Hunt for the Higgs Boson and its Coupling to Fermions

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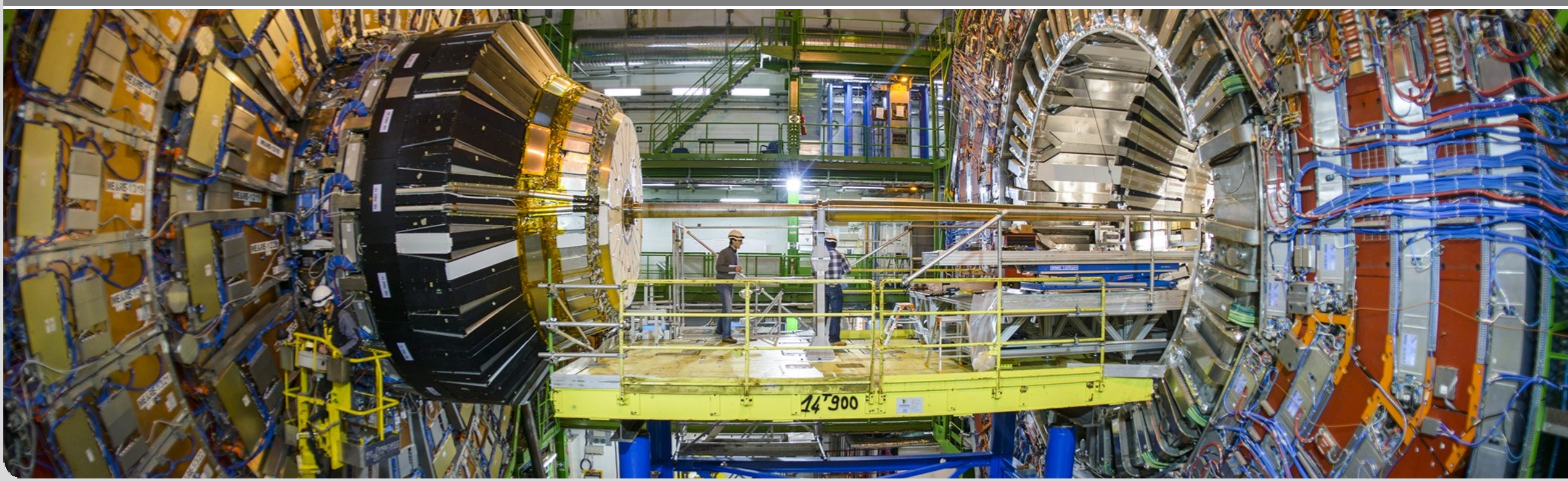
27. June 2014

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY



Constituents of Matter

- All matter we know off today is made up of six quark and six lepton flavors:

	Fermions		
Quarks	u up	c charm	t top
	d down	s strange	b bottom
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	e electron	μ muon	τ tau

- All of them are fermions with spin $1/2$.

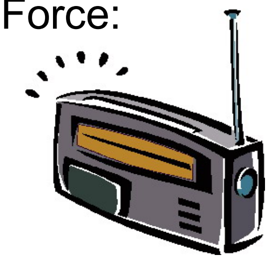
Fundamental Interactions

- We know four fundamental interactions, which act between them:

	Fermions		
Quarks	*u* up	*c* charm	*t* top
	d down	*s* strange	*b* bottom
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	e electron	μ muon	τ tau

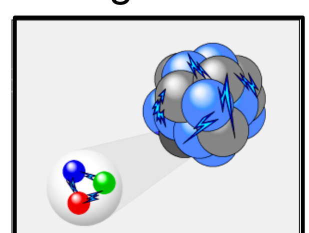
Gravitation:

Electromagnetic Force:



Weak Force:

Strong Force:



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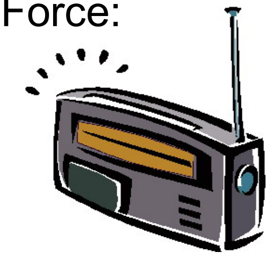
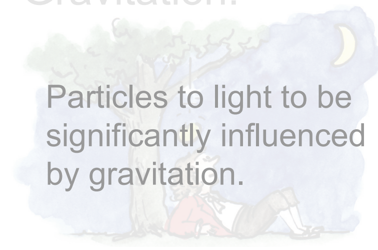


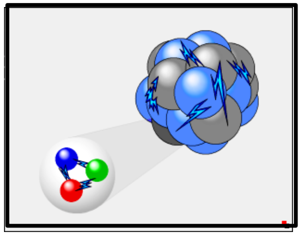
Gravitation:



Particles to light to be significantly influenced by gravitation.

Weak Force:

Strong Force:



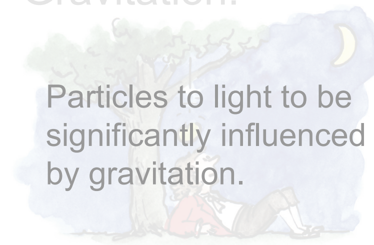
Local Gauge Symmetries

Karlsruhe Institute of Technology

- Structure of fundamental interactions enforced by principle of local gauge symmetries:

	Fermions			Bosons
Quarks	u up	c charm	t top	γ photon
	d down	s strange	b bottom	Z Z boson
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson
	e electron	μ muon	τ tau	g gluon

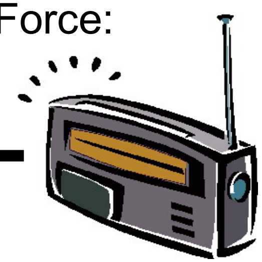
Gravitation:



Particles to light to be significantly influenced by gravitation.

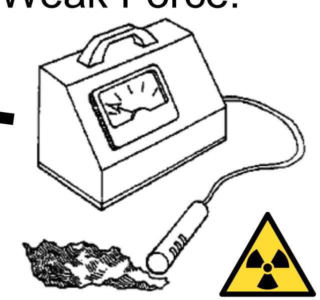
Electromagnetic Force:

$U(1)$



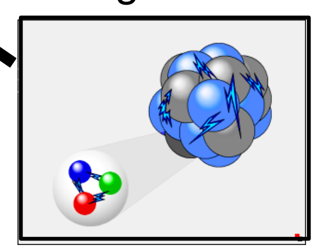
Weak Force:

$SU(2)$



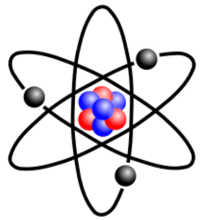
Strong Force:

$SU(3)$



- Lead to introduction of force carrying particles (→ Bosons).

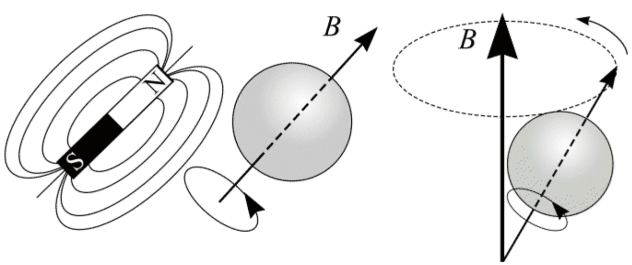
Glory of Local Gauge Symmetries



Lamb shift ($\mathcal{O}(10^{-11})$).

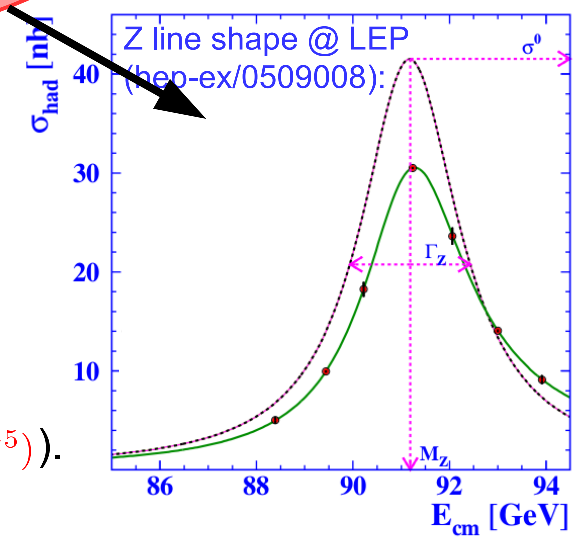
Rare decays at b-factories ($\mathcal{O}(10^{-9})$).

Can describe **plethora of phenomena** (not only of particle physics) to tremendous precision:



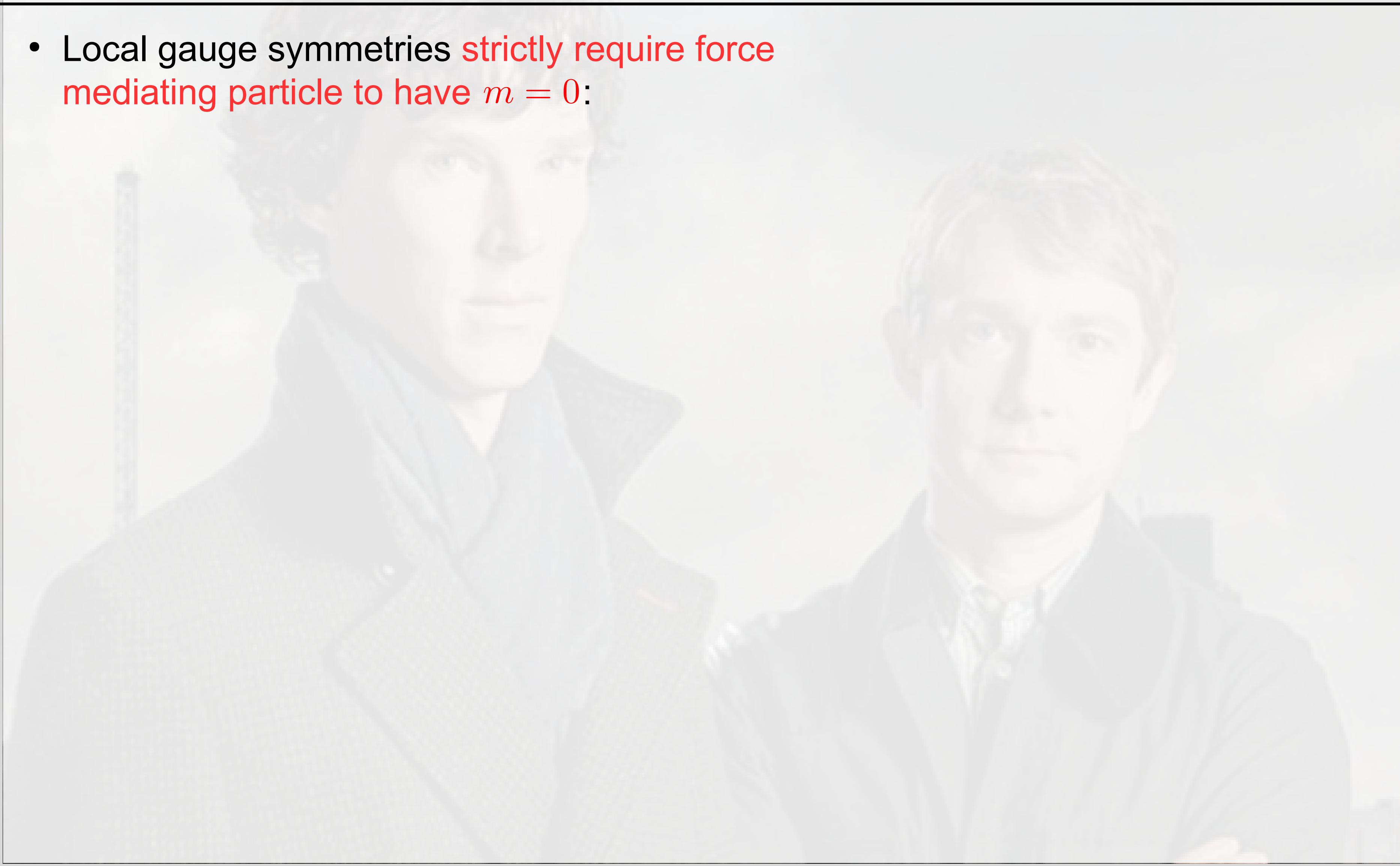
Anomalous magnetic moment of the muon ($\mathcal{O}(10^{-9})$).

High precision data @ particle physics experiments ($\mathcal{O}(10^{-5})$).



Case of Electroweak Symmetry

- Local gauge symmetries strictly require force mediating particle to have $m = 0$:



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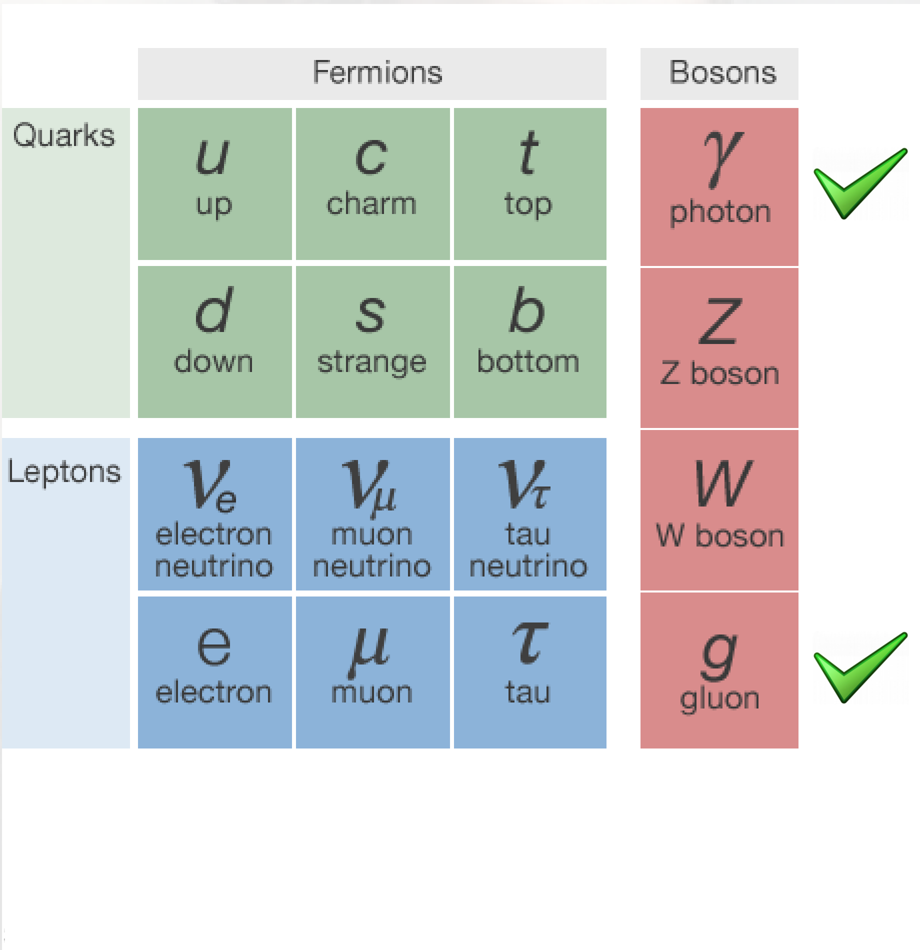

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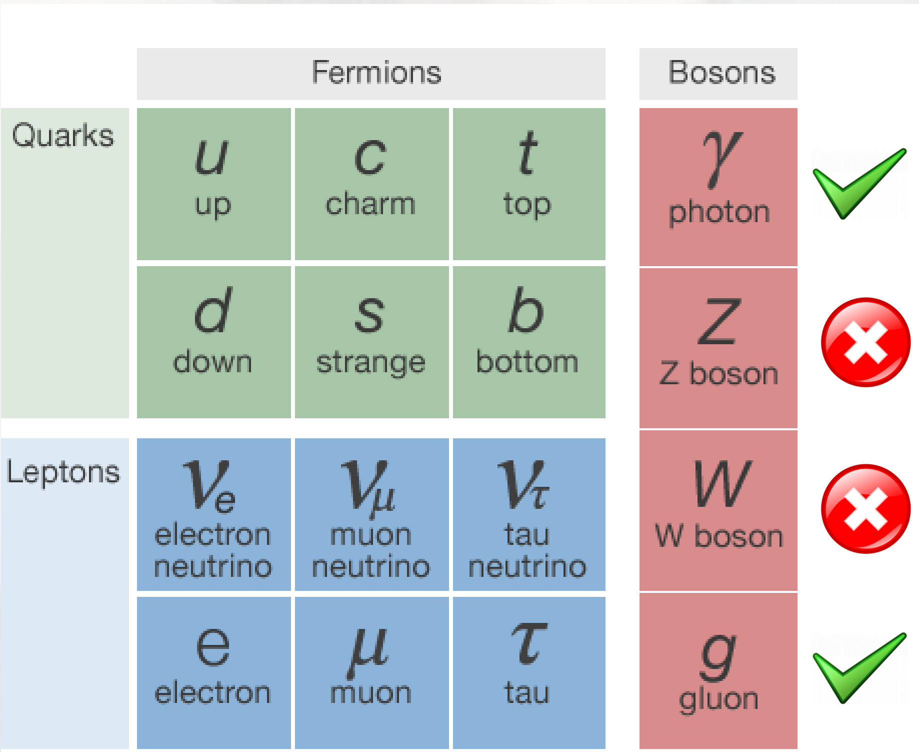

$$m_Z = 91.1876 \pm 0.0021 \text{ GeV}$$
$$m_W = 85.385 \pm 0.015 \text{ GeV}$$

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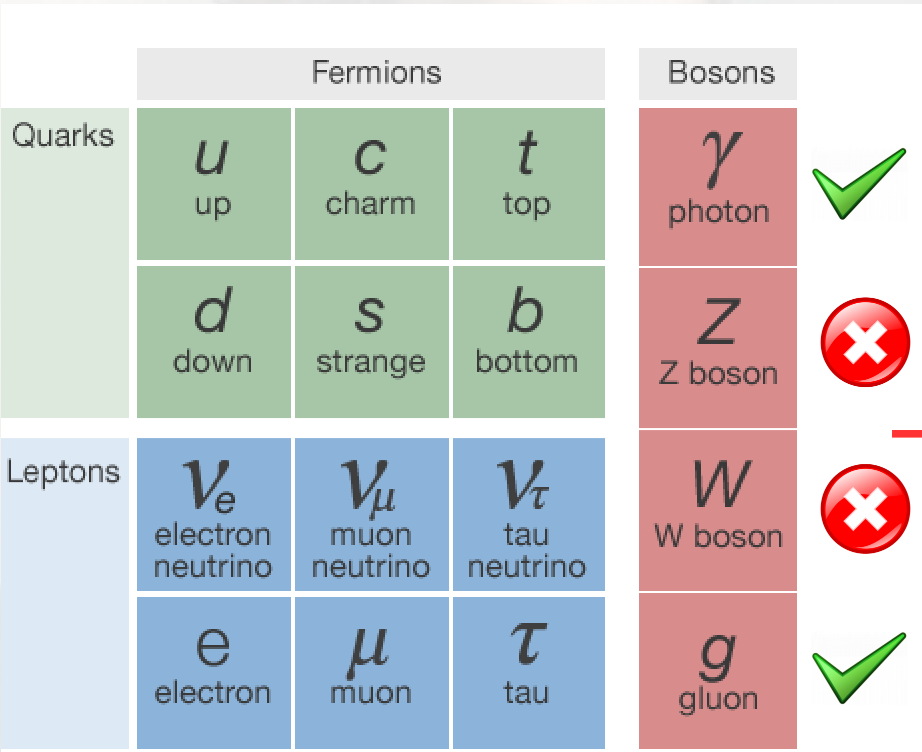

$$m_Z = 91.1876 \pm 0.0021 \text{ GeV}$$
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- Weak interaction makes a difference between left- & right-handed coordinate systems.
- This property destroys local gauge invariance for all weak interactions if fermions have mass $m \neq 0$.

