Electroweak symmetry breaking

Search for the missing piece of the Standard Model

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Plan for today

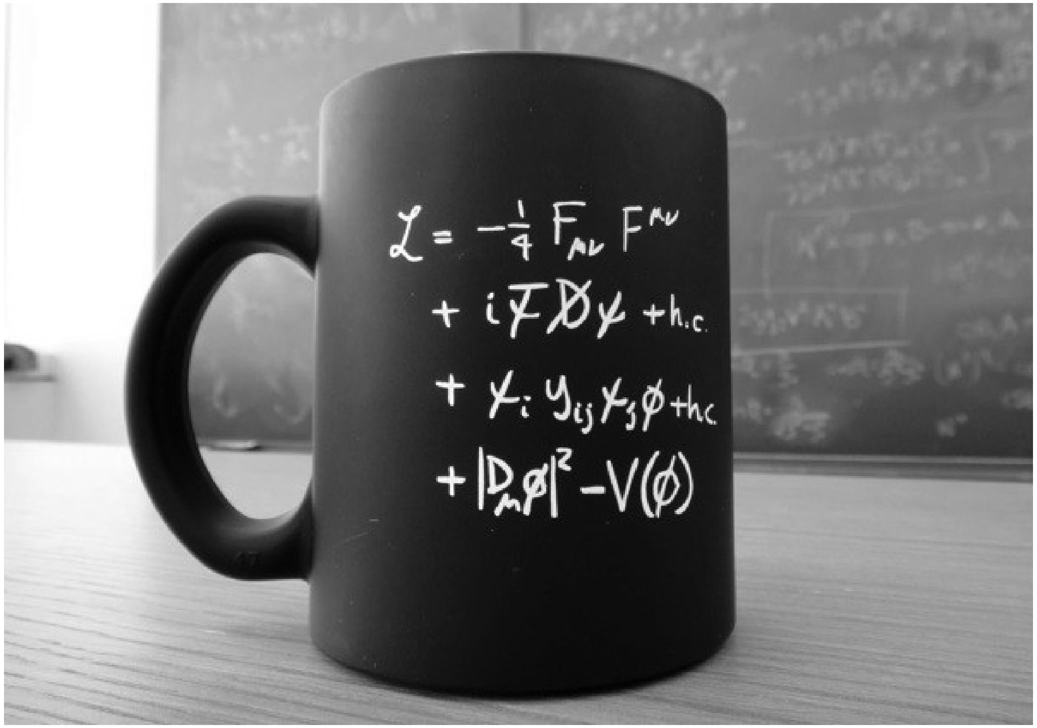
Introduction: a glance at the Standard Model

Some shortcomings of the SM

The Higgs mechanism

Higgs signature at particle colliders

Discovery potential, exclusion limits



Introduction

A glance at the Standard Model

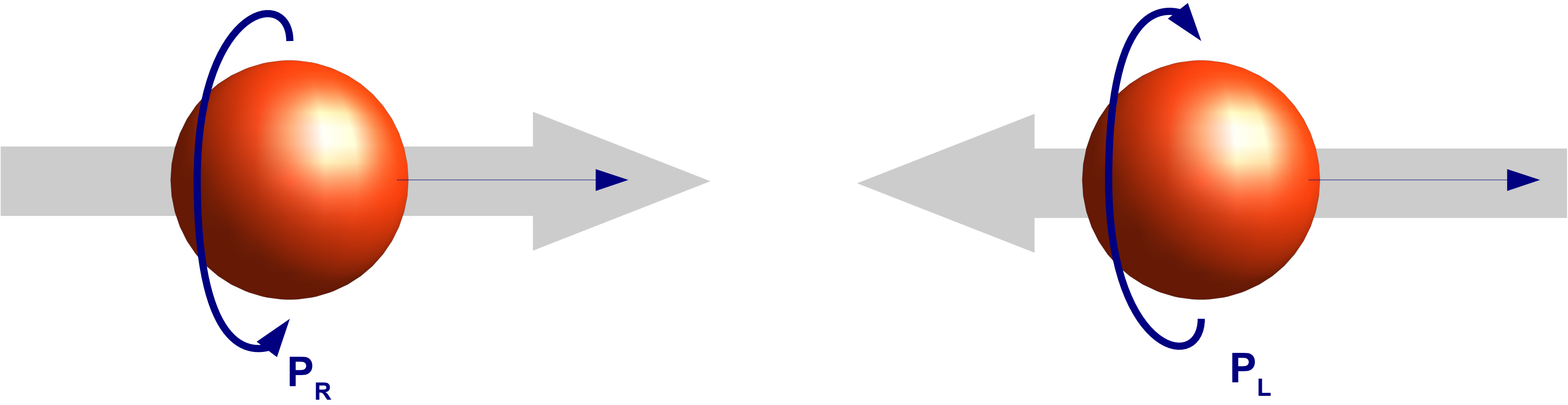
- The SM condenses **two simple observations about fundamental interactions:**

fundamental interactions of particles in nature reflect fundamental **symmetries**

  - the **charges** of the particles are the generators of the so called gauge symmetries

nature distinguishes left-handed and right-handed **polarizations**

  - with more than 1 generation of particles **CP symmetry is violated**



Basis of the Standard Model

- The SM is **based on**:
  - a **gauge symmetry group**

$$G_{\mathrm{SM}} = \underline{SU(3)_{\mathrm{C}}} \times \underline{SU(2)_{\mathrm{L}}} \times \underline{U(1)_{\mathrm{Y}}}$$

Strong sector Weak sector Electromagnetic sector

  - **Three generations of fermions** which are 5 representations of the symm. group:

$$Q_{Li}(3,2)_{+1/6},\ U_{Ri}(3,1)_{+2/3},\ D_{Ri}(3,1)_{-1/3},\ L_{Li}(1,2)_{-1/2},\ E_{Ri}(1,1)_{-1}$$

Left handed quarks are: Color triplets Weak isospin doublets and have this hypercharge : Y= ½ (Q-I_3)

That's all there is to know about the SM! If you don't believe see the next few slides.

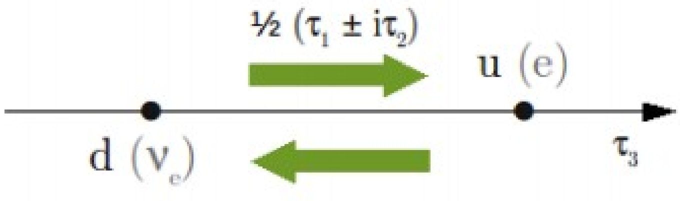
What is gauge invariance?

- It states that under a transformation of the fields the hamiltonian is left unchanged
- I.e. all **gauge transformations are constants of motion**, time independent
- If is ψ a field and ψ→Uψ is a transformation, then:

$$\langle\psi'|\ H\ |\psi'\rangle \ = \ \langle\psi|\ U^\dagger H U\ |\psi\rangle \ = \ \langle\psi|\ H\ |\psi\rangle \ \Rightarrow \ [U,H]=0$$

- The **charges of the particles generate currents** ►

  i.e. transformations within the symmetry group



- The lagrangian is modified by a **covariant derivative** to preserve gauge invariance

$$D^\mu = \partial^\mu + ig_s G^\mu_a L_a + igW^\mu_b T_b + ig' B^\mu Y.$$

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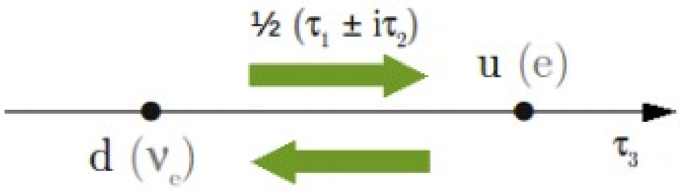

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The couplings to the currents

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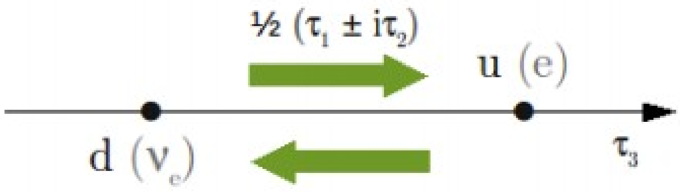

- The lagrangian is modified by a **covariant derivative** to preserve gauge invariance

$$D^\mu = \partial^\mu + i g_s G_a^\mu L_a + i g W_b^\mu T_b + i g' B^\mu Y.$$

The gauge fields:

- 8 gluon
- 3 electroweak interaction bosons
- 1single hypercharge boson

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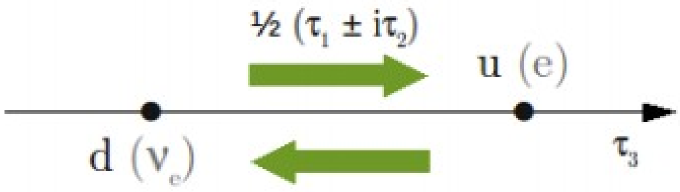


- The lagrangian is modified by a **covariant derivative** to preserve gauge invariance

$$D^\mu = \partial^\mu + ig_s G^\mu_a \boxed{L_a} + igW^\mu_b \boxed{T_b} + ig'B^\mu \boxed{Y.}$$

The charges:

-Gell-Mann matrices for color triplets, 0 for singlets

- Pauli matrices for weak isospin doublets, 0 for singlets

- the hypercharge

Basis of the Standard Model

$$Q_{Li}(3,2)_{+1/6},\ U_{Ri}(3,1)_{+2/3},\ D_{Ri}(3,1)_{-1/3},\ L_{Li}(1,2)_{-1/2},\ E_{Ri}(1,1)_{-1}$$

Left handed quarks are:

Color triplets

Weak isospin doublets

and have this hypercharge : Y= ½ (Q-I_3)

- Using the information above we can write down the kinematics predicted by the SM
- E.g. for a left handed quark:

$$\mathcal{L}_{\text{kinetic}}(Q_L) = i\overline{Q_{Li}}\gamma_\mu \overbrace{\left(\partial^\mu + \underbrace{\frac{i}{2}g_s G^\mu_a \lambda_a}_{\substack{\textit{coupling}\\ \textit{x}\\ \textit{gauge field}\\ \textit{x}\\ \textit{charge}}} + \frac{i}{2} g W^\mu_b \tau_b + \frac{i}{6} g' B^\mu\right)}^{\textit{covariant derivative}} \underbrace{\delta_{ij}}_{\substack{\textit{Unitary}\\ \textit{matrix,}\\ \textit{no flavor mixing}\\ \textit{at this point}}} Q_{Lj}$$

Gauge bosons have self interactions

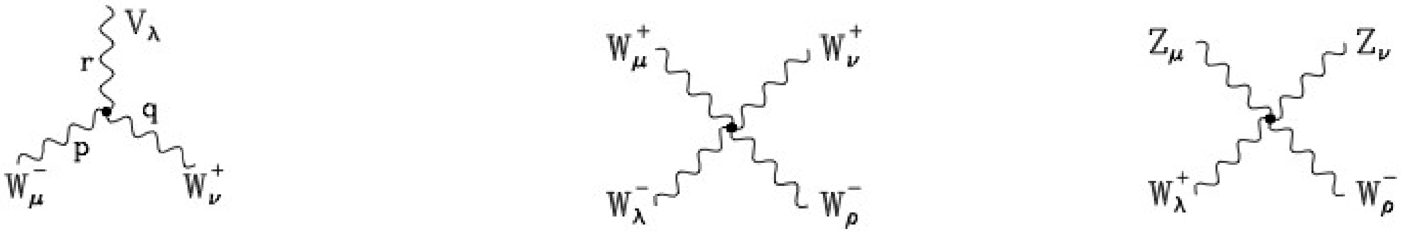
- Besides the fermion kinematics, **pure gauge-bosons interactions are allowed**

$$\mathcal{L}_{\text{gauge-fixing}} = -\frac{1}{4}W_{\mu\nu}^{\ \ i}W^{\mu\nu^i} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$F_{\mu\nu}$ is the field strength tensor which for the electroweak sector is given by:

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g_W \epsilon^{ijk} W^j_\mu W^k_\nu \qquad B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

- This **allows for triple and quartic gauge boson interactions**



etc.

$+ig_V\ [(p-q)_\lambda g_{\mu\nu}+(q-r)_\mu g_{\nu\lambda}+(r-p)_\nu g_{\lambda\mu}]$

(all momenta incoming,
$g_A=e,\ g_Z=g_W\ \cos\theta_W$)

$+ig_W^2[2g_{\mu\nu}g_{\lambda\rho}-g_{\mu\lambda}g_{\nu\rho}-g_{\mu\rho}g_{\nu\lambda}]$

$-ig_W^2\cos^2\theta_W[2g_{\mu\nu}g_{\lambda\rho}-g_{\mu\lambda}g_{\nu\rho}-g_{\mu\rho}g_{\nu\lambda}]$

Longitudinal vector boson scattering

- Longitudinal polarization is possible for the massive vector bosons

- **Scattering of longitudinal polarized W bosons breaks unitarity at high s$^{1/2}$**

$$\sigma(W_L^+ W_L^- \to W_L^+ W_L^-) \sim s$$

- At s$^{1/2}$ ~ 1 TeV interactions become strong unless unitarity is restored

- Scalar boson (H) interaction is a possible mechanism provided that:

$$g_{HWW} \sim M_W \qquad g_f \sim M_f \qquad M_H < 1 \text{ TeV}$$

- Then:

$$A(W^+W^- \to W^+W^-) \xrightarrow{s \gg M_W^2} \frac{1}{v^2}\left[s + t - \frac{s^2}{s - M_H^2} - \frac{t^2}{t - M_H^2}\right]$$

and the cross section satures (i.e.becomes constant) at high s$^{1/2}$

Upper bound for scalar boson mass

- If we decompose the WW scattering amplitude in partial waves we can write simply:

$$A = 16\pi \sum_{l=0}^{\infty}(2l+1)\underbrace{P_l(cos\theta)}_{\text{Legendre polynomial}}\underbrace{a_l}_{\text{Amplitude for l-angular momentum wave}} \longrightarrow \sigma = \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2$$

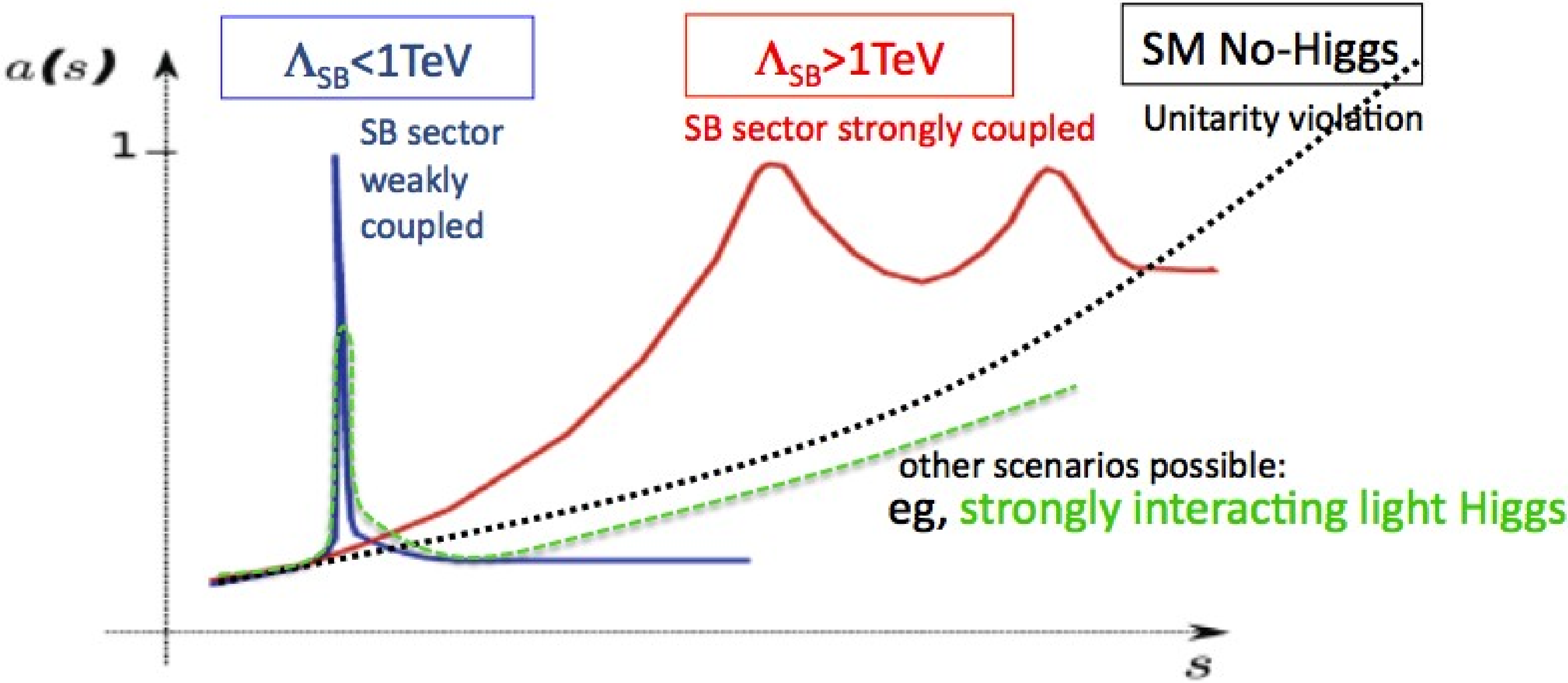
- But from the optical theorem $\sigma = \frac{1}{s}\mathrm{Im}[\mathrm{A}(\theta = 0)]$ which results in : $|\mathrm{Re}(a_\ell)| < \frac{1}{2}$

- The immediate consequence is an upper bound on the mass of the scalar boson:

$$a_0 \xrightarrow{s\gg M_H^2} -\frac{M_H^2}{8\pi v^2} \quad \Rightarrow \quad \boxed{M_H < 870\ \mathrm{GeV}}$$

Possible scenarios for VV scattering

- If the scalar boson is strongly interacting / absent should observe distinct effects



- VV scattering = fundamental probe of how the original EWK symmetry is broken

Some exercises to consolidate

1) Write down the kinetic terms for all fermion representations following the example of slide 10.

2) Why did we only consider longitudinally polarized W bosons?

3) Demonstrate that $|\mathrm{Re}(a_l)|<1/2$

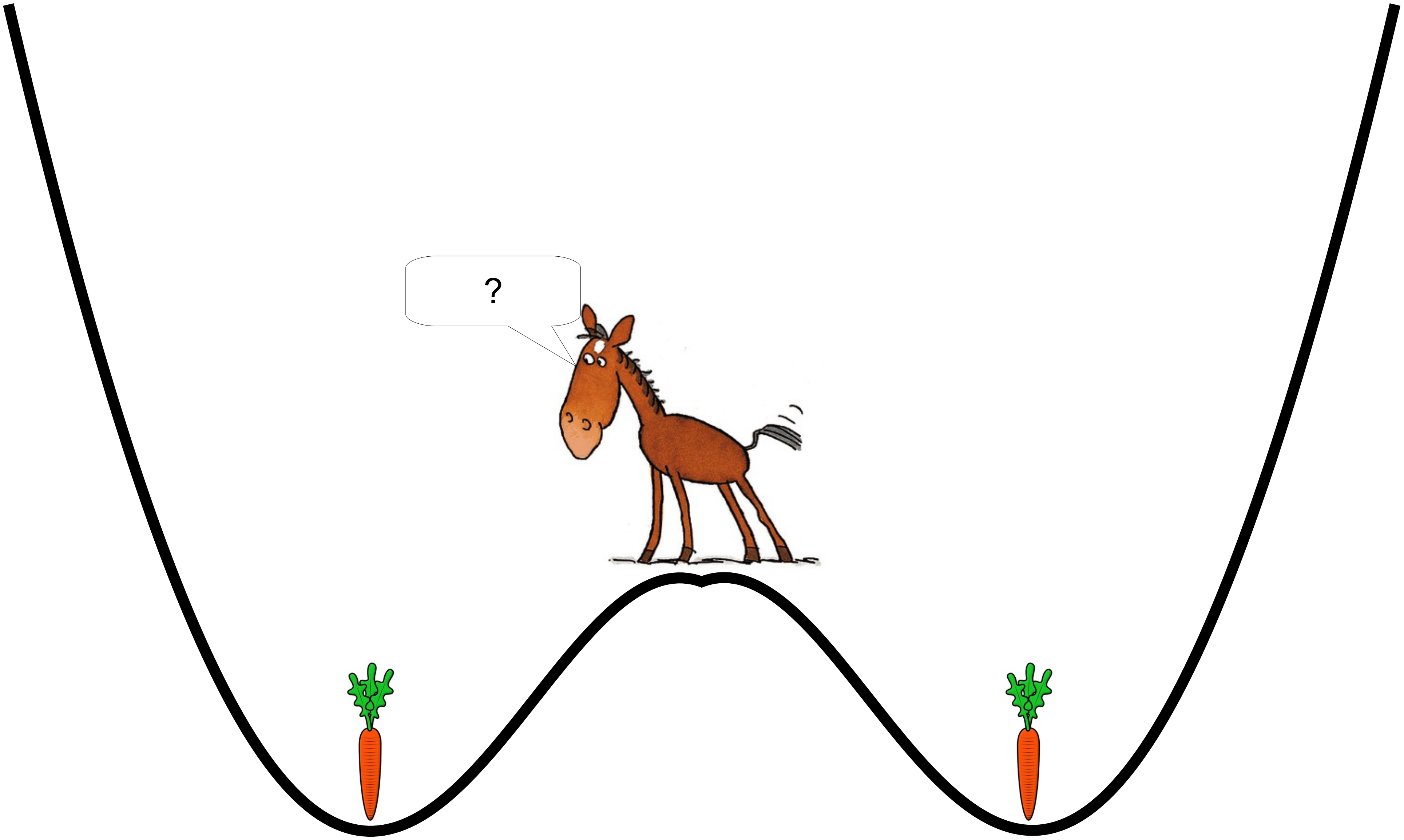
4) In the high $s^{1/2}$ regime where W's can be considered massless, we can write:

$$A(w^+w^- \to w^+w^-) = -\left[2\frac{M_H^2}{v^2} + \left(\frac{M_H^2}{v}\right)^2 \frac{1}{s-M_H^2} + \left(\frac{M_H^2}{v}\right)^2 \frac{1}{t-M_H^2}\right]$$

