Search for hidden sector and invisible particles in the decays of the Higgs boson with the ATLAS detector

Kétévi Adiklè Assamagan

BNL

In this talk

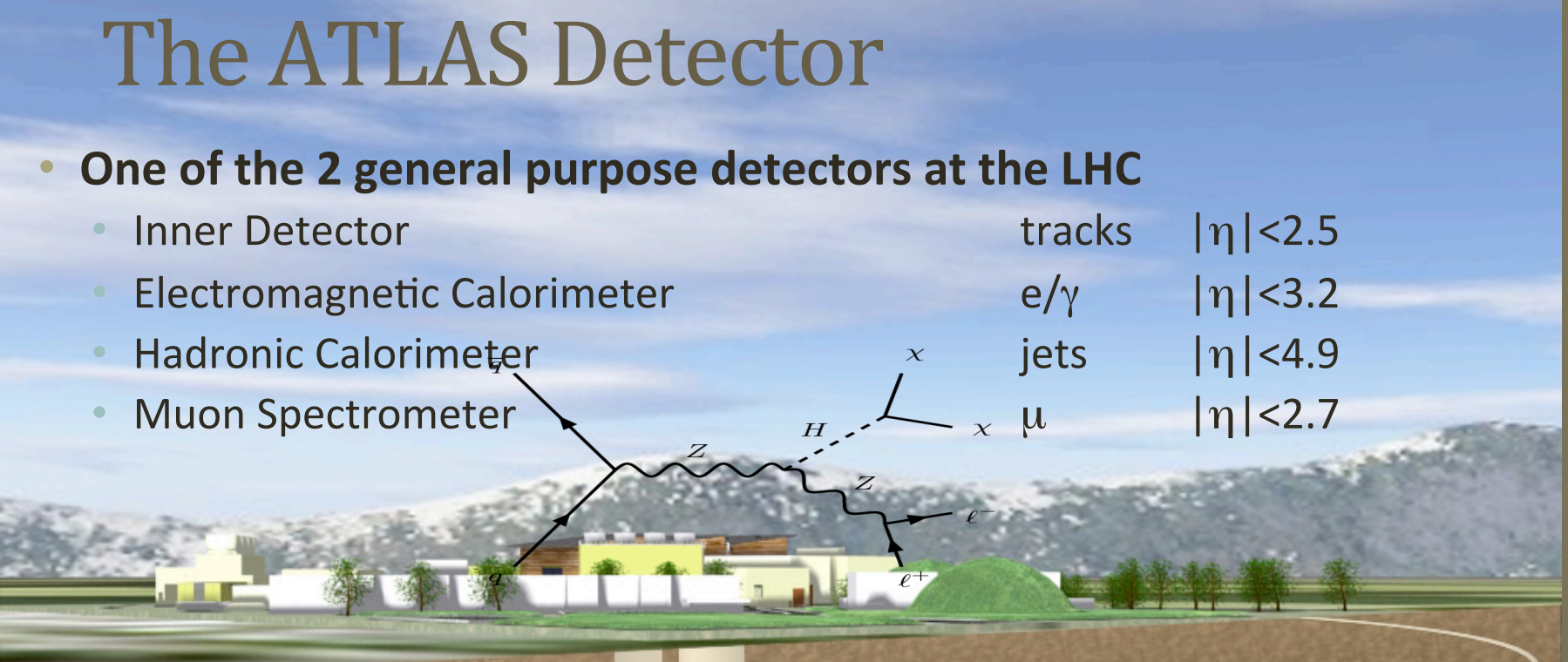
1. **Search for dark sector states in Higgs boson decay to four-lepton events**
   - Leptons: electrons or muons
2. **Search for Higgs boson decay to invisible (undetected) particles in events with large missing energy**
   - Weakly Interacting Massive Particle (WIMP), leading to a momentum imbalance in the detector (missing energy)
3. **Interpretations of search results**
   - Constraints on dark sector state model parameters
   - Comparison to direct dark matter detection experiments

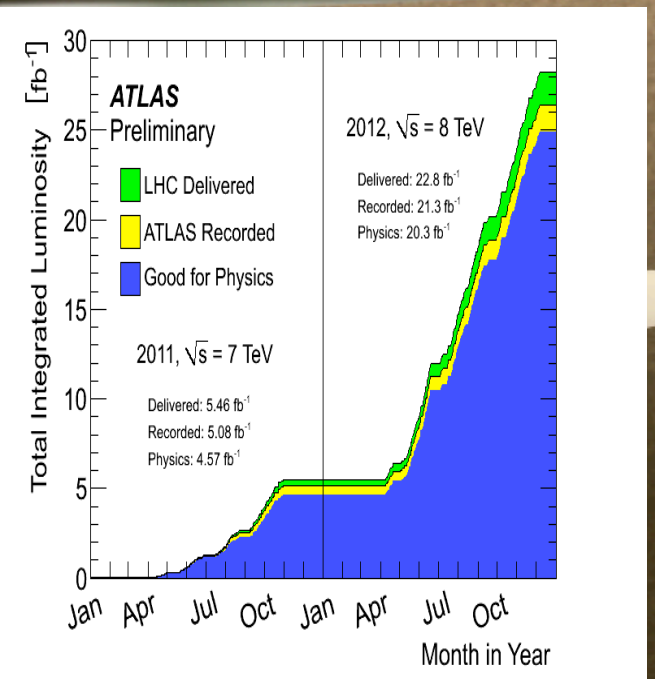
I was involved (first-hand) in the analyses presented in this talk

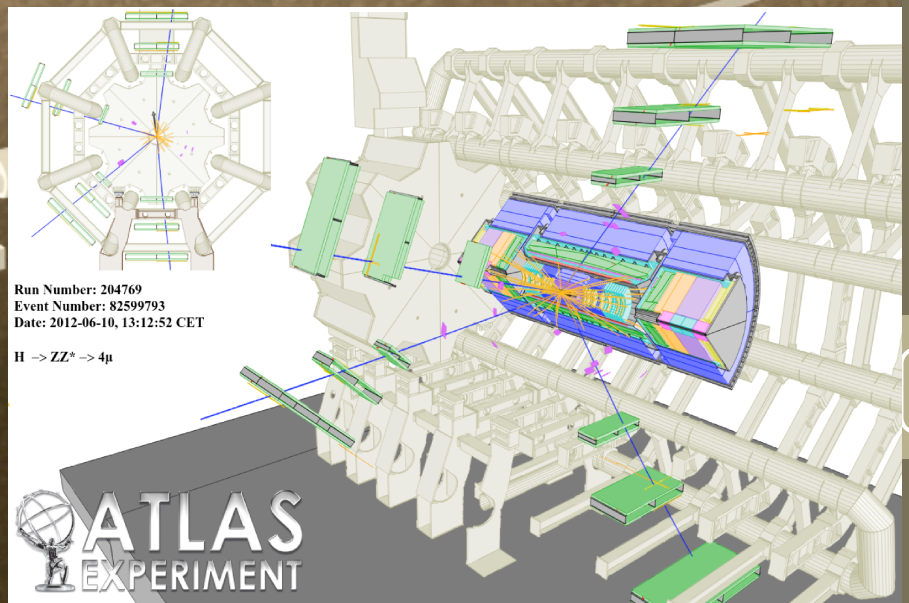
These analyses took 7 months to 2years+3months to complete from beginning to publication, and evolved in parallel

The ATLAS Detector

- **One of the 2 general purpose detectors at the LHC**
  - Inner Detector — tracks — $|\eta|<2.5$
  - Electromagnetic Calorimeter — e/γ — $|\eta|<3.2$
  - Hadronic Calorimeter — jets — $|\eta|<4.9$
  - Muon Spectrometer — μ — $|\eta|<2.7$

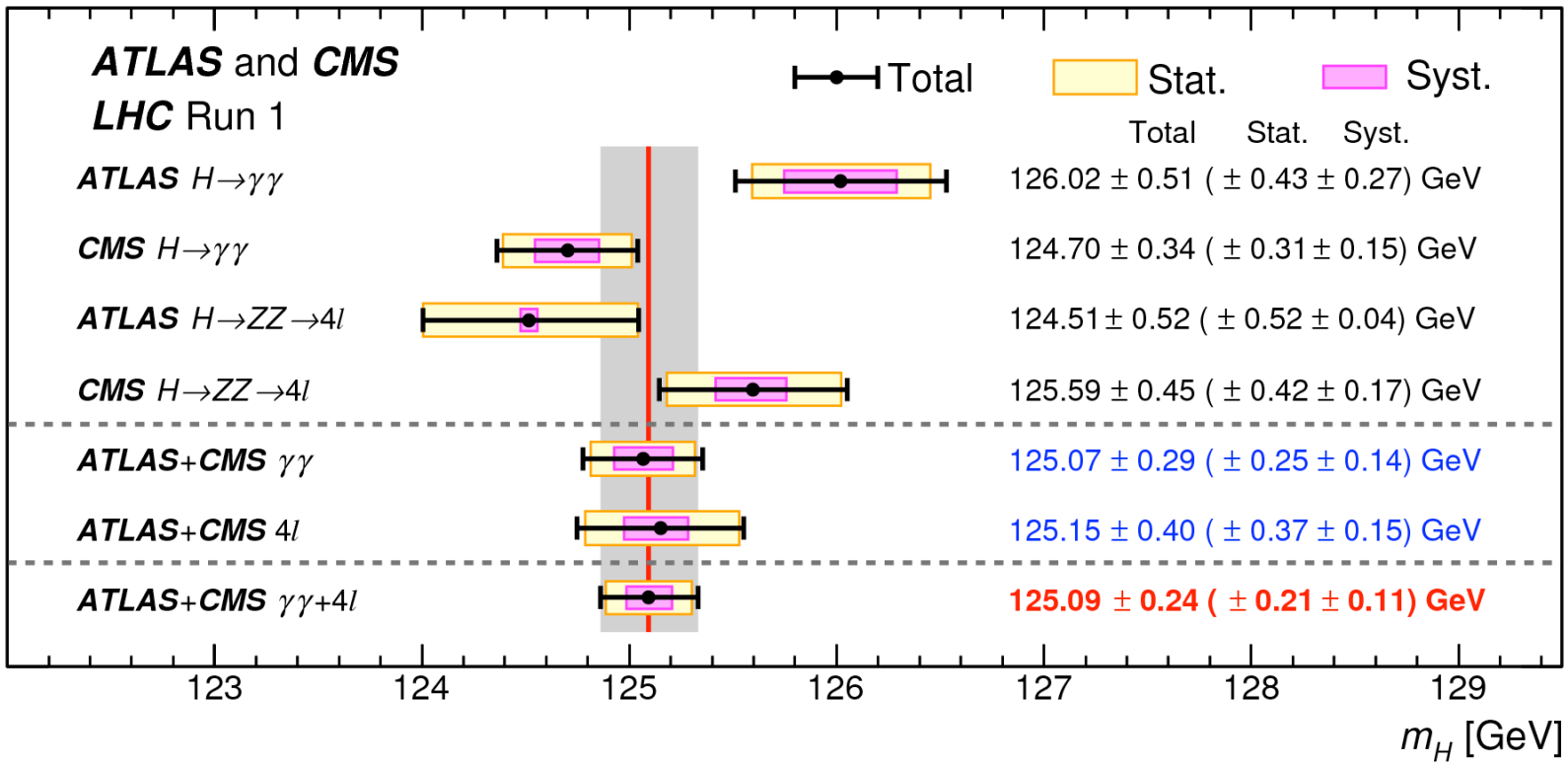






In this talk

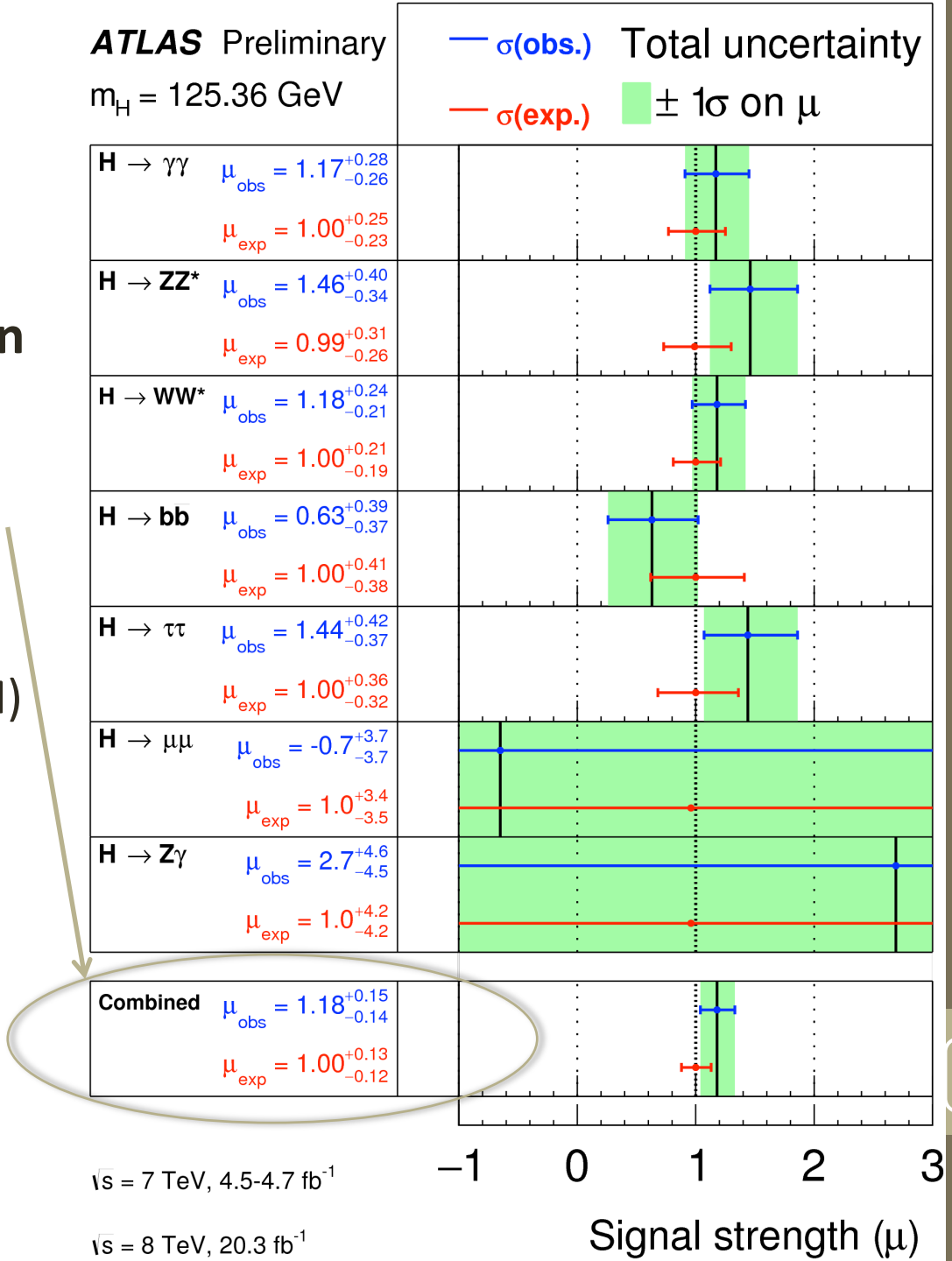
- Combined Higgs mass measurements by ATLAS and CMS