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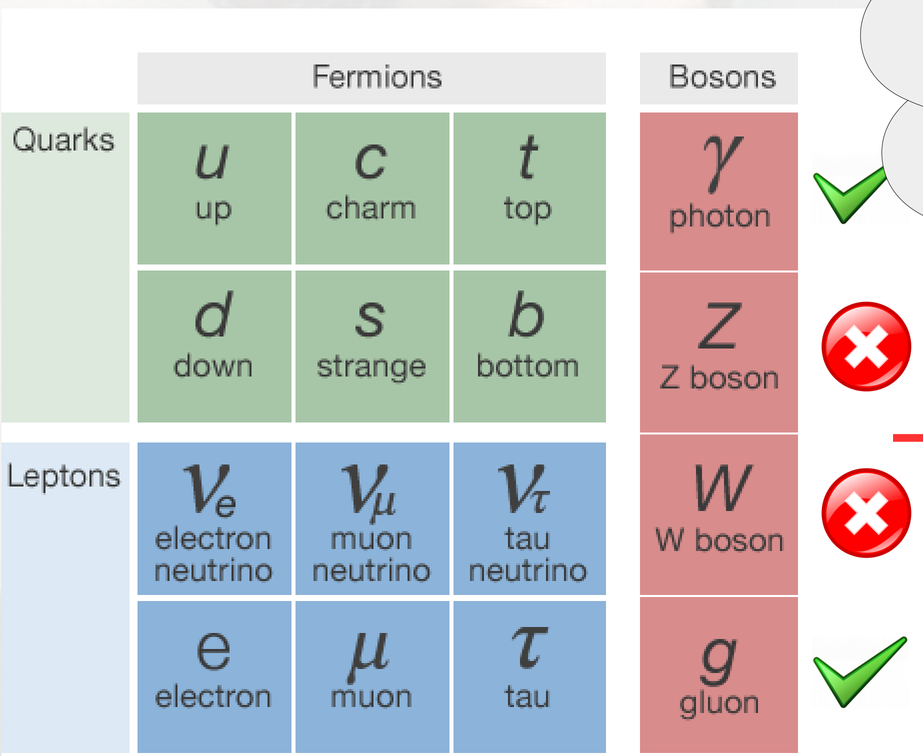
- Local gauge symmetries strictly require force mediating particle to have $m = 0$:



$$m_Z = 91.1876 \pm 0.0021 \text{ GeV}$$
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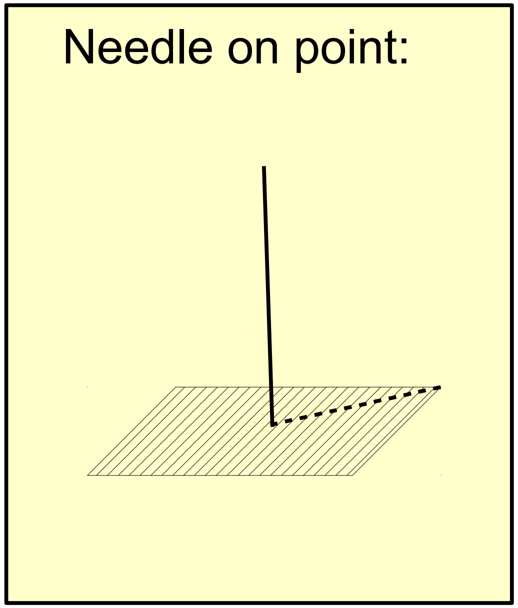
- Weak interactions are described by weak gauge symmetries! → symmetry exists.
- Force mediating particles explicitly break symmetry! → symmetry not realized in nature.

- Weak interaction makes a difference between left- & right-handed coordinate systems.
- This property destroys local gauge invariance for all weak interactions if fermions have mass $m \neq 0$.

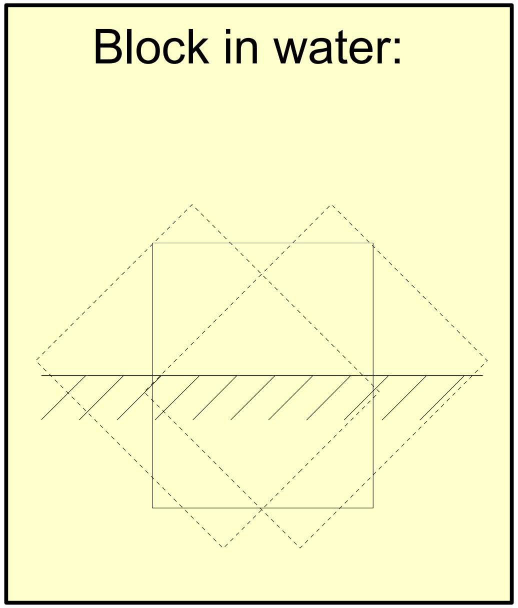
Spontaneous Symmetry Breaking

- Symmetry present in the system (i.e. in Lagrangian density $\mathcal{L}$).
- BUT symmetry broken in energy ground state of the system (=quantum vacuum).

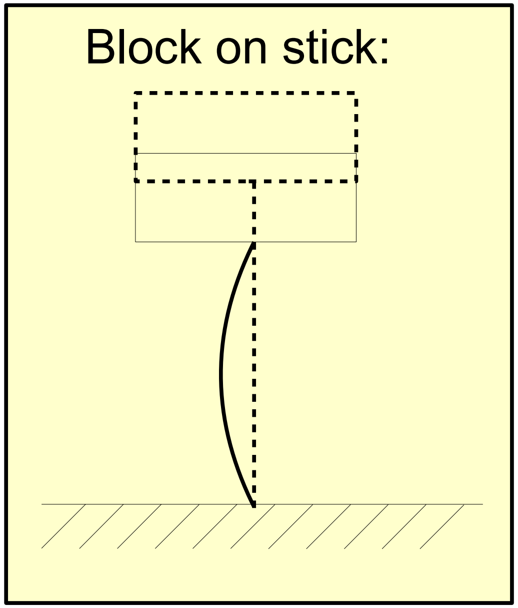
- Three examples from classical mechanics:



φ symmetry



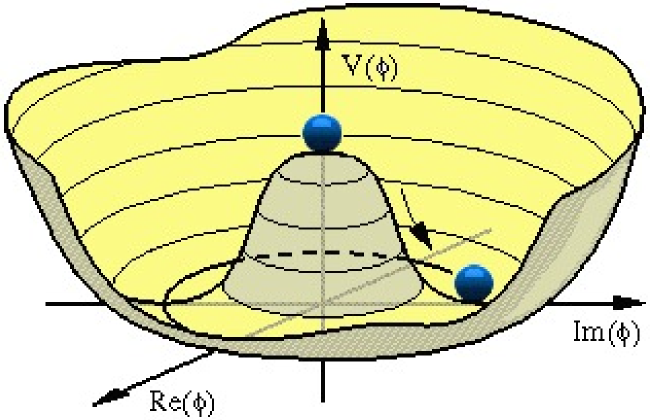
axis-symmetry



φ symmetry

Higgs Mechanism

- Incorporation of spontaneous symmetry breaking in gauge field theory = Higgs mechanism:
- Introduce new field ϕ with characteristic interaction potential.
- Leads to prediction of new particle: $\rightarrow$ Higgs boson!
- Allows to incorporate mass terms in the theory.



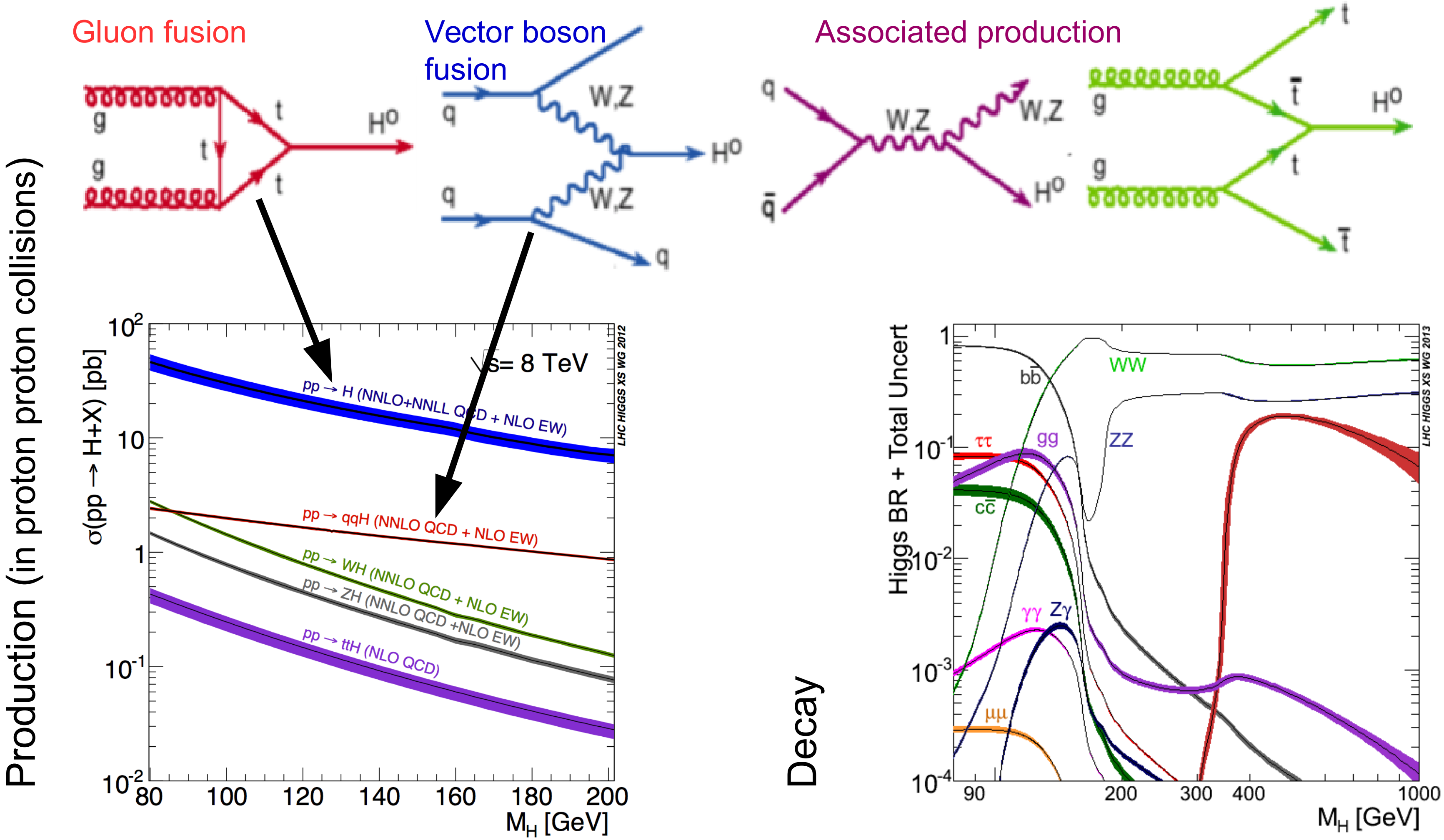
- Gauge symmetry compromising mass terms compensated by characteristic couplings to Higgs particle:

$$\kappa_V = \frac{2m_v^2}{\mathrm{v}} \quad \text{(for force mediating } W \text{ \& } Z \text{ boson).}$$

$$\kappa_f = \frac{m_f}{\mathrm{v}} \quad \text{(for weakly interacting fermions).}$$

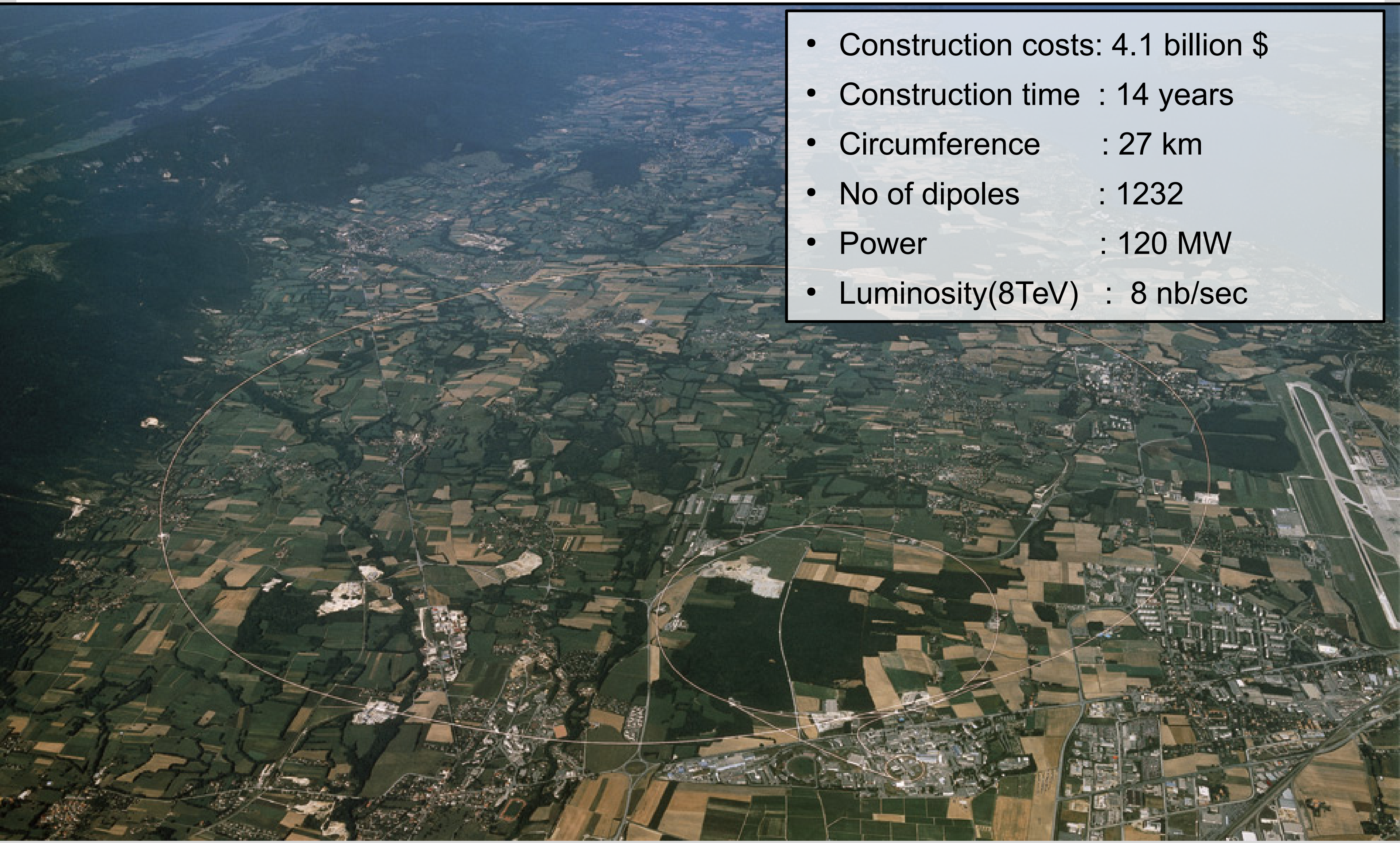
Wanted: Higgs Boson (Dead or Alive)

