Precision Calculations for the LHC

LHC Olympics 2006

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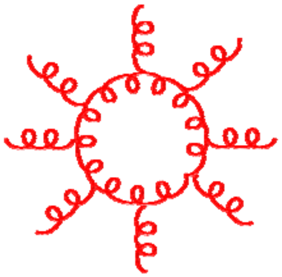
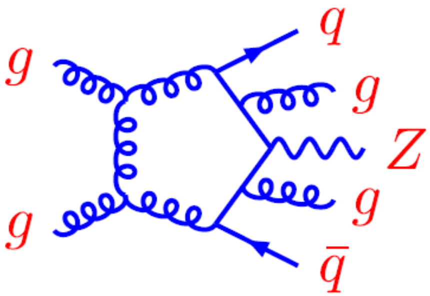
hep-ph/0501240
hep-ph/0505055
hep-ph/0507005
hep-ph/0604195
hep-ph/0607014

Outline

- The need for NLO calculations at the LHC
- The experimenters' wish list.
- The trouble.
- On-shell methods. Rewrite of QFT.
- Example of state-of-the art calculations

- Blackboard lecture, working through a simple example of on-shell recursion.

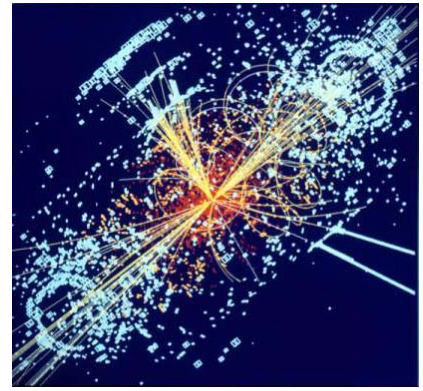


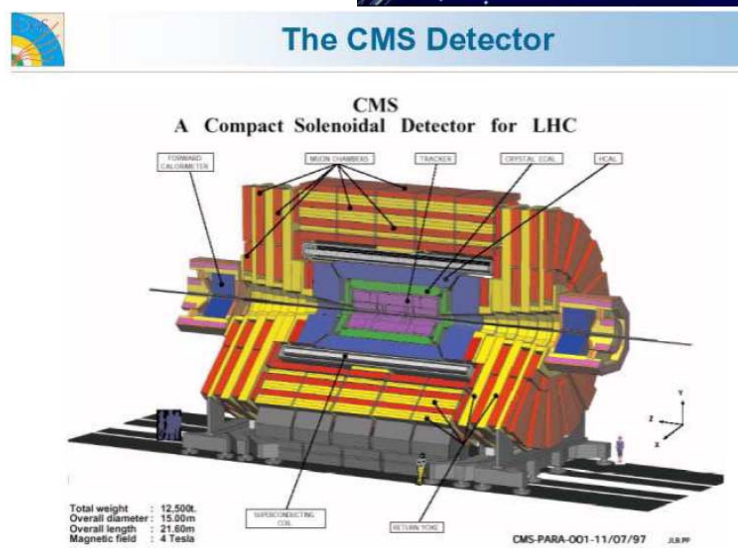


LHC Physics

The LHC will start operations in 2007.

We will have lots of multi-particle processes. Want reliable predictions.

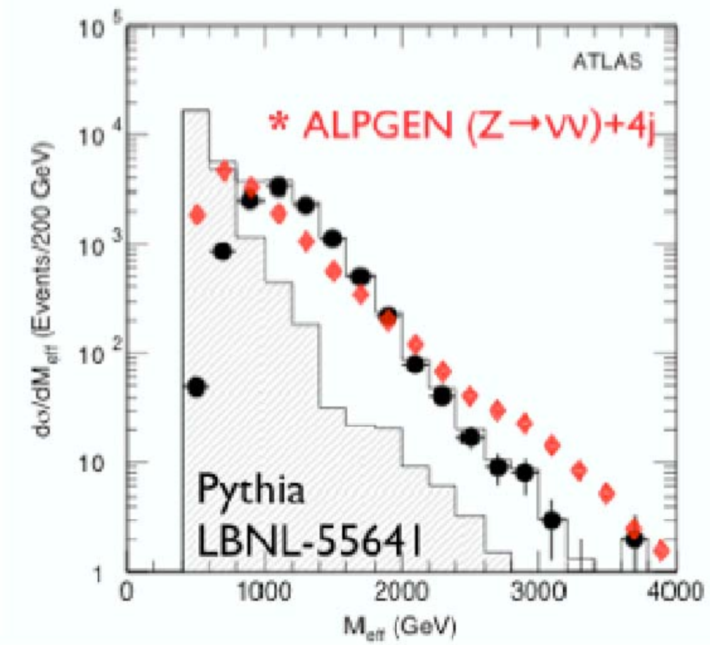


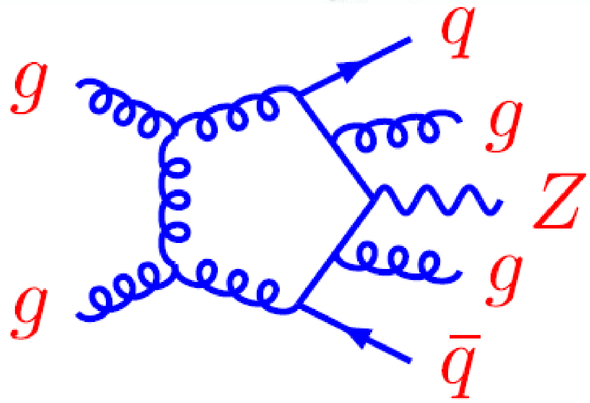


Example: Susy Search

Early ATLAS TDR studies using PYTHIA overly optimistic.

- ALPGEN is based on LO matrix elements and much better at modeling hard jets.
- What will disagreement between ALPGEN and data mean? Hard to tell. Need NLO.

