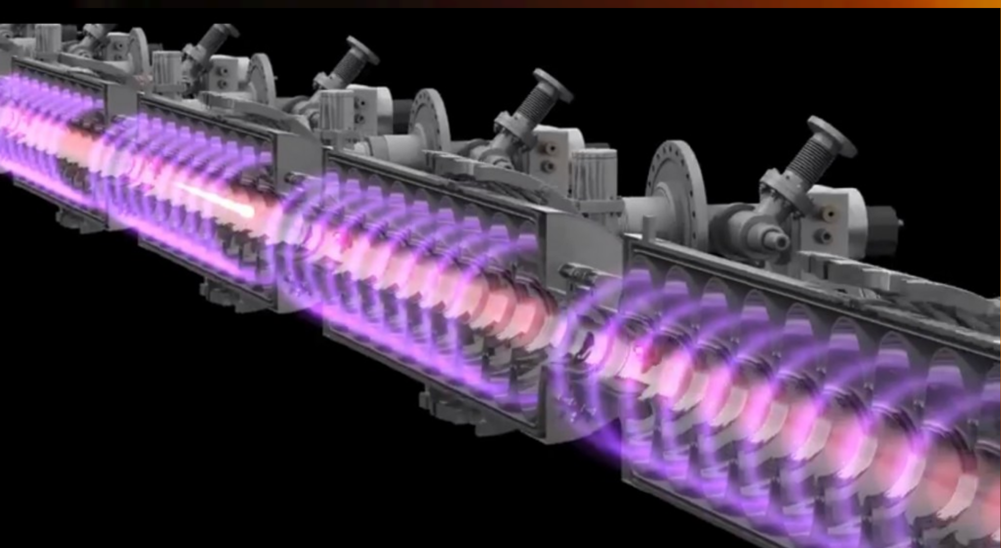
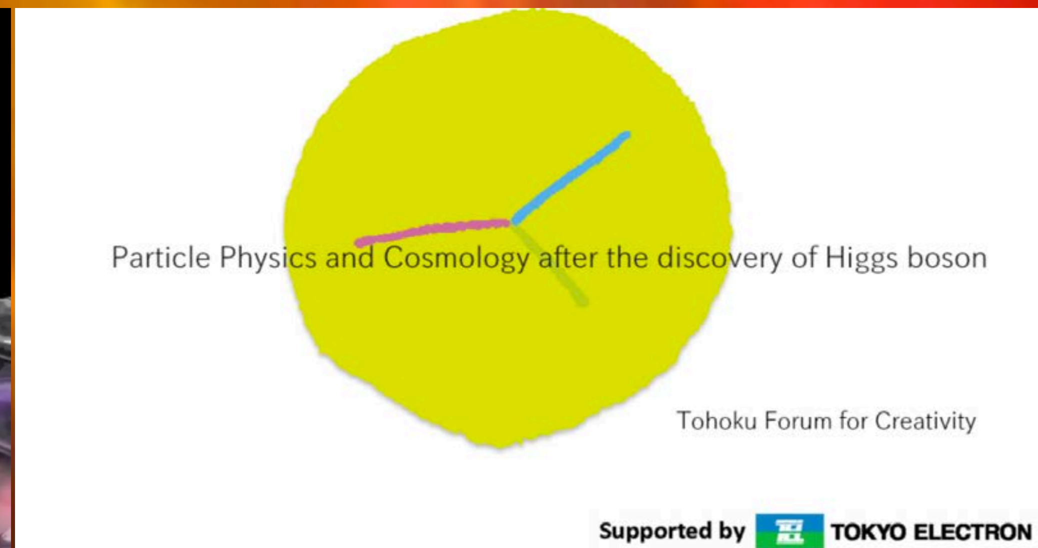
Higgs discovery, precision, and beyond





M.Spiropulu
Caltech

Thanks to
山本 均
and
Tohoku University

October 18, 2013 4:25 pm

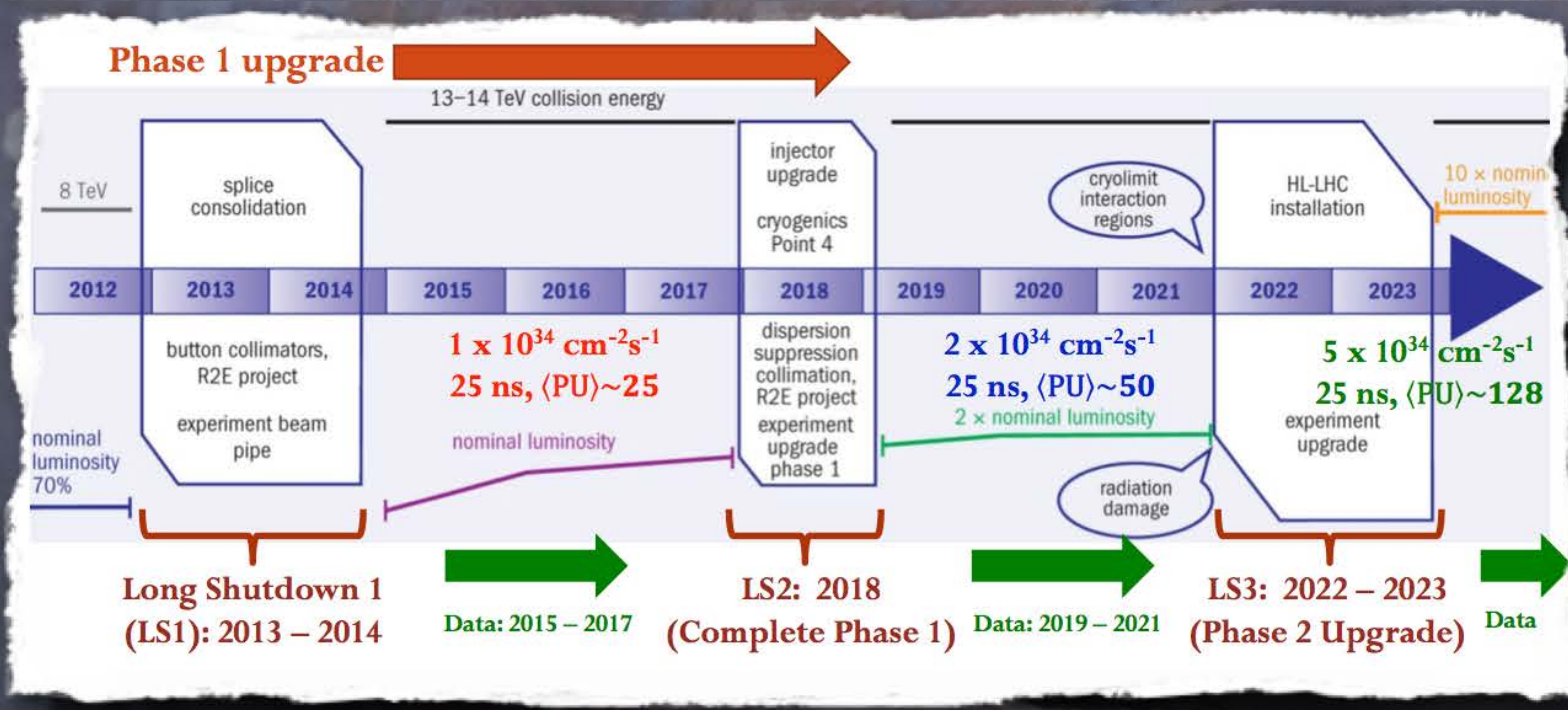
The shape of physics to come

By Clive Cookson

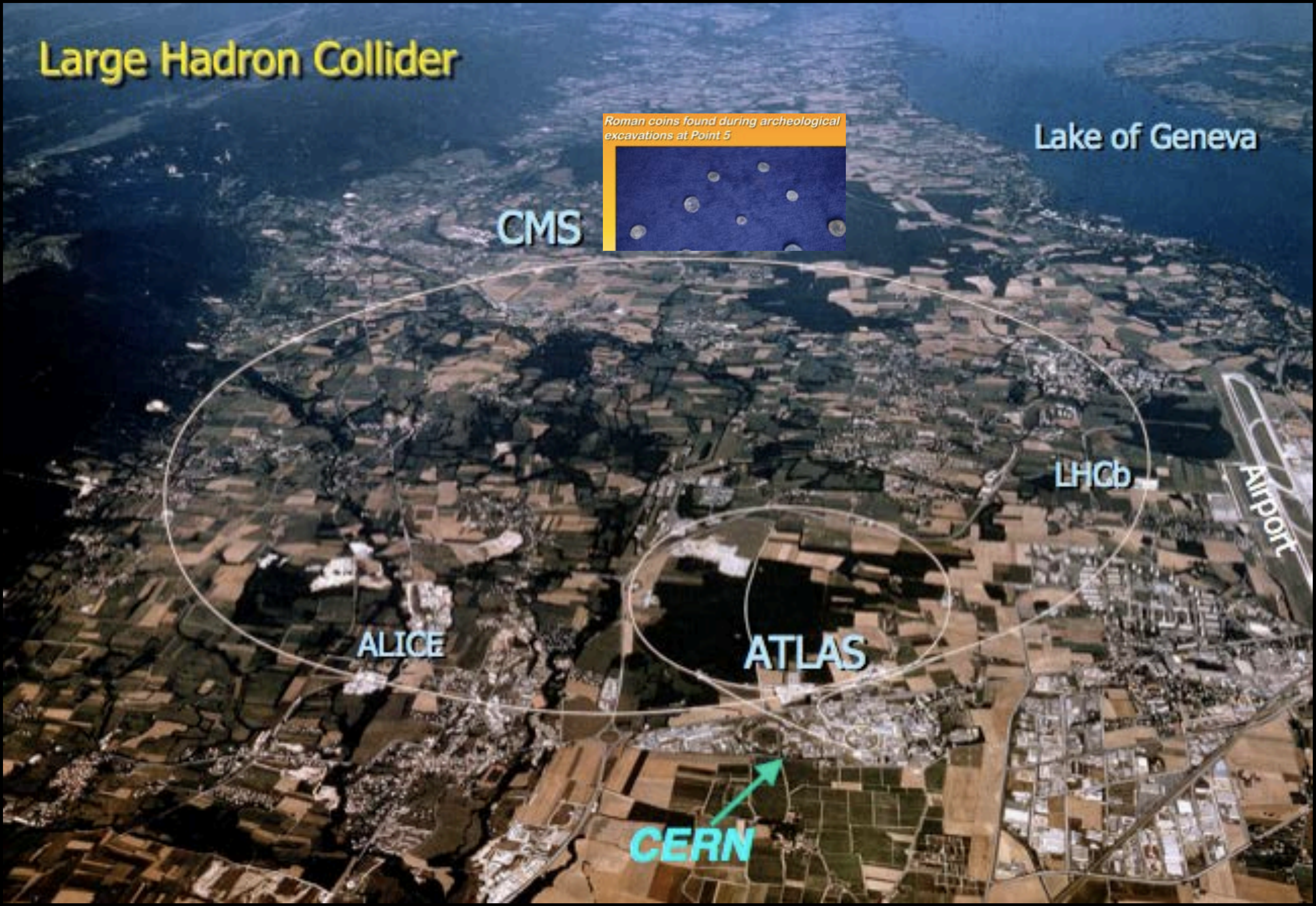
ft.com > life&arts >

FT Magazine

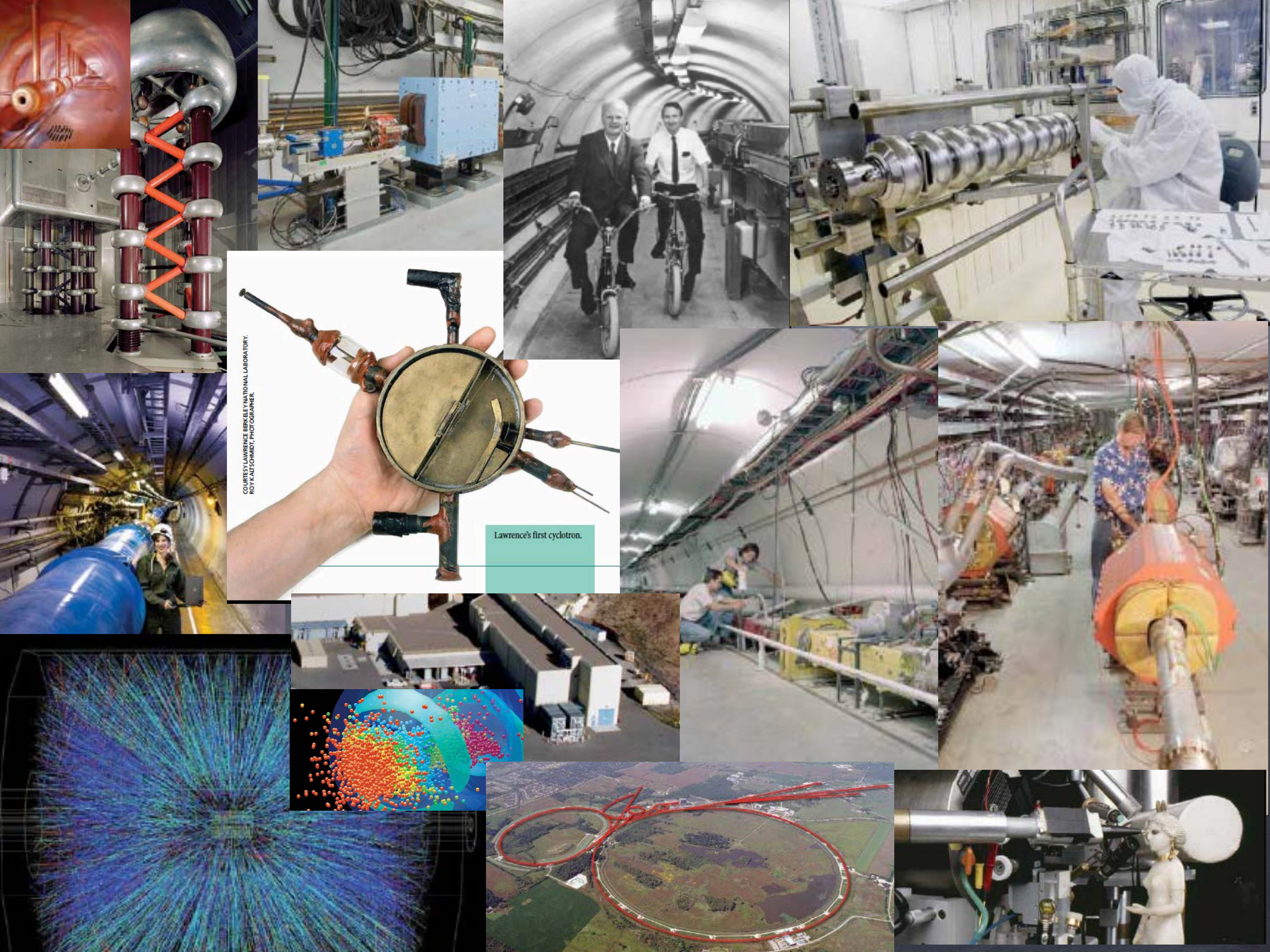
'It will drive further development of technology and knowledge through the 21st century'



Phase 1 upgrade
13–14 TeV collision energy
8 TeV
splice consolidation
injector upgrade
cryogenics Point 4
cryolimit interaction regions
HL-LHC installation
10 × nomin luminosity
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
button collimators, R2E project
experiment beam pipe
1×10^{34} cm^{-2}s^{-1}
25 ns, ⟨PU⟩~25
dispersion suppression collimation, R2E project
experiment upgrade phase 1
2×10^{34} cm^{-2}s^{-1}
25 ns, ⟨PU⟩~50
2 × nominal luminosity
5×10^{34} cm^{-2}s^{-1}
25 ns, ⟨PU⟩~128
experiment upgrade
nominal luminosity 70%
nominal luminosity
radiation damage
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
Roman coins found during archeological excavations at Point 5
Lake of Geneva
CMS
LHCb
Airport
ALICE
ATLAS
CERN

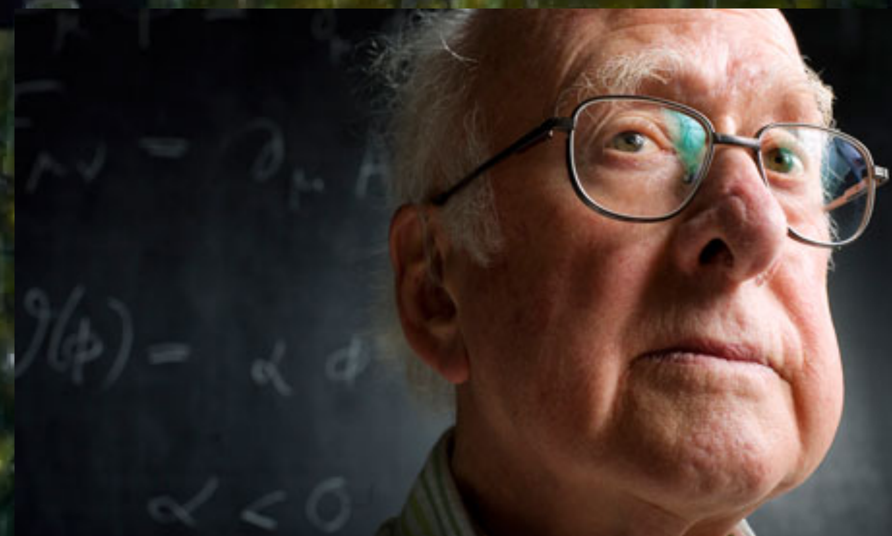

2433



COURTESY LAWRENCE BERKELEY NATIONAL LABORATORY. ROY KALTSCHMIDT, PHOTOGRAPHER.

Lawrence's first cyclotron.

Higgs Quo Vadis
(Stockholm, Dec 12, 2013)

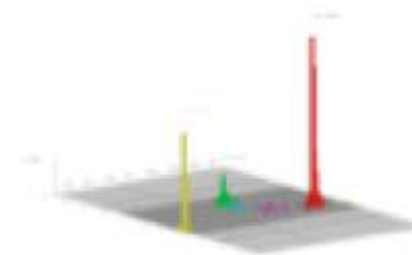


"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the ***discovery of the predicted fundamental particle,*** by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

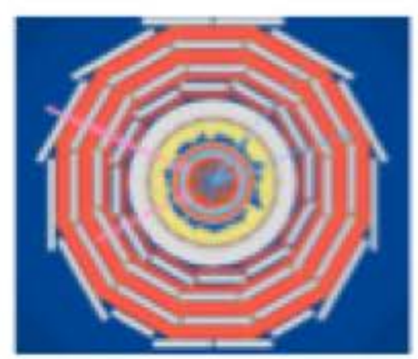
The major physics scope of the LHC

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

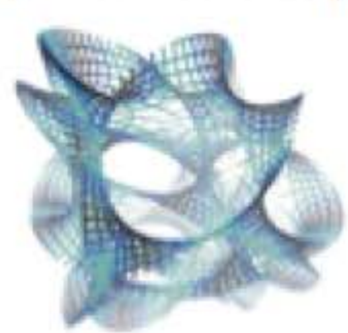
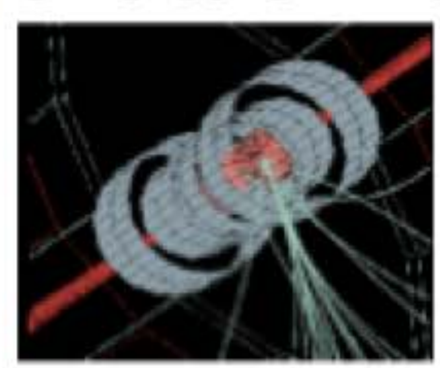


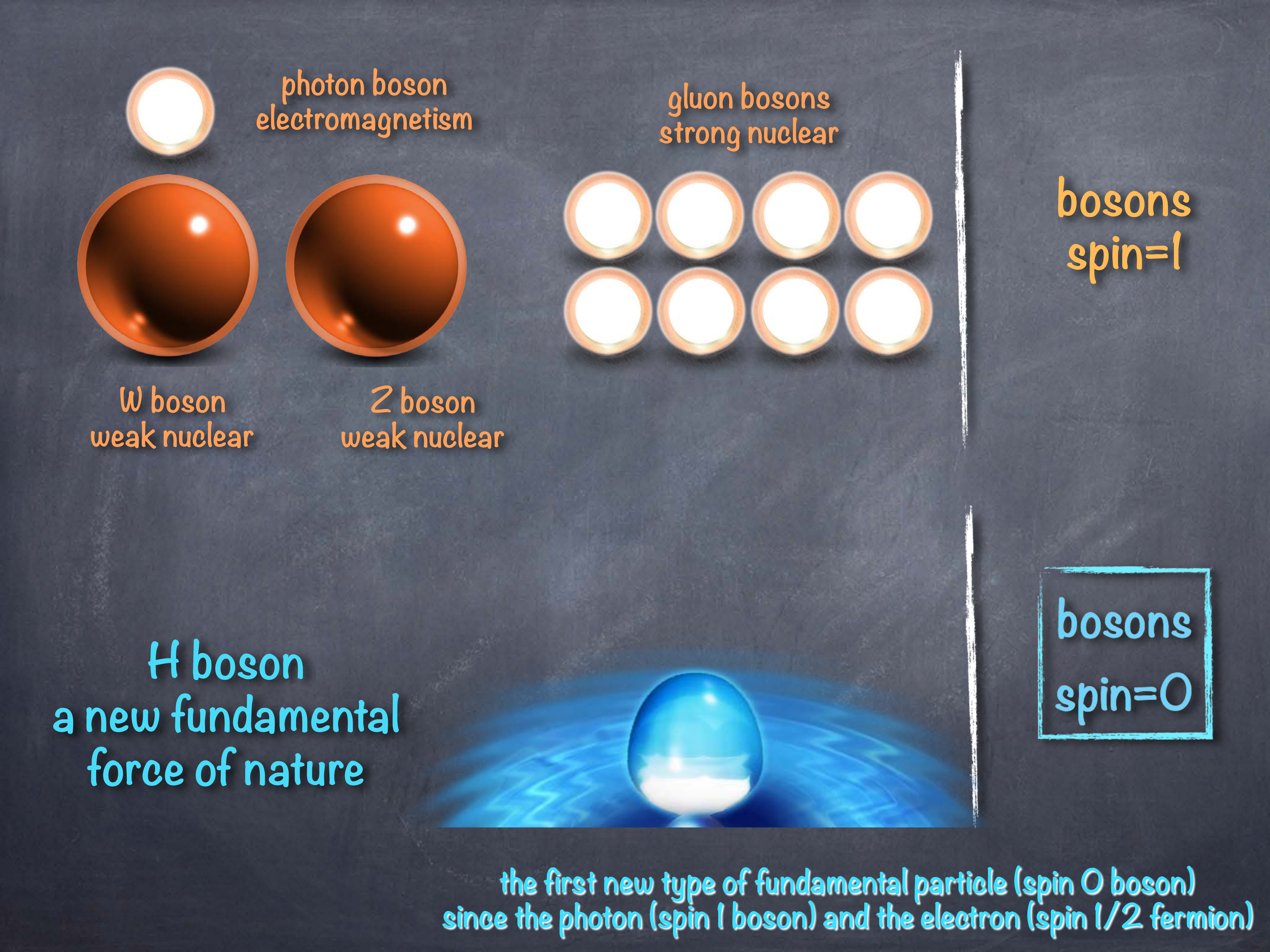


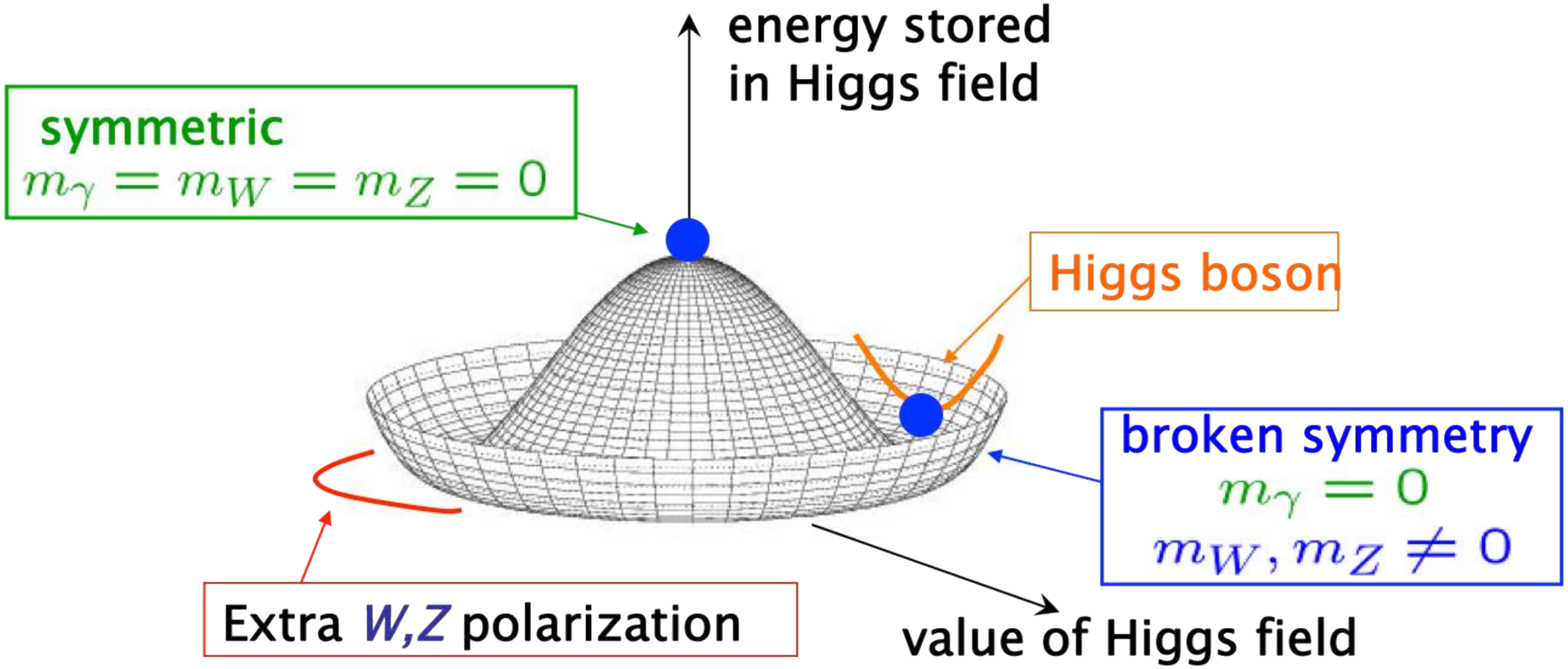

- Find the Higgs particle



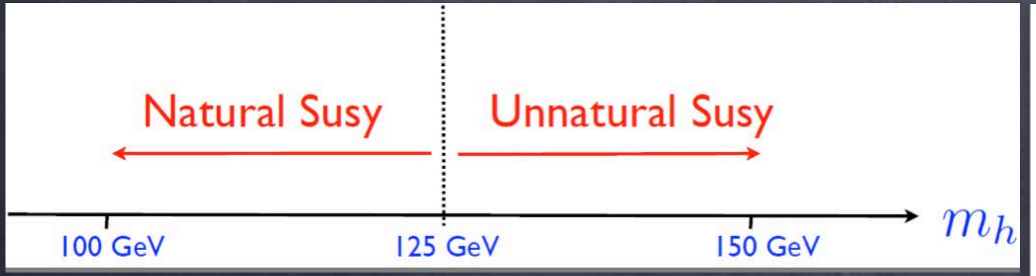
- Find new particles, forces, extra dimensions of space

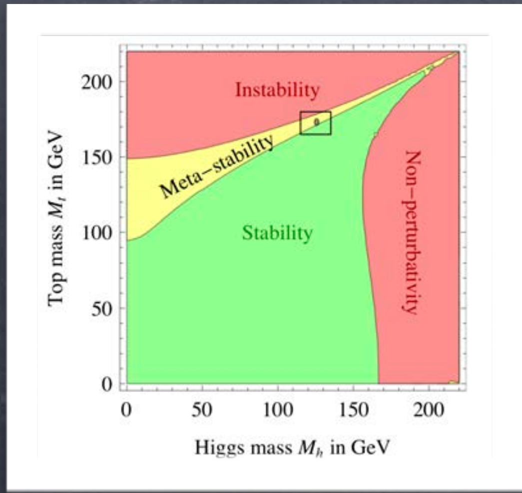



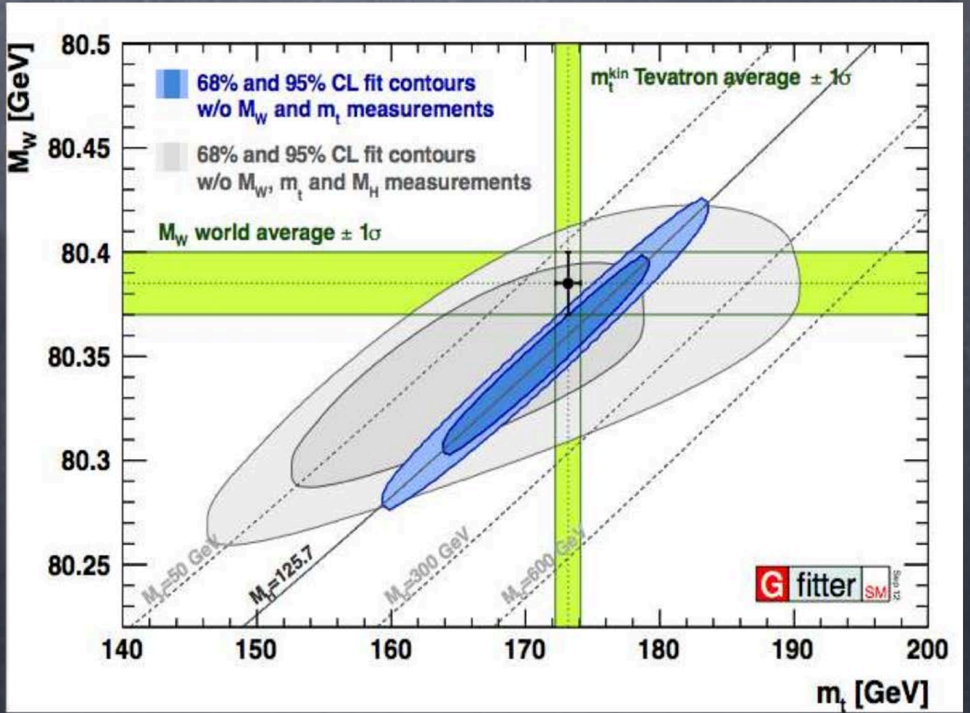

photon boson
electromagnetism
gluon bosons
strong nuclear
bosons
spin=1
W boson
weak nuclear
Z boson
weak nuclear
H boson
a new fundamental
force of nature
bosons
spin=0
the first new type of fundamental particle (spin 0 boson)
since the photon (spin 1 boson) and the electron (spin 1/2 fermion)



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 [n]

Combined Final States $= 1.07 \pm 0.26$ (S = 1.4)
WW^* Final State $= 0.88 \pm 0.33$ (S = 1.1)
ZZ^* 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 Page 4 Created: 7/31/2013 15:19

H^0 DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
WW^*	seen	–
ZZ^*	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 ($m_{H_1^0} < m_{H_2^0}$)

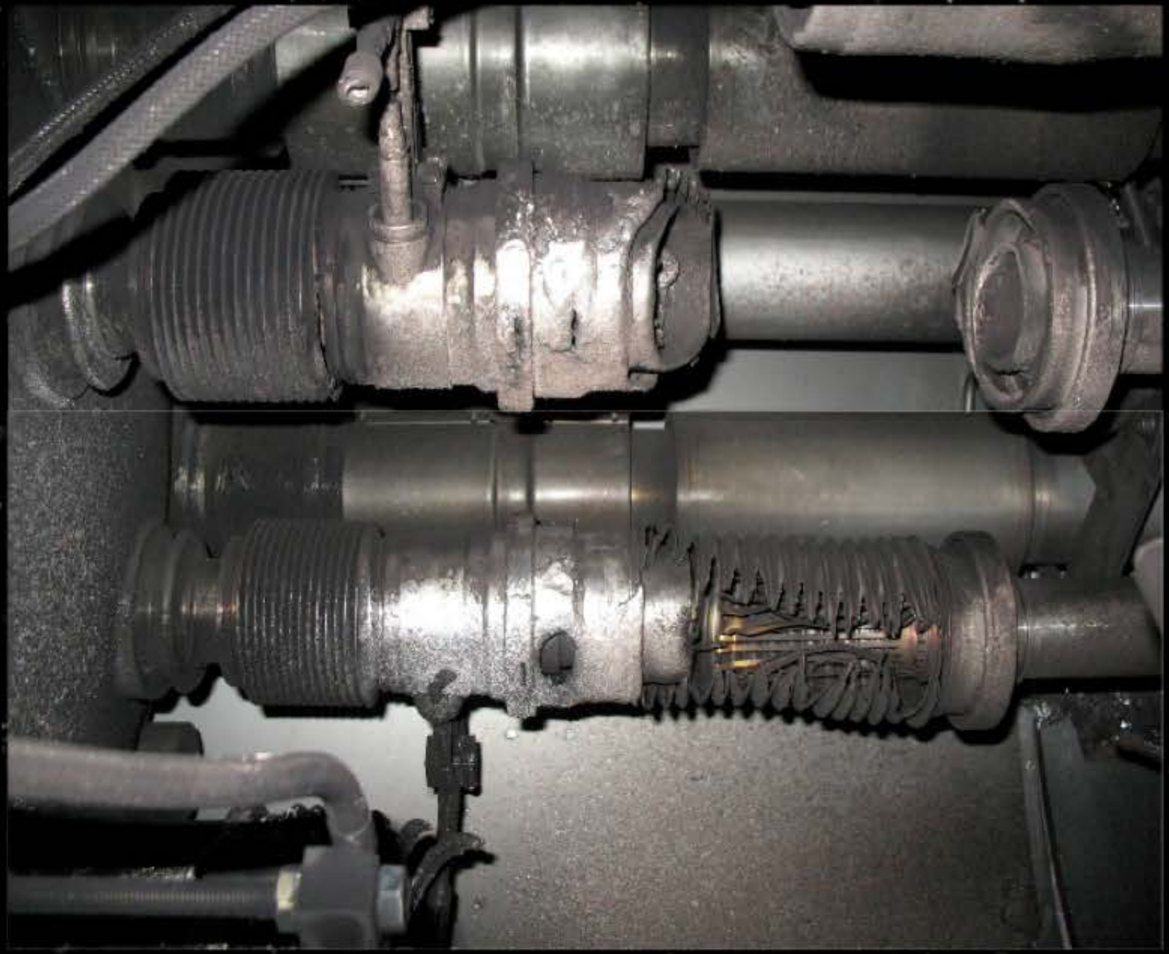
Mass $m > 92.8$ GeV, CL = 95%

A^0 Pseudoscalar Higgs Boson in Supersymmetric Models [o]

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

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

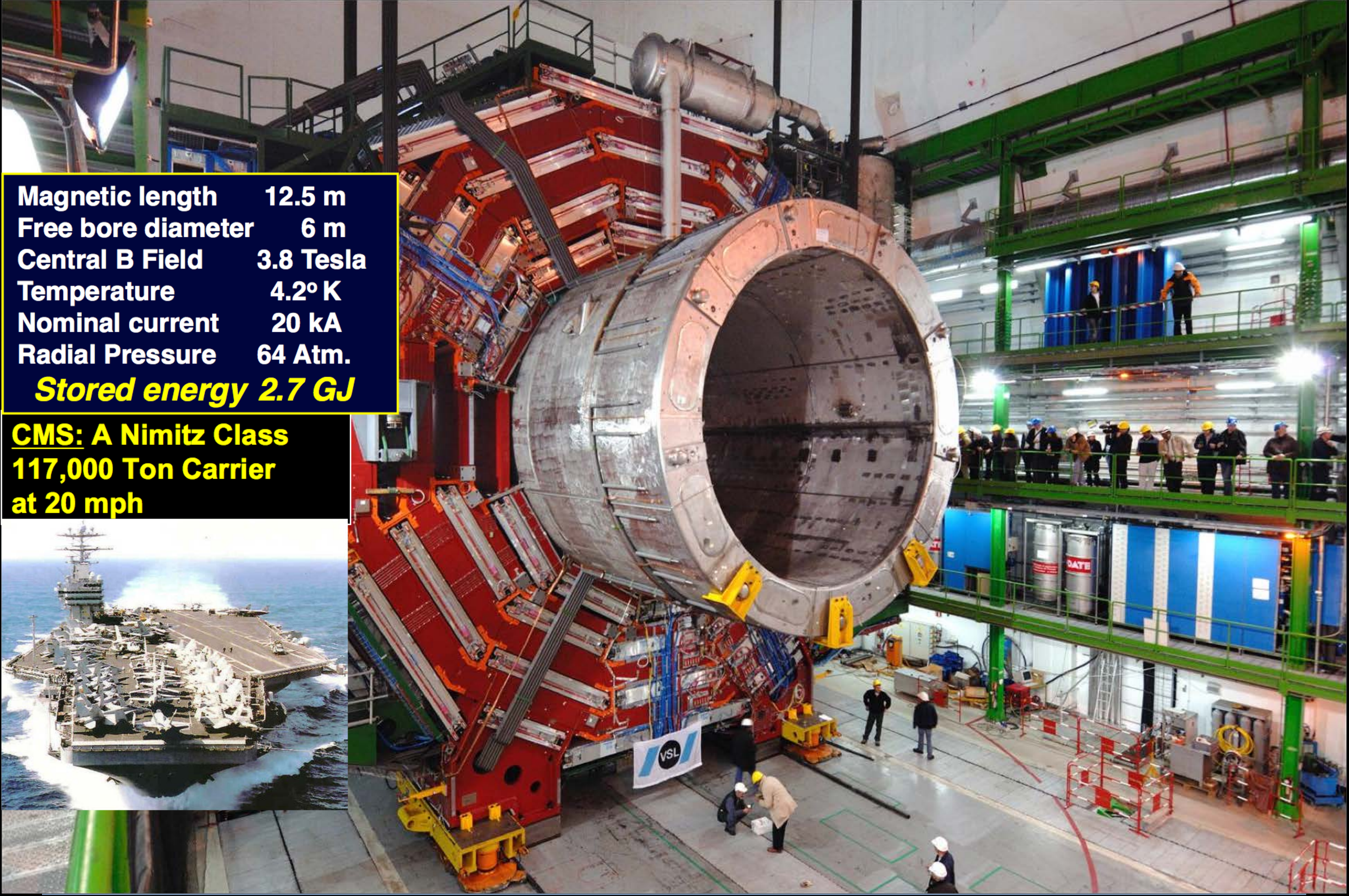
19 Sept 2008



- 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


KRUPP

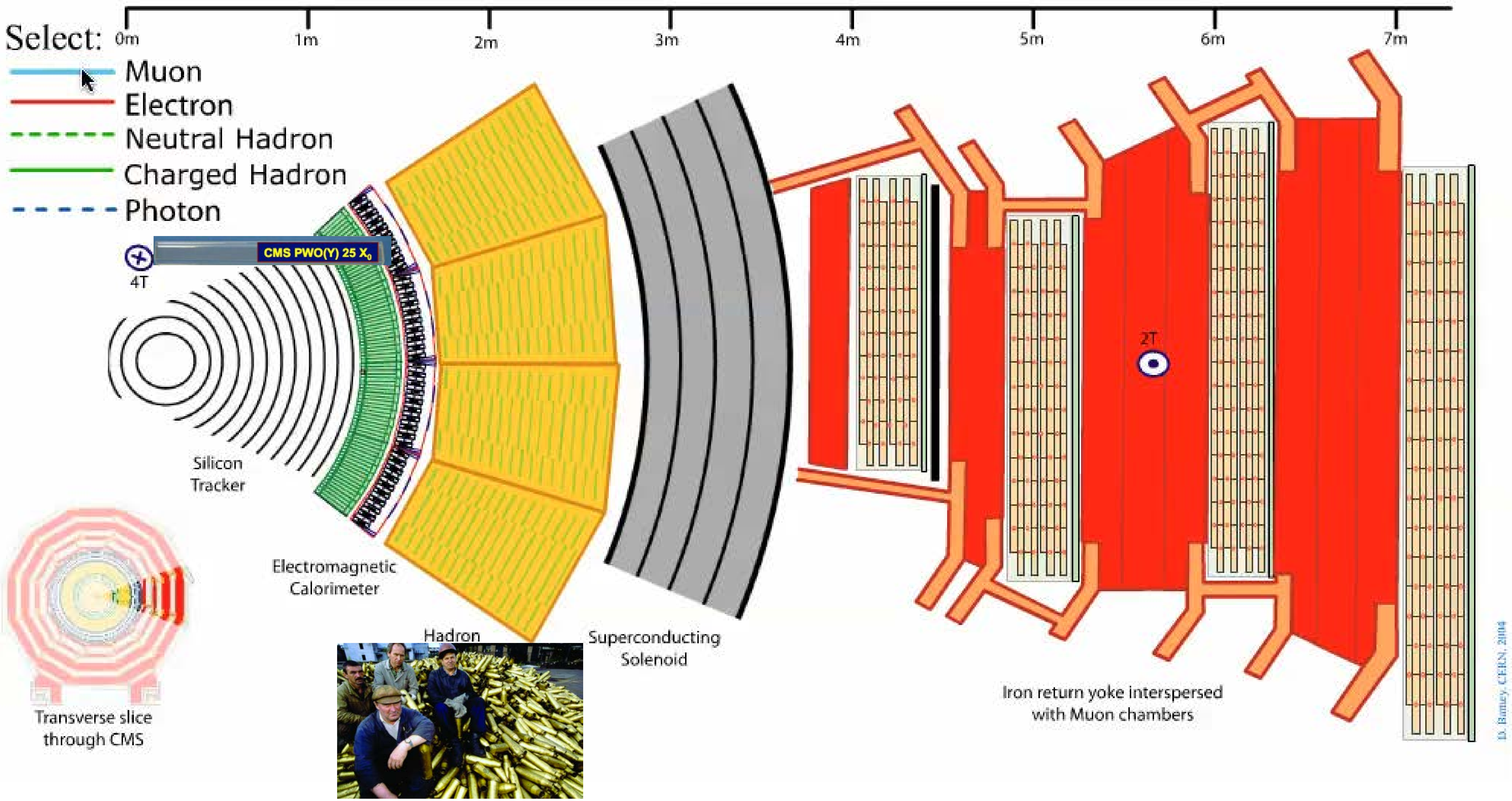

DRAGADOS
CMS

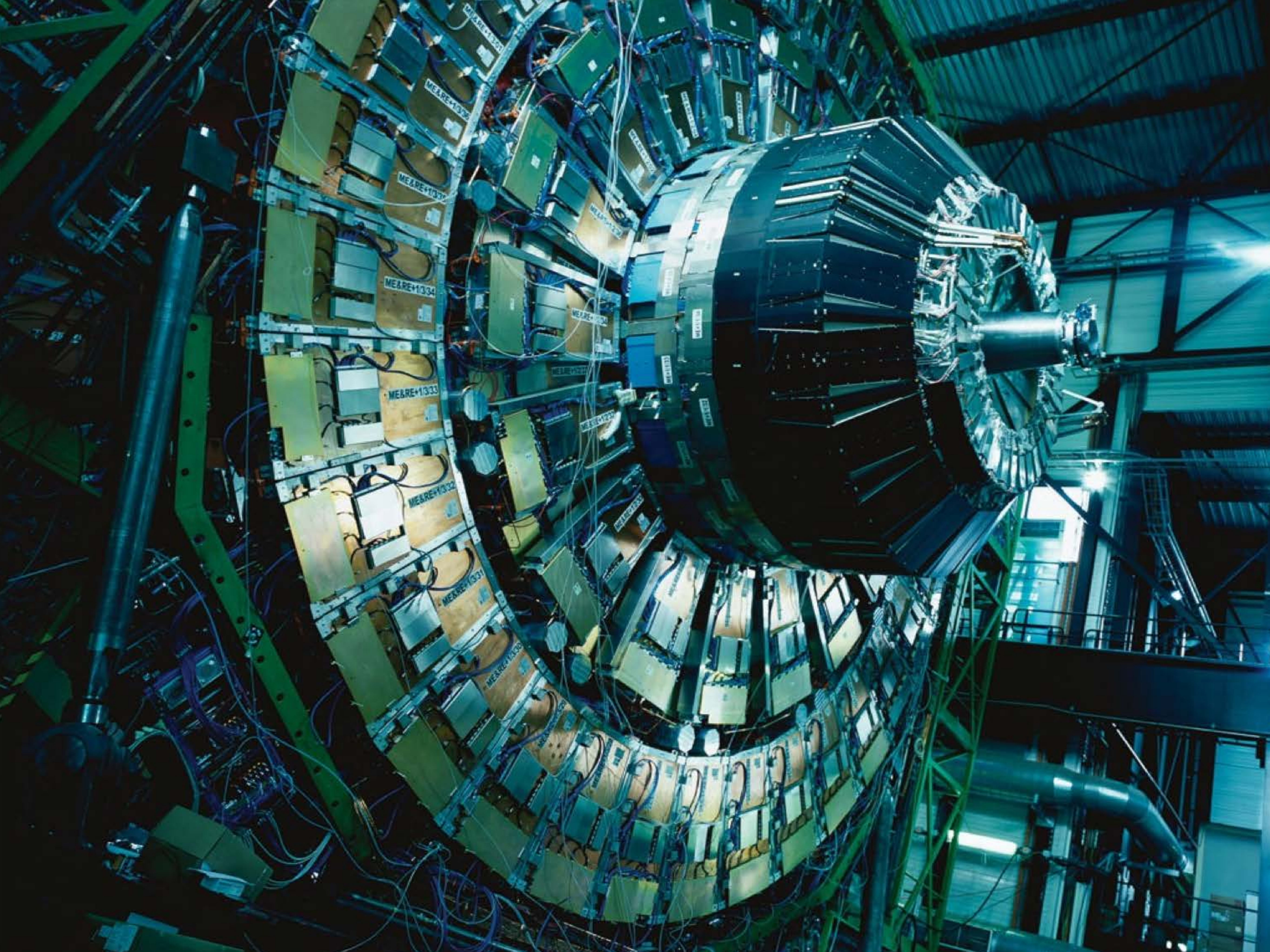


Magnetic length	12.5 m
Free bore diameter	6 m
Central B Field	3.8 Tesla
Temperature	4.2º K
Nominal current	20 kA
Radial Pressure	64 Atm.

