Electroweak symmetry breaking

Searching for the missing piece of the Standard Model

P. Silva (CERN)
psilva@cern.ch

Course on Physics at the LHC

LIP, 20th April 2015

Outline

Introduction : a brief summary of the standard model

The missing piece of the standard model

Hunting the Higgs boson in particle colliders

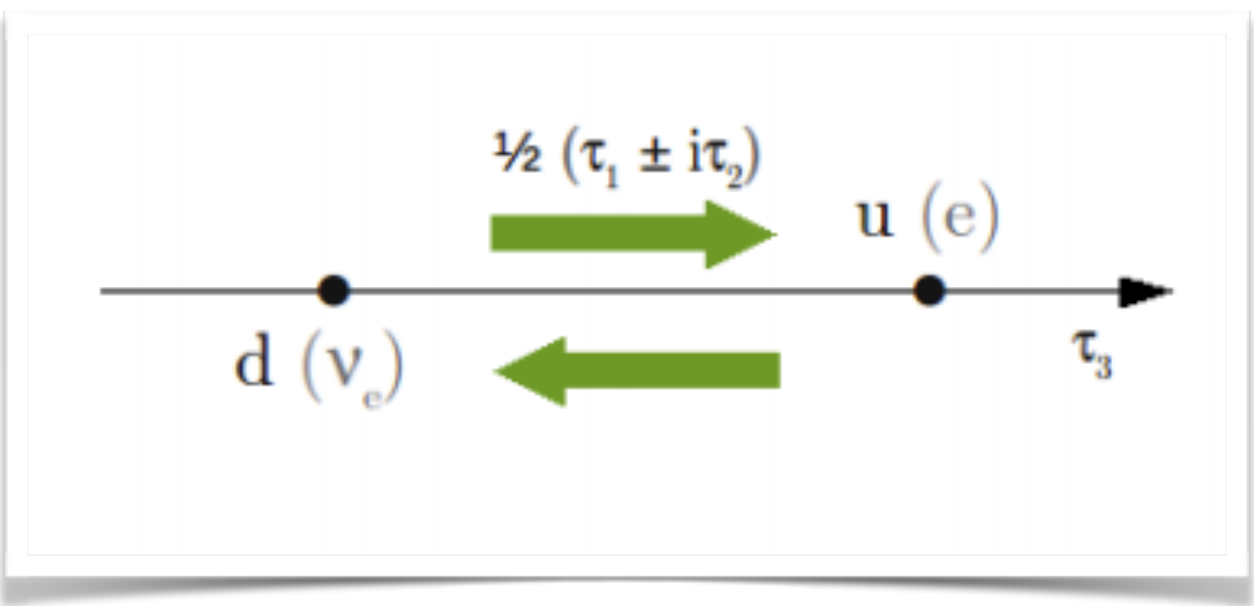
Introduction: a brief summary of the standard model

for more details see lectures by Prof. João Varela: I, II, III

Foundations of the standard model

The standard model (SM) condenses two observations regarding fundamental interactions

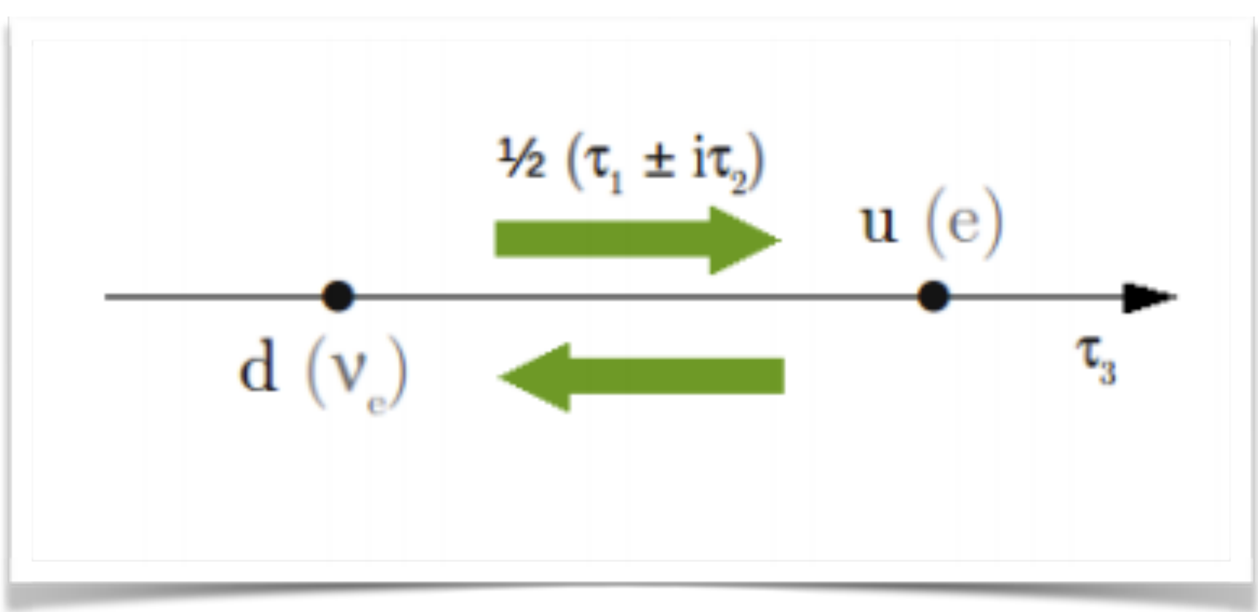
- **Interactions reflect symmetries**
  - the charges of the elementary particles are generators of gauge symmetries



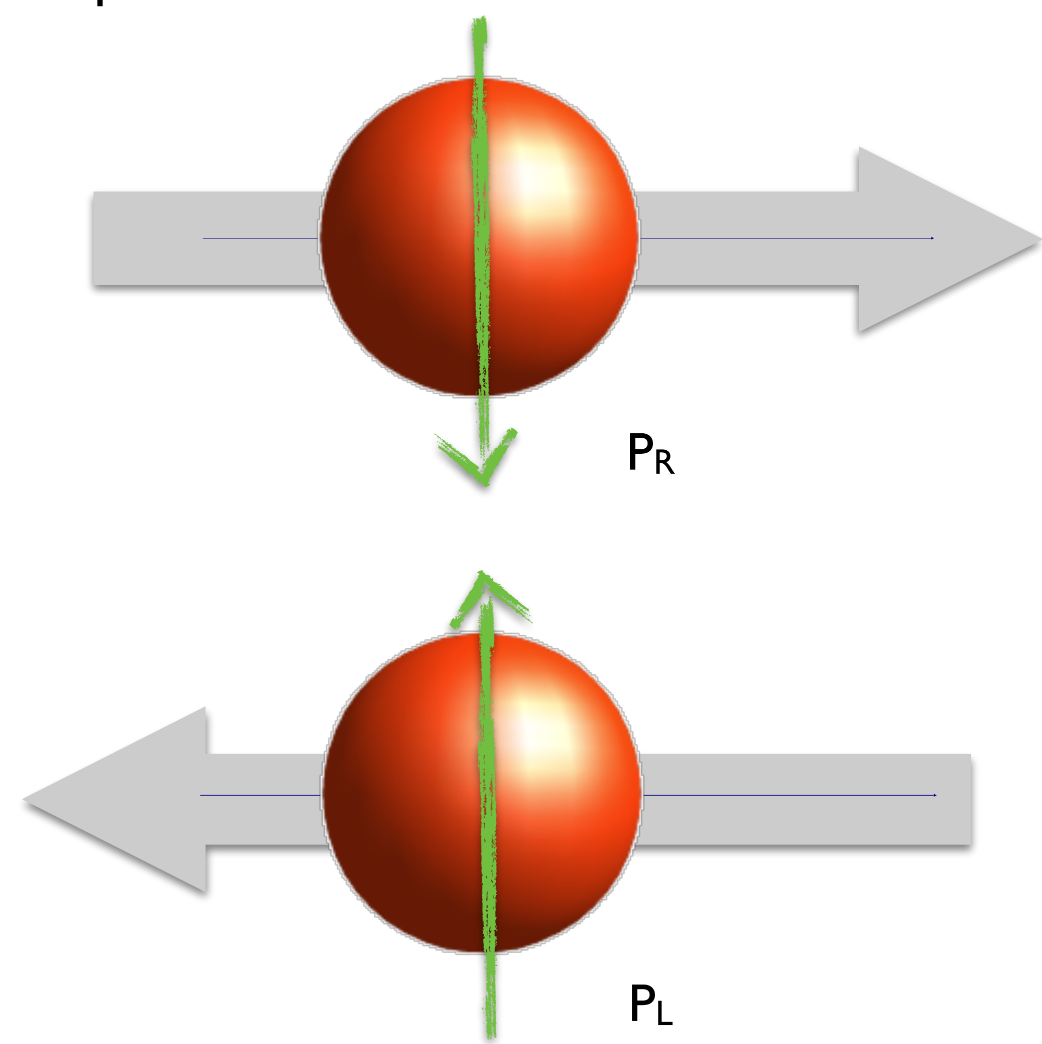
Foundations of the standard model

The standard model (SM) condenses two observations regarding fundamental interactions

- **Interactions reflect symmetries**
  - the charges of the elementary particles are generators of gauge symmetries

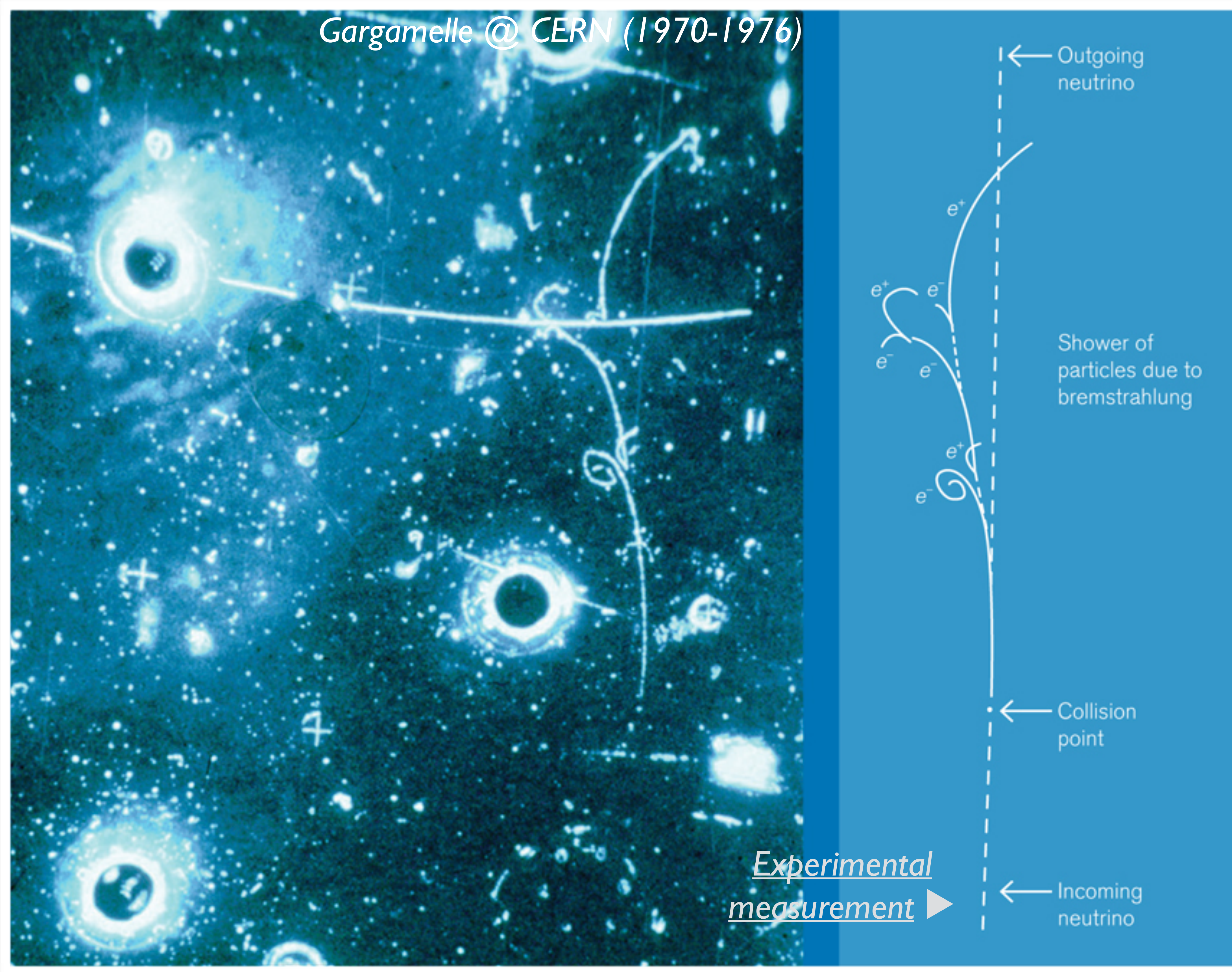


- **Parity is distinguished in nature**
  - left-handed and right-handed polarisation are distinct
  - with more than one generation of particles CP is violated



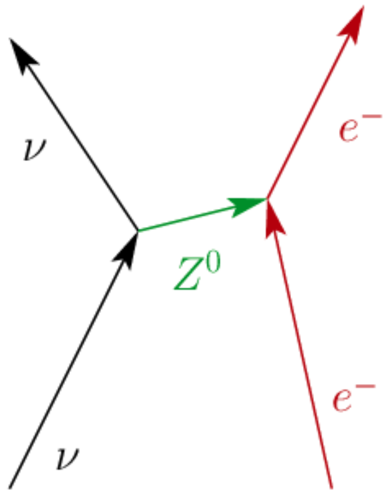
The SM builds on experimental evidence I

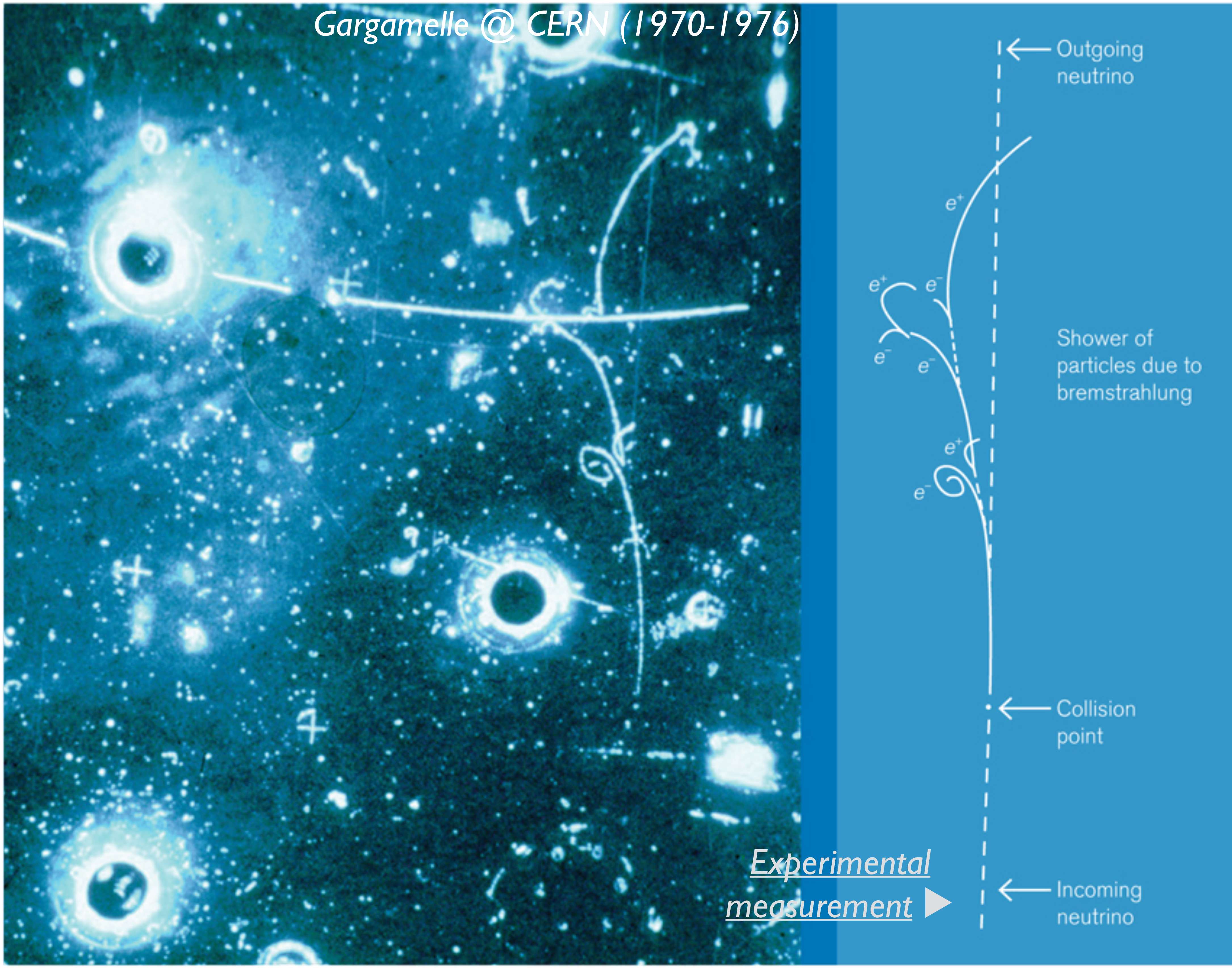
The SM builds on experimental evidence I



The SM builds on experimental evidence I

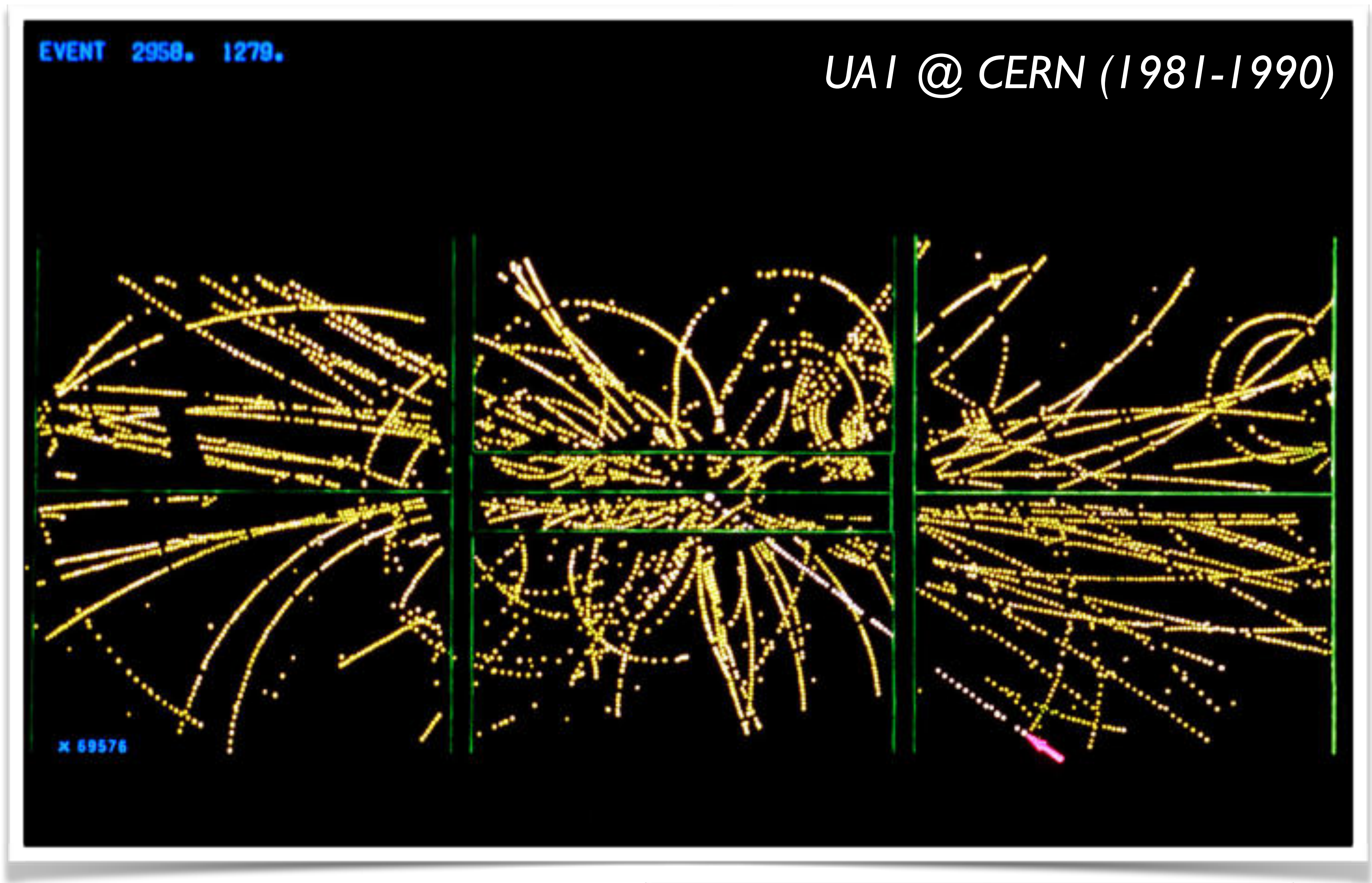
Theoretical interpretation: the neutrino scattering has been **mediated by a neutral interaction** which conserves flavor, **couples proportionally to the weak neutral charge** and gets **masked at low Q^2 by electromagnetic interactions**





Experimental measurement

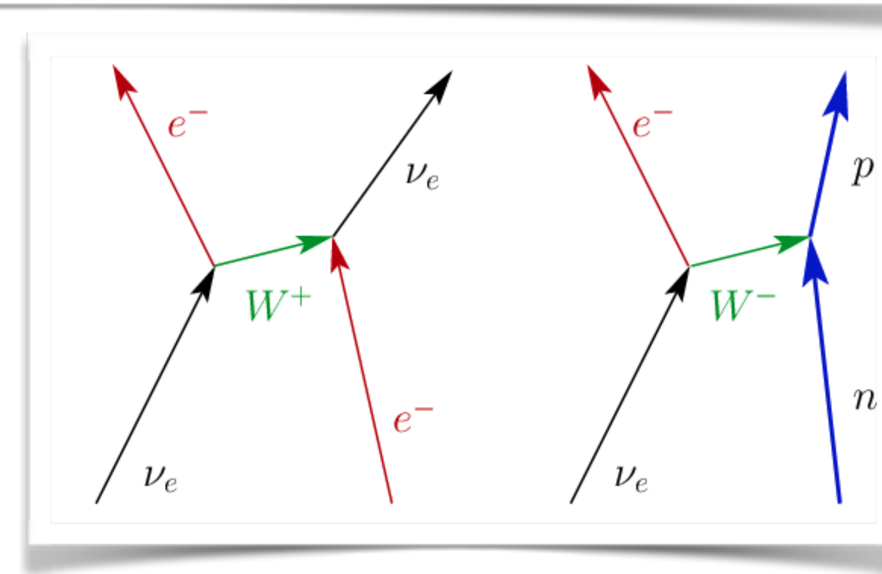
The SM builds on experimental evidence II



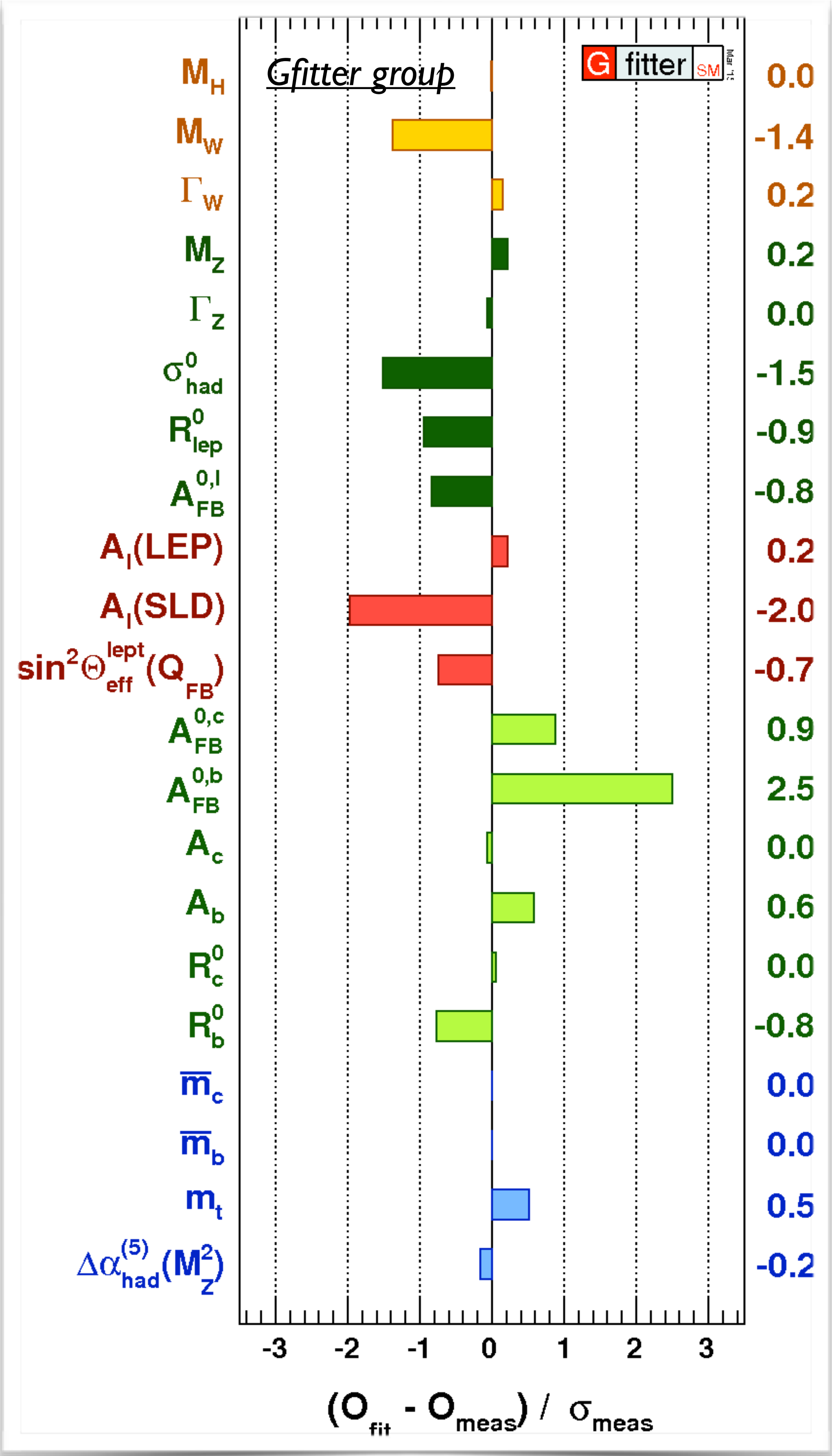
- *Experimental measurement*: an electron is observed along with missing transverse energy after colliding two beams of protons

$$\bar{u} + d \to W^- \to e^- \bar{\nu}_e$$

- *Theoretical interpretation*: charged currents mix the flavour

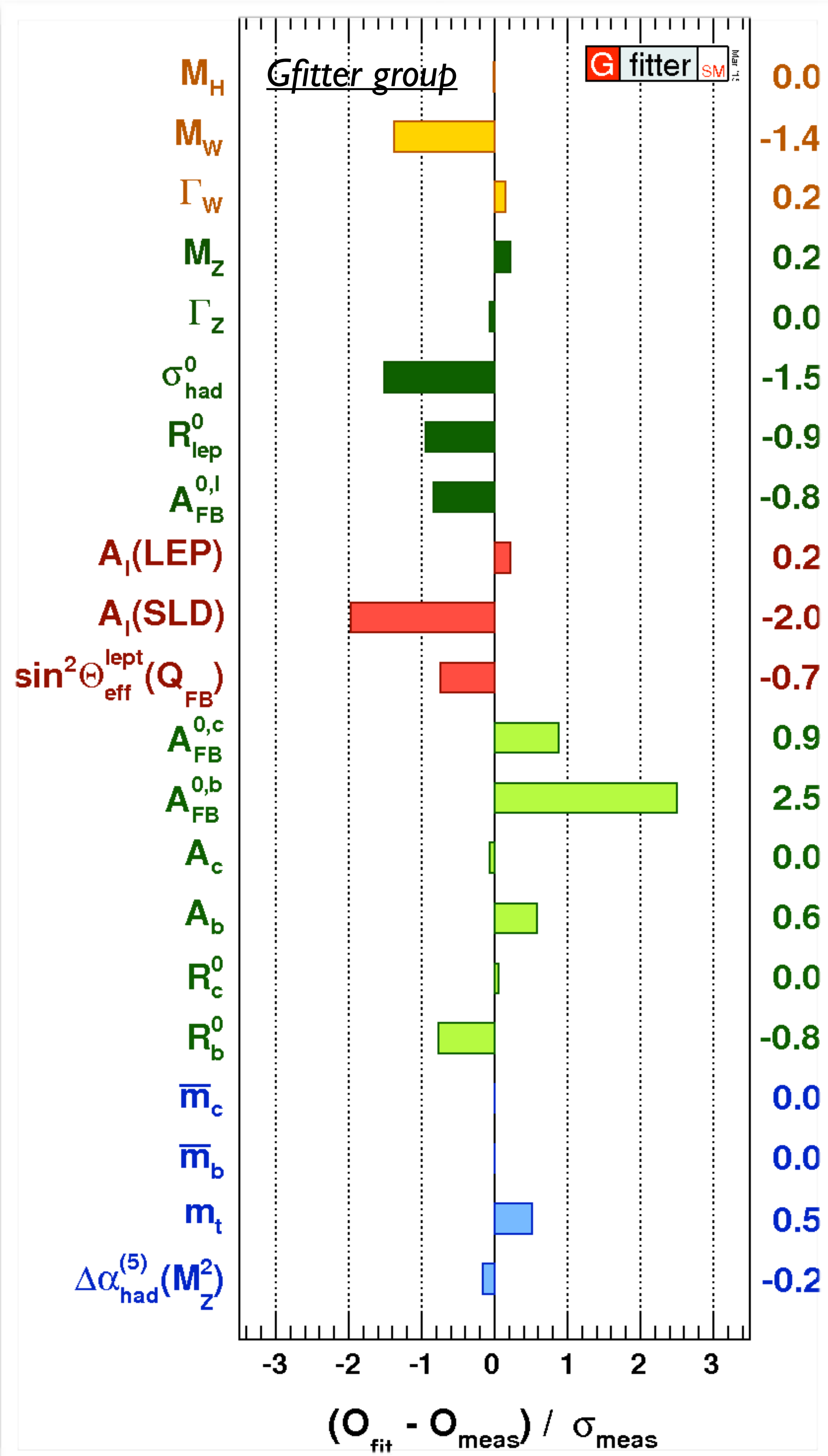


Thus, the SM is a highly predictive theory

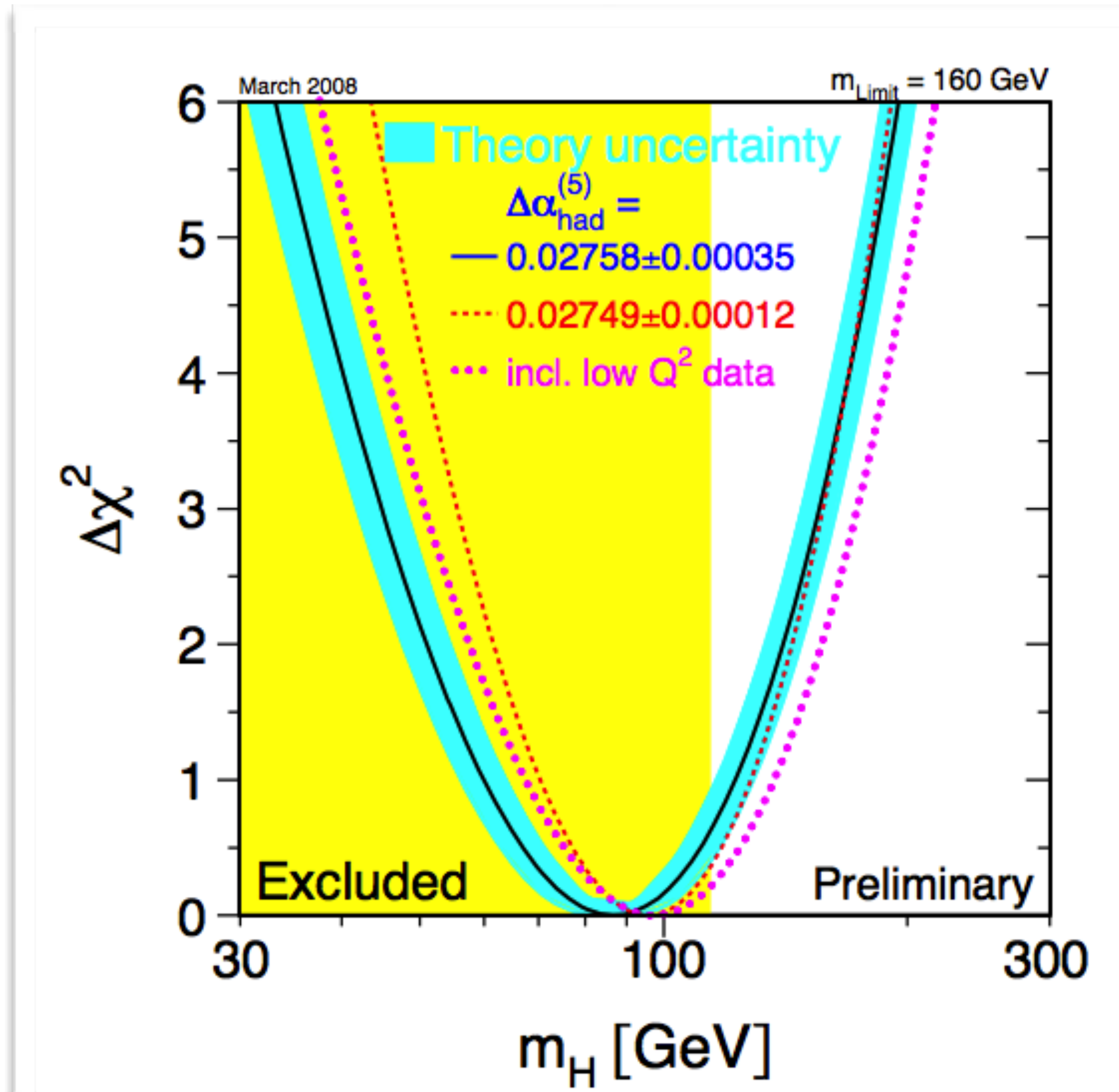


- Measured to incredible precision in e^+e^- colliders
- Largest deviations don't reach 3σ level
- See Phys.Rept. 403-404 (2004) 189-201 for review