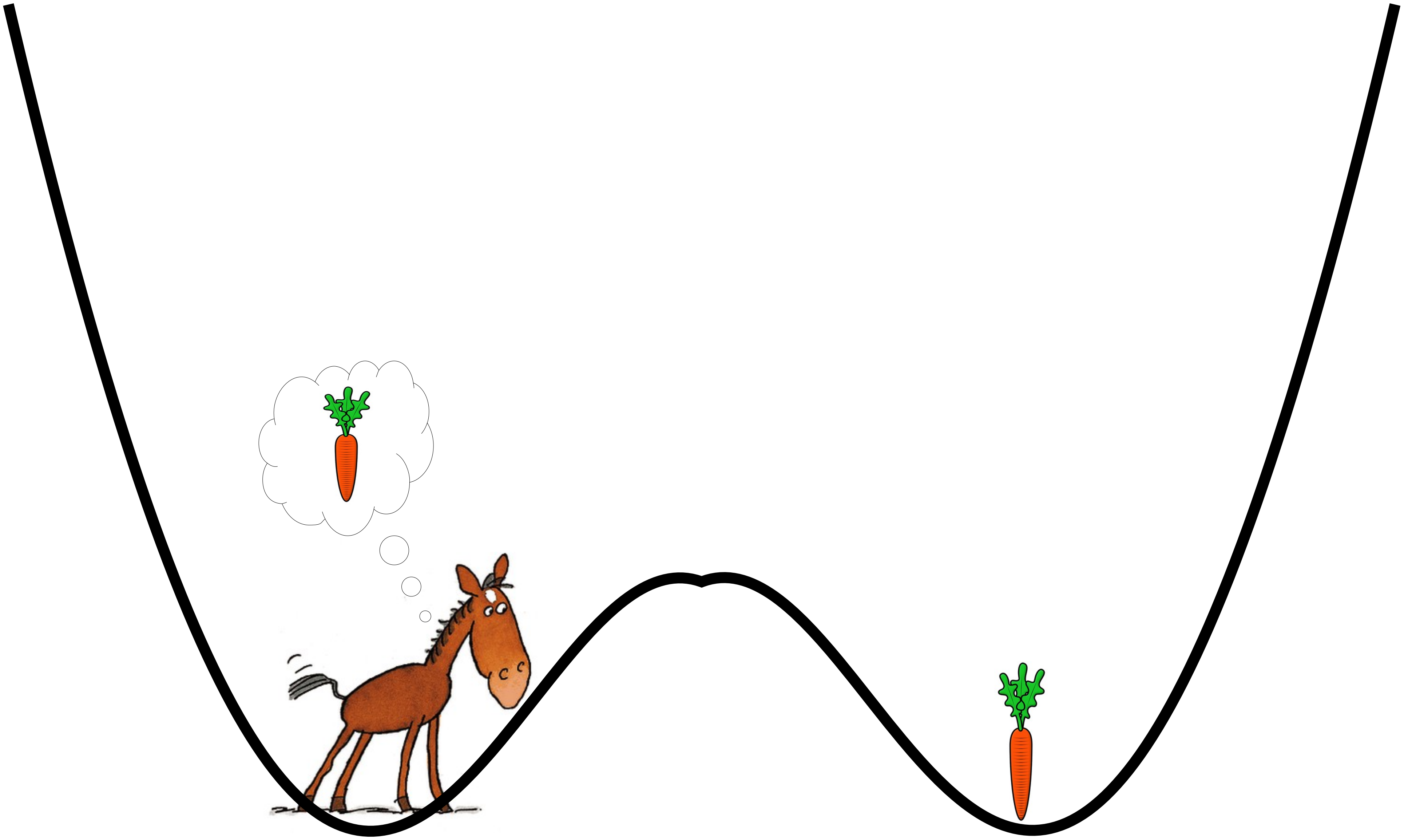
Using this and considering only the J=0 state derive an upper bound for m_H

The Higgs Mechanism

Introducing the Higgs mechanism



Introducing the Higgs mechanism



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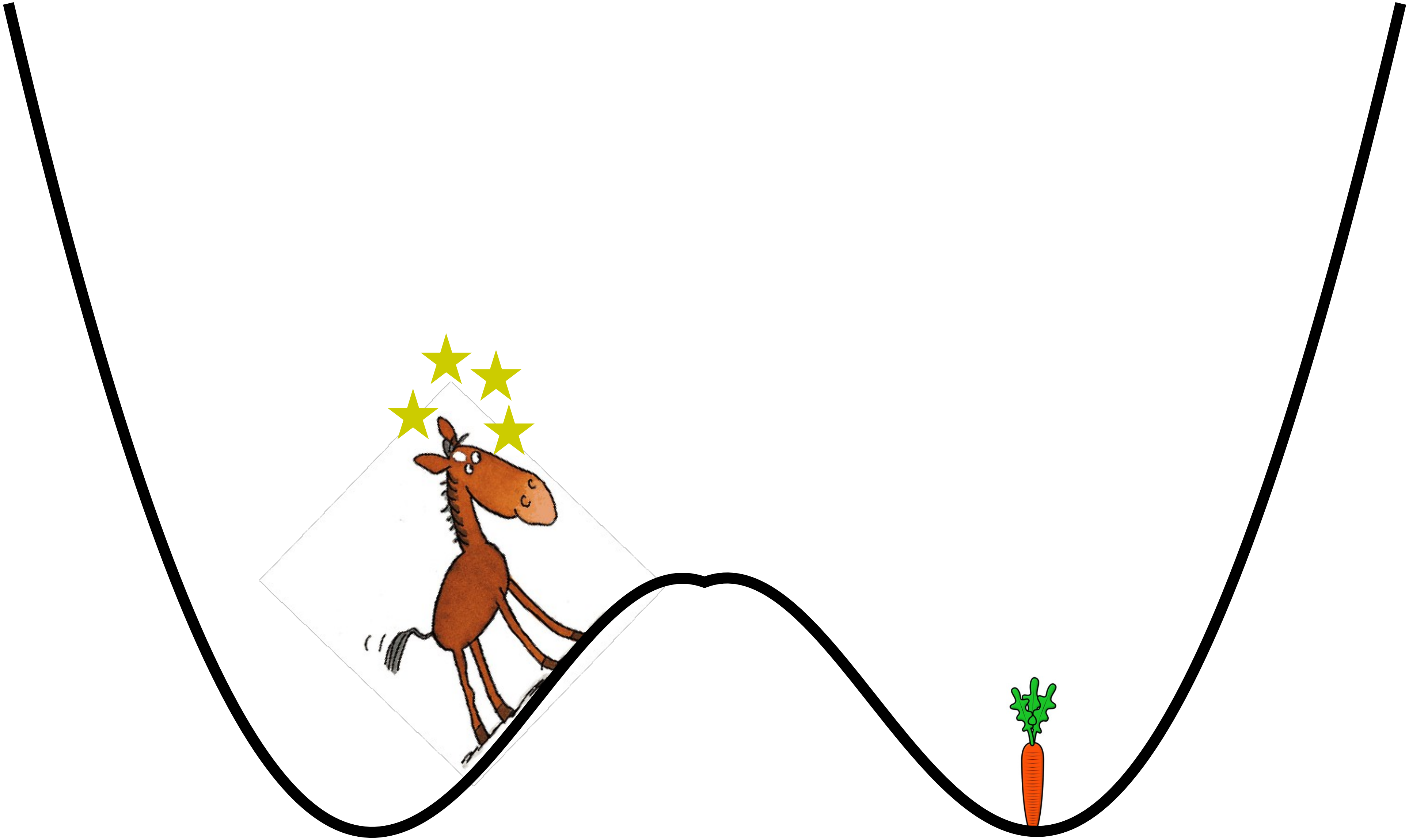
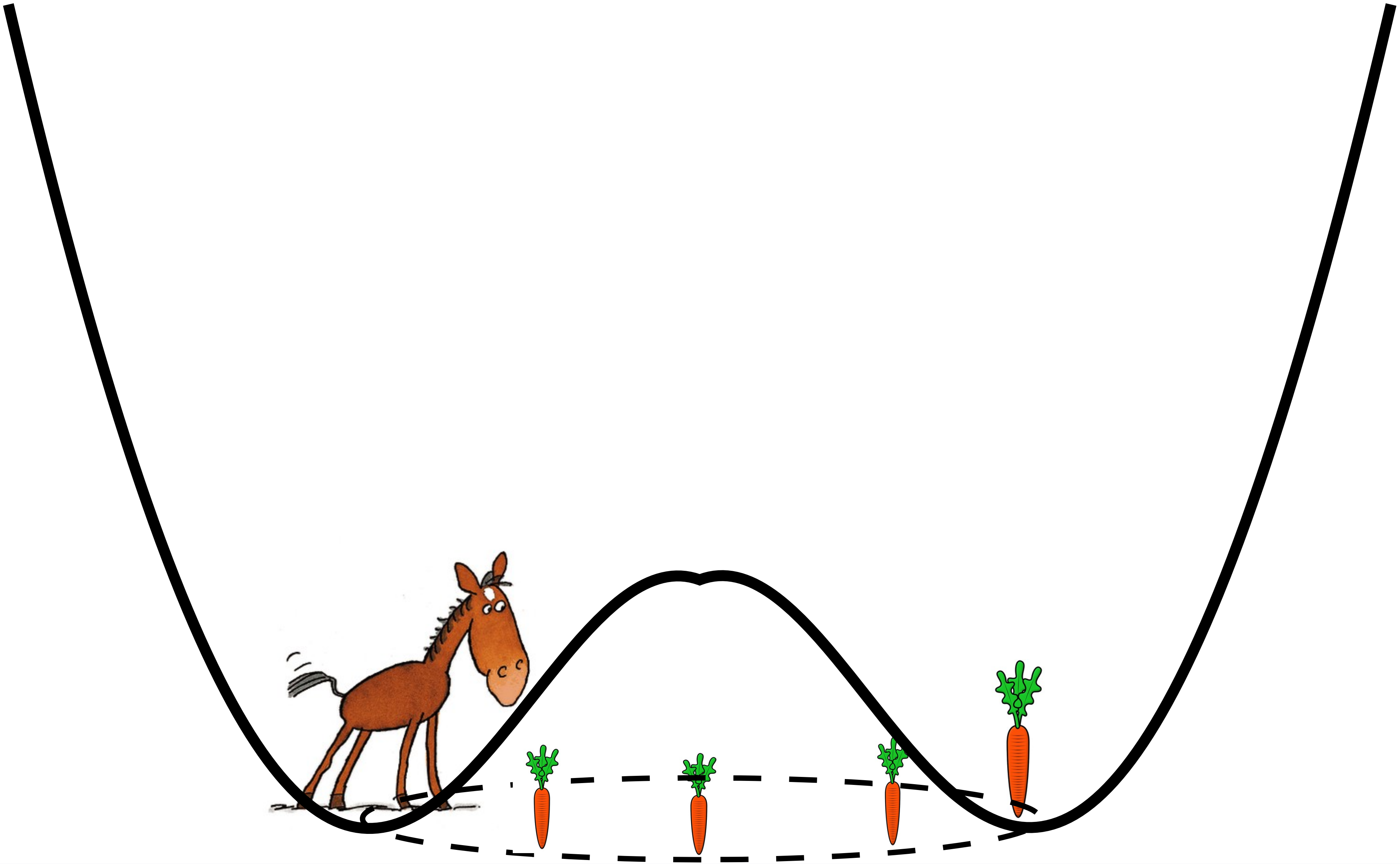
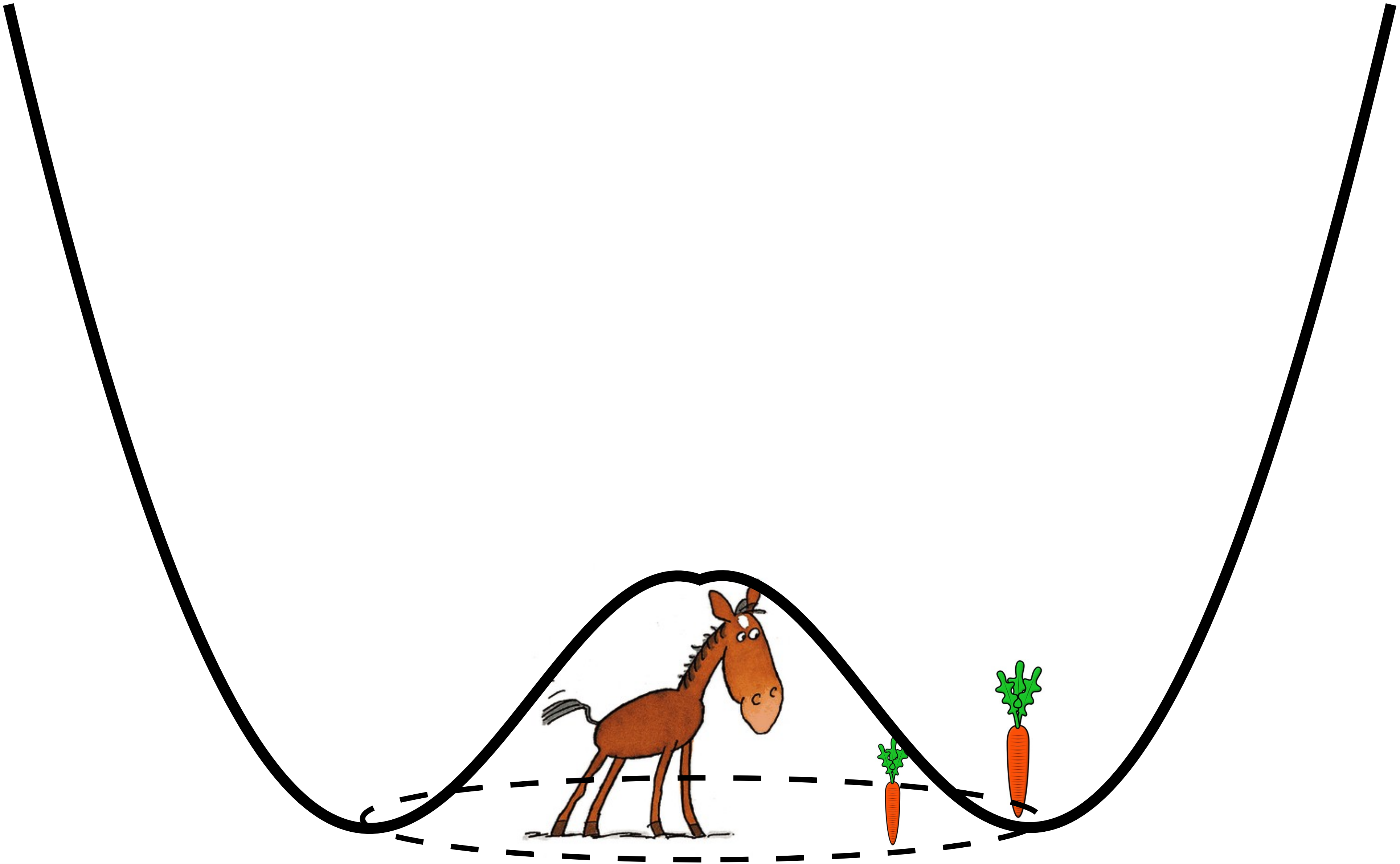


Introducing the Higgs mechanism



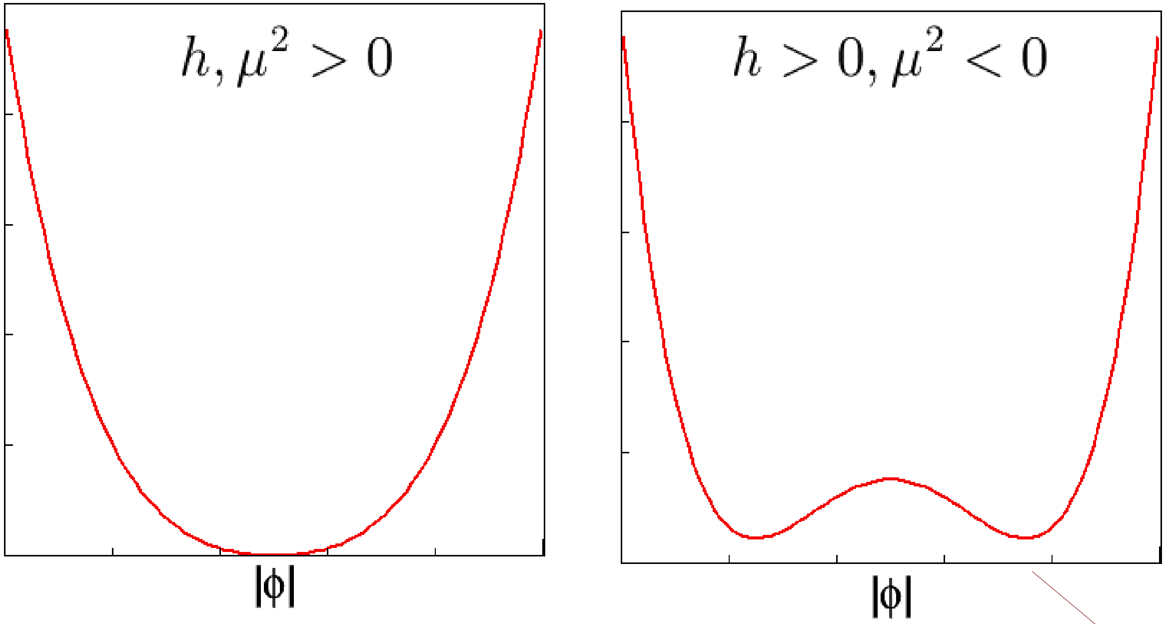
Introducing the Higgs mechanism



Higgs potential

- We introduce a scalar boson: $\mathcal{L}_{\text{higgs}} = \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi)$

  which has a potential with phase symmetry: $V(\phi) = \mu^2 |\phi|^2 + h|\phi|^4$



- In the second case the **vacuum is a set of degenerate minima** due to spontaneous symmetry breaking

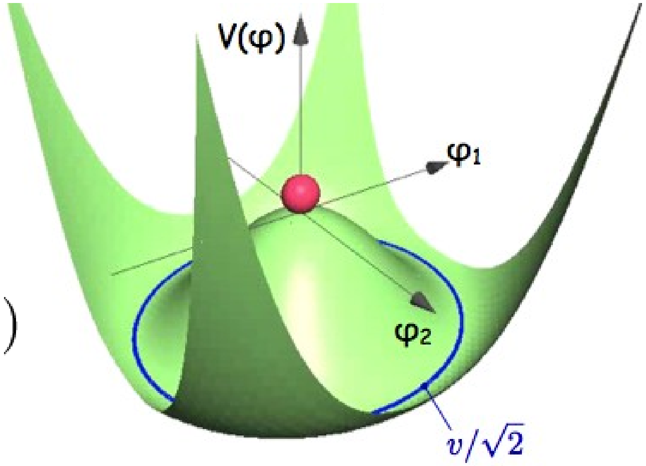
$$|\phi_0| = \sqrt{\frac{-\mu^2}{2h}} = \frac{v}{2} > 0$$

$$V(\phi_0) = -\frac{1}{4} h v^4$$

Spontaneous symmetry breaking

- We can choose to parameterize the vacuum as:

$$\phi = \frac{1}{\sqrt{2}}[v + \varphi_1]e^{i\varphi_2/v}$$



- Substituting this choice in the lagrangian leads to:

$$\mathcal{L}(\phi) = \frac{1}{2}\partial_\mu\varphi_1\partial^\mu\varphi_1 + \frac{1}{2}(1 + \frac{\varphi_1}{v})^2\partial_\mu\varphi_2\partial^\mu\varphi_2 - V(\phi)$$

with $V(\phi) = V(\phi_0) + \frac{1}{2}(-2\mu^2)\varphi_1^2 + hv\varphi_1^3 + \frac{1}{4}h\varphi_1^4$

- The potential depicts an interesting result
  - one of the components acquires mass : $M=-2\mu^2$
  - the second component is a massless Goldstone boson

EWK symmetry breaking

- In SU(2) the boson is a isopsin double

  with hypercharge ½ :

$$\phi = \begin{pmatrix}\phi^{+} \\ \phi^{0}\end{pmatrix}$$

- After spontaneous symmetry breaking

  it becomes:

$$\phi = \frac{1}{\sqrt{2}} e^{-i\frac{\tau}{2}\cdot\theta} \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

