# Particle Physics: (More) Fact and Fantasy

**Saturday June 15th 2013**

**APPEAL, Oxford**

**Prof. Ken Peach**

http://www.adams-institute.ac.uk

Ken.Peach@adams-institute.ac.uk

# Outline – Last year

- Introduction
- The Leptons
  - electron, muon, tau & their neutrinos [& photon]
    - digression – point-like particles
- The Quarks – 1
  - up & down
    - digression – magnetic moments
- The Quarks – 2
  - strange, charm & bottom [& Z]
- The Quarks – 3
  - top
- The last force carriers
  - $W^{\pm}$ & gluon
- And finally (?)
  - the Higgs
- Conclusion

# Outline – This year

- Introduction
- Summary of what we know from last year
- Update on the Higgs
- What is Real an what is Imagined
- Conclusion

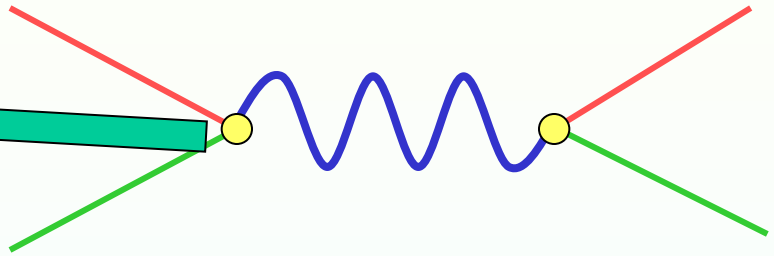
# (From Last Year) The Standard Model

**The Standard Model Effective Lagrangean**

$$
\begin{aligned}
\mathcal{L}_{\text{(Standard Model)}} = \\
[W^{\pm}] \quad & - \frac{1}{2}(\partial_\mu W_\nu - \partial_\nu W_\mu)(\partial^\mu W^{\dagger\nu} - \partial^\nu W^{\dagger\mu}) + M_{\text{W}}^2 W_\mu W^{\dagger\mu} \\
[\text{Photon}] \quad & - \frac{1}{4} F^{\text{A}}_{\mu\nu} F^{\text{A}\mu\nu} \\
[Z^o] \quad & - F^{\text{Z}}_{\mu\nu} F^{\text{Z}\mu\nu} + \frac{1}{2} M_{\text{Z}}^2 Z_\mu Z^\mu \\
[\ell, \nu_\ell] \quad & + \imath \overline{L_\ell} \not{\partial} L_\ell + \imath \overline{R_\ell} \not{\partial} R_\ell - m_\ell \bar{\ell}\ell \\
[W\ell\nu] \quad & - \frac{g}{\sqrt{2}} \overline{L_\ell} (\tau_+ \not{W} + \tau_- \not{W}) L_\ell \\
[\gamma \ell^+ \ell^-] \quad & + e_{e/m} \bar{\ell} \not{A} \ell \\
[Z\ell^+\ell^-, Z\nu\bar{\nu}] \quad & - \frac{g}{\cos\theta_{\text{W}}} \overline{L_\ell} \left( \frac{\tau_3}{2} \cos^2\theta_{\text{W}} - \frac{1}{2}\sin^2\theta_{\text{W}} \right) \not{Z} L_\ell - \frac{g \sin^2\theta_{\text{W}}}{\cos\theta_{\text{W}}} \overline{R_\ell} \not{Z} R_\ell \\
[\text{H}] \quad & + \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\mu^2 H^2 - \frac{1}{2}\lambda^2 H^4 \\
[\text{HH\&H } W^+W^-] \quad & + \frac{g^2}{8}\left( H^2 + \frac{2\mu}{\lambda} H \right) \left( 2 W_\mu W^{\dagger\mu} \right) \\
[\text{HH\&H } ZZ] \quad & + \frac{g^2}{8}\left( H^2 + \frac{2\mu}{\lambda} H \right) \left( \frac{1}{\cos^2\theta_{\text{W}}} Z_\mu Z^\mu \right) \\
[\text{H } \ell^+\ell^-] \quad & - m_\ell \sqrt{\sqrt{2} G_{\text{F}}} \bar{\ell}\ell H \\
[\text{quark } \gamma] \quad & + Q \bar{q} \not{A} q \\
[\text{quark Z}] \quad & - \frac{g}{\cos\theta_{\text{W}}} \overline{L_q} \left( \frac{\tau_3}{2}\cos^2\theta_{\text{W}} + \frac{\sin^2\theta_{\text{W}}}{2} \right) \not{Z} L_q \\
[\text{quark W}] \quad & - \frac{g}{\sqrt{2}} \overline{\mathcal{U}} V_{\text{CKM}} (\tau_+ \not{W} + \tau_- \not{W}) \mathcal{D} \\
[\text{quark H}] \quad & - m_q \sqrt{\sqrt{2} G_{\text{F}}} \bar{q} q H \\
[\text{gluons}] \quad & - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \\
[\text{quarks}] \quad & + \overline{\mathcal{U}}(\imath \not{\partial} - m_{\mathcal{U}})\mathcal{U} + \overline{\mathcal{D}}(\imath \not{\partial} - m_{\mathcal{D}})\mathcal{D} \\
[\text{quark gluon}] \quad & + \imath g T^a \left( \overline{\mathcal{U}} \not{A}^a \mathcal{U} + \overline{\mathcal{D}} \not{A}^a \mathcal{D} \right) \\
[\text{ 3 gluons}] \quad & + \frac{g}{2}\left( \partial_\mu A^a_\nu - \partial_\nu A^a_\mu \right) f^{abc} A^{b\mu} A^{c\nu} \\
[\text{4 gluons}] \quad & - \frac{g^2}{4} f^{abc} f^{axy} A^b_\mu A^c_\nu A^{x\mu} A^{y\nu} \\
\textit{excluding } & \textbf{GRAVITY}
\end{aligned}
$$

- **Take a process**

$e^+e^- \rightarrow \mu^+\mu^-$



$4\pi\alpha^2/3s$

a is the fine structure constant

s is the (C.of.M Energy)$^2$

(neglecting masses and $\sqrt{s} << M_Z$)

(From Last Year) $R = \dfrac{\sum \sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$

- We "derived"

$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{4\pi\alpha^2}{3s}$$

- We can generalize this to

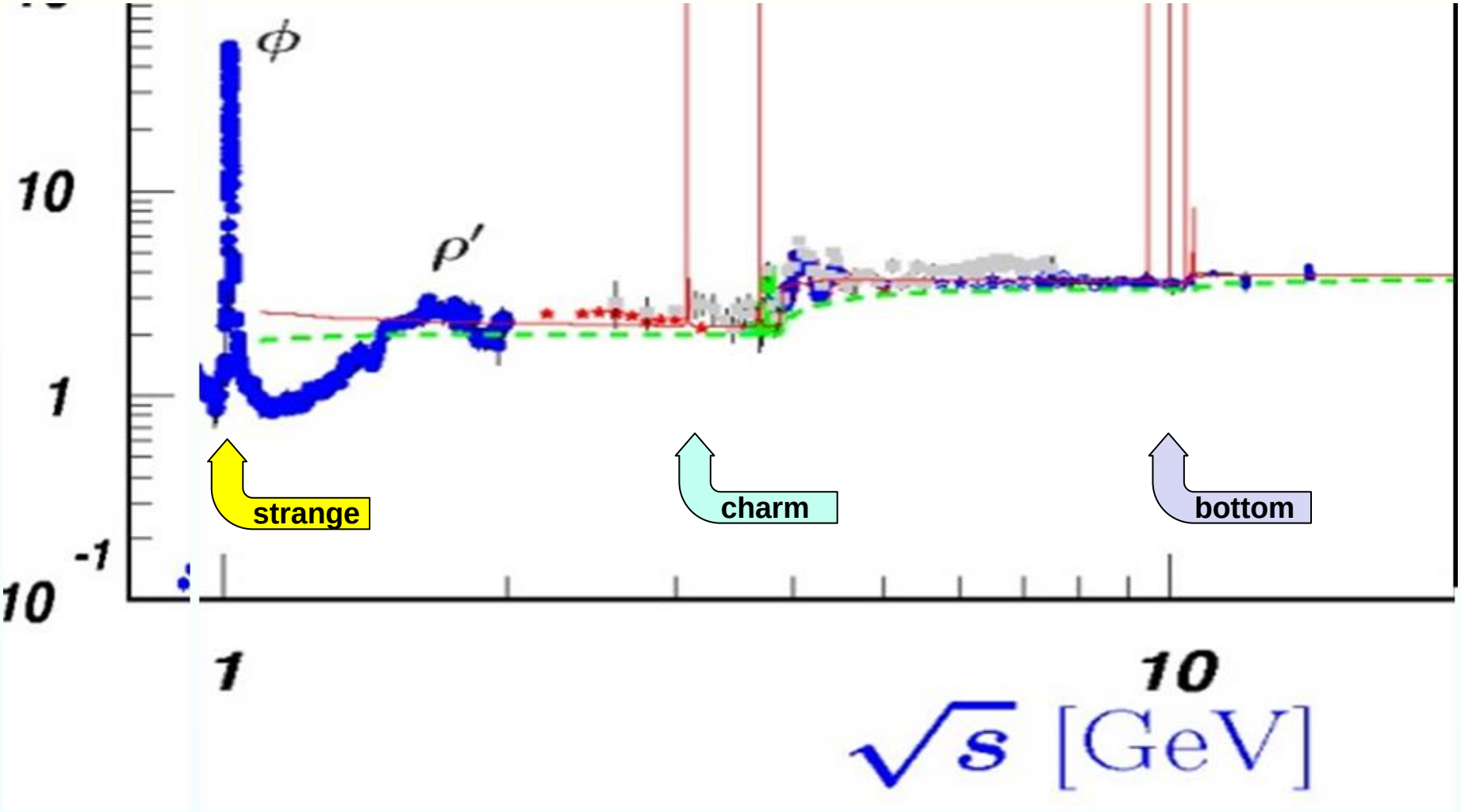
$$\sigma(e^+e^- \to f^+f^-) = Cq_f^2 \frac{4\pi\alpha^2}{3s}$$

(always for $s \gg 4m_f^2$ and $\ll m_Z^2$)

- $C$ is a "colour factor" *(=1 for $\mu, \tau$, 3 for quarks)*
- $q_f$ is the charge of the fermion $f$; $= 1\ (\mu, \tau), \frac{2}{3}$ or $-\frac{1}{3}$ (quarks)

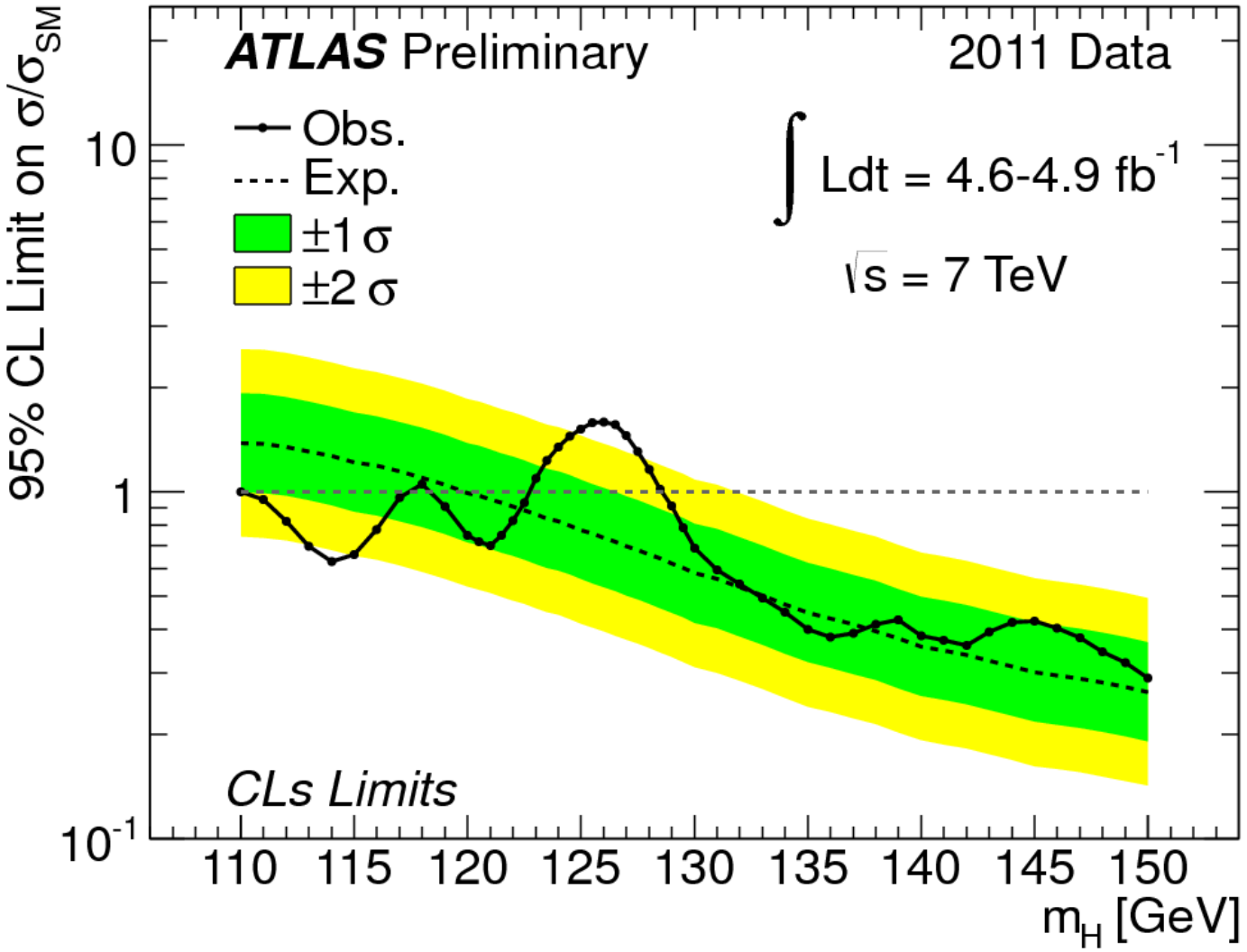
$$R = 3 \sum_{i, m_i \ll \sqrt{s/4}} q_i^2$$

