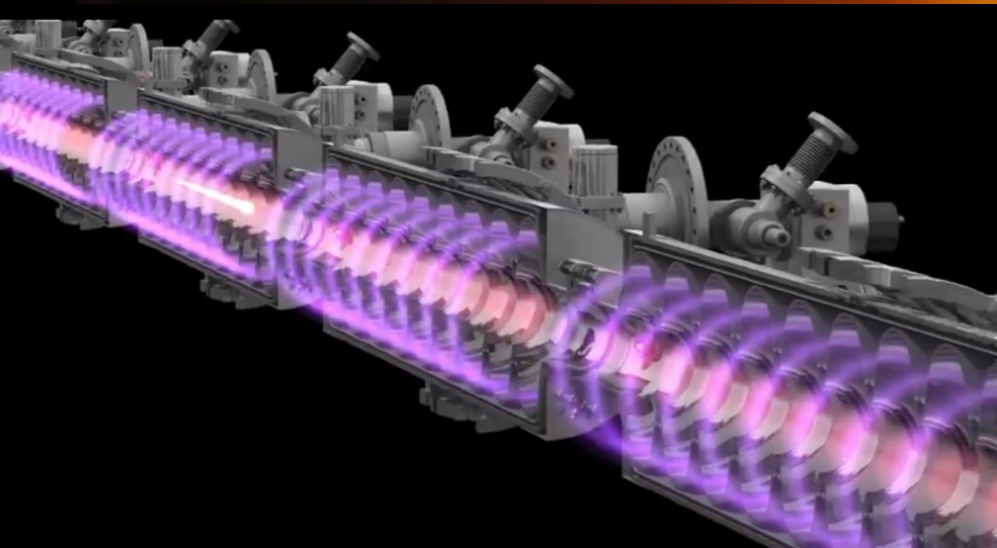
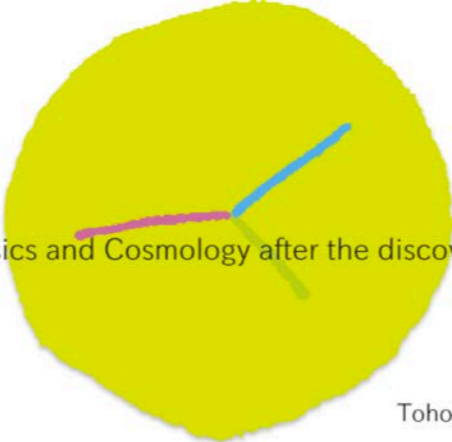





# Higgs discovery, precision, and beyond

Particle Physics and Cosmology after the discovery of Higgs boson

Tohoku Forum for Creativity

Supported by  TOKYO ELECTRON

M. Spiropulu  
Caltech

Thanks to  
山本均  
and  
Tohoku  
University



October 18, 2013 4:25 pm

## The shape of physics to come

[ft.com](#) > [life&arts](#) >

By Clive Cookson

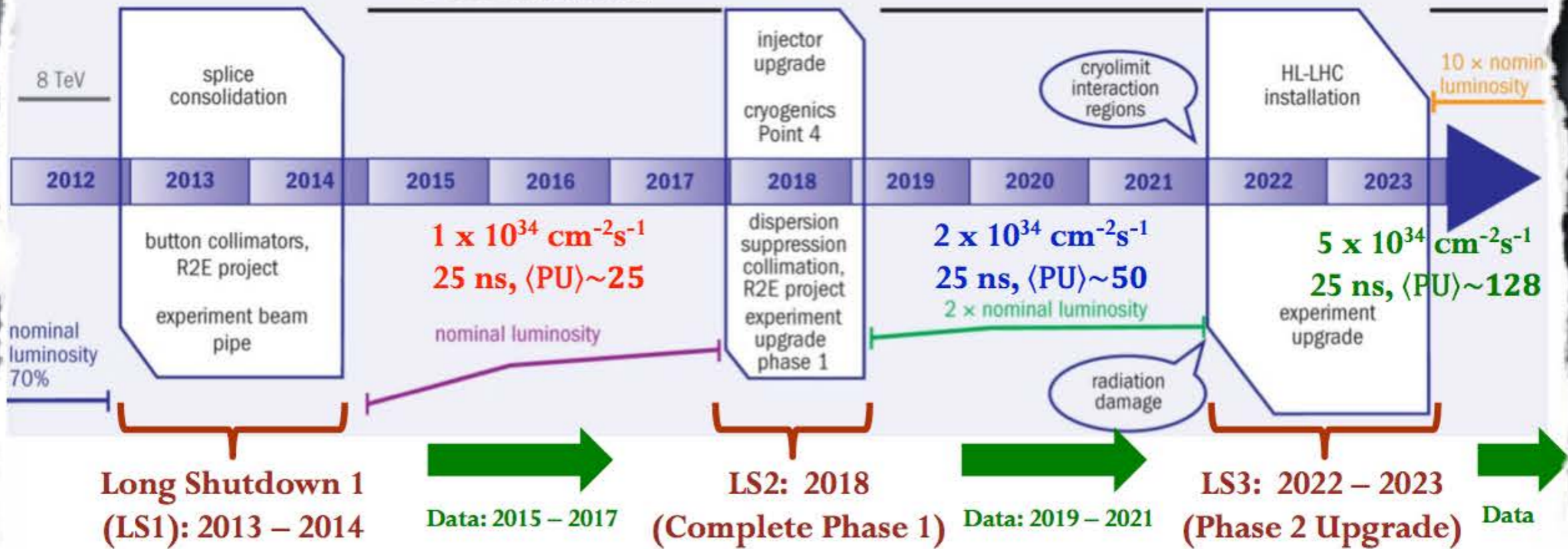
FT Magazine

‘It will drive further development of technology and knowledge through the 21st century’

# Phase 1 upgrade



13–14 TeV collision energy



Long Shutdown 1 (LS1): 2013 – 2014

Data: 2015 – 2017

LS2: 2018 (Complete Phase 1)

Data: 2019 – 2021

LS3: 2022 – 2023 (Phase 2 Upgrade)

Data

# Large Hadron Collider

Lake of Geneva

Roman coins found during archeological excavations at Point 5



CMS

LHCb

Airport

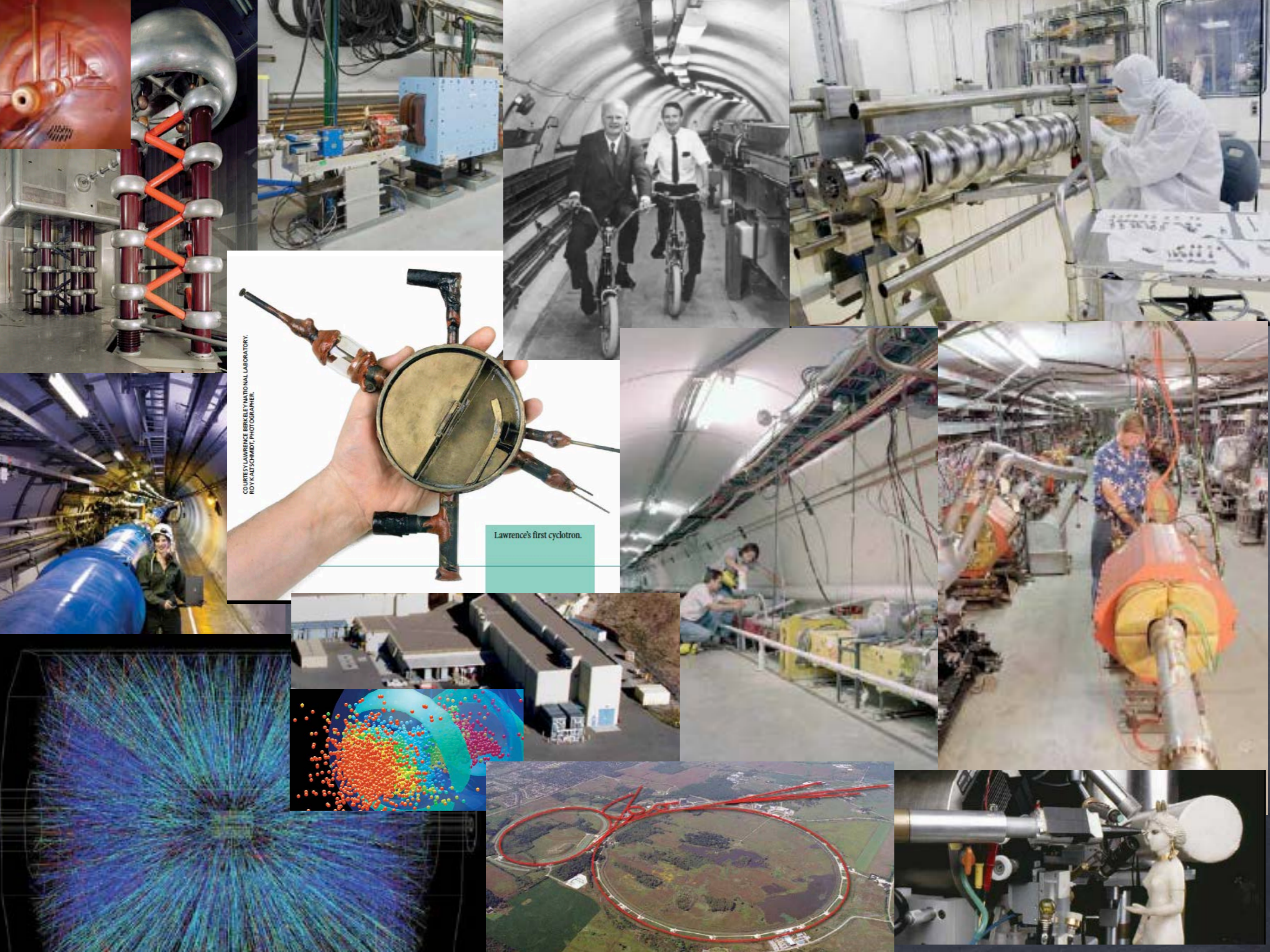
ALICE

ATLAS

CERN



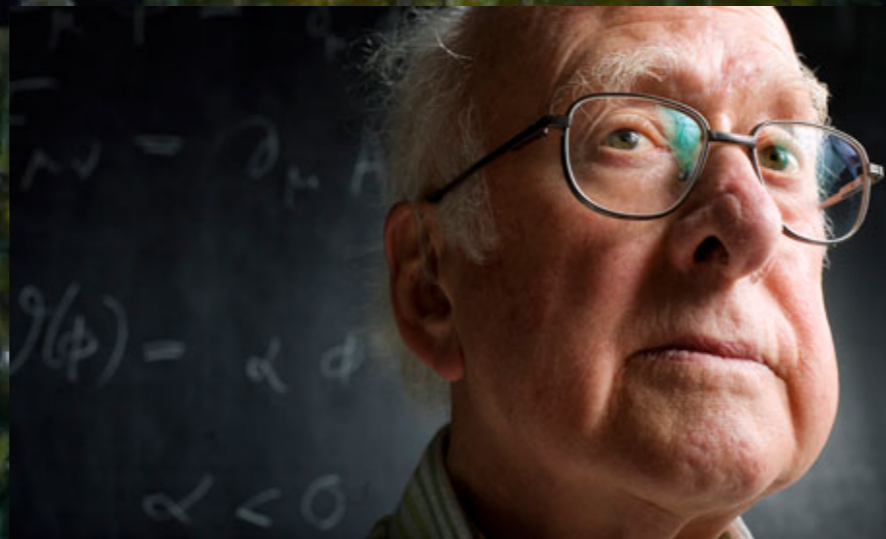




COURTESY LAWRENCE BERKELEY NATIONAL LABORATORY.  
ROY KALTSCHMIDT, PHOTOGRAPHER.

Lawrence's first cyclotron.

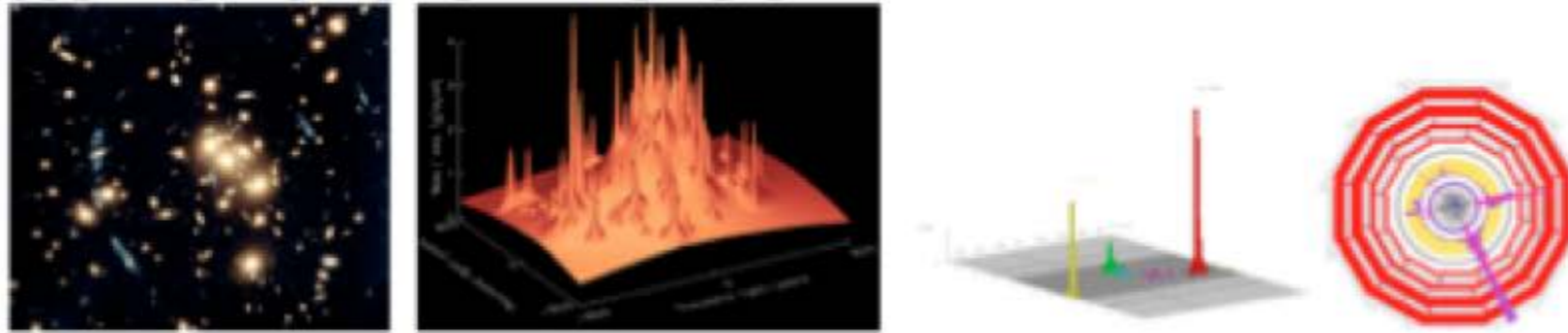
# Higgs Quo Vadis (Stockholm, Dec 12, 2013)



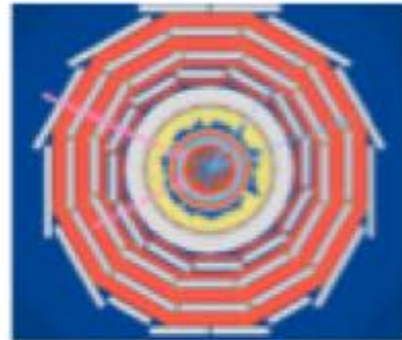
“for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the **discovery of the predicted fundamental particle**, by the ATLAS and CMS experiments at CERN’s Large Hadron Collider”

# The major physics scope of the LHC

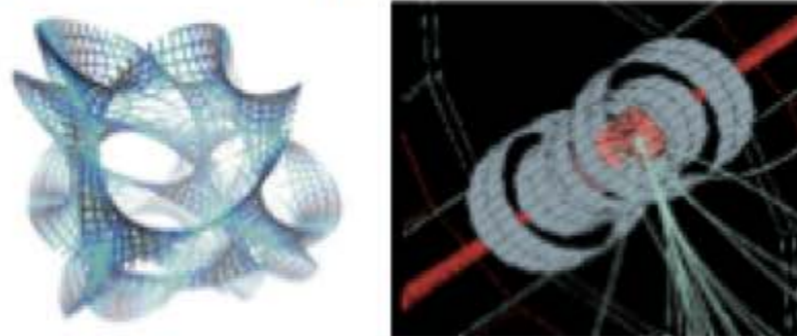
- Find and characterize the new particles that compose the dark matter of the universe



- Find the Higgs particle



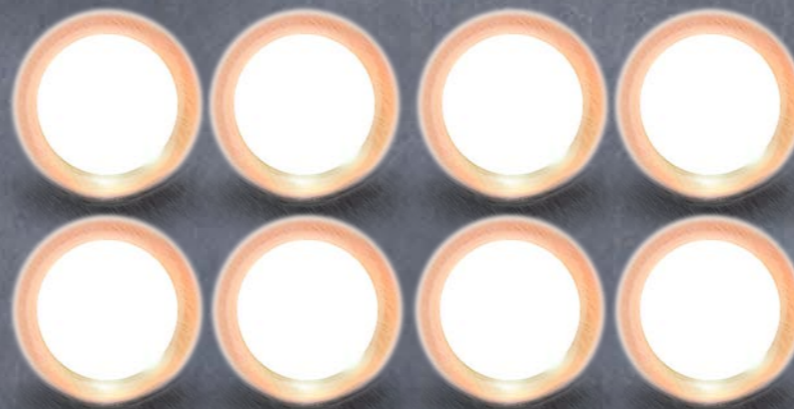
- Find new particles, forces, extra dimensions of space



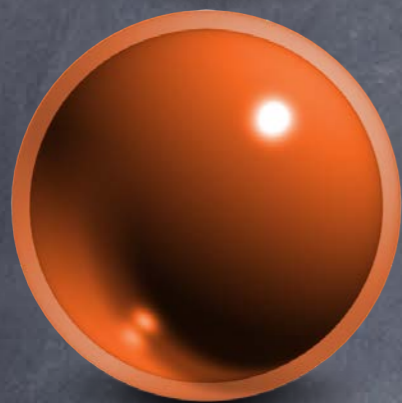


photon boson  
electromagnetism

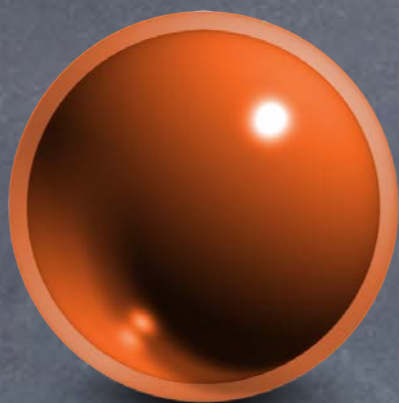
gluon bosons  
strong nuclear



bosons  
spin=1



W boson  
weak nuclear



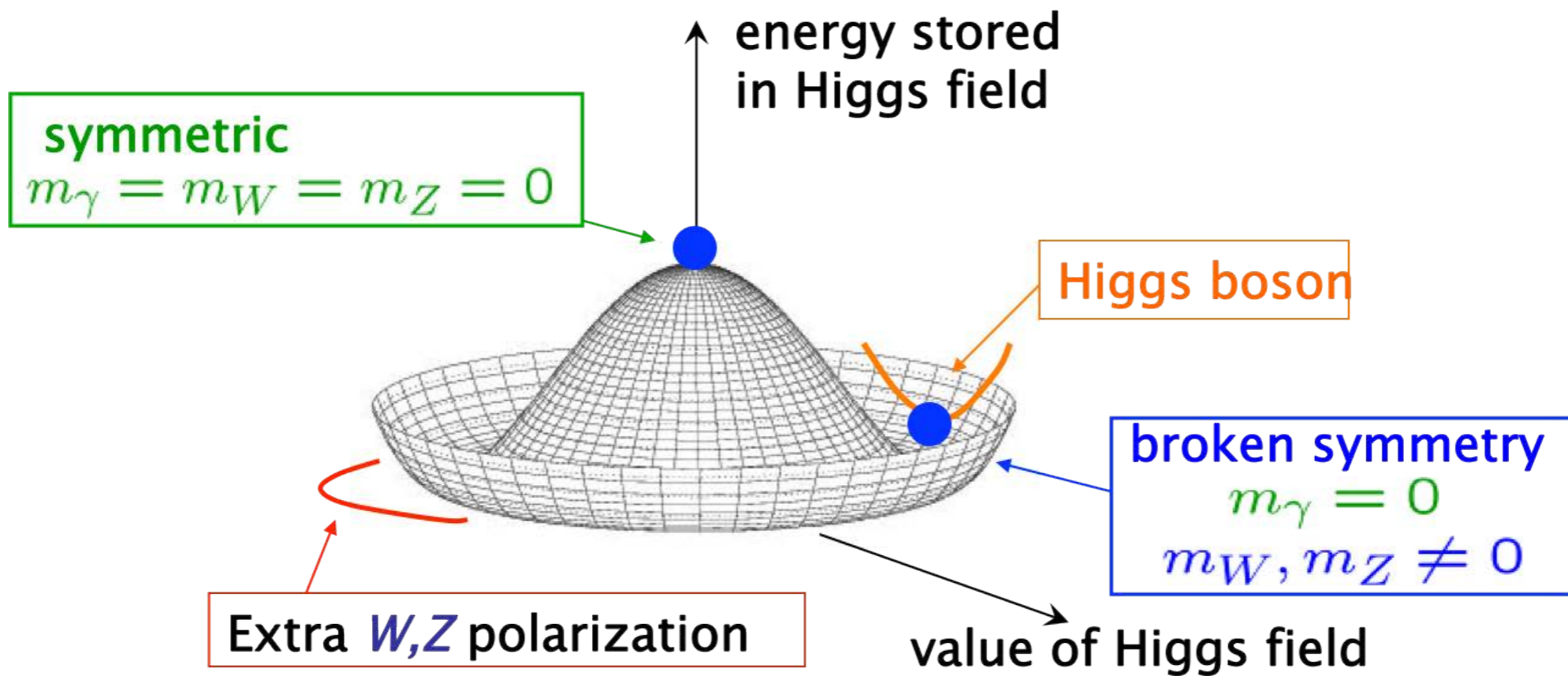
Z boson  
weak nuclear

H boson  
a new fundamental  
force of nature

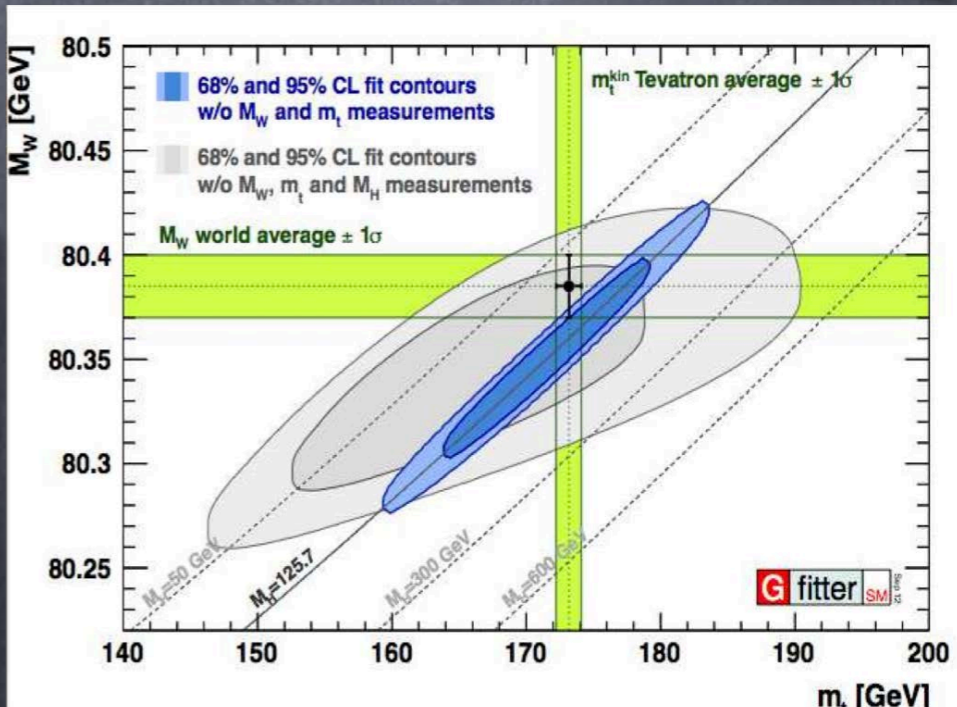
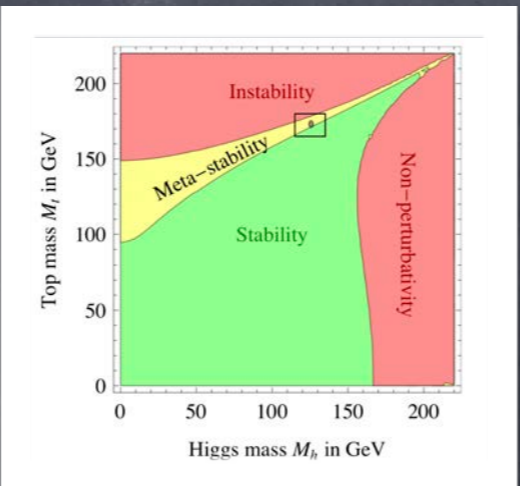
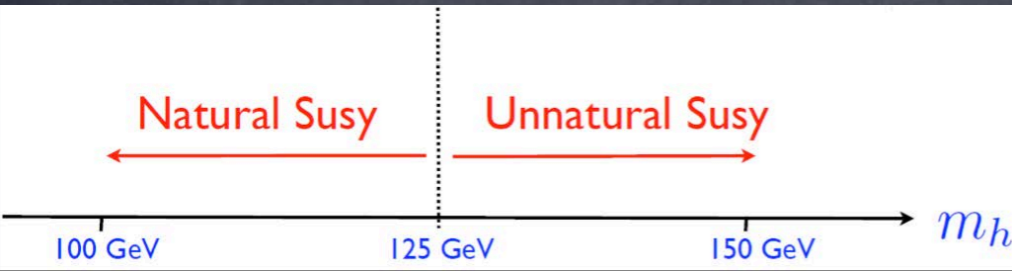


bosons  
spin=0

the first new type of fundamental particle (spin 0 boson)  
since the photon (spin 1 boson) and the electron (spin 1/2 fermion)



# The W-H-t triangle borderline disorder



# WHAT IF EW SYMMETRY WERE NOT BROKEN AS IN SM?

- Chiral symmetry breaking by QCD would break  $SU_L(2)$ !!
- $W$  and  $Z$  would get mass, just only 30 MeV
- Quarks and leptons massless
- Mesons and baryons *would* form.
- Protons heavier than neutrons! Rapid beta decay
- No atoms, chemistry, us...

## OUTREACH ADVICE

When the Higgs is found, don't say it is just a particle. It is (the first step) towards a radically new view of our Universe.

# Higgs Bosons — $H^0$ and $H^\pm$

$H^0$  Mass  $m = 125.9 \pm 0.4$  GeV

$H^0$  signal strengths in different channels  $[\eta]$

Combined Final States =  $1.07 \pm 0.26$  ( $S = 1.4$ )

$W W^*$  Final State =  $0.88 \pm 0.33$  ( $S = 1.1$ )

$Z Z^*$  Final State =  $0.89^{+0.30}_{-0.25}$

$\gamma\gamma$  Final State =  $1.65 \pm 0.33$

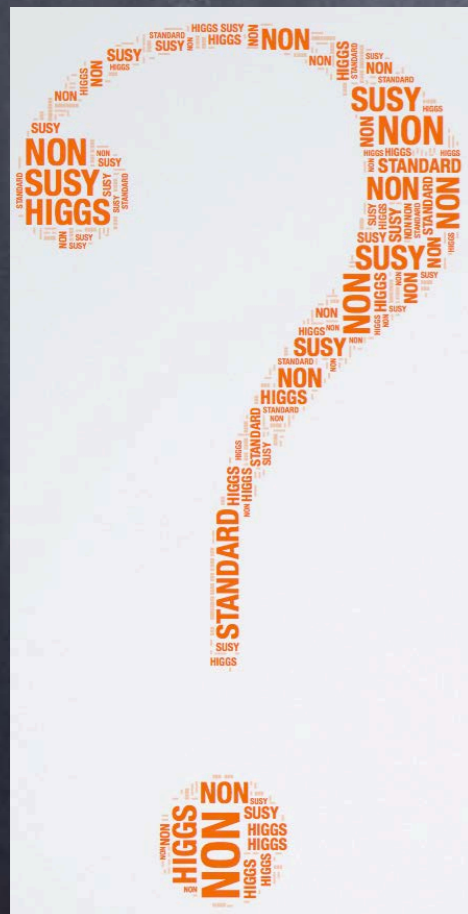
$b\bar{b}$  Final State =  $0.5^{+0.8}_{-0.7}$

$\tau^+\tau^-$  Final State =  $0.1 \pm 0.7$

[HTTP://PDG.LBL.GOV](http://pdg.lbl.gov)

Page 4

Created: 7/31/2013 15:19



## $H^0$ DECAY MODES

| $H^0$ DECAY MODES | Fraction ( $\Gamma_i/\Gamma$ ) | $p$ (MeV/c) |
|-------------------|--------------------------------|-------------|
| $W W^*$           | seen                           | —           |
| $Z Z^*$           | seen                           | —           |
| $\gamma\gamma$    | seen                           | —           |
| $b\bar{b}$        | possibly seen                  | —           |
| $\tau^+\tau^-$    | possibly seen                  | —           |

### Mass Limits for the Standard Model Higgs

Mass  $m > 122$  and none 127–600 GeV, CL = 95%

The limits for  $H_1^0$  and  $A^0$  in supersymmetric models refer to the  $m_h^{\max}$  benchmark scenario for the supersymmetric parameters.

### $H_1^0$ in Supersymmetric Models ( $m_{H_1^0} < m_{H_2^0}$ )

Mass  $m > 92.8$  GeV, CL = 95%

### $A^0$ Pseudoscalar Higgs Boson in Supersymmetric Models $[\circ]$

Mass  $m > 93.4$  GeV, CL = 95%  $\tan\beta > 0.4$

$H^\pm$  Mass  $m > 79.3$  GeV, CL = 95%



19 Sept 2008



- Superconducting joint failed at 8700 amps
- Magnets quenched, dumping their stored energy
- Sent a pressure wave in both directions along the beam line
- Destroyed 53 magnets, coated 4 km of beampipe with soot

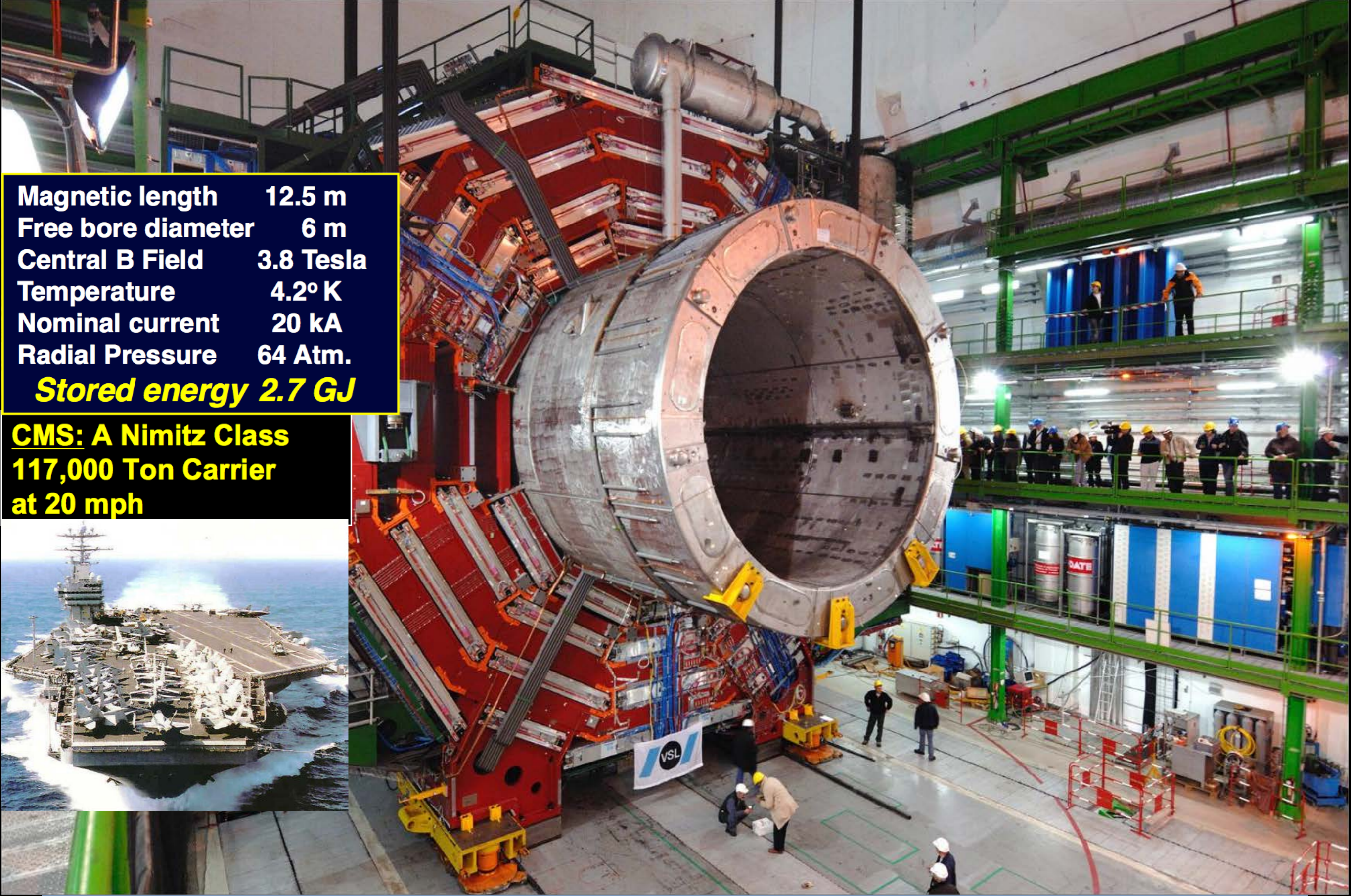












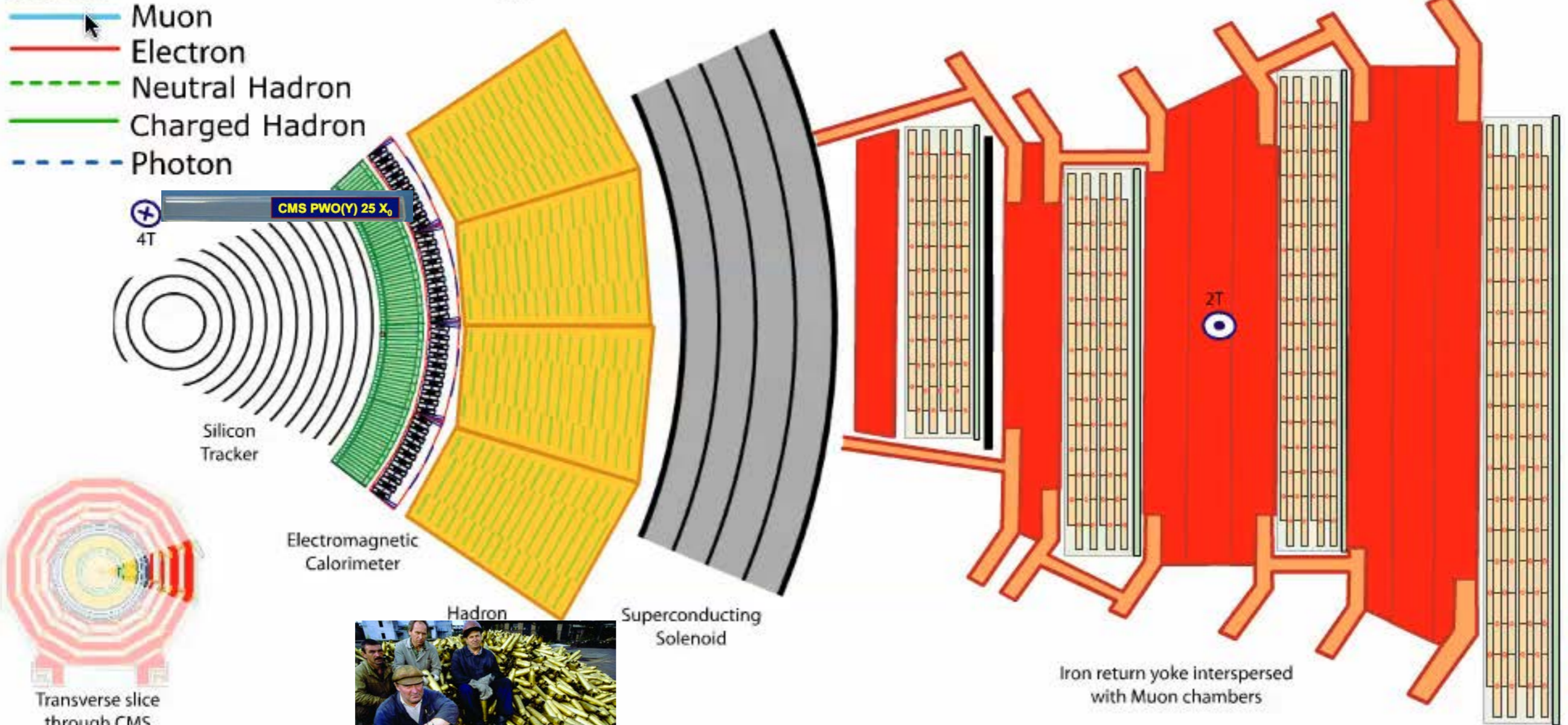
**Magnetic length** 12.5 m  
**Free bore diameter** 6 m  
**Central B Field** 3.8 Tesla  
**Temperature** 4.2° K  
**Nominal current** 20 kA  
**Radial Pressure** 64 Atm.  
**Stored energy** 2.7 GJ

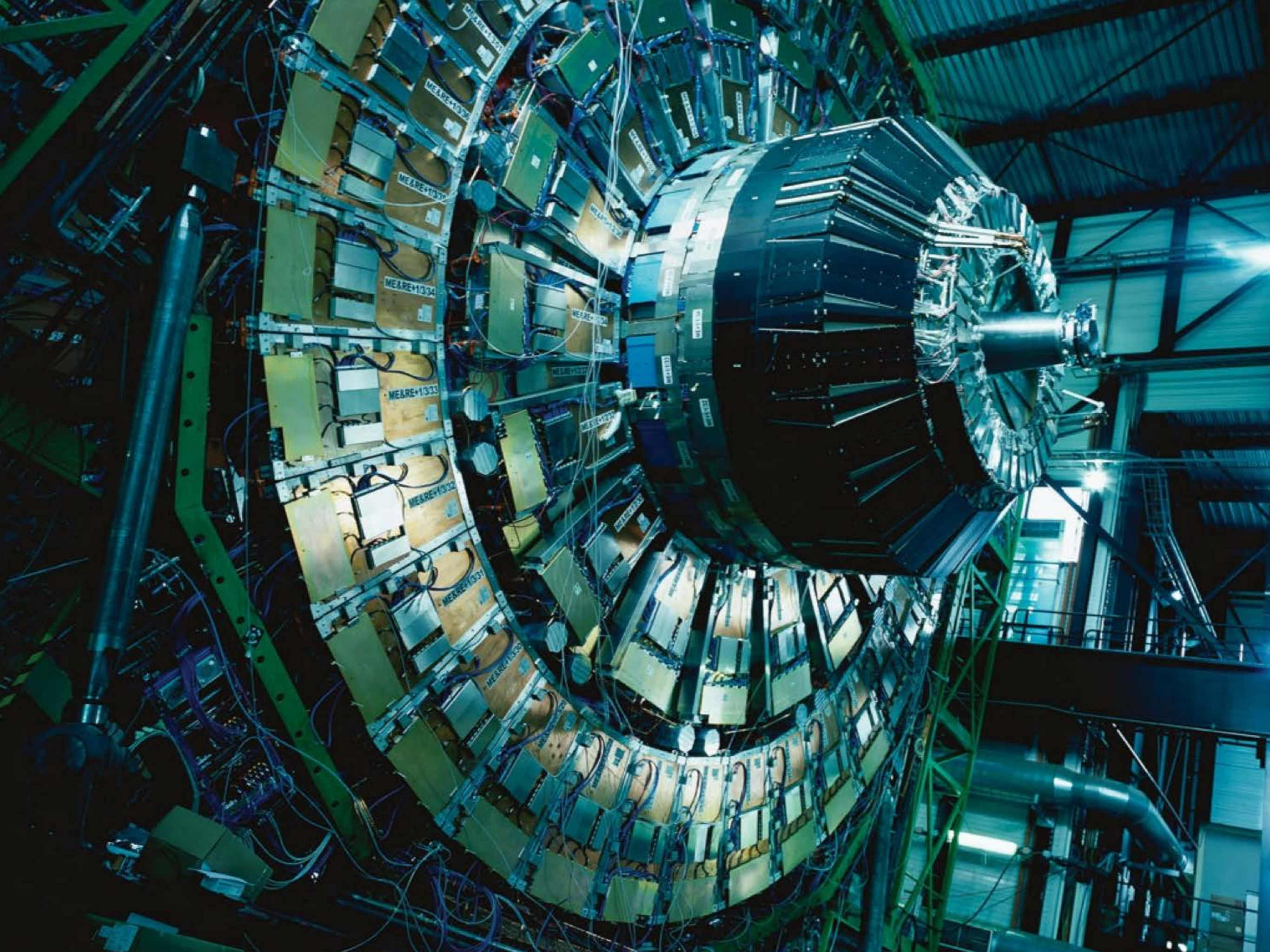
**CMS: A Nimitz Class  
117,000 Ton Carrier  
at 20 mph**



Select:

- Muon
- Electron
- - - Neutral Hadron
- Charged Hadron
- - - Photon

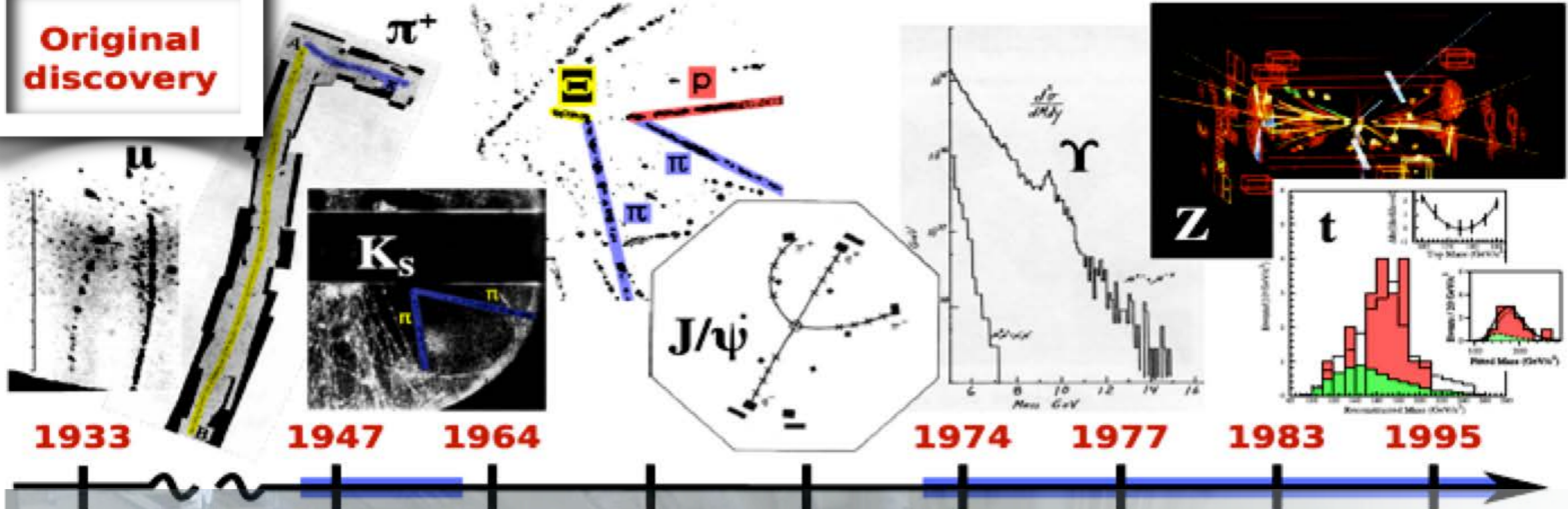




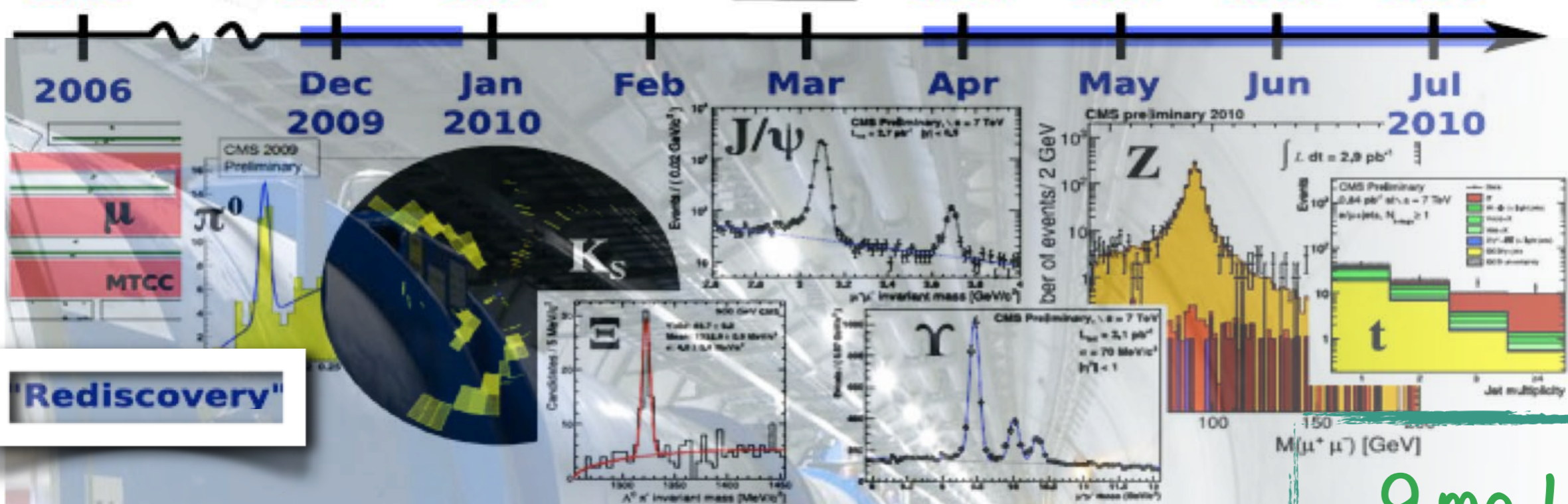
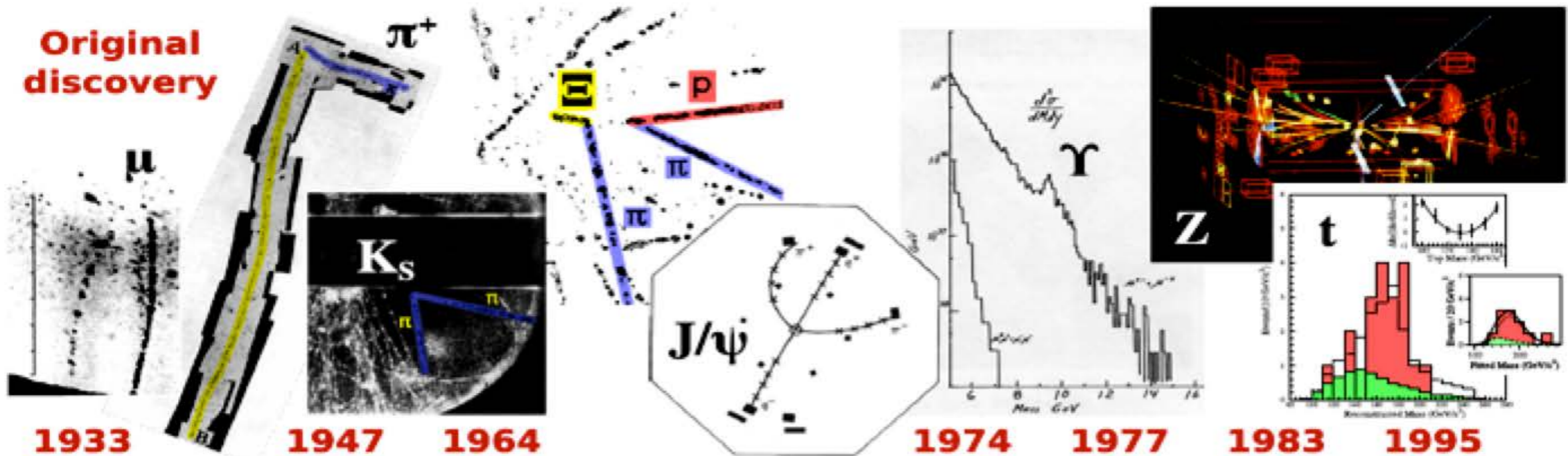