Thus, the SM is a highly predictive theory



- Measured to incredible precision in e^+e^- colliders
- Largest deviations don't reach 3σ level
- See Phys.Rept. 403-404 (2004) 189-201 for review
- After LEP: scale of the "missing piece" accurately predicted



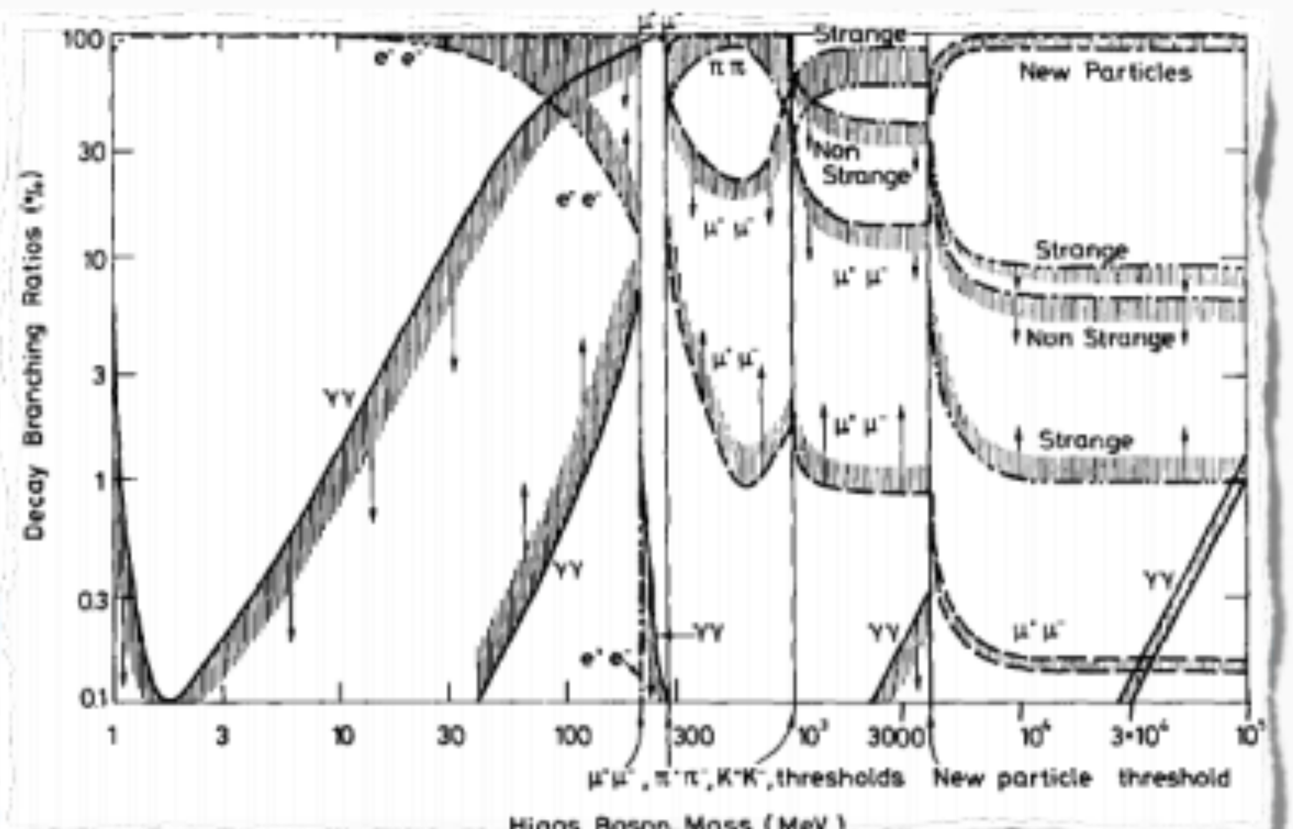
Notice this was not the case before LEP experiments

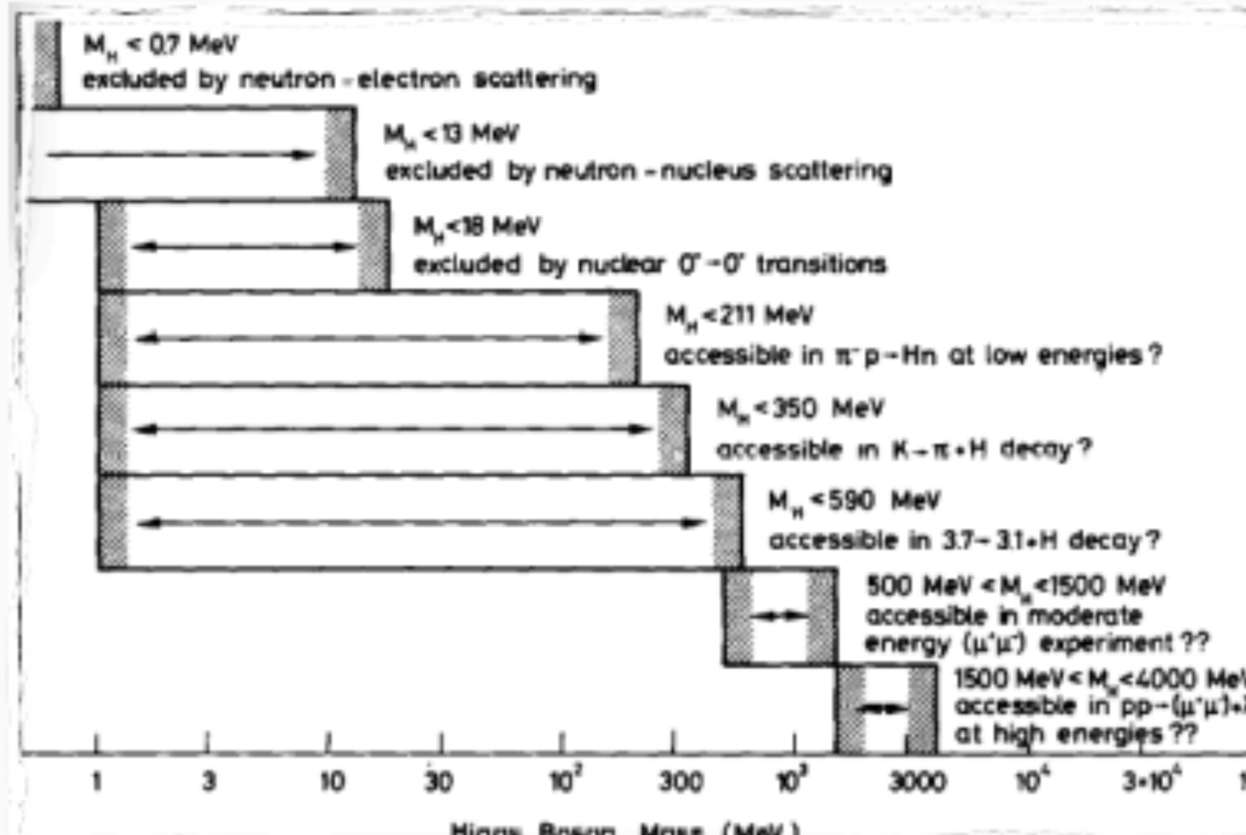
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

Received 7 November 1975

Nucl. Phys. B 106 (1976) 292-340





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.

How do we describe kinematics in the SM?

- Interactions must preserve gauge invariance
    - interactions transform the fields, but must leave the hamiltonean invariant

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

How do we describe kinematics in the SM?

- Interactions must preserve gauge invariance
  - interactions transform the fields, but must leave the hamiltonean invariant

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

  - charges (electric, weak, colour) generate currents, i.e. symmetry transformations

$$\psi(x) \rightarrow e^{-i\xi(x)}\psi(x)$$

How do we describe kinematics in the SM?

- Interactions must preserve gauge invariance
  - interactions transform the fields, but must leave the hamiltonean invariant

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

  - charges (electric, weak, colour) generate currents, i.e. symmetry transformations

$$\psi(x) \to e^{-i\xi(x)}\psi(x)$$

  - to preserve gauge invariance the kinetic term must accommodate the currents

$$i\bar{\psi}\gamma^\mu\partial_\mu\psi \quad \to \quad i\bar{\psi}\gamma^\mu D_\mu\psi$$

How do we describe kinematics in the SM?

- Interactions must preserve gauge invariance
  - interactions transform the fields, but must leave the hamiltonean invariant

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

  - charges (electric, weak, colour) generate currents, i.e. symmetry transformations

$$\psi(x)\rightarrow e^{-i\xi(x)}\psi(x)$$

  - to preserve gauge invariance the kinetic term must accommodate the currents

$$i\bar{\psi}\gamma^\mu\partial_\mu\psi\quad\rightarrow\quad i\bar{\psi}\gamma^\mu D_\mu\psi$$

  - and from a theory-point of view gauge invariance ⇒discover interaction fields

$$D^\mu=\partial^\mu+ig_sG_a^\mu L_a+igW_b^\mu T_b+ig'B^\mu Y.$$

Strong interactions

Charged EWK interactions

Neutral EWK interactions

How do we describe kinematics in the SM?

- Interactions must preserve gauge invariance
  - interactions transform the fields, but must leave the hamiltonean invariant

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

  - charges (electric, weak, colour) generate currents, i.e. symmetry transformations

$$\psi(x) \rightarrow e^{-i\xi(x)}\psi(x)$$

  - to preserve gauge invariance the kinetic term must accommodate the currents

$$i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi \quad\rightarrow\quad i\bar{\psi}\gamma^{\mu}D_{\mu}\psi$$

  - and from a theory-point of view gauge invariance ⇒discover interaction fields

$$D^{\mu} = \partial^{\mu} + ig_s G_a^{\mu} L_a + igW_b^{\mu} T_b + ig' B^{\mu} Y$$

strong coupling constant

combination of Fermi and fine structure constants

How do we describe kinematics in the SM?

- Interactions must preserve gauge invariance
  - interactions transform the fields, but must leave the hamiltonean invariant

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

  - charges (electric, weak, colour) generate currents, i.e. symmetry transformations

$$\psi(x) \rightarrow e^{-i\xi(x)}\psi(x)$$

  - to preserve gauge invariance the kinetic term must accommodate the currents

$$i\bar{\psi}\gamma^\mu\partial_\mu\psi \;\;\rightarrow\;\; i\bar{\psi}\gamma^\mu D_\mu\psi$$

  - and from a theory-point of view gauge invariance ⇒discover interaction fields

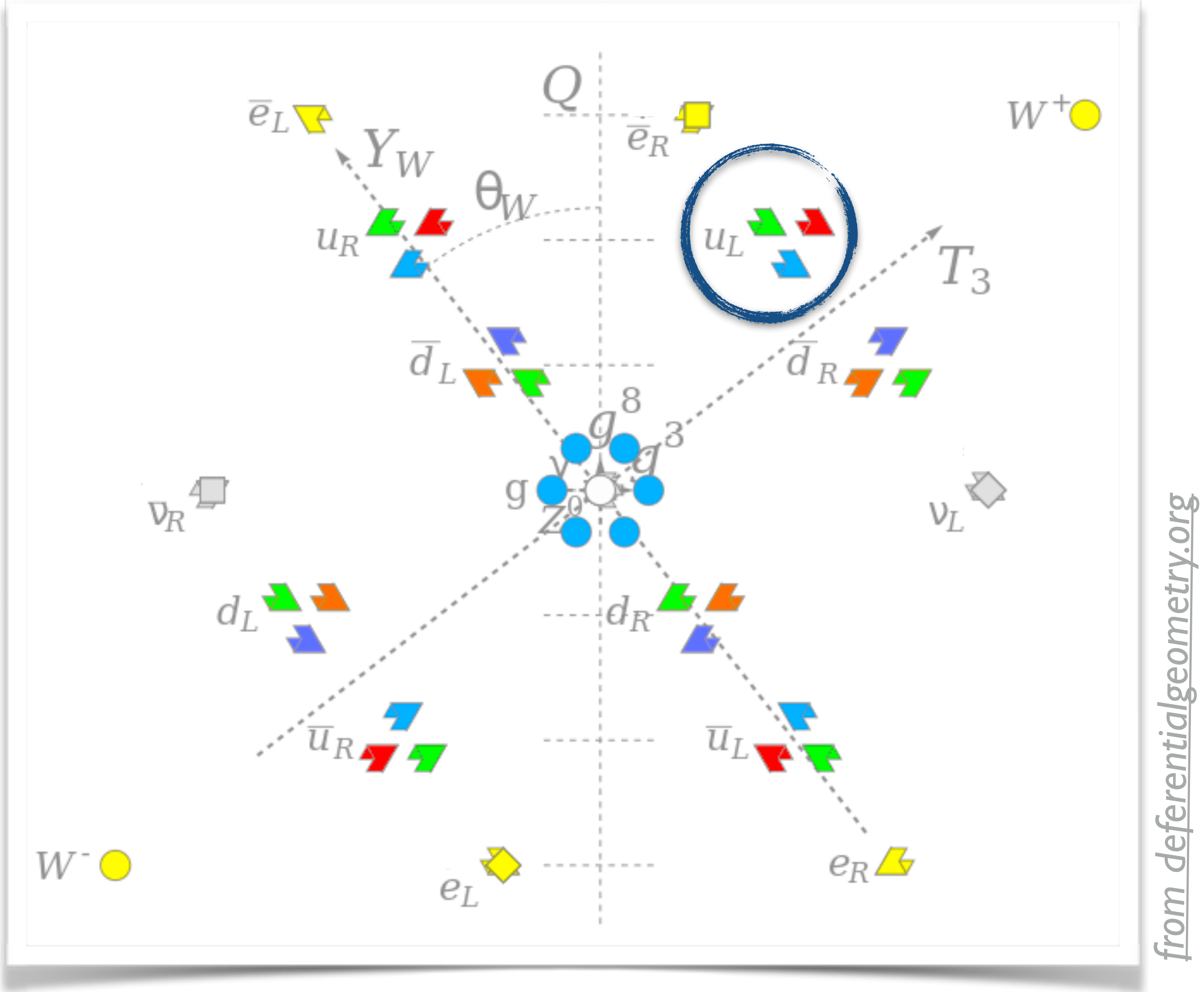
$$D^\mu = \partial^\mu + ig_s G_a^\mu L_a + igW_b^\mu T_b + ig' B^\mu Y$$

Gell-Mann matrices

Pauli matrices

hypercharge (scalar)

SM: particles are representations of the symmetry group



- **e.g. left handed quark:** $Q_{L_i}(3,2)_{+1/6}$ hypercharge : Y= 1/2 x (Q-1/3)

  Color triplets   Weak isospin doublets

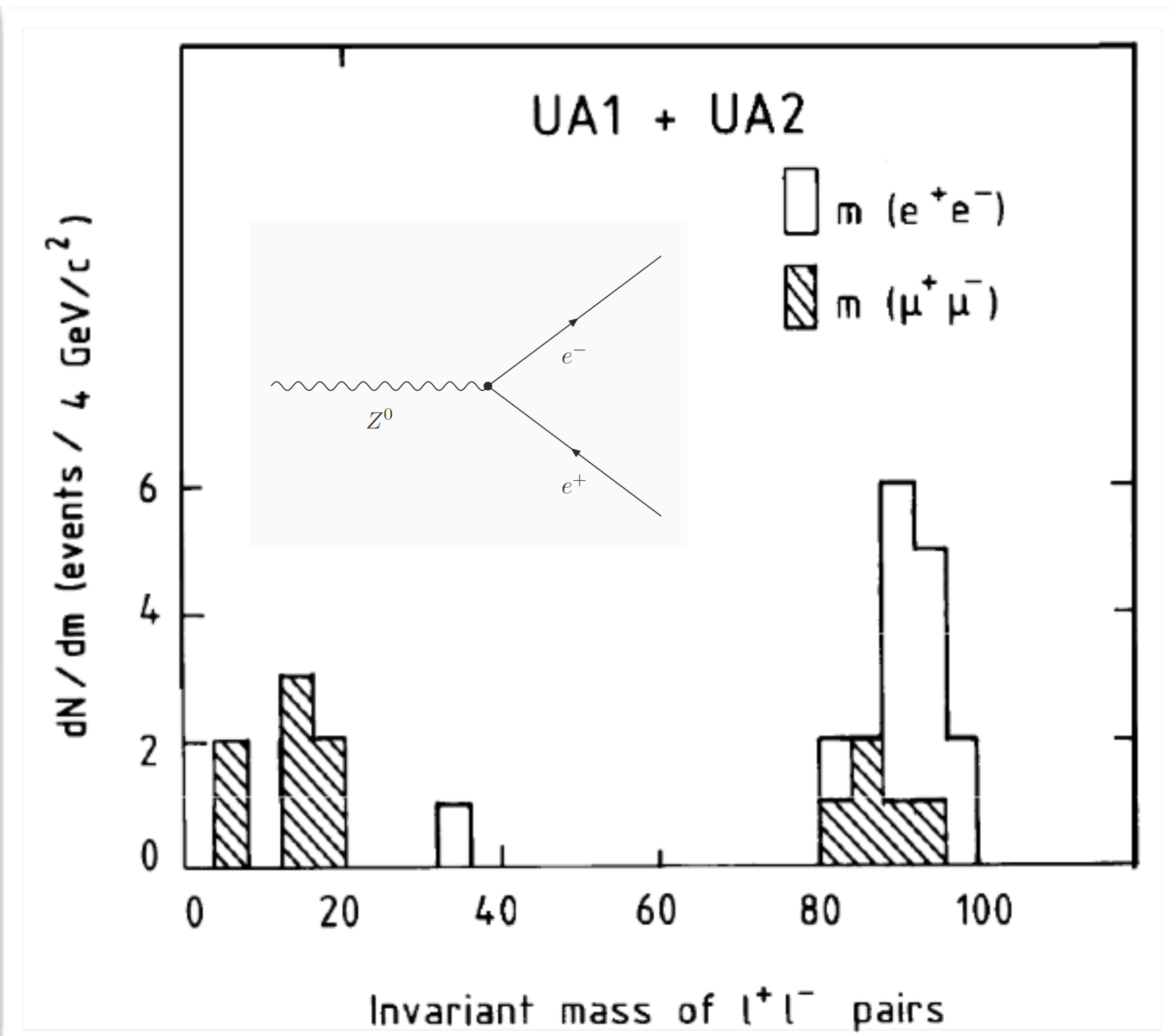
- **Geometry fully defines kinematics**

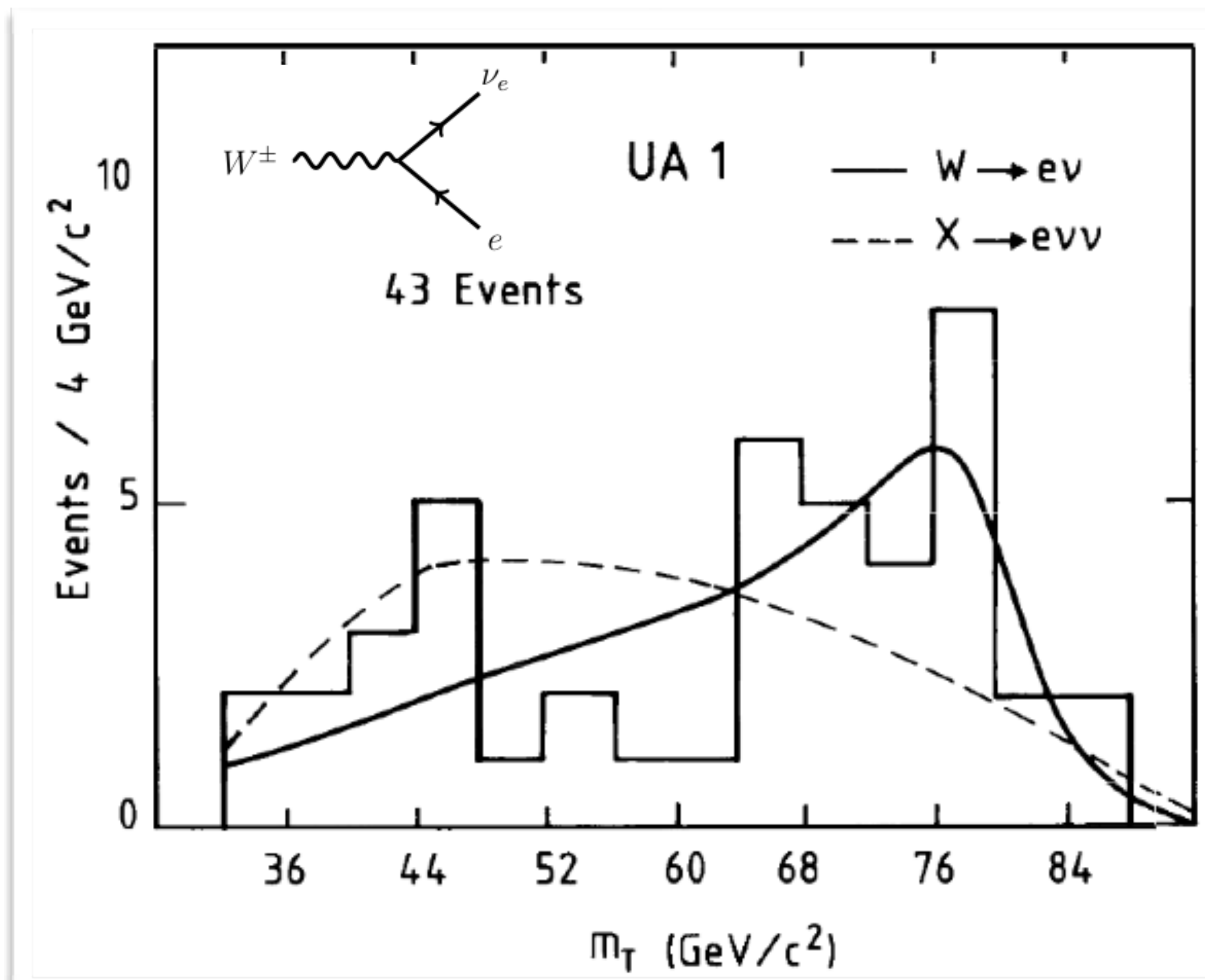
$$\mathcal{L}_{\text{kinetic}}(Q_L) = i\overline{Q_{Li}}\gamma_\mu\left(\partial^\mu + \frac{i}{2}g_s G^\mu_a\lambda_a + \frac{i}{2}gW^\mu_b\tau_b + \frac{i}{6}g'B^\mu\right)\delta_{ij}Q_{Lj}$$

…but symmetry does not expect mass

- Elementary particles have mass and so do the electroweak gauge bosons :W and Z

⇒ electroweak symmetry must be broken at our energy scale





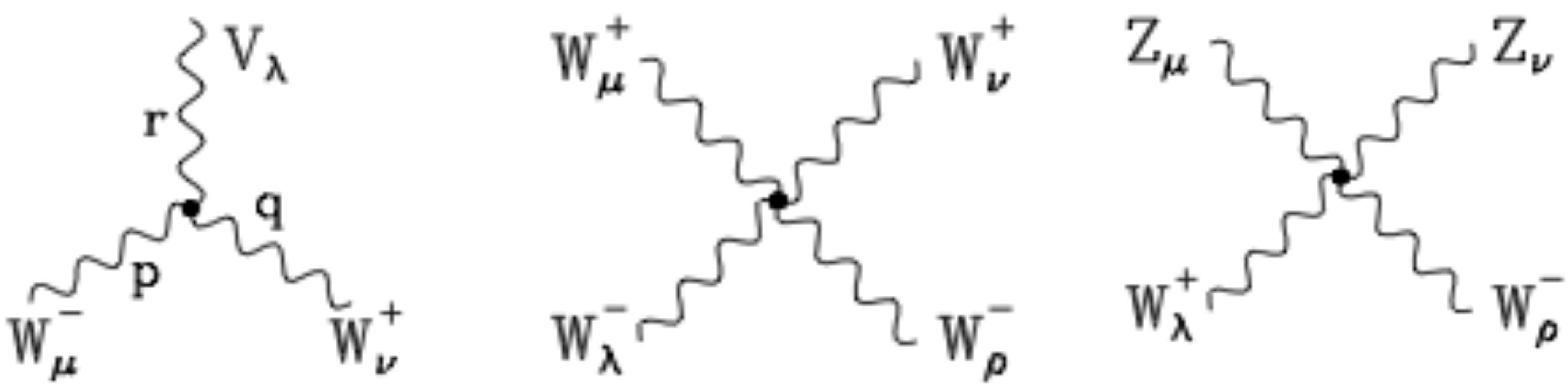
from C. Rubbia's Nobel prize lecture

Pure gauge boson interactions are allowed in the SM…

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

field-strength tensors for charged and neutral bosons

- **Triple and quartic gauge couplings can occur, and preserve gauge invariance**



etc.

