Higgs Working Group: Experimental Summary Report

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"Physics at the TeV Collider Workshop"
Les Houches, June 6th 2003

Summary of Activities

- B. Mellado "VBF Studies in ATLAS"
- W. Wu "Higgs Searches by FNAL/CMS group"
- S. Shevchenko "$qq \rightarrow qqH$, $H \rightarrow \gamma\gamma$"
- F. Moortgat "$A/H \rightarrow SUSY$" and $A/H/h/H^{\pm}$ from SUSY Decays"
- M. Narain "Higgs sensitivity update for Tevatron"
- L. Dudko "Optimization in NN analysis of Higgs searches at the Tevatron"
- P. Gras "$gg \rightarrow bbA/H$, $A/H \rightarrow bb$ in MSSM"
- A. de Roeck "Diffractive Higgs production: $pp \rightarrow ppH$"
- S. Gennai "Radion Searches in CMS"

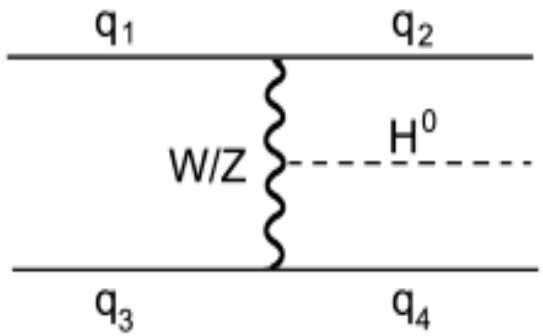
Summary of Activities

- K. Assamagan "$H^{\pm}$ studies in ATLAS"
- S. Lowette "gb $\rightarrow$ t $H^{\pm}$, $H^{\pm} \rightarrow$ tb in CMS"
- S. Lehti "tanβ determination in A/H$\rightarrow$tt in CMS"
- M. Guchait "Higgs $\rightarrow$ Invisible"
- M. Escalier "H$\rightarrow\gamma\gamma$ in ATLAS"
- O. Ravat "WH$\rightarrow l\nu\gamma\gamma$" in CMS
- E. Boos "Intense coupling regime of MSSM"
- K. Mazumdar "Little Higgs Models in CMS"
- T. Barklow "Higgs Couplings Measurements at a 1TeV LC"

Studies of Higgs via VBF in ATLAS

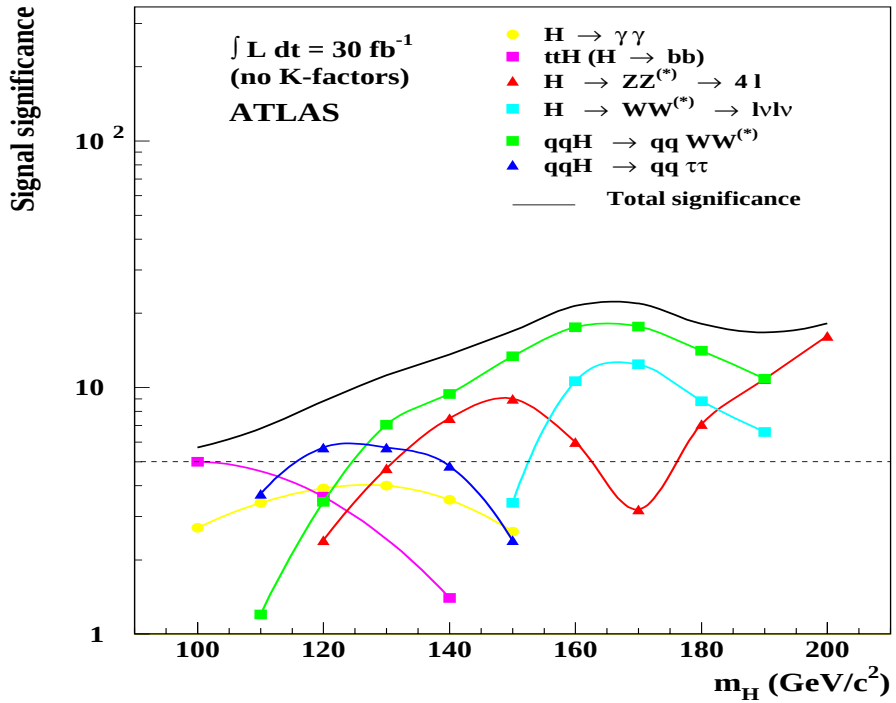
Contributions to the Higgs Working Group

Les Houches 2003



In close collaboration with theorists

U.Baur, S.Frixione, N. Kauer, F.Maltoni, C.Oleari, T.Plehn, D.Rainwater, G.Weiglein, D.Zeppenfeld



VBF ATLAS

- **Central jet veto related issues**
  - **False jet suppression (Mazini, Moraes, Wisconsin)**
    - **Investigate effect of pile up and underlying event**
  - **"Theoretical" central jet veto survival probability (Mazini, Japan, Wisconsin + theorists)**
    - **K factors for VBF. ME and PS matching in MC's**
- **Improvements in MC's for backgrounds**
  - **tt production (Wisconsin + Frixione, Rainwater)**
    - **Comparison of ME and PS. Matching of tt,tt+j,tt+jj**
  - **QCD Zjj (Mazini, Japan, Wisconsin + Rainwater)**
    - **Zjj and Zjjj matching. Application of K factor**
  - **Implementation in Athena (Duehrssen)**

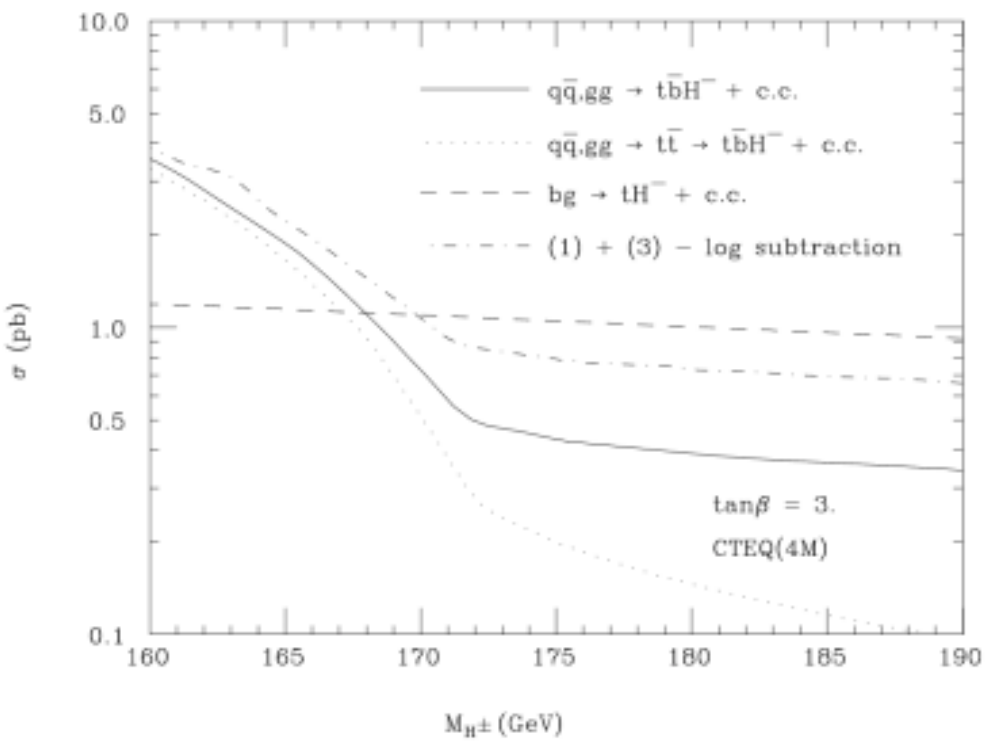
VBF ATLAS

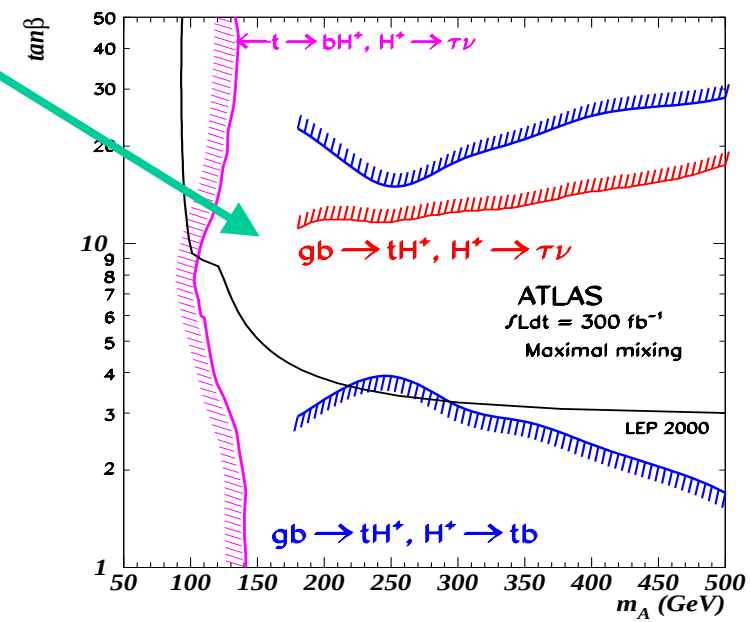
- **K factor for VBF (Escalier, Mazini, Wisconsin + Oleari, Rainwater, Zeppenfeld)**
- **Reducible backgrounds for $\gamma\gamma$ (Escalier, Japan, Wisconsin + Maltoni)**
- **Higgs Couplings**
  - **Extrapolation to high lumi (Duehrssen + theorists)**
  - **For more see D.Zepenfeld's summary talk**
- **Intermediate masses**
  - **H->ZZ->llqq, H->WW->ll (Wisconsin + Zeppenfeld)**
    - **Extension of Higgs coupling studies to intermediate masses**
- **Neural Networks (Wisconsin)**

