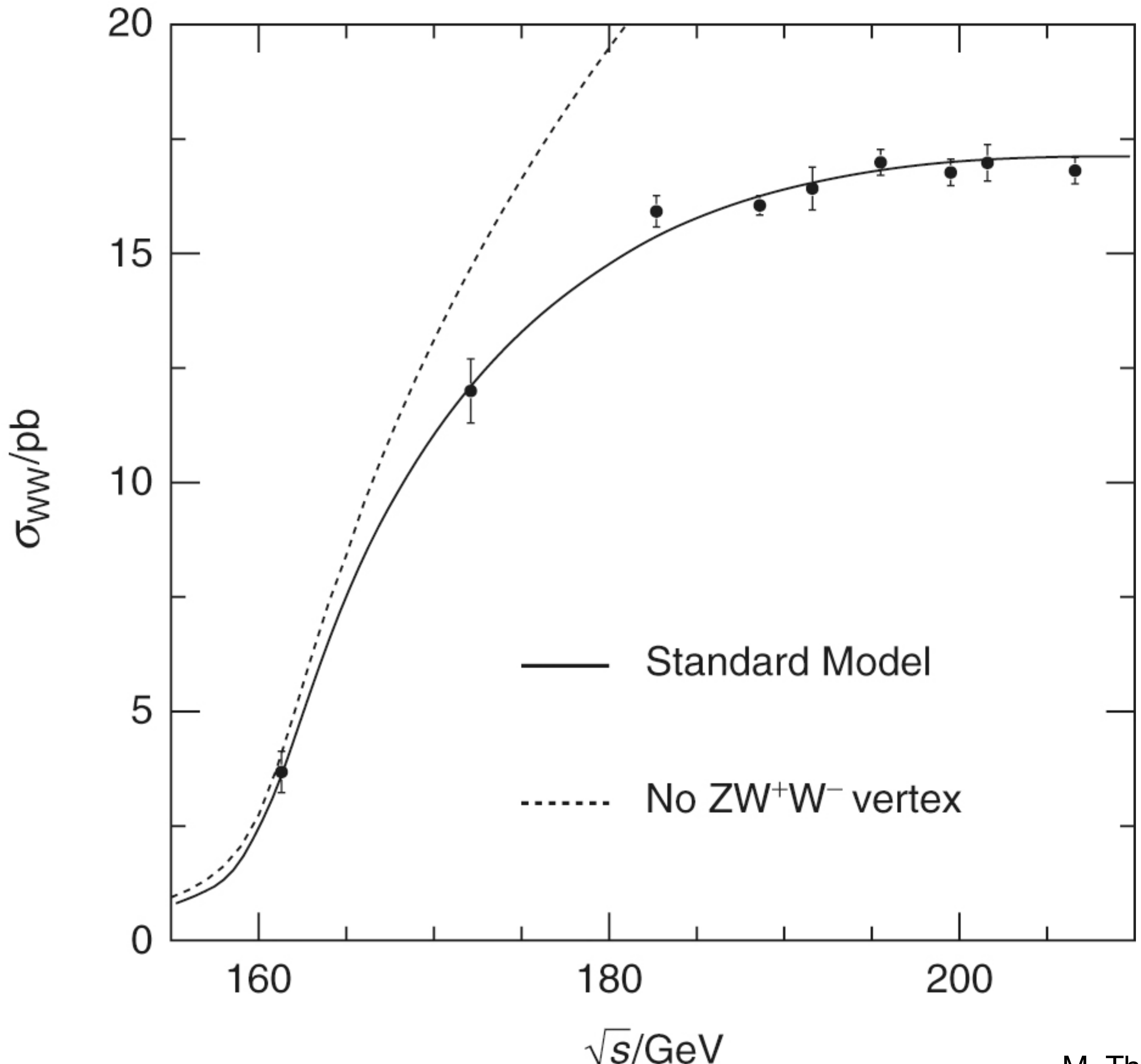
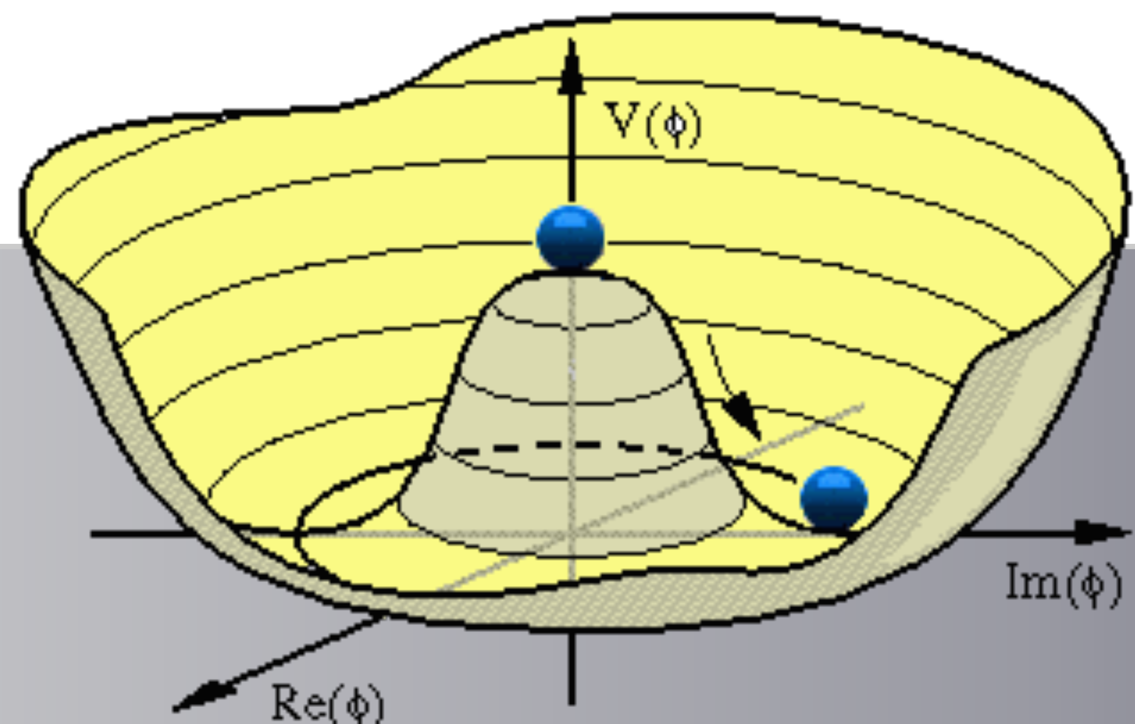
W Pair Production Cross Section



M. Thomson, Modern Particle Physics
© Cambridge University Press 2013

The Higgs Boson

A short introduction ...



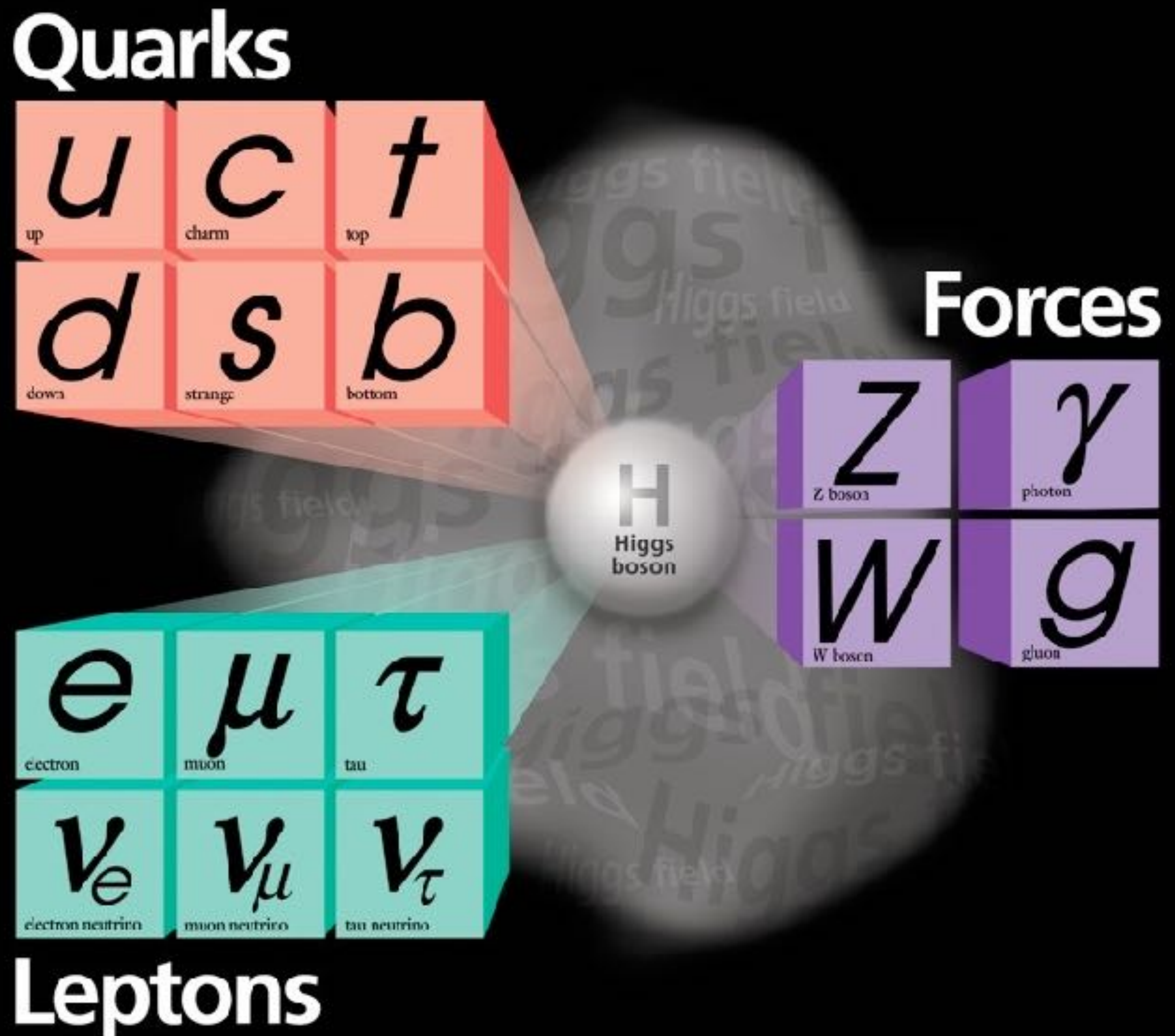
Nobel Prize 2013 ...

The Nobel Prize in Physics 2013 was awarded jointly to

François Englert and Peter W. Higgs

"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 Standard Model
A particle physicist's view of the world ...



The Standard Model

A theorist's view of the world ...

Free Fields

Interaction

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}'$$

Fermions
[kinetic terms]

Mass Terms
[from Yukawa couplings]

$$\mathcal{L}_0 = \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{\text{mass}} + \ldots$$

$$\ldots + \mathcal{L}_{\text{gauge}}$$

Gauge Fields
[kinetic energy]

$$\mathcal{L}' = \mathcal{L}_{WZA} + \mathcal{L}_{\text{gauge}/\psi}$$

Gauge Fields
[triple and quartic couplings]

Interactions
[Fermion-Boson couplings]

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{\text{mass}} + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{gauge}/\psi} \ .$$

$$\mathcal{L}_{\text{Dirac}} = i\bar{e}^i_{\text{L}} \partial\!\!\!/ e^i_{\text{L}} + i\bar{\nu}^i_{\text{L}} \partial\!\!\!/ \nu^i_{\text{L}} + i\bar{e}^i_{\text{R}} \partial\!\!\!/ e^i_{\text{R}} + i\bar{u}^i_{\text{L}} \partial\!\!\!/ u^i_{\text{L}} + i\bar{d}^i_{\text{L}} \partial\!\!\!/ d^i_{\text{L}} + i\bar{u}^i_{\text{R}} \partial\!\!\!/ u^i_{\text{R}} + i\bar{d}^i_{\text{R}} \partial\!\!\!/ d^i_{\text{R}} \ ;$$

$$\mathcal{L}_{\text{mass}} = -v\left(\lambda^i_e \bar{e}^i_{\text{L}} e^i_{\text{R}} + \lambda^i_u \bar{u}^i_{\text{L}} u^i_{\text{R}} + \lambda^i_d \bar{d}^i_{\text{L}} d^i_{\text{R}} + \text{h.c.}\right) - M_W^2 W^+_\mu W^{-\mu} - \frac{M_W^2}{2\cos^2\theta_W} Z_\mu Z^\mu \ ;$$

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}(G^a_{\mu\nu})^2 - \frac{1}{2} W^+_{\mu\nu} W^{-\mu\nu} - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \mathcal{L}_{WZA} \ ,$$

$$\begin{aligned}
G^a_{\mu\nu} &= \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g_3 f^{abc} A^b_\mu A^c_\nu \\
W^\pm_{\mu\nu} &= \partial_\mu W^\pm_\nu - \partial_\nu W^\pm_\mu \\
Z_{\mu\nu} &= \partial_\mu Z_\nu - \partial_\nu Z_\mu \\
F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu \ ,
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{WZA} = \; & i g_2 \cos\theta_{\text{W}} \left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu Z^\nu + W^+_{\mu\nu} W^{-\mu} Z^\nu - W^-_{\mu\nu} W^{+\mu} Z^\nu\right] \\
& + ie\left[\left(W^-_\mu W^+_\nu - W^-_\nu W^+_\mu\right)\partial^\mu A^\nu + W^+_{\mu\nu} W^{-\mu} A^\nu - W^-_{\mu\nu} W^{+\mu} A^\nu\right] \\
& + g_2^2 \cos^2\theta_{\text{W}} \left(W^+_\mu W^-_\nu Z^\mu Z^\nu - W^+_\mu W^{-\mu} Z_\nu Z^\nu\right) \\
& + g_2^2 \left(W^+_\mu W^-_\nu A^\mu A^\nu - W^+_\mu W^{-\mu} A_\nu A^\nu\right) \\
& + g_2 e \cos\theta_{\text{W}} \left[W^+_\mu W^-_\nu \left(Z^\mu A^\nu + Z^\nu A^\mu\right) - 2 W^+_\mu W^{-\mu} Z_\nu A^\nu\right] \\
& + \frac{1}{2} g_2^2 \left(W^+_\mu W^-_\nu\right)\left(W^{+\mu} W^{-\nu} - W^{+\nu} W^{-\mu}\right) \ ;
\end{aligned}$$

$$\mathcal{L}_{\text{gauge}/\psi} = -g_3 A^a_\mu J^{\mu a}_{(3)} - g_2\left(W^+_\mu J^\mu_{W^+} + W^-_\mu J^\mu_{W^-} + Z_\mu J^\mu_Z\right) - e A_\mu J^\mu_A \ ,$$

$$\begin{aligned}
J^{\mu a}_{(3)} &= \bar{u}^i \gamma^\mu T^a_{(3)} u^i + \bar{d}^i \gamma^\mu T^a_{(3)} d^i \\
J^\mu_{W^+} &= \frac{1}{\sqrt{2}}\left(\bar{\nu}^i_{\text{L}} \gamma^\mu e^i_{\text{L}} + V^{ij} \bar{u}^i_{\text{L}} \gamma^\mu d^j_{\text{L}}\right) \\
J^\mu_{W^-} &= (J^\mu_{W^+})^* \\
J^\mu_Z &= \frac{1}{\cos\theta_{\text{W}}}\left[\frac{1}{2}\bar{\nu}^i_{\text{L}}\gamma^\mu\nu^i_{\text{L}} + \left(-\frac{1}{2} + \sin^2\theta_{\text{W}}\right)\bar{e}^i_{\text{L}}\gamma^\mu e^i_{\text{L}} + (\sin^2\theta_{\text{W}})\bar{e}^i_{\text{R}}\gamma^\mu e^i_{\text{R}}\right. \\
& \quad + \left(\frac{1}{2} - \frac{2}{3}\sin^2\theta_{\text{W}}\right)\bar{u}^i_{\text{L}}\gamma^\mu u^i_{\text{L}} + \left(-\frac{2}{3}\sin^2\theta_{\text{W}}\right)\bar{u}^i_{\text{R}}\gamma^\mu u^i_{\text{R}} \\
& \quad \left. + \left(-\frac{1}{2} + \frac{1}{3}\sin^2\theta_{\text{W}}\right)\bar{d}^i_{\text{L}}\gamma^\mu d^i_{\text{L}} + \left(\frac{1}{3}\sin^2\theta_{\text{W}}\right)\bar{d}^i_{\text{R}}\gamma^\mu d^i_{\text{R}}\right] \\
J^\mu_A &= (-1)\bar{e}^i\gamma^\mu e^i + \left(\frac{2}{3}\right)\bar{u}^i\gamma^\mu u^i + \left(-\frac{1}{3}\right)\bar{d}^i\gamma^\mu d^i \ .
\end{aligned}$$

+ Higgs terms

The SM Lagrangian [massless particles]

kinetic & self-coupling
of gauge bosons

kinetic energy
of fermions

interaction between
fermions & fields

$$\boxed{\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi + e\bar{\psi}\gamma^{\mu}A_{\mu}\psi}$$

SM Lagrangian without Higgs

where:

$$eA_{\mu} = \frac{g_s}{2}\lambda_{\nu}G^{\nu}_{\mu} + \frac{g}{2}\vec{\tau}\,\vec{W}_{\mu} + \frac{g'}{2}YB_{\mu}$$

$$F_{\mu\nu}F^{\mu\nu} = G_{\mu\nu}G^{\mu\nu} + W_{\mu\nu}W^{\mu\nu} + B_{\mu\nu}B^{\mu\nu}$$

But: $SU(2)_L$ x $U(1)_Y$ symmetry forbids „ad hoc“ introduction of extra masses terms:

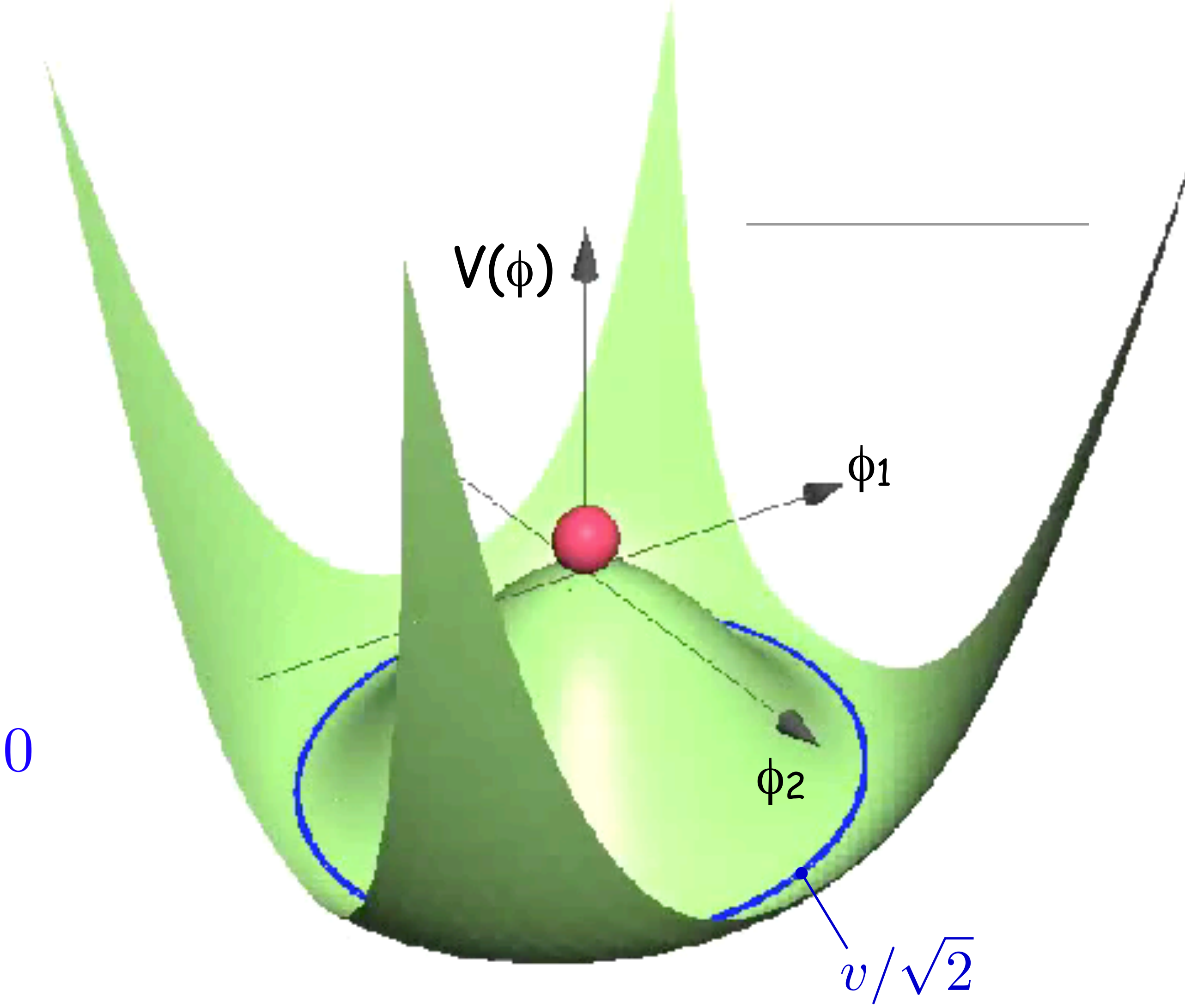
Fermions: $m\bar{\psi}\psi$

Bosons: $m^2A_{\mu}A^{\mu}$

destroy gauge invariance !

But: particles do have mass

The Higgs Mechanism



Introduce:
New doublet of complex scalar fields
[4 degrees of freedom; ‘mexican hat’ potential]

$$V(\phi) = -\mu^2|\phi^\dagger\phi| + \lambda|\phi^\dagger\phi|^2$$
$$\text{with} \;\; \mu, \lambda > 0$$

Lagrangian of scalar field:

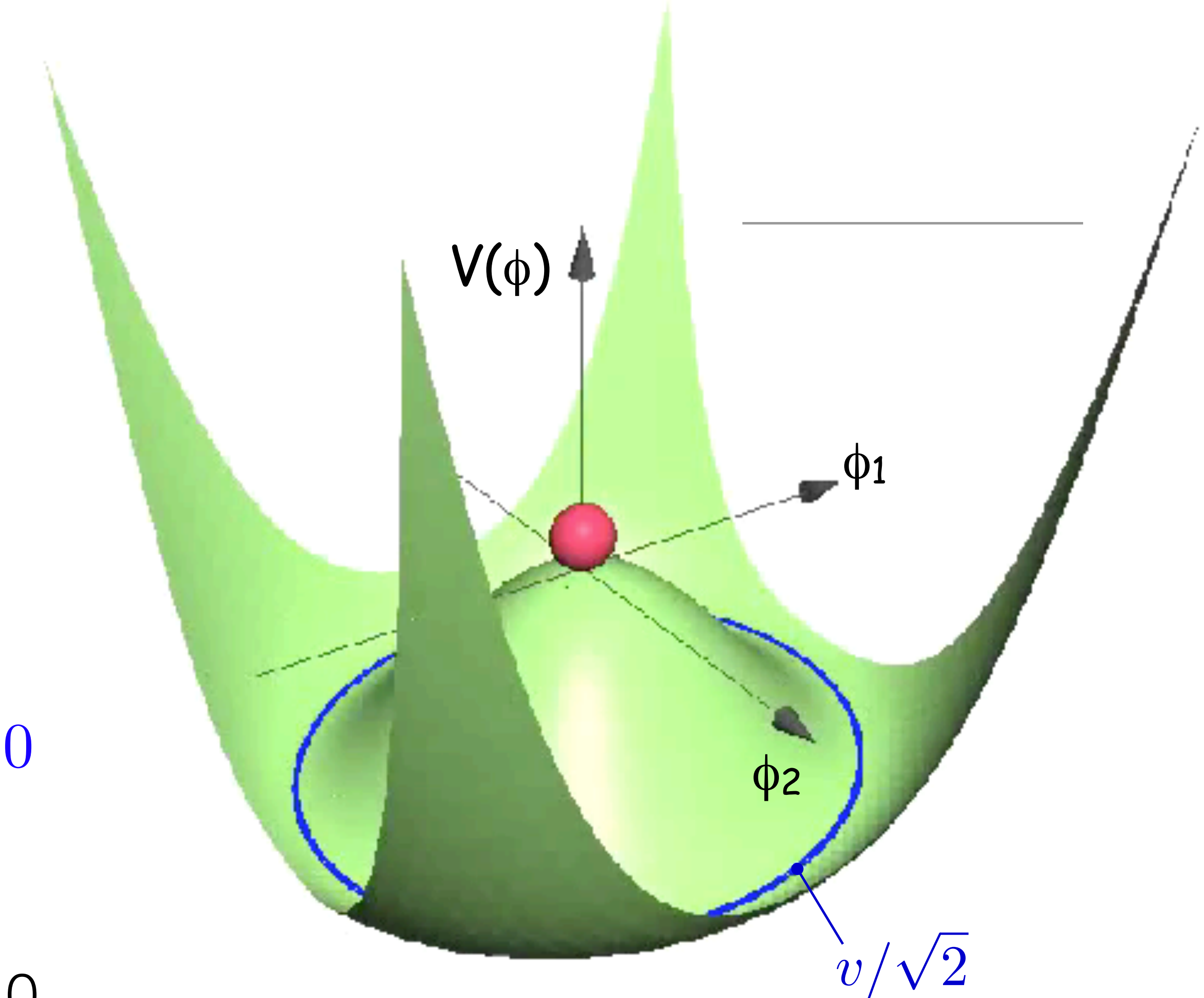
$$\mathcal{L}_\phi = (\partial_\mu\phi^\dagger)(\partial^\mu\phi) - V(\phi)$$

Coupling to bosons via transition to covariant derivative.
Coupling to fermions via “ad-hoc” introduction of “Yukawa” coupling.

$$\mathcal{L}_\phi = (D_\mu\phi^\dagger)(D^\mu\phi) - V(\phi) \quad \text{with} \quad D_\mu = \partial_\mu + ieA_\mu$$
$$\mathcal{L}_{\text{Yuk}} = c_f(\bar{\psi}_L\psi_R\phi + \bar{\psi}_R\psi_L\phi)$$

Introduction into SM Lagrangian maintains invariance under $SU(2)_L \times U(1)_Y$ gauge transformation

The Higgs Mechanism



Introduce:
New doublet of complex scalar fields
[4 degrees of freedom; 'mexican hat' potential]

$$V(\phi) = -\mu^2|\phi^\dagger\phi| + \lambda|\phi^\dagger\phi|^2$$
$$\text{with } \mu, \lambda > 0$$

Spontaneous symmetry breaking:

System falls in to minimum of V at $\phi \neq 0$.