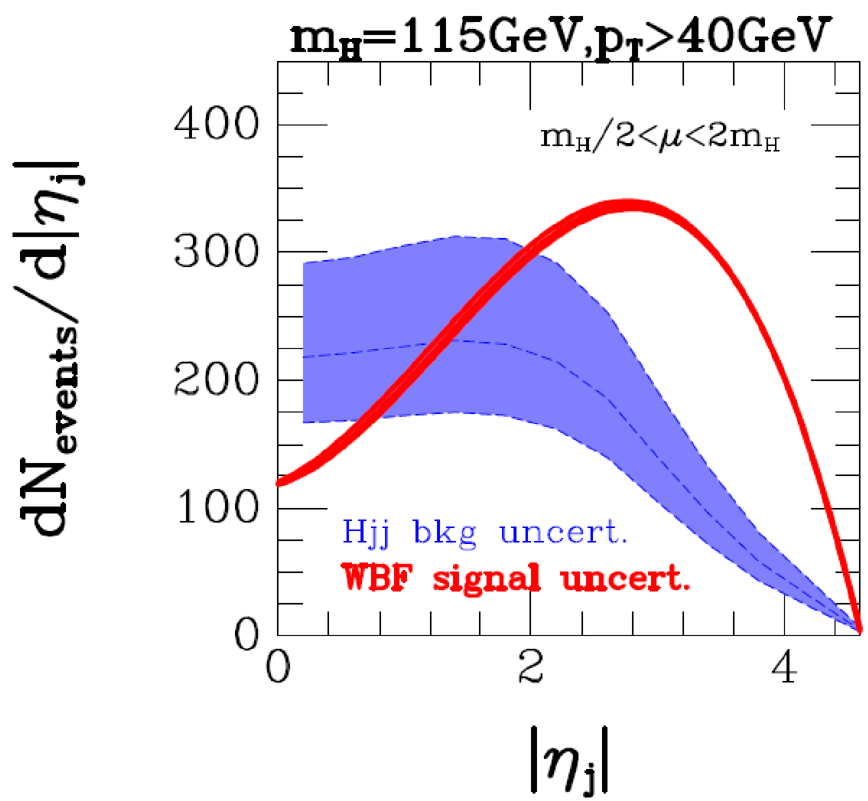




We need $pp \to Z + 4$ jets at NLO

Example: Higgs + 2 jets from Weak Boson Fusion

Figy, Oleari and Zeppenfeld
Berger and Campbell
Campbell, Ellis and Zanderighi



From
Berger and Campbell
hep-ph/0403194
MCFM used

Purpose: After discovery of Higgs Boson measure *HWW* coupling

Background uncertainty is reduced with an NLO calculation.

LHC Experimenter's NLO Wishlist

process ($V \in \{Z, W, \gamma\}$)	background to
1. $pp \to V\,V$ jet	$t\bar{t}H$, new physics
2. $pp \to H + 2$ jets	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2$ jets	$t\bar{t}H$
5. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to V\,V + 2$ jets	VBF$\to H \to VV$
7. $pp \to V + 3$ jets	various new physics signatures
8. $pp \to V\,V\,V$	SUSY trilepton

Les Houches 2005

Large number of high multiplicity processes that we need to compute.

- Numerical approaches. Recent progress.

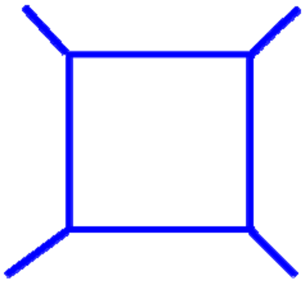
Binoth and Heinrich Kaur; Giele, Glover, Zanderighi; Binoth, Guillet, Heinrich, Pilon, Schubert; Soper and Nagy; Ellis, Giele and Zanderighi; Anastasiou and Daleo; Czakon; Binoth, Heinrich and Ciccolini

- In this talk analytic on-shell methods: spinors, twistors, unitarity method, on-shell bootstrap approach.

Bern, Dixon, Dunbar, Kosower; Bern and Morgan; Cachazo, Svrcek and Witten; Bern, Dixon, Kosower; Bedford, Brandhuber, Spence, Travaglini; Britto, Cachazo, Feng and Witten; Berger, Bern, Dixon, Kosower, Forde; Xiao, Yang and Zhu

Example of difficulty

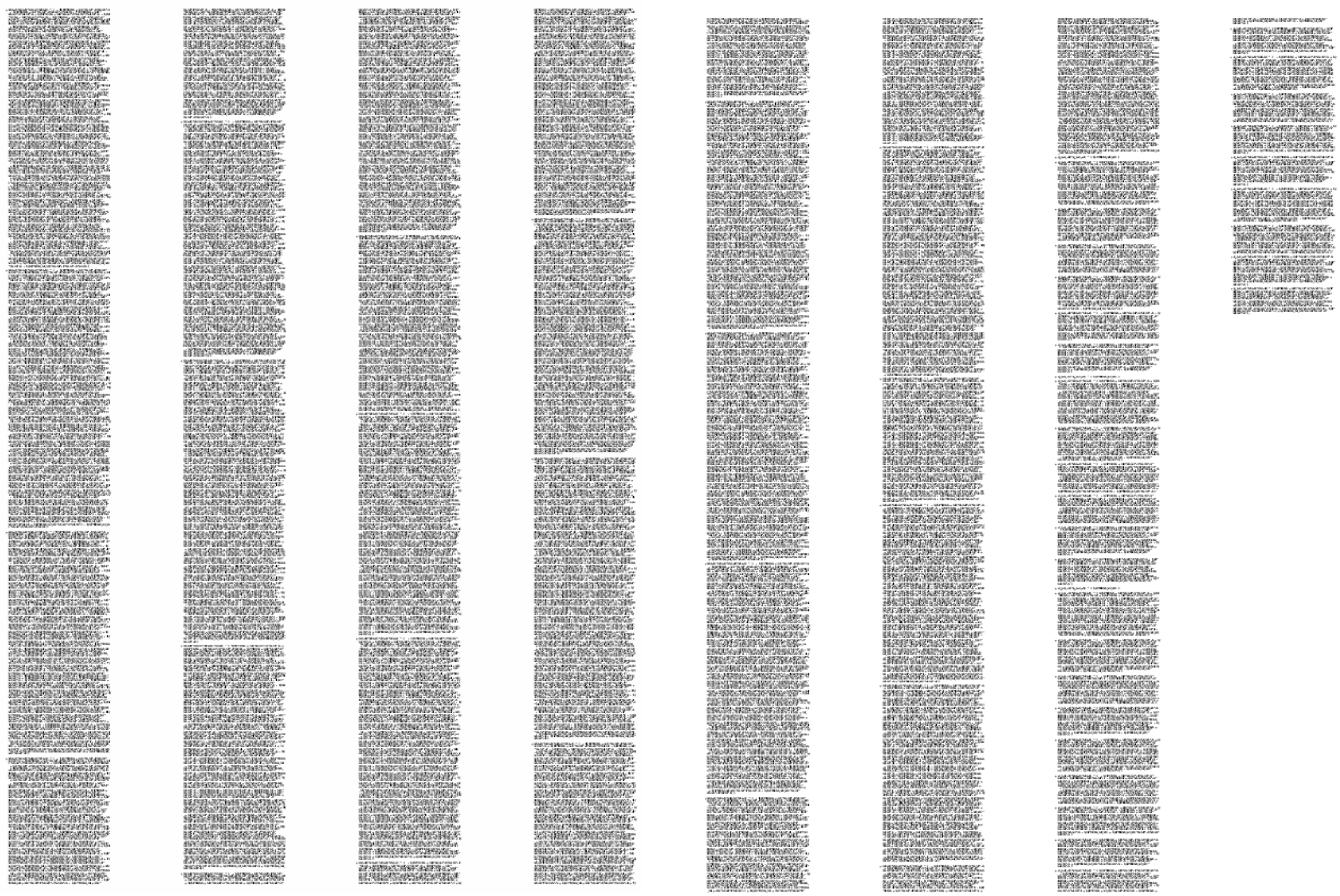
Consider a tensor integral:



