Higgs Working Group
Experimental Studies

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Rutgers University

Tevatron Run 2 SUSY/Higgs Workshop

Nov. 19, 1998

- goals of the Working Group
- Standard Model Higgs results
- (SUSY Higgs projections from SM Higgs)
- strong SUSY Higgs production
- other topics

Goals of the Study

- repeat and extend the previous studies
- combine all possible channels
- simulate "average" of CDF and DØ
- establish SM Higgs discovery thresholds
- interpret SM Higgs results in MSSM
- explore new SUSY Higgs possibilities

$\rightarrow$ express integrated luminosity needed for

- 95% CL limits (1.64σ)
- 3σ observation (prob. < 0.0013)
- 5σ discovery (prob. $< 0.53 \times 10^{-6}$)

$\rightarrow$ show the effects of

- improved $b\bar{b}$ mass resolution
- improved b tagging efficiency

SHW - simple CDF/DØ simulation

$\rightarrow$ go beyond "parton-level" studies

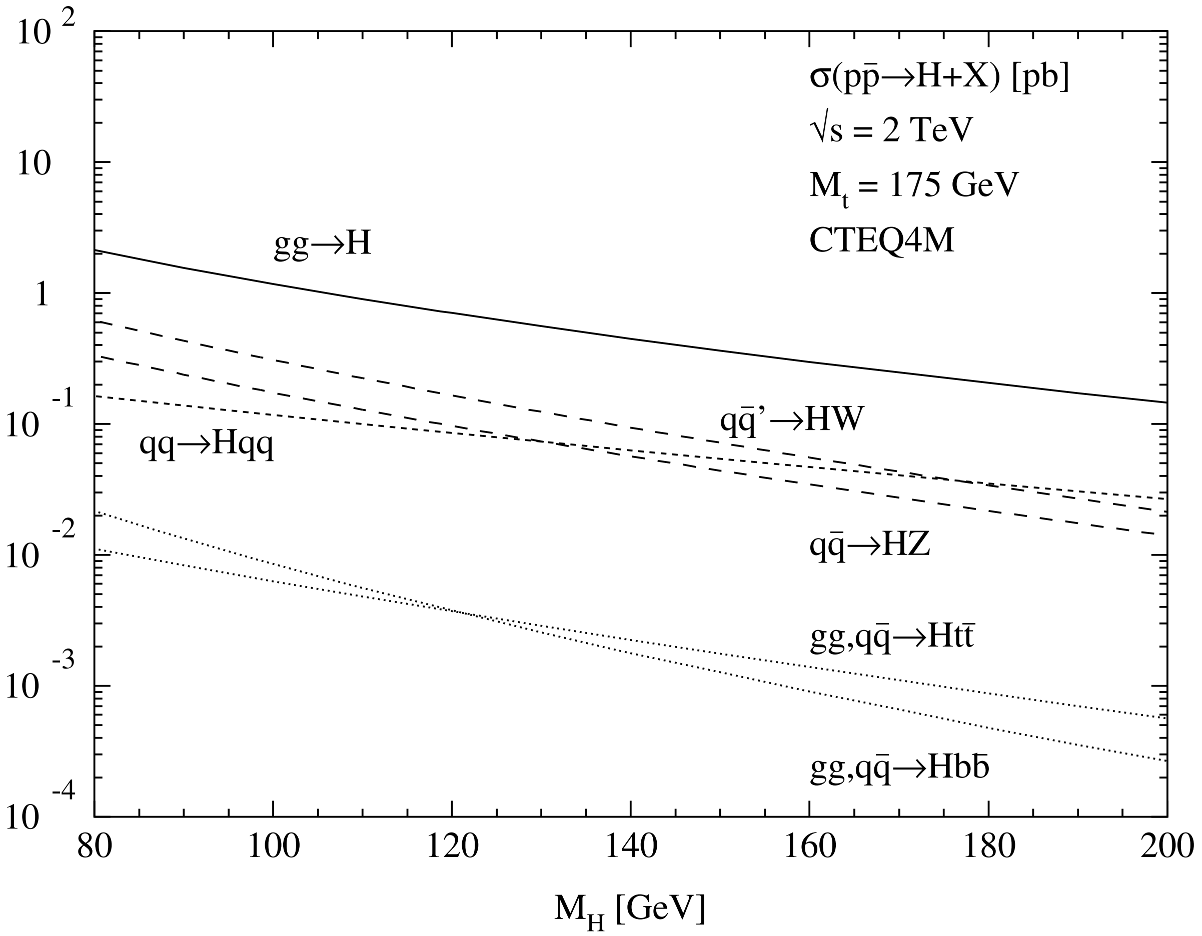
$\rightarrow$ simulate "average" CDF/DØ response

1. generate event (PYTHIA, ISAJET,...)
2. create list of tracks
3. create calorimeter tower energies
4. find calorimeter clusters
5. make list of trigger objects
6. make list of reconstructed objects:
   - γ
   - e
   - μ
   - τ
   - jet (with b- and c-tagging)
   - heavy stable charged particles

$\rightarrow$ use SHW for reasonably accurate trigger, geometric, and identification efficiencies

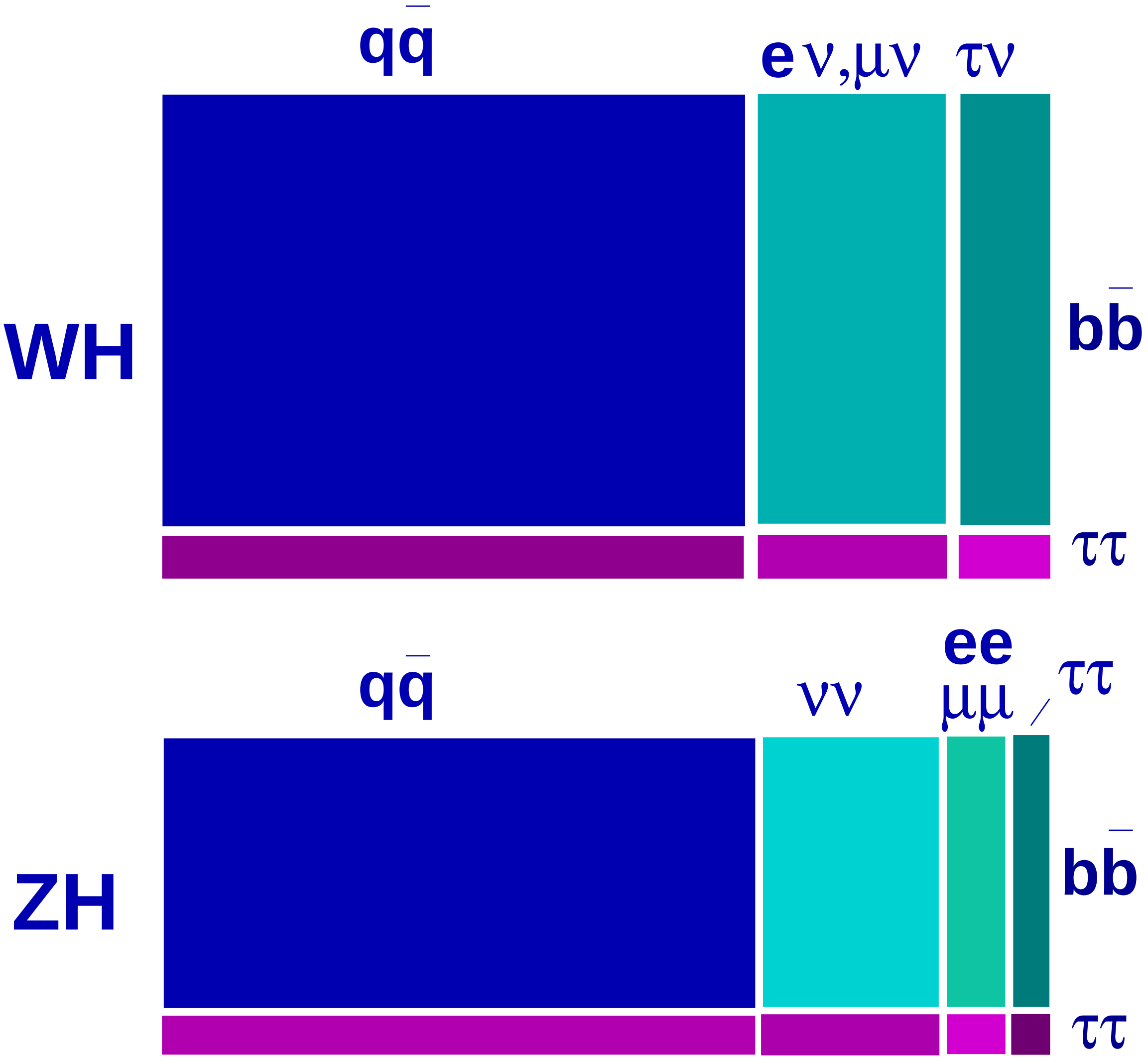
$\rightarrow$ parametrize items such as $b\bar{b}$ mass resolution

Standard Model Neutral Higgs searches



- gg→H dominates, but very difficult to see
- WH, ZH are most accessible
- SUSY enhances some cross sections!

WH/ZH final states, $m(H) \sim 110$ GeV/c^2:

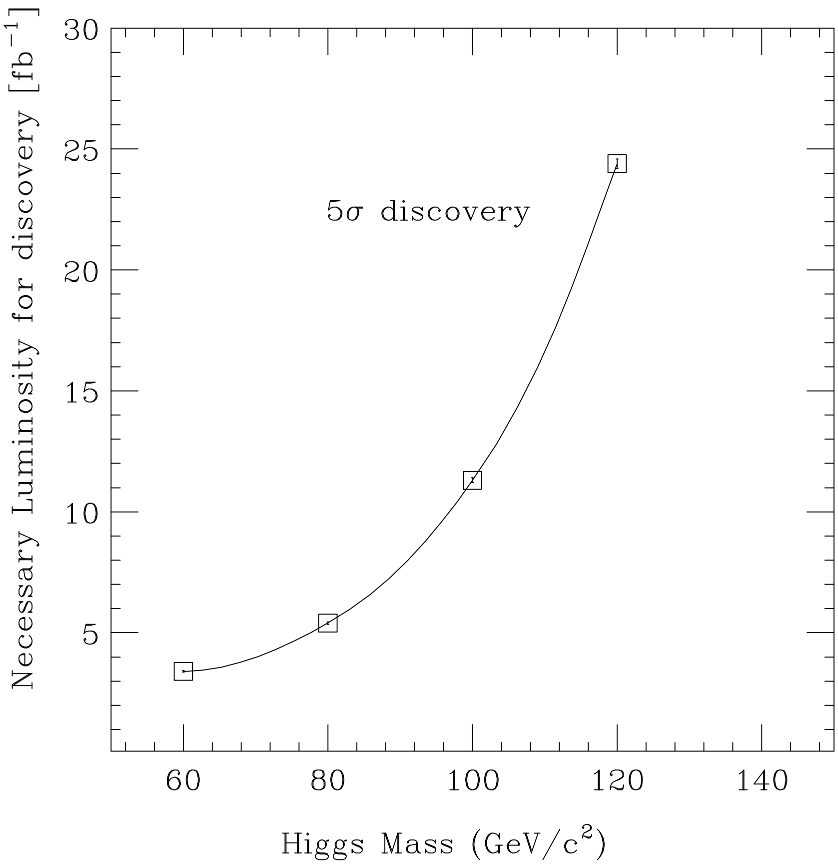


$m(H) < 130$ GeV: $\ell\nu b\bar{b}$, $\nu\bar{\nu}b\bar{b}$, $\ell^+\ell^- b\bar{b}$, $q\bar{q}b\bar{b}$

$m(H) > 130$ GeV: $\ell^+\ell^-\nu\bar{\nu}$, $\ell^\pm\ell^\pm jj$, $\ell^\pm\ell'^\pm\ell^\mp$

TeV33

study result



How do we improve upon previous studies?

- better $b\bar{b}$ mass resolution
- new triggers
- better selection
- add new channels
- combine all channels
- new ideas!

Overview of SM Higgs Channel Sensitivities

(Run 2 improved $m_{b\bar{b}}$ resolution and acceptance)

expected events and sensitivity in 1 fb^{-1}

channel	rate	Higgs mass (GeV/c^2) 90	100	110	120	130
$\nu\bar{\nu}b\bar{b}$	S	2.5	2.2	1.9	1.2	0.6
	B	10.0	9.3	8.0	6.5	4.8
	$S/\sqrt{B}$	0.8	0.7	0.7	0.5	0.3
$\ell\nu b\bar{b}$	S	8.4	6.6	5.0	3.7	2.2
	B	48	52	48	49	42
	$S/\sqrt{B}$	1.2	0.9	0.7	0.5	0.3
$\ell^+\ell^-b\bar{b}$	S	1.0	0.9	0.8	0.5	0.3
	B	3.6	3.1	2.5	1.8	1.1
	$S/\sqrt{B}$	0.5	0.5	0.5	0.4	0.3
$q\bar{q}b\bar{b}$	S	8.1	5.6	3.5	2.5	1.3
	B	6800	3600	2800	2300	2000
	$S/\sqrt{B}$	0.10	0.09	0.07	0.05	0.03

channel	rate	Higgs mass (GeV/c^2) 120	130	140	150	160	170	180
$\ell^\pm\ell'^\pm\ell^\mp$	S	0.04	0.08	0.11	0.12	0.15	0.10	0.09
	B	0.73	0.73	0.73	0.73	0.73	0.73	0.73
	$S/\sqrt{B}$	0.05	0.09	0.13	0.14	0.18	0.12	0.11
$\ell^+\ell^-\nu\bar{\nu}$	S	-	-	2.6	2.8	1.5	1.1	1.0
	B	-	-	44	30	4.4	2.4	3.8
	$S/\sqrt{B}$			0.39	0.51	0.71	0.71	1.9
$\ell^\pm\ell^\pm jj$	S	0.10	0.20	0.34	0.53	0.45	0.38	0.29
	B	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	$S/\sqrt{B}$	0.11	0.22	0.37	0.57	0.49	0.41	0.31

