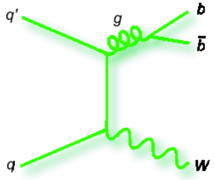
Preparing for Discovery

A Bard's-Eye View

Stephen Mrenna

Computing Division
Fermilab

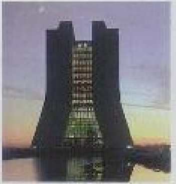
Wine & Cheese, March 2006



SA Perspectives

The Collider Calamity

For decades, the big guns of American science have been the U.S. Department of Energy's particle colliders, which investigate the nature of matter by accelerating subatomic particles and smashing them together. Colliders at the Fermi National Accelerator Laboratory (Fermilab), Stanford Linear Accelerator Center (SLAC) and Brookhaven National Laboratory have discovered exotic particles such as the top quark and revealed phenomena that hint at new laws of physics. But this great American enterprise, like so many others, is now moving overseas. While the Europeans and Japanese build new particle accelerators, the U.S. is poised to shut down its premier colliders at Fermilab and SLAC over the next few years. And funding for Brookhaven's Relativistic Heavy Ion Collider (RHIC) is so tight that the lab could not have run its full slate of experiments this year without $13 million raised by a New York billionaire.



FERMILAB, home of the Tevatron.

The sad story began in 1993, when Congress can-

group designed a device called BTeV that would study the decay of B mesons emanating from collisions in the Tevatron. BTeV employed such sophisticated technology that it could have outperformed a similar detector at the LHC. But last year the Department of Energy canceled BTeV. Without that experiment, most physicists see no compelling reason to keep the Tevatron running after the LHC comes online. SLAC plans to shut down its linear collider when that lab concludes its own B-meson study by 2008. And the National Science Foundation recently killed an experiment called RSVP that would have used Brookhaven's accelerator to investigate rare particle decays that could not be observed at the LHC.

Besides depriving researchers of potential discoveries, these cuts threaten to make the U.S. less economically competitive. The development of high-energy accelerators has led to advances in medicine and electronics, and American expertise in this field will wither if the U.S. ceases to build and operate colliders. Moreover, although American scientists will participate in the research at the LHC, the Europeans will get most of the educational benefits of the facility, which will inspire and train the next generation of


The New York Times

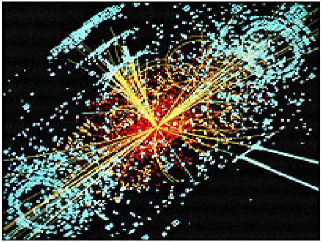
1315 Physicists Report Failure In Search for Supersymmetry

The negative result illustrates

'God particle' may have been seen ... finally

By Paul Rincon
BBC News Online science staff

A scientist says one of the most sought after particles in physics - the Higgs boson - may have been found, but the evidence is still relatively weak.



Once produced, the Higgs boson would decay very quickly

Peter Renton, of the University of Oxford, says the particle may have been detected by researchers at an atom-smashing facility in Switzerland.

The Higgs boson explains why all other particles have mass and is fundamental to a complete understanding of matter.

EXPERIMENTAL EVIDENCE FOR MORE DIMENSIONS REPORTED

Gordon L. Kane
May 2011

The worldview of physicists working on unification theories has been changing rapidly recently. That change culminated in March, at the 46th annual Recontres de Moriond conference in Les Arcs, France, with the announcement of some startling data from CERN's Large Hadron Collider (LHC).

More than two hundred years ago, Charles Augustin Coulomb showed that the electrical force had the same form as the gravitational ory. Because the work was well ahead of its time, and because of World War II, Klein's insight went largely unnoticed. See L. O'Raifeartaigh, *The Dawning of Gauge Theory*, Princeton University Press, 1977.)

The fields of the higher-dimensional theory were the gravitational tensor field, the electromagnetic vector potential field and a scalar field. Of course, the theories of electricity and magnetism were unified without extra dimensions by Maxwell, and the

Shakespeare's Writing Method

- Develop a large vocabulary
- Play with words
- Invent new words and phrases
- Develop the common touch
- Read great literature
- Study the great orators, actors and the popular
- Live with passion
- Write, write, write!!!

Warm-Up

How much does the $t\bar{t}$ cross section change from TeV to LHC?

- $10\times$
- $100\times$
- $500\times$

[Kidonakis]

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- $500\times$

[Kidonakis]

Warm-Up

How much does the $\widetilde{\chi}^{+}\widetilde{\chi}^{-}(m_{\chi} = 200\ \mathrm{GeV})$ cross section change from TeV to LHC?

- $10\times$
- $100\times$
- $500\times$

[Pythia]

Warm-Up

How much does the $\widetilde{\chi}^+\widetilde{\chi}^-(m_\chi = 200\ \mathrm{GeV})$ cross section change from TeV to LHC?

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- $100\times$
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[Pythia]

How much does the $W4j$ cross section change from TeV to LHC?

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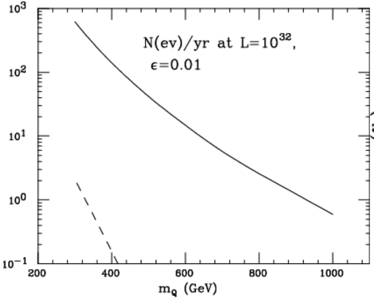
[MadEvent, $k_T > 20$ GeV]

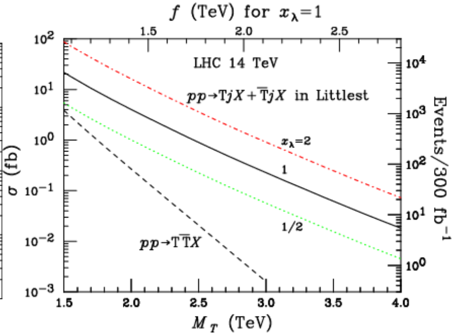
How much does the $W4j$ cross section change from TeV to LHC?

- $10\times$
- $100\times$
- $500\times$

[MadEvent, $k_T > 20$ GeV]

Heavy Colored Objects
Large Kinematic Reach





MLM

HAN,LOGAN,WANG

First Steps

- LHC phenomenology begins with rediscovering the Standard Model
- The path starts at the Tevatron

Understanding W+Jets is Important

- Signature $Wb\bar{b} + X$ is common to unconfirmed Standard Model processes and many new physics processes
- we "know" that Standard Model top is there

$$\text{Top} \equiv \text{Data} - \text{Not-Top}$$

- As JES uncertainty is reduced (CDF m_t), understanding of Not-Top sets/limits understanding of Top
- Advanced (i.e. NN, DT) search techniques exploit differences in many kinematic variables
- Not-Top challenges our tools

$$\text{Better tools} \Rightarrow \text{more challenging questions}$$

Single Top

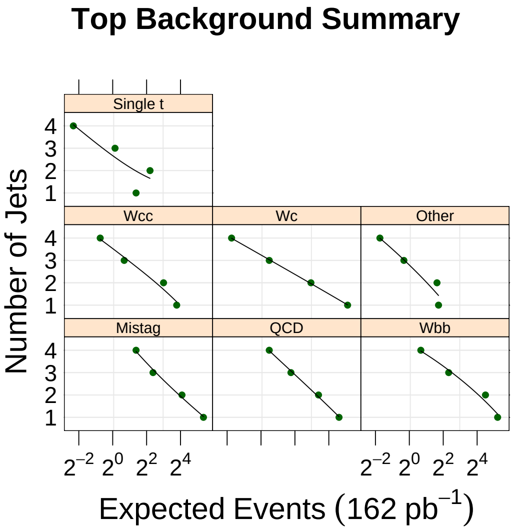
New Physics Warm-Up

- current state of single-Top is where we will be at the LHC with a few quality fb^{-1}
- the size of other NP signals
- it is a playground for new analysis techniques
- it challenges our tools

Not specific to NN analyses: may be more sensitive

Many (11) Kinematic Variables

	Signal-Background Pairs			
	tb		tqb	
	Wbb	$t\bar{t}$	Wbb	$t\bar{t}$
Individual object kinematics				
$p_T(\mathrm{jet1}_{\mathrm{tagged}})$	√	√	√	—
$p_T(\mathrm{jet1}_{\mathrm{untagged}})$	—	—	√	√
$p_T(\mathrm{jet2}_{\mathrm{untagged}})$	—	—	—	√
$p_T(\mathrm{jet1}_{\mathrm{nonbest}})$	√	√	—	—
$p_T(\mathrm{jet2}_{\mathrm{nonbest}})$	√	√	—	—
Global event kinematics				
$M_T(\mathrm{jet1,jet2})$	√	—	—	—
$p_T(\mathrm{jet1,jet2})$	√	—	√	—
$M(\mathrm{alljets})$	√	√	√	√
$H_T(\mathrm{alljets})$	—	—	√	—
$M(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	—	—	√
$H(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	√	—	√
$H_T(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	—	—	√
$p_T(\mathrm{alljets}-\mathrm{jet1}_{\mathrm{tagged}})$	—	√	—	√
$M(\mathrm{alljets}-\mathrm{jet}_{\mathrm{best}})$	—	√	—	—
$H(\mathrm{alljets}-\mathrm{jet}_{\mathrm{best}})$	—	√	—	—
$H_T(\mathrm{alljets}-\mathrm{jet}_{\mathrm{best}})$	—	√	—	—
$M(\mathrm{top}_{\mathrm{tagged}}) = M(W,\mathrm{jet1}_{\mathrm{tagged}})$	√	√	√	√
$M(\mathrm{top}_{\mathrm{best}}) = M(W,\mathrm{jet}_{\mathrm{best}})$	√	—	—	—
$\sqrt{\hat{s}}$	√	—	√	√
Angular variables				
$\Delta R(\mathrm{jet1,jet2})$	√	—	√	—
$Q(\mathrm{lepton}) \times \eta(\mathrm{jet1}_{\mathrm{untagged}})$	—	—	√	√
$\cos(\mathrm{lepton}, Q(\mathrm{lepton}) \times z)_{\mathrm{top}_{\mathrm{best}}}$	√	—	—	—
$\cos(\mathrm{lepton}, \mathrm{jet1}_{\mathrm{untagged}})_{\mathrm{top}_{\mathrm{tagged}}}$	—	—	√	—
$\cos(\mathrm{alljets}, \mathrm{jet1}_{\mathrm{tagged}})_{\mathrm{alljets}}$	—	—	√	√
$\cos(\mathrm{alljets}, \mathrm{jet}_{\mathrm{nonbest}})_{\mathrm{all\ jets}}$	—	√	—	—


