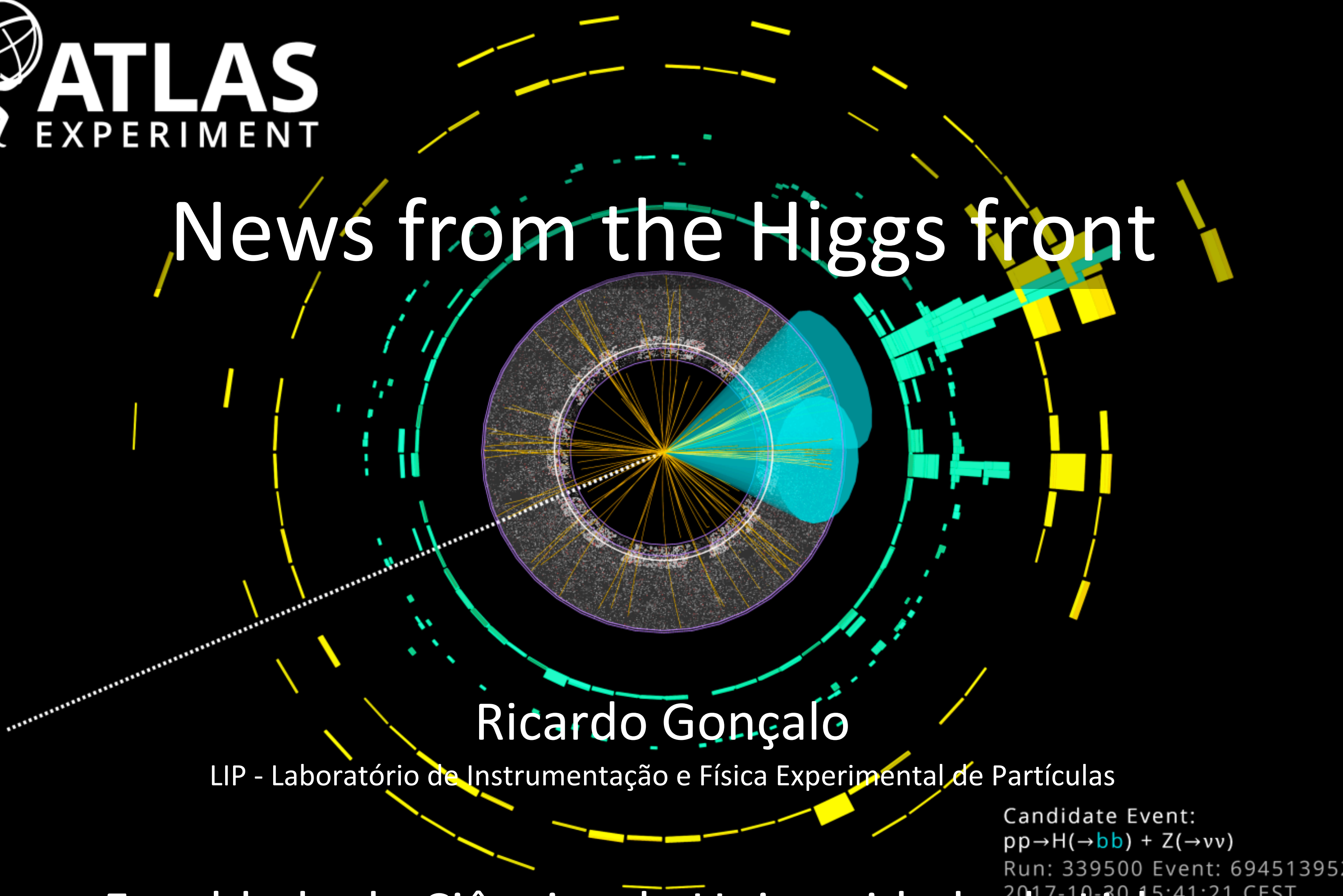
News from the Higgs front



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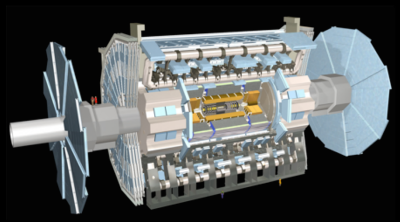
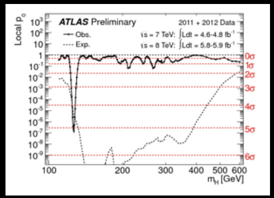
LIP · Ciências ULisboa · FCT Fundação para a Ciência e a Tecnologia · ATLAS Experiment

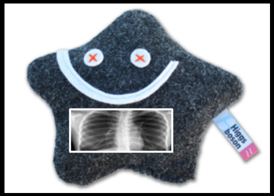
The Standard Model and the Higgs

The LHC and experiments

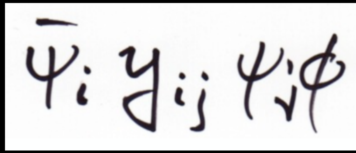




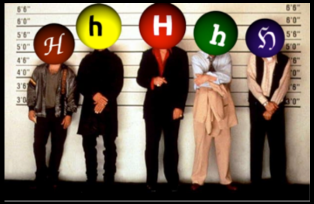
The Run 1 legacy



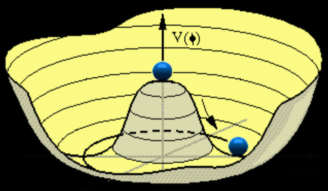
Probing the 125 GeV Higgs



Probing the Yukawa sector

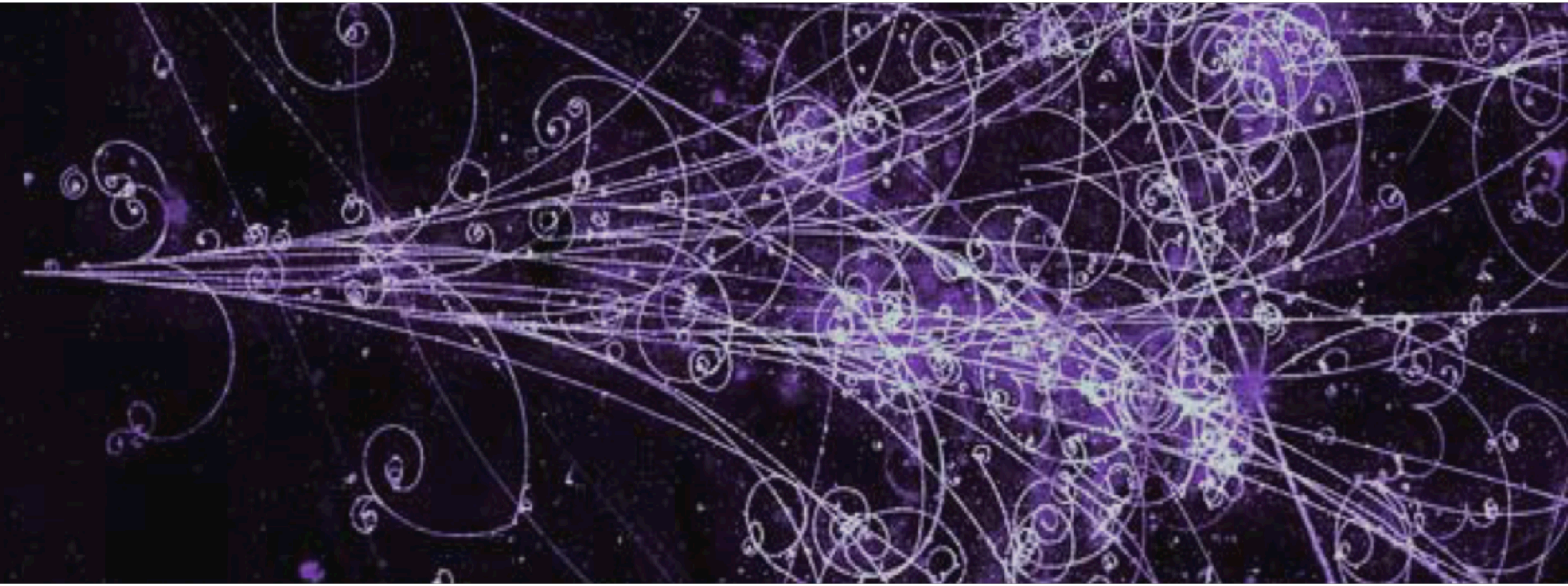


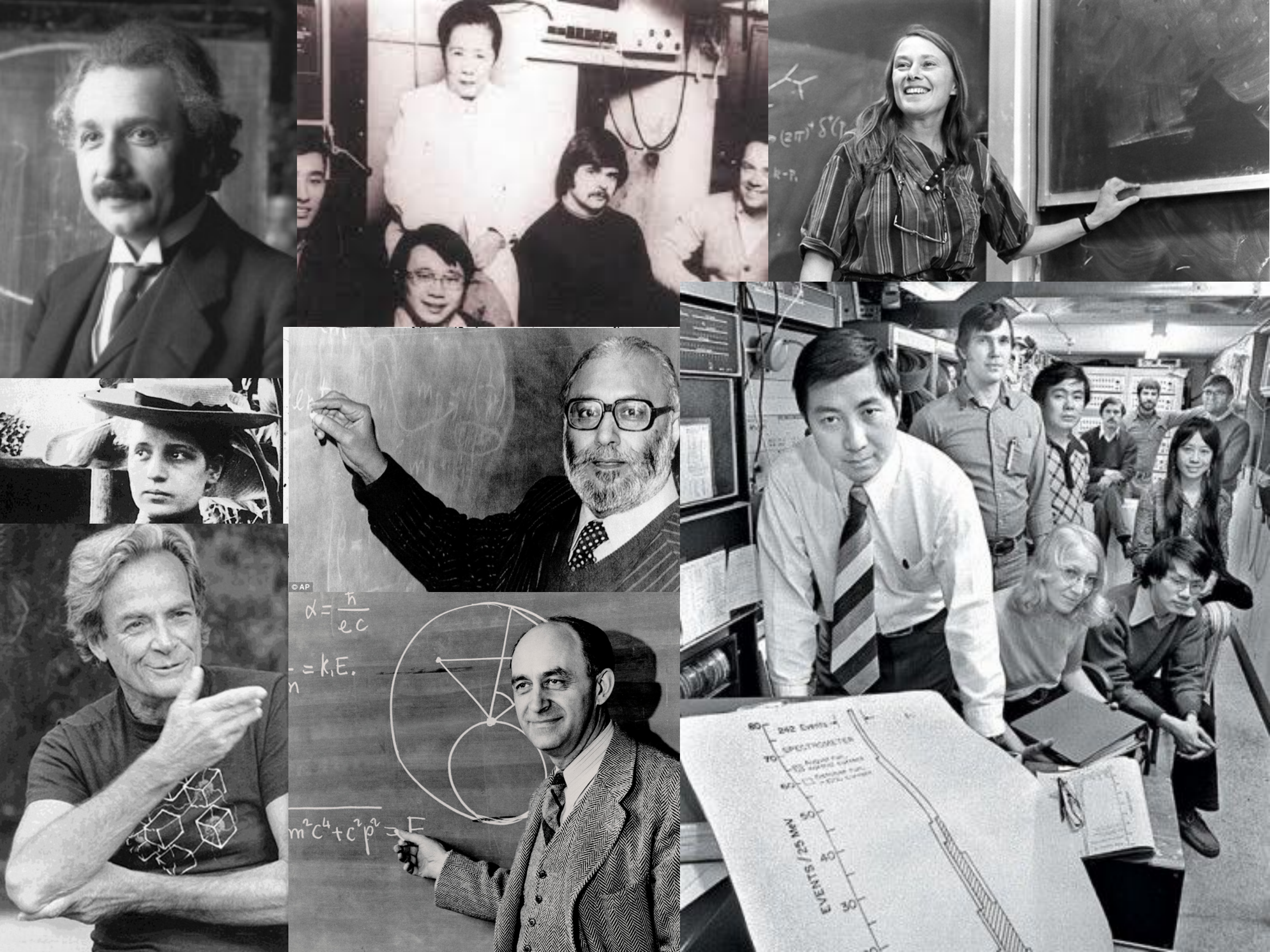
Searching wider



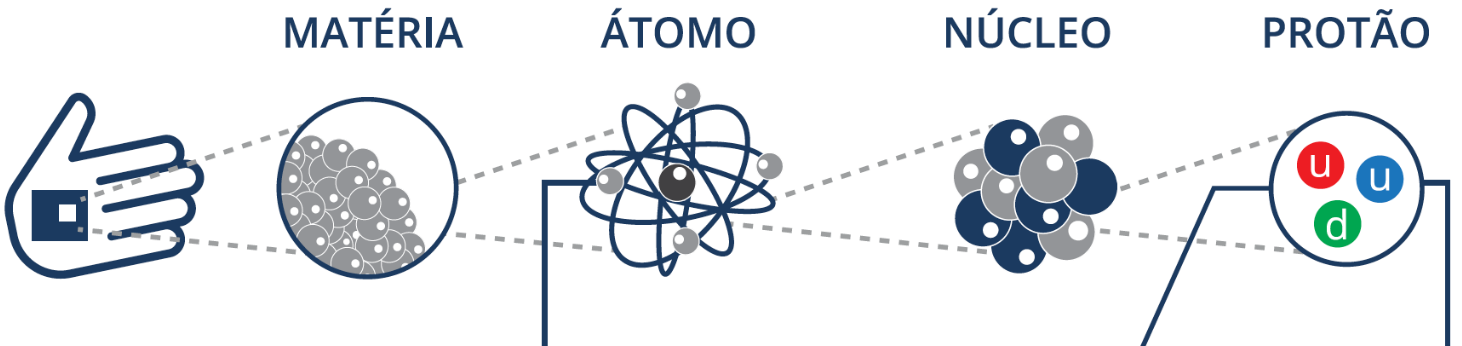
The long run

The Standard Model of Particle Physics





© AP
α = ħ/ec
= k,E.
m²c⁴+c²p² = E
242 Events
SPECTROMETER
EVENTS / 25 MeV
80
70
60
50
40
30



LEPTÕES

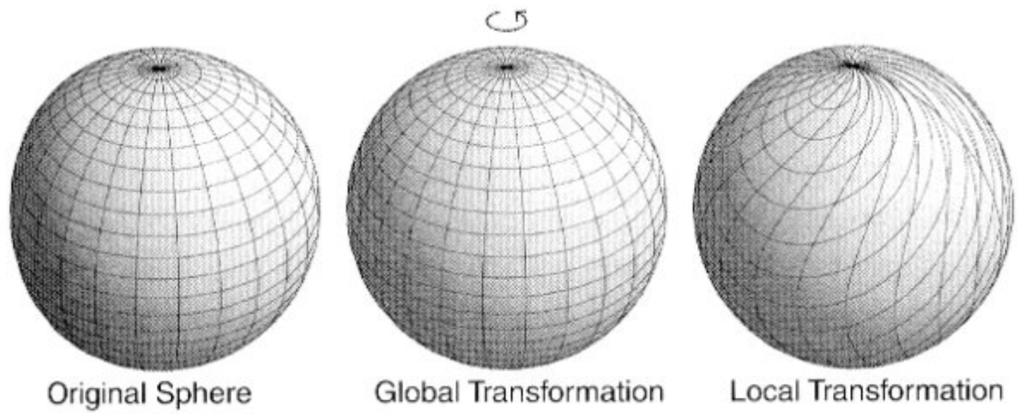
ν_e NEUTRINO DO ELETRÃO 0 ½	e ELETRÃO -1 ½
ν_μ NEUTRINO DO MUÃO 0 ½	μ MUÃO -1 ½
ν_τ NEUTRINO DO TAU 0 ½	τ TAU -1 ½

QUARKS

u UP ⅔ ½	d DOWN -⅓ ½
c CHARM ⅔ ½	s STRANGE -⅓ ½
t TOP ⅔ ½	b BOTTOM -⅓ ½

Symmetries in field theory

- Symmetries → Interactions!
- Equations locally invariant for certain symmetries



Standard Model Symmetry Group

Phase

3D rotation

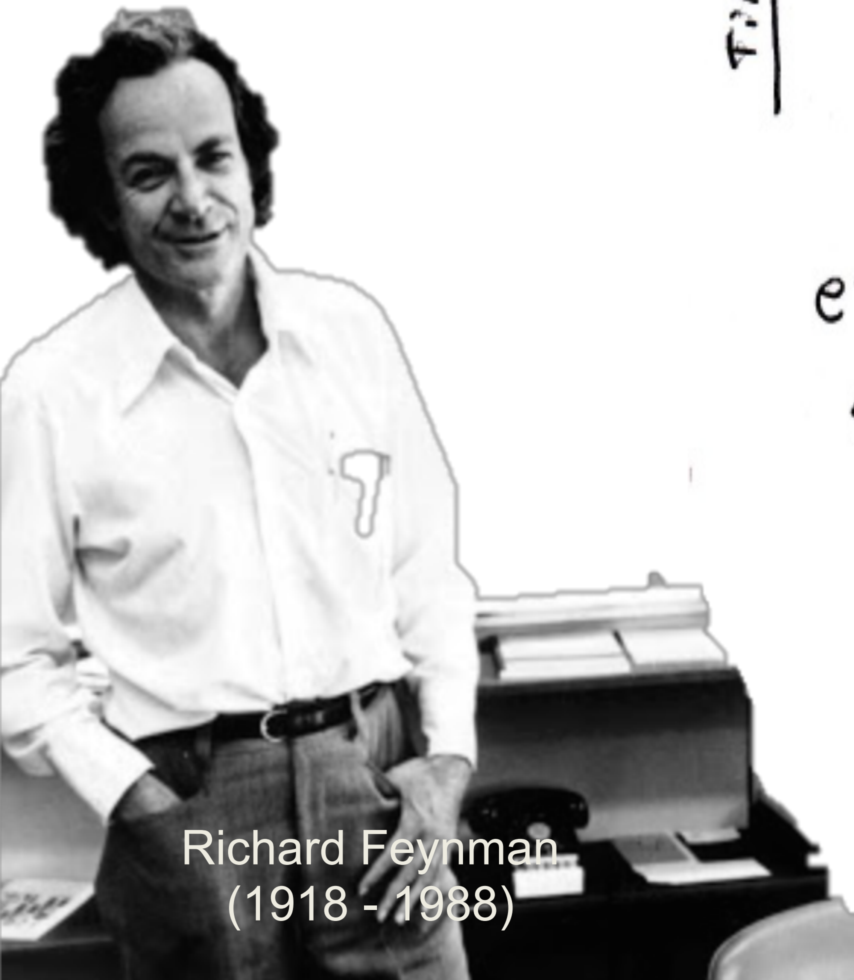
Generalisation of SU(2)

$$U(1) \times SU(2) \times SU(3)$$

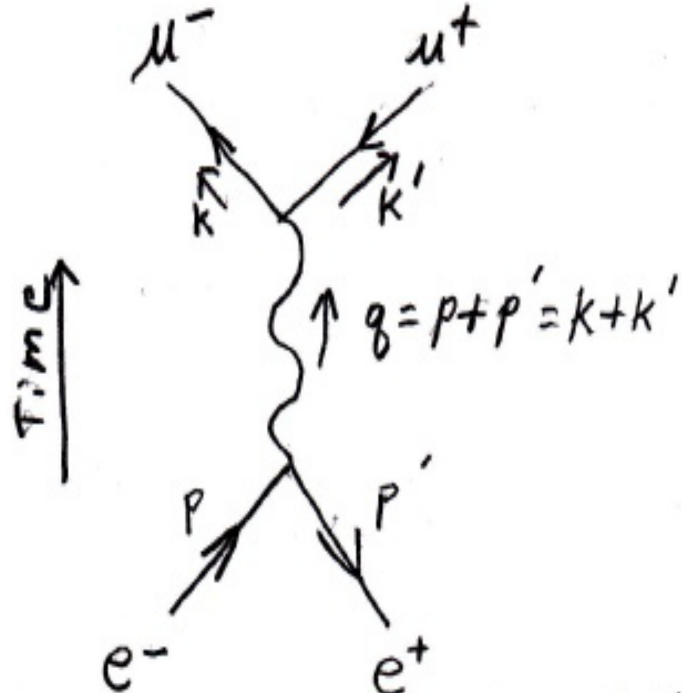
Photon
Electromagnetism

Week interactions
Bosons W^+, W^-, Z

Strong interaction
Gluons



Richard Feynman
(1918 - 1988)

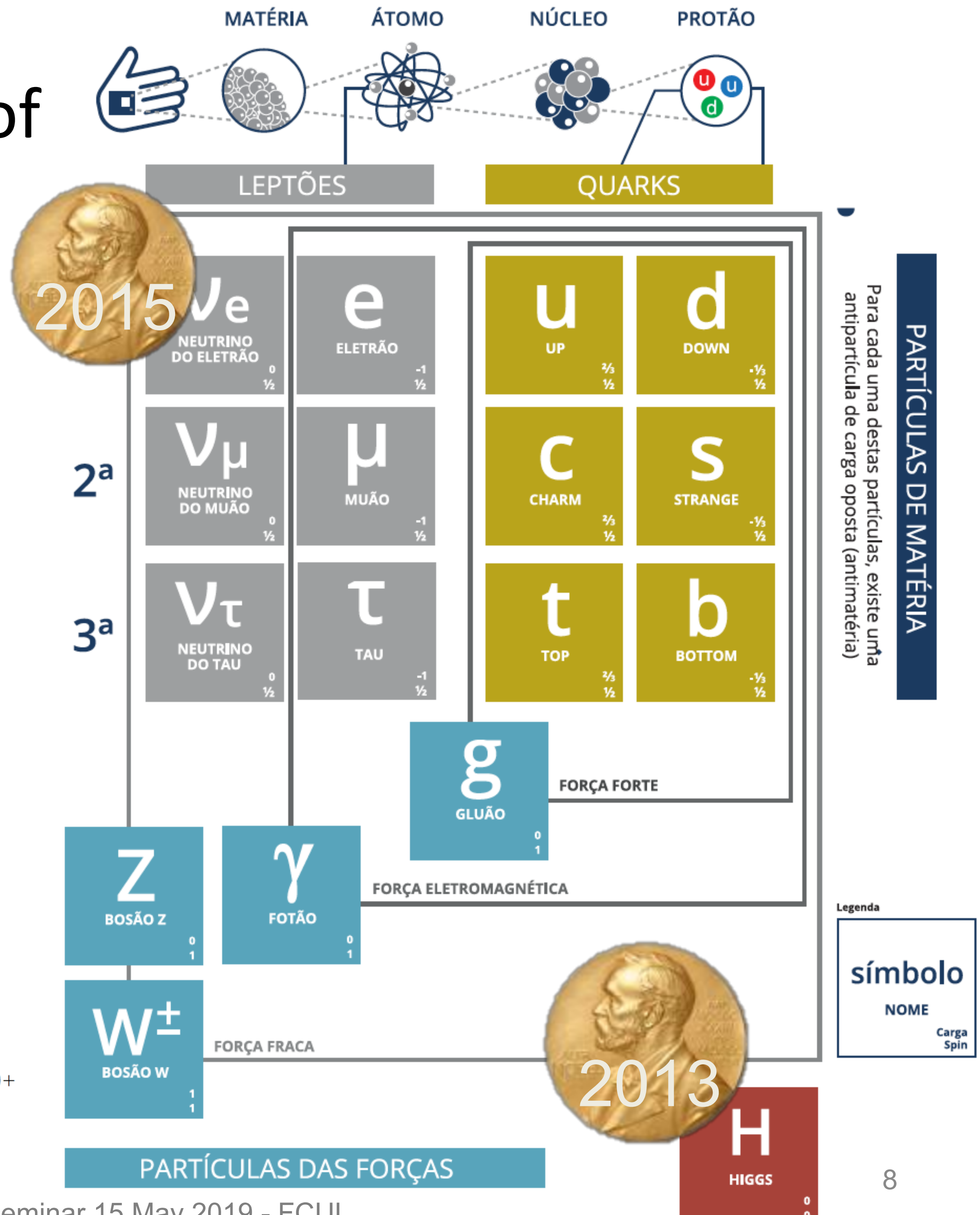


$\langle \text{final state} | H_I | \text{initial state} \rangle$

$\mathcal{M} \sim \langle \mu^+ \mu^- | H_I | \gamma \rangle^{\mu} \langle \gamma | H_I | e^+ e^- \rangle_{\mu}$

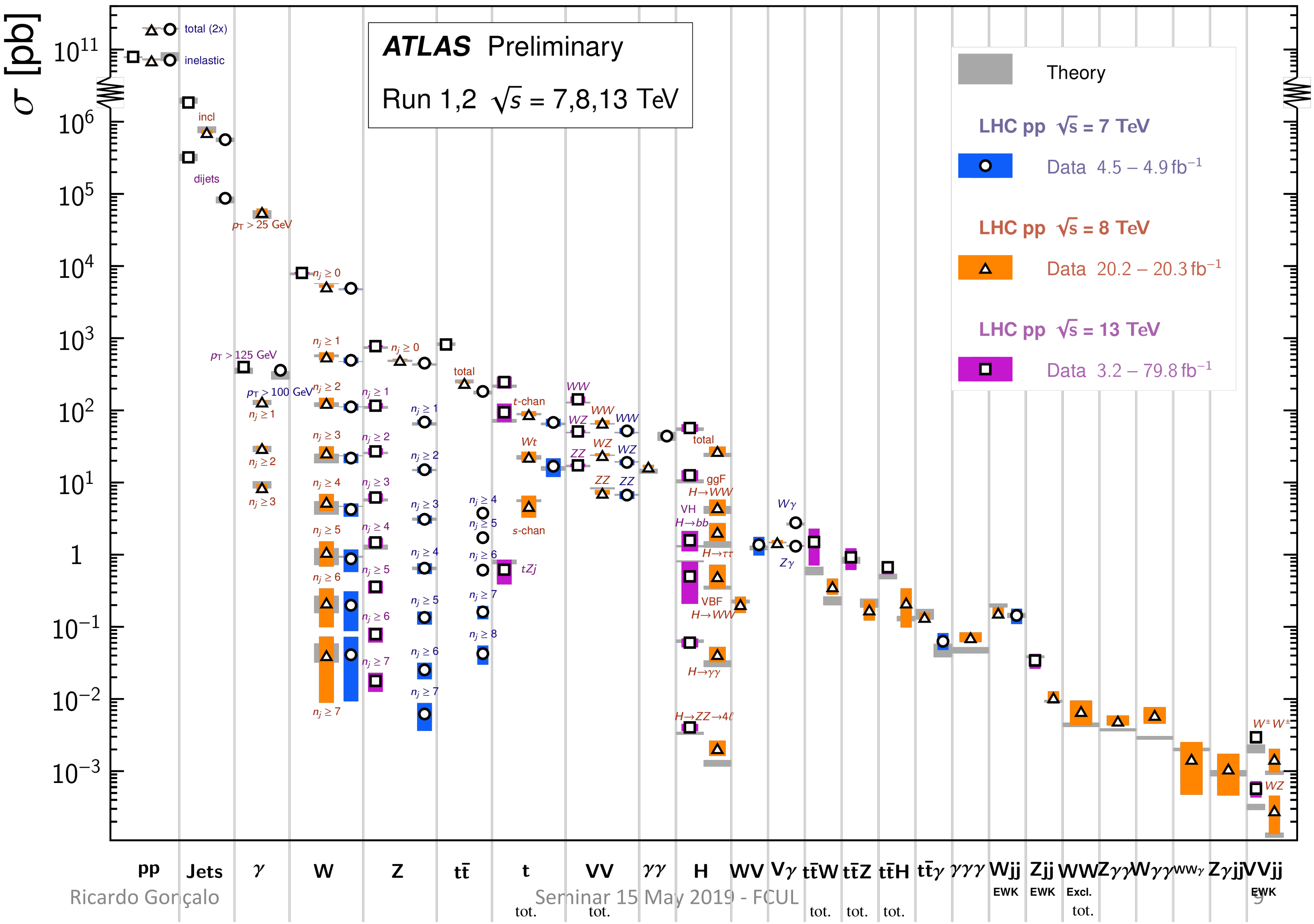
The Standard Model of Particle Physics

$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu\left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right).
\end{gathered}
$$

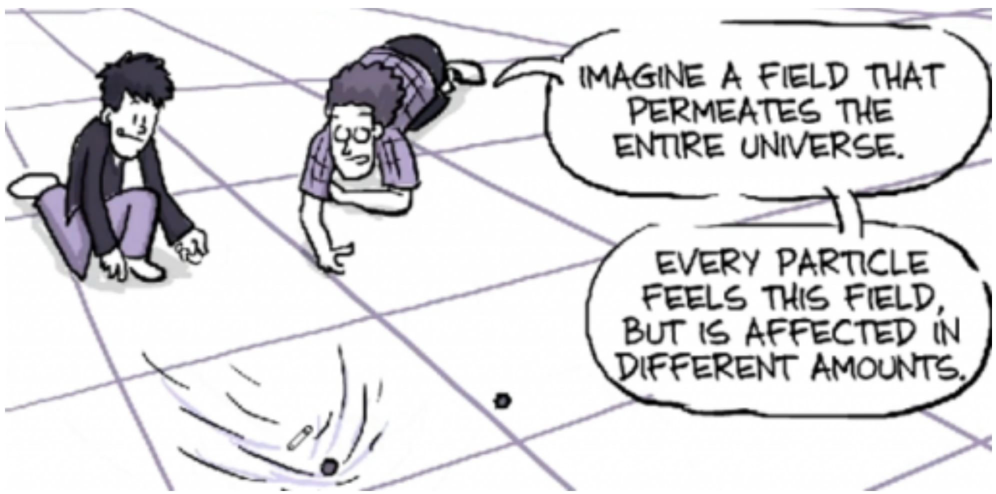


Standard Model Production Cross Section Measurements

Status: July 2018



Why the Higgs?