# (From Last Year) What does $R$ look like?



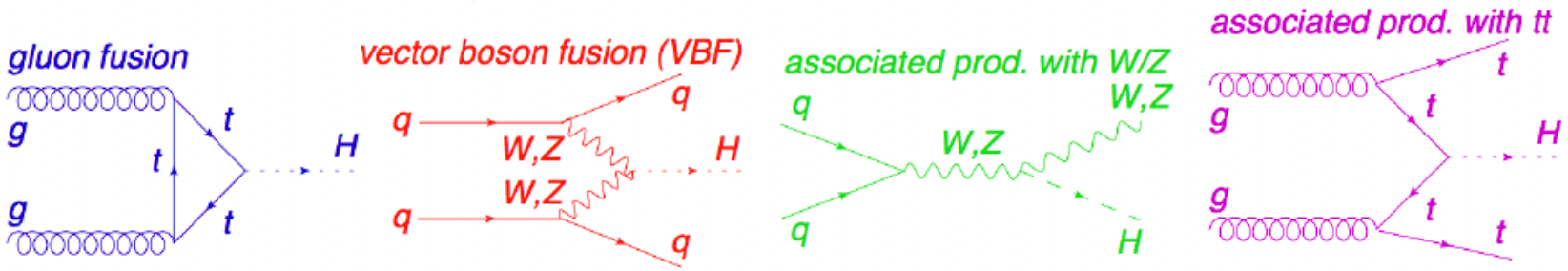
# UPDATE ON THE HIGGS

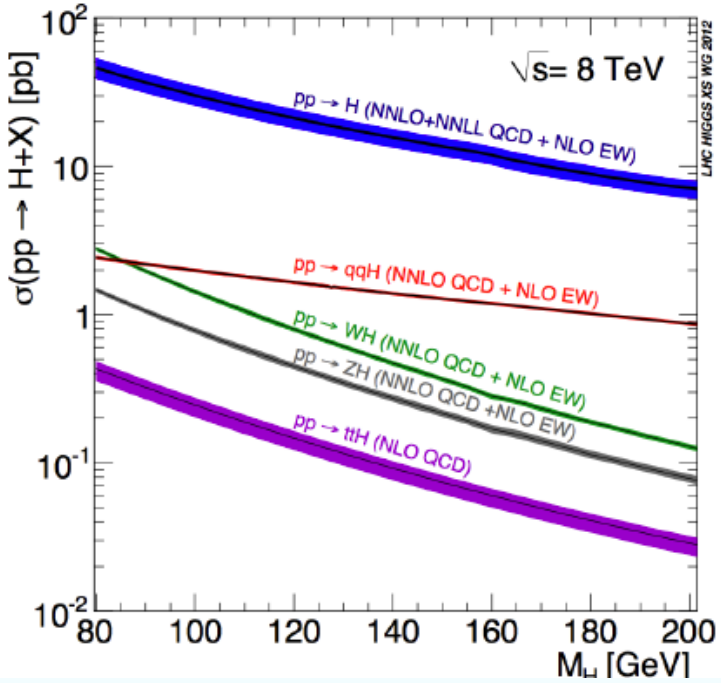
# Higgs limits (or signal) – last year



# How do we expect the Higgs to be produced?

## Higgs production



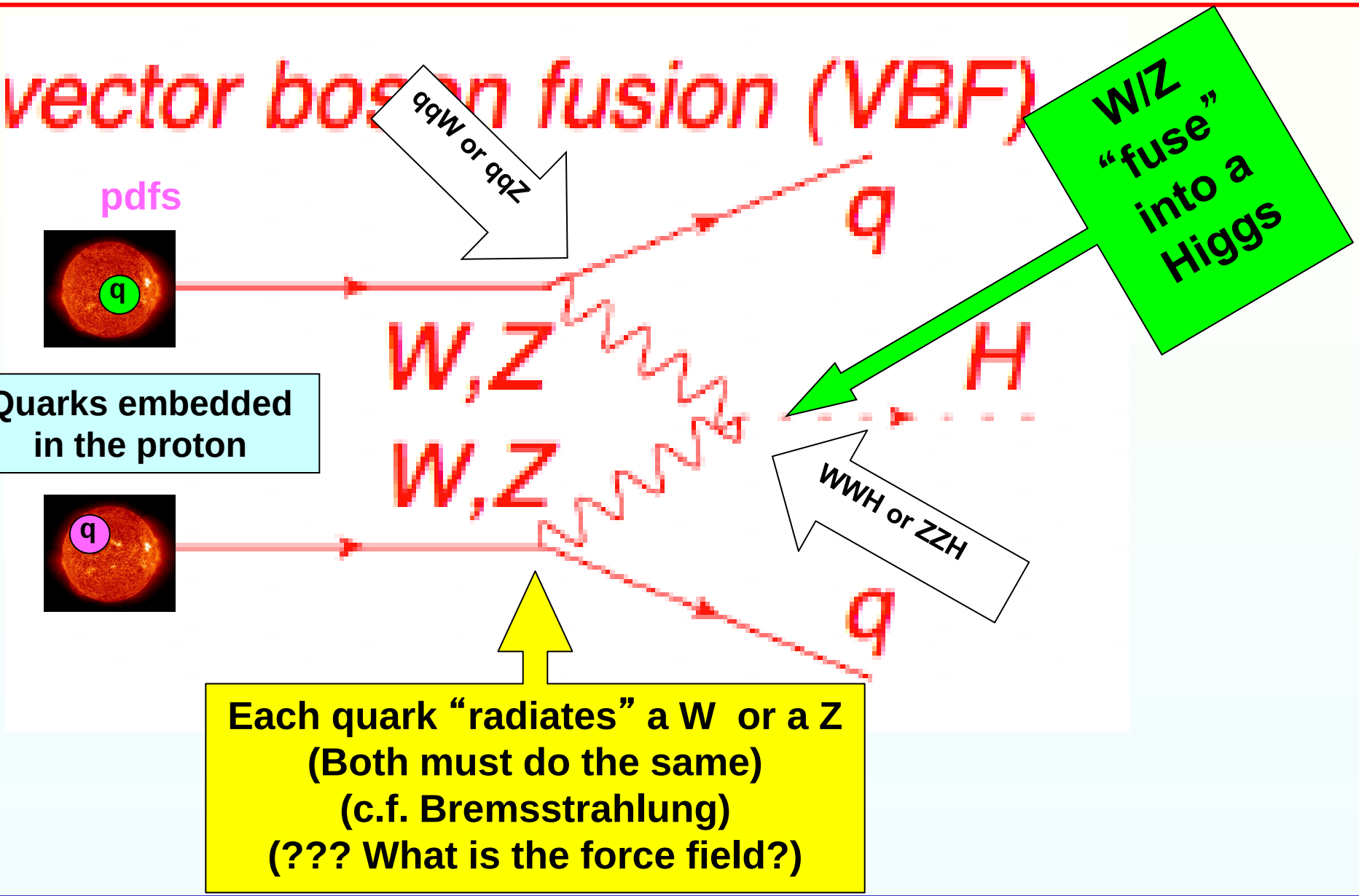




Main production mode via loops. Theory uncertainty *O*(10%)

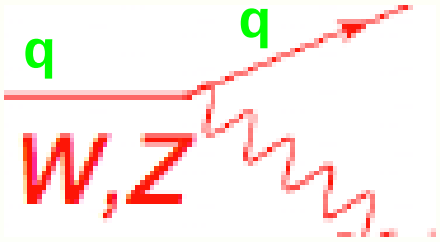
Access to top-quark, W and Z couplings via production cross section

**Krisztian Peters**

# Let us look at one of these in more detail



# More detail … (than you really want?)

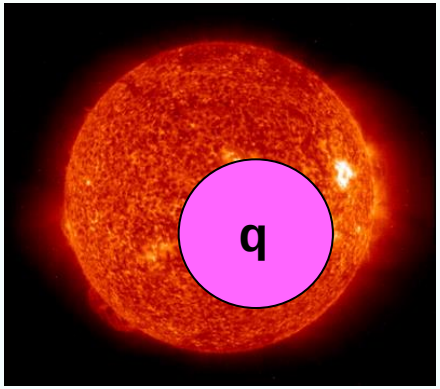


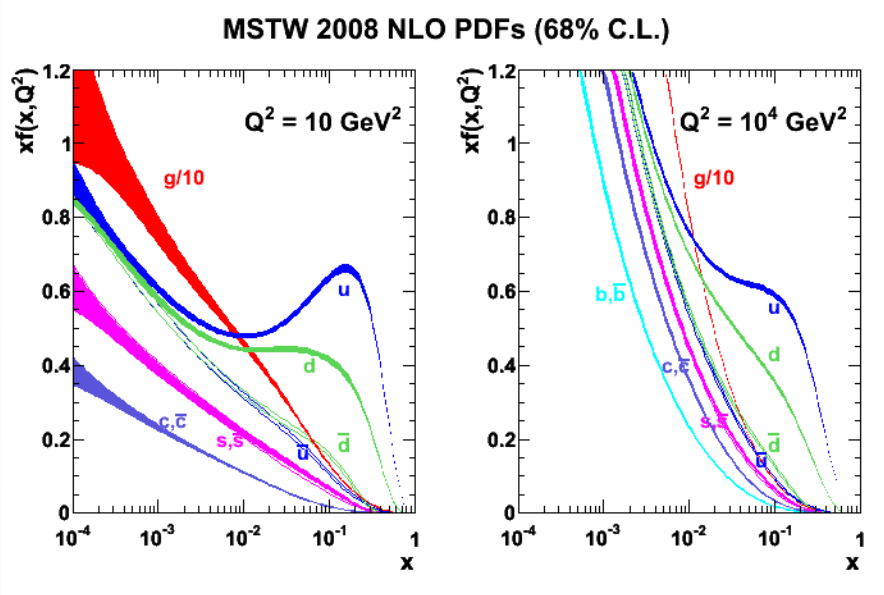

$$[\text{quark Z}] \quad - \frac{g}{\cos\theta_W}\overline{L_q}\left(\frac{\tau_3}{2}\cos^2\theta_W + \frac{\sin^2\theta_W}{2}\right)\not{Z}L_q$$

$$[\text{quark W}] \quad - \frac{g}{\sqrt{2}}\overline{\mathcal{U}}V_{\text{CKM}}\left(\tau_+\not{W} + \tau_-\not{W}\right)\mathcal{D}$$

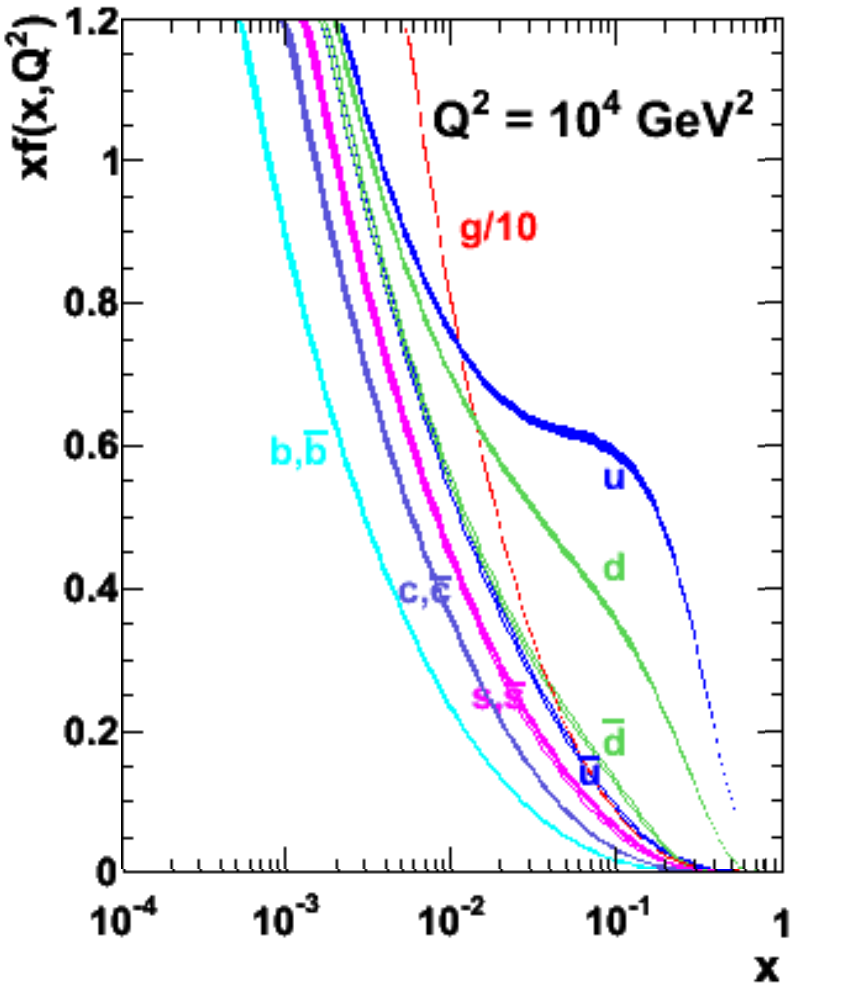

$$[\text{HH\&H } W^+W^-] \quad + \frac{g^2}{8}\left(\cancel{\quad} + \frac{2\mu}{\lambda}H\right)\left(2W_\mu W^{\dagger\mu}\right)$$