Top Background Summary
Single t
Wcc
Wc
Other
Mistag
QCD
Wbb
Number of Jets
4
3
2
1
2^{-2} 2^{0} 2^{2} 2^{4}
Expected Events (162 pb^{-1})

Mixing the Cocktail

Method 2

Monte Carlo ratio
$R = (W + b - jets)/(W + jets)$

- Common factors cancel

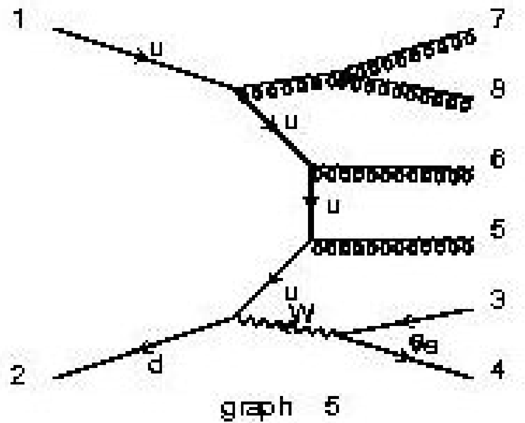
Measure $W + jets$ (no b-tag)

data$(W + b - jets)$ = $R\times$data$(W + jets)$

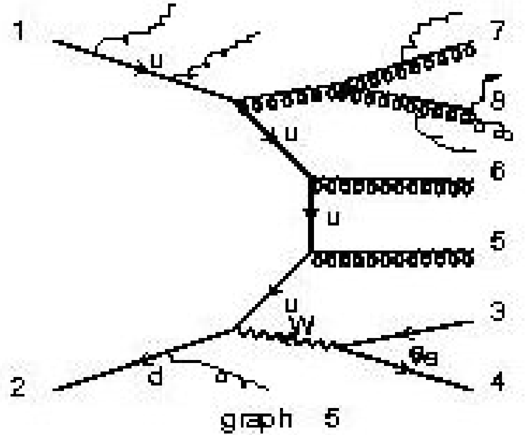
Wcj/Wbb from Monte Carlo

- Several R's

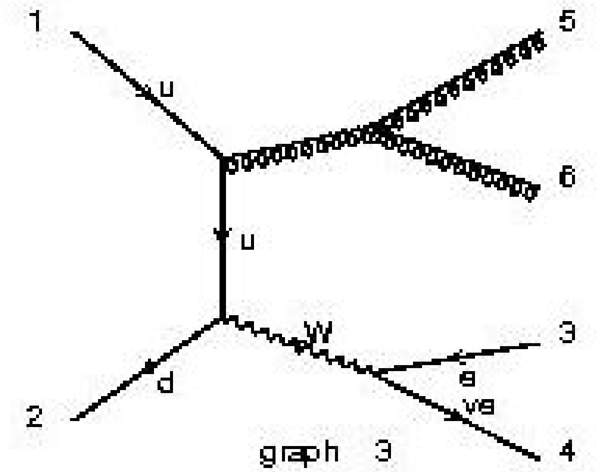
High Multiplicity Tree Graph



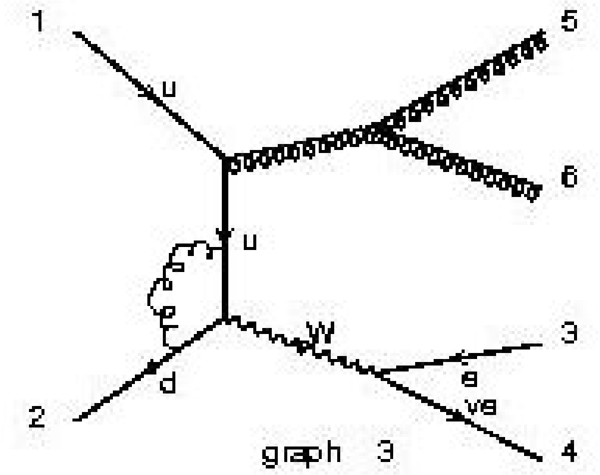
Tree Graph + Parton Shower



Lower Multiplicity Tree Graph

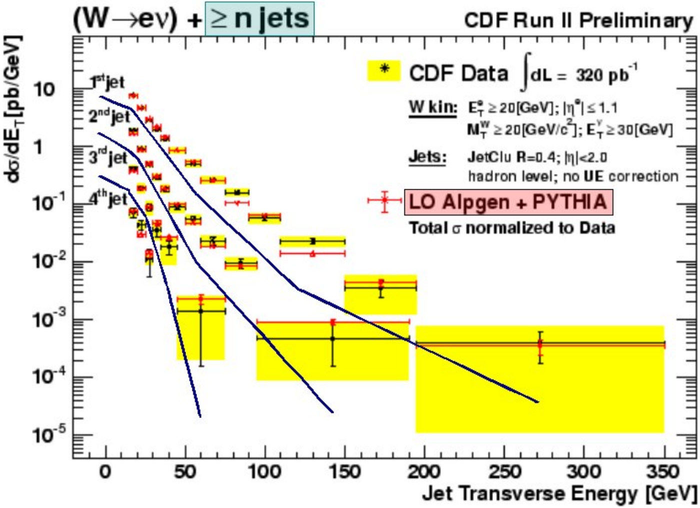


Lower Multiplicity NLO Graph



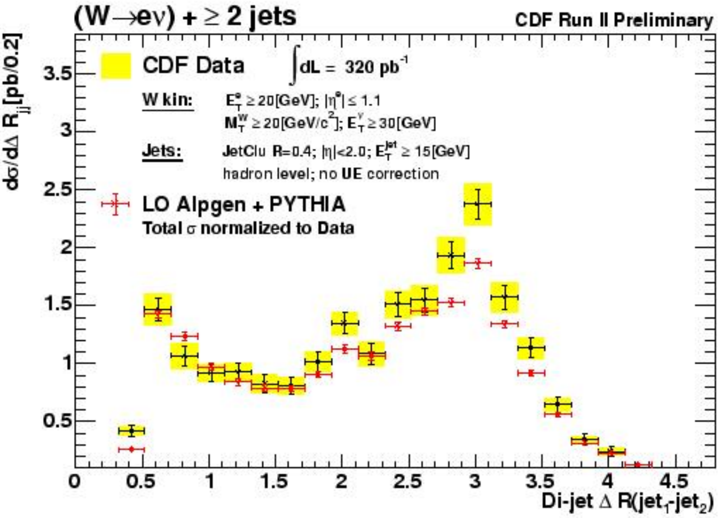
Tree Graphs + Parton Showers

$$Q^2_{ISR} = M^2_W + \sum P^2_{Tj}$$

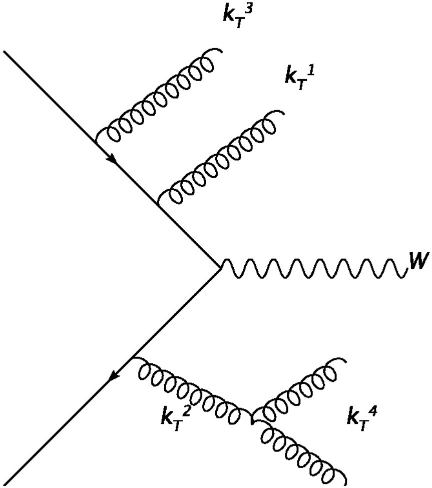


Messina, Cooper, Waters

Tree Graphs + Parton Showers



$$k_T^{\,1} > k_T^{\,2} > k_T^{\,3} > k_T^{\,4} > k_T^{\,cut}$$



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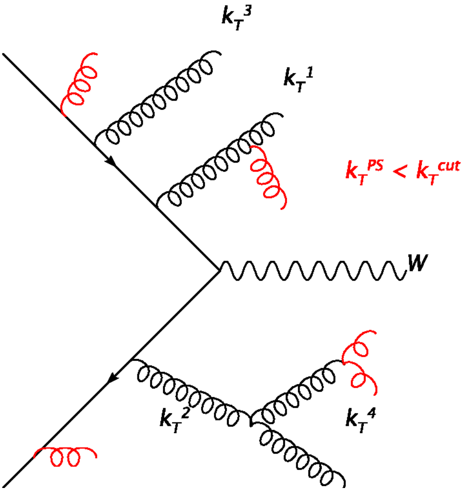

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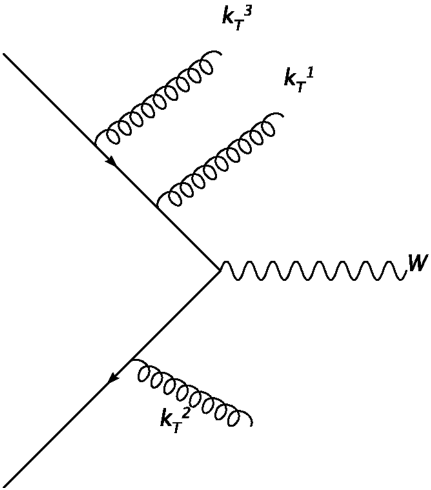
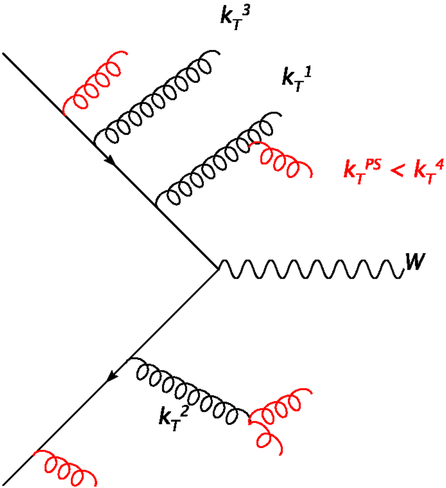


Parton Shower-Matrix Element Movie
Pseudo-shower Method

$k_T^1 > k_T^2 > k_T^3 > k_T^4 > k_T^{cut}$



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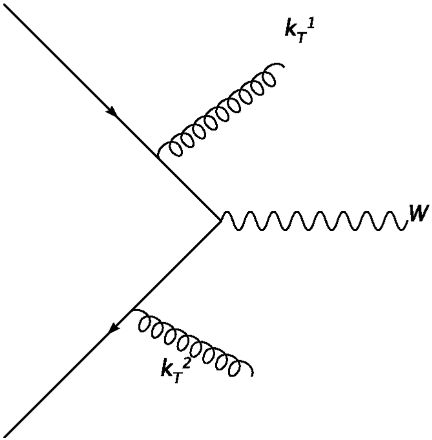