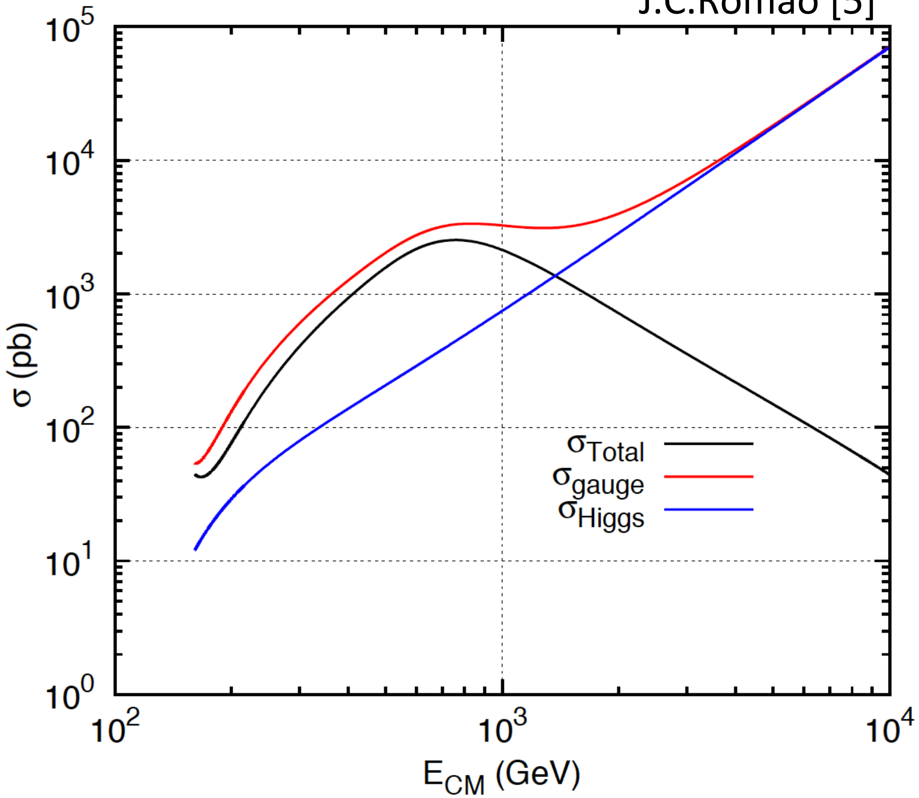


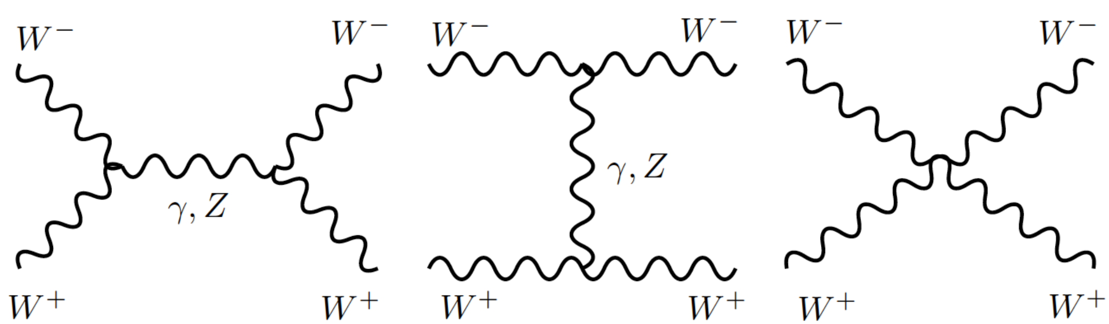
1 Longitudinal gauge-boson scattering

In the absence of the Higgs, some processes have cross sections that grow with the centre of mass energy of the collision…

Breaks unitarity!

J.C.Romão [5]





Feynman diagrams contributing to longitudinal WW scattering

2 Mass of elementary particles and gauge bosons

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu\partial_\mu - m_e)\psi - e\bar{\psi}\gamma^\mu\psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\gamma A_\mu A^\mu$$

To keep the Lagrangian gauge invariant against a U(1) **local** phase transformation:

$$\psi(x) \to \psi'(x) = e^{iq\chi}\psi(x)$$

with $\boldsymbol{\chi} = \boldsymbol{\chi}(x)$. The photon field transforms as:

$$A_\mu \to A'_\mu = A_\mu - \partial_\mu\chi$$

But the $\boldsymbol{A^\mu}$ mass term breaks the invariance of the Lagrangian:

$$\frac{1}{2}m_\gamma A_\mu A^\mu \to \frac{1}{2}m_\gamma(A_\mu - \partial_\mu)(A^\mu - \partial^\mu\chi) \neq \frac{1}{2}m_\gamma A_\mu A^\mu$$

For the $SU(2)_L$ gauge symmetry transformations of the **weak interaction** the fermion mass term $\boldsymbol{m_e\bar{\psi}\psi}$ also breaks invariance!

Bottom line: **the SM (without the Higgs mechanism) results in wrong calculations and gauge invariance breaks down for massive particles**

The Higgs Mechanism

Robert Brout
(1928 – 2011)

Peter Higgs (b. 1929)

François Englert
(b. 1932)

- Introduce a SU(2) doublet of spin-0 complex fields

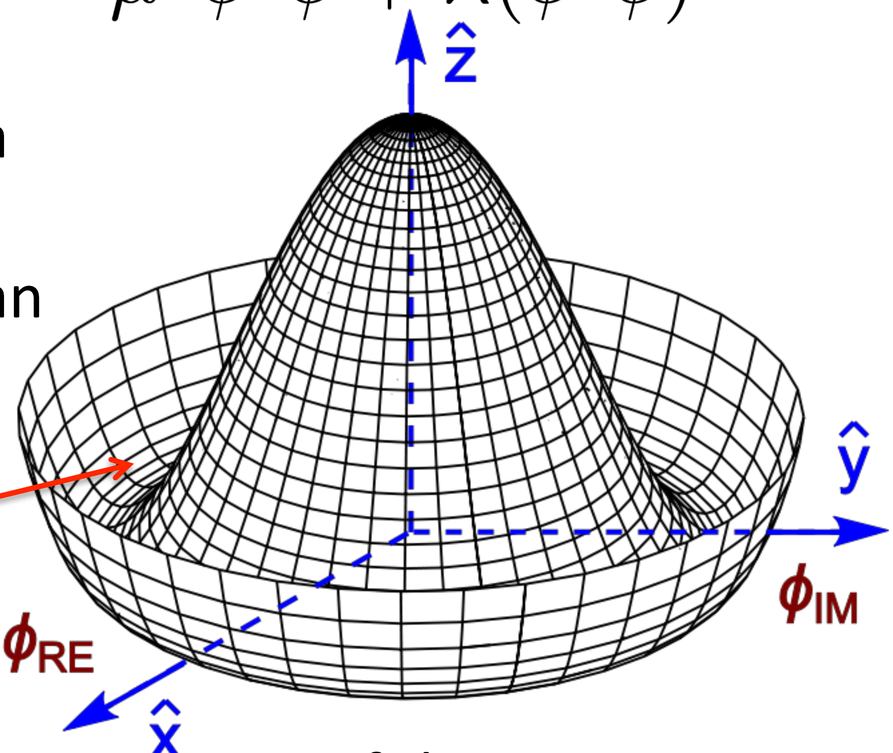
$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi 4 \end{pmatrix}$$

- The Lagrangian term is $\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$

- With a potential $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2$

- For $\lambda>0$, $\mu^2>0$ the potential has a minimum at the origin
- For $\lambda>0$, $\mu^2<0$ the potential has an infinite number of minima at:

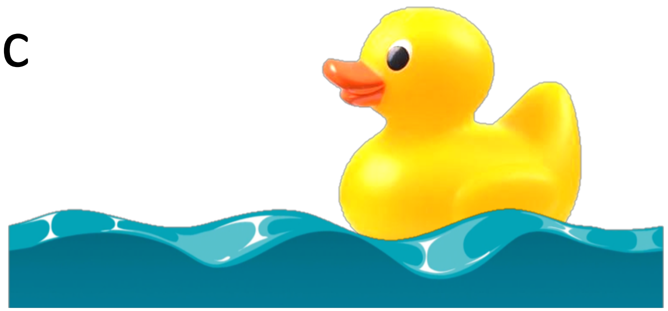
$$|\phi| = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$$



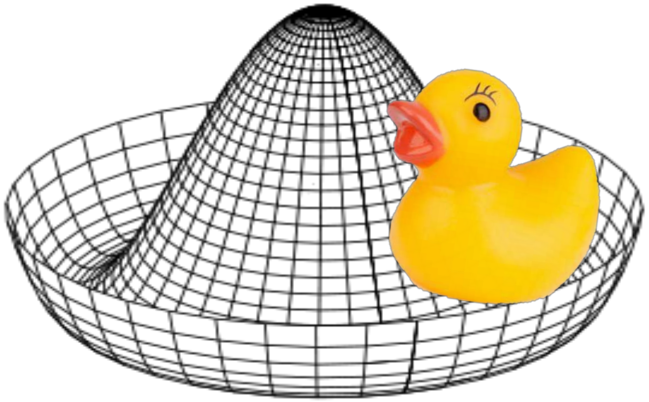
The choice of vacuum (lowest energy state of the field) breaks the symmetry of the Lagrangian

Electroweak symmetry breaking

- In the Standard Model with no Higgs mechanism, interactions are symmetric and **particles do not have mass**

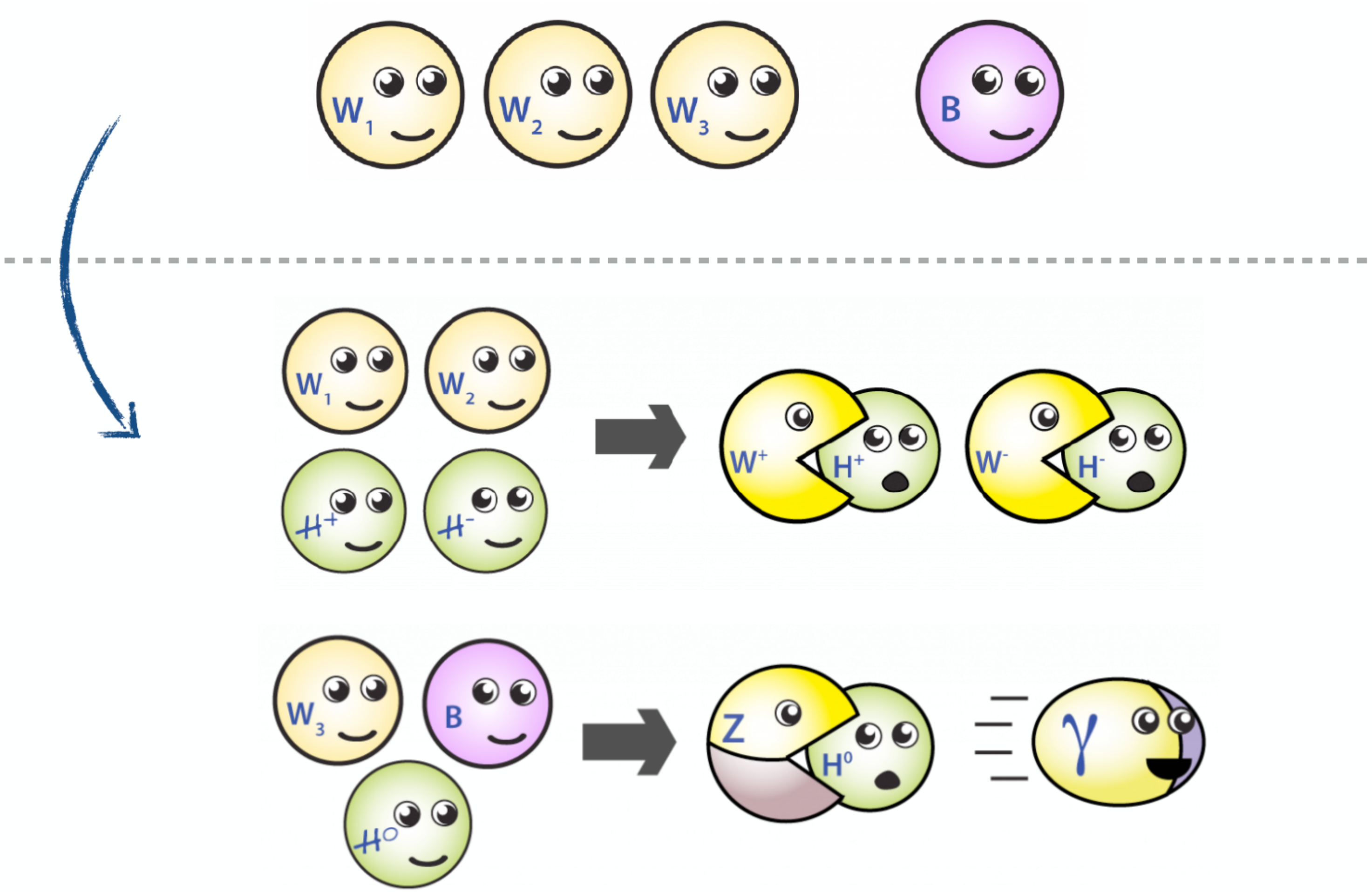


- **Electroweak symmetry is broken**:
  - Photon does not have mass
  - W, Z have a large mass



- Higgs mechanism: mass of W and Z results from the Higgs mechanism
- Masses of fermions come from a direct interaction with the Higgs field

EWK Symmetry Breaking in Pictures

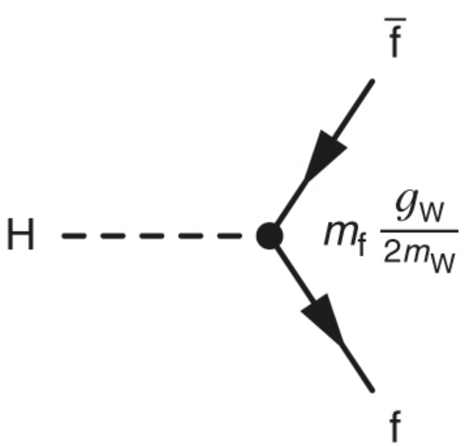


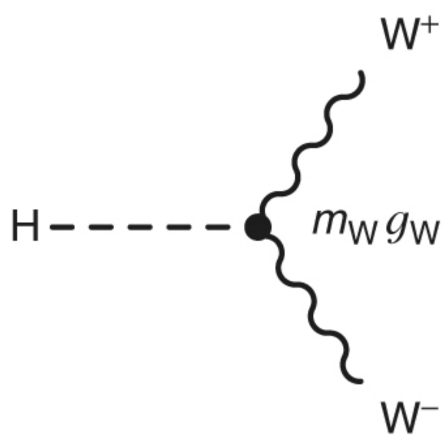
What (we think) we know:

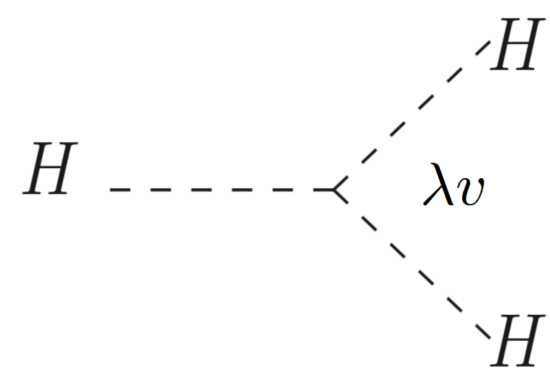
- Higgs mass was(!) the only unknown parameter of the SM

$$m_h = \sqrt{2\lambda}v$$

- We can give mass to $W^{\pm}$ and Z and keep the photon massless
- Higgs couples to W and Z proportionally to their masses
- Higgs couples to fermions proportionally to their mass

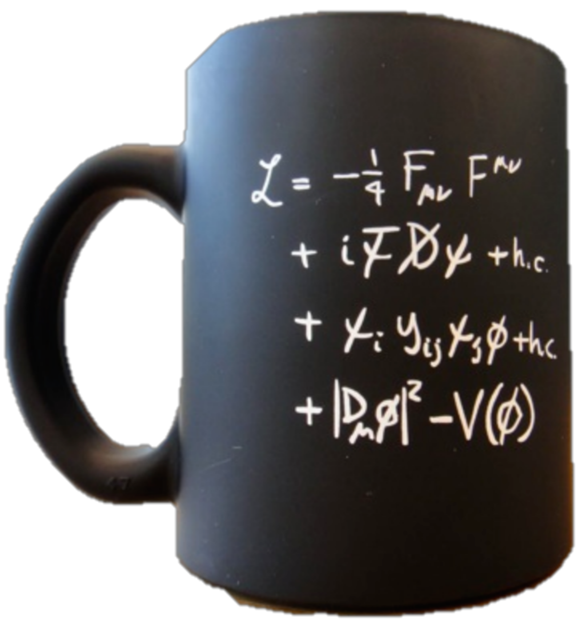




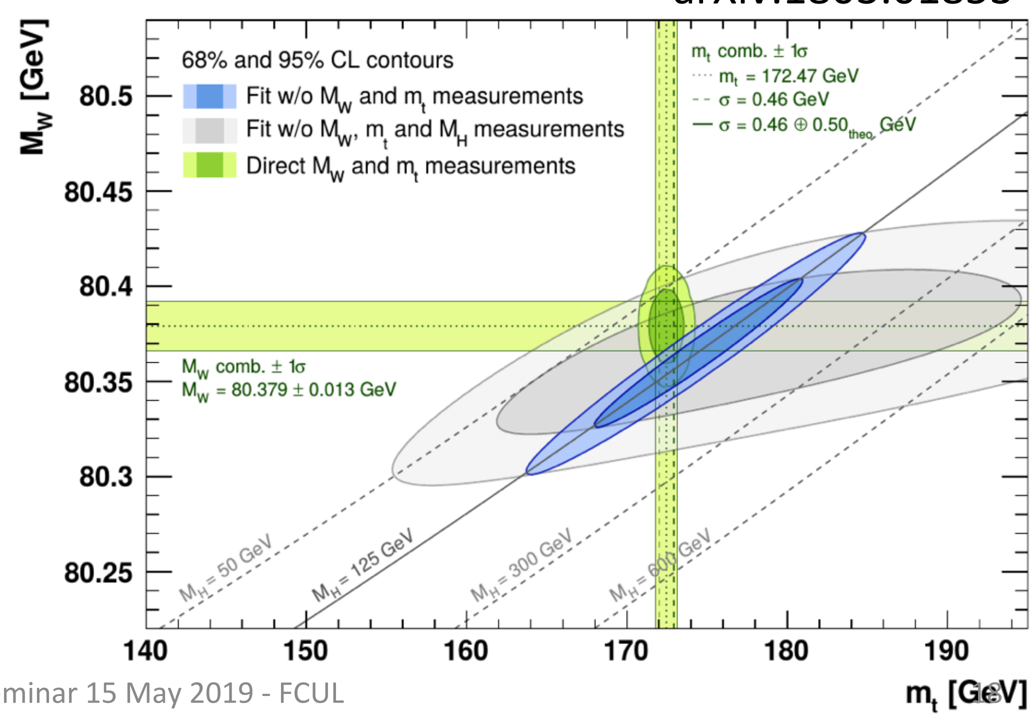


Exploring the electroweak scale

- Precision measurements of m_W, m_t, m_H are stringent tests of the SM at the EW scale
  - E.g. excluding measured m_H, global EW fit gives m_H = 90 ± 21 GeV (1.7 σ tension)



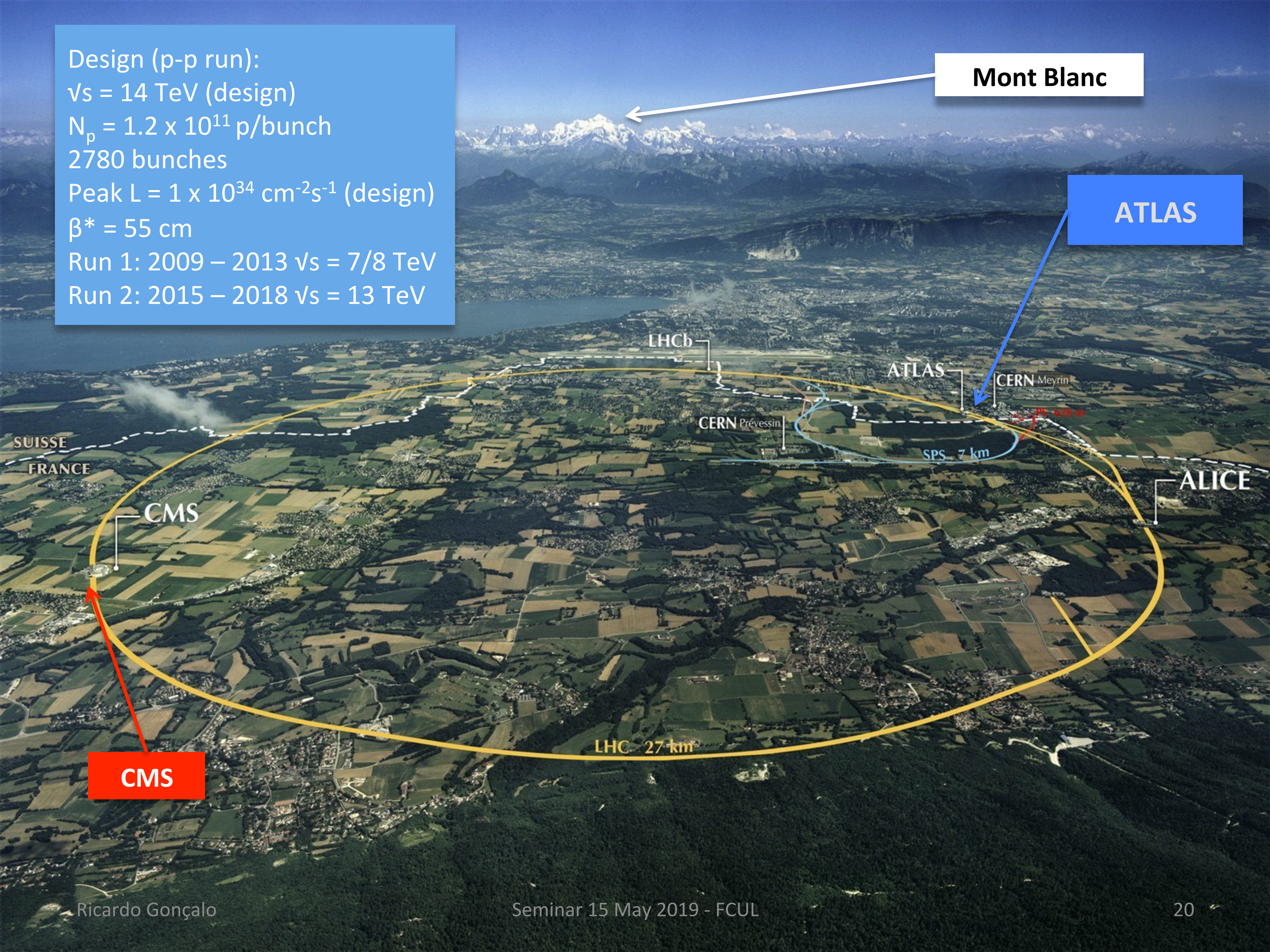
arXiv:1803.01853



Tools of the Trade

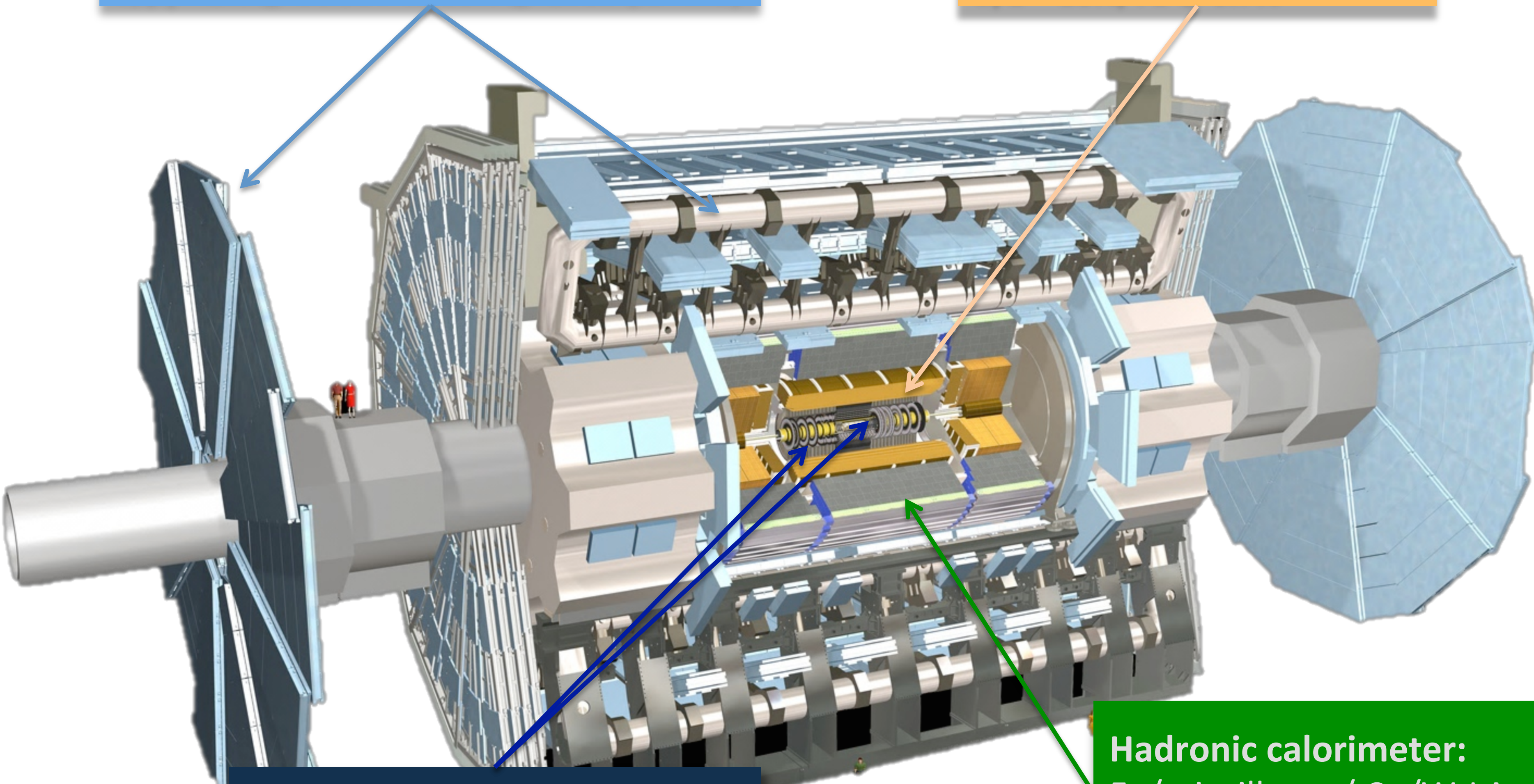
The LHC and its experiments

Design (p-p run):
$\sqrt{s}$ = 14 TeV (design)
$N_p = 1.2 \times 10^{11}$ p/bunch
2780 bunches
Peak L = 1×10^{34} $cm^{-2}s^{-1}$ (design)
β^* = 55 cm
Run 1: 2009 – 2013 $\sqrt{s}$ = 7/8 TeV
Run 2: 2015 – 2018 $\sqrt{s}$ = 13 TeV



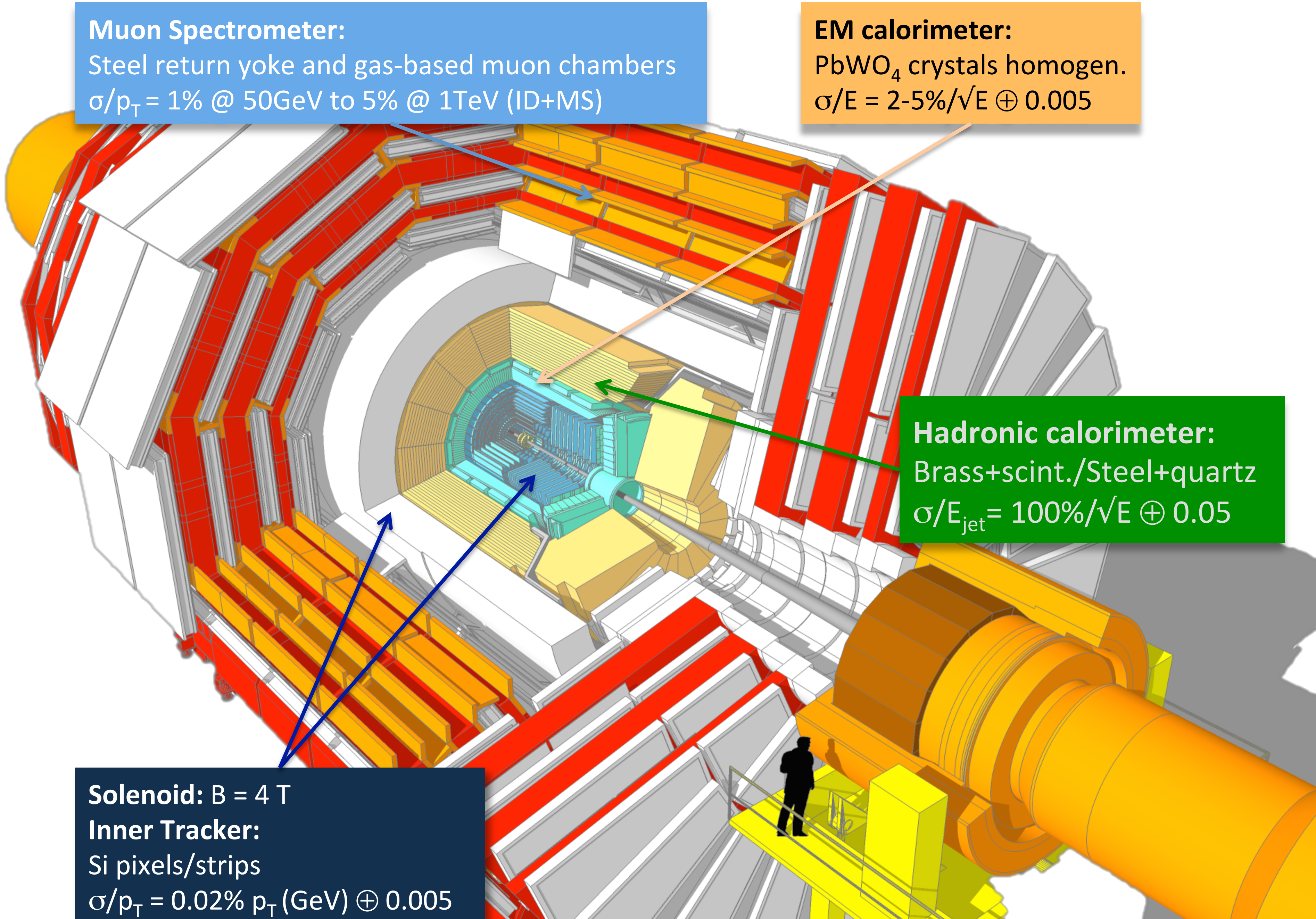
Muon Spectrometer: $|\eta| < 2.7$
Air-core toroid + gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

