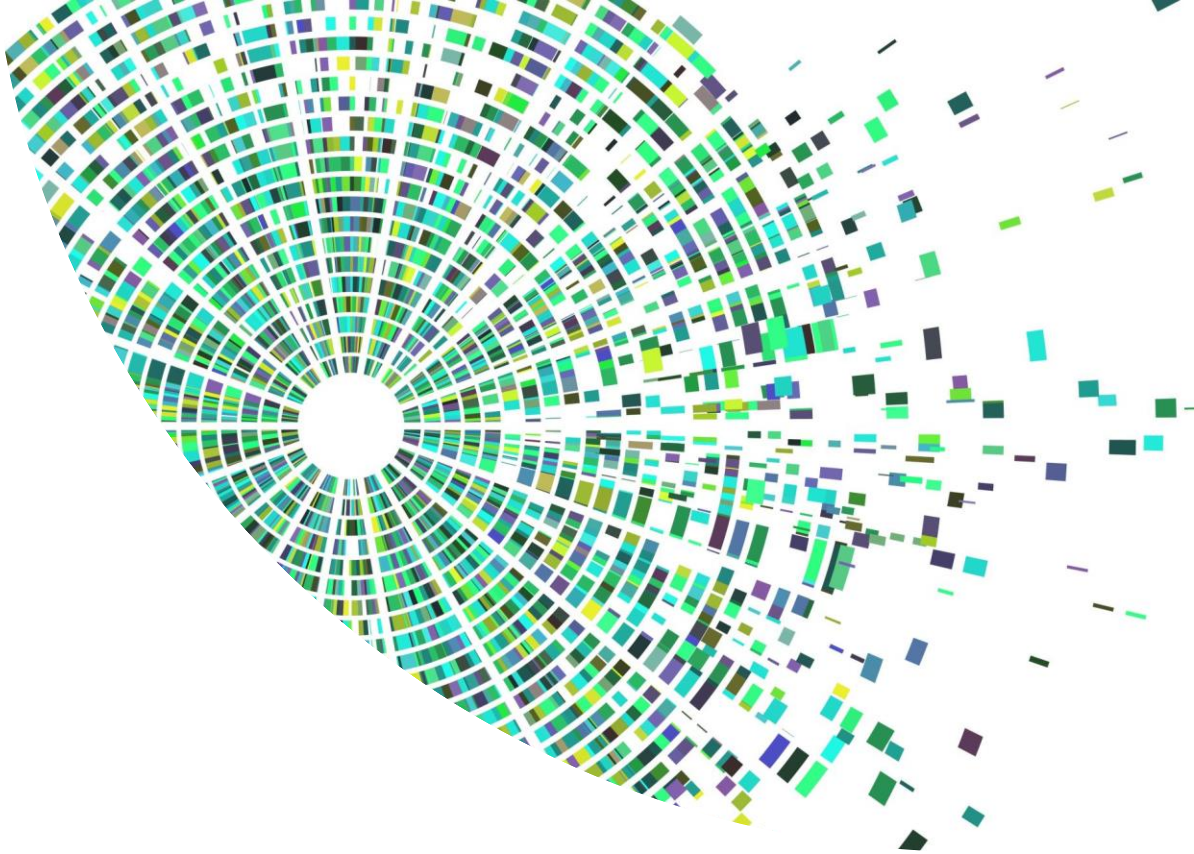
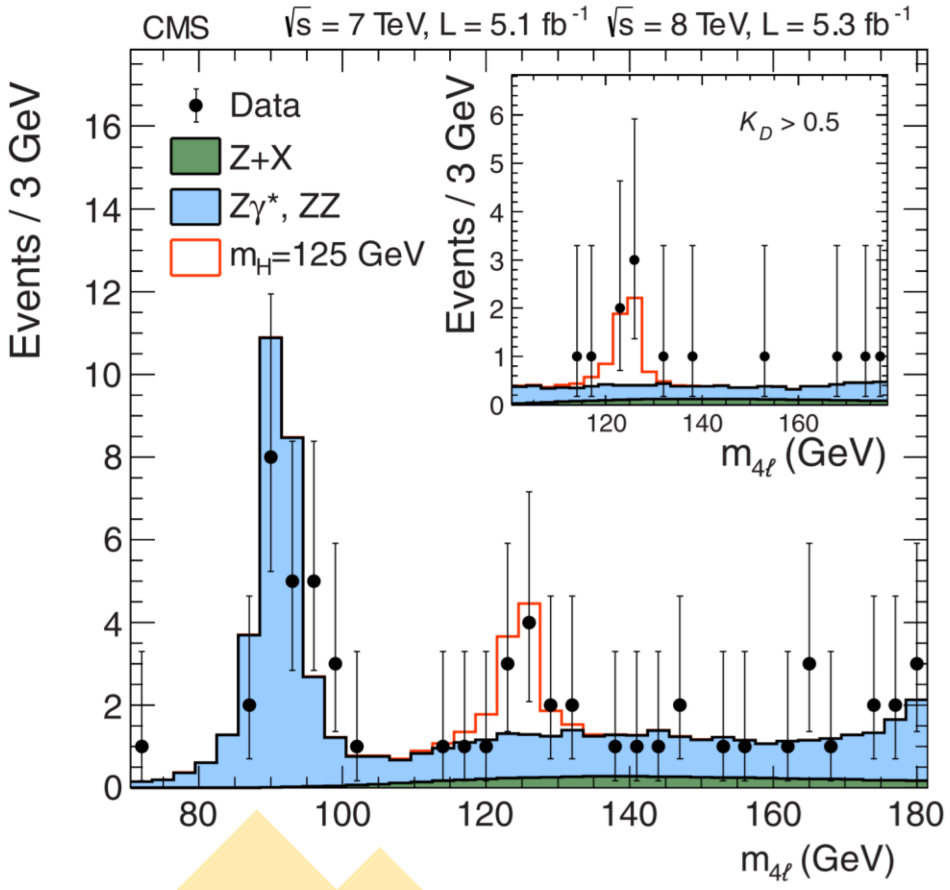


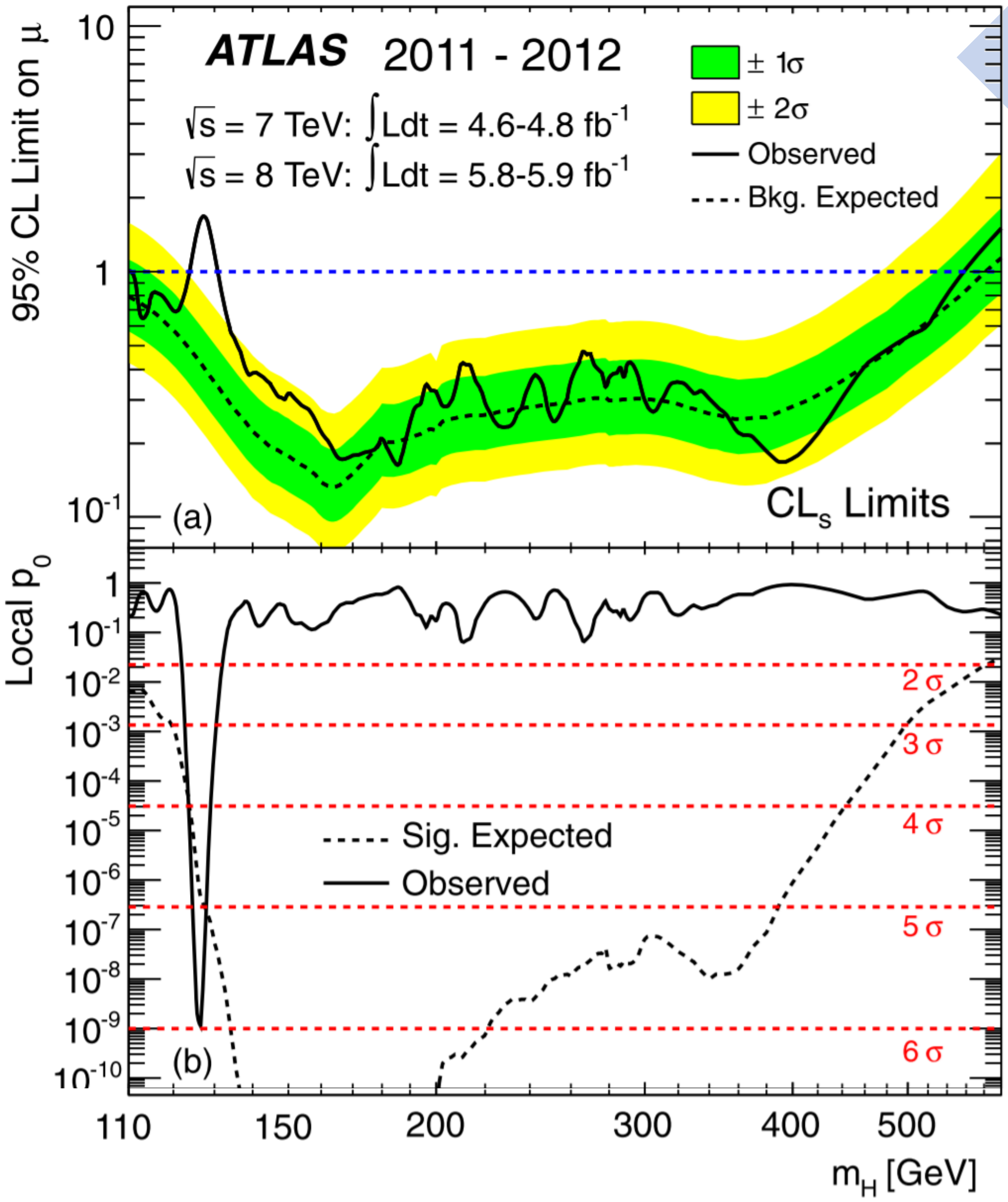
Probing dark sectors with the Higgs Boson

Christian Weber
Brookhaven National Laboratory

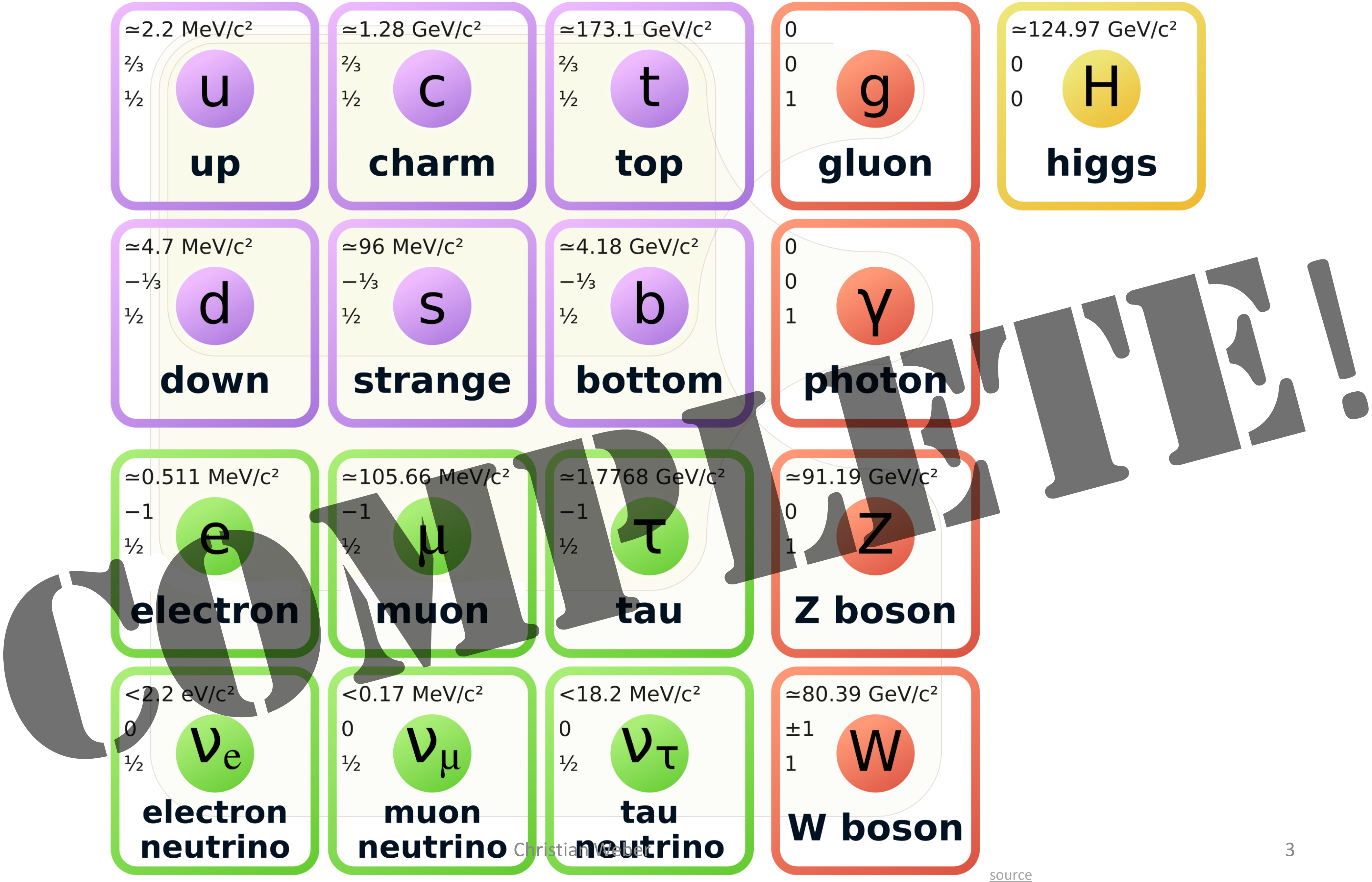
Higgs Boson discovery in 2012



[Physics Letters B 716.1 (2012): 30-61]



