8.882 LHC Physics

Experimental Methods and Measurements

Higgs Physics and Other Essentials

[Lecture 22, April 29, 2009]

Organization

Next week lectures:

- Monday 2pm and Tuesday 9:30am (which room?)

Project 3

- remember, due May 2

Conference Schedule

- worked out

Physics
Colloquium Series

'09 Spring

A Physics and EAPS joint Colloquium

Thursday, April 30 at **4:15** pm in room 34-101

Michael Brown
California Institute of Technology

"The Dwarf Planets of the Outer Solar System"

For a full listing of this semester's colloquia, please visit our website at web.mit.edu/physics

Outline

Higgs Search and Other Essentials

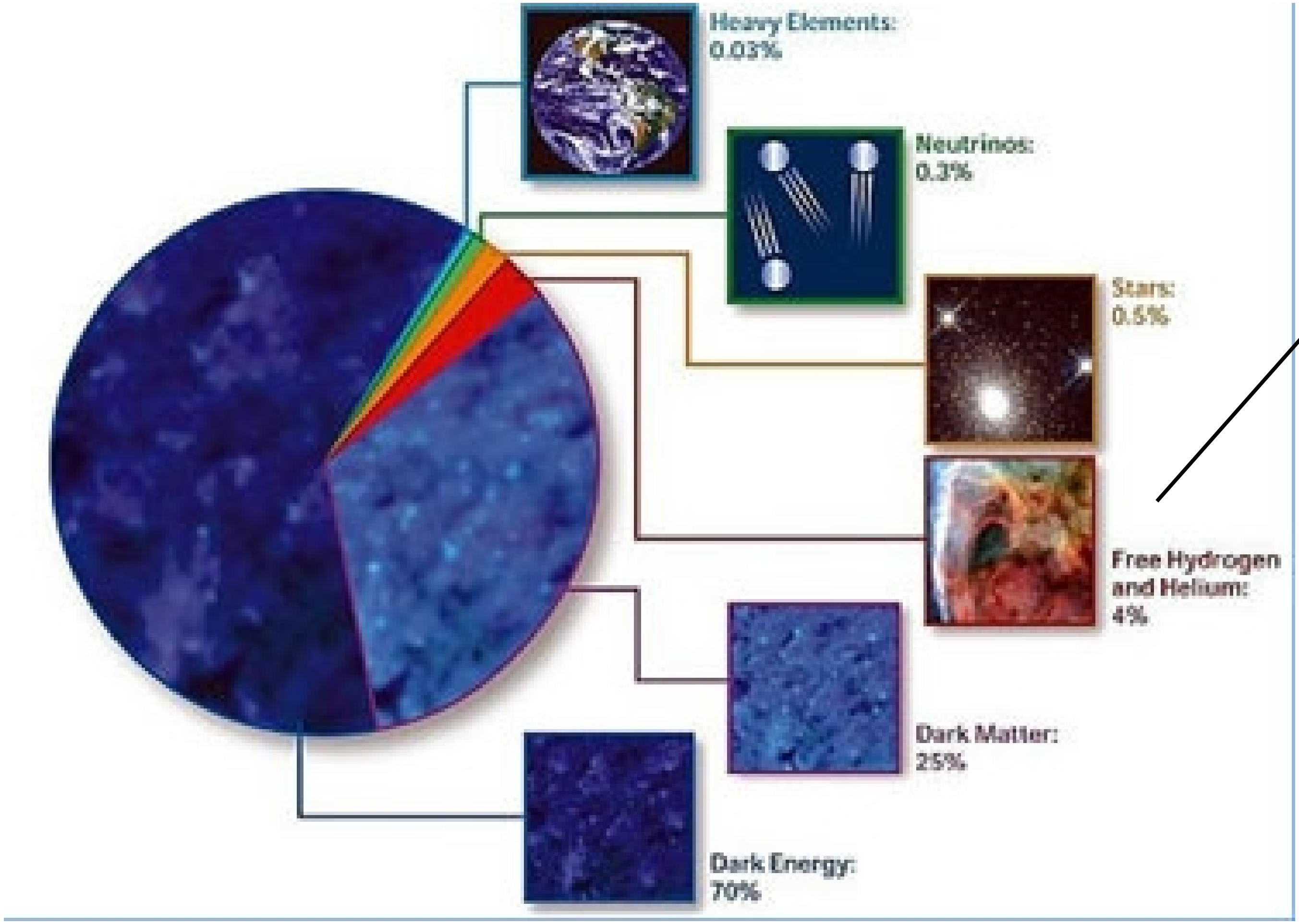
- the fundamental question
- state-of-the-art
- Higgs boson production and decay @ LHC
- closer look at specific channels
- beyond the Standard Model (BSM)
- in 5 years from now - Higgs Boson Properties

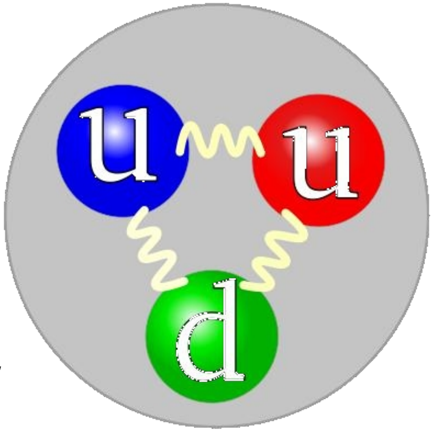
The Fundamental Question

What is the origin of elementary particle masses?

The Fundamental Question

What is around us?





proton mass:
m_p = 938 MeV

quark masses:
m_u = 1.5-4.5 MeV
m_d = 5.0-8.5 MeV

rest mass:
kinetic energy &
QCD effects

The Fundamental Question

How are we effected by elementary particle mass?

electron mass (105 MeV) (Bohr radius $r = 1/ \alpha_{em} m_e$): massless electrons
would result in no atomic binding

u, d quark mass (~1-10MeV): massless quark or $m_u = m_d$
would result in proton decays, different nucleosynthesis, ...

W mass: massless or small mass
would result in rapid fusion in stars

----

mass values for electron, u quark, d quark, W boson are fine tuned for the creation of the universe and life on our planet.

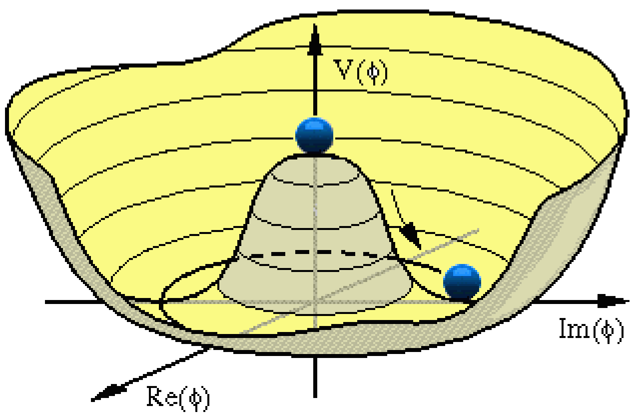
principle of mass creation:	Higgs mechanism (our best guess)
origin of elementary particle mass:	completely unknown

The Fundamental Question

Electroweak Symmetry Breaking (hep-ph/9803257):

- consistent description of nature seems to be based gauge symmetries
- problem: $SU(2)_I \times U(1)_Y$ gauge symmetry → no masses for *W* / *Z* boson
- ad hoc mass terms spoil theory

- incorporated in the Standard Model using a complex scalar field (4 components)
- self interaction creates potential
- vacuum break symmetry spontaneously



- three components absorbed by Z/W bosons.
- one scalar field component is not absorbed resulting in physical particle:

Higgs Boson

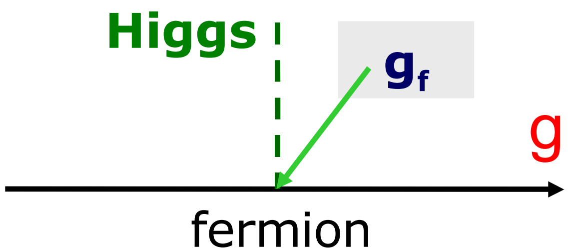
The Fundamental Question

- interaction of particles with Higgs generates mass
- couplings are proportional to masses

v ~ 246 GeV (vacuum expectation value)

Fermions (Yukawa coupling):

$m_f \sim g_f v$



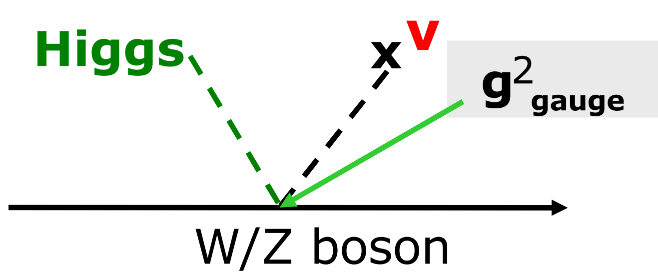
$g_{top} \sim 1$!

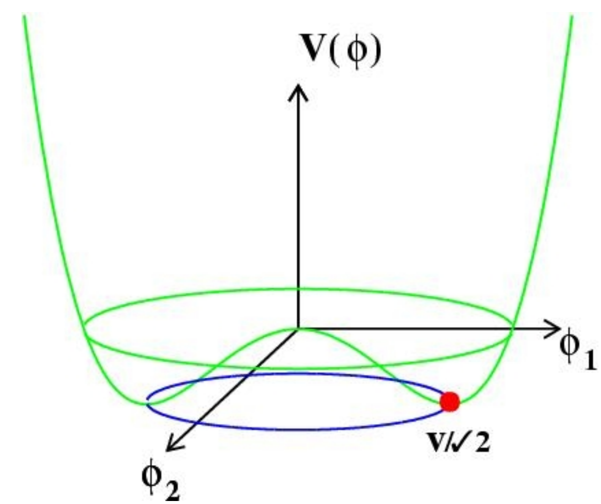
Higgs boson (self coupling):

$M^2 = \lambda v^2$

W/Z bosons (gauge coupling):

$M \sim g v$





The Fundamental Question

W and *Z* masses result from couplings to the Higgs field

Gluon and photon have no such couplings $\rightarrow$ massless

Quark and lepton masses are determined by the strength of their coupling to the Higgs field

What about neutrinos? Do they have the same nature?

Couplings determine quark mixing, CP violation, ...

Is the Higgs field responsible for matter dominance?