$$\int \frac{d^{4-2\epsilon}\ell}{(2\pi)^{4-\epsilon}} \frac{\ell^\mu\, \ell^\nu\, \ell^\rho\, \ell^\lambda}{\ell^2\, (\ell - k_1)^2\, (\ell - k_1 - k_2)^2\, (\ell + k_4)^2}$$

Evaluate this integral via Passarino-Veltman reduction. Result is …

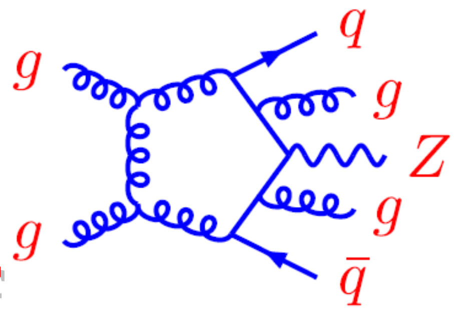
Result of performing the integration



Numerical stability is a key issue.
Clearly, there should be a better way

What we need

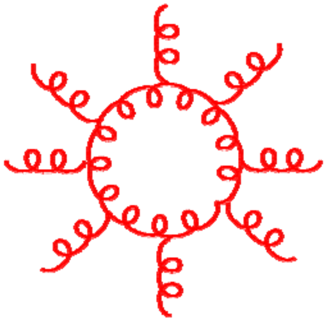
- Numerical stability.
- Scalable to large numbers of external partons.
- A general solution that applies to any process.
- Can be automated.



What we're dreaming of

- A technique where computations undergo modest growth in complexity with increasing number of legs.
- Compact analytic expressions "that fit on a page".

Progress Towards the Dream



Results with on-shell methods:

- Many QCD amplitudes with $n > 5$ legs.

  Berger, Bern, Dixon, Forde and Kosower

- Certain log contributions via on-shell recursion.

  Bern; Bjerrum-Bohr; Dunbar, Ita

- Improved ways to obtain logarithmic contributions via unitarity method.

  Britto,Cachzo, Feng; Britto, Feng and Mastrolia

Key Feature: Modest growth in complexity as *n* increases. No unwanted Gram dets.

Spinors and Twistors

Witten

Spinor helicity for gluon polarizations in QCD:

$$\varepsilon_\mu^+(k;q) = \frac{\langle q^- |\gamma_\mu| k^-\rangle}{\sqrt{2}\,\langle q\,k\rangle}, \qquad \varepsilon_\mu^-(k,q) = \frac{\langle q^+ |\gamma_\mu| k^+\rangle}{\sqrt{2}\,[k\,q]}$$

$$\epsilon^{ab}\lambda_{ja}\lambda_{lb} \longleftrightarrow \langle j\,l\rangle = \langle k_{j\,-}|k_{l+}\rangle = \sqrt{2k_j\cdot k_l}\; e^{i\phi} = \tfrac{1}{2}\bar{u}(k_j)(1+\gamma_5)u(k_l)$$

$$\epsilon_{\dot a\dot b}\tilde\lambda_j^{\dot a}\tilde\lambda_l^{\dot b} \longleftrightarrow [j\,l] = \langle k_{j\,+}|k_{l\,-}\rangle = -\sqrt{2k_j\cdot k_l}\; e^{-i\phi} = \tfrac{1}{2}\bar{u}(k_j)(1-\gamma_5)u(k_l)$$

Penrose Twistor Transform:

$$\tilde{A}(\lambda_i,\mu_i) = \int \prod_i \frac{d^2\tilde\lambda_i}{(2\pi)^2}\, \exp\Big(\sum_j \mu_j^{\dot a}\tilde\lambda_{j\dot a}\Big)\, A(\lambda_i,\tilde\lambda_i)$$

Early work from Nair

Witten's remarkable twistor-space link:

Witten; Roiban, Spradlin and Volovich

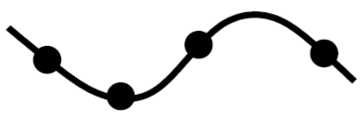
QCD scattering amplitudes ⟷ Topological String Theory

Key implication: Scattering amplitudes have a much much simpler structure than anyone would have believed.