[Physics Letters B 716.1 (2012): 1-29]


$\simeq 2.2$ MeV/c^2
⅔
½
u
up
$\simeq 1.28$ GeV/c^2
⅔
½
c
charm
$\simeq 173.1$ GeV/c^2
⅔
½
t
top
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1
g
gluon
$\simeq 124.97$ GeV/c^2
0
0
H
higgs
$\simeq 4.7$ MeV/c^2
−⅓
½
d
down
$\simeq 96$ MeV/c^2
−⅓
½
s
strange
$\simeq 4.18$ GeV/c^2
−⅓
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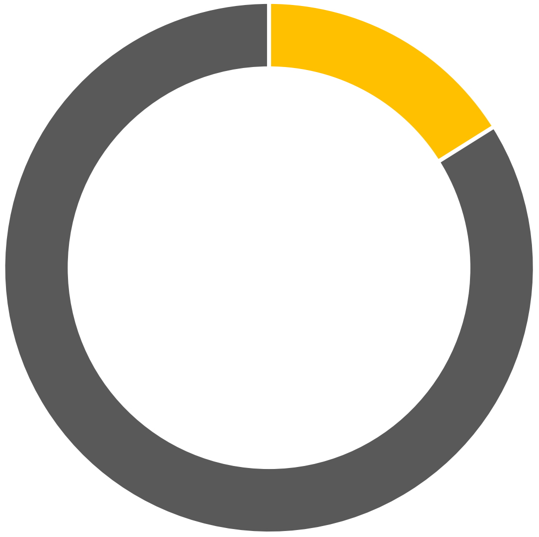
b
bottom
0
0
1
γ
photon
$\simeq 0.511$ MeV/c^2
−1
½
e
electron
$\simeq 105.66$ MeV/c^2
−1
½
μ
muon
$\simeq 1.7768$ GeV/c^2
−1
½
τ
tau
$\simeq 91.19$ GeV/c^2
0
1
Z
Z boson
<2.2 eV/c^2
0
½
ν_e
electron neutrino
<0.17 MeV/c^2
0
½
ν_μ
muon neutrino
<18.2 MeV/c^2
0
½
ν_τ
tau neutrino
$\simeq 80.39$ GeV/c^2
±1
1
W
W boson
COMPLETE!

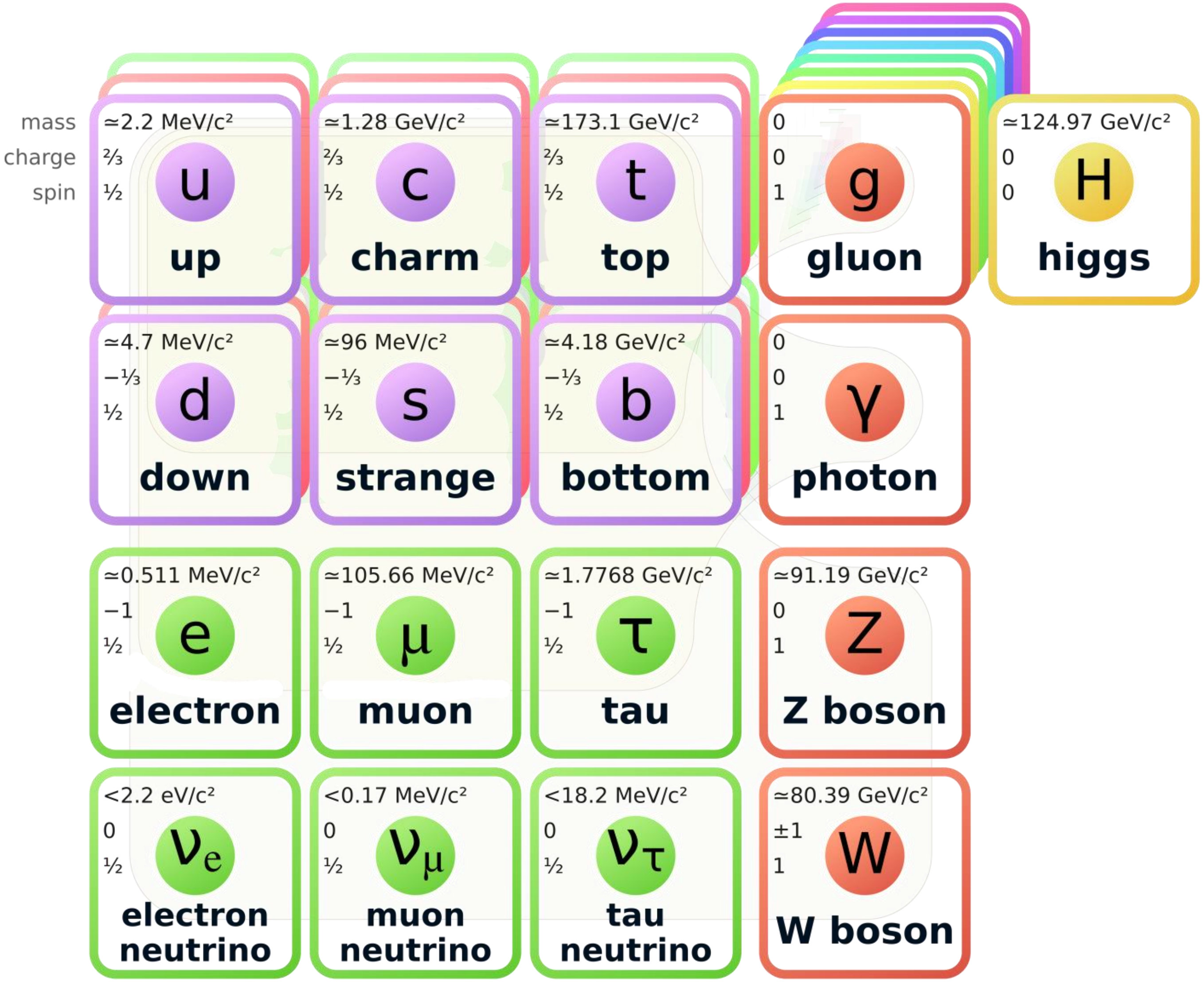
source

The Matter Universe



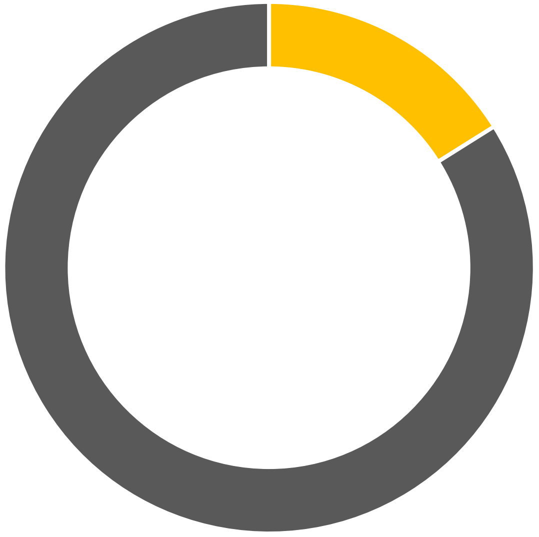
- 14% Regular Matter
- 86% Dark Matter

M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)