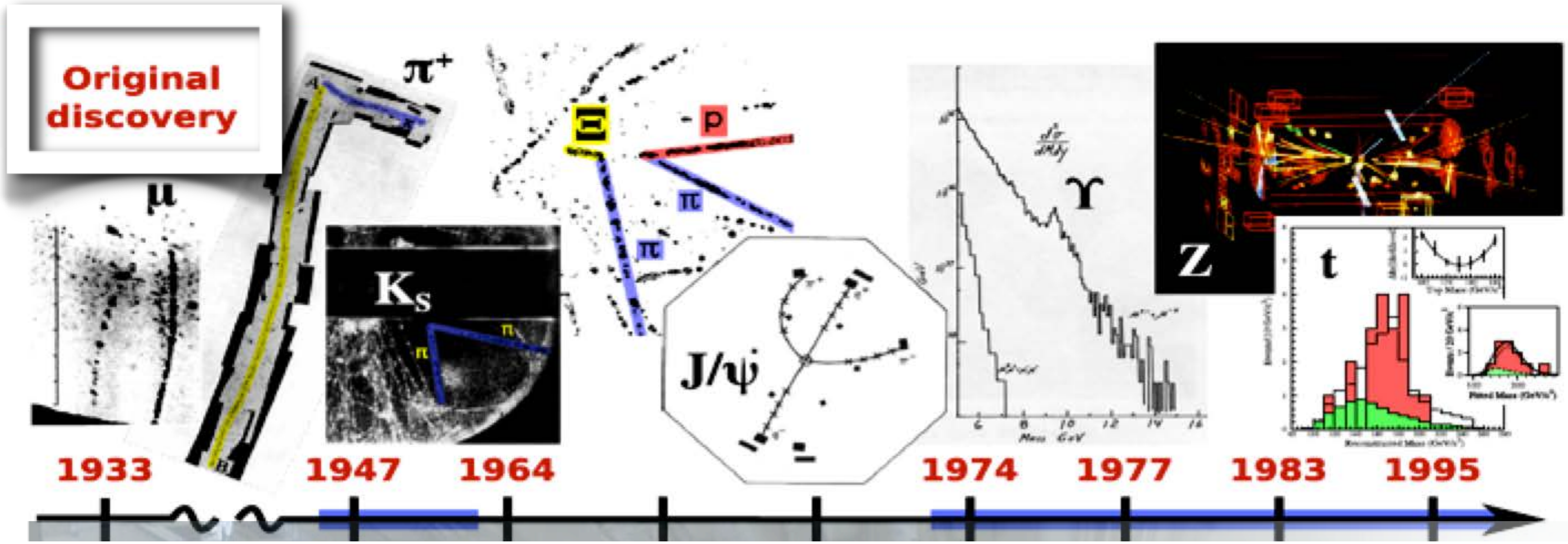
Stored energy 2.7 GJ

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

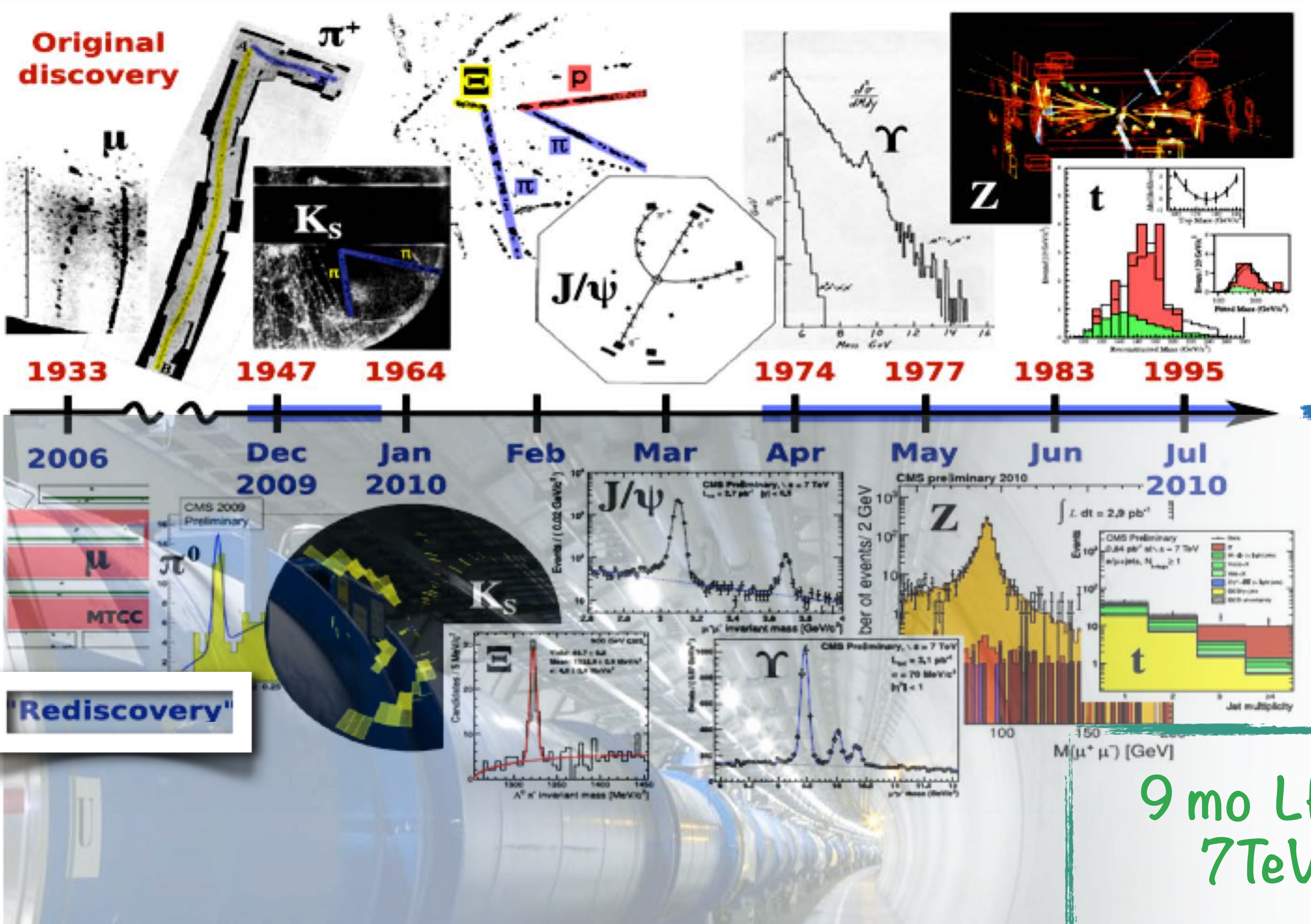

Select:
Muon
Electron
Neutral Hadron
Charged Hadron
Photon
0m
1m
2m
3m
4m
5m
6m
7m
CMS PWO(Y) 25 X0
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D. Barney, CERN, 2004


ME&RE+1/3/34
ME&RE+1/3/33
ME&RE+1/3/32

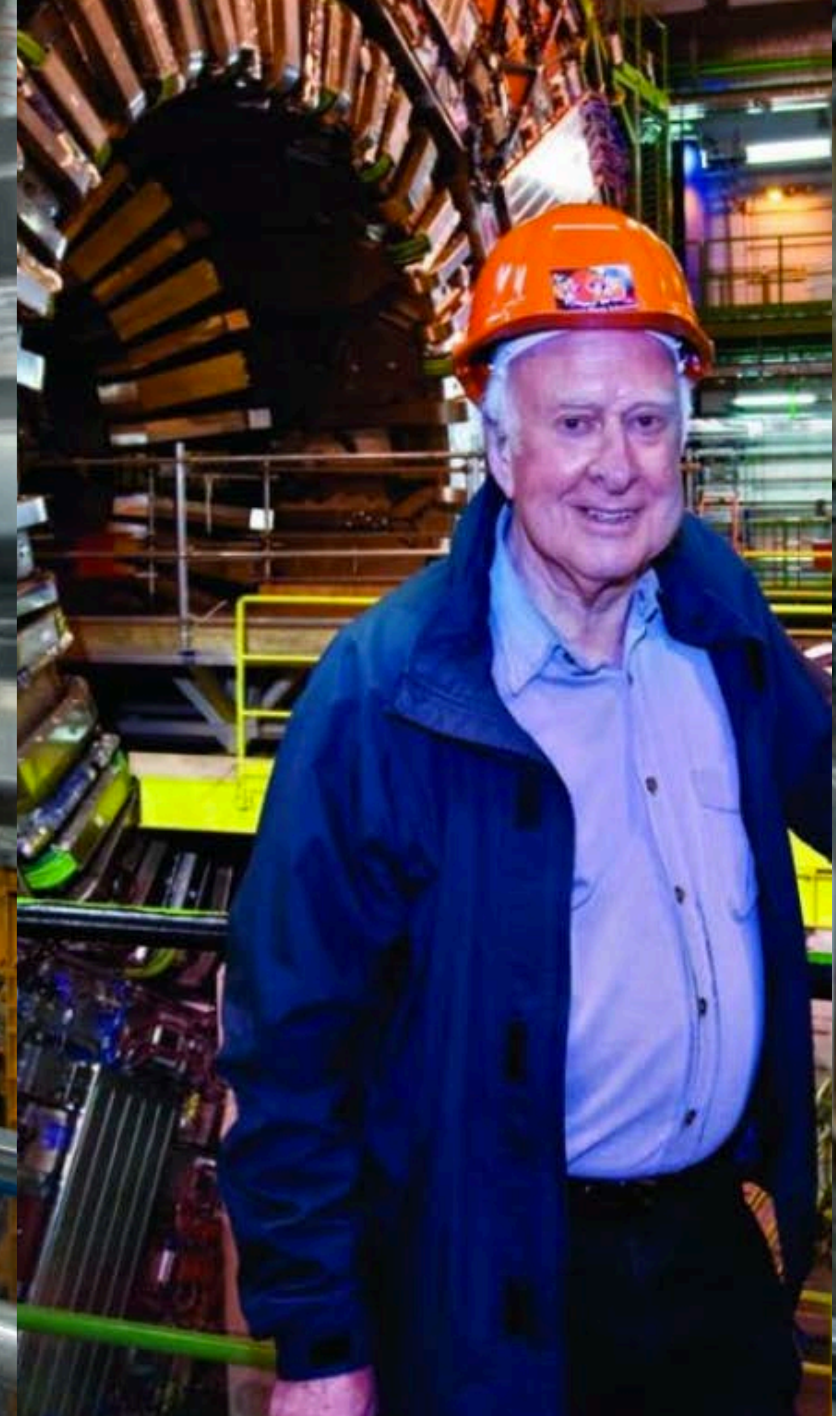
50 years of particle physics discoveries



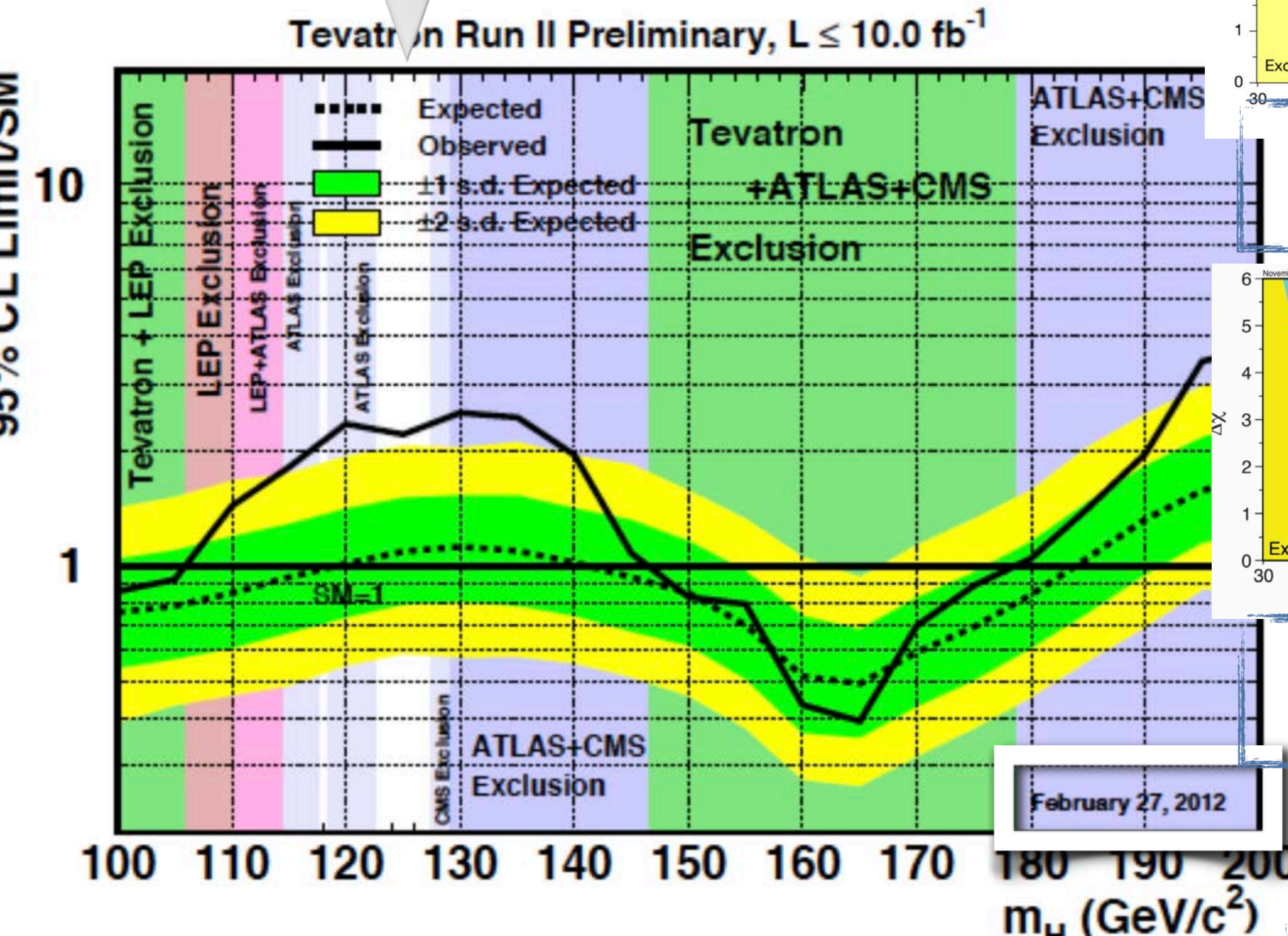
50 years of particle physics discoveries

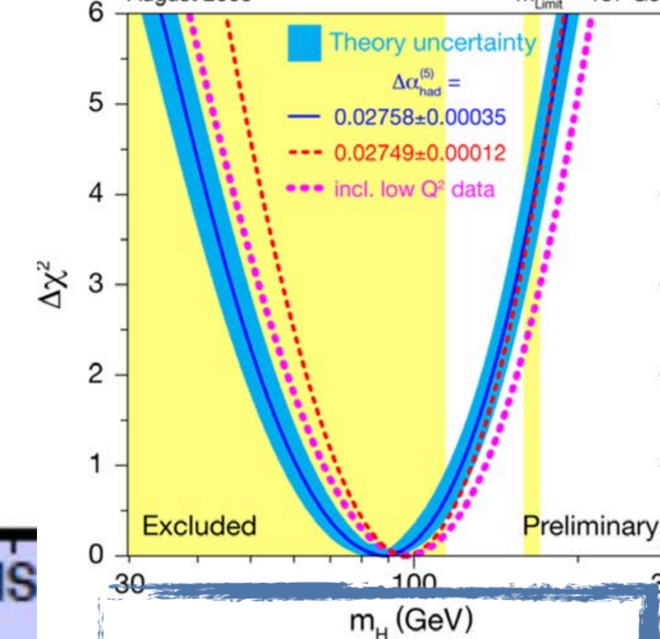


9 mo LHC
7TeV

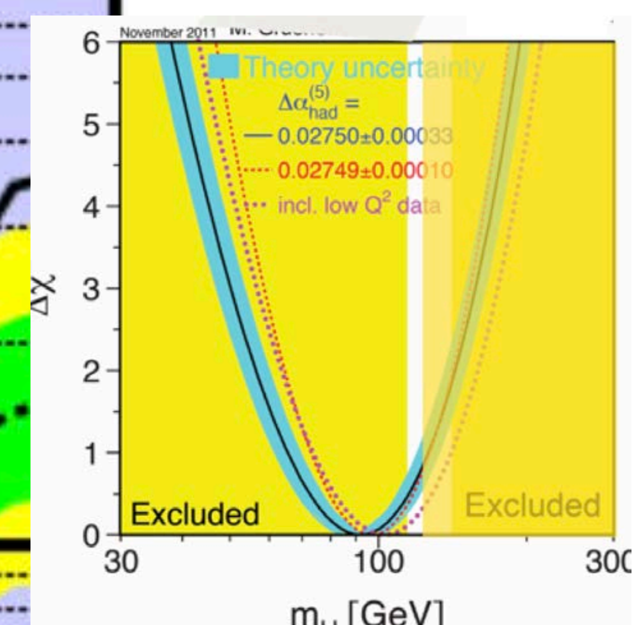



decades of Higgs hunting



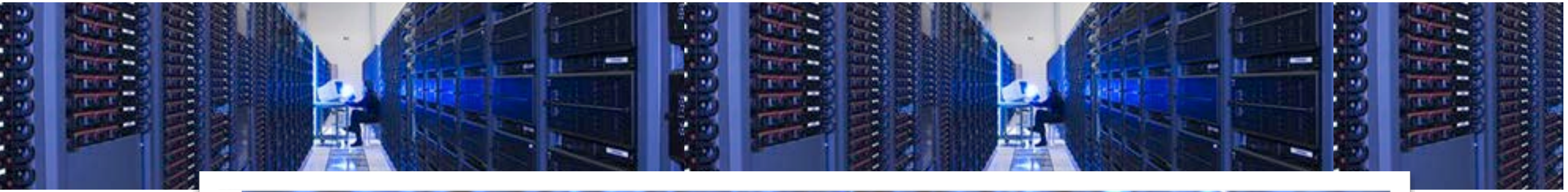


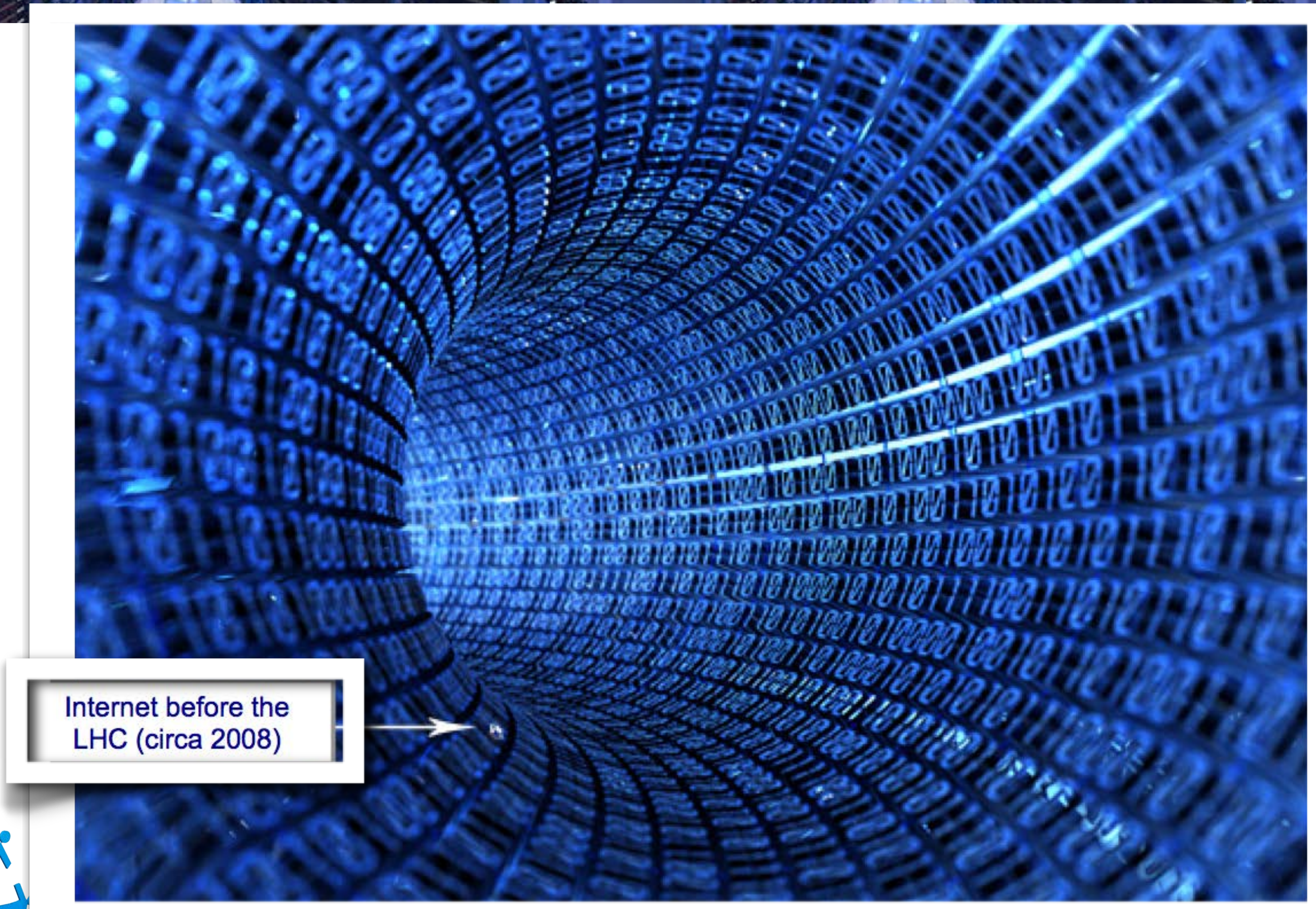
2009



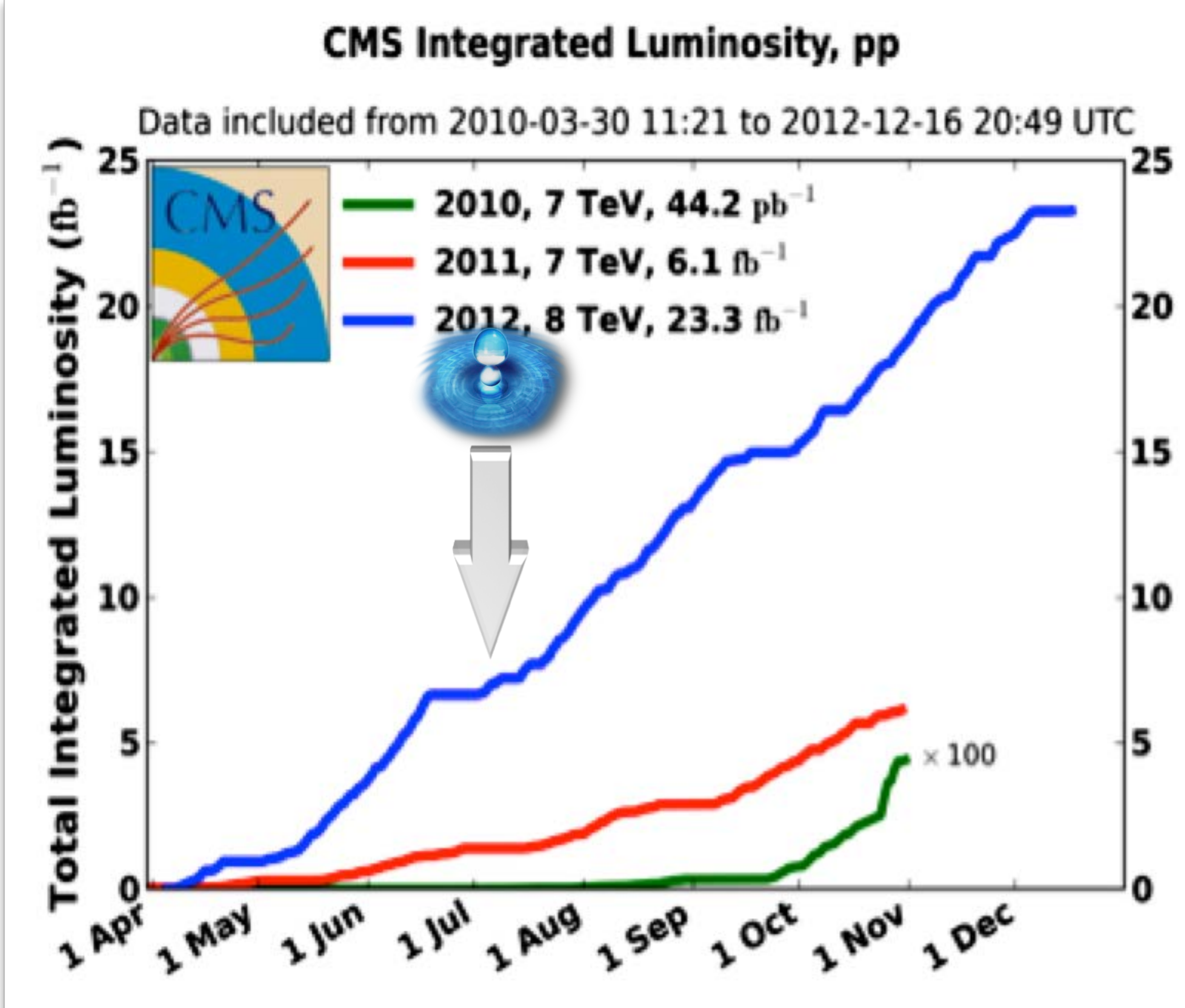
2011

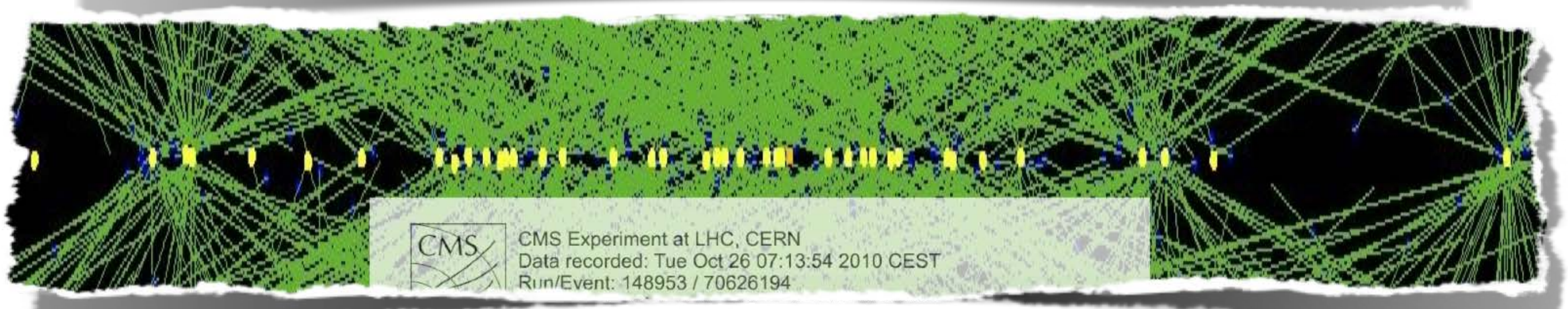
decades of calculating

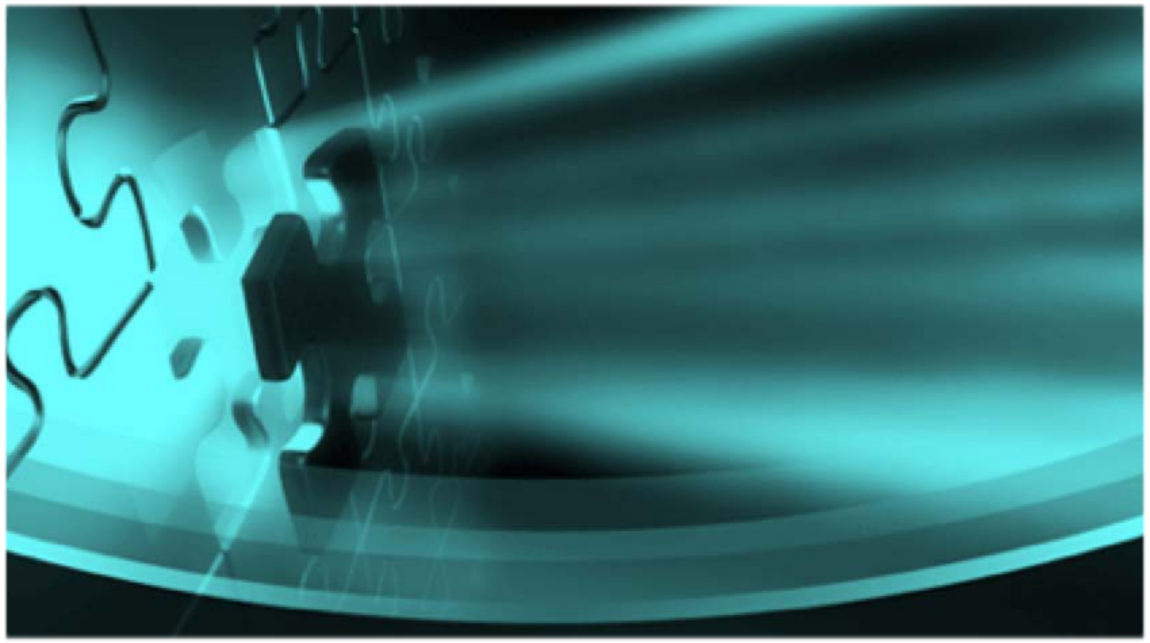


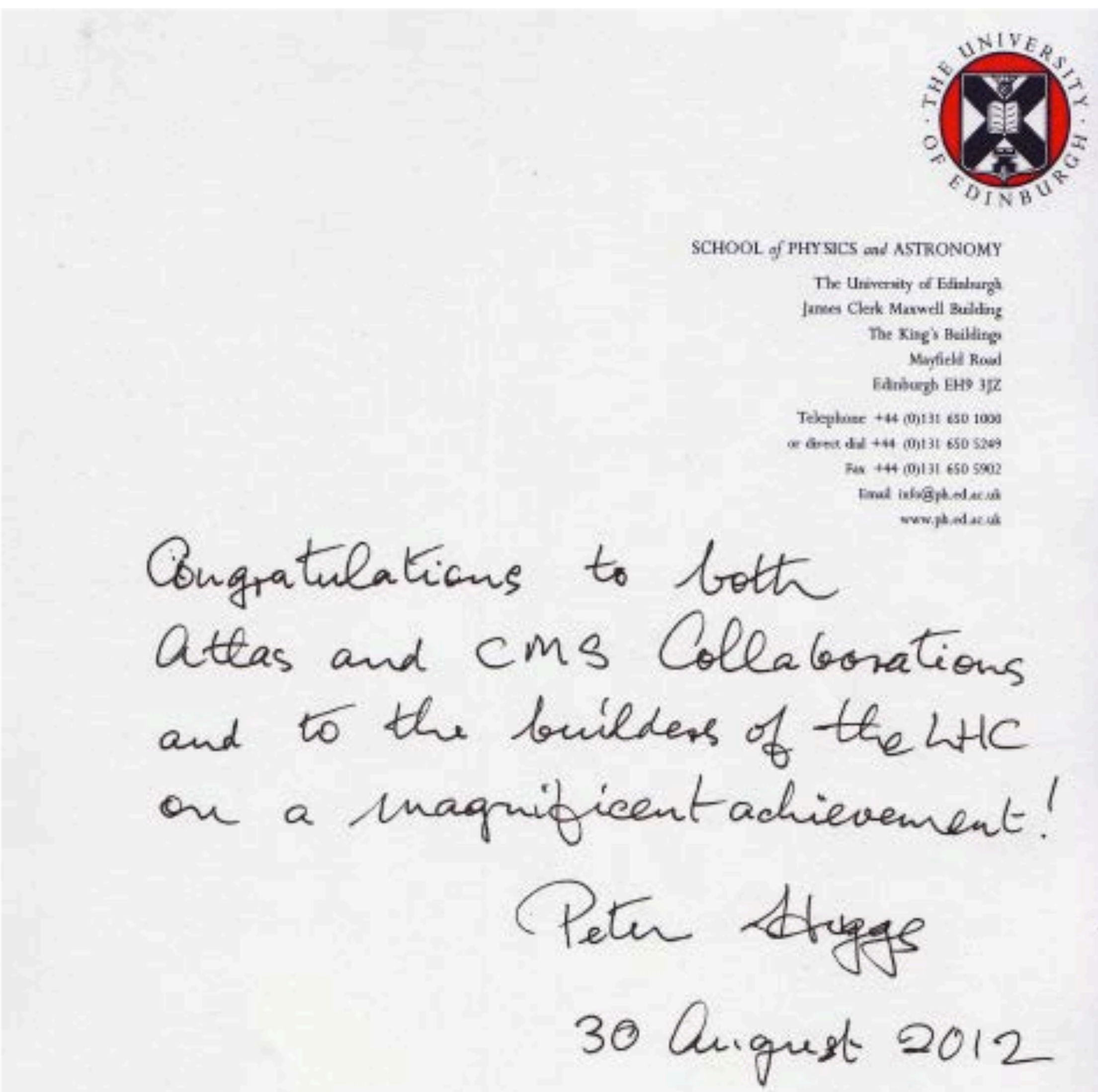


Big Data, Big Models, Data in Motion


CMS Integrated Luminosity, pp
Data included from 2010-03-30 11:21 to 2012-12-16 20:49 UTC
Total Integrated Luminosity (fb⁻¹)
2010, 7 TeV, 44.2 pb⁻¹
2011, 7 TeV, 6.1 fb⁻¹
2012, 8 TeV, 23.3 fb⁻¹
× 100
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec


CMS Experiment at LHC, CERN
Data recorded: Tue Oct 26 07:13:54 2010 CEST
Run/Event: 148953 / 70626194





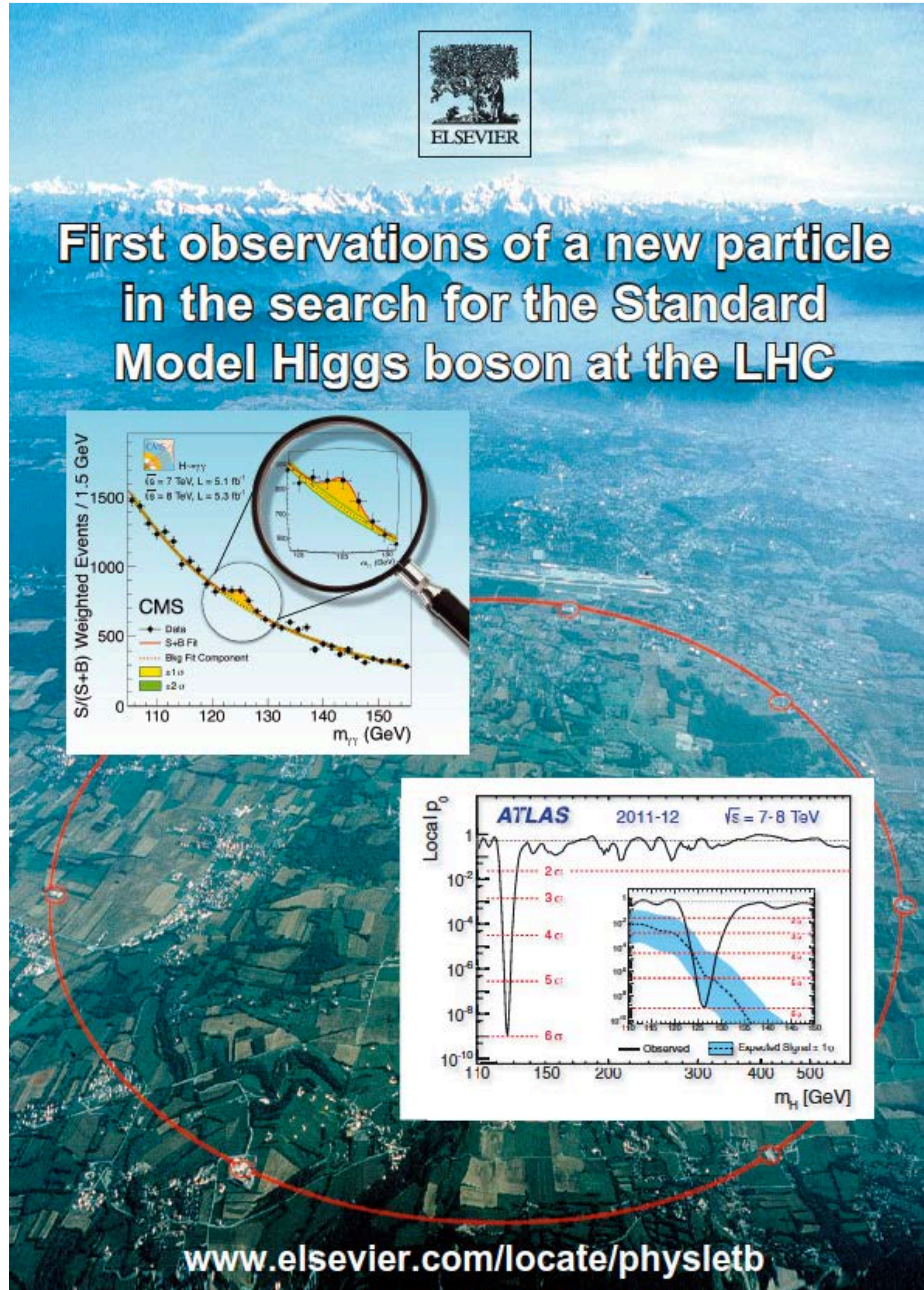
SCHOOL *of* PHYSICS *and* ASTRONOMY
The University of Edinburgh
James Clerk Maxwell Building
The King's Buildings
Mayfield Road
Edinburgh EH9 3JZ

Telephone +44 (0)131 650 1000
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.

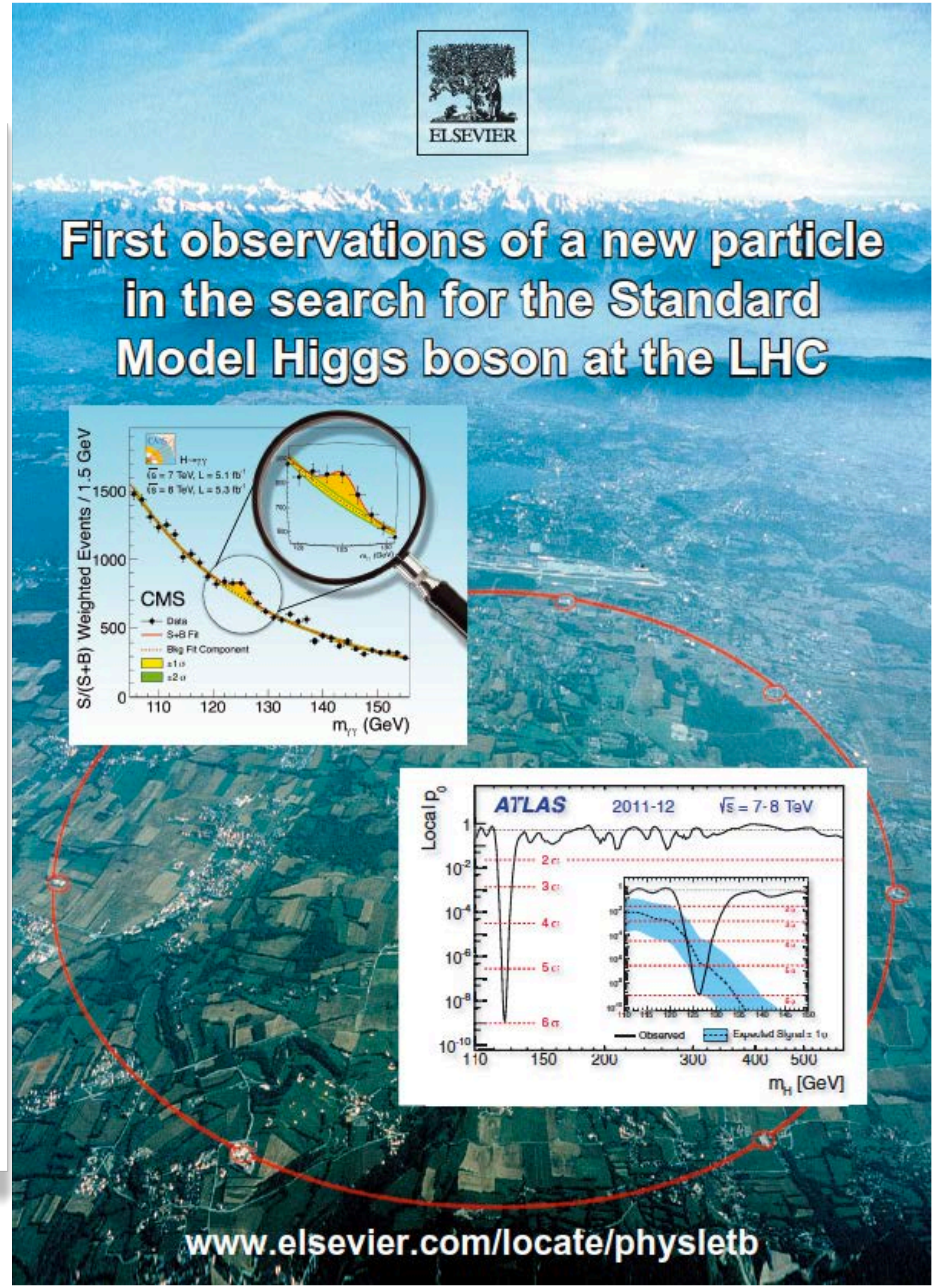
I note with great pride the role US scientists have had in the design, construction, and operation of the CMS detector as well as the leadership of collaboration. Clearly, the scientific expertise and ingenuity of US scientists have been essential components of the discovery. Furthermore, the astounding 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




Chasing the Higgs Boson | INTRODUCTION PROMISED FIREBALLS GAME OF BUMPS STILL MISSING OOZING INTO VIEW OPENING THE BOX

Chasing the Higgs Boson

the Large Hadron Collider near Geneva, two ...es of scientists struggled to close in on physics' ...lusive particle.

...ENNIS OVERBYE
...blished March 5, 2013 | 252 Comments

MEYRIN, Switzerland — Vivek Sharma missed his daughter.