3 degrees of freedom =
3 massless Goldstone bosons

Constant vacuum
condensate

Higgs:
coupling to
matter

- The massless Goldstone bosons can be rotated away due to $SU_L(2)$ invariance

- Set to θ=0 in the unitary gauge and find that the W and Z bosons acquire mass:

$$(D_\mu\phi)^\dagger D^\mu\phi \rightarrow \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{g^2}{4}(v+H)^2 \left[W_\mu^\dagger W^\mu + \frac{1}{2cos^2\theta_W} Z_\mu Z^\mu \right]$$

$$\boxed{M_Z \ \cos\theta_W = M_W = \frac{1}{2} v g}$$

Numbers to keep in mind

$$\boxed{M_Z \cos\theta_W = M_W = \frac{1}{2} v g}$$

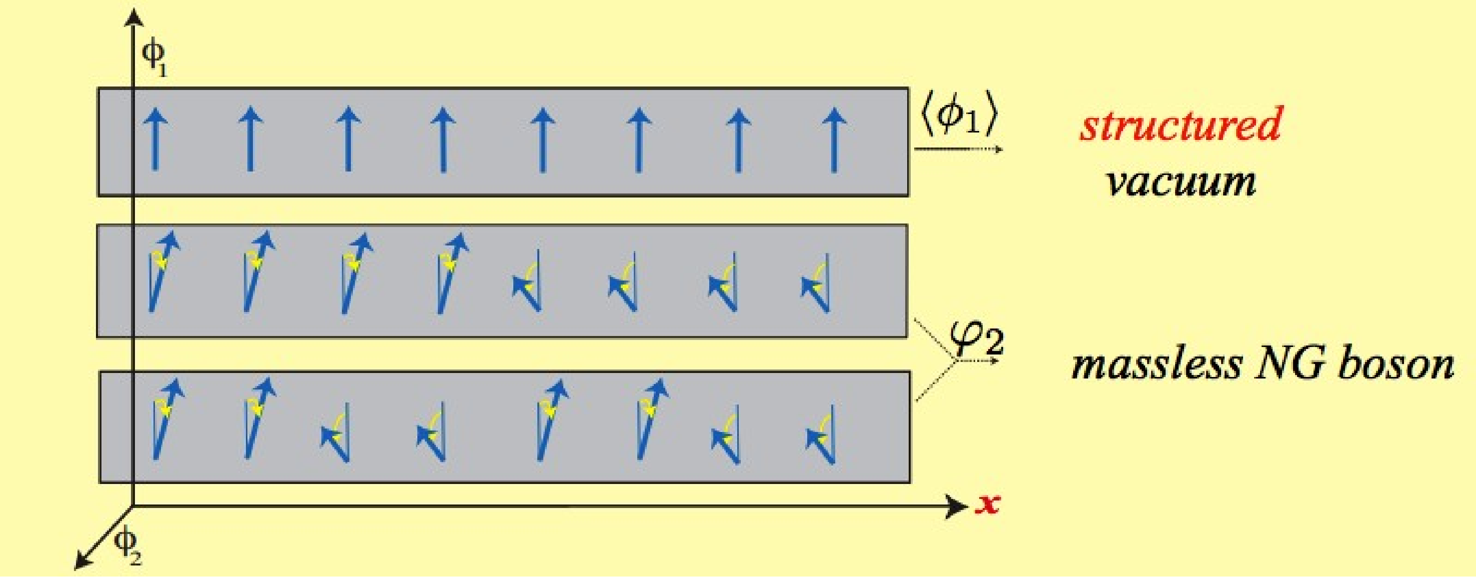
- The coupling constant is related to the Fermi constant $g^2 = 4\sqrt{2} M_W^2 G_F$

  as G_F=1.16637 x 10^{-5} GeV^{-2} M_W=80.932 GeV → **g=0.6574**

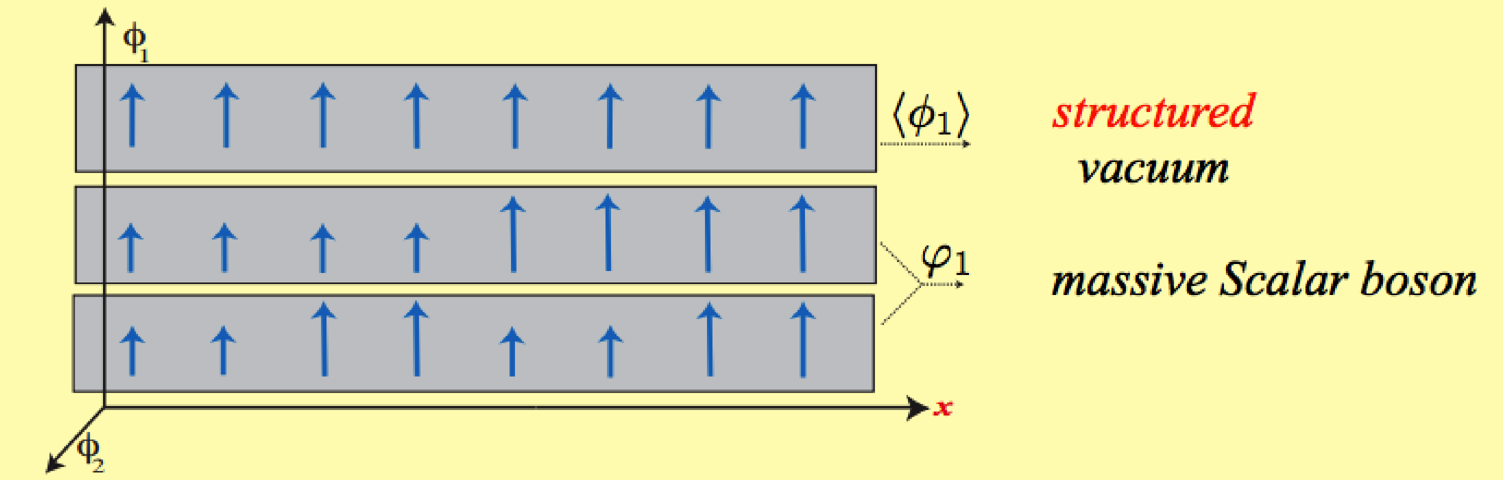
- The vacuum expectation value is **v=246 GeV**

- As for the Weinberg angle, as M_Z=91.1875 GeV, then **$\sin^2\theta_W$ = 0.215**

Original idea behind the Higgs mechanism



►characterizes a continuous SSB



► measures the rigidity of the vacuum

The proponents F. Englert and R. Brout PRL 13-[9] (1964) 321
P.W. Higgs PL 12 (1964) 132 and PRL 13-[16] (1964) 508
G.S. Guralnik, C.R. Hagen and T.W.B. Kibble PRL 13-[20] (1964) 585

Fermions also acquire mass

- **Scalar-fermion interactions** are gauge invariant and therefore allowed

- **Fermion masses are free Yukawa couplings** to the Higgs boson

$$\mathcal{L}_Y = \bar{Q}_L \left[c^d \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} D_R + c^u \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} D_R \right]$$

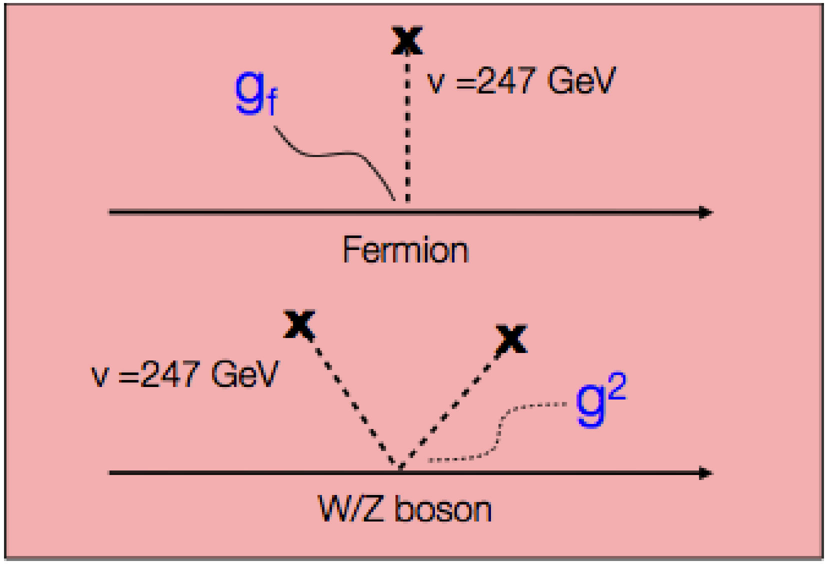
$$\Big\downarrow$$

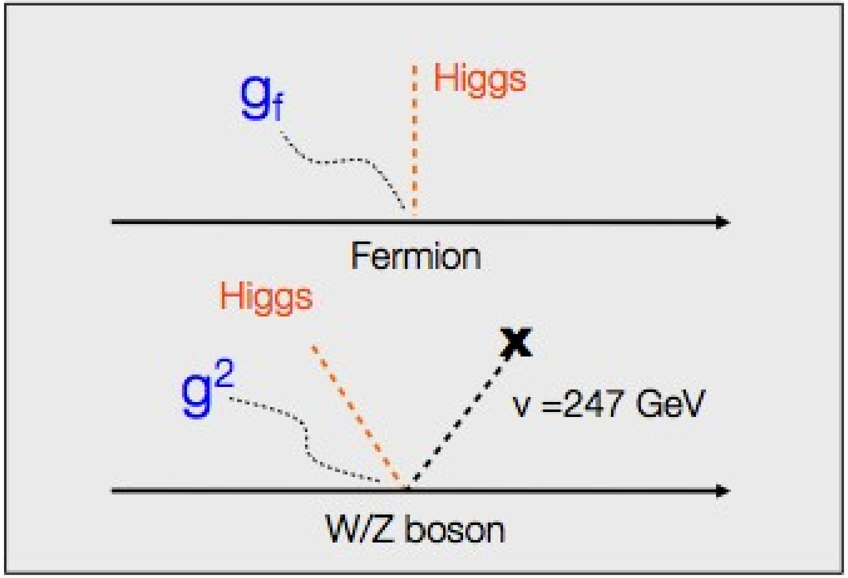
spontaneous symmetry breaking

$$\mathcal{L}_Y = -(1 + \frac{H}{v})(\bar{q}_d \underline{M_d} q_d + \bar{q}_u M_u q_u)$$

- As there are 3 generations of fermions differing by mass, these terms are arbitrary non-diagonal, complex matrices
  - The mass eigenstates do not coincide with the weak eigentstates → mixing

Summary of the interactions





- **With the "ether"**
  - Fermion masses from Yukawa couplings

$$m_f \sim g_f v$$

  - Gauge boson masses from gauge couplings

$$M_V \sim g v$$

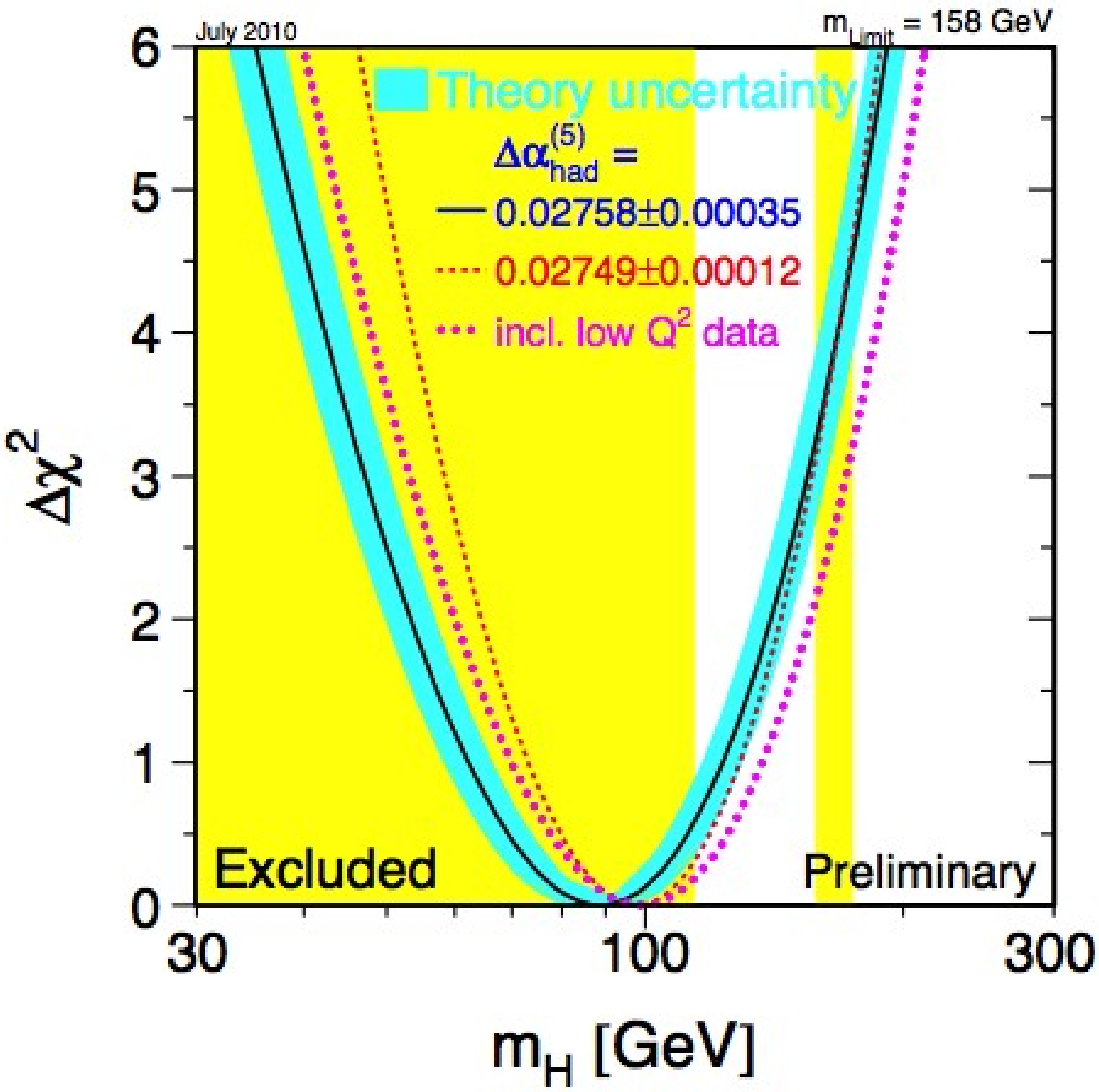
- **With the Higgs boson,** proportional to
  - the fermion masses

$$g_f \sim m_f / v$$

  - the mass squared of gauge bosons

$$g_V \sim M_V^2 / v$$

What else do we know about the Higgs



EW-Fits:

$M_H = 89^{+35}_{-26}$ GeV

$M_H < 158$ GeV @ 95% CL

From direct search at LEP:

$M_H > 114$ GeV

@ 95% CL

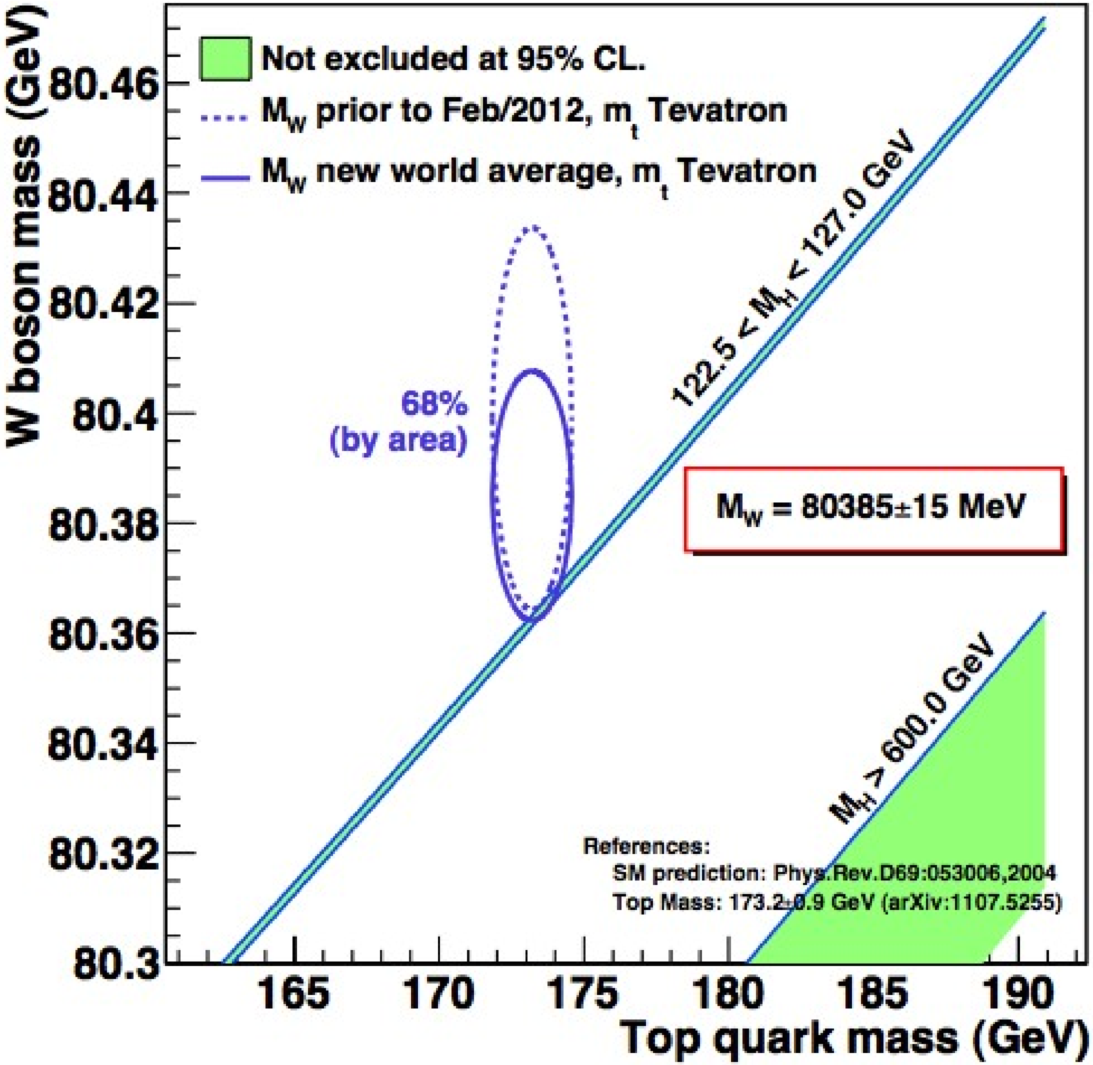
From direct search at Tevatron:

$158 < M_H < 175$ GeV

@ 95% CL

[Updated: Summer 2010]

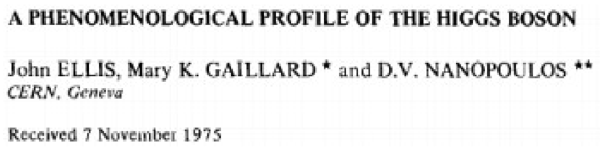
What else do we know about the Higgs



- The mass of the heaviest particles is correlated from loop corrections including the Higgs boson
- The preferred region is compatible at 68% CL with the not yet excluded SM Higgs mass at 95% CL

Higgs signature at particle colliders

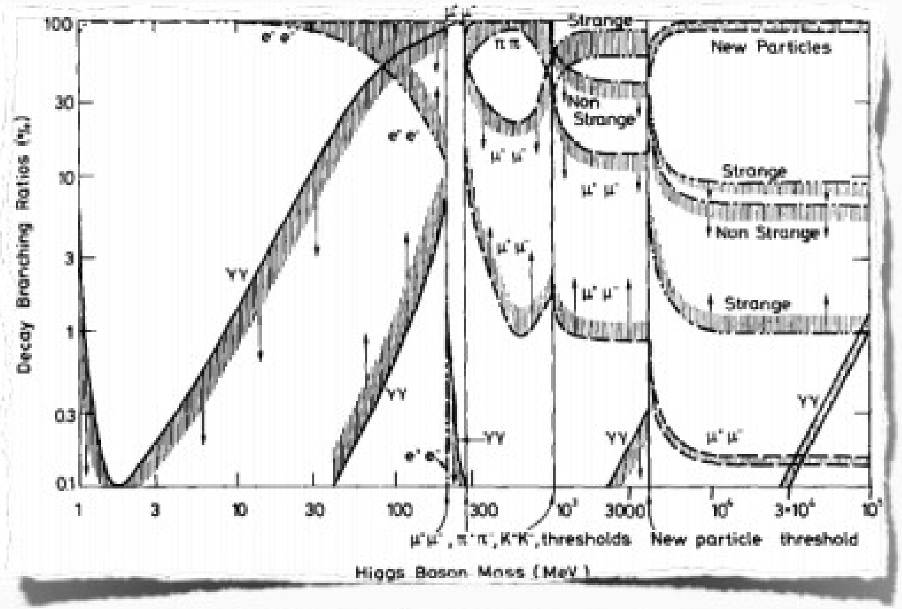
Back in 1975...

