HIGGS PHYSICS AT THE LHC

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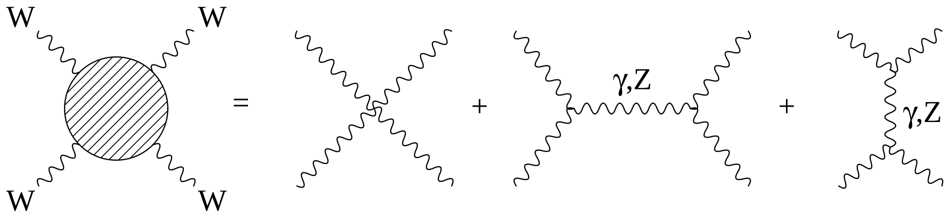
- How to find the Higgs at LHC
- Supersymmetry
- Maximum Significances: Higgs to muons

STANDARD–MODEL HIGGS SECTOR: 1

Theory of W, Z bosons

- start with SU(2) gauge theory [like QED with massless W, Z]
- include measured masses $\mathcal{L} \sim -m_{W,Z} A_\mu A^\mu$

⇒ not gauge invariant, not renormalizable, so what?



Unitarity

- test theory in $WW \to WW$ scattering
  $\to \mathcal{A} \propto G_F E^2$ just like Fermi's theory, not unitary above 1.2 TeV [barely LHC energy]
  $\to$ postulate additional scalar Higgs boson to conserve unitarity
  $\to$ fixed coupling $g_{WWH} \propto m_W$
- add fermions and test $WW \to f\bar{f}$
  $\to$ fixed coupling $g_{ffH} \propto m_f/m_W$
- test new theory in $WW \to WWH$
  $\to$ fixed coupling $g_{HHH} \propto m_H^2/m_W$
- final test: $WW \to HHH$
  $\to$ fixed coupling $g_{HHHH} \propto m_H^2/m_W^2$

⇒ Higgs couplings non-negotiable

STANDARD–MODEL HIGGS SECTOR: 2

Higgs potential

- remember Lagrangian invariant under $SU(2) \times U(1)$
- break symmetry through vacuum: SU(2) doublet with vev
- minimize Higgs potential $\Phi = \big(0, (v+H)/2\big)$ [$v = 246$ GeV known from W, Z masses]

⇒ first attempt: renormalizable Higgs potential [does all we want]

$$\begin{aligned}\mathcal{L}_{\rm Higgs} &= |D_\mu \Phi|^2 - V \\ V &= \lambda \left(|\Phi|^2 - \frac{v^2}{2} \right)^2 = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 + \text{const}\end{aligned}$$

⇒ not the whole story with new scale Λ [first-order EW phase transition: hep-ph/0407019]

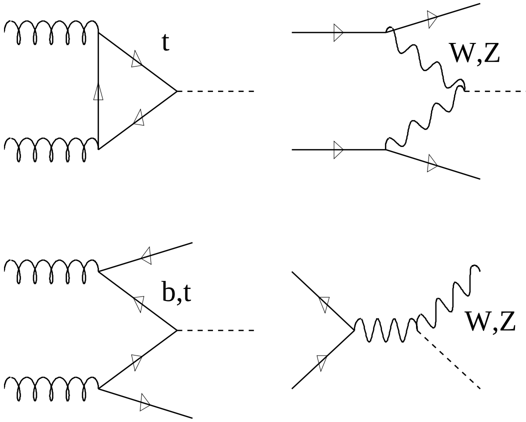
$$V = \sum_{n=0} \frac{\lambda_n}{\Lambda^{2n}} \left(|\Phi|^2 - \frac{v^2}{2} \right)^{2+n}$$

⇒ gauge–invariant D6 Higgs operators $\mathcal{L}'_{\rm Higgs} = \sum f_i/\Lambda^2 \; \mathcal{O}_i$ [hep-ph/0301097]

$$\mathcal{O}_{\rm kin} = \frac{1}{2} \partial_\mu (\Phi^\dagger \Phi) \partial^\mu (\Phi^\dagger \Phi) \qquad \mathcal{O}_{\rm pot} = -\frac{1}{3} (\Phi^\dagger \Phi)^3$$

⇒ measure self couplings

Higgs Production and Decay: 1



Design Higgs searches for the LHC

- (a) unitarity limit: $m_H < 1$ TeV
  (b) electroweak precision tests: $m_H \lesssim 250$ GeV
- production and decay of light Higgs