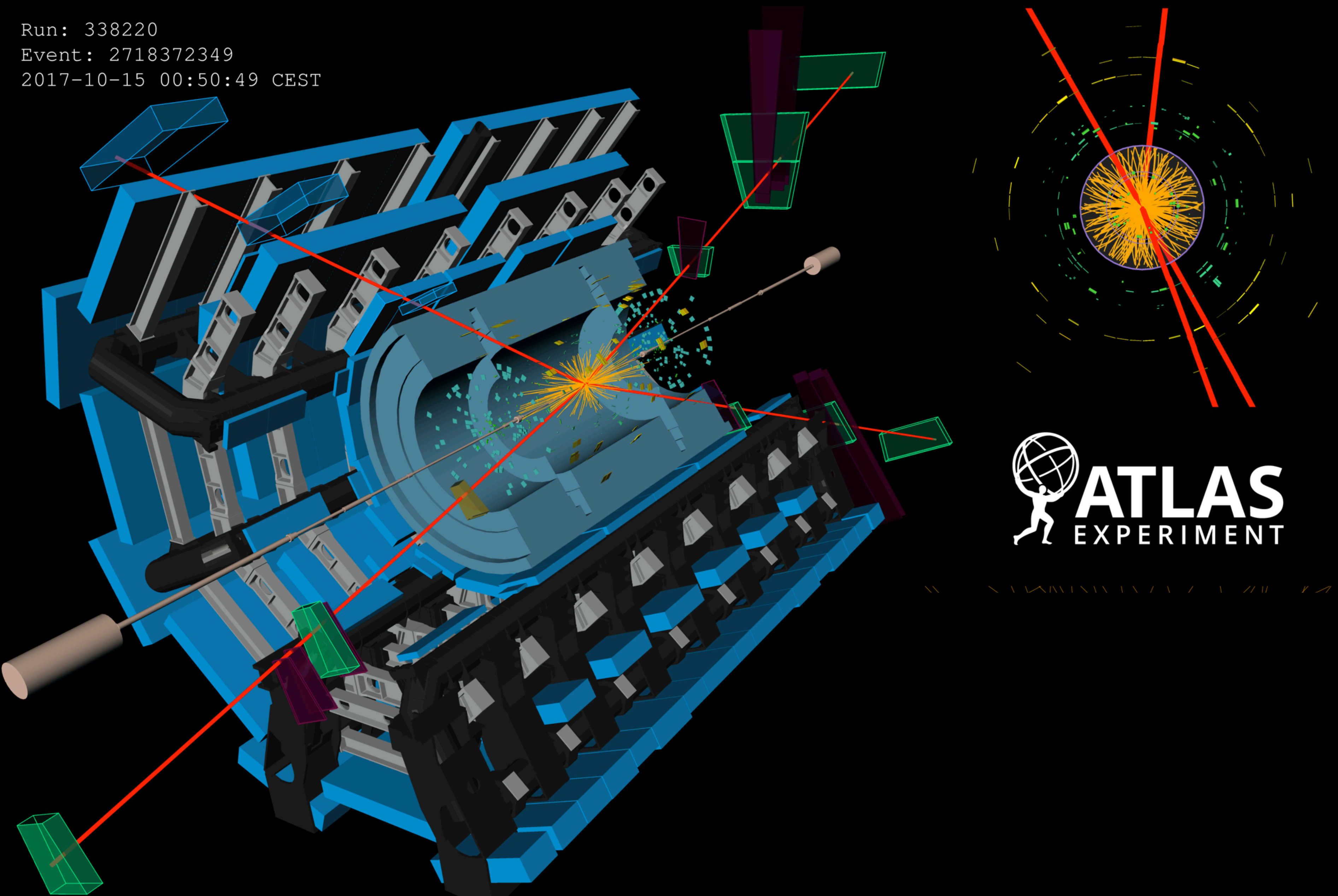
EM calorimeter: $|\eta| < 2.5$ (3.2)
Pb-LAr accordion sampling
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$

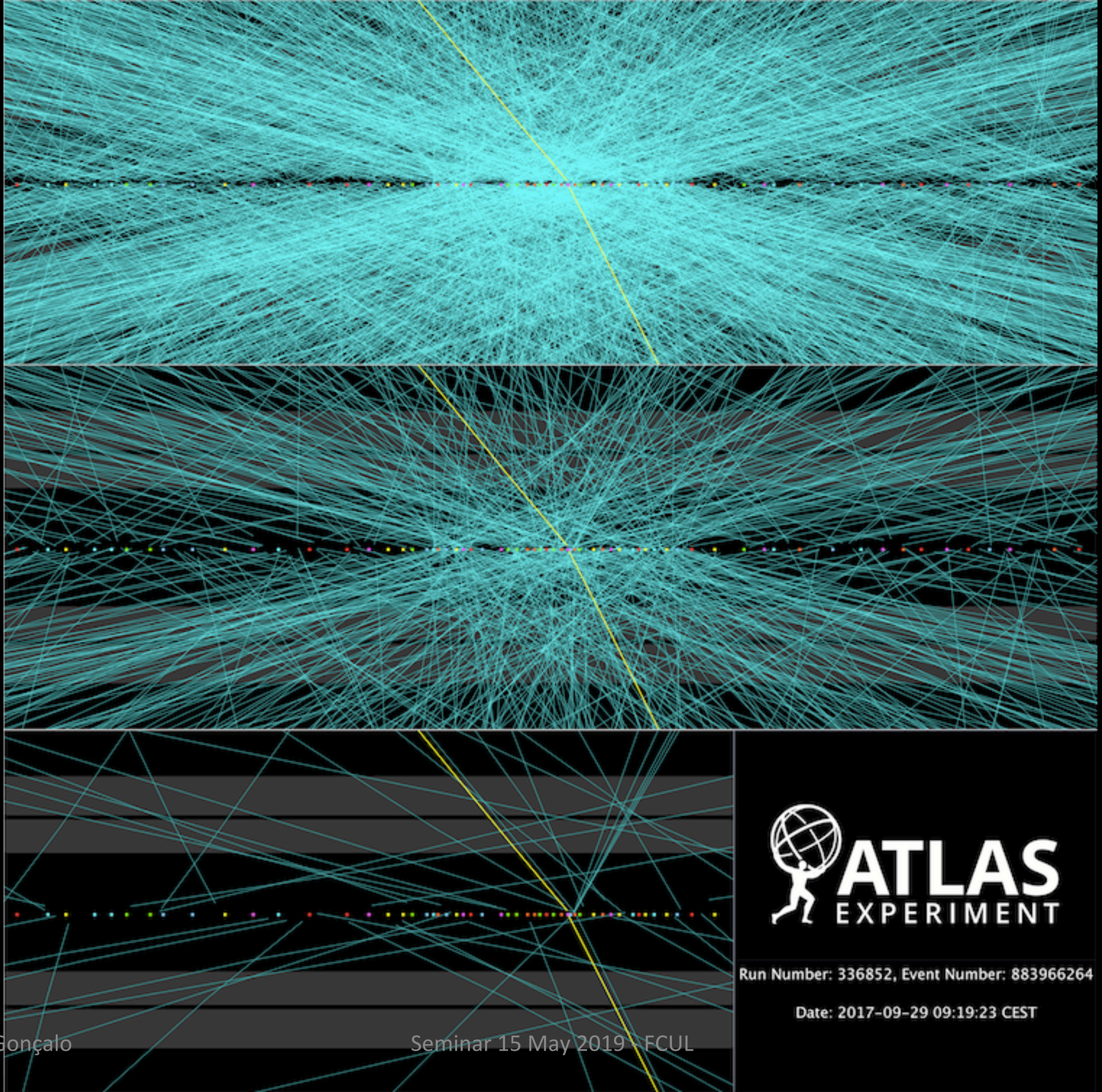


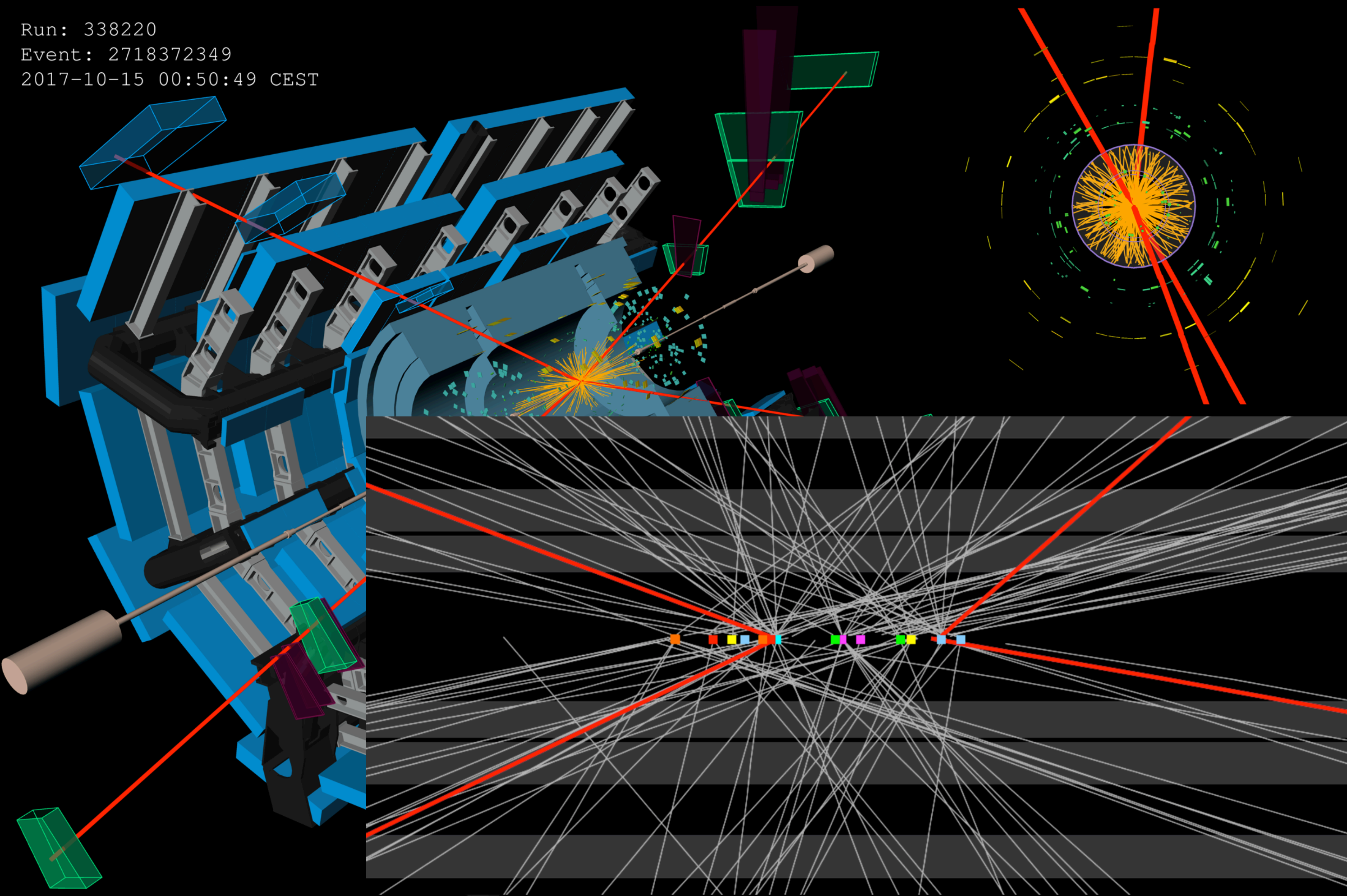
Solenoid: B = 2 T
Inner Tracker: $|\eta| < 2.5$
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\mathrm{GeV}) \oplus 1\%$

Hadronic calorimeter:
Fe/scintillator / Cu/W-LAr
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$


Muon Spectrometer:
Steel return yoke and gas-based muon chambers
σ/p_T = 1% @ 50GeV to 5% @ 1TeV (ID+MS)
EM calorimeter:
$PbWO_4$ crystals homogen.
$\sigma/E = 2\text{-}5\%/\sqrt{E} \oplus 0.005$
Hadronic calorimeter:
Brass+scint./Steel+quartz
$\sigma/E_{jet} = 100\%/\sqrt{E} \oplus 0.05$
Solenoid: B = 4 T
Inner Tracker:
Si pixels/strips
$\sigma/p_T = 0.02\%\ p_T\,(\mathrm{GeV}) \oplus 0.005$

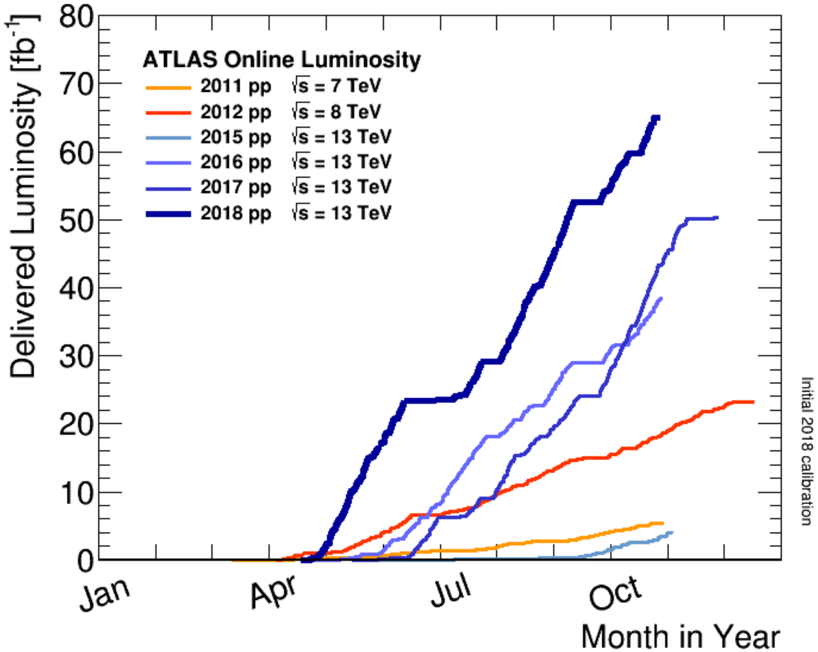

Run: 338220
Event: 2718372349
2017-10-15 00:50:49 CEST
ATLAS
EXPERIMENT

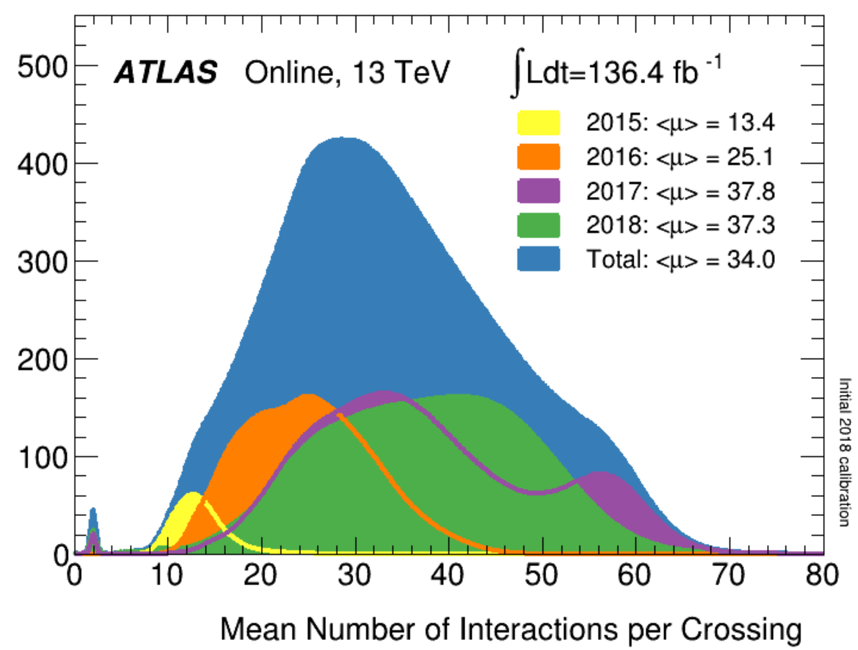

ATLAS
EXPERIMENT
Run Number: 336852, Event Number: 883966264
Date: 2017-09-29 09:19:23 CEST


Run: 338220
Event: 2718372349
2017-10-15 00:50:49 CEST

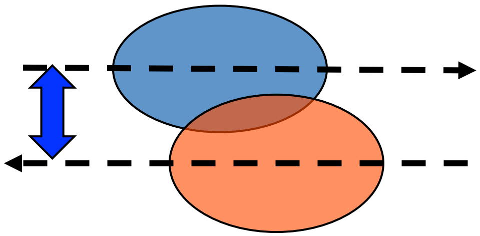
ATLAS, CMS and the LHC

- Run 1: 2009 – 2013; ≈ 5 fb^{-1} at √s = 7 and ≈ 20 fb^{-1} at 8 TeV per experiment
- Run 2: 2013 – 2018; 149 fb^{-1} recorded at √s = 13 TeV by the end of pp run
- Instantaneous luminosity of **2×10^{34} $cm^{-2}s^{-1}$** in 2017 (2x design!)
- Downside is pileup => experimental challenge!
  - Multiple vertices, large occupancy, degraded reconstruction resolution, etc
  - LHC breaking new ground to go around this: leveling!

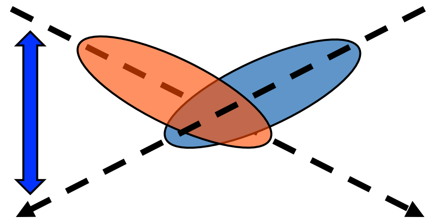




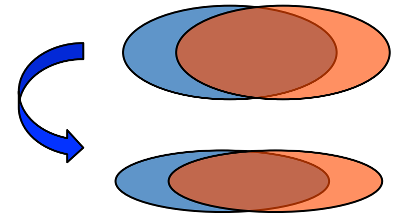
Leveling by beam offset

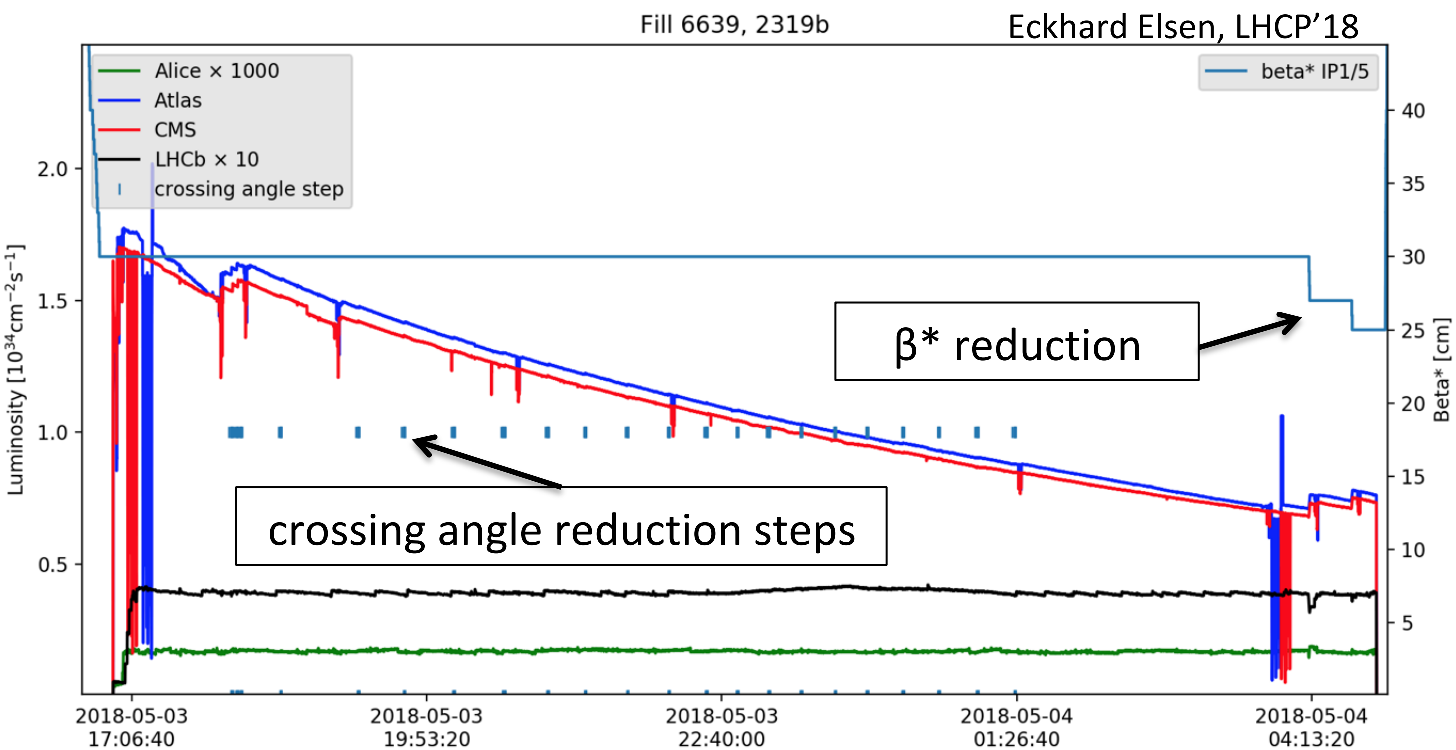


Anti-leveling: crossing angle



Anti-leveling: β* reduction

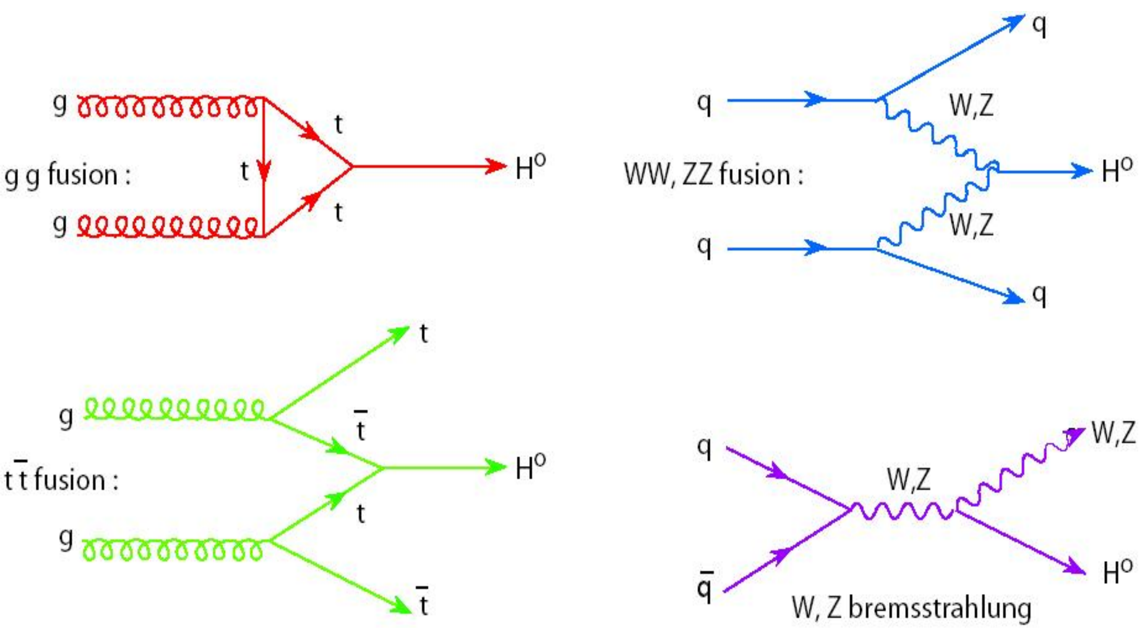


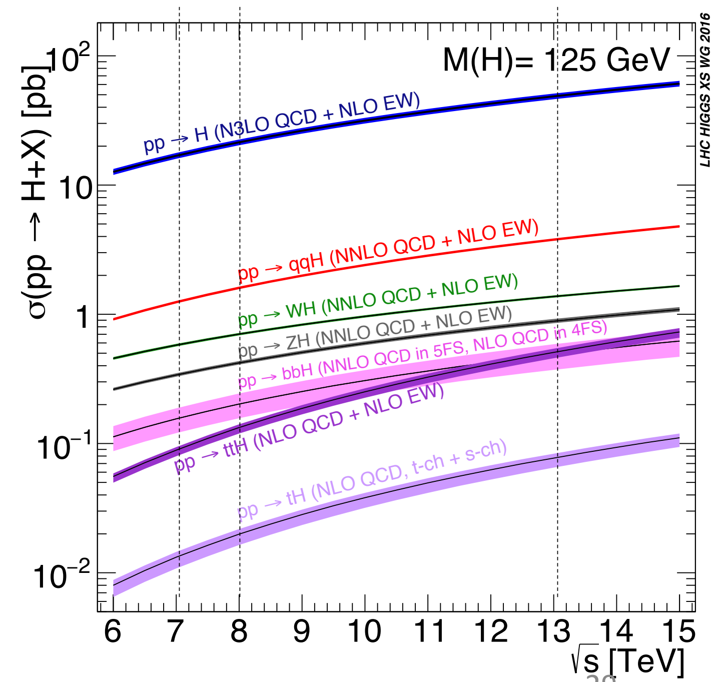


Higgs at the LHC

Higgs @ the LHC

- Many different production and decay mechanisms
  - Span 3 orders of magnitude in cross section and branching ratio
  - Some very clean decays with low BR (γγ, 4l)
  - Other very difficult with higher rates (bb, WW, ττ,...)
- Access Higgs properties through combination of different channels
- Enormous amount of progress since discovery 6 years ago!





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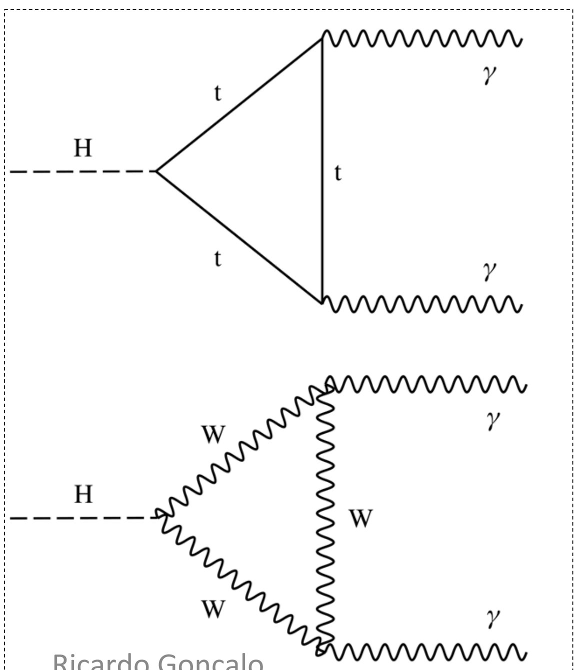
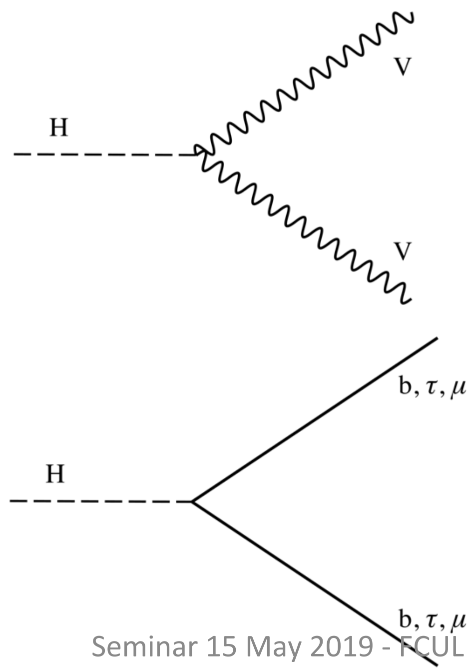
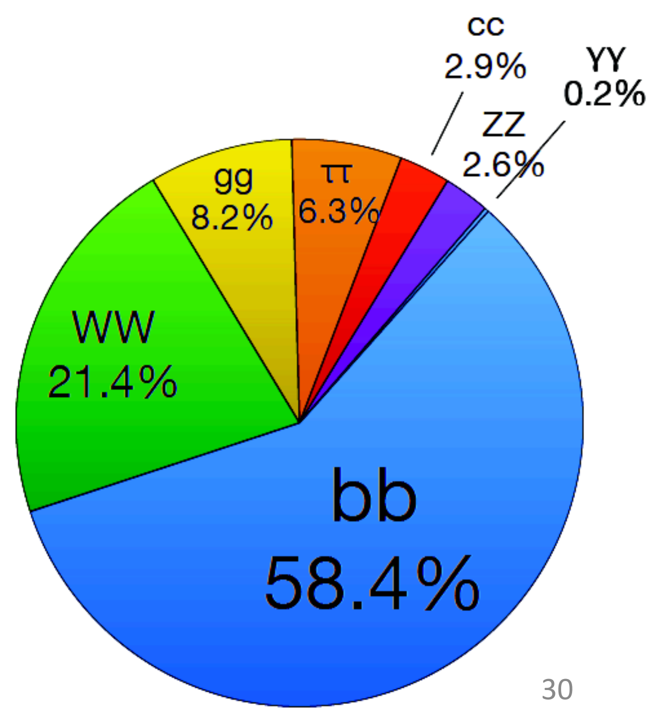
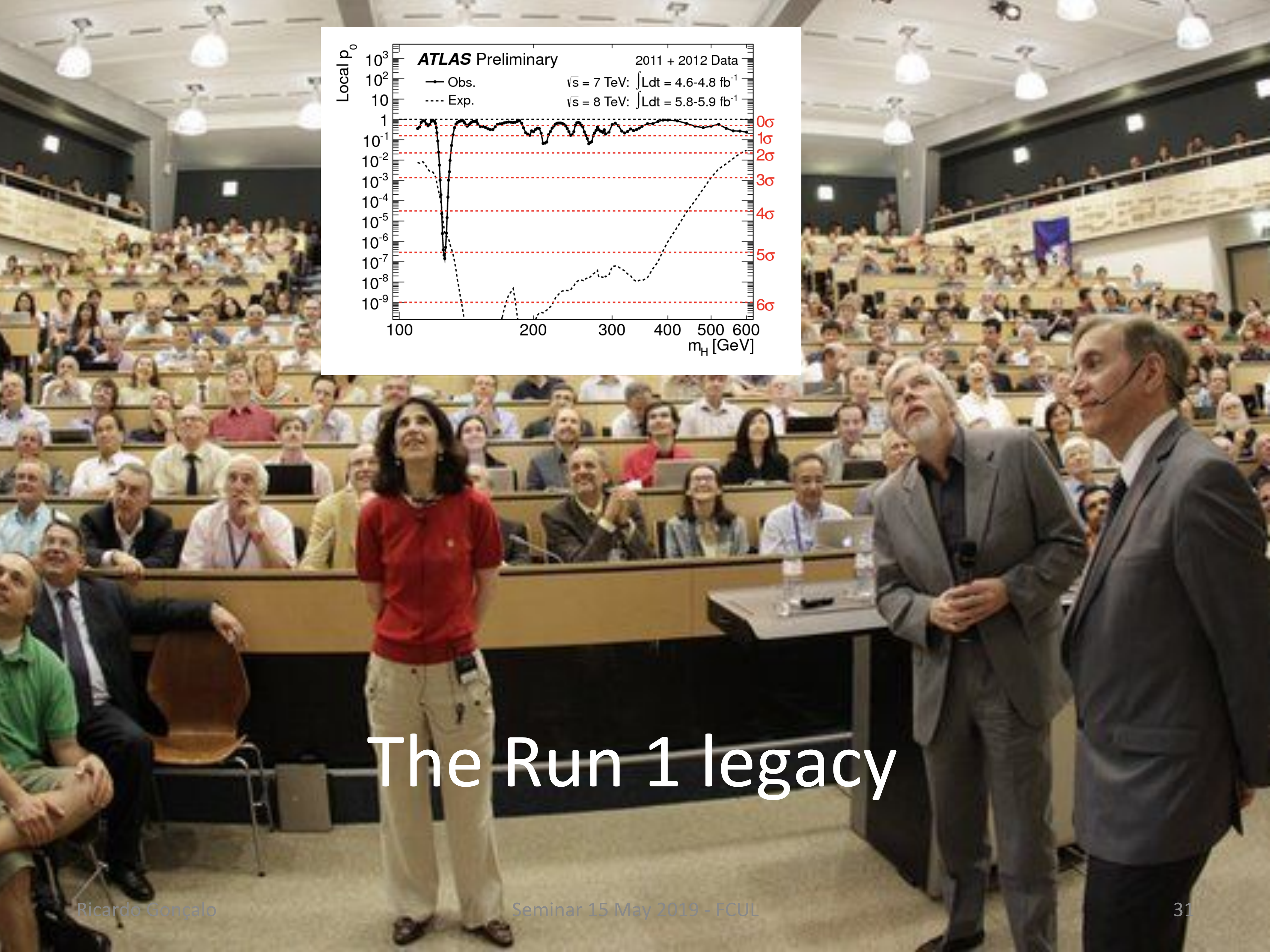