Charged Higgs Studies in ATLAS

K. Assamagan, M. Guchait and S. Moretti

- Transition region: $m_{H\pm} \sim m_t$
  - Signal: $gg \rightarrow tbH^{\pm}$, $H^{\pm} \rightarrow \tau\nu$, $t \rightarrow jjb$
  - Backgrounds: ttbar & W+jets



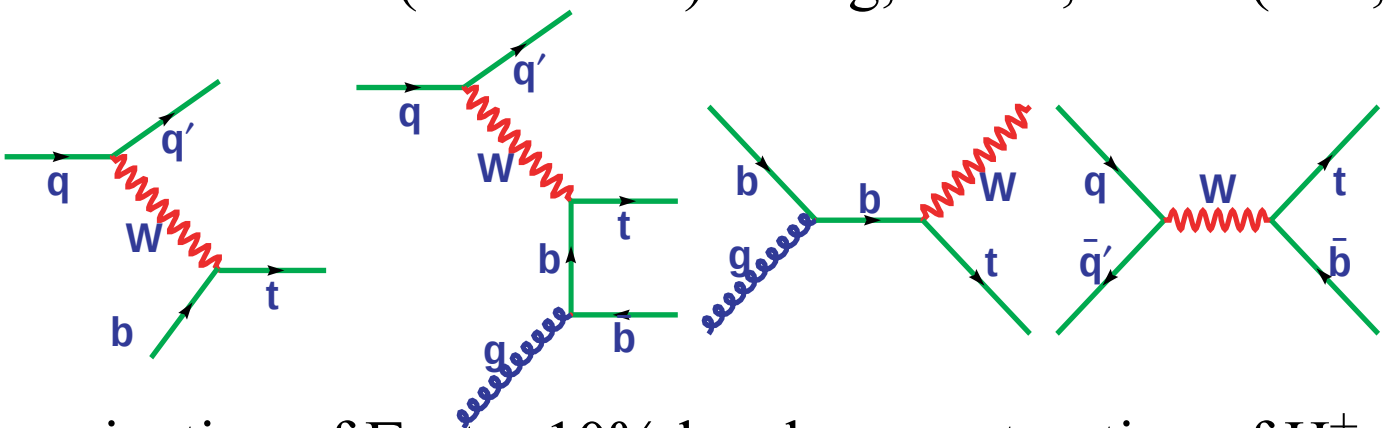


Significant fraction of the Backgrounds already generated

Signal reconstruction also in progress

Charged Higgs Studies in ATLAS

- Determination of Γ_t at LHC to search for new physics: (K. Assamagan & A. Deandrea)
  - By getting $\Gamma(t \rightarrow Wb)$ from measured single top cross-section
  - And $BR(t \rightarrow Wb)$ in ttbar events
  - $t \rightarrow Wb$, $t \rightarrow H^{\pm}b$ (in 2HDM: $H^{+} \rightarrow \tau_L \nu$ and L.E.D.:$H^{+} \rightarrow \tau_L \nu + \tau_R \psi$)
  - FCNC & LFV (2HDM-III): $t \rightarrow cg$, $t \rightarrow cZ$, $t \rightarrow ch$ (h=h,H,A)



Determination of Γ_t at ~ 10% level, reconstruction of $H^{\pm}$ m_T & of charged tracks in 1-prong hadronic t decays $\Rightarrow$evidence for new physics (MSSM or L.E.D.)

Signal generation using TOPREX of CMS (but with ATLFAST!)

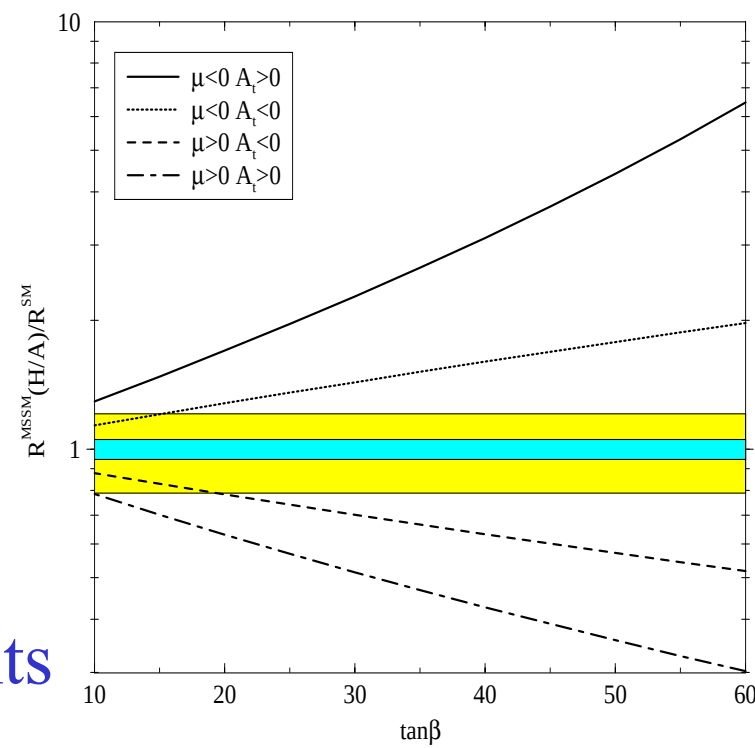
Charged Higgs Studies in ATLAS

K. Assamagan, J. Guasch, S. Moretti & S. Paneranda Rivas

- Determination of the ratio of $H^{\pm} \rightarrow \tau\nu$ / $H^{\pm} \rightarrow tb$ at large tanβ: $A/H \rightarrow bb$ ($\tau\tau$), $H^{\pm} \rightarrow \tau\nu$ and $H^{\pm} \rightarrow tb \propto \tan^2\beta$
  - Sensitivity to SUSY corrections in Δm_b and Δm_τ

$$h_b^{eff} = \frac{m_b}{1 + \Delta m_b}$$

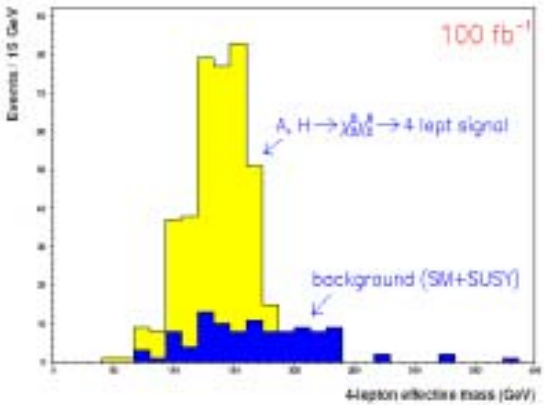
$$\Delta m_b \cong -\alpha_s \frac{\mu m_{\tilde{g}}}{M_{\tilde{b}}^2} \tan\beta$$



- Assume $m_{H\pm}$ is measured in $H^{\pm} \rightarrow \tau\nu$
- Use $m_{H\pm}$ constraint to improve $H^{\pm} \rightarrow tb$ reconstruction: rejection ttbar events