source

The Matter Universe

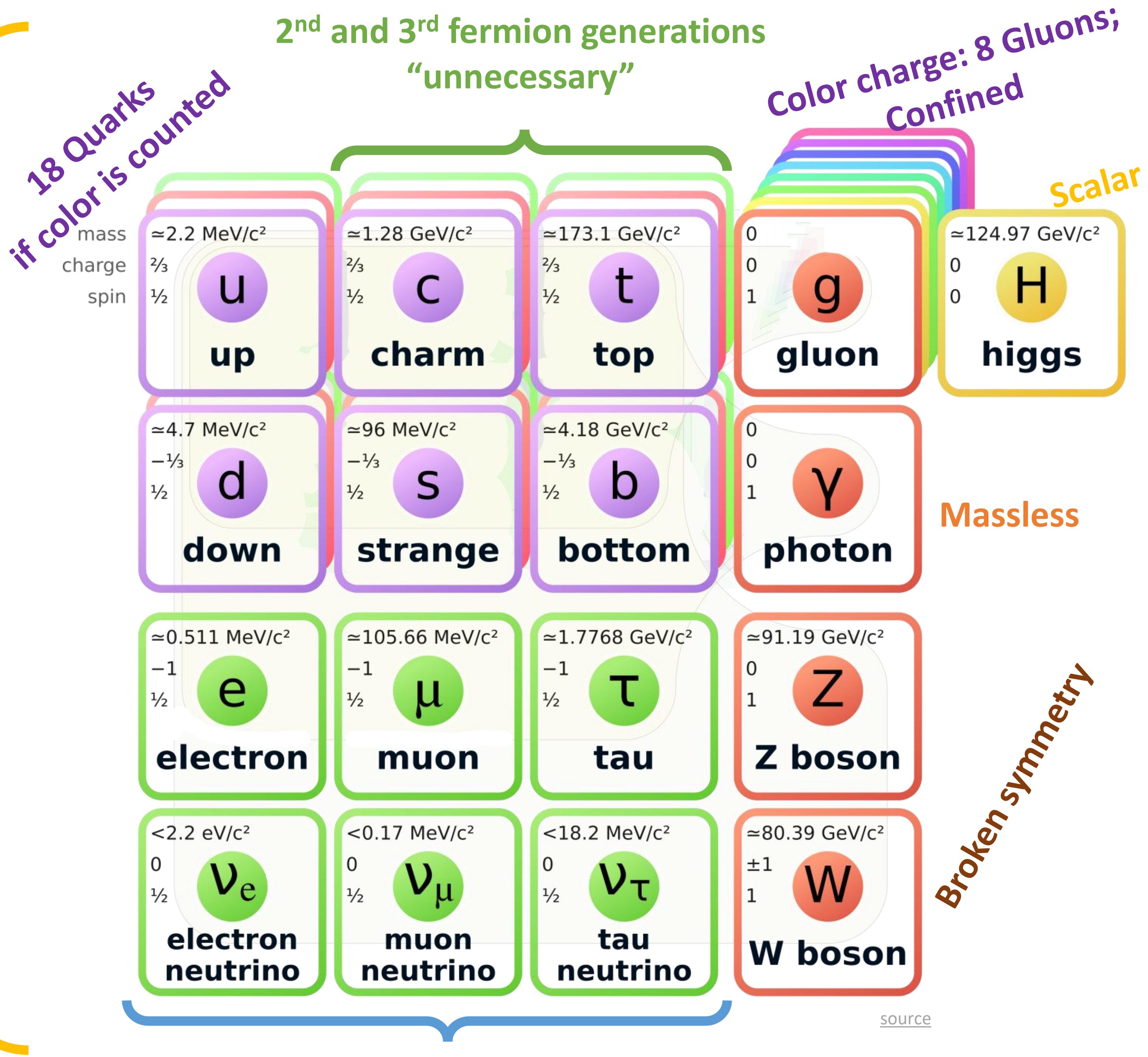


■ 14% Regular Matter

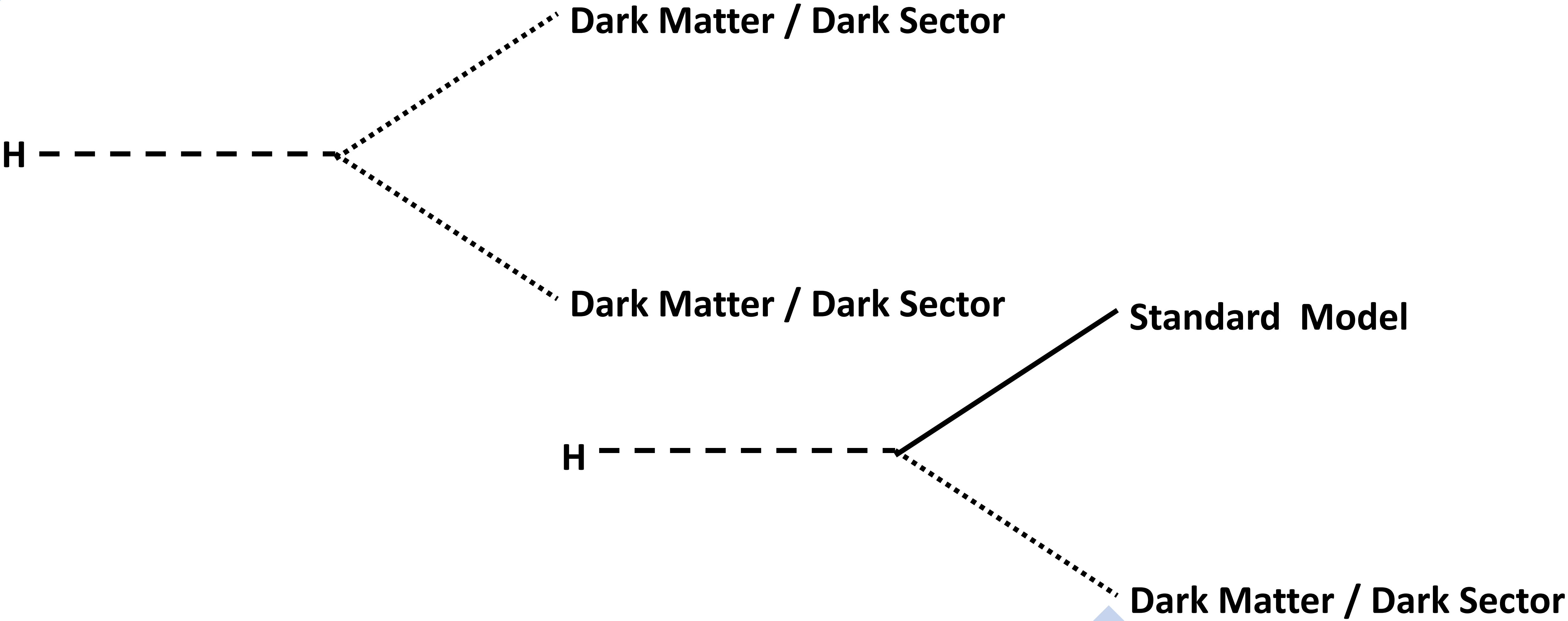
■ 86% Dark Matter

M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018)

¿Maybe more than one particle here?



- The Higgs boson couples to massive particles
- Dark matter must be massive



ATLAS EXPERIMENT

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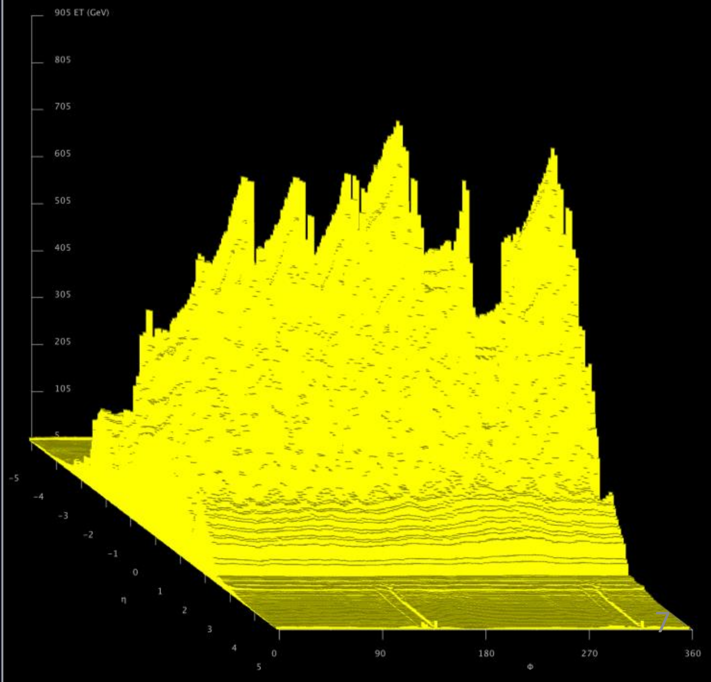
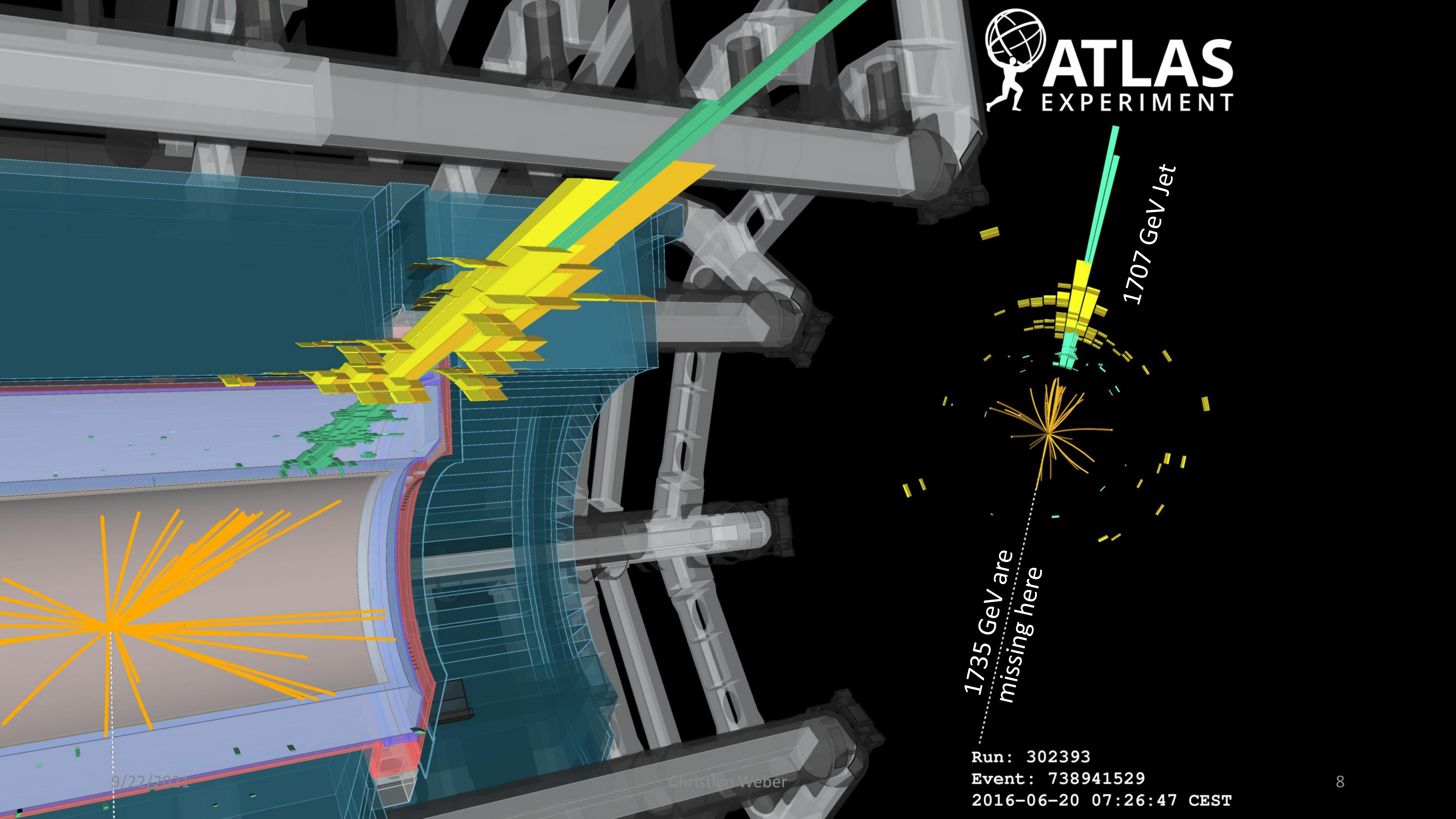
Date: 2015-04-07 21:40:01 CEST




ATLAS
EXPERIMENT
1707 GeV Jet
1735 GeV are
missing here
Run: 302393
Event: 738941529
2016-06-20 07:26:47 CEST

(extended) Standard Model

Standard Model Gauge Symmetries

$$\overbrace{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y} \otimes U(1)_d$$

$$g_i \qquad \underbrace{W^1, W^2, W^3 \qquad B} \qquad Z_d$$

electroweak symmetry breaking

$$\overbrace{W^+, W^-, Z \qquad \gamma}$$

$U(1)$ gauge Lagrangian: $L_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z_d^{\mu\nu} - \frac{1}{4}Z_{d\,\mu\nu}Z_d^{\mu\nu}$

For details see for example
Curtin et al. PhysRevD.90.075004
Curtin et al. J. High Energ. Phys. (2015) 2015: 157

$$L_{HZZ_d} = 2\epsilon_Z \frac{m_{Z_d}^2}{v} H Z_\mu Z_d^\mu$$

$$L_{Z_d \ell\ell} = g_{Z_d ff} Z_d^\mu \bar{f}\gamma_\mu f$$

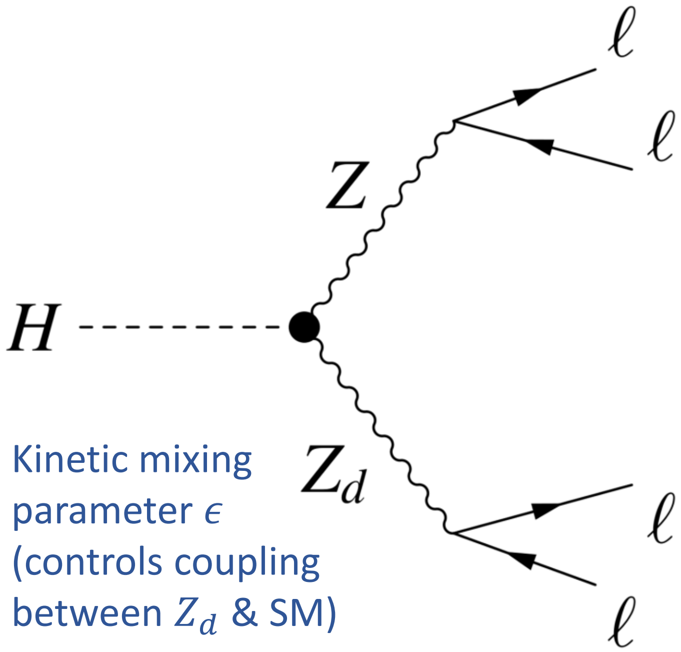
$$L_{HS} = \frac{\kappa}{2} S^2 |H|^2$$

$$L_{HZ_dZ_d} = 2 s_H \frac{m_{Z_d}^2}{v_s} H Z_{d\,\mu} Z_d^\mu$$

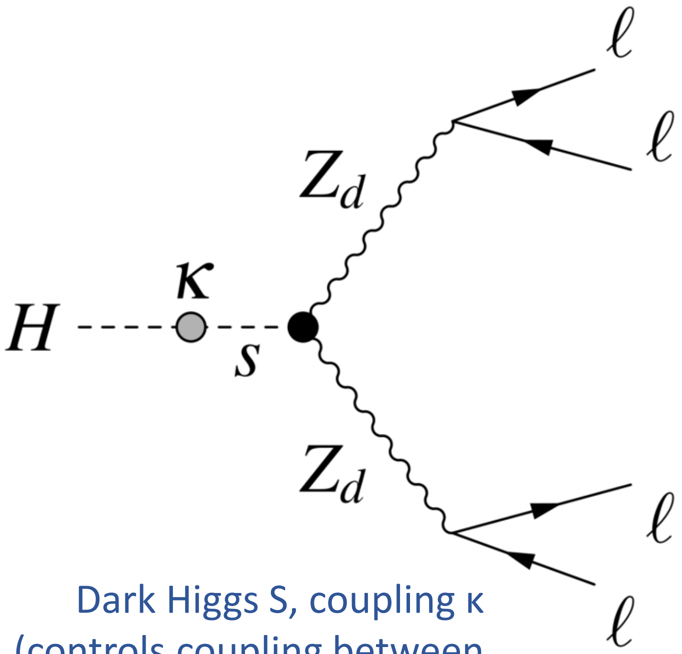
$H \to Z_{(d)} Z_d \to 4\ell$

$$L_{HZZ_d} = 2\epsilon_Z \frac{m_{Z_d}^2}{v} H Z_\mu Z_d^\mu$$
$$L_{Z_d\ell\ell} = g_{Z_dff} Z_d^\mu \bar{f} \gamma_\mu f$$