Combined channel thresholds

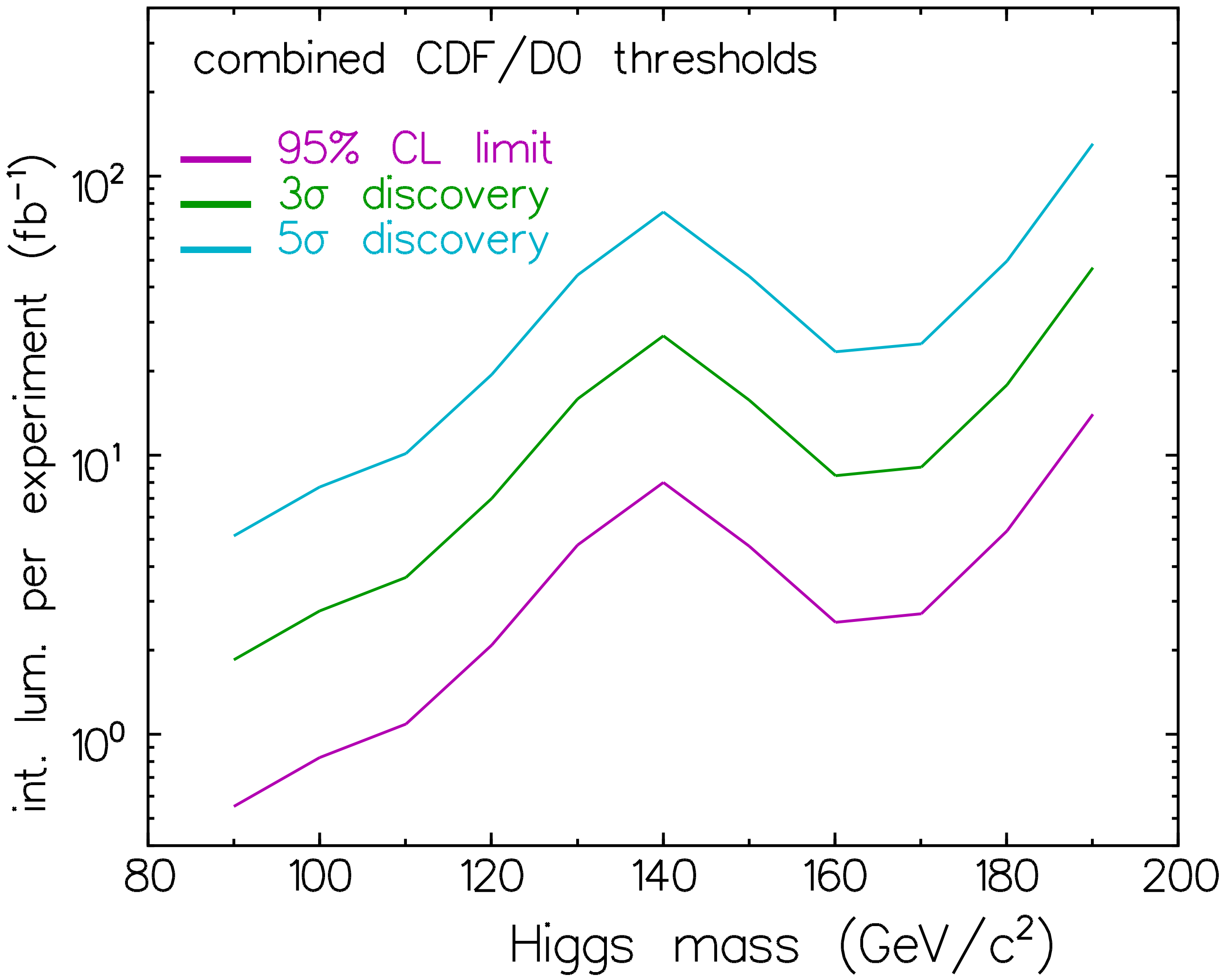
→ Gaussian approximation in combination

→ 30% better $m_{b\bar{b}}$ resolution than Run 1

→ Run 2 acceptance

→ no systematic errors

→ all except $\ell^{\pm}\ell^{\pm}jj$



Combined channel thresholds

$\rightarrow$ Gaussian approximation in combination
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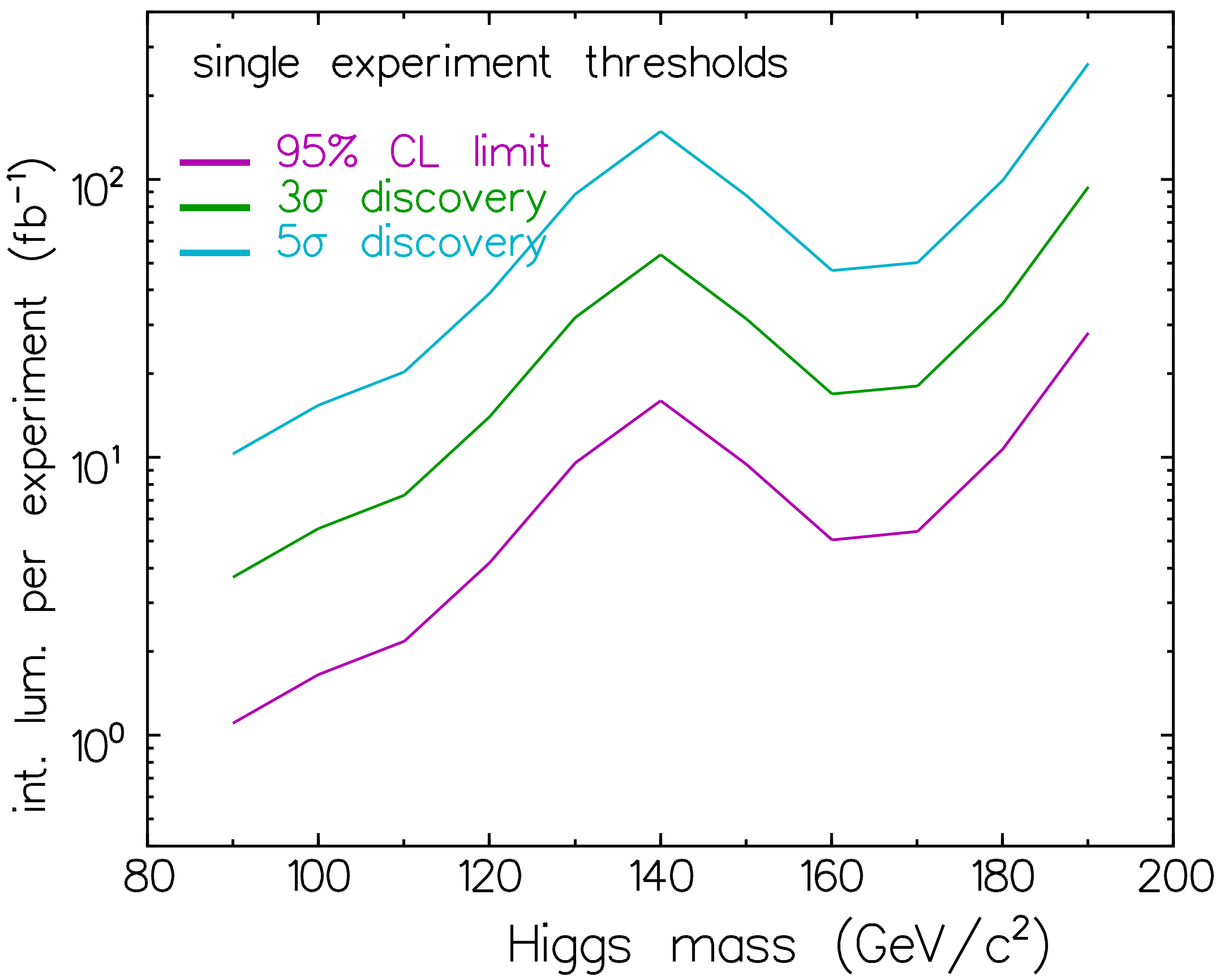


One experiment!

Combined channel thresholds

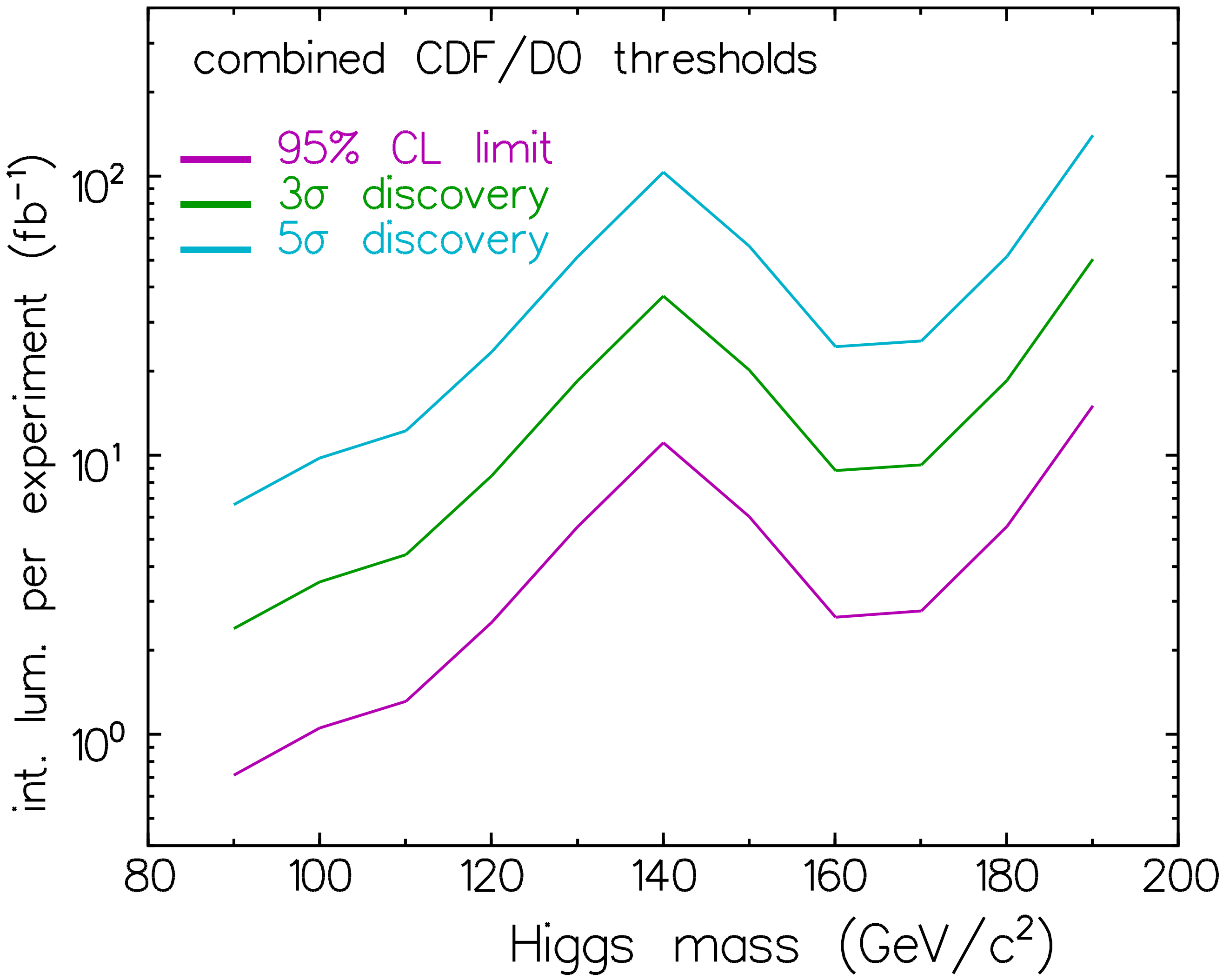
$\rightarrow$ Gaussian approximation in combination

$\rightarrow$ 30% better $m_{b\bar{b}}$ resolution than Run 1

$\rightarrow$ Run 2 acceptance

$\rightarrow$ 10% systematic error on background

$\rightarrow$ all except $\ell^{\pm}\ell^{\pm}jj$



Overview of SM Higgs Channel Sensitivities

(Run 2 improved $m_{b\bar{b}}$ resolution and acceptance,
30% NN improvement)

expected events and sensitivity in 1 fb^{-1}

channel	rate	Higgs mass (GeV/c^2) 90	100	110	120	130
$\nu\bar{\nu}b\bar{b}$	S	3.2	2.9	2.5	1.6	0.8
	B	10.0	9.3	8.0	6.5	4.8
	$S/\sqrt{B}$	1.0	1.0	0.9	0.6	0.4
$\ell\nu b\bar{b}$	S	10.9	8.6	6.5	4.8	2.9
	B	48	52	48	49	42
	$S/\sqrt{B}$	1.6	1.2	0.9	0.7	0.4
$\ell^+\ell^-b\bar{b}$	S	1.4	1.2	1.0	0.7	0.4
	B	3.6	3.1	2.5	1.8	1.1
	$S/\sqrt{B}$	0.7	0.7	0.6	0.5	0.4
$q\bar{q}b\bar{b}$	S	8.1	5.6	3.5	2.5	1.3
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channel	rate	Higgs mass (GeV/c^2) 120	130	140	150	160	170	180
$\ell^\pm\ell'^\pm\ell^\mp$	S	0.04	0.08	0.11	0.12	0.15	0.10	0.09
	B	0.73	0.73	0.73	0.73	0.73	0.73	0.73
	$S/\sqrt{B}$	0.05	0.09	0.13	0.14	0.18	0.12	0.11
$\ell^+\ell^-\nu\bar{\nu}$	S	-	-	2.6	2.8	1.5	1.1	1.0
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	B	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	$S/\sqrt{B}$	0.11	0.22	0.37	0.57	0.49	0.41	0.31