SUSY Higgs

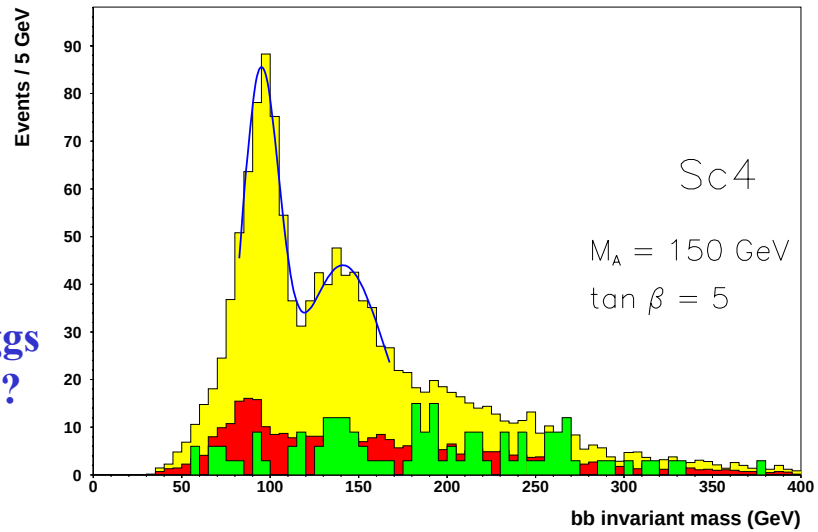
- general in CMS: replacement of gg → Hbb by gb → Hb process
- A, H → $\chi_2^0\ \chi_2^0$ (Willenbrock-Maltoni-Spira-Kraemer- Dawson-…)



- trying to access high mass region (Bisset-Moortgat-Moretti)
- trying new idea for mass reconstruction (TBC) (with M. Nojiri)
- input for LHC/LC complementarity studies

- cascade production of h, A, H , $H^{\pm}$ (Djouadi-Guchait-Moortgat)

- trying new points where BR(h→inv) is large (with R. Godbole)
- can we reconstruct cascade decay chains with Higgs bosons in the final state (instead of using dileptons)?
- LHC/LC complementarity? see next slide



Higgs-sparticle couplings

Measurement of Higgs-sparticle couplings at the LHC+ LC

(Datta-Djouadi-Guchait-Moortgat)

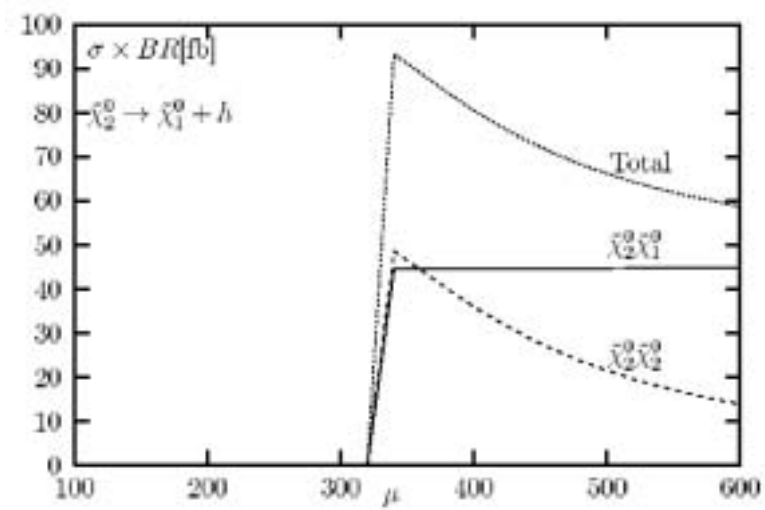
MSSM Higgs production in SUSY cascades at the LHC:

- possibility of little ($\chi_2^0, \chi_1^+ \to \phi$) and big cascades ($\chi_{3,4}^0, \chi_2^+ \to \phi$)
- intricate situation at the LHC
- inject additional info from LC on the little cascades into LHC

Ex: $\sigma(e^+e^- \to \chi_2^0\chi_2^0 + \chi_2^0\chi_1^0) \times Br(\chi_2^0 \to h\chi_1^0)$

LC: measure m($\chi_1^0, \chi_2^0, \chi_1^+$) + BR's

LHC: measure m($\chi_3^0, \chi_4^0, \chi_2^+$) + BR's



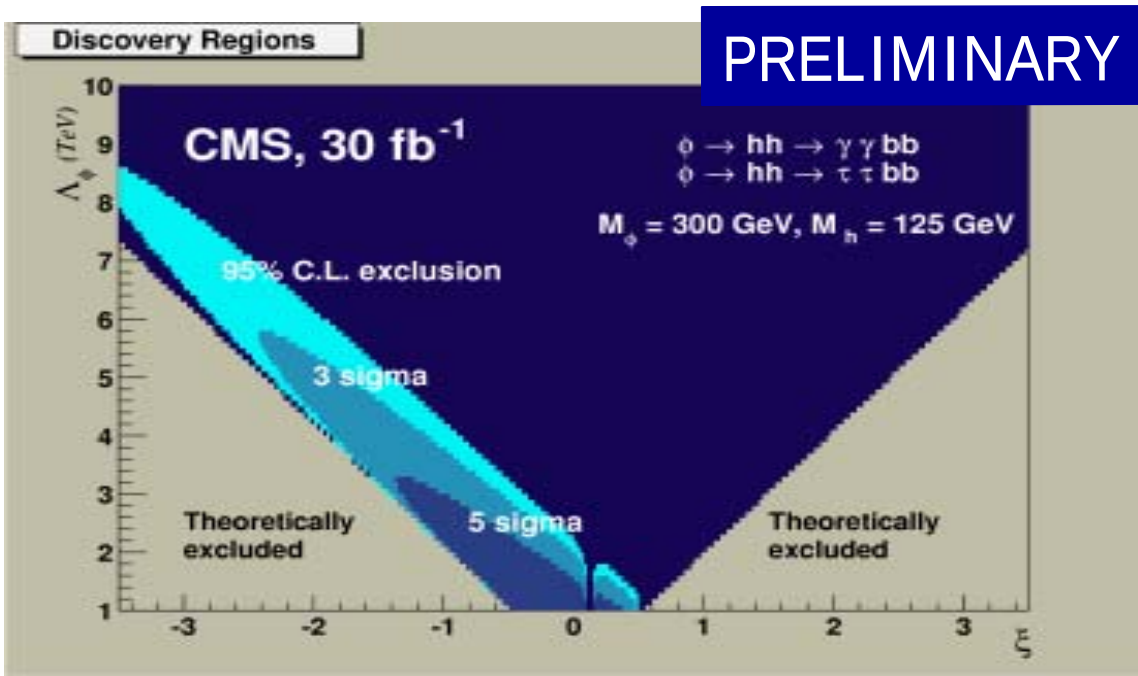
Full analysis to follow …

Radion Search in CMS: $\phi \rightarrow hh \rightarrow \gamma\gamma\ (\tau\tau)\ bb$

G. Dewhirst
L. Fanò
S. Gennai
S. Nikitenko

- We have taken from Dominici et al. The σxBR for ϕ->hh.
  - We have made a preliminary discovery-exclusion plot
- Still we have to understand differences wrt Atlas background
- Starting comparing CompHep's Zbb events with Pythia's Zjj
- We have to add ϕ->hh->bbbb preliminary results to our analysis.

ATLAS study performed By G. Azuelos et al. SN-ATLAS-2002-019



Signal H→γγ inclusive

Pythia 6.210 pdf=CTEQ6L1 (LO)

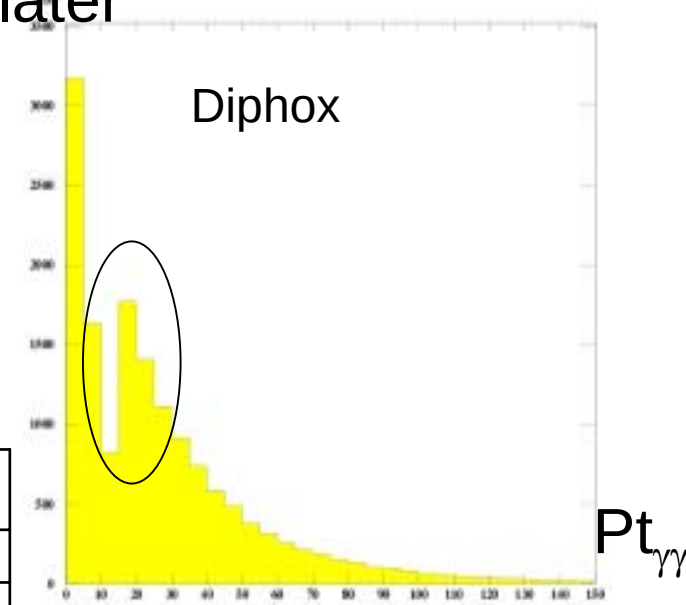
But with **K factor** of HiGlu package (for gg fusion and VBF)

ISUB	process($pp \to h^0 \to \gamma\gamma$)
102	$gg \to h^0$
124	$qq \to qqh^0(W^+W^- fusion)$
26	$q\bar{q} \to W^+h^0$
123	$qq \to qqh^0(Z^0Z^0 fusion)$
3	$q\bar{q} \to h^0$
24	$q\bar{q} \to Z^0h^0$
121	$gg \to Q\bar{Q}h^0$
122	$q\bar{q} \to Q\bar{Q}h^0$

Using correction of **HDecay** for decay H→γγ
Look for K_{NNLO} for gg fusion, develop NLO MC-software for gg fusion and VBF.