$$L_{HS} = \frac{\kappa}{2} S^2 |H|^2$$
$$L_{HZ_dZ_d} = 2 s_H \frac{m_{Z_d}^2}{v_s} H Z_{d\mu} Z_d^\mu$$

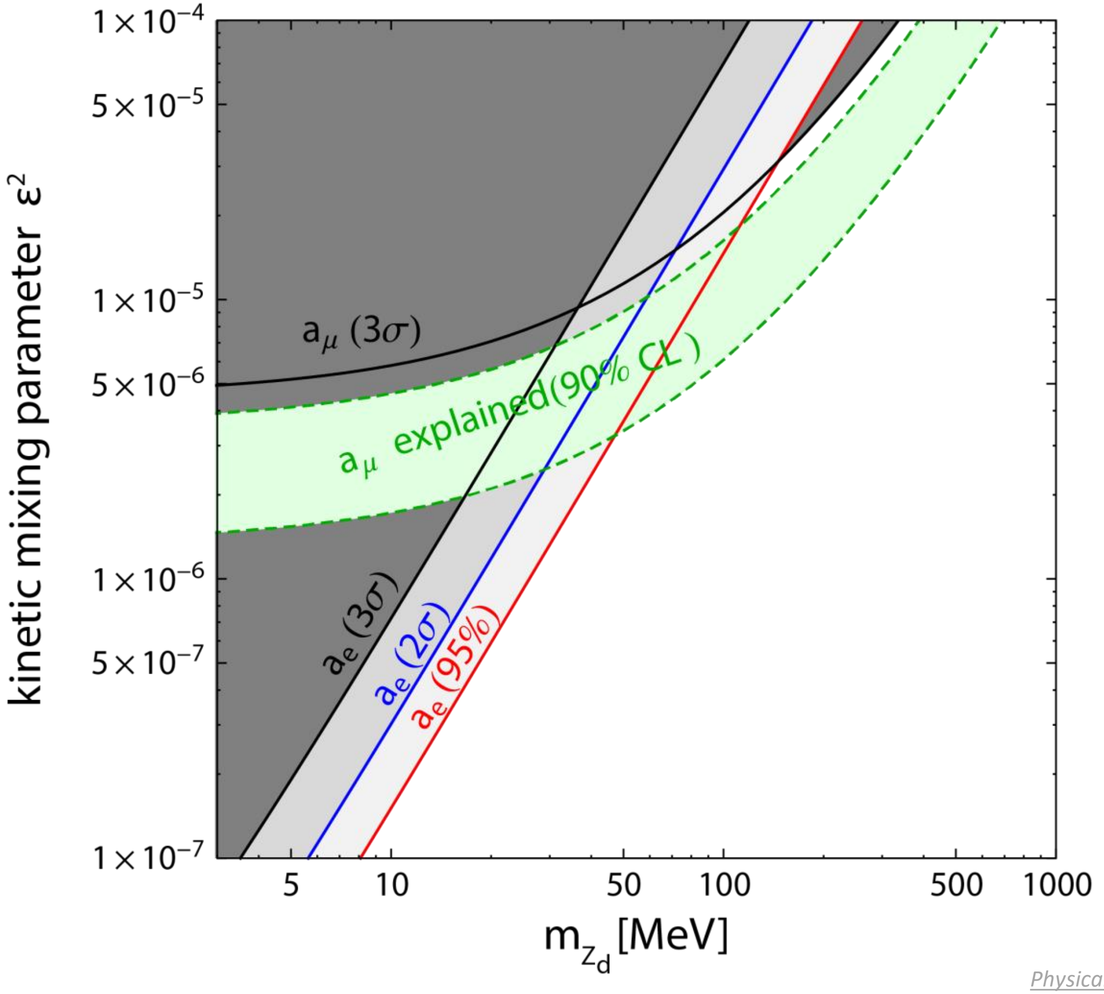


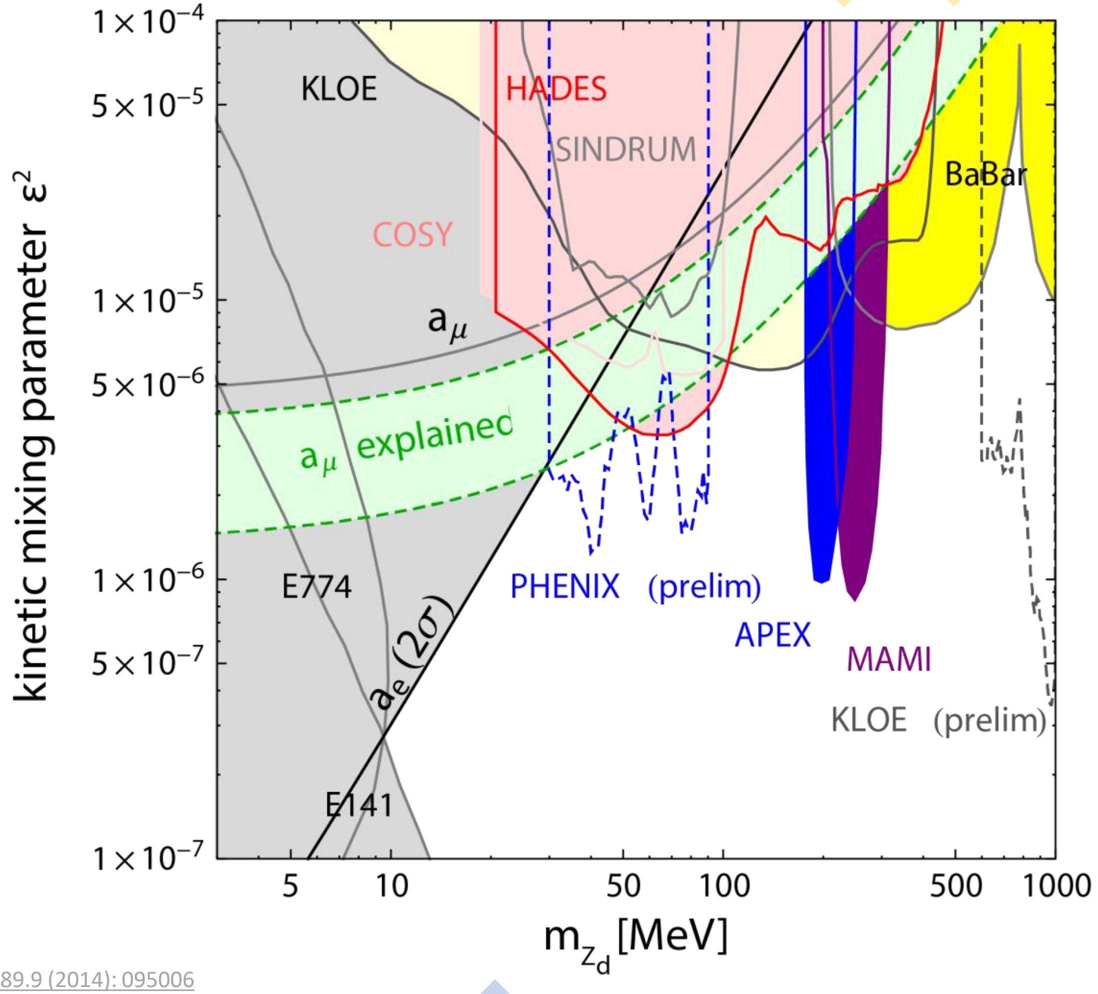
Kinetic mixing parameter ϵ (controls coupling between Z_d & SM)



Dark Higgs S, coupling κ (controls coupling between S and H)

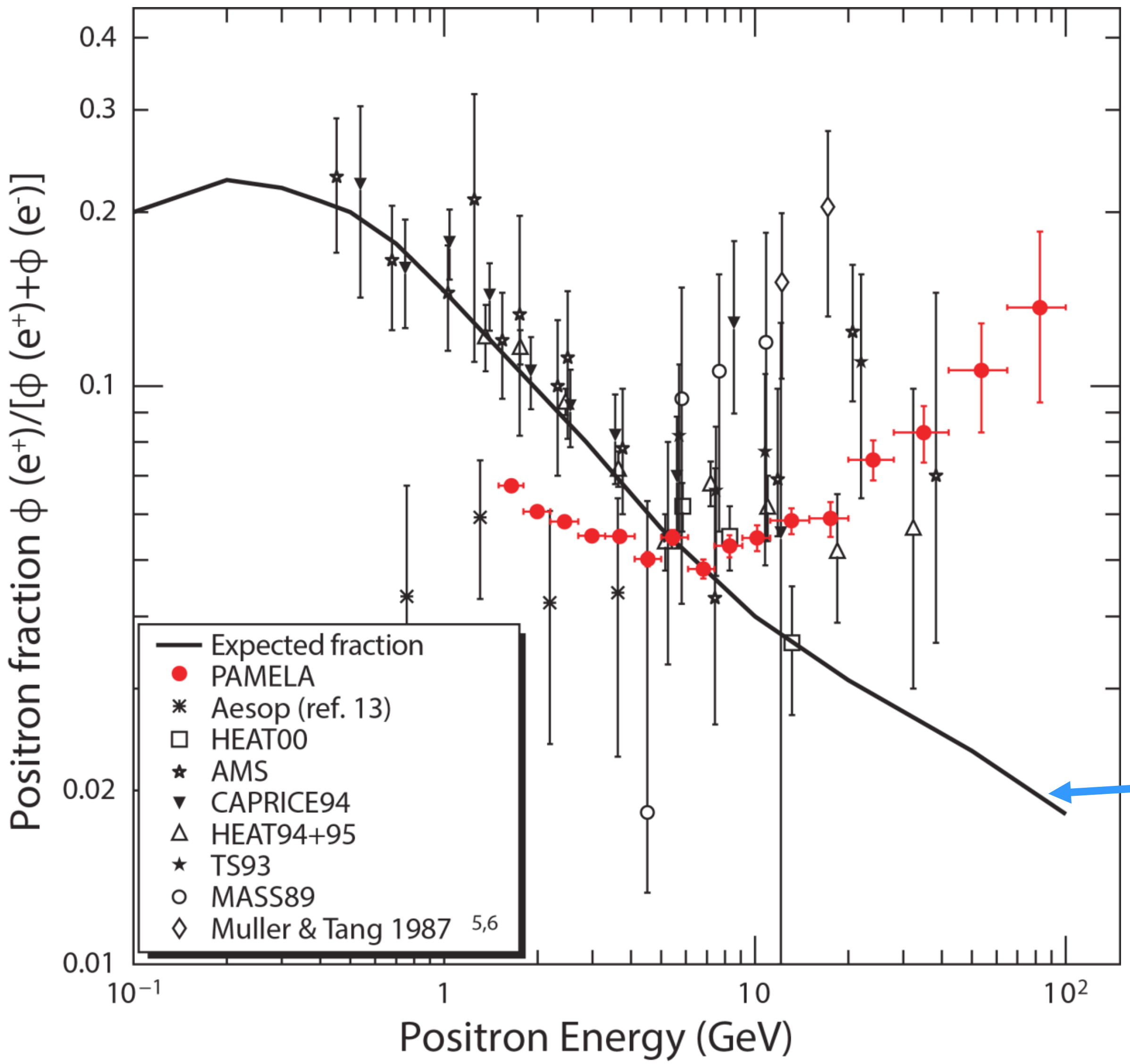
Muon g-2 constraints on Z_d





Physical Review D 89.9 (2014): 095006

Cosmic positron abundance anomaly



Expected positron fraction via production from cosmic rays propagating the galaxy