- We will assume a Higgs boson with mass m_H = 125 GeV in the searches presented in this talk

Motivation

- **Combined Higgs boson signal strength consistent with the Standard Model (SM)**
  - Small deviation could be hint of Beyond the Standard Model (BSM) physics
  - **Search for H → BSM**
    - Interpretation for Dark Matter



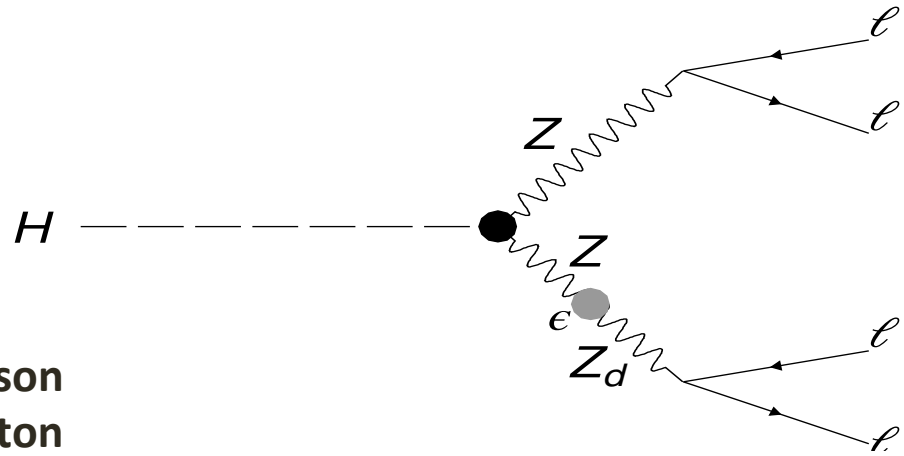
Motivation

- **Dark sector states appear in many extensions to the SM**
  - Curtin et al, arXiv: 1412.0018, arXiv: 1312.4992
  - Davoudiasl et al, arXiv: 1304.4935, arXiv: 1203.2947
  - Wells et al, arXiv: 0803.1243, arXiv: 0801.3456
    - And the references therein
  - Could provide explanation for
    - The discrepancy between observation and the SM prediction of the muon g-2
    - The astrophysical observations of positron excesses
- **Dark Matter may be explained by the existence of WIMP**
  - The discovered Higgs boson might decay to WIMP if kinematically allowed
  - Such a decay is referred to as invisible decay of the Higgs boson

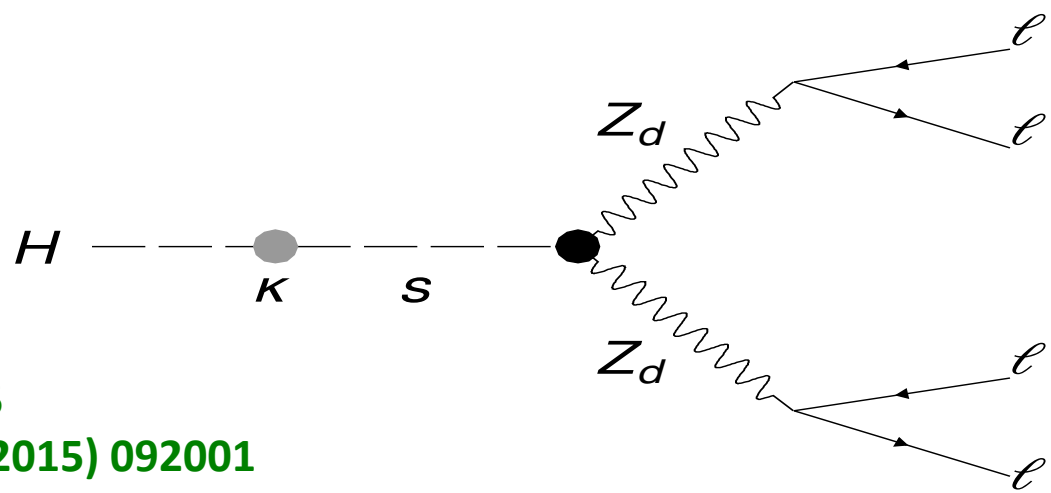
1) Search for dark sector states in Higgs boson to four-lepton events

Search for dark vector bosons in H → 4 leptons events

- **2 searches performed: H → Z Z_d → 4l and H → $Z_d Z_d$ → 4l**
  - The final states of 4e, 4μ, 2e2μ, and their combination



Z_d = Dark Z-boson
= Dark photon

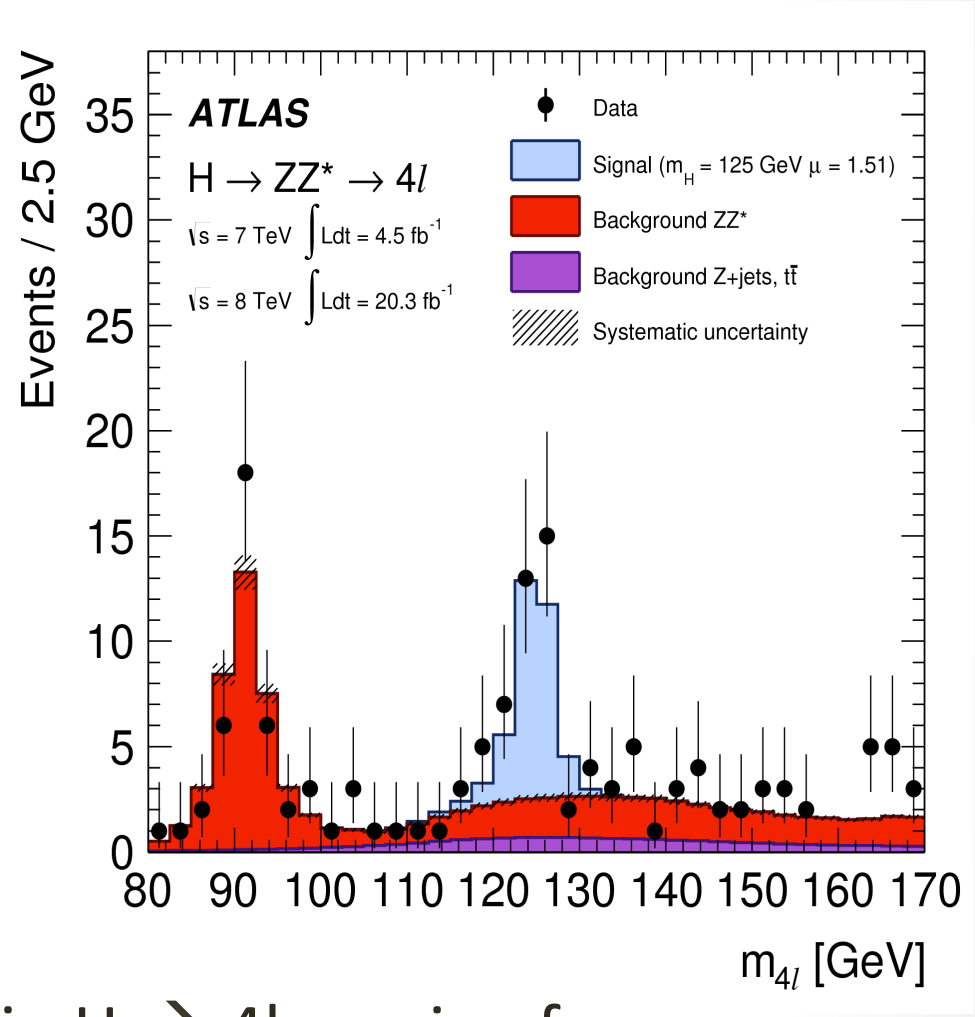


arXiv:1505.07645
Phys. Rev. D 92 (2015) 092001

$H \rightarrow Z Z_d \rightarrow 4l$ and $H \rightarrow Z_d Z_d \rightarrow 4l$

- Standard Model
  - $H \rightarrow ZZ^* \rightarrow 4l$
- Standard Model extended with Hidden Sector States
  - $H \rightarrow ZZ^* \rightarrow 4l$
  - $H \rightarrow ZZ_d \rightarrow 4l$
  - $H \rightarrow Z_d Z_d \rightarrow 4l$

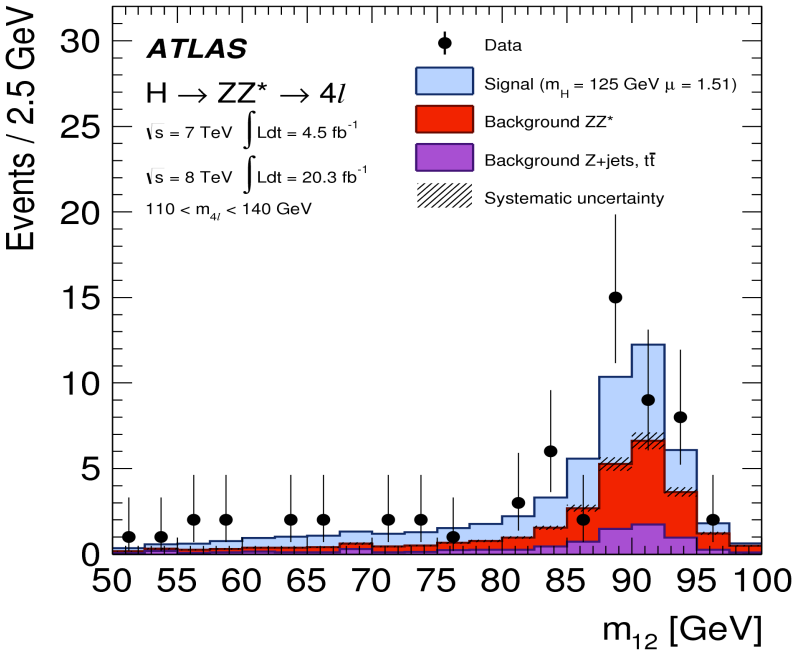
Z_d = Dark vector boson

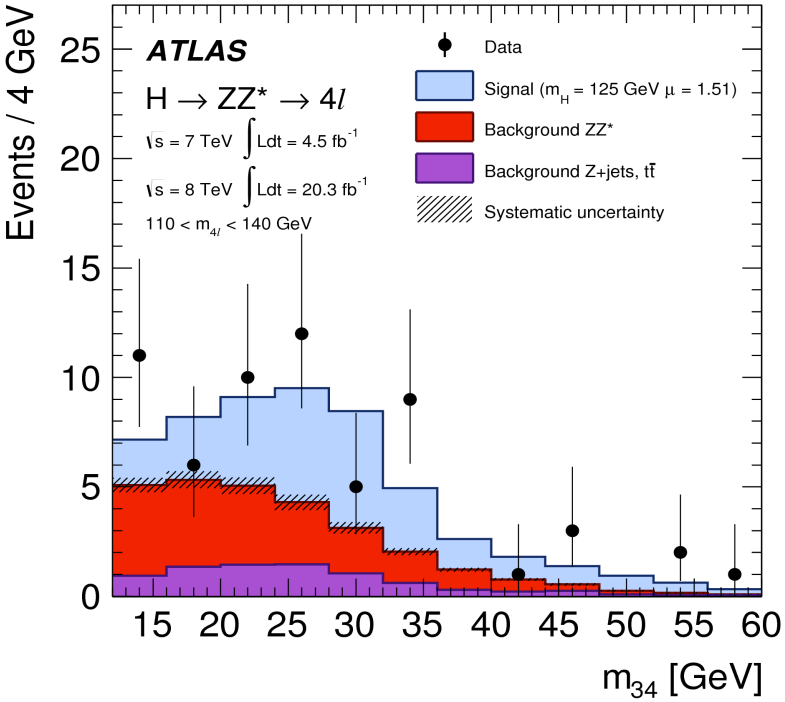


Is the excess of events in $H \rightarrow 4l$ coming from non-SM intermediate states, e.g. $H \rightarrow ZZ_d \rightarrow 4l$?

Search Strategy

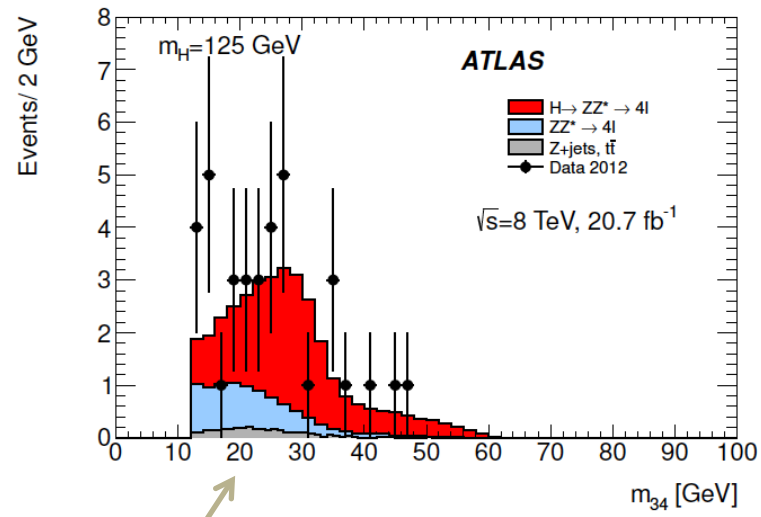
- H → ZZ* → 4l (l=e, or μ)
- Quadruplets of 4l, grouped into 2 pairs of Same Flavor Opposite Sign(SFOS) leptons
- 4l ordered with indices 1, 2, 3 and 4 such that m_{12} (first pair SFOS) and m_{34} (2nd pair SFOS)
- m_{12}, leading pair, assumed to reconstruct the Z-boson
- m_{34}, sub-leading pair, assumed to reconstruct the Z*
- Retain 1 unique quadruplet with the requirement of m_{12} closest to m_Z: $50 < m_{12} < 106$ GeV