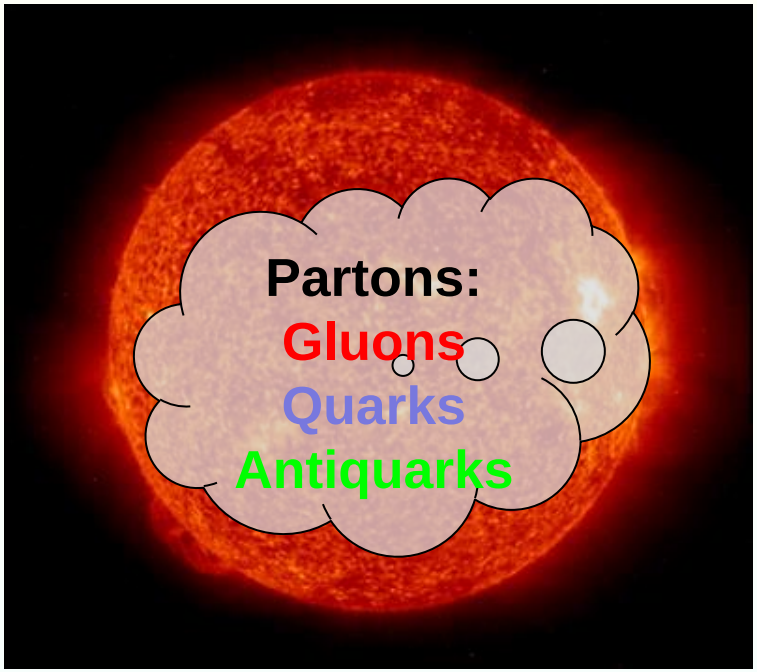
$$[\text{HH\&H } ZZ] \quad + \frac{g^2}{8}\left(\cancel{\quad} + \frac{2\mu}{\lambda}H\right)\left(\frac{1}{\cos^2\theta_W}Z_\mu Z^\mu\right)$$



# Even more detail



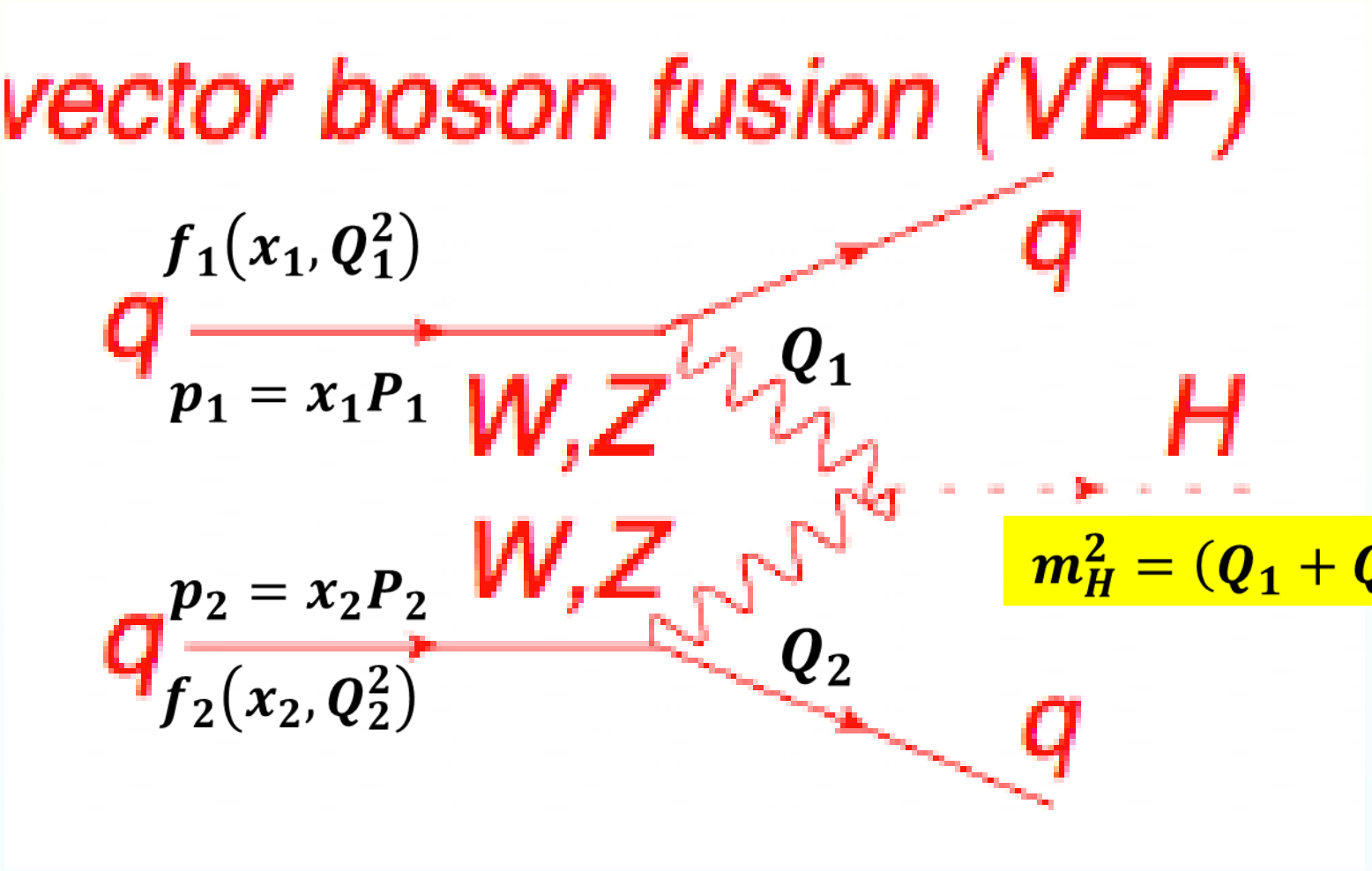




**x: fraction of proton momentum**

**$Q^2$: energy of the (parton) probe**

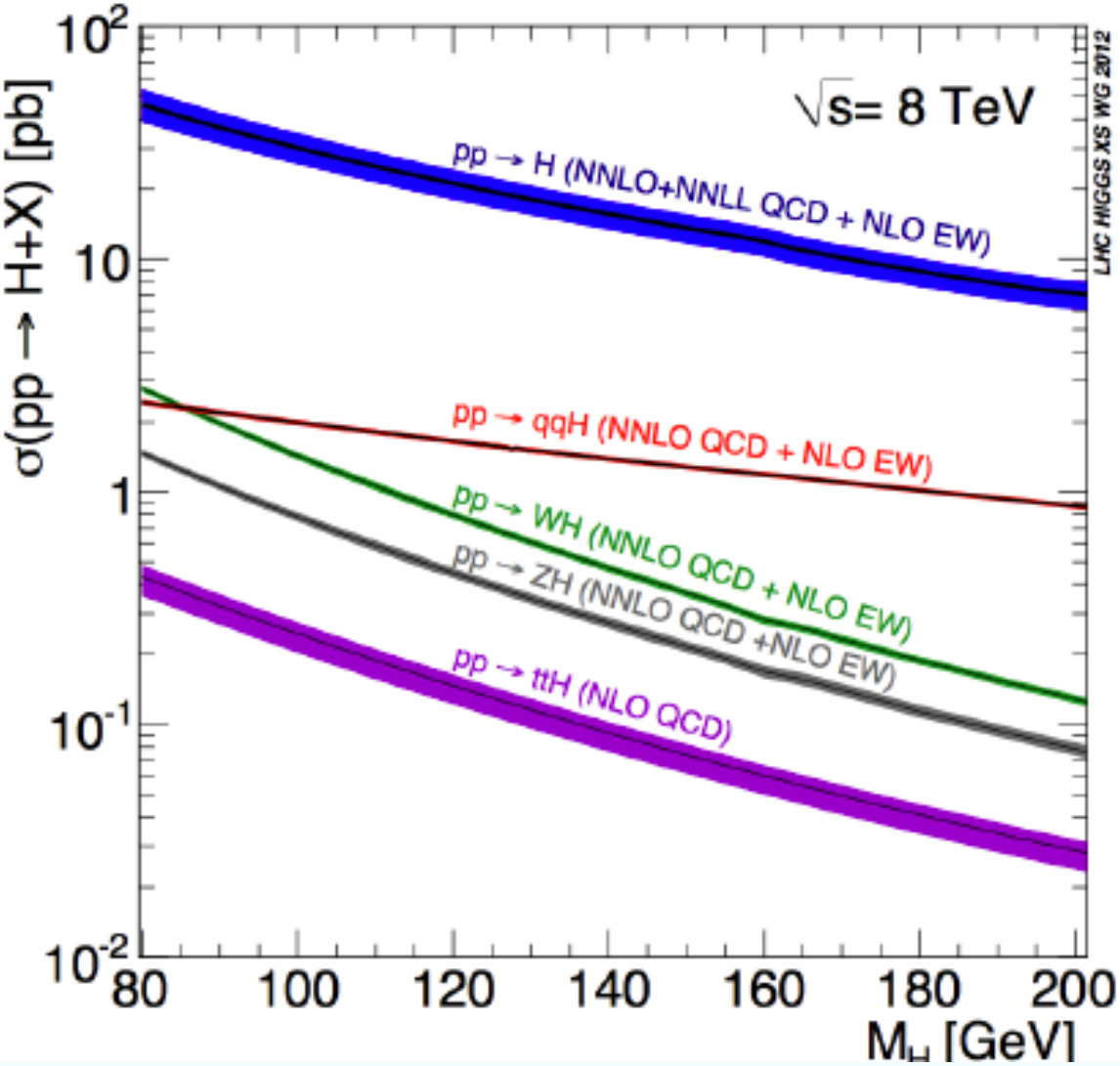
**$f(x,Q^2)$: probability that parton "p" has momentum fraction x when probed at $Q^2$**