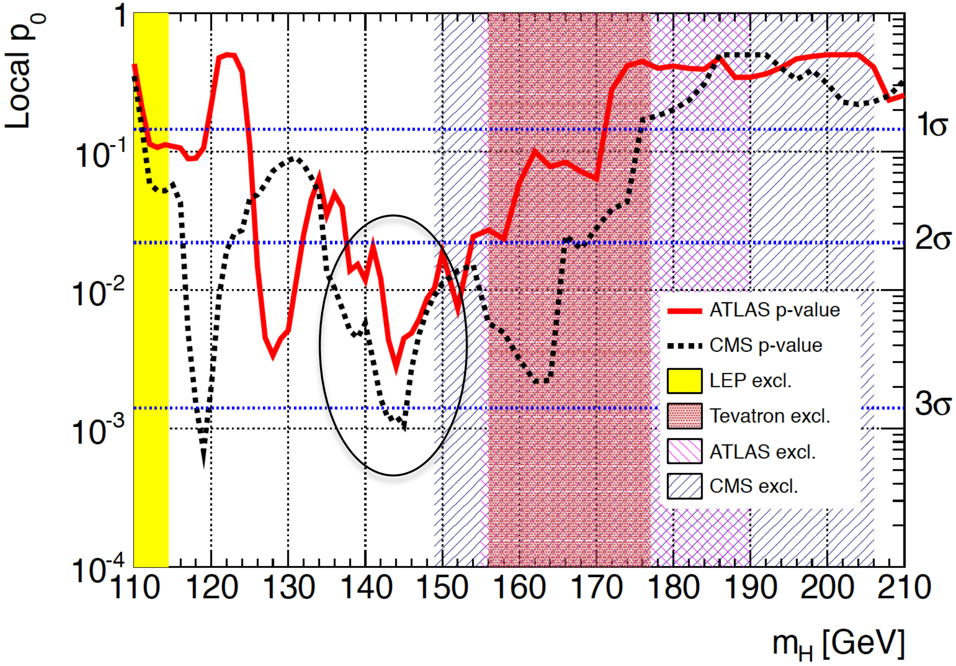


The Run 1 legacy


The INDEPENDENT
EUREKA!
It has taken nearly 50 years and cost £2.6bn. Now, at last, the Higgs boson particle has been found – and a new chapter in our understanding of the universe can begin
Diamond: I'm sorry (but not sorry enough to give up his pay-off)
HOMOPHOBIA, HIP-HOP AND THE STAR WHO CAME OUT
THE L'OREAL FILES: COULD SARKOZY GO DOWN?
MURRAY ONE MATCH FROM THE FINAL
PHYSICS LETTERS B
Volume 716, Issue 1, 17 September 2012
ELSEVIER
SciVerse ScienceDirect
CMS
ATLAS
Le Monde.fr
Le boson de Higgs découvert avec 99,9999 % de certitude
Voici la confirmation tant attendue : une nouvelle particule a été découverte au Centre européen de recherche nucléaire (CERN), près de Genève.
Boson de Higgs : la fin de la traque
Le boson de Higgs : les raisons d'une quête
EL PAÍS
Los científicos del CERN anuncian el descubrimiento de una partícula que podría ser Higgs.
Hallada "la más sólida evidencia" de la existencia del bosón de Higgs
El posible descubrimiento de la partícula es un paso esencial
Registro del CMS que pudiera ser la firma de la partícula de Higgs. / CERN
NEWSPAPER OF THE YEAR
Dramatic victory takes Murray through to semi-finals
Scientists prove existence of 'God particle'
find after 45-year hunt for Higgs boson ... his life's work finally bears fruit ... serves the Nobel Prize, says Hawking
The New York Times
Wednesday, July 4, 2012
New Particle Could Be Physics' Holy Grail
NÉPSZABADSÁG ONLINE
Úgy tűnik, megvan az 'isteni' részecske
Higgs search update

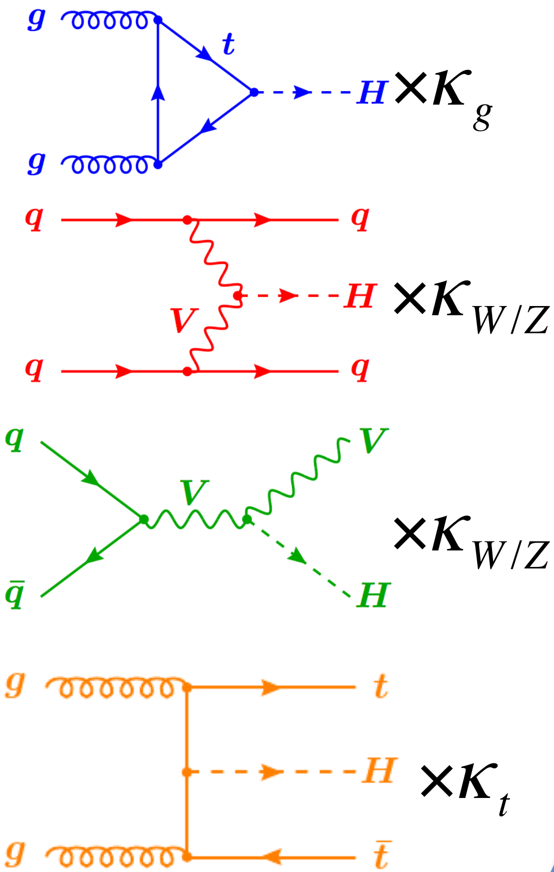
It takes time to get it right

EPS-HEP 2011 conference



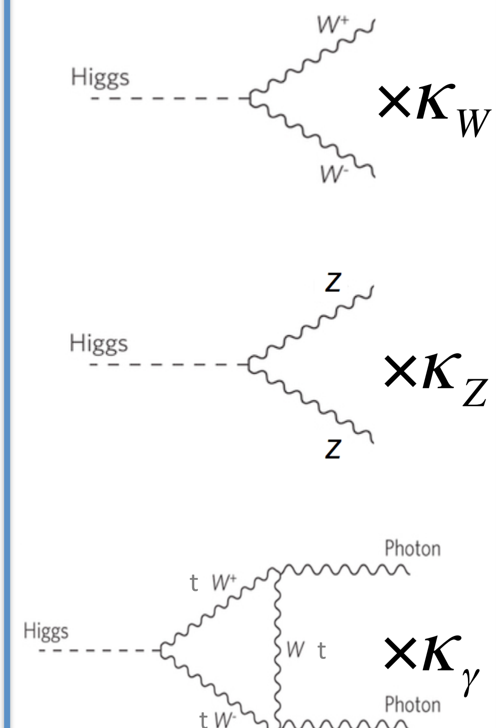
$$\kappa_i^2 = \sigma_i / \sigma_i^{SM} \qquad \kappa_f^2 = \Gamma_f / \Gamma_f^{SM} \qquad \mu = \frac{(\sigma \cdot BR)^{Obs.}}{(\sigma \cdot BR)^{SM}} = \kappa_i^2 \cdot \kappa_f^2$$

Production



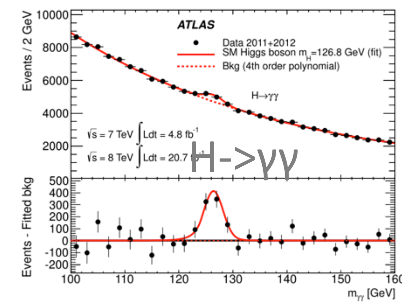
$\times$

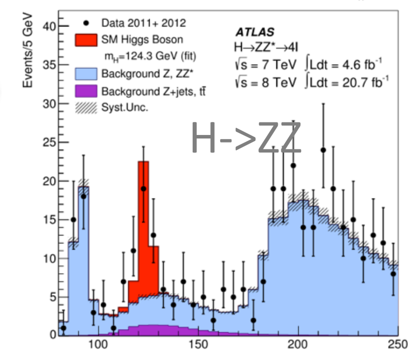
Decay

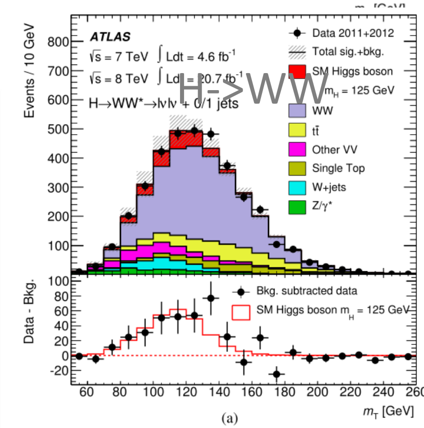


FIT

Backgrounds +





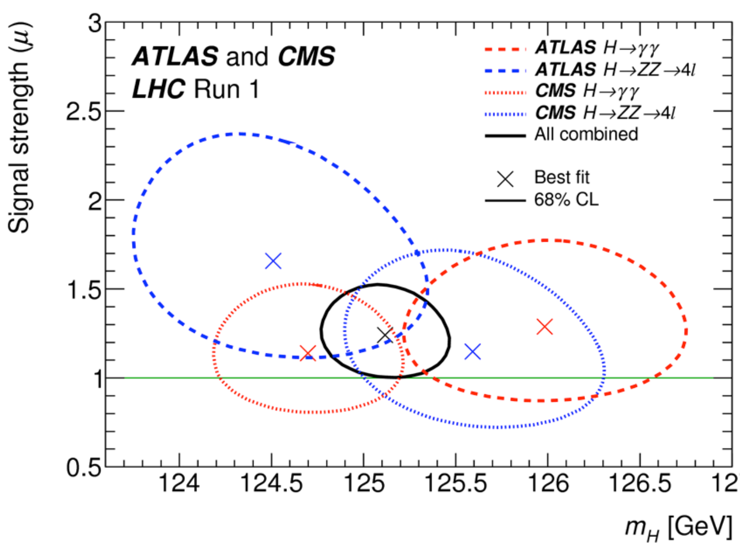


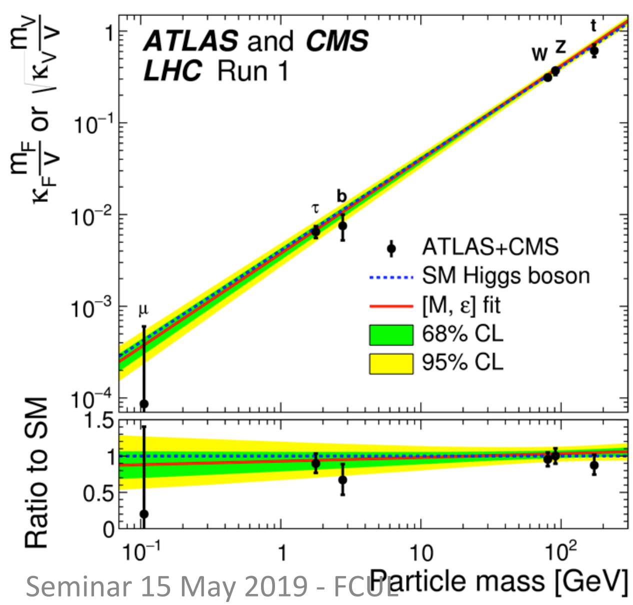
Phys. Rev. Lett. 114 (2015) 191803
JHEP 08 (2016) 045

The Run 1 legacy

- Mass – Higgs mass measured with 0.2% accuracy:
  - **m_H = 125.09 ± 0.21 (stat.) ± 0.11 (scale) ± 0.02 (other) ± 0.01 (theory) GeV**
- Couplings:
  - ggF with H → ZZ,γγ,WW **observed** by individual experiments
  - VBF and H → ττ observed with **>5σ** significance by ATLAS+CMS combination
  - ttH, VH production and H → bb **not observed** during Run1
- Couplings **compatible with SM**:
  - Signal strength: $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.06^{+0.35}_{-0.27}$
  - Coupling modifiers broadly consistent with SM but large uncertainty

$\mu = (\sigma\times BR)_{Obs} / (\sigma\times BR)_{SM}$





Significance (σ)		
Prod.	Obs.	Expect.
VBF	5.4	4.7
VH	3.5	4.2
ttH	4.4	2.0
Decay	Obs.	Expect.
H→ττ	5.5	5.0
H→bb	2.6	3.7

Phys. Rev. Lett. 114 (2015) 191803
JHEP 08 (2016) 045

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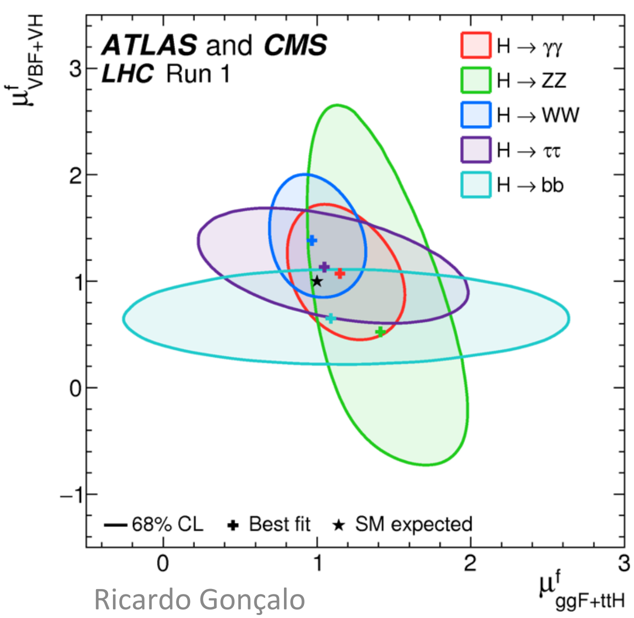

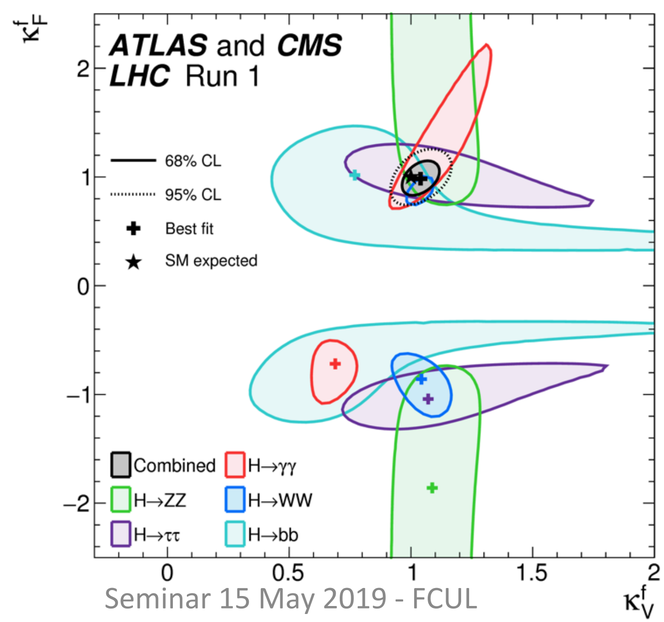

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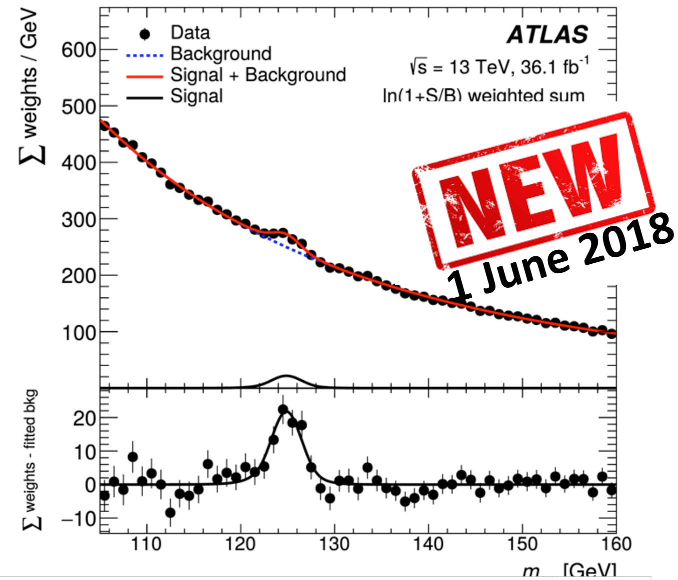
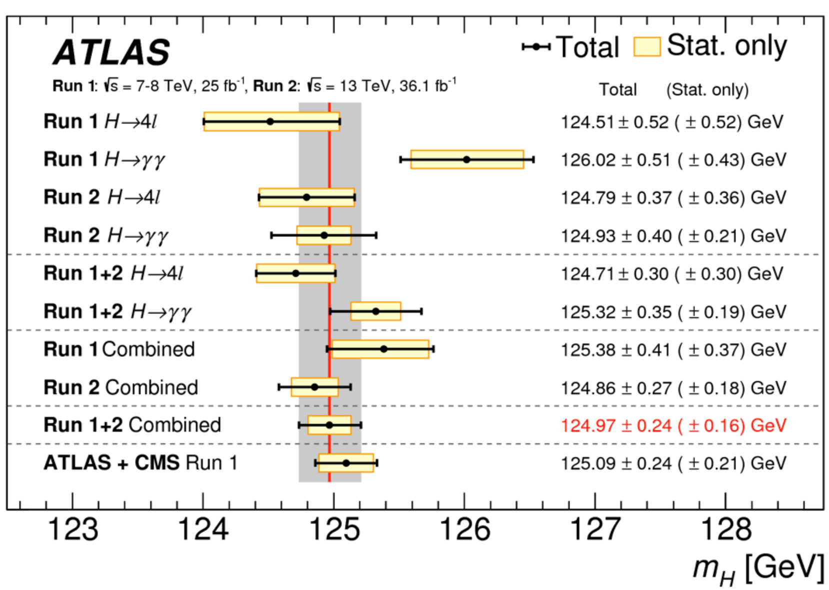
Decay	Obs.	Expect.
H→ττ	5.5	5.0
H→bb	2.6	3.7

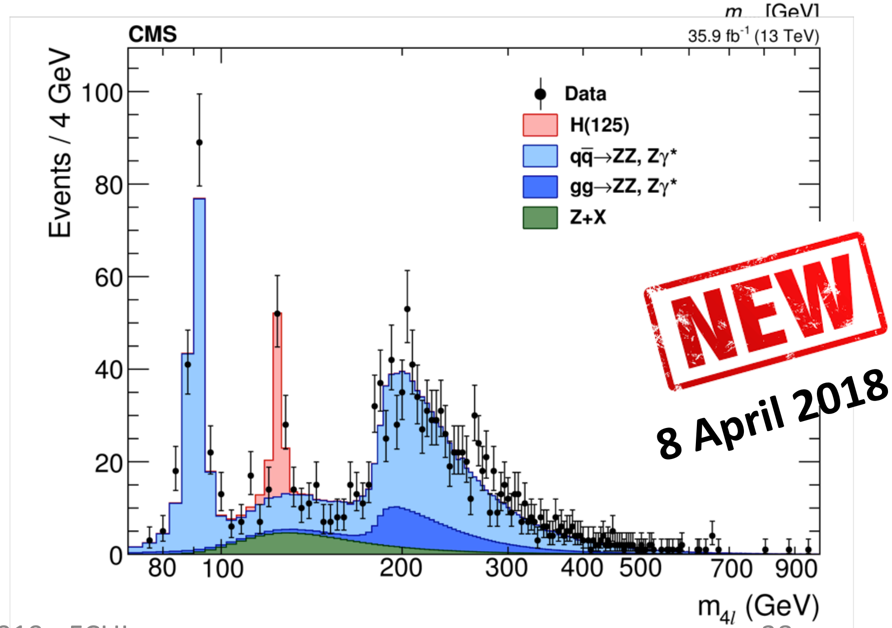
Probing the 125 GeV Higgs in Run 2

Higgs boson mass

- Mass measurement from CMS $H \rightarrow ZZ^* \rightarrow 4l$:
  $m_H^{ZZ^*} = 125.26 \pm 0.20\ (\text{stat}) \pm 0.08\ (\text{syst})$ GeV
- New Measurements from ATLAS
  $H \rightarrow \gamma\gamma$: $m_H^{\gamma\gamma} = 124.93 \pm 0.40$ GeV
  $H \rightarrow ZZ^* \rightarrow 4l$: $m_H^{ZZ^*} = 124.79 \pm 0.37$ GeV
- Run 1+2 combination from ATLAS:
  $m_H = 124.97 \pm 0.19\ (\text{stat}) \pm 0.13\ (\text{syst.})$ GeV



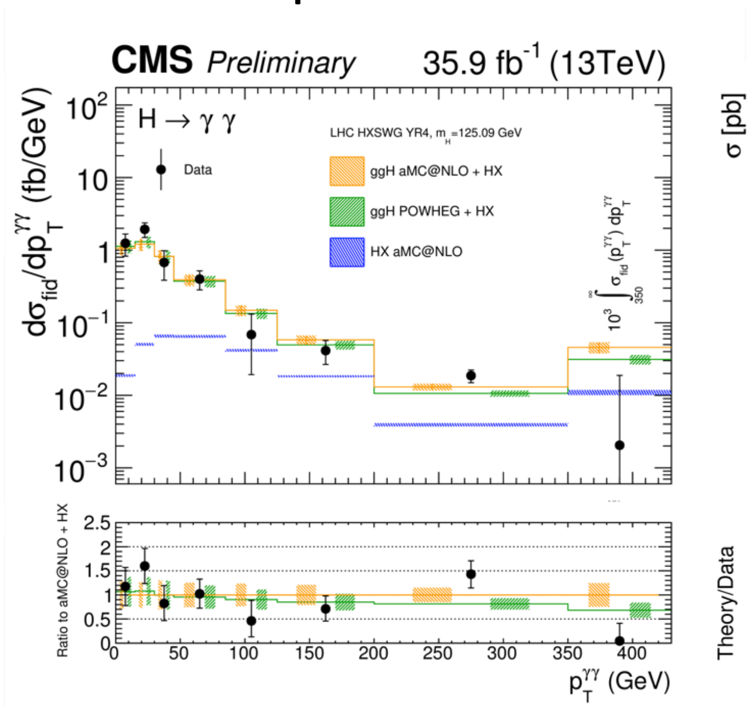


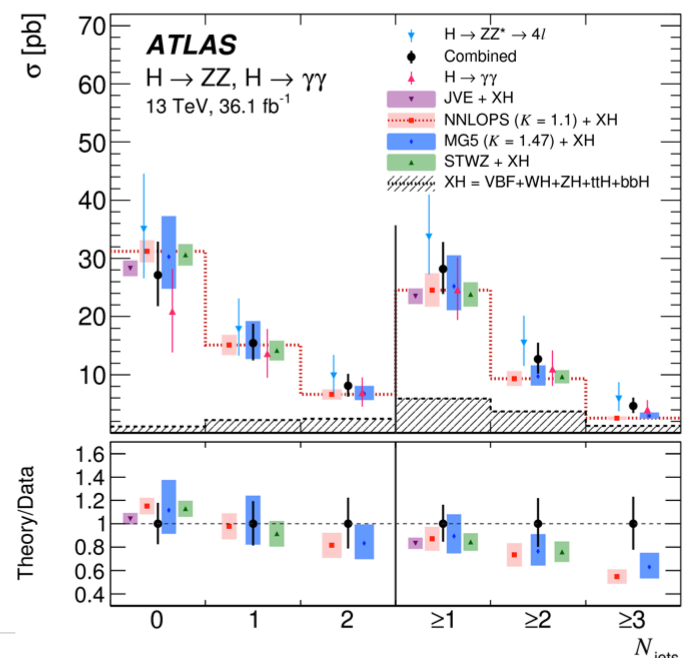


Differential Higgs boson cross sections

- Reached a new phase in the exploration of the Higgs sector!
- Differential cross sections:
  - Higgs p_T sensitive to new physics in gluon-fusion loop
  - Number of jets sensitive to modeling of radiation and different production modes

NEW
May - July 2018





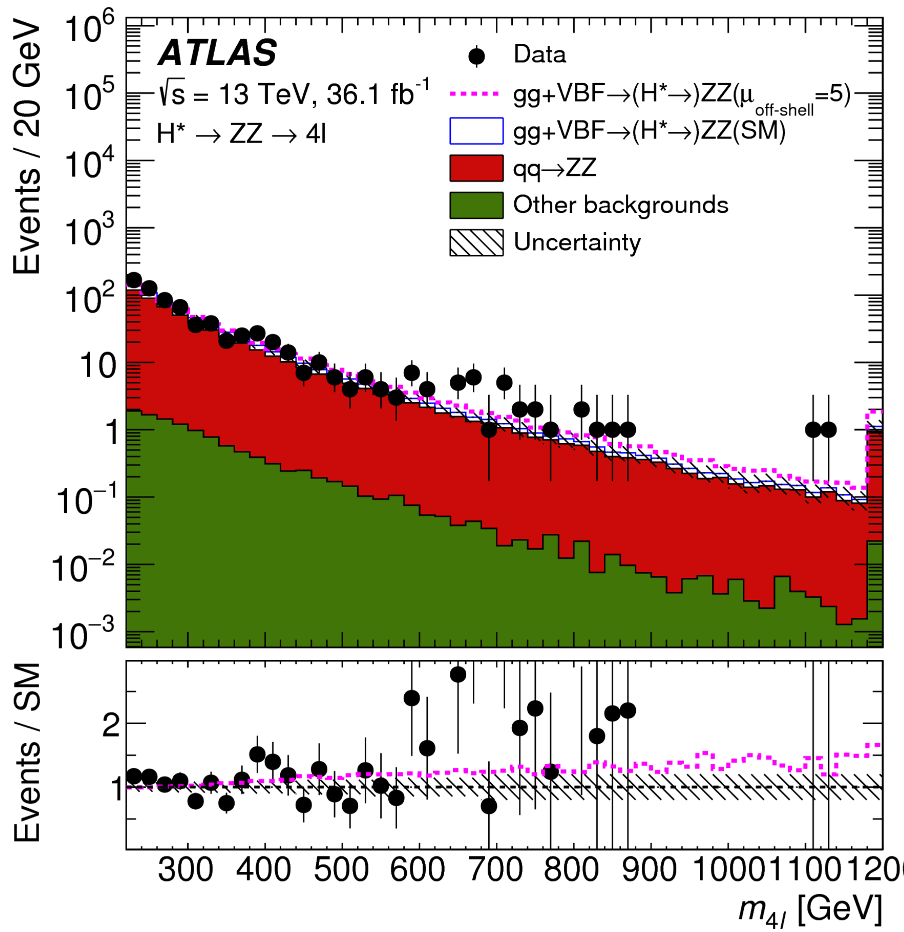
arXiv:1808.01191 [hep-ex]/HIGG-2017-06

Higgs boson width

- SM Higgs width Γ_H~4.1 MeV
  - Too small to be measured directly
  - Best direct limit from CMS:
    - Γ_H < 1.1GeV @ 95% CL
- Off-shell Higgs production sensitive(*) to Γ_H

