KITP Collider Physics Program and LoopFest: Highlights and Outlook

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KITP, LoopFest III
April 3, 2004

Abstract

Exciting times are rapidly approaching:

- Tremendous burst of theoretical activity.
- Approach of the LHC.
- Ongoing collider program at the Tevatron.
- Planning for Linear Collider.

Workshop Topics

- Parton Distribution Functions
  "Santa Barbara Accord", uncertainties, pdf comparison, NNLO, strangeness
- Monte Carlos
  Showers, NLL, evolution variables, underlying events, multiple parton interactions, MC@NLO, merging ME and shower Monte Carlos
- Resummation
  Joint resummation, automated resummation, non-global logarithms
- Higher Order QCD
  NLO, NNLO, backgrounds and signals, rapidity distributions, new techniques, SCET
- Higgs Boson
  Signal, backgrounds, NLO, NNLO, resummations
- Electroweak
  Precision calculations, Sudakov logs, open problems
- Beyond the SM
  Susy, extra dimensions, dark matter, 'little hierarchy' problem
- Connections to string theory
  QCD scattering amplitudes, Maldacena duality and possible connection to QCD

Web page under construction by Joey Huston at
http://www.pa.msu.edu/~huston/santa_barbara/collider04.html

Outline

Two conferences + weekly talks: ~ 110 talks $\rightarrow$ 16 seconds per talk.

Apologies for leaving out so many important topics and issues.

Some highlights of the program, mainly about loops:

1. NLO: Vector bosons, Higgs + heavy quarks, jets.
2. Comments on Monte Carlos. Merging with NLO, underlying events
3. Electroweak: Sudakov Logs, one loop, higher orders.
4. Resummations.
5. NNLO: matrix elements, phase space, rapidity distributions.
6. Parton distribution functions: NNLO splitting functions.
7. QCD scattering amplitudes and topological string theory.

Experimenters NLO Wish List

Bruce Knuteson
John Campbell

Hadron collider cross-sections one would like to know at NLO

Run II Monte Carlo Workshop, April 2001

Single boson	Diboson	Triboson	Heavy flavor
$W + \leq 5j$	$WW + \leq 5j$	$WWW + \leq 3j$	$t\bar{t} + \leq 3j$
$W + b\bar{b} + \leq 3j$	$WW + b\bar{b} + \leq 3j$	$WWW + b\bar{b} + \leq 3j$	$t\bar{t} + \gamma + \leq 2j$
$W + c\bar{c} + \leq 3j$	$WW + c\bar{c} + \leq 3j$	$WWW + \gamma\gamma + \leq 3j$	$t\bar{t} + W + \leq 2j$
$Z + \leq 5j$	$ZZ + \leq 5j$	$Z\gamma\gamma + \leq 3j$	$t\bar{t} + Z + \leq 2j$
$Z + b\bar{b} + \leq 3j$	$ZZ + b\bar{b} + \leq 3j$	$WZZ + \leq 3j$	$t\bar{t} + H + \leq 2j$
$Z + c\bar{c} + \leq 3j$	$ZZ + c\bar{c} + \leq 3j$	$ZZZ + \leq 3j$	$t\bar{b} + \leq 2j$
$\gamma + \leq 5j$	$\gamma\gamma + \leq 5j$		$b\bar{b} + \leq 3j$
$\gamma + b\bar{b} + \leq 3j$	$\gamma\gamma + b\bar{b} + \leq 3j$		$b\bar{b}\, t\bar{t}$
$\gamma + c\bar{c} + \leq 3j$	$\gamma\gamma + c\bar{c} + \leq 3j$		
	$WZ + \leq 5j$		
	$WZ + b\bar{b} + \leq 3j$		
	$WZ + c\bar{c} + \leq 3j$		
	$W\gamma + \leq 3j$		
	$Z\gamma + \leq 3j$		

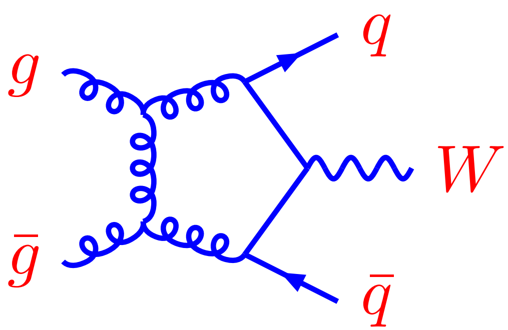
Many of these are well beyond our current capabilities and require new tools. Also need to merge with shower Monte Carlos.

State of the Art at One Loop

Five point is state of the art for generic calculations.

Typical Examples:

$pp \longrightarrow W + 2$ jets

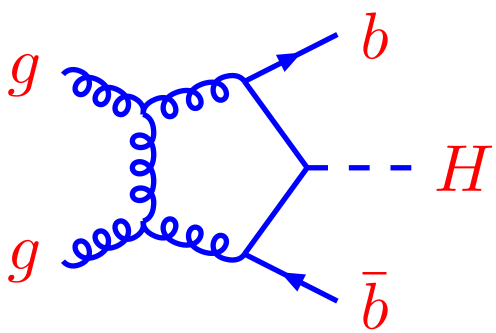


Bern, Dixon, Kosower

Dixon, Kunszt, and Signer

Campbell and Ellis: MCFM

$pp \longrightarrow b\bar{b}H$ or $pp \longrightarrow t\bar{t}H$



Reina, Dawson, Jackson and Wackeroth

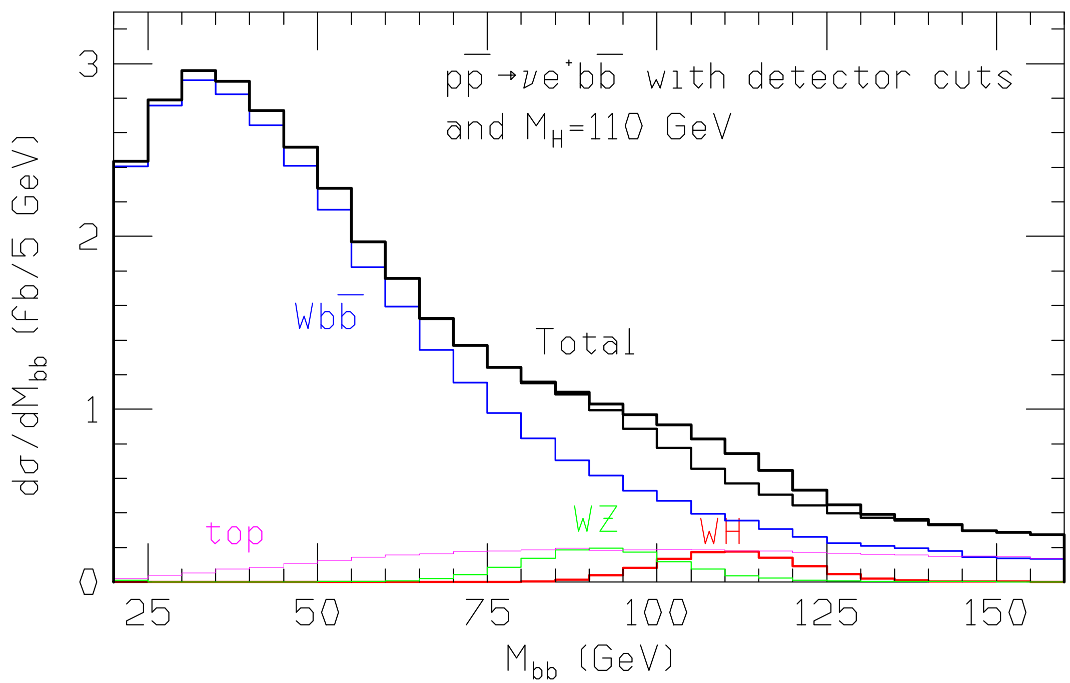
Beenakker, Dittmaier, Kramer, Plumper, Spira

MCFM

Campbell and Ellis

A start towards satisfying NLO wish list in one program.

Fortran package for calculating processes involving vector bosons, Higgs, jets and heavy quarks at hadron colliders.

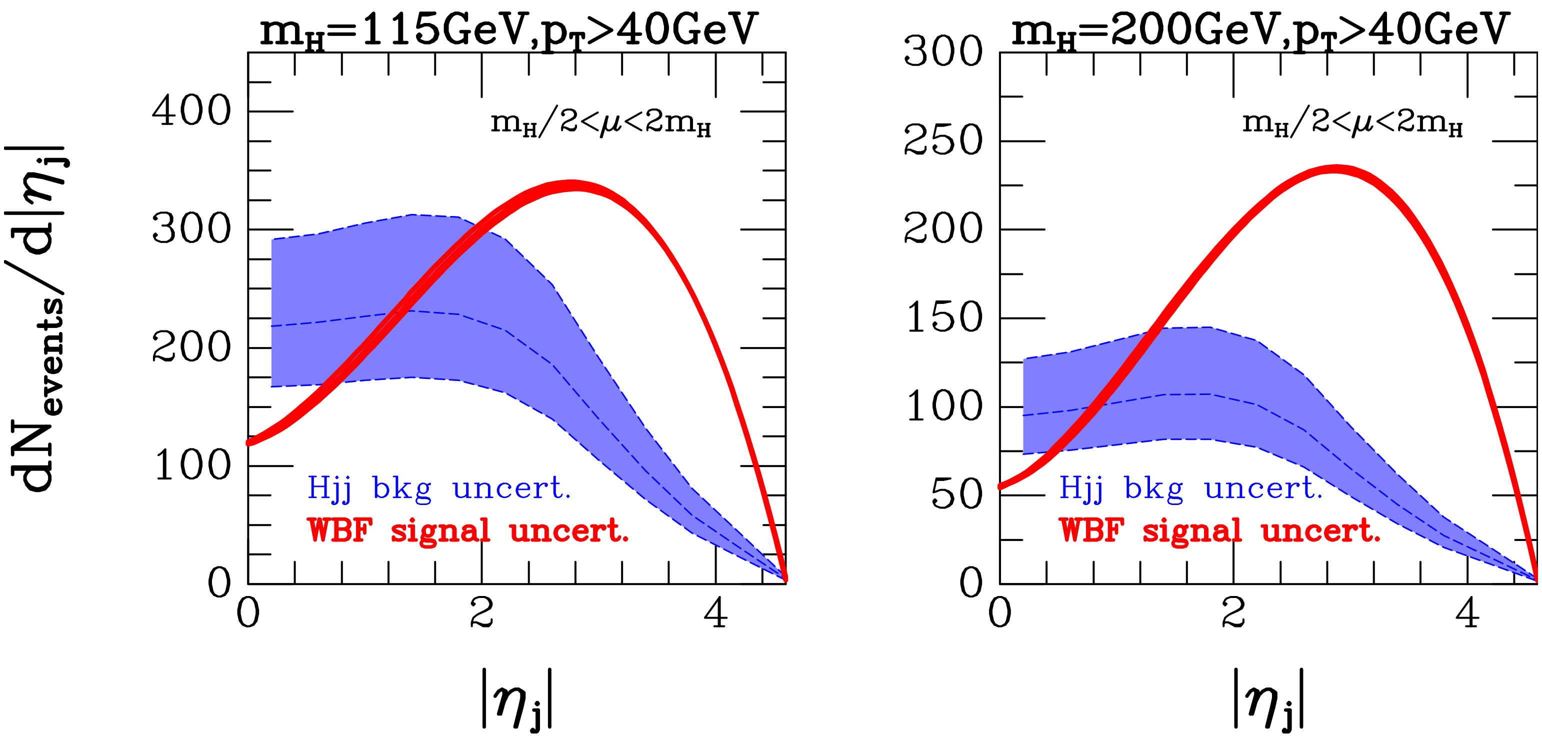


Best channel at Tevatron for Higgs search: $p\bar{p} \to HW$

Classic NLO plot showing difficulty of extracting the Higgs signal from background at Tevatron.