Combined channel thresholds

→ Gaussian approximation in combination

→ 30% better $m_{b\bar{b}}$ resolution than Run 1

→ Run 2 acceptance $\times 1.3$ NN improvement

→ no systematic errors

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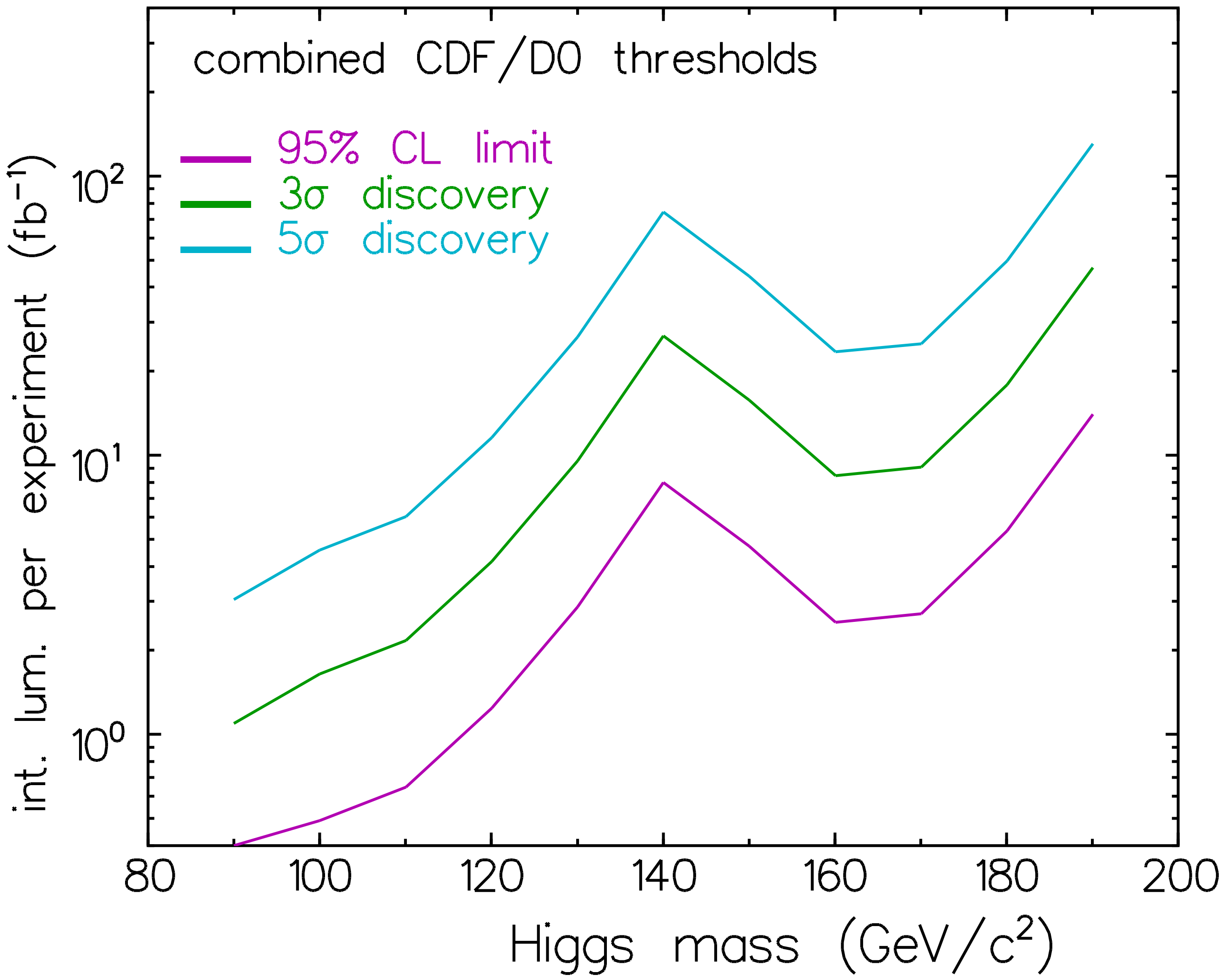
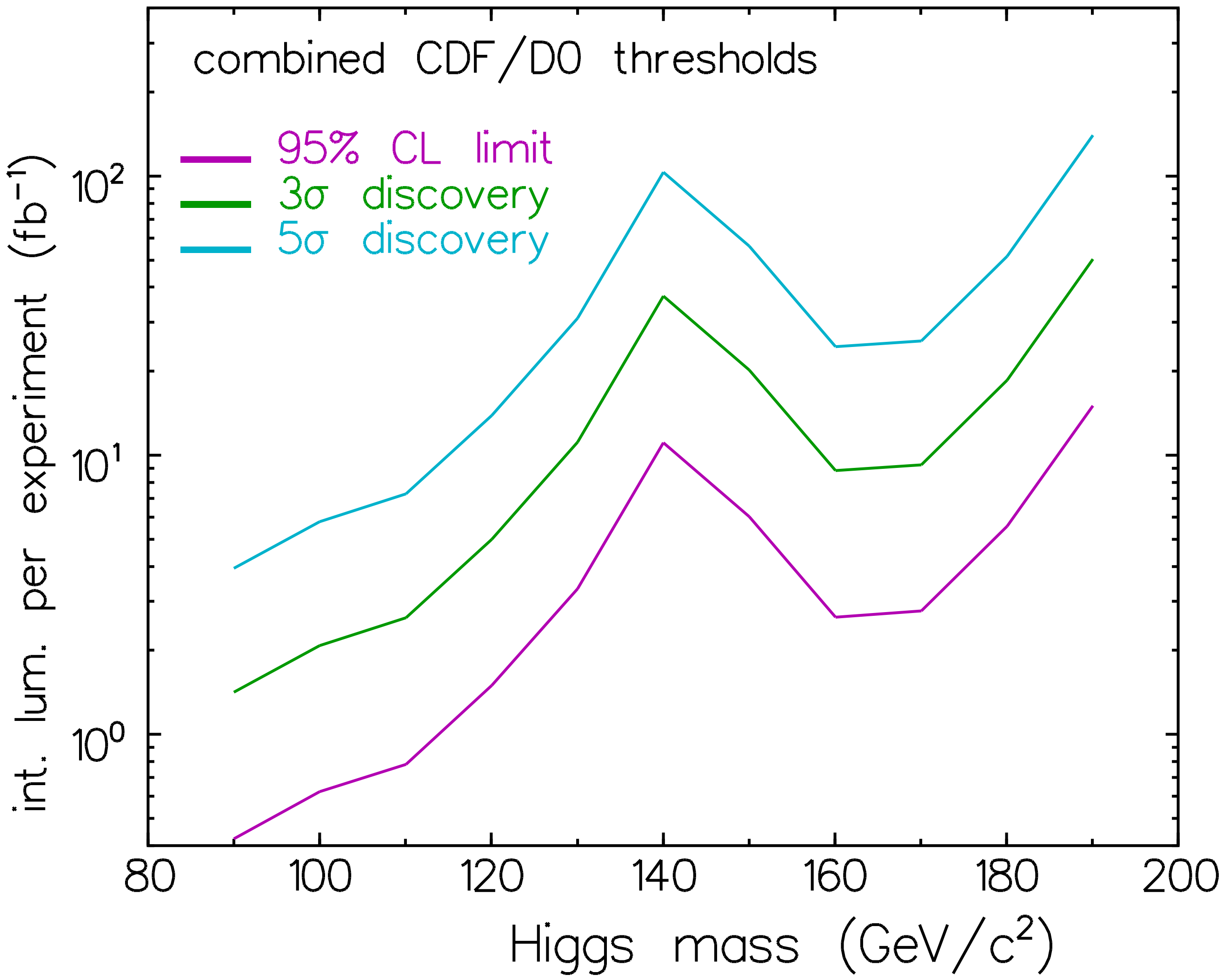


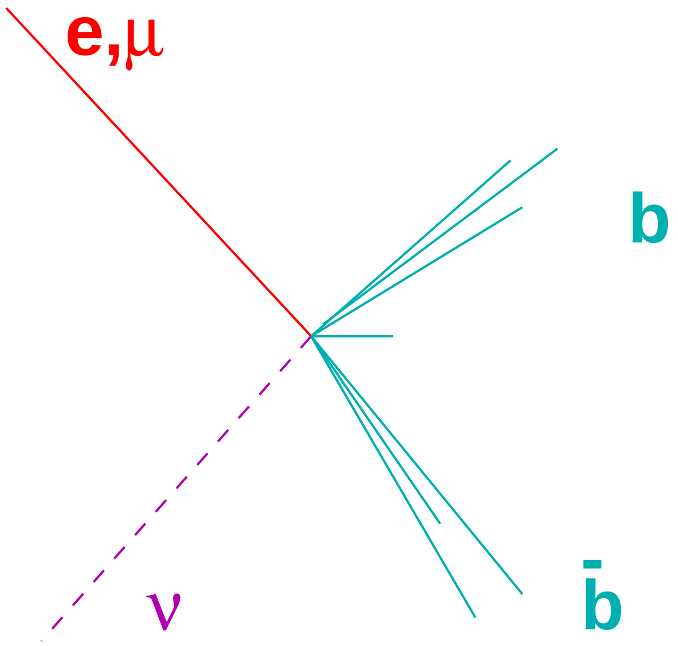
Combined channel thresholds

- $\rightarrow$ Gaussian approximation in combination
- $\rightarrow$ 30% better $m_{b\bar{b}}$ resolution than Run 1
- $\rightarrow$ Run 2 acceptance $\times$1.3 NN improvement
- $\rightarrow$ 10% systematic error on background
- $\rightarrow$ all except $\ell^{\pm}\ell^{\pm}jj$



SM Higgs in $\ell\nu b\bar{b}$ channel

Ela Barberis, Weiming Yao, Pushpa Bhat, Harrison Prosper, Wasiq Bokhari, Russel Gilmartin



typical selection:

- inclusive high-p_T lepton trigger (ϵ_μ ~95%)
- central e, or μ with $\mathrm{E_T(p_T)} > 20$ GeV
- $\not{E}_T$ >20 GeV
- no Z's: $m_{\ell\ell}$ not 75-105 GeV/c^2
- two jets: one tight b, one loose b

main backgrounds: $Wb\bar{b}$, $t\bar{t}$, WZ, single top

Cross check with Snowmass study (events in 10 fb^{-1}):

m(H)=100 GeV/c^2

	Snowmass	Workshop
signal	95	66
background	466	687

m(H)=120 GeV/c^2

	Snowmass	Workshop
signal	49	37
background	248	624

$\rightarrow$ slightly disturbing,but understood

- Snowmass study used parametrized resolutions

- Workshop study used actual detector MC, scaling

E. Barberis: cross check W.M. Yao with SHW

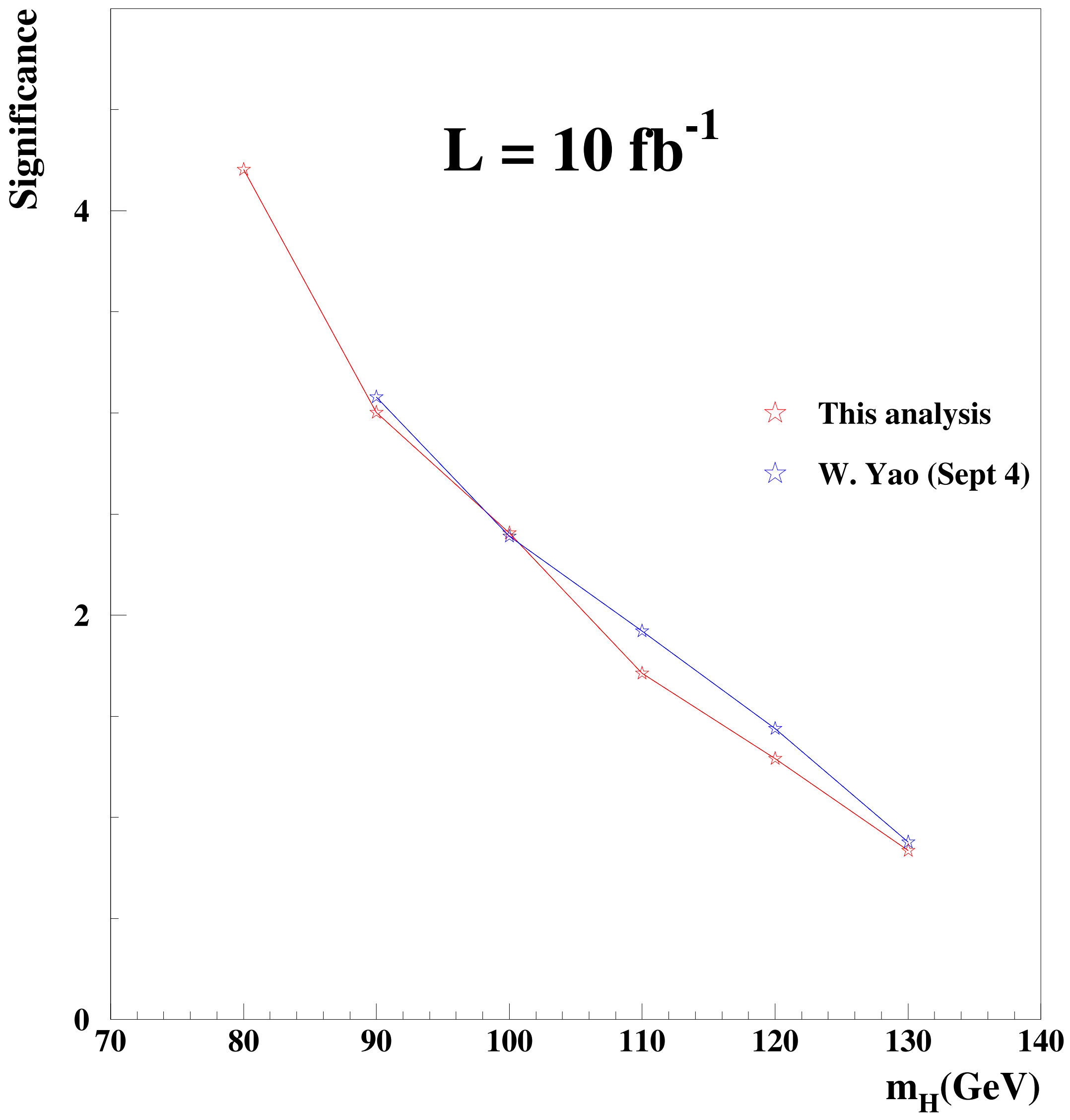
- similar cuts
- same parametrization of b tagging
- PYTHIA/SHW for signal
- COMPHEP for $Wb\bar{b}$ background

Events in 1 fb^{-1} at $m(H) = 110$ GeV/c^2:

	Yao	Barberis
HW	5.0	4.5
$Wb\bar{b}$	27.8	26.8
$t\bar{t}$	14.0	20.6
WZ	7.2	5.9
single top	13.8	9.2
total	62.8	62.5

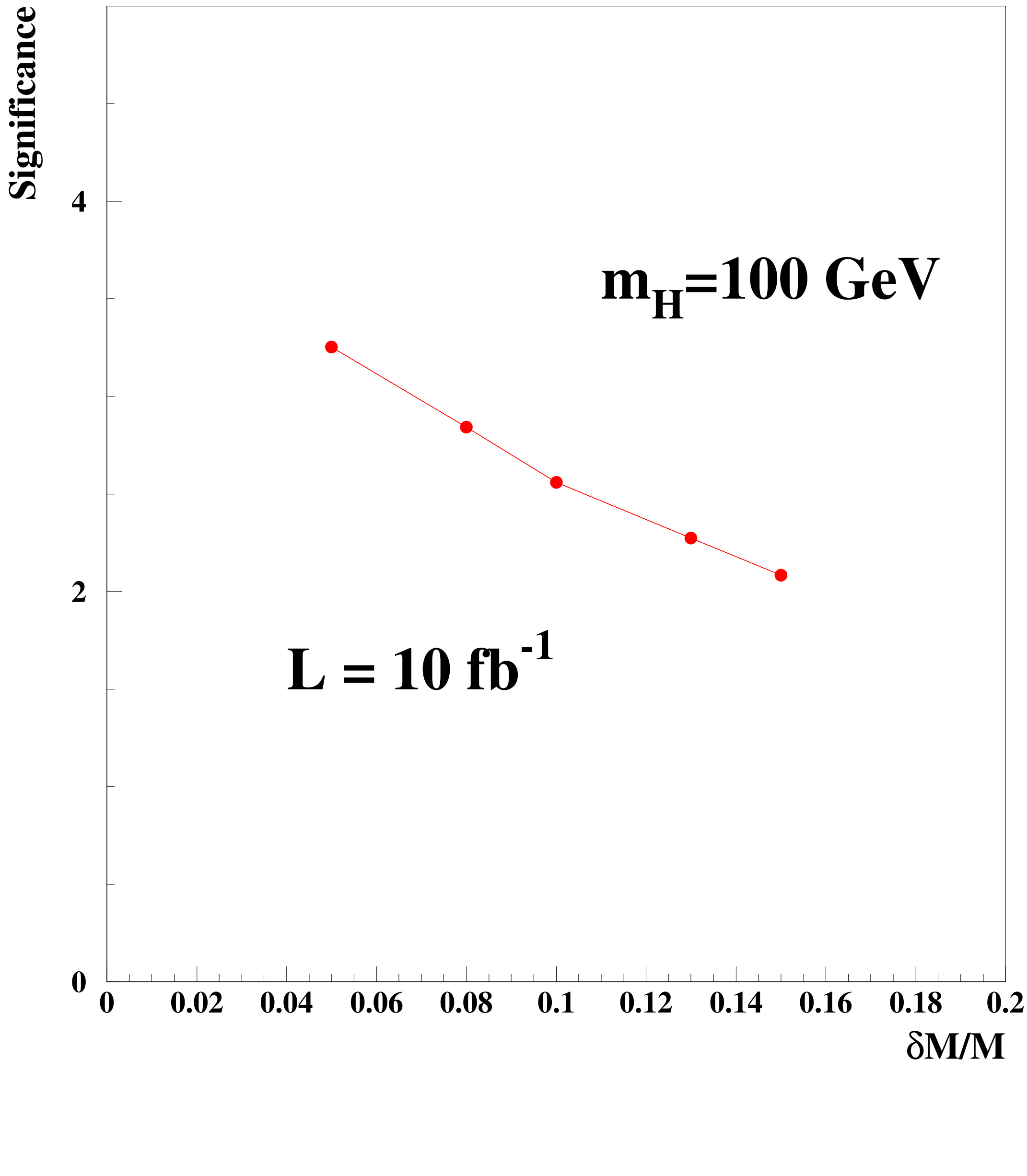
$\rightarrow$ very reasonable agreement!

compare Yao, Barberis/SHW over full mass range:



$\rightarrow$ builds confidence in SHW simulation

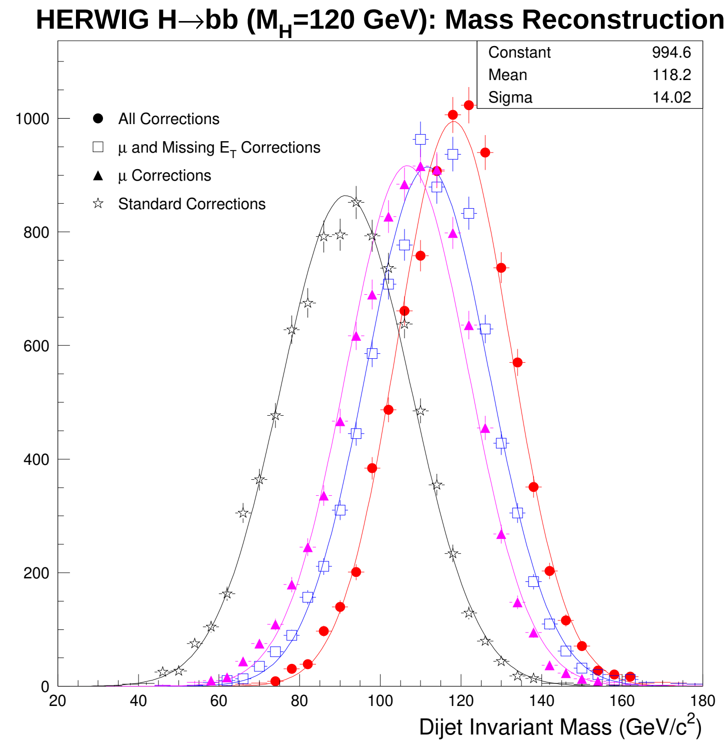
Barberis: dependence on mass resolution



→ can reasonably hope for 10% mass resolution

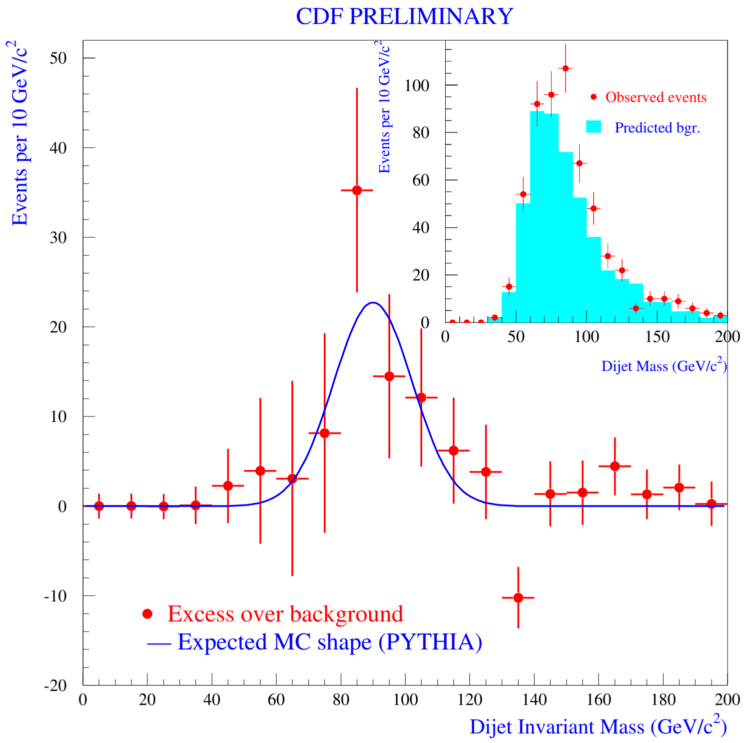
Studies of $b\bar{b}$ mass resolution

Steve Kuhlmann, Stefano Lami, Rob Snihur, Tommaso Dorigo, Alberto Ribon, ...

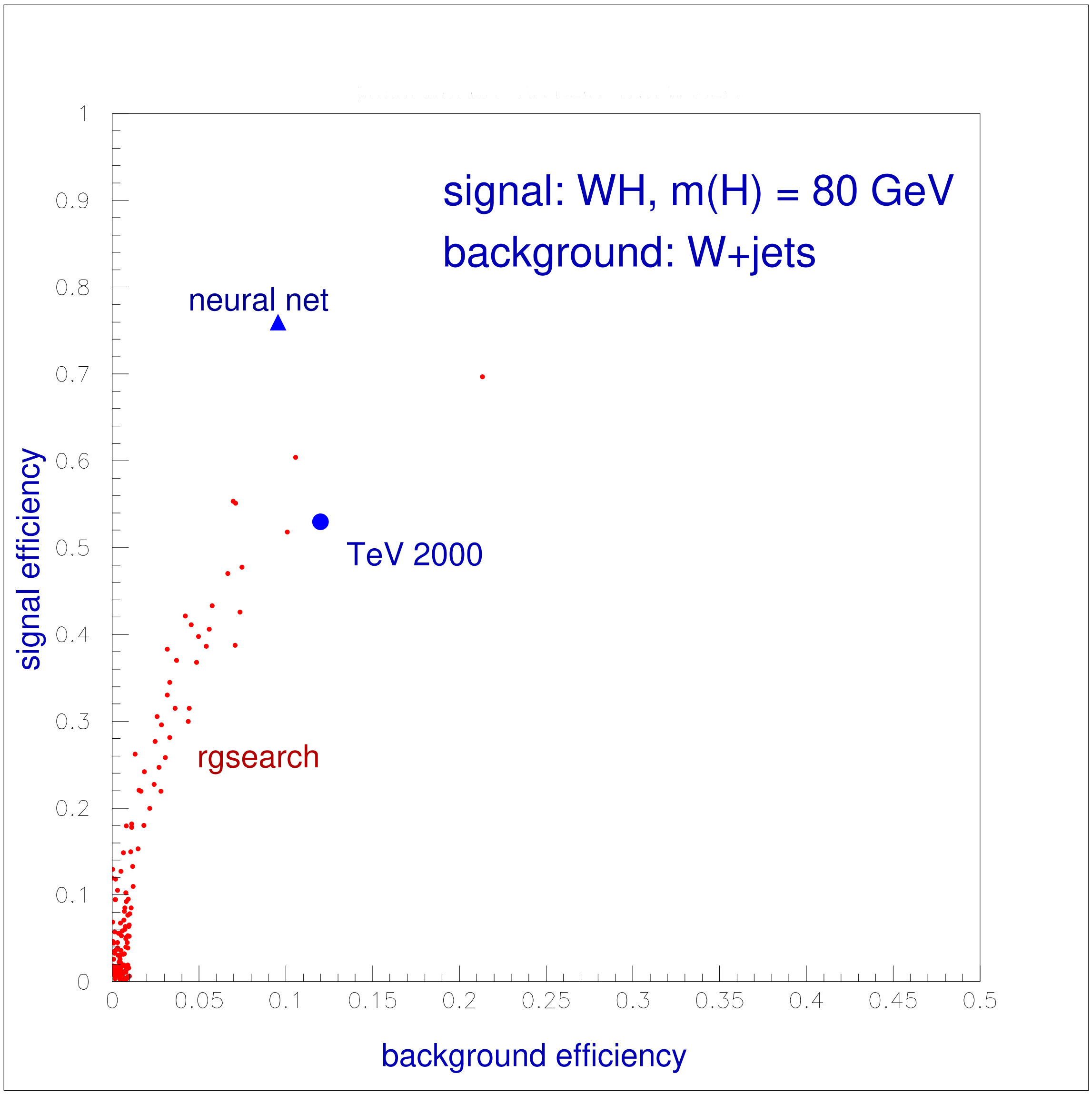


make various corrections...

...can see $Z \to b\bar{b}$



Pushpa Bhat: studies of selection optimization



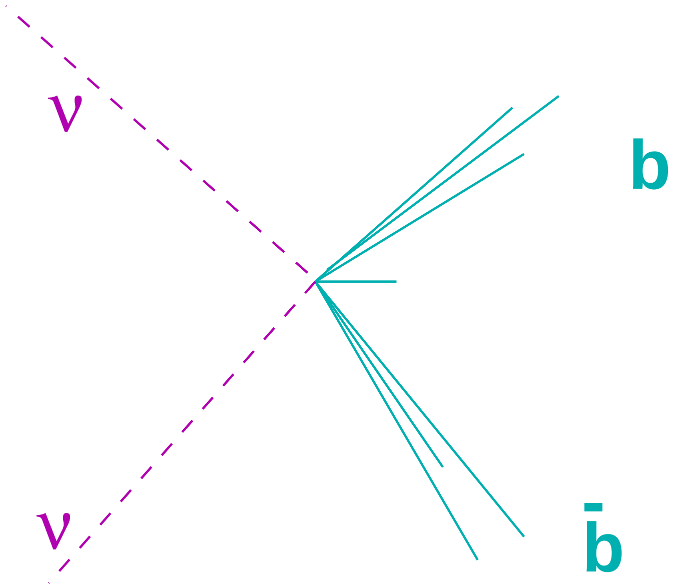
$\rightarrow$ improvement possible with these techniques compare $S/\sqrt{B}$ with and without neural net:

$m(H)$ (GeV/c^2)	cuts	net
80	1.1	1.8
90	0.9	1.3
100	0.7	1.0
110	0.4	0.7
120	0.3	0.6
130	0.2	0.4

$\rightarrow$ significant improvements possible!