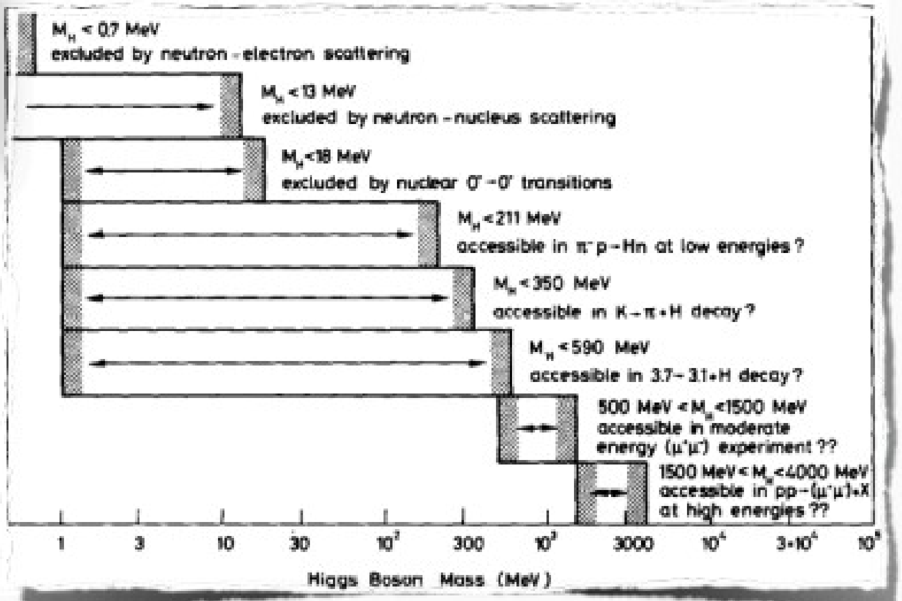


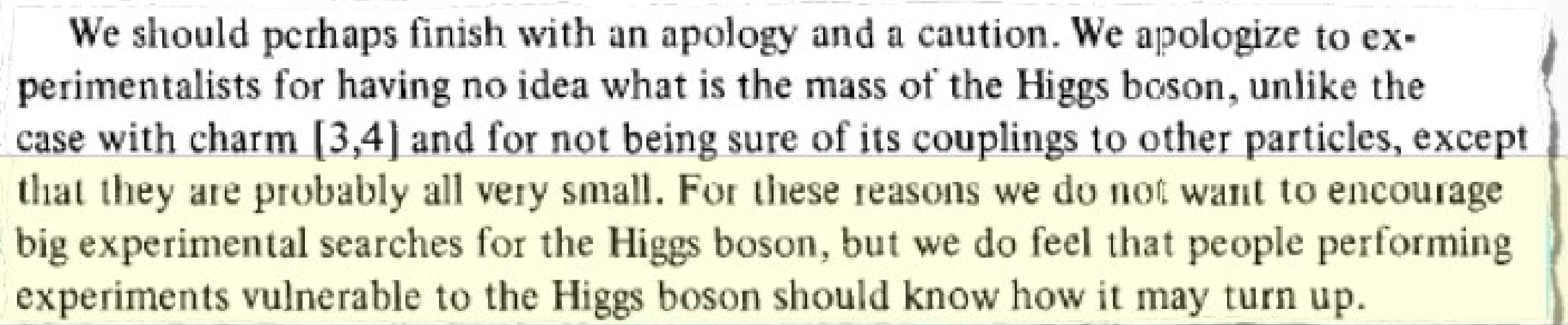
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975







We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Higgs partial widths (tree level)

- **Fermions:** proportional to the mass and velocity dependent (1 factor from the matrix elem.+ 2 from phase space)

$$\boxed{\Gamma_{f\bar{f}} = \frac{N_c G_F m_f^2 M_H}{4\sqrt{2}\pi}\beta^3}$$

where $\beta = \sqrt{1 - \frac{4m_f^2}{M_H^2}}$

- **Vector bosons:** dominate due to the fact the longitudinal polarized bosons couple ~E → coupling to Higgs as to rise as fast

$$\boxed{\Gamma_{VV} = \frac{G_F M_H^3}{16\sqrt{2}\pi}\delta_V \beta\left(1 - x_V + \frac{3}{4}x_V^2\right)}$$

$$\text{where} \begin{cases} \delta_{W,Z} = 2, 1 \\ \beta = \sqrt{1 - x_V} \\ x_V = \frac{4M_V^2}{M_H^2} \end{cases}$$

- **Gluons:** through top quark loops

$$\boxed{\Gamma_{gg} = \frac{\alpha_s^2 G_F M_H^3}{16\sqrt{2}\pi^3}\left|\sum_i \tau_i[1 + (1 - \tau_i)f(\tau_i)]\right|^2}$$

$$\text{with} \quad \tau_i = \frac{4m_f^2}{M_H^2} \quad \text{and} \quad f(\tau) = \begin{cases} \left[\sin^{-1}\sqrt{1/\tau}\right]^2 & \tau \geq 1 \\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases}$$

- **Photons through top and W boson loops** (Zγ partial width is similar in structure)

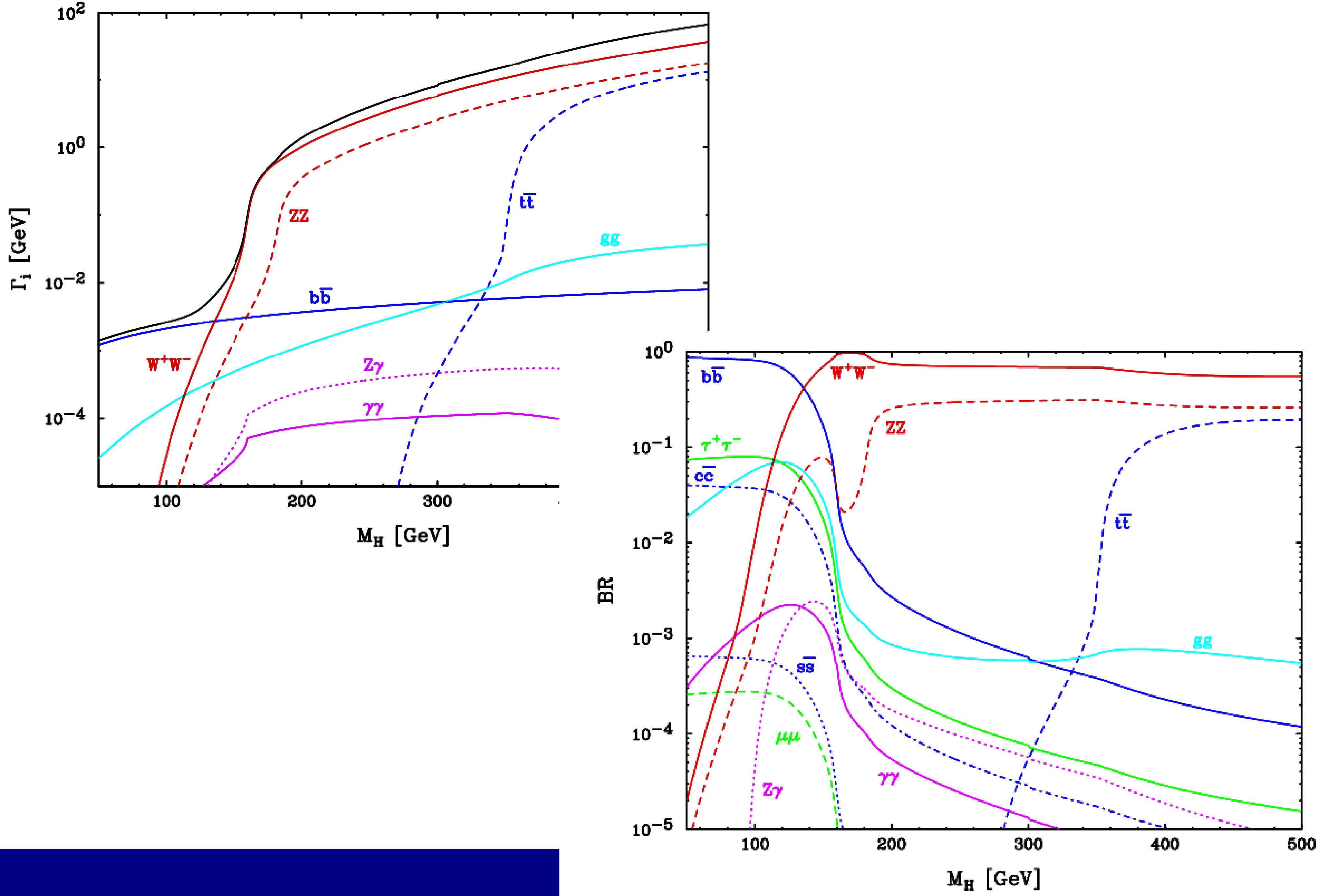
$$\boxed{\Gamma_{\gamma\gamma} = \frac{\alpha^2 G_F M_H^3}{128\sqrt{2}\pi^3}\left|\sum_i N_{c,i} Q_i^2 F_i\right|^2}$$

$$F_1 = 2 + 3\tau[1 + (2 - \tau)f(\tau)]$$

$$F_{1/2} = -2\tau[1 + (1 - \tau)f(\tau)]$$

$$F_0 = \tau[1 - \tau f(\tau)]$$

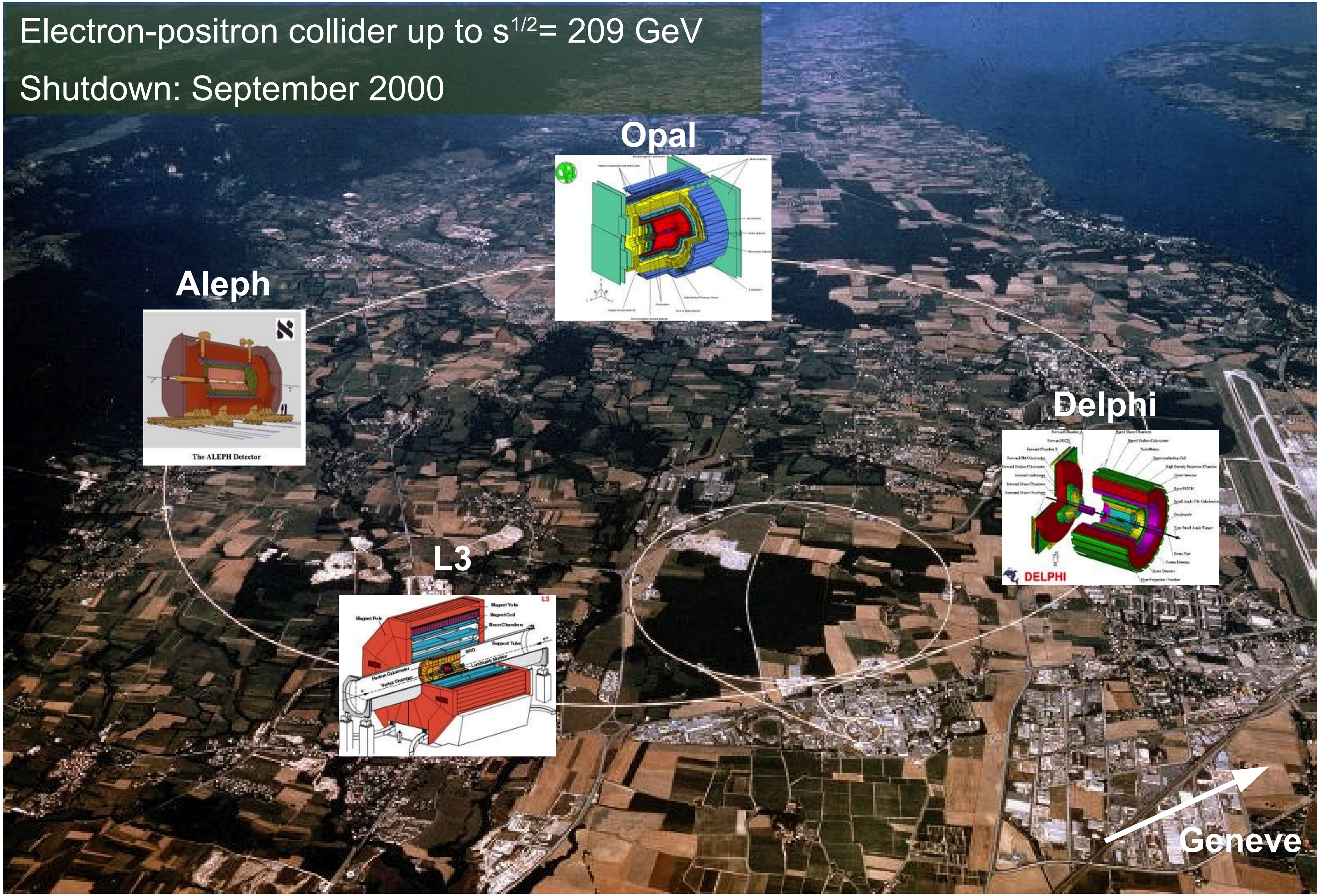
Higgs partial widths and branching ratios



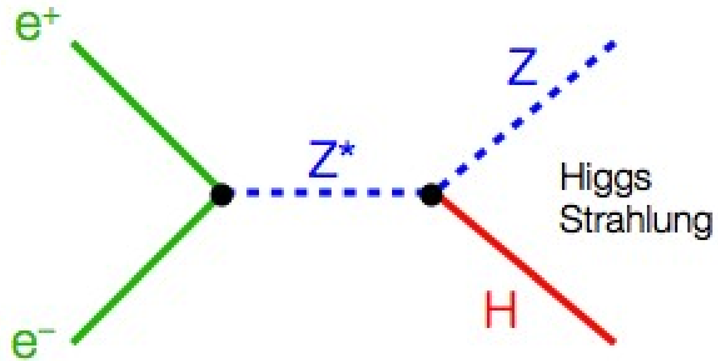
The LEP at CERN

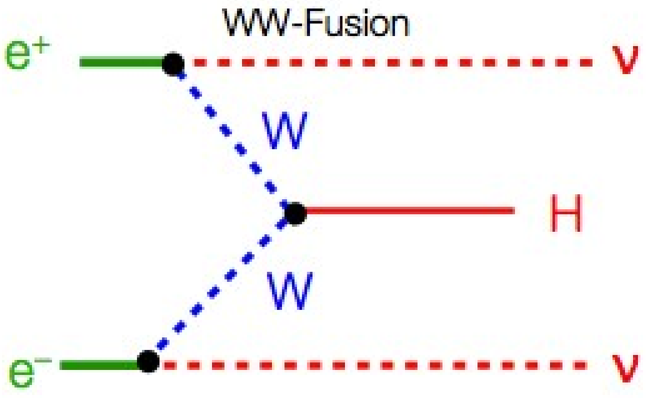
Electron-positron collider up to $s^{1/2}$= 209 GeV

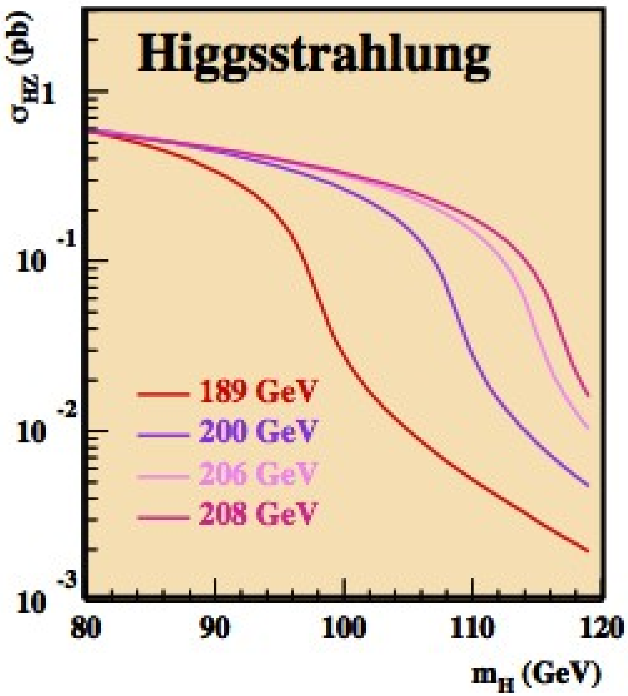
Shutdown: September 2000

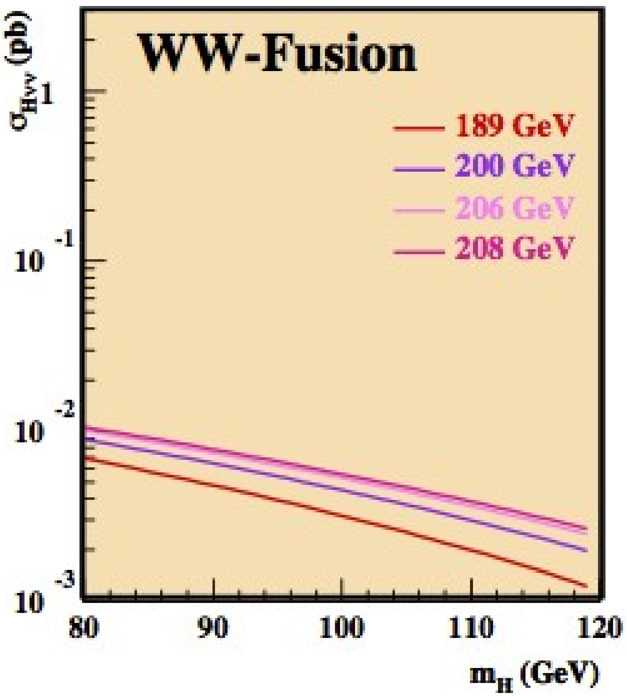


Higgs production at LEP

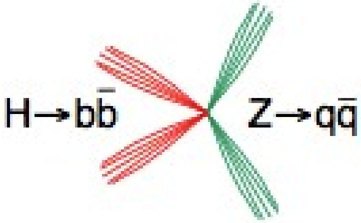
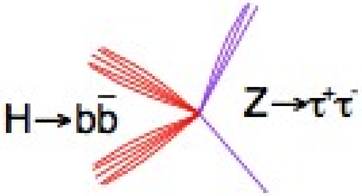
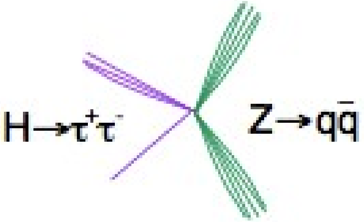
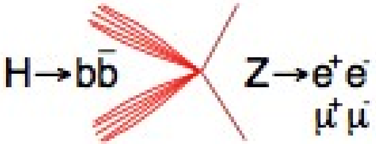




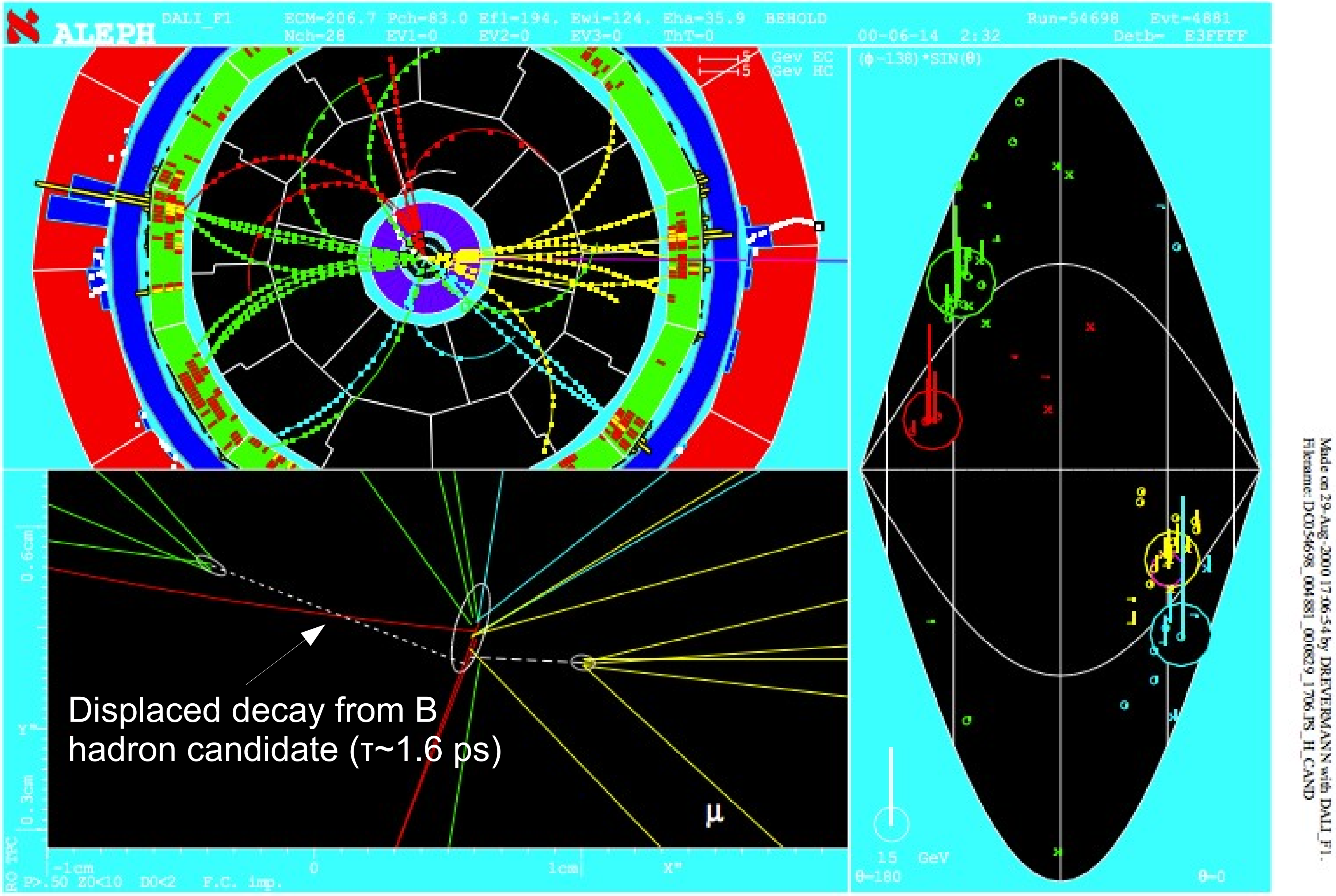




Higgs signatures at LEP

	4-jets	51%	WW → qqqq ZZ → qqqq QCD 4-jets
	missing energy	15%	WW → qqlν ZZ → bbνν
	τ-channel	2.4%	WW → qqτν ZZ → bbττ ZZ → qqττ QCD low mult. jets
	τ-channel	5.1%	
	lepton channel	4.9%	ZZ → bbee ZZ → bbμμ

LEP H → bb candidate



Displaced decay from B hadron candidate (τ~1.6 ps)

