HIGGS PHYSICS AT THE LHC

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– How to find the Higgs at LHC
– Weak boson fusion
– Standard Model vs. Supersymmetry
– Maximum Significances: Higgs to muons

STANDARD–MODEL HIGGS SECTOR

Higgs potential

– remember Lagrangian invariant under $SU(2) \times U(1)$

– break symmetry via 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 [fixes couplings, Higgs mass unknown]

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

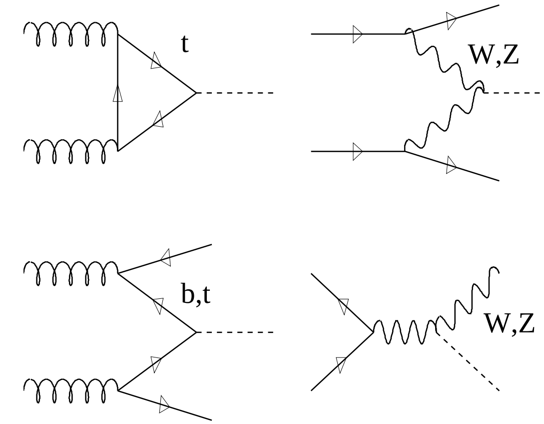
⇒ not the whole story if new scale Λ [first-order EW phase transition: hep-ph/0407019]

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

⇒ 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 all couplings, including self coupling



Design Higgs searches for the LHC

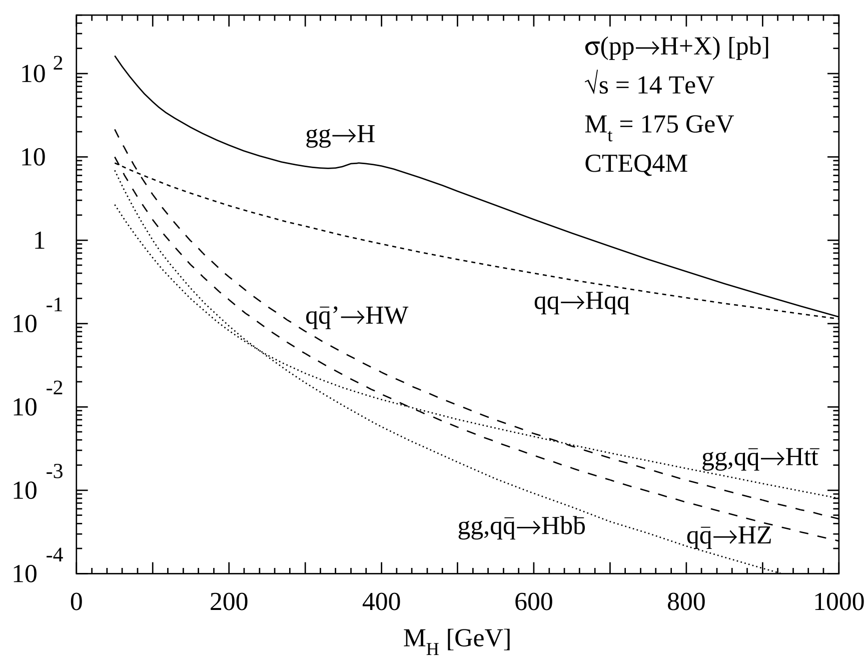
– unitarity limit: $m_H < 1$ TeV
electroweak precision tests: $m_H \lesssim 250$ GeV

– production and decay of light Higgs

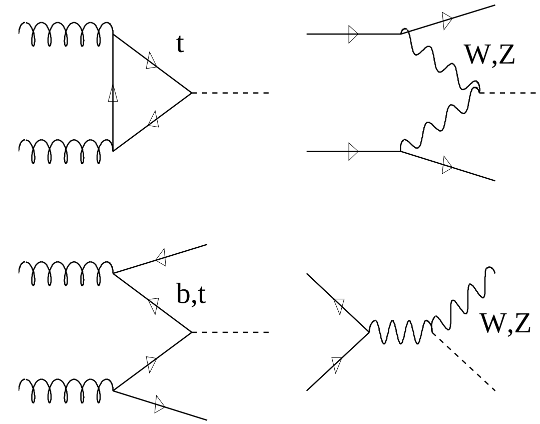
$gg \to H$ $qq \to qqH$ $gg \to t\bar{t}H$ $q\bar{q}' \to WH$	$\leftrightarrow$	signal $\times$ trigger backgrounds systematics $S/\sqrt{B}$ vs. S/B mass resolution...	$\leftrightarrow$	$H \to b\bar{b}$ $H \to WW$ $H \to \tau^+_{\ell h}\tau^-_\ell$ $H \to \gamma\gamma$ $H \to \mu\mu$...