SM Higgs from $ZH, Z \to \nu\bar{\nu}$

Weiming Yao, Wasiq Bokhari, Regina Demina, Mark Kruse, Ben Kilminster, Dave Hedin



typical selection:

- $\not\!\!E_T$ +jets trigger (Run 1: $\not\!\!E_T$ >35 GeV)
- two tagged b-jets, E_T >15 GeV, $|\eta| < 2$
- no extra jets
- no isolated tracks

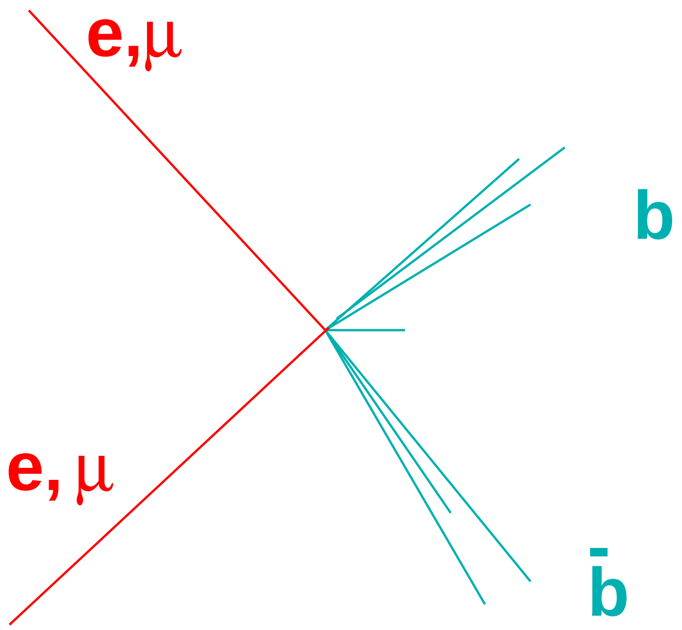
main backgrounds: $Zb\bar{b}$, ZZ, $t\bar{t}$, $W^* \to t\bar{b}$

→ most powerful channel at low masses!

	Yao			Jesik		
mass (GeV/c^2)	S	B	$S/\sqrt{B}$	S	B	$S/\sqrt{B}$
90	2.5	10	0.8	8.6	39	1.2
100	2.2	9.3	0.7	6.4	38	1.0
110	1.9	8.0	0.7	4.4	36	0.7
120	1.2	6.5	0.5	3.1	34	0.5
130	0.6	4.8	0.3	2.0	41	0.3

SM Higgs from $ZH, Z \to \ell^+\ell^-$

Weiming Yao, Mark Kruse, Ben Kilminster



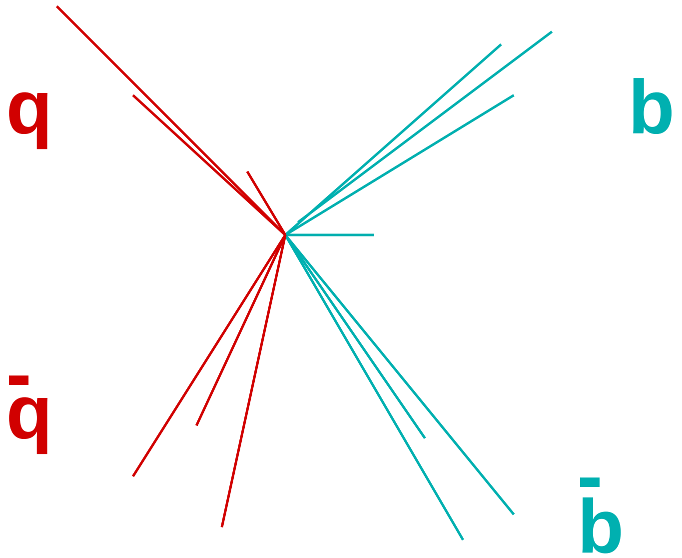
typical selection:

- inclusive lepton trigger
- two leptons (e or μ), E_T >20/10 GeV, $|\eta| < 2$
- two tagged b-jets, E_T >15 GeV, $|\eta| < 2$
- no extra jets

main backgrounds: $Zb\bar{b}$, ZZ, $t\bar{t}$, $W^* \to t\bar{b}$

SM Higgs in the four-jet channel

Anna Goussiou, John Hobbs, Juan Valls, Rocio Vilar



typical selection:

- multijet trigger (Run 1: four jets)
- two tagged b-jets, E_T >15 GeV, $|\eta| < 2$
- two more jets

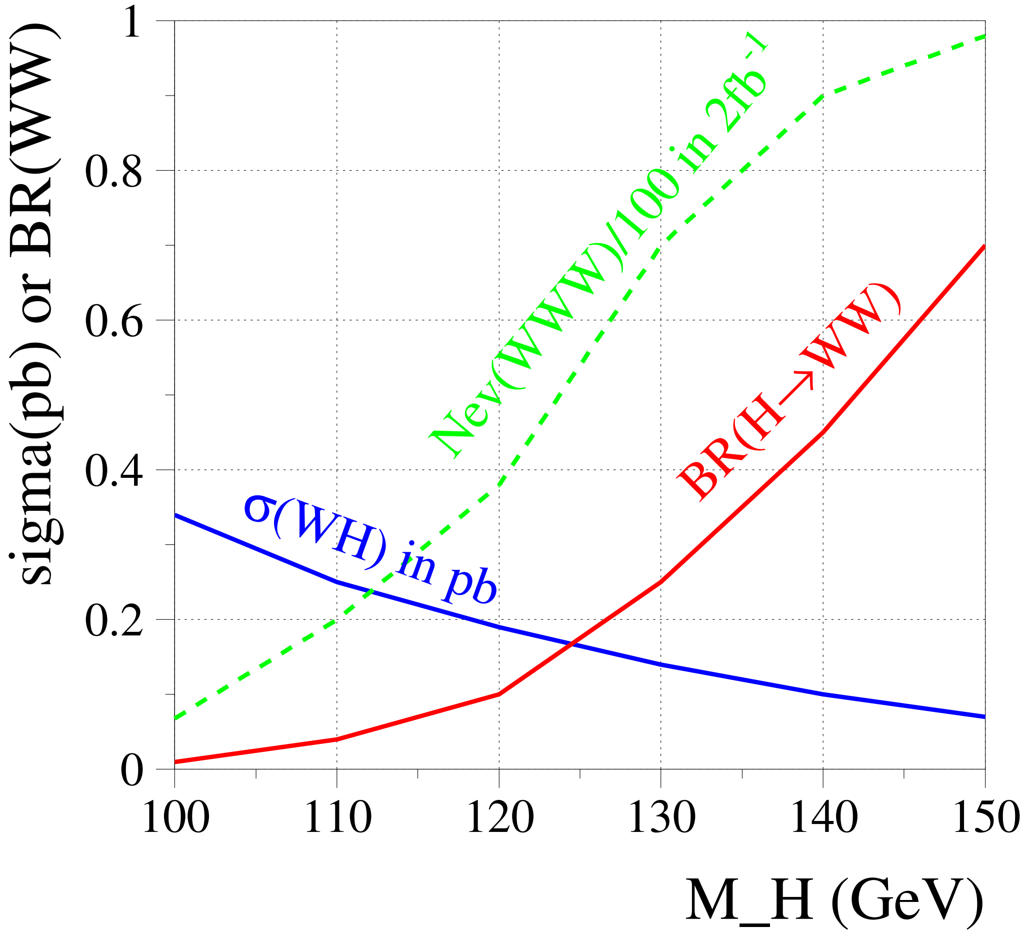
main background: multijet events (lots of 'em)

SM Higgs in WW^*, WWW^*, ZWW^* modes

Michael Schmitt, Andre Turcot

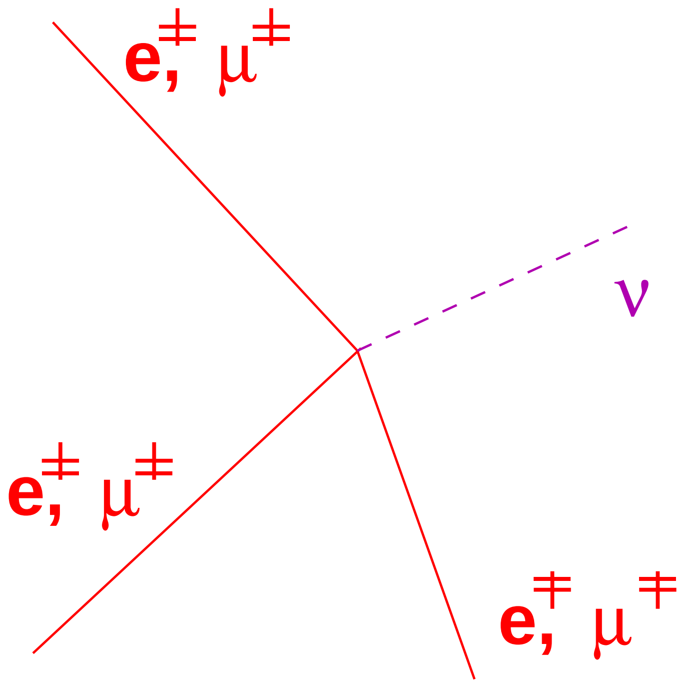
idea: exploit $H \to WW^*$ decays at higher masses

- $gg \to H \to WW^*$
- $ZH \to ZWW^*$
- $WH \to WWW^*$



$\rightarrow$ dilepton, trilepton, like-sign dilepton plus jets

$VH \to WWW^*/ZWW^*$, $\ell^\pm \ell'^\pm \ell^\mp$ channel

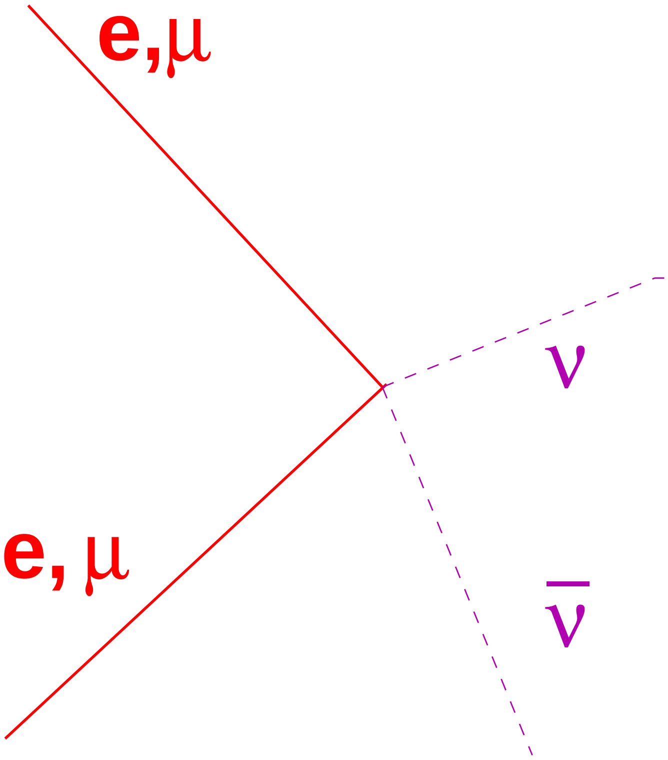


selection:

- dilepton trigger
- two leptons (e or μ), E_T >10/5 GeV, $|\eta| < 2$

main backgrounds: WW, WZ, ZZ

$\underline{gg \to H \to WW^* \to \ell^+\ell'^-\nu\bar{\nu}}$



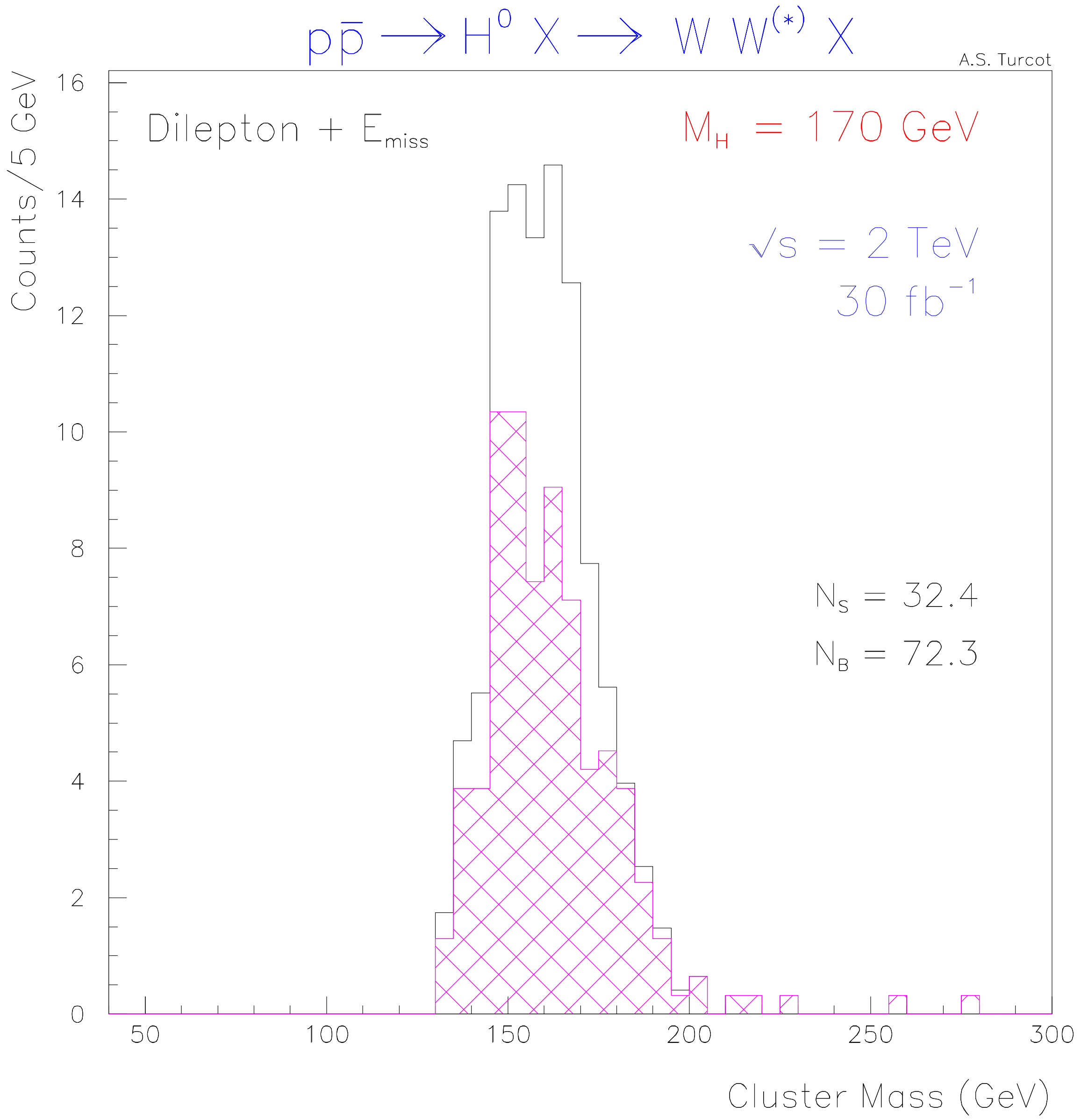
selection:

- dilepton trigger
- two leptons (e or μ), E_T >10/5 GeV, $|\eta| < 2$
- no more leptons
- no other jets, $E_T >$ 15 GeV, $|\eta| < 3$
- $\Delta\phi_{\ell\ell} < 160^\circ$
- $\not{E}_T > 10$ GeV
- not Z
- $-0.3 < \cos\theta^* < 0.8$

main background: WW!