# 50 years of particle physics discoveries

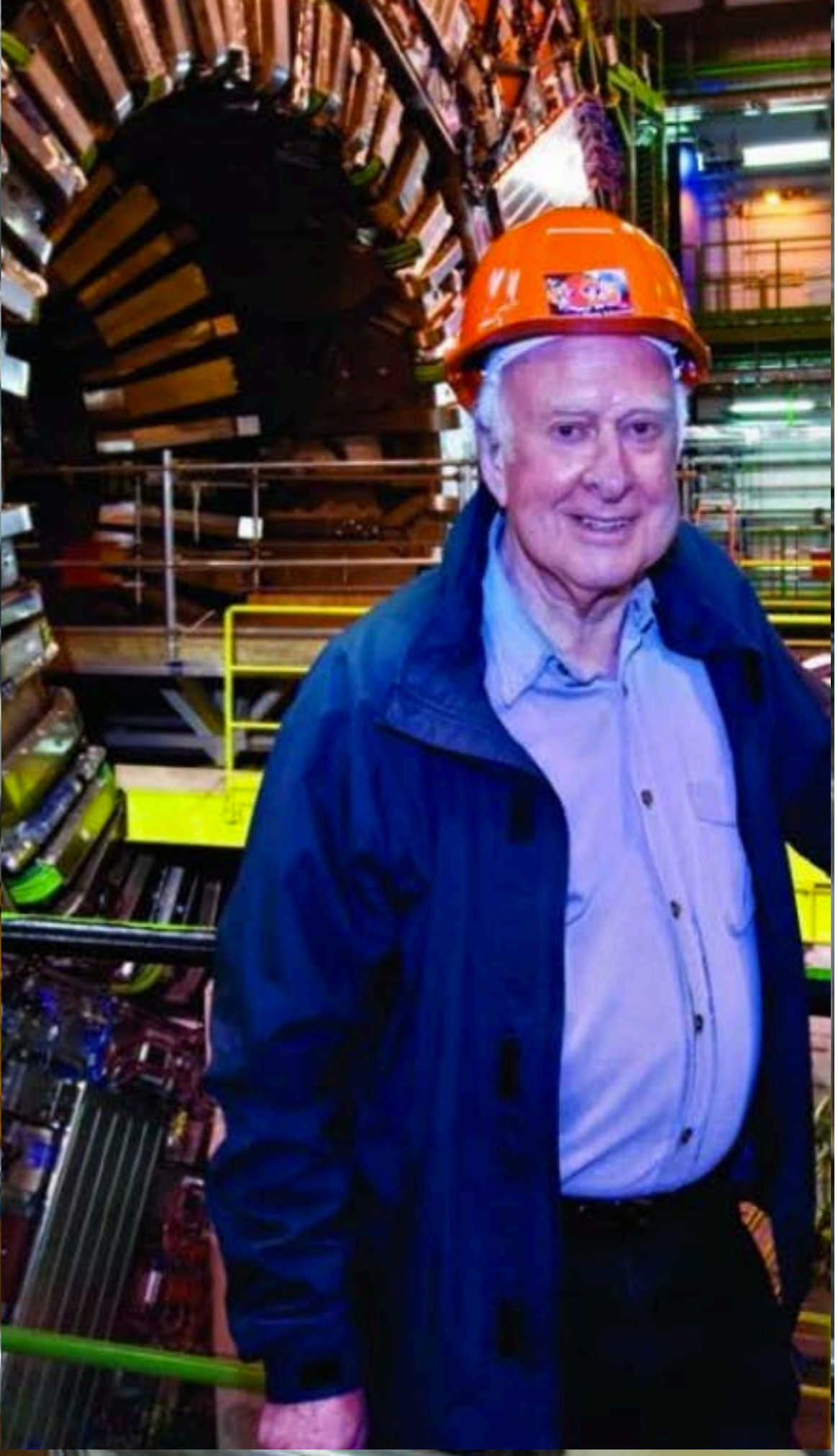
Original discovery

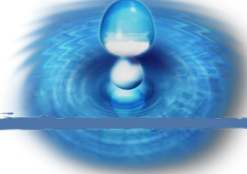


# 50 years of particle physics discoveries

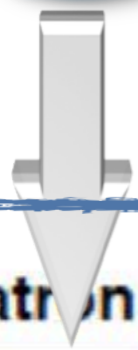


9 mo LHC  
7TeV

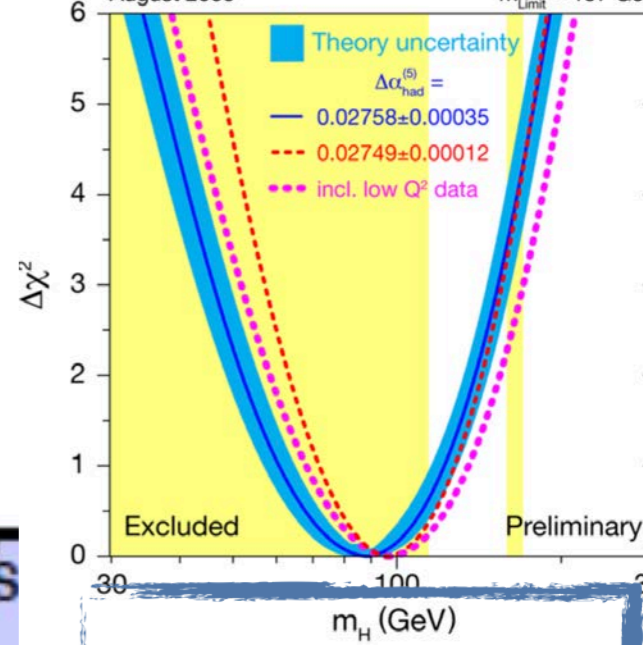
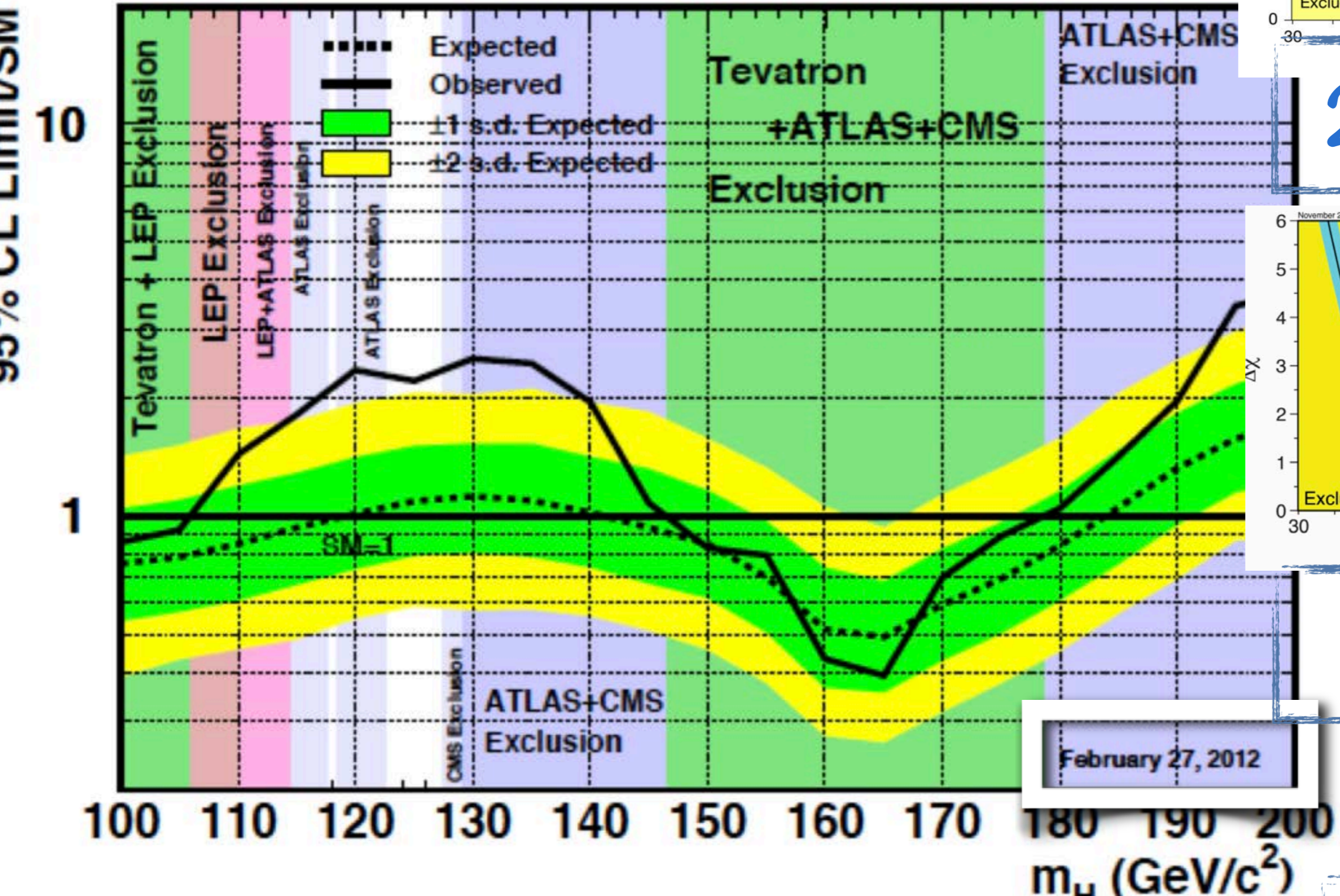




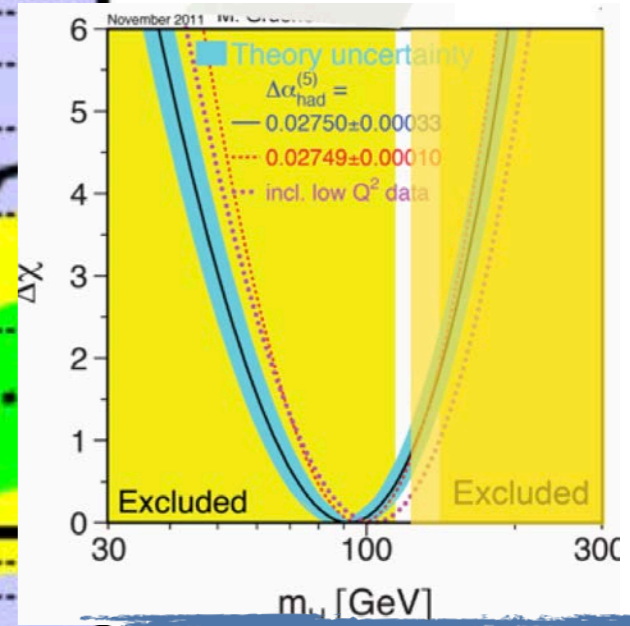
# decades of Higgs hunting



Tevatron Run II Preliminary,  $L \leq 10.0 \text{ fb}^{-1}$



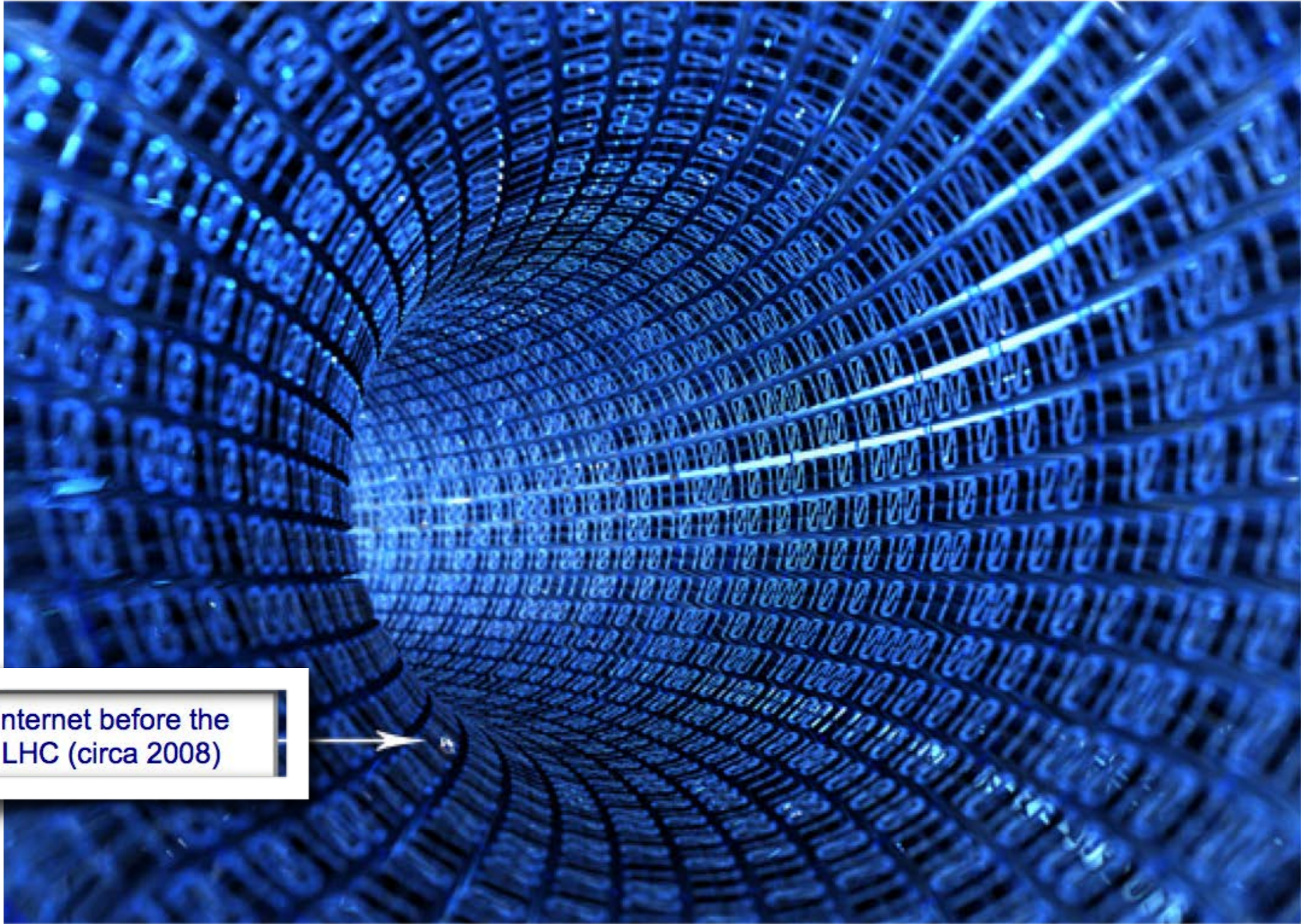
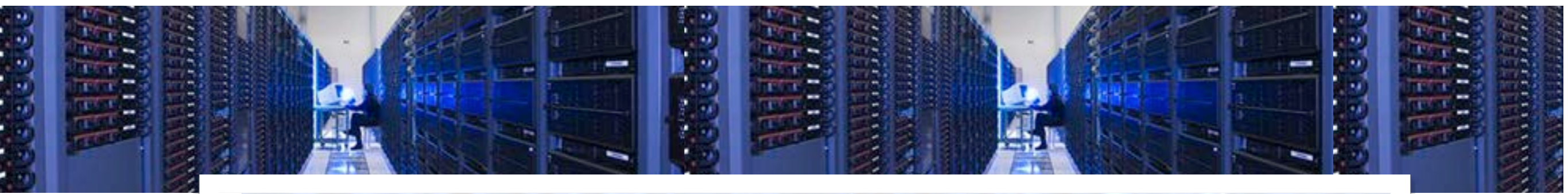
2009



2011

# decades of calculating





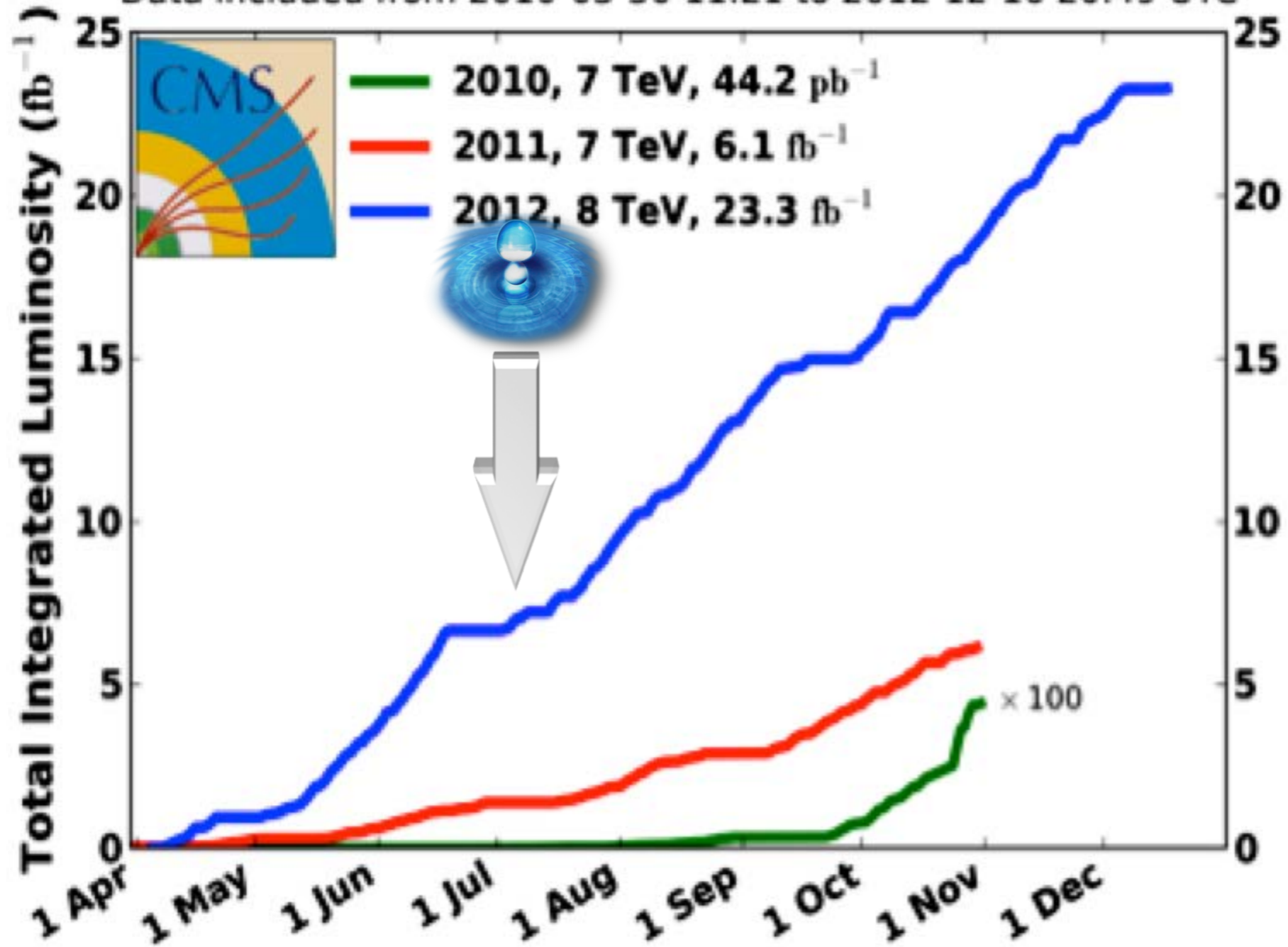
Internet before the  
LHC (circa 2008)

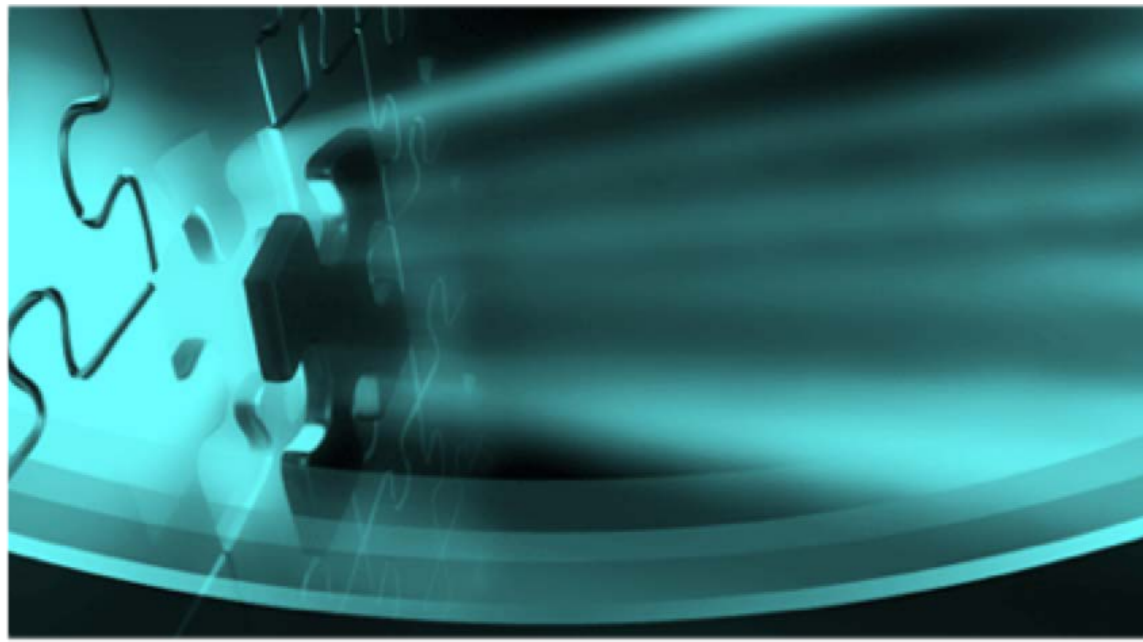


# Big Data, Big Models, Data in Motion

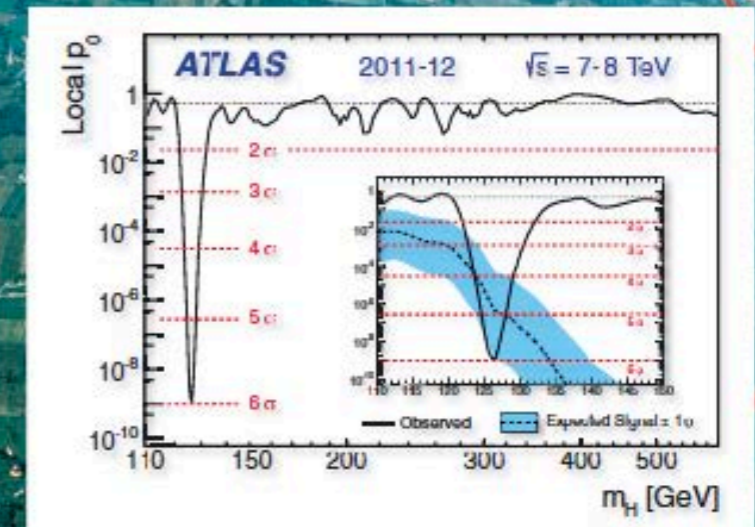
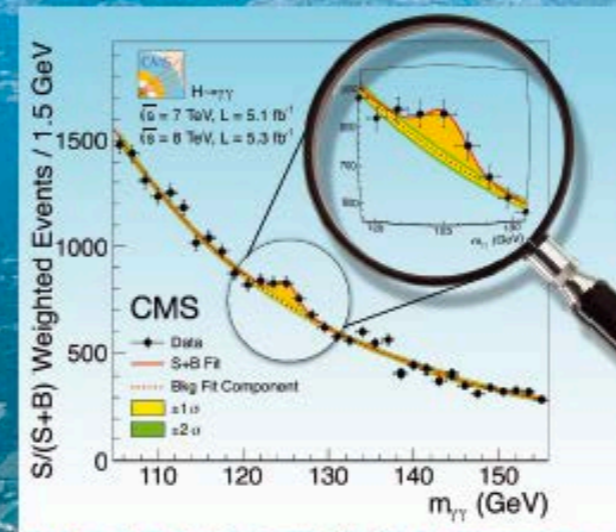
# CMS Integrated Luminosity, pp

Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC





# First observations of a new particle in the search for the Standard Model Higgs boson at the LHC



SCHOOL of PHYSICS and ASTRONOMY

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The King's Buildings  
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Edinburgh EH9 3JZ

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or direct dial +44 (0)131 650 5249  
Fax +44 (0)131 650 5902  
Email info@ph.ed.ac.uk  
www.ph.ed.ac.uk

Congratulations to both  
Atlas and CMS Collaborations  
and to the builders of the LHC  
on a magnificent achievement!

Peter Higgs

30 August 2012

THE WHITE HOUSE  
WASHINGTON  
August 8, 2012

Dr. Joel N. Butler  
Fermilab  
P.O. Box 500  
Batavia, IL 60510-5011

Dr. Butler:

On behalf of the Obama Administration, I would like to congratulate the US-CMS collaboration on the discovery of the Higgs boson. The successful culmination of the long quest for the Higgs boson represents a triumph for fundamental science and paves the way for a deeper understanding of the universe.

I note with great pride the role US scientists have had in the design, construction, and operation of the CMS detector as well as the leadership of collaboration. Clearly, the scientific expertise and ingenuity of US scientists have been essential components of the discovery. Furthermore, the astounding scientific achievement and the technological and educational benefits of your work demonstrate that our national investment in fundamental science has been well placed.

The discovery of the Higgs boson has captured the imagination of the American public, and along with our fellow citizens, I look forward to your continued exploration of the sub-microscopic universe.

Sincerely,

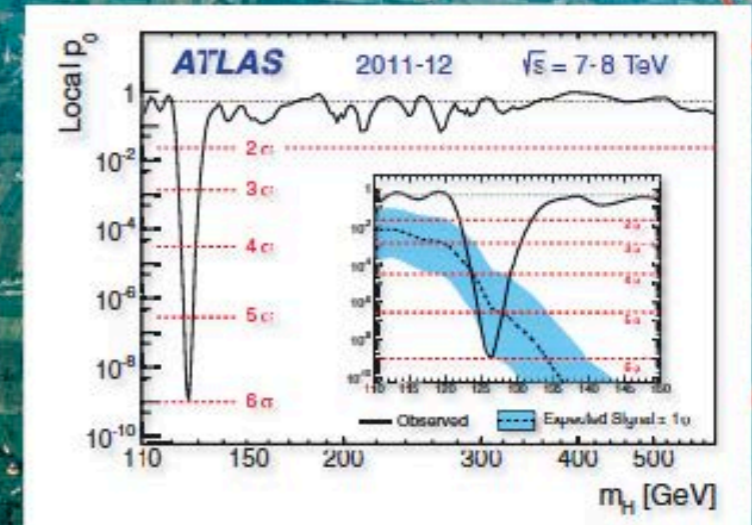
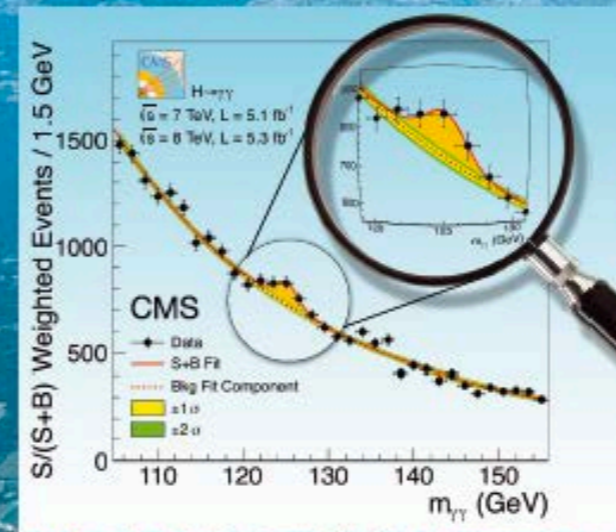


John P. Holdren  
Director, Office of Science and Technology Policy

cc: Professor Dan R. Marlow, Princeton University  
Professor Nicholas J. Hadley, University of Maryland



# First observations of a new particle in the search for the Standard Model Higgs boson at the LHC





# Science

21 December 2012 | \$9

BREAKTHROUGH  
of the YEAR  
The **HIGGS**  
**BOSON**

## Physicists Find Elusive Particle Seen as Key to Universe

### The New York Times



### The Economist

In praise of charter schools  
Britain's banking scandal spreads  
Volkswagen overtakes the rest  
A power struggle at the Vatican  
When Lonesome George met Nora

## A giant leap for science



Finding the Higgs boson

Chasing the Higgs Boson

INTRODUCTION

PROMISED FIREBALLS

GAME OF BUMPS

STILL MISSING

OOZING INTO VIEW

OPENING THE BOX

# Chasing the Higgs Boson

At the Large Hadron Collider near Geneva, two teams of scientists struggled to close in on physics' most elusive particle.

ENNIS OVERBYE

Published March 5, 2013 | 252 Comments



MEYRIN, Switzerland — Vivek Sharma missed his daughter.

iversity of  
Dr. Sharma  
at a time away  
ing a team of  
e Hadron  
side Geneva.  
Meera  
, he flew to



Illustration by Sean McCabe/Photographs by Daniel Auf der Mauer, Toni Albir, Fabrice Coffrini, Fred M... Peter Higgs, center, of the University of Edinburgh, was one of the first to propose the particle's existence. From left, physicists at CERN who helped lead the hunt for it: Sau Lan Wu, Joe Incandela, Guido Tonelli and Fabiola Gianotti.

The first time that the entire NYT Science section is devoted to a single story

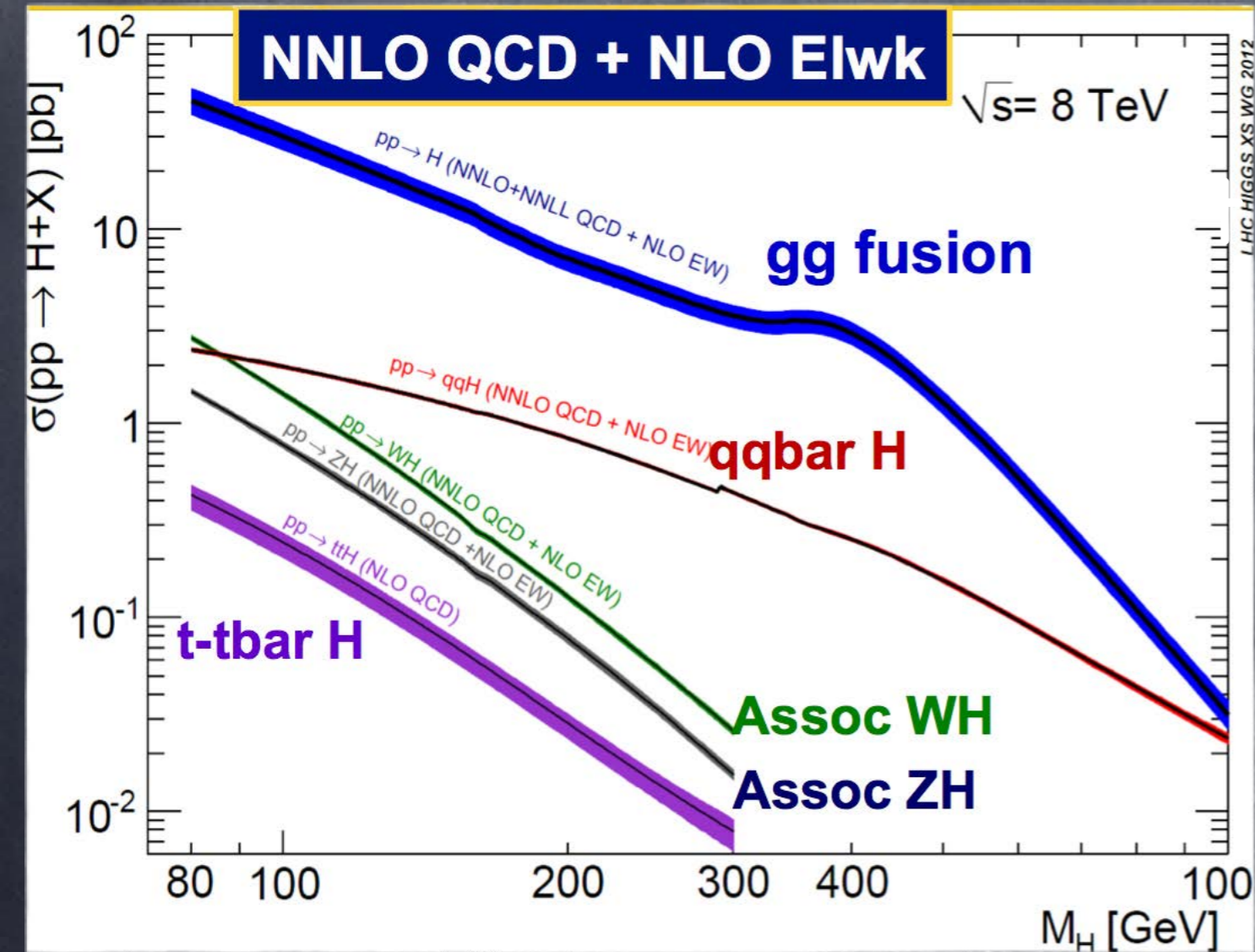
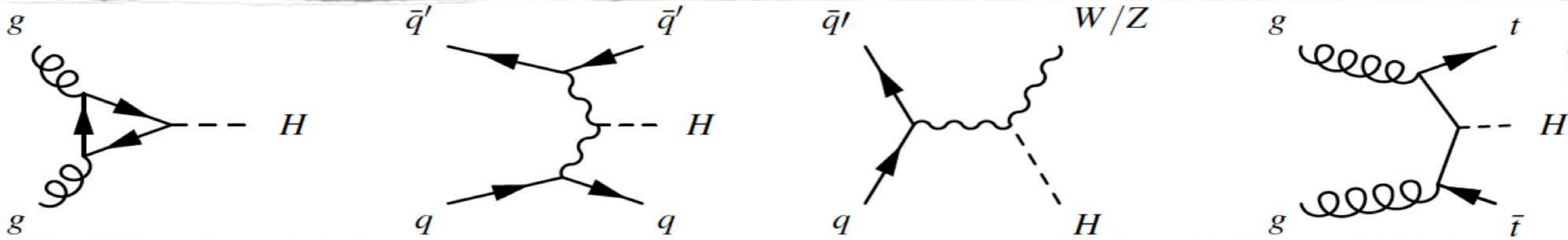
# TIME

Nº5  
PARTICLE  
PHYSICIST  
FABIOLA  
GIANOTTI





# Higgs production at the LHC 7-8 TeV pp collisions (8 TeV +25%)

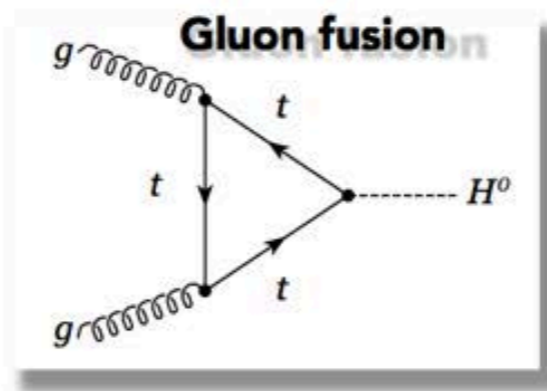


**Dominant production at 125 GeV**  
 $gg \rightarrow H$   
**subdominant but with larger S/B:**  
 VBF: ~13X Less  
 WH + ZH: ~18X Less  
 ttH ~150X Less

( $m_{\text{Higgs}} = 125.5 \text{ GeV @ } 8 \text{ TeV : } 21.84 \text{ pb}$ )

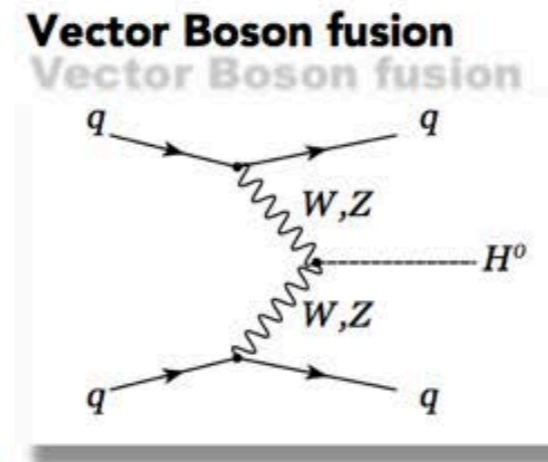
**Gluon Gluon fusion:**

- $gg \rightarrow H$
- 19 pb (87%)
- no specific topology



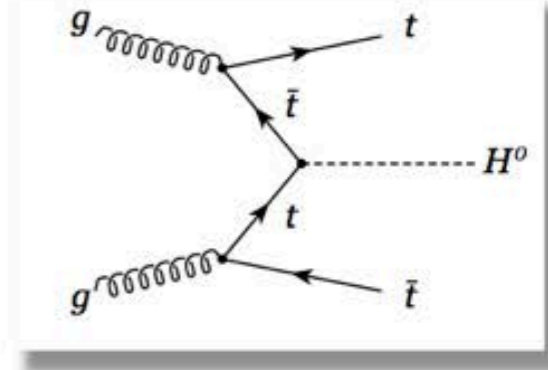
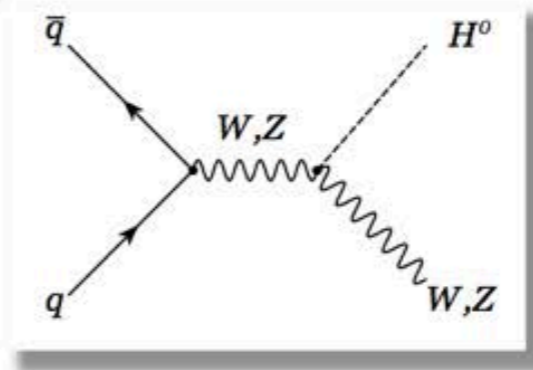
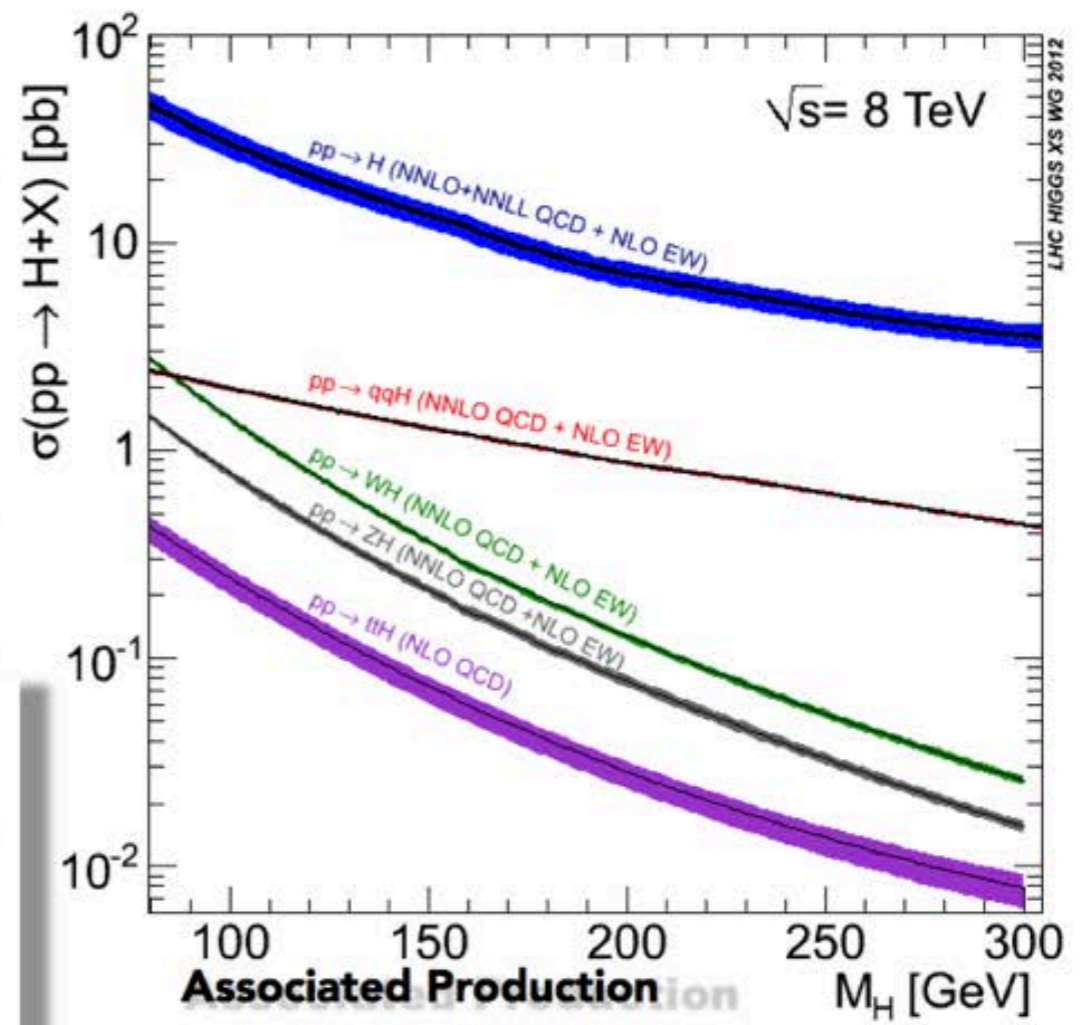
**Vector Boson fusion:**

