the computation of the rates

Problems $\mathcal{P}_1$ and $\mathcal{P}_2$ are going to be acute at TeV-scale colliders: multi-jet channels are standard discovery tools, and huge backgrounds require a precise estimate of the rates. The solutions:

$\mathcal{S}_1$: The improved MC is capable of simulating the emission of n_E extra hard partons

$\mathcal{S}_2$: The improved MC knows how to compute the total rate to N^{k}LO accuracy

Implicit is the notion of Born $\equiv$ LO level, as the process(es) with the smallest number n_B of final-state partons which contributes to a given reaction (usually, but not necessarily, a $2 \to 2$ process).

Implementation of $\mathcal{S}_2$ (multiplication by the K-factor) is not in the spirit of event generators (it's inclusive). And, it doesn't make sense for jets. Thus:

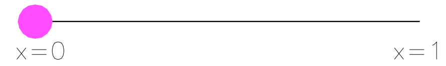
$$\mathcal{S}_1 \quad \Longrightarrow \quad \text{Matrix Element corrections}$$

$$\mathcal{S}_1 \oplus \mathcal{S}_2 \quad \Longrightarrow \quad \text{MC@N}^k\text{LO, with } n_E = k$$

A simple way to understand MC@NLO

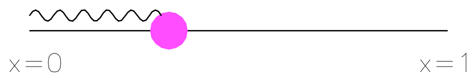
A system S moves along a line between 0 and 1. It can radiate "photons", whose energy we denote with x. S can undergo several further emissions; on the other hand, one photon cannot branch

$$\left(\frac{d\sigma}{dx}\right)_B = B\delta(x) \qquad \longleftrightarrow$$



$$\left(\frac{d\sigma}{dx}\right)_V = \alpha_S\left(\frac{B}{2\epsilon} + V\right)\delta(x) \qquad \longleftrightarrow$$

$$\left(\frac{d\sigma}{dx}\right)_R = \alpha_S\frac{R(x)}{x} \qquad \longleftrightarrow$$



It doesn't need to be QCD, but must behave the same. Thus:

$$\frac{d\sigma}{dO} = \lim_{\epsilon\to 0}\int_0^1 dx\, x^{-2\epsilon}\delta(O - O(S,x))\left[\left(\frac{d\sigma}{dx}\right)_B + \left(\frac{d\sigma}{dx}\right)_V + \left(\frac{d\sigma}{dx}\right)_R\right]$$

is finite, provided that $\lim_{x\to 0} R(x) = B$, as usual in QCD. Note the kinematics:

$$\boxed{\text{B\&V} \Longrightarrow O(S,0),\ \text{R} \Longrightarrow O(S,x)}$$

NLO $\oplus$ MC $\longrightarrow$ MC@NLO?

A: In standard MC's $(S,0)$ happens to be the initial condition for the shower

B: At the NLO, kinematic configurations (S,x) and $(S,0)$ are generated, and used to fill the histogram bins

Try the same at the NLO as at the LO: $(S,0)$ and (S,x) are MC initial conditions

$$\mathcal{F}_{\text{MC@NLO}} = \int_0^1 dx \left[\mathcal{F}_{\text{MC}}(S,x) \frac{\alpha_S R(x)}{x} + \mathcal{F}_{\text{MC}}(S,0) \left(B + \alpha_S V - \frac{\alpha_S B}{x} \right) \right]$$

It doesn't work:

- Cancellations between (S,x) and $(S,0)$ contributions occur after the shower: hopeless from the practical point of view (unweighting impossible)
- $(d\sigma/dO)_{MC@NLO} - (d\sigma/dO)_{NLO} = \mathcal{O}(\alpha_S)$. In words: double counting

The problem is a fundamental one: KLN cancellation is achieved in standard MC's through unitarity, and embedded in Sudakovs. This is no longer possible: IR singularities do appear in hard ME's

MC@NLO: slicing

Exploit a proposal by Baer&Reno to get rid of the soft/unresolved configurations:

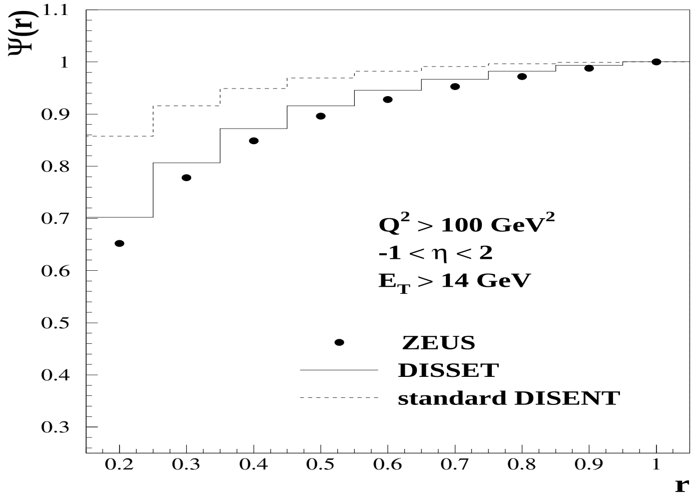
$$B + \alpha_S \left(B \log \delta_0 + V \right) = 0 \quad \Longrightarrow \quad \delta_0 = \exp\left[-\left(B + \alpha_S V \right) / \alpha_S B \right]$$

Another parameter $\delta_{PS} > \delta_0$ separates the shower region from the hard region (Pötter, Schörner, Dobbs)

$$\mathcal{F}_{\text{MC@NLO}} = \alpha_S \int_{\delta_{PS}}^{1} dx \, \mathcal{F}_{\text{MC}}(S, x) \frac{R(x)}{x} + \alpha_S \int_{\delta_0}^{\delta_{PS}} dx \, \mathcal{F}_{\text{MC}}(S, 0) \frac{R(x)}{x}$$

+ Only positive weights

+ Doesn't need to know details of MC implementation



– Double counting for $x < \delta_{PS}$, and discontinuity at $x = \delta_{PS}$ imply dependence upon δ_{PS}, which is hidden by integration over Bjorken x's

– Strictly speaking, the (perturbative) result is non-perturbative, since $\delta_0 \sim \exp(-1/\alpha_S)$

- Applied to: single-V production

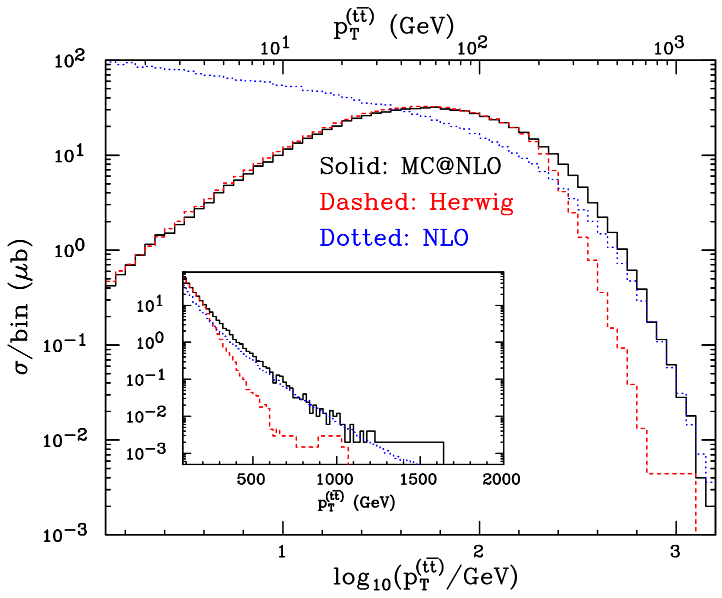
MC@NLO: modified subtraction

Get rid of the MC $\mathcal{O}(\alpha_S)$ contributions by an extra subtraction of the $\mathcal{O}(\alpha_S)$ term in the expansion of the Sudakov, $\alpha_S Q(x)/x$ (Webber & SF):

$$\mathcal{F}_{\mathsf{MC@NLO}} = \int_0^1 dx \left[\mathcal{F}_{\mathsf{MC}}(S,x) \frac{\alpha_S [R(x) - BQ(x)]}{x} + \mathcal{F}_{\mathsf{MC}}(S,0) \left(B + \alpha_S V + \frac{\alpha_S B[Q(x) - 1]}{x} \right) \right]$$

