The Higgs boson –
- discovery and recent results

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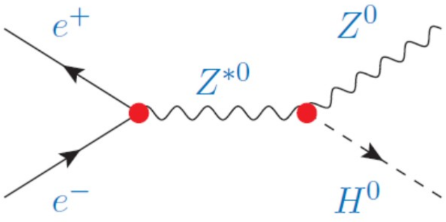
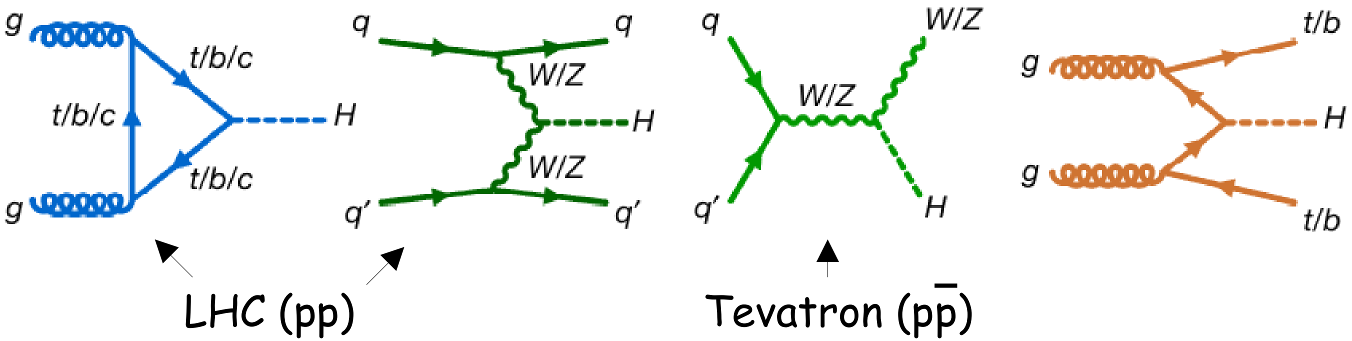
How to search for Higgs boson (1)

- First it needs to be produced in high-energy particle collisions
  - e^+e^- collider: associated production with Z boson dominates
    - the biggest issue is the e^+e^- energy



  - pp or $p\bar{p}$ collider: several production modes, probability depends on energy and pp/$p\bar{p}$

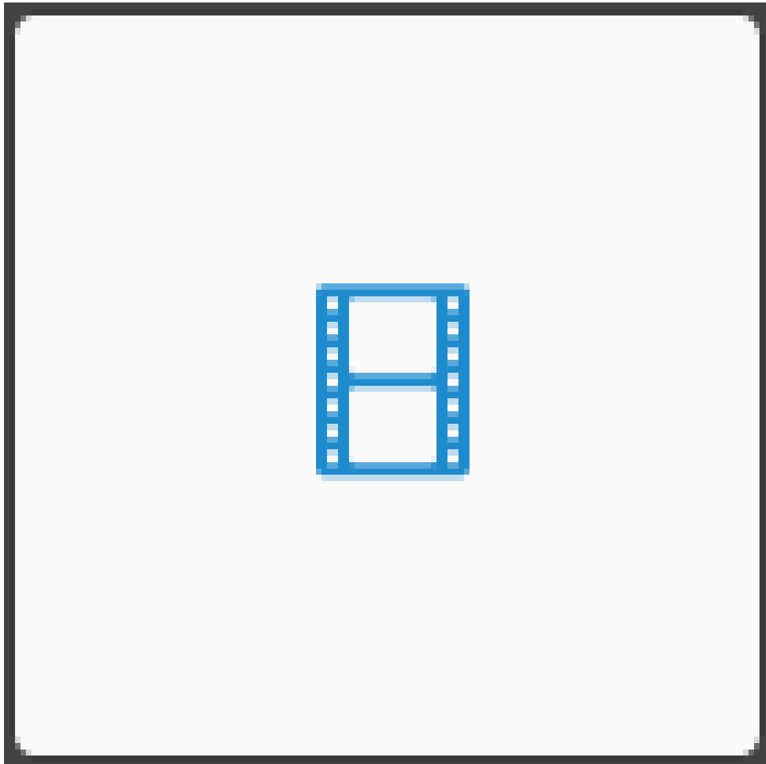


- In all cases, the probability of Higgs boson being born is extremely small (~ 10^{-10} at LHC wrt inelastic pp collision)

How to search for Higgs boson (2)

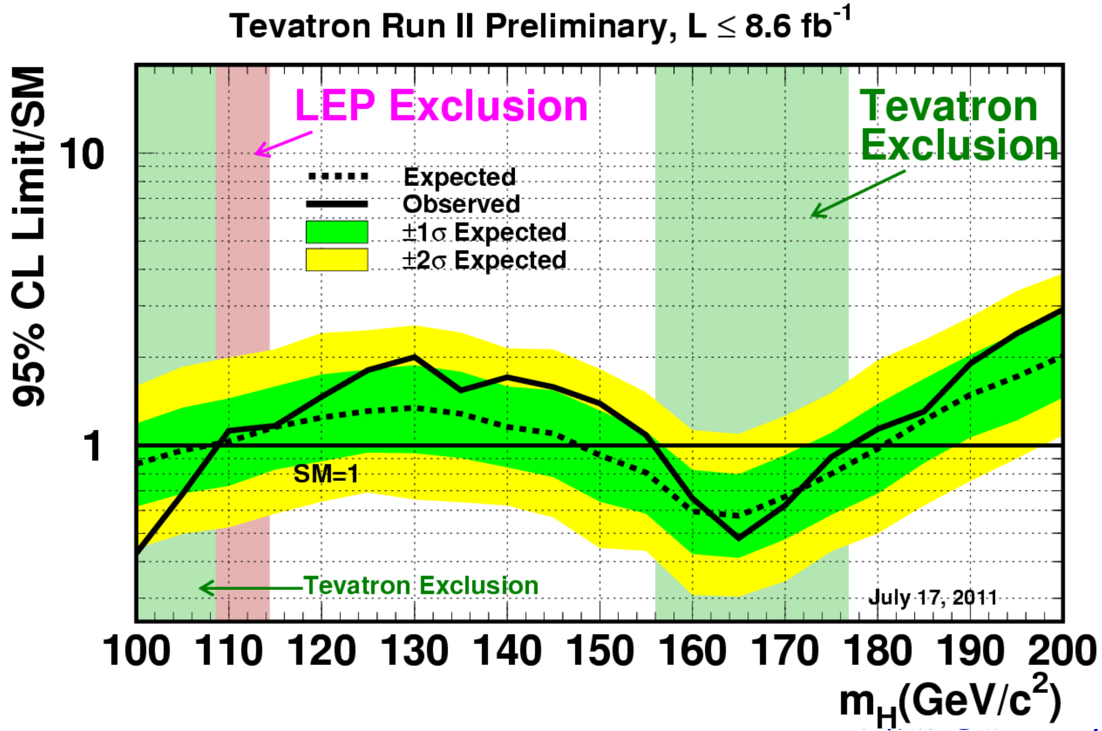
- Detection depends on the decay mode (ℓ=e,μ)
  - „easy" to detect: $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$, $H \to \mu\mu$
  - challenging, but feasible: $H \to WW \to \ell\nu\ell\bar{\nu}$, $H \to \tau\tau$
  - very difficult at pp/p$\bar{\text{p}}$ colliders: $H \to bb$, $H \to cc$, ...

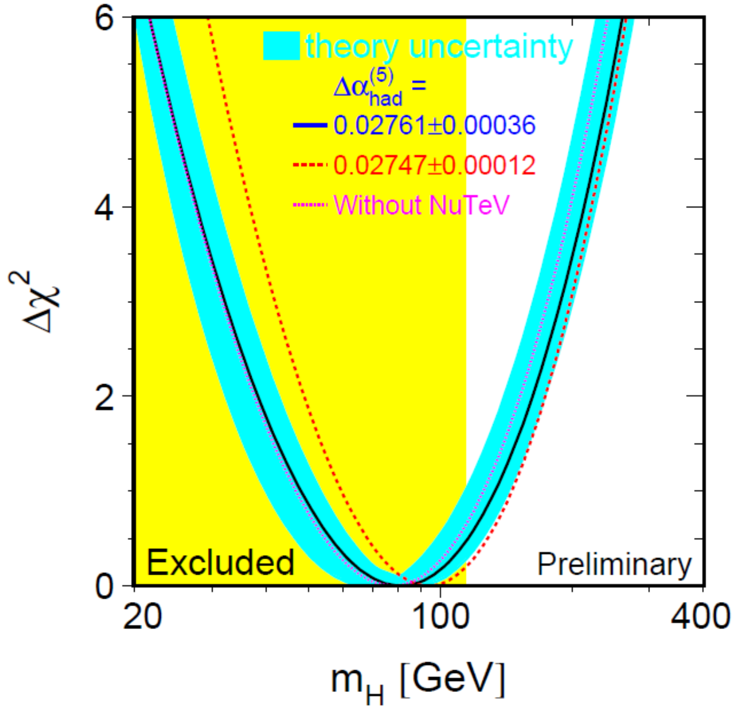
- Example of a pp collision in ATLAS experiment



Searches for Higgs boson (1)

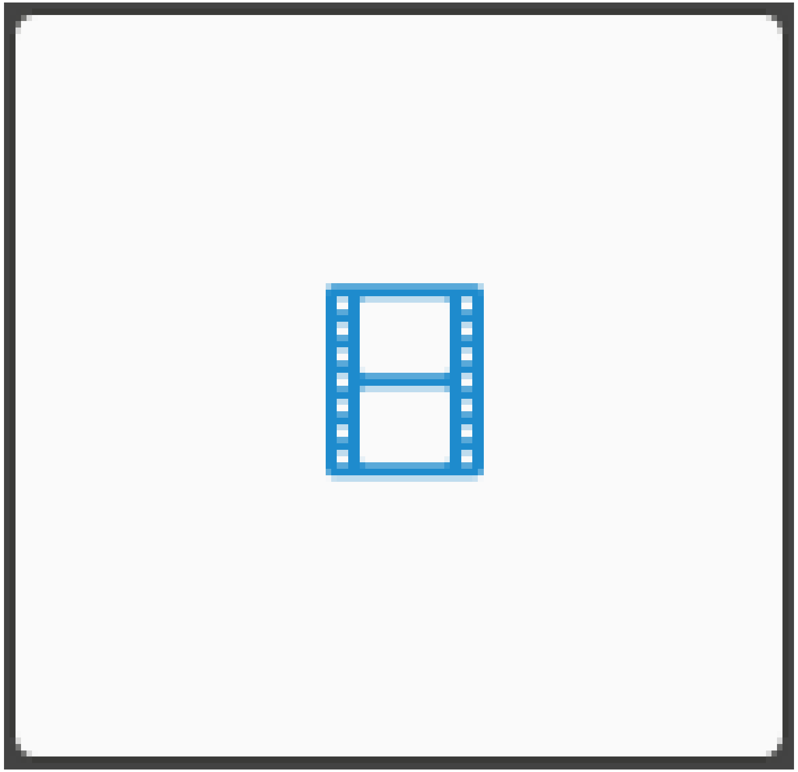
- Direct and indirect searches performed at previous collider experiments at LEP (e^+e^-) and Tevatron ($p\bar{p}$)
  - direct searches excluded Higgs boson with mass $m_H < 114.4$ GeV and $m_H \in (156,177)$ GeV
  - indirect searches indicated $m_H = 81^{+52}_{-33}$ GeV