This results in:

- Three massless excitations along valley ➛ 3 longitudinal d.o.f. for $W^\pm$ and Z
- One massive excitation out of valley ➛ 1 d.o.f. for „physical" Higgs boson

Higgs field has two components: ϕ = "v + H".

1. omnipresent, constant background condensate v = 246 GeV
2. Higgs boson H with unknown mass $M_H = \mu\cdot\sqrt{2} = (2\lambda)^{1/2}\cdot v$

Mass generation and Higgs couplings

Yields Higgs-Boson couplings

Contains Higgs self-couplings

$$\mathcal{L}_\phi = (D_\mu\phi^\dagger)(D^\mu\phi) - V(\phi) \quad \text{with} \quad D_\mu = \partial_\mu + ieA_\mu$$

$$\mathcal{L}_{\text{Yuk}} = c_f(\bar\psi_L\psi_R\phi + \bar\psi_R\psi_L\phi)$$

Higgs-fermion coupling

$$M_W = gv/2$$

$$M_Z = \sqrt{g^2 + g'^2}\, v/2$$

$$M_H = \mu\sqrt{2} = \sqrt{2\lambda}\, v$$

Substitute:

$$\phi \rightarrow \phi' = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(v+H) \end{pmatrix}$$

Unitary gauge

$$\mathcal{L}_{\text{Yuk}} = (\sqrt{2})^{-1} \cdot \left[\, c_f(\bar\psi_L\psi_R H + \bar\psi_R\psi_L H) + c_f v(\bar\psi_L\psi_R + \bar\psi_R\psi_L) \,\right]$$

$$= (\sqrt{2})^{-1} \cdot \left[\, c_f(\bar\psi_L\psi_R H + \bar\psi_R\psi_L H) + m_f\bar\psi\psi \,\right]$$

Mass generation and Higgs couplings

Interaction with „ether“ v=247 GeV:

$M_V \sim gv$ (Gauge coupling)
$m_f \sim g_f v$ (Yukawa coupling)

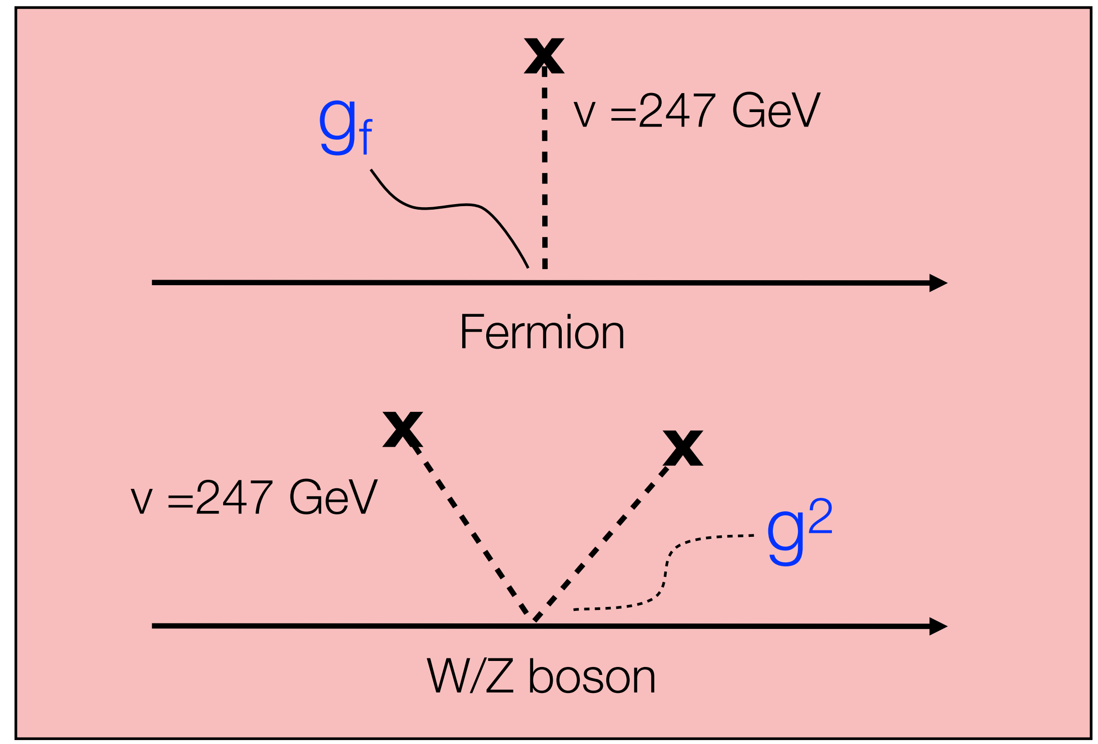
$$\left(\frac{1}{q^2}\right) \qquad \left(\frac{gv}{2}\right)^2\left(\frac{1}{q^2}\right)^2 \qquad \left(\frac{gv}{2}\right)^4\left(\frac{1}{q^2}\right)^3$$

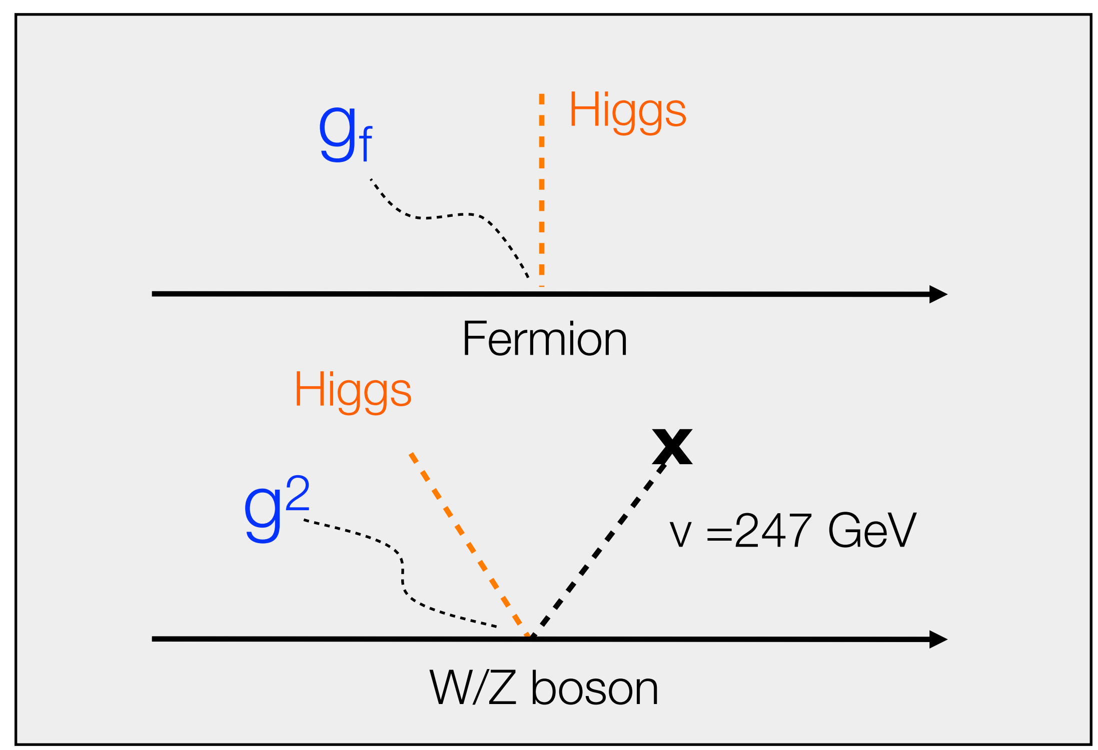
... =

$$\frac{1}{q^2 - M^2} \quad \text{where} \quad M = \frac{gv}{2}$$

Interaction with Higgs boson H:

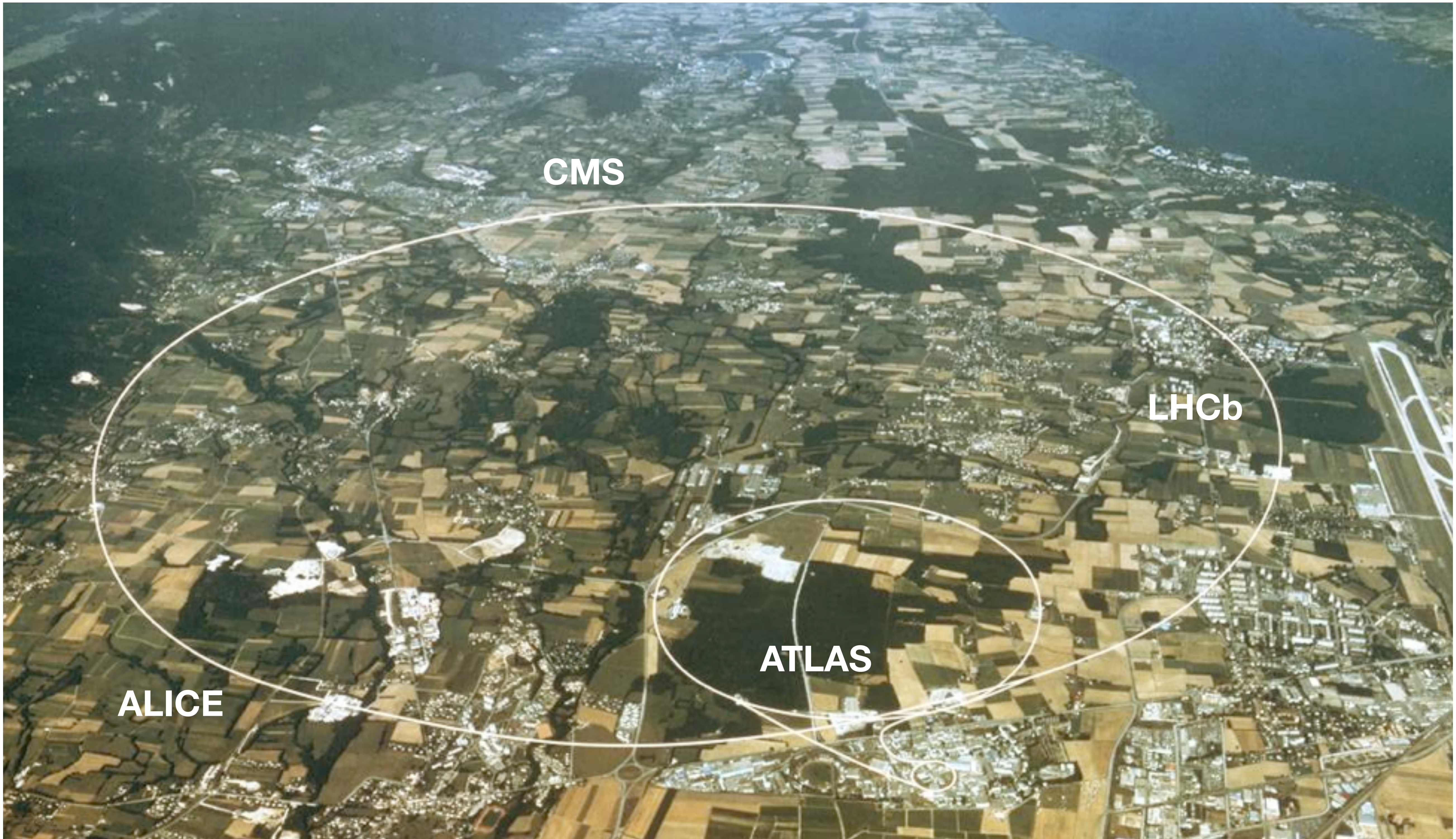
Fermions: $g_f \sim m_f/v$
W/Z bosons: $g_V \sim M_V^2/v = g^2 \cdot v$





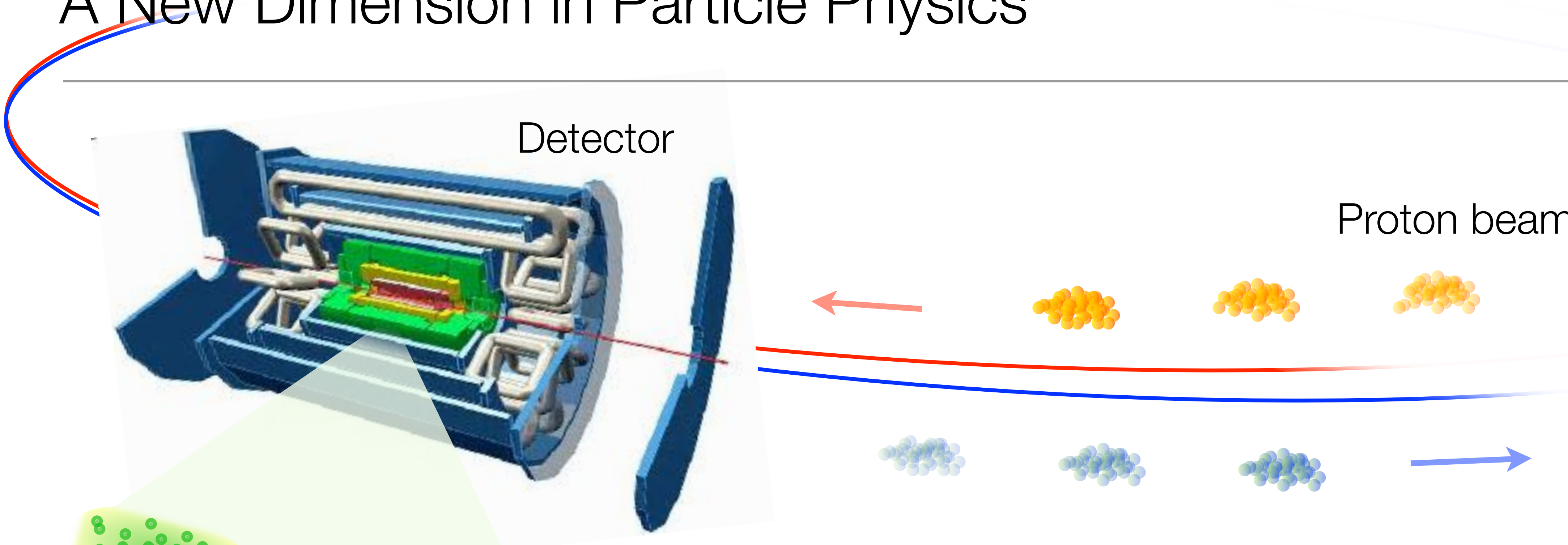
The LHC

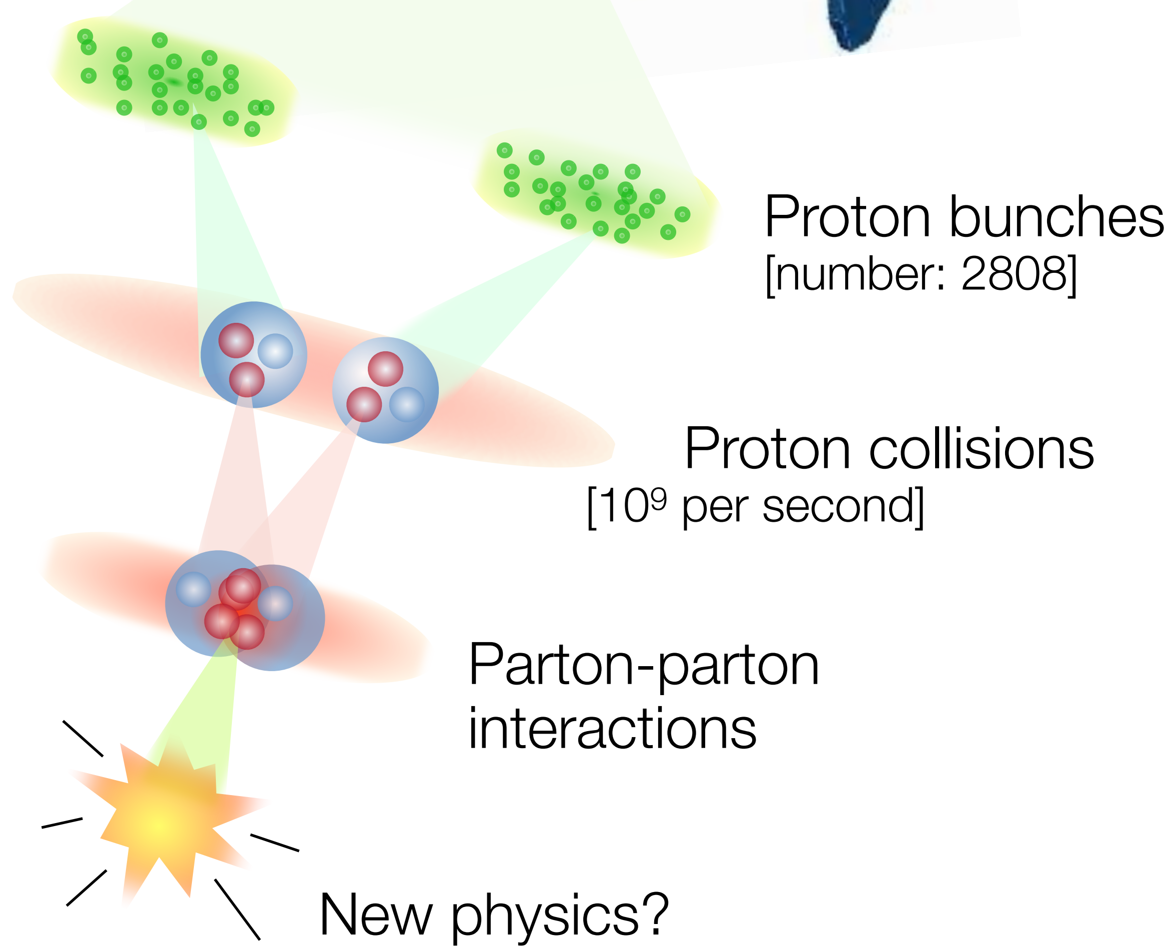
A New Dimension in Particle Physics



The LHC

A New Dimension in Particle Physics





Circumference: 27 km

Collision rate: 40 MHz

CMS-Energy: 14 TeV

Dipols: ca. 1200

[Field: up to 8.3 T]
[Temperature: 1.9 K]
[Stored energy: 9.2 GJ]

The Discovery Channel

10^9 Events/sec

[1 Mbyte/Event]

10^{10}

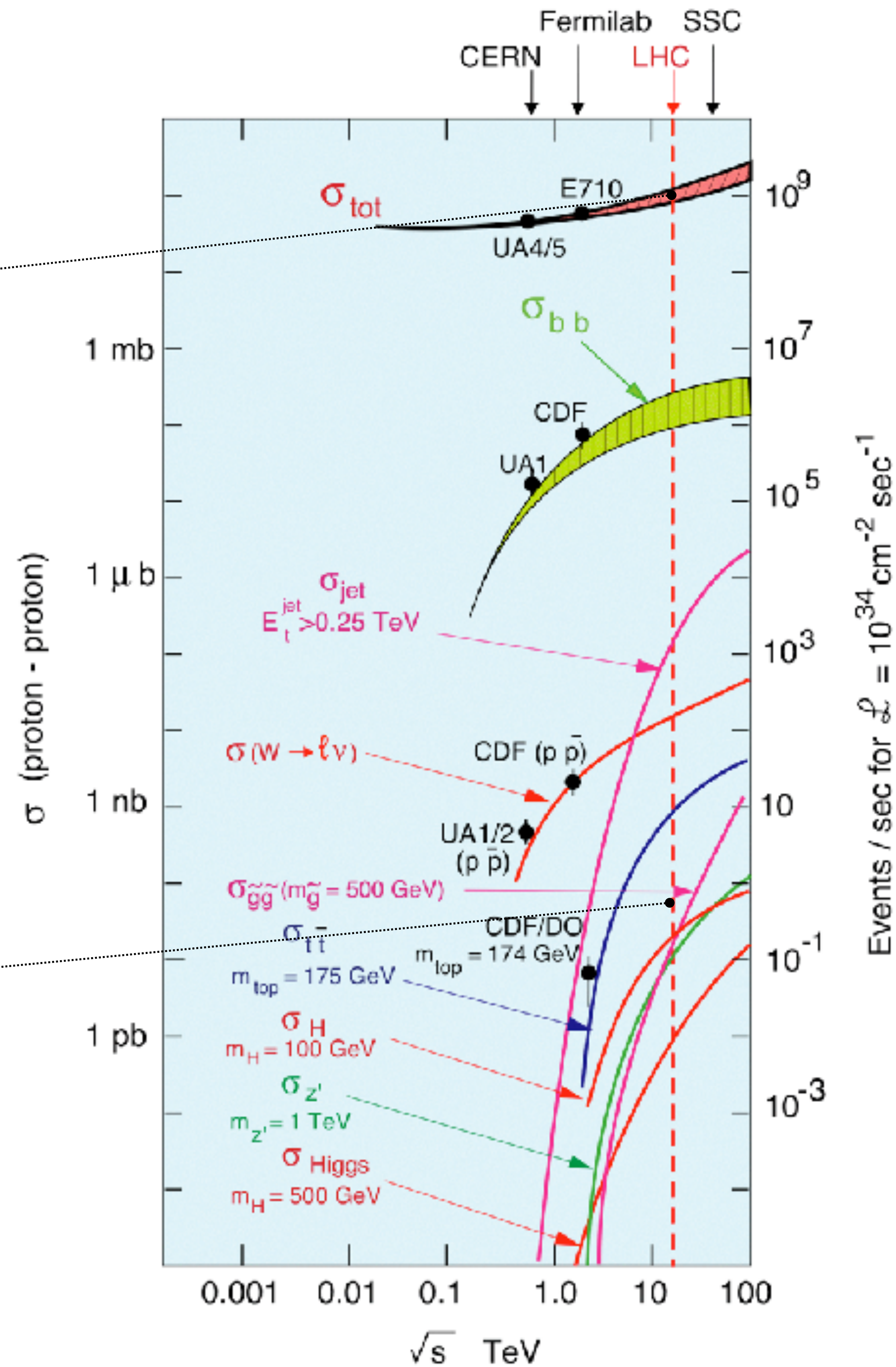
Efficient
rate reduction needed

[Storage rate: 100 Hz]