Example: H + 2 jets from Weak Boson Fusion

Figy, Oleari and Zeppenfeld
Berger and Campbell



From

Berger and Campbell

hep-ph/0403194

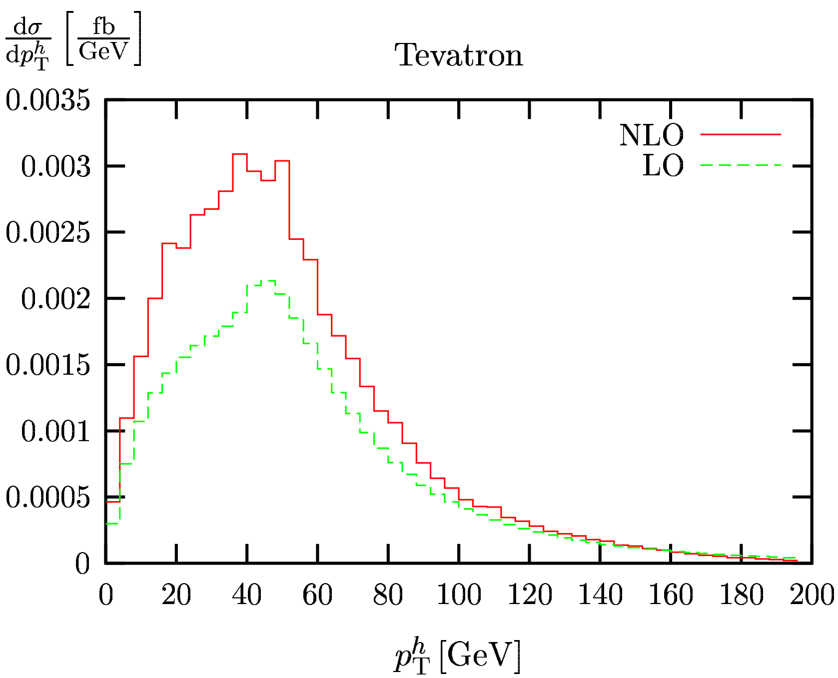
MCFM used

Purpose: After discovery of Higgs Boson measure HWW coupling.

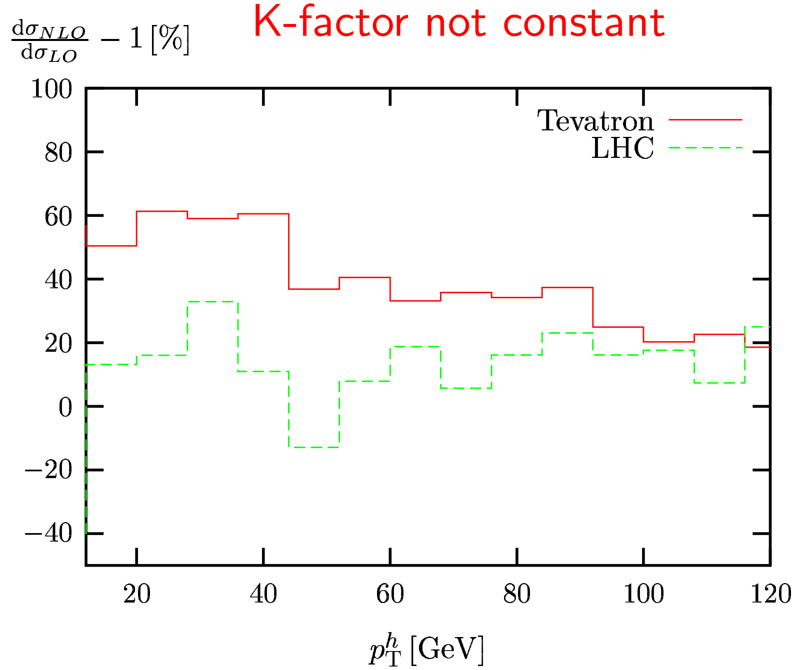
Previous estimates of uncertainties appear too optimistic, but it can be improved.

$pp \to H\bar{b}b$

Dittmaier, Krämer, Spira (2003)
Dawson, Jackson, Reina and Wackeroth (2003)



K-factor not constant



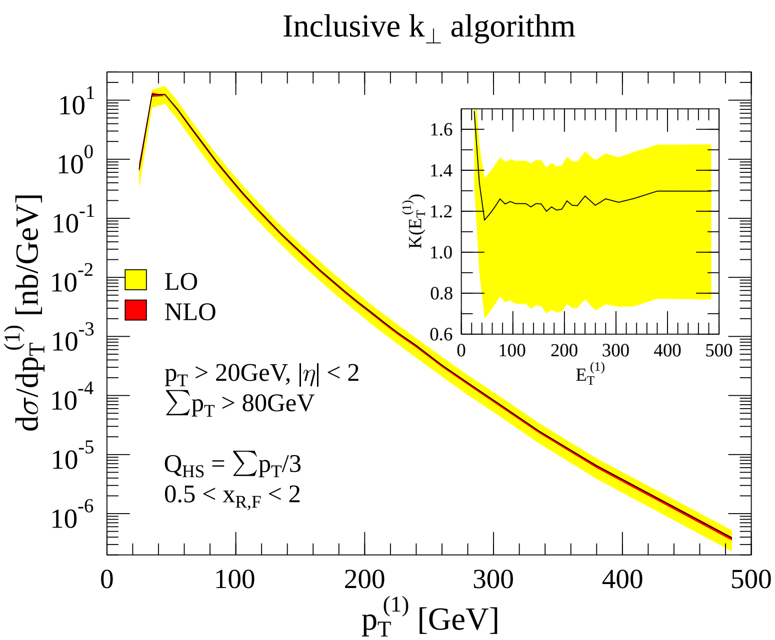
Higgs p_T distribution from Dawson et al