M. Escalier, B. Laforge

Problem of resummation: **C. Balazs and C.P. Yuan** have done resummation, use/compare with RESBOS later



Background:

Irreductible =Diphox (NLO, CTEQ6M)

Reductible =pythia 6.210 (LO, CTEQ6L1)

γ/jet rejection factor in discussion

contributions	TDR	Analysis
direct		16517
onef		8510
twof		883
$\gamma\gamma$ background	29000	25910
γ jet	5800	6737
jet jet	4600	5916
Higgs	1283	1097
$S/\sqrt{B}$	6.5	5.59

- $Pt_{\gamma\gamma}$<30 GeV
- $Pt_{\gamma\gamma}$>30 GeV →8.2

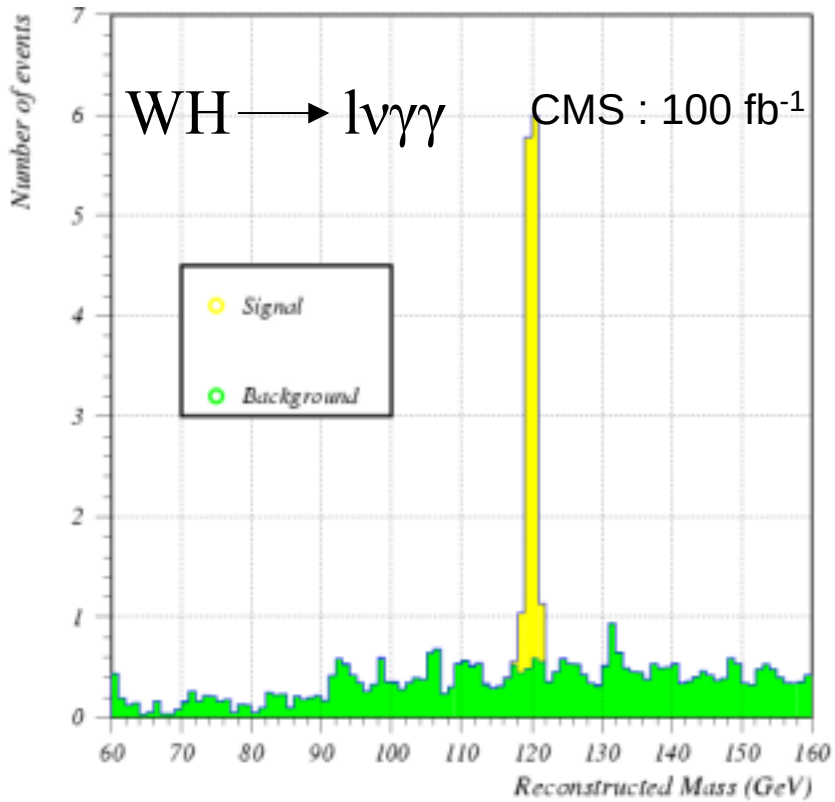
➔ combination=**9.9**

next:use C. Balazs soft. to prevent that hole. Look at γ/j rej.

The pp → WH→lνγγ channel

- ✓Sgn, Bkg generated with CompHEP
- ✓Hadronization, fragmentation with Pythia
- ✓Rick Field's settings for underlying events and minimum bias
- ✓Fast simulation of CMS (CMSJET)

Olivier Ravat



After one year at high luminosity, cuts of 55 GeV on the hard photon and 30 GeV on the soft one :

Higgs Couplings Measurements at a 1 TeV LC

Take cue from Battaglia & DeRoeck results for $B_{h\to\mu\mu}$ at CLIC and investigate branching fraction measurements in WW fusion at a 1 TeV LC.

Tim Barklow

$m_h = 115\,GeV$

$\sigma_{Zh} \rightarrow e^-_{pol} = 0\%$ $\quad e^+_{pol} = 0\%$

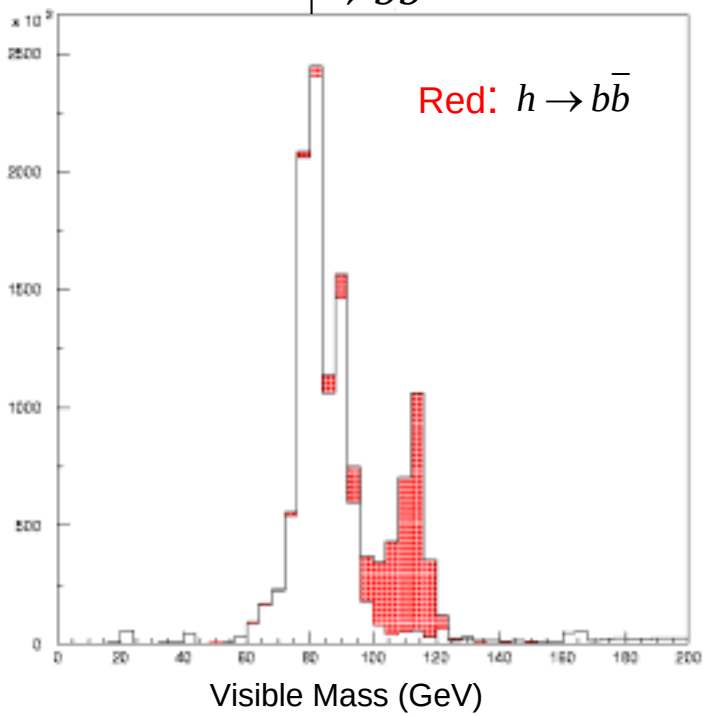
$\sigma_{\nu\nu h} \rightarrow e^-_{pol} = 80\%\,L$ $\quad e^+_{pol} = 50\%\,R$

$\sqrt{s}(GeV)$	$L(fb^{-1})$			
		$L\sigma_{Zh}B_{h\to b\bar{b}}$	$L\sigma_{Zh}B_{h\to WW^*}$	$L\sigma_{Zh}B_{Z\to ee,\mu\mu}$
350	500	48720	5400	4443
		$L\sigma_{\nu\nu h}B_{h\to b\bar{b}}$	$L\sigma_{\nu\nu h}B_{h\to WW^*}$	$L\sigma_{\nu\nu h}B_{h\to ZZ^*}$
500	500	75357	8343	1655
1000	1000	391149	43335	4296

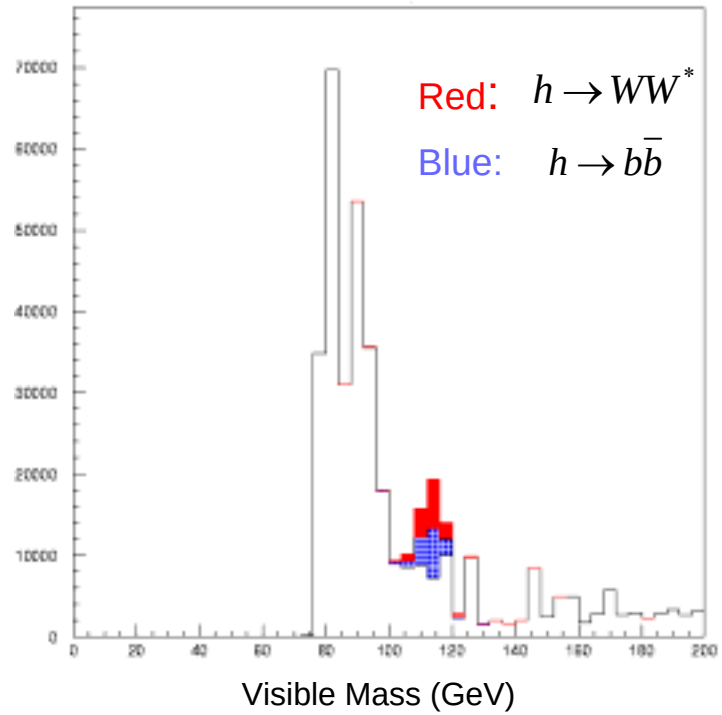
$\sqrt{s} = 1TeV \quad L = 1000\, fb^{-1} \quad m_h = 115\, GeV$

Tim Barklow

$e^+e^- \to \nu_e \overline{\nu_e}\, h_{|\to b\bar{b}}$



$e^+e^- \to \nu_e \overline{\nu_e}\, h_{|\to WW^*}$



x	$B_{h\to b\bar{b}}$	$B_{h\to WW^*}$	Γ_h	σ_{Zh}
$\Delta x / x$ without 1TeV	.024	.064	.070	.024
$\Delta x / x$ with 1TeV	.023	.030	.048	

Status of the $H^{\pm} \rightarrow tb$ Channel in CMS

S. Lowette

Progress...