Summary of LEP Higgs candidates

LEP
final result

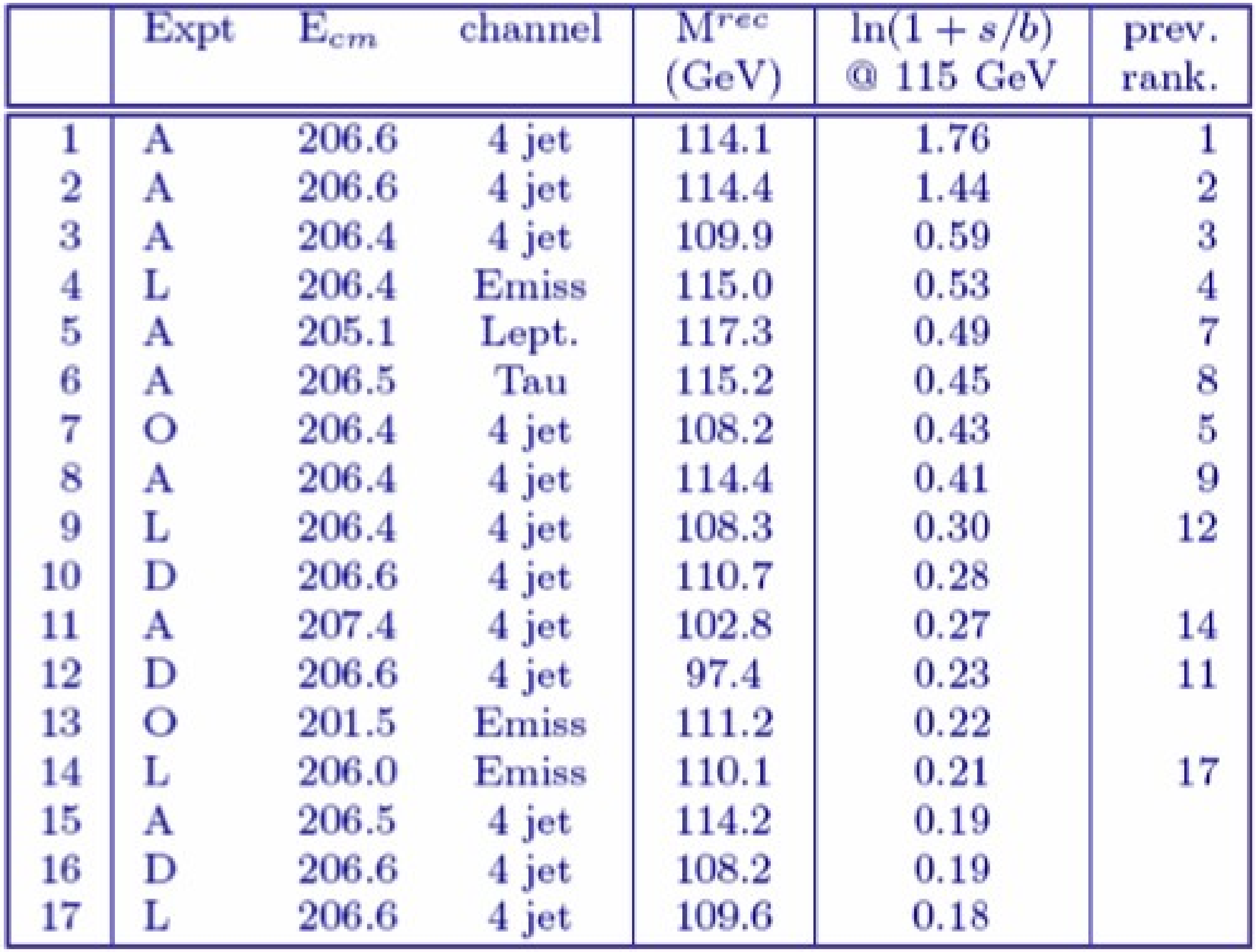
Observation:

17 candidate events

Expectation:

15.8 background events

8.4 signal events for M_H=115 GeV



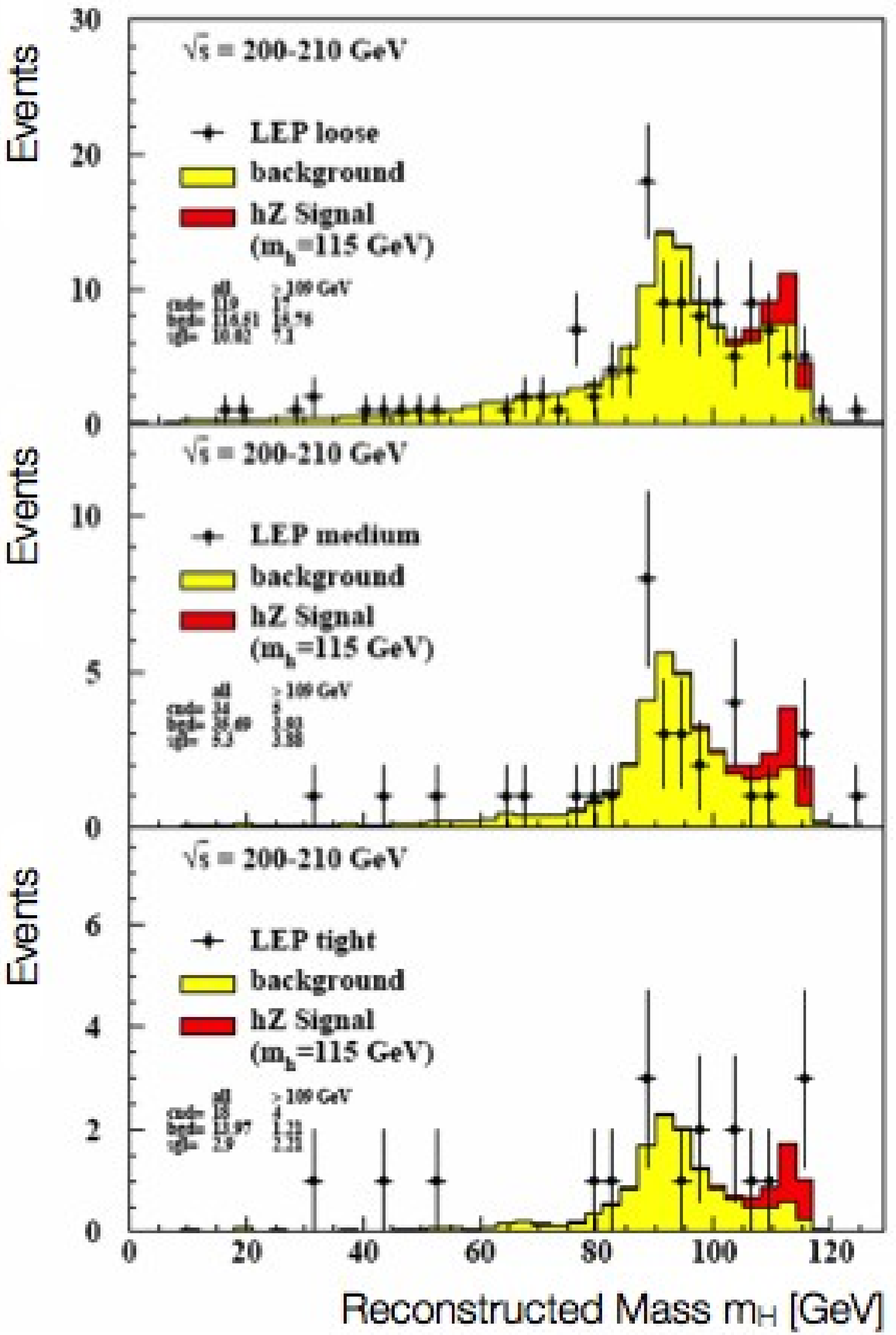
	Expt	E_{cm}	channel	M^{rec} (GeV)	$\ln(1+s/b)$ @ 115 GeV	prev. rank.
1	A	206.6	4 jet	114.1	1.76	1
2	A	206.6	4 jet	114.4	1.44	2
3	A	206.4	4 jet	109.9	0.59	3
4	L	206.4	Emiss	115.0	0.53	4
5	A	205.1	Lept.	117.3	0.49	7
6	A	206.5	Tau	115.2	0.45	8
7	O	206.4	4 jet	108.2	0.43	5
8	A	206.4	4 jet	114.4	0.41	9
9	L	206.4	4 jet	108.3	0.30	12
10	D	206.6	4 jet	110.7	0.28	
11	A	207.4	4 jet	102.8	0.27	14
12	D	206.6	4 jet	97.4	0.23	11
13	O	201.5	Emiss	111.2	0.22	
14	L	206.0	Emiss	110.1	0.21	17
15	A	206.5	4 jet	114.2	0.19	
16	D	206.6	4 jet	108.2	0.19	
17	L	206.6	4 jet	109.6	0.18	

- Observations found to be consistent with background only hypothesis

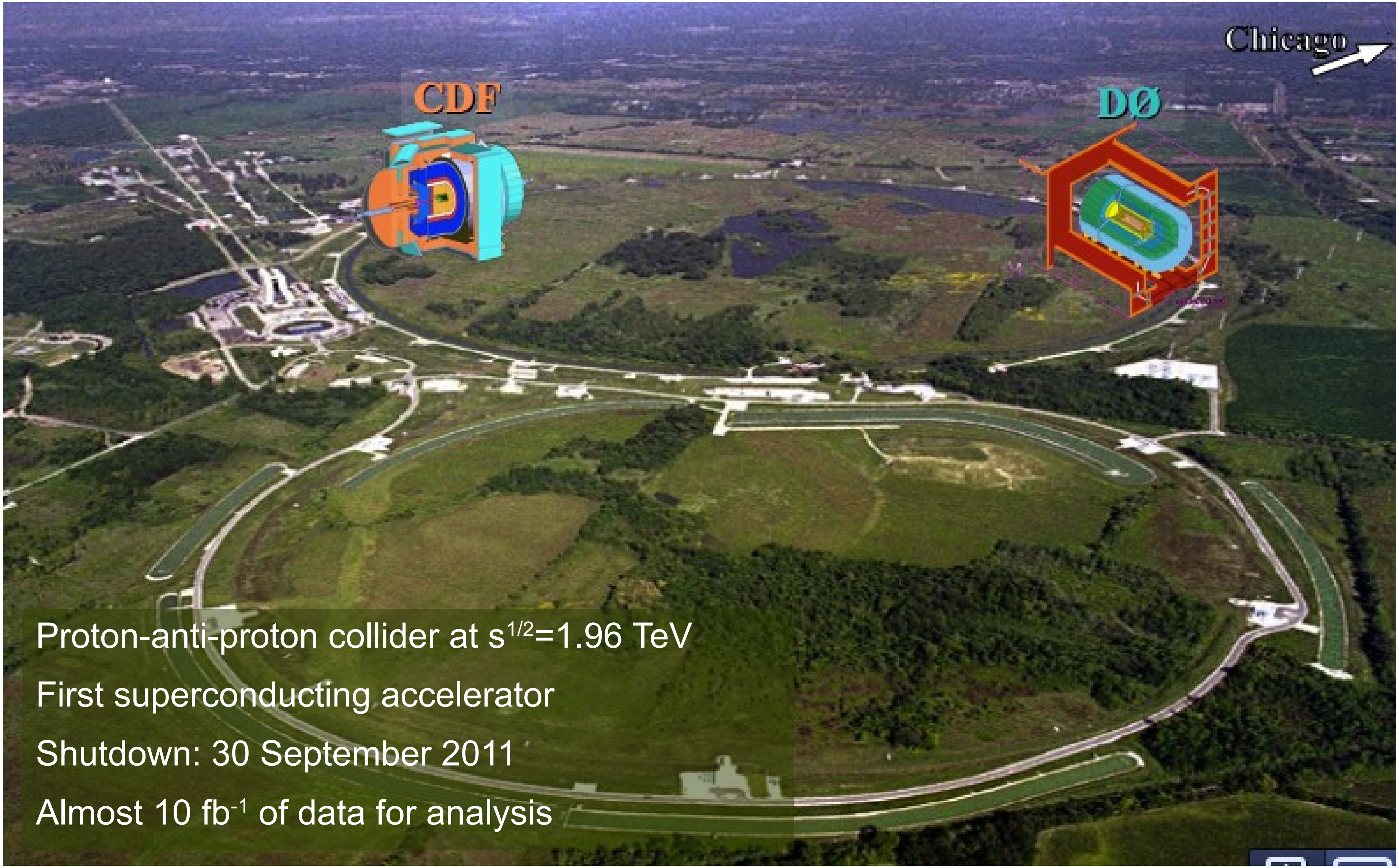
LEP candidates

- The invariant mass spectrum of the candidate events is consistent with background predicitions
- Final verdict from LEP

$M_H > 114.4$ GeV @ 95% CL



The Tevatron at Fermilab



Proton-anti-proton collider at $s^{1/2}$=1.96 TeV

First superconducting accelerator

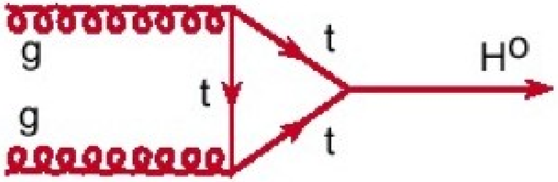
Shutdown: 30 September 2011

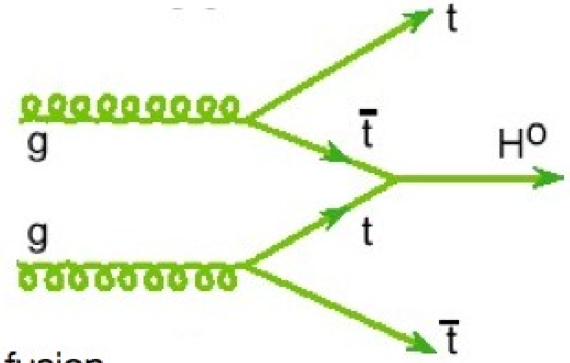
Almost 10 fb^{-1} of data for analysis

Search for the Higgs at the Tevatron

No single channel has enough sensitivity → explore all possibilities and maximize acceptance

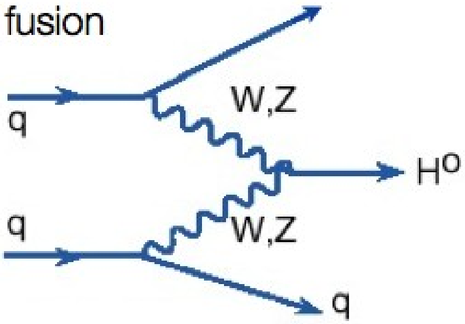
Gluon fusion



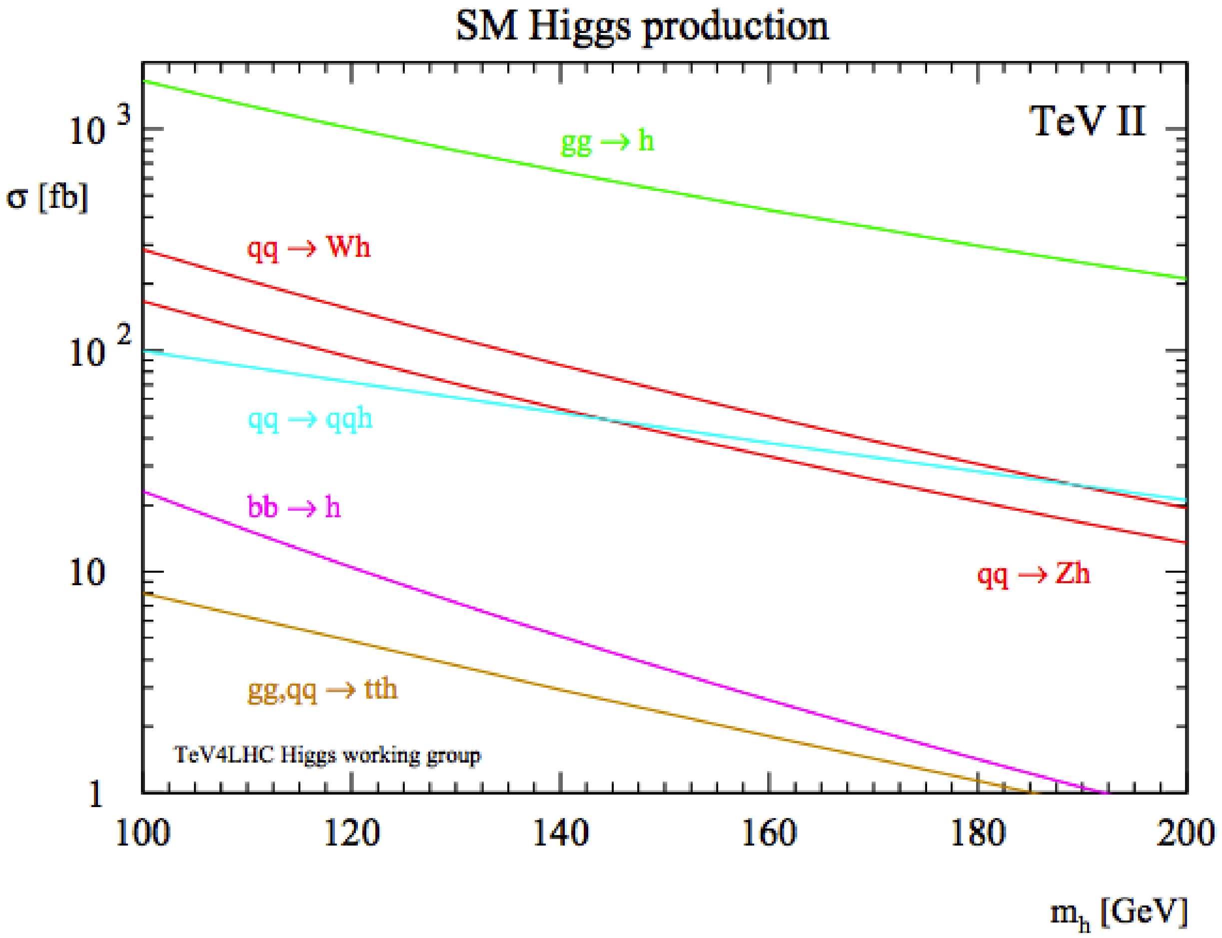


$t\bar{t}$-fusion

Vector boson fusion

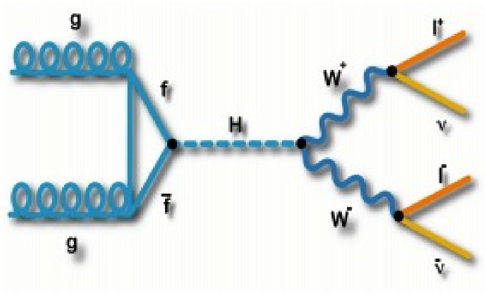


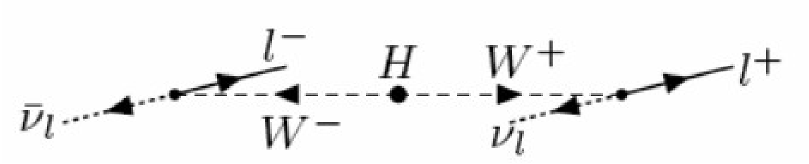
Associated production

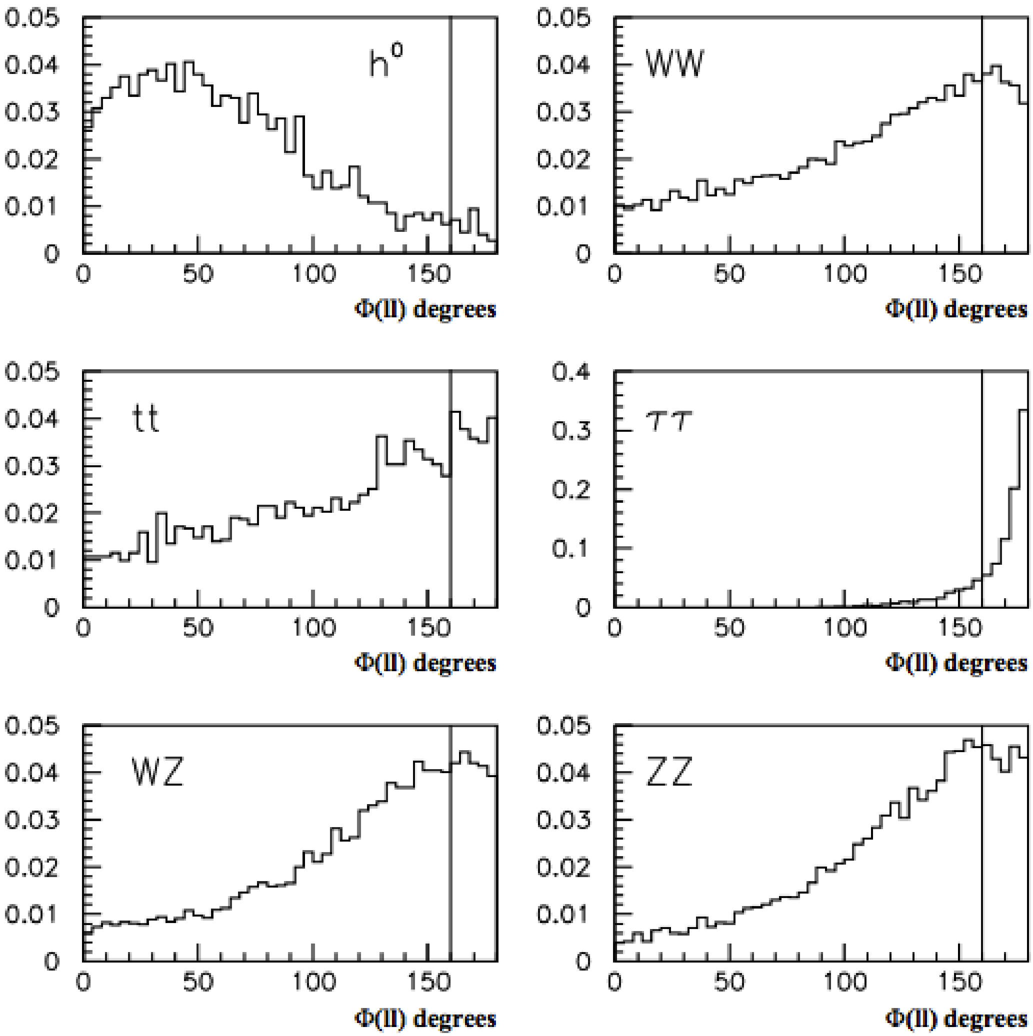


H → WW → 2l 2ν

- One of the **flagship channels at the Tevatron**
  - **key signature I:** polarized op. sign dilepton