# Put it all together …



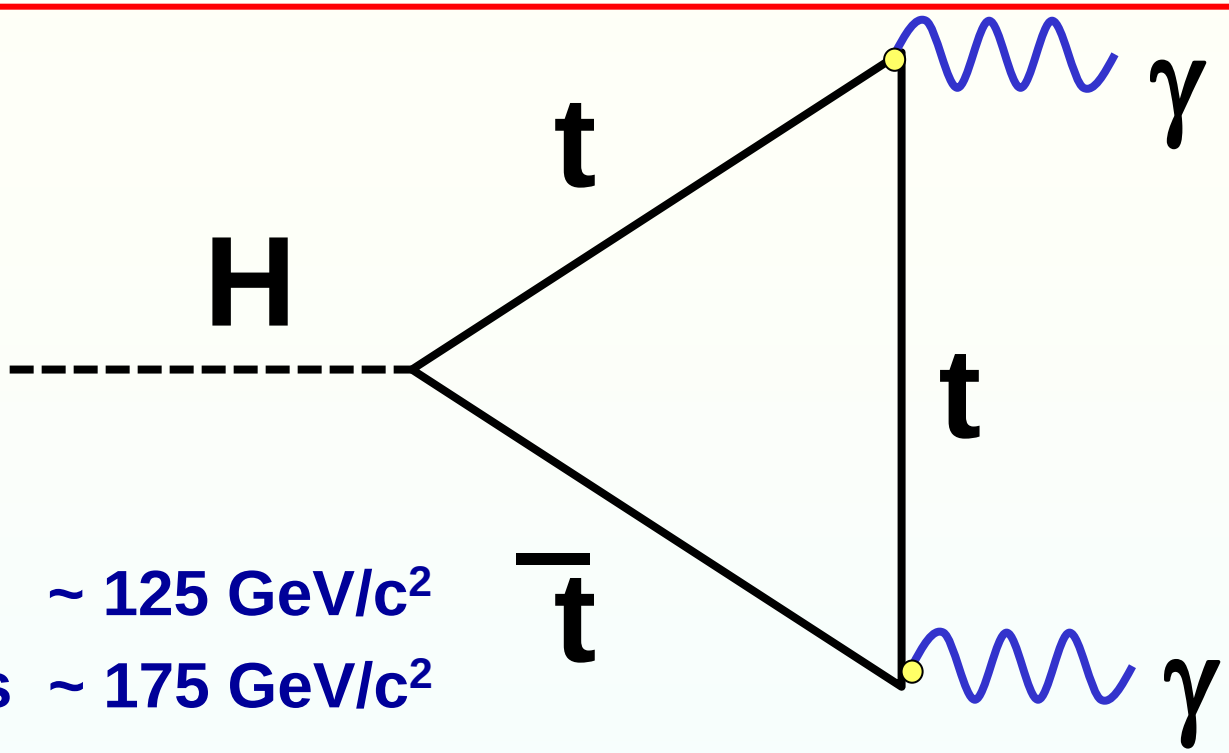
# … and then …

- **Repeat for other Higgs processes**




- **Don't forget the backgrounds also have to be calculated in the same way**

# Now the Higgs has to decay ….



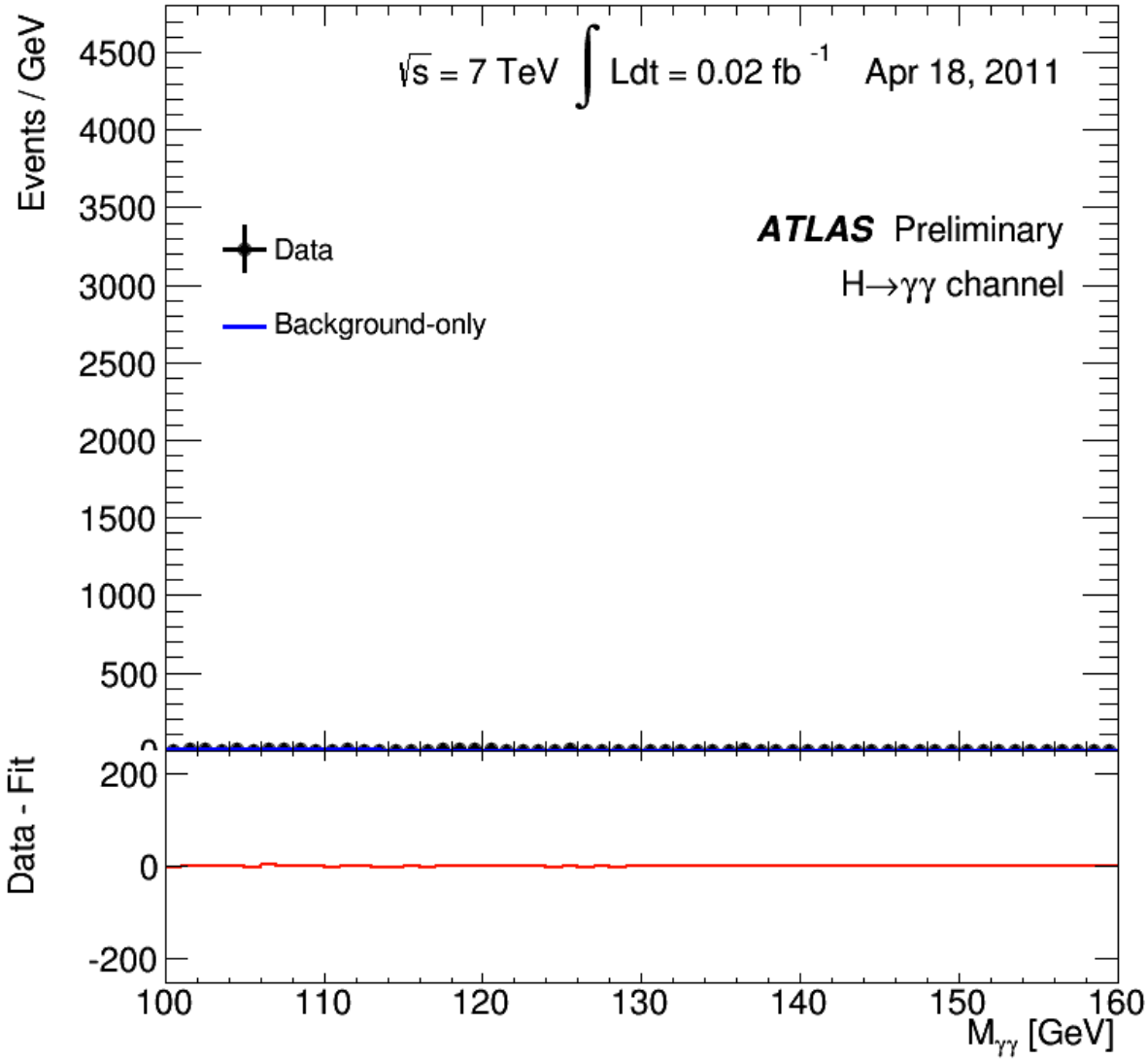

**Higgs Mass** ~ 125 GeV/$c^2$

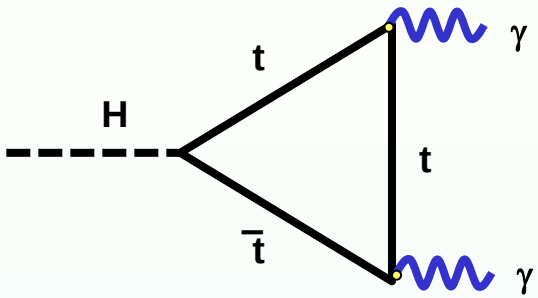
**Top-quark Mass** ~ 175 GeV/$c^2$

$$[\text{quark H}] \quad - \quad m_q\sqrt{\sqrt{2}G_F}\bar{q}qH$$

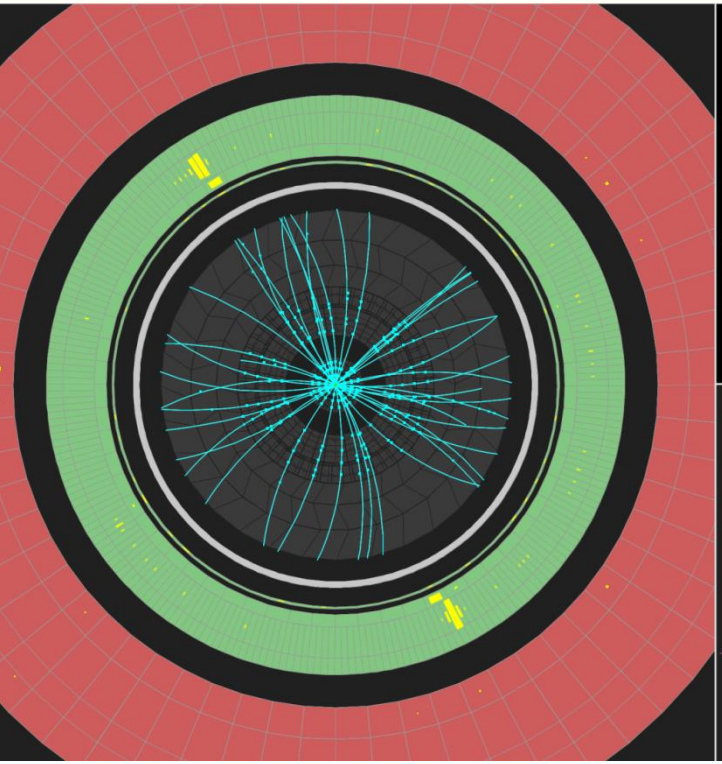
$$[\text{quark } \gamma] \quad + \quad Q\bar{q}\not{A}q$$

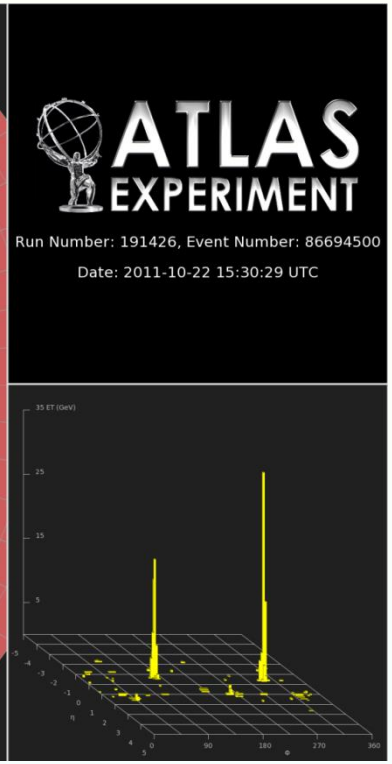
# … and this is what we see!