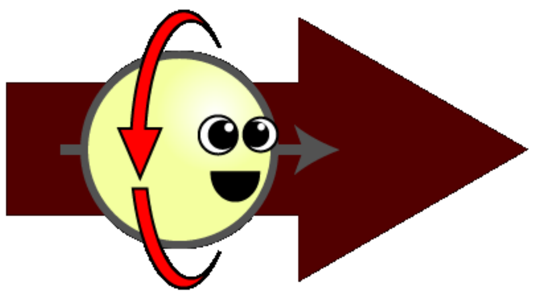
$+ig_V\,[(p-q)_\lambda g_{\mu\nu} + (q-r)_\mu g_{\nu\lambda} + (r-p)_\nu g_{\lambda\mu}]$
(all momenta incoming,
$g_A = e,\ g_Z = g_W\ \cos\theta_W$)

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

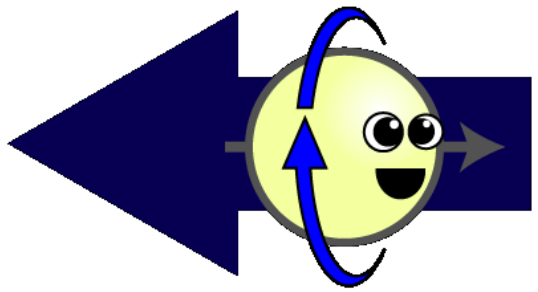
$-ig_W^2\cos^2\theta_W[2g_{\mu\nu}g_{\lambda\rho} - g_{\mu\lambda}g_{\nu\rho} - g_{\mu\rho}g_{\nu\lambda}]$

…and depending on the polarization…

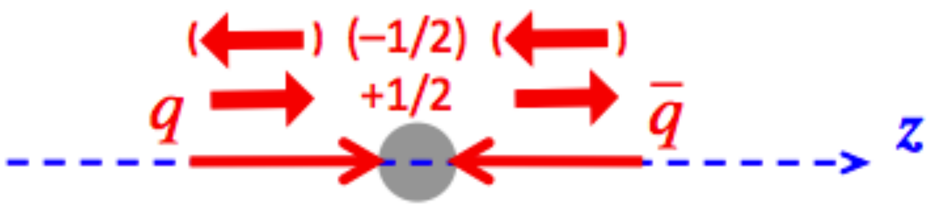
- **Photon-like polarizations are the most common in nature**
    - helicity conservation after an annihilation imposes transverse polarisation of vector-like states



$$\varepsilon^{\mu}_{-} = \frac{1}{\sqrt{2}}(0, 1, -i, 0)$$



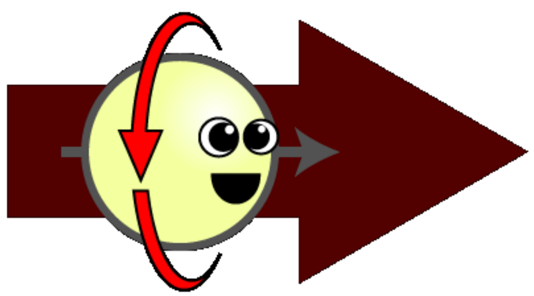
$$\varepsilon^{\mu}_{+} = \frac{1}{\sqrt{2}}(0, 1, i, 0)$$



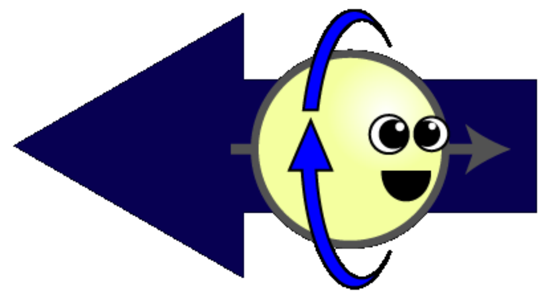
$$|V\rangle = (1, \pm 1)$$

…and depending on the polarization…

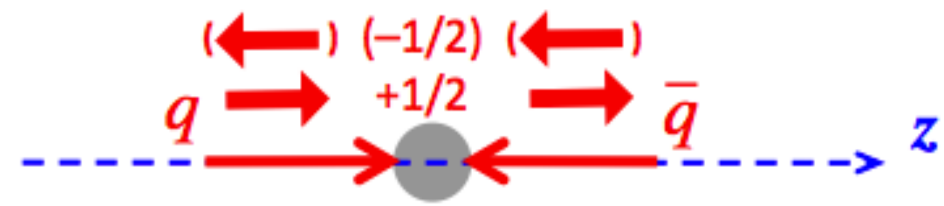
- **Photon-like polarizations are the most common in nature**
  - helicity conservation after an annihilation imposes transverse polarisation of vector-like states



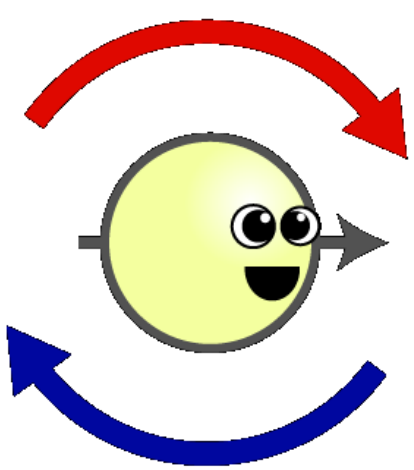
$$\varepsilon^{\mu}_{-} = \frac{1}{\sqrt{2}}(0, 1, -i, 0)$$



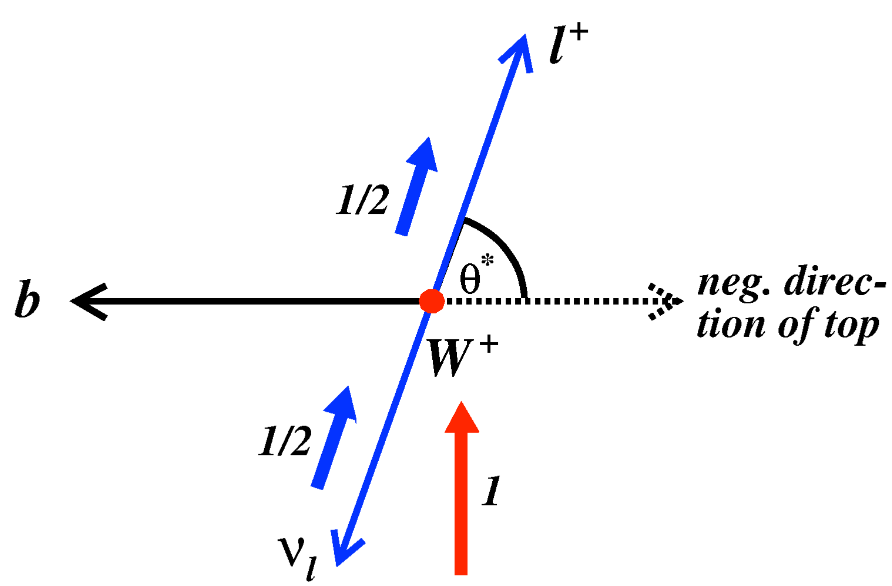
$$\varepsilon^{\mu}_{+} = \frac{1}{\sqrt{2}}(0, 1, i, 0)$$



$$|\mathrm{V}\rangle = (1, \pm 1)$$



$$\varepsilon^{\mu}_{\mathrm{L}} = \frac{1}{m}(p_z, 0, 0, E)$$



Only massive vector bosons have longitudinal polarisations

- e.g. W's produced after a top quark decay acquire mostly (~60%) longitudinal polarisation

see lectures by M. Gallinaro and A. Onofre

…may have unique behavior: $V_L V_L \to V_L V_L$

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

This particular set of processes breaks unitarity for sufficiently large energy

- For $s^{1/2} \simeq 1$ TeV interactions become strong unless underlying mechanism preserves unitarity

…may have unique behavior: $V_L V_L \to V_L V_L$

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

This particular set of processes breaks unitarity for sufficiently large energy

- For $s^{1/2} \simeq 1$ TeV interactions become strong unless underlying mechanism preserves unitarity
- Possibility: an extra interaction with a scalar boson provides necessary cancellations

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

…may have unique behavior: $V_L V_L \rightarrow V_L V_L$

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

This particular set of processes breaks unitarity for sufficiently large energy

- For $s^{1/2} \simeq 1$ TeV interactions become strong unless underlying mechanism preserves unitarity
- Possibility: an extra interaction with a scalar boson provides necessary cancellations

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

- Decomposing the scattering in partial waves (angular momentum decomposition

$$A = 16\pi \sum_{l=0}^{\infty} (2l+1) P_l(cos\theta) a_l \qquad \sigma = \frac{16\pi}{s} \sum_{l=0}^{\infty} (2l+1) |a_l|^2$$

Legendre polynomials

Amplitude for l-th angular momentum wave

- and applying the optical theorem $\sigma = \frac{1}{s}\mathrm{Im}[\mathrm{A}(\theta = 0)] \Rightarrow |\mathrm{Re}(a_\ell)| < \frac{1}{2}$

…may have unique behavior: $V_L V_L \to V_L V_L$

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

This particular set of processes breaks unitarity for sufficiently large energy

- For $s^{1/2} \simeq 1$ TeV interactions become strong unless underlying mechanism preserves unitarity
- Possibility: an extra interaction with a scalar boson provides necessary cancellations

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

- Decomposing the scattering in partial waves (angular momentum decomposition

$$A = 16\pi \sum_{l=0}^{\infty} (2l+1) P_l(cos\theta) a_l \qquad \sigma = \frac{16\pi}{s} \sum_{l=0}^{\infty} (2l+1) |a_l|^2$$

Legendre polynomials

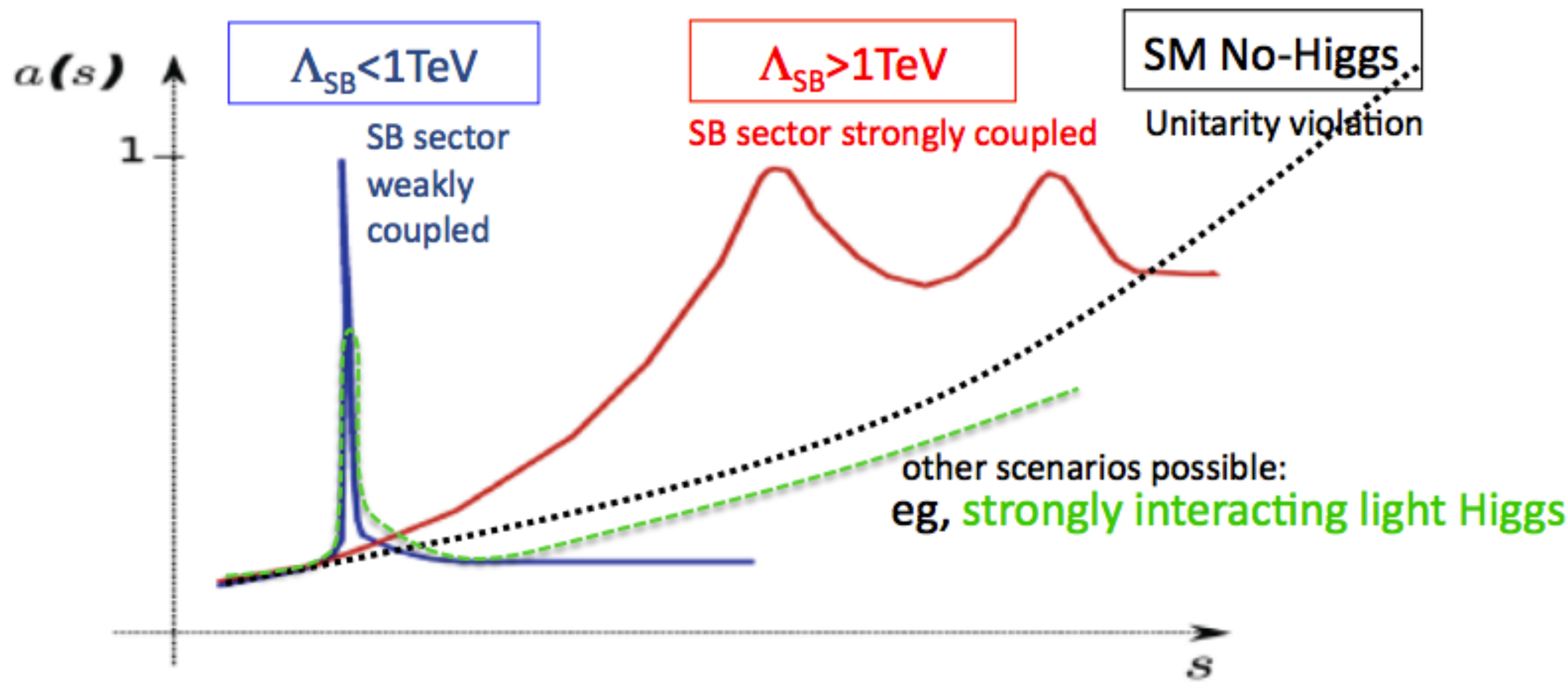
Amplitude for l-th angular momentum wave

- and applying the optical theorem $\sigma = \frac{1}{s}\mathrm{Im}[\mathrm{A}(\theta = 0)] \Rightarrow |\mathrm{Re}(a_\ell)| < \frac{1}{2}$
- which bounds the mass of the scalar $a_0 \xrightarrow{s \gg M_H^2} -\frac{M_H^2}{8\pi v^2} \Rightarrow \boxed{M_H < 870 \text{ GeV}}$

Possible scenarios for (longitudinal) vector boson scattering

- Depending on the nature of the scalar (or would it be absent)
  - the scattering of vector bosons may be resonant, non-resonant, reveal strong behavior at large $s^{1/2}$

⇒ we need to scan a large energy range to test the mechanism which breaks EWK symmetry



The missing piece of the standard model

The Higgs mechanism

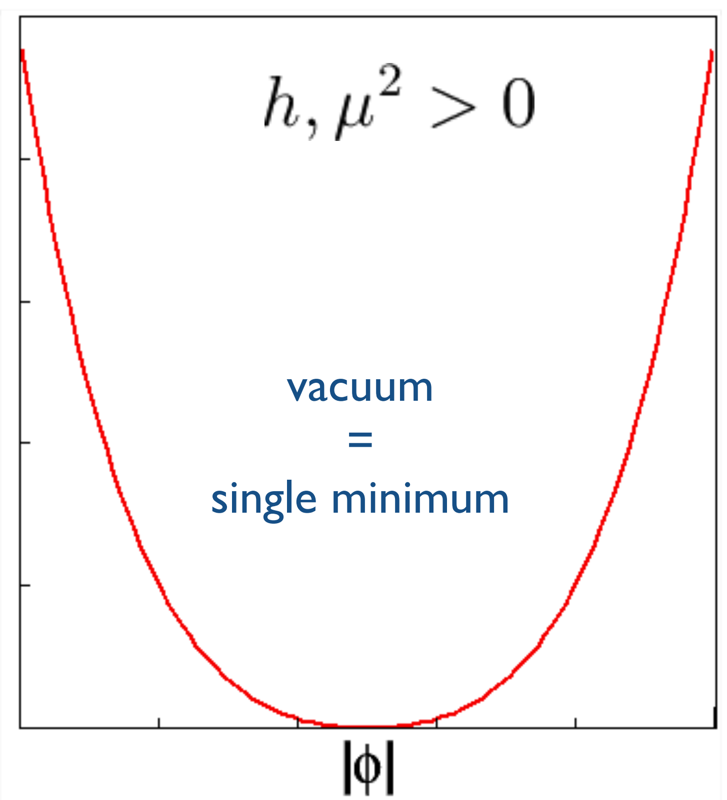
- **A new SU(2) doublet of spin-0 particles is added to the lagrangian**
  - 4 new degrees of freedom: doublet + anti-particles
  - write down the interactions

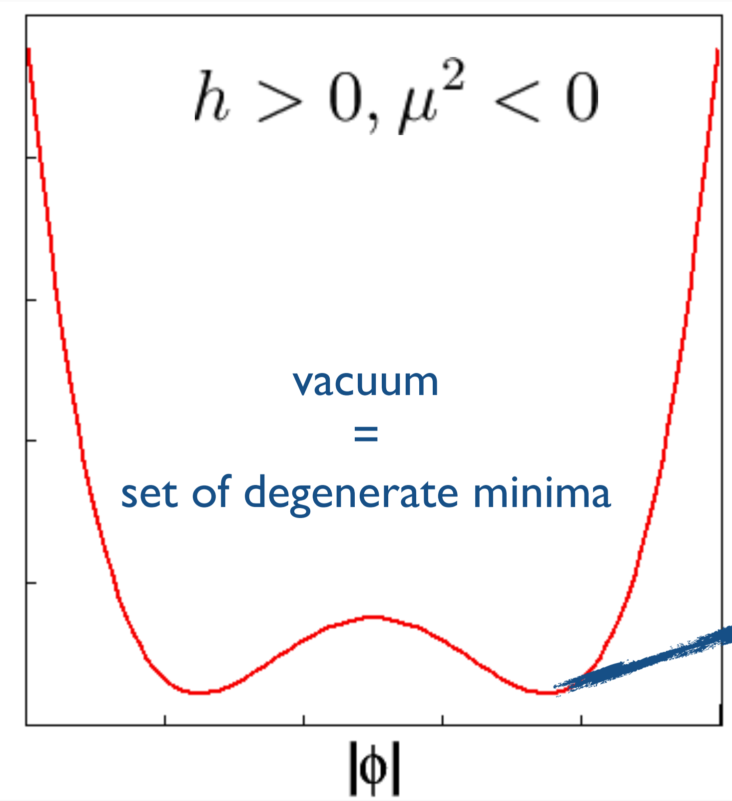
$$\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} \quad \begin{pmatrix} \varphi^- \\ \varphi^{*0} \end{pmatrix}$$

$$\mathcal{L}_{\text{higgs}} = \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi)$$

where V is a phase-symmetric potential

$$V(\phi) = \mu^2 |\phi|^2 + h|\phi|^4$$





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

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

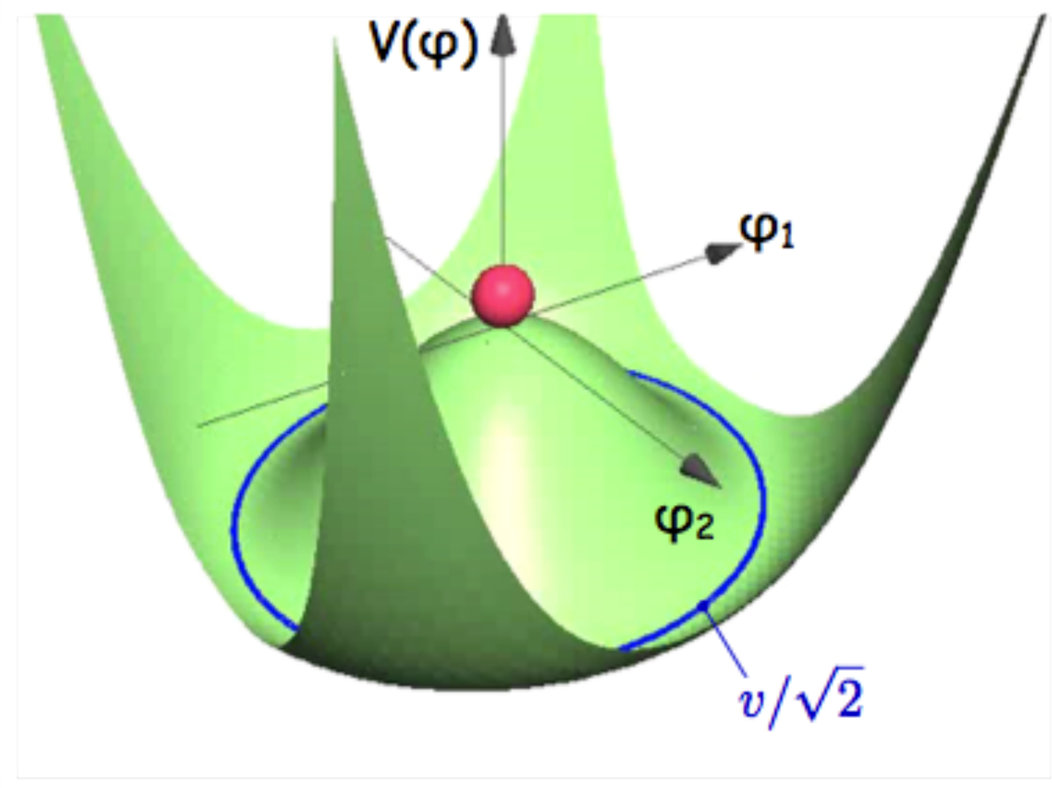
Higgs field potential

- Given the symmetry of the potential we are allowed to parameterise the field in polar form

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

- If you substitute this into the Lagrangian

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



where, by construction, the potential is independent of φ_2

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

φ_2 is masseless
(≡Goldstone boson)

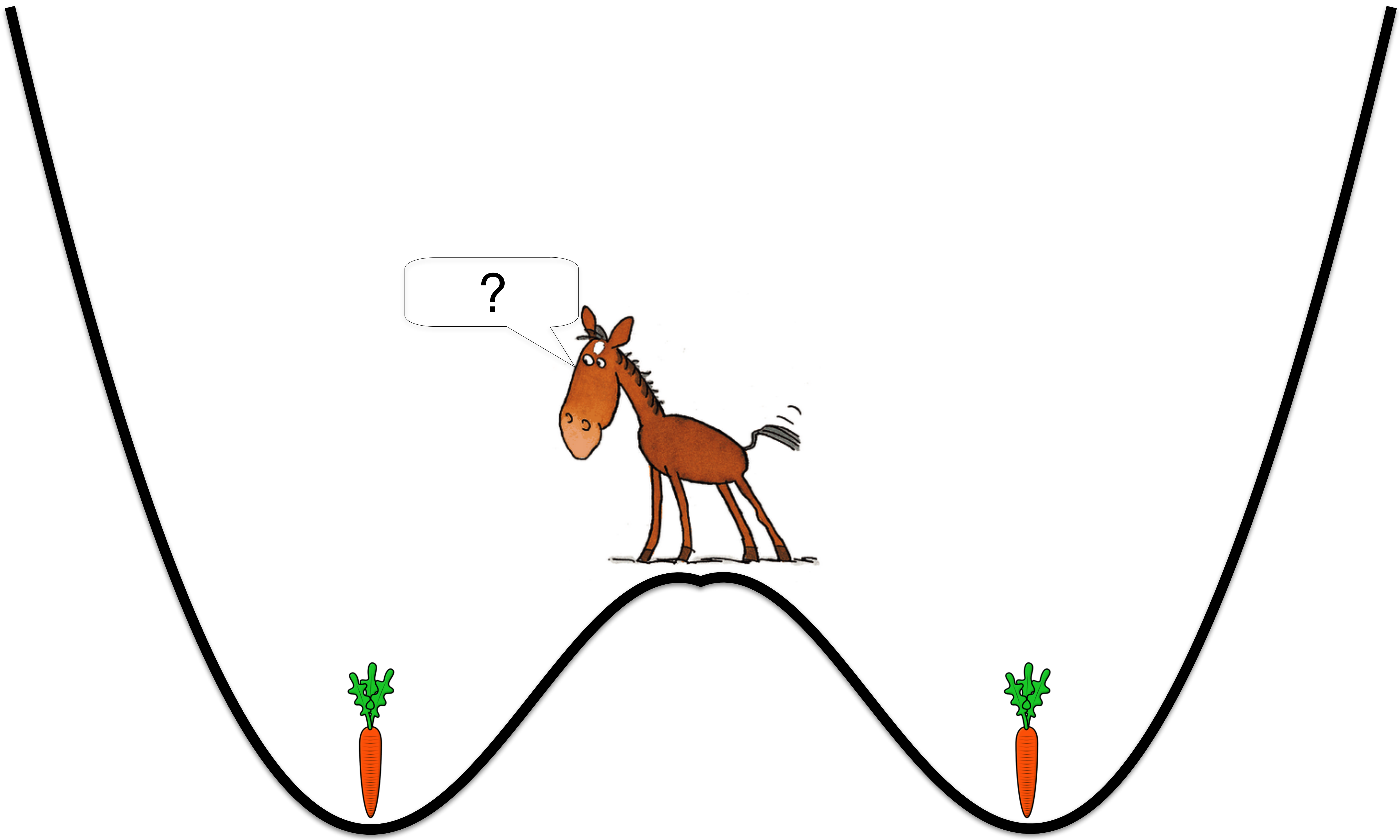
mass of the field

self-interaction of the field
(quartic coupling)

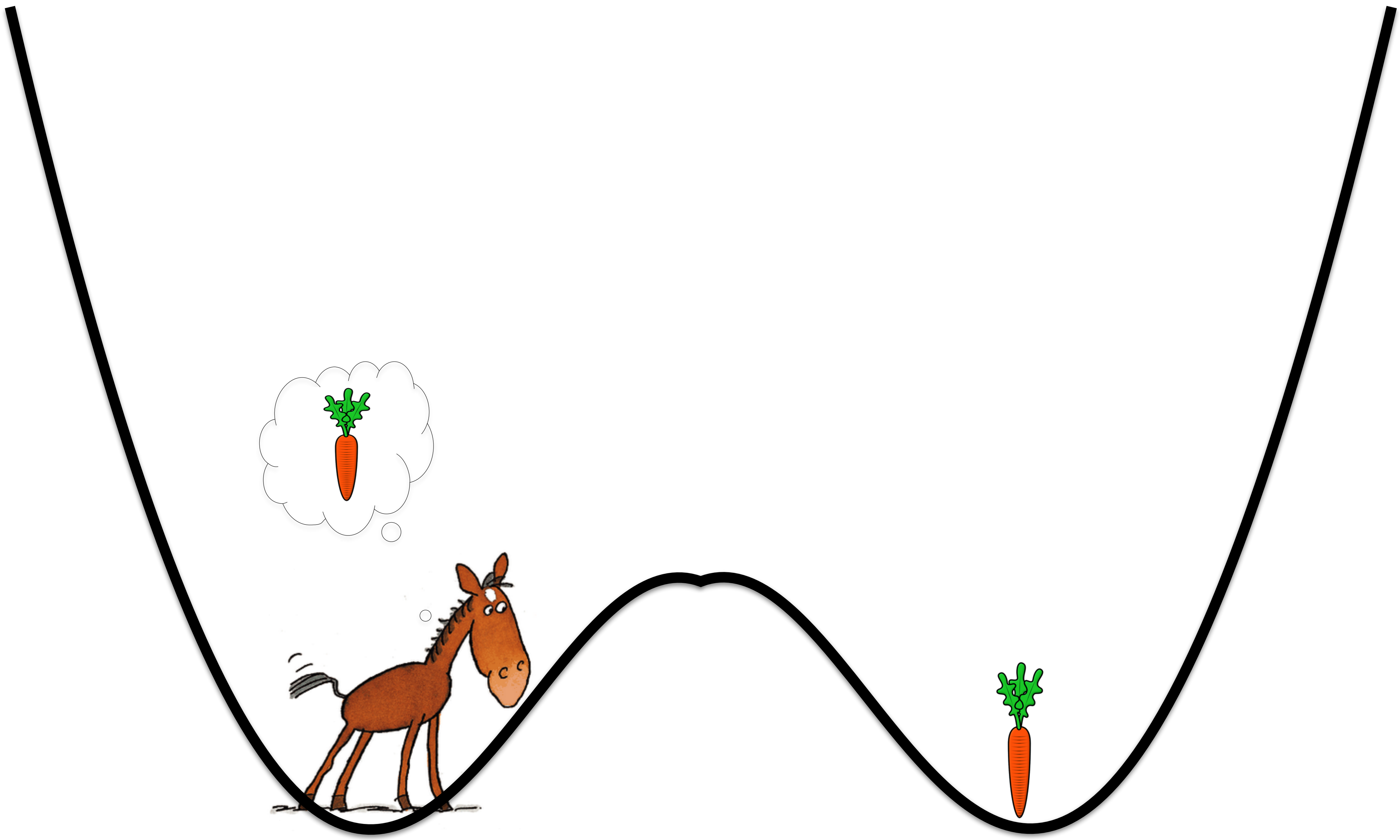
What about other SM fields?

- The **new field is a doublet in SU(2)**
- Therefore it interacts with the electroweak bosons
- In the lagrangian $\partial_\mu \quad \rightarrow \quad D_\mu$
- but I imagine you have had too much formulae at this point, so let's do it differently…