$gg \to H$
$qq \to qqH$
$gg \to t\bar{t}H$
$q\bar{q}' \to WH$

↔

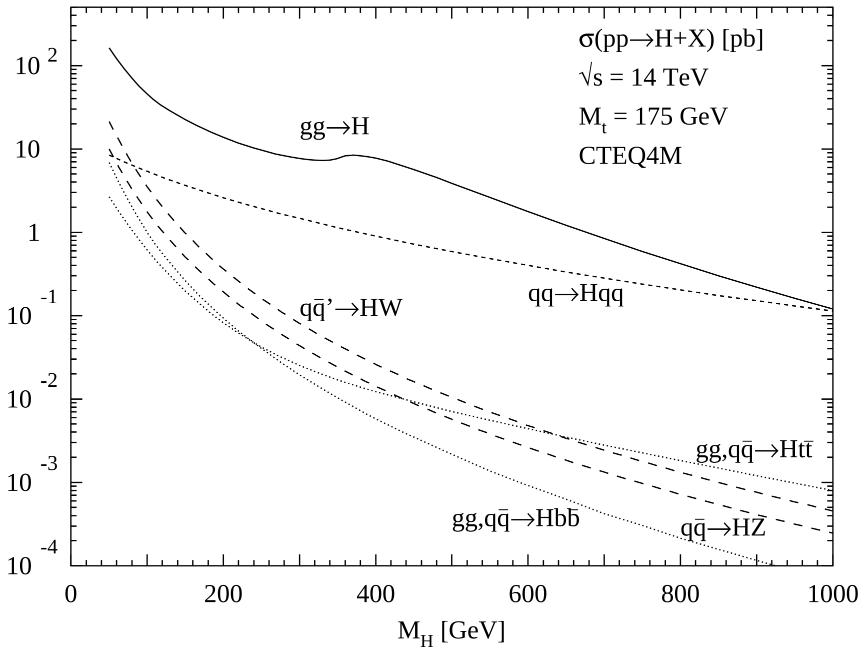
signal × trigger
backgrounds
systematics
$S/\sqrt{B}$ vs. S/B
mass resolution...

↔

$H \to b\bar{b}$
$H \to WW$
$H \to \tau^+_{\ell h}\tau^-_{\ell}$
$H \to \gamma\gamma$
$H \to \mu\mu$...

Production rates

[Spira, Harlander, Melnikov,...]



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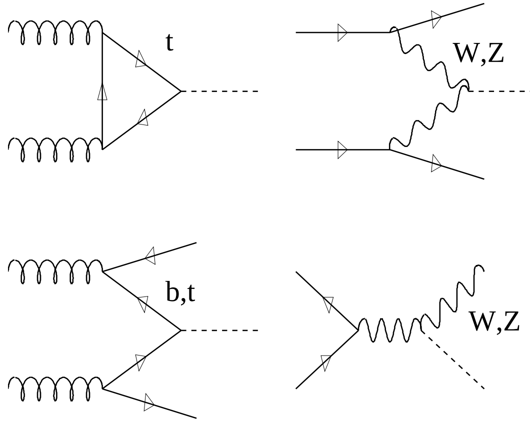

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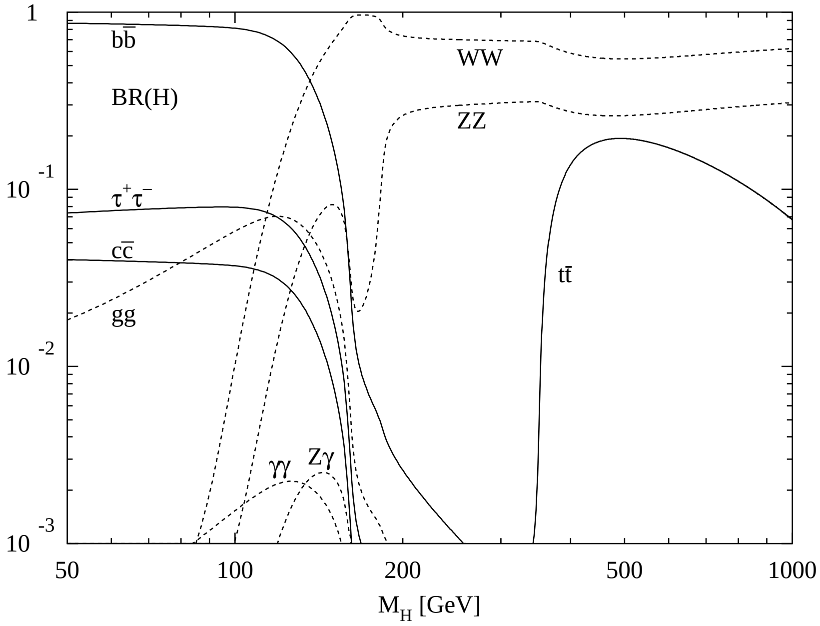
$H \to \mu\mu$...

Branching fractions

[up to 10^6 events]



HIGGS PRODUCTION AND DECAY: 2

Some numbers behind it

– gluon-fusion production and H $\longrightarrow$ ZZ $\longrightarrow$ 4μ no-brainer

['golden channel' above 140 GeV, mass resolution excellent]

– H $\longrightarrow$ WW only slightly harder, but no mass peak

[above 150 GeV, off-shell still not clear, gg $\longrightarrow$ WW background only recently]

– 6 million light Higgses in gluon fusion: gg $\longrightarrow$ H $\longrightarrow$ $\gamma\gamma$

[mass resolution $\Delta m_H / m_H \sim \Gamma / \sqrt{S} < 0.5\%$]

– backgrounds smaller in WW fusion: qq $\longrightarrow$ qqH $\longrightarrow$ qqWW

[works off-shell down to $m_H < 120$ GeV]