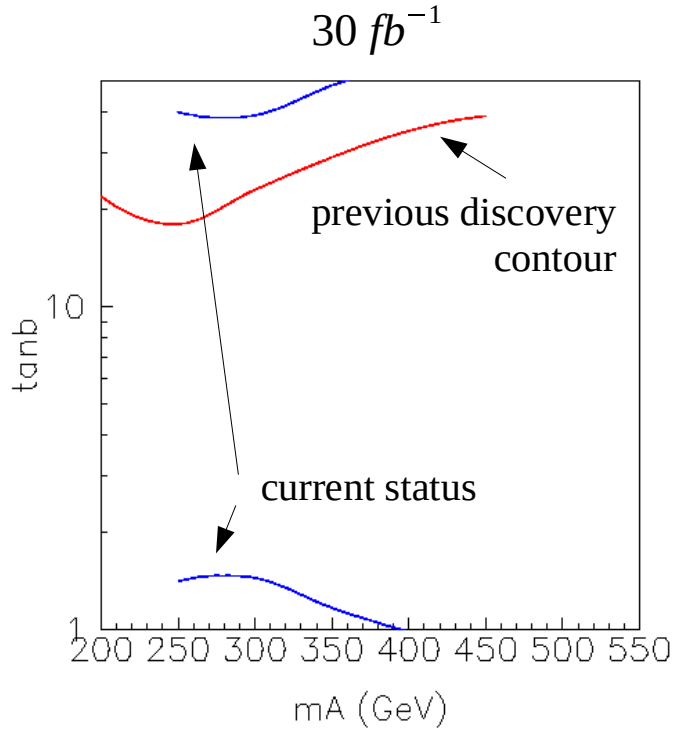
- differences with ATLAS understood (w. Ketevi)
- big influence of systematic uncertainties
- ttbb important background (David)

Ongoing...

- $gb \rightarrow tH^{\pm}$ cross section values still unclear (w. Tilman & Dirk)
- correct ttbar generation on the way (w. Nikolas)
- $gg \rightarrow tbH^{\pm}$ generation

  $\rightarrow$ consistency check with $gb \rightarrow tH^{\pm}$

  $\rightarrow$ use of extra b



S. Lehti

Estimating tanβ at CMS

idea: Compare tanβ from H->ττ and H^+->τν. Ratio may be sensitive to CP violation in Higgs sector (?)

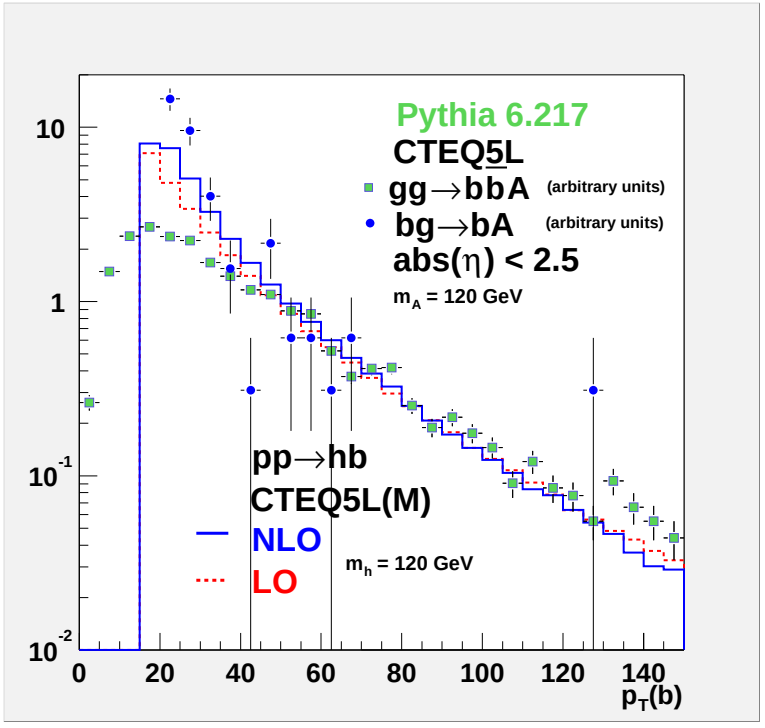
Combining H->ττ->jj, H->ττ->lj, H->ττ->eμ/ll at

m_A = 200 GeV, tanβ = 20

30 fb^{-1}

	S	B	signif	err (statistical)
jj	12	4	3	33.3%
lj*	520	491	16.4	6.1%
eμ	100	176	6.0	16.6%
ll	188	574	6.8	14.7%
total(eμ)	632	671	17.5	5.7%
total(ll)	720	1069	17.0	5.9%

1b tagging, b quark p_T distribution

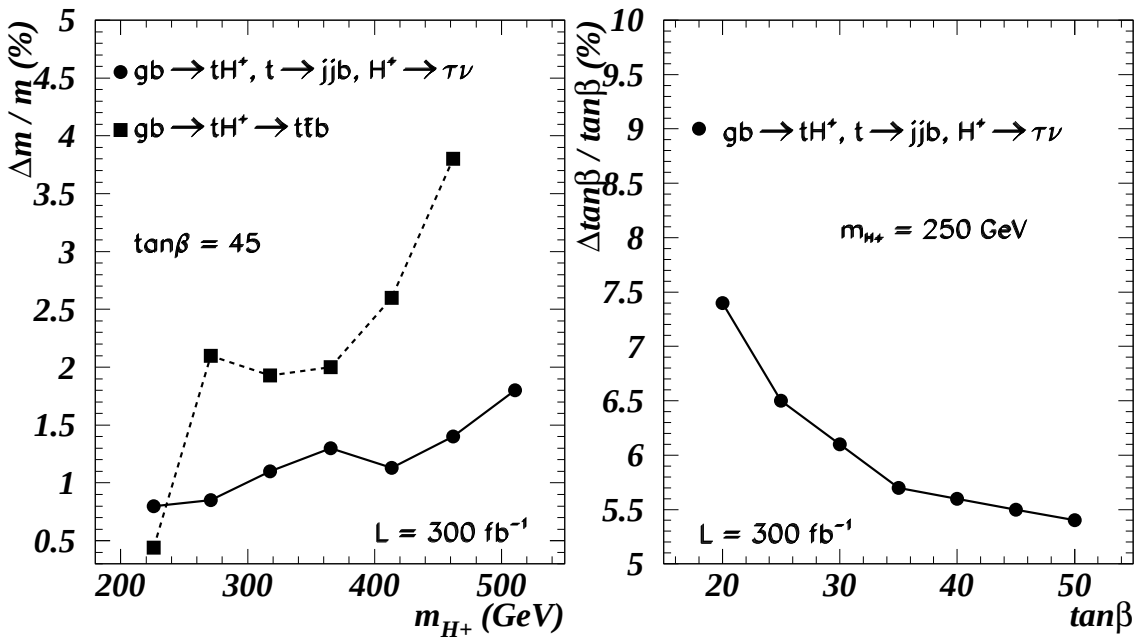


lj*: very rough extrapolation from other mass values, has to be re-evaluated

Prospects for $m_{H^\pm}$, $\tan\beta$ Determination

K. Assamagan & Y. Coadou, EPJdirect C9, 1-13 (2002)

Overall expected precisions on $m_{H^\pm}$ and $\tan\beta$ determination for $\mathcal{L} = 300$ fb^{-1}



- **Better precisions on $m_{H^\pm}$ in $H^\pm \to \tau\nu_\tau$ compared to $H^\pm \to tb$ except at low Higgs masses**
- **Precision on $\tan\beta$ improves as the rate of $H^\pm \to \tau^\pm\nu_\tau$ increases with $\tan\beta$**

R.M.Godbole, M. Guchait, K. Mazumdar, S. Moretti,D.P.Roy

$$\underline{\text{PP}\rightarrow W(\rightarrow \ell\nu)H(\rightarrow \text{Inv}) \Rightarrow \ell + \not{E}_T}$$

Event Selection Cuts:

1. $P_T^\ell > 10$ GeV, η_ℓ <3;
2. Jets are reconstructed with E_T^j >30 GeV and η_j <4.
3. Transverse missing energy is selected with $\not{E}_T$ >80 GeV.

