Signals and Backgrounds for the LHC
II

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Triggering: Rates

As luminosity of 10^{33} cm^{-2} sec^{-1}

Process	$\sigma(nb)$	rate	Events/year
min bias	10^8	100 MHz	$\sim 10^{15}$
top	0.85	0.85 Hz	$\sim 10M$
$Z \rightarrow \mu^+\mu^-$	1.5	1.5	$\sim 10M$
$W \rightarrow e\nu$	15	15	$\sim 100M$
jets with $p_T > 200$ GeV	100	100	$\sim 100M$
WW pairs	0.08	0.08	$\sim 1M$
ZZ pairs 0.011		0.011	$\sim 12k$

Triggering: Event sizes

- Event size approx 100MB (determined by segmentation: go figure)
- Data handling 1PB/year
- Can only take 100 Hz
- Must throw out some physics, by applying thresholds

Trigger Strategy

Cannot reconstruct/calibrate full event fast enough: Decide on incomplete information
Layered structure adding refinements at each layer
Done by combinations of "Physics object" and threshold.

- Jets: Straightforward: Just add energy and apply threshold
- Muons: Almost Straightforward: Bend track and measure curvature
- Photons: Start with jets: Look for narrow one with no hadronic energy and no tracks. Some jet "fakes" will leak in
- Electrons: Like a photon with a track: Require isolation to reduce jet fakes
- Missing ET: Global object: Fakes from, mismeasured/lost jets, incomplete coverage
- (hadronic) Taus: Thin jet with few tracks.

Almost all are trying to get rid of QCD jets
Combine these to get rates down.

What physics passes what trigger

Table 4-1 Trigger menu, showing the inclusive physics triggers. The notation for the selection signatures and the definition of the thresholds are explained in Section 4.4.

Selection signature	Examples of physics coverage
e25i	$W \to e\nu$, $Z \to ee$, top production, $H \to WW^{(*)}/ZZ^{(*)}$, W′,Z′
2e15i	$Z \to ee$, $H \to WW^{(*)}/ZZ^{(*)}$
μ20i	$W \to \mu\nu$, $Z \to \mu\mu$, top production, $H \to WW^{(*)}/ZZ^{(*)}$, W′,Z′
2μ10	$Z \to \mu\mu$, $H \to WW^{(*)}/ZZ^{(*)}$
γ60i	direct photon production, $H \to \gamma\gamma$
2γ20i	$H \to \gamma\gamma$
j400	QCD, SUSY, new resonances
2j350	QCD, SUSY, new resonances
3j165	QCD, SUSY
4j110	QCD, SUSY
τ60i	charged Higgs
μ10 + e15i	$H \to WW^{(*)}/ZZ^{(*)}$, SUSY
τ35i + xE45	$qqH(\tau\tau)$, $W \to \tau\nu$, $Z \to \tau\tau$, SUSY at large tan β
j70 + xE70	SUSY
xE200	new phenomena
E1000	new phenomena
jE1000	new phenomena
2μ6 + $\mu^+\mu^-$ + mass cuts	rare b-hadron decays ($B \to \mu\mu X$) and $B \to J/\psi\ (\psi')X$

Rates

Table 13-11 HLT trigger menu with rates for a luminosity of 2×10^{33} cm^{-2} s^{-1}

HLT signature	Rate (Hz)
e25i	40
2e15i	< 1
γ60i	25
2γ20i	2
μ20i	40
2μ10	10
j400	10
3j165	10
4j110	10
j70+xE70	20
τ35i+xE45	5
2μ6 with vertex, decay-length and mass cuts (J/ψ, ψ', B)	10
Others (prescaled, exclusive, monitor, calibration)	20
Total	**~200**

Life is not so simple

- Lower thresholds are added with filtering ("prescale") See Tully yesterday
- Some triggers must be used for calibration
- Turn on is not theta function: must be measured
- Overlaps are needed to measure efficiencies
  Example Top events will pass several triggers

My signal has to pass the Trigger

- Ideally more that one trigger.
- Be careful to consider prescales
- Part of event not used in analysis might pass the trigger

Trouble with Triggers: I

Worry that trigger will throw something out

Source of the ill-informed remark (usually from e^-e^+ folks): "you can only find what you are looking for"

The basic LHC trigger strategy was set more than 15 years ago. I am not aware of any new physics since then that would have been missed by that strategy. If you think you have an example, tell me.

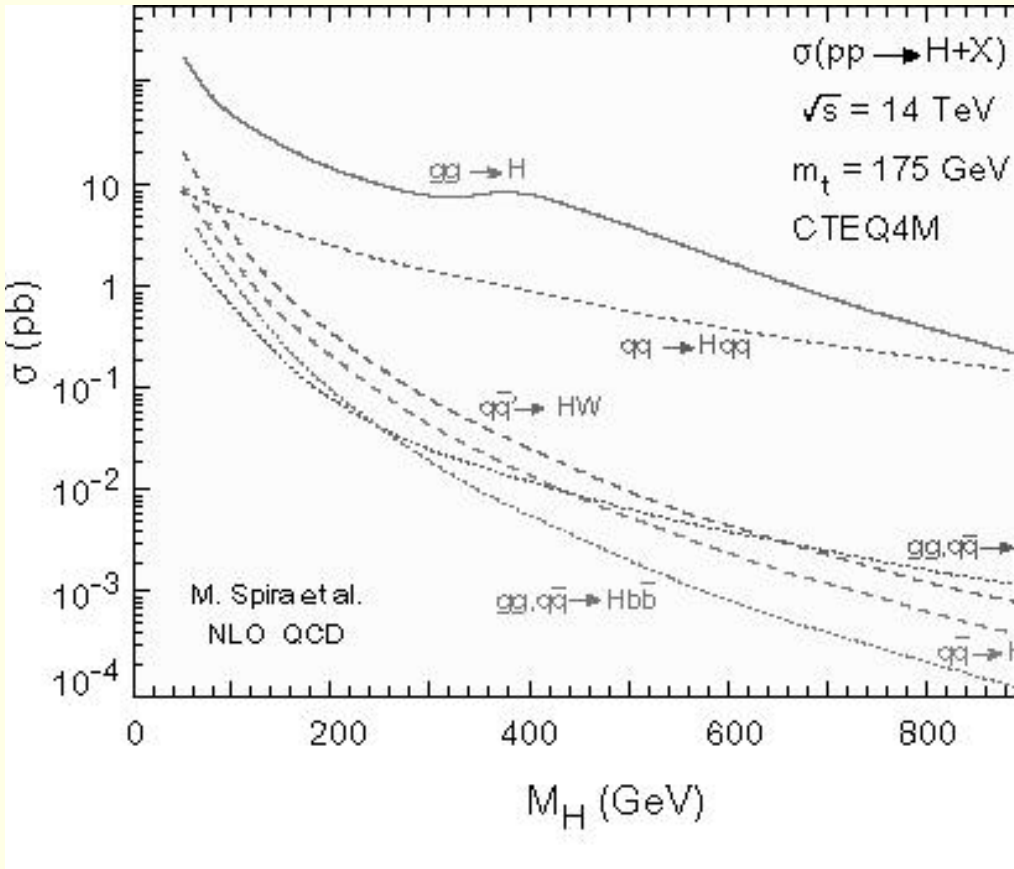
Trouble with Triggers: II

Heavy objects tend to decay into energetic things, so look elsewhere for troubles.

- Things decaying only to jets: might have a problem due to high thresholds, but rates are big, prescales will get it

- Light particles with small cross section

Example: $h \to b\bar{b}$
Gives need $2J50$: swamped by QCD
would need a prescale of 0.00001



Two ways to get clever

Use something else in the event WH or $t\bar{t}H$ final state

Almost fully efficient for $E25I$ or $MU20$

Try to trigger on a b

Even here there is irreducible $gg \to b\bar{b}$

I estimate $2b50$ at 10kHz

still hopeless

- Small mass gaps. Example: $X \to Y + e$: $M_X - m_Y$ small, and Y invisible. May not pass $E25I$
  However, you may be saved by the rest of the event
  Worst case $q\bar{q} \to W_H \to eN$: all you have here is extra jets emitted in the event, typically $p_T \sim M_{W_H}/10$
  SUSY in the focus point region is of this type (if $m_{\tilde{g}}$¿ 2.5 TeV)

- Out of time Events.Example Slow particle that gets to muon system "too late"

Backgrounds – Measuring and Calculating

At present, we rely on MC for signal and background estimates

There are uncertainties in rates from PDF's, higher order QCD

Most of these do no matter at the moment, They will matter once data appears

My concern: underlying and min-bias events

Affects process that need forward jet tagging $e.g.$ $WW - scattering$ or central jet veto (vital for Higgs measurements)

Will be measured once data exists and MC will be tuned to agree...