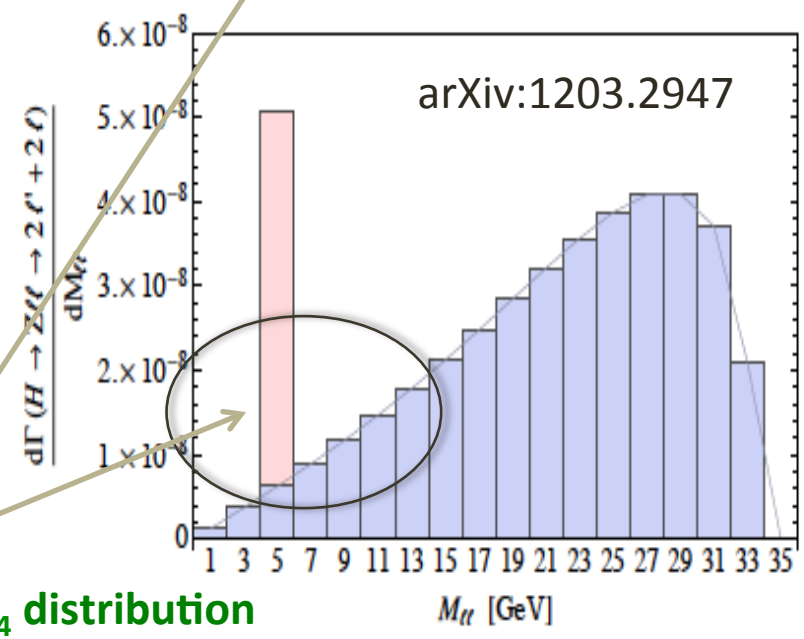




Search Strategy: $H \rightarrow ZZ_d \rightarrow 4l$

- Same as in the standard $H \rightarrow ZZ^* \rightarrow 4l$ search until you get to the m_{34} distribution
- Z_d assumed to be narrow and on-shell
- **Take a model for the signal line shape $Z_d \rightarrow 2l$, smeared with detector resolution, and search for a narrow peak in the m_{34} distribution**
- $115 < m_{4l} < 130$ GeV
- Covers the range $m_{Zd} < m_H - m_Z \sim 35$ GeV
- However, because of this requirement on m_{12}, $50 < m_{12} < 106$ GeV, the coverage in m_{Zd} can be extended to 55 GeV
- **No excess of events seen consistent with : $H \rightarrow ZZ_d \rightarrow 4l$ in $15 < m_{2l} < 55$ GeV**

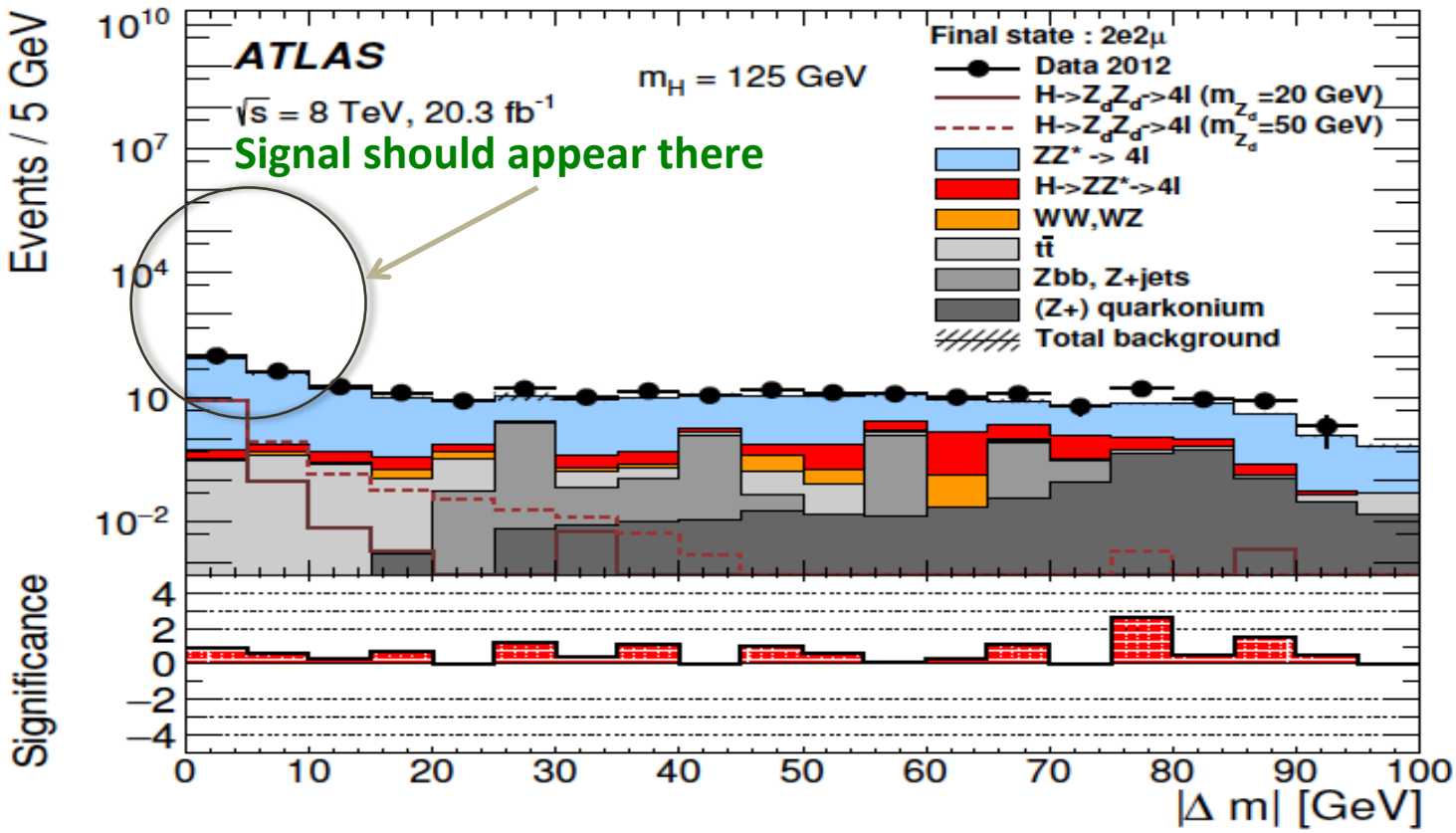




Signal should appear as a narrow peak in m_{34} distribution

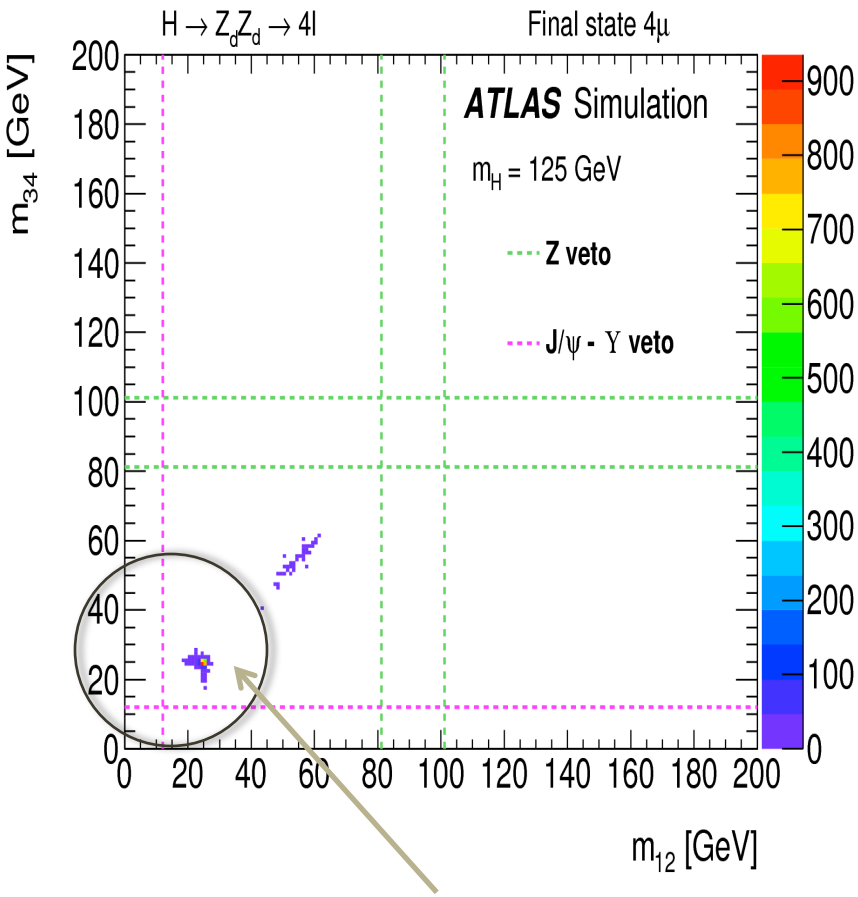
Search Strategy: $H \rightarrow Z_d Z_d \rightarrow 4l$

- Start with the identification of 4leptons as in $H \rightarrow ZZ^* \rightarrow 4l$, and the formation of quadruplets with SFOS
- Select the unique quadruplet by exploiting the mass difference **$\Delta m = |m_{12} - m_{34}|$ minimal**
- $115 < m_{4l} < 130$ GeV

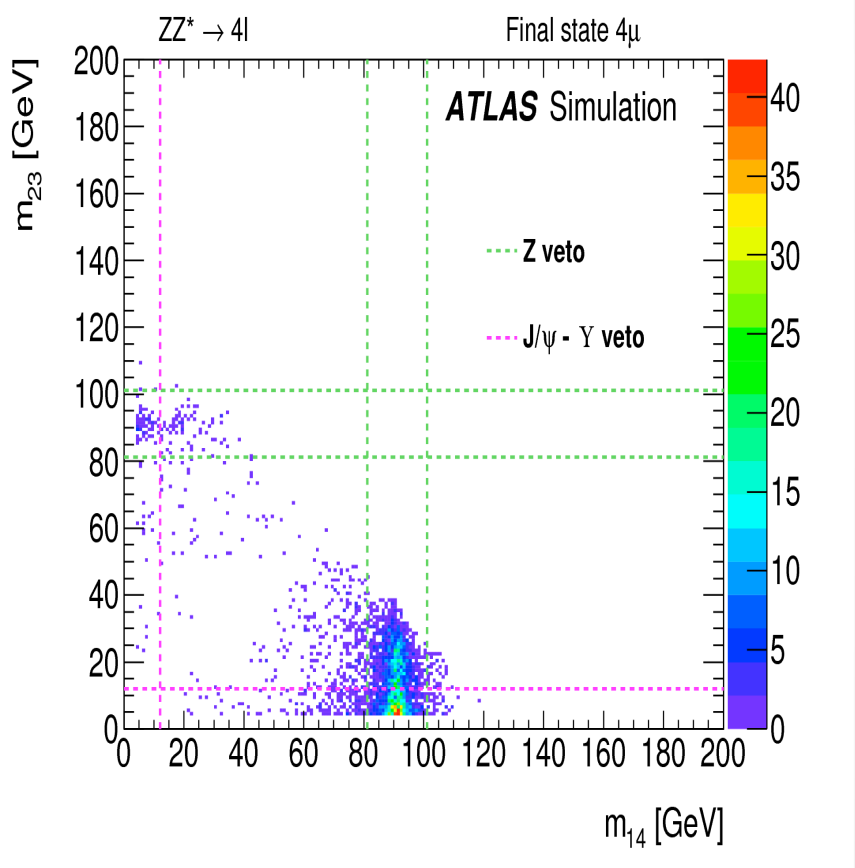


Search Strategy: $H \rightarrow Z_d Z_d \rightarrow 4l$

- Apply Z-veto to suppress H -> ZZ* → 4l, Z+jets and Z+Quarkonia backgrounds
- In addition apply a J/psi and Upsilon veto