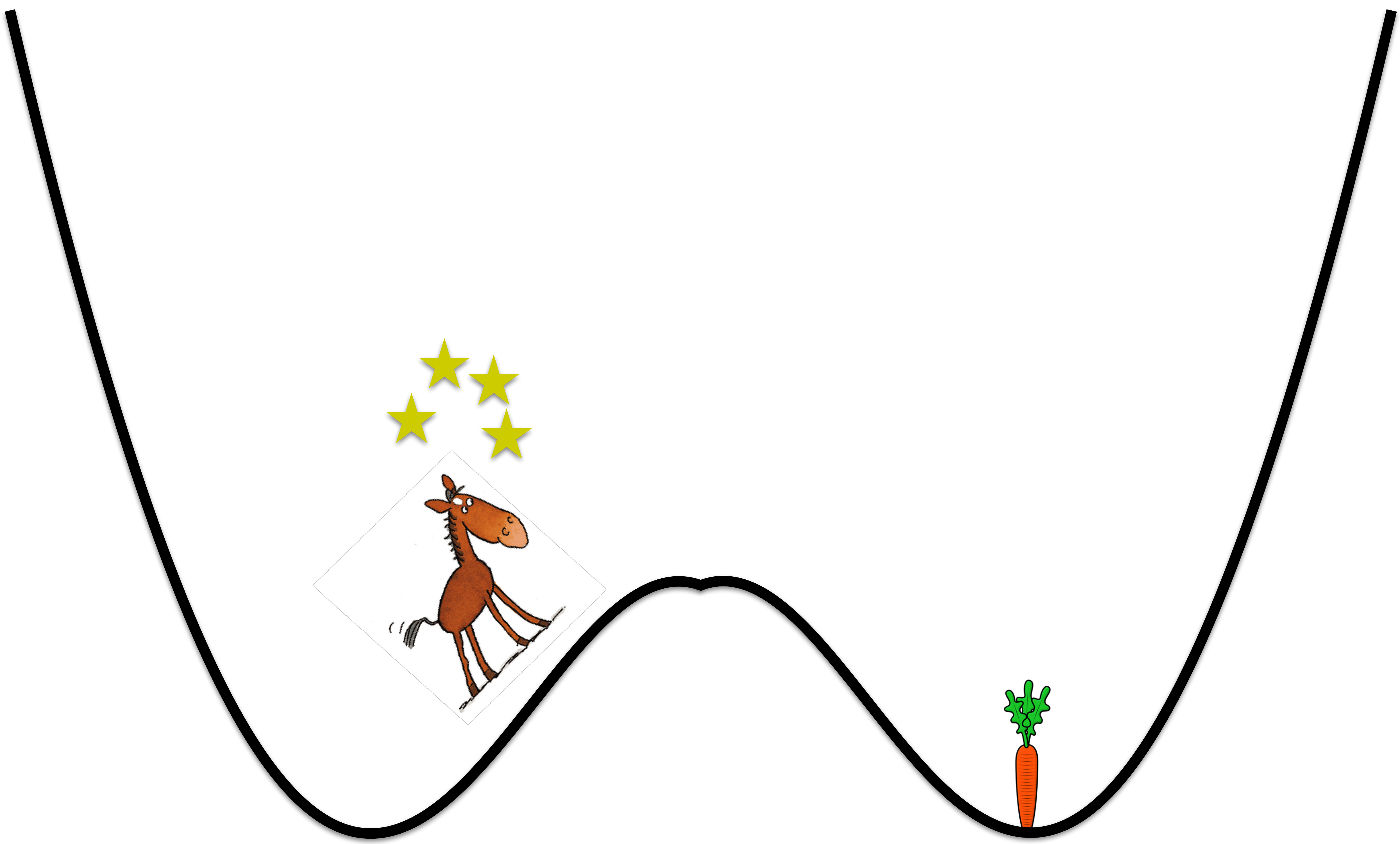
The Higgs mechanism



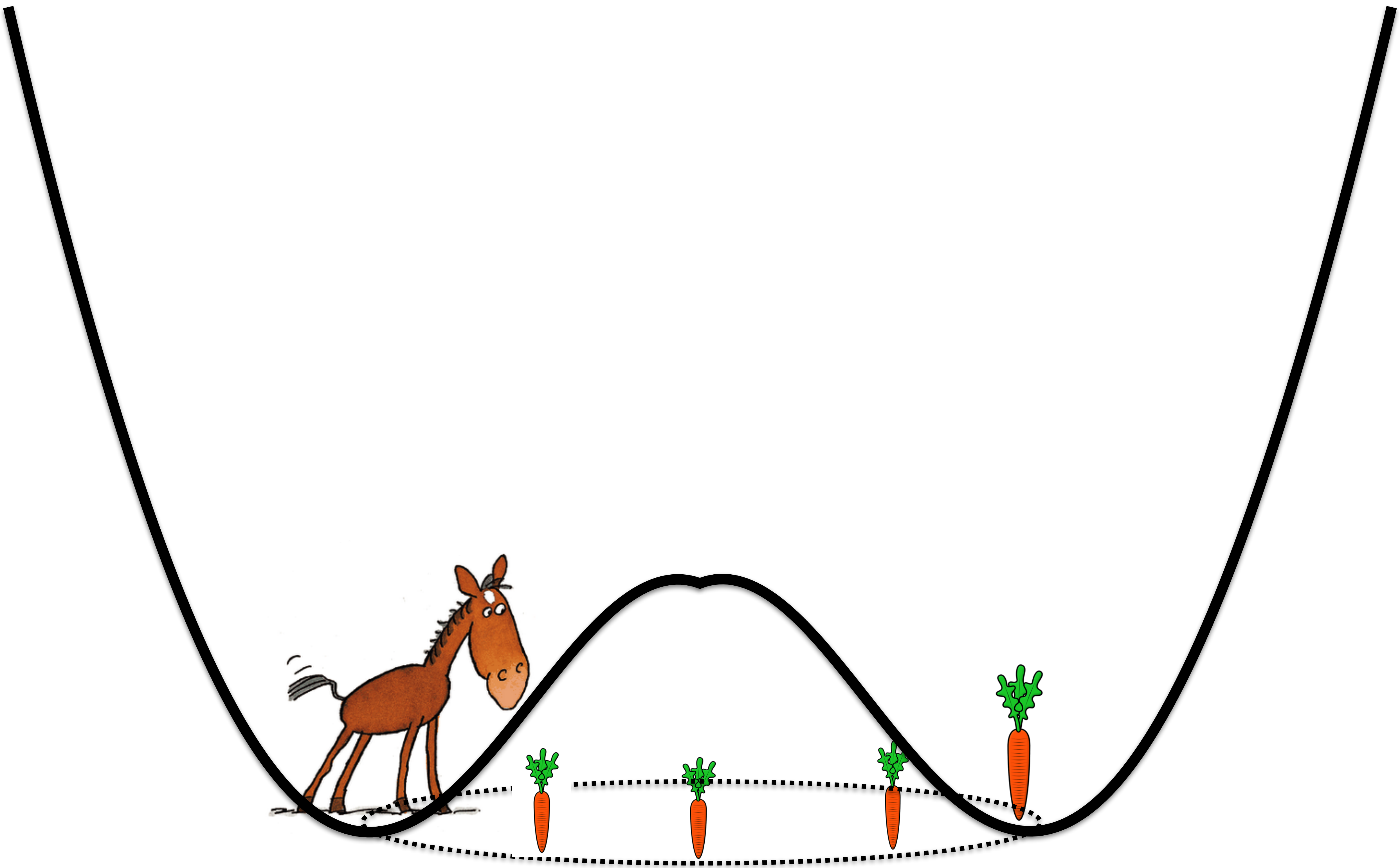
The Higgs mechanism



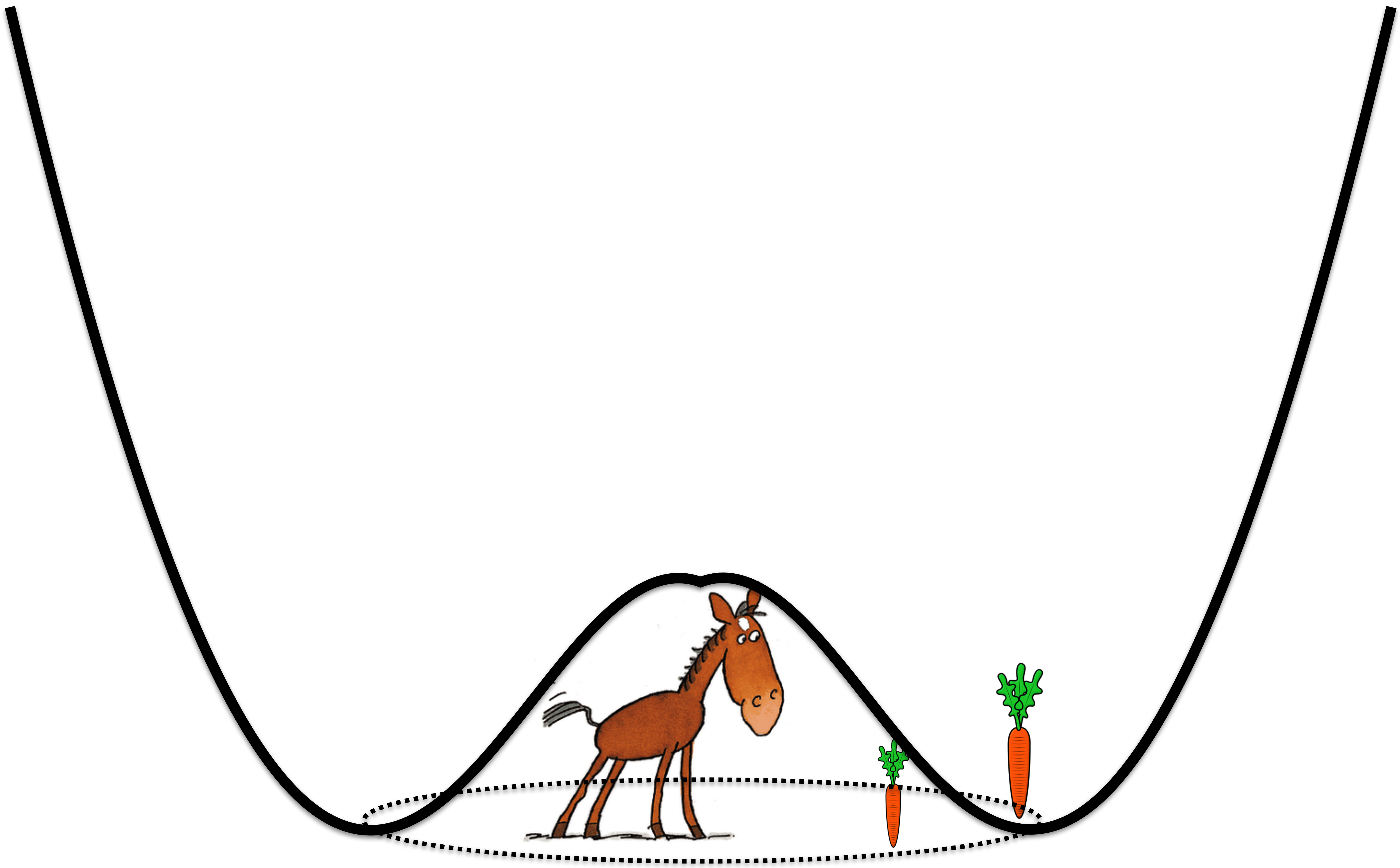
The Higgs mechanism



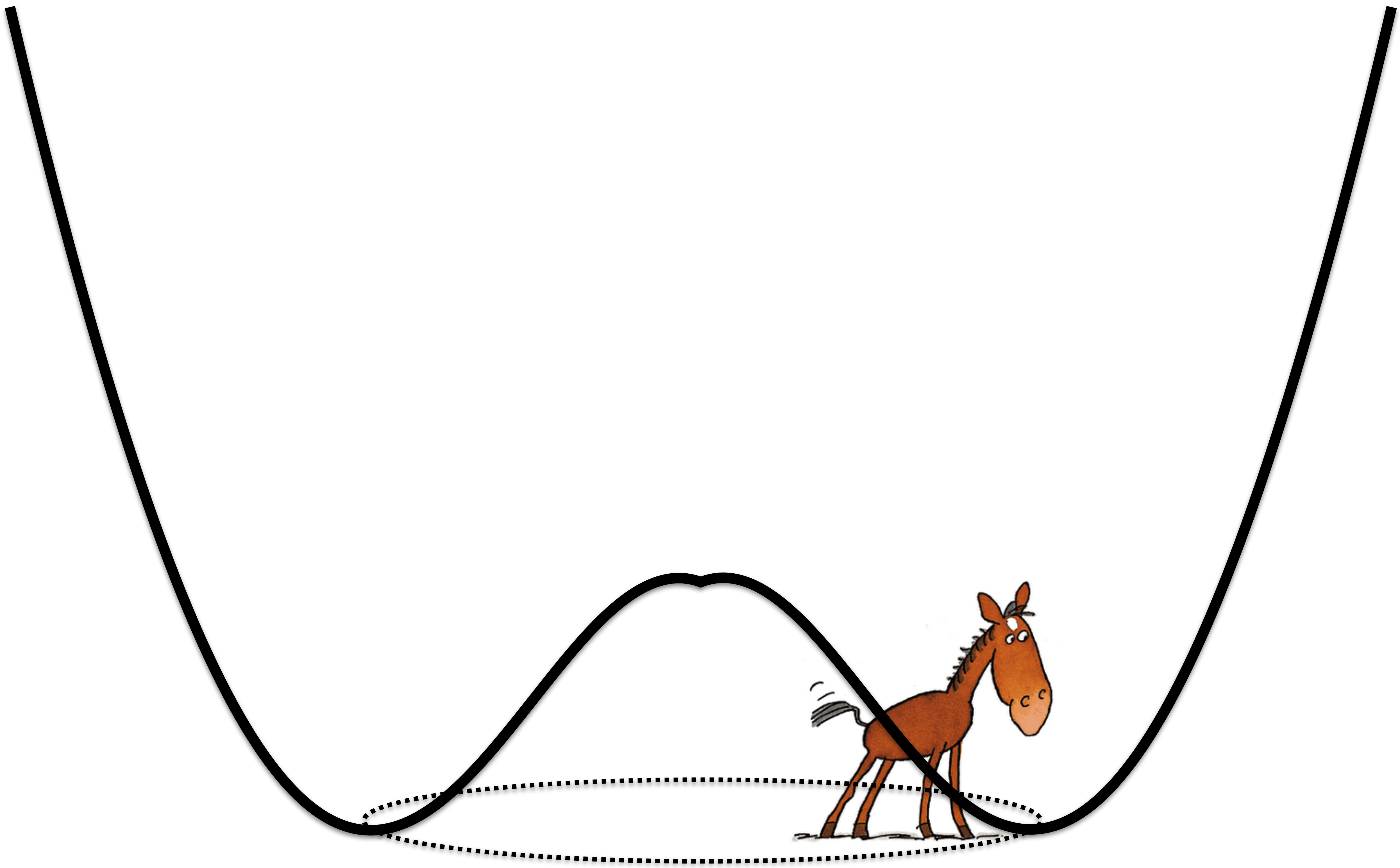
The Higgs mechanism



The Higgs mechanism



The Higgs mechanism



The Higgs mechanism: EWK symmetry breaking

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

- Both **the W and the Z boson acquire mass**
  - the $W^\pm$ interact with the $\varphi^\pm$, the Z^0 interacts with the φ^0
  - by these means the $W^\pm$ and the Z^0 become massive and acquire 3 polarisation states

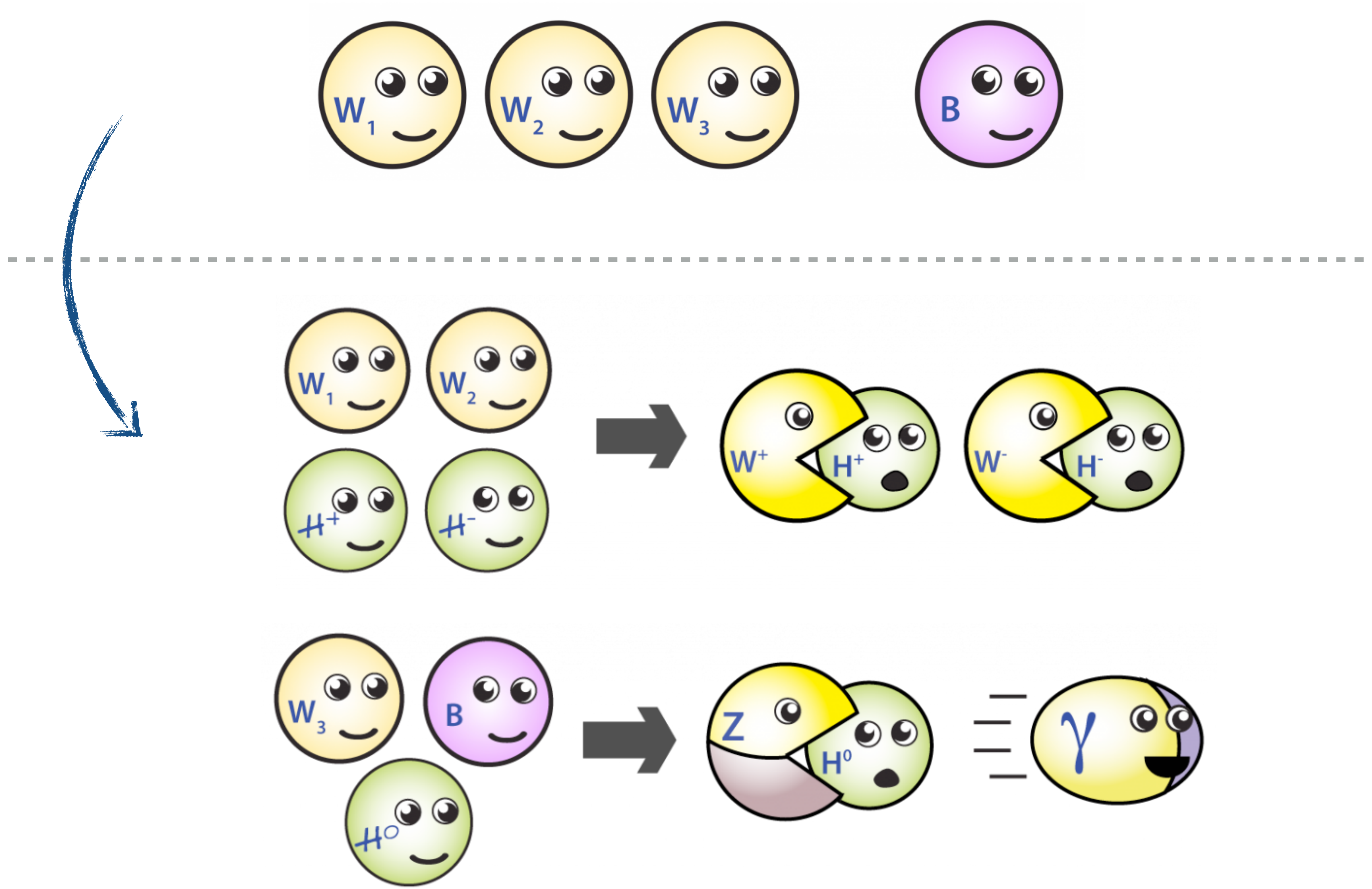
electroweak symmetry has been spontaneously broken

  - Note: the photon (and the gluons) do not mix with any of these states: they are massless

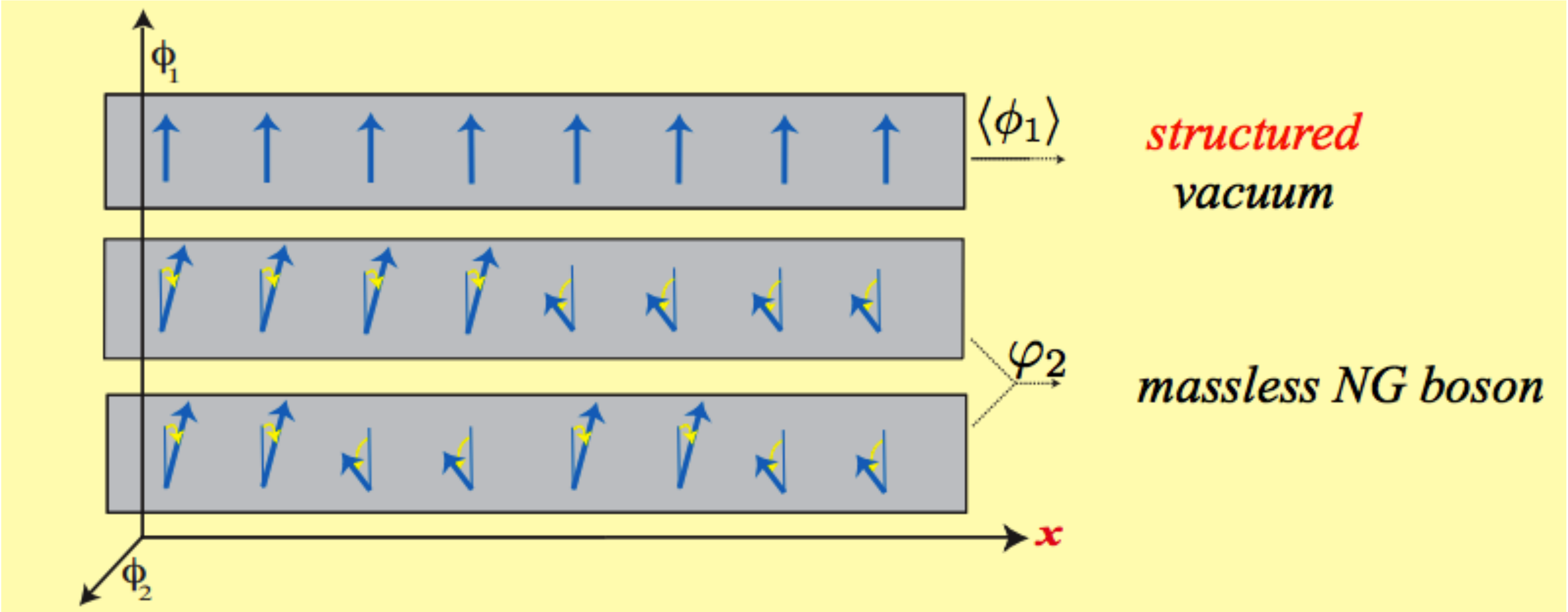
- As a consequence: the W and Z masses are related amongst themselves

$$M_Z \ \cos\theta_W = M_W = \frac{1}{2}vg$$

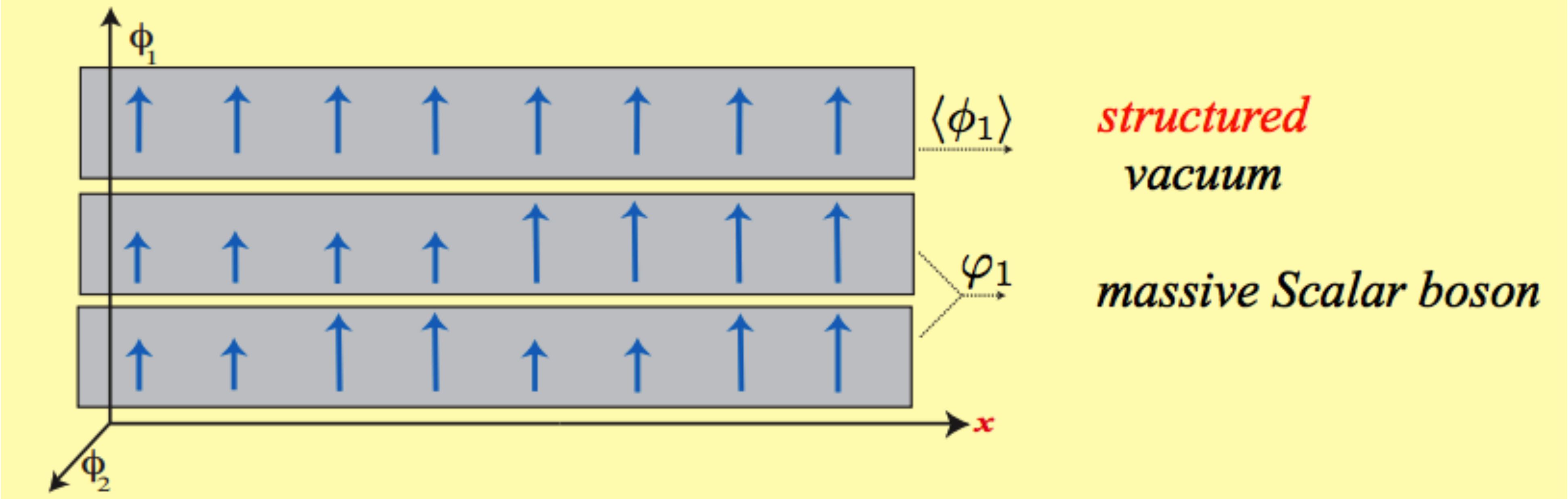
EWK symmetry breaking



Original idea behind the Higgs mechanism (slide from F. Englert)



▶ characterizes a continuous SSB



▶ measures the rigidity of the vacuum

The proponents

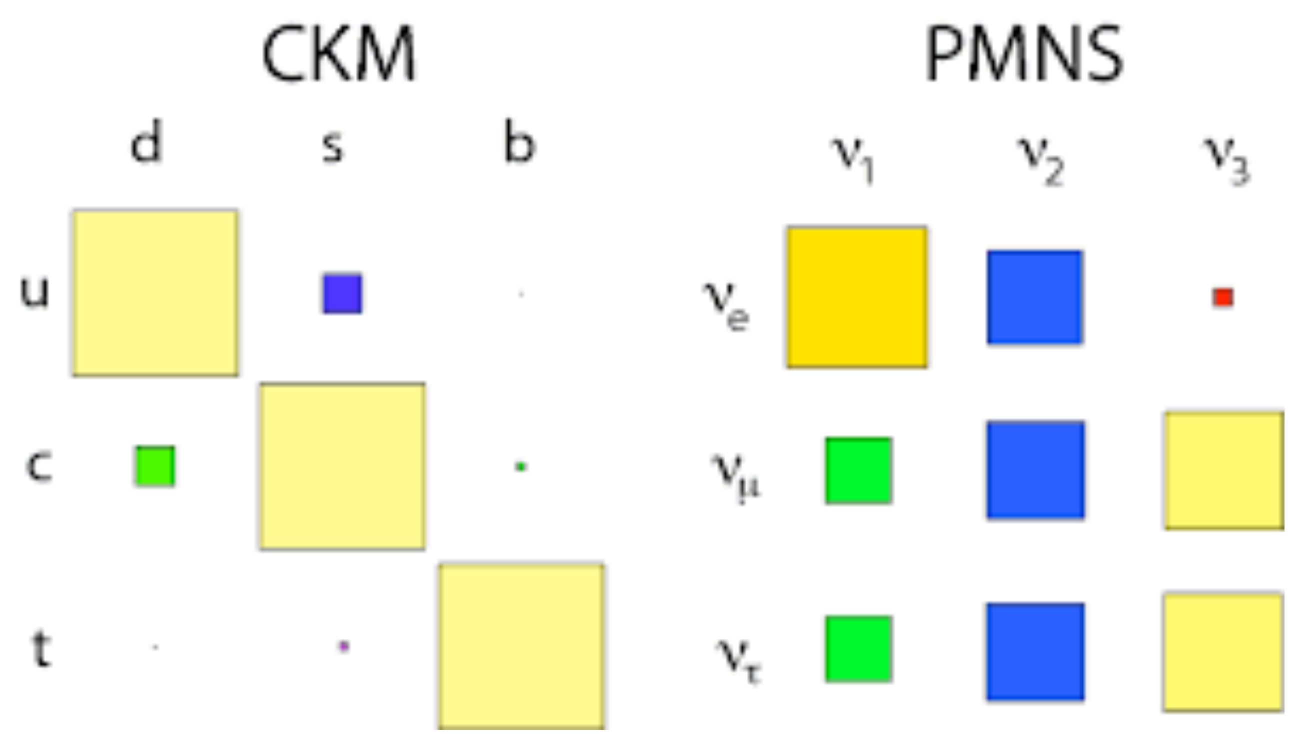
F. Englert and R. Brout PRL 13-[9] (1964) 321
P.W. Higgs PL 12 (1964) 132 and PRL 13-[16] (1964) 508
G.S. Guralnik, C.R. Hagen and T.W.B. Kibble PRL 13-[20] (1964) 585

Giving mass to fermions

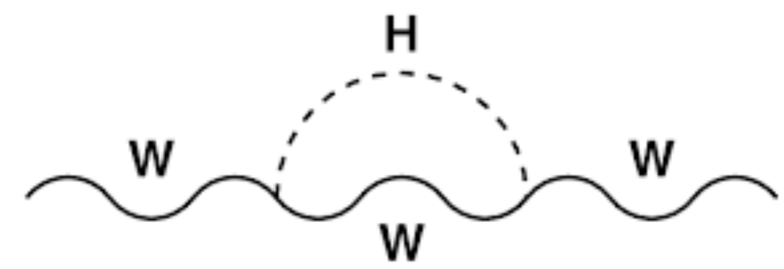
- Yukawa-type of couplings are gauge invariant
  - can add arbitrary mass terms to the lagrangian giving mass to the fermions
  - result in 3x3 matrices, non-diagonal, complex, with free constants

$$\mathcal{L}_Y = \bar{Q}_L \left[c^d \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} D_R + c^u \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} D_R \right] \rightarrow \mathcal{L}_Y = -(1 + \frac{H}{v})(\bar{q}_d M_d q_d + \bar{q}_u M_u q_u)$$

- Notice however that the mass eigenstates are not necessarily the flavour eigenstates
  - this leads to mixing in EWK interactions



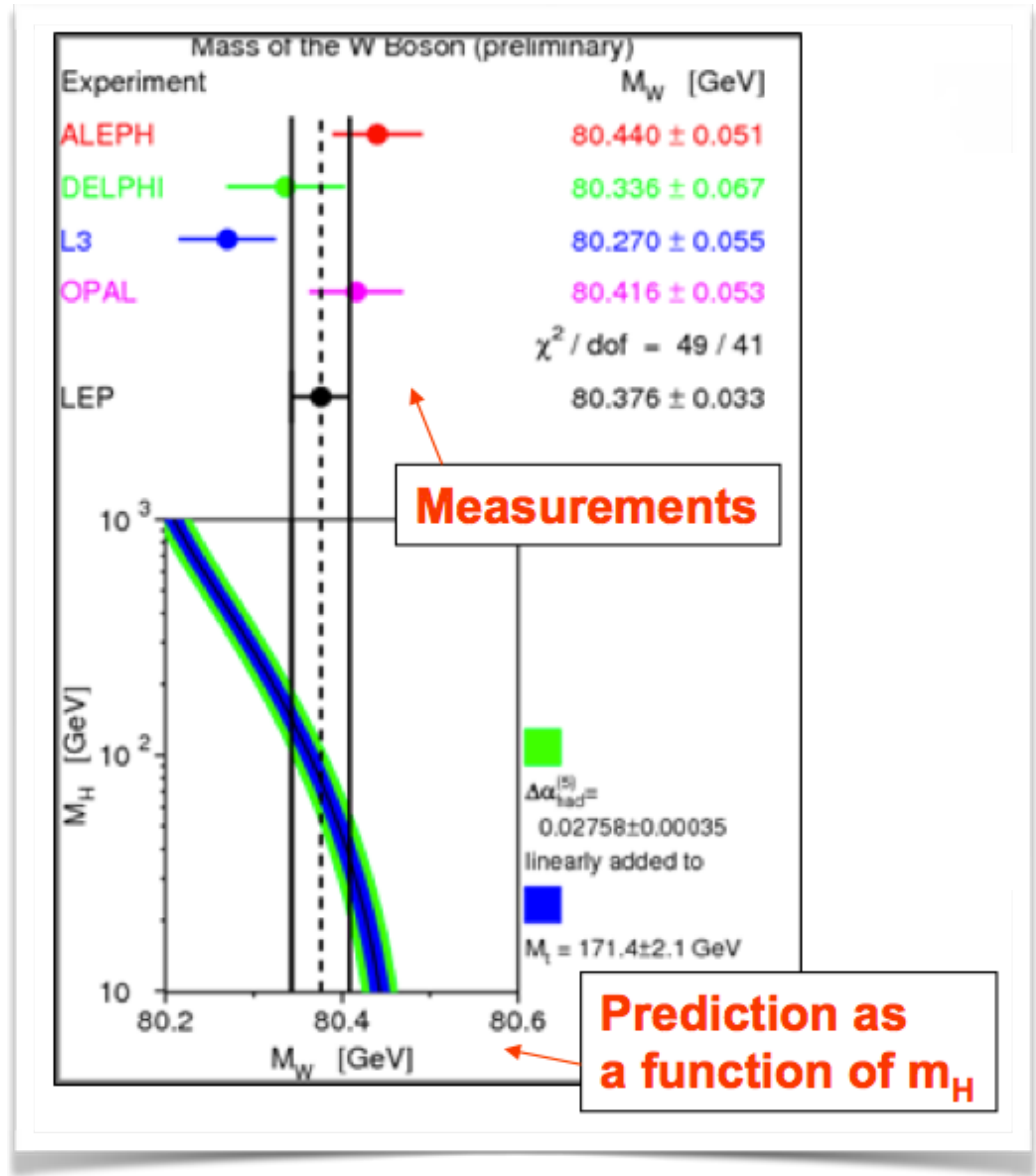
The Higgs mass



- It is not predicted in the SM
  - but it can be related directly or via loops to the mass of known particles and other observables
  - before the top quark was found→
  - including the top, precision measurements yield

$$M_H = 89^{+22}_{-18}\ \mathrm{GeV}$$

(see PDG, GFitter)

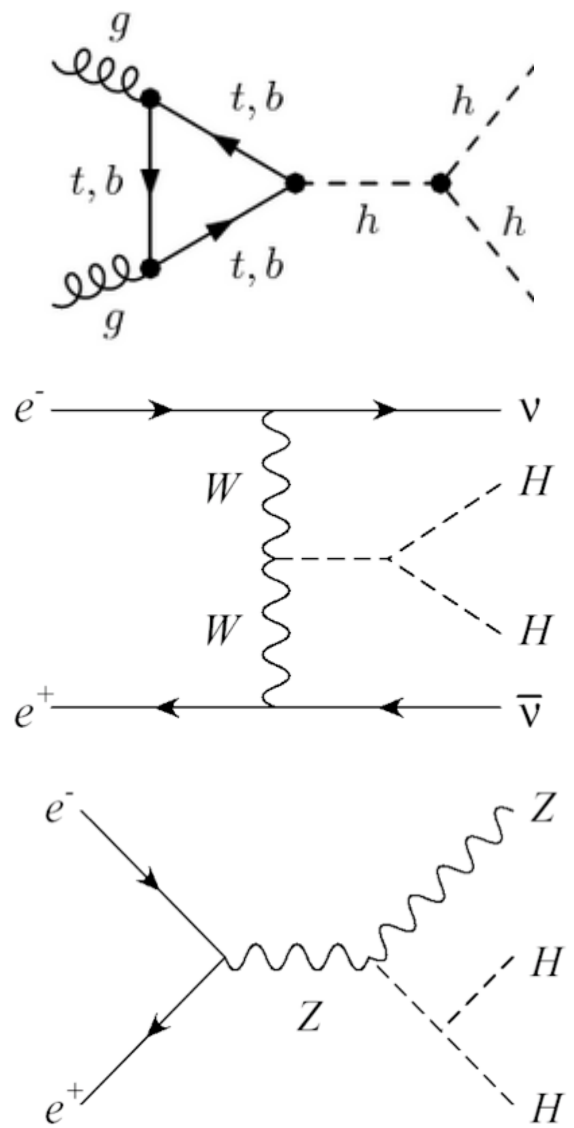


A note on the Higgs self-coupling

Drives the stability of the Higgs potential

- Knowing the Higgs mass, and the vacuum expectation value we know it - *see slides* *29,30*

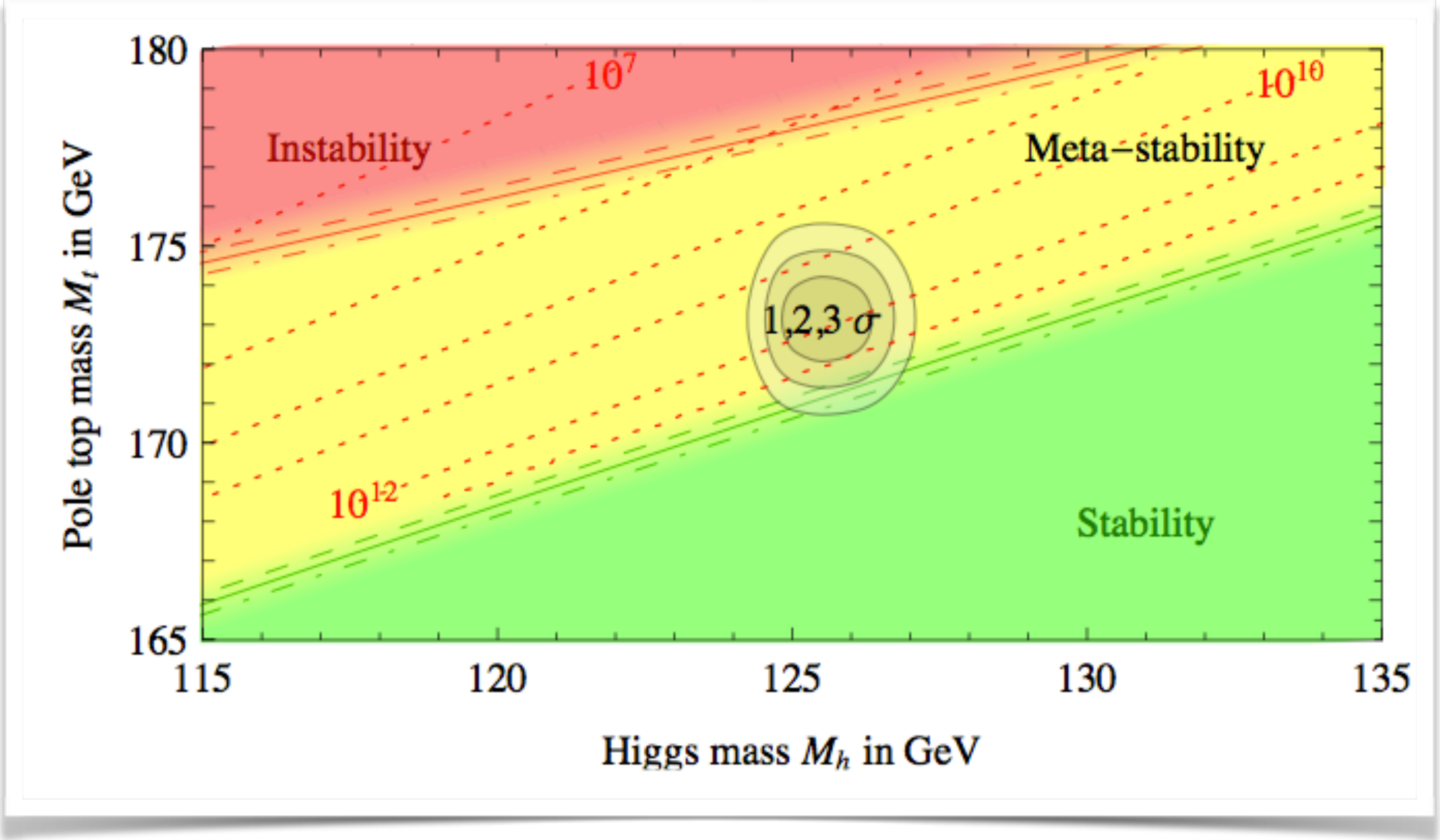
- We can **measure it from rare processes where h →hh**