– Negative weights $(10\% - 20\%)$ – can't be avoided completely

– The subtraction terms are MC-implementation dependent



+ There is no unphysical parameter. Soft and hard emissions are smoothly matched

+ NLO results are recovered upon expansion in α_S

+ The method can be applied to any process

- Applied to: VV, $t\bar{t}$, $b\bar{b}$ production

MC@NLO: hybrid slicing

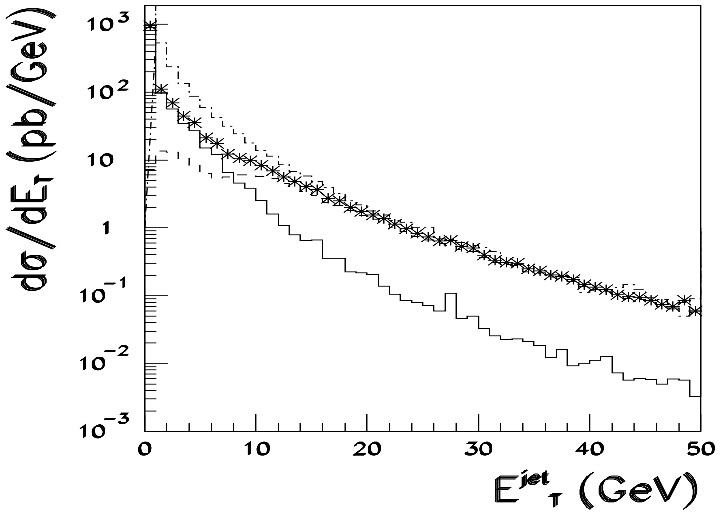
A recent proposal of the GRACE group (Kurihara *et al*): partition the phase space as in standard slicing, but subtract the MC contribution from the hard region:

$$\mathcal{F}_{\text{MC@NLO}} = \alpha_S \int_{\delta}^{1} dx\, \mathcal{F}_{\text{MC}}(S,x) \frac{R(x) - B}{x} + \mathcal{F}_{\text{MC}}(S,0)\,(B + \alpha_S V)$$

This formally coincides with modified subtraction prescription, provided that

$$\delta \longrightarrow 0\,, \qquad Q(x) \equiv 1$$

The second condition cannot, however, be imposed: it must naturally result from the MC implementation



+ All matrix elements generated numerically
– Double counting in the whole x range if $Q(x)$ is not tuned
– Tuning $Q(x)$ implies the construction of an ad-hoc MC. May be difficult to obtain $Q(x) = 1$ in soft regions

- Applied to: single-V production

ME corrections: a closer look

Matrix Element Generation $\longrightarrow$ Event file/ Common blocks $\longrightarrow$ Parton Shower

Most of the recent work done on the first box. The aim: give the MC the information on ME's with n_E as large as possible. Thus, $n_B \to n'_B = n_B + n_E$

Class #1: n'_B is given in input. Processes with different n'_B's are not related

+ The parton shower MC is any standard one: ME computation provides it with the kinematics and the colour flow of the initial configuration

– The results depend on an unphysical parameter δ_{sep}, which must be introduced at the parton level to avoid divergences

Class #2: This improves on the results of class #1: processes with different n'_B's are consistently combined