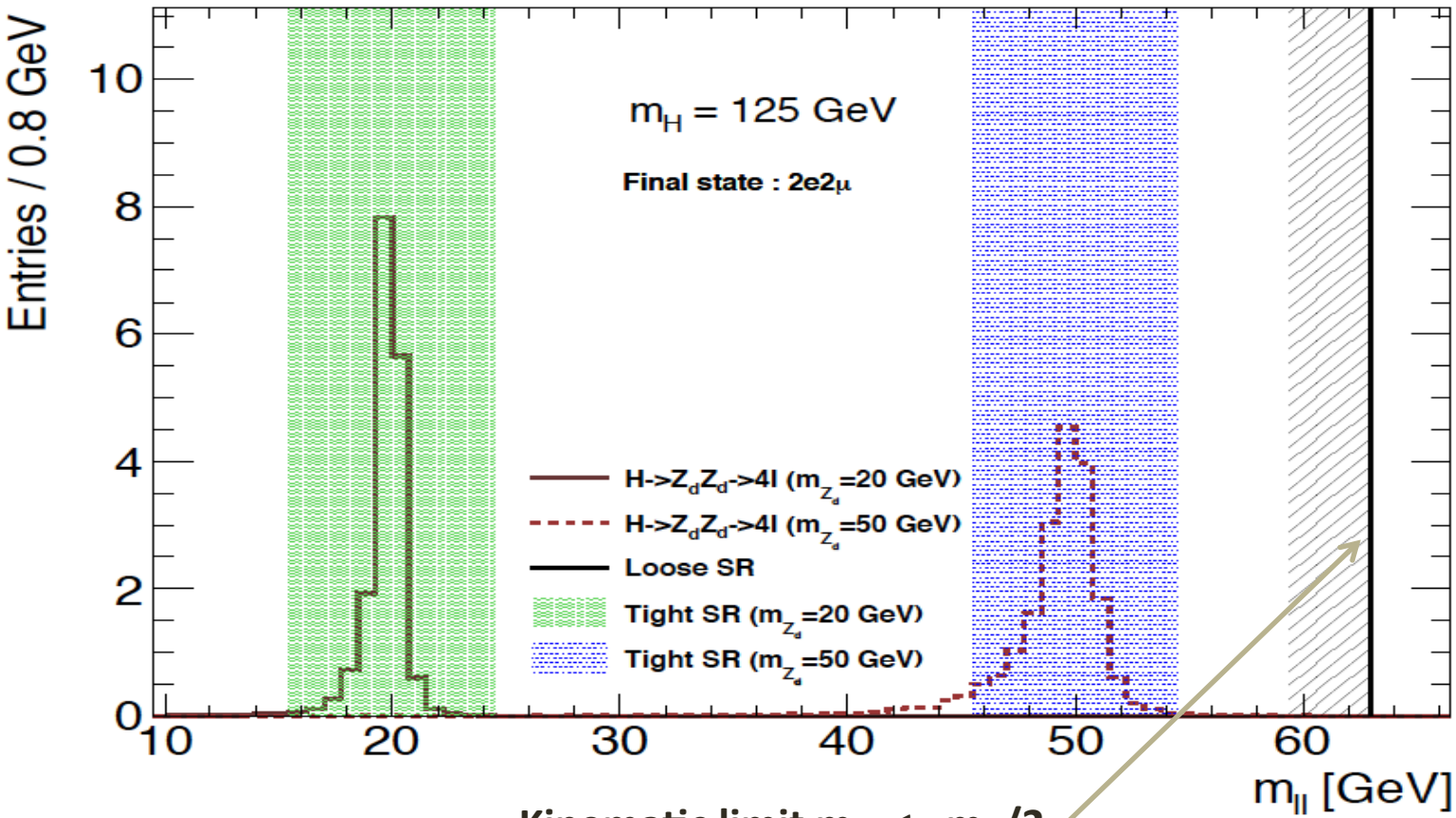
Signal with dark Z mass of 25 GeV



Vetos applied to all combinations of SFOS

Search Strategy: $H \rightarrow Z_d Z_d \rightarrow 4l$

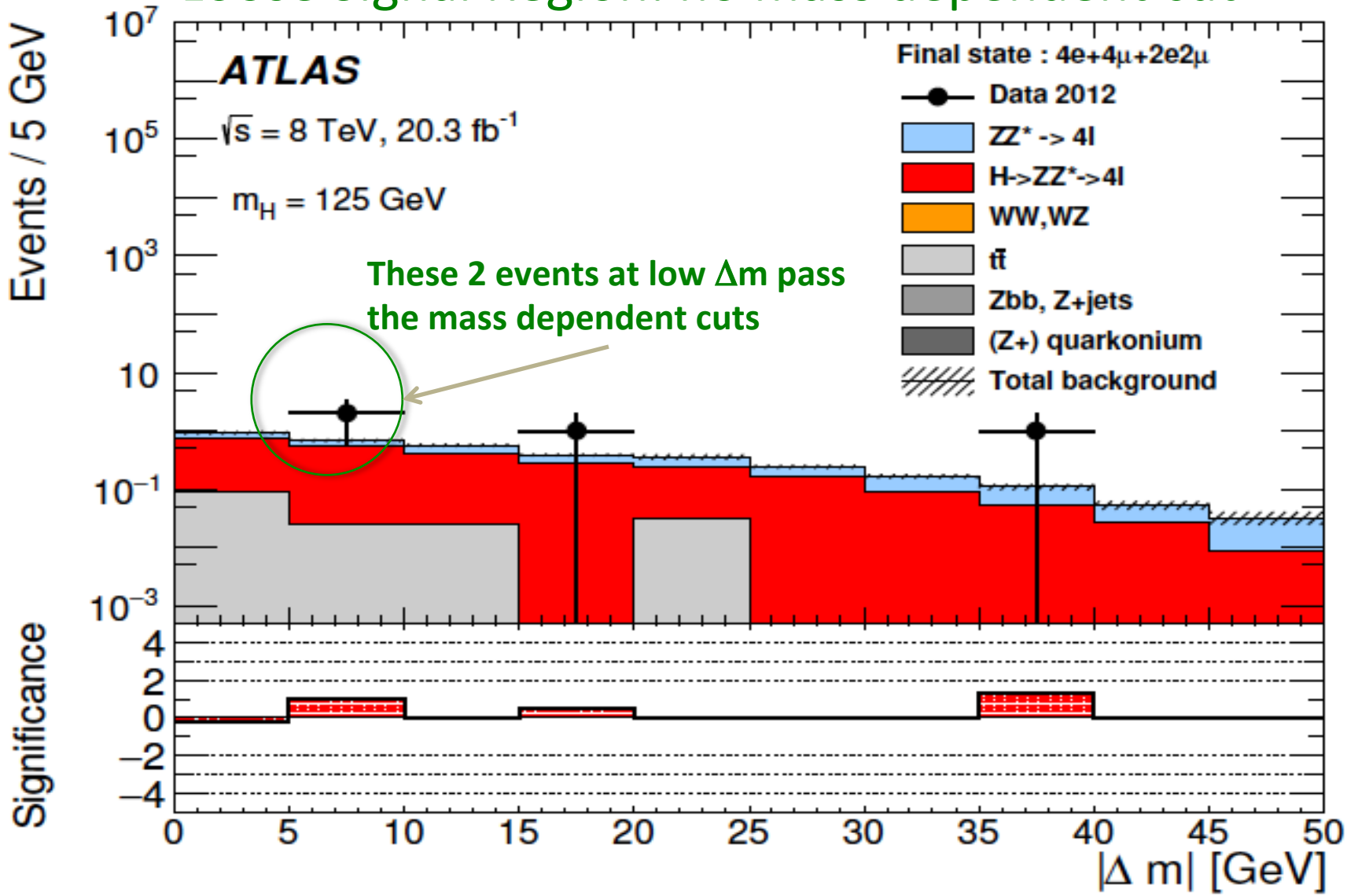
- **Loose Signal Region** (SR): $m_{ll} < m_H/2$
- **Tight Signal Region**: for a tested dark Z mass hypothesis m_{Zd}, narrow the search to reduce the backgrounds further
  - $|m_{12} - m_{Zd}| < \delta m$ && $|m_{34} - m_{Zd}| < \delta m$ ← **Mass dependent cut**
  - The optimized δm values are 5/3/4.5 for 4e/4μ/2e2μ



Kinematic limit $m_{Zd} <= m_H/2$

$H \rightarrow Z_d Z_d \rightarrow 4l$

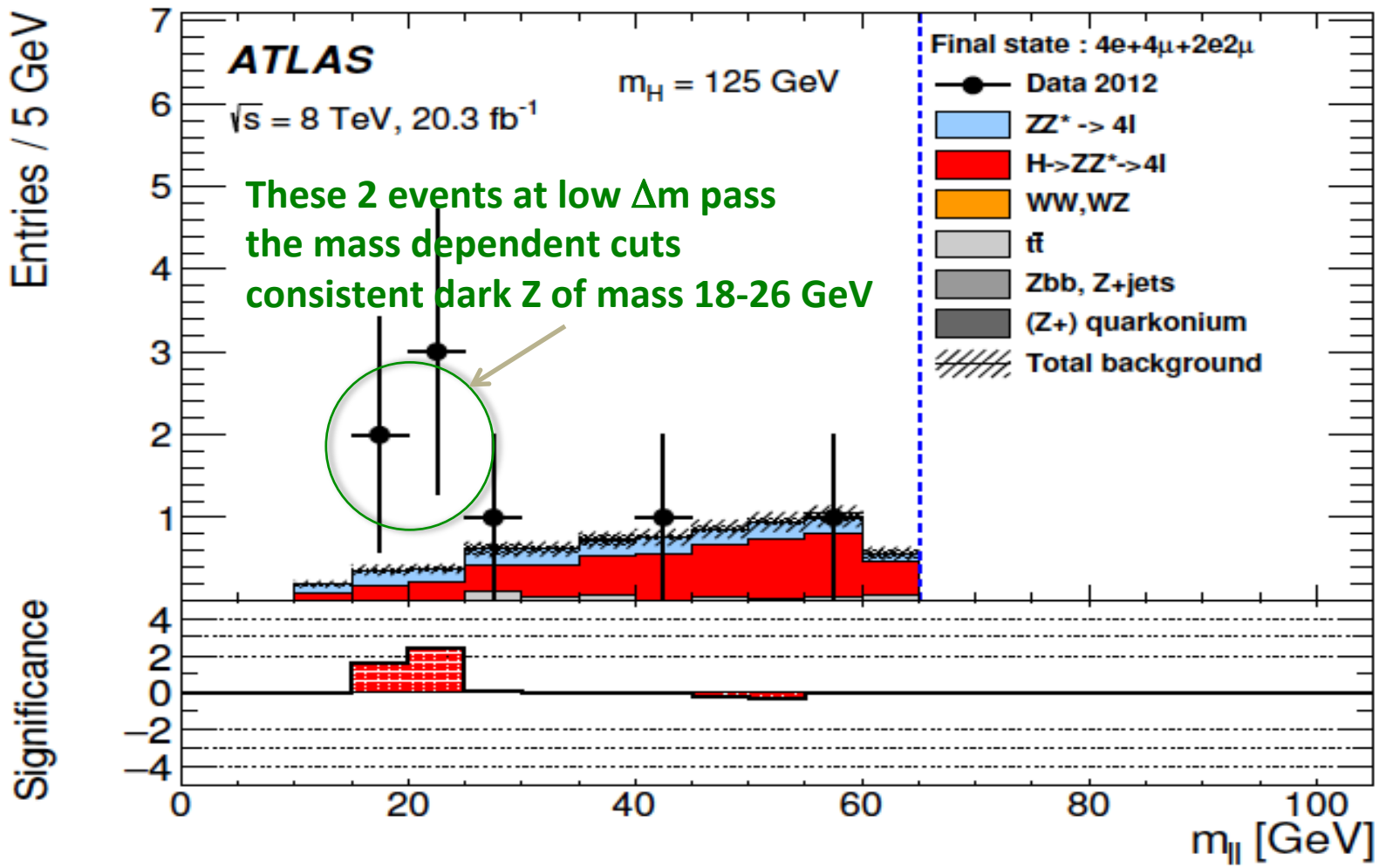
Loose Signal Region: no mass dependent cut



$H \rightarrow Z_d Z_d \rightarrow 4l$

- No significant excess. 1.7σ(4e) and 1.7σ(4μ). 0 event in 2e2μ

Loose Signal Region: $15 < m_{2l} < m_H/2$



$H \rightarrow ZZ_d \rightarrow 4l$ Measurements

- The question is: are there some observed $H \rightarrow 4l$ events associated to $H \rightarrow ZZ_d \rightarrow 4l$?
  - We assume the production of the H is irrelevant to the question The issue is in the decay $H \rightarrow 4l$. Only $H \rightarrow ZZ^*$ or also $H \rightarrow ZZ_d$?
  - We measure the relative branching ratio

$$R_B = \frac{\mathrm{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)}{\mathrm{BR}(H \rightarrow 4\ell)}$$
$$= \frac{\mathrm{BR}(H \rightarrow ZZ_d \rightarrow 4\ell)}{\mathrm{BR}(H \rightarrow ZZ_d \rightarrow 4\ell) + \mathrm{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)}$$

- **No excess of events observed consistent with $H \rightarrow ZZ_d \rightarrow 4l$, so we proceed to set 95% CL upper bounds on R_B**

$H \rightarrow ZZ_d \rightarrow 4l$ Measurements

- Background estimations (based of $H \rightarrow ZZ^* \rightarrow 4l$ search) and systematics

$$n(H \rightarrow 4\ell) = n(4\ell) - n(ZZ^*) - n(t\bar{t}) - n(Z + \text{jets}).$$

Method	Estimated background
	4μ
m_{12} fit: Z+jets contribution	$2.4 \pm 0.5 \pm 0.6$
m_{12} fit: $t\bar{t}$ contribution	$0.14 \pm 0.03 \pm 0.03$
	$2e2\mu$
m_{12} fit: Z+jets contribution	$2.5 \pm 0.5 \pm 0.6$
m_{12} fit: $t\bar{t}$ contribution	$0.10 \pm 0.02 \pm 0.02$
	$2\mu 2e$
$\ell\ell + e^{\pm}e^{\mp}$ relaxed requirements: sum of Z + jets and $t\bar{t}$ contributions	$5.2 \pm 0.4 \pm 0.5$
	$4e$
$\ell\ell + e^{\pm}e^{\mp}$ relaxed requirements: sum of Z + jets and $t\bar{t}$ contributions	$3.2 \pm 0.5 \pm 0.4$

Systematic Uncertainties (%)				
Source	4μ	4e	$2\mu 2e$	$2e2\mu$
Electron Identification	–	9.4	8.7	2.4
Electron Energy Scale	–	0.4	–	0.2
Muon Identification	0.8	–	0.4	0.7
Muon Momentum Scale	0.2	–	0.1	–
Luminosity	3.6	3.6	3.6	3.6
$t\bar{t}$ and Z+jets Normalization	25.0	25.0	25.0	25.0
ZZ^* (QCD scale)	5.0	5.0	5.0	5.0
ZZ^* ($q\bar{q}$/PDF and α_S)	4.0	4.0	4.0	4.0
ZZ^* (gg/PDF and α_s)	8.0	8.0	8.0	8.0

After all signal region requirements

Channel	ZZ^*	$t\bar{t}$ + Z+jets	Sum	Observed	$H \rightarrow 4\ell$
4μ	$3.1 \pm 0.02 \pm 0.4$	$0.6 \pm 0.04 \pm 0.2$	$3.7 \pm 0.04 \pm 0.6$	12	$8.3 \pm 0.04 \pm 0.6$
4e	$1.3 \pm 0.02 \pm 0.5$	$0.8 \pm 0.07 \pm 0.4$	$2.1 \pm 0.07 \pm 0.9$	9	$6.9 \pm 0.07 \pm 0.9$
$2\mu 2e$	$1.4 \pm 0.01 \pm 0.3$	$1.2 \pm 0.10 \pm 0.4$	$2.6 \pm 0.10 \pm 0.6$	7	$4.4 \pm 0.10 \pm 0.6$
$2e2\mu$	$2.1 \pm 0.02 \pm 0.3$	$0.6 \pm 0.04 \pm 0.2$	$2.7 \pm 0.10 \pm 0.5$	8	$5.3 \pm 0.04 \pm 0.5$
all	$7.8 \pm 0.04 \pm 1.2$	$3.2 \pm 0.1 \pm 1.0$	$11.1 \pm 0.1 \pm 1.8$	36	$24.9 \pm 0.1 \pm 1.8$

$H \rightarrow ZZ_d \rightarrow 4l$ Statistical Model

- Statistical model

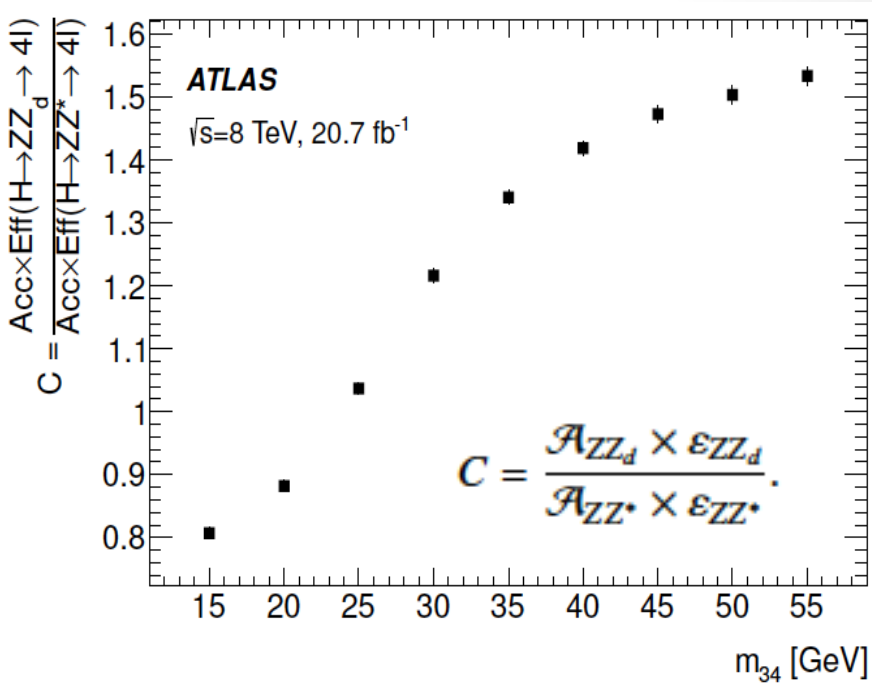
$n(H \rightarrow 4l) = n(H \rightarrow ZZ^* \rightarrow 4l) + n(H \rightarrow ZZ_d \rightarrow 4l)$