- If m_H is given all properties of the (SM) Higgs boson are known:

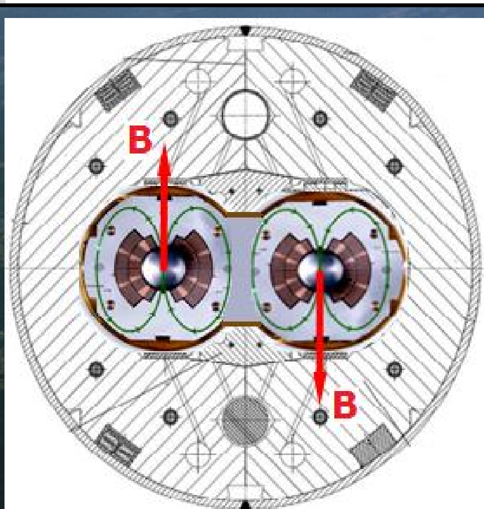


The Large Hadron Collider

- Construction costs: 4.1 billion $
- Construction time : 14 years
- Circumference : 27 km
- No of dipoles : 1232
- Power : 120 MW
- Luminosity(8TeV) : 8 nb/sec



The Large Hadron Collider



- 8.3 T
- 11.8 kA
- 160 cyc

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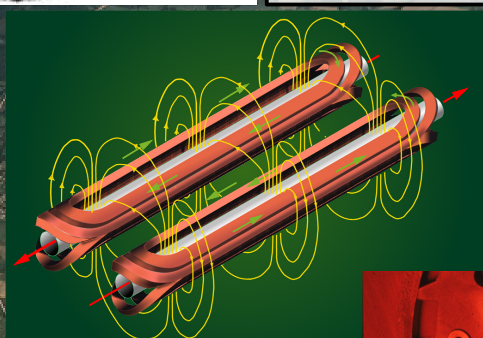
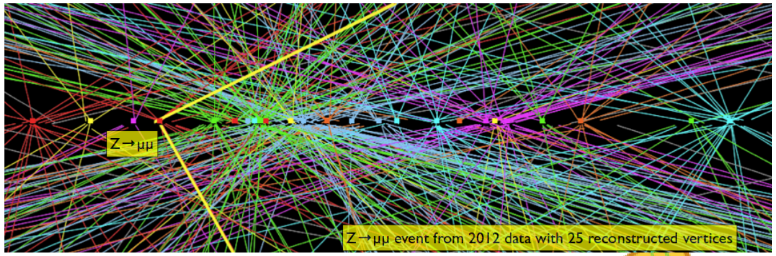


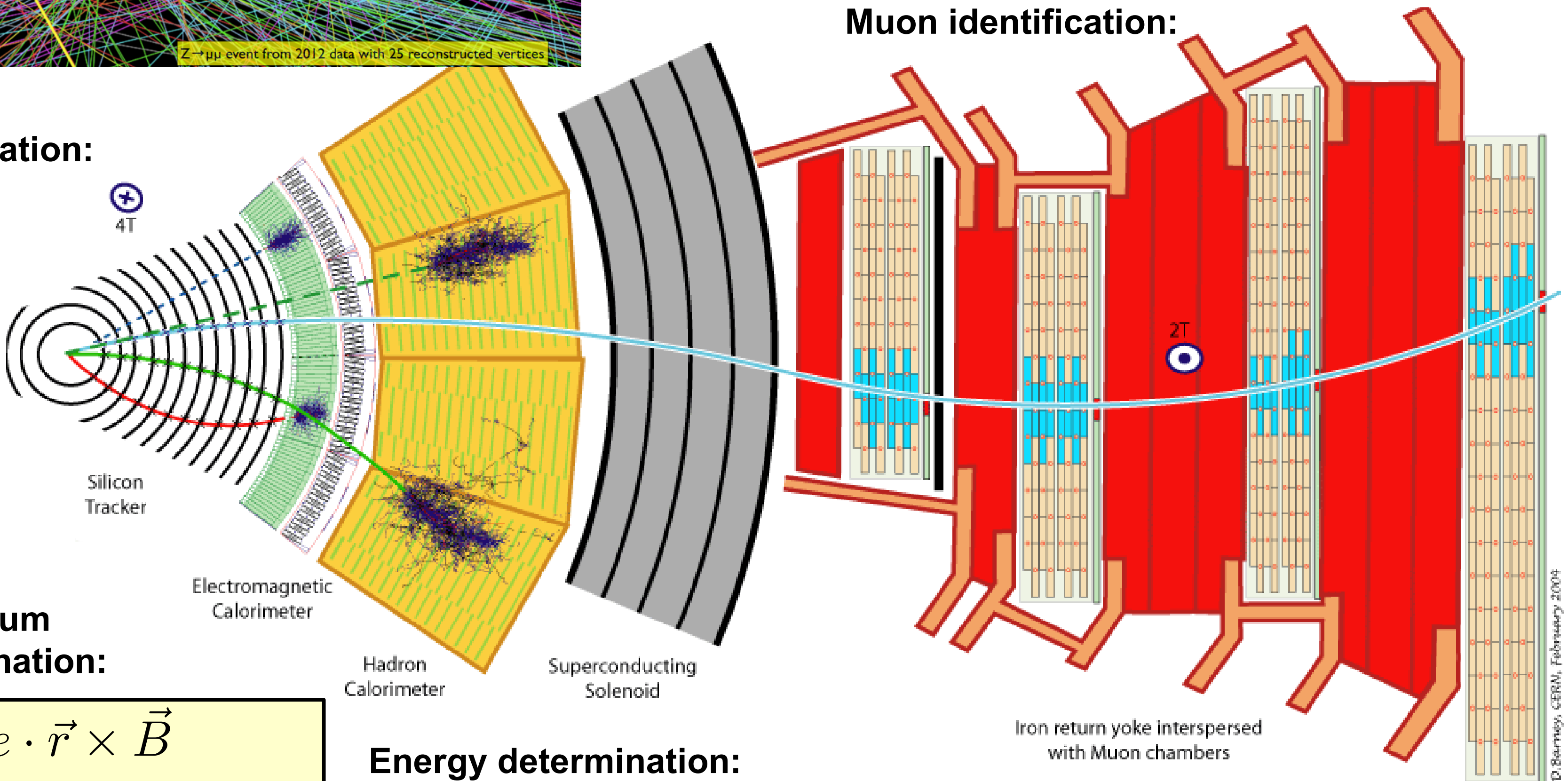
- Energy density 500 kJ/m
- Tension 200'000 t/m

Key demands on Experiments



Vertex identification:

Muon identification:



Momentum determination:

$$\vec{p} = e \cdot \vec{r} \times \vec{B}$$

$$\frac{\delta p}{p} = \frac{1}{erB} (\delta B \oplus \delta r)$$

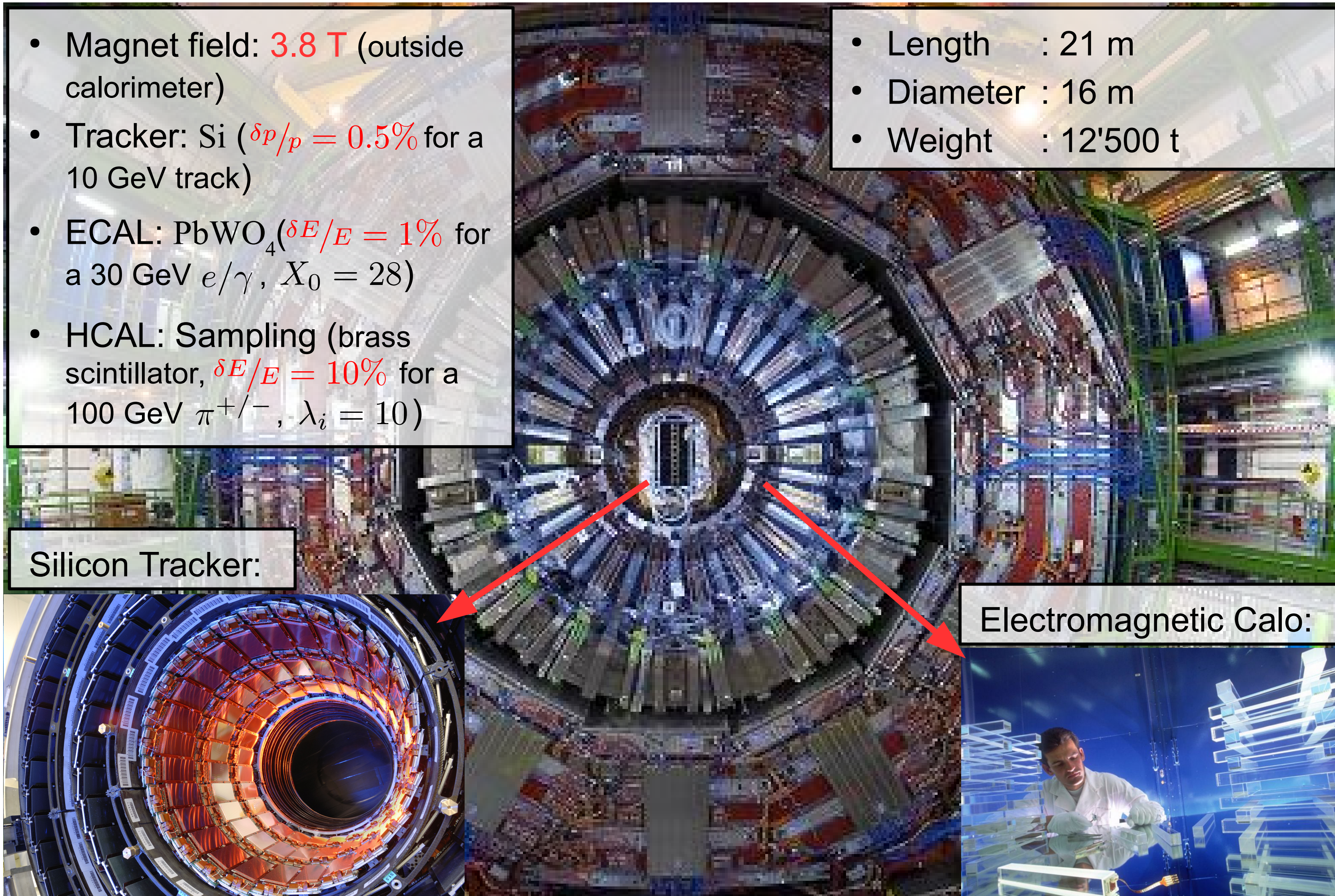
Energy determination:

- Energy resolution
- Stopping power

The Compact Solution (CMS)

- Magnet field: 3.8 T (outside calorimeter)
- Tracker: Si ($\delta p/p = 0.5\%$ for a 10 GeV track)
- ECAL: $PbWO_4$($\delta E/E = 1\%$ for a 30 GeV e/γ, $X_0 = 28$)
- HCAL: Sampling (brass scintillator, $\delta E/E = 10\%$ for a 100 GeV $\pi^{+/-}$, $\lambda_i = 10$)

- Length : 21 m
- Diameter : 16 m
- Weight : 12'500 t



Silicon Tracker:

Electromagnetic Calo:

LHC History (measured in physics measurements)

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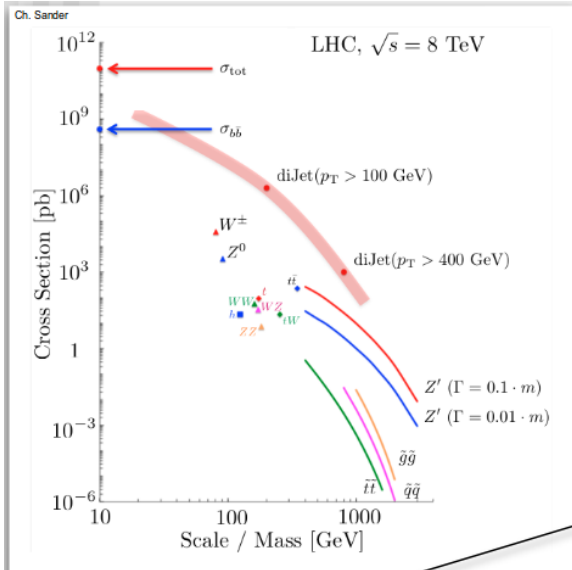
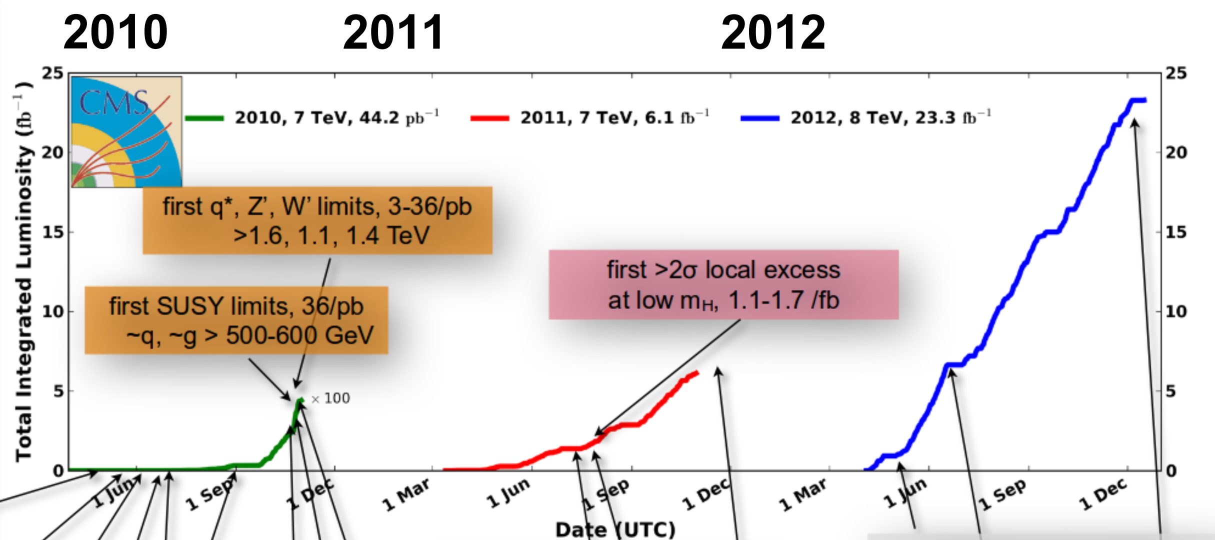