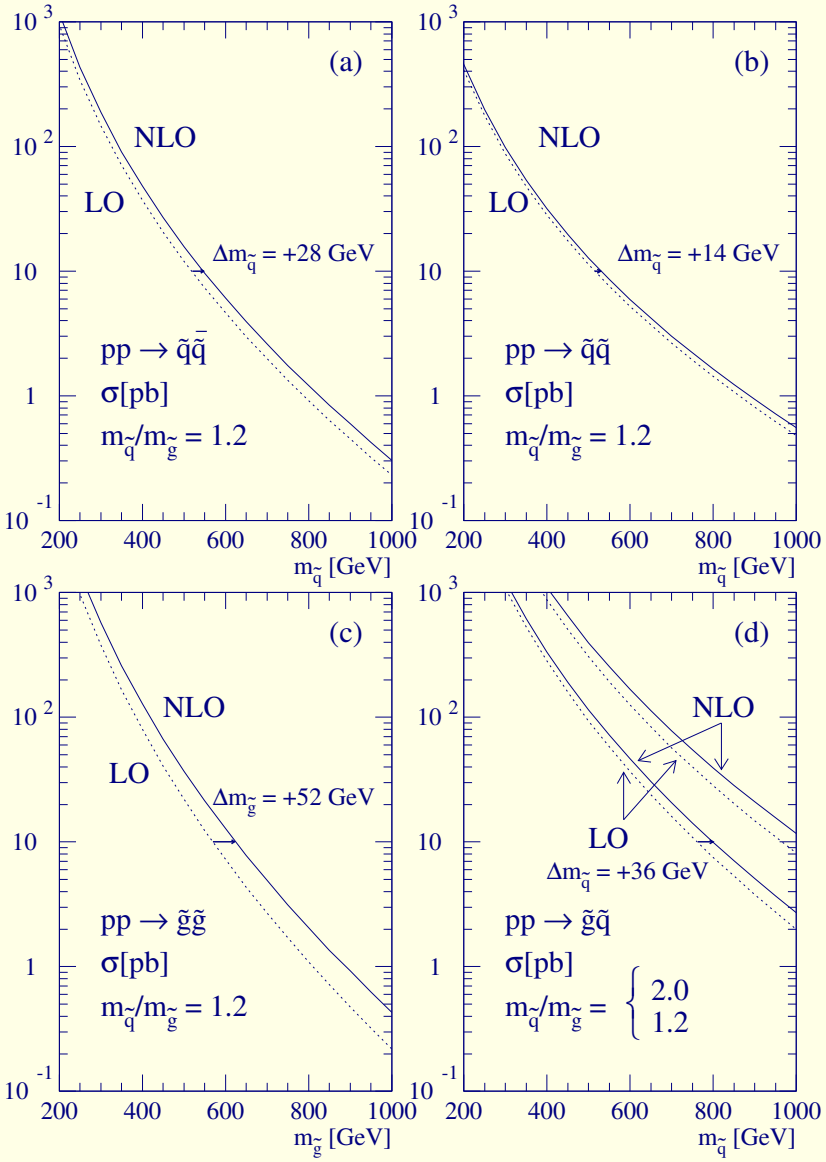
MC are a vital theoretical tool: I can discuss more if you want it

Rates: New particles with Strong interactions

$q\bar{q} \to X\overline{X}$ or $gg \to X\overline{X}$
rates depend on mass and color content of X These plots are for SUSY

Rule of thumb
$\sigma \sim M^{-5}$

Lowest order QCD is a good approximation

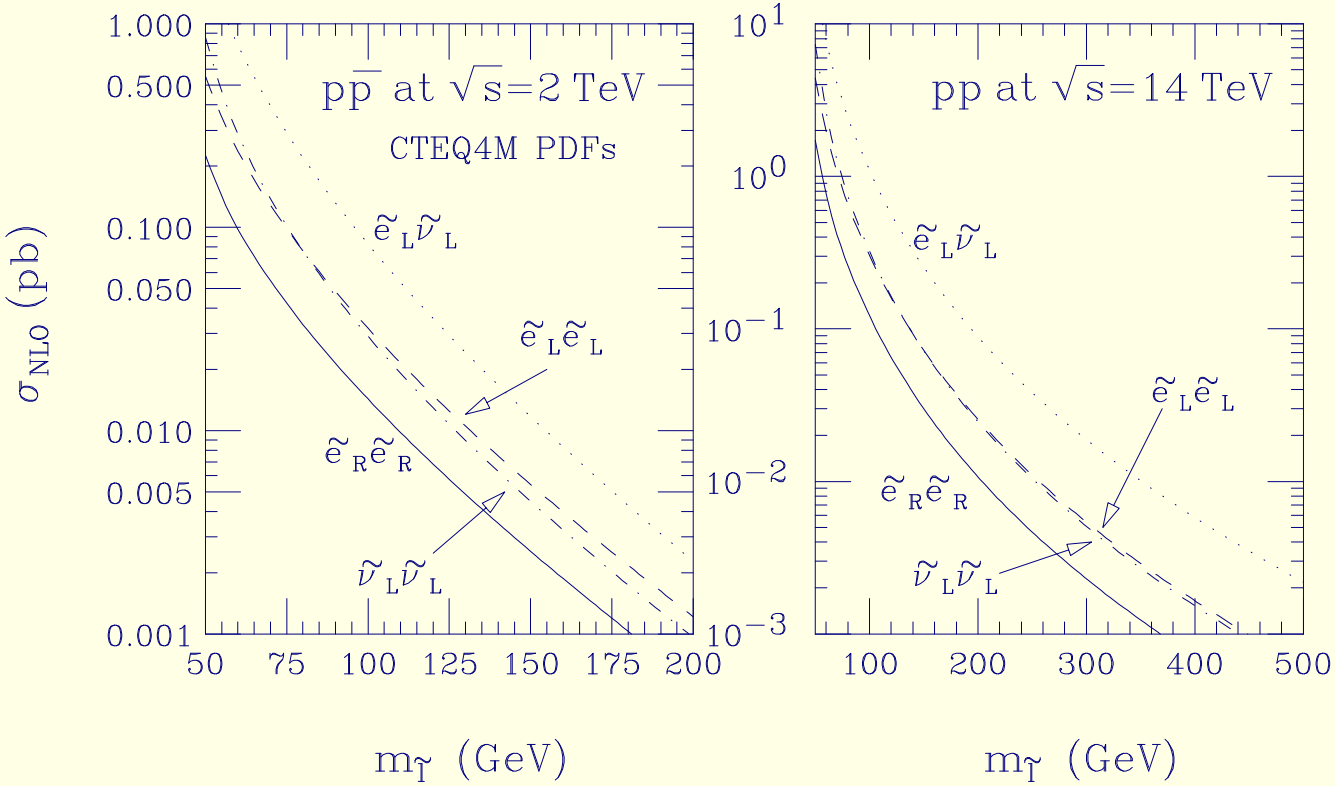


Rates: Single production of electroweak particles

- $q\overline{q} \to X$
  rates depend on mass and color content of X
- Same mechanism as W or Z
- Known to NNLO in QCD
- $gg \to X$. Example Higgs, known to NNLO

Rates: Pair production of electroweak particles

$q\bar{q} \to X\overline{X}$ or $q\bar{q} \to X\overline{X}$



Case Study I: Extra dimensions

Many theories ($e.g.$ string) predict extra dimensions of size R

What is R?. Old ideas $\Rightarrow 1/M_P$. Unobservable.

Larger value of R can allow scale of Gravity to be smaller Arkani-Hamed...

$$G_N = 8\pi R^\delta M_D^{-(2+\delta)}$$

$M_D \sim 1$ TeV $R \sim 10^{32/\delta - 16}$ mm

Attractive because no hierarchy between M_W and M_D

But hierarchy between $1/R$ and M_W still exists

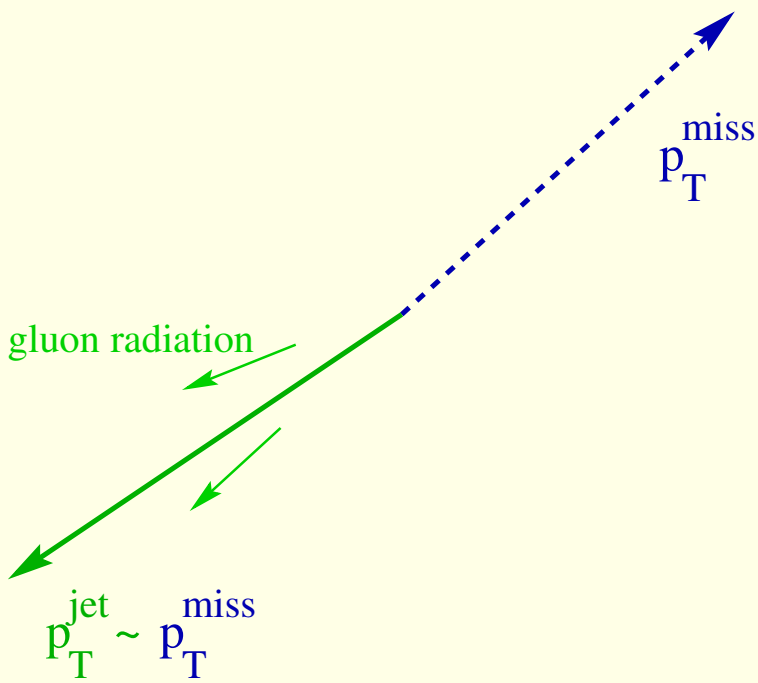
Compactified dimension implies tower of states with $\Delta m \sim 1/R$

$\Rightarrow$ Standard Model fields must be stuck in $d = 4$ But many graviton (G) excitations can exist.