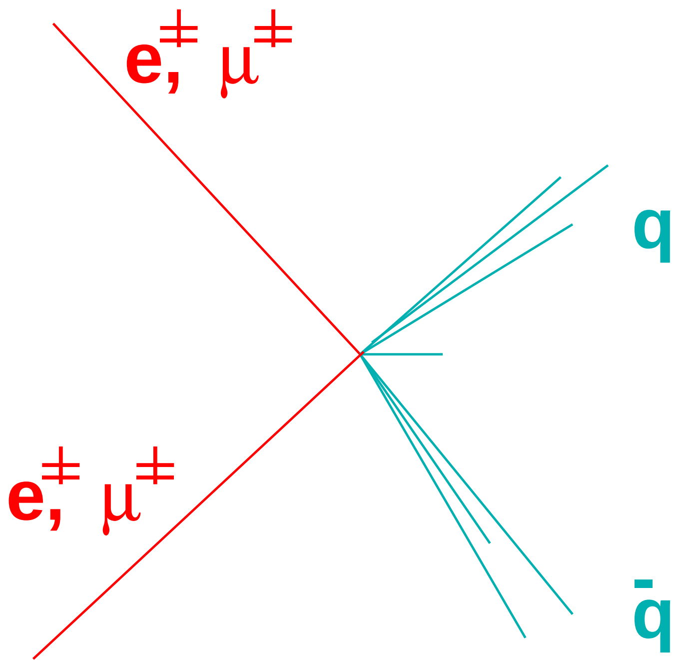
$\rightarrow$ lots of finely tuned cuts

$\rightarrow$ use "cluster transverse mass" to sharpen mass



$$M_C \equiv \sqrt{p_T^2(\ell\ell) + m^2(\ell\ell)} + \not{E}_T$$

$VH \rightarrow WWW^*/ZWW^*$, $\ell^{\pm}\ell^{\pm}jj$ channel



selection:

- dilepton trigger
- two leptons (e or μ), E_T >10/5 GeV, $|\eta| < 1.5$
- same sign
- $\Delta R_{\ell j} > 0.4$
- $\not{E}_T > 10$ GeV
- $N_{jet} > 2$, $|\eta| < 1.5$, $E_T > 20$ GeV, not b
- $25 < m_{jj} < 110$ GeV

main backgrounds: WZ, ZZ

$\rightarrow$ most powerful channel at high masses!

Compare two similar selections for $\ell^{\pm}\ell^{\pm}jj$:

mass	Turcot			Schmitt		
(GeV/c^2)	S	B	$S/\sqrt{B}$	S	B	$S/\sqrt{B}$
120	0.10	0.85	0.11	0.04	1.53	0.03
130	0.20	0.85	0.22	0.08	1.53	0.07
140	0.34	0.85	0.37	0.11	1.53	0.09
150	0.53	0.85	0.57	0.15	1.53	0.12
160	0.45	0.85	0.49	0.08	1.53	0.08
170	0.38	0.85	0.41	0.06	1.53	0.07
180	0.29	0.85	0.31	0.04	1.53	0.03
190	0.20	0.85	0.22	0.02	1.53	0.016
200	0.16	0.85	0.17	0.02	1.53	0.016

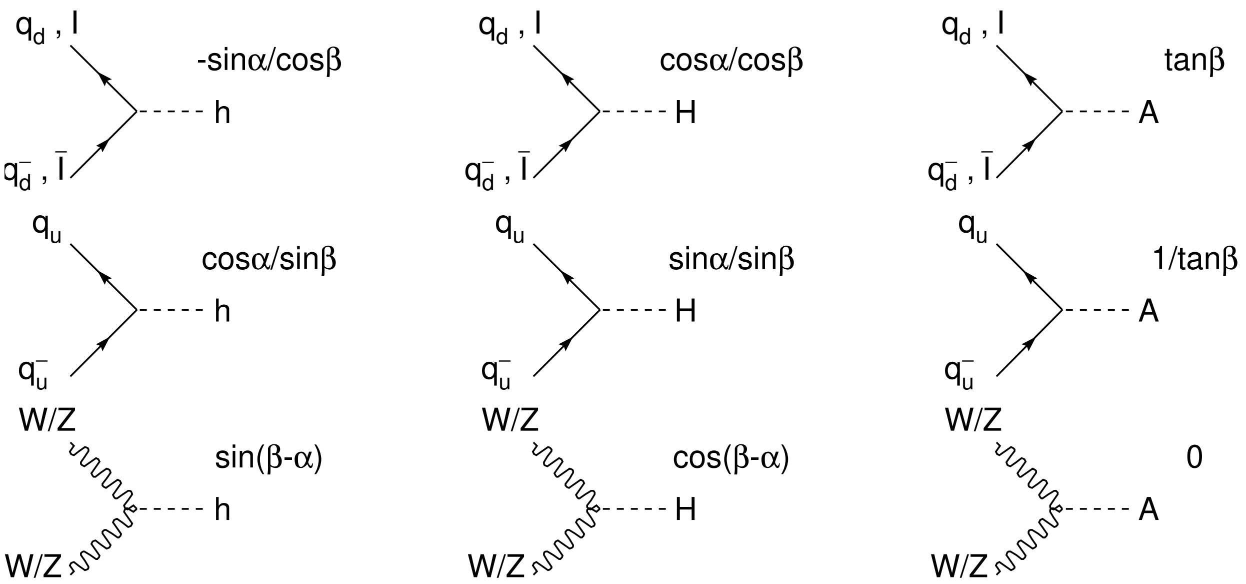
Background breakdown:

	WW	WZ	ZZ	$t\bar{t}$	VVV	ttV	DY	Wjj	total
Turcot	-	0.26	0.06	0.18	0.07	0.2	-	0.1	0.85
Schmitt	0.4	0.2	0.1	0.8	-	-	0	-	1.5

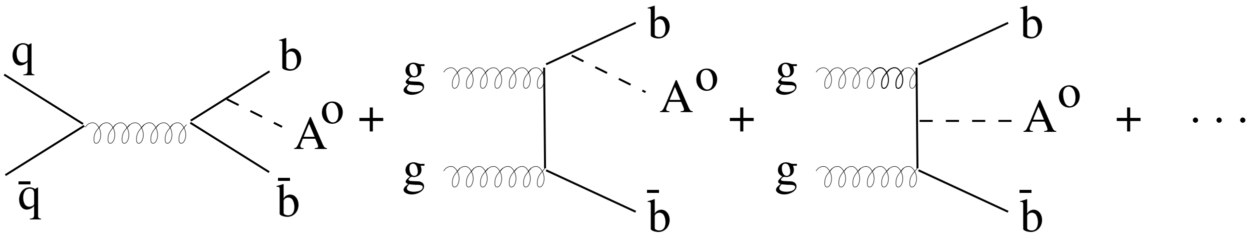
$\rightarrow$ resolve this before including in combination

Strong SUSY Higgs Production

Maria Roco, A. Belyaev, Juan Valls, John Conway, Leslie Groer



$\rightarrow$ $b\bar{b}A/b\bar{b}h/b\bar{b}H$ enhanced at large tan β



search modes:

- $b\bar{b}b\bar{b}$
- $\tau\tau j \not{E}_T$
- $\tau b j \not{E}_T$

$\rightarrow$ very exciting, theoretically and experientally

Strong SUSY Higgs event generation

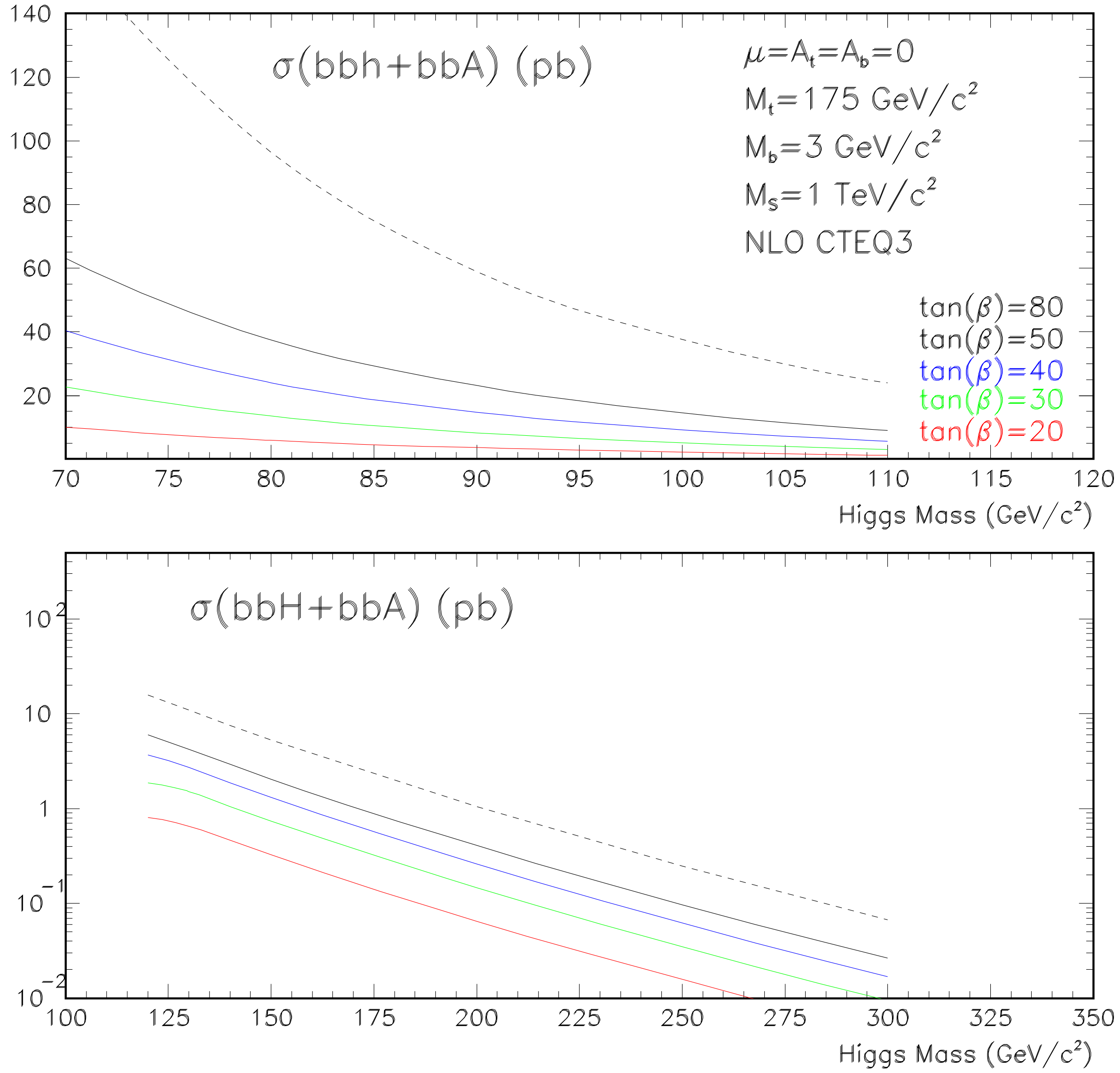
There are at least six generators for $b\bar{b}\phi$:

- PYTHIA (old implementation)
- Drees/Guchait/Roy (PRL.80:2047-2050,1998)
- "Tait-1" generator (modified PAPAGENO)
- Carena/Mrenna/Wagner (hep-ph/9808312)
- "Tait-2" generator (C++, MADGRAPH)
- COMPHEP

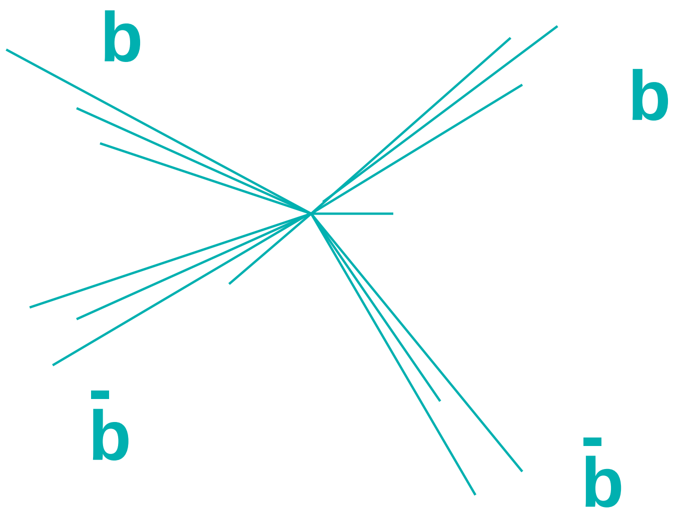
$\rightarrow$ lots of work in verifying final state kinematics and cross sections

$\rightarrow$ we are using Mrenna generator and COMPHEP

cross sections are large!