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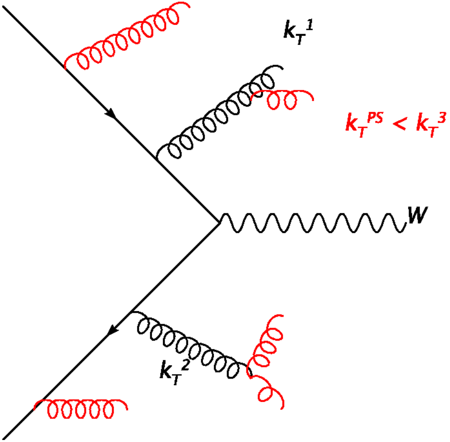

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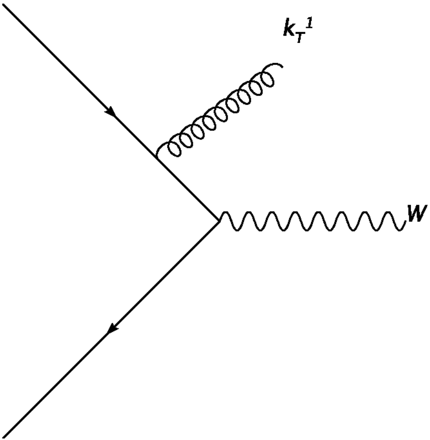

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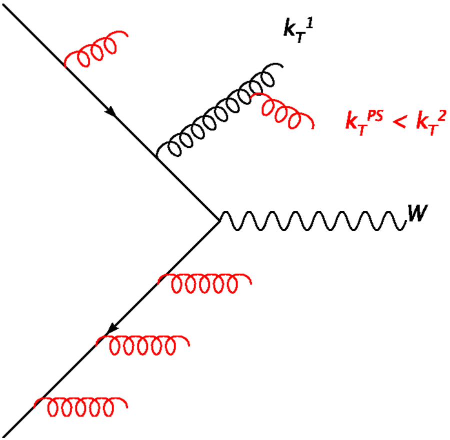
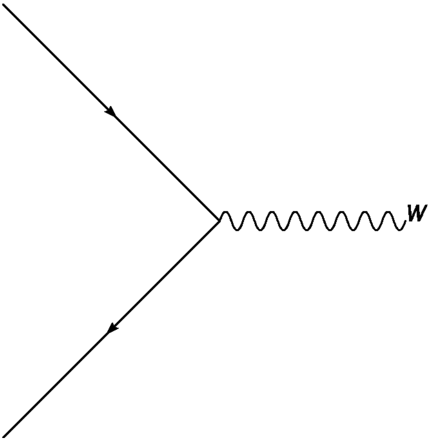
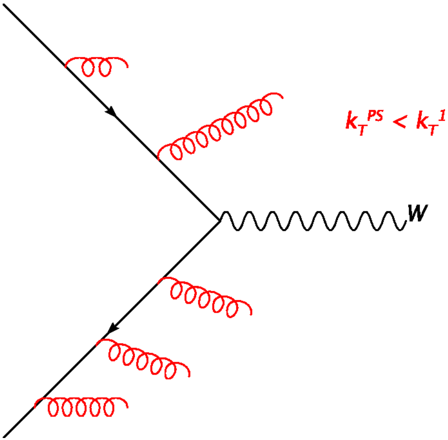


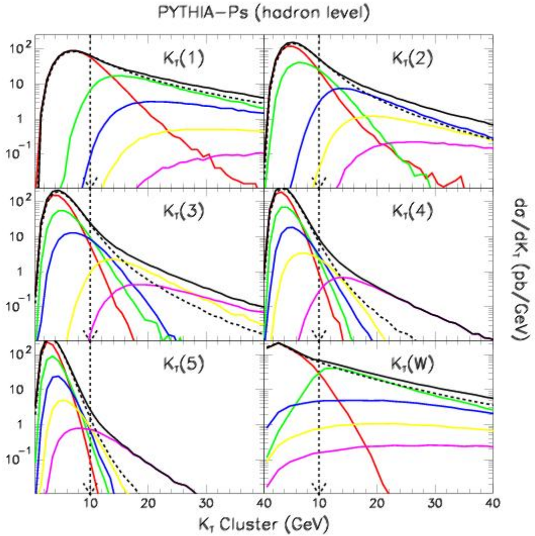
$$k_T^1 > k_T^2 > k_T^3 > k_T^4 > k_T^{cut}$$



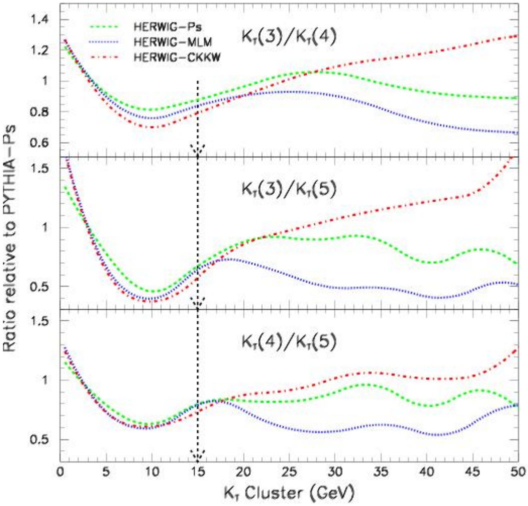
$k_T{}^1 > k_T{}^2 > k_T{}^3 > k_T{}^4 > k_T{}^{cut}$



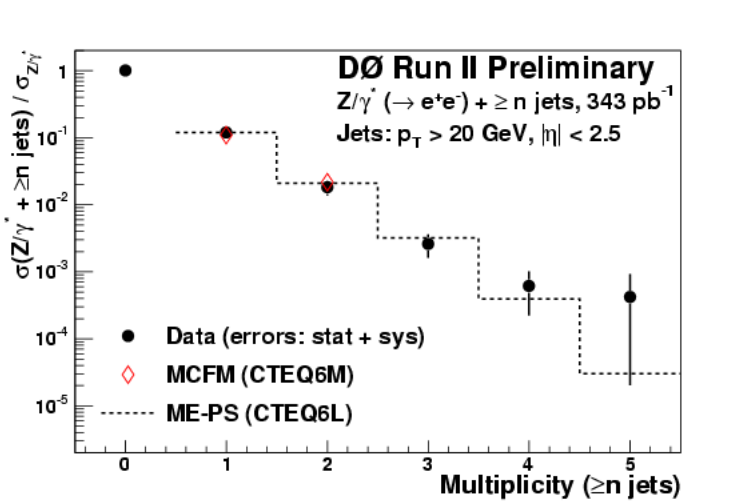
Make Better Predictions



Address Uncertainty



Cross check on Run2 data

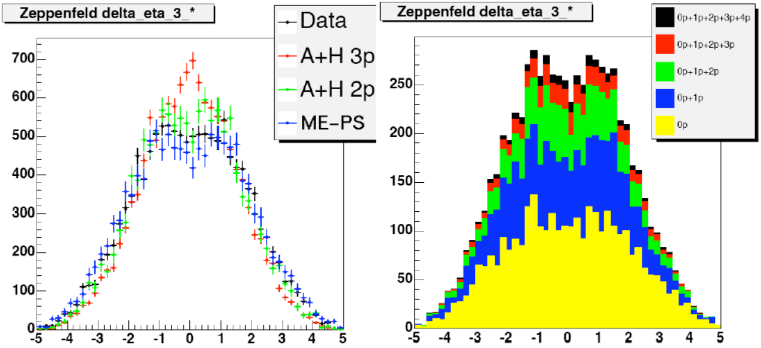


Includes up to $Zjjj$, $j = q, g$

Kinematic comparisons with Run2 data

Tag jets > 8 GeV/c; 3rd jet > 8 GeV/c; $\Delta\eta > 1$

- ME–PS decomposition



$$\eta_3^* = \eta_3 - \frac{\eta_1 + \eta_2}{2},$$ A+H ≡ Alpgen+Herwig

- To understand the data, look at the Vista of final states

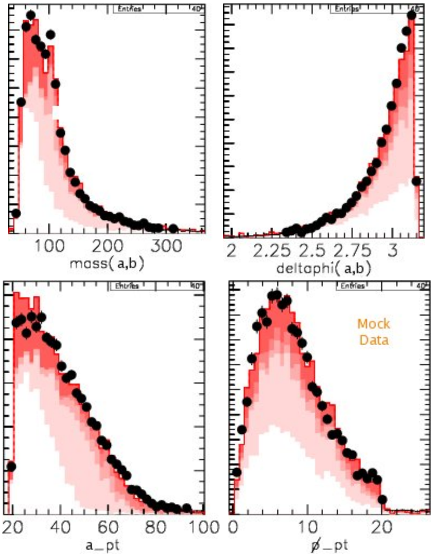
Final State	Chi2	data	bkg			
1b3j1pmiss_sumPt400+ [73]	9.0	451	374.5	+-	18	(pyth_jj_200 = 1
2b1e+2j [-]	8.0	15	6.5	+-	1.9	(ttop0z = 2.3 ,
2j_sumPt0-400 [161]	6.0	69704	67013.6	+-	1171.2	(pyth_jj_018 = 3
2j2mu+1pmiss [-]	-5.0	2	12.2	+-	3	(mad_mu+mu-jj =
1b2e+2j [-]	5.0	9	3.9	+-	1.5	(mrenna_e+e-jjj
1j1ph1pmiss [5]	4.0	2591	2470.1	+-	37.7	(pyth_pj_045 = 7
2j1mu+1ph [-]	4.0	11	11.2	+-	2.2	(mrenna_mu+mu-jj
1e+1j1mu+ [-]	4.0	13	6.6	+-	2.1	(ztop5i = 3.4 ,
1e+2j1ph [-]	4.0	31	20.9	+-	2.7	(mad_aajj = 6.3
3j2mu+ [-]	4.0	34	23.2	+-	2.7	(mrenna_mu+mu-jj
2b2j1pmiss_sumPt400+ [-]	-3.0	17	30.4	+-	4.2	(pyth_jj_200 = 1
1b2j_sumPt400+ [229]	3.0	4669	4518.6	+-	72.7	(pyth_jj_200 = 2
4j_sumPt0-400 [253]	-3.0	2611	2736.9	+-	42.3	(pyth_jj_040 = 1
2b1j1ph1pmiss [-]	3.0	6	2.7	+-	1.5	(pyth_jj_200 = 0
1b1j1mu+ [-]	3.0	67	53.8	+-	4.3	(pyth_jj_018 = 1
1j1ph [277]	3.0	31738	31149.8	+-	352.1	(pyth_pj_045 = 1
1e+1mu+ [-]	3.0	66	53.5	+-	3.2	(ztop5i = 38.8 ,
4j1mu+ [-]	3.0	73	61.3	+-	2.6	(pyth_jj_040 = 1
5j [269]	3.0	448	406	+-	14.5	(pyth_jj_040 = 1
1b5j [-]	3.0	8	8.9	+-	1.7	(pyth_jj_060 = 1
1b1j1pmiss_sumPt0-400 [-]	2.0	120	104	+-	7.2	(pyth_jj_040 = 3
2j1pmiss_sumPt0-400 [37]	2.0	2381	2281.2	+-	73.9	(pyth_jj_018 = 1

...