In simplest models processes such as $qg \to qG$ or $q\bar{q} \to \gamma G$ give missing energy signatures or distortions in rates due to exchanges

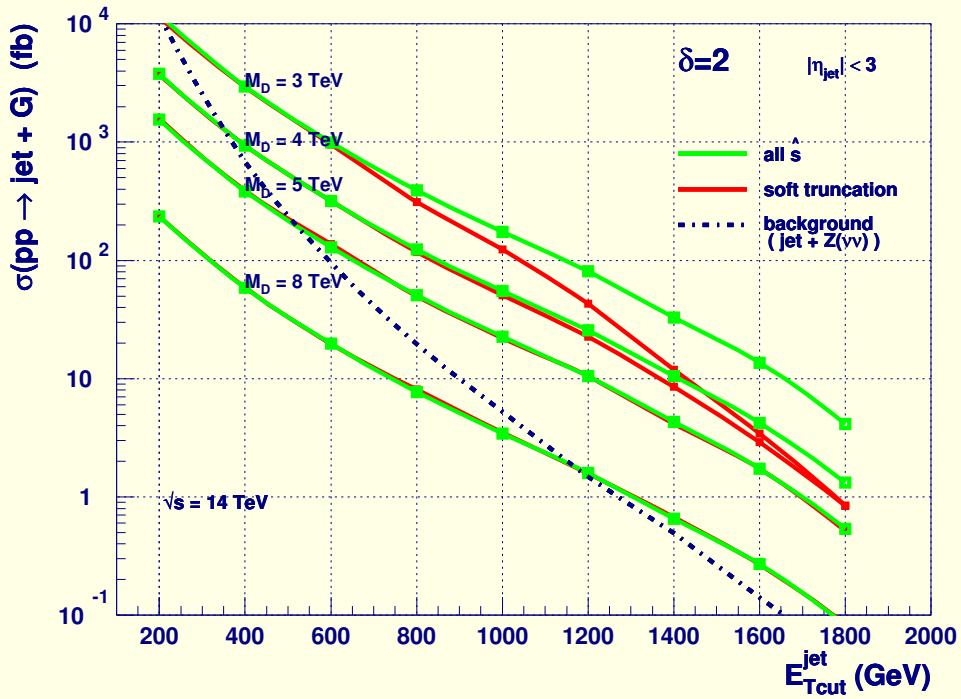
Can emit an graviton, must integrate up to kinematic limit

$$\frac{d^6\sigma}{dm^2 dp^2_{T_{jet,\gamma}} dy_{jet,\gamma} dy_G} = \frac{m_G^{\delta-2}}{2} \frac{S_{\delta-1}}{M_D^{\delta+2}} \frac{d\sigma_m}{dt} \sum_{i,j} \frac{f_i(x_1)}{x_1} \frac{f_j(x_2)}{x_2}$$



Be careful not to use this where it is no good

Result not valid for $E > M_D$
Check that expt is not sensitive to this



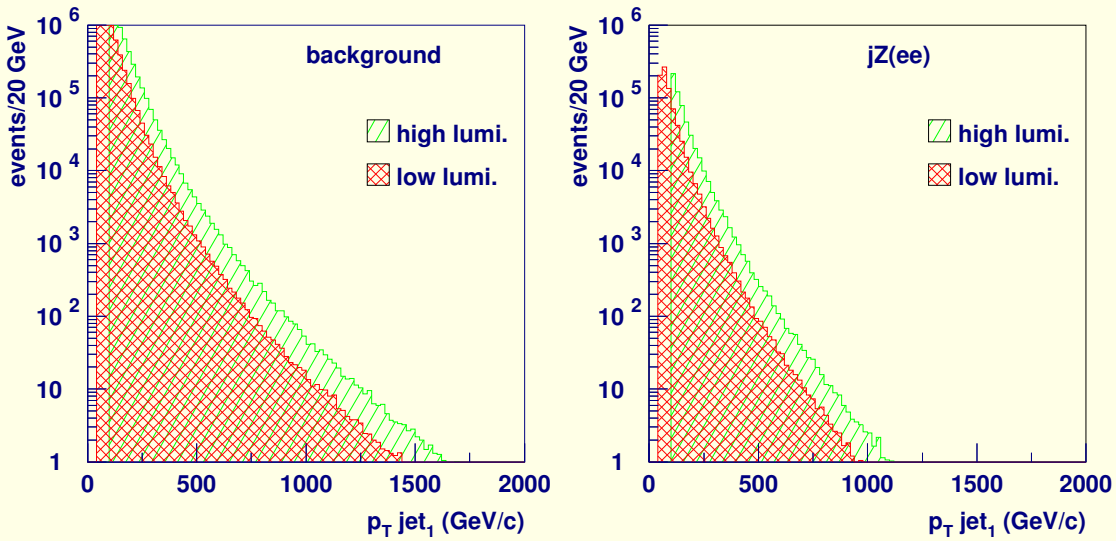
Plot shows rate with $E_T > E_T(out)$

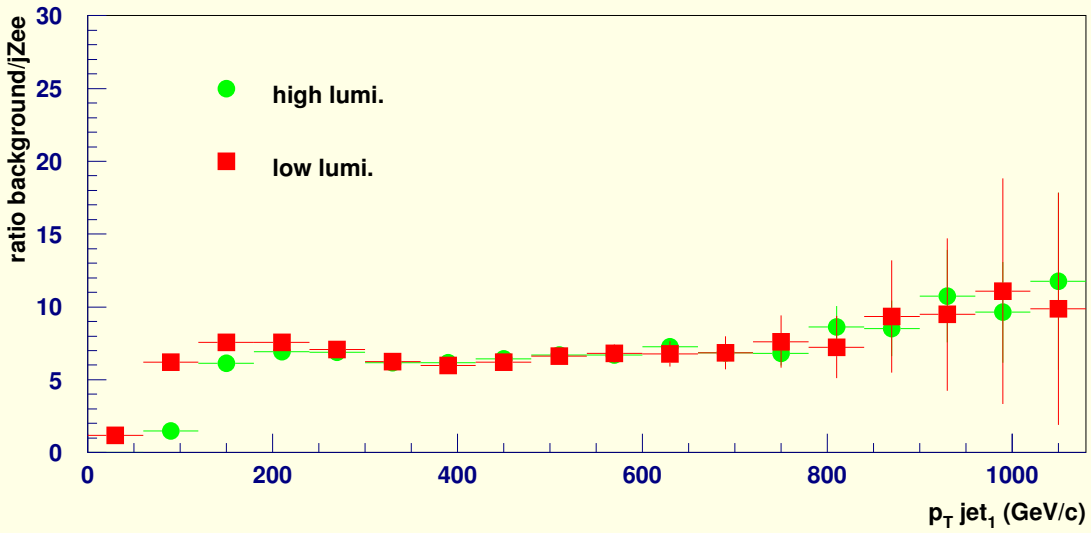
Background

Signal is jet $E_T(miss)$

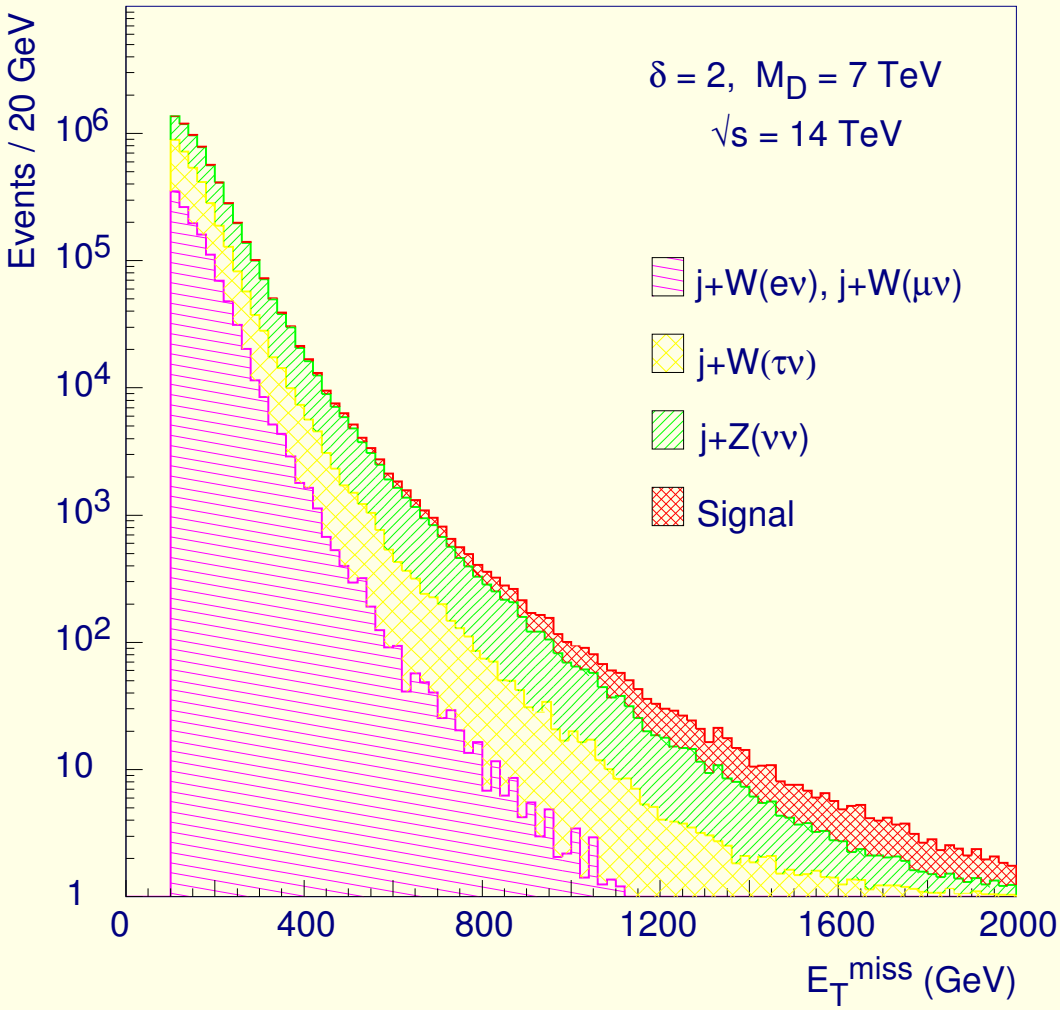
- $Z \rightarrow \nu\nu$: Calculate
- $W \rightarrow \mu\nu$, muon lost: Calculate and check by measure when muon is not lost
- $W \rightarrow \tau\nu$: Could be reduced by vetoing: Measure/calculate and extrapolate