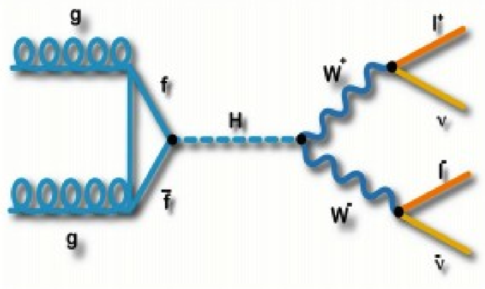


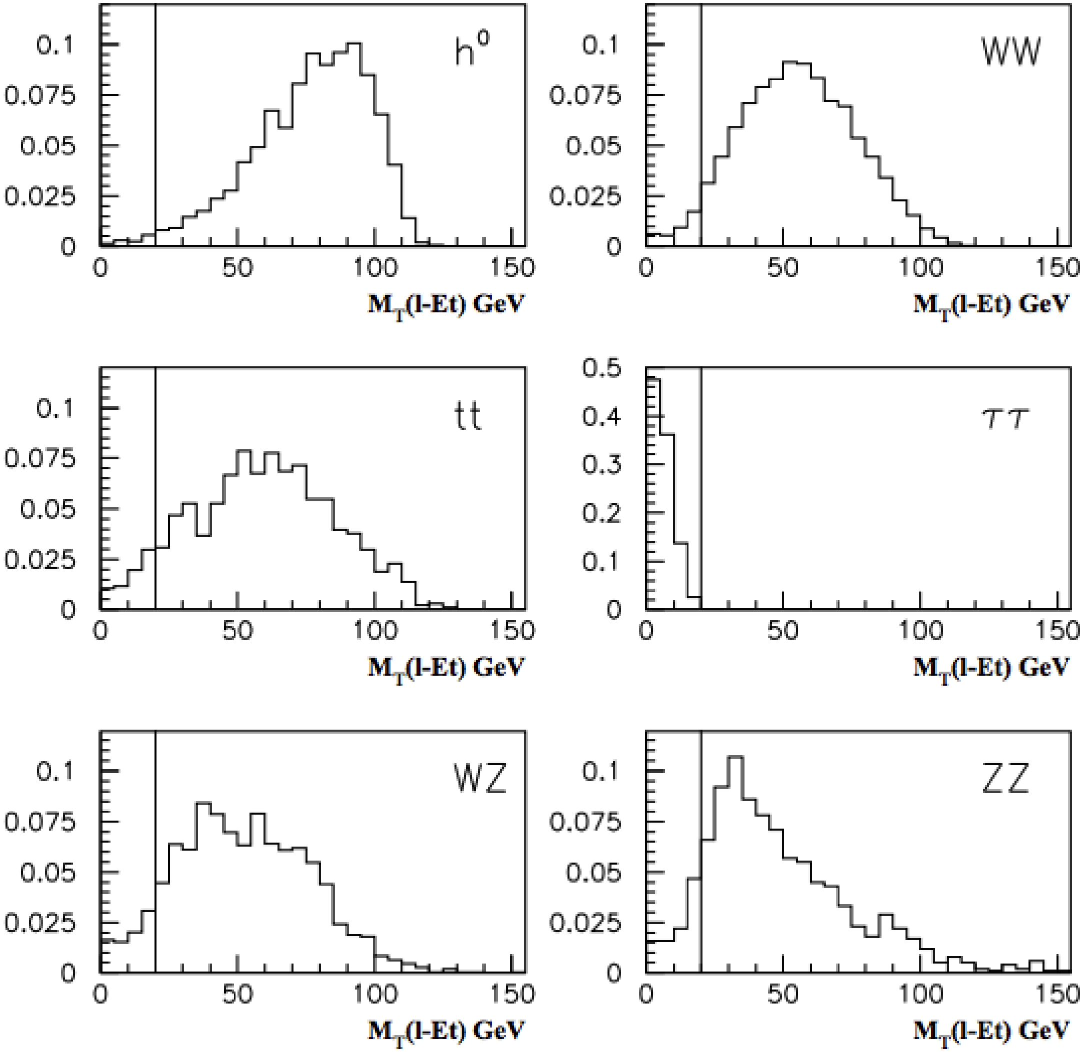


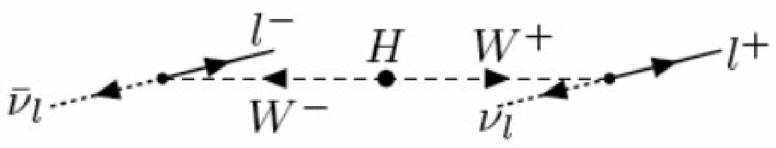


H → WW → 2l 2ν

- One of the **flagship channels at the Tevatron**
  - **key signature II:** missing transverse energy







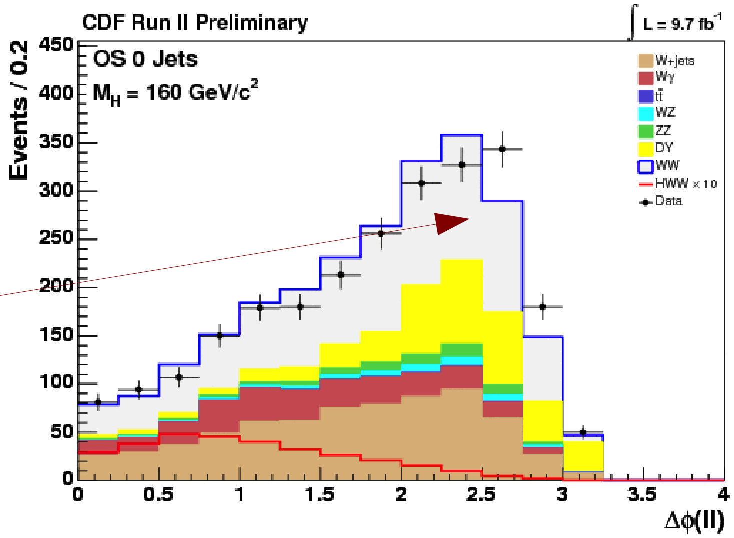
$$E_{T_{\ell^+\ell^-}} = \sqrt{\vec{p}^{\,2}_{T_{\ell^+\ell^-}} + m^2_{\ell^+\ell^-}}$$

$$\not{E}_T = \sqrt{\vec{\not{p}}^{\,2}_T + m^2_{\ell^+\ell^-}}$$

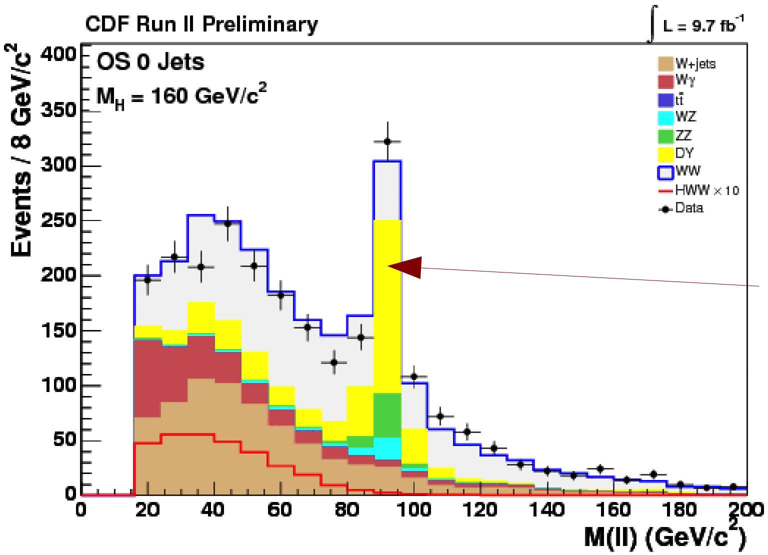
$$\boxed{M_{T_{WW}} = \sqrt{(\not{E}_T + E_{T_{\ell^+\ell^-}})^2 - (\vec{p}_{T_{\ell^+\ell^-}} + \vec{\not{p}}_T)^2}}$$

H → WW → 2l 2ν

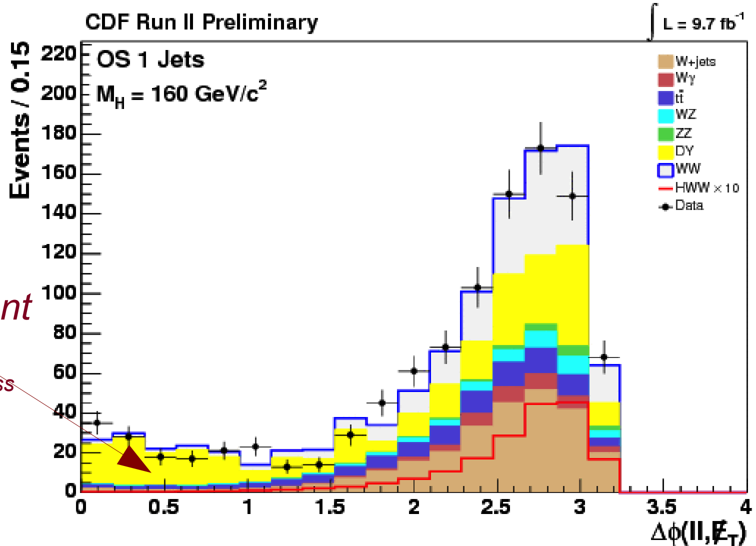
- **Major backgrounds:** di-boson production, Drell-Yan, top pair production
- Use all possible discriminating variables. Some examples are given below:



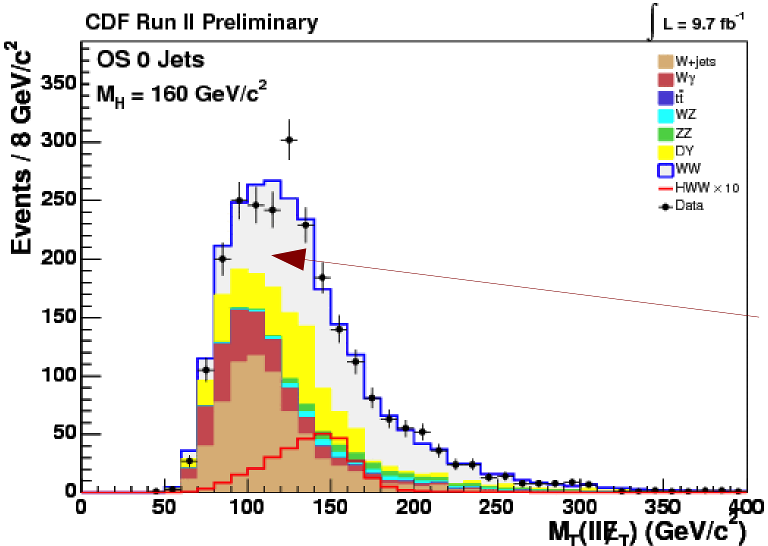
WW production is not polarized



Z, ZZ, WZ are resonant backgrounds



In DY recoil mis-measurement leads to artifical E_T^{miss}



Dilepton+E_T^{miss} are non resonant for backgrounds

Signal vs background discrimination

- One can define the probability to reconstruct a given final state - x_{obs}

$$P_m(x_{obs}) = \frac{1}{< \sigma_m >} \int \frac{d\sigma^{th}_m(y)}{dy} \epsilon(y) G(x_{obs}, y) dy$$

This refers to a given process: e.g. WW, H→WW

normalization factor

Matrix element prediction

Efficiency x acceptance

Analytical model for detector resolution effects

- Event probability densities can be used to define a so-called likelihood ratio
  - as an event is either signal or background we write the signal probability as

$$LR_S(x_{obs}) \equiv \frac{P_S(x_{obs})}{P_S(x_{obs}) + \Sigma_i k_i P_i(x_{obs})}$$

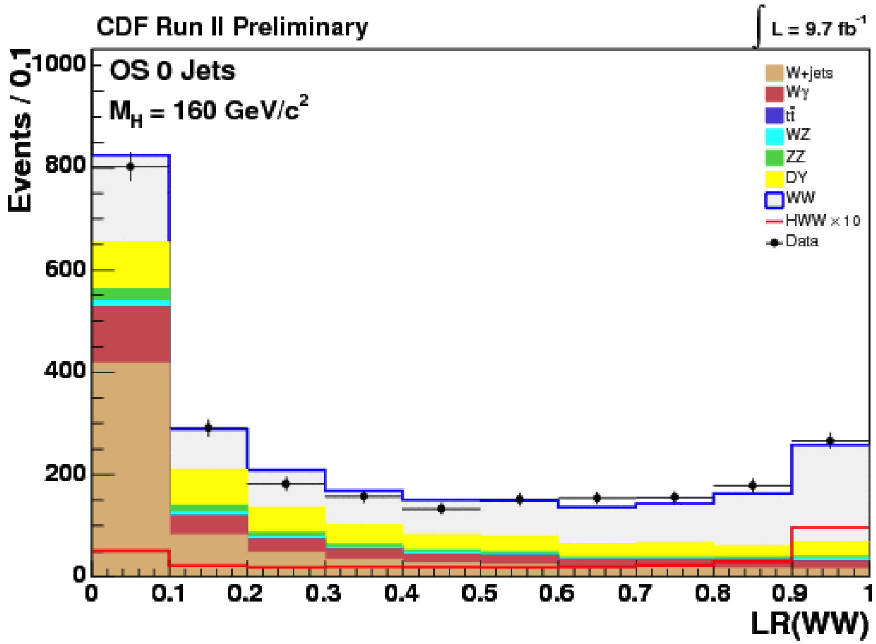
Normalizes the probability using the expected fractions from each background process, i.e. ∑ k_i=1

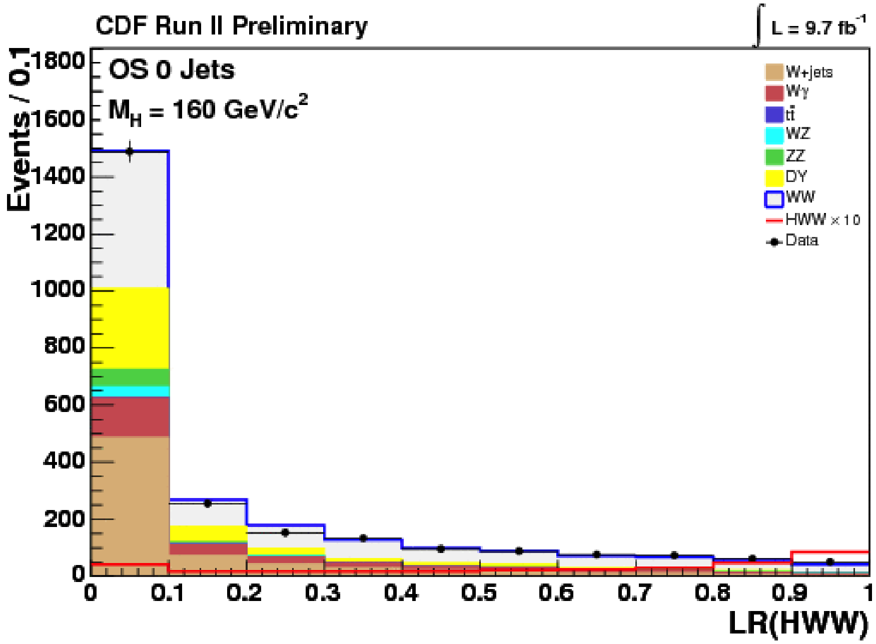
Likelihood ratio discriminator

- For **each event we compute LR$_s$** and obtain the likelihood ratio discriminator

Test to discriminate SM WW production

Discriminate H(160) → WW





- Cut and count at a given LR$_S$ value: similar to σ measurement

- Fit the shapes: powerful tecnique to fully exploit signal vs. background discrimination

Short note on multivariate analysis

- Likelihood ratios are simple discriminators but loose power if variables are correlated (only the projections are used)

- Other more sophisticated techniques are available (neural networks, boosted decision trees, etc.) but we won't cover the details here:

  - An analysis usually tests several of these discriminators

  - Check for **performance of the classification**

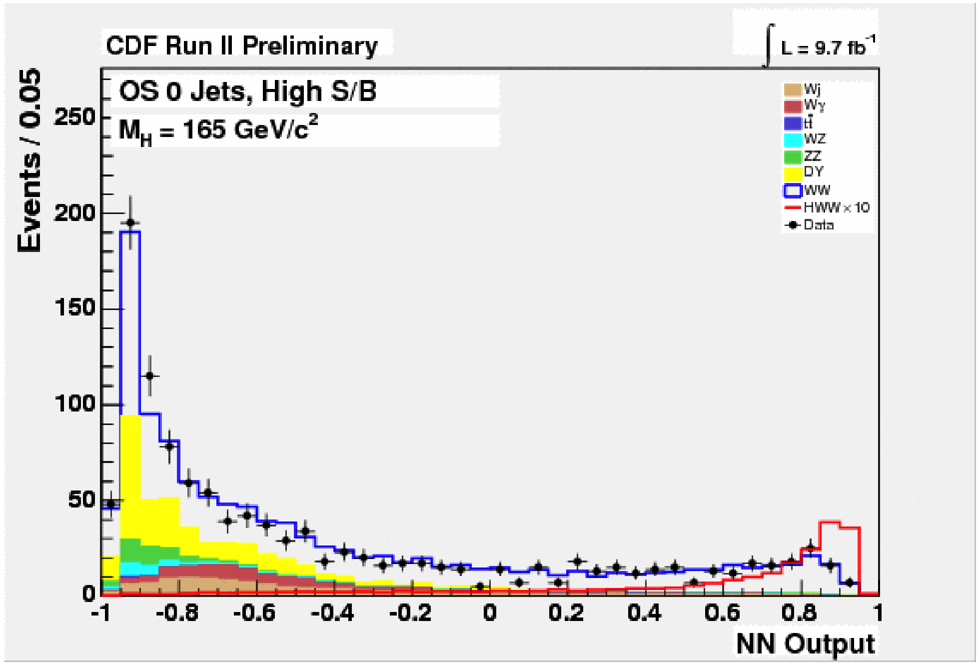
    Signal vs. background efficiency / Separation: $\langle S^2 \rangle = \frac{1}{2} \int \frac{(\hat{y}_S(y) - \hat{y}_B(y))^2}{\hat{y}_S(y) + \hat{y}_B(y)} dy$ / Significance: $\frac{N_S - N_B}{\sqrt{N_S + N_B}}$

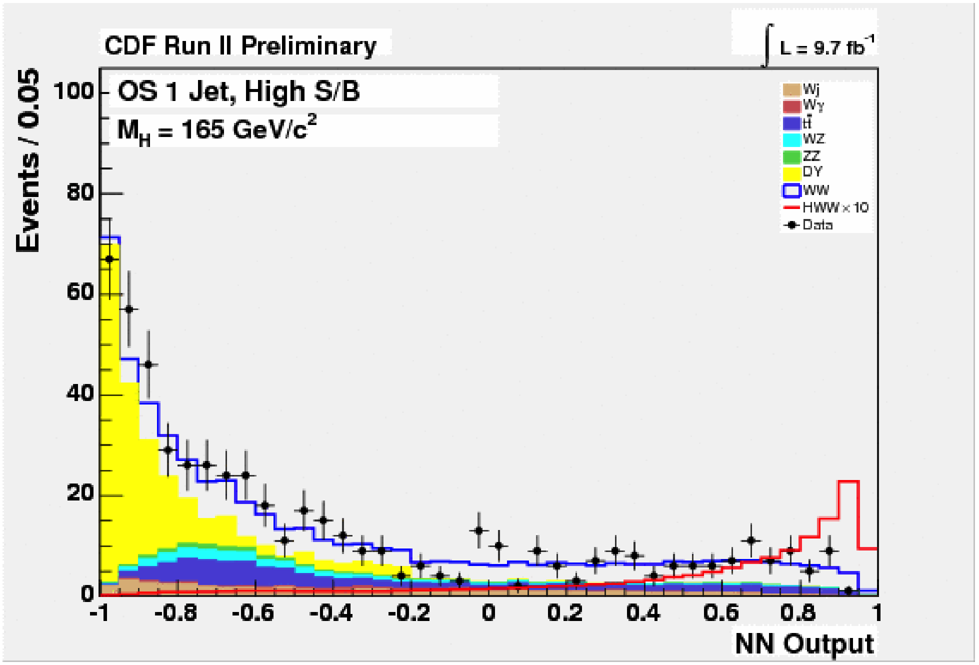
  - Check for **overtraining**: when problem as low number of degrees of freedom

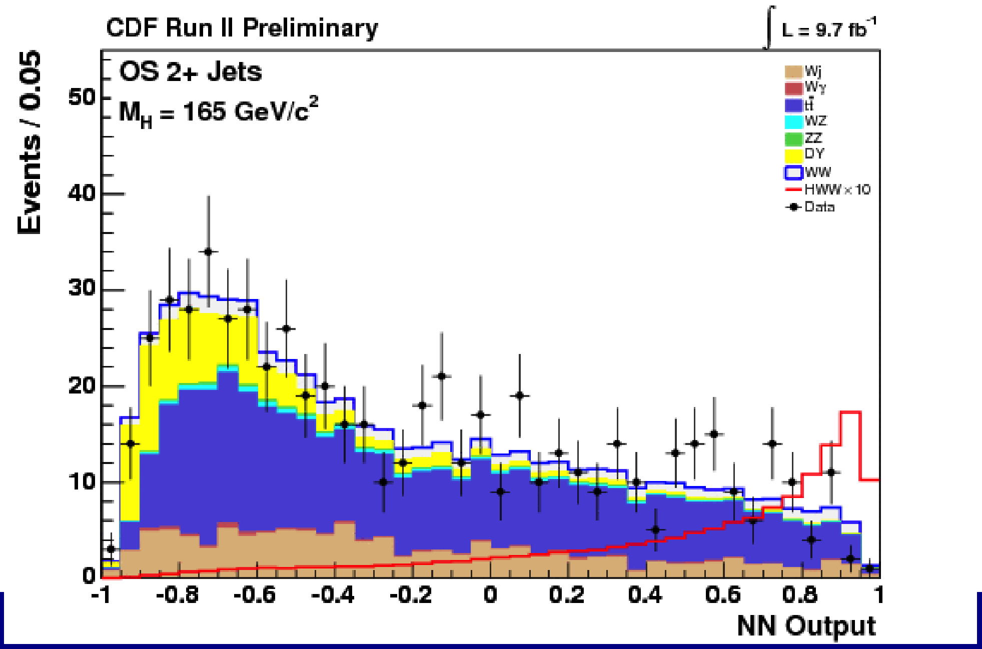
    Sample is sub-divided in training and test sub-samples to counteract on overtraining