- $qq \rightarrow qqH$
- 1.6 pb (7.3%)
- specific jet topology



**Associated Production:**

- $qq \rightarrow WH, ZH, ttH$
- 0.70/0.41/0.13 pb (5.7%)



Typical uncertainties on total cross-sections

|        |         |                      |
|--------|---------|----------------------|
| gg     | 15-20 % | NNLO + NNLL + NLO EW |
| VBF    | 5 %     | NNLO + NLO EW        |
| WH, ZH | 5 %     | NNLO + NLO EW        |
| ttH    | 15 %    | NNLO                 |

For a detailed description and a complete set of references see CERN Yellow Reports I, II and III ([arXiv:1101.0593](https://arxiv.org/abs/1101.0593), [arXiv:1201.3084](https://arxiv.org/abs/1201.3084) and [arXiv:1307.1347](https://arxiv.org/abs/1307.1347)) <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections>

**H → bb:**

- BR(H → bb) : 56.9%
- with associated production, large BR, Yukawa coupling

**H → WW(\*) → lνlν**

- BR(H → WW) : 22.3%
- large BR, gauge boson coupling

**H → γγ**

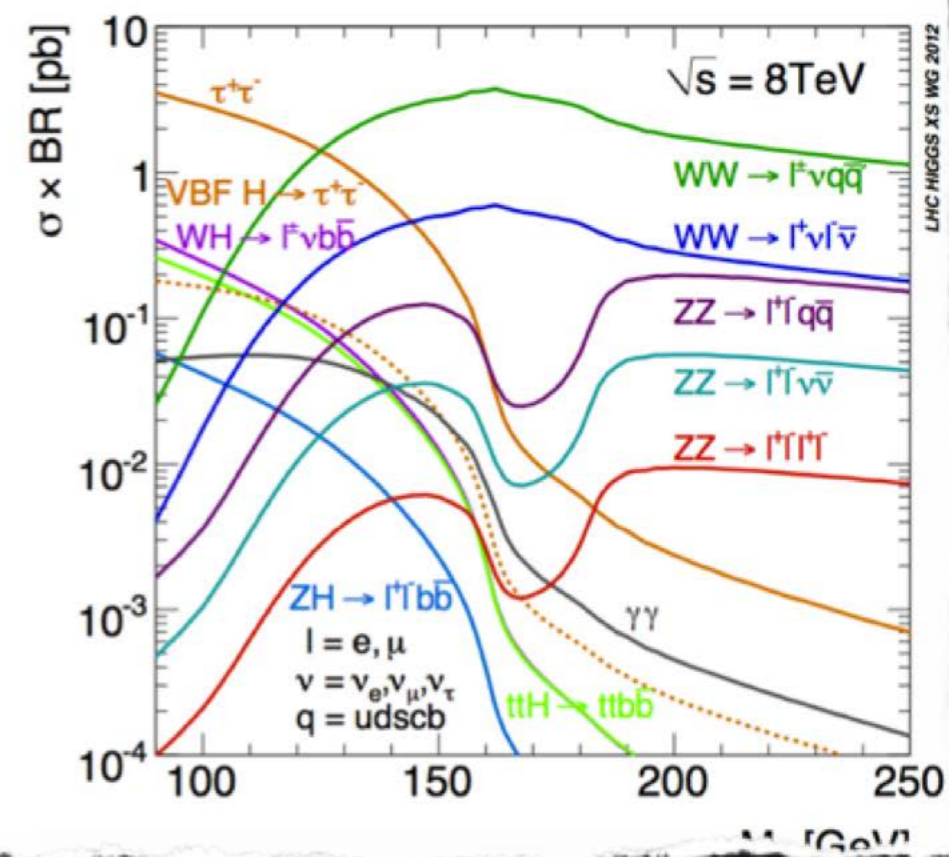
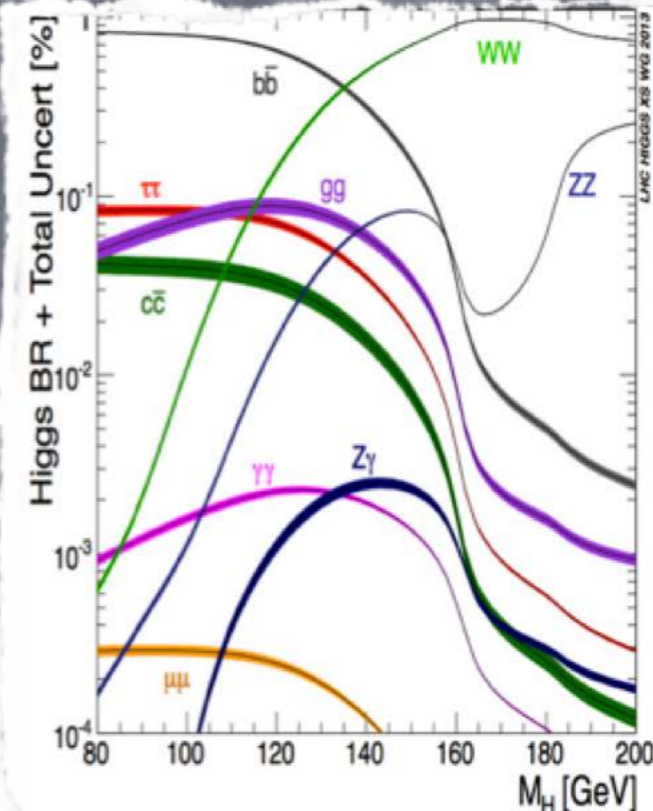
- BR(H → γγ) : 0.24%
- high mass resolution, loop coupling

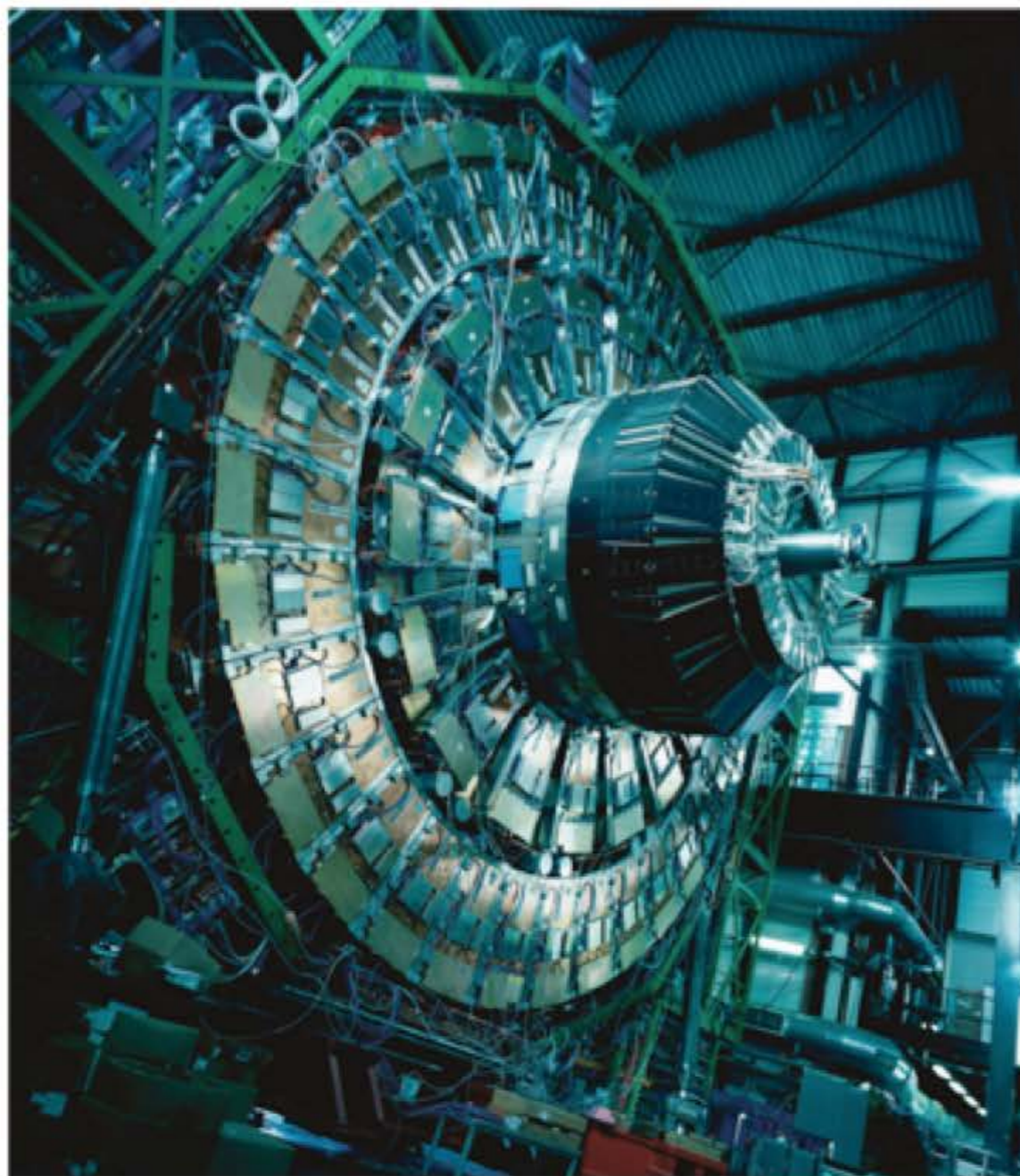
**H → ZZ(\*) → ll**

- BR(H → ZZ(\*) → ll) : ~0.2%
- BR(H → ZZ) : 2.8%
- high mass resolution, gauge boson coupling

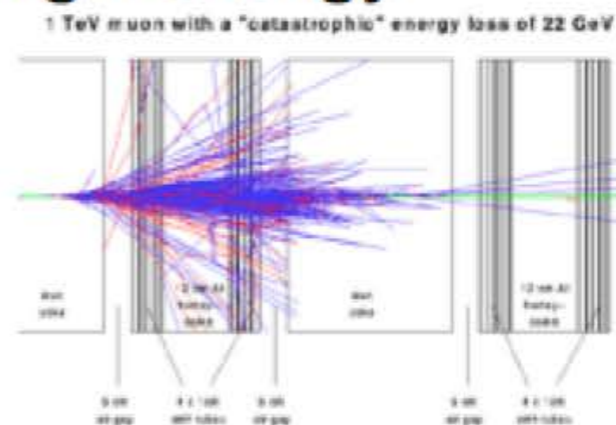
**H → ττ**

- BR(H → ττ) : 6.2% - Yukawa coupling



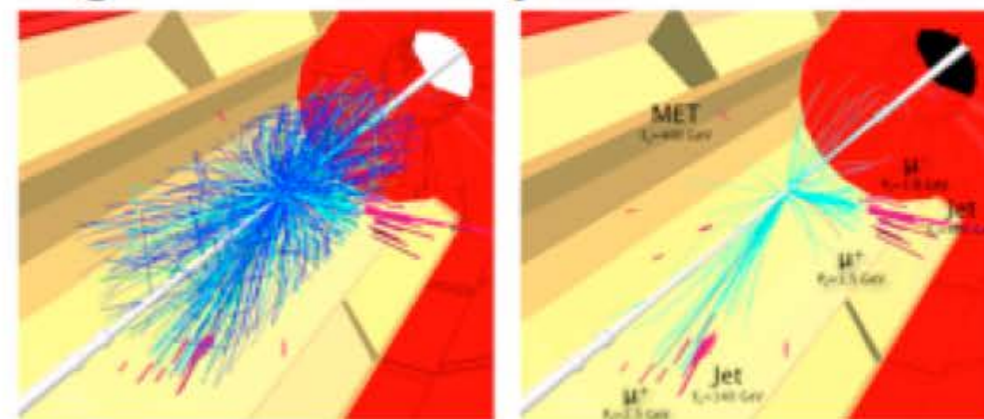


- high energy But not as high as specs



much higher than specs

- high luminosity




- high data rates (**trigger, GRID**)

we can tinker with this

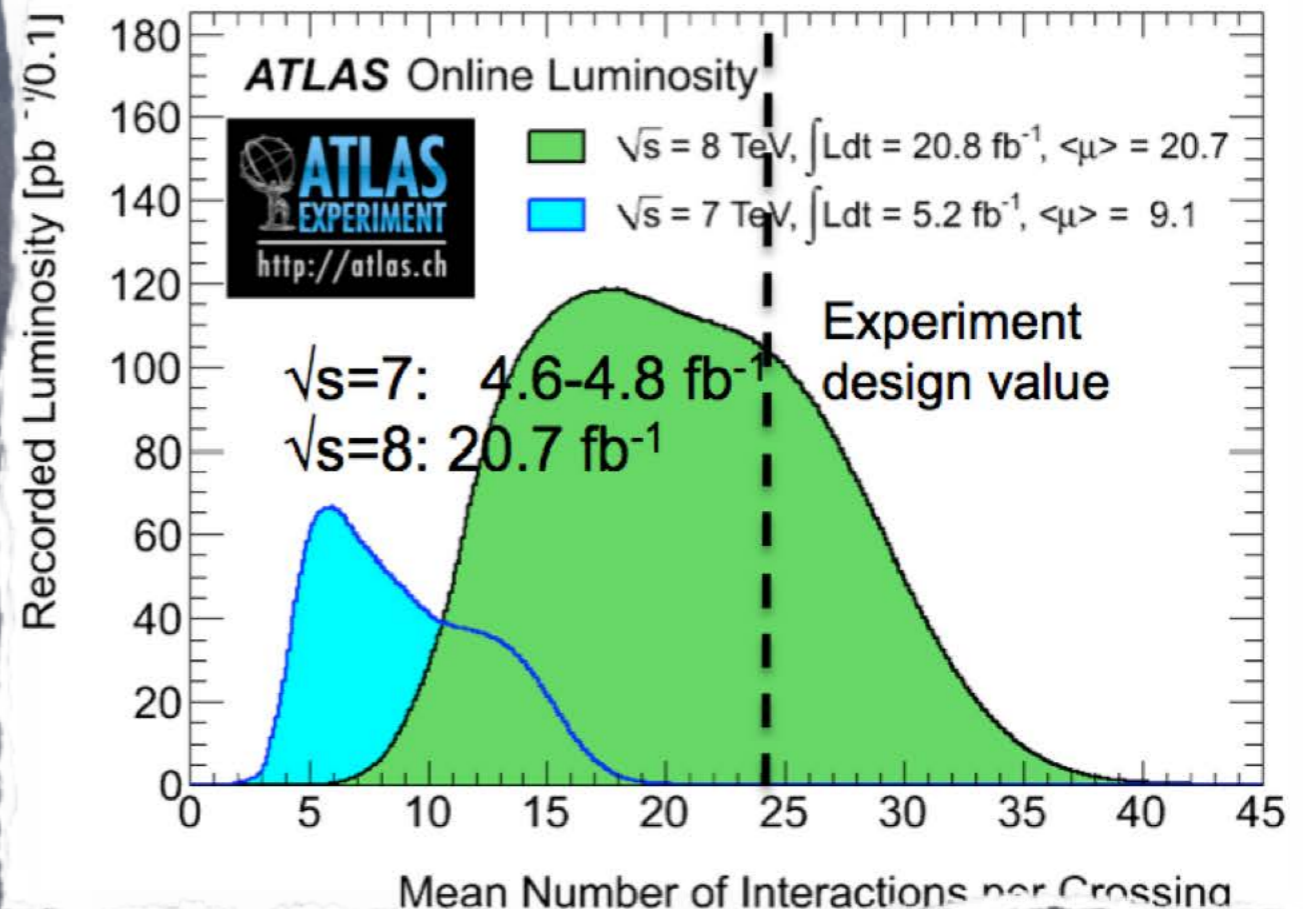
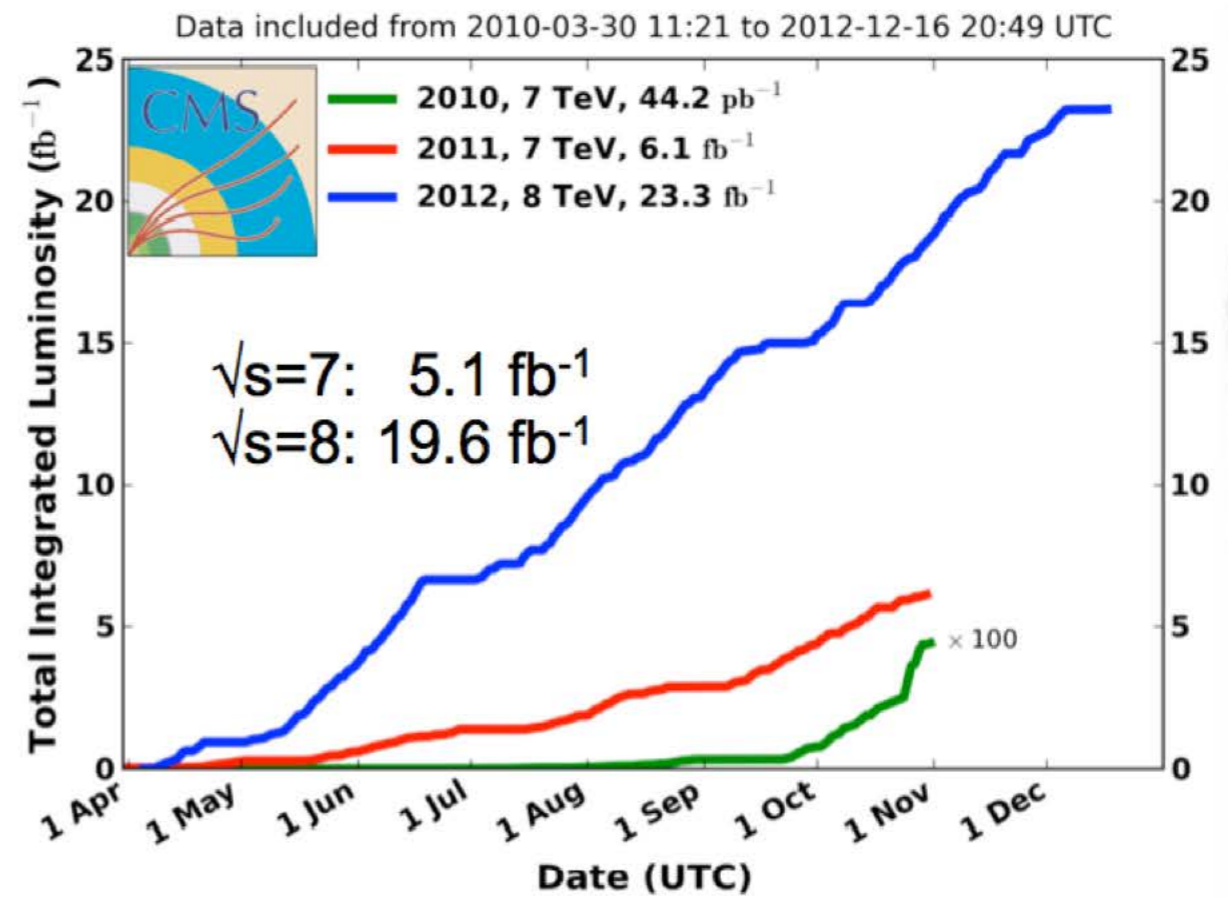
- ...not a walk in the park

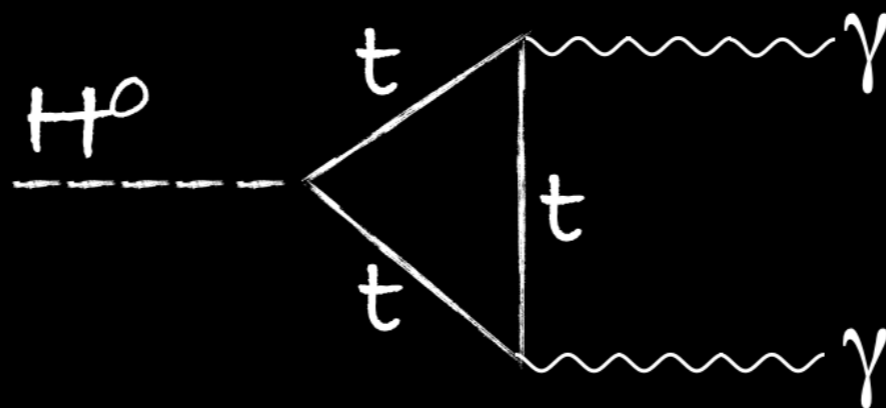
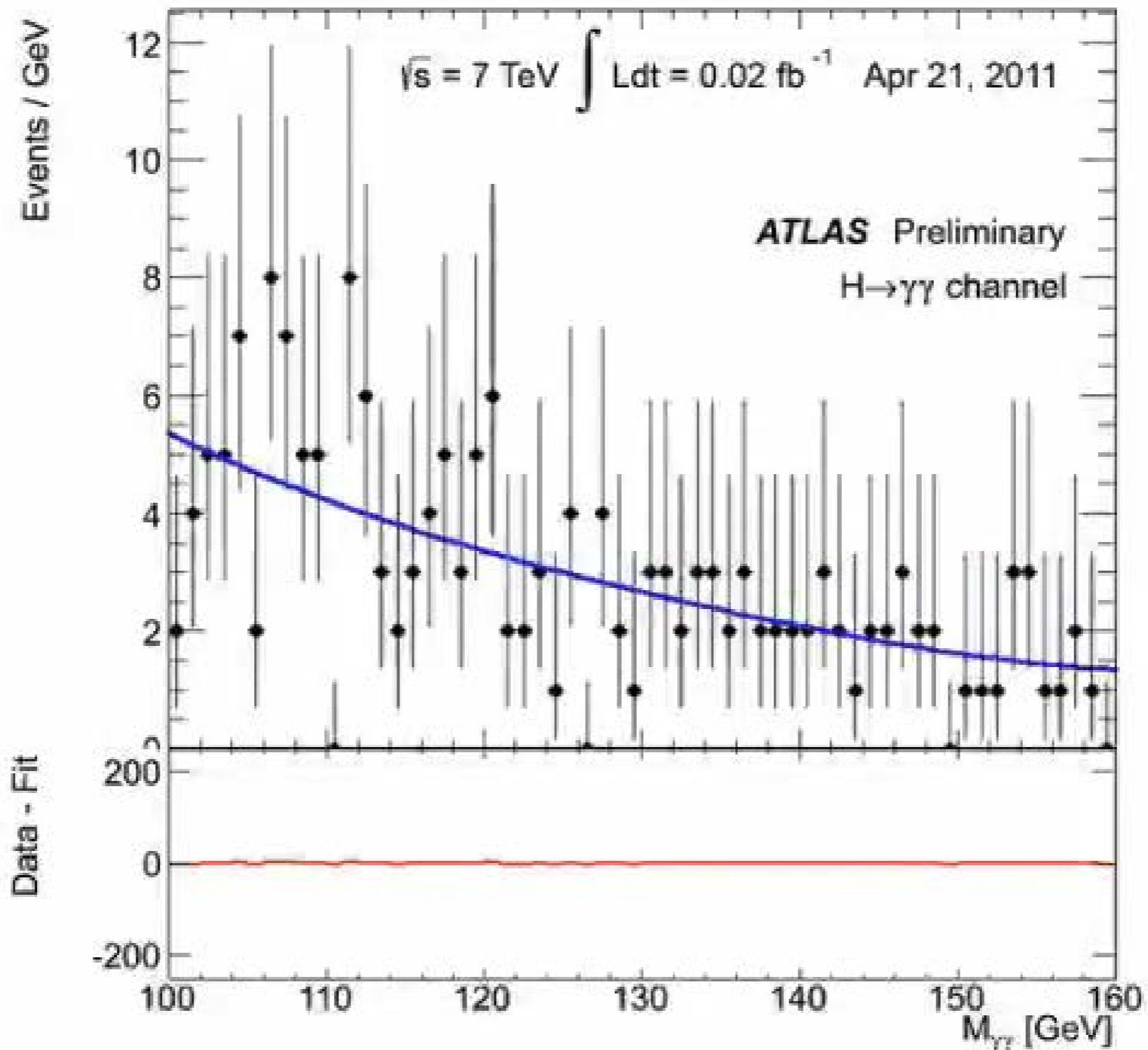
LHC performance ✓  
 ATLAS, CMS ✓  
 data efficiency ✓

2011 (7 TeV)  $\Rightarrow$  5/fb  
 2012 (8 TeV)  $\Rightarrow$  20/fb

pileup   
 challenging everything  
 (trigger, compu, reco, id,  
 fakes &tc)

CMS Integrated Luminosity, pp





$$m_{\gamma\gamma}^2 = 2E_{\gamma_1}E_{\gamma_2}(1 - \cos\theta_{12})$$

### primary vertex

- **BDT** using  $\sum p_T^2$ , vertex recoil wrt di-photon system, pointing from converted photons
- check with **Z**→**μμ** (unconverted) and **γ+jet** (converted)

energy calibration:

- energy **regression correction** using **BDT**

(energy density, shower shapes, cluster position) - monitor with **Z**→**ee**

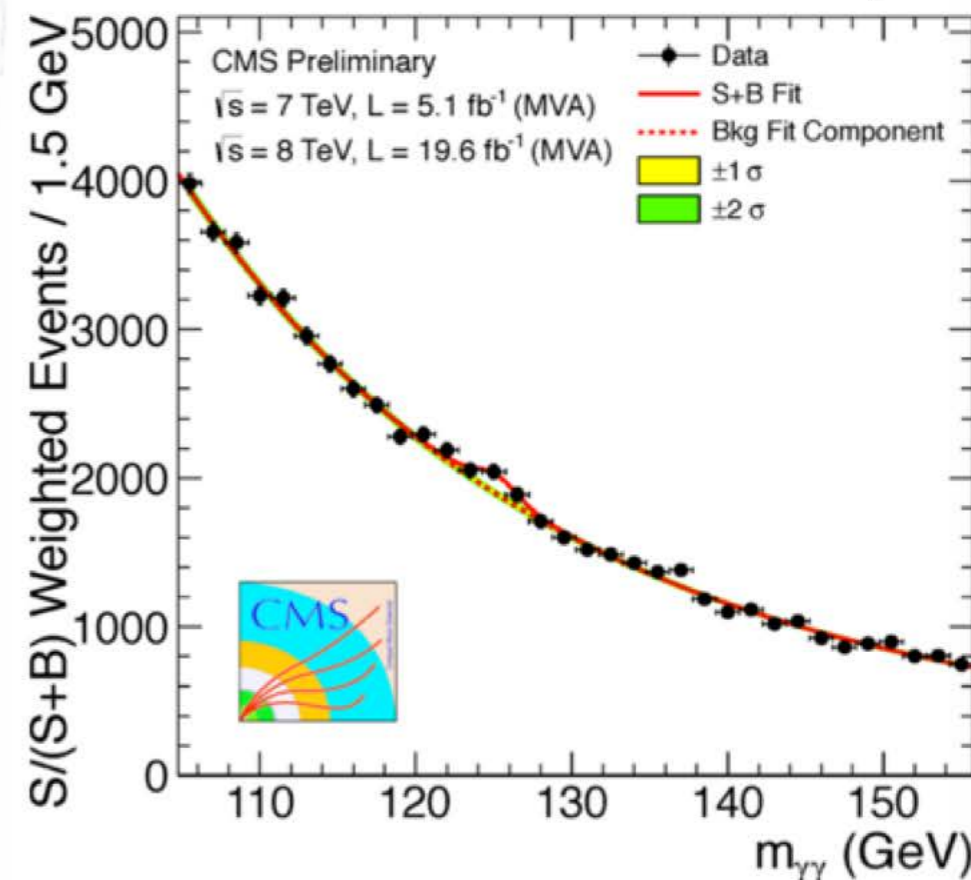
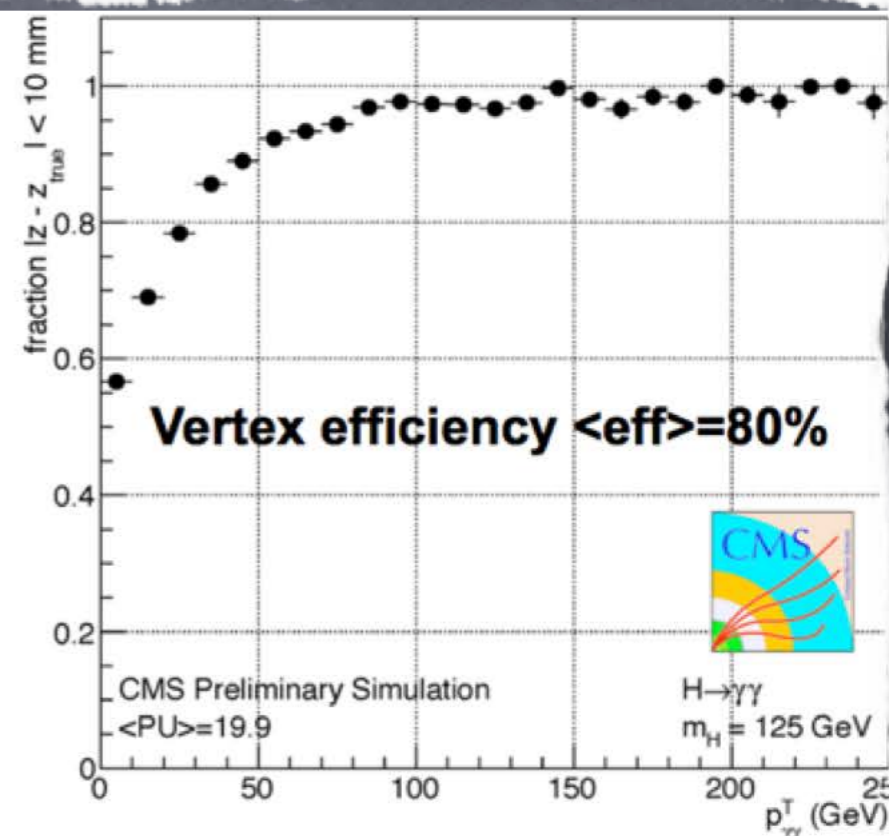
- systematic uncertainties (0.47%) :

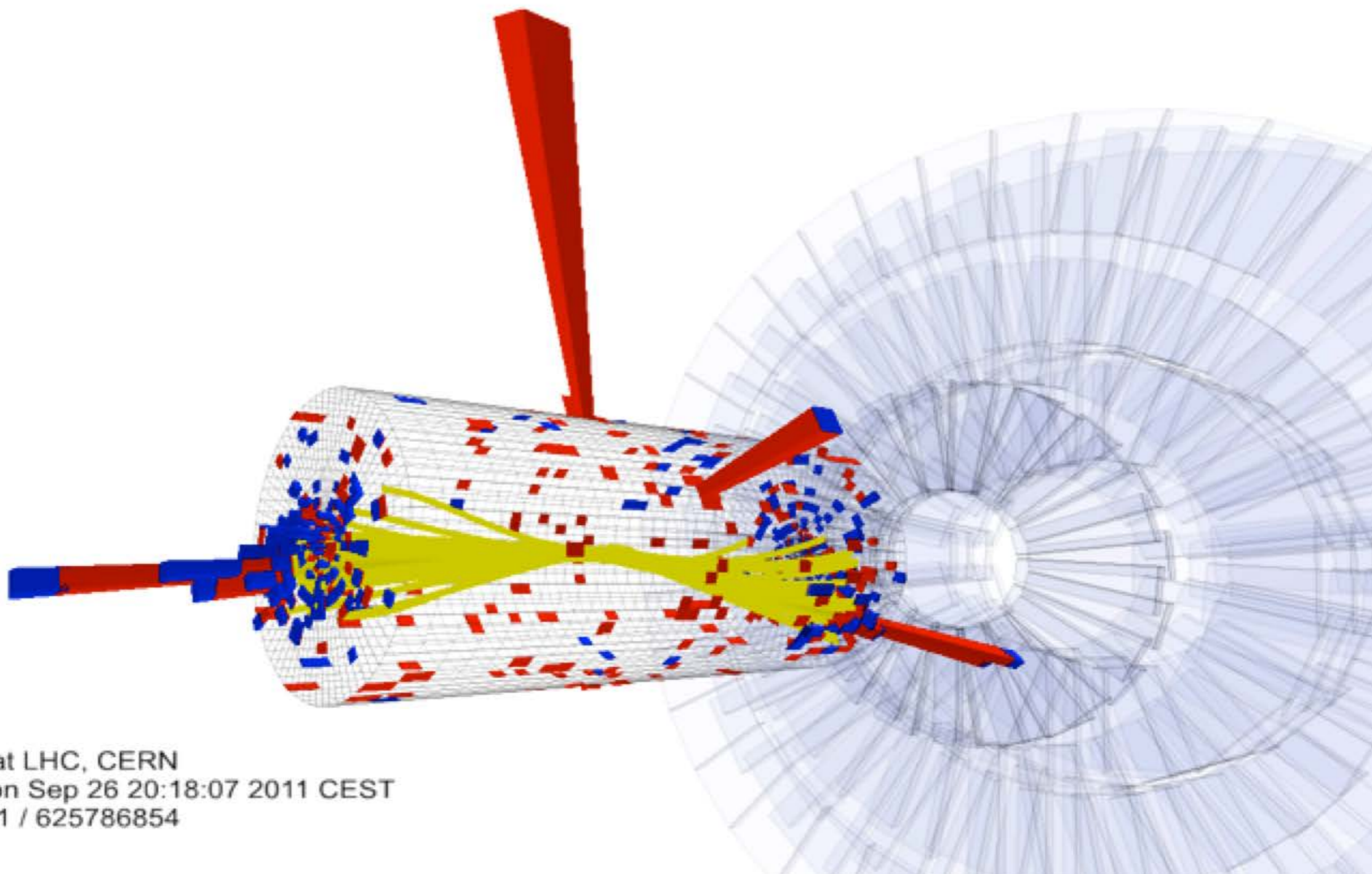
| source                                  | systematic uncertainties |
|---|--------------------------|
| non linearity when extrapolating from Z | ± 0.4%                   |
| upstream material simulation            | ± 0.25%                  |

mass measurement

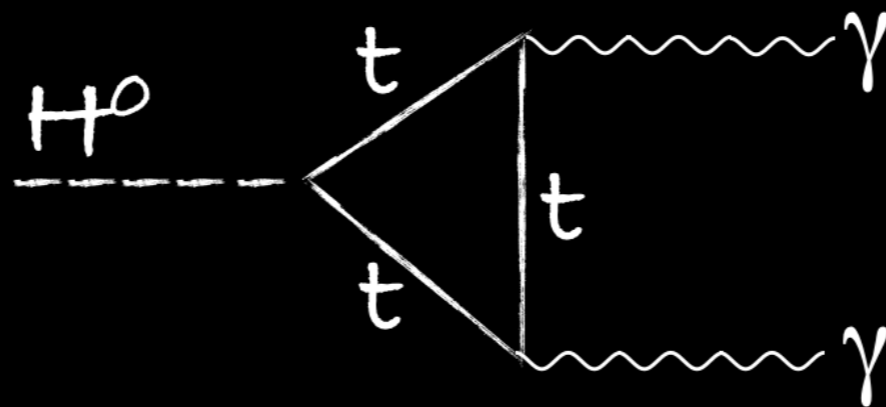
**fit** with both signal position and normalization free

$$m_{\text{Higgs}} = 125.4 \pm 0.5 \text{ (stat.)} \pm 0.6 \text{ (syst.) GeV}$$

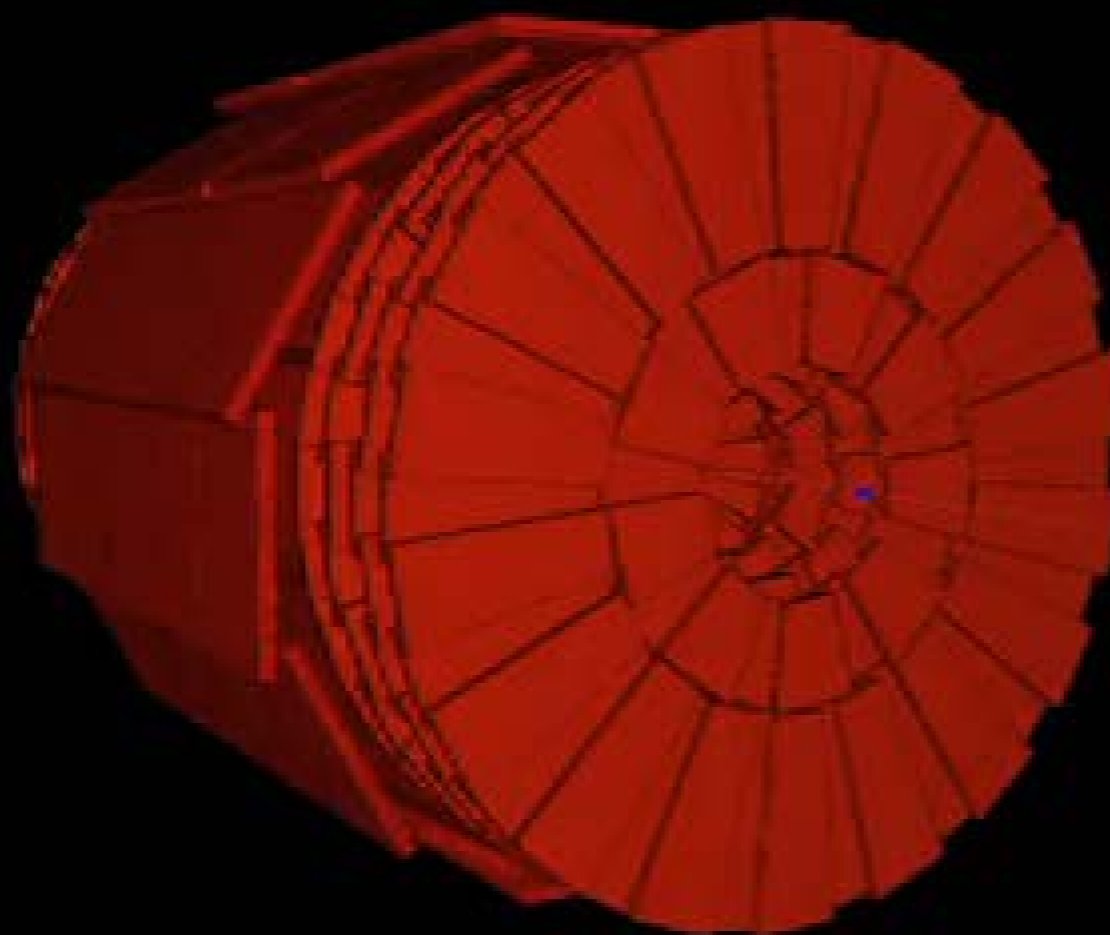
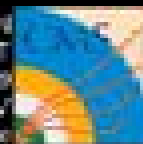




CMS Experiment at LHC, CERN  
Data recorded: Mon Sep 26 20:18:07 2011 CEST  
Run/Event: 177201 / 625786854  
Lumi section: 450



CMS Experiment at the LHC, CERN  
Sat 2011-Apr-23 06:06:17 CET  
Run 143346 Event 27907479  
C.D.M. Energy 7.007eV  
H $\rightarrow$ GammaGamma candidate



$$m_{\gamma\gamma}^2 = 2E_{\gamma_1}E_{\gamma_2}(1 - \cos \theta_{12})$$

primary vertex

**likelihood discriminant** combining calorimeter pointing, photon conversion, track recoil

energy calibration

- from **Z** → **ee** data and **extrapolation e** → **γ**
- require **excellent material budget** knowledge - **check** with **Z** → **llγ** events
- very good **stability** with **pile-up**

systematic uncertainties (0.55%)

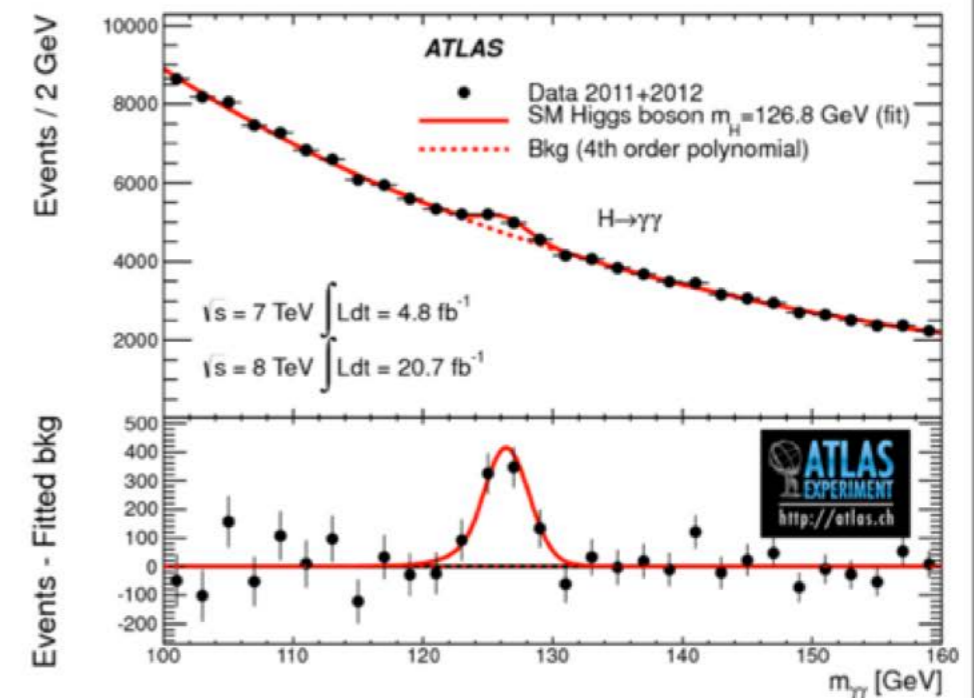
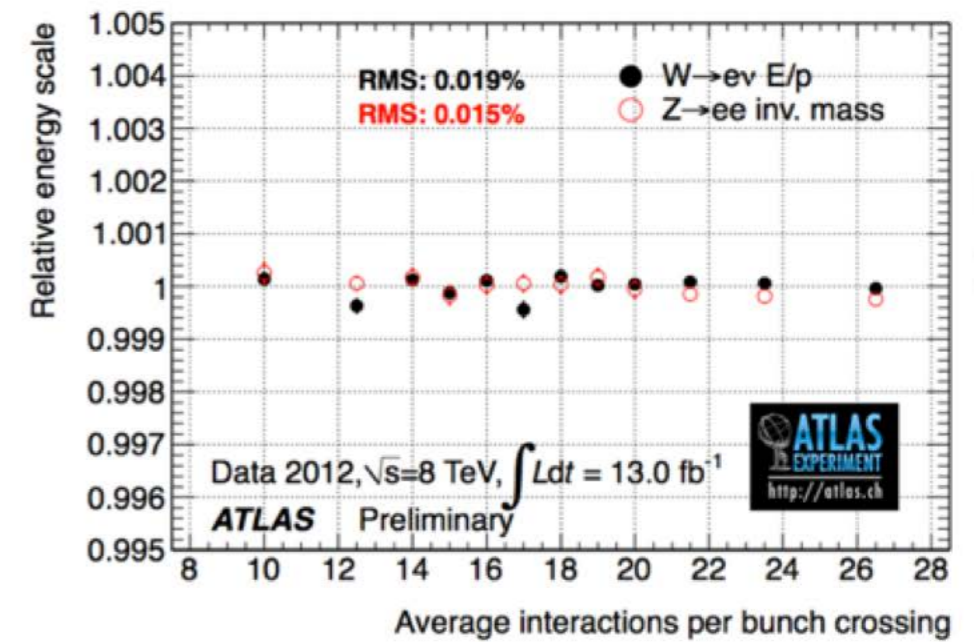
| source                                  | systematic uncertainties |
|---|--------------------------|
| absolute energy scale (Z→ee)            | ± 0.3%                   |
| upstream material simulation accuracies | ± 0.3%                   |
| presampler energy scale                 | ± 0.1 %                  |
| additional                              | ± 0.32 %                 |