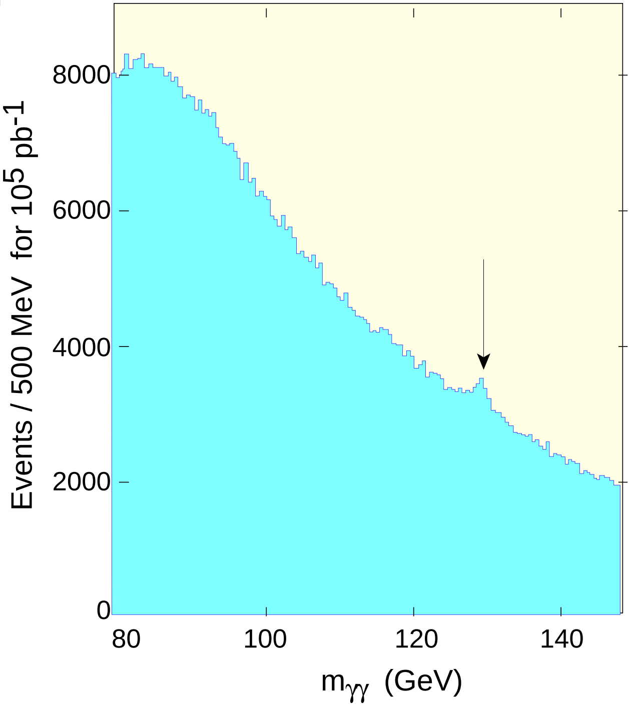
– light Higgs: qq $\longrightarrow$ qqH $\longrightarrow$ qq$\tau\tau$ [will discuss later]

– more challenging strategies:

gg $\longrightarrow$ $t\bar{t}$H $\longrightarrow$ $t\bar{t}b\bar{b}$ [likely dead]
gg $\longrightarrow$ $t\bar{t}$H $\longrightarrow$ $t\bar{t}$WW [likely to work]
gg $\longrightarrow$ $t\bar{t}$H $\longrightarrow$ $t\bar{t}\tau\tau$ [yet unclear]
$q\bar{q}'$ $\longrightarrow$ WH $\longrightarrow$ W$b\bar{b}$ [killer QCD backgrounds, ask John]
qq $\longrightarrow$ qqH $\longrightarrow$ qq$b\bar{b}$ [no ATLAS trigger]
qq $\longrightarrow$ qqH $\longrightarrow$ qq$\mu\mu$ [later]

$\Rightarrow$ Very cool, just H $\longrightarrow$ $b\bar{b}$ a sad story...

$H_{SM} \longrightarrow \gamma\gamma$



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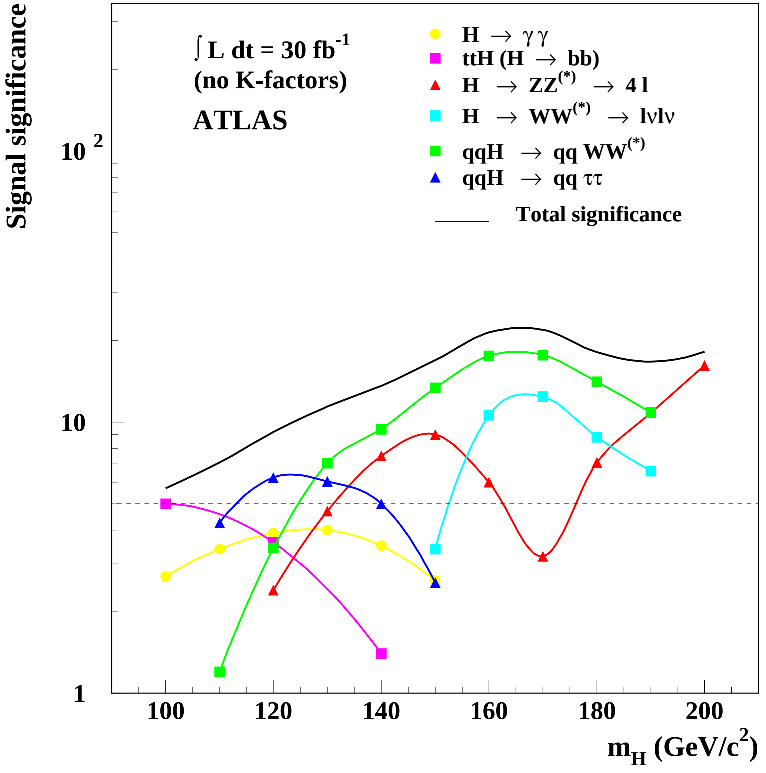


WBF HIGGS PRODUCTION

two hard, isolated leptons
missing transverse momentum
two forward tagging jets
90 GeV$<$ $m_{\tau\tau}^{\text{coll}}$ $<$160 GeV

Signal: $H \to \tau\tau \to e^{\pm}\mu^{\mp}4\nu$ [TP, Rainwater, Zeppenfeld]

- $\tau \to \ell\bar{\nu}_\ell\nu_\tau$ not reconstructable
- τ from Higgs decay strongly boosted

[lepton ($\vec{k}$) and τ ($\vec{p}$) approximately collinear: momentum fraction x]

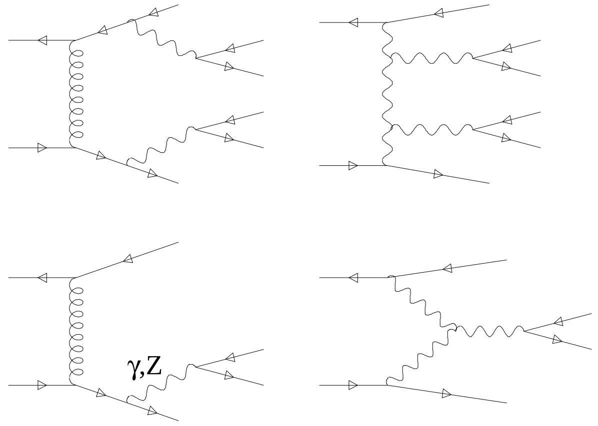
$\Rightarrow$ solve eqs: $\vec{k}_{T,1}/x_1 + \vec{k}_{T,2}/x_2 = \vec{p}_{T,1} + \vec{p}_{T,2} = \vec{k}_{T,1} + \vec{k}_{T,2} + \vec{p}_{T,\text{miss}}$