  - Commonly we use **TMVA**: **http://tmva.sourceforge.net/**

H → WW multivariate analysis



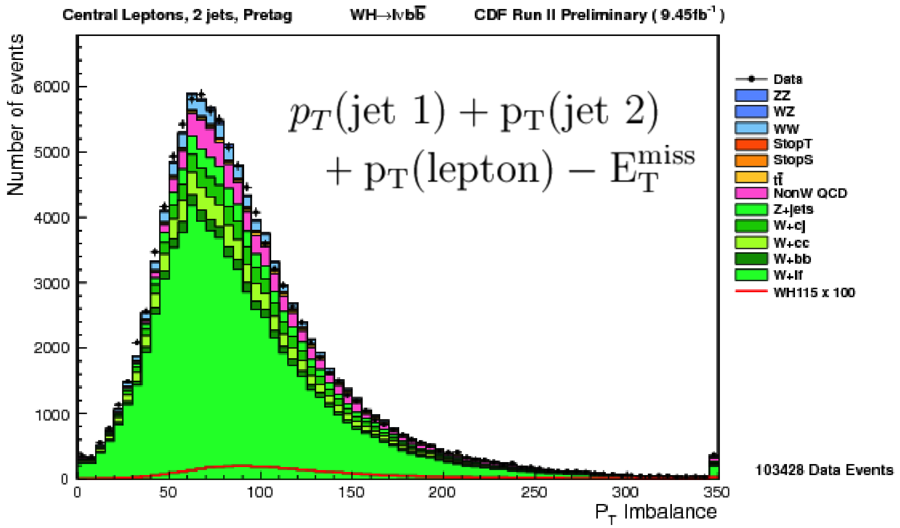


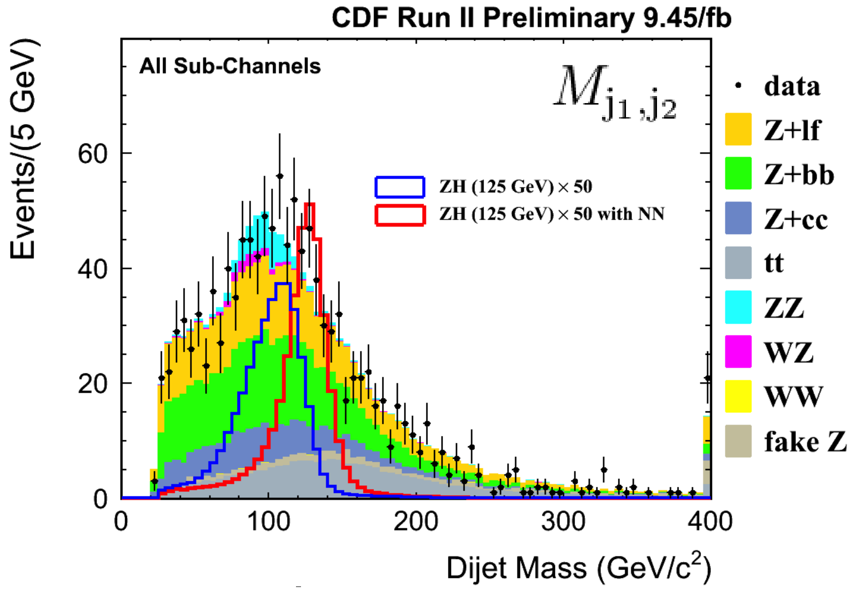


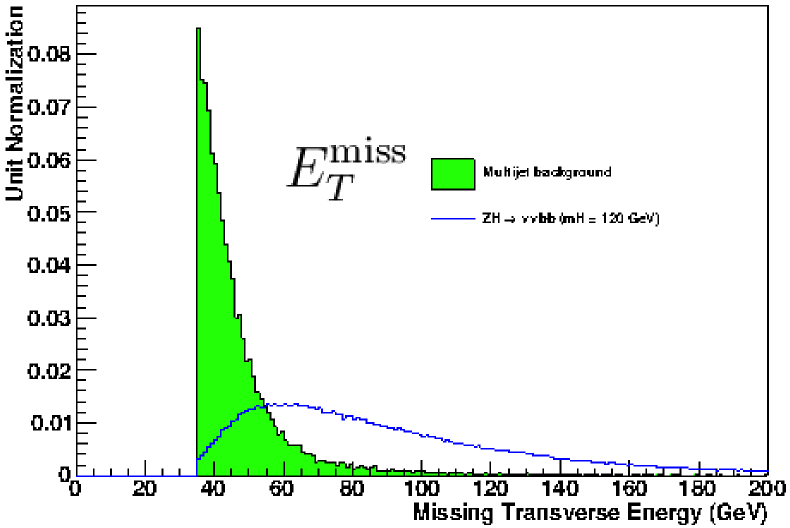
- **Events are categorized** in different jet multiplicity bins, dilepton invariant mass, sign of the dilepton, trilepton events
- **Best attained S:B = 1:1**
- **Data is compatible with background hyp.**

VH → lvb$\bar{b}$ / llb$\bar{b}$ / vvb$\bar{b}$

- **Higgs decays in two b-jets is sought in associated production**
  - Main backgrounds: QCD bb production, top pair production, V+heavy flavor

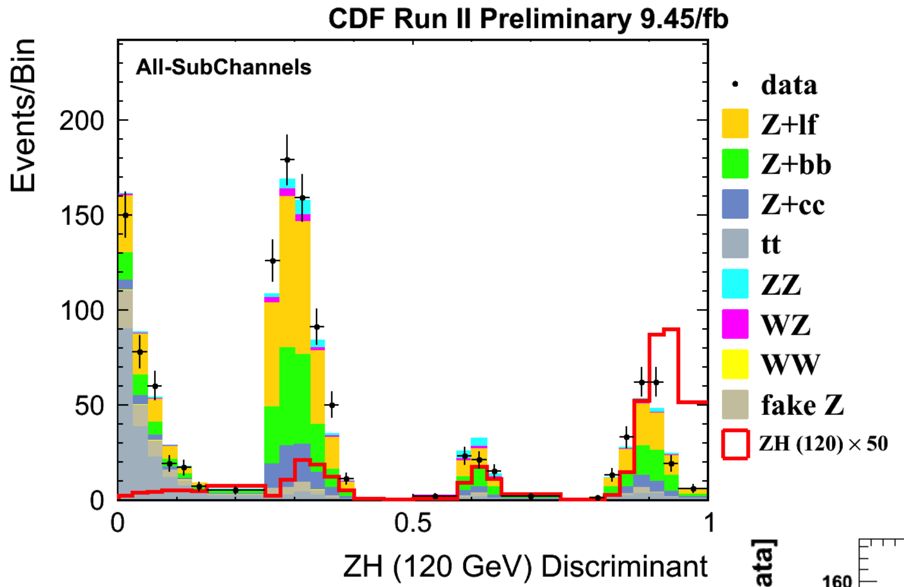


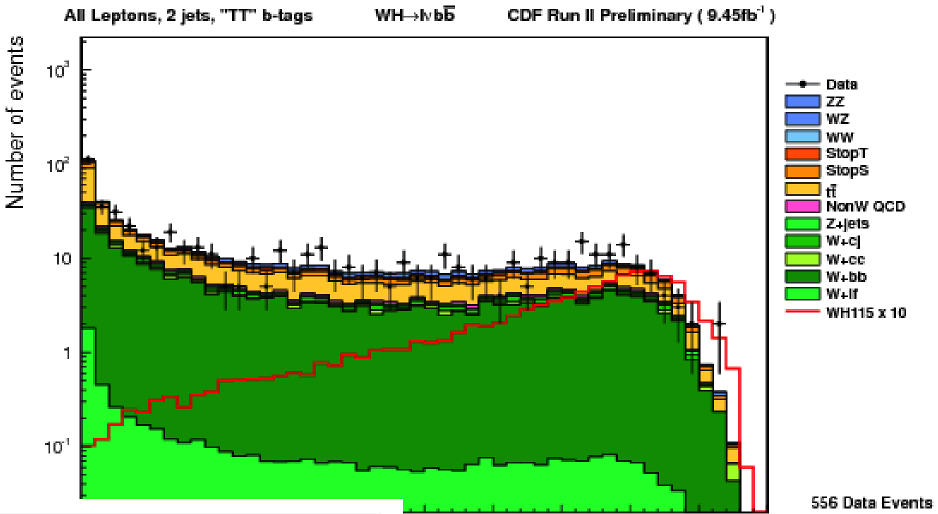


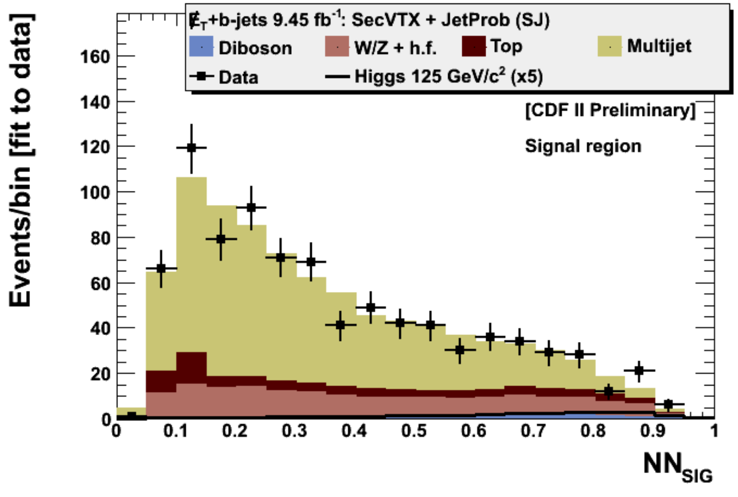


VH → lvb$\bar{b}$ / llb$\bar{b}$ / vvb$\bar{b}$

- **Higgs decays in two b-jets is sought in associated production**
  - Main backgrounds: QCD bb production, top pair production, V+heavy flavor
  - Multivariate analysis is applied with several control regions for each background







No visible excess (>2σ) is observed in all channels

Some exercises to consolidate

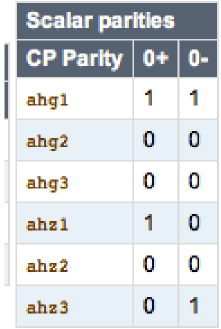
1) **Angular analysis of H → ZZ → 4l**

Download and install the JHU generator from

http://www.pha.jhu.edu/spin/Supporting_Material_for_.html

Generate 100k events X → ZZ → 4l with different J^P parities

For each *mod_Parameters.F90* must be modified, recompiled and re-run. The parameters are given in the following table. ►

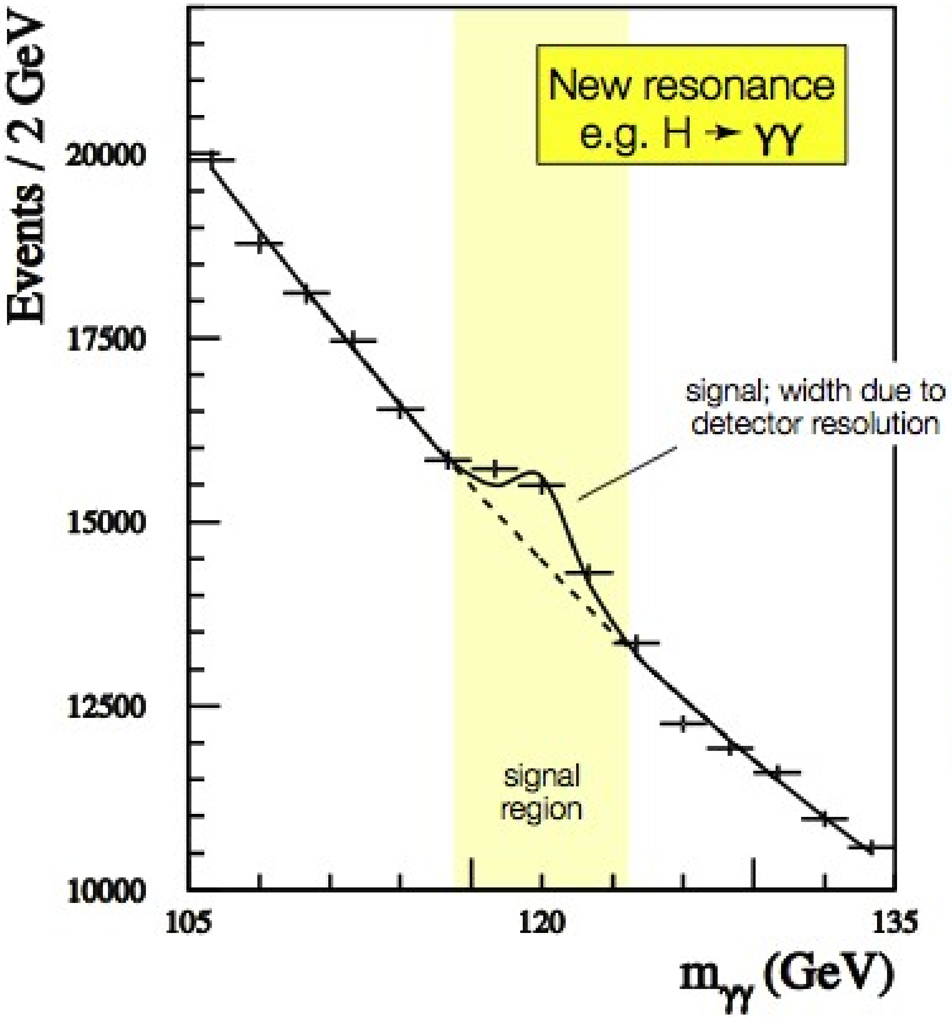


Scalar parities		
CP Parity	0+	0-
ahg1	1	1
ahg2	0	0
ahg3	0	0
ahz1	1	0
ahz2	0	0
ahz3	0	1

Compare the PDFs for the transverse momentum and rapidity of each lepton, the transverse momentum and mass of each dilepton system, the azimuthal angle between the two dileptons and the mass of the 4l system.

Discovery potential, exclusion limits, the final word from the Tevatron

When to claim discovery



Signal significance:

$$S = \frac{N_S}{\sqrt{N_B + N_S}}$$

N_S: # signal events
N_B: # background events

... in peak region

S > 5:

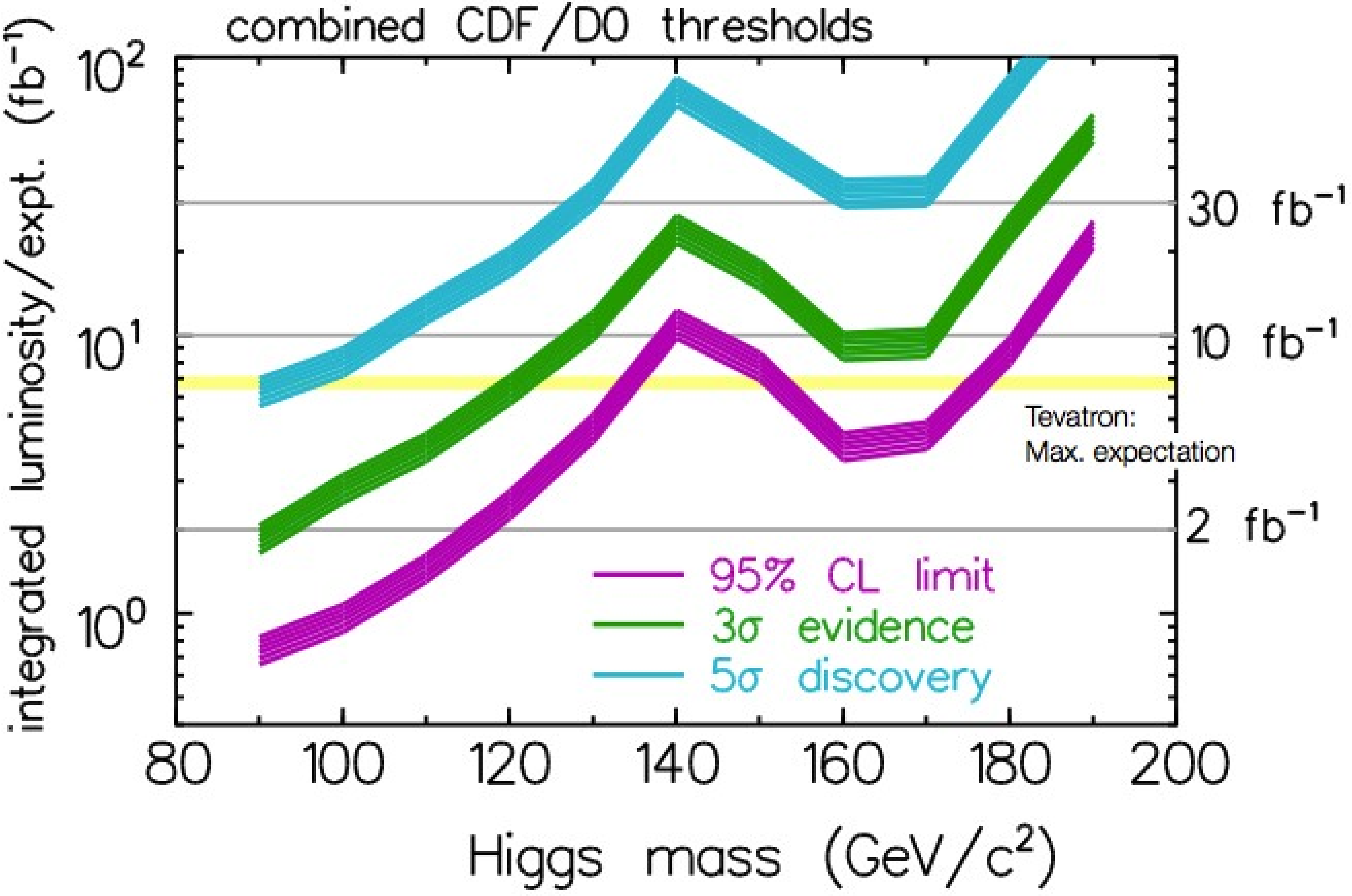
Signal $N_S = N_{tot} - N_B$ is 5 times larger than statistical uncertainty on N_B+N_S ...

Gaussian probability that upward fluctuation by more than 5σ is observed ...

$P_{5\sigma} = 10^{-7}$.

Discovery!

Higgs discovery potential at the Tevatron



Setting limits on Higgs production

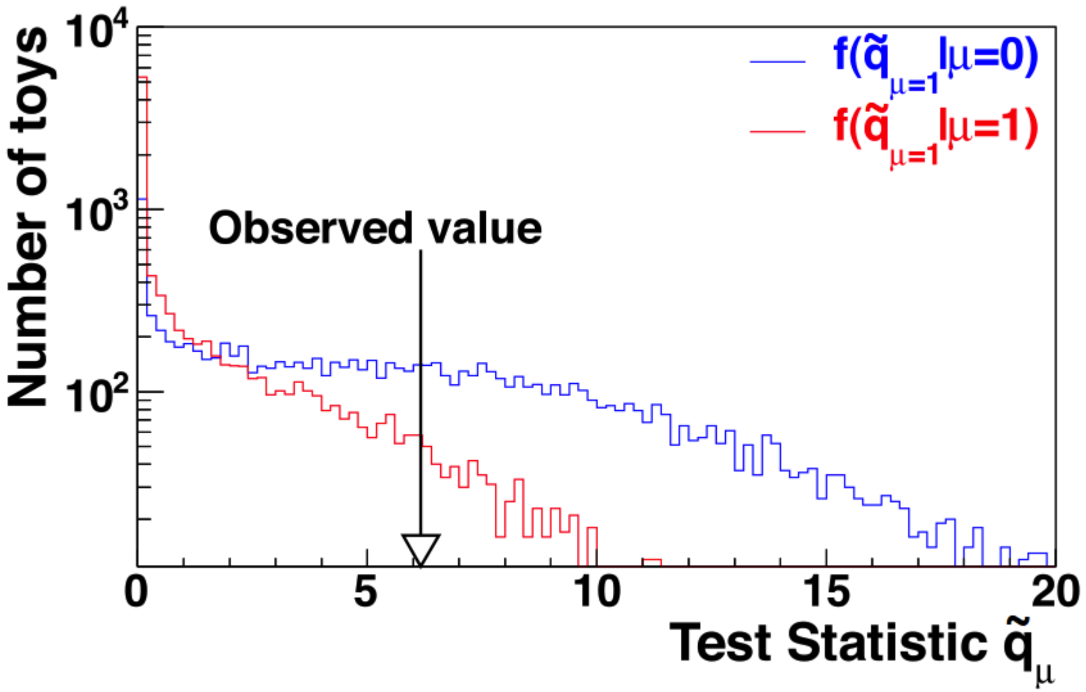
- **When no excess is observed the strategy is to set limits on σ(H)**
  - Assess from data what is the allowed signal strength i.e. $\mu=\sigma/\sigma_{SM}$
  - We measure the compatibility of the data with the signal hypothesis using a test statistics
- **Likelihood and test statistics definition**
  - The data vs S+B hypothesis is tested with a likelihood

$$\mathcal{L}(\text{data}\,|\,\mu,\theta) = \text{Poisson}\,(\,\text{data}\,|\,\mu\cdot\underbrace{s(\theta)}_{\text{Signal expected}}+\underbrace{b(\theta)}_{\text{background expected}}\,)\cdot\underbrace{p(\tilde{\theta}|\theta)}_{\text{nuisance paramters: uncertainty on rates, shapes, etc.}}$$

  - Signal+background and background only hypothesis tested with $\tilde{q}_\mu = -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\text{data}\underbrace{|\hat{\mu},\hat{\theta})}_{\text{maximize likelihood}}}$