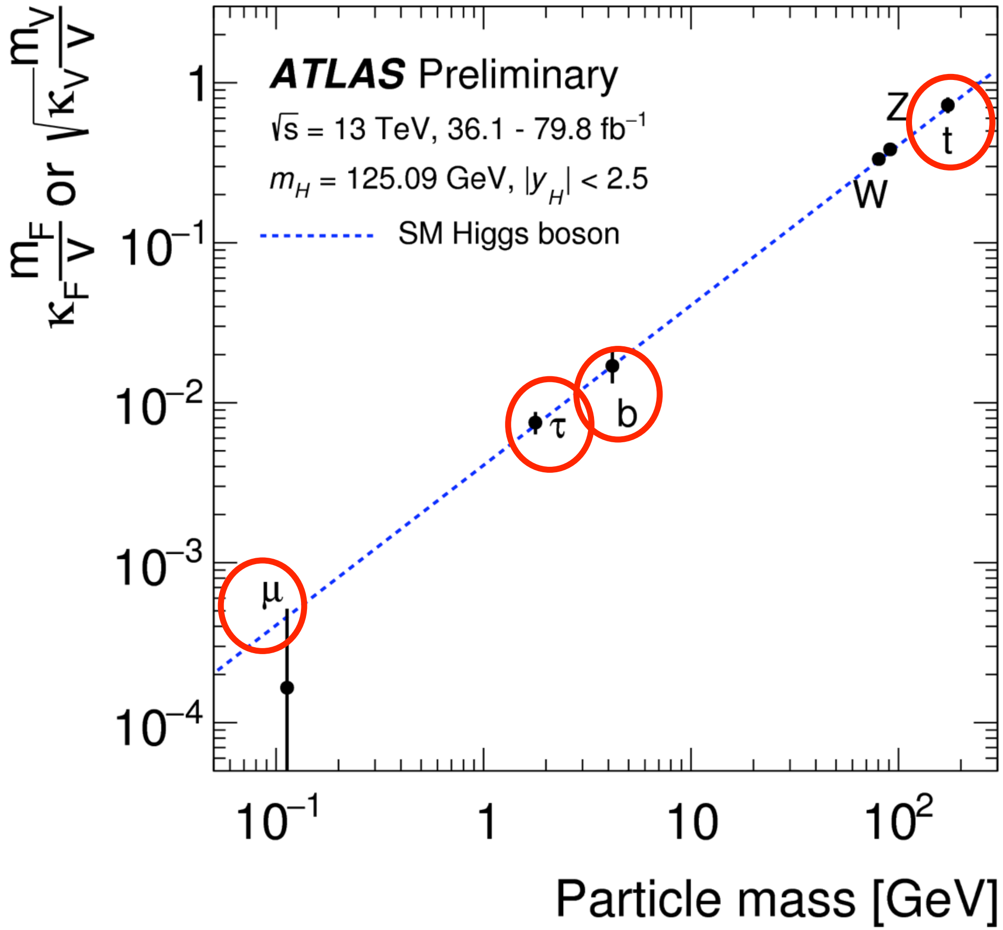
$$\frac{\mu_{off-shell}}{\mu_{on-shell}} = \frac{\kappa^2_{g,off-shell} \cdot \kappa^2_{Z,off-shell}}{\kappa^2_{g,on-shell} \cdot \kappa^2_{Z,on-shell}} \frac{\Gamma_H}{\Gamma_H^{SM}}$$

- ATLAS measurement:
  - **pp→H→ZZ→4l** and ZZ→2l2ν
  - **m(H) > 2 m(Z)**
  - 36.1 fb^{-1} of 13 TeV data
  - Observed (expected) limit:
    - Γ_H < 14.4 (15.2) MeV



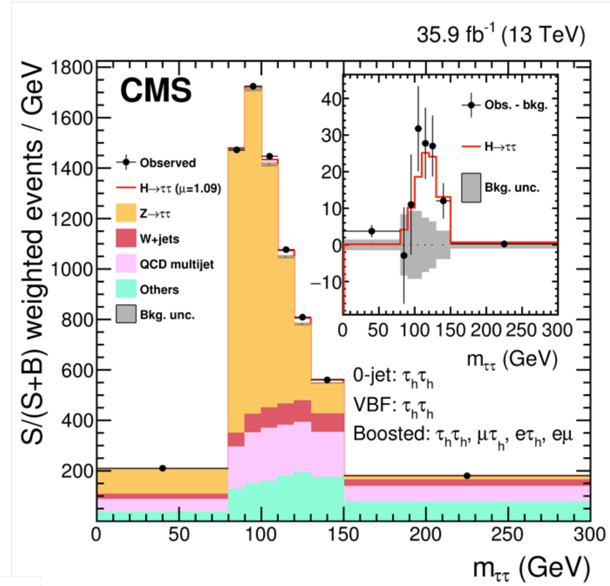
(*) Assume interference term with $gg \to ZZ$ proportional to $\kappa_{g,\text{off-shell}} \cdot \kappa_{Z,\text{off-shell}}$

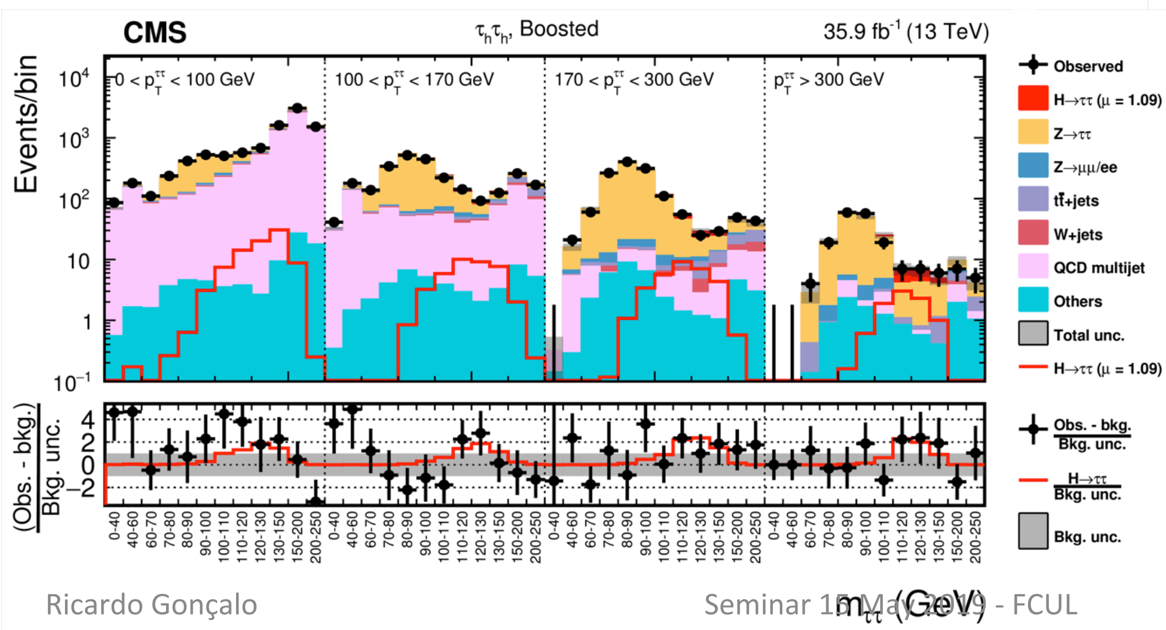
Exploring the Yukawa sector

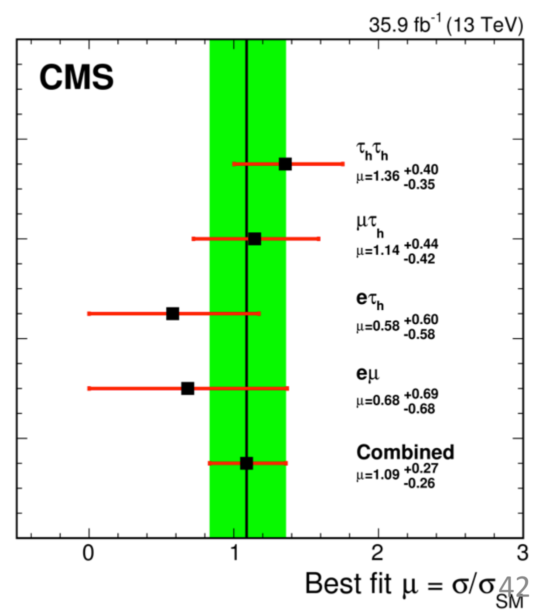


Observation of H→ττ

- Combine all final: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_{lep}\tau_{lep}$
- 3 categories: 0-jet, VBF and boosted (mostly ggF)
- 35.9 fb-1 of 13 TeV data
- 2D likelihood fit using $m_{\tau\tau}$, m_{jj} or $p_T^{\tau\tau}$
- Observed (expected) significance of 4.9σ (4.7σ)
- Combining with Run 1:
  - 36 fb-1 of 13 TeV data: 4.9 σ observed; 4.7 σ expected
  - Combining with Run 1: 5.9 σ observed; 5.9 σ expected
  - μ = 0.98 ± 0.18



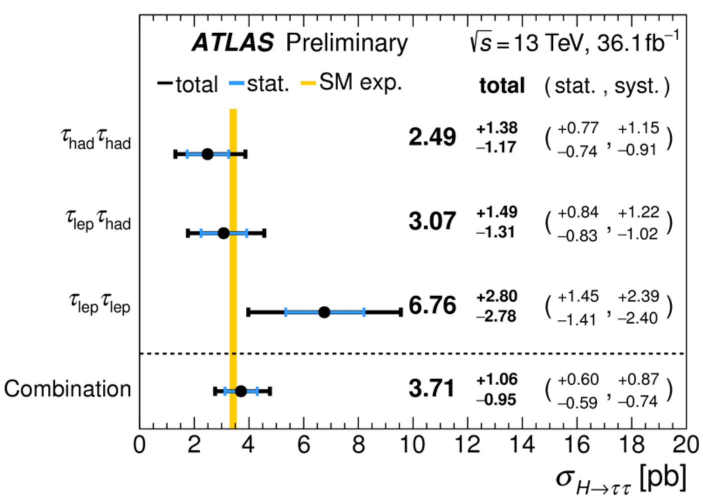


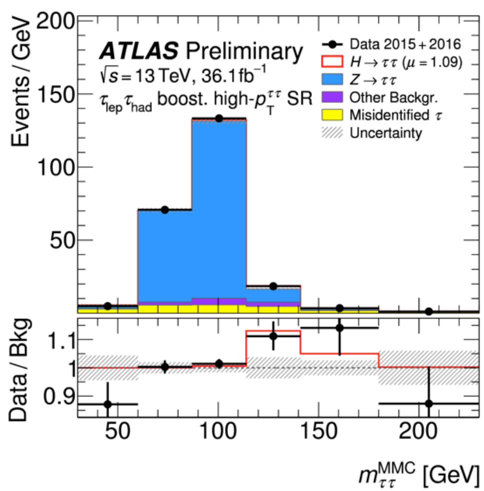


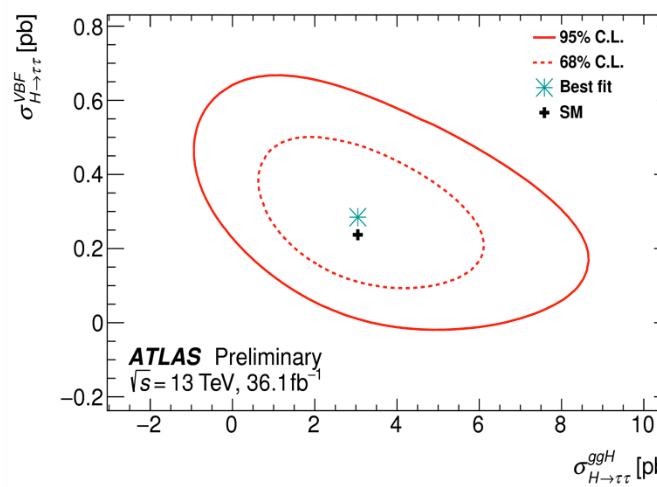
Observation of H→ττ

NEW
3 June 2018

- Combine all final: $\tau_{had}\tau_{had}$, $\tau_{lep}\tau_{had}$, $\tau_{lep}\tau_{lep}$
- Categories targeting boosted Higgs (mostly ggF) and VBF (additional jets)
- Dominant backgrounds from $Z\to\tau\tau$ and jets faking taus
- Cut-based analysis using fit to $m\tau\tau$ distribution in 13 signal regions
- Largest uncertainties: data and MC statistics, signal modelling and jets
- Cross section measurement (13 TeV):
- $\sigma^{ggF} = 3.0 \pm 1.0$ (stat.) $^{+1.6}_{-1.2}$ (syst.) pb; $\sigma^{VBF} = 0.28 \pm 0.09$ (stat.) $\pm$ 0.10 (syst.) pb
- Significance:
  - 36 fb^{-1} of 13 TeV data: 4.4 σ observed; 4.1 σ expected
  - Combining with 7 and 8 TeV data: 6.4 σ observed; 5.4 σ expected







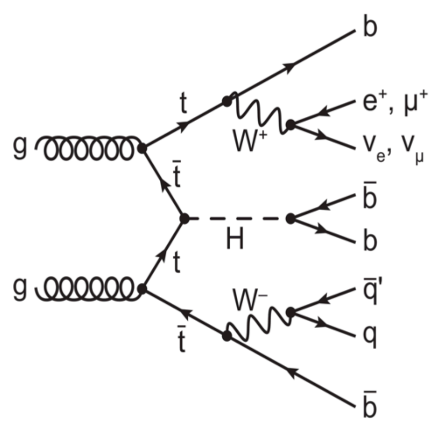
arXiv:1804.02610 [hep-ex]; arXiv:1806.00425 [hep-ex];

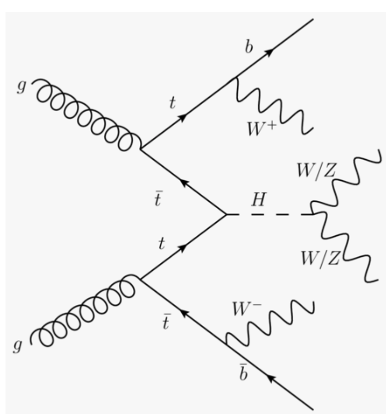
Observation of ttH production

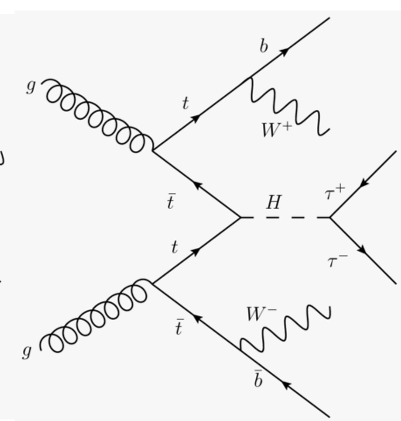
- **Direct** access to top Yukawa coupling
- Experimental tour-de-force!
  - Complex final states
  - Large irreducible backgrounds
  - Small cross sections: O(0.5)pb @ 13 TeV
- Use all available final states:
  - **H→bb**: high stats but low purity BR≈58%, S/B≈1-6%
  - **Multileptons:** H→$\tau\tau$, H→WW*, H→ZZ* BR = 30%, S/B=4-34%
  - **H→$\gamma\gamma$**: clean but low stats BR = 0.23%, S/B=5-200%
  - **H→ZZ*→4lep**: clean but very low stats BR = 0.01%, S/B=50-500%

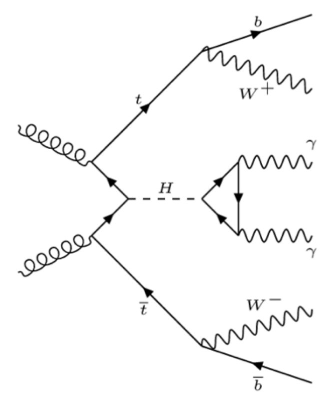
NEW

April - June 2018





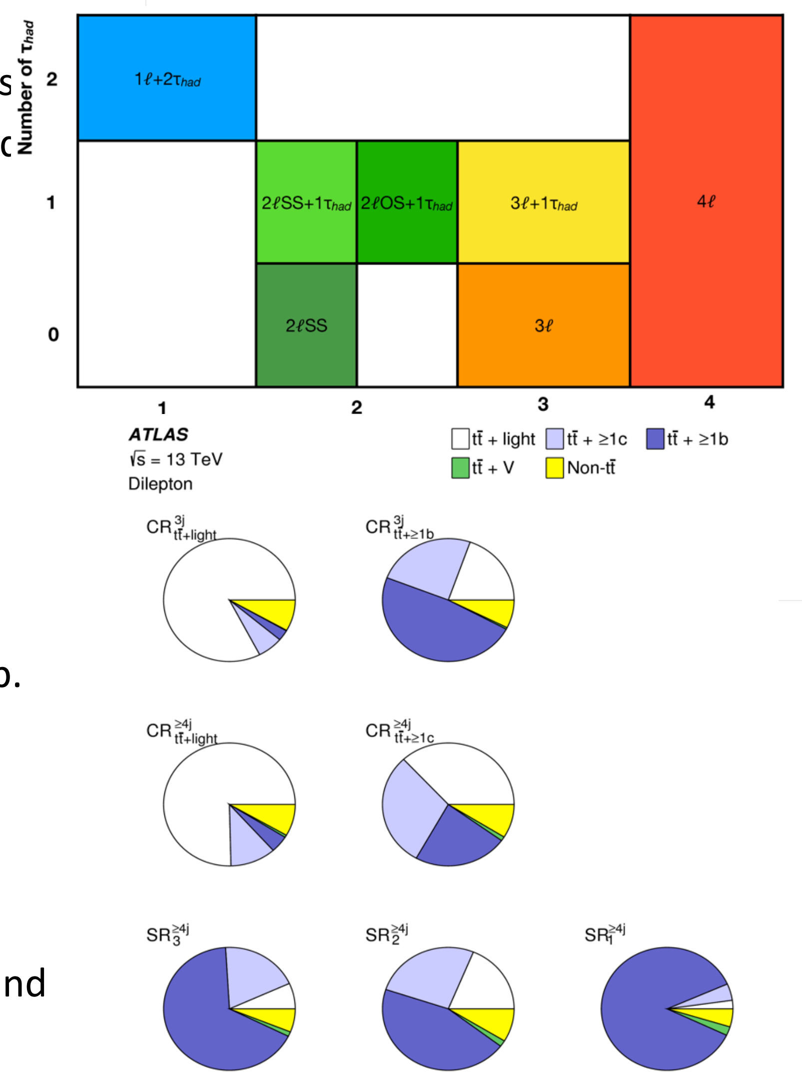




ttH observation: bb and Multileptons

ttH(H→leptons)

- Sensitive to: H→$\tau\tau$, H→WW* and H→ZZ*
- Backgrounds: ttW/ttZ, non-prompt leptons and fake taus
- Main uncertainties: signal modelling, jet energy scale and non-prompt lepton estimate
- ATLAS: 4.1σ observed; 2.8σ expected
- CMS: 3.2σ observed; 2.8σ expected



ttH(H→bb):

- Profit from large H→bb branching ratio (58.4%)
- But challenging final state: large ttbb irreducible background, theory uncertainties, combinatorics...
- Main uncertainties: tt+heavy flavours, b tagging, jet calib.
- ATLAS: 1.2σ observed; 1.6σ expected
- CMS: 1.6σ observed; 2.2σ expected

For **both** channels:

- Intensive use of dedicated machine learning (NN, BDT) and matrix element methods: suppress fake leptons, reconstruct events, flavour tagging, and enhance S/B arXiv:1806.00425 [hep-ex]; arXiv:1804.02610 [hep-ex]

ttH observation

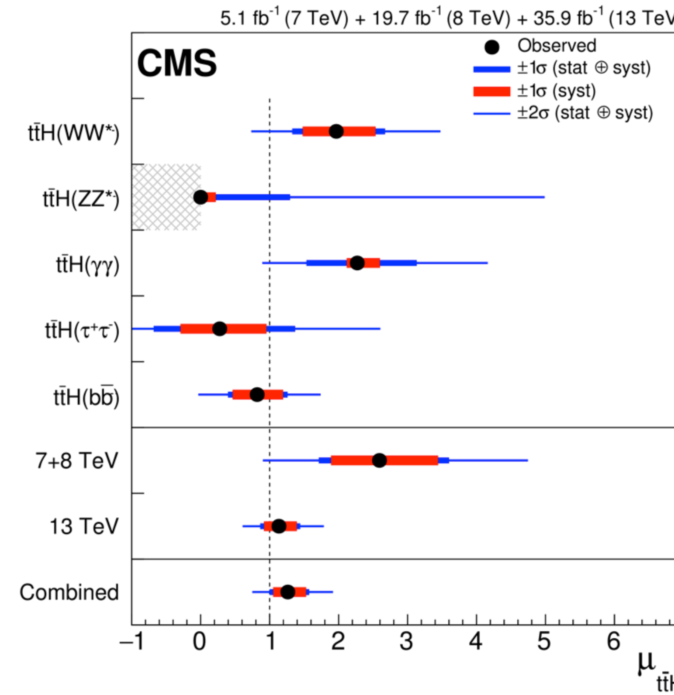
CMS:

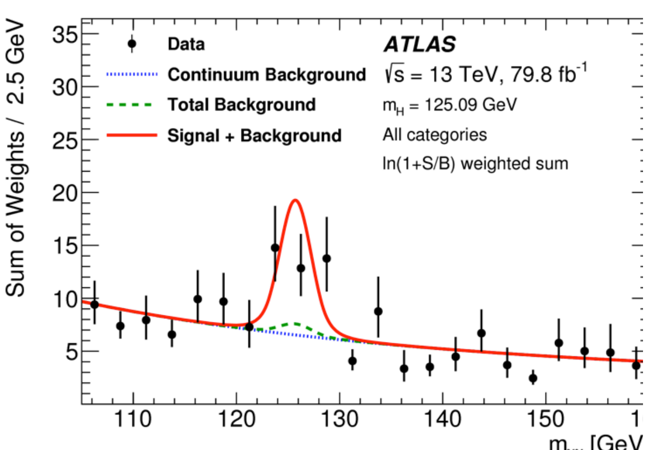
- Combined Run 1 + 36.1 fb^{-1} Run 2:
- 5.2 σ observed, 4.2 σ expected

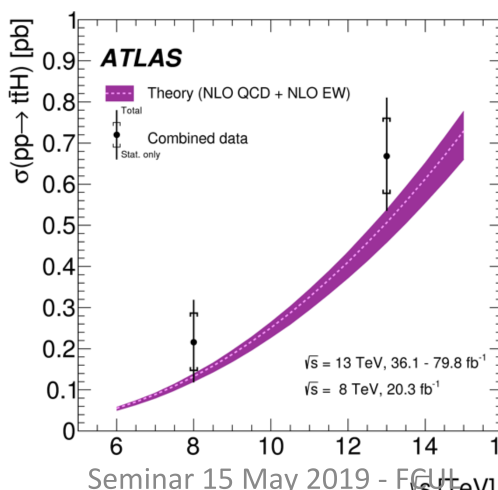
ATLAS:

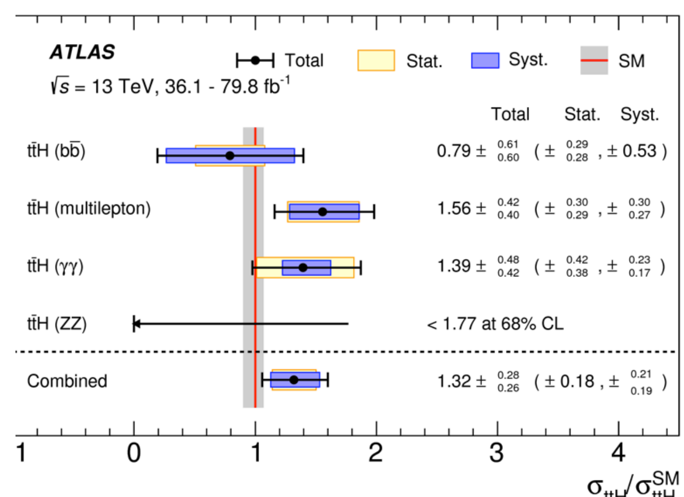
- ttH(H→$\gamma\gamma$):
  - New signal categories from BDT discriminant
  - **Sensitivity increased by 50%**
- Run 2 data from 2015+2016+2017 ($\gamma\gamma$/ZZ): **79.8 fb^{-1}**
  - 5.2 σ observed, 4.9 σ expected
- Adding Run 1: 6.3 σ observed, 5.1 σ expected
- Measured production cross section at 13 TeV:

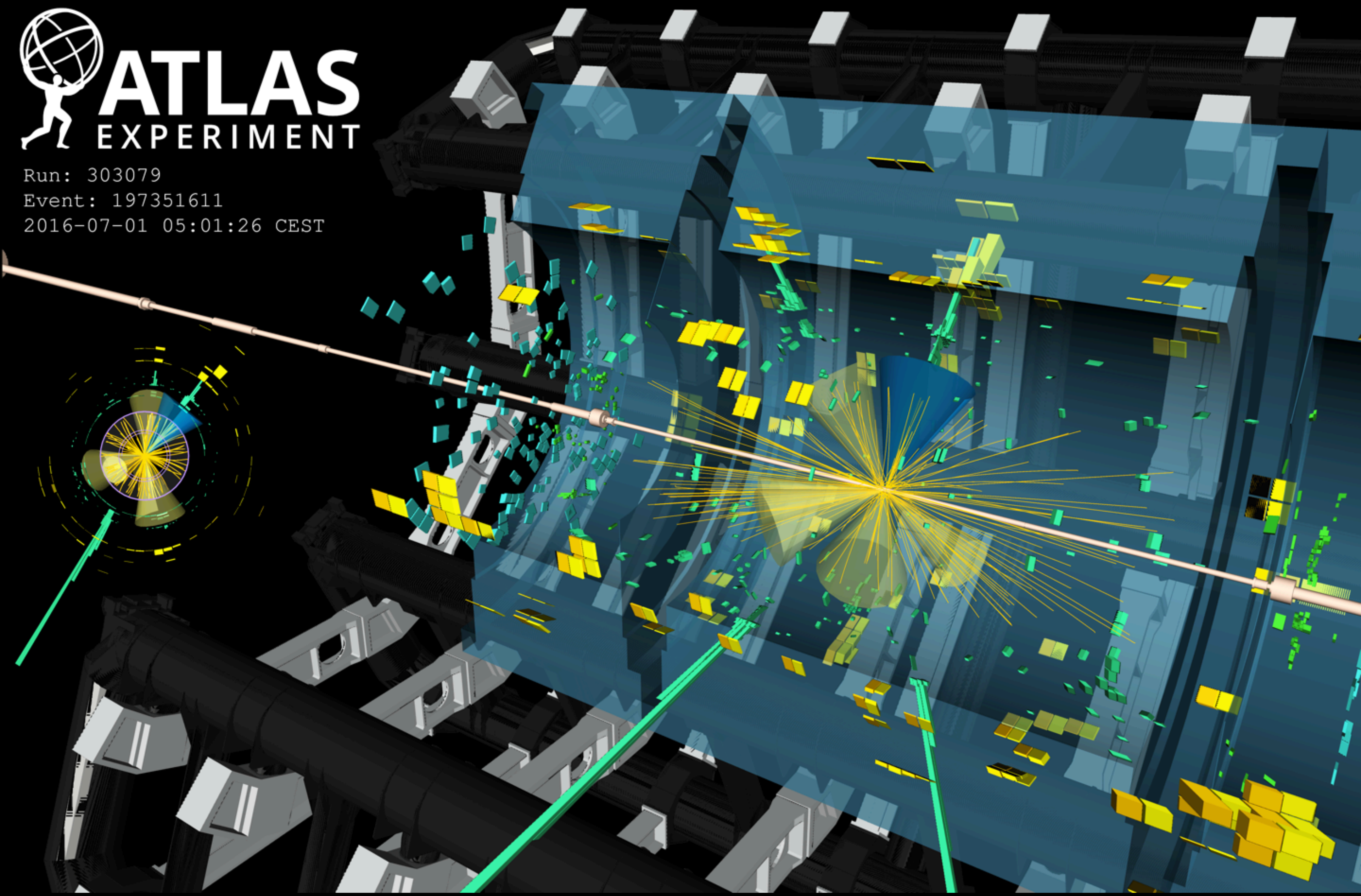
  670 ± 90 (stat.) +110−100 (syst.) fb









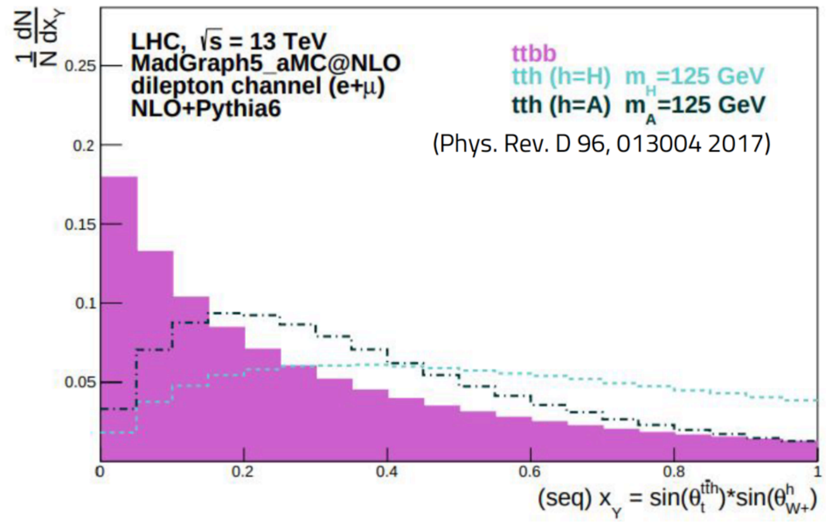

ATLAS
EXPERIMENT
Run: 303079
Event: 197351611
2016-07-01 05:01:26 CEST

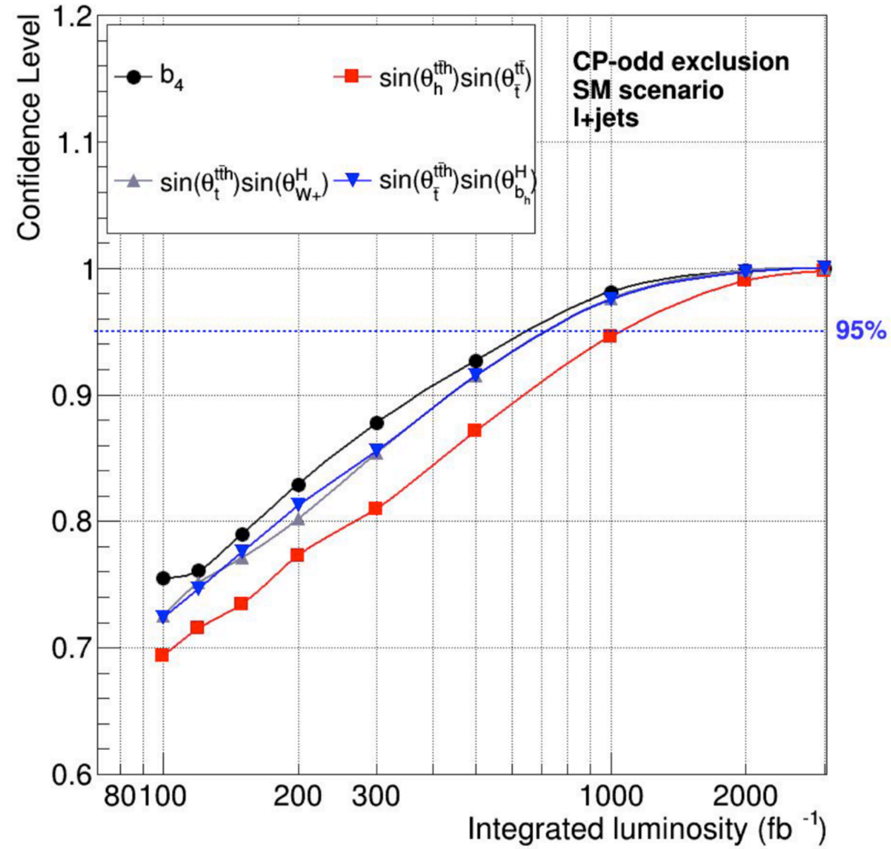
Next steps in ttH(→bb) @ LIP

- In BSM scenarios could have mixed-CP structure of top Yukawa coupling

$$\mathcal{L} = \kappa\, y_t\, \bar{t}\,(\cos\alpha + i\gamma_5 \sin\alpha)\, t\, h$$