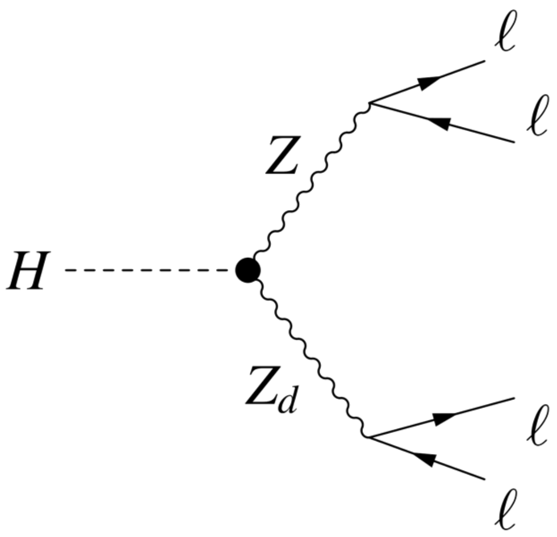
Nature 458.7238 (2009): 607-609.

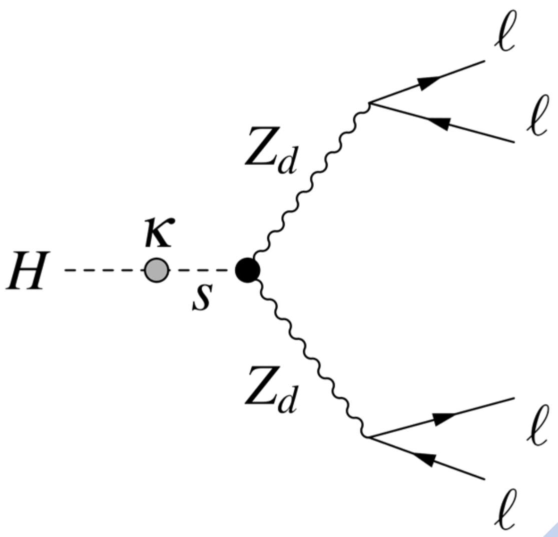
Search for Higgs bosons decaying to new spin-0 or spin-1 particles in four-lepton final states at the ATLAS detector with 139 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV

ATLAS-CONF-2021-034

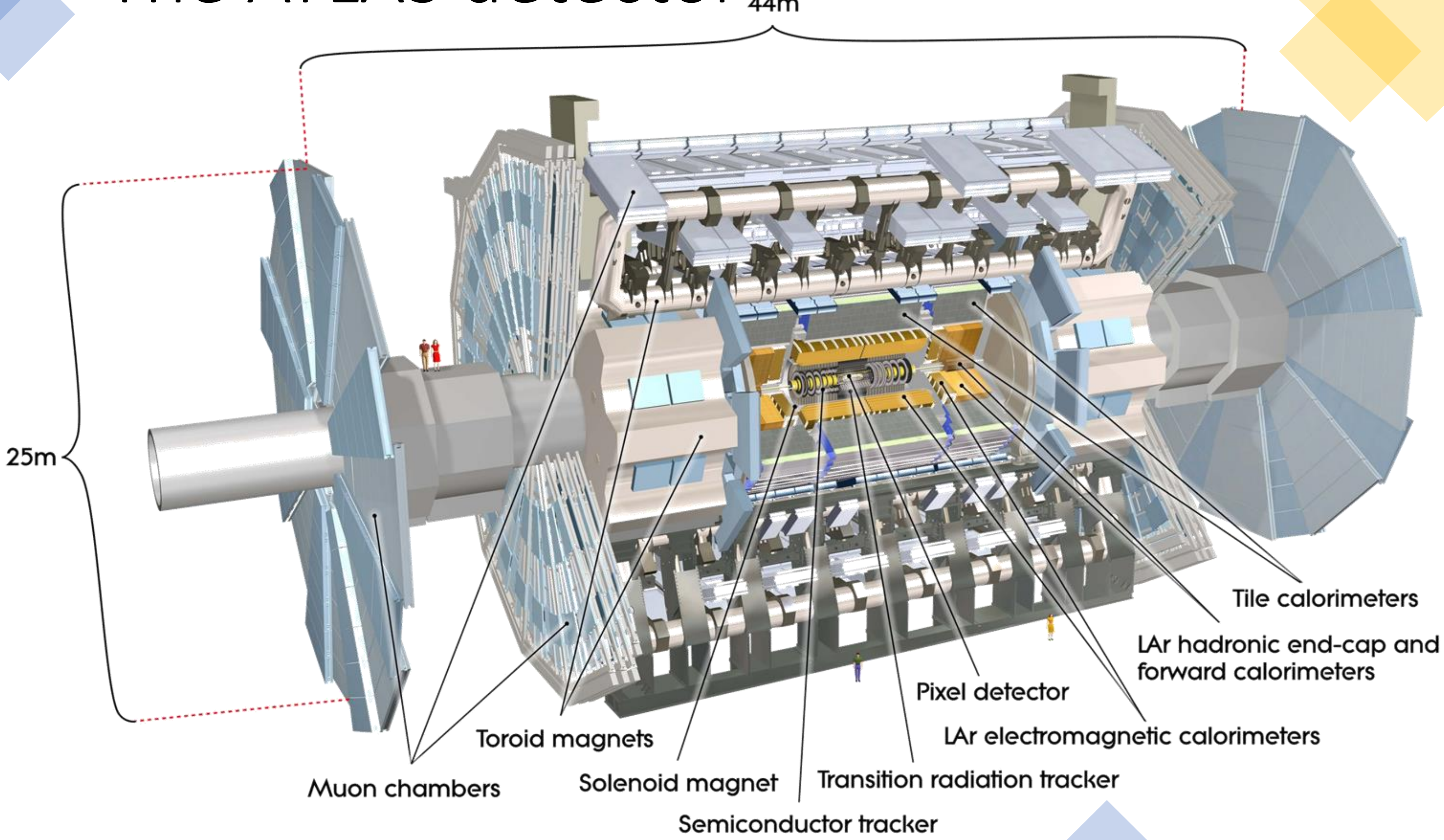
Search for exotic decays of the Higgs in four lepton final states, three channels

High-mass:	$\mathrm{H} \rightarrow Z_d Z_d \rightarrow 4\ell$	$15\ \mathrm{GeV} < m_{Z_d} < 60\ \mathrm{GeV}$	$\ell = \mathrm{e}, \mu$
Low-mass:	$H \rightarrow Z_d Z_d \rightarrow 4\mu$	$1\ \mathrm{GeV} < m_{Z_d} < 15\ \mathrm{GeV}$	
ZX channel:	$\mathrm{H} \rightarrow Z Z_d \rightarrow 4\ell$	$15\ \mathrm{GeV} < m_{Z_d} < 55\ \mathrm{GeV}$	$\ell = e, \mu$

