Selected Topics in

LHC Phenomenology

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THE UNIVERSITY of MANCHESTER

IoP "Particle Physics 2004", Birmingham, April 2004

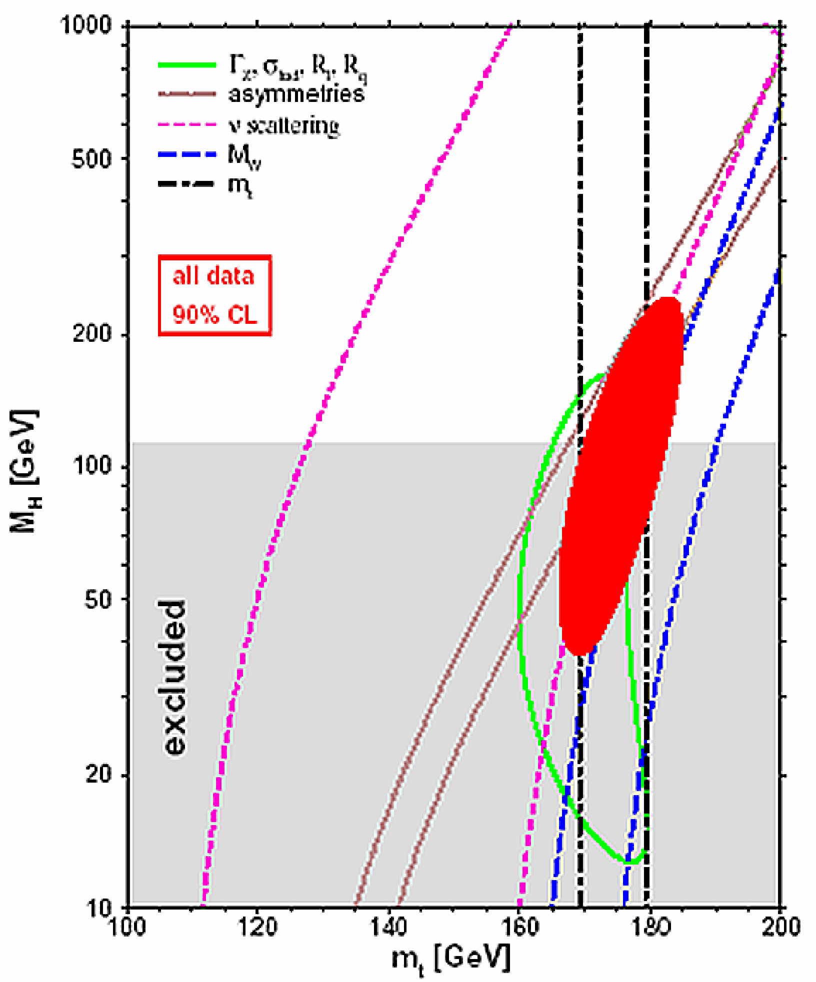
- ✓ Electroweak symmetry breaking
  Fine tuning: SUSY, Little Higgs and Extra Dimensions
- ✓ Heavy Higgs
  Triplet Higgs: a simple “no light Higgs” scenario
- ✓ Standard Model Higgs
  Discovery potential at LHC
- ✓ Very Light Higgs
  MSSM with explicit CP violation. Tagged protons at LHC.
- ✓ Invisible Higgs
- ✓ No Higgs
  WW scattering

In collaboration with Douglas Ross (Southampton), Agustin Sabio-Vera (Hamburg), Ben White (Manchester), Jon Butterworth (UCL), Brian Cox (Manchester), Jae Sik Lee (Manchester), James Monk (Manchester), Apostolos Pilaftsis (Manchester).

Precise data (0.1%) from LEP, SLC and Tevatron imply a light Higgs boson when interpreted within the Standard Model

$$m_h = 81^{+52}_{-33}\ \mathrm{GeV}$$

See lepewwg.web.cern.ch



Similar conclusions in minimal SUSY extensions, i.e. < 135 GeV

More generally…

- ✓ **There is a light Higgs boson**

  Supported by precision data from LEP & Tevatron. However to avoid fine tuning one would wish to invoke NEW physics below ~1 TeV. This new physics should not disturb the good agreement with the precision data.
  Candidates: supersymmetry, extra dimensions, Little Higgs…

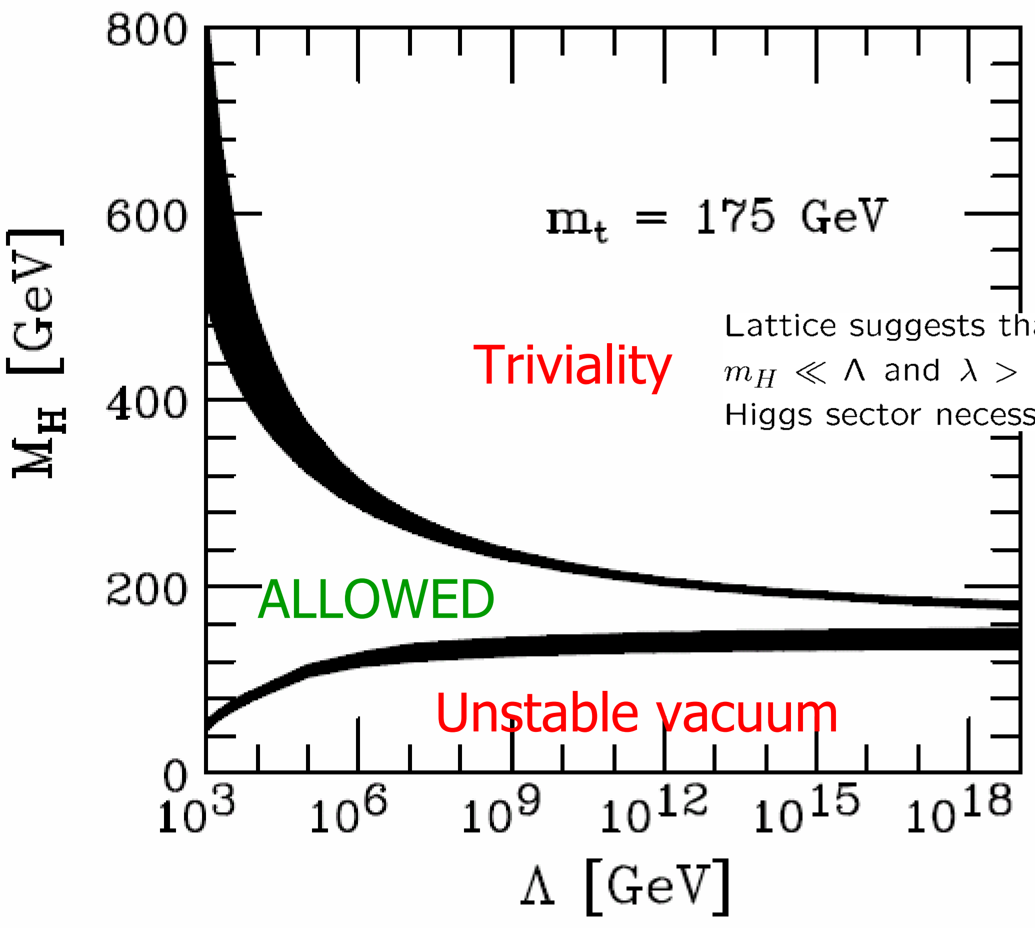
$$\begin{aligned} \delta m^2_{\text{top}} &\sim \lambda_t^2 \Lambda^2 \sim (200\ \text{GeV})^2 \\ \delta m^2_{\text{gauge}} &\sim g^2 \Lambda^2 \sim -(75\text{GeV})^2 \qquad \Lambda = 1\text{TeV} \\ \delta m^2_{\text{higgs}} &\sim \lambda\, \Lambda^2 \sim -(m_H/8)^2 \end{aligned}$$

- ✓ **There is a heavy Higgs boson**

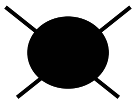
  Need NEW physics in order to explain the precision data.
  Triviality implies new physics too.

- ✓ **There is no Higgs boson**

  Need NEW physics in order to explain the precision data, electroweak symmetry breaking and since the Standard Model without a Higgs is not renormalizable. W bosons become strongly interacting at 1.2 TeV unless the new physics enters below this scale.
  Candidates: new strong interaction theories (technicolor, extra dimensions…)

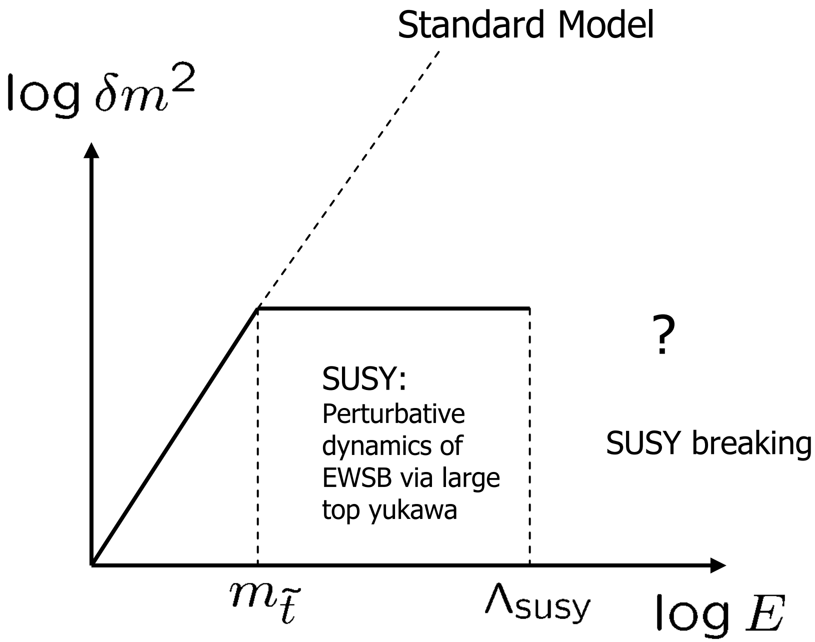


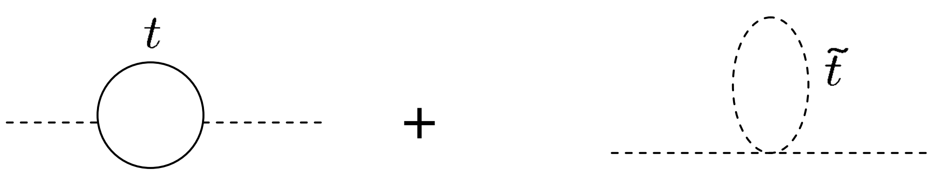
Lattice suggests that there is no region where $m_H \ll \Lambda$ and $\lambda > 1$, i.e. a strongly coupled Higgs sector necessarily involves new physics.

 $\sim \lambda$

Hambye & Riesselmann

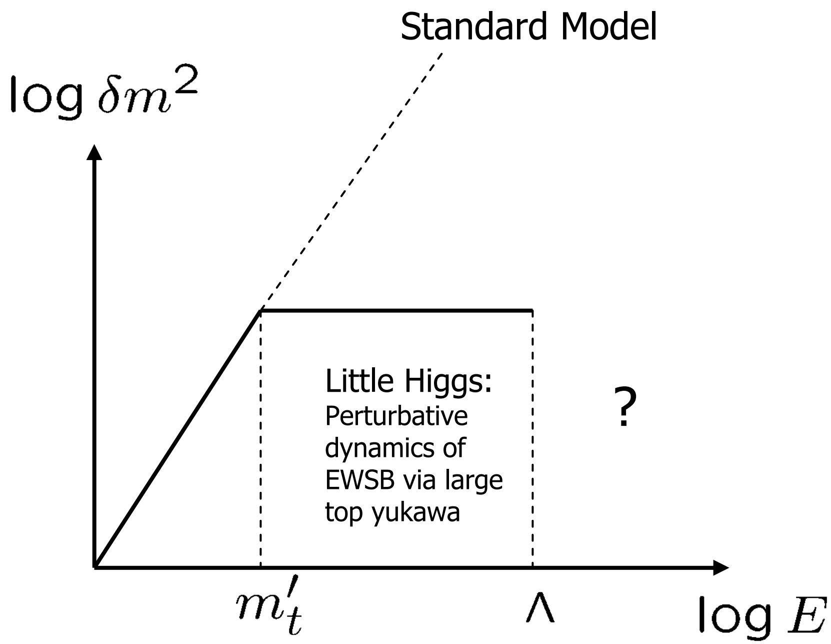
Avoiding fine tuning using supersymmetry





$\delta m^2 \sim E^2$ $\qquad$ $\delta m^2 \sim -E^2 + \log E$

[Similar cancellations for gauge boson and Higgs loops]



Avoiding fine tuning using the idea of the Higgs as a pseudo-Goldstone boson

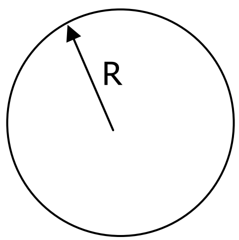
Higgs would be a Goldstone boson under two (or more) global symmetry groups. Gauge interactions break these symmetries and radiatively generate a Higgs mass. But no single gauge interaction breaks both global symmetries. This ensures that there are no $\sim \Lambda^2$ terms in δm^2 at one-loop.

"Big Higgs"?!

Minimal approach "Littlest Higgs" contains no new particles below ~1 TeV. Beyond 1 TeV, there is a heavy fermion (to cancel the top loops), new W′, Z′ & A′ (cancel gauge boson loops) and a complex scalar triplet (cancel Higgs loops).

[Arkani-Hamed, Cohen, Katz, Nelson]

Extra dimensional view of little Higgs concept



Imagine a 5-dimensional gauge theory compactified on a circle

The component of the gauge field in the 5th dimension looks like a scalar field in the 4D effective theory which manifests itself at energies E << 1/R.