Strong SUSY Higgs: $b\bar{b}b\bar{b}$ mode



Roco selection:

- multijet trigger
- 4 jets, $E_T > 15$ GeV, $|\eta| < 2$
- leading jet $E_T > M(H)/2 - 5$ GeV
- $\sum E_T$ of jets 3 and 4 > 30 GeV
- at least 3 b tags

$\rightarrow$ plot all mass combinations, use window signal/background after $b\bar{b}b\bar{b}$ selection:

mass (GeV/c^2)	S ($\tan\beta = 1$)	S ($\tan\beta = 40$)	B	$S/\sqrt{B}$
90	0.24	379	4308	5.78
100	0.19	310	4040	4.88
110	0.16	253	3818	4.09
120	0.12	196	3564	3.28
130	0.10	157	3270	2.74
140	0.07	119	2835	2.24
200	0.02	28	1229	0.80
250	0.01	8	585	0.34
300	0.00	3	334	0.14

$\rightarrow$ next apply mass wondow cuts

$\rightarrow$ then add together $Ab\bar{b}$, $Hb\bar{b}$, and $hb\bar{b}$

Note: at large $\tan\beta$, $h/H \rightarrow b\bar{b}$ still dominates!

Compare the two analyses (SM $b\bar{b}H$):

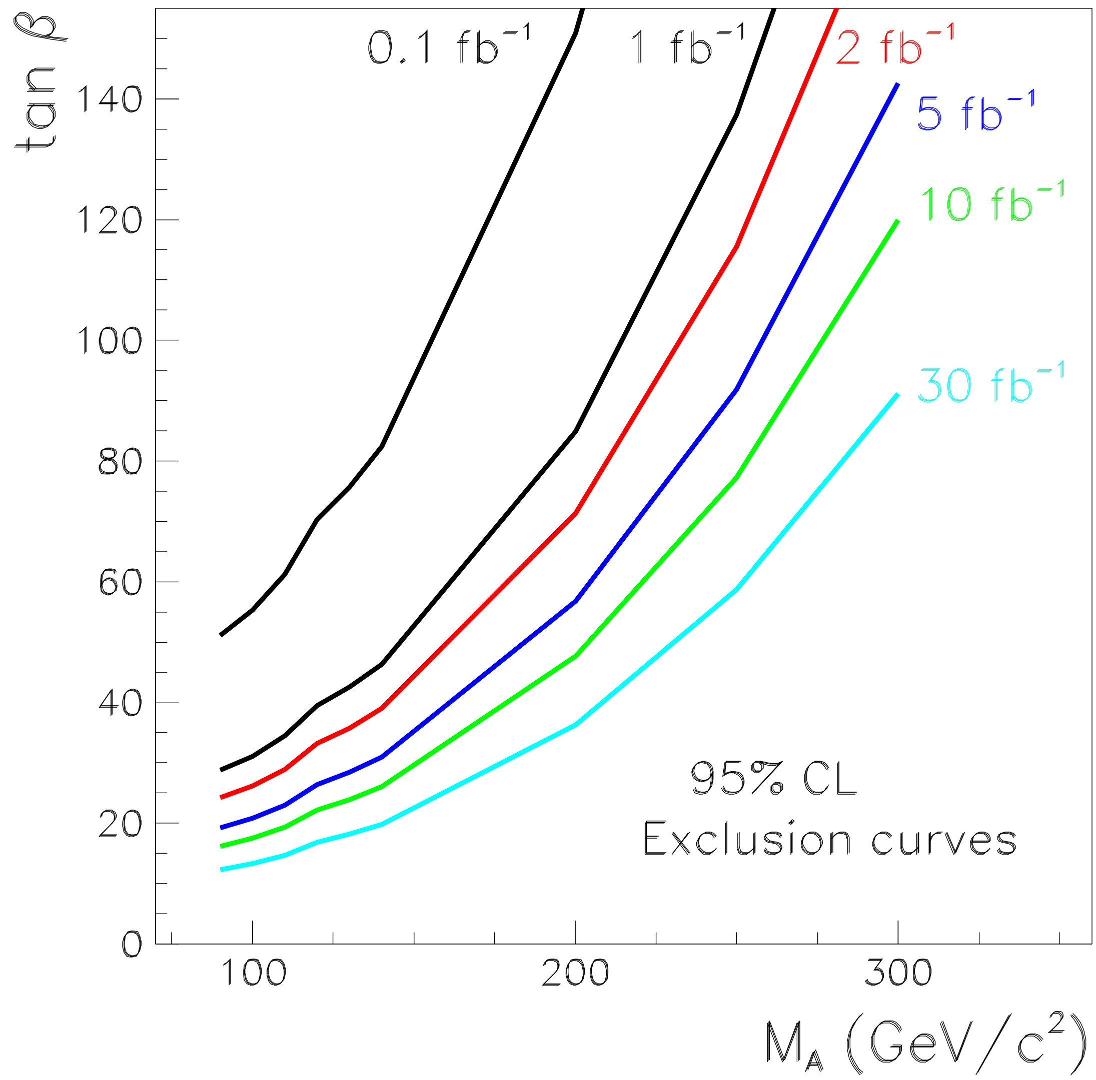
mass (GeV)	Roco S	Roco B	Roco $S/\sqrt{B}$	Valls S	Valls B	Valls $S/\sqrt{B}$
90	0.12	3141	0.00218	0.0178	84.2	0.00194
100	0.10	2920	0.00187	0.0159	73.7	0.00185
110	0.082	2917	0.00153	0.0072	67.4	0.00088
120	0.057	2462	0.00116	0.0049	65.3	0.00061
130	0.046	2094	0.00100	0.0025	63.0	0.00031
140	0.033	1600	0.00085	0.0012	46.3	0.00018

Valls:

Mrenna generator, background from data, no mass cut

Roco:

COMPHEP signal, PYTHIA background, mass window limits in $\tan\beta$ versus m_A plane:

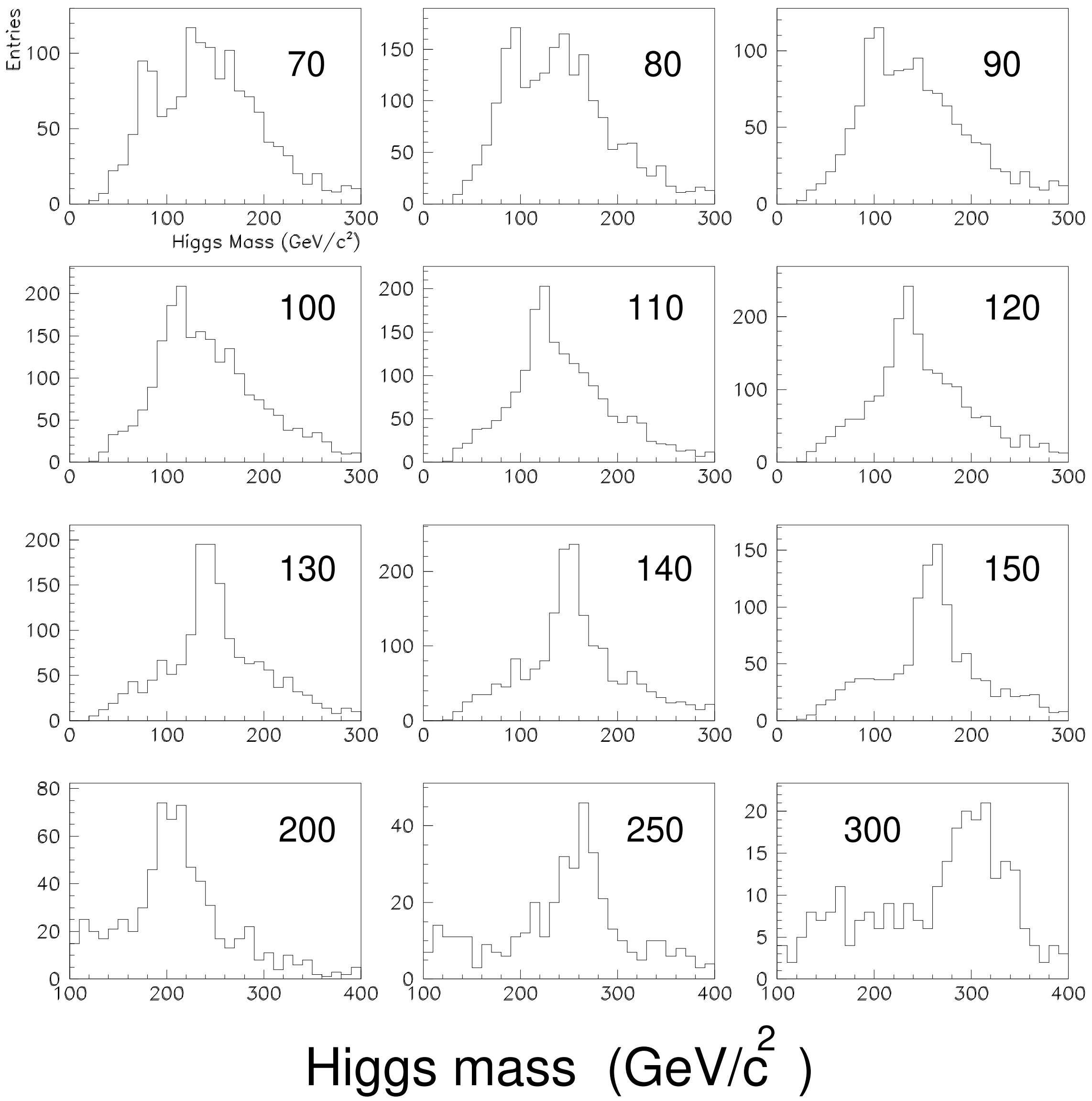


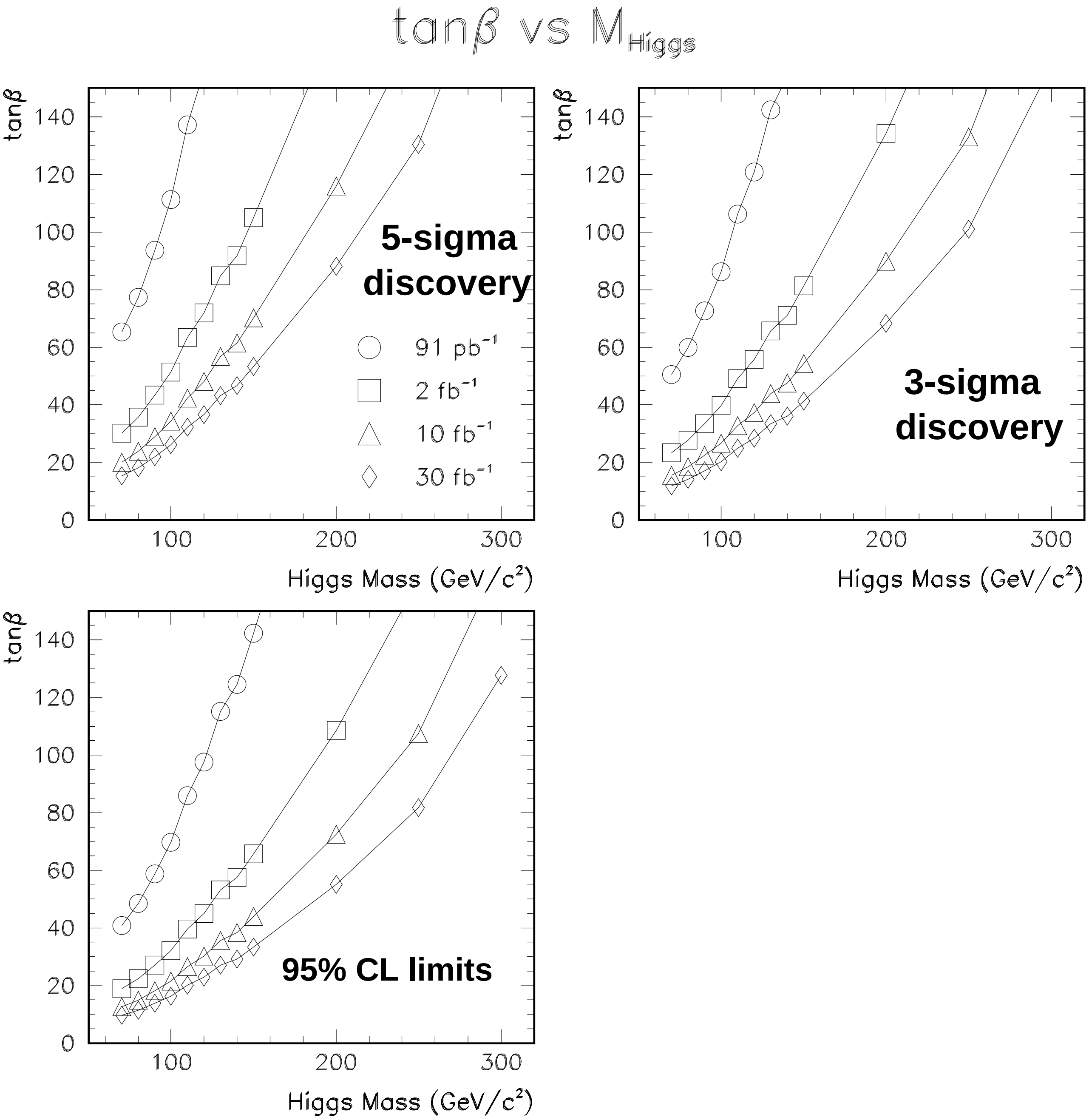
Valls selection:

- multijet trigger
- 4 jets, $E_T > 15$ GeV, $|\eta| < 2.1$
- at least 3 b tags

$\rightarrow$ get background normalization from data

$\rightarrow$ choose only one mass combination

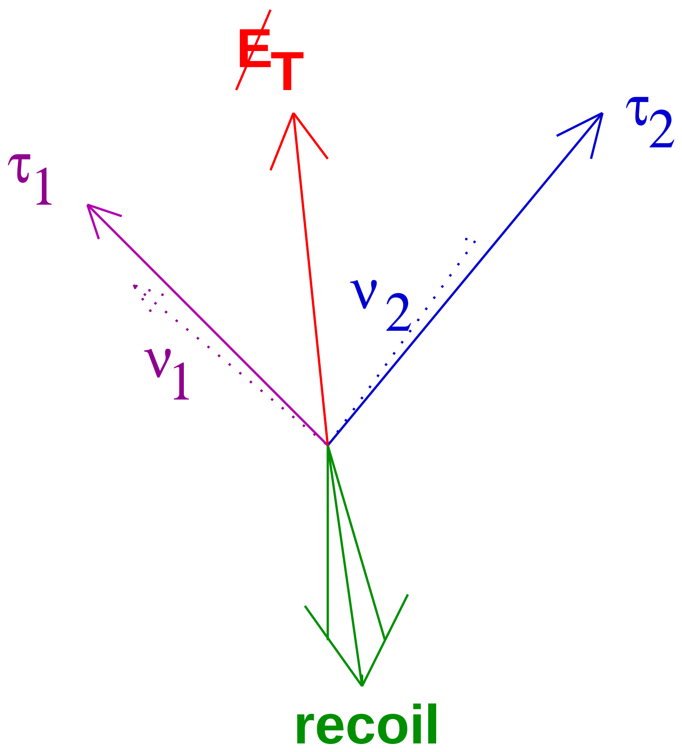



tanβ vs M_Higgs
5-sigma discovery
3-sigma discovery
95% CL limits
91 pb⁻¹
2 fb⁻¹
10 fb⁻¹
30 fb⁻¹
tanβ
Higgs Mass (GeV/c²)