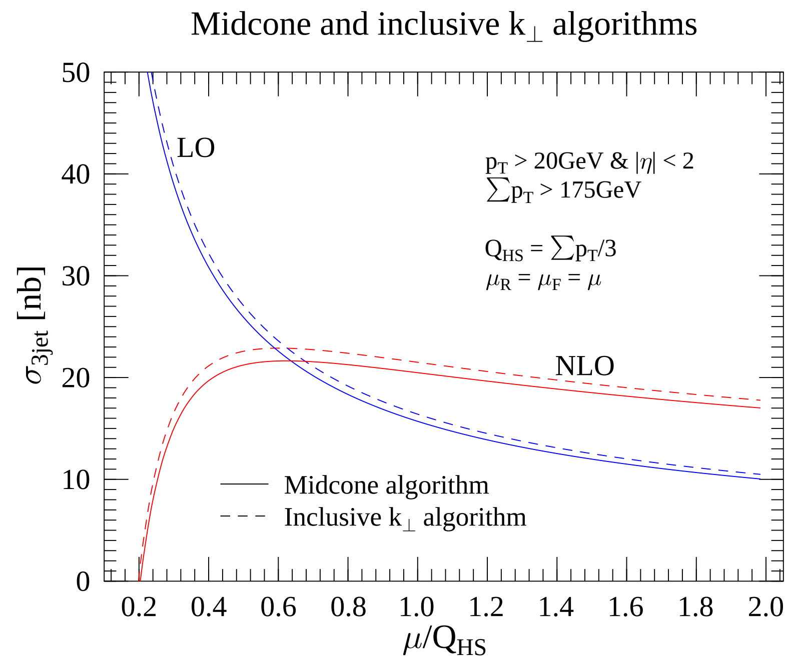
$b\bar{b}H$ production can be greatly enhanced in MSSM for large $\tan\beta$.

Example: NLO 3-jet production

Giele and Kilgore
Zoltan Nagy

From Nagy's NLOJET++:





High speed of Nagy's NLOJET++ program bodes well for pushing onwards to more complicated one-loop processes and to NNLO.

Pushing beyond five point

At 6 points complete answers only for very special theories: $N = 4$ supersymmetric Yang-Mills and the Yukawa Model.

Bern, Dixon, Dunbar and Kosower
Binoth, Guillet, Heinrich and Schubert

Arbitrary numbers of legs worked out in massless QCD and susy gauge theories, but limited to special (MHV) helicity configurations.

Bern, Chalmers, Dixon, Kosower; Mahlon; Bern, Dixon, Dunbar and Kosower

Optimistic this situation will change soon.

Various ideas we heard about:

- Unitarity approach — Bern, Dixon, Kosower
- Analytical approach — Binoth, Guillet, Heinrich, Schubert
- Numerical approaches — Binoth, Heinrich and Kaur; Krämer, Nagy and Soper
- Hybrid analytical/numerical approach. — Giele, Glover and Zanderighi
- Automated approach — GRACE
- Infrared rearrangements — D.A. Forde and A. Signer

Outlook for Higher Order Electroweak Corrections

discussed by U. Baur, S. Dittmaier, J. Hollik

We all know of the great success of precision electroweak.

talks from Clare and Sirlin

Almost complete calculation of $\sin^2\theta_{\rm eff}$ talks from Awramik

Reasons to further consider higher order electroweak

- At hadron colliders NLO electroweak $\sim$ NNLO QCD, $\alpha_s^2 \sim \alpha_W$
- Inclusion of Sudakov logs of the type $\log^2(p_T/M_W)$ Kühn's talk
- Linear Collider Physics & GigaZ Dittmaier's talk

Examples of processes where electroweak corrections are needed:

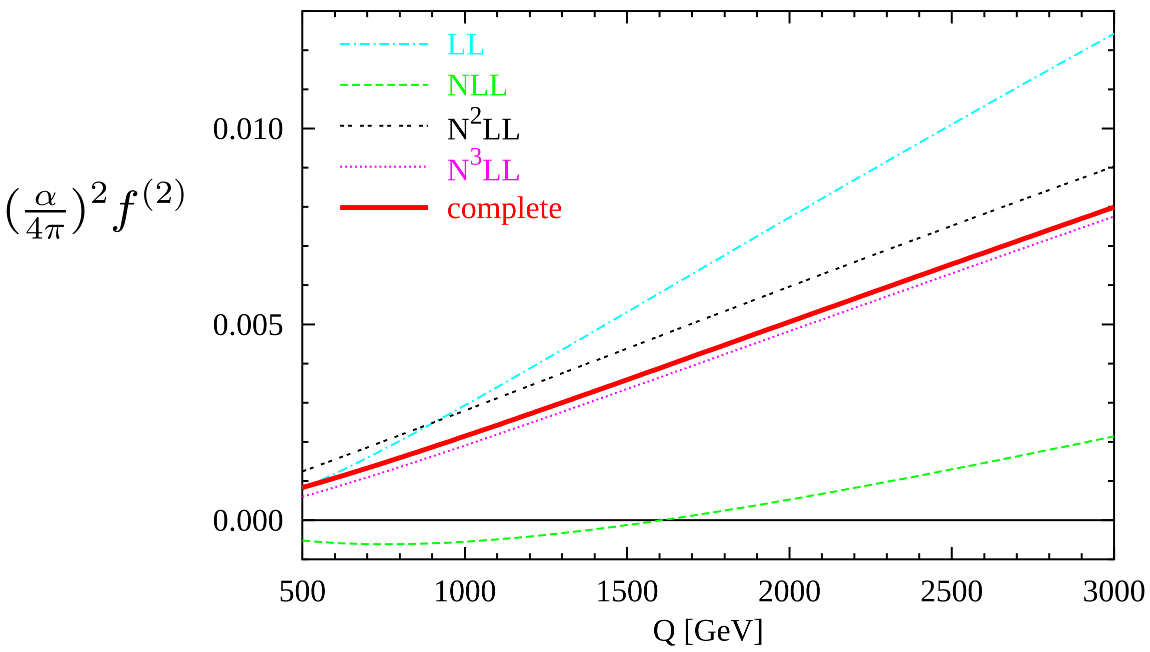
- Precision Drell-Yan at higher energies
- VV production ($V = W, Z, \gamma$)
- Gauge boson + jet production
- Higgs production, especially in WW fusion channel
- A future precise measurement of M_W requires $e^+e^- \to 4$ fermions both for signal and background. Requires hexagon integrals.

Sudakov Logs in Four Fermion Process

J. Kühn, Feucht, Penin and Smirnov

Example: Complete two-loop form factors in massive abelian theory

$$\mathcal{F}(\alpha, M, Q) = 1 + \frac{\alpha}{4\pi} f^{(1)} + \left(\frac{\alpha}{4\pi}\right)^2 f^{(2)} + \cdots$$



$\sim$ few percent effect for four fermion processes.

MC@NLO

Dobbs and Lefebvre
Kurihara *et al*
Frixione and Webber
Soper' talk

Good properties of MC's, *e.g.* Herwig or Pythia:

Soft and collinear emission, hadronization, outputs events, key tool for experimenters.