  - e.g. 2HDM
  - α = 0 recovers SM
- Study done with fast simulation so far
- See e.g.:
  Phys. Rev. D 96, 013004 2017
  Phys. Rev. D 98, 033004 2018





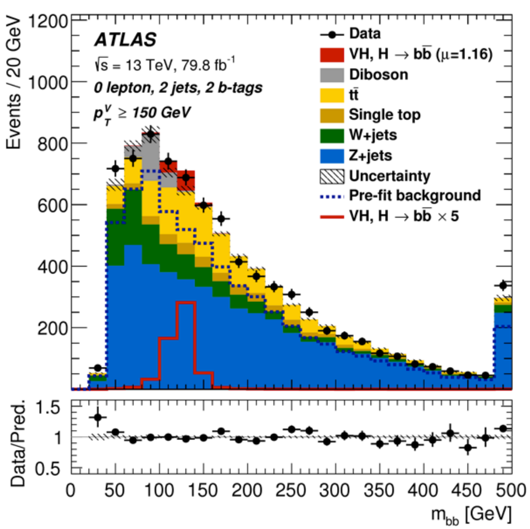
arXiv:1808.08238; arXiv:1808.08242 [hep-ex]

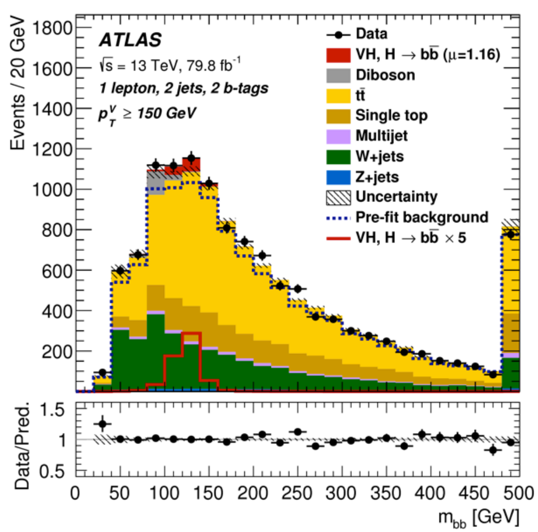
Observation of H→bb

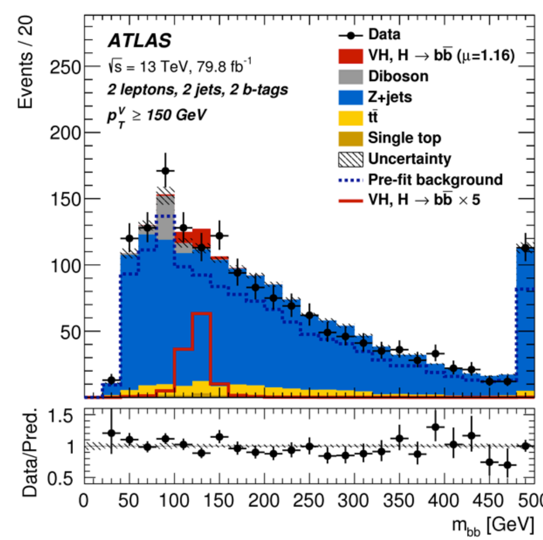
- See **CERN seminar: observation in ATLAS and CMS**
  - https://indico.cern.ch/event/750541/
- Largest branching fraction (58.4%) but huge background from heavy flavour production
- Must use associated production: WH/ZH
  - Require 2 b jets + 0 (Z→$\nu\nu$), 1 (W→$\ell\nu$) or 2 (Z→$\ell\ell$) leptons
- Largest backgrounds:
  - Z+heavy flavour (0- and 2-lepton) and tt (1-lepton)
  - Irreducible background from VZ with Z→bb

NEW

9 July 2018



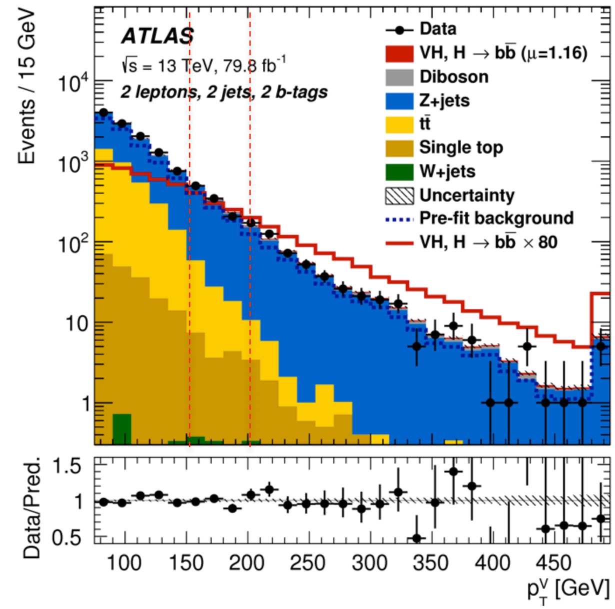




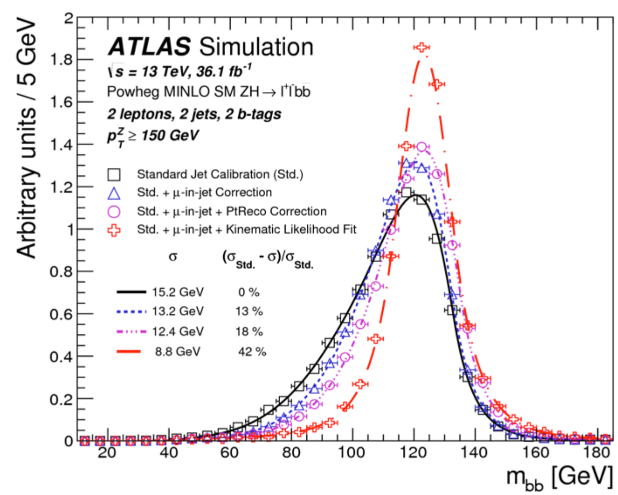
arXiv:1808.08238

Observation of H→bb

- Harder p_T spectrum for signal than backgrounds
  - Go to high p_T to improve S/B
- Use for event categories:
  - $75 < p_T^V < 150$ GeV (2ℓ only)
  - $150 < p_T^V < 200$ GeV
  - $p_T^V > 200$ GeV



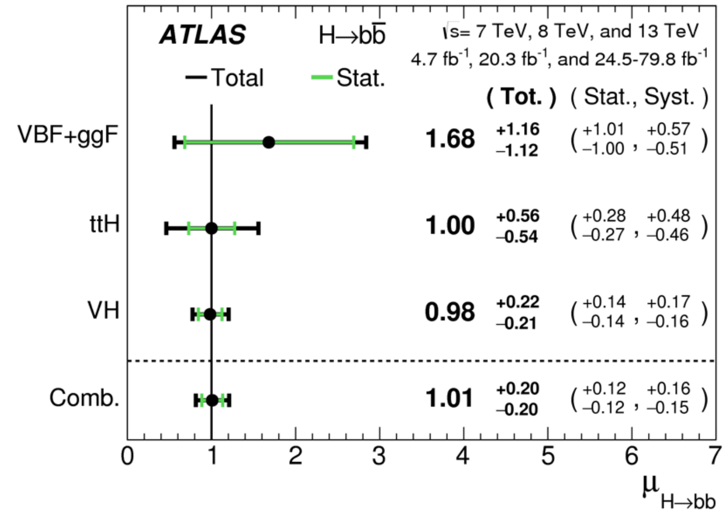
- Main discriminant variables m_{bb}, p_T^V and ΔR_{bb}
  - m_{bb} resolution extremely important!

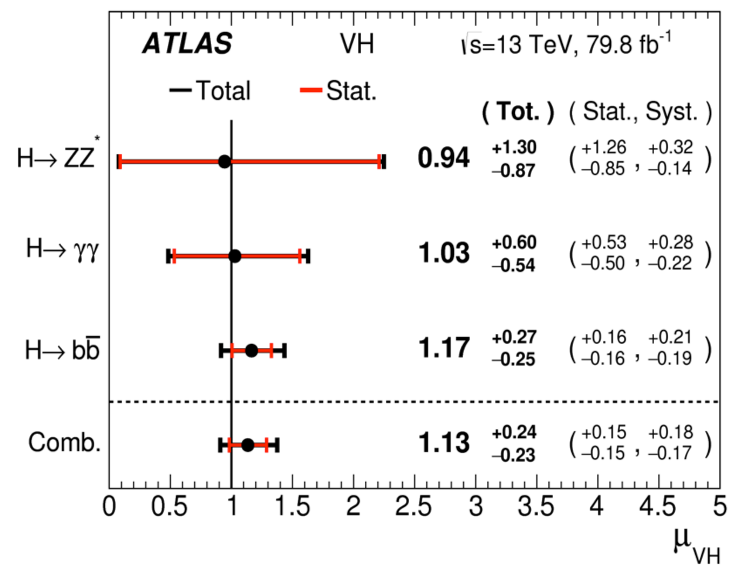


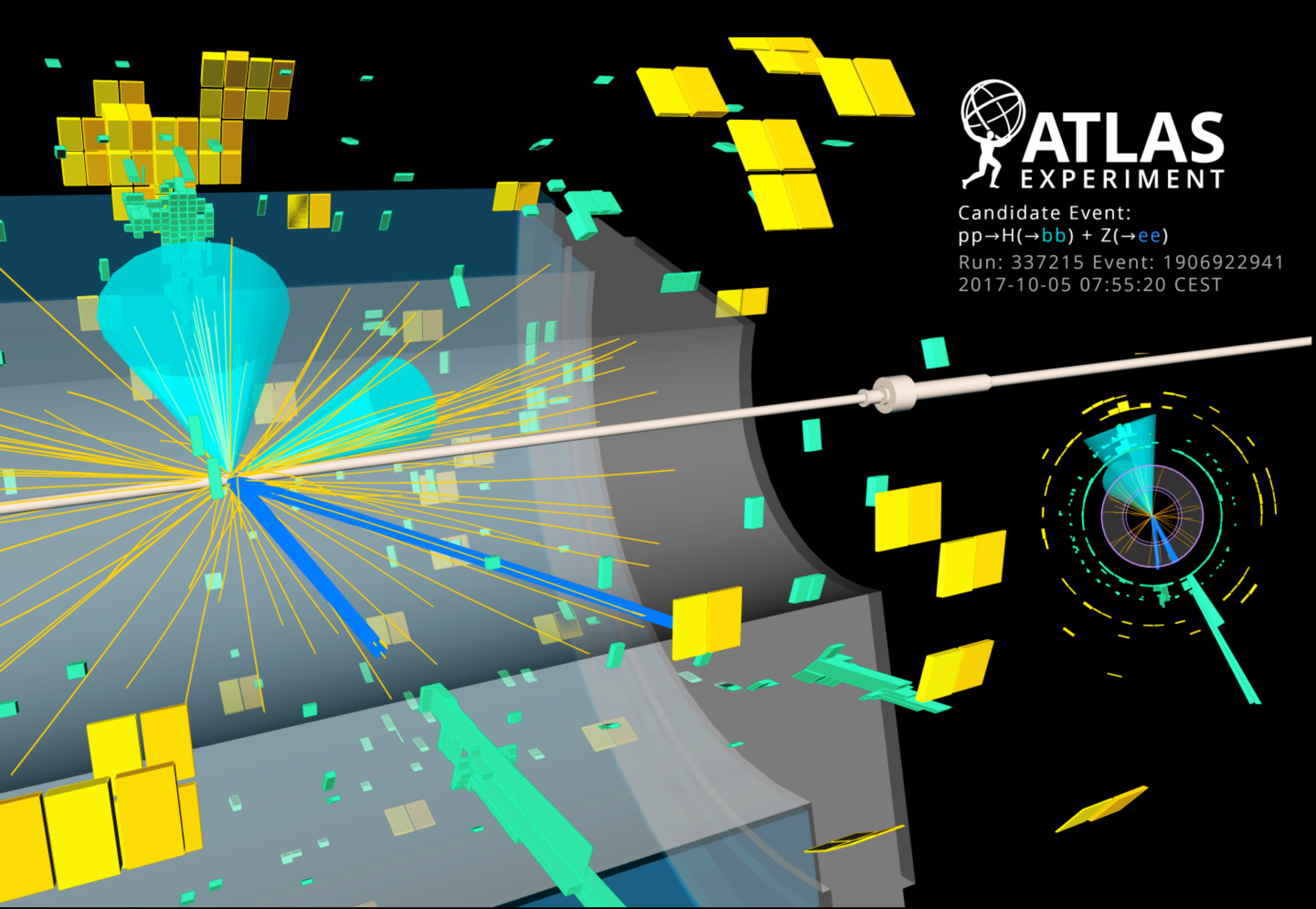
arXiv:1808.08238

Observation of H→bb

- Run 2:
  - Observed (expected) of 4.9σ (4.3σ)
- Adding Run 1:
  - Observed (expected) of 4.9σ (5.1σ)
- Adding ttH and VBF:
  - Observed (expected) of 5.4σ (5.5σ)
  - **Observation of H→bb decays**
- Adding H→ZZ and H→γγ:
  - Observed (expected) of 5.3σ (4.8σ)
  - **Observation of VH production**

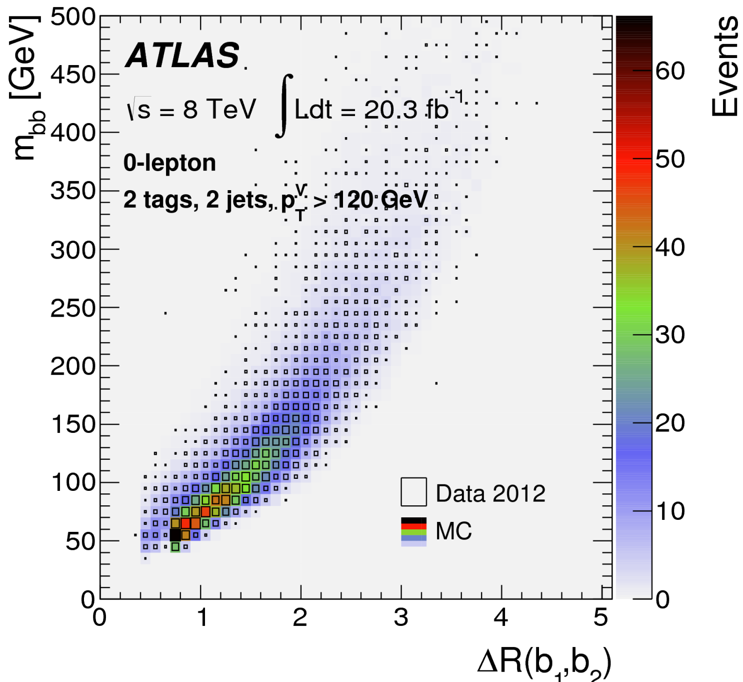





ATLAS
EXPERIMENT
Candidate Event:
pp→H(→bb) + Z(→ee)
Run: 337215 Event: 1906922941
2017-10-05 07:55:20 CEST

H→bb @ LIP

- Boosted decision tree (BDT)
- Combine many different variables
- Trained in 8 categories: 3 lepton, 2/3 jets, low/high p_T^V bin (2 lepton channel)
- Most discrimination from m_{bb} and DR(b_1,b_2)



Variable	0-lepton	1-lepton	2-lepton
p_T^V		×	×
E_T^{miss}	×	×	×
$p_T^{b_1}$	×	×	×
$p_T^{b_2}$	×	×	×
m_{bb}	×	×	×
$\Delta R(b_1, b_2)$	×	×	×
$\lvert\Delta\eta(b_1, b_2)\rvert$	×		×
$\Delta\phi(V, bb)$	×	×	×
$\lvert\Delta\eta(V, bb)\rvert$			×
H_T	×		
$\min[\Delta\phi(\ell, b)]$		×	
m_T^W		×	
m_{ll}			×
m_{Top}		×	
$\lvert\Delta Y(V, H)\rvert$		×	
	Only in 3-jet events		
$p_T^{jet_3}$	×	×	×
m_{bbj}	×	×	×

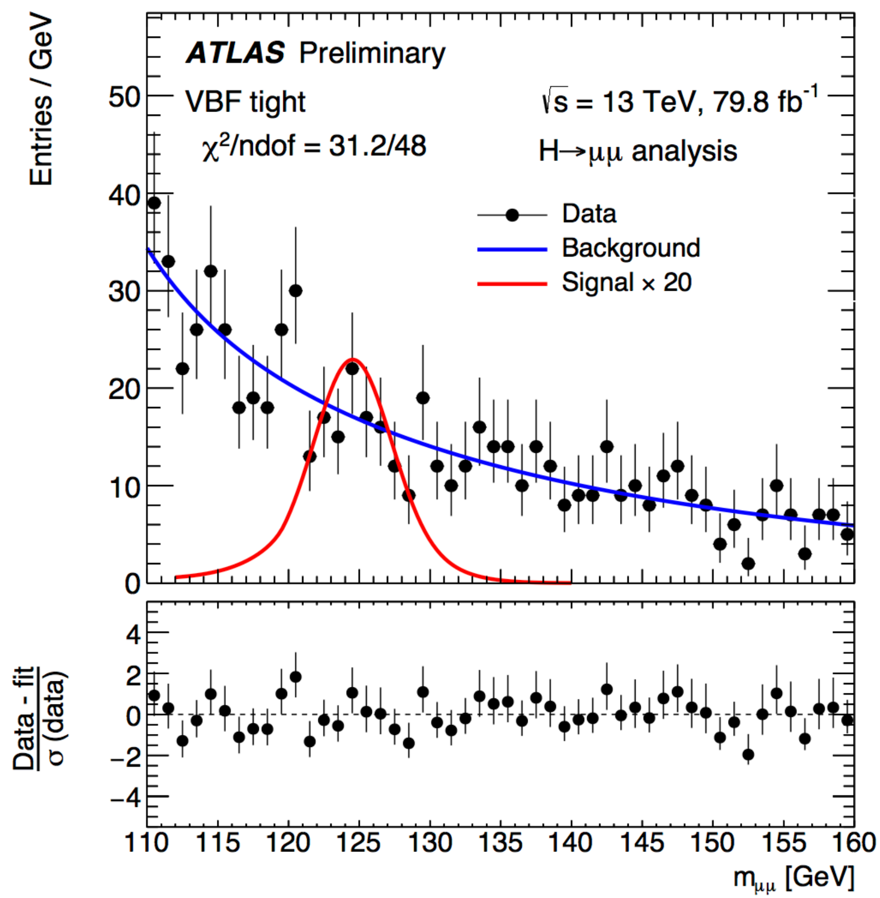
New in run 2:

m_{Top}, |DY(V,H)| → +7% in sensitivity

NEW
2 July 2018

2nd generation Yukawa: H→μμ

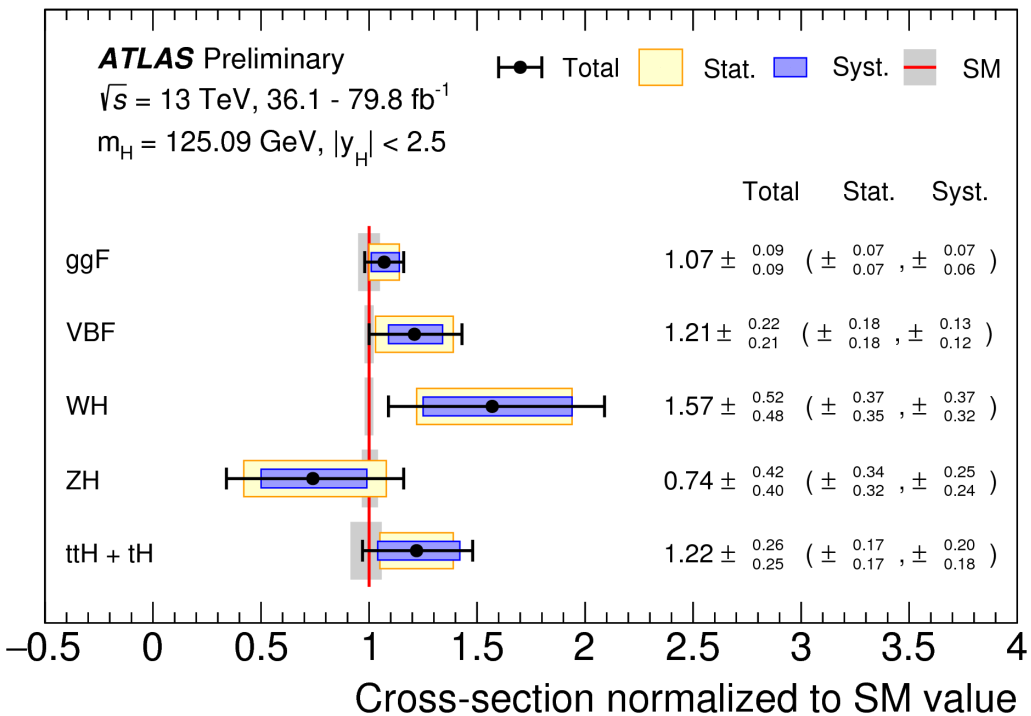
- Easy to trigger on, but very rare
- Used 80 fb^{-1} of 13 TeV data
- Event categories based on muon η, $p_T^{\mu\mu}$, and VBF (BDT)
- Search peak in $m_{\mu\mu}$
- Background from sidebands à la H→γγ analysis
- 95% CL limits:
  2.1 (obs), 2.0 (exp)
- **Getting close to SM sensitivity!**



Combination

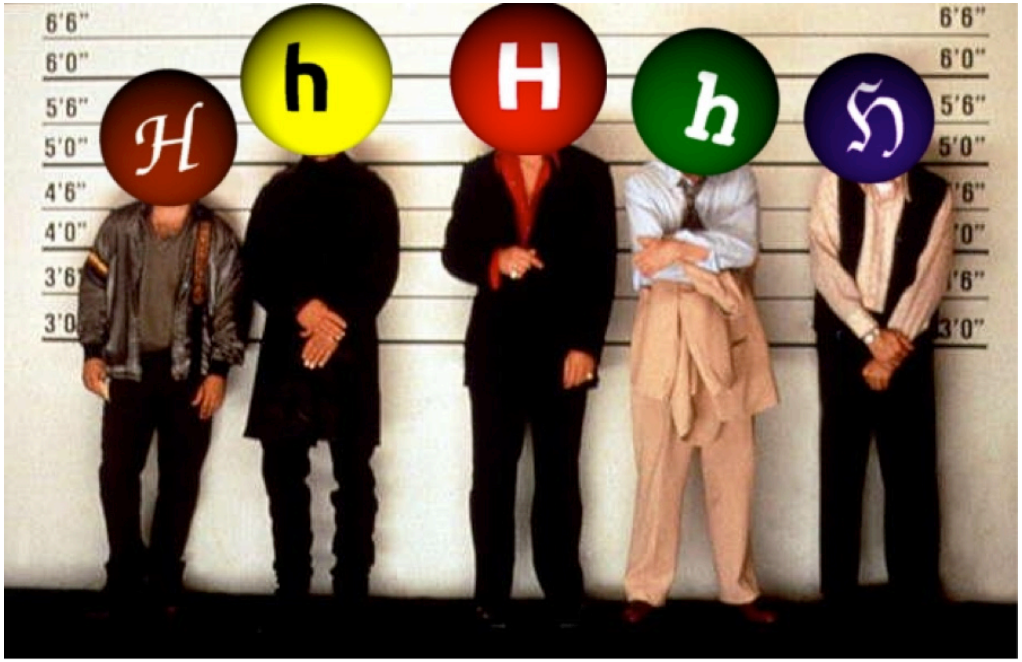
- Combined γγ, ZZ, WW,ττ, μμ and bb (incl. ttH+tH modes)
  - Up to 79.8 fb^{-1} of √s = 13 TeV data
- Combination yields VBF significance 6.5σ (5.3σ expected) **from ATLAS alone**
- Main production modes (ggF, VBF, VH, ttH) have all been observed!!
- Good agreement with SM predictions
- Overall signal strength:

  $\mu = 1.13^{+0.09}_{-0.08}$
- Quantified space for undetectable decays or modified BR (e.g. BSM H→cc)
  - B_{BSM} < 0.13 at 95% CL.(*)



(*) In determination of κ_g and κ_γ - assumption dependent

Casting a wider net

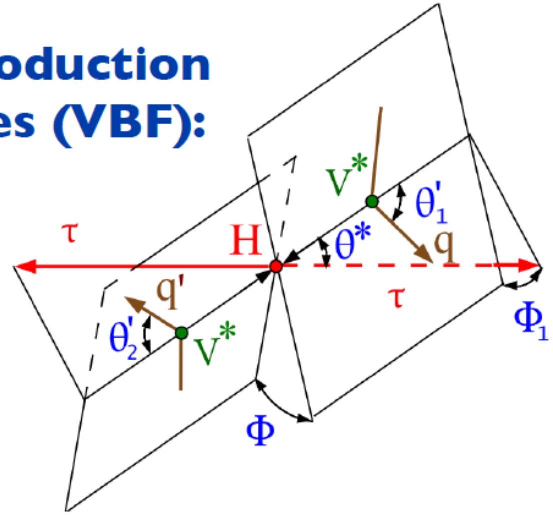


Higgs Boson Properties: J^{CP}

Trevor Vickey
IoP HEP Conf.2019

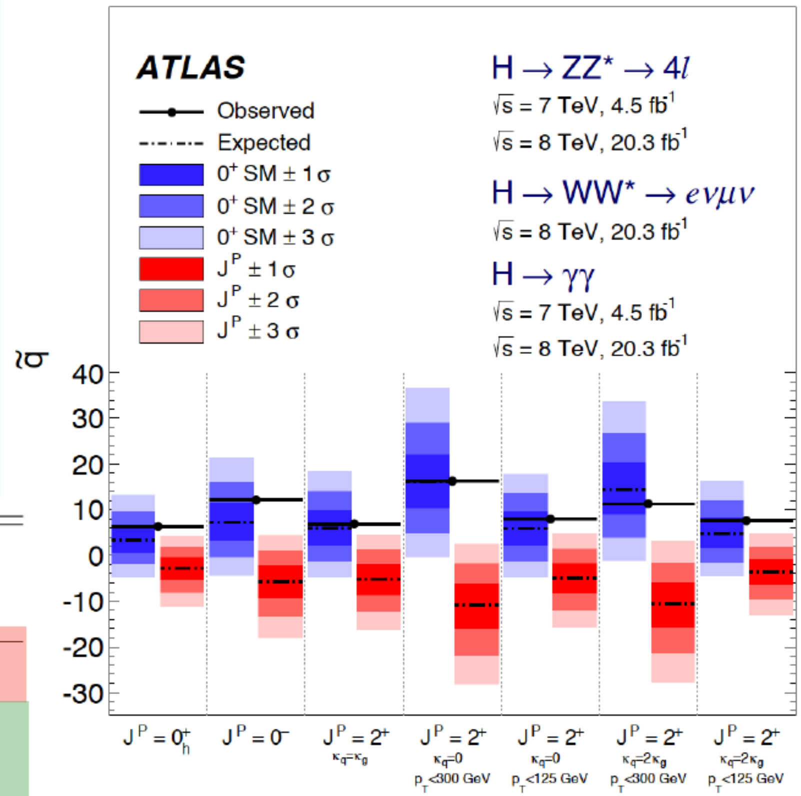
- Predicted by the Standard Model: CP-even with spin and parity $J^{PC} = 0^{++}$
- Most investigations to-date have focused on the couplings to bosons
- Admixtures of CP even and CP odd couplings are certainly still allowed

Definition of production and decay angles (VBF):



CMS

Parameter	Observed / (10^{-3}) 68% CL	Observed / (10^{-3}) 95% CL	Expected / (10^{-3}) 68% CL	Expected / (10^{-3}) 95% CL
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27	$[-92, 14]$	0.00 ± 0.23	$[-1.2, 1.2]$
$f_{a2}\cos(\phi_{a2})$	$0.08^{+1.04}_{-0.21}$	$[-1.1, 3.4]$	$0.0^{+1.3}_{-1.1}$	$[-4.0, 4.2]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.00^{+0.53}_{-0.09}$	$[-0.4, 1.8]$	$0.00^{+0.48}_{-0.12}$	$[-0.5, 1.7]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.0^{+1.1}_{-1.3}$	$[-6.5, 5.7]$	$0.0^{+2.6}_{-3.6}$	$[-11, 8.0]$