10 Events/min

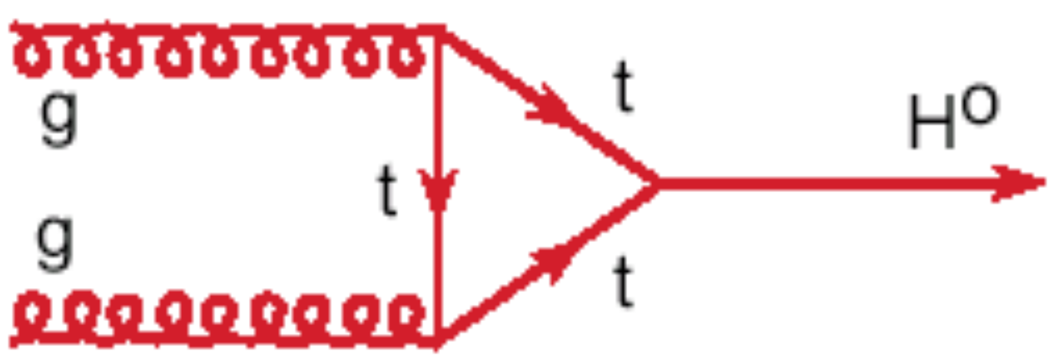
[$m_H \approx 100$ GeV]

with 0.2% $H \rightarrow \gamma\gamma$
1.5% $H \rightarrow ZZ$

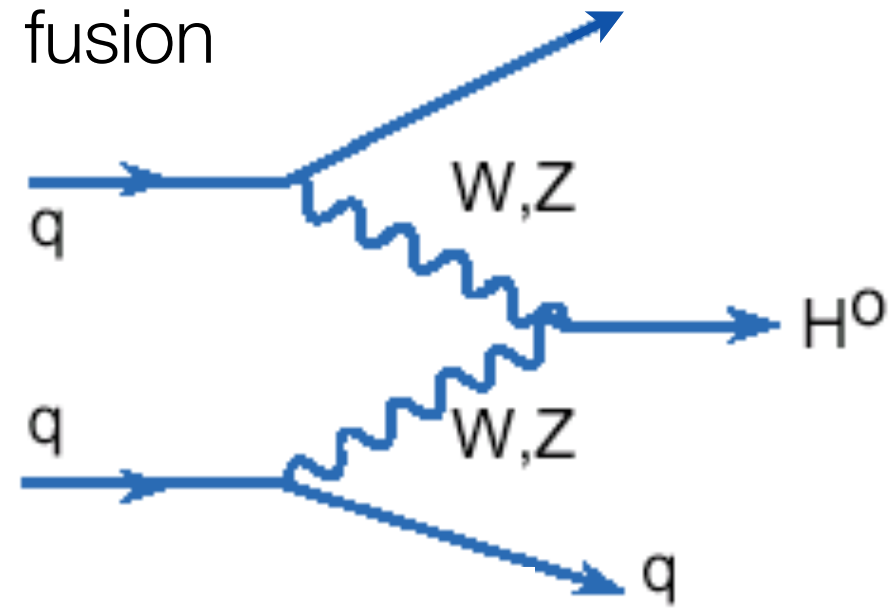


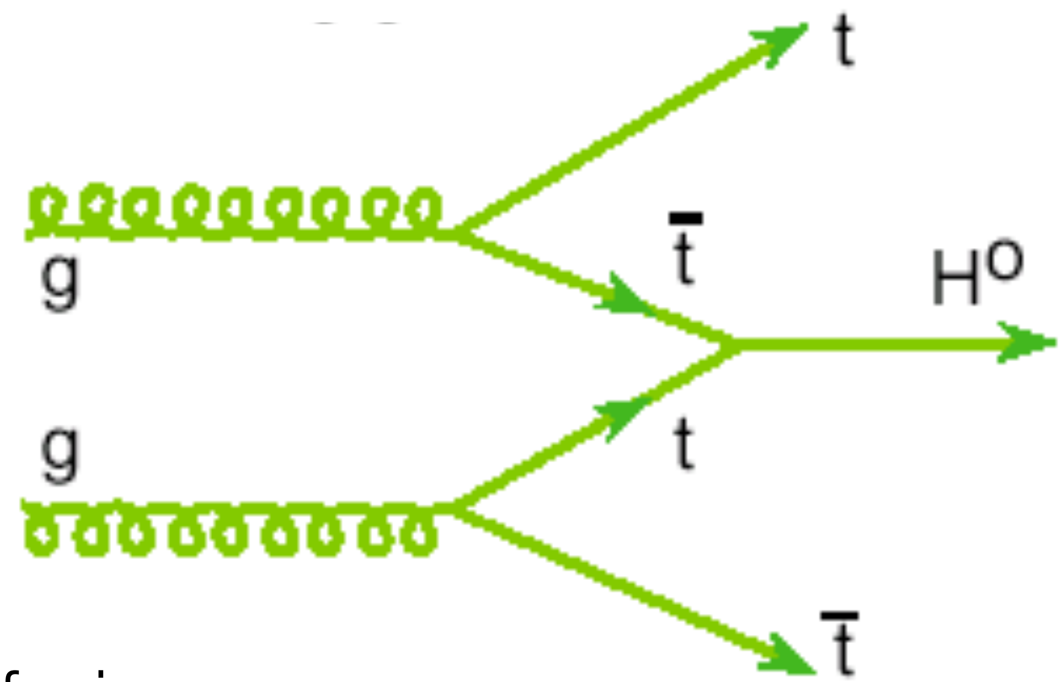
Higgs Production Mechanisms

Gluon fusion

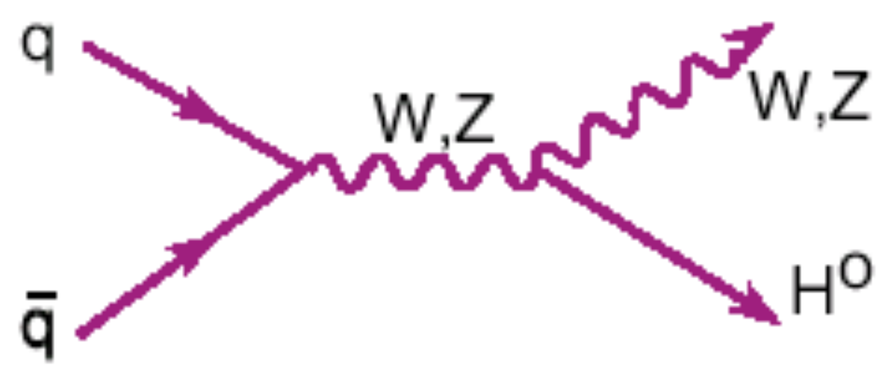


Vector boson fusion



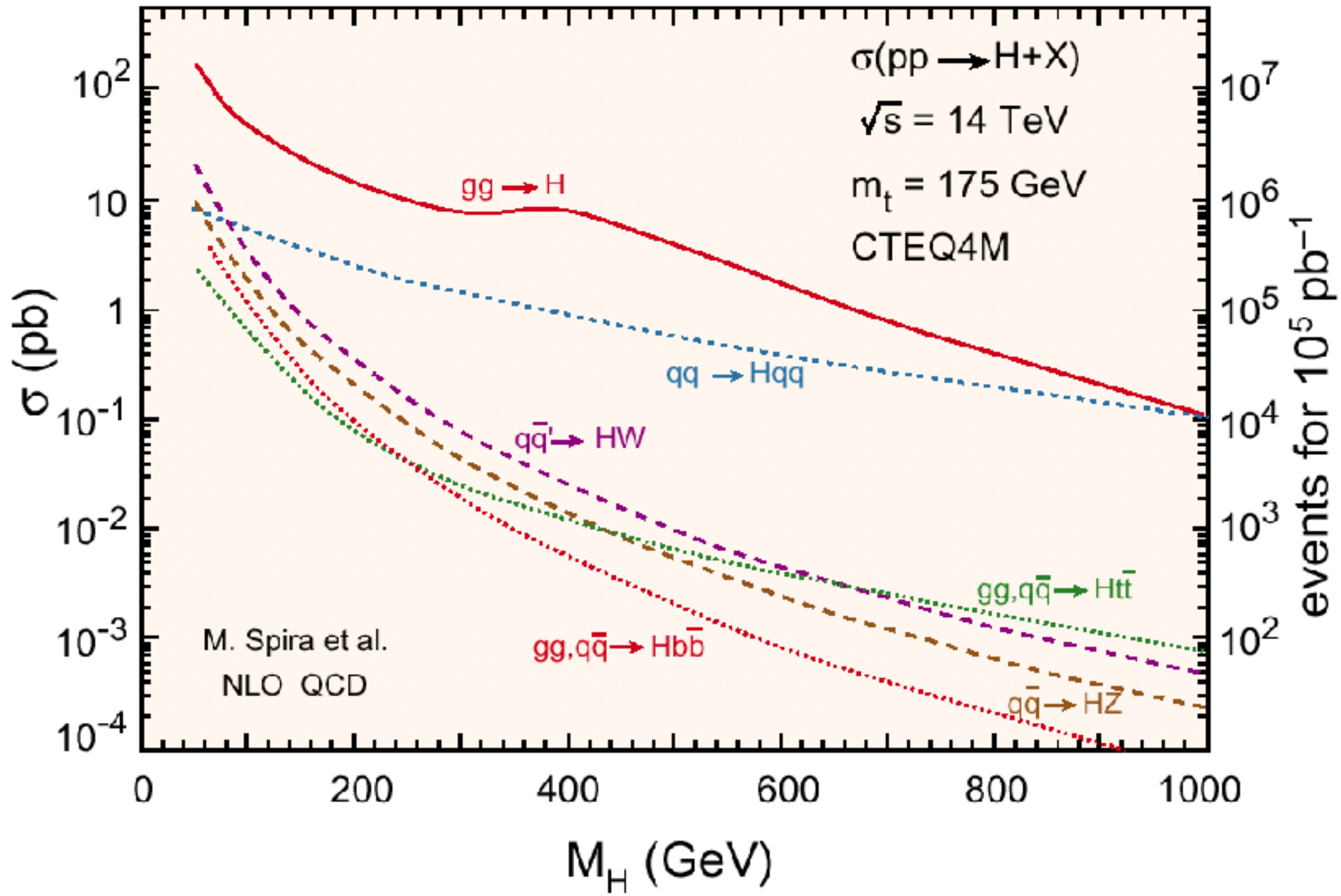


$t\bar{t}$-fusion



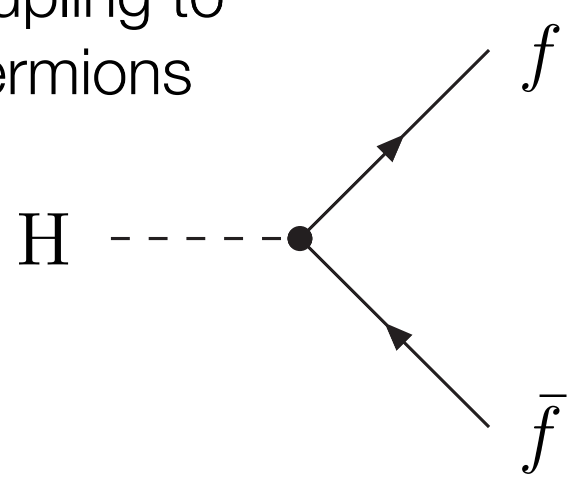
Associated production

Higgs Production Cross Sections

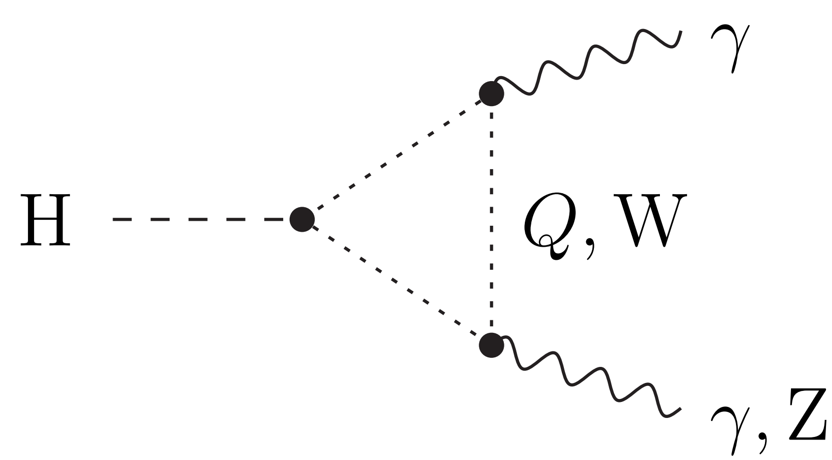


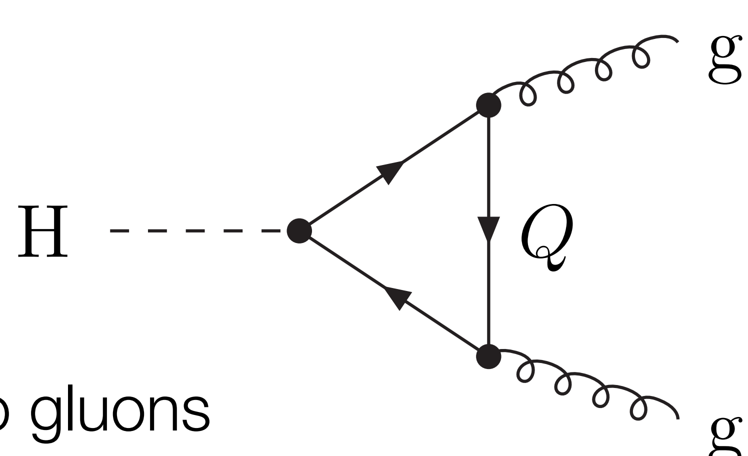
Higgs Couplings – Examples

Coupling to
Fermions

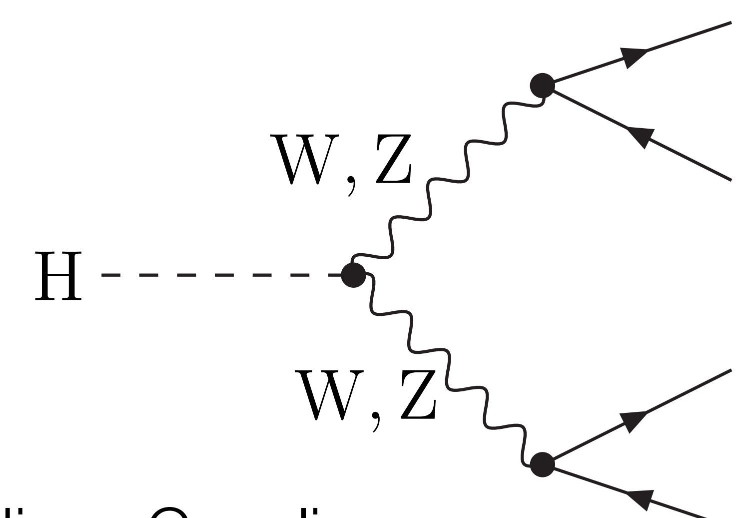


Coupling to photons
[via charged particle loops]



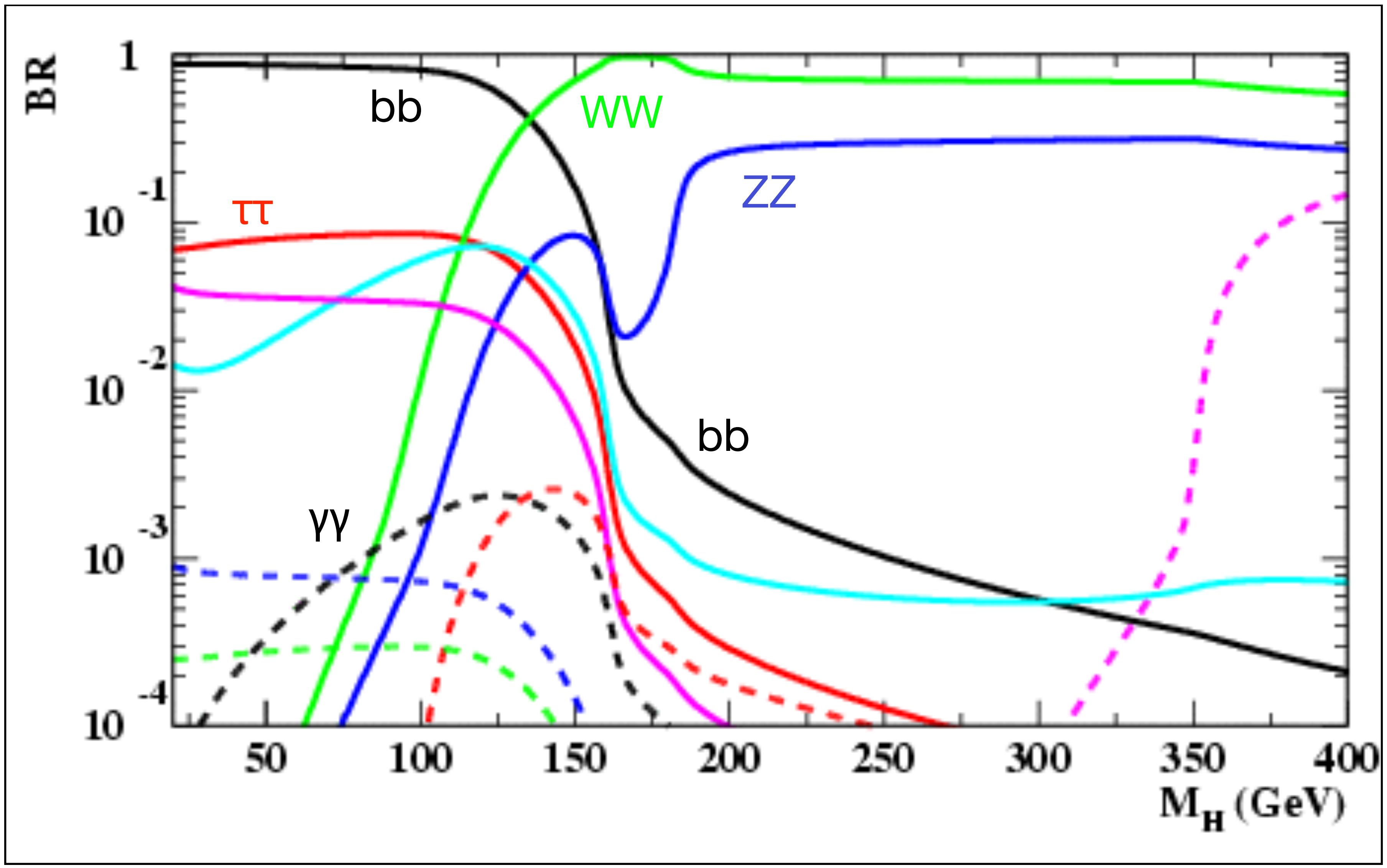


Coupling to gluons
[via heavy particle loops]



Higgs Coupling
to Gauge Boson

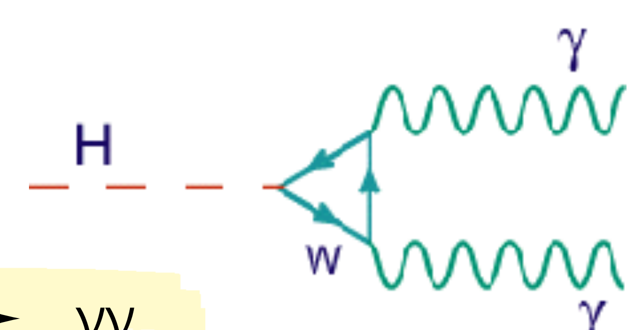
Higgs Boson Decays



For M < 135 GeV: H ➛ bb, ττ dominant

For M > 135 GeV: H ➛ WW, ZZ dominant

Tiny but also important: H ➛ γγ



Direct Higgs Channels

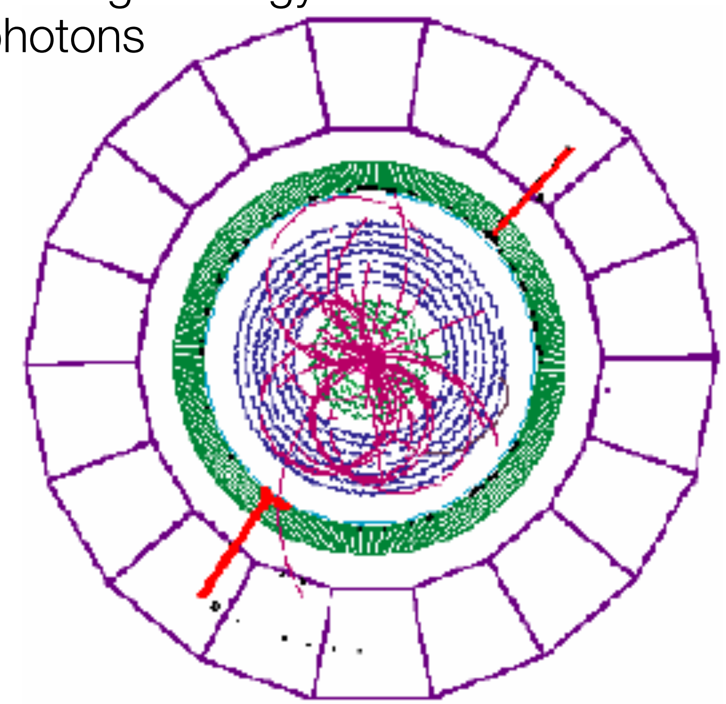
Channel	LHC Potential
$gg \to H \to bb$	Huge QCD background ($gg \to bb$); extremely difficult
$gg \to H \to \tau\tau$	Higgs with low p_T, hard to discriminate from background; problematic
$gg \to H \to \gamma\gamma$	Small rate, large combinatorial background, but excellent determination of m_H (CMS: crystal calorimeter)
$gg \to H \to WW$	Large rate, but 2 neutrinos in leptonic decay, Higgs spin accessible via lepton angular correlations
$gg \to H \to ZZ$	$ZZ \to 4\mu$: "gold-plated" channel for high-mass Higgs (ATLAS: muon spectrometer)

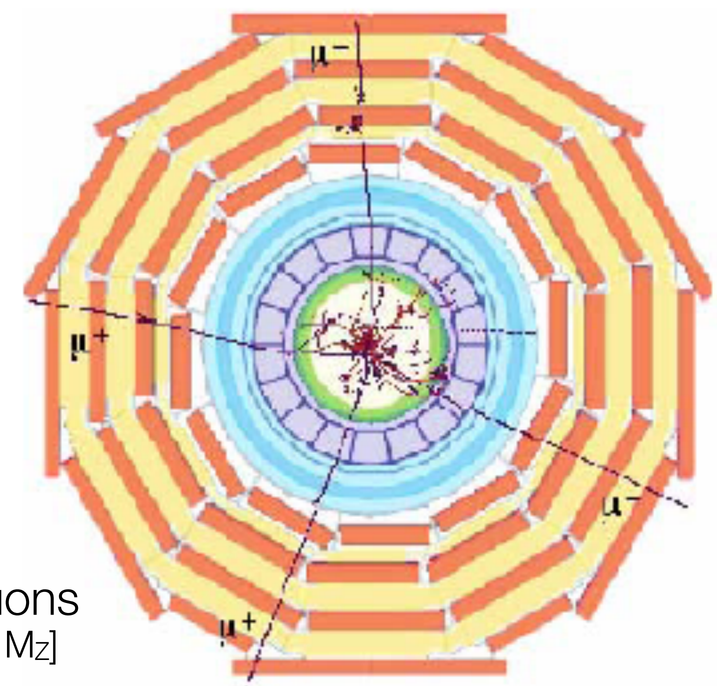
Vector Boson Fusion

Channel	LHC Potential
qq ➛ qq H [with H ➛ bb]	Very large QCD background (gg/qq ➛ bbqq); still very difficult
qq ➛ qq H [with H ➛ ττ]	Higher p_T than direct channel; interesting discovery channel for $m_H < 135$ GeV
qq ➛ qq H [with H ➛ γγ]	Most likely combined with gg ➛ H ➛ γγ to inclusive diphoton signal
qq ➛ qq H [with H ➛ WW]	Additional background suppression w.r.t. direct channel; interesting discovery channel for $m_H > 135$ GeV
gg ➛ ttH [with H ➛ bb]	Top-associated production; Seemed very promising, but overwhelmed by SM ttbb production