Good properties of fixed order:

Hard emissions, total rates, systematic approximation, key tool for theorists.

Obviously we want the best of both worlds in one program.

Various issues: Double counting, negative weights, infrared divergences

MC@NLO implements this so far for V, H, VV, $b\bar{b}$ and $t\bar{t}$

Frixione, Nason and Webber

Monte Carlos

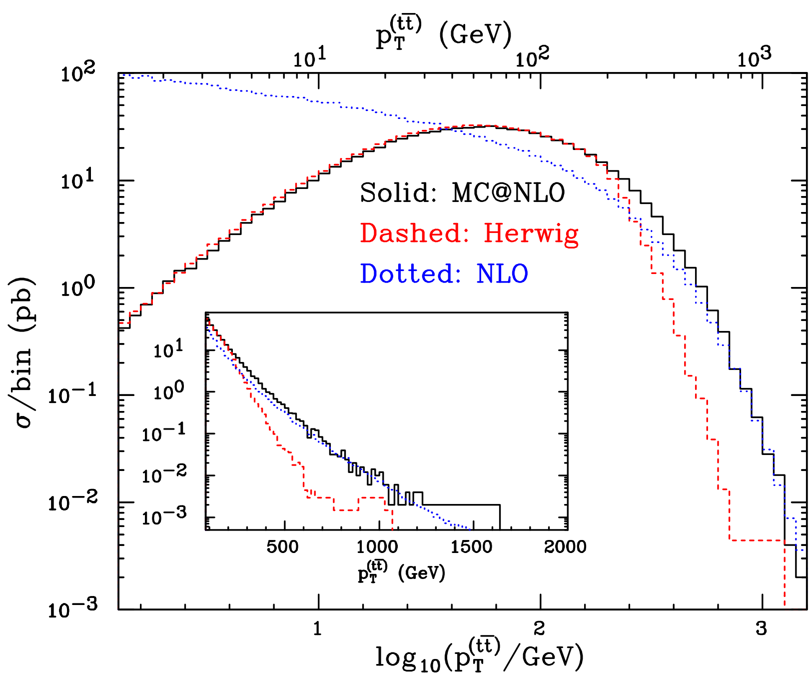
Also other new approaches to the problem of merging NLO to MC

Krämer, Nagy and Soper

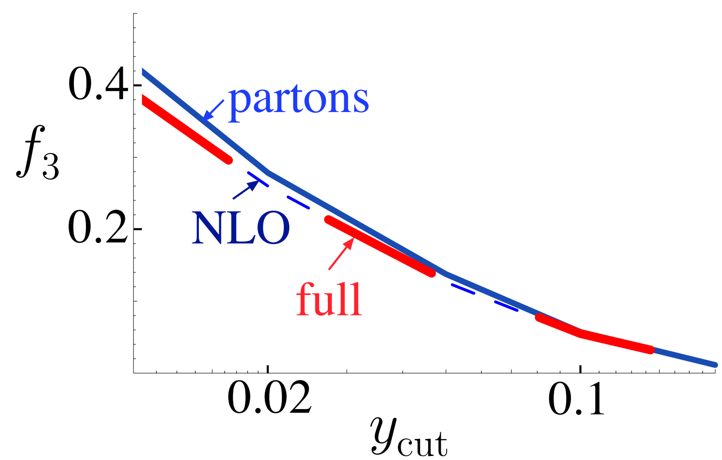
Another important development is new techniques for merging LO multijet matrix elements to shower MC. Catani, Krauss, Kühn, Webber (CKKW); Lönnblad; Mrenna and Richardson; Giele and Kosower

A lot of discussion and excitement about underlying events.

Fields, Sjöstrand, Skands



LHC p_T distribution for $t\bar{t}$ Frixione, Nason and Webber



LEP/SLC 3 jet fraction Soper's talk

Resummation

Fixed order perturbation theory is bound to fail sufficiently close to phase space boundaries.

Threshold Logs: $\alpha_s^n \ln^{2n-1}(1-z)/(1-z)$ when $z = Q^2/\hat{s} \to 1$, where Q is invariant mass of produced system.

Recoil Logs: $\alpha_s^n \ln^{2n-1}(Q^2/Q_T^2)$.

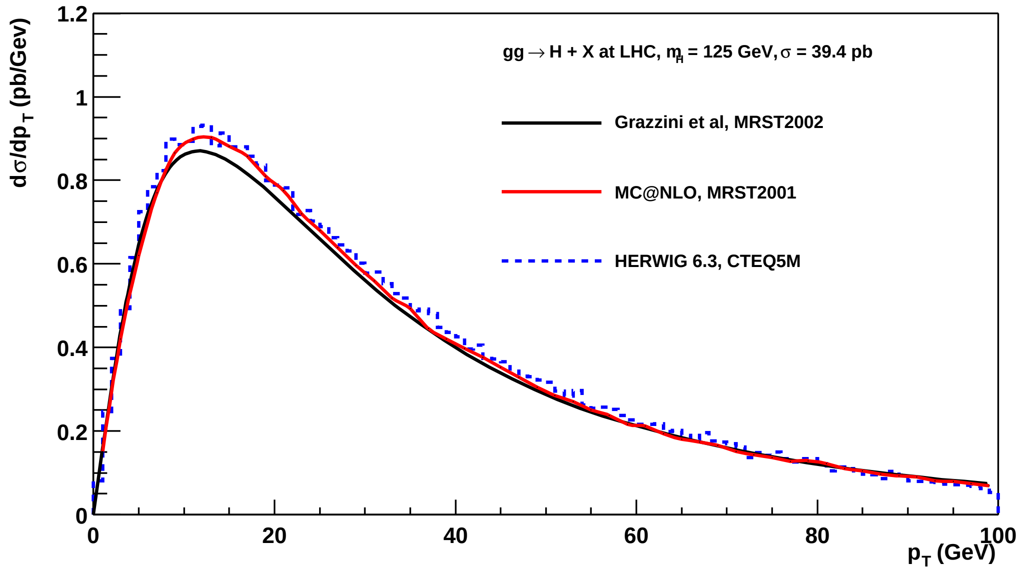
Considerable recent progress:

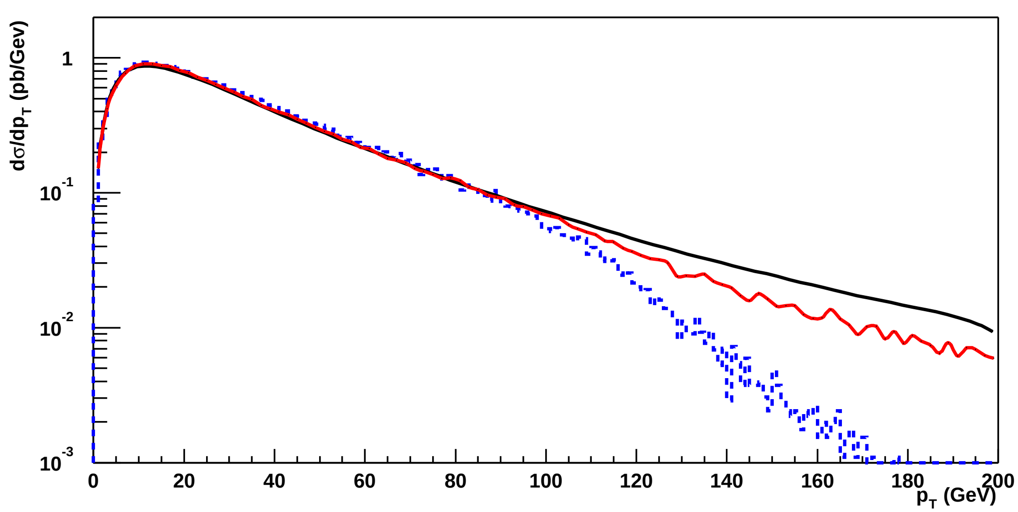
- NNLO + NNLL in some case, e.g. Higgs production

  Catani, de Florian, Grazzini, Nason
- NLL joint resummation. Resum both threshold and recoil logs simultaneously. Laenen, Sterman and Vogelsang; Kulesza, Sterman and Vogelsang
- Automated resummation (CAESAR) Banfi, Salam, and Zanderighi
- Resummation methods for heavy flavors Nadolsky, Kidonakis, Olness and Yuan

Resummation for Higgs p_T Distribution

ResBos, Herwig
Kulesza, Sterman, Vogelsang
Berger and Qiu
Catani, de Florian, Grazzini, Nason
Frixione, Webber





Comparison of Catani et al to MC@NLO and Herwig.

From hep-ph/0403052

Balazs, Grazzini, Huston, Kulesza and Puljak

Standard Arguments in Favour for NNLO

From R.K. Ellis and E.W.N Glover discussion

- Reduced renormalisation scale dependence.
- Event has more partons in the final state and hence closer to the real world.
- Better description of transverse momentum of final state due to double radiation off initial states.
- Reduced power correction as higher perturbative power of $1/\ln(Q/\Lambda)$ mimic genuine power corrections like $1/Q$.
- Full NNLO global fit of PDF's should also reduce the factorisation scale uncertainty.
- NNLO is the first serious estimate of the error.
- Obvious application: Reduction of uncertainty in α_s at e^+e^- colliders. Currently: $\alpha_s = 0.121 \pm 0.001$(exp) $\pm\, 0.006$(theory) (resummed NLO)

Bethke (2000)

Motivation for NNLO

Are the above arguments strong enough?

Why is so much theoretical effort currently going into NNLO where there are still large numbers of problems to be solved in other areas?

- Important NLO problems remain.
- Monte Carlos need further improvements. Merging with NLO.
- Uncertainties in PDF's.
- Resummations can be essential.
- Power corrections.
- Underlying events.

Key point to note in arguments for NNLO: The "standard arguments" for NNLO are a lower bound on the impact it will have.

There are already hints of the impact NNLO will have.

1. Developments at NNLO will surely feed into other areas.
   (a) Improved understanding of NNLO IR structure will very likely lead to improved parton showering: see David Kosower's LoopFest talk.
   (b) Surprise in small x behavior of splitting function. Moch, Vermaseren, and Vogt
   (c) Reducing uncertainties in pdfs using Drell-Yan. Anastasiou, Dixon, Melnikov and Petriello
2. Honest control over uncertainties from higher order.
3. Potent theoretical tool for exploring perturbation theory.
   (a) Behavior of higher order perturbation theory.
   (b) Remarkably simple structure of two-loop $N = 4$ super-Yang-Mills amplitudes. Anastasiou, Bern, Dixon, Kosower
   This helped stimulate the recent string theory interest in scattering amplitudes. $N = 4$ super-Yang-Mills appears in Maldacena conjecture.

The new higher loop developments will surely lead to many new and unexpected important insights.

Two-loop Revolution

Two-loop computations involving more than 1 kinematic variable is a new art only a few years old. New loop integration technology

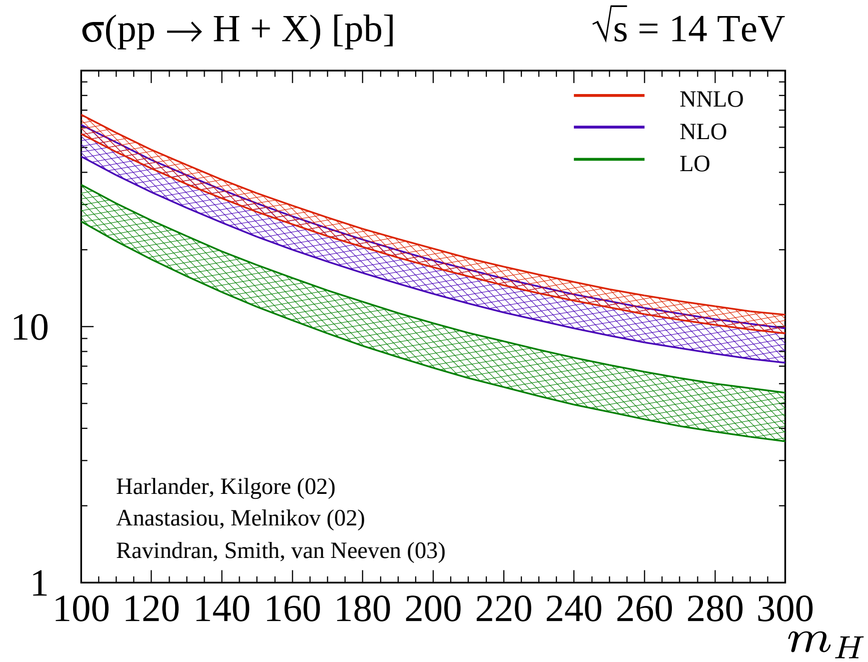
Tkachov, Chetyrkin and Tkachov; Smirnov; Smirnov and Veritin; Tausk; Gehrmann and Remiddi; Anastasiou, Glover and Oleari; Laporta; Moch, Uwer Weinzierl;

In the past few years the field of loop computations has gotten a tremendous boost due to the influx of energetic bright young people.