5D gauge invariance implies that this scalar field is massless.

But dynamics in the 5D theory can generate an effective mass in the 4D theory

$$|\mathrm{Tr}(W)|^2 \quad \text{where} \quad W = \mathrm{P}\exp(i \int dx_5 A_5)$$

Wilson line is non-local in 5D theory but can appear in 4D Lagrangian

To build the Standard Model this way requires more work, e.g. need to get the scalar field into the fundamental representation…

Gauge Theories on an interval

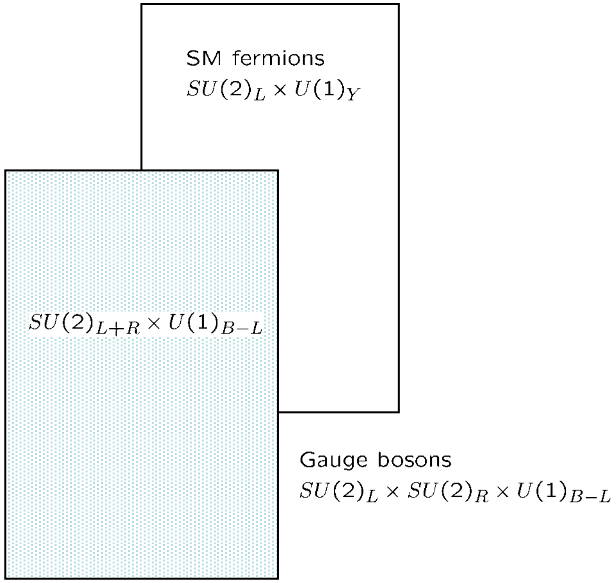
Avoiding fine tuning by abolishing the Higgs

Imagine a 5D gauge theory on a finite interval. One can explicitly break the gauge invariance of the action by one's choice of boundary conditions.

The low energy 4D theory typically looks like a theory with new strong interactions at the TeV scale. Challenge is to still fit the precision data.

Alternatively one can leave the Higgs in the theory but avoid the fine tuning problem by making it heavy.

Typically now have excitations in the extra dimension, e.g. W',Z', t', H'…

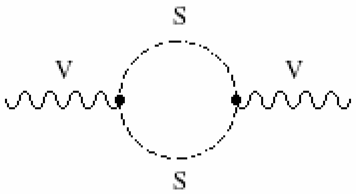


Csaki, Grojean, Murayama, Pilo, Terning; Barbieri, Pomarol, Rattazzi

Real Triplet : a simple model which has no light Higgs

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{1}{\sqrt{2}}(v + \phi_R^0 + i\phi_I^0) \end{pmatrix}, \qquad H = \begin{pmatrix} \eta^+ \\ \frac{1}{2} v t_\beta + \eta^0 \\ -\eta^- \end{pmatrix}.$$

$$\Pi_{\mu\nu}(q) \equiv g_{\mu\nu}\Pi(q^2) + \cdots \quad =$$



$$+ \quad \cdots$$

$$\Delta\Pi(m) \equiv \Pi(m^2) - \Pi(0)$$

$$\begin{aligned}
\alpha S &= \frac{4 s_W^2 c_W^2}{m_Z^2}\left(\Delta\Pi^{ZZ}(m_Z) - \frac{c_W^2 - s_W^2}{s_W c_W}\Delta\Pi^{\gamma Z}(m_Z) - \Delta\Pi^{\gamma\gamma}(m_Z)\right) \\
\alpha T &= \frac{1}{m_W^2}\left(\Pi^{WW}(0) - c_W^2\,\Pi^{ZZ}(0)\right), \\
\alpha(S+U) &= 4 s_W^2\left(\frac{\Delta\Pi^{WW}(m_W)}{m_W^2} - \frac{c_W}{s_W}\frac{\Delta\Pi^{\gamma Z}(m_Z)}{m_Z^2} - \frac{\Delta\Pi^{\gamma\gamma}(m_Z)}{m_Z^2}\right),
\end{aligned}$$

[Lynn & Nardi; Blank & Hollik; JF, D.Ross, White]

Quantum corrections are naturally small and <u>tree level</u> corrections are interesting:

- Direct correction to W mass since

$$M_W^2 \approx M_Z^2 \cos^2\theta_W \,(1+\beta^2)$$

- Indirect correction to *all* observables since

$$G_F \approx G_F^{SM}\,(1-\beta^2)$$

tree level $= \beta^2$

$$\sigma \approx \sigma_{SM}(m_h) + A_{SM}\alpha S_{TM}(m_k, m_\pm) + B_{SM}(\alpha T_{TM}(m_k, m_\pm) + \delta_{\text{tree}}) + C_{SM}\alpha U_{TM}(m_k, m_\pm)$$

For SM contribution

Use **ZFITTER**:
13 observables

$G_F = 1.6639 \times 10^{-5}$ GeV^{-2}

$\alpha_s = 0.119$

		Measurement with Total Error	Systematic Error	Standard Model fit	Pull
	$\Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2)$ [190, 191]	0.02804 ± 0.00065	0.00064	0.02804	0.0
a)	LEP				
	line-shape and lepton asymmetries:				
	m_Z [GeV]	91.1875 ± 0.0021	$^{(a)}0.0017$	91.1874	0.0
	Γ_Z [GeV]	2.4952 ± 0.0023	$^{(a)}0.0012$	2.4962	-0.4
	σ^0_{h} [nb]	41.540 ± 0.037	$^{(b)}0.028$	41.480	1.6
	R_ℓ	20.767 ± 0.025	$^{(b)}0.007$	20.740	1.1
	$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010	$^{(b)}0.0003$	0.0164	0.8
	+ correlation matrix Table 3				
	τ polarisation:				
	$\mathcal{A}_\tau$	0.1439 ± 0.0042	0.0026	0.1480	-1.0
	$\mathcal{A}_{\mathrm{e}}$	0.1498 ± 0.0048	0.0009	0.1480	0.4
	$\mathrm{q\overline{q}}$ charge asymmetry:				
	$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ ($\langle Q_{\mathrm{FB}}\rangle$)	0.2321 ± 0.0010	0.0008	0.23140	0.7
	m_W [GeV]	80.427 ± 0.046	0.035	80.402	0.5
b)	SLD [177]				
	$\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$ ($\mathcal{A}_\ell$)	0.23098 ± 0.00026	0.00018	0.23140	-1.6
c)	LEP and SLD Heavy Flavour				
	R^0_{b}	0.21653 ± 0.00069	0.00053	0.21578	1.1
	R^0_{c}	0.1709 ± 0.0034	0.0022	0.1723	-0.4
	$A^{0,\mathrm{b}}_{\mathrm{FB}}$	0.0990 ± 0.0020	0.0009	0.1038	-2.4
	$A^{0,\mathrm{c}}_{\mathrm{FB}}$	0.0689 ± 0.0035	0.0017	0.0742	-1.5
	$\mathcal{A}_{\mathrm{b}}$	0.922 ± 0.023	0.016	0.935	-0.6
	$\mathcal{A}_{\mathrm{c}}$	0.631 ± 0.026	0.016	0.668	-1.4
	+ correlation matrix Table 10				
d)	$\mathrm{p\overline{p}}$ and νN				
	m_W [GeV] ($\mathrm{p\overline{p}}$ [183])	80.452 ± 0.062	0.050	80.402	0.8
	$1 - m_W^2/m_Z^2$ (νN [187, 188])	0.2255 ± 0.0021	0.0010	0.2226	1.2
	m_t [GeV] ($\mathrm{p\overline{p}}$ [186])	174.3 ± 5.1	4.0	174.3	0.0

Tree Level: $\Delta T > 0 \quad \Delta S = 0$

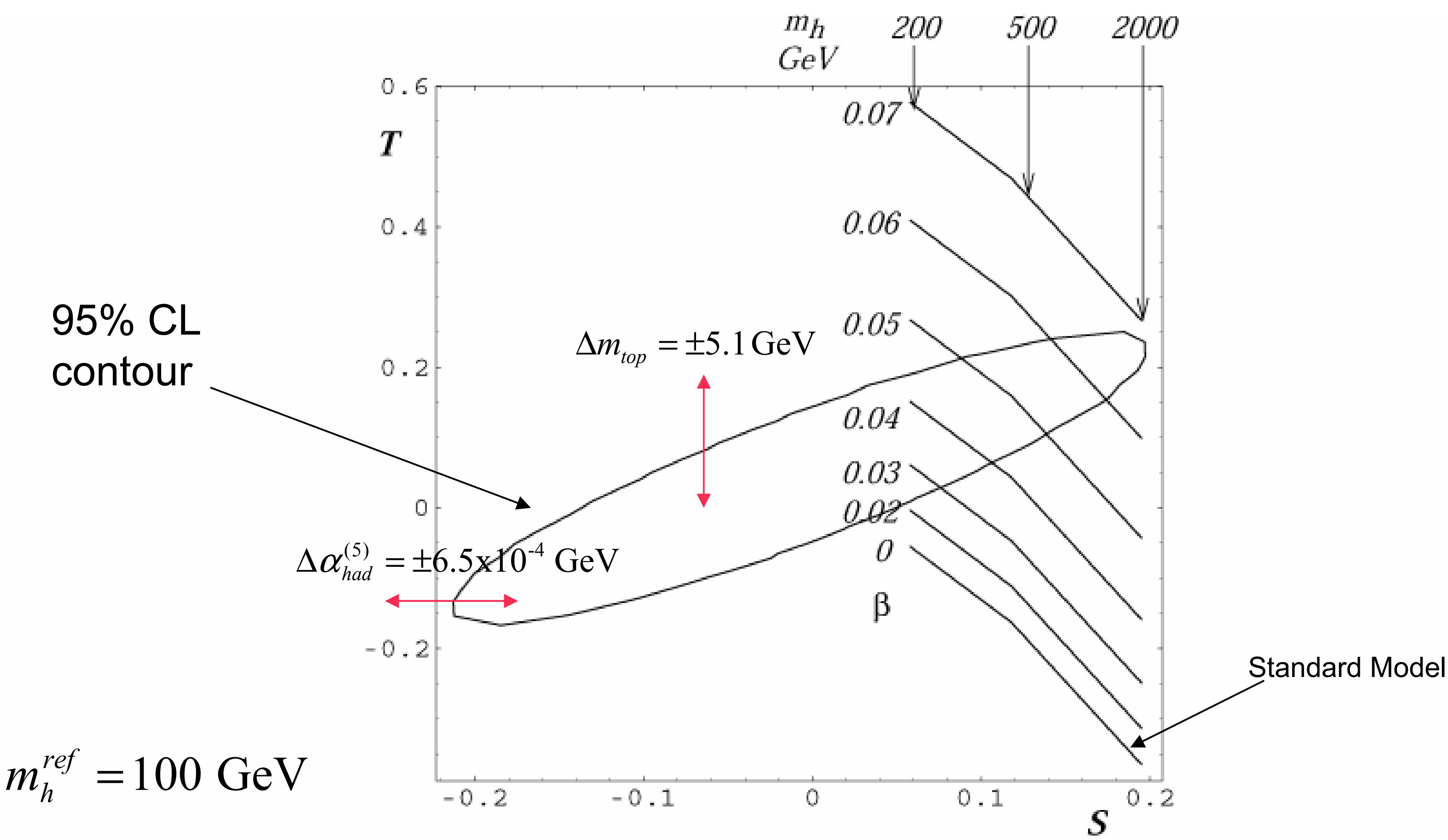


Figure 1: Ellipse encloses the region allowed by data. Curves show results in the TM for various values of β and various doublet Higgs masses. $\Delta m = 0$ and $U = 0$ in this plot.

Lightest Higgs can have mass up to strong dynamics scale (500 GeV) without *any* other consequences.

[No problems with fermion masses…]

There are other ways to accommodate a heavier higgs boson:

- $S < 0$

  extra SU(2)xSU(2) multiplets [Dugan & Randall]

  new singlet majorana fermions [Gates & Terning]

- $T > 0$

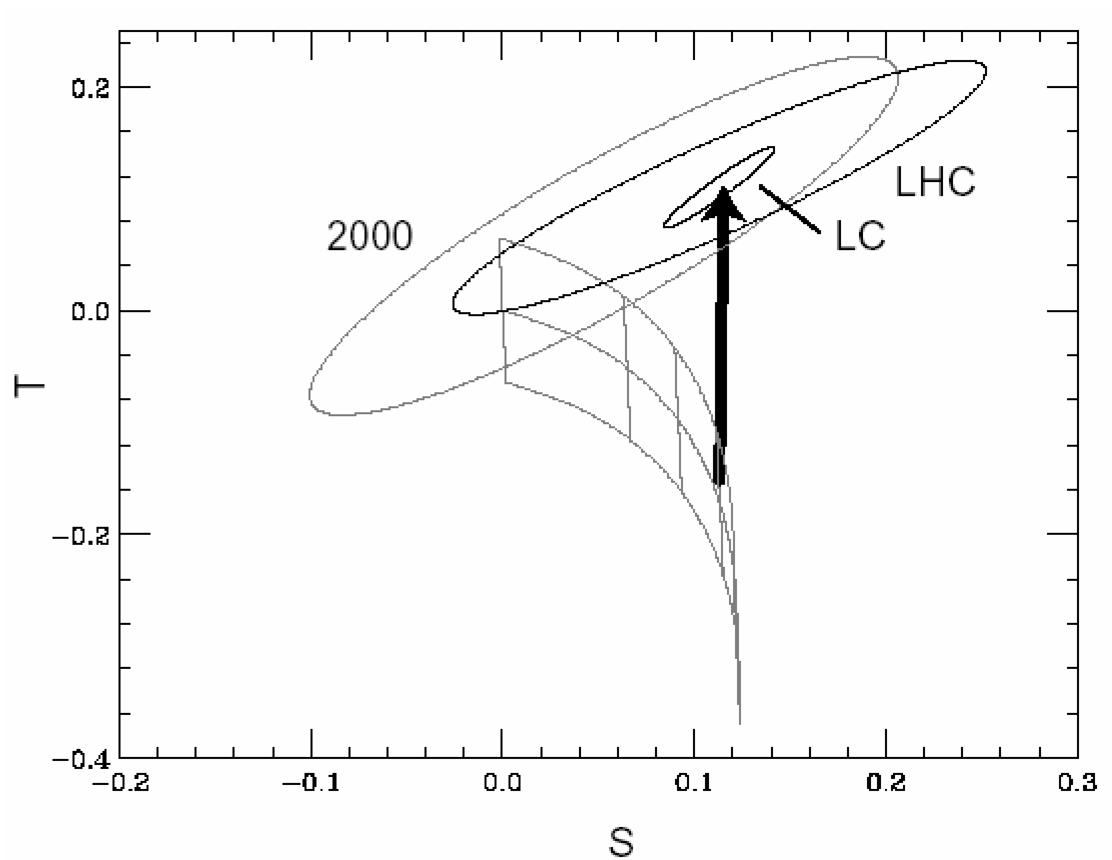
  4^{th} generation [e.g. Dobrescu & Hill]

  2 Higgs doublets [Chankowski et al]

- New vector bosons [e.g. Casalbuoni et al, extra dimensions]

  would be seen at LHC

If NO new particles at LHC/FLC then the crucial information could come from even more precise electroweak measurements: GigaZ (~1 month of linear collider) and/or $\delta M_W \approx 15\,\mathrm{MeV}$ (LHC).



