High Energy Physics

Searches for New Physics at the LHC: an experimentalist's perspective

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What this talk is trying to do

- Aimed at theorists
- Give a sense of how searches for New Physics are carried out
- Give some rules-of-thumb to help think about them
- Point out issues on the theoretical side

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Outline

- Cross sections (parton luminosities)
- Ingredients for discoveries
- Different type of searches
  - examples
  - comments on theoretical issues

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Parton-Parton luminosities

- LHC opens up new energy regime
  - obvious
- A way to think about this and develop a semi-quantitative intuition:

  Look at parton-parton luminosities
- Hadron collider = collisions of two broadband beams of partons (q, q, and gluons)
- Define "effective luminosity" for parton-parton collisions as a function of the E_{CM} of the parton-parton system

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Parton-Parton luminosities (2)

- Parton-parton x-section, i+j → X:

  $\widehat{\sigma}_{ij}(\widehat{s})$ at $E_{CM} = \sqrt{\widehat{s}}$

EHLQ
RMP 56 579 (1984)

- pp (or pp) x-section, pp→X or pp→X:

  $\sigma = \sum \int dx_i dx_j f_i(x_i) f_j(x_j) \widehat{\sigma}_{ij}$

  (the sum is over all the i's and j's that result in X)

- Rewrite it as: $\frac{d\sigma}{d\tau} = \sum \frac{dL_{ij}}{d\tau} \widehat{\sigma}_{ij}$ $\quad \tau \equiv \frac{\widehat{s}}{s}$

$$\frac{dL_{ij}}{d\tau} \equiv \frac{1}{1+\delta_{ij}} \int_{\tau}^{1} \frac{dx}{x} [f_i(x) f_j(\frac{\tau}{x}) + f_j(x) f_i(\frac{\tau}{x})]$$

Luminosity for parton-parton collisions as a function of parton-parton E_{CM}

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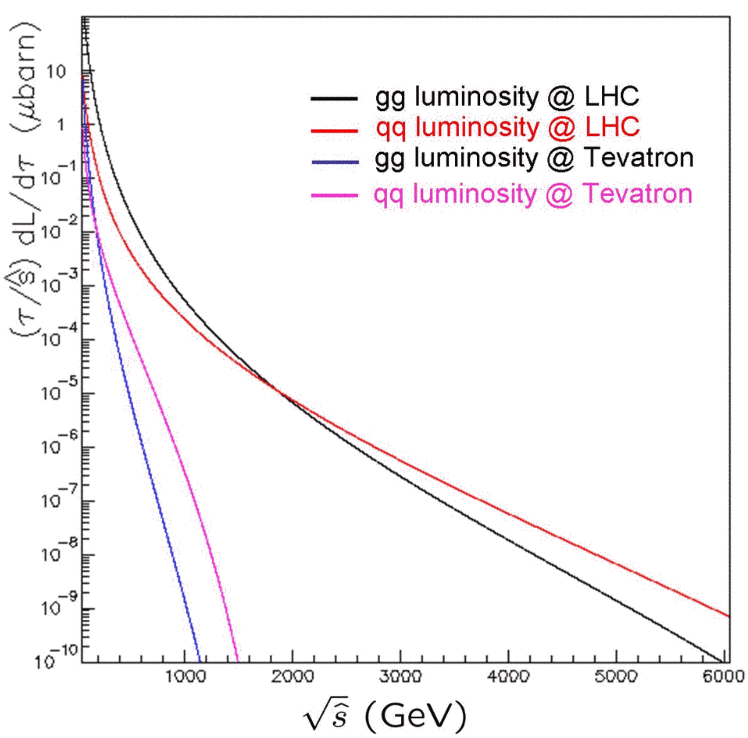
Parton-Parton luminosities (3)



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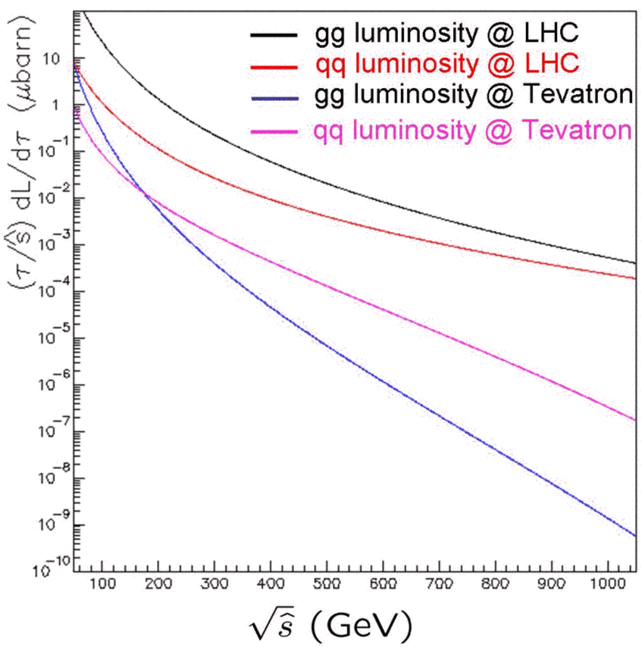
Zooming-in on the < 1 TeV region