Final State	Chi2	data	bkg
1b2e+2j [-]	5.0	9	3.9 +- 1.5

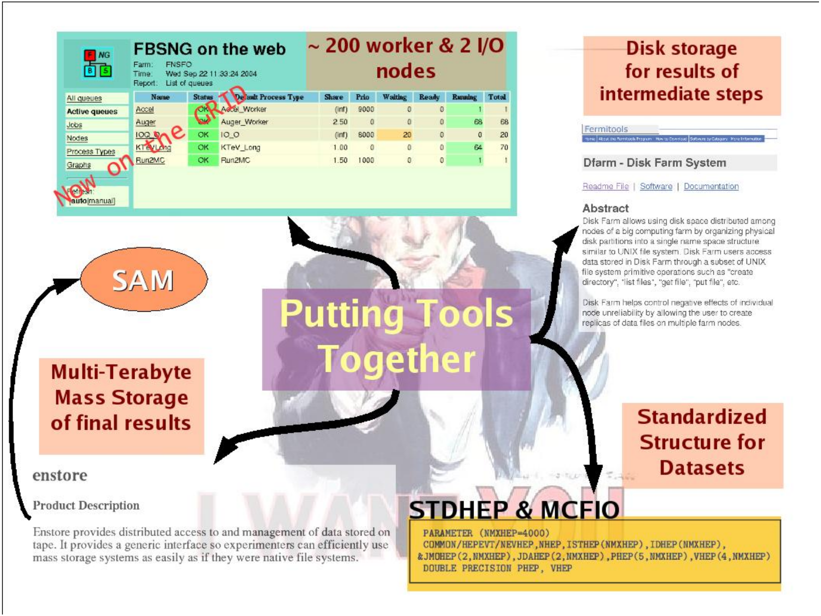
(mrenna_e+e-jjj = 1.9 , mad_e+e-jj = 0.5 , mrenna_e+e-jj = 0.4 , mad_e+e-b-b = 0.4 , ztopcz = 0.3 , pyth_jj_040 = 0.2 , mad_aajj = 0.1 , mrenna_e+vejjjj = 0.1 , hewk03 = 0.1 , wtop1z = 0.1)

Distributions



- Give a complete description of the Standard Model with the best tools

Patriot


FBSNG on the web
Farm: FNSFO
Time: Wed Sep 22 11:33:24 2004
Report: List of queues
All queues
Active queues
Jobs
Nodes
Process Types
Graphs
Refresh: auto|manual
Name | Status | Default Process Type | Share | Prio | Waiting | Ready | Running | Total
Accel | OK | Accel_Worker | (inf) | 9000 | 0 | 0 | 1 | 1
Auger | OK | Auger_Worker | 2.50 | 0 | 0 | 0 | 68 | 68
IOQ_0 | OK | IO_O | (inf) | 8000 | 20 | 0 | 0 | 20
KTeVLong | OK | KTeV_Long | 1.00 | 0 | 0 | 0 | 64 | 70
Run2MC | OK | Run2MC | 1.50 | 1000 | 0 | 0 | 1 | 1
Now on the GRID
~ 200 worker & 2 I/O nodes
Disk storage for results of intermediate steps
Fermitools
Dfarm - Disk Farm System
Readme File | Software | Documentation
Abstract
Disk Farm allows using disk space distributed among nodes of a big computing farm by organizing physical disk partitions into a single name space structure similar to UNIX file system. Disk Farm users access data stored in Disk Farm through a subset of UNIX file system primitive operations such as "create directory", "list files", "get file", "put file", etc.
Disk Farm helps control negative effects of individual node unreliability by allowing the user to create replicas of data files on multiple farm nodes.
SAM
Putting Tools Together
Multi-Terabyte Mass Storage of final results
Standardized Structure for Datasets
enstore
Product Description
Enstore provides distributed access to and management of data stored on tape. It provides a generic interface so experimenters can efficiently use mass storage systems as easily as if they were native file systems.
STDHEP & MCFIO
PARAMETER (NMXHEP=4000)
COMMON/HEPEVT/NEVHEP,NHEP,ISTHEP(NMXHEP),IDHEP(NMXHEP),
&JMOHEP(2,NMXHEP),JDAHEP(2,NMXHEP),PHEP(5,NMXHEP),VHEP(4,NMXHEP)
DOUBLE PRECISION PHEP, VHEP

Model-Independent and Quasi-Model-Independent Search for New Physics at CDF

Georgios Choudalakis,[*] Khaldoun Makhoul,[†] Markus Klute,[‡] Conor Henderson,[§] and Bruce Knuteson[¶]
MIT

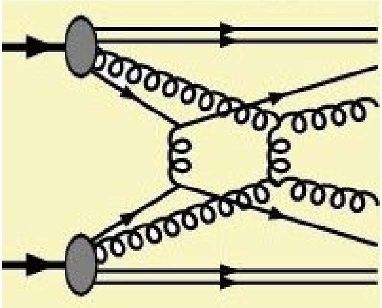
Ray Culbertson[**]
FNAL

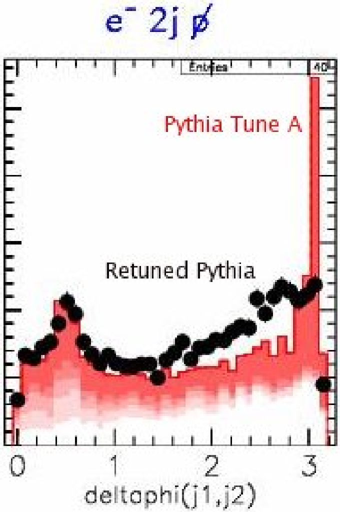
CDF Collaboration[††]
(Dated: February 1, 2006)

Data collected in Run II of the Fermilab Tevatron are searched for indications of new electroweak scale physics. Rather than focusing on particular new physics scenarios, CDF data are analyzed for discrepancies with the Standard Model prediction. A model-independent approach considers the gross features of the data, and is sensitive to new large cross section physics. A quasi-model-independent approach emphasizes the high-p_T tails, and is particularly sensitive to new electroweak scale physics. This global search for new physics in ≈ 600 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV reveals no indication of physics beyond the Standard Model.

Contents

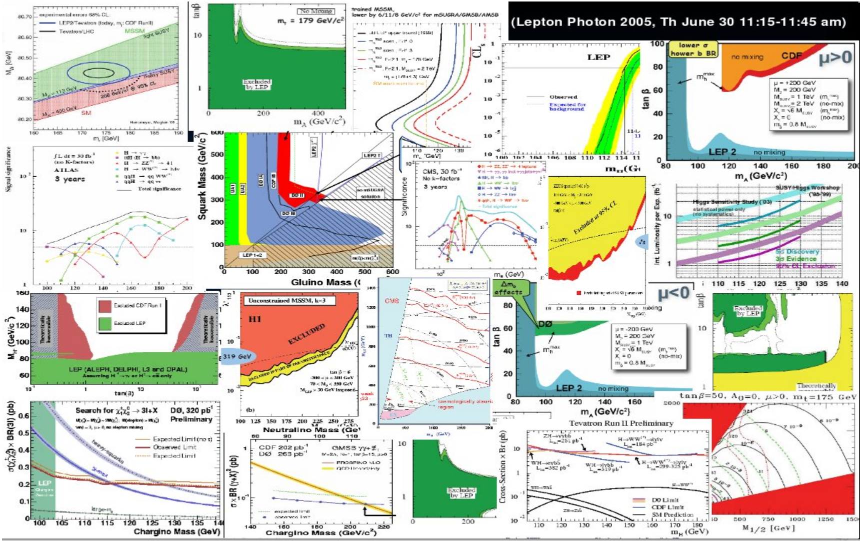
I. MOTIVATION




e⁻ 2j ₚ̸
Entries
40
Pythia Tune A
Retuned Pythia
0
1
2
3
deltaphi(j1,j2)

Midterm Summary

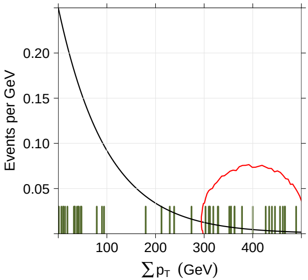
- The first New Physics to find is the Standard Model
- Need complete description of most important processes
- Understanding comes from looking at consistency of full dataset
- Then, how do we find New Physics?