We have no understanding of the origin of those couplings

State-Of-The-Art

What do we know about the Standard Model Higgs Boson?

theory: unitarity in WW scattering requires $M_H < 1$ TeV

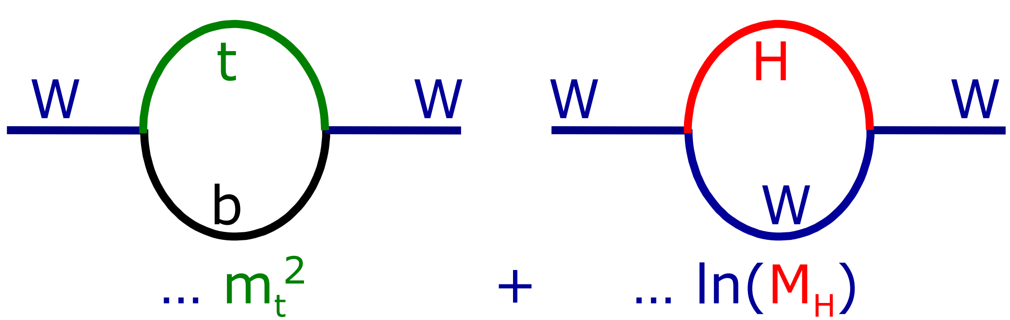
direct searches at LEP: $M_H < 114.4$ GeV excluded with 95%CL

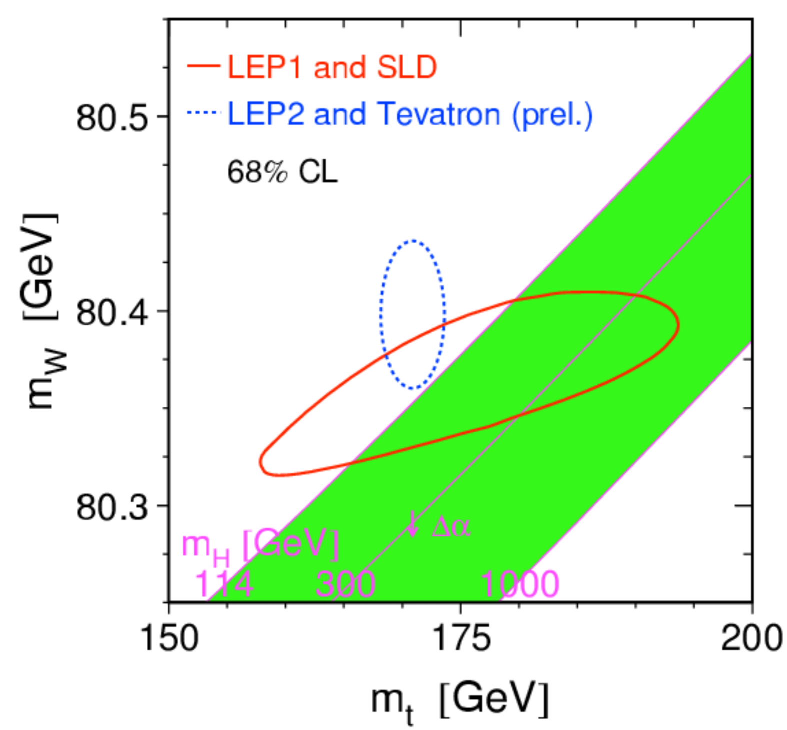
(talk by itself: ALEPH candidate events; end of LEP data taking in 2000)

indirect prediction in SM:

$M_H > 144$ GeV excluded with 95% CL

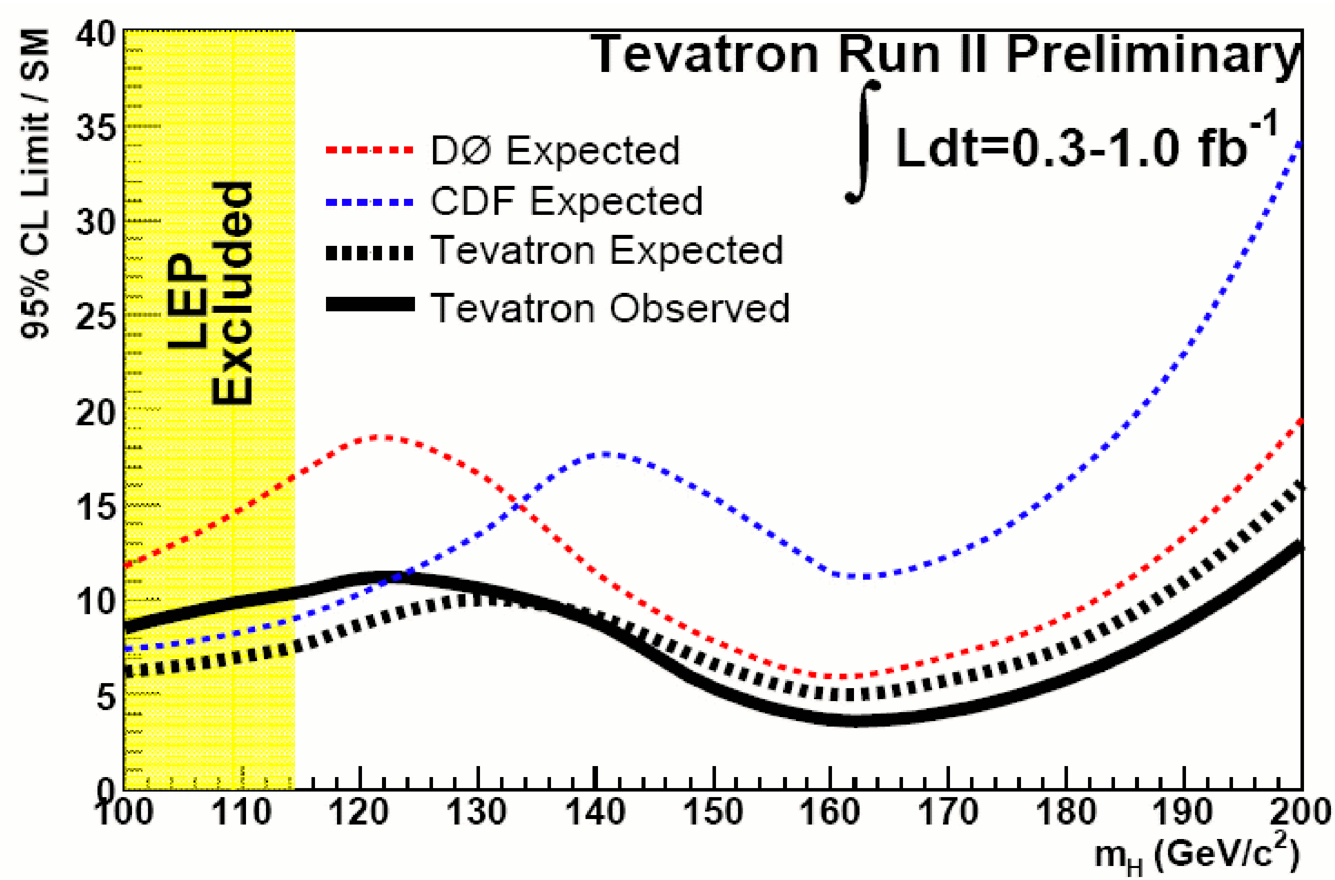
$M_W(\text{Phys}) = \quad M_W(\text{Born}) +$





State-Of-The-Art, 2007

What do we know about the Standard Model Higgs Boson?



2007 sensitivity:

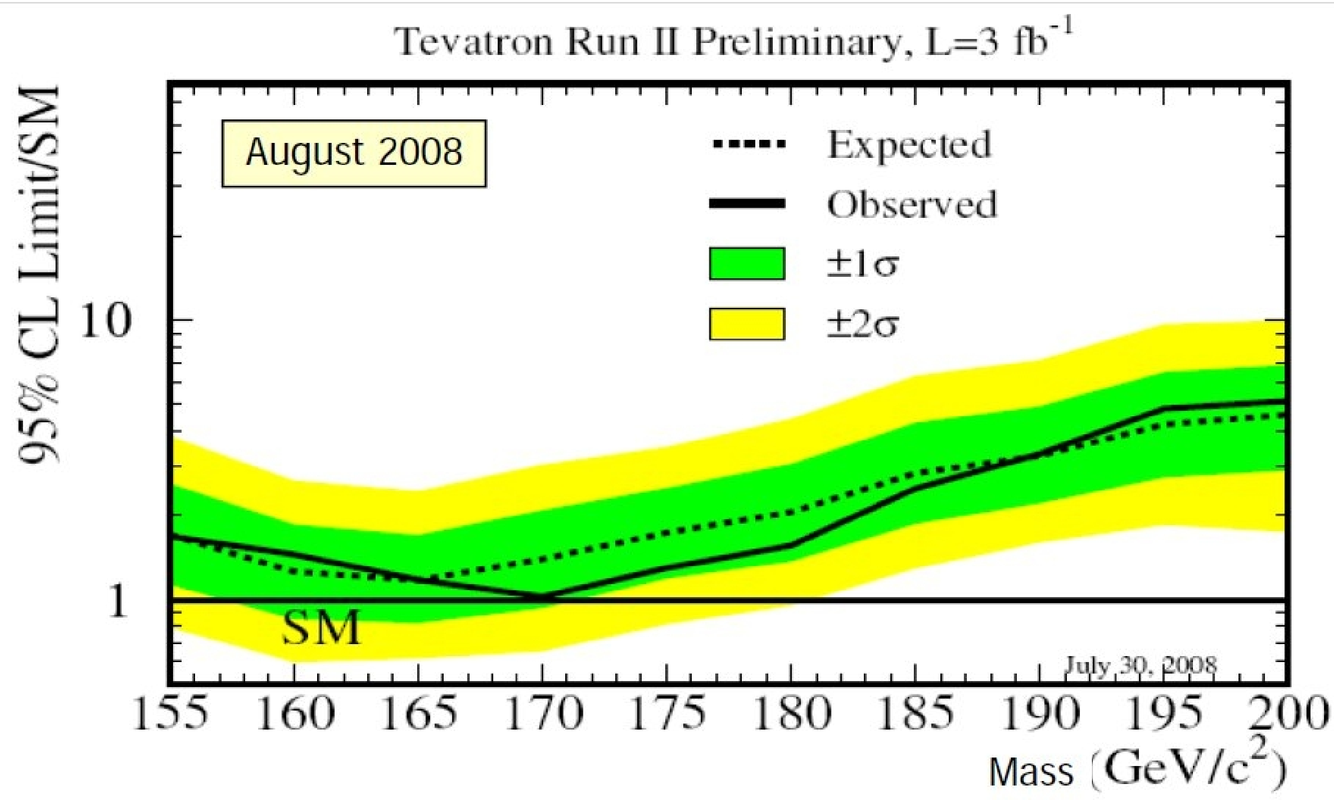
4-12 time SM cross section.

1fb^{-1} analyzed by CDF
400pb^{-1} analyzed by D0
< 50% of available data.

~ 8fb^{-1} needed to exclude SM ~ 160GeV

State-Of-The-Art, 2008

What do we know about the Standard Model Higgs Boson?