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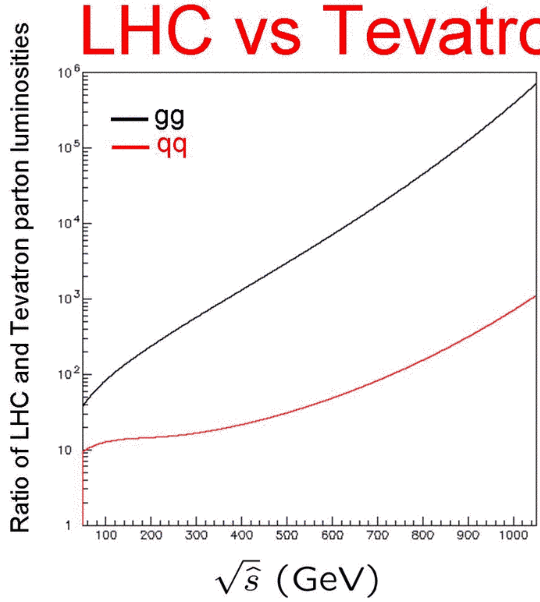
LHC vs Tevatron



1st (simplistic) rule of thumb:

- For 1 TeV gg processes, 1 fb^{-1} at FNAL is like 1 nb^{-1} at LHC
- For 1 TeV qq processes, 1 fb^{-1} at FNAL is like 1 pb^{-1} at LHC

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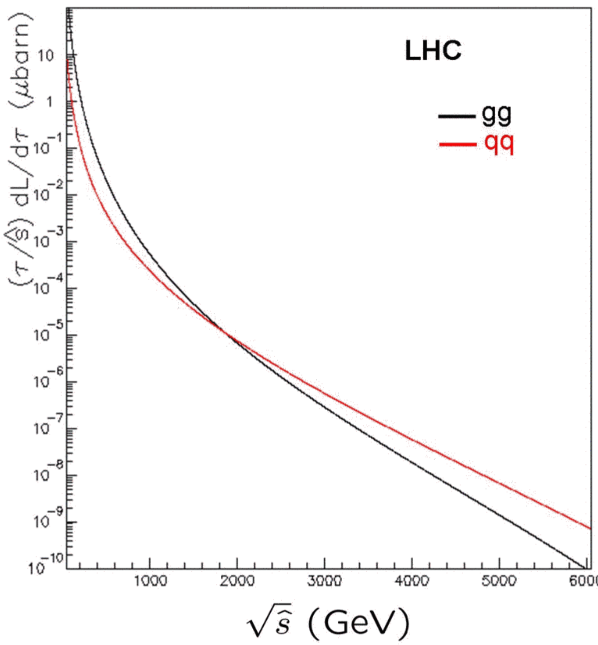
Another rule of thumb:

dL/dτ falls steeply with E_{CM}

- In multi-TeV region, ~ by factor 10 every 600 GeV
- New states produced near threshold
- Suppose you have a limit on some pair-produced object, M > 1 TeV
- How does your sensitivity improve with more data?

Answer: by ~ (600/2)=300 GeV = 30% for 10 times more lumi



Improving sensitivity with luminosity is tough...

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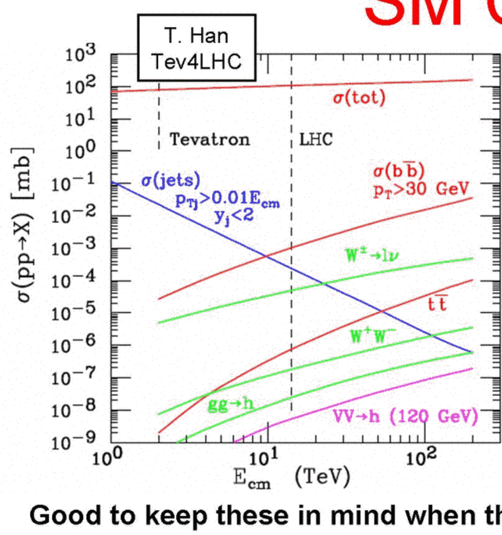
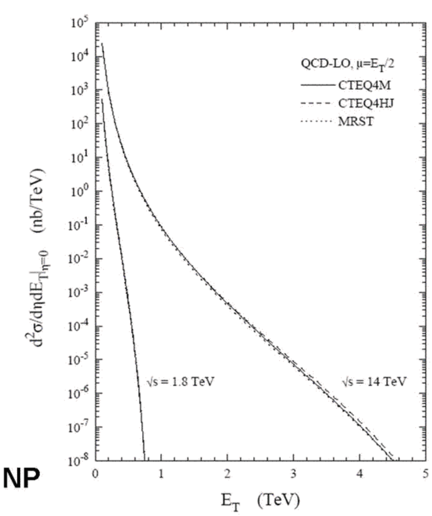
SM Cross Sections





Good to keep these in mind when thinking about NP

- σ(bb, high P_T) ~ 1 μb
- σ(W → lν) ~ 60 nb
- σ(WW) ~ 200 pb
- σ(tt) ~ 1 nb

Jet rates are enormous
~ 10 μb/GeV @ 100 GeV
~ 0.1 pb/GeV @ 1 TeV

Also, another useful rule of thumb:
σ(X+1jet) ~ 1/10 σ(X) for moderate (~ 30 GeV) P_T jet

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NP discoveries at the LHC

3 + 1 ingredients

0. **Detector and machine:** *If they don't work, forget it*
   - How fast will they come up? Don't know, but probably not fast.
1. **Trigger:** *If you didn't trigger on it, it never happened*
   - See next slide
2. **Backgrounds:** *It's the background, stupid*
   - Need to understand SM and instrumental backgrounds
     - Instrumental BG: experimentalists, mostly
     - Physics BG: theorists, mostly
   - There are exceptions....
3. **Searches:** *If you look for something, you may not find it. But if you don't look, you will never find it*
   - Model independent vs model dependent searches