first q*, Z', W' limits, 3-36/pb
>1.6, 1.1, 1.4 TeV

first SUSY limits, 36/pb
~q, ~g > 500-600 GeV

first >2σ local excess
at low m_H, 1.1-1.7 /fb

repeating the program
at 8 TeV

first MinBias / UE
studies, particle multiplicities

first top xsec, 3/pb
δ ~ 40%

first ZZ xsec, 1.1 /fb
δ ~ 40%

first incl. b x-section, 8/nb
δ ~ 15 %

first single top xsec,
t-chan., 36/pb
δ ~ 36%

going more differential,
e.g. Z/W + j,b,c

a new boson is
announced, 5 /fb

first incl. jet x-section, PF jets
60/nb δ ~ 20-30%

first m_{top}, 36/pb
Δ ~ 6.5 GeV

first significant limit on
$B_s \to \mu\mu$, BR<1.9x10^{-8}

first incl. W/Z x-sections, 200/nb
δ ~ 4-6%, +11% lumi

first WW xsec, 36/pb
δ ~ 40%
first limit on HWW

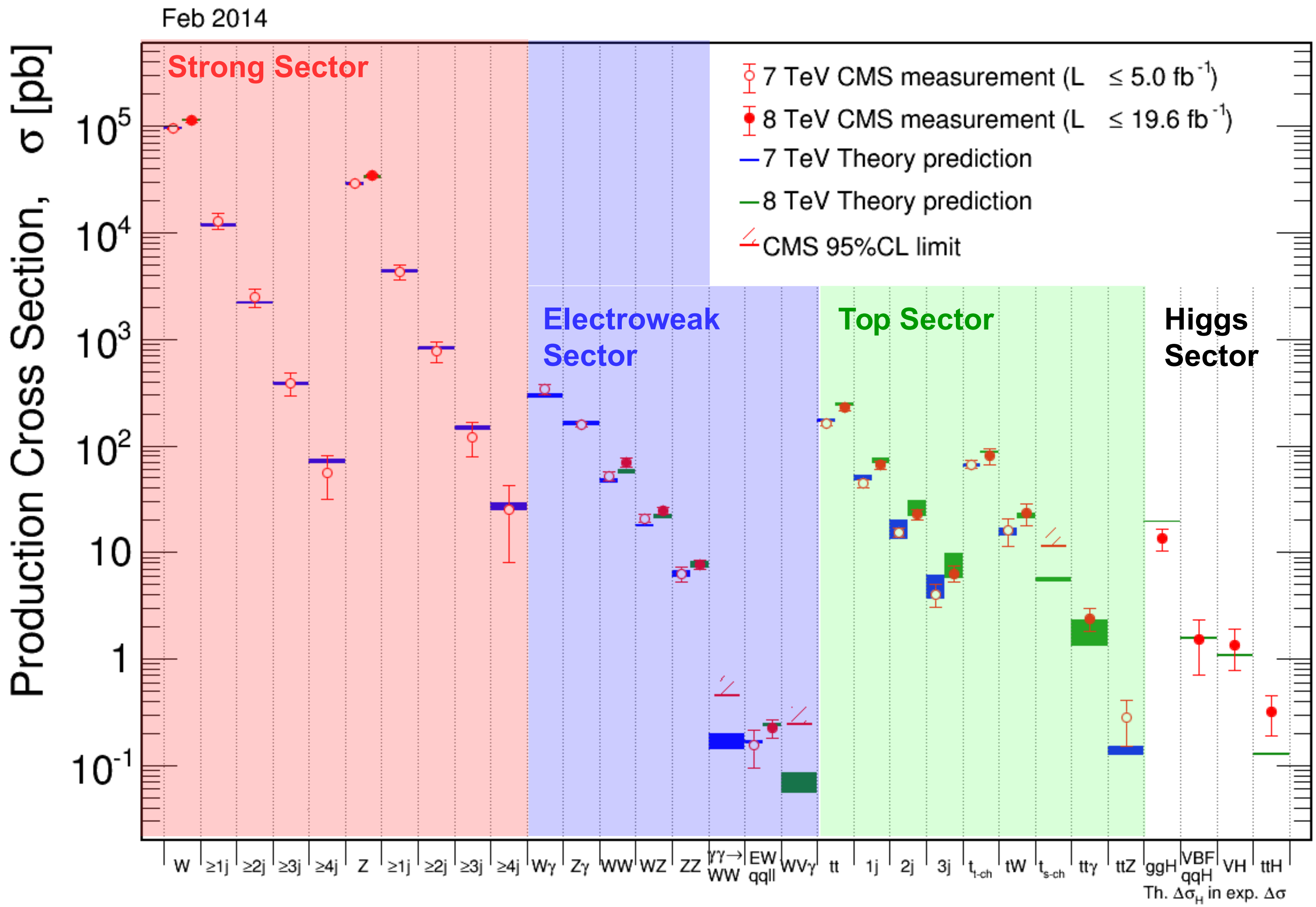
first particle discovered
by CMS: Ξ_b

first incl. J/Ψ x-section, 100/nb
δ ~ 20%

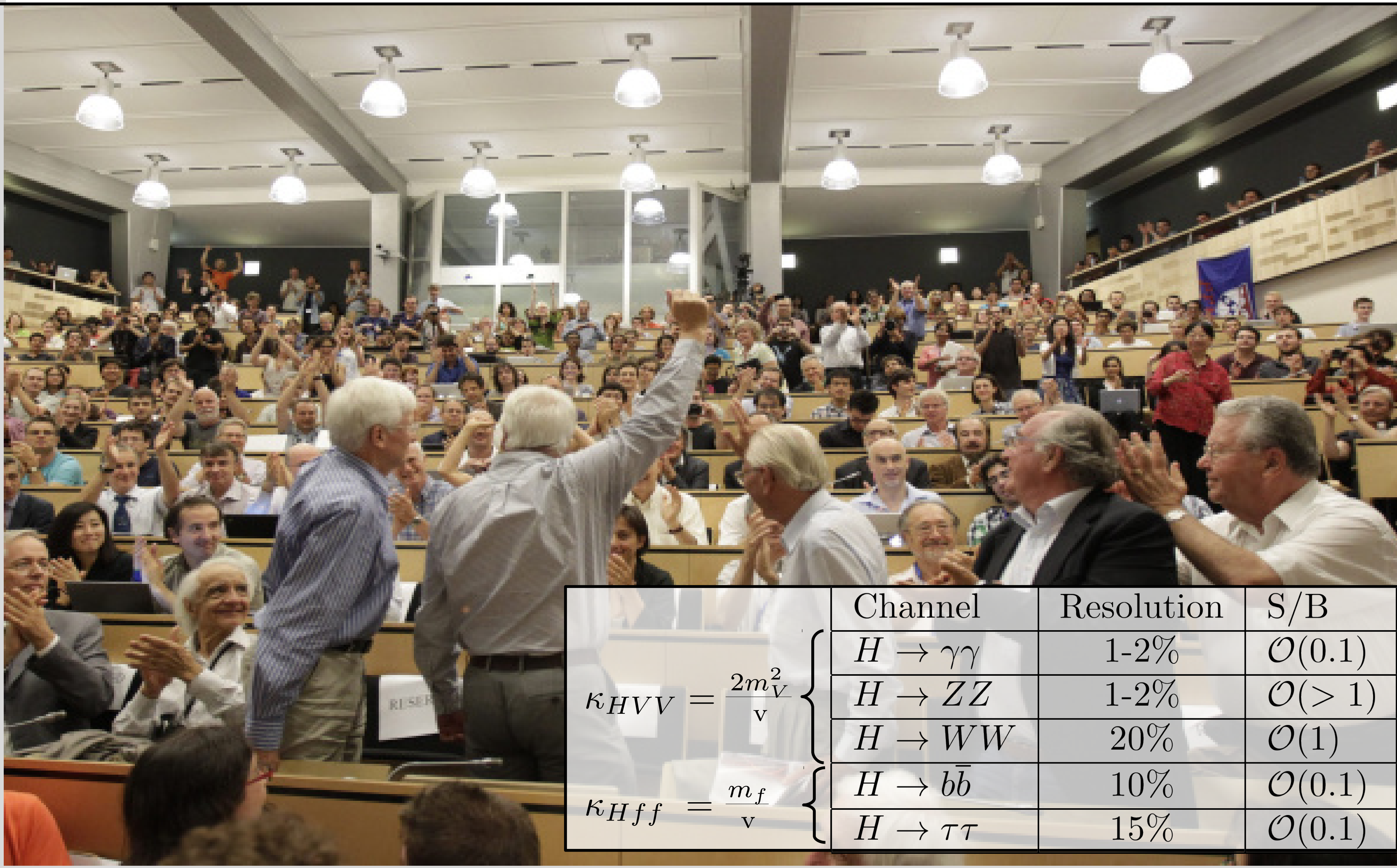
BSM searches continue,
limits pushed

first spin parity
analysis of the boson,
17 /fb

Snapshot of our Physics Understanding of Today



Discovery of a new particle 4th July 2012



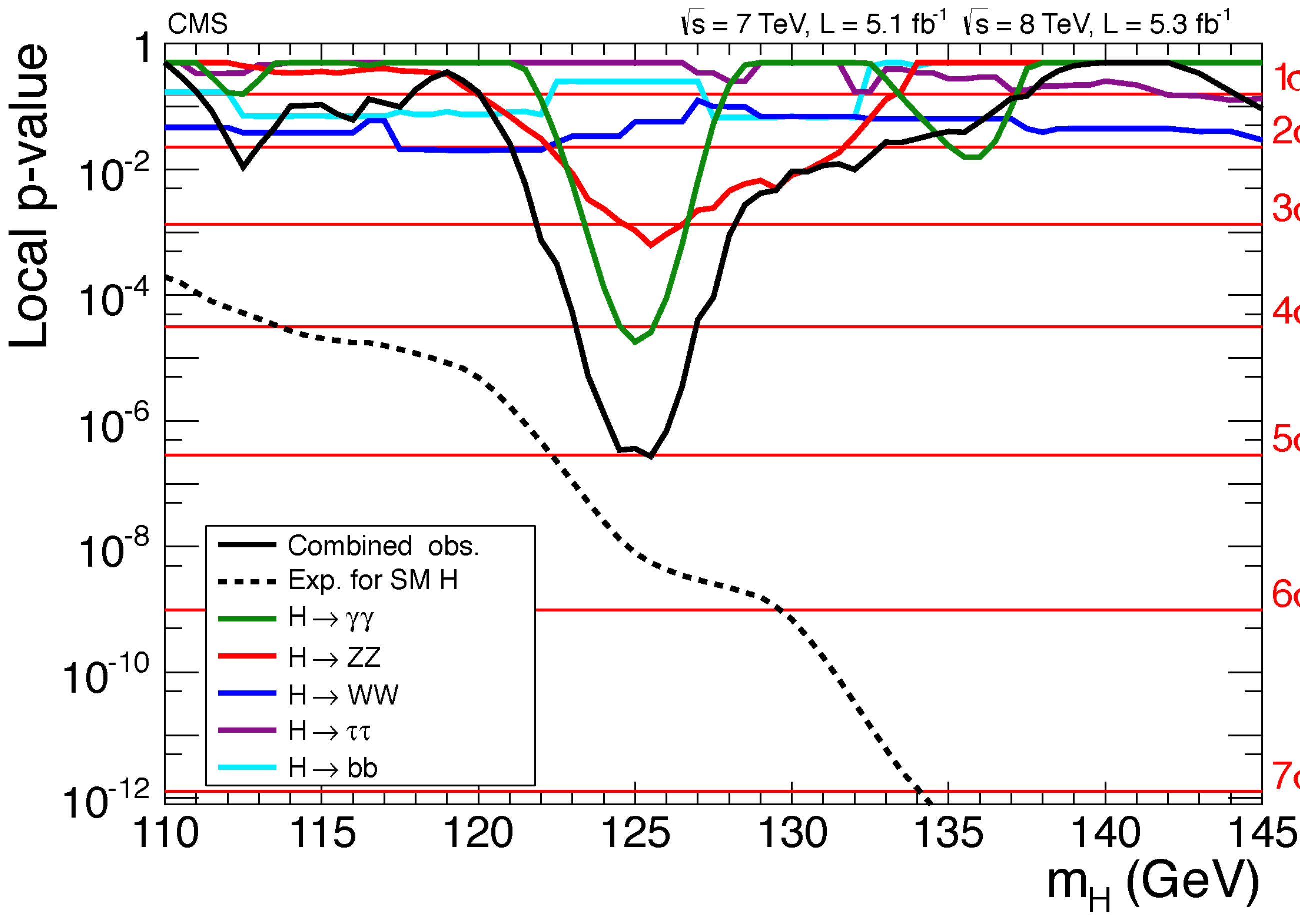
$$\kappa_{HVV} = \frac{2m_V^2}{\mathrm{v}} \quad (H \to \gamma\gamma,\ H \to ZZ,\ H \to WW)$$

$$\kappa_{Hff} = \frac{m_f}{\mathrm{v}} \quad (H \to b\bar{b},\ H \to \tau\tau)$$

Channel	Resolution	S/B
$H \to \gamma\gamma$	1-2%	$\mathcal{O}(0.1)$
$H \to ZZ$	1-2%	$\mathcal{O}(>1)$
$H \to WW$	20%	$\mathcal{O}(1)$
$H \to b\bar{b}$	10%	$\mathcal{O}(0.1)$
$H \to \tau\tau$	15%	$\mathcal{O}(0.1)$

Discovery of a new particle 4th July 2012

- Scratching magic 5σ boundary.
- Discovery driven by high resolution channels ($H \to \gamma\gamma$ & $H \to ZZ$).
- Broad moderate excesses for $H \to WW$.
- No signal seen in fermionic decay channels.

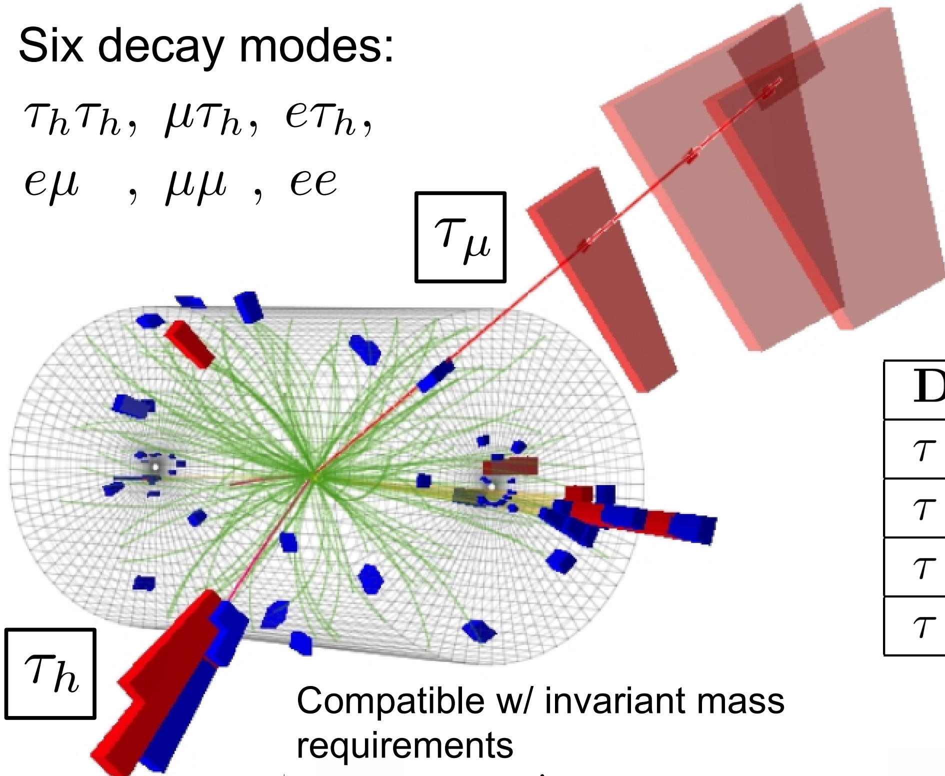


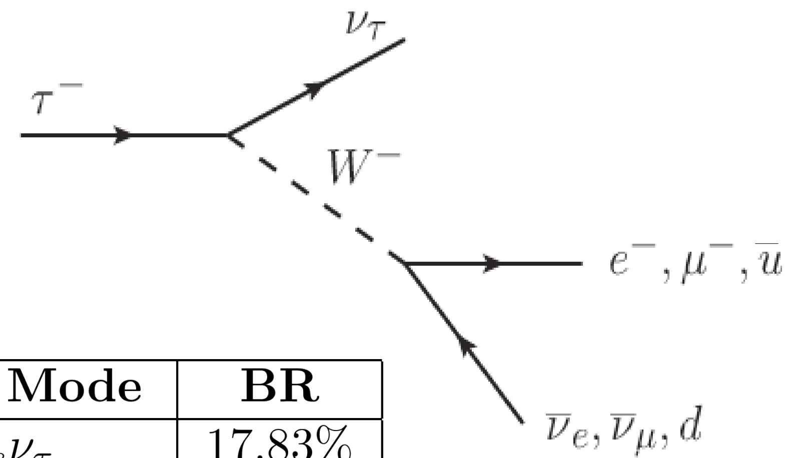
Does the new particle couple to fermions?

$H \to \tau\tau$ Decay Channel

Six decay modes:

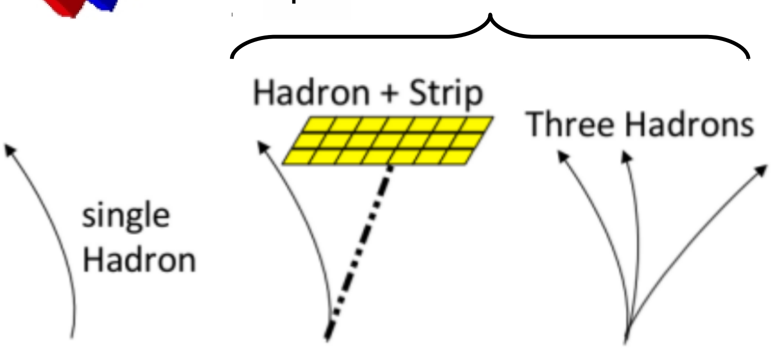
$\tau_h\tau_h,\ \mu\tau_h,\ e\tau_h,$
$e\mu\ ,\ \mu\mu\ ,\ ee$





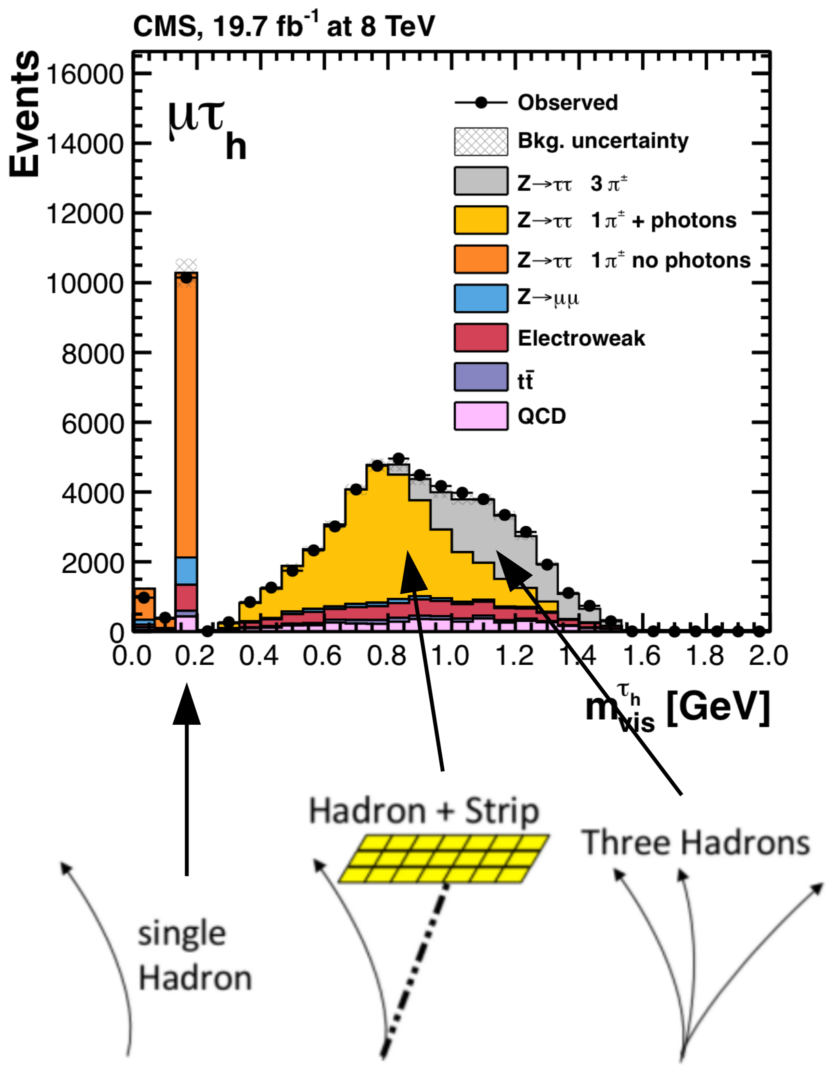
Decay Mode	BR
$\tau \to e\nu_e\nu_\tau$	17.83%
$\tau \to \mu\nu_\mu\nu_\tau$	17.41%
$\tau \to$ 1-prong ν_τ	37.10%
$\tau \to$ 3-prong ν_τ	15.20%