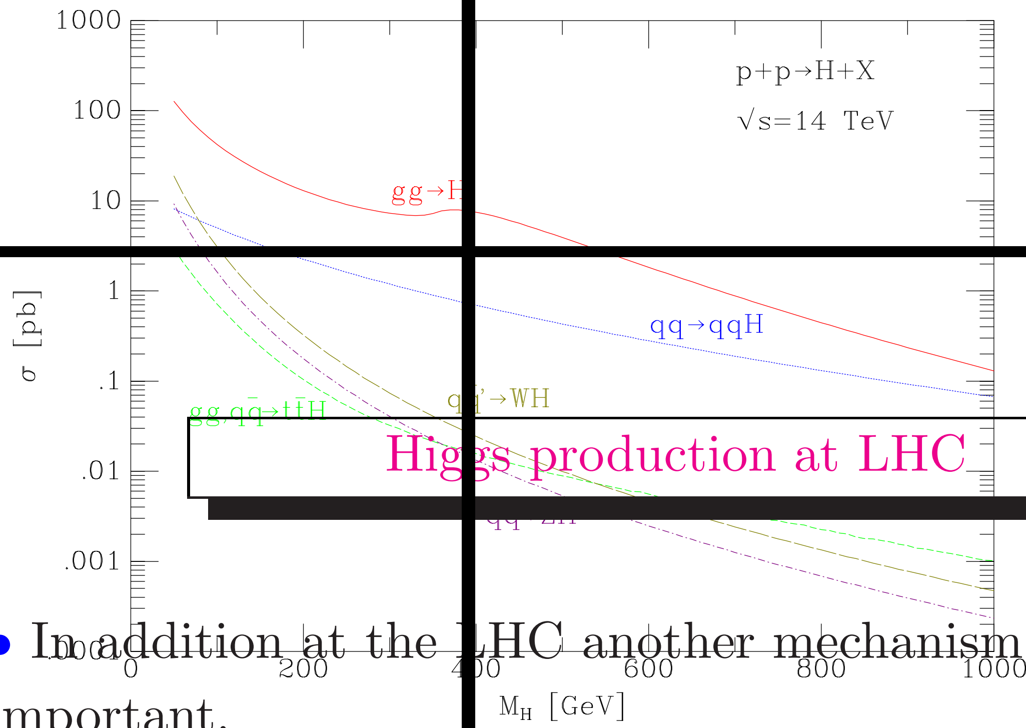
[Figure from Peskin & Wells]

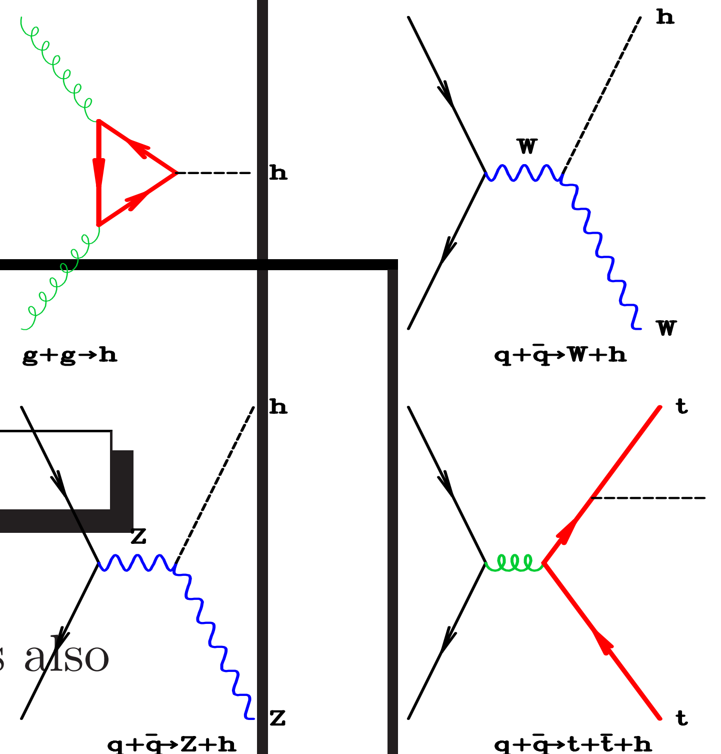
r boson fusion $qq \to Hqq$

acteristic signature - forward jets.

Standard Model Higgs production at LHC

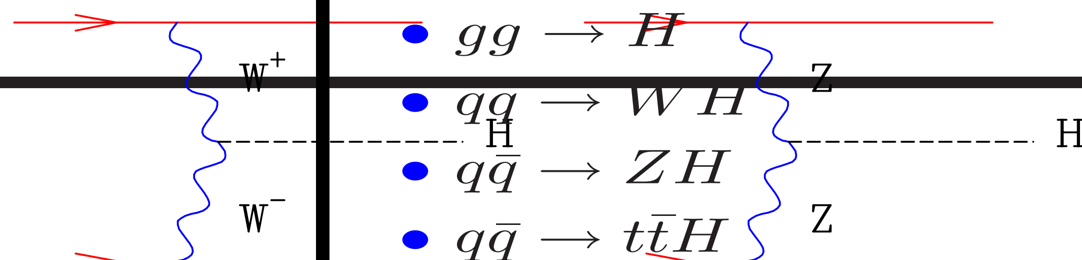
Higgs production mechanisms Teva





Higgs production at LHC

- In addition at the LHC another mechanism is also important.

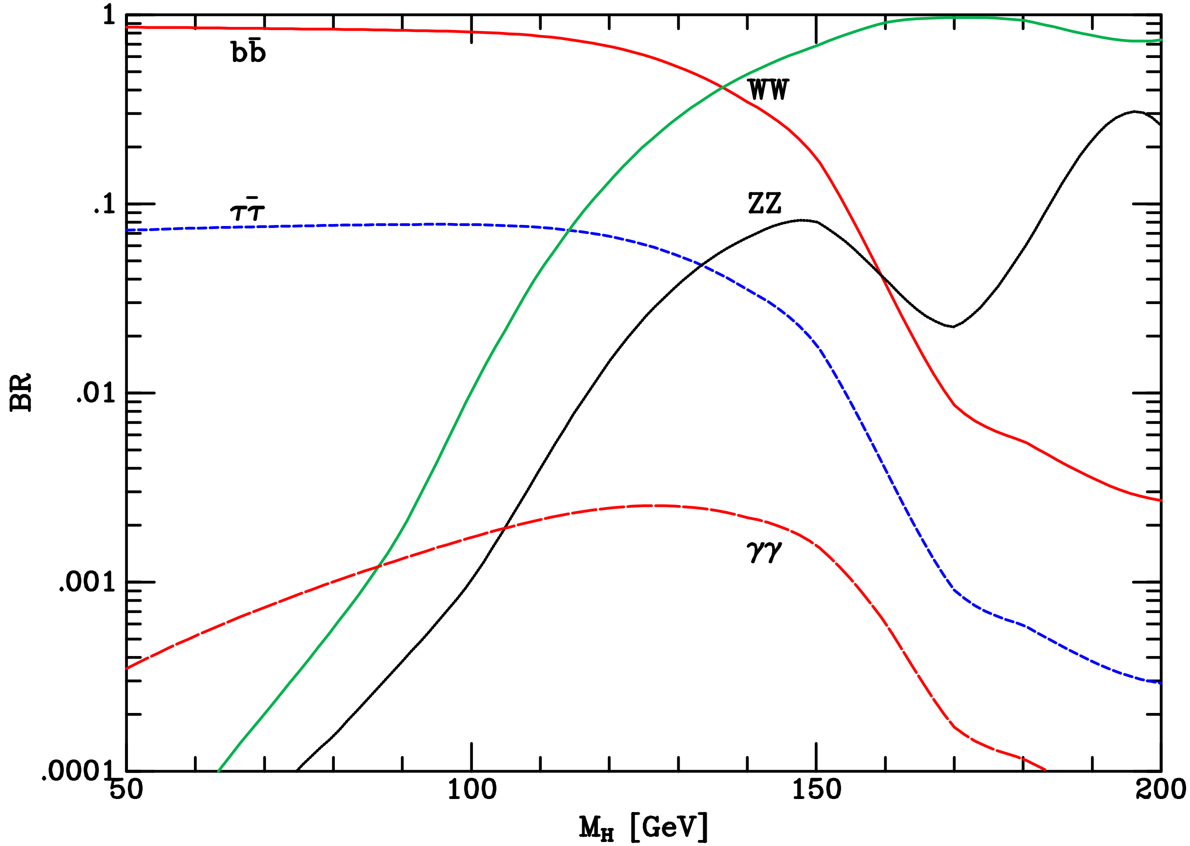


- $gg \to H$
- $qq \to WH$
- $q\bar{q} \to ZH$
- $q\bar{q} \to t\bar{t}H$

- Vector boson fusion $qq \to Hqq$
- Characteristic signature - forward jets.

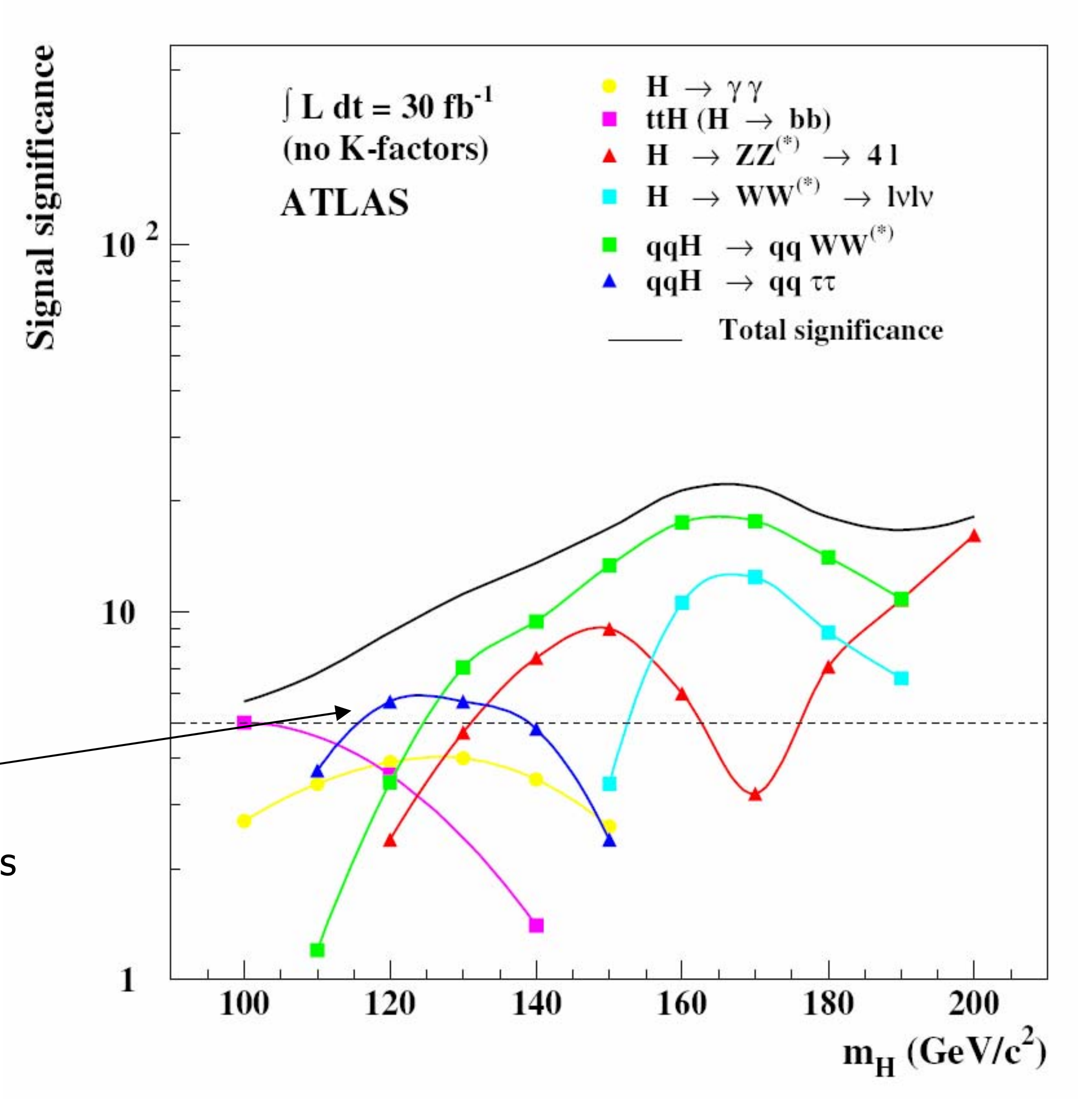
from Keith Ellis

Higgs decay Branching ratios



- $m_h \leq 135,\ H \to b\bar{b}$
- $m_h \geq 135,\ H \to WW^*$

Discovery potential for a SM Higgs



Note new role of VBF for "low" mass Higgs

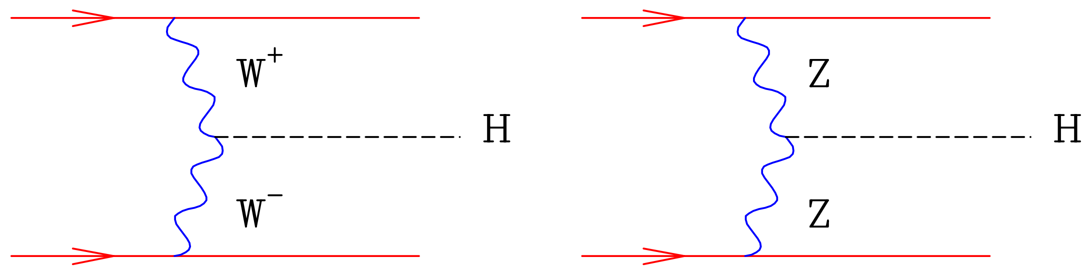
e.g. see LHC Higgs working Group meetings
(Cranmer, Mellado, Quayle,Wu et al: 5σ in each of dilepton and l+jet channels and room for improvement!)