Trigger

- Inelastic cross section O(100 mb)
- For low luminosity ~ 10^{33} cm^{-2} sec^{-1}, event rate ~ 100 MHz
- Data Acquisition Capability: ~ 100 Hz

Most of the events are thrown away

Example of possible CMS trigger menu (L=2 x 10^{33})

Trigger	Threshold (GeV or GeV/c)	Rate (Hz)	Cumulative Rate (Hz)
Inclusive electron	29	33	33
Di-electrons	17	1	34
Inclusive photons	80	4	38
Di-photons	40, 25	5	43
Inclusive muon	19	25	68
Di-muons	7	4	72
Inclusive τ-jets	86	3	75
Di-τ-jets	59	1	76
1-jet * E_T^{miss}	180 * 123	5	81
1-jet OR 3-jets OR 4-jets	657, 247, 113	9	89
Electron * Jet	19 * 45	2	90
Inclusive b-jets	237	5	95
Calibration and other events (10%)		10	105
TOTAL			**105**

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NP discovery ingredients

- Carefully crafted combinations of
  - photons
  - electrons
  - muons
  - taus
  - jets
  - b-tagged jets
  - missing transverse energy (MET)
- Or, something much more exotic, eg CHAMPS
- A quick look at the ingredients to develop intuition about them
  - **particularly the questions of BG & fake rates**

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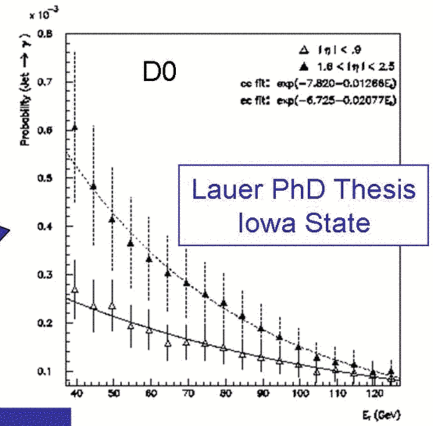
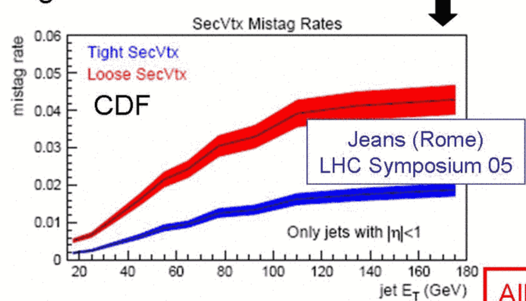
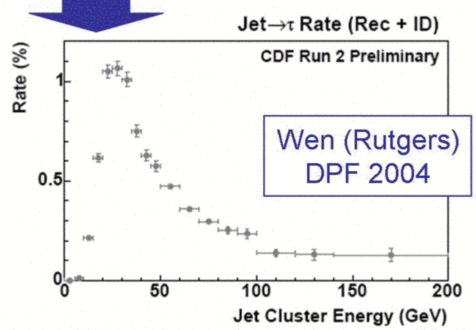
Jets

- Jets are everywhere
- Jets can fake isolated high P_T γ, e, μ, τ signatures
  - Probability of jet faking a γ: ~ few 10^{-4}.
  - Probability of faking e or μ ~ 1 order of magnitude smaller
    - But some jets have real lepton, e.g., b-jets
  - Probability of faking a τ: ~ few 10^{-3}
- Light quark or gluon jets fake b-quark signature at the % level







All of these to be measured on data (not MC)

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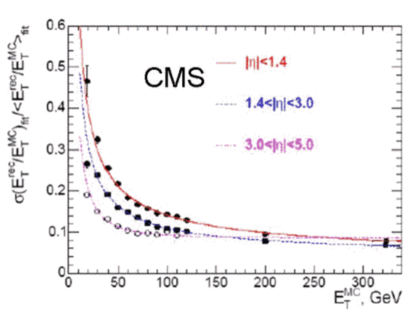
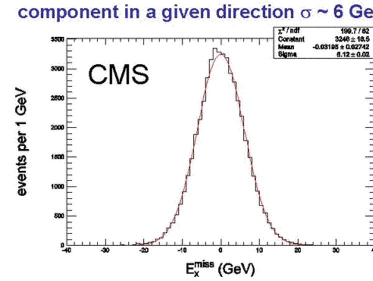
Missing Transverse Energy

- Fake MET mostly from jets, resolutions and tails
- Also from missed muons
- Also from "underlying event"

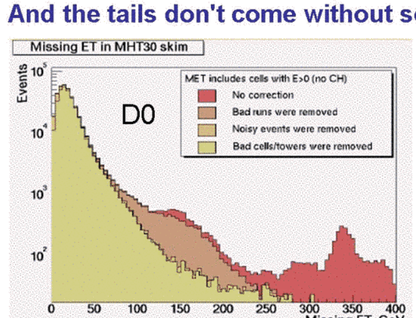
Jet E_T Resolution



1 min bias event contribution to MET component in a given direction σ ~ 6 GeV



And the tails don't come without some work....