Lots of Two-Loop Scattering Amplitudes

- Two-loop Bhabha scattering in massless QED — Bern, Dixon and Ghinculov
- All two-loop $2 \to 2$ QCD processes. — Anastasiou, Glover, Oleari and Tejeda-Yeomans; Bern, De Freitas, and Dixon
- $\gamma\gamma \to \gamma\gamma$ — Bern, Dixon, De Freitas, A. Ghinculov and H.L. Wong
- $gg \to \gamma\gamma$. (Background to Higgs decay.) — Bern, De Freitas, Dixon
- $\bar{q}q \to \gamma\gamma$, $\bar{q}q \to g\gamma$, $e^+e^- \to \gamma\gamma$ — Anastasiou, Glover and Tejeda-Yeomans
- $e^+e^- \to 3$ partons — Garland, Gehrmann, Glover, Koukoutsakis and Remiddi; Moch, Uwer, Weinzierl
- DIS 2 jet and $pp \to W, Z + 1$ jet — Gehrmann and Remiddi

NNLO Inclusive Higgs Production at LHC



Harlander and Kilgore
Anastasiou and Melnikov
Ravindran, Smith and van Neerven

NNLO pdfs approximate

Fact that the NNLO value is close to to the NLO value suggests perturbation theory is under control.

Result is also close to earlier resummation calculation.

Catani, de Florian and Grazzini; Krämer, Laenen, Spira

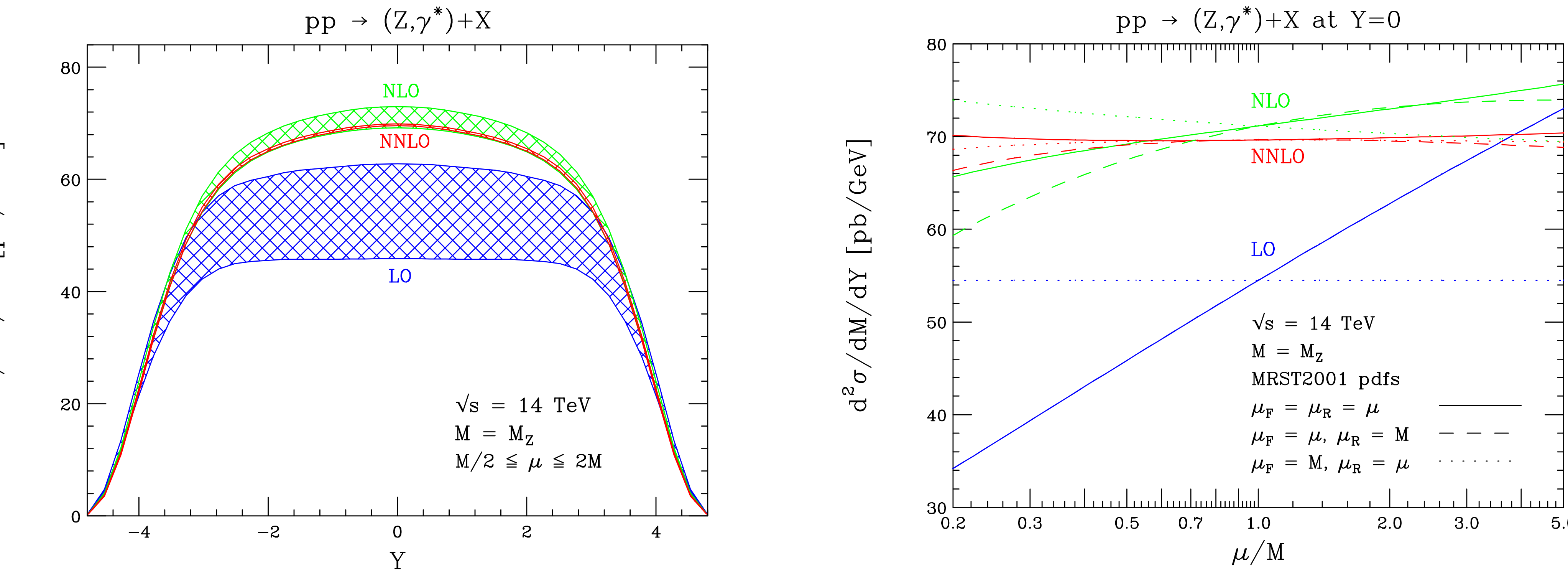
These have been somewhat improved with resummation, NNLO + NNLL resummation. First calculation ever at this order.

Catani, de Florian, Grazzini, Nason

Another nice example: Inclusive $\bar{b}b \to H$ at NNLO discussed in Kilgore's talk.

Drell-Yan Rapidity Distributions

Anastasiou, Dixon, Melnikov and Petriello



• Amazingly good stability of the answer.

• Predictions good to $\sim 1\%$.

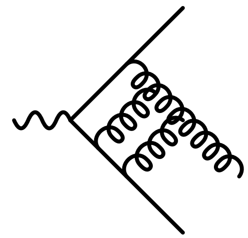
• Strengthens proposal to use W and Z production to determine parton-parton luminosities and to constrain parton distributions.