$\Rightarrow$ obtain $m_{\tau\tau}^{\text{coll}} \sim 2(k_1 \cdot k_2)/(x_1x_2)$

$\Rightarrow$ mass measurement $\Delta m_H/m_H \sim 15\,\text{GeV}/\sqrt{S} \sim 5\,\text{GeV}$

After acceptance cuts, before reconstruction

2.2 fb	signal $pp \to H_{SM} + jj$ [$m_H = 120$ GeV]
1230 fb	$pp \to t\bar{t} + \text{jets}$ [tagging jet either $t \to bW$ or additional jet]
1050 fb	$pp \to b\bar{b} + jj$ [with $b \to \ell\nu c$]
4.9 fb	$pp \to W^+W^- + jj$ (QCD) [with $W \to \ell\nu$]
3.3 fb	$pp \to W^+W^- + jj$ (EW)
57 fb	$pp \to \tau\tau + jj$ (QCD)
2.3 fb	$pp \to \tau\tau + jj$ (EW)
	$pp \to H_{SM} + jj \to W^+W^- + jj$



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More anti-QCD: central mini-jet veto

- additional jet emission cross section large (e.g. $t\bar{t}$, $t\bar{t}j$, $t\bar{t}jj$)

$$\sigma_2 \lesssim \sigma_{2+j} \equiv \int_{p_{T,\rm min}}^{\infty} d\sigma_{2+j} \qquad \text{for} \quad p_{T,\rm min} \sim 10\,\text{GeV (WBF)} \qquad p_{T,\rm min} \sim 40\,\text{GeV (QCD)}$$

- veto $p_{T_j} > 20$ GeV and $\eta_{j,\rm min} < \eta_j < \eta_{j,\rm max}$ to suppress QCD
- theoretical treatment difficult, efficiencies to be measured?

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Both $\tau\tau$ channels with safe margins [Standard Model with 60fb^{-1}]

M_H[GeV]	100	110	120	130	140	150
$\epsilon \cdot \sigma_{sig}$ (fb)	0.62	0.58	0.50	0.37	0.23	0.11
S	37.4	35.0	30.0	22.3	13.7	6.5
B	67.5	27.0	10.8	6.7	5.7	5.3
S/B	0.6	1.3	2.8	3.3	2.4	1.2
σ_{Gauss} (dual leptonic)	4.2	5.7	6.9	6.2	4.4	2.3
σ_{Gauss} (lepton-hadron)		5.7	7.4	6.3	4.7	2.6

SUPERSYMMETRIC HIGGS SECTOR: 1

Why Supersymmetry?

– divergent one-loop corrections to m_H: $\delta m_H^2 \propto \Lambda^2 \;\left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right)$

– Higgs mass always driven to cutoff scale

– invent theory with mirror particles which enter above with (-1)
$\longrightarrow$ remember spin–statistics: change spin by 1/2
$\longrightarrow$ call it supersymmetry $\longrightarrow$ stabilize proton $\longrightarrow$ explain dark matter ...

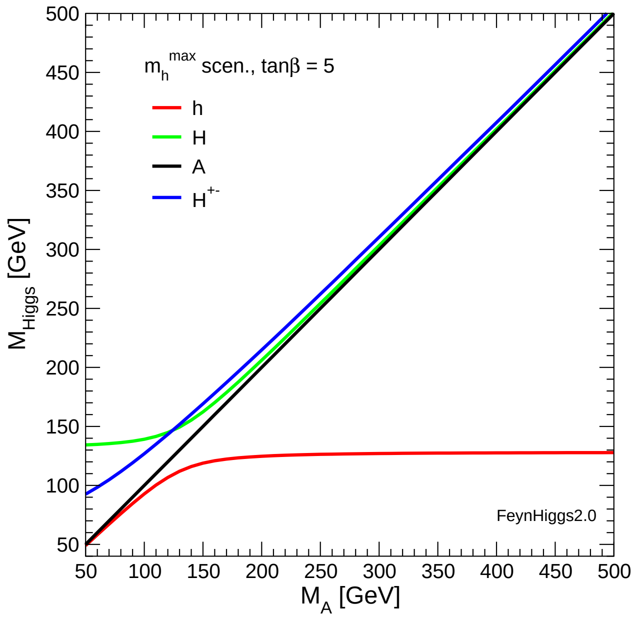
Required by Supersymmetry: two Higgs doublet model

– one (complex) Higgs doublet: 4 degrees of freedom
$\longrightarrow$ three for longitudinal W, Z, one for scalar Higgs

– two Higgs doublet: 8 degrees of freedom
$\longrightarrow$ three for W, Z, five for Higgs particles
$\longrightarrow$ scalars h^0, H^0, pseudoscalar A^0, charged $H^\pm$

– free parameters
(1) still only one free mass scale: m_A
(2) two vacuum expectation values: $\tan\beta = v_t/v_b$

$\Rightarrow$ prediction: $m_h < 135$ GeV [Heinemeyer, Hollik, Weiglein,...]