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- A little bit of intuition/knowledge of
  - cross-sections
  - triggers
  - fake rates

  is necessary to estimate whether something is feasible or not
- Hardest intuition is on MET tails

- Have easy to use tools to calculate x-section, kinematical distribution for many LO processes

  e.g., COMPHEP

New Physics discoveries @ LHC

Broadly speaking, three possibilities

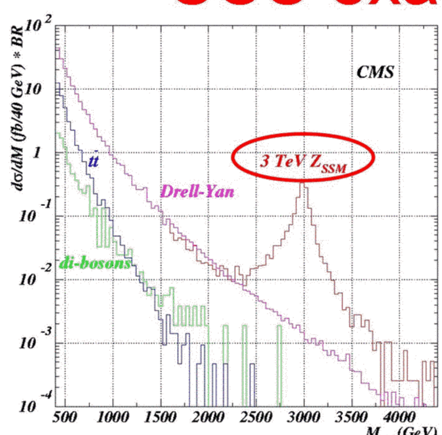
1. ***Self Calibrating***
   - e.g., a mass peak
2. ***Counting experiments***
   - The number of observed events of some type is >> than the SM prediction
3. ***Distributions***
   - The distribution of some kinematical quantity is inconsistent with the SM prediction

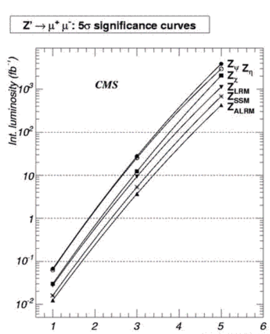
NB: the distinction is not always clean, but still useful to think in these terms

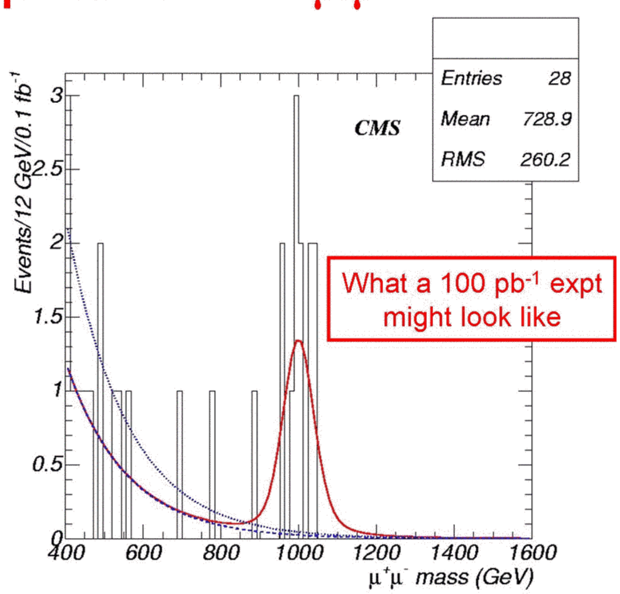
Self Calibrating Signals (SCS)

- A NP signal that stands out and *punches you in the face*
  - where you do not need to know the SM BG very precisely
    - or do you?
    - watch out for *irrational exuberance*
- For example:
  - A mass peak
  - A <u>huge</u> distortion to some kinematical distribution
  - Something truly weird, e.g., a heavy slow particle

SCS example: Z' → μμ







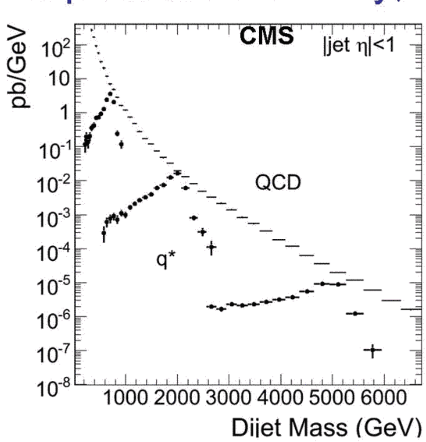
Cousins, Mumford, Valuev
UCLA

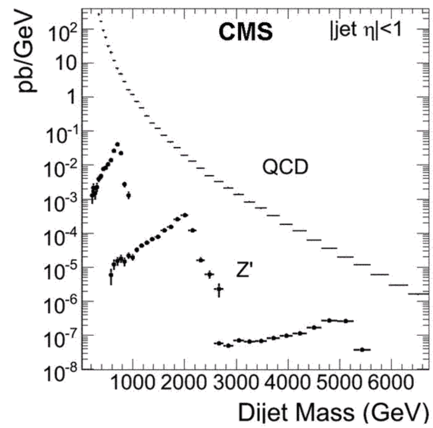
Another SCS example: di-jet resonances

e.g., excited quarks, axigluons, E6 di-quarks, Z', W',...