Phase Space Integration Developments

Ingredients in NNLO calculation:

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

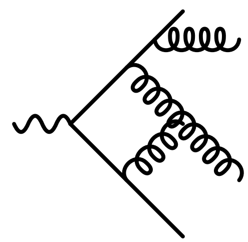
- Amplitudes with n legs and 2 loops



$q\bar{q}g$

Garland, Gehrmann, Glover, Koukoutsakis and Remiddi

- Amplitudes with $n+1$ legs and 1 loops

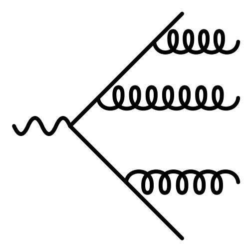


$q\bar{q}gg$

Bern, Dixon, Kosower

Campbell, Glover, Miller

- Amplitudes with $n+2$ legs and no loops



$q\bar{q}ggg$

Hagiwara and Zeppenfeld

Berends, Giele, Kuijf

Falck, Graudenz, Kramer

Phase Space Integration Developments

No final solution yet, but very rapid development.

Two basic approaches

- Subtraction approaches — Weinzierl; Kosower; Kilgore; Gehrmann-De Ridder, Gehrmann, Heinrich
- Sector decomposition — Binoth and Heinrich; Anastasiou, Melnikov and Petriello

Already applied to $e^+e^- \to 2$ jets. — Anastasiou, Melnikov and Petriello; Gehrmann-De Ridder, Gehrmann, Glover; Binoth and Heinrich

$e^+e^- \to 3$ jets is on the horizon.

LEP and SLC Data will need to be reanalyzed.

NNLO Nonsinglet Splitting Function

There has been a large amount of previous work on NNLO contributions to the splitting functions.

van Neerven and Zijlstra (1993); Catani and Hautman(1994)
Larin, Nogueira, Retey, van Ritbergen, Vermaseren (1997)

van Neerven and Vogt (2000); Retey and Vermaseren (2001)

Approximate NNLO implemented in fits for pdfs.

Martin, Roberts, Stirling, Thorne; Alekhin

Major Milestone: Moch, Vermaseren, and Vogt have completed promised full calculation of the non-singlet splitting functions. Extremely non-trivial.

- Leading $\ln(x)$ approximations found not to be a good approximation
- New, unpredicted leading log found for color structure $d^{abc}d^{abc}$: Surprise leading $\ln^4(x)$ term.
- Singlet should be finished soon.
- Precision evolution (at all but very small x) will be possible.

Topological String Theory and QCD Scattering

Delighted that we had string theorists, including Ed Witten, participate in the Collider Program. Brought together two communities.

Topic of discussion: Multi-particle scattering amplitudes in QCD. (Actually $N = 4$ super-Yang-Mills, but distinction not important at tree level.)

Tree-level QCD scattering amplitudes $\leftrightarrow$ 'Twistor-space' $\leftrightarrow$ Topological String Theory

E. Witten; Roiban, Spradlin, and Volovich

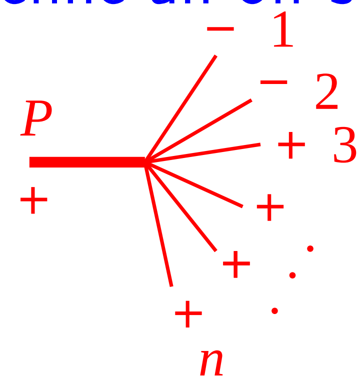
'Twistor-space': Use spinor helicity then Fourier transform wrt plus helicity spinors. Witten observed that in twistor space external points lie on certain curves.

Non-trivial "Duality"

Surprising implication: Simple structure in twistor space implies QCD tree amplitudes must have simple factorization properties.

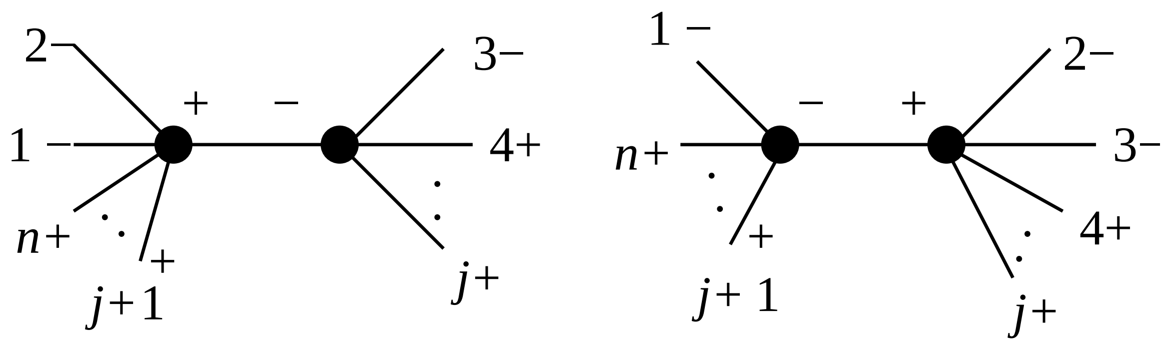
Start from QCD Parke-Taylor gluon amplitudes and define an off-shell "MHV vertex" Cachazo, Svrcek and Witten

$$V(1^-,2^-,3^+,\ldots,n^+,P^+) = \frac{\langle 1\,2\rangle^4}{\langle 1\,2\rangle \cdots \langle n-1,\,n\rangle\,\langle n\,P\rangle\,\langle P\,1\rangle}$$



Continue spinor off-shell $(P^2 \neq 0)$: $\langle i\,P\rangle = \eta \sum_{j=1}^{n} \langle i^- | \not{k}_j | q^- \rangle$
where $P = k_1 + k_2 + \cdots k_n$ and q auxiliary, satisfying $q^2 = 0$.

Get a beautifully simple formula for *e.g.* 3 minus and rest plus helicity in QCD



It will be very interesting to see what other structures are uncovered by our string theory friends, especially for loops.

Summary

We can expect many exciting years ahead due to anticipated experimental discoveries at colliders.

This is already driving exciting advances in phenomenology and related theoretical tools.

Need to support the young people who are pushing things forward.

Let's do it again in 2007!

Thank you David Gross, Dan Hone, Deborah Storm, Sue Alemdar and the rest of the wonderful staff at the KITP for making the program and conference possible!

Thank you Ulrich Baur, Sally Dawson, Michael Peskin and Doreen Wackeroth for LoopFest III.

Many thanks also to my co-organizers Joey Huston, Zoltan Kunszt and Kirill Melnikov.