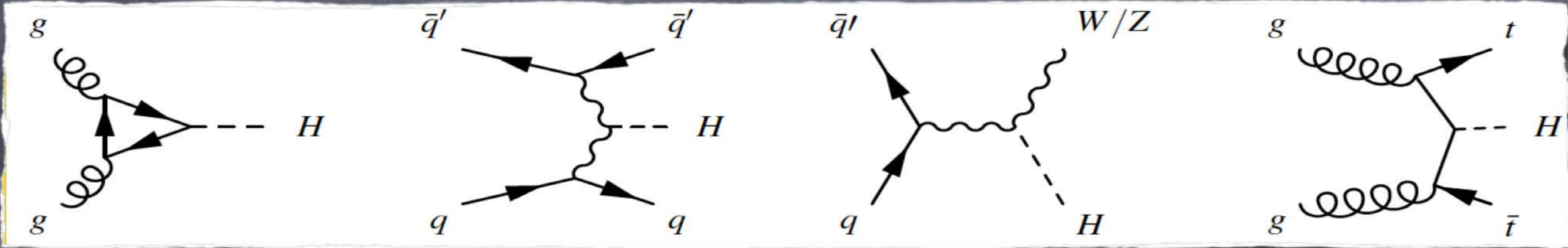
...versity of ... Dr. Sharma ...at a time away ...ing a team of ... Hadron ...side Geneva. ... Meera ..., he flew to

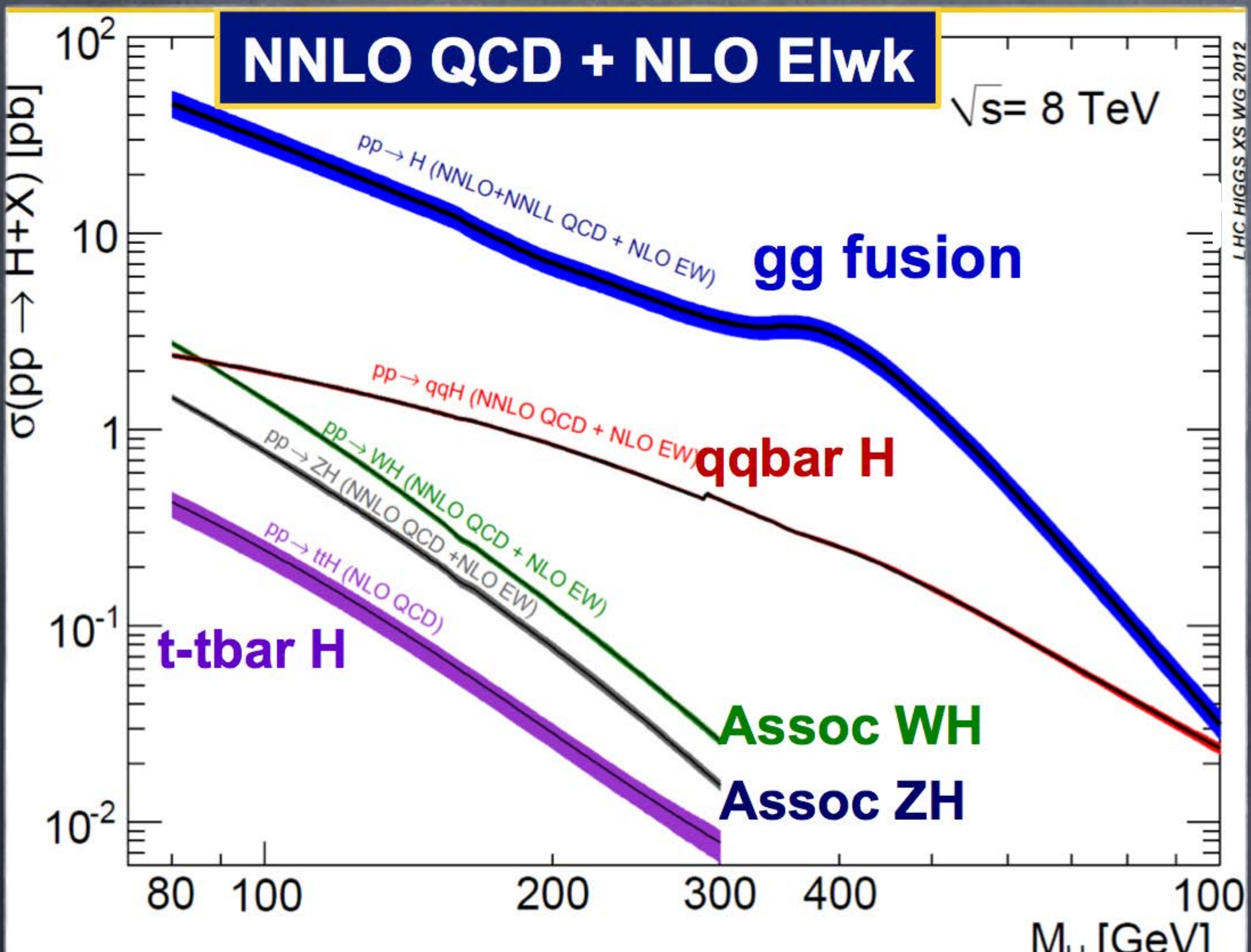
Illustration by Sean McCabe/Photographs by Daniel Auf der Mauer, Toni Albir, Fabrice Coffrini, Fred Me...

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

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





Dominant production at 125 GeV

gg→ H

subdominant but with larger S/B:

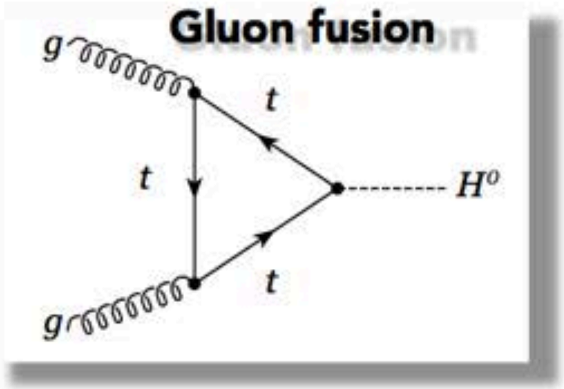
VBF: ~13X Less

WH + ZH: ~18X Less

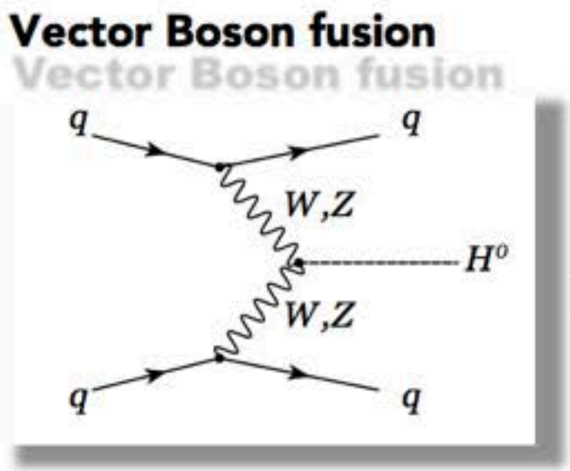
ttH ~150X Less

(m_{Higgs} 125.5 GeV @ 8 TeV : 21.84 pb)

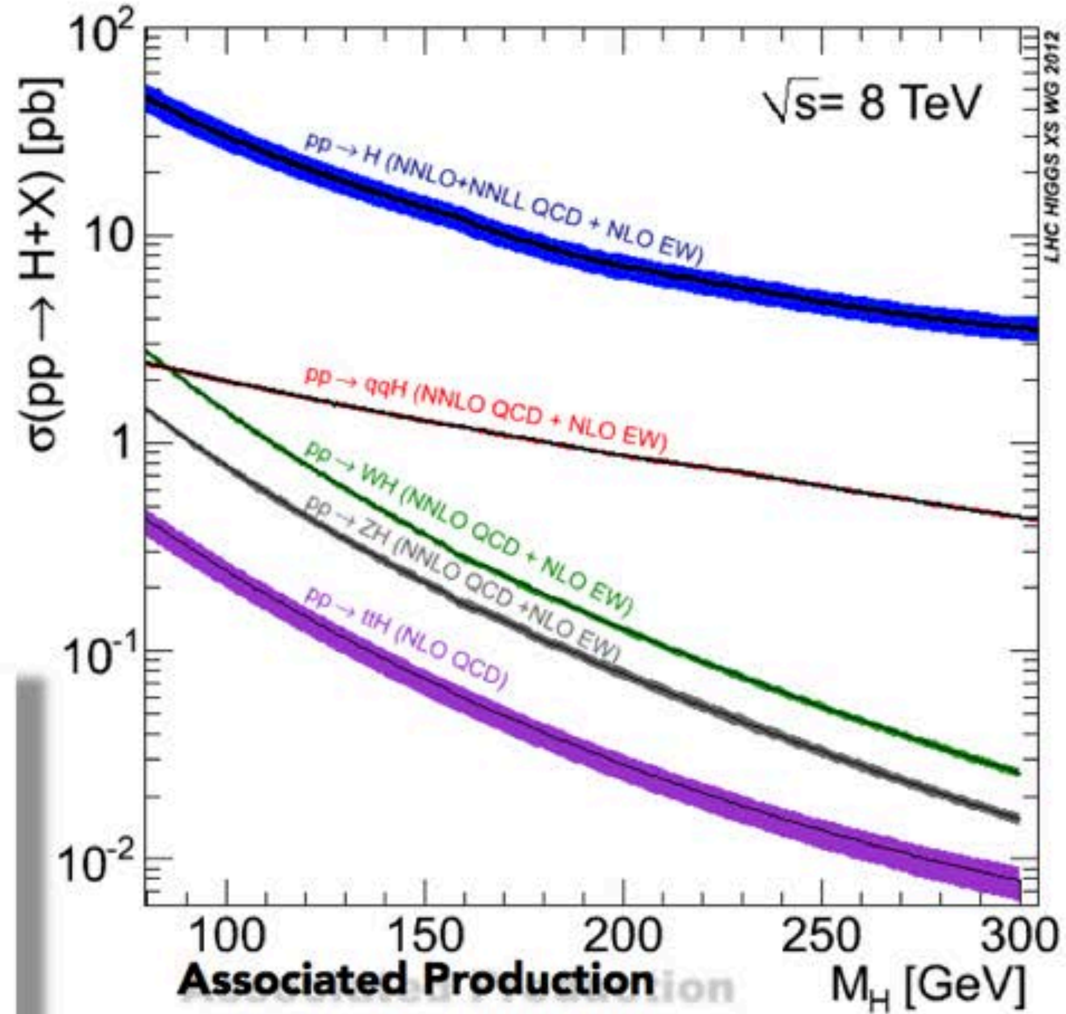
Gluon Gluon fusion:
- gg → H
- 19 pb (87%)
- no specific topology



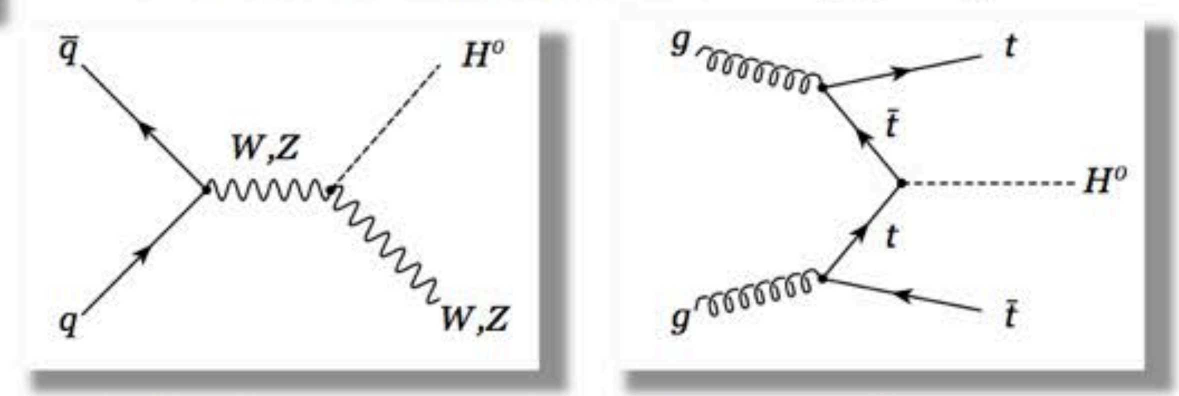
Vector Boson fusion:
- qq → qqH
- 1.6 pb (7.3%)
- specific jet topology



Associated Production:
- qq → WH,ZH, ttH
- 0.70/0.41/0.13 pb (5.7%)



Associated Production



Typical uncertainties on total cross-sections

gg	15-20 %	NNLO + NNLL + NLO EW
VBF	5 %	NNLO + NLO EW
WH, ZH	5 %	NNLO + NLO EW
$t\bar{t}$H	15 %	NNLO

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

H → bb:

- **BR(H →bb)** : 56.9%
- **with associated production, large BR, <u>Yukawa coupling</u>**

H → WW$^{(*)}$ → lνlν

- **BR(H → WW)**: 22.3%
- **large BR, <u>gauge boson coupling</u>**

H → γγ

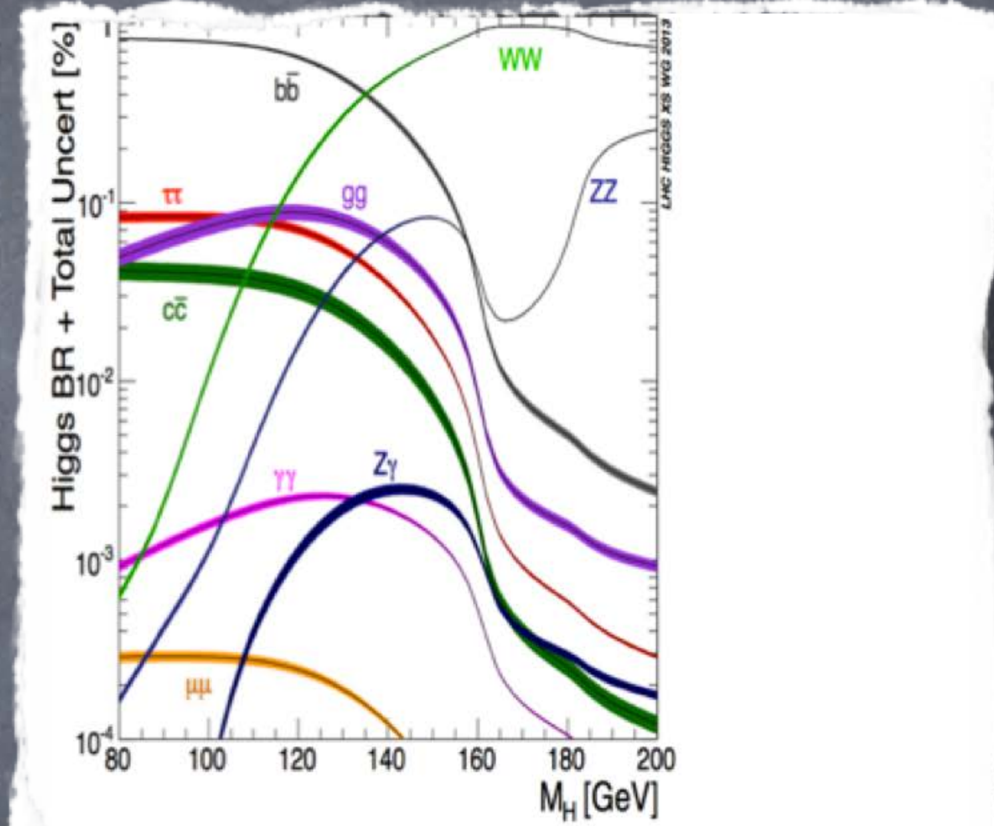
- **BR(H → γγ)**: 0.24%
- **high mass resolution, <u>loop coupling</u>**

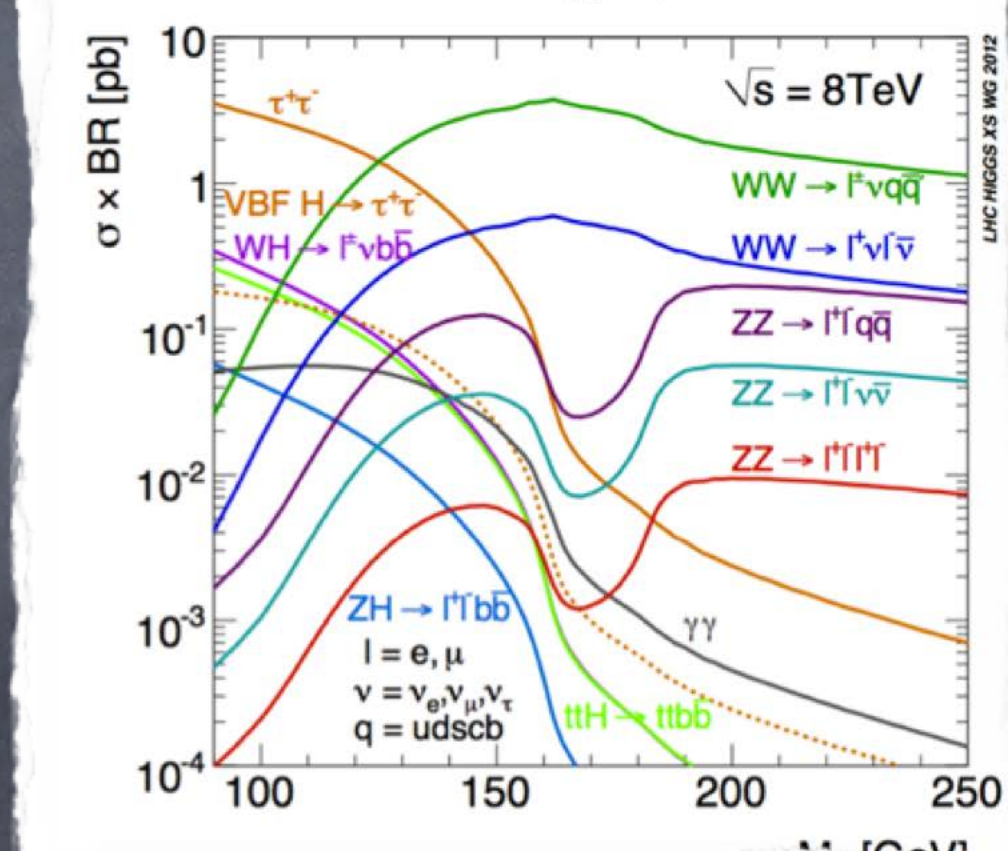
H → ZZ$^{(*)}$→ lll

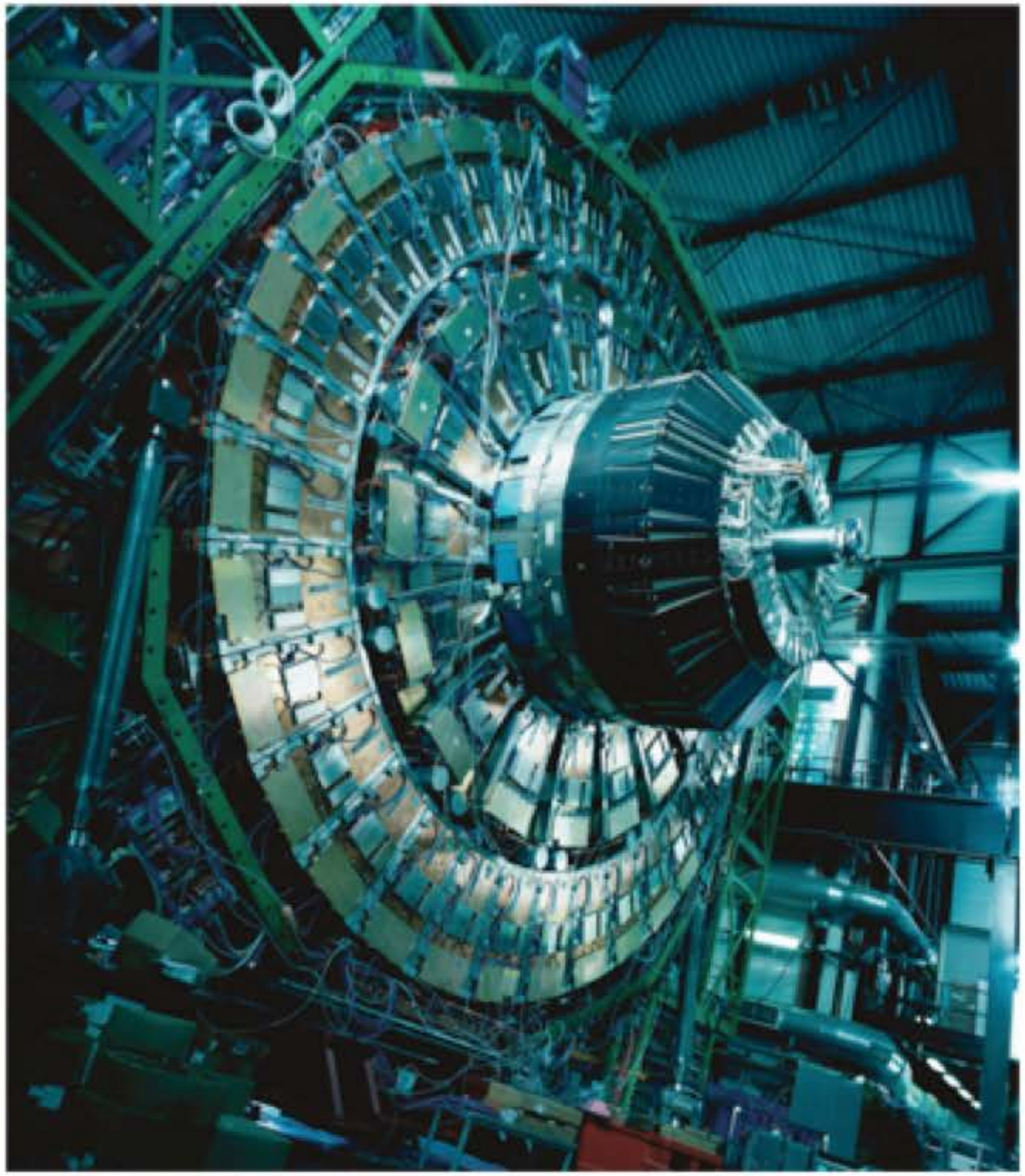
- **BR(H → ZZ$^{(*)}$ → llll)**: ~0.2%
- **BR(H → ZZ)**: 2.8%
- **high mass resolution, <u>gauge boson coupling</u>**

H → ττ

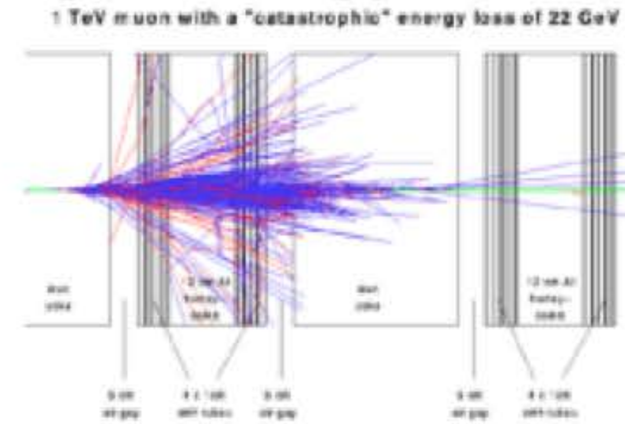
- **BR(H → ττ): 6.2%** - **<u>Yukawa coupling</u>**





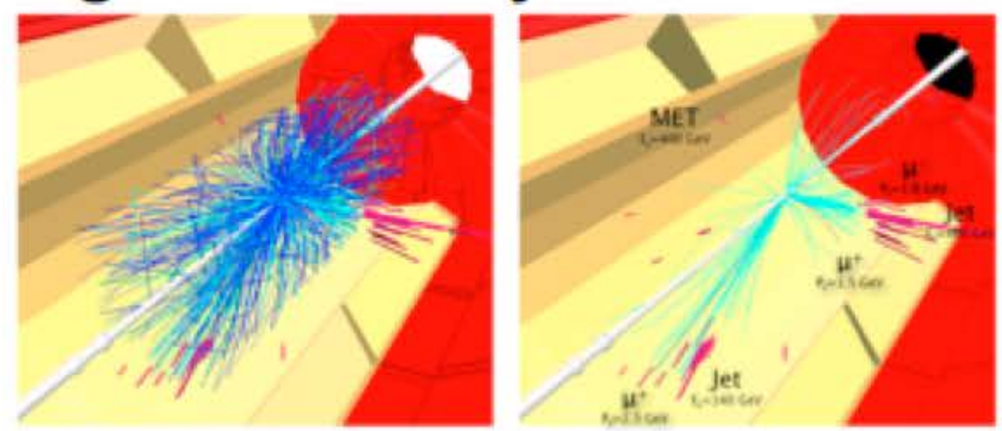


- high energy **But not as high as specs**



much higher than specs

- high luminosity

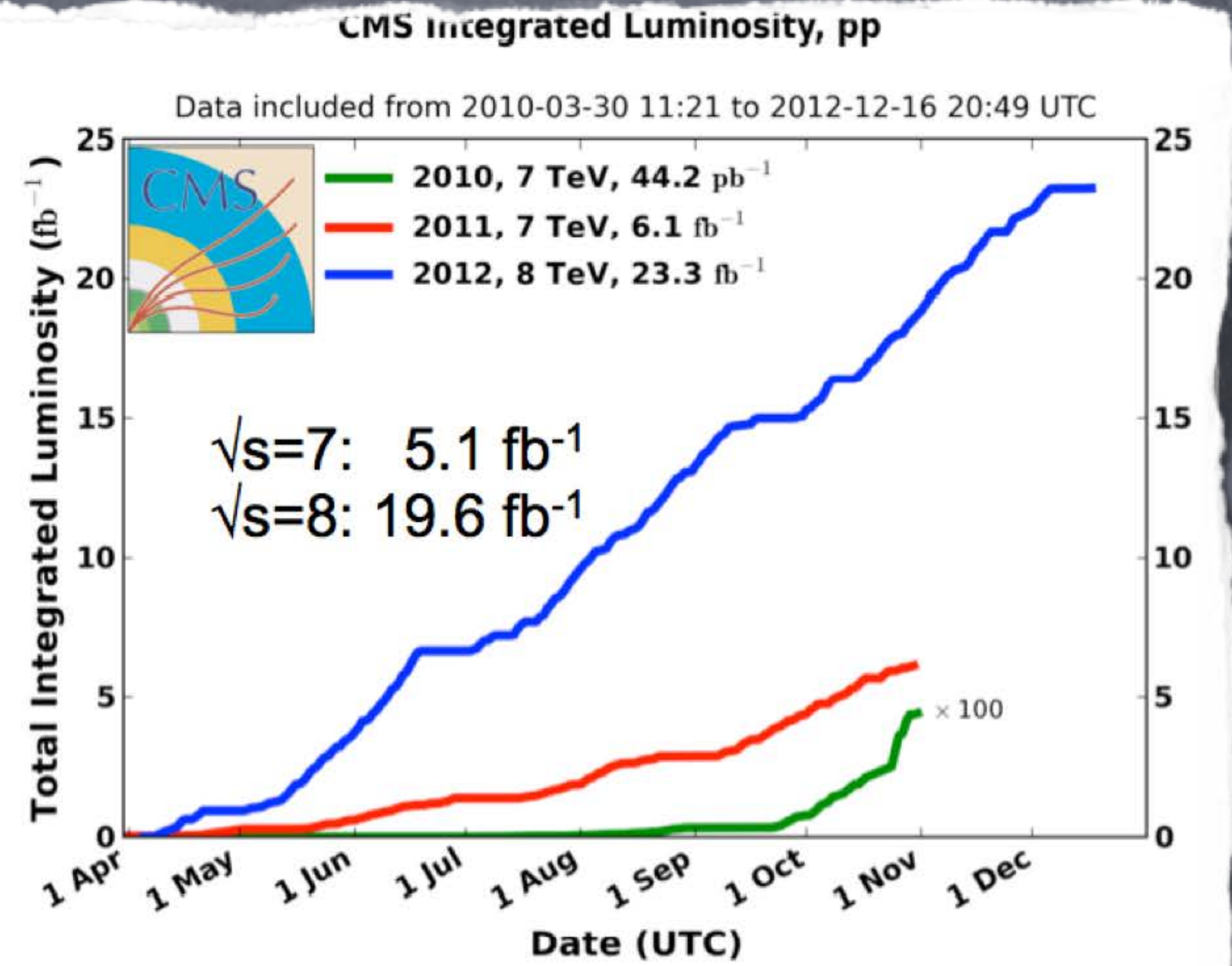


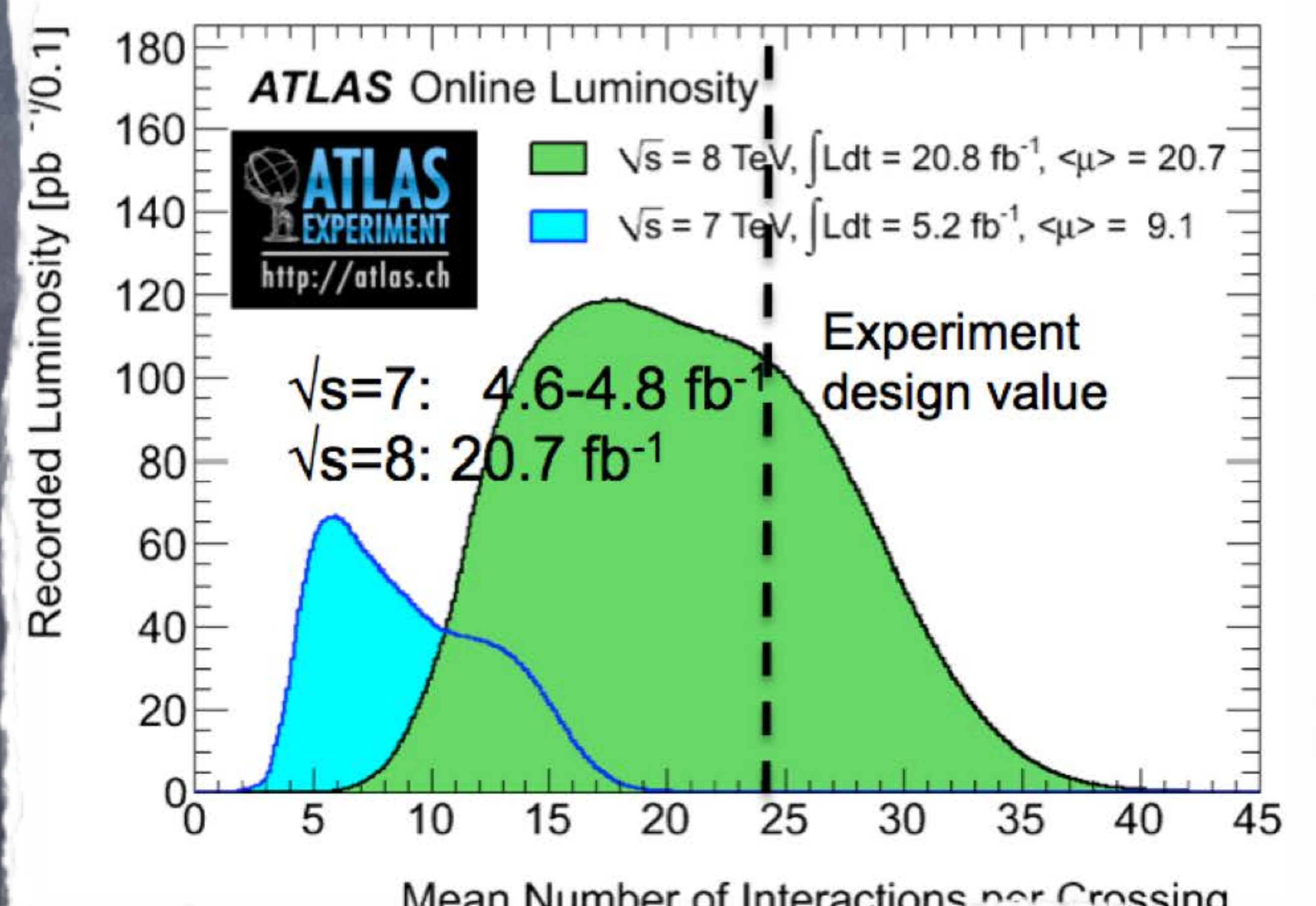
- high data rates (trigger, GRID) **we can tinker with this**
- ...not a walk in the park

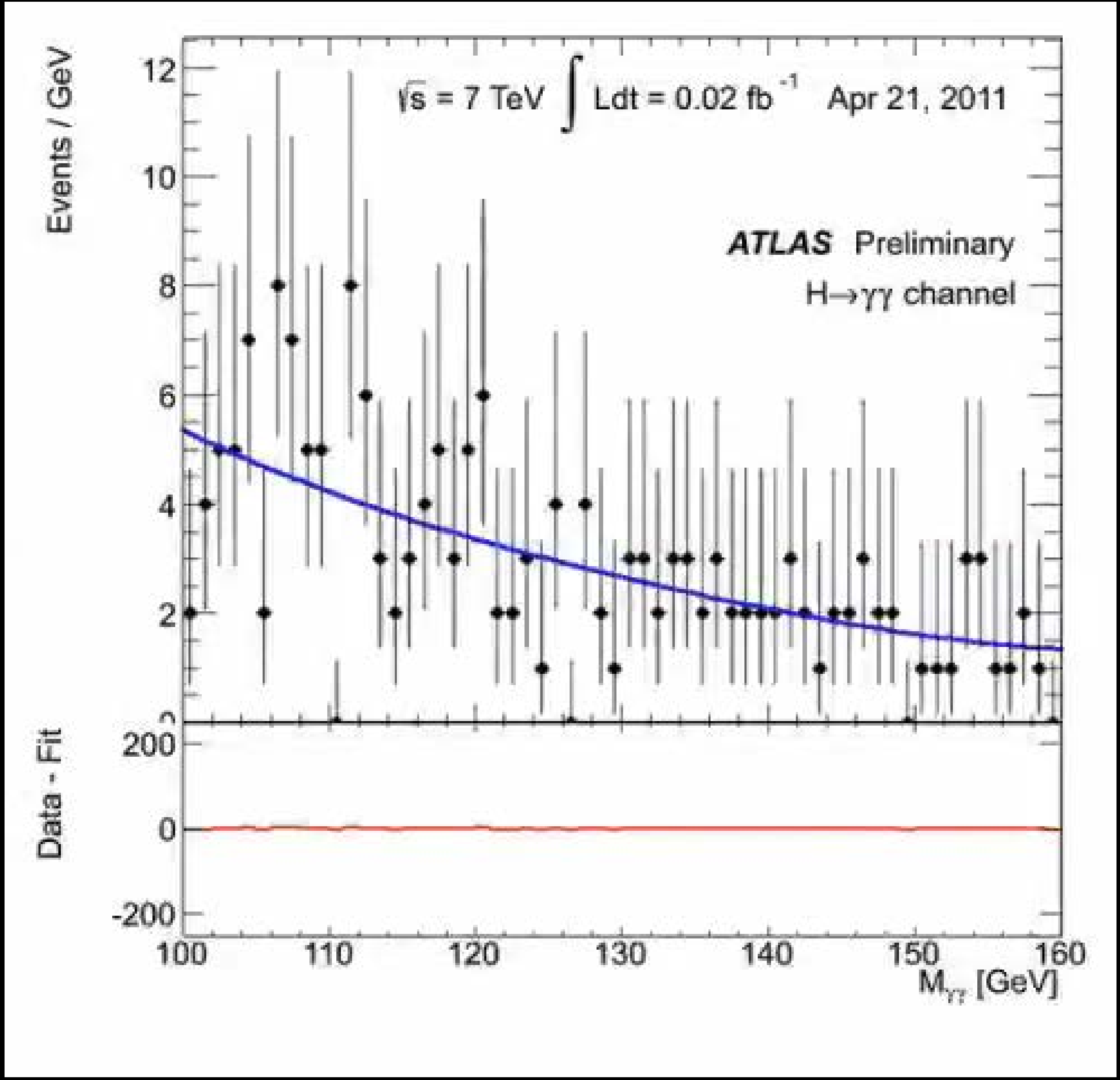
LHC performance ✔
ATLAS, CMS ✔
data efficiency ✔

2011 (7 TeV) ➩ 5/fb
2012 (8 TeV) ➩ 20/fb

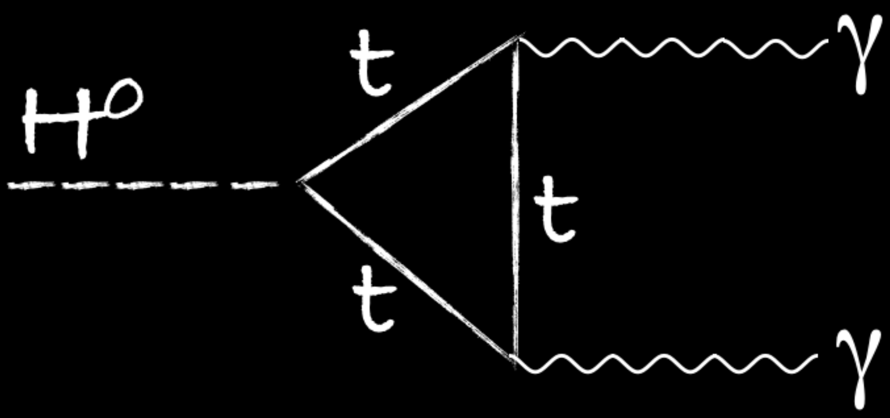
pileup ⇧
challenging everything
(trigger, compu, reco, id, fakes &tc)







√s = 7 TeV ∫ Ldt = 0.02 fb^-1 Apr 21, 2011
ATLAS Preliminary
H→γγ channel
Events / GeV
Data - Fit
M_γγ [GeV]



H°
t
t
t
γ
γ

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

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**

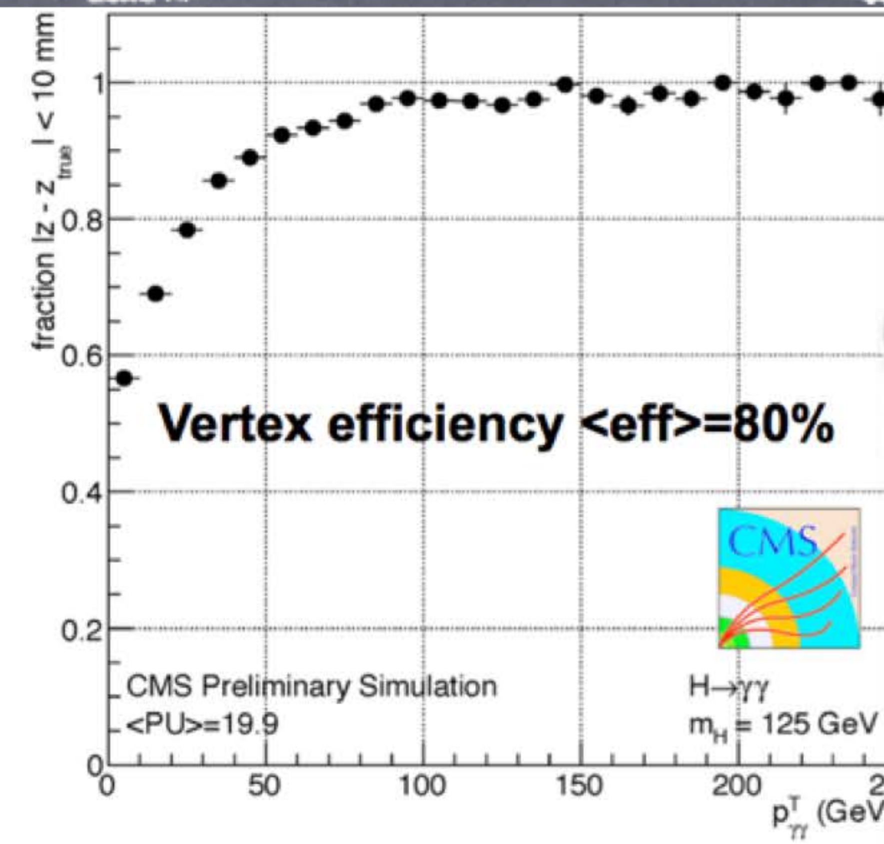
- systematic uncertainties (0.47%) :

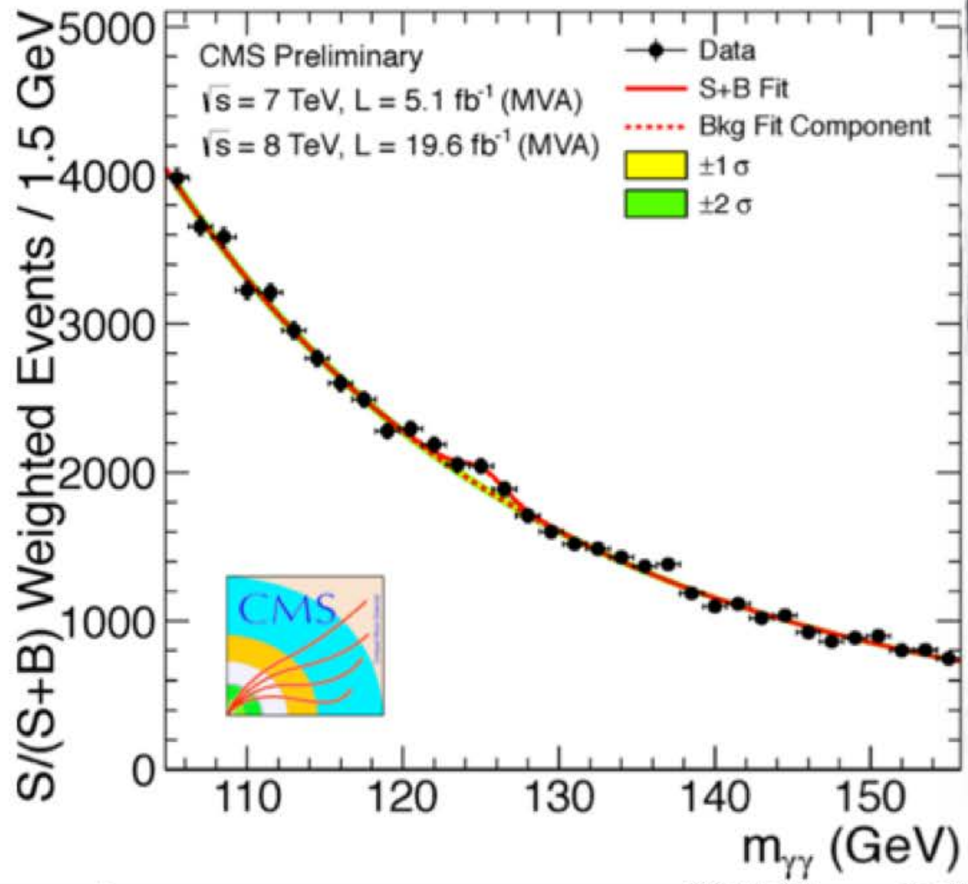
source	systematic uncertainties
non linearity when extrapolating from Z	± 0.4%
upstream material simulation	± 0.25%

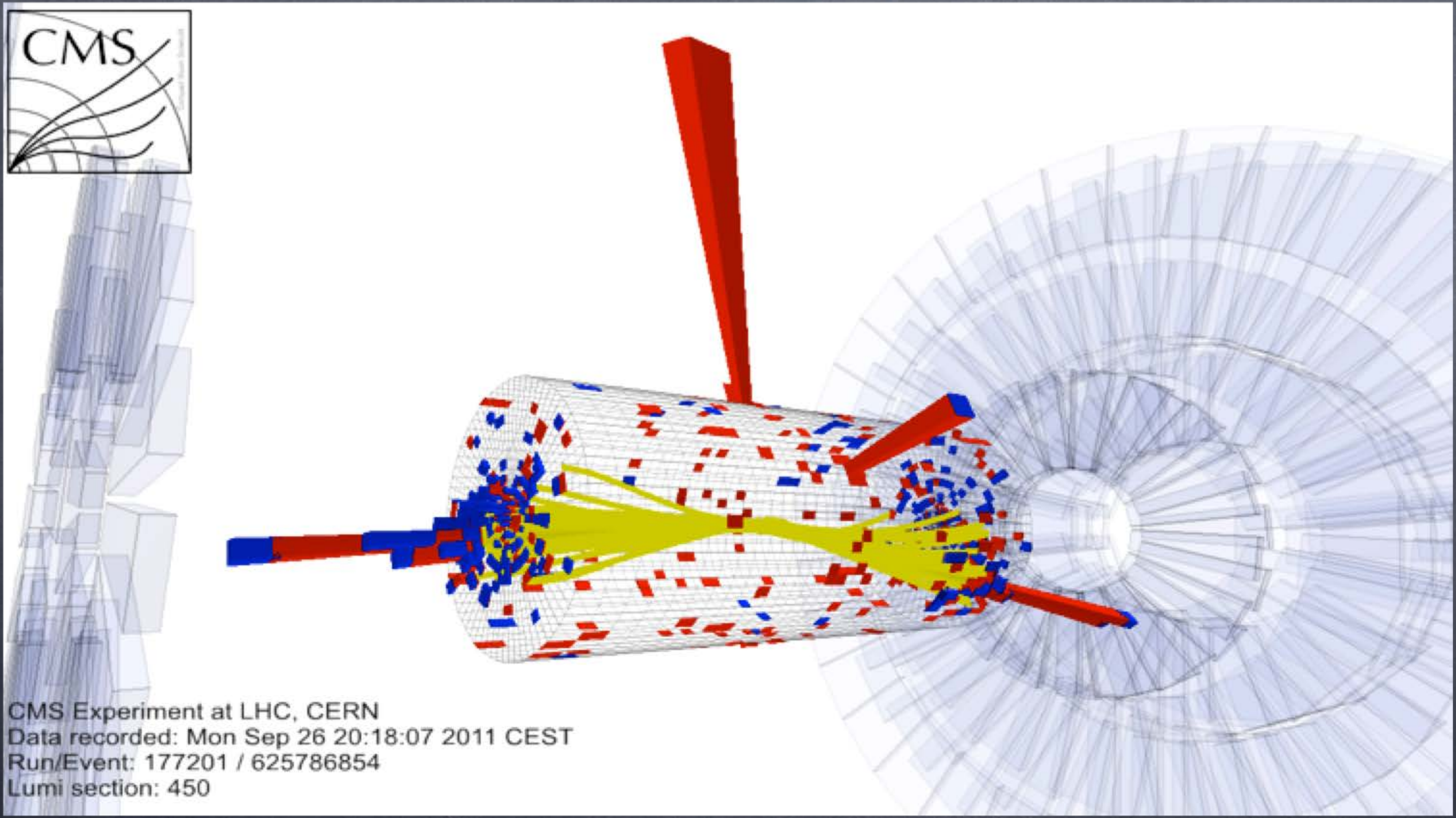
mass measurement

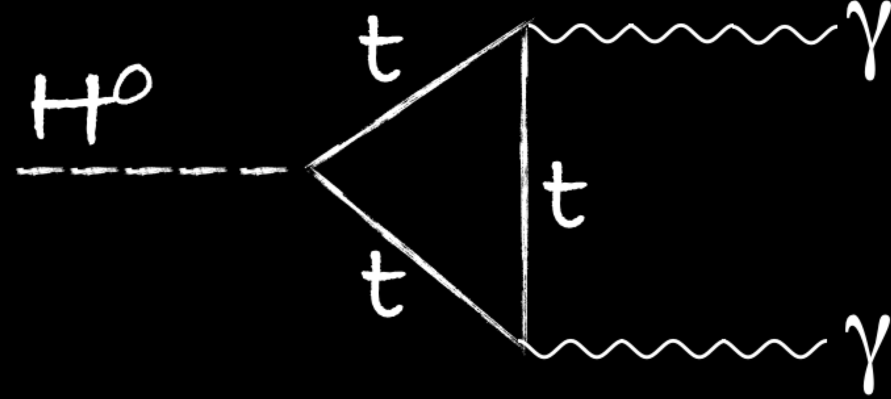
fit with both signal position and normalization free