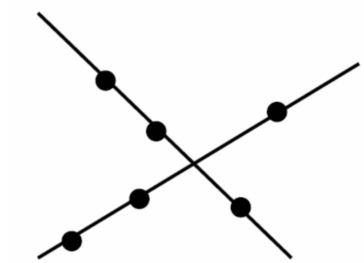
Amazing Simplicity

Witten conjectured that in twistor –space gauge theory amplitudes have delta-function support on curves of degree:

$$d = q - 1 + L, \quad q = \#\ \text{negative helicities}, \quad L = \#\ \text{loops},$$



Connected picture



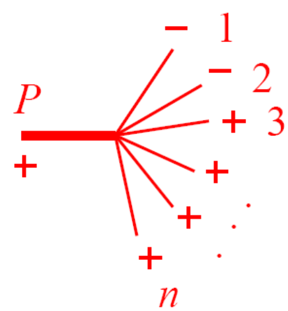
Disconnected picture

Witten
Roiban, Spradlin and Volovich
Cachazo, Svrcek and Witten
Gukov, Motl and Neitzke
Bena, Bern and Kosower

Structures imply an amazing simplicity in the scattering amplitudes.

MHV vertices for building amplitudes

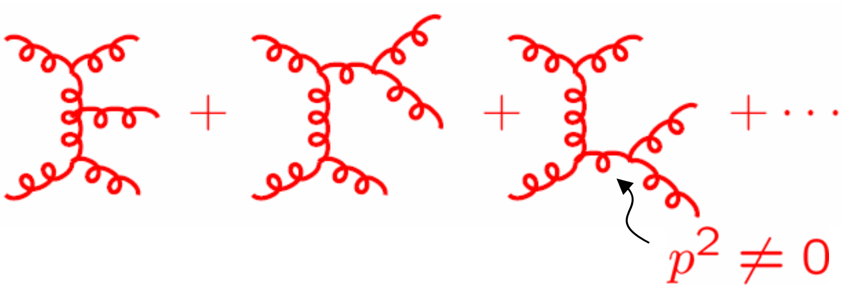
Cachazo, Svrcek and Witten

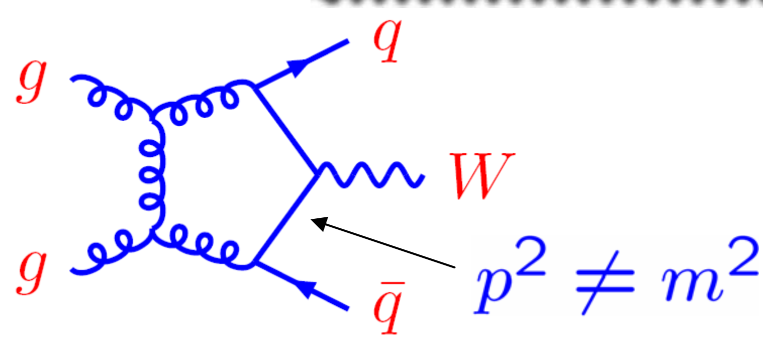


Much of the simplicity survives addition of masses or loops

Why are Feynman diagrams clumsy for high-multiplicity processes?

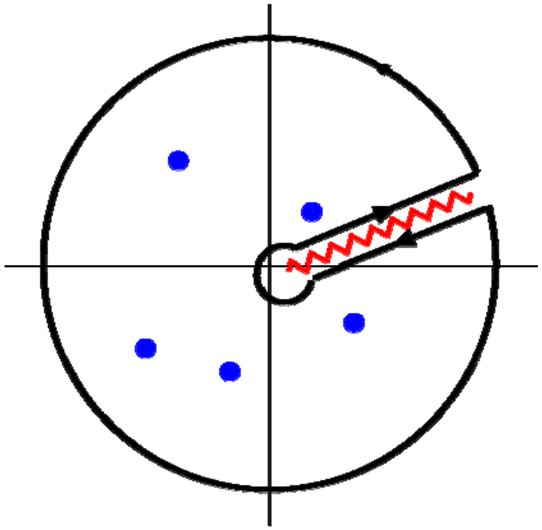
- Vertices and propagators involve gauge-dependent off-shell states. Origin of the complexity.

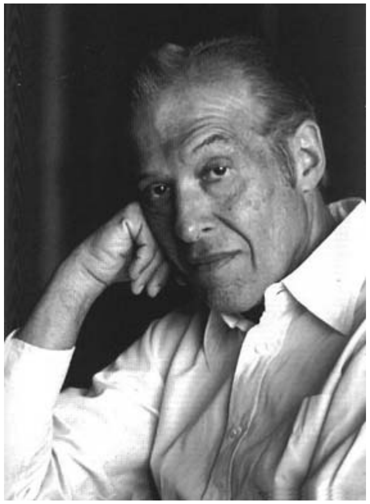




- To get at root cause of the trouble we must rewrite perturbative quantum field theory.

- **All steps should be in terms of gauge invariant on-shell states.** $p^2 = m^2$
- **Radical rewriting of perturbative QCD needed.**





"One of the most remarkable discoveries in elementary particle physics has been that of the existence of the complex plane."

J. Schwinger in "Particles, Sources and Fields" Vol 1

On-shell Formalisms

With on-shell formalisms we can exploit analytic properties.

- **Curiously, a practical on-shell formalism was constructed at loop level prior to tree level: unitarity method.** Bern, Dixon, Dunbar, Kosower **(1994)**

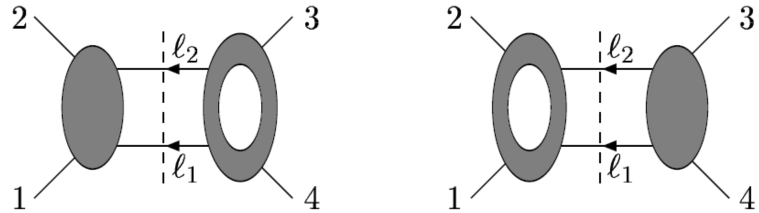
- **Solution at tree-level had to await Witten's twistor inspiration. (2004)**
  - **-- MHV vertices** Cachazo, Svrcek Witten; Brandhuber, Spence, Travaglini
  - **-- On-shell recursion** Britto, Cachazo, Feng, Witten

- **Combining unitarity method with on-shell recursion gives loop-level on-shell bootstrap. (2006)**
  Berger, Bern, Dixon, Forde, Kosower