- Alternatively **test if the SM consistent at higher scales**

→ depending on the top mass the universe might be unstable

see JHEP 1208 (2012) 098

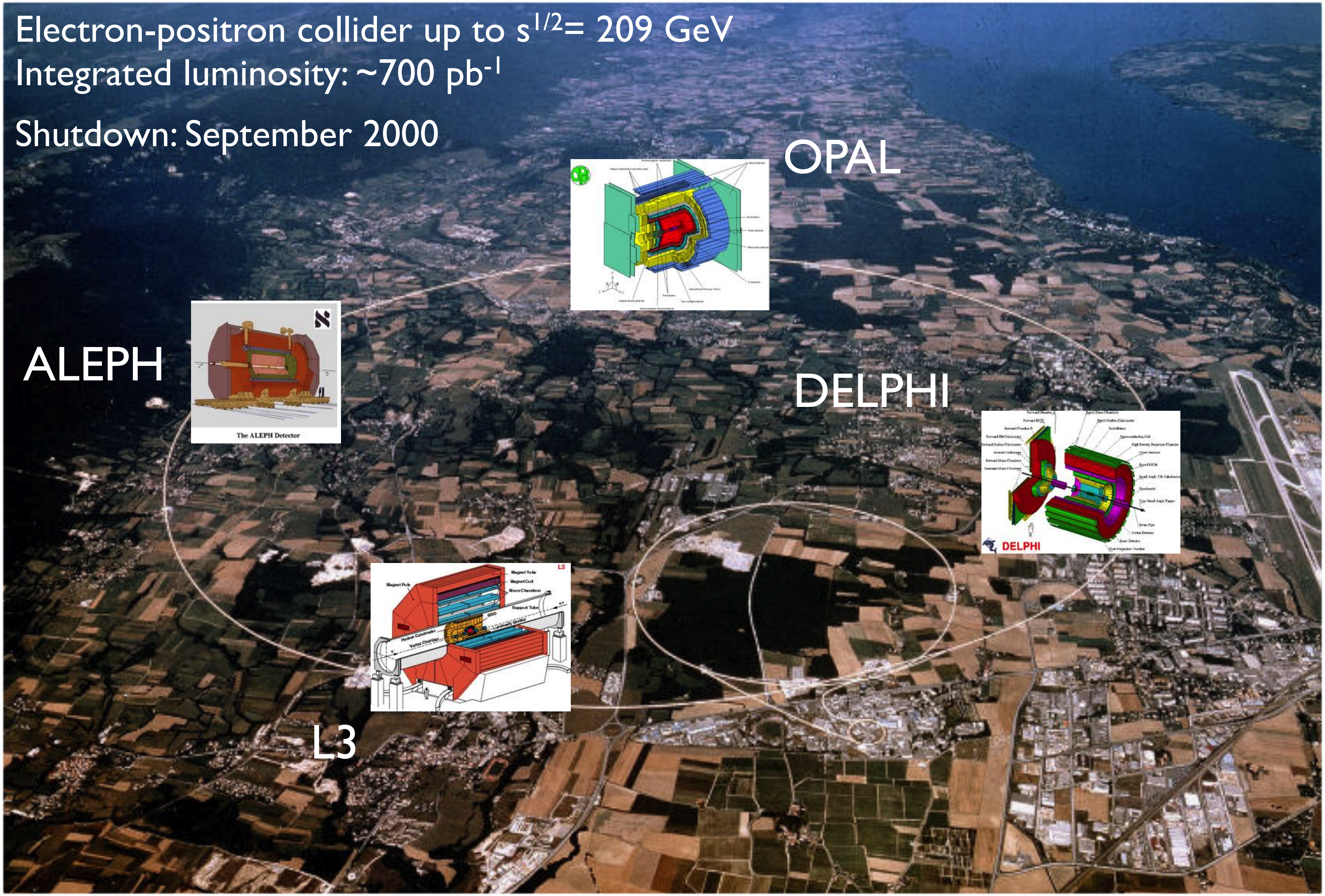


Hunting the Higgs boson in particle colliders

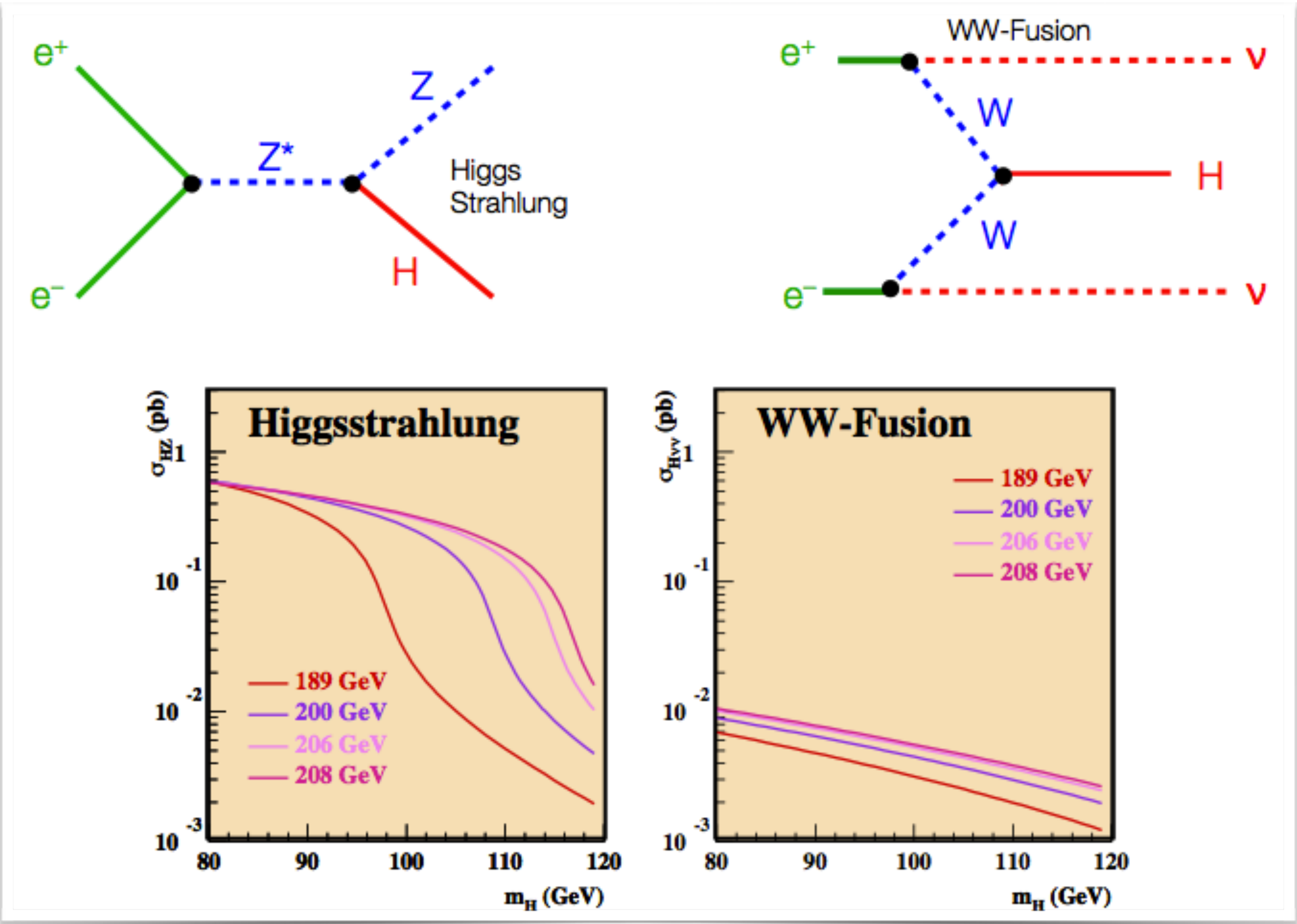
It has been searched for at LEP....

Electron-positron collider up to $s^{1/2}$= 209 GeV
Integrated luminosity: ~700 pb^{-1}

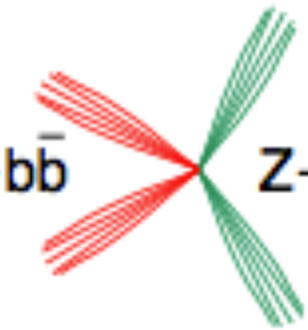
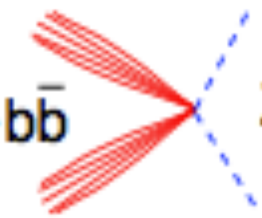
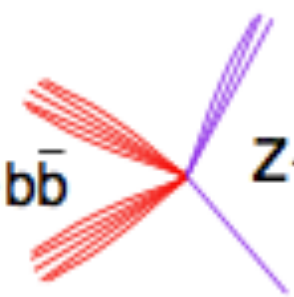
Shutdown: September 2000



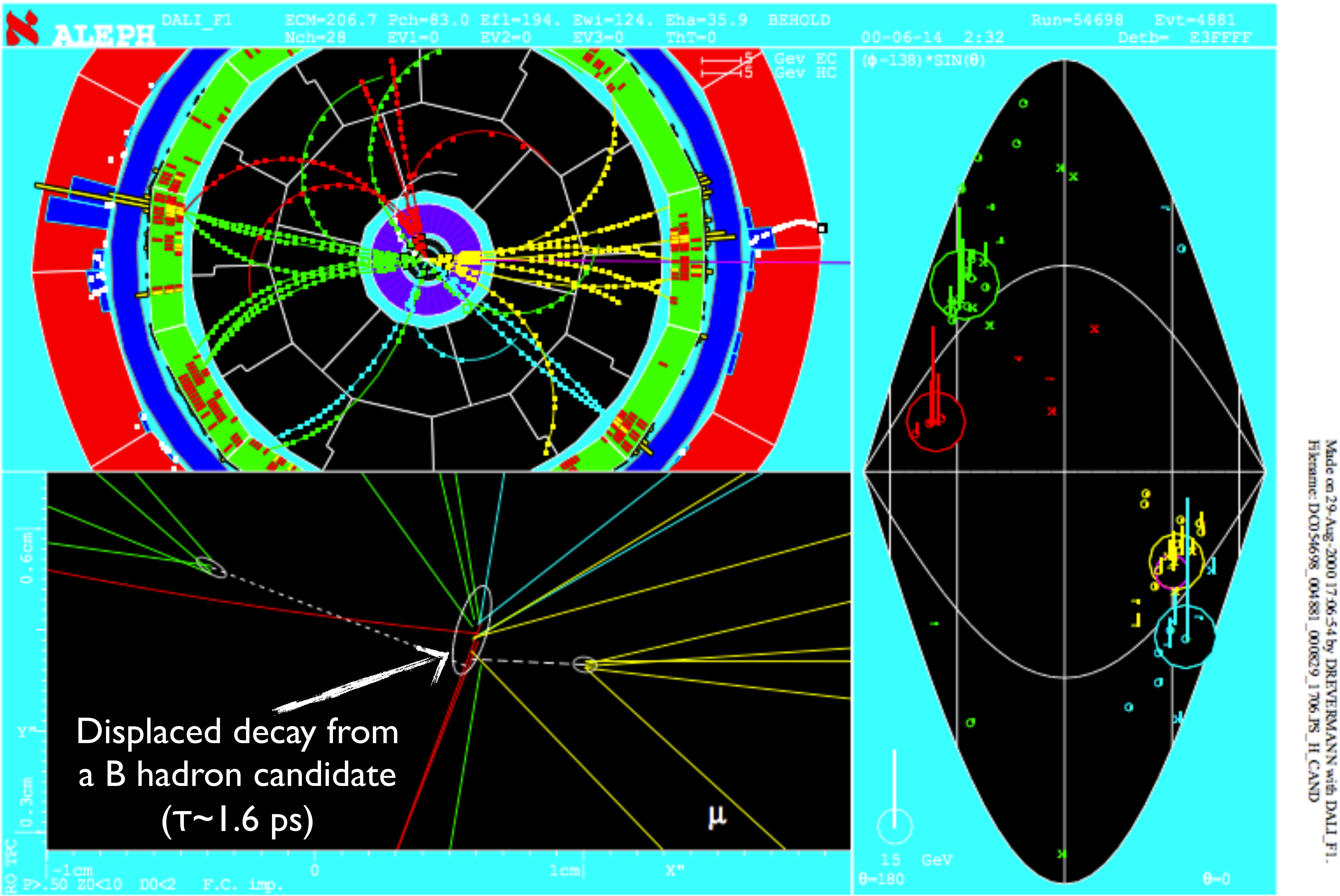
Higgs production at LEP



At LEP: look for 3rd generation decays

$H\to b\bar{b}$  $Z\to q\bar{q}$		4-jets	51%	$WW\to qqqq$ $ZZ\to qqqq$ QCD 4-jets
$H\to b\bar{b}$  $Z\to\nu\bar{\nu}$		missing energy	15%	$WW\to qql\nu$ $ZZ\to bb\nu\nu$
$H\to b\bar{b}$  $Z\to\tau^+\tau^-$		τ-channel	2.4%	$WW\to qq\tau\nu$ $ZZ\to bb\tau\tau$ $ZZ\to qq\tau\tau$ QCD low mult. jets
$H\to\tau^+\tau^-$  $Z\to q\bar{q}$		τ-channel	5.1%	
$H\to b\bar{b}$  $Z\to e^+e^-$, $\mu^+\mu^-$		lepton channel	4.9%	$ZZ\to bbee$ $ZZ\to bb\mu\mu$

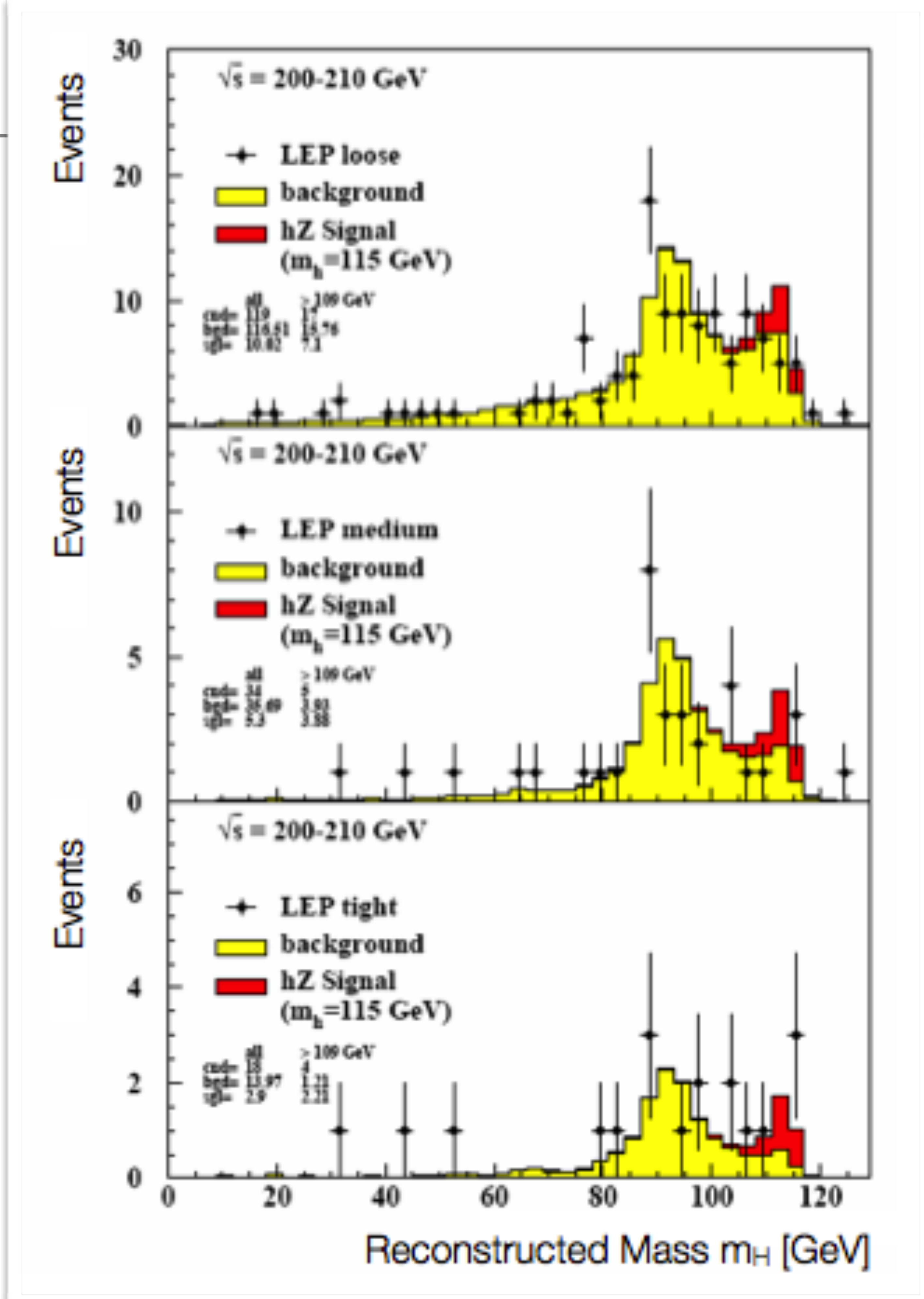
LEP H → bb candidate



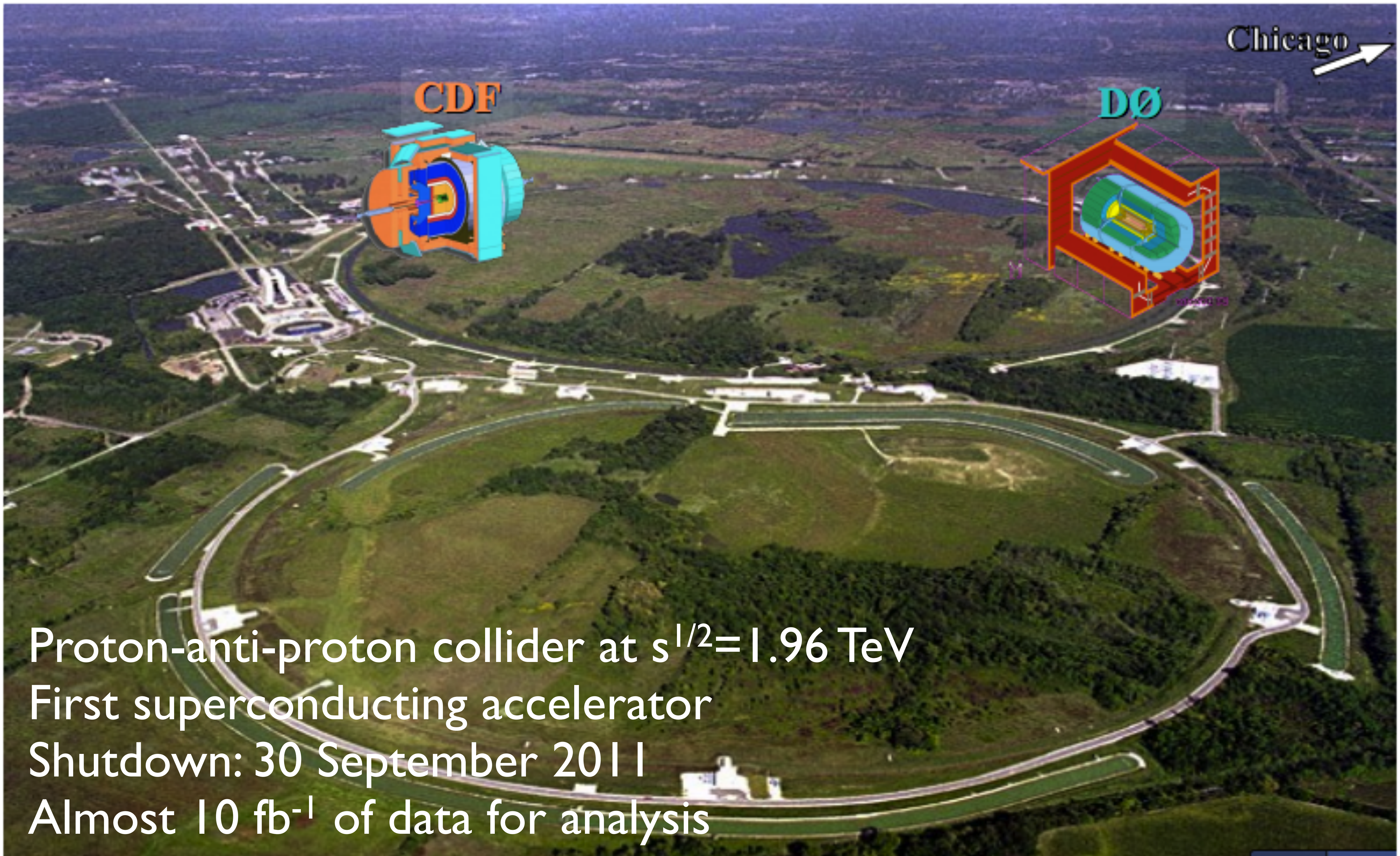
Summary of all Higgs candidates found at LEP

- Invariant mass of all candidates
- In total 17 candidates selected
  - 15.8 background events expected
- Expectation for m_H=115 GeV
  - 8.4 events
- **Corresponding excess was not observed**
- Final verdict from LEP

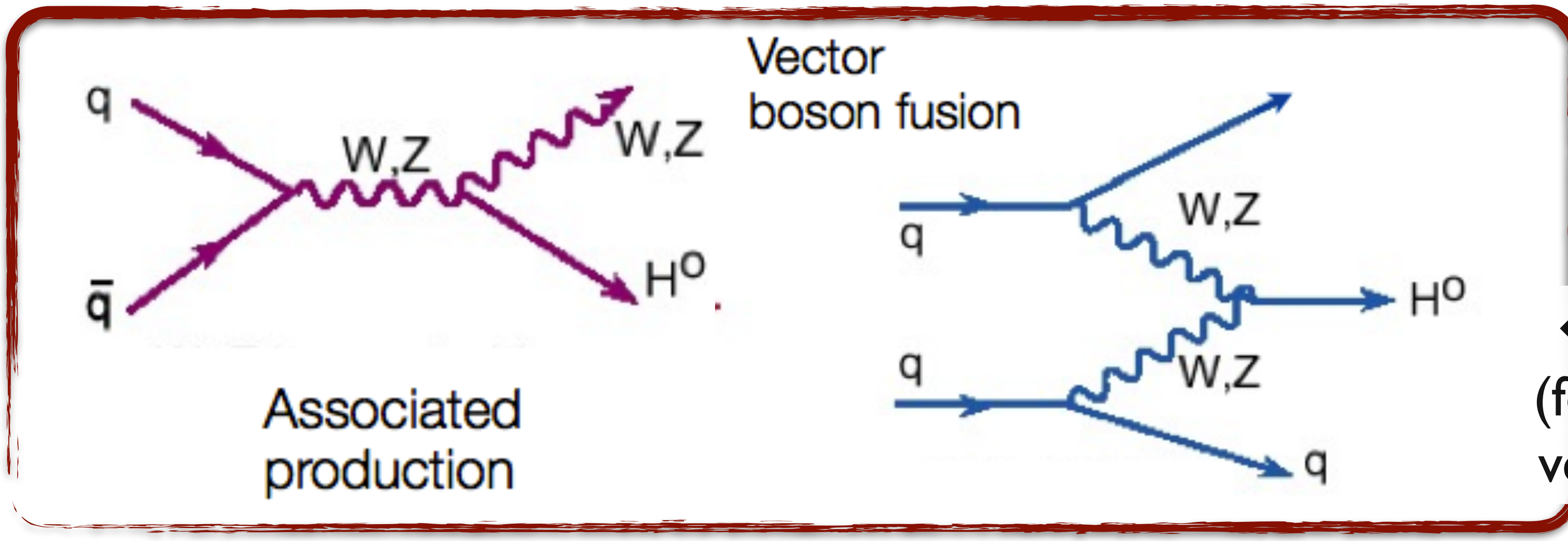
m_H>114.4 GeV @ 95% CL



...and searched for at the Tevatron...

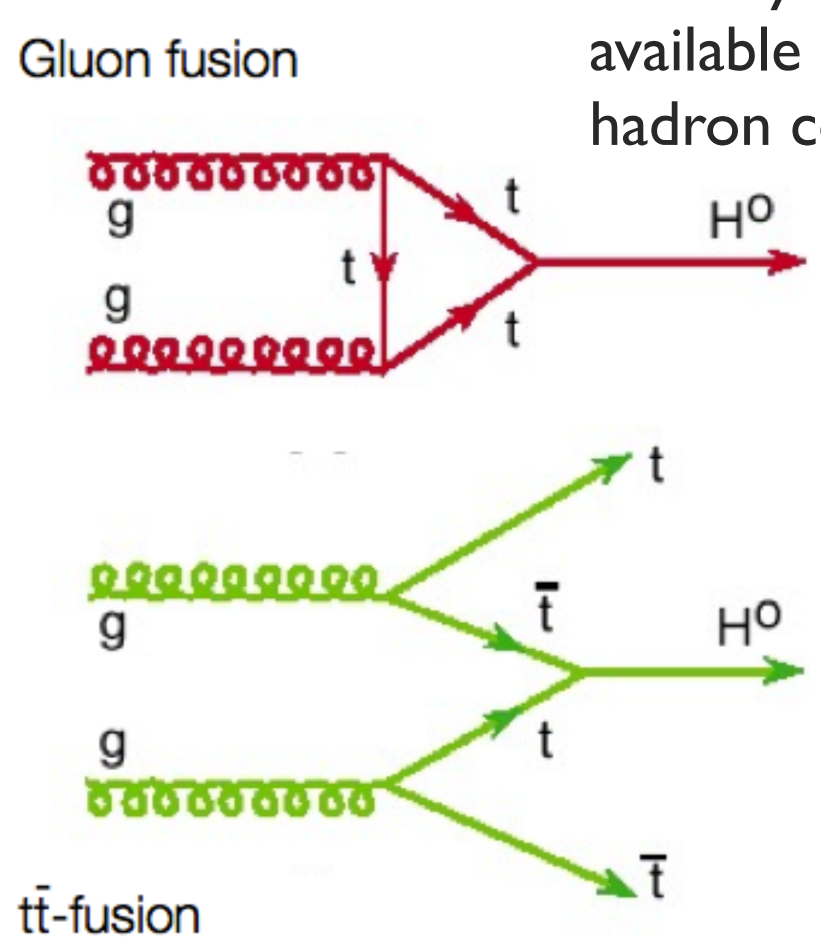


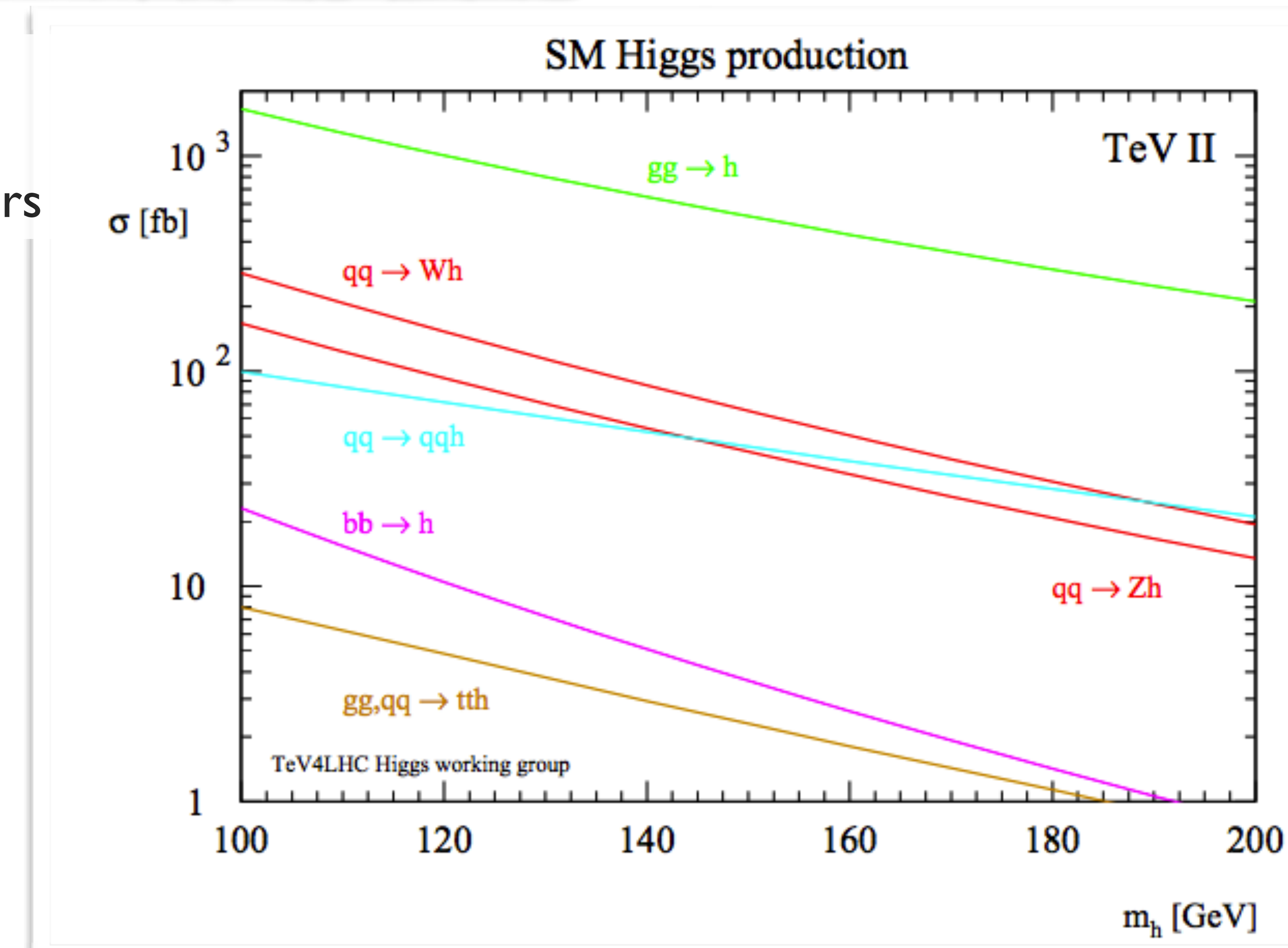
Higgs production in hadron colliders



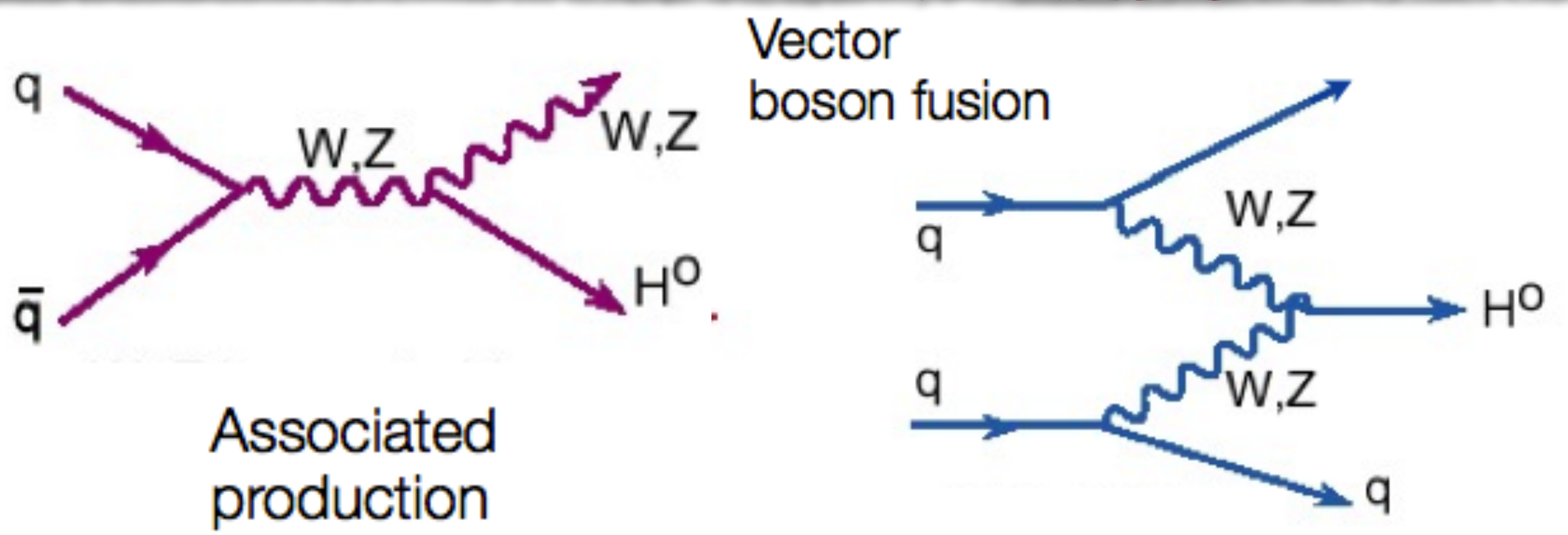
← (fermion annihilation and vector boson scattering)

