Electroweak symmetry breaking

Understanding a missing piece of the Standard Model

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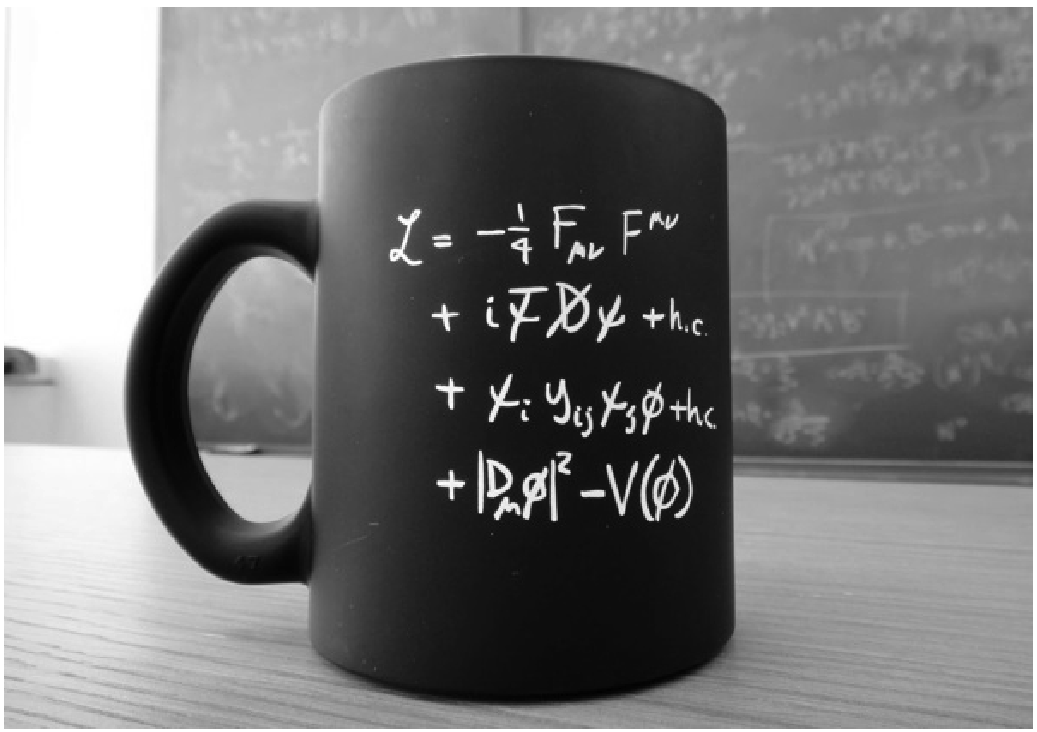
Outline

Foundations: a glance at the Standard Model

Introducing a new fundamental interaction

Tracing the Higgs signature at particle colliders: LEP, Tevatron LHC



Foundations

A glance at the Standard Model

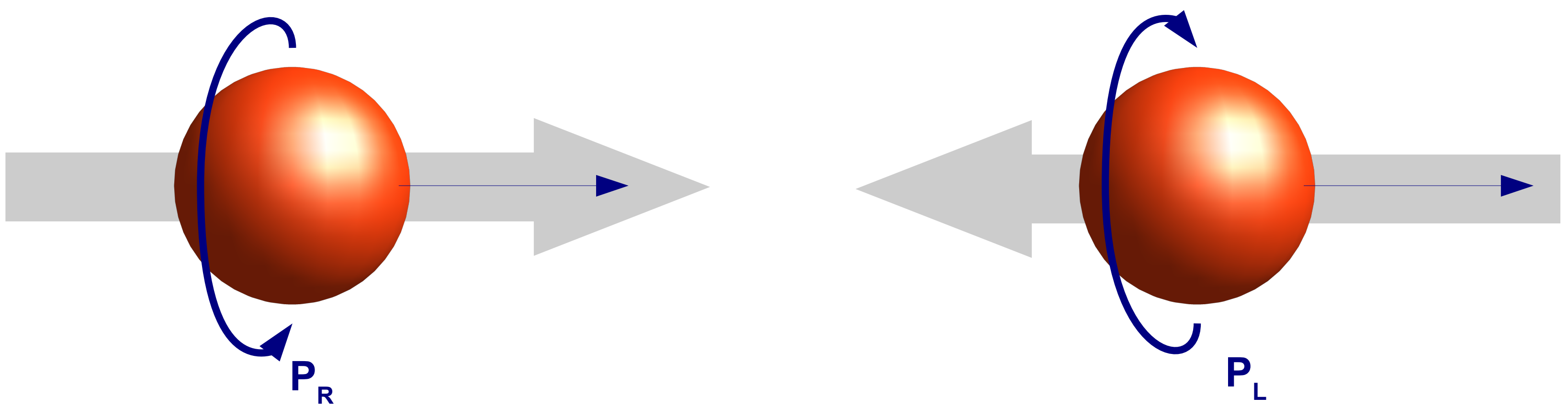
- The SM condenses **two simple observations about fundamental interactions:**

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

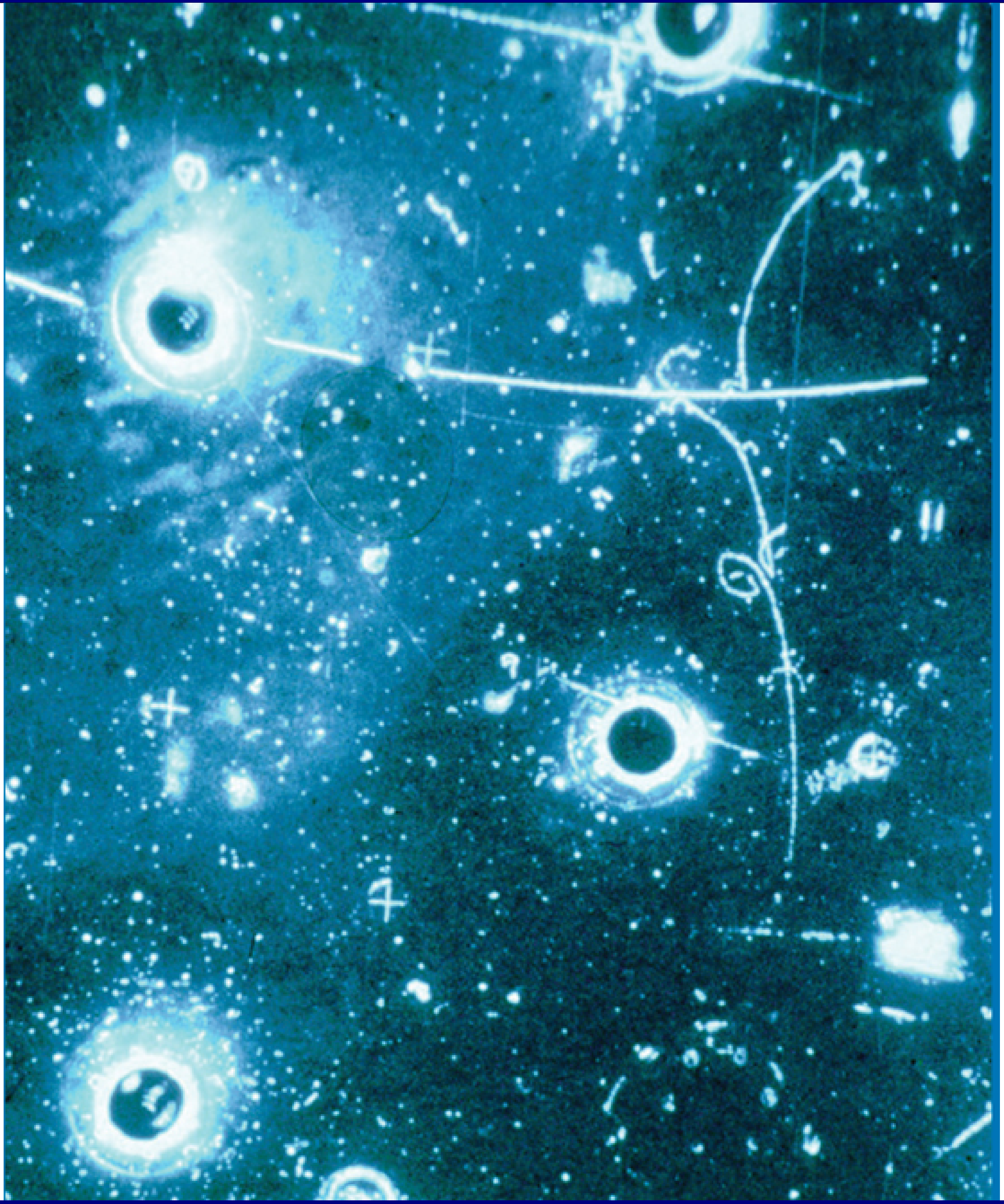
- the **charges** of the particles are the generators of the so called gauge symmetries

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

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

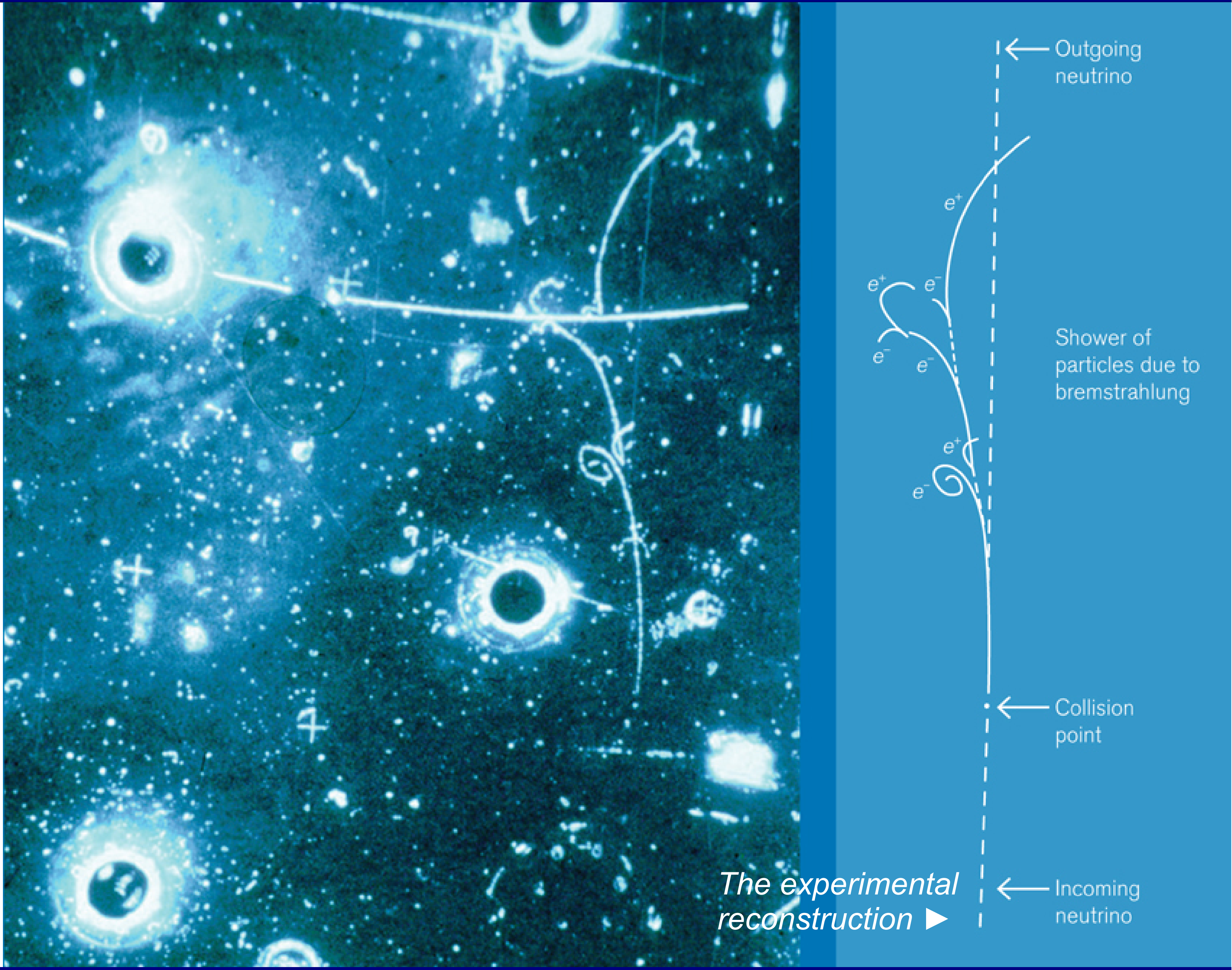


The SM is an effective theory, following true discoveries...



One out of the 7×10^5 pictures taken by Gargamelle at CERN ►

The SM is an effective theory, following true discoveries...



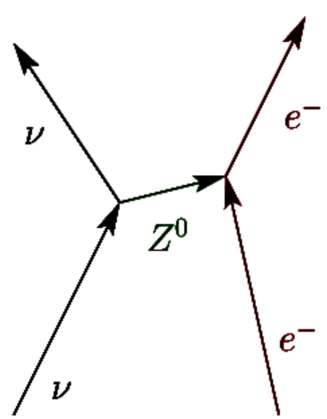
The experimental reconstruction ▶

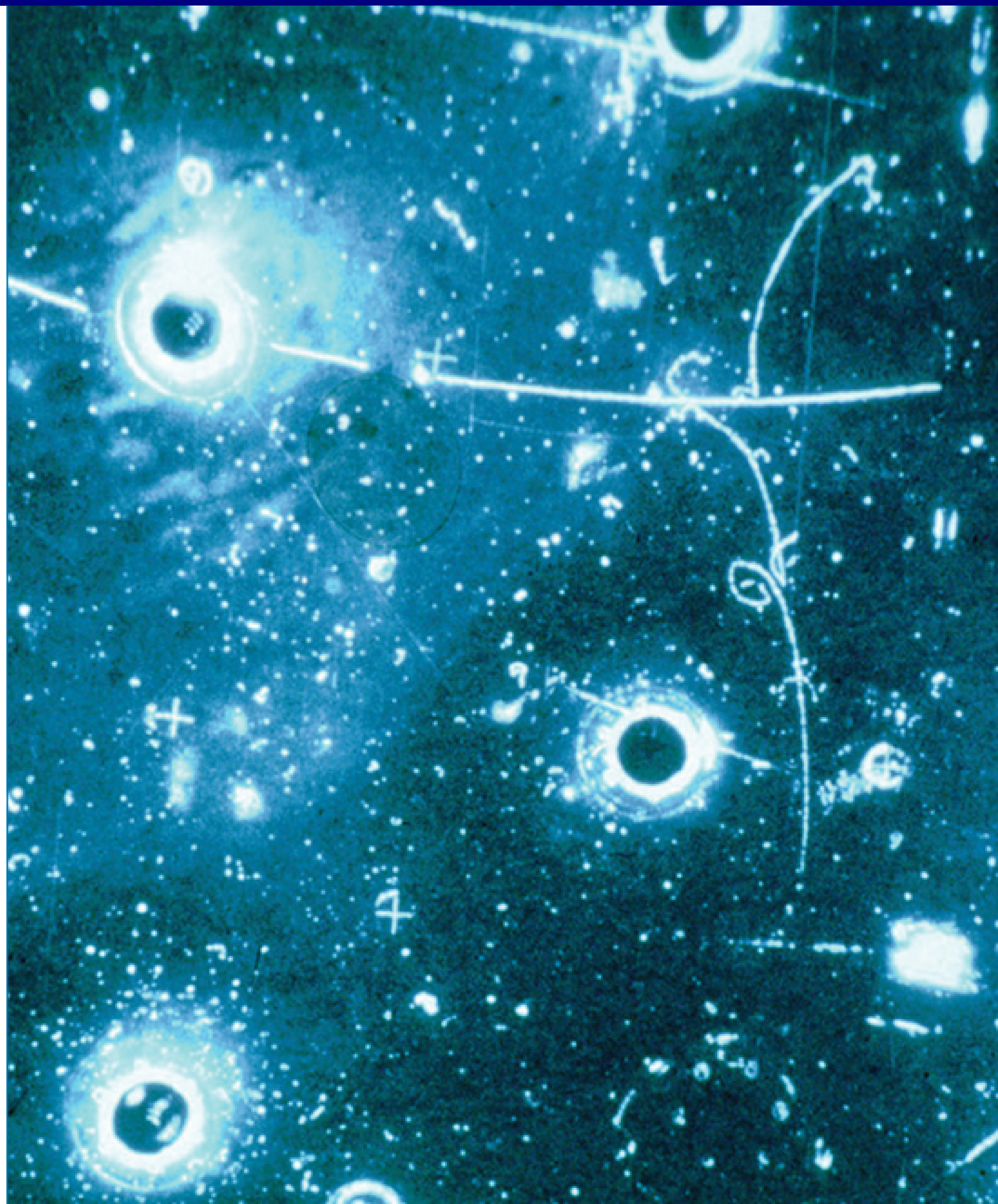
The SM is an effective theory, following true discoveries...

… and the theoretical interpretation ▼

$$\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^-$$

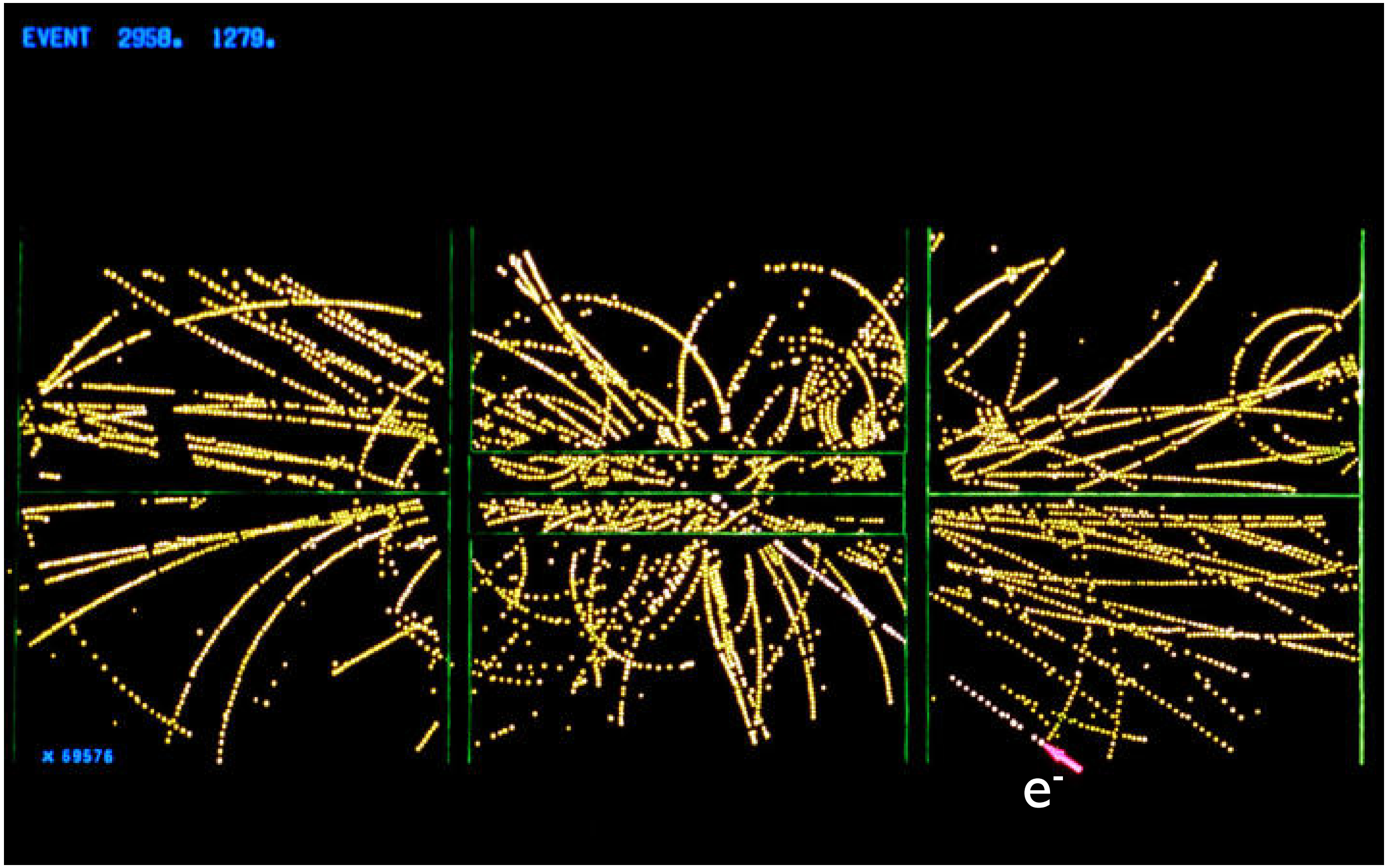
has been **mediated by a neutral interaction** which **conserves flavor**, couples proportionally to the **weak neutral charge** and gets **masked at low Q^2 by electromagnetic interactons**



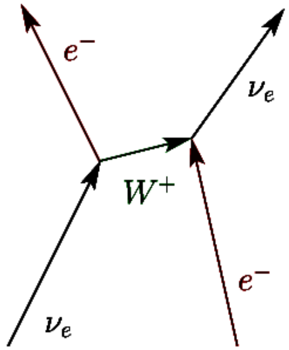


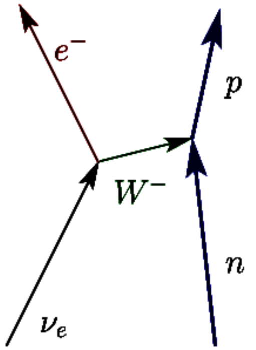
The SM is an effective theory, following true discoveries...

Proton-anti-proton collision recorded by UA1 ►

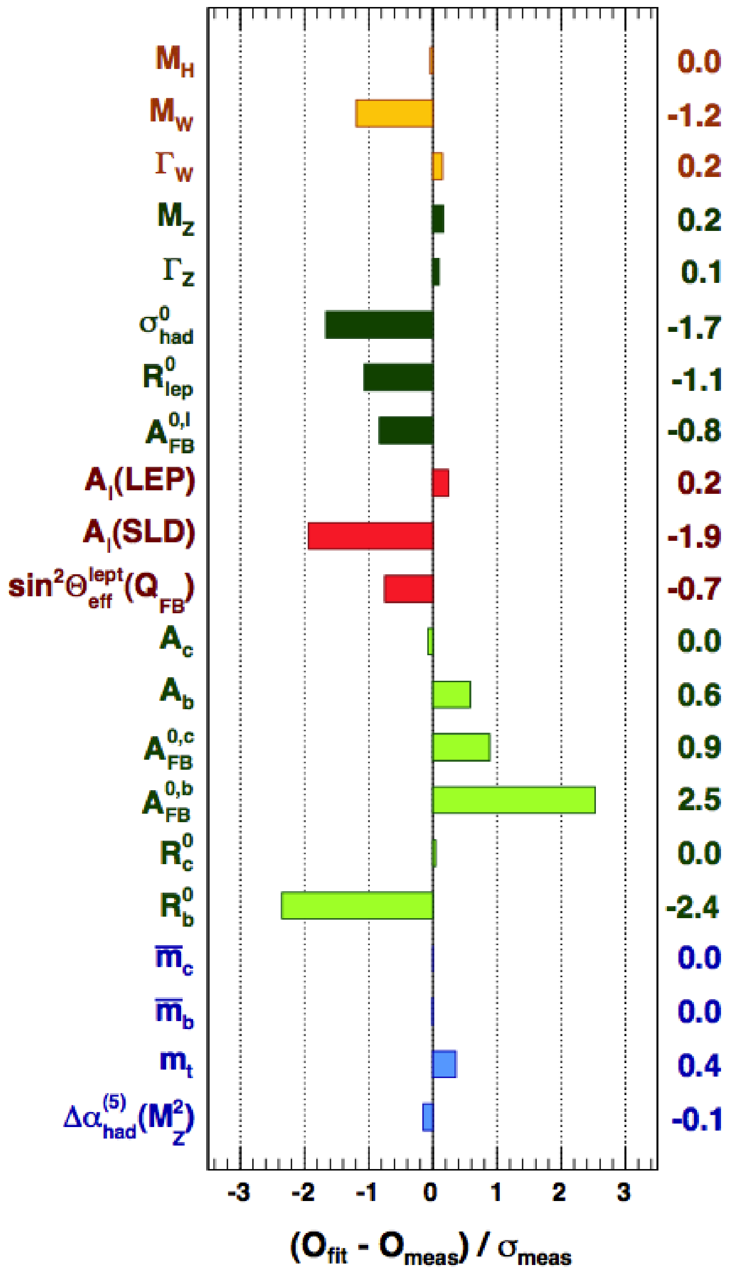


- Charged currents change flavor: $\bar{u} + d \rightarrow W^- \rightarrow e^- \bar{\nu}_e$
- CC/NC connected via weak mixing angle: $\dfrac{m_W^2}{m_Z^2 \cos\theta_W} = 1$

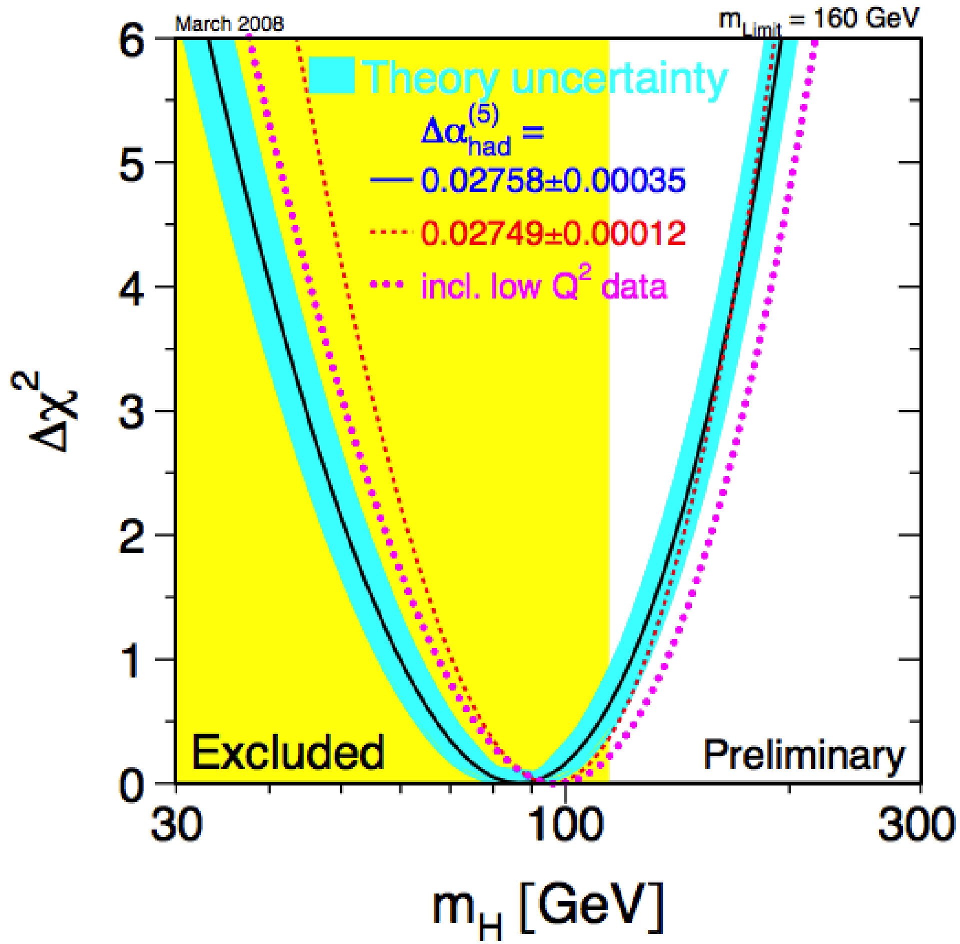




...which lead to a highly predictive theory



- Measured to incredible precision at LEP
- Largest deviation at 3σ level on R_b, $A_{FB}^{0,b}$
- See [Phys.Rept. 403-404 (2004) 189-201] for review
- Precise prediction for the “missing piece” ▼



Two lines summarize gauge interactions

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

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

Strong sector   Weak sector   Electromagnetic sector

  - **Three generations of fermions** which are 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 gauge sector in theSM!
If you don't believe see the next few slides.

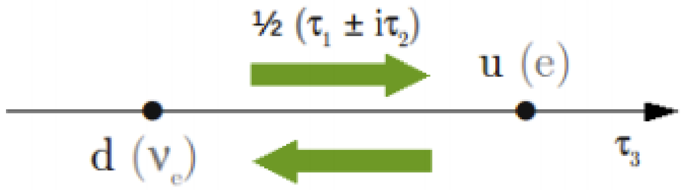
Gauge invariance of the theory

- 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



- To preserve gauge invariance the lagrangian is modified by a **covariant derivative**

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

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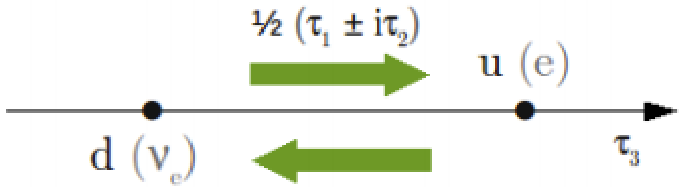

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We “discover” gauge fields: Strong interactions | Charged EWK interactions | Neutral EWK interactions

What is gauge invariance?

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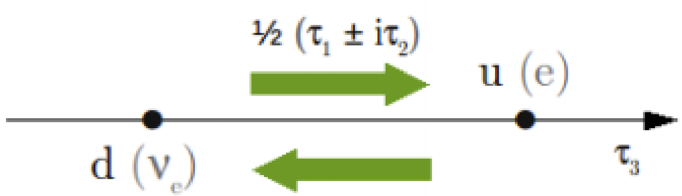

- The lagrangian is modified by a **covariant derivative** to preserve gauge invariance

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

each one has a specific coupling...

Strong coupling

Mixing Fermi constant and fine structure constant

What is gauge invariance?