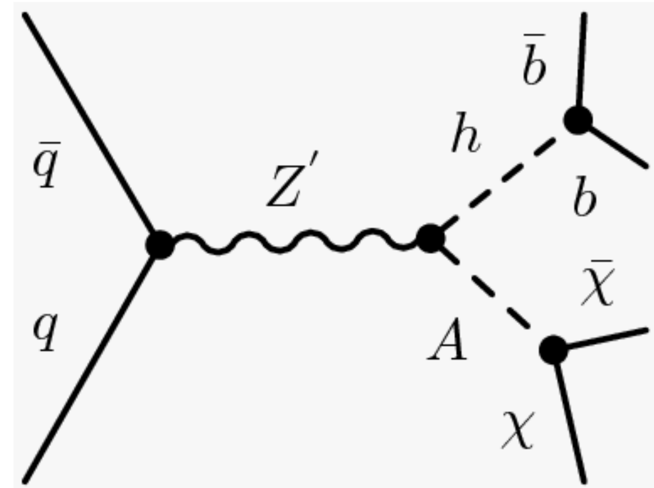
EPJC 75 (2015) 476

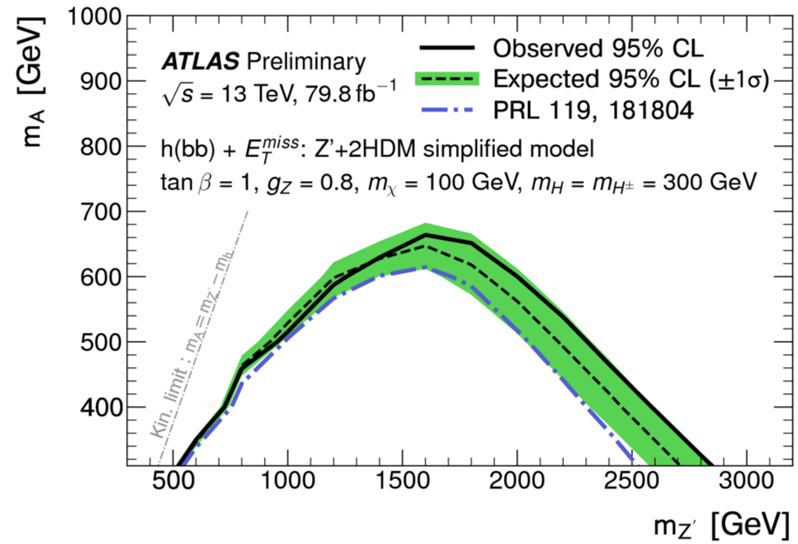
- Results from CMS for CP-violating and CP-conserving parameters (above) are consistent with the SM

arXiv:1903.06973

Higgs + Dark Matter

- Used 79.8 fb^{-1} of 13 TeV data
  - High E_T^{miss} (>150GeV) and b-tagging to suppress backgrounds
  - Reconstruct b-jets as 2 small jets or merged variable-radius (VR) track jets
- Signal benchmark: Type-II 2HDM + $U(1)_{Z'}$ symmetry (Z'-2HDM)
- Main backgrounds: tt, W/Z+jets
- Excluded region in $m_A - m_{Z'}$ plane



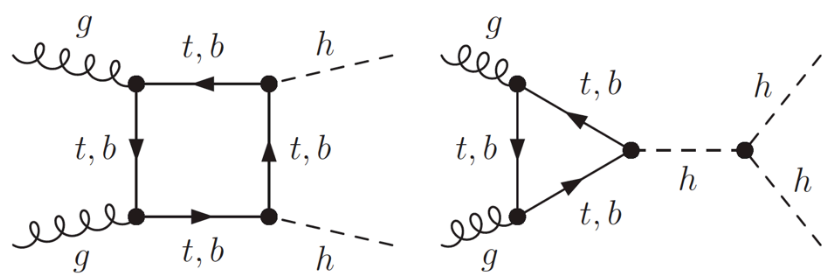


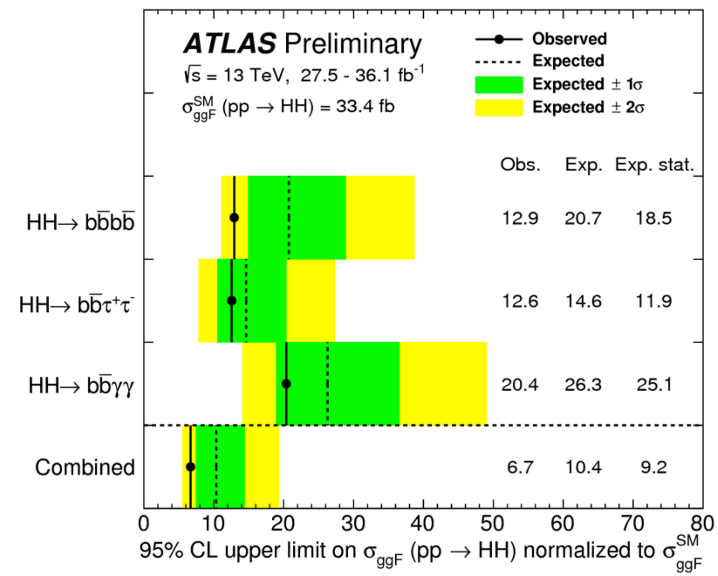
7 July 2018
4 Sep 2018

Triple Higgs coupling

- The triple Higgs coupling λ_{HHH} can be probed through di-Higgs production
- Very suppressed in SM!
  - Negative interference between LO diagrams
  - Cross section 1500x less than ggF
- Wide range of decay BR and channel purity
- bbττ analysis:
  - Used 36 fb^{-1} of 13 TeV data
  - Final state BR(bbττ)=7%
  - Non-Resonant 95% CL limit:
    μ < 12.7 observed (14.8 expexcted)
- Combination: at ≈10 x SM sensitivity – with 3% of the HL-LHC luminosity analyzed

$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

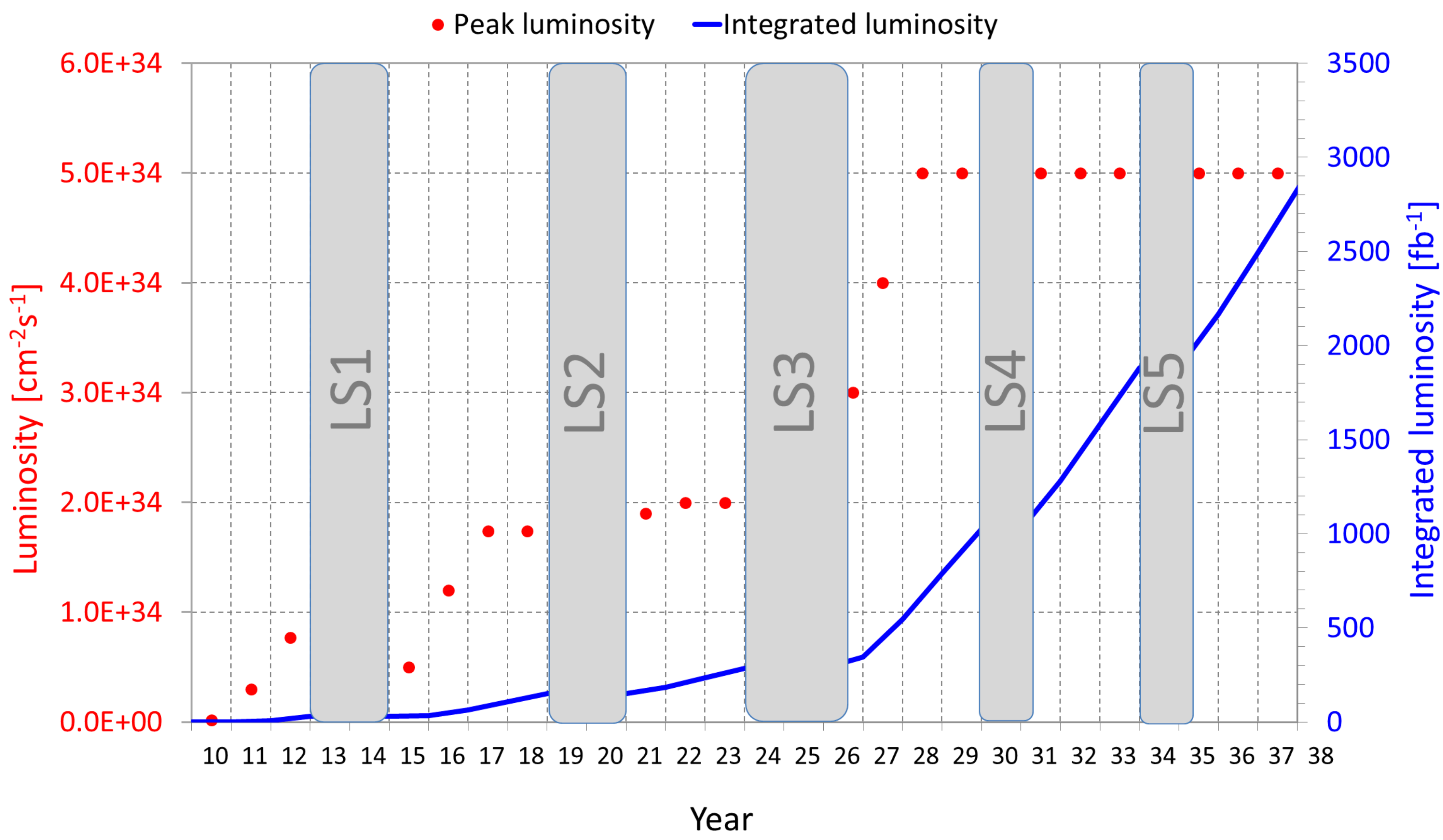




Di-Higgs combination plot [here]

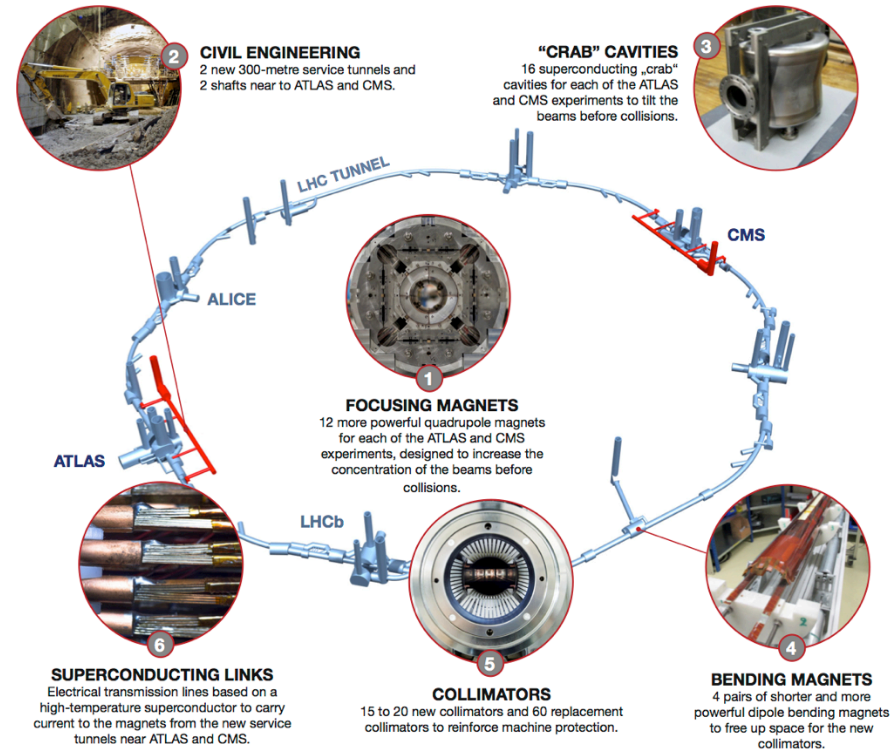
The future

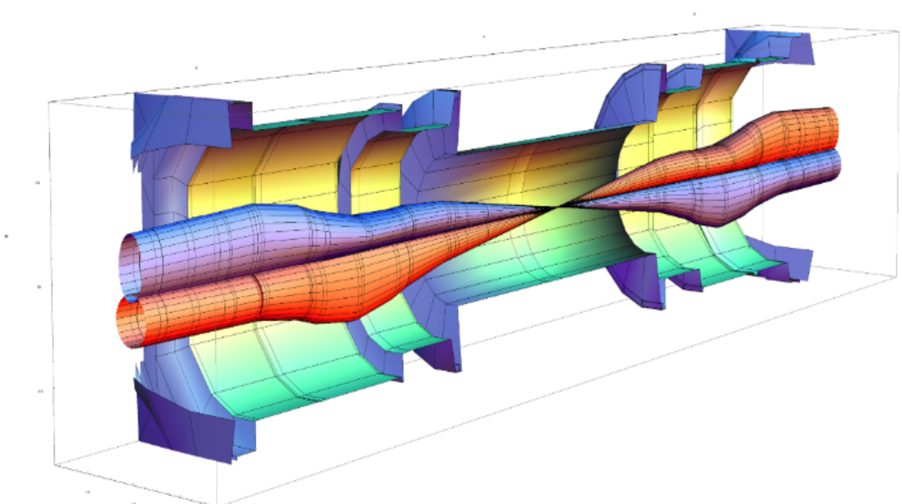
LHC and HL-LHC timeline

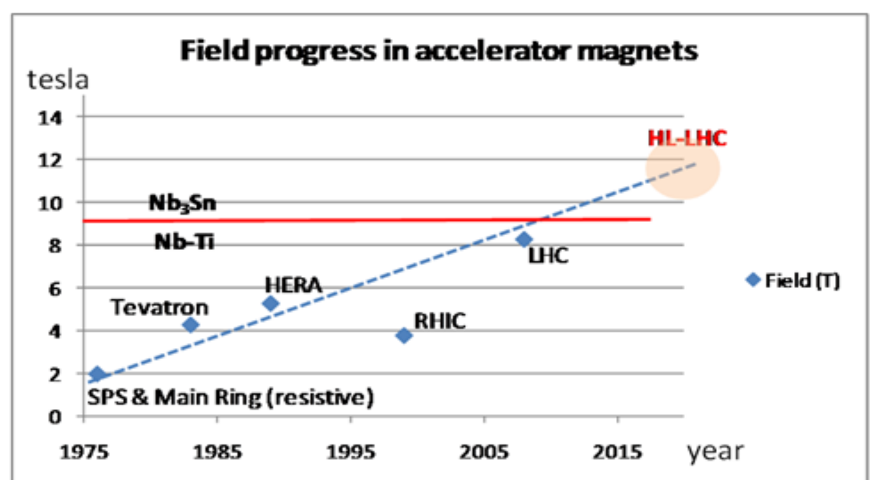


LHC Upgrades

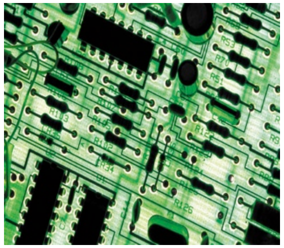
- Development of a new generation of superconducting magnets with higher critical field (Nb_3Sn):
  - 13.5 T instead of 8 T (LHC, NbTi)
- Development of “crab cavities” to increase bunch overlap
- Colimators, connectors, civil eng., etc





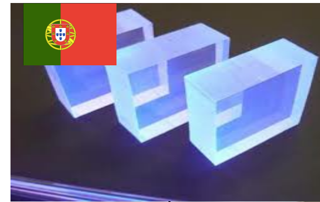


R. Gonçalo - LIP Ciência 2018 62

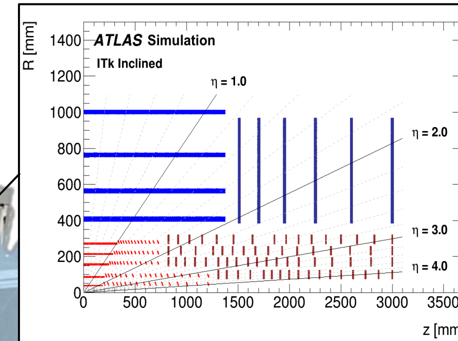


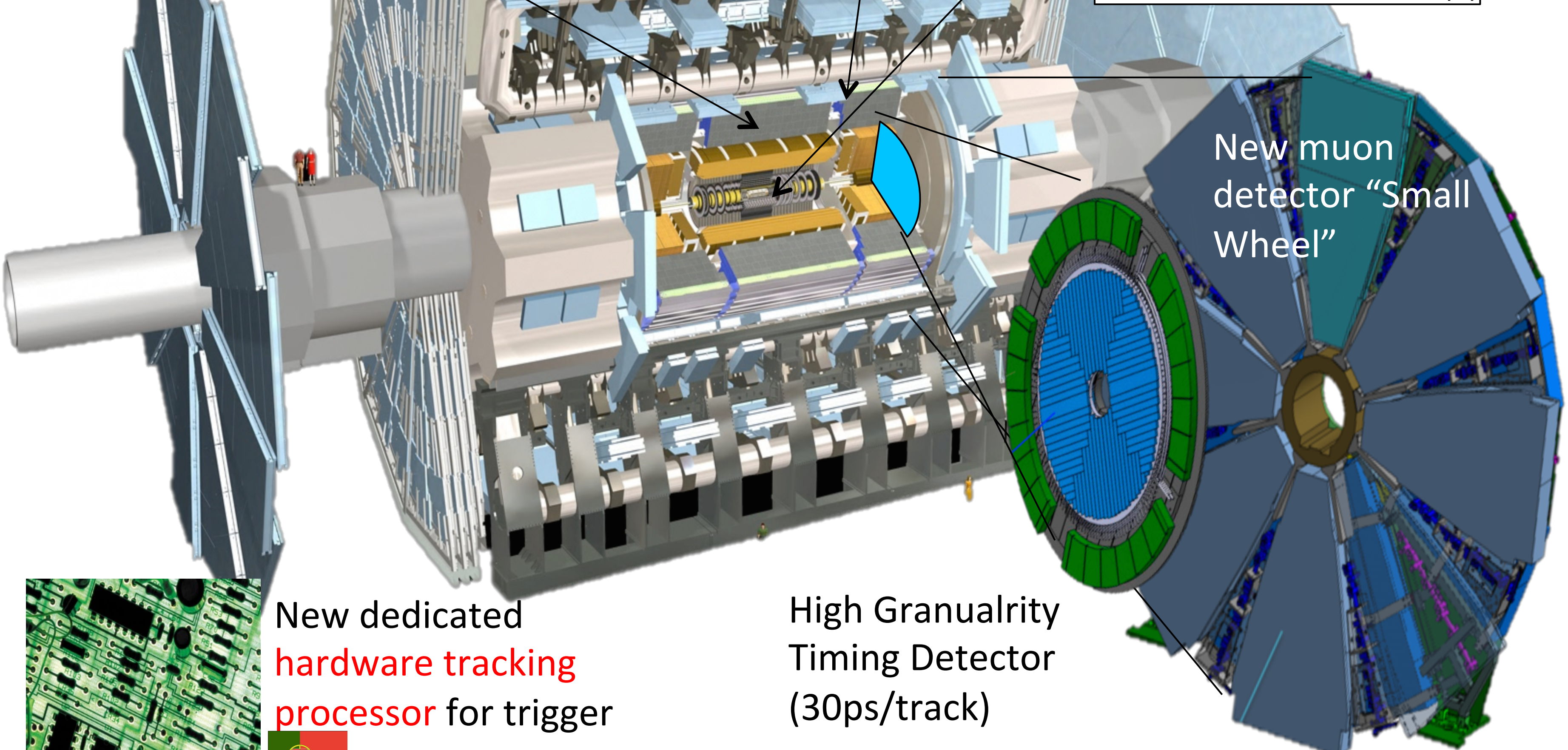
Calorimeter: new DAQ electronics, HV sources and gap scintillators

Gap scintillators



New tracking detector



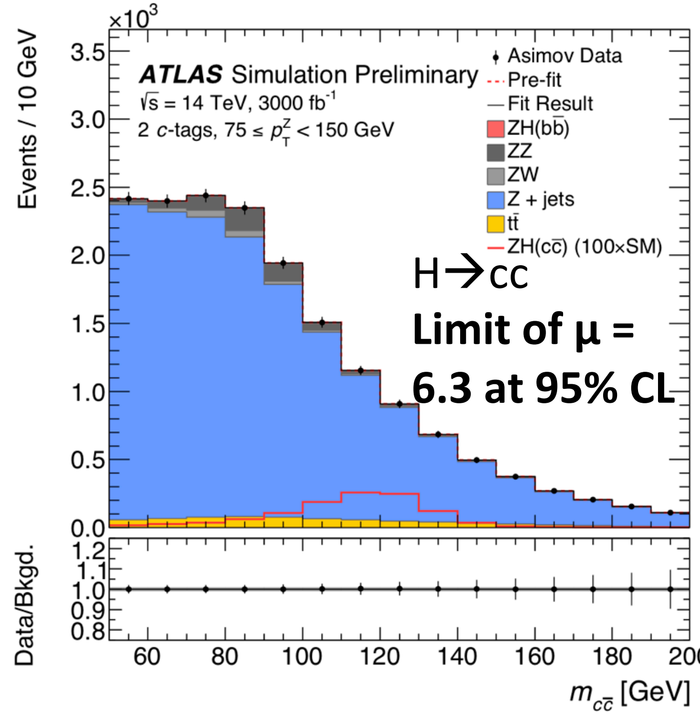


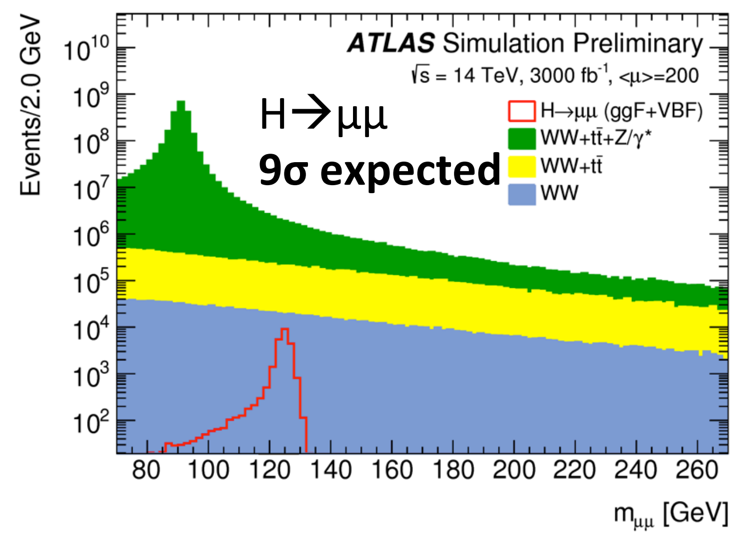
New dedicated hardware tracking processor for trigger

High Granualrity Timing Detector (30ps/track)

Future of Higgs: HL-LHC

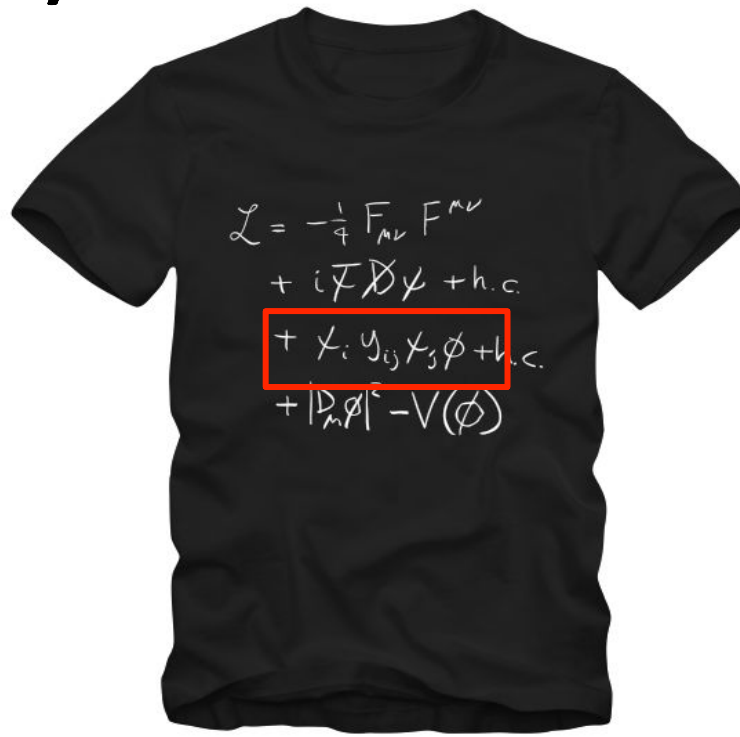
- A lot can be done with $3000 fb^{-1}$!!!





Summary

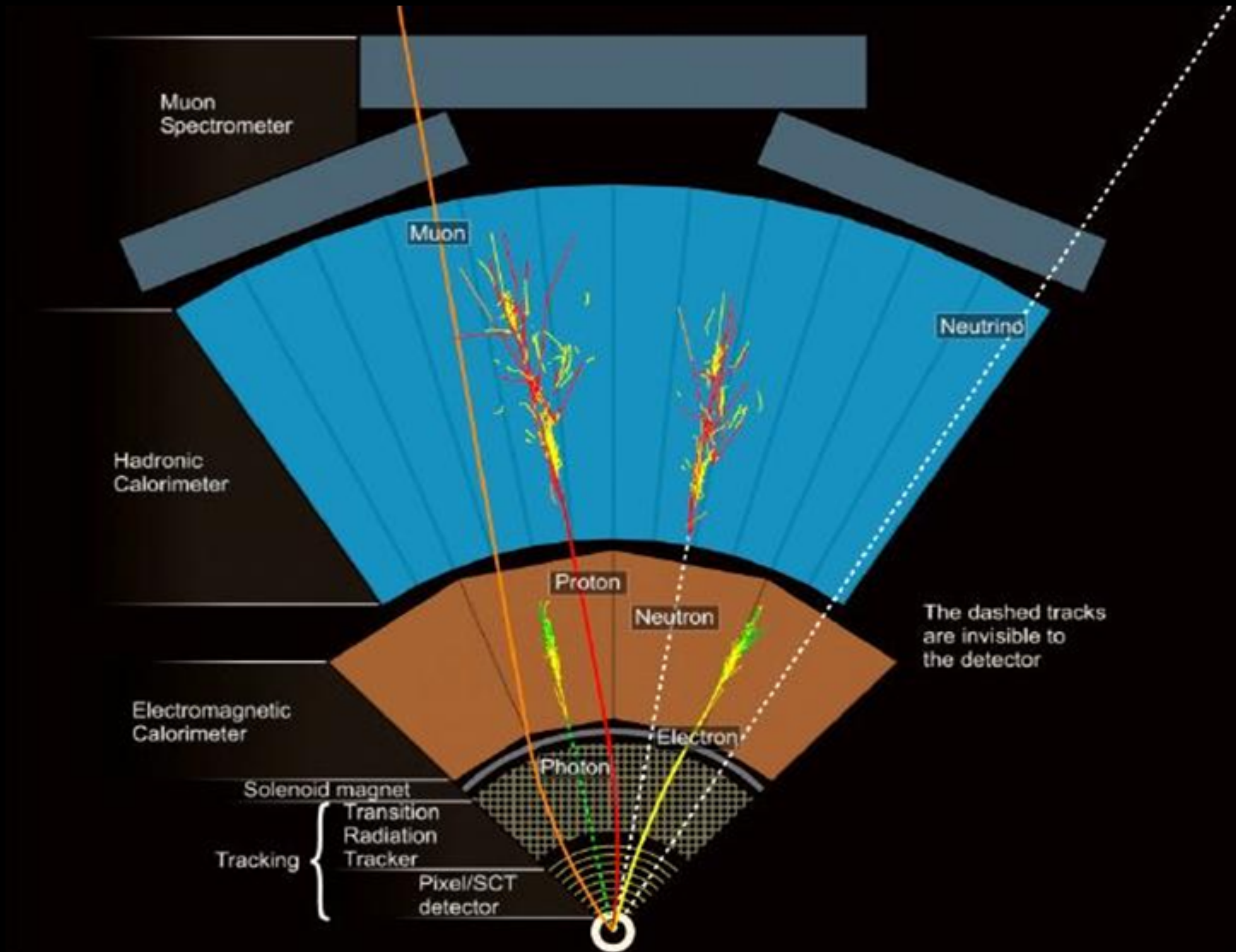
- Important milestones crossed last year with **ttH** and **H→bb** observations!
- Main production modes (ggF, VBF, VH, ttH) **have all been obser**ved!!
- The Higgs sector continues to look SM-like
- **But!**
- We know **there is new physics out there**!
- ≈ 3000 fb^{-1} of data expected at the HL-LHC
- We have a strong programme of **precision measurements** and **searches** for new Higgs states and decays



Overall highlight from the past year (very personal bias!):
"***The >5σ observations of ttH and H → ττ, independently by ATLAS and CMS, firmly establish the existence of a new kind of fundamental interaction, Yukawa interactions***."
Gavin Salam (LHCP'18)

See here for more: ATLAS Public results page

Free Bonus Slides


Muon Spectrometer
Muon
Hadronic Calorimeter
Neutrino
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Transition Radiation Tracker
Tracking
Pixel/SCT detector

Two Higgs Doublet Model (2HDM)

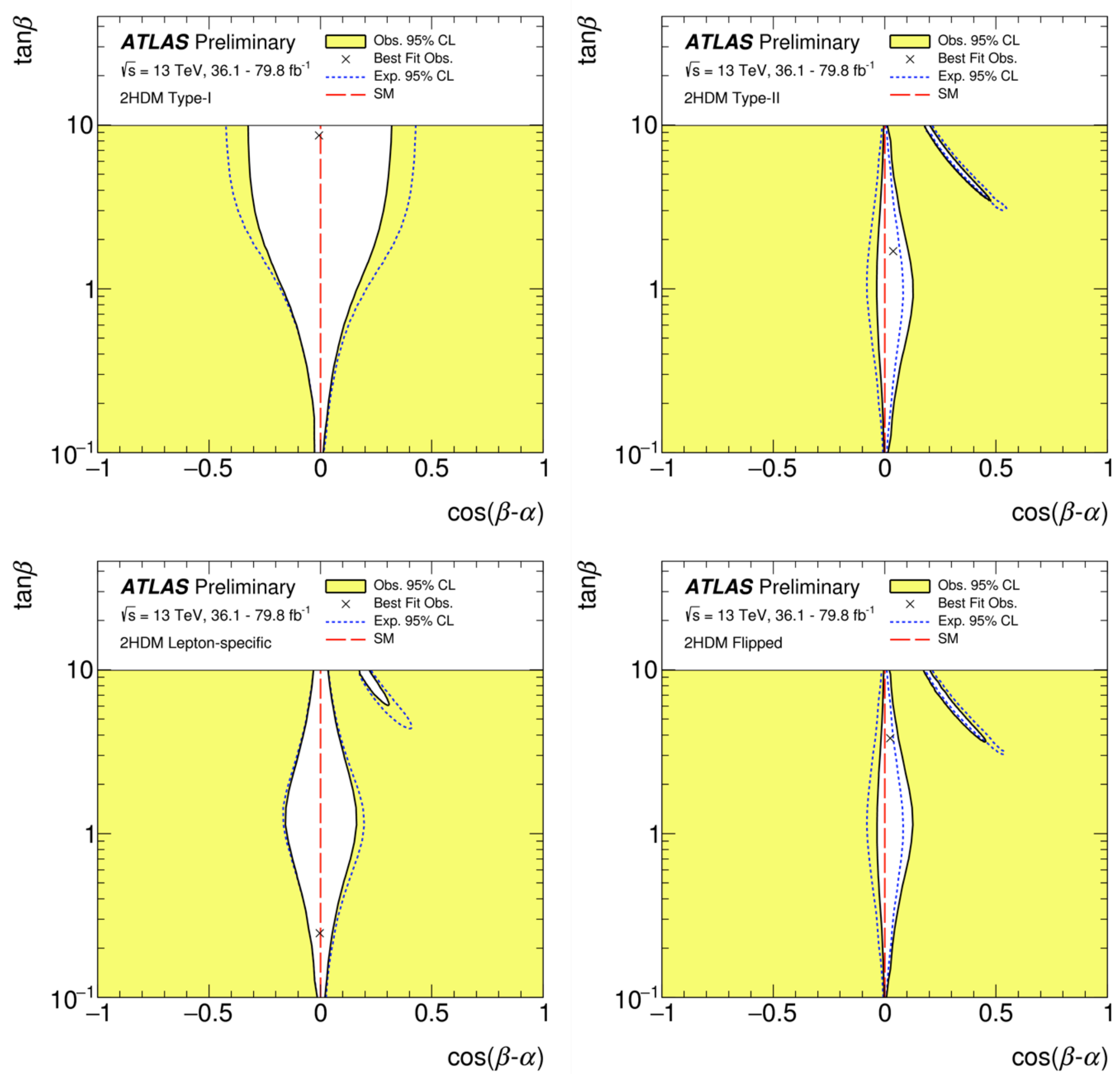
- Two Higgs doublets: Φ_1 and Φ_2 → 5 Higgs bosons incl. 2 charged
- Free parameters:
  - 4 masses (Do we know one? Assume it's m_h)
  - $\tan\beta = v_1/v_2$ ratio of v.e.v.'s of Φ_1 and Φ_2
  - Mixing angle of h and H: α
- 4 possible Yukawa coupling arrangements ("types") with no FCNC
- Most common SUSY benchmark (MSSM) is based on Type II
- If $\cos(\beta-\alpha) = 0$, h = Standard Model H^0