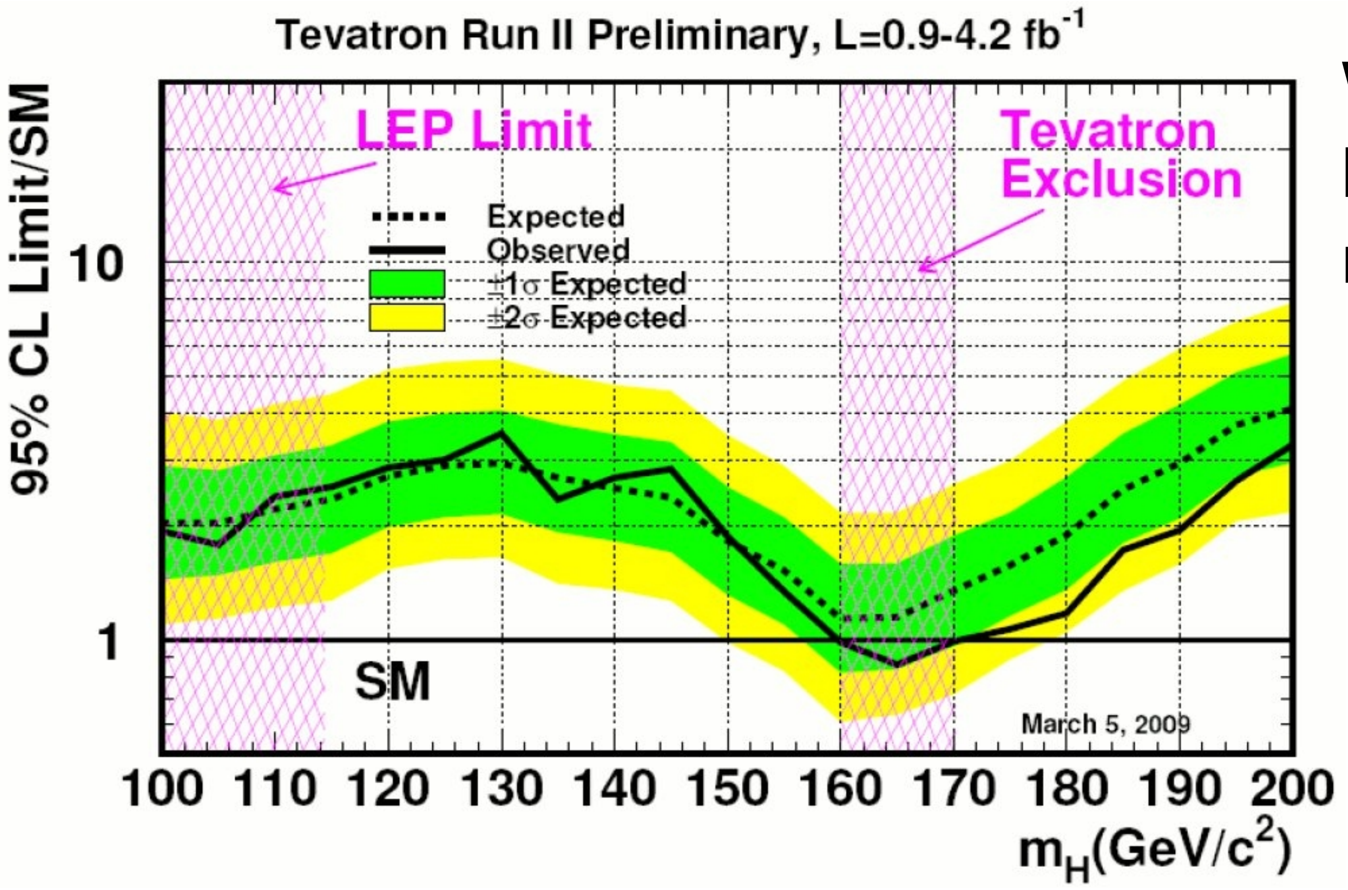


Winter 2008 first tangible results on the Higgs from the Tevatron

Dedicated effort combines CDF and D0 and finds first new exclusion 'point' since the LEP2 experiments (finished 2001).

State-Of-The-Art, 2009

What do we know about the Standard Model Higgs Boson?



Winter 2009 brought exciting new results

Dedicated effort combines CDF and D0 and finds first new exclusion area since the LEP2 experiments (finished 2001).

Higgs Boson Production and Decay

Job Description (for experimentalist):

Discover the Higgs Boson and explore its properties.

In more Detail:

Does the Higgs Boson exist? One or more?

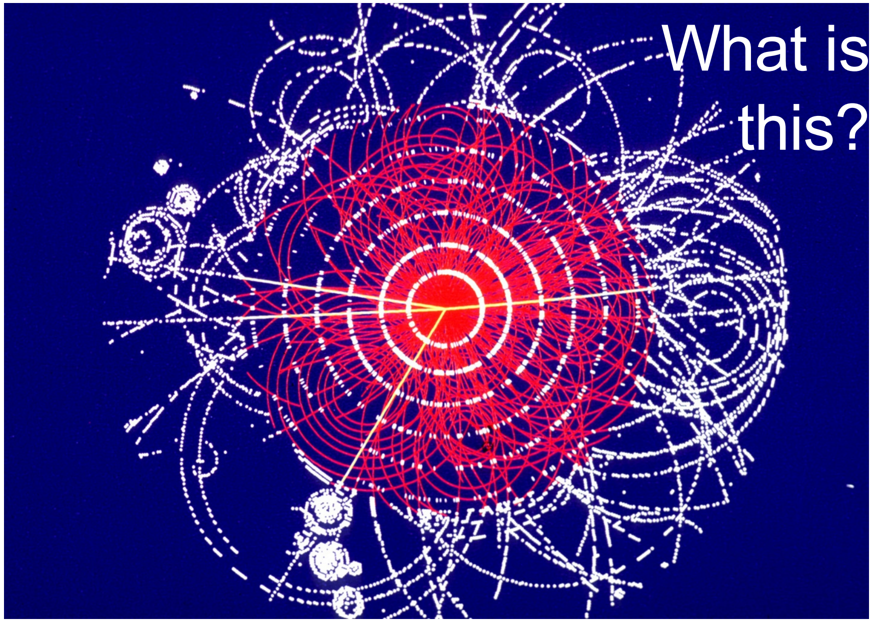
Is the Higgs Boson a scalar boson?

Does the Higgs Boson generate the masses of gauge bosons and fermions?

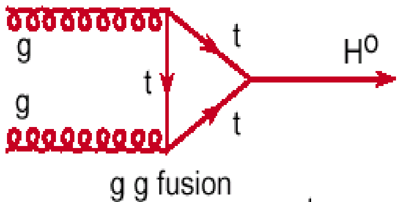
Does the Higgs Boson couple to itself?

Higgs Boson Production and Decay

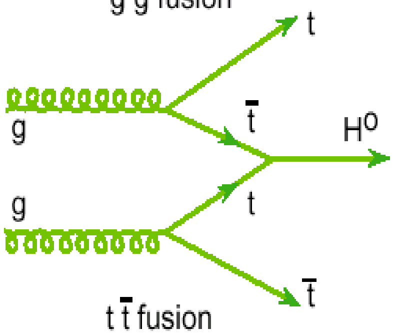
LHC:
pp collisions
@ 14 TeV



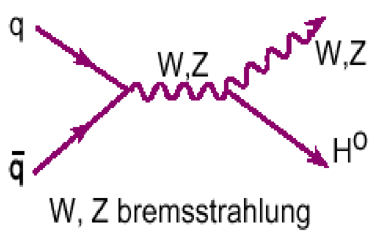
Higgs Boson Production and Decay



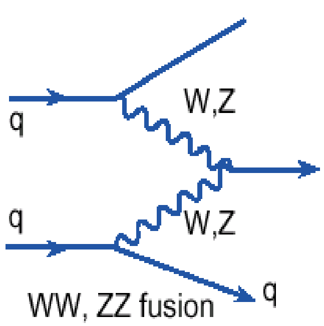
K ~ 2



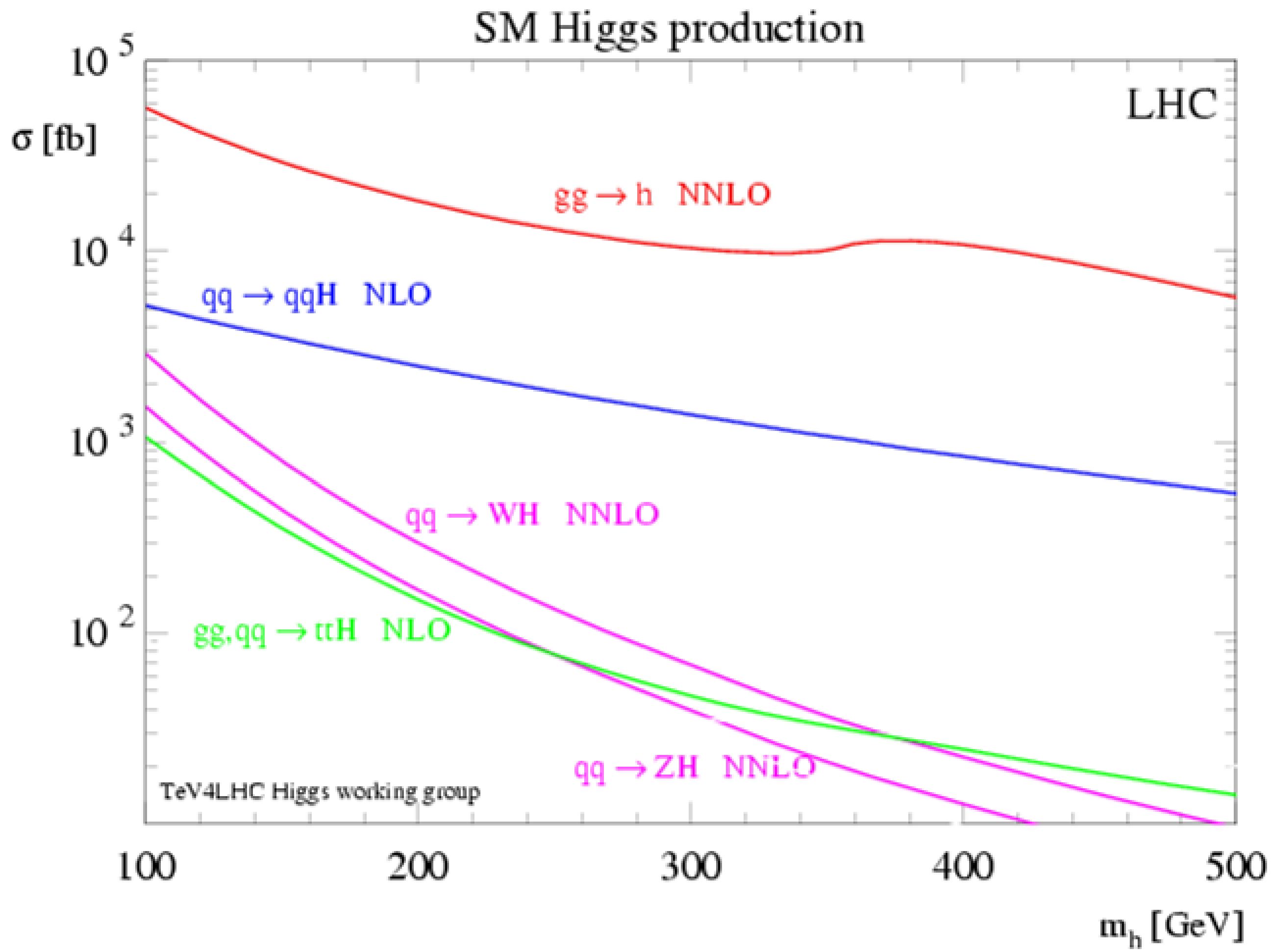
K ~ 1.2



K ~ 1.4



K ~ 1.1



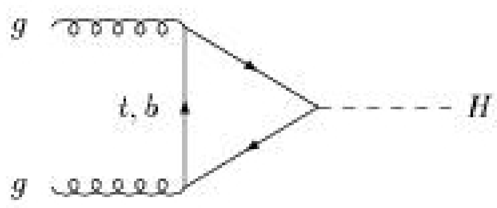
$K = \sigma_{(N)NLO} / \sigma_{LO}$

Higgs Boson Production and Decay

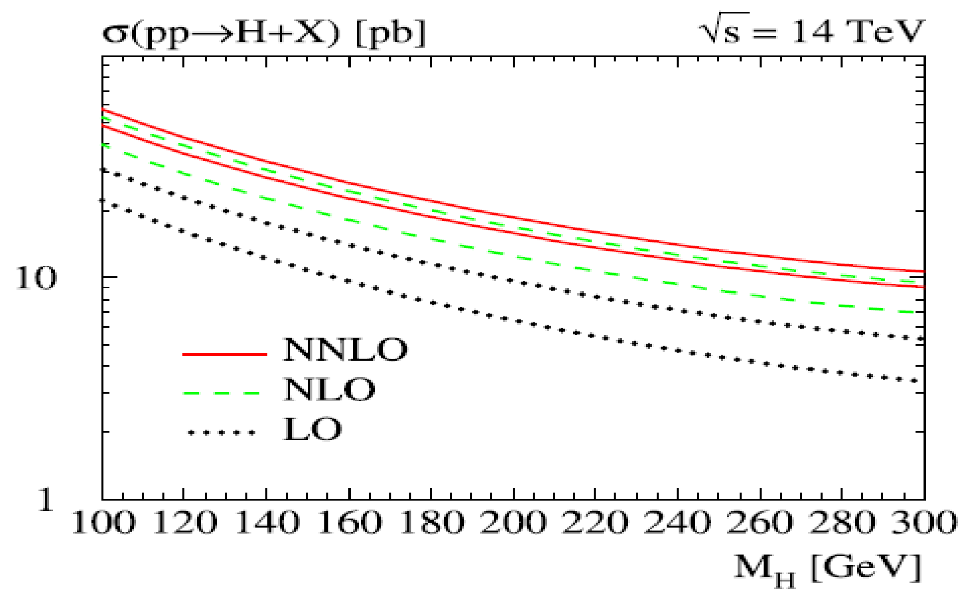
Some more words on K-factors - K = $\sigma_{(N)NLO}$ / σ_{LO}