Expect that Background is dominated by $Z \to \nu\nu$: check from $Z \to e^- e^-$





ADD extra dimensions produce jets $+ \not{E}_T$, $\gamma + \not{E}_T$ signals from graviton emission



red region is signal from jets for $100\ \mathrm{fb}^{-1}$

Sensitivity

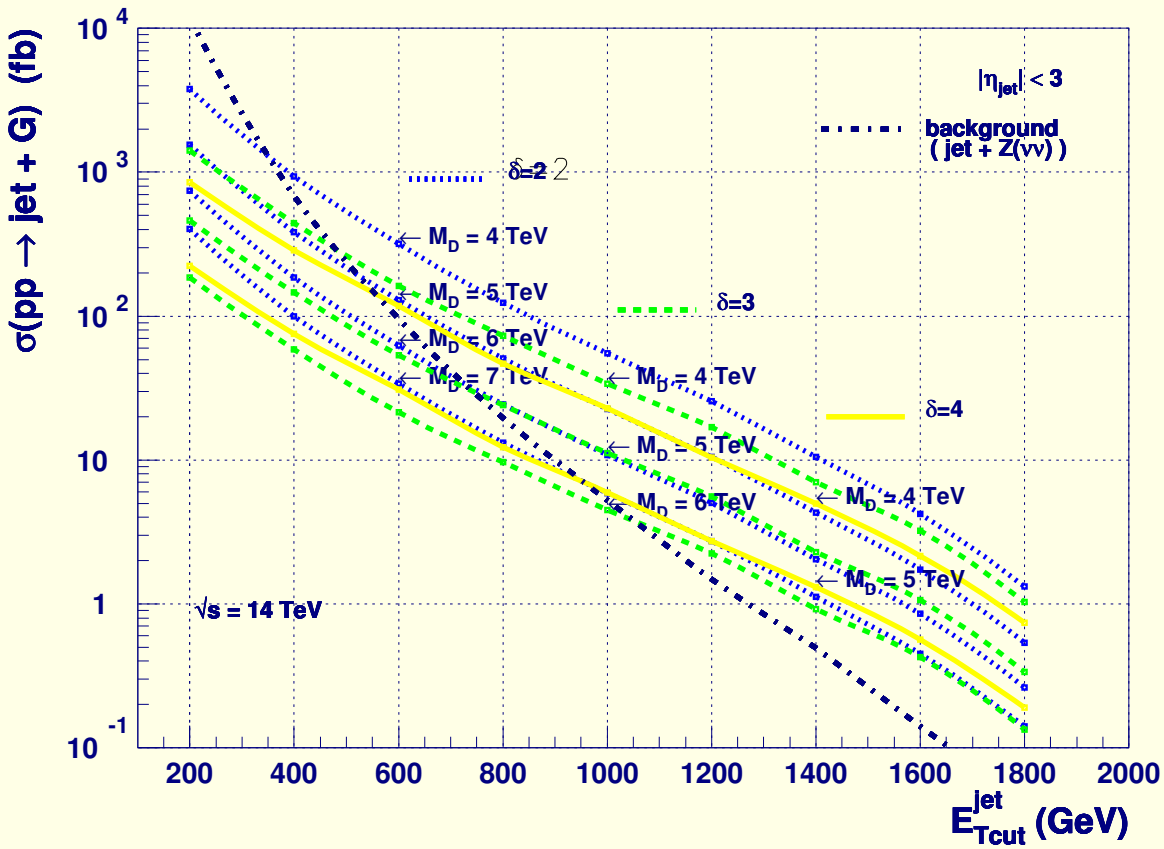
δ	M_D^{max} (TeV)
2	9
3	7
4	6

How do I know I have a signal??

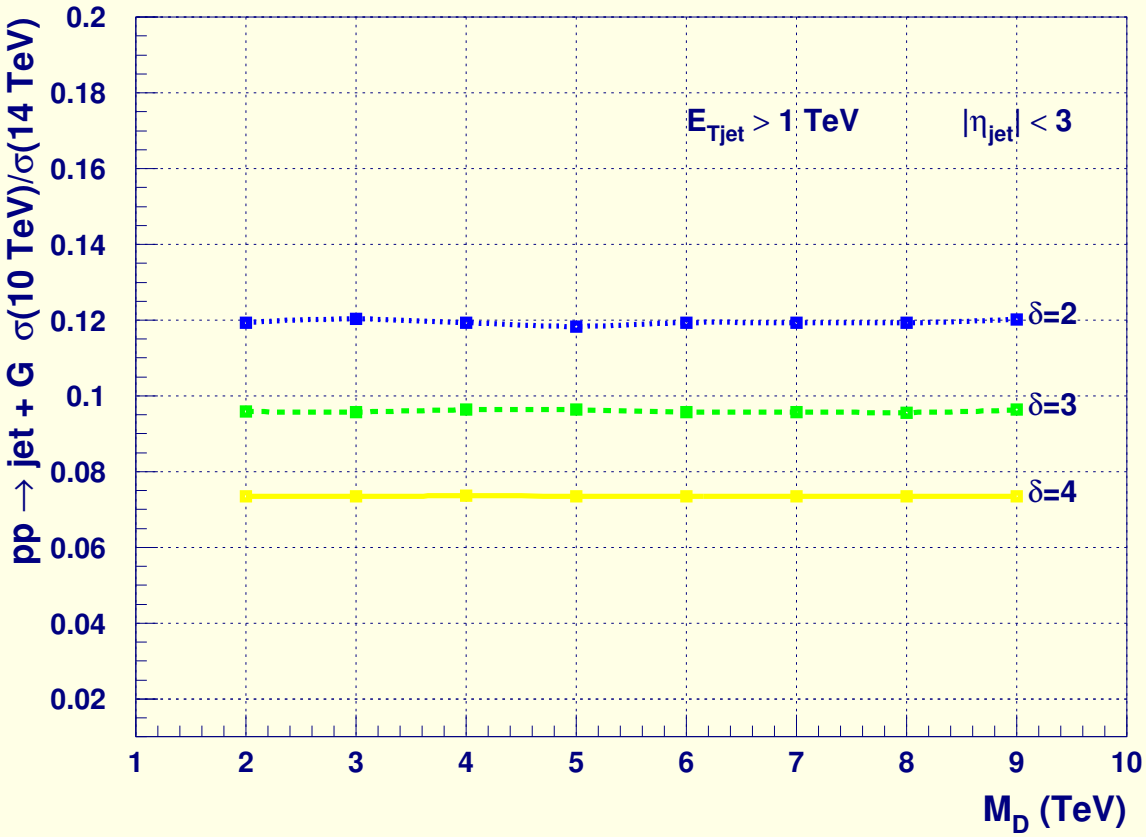
- Its a counting experiment
- Must know what to expect with no signal;
- Should be $Z(\rightarrow \nu\nu)$, $W \rightarrow \tau\nu$ $etc.$
- Measure at lower E_T
- Did I get $Z \rightarrow \mu^+\mu^-$ right?

A signal is better than a limit?

Now must measure the fundamental parameters M_D and δ
However:

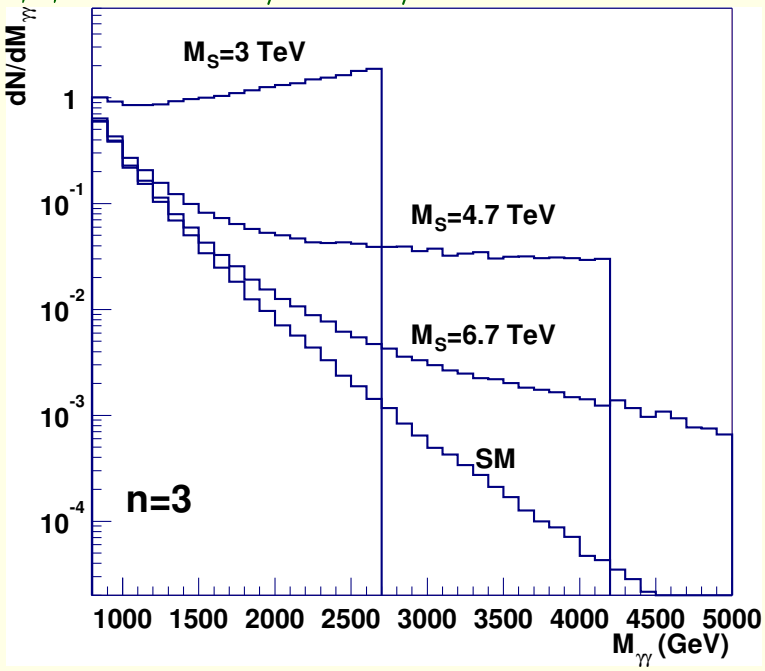


Try varying the beam energy!!