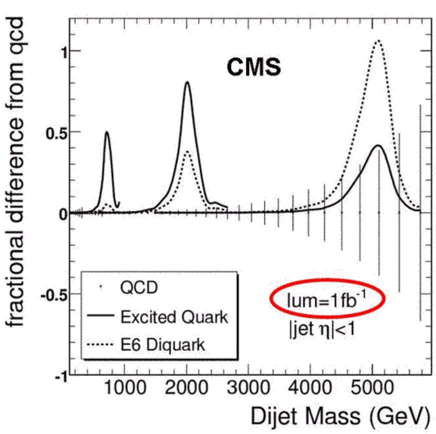
Rules of thumb:

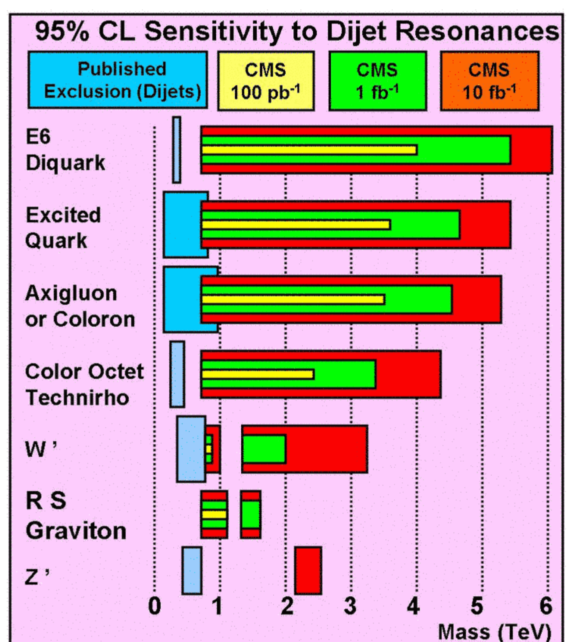
- If produced strongly → about same cross section as QCD at same mass, fairly easy to see
- If produced weakly, tougher





Di-jet resonances (cont.)

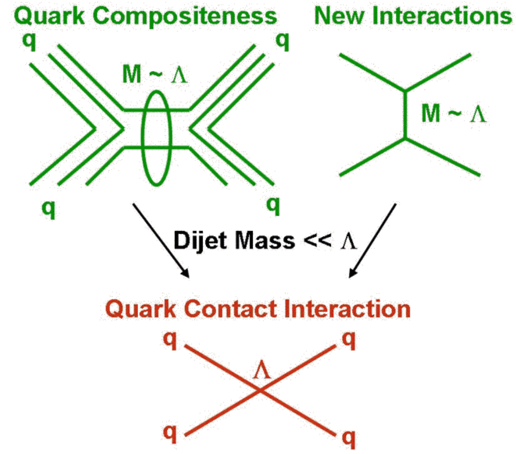


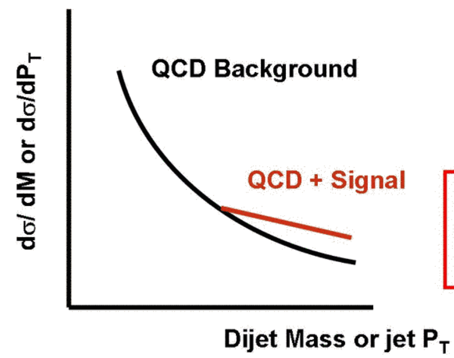


Esen and Harris (FNAL)
Gumus and Akchurin (Texas Tech)

(Yet) Another SCS example: di-jet mass distribution

- Distorts angular distributions
- More scatters at high angles
  - More jets at high P_T
  - More di-jets at high mass
- Like Rutherford scattering, but with quarks!





If the "edge" is low enough, this could be a relatively easy discovery (*Self-calibrating* variety)

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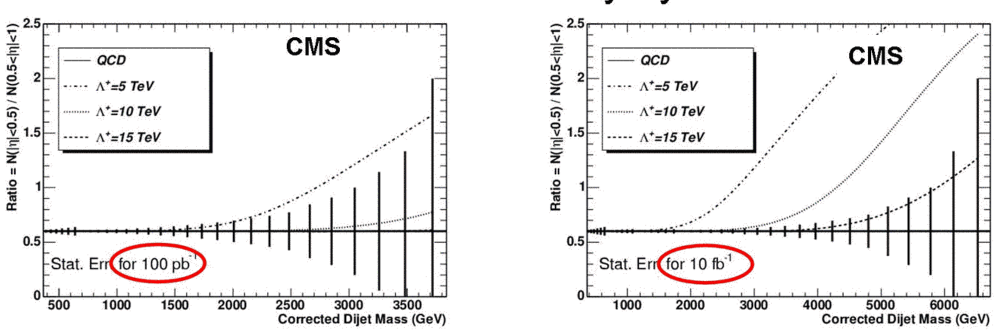
Di-jet mass distribution distortion

- Ratio of events at high-low η is a sensitive variable that eliminates many syst uncertaintes



Left-Handed Quark Contact Interaction	Λ^+ for 100 pb^{-1} (TeV)	Λ^+ for 1 fb^{-1} (TeV)	Λ^+ for 10 fb^{-1} (TeV)
95% CL Exclusion	6.2	10.4	14.8
5σ Discovery	4.7	7.8	12.0

Esen and Harris (FNAL)
Gumus and Akchurin (Texas Tech)