+ The dependence on the unphysical parameter is much reduced

– The parton shower MC must admit the possibility of vetoed emissions

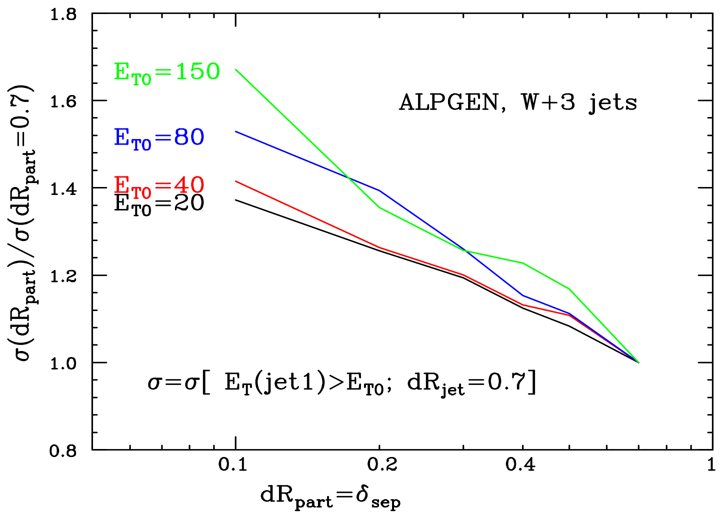
– Computing intensive

Class #1 ME generators

This is a *very* active field (AcerMC, ALPGEN, AMEGIC++, CompHEP, Grace, MadEvent), which motivates the definition of a standard (*Les Houches accord #1*) for the output format. The main problems to be solved:

- Efficient ME generation for n-parton final states. ALPGEN is the only one not based on diagrammatics, thus deals with larger n (thanks to Alpha – Caravaglios&Moretti)
- Efficient phase-space generation – highly non-trivial for many-leg processes. Different approaches: dedicated process codes (ALPGEN), automatic determination of "peaks" through Feynman diagrams (MadEvent, AMEGIC++, ...)

M. Mangano (with ALPGEN)



WARNING! Physical predictions do depend on the unphysical parameter δ_{sep}

The cross section is known at the 10–20% level

Still, a very significant improvement wrt standard MC's

$\longrightarrow$ see Joey's talk

Getting rid of δ_{sep} dependence: class #2

When $n_E = 1$, just reweight the MC cross section to match smoothly the ME result (Seymour, Sjöstrand)

In the context of e^+e^- physics, Catani, Krauss, Kuhn & Webber show that the problem cannot be solved at fixed n'_B. Extended to colour dipoles by Lönnblad; extended to hadronic collisions by Krauss

- In the n-jet region, any observable is accurate to $\mathcal{O}(\alpha_S^{n-2})$, for any n
- In the n-jet region, large logs of the observable O are resummed to NLL accuracy

$$\sigma_n \sim \alpha_S^{n-2} \sum_k \left(a_k \alpha_S^k \log^{2k} O + b_k \alpha_S^k \log^{2k-1} O \right)$$

- The dependence upon δ_{sep} is:

$$\sigma_n \sim \alpha_S^{n-2} \left(\delta_{sep}^a + \sum_k c_k \alpha_S^k \log^{2k-2} \delta_{sep} \right)$$

When only $n \leq N$ ME's are available, results are accurate to $\mathcal{O}(\alpha_S^{N-1})$

CKKW in e^+e^- collisions

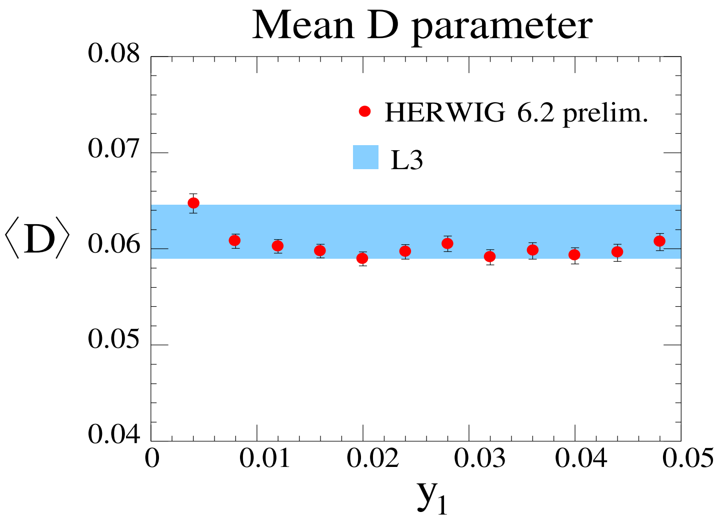
The procedure implies a modification of both the ME's and the shower evolution. After fixing δ_{sep}:

- Choose n according to the jet rates obtained with resolution δ_{sep}: $y_{ij} > \delta_{sep}$, with

$$y_{ij} = 2\min\{E_i^2, E_j^2\}(1-\cos\theta_{ij})/Q^2$$

- Generate an n-parton kinematic configuration according to ME, and reweight it by the probability of no further branchings (a combination of Sudakovs)
- After successful unweighting, use the n-parton kinematics as initial condition for the shower, vetoing all branchings such that $y_{ij} > \delta_{sep}$

B. Webber (with HERWIG)



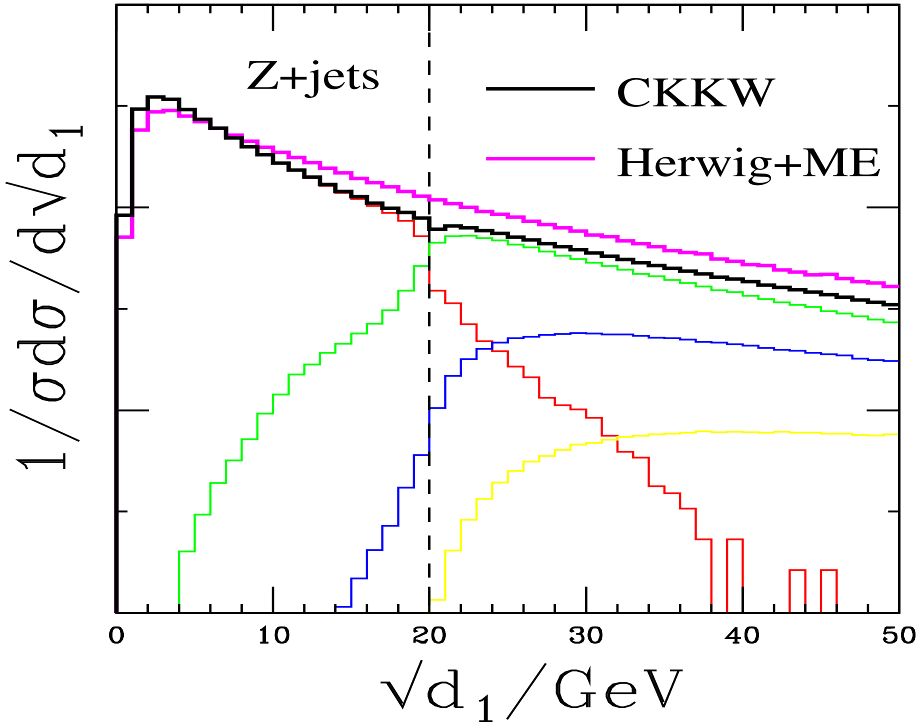
… and additional (important) prescriptions, concerning choice of scales, Sudakov form, α_S, recombination scheme

- n-parton contributions may have LL ($\alpha_S^k \log^{2k}\delta_{sep}$) dependence, which reduces to NNLL when all n are included
- The possible presence of powers of δ_{sep} implies a restricted range for this parameter