Setting limits – CL$_s$ method

- In data we **compute** the **observed value of the test statistics** and find the best values of all nuisance parameters to fit background and background only hypothesis $\hat{\theta}_0^{obs}$ and $\hat{\theta}_\mu^{obs}$
- From MC/data-driven expectations we generate pseudo-experiments for each hypothesis



$$CL_s(\mu) = \frac{p_\mu}{1 - p_b}$$

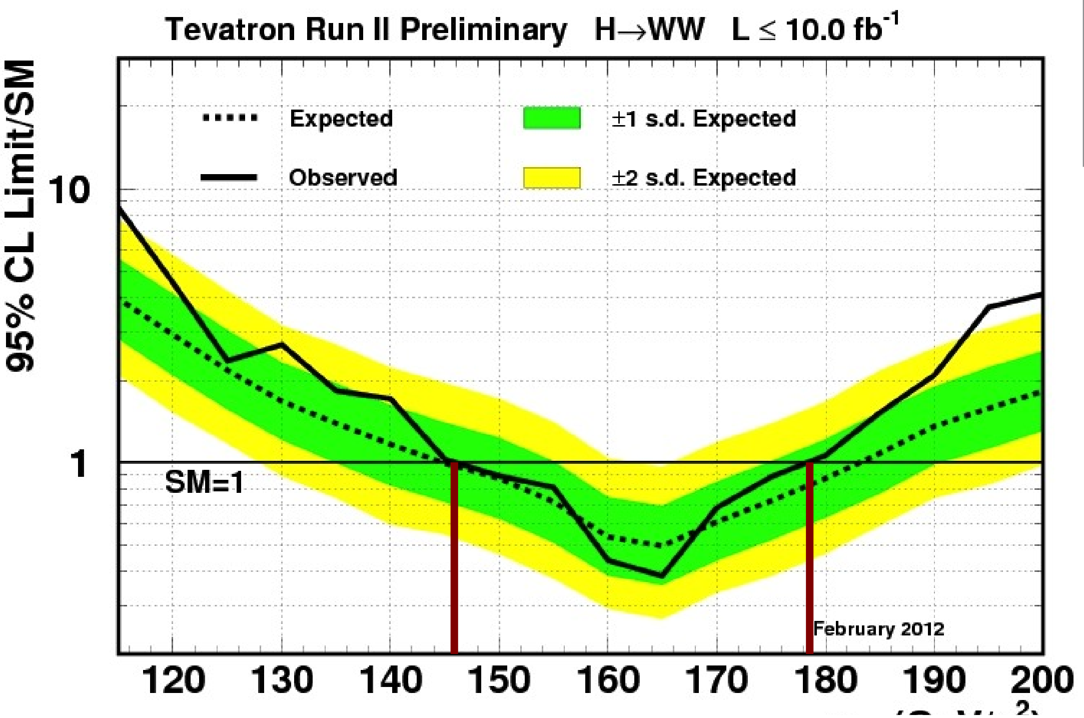
Probability that S+B test statistics exceeds the observed value in S+B hypothesis

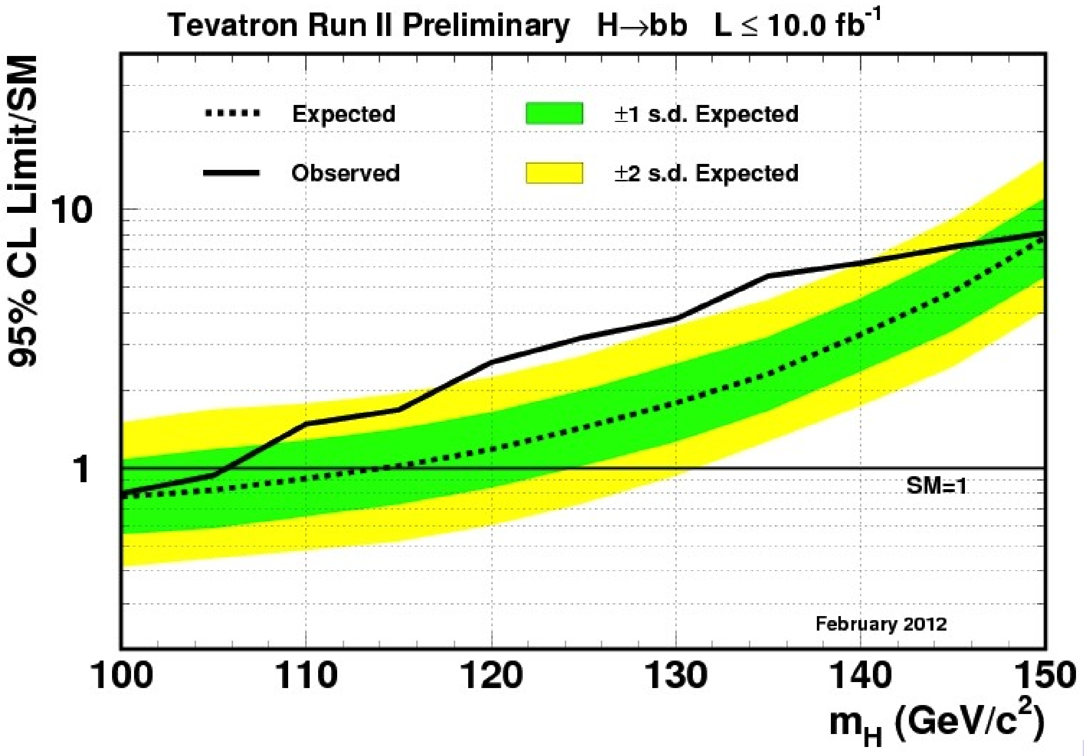
Similar, for background only hypothesis

- If **CL$_s$ < 5% signal is excluded at 95%**
- We call **upper endpoint**, i.e. μ_{up}, to the **signal strength for which CL$_s$=5%**

Limits per channel

- For the 2 channels shown before
- H → WW results are compatible with the expected within 68% CL
  - Exclusion in the range 146-178
  - Slight excess at high/low mass
- H → bb results show an overall excess >2σ
  - Not yet expected to be excluded
  - But no more data will be taken...





Ingredients for the Tevatron combination

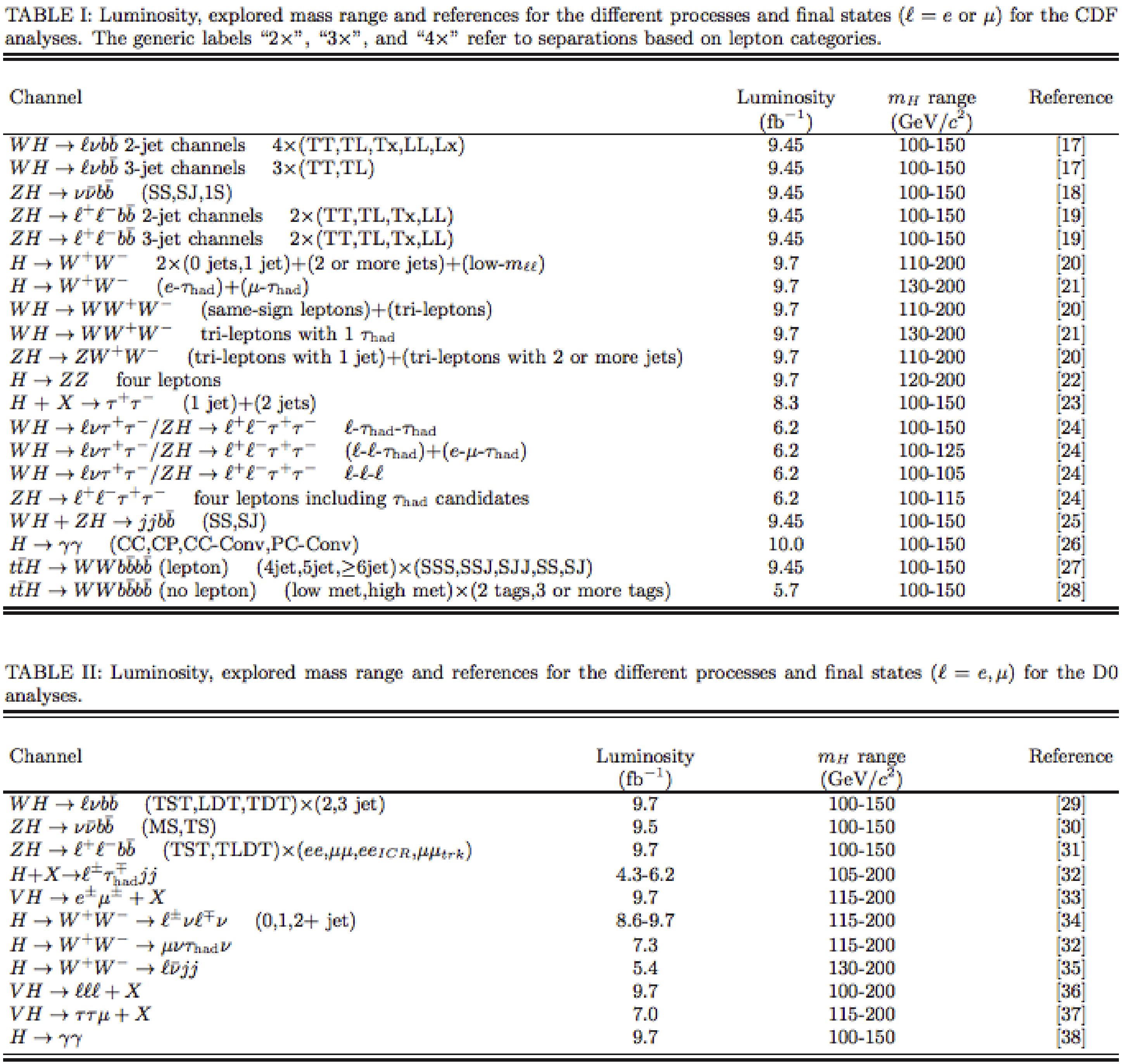


TABLE I: Luminosity, explored mass range and references for the different processes and final states ($\ell = e$ or μ) for the CDF analyses. The generic labels "2×", "3×", and "4×" refer to separations based on lepton categories.

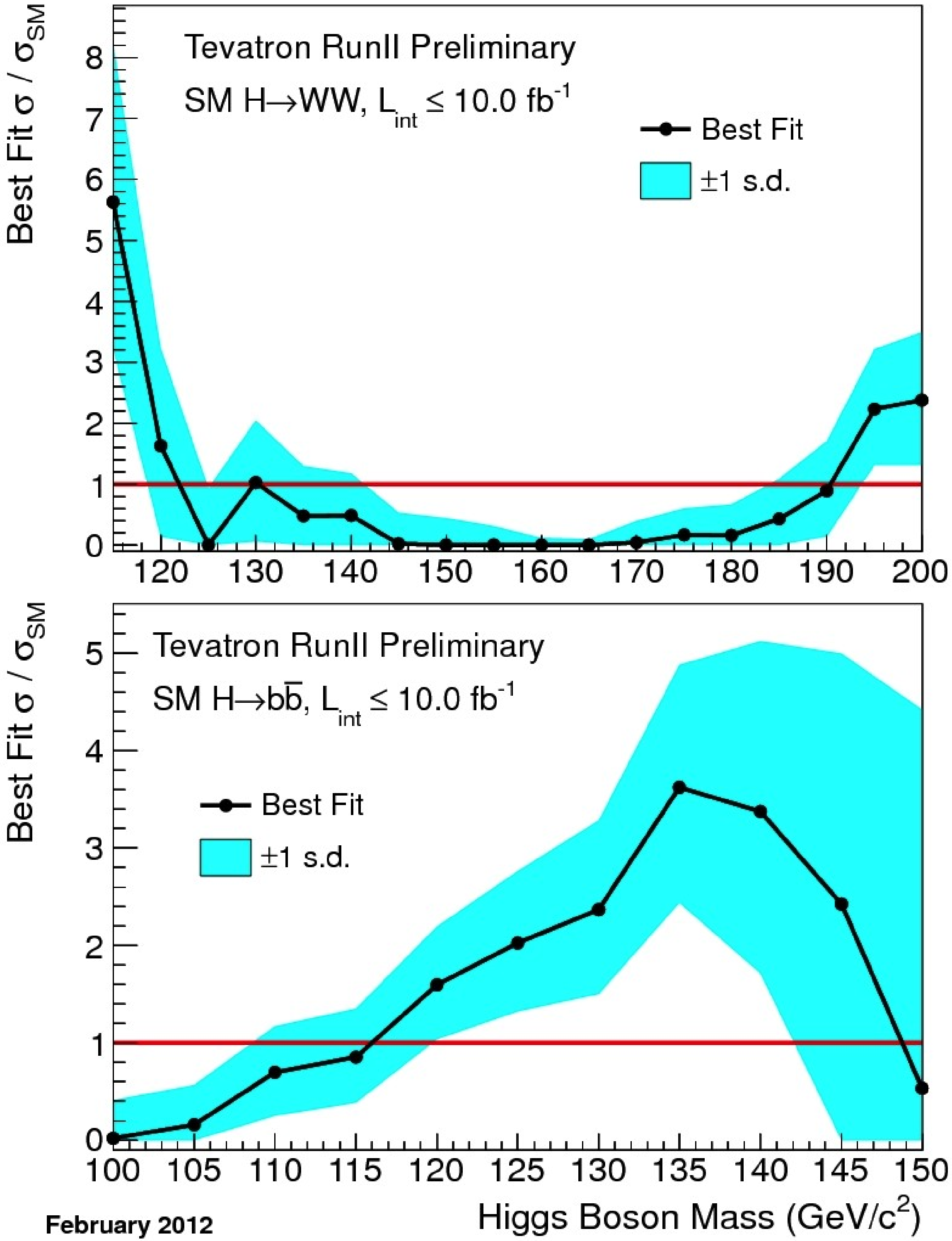
Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(TT,TL,Tx,LL,Lx)	9.45	100-150	[17]
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(TT,TL)	9.45	100-150	[17]
$ZH \to \nu\bar{\nu}b\bar{b}$ (SS,SJ,1S)	9.45	100-150	[18]
$ZH \to \ell^+\ell^-b\bar{b}$ 2-jet channels 2×(TT,TL,Tx,LL)	9.45	100-150	[19]
$ZH \to \ell^+\ell^-b\bar{b}$ 3-jet channels 2×(TT,TL,Tx,LL)	9.45	100-150	[19]
$H \to W^+W^-$ 2×(0 jets,1 jet)+(2 or more jets)+(low-$m_{\ell\ell}$)	9.7	110-200	[20]
$H \to W^+W^-$ (e-$\tau_{\rm had}$)+(μ-$\tau_{\rm had}$)	9.7	130-200	[21]
$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)	9.7	110-200	[20]
$WH \to WW^+W^-$ tri-leptons with 1 $\tau_{\rm had}$	9.7	130-200	[21]
$ZH \to ZW^+W^-$ (tri-leptons with 1 jet)+(tri-leptons with 2 or more jets)	9.7	110-200	[20]
$H \to ZZ$ four leptons	9.7	120-200	[22]
$H + X \to \tau^+\tau^-$ (1 jet)+(2 jets)	8.3	100-150	[23]
$WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ ℓ-$\tau_{\rm had}$-$\tau_{\rm had}$	6.2	100-150	[24]
$WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ (ℓ-ℓ-$\tau_{\rm had}$)+(e-μ-$\tau_{\rm had}$)	6.2	100-125	[24]
$WH \to \ell\nu\tau^+\tau^-/ZH \to \ell^+\ell^-\tau^+\tau^-$ ℓ-ℓ-ℓ	6.2	100-105	[24]
$ZH \to \ell^+\ell^-\tau^+\tau^-$ four leptons including $\tau_{\rm had}$ candidates	6.2	100-115	[24]
$WH + ZH \to jjb\bar{b}$ (SS,SJ)	9.45	100-150	[25]
$H \to \gamma\gamma$ (CC,CP,CC-Conv,PC-Conv)	10.0	100-150	[26]
$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (lepton) (4jet,5jet,≥6jet)×(SSS,SSJ,SJJ,SS,SJ)	9.45	100-150	[27]
$t\bar{t}H \to WWb\bar{b}b\bar{b}$ (no lepton) (low met,high met)×(2 tags,3 or more tags)	5.7	100-150	[28]

TABLE II: Luminosity, explored mass range and references for the different processes and final states ($\ell = e, \mu$) for the D0 analyses.

Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu b\bar{b}$ (TST,LDT,TDT)×(2,3 jet)	9.7	100-150	[29]
$ZH \to \nu\bar{\nu}b\bar{b}$ (MS,TS)	9.5	100-150	[30]
$ZH \to \ell^+\ell^-b\bar{b}$ (TST,TLDT)×($ee,\mu\mu,ee_{ICR},\mu\mu_{trk}$)	9.7	100-150	[31]
$H{+}X{\to}\ell^{\pm}\tau^{\mp}_{\rm had}jj$	4.3-6.2	105-200	[32]
$VH \to e^{\pm}\mu^{\pm} + X$	9.7	115-200	[33]
$H \to W^+W^- \to \ell^{\pm}\nu\ell^{\mp}\nu$ (0,1,2+ jet)	8.6-9.7	115-200	[34]
$H \to W^+W^- \to \mu\nu\tau_{\rm had}\nu$	7.3	115-200	[32]
$H \to W^+W^- \to \ell\bar{\nu}jj$	5.4	130-200	[35]
$VH \to \ell\ell\ell + X$	9.7	100-200	[36]
$VH \to \tau\tau\mu + X$	7.0	115-200	[37]
$H \to \gamma\gamma$	9.7	100-150	[38]

Best fit σ/σ_{SM}

- The problem can be reversed in case of deviations
- What is the value of μ which best fits the data
- In the region of the $H \rightarrow bb$ excess the result is above the SM prediction by >1σ
  - If real signal, the best μ must be in accordance for the different decay channels allowed



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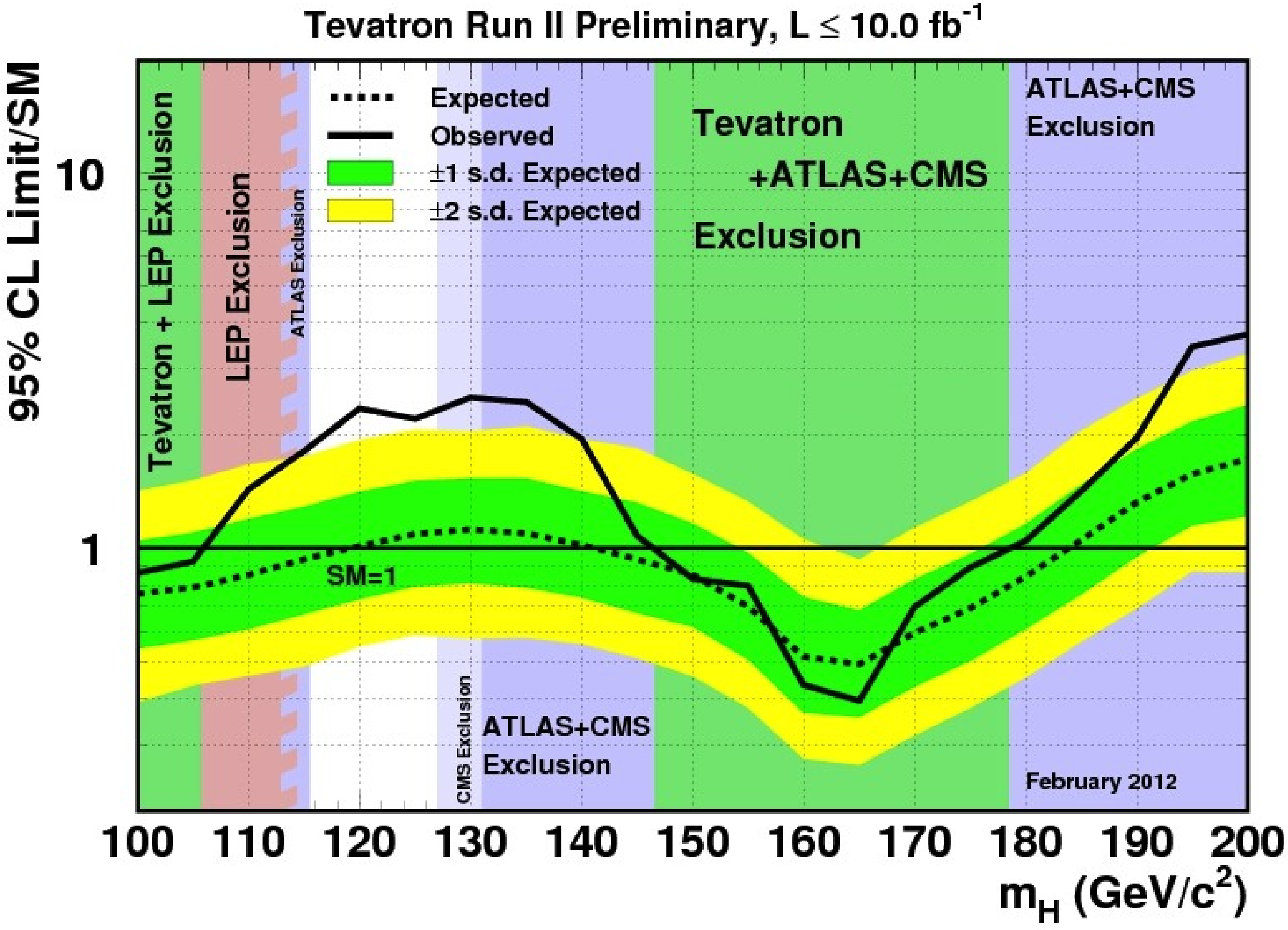
Putting it all together

- A **broad excess @ > 2σ is observed** at the Tevatron
  - Mostly dominated from VH → Vbb channels
  - **LHC will have the final word soon** and you will hear about it from Andre and Patricia!



End of Lecture I on Higgs Physics

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