Compatible w/ invariant mass requirements

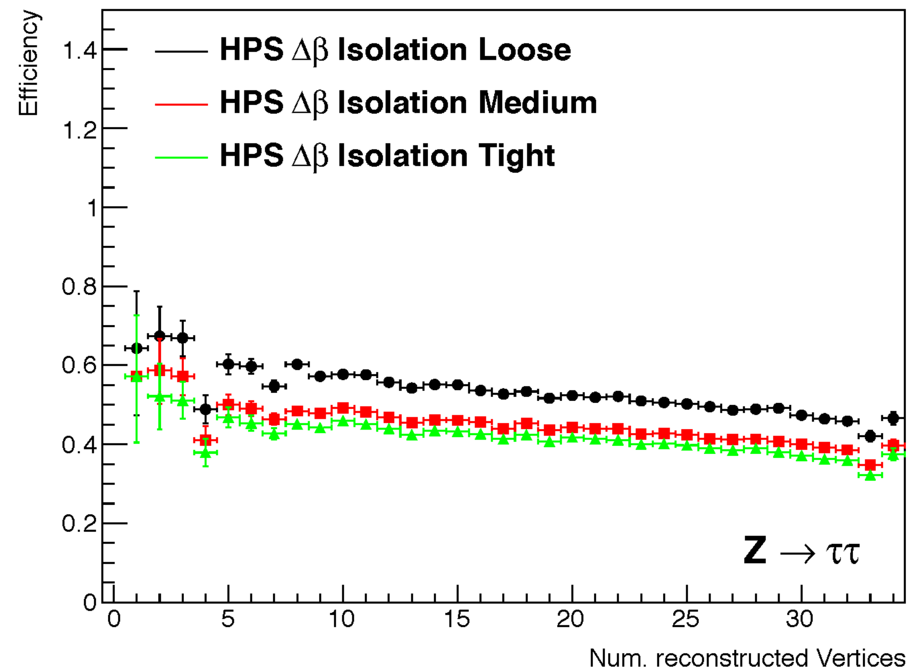


- Isolation (based on energy deposits in vicinity of reconstructed τ_h candidate).
- Discrimination against electrons (based on shower shape & E/p).
- Discrimination against muons.

Performance of Hadronic τ Reconstruction



- Efficiency $\approx 60\%$ ($\approx 3\%$ fakerate), flat for $p_T(\tau) > 30\ \mathrm{GeV}$ & independent from pileup events.



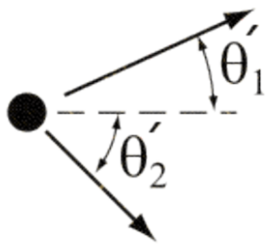
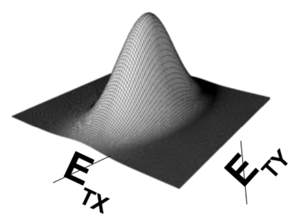
Analysis Strategy

- Analyze all six inclusive decay channels ($\tau_h\tau_h,\ \mu\tau_h,\ e\tau_h,\ e\mu,\ \mu\mu,\ ee$) & many more exclusive decay channels for VH production ($Z \rightarrow \ell\ell,\ W \rightarrow \ell\nu$).

- Select two isolated leptons ($\tau_h,\ \mu,\ e$).

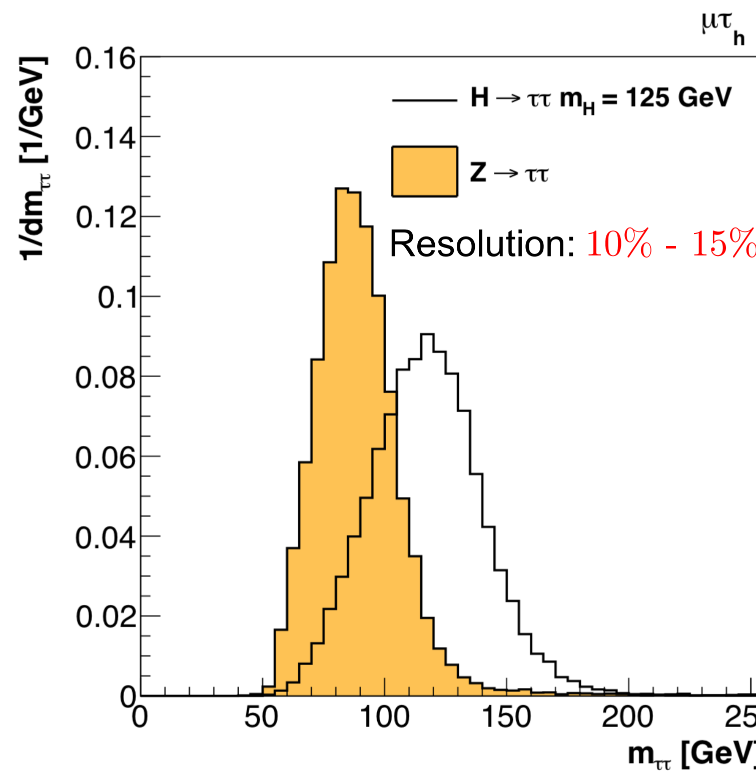
- Restrict $\not{E}_T$ to reduce background from $W + \mathrm{jets}$ events.

- Use fully reconstructed $m_{\tau\tau}$ as discriminating variable:

$\mathcal{L} =$  $\times$ 

- Inputs: visible leptons, x-, y-component of $\not{E}_T$.

- Free parameters: φ, θ^*, ($m_{\nu\nu}$) per τ.



Background Control

$Z \to \tau\tau$

- Embedding (in $Z \to \mu\mu$ replace μ by sim τ).
- Norm from $Z \to \mu\mu$.

$Z \to \ell\ell$

- From simulation
- Corrected for $jet \to \tau$ or $e/\mu \to \tau$ fakerate.

tt

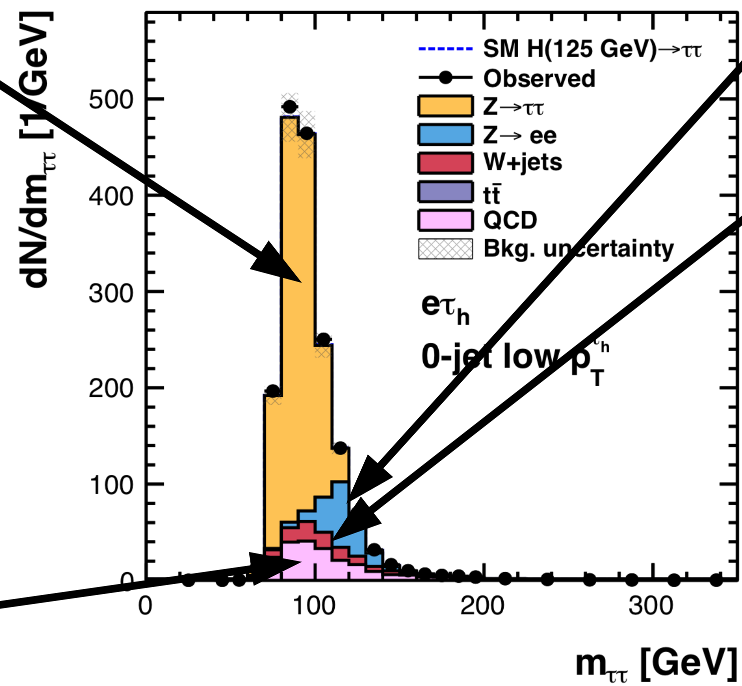
- From simulation.
- Normalization from sideband.

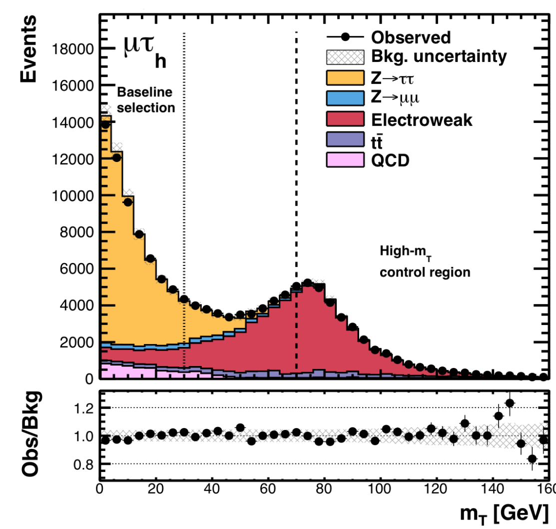
$W + jets$, Diboson

- From simulation
- Normalization from sidebands.

QCD multijet

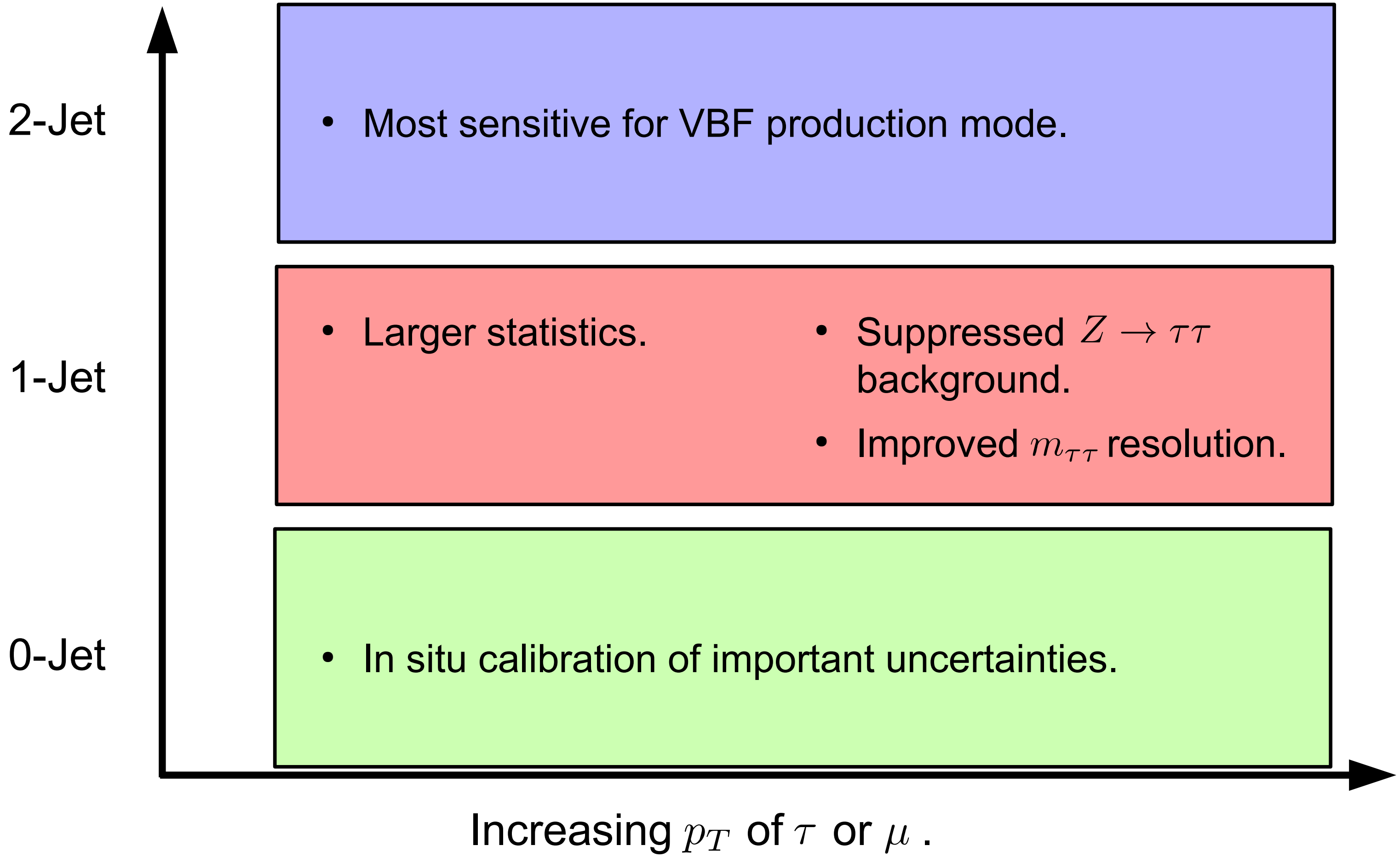
- Normalization & shape taken from LS/OS or fakerate.





Further Event Categorization

- Further event categorization to increase sensitivity of the analysis:



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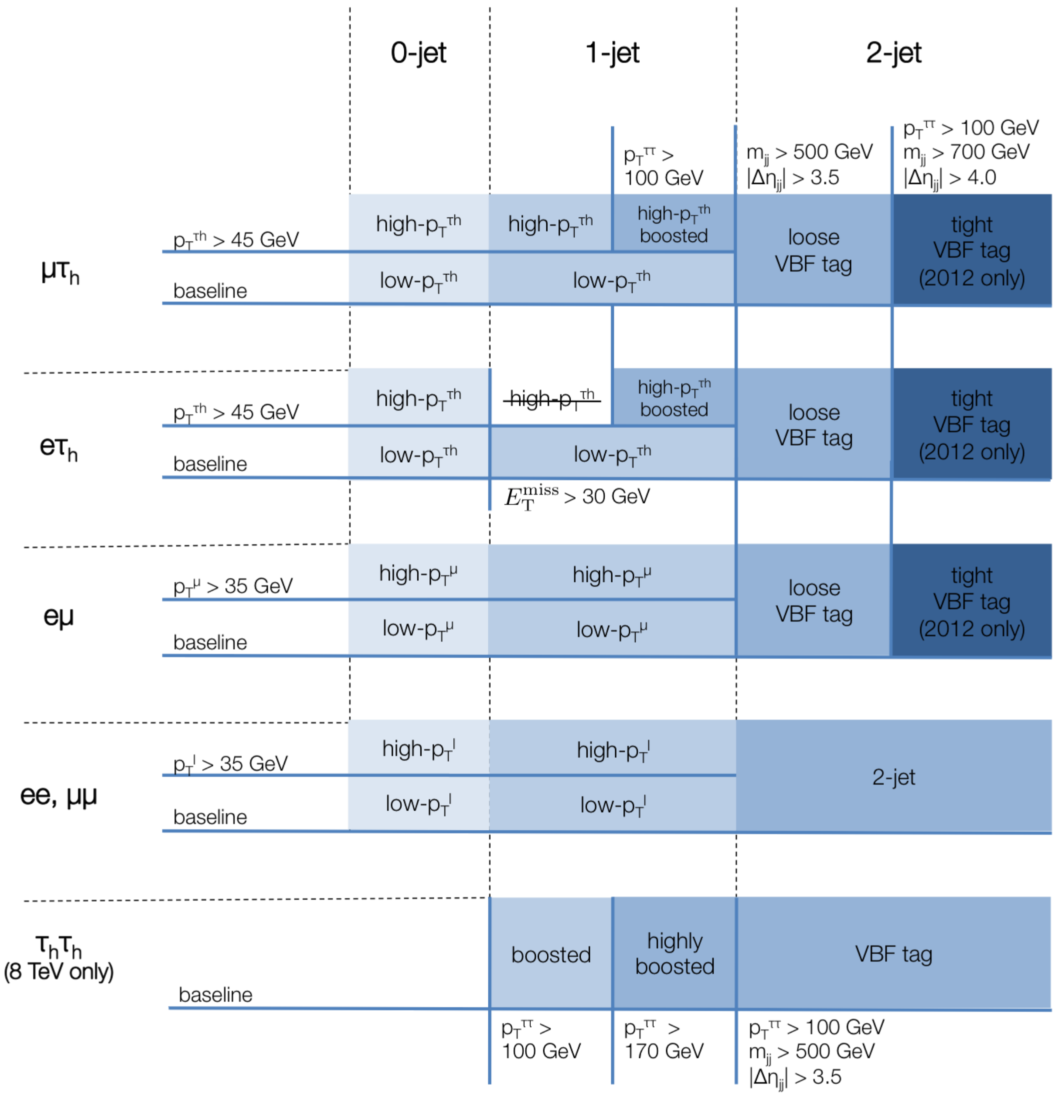
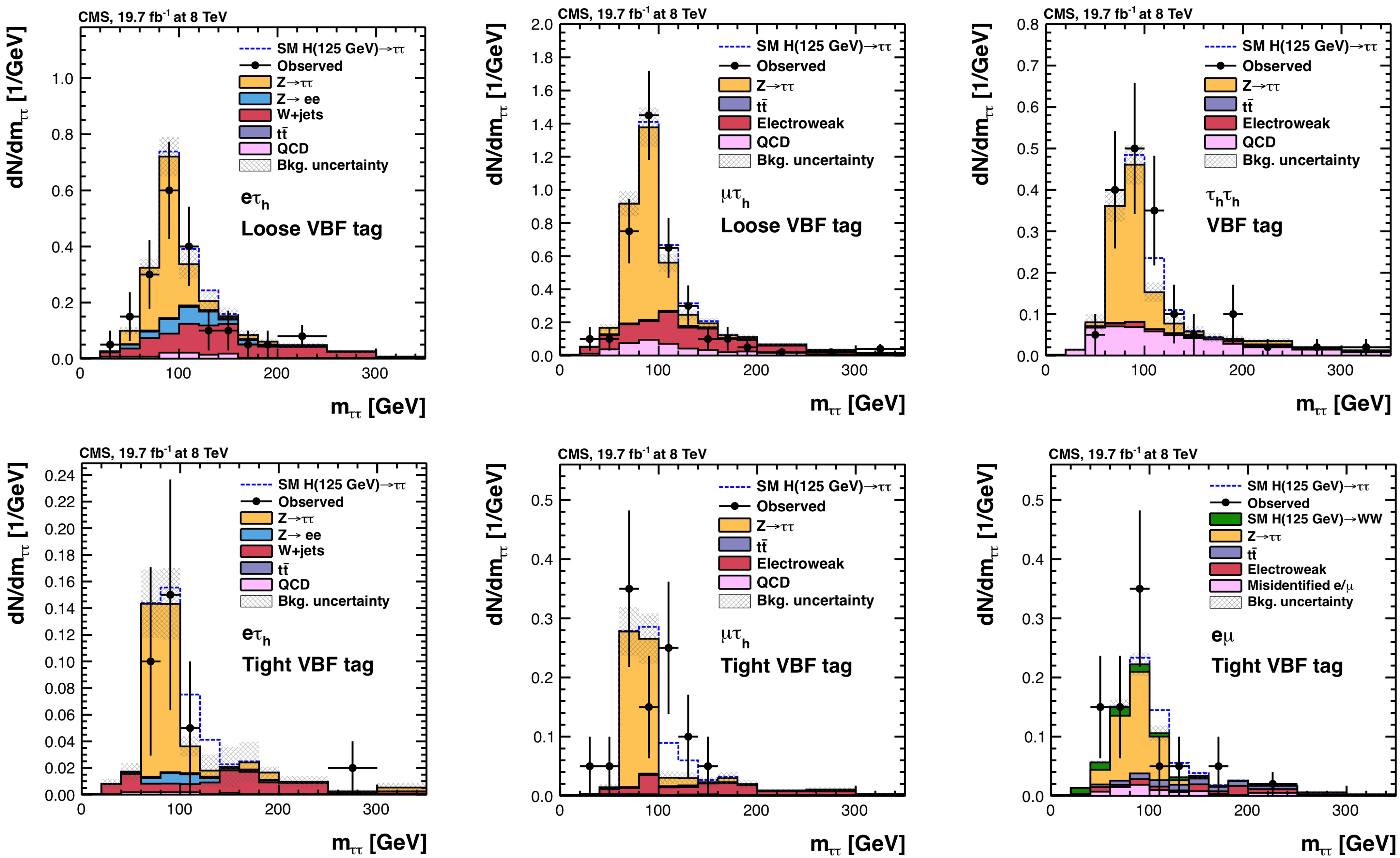
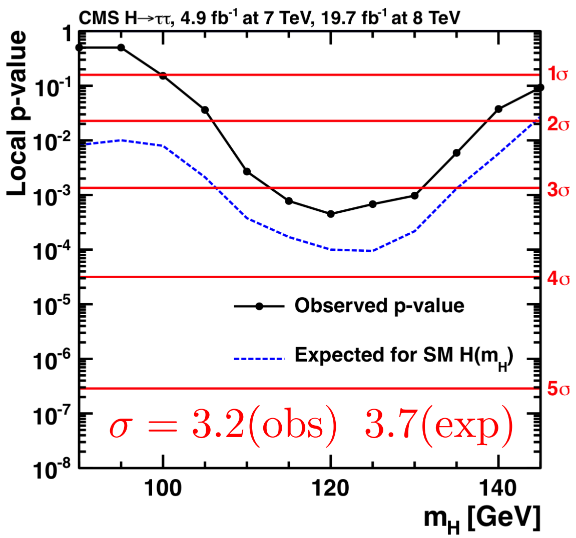


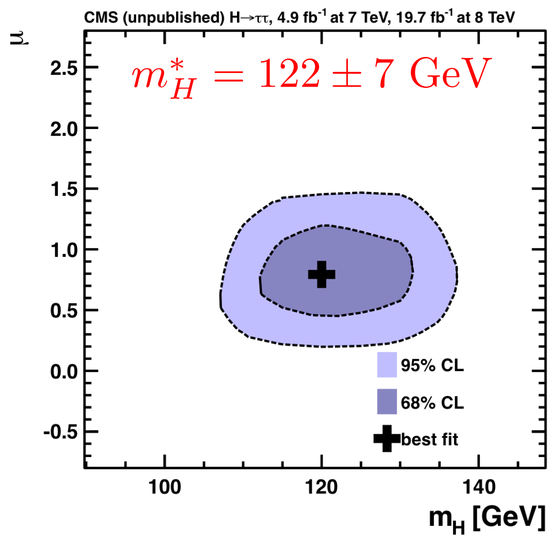
- Nearly 100 exclusive event categories.
- 6 inclusive decay channels.
- Exclusive decay channels for production in association with W, Z bosons.
- On 7 TeV and 8 TeV dataset.

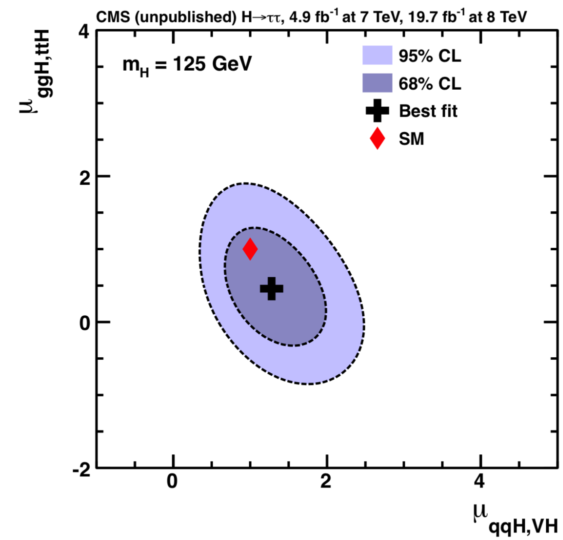
Distribution of $m_{\tau\tau}$

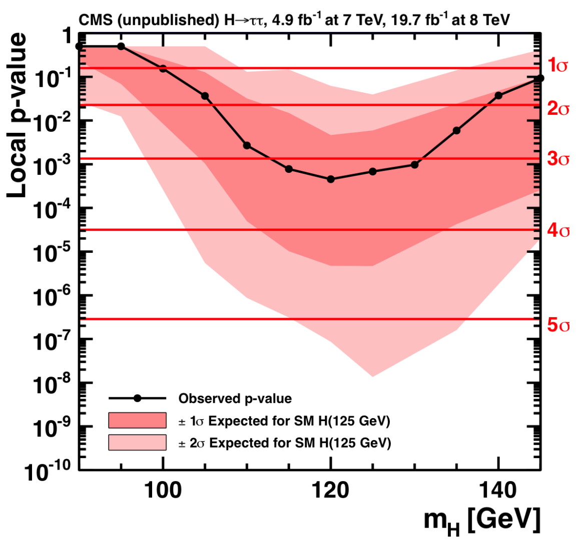


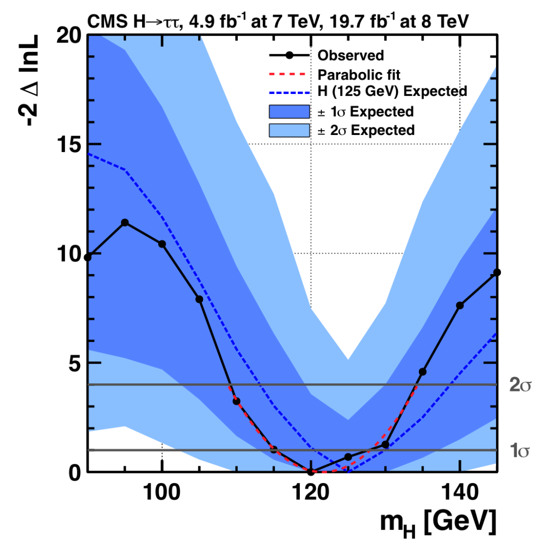
3σ Evidence of Higgs Coupling to Fermions

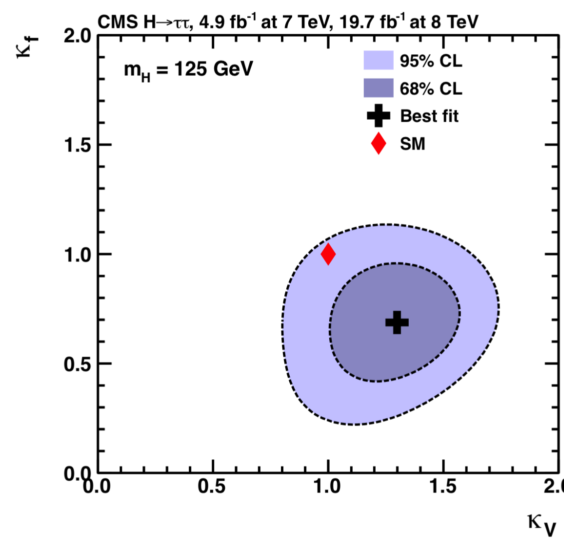






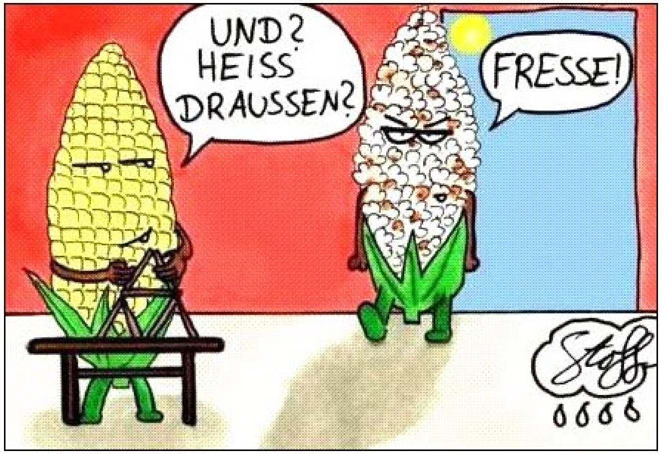






Quo Vadis $H \to \tau\tau$

- Why is $H \to \tau\tau$ still hot?
  - Most promising channel to have access to Higgs fermion couplings.
  - $H \to \tau\tau$ needs to be rediscovered in 2015 data.
  - 3σ need to be turned into an unquestionable 5σ discovery.



  - $H \to \tau\tau$ is the only channel to measure direct CP violation in the Higgs sector.
  - Exciting for two reasons:
    - CP violation alone as in the SM cannot explain that our universe today is made of matter and not of matter and anti-matter to more equal parts.
    - A CP odd Higgs boson is theoretically a very interesting candidate to find another Higgs boson! Very generally a CP odd Higgs boson does not couple to bosons at tree level BUT to fermions!

How to Measure CP in $H \to \tau\tau$ (in a nutshell)

- Easy generic extension of the SM to introduce CP violating Yukawa couplings:

$$\mathcal{L}_Y = -N\left(\cos\phi\tau\tau + \sin\phi\tau i\gamma_5\tau\right)H$$

CP violating phase

- Recapping C and P : $f:\quad P=+1$; $\bar{f}:\quad P=-1$ (Intrinsic parities)

$$P = (-1)^L \prod_i(-1) = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$

- How can we distinguish $CP=-1$ from $CP=+1$?

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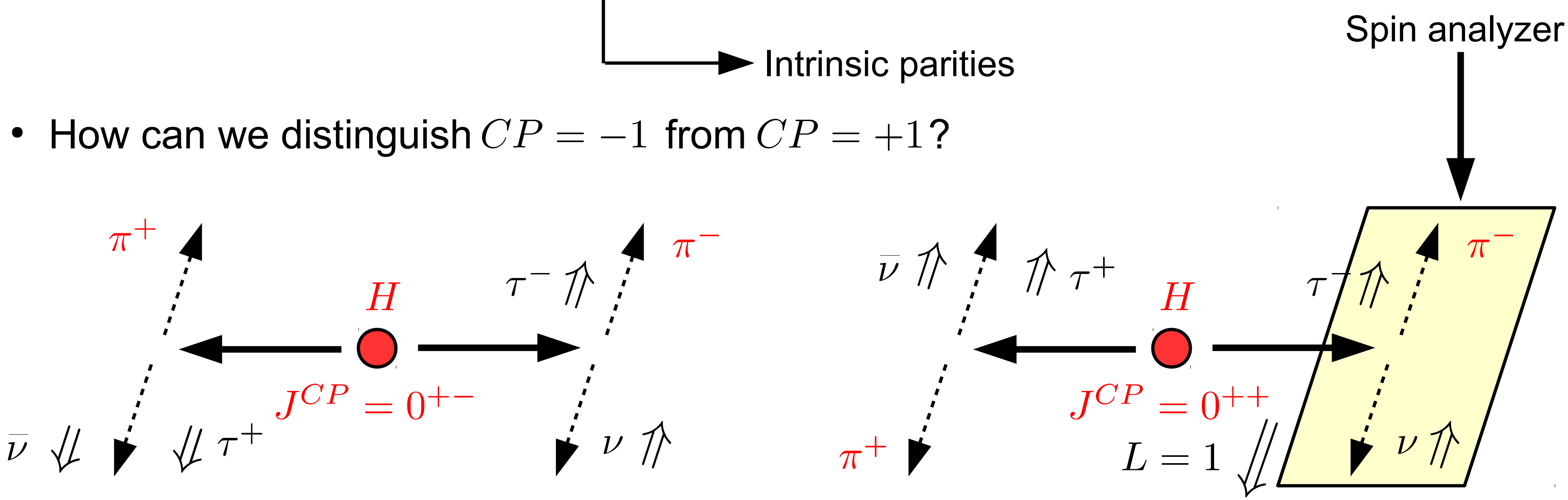


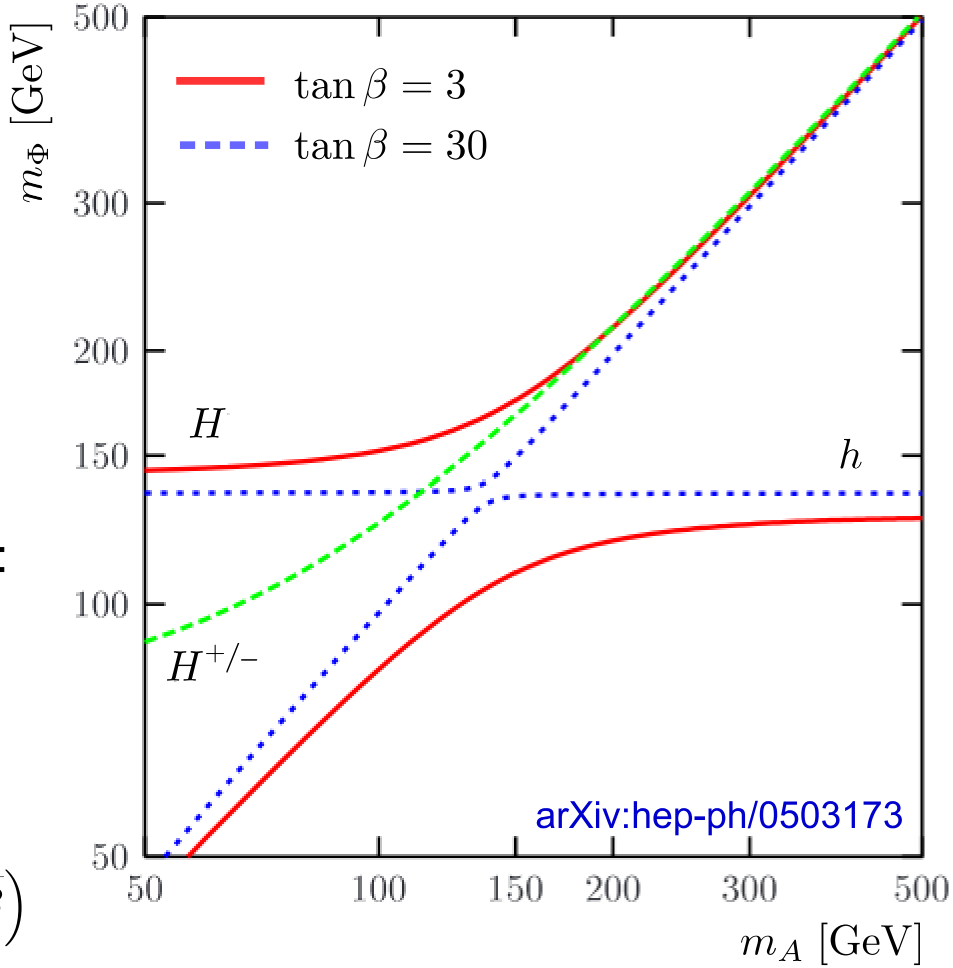
Theoretical Motivation of $CP = -1 \rightarrow$ MSSM