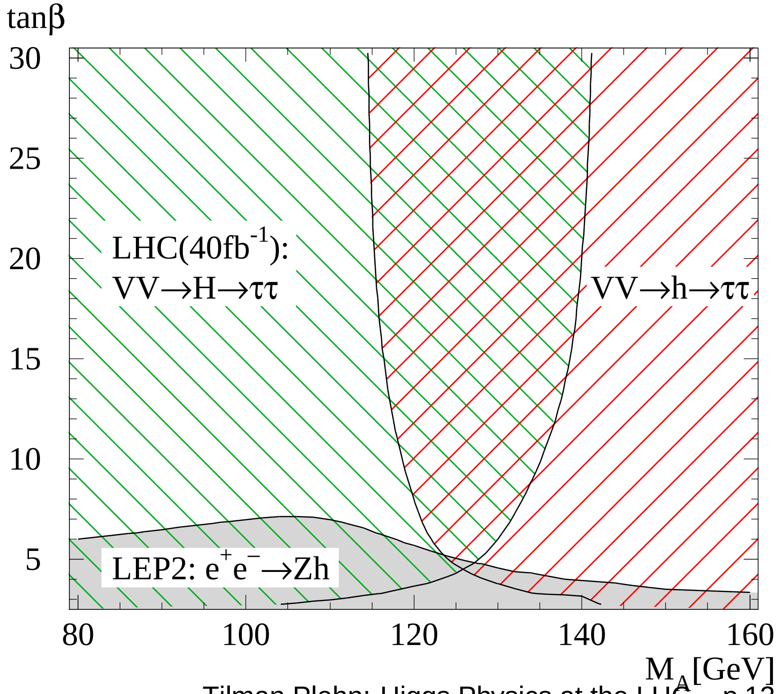
SUPERSYMMETRIC HIGGS SECTOR: 2

Supersymmetric Higgs bosons and qq $\rightarrow$ qqH $\rightarrow$ qq$\tau\tau$

- allowed light Higgs mass: $m_Z \ll m_h < 135$ GeV
- ‘decoupling regime’ $m_A \gtrsim 160$ GeV
  $\rightarrow$ $A^0, H^0, H^\pm$ heavy
  $\rightarrow$ h^0 looks like SM Higgs [of corresponding mass]
  $\rightarrow$ production rate: g_{WWh} like SM
  $\rightarrow$ branching fraction: $\text{BR}(h^0 \rightarrow \tau\tau) > \text{BR}(H_{SM} \rightarrow \tau\tau)$
  $\rightarrow$ qq $\rightarrow$ qqh^0 $\rightarrow$ qq$\tau\tau$ better than SM
- opposite case $m_A \lesssim 120$ GeV
  $\rightarrow$ H^0 around 135 GeV
  $\rightarrow$ qq $\rightarrow$ qqH^0 $\rightarrow$ qq$\tau\tau$ as in SM
- intermediate case $m_A \sim 120$ GeV
  $\rightarrow$ $h^0, H^0 \rightarrow \tau\tau$ just add up

$\Rightarrow$ No-lose theorem: qq $\rightarrow$ qq$\{h^0, H^0\}$ $\rightarrow$ qq$\tau\tau$

[TP, Rainwater, Zeppenfeld]

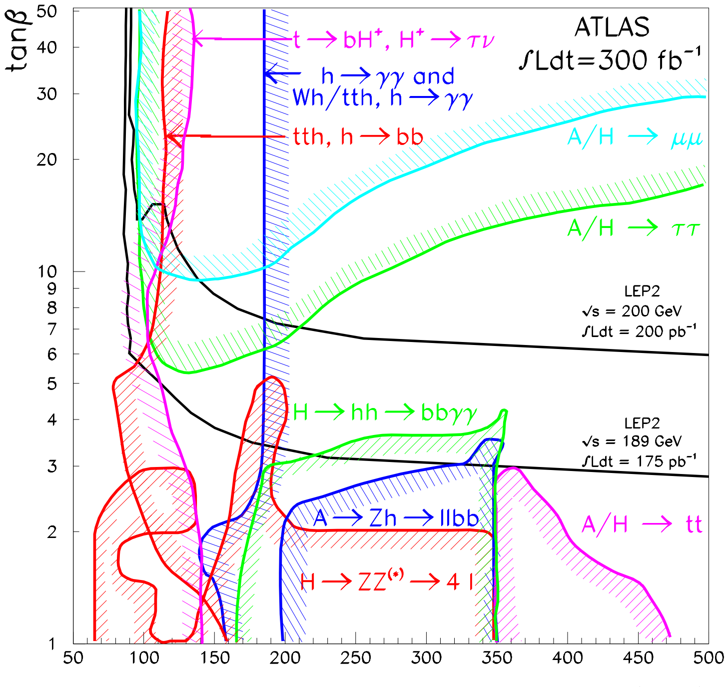


SUPERSYMMETRIC HIGGS SECTOR: 3

Tell it is two Higgs doublets: find more Higgses

- intermediate $m_A \sim 120$ GeV:
  - $\to$ lots of Higgs bosons h^0, H^0, A^0 observable
  - $\to$ problem distinguishing them: $H^0 \to \mu\mu$ [Boos, Djouadi, Mühlleitner,...]
  - $\to$ top quark decays $t \to bH^+$?
- decoupling regime $m_A \gtrsim 160$ GeV
  - $\to$ light SM–like h^0 guaranteed
  - $\to$ Yukawa coupling for $H^0, A^0, H^\pm$: $m_b \tan\beta$ and $m_t / \tan\beta$
  - $\to \tan\beta < 20$? [possibly $gg \to H^0 \to h^0 h^0$]
- $m_A \gtrsim 160$ GeV and $\tan\beta > 20$
  - $\to$ bottom Yukawa coupling $m_b \tan\beta \gtrsim 100$ GeV
  - $\to$ production $b\bar{b} \to H^0$ or $gb \to tH^-$
  - $\to$ decays $H^0 \to \tau\tau, \mu\mu$ or $H^- \to \tau\bar{\nu}$
  - $\to$ supersymmetry:

    $m_b/(1-\Delta_b)$ with $\Delta_b \propto \mu m_{\tilde{g}}/M^2_{\mathrm{SUSY}}$



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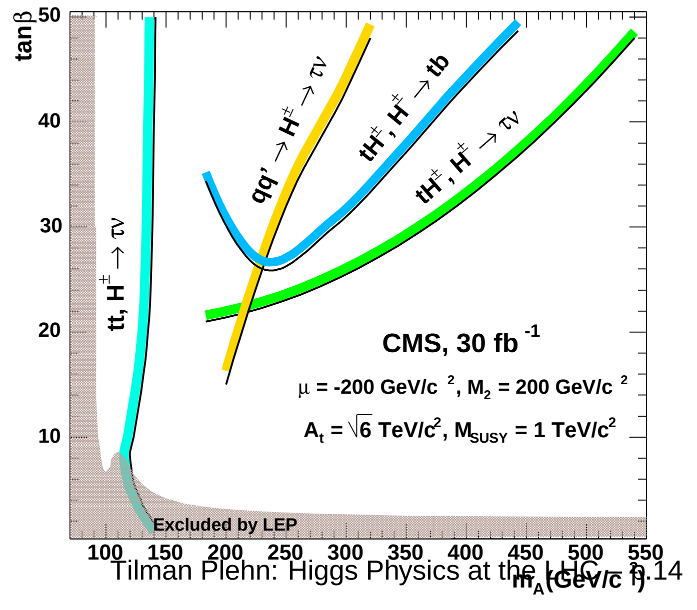
  $\to$ supersymmetry:
  $m_b/(1 - \Delta_b)$ with $\Delta_b \propto \mu m_{\tilde{g}}/M^2_{SUSY}$
- my favorite: charged Higgs only in 2HDM



HIGGS STATISTICS: 1

An example from real life [TP, Rainwater, Zeppenfeld vs. Cranmer, Mellado, Quayle, Wu]

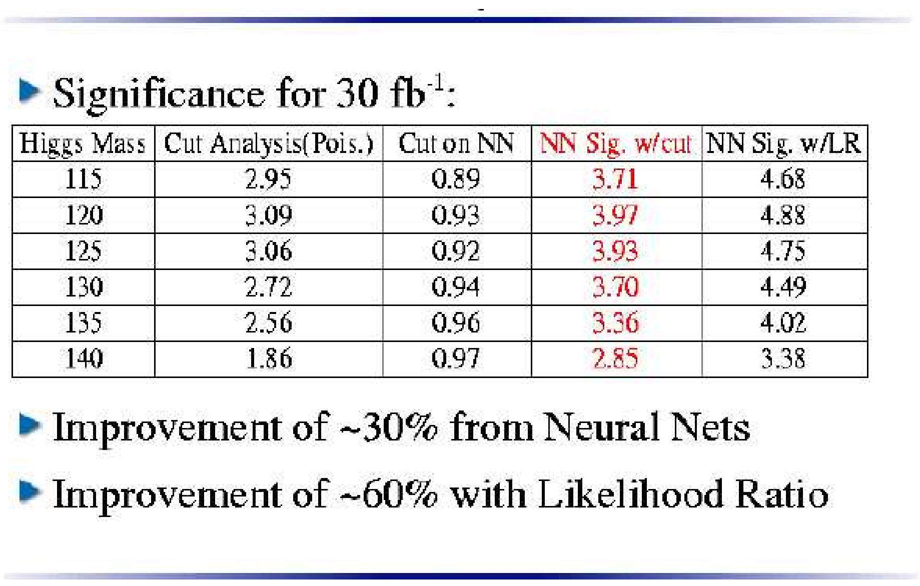
– WBF H $\to \tau\tau$ in Standard Model [and MSSM]

– cut analysis promising, experimentalists convinced

– neural net even better with LEP-type events weighting

– new Higgs discovery channel

⇒ could we have predicted this outcome?



- Significance for 30 fb^{-1}:

Higgs Mass	Cut Analysis(Pois.)	Cut on NN	NN Sig. w/cut	NN Sig. w/LR
115	2.95	0.89	3.71	4.68
120	3.09	0.93	3.97	4.88
125	3.06	0.92	3.93	4.75
130	2.72	0.94	3.70	4.49
135	2.56	0.96	3.36	4.02
140	1.86	0.97	2.85	3.38

- Improvement of ~30% from Neural Nets
- Improvement of ~60% with Likelihood Ratio

[B. Quayle, ATLAS Higgs meeting, 2003]

HIGGS STATISTICS: 2

Likelihood ratio and maximum significance [Cranmer, TP]

- Neyman–Pearson lemma: likelihood ratio most powerful estimator

  [assuming signal true: lowest probability to mistake signal for background fluctuation (type-II error)]