pp → jet + G σ(10 TeV)/σ(14 TeV)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
E_Tjet > 1 TeV
|η_jet| < 3
δ=2
δ=3
δ=4
1
2
3
4
5
6
7
8
9
10
M_D (TeV)

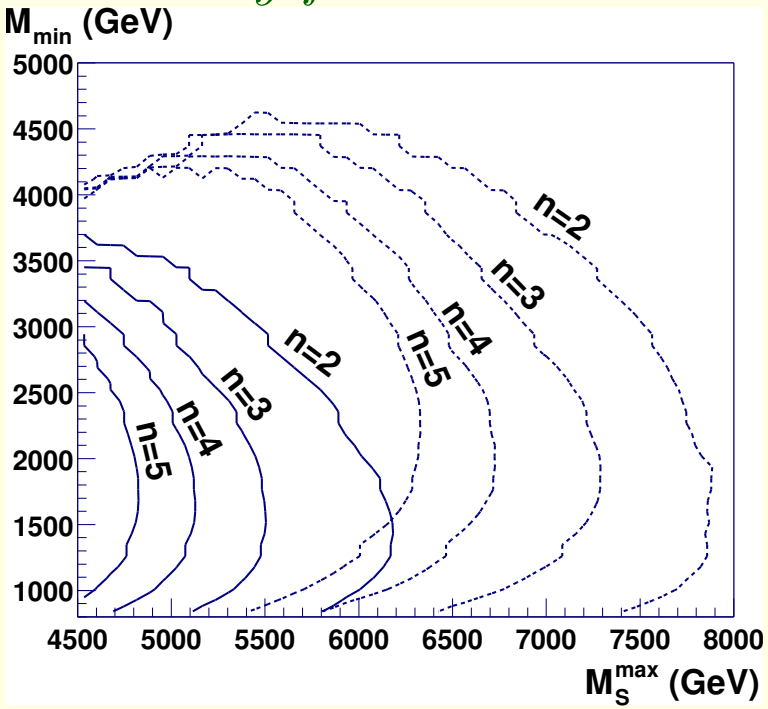
Virtual effects from graviton exchange show up as excesses in the production rates

$\gamma\gamma$ *Events/GeV/10* fb^{-1}



ATLAS

Sensitivity for 10 *and* 100 fb^{-1}



ATLAS

This is straightforward as $\gamma\gamma$ rate is well understood in QCD

Comment on indirect signals

Digression: What is pile up?

- LHC is a bunched machine with 25ns between proton bunch crossings
- More luminosity means either more bunches or more particles per bunch
- Events in a single crossing all get recorded: one is triggered, N are recorded.
- N depends on, total cross section and luminosity
- N are low p_T (minimum bias) events
- Presence compromises measurements: enter jet cones, spoil tracks, isolation *etc.*
- $N \sim 20$ at 10^{34} luminosity.

Sometimes do not get full advantage of larger rate *etc.* $H \to \gamma\gamma$

Warped Extra Dimensions – Randall Sundrum models

Model of 5-dim space with two branes of 4-dim. SM fields are stuck on one brane. Metric is "non-factorisable"

$$ds^2 = e^{-kR\phi}\eta_{\mu,\nu}dx^\mu dx^\nu + R^2 d\phi^2$$

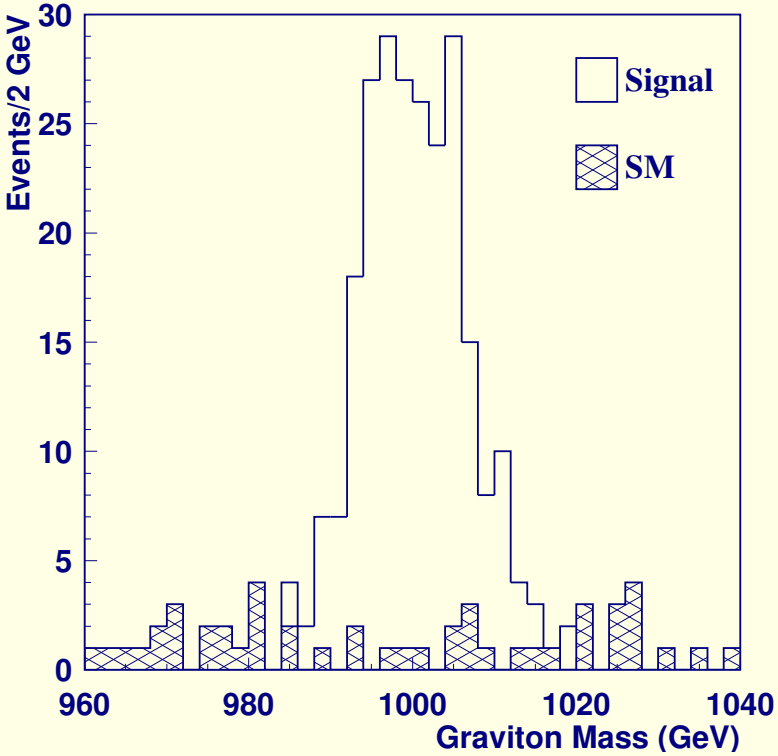
Scale $\Lambda = ke^{-kR\pi}$ in 4-D world

Can get $\Lambda \sim 1$ TeV with $Rk \sim 12$ and $k \sim M_P$

Graviton excited states have mass gaps of order Λ

Properties are determined by k/M_P.

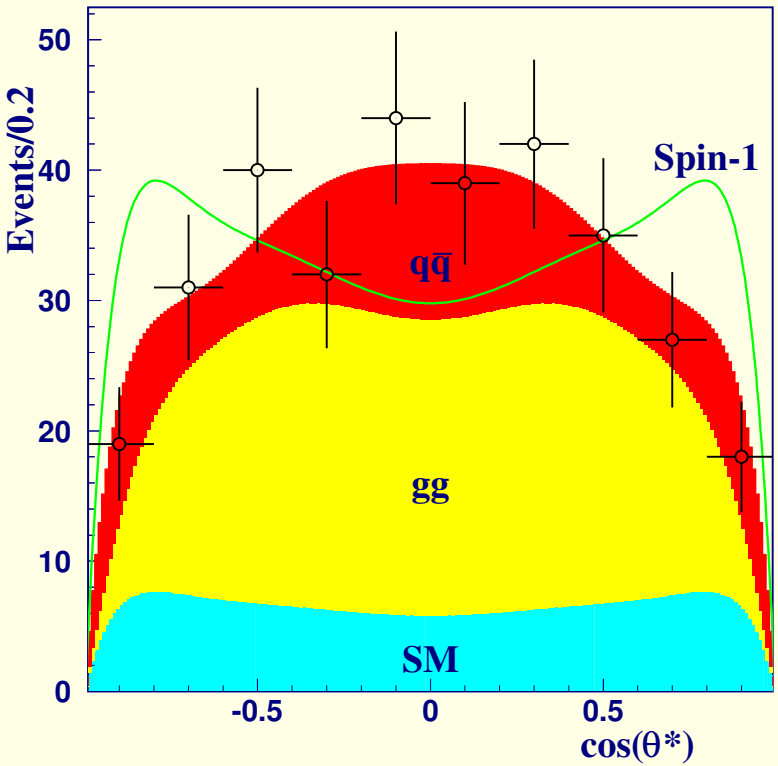
Simple models have $k/M_P \sim 0.01$; excited states are then narrow and weakly coupled



Look for a resonance in dilepton final states $e.g.\ gg \to e^+e^-$ Discovery limit is $\sim 1.8TeV$ for 100 fb^{-1}

This is the cleanest type of signal: A clear peak and a background that is well measured