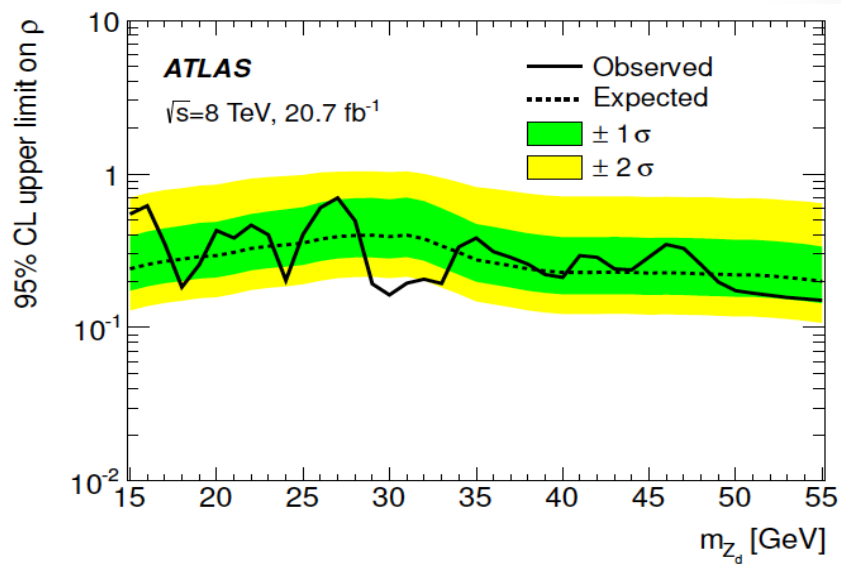
$$\mathcal{L}(\rho, \mu_H, \nu) = \prod_{i=1}^{N_{\text{bins}}} \mathcal{P}(n_i^{\text{obs}} | n_i^{\text{exp}})$$

$$= \prod_{i=1}^{N_{\text{bins}}} \mathcal{P}(n_i^{\text{obs}} | \mu_H \times (n_i^{Z^*} + \rho \times n_i^{Z_d}) + b_i(\nu)),$$

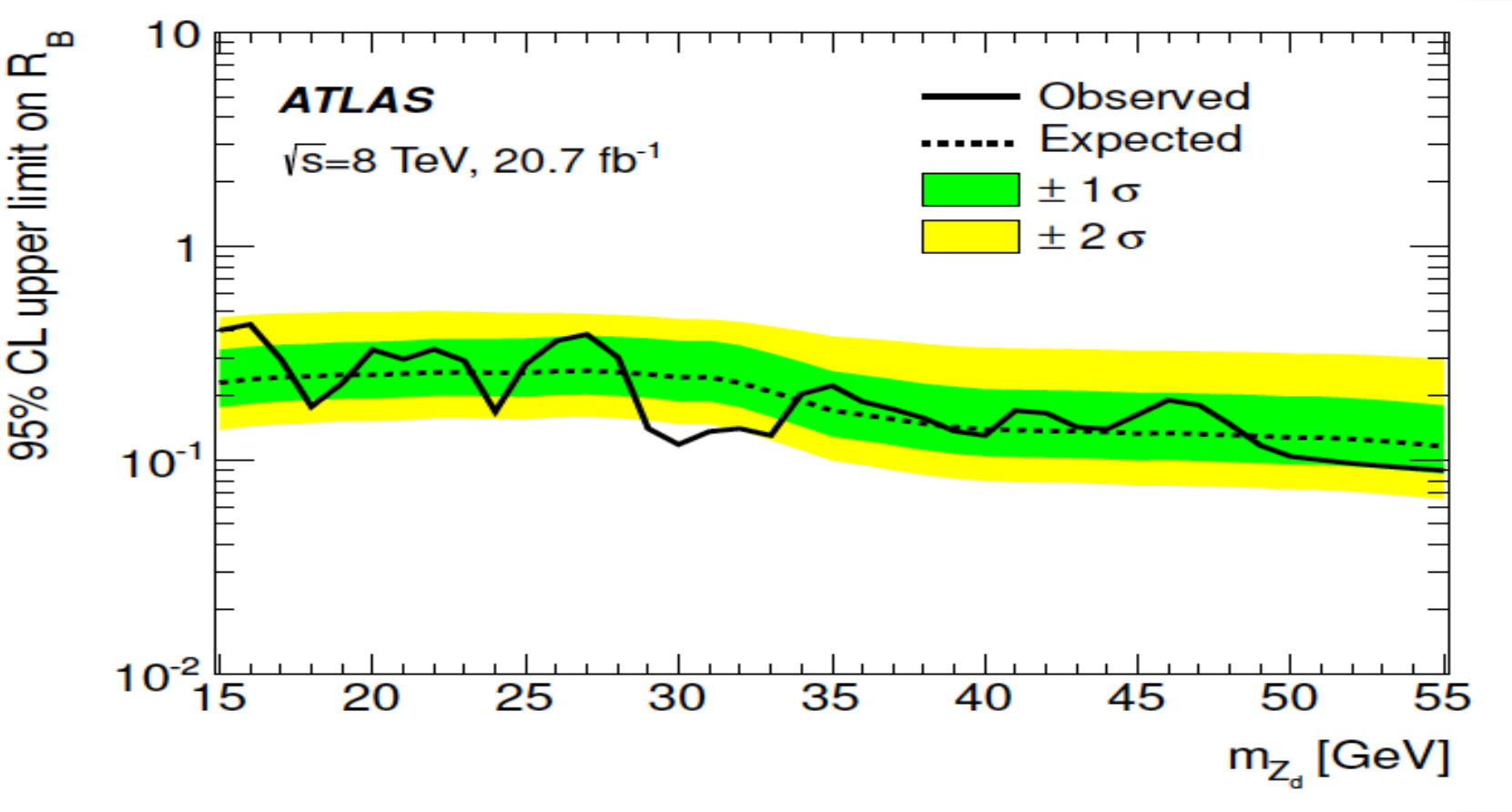
$$R_B = \frac{\rho \times \mu_H \times n(H \rightarrow 4\ell)}{\rho \times \mu_H \times n(H \rightarrow 4\ell) + C \times \mu_H \times n(H \rightarrow 4\ell)}$$

$$= \frac{\rho}{\rho + C},$$



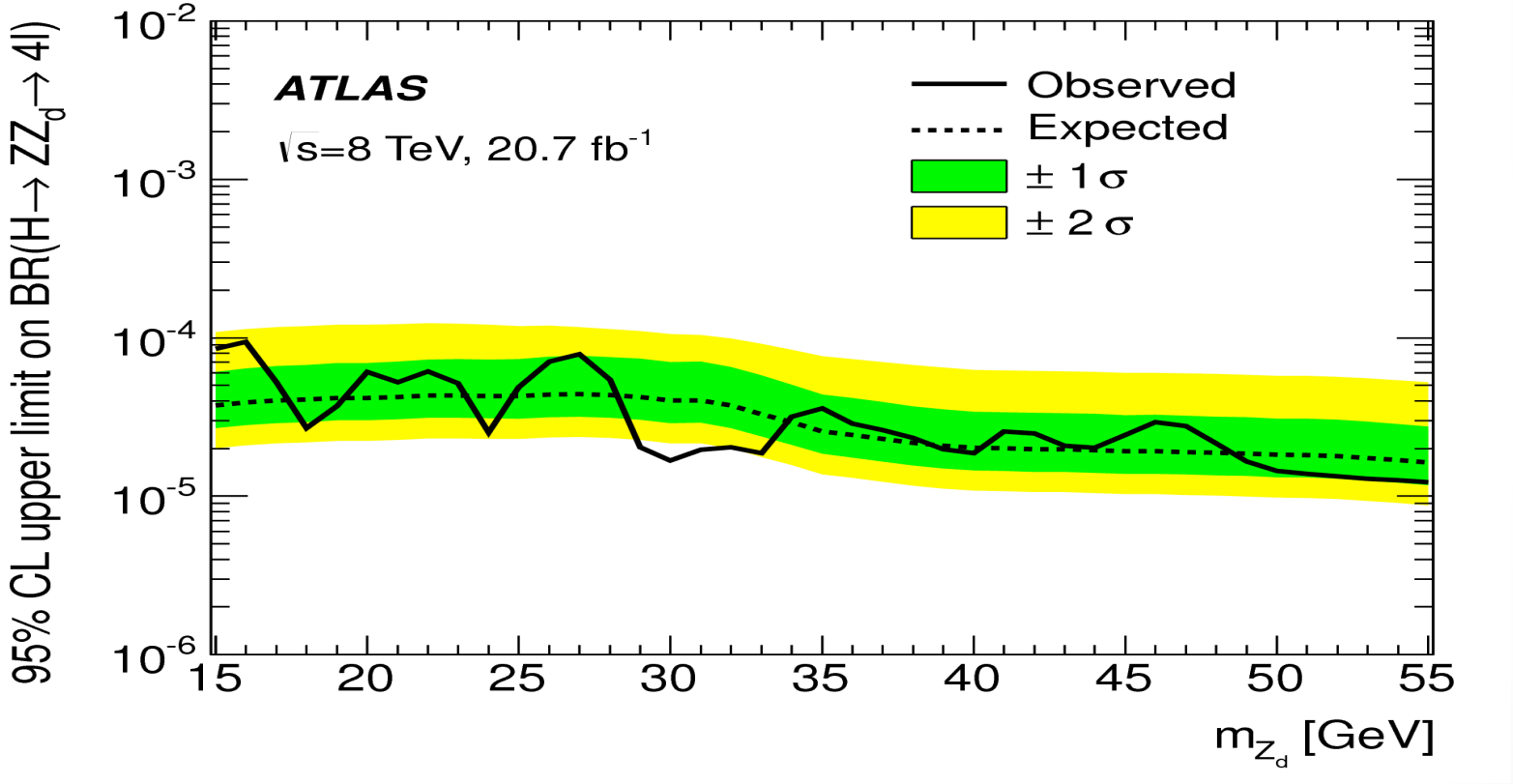


$H \rightarrow ZZ_d \rightarrow 4l$ Model Results



The 95% upper bound on R_B is at level of ~20%

$H \rightarrow ZZ_d \rightarrow 4l$ Model Results



- 95% CL upper bound on BR ($H \rightarrow ZZ_d \rightarrow 4l$) = (1-9) x 10^{-5} assuming the SM BR ($H \rightarrow ZZ^* \rightarrow 4l$)

$H \rightarrow Z_d Z_d \rightarrow 4l$ Measurements

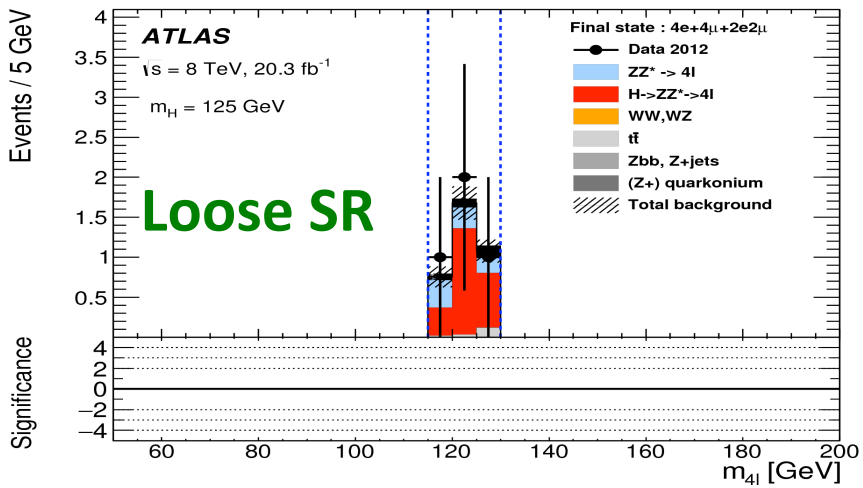
- Here, the search is "orthogonal" to the $H \rightarrow ZZ^*/ZZ_d \rightarrow 4l$ searches by the requirement of the Z-veto
- The question is no longer about the fraction of $H \rightarrow Z_d Z_d \rightarrow 4l$ events in the $H \rightarrow 4l$ sample since the $H \rightarrow 4l$ sample is based on the requirement of m_{12} being consistent with Z
- For the $H \rightarrow Z_d Z_d \rightarrow 4l$, we measure signal strength

$$\mu_d = \frac{\sigma \times \mathrm{BR}(H \rightarrow Z_d Z_d \rightarrow 4\ell)}{[\sigma \times \mathrm{BR}(H \rightarrow ZZ^* \rightarrow 4\ell)]_{\mathrm{SM}}}.$$

- The denominator is a constant, just a normalization factor
- Assuming that the discovered Higgs is the SM Higgs boson, μ_d is a measurement of BR ($H \rightarrow Z_d Z_d \rightarrow 4l$) relative to fixed SM BR($H \rightarrow ZZ^* \rightarrow 4l$)

$H \rightarrow Z_d Z_d \rightarrow 4l$ Measurements

- Situation of zero backgrounds after all the tight signal region (SR) requirements



Systematic Uncertainties (%)			
Source	4μ	4e	$2e2\mu$
Electron Identification	–	6.7	3.2
Electron Energy Scale	–	0.8	0.3
Muon Identification	2.6	–	1.3
Muon Momentum Scale	0.1	–	0.1
Luminosity	2.8	2.8	2.8
ggF QCD	7.8	7.8	7.8
ggF PDFs and α_S	7.5	7.5	7.5
ZZ^* Normalization	5.0	5.0	5.0