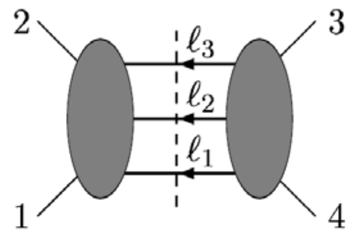
Bern, Dixon, Dunbar and Kosower

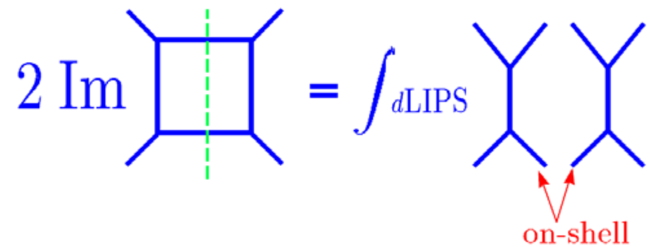
Unitarity Method

Two-particle cut:



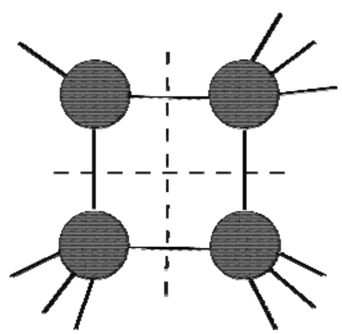
Three- particle cut:





Generalized unitarity:

Bern, Dixon and Kosower



As observed by Britto, Cachazo and Feng quadruple cut freezes integral:
Coefficients of box integrals always easy.

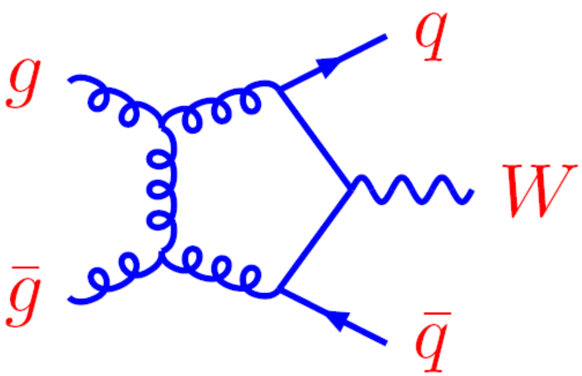
Generalized cut interpreted as cut propagators not canceling.

A number of recent improvements to method

Britto, Buchbinder, Cachazo and Feng; Berger, Bern, Dixon, Forde and Kosower; Britto, Feng and Mastrolia; Xiao, Yang and Zhu

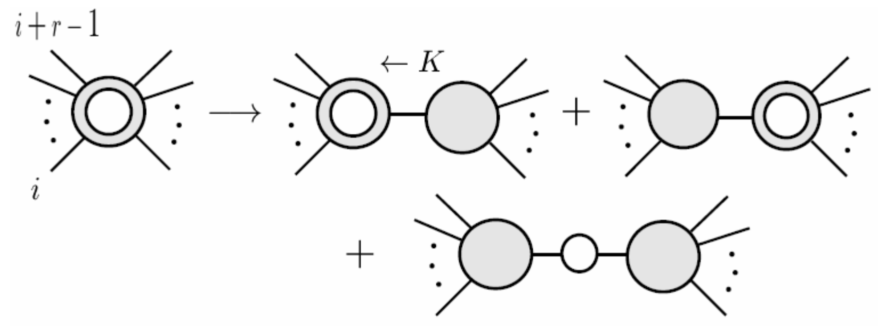
Early On-Shell Bootstrap

Bern, Dixon, Kosower
hep-ph/9708239



$e^+e^- \to Z \to 4$ partons

$pp \to W, Z + 2$ partons



Early Approach:

- Use Unitarity Method with $D = 4$ helicity states. Efficient means for obtaining logs and polylogs.
- Use factorization properties to find rational function contributions.

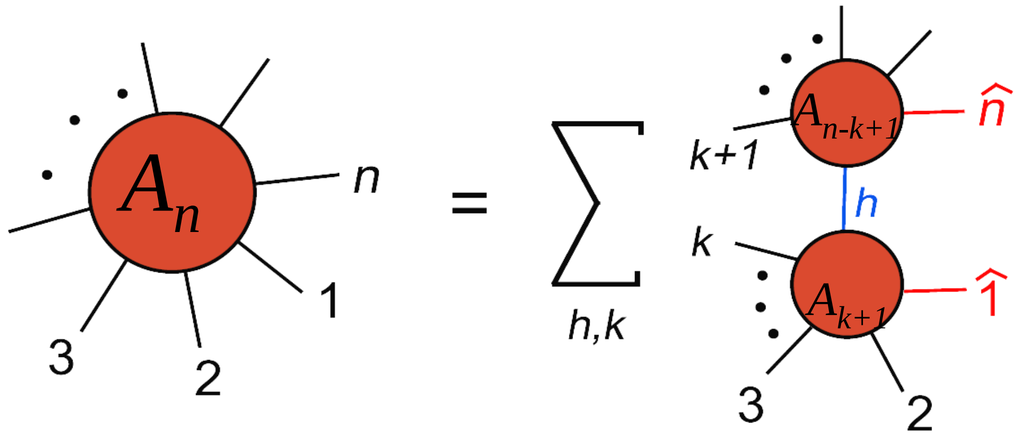
Key problems preventing widespread applications:

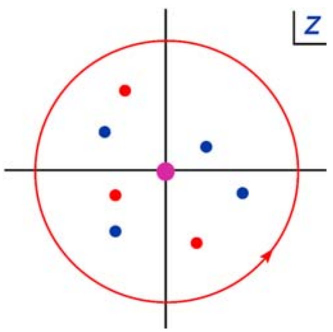
- Difficult to find rational functions with desired factorization properties.
- Systematization unclear – key problem.

Tree-Level On-Shell Recursion

New representations of tree amplitudes from IR consistency of one-loop amplitudes in $N = 4$ super-Yang-Mills theory. Bern, Del Duca, Dixon, Kosower; Roiban, Spradlin, Volovich

Using intuition from twistors and generalized unitarity: Britto, Cachazo, Feng; BCF + Witten





$$p_1^\mu(z) = p_1^\mu - \frac{z}{2}\langle 1^-|\gamma^\mu|n^-\rangle \qquad p_n^\mu(z) = p_n^\mu + \frac{z}{2}\langle 1^-|\gamma^\mu|n^-\rangle$$

On-shell conditions maintained by shift.