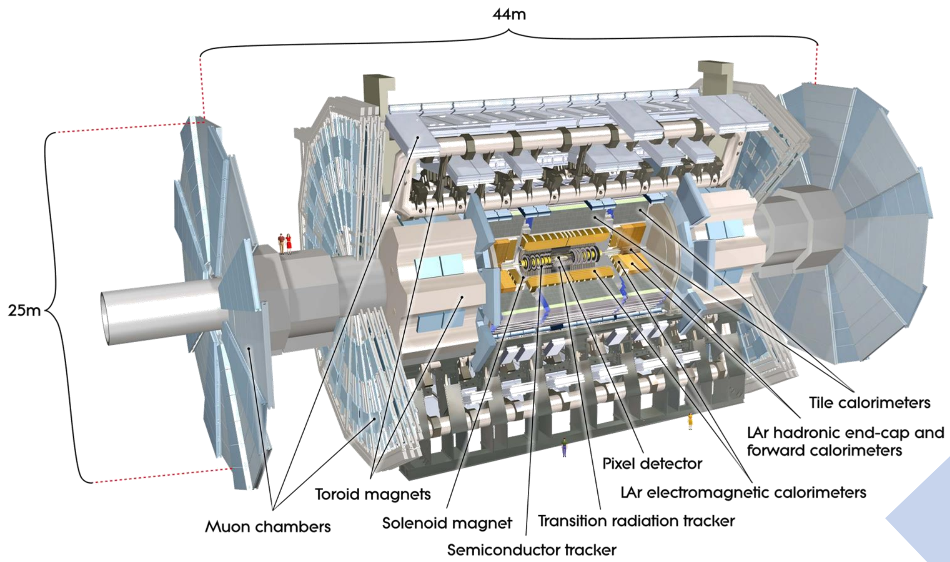




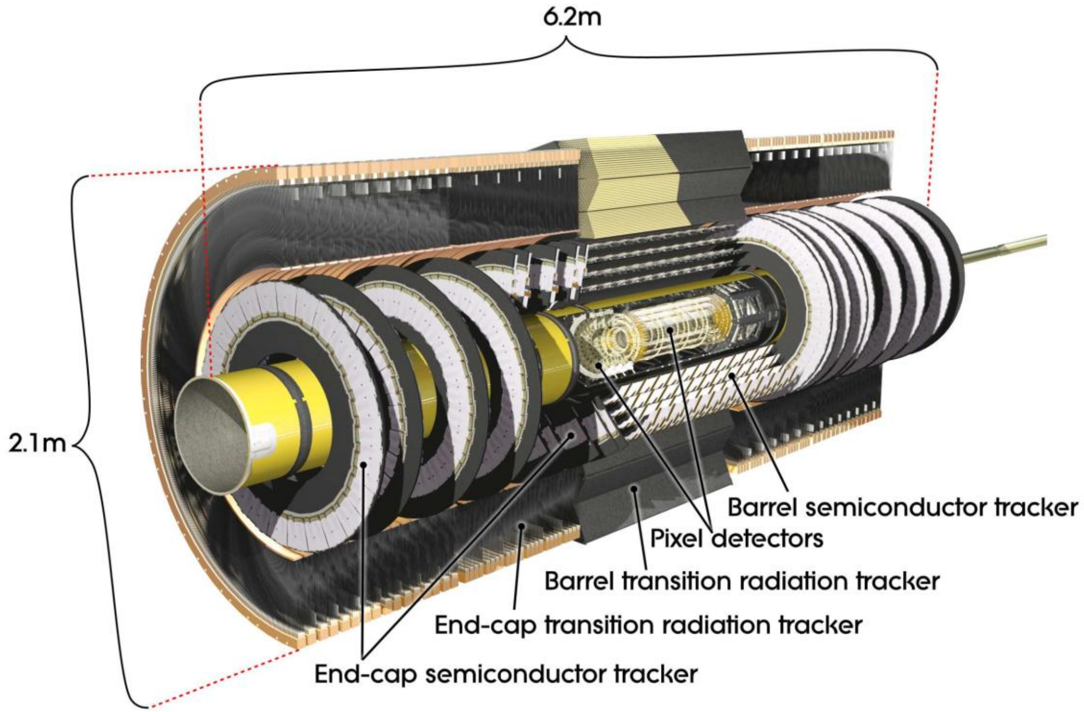
The ATLAS detector



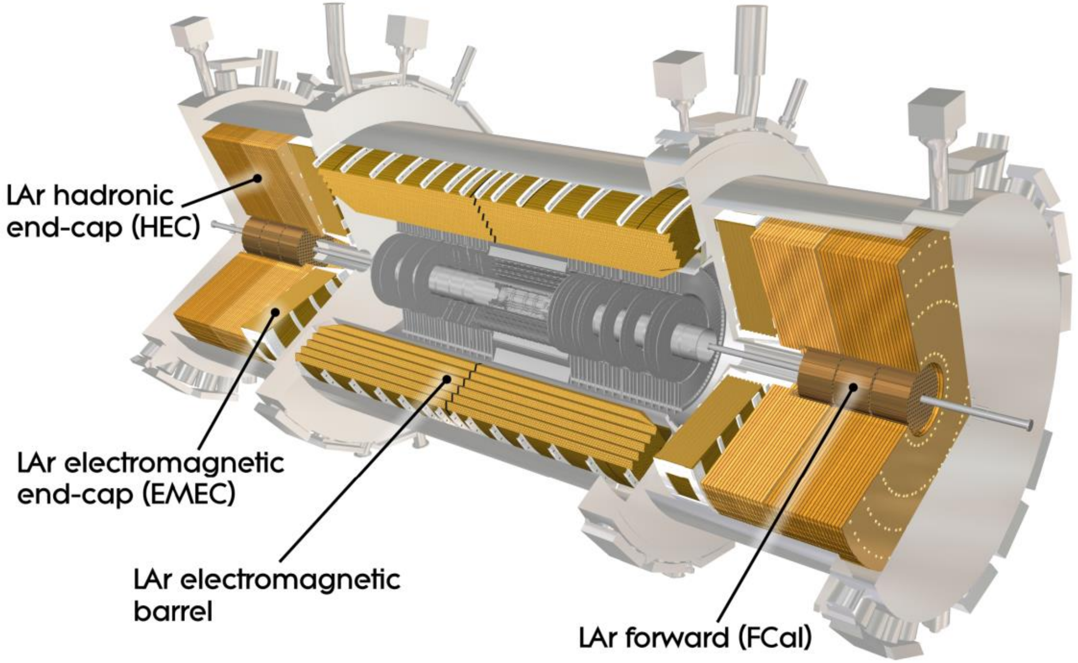
The ATLAS detector



Inner Detector



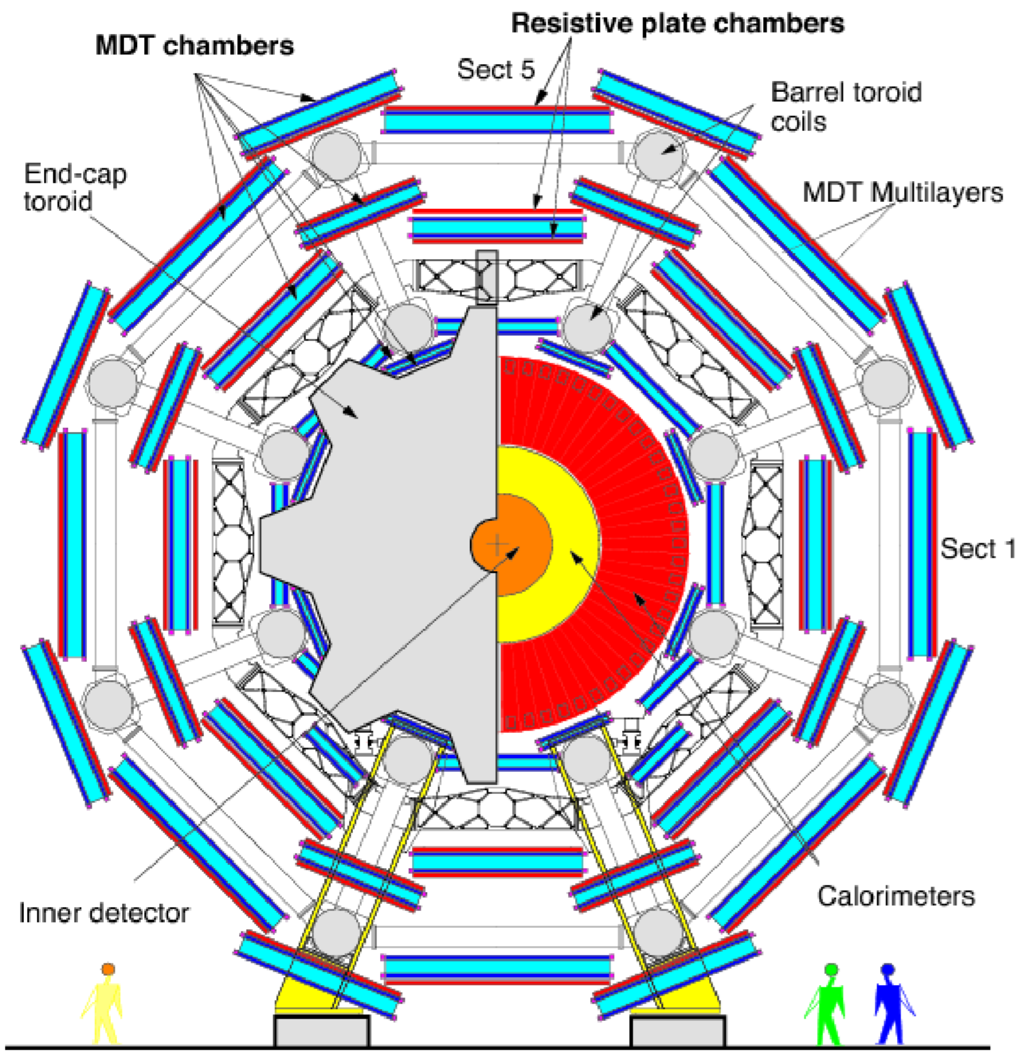
Liquid Argon Calorimeter

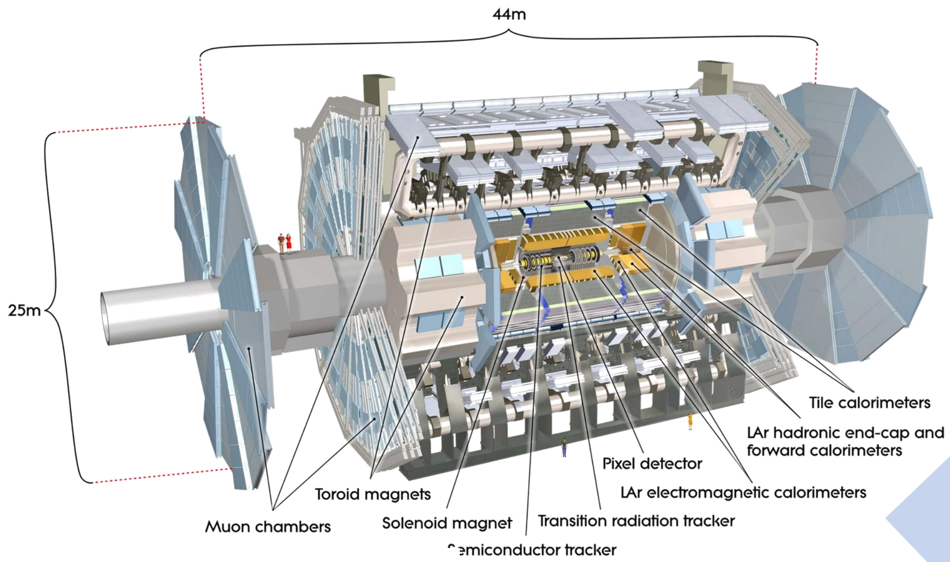


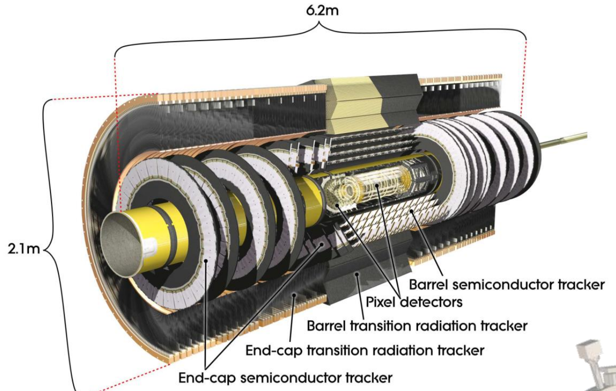
The ATLAS detector

ATLAS

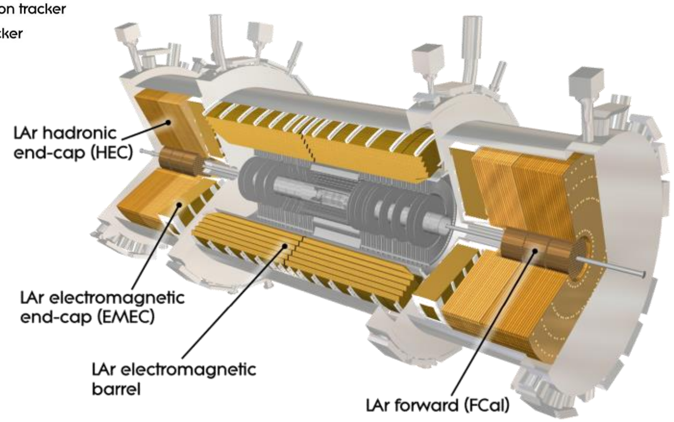
Muon Spectrometer





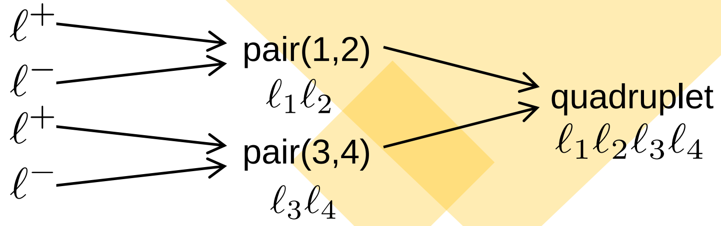


Inner Detector



Liquid Argon Calorimeter

Analysis Scheme



All analysis channels

- Search for two pairs of prompt same-flavor opposite sign leptons, or just muons
- Four-lepton invariant mass compatible with Higgs Boson mass

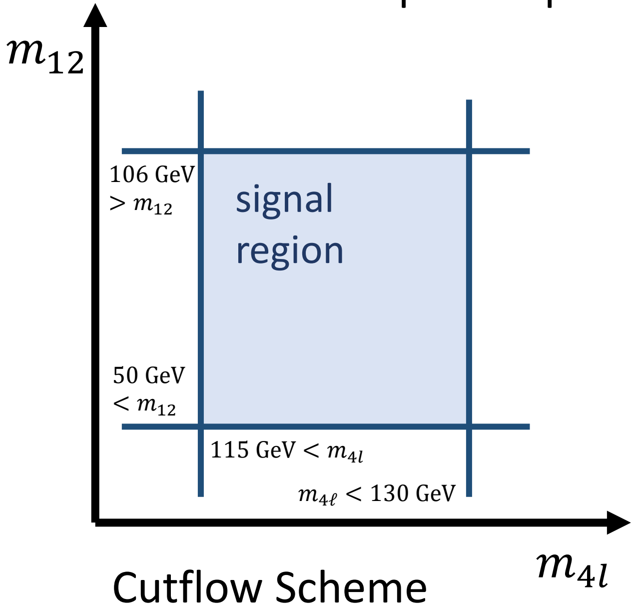
$H \to ZZ_d \to 4\ell$

- One di-lepton pair invariant mass compatible with Z boson mass
- Signal region is the spectrum of the other di-lepton pair's invariant mass

$H \to Z_d Z_d \to 4\ell$ / 4μ

- No dilepton pair's invariant mass compatible with m_Z (High Mass only)
- Both dilepton pair's invariant mass sufficiently similar
- Signal region is the average dilepton invariant mass $m_{\ell\ell} = \frac{1}{2}(m_{12} + m_{34})$