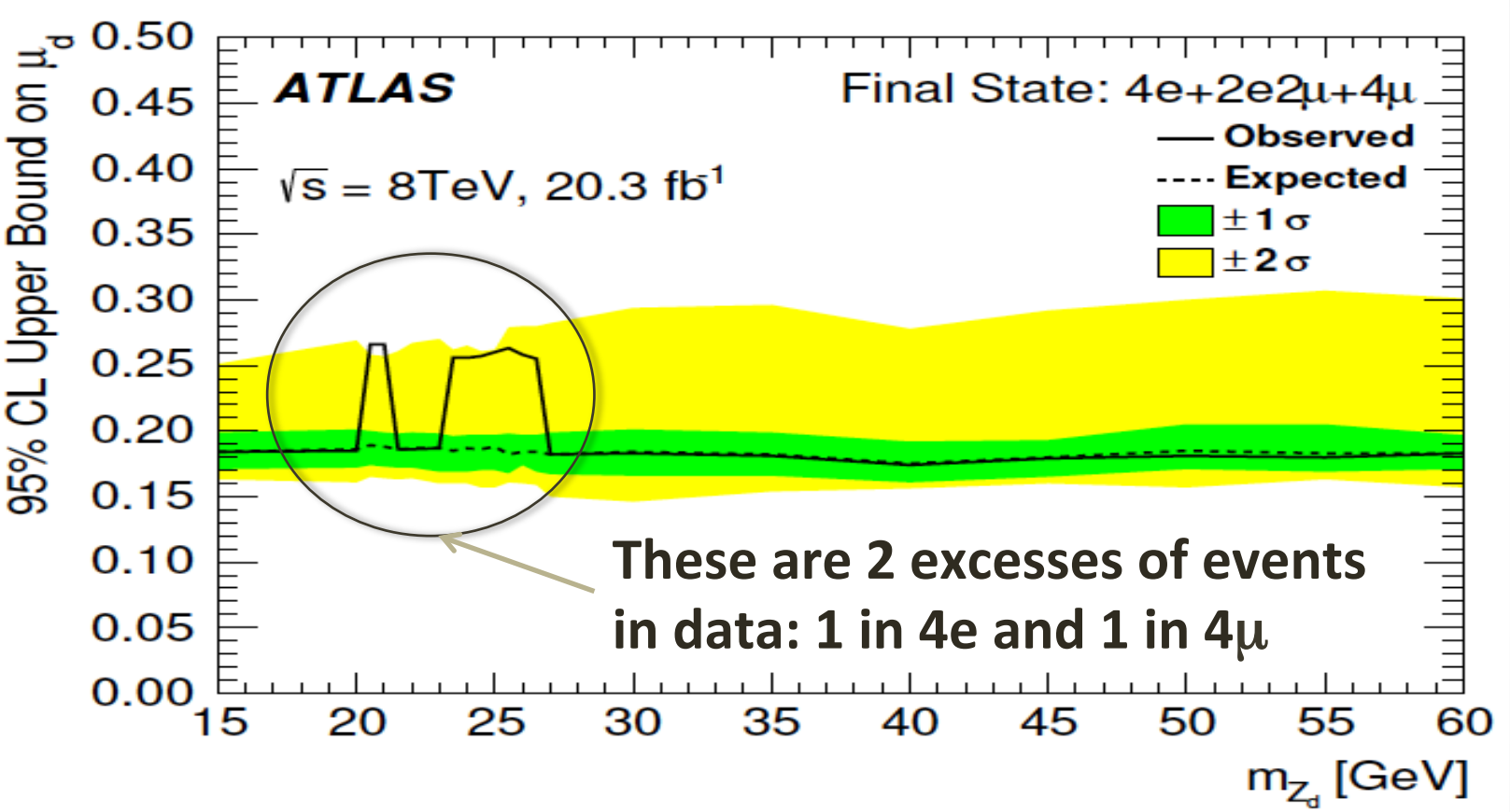
Tight SR

$$N_{\text{background}} < L \times \sigma \times \left(\frac{1.14}{N_{\text{tot}}}\right)$$

Process	$4e$	4μ	$2e2\mu$
$H \rightarrow ZZ^* \rightarrow 4\ell$	$(1.5 \pm 0.3 \pm 0.2) \times 10^{-2}$	$(1.0 \pm 0.3 \pm 0.3) \times 10^{-2}$	$(2.9 \pm 1.0 \pm 2.0) \times 10^{-3}$
$ZZ^* \rightarrow 4\ell$	$(7.1 \pm 3.6 \pm 0.5) \times 10^{-4}$	$(8.4 \pm 3.8 \pm 0.5) \times 10^{-3}$	$(9.1 \pm 3.6 \pm 0.6) \times 10^{-3}$
WW, WZ	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$
$t\bar{t}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$
Zbb, Z+jets	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$
ZJ/ψ and $Z\Upsilon$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$
Total background	$< 5.6 \times 10^{-2}$	$< 5.9 \times 10^{-2}$	$< 5.3 \times 10^{-2}$
Data	1	0	0
$H \rightarrow ZZ^* \rightarrow 4\ell$	$(1.2 \pm 0.3 \pm 0.2) \times 10^{-2}$	$(5.8 \pm 2.0 \pm 2.0) \times 10^{-3}$	$(2.6 \pm 1.0 \pm 0.2) \times 10^{-3}$
$ZZ^* \rightarrow 4\ell$	$(3.5 \pm 2.0 \pm 0.2) \times 10^{-3}$	$(4.1 \pm 2.7 \pm 0.2) \times 10^{-3}$	$(2.0 \pm 0.6 \pm 0.1) \times 10^{-2}$
WW, WZ	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$	$< 0.7 \times 10^{-2}$
$t\bar{t}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$	$< 3.0 \times 10^{-2}$
Zbb, Z+jets	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$	$< 0.2 \times 10^{-2}$
ZJ/ψ and $Z\Upsilon$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$	$< 2.3 \times 10^{-3}$
Total background	$< 5.3 \times 10^{-2}$	$< 5.1 \times 10^{-2}$	$< 6.4 \times 10^{-2}$
Data	0	1	0

Acceptance×Reconstruction Efficiency, $\mathcal{A}\varepsilon(\%)$, for $H \rightarrow Z_d Z_d \rightarrow 4\ell$			
m_{Z_d} [GeV]	$\mathcal{A}\varepsilon$: $4e$	$\mathcal{A}\varepsilon$: 4μ	$\mathcal{A}\varepsilon$: $2e2\mu$
15	18.7 ± 0.3	35.0 ± 0.5	36.5 ± 0.5
20	18.5 ± 0.3	35.9 ± 0.5	35.8 ± 0.5
25	19.3 ± 0.3	38.4 ± 0.6	34.7 ± 0.5
30	20.1 ± 0.3	38.0 ± 0.6	35.9 ± 0.5
35	20.0 ± 0.3	39.5 ± 0.6	37.0 ± 0.6
40	21.6 ± 0.3	43.8 ± 0.7	37.6 ± 0.6
45	21.7 ± 0.3	43.6 ± 0.7	38.2 ± 0.6
50	22.3 ± 0.3	44.3 ± 0.7	39.7 ± 0.6
55	22.1 ± 0.3	44.1 ± 0.7	42.0 ± 0.6
60	22.3 ± 0.3	43.6 ± 0.7	40.7 ± 0.6

$H \rightarrow Z_d Z_d \rightarrow 4l$ Measurements



- SM: BR ($H \rightarrow ZZ^* \rightarrow 4l$) = 1.25×10^{-4}
- **Our Measurement: BR ($H \rightarrow Z_d Z_d \rightarrow 4l$) < 2.5×10^{-5} @ 95% CL**

2) Search for Higgs boson decay to invisible particles

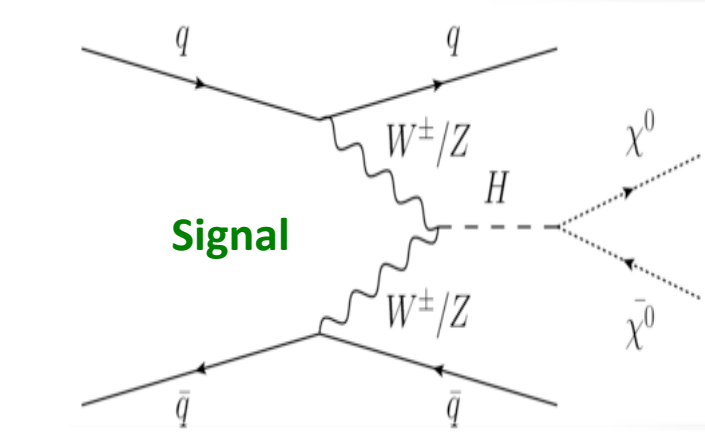
ATLAS H → invisible Run 1 Results

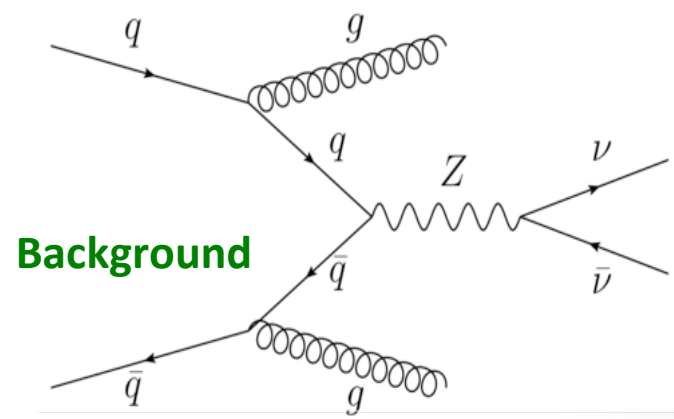
- **ZH, Z → ll (l=e, μ) and H → invisible**
  - Phys. Rev. Lett. 112, 201802 (2014)
  - Upper bound on BR (H → invisible): Obs (Exp) 0.75 (0.62)
- **VH, V → jj and H → invisible**
  - Eur. Phys. J. C75.7 (2015) 337, arXiv: 1504.04324 [hep-ex]
  - Upper bound on BR (H → invisible): Obs (Exp) 0.78 (0.86)
- **Monojet search with H → invisible interpretation**
  - Eur. Phys. J. C75 (2015) no. 7, 299, arXiv:1502.01518
  - Limit on σ x BR (H → invisible)
  - Not sensitive as BR (H → invisible) measurement
- **VBF H → invisible**
  - Submitted to JHEP, arXiv:1508.07869
  - Upper bound on BR (H → invisible): Obs (Exp) 0.29 (0.35)
  - Combination of two categories of searches
    - VBF combined results. Obs (Exp) 0.28 (0.31)
- **Grand combination of ATLAS H → invisible measurements**
  - JHEP 11 (2015) 206, arXiv:1509.00672
  - Combination of Z(→ll), V(→jj), and VBF
  - Obs (Exp) 0.25 (0.27)

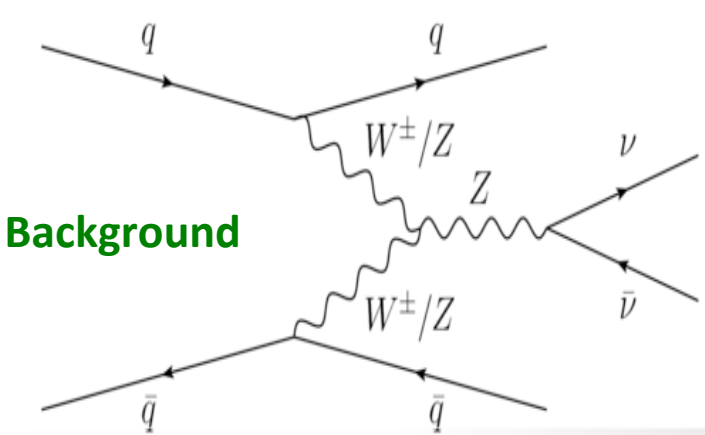
I will focus only on these 2 in this talk

VBF H → invisible in ATLAS

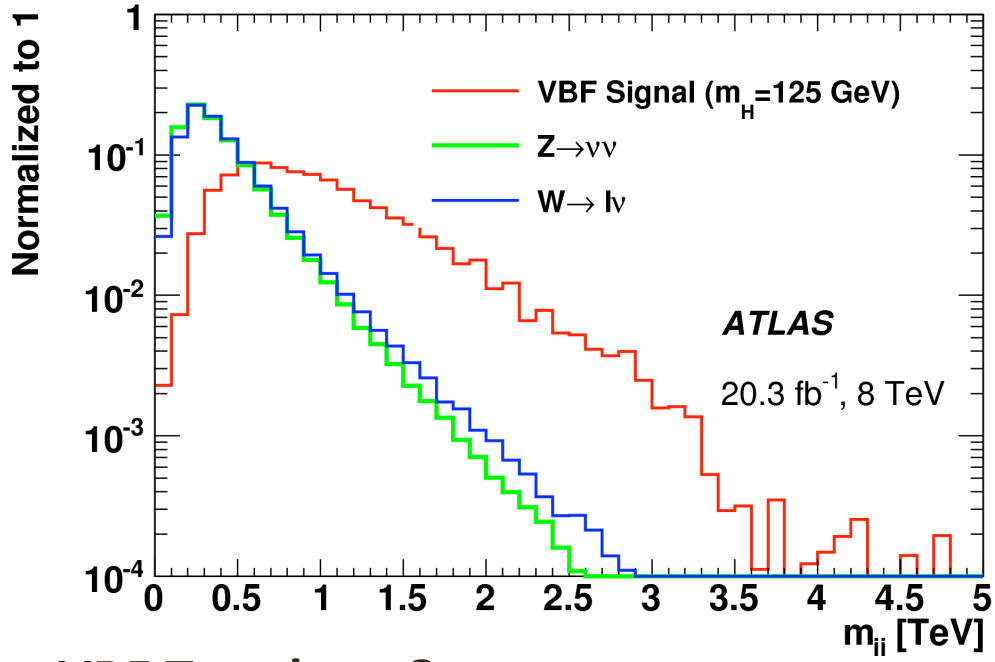
- **Two forward jets with large rapidity gap**
  - Minimal or no central jet activities
- **Higgs decaying to undetected particles (invisible)**
  - Thus expecting large missing energy (MET) associated to 2 jets with large rapidity gap
  - e.g. H → WIMPs
  - H → $\chi^0\chi^0$ where $m_{\chi 0} < m_H/2$
- **MET trigger used**
- **Signals**
  - VBF Higgs production
  - Also ggF+2jets (~20%).
  - Simulate H → invisible with H → ZZ → 4ν
- **Backgrounds**
  - Z+jets with Z → νν
  - W+jets with W → lν (undetected lepton)
  - Multijets
  - ttbar, single top and dibosons