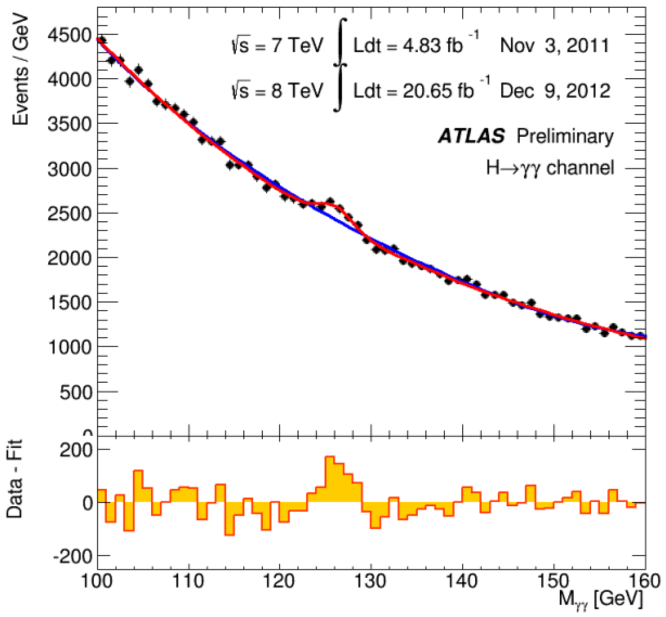
Searches for Higgs boson (2)

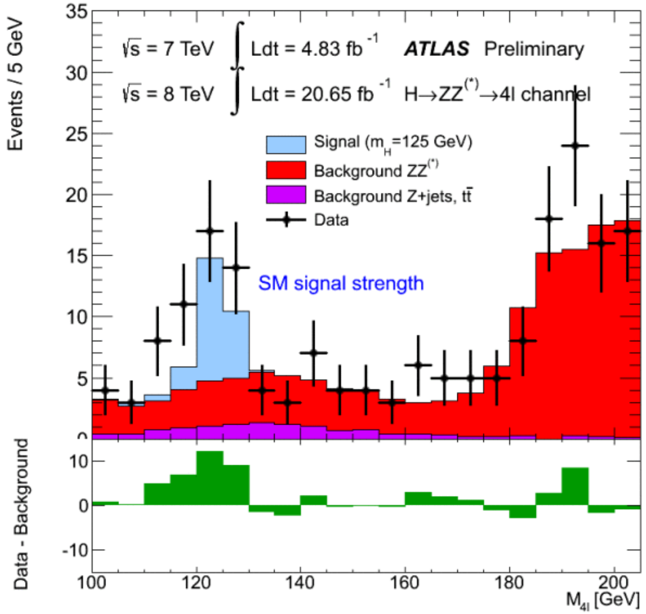
- Discovery by ATLAS and CMS experiments at LHC (2012)
  - kinematic peak observed in the $H \rightarrow \gamma\gamma$, m_H ~ 125 GeV

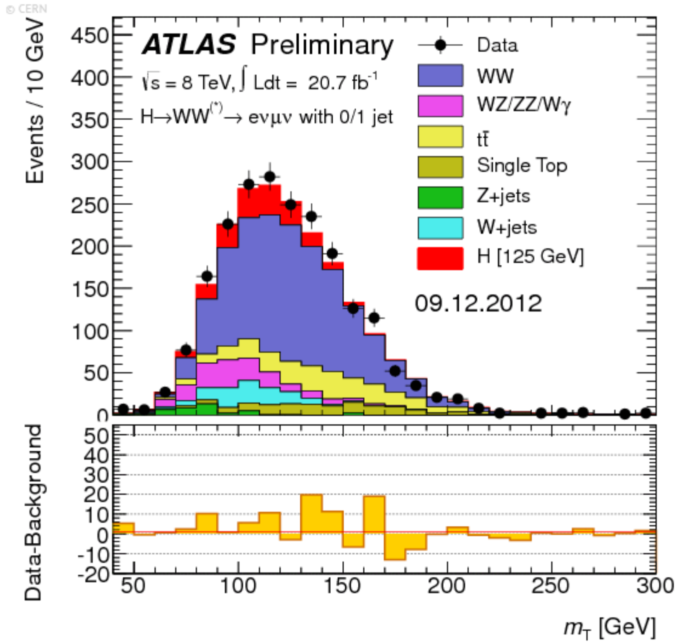


Searches for Higgs boson (3)

- Discovery by ATLAS and CMS experiments at LHC (2012), cont'd
  - kinematic peaks observed in the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decay channels, m_H ~ 125 GeV
  - excess of events compatible with such Higgs boson observed in $H \to WW^* \to \ell\nu\ell\bar{\nu}$ channel

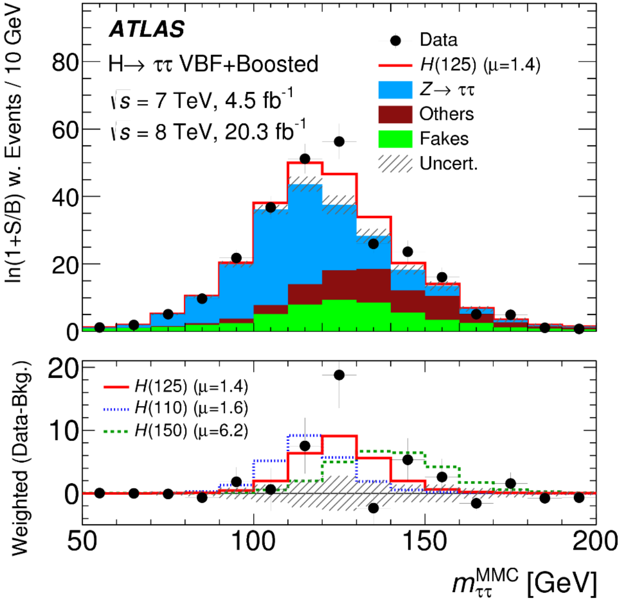




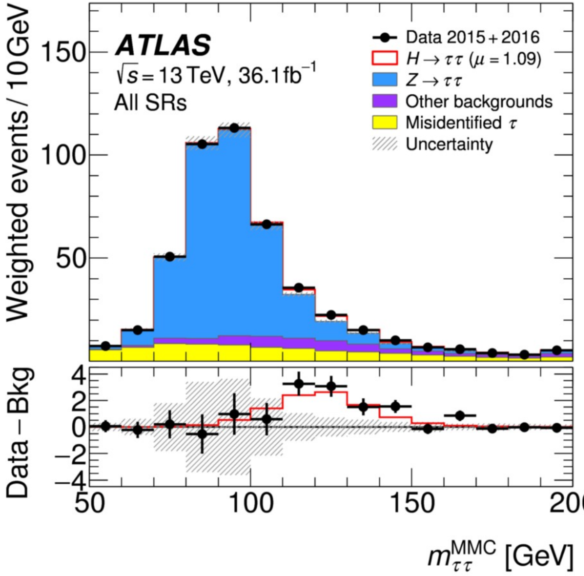


Further Higgs measurements (1)

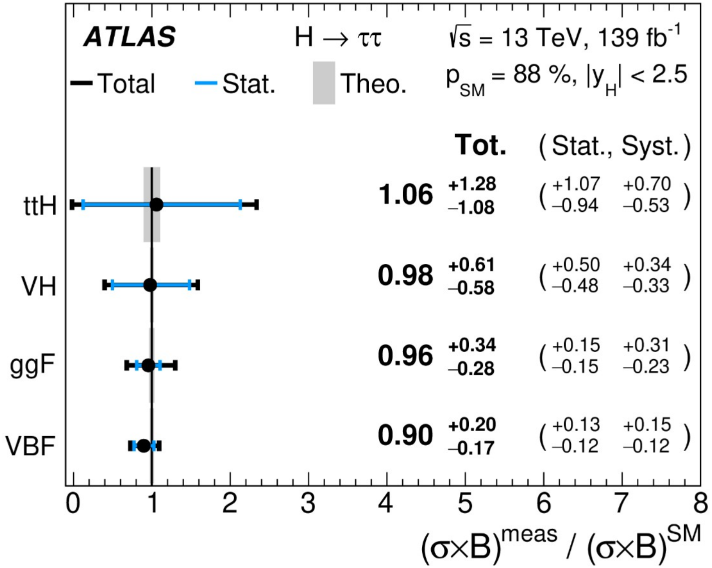
- Focus changed to precision measurements of all possible Higgs features
  - interaction strength (coupling) with other particles ($H \to \tau\tau$, $H \to bb$, ttH, ...)



evidence for $H \to \tau\tau$,
JHEP 04 (2015) 117



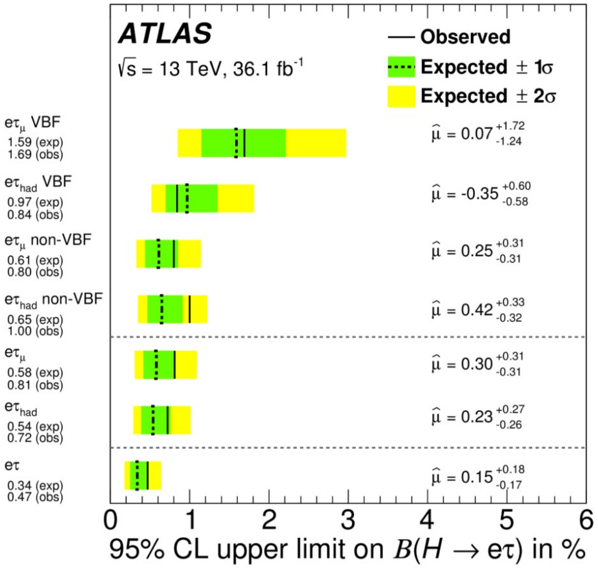
observation of $H \to \tau\tau$,
Phys. Rev. D 99 (2019) 072001

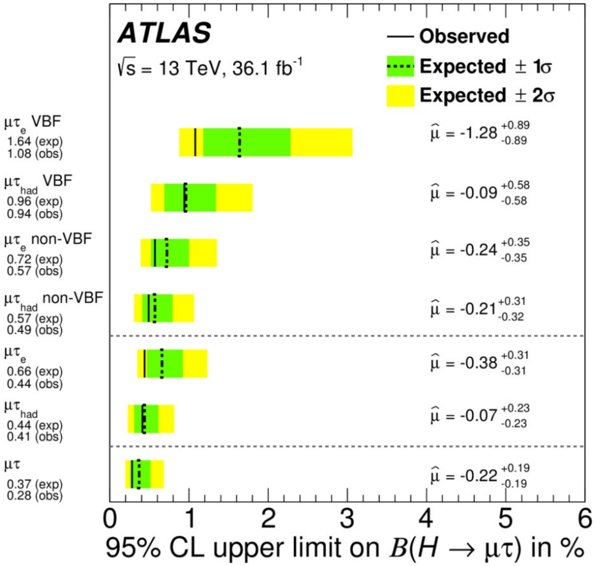


latest $H \to \tau\tau$ results,
JHEP 08 (2022) 175

Further Higgs measurements (2)

- … precision measurements of all possible Higgs features (cont'd)
  - spin and CP measurements
  - differential cross-section measurements (e.g. cross-section measurements as a function of e.g. transverse momentum, …)
  - search for decays forbidden by SM (e.g. $H \to e\tau$, $H \to \mu\tau$)





no lepton-flavour-violating Higgs decays observed, Phys. Lett. B 800 (2020) 135069

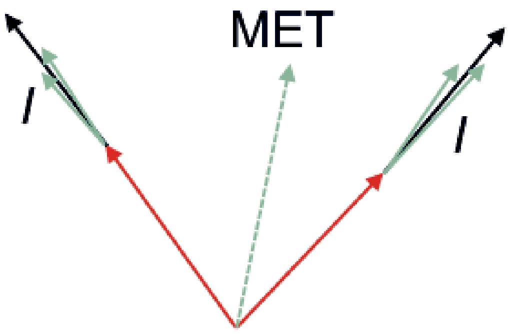
$H \to \tau\,\tau$ (1)