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- If is ψ a field and ψ→Uψ is a transformation, then:

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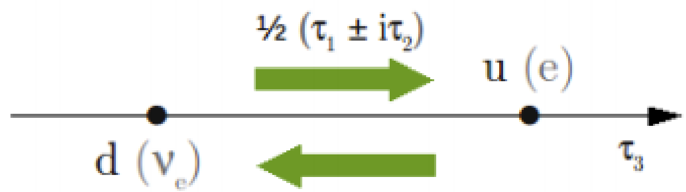


- The lagrangian is modified by a **covariant derivative** to preserve gauge invariance

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

Gell-Mann matrices

Pauli matrices

hypercharge

...which makes charge flow

Unrolling the gauge sector of the SM

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

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

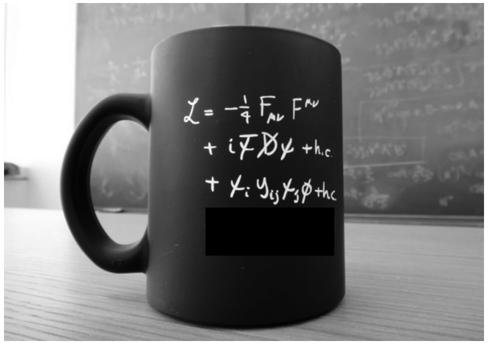
- Using the information above we can write down the kinematics predicted by the SM
- E.g. for a left handed quark:

covariant derivative

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

coupling x gauge field x charge

Unitary matrix, no flavor mixing at this point



Gauge bosons have self interactions

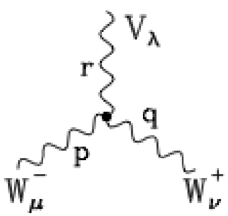
- Besides the fermion kinematics, **pure gauge-bosons interactions are allowed**

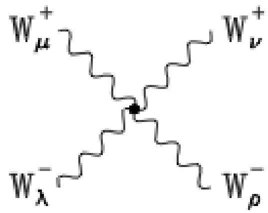
$$\mathcal{L}_{\text{gauge-fixing}} = -\frac{1}{4} W_{\mu\nu}^{\;\;i} W^{\mu\nu^i} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

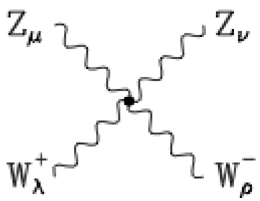
$F_{\mu\nu}$ is the field strength tensor which for the electroweak sector is given by:

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

- 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,
$g_A = e$, $g_Z = g_W \cos\theta_W$)

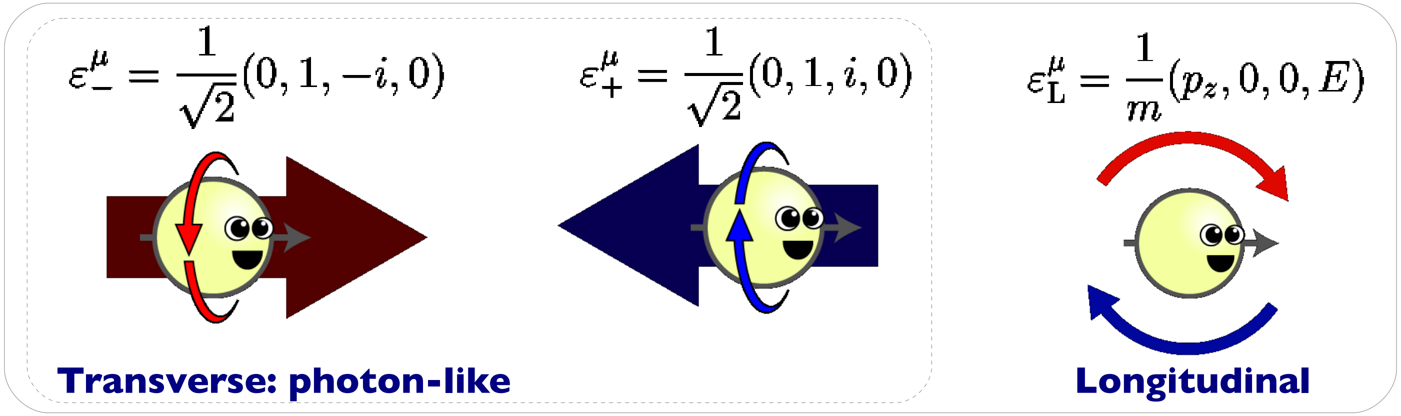
$+ig_W^2[2g_{\mu\nu}g_{\lambda\rho} - g_{\mu\lambda}g_{\nu\rho} - g_{\mu\rho}g_{\nu\lambda}]$

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

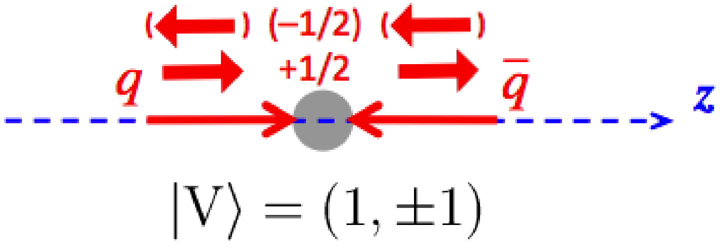
...and are polarized

$$B^\mu = \varepsilon^\mu e^{-iP_\nu x^\nu}$$

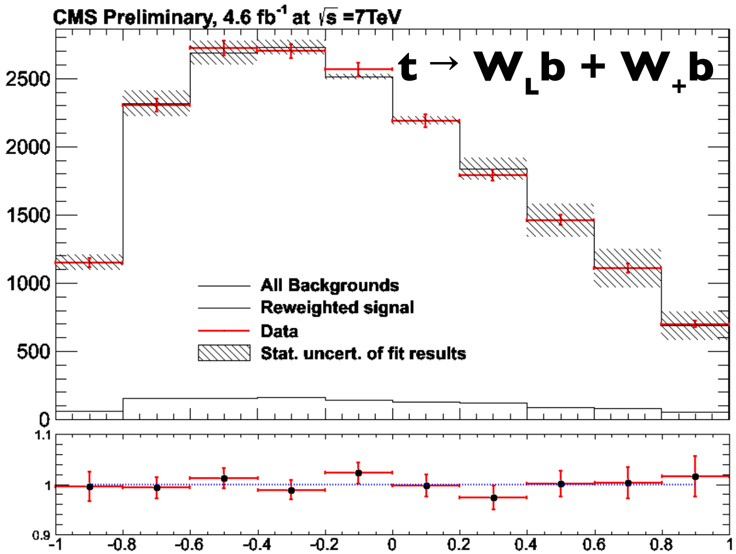
- Wave functions depend on polarization state
  - note definition is relative to the polarization plane (not to direction of motion)



- **Photon-like polarizations** tend to be common: helicity-conservation in fermion annihilation processes imposes transverse polarization of vector-like states



- **Longitudinal polarizations** are characteristic of massive gauge bosons



Longitudinal vector boson scattering

- Longitudinal polarization is only possible for 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**

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

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

- Then:

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

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:

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

Legendre polynomial (P_l) — Amplitude for l-angular momentum wave (a_l)

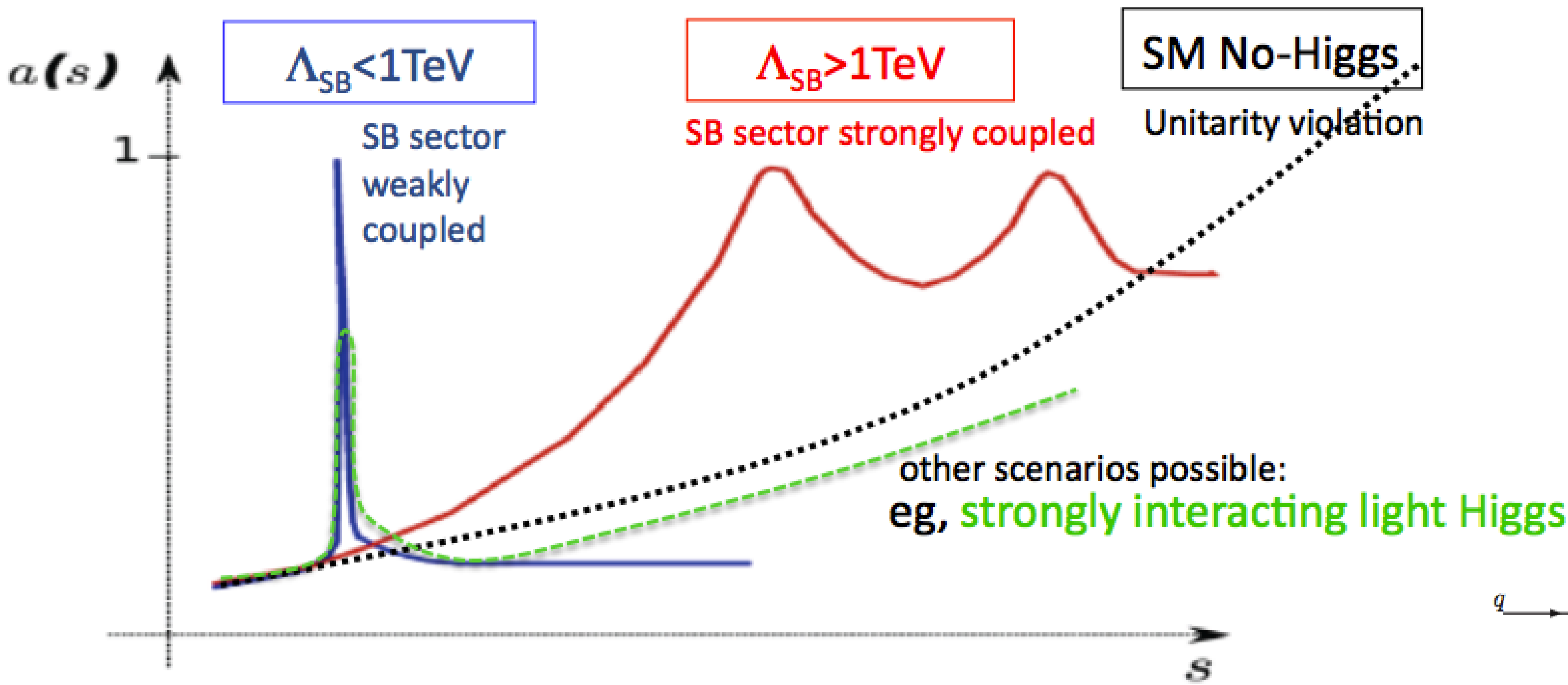
- But from the optical theorem $\sigma = \frac{1}{s}\mathrm{Im}[\mathrm{A}(\theta = 0)]$ which results in : $|\mathrm{Re}(a_\ell)| < \frac{1}{2}$

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

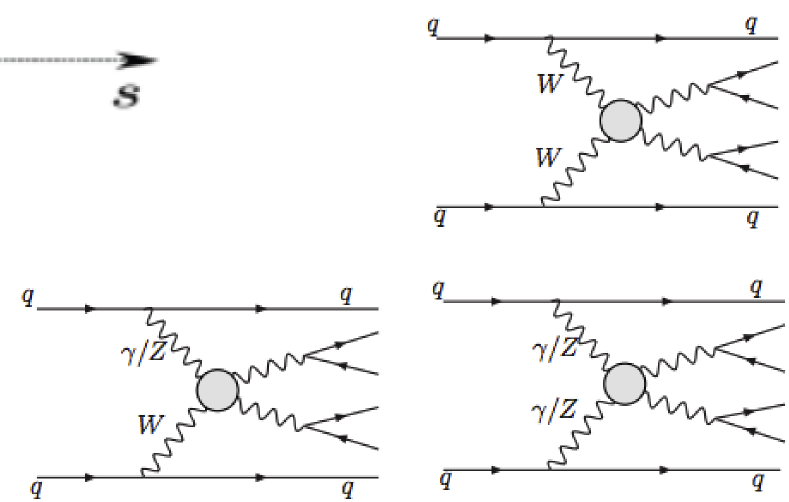
$$a_0 \overset{s \gg M_H^2}{\longrightarrow} -\frac{M_H^2}{8\pi v^2} \Rightarrow \boxed{M_H < 870 \text{ GeV}}$$

Possible scenarios for $V_L V_L$ scattering

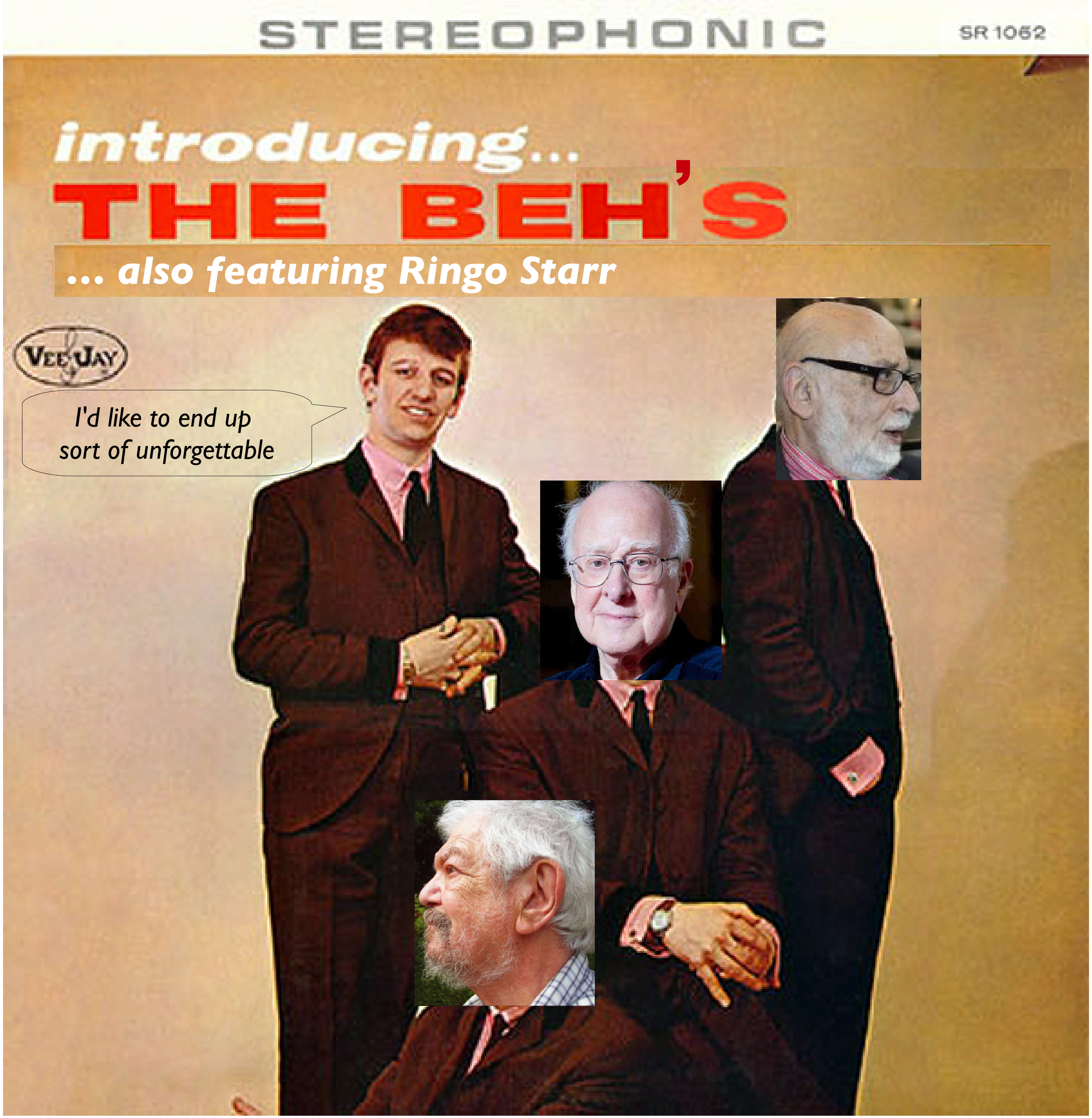
- Depending on the nature of the scalar boson (~~or its absence~~) expect distinct effects



VV scattering wil be the ultimate probe for the EWK symmetry breaking mechanism

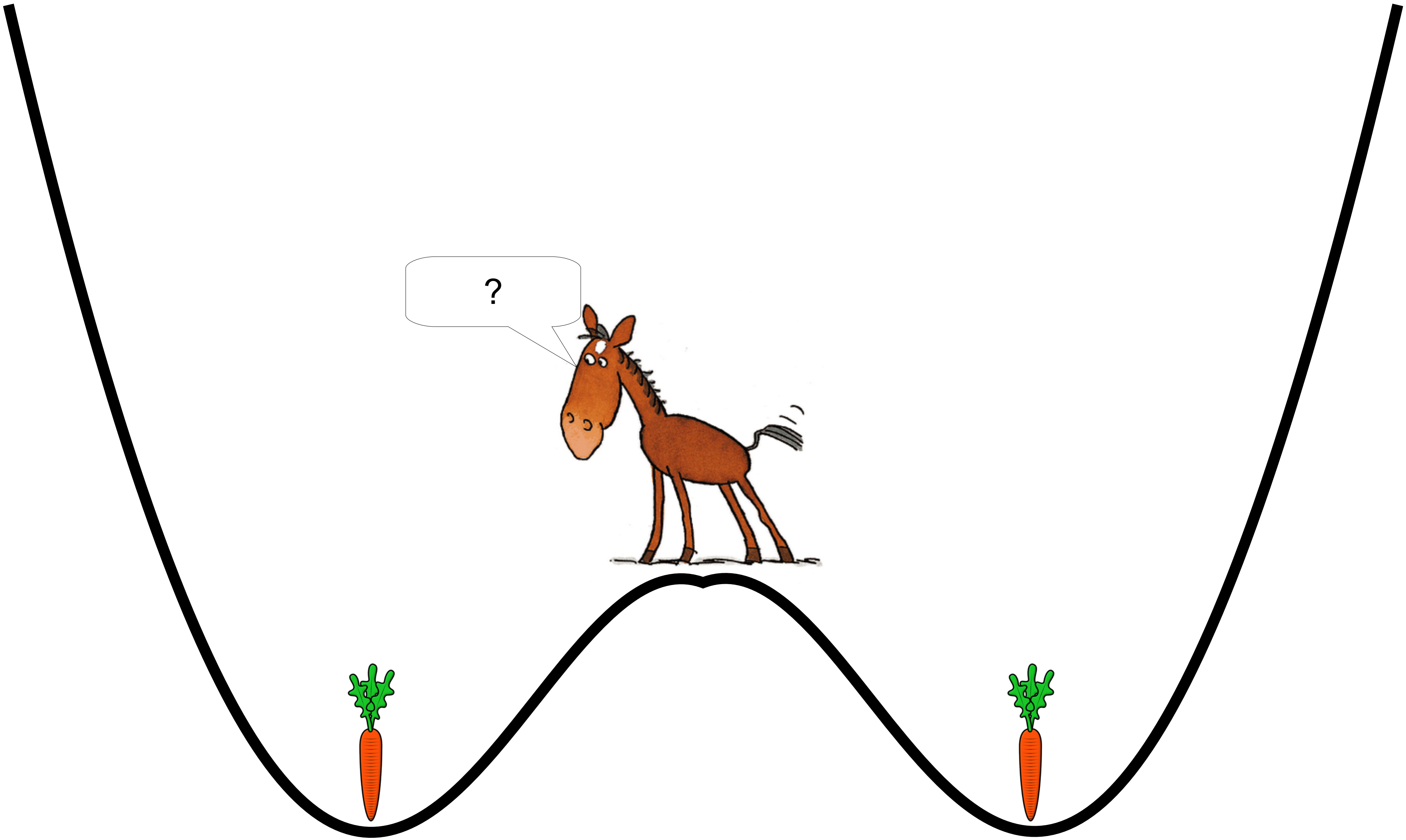



STEREOPHONIC
SR 1062
introducing...
THE BEATLES
ENGLANDS No.1 VOCAL GROUP
VEE JAY



STEREOPHONIC
SR 1062
introducing...
THE BEH'S
... also featuring Ringo Starr
VEE JAY
I'd like to end up
sort of unforgettable

Introducing the Higgs mechanism



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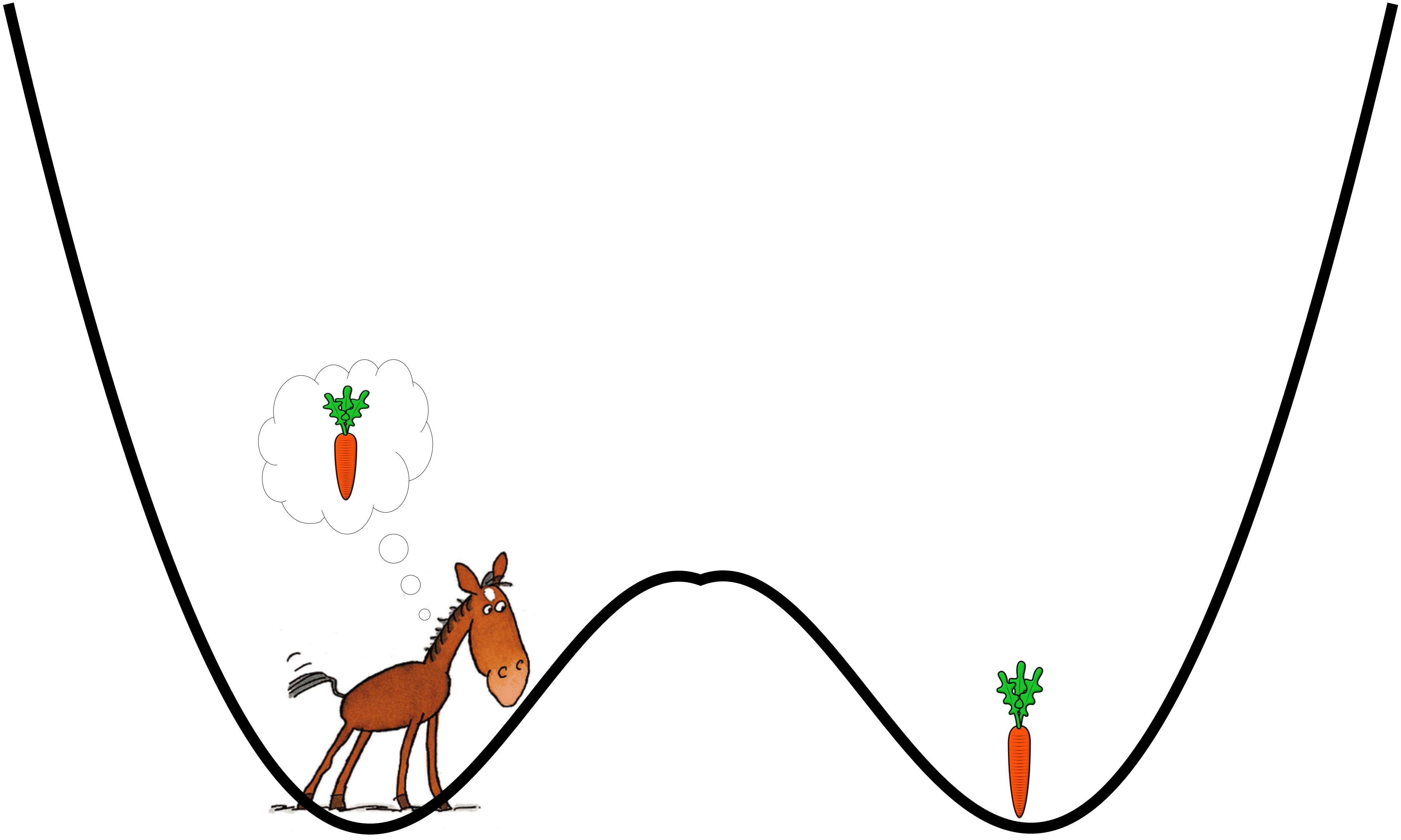

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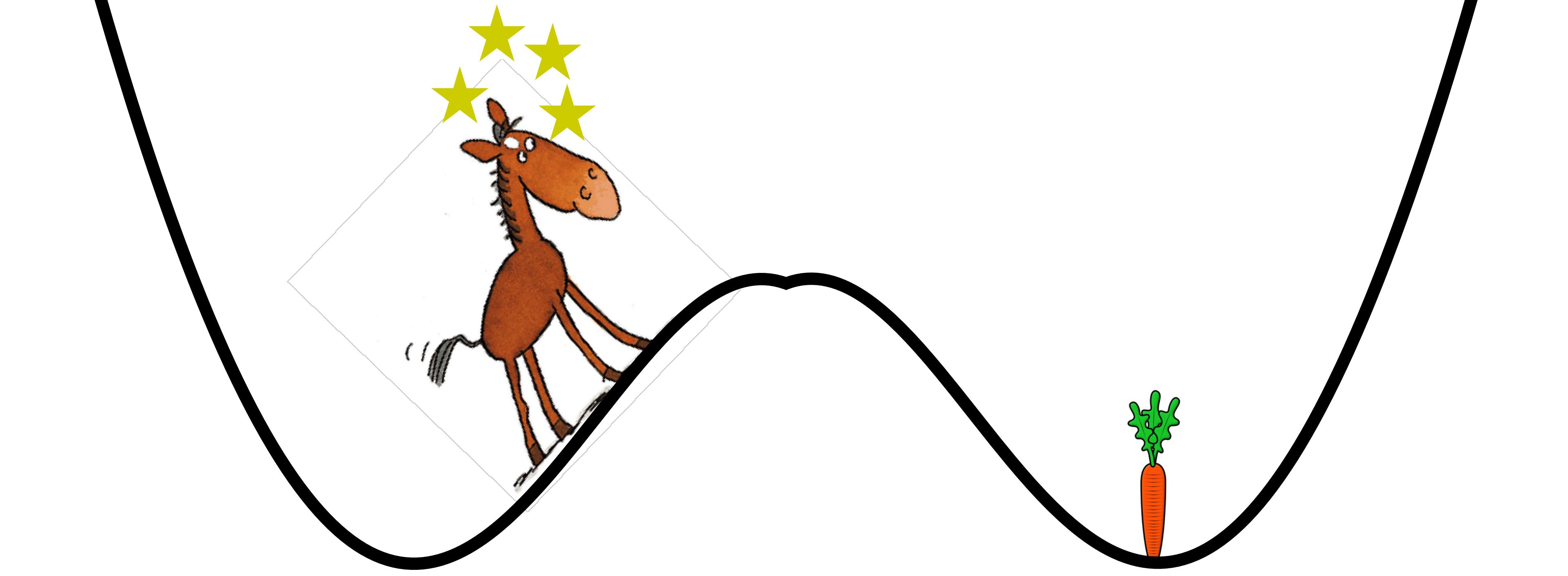

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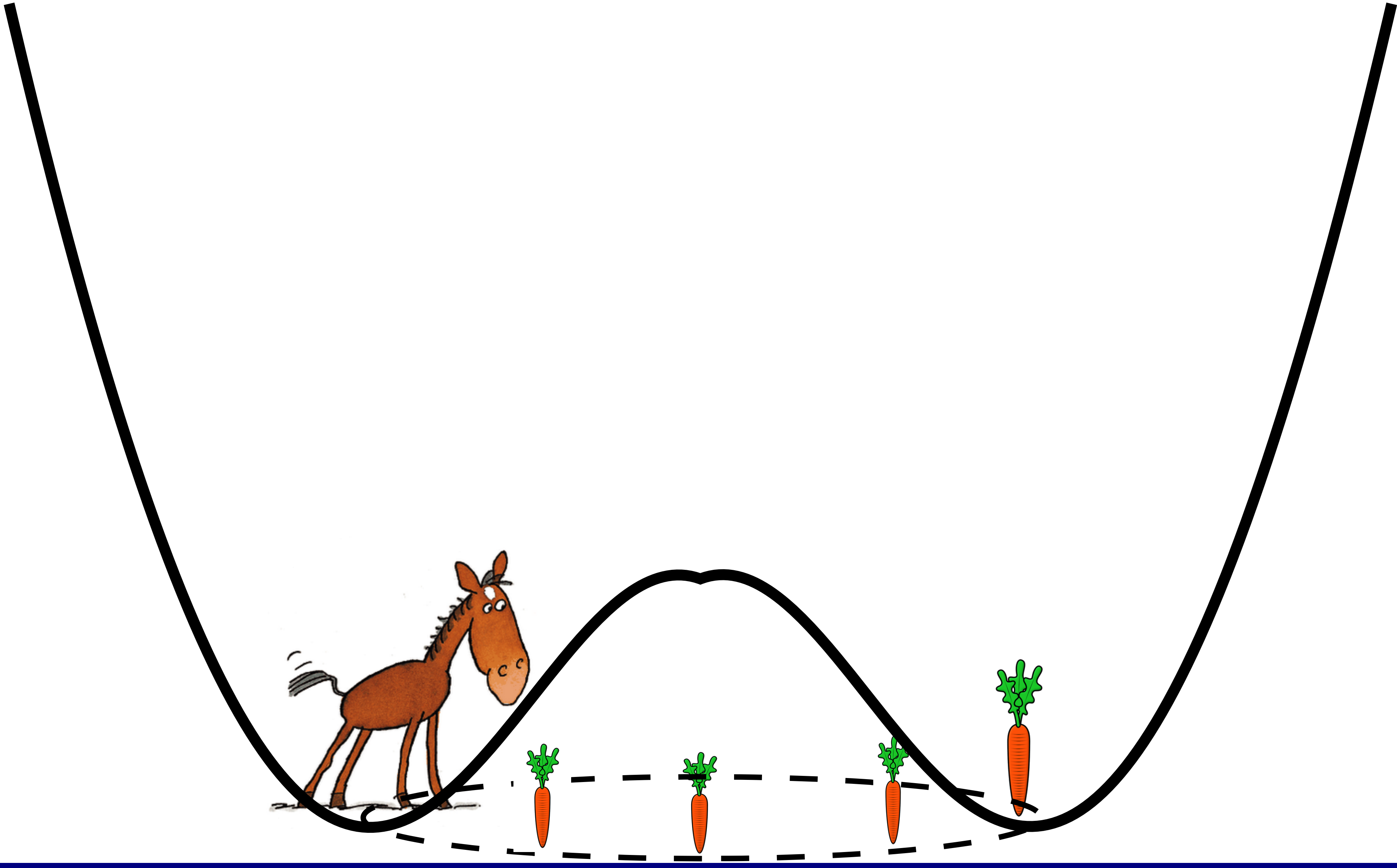