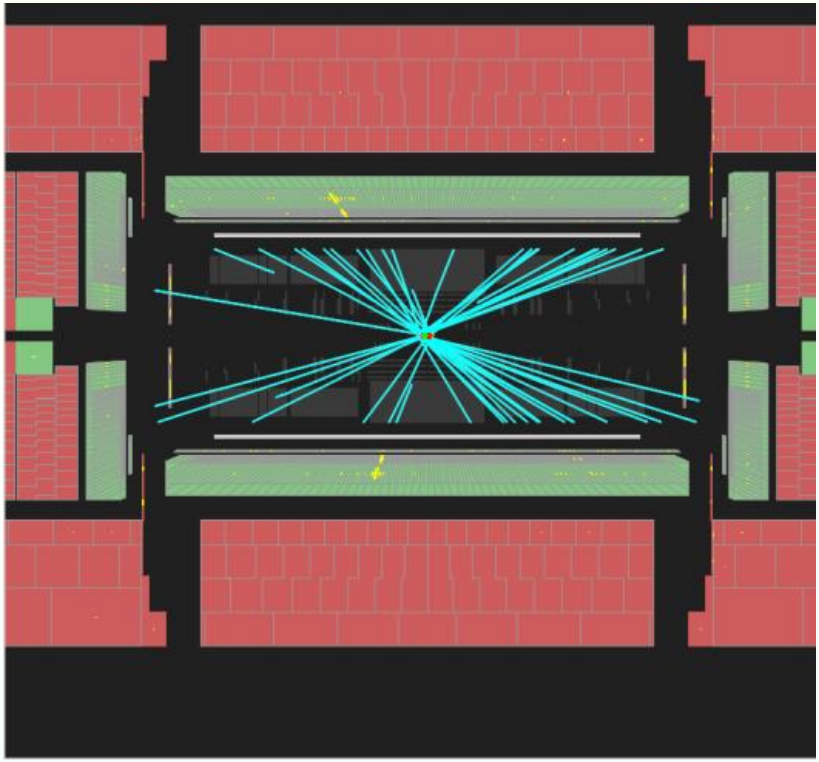


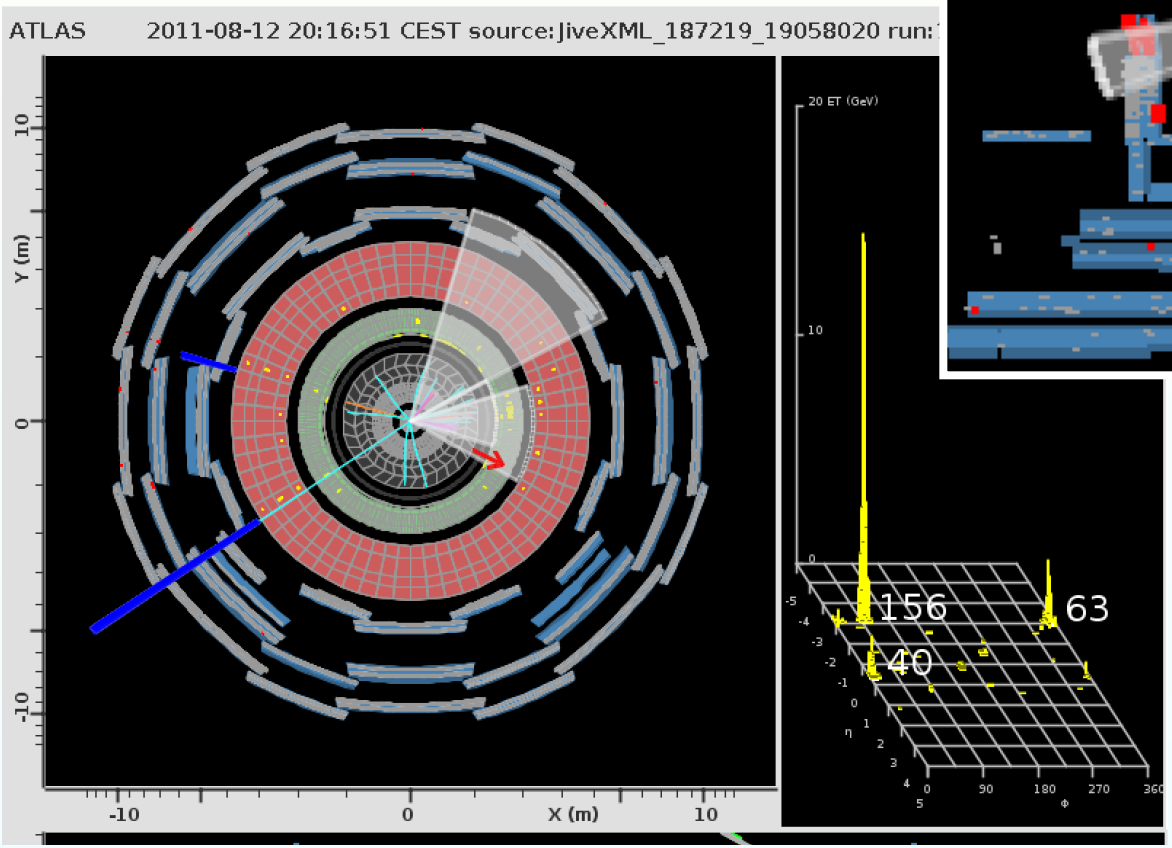
# A “typical” Higgs Candidate event

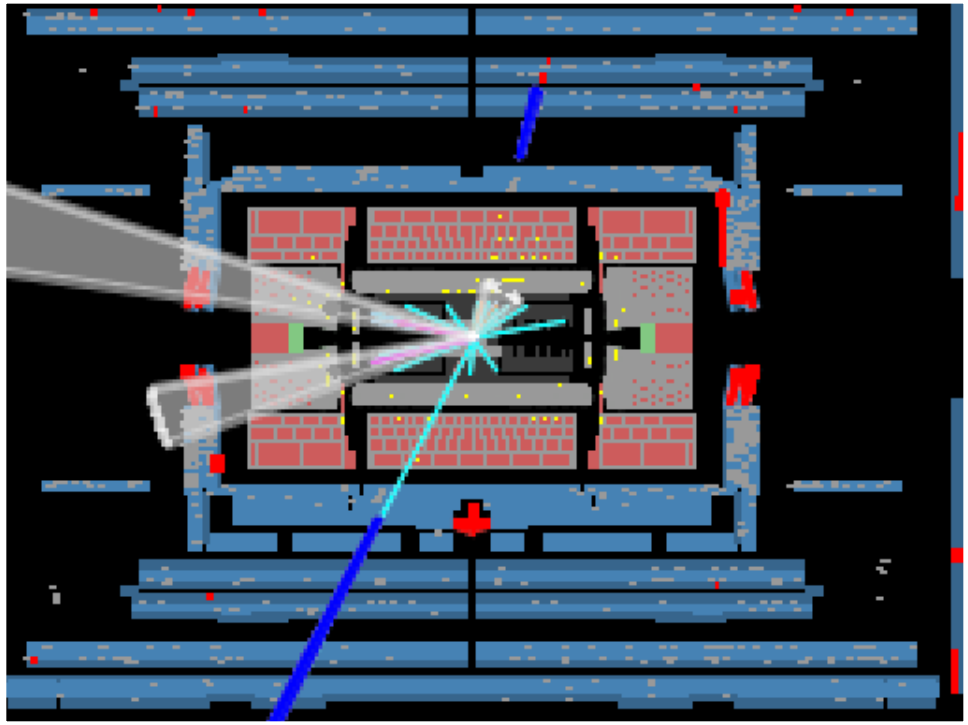




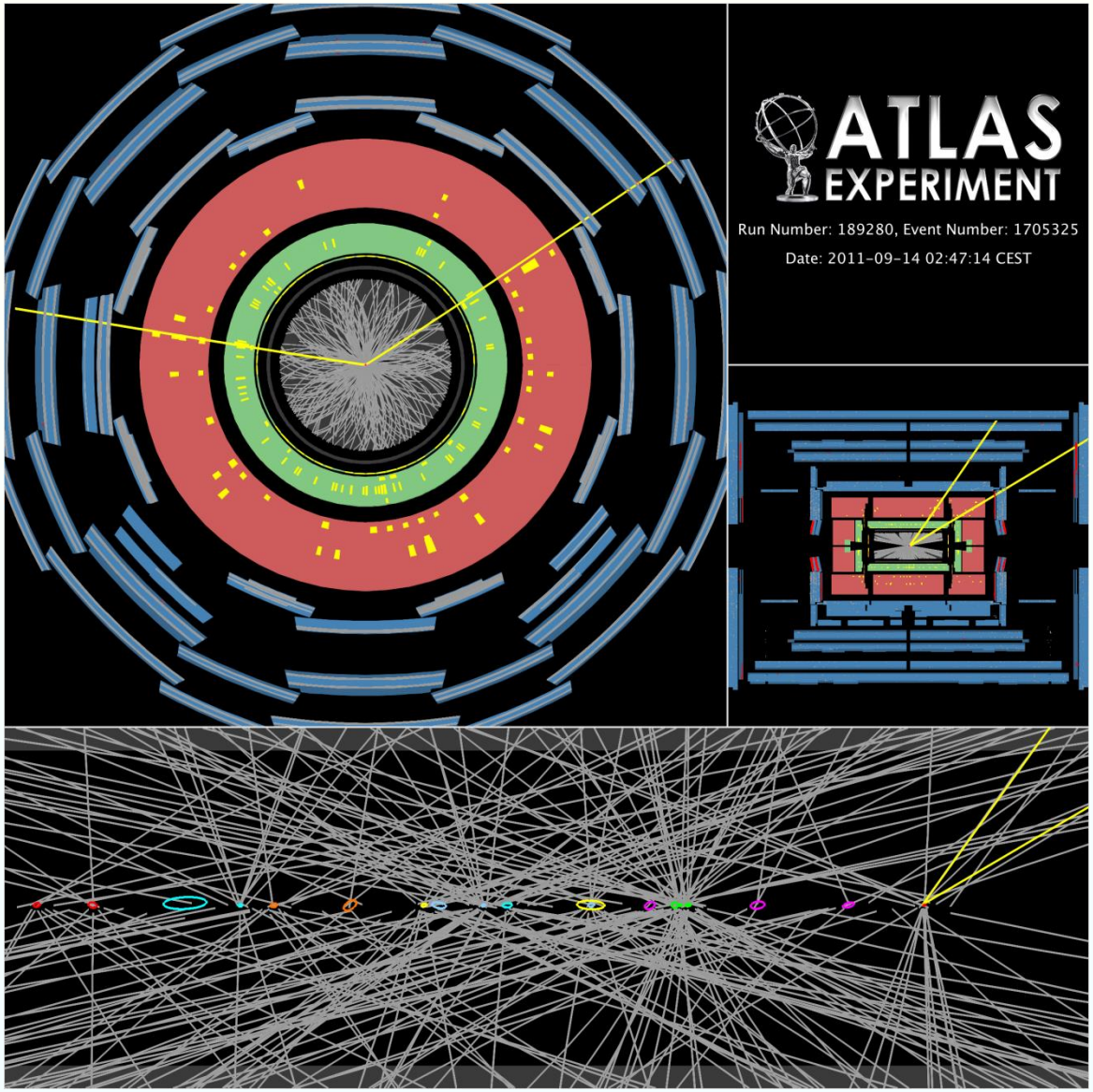
# Another (more) typical event



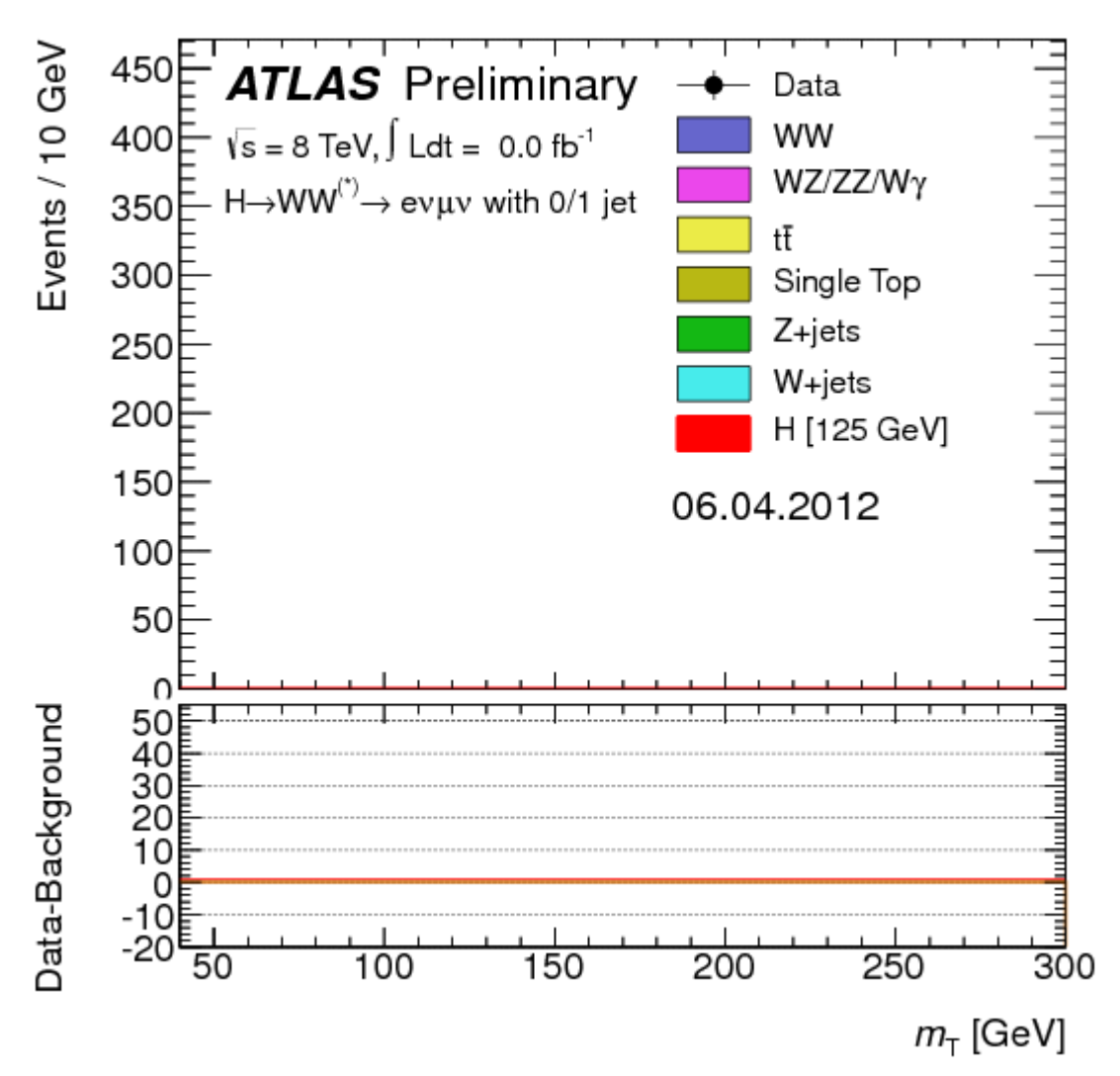



H→μμbb

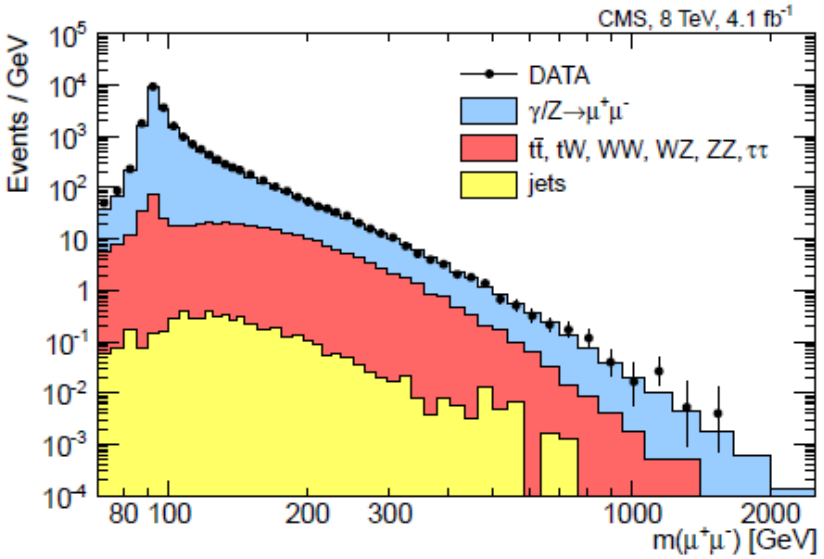
# Many events in one bunch crossing

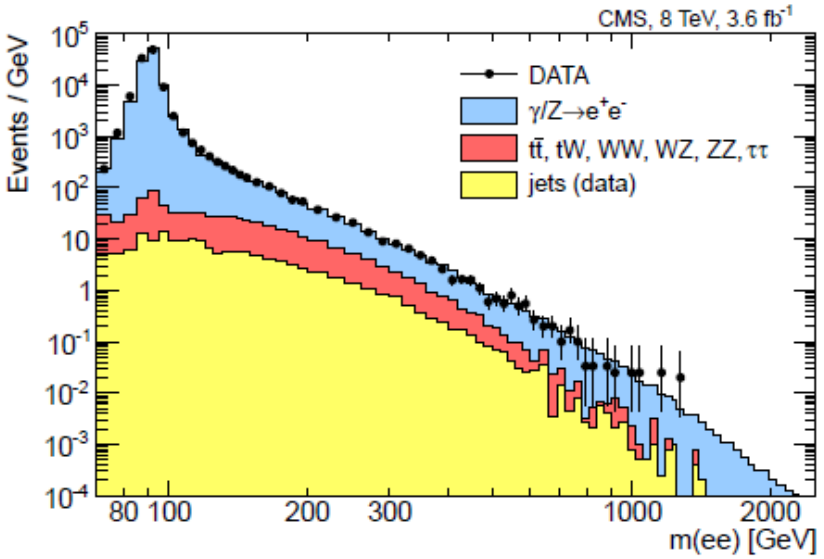


# And another accumulation …



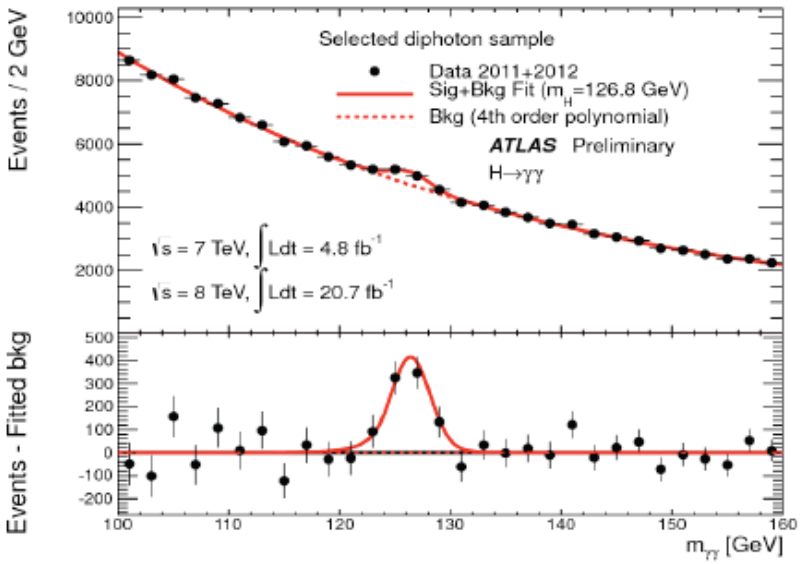
# A not-so-happy story

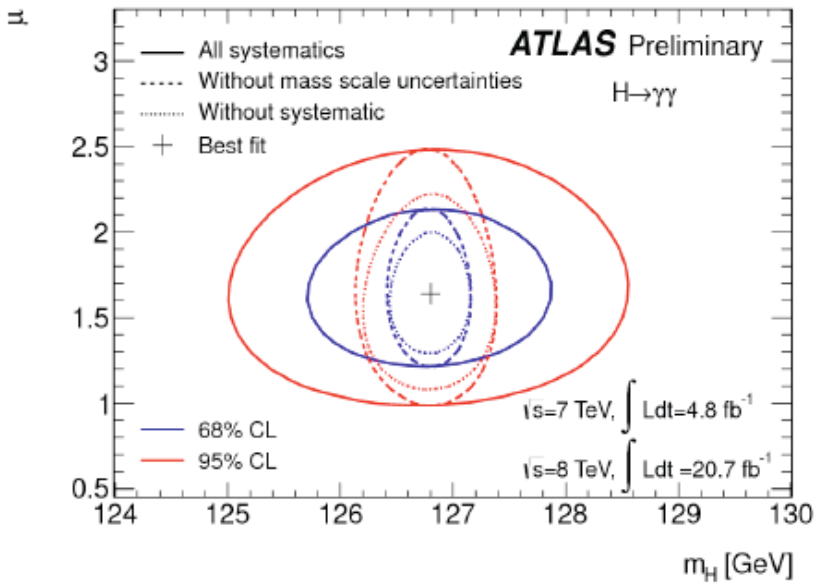



- **In both the $\mu^+\mu^-$ & $e^+e^-$ channels**
  - **excess of events > 500 GeV @ 7 TeV ☺?**
  - **Disappears at 4x luminosity & 8 TeV ☹!!**

# Errors




Observed significance 7.4σ (expected 4.1σ), consistent result w/o categories

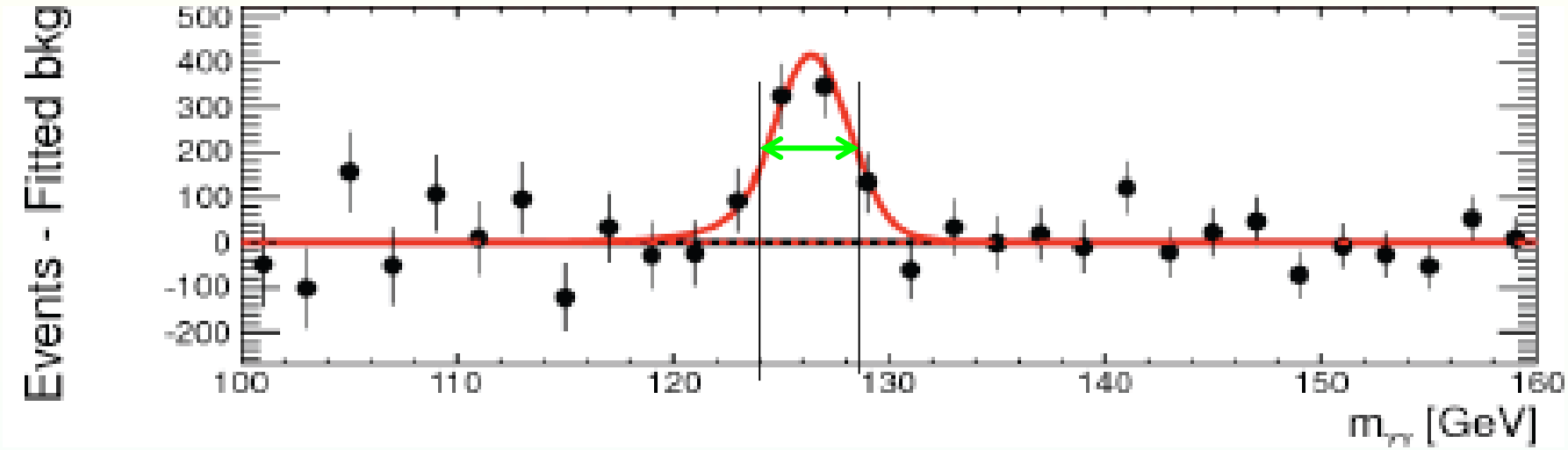
Mass: $m_H$ =126.8 ± 0.2(stat) ± 0.7(syst) GeV