- The final state depends on the τ-lepton decay mode
  - di-lepton channel: $H \to \tau\,\tau \to 2\ell\ 4\nu$
  - semi-lepton channel: $H \to \tau\,\tau \to \ell\ n\pi\ 3\nu$ (n=1 - 3)
  - hadronic channel: $H \to \tau\,\tau \to n\pi\ 2\nu$

- Signatures in the detector
  - isolated electron(s) and/or muon(s)
  - missing transverse energy
  - reconstructed hadronic τ
  - accompanying jets (reflect the production mechanism)
- Search splitted into 2 categories (boosted, VBF) targetting the individual production mode
- Dominant background comes from $Z \to \tau\,\tau$; also top, $Z \to \ell\ell$ and fakes contribute

H → τ τ (2)

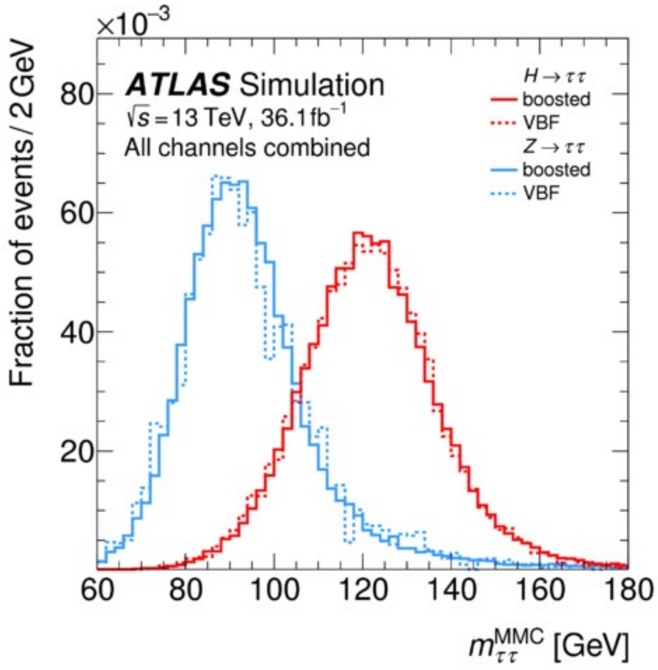
- Invariant mass cannot be properly reconstructed due to 2-4 neutrinos



- **Collinear mass approximation**
  - assumes all τ-decay products are collinear

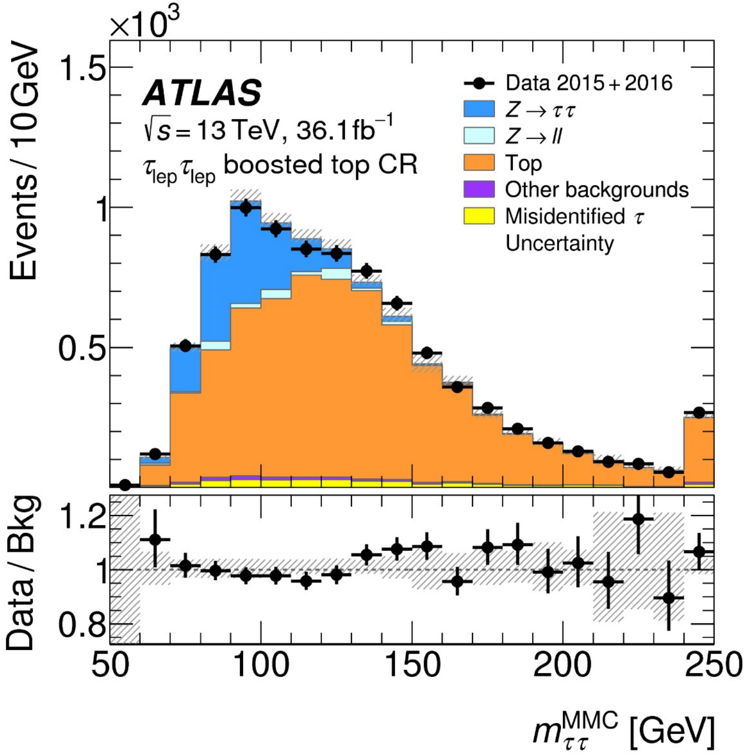
$$\vec{p}^{miss} = k_1 \vec{p}_{vis\,1} + k_2 \vec{p}_{vis\,2}$$

- **Missing Mass Calculator**
  - takes into account the probability of the angular distribution between the τ-decay products (NIM A **654** (2011))
  - better resolution than collinear mass, critically depends on the MET resolution



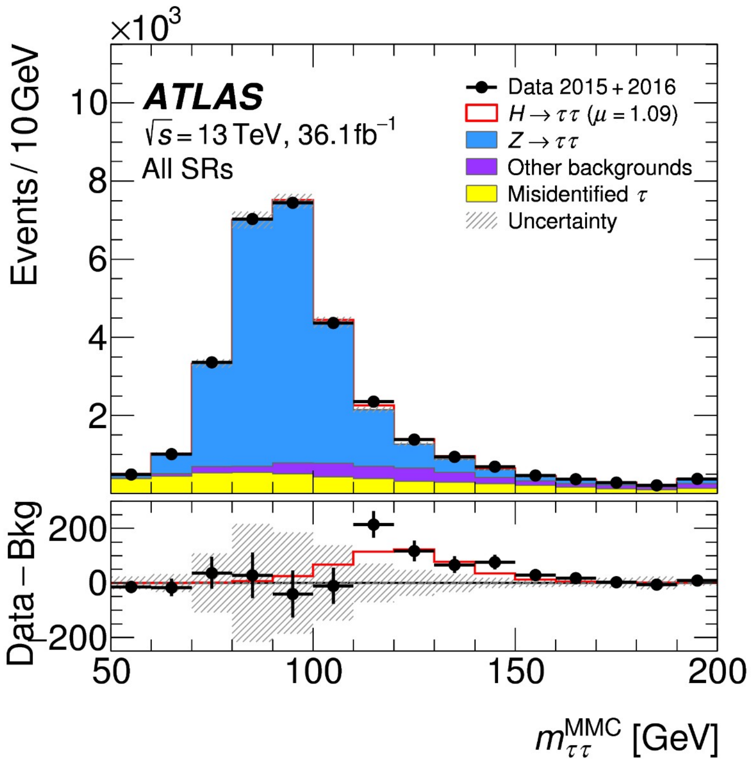
H → τ τ (3)

- We are looking for a small bump on the Z → τ τ peak shoulder, need to predict the background as precisely as possible
- Let's demonstrate the background prediction for top background
  - in case of di-lepton channel, $t\bar{t} \to WbW\bar{b} \to \ell\nu b\ell\nu\bar{b}$ contributes to the background
  - background modelled with MC, but checked with data in a control region
    - same selection criteria as for signal region, one criterion is inverted (here b-veto)
- Misidentified τ-leptons obtained in purely data-driven way



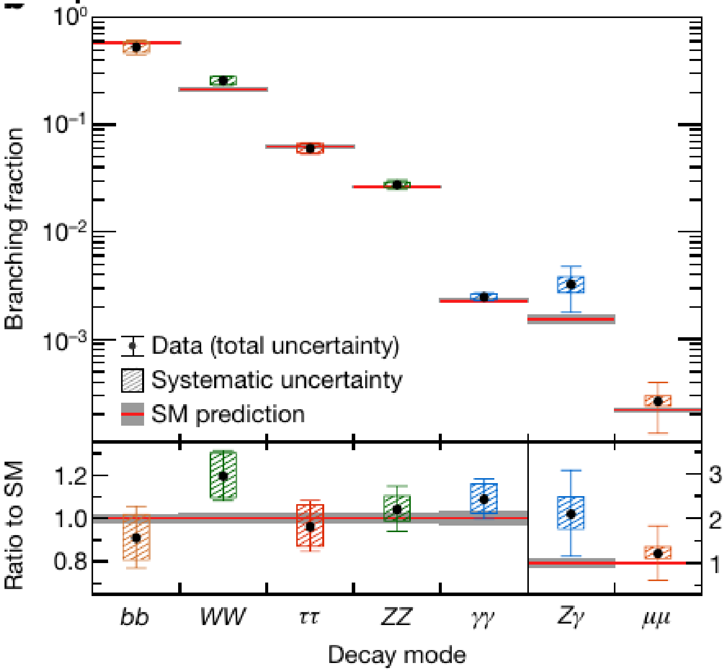
H → τ τ (4)

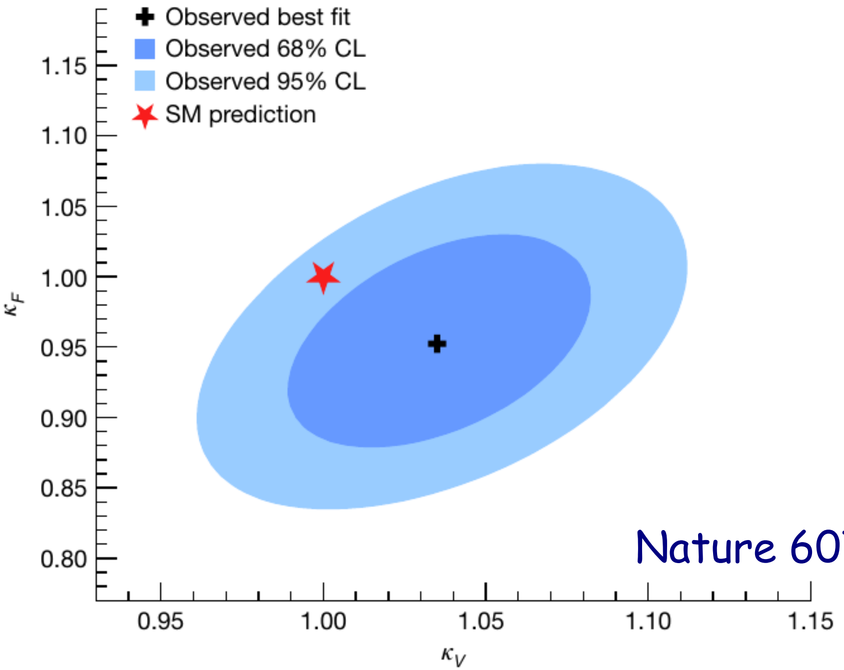
- Amount of individual (main) background components is obtained from the combined fit
  - signal and all control regions fitted together
  - as the background is well under control, even a relatively small signal peak can be significant enough
  - significance obtained with 2015+2016 data = 4.4σ, combined with earlier dataset = 6.4σ



Recent results

- All four production processes (slide 2) and decay modes ($H\to\gamma\gamma$, $H\to ZZ$, $H\to WW$, $H\to b\bar{b}$, $H\to\tau\tau$) have been already measured with large significance
  - in general, very good agreement with SM predictions
  - global fit to coupling modifiers maybe suggest small tension, need more data/better precision to address that



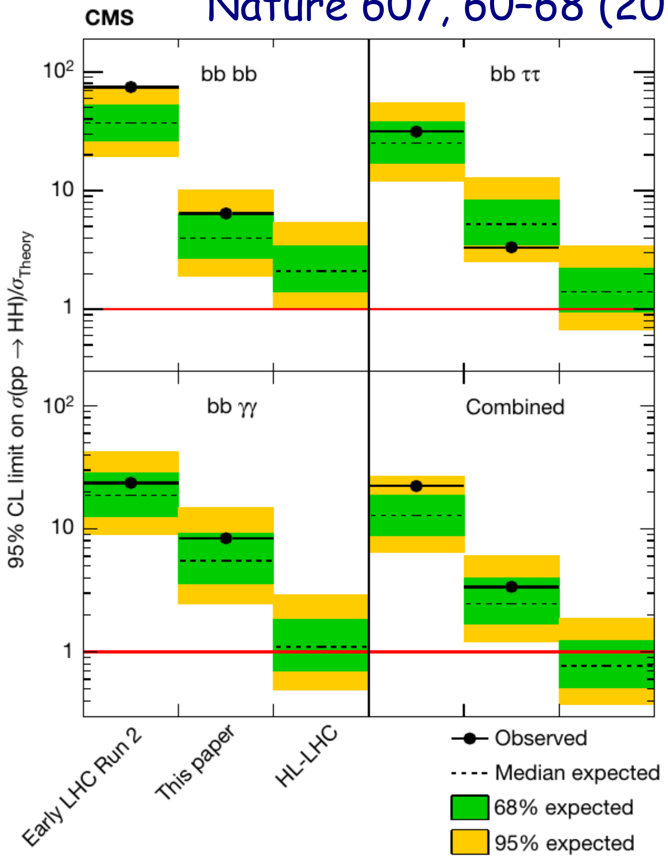


Nature 607, 52-59 (2022)