Production rates

[Spira, Harlander, Melnikov,...]



HIGGS PRODUCTION AND DECAY: 1



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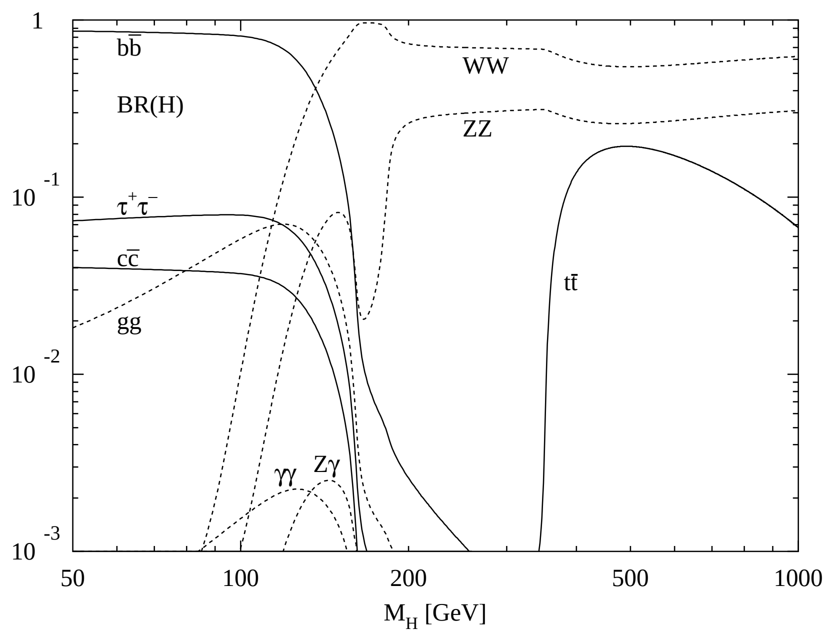
$qq \to qqH$		backgrounds		$H \to WW$
$gg \to t\bar{t}H$		systematics		$H \to \tau_{\ell h}^{+} \tau_{\ell}^{-}$
$q\bar{q}' \to WH$		$S/\sqrt{B}$ vs. S/B		$H \to \gamma\gamma$
		mass resolution...		$H \to \mu\mu$...

Branching fractions

[up to 10^6 events; Hdecay]



Higgs Production and Decay: 2

Some numbers [30 years of citations skipped]

– $gg \to H \to ZZ \to 4\mu$ no-brainer

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

– $gg \to H \to WW$ similar, but no mass peak

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

– $gg \to H \to \gamma\gamma$ with 6 million light Higgses produced

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

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

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

– light Higgs: $qq \to qqH \to qq\tau\tau$ [later]

– more challenging strategies:

$gg \to t\bar{t}H \to t\bar{t}b\bar{b}$ [likely dead]

$gg \to t\bar{t}H \to t\bar{t}WW$ [likely okay]

$gg \to t\bar{t}H \to t\bar{t}\tau\tau$ [unclear]