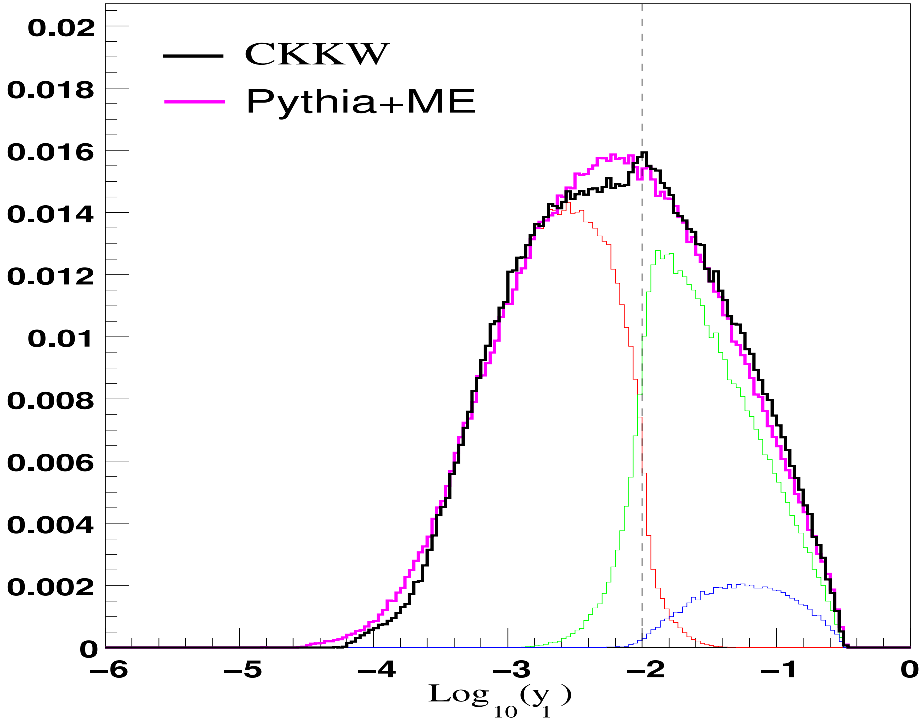
CKKW in hadronic collisions

- Works similarly to e^+e^-: initial-state branchings are not a problem of principle
- CKKW use the jet-finding algorithm to separate the PS and ME regions. A given algorithm may help to minimize the δ_{sep} dependence

P. Richardson



F. Krauss



In CKKW, the δ_{sep} dependence cannot be completely eliminated, since virtual corrections are not included. So tuning of parameters is necessary. Being done!

■ A project for the future: incorporate virtual corrections into CKKW $\Longrightarrow$ an approximation to MC@NNLO

A quick summary on MC's

- Matrix Element correction techniques have reached a mature stage. Although work remains to be done, especially in hadronic collisions, these MC's will soon become a standard tool of analysis
- MC@NLO are emerging from infancy, and are reaching production stage. Expect more ideas to come in the next few years. We now need to start building a library of processes: experimentalists' advice appreciated!

Stay tuned: Joey's and Torbjorn's talks today
Wed session (ME corr and MC@NLO news)