Outlook (1)

- Some processes not yet observed with enough significance (e.g. $H \to \mu\mu$, $H \to Z\gamma$), should be possible with Run-3 (2022-2025) data
- Other processes not measured yet (di-Higgs production, probes of HHH and HHHH couplings, ….)
  - observation of di-Higgs production is one of the main goals for the **High Luminosity LHC** (2029-2038)
- Further improvements with next-generation accelerators, ideally FCC combining e^+e^- (1st stage) and pp (2nd stage) collisions
  - can probe the Higgs self-interaction to ~5% precision

Nature 607, 60–68 (2022)



Outlook (2)

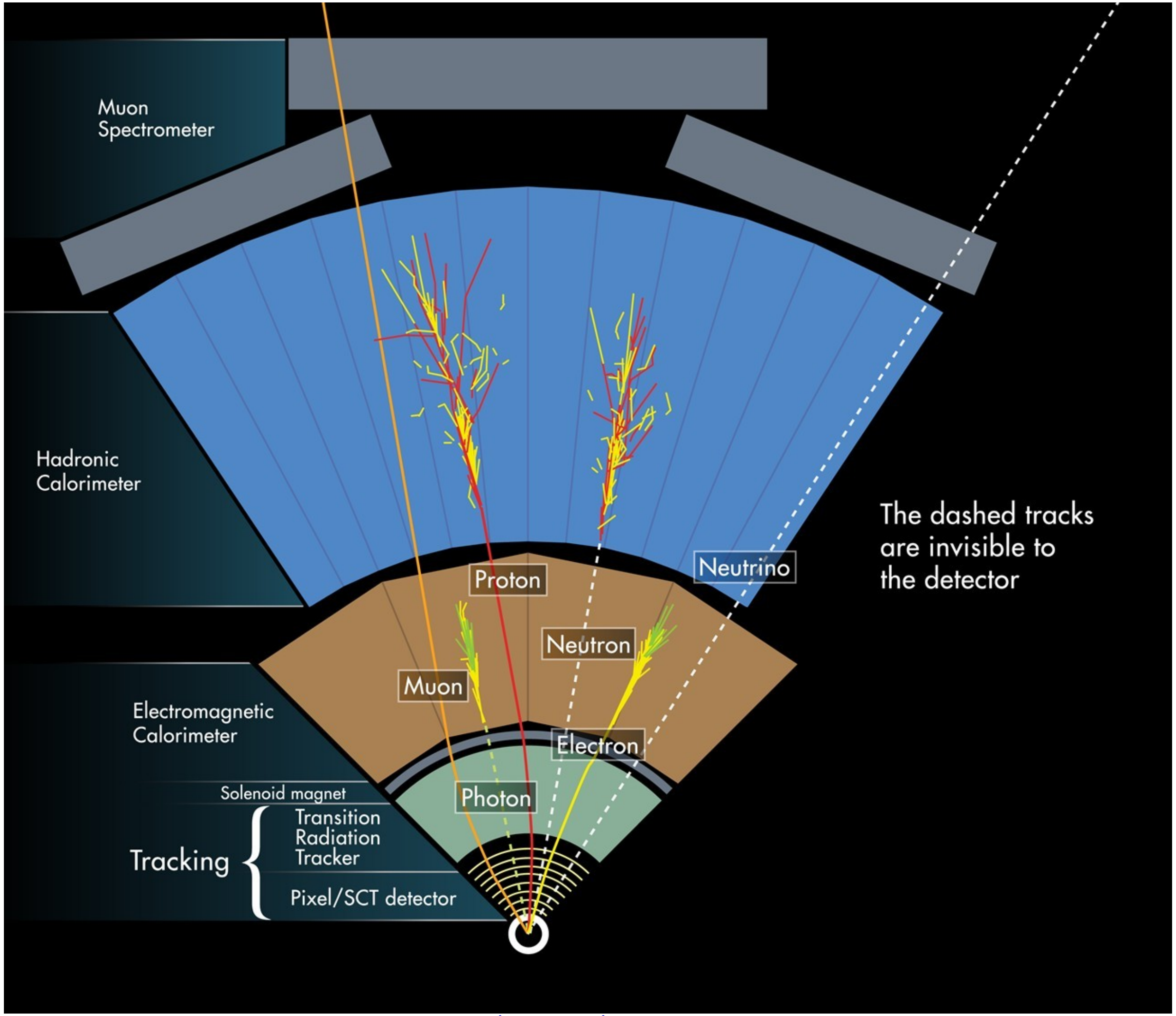
- So far all measurements compatible with the SM Higgs boson, but other options are not excluded yet
  - more Higgs bosons? For instance, 3 neutral and 2 charged Higgses (2HDM)
  - composite nature of Higgs?
  - …. and there is still room for unexpected decays and/or other „exotic" features

Conclusions

- Higgs boson measurements moved from the discovery (2012) to precision era
- No evidence for deviations from Standard model observed so far, but uncertainties in many cases are still way too large. Still room for beyond-SM physics phenomena!
- Improvements in precision and observation of very rare Higgs-related processes expected with Run-3 (2022-2025) and especially HL-LHC (2029-2038) data
- Further improvements possible only with next-generation accelerator experiments

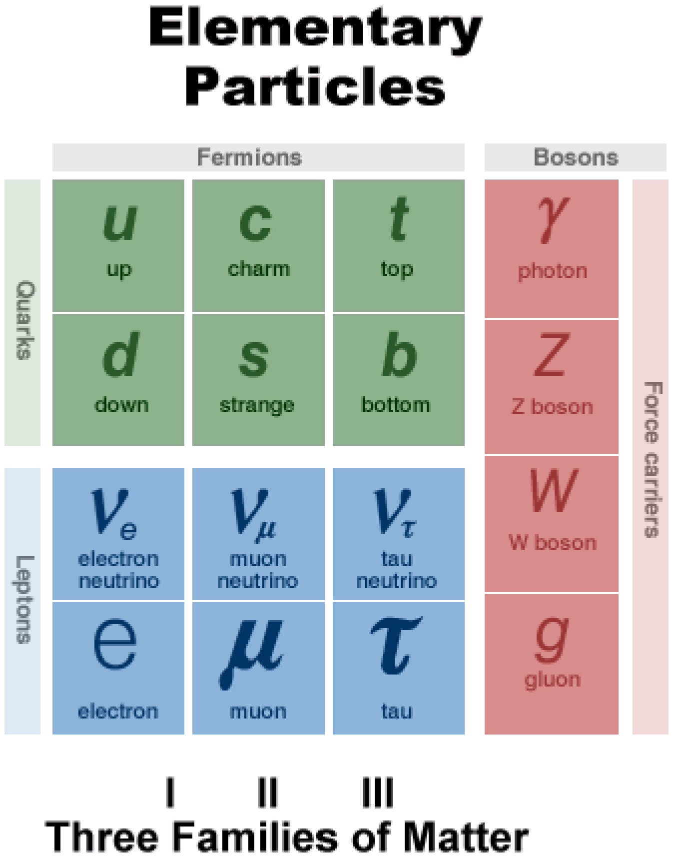
BACKUP

Principles of particle detection



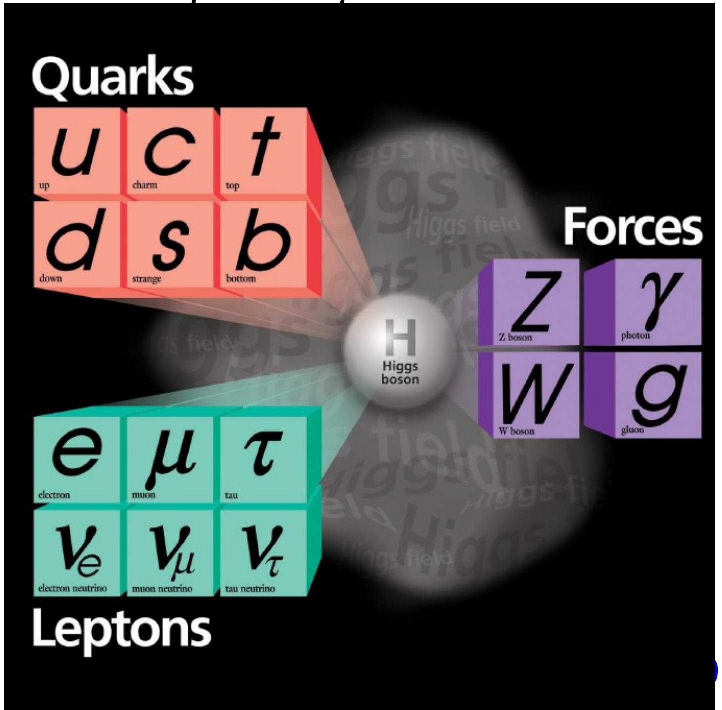
Standard Model (1)

- All matter is composed of fermions with spin ½ – quarks and leptons
  - three families (generations) of fermions
  - all stable matter in Universe is made of 1st family fermions
- Interactions are described through the exchange of spin 1 bosons within the QFT
- Is that all? No…



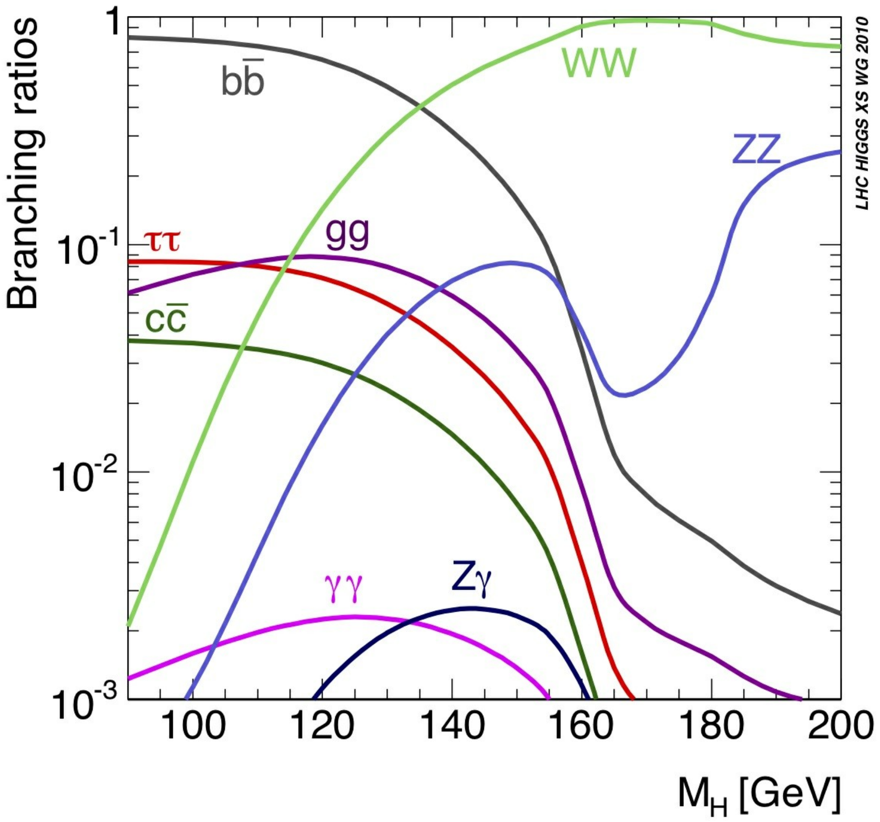
Standard Model (2)