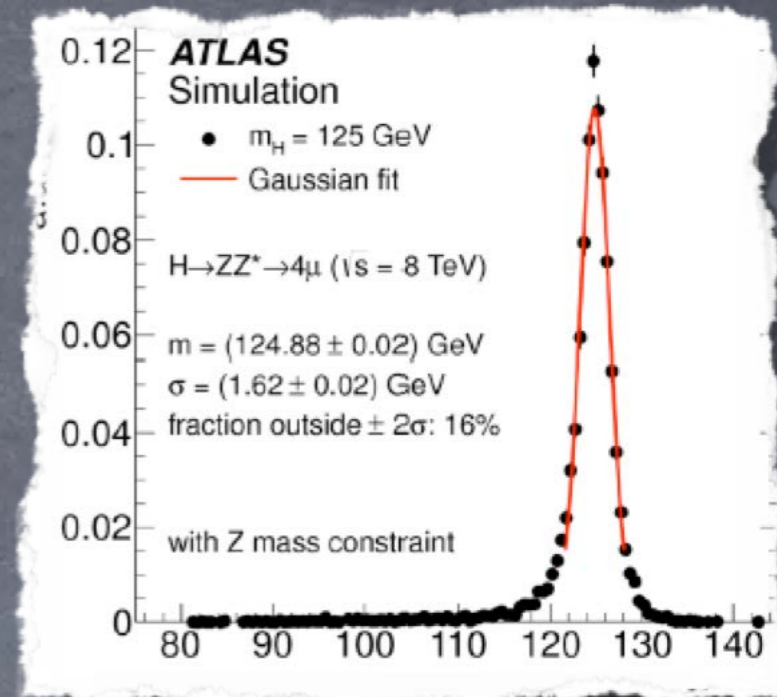
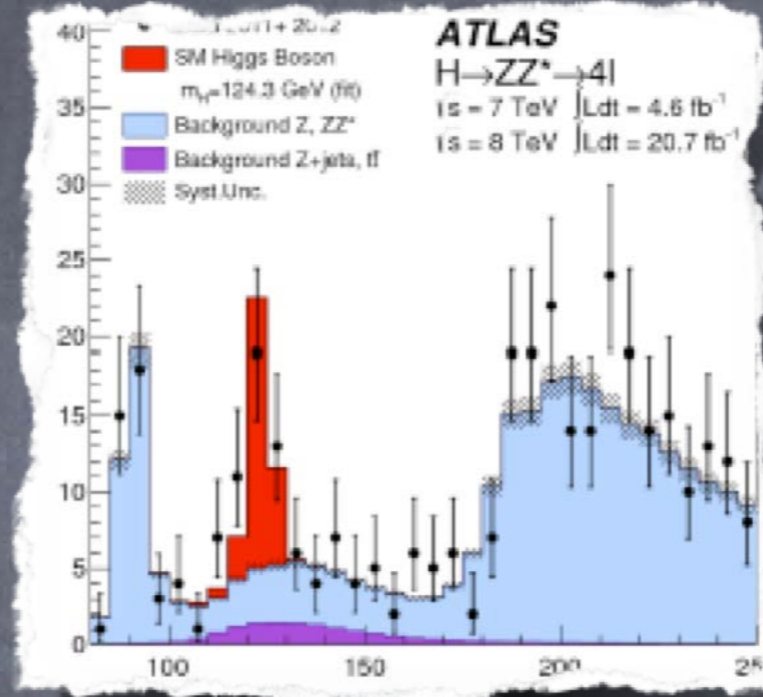
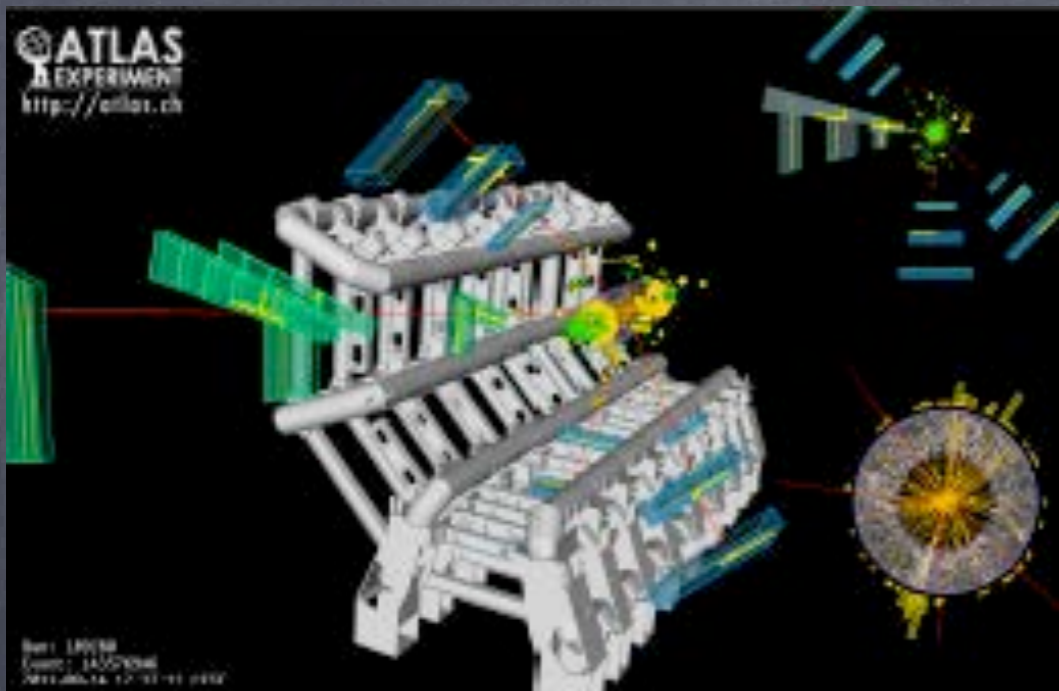
mass measurement:

fit with both signal position and normalization free

$$m_{\text{Higgs}} = 126.8 \pm 0.2 \text{ (stat.)} \pm 0.7 \text{ (syst.) GeV}$$

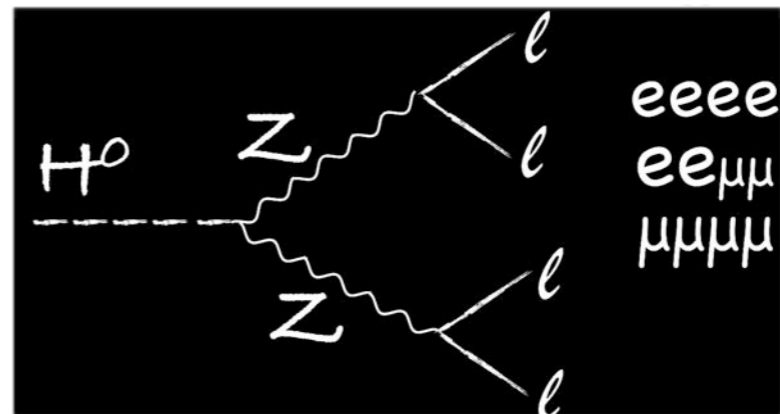
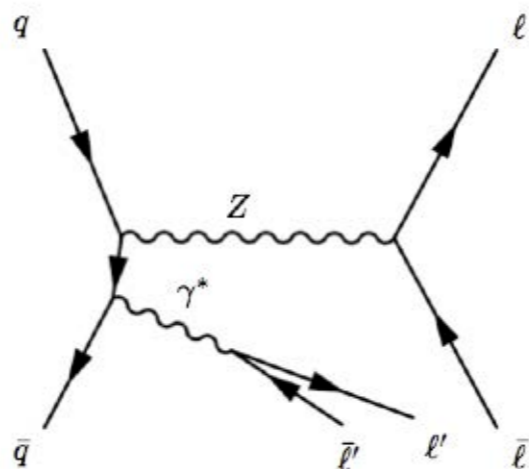
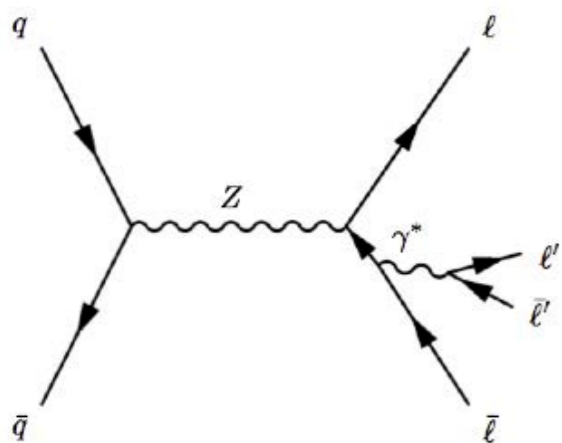
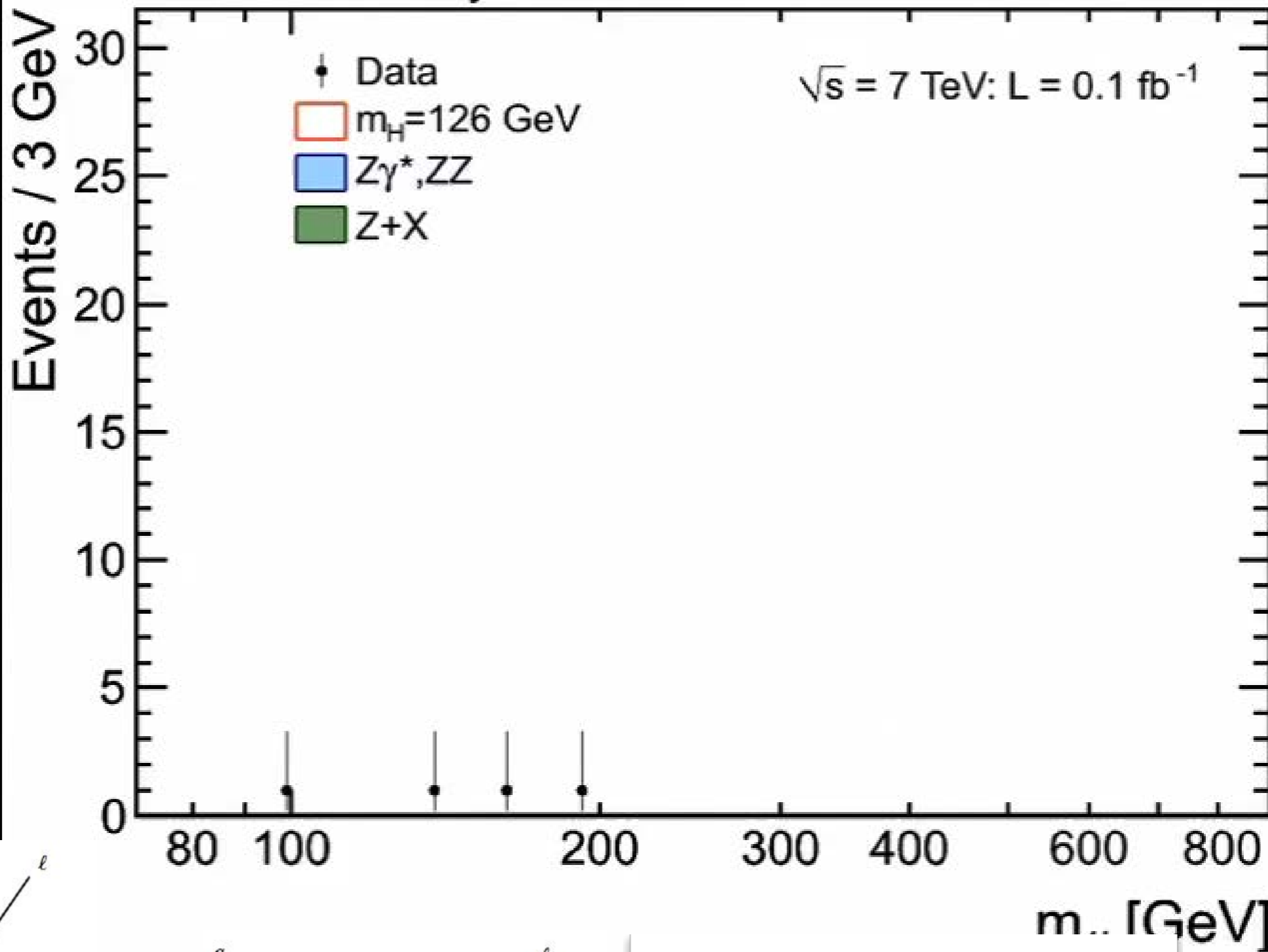
### Stability of EM calorimeter response vs time (and pile-up) <0.1%



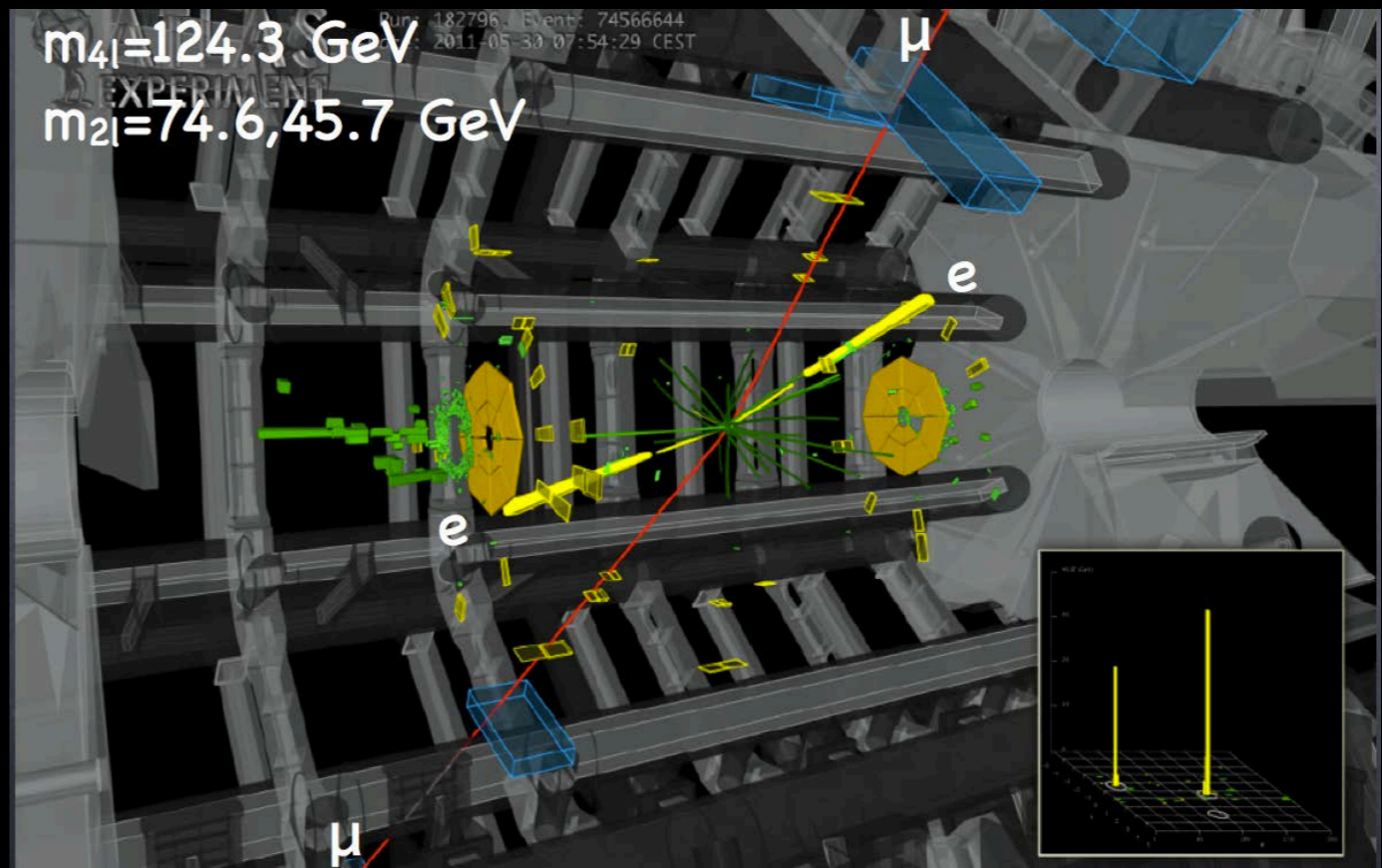
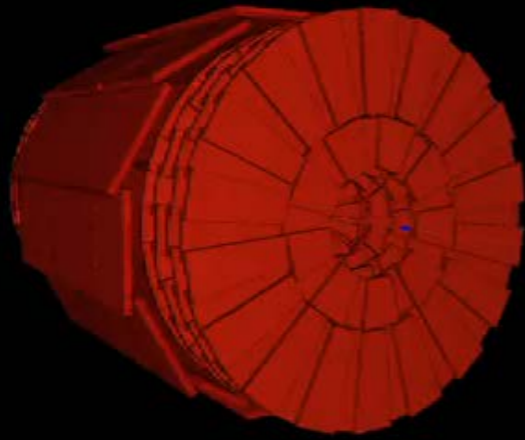


- clean, closed, fully reconstructed mass ✓
- high resolution ✓
- 4e, 2e2μ, 2μ2e and 4μ, use Z-candle mass ✓
- low signal rates ✗
- low background rates ✓
- ZZ\* continuum irreducible ✓
  - well understood, handles from data and MC
- low mass Zbb/jets, tt, reducible ✓
  - many handles from data and MC

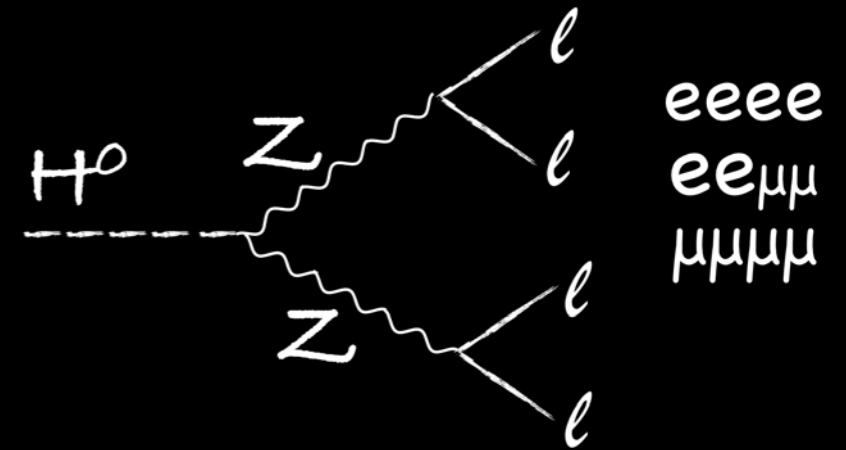
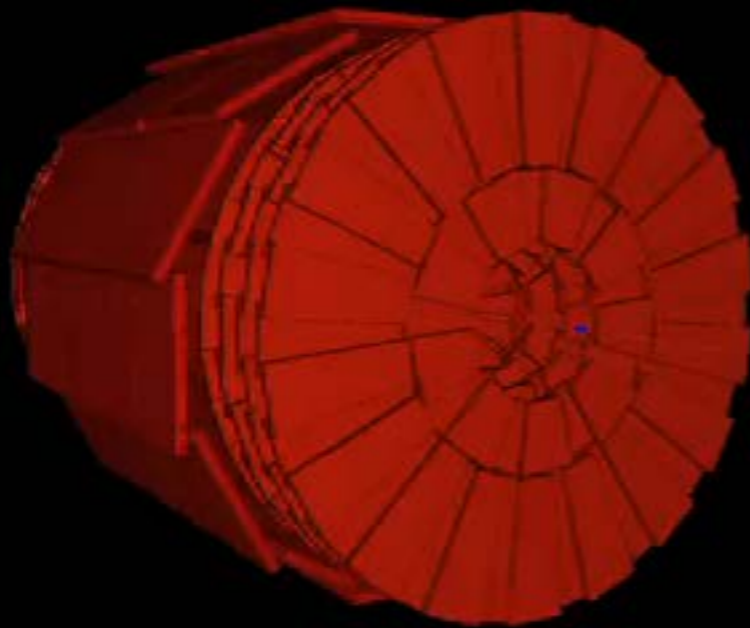
CMS Preliminary



CMS Experiment at the LHC, CERN  
 Sat 2011-05-29 08:56:28 CEST  
 Run 172822 Event 2054339903  
 C.D.M. Energy: 7.00 TeV  
 H<sub>ZZ</sub>-le candidate



CMS Experiment at the LHC, CERN  
 Sat 2011-06-25 08:34:20 CEST  
 Run 187673 Event 879650967  
 C.D.M. Energy: 7.00 TeV  
 H<sub>ZZ</sub>-le candidate



Excellent energy/momentum scale and resolution  
 - **validation** with **Z**, **Y** and **J/ψ** ( $\rightarrow 2l$ )  
 - single-resonant **Z**  $\rightarrow 4l$  for **validation**

Systematic uncertainties :

| source                           | systematic uncertainties                            |
|----------------------------------|---|
| muon momentum scale uncertainty% | $\pm 0.2\%$ ( $4\mu$ )<br>$\pm 0.1\%$ ( $2\mu 2e$ ) |
| electron energy uncertainty%     | $\pm 0.4\%$ ( $4e$ )<br>$\pm 0.2\%$ ( $2e 2\mu$ )   |

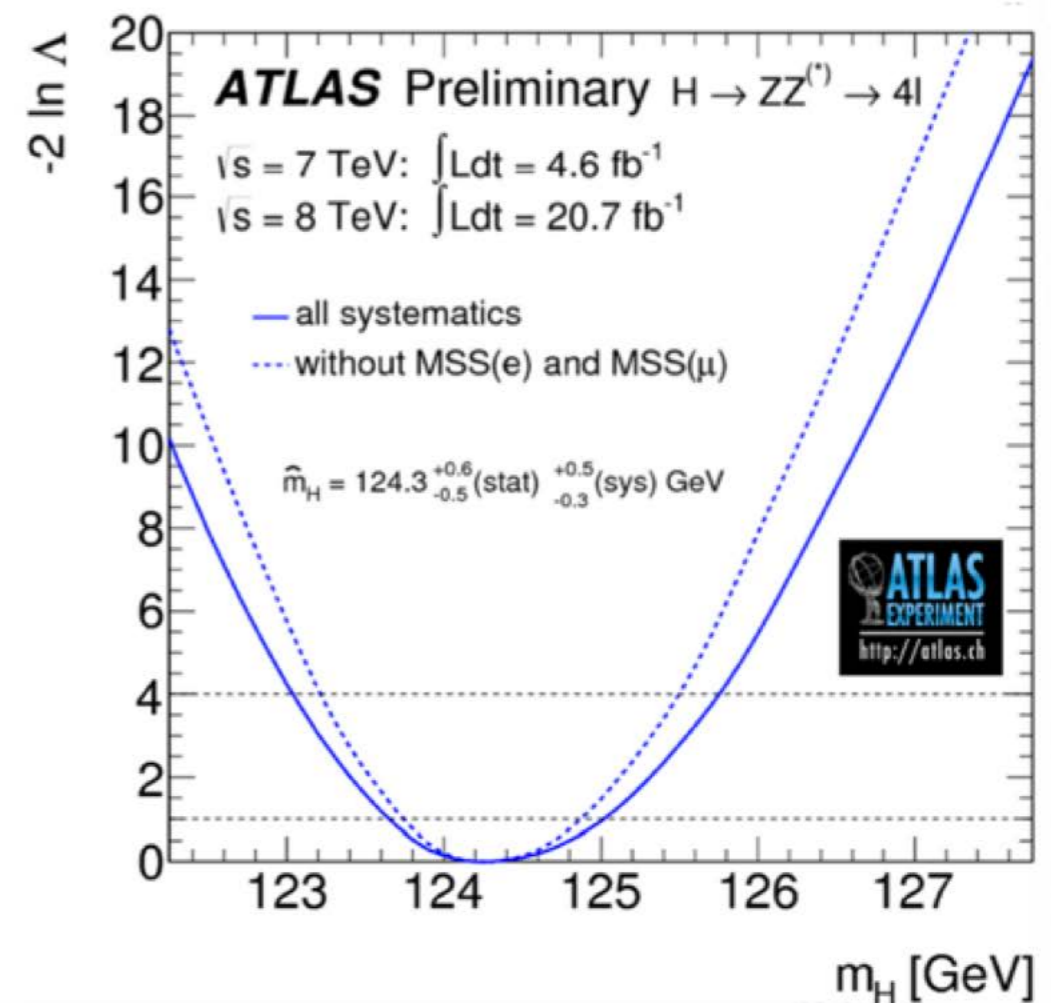
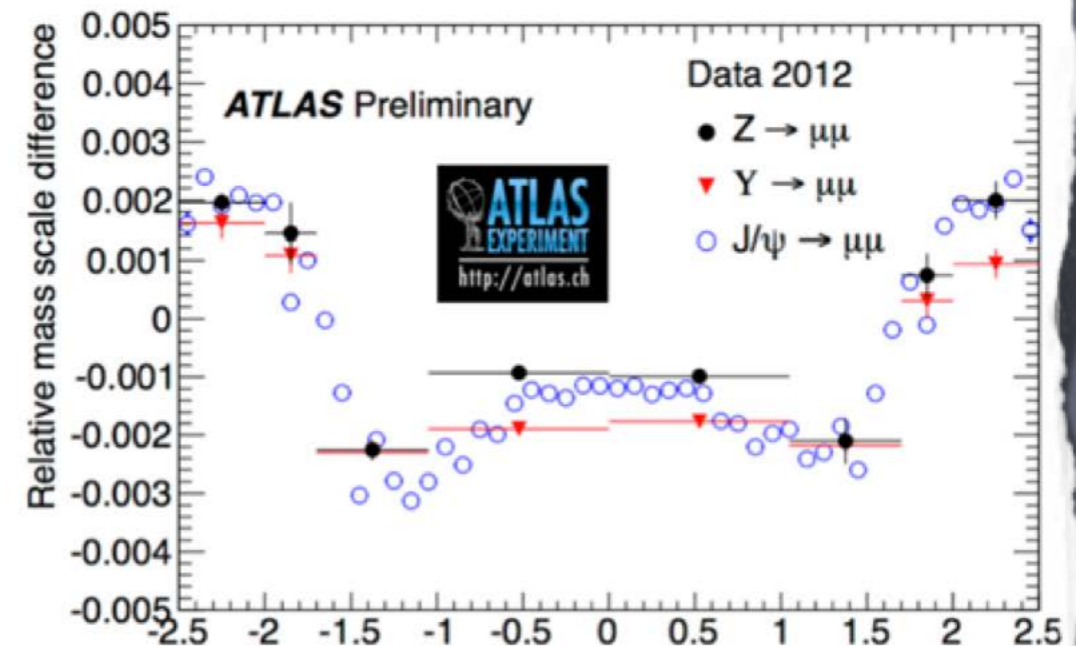
Low statistic, in region  $m_{4l}$  [120-130] GeV

**32** events **observed**

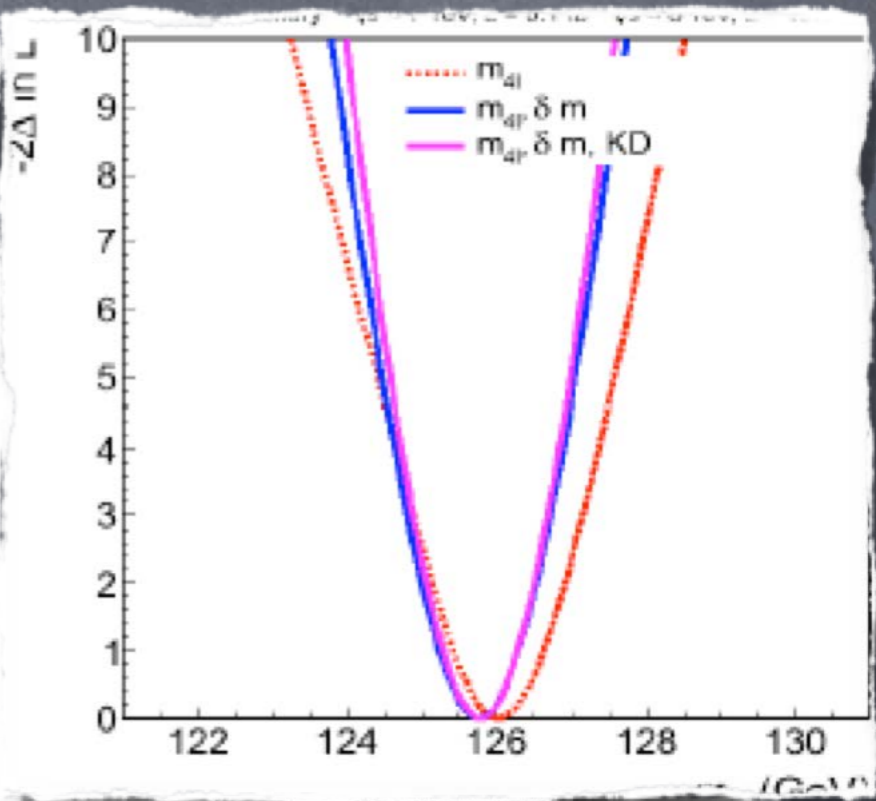
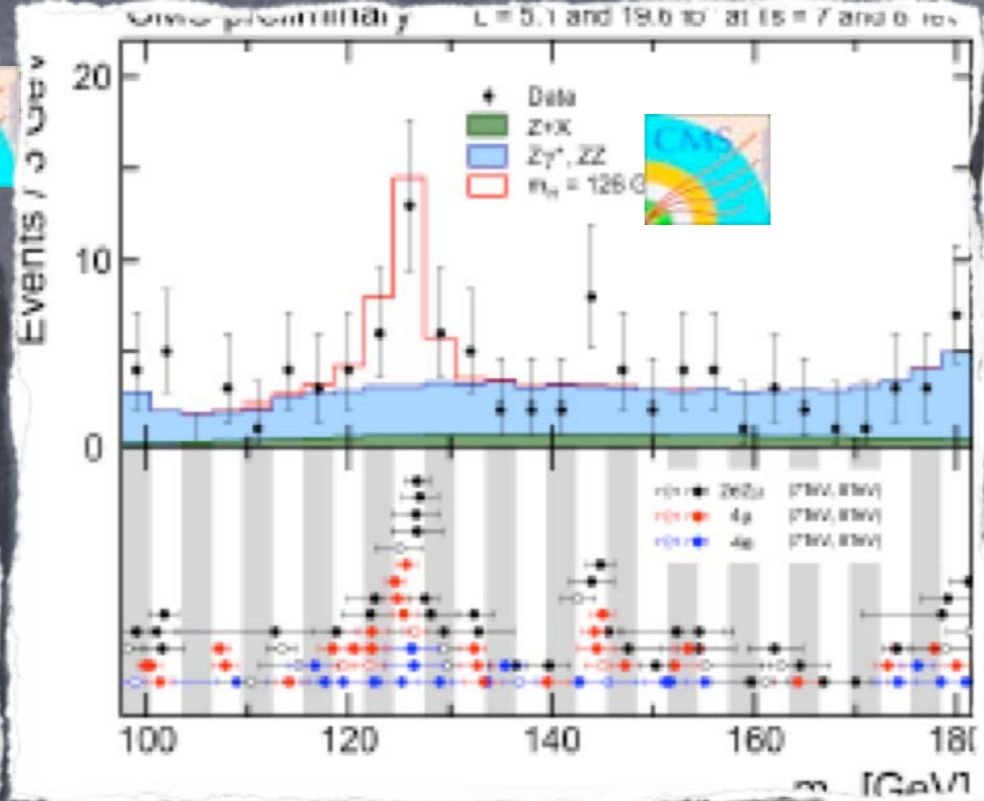
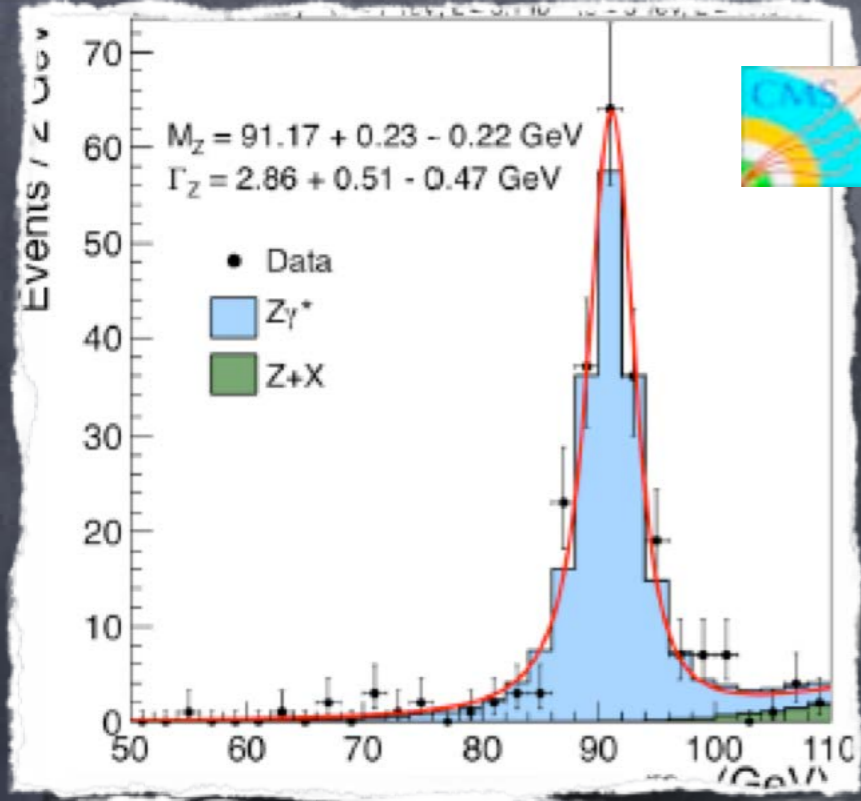
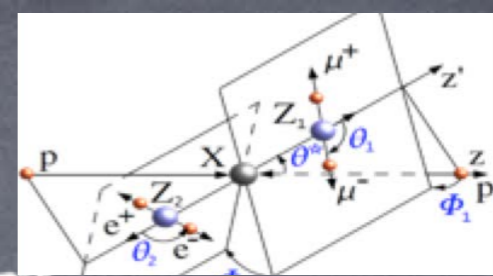
$11.1 \pm 1.3$  background predicted

$15.9 \pm 2.1$  signal predicted

$$m_{\text{Higgs}} = 123.4 \pm {}^{+0.6}_{-0.5} (\text{stat.}) \pm {}^{+0.5}_{-0.3} (\text{syst.}) \text{ GeV}$$

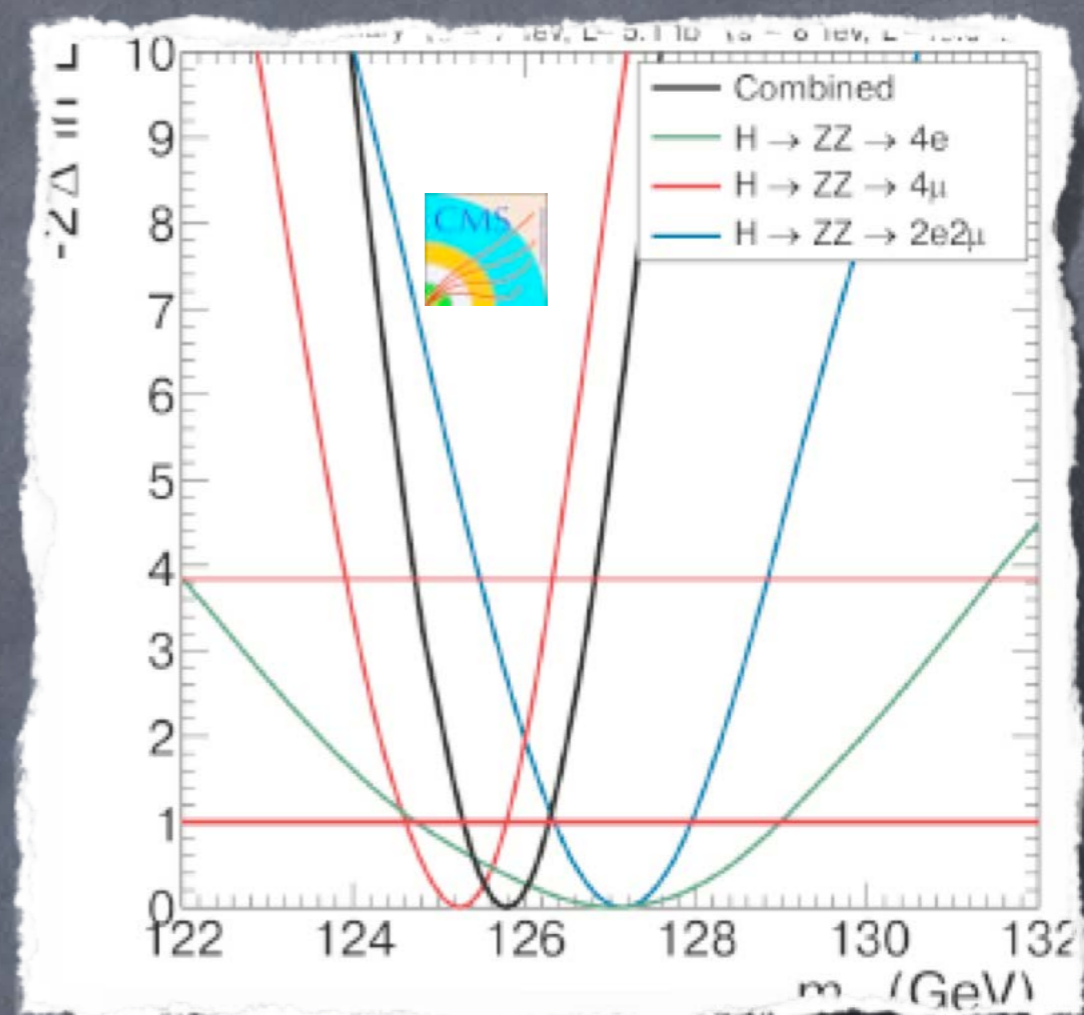
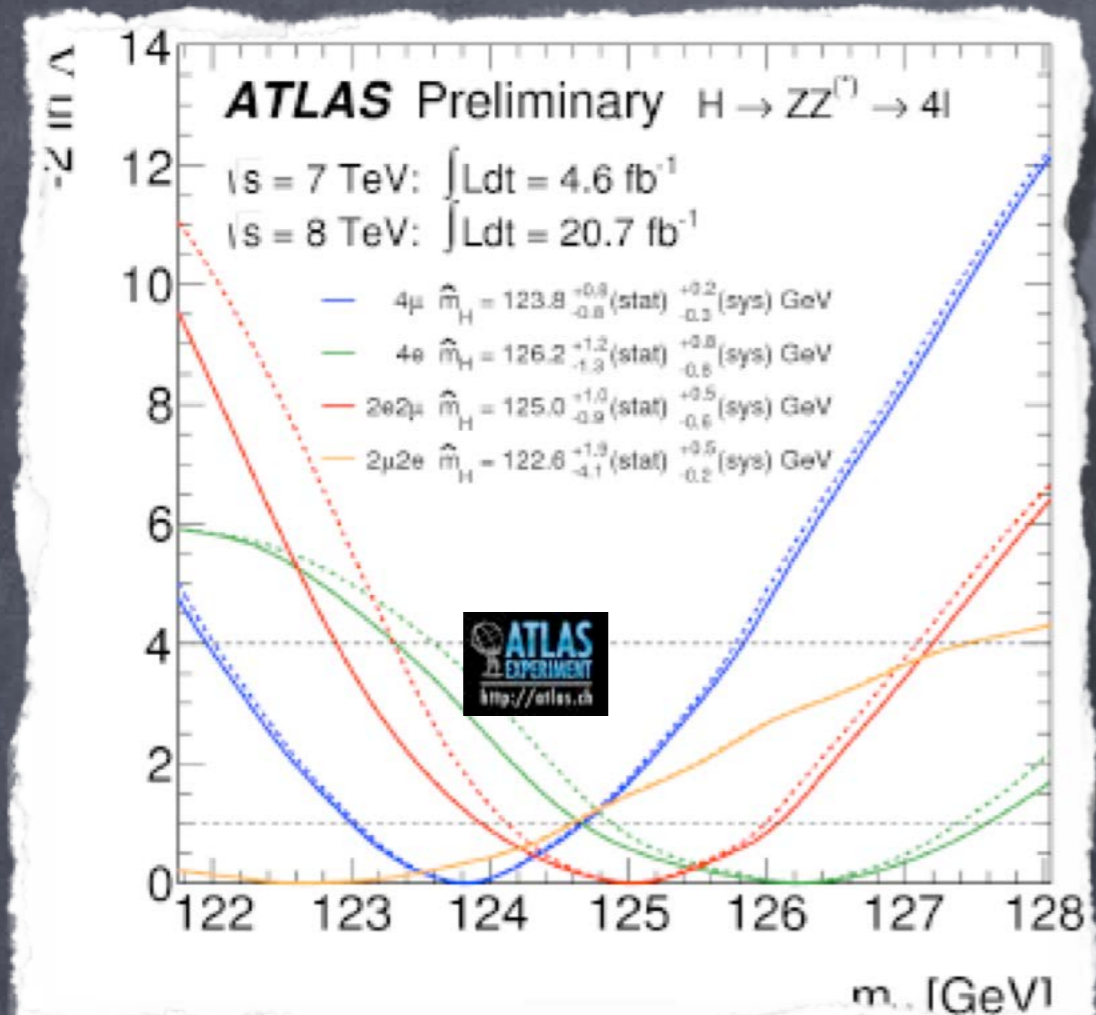


$$KD = \frac{\mathcal{P}_{\text{sig}}}{\mathcal{P}_{\text{sig}} + c \times \mathcal{P}_{\text{bkg}}} = \left[ 1 + \frac{c \times \mathcal{P}_{\text{bkg}}(m_1, m_2, \vec{\Omega} | m_{4\ell})}{\mathcal{P}_{\text{sig}}(m_1, m_2, \vec{\Omega} | m_{4\ell})} \right]^{-1}$$



ditto+

- kinematic discriminant (KDME), S/B optimization ✓
- even-by-event mass uncertainties ✓ weight individual events in the mass fit according to their mass uncertainties  $\delta m_{4l}$
- expected improvement of 8% on the mass uncertainty ✓
- [120.5-130.5] observed 25, expected 18.6 signal, 9.4 background



$$m_H^{\text{ATLAS}} = 123.4^{+0.6}_{-0.5} \text{ (stat.) } ^{+0.5}_{-0.3} \text{ (syst.) GeV}$$

high  $p_T$  cuts, tight Z mass constraints

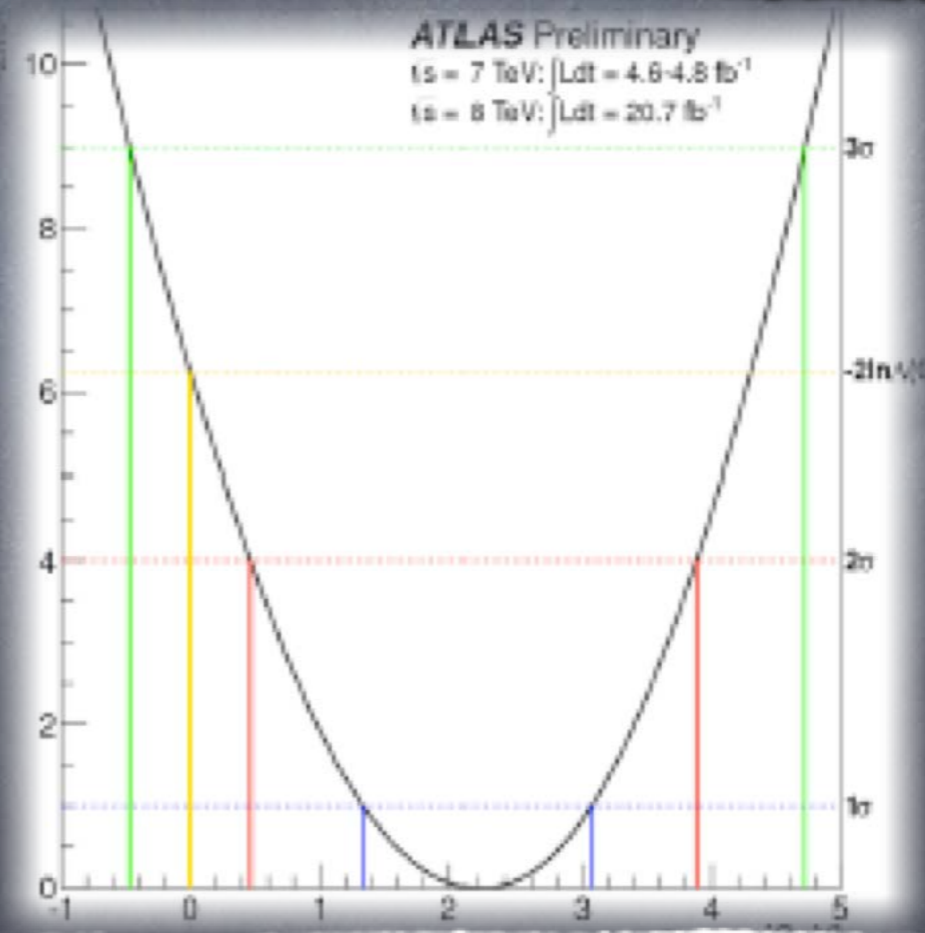
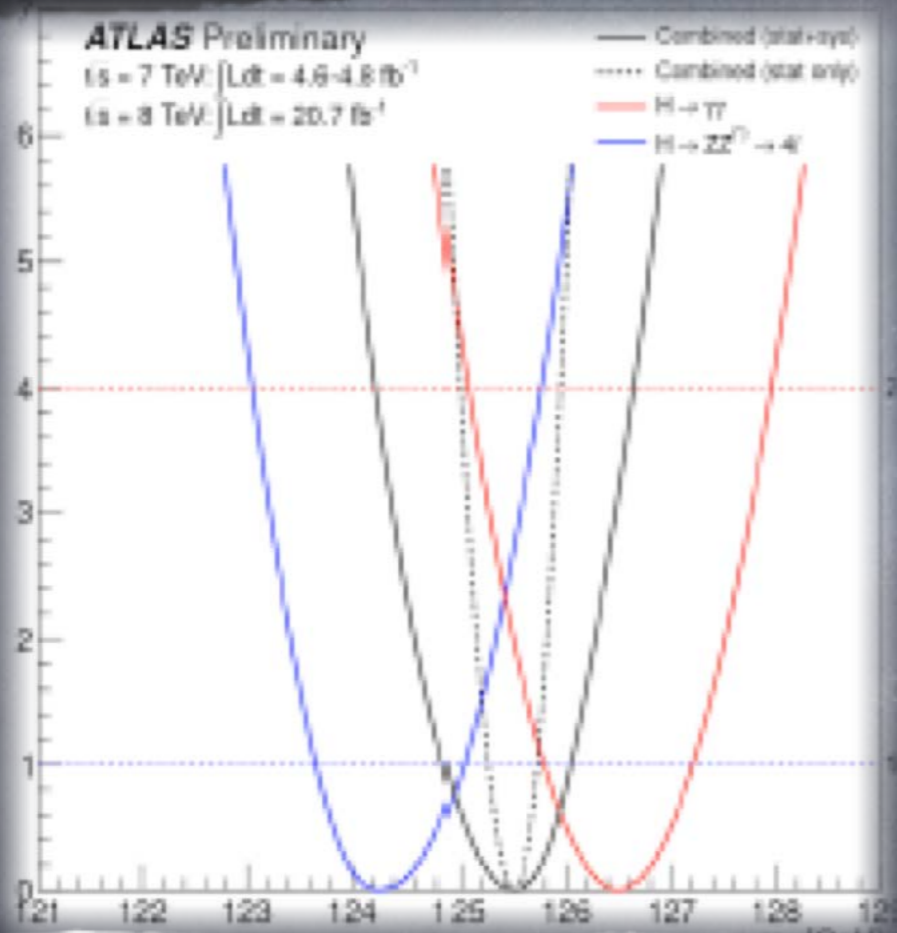
$$m_H^{\text{CMS}} = 125.8^{+0.6}_{-0.5} \text{ (stat.) } ^{+0.5}_{-0.2} \text{ (syst.) GeV}$$