Is it possible to improve even more in the < 140 GeV region?

✓ De Roeck, Khoze, Martin and Ryskin propose to sidestep pileup even at high luminosity by using tracking information. Could then allow to use H->bb decay channel. Identify primary vertex and cut on tracks emanating from there, e.g. no tracks above some threshold ~1 GeV between tag jets and b-jets.

Higgs production at LHC

- In addition at the LHC another mechanism is also important.



- Vector boson fusion $qq \to Hqq$
- Characteristic signature - forward jets.

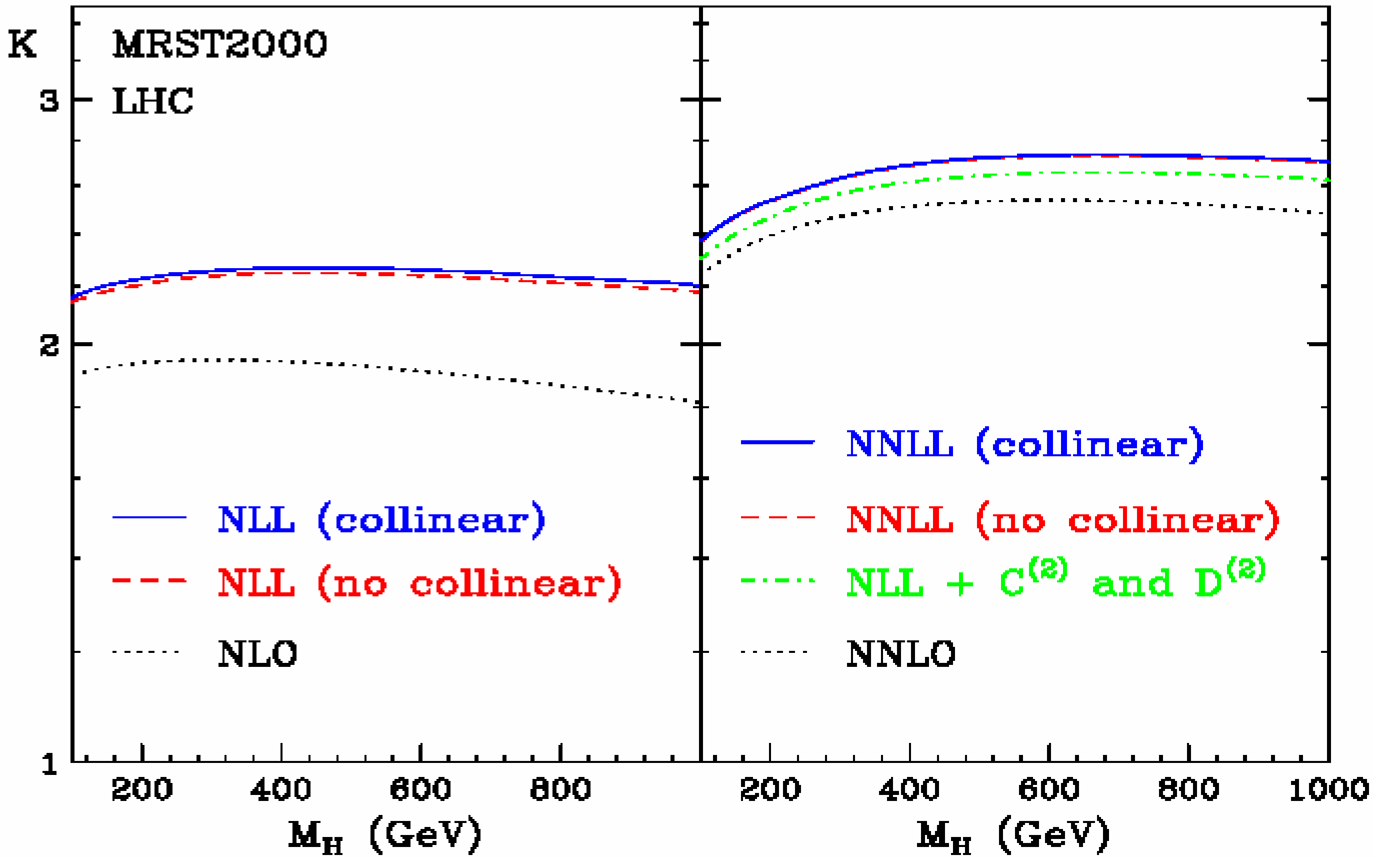
✓ Needs experimental study.

See also Mangano et al (precise knowledge of b/g needed)

Progress in Standard Model calculations

- ✓ Resummation technology
  Threshold and other soft gluon resummations at NLL and NNLL.
  Electroweak high energy logarithms
- ✓ NLO for most backgrounds
- ✓ NNLO for key signal processes
- ✓ Parton densities at NNLO (soon?)
- ✓ NLO/multiparticle Monte Carlo event generators
  e.g. MC@NLO, modifications to HERWIG & PYTHIA, ALPGEN, MCFM, AcerMC, MadCUP. Matrix element generators: CompHEP, Madgraph, Feyncalc, Grace, Helas.

$gg \to H$



Resummation of soft gluon (threshold) logs to NNLL

From QCD/SM Les Houches 2001

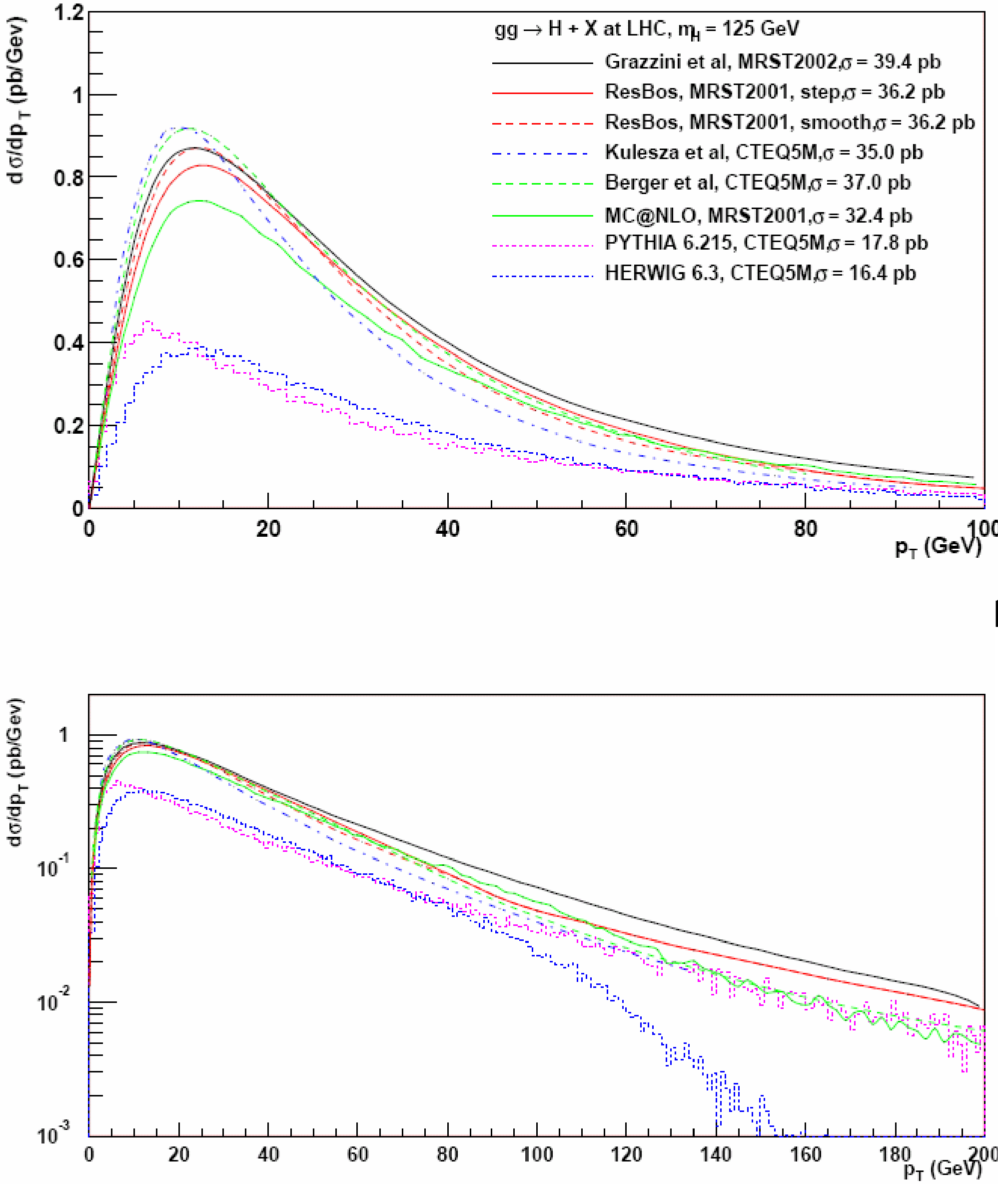


Fig. 1: The absolute predictions for the production of a 125 GeV mass Higgs boson at the LHC.

NLO calculation of Higgs p_T spectrum.

- Low p_T resummation
- NLO matrix elements

from Balazs et al
hep-ph/0403052

MSSM with CP Violation: Light Higgs

- ✓ Higgs sector CP violation natural
  Since the soft SUSY breaking trilinear couplings and gaugino masses can be complex

$$(h, H, A) \rightarrow (H_1, H_2, H_3)$$

- ✓ Easy to arrange for lightest Higgs to have weak coupling to Z.
  Hence it *may not have been* seen at CERN

- ✓ Light Higgs scenario is more general*, e.g. if Higgs mixes with anything with a reduced coupling to the Z (as occurs with the radion in Randall-Sundrum).

[Pilaftsis; Carena, Ellis, Pilaftsis, Wagner]