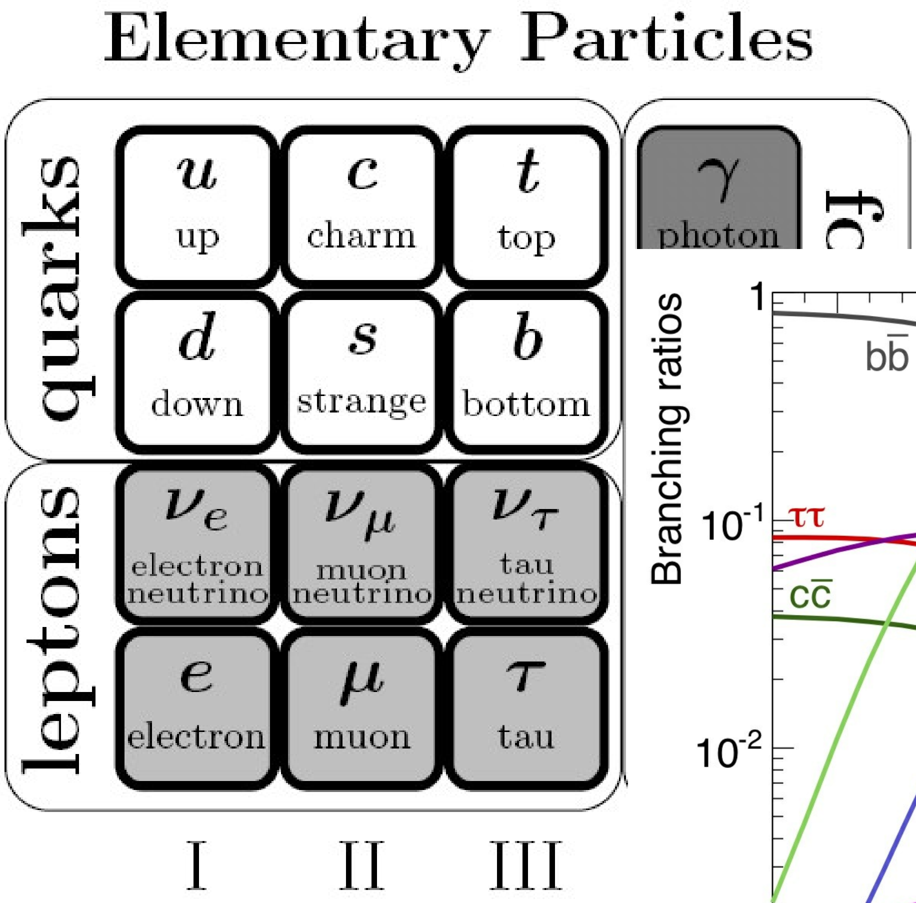
- The SM is perfectly consistent if particles (especially spin 1 bosons) are massless
  - W, Z are massive – can we just add the mass terms in the lagrangian?
  - very good description of processes at low energies, but we face infinite raise of cross-sections (probabilities of interactions) for certain processes at high energies
- Solution: introduction of spin 0 Higgs field and associated Higgs boson
  - its interaction with W, Z provides their mass terms, similarly for fermions → the strength of the Higgs interaction is proportional to particles' masses
  - additional interactions remove the divergencies of the cross-sections



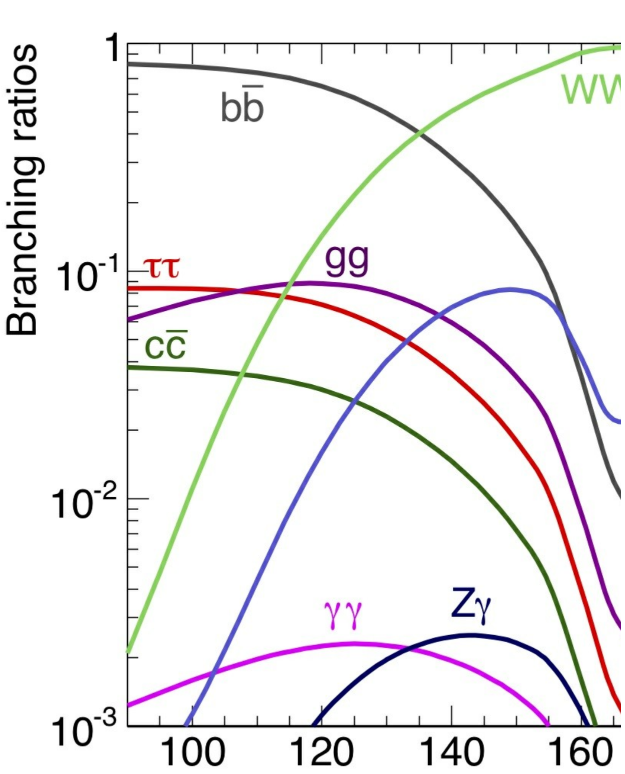
Standard Model (3)

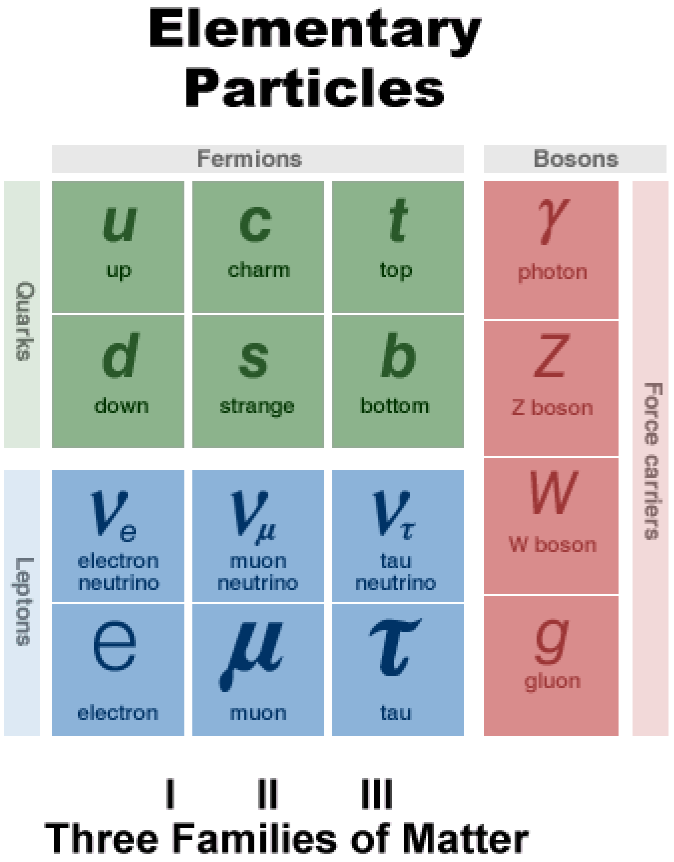
- The Higgs boson mass is a free parameter in the theory
  - decays modes strongly depend on Higgs mass, making the experimental search more challenging
  - once Higgs mass is fixed, all its properties are defined

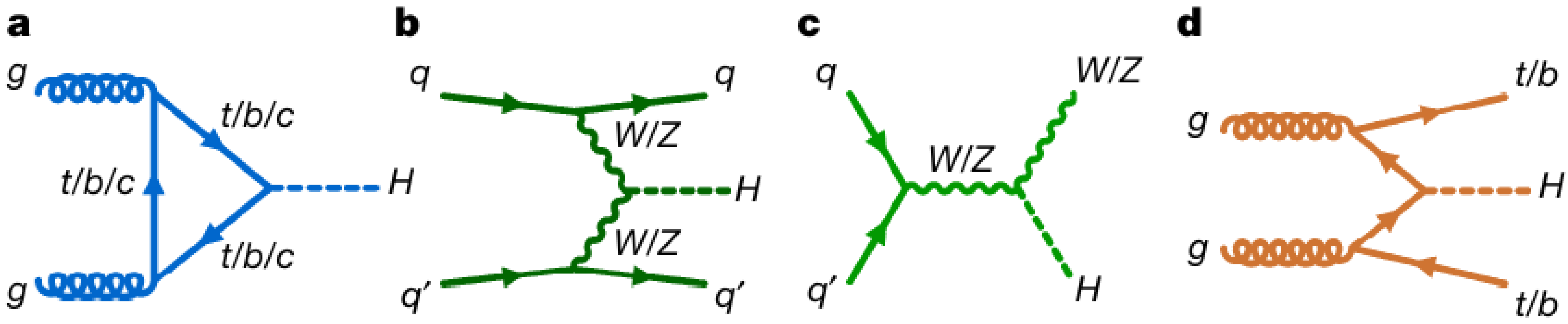


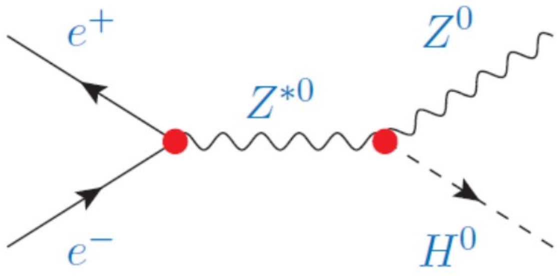

Elementary Particles
quarks
u up
c charm
t top
d down
s strange
b bottom
leptons
ν_e electron neutrino
ν_μ muon neutrino
ν_τ tau neutrino
e electron
μ muon
τ tau
γ photon
I
II
III

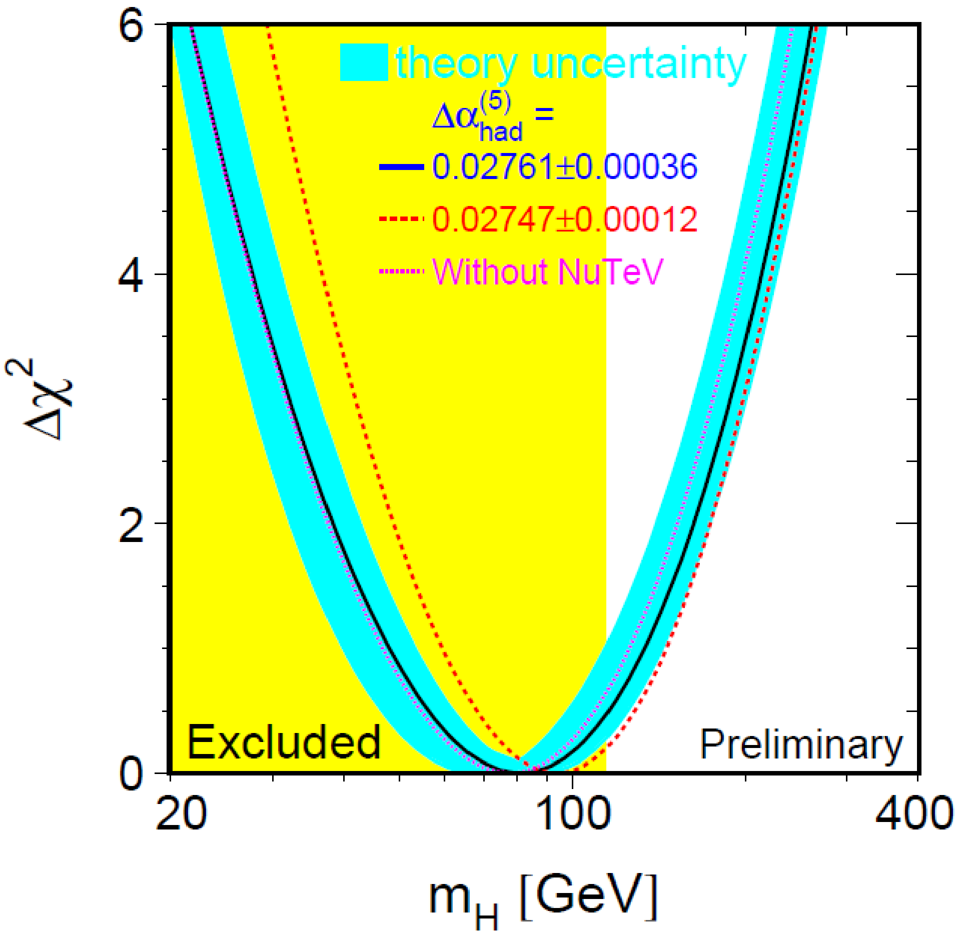

Quarks
u
c
t
up
charm
top


Branching ratios
1
10^{-1}
10^{-2}
10^{-3}
100
120
140
160
$b\bar{b}$
WW
$\tau\tau$
gg
$c\bar{c}$
$\gamma\gamma$
$Z\gamma$