	Type I	Type II	Lepton Specific	Flipped
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Implications for 2HDM

- H(125) assumed to be light CP-even neutral scalar *h* in 2HDM

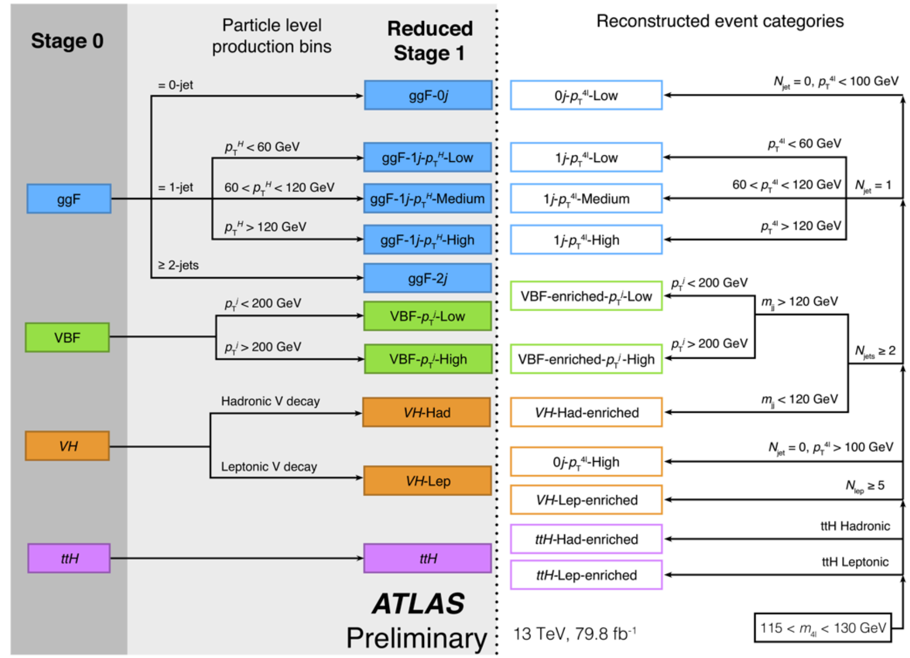
- *h* production and decay same as for SM Higgs boson

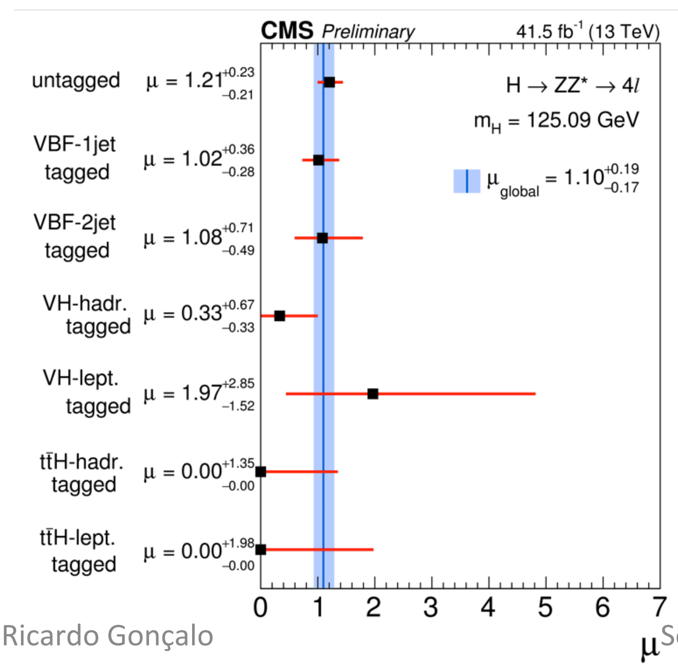


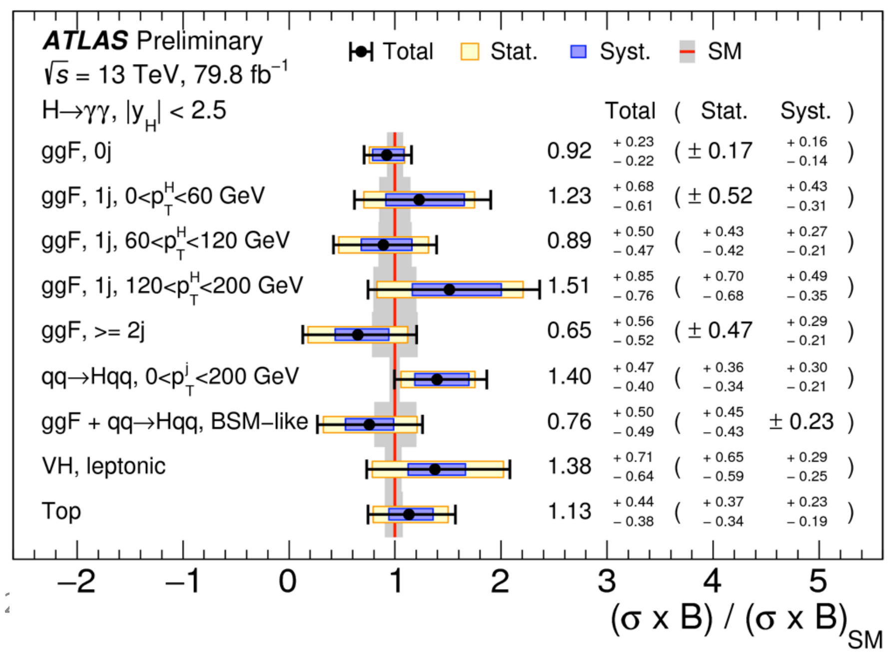
ATLAS-CONF-2017-047; ATLAS-CONF-2018-028

NEW 5 July 2018

- Simplified template cross sections (STXS):
  - Independent, simple fiducial region definition for each production mode
  - Common for ATLAS, CMS and theory
  - Good balance between experimental precision and theory uncertainty

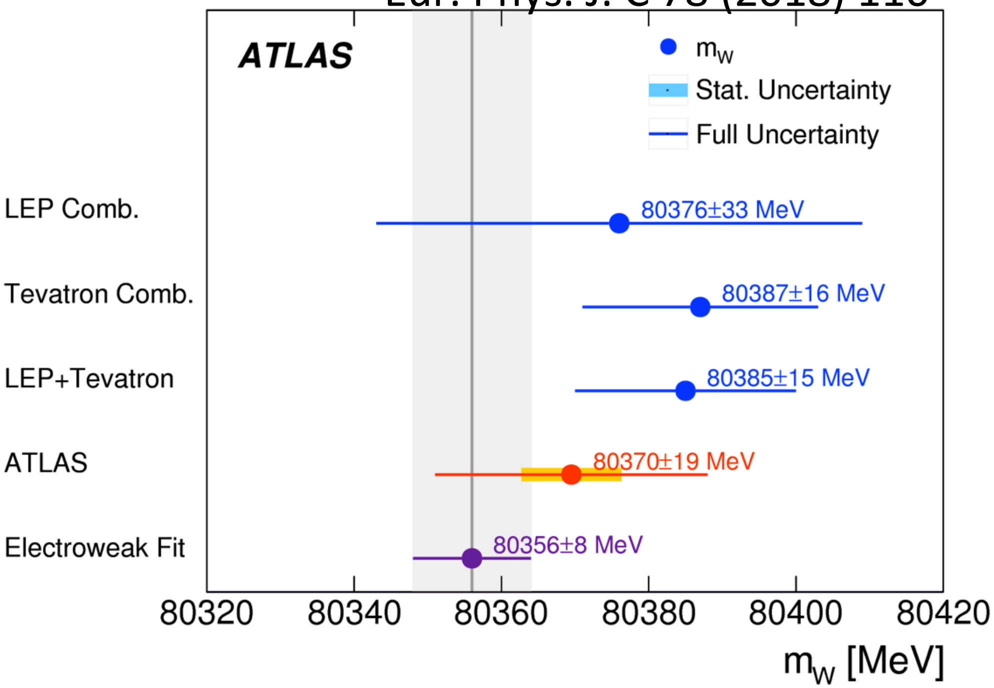


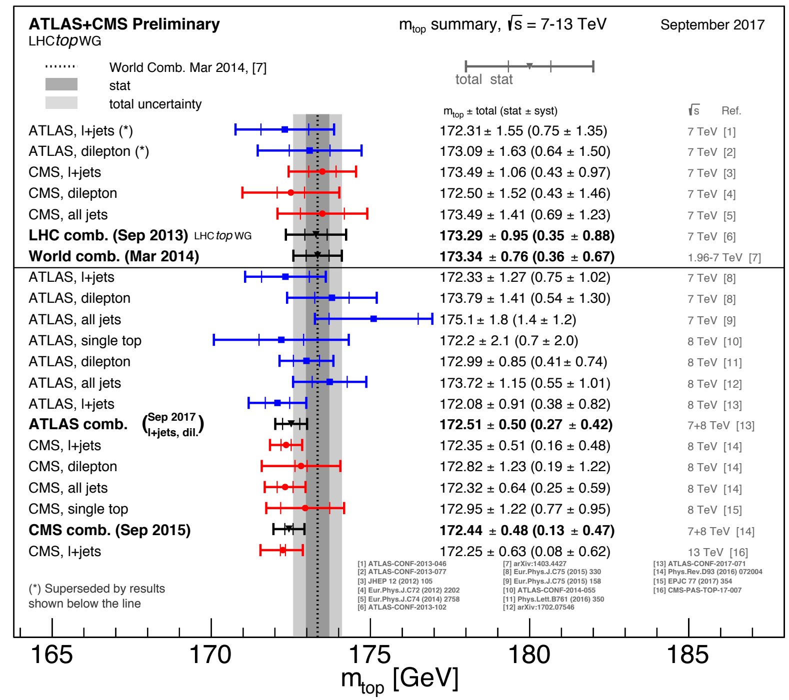




M_W AND M_T: THE STORY SO FAR…

Eur. Phys. J. C 78 (2018) 110





https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots

Per mille precision!

Lagrangians, symmetries and all that

Emmy Noether (1882 – 1935)

Leonhard Euler(1707–1783)

Joseph-Louis Lagrange (1736–1813)

Reminder: Lagrangians in classical mechanics

The equations of motion of a system are derived from a scalar **Lagrangian** function of **generalized coordinates** and **velocities** (time derivatives)

$$L(q, \dot{q}) = T - V$$

and from the **Euler-Lagrange's equations**:

$$\frac{\partial L}{\partial q_j} - \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_j} = 0$$

Example

Particle in a conservative potential V. The Lagrangian

$$L = \frac{1}{2}m(\dot{x}^2 + \dot{y}^2 + \dot{z}^2) - V(x, y, z)$$

has derivatives (e.g. for *x*)

$$\frac{\partial L}{\partial x} = -\frac{\partial V}{\partial x}, \frac{\partial L}{\partial \dot{x}} = m\dot{x}, \frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = m\ddot{x}$$

and Euler-Lagrange's equations

$$\frac{\partial L}{\partial q_j} - \frac{d}{dt}\frac{\partial L}{\partial \dot{q}_j} = 0$$

finally give us Newton's familiar 2nd law!

$$m\ddot{x} = -\frac{\partial V}{\partial x}, m\ddot{y} = -\frac{\partial V}{\partial y}, m\ddot{z} = -\frac{\partial V}{\partial z} \Leftrightarrow m\vec{a} = \vec{F}$$

Symmetries and conservation laws

Noether's theorem:

If a system has a continuous symmetry property, then there are corresponding quantities whose values are conserved in time.

Simplest case: Coordinates not explicitly appearing in the Lagrangian

$\Rightarrow$ Lagrangian invariant over a continuous transformation of the coordinates

Example: mass **m** orbiting in the field of a fixed mass **M**

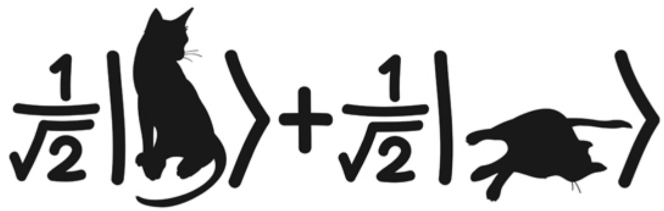
$$L(r,\phi,\dot{r},\dot{\phi}) = T - V = \frac{1}{2}m\dot{r}^2 + \frac{1}{2}mr^2\dot{\phi}^2 + \frac{GMm}{r}$$

Since the lagrangian doesn't depend explicitly on **ϕ** (symmetry with respect to rotations in space), the Euler-Lagrange equation gives

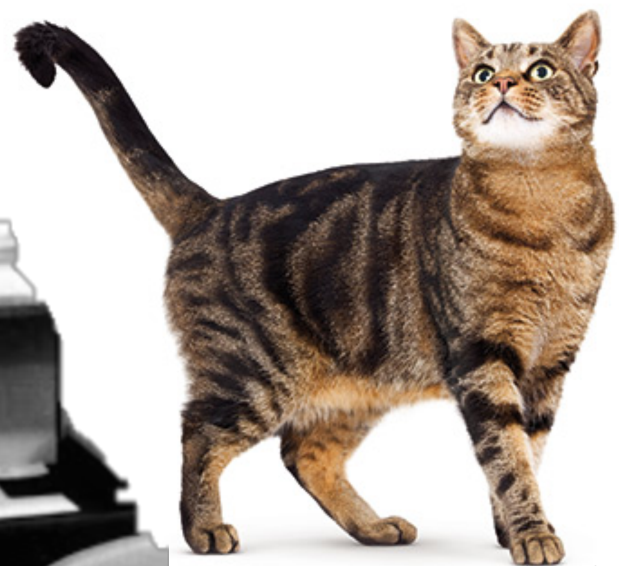
$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{\phi}}\right) = 0 \Leftrightarrow \frac{\partial L}{\partial\dot{\phi}} = mr^2\dot{\phi} = J$$

Where the **angular momentum J** is a constant of motion!

Let’s go to quantum fields...



Richard Feynman
(1918 - 1988)

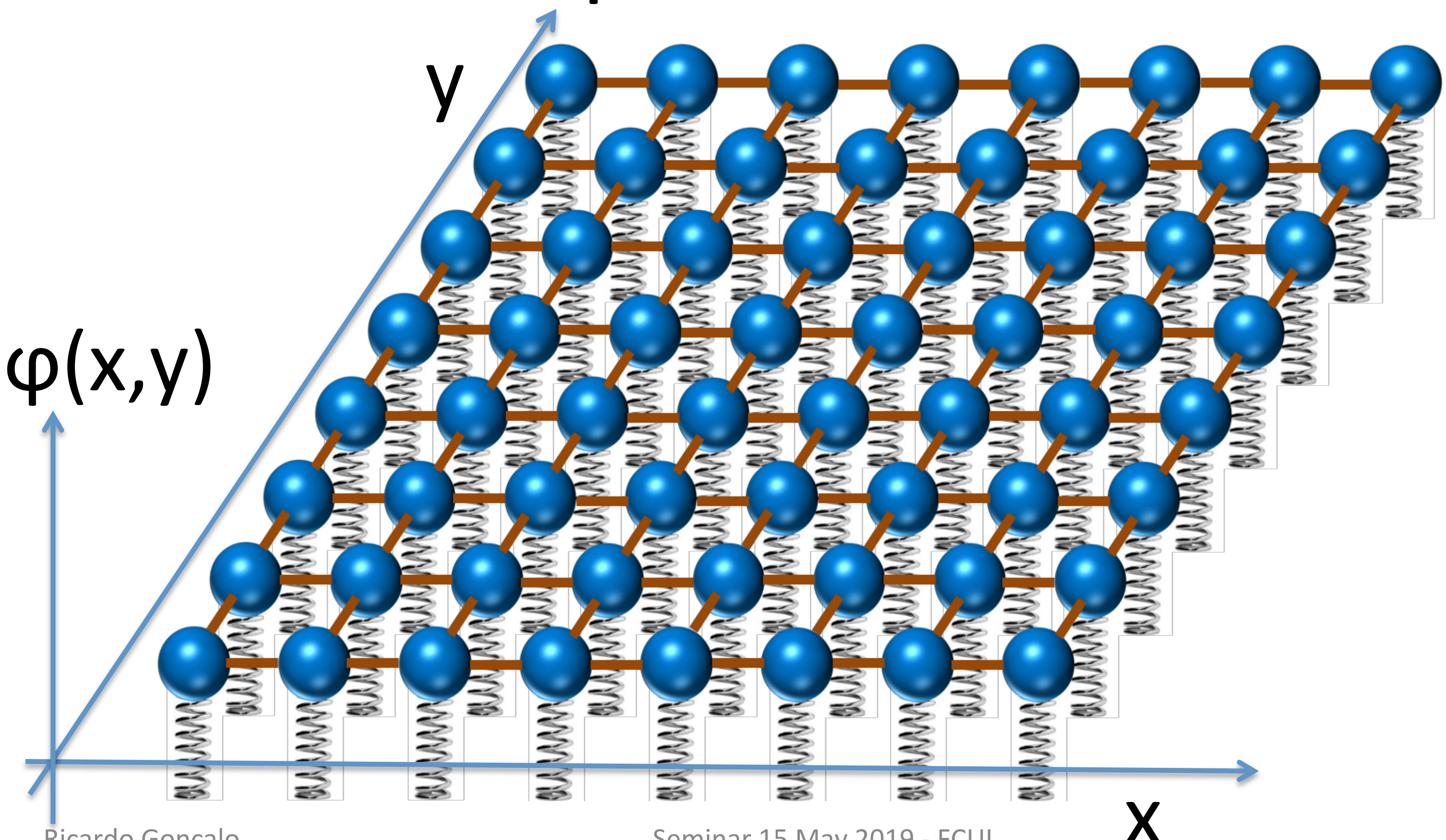


Schrödinger’s cat (?-?)

Erwin
Schrödinger
(1887 - 1961)

Now in quantum field theory…

Imagine space as an infinite continuum of balls and springs, where each ball is connected to its neighbours by elastic bands. **Particles are perturbations of this field**



Generalized coordinates are now **fields** (dislocation of each spring)

$$q_i \rightarrow \phi_i(x^\mu)$$

In a relativistic theory we must treat space and time coordinates on an equal footing, so the derivatives in the classical equations are now

$$\frac{d}{dt}, \nabla \rightarrow \partial_\mu = (\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z})$$

In place of a Lagrangian we have a **Lagrangian density** (we call it Lagrangian anyway, just to be confusing)

$$L(q_i, \frac{dq_i}{dt}) \rightarrow \mathcal{L}(\phi_i, \partial_\mu \phi_i) \quad \text{with:} \quad L = \int \mathcal{L} d^3\boldsymbol{x}$$

The new Euler-Lagrange equation now becomes

$$\partial_\mu (\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi_i)}) - \frac{\partial \mathcal{L}}{\partial \phi_i} = 0$$

Gauge invariance

Take the Dirac Lagrangian for a field ψ representing a spin-½ particle, for example an electron:

$$\mathcal{L} = i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi$$

It is invariant under a global U(1) phase transformation like:

$$\psi(x) \to \psi'(x) = e^{iq\chi}\psi(x)$$

Where **χ** is a constant

$$\mathcal{L}' = e^{-iq\chi}e^{iq\chi}(i\hbar\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi) = \mathcal{L}$$

Local gauge invariance and interactions

If **χ** = **χ** (*x*) then we get extra terms in the Lagrangian:

$$\begin{aligned}\mathcal{L}' &= ie^{-iq\chi}\bar{\psi}\gamma^{\mu}[e^{iq\chi}\partial_{\mu}\psi + iq(\partial_{\mu}\chi)e^{iq\chi}\psi] - me^{-iq\chi}e^{iq\chi}\bar{\psi}\psi \\ &= \mathcal{L}' - q\bar{\psi}\gamma^{\mu}(\partial_{\mu}\chi)\psi\end{aligned}$$

But we can now make the Lagrangian invariant by adding an ***interaction term*** with a new **gauge** field $\boldsymbol{A_\mu}$ which transforms as:

$$A_{\mu} \rightarrow A'_{\mu} = A_{\mu} - \partial_{\mu}\chi$$

We get:

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi - q\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

A few things to note:

1. Gauge theories are renormalizable, i.e. calculable without infinities popping up everywhere (Nobel prize of t'Hooft and Veltman)
2. The new gauge field $\boldsymbol{A_\mu}$ is the photon in QED
3. The mass of the fermion is the coefficient of the term on $\boldsymbol{\psi\bar{\psi}}$
4. There is no term in $\boldsymbol{A_\mu A^\mu}$ (the photon has zero mass) → this is the beginning of the Higgs story…

Now for the problems…

1: Mass of elementary particles and gauge bosons

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu \partial_\mu - m_e)\psi - e\bar{\psi}\gamma^\mu \psi A_\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\gamma A_\mu A^\mu$$

To keep the Lagrangian gauge invariant against a U(1) **local** phase transformation:

$$\psi(x) \to \psi'(x) = e^{iq\chi}\psi(x)$$

with $\boldsymbol{\chi} = \boldsymbol{\chi}\,(x)$. The photon field transforms as:

$$A_\mu \to A'_\mu = A_\mu - \partial_\mu \chi$$

But the $\boldsymbol{A^\mu}$ mass term breaks the invariance of the Lagrangian:

$$\frac{1}{2}m_\gamma A_\mu A^\mu \to \frac{1}{2}m_\gamma (A_\mu - \partial_\mu)(A^\mu - \partial^\mu \chi) \neq \frac{1}{2}m_\gamma A_\mu A^\mu$$

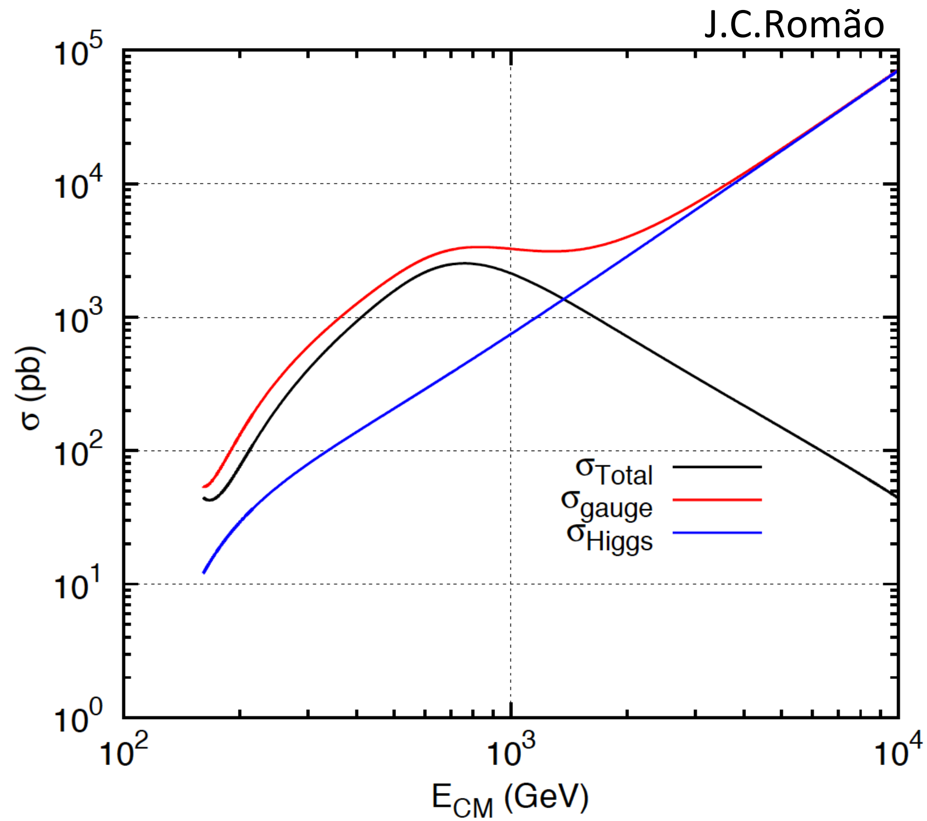
For the $SU(2)_L$ gauge symmetry transformations of the **weak interaction** the fermion mass term $\boldsymbol{m_e\bar{\Psi}\psi}$ also breaks invariance!

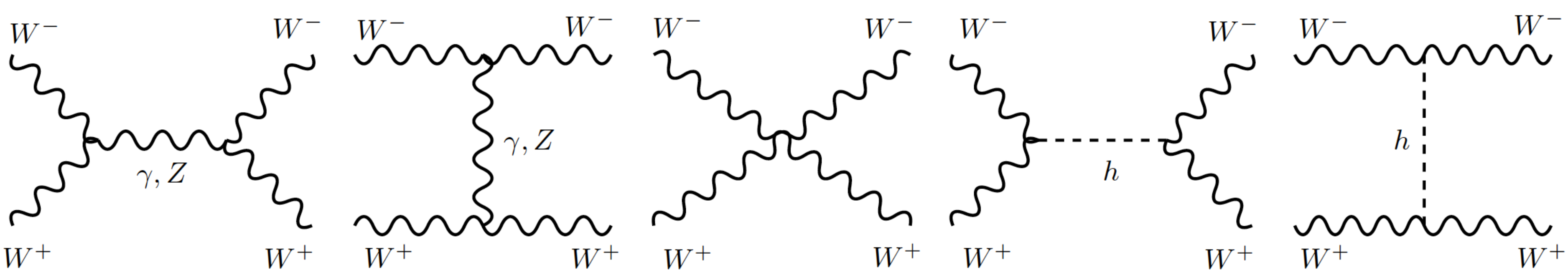
Bottom line: **the SM (without the Higgs mechanism) results in wrong calculations and breaks down for massive particles**

2: Longitudinal gauge-boson scattering

In the absence of the Higgs, some processes have cross sections that grow with the centre of mass energy of the collision… i.e. breaks unitarity!

The Higgs regulates the cross section through negative interference



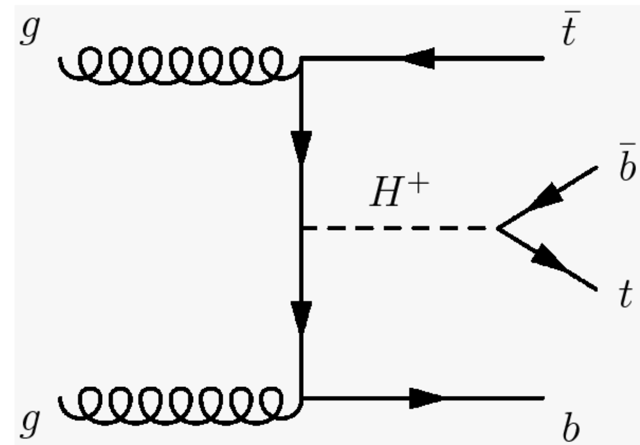


Feynman diagrams contributing to longitudinal WW scattering

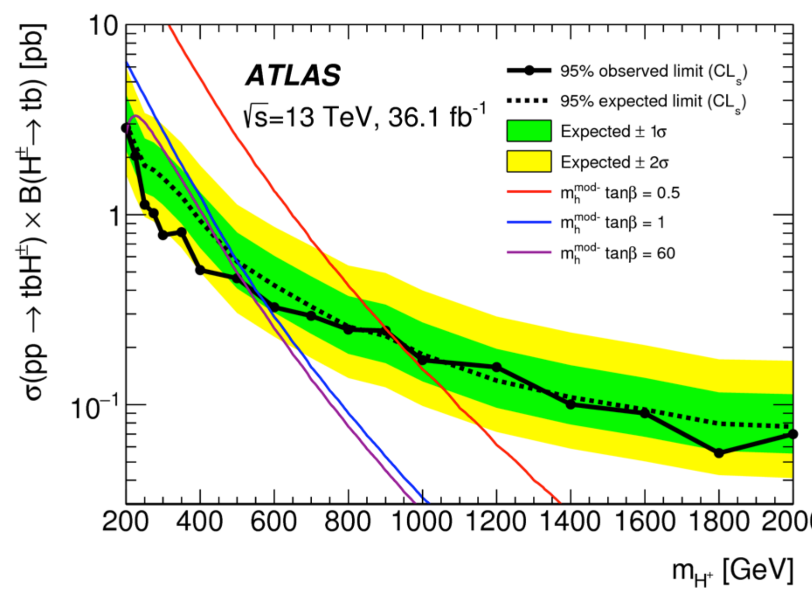
arXiv:1808.03599

Charged Higgs: $H^+ \rightarrow tb$

- Explored single-lepton and dilepton tt final states
  - In range m_{H+}: 200 – 2000 GeV
- 36.1 fb^{-1} of 13 TeV data



- Events categories: N_{jets} and $N_{b\text{-}tags}$
  - Allow to constrain backgrounds in simultaneous fit



- BDTs trained in signal regions
  - Separate signal and background for 18 mass points
  - Matrix method used in single-lepton channel
- Extracted limits on σ x BR and on m_{H+} - tan β plane for two MSSM scenarios