*See also 2HDM

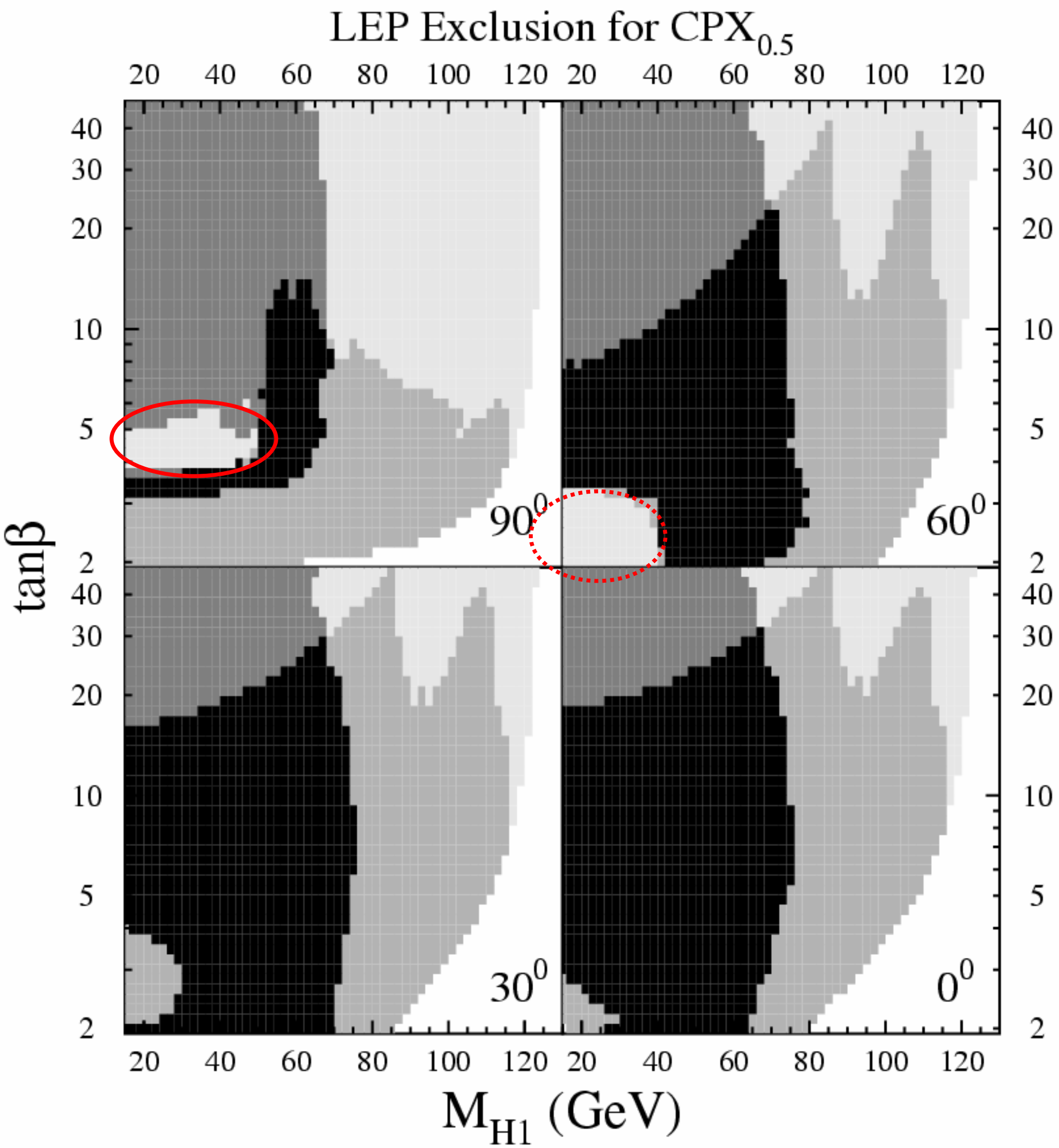
CPX Scenario

- ✓ Mixing of h, H and A via top and bottom squark loops at one-loop (and gluino loops at two-loop).
- ✓ EDM constraints can be avoided without fine-tuning.
- ✓ Benchmark scenario (CPX):

$$M_{squark} = 500 \text{ GeV}; \quad |M_{gluino}| = 1 \text{ TeV};$$

$$\mu = 2 \text{ TeV}; \quad |A_{t,b}| = 1 \text{ TeV};$$

$$\arg(A_{t,b}) = \arg(M_{gluino}) = \Phi_{CP}$$



Carena, Ellis, Pilaftsis, Wagner

Figure 1: *Approximate LEP exclusion limits in the* M_{H_1}–$\tan\beta$ *plane for various CPX scenarios, using combined LEP results. The light grey covers all the region of parameter space that is consistent with electroweak symmetry breaking, the medium grey shows the exclusion from* $e^+e^- \to ZH_i$, *the dark grey shows the region excluded by* $Z^* \to H_iH_j \to 4b$ *searches, and the black region is excluded by both searches.*

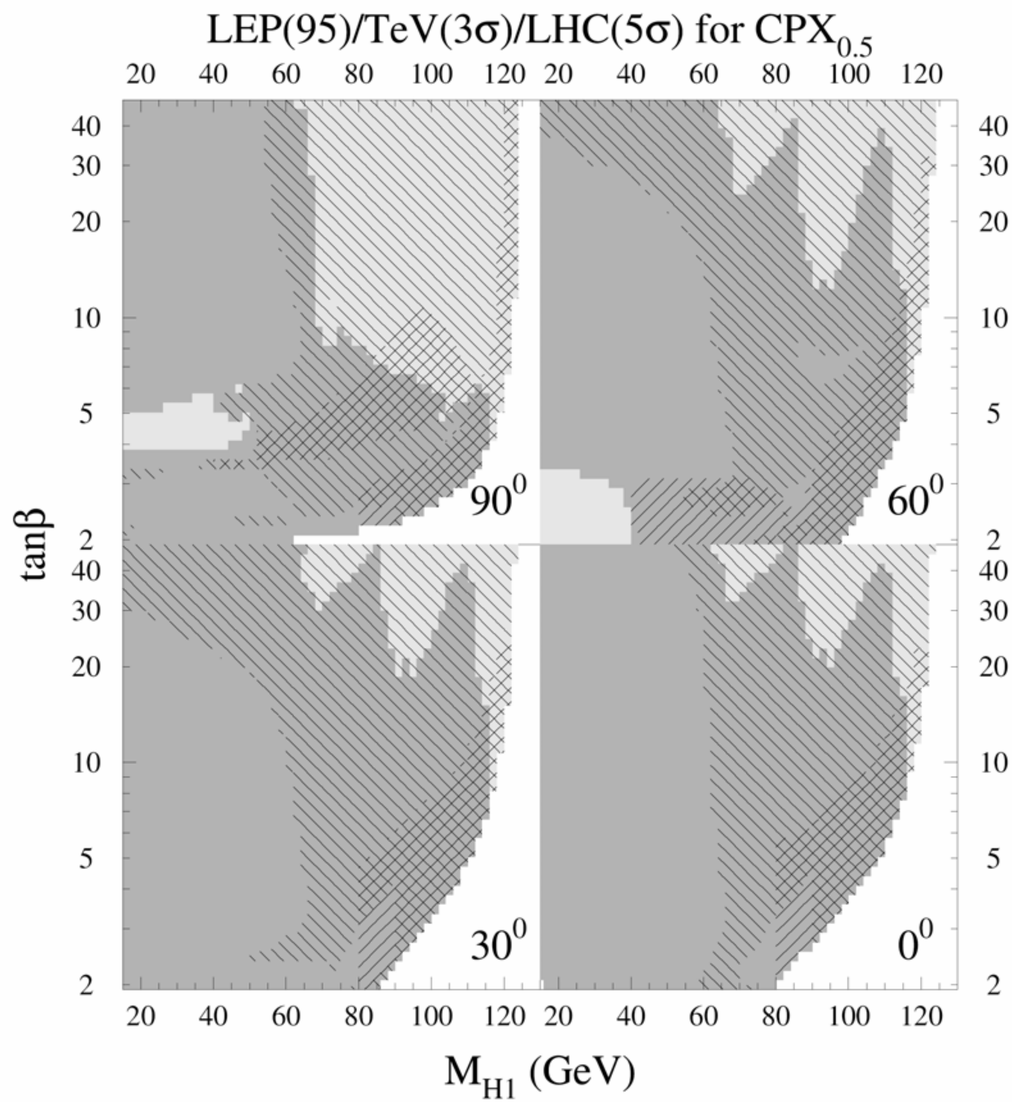
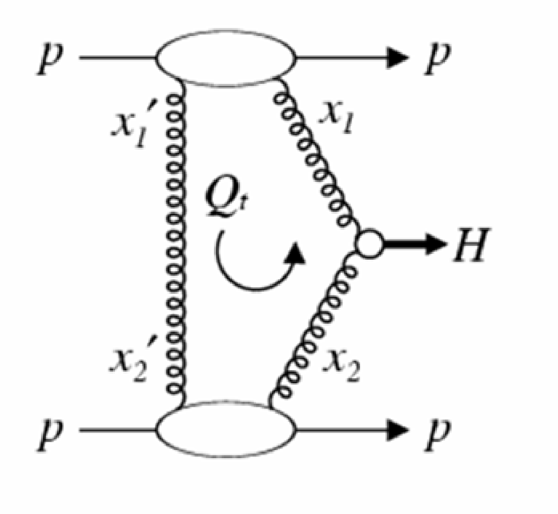


Figure 5: *Approximate Tevatron/LHC discovery and LEP exclusion limits in the* M_{H_1}–$\tan\beta$ *plane for the CPX scenario with both phases set to: (a)* 90°*, (b)* 60°*, (c)* 30°*, and (d)* 0°*. The reach of the Tevatron* $W/ZH_i(\to b\bar{b})$ *search is shown as* 45° *lines and that of the combined LHC search channels as* 135° *lines.The combined LEP exclusion is shown in medium gray, superimposed on the theoretically allowed region in light grey.*

- ✓ Difficulties in detecting such a light Higgs at Tevatron and LHC via conventional search channels.
- ✓ Dedicated LEP analysis underway in an attempt to exclude the low mass regions.
- ✓ Possibility to utilize tagged protons?

Standard Model Higgs



KMR predict 3 fb for a 115 GeV Higgs
includes "gap survival" factor 1/50

LHC: $100\ \mathrm{fb}^{-1}$

[Khoze, Martin & Ryskin]

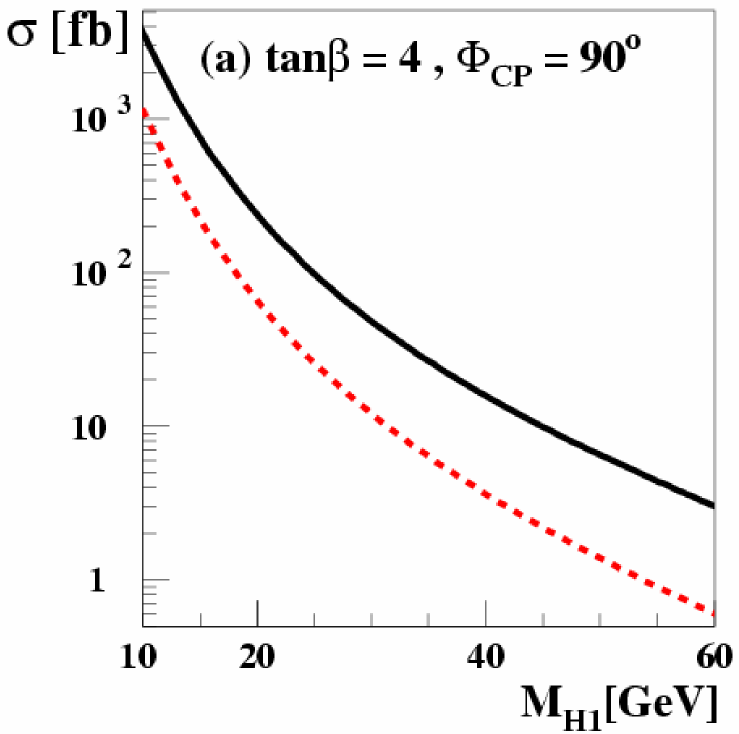
Decay to b quarks viable since QCD background is heavily suppressed.

$\Delta m \approx 1$ GeV (tagged protons needed)

S/B > 1 anticipated at LHC (de Roeck et al)

Valuable to measure "exclusive" dijets at Tevatron to check the theoretical calculations.

CPX scenario



Central Higgs production cross-section at LHC (solid) and Tevatron (dotted). MSSM parameters chosen to lie in the region not currently excluded by LEP, i.e.

$$3 < \tan\beta < 5$$

$$m_{H_1} < 60 \text{ GeV}$$

Cox, JF, Lee, Monk, Pilaftsis

CPX MSSM Higgs

b bbar very difficult because of large background:

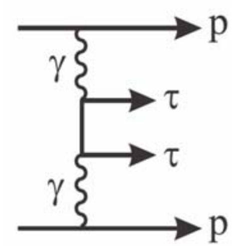
0^{++} Selection rule

QCD Background ~ $\frac{m_b^2}{E_T^2} \frac{\alpha_S^2}{M_{b\bar{b}}^2 E_T^2}$

Also, since resolution of taggers > Higgs width:

$$S/B \propto \Gamma(H \to gg)/\Delta M \propto G_F M_H^3/\Delta M$$

But ττ mode has only QED background



$$A = \frac{\sigma(\varphi < \pi) - \sigma(\varphi > \pi)}{\sigma(\varphi < \pi) + \sigma(\varphi > \pi)}$$

$M(H_1)$ GeV	cuts	30	40	50
$\sigma(H_1)\mathrm{Br}(\tau\tau)$	a, b	1.9	0.6	0.3
$\sigma^{\mathrm{QED}}(\tau\tau)$	a, b	0.2	0.1	0.04
$A_{\tau\tau}$	b	0.2	0.1	0.05

σ in fb

(b) $p_i^\perp > 300$ MeV for the forward outgoing protons

Direct evidence for CP violation in Higgs sector

$$\mathcal{M} = g_S \cdot (e_1^\perp \cdot e_2^\perp) - g_P \cdot \varepsilon^{\mu\nu\alpha\beta} e_{1\mu} e_{2\nu} p_{1\alpha} p_{2\beta} / (p_1 \cdot p_2)$$