← Only available at hadron colliders



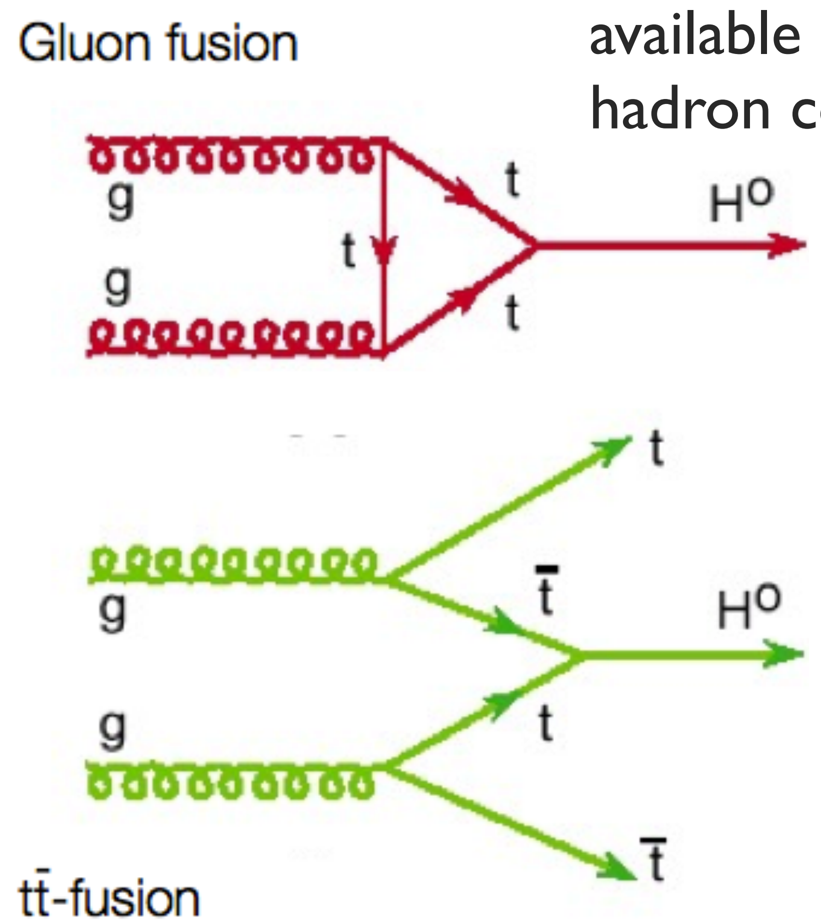


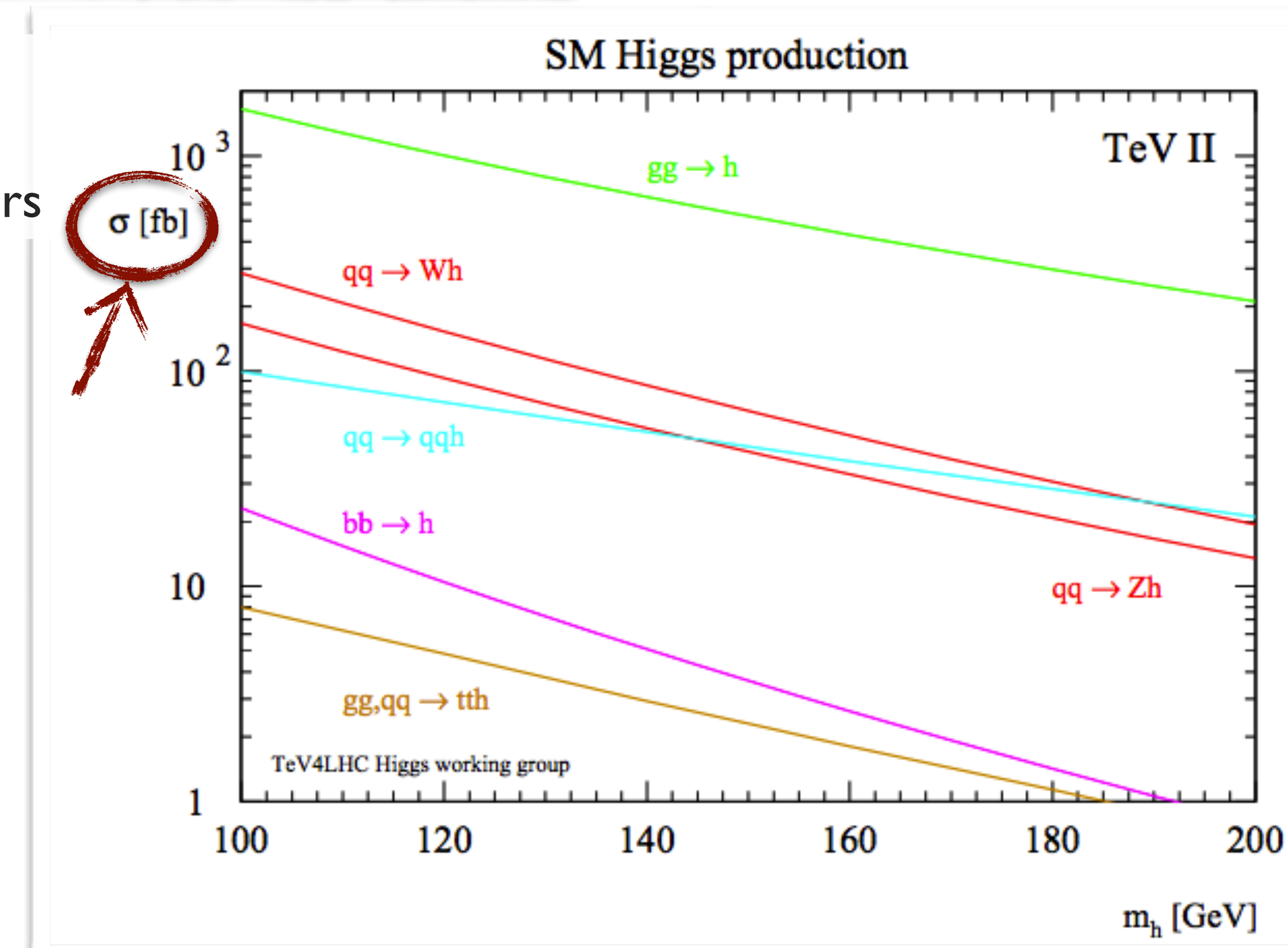
Higgs production in hadron colliders



← (fermion annihilation and vector boson scattering)

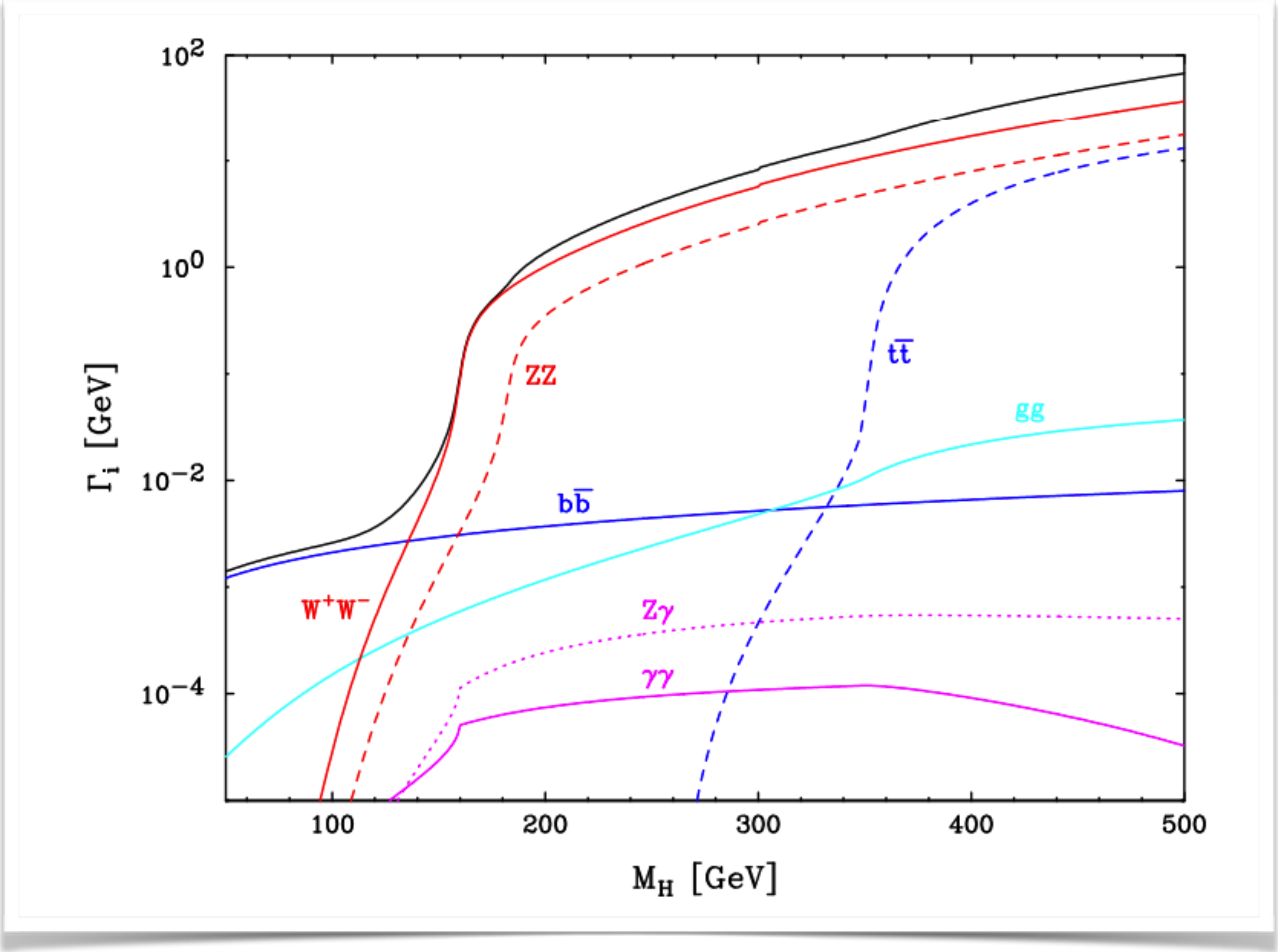
← Only available at hadron colliders





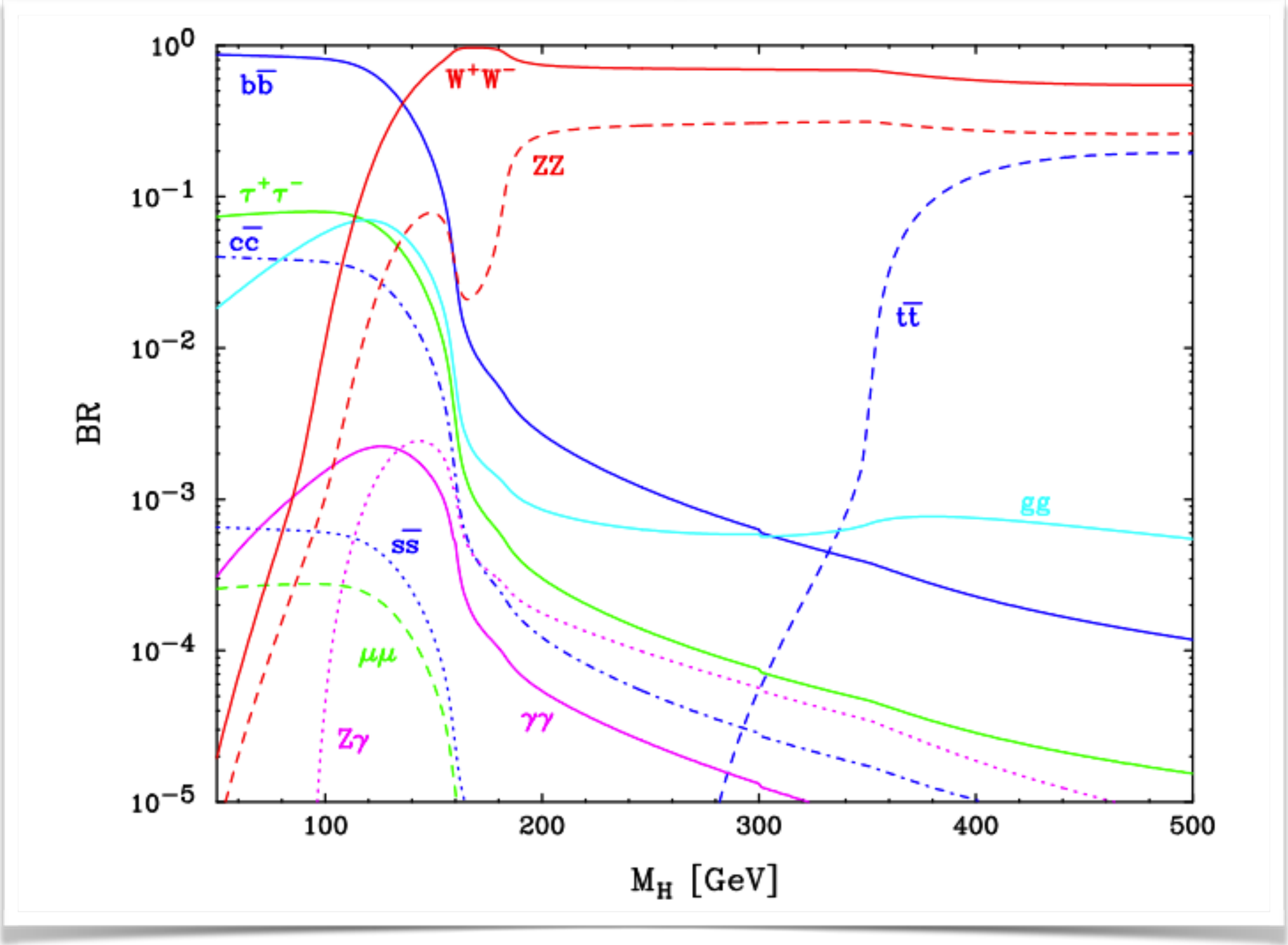
Look for all possible decays I

- If light, the **Higgs resonance is very narrow** - O(100) MeV
- **Decays to WW and ZZ pairs dominate over most of the mass range**
  - rise with energy due to coupling through longitudinal components (see slide 28)

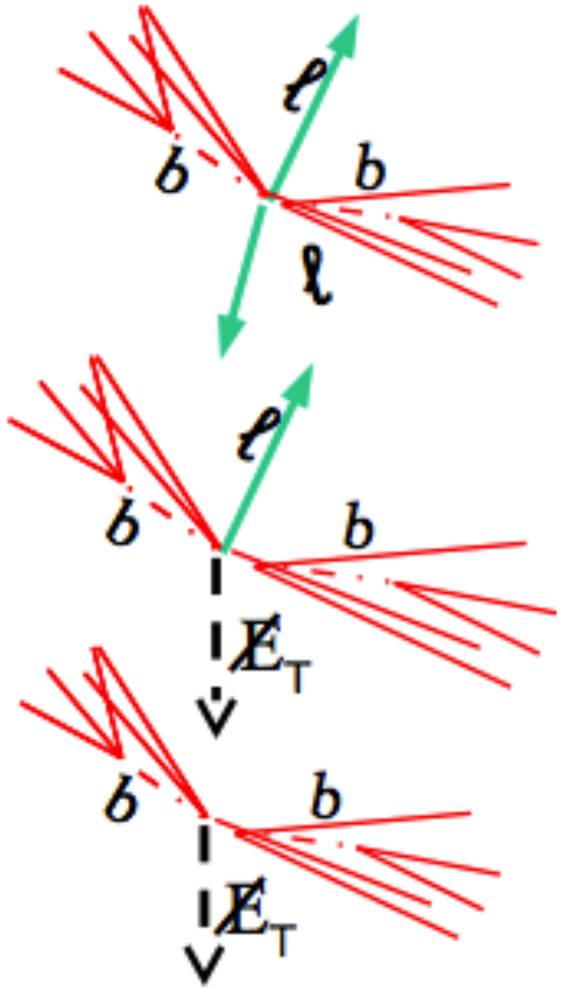


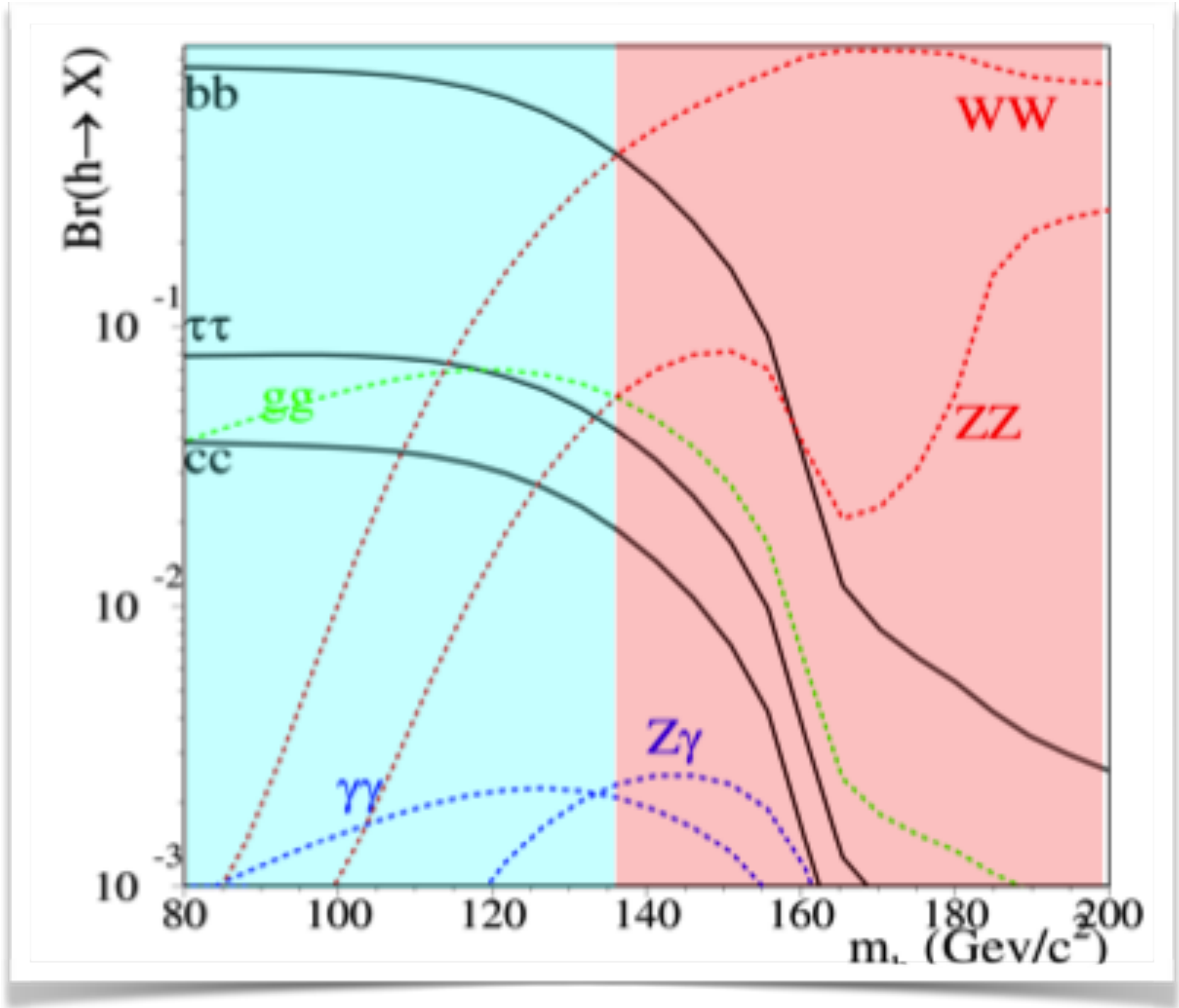
Look for all possible decays II

- **Window of maximum opportunity** (most democratic all available channels) **at ~125 GeV**
  - couplings to gluons and photons available through top and W loops



Most sensitive channels at the Tevatron





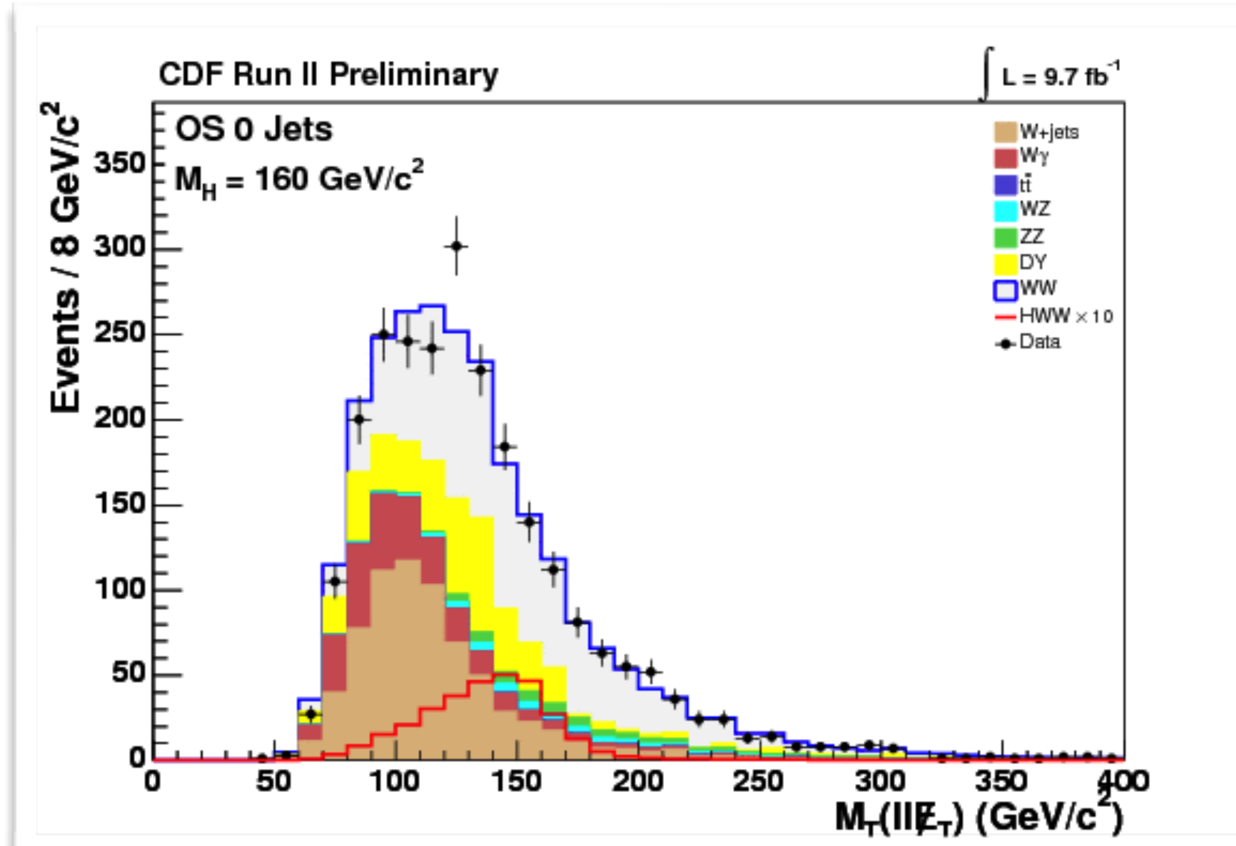
- At **low mass use h→bb final states**
  - associated production with W or Z
  - challenging: b-tagging, jet resolution
  - backgrounds: top, W/Z+heavy flavour di-bosons

- At **high mass use H→WW final states**
  - benefit from high gluon-gluon cross section
  - challenging: lepton acceptance, missing energy
  - backgrounds: top, di-bosons

The H → WW → 2l2ν channel

- **Decay products from resonance**
  - 2ν leave one degree of freedom
  - can't reconstruct full mass lineshape
  - use transverse mass (jacobian peak)

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

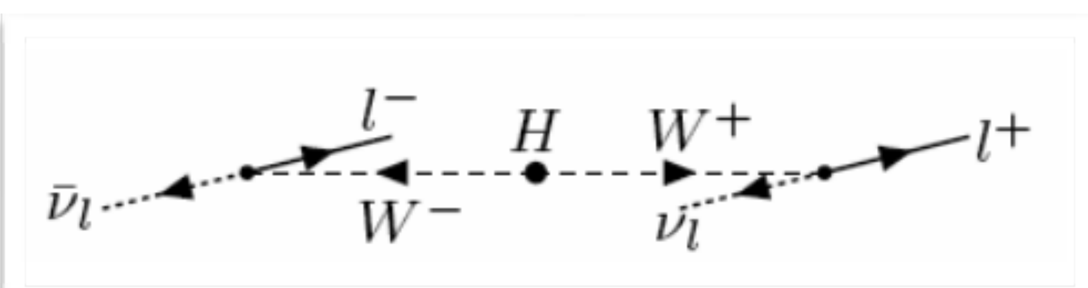


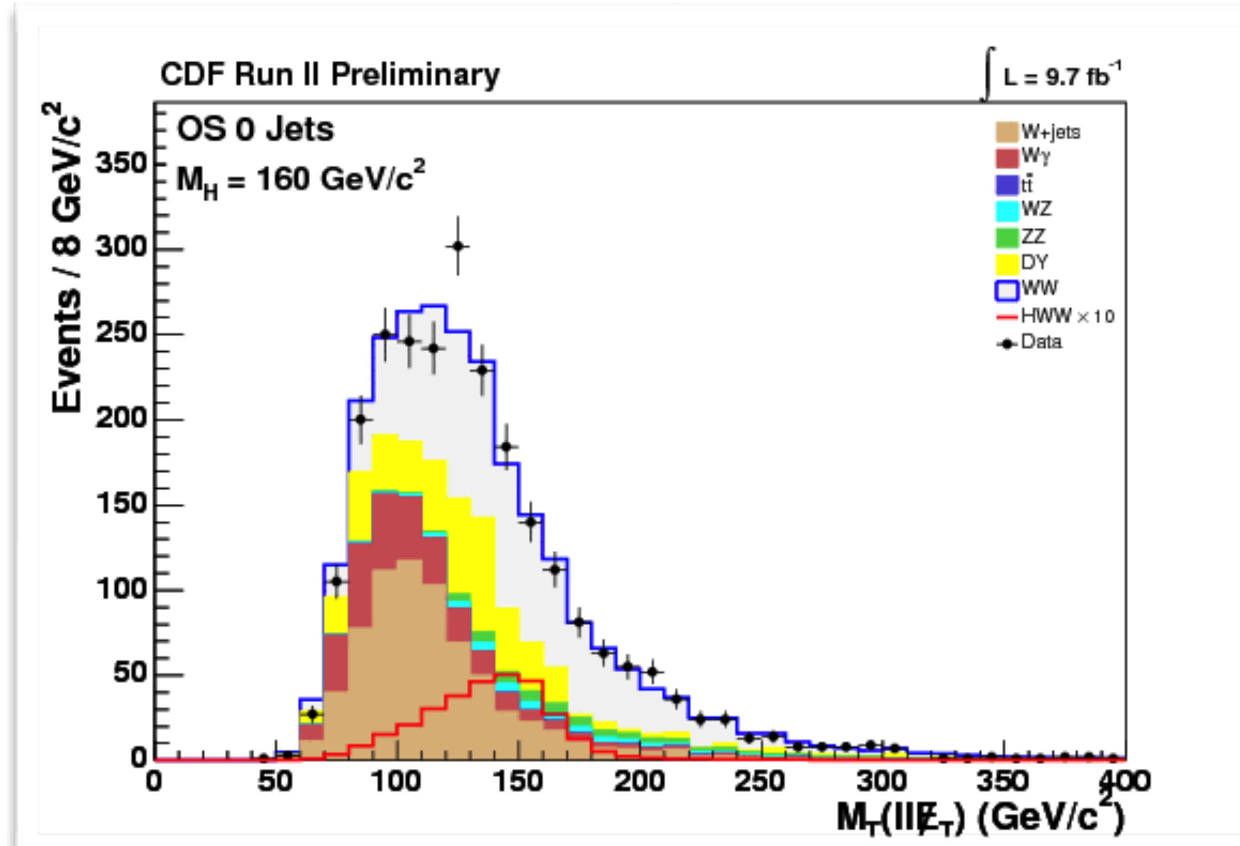
The H → WW → 2l2ν channel

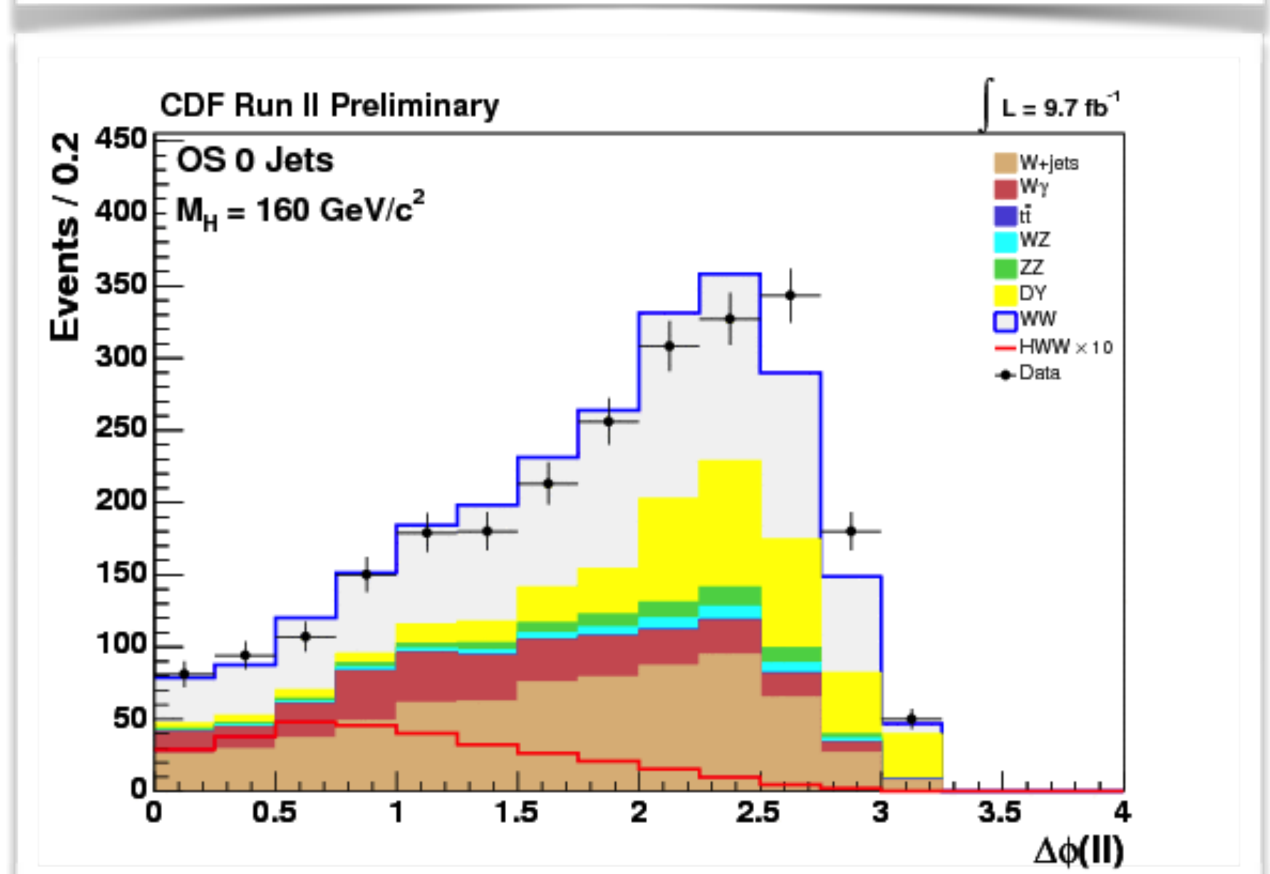
- **Decay products from resonance**
  - 2ν leave one degree of freedom
  - can't reconstruct full mass lineshape
  - use transverse mass (jacobian peak)