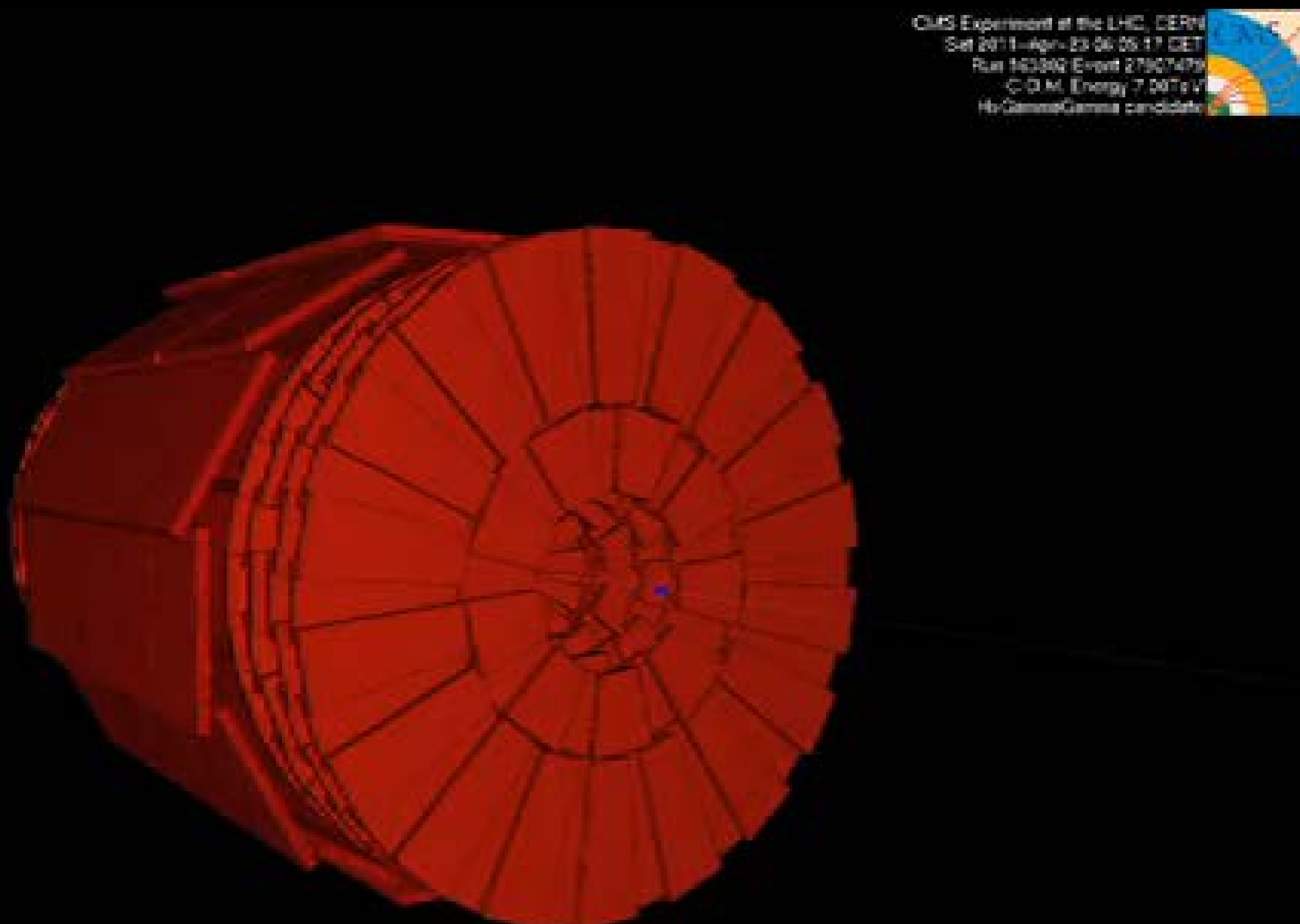
m_{Higgs} = 125.4 ± 0.5 (stat.) ± 0.6 (syst.) GeV






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


H°
t
t
t
γ
γ


CMS Experiment at the LHC, CERN

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

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%)

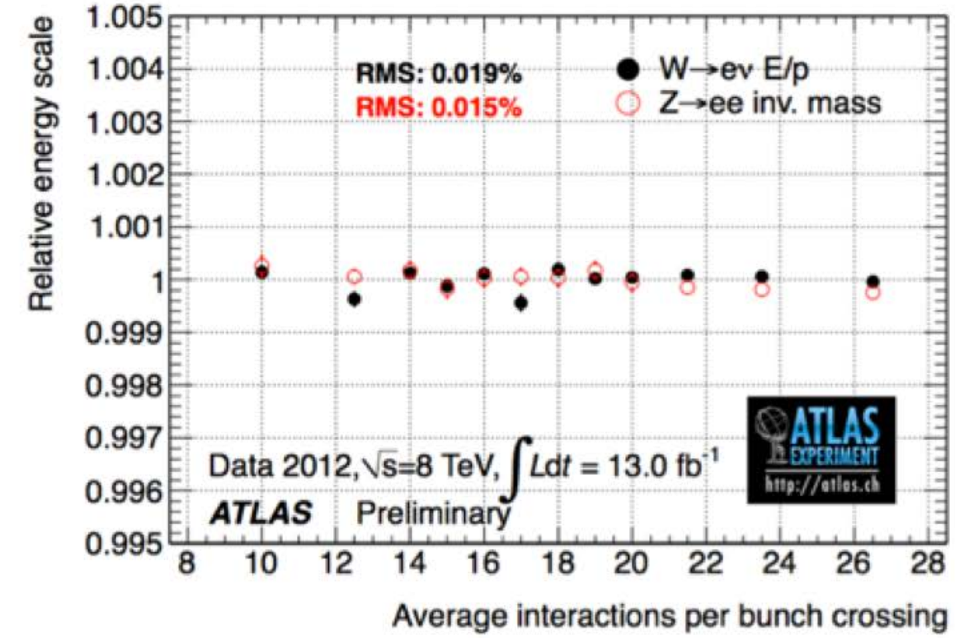
source	systematic uncertainties
absolute energy scale (Z→ee)	± 0.3%
upstream material simulation accuracies	± 0.3%
presampler energy scale	± 0.1 %
additional	± 0.32 %

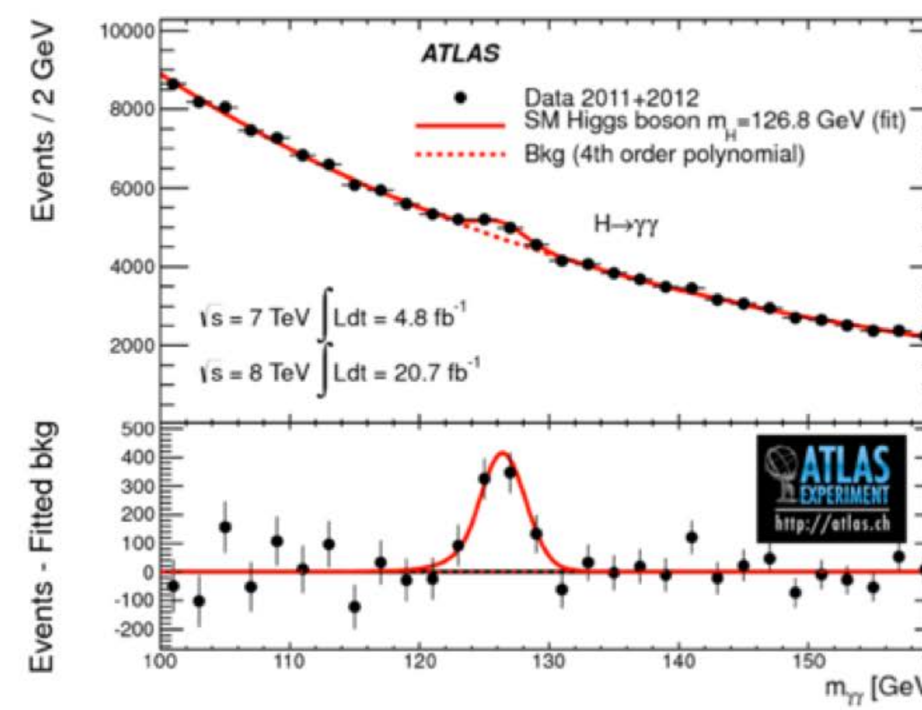
mass measurement:

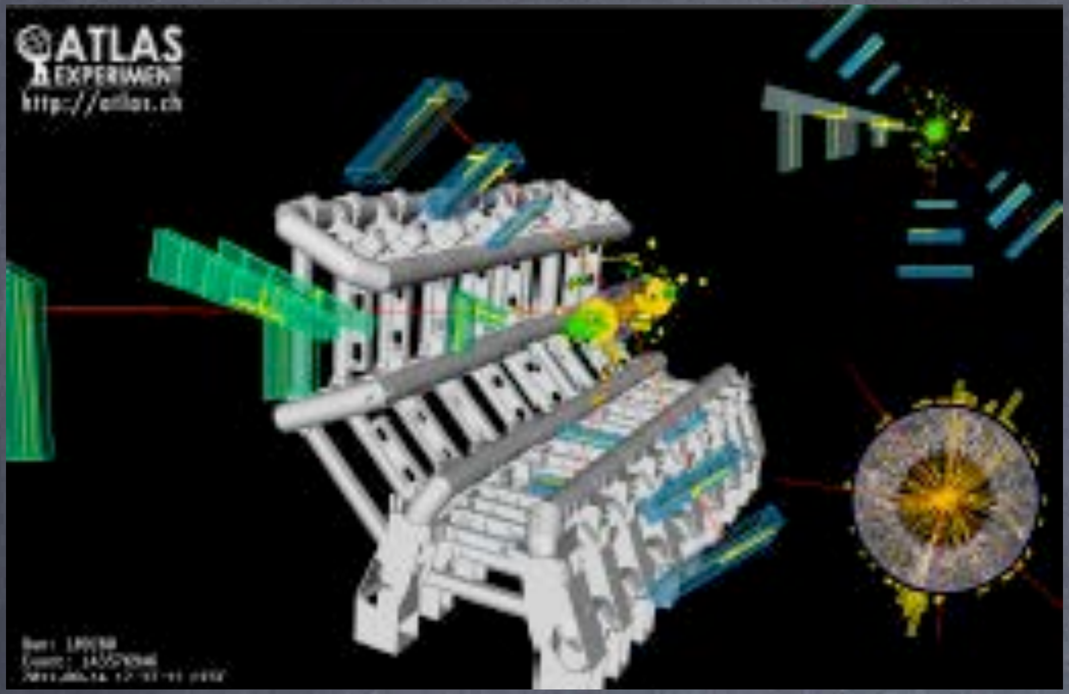
fit with both signal position and normalization free

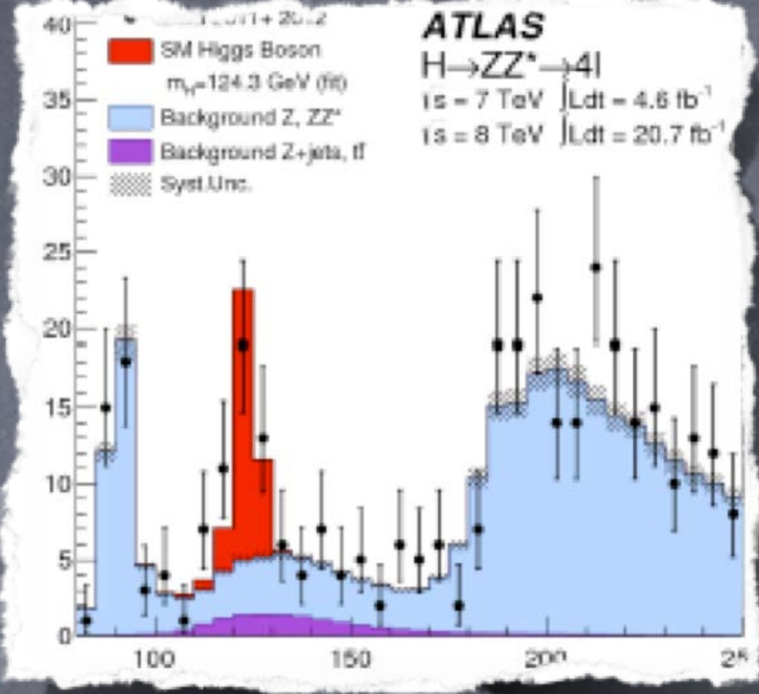
m_{Higgs} = 126.8 ± 0.2 (stat.) ± 0.7 (syst.) GeV

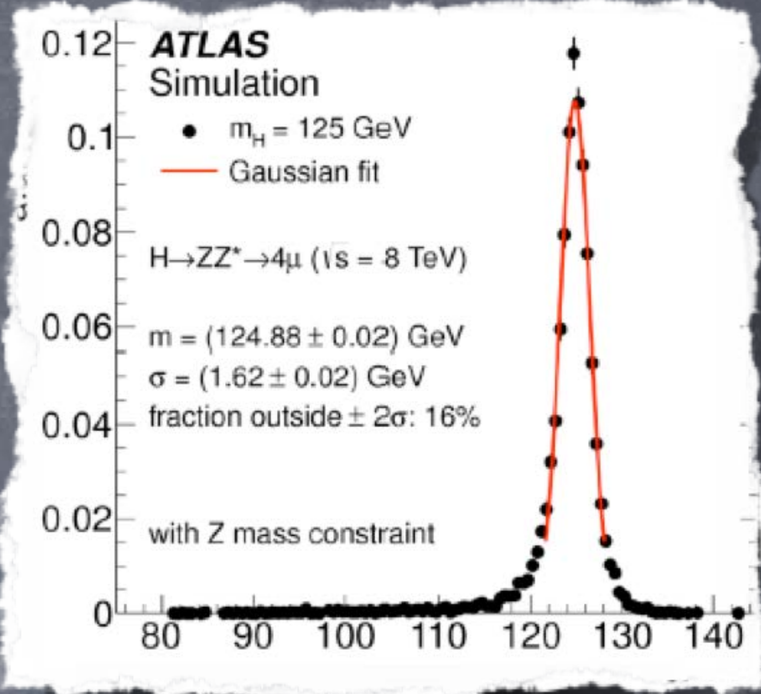
Stability of EM calorimeter response vs time (and pile-up) <0.1%











clean, closed, fully reconstructed mass ✔

high resolution ✔

4e, 2e2μ, 2μ2e and 4μ, use Z-candle mass ✔

low signal rates ✘

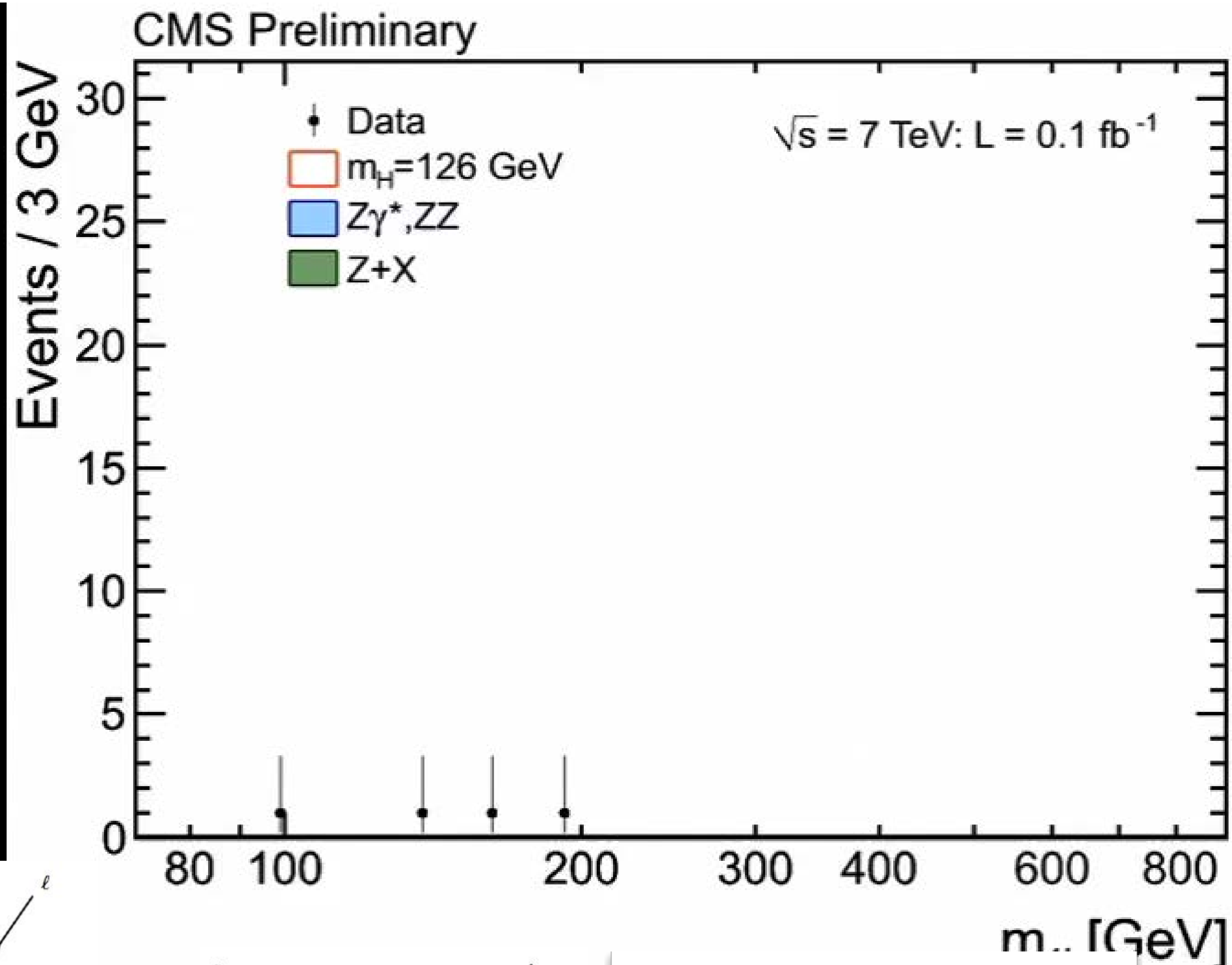
low background rates ✔

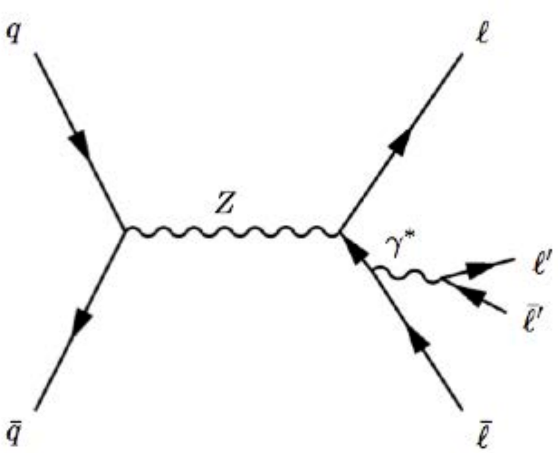
ZZ* continuum irreducible ✔

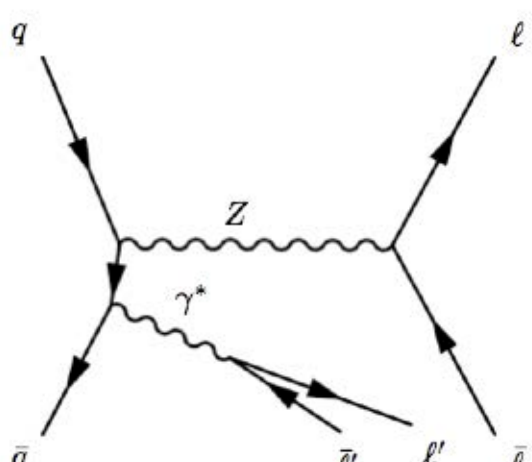
well understood, handles from data and MC

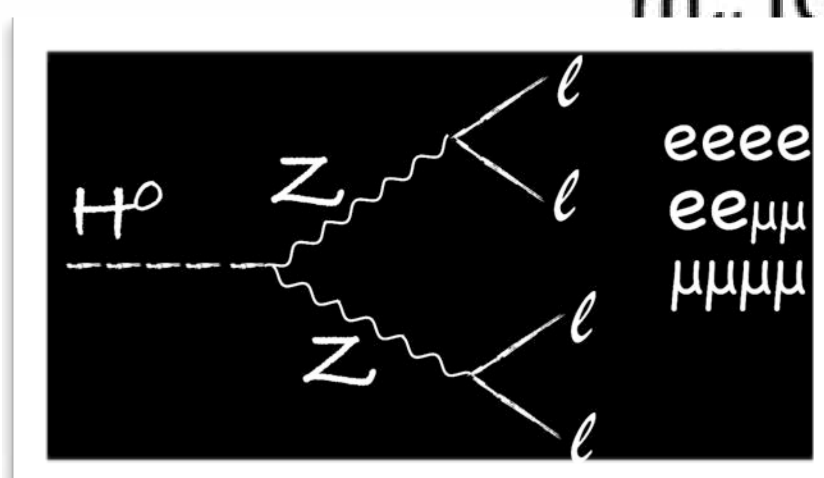
low mass Zbb/jets, tt, reducible ✔

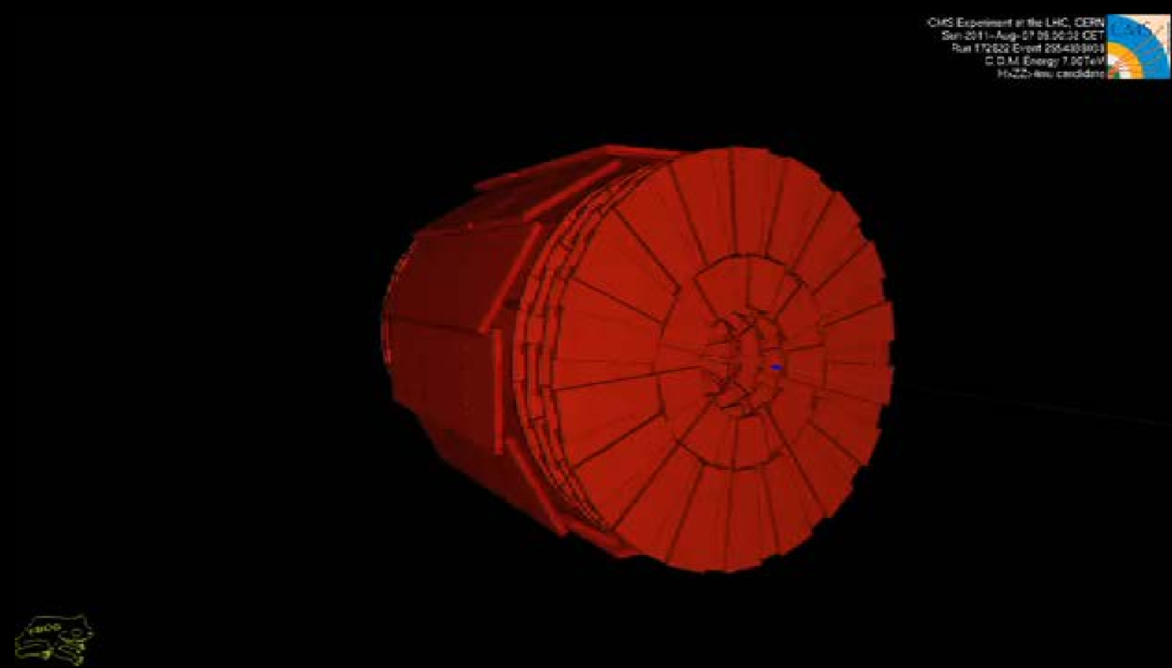
many handles from data and MC

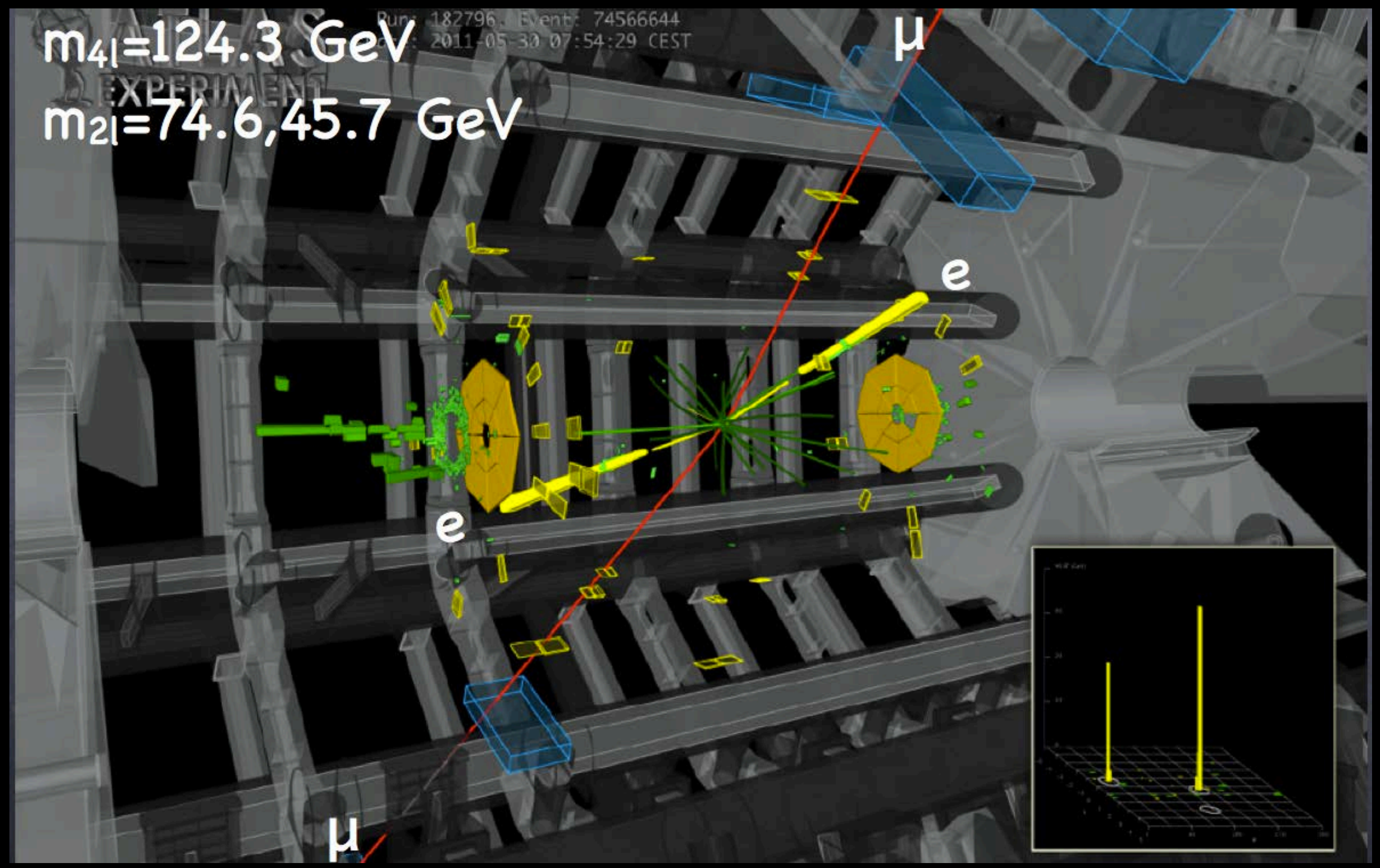

CMS Preliminary
Events / 3 GeV
Data
m_H=126 GeV
$Z\gamma^*$,ZZ
Z+X
$\sqrt{s}$ = 7 TeV: L = 0.1 fb^{-1}
0
5
10
15
20
25
30
80
100
200
300
400
600
800
m [GeV]

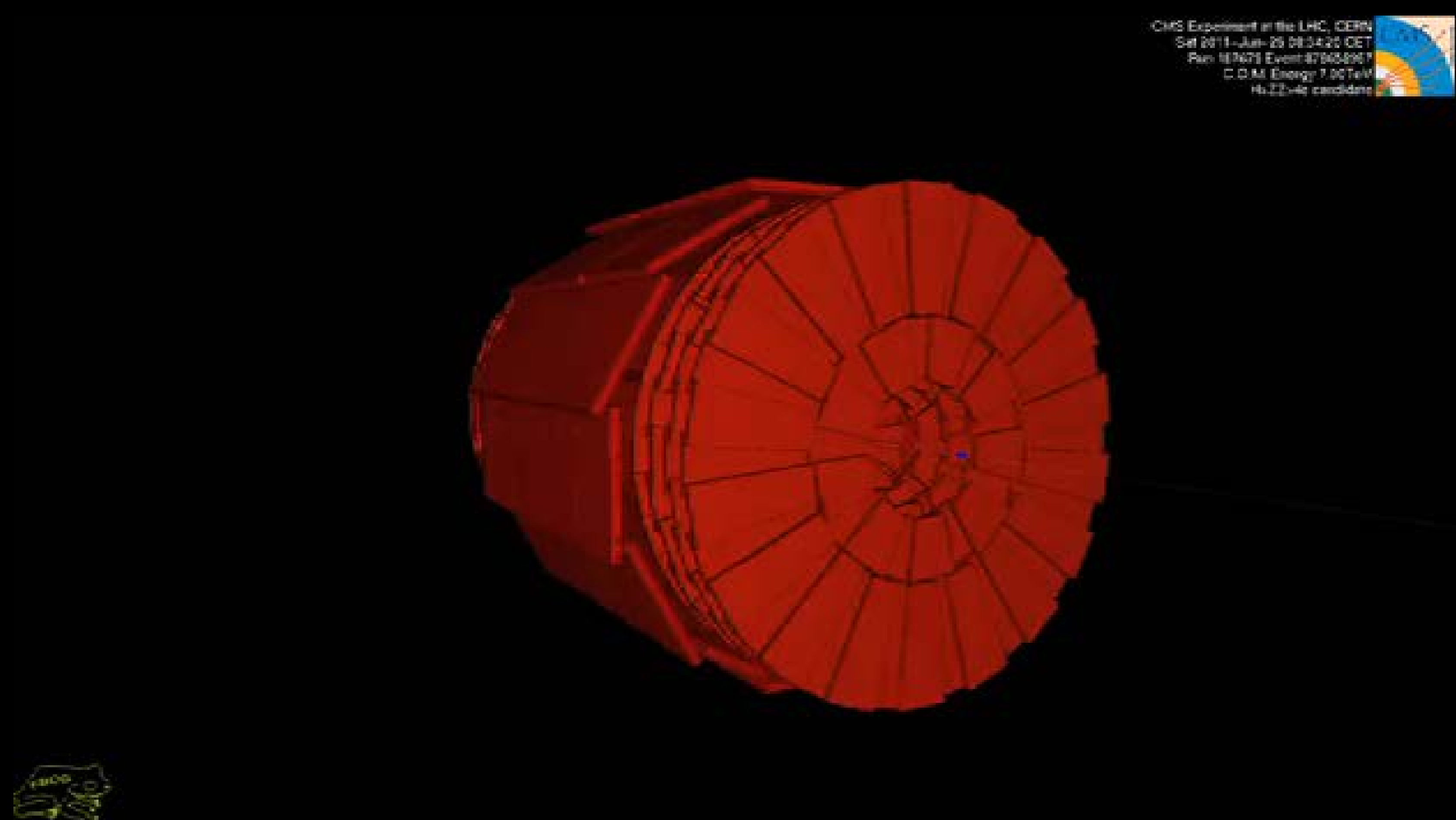

q
$\bar{q}$
Z
γ^*
ℓ
ℓ'
$\bar{\ell}'$
$\bar{\ell}$

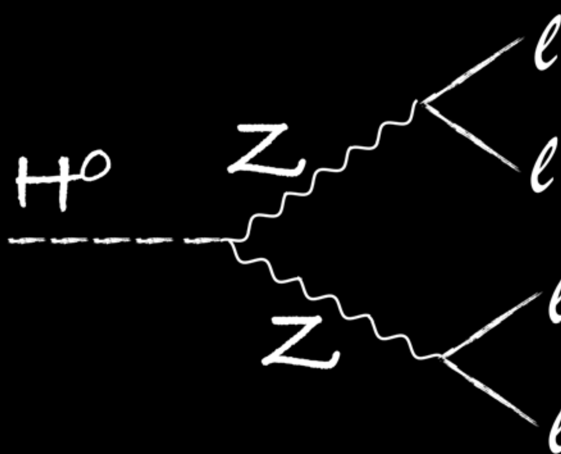

q
$\bar{q}$
Z
γ^*
ℓ
$\bar{\ell}'$
ℓ'
$\bar{\ell}$


H^0
Z
Z
ℓ
ℓ
ℓ
ℓ
eeee
eeμμ
μμμμ









eeee
eeμμ
μμμμ

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

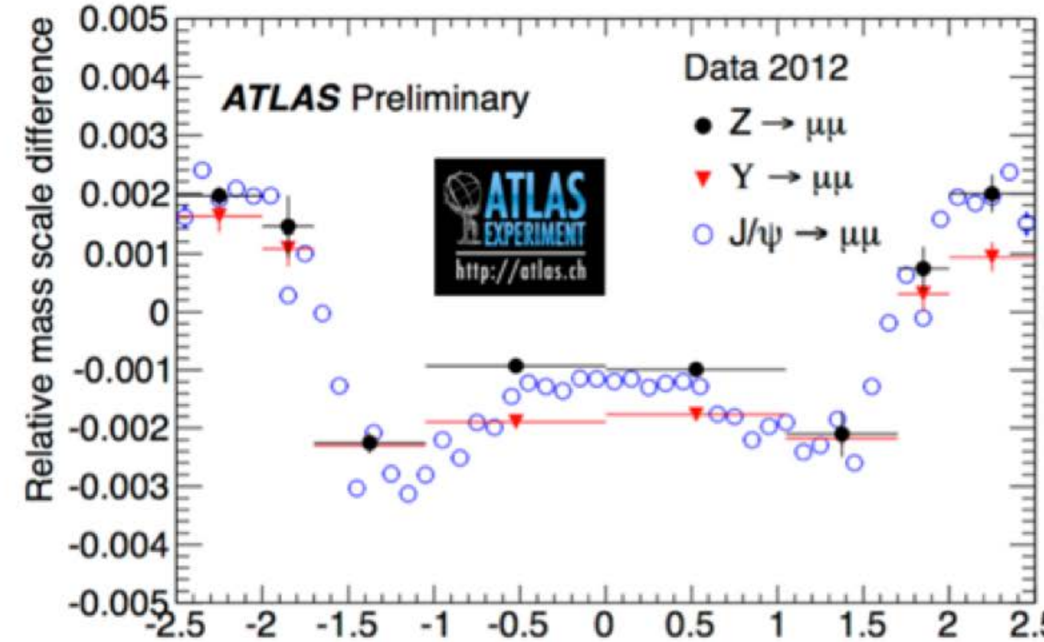
Systematic uncertainties :

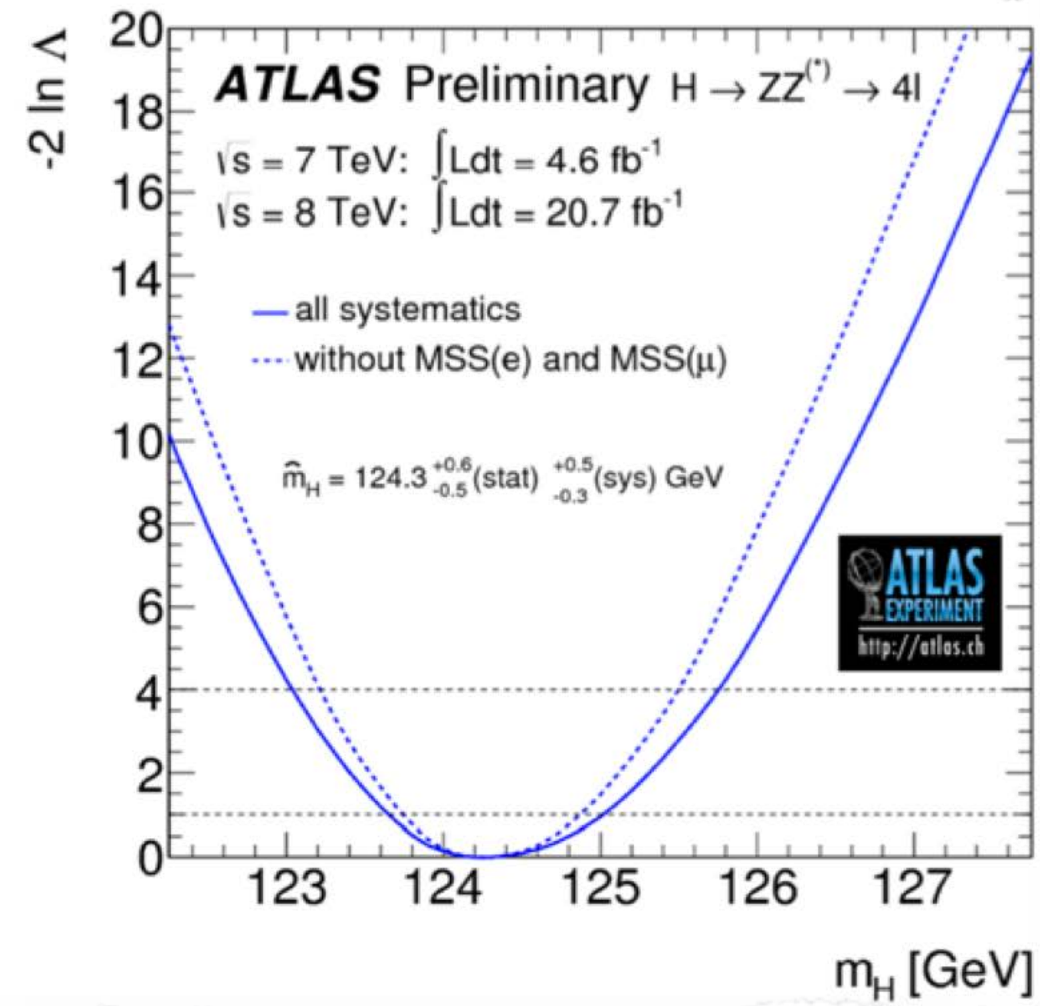
source	**systematic uncertainties**
muon momentum scale uncertainty%	± 0.2% (4μ) ± 0.1% (2μ2e)
electron energy uncertainty%	± 0.4% (4e) ± 0.2% (2e2μ)

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

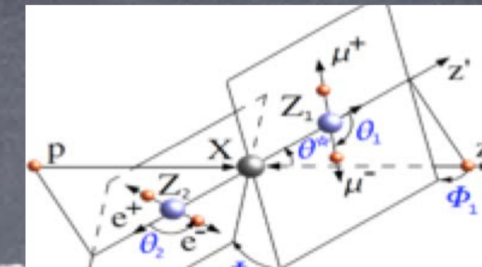
32 events **observed**
11.1±1.3 background predicted
15.9±2.1 signal predicted

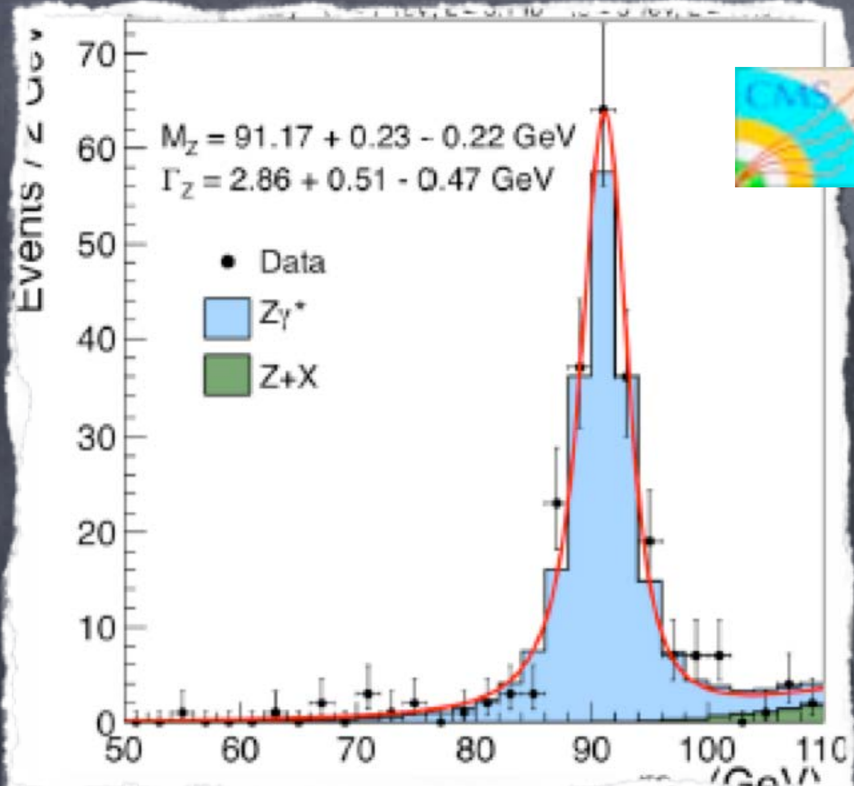
$m_{Higgs} = 123.4 \pm {}^{+0.6}_{-0.5}$ **(stat.)** $\pm {}^{+0.5}_{-0.3}$ **(syst.) GeV**

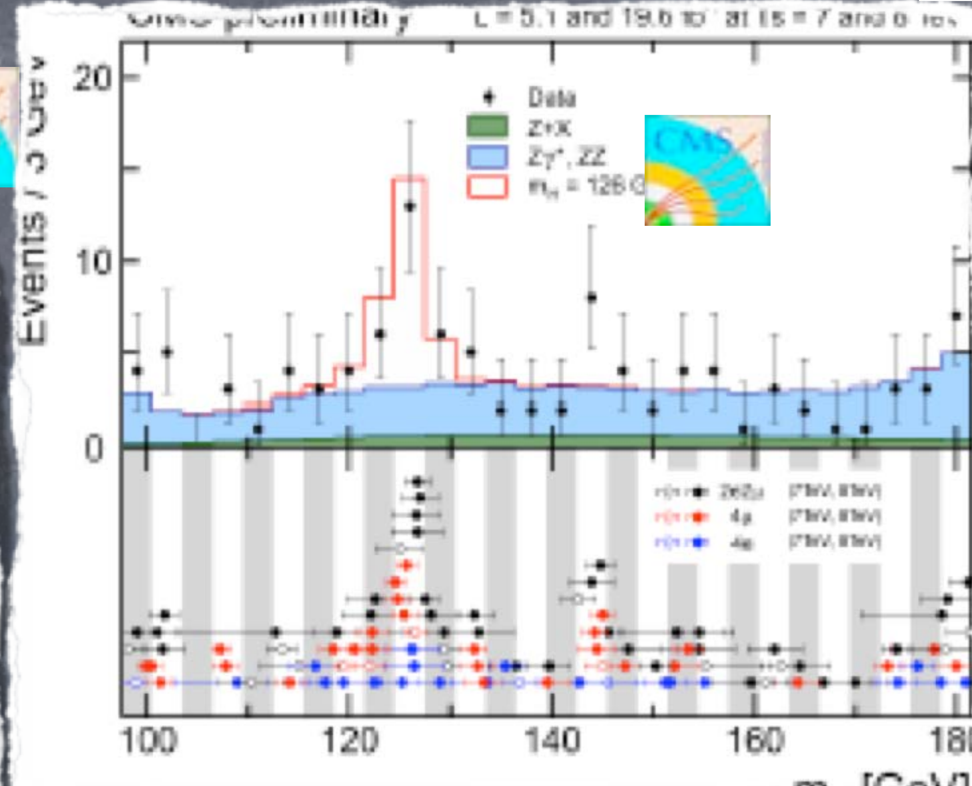


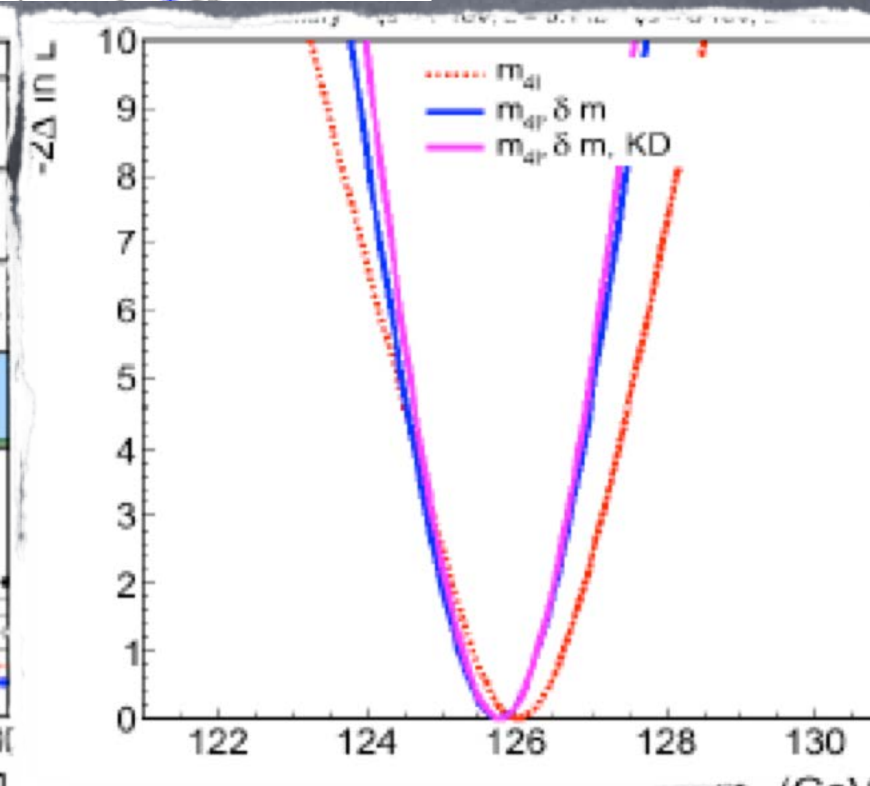


$$\mathrm{KD} = \frac{\mathcal{P}_{\mathrm{sig}}}{\mathcal{P}_{\mathrm{sig}} + c \times \mathcal{P}_{\mathrm{bkg}}} = \left[1 + \frac{c \times \mathcal{P}_{\mathrm{bkg}}(m_1, m_2, \vec{\Omega} | m_{4\ell})}{\mathcal{P}_{\mathrm{sig}}(m_1, m_2, \vec{\Omega} | m_{4\ell})}\right]^{-1}$$