Leading Order $O(\alpha^2_s)$:

gg → H



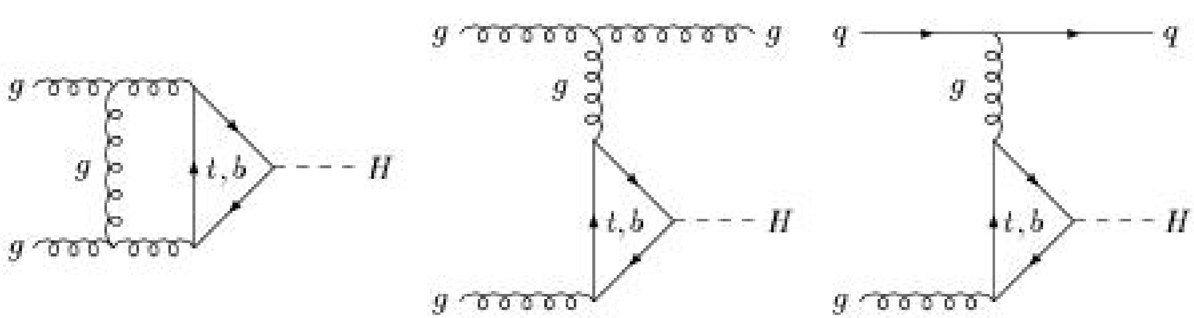
$\Delta\sigma$ ~ 4-15% + Δ ~ 5-15% from PDF



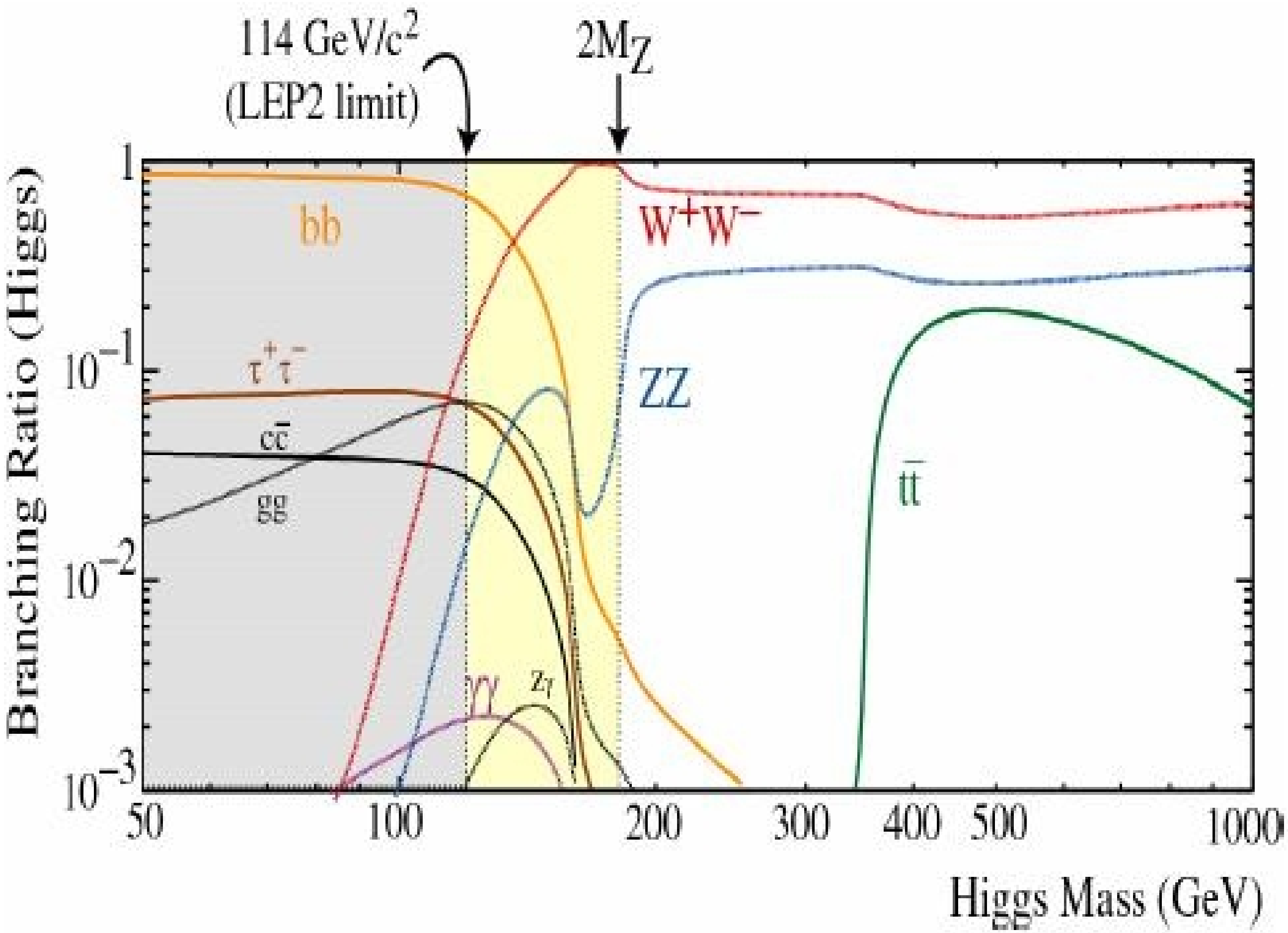
Next to Leading Order $O(\alpha^3_s)$:

gg → H

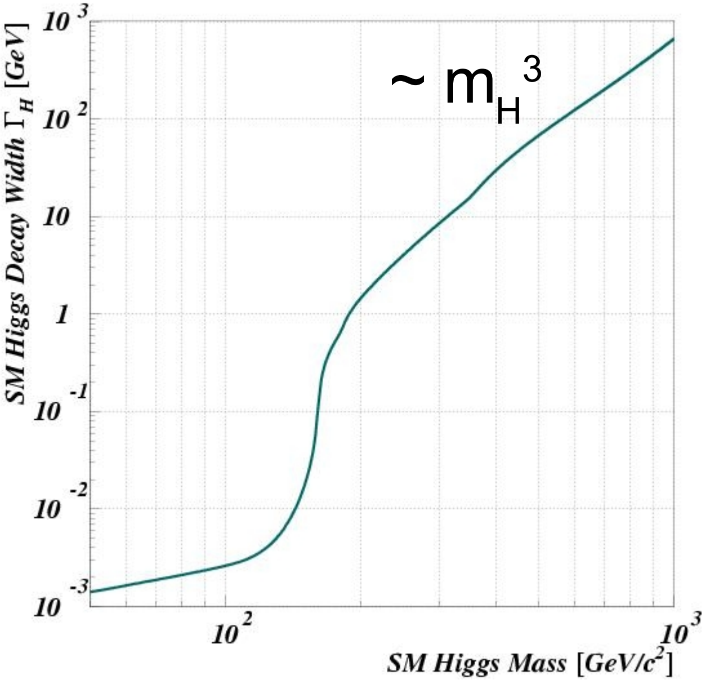
gg → gH, gq → qH, ...



Higgs Boson Production and Decay



mH < 135 GeV:
bb, ττ dominant
mH > 135 GeV:
WW, ZZ dominant



$\Gamma_{Hff} \sim m_f^2$

$\Gamma_{HVV} \sim m_V^4$

Higgs Boson Production and Decay

Branching fraction reminder:

W boson decays:

in $e\nu$, $\mu\nu$, $\tau\nu$, 3*ud, 3*sc

BR($l\nu$) ~ 11%

BR(hadrons) ~ 68%

τ decays:

in $e\nu\nu$, $\mu\nu\nu$, hadronic+ν

BR($l\nu\nu$) ~ 18 %

BR(hadrons) ~ 64 %

Z boson decays:

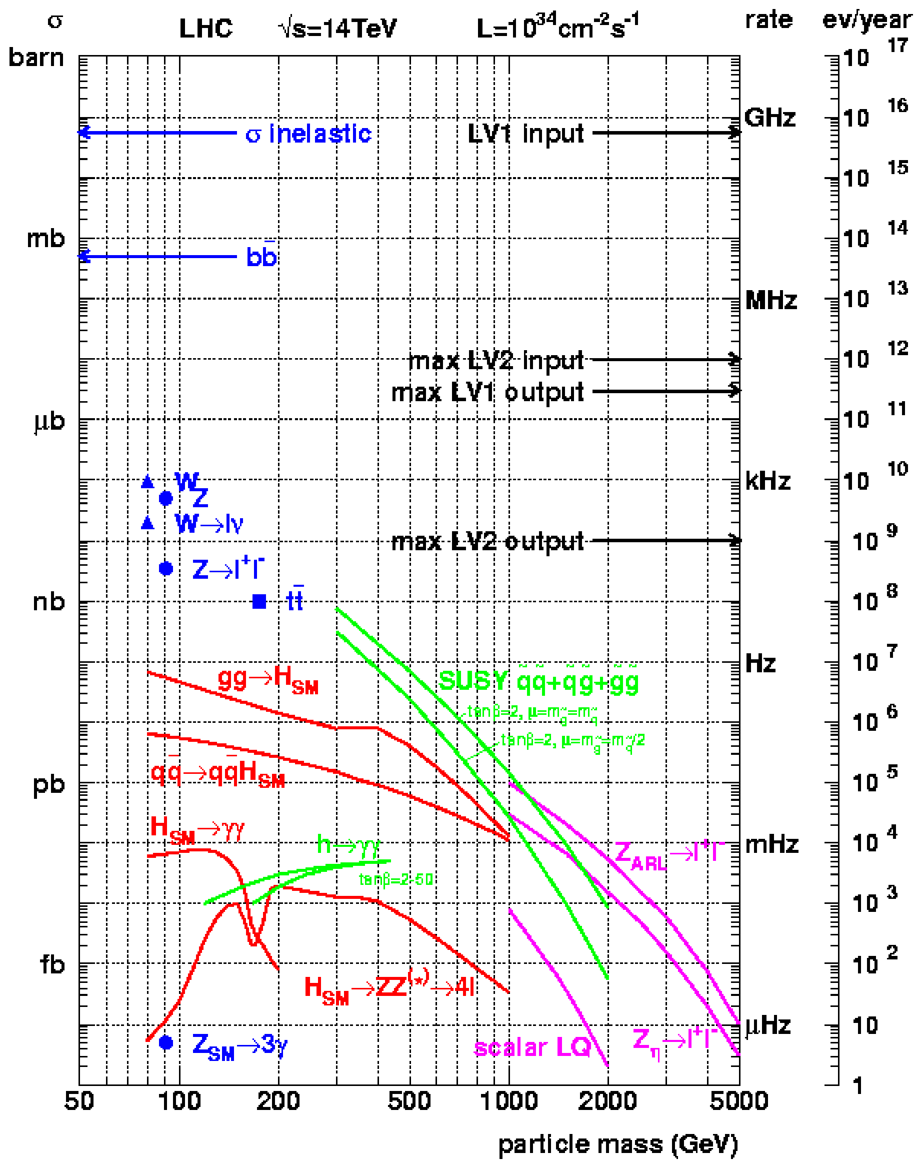
in ee, $\mu\mu$, $\tau\tau$, $\nu\nu$, hadronic