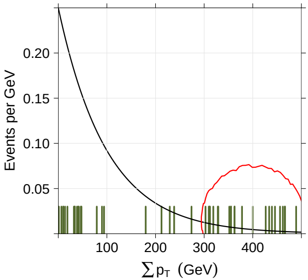
(Lepton Photon 2005, Th June 30 11:15-11:45 am)
MSSM
SM
No Mixing
Excluded by LEP
LEP
Observed
Expected for background
lower σ
higher b BR
no mixing
CDF
μ>0
LEP 2
ATLAS
3 years
Total significance
Squark Mass (GeV/c²)
CMS, 30 fb⁻¹
No k-factors
3 years
Higgs Sensitivity Study ('03)
SUSY/Higgs Workshop ('98-'99)
5σ Discovery
3σ Evidence
95% CL Exclusion
Excluded CDF Run I
Excluded LEP
LEP (ALEPH, DELPHI, L3 and OPAL)
Unconstrained MSSM, k=3
H1
EXCLUDED
319 GeV
Δm_b effects
DØ
μ<0
cosmologically plausible region
Search for $\tilde\chi_1^\pm\tilde\chi_2^0 \to 3l+X$
DØ, 320 pb⁻¹
Preliminary
Expected Limit
Observed Limit
Chargino Mass (GeV)
CDF 202 pb⁻¹
DØ 263 pb⁻¹
Chargino Mass (GeV/c²)
Neutralino Mass (GeV)
Tevatron Run II Preliminary
DO Limit
CDF Limit
SM Prediction
Cross-Section × Br (pb)
tanβ=50, A₀=0, μ>0, m_t=175 GeV
Theoretically inaccessible

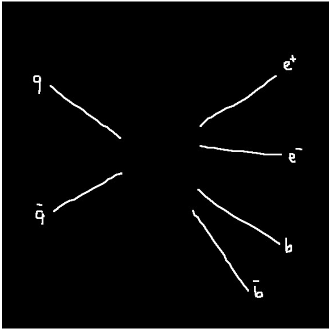

NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
TC - TC
composite Higgs
hypercolor
supercolor
extended TC
4th gen
5th gen
6th gen
sterile ν
heavy Majorana ν
lepto quark
fractionally charged
milli-charged
vectorlike fermions
S, T, U
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDM
spontaneous CP
superweak
milli-weak
Weinberg's 3HD
Majoron
axion
familon
NGB
quintessence
composite W, Z
contact int.
string
NMSSM
MSSM

$e^+e^- b\bar{b}$ Final State

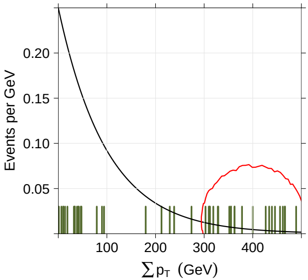


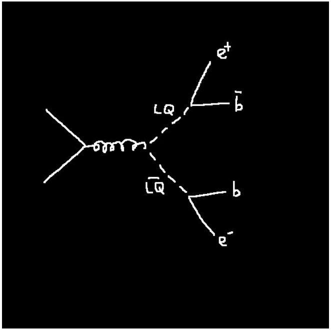
$e^+e^- b\bar{b}$ Final State



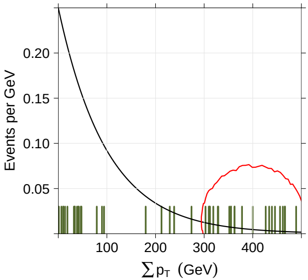


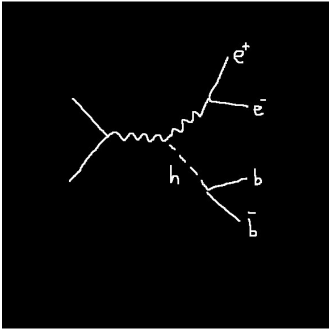
$e^+e^-b\bar{b}$ Final State



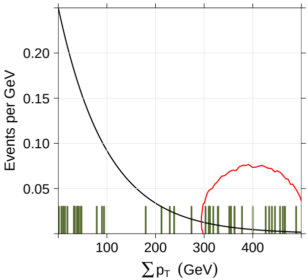


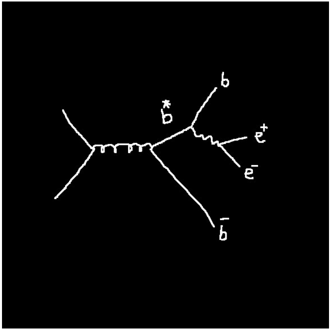
$e^+e^-b\bar{b}$ Final State

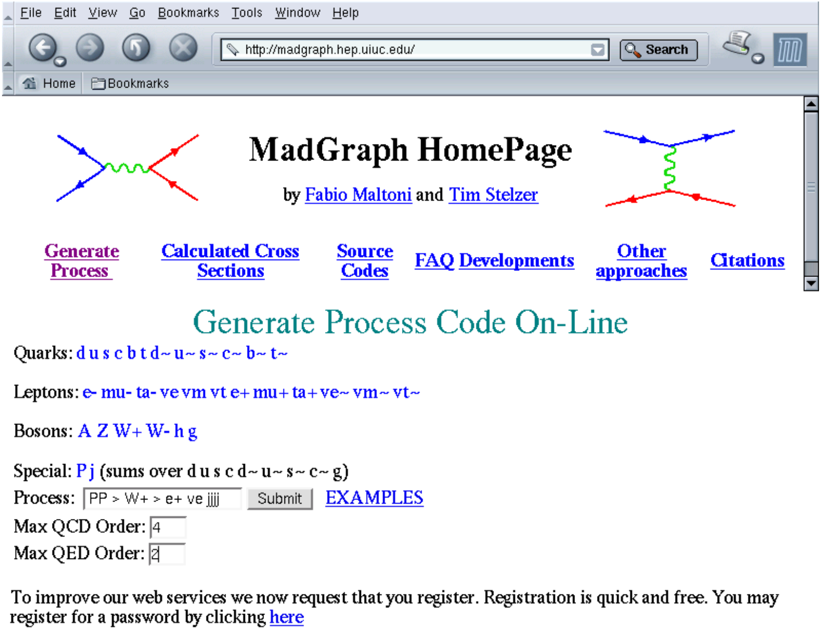




$e^+e^- b\bar{b}$ Final State



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http://madgraph.hep.uiuc.edu/
Search
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Bookmarks
MadGraph HomePage
by Fabio Maltoni and Tim Stelzer
Generate Process
Calculated Cross Sections
Source Codes
FAQ
Developments
Other approaches
Citations
Generate Process Code On-Line
Quarks: d u s c b t d~ u~ s~ c~ b~ t~
Leptons: e- mu- ta- ve vm vt e+ mu+ ta+ ve~ vm~ vt~
Bosons: A Z W+ W- h g
Special: P j (sums over d u s c d~ u~ s~ c~ g)
Process: PP > W+ > e+ ve jjjj
Submit
EXAMPLES
Max QCD Order: 4
Max QED Order: 2
To improve our web services we now request that you register. Registration is quick and free. You may register for a password by clicking here

Generic Particles and Vertices

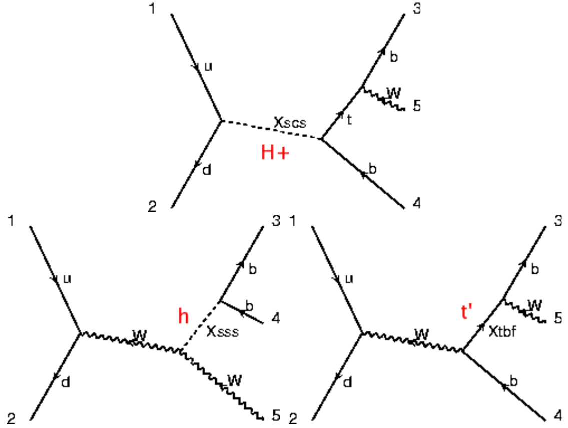
$$\mathcal{L}_{\texttt{FFV}} = \bar{f}'\gamma^{\mu}\left(\texttt{G}(1)\frac{1-\gamma_5}{2} + \texttt{G}(2)\frac{1+\gamma_5}{2}\right) f V_{\mu}^{*}$$

$$\mathcal{L}_{\texttt{FFS}} = \bar{f}'\left(\texttt{GC}(1)\frac{1-\gamma_5}{2} + \texttt{GC}(2)\frac{1+\gamma_5}{2}\right) f S^{*}$$

$$\begin{aligned}\mathcal{L}_{\texttt{VVV}} &= -i\texttt{G} \quad \{ (\partial_{\mu}V_{1\nu}^{*})(V_2^{\mu *}V_3^{\nu *} - V_2^{\nu *}V_3^{\mu *}) \\ &\qquad +(\partial_{\mu}V_{2\nu}^{*})(V_3^{\mu *}V_1^{\nu *} - V_3^{\nu *}V_1^{\mu *}) \\ &\qquad +(\partial_{\mu}V_{3\nu}^{*})(V_1^{\mu *}V_2^{\nu *} - V_1^{\nu *}V_2^{\mu *})\}\end{aligned}$$

$$\mathcal{L}_{\texttt{VVS}} = \texttt{G}V_1^{\mu *}V_{2\mu}^{*}S^{*}$$

$$\mathcal{L}_{\texttt{SSS}} = \texttt{G}\, S_1^{*}S_2^{*}S_3^{*} \qquad\qquad \mathcal{L}_{\texttt{VSS}} = i\texttt{G}V_{\mu}^{*}S_2^{*} \overset{\leftrightarrow}{\partial}{}^{\mu} S_1^{*}$$