- combined likelihood for N-event Poisson statistics [independent channels]

$$\mathcal{L}_b = \frac{e^{-b}\, b^N}{N!} \qquad\qquad \mathcal{L}_{s+b} = \frac{e^{-(s+b)}\, (s+b)^N}{N!}$$

$$q = \log \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b} = -s + N\, \log\left(1 + \frac{s}{b}\right) \longrightarrow -\sum_j s_j + \sum_j N_j\, \log\left(1 + \frac{s_j}{b_j}\right)$$

→ integration over entire phase space replacing $s, b \to |\mathcal{M}_{s,b}|^2$ [LEP–Higgs inspired]

$$q(\vec{r}) = -\sigma_s \mathcal{L} + \log\left(1 + \frac{|\mathcal{M}_s(\vec{r})|^2}{|\mathcal{M}_b(\vec{r})|^2}\right)$$

→ extraction of probability distribution function via Fourier transform: $\rho_{s,b}(q)$

→ mathematically optimal significance $CL_b(q) = \int_q^\infty dq' \rho_b(q')$ [5σ is $CL_b = 2.85\, 10^{-7}$]

HIGGS STATISTICS: 3

Irreducible + unsmeared and beyond

– irreducible & unsmeared: signal and background phase space identical

$$\sigma_{\text{tot}} = \int d\text{PS}\ M_{\text{PS}}\ d\sigma_{\text{PS}} = \int d\vec{r}\ M(\vec{r})\ d\sigma(\vec{r})$$

→ random numbers $\vec{r}$ basis for phase space configurations

→ smearing! otherwise e.g. $\Delta m_{\mu\mu}^{\text{width}} \ll \Delta m_{\mu\mu}^{\text{meas}}$ too distinctive

→ smear observable/random number with Gaussian W

$$\sigma_{\text{tot}} = \int d\vec{r}_\perp dr_m^* \int_{-\infty}^{\infty} dr_m\ M(\vec{r})\ d\sigma(\vec{r})\ W(r_m, r_m^*)$$

→ modified phase space vector $\vec{r} = \{\vec{r}_\perp, r_m\}$ without back door

→ complete smearing: replace phase space by set of distributions

[lose mathematical maximum significance claim]

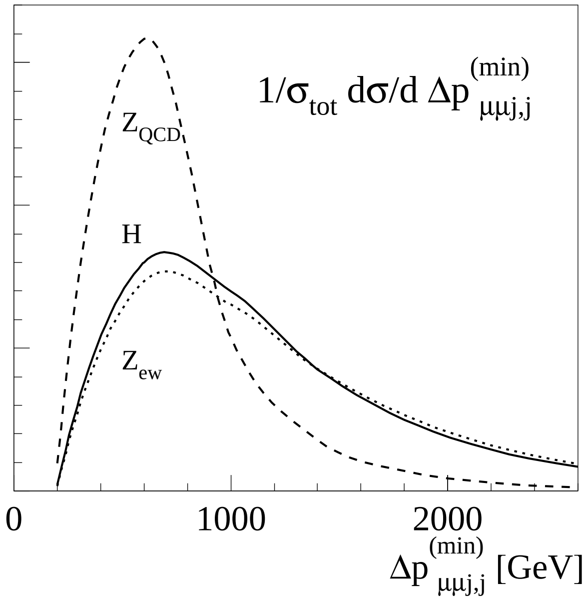
→ about to be be implemented in Whizard [Cranmer, TP, Reuter]

WBF-HIGGS TO MUONS: 1

WBF Higgs with decay H $\longrightarrow \mu\mu$ [TP, Rainwater]

- number of signal events small [$\sigma \cdot$ BR ~ 0.25fb]
- no distribution with golden cut

$\longrightarrow$ perfect form multivariate analysis



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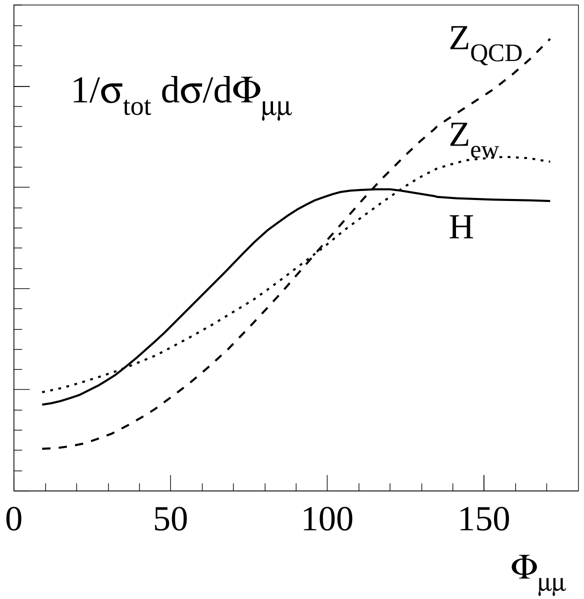

Old results [leading (irreducible) backgrounds]

$\sqrt{S}$ [TeV]	M_H [GeV]	σ_H [fb]	σ_Z^{QCD} [fb]	σ_Z^{ew} [fb]	S/B	significance σ	$\triangle\sigma/\sigma$	$\mathcal{L}_{5\sigma}$ [fb^{-1}]
14	115	0.25	3.57	0.40	1/9.1	1.7	60%	2600
14	120	0.22	2.60	0.33	1/7.5	1.8	60%	2300
14	130	0.17	1.61	0.24	1/6.5	1.7	65%	2700
14	140	0.10	1.11	0.19	1/7.5	1.2	85%	4900
200	115	2.57	39.6	5.3	1/10.1	5.3	20%	270
200	120	2.36	29.2	4.0	1/8.0	5.7	20%	230
200	130	1.80	18.7	2.7	1/6.9	5.3	20%	260
200	140	1.14	13.4	2.0	1/7.9	4.0	27%	500

WBF-HIGGS TO MUONS: 2

Statistical promise of WBF H $\rightarrow \mu\mu$

– relevant for physics: confirm Yukawa coupling to 2nd generation

– gluon–fusion channel helpful? [Han & McElrath, Boos etal.]