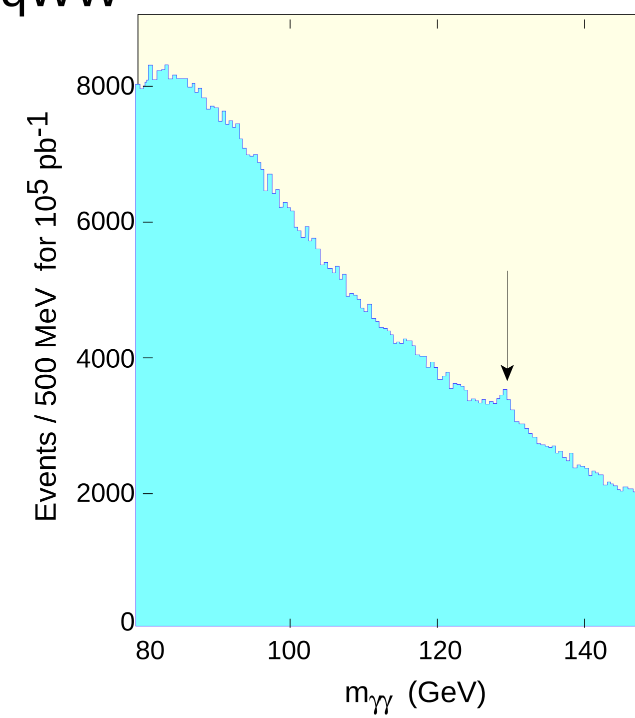
$q\bar{q}' \to WH \to Wb\bar{b}$ [killer QCD backgrounds]

$qq \to qqH \to qqb\bar{b}$ [no ATLAS trigger]

$qq \to qqH \to qq\mu\mu$ [later]

$\Rightarrow$ Very cool, $H \to b\bar{b}$ embarassing

$H_{SM} \to \gamma\gamma$



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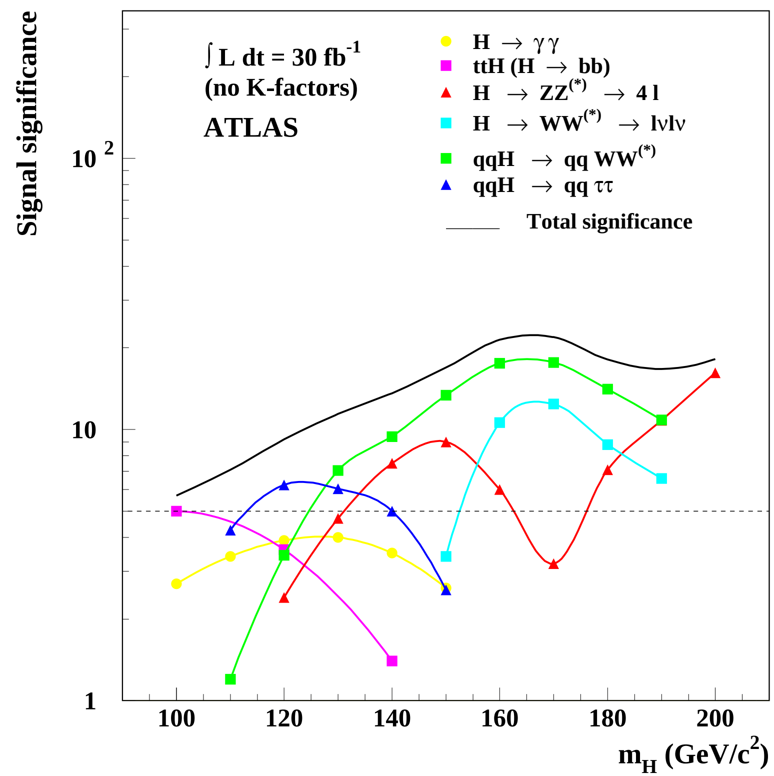


WBF Higgs Production

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

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

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

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

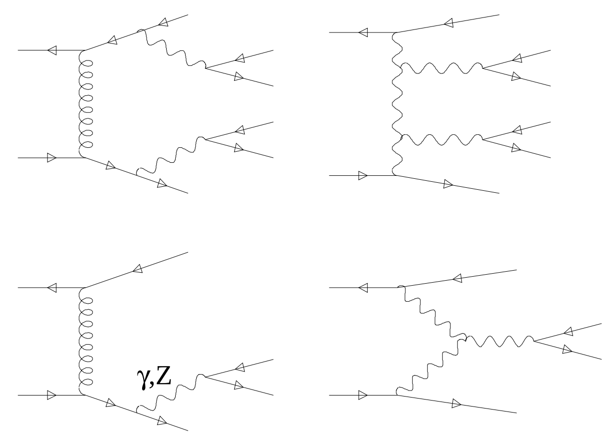
$\Rightarrow$ solve $\vec{k}_{T,1}/x_1 + \vec{k}_{T,2}/x_2 = \vec{p}_{T,1} + \vec{p}_{T,2} = \vec{k}_{T,1} + \vec{k}_{T,2} + \vec{p}_{T,miss}$

$\Rightarrow$ obtain $m_{\tau\tau}^{coll} \sim 2(k_1 \cdot k_2)/(x_1 x_2)$ [does anyone know original paper?]