Higgs Searches @ LHC: Examples

Two high-energy photons



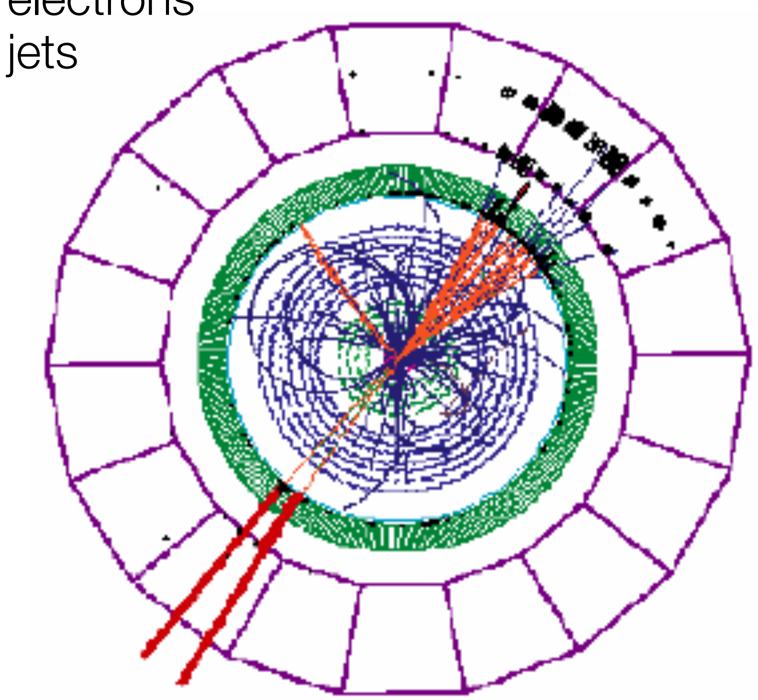


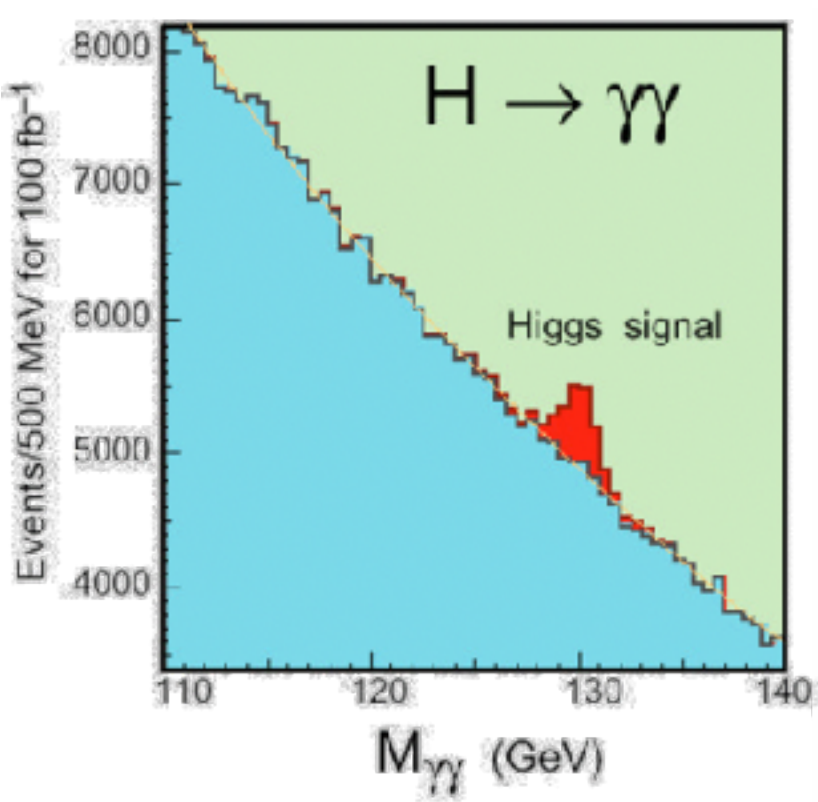
4 muons

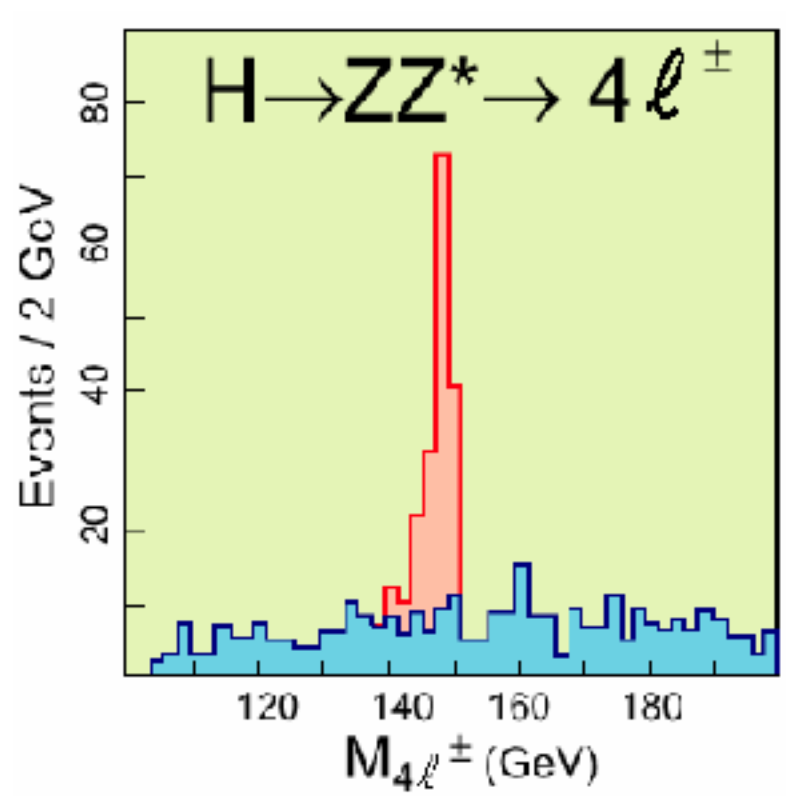
[$M_{\mu\mu} = M_Z$]

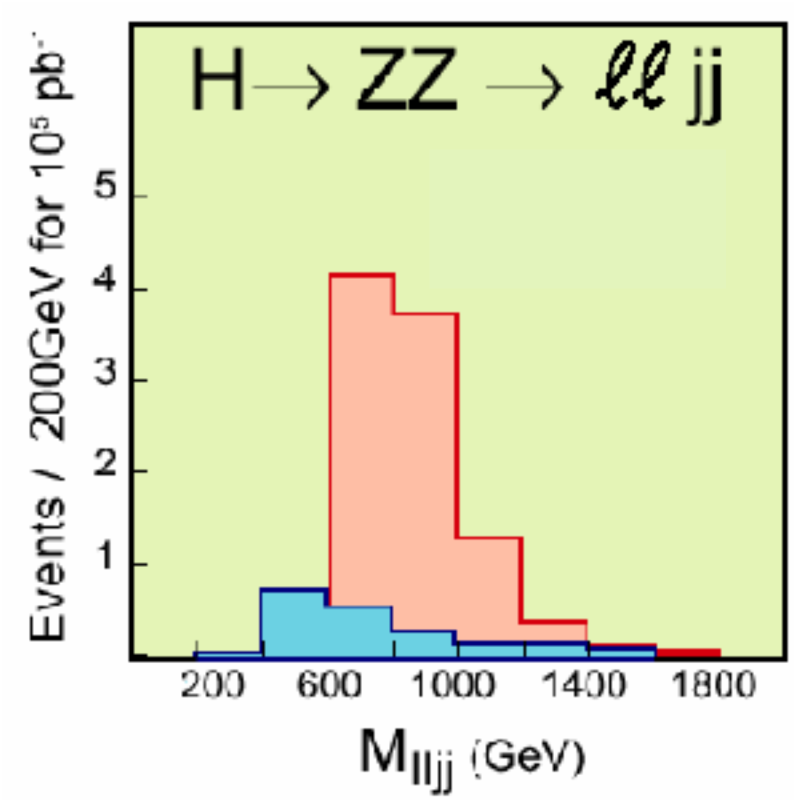
2 electrons

2 jets



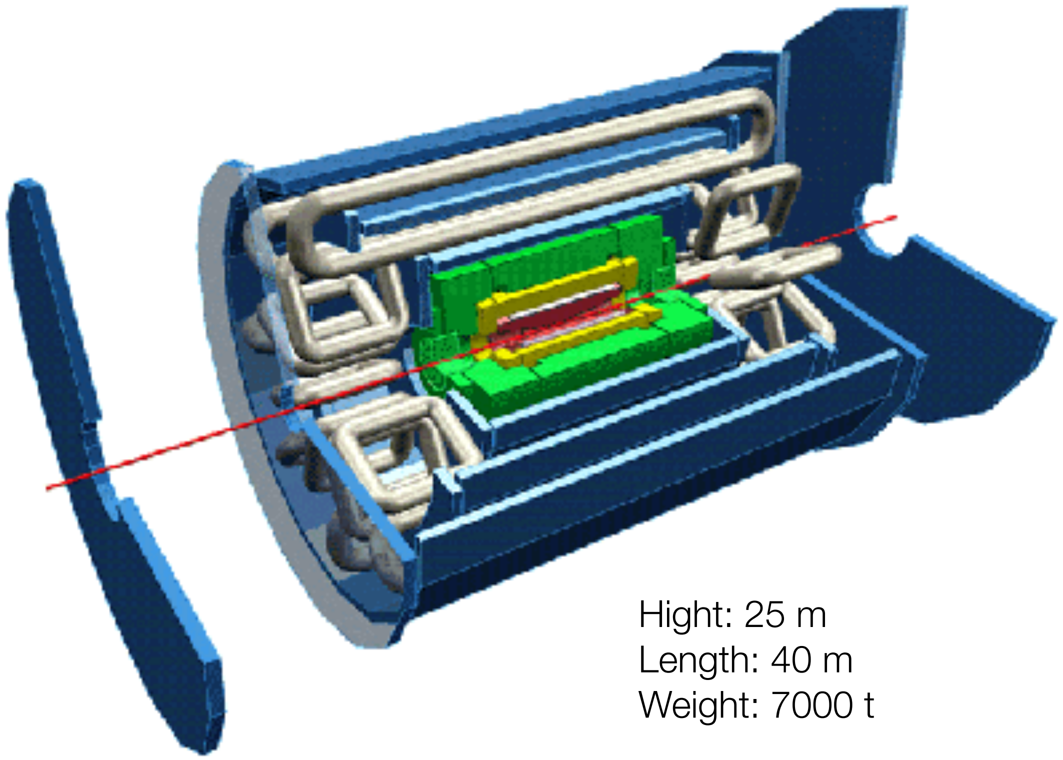






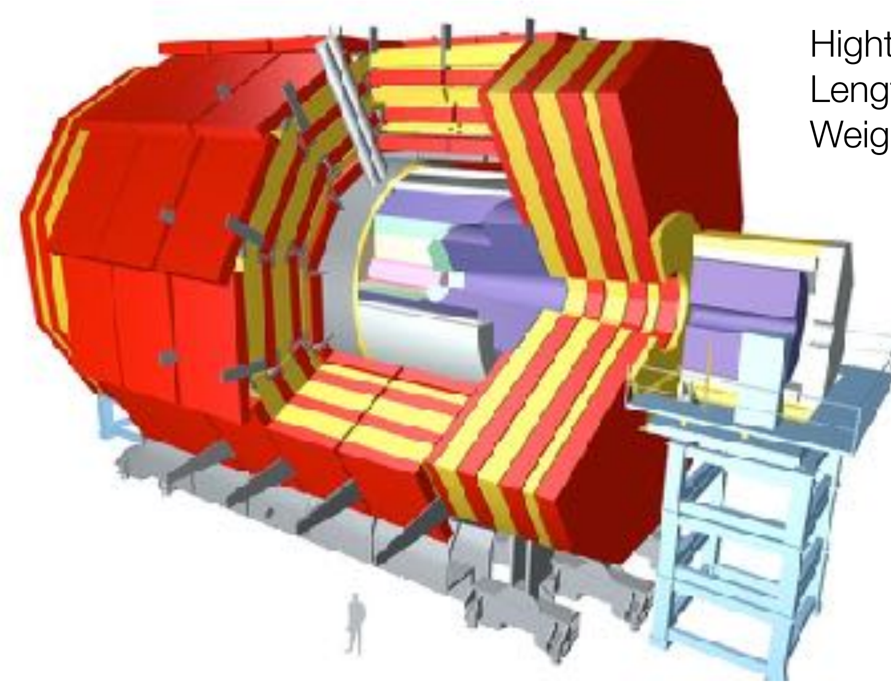
Two Omni-Purpose Detectors

ATLAS: A Toroidal LHC ApparatuS

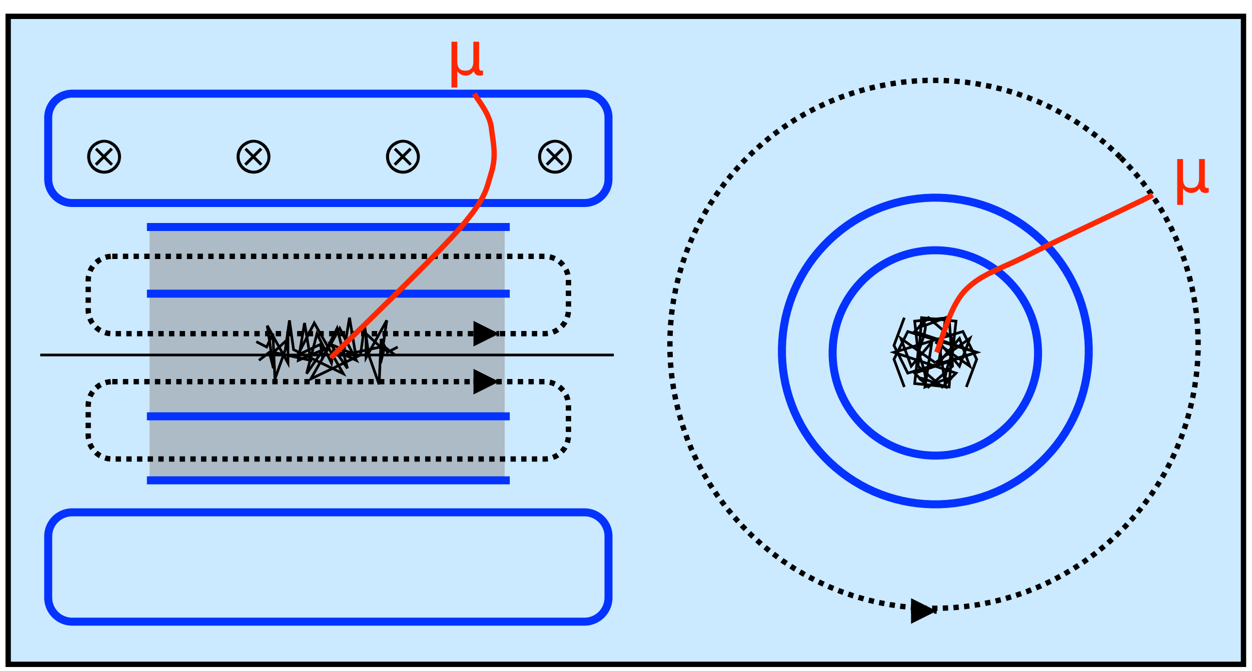


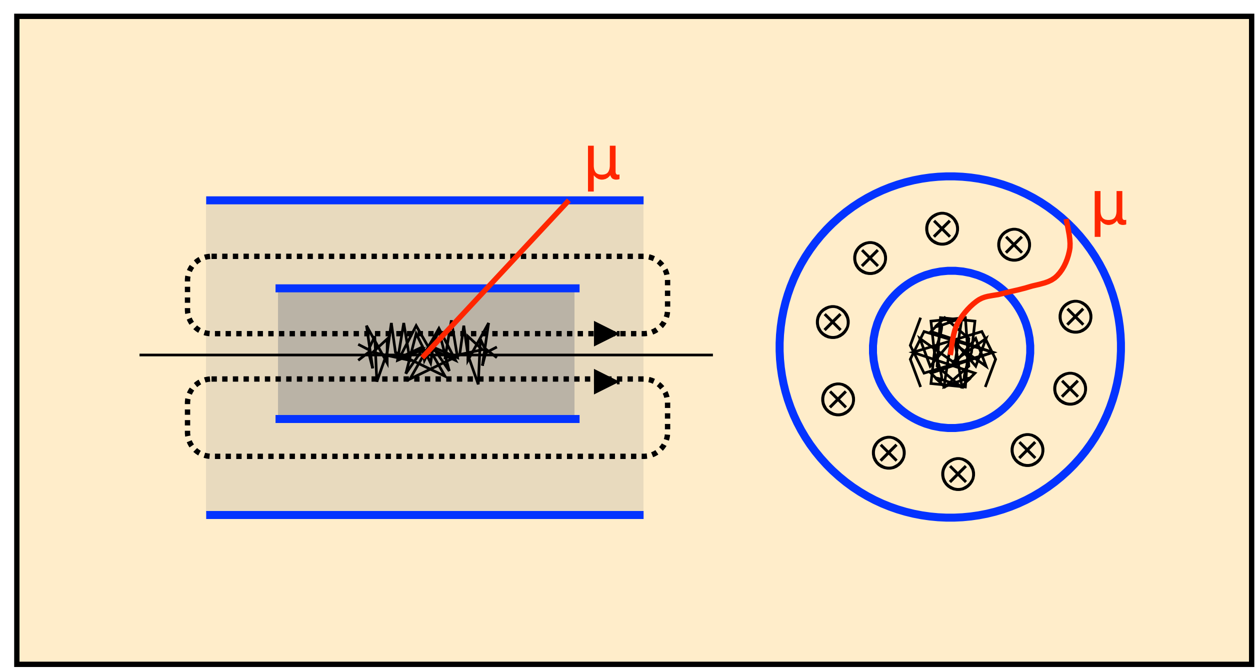
Hight: 25 m
Length: 40 m
Weight: 7000 t

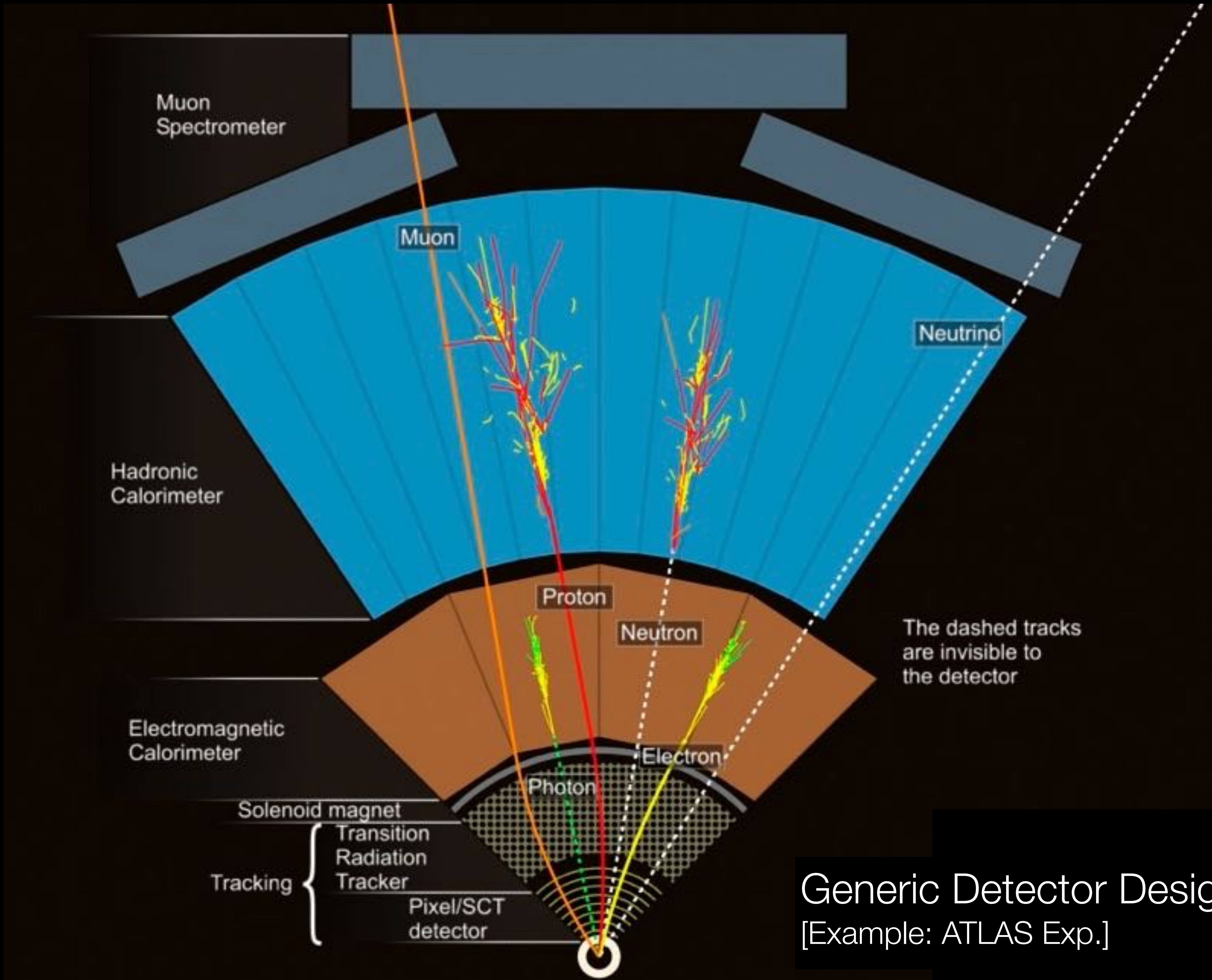
CMS: Compact Muon Solenoid



Hight: 15 m
Length: 22 m
Weight: 12500 t







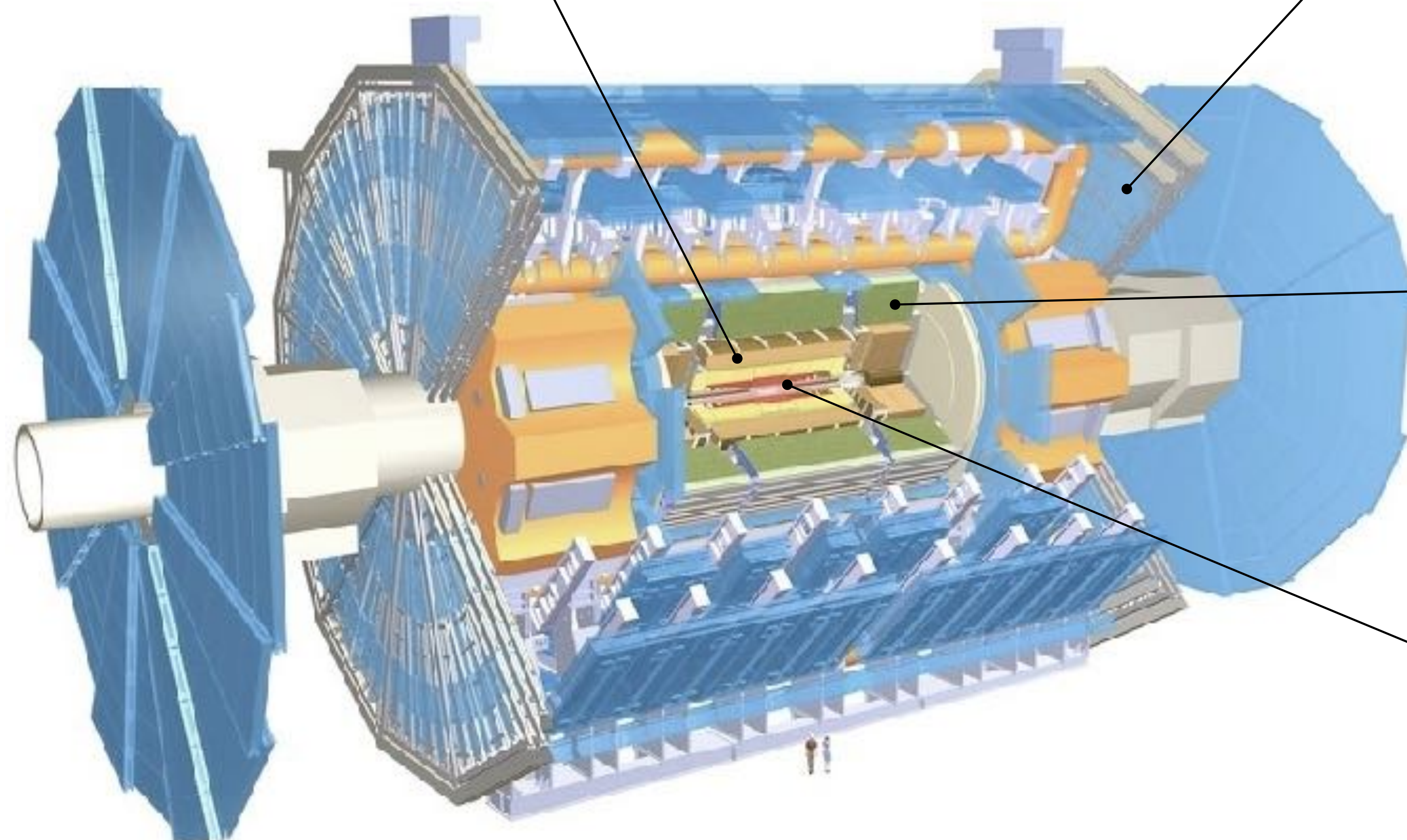
Generic Detector Design

[Example: ATLAS Exp.]