- A CP odd Higgs boson is theoretically predicted in Two Higgs Doublet models (2HDM) like the MSSM:

$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}, \quad Y_{H_1} = -1, \quad v_1 : \mathrm{VEV}_1$$

$$H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}, \quad Y_{H_2} = +1, \quad v_2 : \mathrm{VEV}_2$$

$$N_{\mathrm{ndof}} = 8 - \underbrace{3}_{W,\ Z} = \underbrace{5}_{H^{+/-},\ H,\ h,\ A}$$



- Strong mass requirements at tree level:

Two free parameters: m_A , $\tan\beta = v_1/v_2$

$$m_{H^{+/-}} = m_A^2 + m_W^2$$

$$m_{H,\,h} = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2 + m_Z^2)^2 \pm 4_A^2 m_Z^2 \cos^2 2\beta}\right)$$

MSSM and $H \to \tau\tau$

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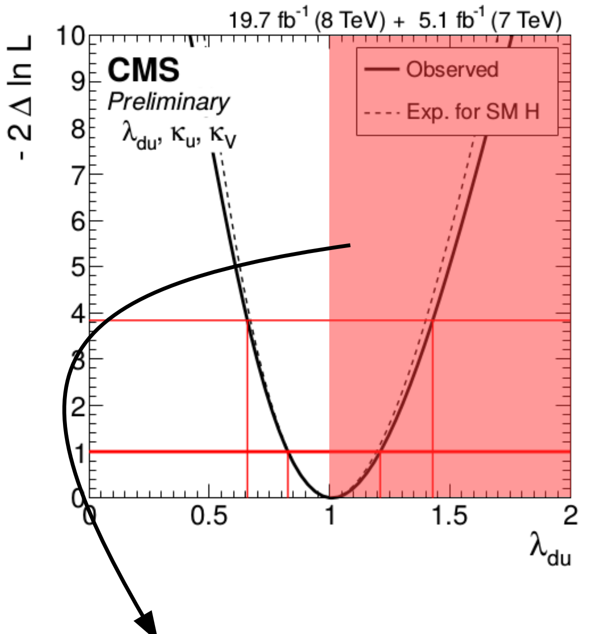
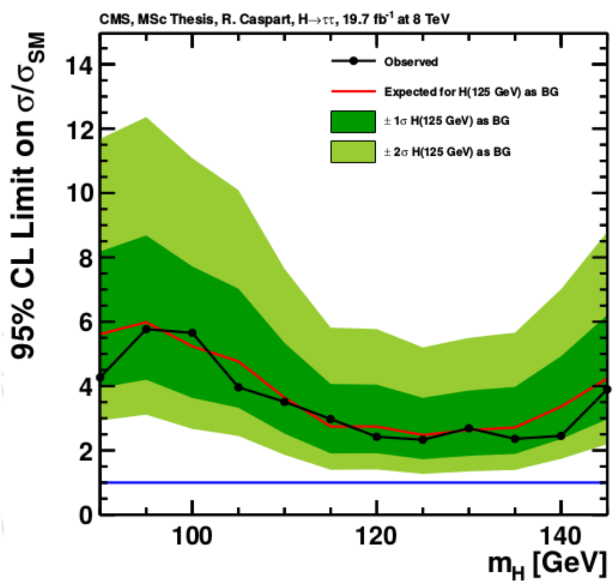
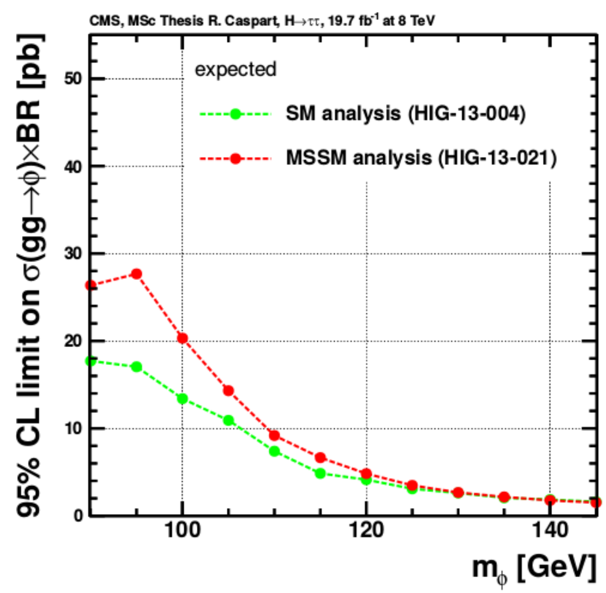
- The combination of MSSM (as 2HDM) and $H \to \tau\tau$ is even more interesting!
- Different coupling to up-type and down-type fermions (usually down-type enhanced).
- Quick check with slightly modified SM analysis:







would expect MSSM here.

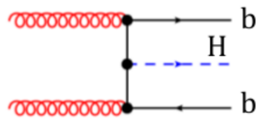
Modify SM $H \to \tau\tau$ analysis to scan for an additional CP odd Higgs boson between $110\ \mathrm{GeV}$ and $145\ \mathrm{GeV}$.

Search for additional neutral Higgs Bosons

- Exploit predicted increased sensitivity to down-type fermions and remain as model independent as possible:

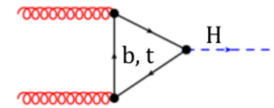
B-Tag category:

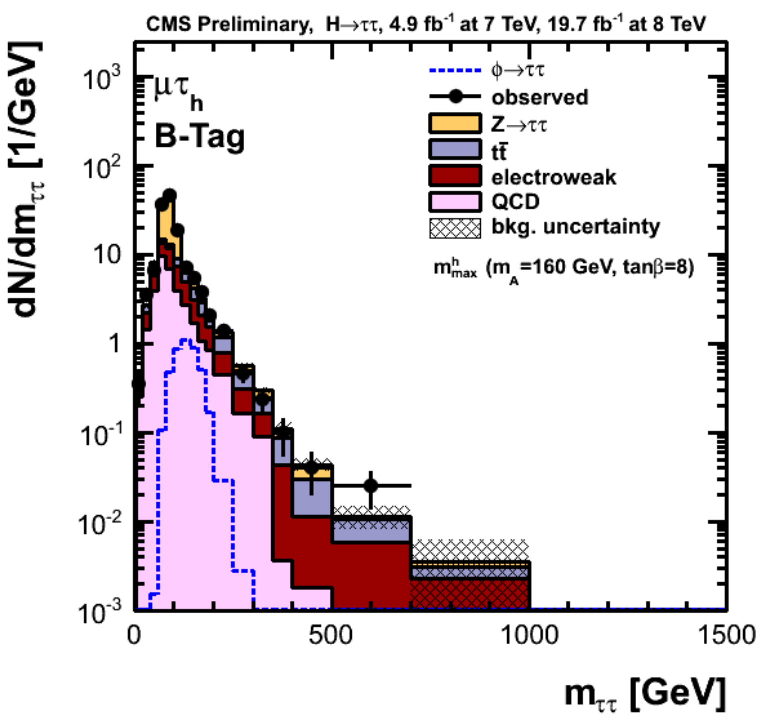
$$N(\text{B Tag}) \geq 1$$
$$N(\text{Jet}) \leq 1$$

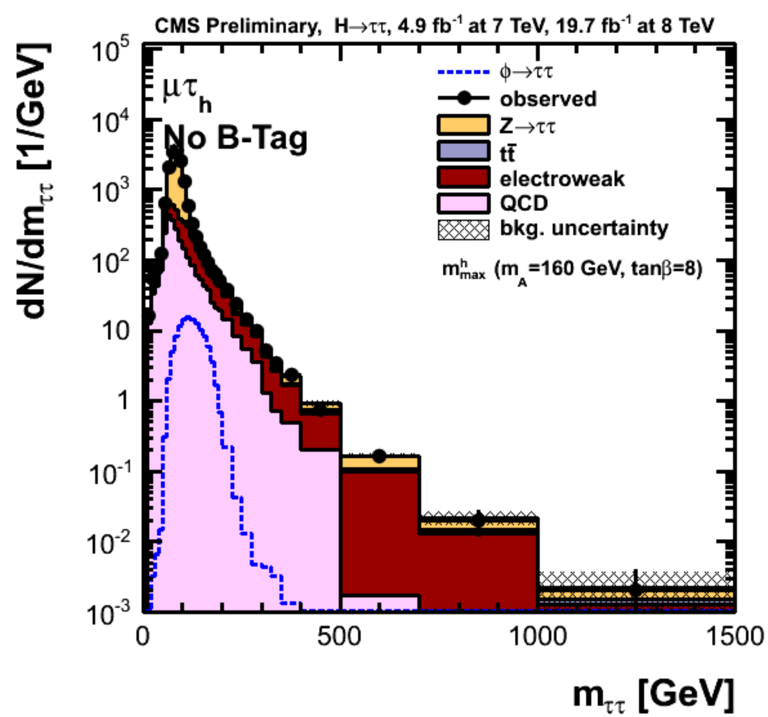


No B-Tag category:

$$N(\text{B Tag}) = 0$$

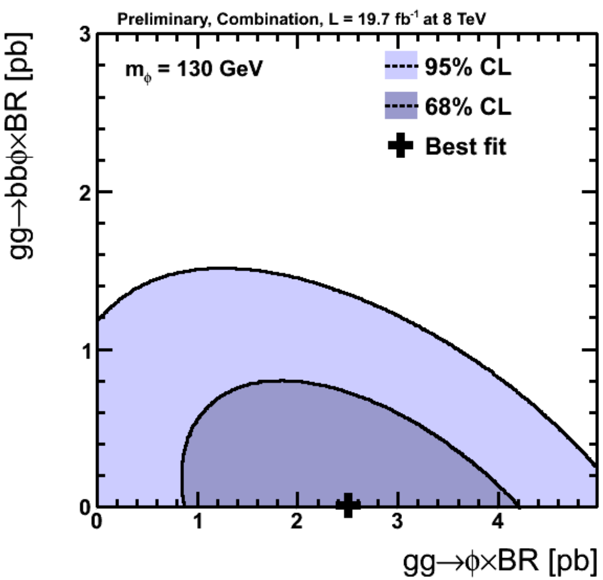


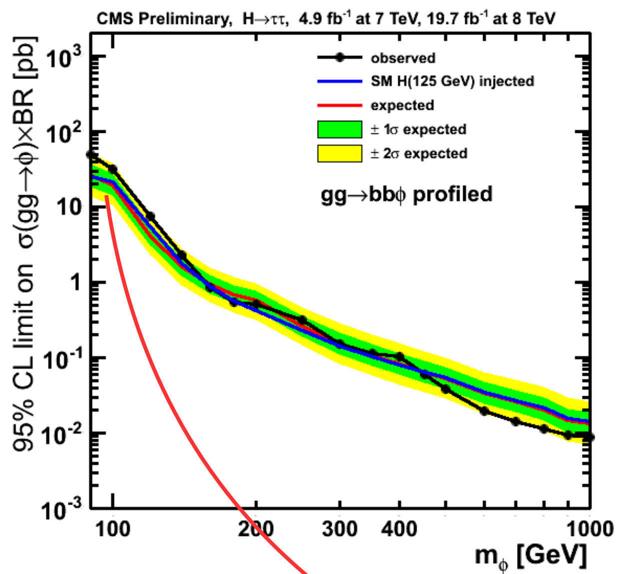


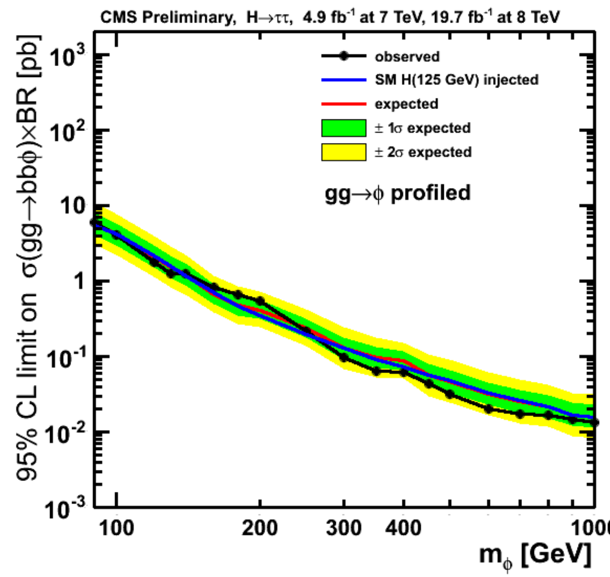


Model independent limits

- Search for a narrow resonance in $gg \rightarrow H$ & $bb \rightarrow H$ production mode:

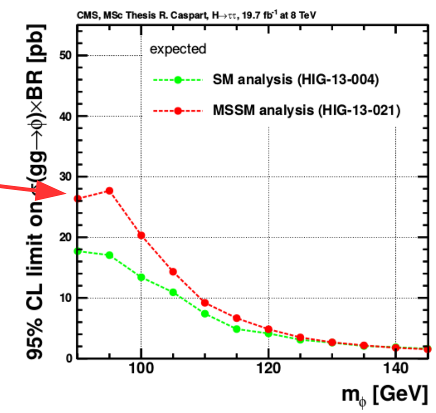






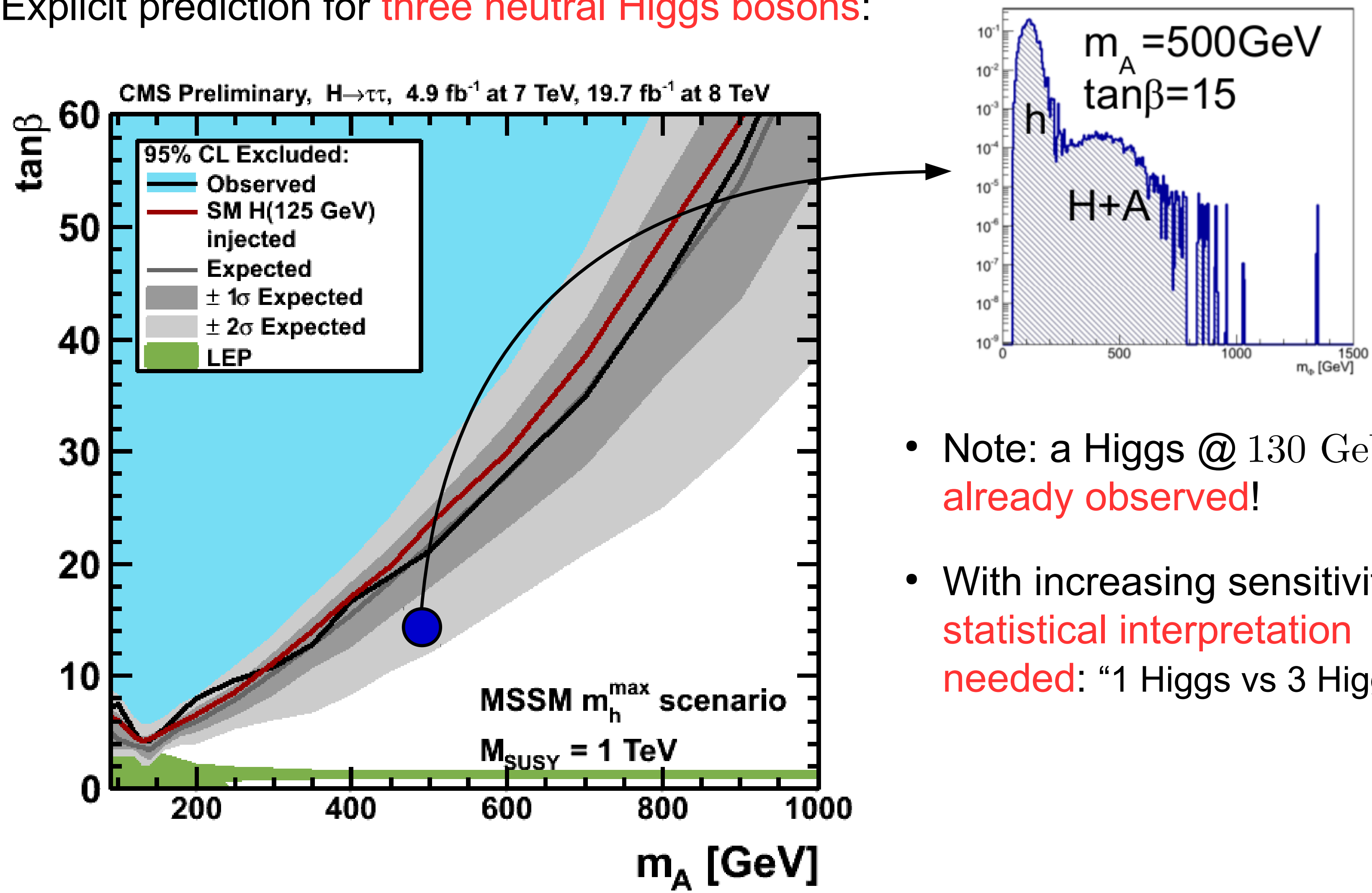
- 2D limit contours from scan of likelihood function.
- 1D limit contours on $gg \rightarrow H$ & $bb \rightarrow H$ profiling corresponding other component.

from two slides before



Limits in dedicated MSSM Benchmark Models

- Explicit prediction for three neutral Higgs bosons:



- Note: a Higgs @ $130\ \mathrm{GeV}$ already observed!
- With increasing sensitivity new statistical interpretation needed: “1 Higgs vs 3 Higgses”.