→ for now try WBF alone

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– event weighting promising

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– smearing only relevant for $m_{\mu\mu}$ [mimic by Γ'_H]

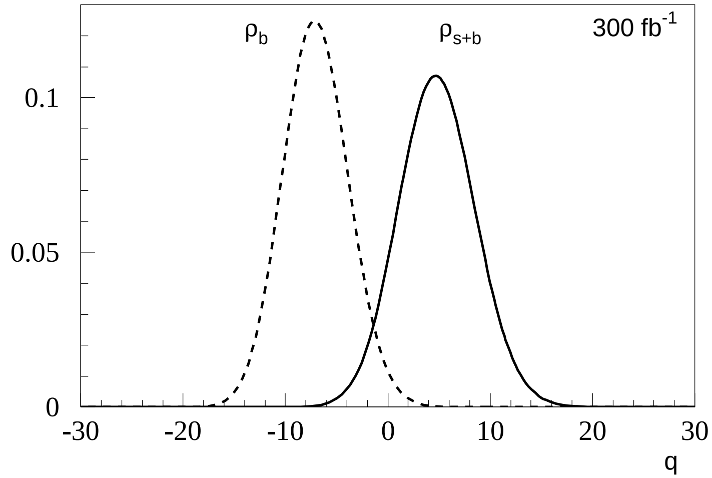
→ compute likelihood from matrix elements

→ upper limit on parton level significance

→ WBF H $\rightarrow \mu\mu$: 3.5 sigma in 300 fb^{-1}

[$\sim 4.2\sigma$ with jet veto; $\gtrsim 5\sigma$ for Atlas+CMS]

⇒ see if we can find an experimental group now



WBF-HIGGS TO MUONS: 2

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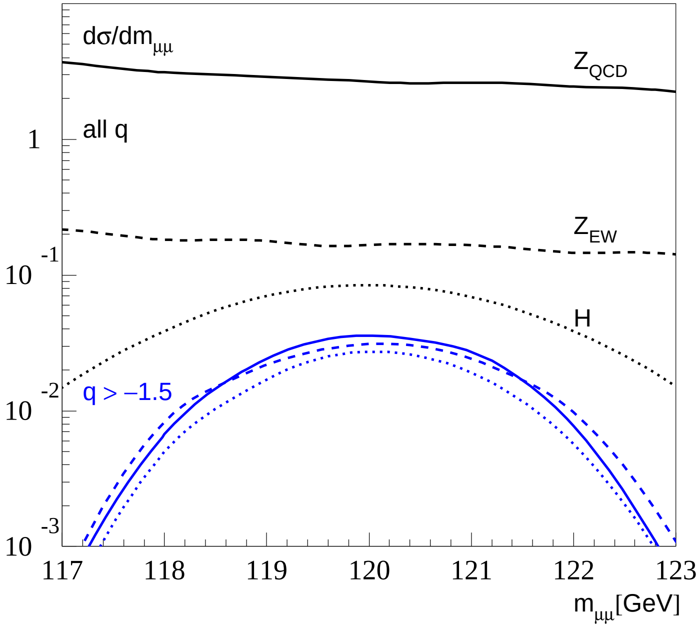

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$\Rightarrow$ see if we can find an experimental group now

OUTLOOK

Higgs boson at the LHC

- we will find it in more than one channel
- we will measure many properties more or less well:

  set of couplings and width
  self coupling (only λ_{HHH})
  CP properties and WWH coupling structure
  invisible decays
  Higgs to muons (2nd generation Yukawa)
  former stealth models...

- one Higgs in SUSY is no problem
- there are still channels to be explored
- there are still ideas waiting to be tested

⇒ LHC will be way cool!

HIGGS POTENTIAL AND SELF COUPLINGS

Higgs self coupling

- scalar with Yukawa couplings to fermions, so what?
- renormalizable SM potential: $\mu^2 = -\lambda v^2$ with $\lambda = m_H^2/(2v^2)$
  and self couplings $\lambda_{3H}/\lambda_{4H} = v$
- MSSM: $\lambda_{3h}/\lambda_{4h} = v \sin(\beta + \alpha)/\cos 2\alpha$ and m_h à la 2nd floor
- D6 operator: $\mu^2/v^2 = -\lambda_0 + 3\lambda_1 v^2/(4\Lambda^2)$ and $\lambda = \lambda_0 - 3\lambda_1 v^2/(2\Lambda^2)$.

Higgs pair production

- HH → 4W: serious detector simulation needed, not hopeless
  [use observable m_{vis} to determine λ_{HHH}, need NLO $\sigma(t\bar{t}j)$]
- HH → $b\bar{b}\tau\tau$: miracle required
- HH → 4b: several major miracles mandatory

  [ILC in better shape]
- HH → $b\bar{b}\mu\mu$: small miracle would be helpful
  [might come out of $\mu\mu$ mass resolution]
- HH → $b\bar{b}\gamma\gamma$: some enhancement needed

⇒ serious challenge to detectors and machine