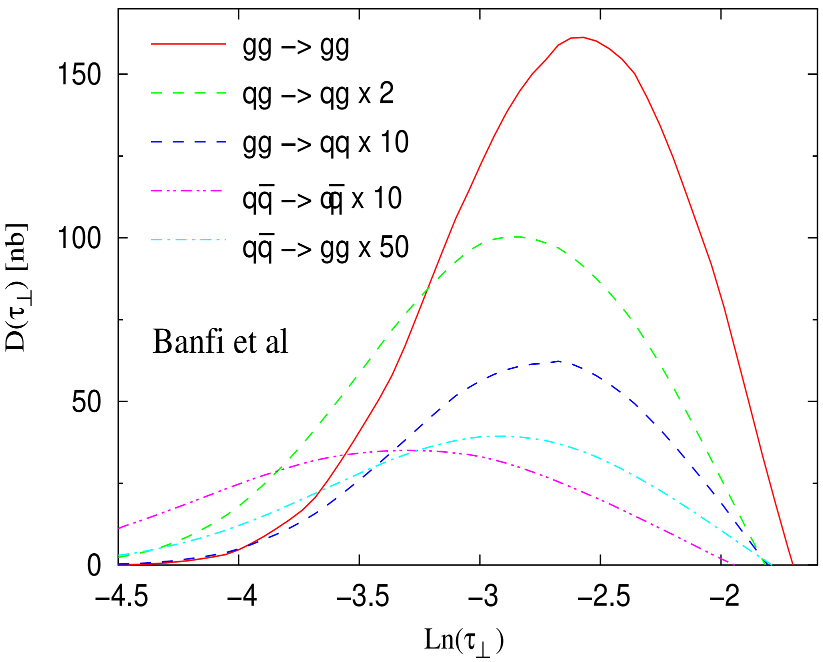
Numerical resummations

Beyond-LL results are difficult to obtain analytically because of multiple-emission ($\sim$ recoil) effects. Can use MC's, which however lack terms in any N^{k}LL towers

According to Banfi, Salam & Zanderighi: given the observable $\mathcal{T}$, define a "simple" observable $\mathcal{T}_s$ which has the same LL structure as $\mathcal{T}$, but is trivial to exponentiate:

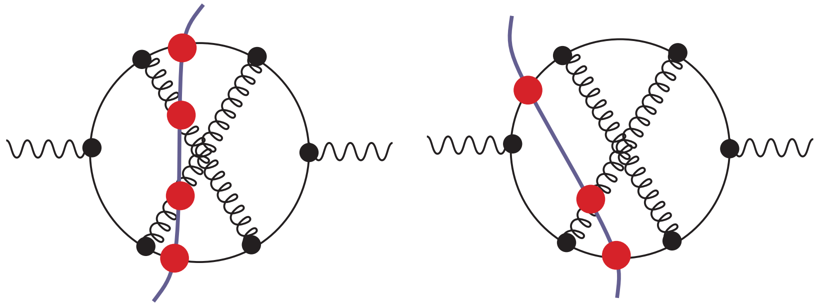
$$\frac{d\sigma}{d\log\mathcal{T}} = \frac{d\sigma_s}{d\log\mathcal{T}_s}\mathcal{F}(\mathcal{T},\mathcal{T}_s)$$

$\mathcal{F}$ includes all the recoil effects, and is computed numerically



- Flexible: previously unknown results in e^+e^- have been obtained (T_M, O, y_3)
- Improved: in a new paper (hep-ph/0304148) the analytic formula of the resummed observable is given, with *all* coefficients computed numerically (the proof is pending)
- Some restrictions on the observables (thrust in 3-jet region, Jade jets *not* included). Matching not yet achieved in hadronic collisions

Numerical higher-order computations



Consider $e^+e^- \to 3\ jets$:

$$\sigma(\mathcal{O}(\alpha_S^2)) = \sum_G \sum_C \int d\vec{l_1} d\vec{l_2} d\vec{l_3}\, \mathcal{G}(G, C; \vec{l_i})$$

Jet observables to NLO (Soper): move $\sum_C$ under the integral sign, exploit analyticity to deform the integral contour, and perform the integral by MC methods

- Extra work required for more partons (contour deformation), or new UV-divergent graphs. IR divergences problem solved for any number of partons
- Results in Coulomb gauge available (Krämer&Soper), as is desirable to interface with showers. Without any cutoffs, only weighted events produced

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Loop integrals to N^{k}LO (Binoth&Heinrich): use sector decomposition (Hepp) to disentangle overlapping divergences, then compute pole coefficients numerically

- Works iteratively. Non-euclidean configurations considered at one loop (Binoth, Heinrich & Kauer). Two-loop analytical results cross-checked
- It may be possible to extend the technique to phase-space integrals. The current version needs preliminary analytical integration

Conclusions

I wish I could have mentioned:

- New NLO computations
- Global logarithms
- Small-x physics

and more...

Discussions (and a few talks) are scheduled, concerning

- Monte Carlos (perturbative and non-perturbative issues)
- Higher-order computations
- Resummations and matching

First meeting of the QCD and SM working group:

today, 6pm