BR(ll) ~ 3.3%

BR($\nu\nu$) ~ 20 %

BR(hadrons) ~ 70 %

Higgs Boson Production and Decay



m_H= 150 GeV: S/B ~ 10^{-10}

trigger: 10^{-7} reduction,
on leptons, photons
and missing ET

no track trigger @ L1

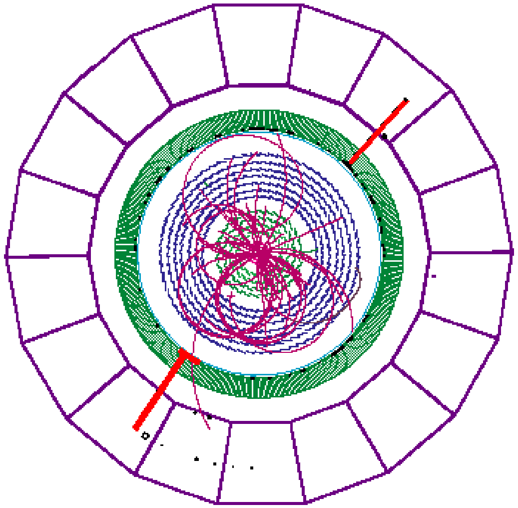
Considerations for discovery channel:

- sufficient signal rate
- efficient trigger
- Higgs mass reconstruction
- control of background

A Closer Look at Specific Channels

$H \to \gamma\gamma$: σ_H = 44.2 pb   BR ($H \to \gamma\gamma$) = 0.0022 (mH=120GeV)

↘ ~100 evts/fb



signal: 2 isolated high pT photons

background: irreducible $pp \to \gamma\gamma + x$

reducible $pp \to \gamma j + x, jj + x$

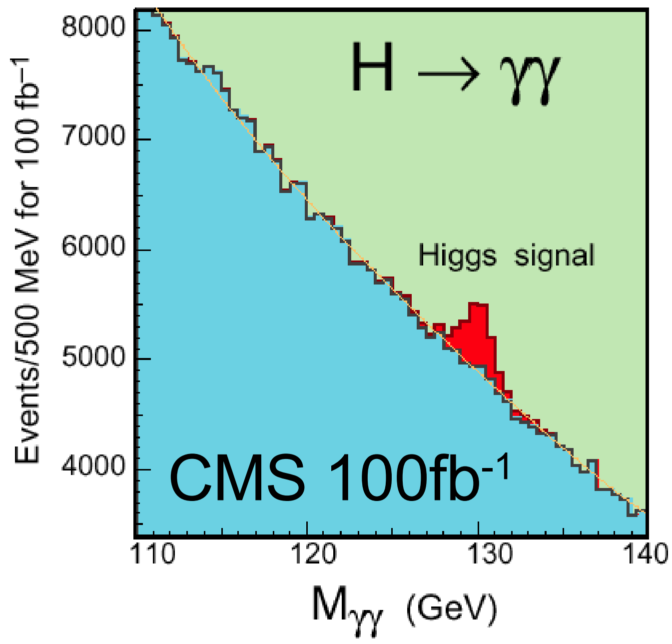
exp. challenge: mass resolution $\sigma_M/M \sim 0.7\%$

vertex constraint

photon conversions

π^0 rejection

background estimation

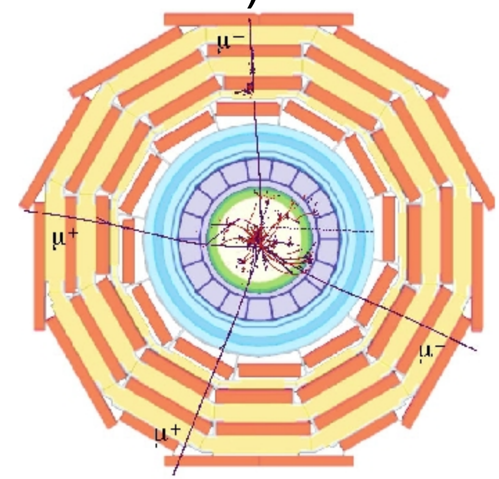


A Closer Look at Specific Channels

H → ZZ*: σ_H = 21.6 pb BR (H → ZZ) = 0.058 (mH=180GeV)

BR(ZZ →4l) = 0.005

➘ ~7 evts/fb



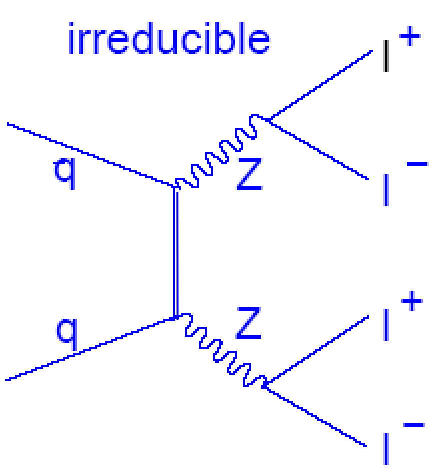
signal: 4 isolated leptons

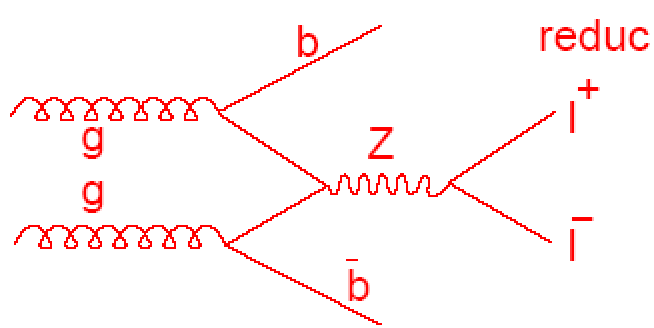
background: irreducible pp → ZZ → 4l

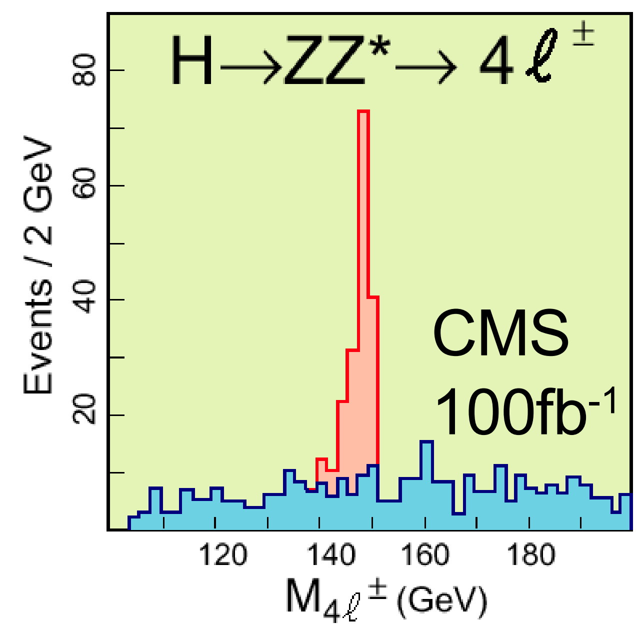
reducible tt, Zbb

exp. challenge: mass resolution σ_M /M < 1%

background estimation





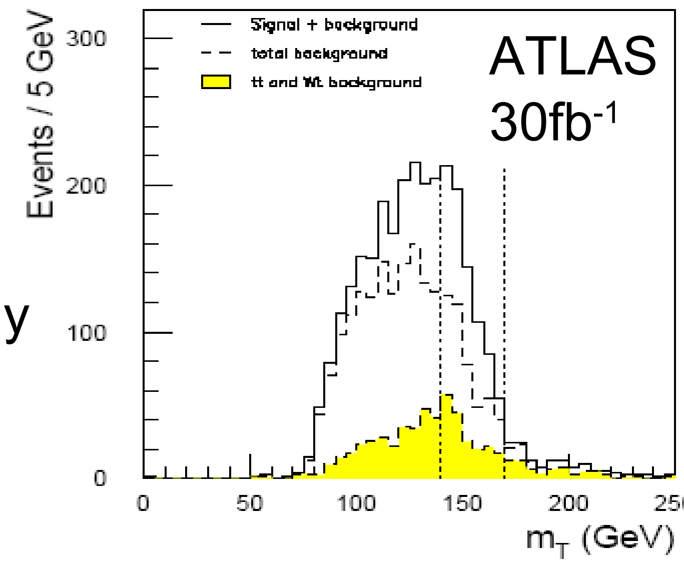


A Closer Look at Specific Channels

H → WW*: σ_H = 26.6 pb   BR (H → WW) = 0.9 (mH=160GeV)

BR(WW → 2l 2v) = 0.05

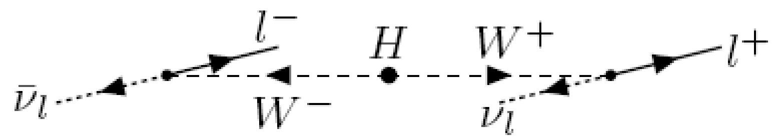
➘ ~1200 evts / fb



signal: 2 isolated leptons, missing transverse energy, no mass peak

→ use transverse mass

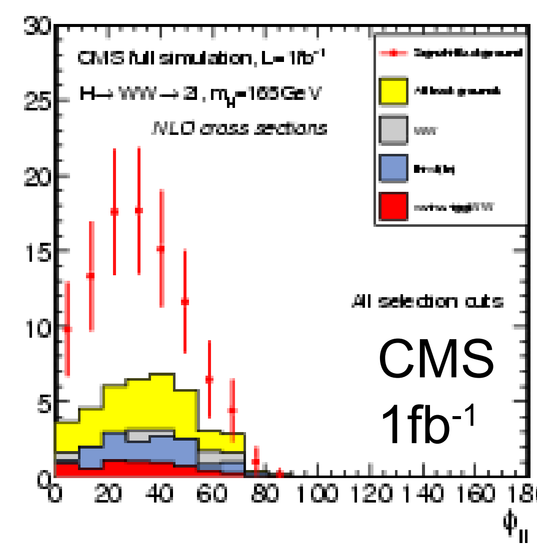
$$m_T = \sqrt{2\ P_T{}^{\ell\ell} \not{E}_T\ (1 - \cos\Delta\varphi)}$$