Expect first LHC new physics limits/discoveries here

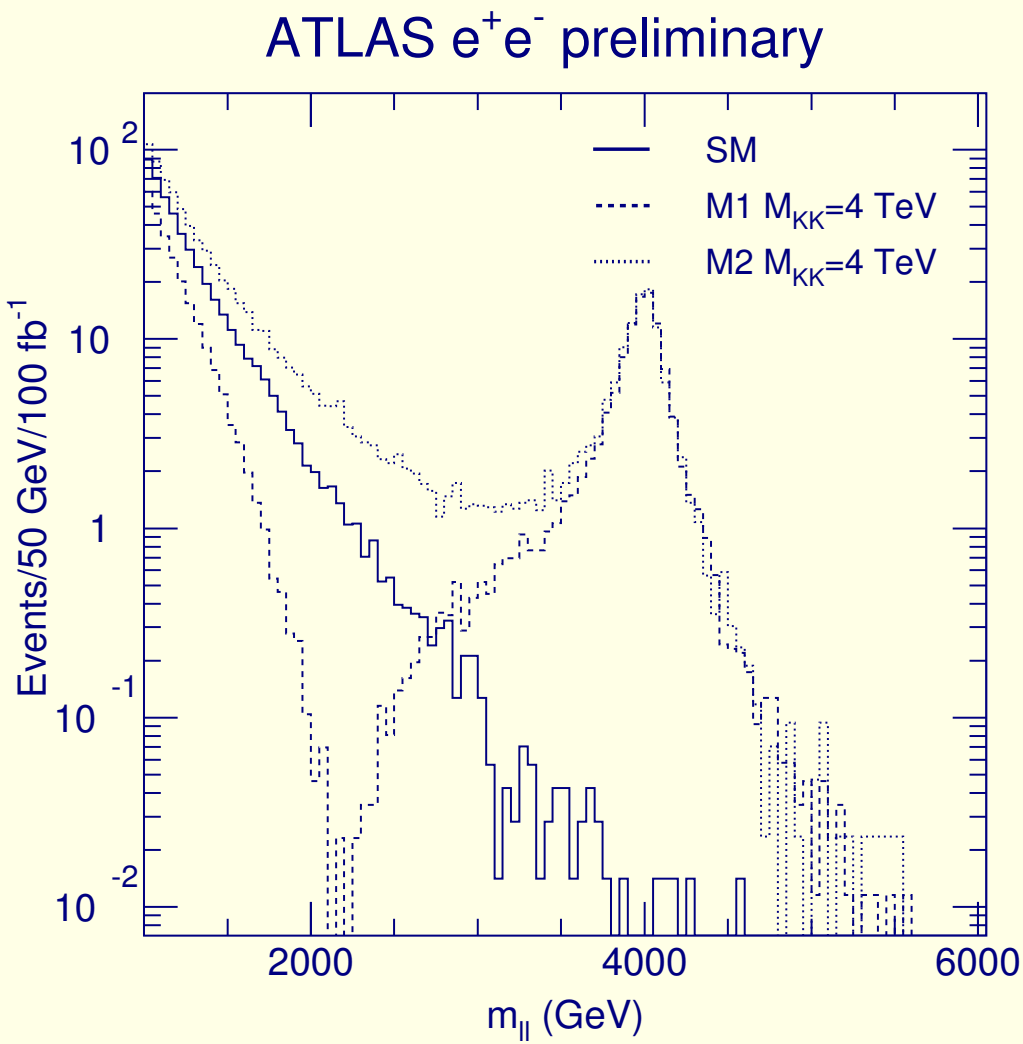


Resonance is Spin-2, confirm this by looking at lepton angular distribution

Can determine spin properties for $M < 1.4TeV$ for 100 fb^{-1}

Can also have standard model fields in extra dim.

Excitations of SM particles



Insufficient reach to see second resonance

Case Study II:Little Higgs Models

All data consistent with SM ($g-2$???)

New particles of mass $\lesssim 10\mathrm{TeV}$ are constrained EW fits, FCNC limits etc

Calculate with a cut off $\Lambda = 10TeV$

top loop $\delta m_h^2 = \frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \sim (2TeV)^2$

W/Z loops $\delta m_h^2 \sim \alpha_w\Lambda^2 \sim -(750GeV)^2$

Higgs loop $\delta m_h^2 \sim \frac{\lambda}{16\pi^2}\Lambda^2 \sim -(1.25m_h)^2$

$m_h^2 \sim (100GeV)^2$

Fine tuning of Higgs mass seems to require something else $\sim 1\mathrm{TeV}$

Most dangerous terms are top loop, Higgs loop, W/Z loops

Solve these and problem is $\gtrsim 10\mathrm{TeV}$ where we know nothing

SUSY solves it up to $\sim M_{Planck}$ by removing all quadratic divergences.

Can arrange ad-hoc cancellations by adding a few particles but need a symmetry

Little Higgs models (2)

- Models try to arrange new particles to cancel these effects
- Do this by extending the symmetries of the Standard Model so that the cancellations are forced by the new symmetries – SUSY is best example
- Need a theory with a broken global symmetry to get a massless Goldstone boson.
- Must break the symmetry "in a small way" so that this Goldstone Boson can have interactions and a VEV and play the role of the Higgs.
- Will solve the hierarchy problem; cancellations will appear as needed.
- The models are not simple (they may be "elegant") and not complete.

Arkani-Hamed, Georgi, Burdman, Schmalz, ...

LHC signals

What is the minimal stuff??

- Something to cancel the top loop.
  In the example this is T decays via $T \to Zt$, $T \to Wb$, $T \to ht$ with BR in the proportion $1:2:1$
  Ratio is test of model

- Something to deal with the W loop
  In the example this is the gauge bosons of the other $SU(2) \times U(1)$.
  Once the masses are specified their couplings have one free parameter (θ)

- Something to deal with the H loop
  In the example here this is the Higgs triplet ϕ which is produced via WW fusion

- Very small effects $< 5\%$ in $h \to gg$ and $h \to \gamma\gamma$

Masses and decays are model dependent. Higgs sector is most model dependent

Expected range of masses

- Fine tuning means that $f = \frac{\Lambda}{4\pi} < 1TeV(\frac{m_H}{200GeV})^2$
- $m_T < 2TeV(\frac{m_H}{200GeV})^2$
- $M_{W_H} < 6TeV(\frac{m_H}{200GeV})^2$
- $m_\phi < 10TeV$

New Quark

Properties determined by two parameters λ_1/λ_2 and mass.

Two production mechanisms $qb \to q'T$ and $gg \to T\overline{T}$: Former depends on $t - T$ mixing and therefore on λ_1/λ_2

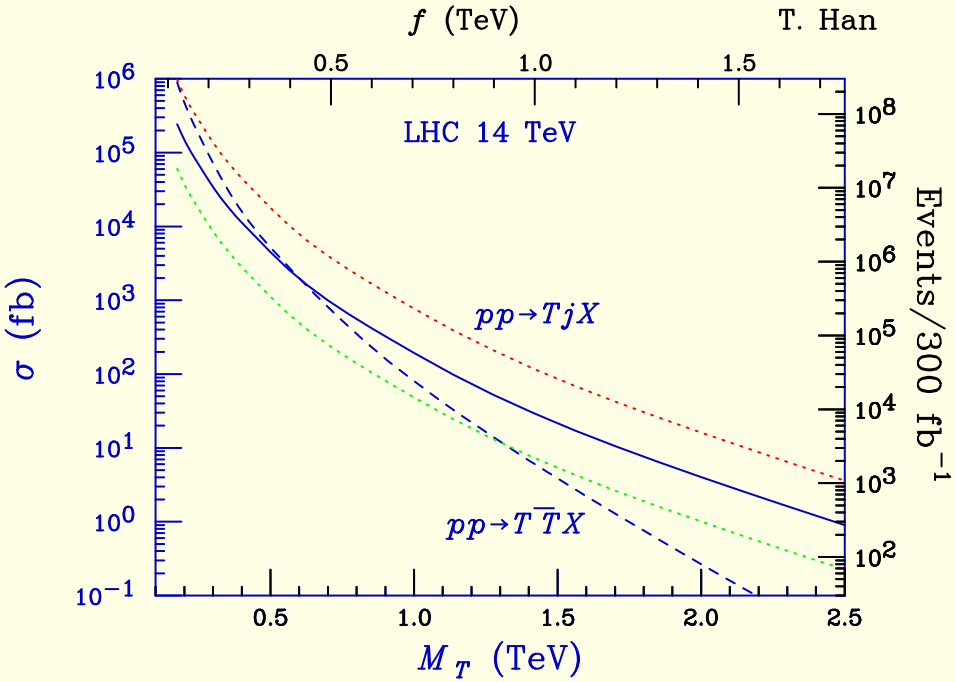


Figure from Han

Single production dominates at large masses

Three single production curves are for $\lambda_1/\lambda_2 = 2, 1, 0.5$

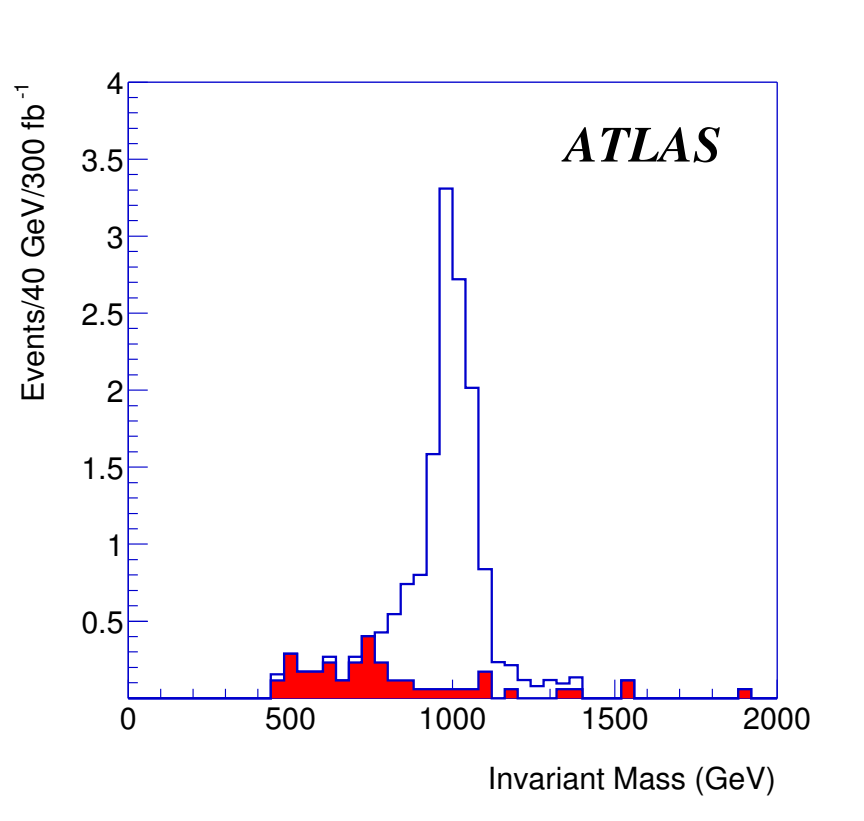
Width is small

Single Production is used in the following: note recoil jet.