The ATLAS Detector

EM Calorimeters: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$
excellent e/γ identification
good energy resolution (e.g. for $H \rightarrow \gamma\gamma$)

Precision Muon Spectrometer: $\sigma/p_t \approx 10\%$ @ 1 TeV
fast trigger response
good momentum resolution
(e.g. $H \rightarrow ZZ \rightarrow 4\mu$)

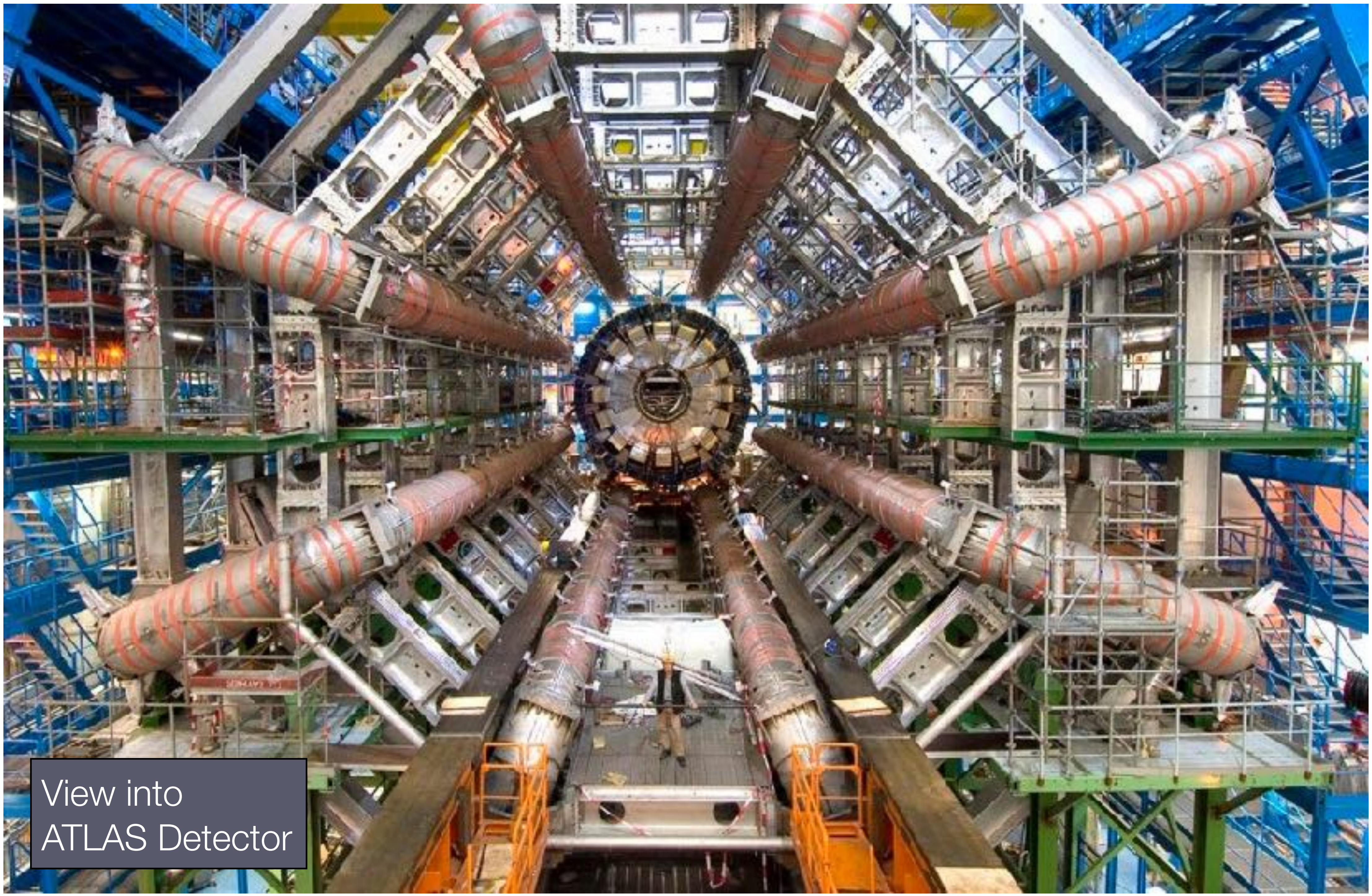


Hadron Calorimeter:
$\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$
good jet resolution
good missing E_T resolution
(e.g. $H \rightarrow \tau\tau$)

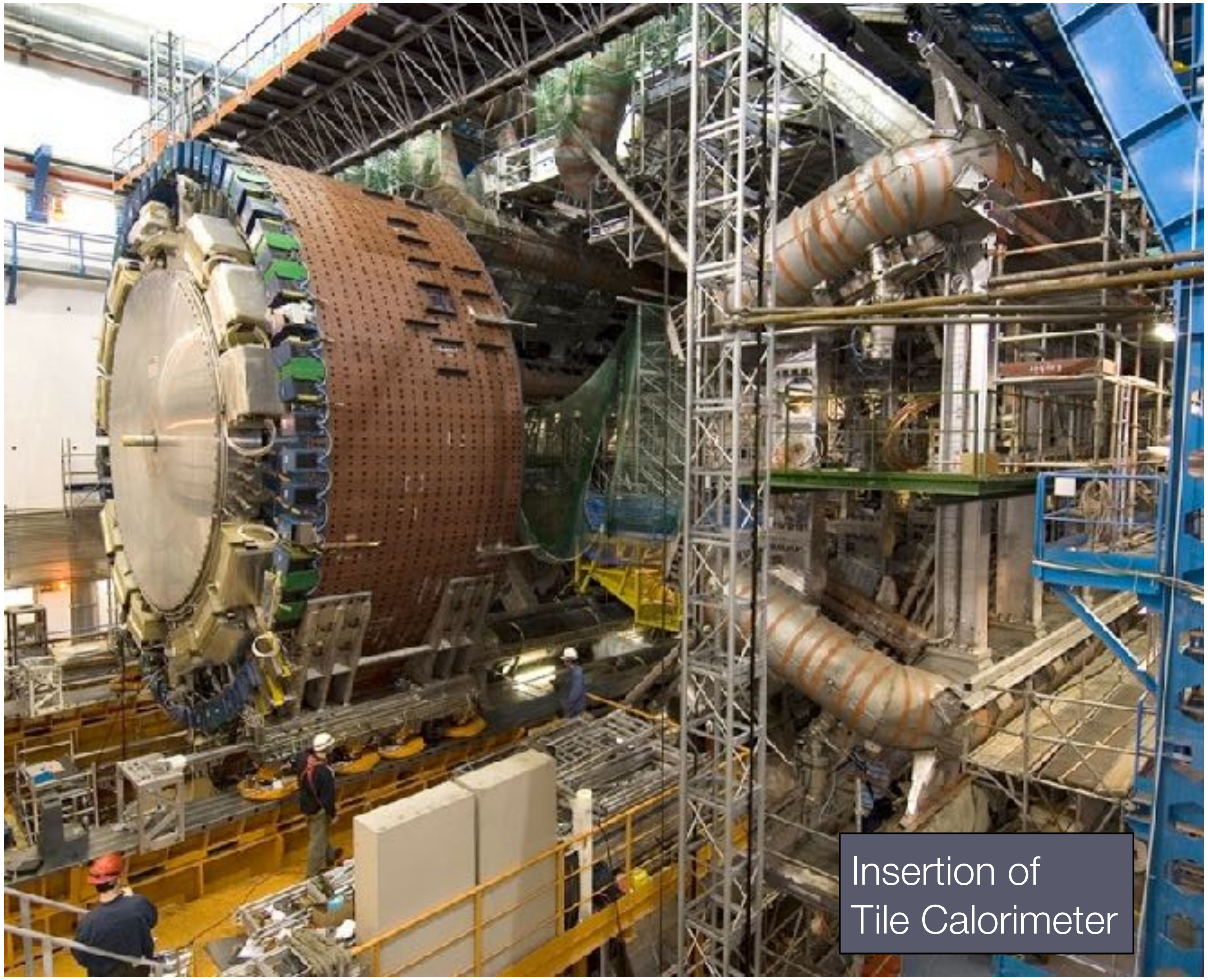
Inner Detector:
Si Pixel & strips; TRT
$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$
good impact parameter res., i.e.
$\sigma(d_0) \approx 15\ \mu m$ @ 20 GeV
(e.g. $H \rightarrow bb$)

Magnets:
Solenoid (inner detector): 2 T
Toroid (muon spectrometer): 0.5 T

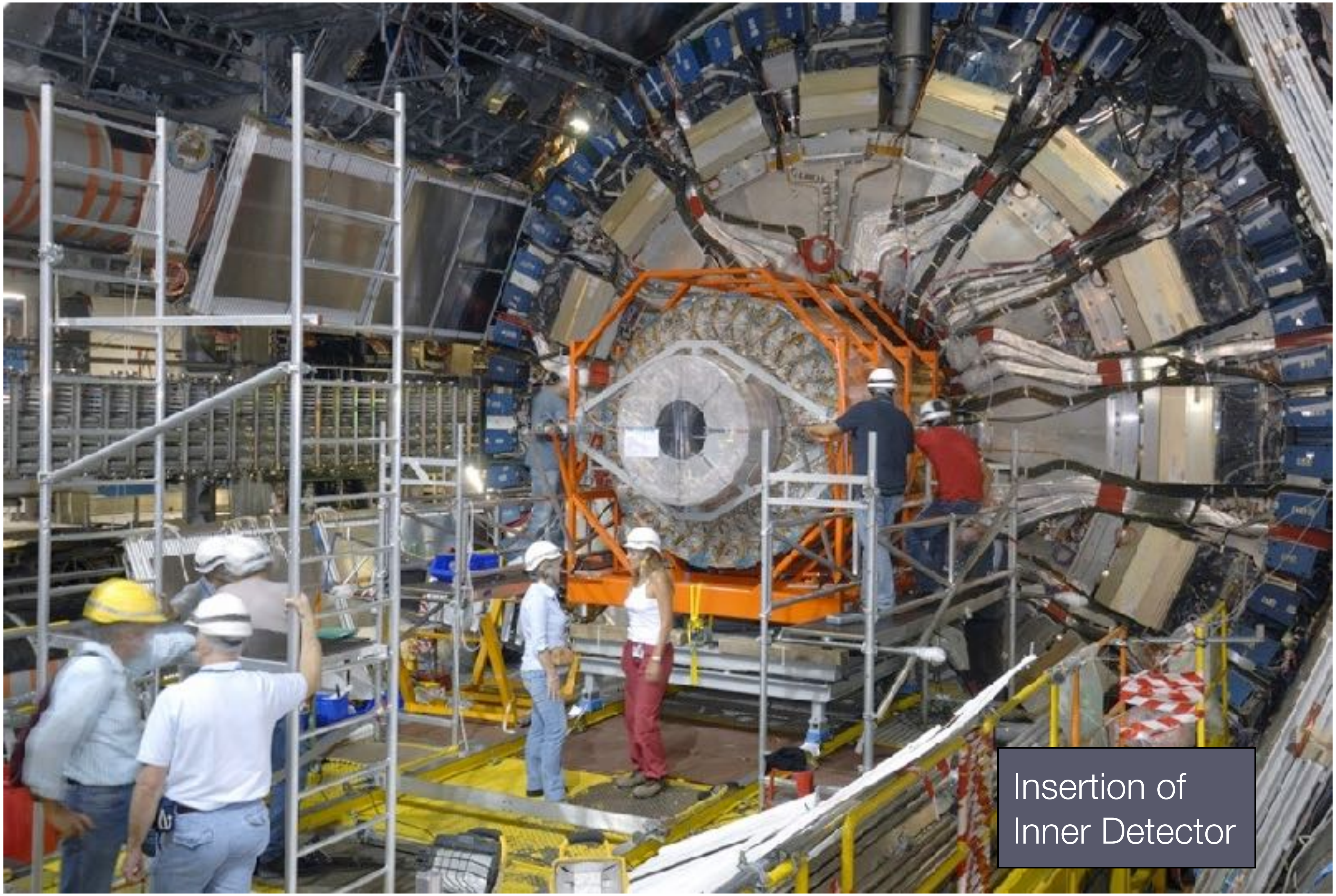
ATLAS October 2005



ATLAS July 2006



ATLAS August 2006



The CMS Detector

Inner Detector:

$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$

[vergl. ATLAS $\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$]

EM Calorimeters:

$\sigma/E \approx 3\%/\sqrt{E} \oplus 0.5\%$

[vergl. ATLAS: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$]

Hadron Calorimeter:

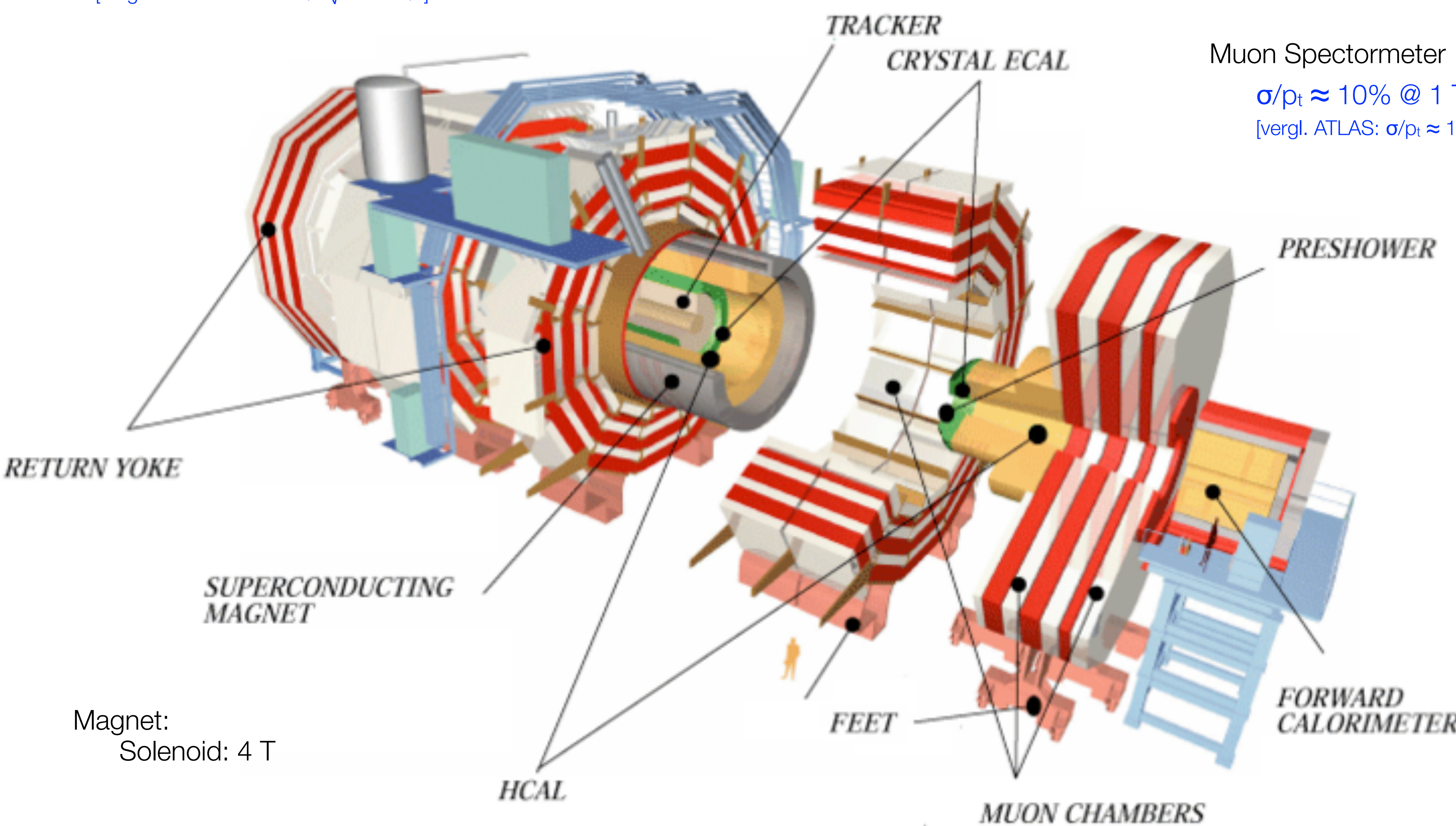
$\sigma/E \approx 100\%/\sqrt{E} \oplus 5\%$

[vergl. ATLAS: $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$]

Muon Spectormeter

$\sigma/p_t \approx 10\%$ @ 1 TeV

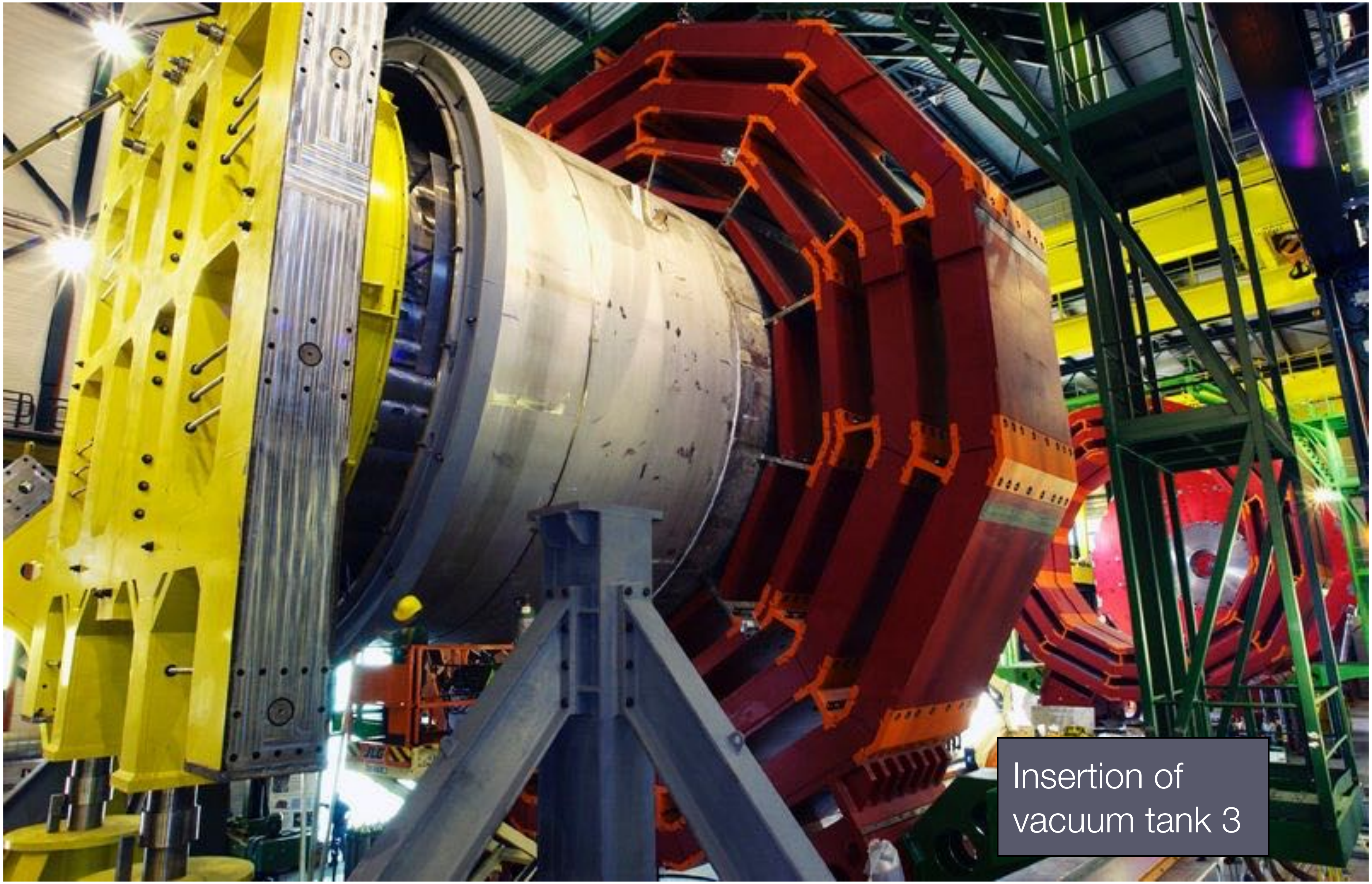
[vergl. ATLAS: $\sigma/p_t \approx 10\%$ @ 1 TeV]



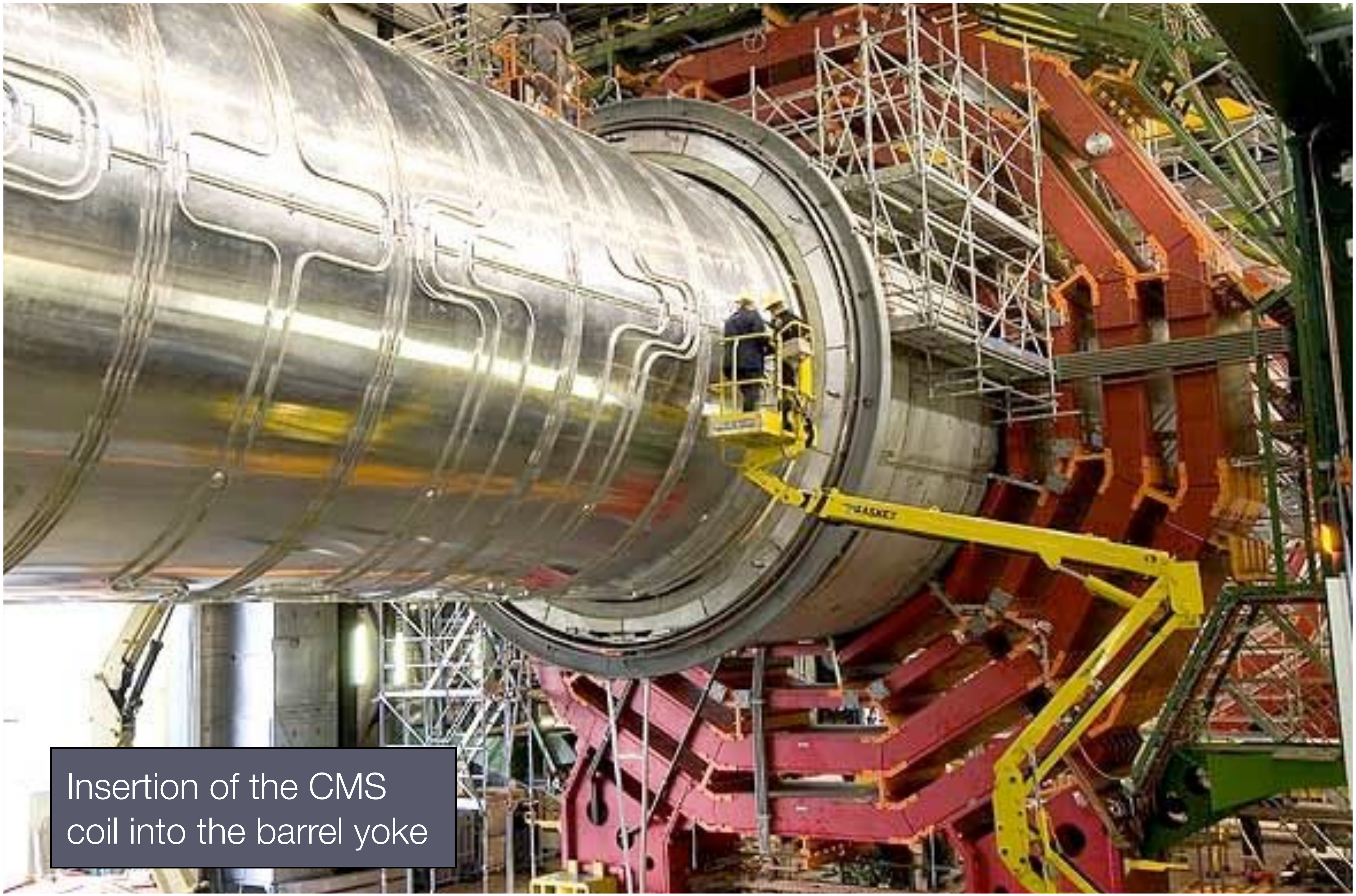
Magnet:

Solenoid: 4 T

CMS June 2002

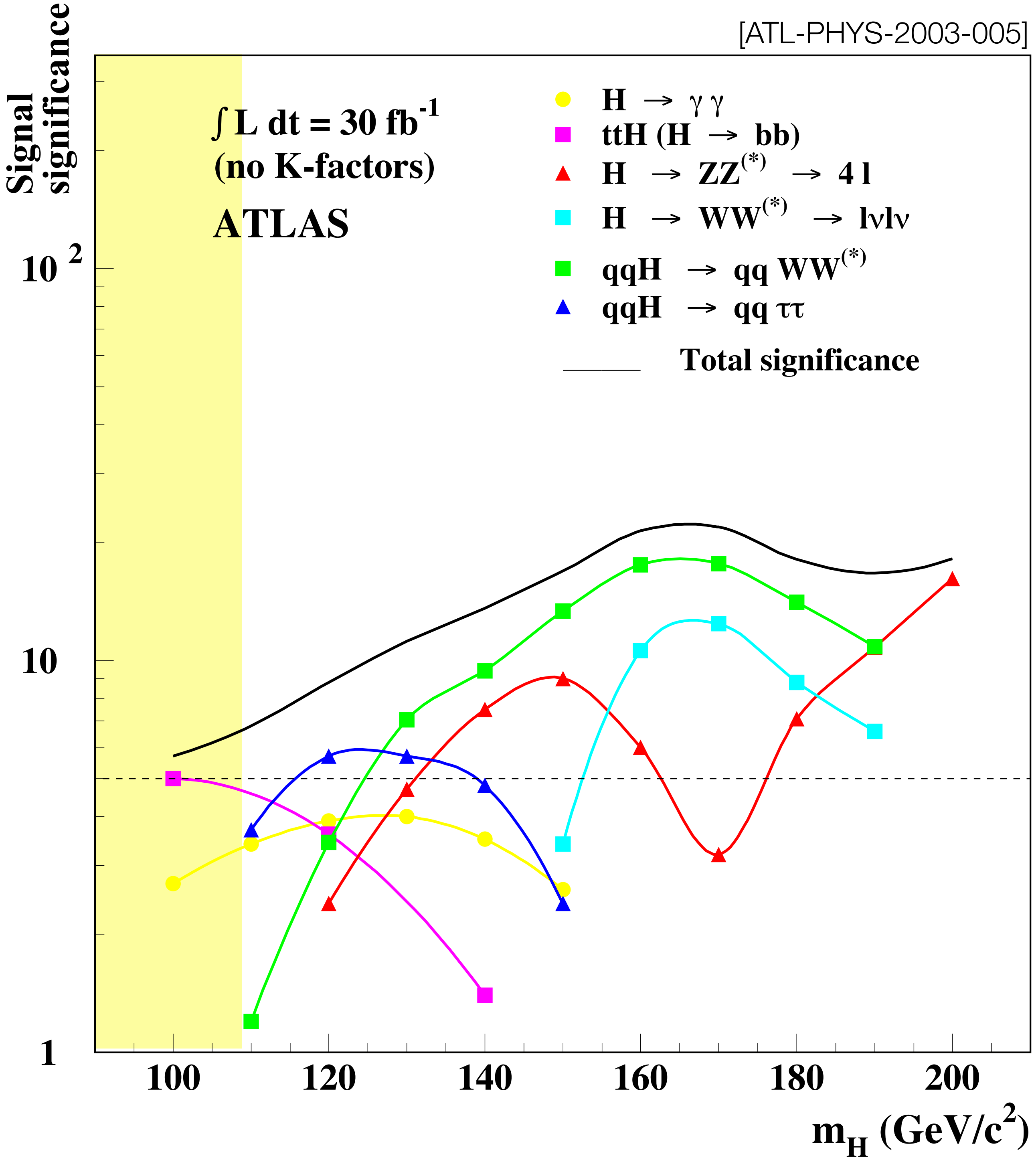


CMS September 2005



Insertion of the CMS coil into the barrel yoke

LHC: Higgs Discovery Potential



ATLAS
estimates 2005:

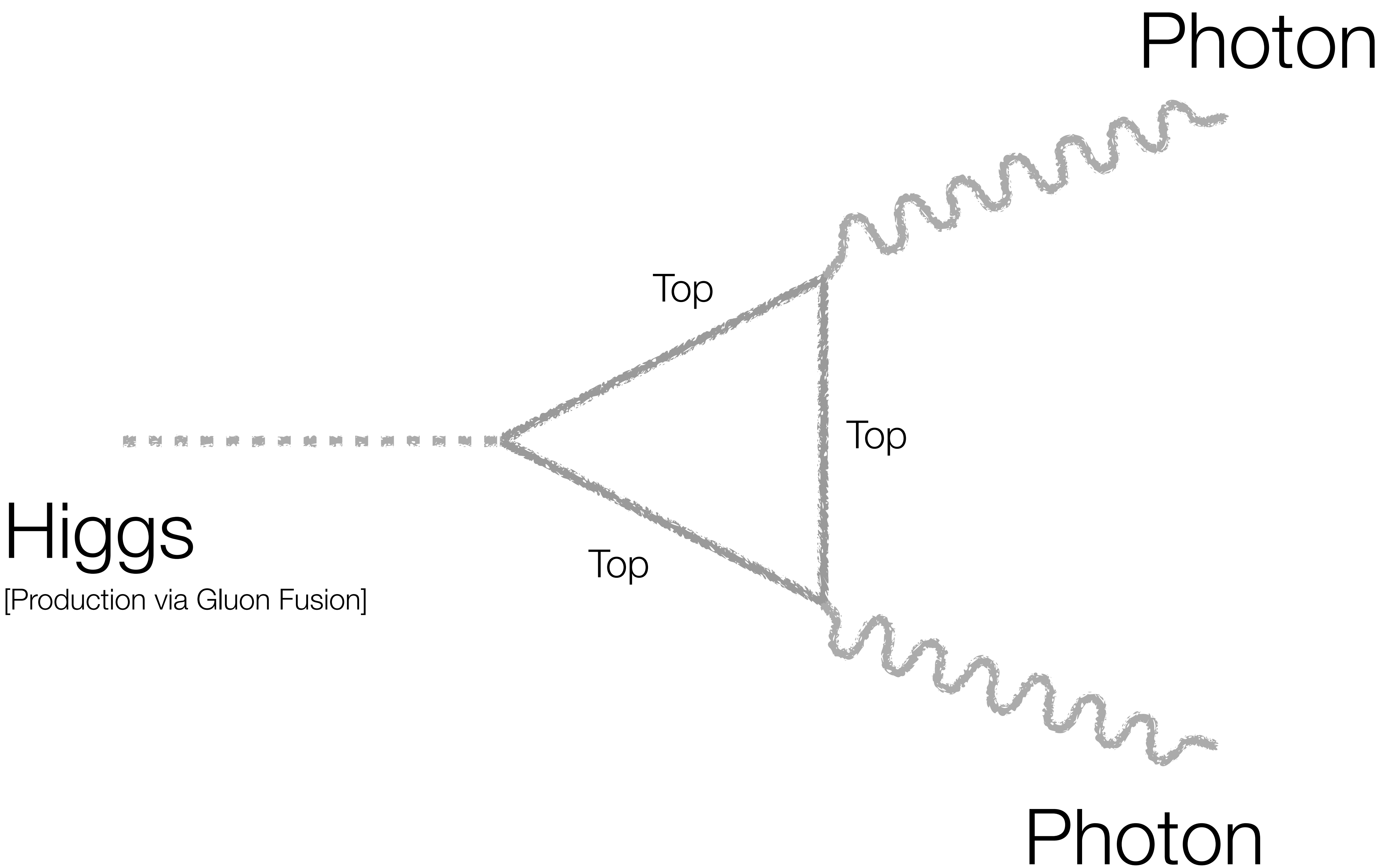
Full mass range can already be covered after a few years at low luminosity

Several channels available over a large range of masses

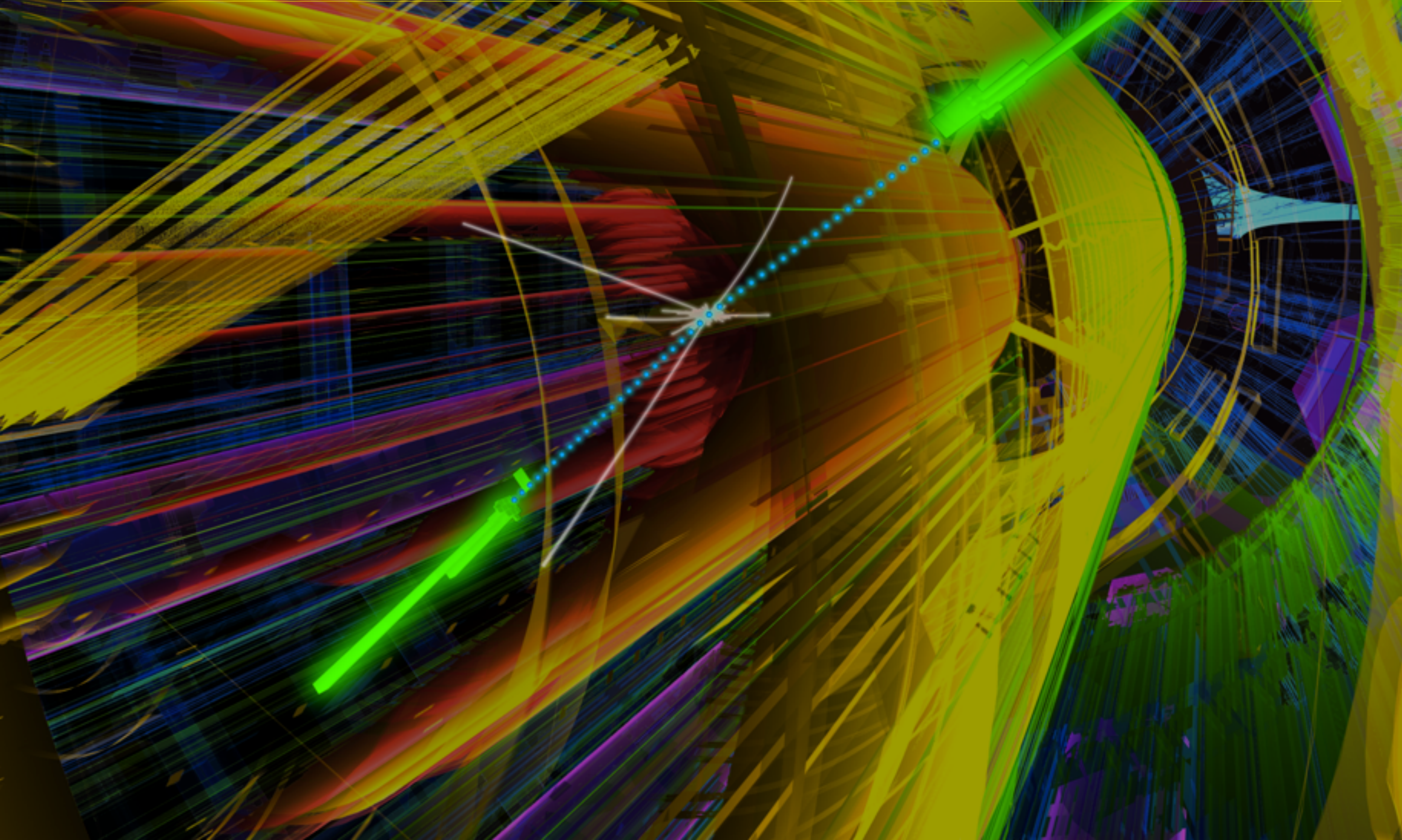
Low mass discovery requires combination of three of the most demanding channels

Comparable situation for the CMS experiment

The Discovery Channel



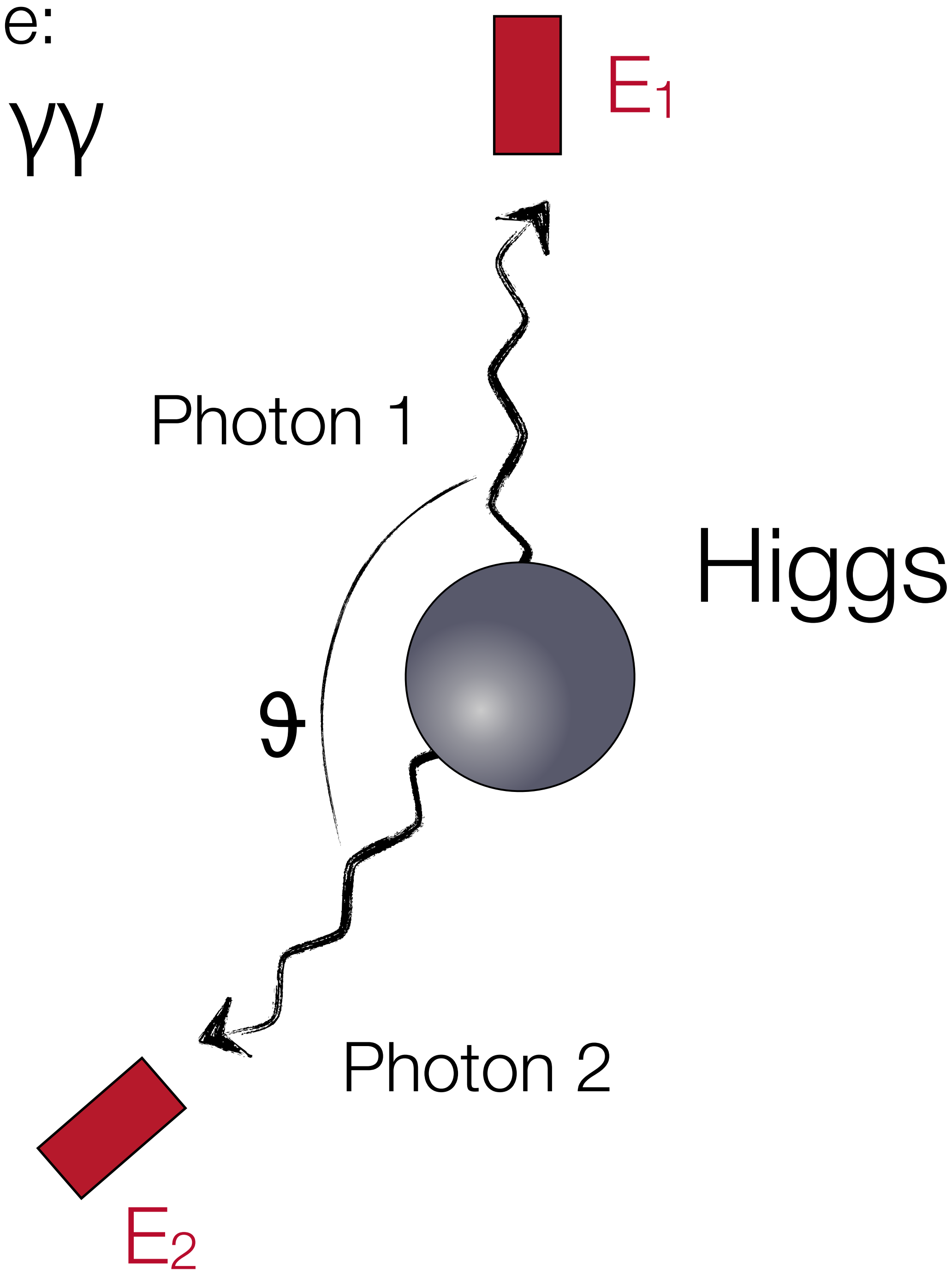
The Discovery Channel

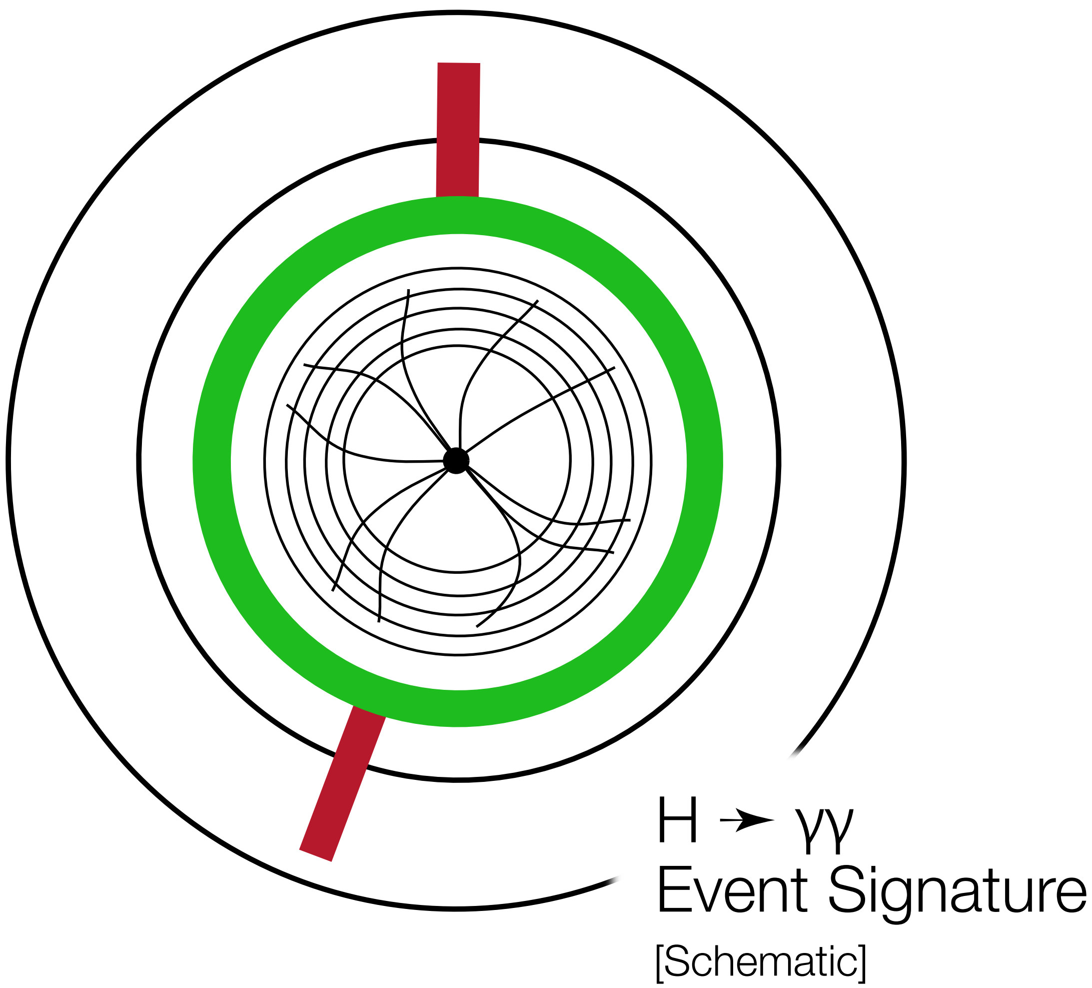


Basic Analysis Principle

Example:

$H \rightarrow \gamma\gamma$

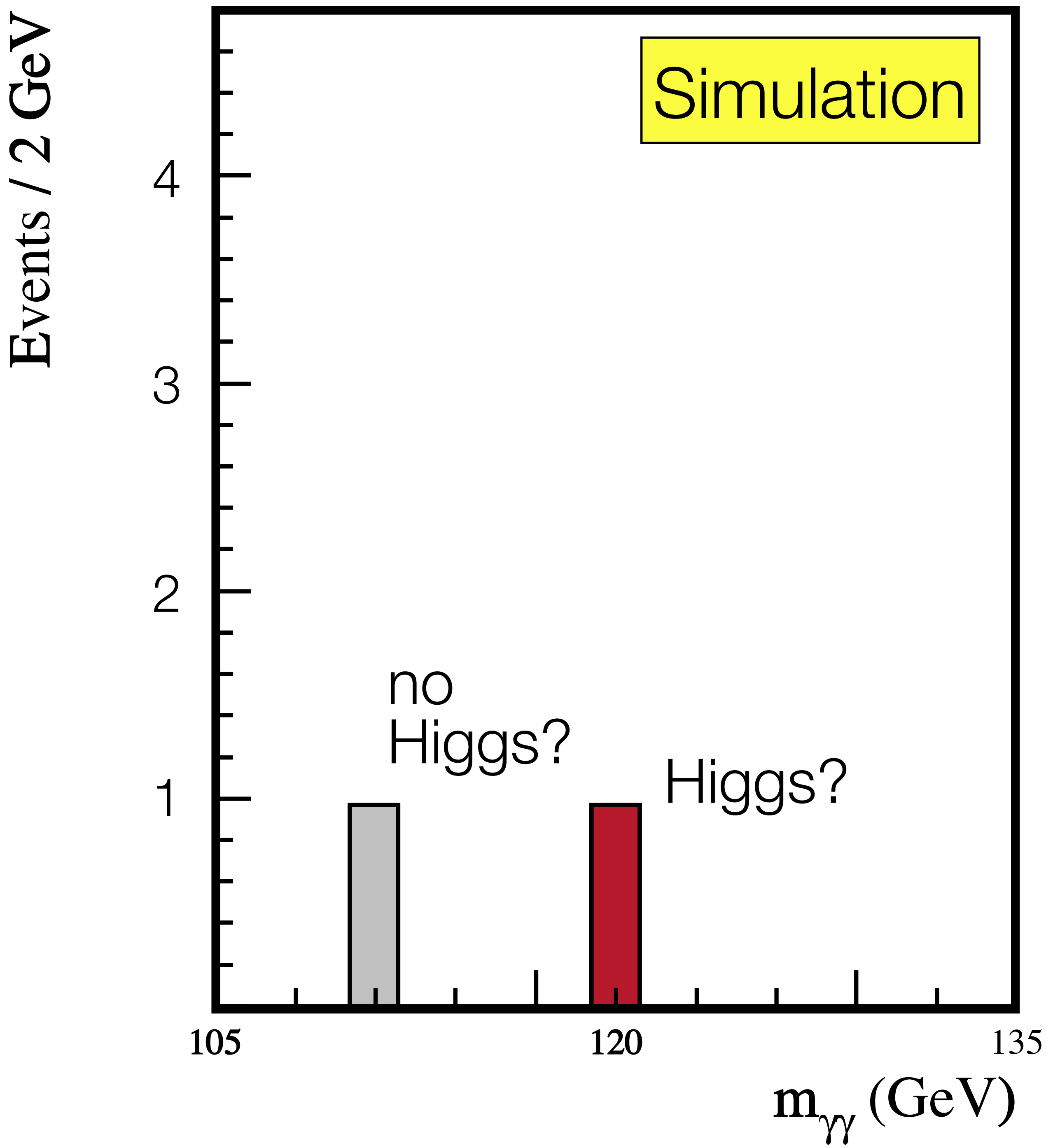


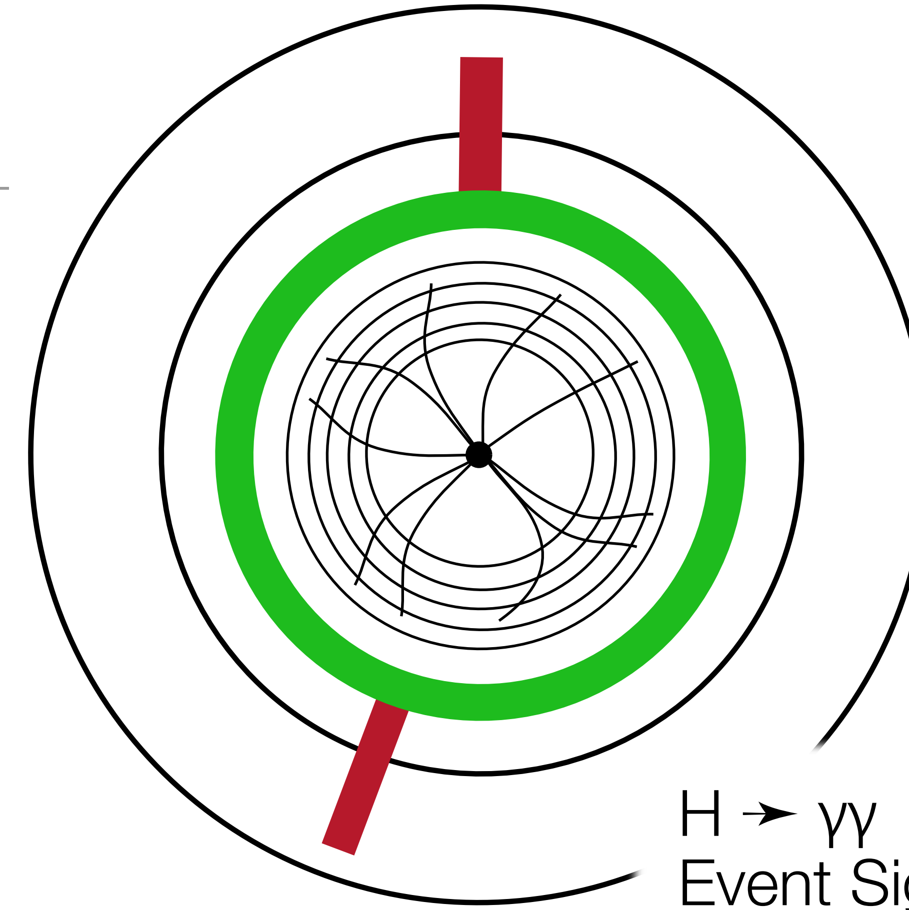


Invariant Mass:

$$m_{\gamma\gamma}^2 = 2\,E_1E_2\,(1-\cos\vartheta)$$

Basic Analysis Principle



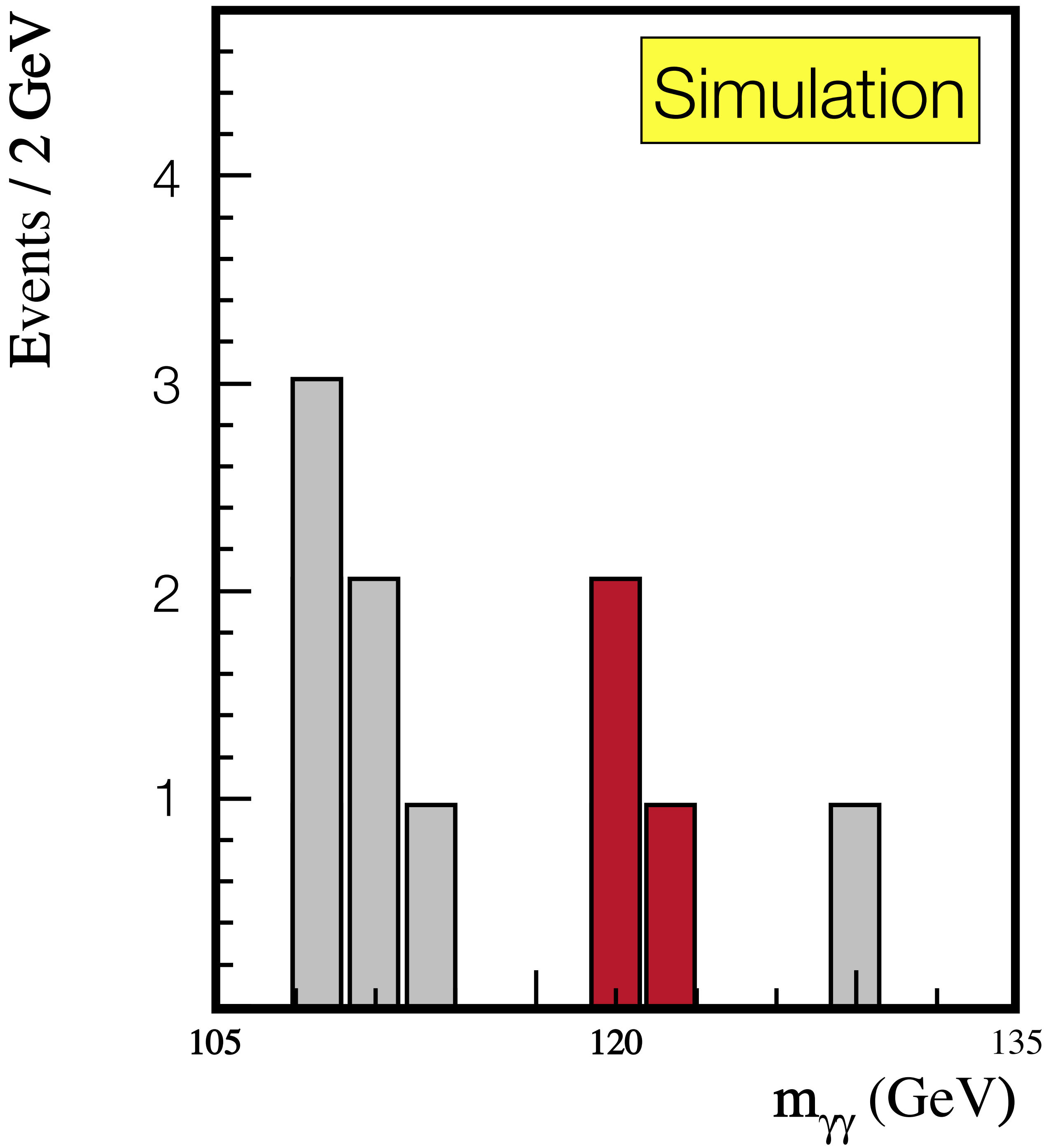


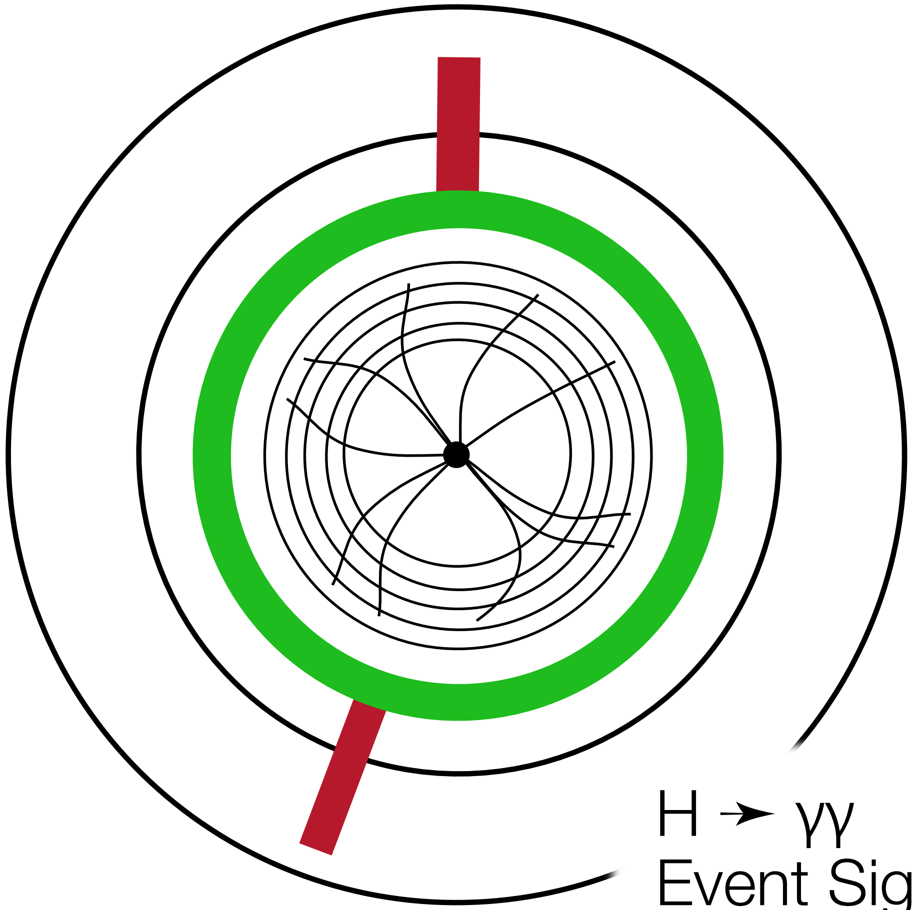
H ➔ γγ
Event Signature
[Schematic]

Invariant Mass:

$$m^2_{\gamma\gamma} = 2\,E_1E_2\,(1-\cos\vartheta)$$

Basic Analysis Principle





$H \rightarrow \gamma\gamma$

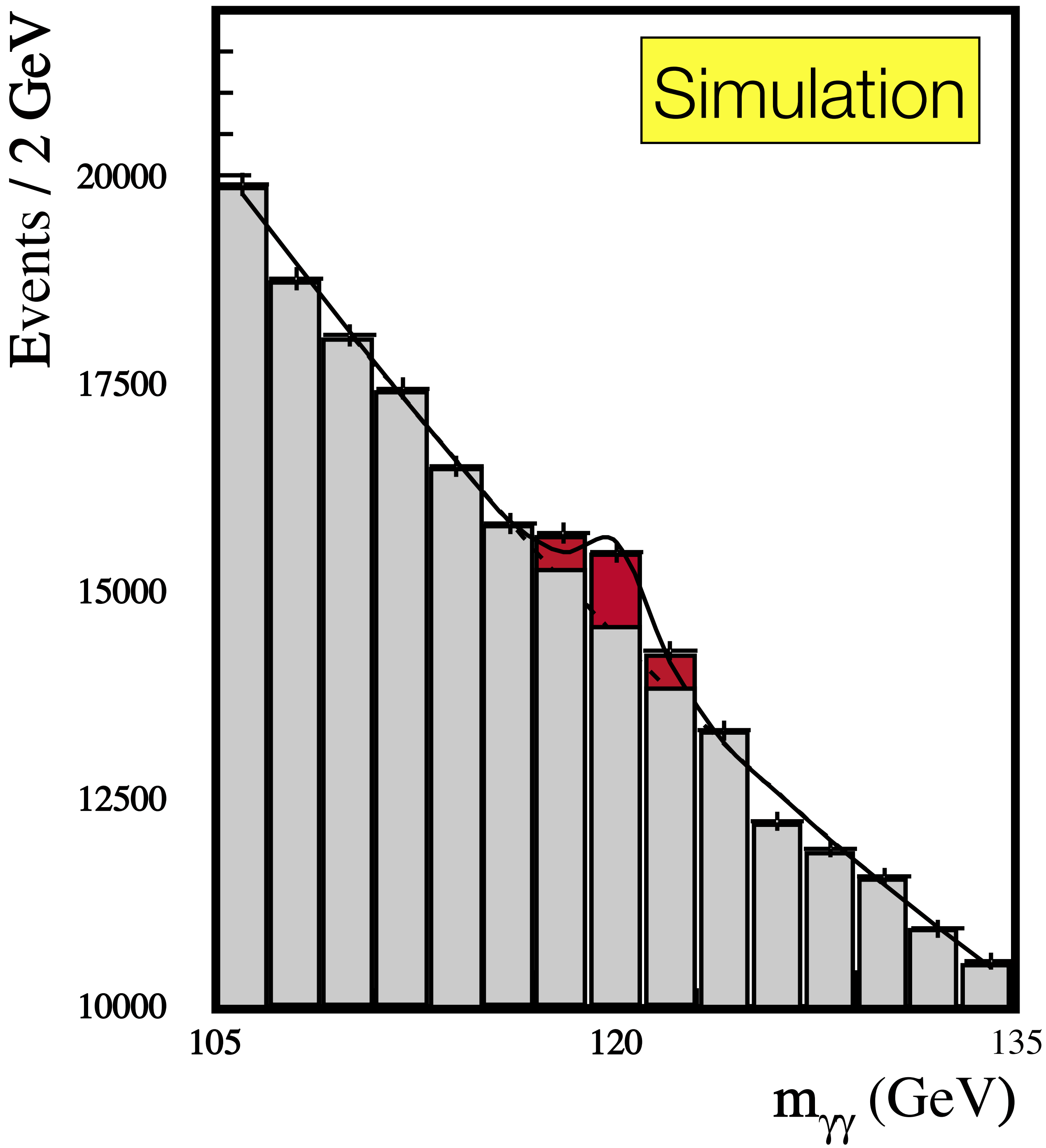
Event Signature

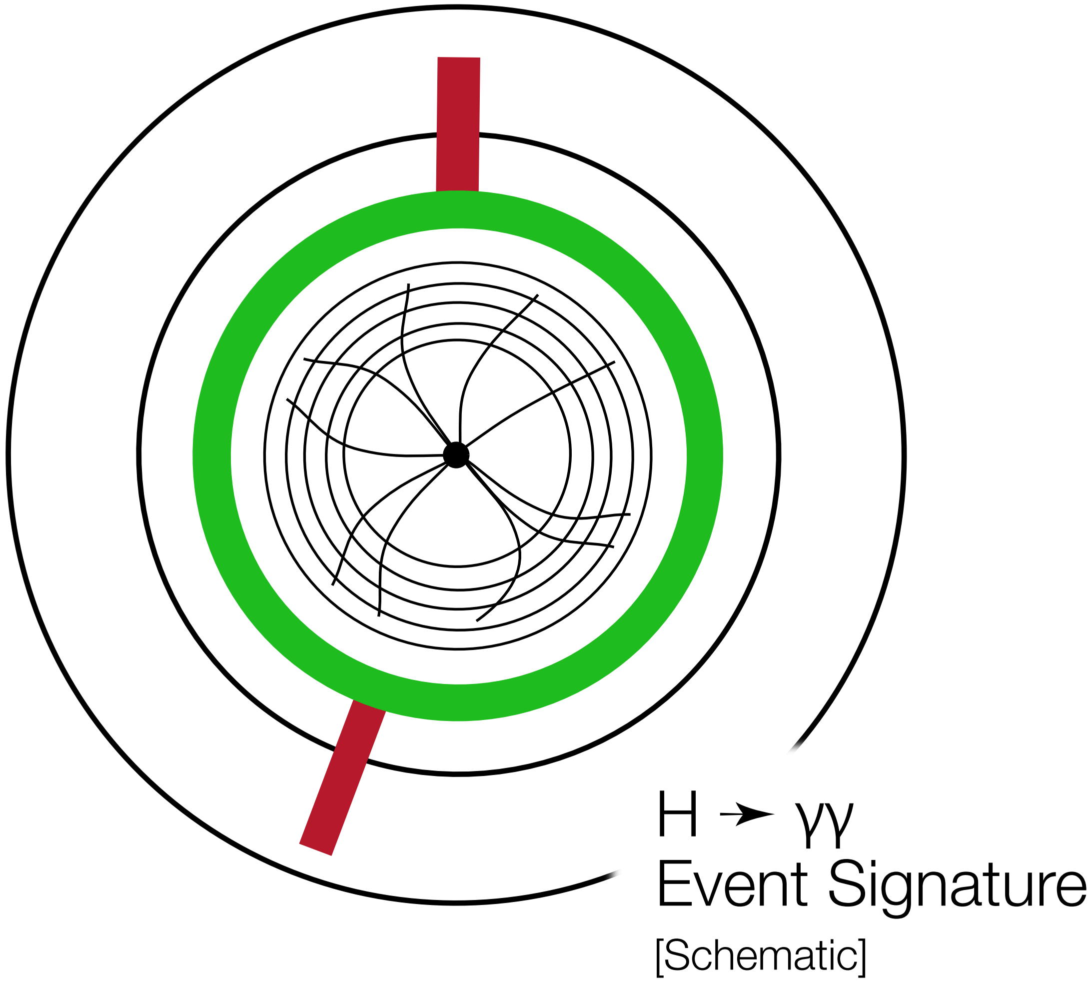
[Schematic]

Invariant Mass:

$$m^2_{\gamma\gamma} = 2 E_1 E_2 \, (1 - \cos\vartheta)$$

Basic Analysis Principle

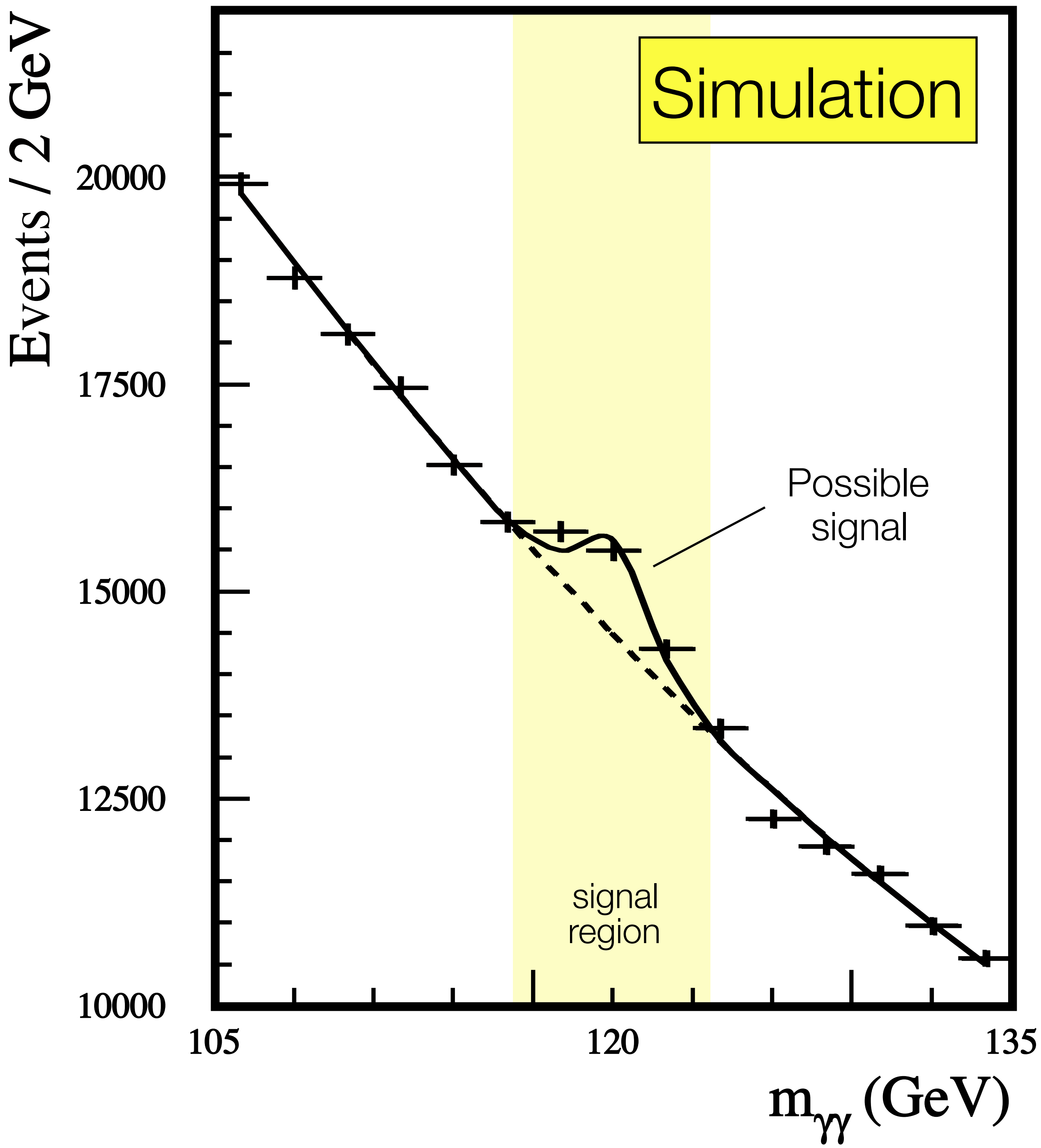


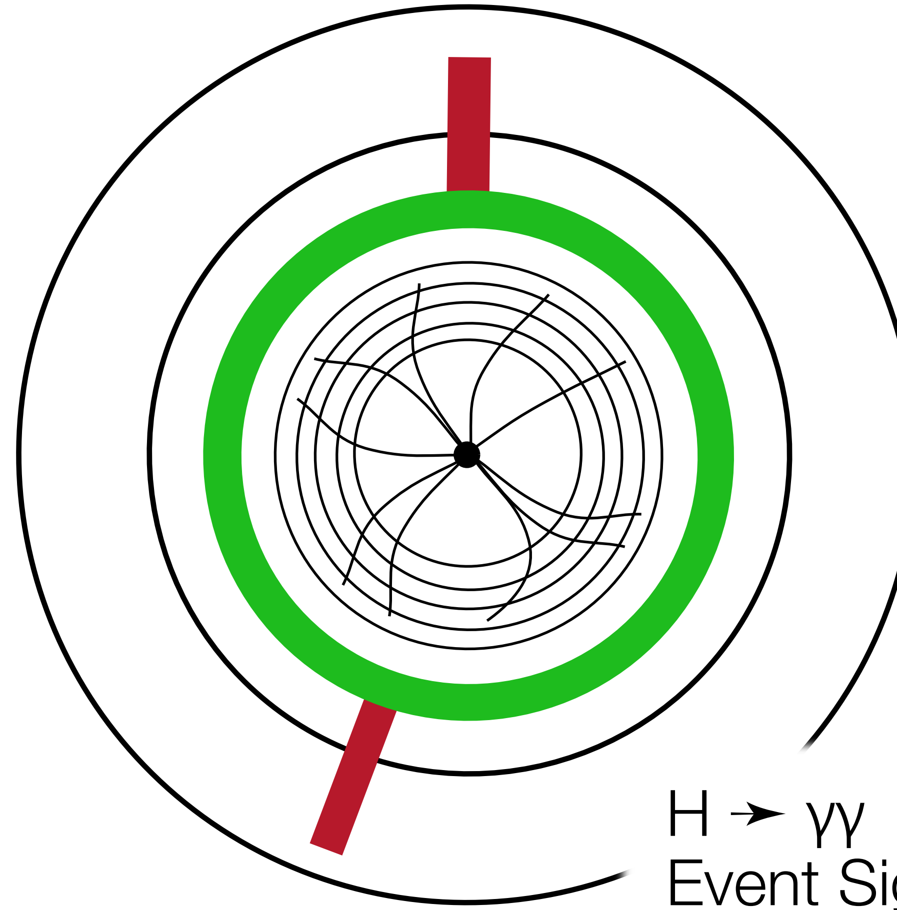


Invariant Mass:

$$m_{\gamma\gamma}^2 = 2\,E_1E_2\,(1-\cos\vartheta)$$

Basic Analysis Principle



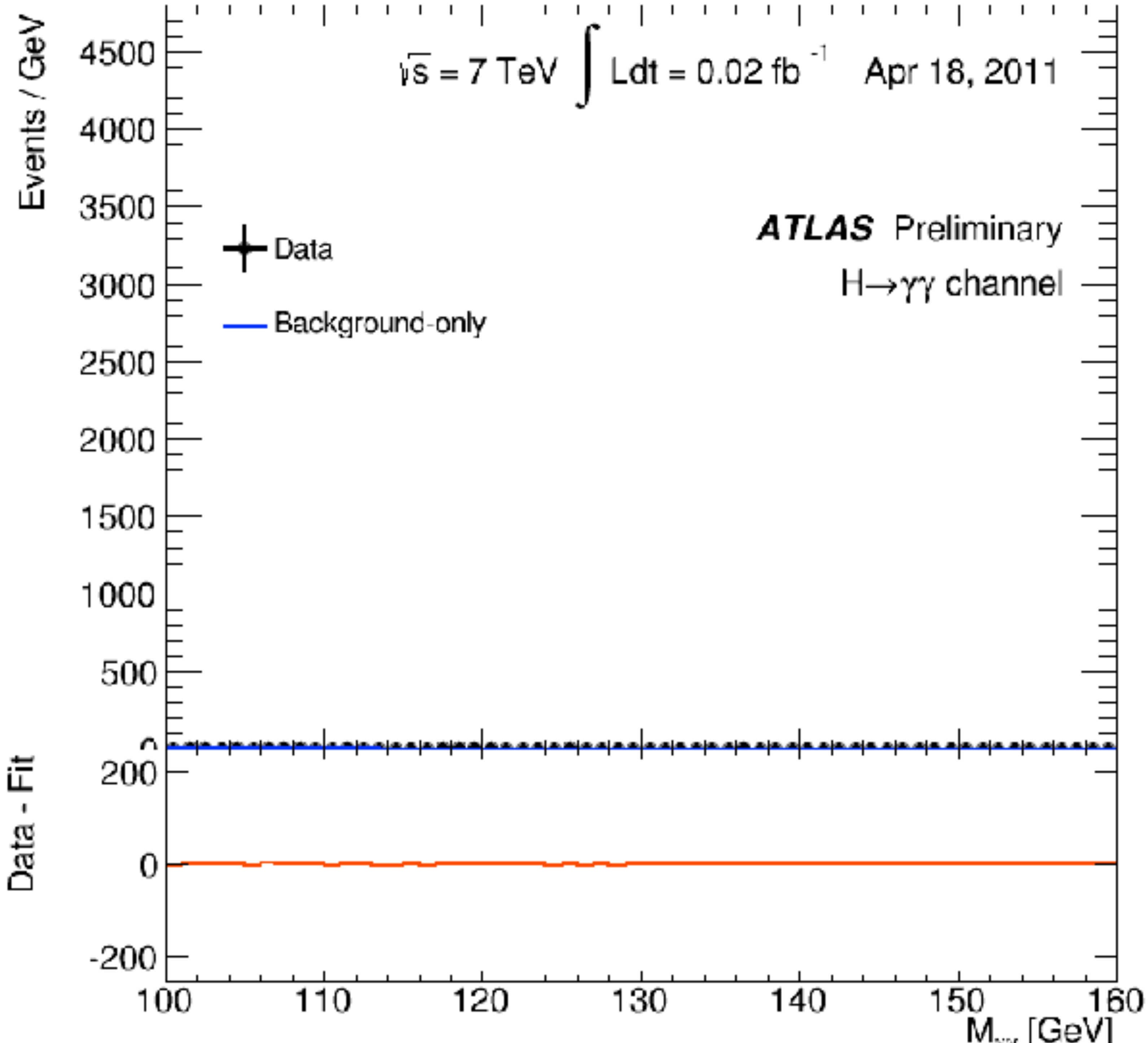


H ➛ γγ
Event Signature
[Schematic]