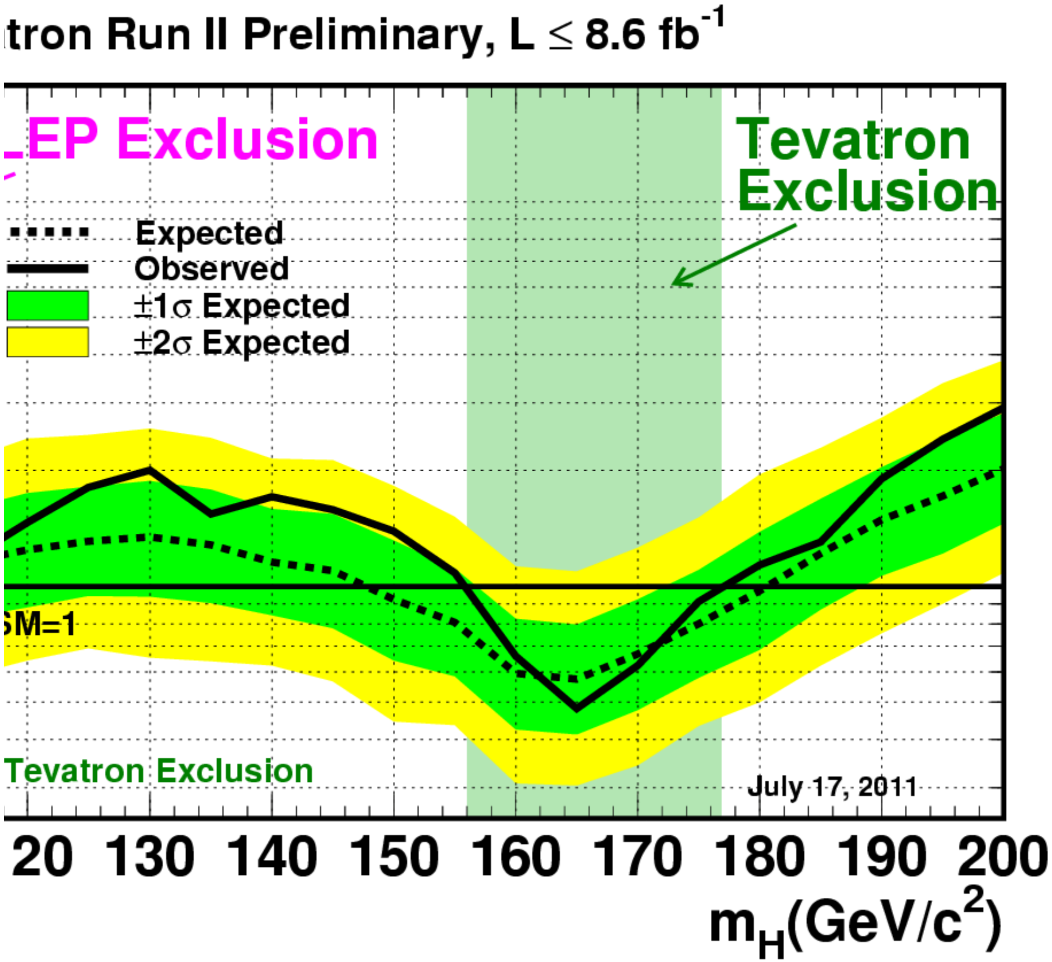

Elementary Particles
Fermions
Bosons
Quarks
u up
c charm
t top
d down
s strange
b bottom
Leptons
ν_e electron neutrino
ν_μ muon neutrino
ν_τ tau neutrino
e electron
μ muon
τ tau
γ photon
Z Z boson
W W boson
g gluon
Force carriers
I
II
III
Three Families of Matter


a
g
t/b/c
t/b/c
H
t/b/c
g
b
q
q
W/Z
H
W/Z
q′
q′
c
q
W/Z
W/Z
q′
H
d
t/b
g
H
g
t/b

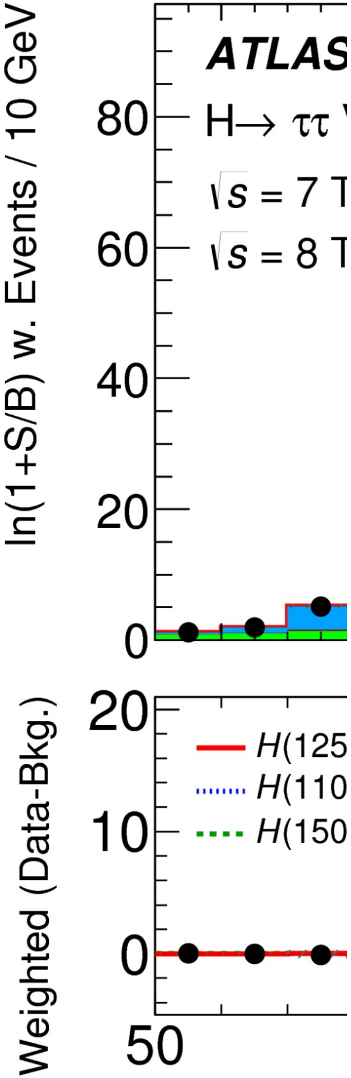

e^+
Z^0
Z^{*0}
e^-
H^0

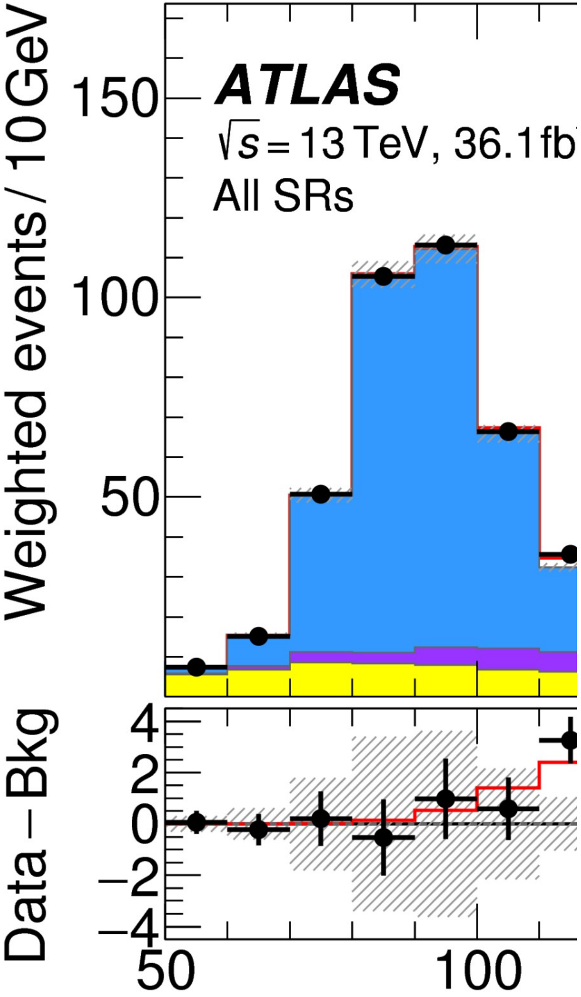


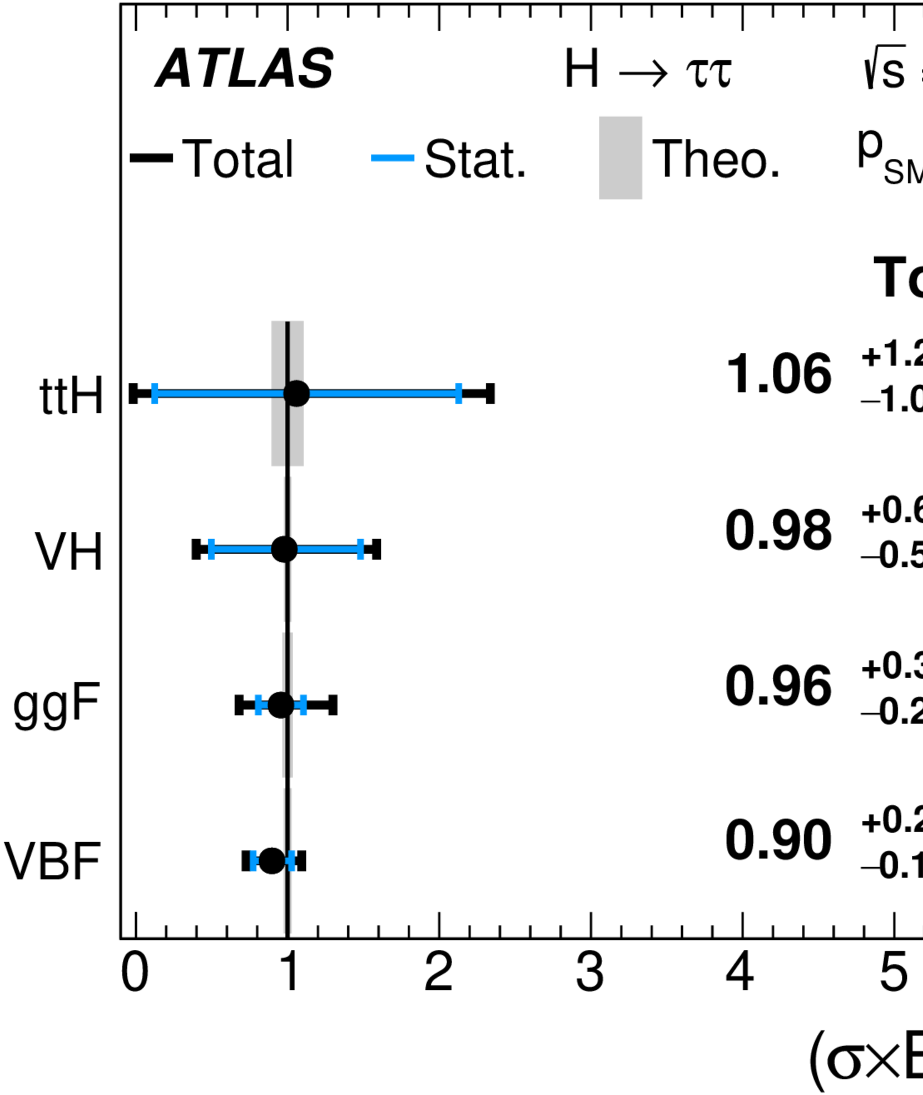
theory uncertainty
Δα(5)had =
0.02761±0.00036
0.02747±0.00012
Without NuTeV
Excluded
Preliminary
6
4
2
0
20
100
400
Δχ2
mH [GeV]