$T \to Zt$

Reconstruct from $Z \to \ell^+\ell^-$ and $t \to b\ell\nu$

Three isolated leptons (either e or μ) with $p_T >$ 40 GeV and $\mid \eta \mid < 2.5$ one of which has $p_T >$ 100 GeV
No other leptons with $p_T >$ 15 GeV
One pair of leptons within 10 GeV of Z mass.
$\not{E}_T > 100$ GeV
At least one tagged $b-$ jet with $p_T >$ 30 GeV

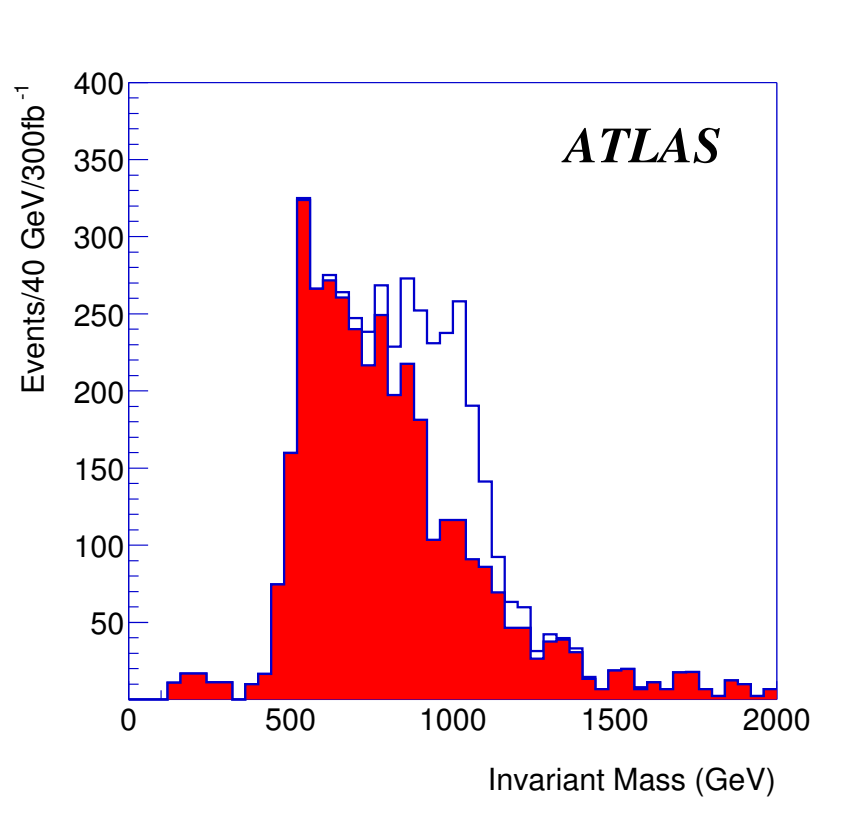


Background is dominated by tbZ

$T \to Wb$

Reconstruct from $T \to b\ell\nu$

One isolated lepton (either e or μ) with $p_T >$100 GeV and $\mid \eta \mid < 2.5$
No other leptons with $p_T >$ 15 GeV No more than 2 jets with $p_T >$ 50 GeV and $M(j1, j2) > 200$ GeV
$\not{E}_T > 100$ GeV
at least one tagged $b-$ jet with $p_T >$ 200 GeV

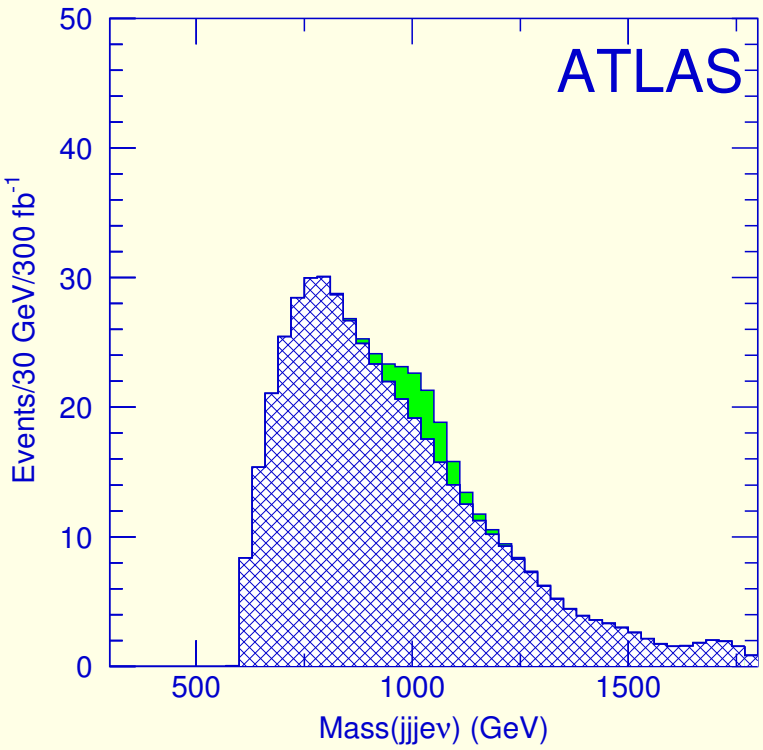


Background is dominated by $t\bar{t}$

$T \to ht$

Reconstruct from $h \to b\bar{b}$ and $t \to b\ell\nu$

One isolated e or μ with $p_T > 100$ GeV and $|\eta| < 2.5$.
Three jets with $p_T > 130$ GeV.
Four jets with $p_T > 15$ GeV.
At least one jet tagged as a $b-$jet
Mass of dijet system within 20 GeV of Higgs mass (assumed to be 120 GeV)



Background dominated by $t\bar{t}$

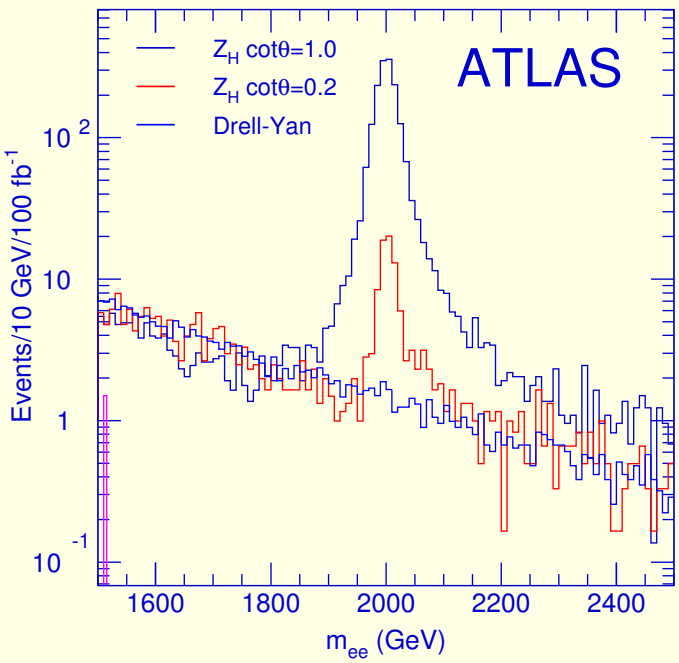
New Bosons

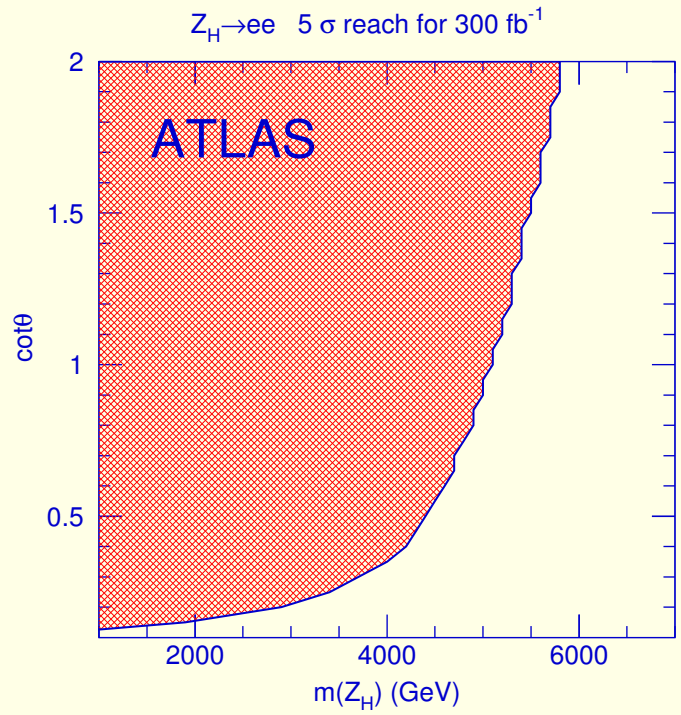
Expect two neutral and two charged: $Z_H, A_H, W_H^{\pm}$
Model has two additional couplings corresponding to the extra $SU(2) \times U(1)$,

Bosons will be discovered via leptonic decays **But critical test is cascades such as** $Z_H \to Zh$