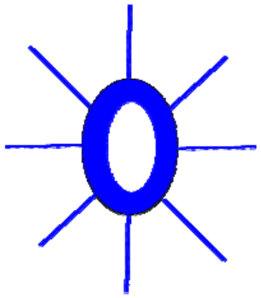
Proof relies on so little. Power comes from generality

- **Cauchy's theorem**
- **Basic field theory factorization properties**

Construction of Loop Amplitudes

Berger, Bern, Dixon, Forde, Kosower

Shifted amplitude function of a complex parameter



$A(z)$

$$p_1^\mu(z) = p_1^\mu - \frac{z}{2}\langle 1^-|\gamma^\mu|2^-\rangle$$

$$p_2^\mu(z) = p_2^\mu + \frac{z}{2}\langle 1^-|\gamma^\mu|2^-\rangle$$

Shift maintains on-shellness and momentum conservation

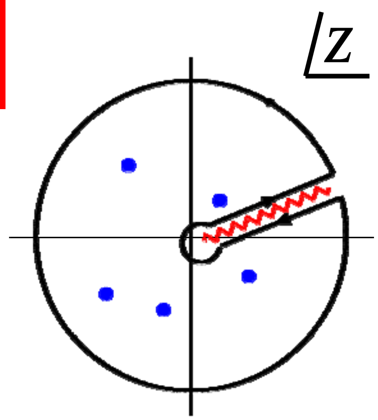
$$A(z) = \sum \text{polylog terms}$$ ← **Use unitarity method**
(in special cases on-shell recursion)

$$+ \sum_i \frac{\text{Res}_i}{(z - z_i)}$$ ← **Use on-shell recursion**

$$+ \sum_i a_i\, z^i$$ ← **Use auxiliary on-shell recursion in another variable**

hep-ph/0604195

Loop-Level Recursion



New Features:

- **Presence of branch cuts.**
- **Unreal poles – new poles appear with complex momenta.**

$$\frac{[a\,b]}{\langle a\,b\rangle}$$ Pure phase for real momenta

- **Double poles.** $\frac{[a\,b]}{\langle a\,b\rangle^2}$

- **Spurious singularities that cancel only against polylogs.**
- **Double count between cut and recursive contributions.**

On shell bootstrap deals with these features.

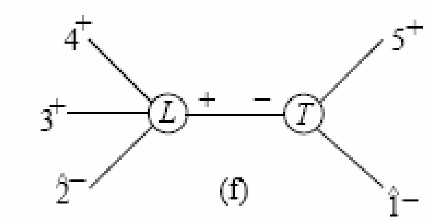
One-Loop Five-Point Example

The most challenging part was rational function terms – at the end of chain of integral reductions.

Assume we already have log terms computed from $D = 4$ cuts.

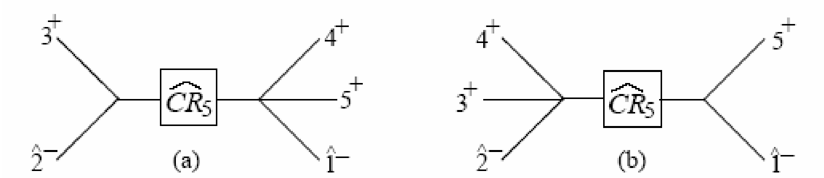
Only one non-vanishing recursive diagram: $- - + + +$

$$D_5 = -\frac{1}{3}\frac{[2\,4]\,[3\,5]^3}{\langle 3\,4\rangle\,[1\,2]\,[1\,5]\,[2\,3]^2}.$$



Tree-like calculations

Only two double-count diagrams:



$$O_5^{(a)} = -\frac{1}{6}\frac{\langle 1\,2\rangle^2\,\langle 1\,4\rangle\,[3\,4]}{\langle 1\,5\rangle\,\langle 2\,3\rangle\,\langle 3\,4\rangle\,\langle 4\,5\rangle\,[2\,3]}$$

$$O_5^{(b)} = \frac{1}{6}\frac{\langle 1\,4\rangle\,[3\,4]\,[3\,5]\,(\langle 1\,4\rangle\,[3\,4] - \langle 1\,5\rangle\,[3\,5])}{\langle 1\,5\rangle\,\langle 3\,4\rangle\,\langle 4\,5\rangle\,[1\,5]\,[2\,3]^2}$$

These are computed by taking residues

Rational function terms obtained from tree-like calculation!

No integral reductions. No unwanted "Grim" dets.

Six-Point Example

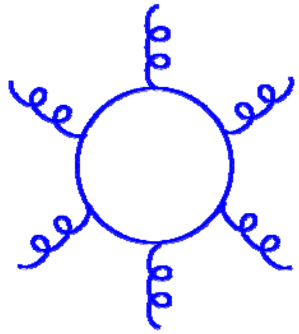
$$\widehat{R}_6^{\rm scalar}(1^-,2^-,3^+,4^+,5^+,6^+)$$

$$A_{n;1}^{\rm fermion} = A_{n;1}^{\mathcal{N}=1} - A_{n;1}^{\rm scalar}$$
$$A_{n;1}^{\rm gluon} = A_{n;1}^{\mathcal{N}=4} - 4A_{n;1}^{\mathcal{N}=1} + A_{n;1}^{\rm scalar}$$