CP even

CP odd active at non-zero t

B.C., Forshaw, Lee, Monk and Pilaftsis hep-ph/0303206

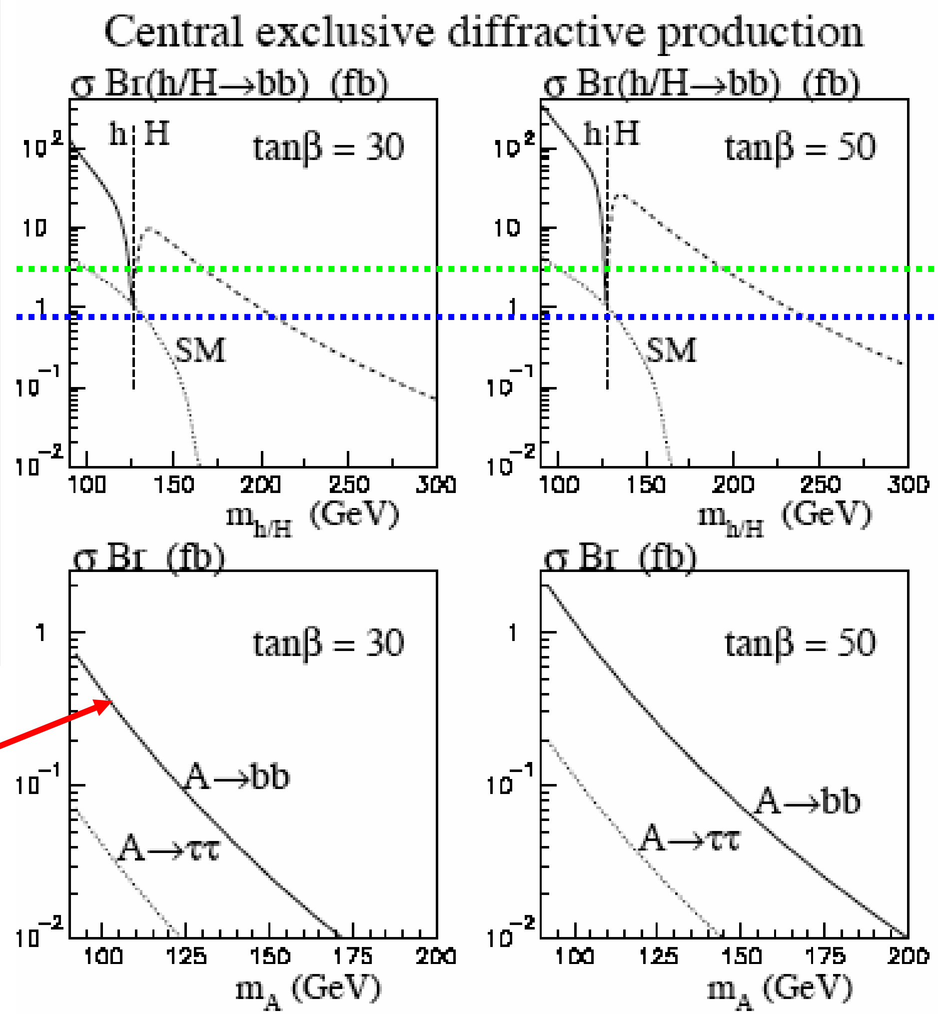
Khoze, Martin and Ryskin hep-ph/0401078

Another example : The intense coupling regime of the MSSM

e.g. m_A = 130 GeV, tan β = 50
(difficult for conventional detection, but exclusive diffractive favourable)
L = 30 fb^{-1}, ΔM = 1 GeV

	S	B	
m_h = 124.4 GeV	71	3	events
m_H = 135.5 GeV	124	2	
m_A = 130 GeV	1	2	

Alan Martin Manchester Dec 2003



0^{++} selection rule suppresses A production:

'filters out' pseudoscalar production, leaving pure H sample for study

For 5 σ with 300 (30) fb^{-1} $\mathrm{Br}(b\bar{b}) \cdot \sigma > 0.7 \text{ fb } (2.7 \text{ fb})$

Kaidalov, Khoze, Martin, Ryskin hep-ph/0311023

Conclusions: Light Higgs

- ✓ Rates may well be high enough to be explored at the LHC – especially in tau decay channel

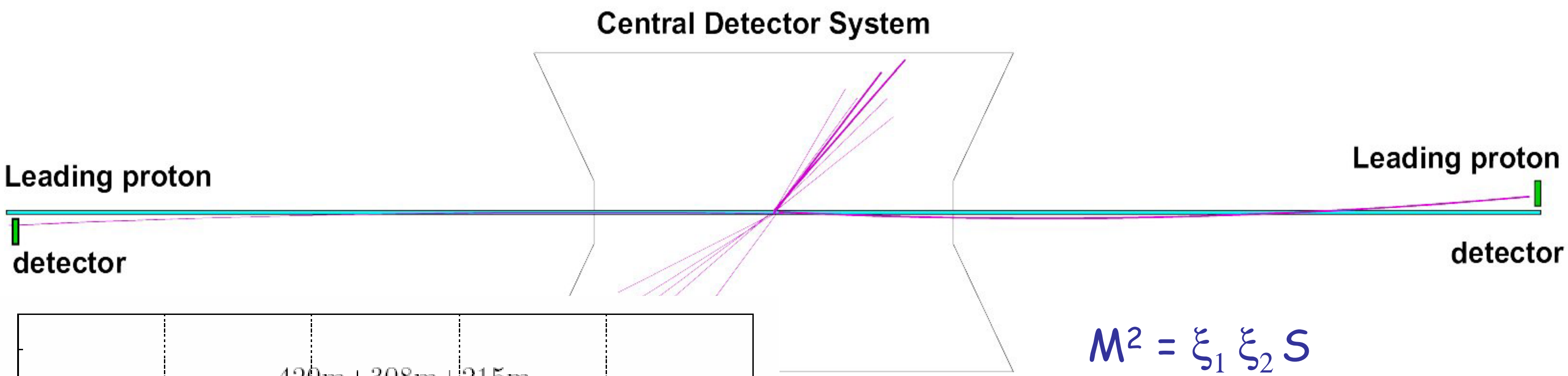
- ✓ Central production with tagged protons may well be a useful tool which is able to complement more traditional search strategies. Especially if the new physics has strong coupling to gluons.

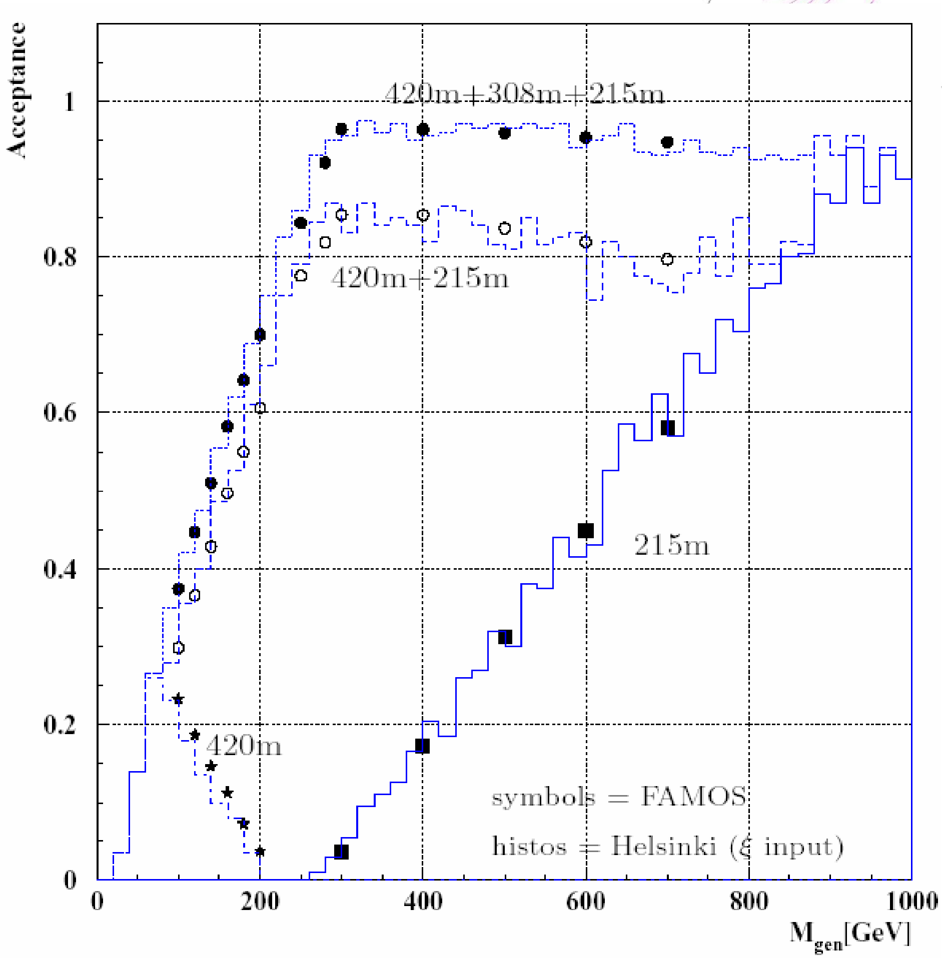
- ✓ Need for suitable forward detectors.

Just started: HERA-LHC Workshop (CERN & DESY).
Next meeting in Hamburg June 1-4.

`http://www.desy.de/~heralhc/`

Double Proton Tagging at LHC





$M^2 = \xi_1 \xi_2 S$

Where $\xi_{1,2}$ are the fractional momentum losses of the outgoing protons

Curves: Helsinki Group

Dots FAMOS simulation

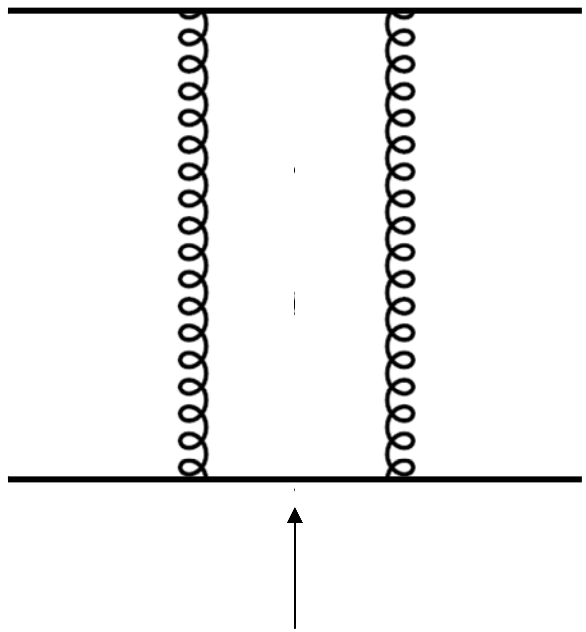
Need 420m detectors.

A. DeRoeck

Invisible Higgs

- ✓ Not hard to imagine models where the Higgs decays invisibly, e.g. to a pair of neutralinos.
- ✓ Zeppenfeld & Eboli propose that such a Higgs could be discovered in VBF: "gaps between jets with missing ET" signature.
- ✓ Would need to work in low lumi phase.
- ✓ ATLAS & CMS have supported the original idea with detailed studies: 5 sigma discovery with 30/fb for a wide range of parameter space.

QCD backgrounds:



Large momentum transfer colour singlet

- Cut on missing ET>100 GeV helps kill QCD background.
- Signal has tag jets close in azimuth and this is also effective in reducing QCD background
- Absence of QCD radiation in interjet region suppresses LO QCD jj but <u>not</u> QCD singlet exchange.
- NLO QCD corrections probably vital

May need to fall back on ZH->dilepton+missing ET…

Godbole, Guchait, Mazumbar, Moretti, Roy

What if there is no new "light" physics?

- Suppose new physics is at a scale Q >> E (E = energy of experiment) [e.g. could be a heavy Standard Model Higgs or some new strong dynamics]
- Can use effective field theory approach to parametrize ignorance of the new physics
- Q cannot be much beyond 1 TeV since we know that the Standard Model without a Higgs breaks down at around 1 TeV (WW -> WW violates unitarity)

Electroweak chiral lagrangian

Global: $SU(2)_L \otimes SU(2)_R \rightarrow SU(2)_C$

Local: $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_Q$

$$U = \exp\left(i\frac{\vec{\pi}\cdot\vec{\tau}}{v}\right)$$

← Goldstone bosons of the broken chiral symmetry (eaten to make heavy W and Z)

$$\mathcal{L}^{(2)} = \frac{v^2}{4}\langle D_\mu U D^\mu U^\dagger \rangle$$

← The only dimension two operator allowed by gauge invariance and custodial symmetry

Longhitano;
Appelquist & Bernard

Can relax the assumption of custodial symmetry without any problem – just more parameters. Actually we need to do this if we are to get away with no light higgs boson (i.e. in light of precision data). Bagger, Falk & Swarz

Focus on quartic couplings of vector bosons:

$$\mathcal{L}^{(4)} = \boxed{a_4}(\langle D_\mu U D^\nu U^\dagger \rangle)^2 + \boxed{a_5}(\langle D_\mu U D^\mu U^\dagger \rangle)^2$$

$$\begin{aligned} \mathcal{A}(s,t,u) \quad = \quad & \frac{s}{v^2} + \frac{4}{v^4}\left[2a_5(\mu)s^2 + a_4(\mu)(t^2+u^2) + \frac{1}{(4\pi)^2}\frac{10s^2+13(t^2+u^2)}{72}\right] \\ & - \frac{1}{96\pi^2 v^4}\left[t(s+2t)\log(\frac{-t}{\mu^2}) + u(s+2u)\log(\frac{-u}{\mu^2}) + 3s^2\log(\frac{-s}{\mu^2})\right] \end{aligned}$$

One-loop amplitude for WW->WW. Calculated using the equivalence theorem. Physical WW->WW amplitudes obtained by crossing and isospin symmetry

Unitarization

- Effective theory only valid for E<<Q
- Can try to extrapolate to higher E by insisting that partial waves are unitary [considerable ambiguity]

$$A_I(s,t,u) = 32\pi \sum_{J=0}^{\infty} (2J+1) t_{IJ} P_J(\cos\theta)$$

$$t_{IJ}^{-1} = \mathrm{Re}(t_{IJ}^{-1}) - i \qquad t_{IJ} = t_{IJ}^{(2)} + t_{IJ}^{(4)} + \cdots$$