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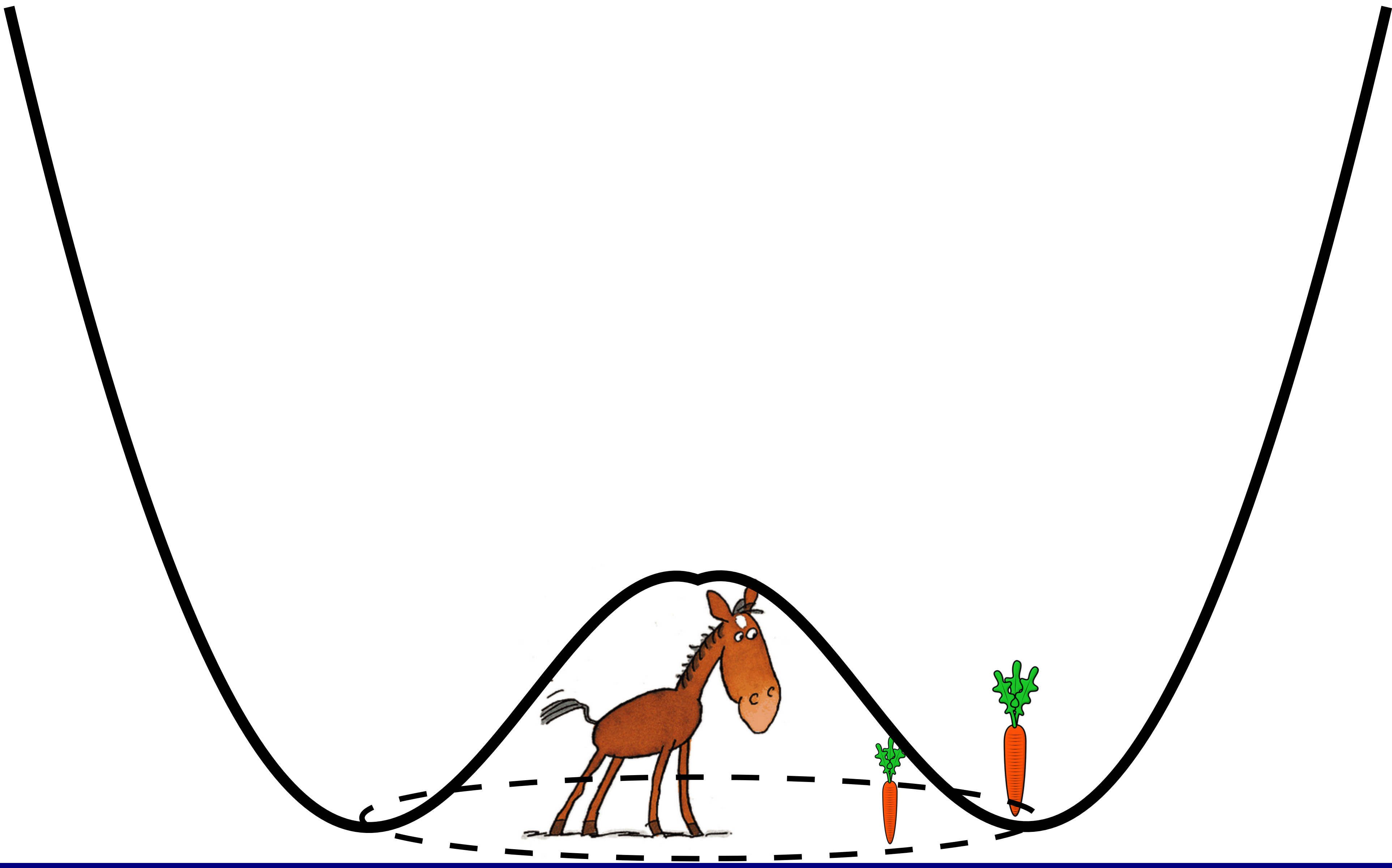
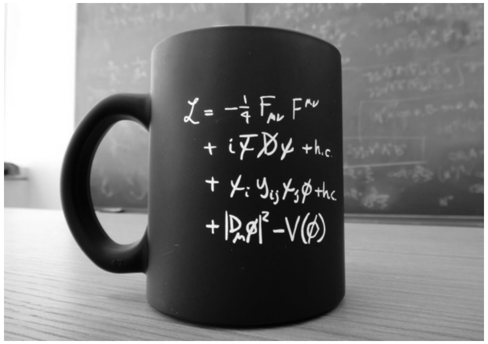
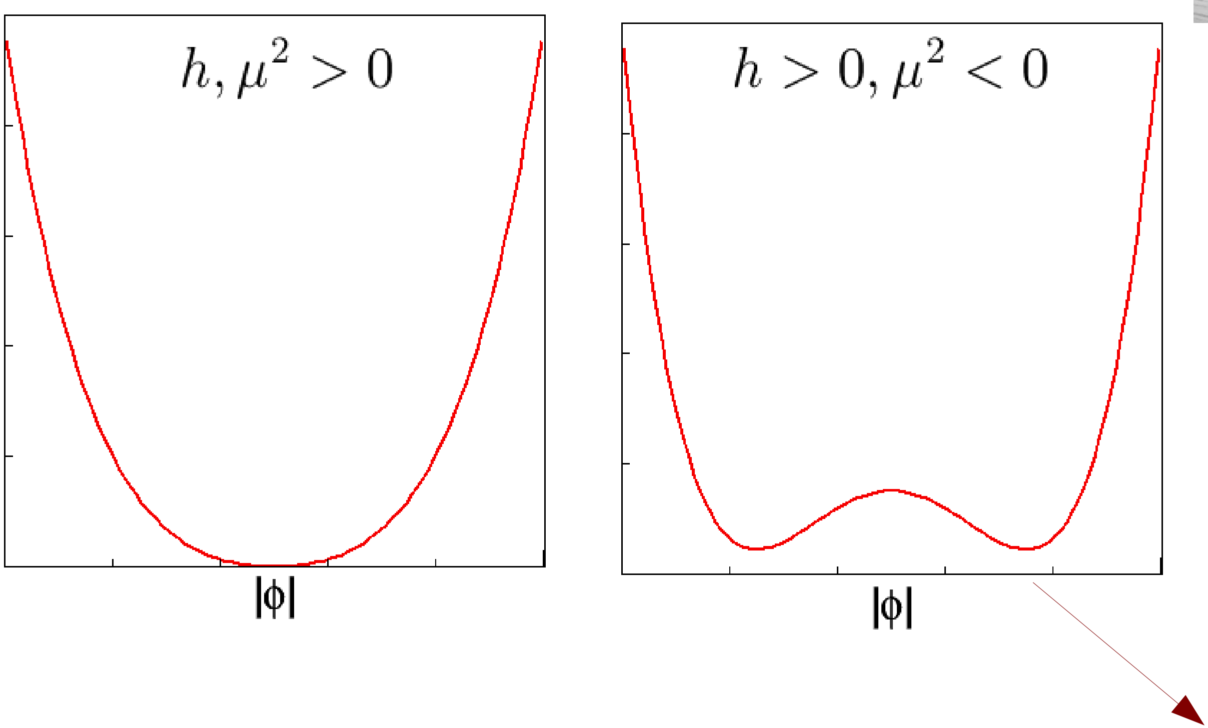


Higgs potential



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

  which has phase-symmetric potential: $V(\phi) = \mu^2 |\phi|^2 + h|\phi|^4$



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

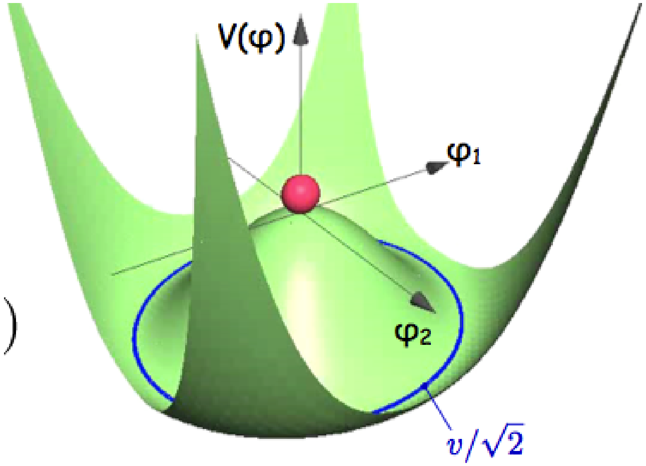
$$|\phi_0| = \sqrt{\frac{-\mu^2}{2h}} = \frac{v}{2} > 0$$

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

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

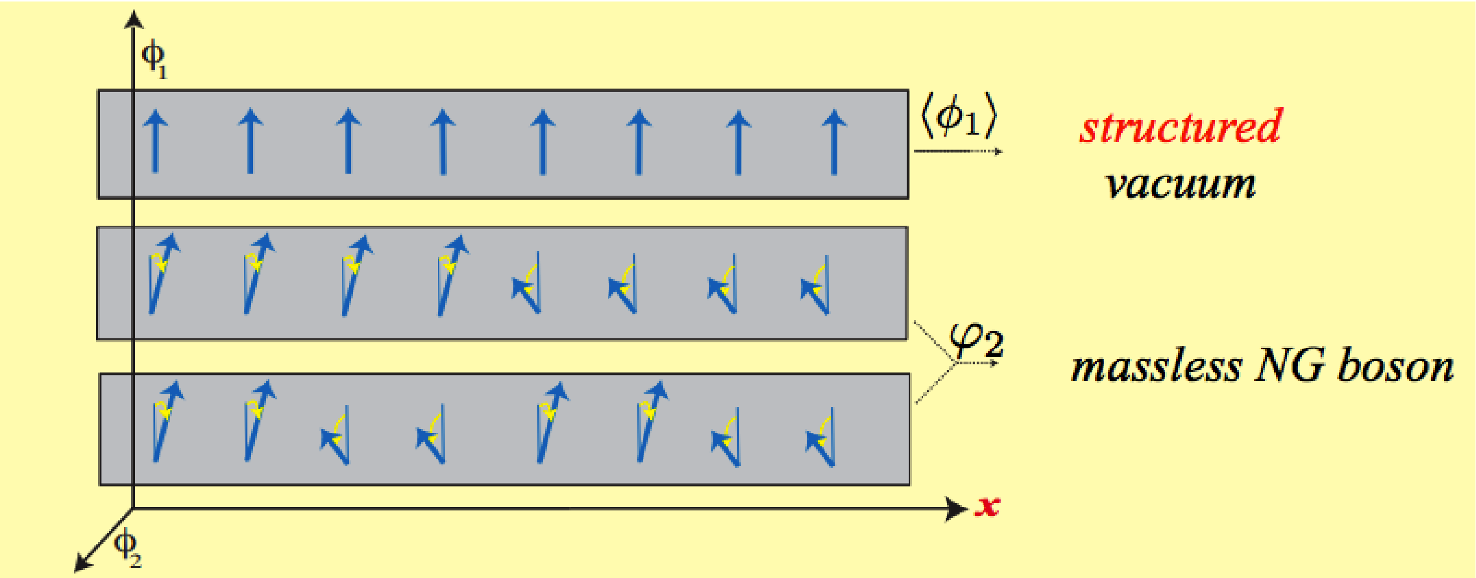
- The massless Goldstone bosons can be rotated away due to $SU_L(2)$ invariance

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

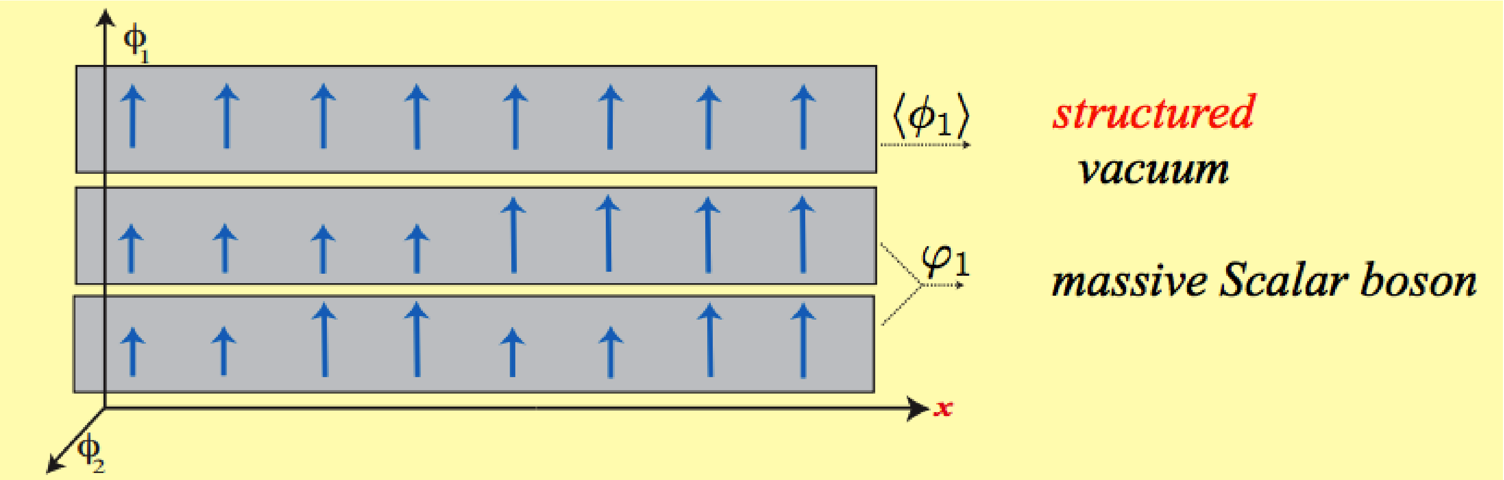
$$(D_\mu\phi)^\dagger D^\mu\phi \rightarrow \frac{1}{2}\partial_\mu H \partial^\mu H + \frac{g^2}{4}(v+H)^2 \left[W_\mu^\dagger W^\mu + \frac{1}{2cos^2\theta_W} Z_\mu Z^\mu \right]$$

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

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

More on Goldstone bosons

- **Picture an infinite straight rope** (it has translation invariance)
  - break its translational invariance in direction perpendicular to it

$$\frac{1}{c^2}\frac{\partial^2\phi}{\partial t^2} = \frac{\partial^2\phi}{\partial x^2} \quad \longrightarrow w^2 = c^2 k^2$$

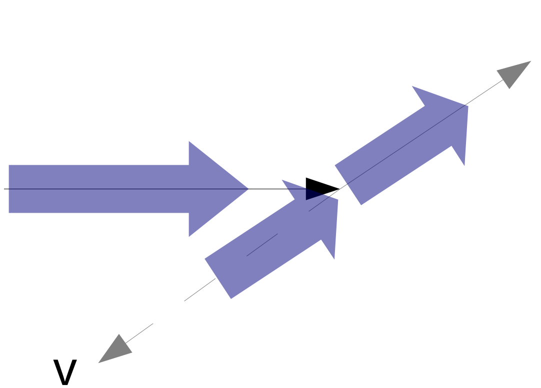
  - the **transverse waves** are the **Goldstone modes**
  - Waves can propagate with arbitrary frequency

    → after quantization will generate massless particles

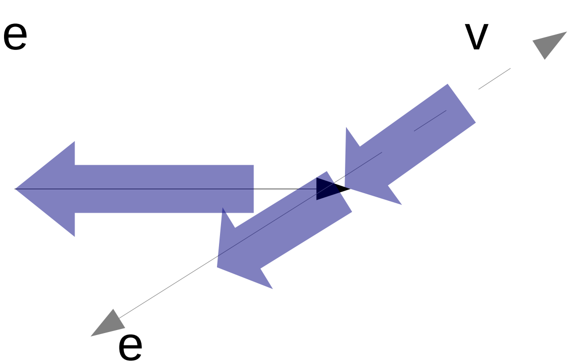
- **EWK ground state / the vacuum is said to be “spontaneously broken”**
  - A spontaneously broken symmetry always produces a massless scalar particle.
  - If the symmetry is approximate, the particle won’t be massless, but can be very light.

Vector bosons at high energy

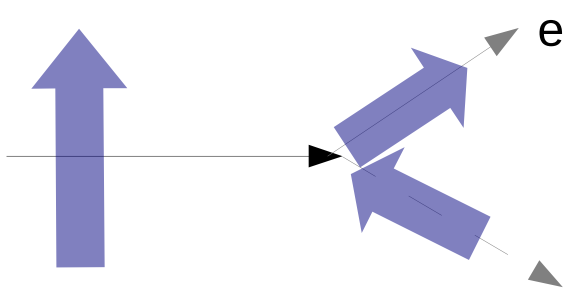
- **In the limit $m_V/s^{1/2} \rightarrow 0$**
  - the mass can be neglected, vector bosons acquire large boost
  - W/Z become effectively goldstone bosons because longitudinal polarization dominates



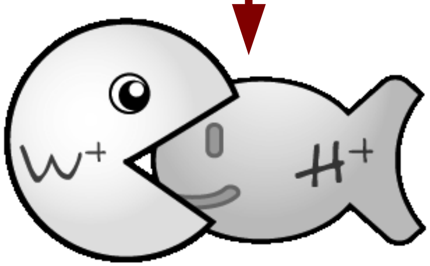
right-handed



left-handed



longitudinal-polarization



- **The longitudinal component corresponds in practice to a "swallowed" goldstone bosons ►**

Fermions also acquire mass

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

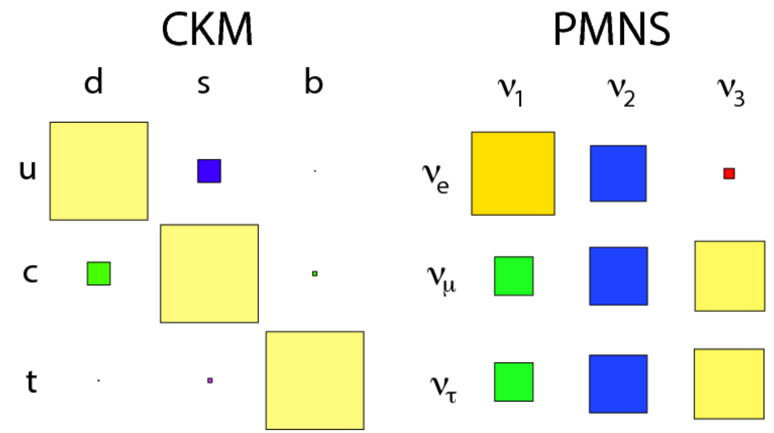
- **Fermion masses are free Yukawa couplings** to the Higgs boson

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

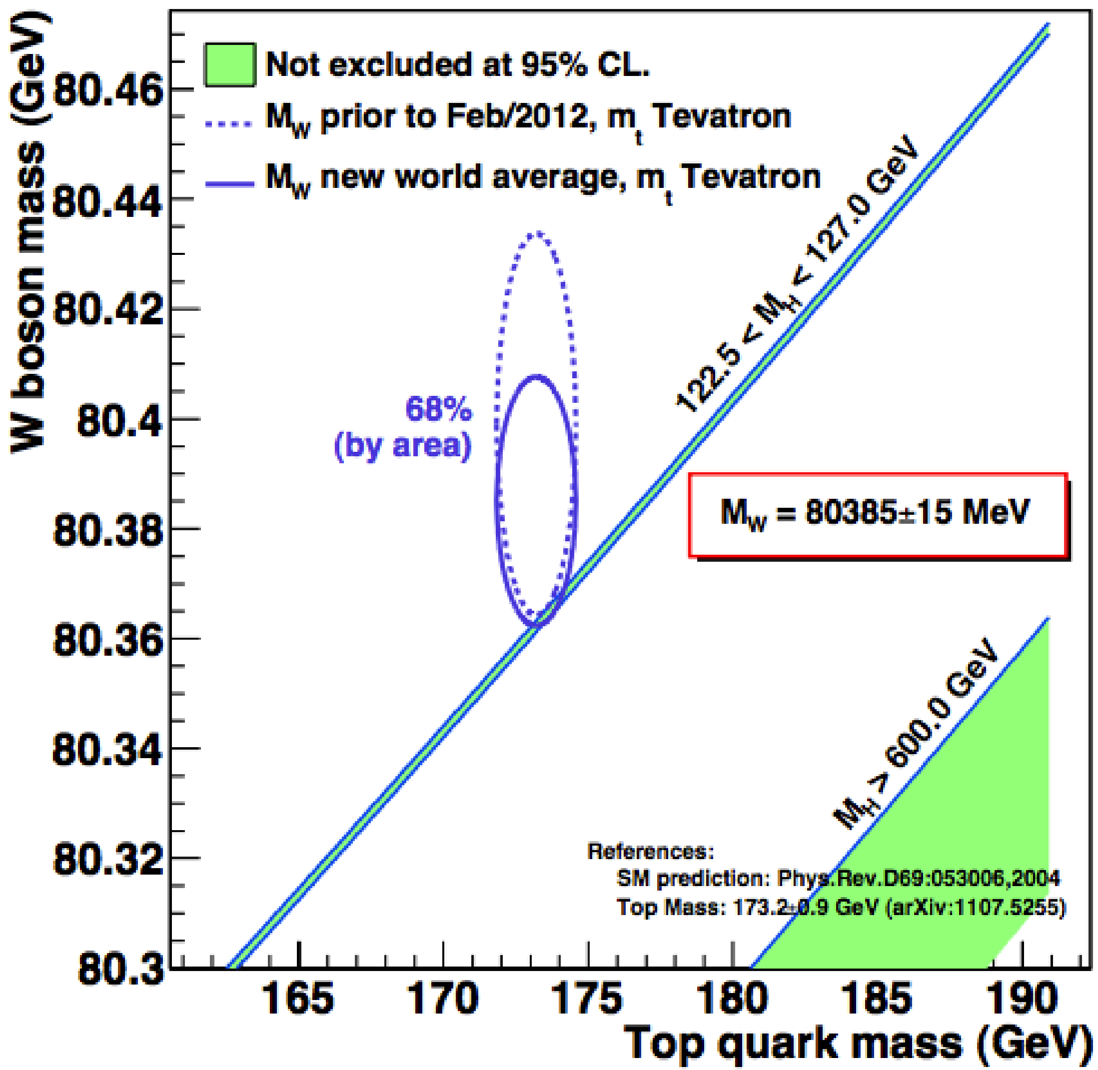
spontaneous symmetry breaking

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

- As there are 3 generations of fermions differing by mass
  - these terms are arbitrary non-diagonal, complex matrices
  - **mass eigenstates ≠ weak eigenstates** → **mixing**

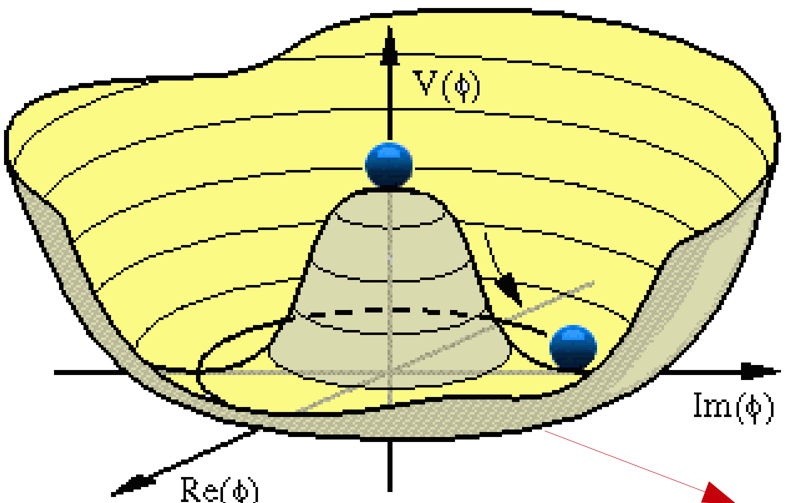


And what about the Higgs mass?

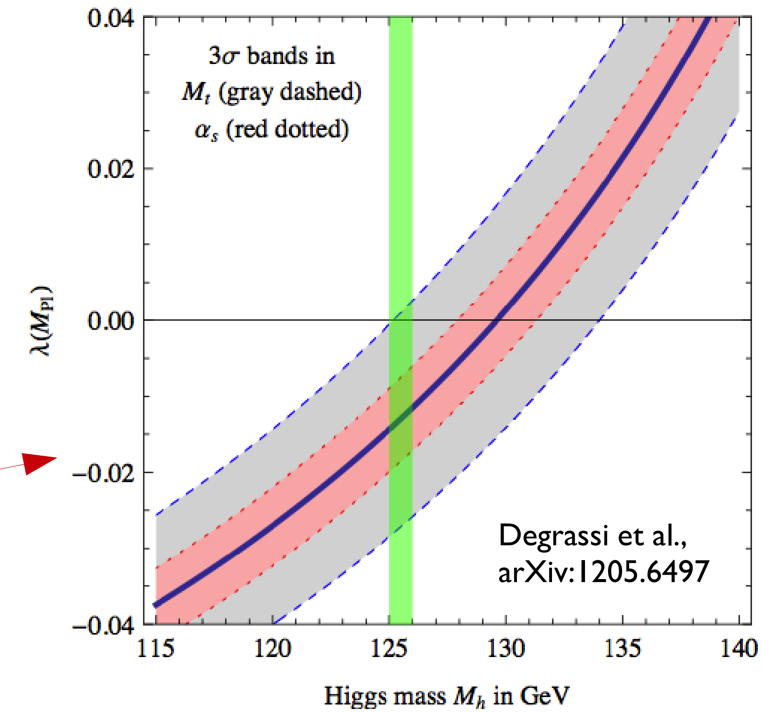


- The mass of the heaviest particles is correlated from loop corrections including the Higgs boson
- The preferred region is compatible at 68% CL with the SM Higgs boson candidate mass at 95% CL

Higgs mass and vacuum stability



$$|\phi_0| = \frac{v}{2} = \sqrt{\frac{-\mu^2}{2\lambda}}$$

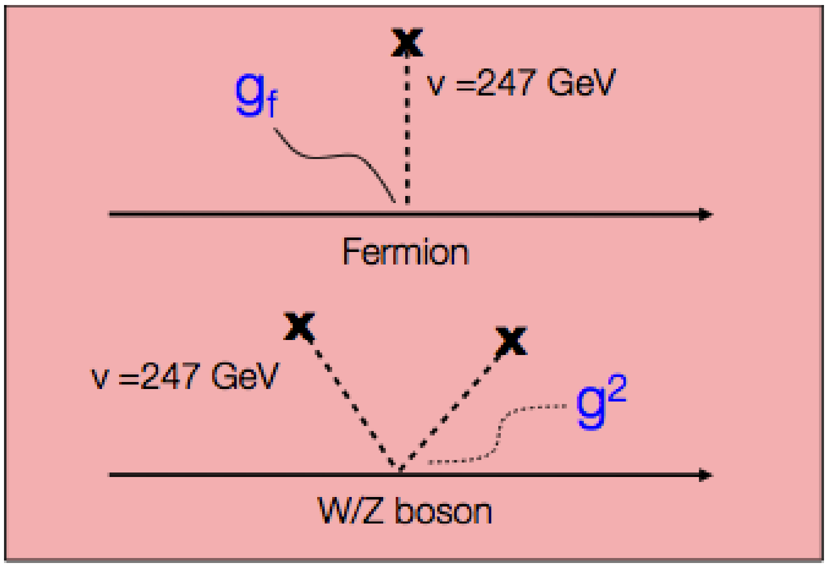


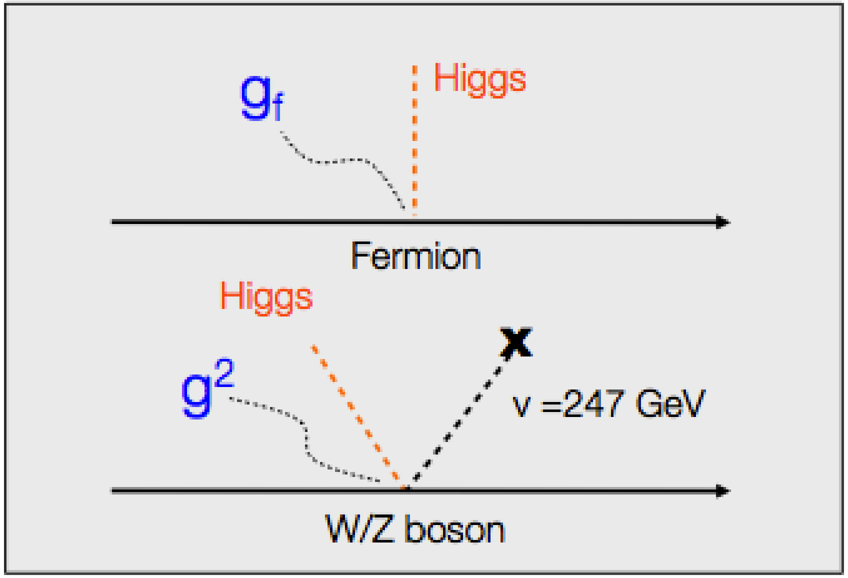
- The Higgs mass has a strong dependency on m_{top} → influence on quartic coupling
- Using current measurements vacuum stability up to the Planck scale may be excluded at 2-σ

$$M_h\ [\mathrm{GeV}] > 129.4 + 1.4\left(\frac{M_t\ [\mathrm{GeV}] - 173.1}{0.7}\right) - 0.5\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1.0_{\rm th}$$