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

- **Helicity conservation after H decay**
  - ν helicity is pre-determined (massless)
  - dilepton recoils against 2ν preferentially







Discriminating signal above the background

- **Often**, a **single variable does not often enough discriminating power**
  - the solution is to combine several variables : cut sequentially? build a discriminator?
  - most of the work is to find the most performant solution
- A distribution in a given observable x_{obs} may be written as

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

This refers to a process: signal or background

normalization factor

Differential cross section

Theory input

Efficiency x acceptance

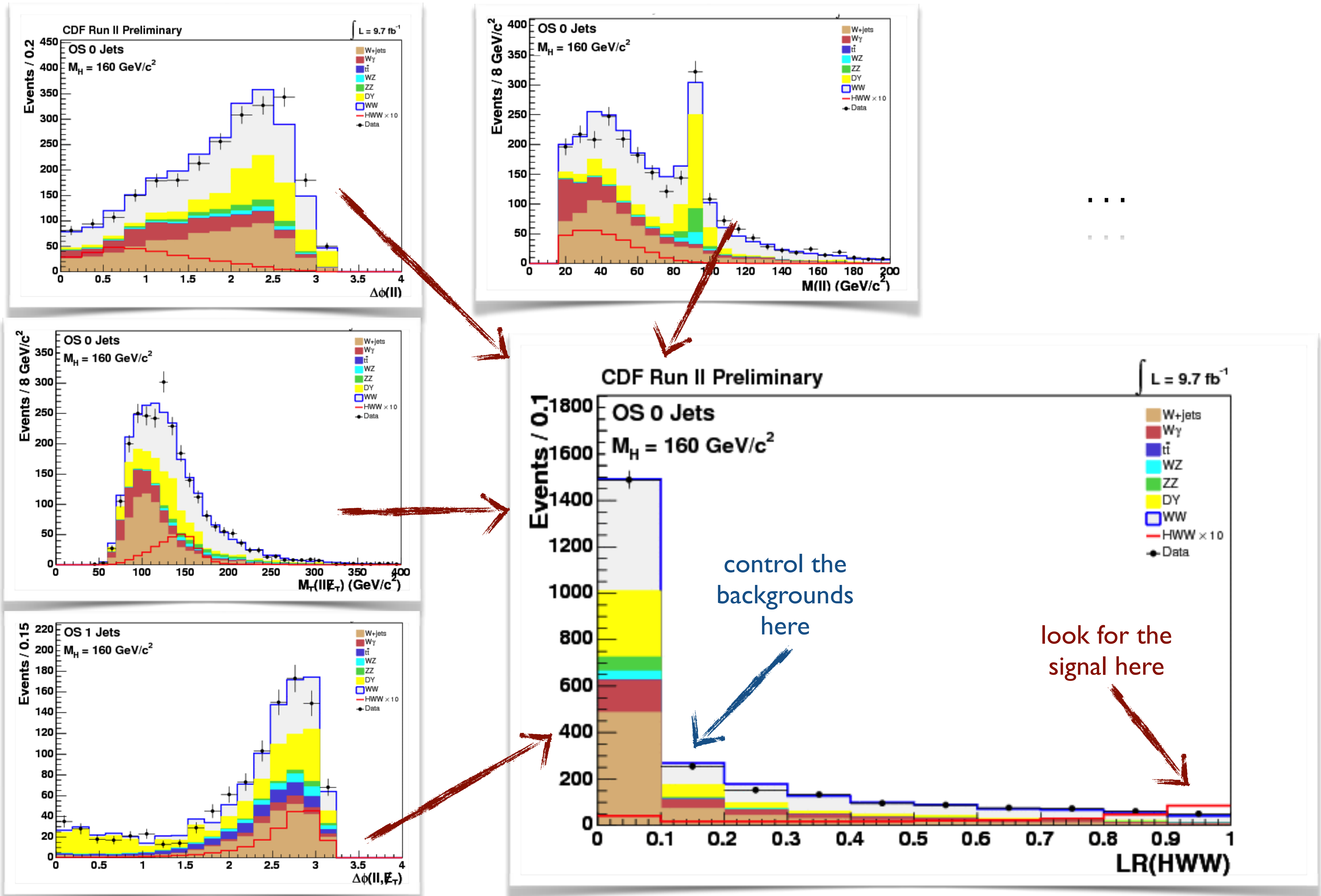
Detector resolution

Experimental input

- Can **combine different PDFs to discriminate S from B**
  - assign event-per-event weight based on the ratio
  - this is known as the <u>likelihood ratio method</u>
  - one amongst multivariate classifiers - see <u>TMVA</u>

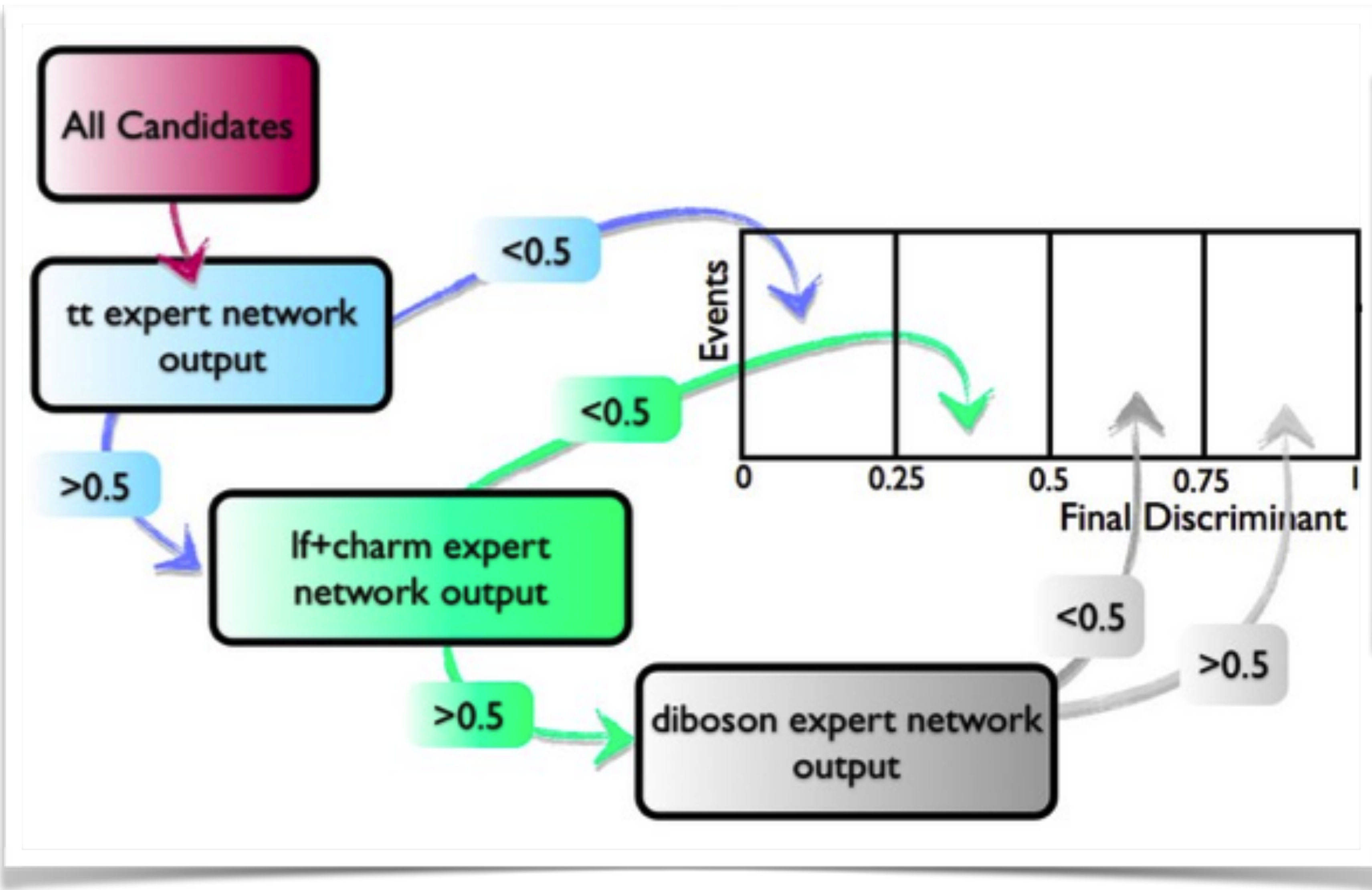
$$LR_S(x_{obs}) \equiv \frac{P_S(x_{obs})}{P_S(x_{obs}) + \Sigma_i k_i P_i(x_{obs})}$$

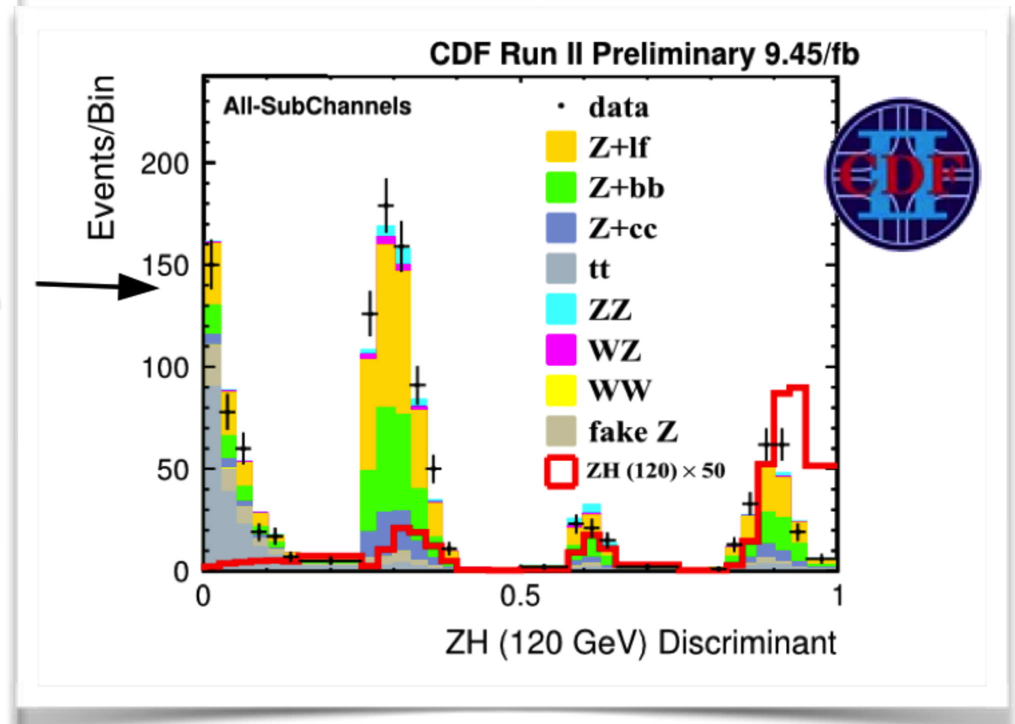
The H → WW → 2l2ν discriminator

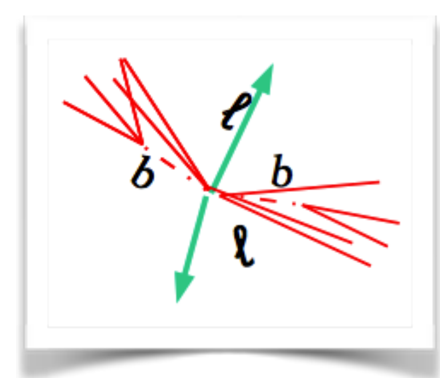


More complex multivariate analyses

- **Generalise the multivariate analysis concept!**
    - address specific experimental effects: improve resolution, energy scale, identification criteria
    - reject specific backgrounds
    - keep everything in the analysis: if there is any problem it will appear in the control region







Limits, measurements and related

- **How much “space” is statistically allowed for the signal?**
  - free parameter is usually the signal strength $\mu=\sigma_{obs}/\sigma_{theory}$
  - **compare the data with the expectations** using a maximum likelihood

$$\mathcal{L}(\text{data}\,|\,\mu,\theta) = \text{Poisson}\left(\,\text{data}\,|\,\mu\cdot s(\theta) + b(\theta)\,\right)\cdot p(\tilde{\theta}|\theta)$$

Signal expected

background expected

PDF for nuisance parameters affecting rates or shapes

- Nuisance parameters quantify uncertainties in the rates and can be profiled away
  - use the **profile likelihood ratio as the test statistics**

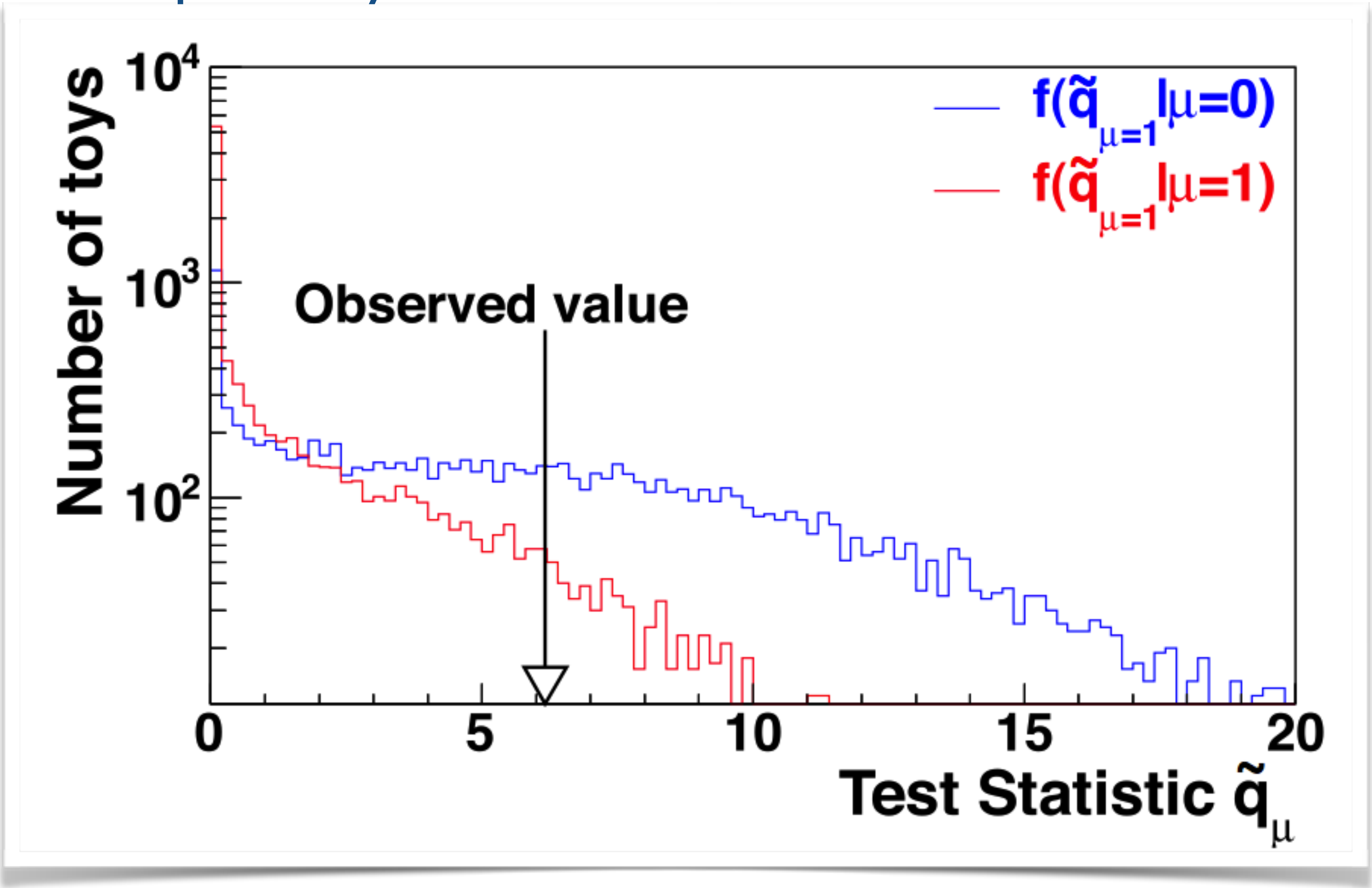
$$\tilde{q}_\mu \;=\; -2\ln\frac{\mathcal{L}(\text{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\hat{\mu},\hat{\theta})}$$

Best fit at fixed signal strength

Combined fit with μ and θ

The CLs method for limit setting

- Use pseudo-experiments and obtain the distribution of the test statistics
  - background-only case μ=0 signal+background case μ=1
  - the best values for the nuisances fit to data in each case must be used coherently
- **What is the probability that each case exceeds the observed value?**



The CL_S method for limit setting

- Use pseudo-experiments and obtain the distribution of the test statistics
  - background-only case μ=0 signal+background case μ=1
  - the best values for the nuisances fit to data in each case must be used coherently
- **What is the probability that each case exceeds the observed value?**

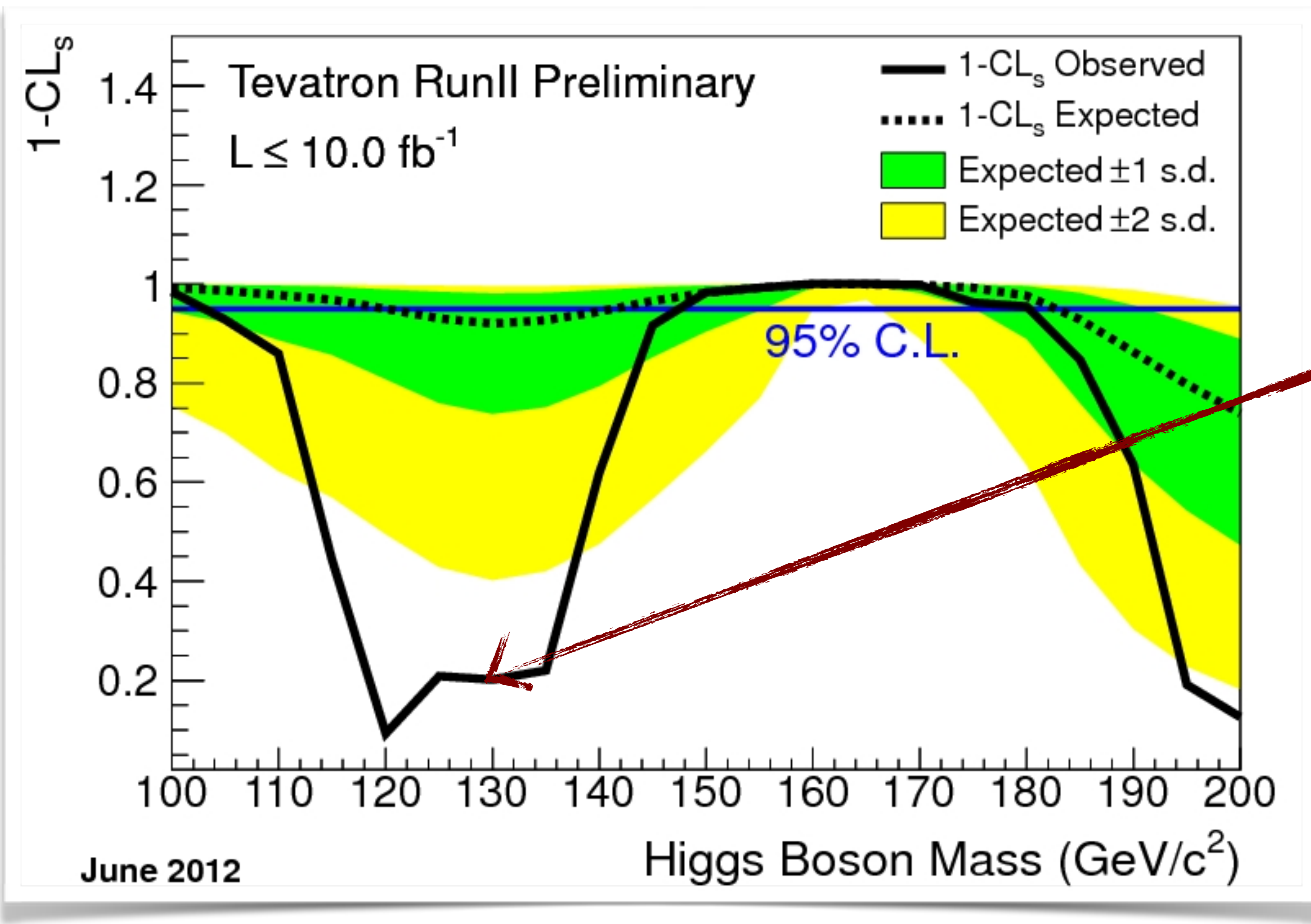
$$CL_s(\mu) = \frac{p_\mu}{1 - p_b}$$

All values of μ for which CLS<5% can be excluded at 95% CL

The value of μ for which CL_S=5% defines the upper endpoint (upper limit on μ at 95%)

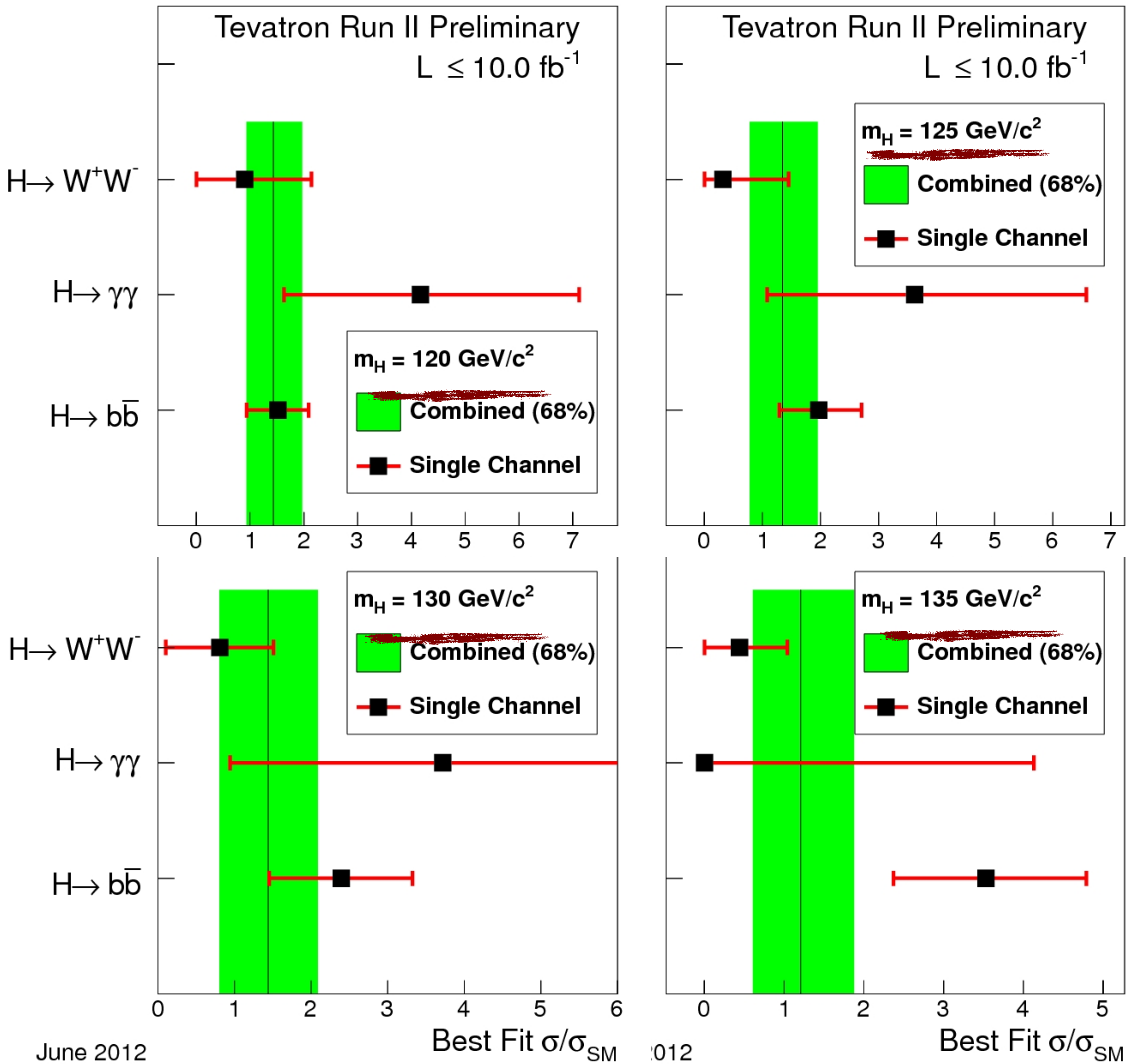
The CLs method for limit setting

- Use pseudo-experiments and obtain the distribution of the test statistics
  - background-only case μ=0 signal+background case μ=1
  - the best values for the nuisances fit to data in each case must be used coherently
- **What is the probability that each case exceeds the observed value?**



Combination points to s.th. Incompatible with background only hypothesis at the 3σ-level

Quantifying the excess observed at the Tevatron

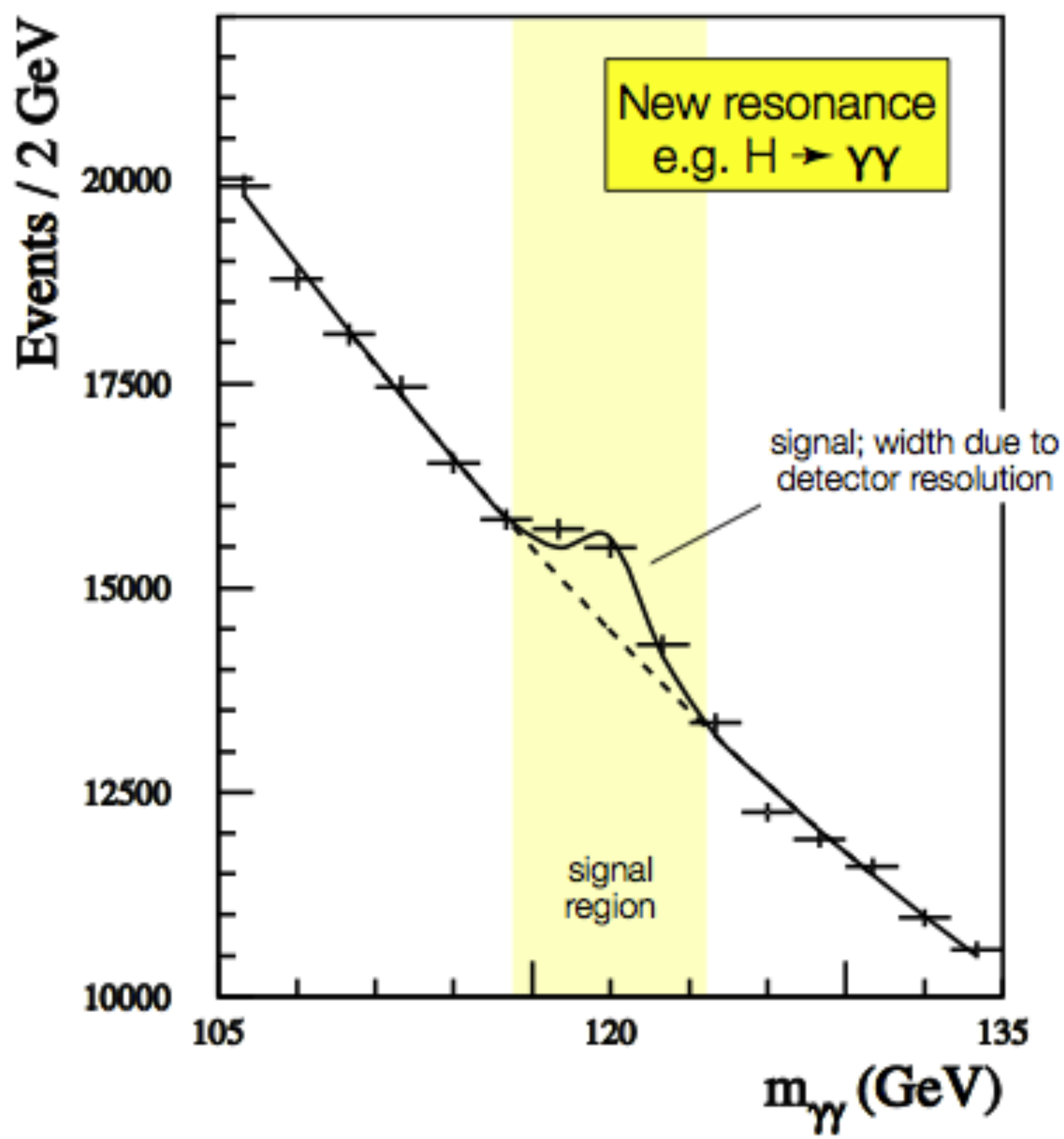


- Scan the mass looking for compatibility of the different channels
- At 125 GeV

  μ=1.4±0.7

- Consistent between different channels and with the indirect limits from precision measurements

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:

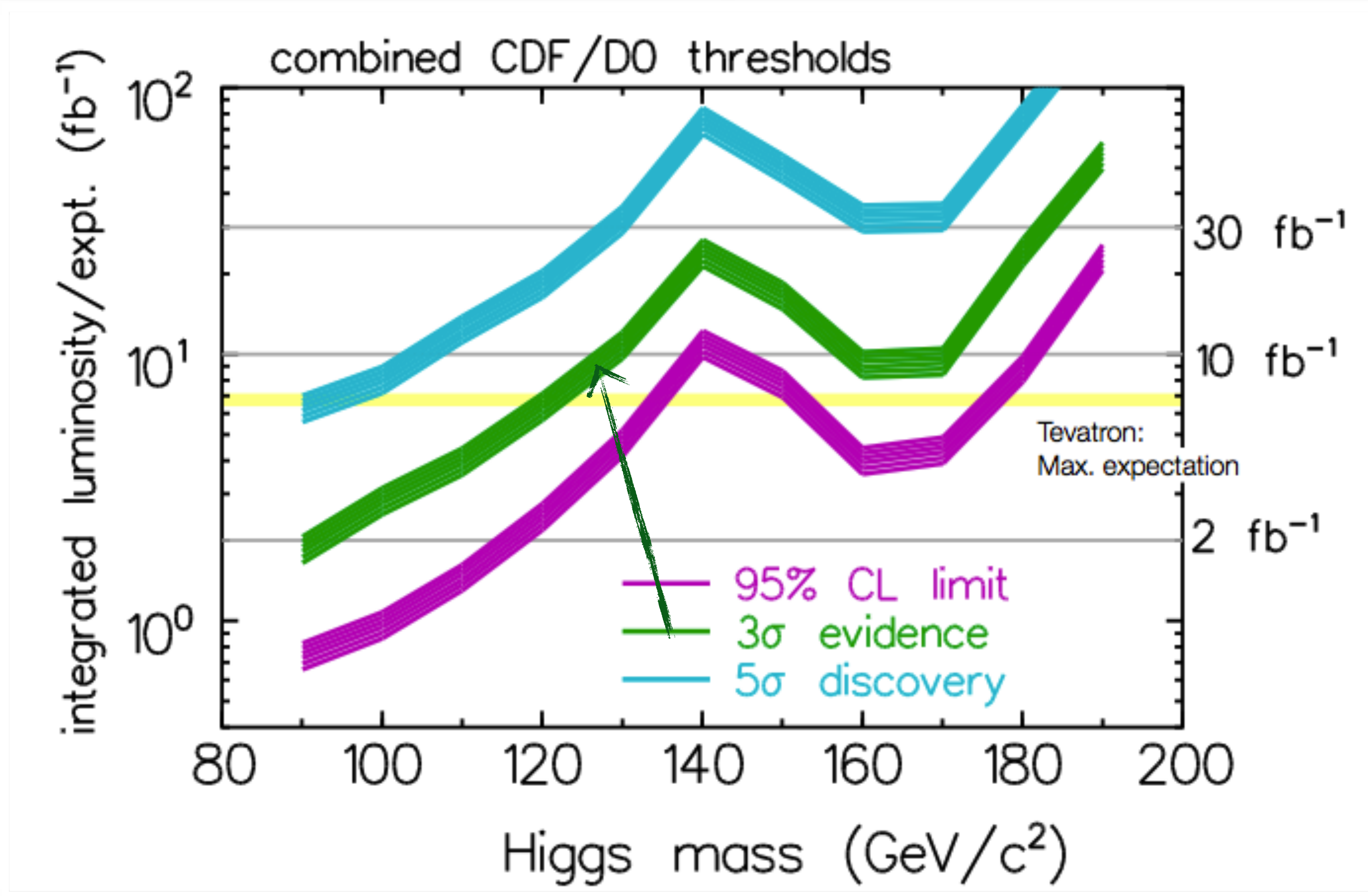
Signal $N_S = N_{tot} - N_B$ is 5 times larger than statistical uncertainty on N_B+N_S ...