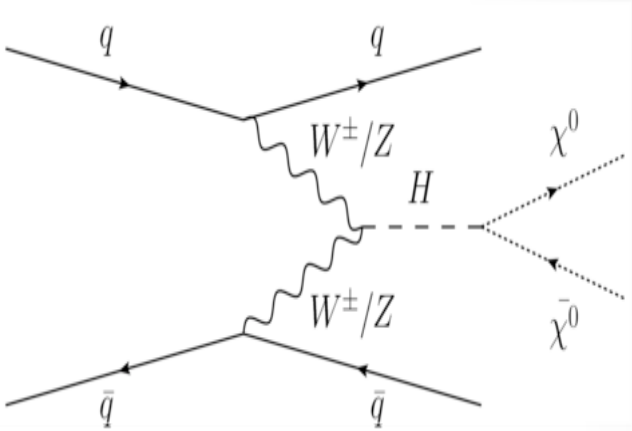






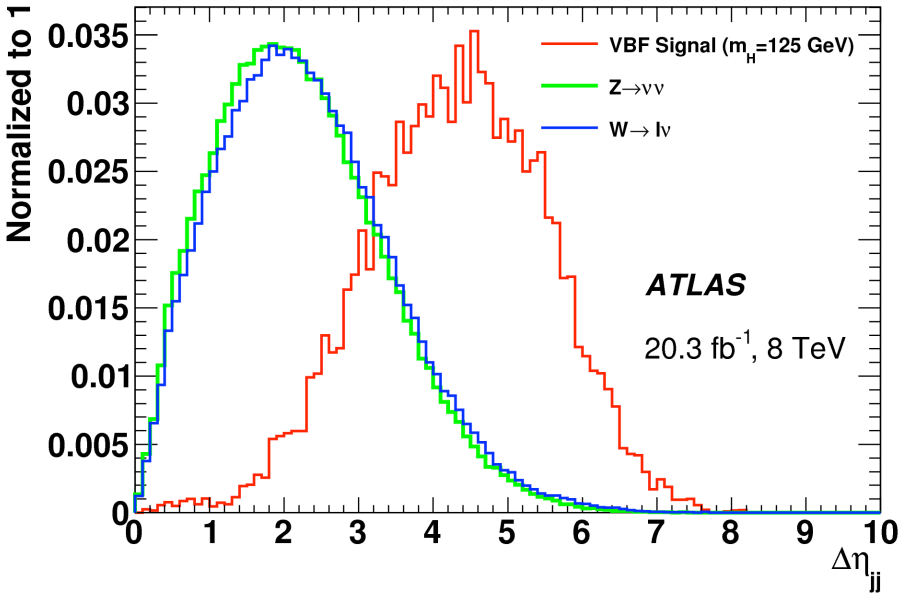
VBF H → invisible in ATLAS





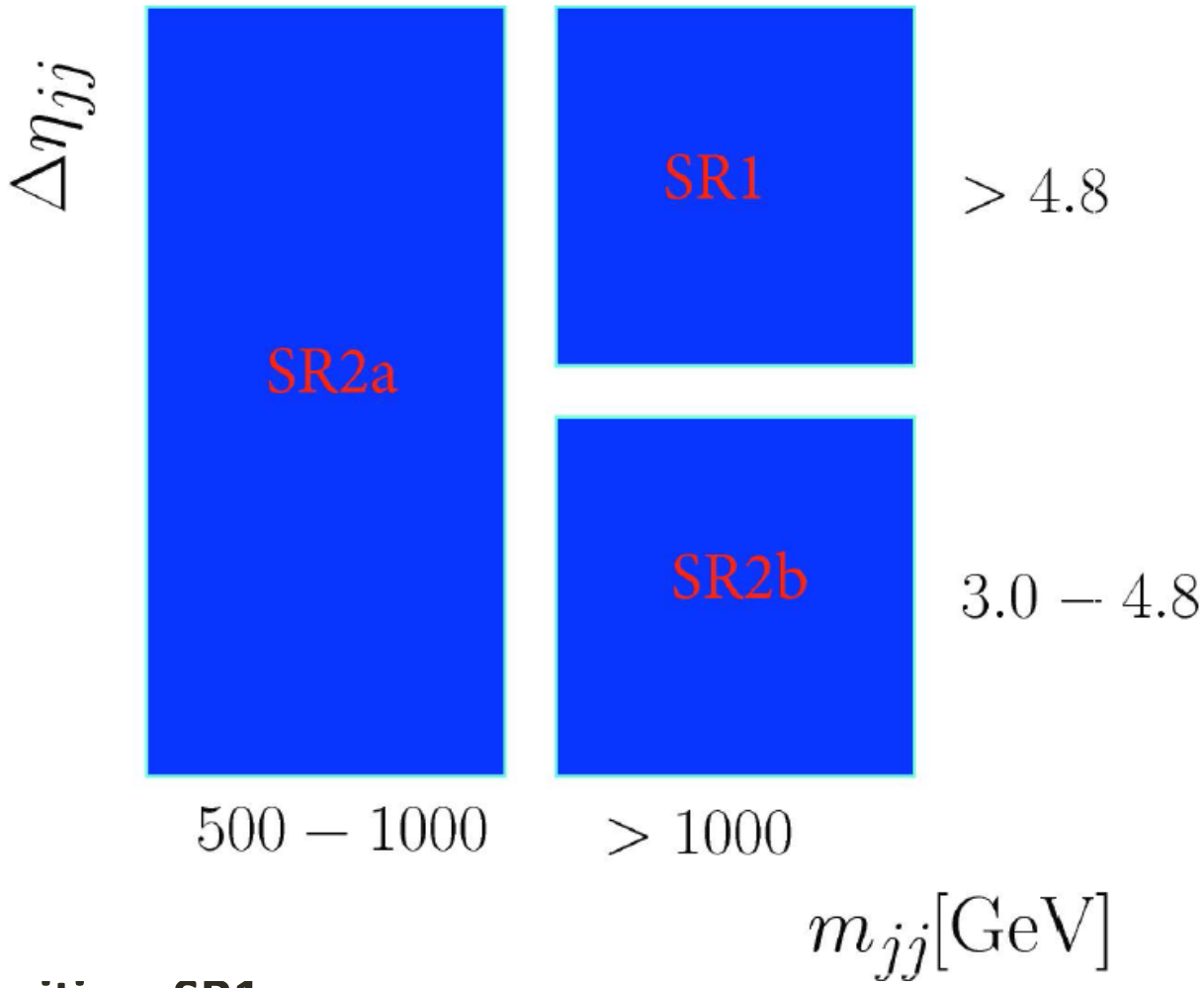
VBF Signal

- **VBF Topology & Characteristics**
  - 2 forward jet at high rapidity, large $\Delta\eta_{jj}$
  - High di-jet invariant mass
  - In the central region of the detector: low gluon radiation due to colorless W/Z exchange
    - Veto on central jets



VBF H → invisible in ATLAS

- Three categories of searches based on
  - The di-jet invariant mass m_{jj}
  - And the rapidity gap between the jets, $\Delta\eta_{jj}$



Most Sensitive: SR1

SR2 was meant as a complement to SR1 to improve sensitivity

VBF H → invisible in ATLAS

Table 1: Summary of the main kinematic requirements in the three signal regions.

Requirement	SR1	SR2a	SR2b
Leading Jet p_T	>75 GeV	>120 GeV	>120 GeV
Leading Jet Charge Fraction	N/A	>10%	>10%
Second Jet p_T	>50 GeV	>35 GeV	>35 GeV
m_{jj}	>1 TeV	$0.5 < m_{jj} < 1$ TeV	> 1 TeV
$\eta_{j1} \times \eta_{j2}$		<0	
$\lvert\Delta\eta_{jj}\rvert$	>4.8	>3	$3 < \lvert\Delta\eta_{jj}\rvert < 4.8$
$\lvert\Delta\phi_{jj}\rvert$	<2.5	N/A	
Third Jet Veto p_T Threshold	30 GeV		
$\lvert\Delta\phi_{j,E_T^{miss}}\rvert$	>1.6 for j_1, >1 otherwise	>0.5	
E_T^{miss}	>150 GeV	>200 GeV	

SR2 requirements motivated by the dark matter search in mono-jet+Missing Energy events:

Eur. Phys. J. C75 (2015) no. 7, 299, arXiv:1502.01518

VBF H → invisible in ATLAS

- **Z+jets with Z→νν background estimated from**
  - Z+jets with Z→ll data control regions (CR)
  - And W+jets with W → lν data control regions
- **W+jets with W→lν background estimated from**
  - W+jets with W→lν data control region
- **Multijet background estimated from**
  - Multijet enriched data control samples by reserving the requirements of $\Delta\phi_{jj}$ and $\Delta\phi_{j,MET}$
- **ttbar, single top and di-bosons estimated from**
  - Monte Carlo
- **Residual background contamination in the Z→ll CR**
  - subtracted using MC predictions
- **Multijet background in the W→lν CR subtracted by a fit to the transverse mass distribution**

$$m_T = \sqrt{2p_T^{\ell}E_T^{miss}\left[1-\cos(\Delta\phi_{\ell,E_T^{miss}})\right]}$$

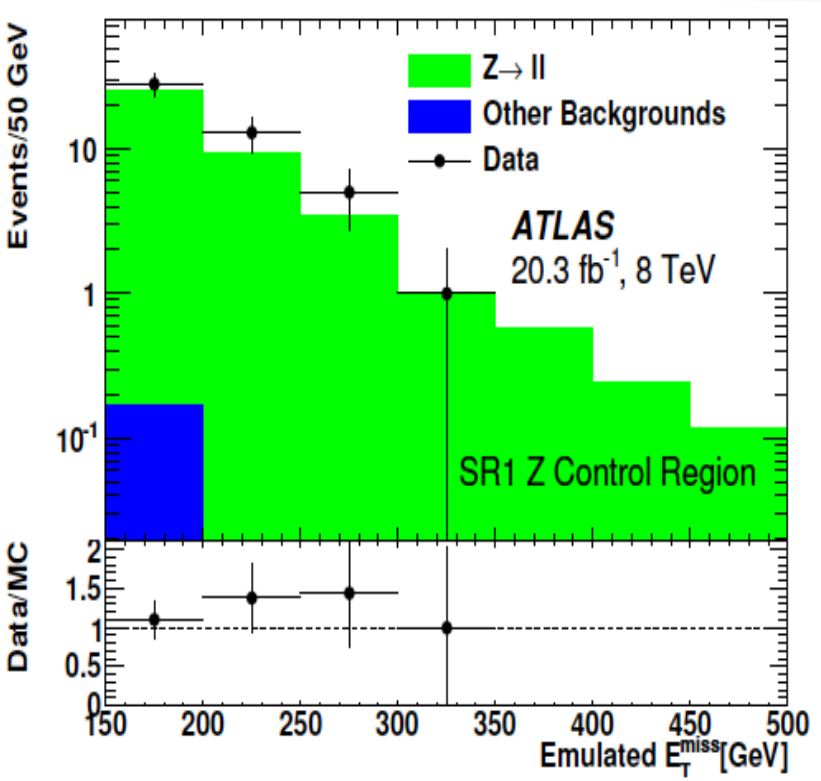
- **Unique estimates of Z→νν and W→lν background obtained from**
  - A simultaneous fit to the SR and the CRs

$$Z_{SR} \sim (Z_{SR}/Z_{CR})^{MC} \times Z_{CR}^{data},$$
$$Z_{SR} \sim (Z_{SR}/W_{CR})^{MC} \times W_{CR}^{data},$$
$$W_{SR} \sim (W_{SR}/W_{CR})^{MC} \times W_{CR}^{data}.$$

VBF H → invisible Z→ ll CR

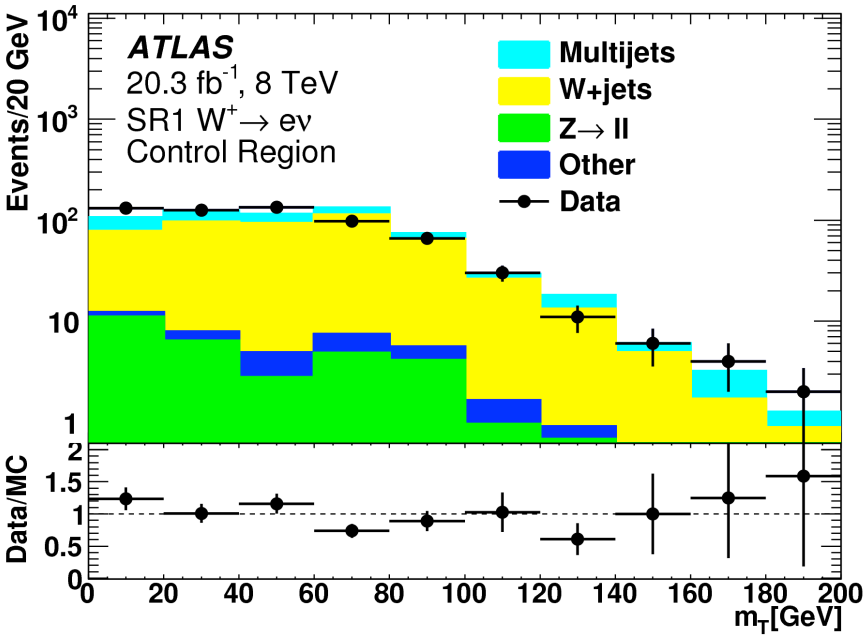
- Require 2 leptons whose invariant mass is consistent with the Z-boson mass
- Emulate MET by vectorially adding the p_T of the leptons
- All other SR requirements applied

Background	SR1 Z Control Regions $Z(\rightarrow ee)$+jets	$Z(\rightarrow \mu\mu)$+jets
QCD $Z \rightarrow \ell\ell$	10.4 ± 1.5	14.0 ± 1.5
EW $Z \rightarrow \ell\ell$	7.4 ± 0.8	8.2 ± 0.8
Other Backgrounds	0.3 ± 0.2	0.2 ± 0.1
Total	18.1 ± 1.7	22.4 ± 1.7
Data	22	25



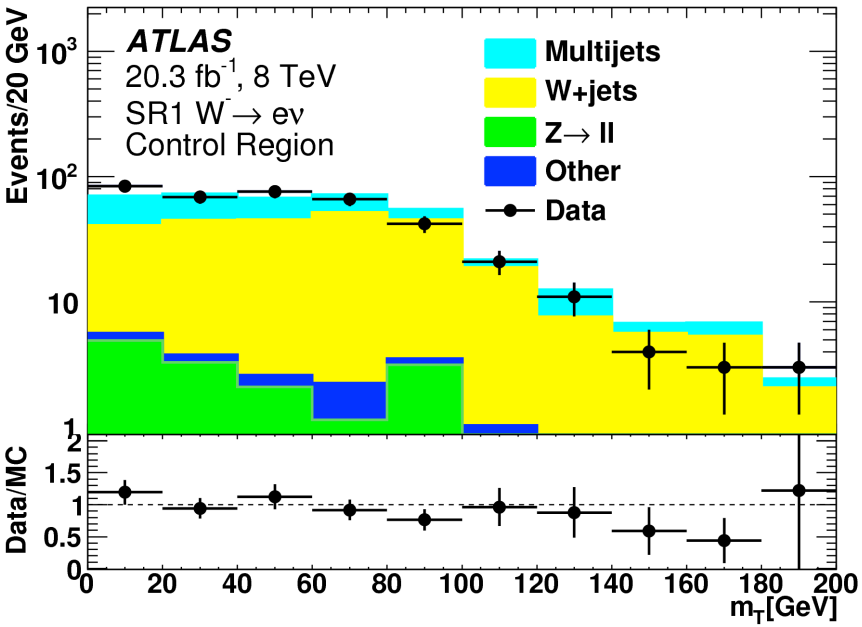
Uncertainties are statistical only
Z→ll CR lack sufficient statistics so we combine with W→lν CR