3D fits, event-by-event-errors, kinematic discriminant

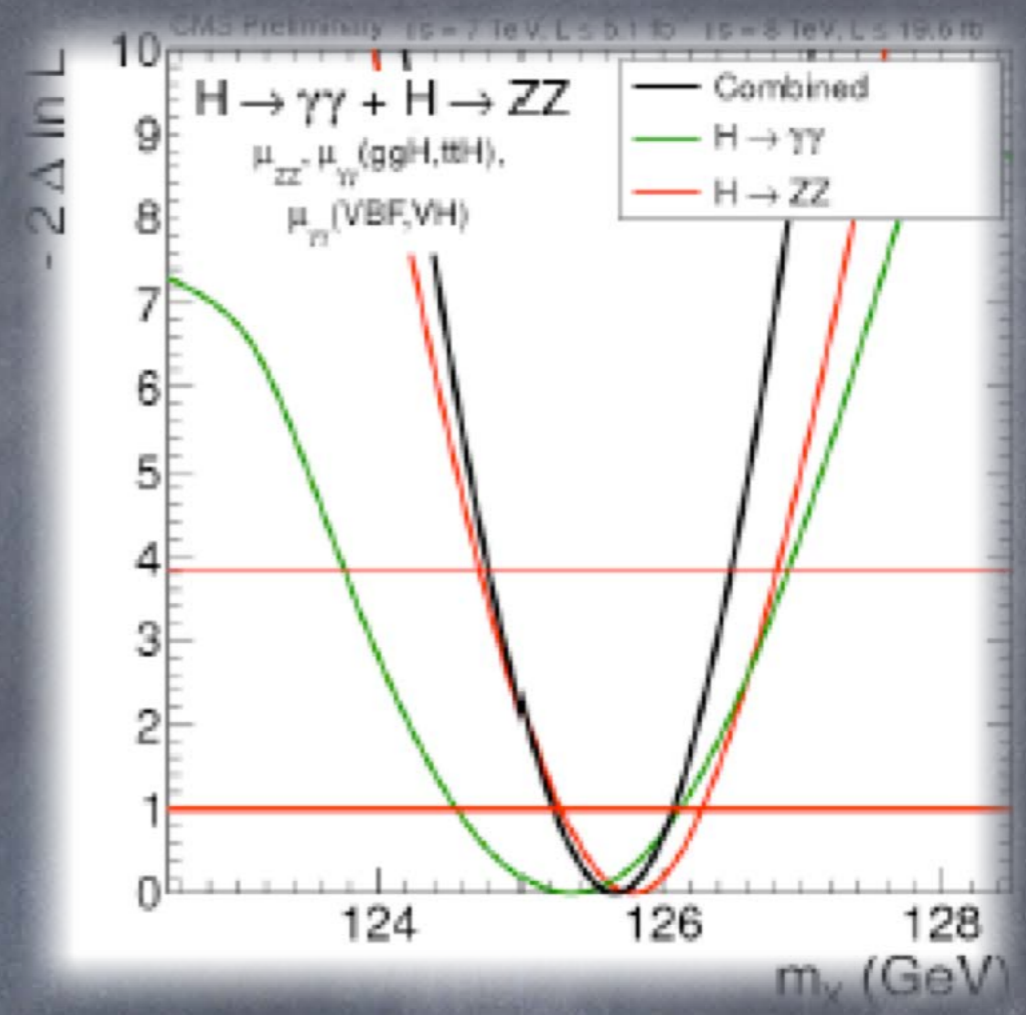
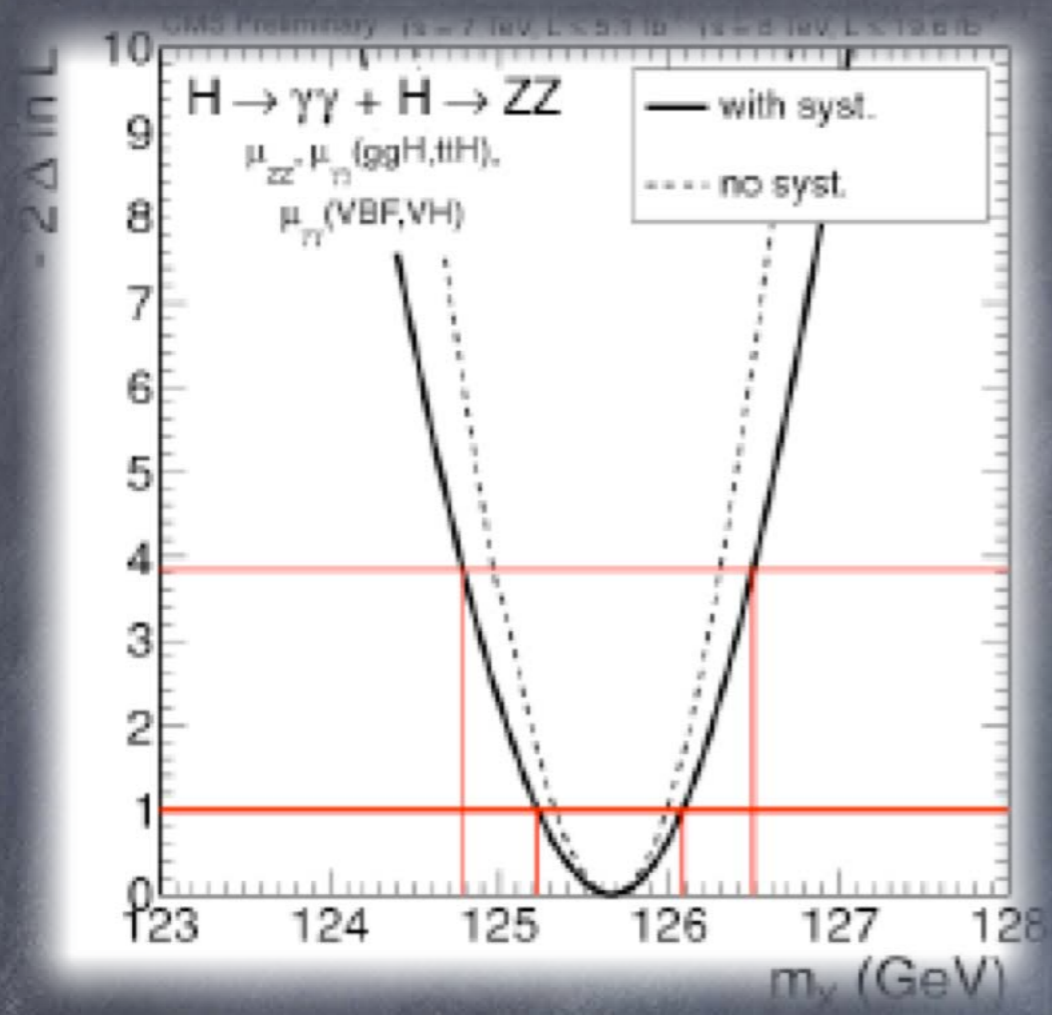
$$\Delta m_H^{\text{ATLAS}} = : m_{\gamma\gamma}^{\text{ATLAS}} - m_{4l}^{\text{ATLAS}} =$$

$$= 2.3^{+0.6}_{-0.7} (\text{stat}) \pm 0.6 (\text{sys}) \text{ GeV}$$

2.4  $\sigma$  away from  $\Delta m_H = 0$  ( p-value = 1.5% )  
 [ 8% ( $<1.5 \sigma$ ) using a conservative treatment of the uncertainties ]



$$m_H^{\text{ATLAS}} (\gamma\gamma, 4l) = 125.5 \pm 0.3 (\text{stat})^{+0.5}_{-0.6} (\text{syst.}) \text{ GeV}$$



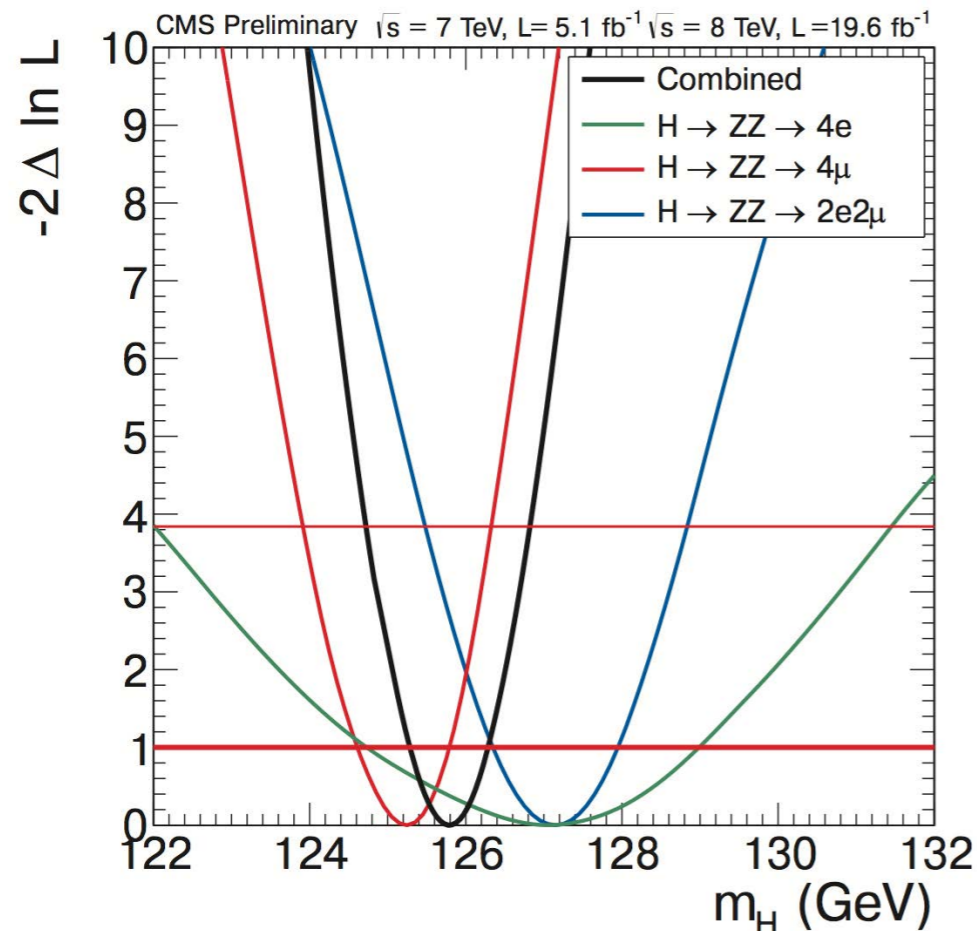
Combine  $\gamma\gamma$  and  $4l$  mass measurements, signal strengths  $m_{\gamma\gamma}(ggF)$ ,  $m_{\gamma\gamma}(VBF)$  and  $m_{4l}$ , allowed to vary independently - don't assume SM couplings

$$m_H^{\text{CMS}(ggF, VBF, 4l)} = 125.7 \pm 0.3 \text{ (stat)} \pm 0.3 \text{ (sys)} \text{ GeV}$$

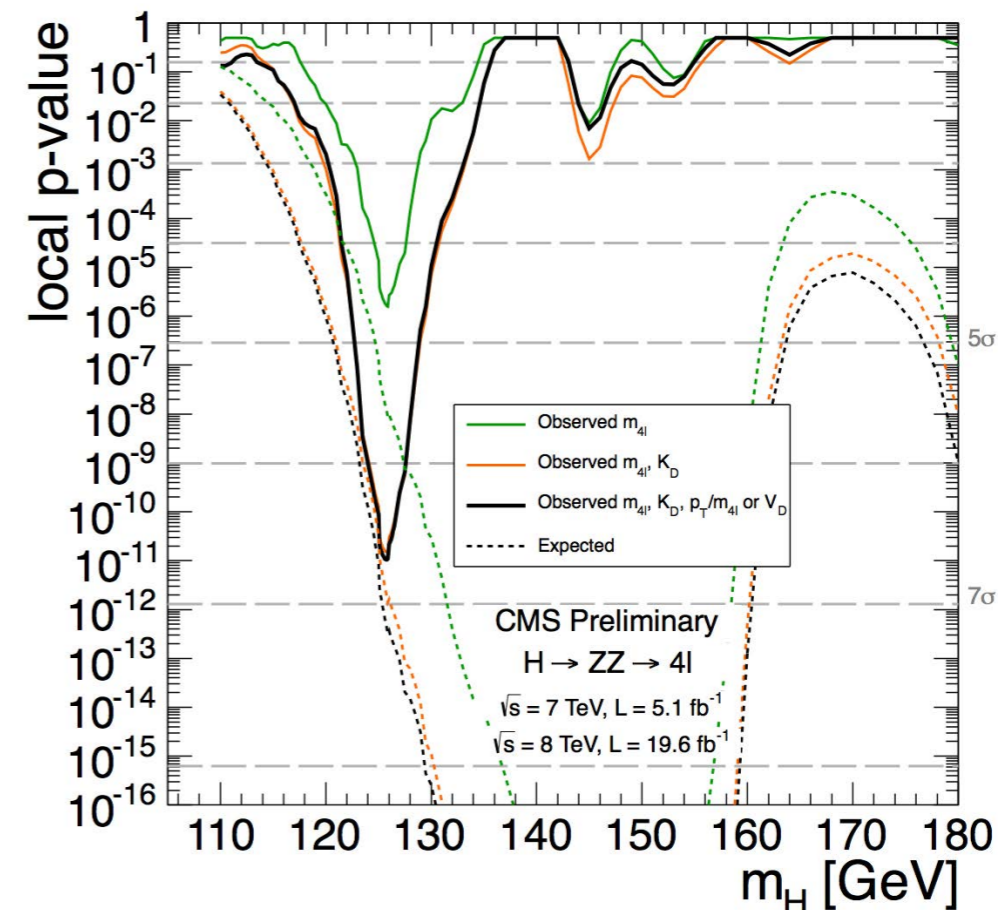
# $H \rightarrow ZZ \rightarrow 4l$ : state of art



- $H \rightarrow 4l$  in CMS provide the best measurement of the Higgs mass:
  - $m_H = 125.8 \pm 0.5$  (stat.)  $\pm 0.2$  (syst.)
  - reasons of the success:
    - highly sensitive analysis (3D fit maximizing the efficiency of a rare process)
    - accurate detector and leptons momentum calibrations



mass scan for  $4e$ ,  $4\mu$ ,  $2e2\mu$



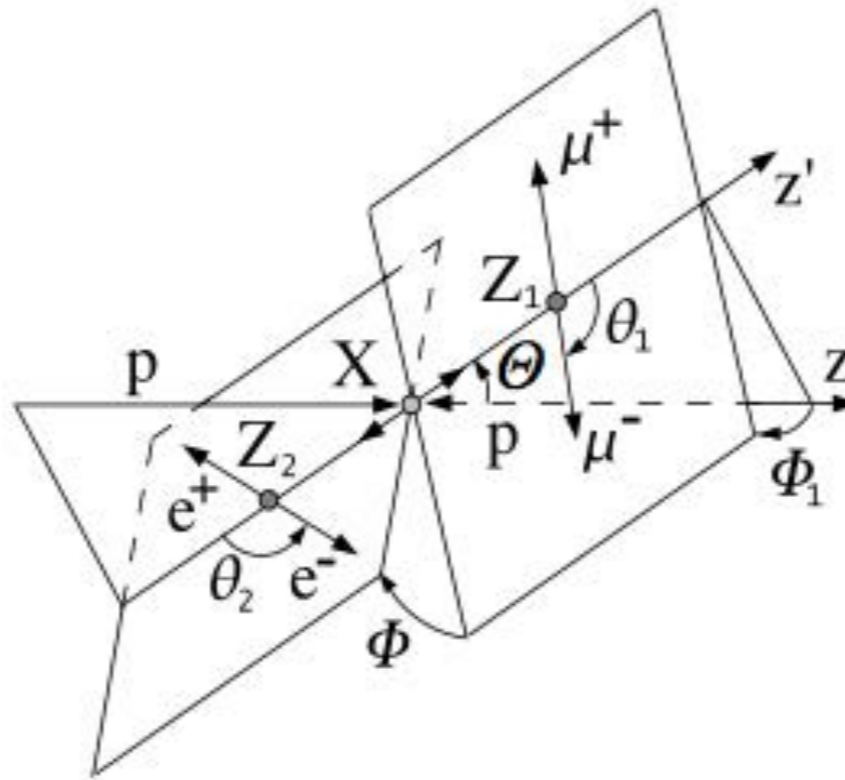
min. p-value:  $6.7\sigma$

# Higgs Golden Channel kinematics

- Ignoring production there are 8 observables in CM frame per event

$(\Theta, \theta_1, \theta_2, \Phi_1, \Phi)$  (N. Cabibbo, A. Maksymowicz, Phys. Rev. 137 (1968))

$M_{4\ell}, M_{Z_1}, M_{Z_2}$



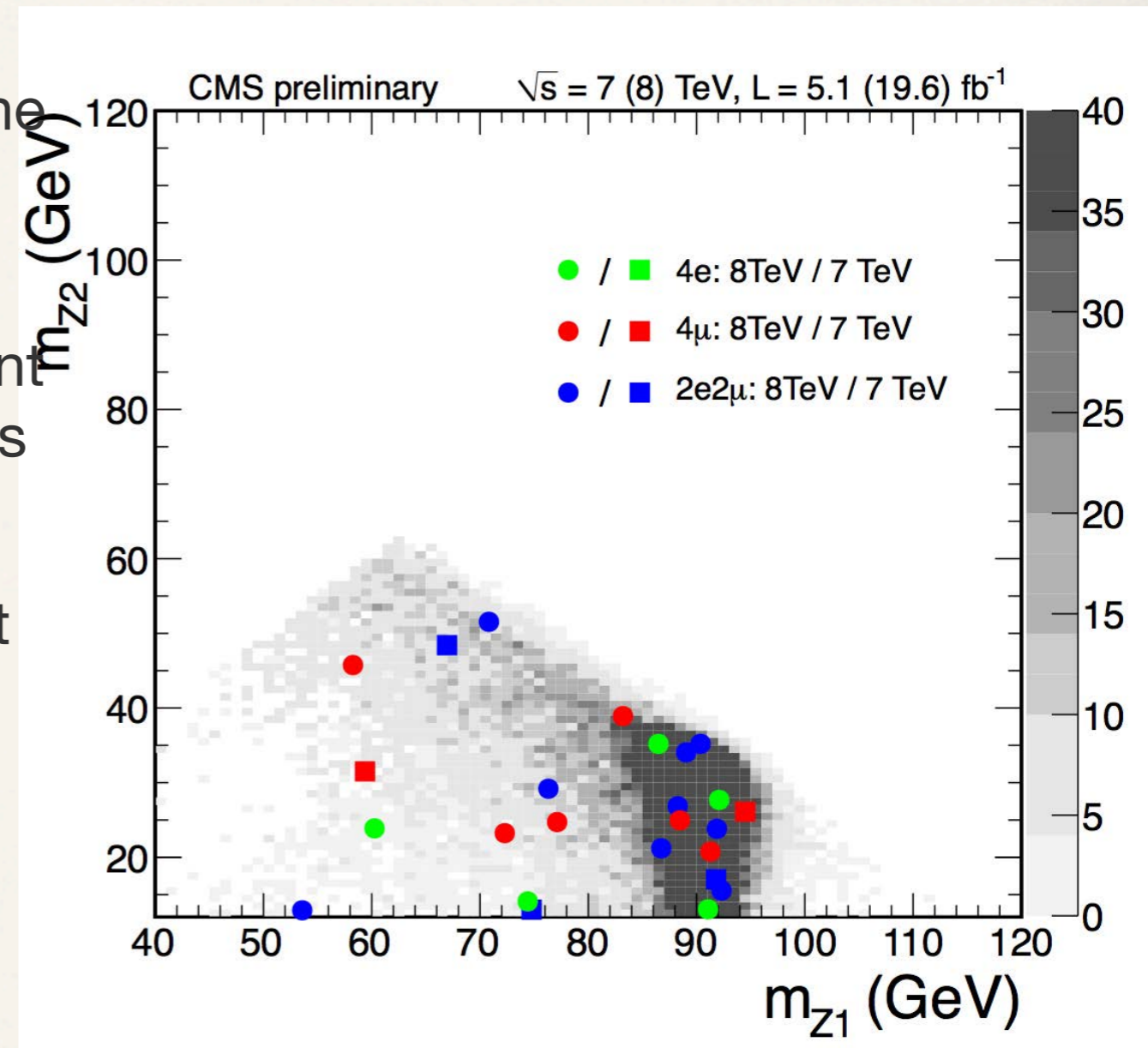
(Y. Chen, N. Tran, RVM: 1211.1959)

- All angles defined in  $4\ell$  CM frame (or X in case of signal)
- Correlations between lepton angles studied for some time

J.F. Gunion, Z. Kunszt (1986); Maturra, J.J. Van Der Bij (1991), + many others

# Higgs Golden Channel kinematics

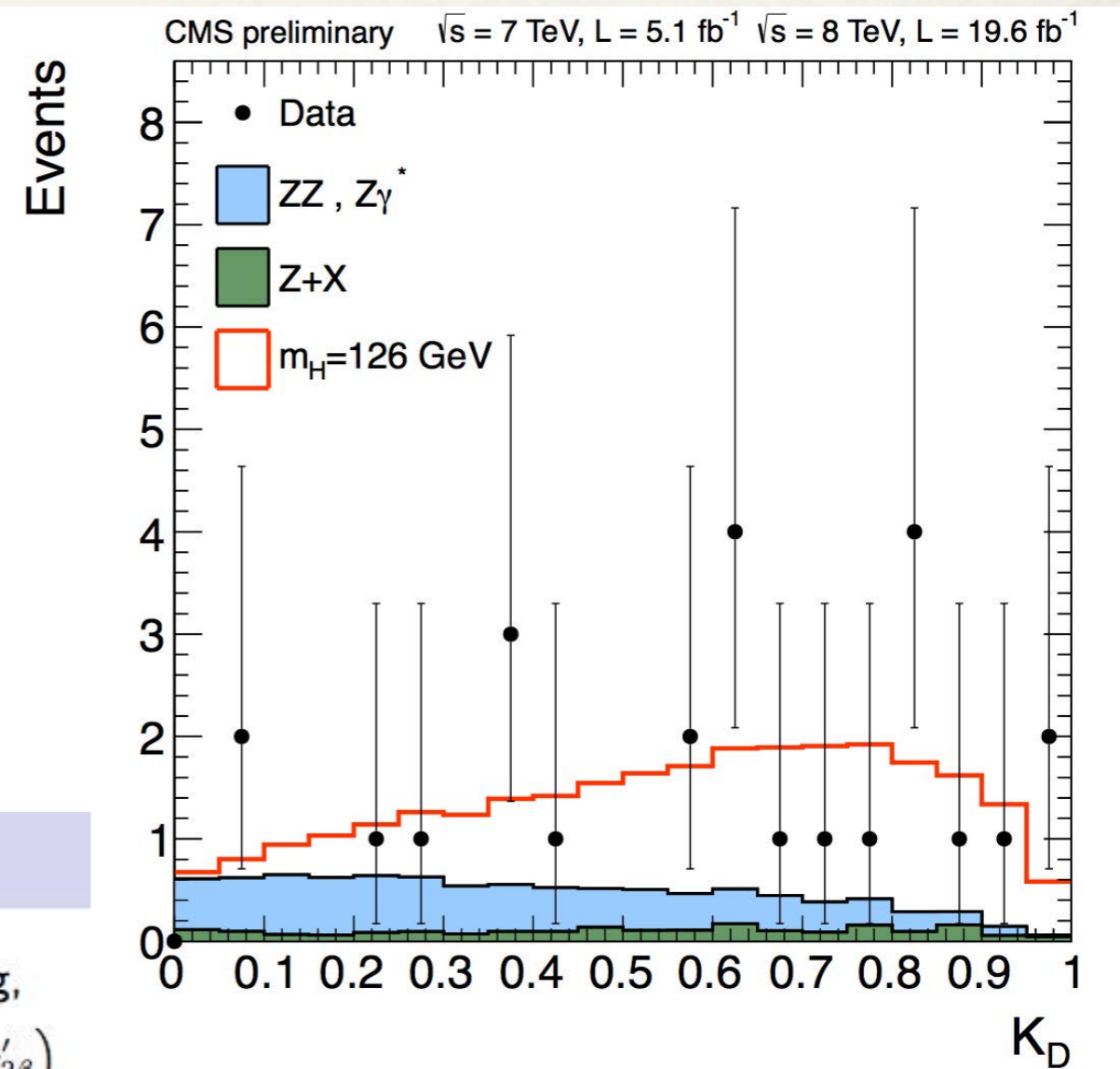
- For a 126 GeV Higgs, one of the Z's in the decay is always badly off shell, and the other one can be pretty off shell too
- Also about 1% of the time the signal event is actually from Higgs decays to 4 leptons through  $Z\gamma$  or  $\gamma\gamma$ , not  $ZZ$
- The two "Z" masses reconstructed event by event are important discriminators
- This was not noticed until recently!



See A. De Rujula, JL, M. Pierini, C. Rogan, M. Spiropulu, arXiv:1001.5300

# What can we do with ALL of the decay information?

- The 0.5% CMS mass measurement uses a 3D fit, where all 8D of the kinematics is processed into a 1D discriminator  $K_D$
- But in principle you could do a 9D fit, using ALL of the (decay) kinematic information
- Of course this presupposes that what you have is in fact a SM Higgs...



## Scalar Signal Parametrization

- Parametrize **scalar couplings to vector boson pairs** as the following,

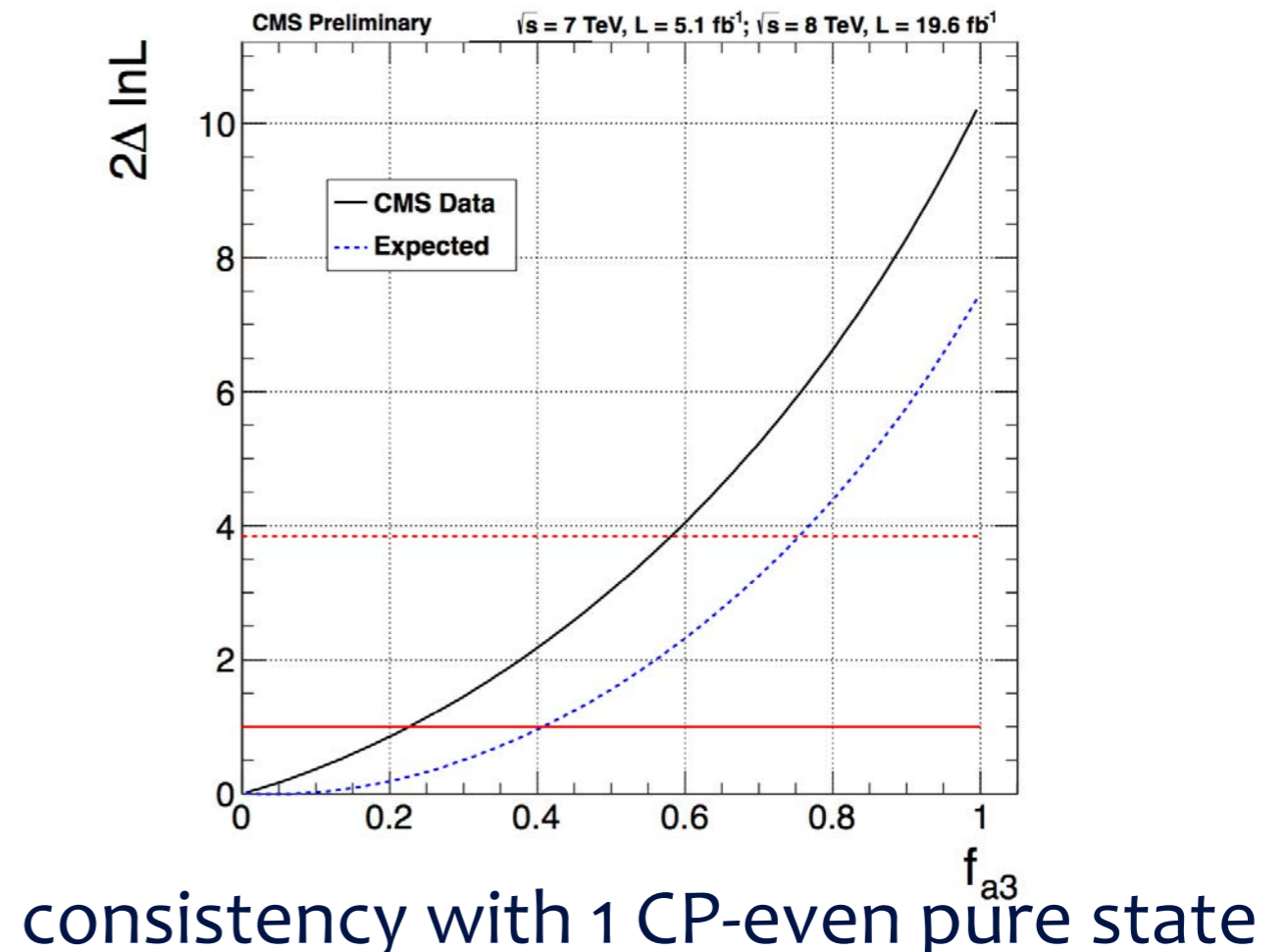
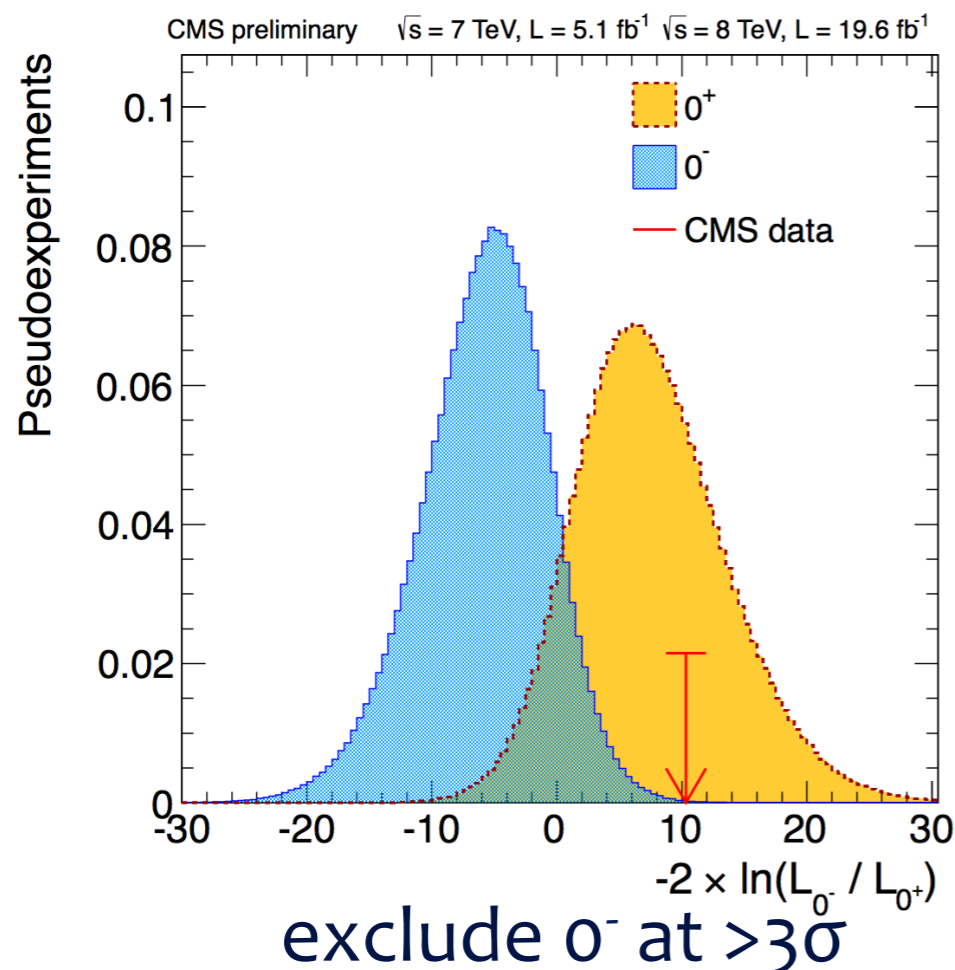
$$\Gamma_{ij}^{\mu\nu}(k, k') = \frac{1}{v} \left( A_{1ij} m_Z^2 g^{\mu\nu} + A_{2ij} (k^\nu k'^\mu - k \cdot k' g^{\mu\nu}) + A_{3ij} \epsilon^{\mu\nu\alpha\beta} k_\alpha k'_\beta \right)$$

- The  $A_{nij}$  in principal complex and  $ij = ZZ, Z\gamma, \gamma\gamma$  ( $A_{1Z\gamma} = A_{1\gamma\gamma} = 0$ )
- $k, k'$  momentum of vector bosons (or lepton pair system)

# H → ZZ → 4l: properties

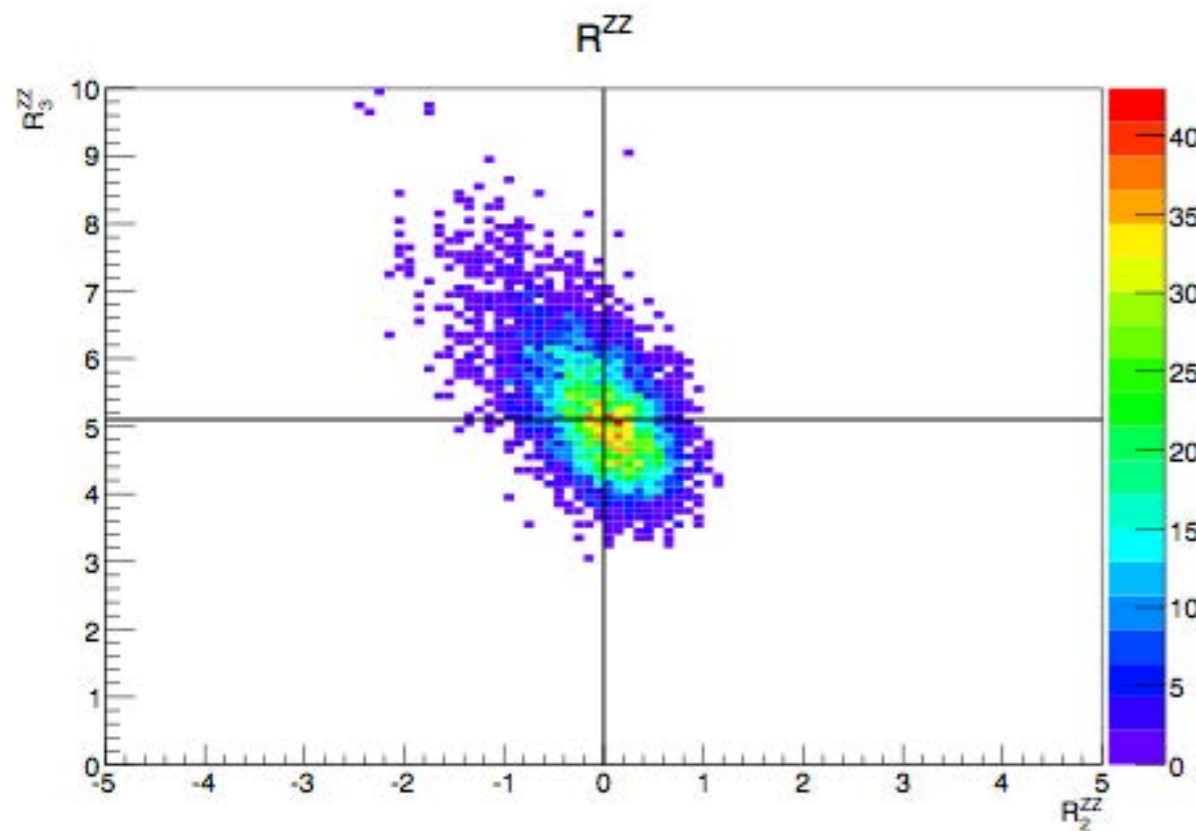


- Already used as a “properties measurement” channel:
  - $J^P$ : due to limited stat., for the moment do hypothesis test with 1D fit using a discriminant optimized against each alt. hypothesis
  - CP: measure possible CP-odd contributions with a fit to  $f_{a3} = |A_3|^2 / (|A_1|^2 + |A_3|^2)$
  - can be done for  $f_{a3}$ , but for other amplitudes, need to consider rates and phases together ⇒ multi-D fits / tests to groups of reduced sets of parameters