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

After acceptance cuts

2.2 fb	signal $pp \to H_{SM} + jj$ [$m_H = 120$ GeV]
1230 fb	$pp \to t\bar{t} + \text{jets}$ [tag either b 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. $t\bar{t}$, $t\bar{t}j$, $t\bar{t}jj$)

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

– veto $p_{T_j} > 20$ GeV and $\eta_{j,\rm min} < \eta_j < \eta_{j,\rm max}$ to suppress QCD

– Forget NLO codes, here is the important theory problem

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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 $\rightarrow$ stabilize proton $\rightarrow$ explain dark matter ...

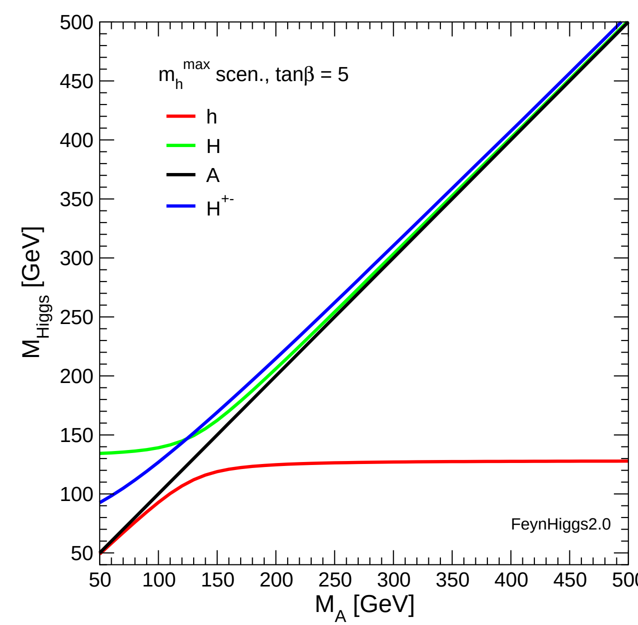
Required by Supersymmetry: two Higgs doublet model

– complex Higgs doublet: 4 degrees of freedom
$\longrightarrow$ 3 for W_L, Z_L; 1 for Higgs scalar

– two doublets: 8 degrees of freedom
$\longrightarrow$ 5 left for Higgses
$\longrightarrow$ scalars h^0, H^0; pseudoscalar A^0; charged $H^\pm$

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

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



Supersymmetric Higgses and $qq \to qqH \to qq\tau\tau$ [TP, Rainwater, Zeppenfeld]