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

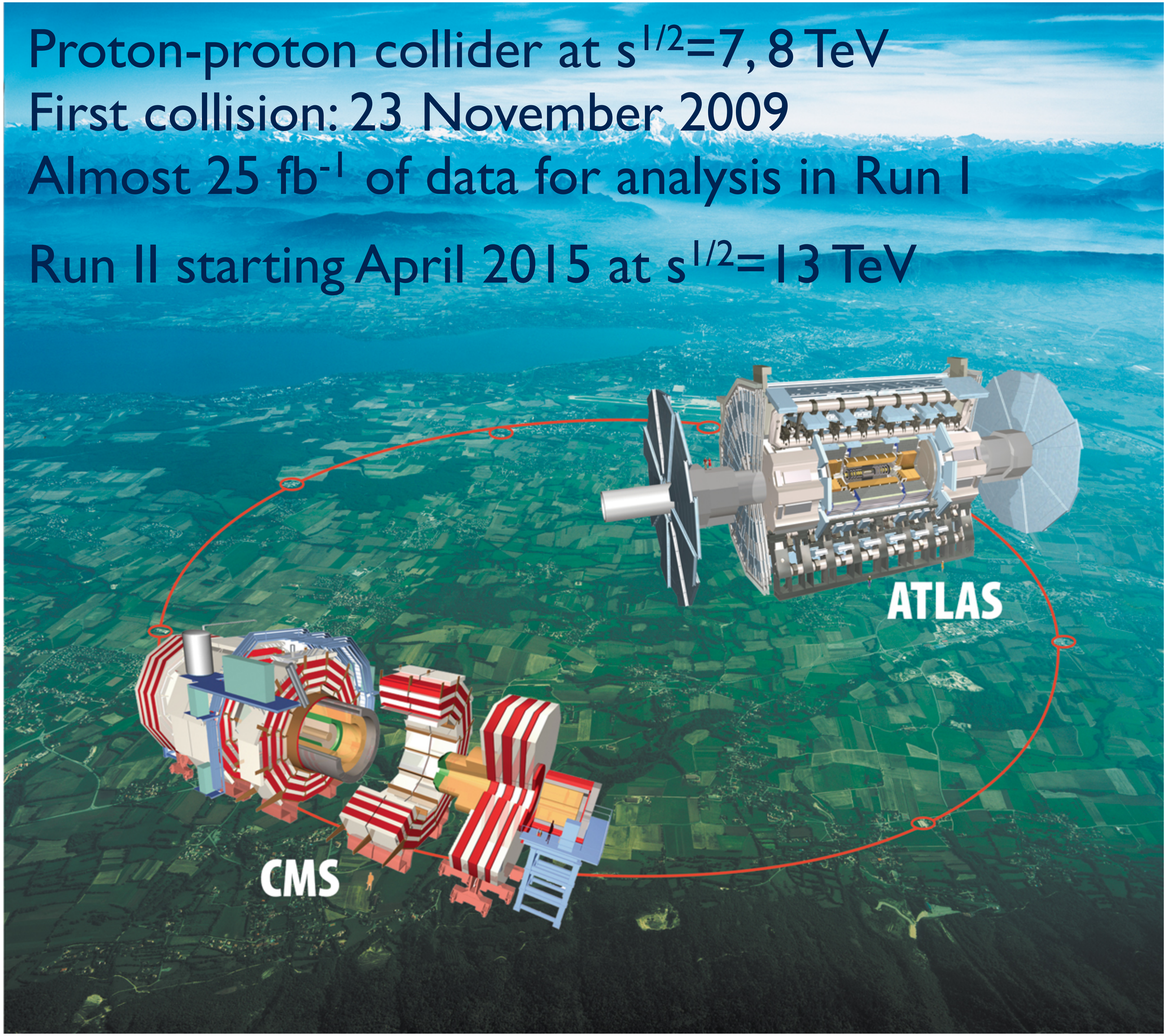
$$P_{5\sigma} = 10^{-7}.$$

Discovery!

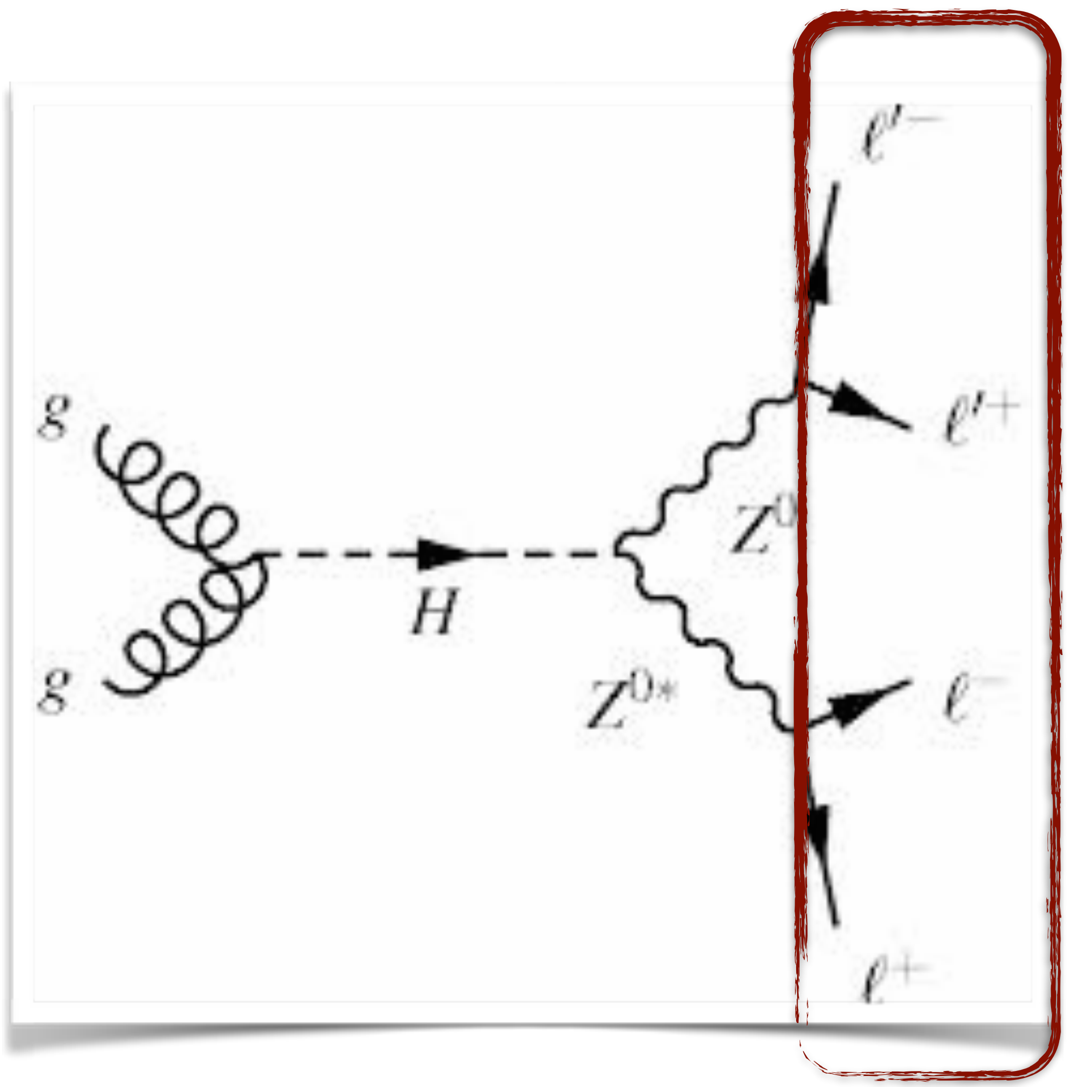
Tevatron reached the evidence threshold

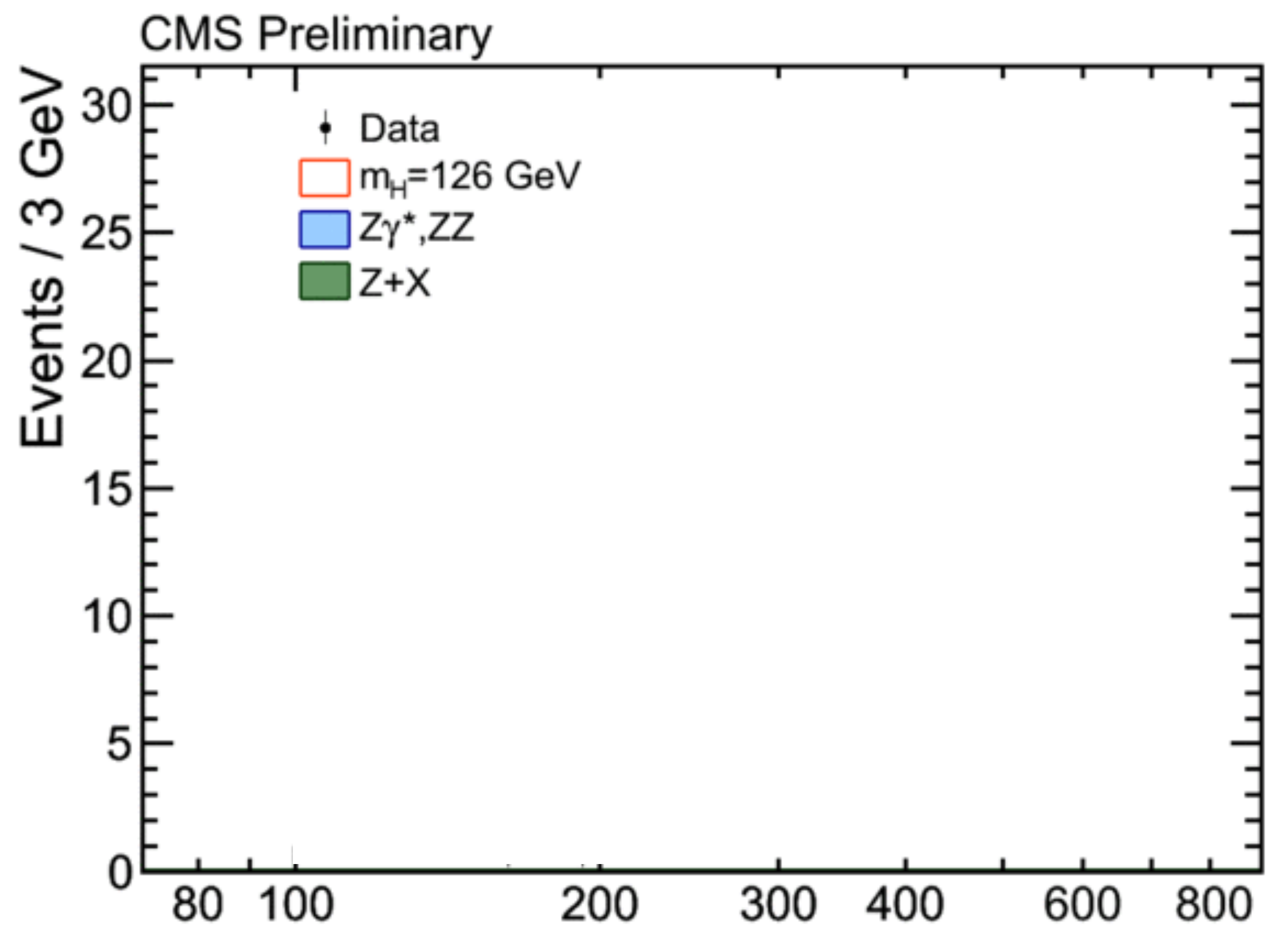


...and finally, it was found at the LHC.

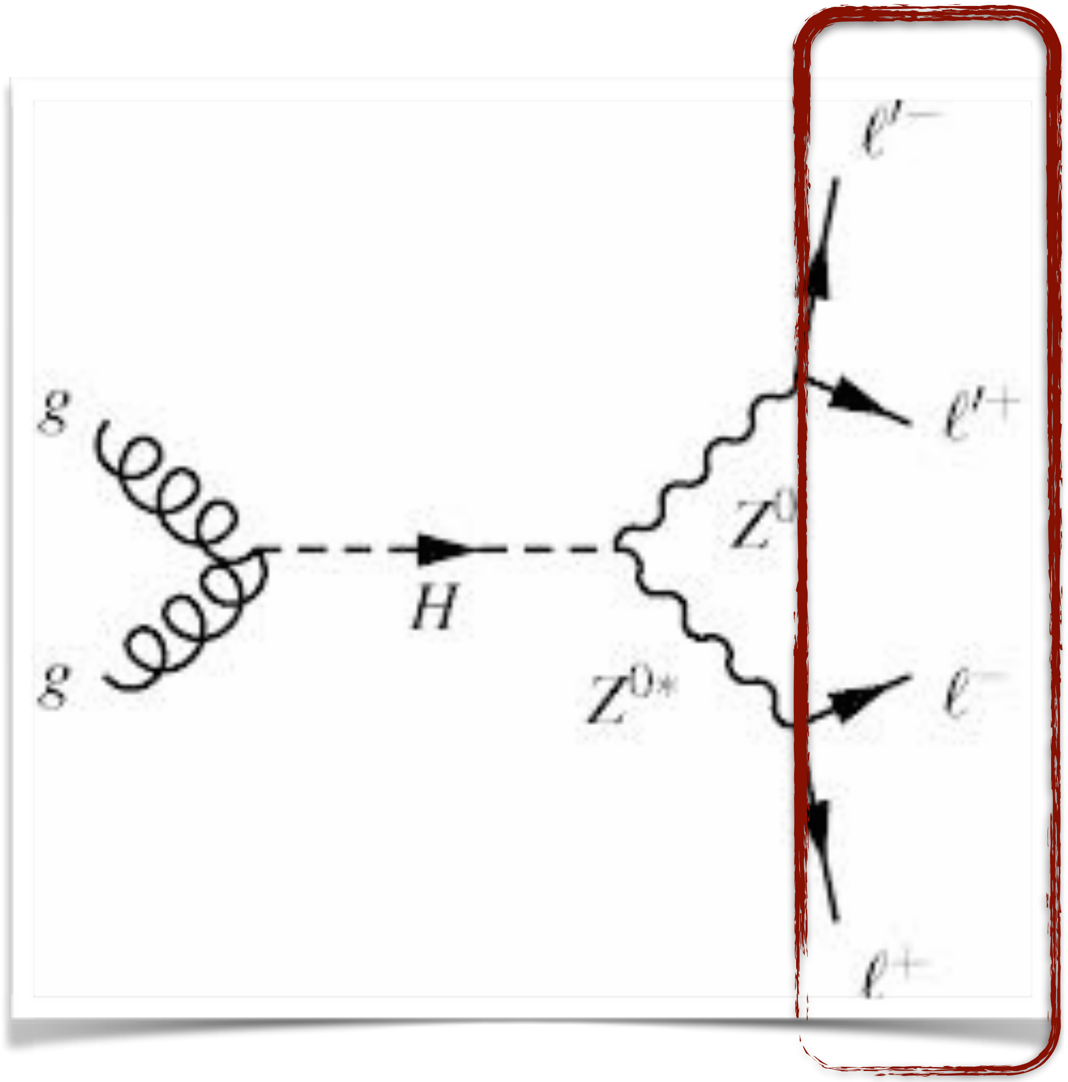


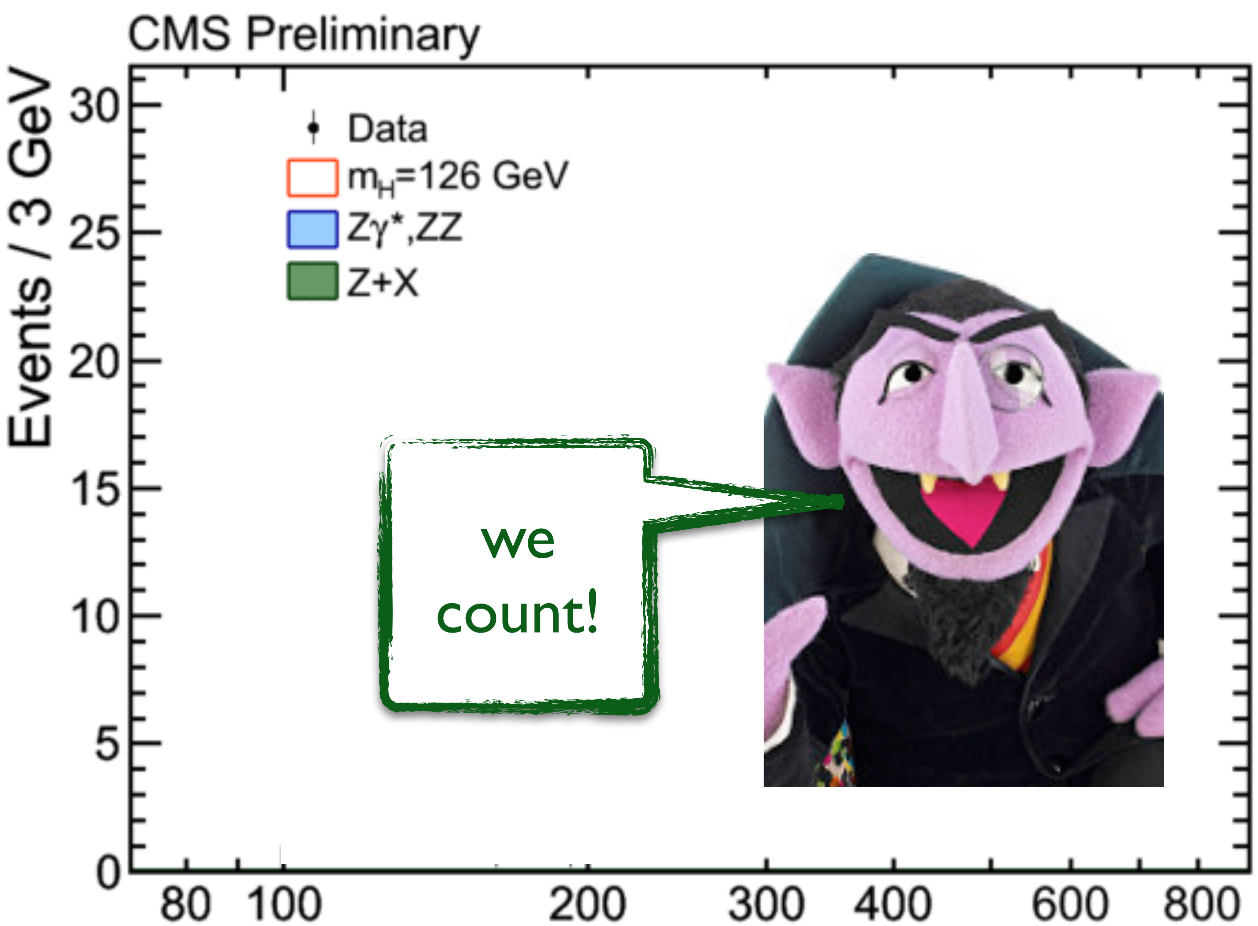
In HEP, we do one kind of measurement

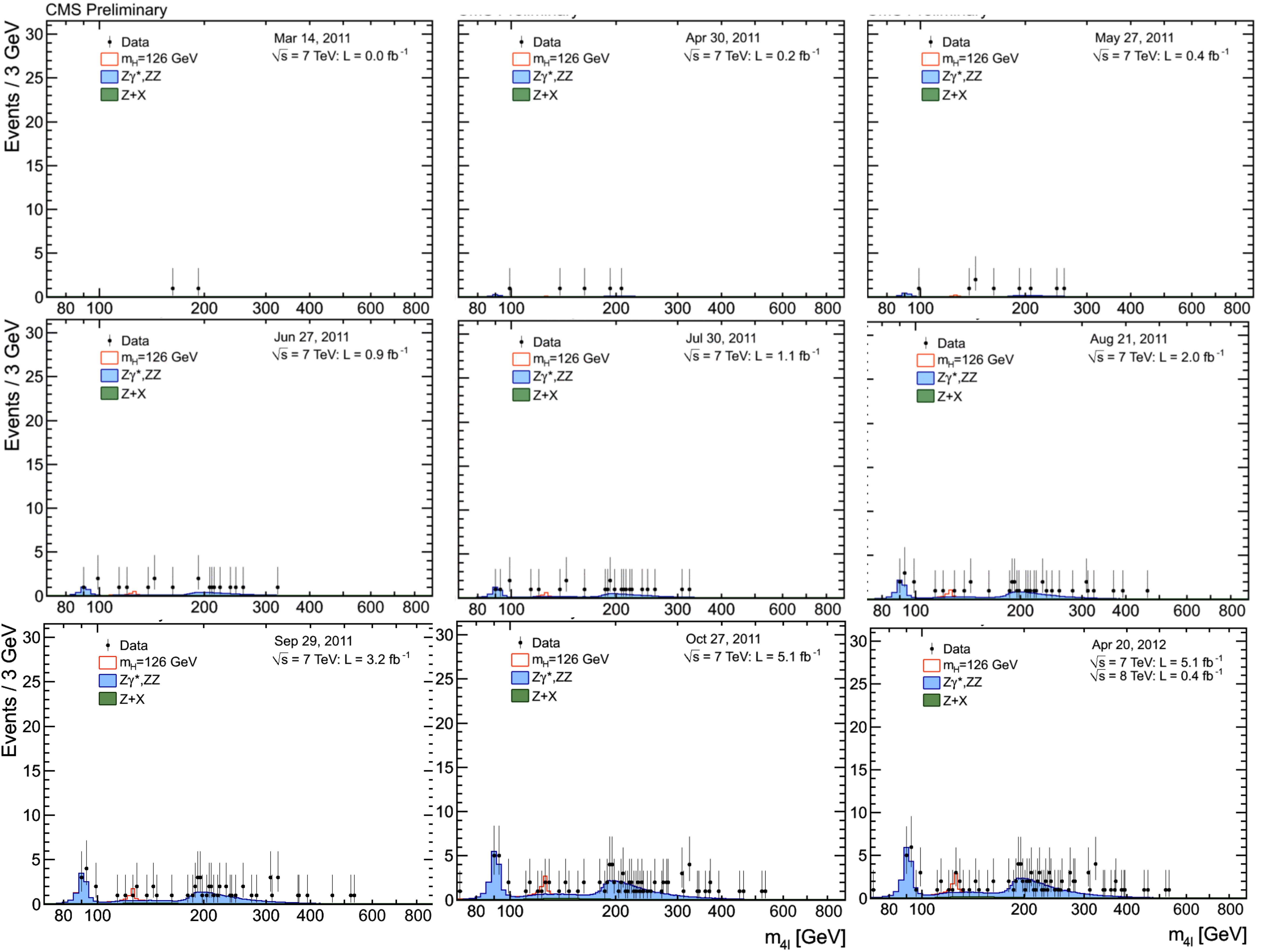




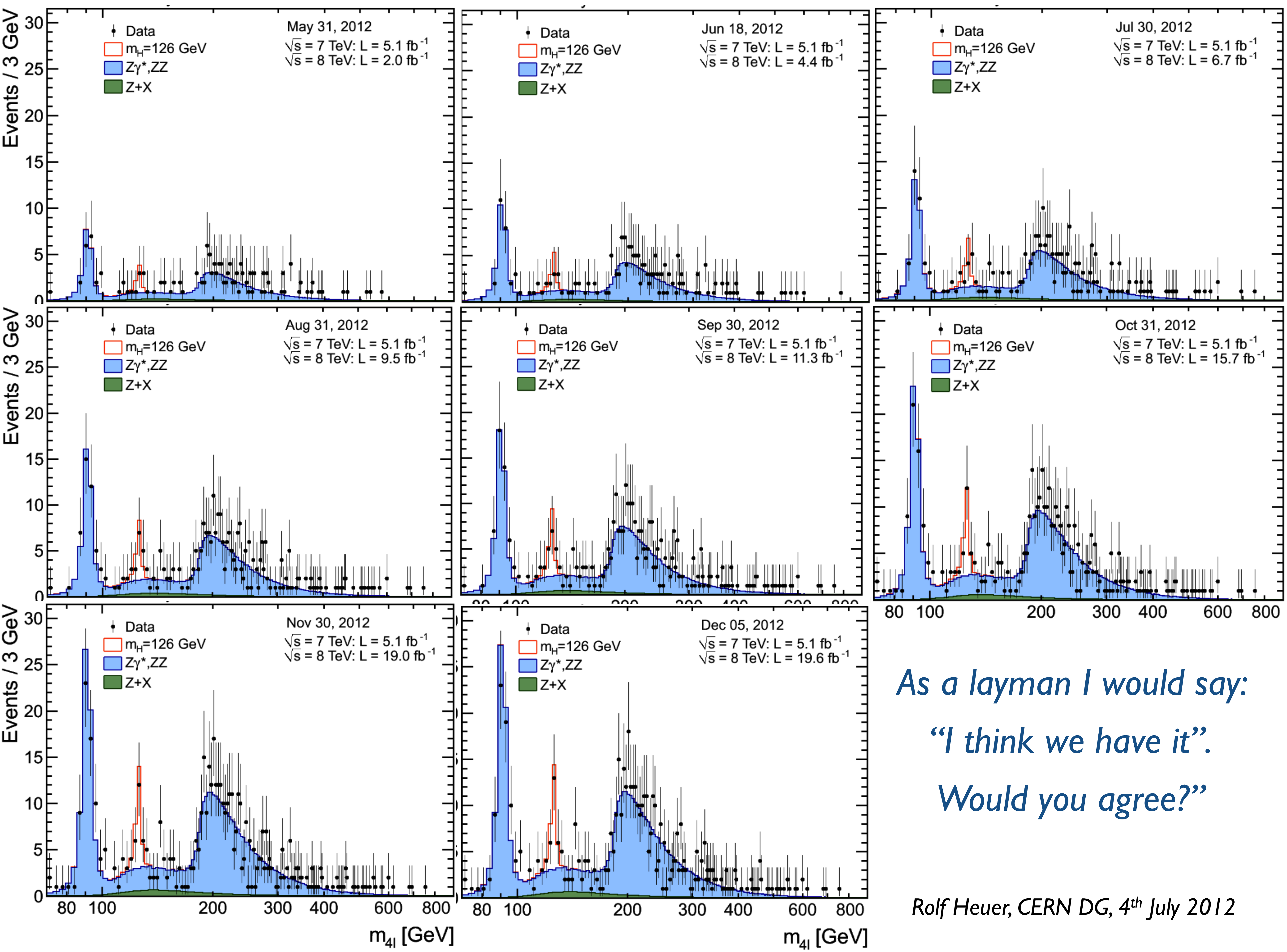
In HEP, we do one kind of measurement







CMS Preliminary
Events / 3 GeV
Data
m_H=126 GeV
Zγ*,ZZ
Z+X
Mar 14, 2011
$\sqrt{s}$ = 7 TeV: L = 0.0 fb^{-1}
Apr 30, 2011
$\sqrt{s}$ = 7 TeV: L = 0.2 fb^{-1}
May 27, 2011
$\sqrt{s}$ = 7 TeV: L = 0.4 fb^{-1}
Jun 27, 2011
$\sqrt{s}$ = 7 TeV: L = 0.9 fb^{-1}
Jul 30, 2011
$\sqrt{s}$ = 7 TeV: L = 1.1 fb^{-1}
Aug 21, 2011
$\sqrt{s}$ = 7 TeV: L = 2.0 fb^{-1}
Sep 29, 2011
$\sqrt{s}$ = 7 TeV: L = 3.2 fb^{-1}
Oct 27, 2011
$\sqrt{s}$ = 7 TeV: L = 5.1 fb^{-1}
Apr 20, 2012
$\sqrt{s}$ = 7 TeV: L = 5.1 fb^{-1}
$\sqrt{s}$ = 8 TeV: L = 0.4 fb^{-1}
m_{4l} [GeV]



As a layman I would say:

"I think we have it".

Would you agree?"

Rolf Heuer, CERN DG, 4th July 2012

All the details about ~~counting~~ LHC results and their interpretation in the next sessions

Monday, 27 April 2015

18:00 - 19:30 **Higgs Physics 2** *1h30'*

Combination of search results.
Models, properties, and interpretation.
Case-study of the coupling strengths.
Case-study of the hypothesis test for different spin-parity assignments.

Speaker: Andre Tinoco Mendes (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

Monday, 4 May 2015

18:00 - 19:30 **Higgs Physics 3** *1h30'*

Summary of results from the discovery in the different channels.
Case-study of the H->WW search at ATLAS.

Speaker: Dr. Patricia Conde Muino (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)

Monday, 11 May 2015

18:00 - 19:30 **Higgs Physics 4** *1h30'*

Speaker: Ricardo Jose Morais Silva Goncalo (LIP Laboratorio de Instrumentacao e Fisica Experimental de Part)