$$\begin{aligned}
\widehat{R}_6 = \frac{1}{6}\Bigg\{ & -2\frac{\langle 3\,5\rangle\,[3\,5]\,\langle 4^-|\,(1+2)\,|3^-\rangle\,\langle 4^-|\,(1+2)\,|6^-\rangle\,\langle 5^-|\,(1+2)\,|6^-\rangle}{[1\,2]\,\langle 3\,4\rangle^2\langle 4\,5\rangle^2\,[6\,1]\,\langle 5^-|\,(3+4)\,|2^-\rangle\,\langle 6^-|\,(1+2)\,|3^-\rangle} \\
& -2\frac{\langle 3\,5\rangle\,[3\,6]\,\langle 4^-|\,(1+2)\,|6^-\rangle^2}{[1\,2]\,\langle 3\,4\rangle^2\langle 4\,5\rangle^2\,[6\,1]\,\langle 5^-|\,(3+4)\,|2^-\rangle} \\
& +2\frac{\langle 1\,2\rangle\,\langle 2\,4\rangle\,\langle 3\,5\rangle\,[3\,5]^2\,[5\,6]\,\langle 5^-|\,(1+2)\,|6^-\rangle}{\langle 3\,4\rangle^2\,\langle 4\,5\rangle\,[6\,1]\,\langle 2^-|\,(1+6)\,|5^-\rangle\,\langle 5^-|\,(3+4)\,|2^-\rangle\,\langle 6^-|\,(1+2)\,|3^-\rangle} \\
& +2\frac{\langle 1\,2\rangle^2[3\,5]^2(\langle 5^-|\,(3+4)\,2\,|1^+\rangle + \langle 5^-|\,3\,5\,|1^+\rangle)}{\langle 3\,4\rangle\,\langle 4\,5\rangle\,\langle 6\,1\rangle\,\langle 2^-|\,(1+6)\,|5^-\rangle\,\langle 5^-|\,(3+4)\,|2^-\rangle\,\langle 6^-|\,(1+2)\,|3^-\rangle} \\
& -\frac{\langle 1\,2\rangle^3\,\langle 3\,5\rangle\,[4\,6]\,[5\,6]}{\langle 2\,3\rangle\,\langle 3\,4\rangle\,\langle 4\,5\rangle\,\langle 5\,6\rangle\,\langle 1^-|\,(2+3)\,|4^-\rangle\,\langle 3^-|\,(1+2)\,|6^-\rangle} + 2\frac{[3\,6]^3}{[1\,2]\,[2\,3]\,\langle 4\,5\rangle^2\,[6\,1]} \\
& -\frac{[5\,6]\,\langle 5^-|\,(1+2)\,|6^-\rangle^2(2\,\langle 4^-|\,(3+5)(1+2)\,|5^+\rangle + \langle 1\,2\rangle\,[1\,2]\,\langle 4\,5\rangle)}{[1\,2]\,\langle 3\,4\rangle\,\langle 4\,5\rangle^2\,\langle 5\,6\rangle\,[6\,1]\,\langle 3^-|\,(1+2)\,|6^-\rangle\,\langle 5^-|\,(3+4)\,|2^-\rangle} \\
& +2\frac{\langle 1\,5\rangle^2[3\,4]^2\,[5\,6]\,(\langle 1\,6\rangle\,[3\,4]\,\langle 4\,5\rangle - \langle 1^-|\,(2+4)\,|3^-\rangle\,\langle 5\,6\rangle)}{[2\,3]\,\langle 4\,5\rangle\,\langle 5\,6\rangle^2 s_{234}\,\langle 1^-|\,(2+3)\,|4^-\rangle\,\langle 5^-|\,(3+4)\,|2^-\rangle} \\
& -\frac{\langle 1\,2\rangle\,\langle 1\,5\rangle\,[3\,4]\,[5\,6]\,\langle 1^-|\,(5+6)(3+4)\,|5^+\rangle}{\langle 3\,4\rangle\,\langle 4\,5\rangle\,\langle 5\,6\rangle\,s_{234}\,\langle 1^-|\,(2+3)\,|4^-\rangle\,\langle 5^-|\,(3+4)\,|2^-\rangle} \\
& +2\frac{\langle 3\,5\rangle\,\langle 1^-|\,(2+4)\,|3^-\rangle^3}{[2\,3]\,\langle 3\,4\rangle\,\langle 4\,5\rangle\,\langle 5\,6\rangle\,\langle 6\,1\rangle\,s_{234}\,\langle 5^-|\,(3+4)\,|2^-\rangle} \\
& -\frac{\langle 1\,2\rangle\,\langle 1^-|\,(2+4)\,|3^-\rangle\,(2\,\langle 1^-|\,(2+4)\,|3^-\rangle + \langle 1^-|\,4\,|3^-\rangle)}{[2\,3]\,\langle 3\,4\rangle\,\langle 4\,5\rangle\,\langle 5\,6\rangle\,\langle 6\,1\rangle\,s_{234}} \\
& +2\frac{\langle 1\,2\rangle^3[4\,6]^2\,\langle 5^-|\,(4+6)\,|5^-\rangle}{\langle 2\,3\rangle\,\langle 4\,5\rangle\,\langle 5\,6\rangle\,s_{123}\,\langle 1^-|\,(2+3)\,|4^-\rangle\,\langle 3^-|\,(1+2)\,|6^-\rangle} \\
& +2\frac{\langle 1\,2\rangle^3[3\,5]^2\,\langle 4^-|\,(3+5)\,|4^-\rangle}{\langle 3\,4\rangle\,\langle 4\,5\rangle\,\langle 6\,1\rangle\,s_{612}\,\langle 2^-|\,(1+6)\,|5^-\rangle\,\langle 6^-|\,(1+2)\,|3^-\rangle} \\
& -\frac{\langle 1\,2\rangle^2}{\langle 2\,3\rangle\,\langle 3\,4\rangle\,\langle 4\,5\rangle\,\langle 5\,6\rangle\,\langle 6\,1\rangle}\left[\frac{\langle 1^-|\,4\,|3^-\rangle}{[2\,3]} + \frac{\langle 2^-|\,5\,|6^-\rangle}{[6\,1]}\right]\Bigg\}
\end{aligned}$$

$$\langle a^-|(b+c)|d^-\rangle \equiv \langle a\,b\rangle\,[b\,d] + \langle a\,c\rangle\,[c\,d]$$

Rational function parts of scalar loops were by far most difficult to calculate.



Using on-shell bootstrap rational parts are given by tree-like calculations. No integral reductions.