background: WW, WZ, tt, QCD

exp. challenge: missing energy resolution

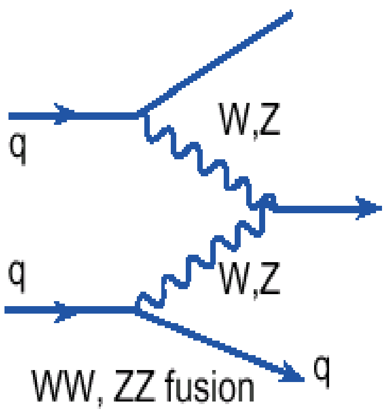
tt (or jet) – veto

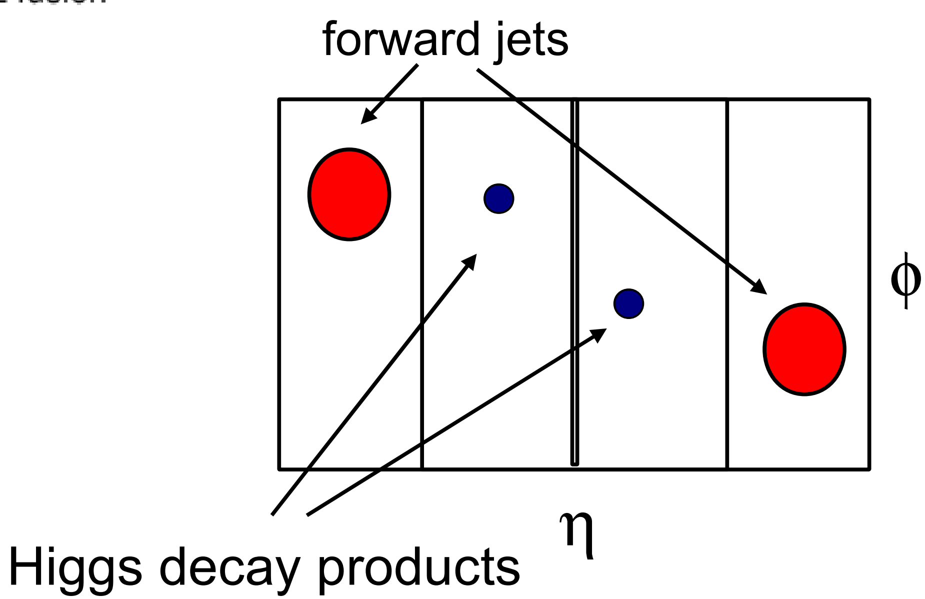


A Closer Look at Specific Channels

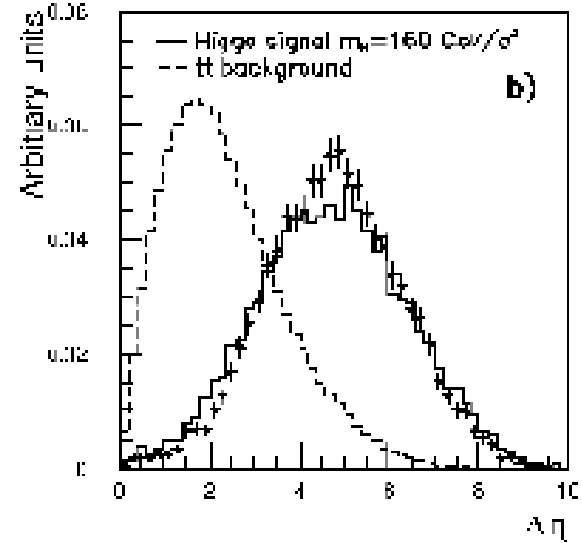
Vector Boson Fusion: pp → qqH

signature: ✘ 2 forward jets with large rapidity gap
✘ only Higgs decay products in central det.

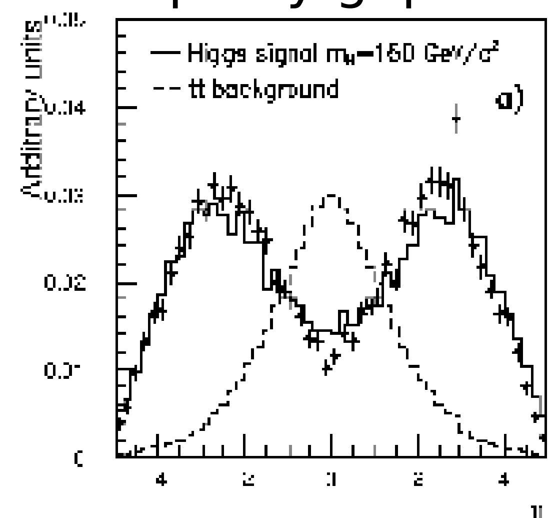




tagging jet rapidity



rapidity gap



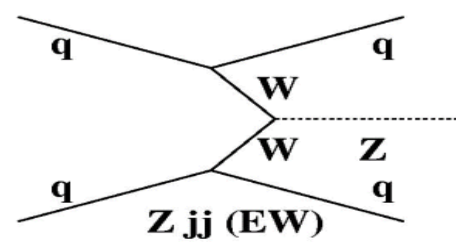
A Closer Look at Specific Channels

qqH → qqττ : σ_H = 4.5 pb BR (H → ττ) = 0.069 (mH=120GeV)

↘ ~180 evts/fb

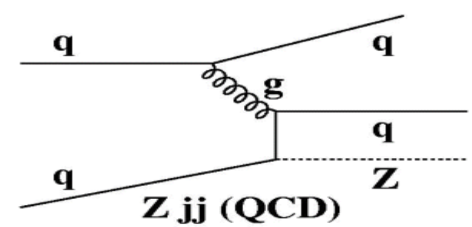
$\tau\tau$ decay mode	BR
$\ell\ell\,\nu$	12 %
ℓjet ν	46 %
jet jet ν	42 %

signal: VBF signature
high pT lepton, hadronic , missing er
or two high pT leptons, missing ener



background: pp → Z → ττ (EWK, QCD)
tt, WW, bbjj

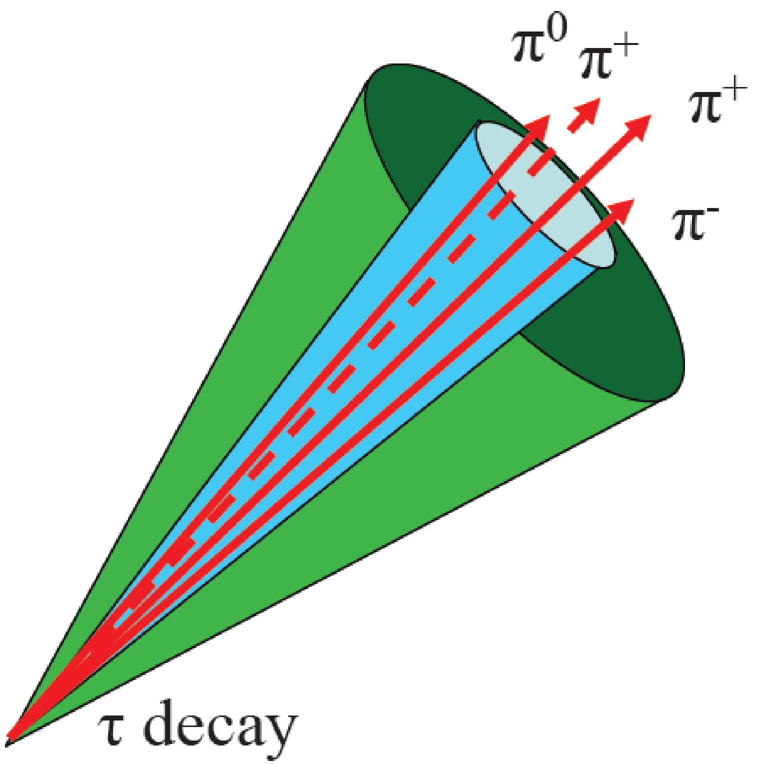
exp. challenge: missing Et resolution (Higgs mass)
central jet veto
forward jet tagging
all detector components involved



A Closer Look at Specific Channels

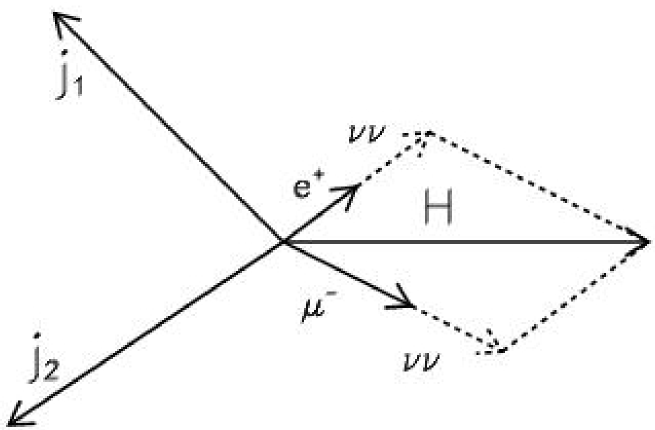
Hadronic τ reconstruction:

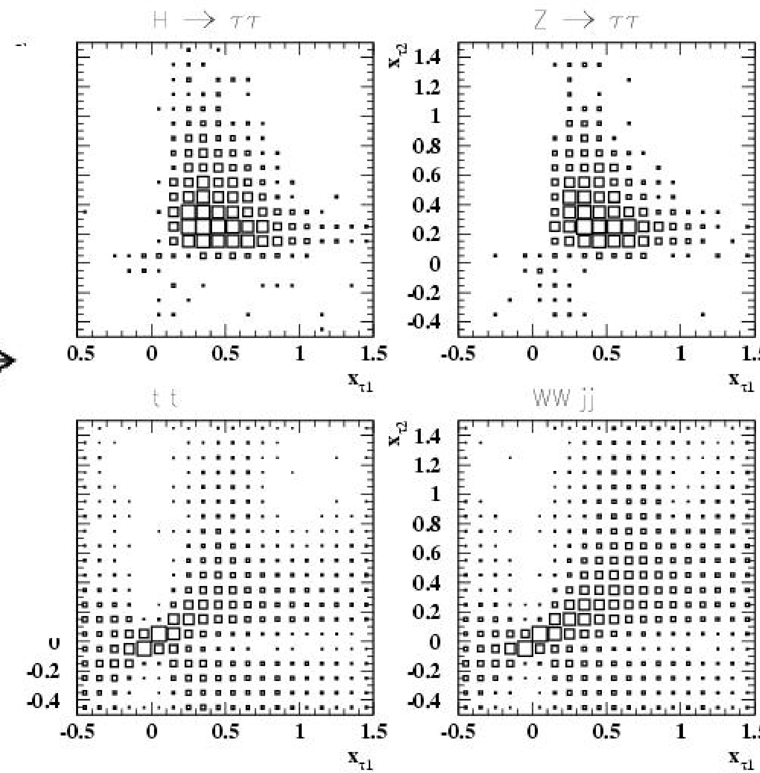
- $c\tau \sim= 87\,\mu m$, $m_\tau = 1.78$ Gev/c²
- Leptonical decays
  - $\tau \to e(\mu)\,\nu\ \nu$: ~ 35.2 %
    - Identification done through the final lepton
- Hadronical decays
  - 1 prong
    - $\tau \to \nu_\tau + \pi^{+/-} + n(\pi^o)$: 49.5 %
  - 3 prongs
    - $\tau \to \nu_\tau + 3\pi^{+/-} + n(\pi^o)$: 15.2 %
  - **"τ –jet" is produced**

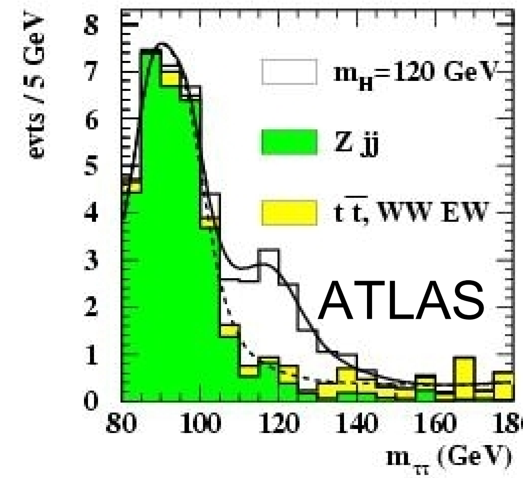


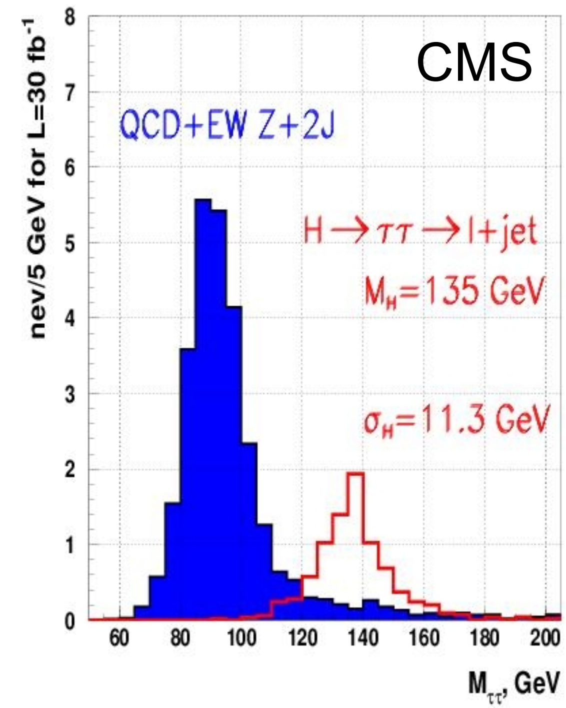
A Closer Look at Specific Channels

Higgs mass reconstruction:









$p(l) = x * p(\tau)$, collinear approximation

$p_T(H) = p_T(\tau 1) + p_T(\tau 2) = p_T(e) + p_T(\mu) + \not{p}_T$

$m^2_{\tau\tau} = m^2_{e\mu} / (x_{\tau e} * x_{\tau\mu})$

A Closer Look at Specific Channels

other SM Higgs channels of interest:

$H \rightarrow WW^* \rightarrow l\nu jj$

$ttH \rightarrow tt\ bb$

$WH \rightarrow l\nu\ bb$

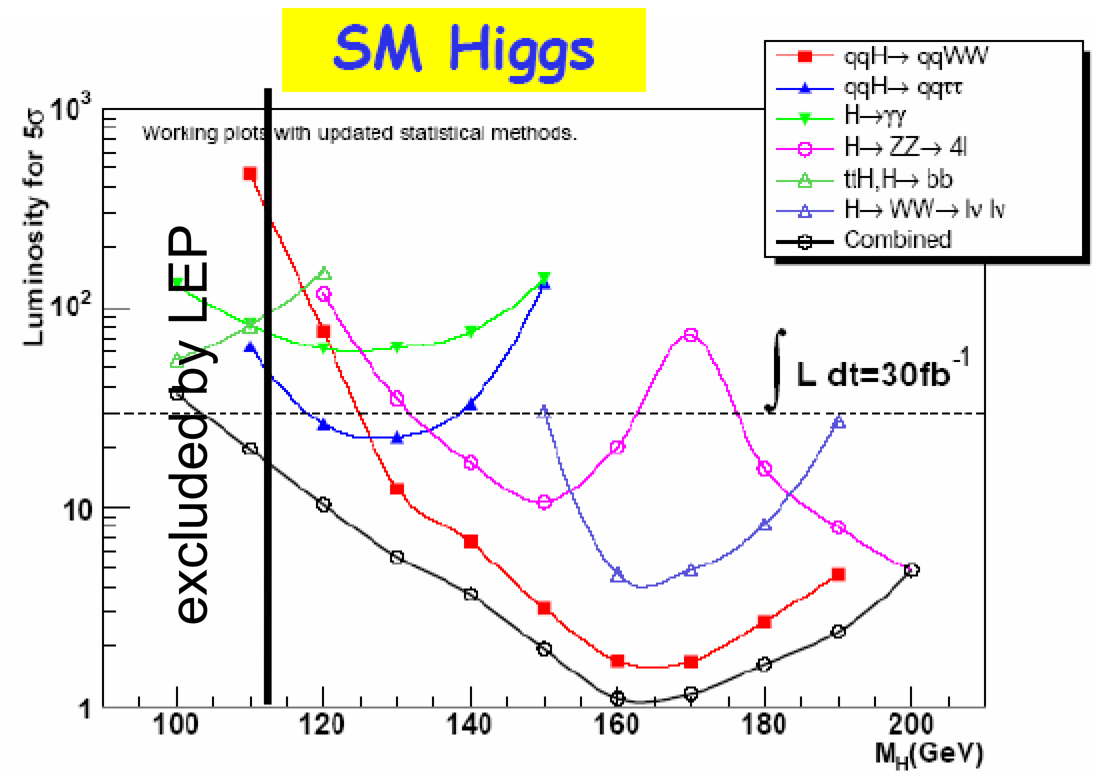
$qqH \rightarrow qq\ WW^*$

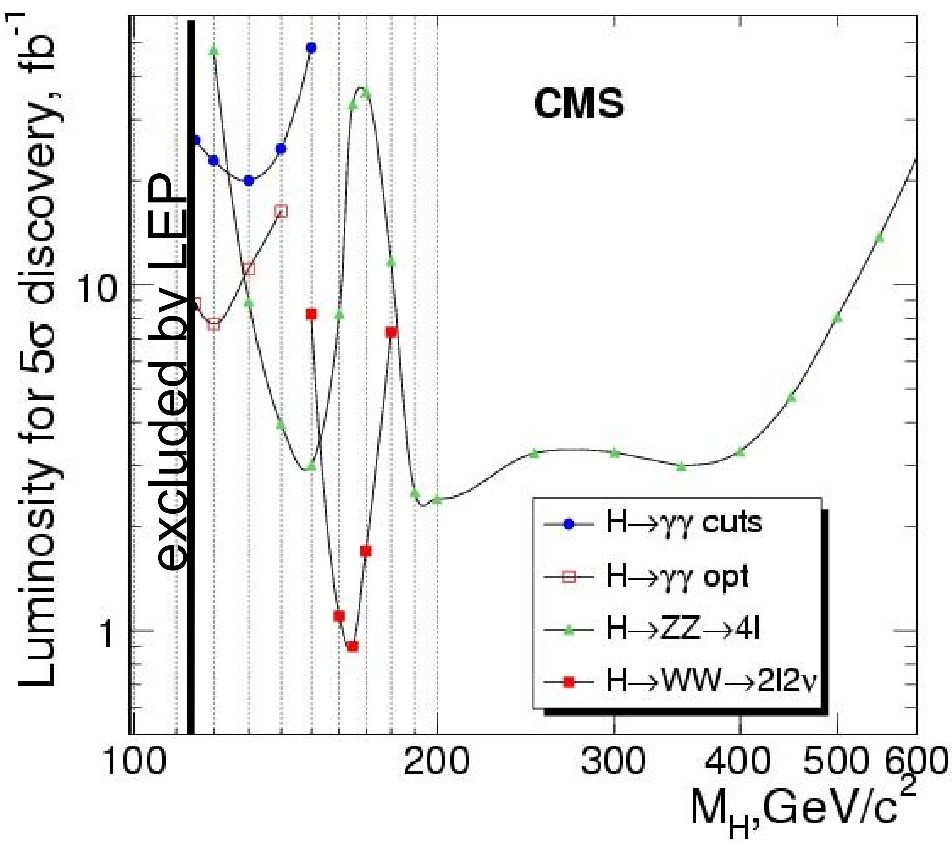
$qqH \rightarrow qq\ \gamma\gamma$

$qqH \rightarrow qq\ ZZ^* \rightarrow qq\ ll\nu\nu$

A Closer Look at Specific Channels

How much luminosity do we need to find the Higgs?





A Closer Look at Specific Channels

Why are the discovery potential plots so different?

ATLAS: K = 1 and LO MC for signal and background
CMS: K-factors for gluon fusion and estimates for background

Both: instrumental backgrounds are not fully considered

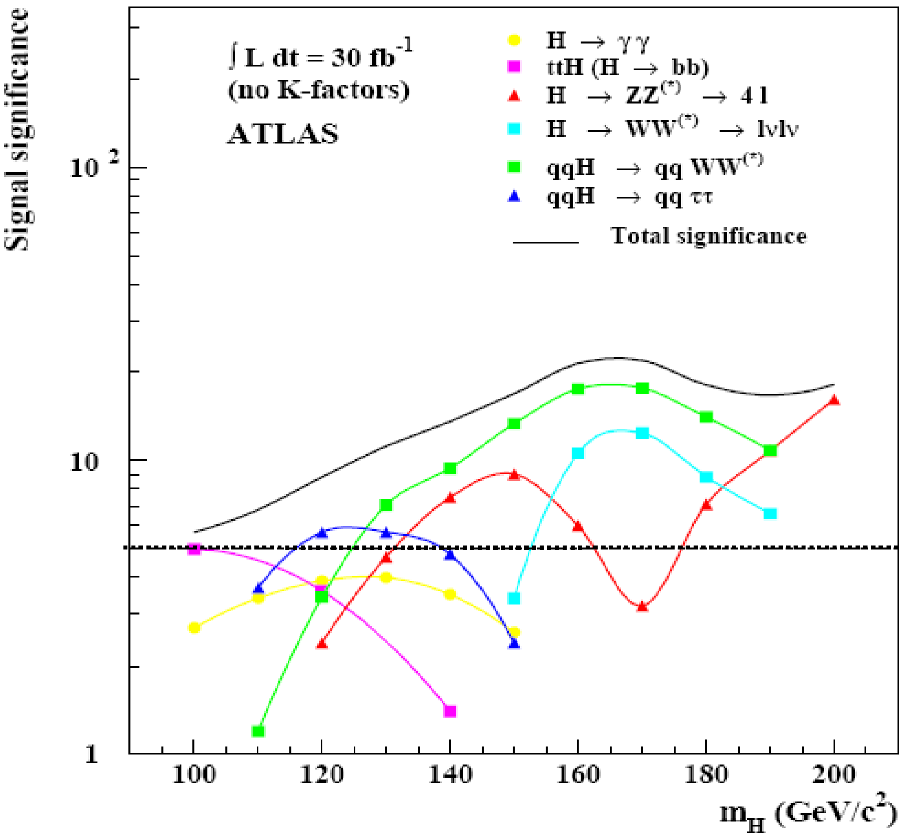
Result:
- ✘ More signal for CMS
- ✘ More background for CMS
- ✘ Imbalance between GF and VBF channels

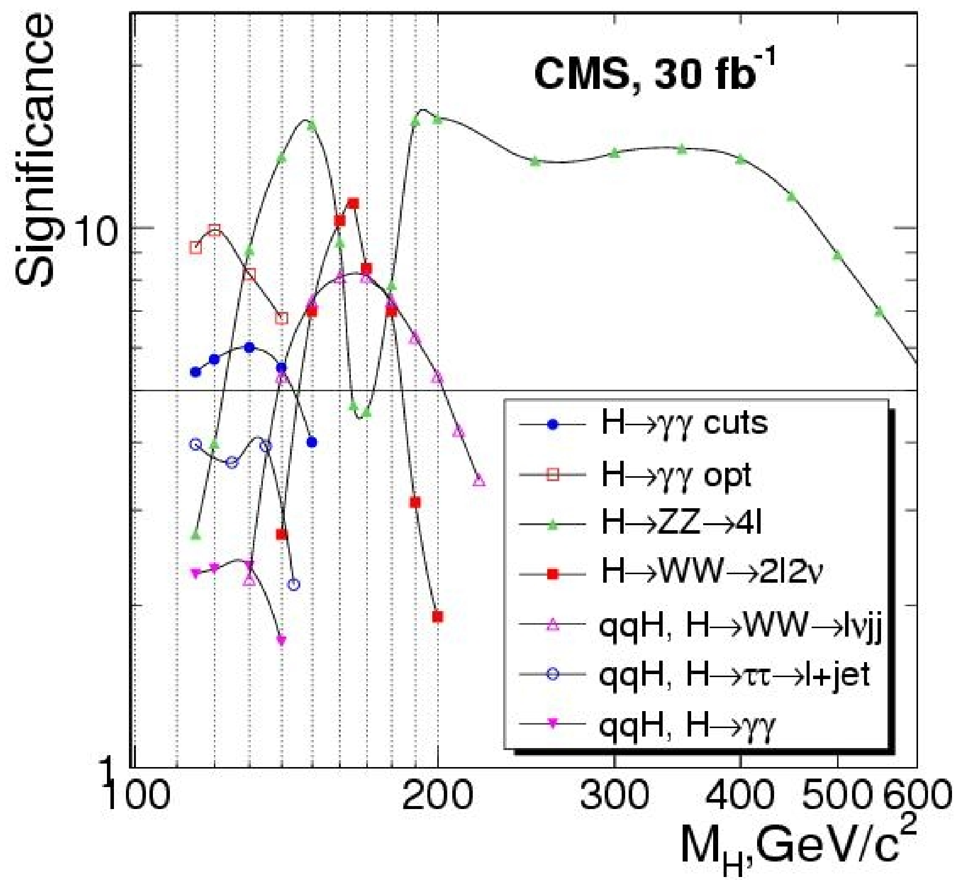
How do we have to read those plots?