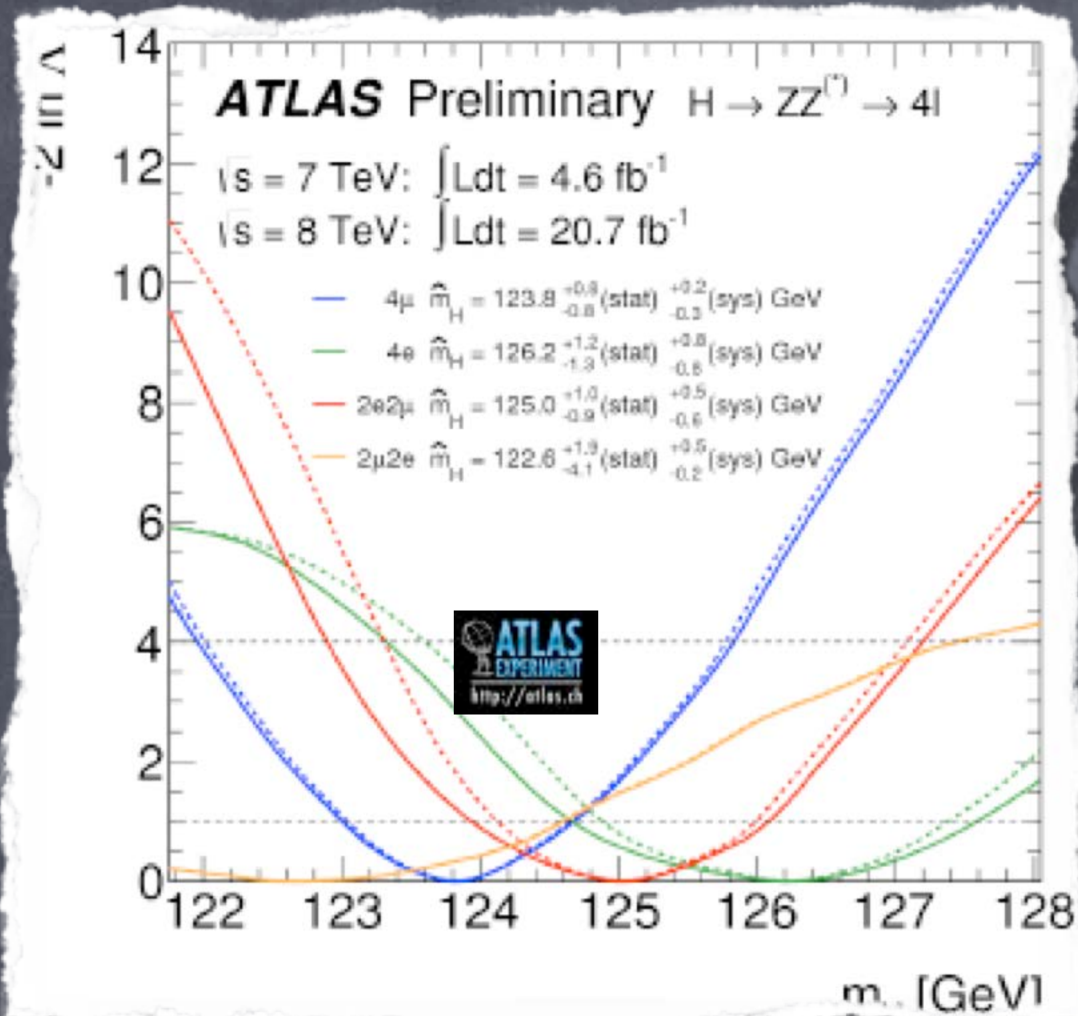
ditto+

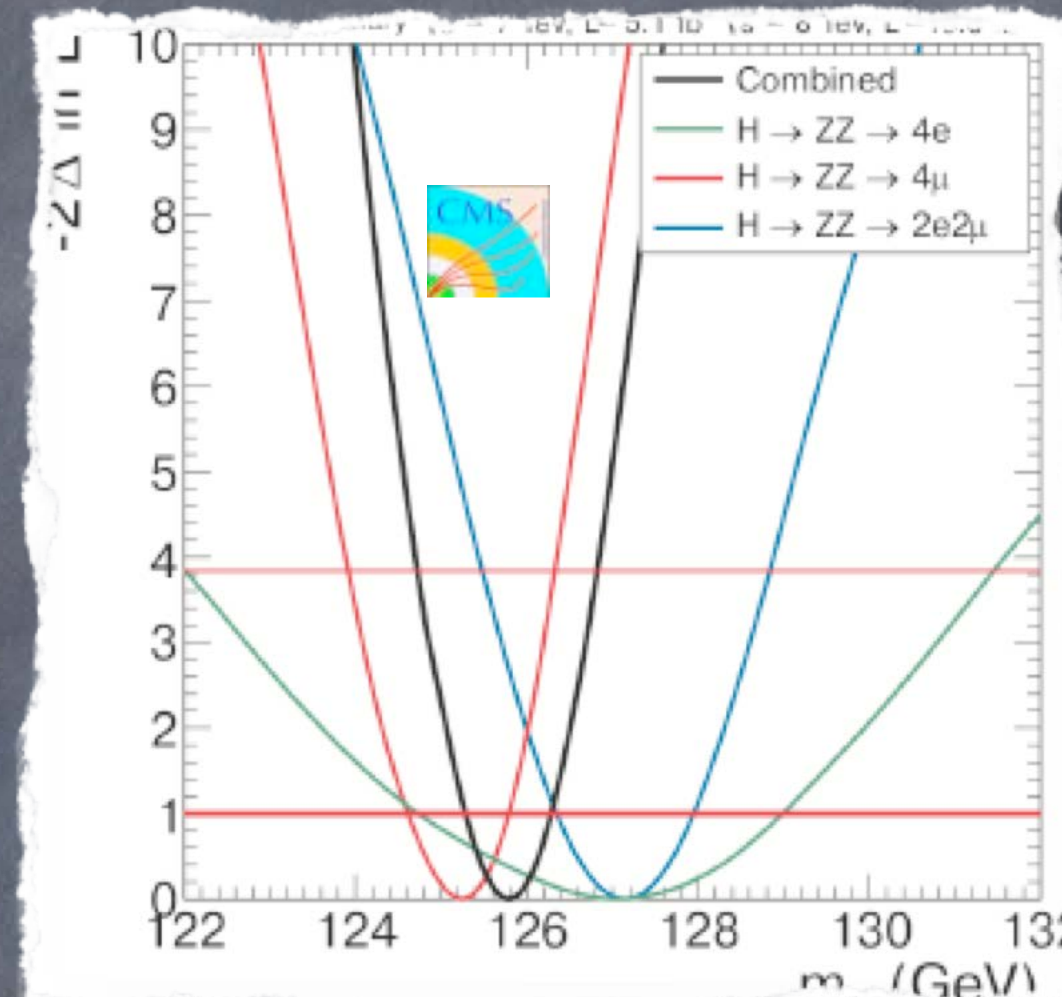
kinematic discriminant (KDME) , S/B optimization ✔

even-by-event mass uncertainties ✔ weight individual events in the mass fit according too their mass uncertainties δm4l

expected improvement of 8% on the mass uncertainty ✔

[120.5-130.5] observed 25, expected 18.6 signal, 9.4 background





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

high pT cuts, tight Z mass constraints

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

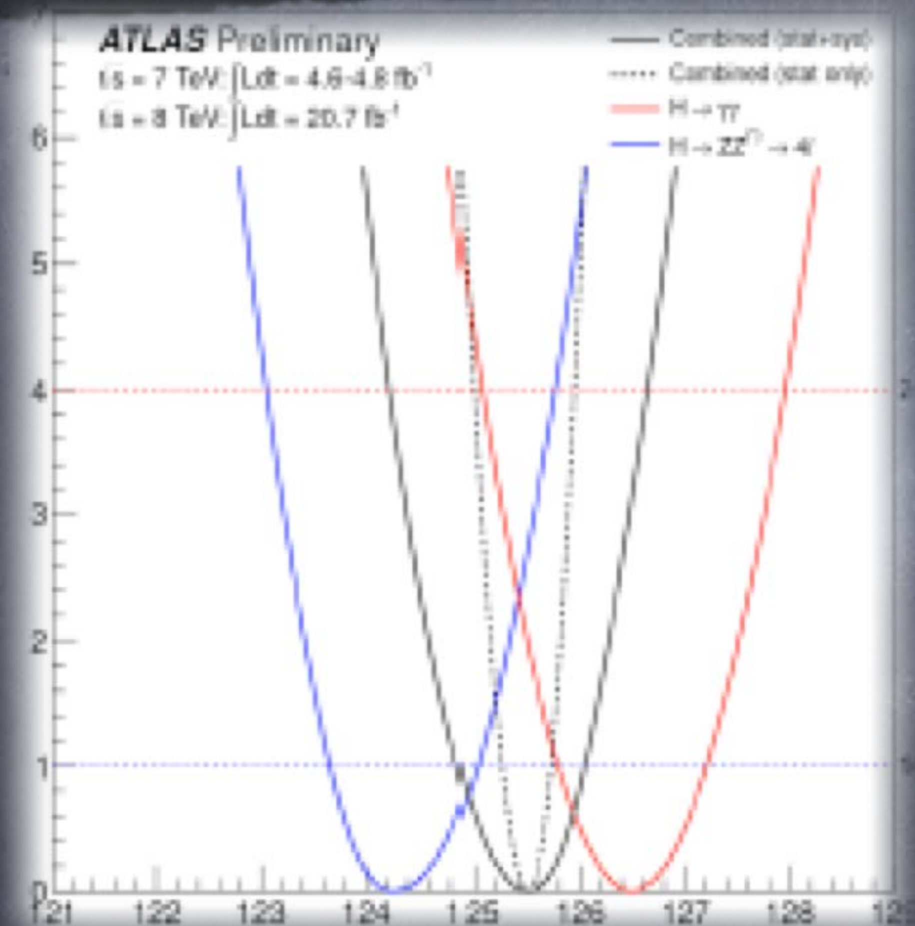
3D fits, event-by-event-errors, kinematic discriminant

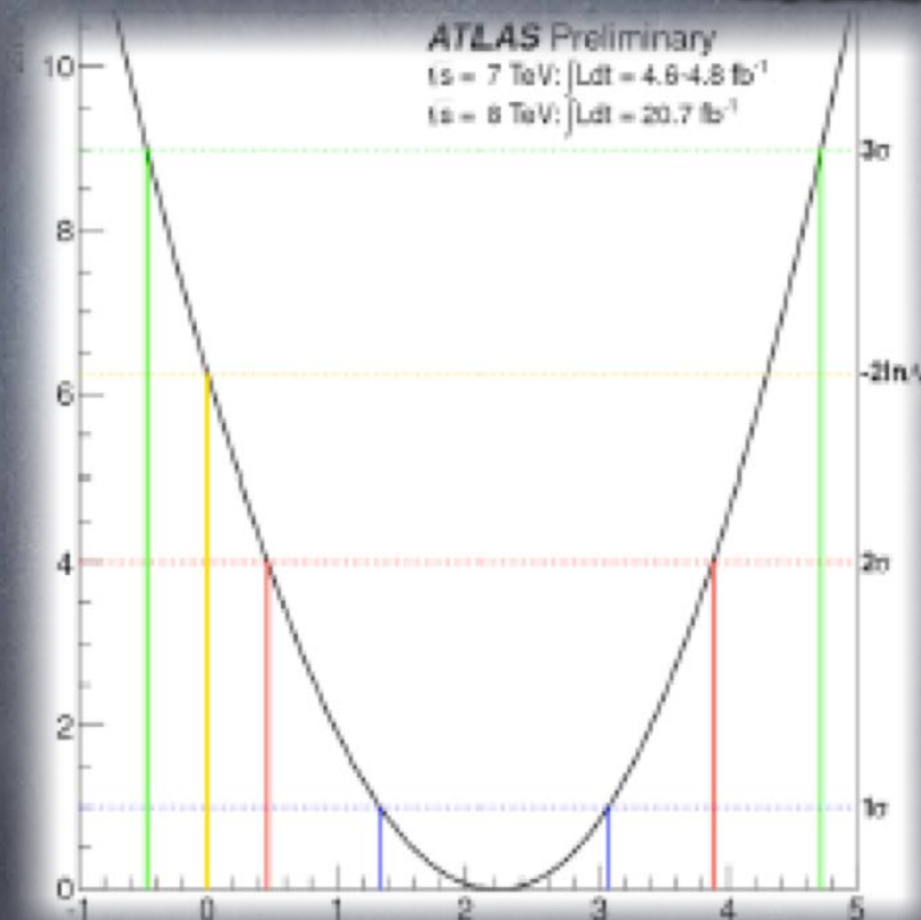
$\Delta m_H^{ATLAS} =: m_{\gamma\gamma}^{ATLAS} - m_{4l}^{ATLAS} =$

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

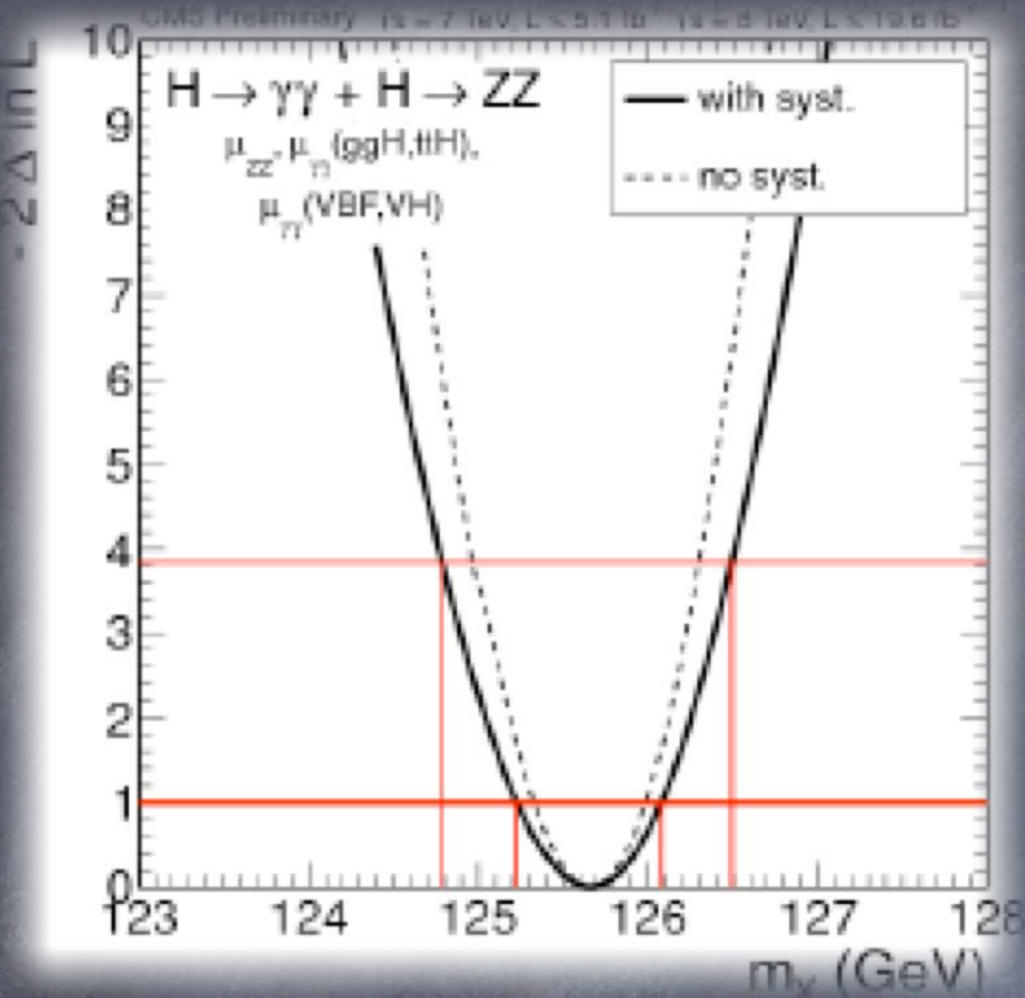
2.4 σ away from $\Delta m_H = 0$ (p-value = 1.5%)

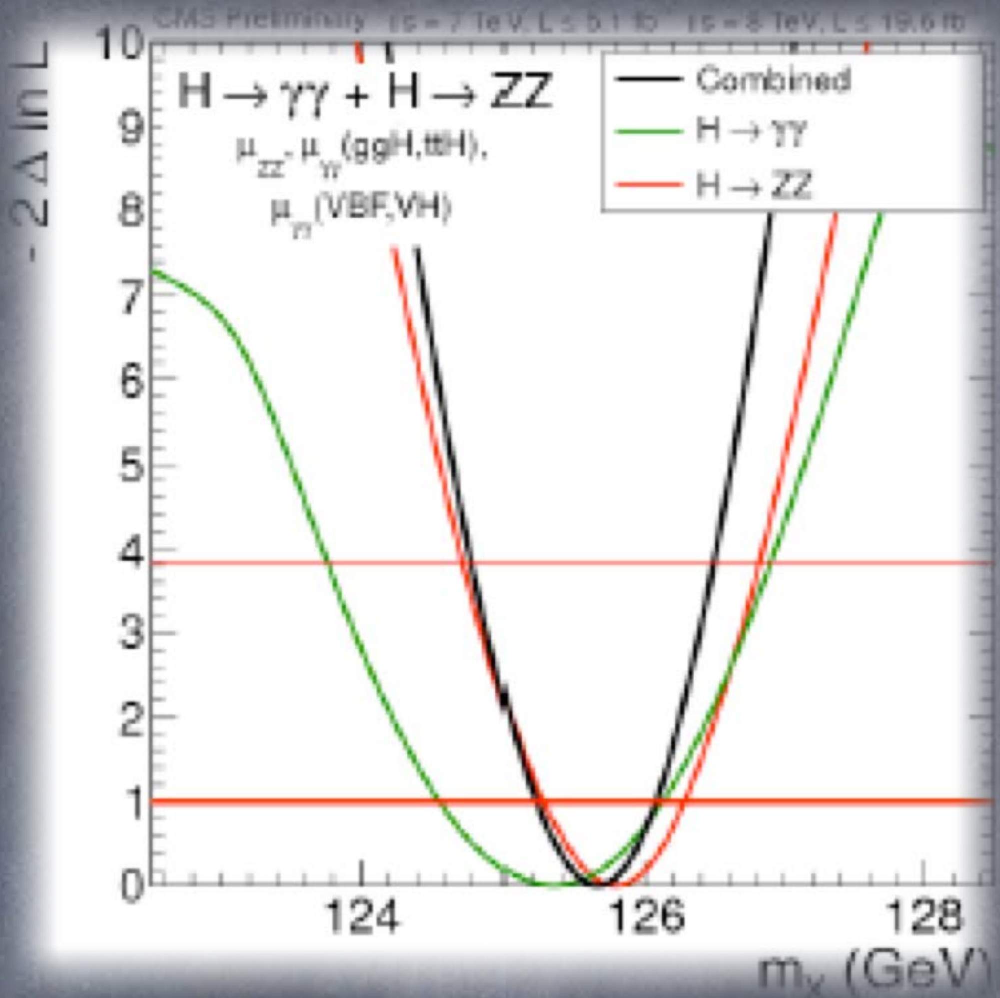
[8% (<1.5 σ) using a conservative treatment of the uncertainties]





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



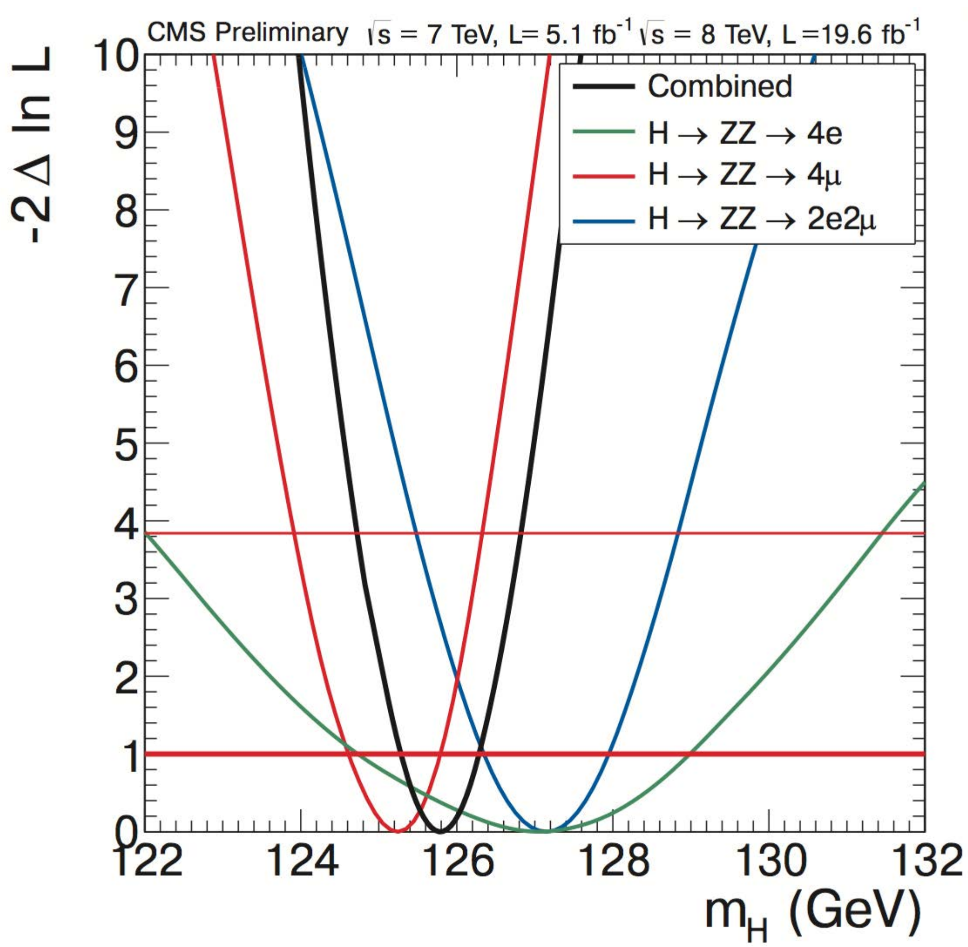


Combine γγ and 4l mass measurements, signal strengths. $m_{\gamma\gamma}(ggF)$, $m_{\gamma\gamma}(VBF)$ and m_{4l}, allowed to vary independently - don't assume SM couplings

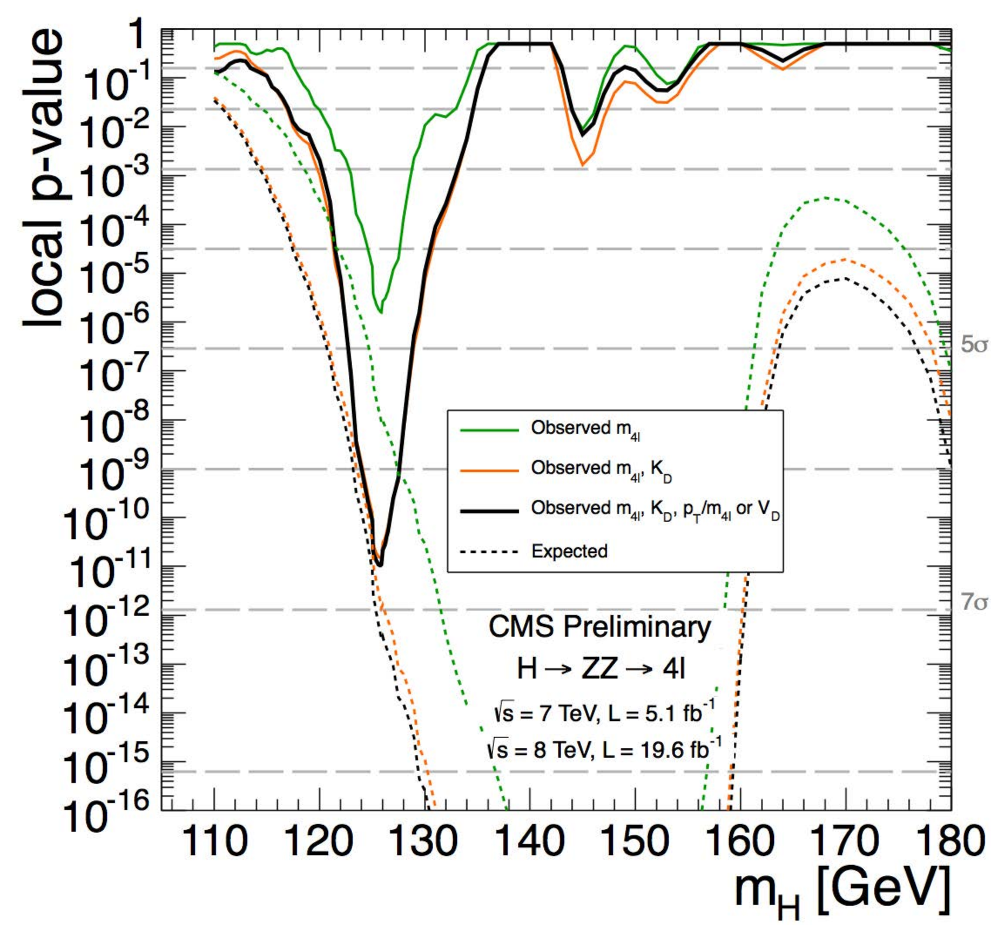
$m_H^{CMS(ggF, VBF, 4l)}$ = 125.7 ± 0.3 (stat) ± 0.3 (sys) GeV

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

- $H \rightarrow 4l$ in CMS provide the best measurement of the Higgs mass:
  - $m_H = 125.8 \pm 0.5$ (stat.) ± 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, 4μ, 2e2μ



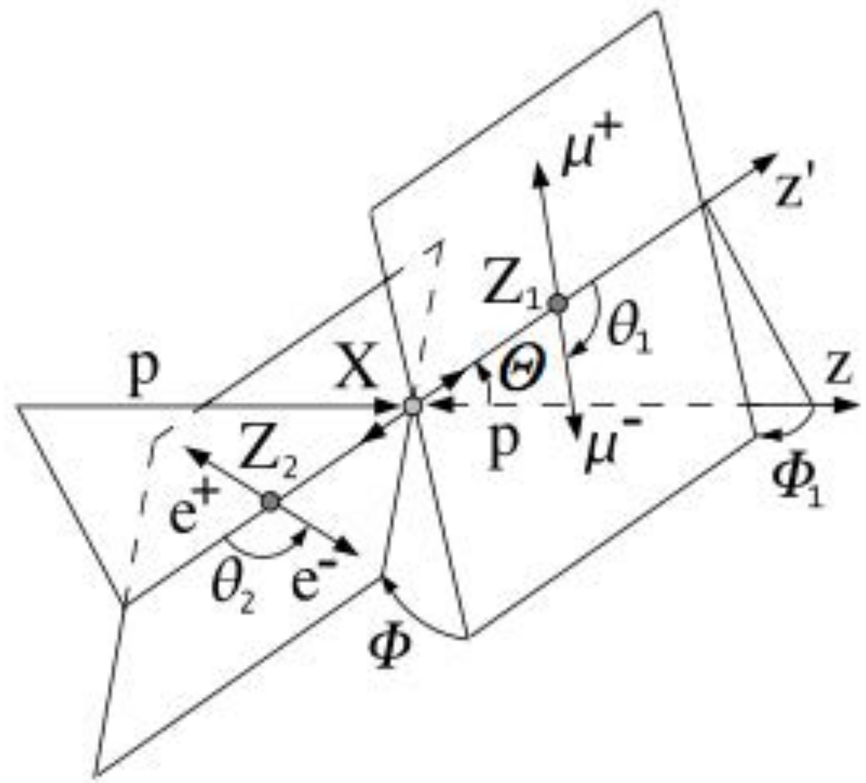
min. p-value: 6.7σ

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))

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



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

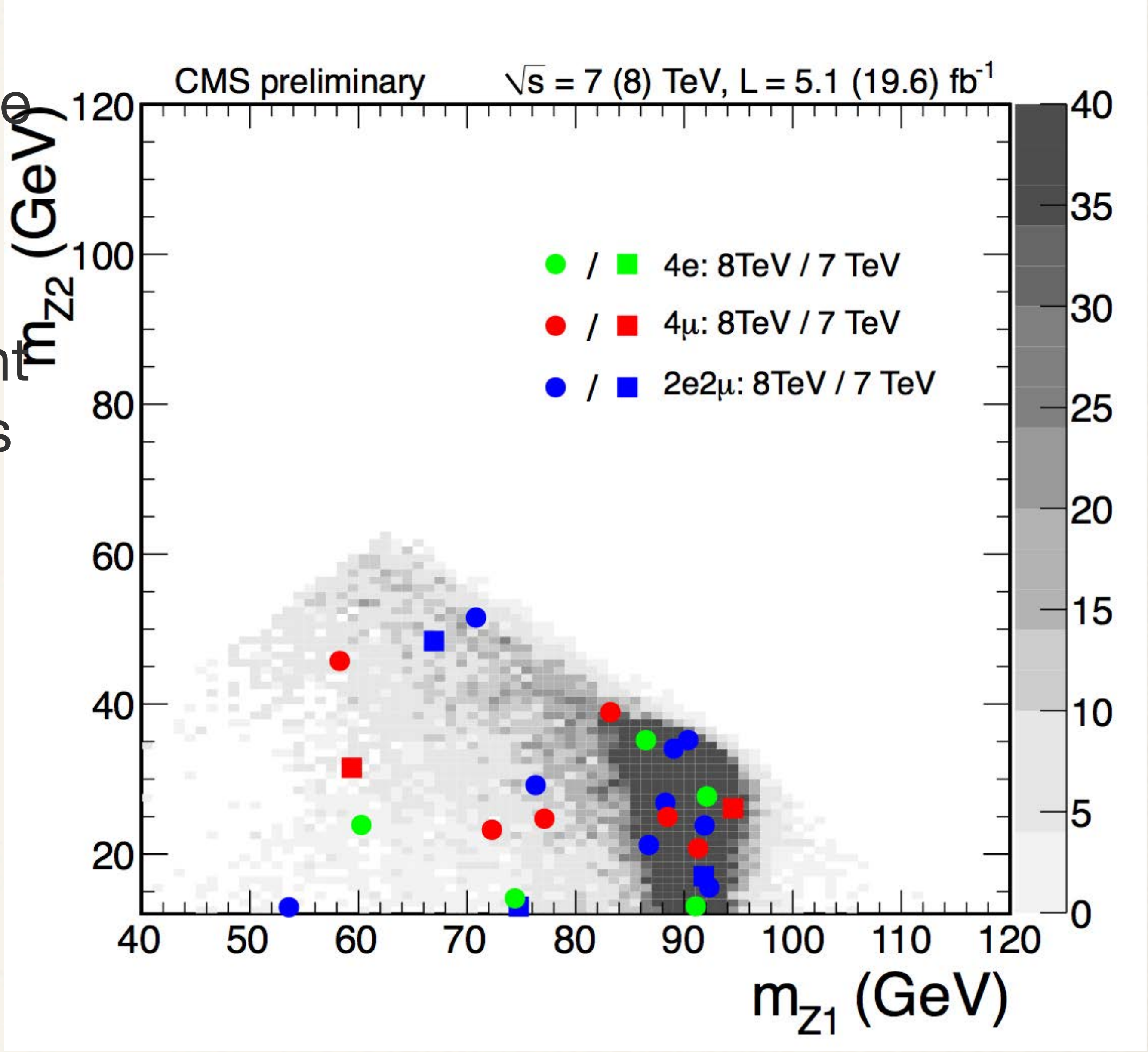
- All angles defined in 4ℓ CM frame (or X in case of signal)
- Correlations between lepton angles studied for some time

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

Slide from Roberto Vega-Morales

Higgs Golden Channel kinematics

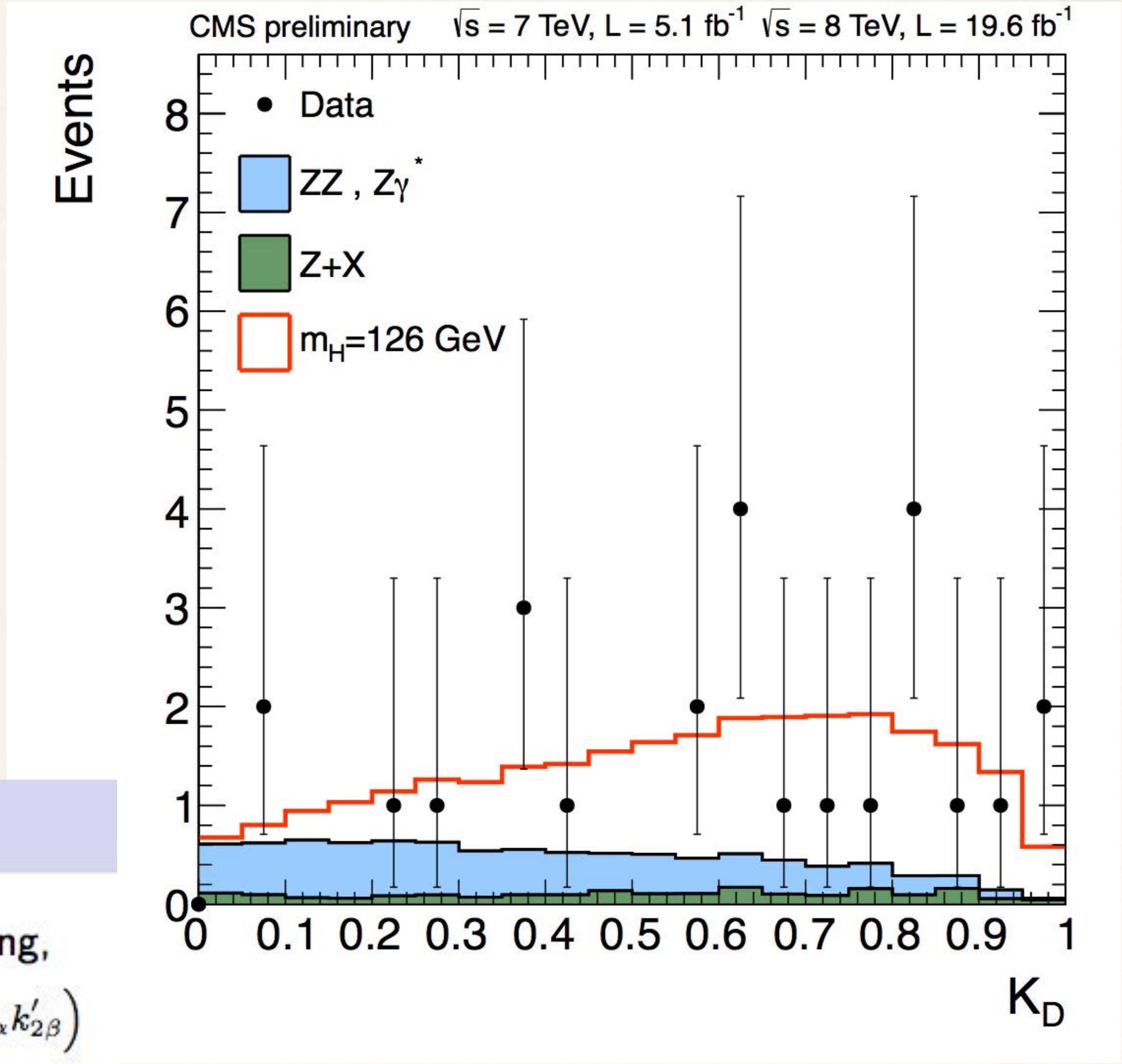
- For a 126 GeV Higgs, one of the Z's in the decay is always badly off shell, and the other one can be pretty off shell too
- Also about 1% of the time the signal event is actually from Higgs decays to 4 leptons through $\mathbf{Z}\gamma$ or $\gamma\gamma$, not $\mathbf{Z}\,\mathbf{Z}$
- The two "Z" 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

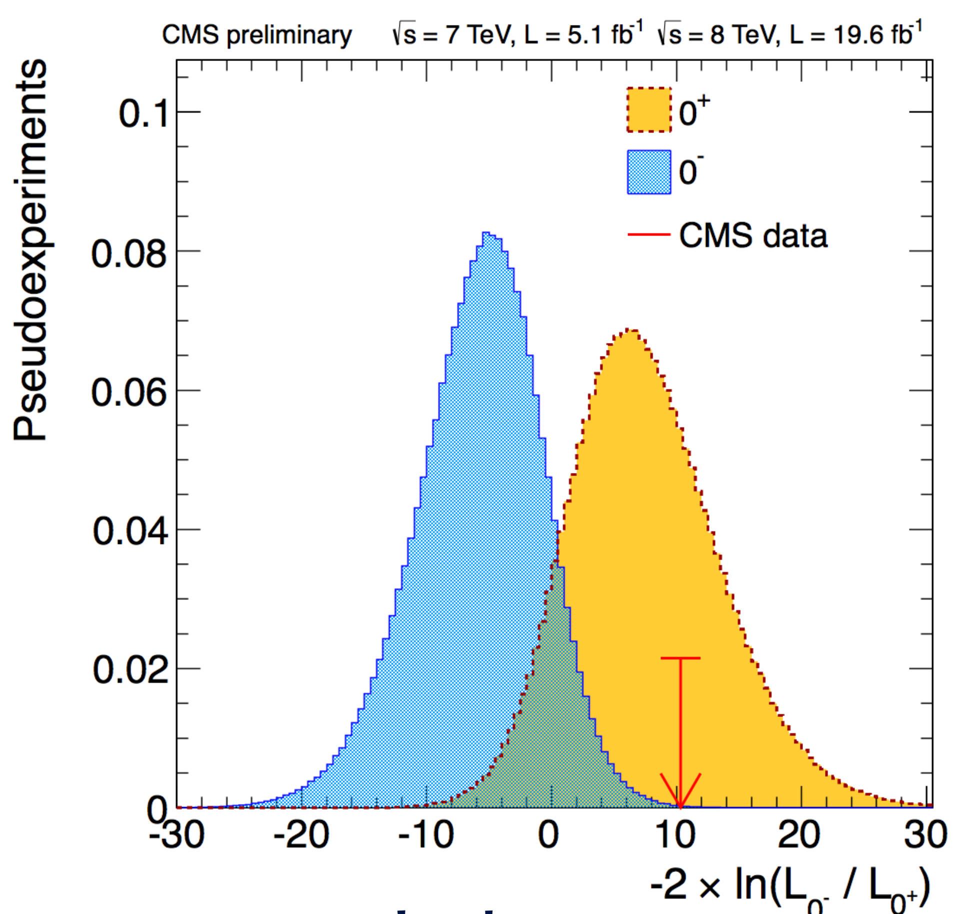
- Parametrize scalar couplings to vector boson pairs as the following,

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

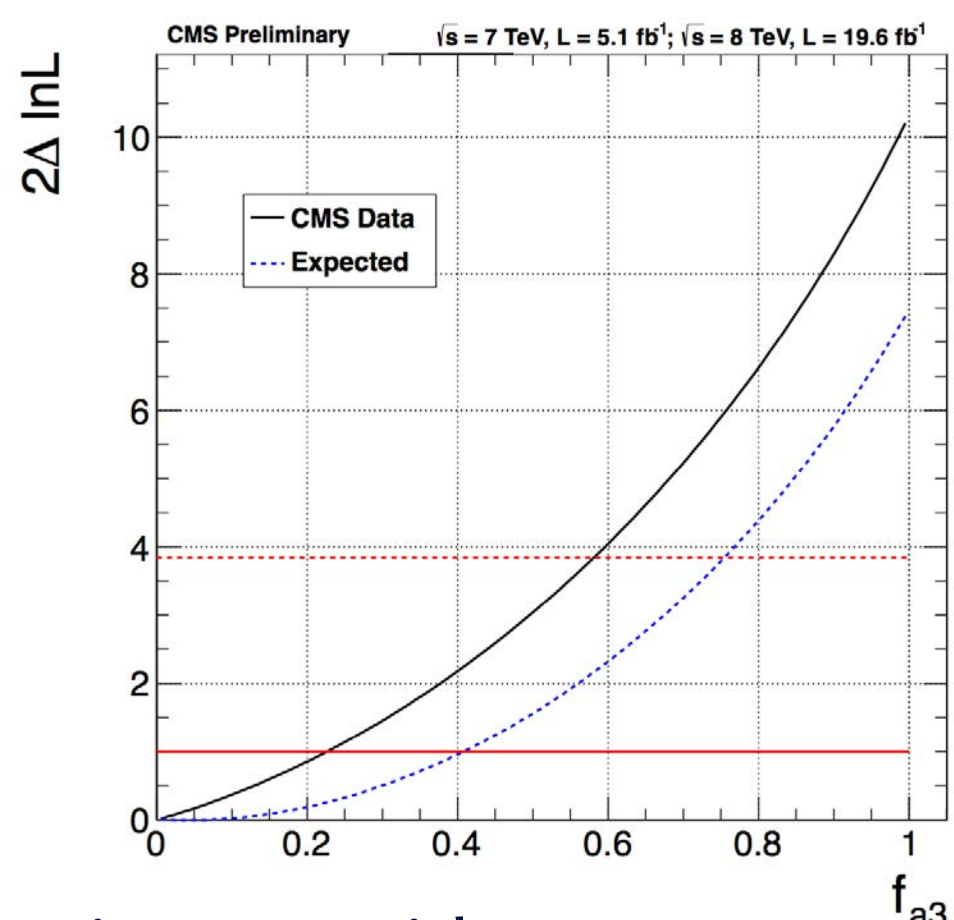
- The A_{nij} in principal complex and $ij = ZZ, Z\gamma, \gamma\gamma$ ($A_{1Z\gamma} = A_{1\gamma\gamma} = 0$)
- k, k' momentum of vector bosons (or lepton pair system)

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 fa3, but for other amplitudes, need to consider rates and phases together ⇒ multi-D fits / tests to groups of reduced sets of parameters