  - exp. uncertainties dominate: 1.4 GeV from m_{top} and 0.5 GeV from α_s

Summarizing the nature of the new interaction





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

    $$m_f \sim g_f v$$

  - Gauge boson masses from gauge couplings

    $$M_V \sim g v$$

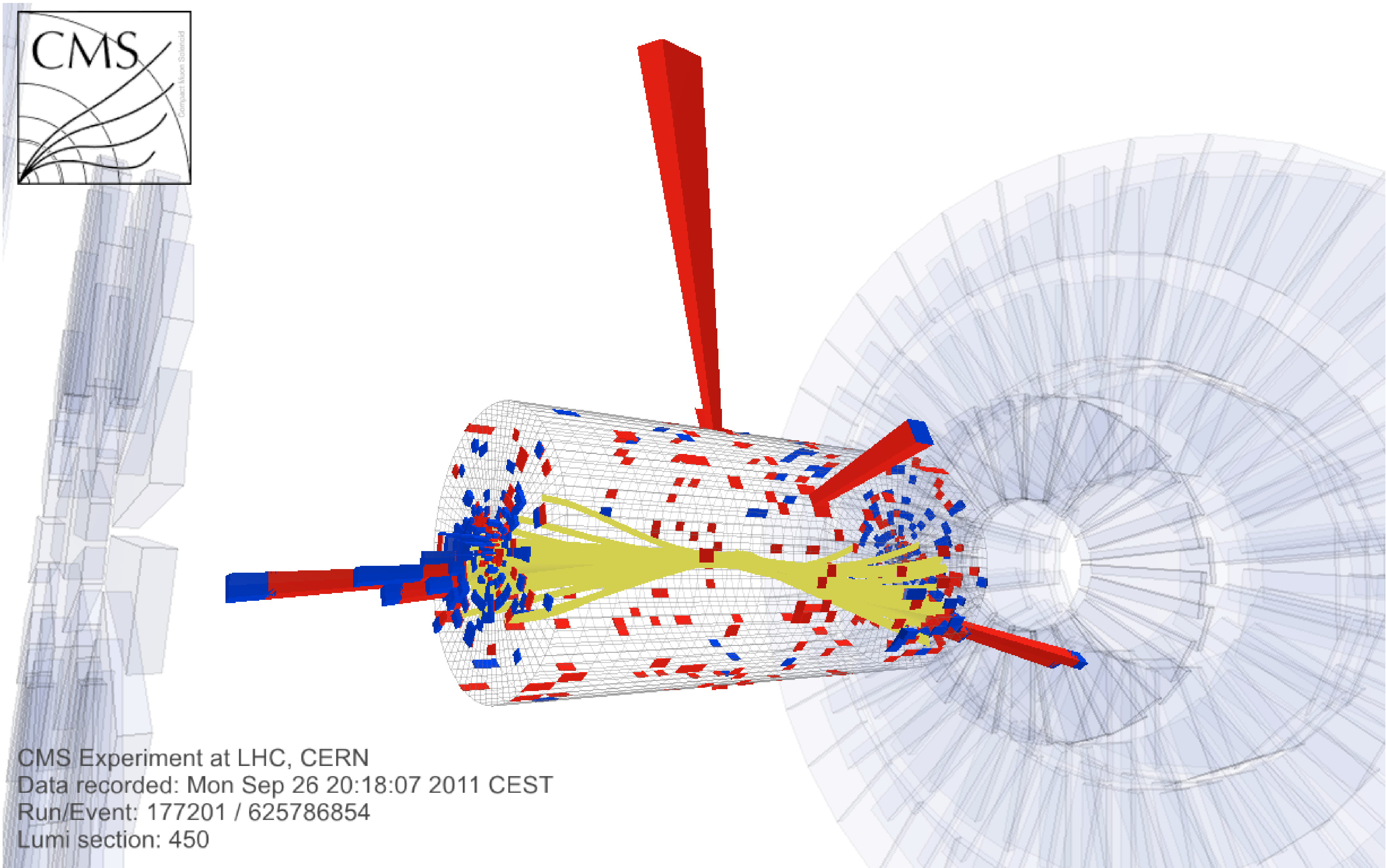
- **With the Higgs boson,** proportional to
  - the fermion masses

    $$g_f \sim m_f / v$$

  - the mass squared of gauge bosons

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

Tracing the Higgs boson at particle colliders

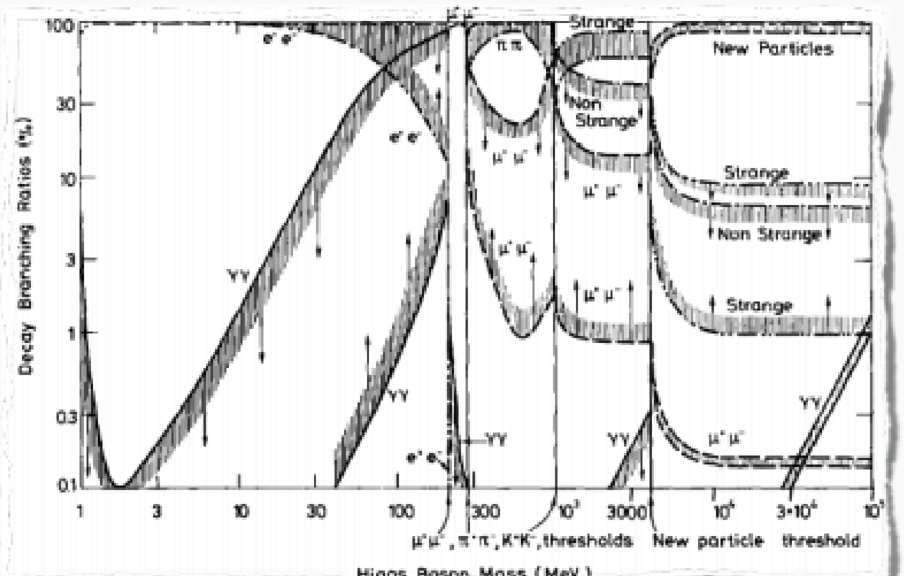


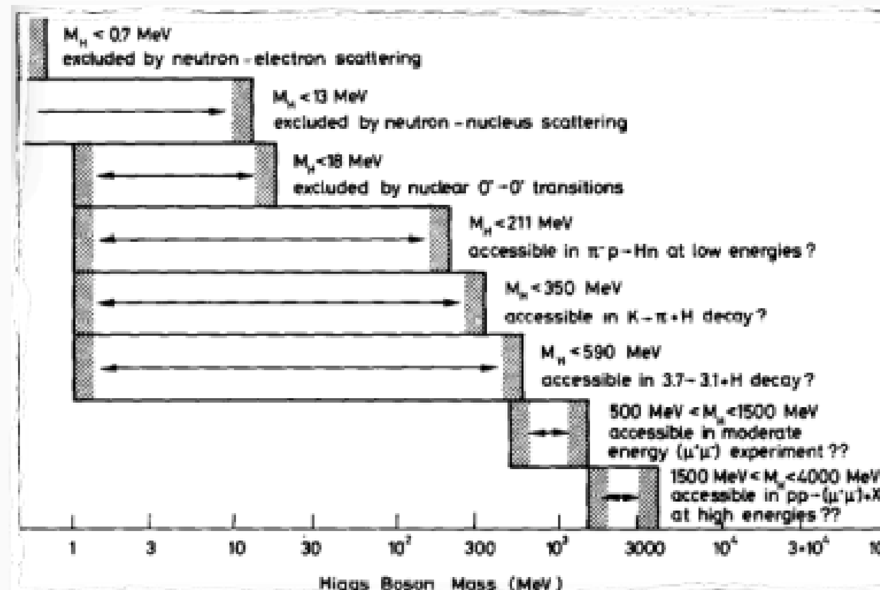
Back in 1975...

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

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

Received 7 November 1975





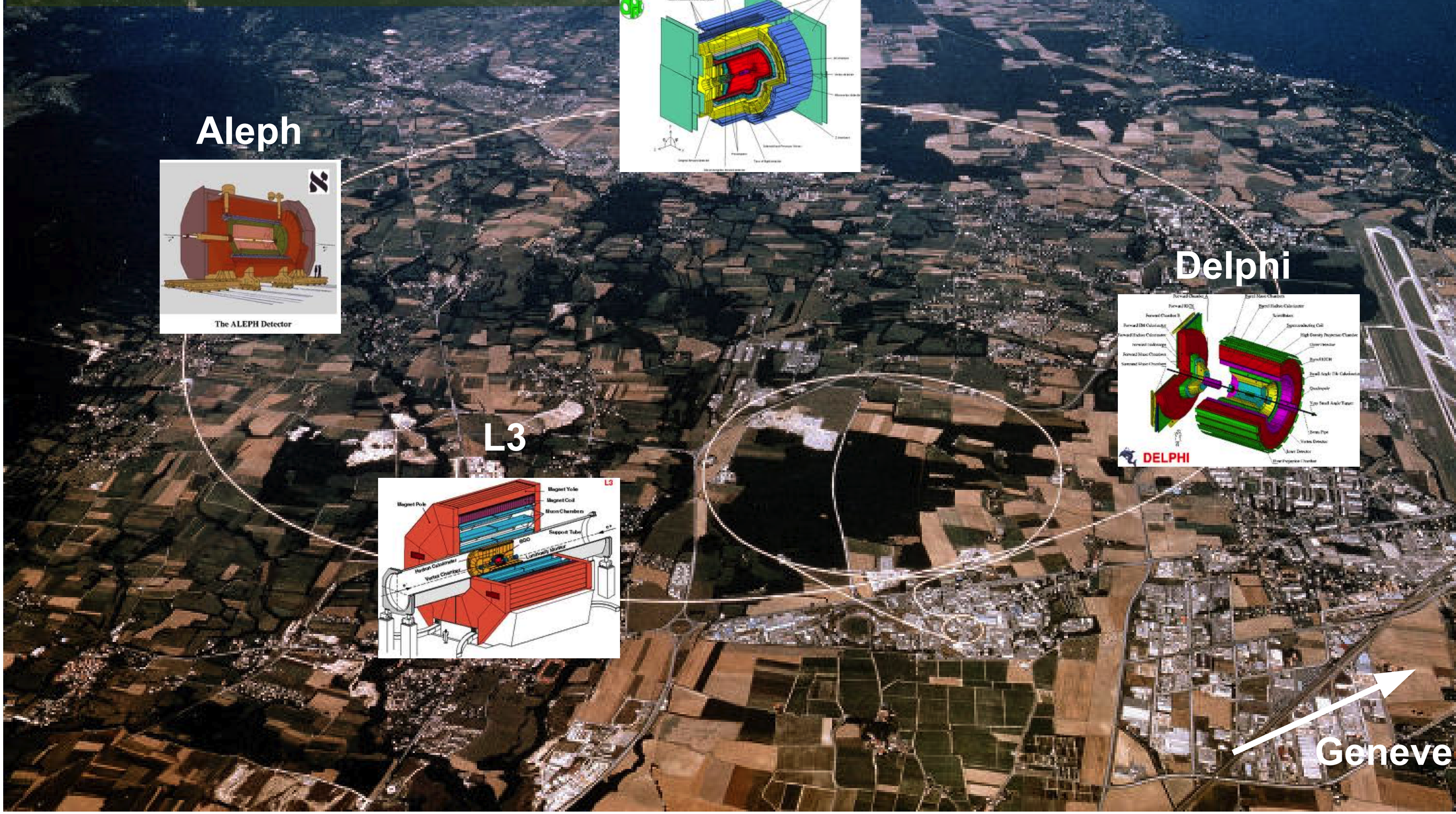
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons 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.

...and so they searched for it at LEP....

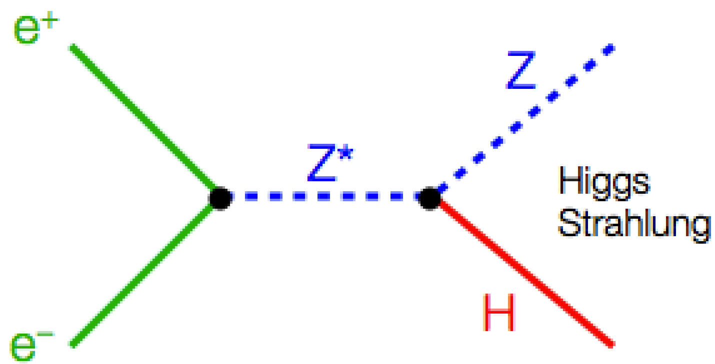
Electron-positron collider up to $s^{1/2}$= 209 GeV

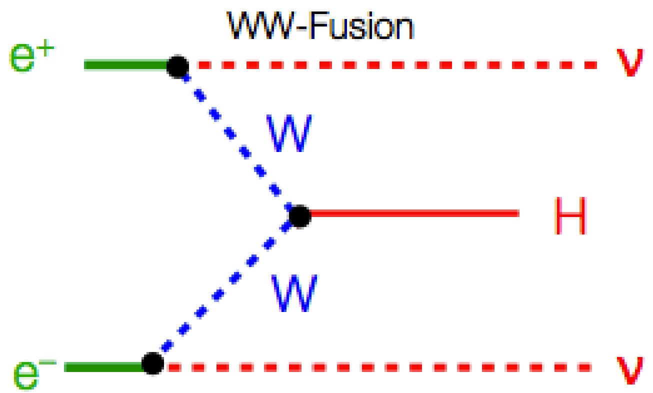
Integrated luminosity: ~700 pb^{-1}

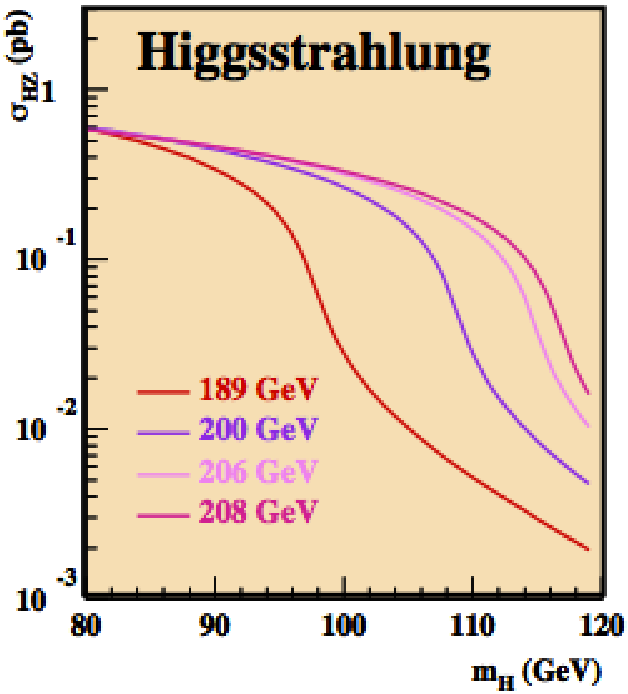
Shutdown: September 2000

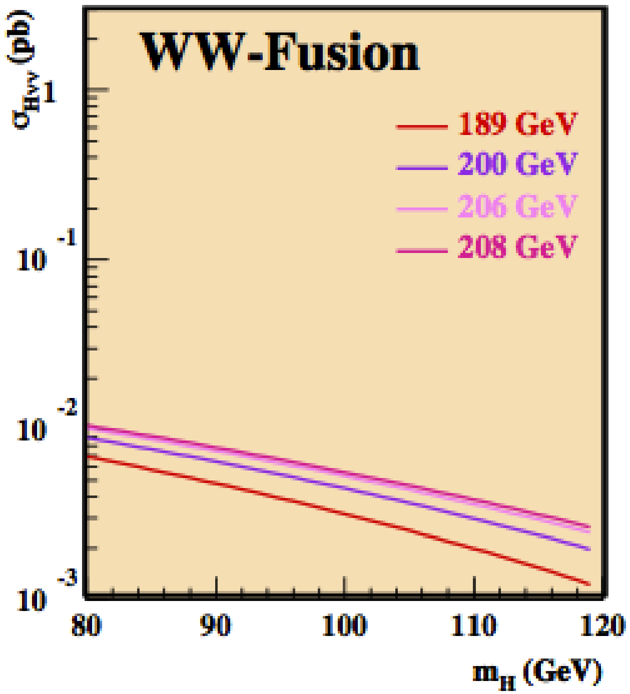


Higgs production at LEP

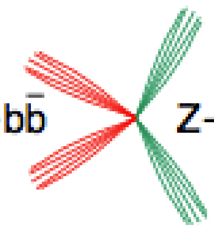
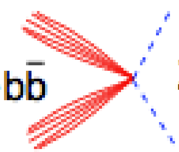
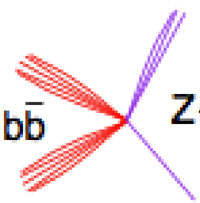
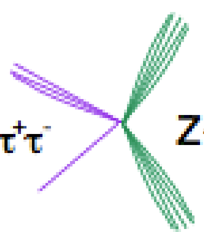




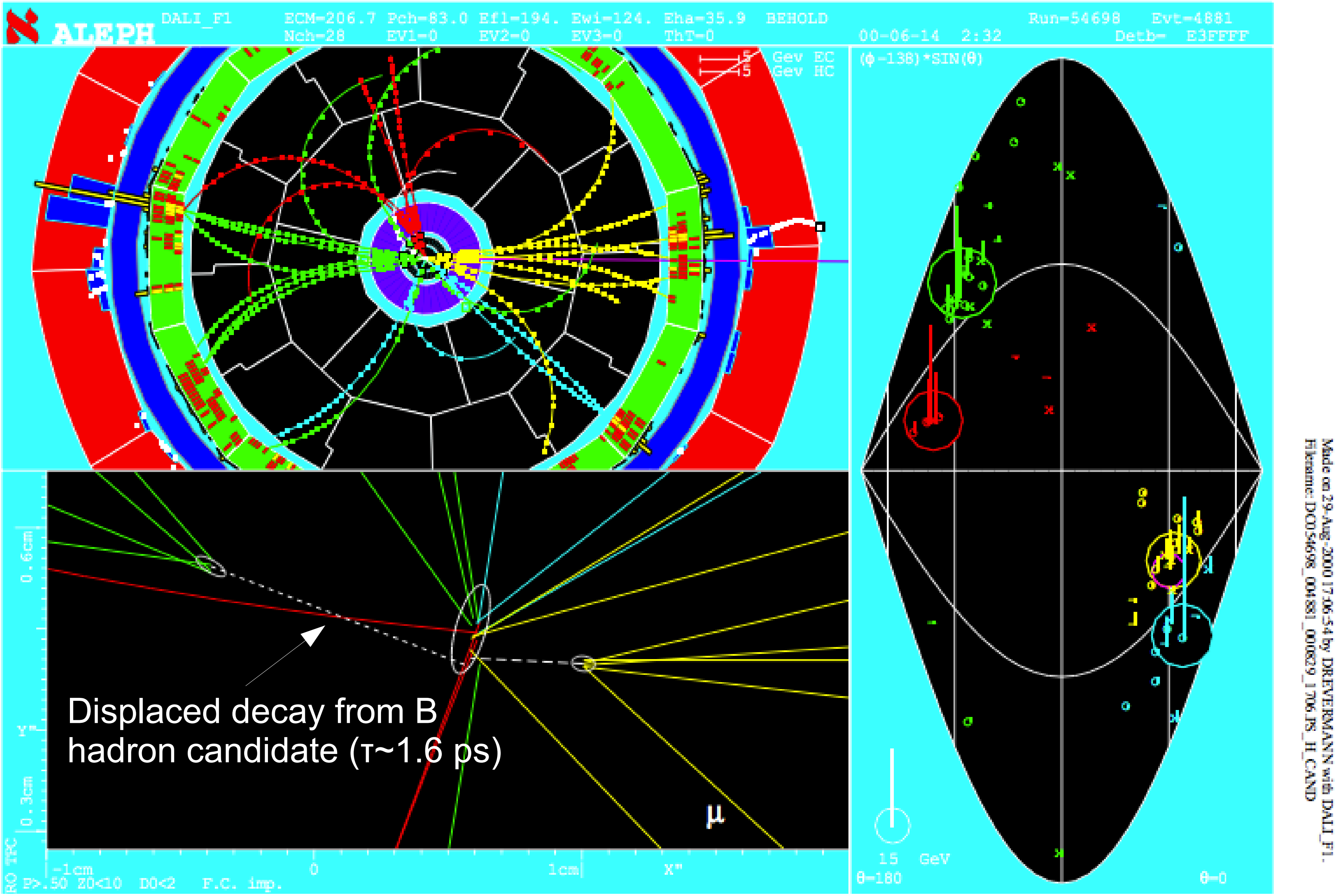




At LEP: look for 3rd generation decays

	$H \to b\bar{b}$, $Z \to q\bar{q}$	4-jets	51%	WW → qqqq ZZ → qqqq QCD 4-jets
	$H \to b\bar{b}$, $Z \to \nu\bar{\nu}$	missing energy	15%	WW → qqlν ZZ → bbνν
	$H \to b\bar{b}$, $Z \to \tau^+\tau^-$	τ-channel	2.4%	WW → qqτν ZZ → bbττ ZZ → qqττ 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 → bbee ZZ → bbμμ

LEP H → bb candidate



Candidates @ LEP

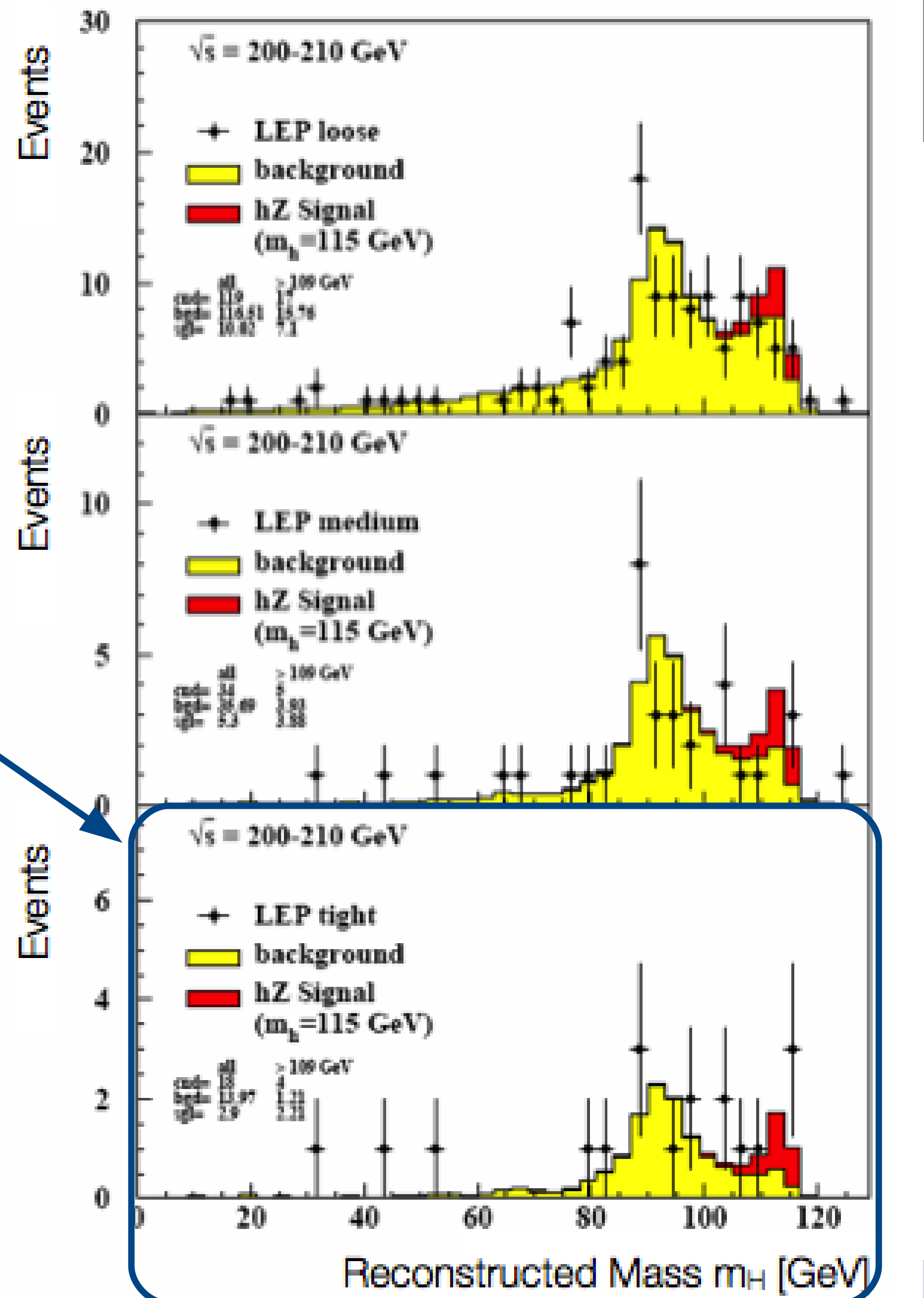
- **Invariant mass** of the candidate events
  - 17 candidates are observed

    15.8 background events expected

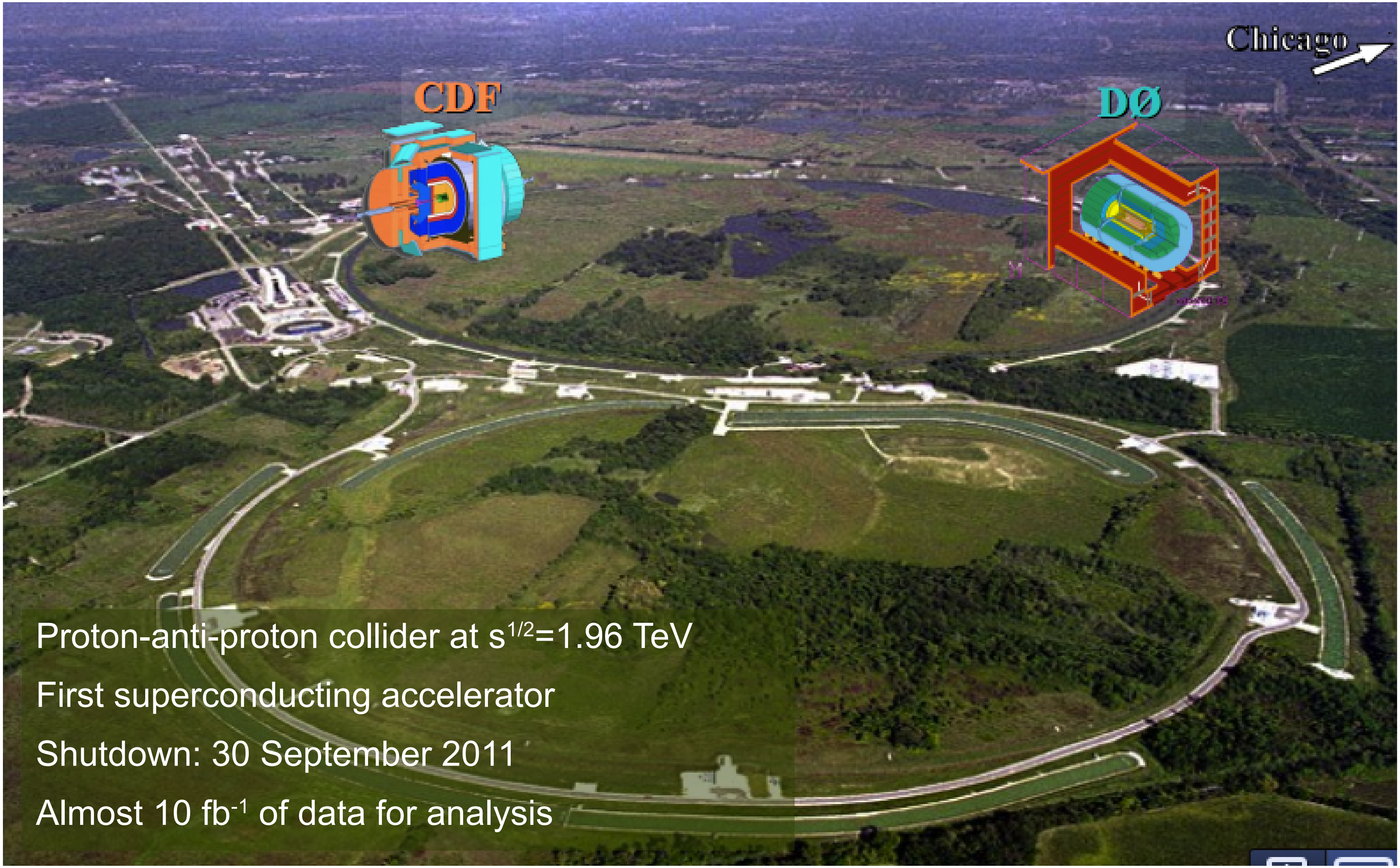
    8.4 signal events expected (m_H=115 GeV)
  - consistent with background predictions