Background rejection cuts:
P_T^ℓ >100 GeV and $M_T > 200$ GeV; $M_T = \sqrt{2.p_T^\ell \not{p}_T[1 - \cos\phi(\ell, \not{p}_T)]}$

m_H =120 GeV and Br(H $\rightarrow$ Inv)=1

Process	σ (no BRs) [pb]	Add $M_T^{1\ell} > 200$ GeV	ϵ	Events after $\mathcal{L}$=100 fb^{-1}
WH	1.2	13030	0.013	1564
ZH	.69	702	0.00070	48
WW	64.	235	0.00024	1504
ZZ	10.	253	0.00025	253
WZ	26.	1049	0.0010	2727
W	1.4×10^5	24	2.4×10^{-5}	336000
Z	7.5×10^4	0	0	0
$t\bar{t}$	441.	41	4.1×10^{-5}	1808
tq + c.c.	146.	0	0	0

$\Rightarrow \frac{S}{\sqrt{B}} \sim 2.5$

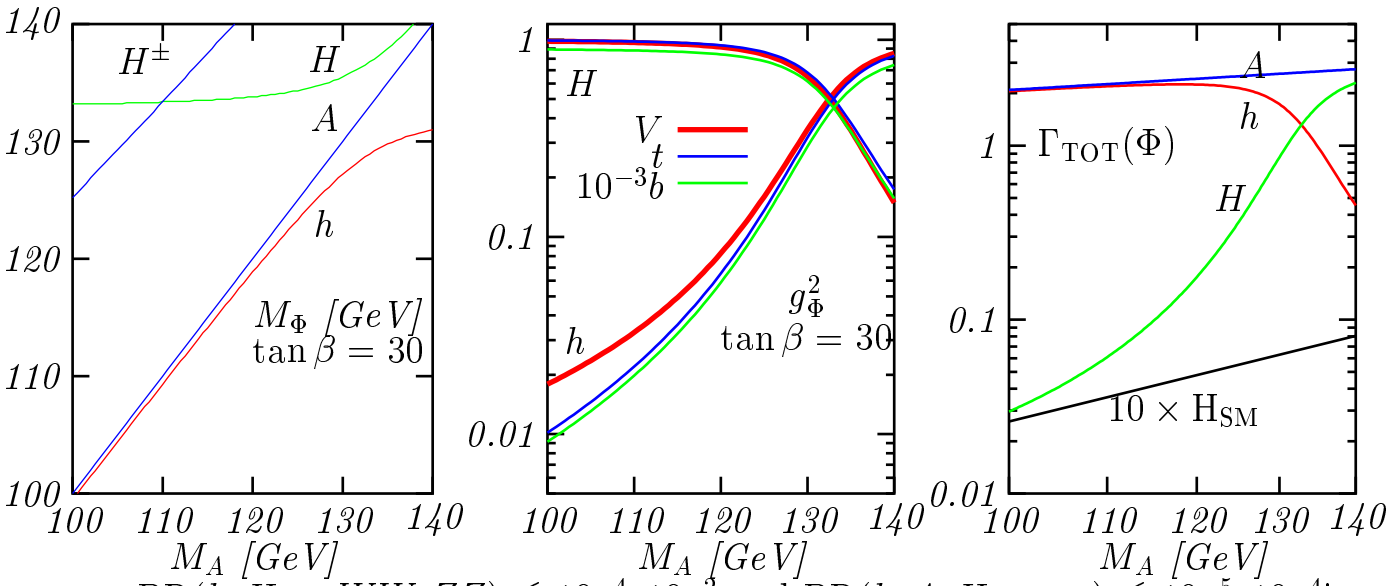
The intense coupling regime at the LHC

Edward Boos, Abdelhak Djouadi, Sasha Nikitenko

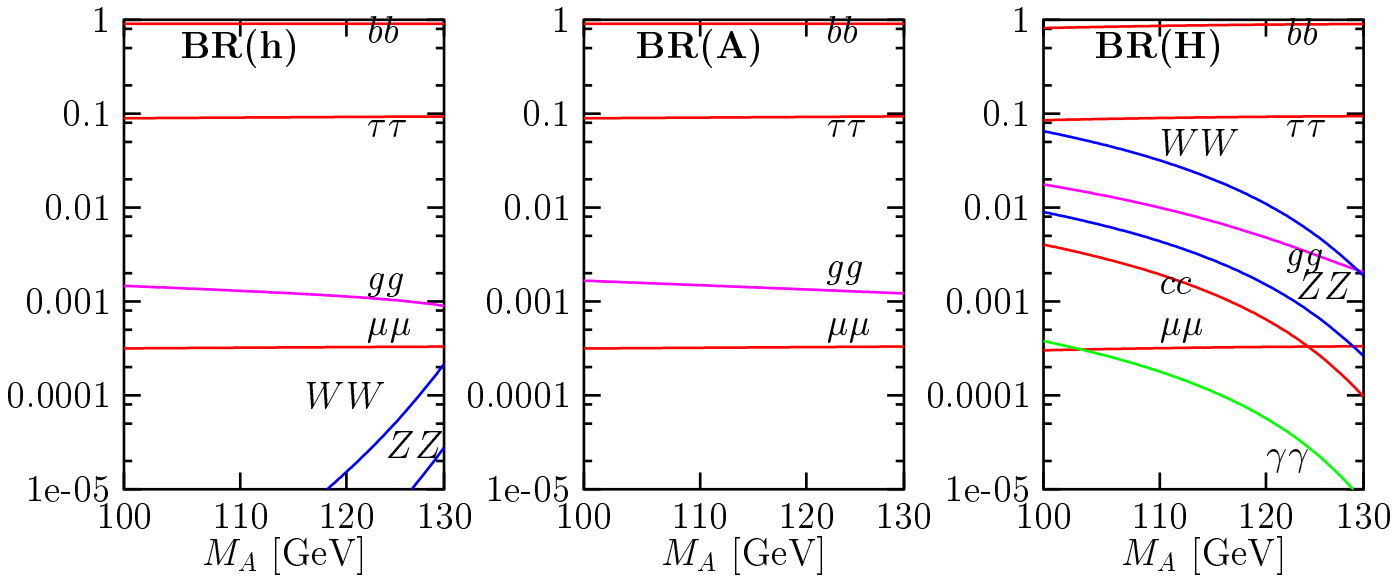
The MSSM neutral Higgsses in the ICR: $M_A \sim M_h^{\max}$ and $\tan\beta \sim 30$:

- The masses are very close to each other, $\Delta M \sim$ a few GeV.
- The couplings to b are large and to t, W, Z small.
- The total decay widths are large, $\Gamma \sim$ a few GeV.

E. Boos, A. Djouadi, M. Mühlleitner, A. Vologdin



- $\mathrm{BR}(h, H \to WW, ZZ) \lesssim 10^{-4}, 10^{-2}$ and $\mathrm{BR}(h, A, H \to \gamma\gamma) \lesssim 10^{-5}, 10^{-4}$!
- $\Phi \to b\bar{b}$ useless (backg) and no good resolution for $\Phi \to \tau^+\tau^-$ (for separation).



Go for $\Phi \to \mu^+\mu^-$!!!

- Clean with not so large backgrounds (watch out DY for $M_\Phi \sim M_Z$!).
- Very good resolution ($\sim$ 1 GeV) for peak separation.
- Not that small BR's, BR$(h, H, A \to \mu^+\mu^-) \sim 3.5 \times 10^{-4}$.
- Compensated by large production rates in the two channels

$$\begin{aligned} gg &\to h, H, A \to \mu^+\mu^- \\ gg/qq &\to b\bar{b} + h, H, A \to b\bar{b} + \mu^+\mu^- \end{aligned}$$

But: inclusive $pp \to \Phi \to \mu^+\mu^-$ hopeless....
Rely on: $pp \to b\bar{b}\Phi \to b\bar{b}\mu^+\mu^-$ with $p_T^{b,\bar{b}} > 20$ GeV:

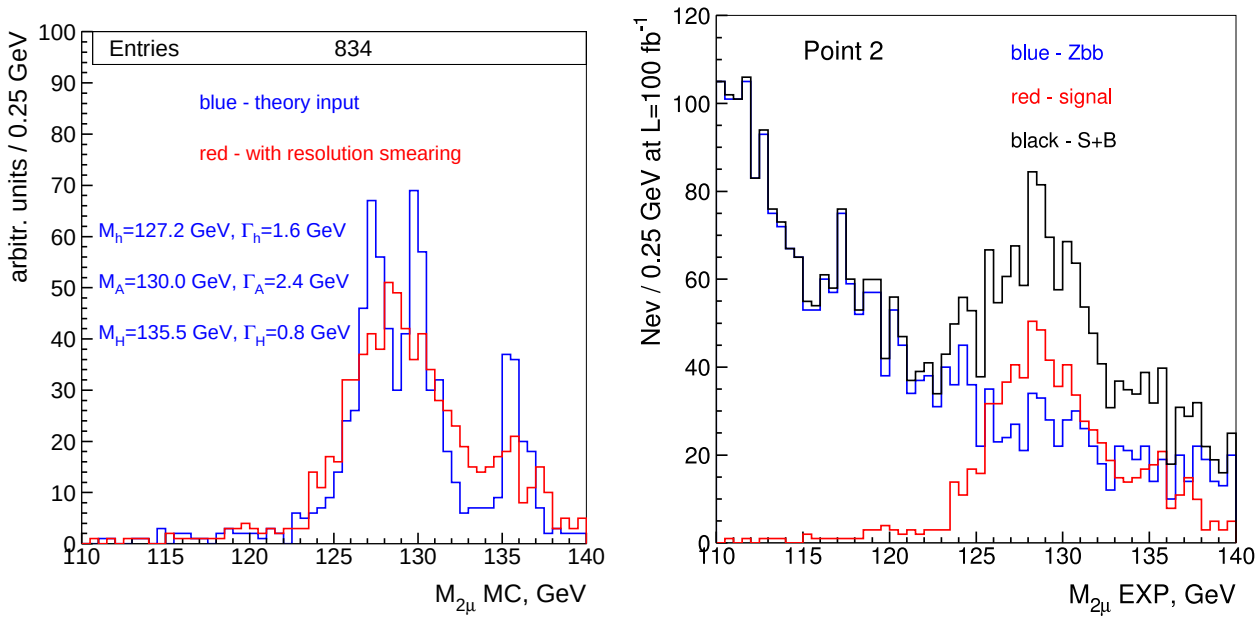


Figure 1: Simulation of $q\bar{q}/gg \to b\bar{b}\Phi \to b\bar{b}\mu^+\mu^-$ (signal+ $4f$-background) with$p_t^{b,\bar{b}} > 20$ GeV including fast simulation: `HDECAY` $\to$ `CompHEP` $\to$ `PYTHIA` $\to$ CMSJET with realistic μ resolution. Left: signal for $M_A = 130$ GeV and $\tan\beta = 30$. Right: signal + $2b2\mu$ background.