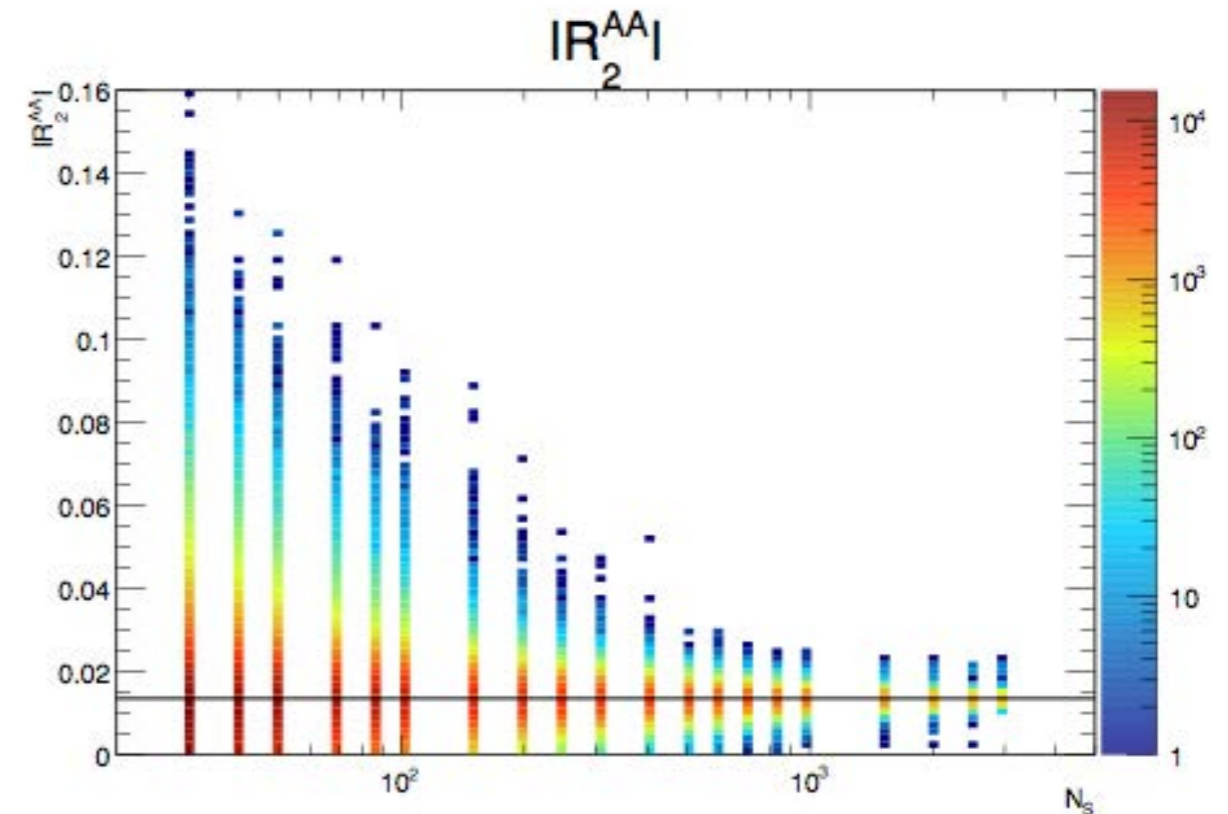


# $H \rightarrow ZZ \rightarrow 4l$ : future?

- with larger statistics, try to measure directly Lagrangian parameters:
  - analytical: complex, but powerful. Kinematical observables connected to Lagrangian couplings through detector transfer functions in a 8D Likelihood
  - discrete: simpler, use full simulation to build 1D discriminants for each measurement of pairs of parameters



toys: unbiased estimation  
of Higgs couplings

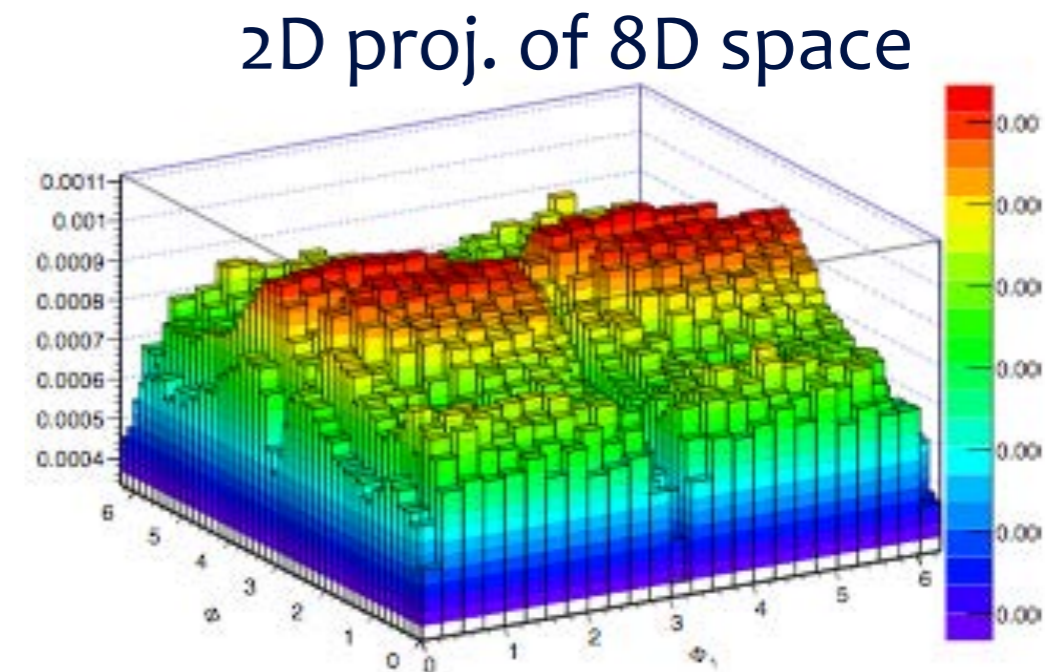
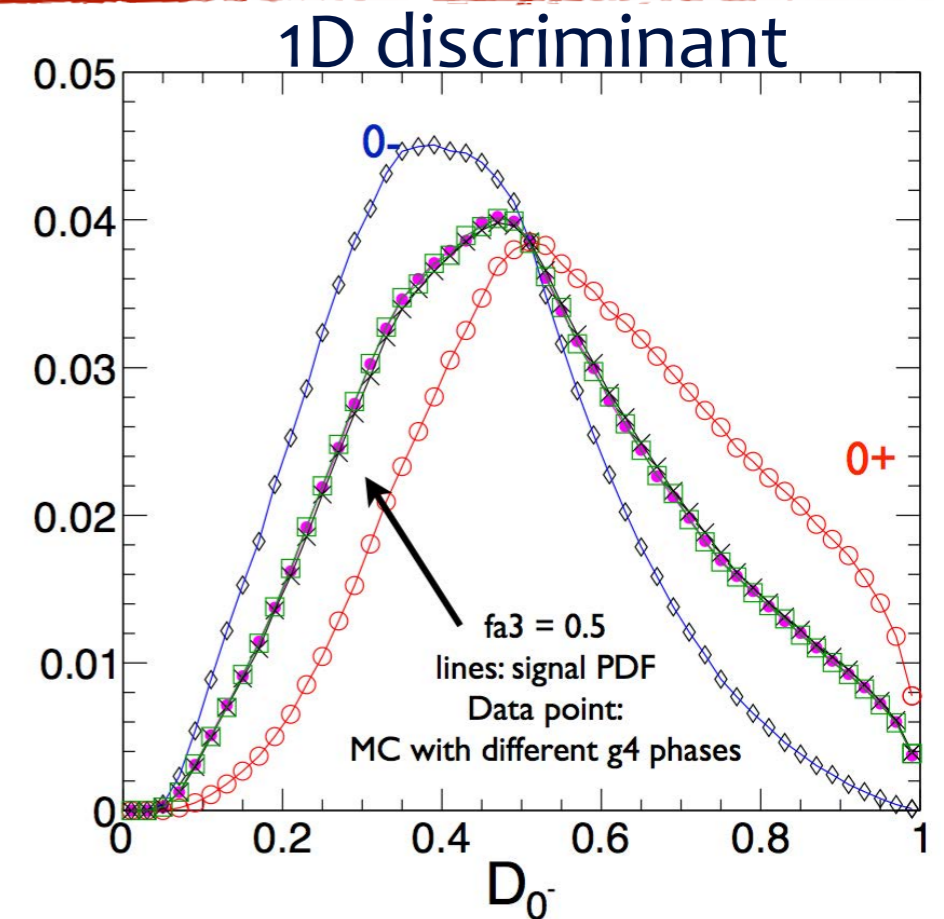


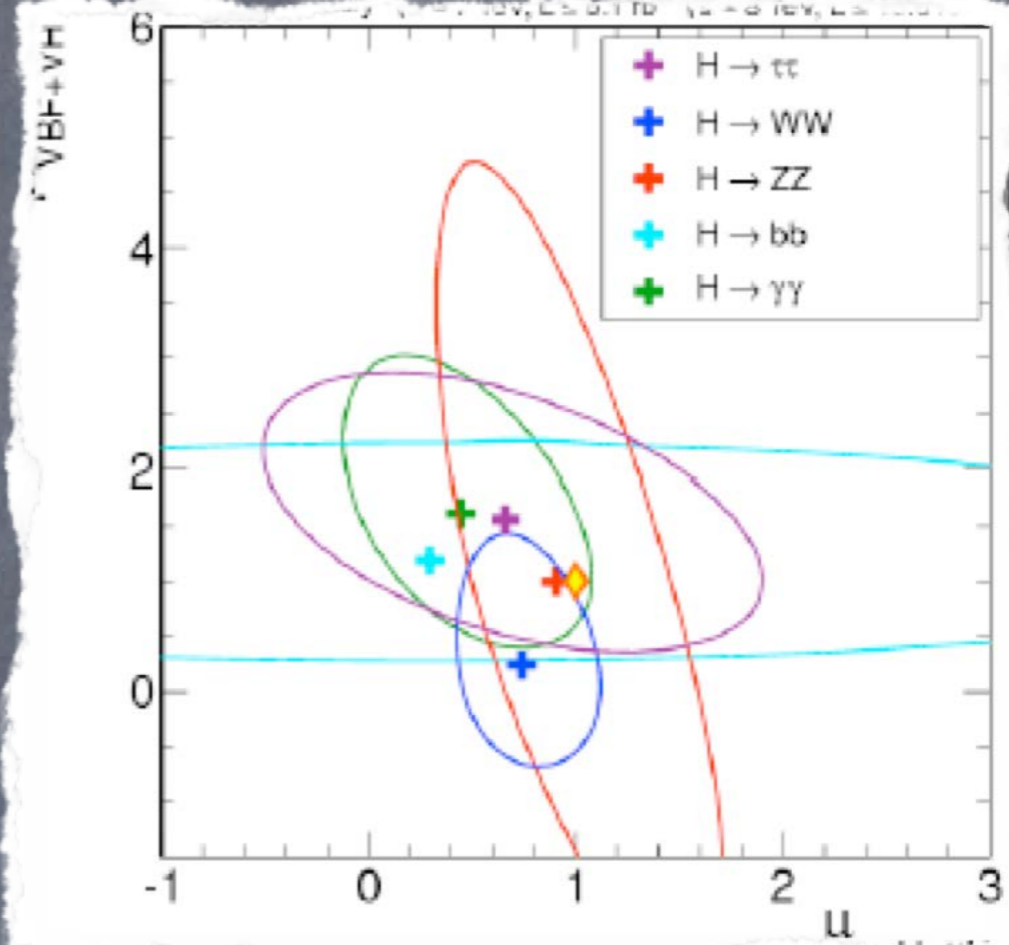
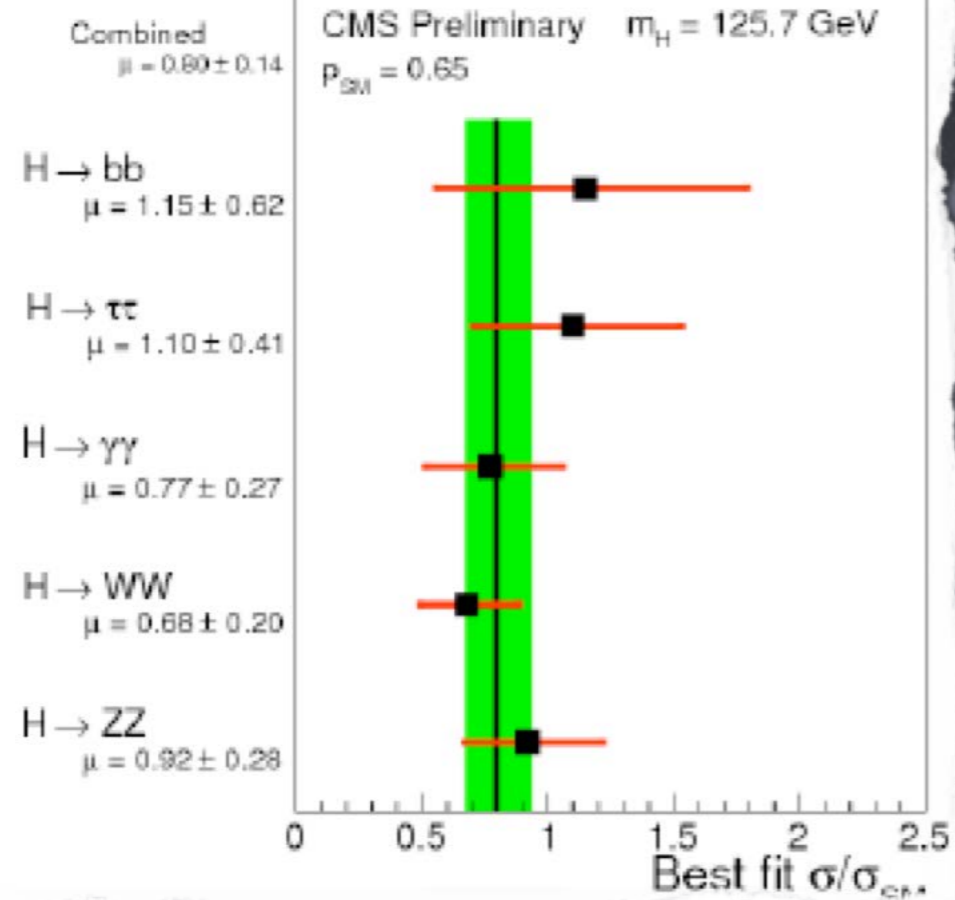
toys: scaling of precision with lumi:  
from 30 (current)  $\rightarrow$  3000 events

# What are the challenges?

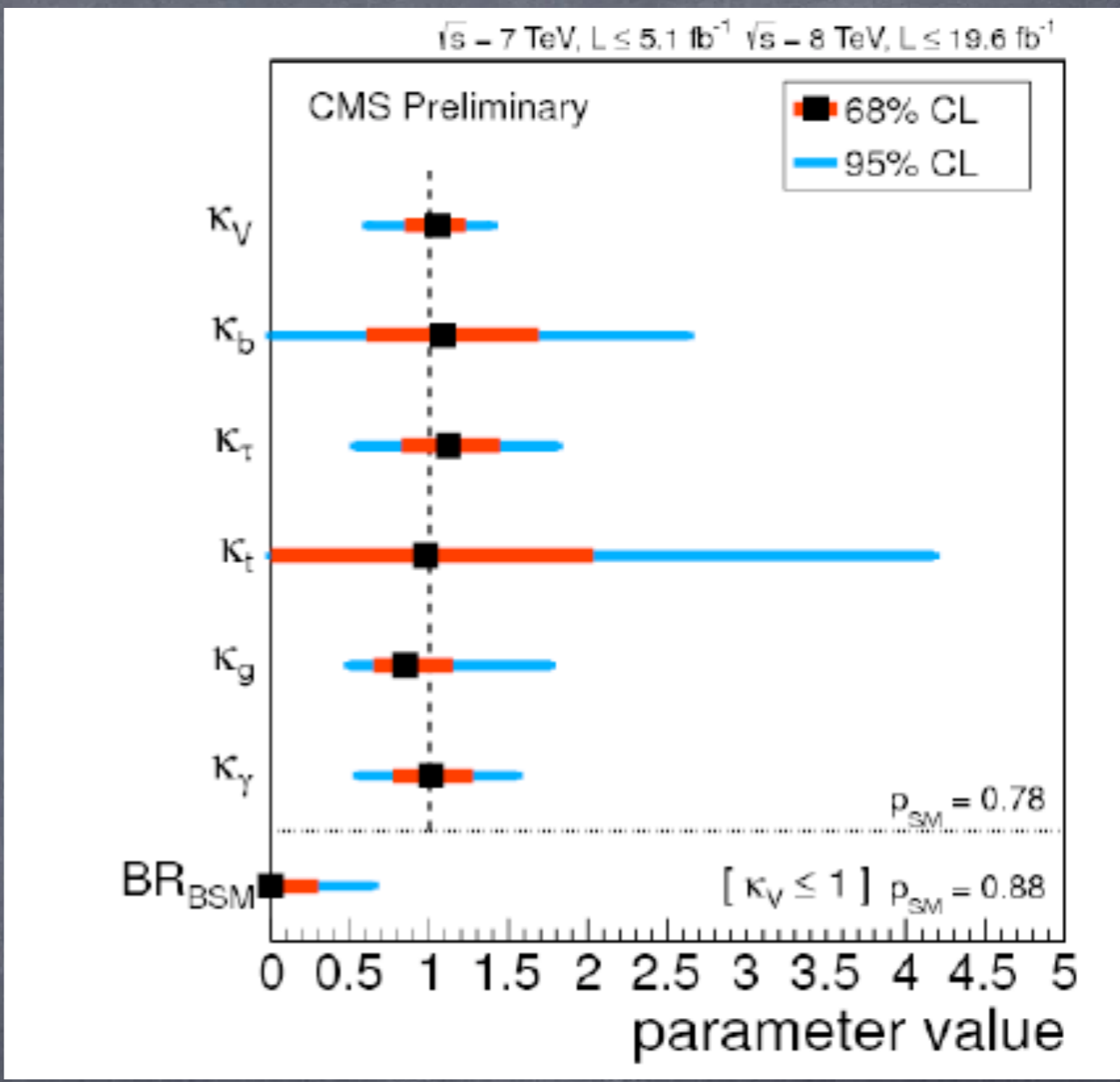
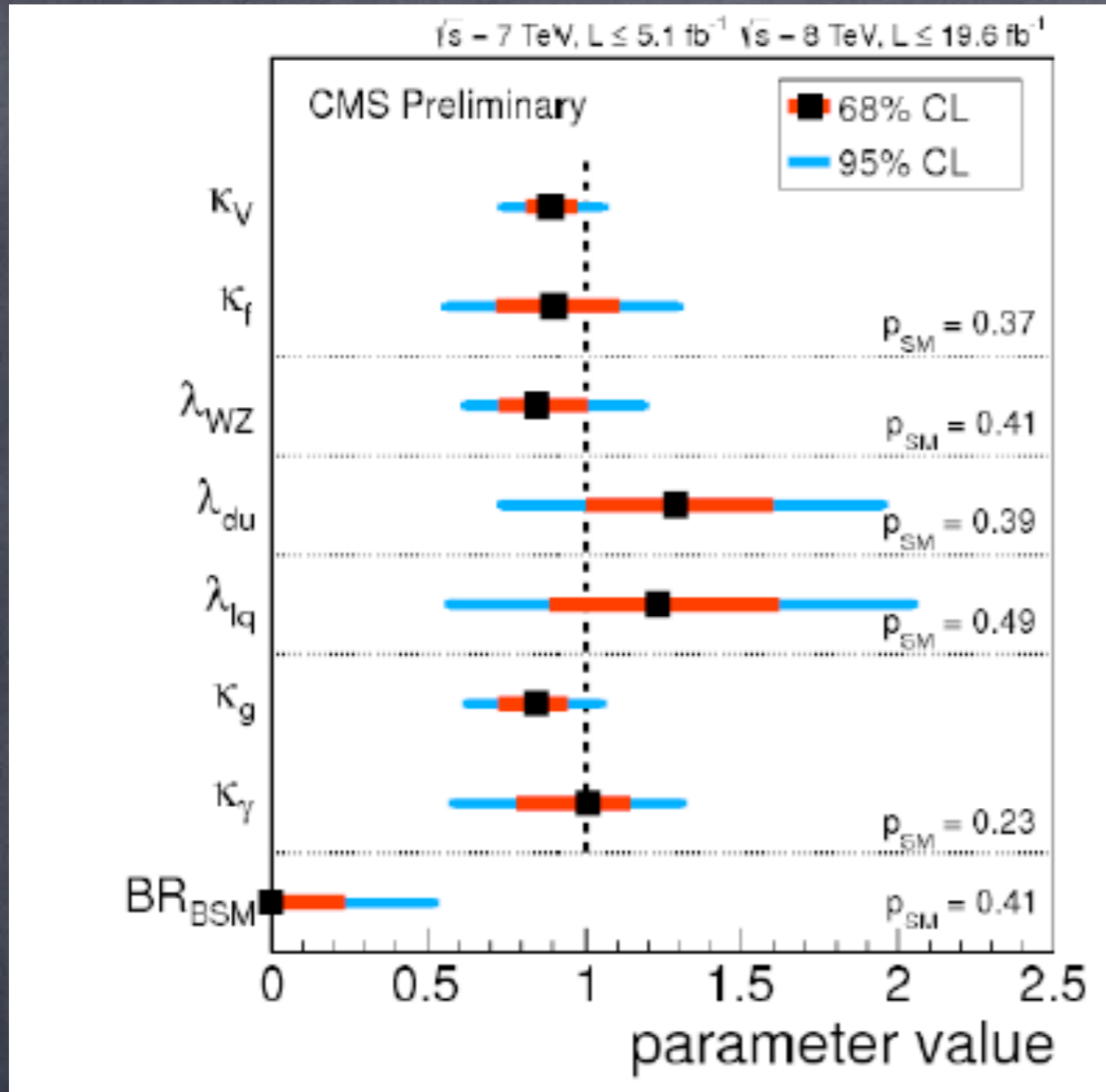


- 1D “discriminant” fit:
  - pro: Simpler. Build templates from full sim
  - cons: cannot measure all parameters at a time. Need to build discriminant for each measurement
- 8D fit:
  - pros:
    - perform the measurement of all the parameters, rates and interference, at the same time.
    - provides the best precision
  - cons:
    - need to fill 8D pdf: doable for components with analytical calculations (ggH, qqZZ), need tricks ggZZ, reducible backgrounds
    - need careful checks of the 8D space

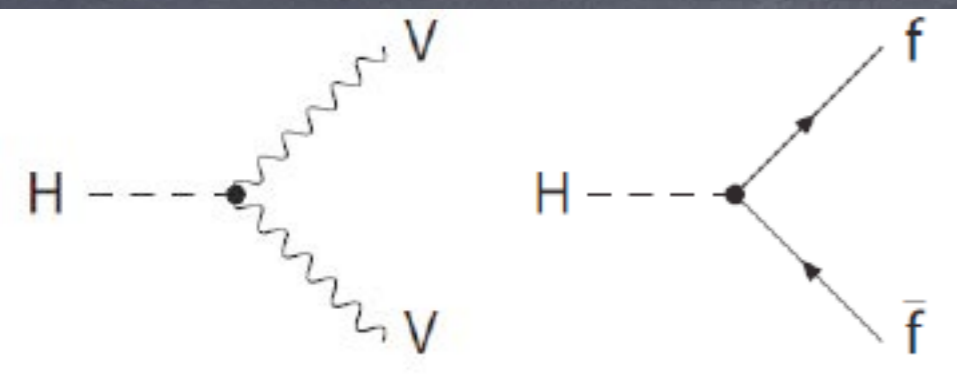




- Results from the individual modes close to the SM Higgs predictions probe the couplings by expanding around that reference point.
- couplings= searches for deviations from the SM Predictions in the scalar couplings (LHC XS WG, arxiv:1209.0040); use benchmark models
- BSM decays, when allowed in the models, scale down the BRs of all SM decays uniformly.



fermion vs vector boson couplings:  $\kappa_V$   $\kappa_f$ ; search for asymmetries:  $\lambda_{WZ}$ ,  $\lambda_{du}$ ,  $\lambda_{lq}$  new physics in loops:  $\kappa_g$   $\kappa_\gamma$   $BR_{BSM}$ ; simultaneous fits of all couplings; indirect limit on  $BR_{BSM}$ ; Results for all the LHC XS WG benchmark BSM models  
 ©approximate p-values of SM H hypothesis given for each test;



$$g_V = 2 m_V^2/v \quad \lambda_f = m_f/v$$

Define couplings from the kappa's:

$$\lambda_f = \kappa_f m_f/v, \quad g_V = \kappa_V m_V^2/v$$

Coupling-Mass Relation

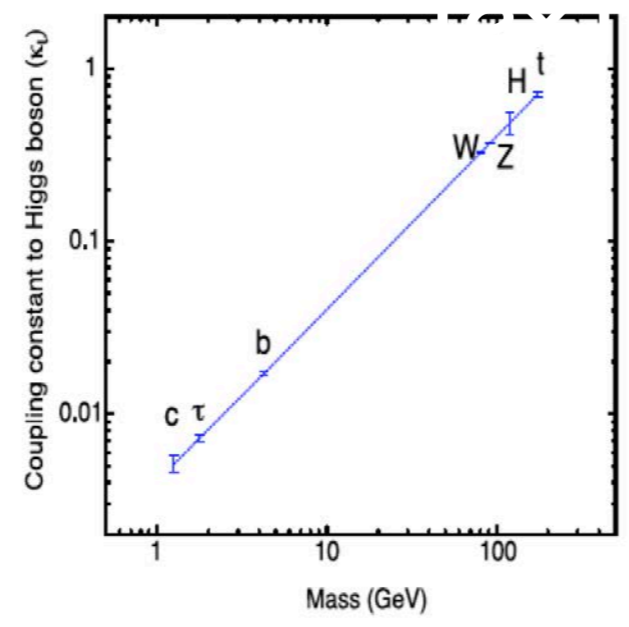
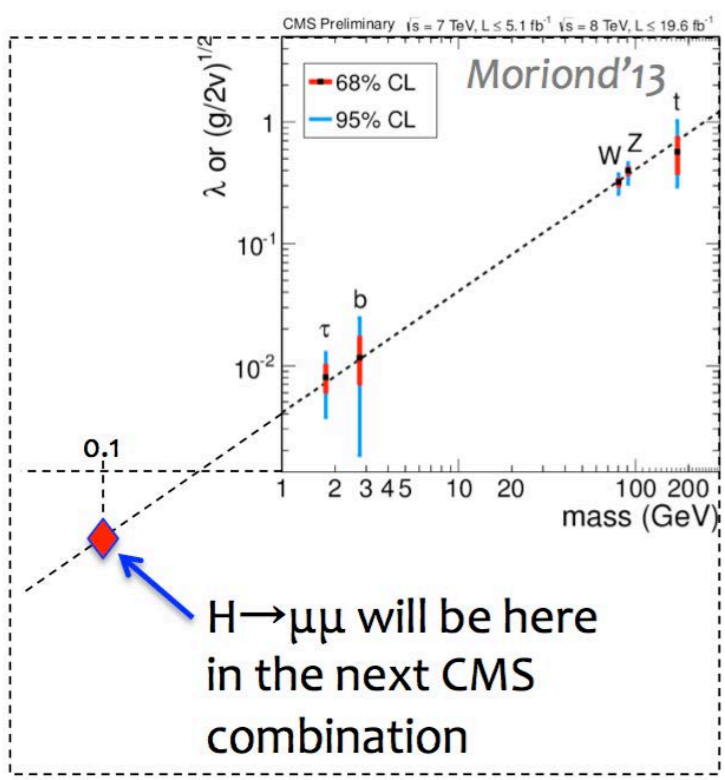
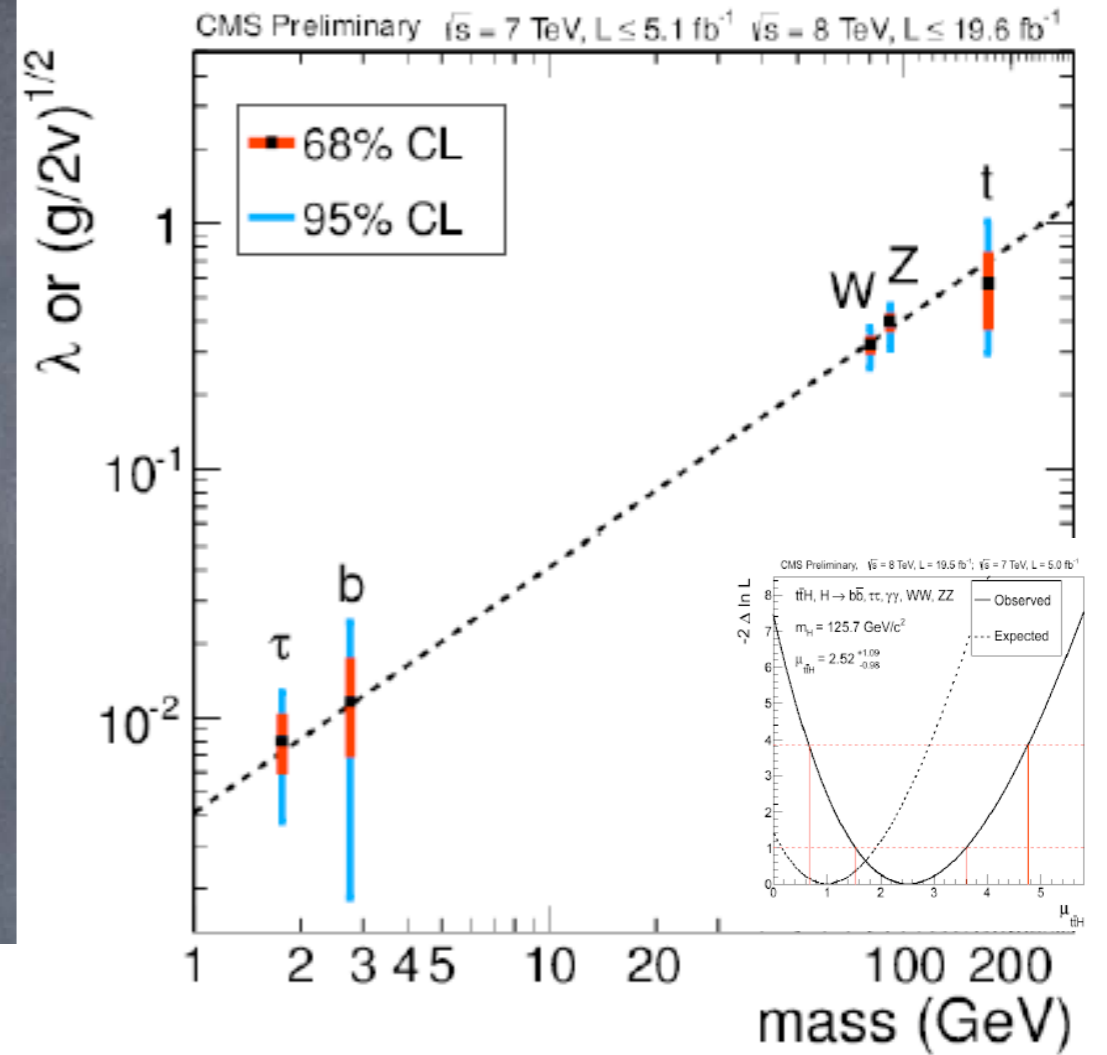


Fig. 5 The relation between the Higgs coupling of a particle and its mass in the SM. The error bars correspond to the accuracy expected from the ILC data [44]

**Disclaimer:** in most channels we do not yet have the discovery and in some the sensitivity is just about becoming 1xSM

No significant deviation from SM predictions observed within the uncertainties (10-100%)

## next step

**ILC** plans to provide the next significant step in the precision study of Higgs boson properties. LHC precision measurements in the **5–10%** range could be brought down to the level of **1%**.

Any remaining deviations at the LHC  
will be probed at the ILC

# H → WW razor : who knew!

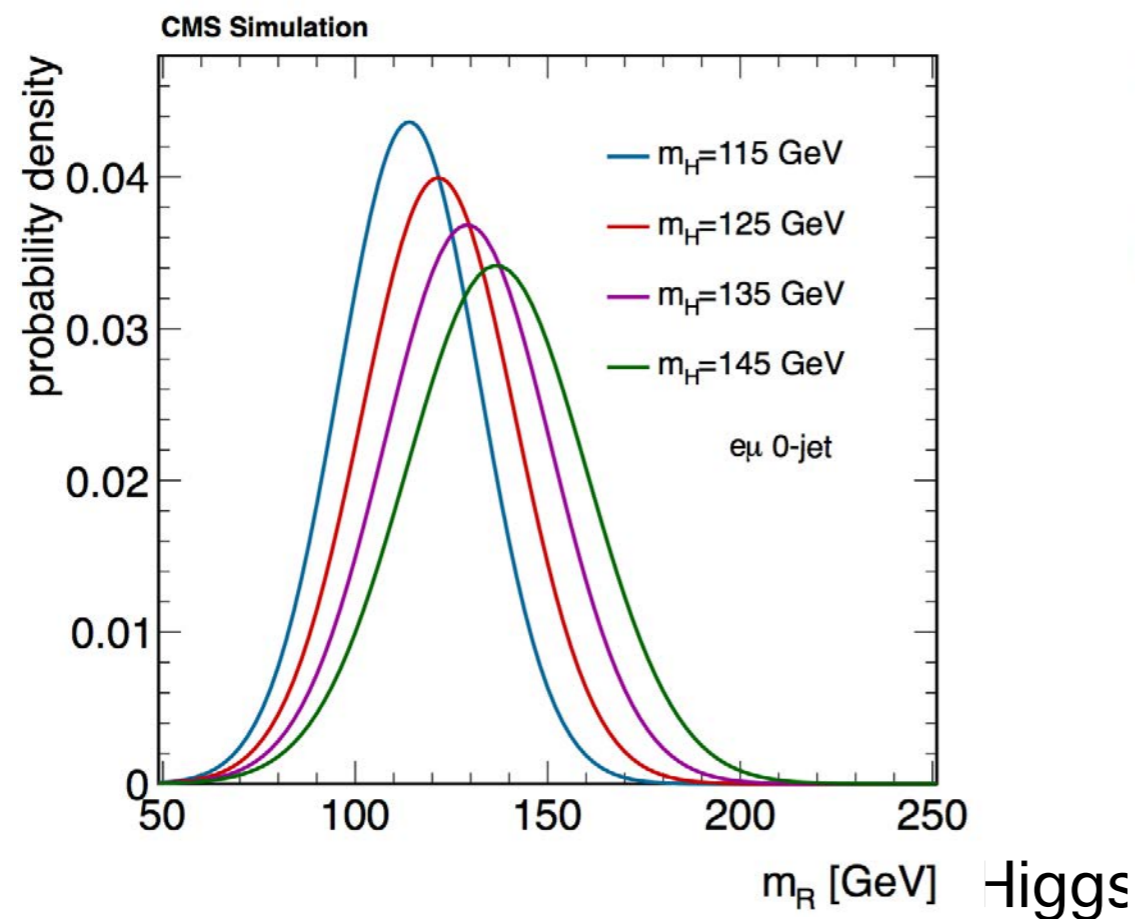


- Per-event estimator of the Higgs mass,  $m_R$ :

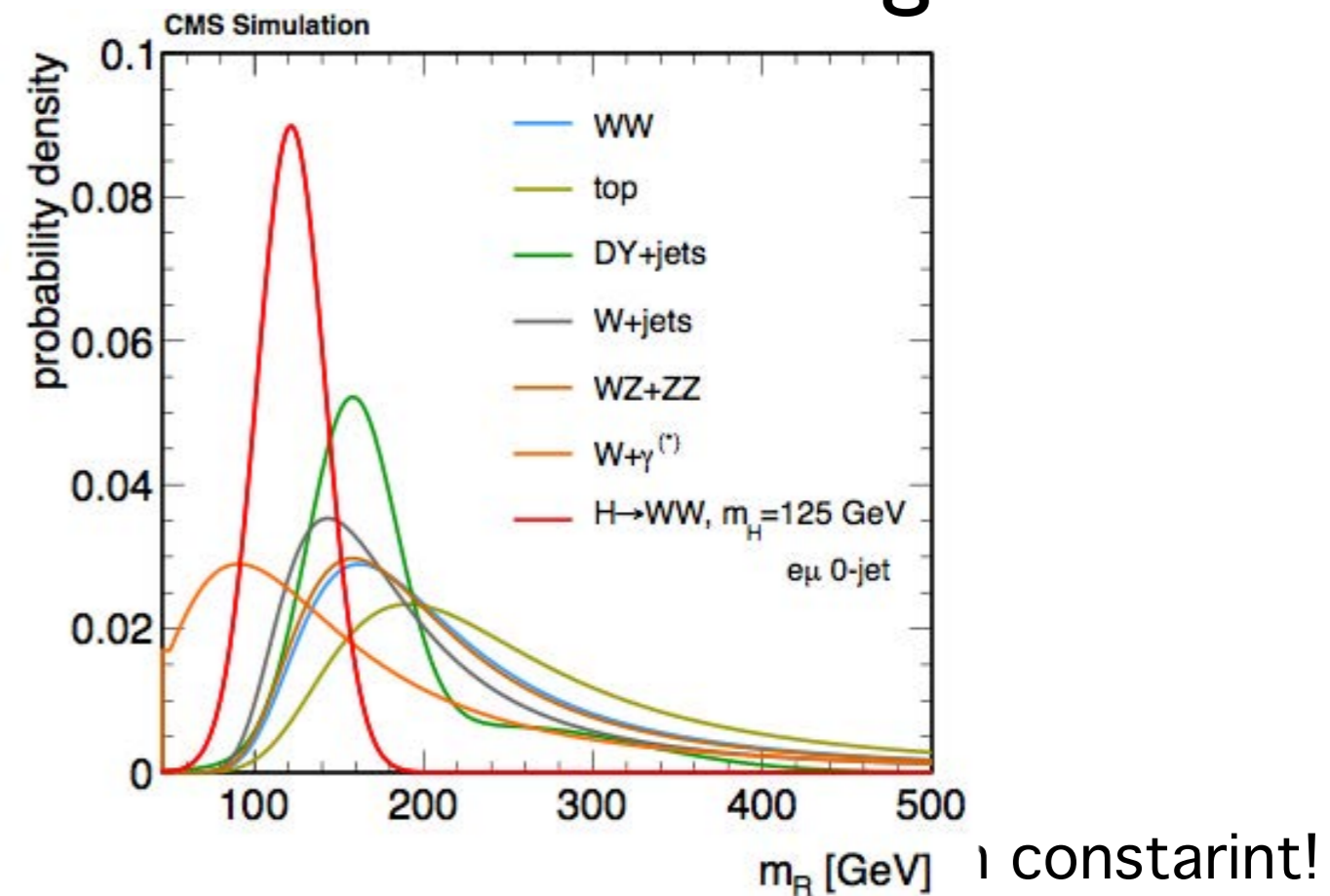
$$m_R = \sqrt{\frac{1}{2} \left[ m_{\ell\ell}^2 - \vec{E}_T^{\text{miss}} \cdot \vec{p}_T^{\ell\ell} + \sqrt{(m_{\ell\ell}^2 + p_T^{\ell\ell 2})(m_{\ell\ell}^2 + E_T^{\text{miss} 2})} \right]}.$$

- high sensitivity, due to good resolution (determined by lepton-only momenta)
- MET used to correct for Higgs  $p_T$ : peaks at  $m_H$  for each jet multiplicity

## $m_R$ for different $m_H$



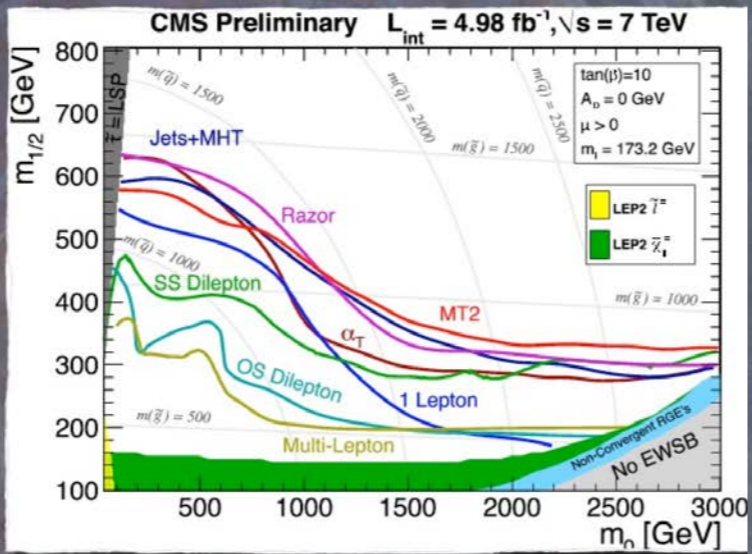
## $m_R$ for H and bkg



# Razor what? the SUSY connection

## Searching for SUSY @8TeV

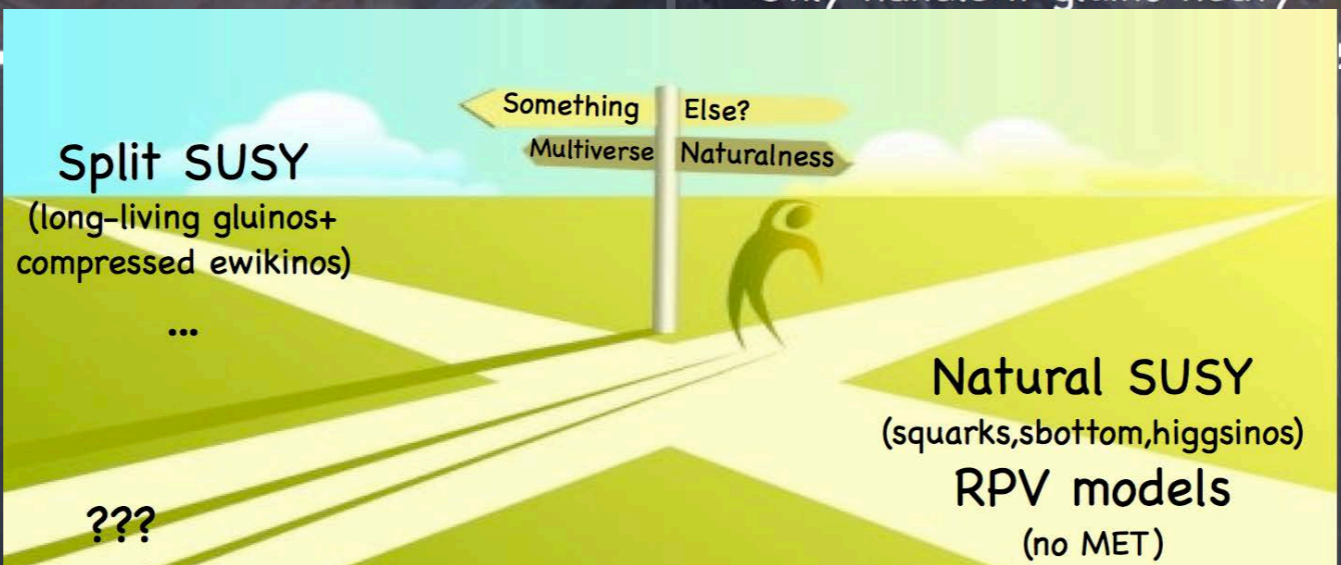
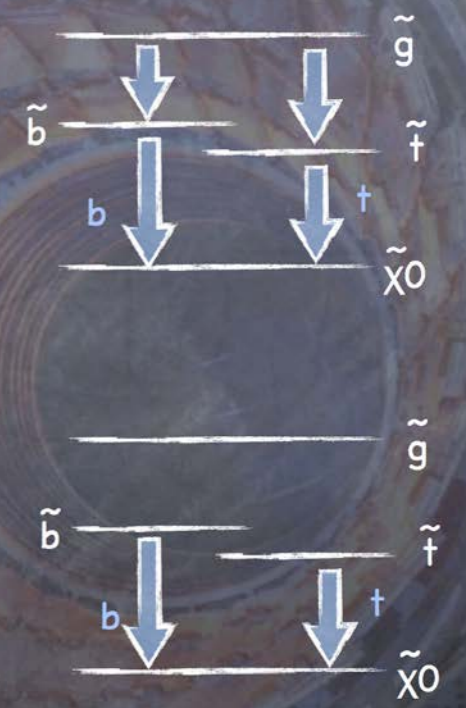
- With  $5\text{fb}^{-1}$  of 7TeV data the exclusion curve removed a large fraction of the accessible parameter space
- After this, any improvement on the high-mass front became adiabatic
- This was not true anymore if one changes the SUSY paradigm



The ballpark of what we could discover was gone quite quickly  
The Higgs was found  
We turned our attention to some special kind of SUSY

## Natural SUSY

- **Glino-mediated searches**  
Larger cross section  
4b quarks in the final state, with or w/o leptons  
More handles for bkg discrimination  
Glunos might be too heavy for these searches to be effective
- **Direct squark searches**  
Smaller cross section  
Final state similar to  $t\bar{t}$  in the bulk of the parameter space  
Reduced bkg discrimination power  
Only handle if gluino heavy



# Razor Inclusive Search

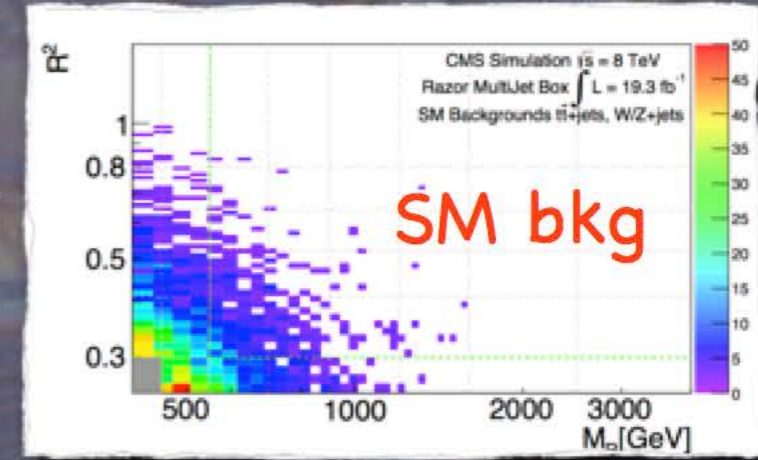
CMS PAS SUS-13-004

Suppress QCD cutting on  $R$  & exploit peaking behavior of  $M_R$  (SUSY search as a "resonance" search)

$R =$

$$M_T^R \equiv \sqrt{\frac{E_T^{miss} (p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{j1} + \vec{p}_T^{j2})}{2}}$$