- **Final verdict from LEP:**

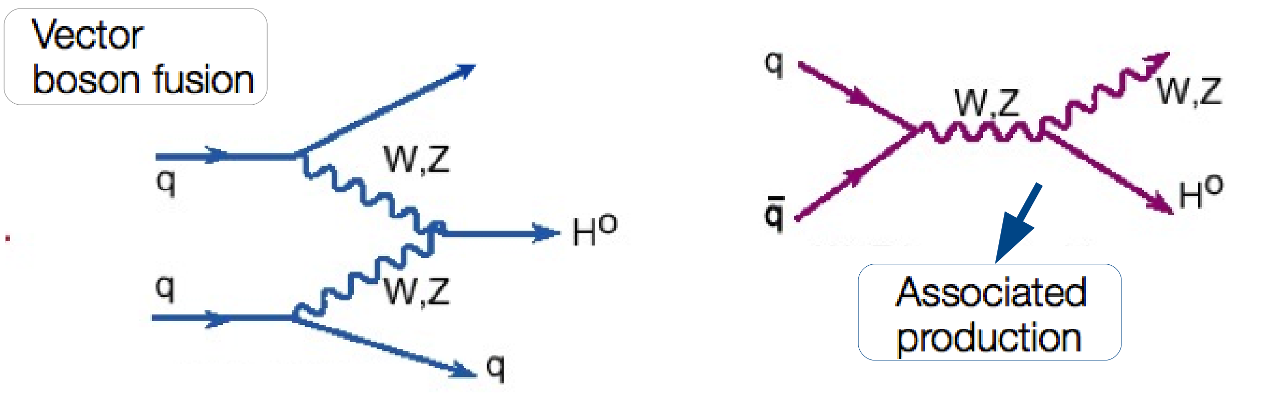
M_H > 114.4 GeV @ 95% CL



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



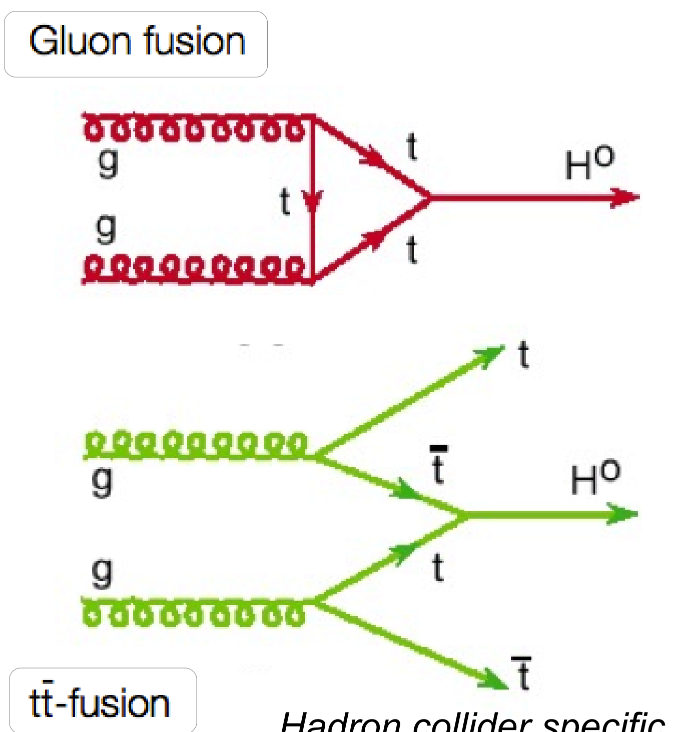
Search for the Higgs at the Tevatron



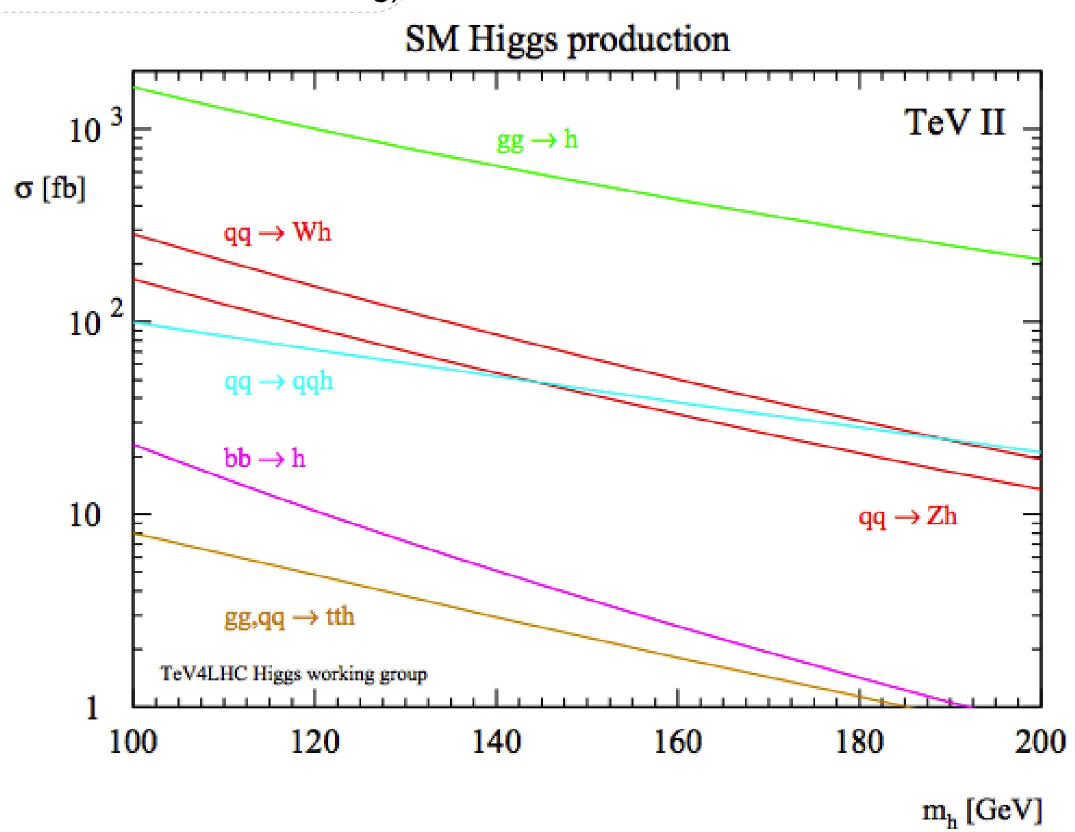
Similar to LEP (fermion annihilation/scattering)

No single channel has enough sensitivity

Explore all possibilities and maximize acceptance



Hadron collider specific



Look for all possible decays

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

$$\Gamma_{f\bar{f}} = \frac{N_c G_F m_f^2 M_H}{4\sqrt{2}\pi}\beta^3 \quad \text{where } \beta = \sqrt{1-\frac{4m_f^2}{M_H^2}}$$

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

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

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

- **Gluons:** through top quark loops

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

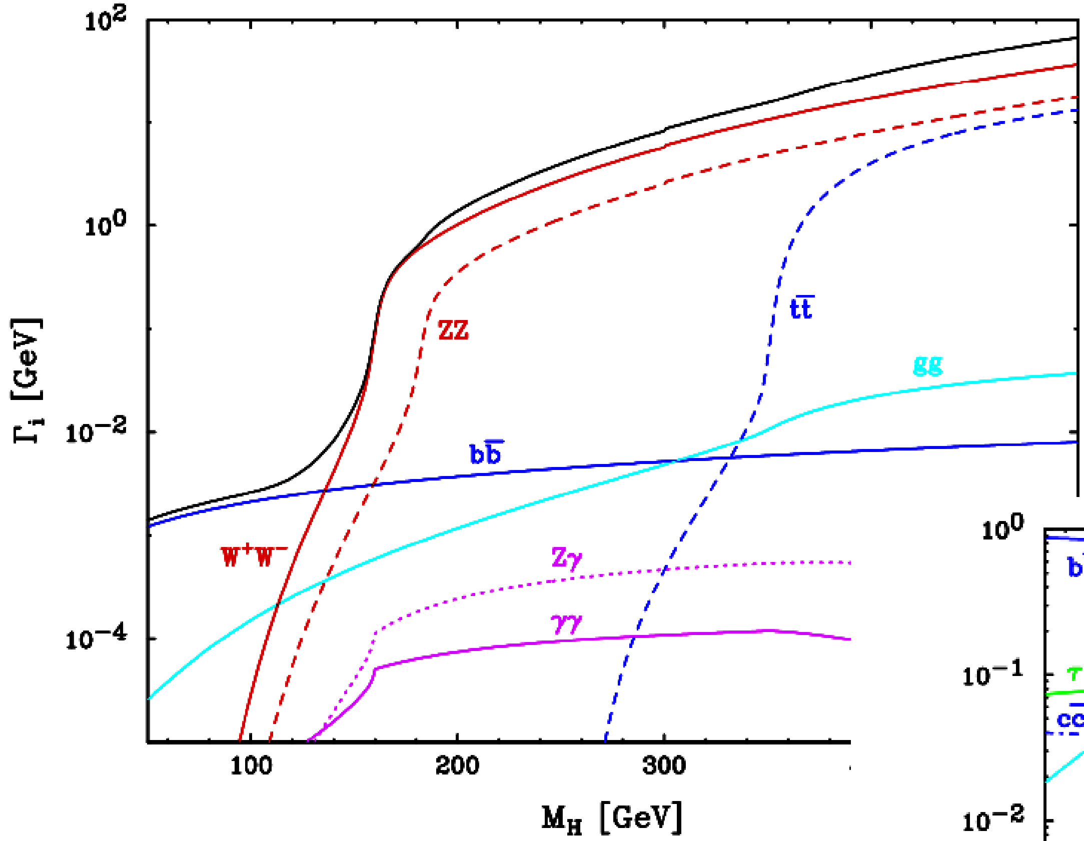
$$\text{with } \tau_i = \frac{4m_f^2}{M_H^2} \text{ and } f(\tau) = \begin{cases} \left[\sin^{-1}\sqrt{1/\tau}\right]^2 & \tau \geq 1 \\ -\frac{1}{4}\left[\ln\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 & \tau < 1 \end{cases}$$

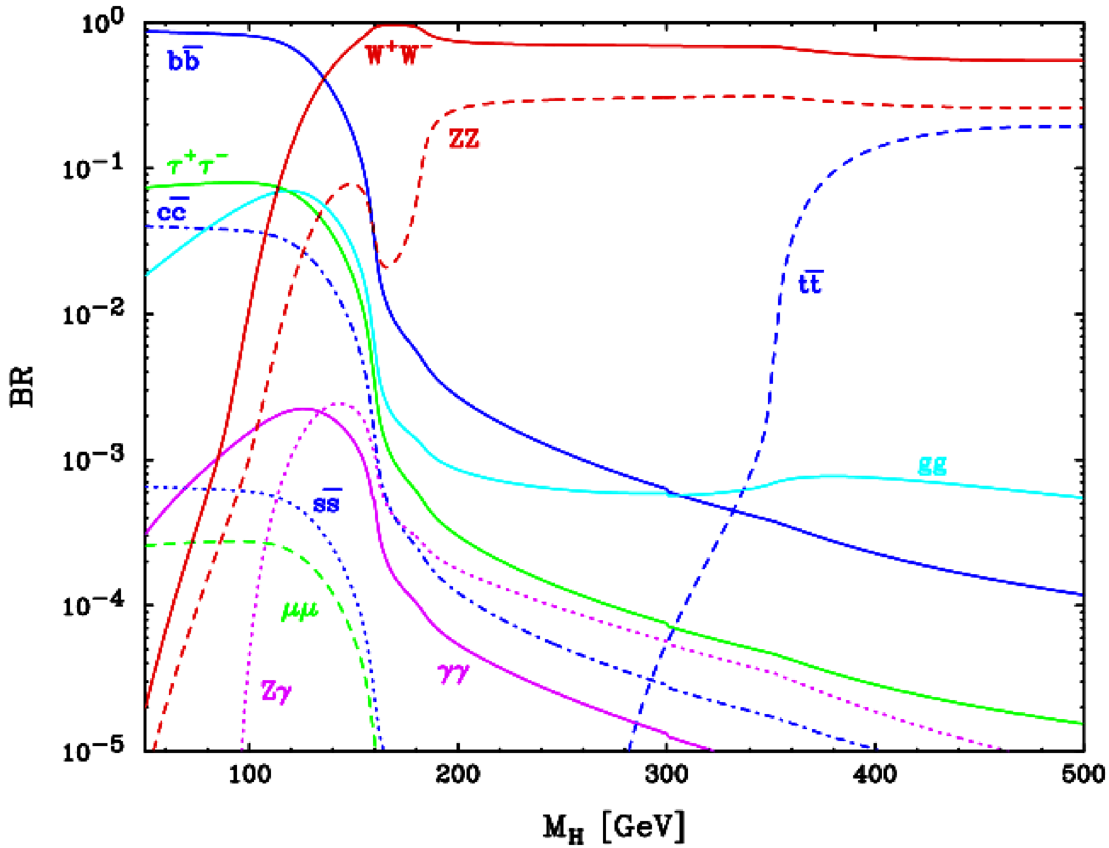
- **Photons through top and W boson loops** (Zγ partial width is similar in structure)

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

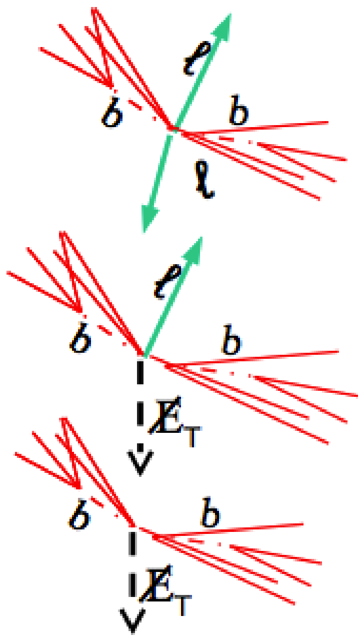
$$F_1 = 2 + 3\tau[1+(2-\tau)f(\tau)]$$
$$F_{1/2} = -2\tau[1+(1-\tau)f(\tau)]$$
$$F_0 = \tau[1-\tau f(\tau)]$$

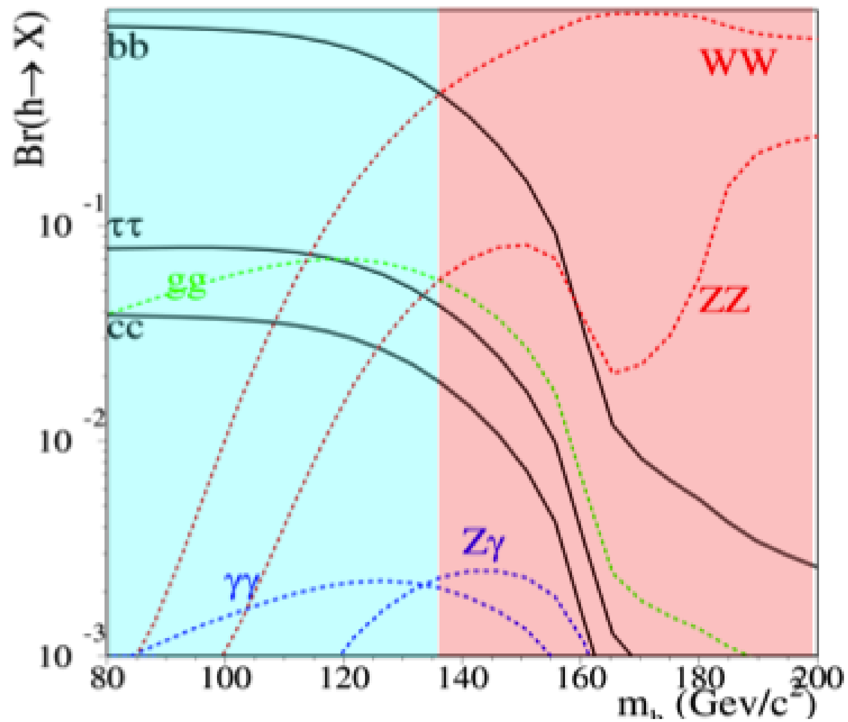
Look for all possible decays – cont.

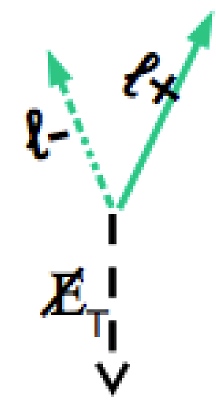




Most sensitive channels at the Tevatron



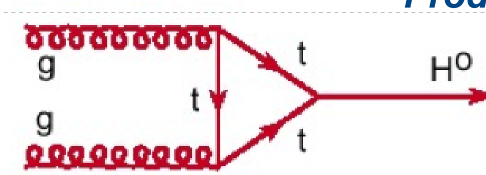




Topology

- bb+X final states
- 2l2v final states

Production mode



Requires

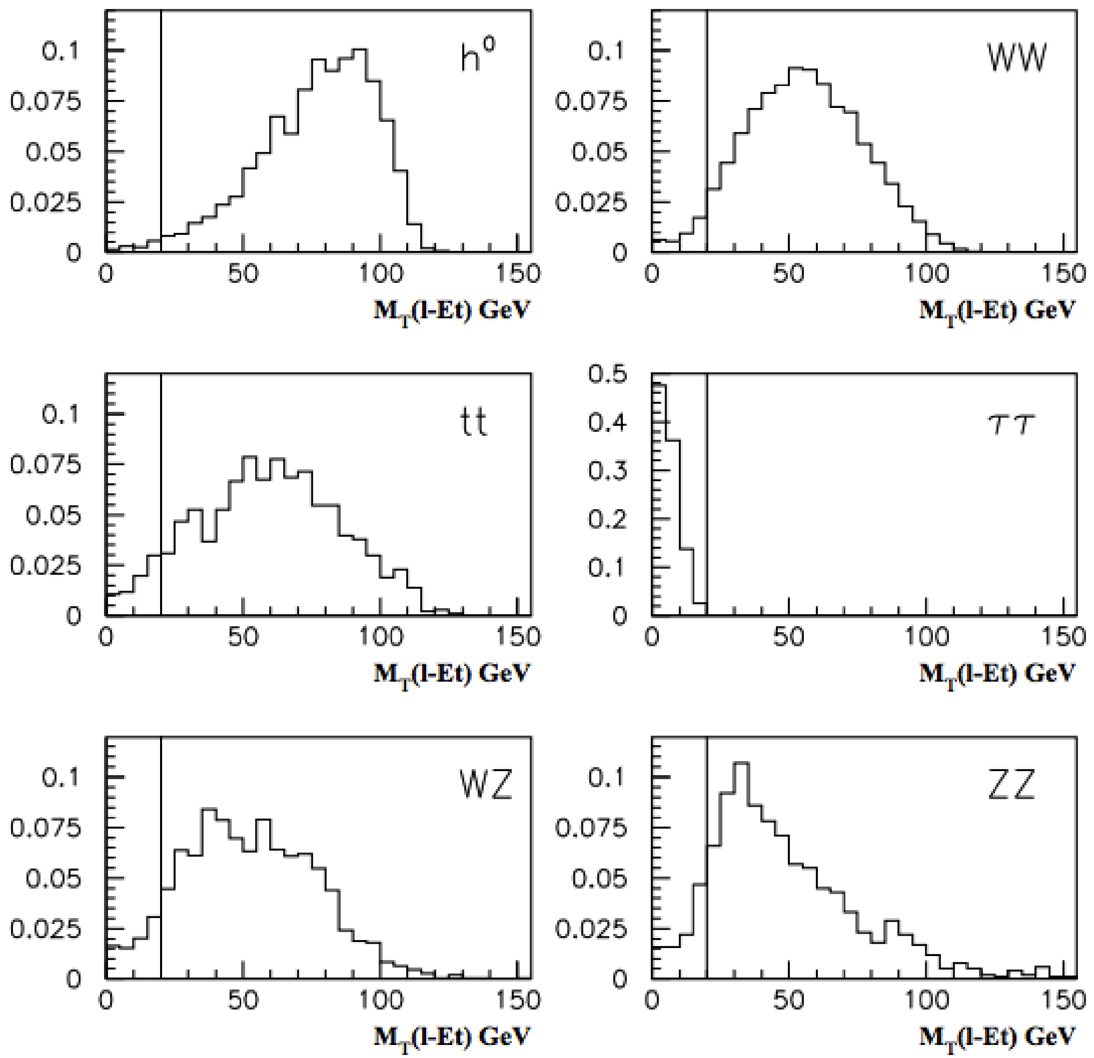
- b-tagging, dijet resolution, lepton acceptance
- Lepton acceptance, well modeled E_t^{miss}

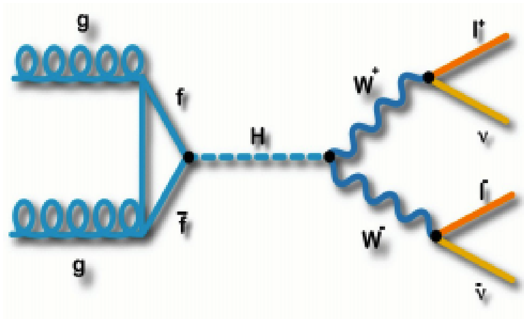
Main backgrounds

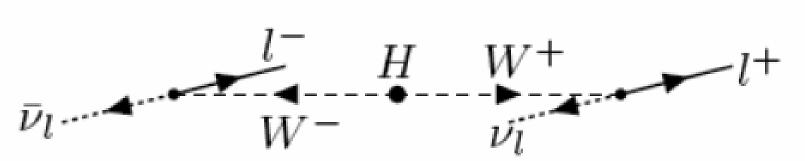
- W/Z+heavy flavors, top quark, di-bosons
- Diboson production, top quark, multijets

H → WW → 2l 2v

- One of the **flagship channels at the Tevatron**
- **Key signature** missing transverse energy







- **Helicity conservation**: charged leptons recoil against neutrinos
- One degree of freedom → measure **transverse mass**

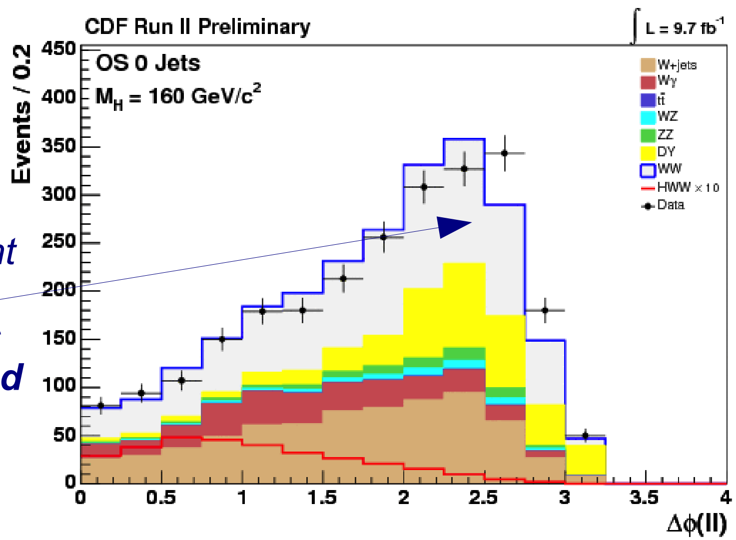
$$E_{T_{\ell^+\ell^-}} = \sqrt{\vec{p}^{\,2}_{T_{\ell^+\ell^-}} + m^2_{\ell^+\ell^-}} \quad \not{E}_T = \sqrt{\not{\vec{p}}^{\,2}_T + m^2_{\ell^+\ell^-}}$$

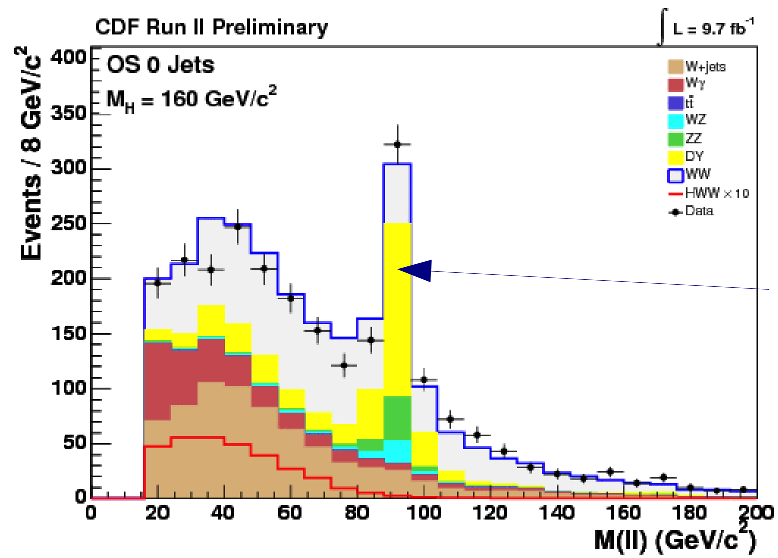
$$M_{T_{WW}} = \sqrt{(\not{E}_T + E_{T_{\ell^+\ell^-}})^2 - (\vec{p}_{T_{\ell^+\ell^-}} + \not{\vec{p}}_T)^2}$$

H → WW → 2l 2ν

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

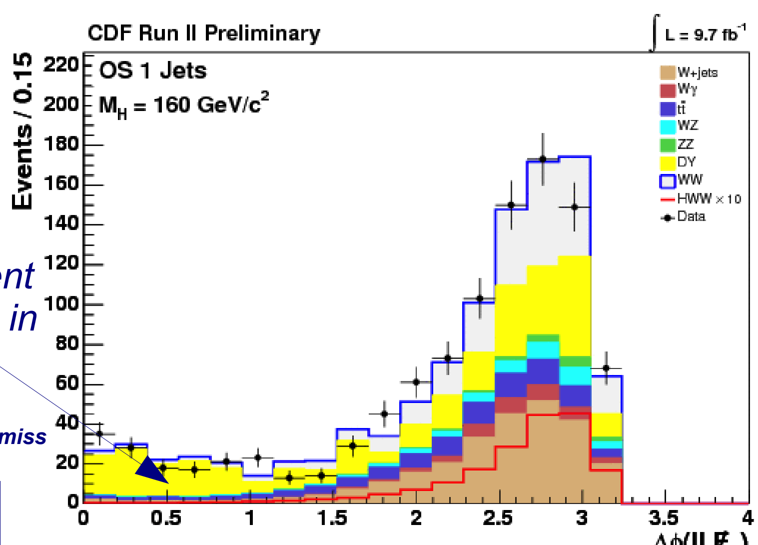
Non-resonant ***WW*** *production is* ***not polarized***

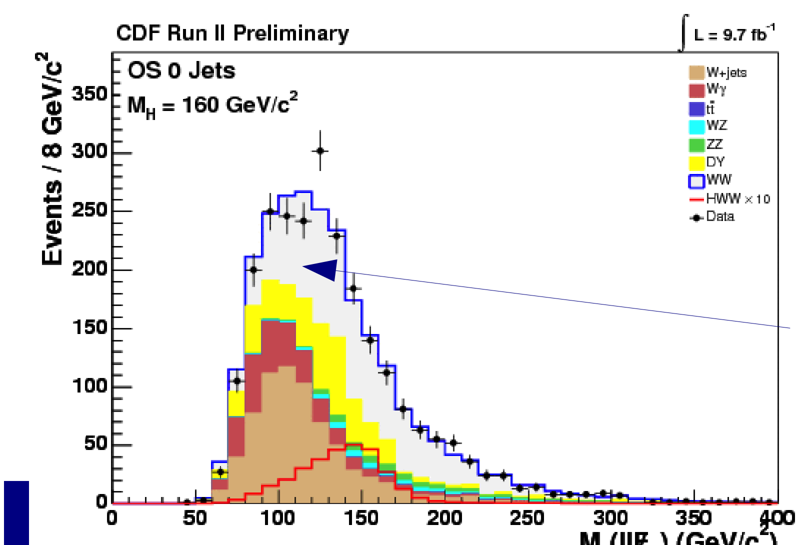




Z, ZZ, WZ are ***resonant backgrounds***

Mis-measurement of the recoil in DY events leads to ***artificial*** E_T^{miss}





Backgrounds shape due to kinematic cuts

Signal vs background discrimination

- Define the **probability to observe a given kinematics value - x_{obs}**

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

This refers to a process: signal or background

normalization factor

Differential cross section

Theory input

Efficiency x acceptance

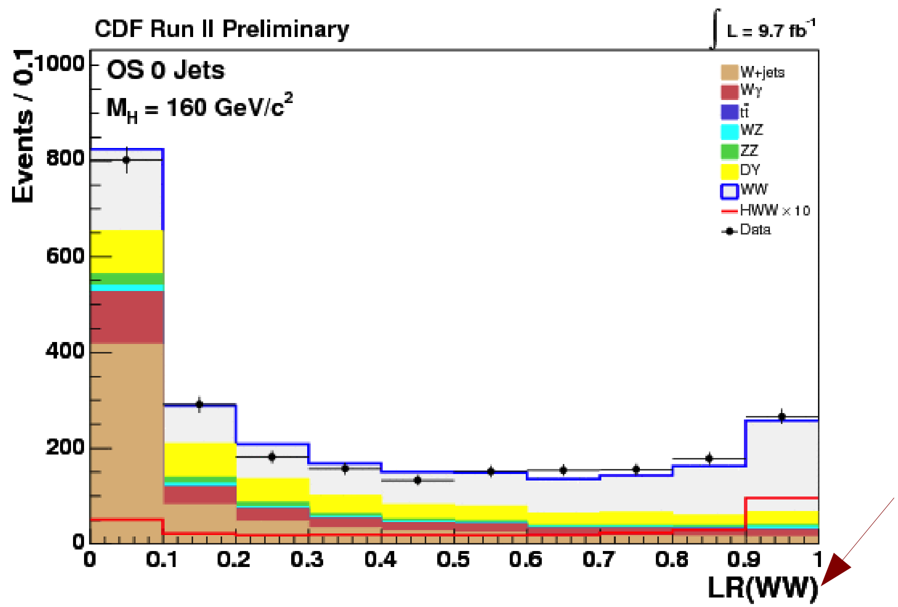
Detector resolution

Experimental input

- For each event **combine different observables** and **define likelihood ratio**

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

- Ratio is normalized using the expected fractions for each background ($\Sigma k_i = 1$)
- Any correlation between observables is neglected (probabilities projected independently)



Signal vs background discrimination

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

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- For each event **combine different observables** and **define likelihood ratio**

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

- Ratio is normalized using the expected fractions for each background ($\Sigma\ k_i=1$)
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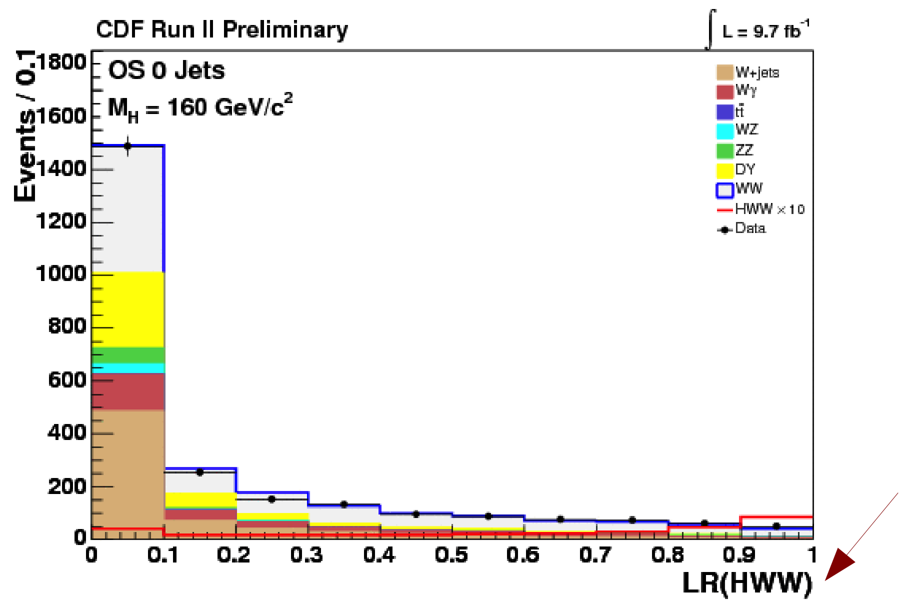