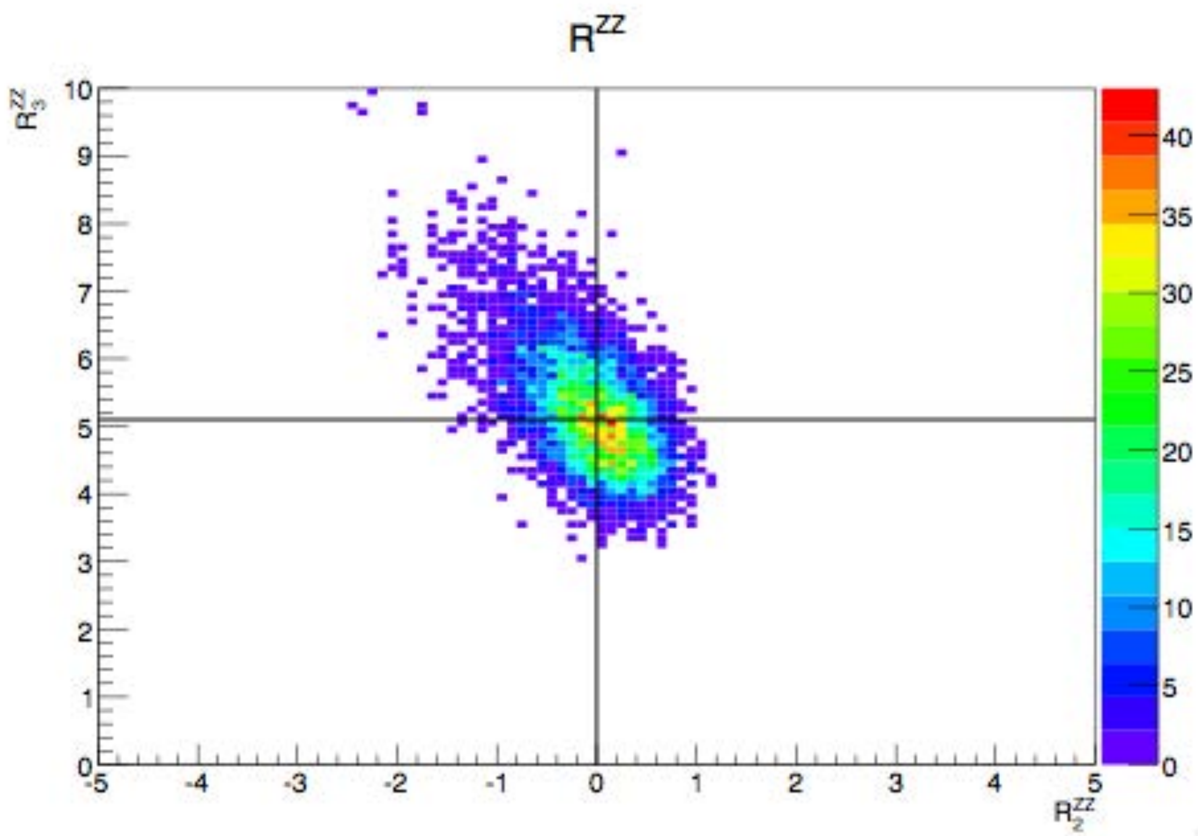
exclude 0^- at $>3\sigma$



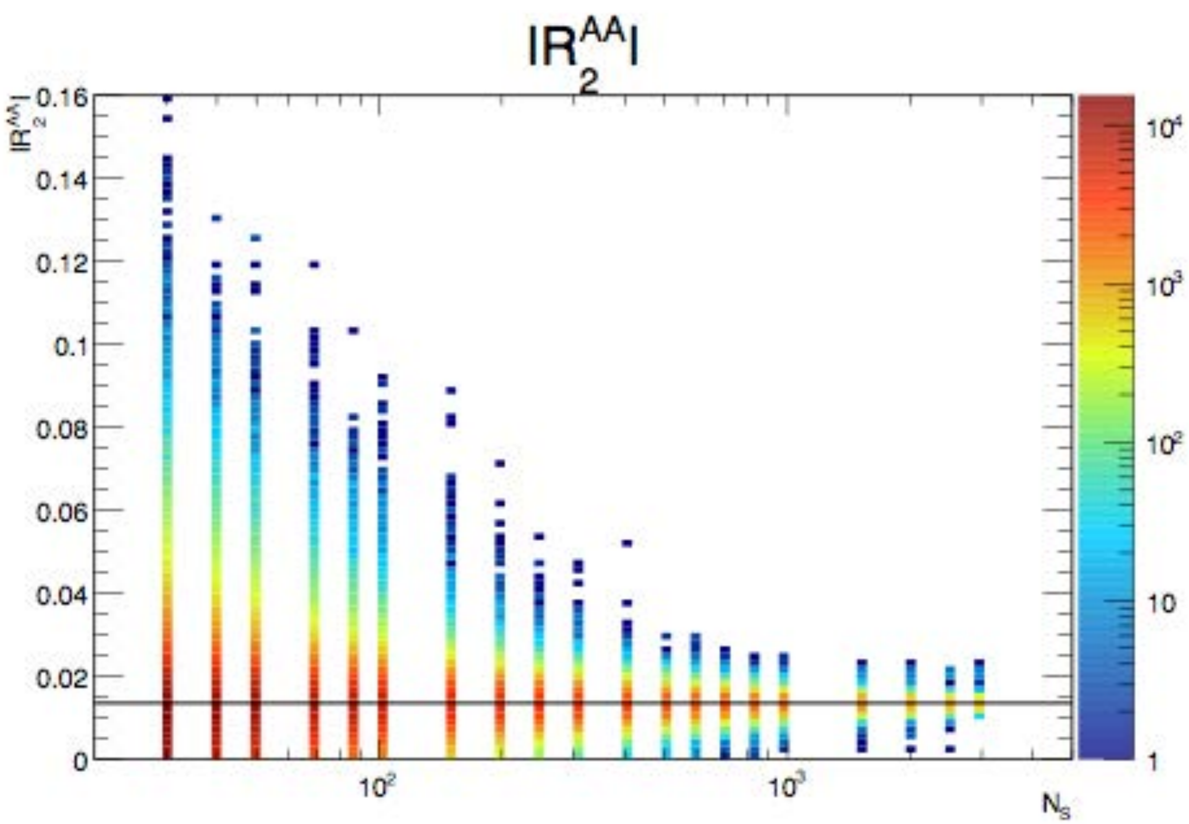
consistency with 1 CP-even pure state

H→ZZ→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

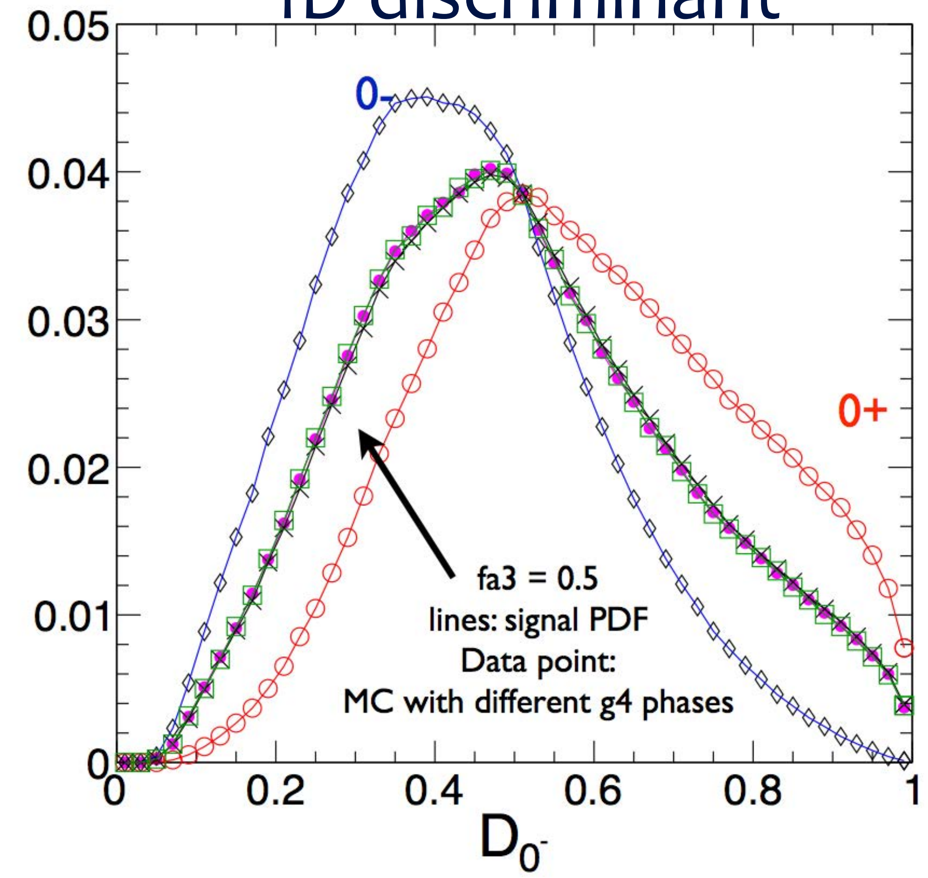


toys: scaling of precision with lumi: from 30 (current) → 3000 events

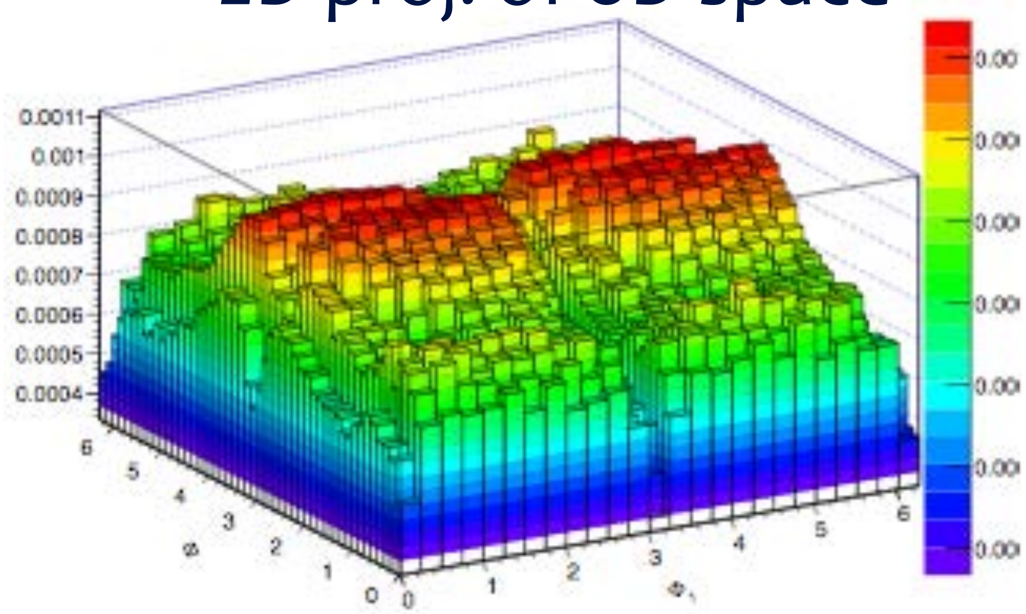
What are the challenges?

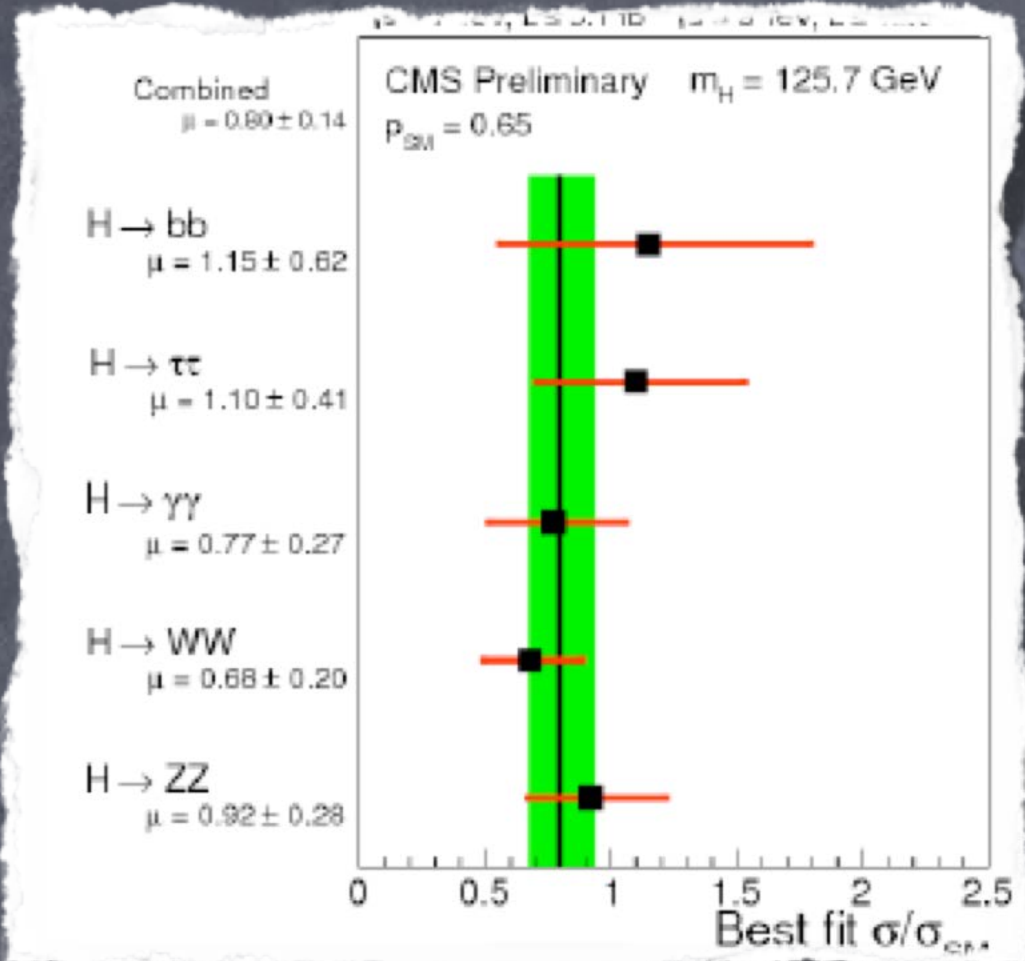
- 1D "discriminant" fit:
  - pro: Simpler. Build templates from full sim
  - cons: cannot measure all parameters at a time. Need to build discriminant for each measurement
- 8D fit:
  - pros:
    - perform the measurement of all the parameters, rates and interference, at the same time.
    - provides 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

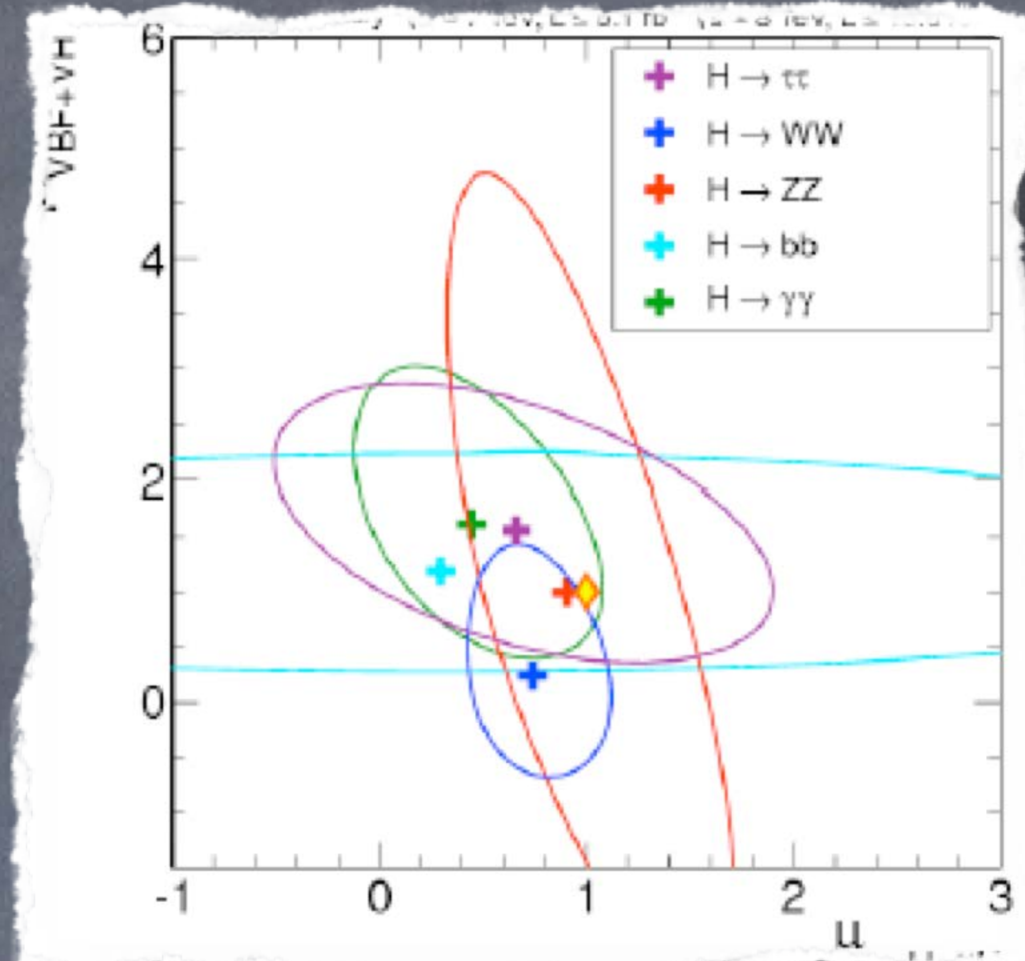
1D discriminant



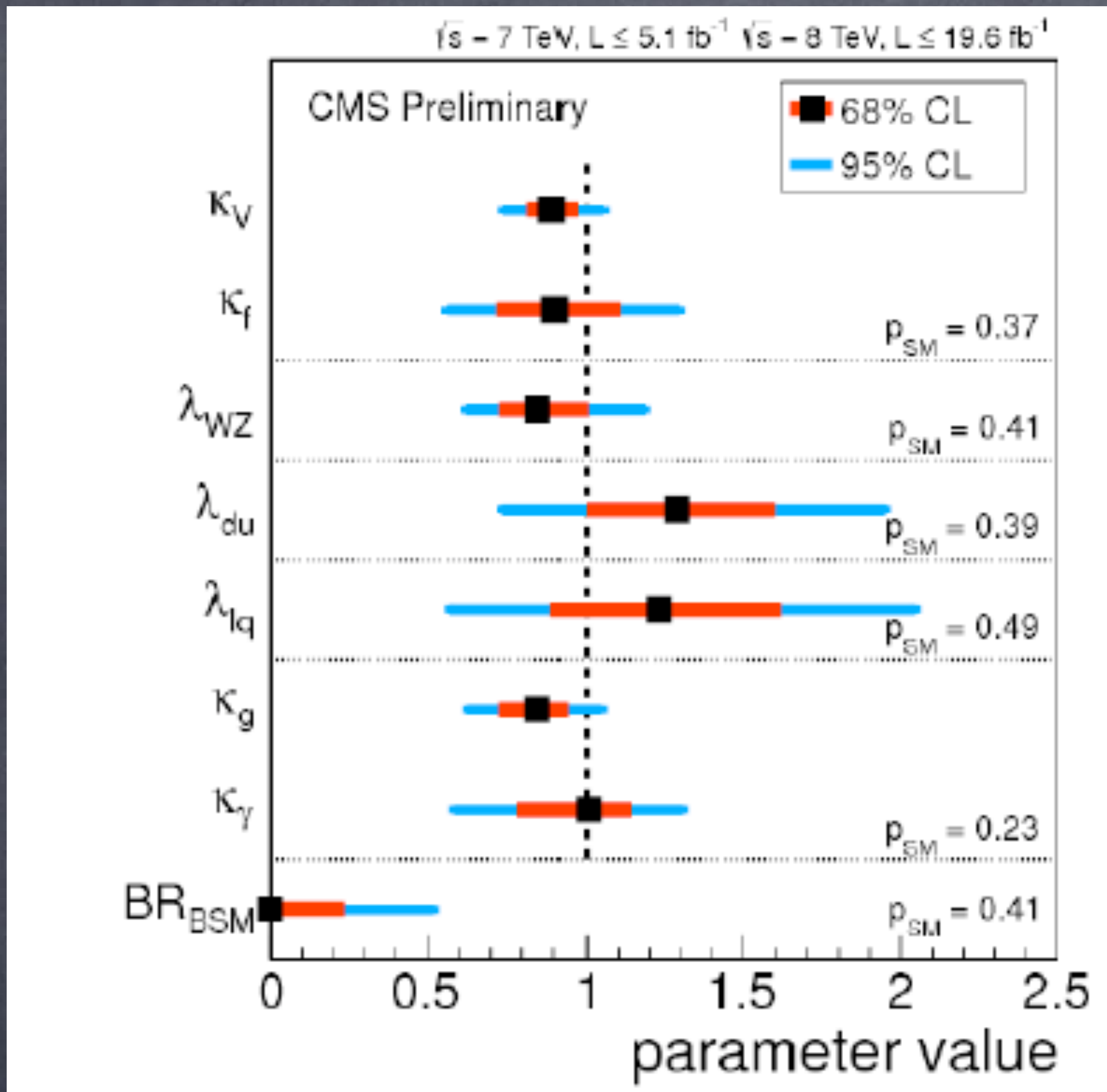
2D proj. of 8D space

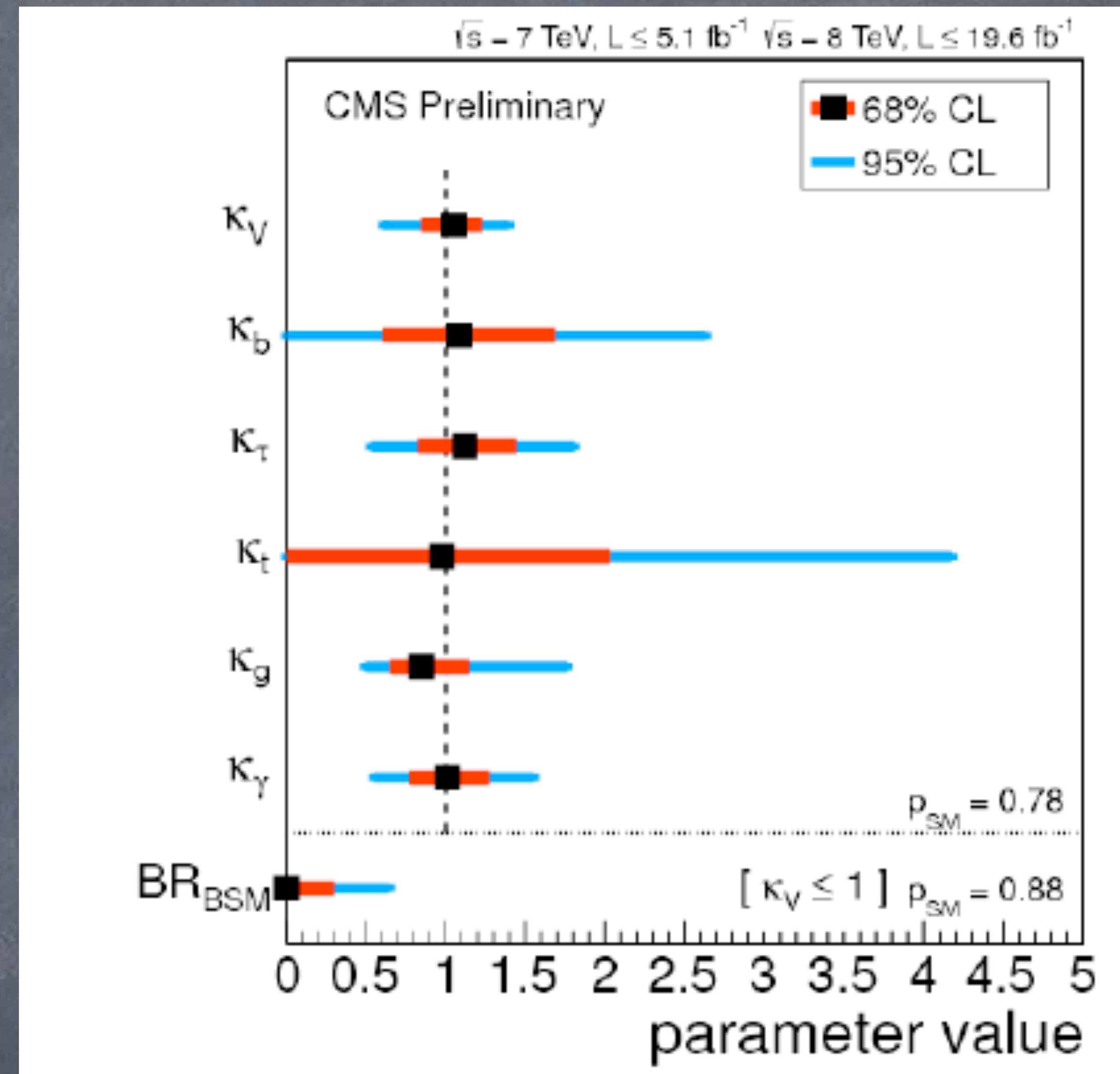






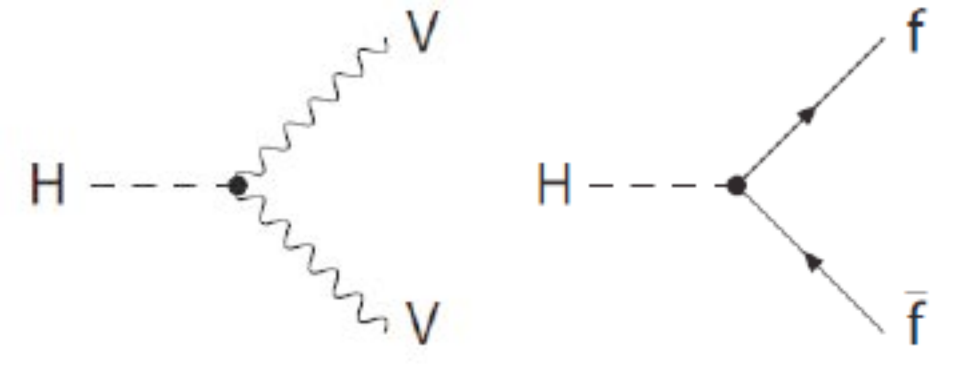
◉ Results from the individual modes close to the SM Higgs predictions probe the couplings by expanding around that reference point.
◉ couplings=searches for deviations from the SM Predictions in the scalar couplings (LHC XS WG, arxiv:1209.0040)); use benchmark models
◉ BSM decays , when allowed in the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



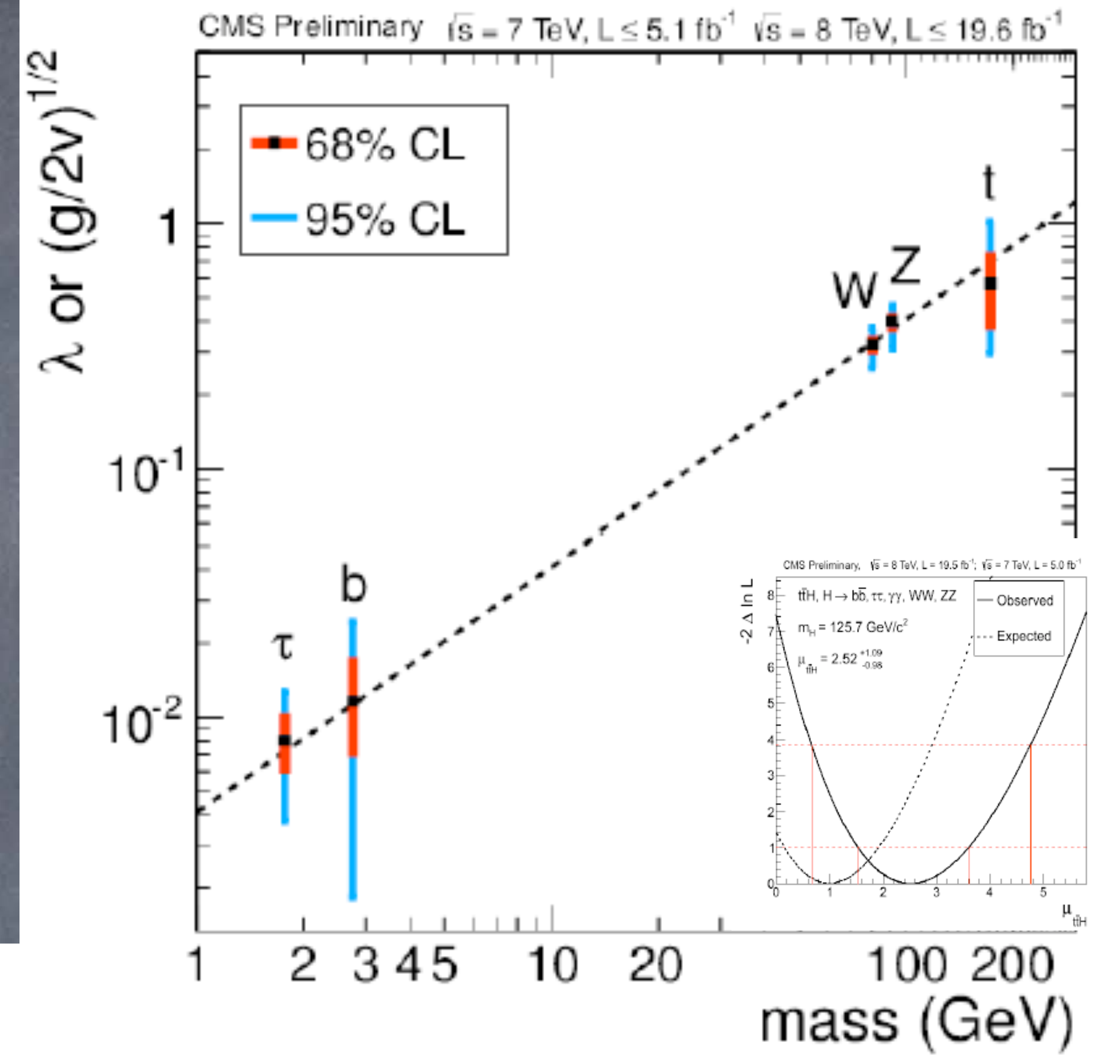


fermion vs vector boson couplings: κ_V κ_f ; search for asymmetries: λ_{WZ}, λ_{du}, λ_{lq} new physics in loops: κ_g κ_γ BR_{BSM}; simultaneous fits of all couplings; indirect limit on BR_{BSM}; Results for all the LHC XS WG benchmark BSM models

- approximate p-values of SM H hypothesis given for each test;

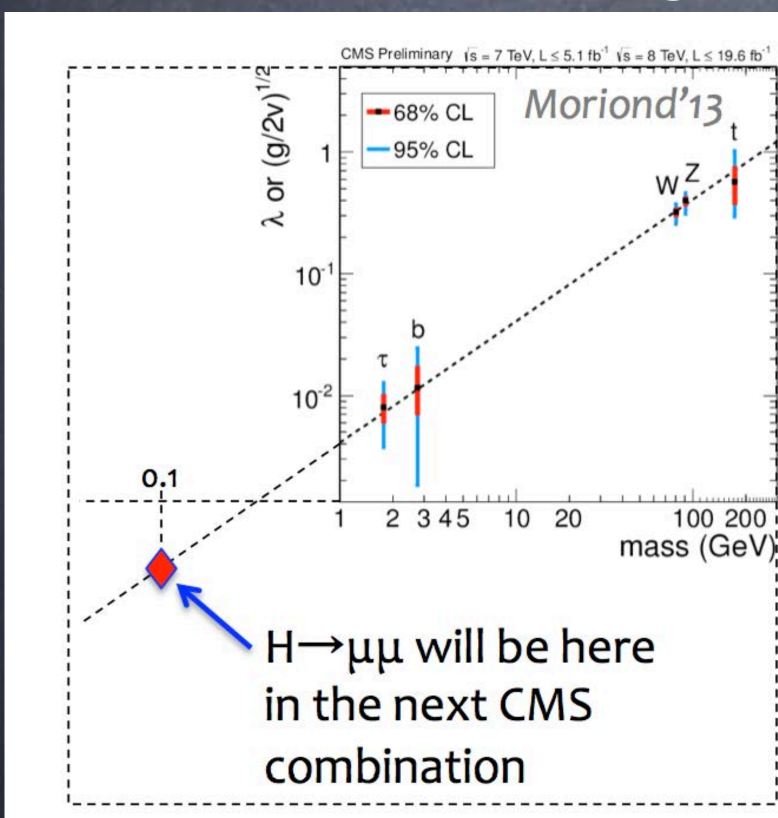


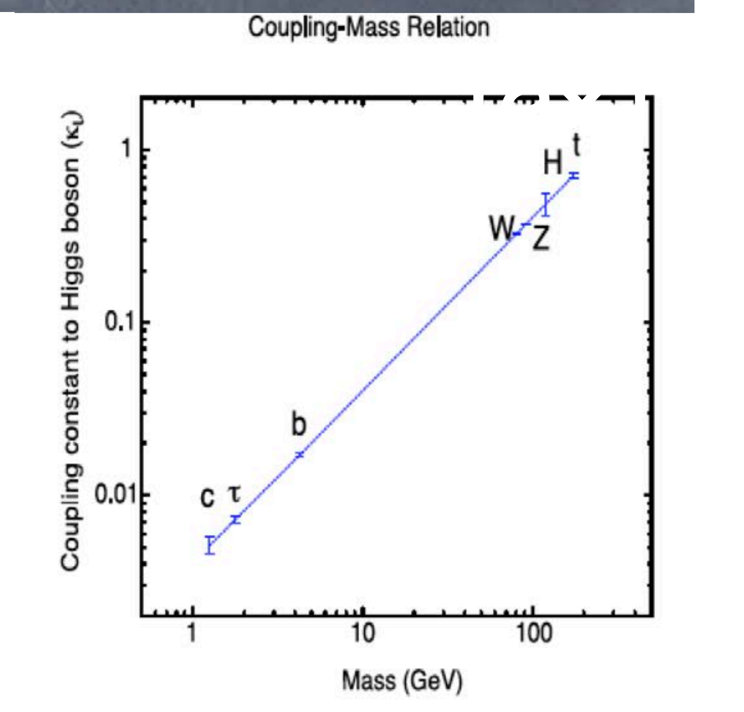
$g_V = 2\, m^2_V/v$ $\lambda_f = m_f/v$



Define couplings from the kappa’s:

$\lambda_f = \kappa_f\, m_f/v$, $g_V = \kappa_V m^2_V/v$





ig. 5 The relation between the Higgs coupling of a particle and its nass in the SM. The error bars correspond to the accuracy expected rom 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 sould be brought down to the level of **1%**.

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

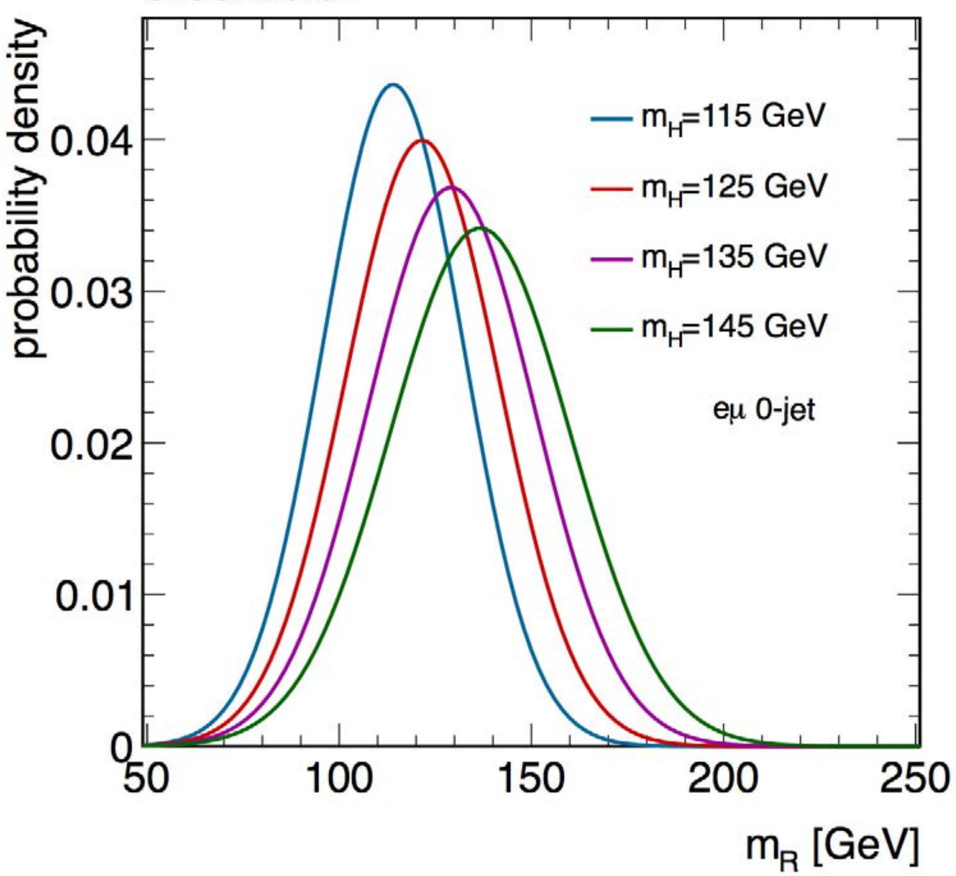
H→WW razor : who knew!

- Per-event estimator of the Higgs mass, mR:

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

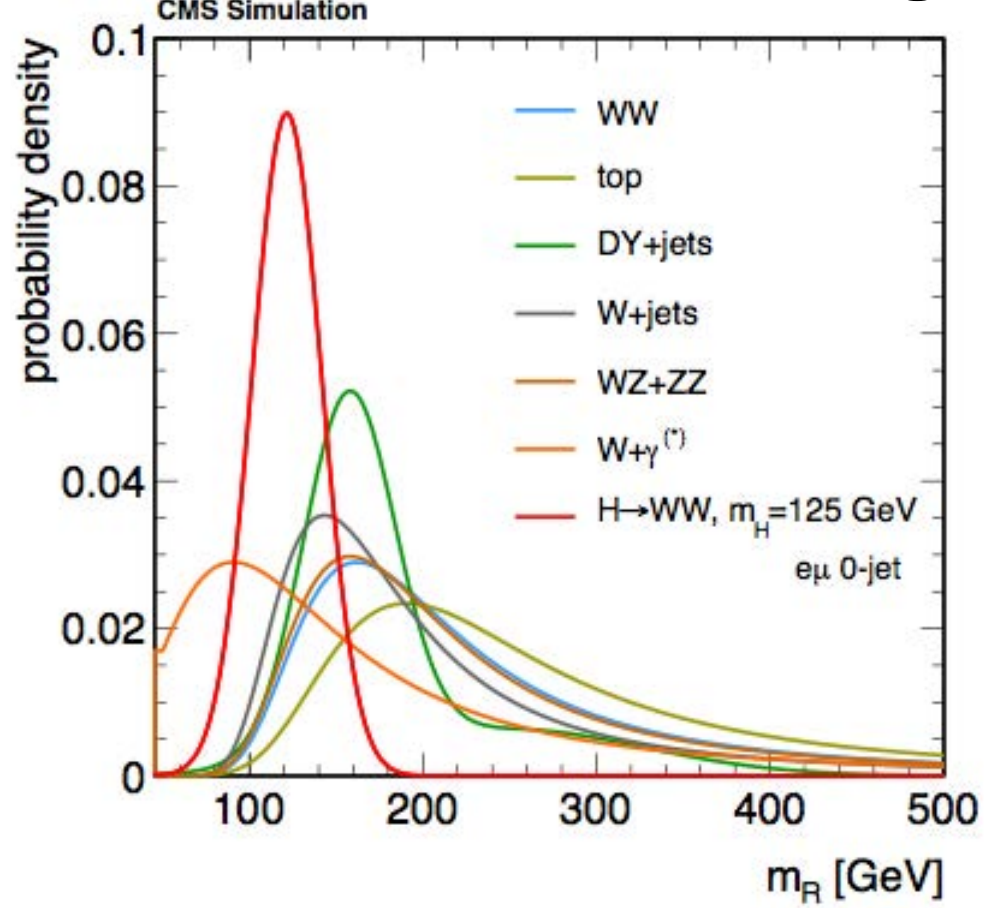
  - high sensitivity, due to good resolution (determined by lepton-only momenta)
  - MET used to correct for Higgs pT: peaks at mH for each jet multiplicity

mR for different mH



Higgs

mR for H and bkg

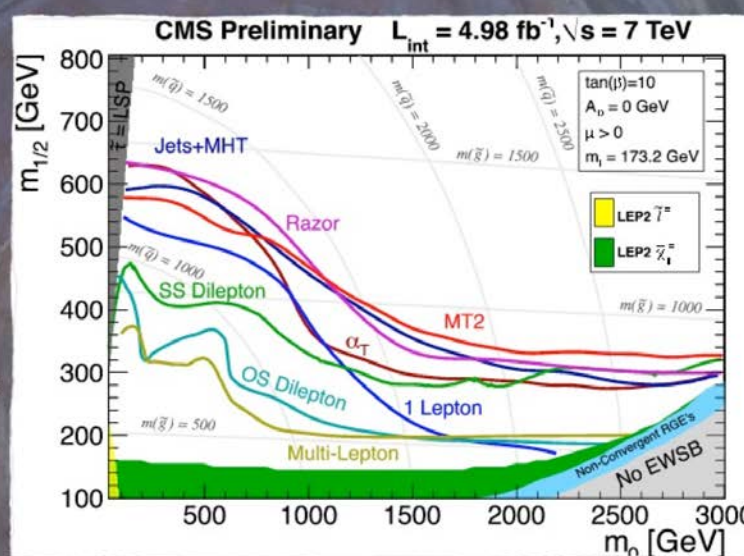


constarint!