1
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W
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Xscs
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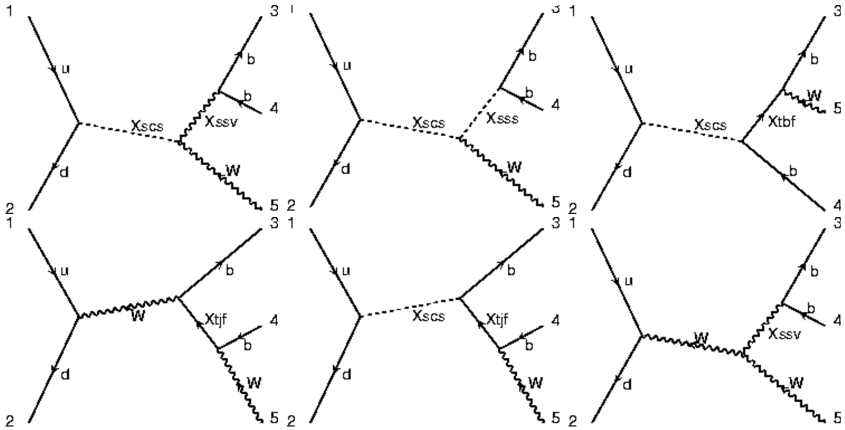
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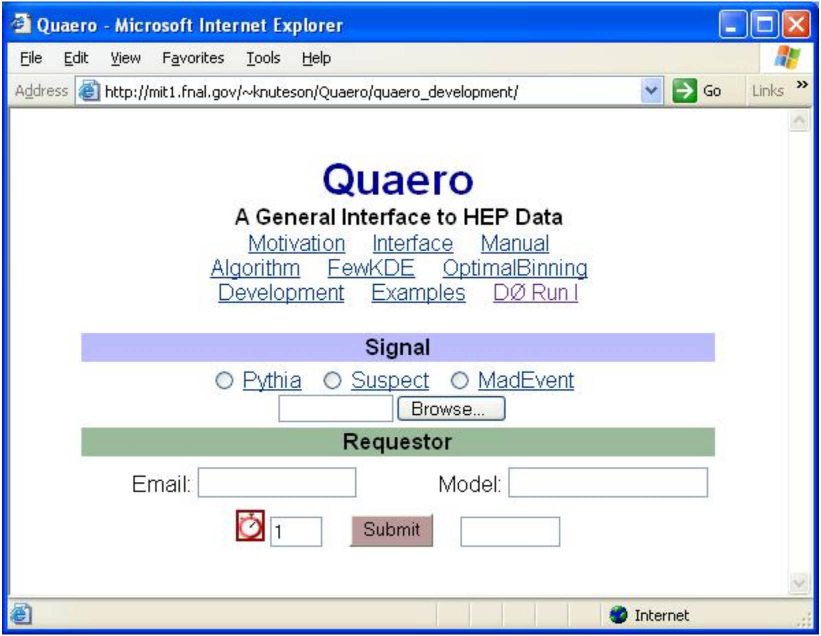
Quaero - Microsoft Internet Explorer
File Edit View Favorites Tools Help
Address http://mit1.fnal.gov/~knuteson/Quaero/quaero_development/
Go
Links
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A General Interface to HEP Data
Motivation Interface Manual
Algorithm FewKDE OptimalBinning
Development Examples DØ Run I
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Pythia Suspect MadEvent
Browse...
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Model:
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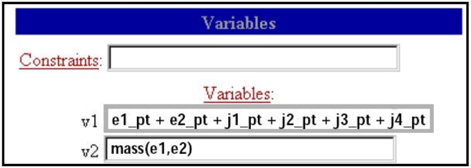
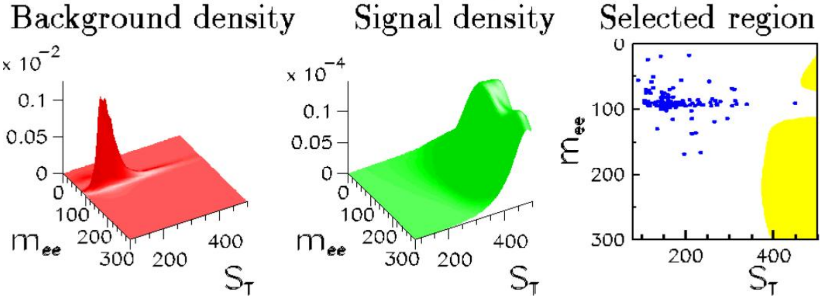
Leptoquarks $\rightarrow$ ee 2j



ε_{sig}	33%
$\hat{b}$	0.3 ± 0.1
N_{obs}	0
$\sigma^{95\%} \times \mathcal{B}$	0.07 pb



DESY 04–140 ISSN 0918–9833

A general search for new phenomena in *ep* scattering at HERA

H1 Collaboration

Abstract

A model-independent search for deviations from the Standard Model prediction is performed in e^+p and e^-p collisions at HERA using H1 data corresponding to an integrated luminosity of 117 pb^{-1}. For the first time all event topologies involving isolated electrons, photons, muons, neutrinos and jets with high transverse momenta are investigated in a single analysis. Events are assigned to exclusive classes according to their final state. A statistical algorithm is developed to search for deviations from the Standard Model in the distributions of the scalar sum of transverse momenta or invariant mass of final state particles and to quantify their significance. A good agreement with the Standard Model prediction is observed in most of the event classes. The most significant deviation is found for a topology containing an isolated muon, missing transverse momentum and a jet, consistent with a previously reported observation.

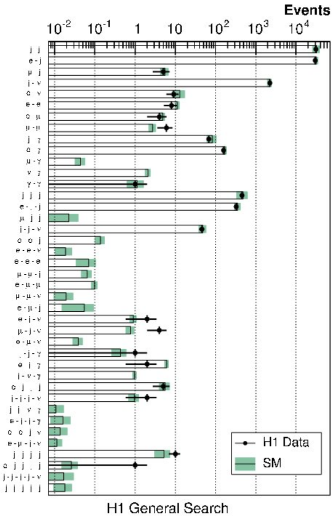


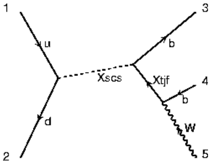
Figure 1: The data and the SM expectation for all event classes with a SM expectation greater than 0.01 events. The analysed data sample corresponds to an integrated luminosity of 117 pb^{-1}. The error bands on the predictions include model uncertainties and experimental systematic errors added in quadrature.

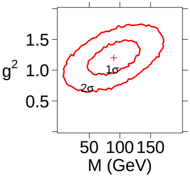
- ALEPH and L3 analyses underway

Quaero: DØ, hep-ex/0106039

Process	$\epsilon_{\rm sig}$	$\hat{b}$	$N_{\rm data}$	$\sigma^{95\%} \times \mathcal{B}$
$WW \to e\mu\not{E}_T$	0.14	19.0 ± 4.0	23	1.1 pb
$ZZ \to ee\,2j$	0.12	19.7 ± 4.1	19	0.8 pb
$t\bar{t} \to e\not{E}_T\,4j$	0.13	3.1 ± 0.9	8	0.8 pb
$t\bar{t} \to e\mu\not{E}_T\,2j$	0.14	0.6 ± 0.2	2	0.4 pb
$h_{175} \to WW \to e\not{E}_T\,2j$	0.02	29.6 ± 6.5	32	11.0 pb
$h_{200} \to WW \to e\not{E}_T\,2j$	0.07	66.0 ± 13.8	69	4.4 pb
$h_{225} \to WW \to e\not{E}_T\,2j$	0.06	43.1 ± 9.2	44	3.6 pb
$h_{200} \to ZZ \to ee\,2j$	0.15	17.9 ± 3.7	15	0.6 pb
$h_{225} \to ZZ \to ee\,2j$	0.15	18.8 ± 3.8	12	0.4 pb
$h_{250} \to ZZ \to ee\,2j$	0.17	18.1 ± 3.7	18	0.6 pb
$W'_{200} \to WZ \to e\not{E}_T\,2j$	0.05	27.7 ± 6.3	29	3.4 pb
$W'_{350} \to WZ \to e\not{E}_T\,2j$	0.23	22.7 ± 5.2	27	0.7 pb
$W'_{500} \to WZ \to e\not{E}_T\,2j$	0.26	2.1 ± 0.8	2	0.2 pb
$Z'_{350} \to t\bar{t} \to e\not{E}_T\,4j$	0.11	18.7 ± 4.0	20	1.1 pb
$Z'_{450} \to t\bar{t} \to e\not{E}_T\,4j$	0.14	18.7 ± 4.0	20	0.9 pb
$Z'_{550} \to t\bar{t} \to e\not{E}_T\,4j$	0.14	3.8 ± 1.0	2	0.3 pb
$Wh_{115} \to e\not{E}_T\,2j$	0.08	37.3 ± 8.2	32	2.0 pb
$Zh_{115} \to ee\,2j$	0.20	19.5 ± 4.1	25	0.8 pb
$LQ_{225}\overline{LQ}_{225} \to ee\,2j$	0.33	0.3 ± 0.1	0	0.07 pb

Story | **Fit** | $\log_{10}\frac{p(s+b)}{p(b)}$





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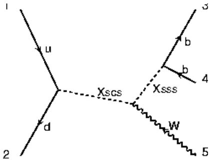

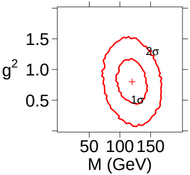

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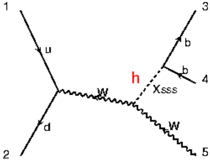
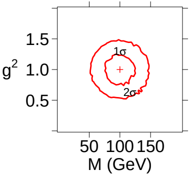




3

BARD: Interpreting New Frontier Energy Collider Physics

Bruce Knuteson*
MIT

Stephen Mrenna†
FNAL

No systematic procedure currently exists for inferring the underlying physics from discrepancies observed in high energy collider data. We present BARD, an algorithm designed to facilitate the process of model construction at the energy frontier. Top-down scans of model parameter space are discarded in favor of bottom-up diagrammatic explanations of particular discrepancies, an explanation space that can be exhaustively searched and conveniently tested with existing analysis tools.

New Particles

sss	sss	s	d	npm(1)	npW	s	Xsss	31
ssf	ssf~	f	s	npm(2)	npW	s	Xssf	32
szs	szs	s	d	npm(3)	npW	s	Xszs	33
szf	szf~	f	s	npm(4)	npW	s	Xszf	34
sas	sas~	s	d	npm(5)	npW	s	Xsas	35
saf	saf~	f	s	npm(6)	npW	s	Xsaf	36
sbs	sbs~	s	d	npm(7)	npW	s	Xsbs	37
sbf	sbf~	f	s	npm(8)	npW	s	Xsbf	38
scs	scs~	s	d	npm(9)	npW	s	Xscs	39
scf	scf~	f	s	npm(10)	npW	s	Xscf	40
...								
oss	oss	s	d	npm(51)	npW	o	Xoss	81
osf	osf~	f	s	npm(52)	npW	o	Xosf	82
ozs	ozs	s	d	npm(53)	npW	o	Xozs	83
ozf	ozf~	f	s	npm(54)	npW	o	Xozf	84
ssv	ssv	v	w	npm(55)	npW	s	Xssv	85
osv	osv	v	w	npm(56)	npW	s	Xosv	86
scv	scv~	v	w	npm(57)	npW	s	Xscv	87
...								