New Bosons – Leptonic decays

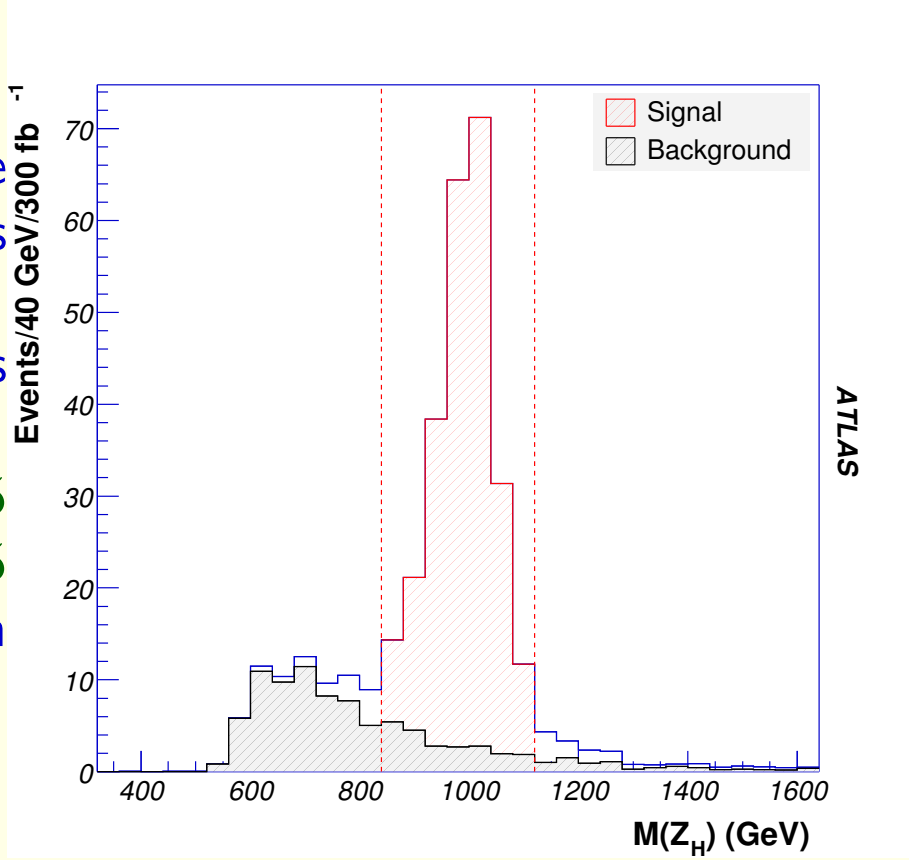
Clear signal over Drell-Yan background. Plot shows 2 TeV mass for Z_H





New Bosons – Cascade decay $Z_H \to Zh \to \ell^+\ell^- b\bar{b}$

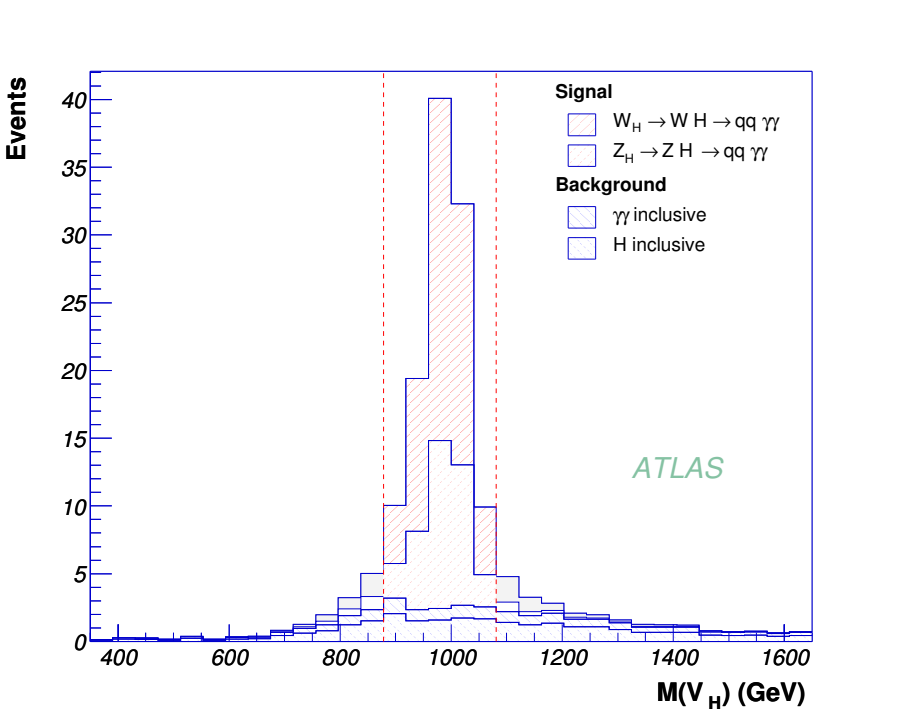
Two leptons of opposite charge and same flavor with $p_T > 6(5)$ GeV for muons (electrons) and $\mid \eta \mid < 2.5$
The lepton pair should have a mass between 76 and 116 GeV
Two reconstructed $b - jets$ with $p_T > 25$ and $\mid \eta \mid < 2.5$, which are within $\Delta R < 1.5$
The $b-jet$ pair should have a mass between 60 and 180 GeV



$Z_H \to Zh$, $h \to \gamma\gamma$

Must use all hadronic mode of Z: Cannot distinguish W_H from Z_H

Two isolated photons one having $p_T(1) >$ 25 GeV, $p_T(2) > 40$ GeV.
$M(\gamma\gamma) = m_h \pm 2\sigma$
The jet pair with invariant mass closest to M_W is selected.
Pair has a combined $p_T > 200$ GeV



Can also extract signal via Jacobian peak in the P_T dist of Higgs

Extra Higgs

ϕ^{++} produced by WW fusion: So must use the forward tagging jets

Two reconstructed positively charged isolated leptons (electrons or muons) with $|\eta| < 2.5$

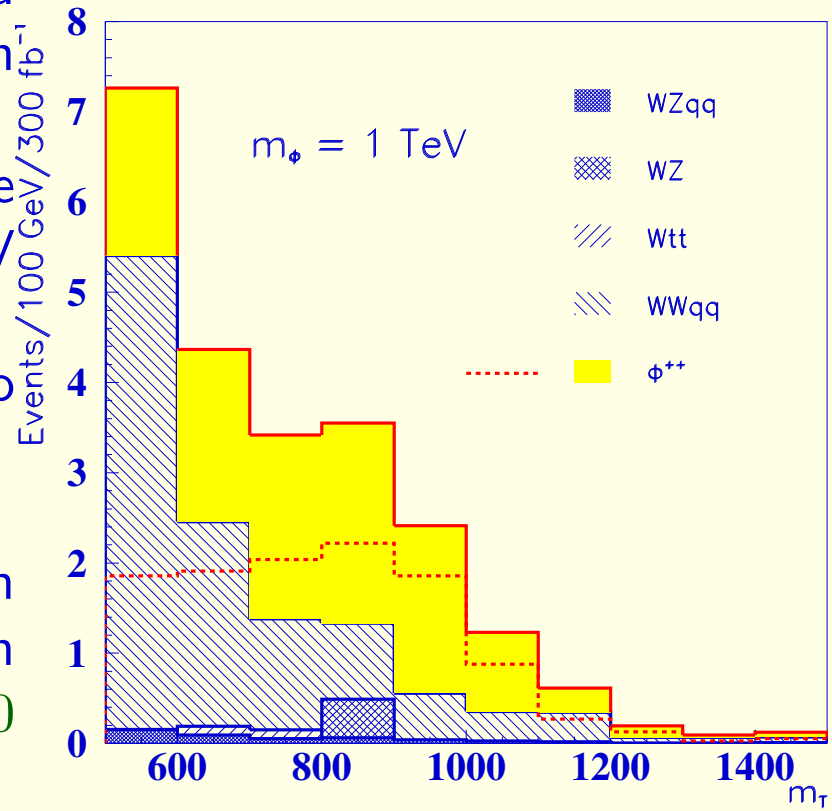
One of the leptons was required to have $p_T > 150$ GeV and the other $p_T > 20$ GeV

$|p_{T1} - p_{Ts}| > 200$ GeV

the difference in pseudorapidity of the two leptons $|\eta_1 - \eta_2| < 2$.

$\not{E}_T > 50$ GeV

Two jets each with $p_T > 15$ GeV, with rapidities of opposite sign, separated in rapidity $|\eta_1 - \eta_2| > 5$; one jet has $E > 200$ GeV and the other $E > 100$ GeV



Summary of sensitivity

- T Observable in both $h(120)t$ (up to mass of 1.2 TeV) and Zt (up to mass 1.0 TeV): Wb is observable up to 1.3 TeV for $\lambda_1/\lambda_2 = 1$

- Z_H observable in e^+e^- to mass of 4.5 TeV for $\cot\theta = 0.5$
  $Z_H \to Zh(120) \to Zb\bar{b}$ observable for mass up to 2 TeV
  $Z_H \to Zh(120) \to Z\gamma\gamma$ observable for masses up to 1.1 TeV

- ϕ^{++} may be observable in W^+W^+ at 1.5 TeV

- More work needed for $m_h \gtrsim 150$ GeV

LHC finds it or motivation disappears