Razor what? the SUSY connection

Searching for SUSY @8TeV

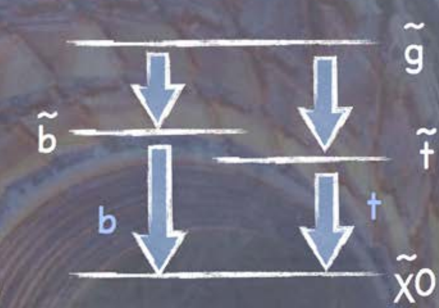
- With $5fb^{-1}$ of 7TeV data the exclusion curve removed a large fraction of the accessible parameter space
- After this, any improvement on the high-mass front became adiabatic
- This was not true anymore if one changes the SUSY paradigm



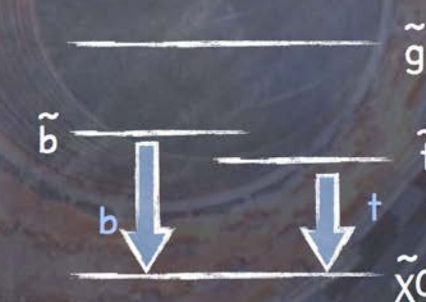
The ballpark of what we could discover was gone quite quickly
The Higgs was found
We turned our attention to some special kind of SUSY

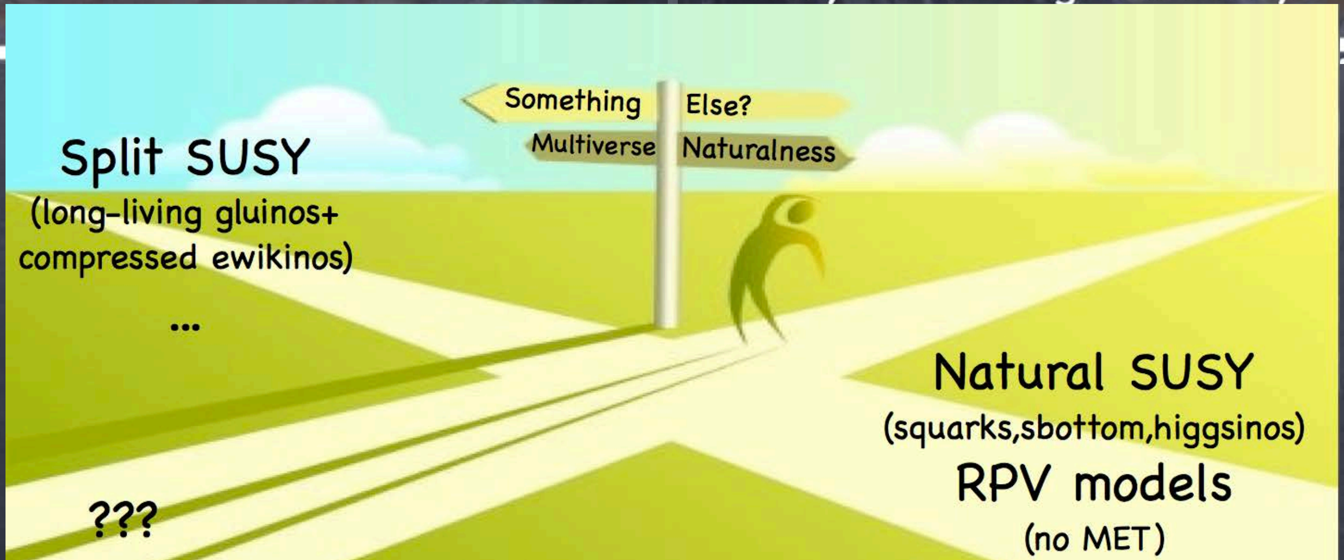
Natural SUSY

- Gluino-mediated searches
  Larger cross section
  4b quarks in the final state, with or w/o leptons
  More handles for bkg discrimination
  Gluinos might be too heavy for these searches to be effective



- Direct squark searches
  Smaller cross section
  Final state similar to tt in the bulk of the parameter space
  Reduced bkg discrimination power
  Only handle if gluino heavy





Razor Inclusive Search

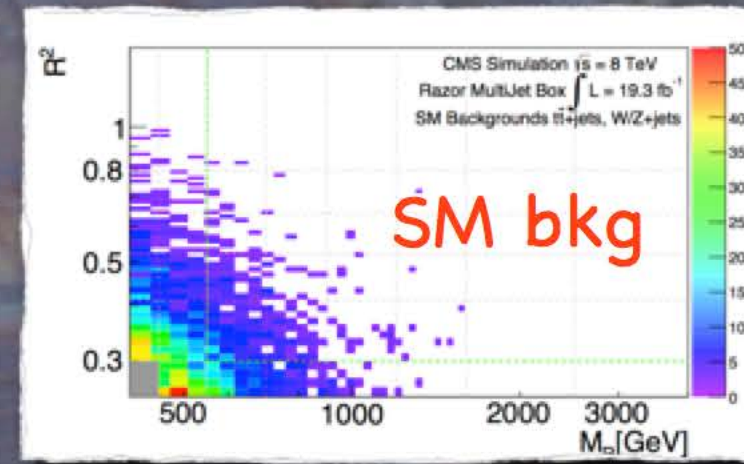
CMS PAS SUS-13-004

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

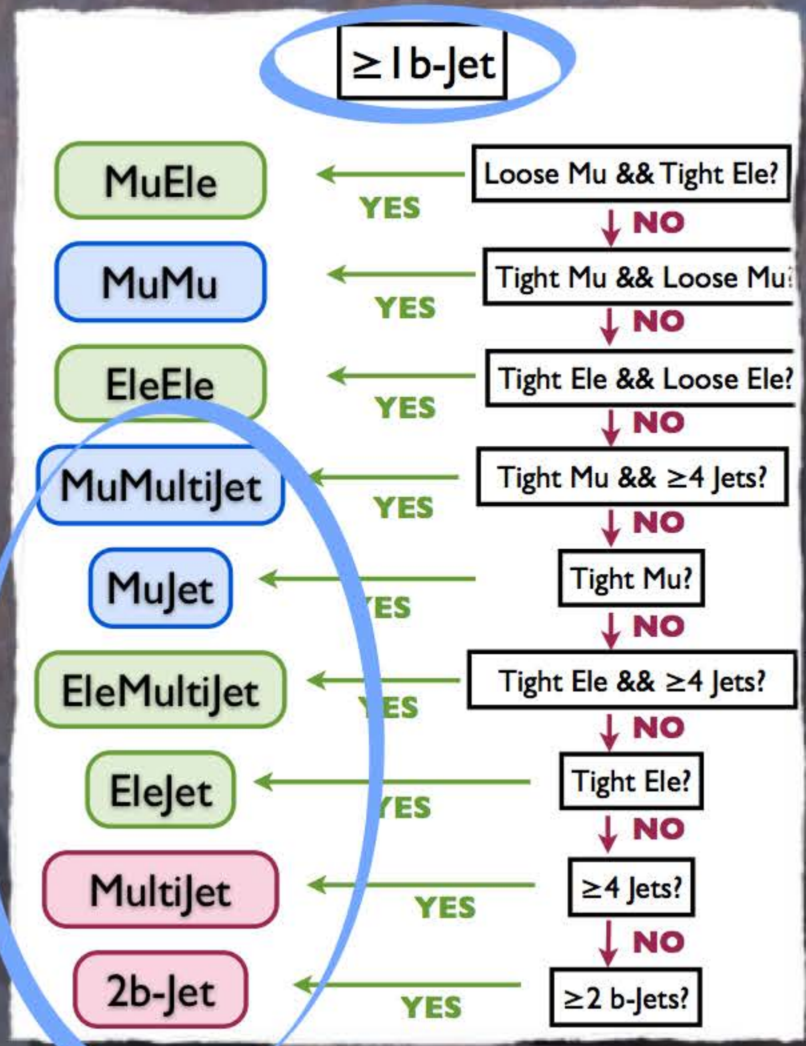
$$R = \frac{M_T^R}{M_R}$$

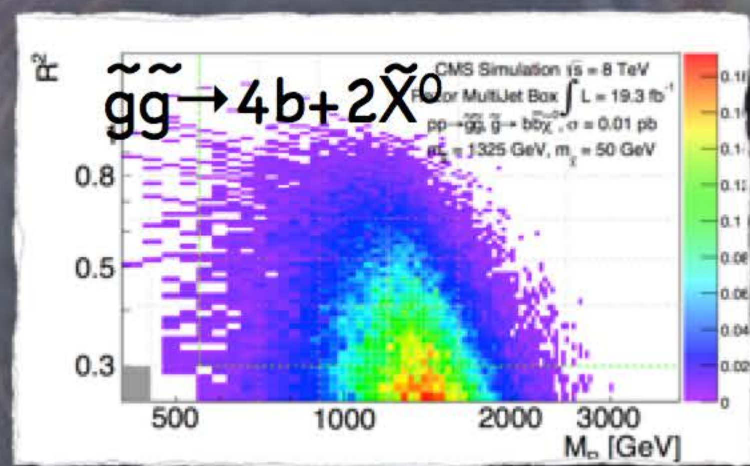
$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1}+p_T^{j2}) - \vec{E}_T^{miss}\cdot(\vec{p}_T^{\,j1}+\vec{p}_T^{\,j2})}{2}}$$

$$M_R \equiv \sqrt{(p_{j_1}+p_{j_2})^2 - (p_z^{j_1}+p_z^{j_2})^2}$$



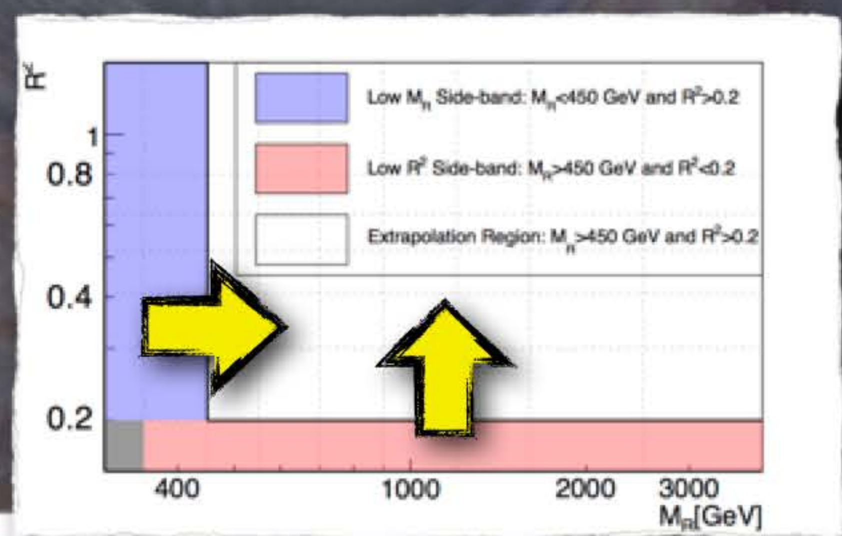
- Combine searches in different final states: overall result is inclusive





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

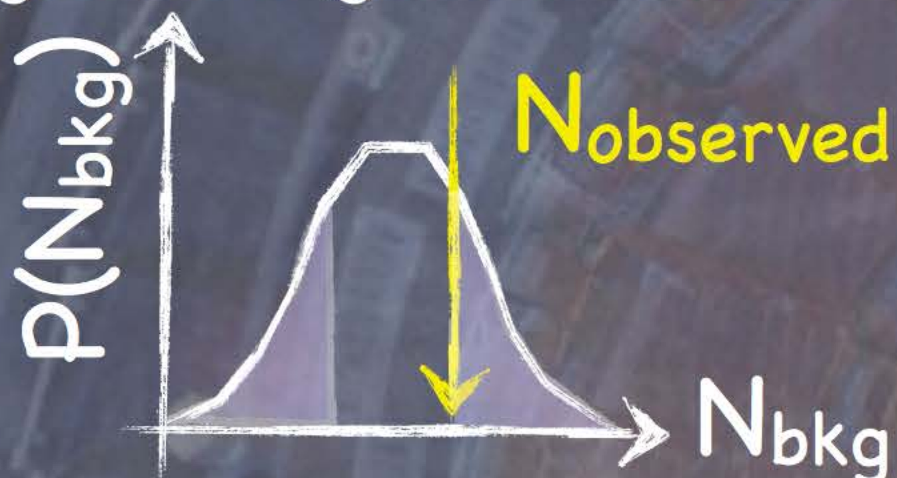
- Determine the bkg with a sideband shape fit+extrapolation

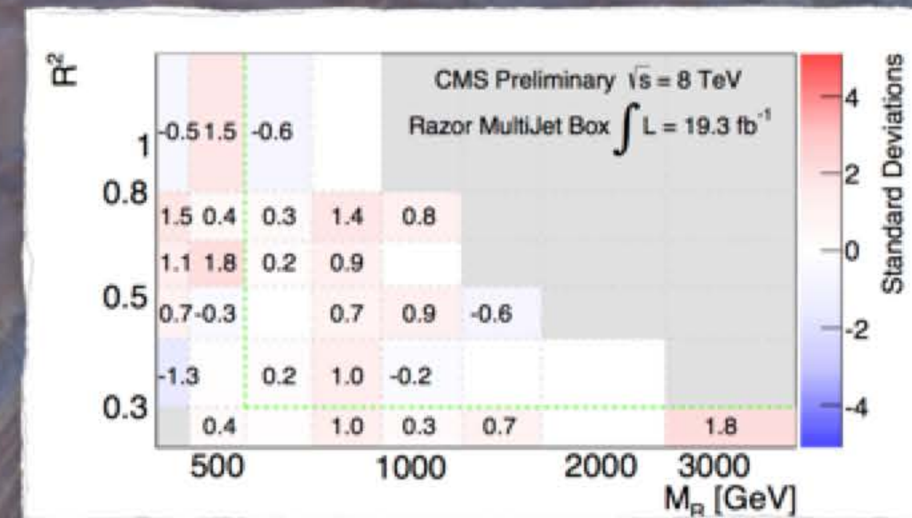


Razor Inclusive Search

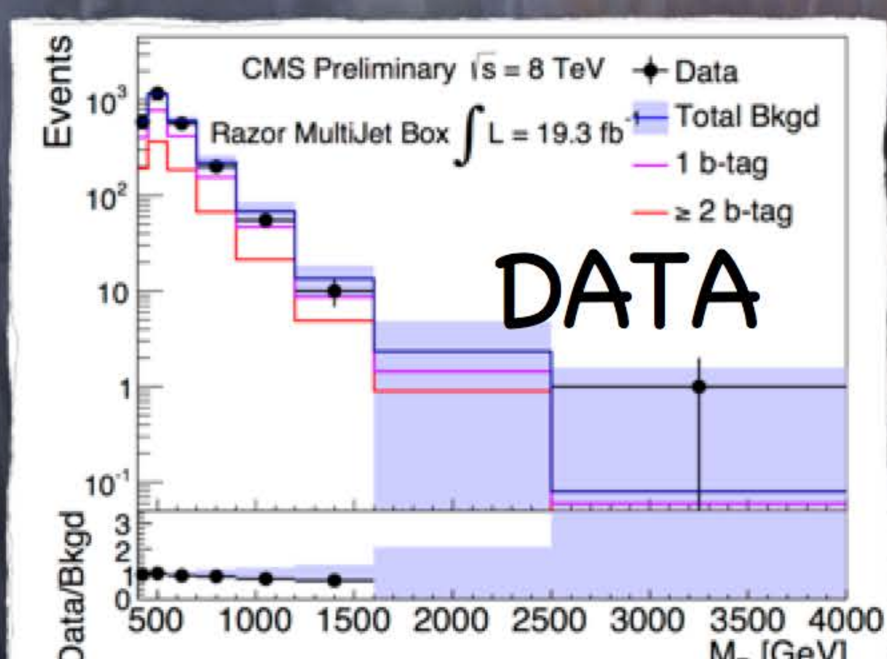
CMS PAS SUS-13-004

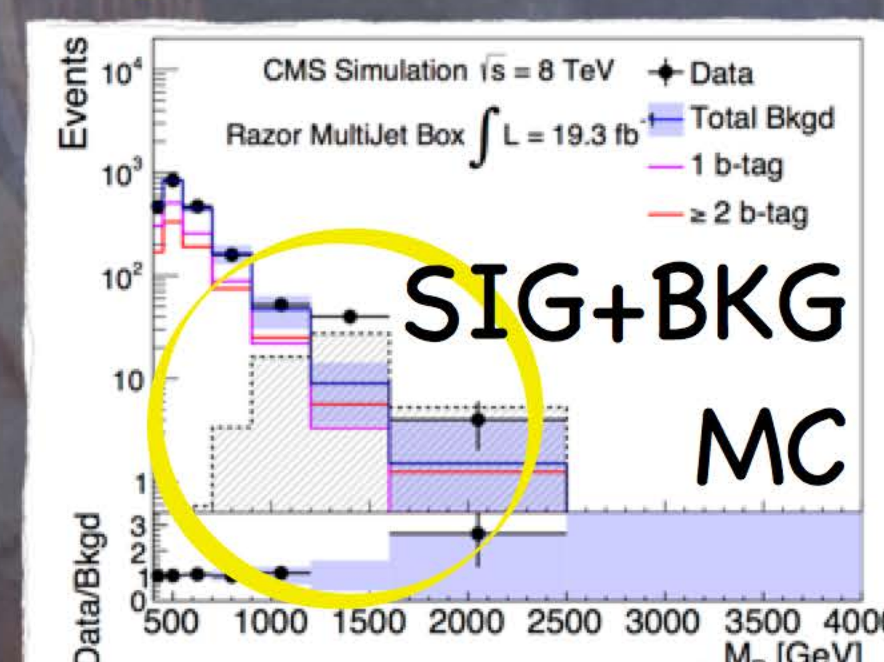
- The extrapolated background prediction is compared to data to evaluate the agreement (given in standard deviations)



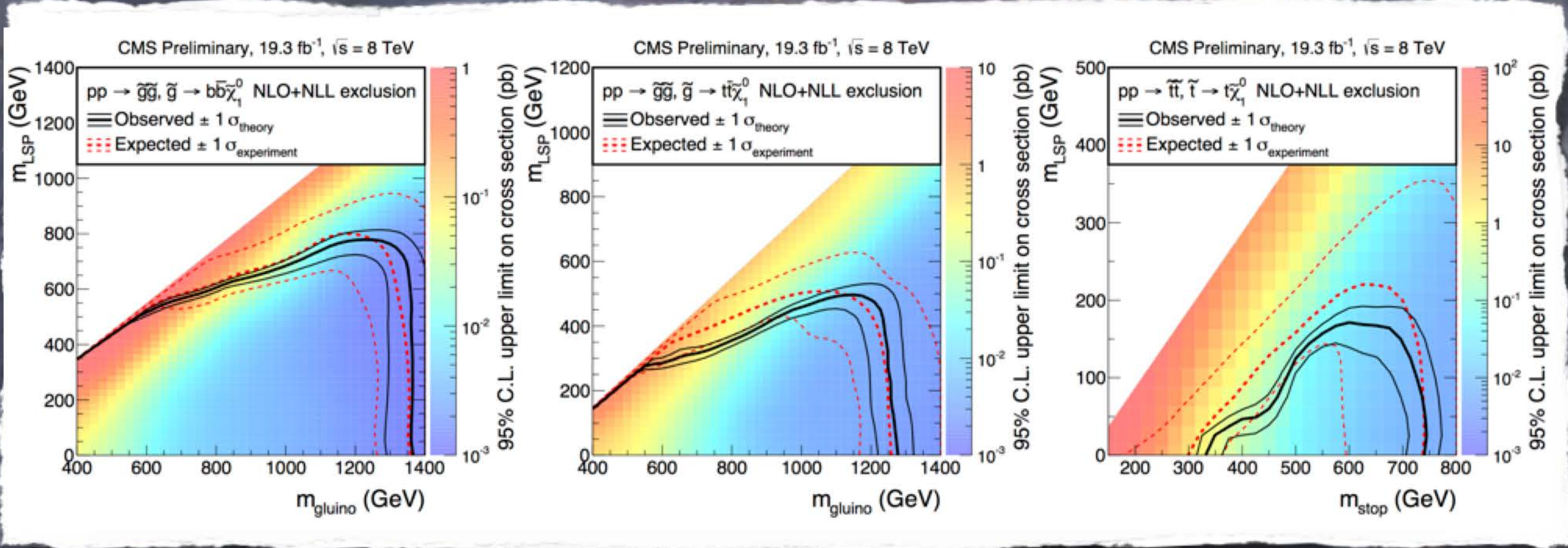


- The projections on M_R and R^2 show now discrepancy. A signal would emerge as a peak in M_R, more significant at large R^2

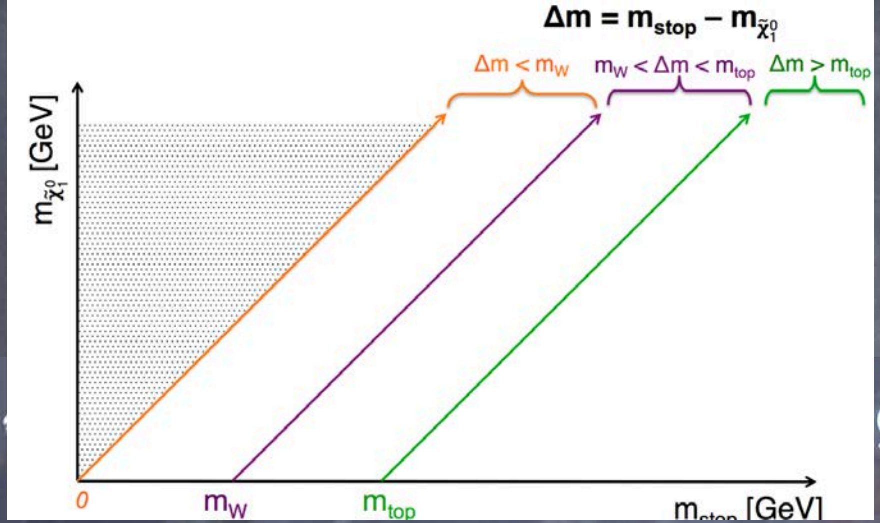




Razor Bounds on Natural SUSY



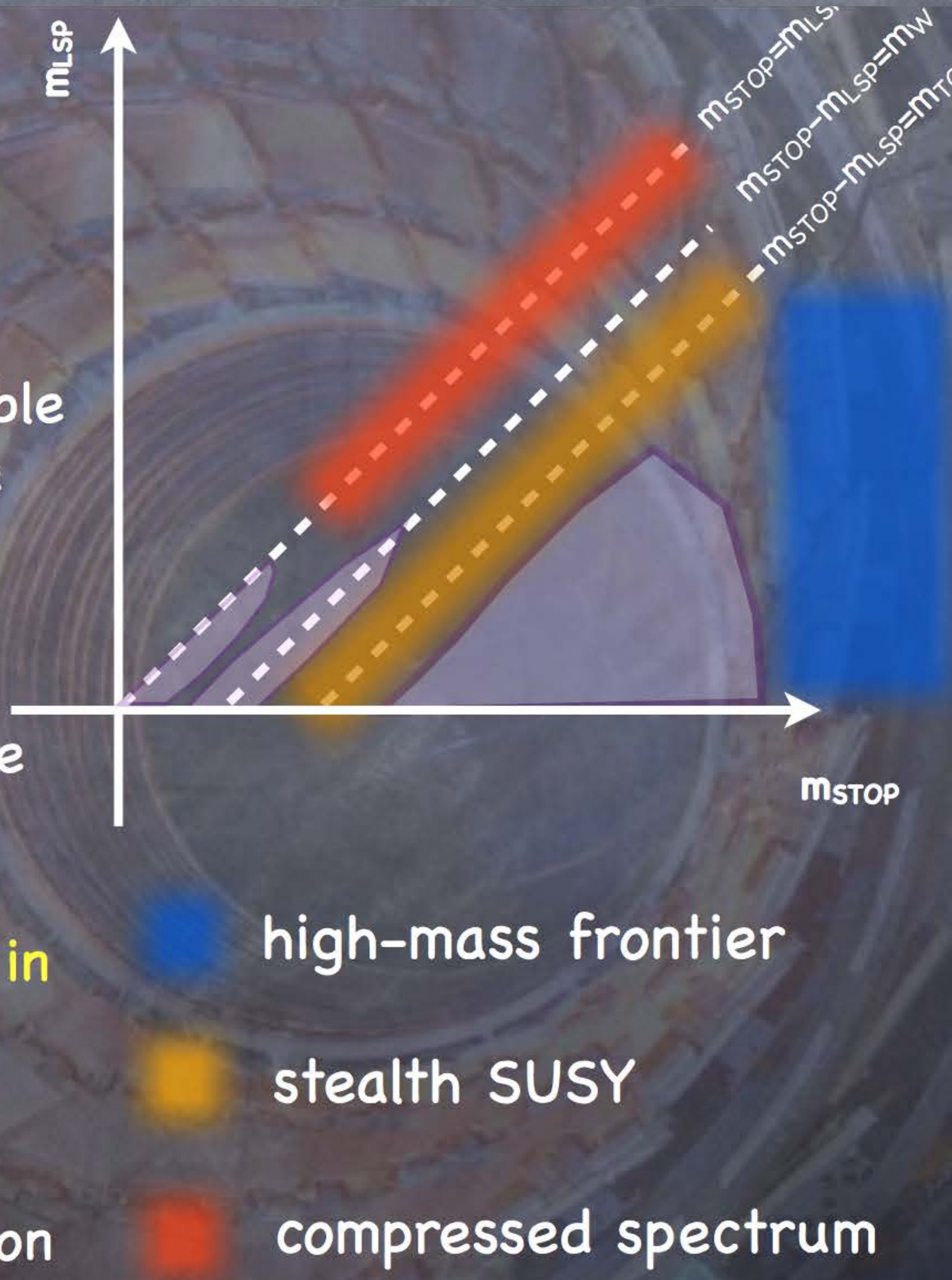
- A ~10% fine-tuning implies squarks(gluinos) lighter than ~700 GeV (~1500 GeV)
- The current exclusion at high mass almost saturate the bounds
- The limits are weaker for lighter sparticles once the LSP is made heavier (compressed spectra)

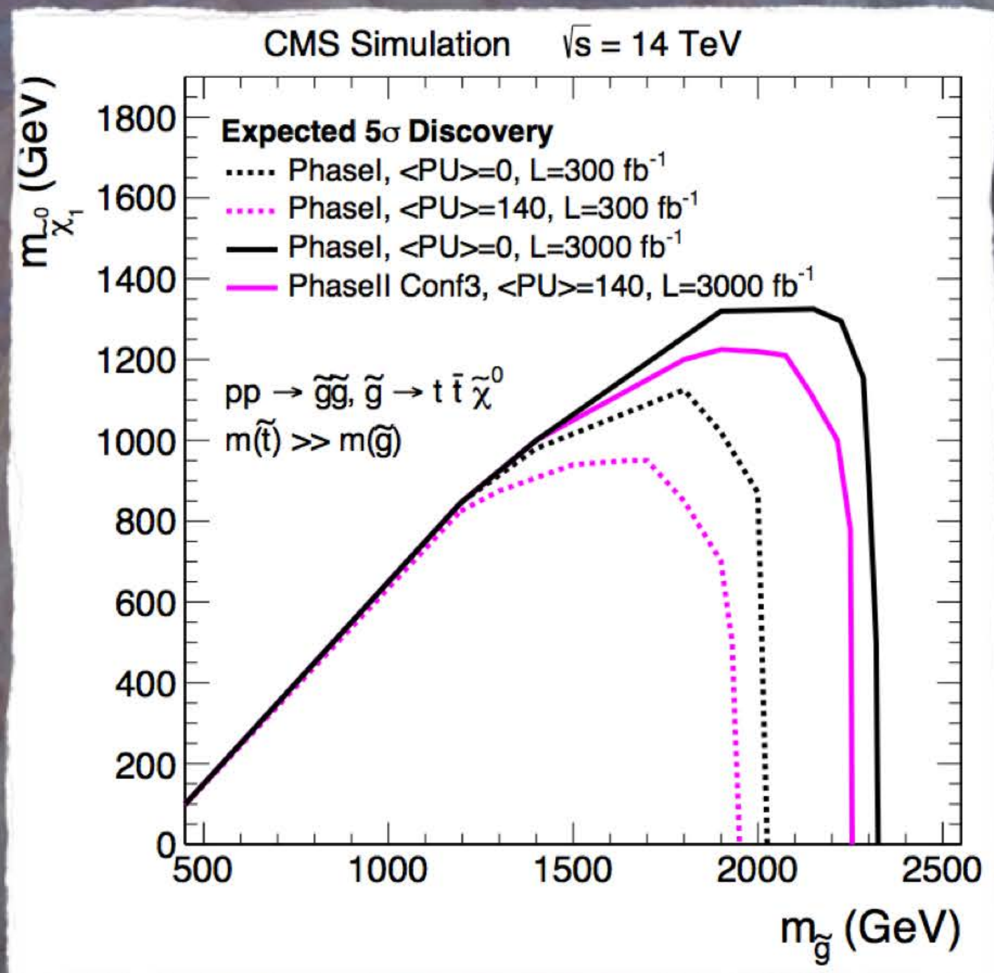


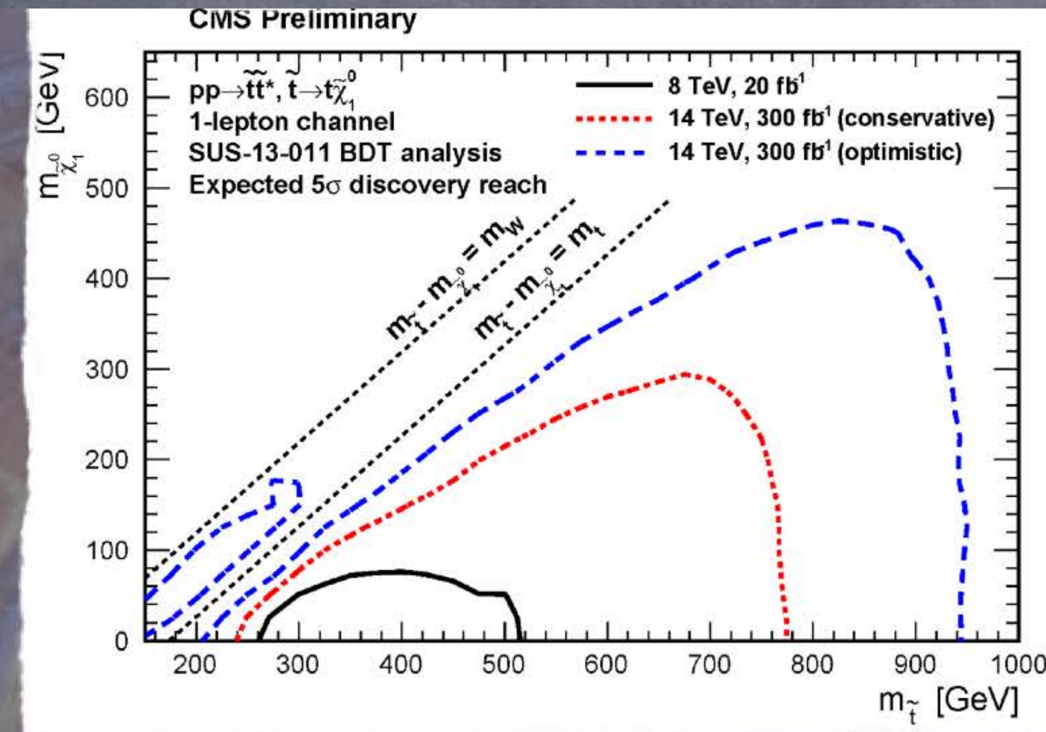
Desperately seeking light stops

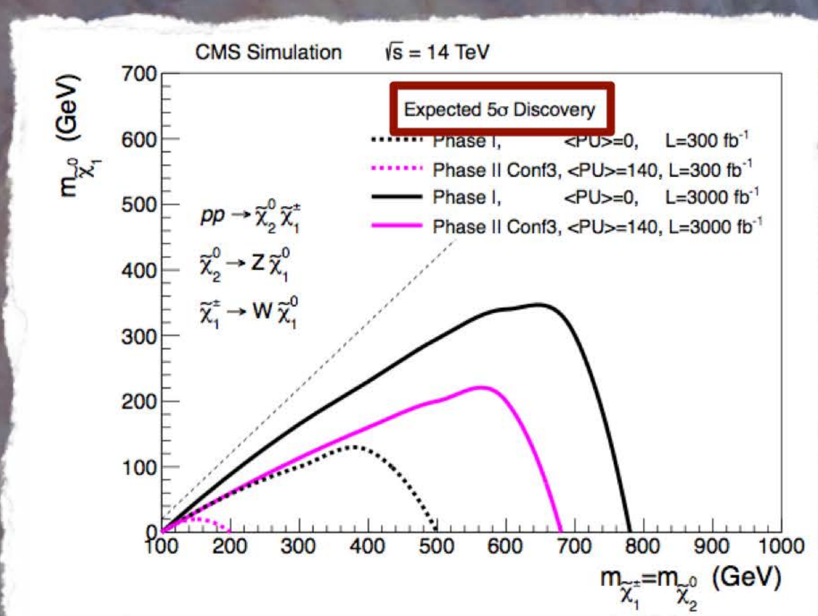
ght stop

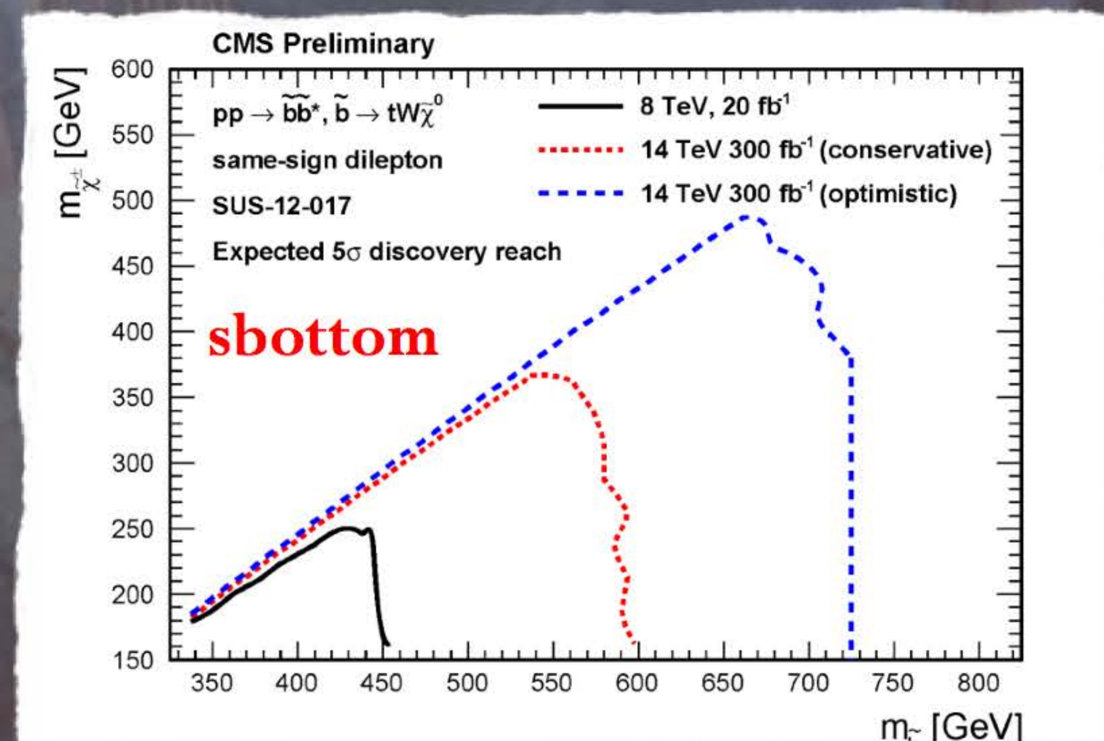
- The current stop searches have three blind spots
- As long as the gluino is kinematically accessible @LHC, these blind spots are covered to some extent
- If not, direct stop/sbottom searches are the most powerful probe (but other ways possible with more light sparticles)
- Gluinos are pushed > 1300 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

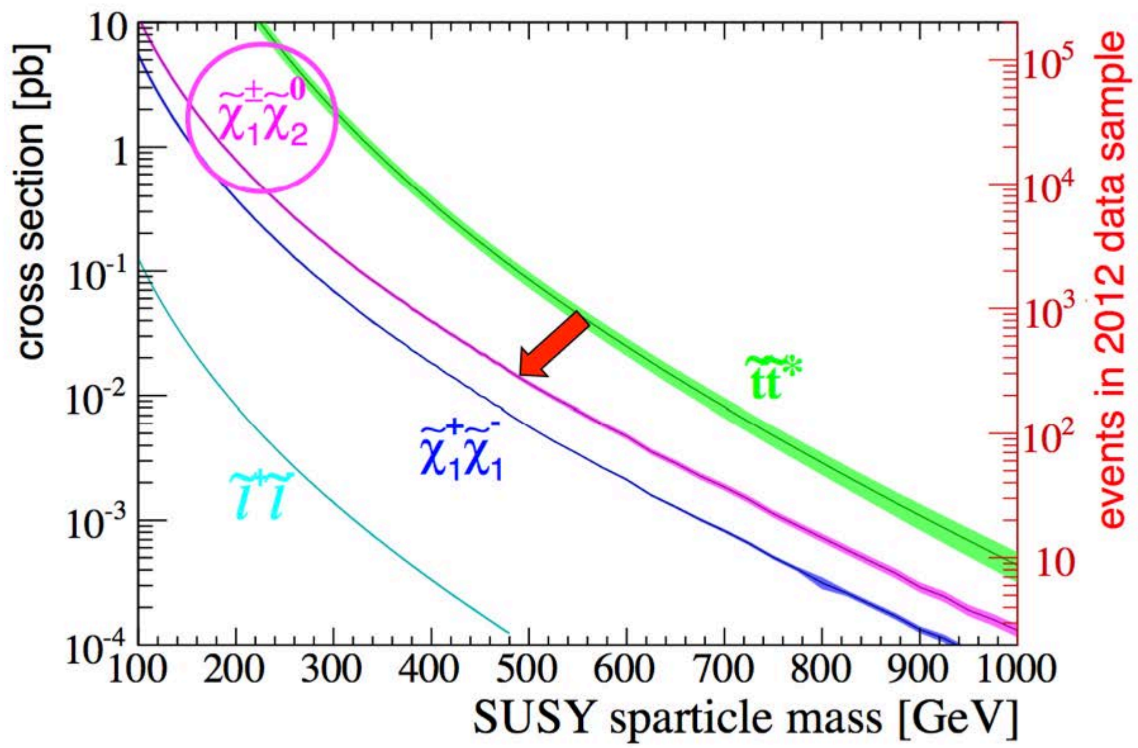



CMS Simulation √s = 14 TeV
Expected 5σ Discovery
PhaseI, <PU>=0, L=300 fb-1
PhaseI, <PU>=140, L=300 fb-1
PhaseI, <PU>=0, L=3000 fb-1
PhaseII Conf3, <PU>=140, L=3000 fb-1
pp → g̃g̃, g̃ → t t̄ χ̃0
m(t̃) >> m(g̃)
m χ̃01 (GeV)
m g̃ (GeV)

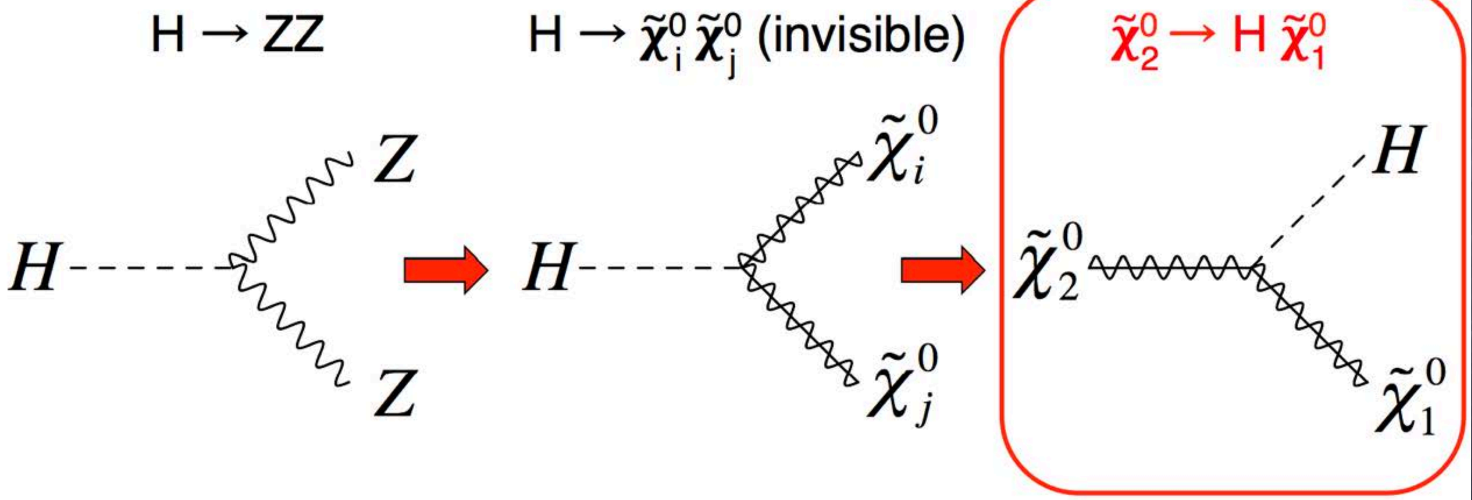

CMS Preliminary
pp→t̃t̃*, t̃→tχ̃01
1-lepton channel
SUS-13-011 BDT analysis
Expected 5σ discovery reach
8 TeV, 20 fb-1
14 TeV, 300 fb-1 (conservative)
14 TeV, 300 fb-1 (optimistic)
m t̃ - m χ̃01 = mW
m t̃ - m χ̃01 = mt
m χ̃01 [GeV]
m t̃ [GeV]


CMS Simulation √s = 14 TeV
Expected 5σ Discovery
Phase I, <PU>=0, L=300 fb-1
Phase II Conf3, <PU>=140, L=300 fb-1
Phase I, <PU>=0, L=3000 fb-1
Phase II Conf3, <PU>=140, L=3000 fb-1
pp → χ̃02 χ̃±1
χ̃02 → Z χ̃01
χ̃±1 → W χ̃01
m χ̃01 (GeV)
m χ̃±1 = m χ̃02 (GeV)


CMS Preliminary
pp → b̃b̃*, b̃ → tWχ̃0
same-sign dilepton
SUS-12-017
Expected 5σ discovery reach
8 TeV, 20 fb-1
14 TeV 300 fb-1 (conservative)
14 TeV 300 fb-1 (optimistic)
sbottom
m χ̃± [GeV]
m b̃ [GeV]

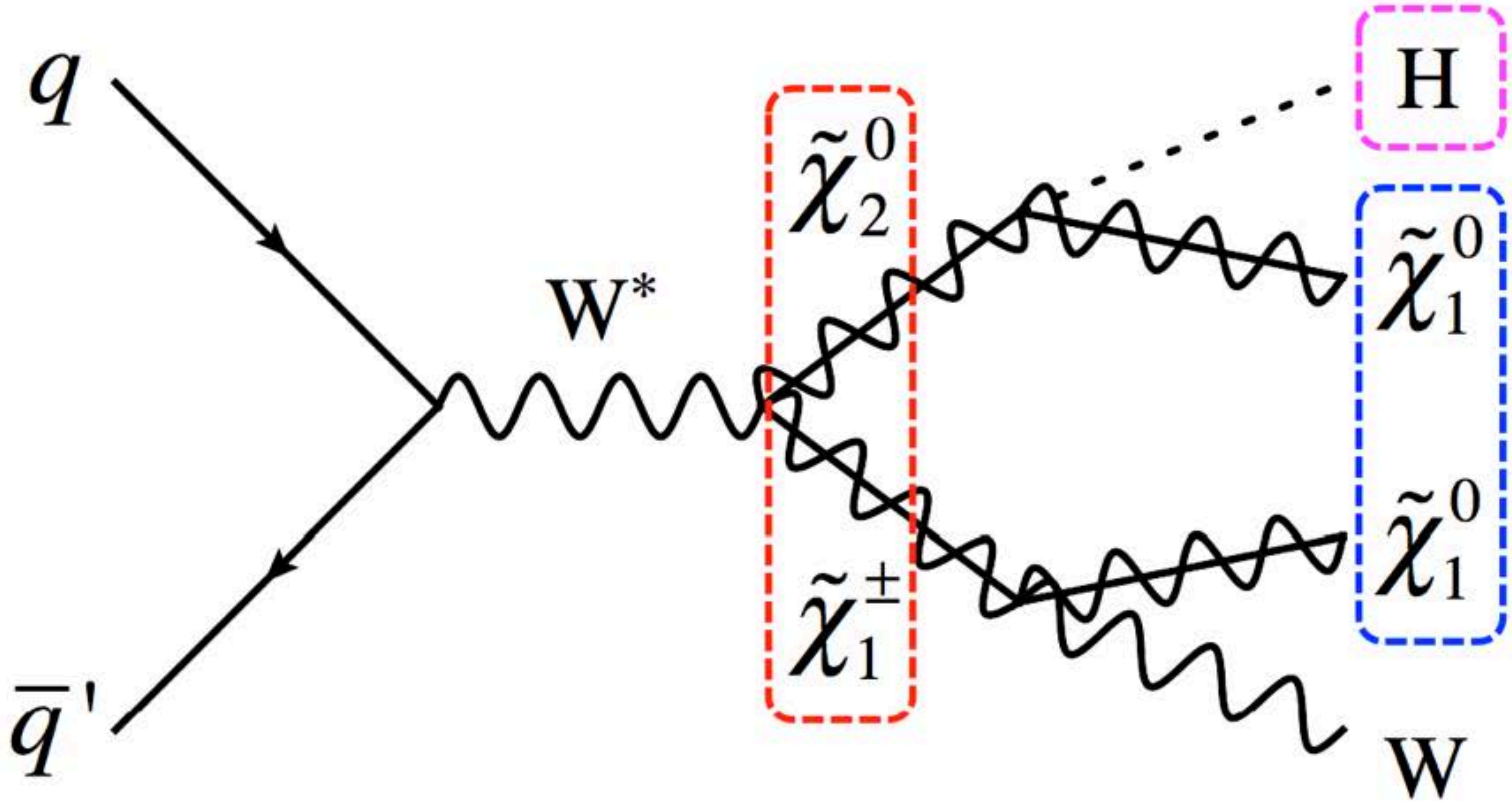


- Search for **chargino-neutralino** pair production
- $\tilde{\chi}_2^0$ often decays to Higgs boson → **use Higgs as "probe"**



- 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

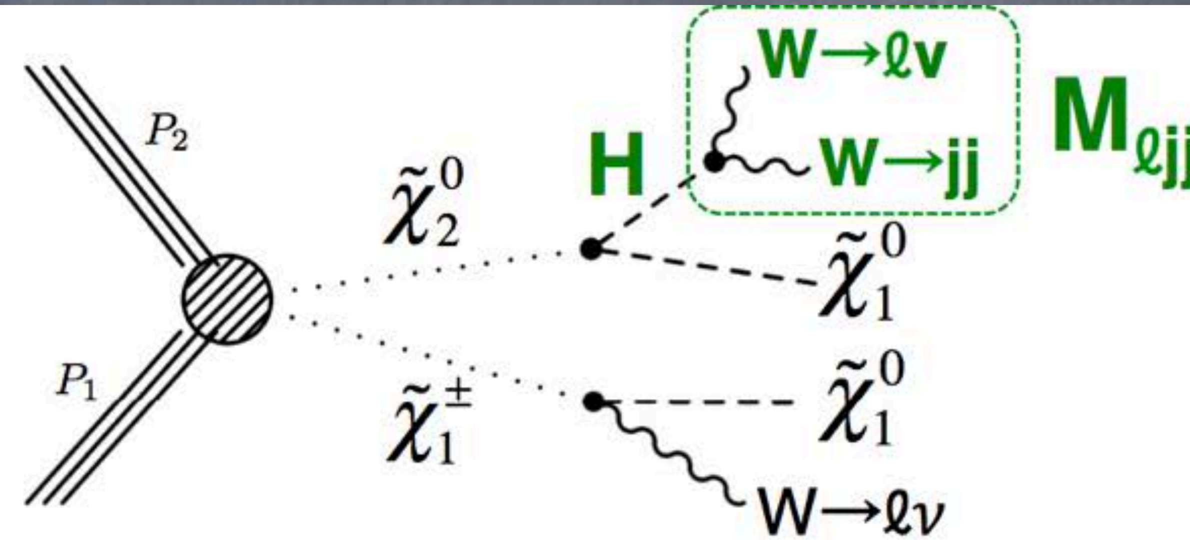
1] Howe & Saraswat, JHEP 1210 (2012) 065