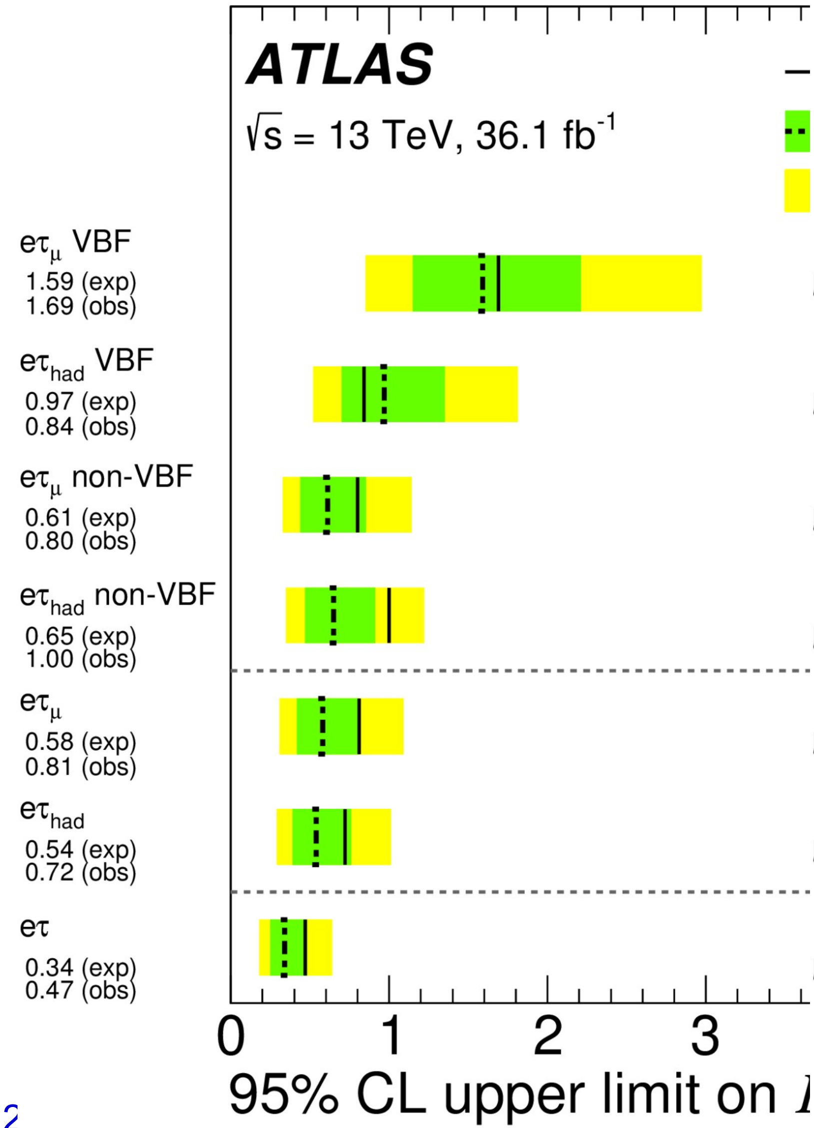


tron Run II Preliminary, L ≤ 8.6 fb-1
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
Tevatron Exclusion
July 17, 2011
20
130
140
150
160
170
180
190
200
mH(GeV/c2)

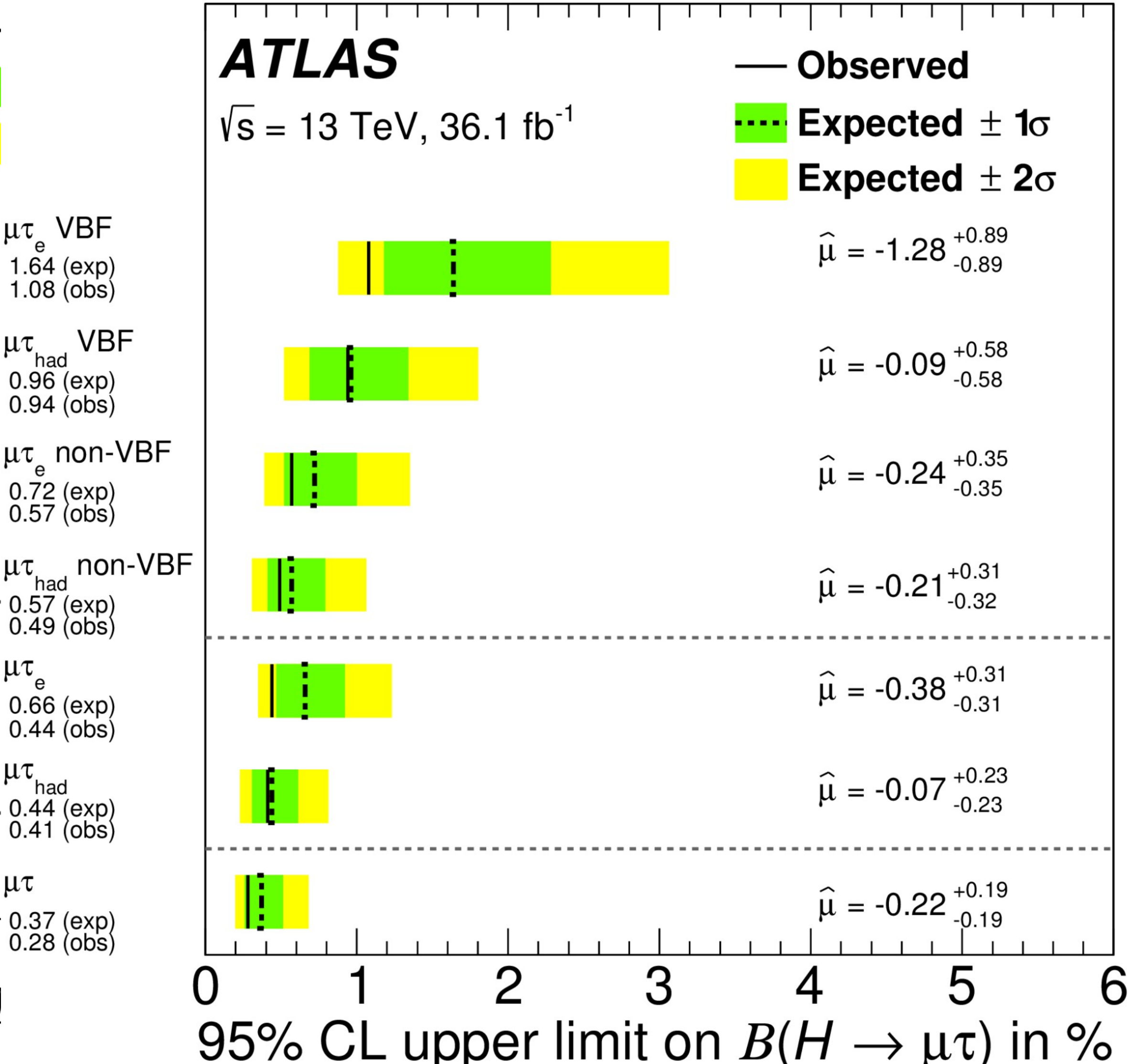

ATLAS
H→ ττ
√s = 7 T
√s = 8 T
ln(1+S/B) w. Events / 10 GeV
80
60
40
20
0
Weighted (Data-Bkg.)
20
10
0
H(125
H(110
H(150
50


ATLAS
√s = 13 TeV, 36.1 fb
All SRs
Weighted events / 10GeV
150
100
50
Data – Bkg
4
2
0
−2
−4
50
100

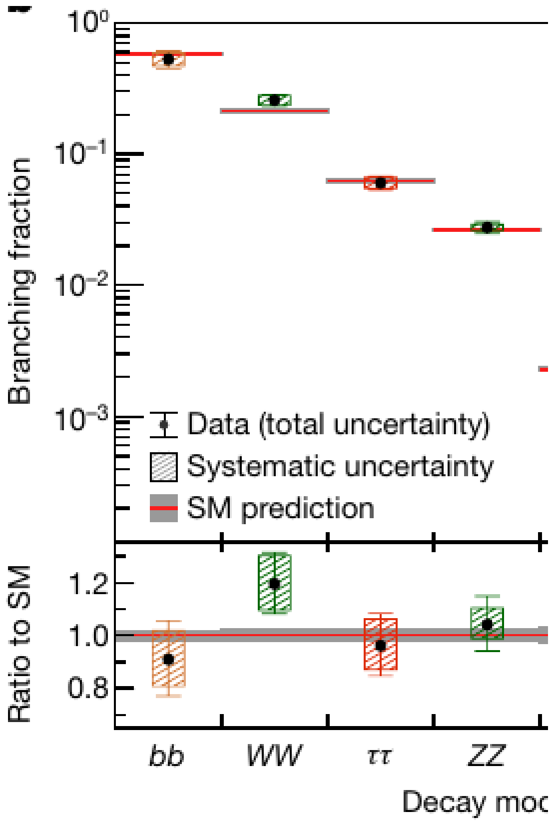

ATLAS
H → ττ
Total
Stat.
Theo.
ttH
VH
ggF
VBF
1.06
0.98
0.96
0.90
0
1
2
3
4
5



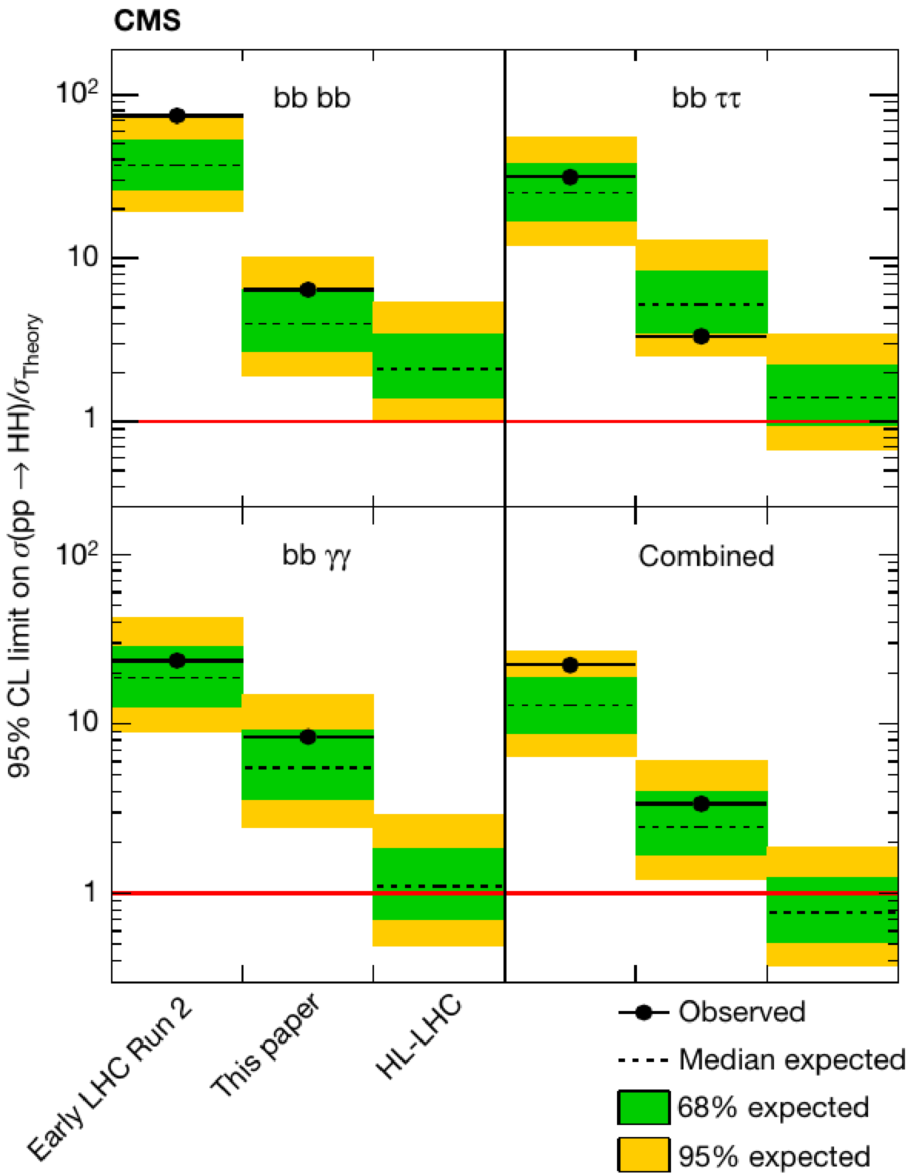
ATLAS
√s = 13 TeV, 36.1 fb⁻¹
eτ_μ VBF
1.59 (exp)
1.69 (obs)
eτ_had VBF
0.97 (exp)
0.84 (obs)
eτ_μ non-VBF
0.61 (exp)
0.80 (obs)
eτ_had non-VBF
0.65 (exp)
1.00 (obs)
eτ_μ
0.58 (exp)
0.81 (obs)
eτ_had
0.54 (exp)
0.72 (obs)
eτ
0.34 (exp)
0.47 (obs)
0
1
2
3
95% CL upper limit on