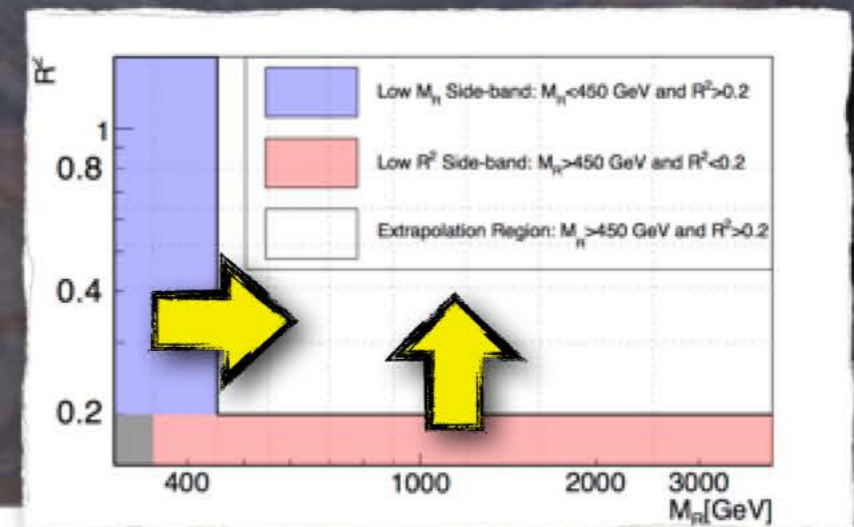
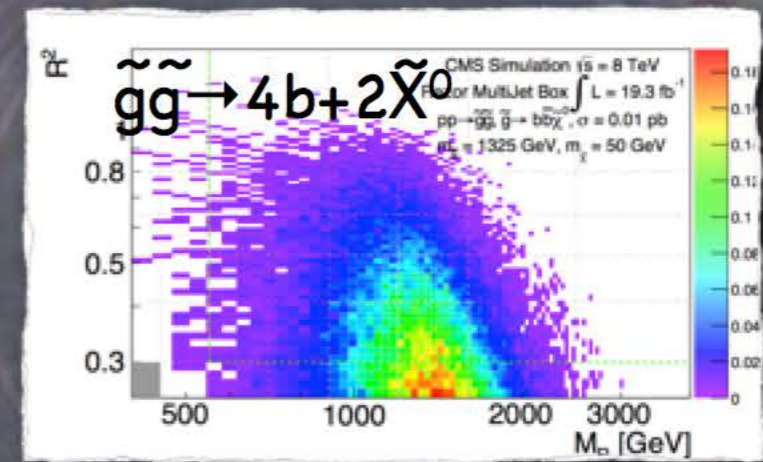
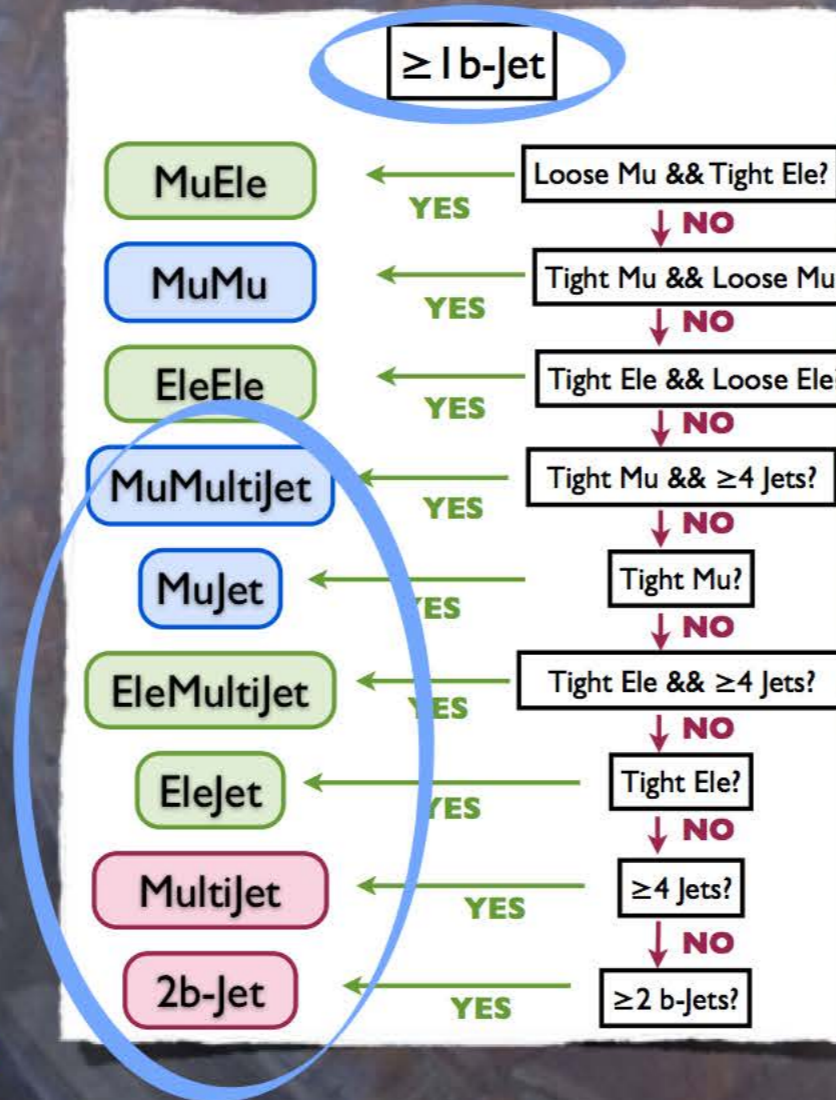
$$M_R \equiv \sqrt{(p_{j1} + p_{j2})^2 - (p_z^{j1} + p_z^{j2})^2}$$



Combine searches in different final states: overall result is inclusive

Use  $b$ -tag multiplicity to enhance the sensitivity to natural SUSY models

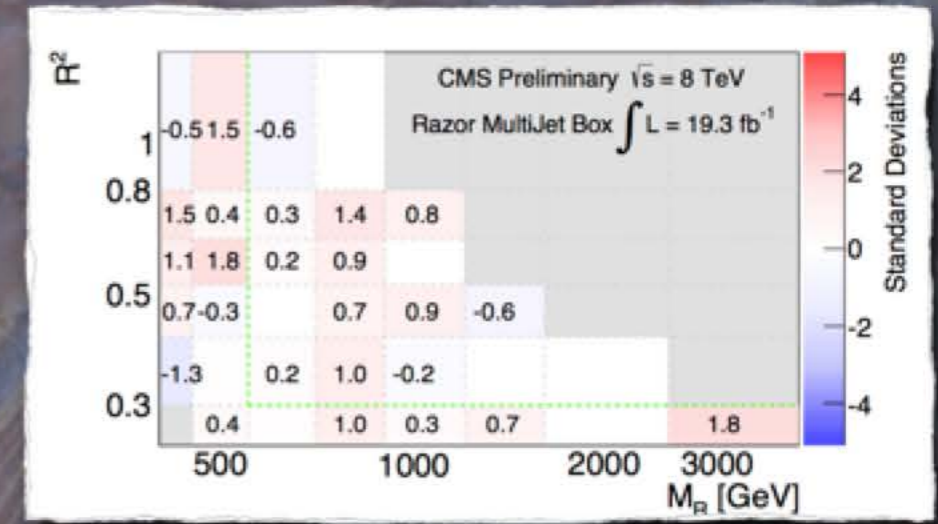
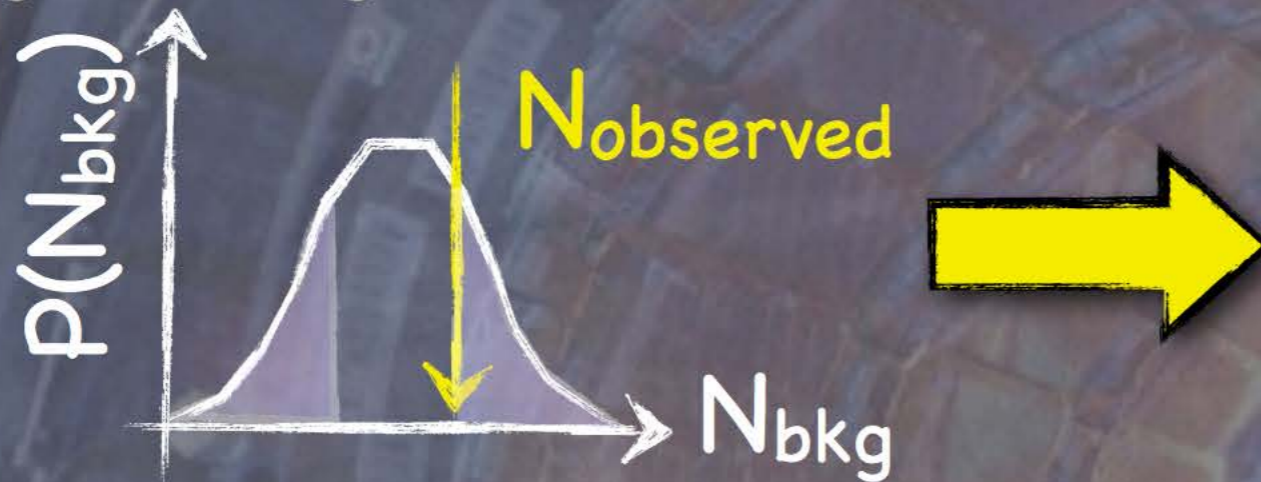
Determine the bkg with a **sideband shape fit+extrapolation**



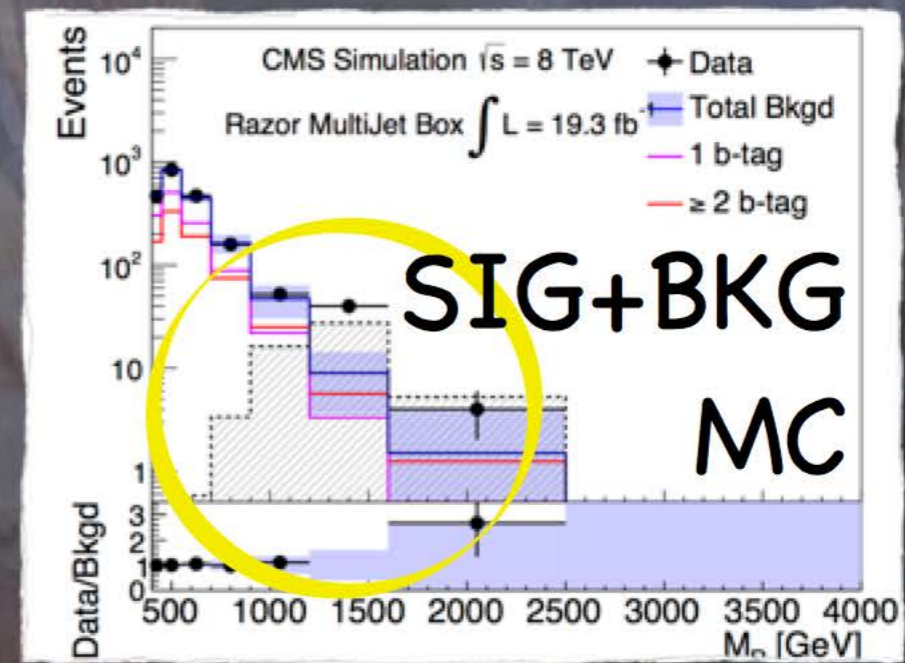
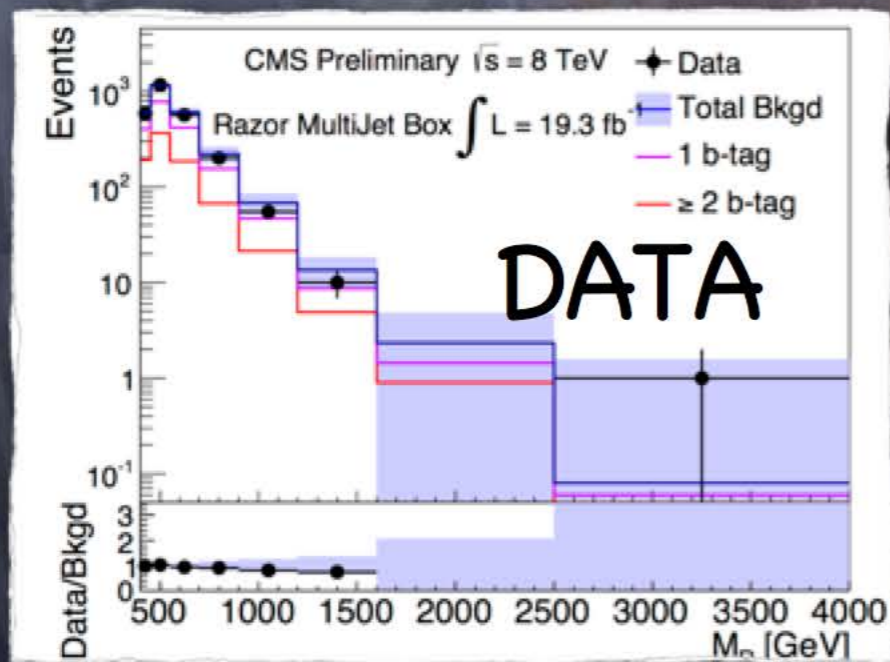
# Razor Inclusive Search

CMS PAS SUS-13-004

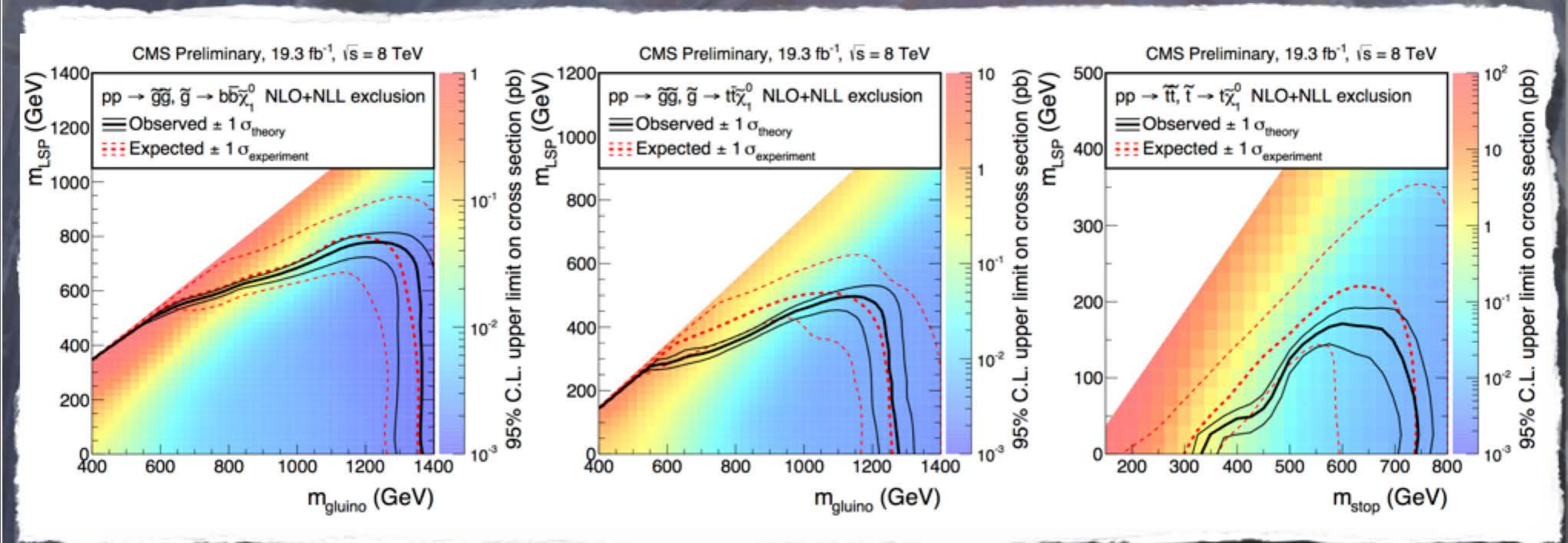
- The extrapolated background prediction is compared to data to evaluate the agreement (given in standard deviations)



- The projections on  $M_R$  and  $R^2$  show now discrepancy. **A signal would emerge as a peak in  $M_R$ , more significant at large  $R^2$**

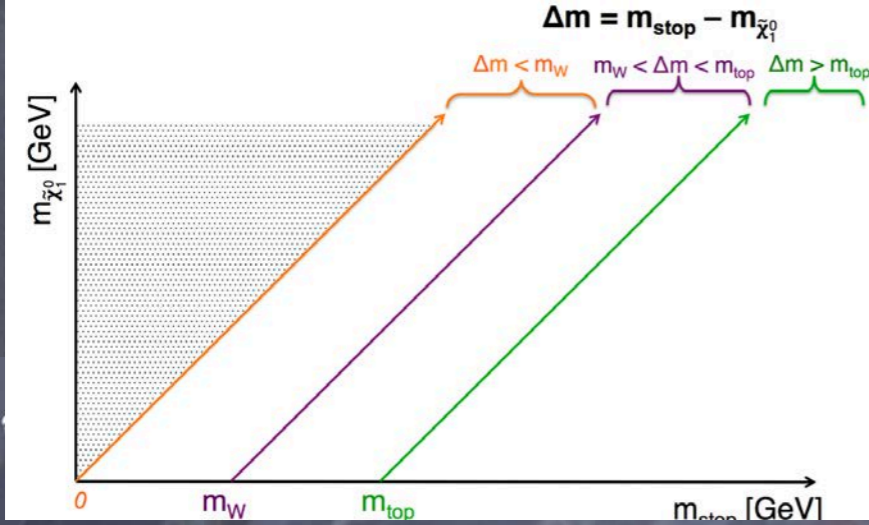


# Razor Bounds on Natural SUSY



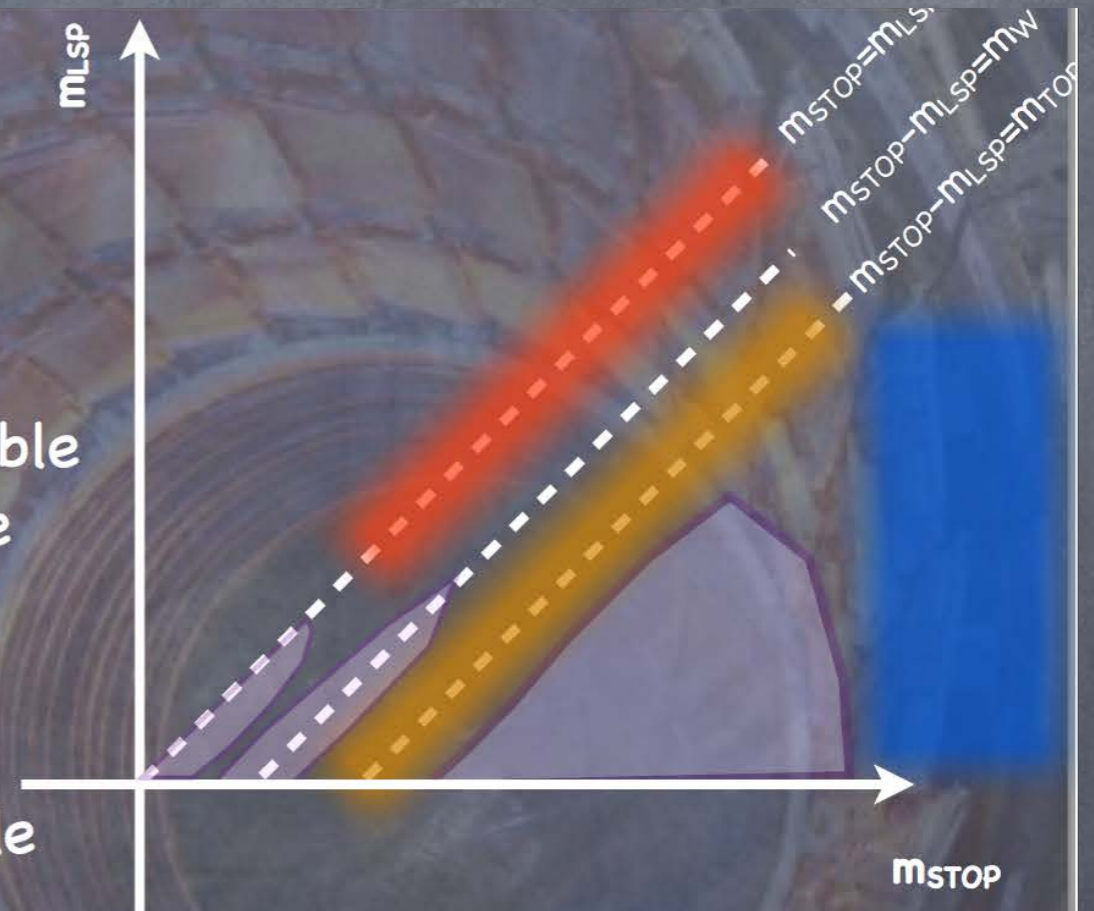
- A ~10% fine-tuning implies squarks(gluinos) lighter than ~700 GeV (~1500 GeV)
- The current exclusion at high mass almost saturate the bounds
- The limits are weaker for lighter sparticles once the LSP is made heavier (compressed spectra)

# Desperately seeking light stops



light stop

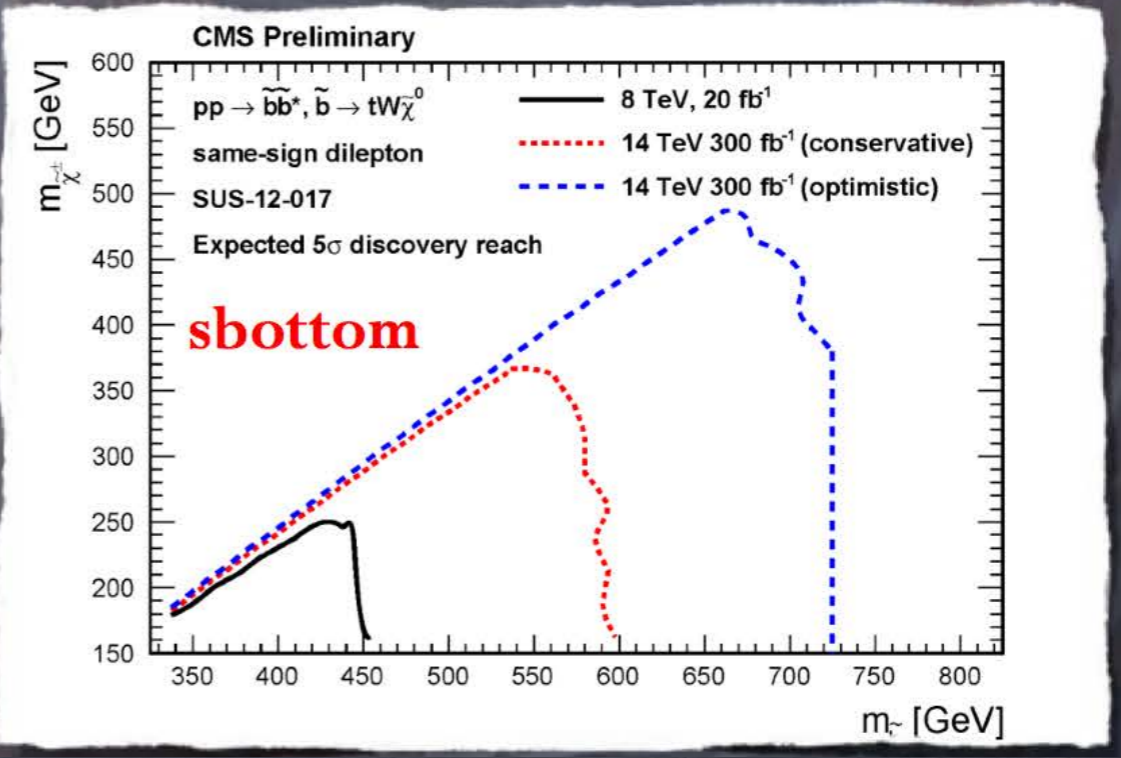
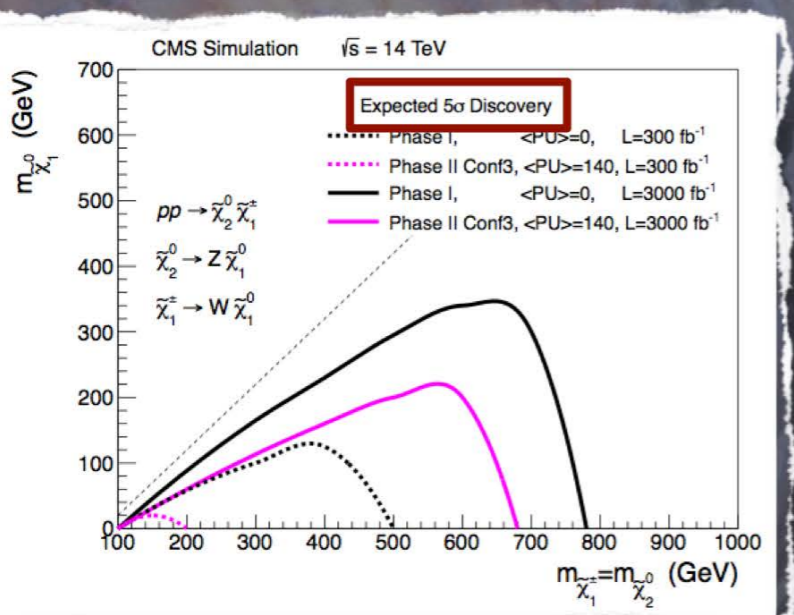
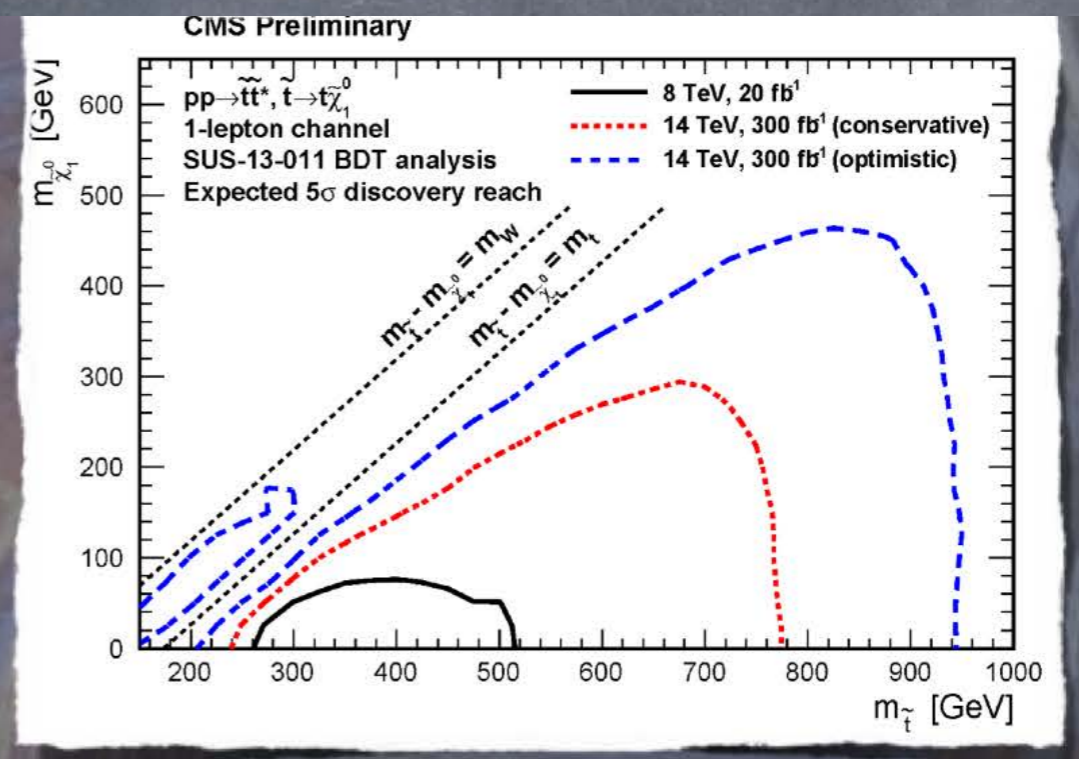
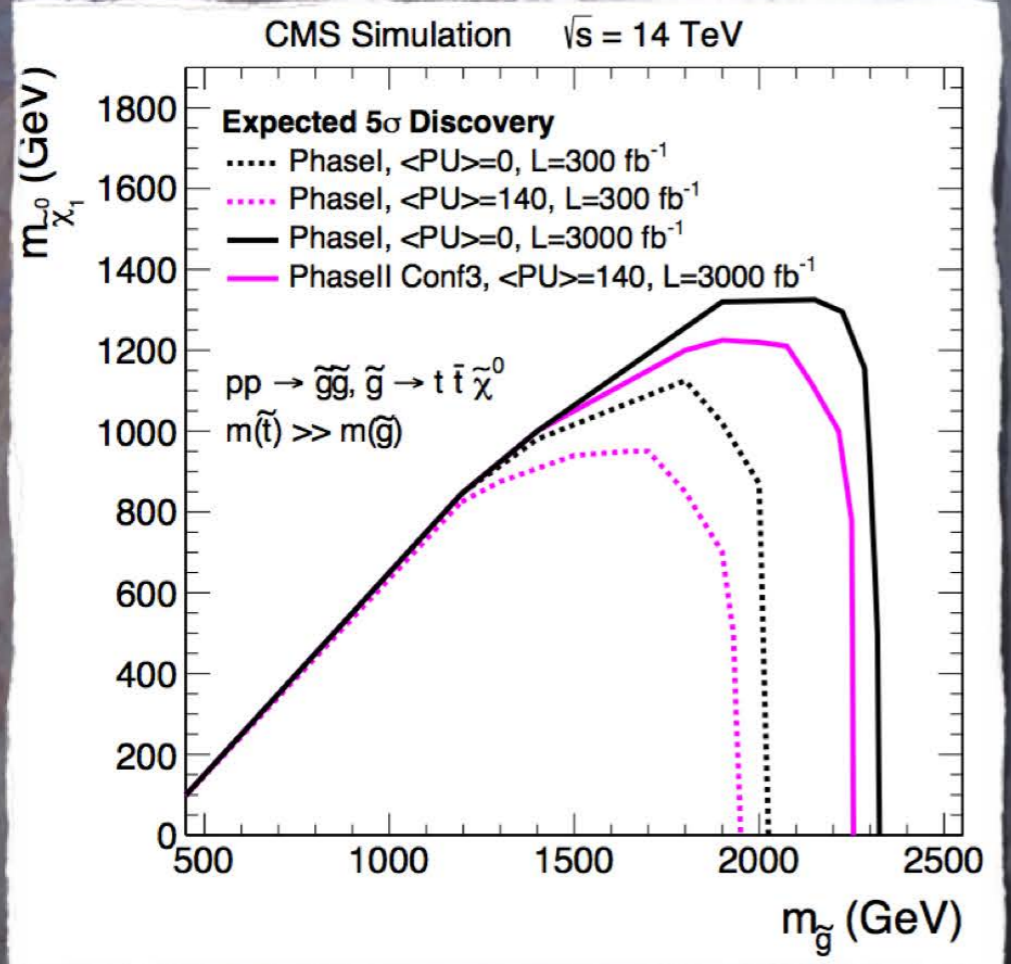
- The current stop searches have three blind spots
- As long as the gluino is kinematically accessible @LHC, these blind spots are covered to some extent
- If not, direct stop/sbottom searches are the most powerful probe (but other ways possible with more light sparticles)
- Gluinos are pushed  $> 1300$  GeV and the stop in one of the blind spots, for natural SUSY to survive 8 TeV data
- The main impact of 13 TeV run is the extension of the gluino reach

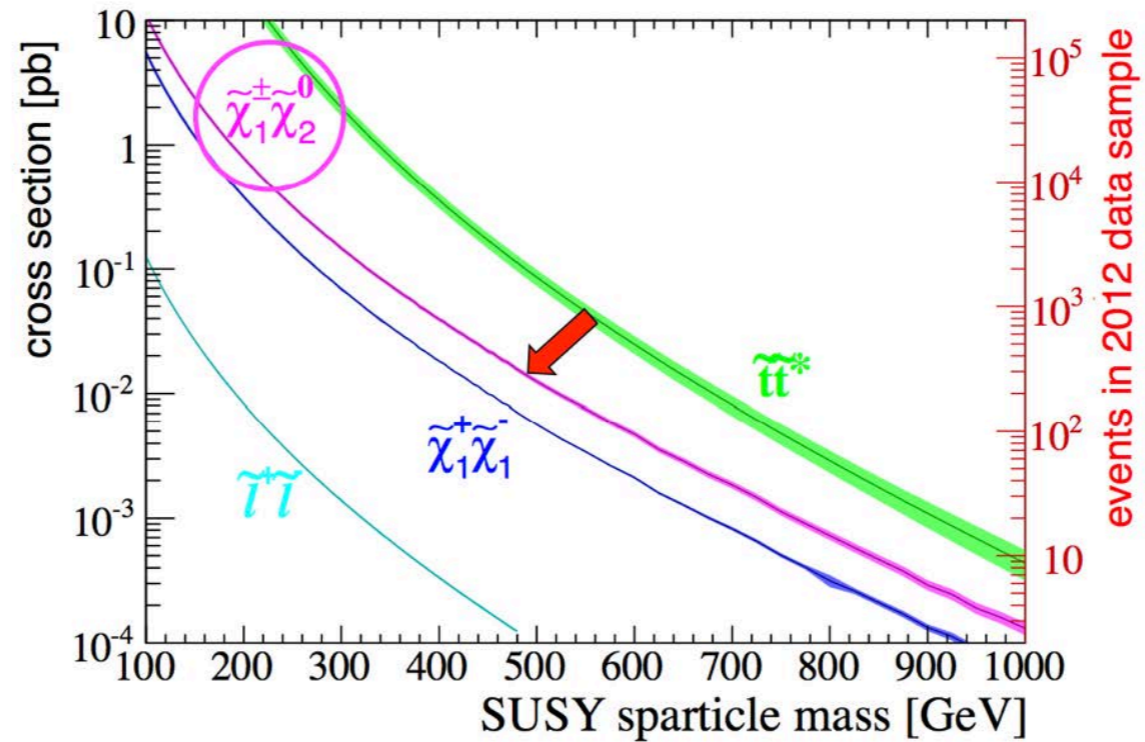


high-mass frontier

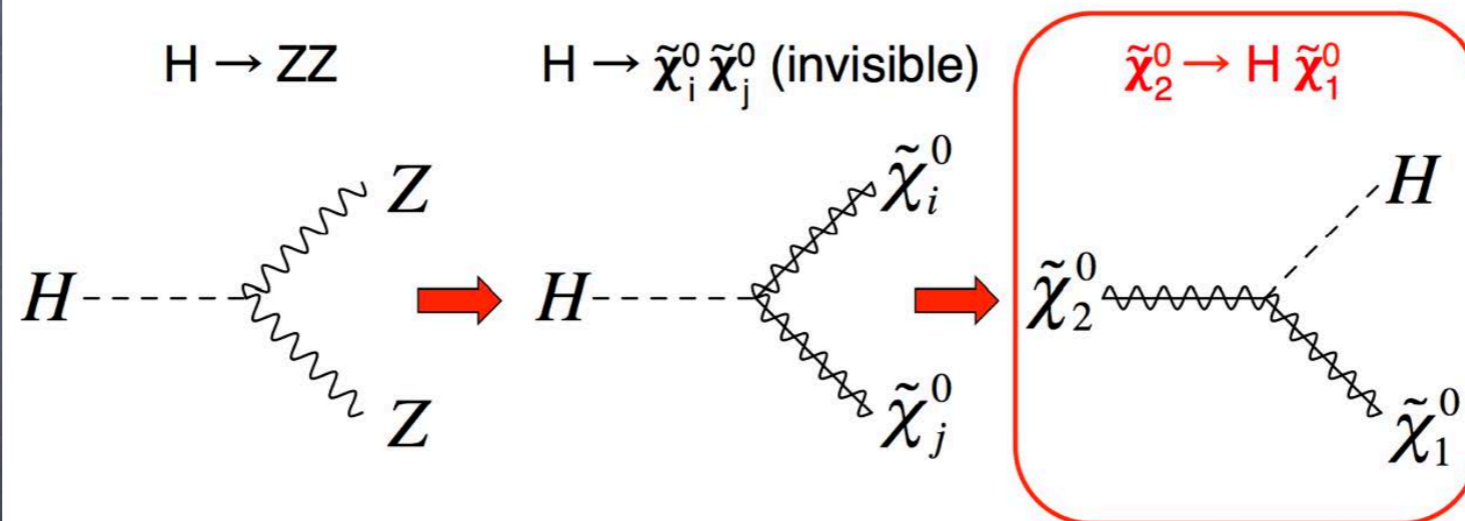
stealth SUSY

compressed spectrum

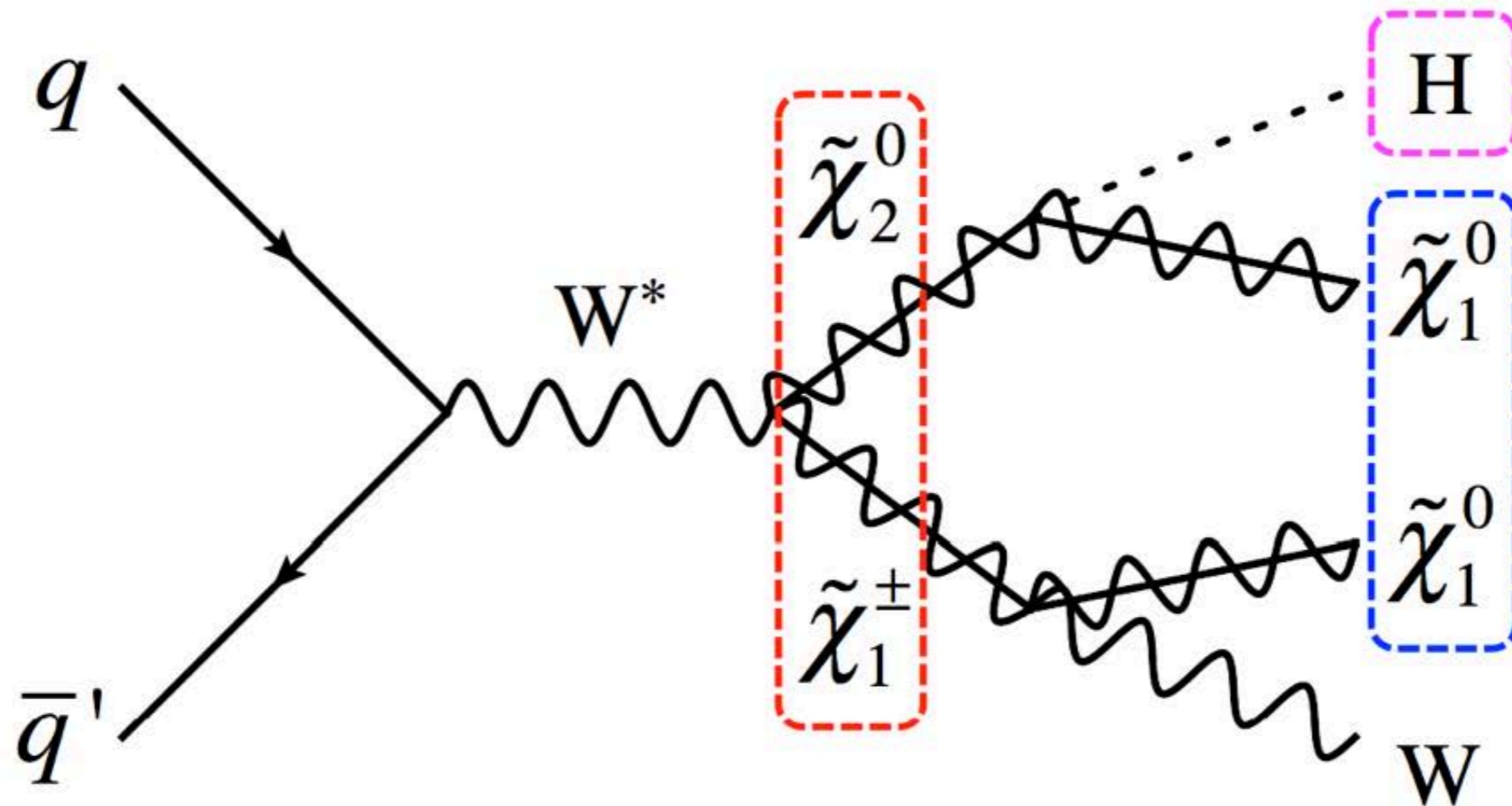




- Search for **chargino-neutralino** pair production
- $\tilde{\chi}_2^0$  often decays to Higgs boson → **use Higgs as “probe”**



- **Higgs boson produced in SUSY neutralino decay**
  - If no other light SUSY particles and open → **dominant decay** [1]
- New method to search for SUSY → **“Higgs-tagging”**
  - Observation would demonstrate **coupling of new particles to Higgs**



- Direct  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  production from s-channel  $W^*$  diagram
  - $\tilde{\chi}_1^\pm$  decays to  $W \tilde{\chi}_1^0$
  - $\tilde{\chi}_2^0$  decays to  $H \tilde{\chi}_1^0$
 } **WH+E<sub>T</sub><sup>miss</sup>**
- **SUSY**, **Higgs**, and **DM WIMPs** in the same event