Invariant Mass:

$$m_{\gamma\gamma}^2 = 2\,E_1 E_2\,(1-\cos\vartheta)$$

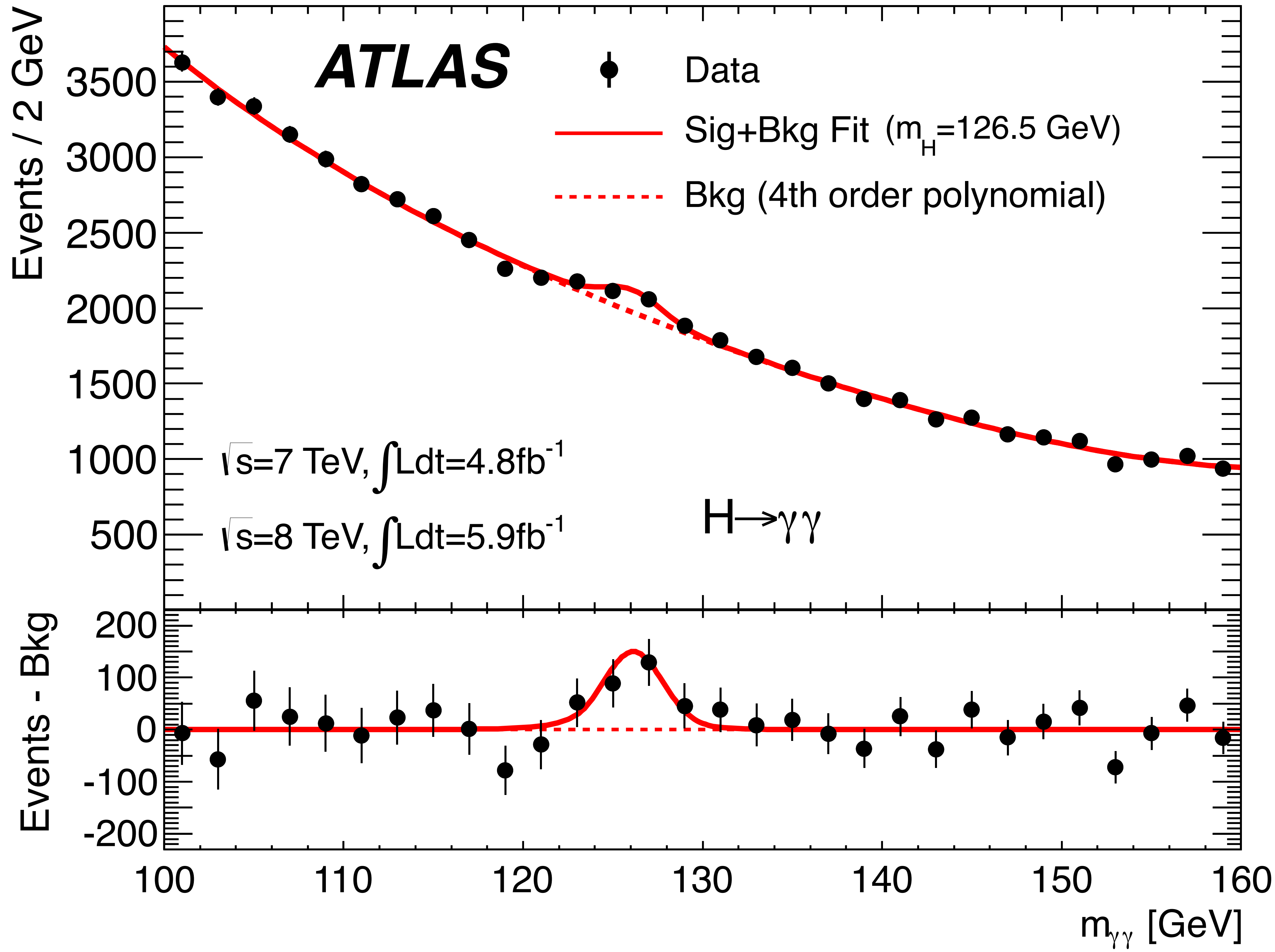
Datenanalyse
Zeitliche Entwicklung des Higgssignals



ATLAS Result

Observation of a New Particle [H ➛ γγ]

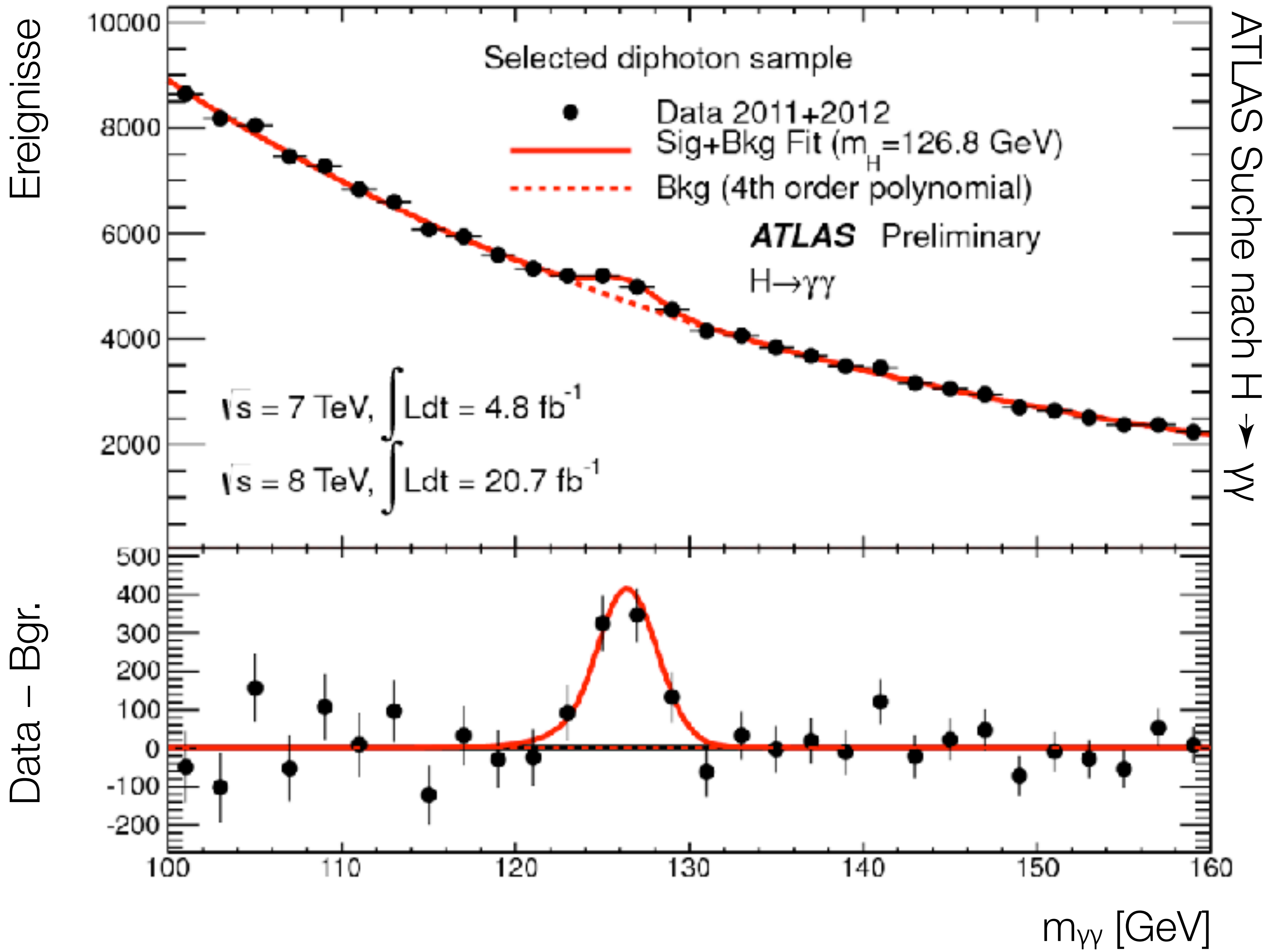
[Summer 2012]



ATLAS Result

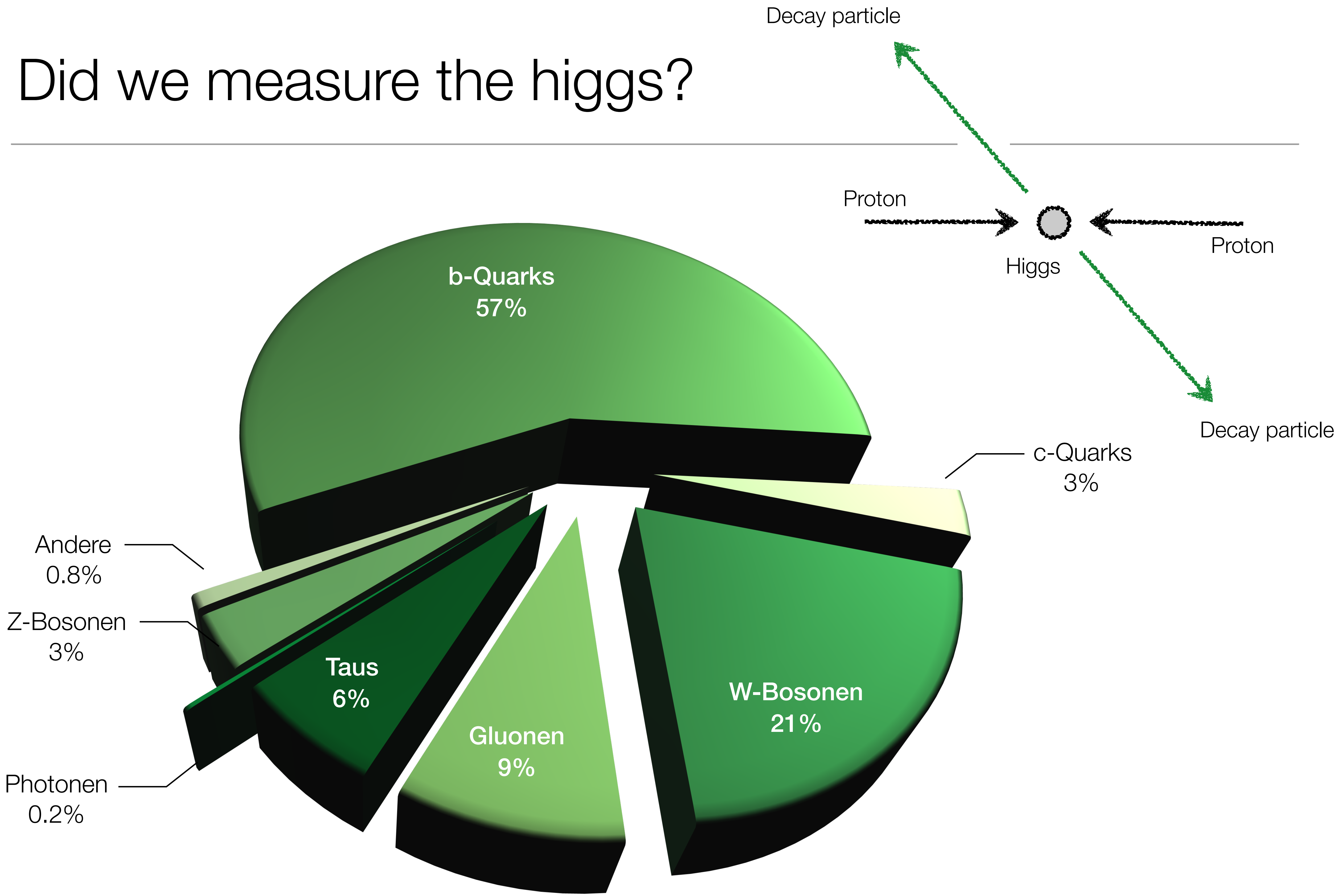
Observation of a New Particle [H ➛ γγ]

[Spring 2013]

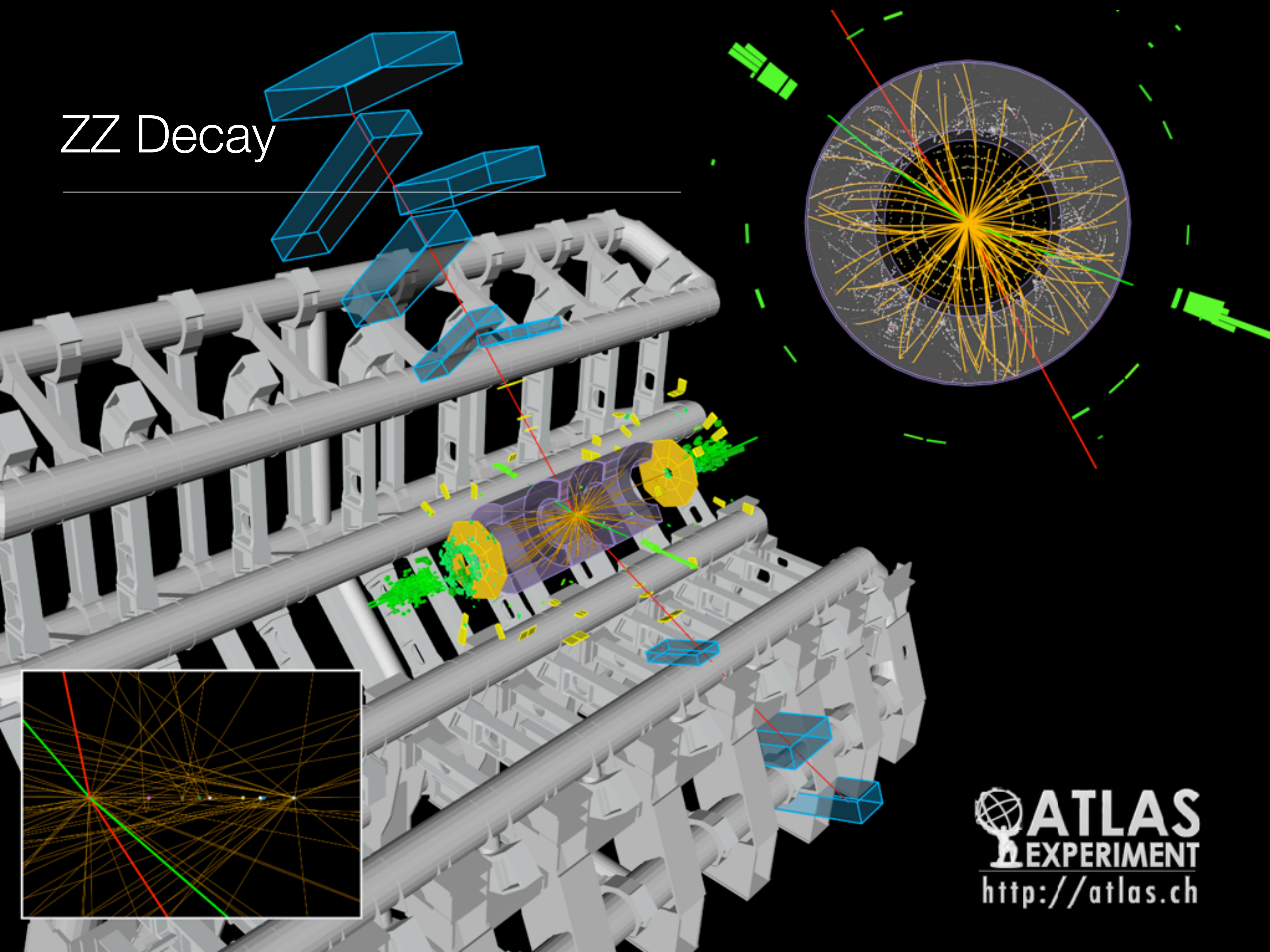


ATLAS-CONF-2013-012

Did we measure the higgs?

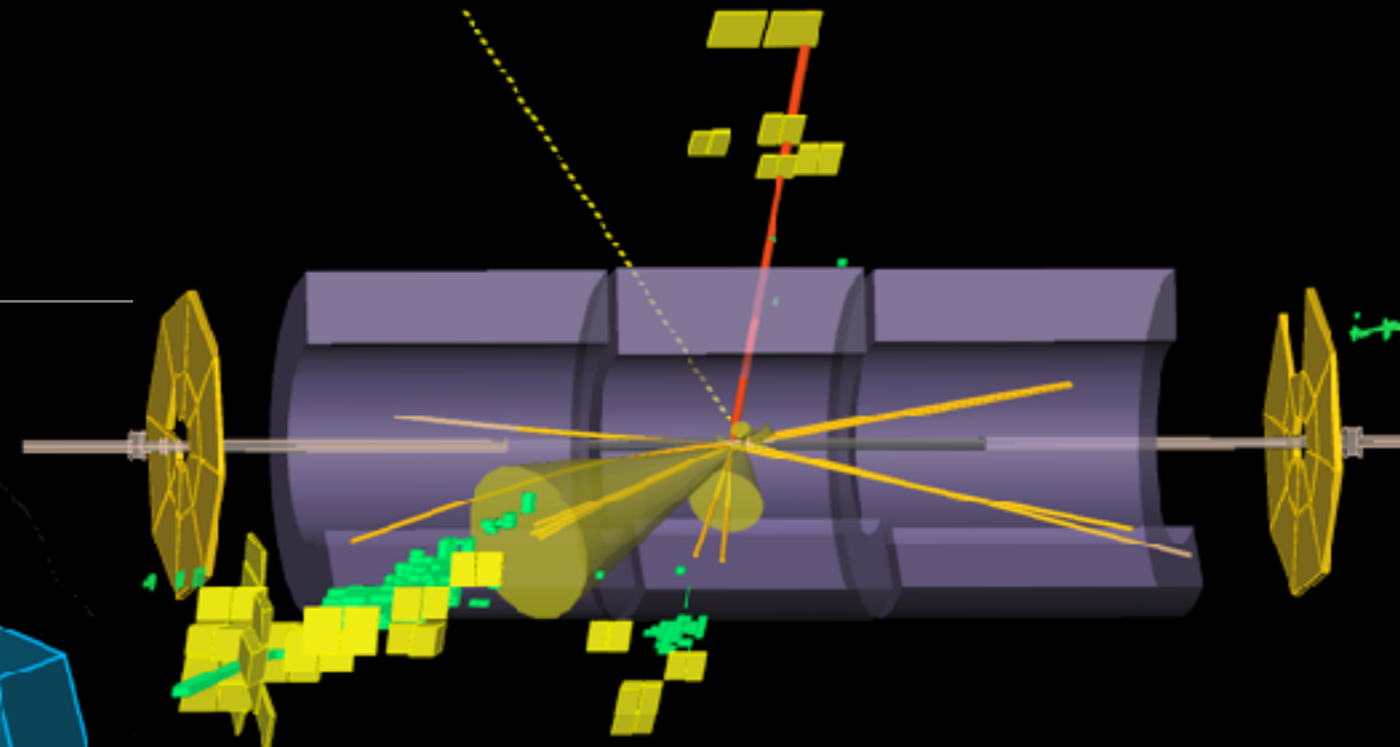


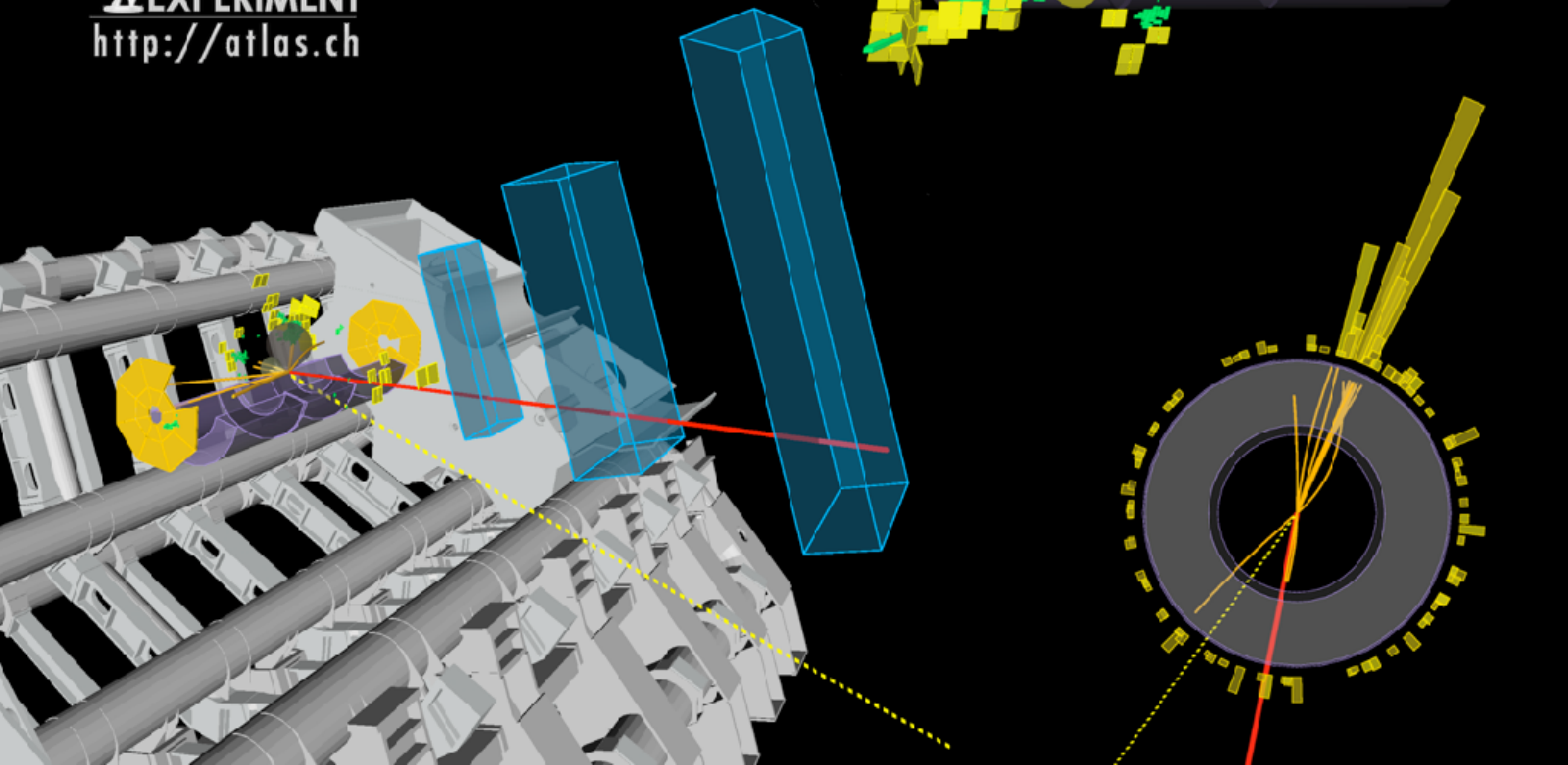
ZZ Decay



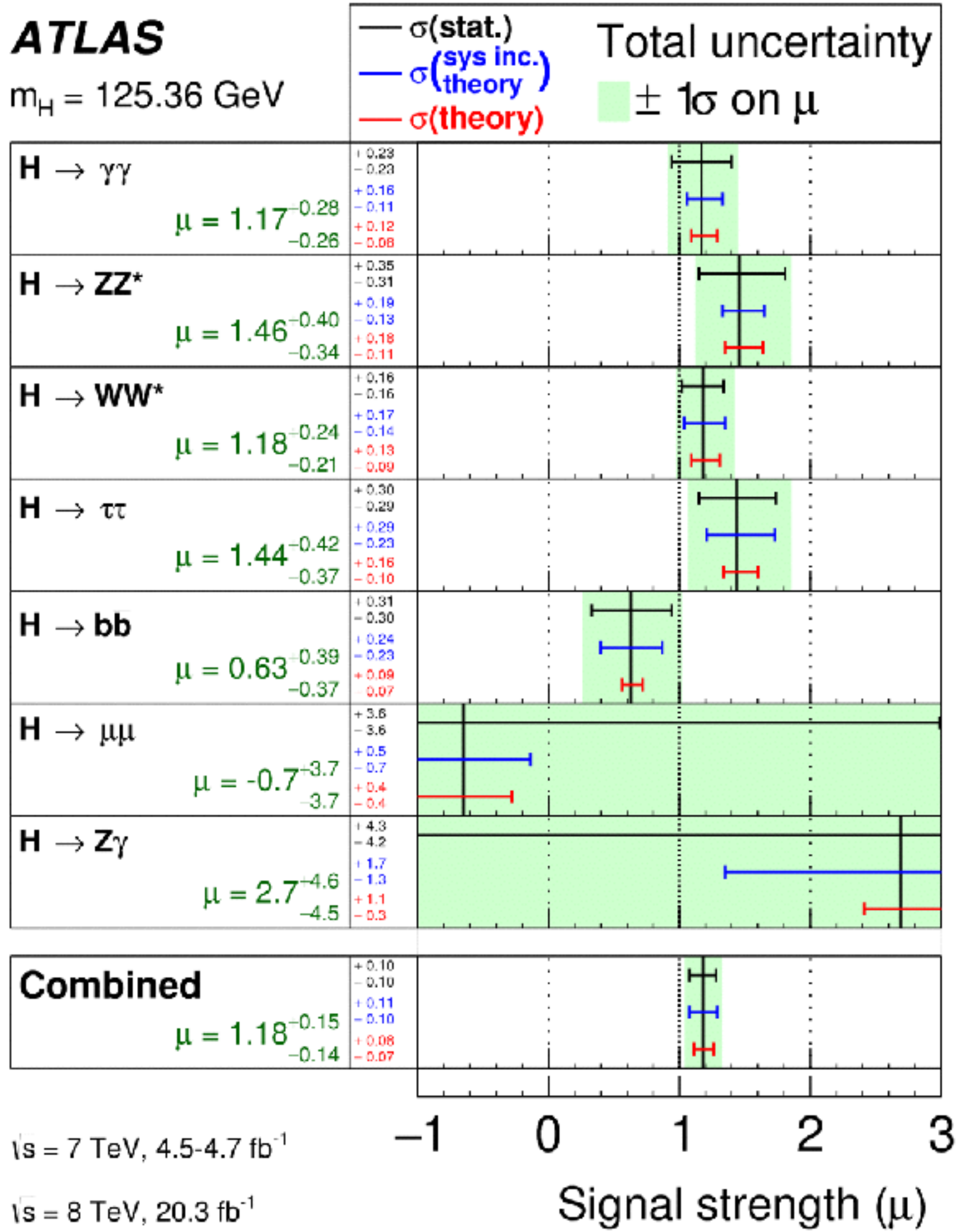
WW decay

ATLAS EXPERIMENT
http://atlas.ch





Measuring the Higgs couplings




Science
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BREAKTHROUGH
of the YEAR
The HIGGS
BOSON