Signal strength: μ = 1.65 ± 0.24(stat) ± 0.22(syst) [2.3σ compatibility with SM]

Fit prefers narrower than nominal mass resolution by 1.8σ. This is better than with a perfectly uniform calorimeter, likely due to background fluctuation

Fitting without resolution constraint gives a ~10% lower signal strength

# Errors




$$m_H = 126.8 \pm 0.2 \text{ (stat)} \pm 0.7 \text{ (syst)} \text{ GeV}/c^2$$

**FWHM = 4.5 GeV/$c^2$ = 2.36 $\sigma$ ➔ $\sigma$ = 1.9 GeV$^2$**

**Statistical error on the mean is usually ~$\sigma$ / $\sqrt{N}$**

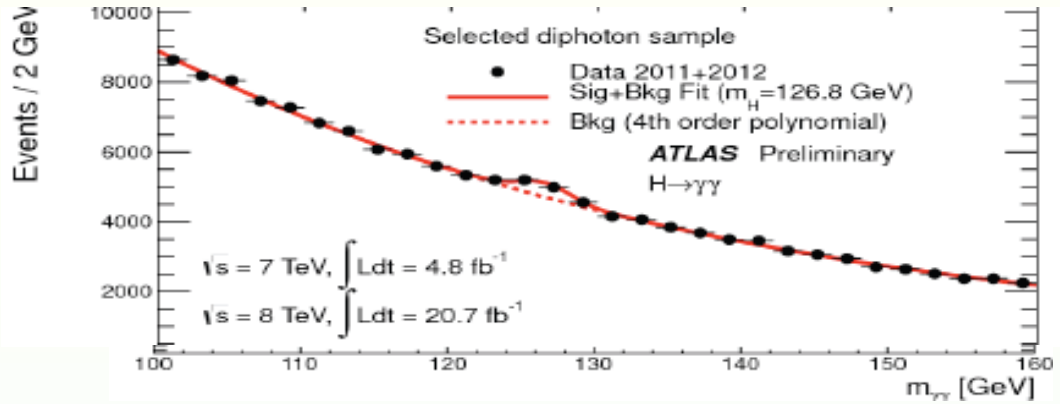
**- what is N?**

**~ 900 ev in signal would give ~0.07 GeV$^2$**

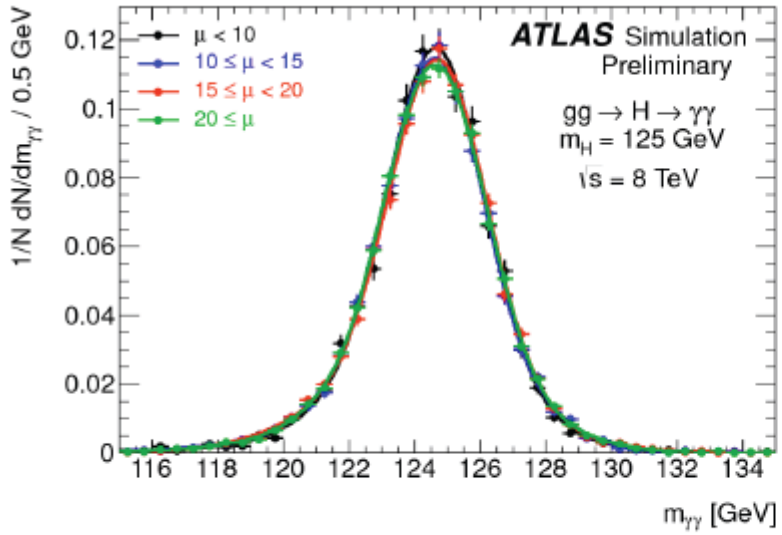
**But there is a background (~2700 events) which dilutes the signal**

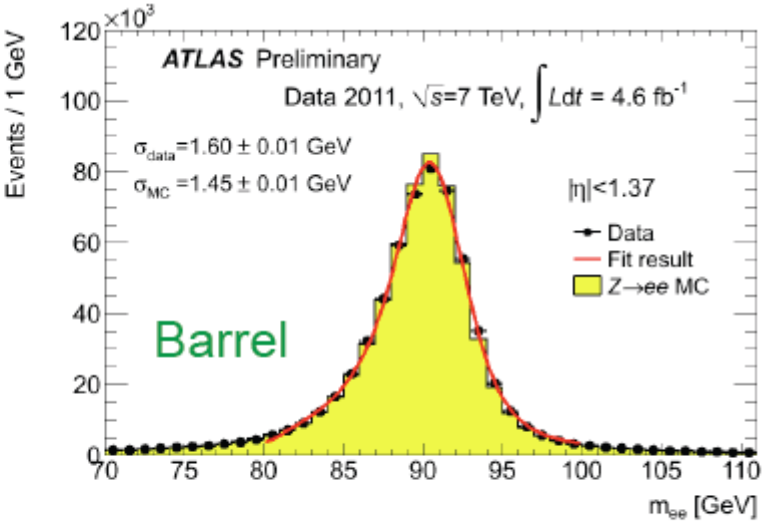
**$\sigma_{stat}$ ~ 3 × .07 = 0.21 GeV$^2$ (c.f. 0.2 above)**