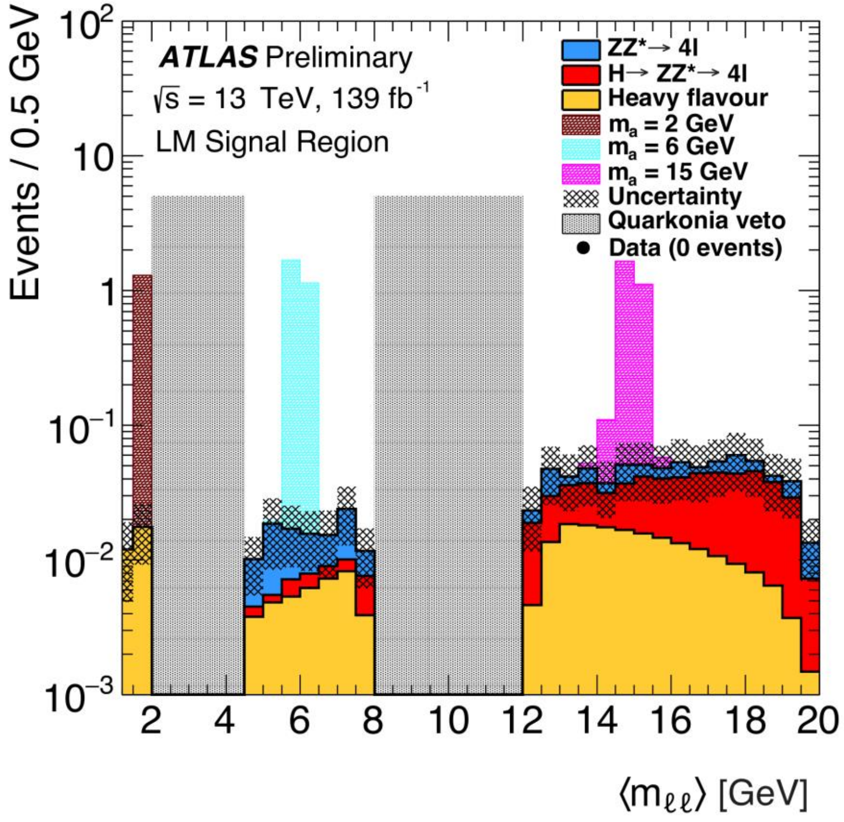
Kinematic phase space



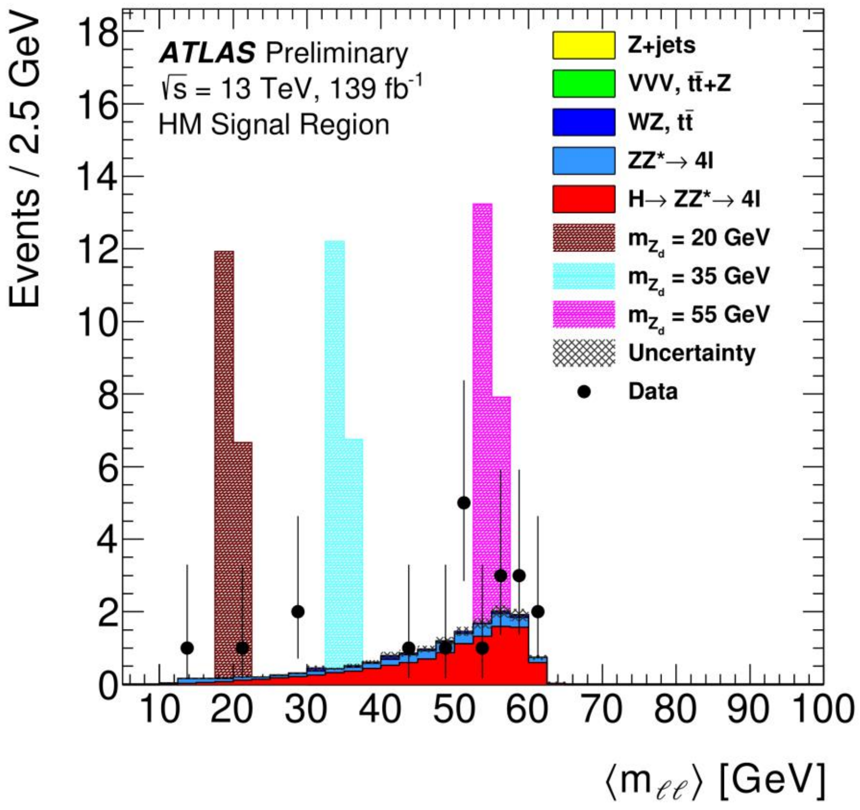
Cutflow Scheme

Signal Regions

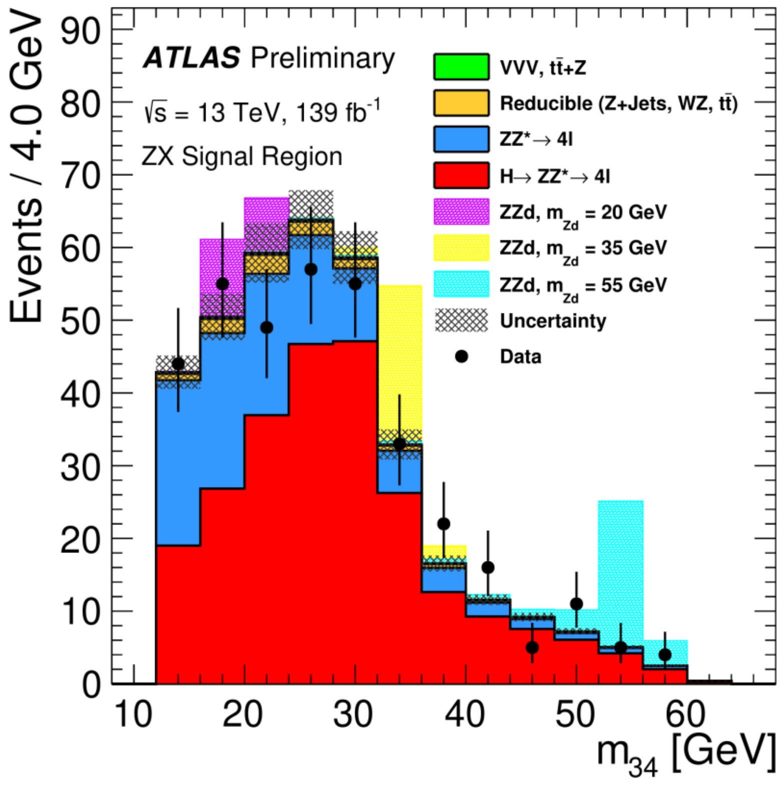
Low Mass $H \rightarrow Z_d Z_d \rightarrow 4\mu$



High Mass $H \rightarrow Z_d Z_d \rightarrow 4\ell$



ZX $H \rightarrow ZZ_d \rightarrow 4\ell$



Statistical Analysis

Profile Likelihood Ratio

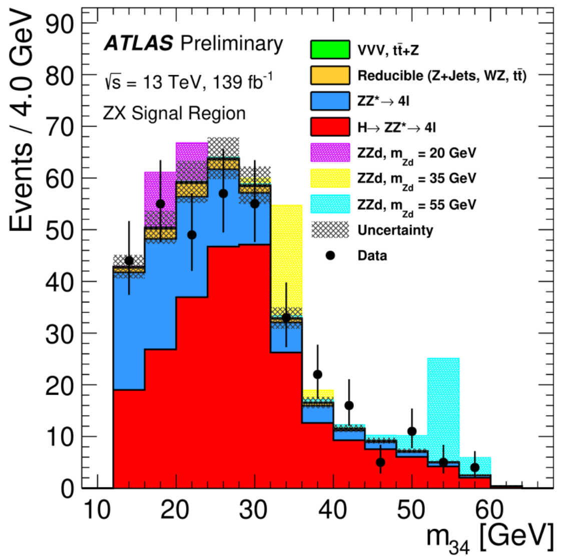
Likelihood $L(\mu, \sigma) = \prod_i L_i(B_i(\sigma) + \mu\, S_i(\sigma)|n_i)$

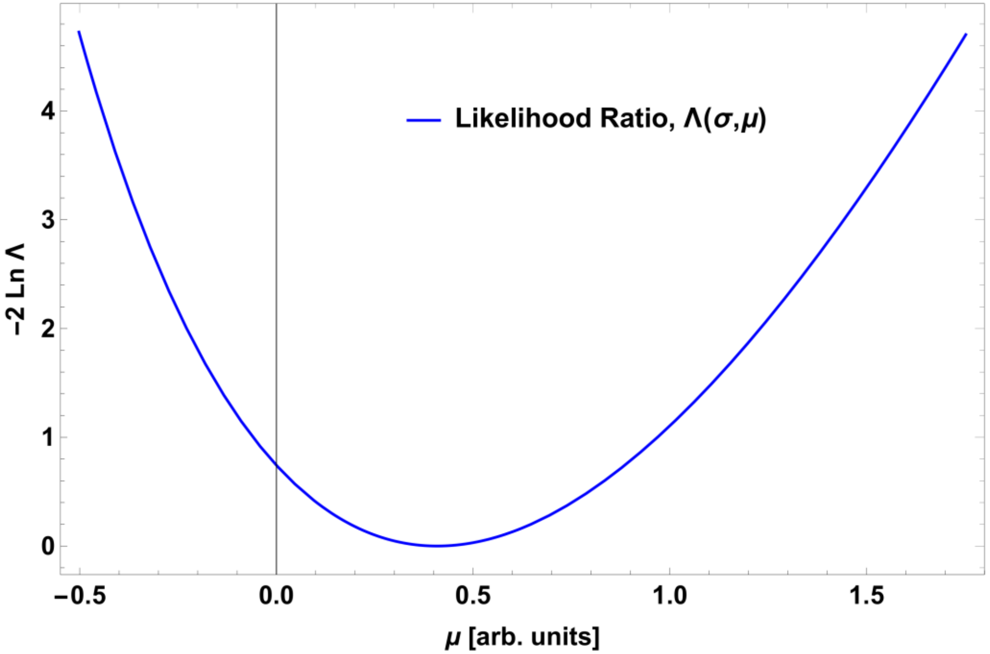
Likelihood ratio $\Lambda(\mu) = \frac{L(\mu, \hat{\hat{\sigma}})}{L(\hat{\mu}, \hat{\sigma})}$

$\hat{\mu}, \hat{\sigma}$ global maximum of likelihood $\frac{d}{d\mu}\frac{d}{d\sigma}\, L(\mu, \sigma)\Big|_{\mu=\hat{\mu}, \sigma=\hat{\sigma}} = 0$

$\hat{\hat{\sigma}}$ local maximum of L at μ $\frac{d}{d\sigma} L(\mu, \sigma)\Big|_{\sigma=\hat{\hat{\sigma}}} = 0$

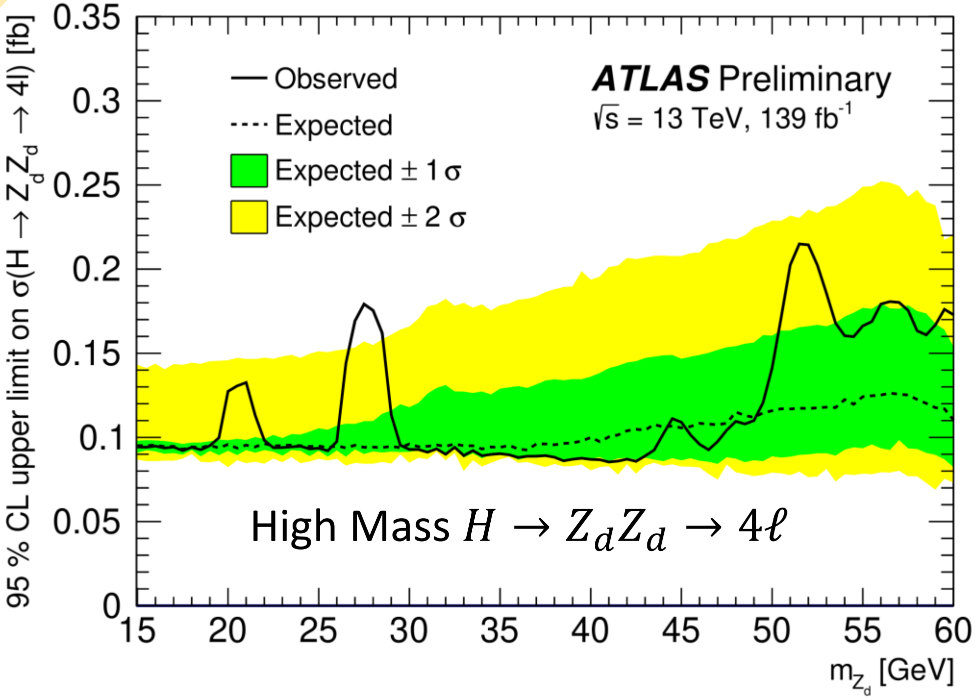
$\sqrt{2 \ln \Lambda(\mu)}$ ≈ Gaussian Significance of μ