– light MSSM Higgs mass: $m_Z \ll m_h < 135$ GeV

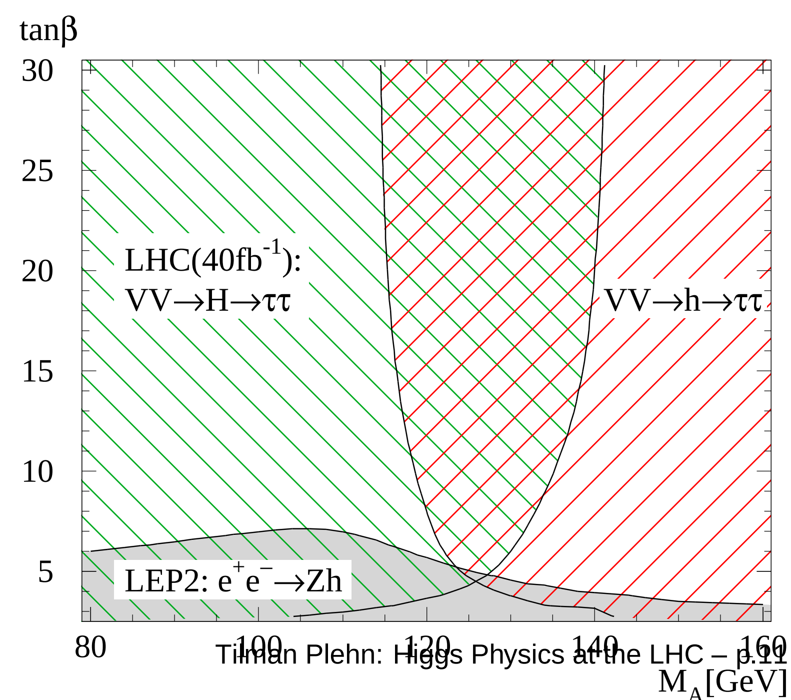
– decoupling regime $m_A \gtrsim 160$ GeV
$\to A^0, H^0, H^\pm$ heavy
$\to h^0$ like SM Higgs [of corresponding mass]
$\to$ production rate: g_{WWh} like SM
$\to$ branching fraction: $BR(h^0 \to \tau\tau) > BR(H_{SM} \to \tau\tau)$
$\to qq \to qqh^0 \to qq\tau\tau$ better in MSSM

– opposite case $m_A \lesssim 115$ GeV
$\to H^0$ around 135 GeV
$\to qq \to qqH^0 \to qq\tau\tau$ as in SM

– intermediate case $m_A \sim 120$ GeV
$\to h^0, H^0 \to \tau\tau$ just add up

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

[fi nding other Higgses is hell]



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 event weighting

– new Higgs discovery channel

$\Rightarrow$ predict 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]

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

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

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

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

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

$\longrightarrow$ 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

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

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

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

$\longrightarrow$ smear observable/random number with Gaussian W

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

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

$\longrightarrow$ complete smearing: replace phase space by set of distributions

[lose mathematical maximum signifi cance claim]

$\longrightarrow$ about to be be implemented in Whizard [Cranmer, TP, Reuter]

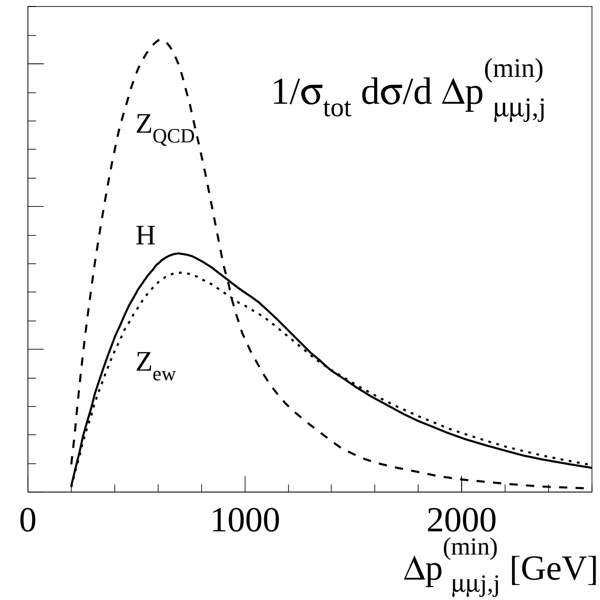
WBF-Higgs to Muons: 1

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

– number of signal events small [$\sigma \cdot$ BR $\sim$ 0.25fb]

– no distribution with golden cut

$\longrightarrow$ perfect for multivariate analysis



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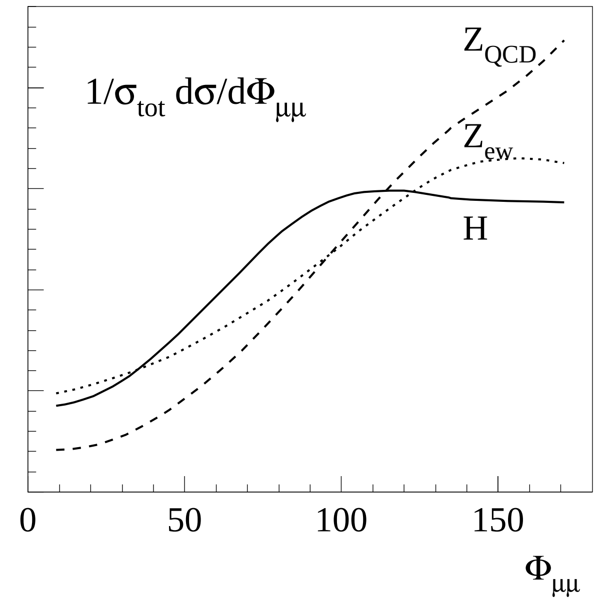