# Errors – systematic errors



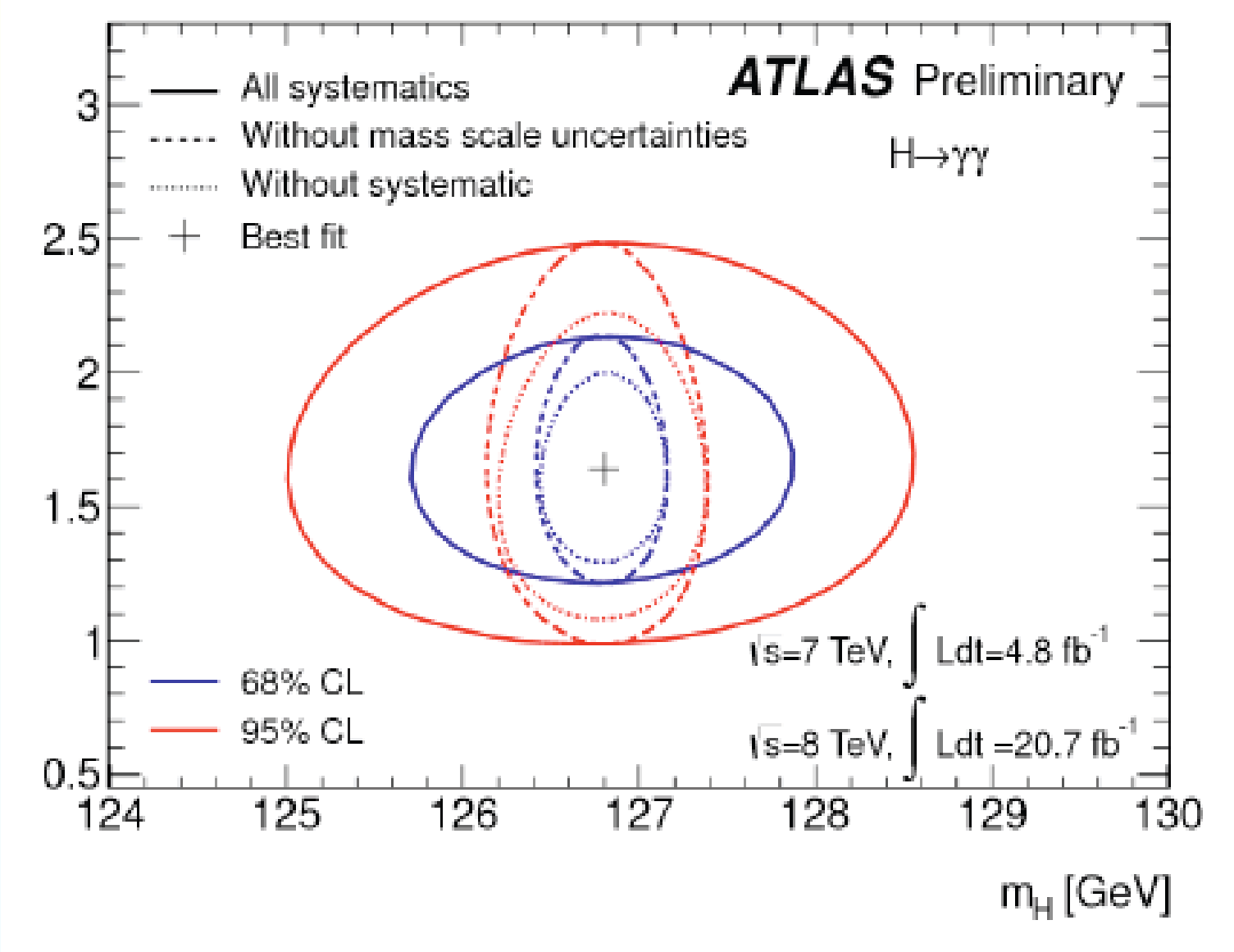

$m_H = 126.8 \pm 0.2$ (stat) $\pm$ 0.7 (syst) GeV/$c^2$



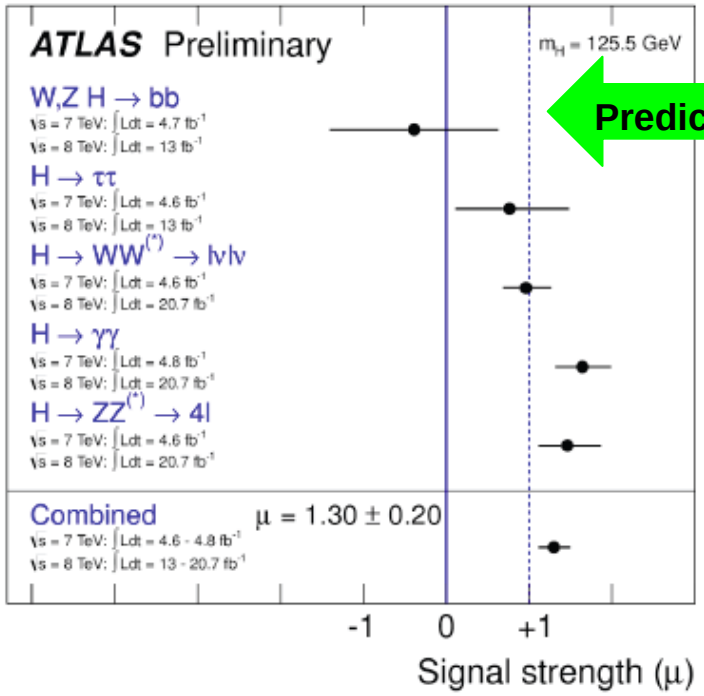




Uncertainty on photon energy resolution (14 − 23%):

# H→γγ versus the Standard Model



# Add information from all channels




**Predicted Standard Model SIgnal Strength**

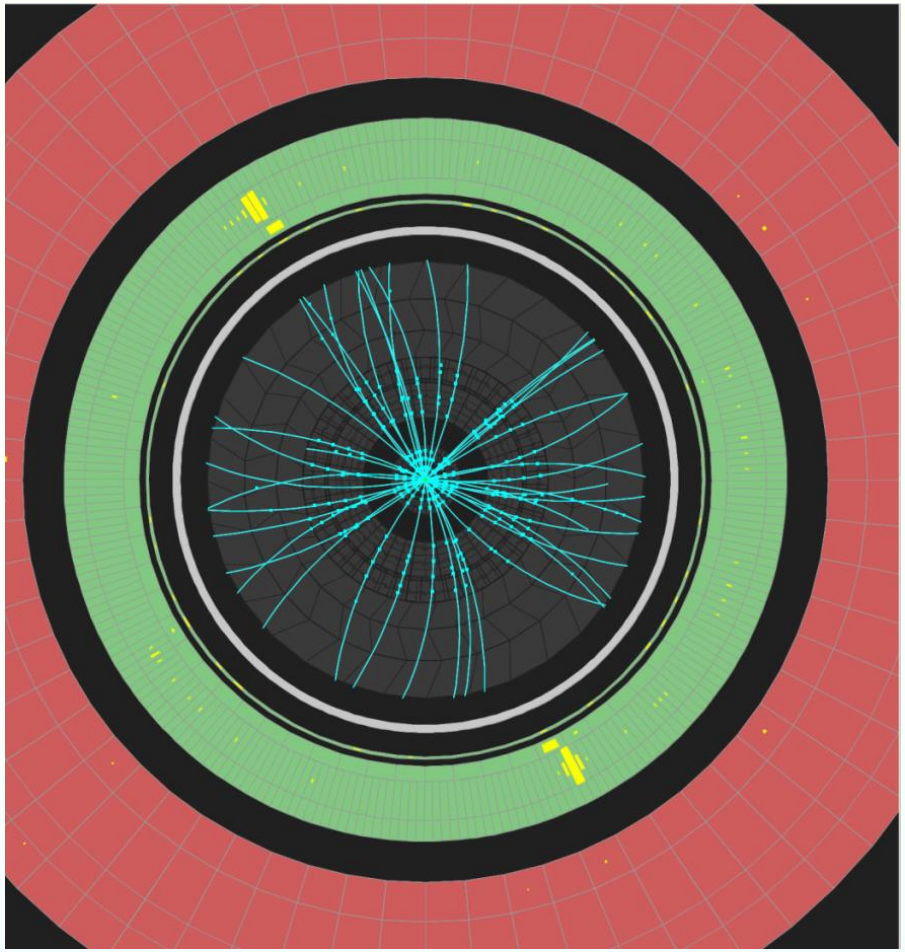
| Higgs Boson Decay | $\mu$ ($m_H$=125.5 GeV) |
|---|---|
| $VH \to Vbb$ | $-0.4 \pm 1.0$ |
| $H \to \tau\tau$ | $0.8 \pm 0.7$ |
| $H \to WW^{(*)}$ | $1.0 \pm 0.3$ |
| $H \to \gamma\gamma$ | $1.6 \pm 0.3$ |
| $H \to ZZ^{(*)}$ | $1.5 \pm 0.4$ |
| Combined | $1.30 \pm 0.20$ |

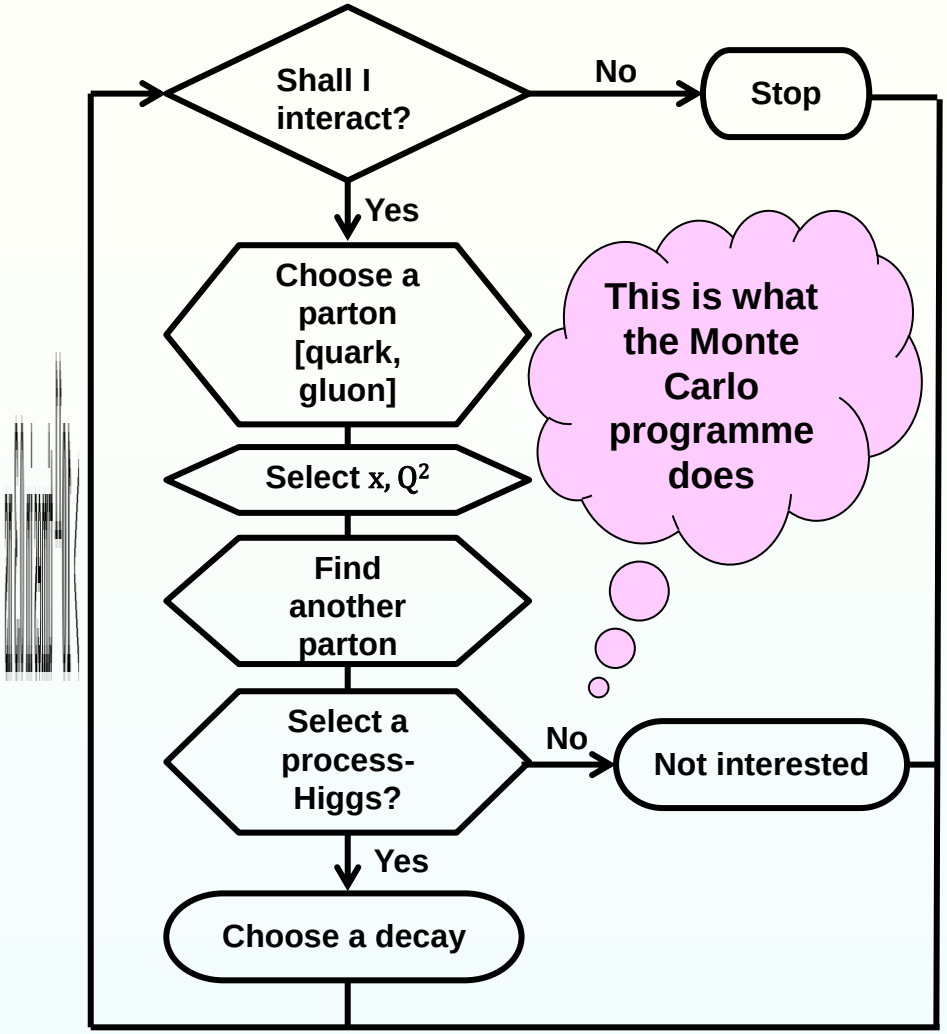
Combined signal strength μ =1.30 ± 0.13 (stat) ± 0.14 (syst)

Global compatibility between the 5 channels and the SM expectation is 8%

Dependence of the combined μ on the mass is weak
(4% for 124.5 - 126.5 GeV)

# … so … is this how it happens?






**20,000,000 times/second**

Bunch length ~9 cm Time for bunches to cross = $9/(3\times10^{10})\sim 0.3$ ns

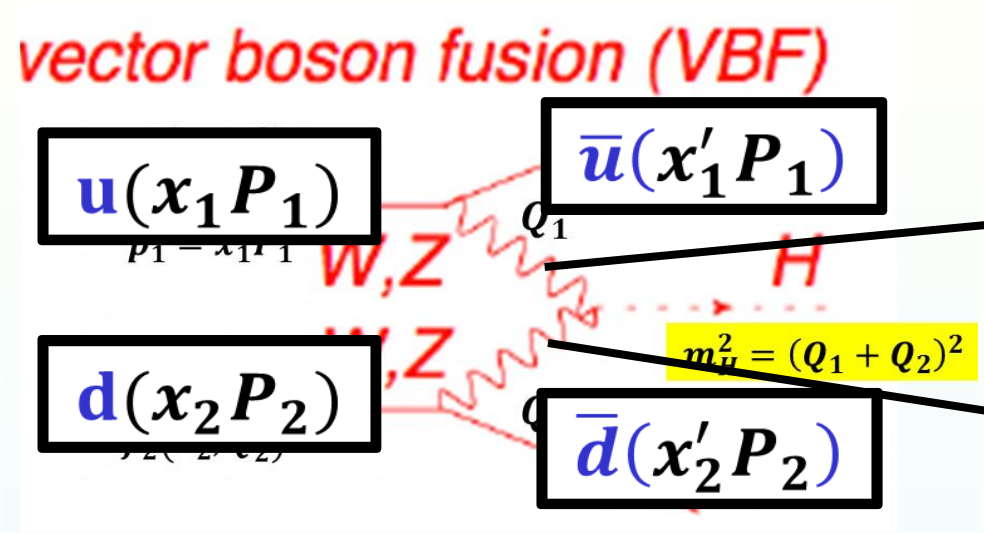
# ??????????????