As you see, life will be a nightmare if the 3 h, H, A peaks have to be distinguished!

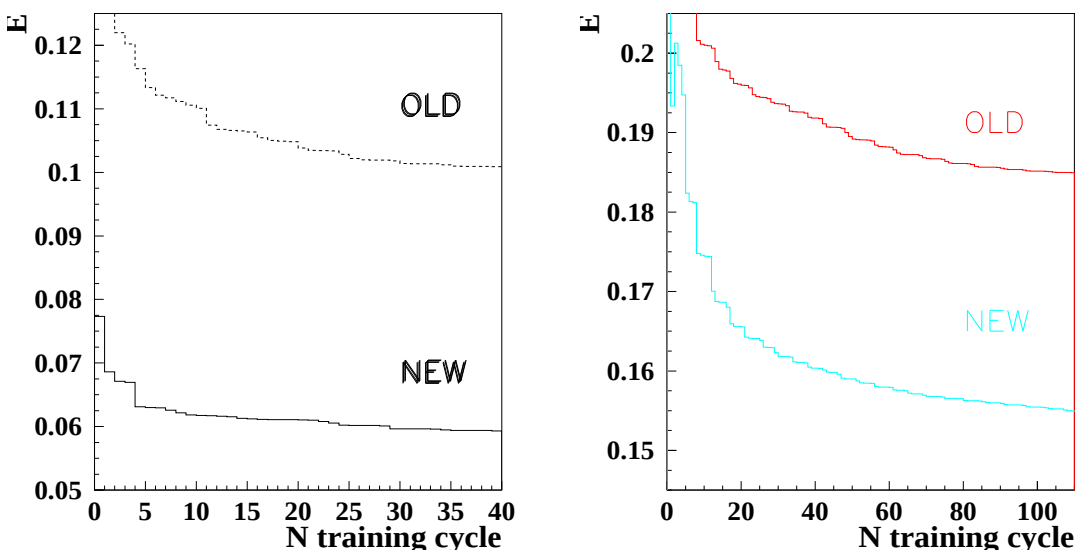
A lot of hard work is needed before the next les Houches workshop:
– Try with only one b–tag: more statistics would maybe help...
– Try with one light jet: probably hopeless but who knows...
– Try to seperate at least h and H by other means ($WW \to \phi \to \mu^+\mu^-$..)
– Try diffractive Higgs production (a good job for our russian friends).
LC will surely be able to sort this out! Should we give it a chance?

Method of Sensitive Variables

- The efficient and universal way to construct the optimal set of input variables for NNs. (E.Boos, L.Dudko hep-ph/0302088)
  - "Singular" variables (denominator of Feynman diagrams)
  - "Angular" variables (numerator of Feynman diagrams)
  - "Threshold" variables
- Direct implementation to the Higgs search (115 GeV, Tevatron), significantly improve the efficiency of the NNs

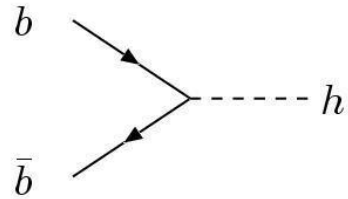
NN Error function for the $WH - t\bar{t}$ (left plot) and $WH - WZ$ networks (right plot).

$$E = \frac{1}{N}\sum_{i=1}^{N}(d_i - o_i)^2$$



Higgs production processes involving b's

- The largest rate is from the fusion process, but hard to control the backgrounds



- Process with a recoiling high p_T b-quark may facilitate signal selection in h→bb or h→*tt* final states

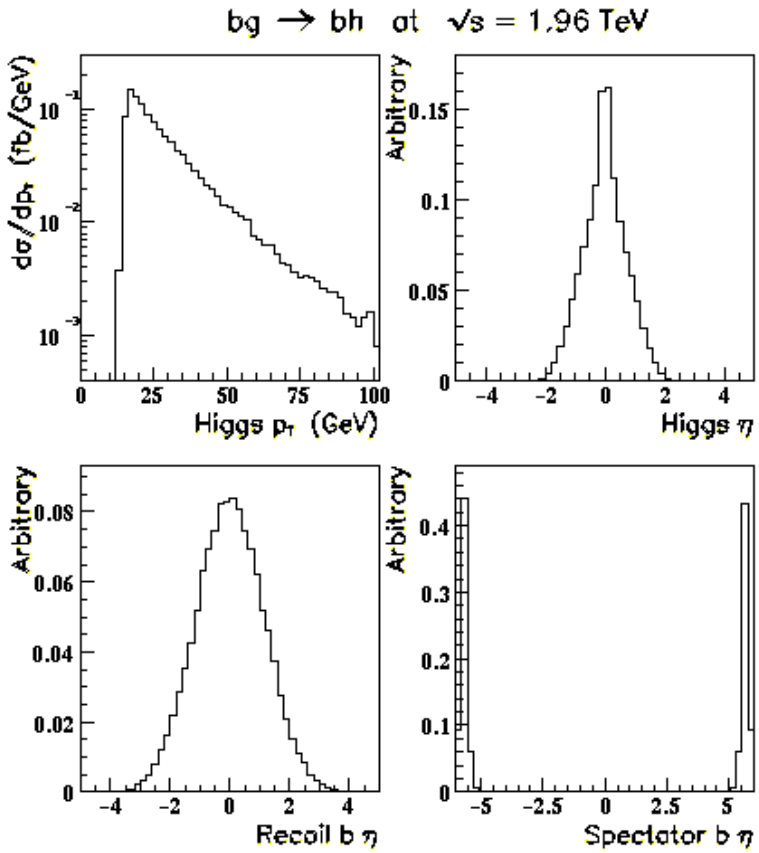
  - Was first suggested by C.Huang and S.Zhu, Phys. Rev. D60 (1999) 075012
  - Have now NLO calculations by J.Campbell, R.Ellis, F.Maltoni and S.Willenbrock, hep-ph/0204093

- More attention was devoted to the Higgs associated production with two b's – main subject of this talk

- In the context of SUSY models the Higgs-b coupling is proportional to tanb making the searches very promising

*b*g →*b*h cross section and kinematics

- LO cross sections given by CompHEP coincide with the published results; e.g. σ=2.8 fb for m_h = 120 GeV and p^h_T > 15 GeV



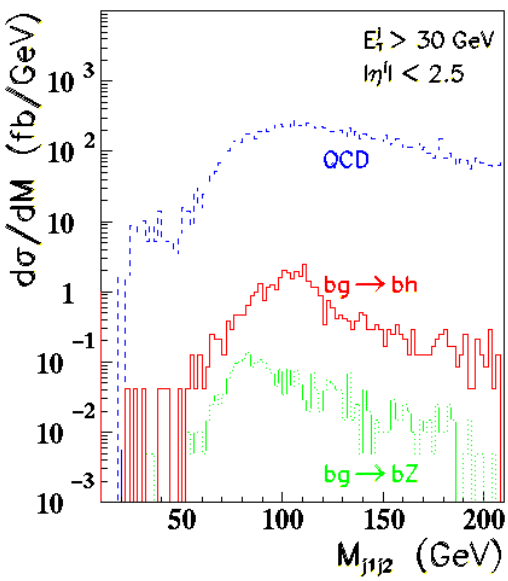
- Expect three central high-E_T *b*-jets
- Or a *b*-jet plus two taus from h →$\tau\tau$ decays

- Shapes of the p^h_T spectra above a cut value are similar at LO and NLO (hep-ph/0204093)