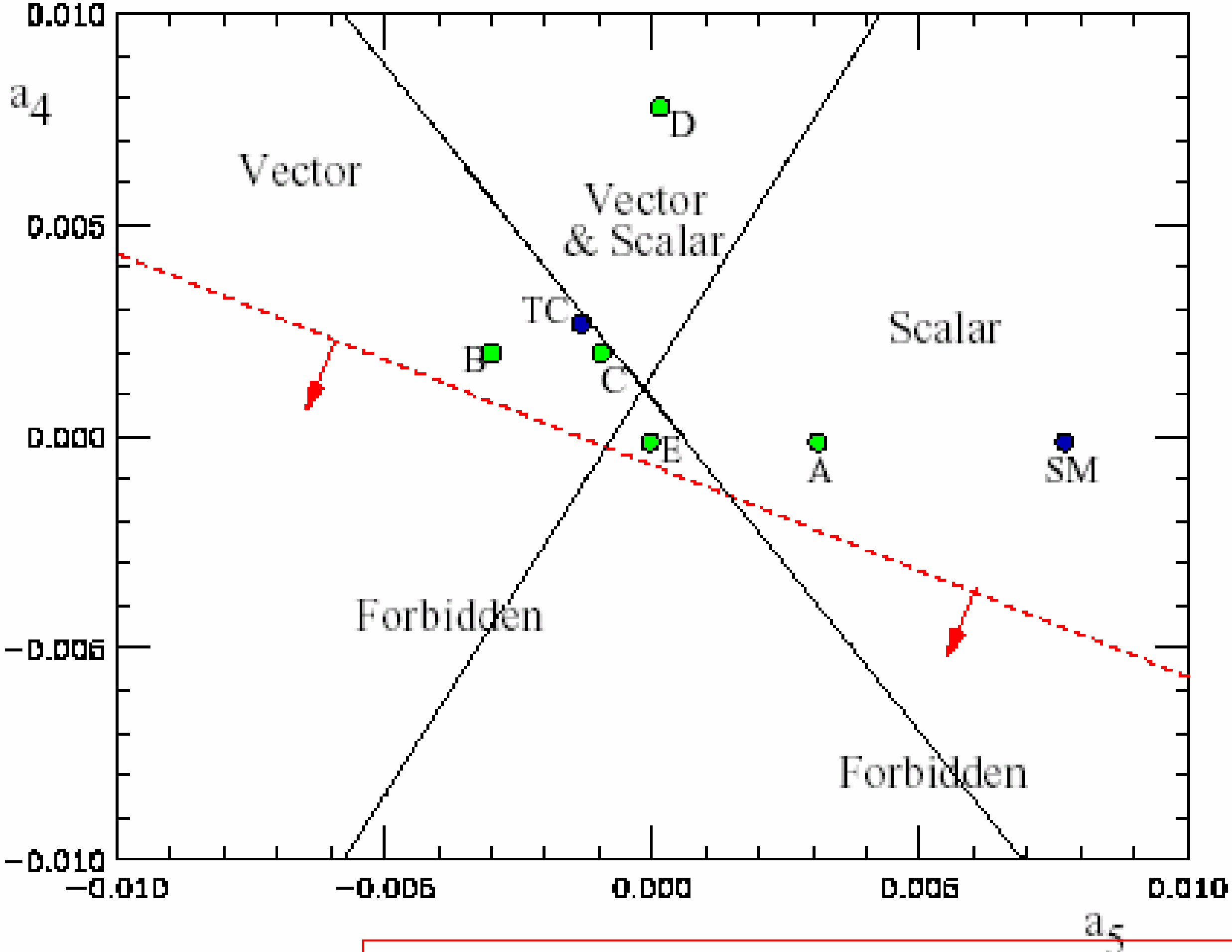
Elastic unitarity

$$\Rightarrow \quad t_{IJ} = \frac{t_{IJ}^{(2)}}{\left(1 - \frac{t_{IJ}^{(4)}(s)}{t_{IJ}^{(2)}(s)}\right)}$$

Pade approximation. Matches one-loop perturbation theory result

- Pade (and N/D) schemes have been implemented into PYTHIA

Resonance Map in Pade scheme



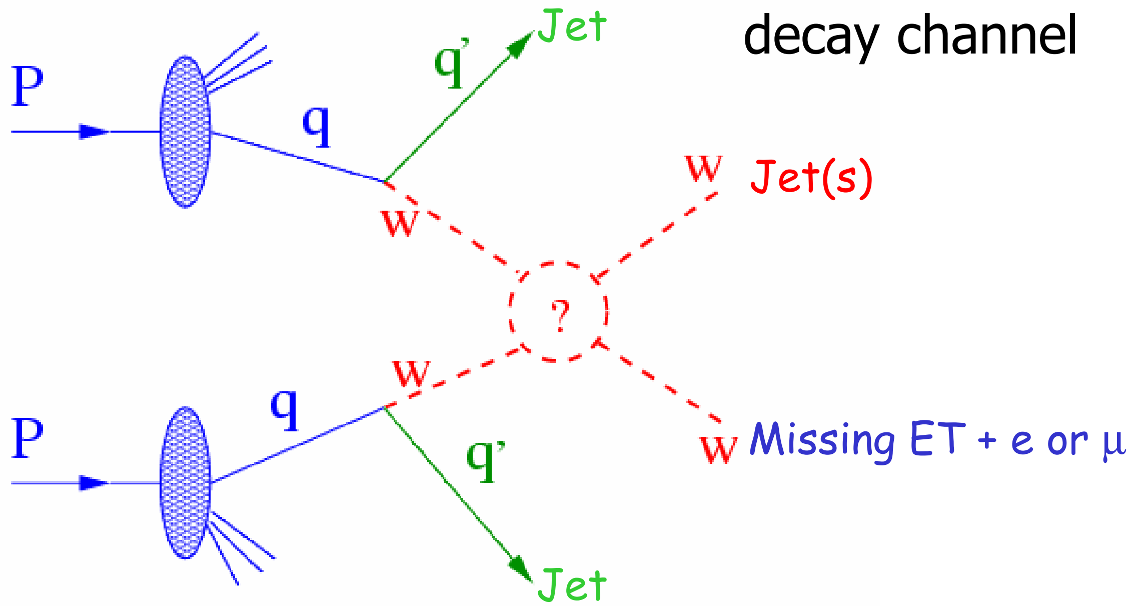
A = 900 GeV scalar
B = 1300 GeV vector
C = 1800 GeV vector
D = 800 GeV scalar and 1300 GeV vector
E = no resonances
SM = 1 TeV Higgs
TC = Re-scaled QCD

What can LHC do in 1 year in scenarios A-E?

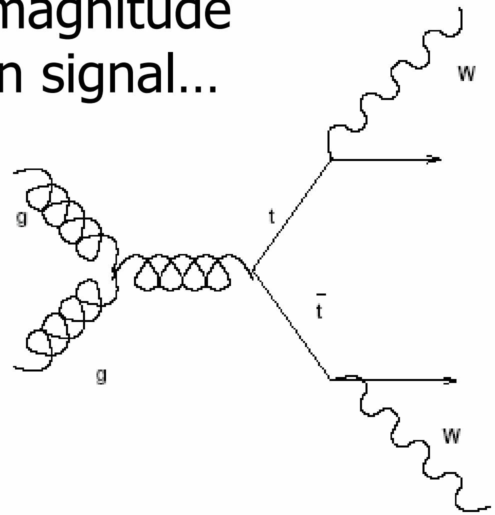
See Dobado et al

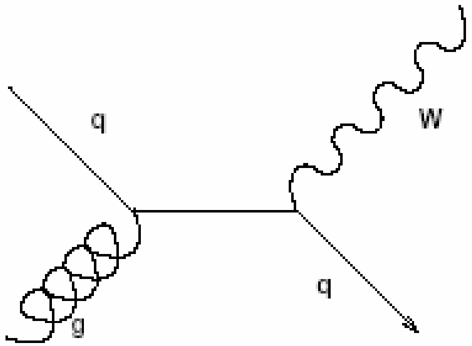
Probing the new physics at LHC

Focus on semi-leptonic decay channel



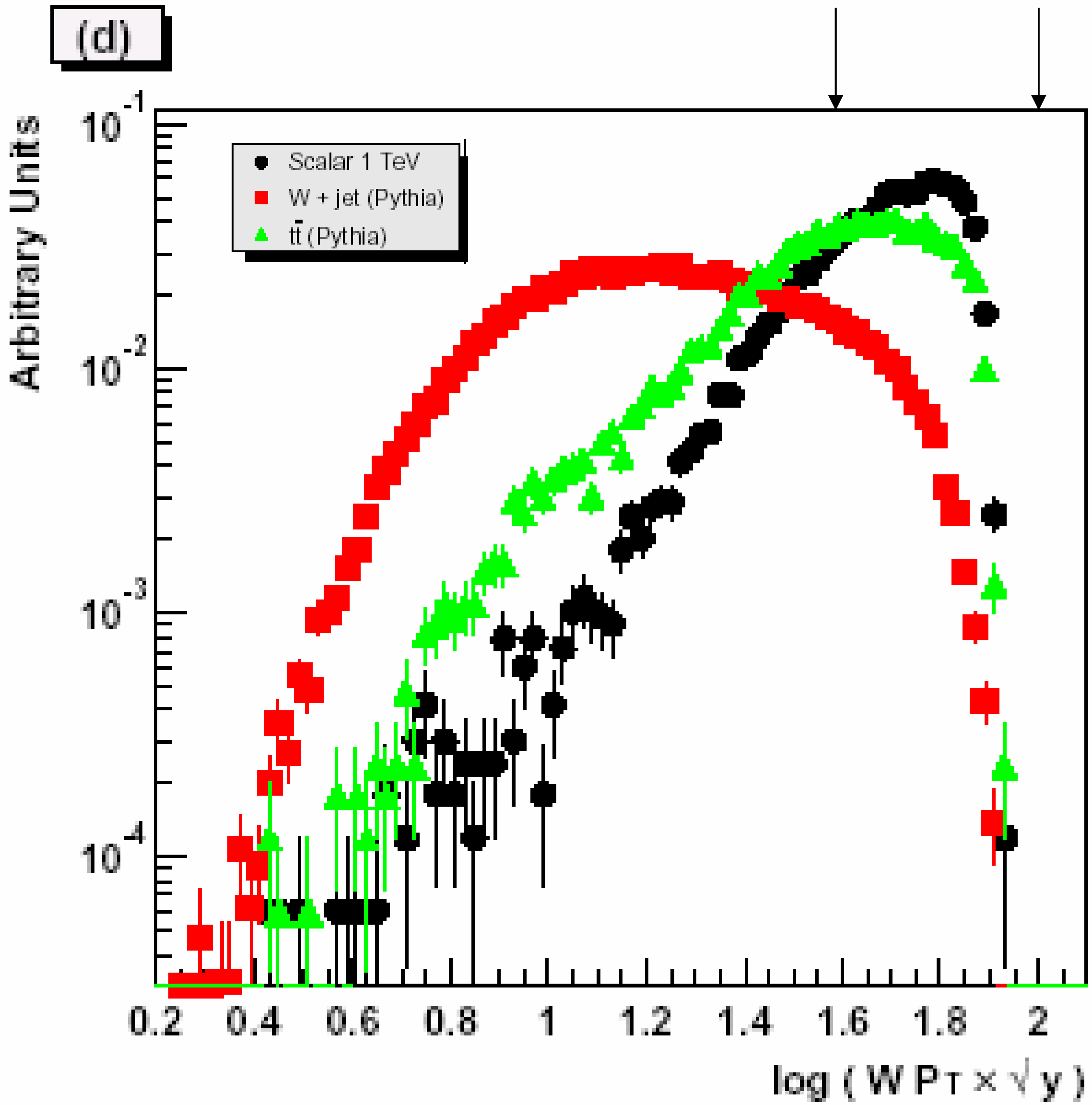
Background is many orders of magnitude bigger than signal…





Subjet method for identifying energetic W bosons

Cut: $1.6 < \log(p_T y^{1/2}) < 2.0$



Use kt algorithm to find scale at which W-jet candidate resolves into two subjets.

For a genuine W, we expect the scale at which the subjets are resolved (i.e. yp_T^2) to be of order M_W^2

Seymour

Butterworth, Cox, JF

Cuts	Efficiency	Signal σ (fb)	$t\bar{t}$ σ (fb)	W+Jets σ (fb)	Sig/B
Generated	A:100%	72	Pythia		8.7×10^{-4}
	B:100%	104	18,000	65,000	1.3×10^{-3}
	C:100%	44	Herwig		5.3×10^{-4}
	D:100%	113	14,000	53,000	1.4×10^{-3}
	E:100%	47			5.0×10^{-4}
p_T (Lep. W) > 320 GeV and p_T (Had. W) > 320 GeV	A:11%	8.2	Pythia		1.5×10^{-3}
	B:11%	11	910	4400	2.1×10^{-3}
	C:10%	4.4	Herwig		8.3×10^{-4}
	D:10%	11	750	3600	2.1×10^{-3}
	E:10%	4.7			8.8×10^{-4}
70 GeV < M(Had. W) < 90 GeV	A:6.7%	4.8	Pythia		6.3×10^{-3}
	B:6.2%	6.4	56	700	8.4×10^{-3}
	C:5.8%	2.6	Herwig		3.4×10^{-3}
	D:5.6%	6.3	52	480	8.3×10^{-3}
	E:5.8%	2.7			3.6×10^{-3}
$1.6 < \log(p_T \times \sqrt{y}) < 2.0$	A:4.7%	3.4	Pythia		3.2×10^{-2}
	B:4.4%	4.5	28	78	4.3×10^{-2}
	C:4.1%	1.8	Herwig		1.7×10^{-2}
	D:4.0%	4.5	27	66	4.3×10^{-2}
	E:4.1%	1.9			1.8×10^{-2}
Top quark veto (see text)	A:4.3%	3.1	Pythia		5.6×10^{-2}
	B:4.0%	4.2	3.2	52	7.5×10^{-2}
	C:3.8%	1.7	Herwig		3.0×10^{-2}
	D:3.6%	4.1	3.4	43	7.3×10^{-2}
	E:3.8%	1.8			3.2×10^{-2}
Tag jets $p_T > 20$ GeV, $E > 300$ GeV (see text)	A:1.6%	1.1	Pythia		2.7
	B:1.5%	1.6	0.030	0.38	3.8
	C:1.4%	0.63	Herwig		1.5
	D:1.3%	1.5	0.082	0.42	3.6
	E:1.4%	0.67			1.6
Hard $p_T < 50$ GeV	A:1.5%	1.1	Pythia		3.2
	B:1.5%	1.5	0.020	0.32	4.5
	C:1.4%	0.61	Herwig		1.8
	D:1.3%	1.4	0.048	0.37	4.3
	E:1.4%	0.65			1.9
Minijet veto $p_T > 15$ GeV, see text	A:1.5%	1.1	Pythia		4.3
	B:1.5%	1.5	0.013	0.24	6.0
	C:1.4%	0.61	Herwig		2.4
	D:1.3%	1.4	0.048	0.36	5.6
	E:1.4%	0.65			2.6