Multivariate analysis

- **Likelihood ratios** are **“simple” multivariate analysis**
  - Based on single variable probability density functions
  - May loose power if variables are correlated (only projections are used)
- **Other sophisticated techniques** are available (won't cover in any detail)
  - neural networks, boosted decision trees usually yield best performance
  - typically test performance of each one in an analysis and choose best

separation

$$\langle S^2 \rangle = \frac{1}{2} \int \frac{(\hat{y}_S(y) - \hat{y}_B(y))^2}{\hat{y}_S(y) + \hat{y}_B(y)} dy$$

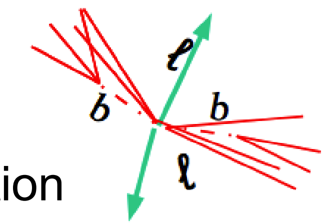
significance

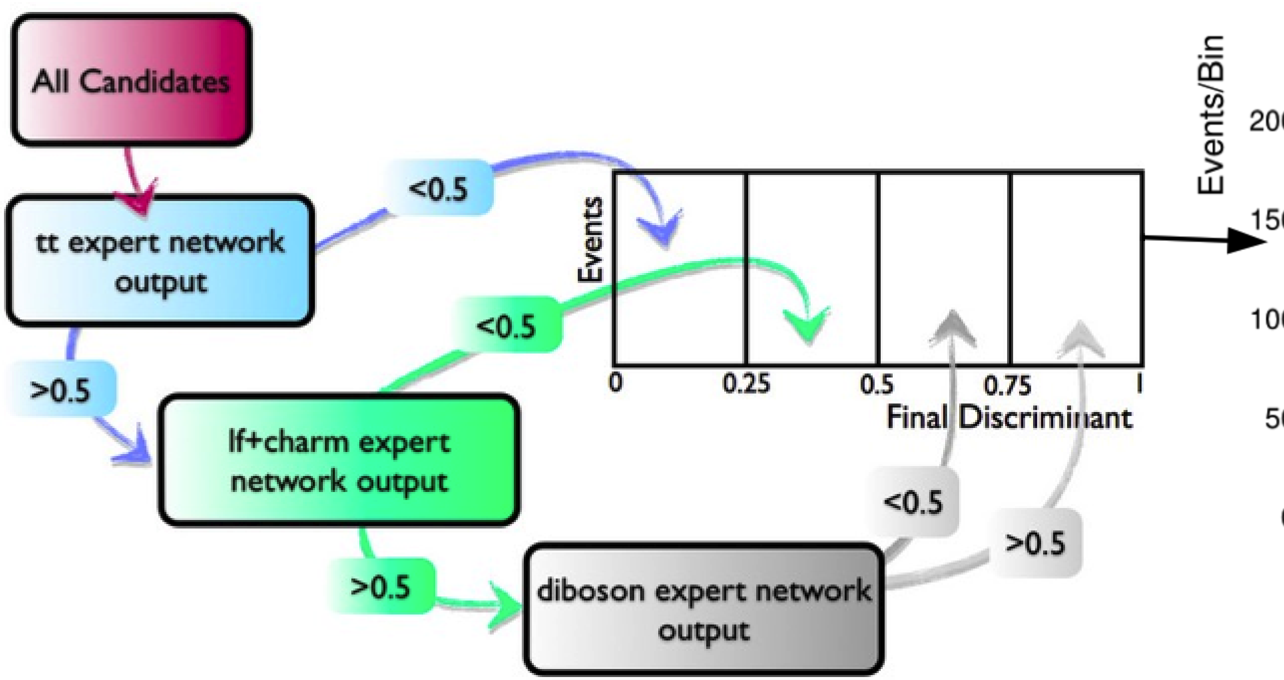
$$\frac{N_S - N_B}{\sqrt{N_S + N_B}}$$

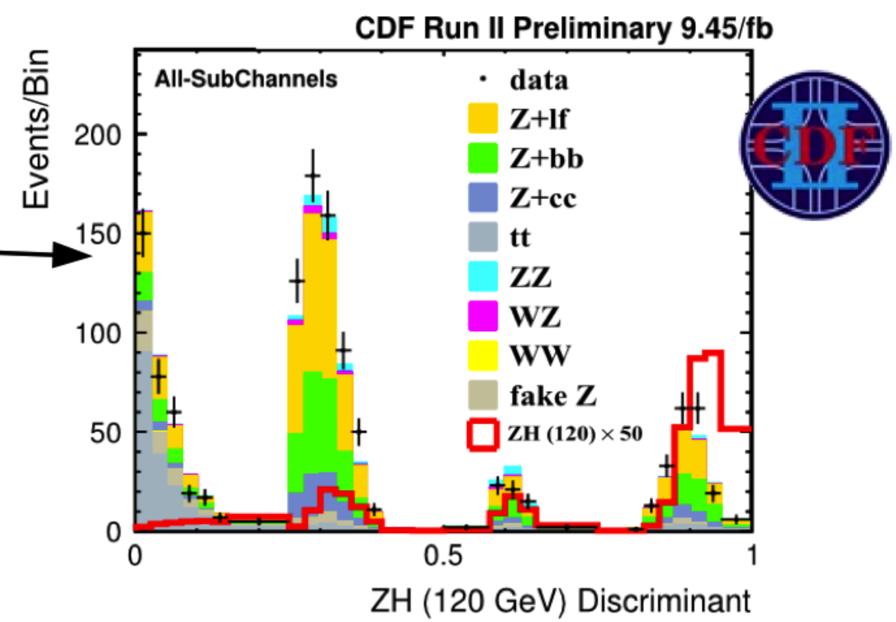
  - Check for **overtraining**: when problem has low number of degrees of freedom
  - Automated tools commonly used in HEP available in **TMVA**: **http://tmva.sourceforge.net/**

Structuring a multivariate analysis - I

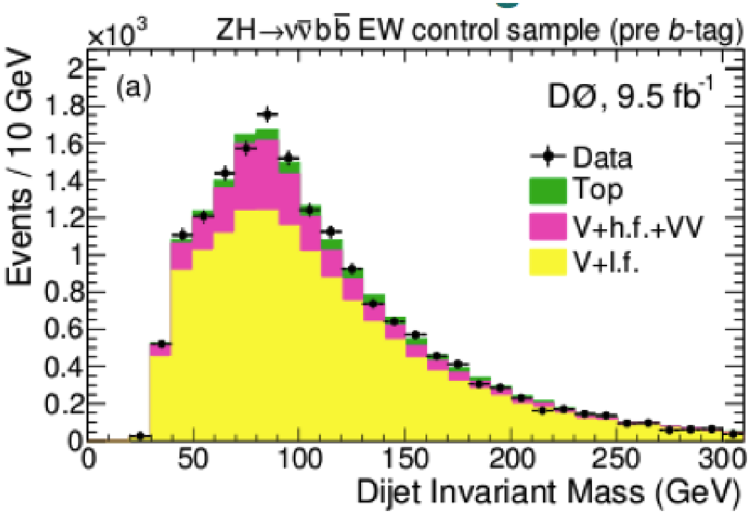
- No need to clutter all variables to a single multivariate
- Factorize to improve on detector-related effects, specific background rejection
- If some problem is found: easier to trace down where is the model failing

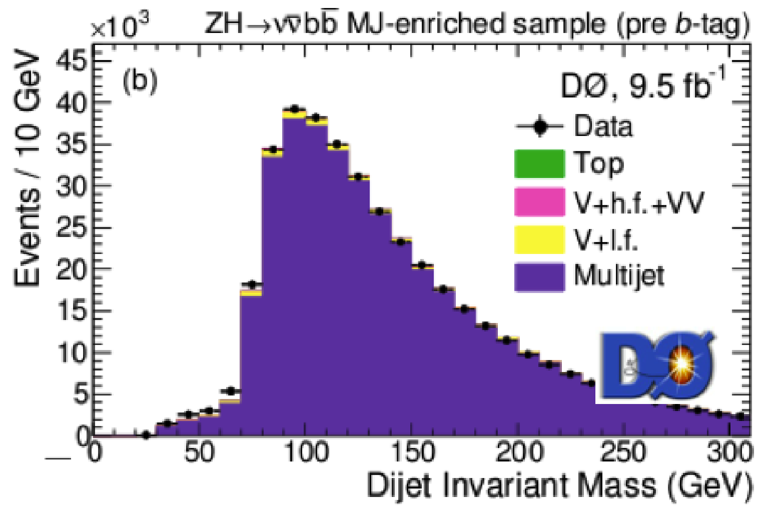






Structuring a multivariate analysis - II

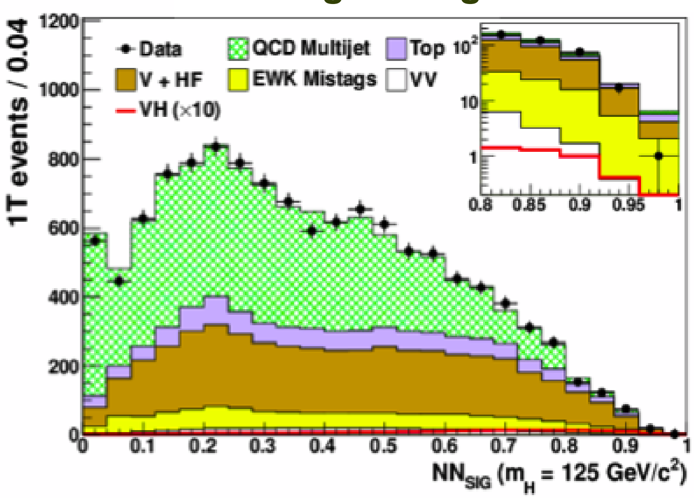




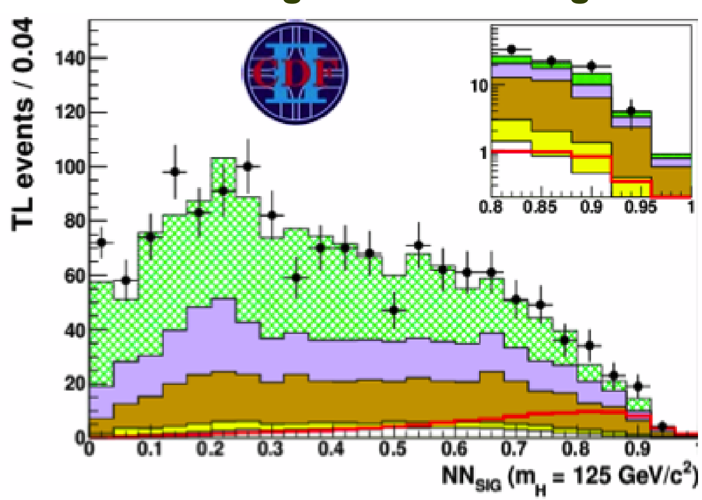
- Check input variables and correlations on control samples
- Check instrumentation effects, background normalizations.

- **Divide in categories according to S/B**: background-enriched vs background depleted
- More **handles to control background level and systematic uncertainties**

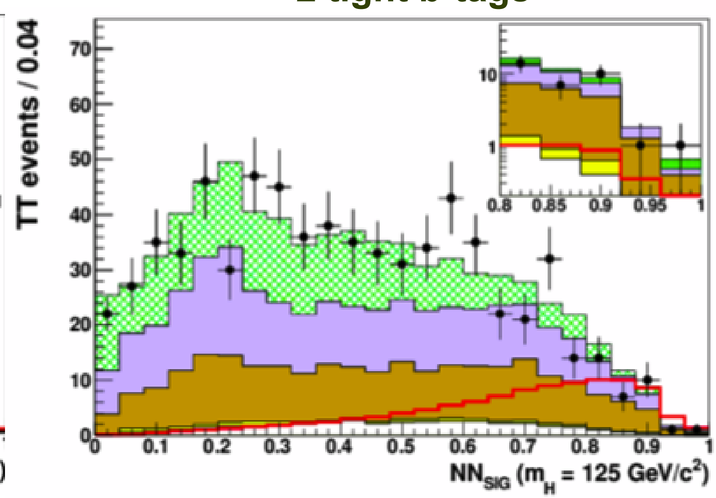
1 tight b-tag



1 tight+1 loose b-tag



2 tight b-tags



Setting limits on Higgs production

- **In the previous analysis: no excess above background is observed**
  - the strategy followed is to **set limits on the production cross section σ(H)**
  - use the data to assess how much "free space" there is to allow a signal strength **$\mu=\sigma/\sigma_{SM}$**
  - **Measure** data, background and signal **compatibility using a test statistics**

- **Define a likelihood:**

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

$\mu\cdot s(\theta)$: **Signal expected**

$b(\theta)$: background expected

$p(\tilde{\theta}|\theta)$: PDF for nuisance parameters affecting rates or shapes

- **Profile the nuisances** (test statistics):

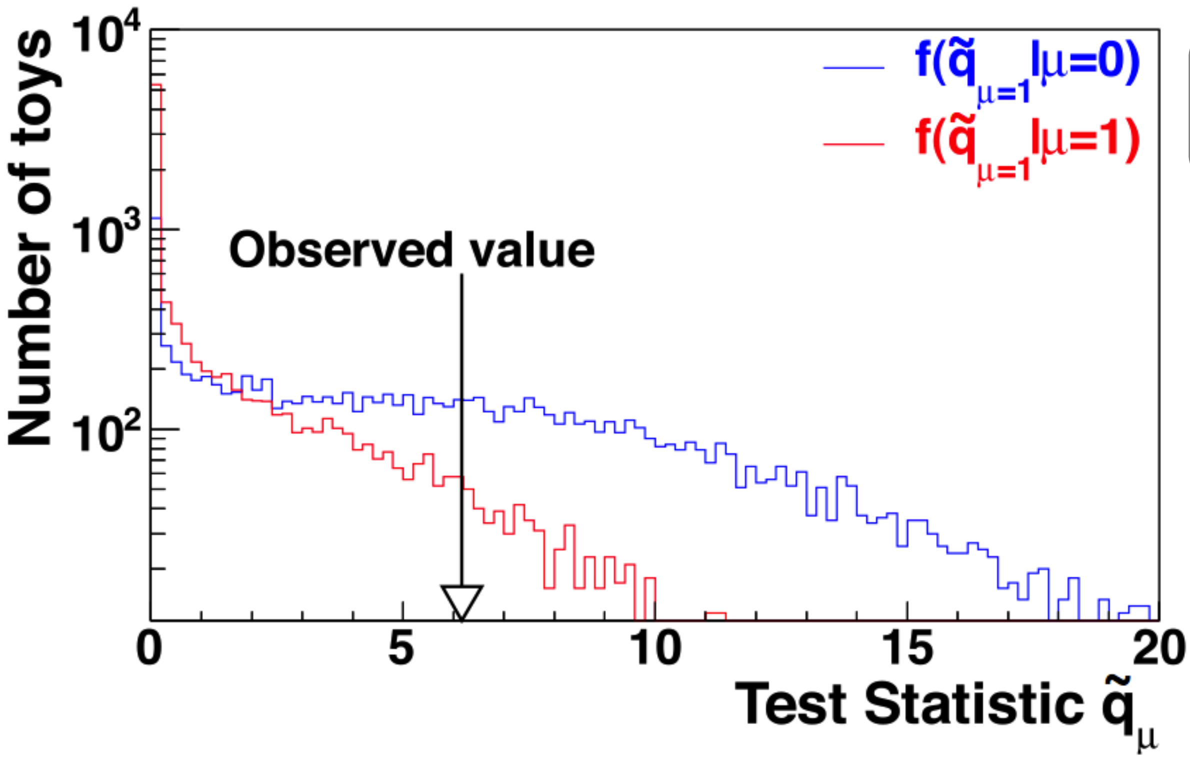
$$\tilde{q}_\mu = -2\ln\frac{\mathcal{L}(\mathrm{data}|\mu,\hat{\theta}_\mu)}{\mathcal{L}(\mathrm{data}|\hat{\mu},\hat{\theta})}$$

$\mu,\hat{\theta}_\mu$: **Profiled** values for each μ hypothesis

$\hat{\mu},\hat{\theta}$: **Best** values from fit to data

The CL_s method for limit setting

- **Compute** the **observed value of the test statistics**
  - Consider signal+background and background only hypothesis
  - Fit to obtain best values of all nuisance parameters $\hat{\theta}^{obs}_{\mu=0}$ and $\hat{\theta}^{obs}_{\mu}$
- Based on expectations we generate pseudo-experiments for each hypothesis and define:



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

p_μ → probability that test statistics exceeds the observed value for **S+B**

p_b → similar as above for **B**

$CL_s(\mu)$=5% → $\mu^{95\%CL}$ upper endpoint

(commonly we say upper limit)

CL_s<5% → exclude signal at 95% CL

The CL_s method for limit setting

CERN-OPEN-2000-205 , CMS-NOTE-2011-005

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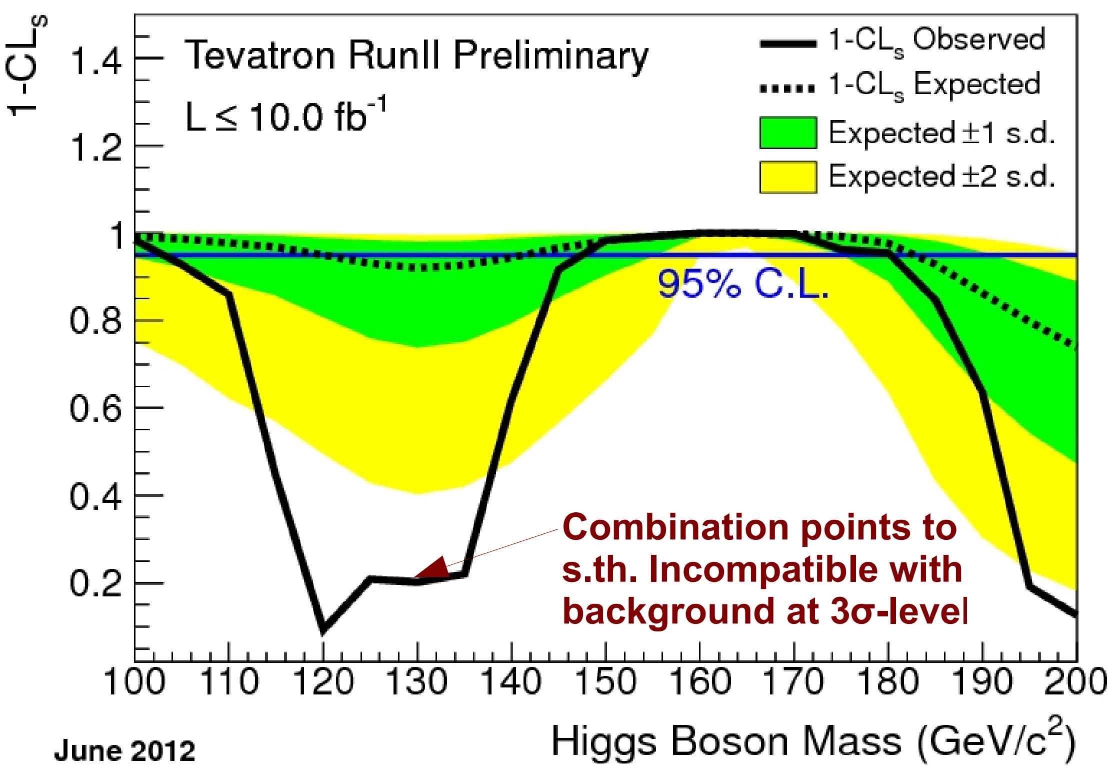

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What went in the combination ?

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.

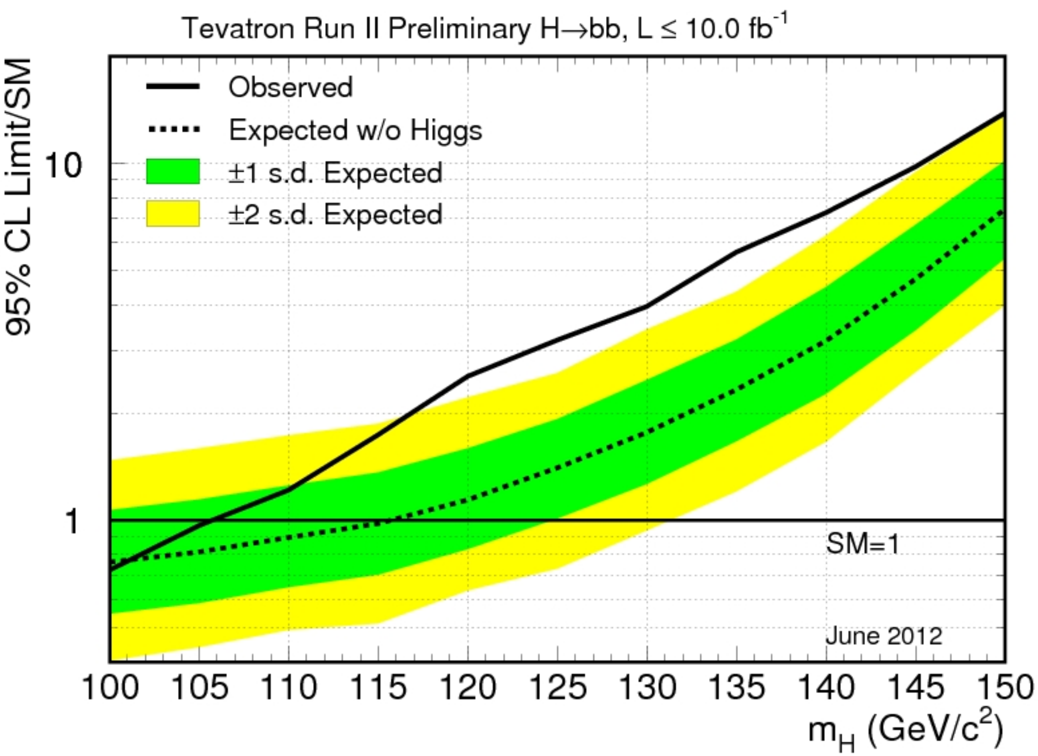
Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(TT,TL,Tx,LL,Lx)	9.45	100-150	[17]
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(TT,TL)	9.45	100-150	[17]
$ZH \to \nu\bar{\nu} b\bar{b}$ (SS,SJ,1S)	9.45	100-150	[18]
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet 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-τ_{had})+(μ-τ_{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 τ_{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-τ_{had}-τ_{had}	6.2	100-150	[24]
$WH \to \ell\nu\tau^+\tau^- / ZH \to \ell^+\ell^-\tau^+\tau^-$ (ℓ-ℓ-τ_{had})+(e-μ-τ_{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 τ_{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]

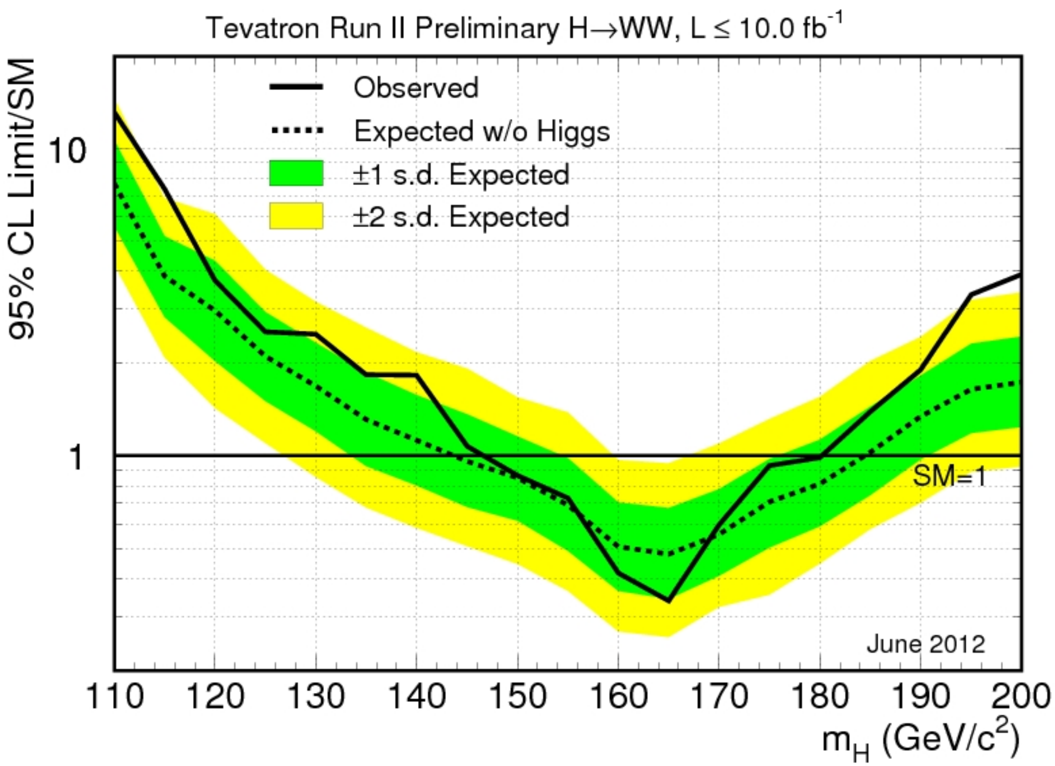
TABLE II: Luminosity, explored mass range and references for the different processes and final states ($\ell = e, \mu$) for the D0 analyses.

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→$\ell^{\pm}\tau^{\mp}_{had}jj$	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]
$H \to W^+W^- \to \mu\nu\tau_{had}\nu$	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]

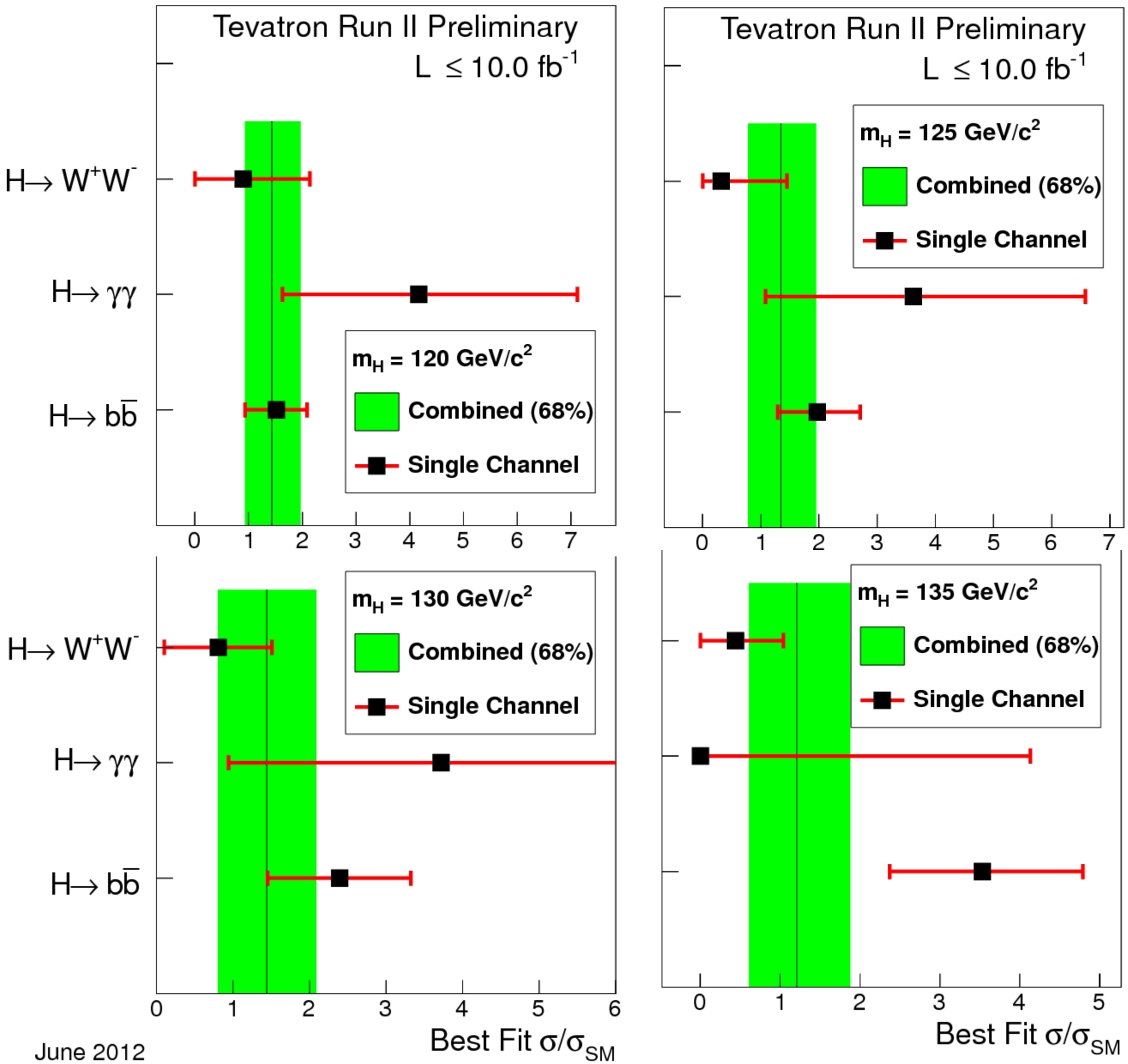
Where is the excess coming from?