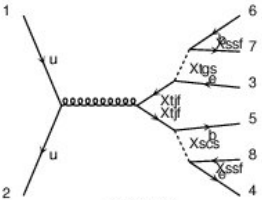
New Interactions

```
a     sas   sas~   np_coupl_c(453)   QNP
a     sbs   sbs~   np_coupl_c(455)   QNP
a     scs   scs~   np_coupl_c(457)   QNP
...
b     u     scs~   np_coupl_cLR(261)   QNP
b     u     scv~   np_coupl_rLR(41)   QNP
d     b     oss    np_coupl_cLR(408)   QNP
d     b     osv    np_coupl_rLR(27)   QNP
d     b     ozs    np_coupl_cLR(418)   QNP
d     b     sss    np_coupl_cLR(183)   QNP
...
z     tss   tzs~   np_coupl_c(466)   QNP
z     tzs   tzs~   np_coupl_c(474)   QNP
z     w+    scs~   np_coupl_c(438)   QNP
...
```

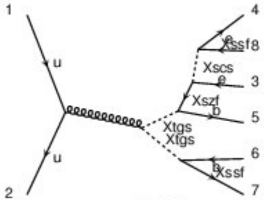
Pruning Rules

1. NP must couple to the initial state or an annihilation particle
2. SM particles must couple to either the initial or final state
3. No more than n NP particles can appear in a given diagram
4. NP particles can appear twice only in separate chains
5. . . .

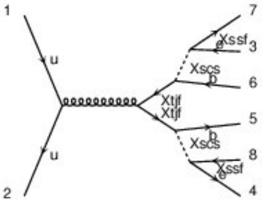
Pmiss Final States



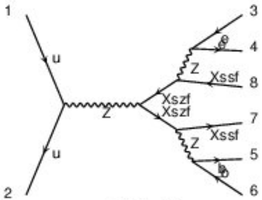
graph 13



graph 20



graph 37



graph 90

Compose: New Physics <2>

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Send Address Attach Spell Security Save

From: Bard <bard@fnal.gov>

To: witten@ias.princeton.edu

Subject: New Physics

```
Dear Prof Witten,

    I have analyzed the excesses observed in the data,
and have determined the following stories, ranked in descending
log likelihood:

Story 1
Particles (SU(3),Q,type)
          sss            osv           t4/3f

Mass (GeV)
          251+/-12       1043+/-102    341+/-73

Interactions
          sss b b        sss w+ w-     sss t4/3f t4/3f~ ....

Coupling
          .1+/-.03       .3+/-.1       1.0+/-0.3  ....

Story 2
...
...


Could you please tell us the correct string vacuum?


Sincerely,
the Bard
```

Table 1. Quantum numbers of scalar and vector leptoquarks with $SU(3) \times SU(2) \times U(1)$ invariant couplings to quark-lepton pairs ($Y = Q_{em} - T_3$).

	Spin	F = 3B + L	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
S_1	0	-2	3^*	1	$\frac{1}{3}$
$\tilde{S}_1$	0	-2	3^*	1	$\frac{4}{3}$
$\vec{S}_3$	0	-2	3^*	3	$\frac{1}{3}$
V_2	1	-2	3^*	2	$\frac{5}{6}$
$\tilde{V}_2$	1	-2	3^*	2	$-\frac{1}{6}$
R_2	0	0	3	2	$\frac{7}{6}$
$\tilde{R}_2$	0	0	3	2	$\frac{1}{6}$
U_1	1	0	3	1	$\frac{2}{3}$
$\tilde{U}_1$	1	0	3	1	$\frac{5}{3}$
$\vec{U}_3$	1	0	3	3	$\frac{2}{3}$

Table 2. Couplings of scalar and vector leptoquarks to quark-lepton pairs. The subscripts L,R of the couplings refer to the lepton chirality.

	F = -2, scalars			F = -2, vectors	
channel	S_1	$\tilde{S}_1$	$\vec{S}_3$	V_2	$\tilde{V}_2$
$e^-_{L,R}\ u$	$g_{1L,R}$	-	$-g_{3L}$	g_{2R}	$\tilde{g}_{2L}$
$\nu_L\ d$	$-g_{1L}$	-	$-g_{3L}$	g_{2L}	-
$e^-_{L,R}\ d$	-	$\tilde{g}_{1R}$	$-\sqrt{2}\, g_{3L}$	$g_{2L,R}$	-
$\nu_L\ u$	-	-	$\sqrt{2}\, g_{3L}$	-	$\tilde{g}_{2L}$
	F = 0, vectors			F = 0, scalars	
channel	U_1	$\tilde{U}_1$	$\vec{U}_3$	R_2	$\tilde{R}_2$
$e^-_{L,R}\ \bar{d}\ \bar{b}$	$h_{1L,R}$	-	$-h_{3L}$	$-h_{2R}$	$\tilde{h}_{2L}$
$\nu_L\ \bar{u}\ \bar{t}$	h_{1L}	-	h_{3L}	h_{2L}	-
$e^-_{L,R}\ \bar{u}\ \bar{t}$	-	$\tilde{h}_{1R}$	$\sqrt{2}\, h_{3L}$	$h_{2L,R}$	-
$\nu_L\ \bar{d}\ \bar{b}$	-	-	$\sqrt{2}\, h_{3L}$	-	$\tilde{h}_{2L}$

Büchmuller *et al.*

Table 2. Standard model representations carried by the scalars and vector bosons when coupling to two light fermions; (r, s, h) denotes a boson of hypercharge h carrying the r and s representations of $SU(3)$ and $SU(2)$, respectively. Entries with a * vanish when both light fermions belong to the same family; those marked by a $^{\mathrm{B}}$ generate baryon-number violating operators.

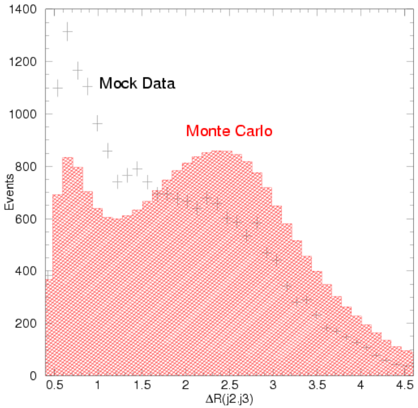
$X_{(r,s,h)}$		
	ℓ	q
$\bar{\ell}$	$(1, 1, 0)\ (1, 3, 0)$	$(3, 1, \frac{2}{3})$
$\bar{q}$	$(\bar{3}, 1, -\frac{2}{3})$	$(1, 1, 0)\ (1, 3, 0)\ (8, 1, 0)$
$\bar{\nu}^c$	$(1, 2, -\frac{1}{2})$	$(3, 2, \frac{1}{6})^{\mathrm{B}}$
$\bar{e}^c$	$(1, 2, -\frac{3}{2})$	$(3, 2, -\frac{5}{6})^{\mathrm{B}}$
$\bar{u}^c$	$(3, 2, \frac{1}{6})^{\mathrm{B}}$	$(\bar{3}, 2, \frac{5}{6})^{\mathrm{B}}$
$\bar{d}^c$	$(3, 2, -\frac{5}{6})^{\mathrm{B}}$	$(\bar{3}, 2, -\frac{1}{6})^{\mathrm{B}}$

$X_{(r,s,h)}$				
	ν	e	u	d
$\bar{\nu}$	$(1, 1, 0)$	$(1, 1, -1)$	$(3, 1, \frac{2}{3})$	$(3, 1, -\frac{1}{3})$
$\bar{e}$	$(1, 1, 1)$	$(1, 1, 0)$	$(3, 1, \frac{5}{3})$	$(3, 1, \frac{2}{3})$
$\bar{u}$	$(\bar{3}, 1, -\frac{2}{3})$	$(\bar{3}, 1, -\frac{5}{3})$	$(1, 1, 0)\ (8, 1, 0)$	$(1, 1, -1)$
$\bar{d}$	$(\bar{3}, 1, \frac{1}{3})$	$(\bar{3}, 1, -\frac{2}{3})$	$(1, 1, 1)$	$(1, 1, 0)\ (8, 1, 0)$

$\Phi_{(r,s,h)}$		
	ℓ	q
$\bar{\ell}^c$	$(1, 1, 1)^*\ (1, 3, 1)$	$(3, 1, -\frac{1}{3})^{\mathrm{B}}\ (3, 3, -\frac{1}{3})$
$\bar{q}^c$	$(\bar{3}, 1, \frac{1}{3})^{\mathrm{B}}\ (\bar{3}, 3, \frac{1}{3})$	$(\bar{3}, 1, \frac{1}{3})^{\mathrm{B}}\ (\bar{3}, 3, \frac{1}{3})^*$ $(6, 1, \frac{1}{3})^*\ (6, 3, \frac{1}{3})$

$\Phi_{(r,s,h)}$				
	ν	e	u	d
$\bar{\ell}$	$(1, 2, \frac{1}{2})$	$(1, 2, -\frac{1}{2})$	$(3, 2, \frac{7}{6})$	$(3, 2, \frac{1}{6})$
$\bar{q}$	$(\bar{3}, 2, -\frac{1}{6})$	$(\bar{3}, 2, -\frac{7}{6})$	$(1, 2, \frac{1}{2})\ (8, 2, \frac{1}{2})$	$(1, 2, -\frac{1}{2})\ (8, 2, -\frac{1}{2})$
$\bar{\nu}^c$	$(1, 1, 0)$	$(1, 1, -1)$	$(3, 1, \frac{2}{3})^{\mathrm{B}}$	$(3, 1, -\frac{1}{3})^{\mathrm{B}}$
$\bar{e}^c$	$(1, 1, 1)$	$(1, 1, -2)$	$(3, 1, -\frac{1}{3})^{\mathrm{B}}$	$(3, 1, -\frac{4}{3})^{\mathrm{B}}$
$\bar{u}^c$	$(3, 1, \frac{2}{3})^{\mathrm{B}}$	$(3, 1, -\frac{1}{3})^{\mathrm{B}}$	$(\bar{3}, 1, \frac{4}{3})^*\ (6, 1, \frac{4}{3})$	$(\bar{3}, 1, \frac{1}{3})^{\mathrm{B}}\ (6, 1, \frac{1}{3})$
$\bar{d}^c$	$(3, 1, -\frac{1}{3})^{\mathrm{B}}$	$(3, 1, -\frac{4}{3})^{\mathrm{B}}$	$(\bar{3}, 1, \frac{1}{3})^{\mathrm{B}}\ (6, 1, \frac{1}{3})$	$(\bar{3}, 1, -\frac{2}{3})^{*\mathrm{B}}\ (6, 1, -\frac{2}{3})$