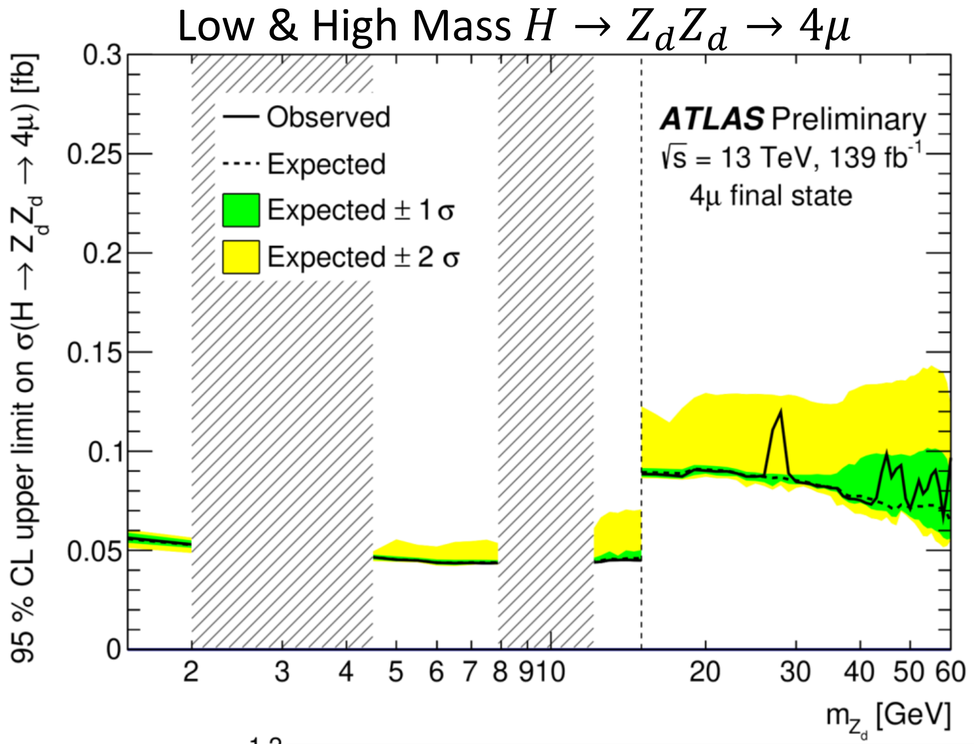




Example likelihood ratio profile

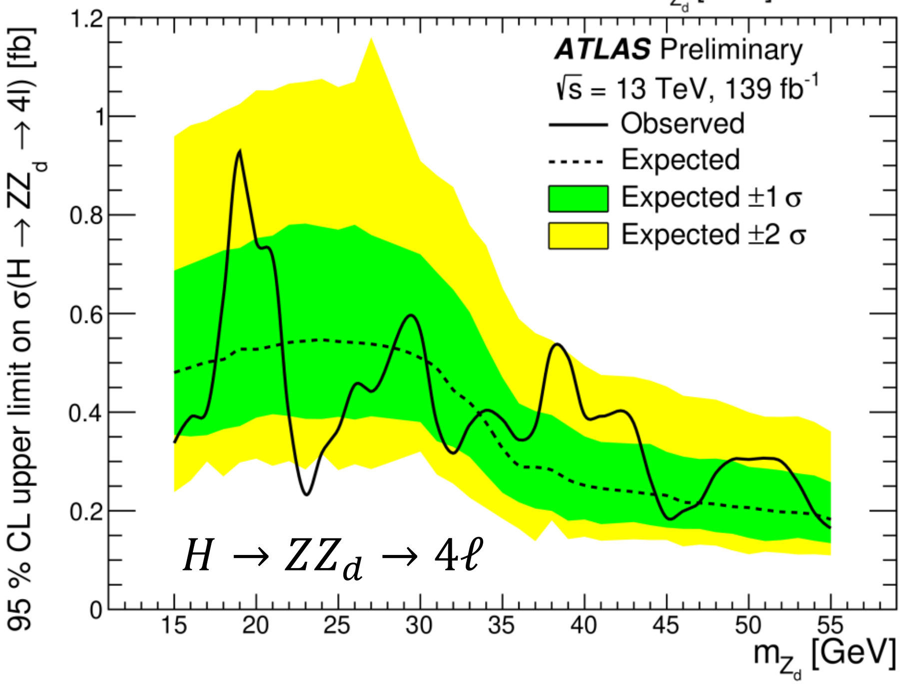
Results





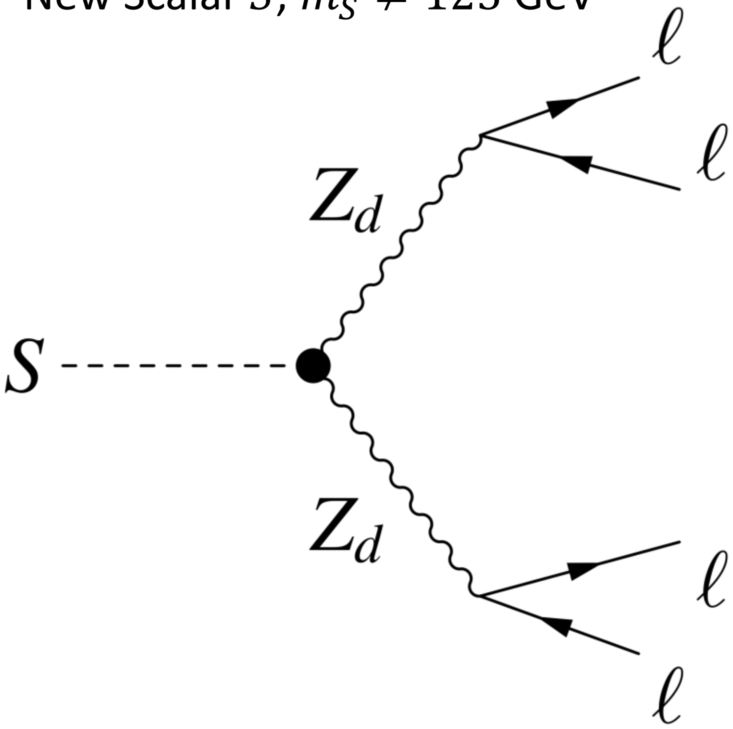
Additional limits & interpretations in Conf Note

- $H \to XX\ /\ ZX$ fiducial limits
- $H \to aa\ /\ Za \to 4\mu$
- Higgs Coupling parameter κ
- kinematic mixing, mass mixing
- 2HDM+S in different Yukawa couplings

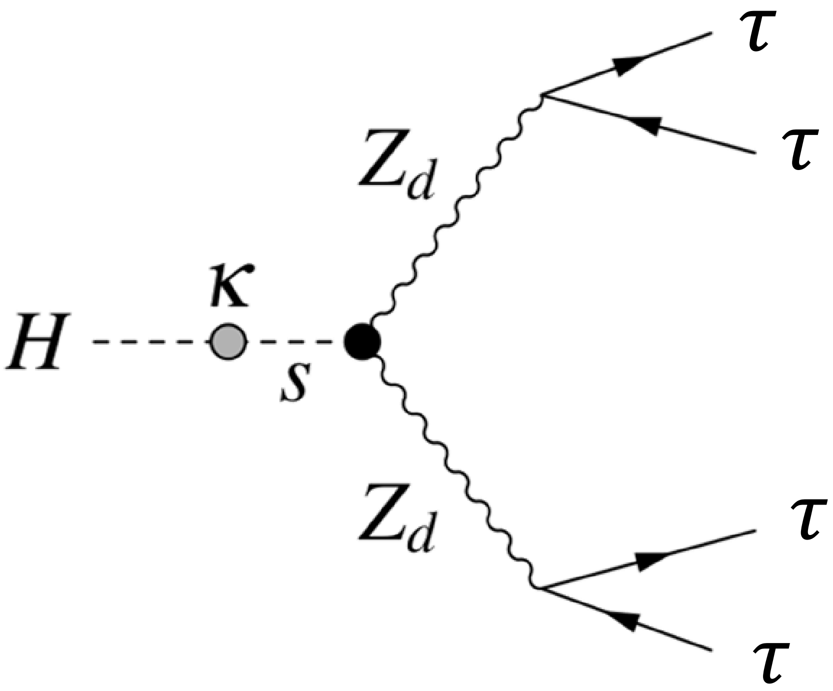


Work in progress - Analyses

$S \to Z_d Z_d \to 4\ell$
New Scalar S, $m_S \neq 125$ GeV



$H \to Z_d Z_d \to 4\tau$
various τ decay channels



Work in progress – Snowmass

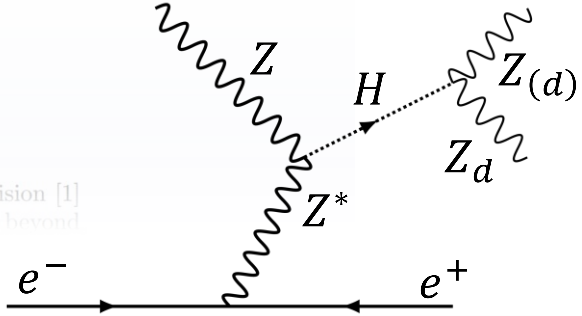
Snowmass 2021 | Letter of Intent

Sensitivity for $h \to Z_{(d)} Z_d$ at future colliders

K. Assamagan, S. Snyder, C. Weber - Brookhaven National Laboratory
S. Connell, L. Truong, D. Boye - University of Johannesburg
L. Leeuw - University of Western Cape

Proposal

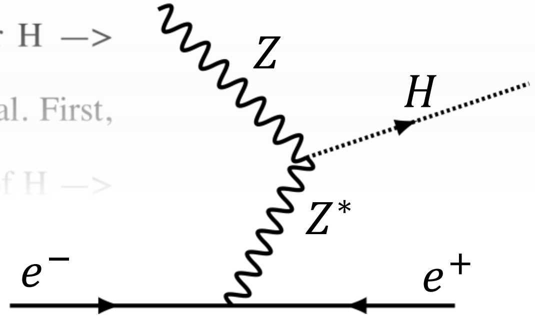
Future colliders will search for new phenomena by probing the Standard Model either at greater precision [1] or at higher collision energies [2]. The impetus for this comes from phenomena that hint at physics beyond



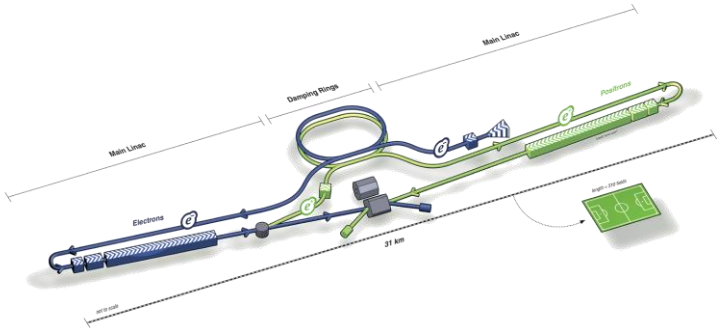
SNOWMASS21-EF2-018

Snowmass 2021 LOI on H —> invisible

In the context of Snowmass 2021, we intend to study the prospects for H —> invisible searches at future colliders. There are two aspects to our proposal. First, we aim to use H —> invisible results at the LHC [1, 2] to do projections of H —>



SNOWMASS21-EF10_EF2_Ketevi_Assamagan-035



Conclusion

- Precision Higgs studies and Dark Sector searches are both exciting avenues for new physics searches
- Published set of analyses that combines both in conf note - ATLAS-CONF-2021-034
  - Full publication in preparation
- Finishing additional analyses covering adjacent phase space
- Planning for ATLAS phase 3, and exploring new final states
- Snowmass studies ongoing

Thank you!

End of Presentation!