- From the **most sensitive channels**: ZH → bb and H → WW
- In both cases mass resolution is poor + low stats → lead to the spread of the excess
- **Consistent between** both **experiments** and enhanced by the combination





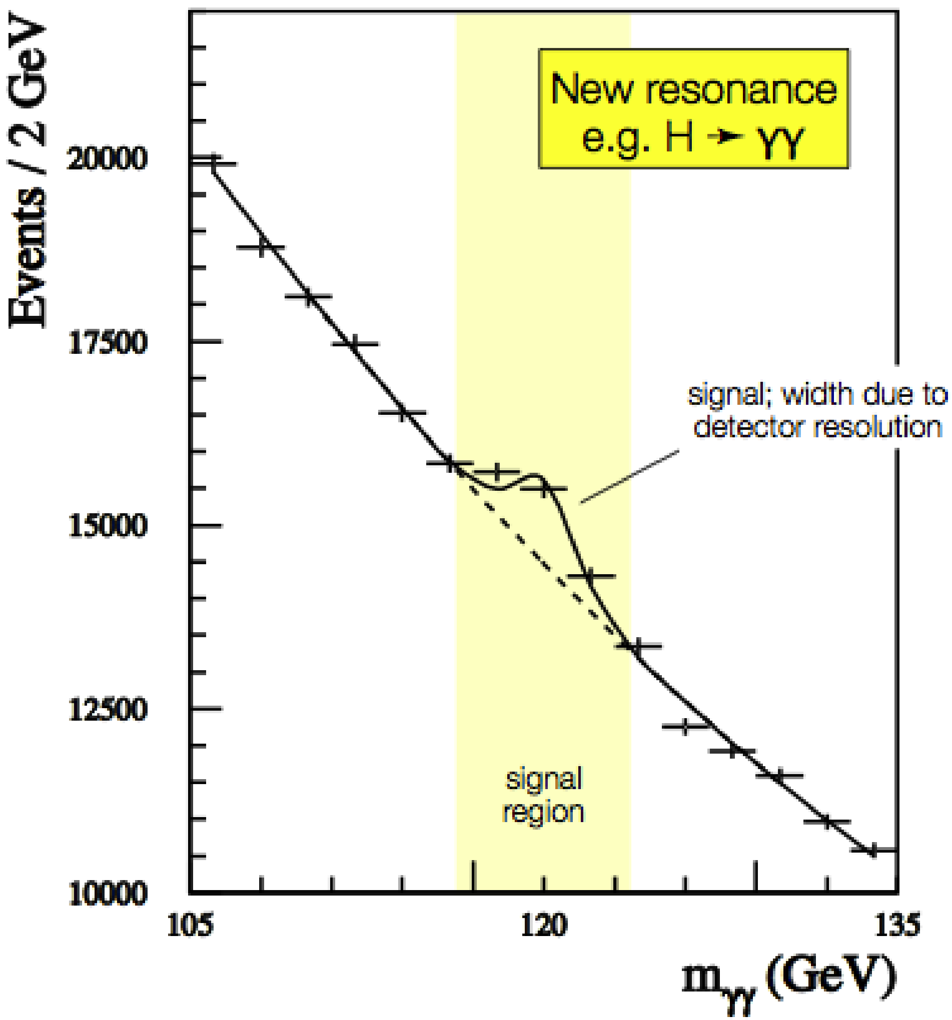
Quantifying the excess



- We revert our perspective (limit setting) and **fit for the signal strength**
- Scan region of excess and find best fit for different m_H
- **μ=1.4±0.7 @ 125 GeV**

  Consistent with the SM and amongst all channels

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 ...

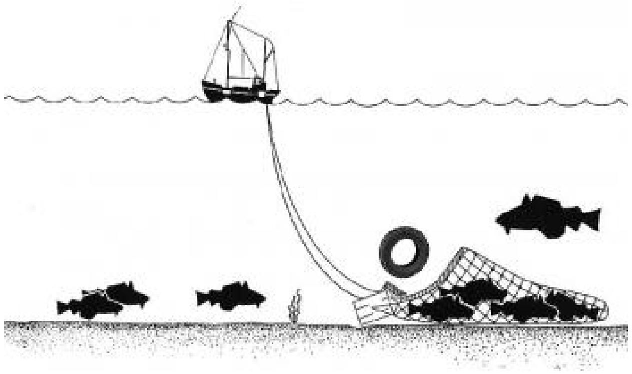
$$P_{5\sigma} = 10^{-7}.$$

Discovery!

Look elsewhere effect

Eur.Phys.J.C70:525-530,2010

- **Studying the probability of the background-only hypothesis over large range**
  - Probable to **enhance signal-like fluctuations**
  - **Significance must be corrected** for this effect



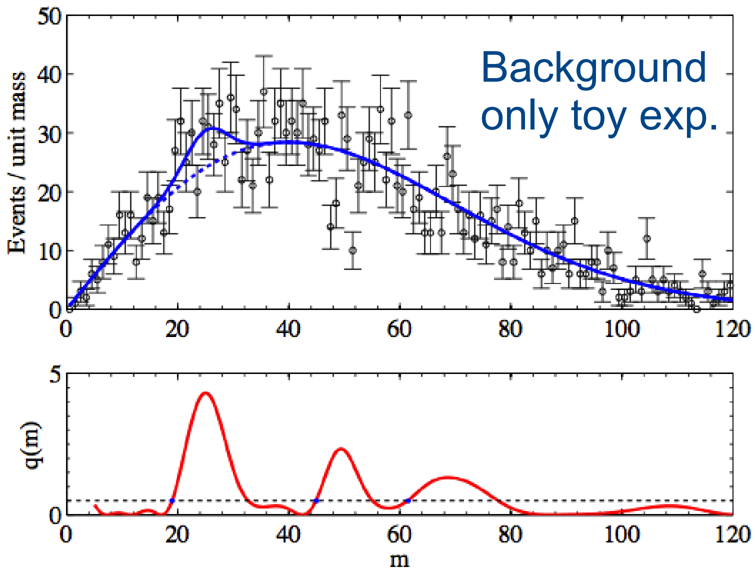
- **Quantify** signal-like fluctuation probability **from trial-factors**

$$trial\# = \frac{P(q(\hat{\theta}) > c)}{P(q(\theta) > c)}$$

→ probability to observe excess at fixed mass point

→ probability to observe it anywhere else in the search range

- Full simulation-based estimation of trial factors is CPU intensive: approximate asymptotically



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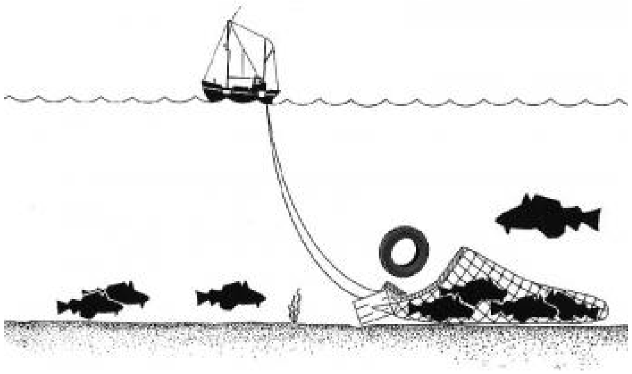

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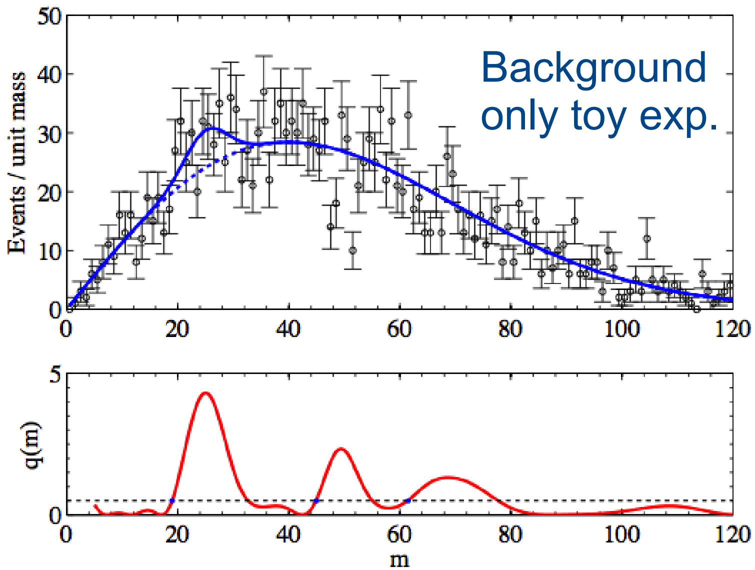

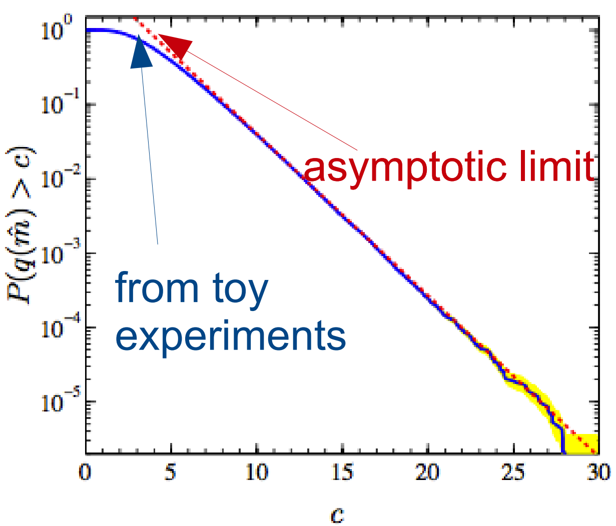

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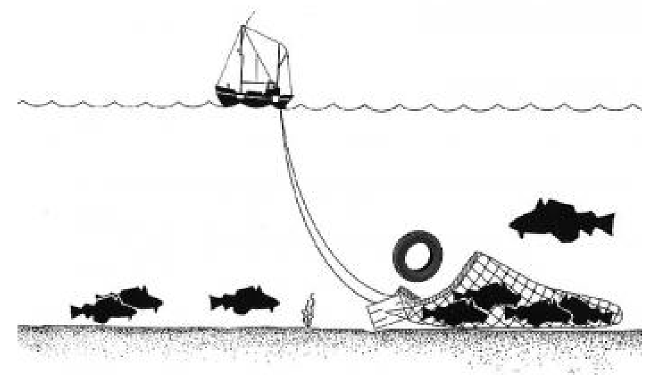

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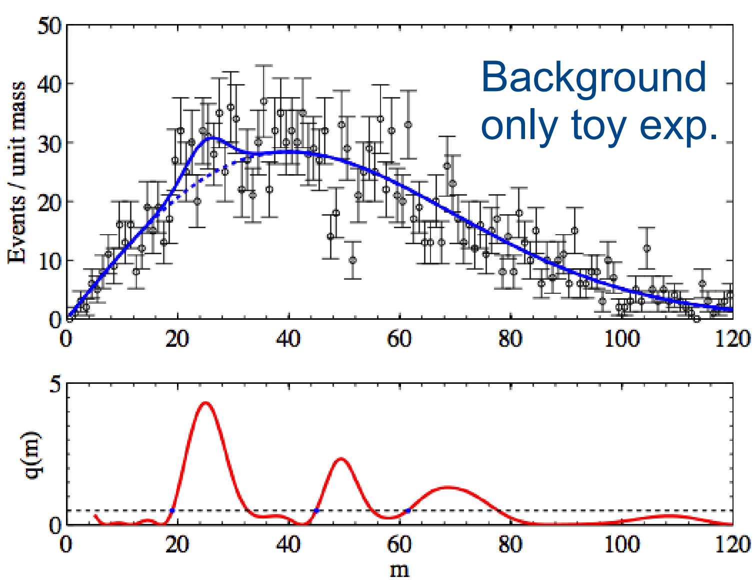
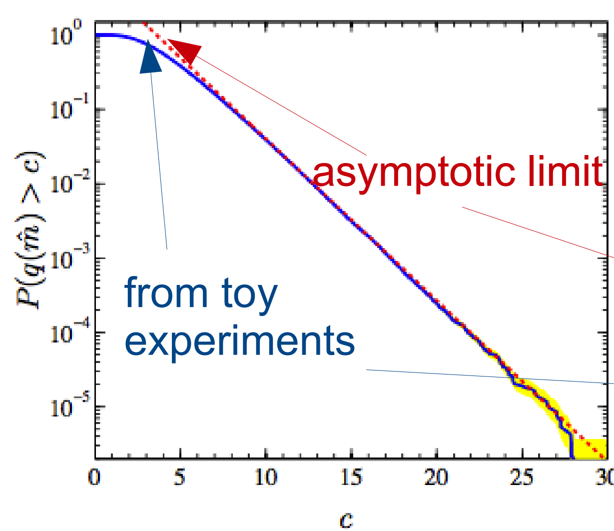
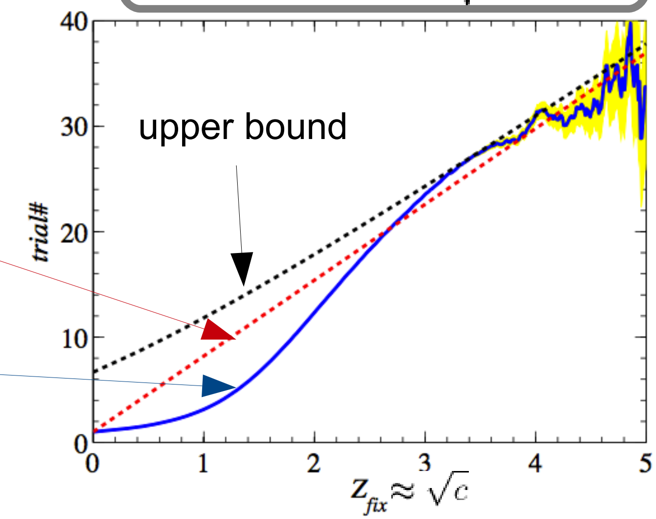
- Full simulation-based estimation of trial factors is CPU intensive: approximate asymptotically

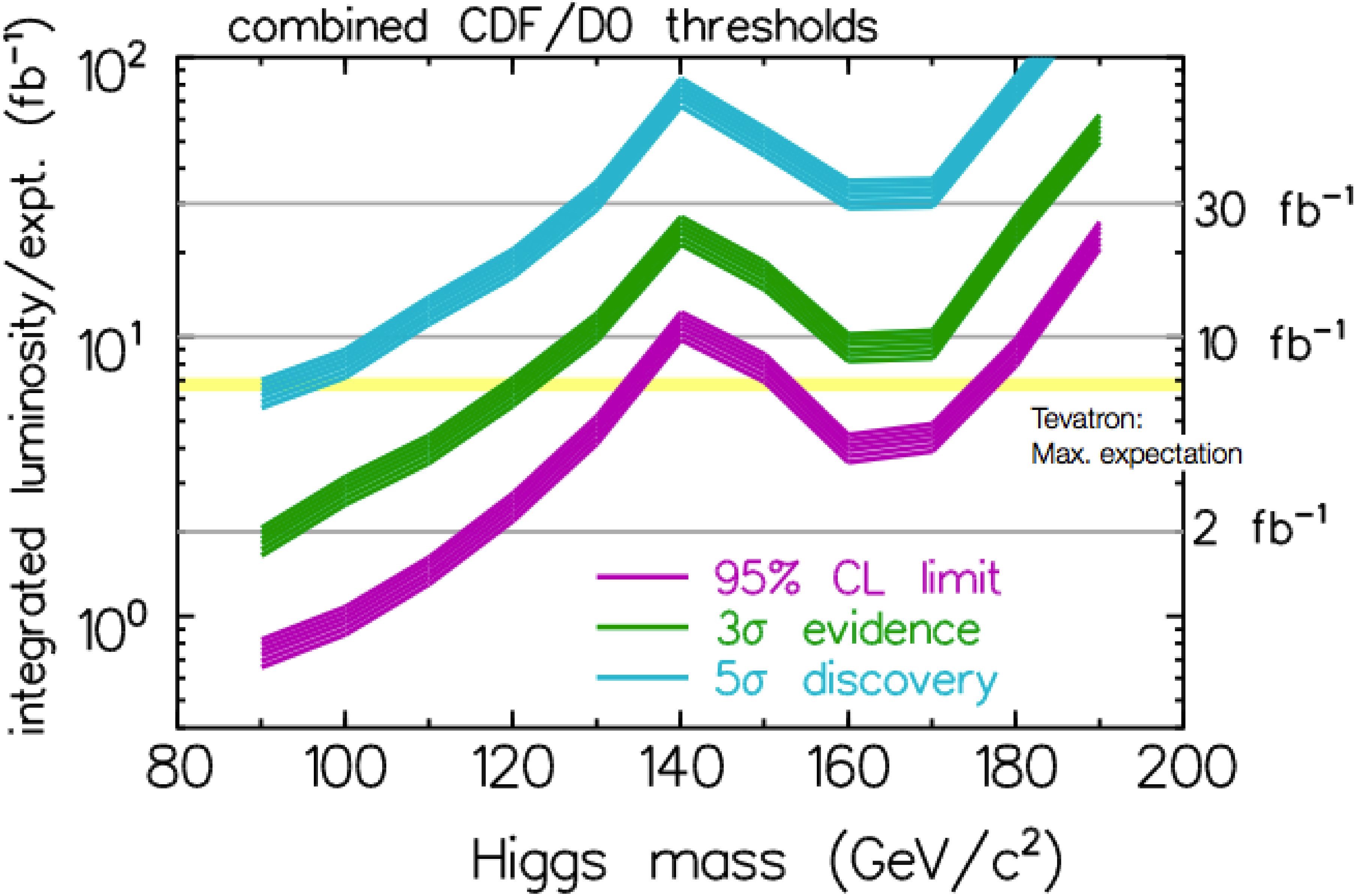
$$trial\#_{s=1} \approx 1 + \sqrt{\frac{\pi}{2}}\mathcal{N} Z_{fix}$$







Tevatron has reached the evidence threshold

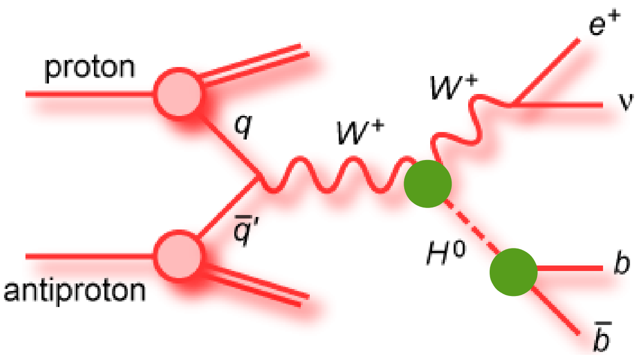


Looking ahead for coupling properties

- In Higgs production **couplings are present in production and in decay**
  - Needs careful prescription for each channel and production mode
  - Assume SM width and write: $(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$
  - **Search for deviations re-scaling the couplings** at production (σ_{ii}) and decay (Γ_{ff})
  - E.g. for VH → bb+X re-scale

    radiative vertex by k_V +decay vertex by k_f

    $$(\sigma \cdot BR)(VH \to b\bar{b}) = \sigma_{\mathrm{SM}}(VH) \cdot BR_{\mathrm{SM}}(H \to b\bar{b}) \cdot \frac{\kappa_f^2 \kappa_V^2}{\kappa_H^2}$$



  - if needed effective couplings can be further disambiguated for hypothesis testing ($\lambda_{ij} = \kappa_i / \kappa_j$)
- Loops in production (gg→H) or decay (H →γγ/Zγ) sensitive to the sign of the couplings due to interference interms (e.g. top ↔ bottom)

General approach to trace deviation in couplings

General parametrization allowing other couplings to float

Free parameters: $\kappa_{gZ}(=\kappa_g\cdot\kappa_Z/\kappa_H)$, $\lambda_{\gamma Z}(=\kappa_\gamma/\kappa_Z)$, $\lambda_{WZ}(=\kappa_W/\kappa_Z)$, $\lambda_{bZ}(=\kappa_b/\kappa_Z)$, $\lambda_{\tau Z}(=\kappa_\tau/\kappa_Z)$, $\lambda_{Zg}(=\kappa_Z/\kappa_g)$, $\lambda_{tg}(=\kappa_t/\kappa_g)$.

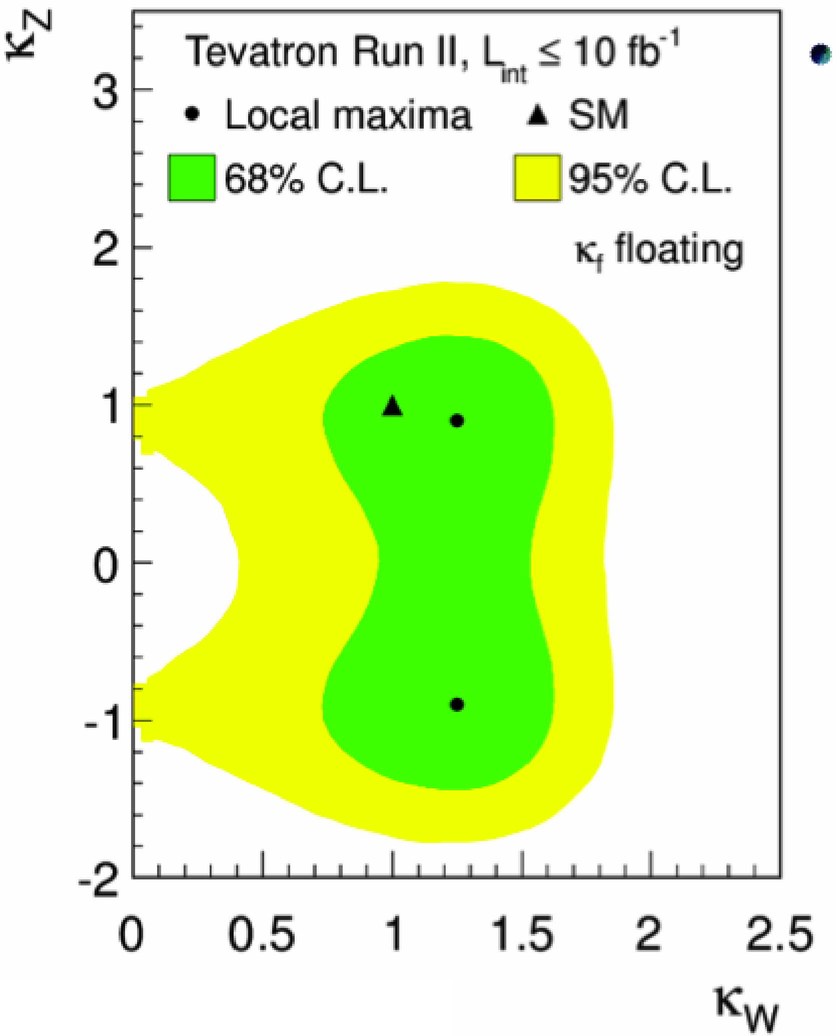
	$H\to\gamma\gamma$	$H\to ZZ^{(*)}$	$H\to WW^{(*)}$	$H\to b\bar{b}$	$H\to\tau^-\tau^+$
ggH	κ_{gZ}^2 1 $\lambda_{\gamma Z}^2$	κ_{gZ}^2 1 1	κ_{gZ}^2 1 λ_{WZ}^2	κ_{gZ}^2 1 λ_{bZ}^2	κ_{gZ}^2 1 $\lambda_{\tau Z}^2$
$t\bar{t}H$	κ_{gZ}^2 λ_{tg}^2 $\lambda_{\gamma Z}^2$	κ_{gZ}^2 λ_{tg}^2 1	κ_{gZ}^2 λ_{tg}^2 λ_{WZ}^2	κ_{gZ}^2 λ_{tg}^2 λ_{bZ}^2	κ_{gZ}^2 λ_{tg}^2 $\lambda_{\tau Z}^2$
VBF	$\kappa_{gZ}^2\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})\lambda_{\gamma Z}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})1$	$\kappa_{gZ}^2\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})\lambda_{WZ}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})\lambda_{bZ}^2$	$\kappa_{gZ}^2\lambda_{Zg}^2\kappa_{VBF}^2(1,\lambda_{WZ})\lambda_{\tau Z}^2$
WH	κ_{gZ}^2 $\lambda_{Zg}^2\lambda_{WZ}^2$ $\lambda_{\gamma Z}^2$	κ_{gZ}^2 $\lambda_{Zg}^2\lambda_{WZ}^2$ 1	κ_{gZ}^2 $\lambda_{Zg}^2\lambda_{WZ}^2$ λ_{WZ}^2	κ_{gZ}^2 $\lambda_{Zg}^2\lambda_{WZ}^2$ λ_{bZ}^2	κ_{gZ}^2 $\lambda_{Zg}^2\lambda_{WZ}^2$ $\lambda_{\tau Z}^2$
ZH	κ_{gZ}^2 λ_{Zg}^2 $\lambda_{\gamma Z}^2$	κ_{gZ}^2 λ_{Zg}^2 1	κ_{gZ}^2 λ_{Zg}^2 λ_{WZ}^2	κ_{gZ}^2 λ_{Zg}^2 λ_{bZ}^2	κ_{gZ}^2 λ_{Zg}^2 $\lambda_{\tau Z}^2$

$\kappa_i^2 = \Gamma_{ii}/\Gamma_{ii}^{SM}$

Table A.1: A benchmark parametrization without further assumptions and maximum degrees of freedom. The colors denote the common factor (black) and the factors related to the production (blue) and decay modes (red). Ones are used to denote the trivial factor.

- Number of free parameters is too large to make this fit feasible with low statistics
- Vector boson scattering based couplings only accessible in HL-LHC / SLHC

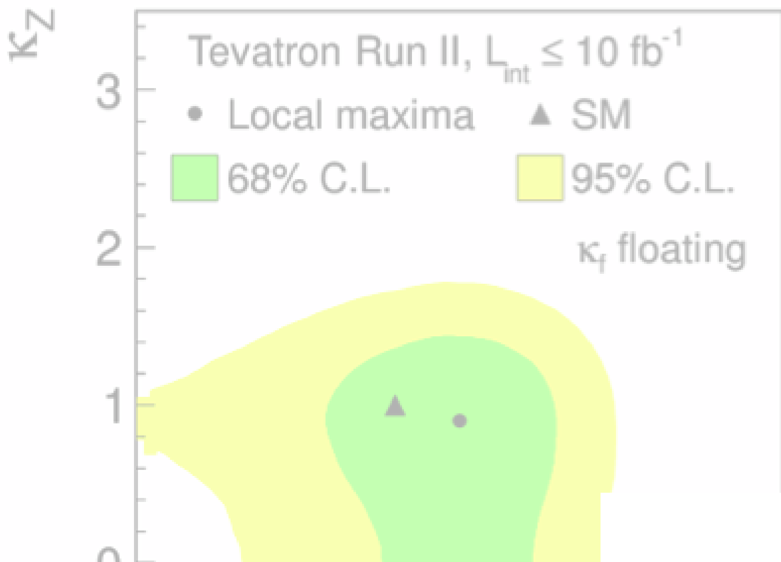
Results for couplings at Tevatron

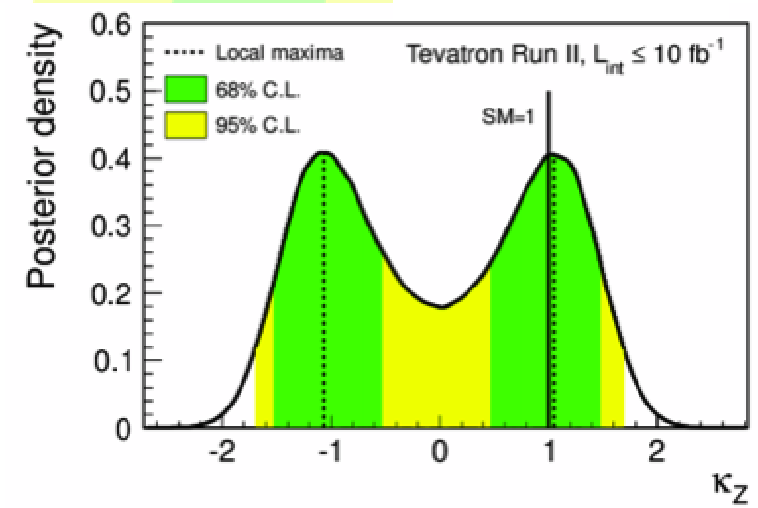


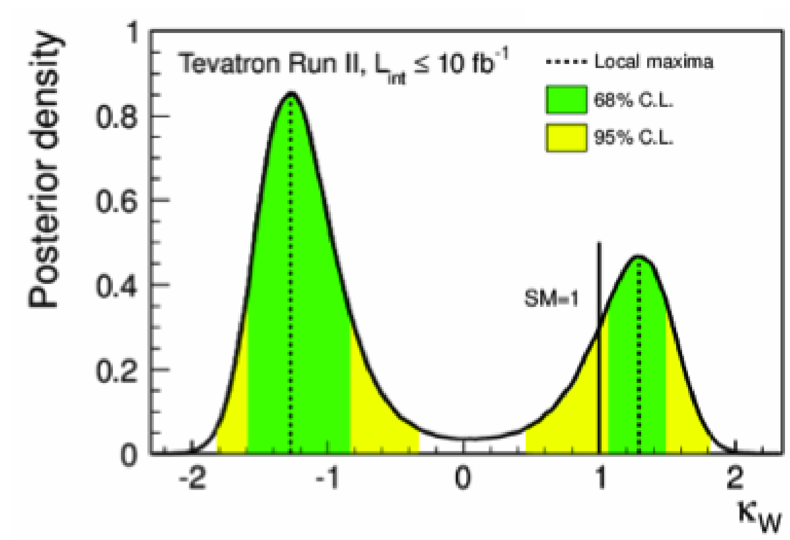
- Fermion couplings floating freely → $(k_W,k_Z)=(1.25,\pm0.90)$

Results for couplings at Tevatron

- Fermion couplings floating freely → $(k_W,k_Z)=(1.25,\pm 0.90)$
- Assume SM for fermions and
  - W boson → $k_Z = \pm\ 1.05^{+0.45}_{-0.55}$
  - Z boson → $k_W = -1.27\ ^{+0.46}_{-0.29} \vee 1.04 – 1.51$