Useful Theorists


Mock Data
Monte Carlo
Events
1400
1200
1000
800
600
400
200
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
ΔR(j2,j3)

The Bard at the LHC

- LHC phenomenology begins with the Standard Model
- Need complete description of most important processes
- Understanding comes from looking at consistency of full dataset
- Discrepancies can and will arise in specific final states
- Bard can write a series of ranked stories to describe each
  - bottom-up
- Can test this on Run2 data

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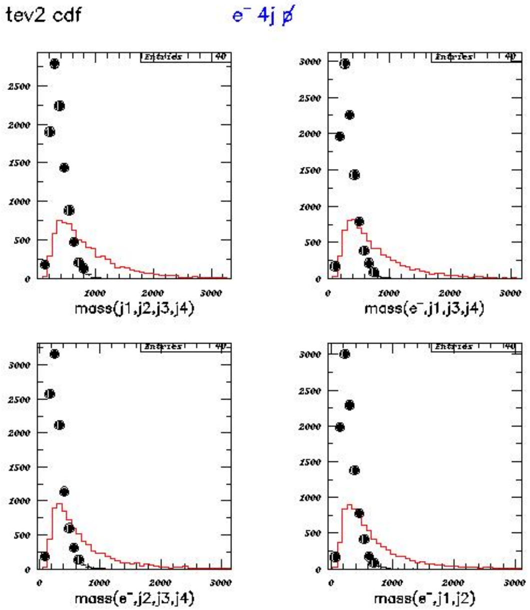
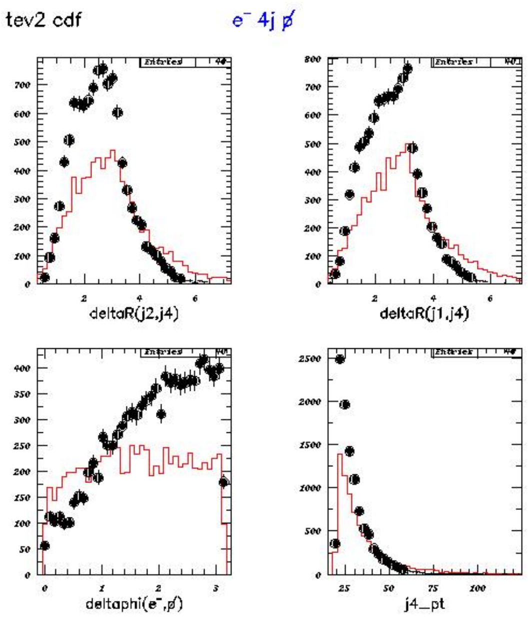
- Bard can write a series of ranked stories to describe each
  - bottom-up
- Can test this on Run2 data
- It works
- No, we haven't found anything $\cdots$ yet

Extra Slides

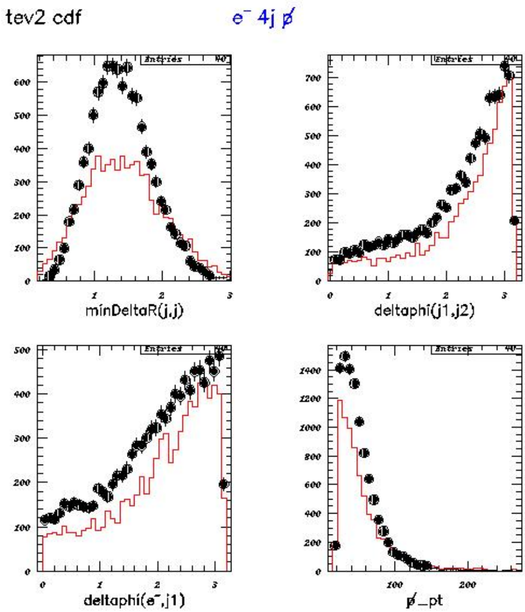
Kinematic Overlap between TeV and LHC



Kinematic Overlap between TeV and LHC

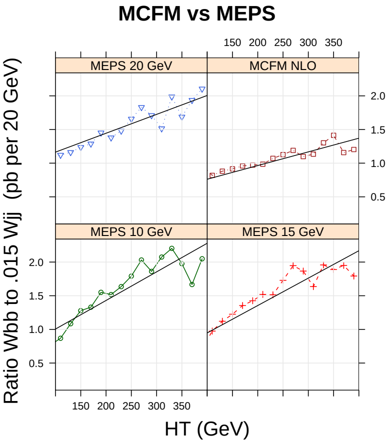


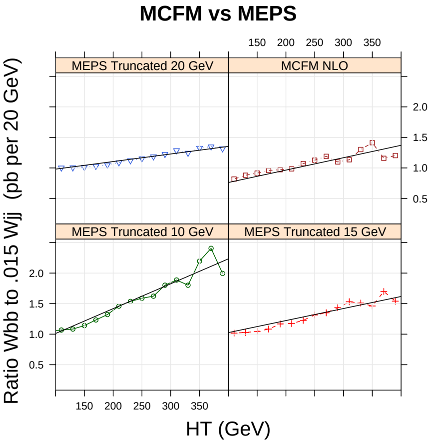
Kinematic Overlap between TeV and LHC



Kinematic Overlap between TeV and LHC

W+4 partons			
TEVATRON		LHC	
Graph	Cross Sect(fb)	Graph	Cross Sect(pb)
Sum	1035.004	Sum	577.948
ug_e+vedggg	112.250	gu_e+vedggg	89.815
gux_e-vexdxggg	112.040	ug_e+vedggg	89.603
uux_e-vexudxgg	112.010	gd_e-vexuggg	45.522
uux_e+veuxdgg	111.900	dg_e-vexuggg	45.342
dux_e-vexddxgg	46.423	uu_e+veudgg	34.174
udx_e+veuuxgg	46.388	dxg_e+veuxggg	15.346
dux_e-vexuuxgg	46.349	gdx_e+veuxggg	15.341
udx_e+veddxgg	46.330	uxg_e-vexdxggg	10.868
gdx_e+veuxggg	40.234	gux_e-vexdxggg	10.866
dg_e-vexuggg	40.122	gg_e+veuxdgg	9.920
udx_e+vegggg	30.906	gg_e+vescxgg	9.907
dux_e-vexgggg	30.867	gg_e-vexsxcgg	9.907
ddx_e-vexudxgg	15.189	gg_e-vexudxgg	9.842
ddx_e+veuxdgg	15.171	du_e+veddgg	8.903
...	...	...	...





Matched Datasets have consistently steeper slopes (note: MCFM steeper than LO)

Truncated Datasets contain only $Wb\bar{b} + Wb\bar{b}j$

Slopes more consistent with MCFM

Algorithm — Signal events

1) The signal Monte Carlo is processed

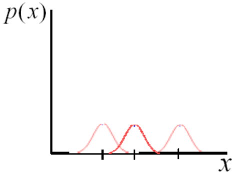
- (events are generated using Pythia, if requested)
- events are smeared with a fast detector simulation
- selection criteria are applied for desired final state
- particle identification efficiencies are considered

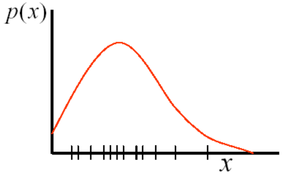
This gives

- total number of expected signal events in final state
- Monte Carlo signal events as they would look in the detector

2) An optimal region is chosen in the variables provided

a) Estimate signal and background densities using kernels





1) place "bumps of probability" around each Monte Carlo point

2) sum these bumps into a continuous distribution

$$p(x) = \sum_{i=1}^{N} \mathrm{gauss}(x - x_i)$$

The multivariate generalization is immediate

b) Define a *discriminant*

$$D(x) = \frac{p(x \mid s)}{p(x \mid s) + p(x \mid b)}$$

and choose a cut on D(x) that minimizes

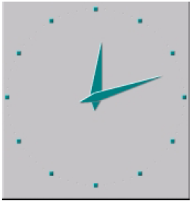
the 95% CL cross section limit you would expect to set assuming the data contains no signal.

We call 1/this quantity the "sensitivity"

Note that so far we have made no use of the data

3) Comparing number of observed events in the data to expected bkg, set 95% CL cross section limit on signal

4) Result is returned by email



Total elapsed time ≈ 1 hour

From: quaero@fnal.gov
Subject: Quaero Request #29

$W_R \to t\bar{b} \to e \not{E}_T\ 2j$

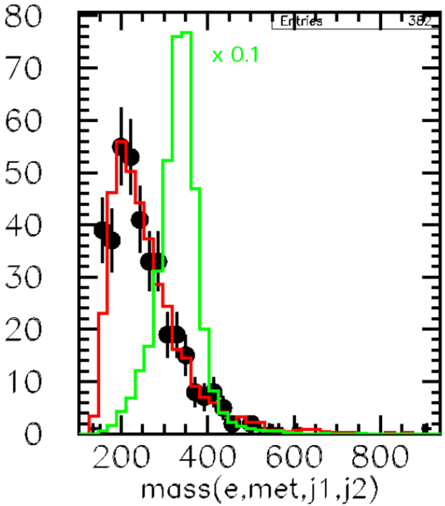
Result

Pythia cross section x branching ratio = 1.68 pb.

Upper limits on the cross section to this process at confidence levels of 50%, 90%, and 95% are found to be 0.8 pb, 1.8 pb, and 2.1 pb, respectively. Maximal sensitivity (0.73 pb^{-1}) is achieved in a region of variable space with 17.6 signal events expected, 32.7 +- 7.1 background events expected, and 36 events observed in the data.

Plots

Plots of the variables that you used are available for viewing at http://quaero.fnal.gov/quaero/requests/plots/29.ps. The red curve is the expected background; the green curve is your signal multiplied by a factor of 10; the black dots are D0 data.


Entries
382
x 0.1
80
70
60
50
40
30
20
10
0
200
400
600
800
mass(e,met,j1,j2)

Leptoquarks $\to$ ee 2j

Variables

Constraints:

Variables:

v1 e1_pt + e2_pt + j1_pt + j2_pt + j3_pt + j4_pt

v2 mass(e1,e2)

ε_{sig}	33%
$\hat{b}$	0.3 ± 0.1
N_{obs}	0
$\sigma^{95\%} \times \mathcal{B}$	0.07 pb

Background density Signal density Selected region