- very carefully!

A Closer Look at Specific Channels

Sensitivity with 30 fb^{-1}:

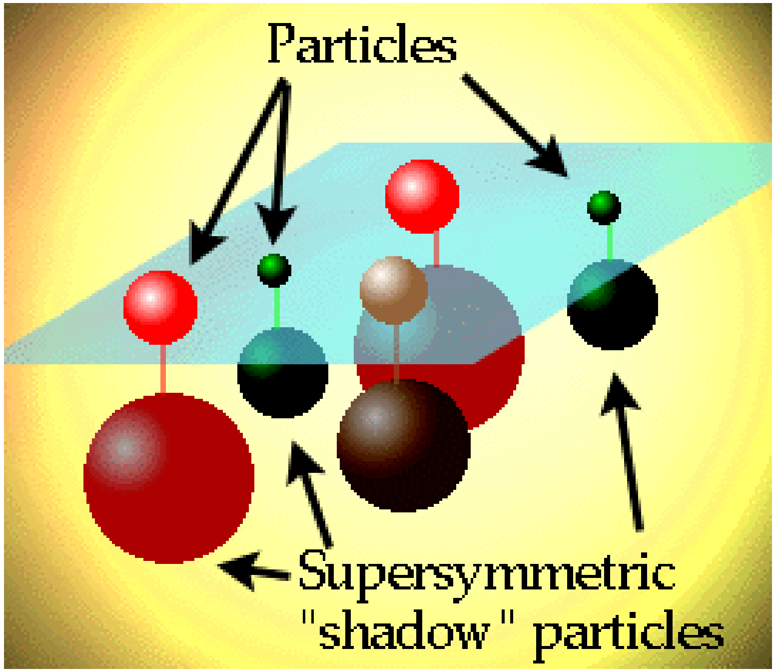




Beyond the Standard Model

Why do we want to go beyond the Standard Model?
- hierachy problem: why v = 246 GeV << Mpl. = 10^{19}GeV
- origin of all this new couplings
- dark matter and baryon asymmetry

SUSY might be a solution but has large problems itself:
- it is broken & 105 new parameters



Study constrained models:
- MSSM with 5 (6) additional parameter

Very rich phenomenology:
- minimal Higgs sector has 5 physical boson h, H, A, H+, H-
- Higgs bosons can decay into particles and sparticles

More on (Higgs-) physics beyond the Standard Model in the following lectures

In 5 Years from Now

These could be the topics of your thesis!!

ATLAS and CMS have datasets of ~100 fb^{-1}

The Higgs Boson was discovered 2010, confirmed by both experiments and in different channels (topic of your thesis if you come here right away!!)

Nothing else but the Higgs Boson was discovered so far

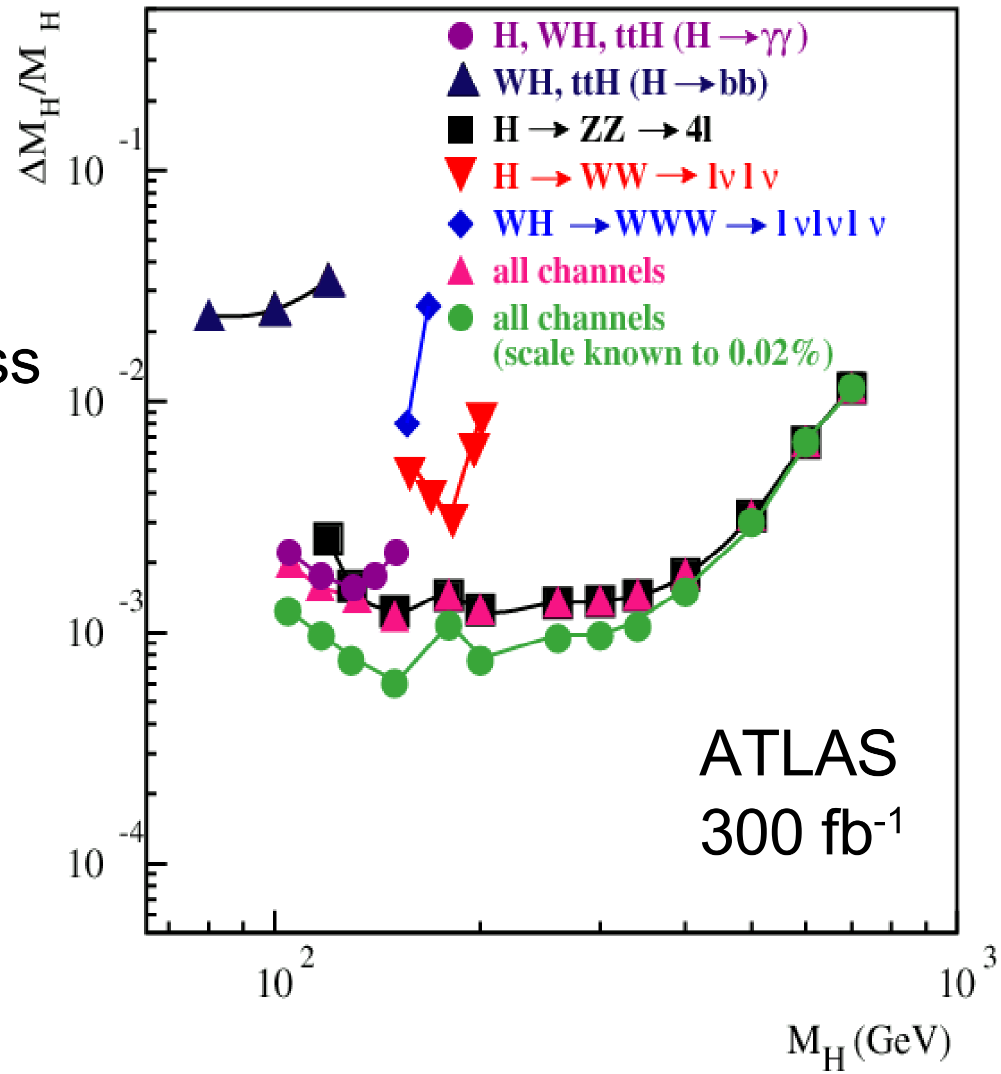
Obvious three interesting topics
- measure Higgs Boson properties
- other SM precision measurements
- keep searching for new physics

Higgs Boson Properties

Higgs Boson mass:

direct mass peaks from:
  $H \rightarrow \gamma\gamma$, $H \rightarrow bb$, $H \rightarrow \tau\tau$, $H \rightarrow ZZ \rightarrow 4l$

indirect from fits to transverse mass spectrum:
  $H \rightarrow WW \rightarrow l\nu l\nu, WH \rightarrow WWW \rightarrow l\nu l\nu l\nu$



uncertainties:
  a) statistical
  b) absolute energy scale
  c) background

estimated precision:
  $\Delta M/M$: 0.1-1.0 %

Higgs Boson Properties

Higgs Boson couplings:

production:

$\sigma_{Hx} = const * \Gamma_{Hx}$

decay:

$BR(H\rightarrow yy) = \Gamma_{Hy}/\Gamma_{tot}$

event rate:

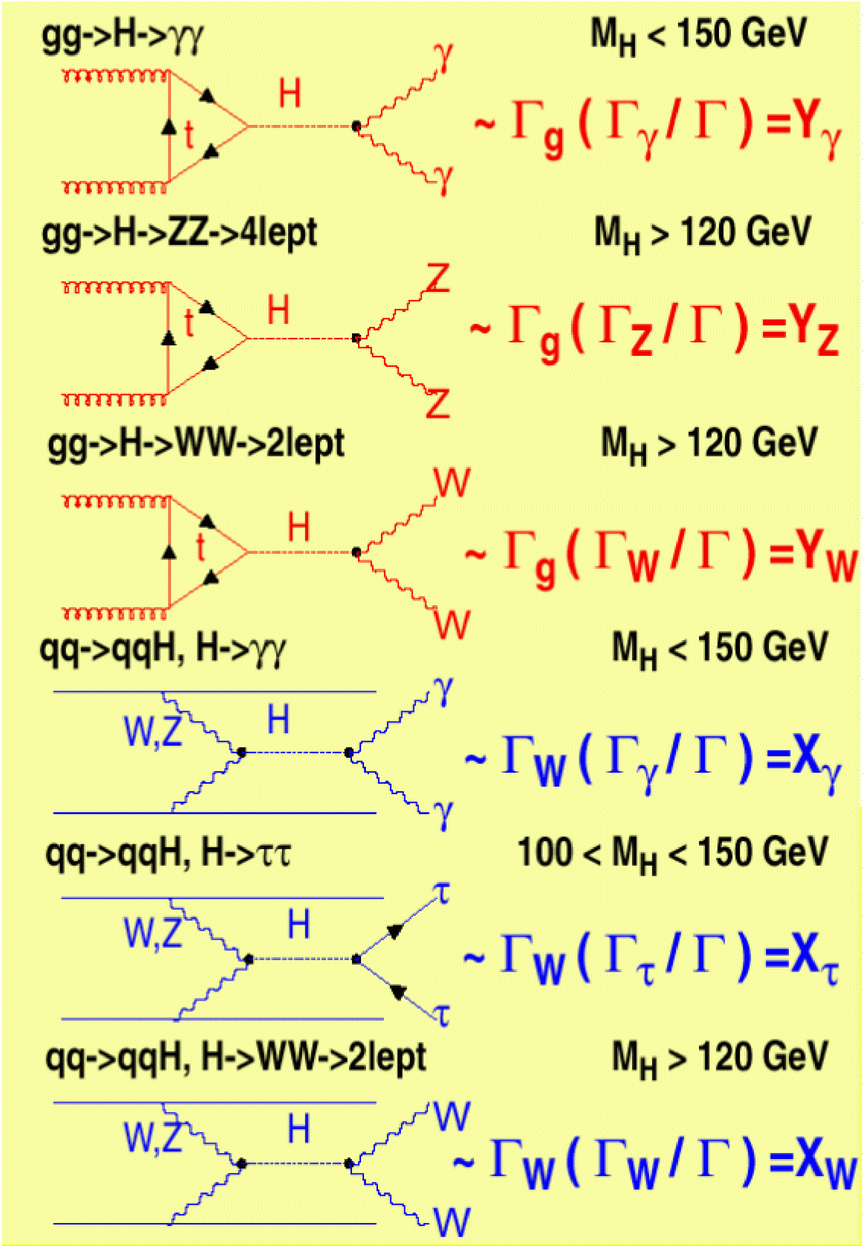
$\sigma_{Hx} * BR = const * \Gamma_{Hx} * \Gamma_{Hy}/\Gamma_{tot}$

coupling:

$\Gamma_{Hz} \sim g_{Hz}^2$

challenge:

disentangle contributions from production and decay



Projects

a) $H \rightarrow ZZ^* \rightarrow 4l$
b) $H \rightarrow WW^* \rightarrow l\nu l\nu$
c) $qqH \rightarrow qqWW^* \rightarrow$ jet jet $l\nu l\nu$

Goal 1:

How much luminosity to you need as a function of m_H (two point) to discover the Higgs boson.

Goal 2:

Measure the relative fraction of Higgs production cross section in vector boson fusion.

Details are on the twiki. Feel free to ask questions!

Conclusion

Fundamental question

What is the origin of elementary particle mass?

Principal of mass creation

Higgs mechanism

LHC experiments will find the SM Higgs boson with 1-10fb-1.

Able to measure or at least constrain Higgs Boson properties

Next Lecture