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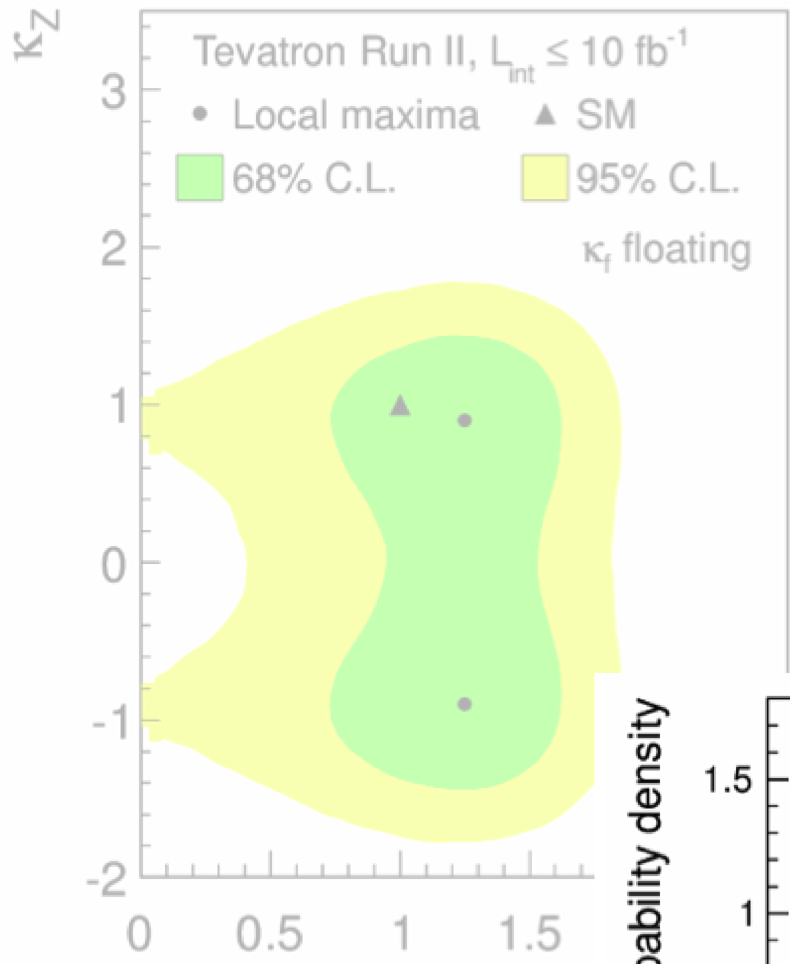

- κ_f floating

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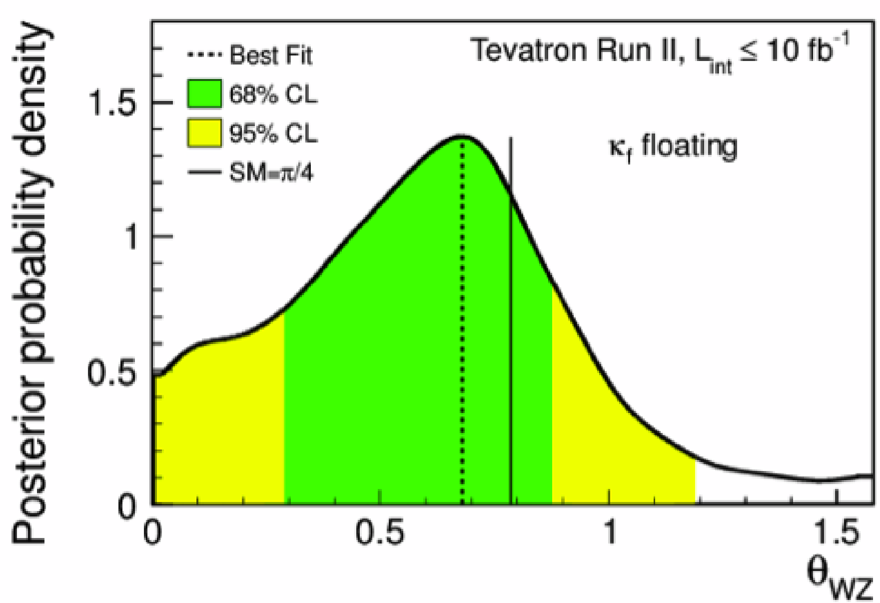
  - Z boson → $k_W = -1.27^{+0.46}_{-0.29} \vee 1.04 - 1.51$
  - Test custodial symmetry arc tg $(\lambda_{ZW}) = 0.68^{+0.21}_{-0.41}$



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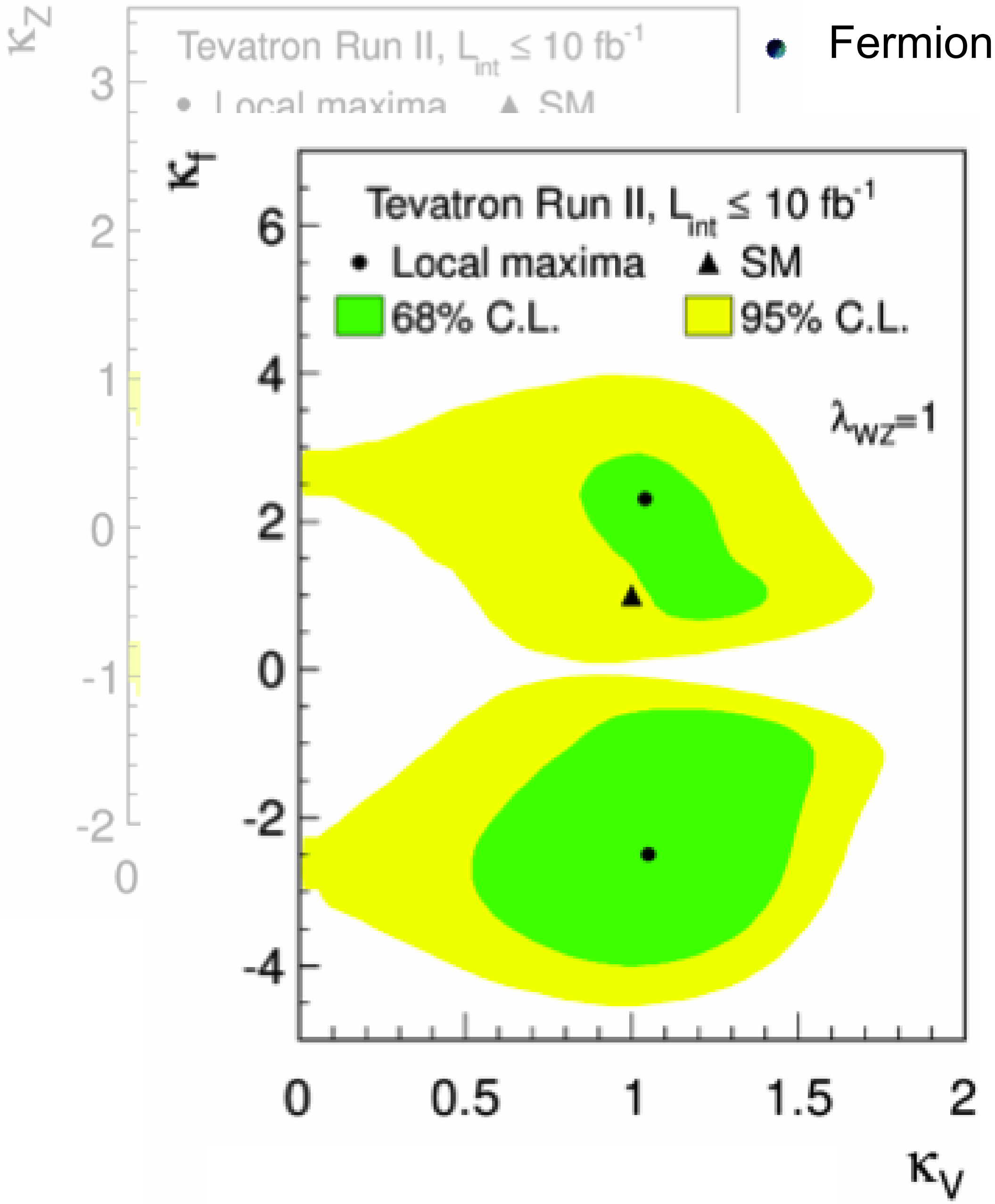
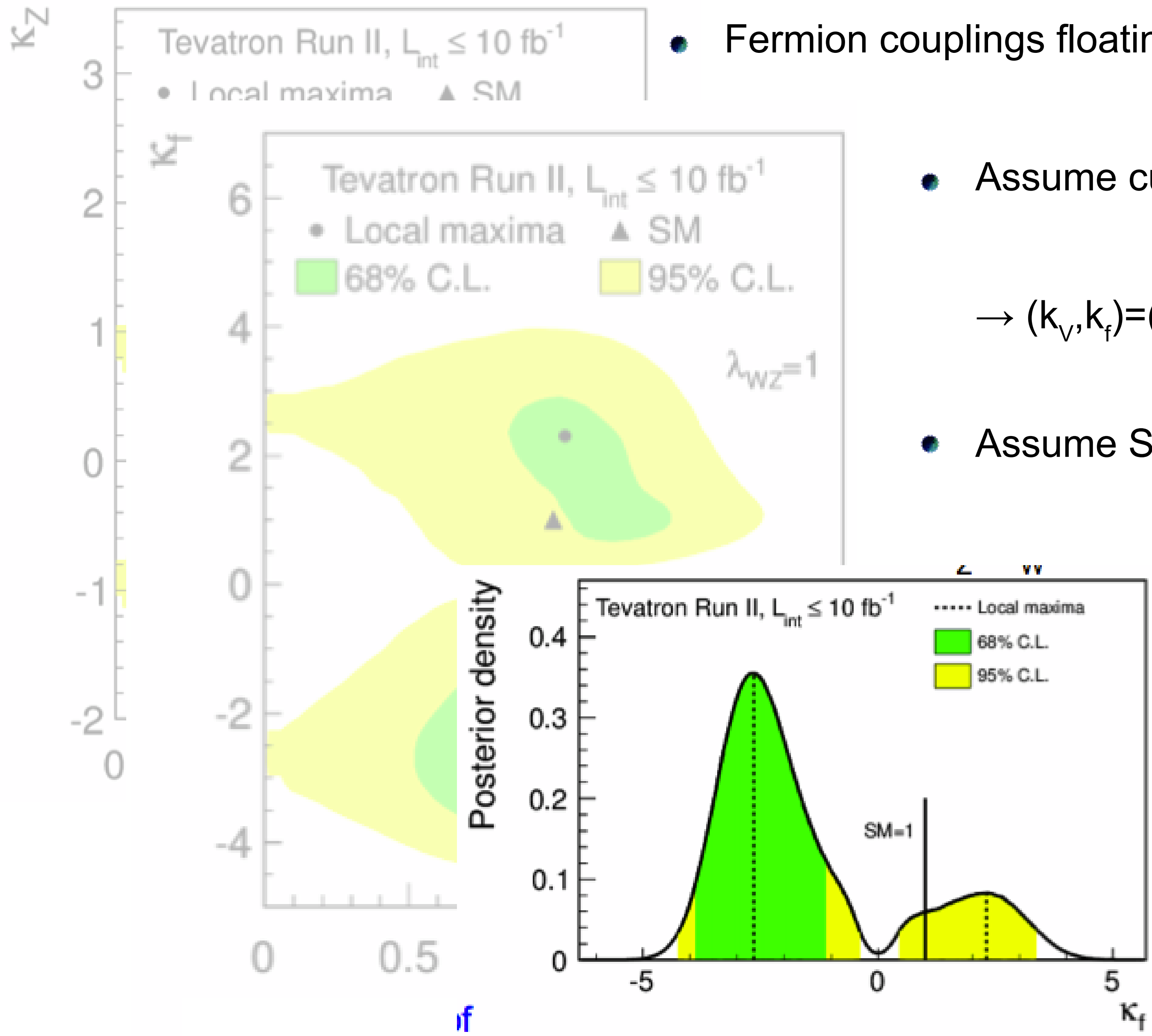


- Fermion couplings floating freely → $(k_W, k_Z) = (1.25, \pm 0.90)$

- Assume custodial symmetry ($\lambda_{WZ}=1$)

  → $(k_V, k_f) = (1.05, -2.40)$ or $(1.05, 2.30)$

Results for couplings at Tevatron



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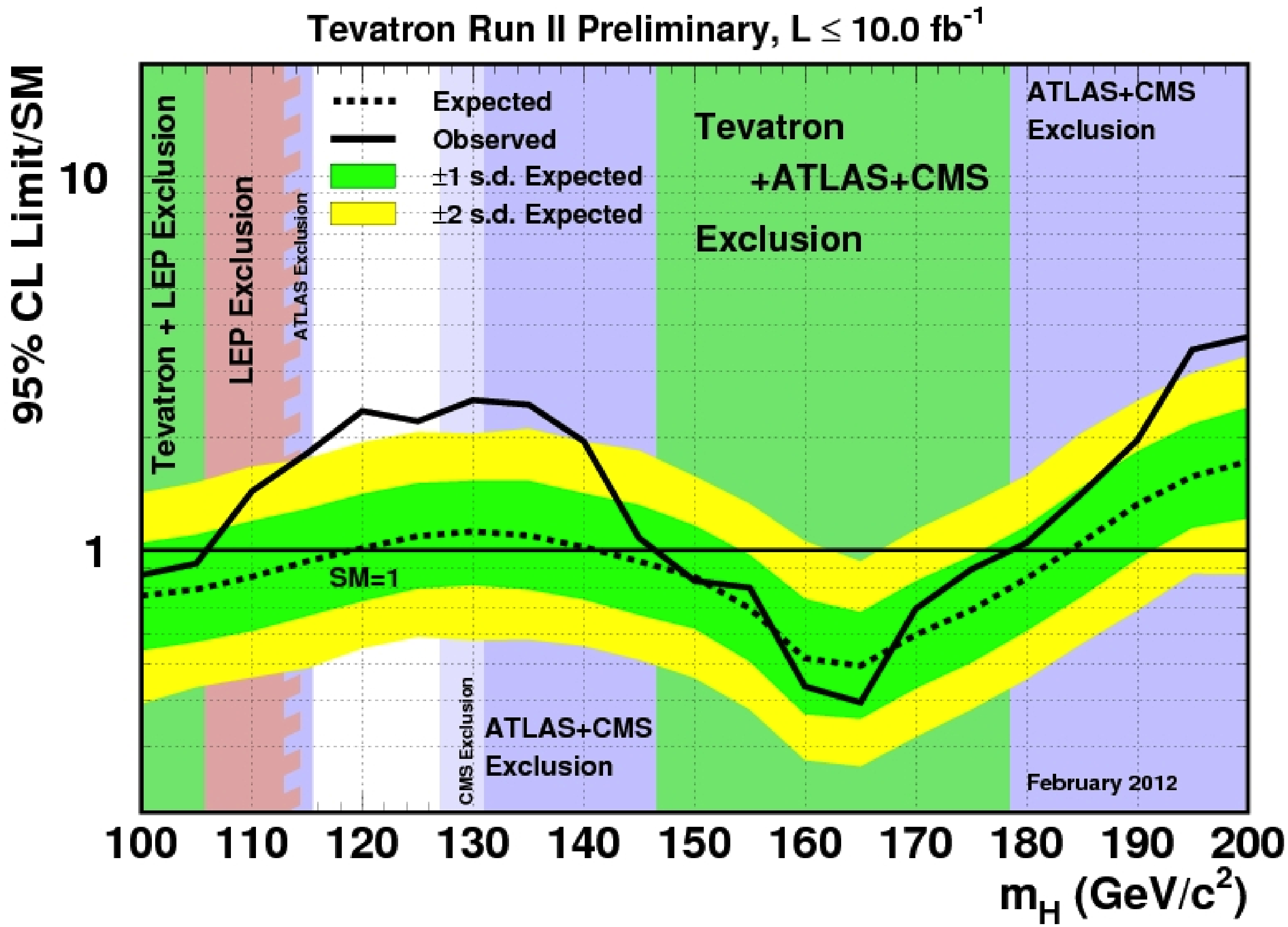
- Assume custodial symmetry ($\lambda_{WZ}=1$)

  → $(k_V,k_f)=(1.05, -2.40)$ or $(1.05, 2.30)$
- Assume SM for W and Z and extract
  - $k_f=-2.64^{+1.59}_{-1.30}$
  - Negative value driven by excess in H → gg (incompatible with H_{125})

The Tevatron Higgs legacy

- A **broad excess @ > 2σ is observed** at the Tevatron
  - Mostly dominated from VH → Vbb channels
  - 3-σ local p-value
  - Couplings close to nominal SM

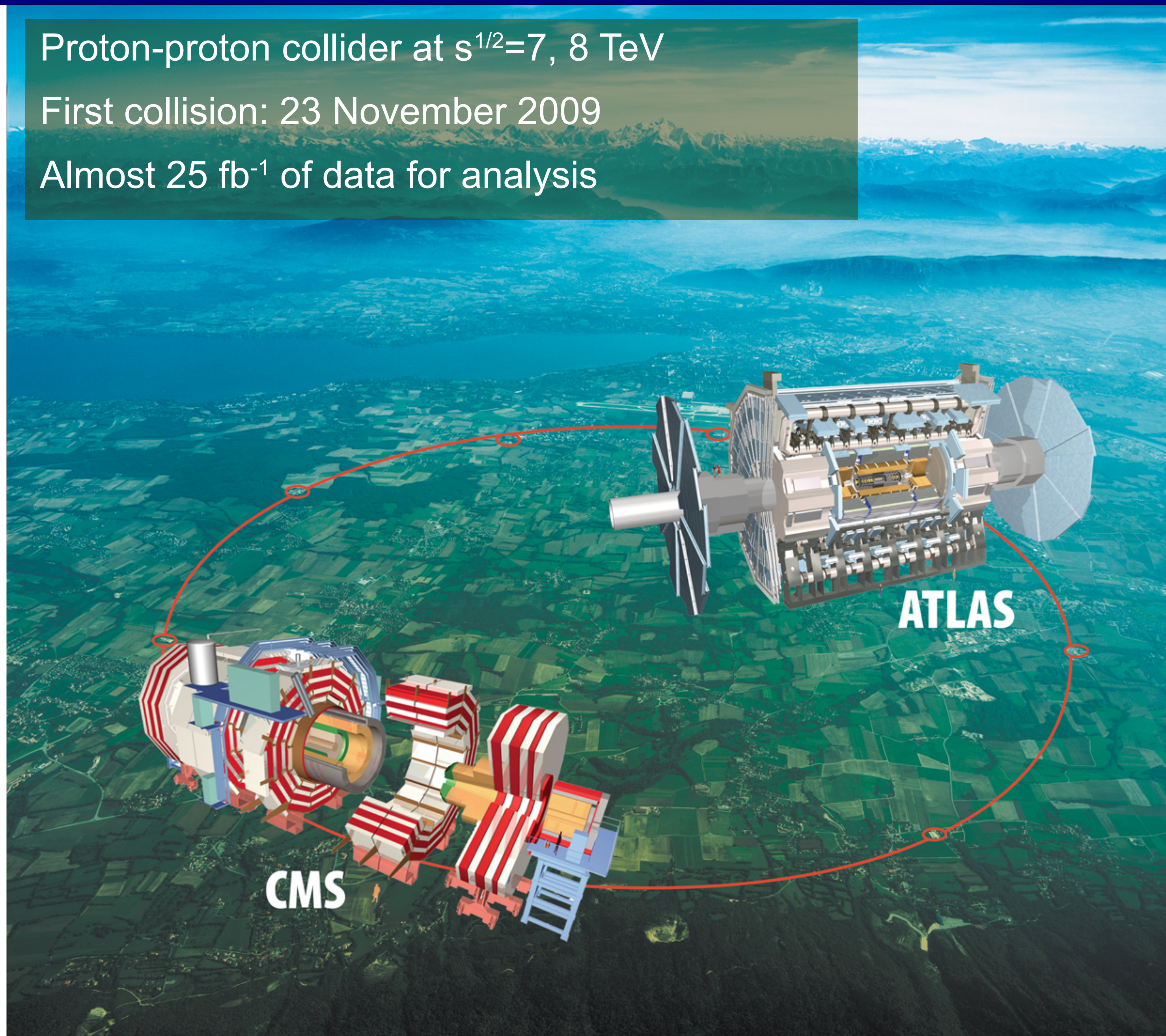


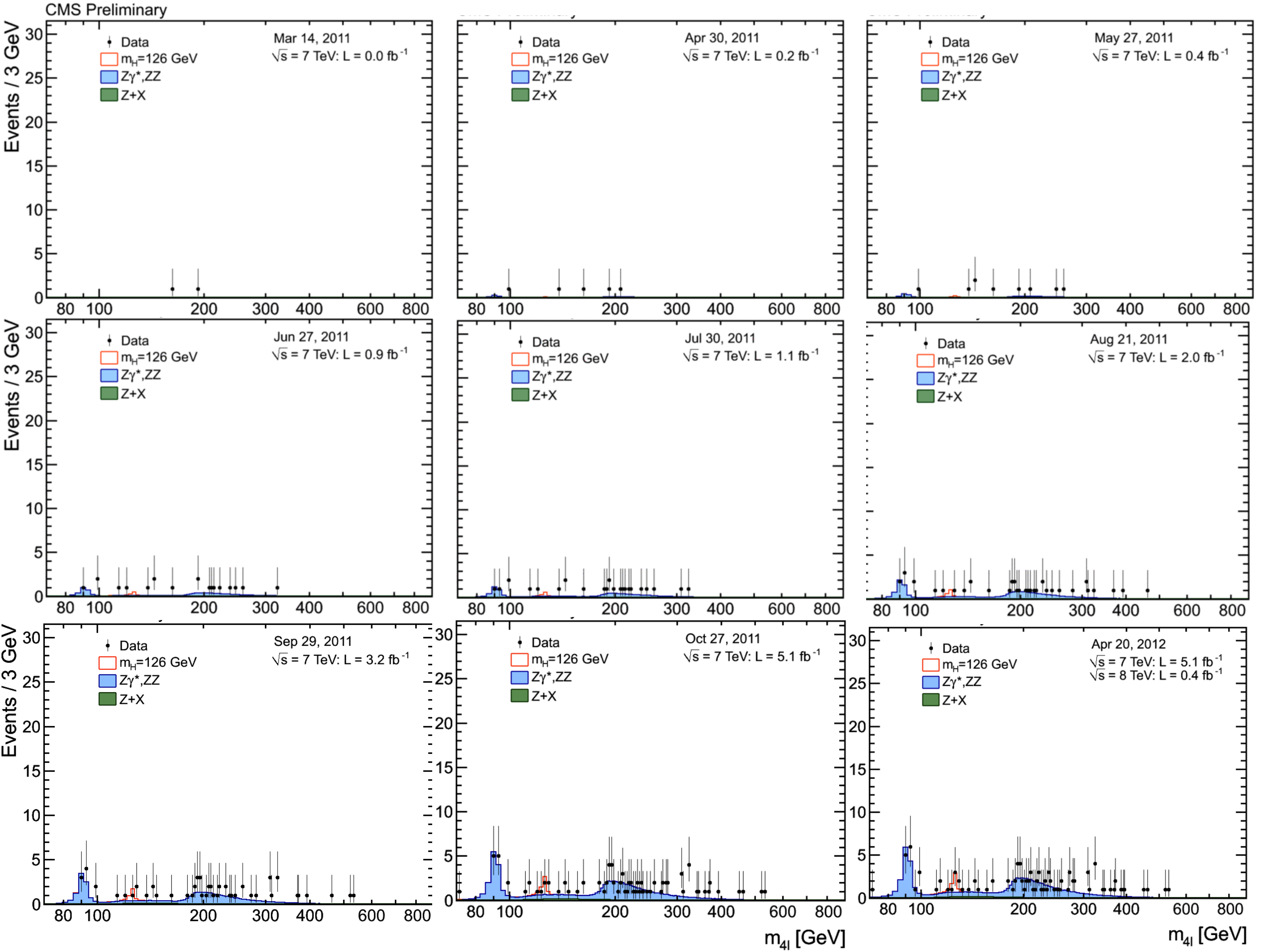
...and finally we have searched for it at the LHC.

Proton-proton collider at $s^{1/2}$=7, 8 TeV

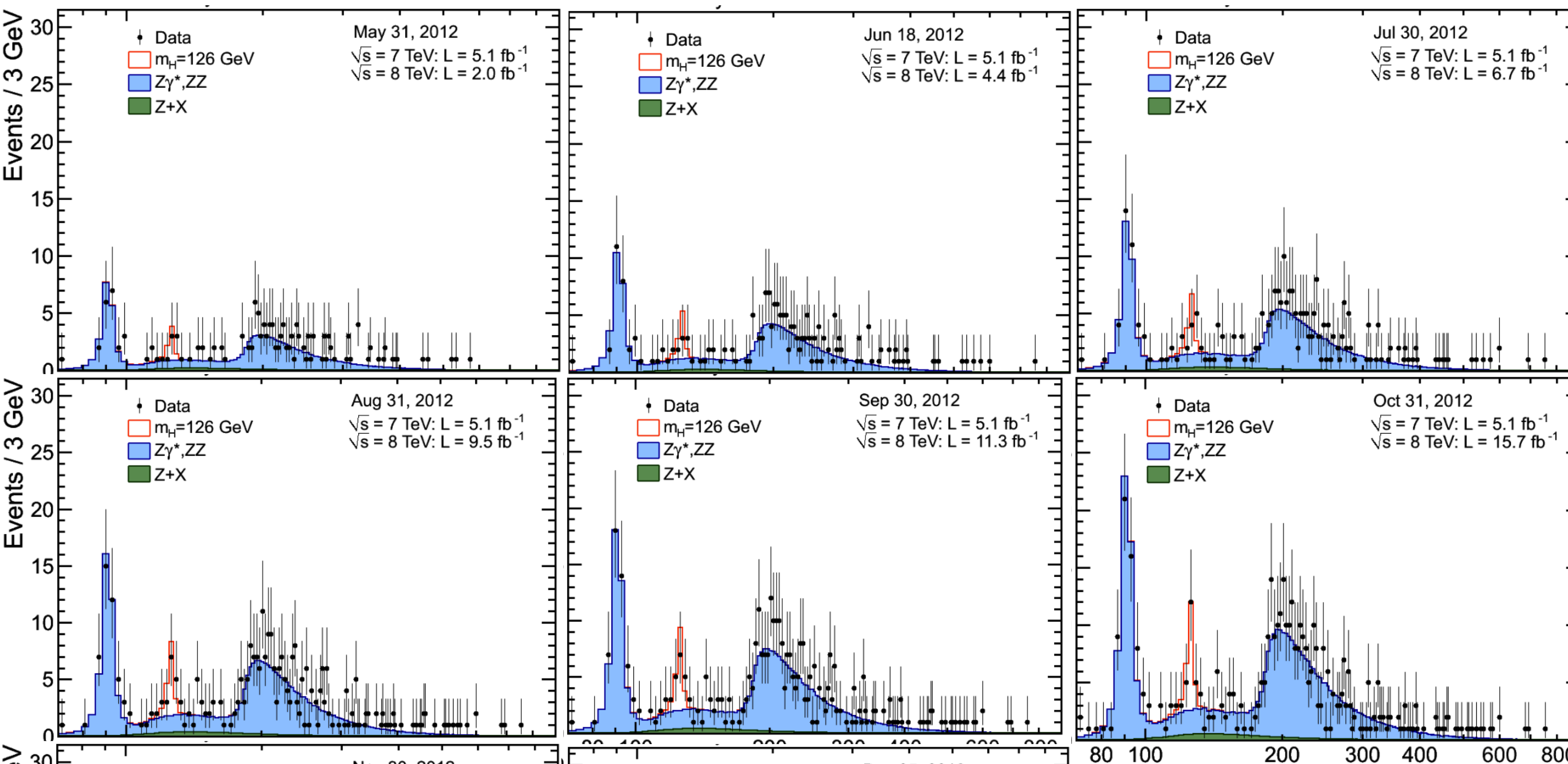
First collision: 23 November 2009

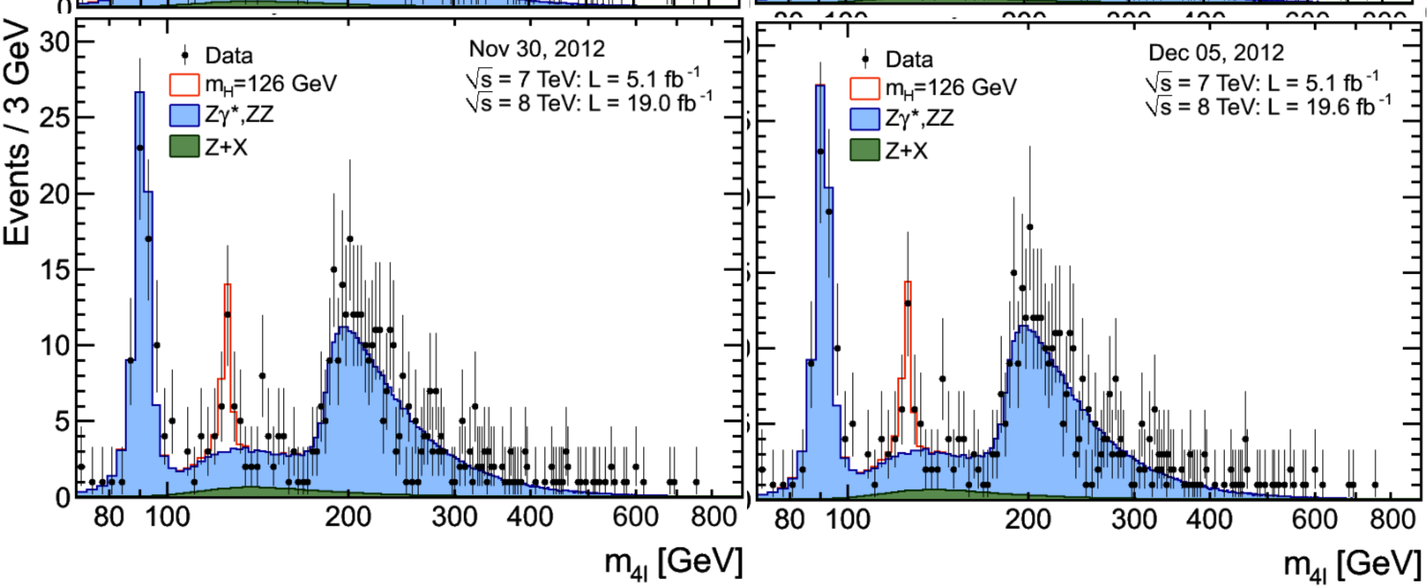
Almost 25 fb^{-1} of data for analysis





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]





"I think we have it.

Do you agree ?"

Rolf Heuer, CERN DG, 4th July

It was not as easy as counting...

All the details about the LHC results and interpretation in the next sessions

Monday, 12 May 2014

18:00 - 19:30 Higgs Physics 2 *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, 19 May 2014

18:00 - 19:30 Higgs Physics 3 *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, 26 May 2014

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

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