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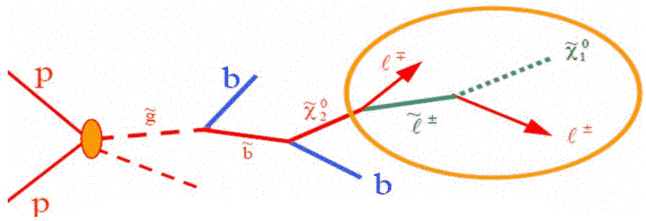
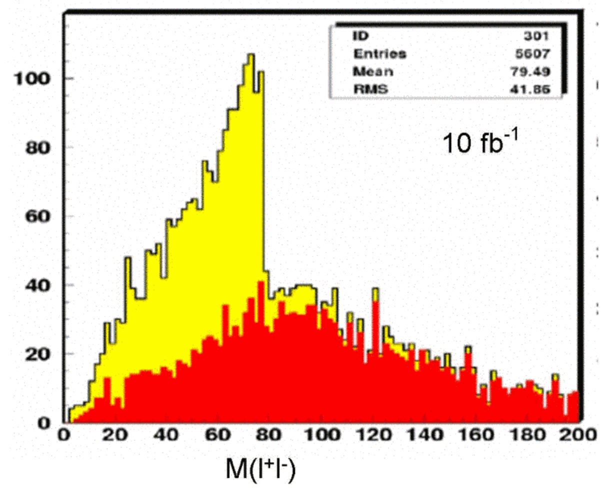
SCS: Edges





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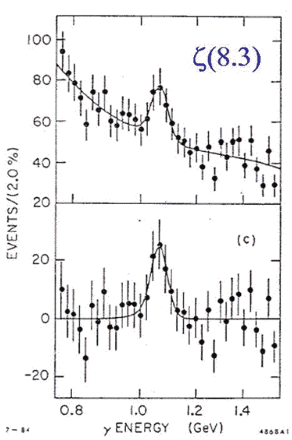
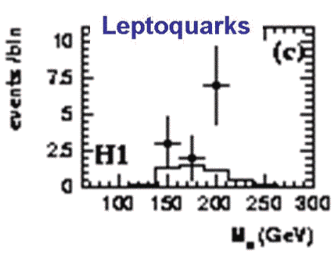
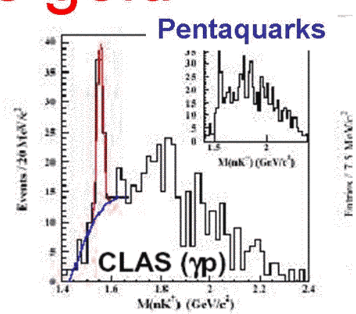
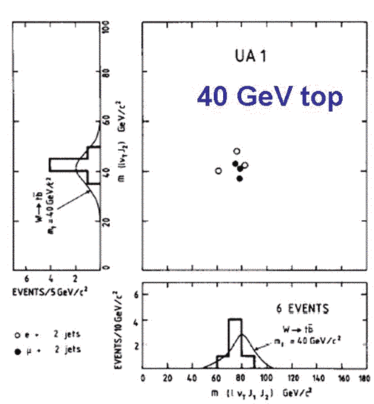
Not all that glitters is gold





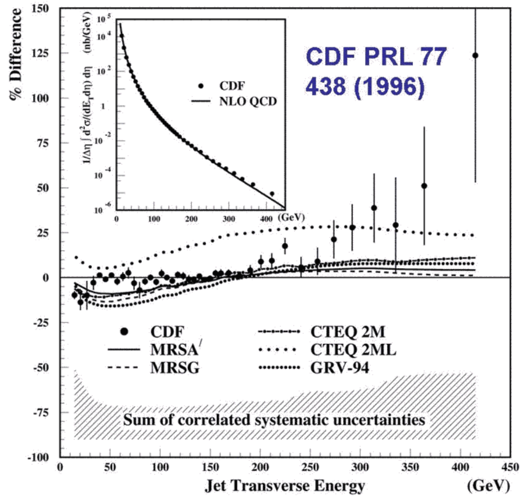




Buyer beware.
Especially in the tails of distributions

An aside

Tail of the jet E_T distribution. Definitely not a *self calibrating signal (SCS)*



- Data in the tail not consistent with QCD + (then) existing sets of parton distribution functions (PDFs)
- Looks like contact term Λ ~ 1.6 TeV
- Further PDF analysis found that the discrepancy could be absorbed by modifying gluon distribution
  - <u>**without conflicting with other data**</u>
  - <u>**even though all existing PDF fits were "low"**</u>
- Modern PDFs include uncertainties
- <u>A great step forward</u>

Example of careful, not-so-glamorous, phenomenological work that has a major impact

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Counting experiments, distributions

- Not all NP signals are as dramatic as a mass peak
- Need to establish whether data is or is not compatible with SM

  → <u>**Need the SM prediction**</u>
- In some cases the SM prediction <u>can come entirely from the experiment (data driven)</u>
  - Robust
- In other cases the SM prediction <u>relies heavily on theory</u>
  - Not so robust
- A couple of examples to understand typical issues

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Example 1: CDF search for NP in lep + γ + MET

- www-cdf.fnal.gov/physics/exotic/r2a/20050714.loginovLepPhotonX/
- A fairly simple final state
- Motivated by a few weird events in Run 1
- Select events, then compare with SM
  - both number of events and kinematical distributions
- Requires careful accounting of SM sources
- A lot of work!
  - typical for this type of searches
  - painstaking accounting of many BG sources
  - you don't just "run the Monte Carlo"