Conclusions

- Hunt for the Higgs boson has been exciting!
- One of the main questions: does the new particle couple to fermions has been answered.
- The $H \rightarrow \tau\tau$ decay channel remains exciting in future:
  - Re-discovery & establish 5σ.
  - Direct measurement of CP.
  - Exciting channel for discovery of additional Higgs bosons.
- (Higgs) physics with τ at the LHC remains fun!

Backup

Local Gauge Symmetries (Crash Course)

- Equations that describe quantum mechanical system are invariant under global phase transformations (example $U(1)$ symmetry):

- Can choose arbitrary phase ϑ for wave functions $\psi(\vec{x},t) \rightarrow \psi(\vec{x},t)e^{i\vartheta}$.
- But phase must be the same at any point in space, at any time! ($\rightarrow$ global symmetry)

Local Gauge Symmetries (Crash Course)

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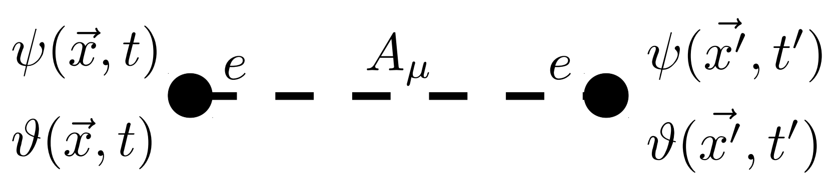
- Possible to allow arbitrary phase $\vartheta(\vec{x},t)$ of $\psi(\vec{x},t)$ at each point in space and any time. ($\rightarrow$ local symmetry)
- But this requires introduction of a mediating field A_μ, which transports phase information from point to point:



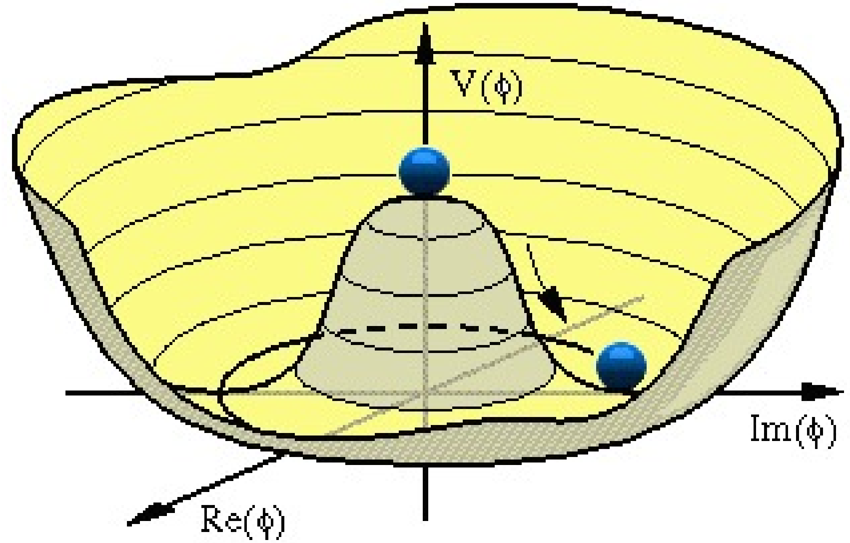
Application to Particle Physics

- *Goldstone* Potential:

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$

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

$$\mathcal{L}(\phi) = \partial_\mu\phi\partial^\mu\phi^* - V(\phi)$$



- invariant under $U(1)$ transformations (i.e. φ symmetric).
- metastable in $\phi = 0$.
- ground state breaks $U(1)$ symmetry, BUT at the same time all ground states are in-distinguishable in φ.

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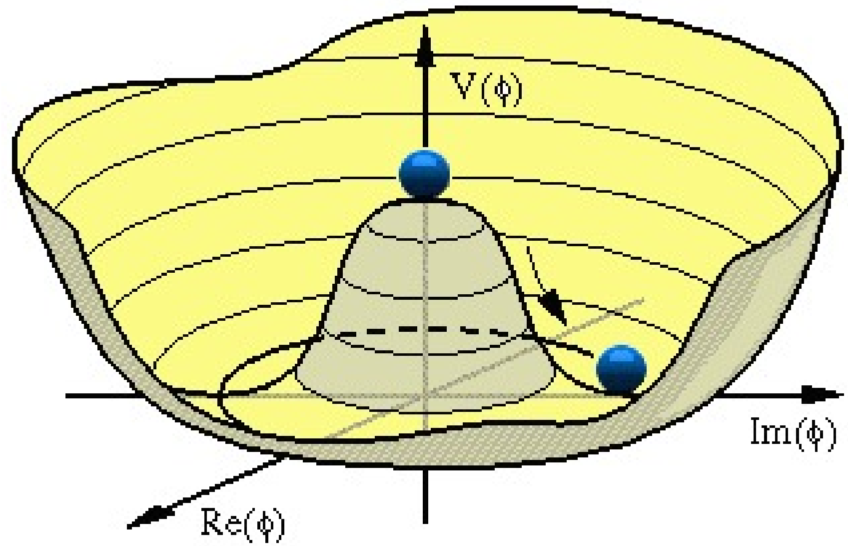

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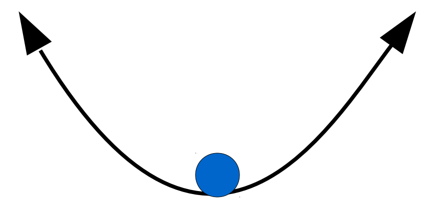
- ϕ has radial excitations in the potential $V(\phi)$.



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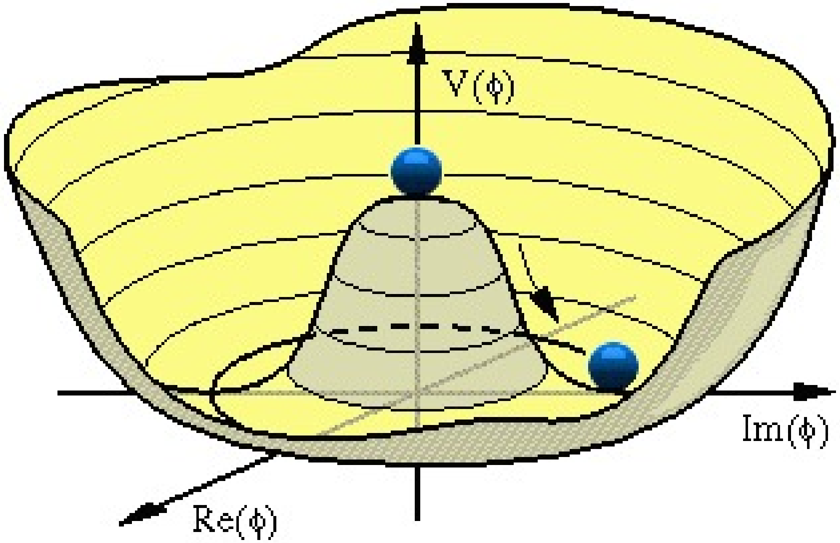

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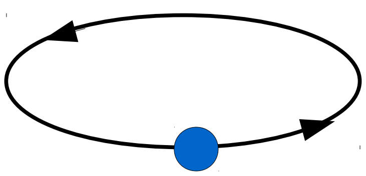
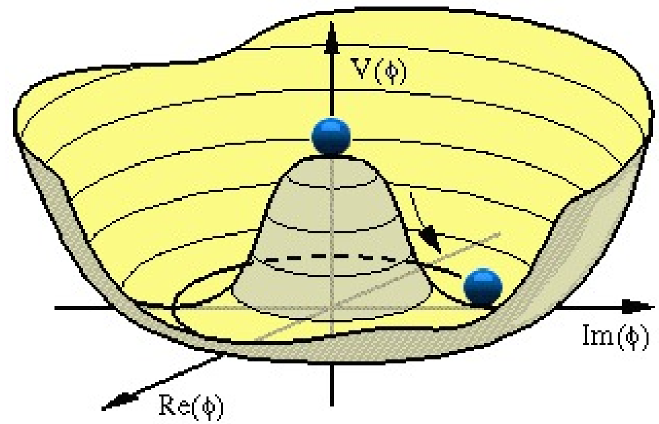
- ϕ can move freely in the circle that corresponds to the minimum of $V(\phi)$.

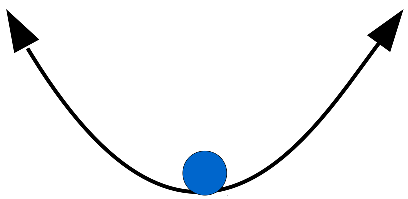


Higgs Mechanism

- Incorporation of spontaneous symmetry breaking in gauge field theory = Higgs mechanism:
- Introduce new field ϕ with characteristic potential.
- Leads to prediction of new particle: → Higgs boson!



- W & Z boson via local gauge invariance requirement.
- Fermion masses via simple (=Yukawa) coupling to Higgs boson.
- Higgs boson itself obtains mass from Higgs potential.



- Gauge invariance compromising mass terms compensated by characteristic couplings to Higgs particle:

$$\kappa_V = \frac{2m_v^2}{\mathrm{v}}$$

$$\kappa_f = \frac{m_f}{\mathrm{v}}$$

A Long Road of Theory Developments

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$gg \to H$
- NNLO+NNLL(α_s)
- NLO(α)
- Precision 15%

$qq \to qqH$
- NNLO(α_s)
- NLO(α)
- Precision 3%

$qq \to VH$
- NNLO(α_s)
- NLO(α)
- Precision 4%

tt production
- NNLO+NNLL(α_s)
- Precision 4%

Single top production
- NNLO(α_s)
- Precision 4%

How this precsion was obtained:

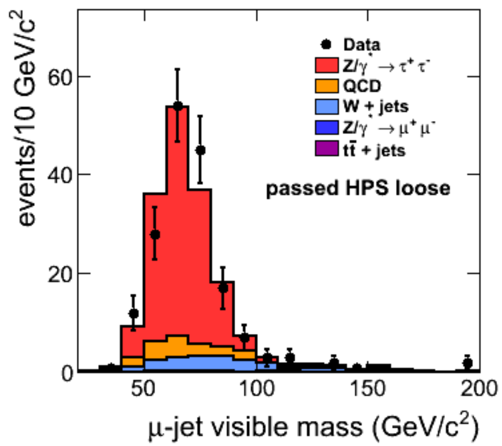
W + additional jets
- NNLO(α_s)
- Precision 5%

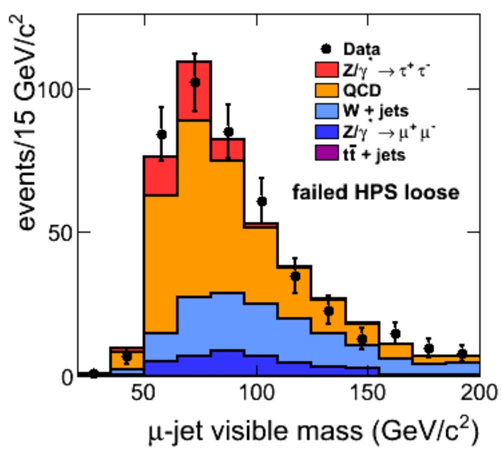
Z + additional jets
- NNLO(α_s)
- Precision 5%

$WW \quad WZ \quad ZZ$
- NLO(α_s)
- Precision 10%

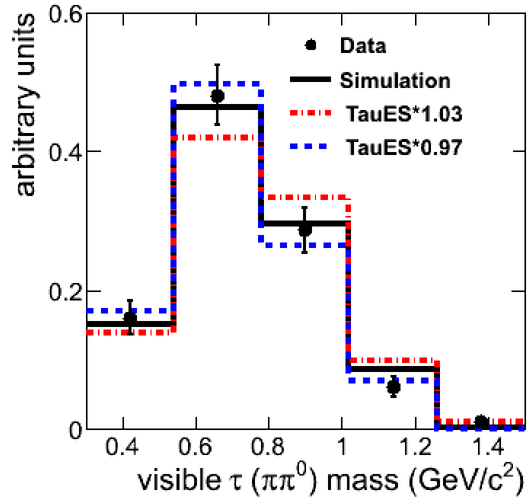
Performance of Hadronic τ Reconstruction

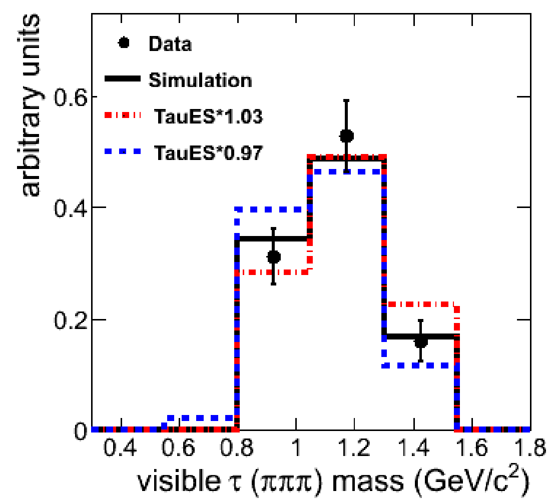
- Control efficiency within $\pm 7\%$ using tag & probe methods:





- Control τ_h energy scale within $\pm 3\%$ from fits to $m_{\tau,\mathrm{vis}}$:

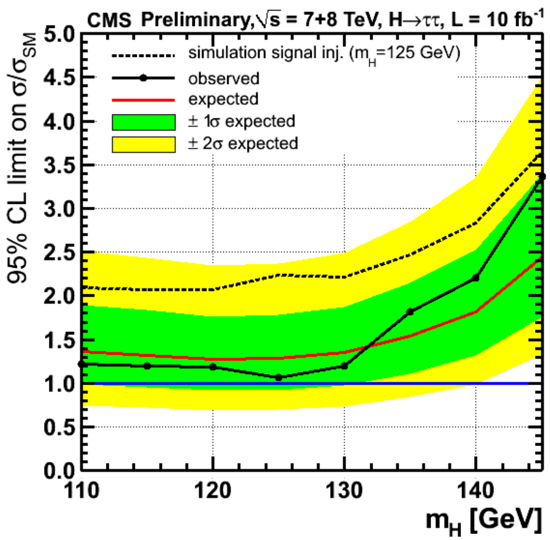




- Uncertainties further constrained by maximum likelihood fit in the statistical inference for signal extraction.

$H \to \tau\tau$ Decay Channel

Status **July 2012**:

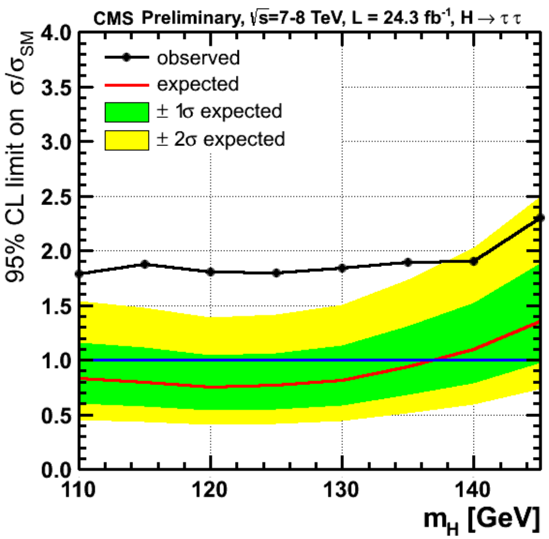


$$\mu = \mathrm{N.A.}$$

$$\sigma = 0(\mathrm{obs}) \;\; 1.4(\mathrm{exp})$$

@ $m_H \approx 125$ GeV

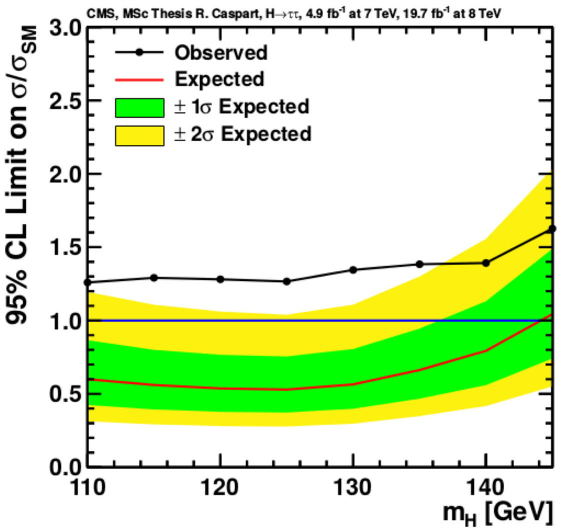
Status **March 2013**:



$$\mu = 1.1 \pm 0.4$$

$$\sigma = 2.9(\mathrm{obs}) \;\; 2.6(\mathrm{exp})$$

Status **Summer 2014**:



$$\mu = 0.8 \pm 0.3$$

$$\sigma = 3.2(\mathrm{obs}) \;\; 3.7(\mathrm{exp})$$

Treating contributions from $H \to WW$ as background.