- **Event selection**

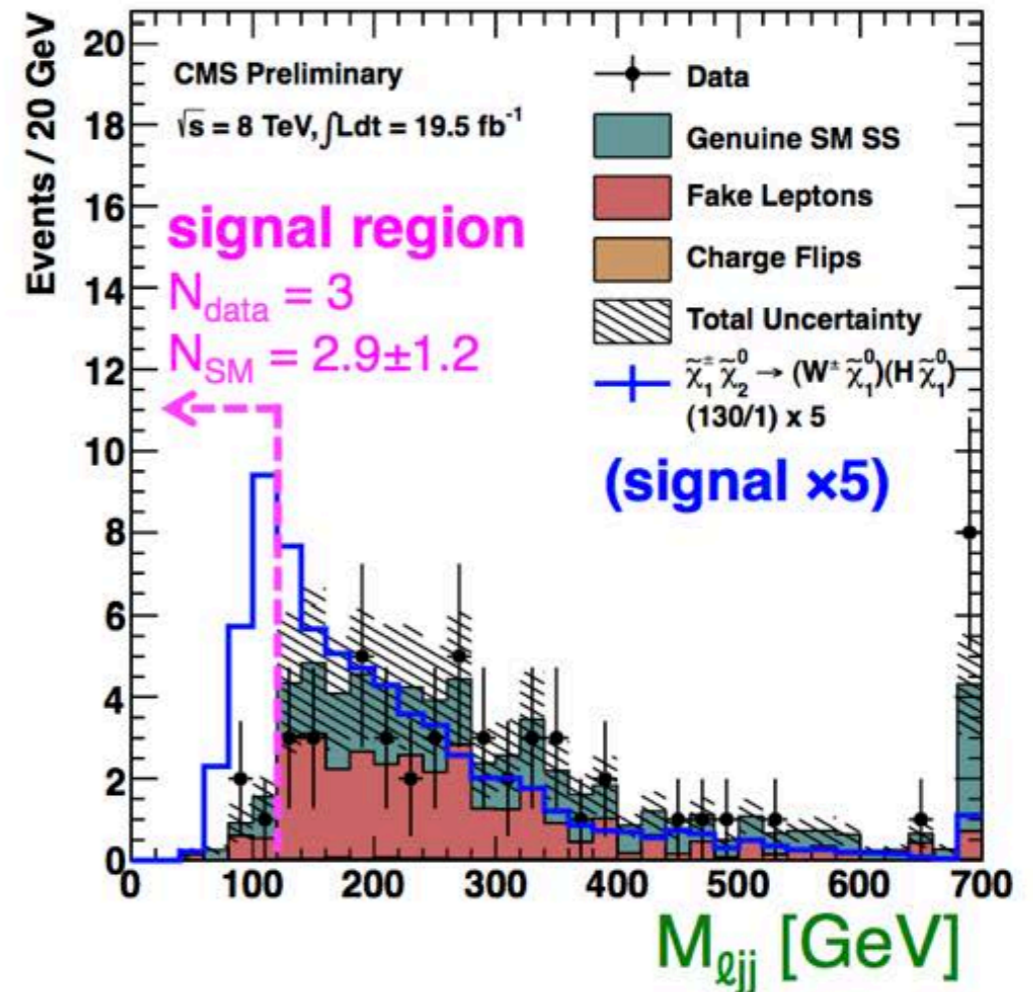
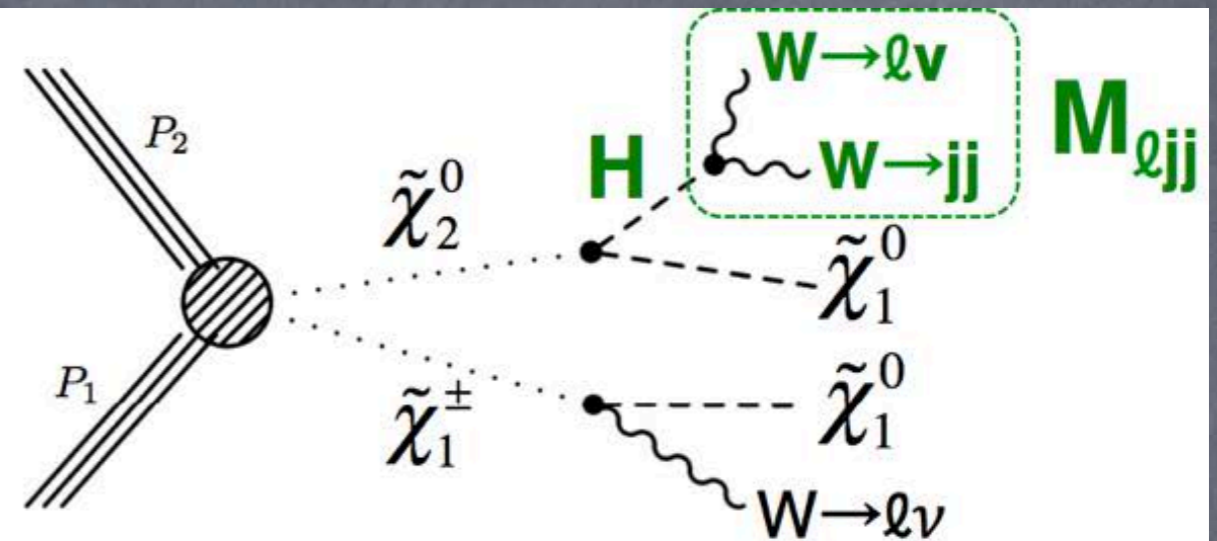
- Exactly 2 SS (ee/eμ/μμ) leptons
- 2 or 3 jets, b-veto
- Moderate  $E_T^{\text{miss}}$

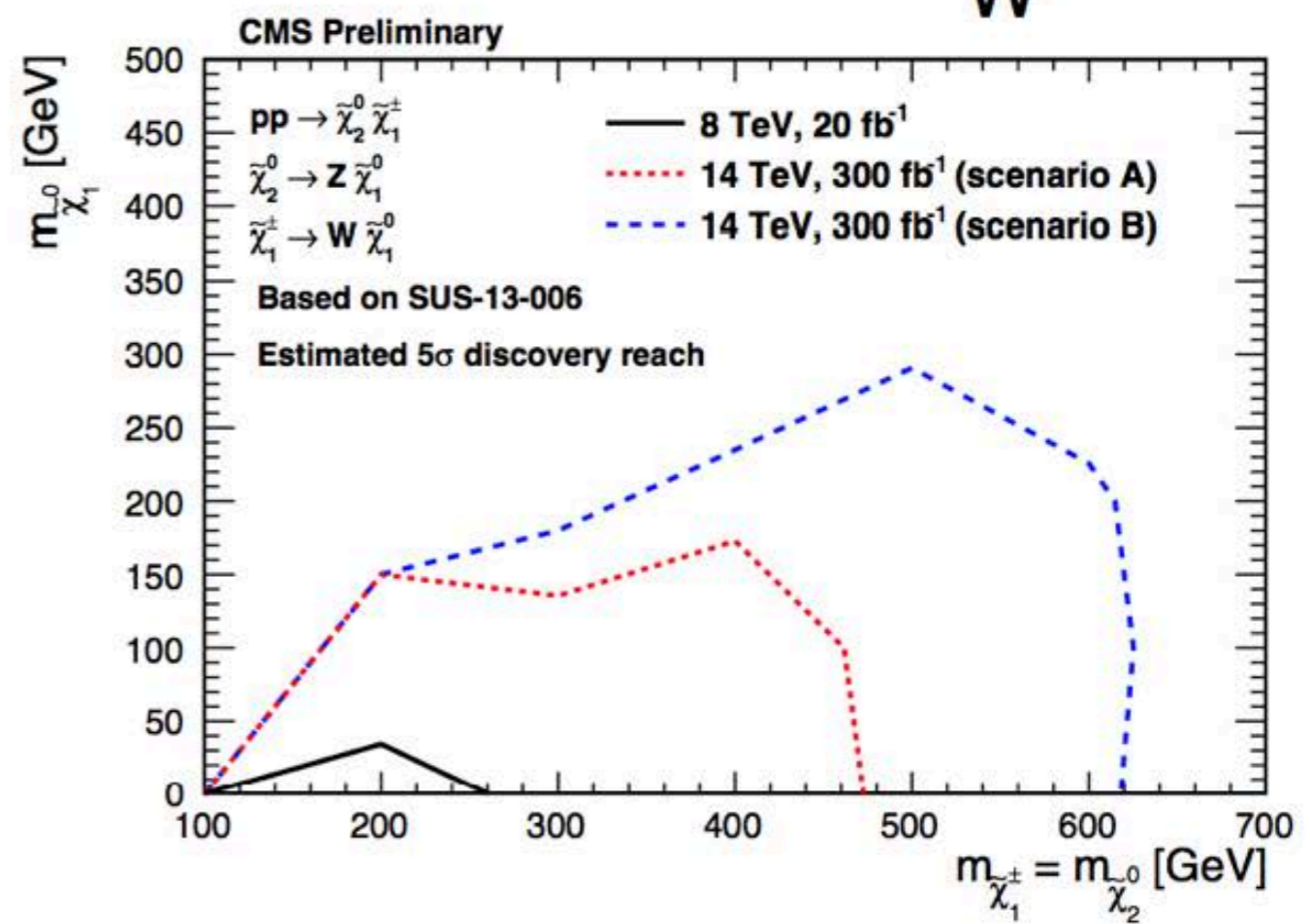
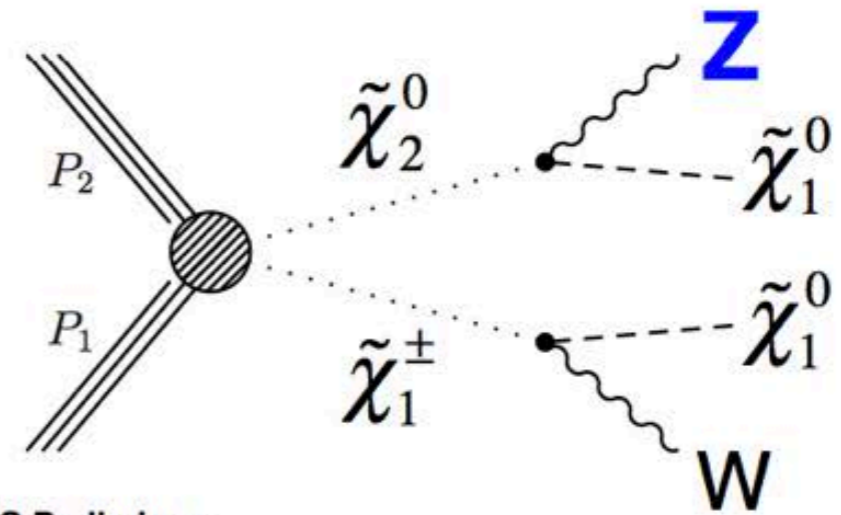
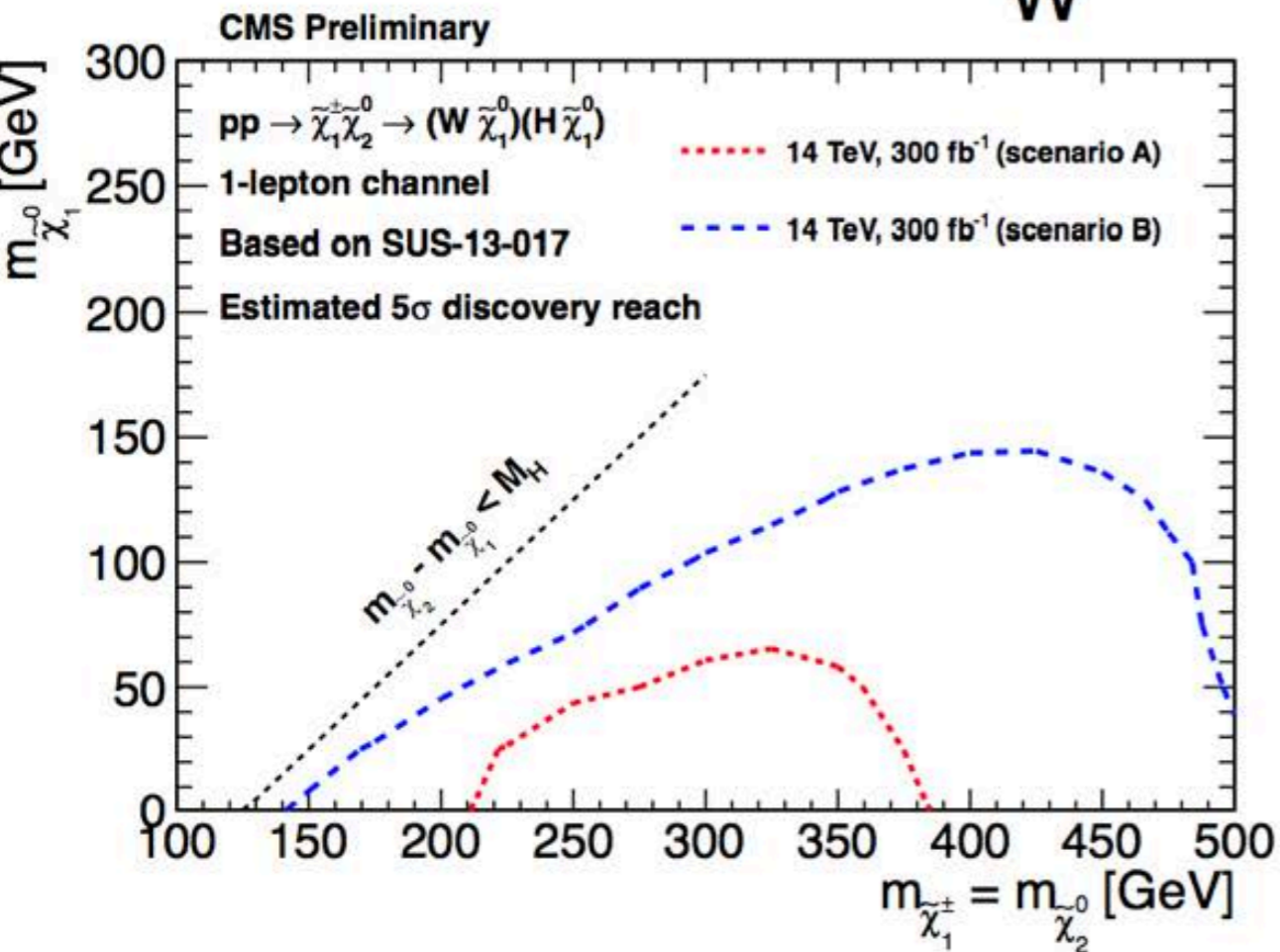
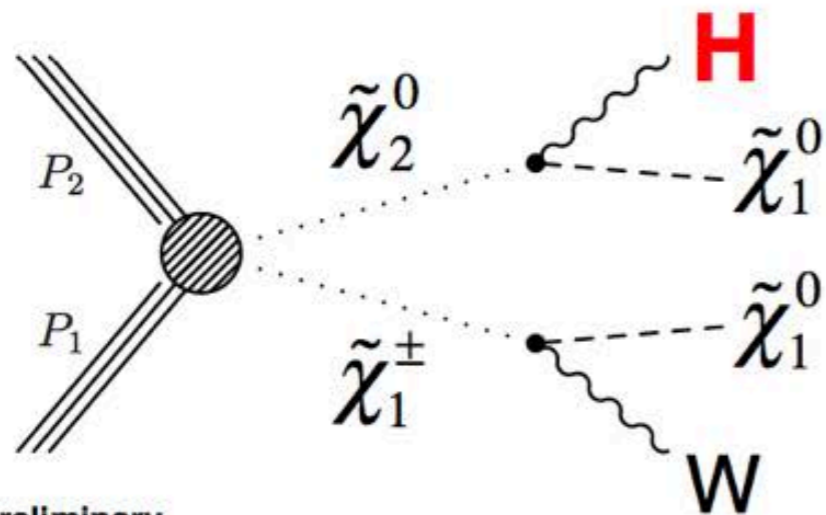
- **Strategy**

- Suppress SM backgrounds with  $E_T^{\text{miss}}$  and related quantities
- Search for bump in  $M_{\ell jj} \sim M_H$

- **Results**

- Data consistent with background  
→ **no evidence for a bump in  $M_{\ell jj}$**





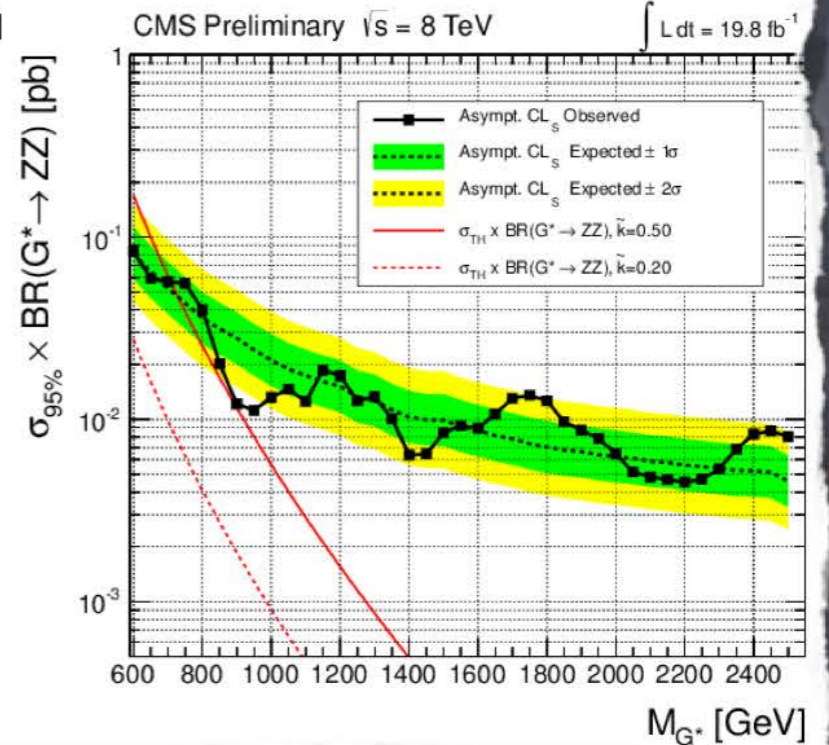
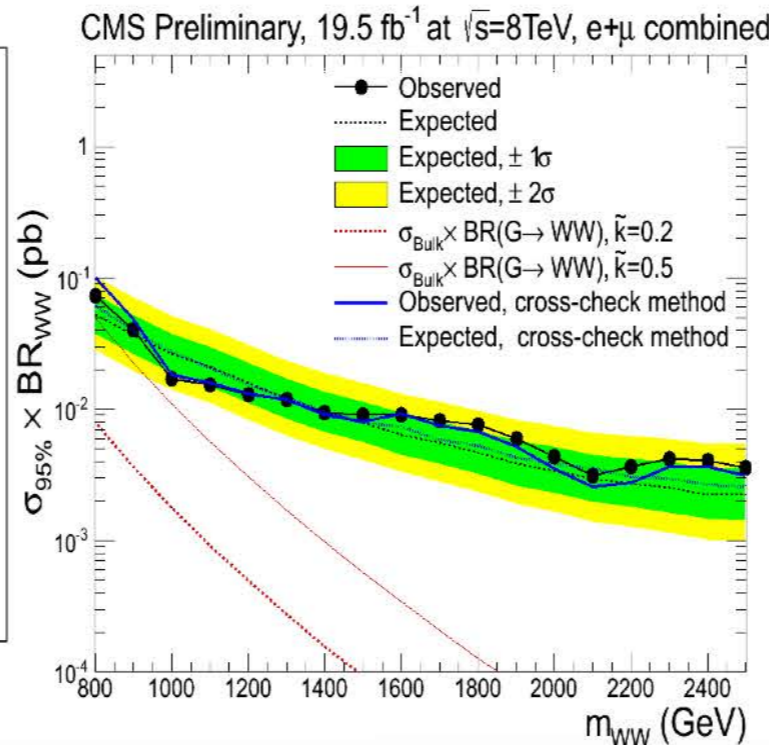
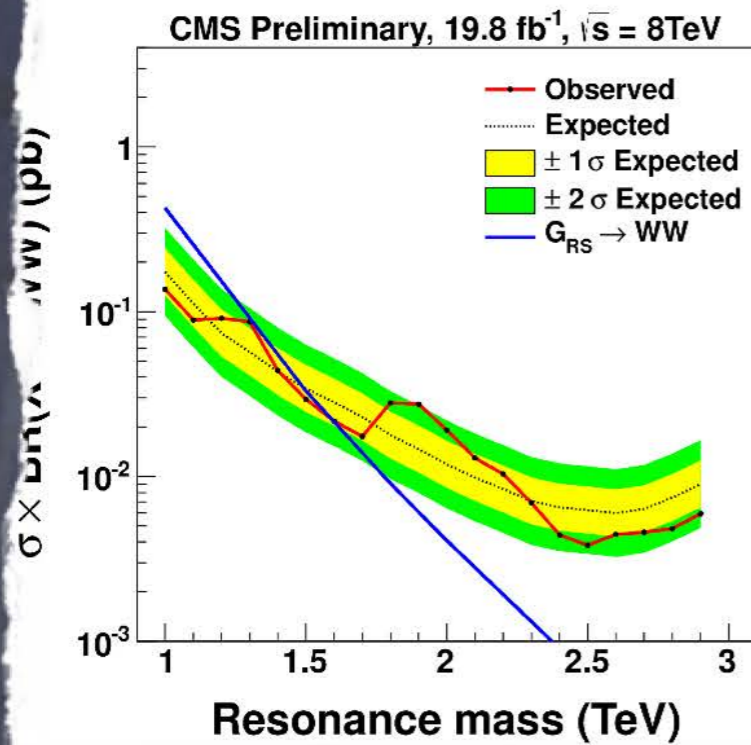
•  $5\sigma$  discovery reach **up to ~400-600 GeV** with 300 fb<sup>-1</sup> 14 TeV data

# Bump hunting $X \rightarrow VV$

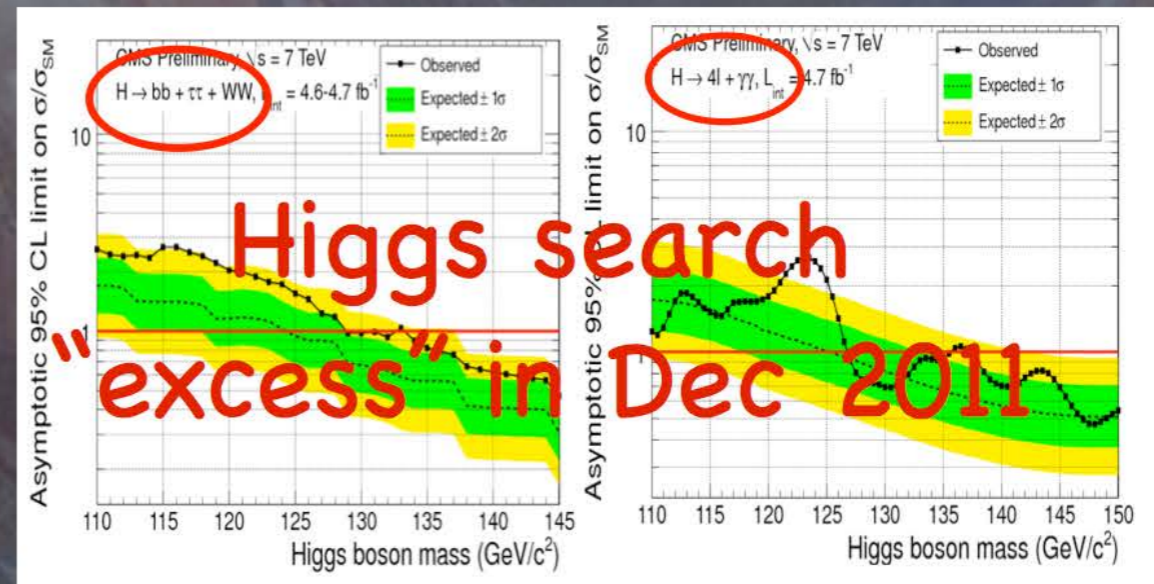
**VV  $\rightarrow$  fully hadronic**

**WV  $\rightarrow$  semileptonic**

**ZV  $\rightarrow$  semileptonic**



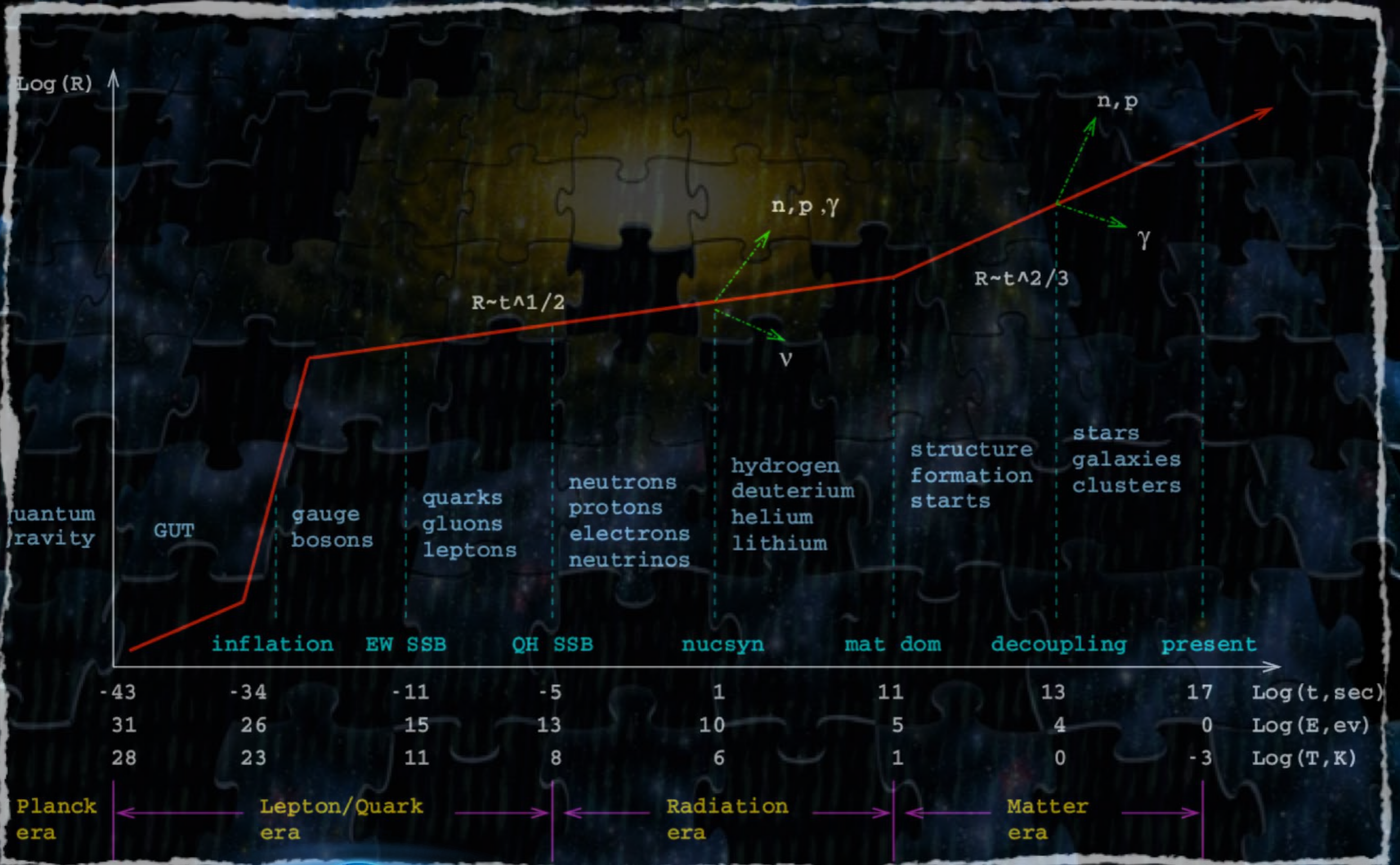
We see excesses around 1900 GeV in 4/5 channels (counting e and  $\mu$  as 2 different channels)  
It looks like...



H boson : is it the Standard Model? Does it behave as predicted? Is there more than one? how many more? Finding heavy Higgs bosons with non-standard interactions is a major long-term challenge for the LHC; supersymmetry predicts at least five kinds of Higgs bosons, differing in their mass and other properties, is it connected with DM ? DE?



H boson  
 implies the earliest known event of the Big Bang:  
 the "electroweak phase transition"



# Chosen & the Dark Matter

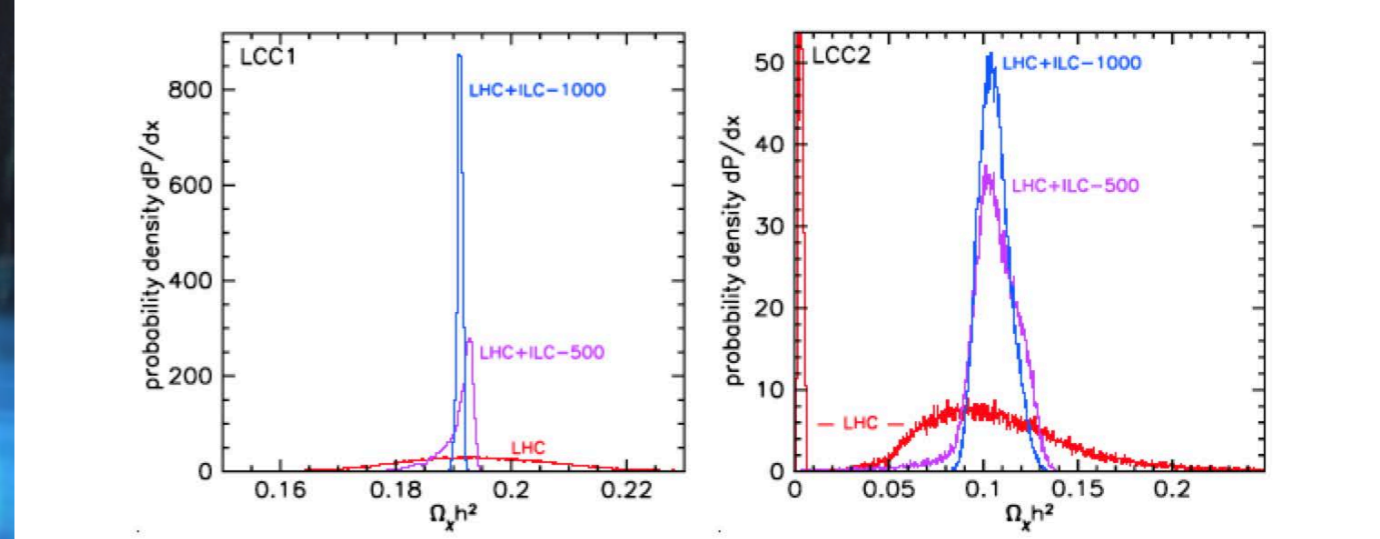
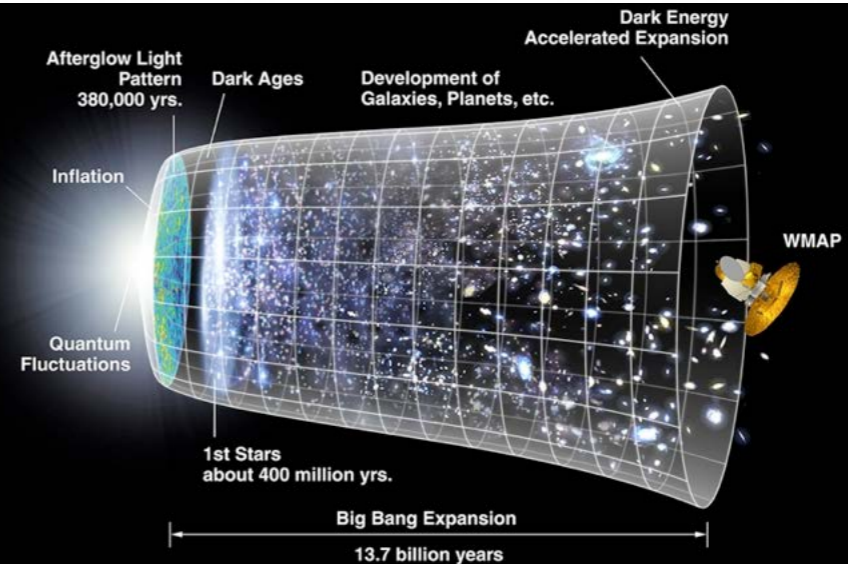
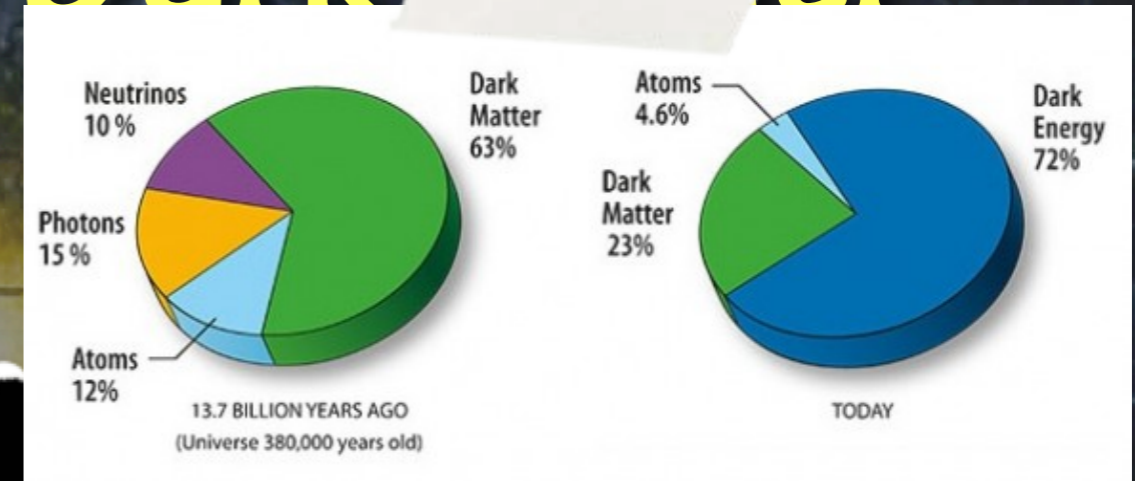
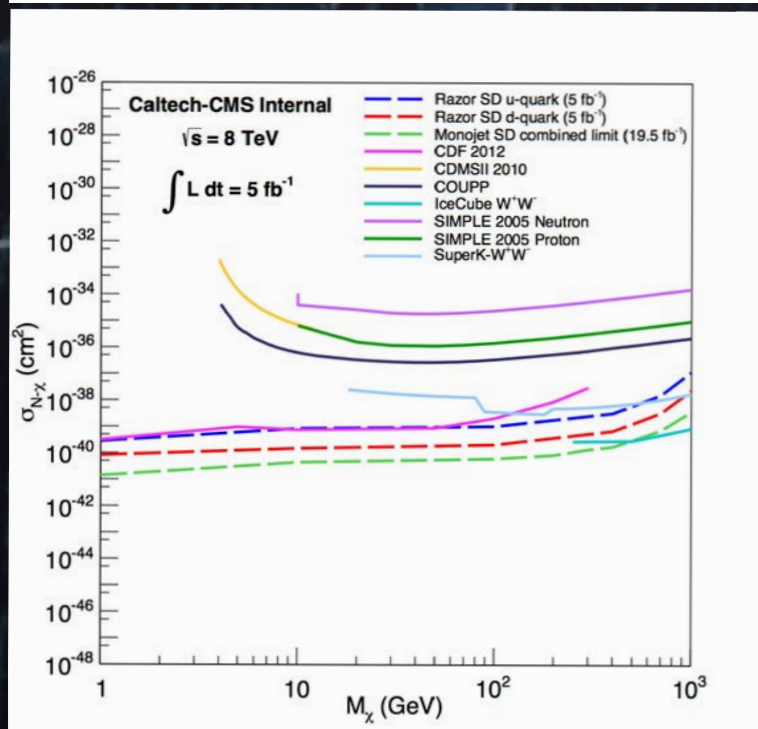
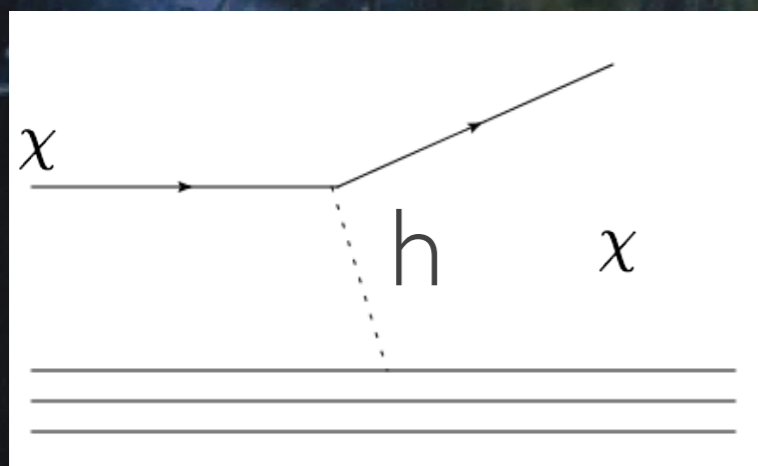
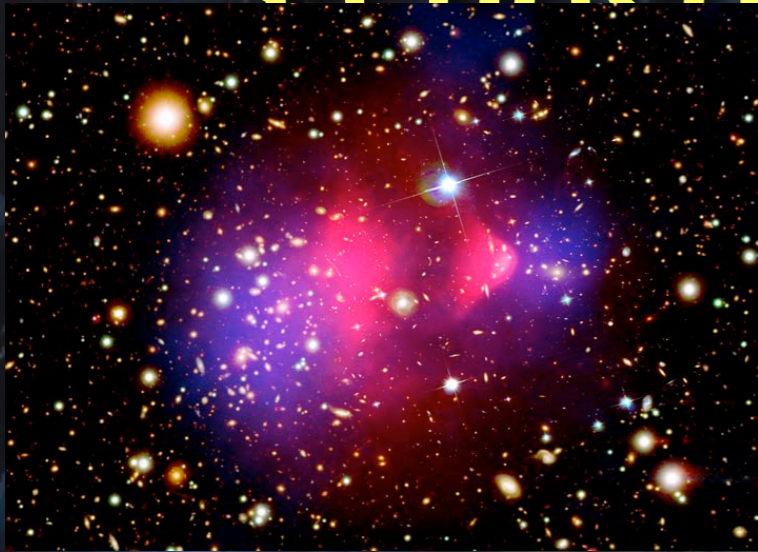
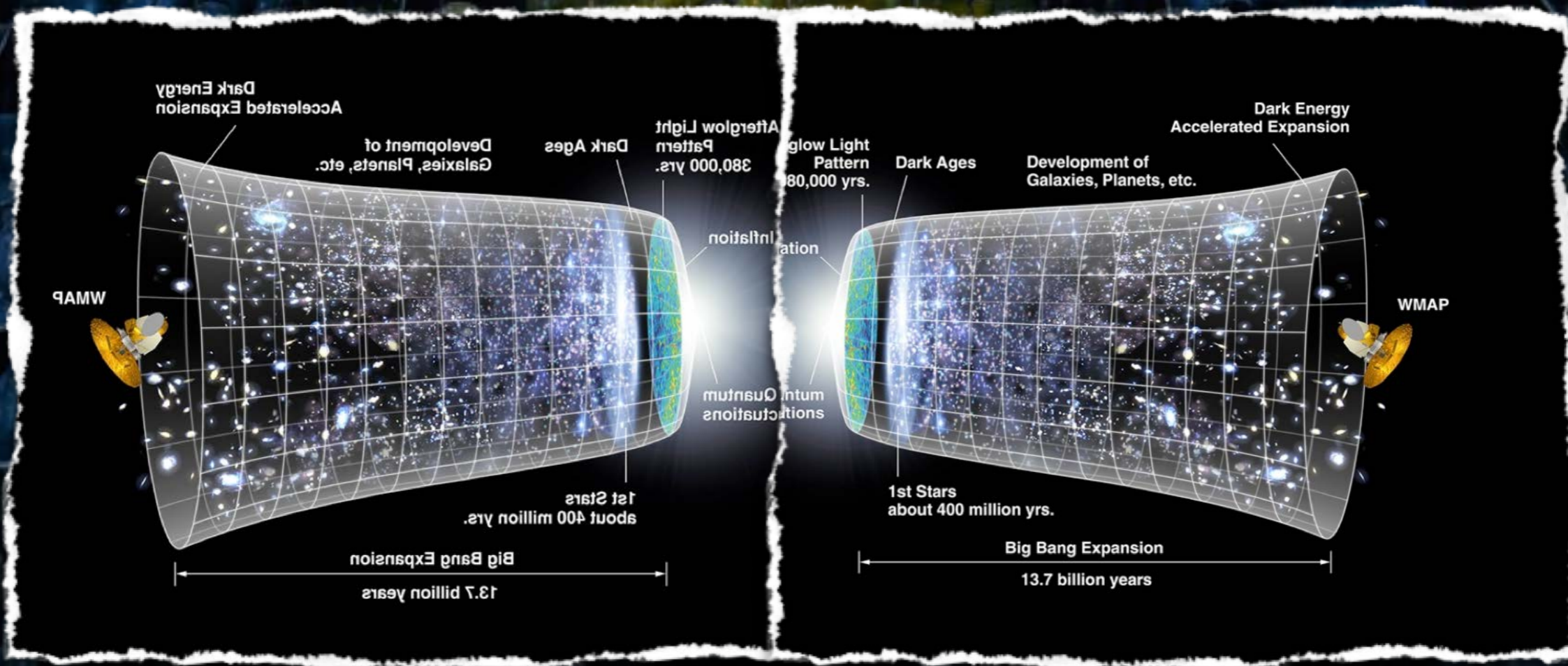
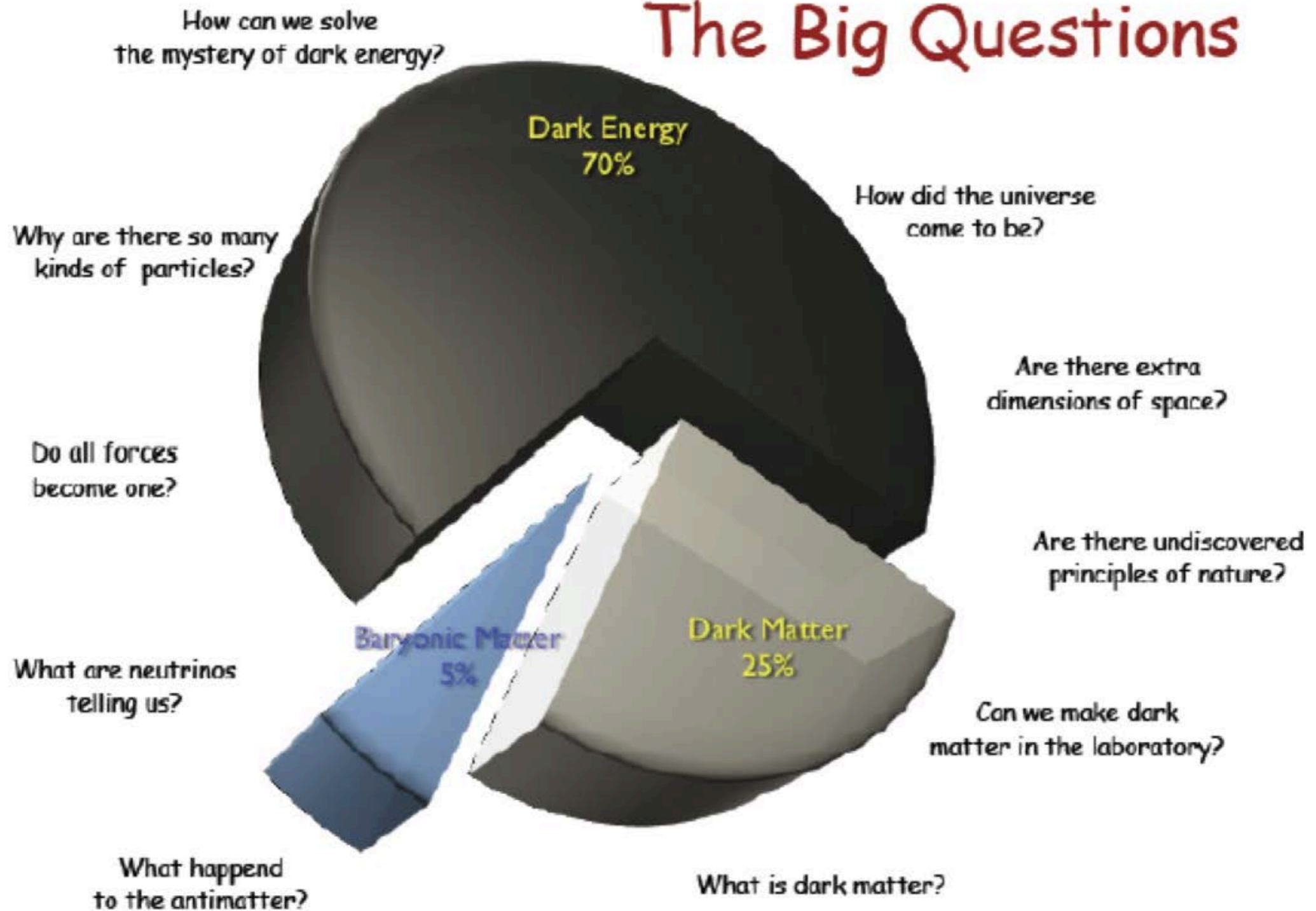


Fig. 17 Probability distribution of predictions for  $\Omega_\chi h^2$  for the LCC1 [SPS1a'] "bulk" point and the LCC2 "focus-point" point from measurements at ILC with  $\sqrt{s} = 0.5$  and 1 TeV, and LHC (after qualitative identification of the model) [122]

# H boson & the Universe Dynamics



# The Big Questions



# getting back to complexity (cocktails and blends)

★  $\frac{2}{3}$  of SM,  $\frac{1}{6}$  of Majorana neutrinos,  $\frac{1}{6}$  of axions, add Peccei - Quinn global symmetry, strain the result





**Fundamental Building Blocks of Nature**

**Original Elements**

**Advanced Materials**

**Biological Sciences**

**Light Sources**

**Neutron Sources**

**Colliders**

**Beam Dynamics**

**Accelerators and Beams Tools of Discovery**

**Medical Accelerators**

**Industry**

**Industrial Accelerators**

**Source Technology**

**Medicine**

**Particle Acceleration**

**Ion Implanters**

**National Security**

**Energy**

**Education**