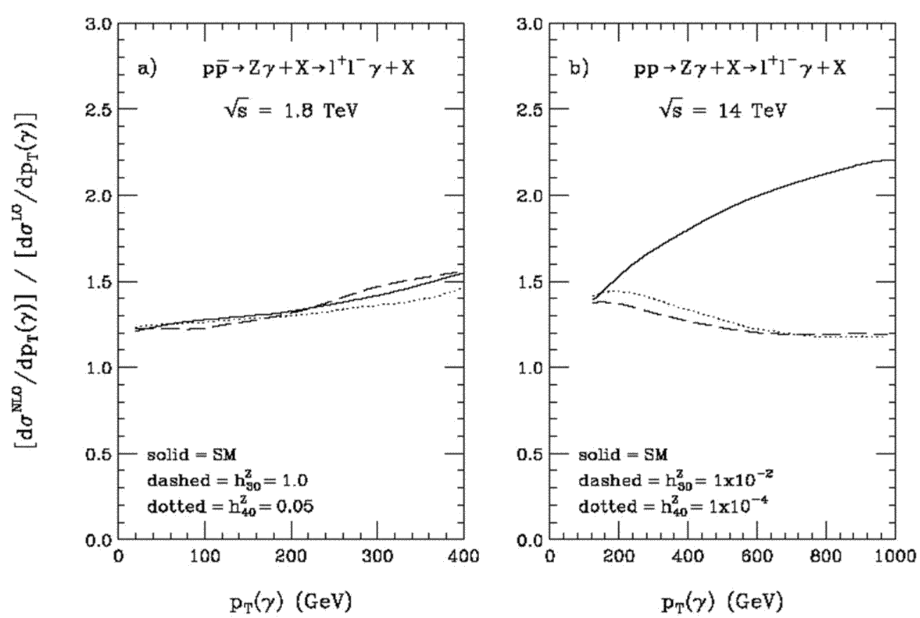
SM contributions to lep+γ+MET (1)

- pp → W+jet, W→lep ν, jet fakes γ
  - estimated from observed rate of W+jet and measured probability for jet to fake a γ
  - difficult (100% uncertainty), but data driven
- Drell-Yan e^+e^- pairs with hard brehmstrahlung, where the electron is lost and looks like a γ and the MET fluctuates high
  - estimated from observed rate of Z→ee and Z→e"γ" and observed MET distribution
  - data driven
- pp → jets, jets fake leptons
  - estimated from data by relaxing the lepton quality requirements, and extrapolating

SM contributions to lep+γ+MET (2)

- pp → Wγ or Zγ
  - This turns out to be the main background
  - Need theoretical input
  - Tools are:
    - LO parton level event generators, interfaced to Pythia
      - yes: more than one
    - NLO calculation
  - Good case because the NLO calculation exist
    - Often it doesn't
    - The NLO/LO K-factor is ~ 1.5, but it varies across phase space
    - The LO MC is then "fudged" to account for that

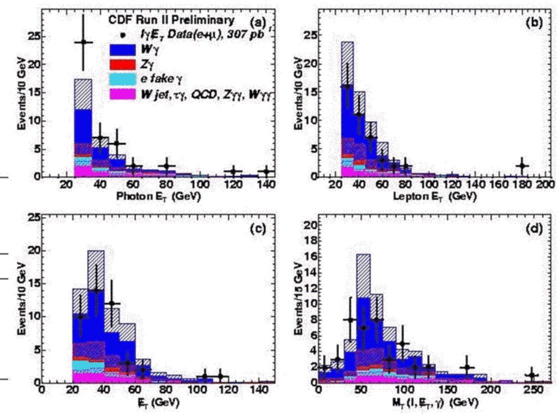
Baur, Han, and Ohnemus. PRD 57 (1998) 2823



NLO changes shape of distributions

Results of CDF lep + γ + MET search

Decent agreement in shape and normalization



Lepton+Photon+$\not{E}_T$ Predicted Events

SM Source	$e\gamma\not{E}_T$	$\mu\gamma\not{E}_T$	$(e+\mu)\gamma\not{E}_T$
$W^{\pm}\gamma$	11.9 ±2.0	9.0 ±1.4	20.9 ±2.8
$Z^0/\gamma+\gamma$	1.2±0.3	4.2±0.7	5.4±1.0
$W^{\pm}\gamma\gamma, Z^0/\gamma+\gamma\gamma$	0.14±0.02	0.18±0.02	0.32±0.04
$\tau\gamma$	0.7±0.2	0.3±0.1	1.0±0.2
$W^{\pm}$+Jet faking γ	2.8±2.8	1.6±1.6	4.4±4.4
$Z^0/\gamma \to e^+e^-, e\to\gamma$	2.5±0.2	-	2.5±0.2
Jets faking $\ell+\not{E}_T$	0.6±0.1	< 0.1	0.6±0.1
Total SM Prediction	**19.8±3.2**	**15.3±2.2**	**35.1±5.3**
Observed in Data	**25**	**18**	**43**

Without NLO,SM prediction ~ 26 ± ?
What would you have concluded?

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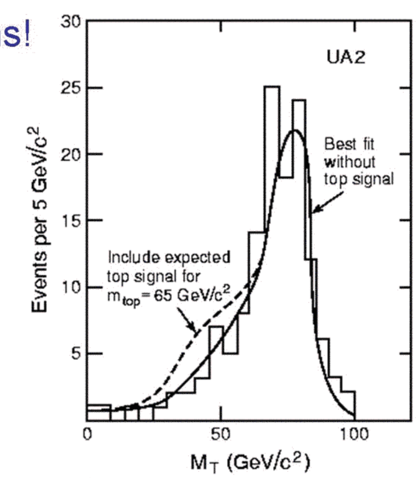
Example 2: UA2 W→tb search (1989)

- Ancient, but an example of a search based on a shape analysis that is <u>independent of theoretical assumptions</u>
  - yes, sometimes this happens!
- Signal is W→tb, t→eνb
  - M(eν) < M_W
- BG is W+jets, W→eν
  - M(eν) = M_W