- **Probably not**
  - **This is our *description* of what happens and our *explanation* of what happens**
- **It has the merit of "accuracy"**
  - **when used to *predict* what will happen**

# A bit more detail on the calculation …

## Remember this?

## "momentum-space"




$$\frac{g/\sqrt{2}}{Q_1^2 - m_W^2}$$

$$\frac{g/\sqrt{2}}{Q_2^2 - m_W^2}$$

$$x_1 P_1 - x_1' P_1 - Q_1 = 0$$

$$x_2 P_2 - x_2' P_2 - Q_2 = 0$$

$$\int dx_1 dx_2 dQ_1 dQ_2 \bar{u}(x_1' P_1)\bar{d}(x_2' P_2) \frac{g/\sqrt{2}}{Q_1^2 - m_W^2} \frac{g/\sqrt{2}}{Q_2^2 - m_W^2} \bar{u}(x_1' P_1)\, \bar{d}(x_2' P_2)\, \delta(Q_1 + Q_2 - m_H)$$

**Note: I have left out hundreds of indices (relativity, quantum mechanics) !!!!!!!**

**Finally: We *know precisely* all the particle momenta**

**∴ We (Heisenberg) have no idea where they are!!!!**

# QUESTION?

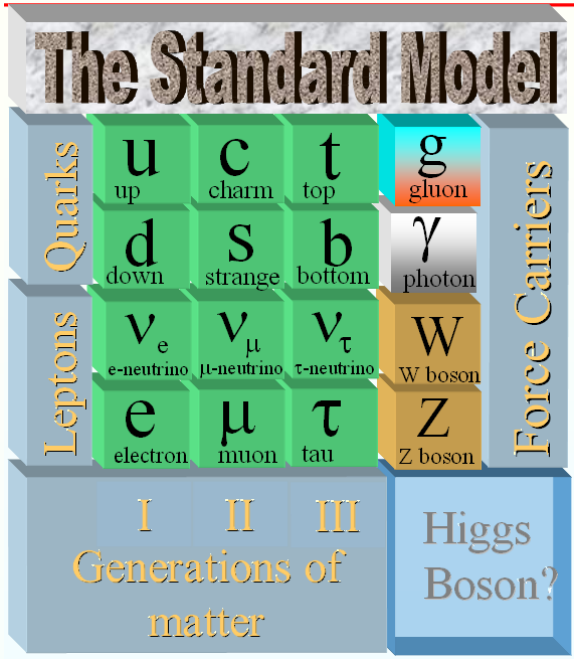
**Is this *fact*?**

**or**

**Is this fantasy?**

# Conclusion (almost as last year)

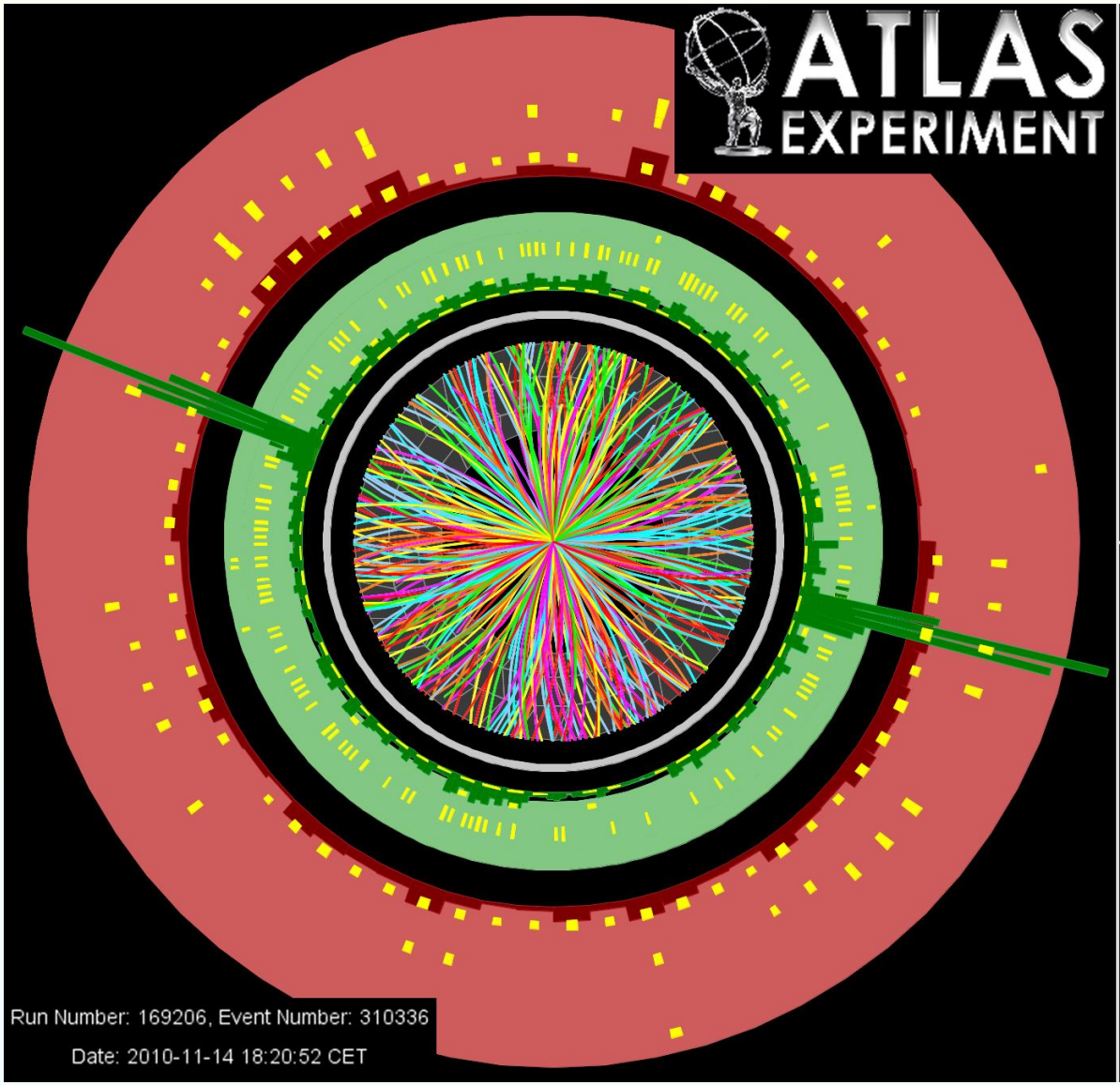
- **We have a wonderful "model" to describe the particle world**
  - **but it is not a theory**
    - **it *describes* but does not *explain***
  - **and has "missing links"**
    - **What about gravity?**
    - **Why 3 forces?**
    - **Why 3 generations?**
    - **How does the matter-antimatter asymmetry arise?**
    - **Why 3 space and 1 time dimension?**
    - **Are there more dimensions?**
    - **…**
- **We can model it**
  - **but do we understand it?**

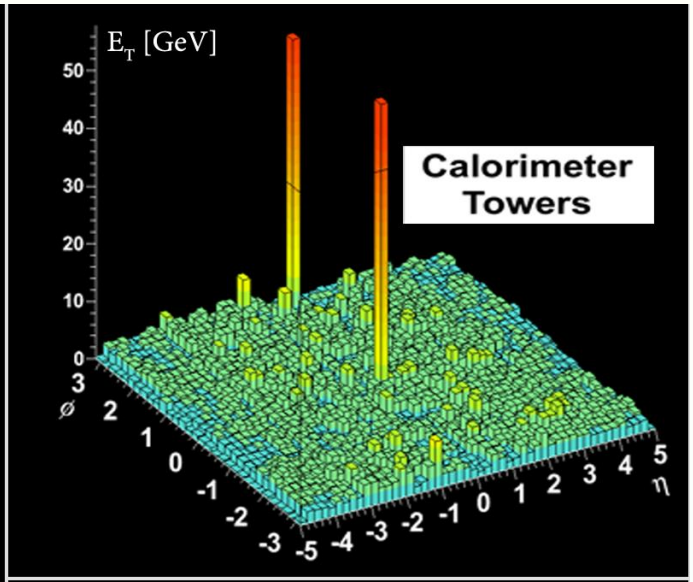


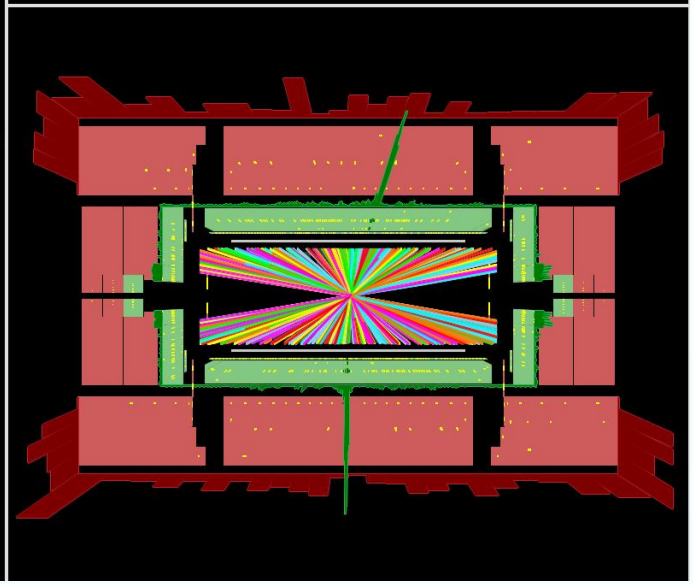
# LEAD-LEAD COLLISIONS

# Something Different

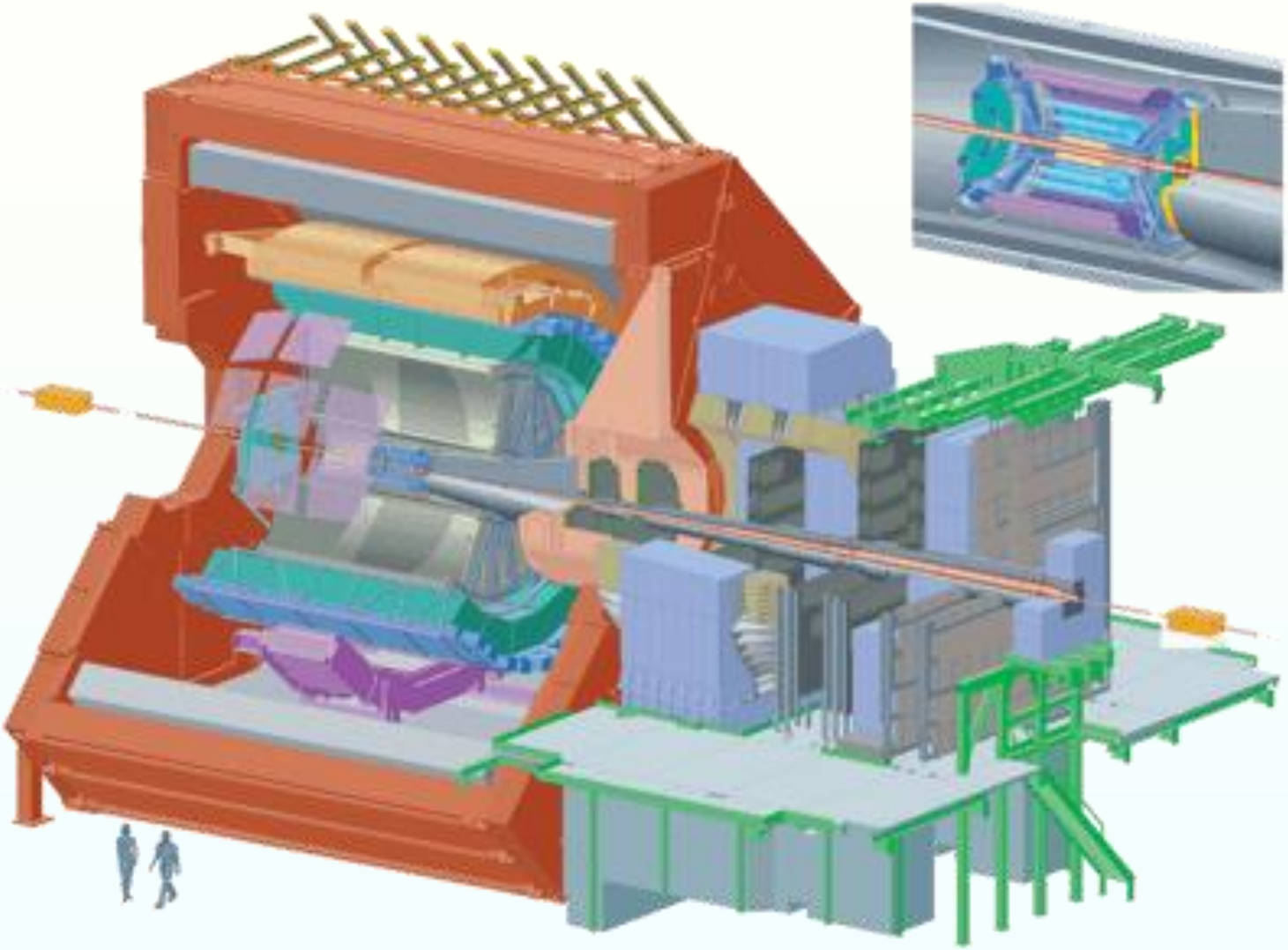
# Lead-Lead collisions



# ALICE: A Large Ion Collider Experiment



# An ALICE Event