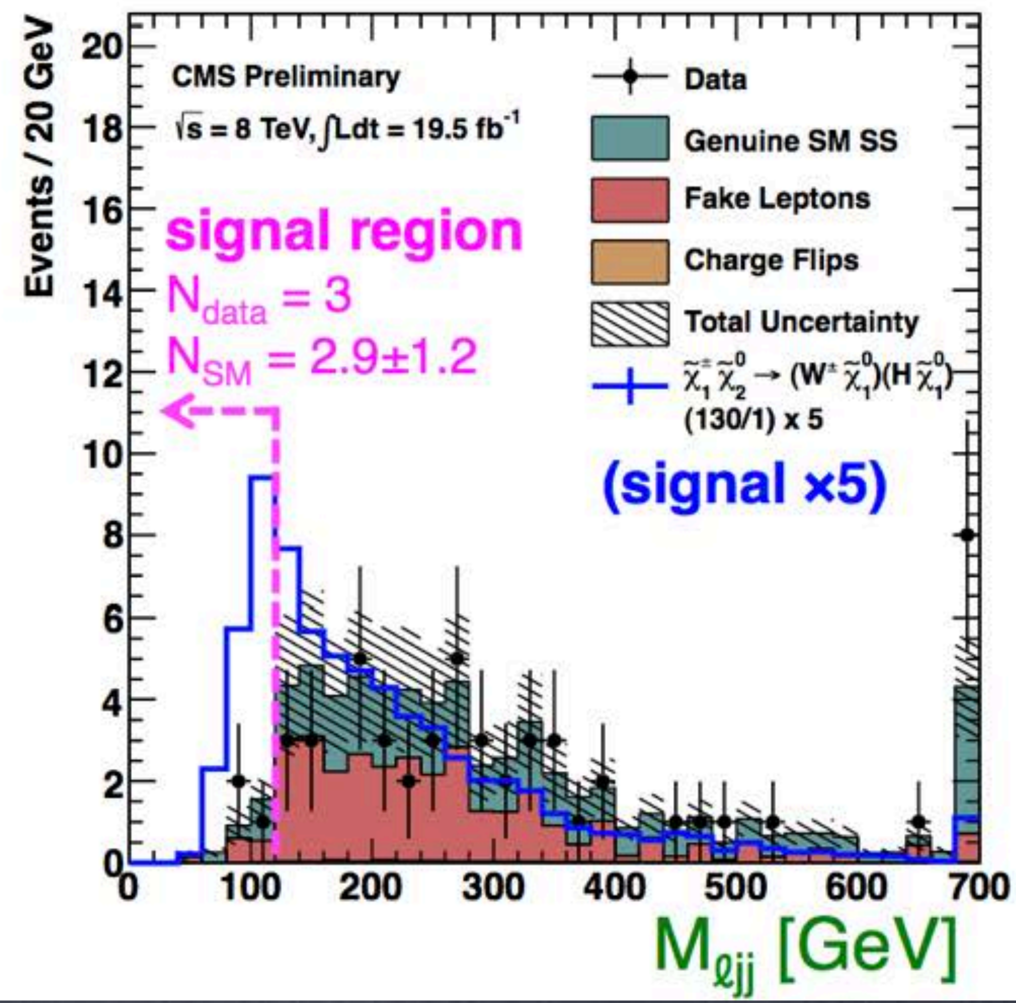


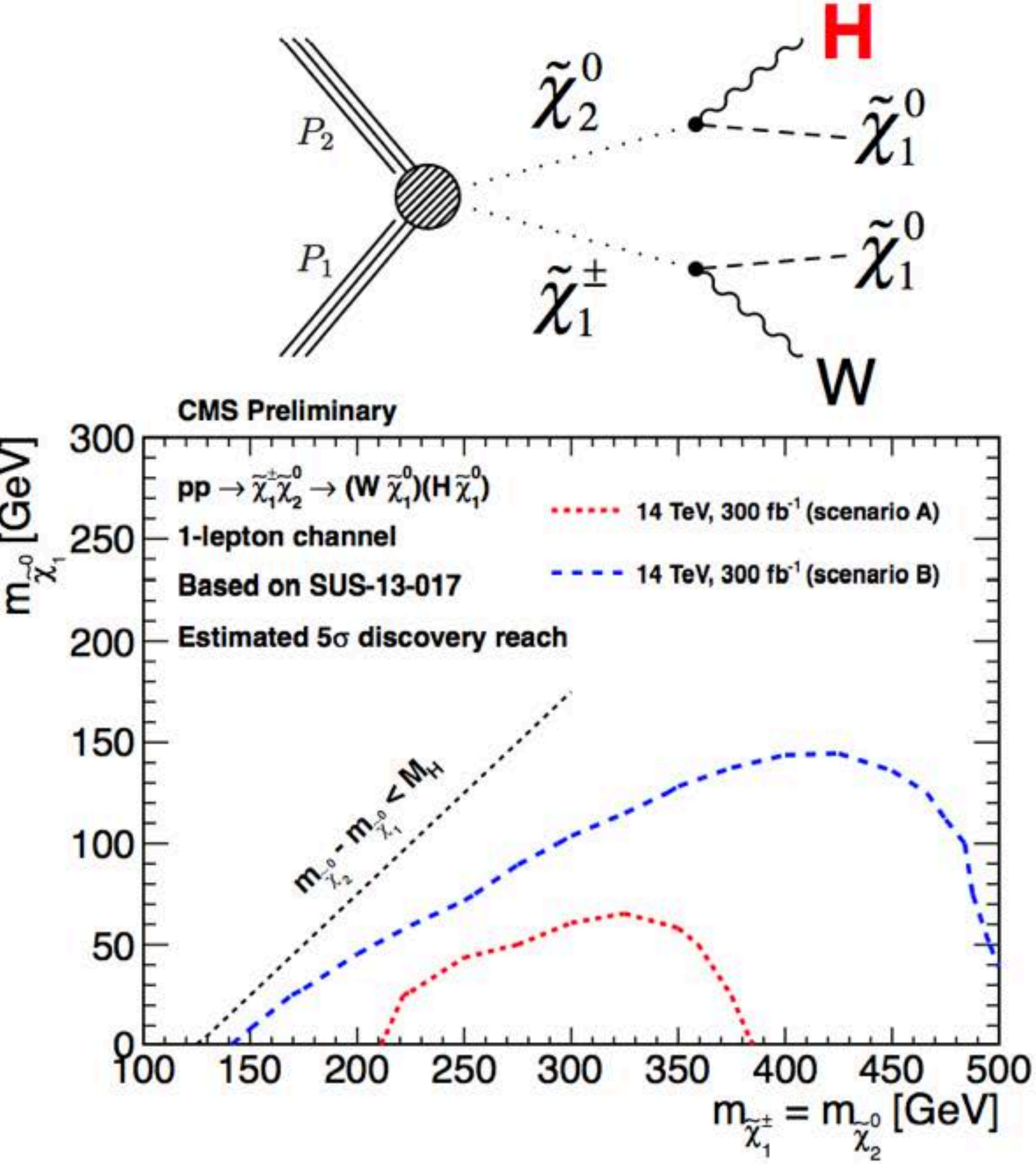
- Direct $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ production from s-channel W* diagram
  - $\tilde{\chi}_1^\pm$ decays to W $\tilde{\chi}_1^0$
  - $\tilde{\chi}_2^0$ decays to H $\tilde{\chi}_1^0$

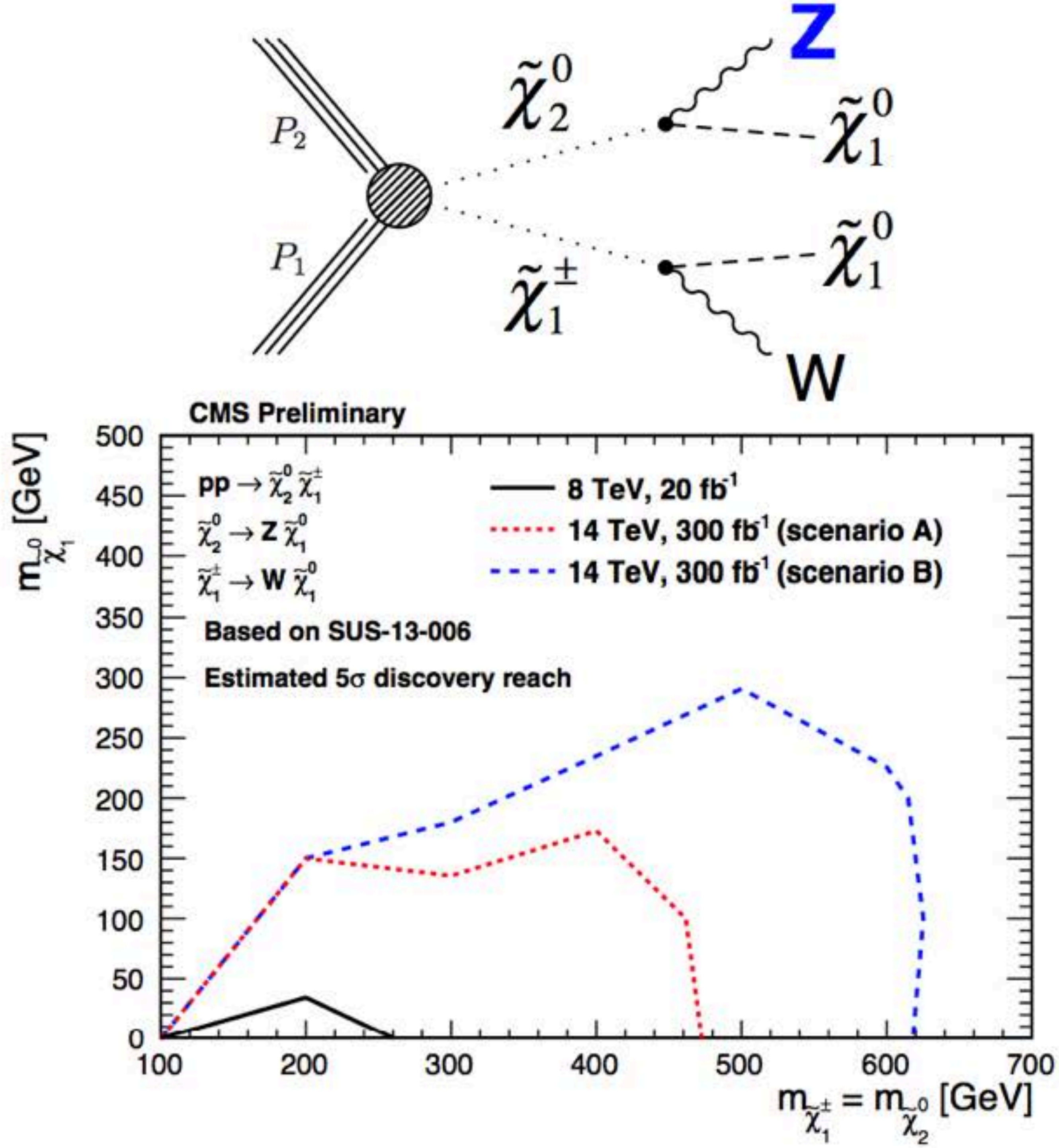
  } **WH+E_T^{miss}**
- **SUSY, Higgs, and DM WIMPs in the same event**

- **Event selection**
  - Exactly 2 SS (ee/eμ/μμ) leptons
  - 2 or 3 jets, b-veto
  - Moderate E_T^{miss}
- **Strategy**
  - Suppress SM backgrounds with E_T^{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 $M_{\ell jj}$**



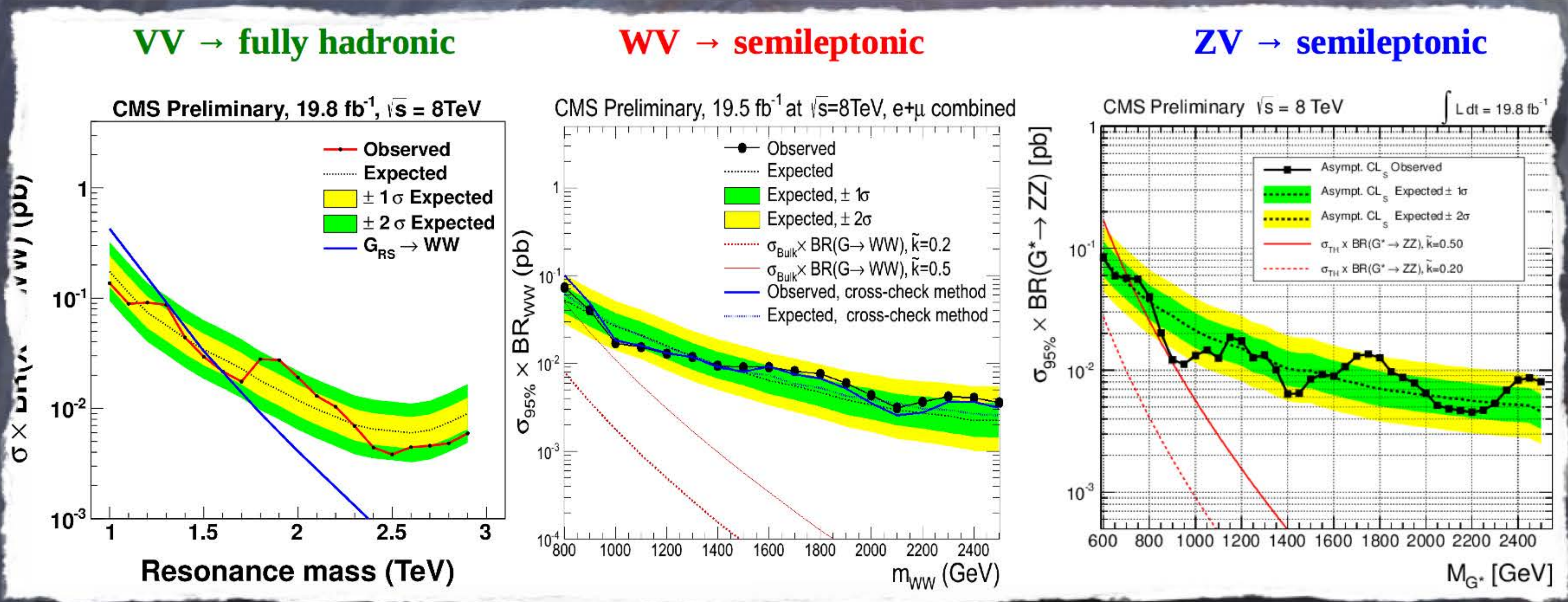




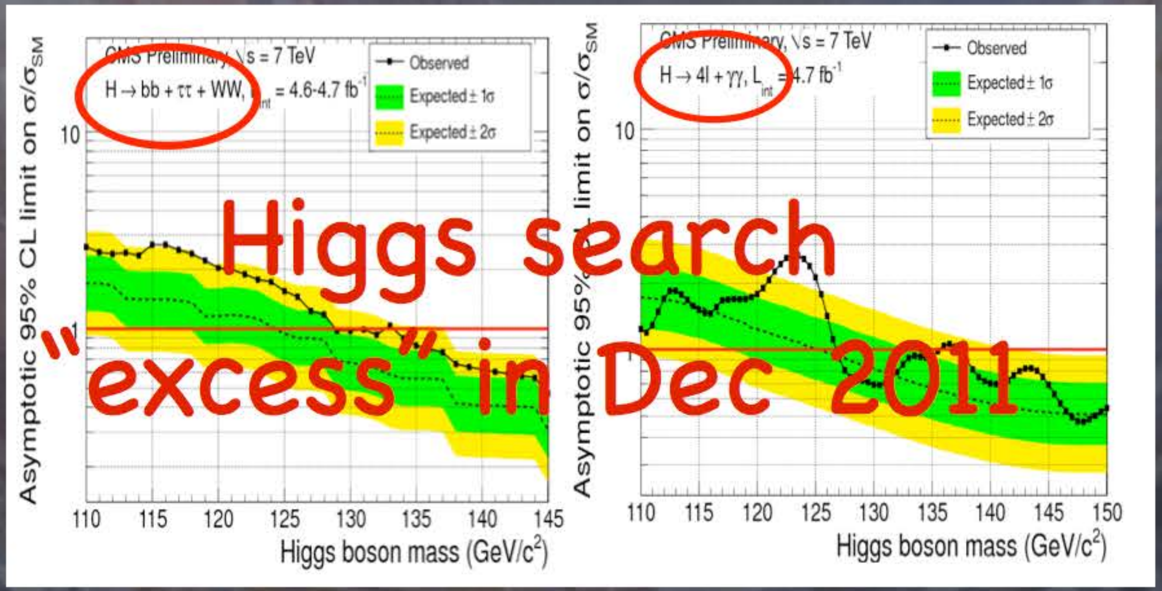


- 5σ discovery reach **up to ~400-600 GeV** with 300 fb^{-1} 14 TeV data

Bump hunting X->VV

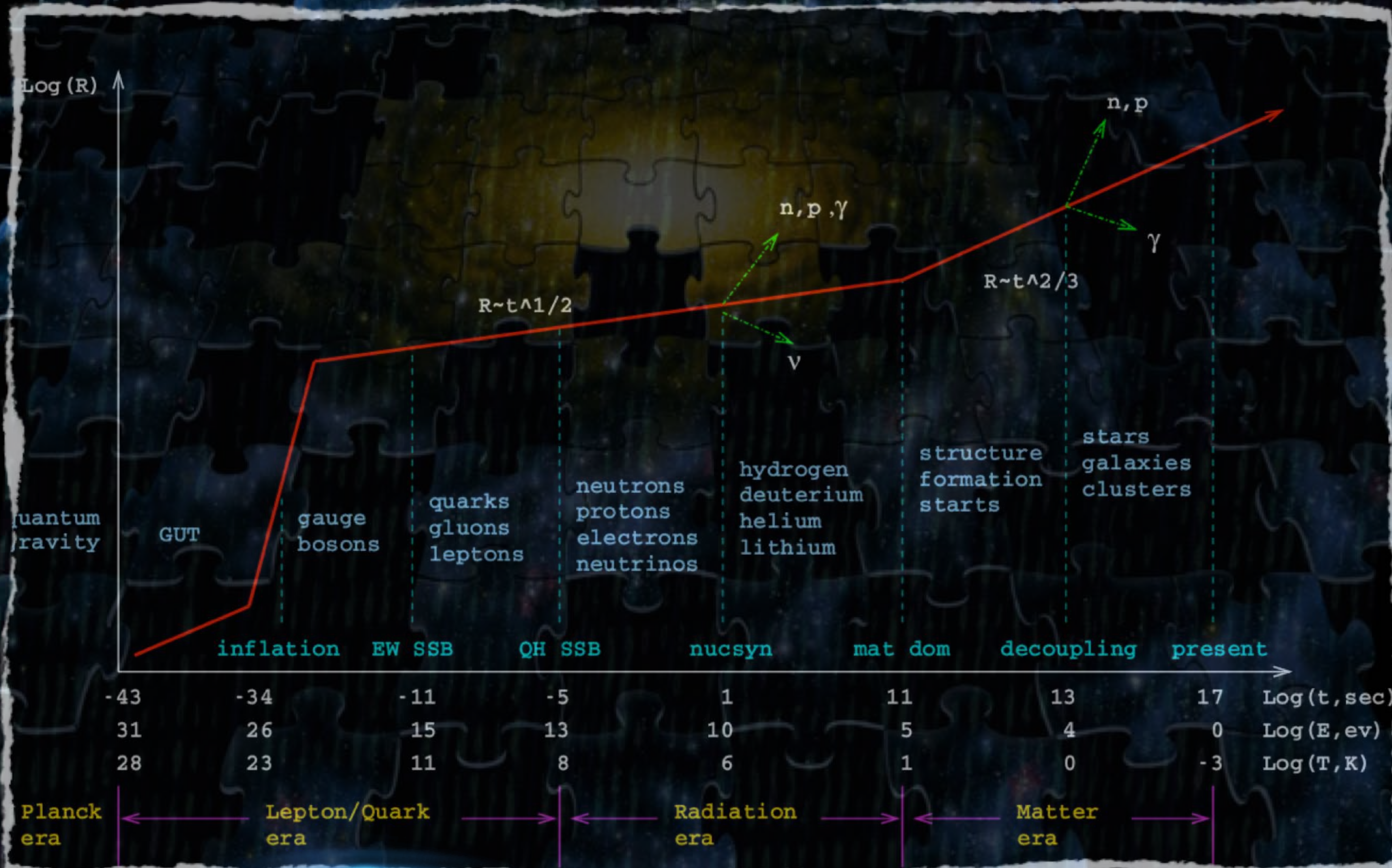


We see excesses around 1900 GeV in 4/5 channels (counting e and m as 2 different channels)
It looks like...

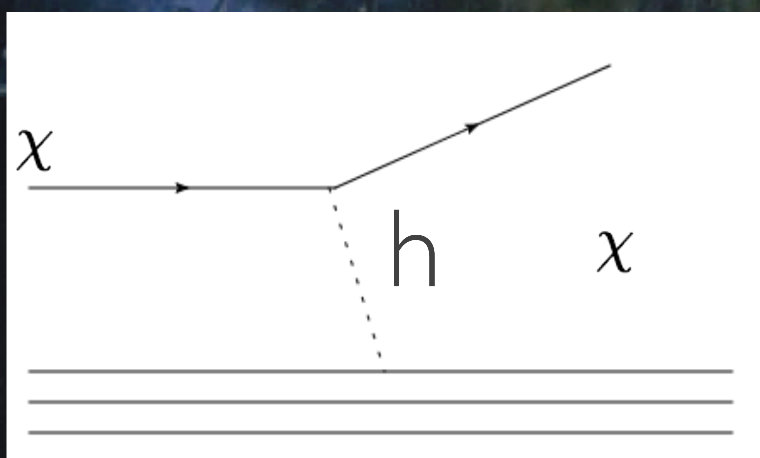


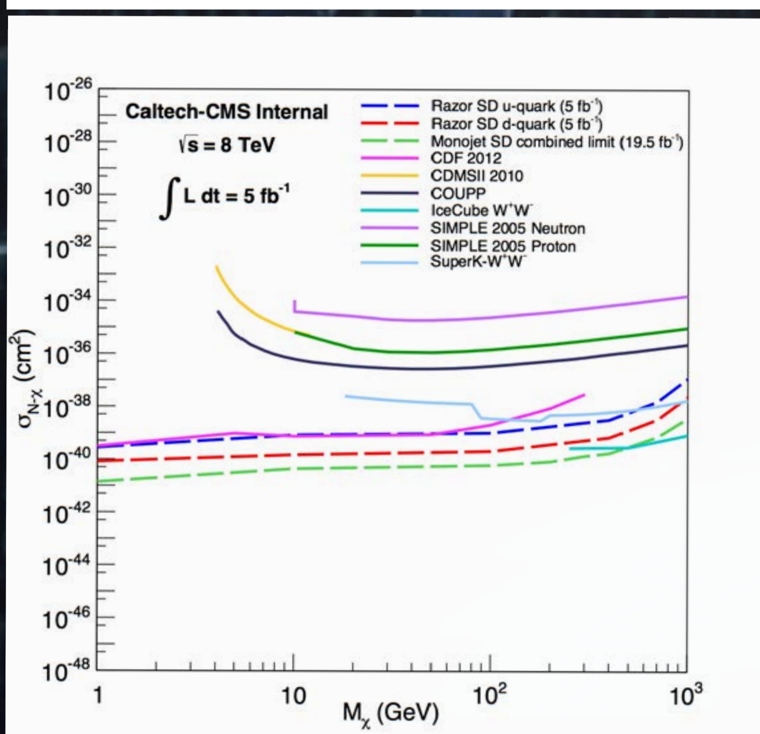
H boson : is it the Standard Model? Does it behave as predicted? Is there more than one? how many more? Finding heavy Higgs bosons with non-standard interactions is a major long-term challenge for the LHC; supersymmetry predicts at least five kinds of Higgs bosons, differing in their mass and other properties,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

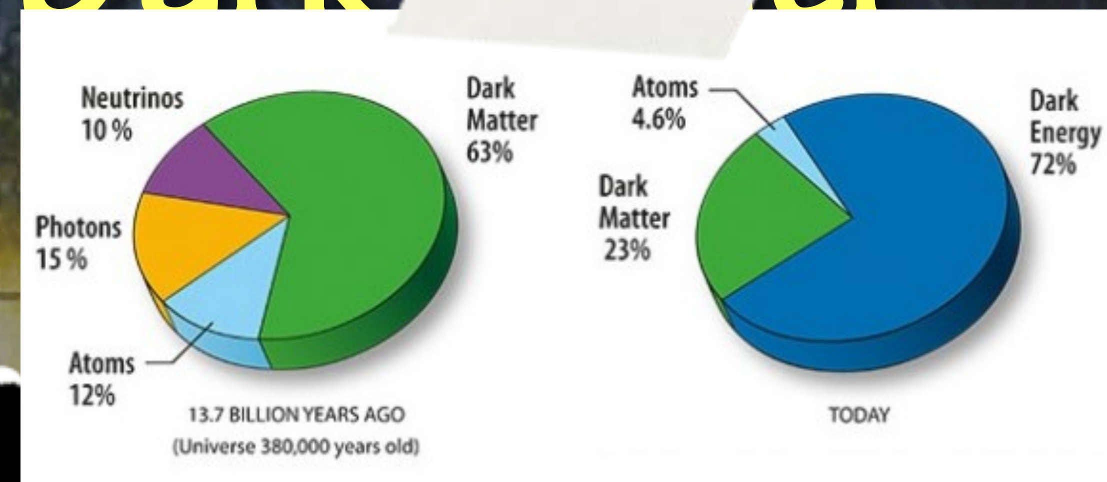
H boson
implies the earliest known event of the Big Bang:
the "electroweak phase transition"

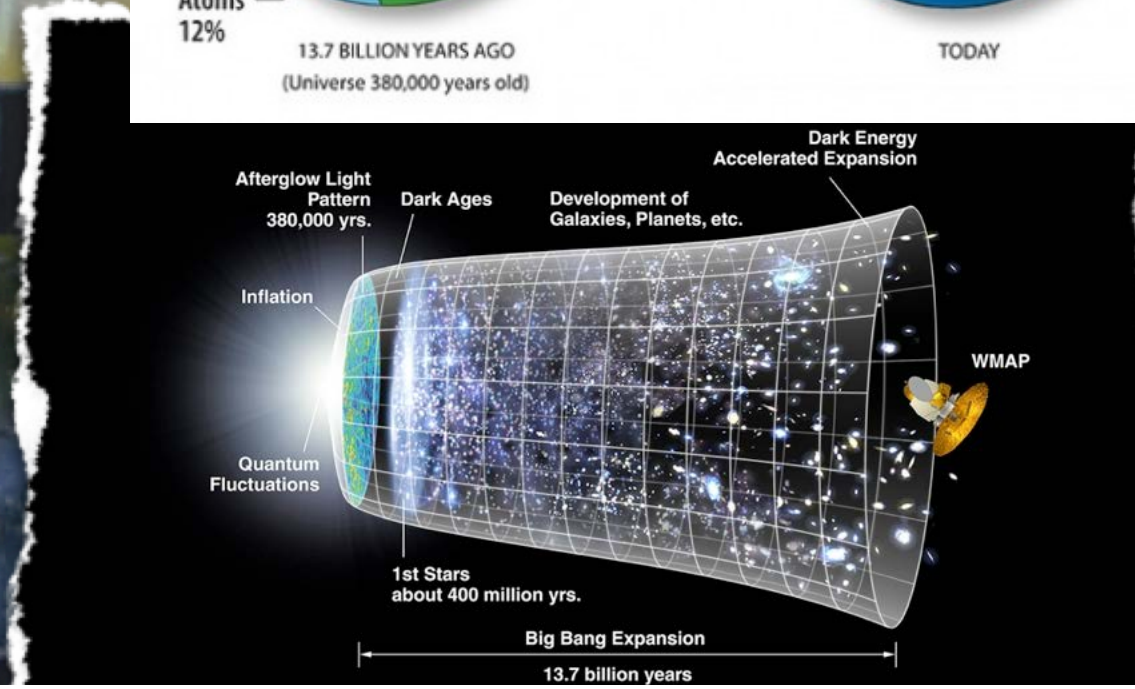


H boson & the Dark Matter









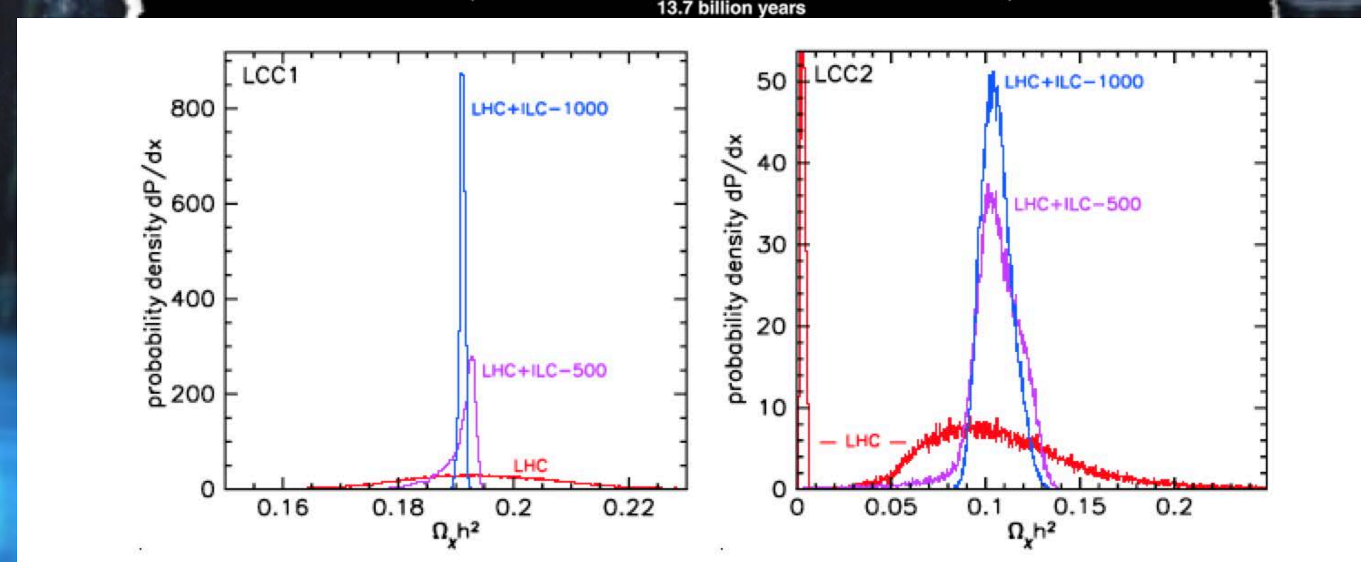
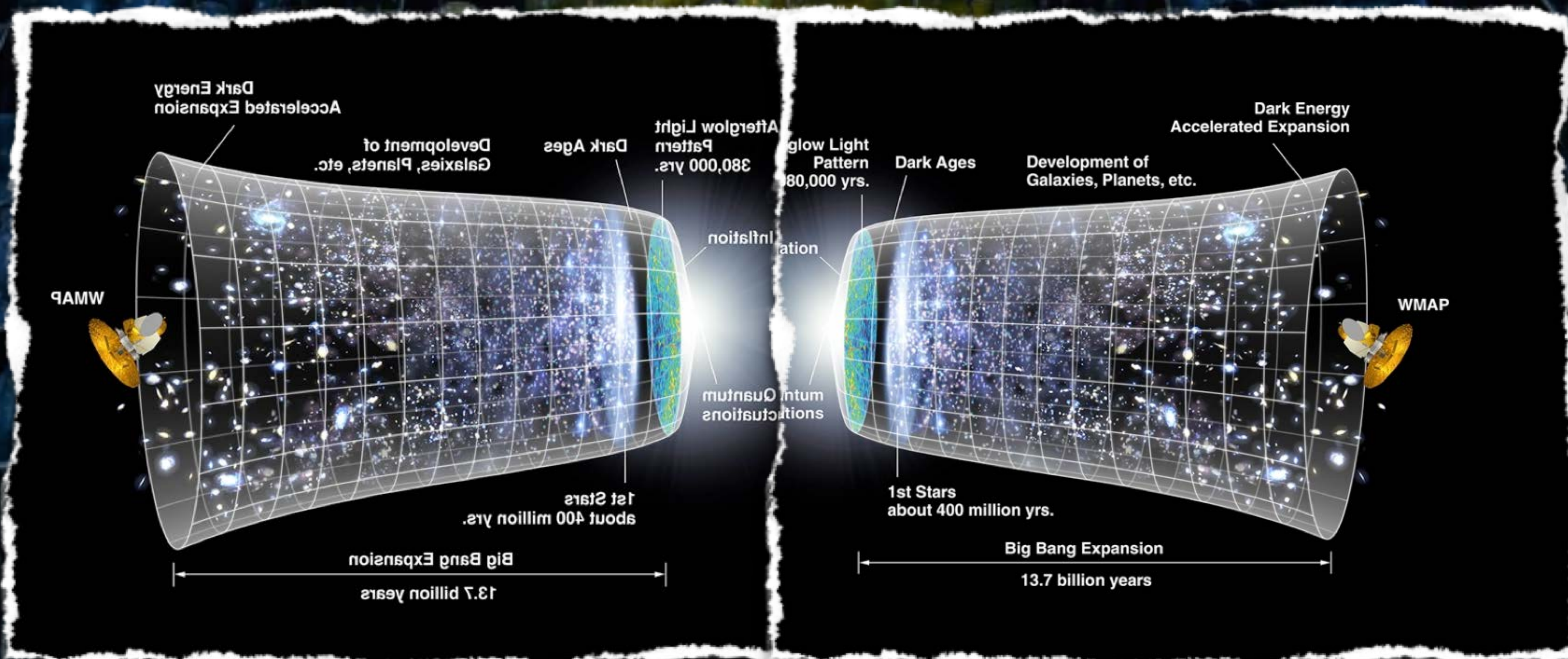
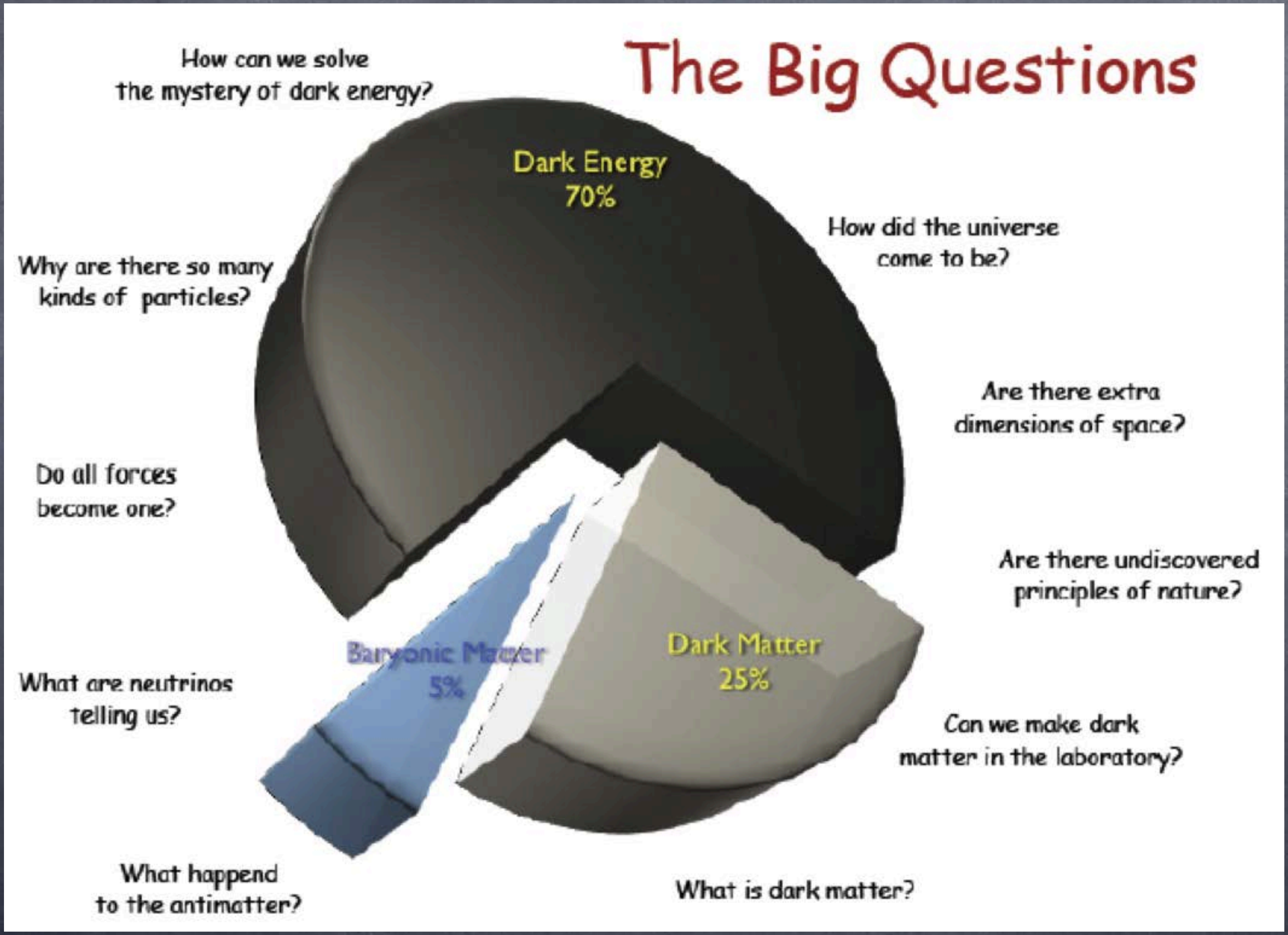


Fig. 17 Probability distribution of predictions for $\Omega_\chi h^2$ for the LCC1 [SPS1a′] "bulk" point and the LCC2 "focus-point" point from measurements at ILC with $\sqrt{s} = 0.5$ and 1 TeV, and LHC (after qualitative identification of the model) [122]

H boson & the Universe Dynamics

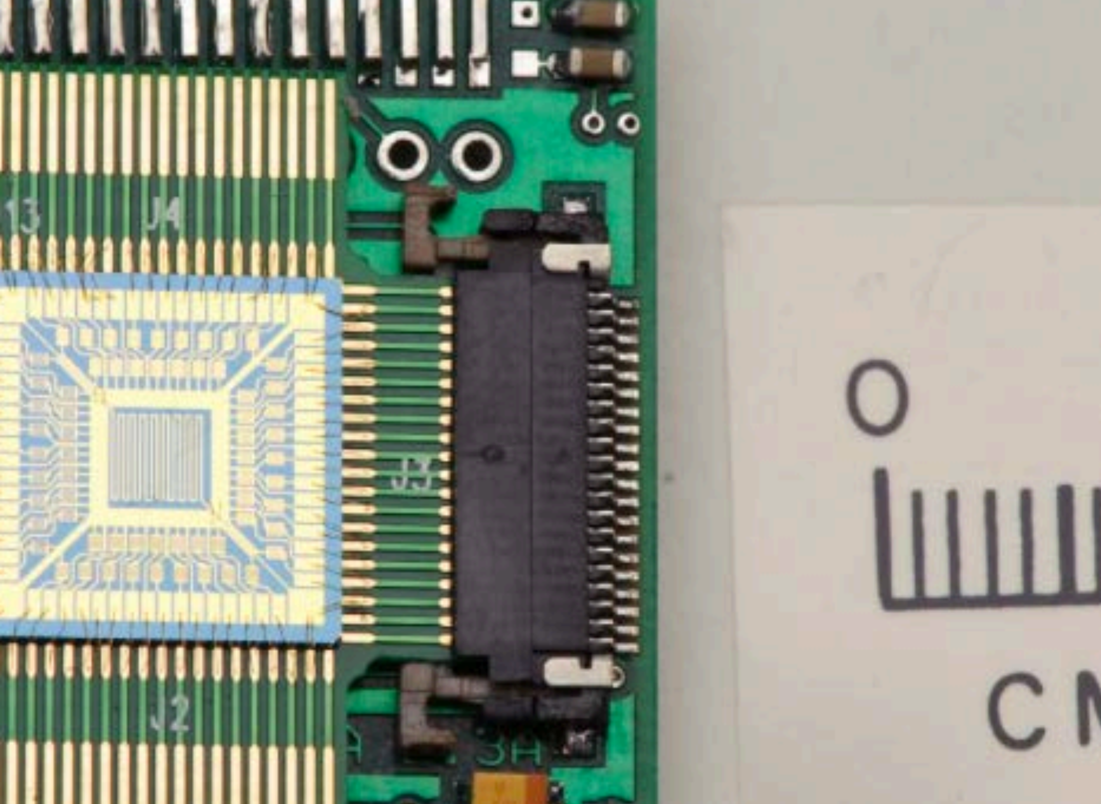


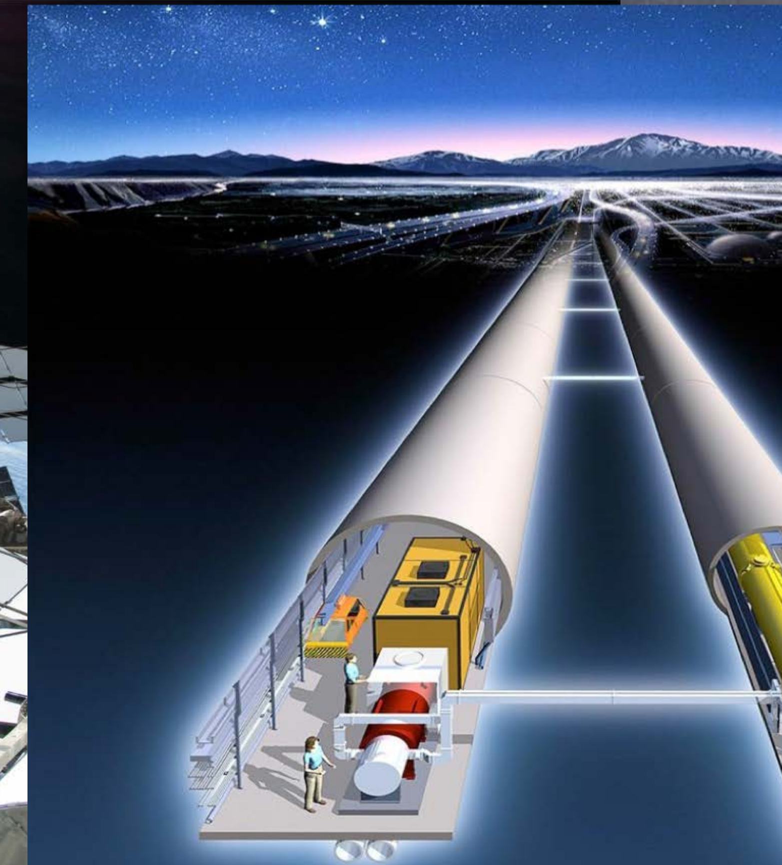

The Big Questions
How can we solve the mystery of dark energy?
Dark Energy 70%
How did the universe come to be?
Why are there so many kinds of particles?
Are there extra dimensions of space?
Do all forces become one?
Are there undiscovered principles of nature?
Baryonic Matter 5%
Dark Matter 25%
What are neutrinos telling us?
Can we make dark matter in the laboratory?
What happend to the antimatter?
What is dark matter?

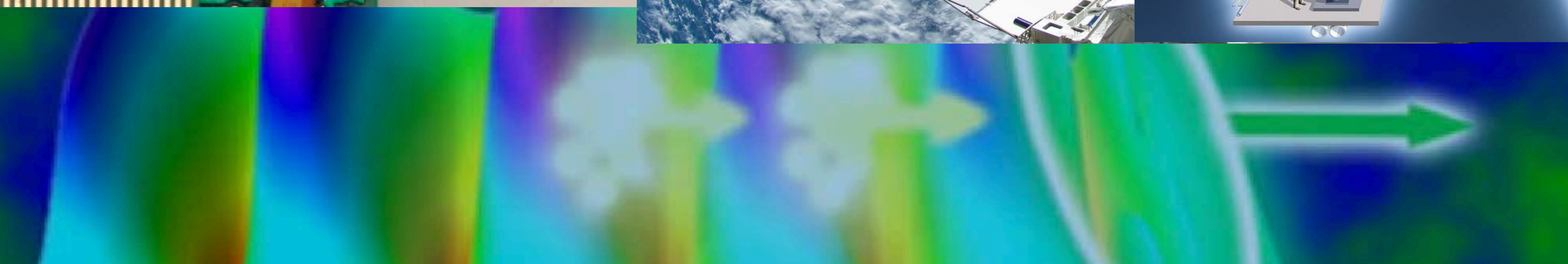
getting back to complexity (cocktails and blends)

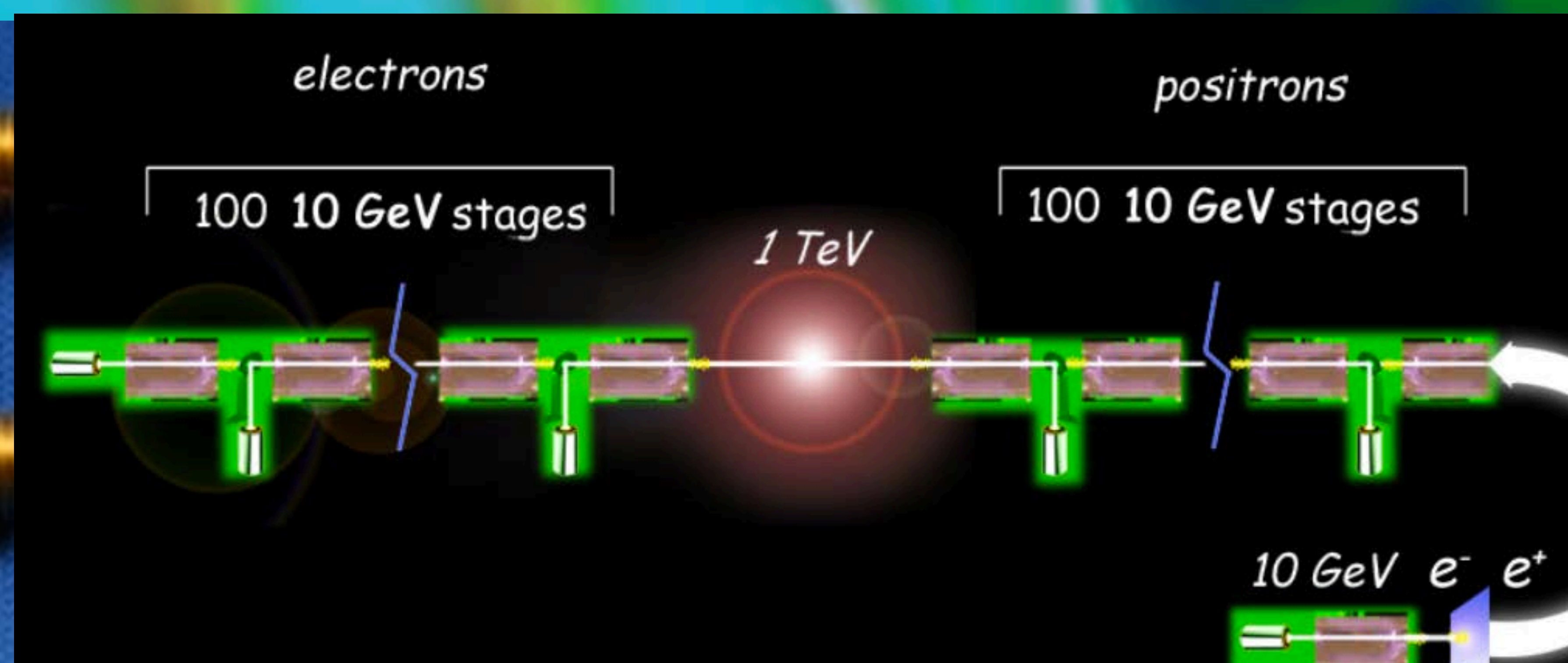
★ **2/3** of SM, **1/6** of Majorana neutrinos, **1/6** of axions, add Peccei - Quinn global symmetry, strain the result


Original Elements
Advanced Materials
Fundamental Building Blocks of Nature
Biological Sciences
Light Sources
Colliders
Neutron Sources
Beam Dynamics
Accelerators and Beams
Tools of Discovery
Industry
Medical Accelerators
Source Technology
Industrial Accelerators
Medicine
Particle Acceleration
Ion Implanters
National Security
Energy
Education








electrons
positrons
100 10 GeV stages
1 TeV
100 10 GeV stages
10 GeV e- e+