ATLAS
√s = 13 TeV, 36.1 fb⁻¹
Observed
Expected ± 1σ
Expected ± 2σ
μτ_e VBF
1.64 (exp)
1.08 (obs)
μ̂ = -1.28 +0.89 -0.89
μτ_had VBF
0.96 (exp)
0.94 (obs)
μ̂ = -0.09 +0.58 -0.58
μτ_e non-VBF
0.72 (exp)
0.57 (obs)
μ̂ = -0.24 +0.35 -0.35
μτ_had non-VBF
0.57 (exp)
0.49 (obs)
μ̂ = -0.21 +0.31 -0.32
μτ_e
0.66 (exp)
0.44 (obs)
μ̂ = -0.38 +0.31 -0.31
μτ_had
0.44 (exp)
0.41 (obs)
μ̂ = -0.07 +0.23 -0.23
μτ
0.37 (exp)
0.28 (obs)
μ̂ = -0.22 +0.19 -0.19
0
1
2
3
4
5
6
95% CL upper limit on B(H → μτ) in %

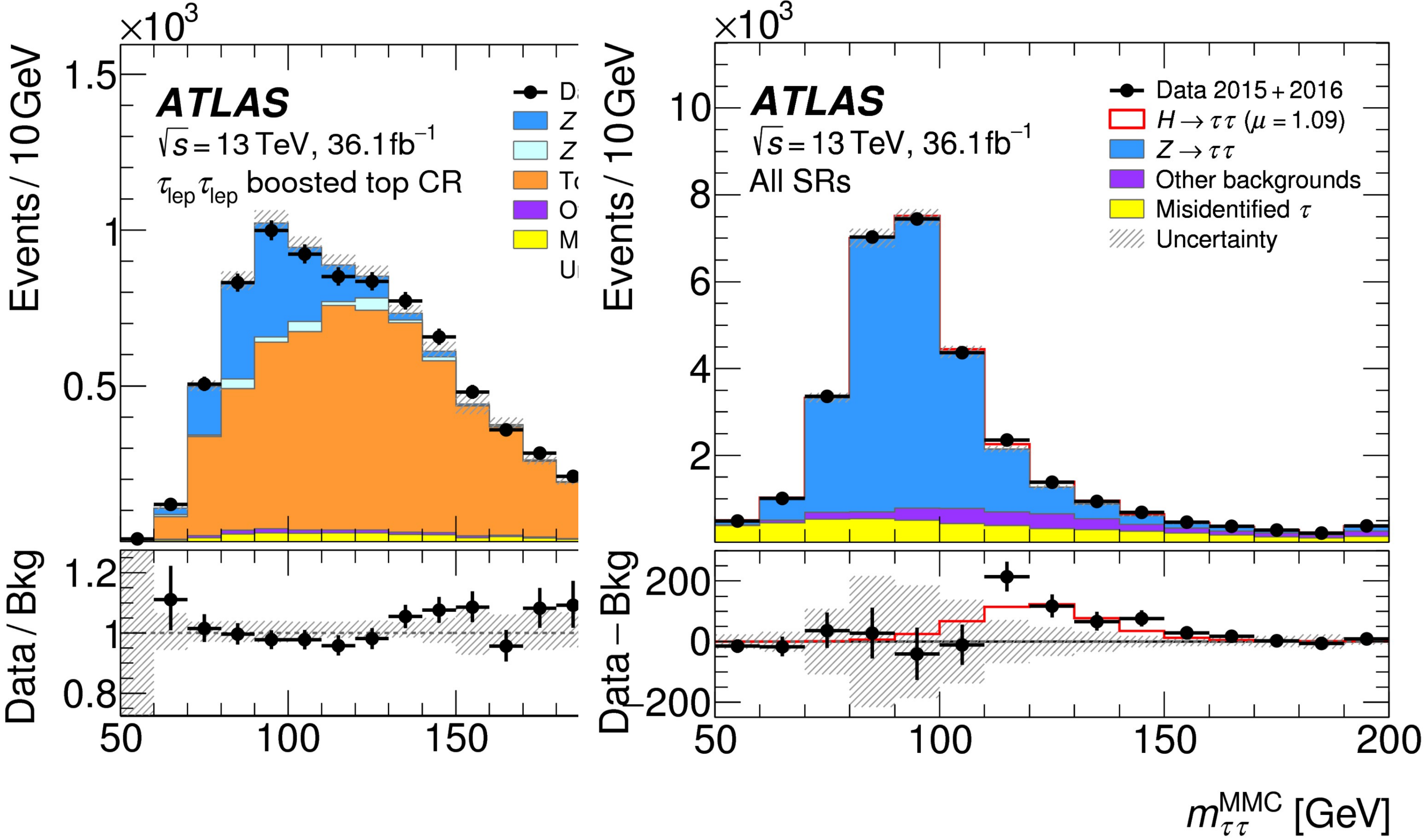


Branching fraction
Data (total uncertainty)
Systematic uncertainty
SM prediction
Ratio to SM
bb
WW
ττ
ZZ
Decay moc



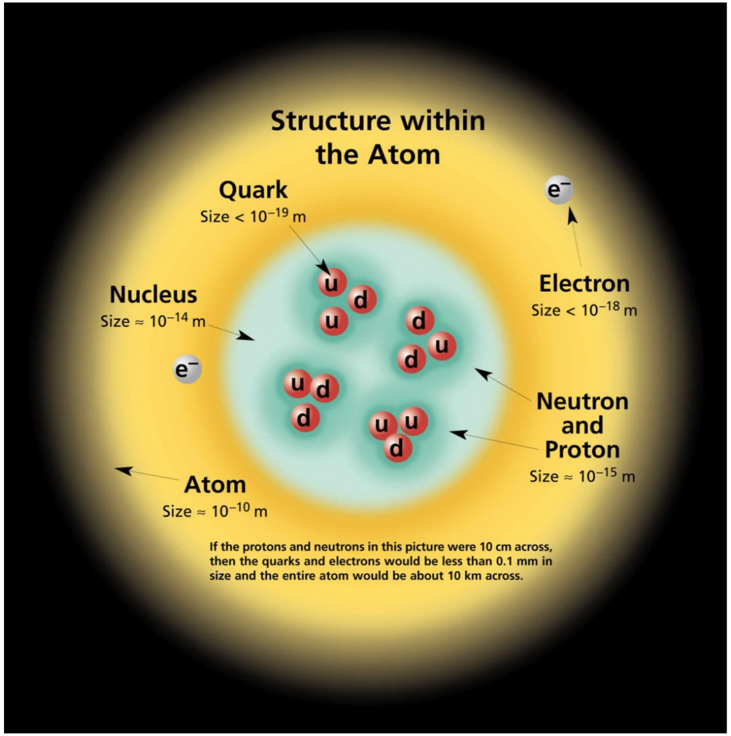
CMS
bb bb
bb ττ
bb γγ
Combined
95% CL limit on σ(pp → HH)/σ_Theory
Early LHC Run 2
This paper
HL-LHC
Observed
Median expected
68% expected
95% expected

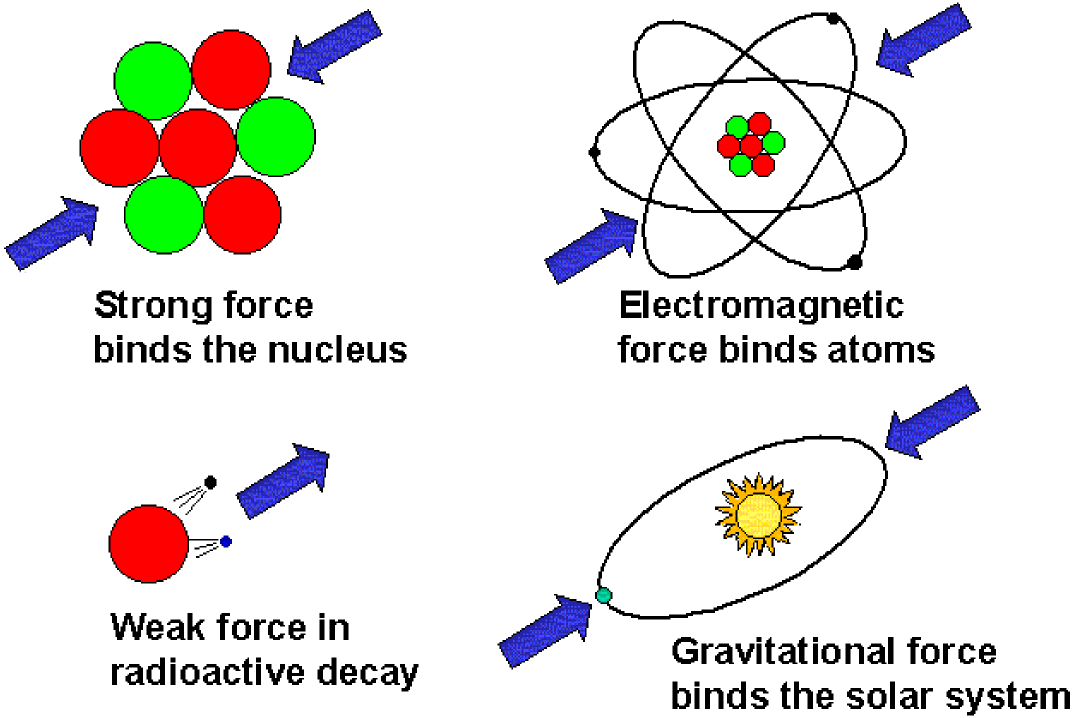
1.10
1.15


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
$\tau_{lep}\tau_{lep}$ boosted top CR
Events / 10GeV
Data / Bkg
ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
All SRs
Data 2015 + 2016
$H \to \tau\tau$ (μ = 1.09)
$Z \to \tau\tau$
Other backgrounds
Misidentified τ
Uncertainty
Events / 10GeV
Data − Bkg
$m_{\tau\tau}^{MMC}$ [GeV]

Structure of matter and iteractions (1)

- Particle physics investigates elementary building blocks of matter and their interactions





- Gravity is too weak in the world of elementary particles → neglected

Structure of matter and iteractions (2)

- The three interactions are described through the exchange particles
  - electromagnetic – **photon (γ)**
  - weak – **intermediate bosons W, Z**
  - strong – **gluons (g)**
- The elementary building blocks and their interactions are described within the quantum field theory (QFT) by the corresponding Lagrangian
  - relevant quantities are the amplitudes of a scattering or a decay
  - we measure cross-sections or probabilities of decays, proportional to $|\text{amplitude}|^2$