Awful old results [leading backgrounds irreducible]

$\sqrt{S}$ [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

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

– cut analysis impossible [no good cuts]

– event weighting only chance [few events]

– mostly irreducible backgrounds

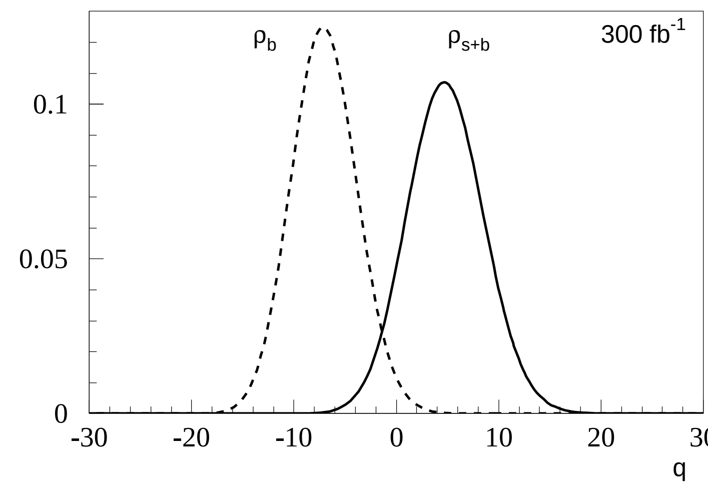
– smearing only relevant for $m_{\mu\mu}$ [even mimic by Γ'_H?]

– compute likelihood from matrix elements

$\to$ upper limit on parton level significance

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

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



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

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

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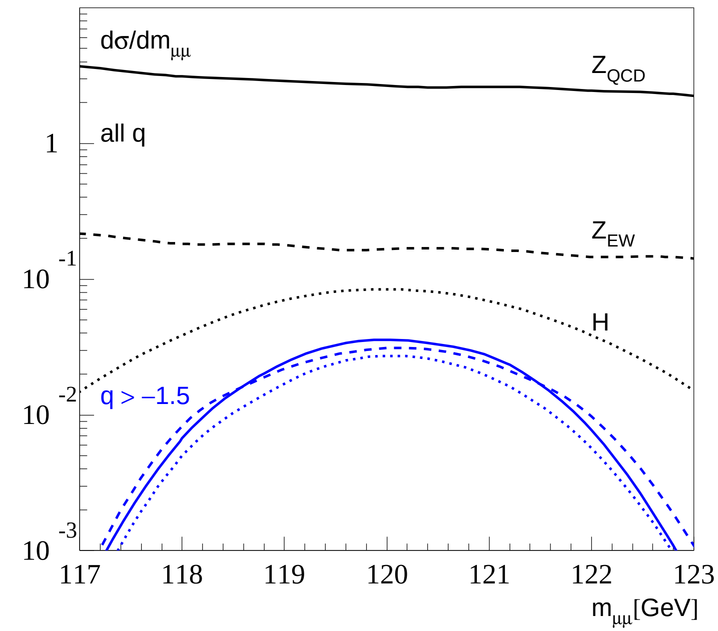

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OUTLOOK

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

$\Rightarrow$ LHC will be way cool!

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

– $HH \to 4W$: serious detector simulation needed, not hopeless
[use observable m_{vis} to determine λ_{HHH}, need NLO $\sigma(t\bar{t}j)$]

– $HH \to b\bar{b}\tau\tau$: miracle required

– $HH \to 4b$: several major miracles mandatory

[ILC in better shape]

– $HH \to b\bar{b}\mu\mu$: small miracle would be helpful
[might come out of $\mu\mu$ mass resolution]

– $HH \to b\bar{b}\gamma\gamma$: some enhancement needed

⇒ serious challenge to detectors and machine