WW mass and cos θ* distributions

A = 900 GeV scalar
B = 1300 GeV vector
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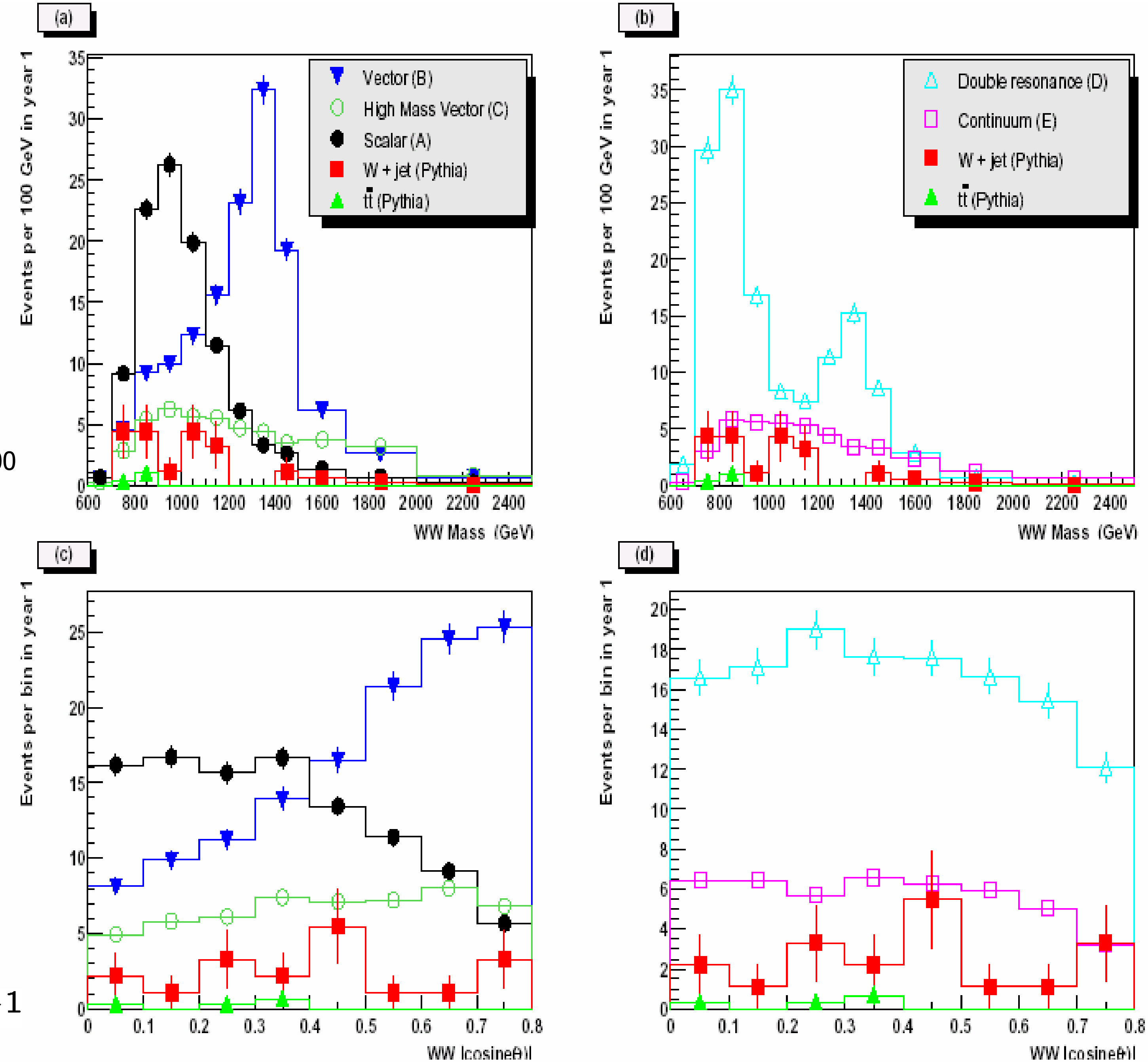
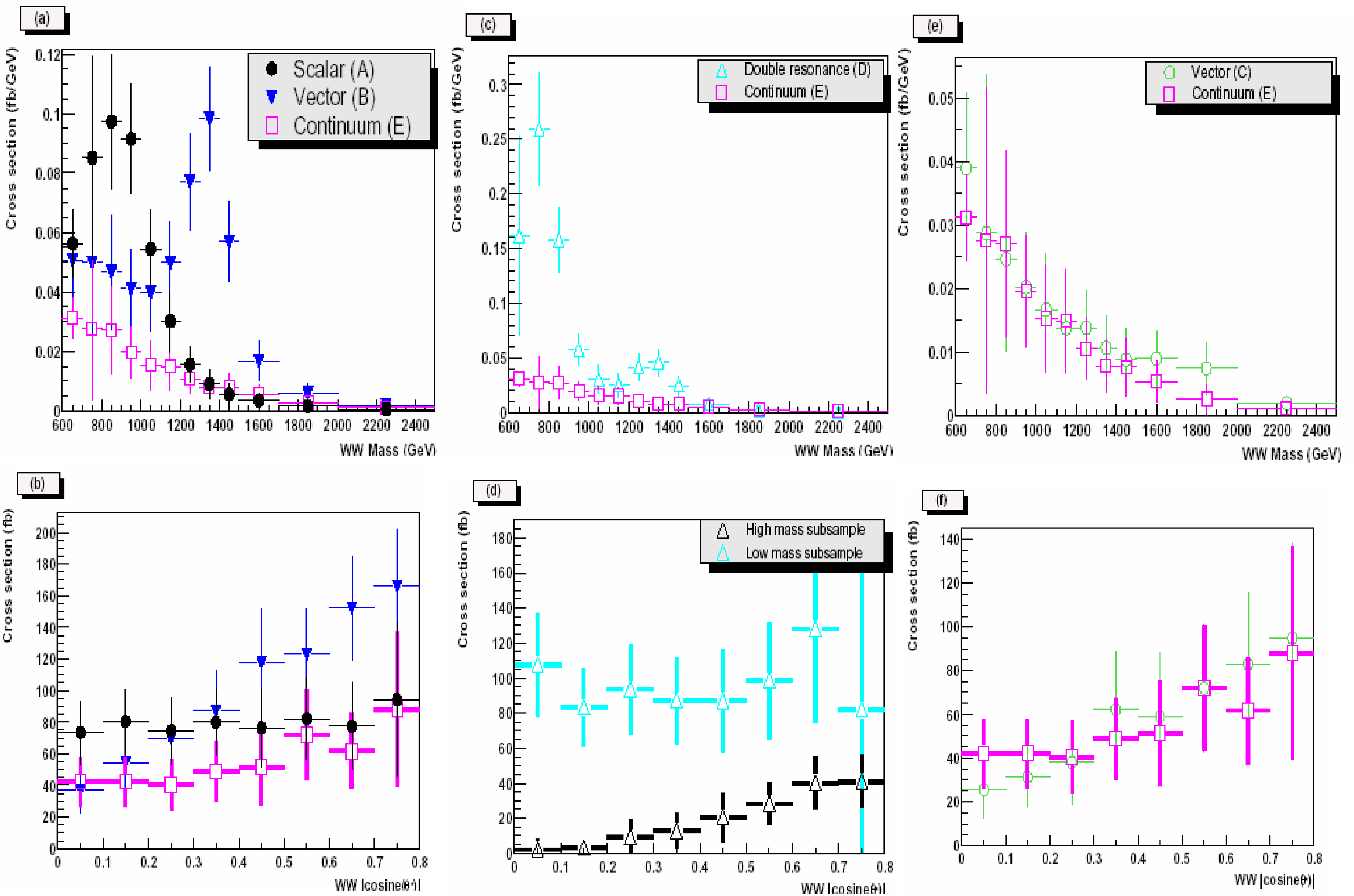
E = no resonances



$100\ \text{fb}^{-1}$

Simulated measurement 100 fb^{-1}



Underlying Event

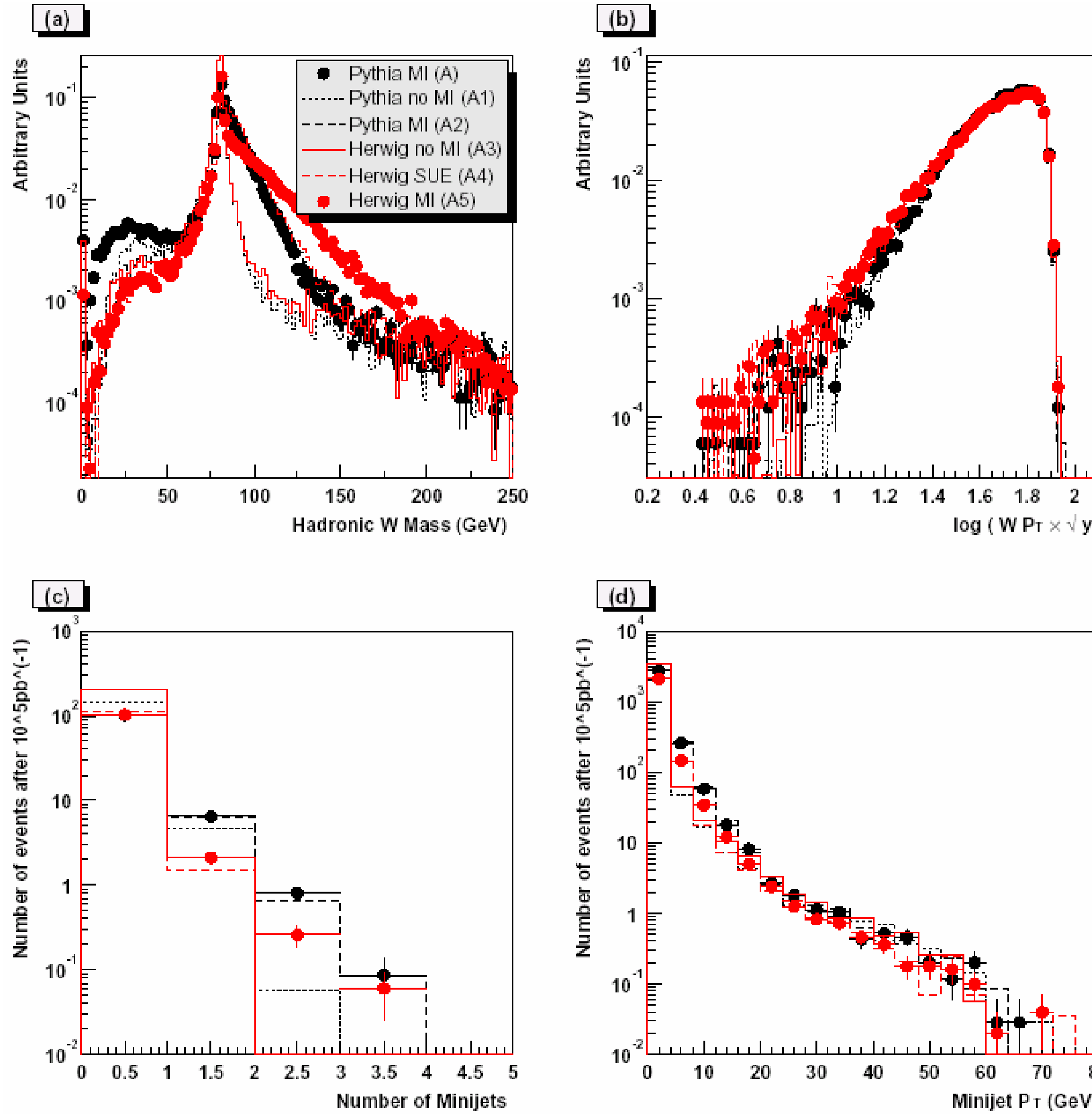
The minijet cut is sensitive to underlying event (and pileup) although the approach developed here is less sensitive than in previous analyses

(a) Hadronic W width affected greatly by underlying event model

(b) Subjet analysis insensitive to models

(c) and (d) : The minijet distributions are sensitive, particularly below 20 GeV. The 15 GeV threshold we use is marginal …

but measurement of the underlying event in data should allow tuning of models and cut



- ✓ It may be that there is no new physics until we enter the TeV region (LHC). In which case we may well want a ~2 TeV linear collider and/or a new hadron collider.

- ✓ WW scattering is an excellent place to look for evidence of the new physics:

  "With 1 year high luminosity should be able to measure WW cross-section differential in WW mass and hence the mass of any new resonances (up to about 1.5 TeV). In some scenarios, it may be possible to measure the spin of the resonance(s) too."

Conclusions

- $v \approx 246$ GeV
- $\rho \approx 1$
- Precision data

✓ We do not know much about the origin of EWSB. Many possibilities still open: SUSY? Extra Dimensions? New Strong Interactions?

✓ Understanding of signals & backgrounds improving daily. Powerful methods being brought to bear: NNLO, NLO MC's, resummation, multiparticle final states.

✓ Tagging both protons at the LHC could provide very exciting options.