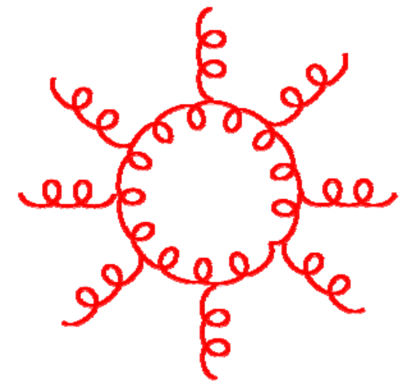
Numerical results for *n* gluons

Choose specific points in phase-space – see hep-ph/0604195

Scalar loop contributions

	Helicity	$1/\epsilon$	ϵ^0
6 points	$++++++$	0	$0.1024706290 + i\,0.5198025397$
	$-+++++$	0	$2.749806130 + i\,1.750985849$
	$--++++$	$-9.370119558 + i\,1.547789294$	$-45.80779561 + i\,13.03695870$
	$---+++$	$-0.2614534328 - i\,0.6288641470$	$0.3883482043 - i\,5.830791857$
7 points	$+++++++$	0	$0.1815778027 + i\,1.941357266$
	$-++++++$	0	$22.52927821 + i\,5.464377788$
	$--+++++$	$-34.85372799 + i\,15.11569825$	$-176.2169235 + i\,87.93931019$
	$---++++$	$0.3564513374 - i\,0.4914226070$	$0.7087164424 - i\,11.32916632$
8 points	$++++++++$	0	$-0.0009856214410 + i\,0.002143695508$
	$-+++++++$	0	$0.001078316199 + i\,0.03129931739$
	$--++++++$	$-0.05330088846 - i\,0.04051789981$	$0.05513350697 + i\,0.1659518861$
	$---+++++$	$-0.003622640270 - i\,0.0007910999246$	$0.02719752089 - i\,0.02586206549$
	$----++++$	$-0.002273559586 - i\,0.001209645382$	$0.01154855076 - i\,0.0008935357840$

amusing count



+ 3,017,489 other diagrams

Modest growth in complexity as number of legs increases

At 6 points these agree with numerical results of Ellis, Giele and Zanderighi

What should be done?

- **Attack items on experimenters' wishlist.**
- **Automation for general processes.**
- **Assembly of full cross-sections, *e.g.*, Catani-Seymour formalism.**
- **Massive loops -- tree recursion understood.**

Badger, Glover, Khoze, Svrcek

- **First principles derivation of formalism:**

  Large *z* behavior of loop amplitudes.

  General understanding of unreal poles.

- **Connection to Lagrangian**

Vaman and Yao; Draggiotis, Kleiss, Lazopolous, Papadopoulos

Other Applications

On-shell methods applied in a variety of problems:

- **Computations of two-loop 2 to 2 QCD amplitudes.**

Bern, Dixon, Kosower
Bern, De Frietas, Dixon

- **Ansatz for planar MHV amplitudes to *all* loop orders in $N = 4$ super-Yang-Mills.**

Anastasiou, Bern, Dixon, Kosower
Bern, Dixon, Smirnov
Cachazo, Spradlin and Volovich

- **Applications to gravity.**

Bern, Dixon, Dunbar, Perelstein and Rozowsky
Bern, Bjerrum-Bohr and Dunbar
Brandhuber, Spence and Travaglini
Cachazo and Svrcek

Summary

- **We need bold action to provide the full range of NLO calculations for the LHC.**
- **On-shell bootstrap – unitarity and factorization.**
- **New results for one-loop $n \geq 6$ gluons.**
- **Explicit numerical results for up to eight gluons.**
- **Technology should apply as is to external mass cases.**
- **Important issues remain: automation, massive loops, construction of physical cross sections with experimental cuts.**

Experimenters' wish list awaits us!

Experimenter's Wish List

Les Houches 2005

process ($V \in \{Z, W, \gamma\}$)	background to
1. $pp \to V\,V\,\mathrm{jet}$	$t\bar{t}H$, new physics
2. $pp \to H + 2\,\mathrm{jets}$	H production by vector boson fusion (VBF)
3. $pp \to t\bar{t}\,b\bar{b}$	$t\bar{t}H$
4. $pp \to t\bar{t} + 2\,\mathrm{jets}$	$t\bar{t}H$
5. $pp \to V\,V\,b\bar{b}$	VBF$\to H \to VV$, $t\bar{t}H$, new physics
6. $pp \to V\,V + 2\,\mathrm{jets}$	VBF$\to H \to VV$
7. $pp \to V + 3\,\mathrm{jets}$	various new physics signatures
8. $pp \to V\,V\,V$	SUSY trilepton

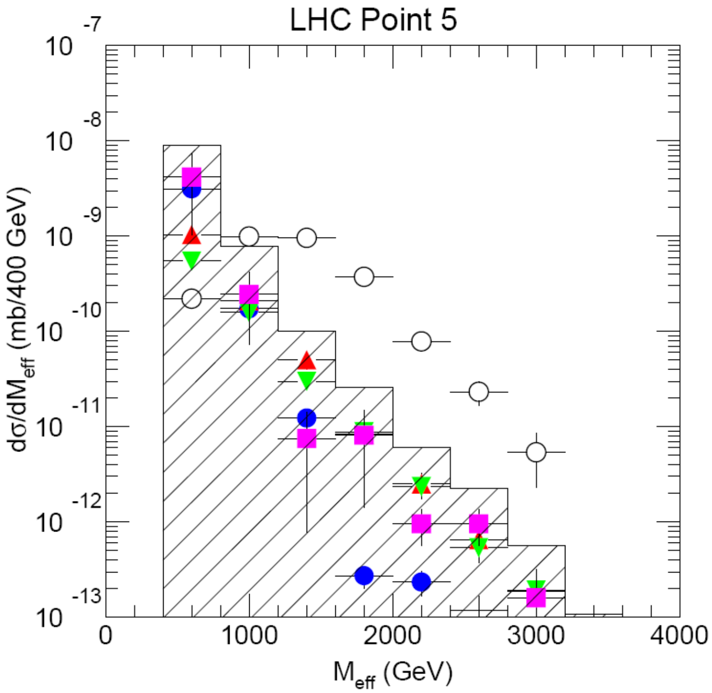
Complete List

Run II Monte Carlo Workshop, April 2001

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

Extra Transparancies

Incorrect Plot from ATLAS TDR



igure 20-4 M_{eff} distribution for the Point 5 signal
pen circles) and for the sum of all Standard Model
ackgrounds (histogram); the latter includes $t\bar{t}$ (solid
ircles), $W + \mathrm{jets}$ (triangles), $Z + \mathrm{jets}$ (downward tri-
ngles), and QCD jets (squares).

Background is actually 10 times larger.