Z. Phys. C46, 179 1990

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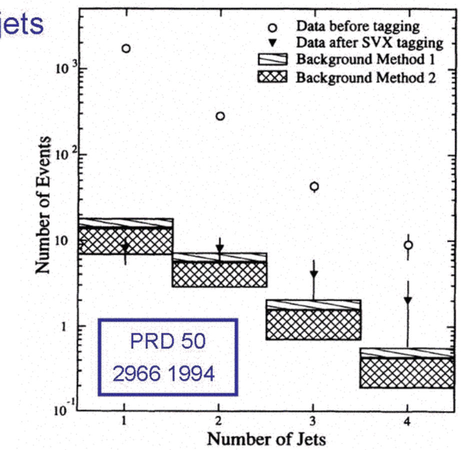
Example 3: CDF tt evidence (1994)

- Also ancient, but example of counting expt independent of theoretical assumptions
- Signal: lep + MET + ≥ 3 jets (≥ 1 of them b-tagged)
- Background: W+jets (fake b-tag), or Wbb (real b-tag)
- Background estimate, <u>entirely data-driven</u>:
  - measure b-tagging rate per jet in pp→jets
    - includes fake and real tags
  - apply to jets in W + jets sample
    - conservative
    - b-content of pp→jets >> pp→W+jets)



Comments

- Often <u>purely</u> data driven BG estimates do not work
- SM BG to LO have large normalization uncertainties
  - Makes counting experiments difficult
- SM LO event generators can have large shape uncertainties
  - Makes shape analyses difficult
- What are the uncertainties at LO? at NLO?
  - Often can get handle from data, e.g., W+jets vs Z+jets
- **<u>Where is the smoking gun?</u>**
  - As an experimentalist, more comfortable if uncertainties are under my control ☺
  - A theorist might feel differently ☹
  - Should you ask how sausages are made?

What can theorists do for experiments?

Slides from Z. Bern at LBNL LHC West Coast Theory Network meeting

Experimenters to theorists: "Please calculate the following at NLO"

Run II Monte Carlo Workshop, April 2001

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

Theorists to experimenters: "In your dreams"

More Realistic Experimenter's Wish List

Les Houches 2005

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

Also: implement calculation in a MC so that they can be used easily ☺

<u>Now that we are about to get data, nuts-and-bolts contributions can be more useful than suggestions for yet another beyond the SM theory</u>

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Model dependent vs. model independent searches

- Can search for generic NP signatures
  - e.g., the lep + γ + MET CDF search described earlier
- Or, for very specific, complicated signatures
  - e.g., pp→TT, T→tZ T→bW, t→eνb Z→$\mu\mu$, W→$\mu\nu$
- Because we do not know what the NP is, generic searches are very powerful
- But in a generic search <u>worry about missing complicated signature</u>
- With O(1000) physicists both approaches will be pursued

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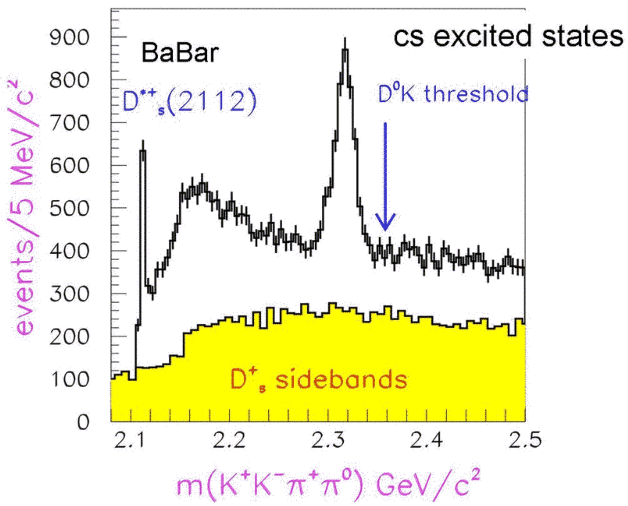

Palano (Bari)
$D_{sJ}(2317) \rightarrow D_S\, \pi^0$
PRL90 242001 (2003)

This huge signal had been in various data sets for many years.

- What is hiding in the Tevatron data sets?
- What was missed by the Tevatron triggers?

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A case study: tt at the Tevatron

- The high P_T discovery at Tevatron
- Not NP, the ultimate *known unknown*
- Complicated signature, search narrowly focused on expected SM properties

Would it have been seen in generic search?

- In the high statistics lep+jets channel probably not for a long time
  - Lots of BG, theoretical tools (W+multijet & Wbb calculations/MC), analysis techniques developed specifically for the search
- In the dilepton channel would have slowly emerged as excess of events with jets (and eventually, b-jets)

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Power of multi-lepton searches

If we see NP, can we tell what it is?

- Great question, great fun
  - *Supersymmetry and the LHC inverse problem* (hep-ph/0512190)
  - Olympics.....

- Emphasis shifts to *"Given that you see X, if the NP is Y, you should see Z"*
  - suggestions with Z experimentally impossible not very useful ☹
    - but do not underestimate your experimental colleagues!
  - a well developed feel for experimental issues could make a difference

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Conclusion

- After a long wait, exploration of the TeV scale is about to start in earnest

- There are many ideas about NP, but we don't know what it is

- Nuts-and-bolts contributions from theory community extremely important and perhaps underappreciated

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