Di-jet rates

- *bh*(→*bb)* signal and *bZ*(→*bb)* background samples are generated with CompHEP+Pythia
- *bb*+j bkgd sample is extracted from inclusive Pythia QCD processes – 22 M events are generated in total
- Require at least 3 jets of $E_T > 30$ GeV in $|\eta| < 2.5$
- Assume $\varepsilon_{3b} = 0.5\times0.5\times0.05$ in QCD and $\varepsilon_{3b} = 0.5\times0.5\times0.6$ in *b*h, *b*Z samples and σ(*b*h) scaled up by 2000

Two leading jets invariant mass



- Expect ~100 times larger QCD rate than the signal
  - Result is not encouraging (with this simple selections)
  - Need detailed simulations w. all backgrounds
- One should also look at h→$\tau\tau$ final states

Little Higgs Searches at the LHC

The Little Higgs task force

S. Asai, G. Azuelos, K. Benslama, D. Costanzo, G. Couture, J. E. Garcia, F. Gianotti, I. Hinchliffe, N. Kanaya, M. Lechowski, R. Mehdiyev, G. Polesello, E. Ros, D. Rousseau

Preliminary ATLAS results presented at the 4th ATLAS Physics Workshop: Athens Mai 21-25 2003

CMS Analysis carried out K. Mazumdar

We have to look for the following particles:

1. T heavy top

2. $W_H^{\pm}$ → heavy $W^{\pm}$ $\quad$ Z_H → heavy Z $\quad$ A_H → heavy γ

3. Higgs triplet $\underbrace{\phi^0, \phi^+, \phi^{++}}_{\text{heavy Higgs bosons}}$

Search for Z_H

$M(Z_H)$ = 2 TeV $L = 3 \cdot 10^5\ pb^{-1}$

$q\bar{q} \longrightarrow Z_H \longrightarrow e^+e^-$

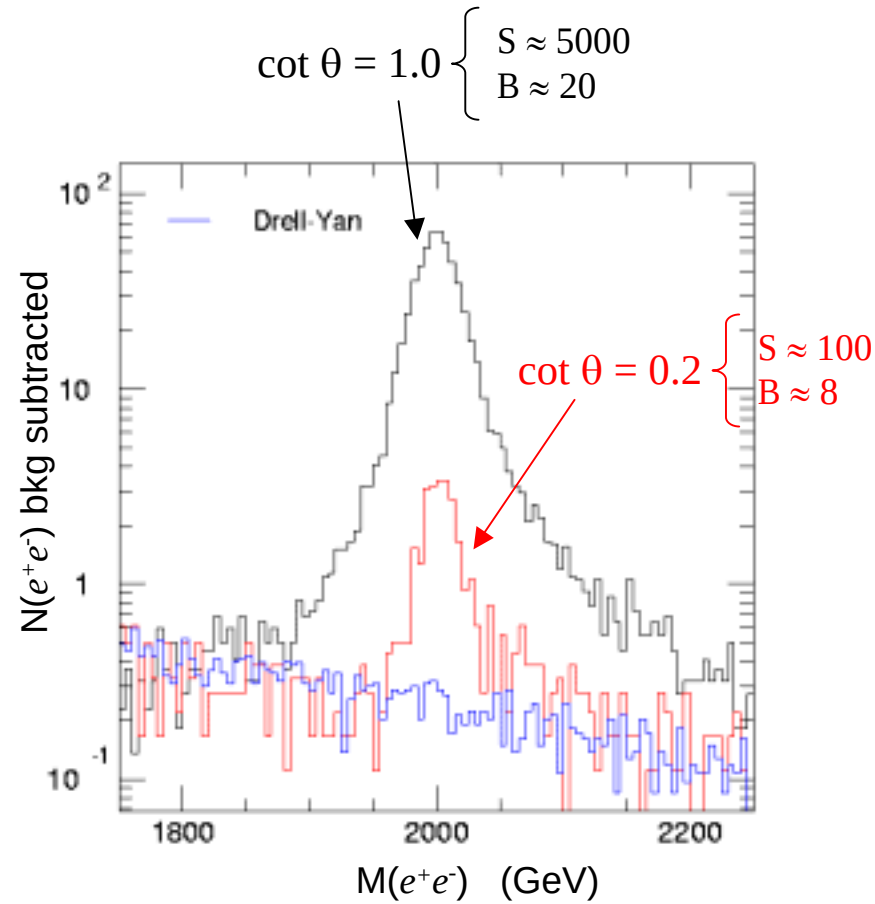
$\mu^+\mu^-$ not used due to invariant mass resolution

Selection cuts:

- 2 isolated electrons with $p_T > 20$ GeV and $|\eta| < 2.5$
- minimum invariant mass equal to 800 GeV

Background:

Drell-Yan ($q\bar{q} \rightarrow Z/\gamma \rightarrow e^+e^-$)
other bkg's are under evaluation



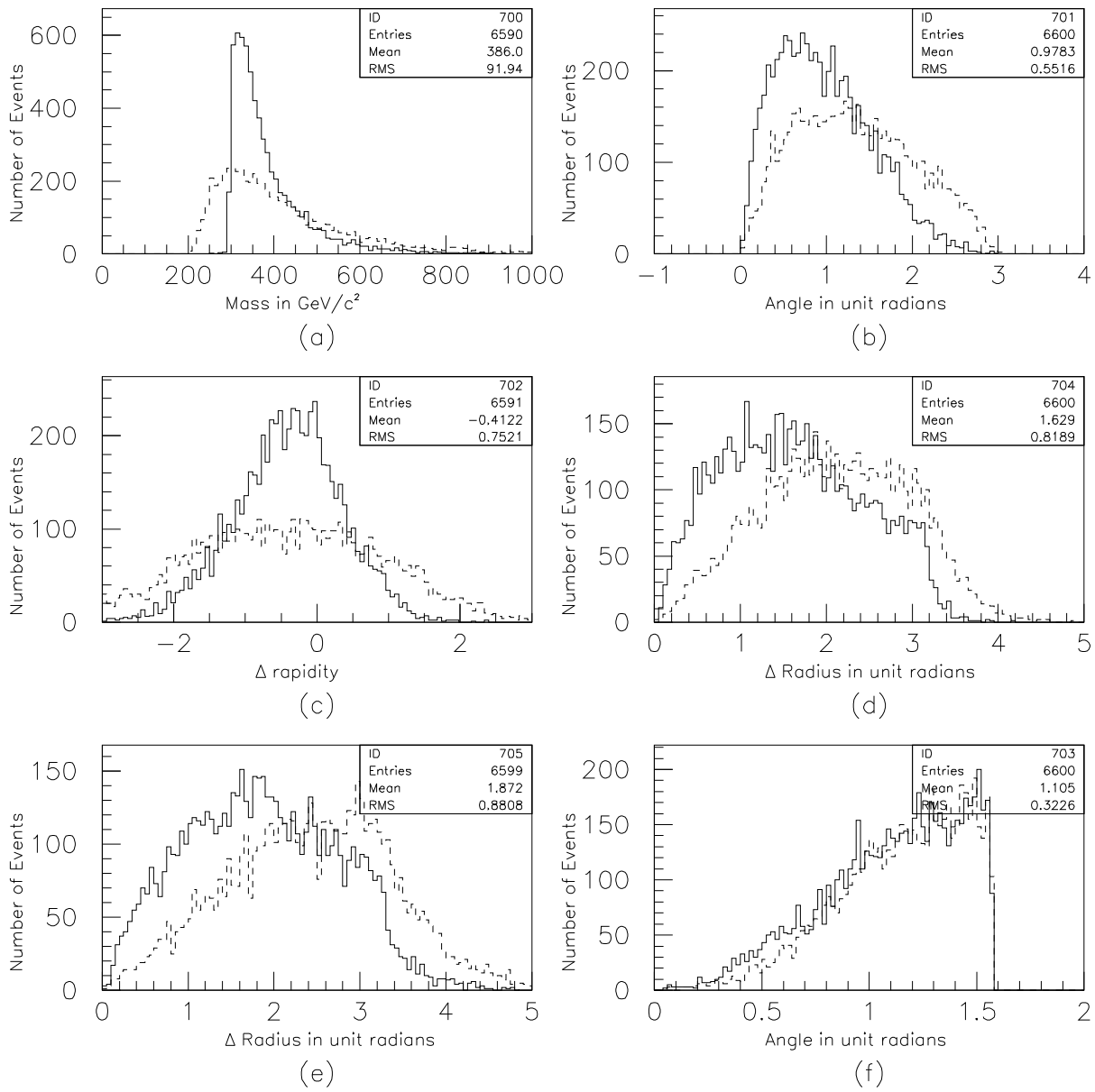


Figure 5: Distribution of the kinematics variables for $t\bar{t}$ + H (solid) and $t\bar{t} + b\bar{b}$ (dash) events (see text for the definitions of these variables).

Dy Cut May improve signal selection