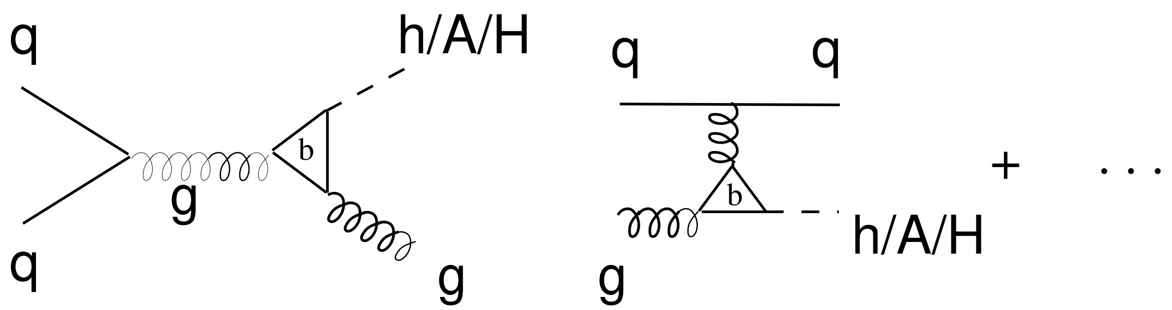
Strong SUSY Higgs: $b\bar{b}\tau\tau$ mode

$\rightarrow$ smaller signal (x10) but smaller background (x6)!

$\rightarrow$ can reconstruct tau pair mass in $\tau\tau j \not{E}_T$ mode:



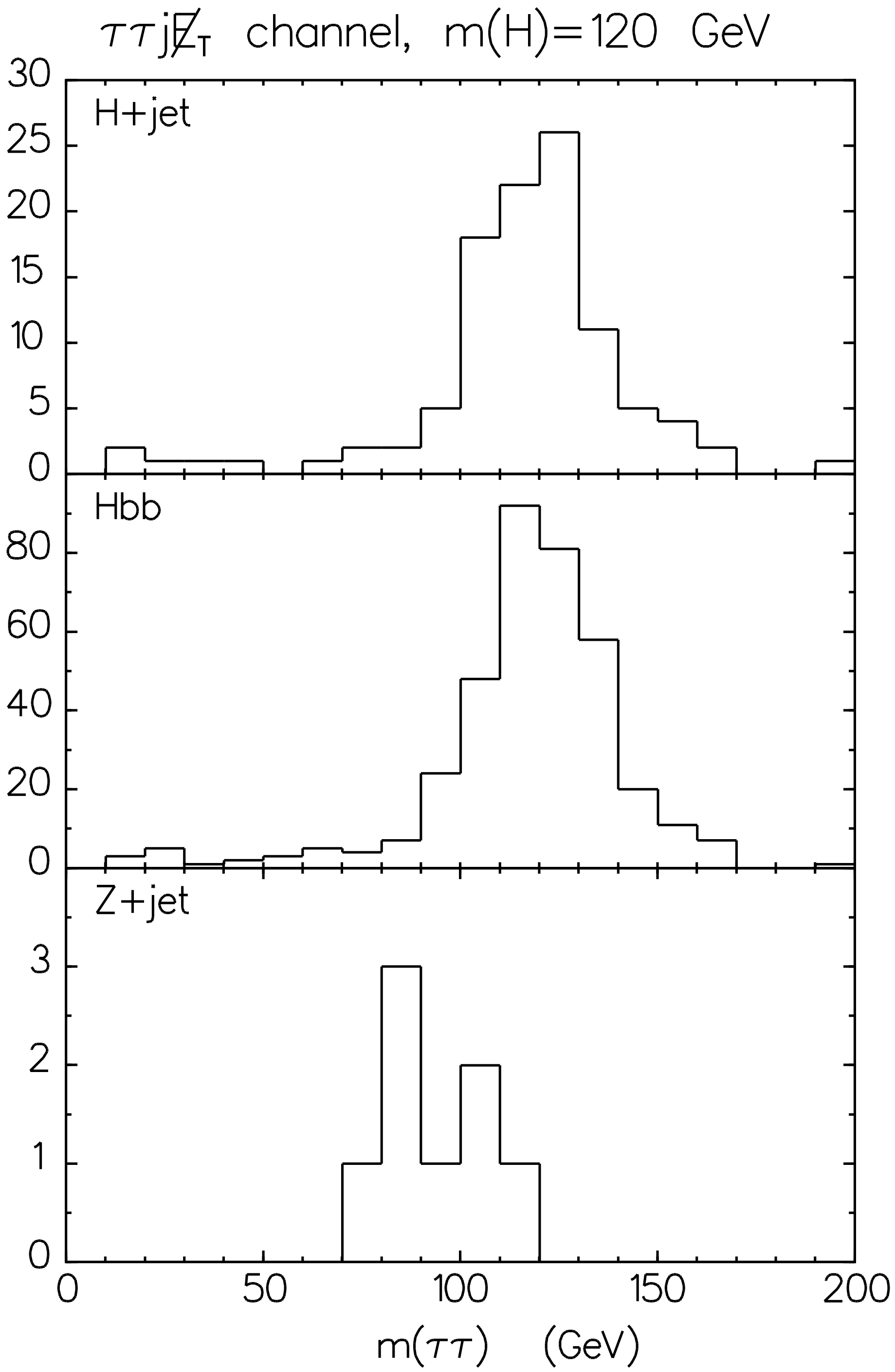
$\rightarrow$ sensitive to $b\bar{b}\phi$, and also ϕ+jet:



tau pair mass in $\tau\tau j \not{E}_T$ channel

selection:

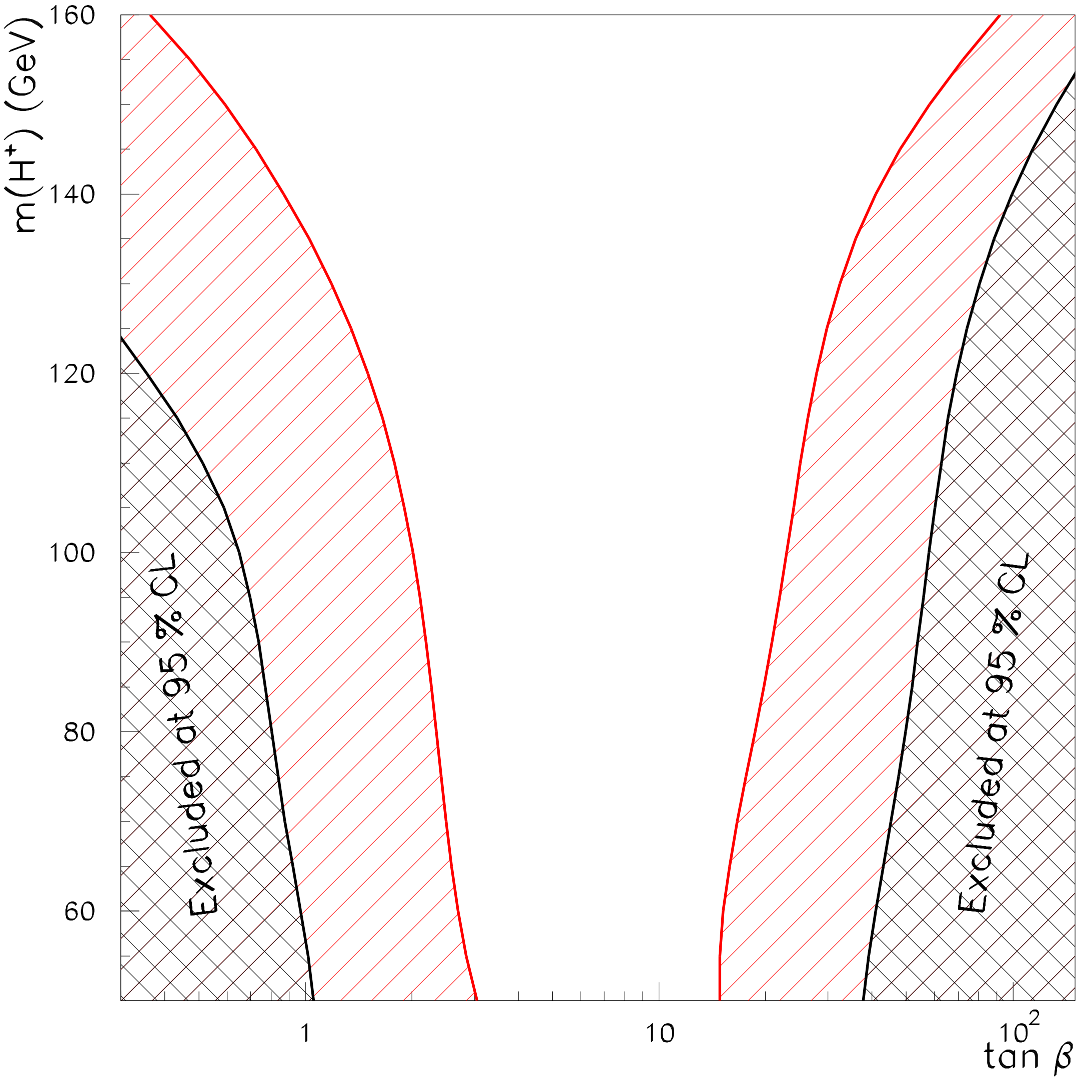
- τ (hadronically decaying), $E_T > 20$ GeV
- e, μ, or τ, $E_T > 20$ GeV
- $\not{E}_T > 30$ GeV
- $\Delta\phi_{\tau\tau} < 140°$



charged Higgs

Dhiman Chakraborty

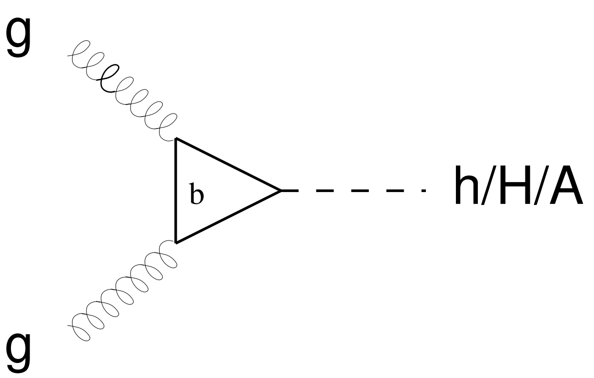
From standard $t\bar{t}$ analyses, can rule out competing decay mode of $t \to H^{\pm}b$:

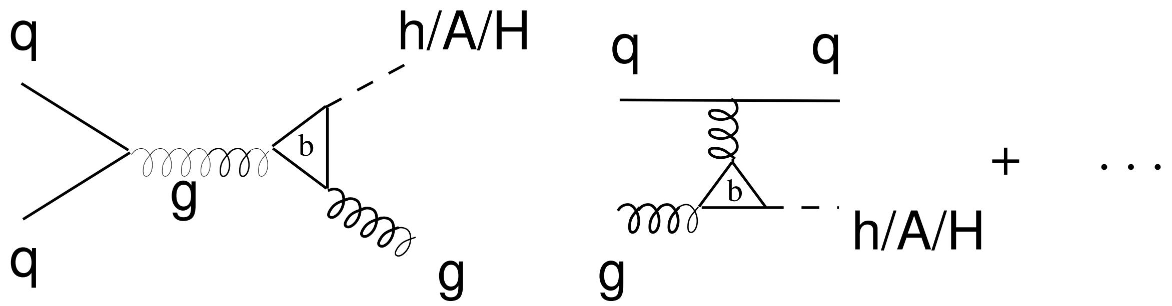


$\to$ other modes possible: H^+H^-, W^+H^-, ...

Have we left any stones unturned?

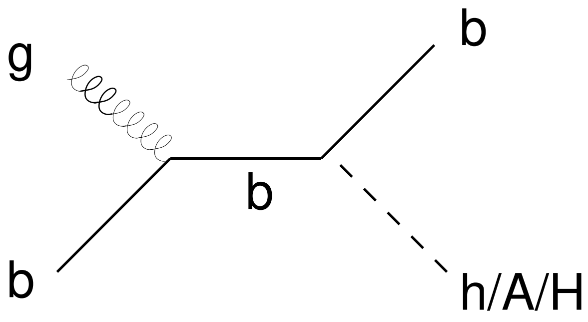
SUSY single Higgs and Higgs plus jet are enhanced at large $\tan\beta$:





...and...

Choudhury, et al.
hep-ph/9809552



$\rightarrow$ need predictions for cross section, kinematics!

Theorists are very excited about other strong SUSY Higgs production modes...this is a growth industry!

Summary: SM Higgs

- We have greatly extended the depth and breadth of previous studies of Higgs reach at Run 2 and beyond.

- There is no single, golden discovery channel: combining all channels, and both experiments, is crucial!

- If there is no SM Higgs, we can exclude it at 95% CL up to 120 GeV mass in Run 2, and with 10 fb^{-1} can extend the exclusion up to 190 GeV mass.

- If there is a Higgs, we can discover it at the 3-5σ level with 30 fb^{-1} per experiment, up to 190 GeV mass.

- To do this we need:
  - solid control of $Wb\bar{b}$, $Zb\bar{b}$, diboson backgrounds
  - improved $m_{b\bar{b}}$ resolution, $\sim$ 10% or better
  - better b tagging efficiency/purity
  - lepton coverage for $|\eta| < 2$
  - both experiments' data!