VBF H → invisible W→ eν CR

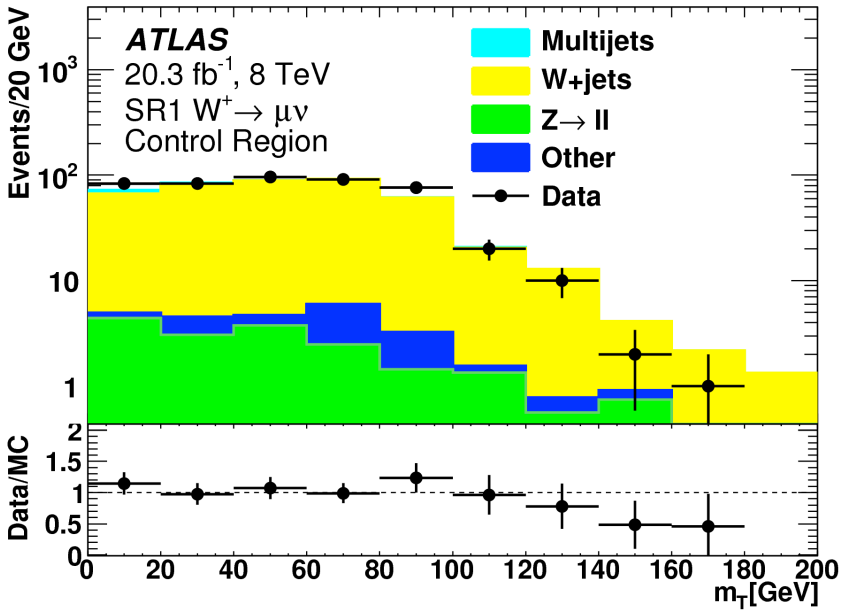


- Built from 1 isolated electron
- Similar MET emulation as for the Z→ll CR
- Exploit the W$^+$/W$^-$ charge asymmetry at the LHC

Data/MC agreement in the W → eν control region

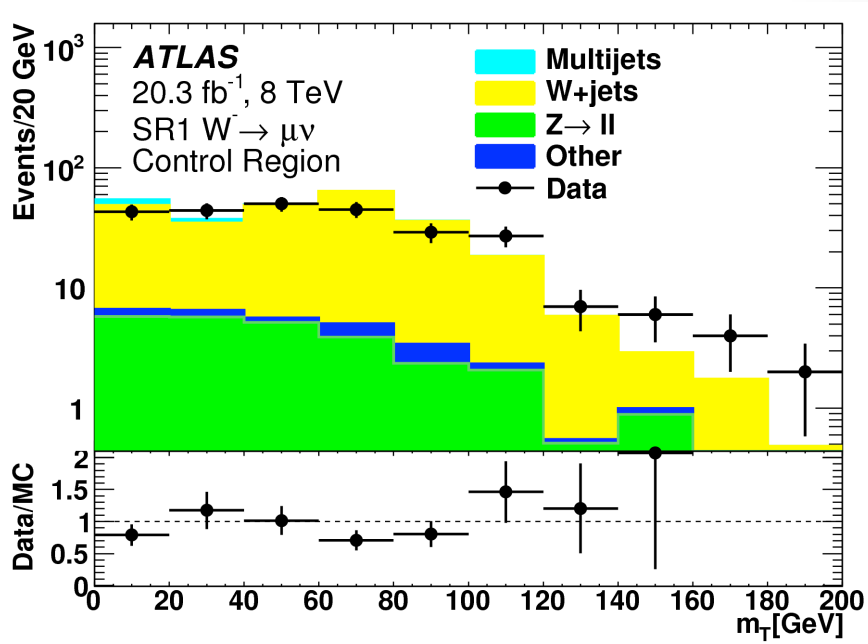


VBF H → invisible W→ μν CR



- Built from 1 isolated muon
- Similar MET emulation as for the Z→ll CR
- Exploit the W^+/W^- charge asymmetry at the LHC

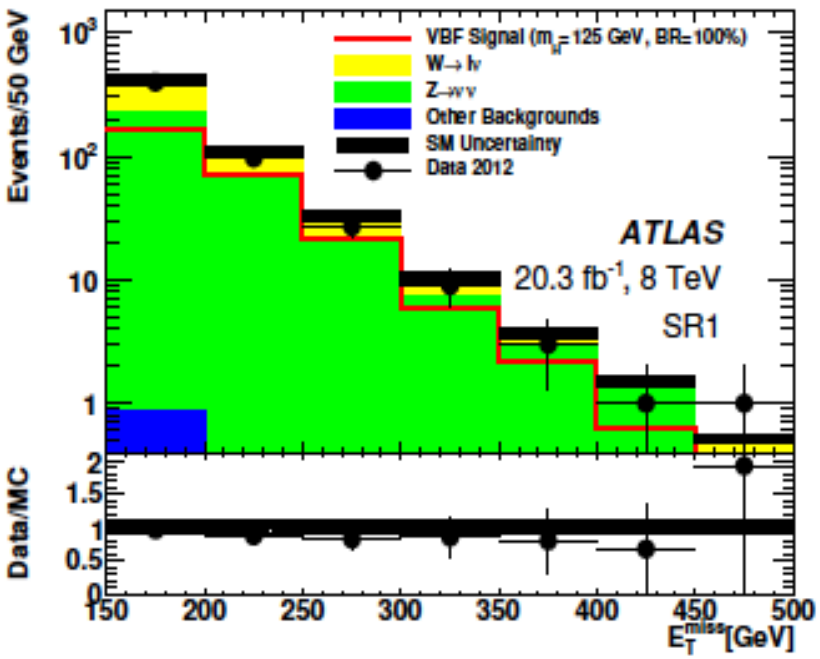
Data/MC agreement in the W → μν control region



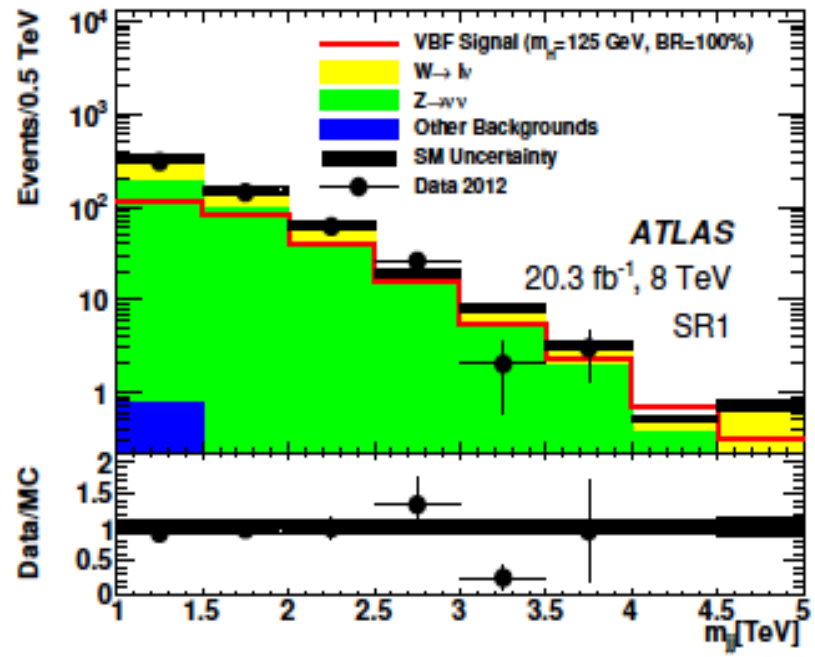
VBF H → invisible Systematic Uncertainties

Uncertainty	VBF	ggF	Z or W	Z_{SR}/W_{CR} or W_{SR}/W_{CR}
Jet energy scale	16 9	43 12	17–33 0–11	3–5 1–4
Jet energy resolution	Negligible 3.1	Negligible 3.2	Negligible 0.2–7.6	Negligible 0.5–5.8
Luminosity	2.8	2.8	2.8	Irrelevant
QCD scale	0.2	7.8	5–36 7.5–21	7.8–12 1–2
PDF	2.3 2.8	7.5	3–5 0.1-2.6	1–2
Parton shower	4.4	41 29	9–10	5
Veto on third jet			Negligible	Negligible
Higgs boson p_T	Negligible	9.7	Irrelevant	Irrelevant
MC statistics	2 0.6	46 13	2.3–6.4 0.8–4.5	3.3–6.6

VBF H → invisible Results



(a) E_T^{miss} distribution



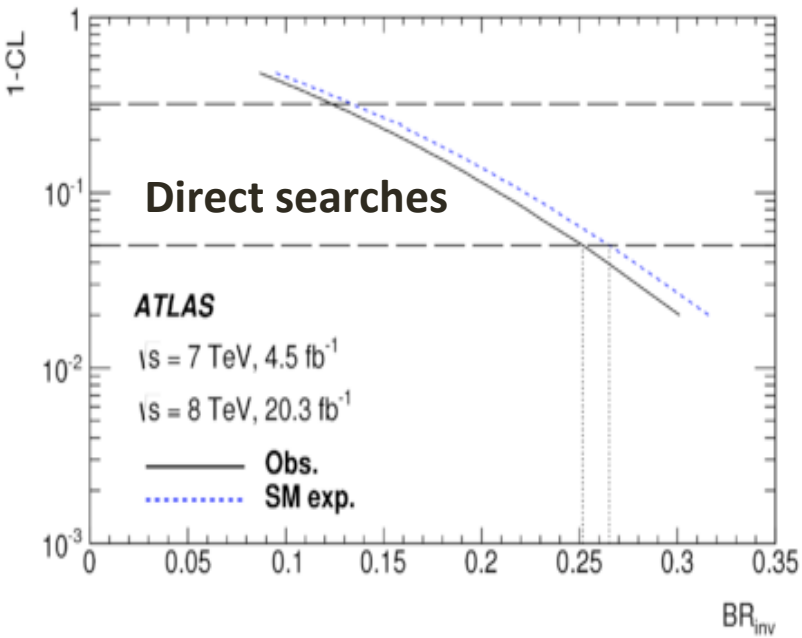
(b) m_{jj} distribution

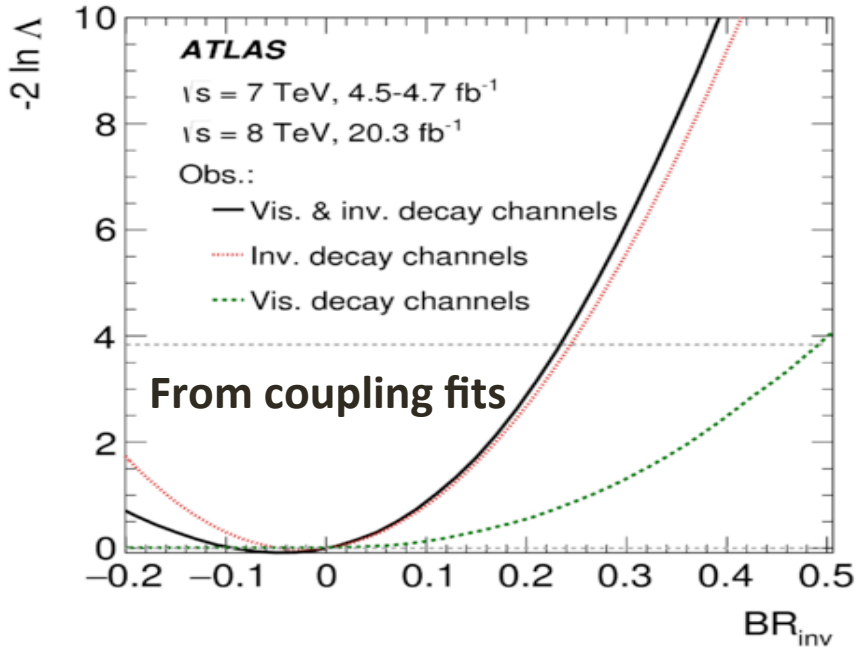
No excess

Post-fit distributions and estimates

Signal region Process	SR1	SR2a	SR2b
ggF signal	20± 15	58± 22	19± 8
VBF signal	286± 57	182± 19	105±15
$Z(\rightarrow \nu\nu)$+jets	339± 37	1580± 90	335±23
$W(\rightarrow \ell\nu)$+jets	235± 42	1010± 50	225±16
Multijet	2± 2	20± 20	4± 4
Other backgrounds	1±0.4	64± 9	19± 6
Total background	577± 62	2680±130	583±34
Data	539	2654	636

Combined H → invisible Results





Results	Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
VBF h	0.28	0.16	0.21	0.31	0.41	0.56
$Z(\to \ell\ell)h$	0.75	0.33	0.45	0.62	0.86	1.19
$V(\to jj)h$	0.78	0.46	0.62	0.86	1.19	1.60
Combined Results	0.25	0.13	0.18	0.27	0.35	0.47

ATLAS VBF H → invisible: best direct search result at the LHC

3) Interpretations of search results

Hidden Sector

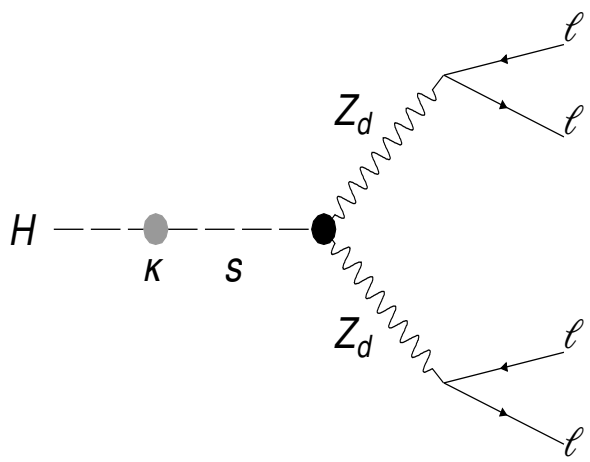
- Spontaneously broken "dark" gauge symmetry, U(1)d, mediated by a dark gauge boson Z_d
- Z_d interacts with the SM thru kinetic mixing with hypercharge gauge boson
  - Kinetic mixing parameter ε
- Also, a dark Higgs mechanism could spontaneously break the U(1)d gauge symmetry
  - Mixing between the SM-Higgs and dark Higgs boson, mixing parameter κ
- The U(1)d kinetic mixing scenario could be generalized to include to a mixing between the SM-Z and the Z_d,
  - Mixing parameter δ

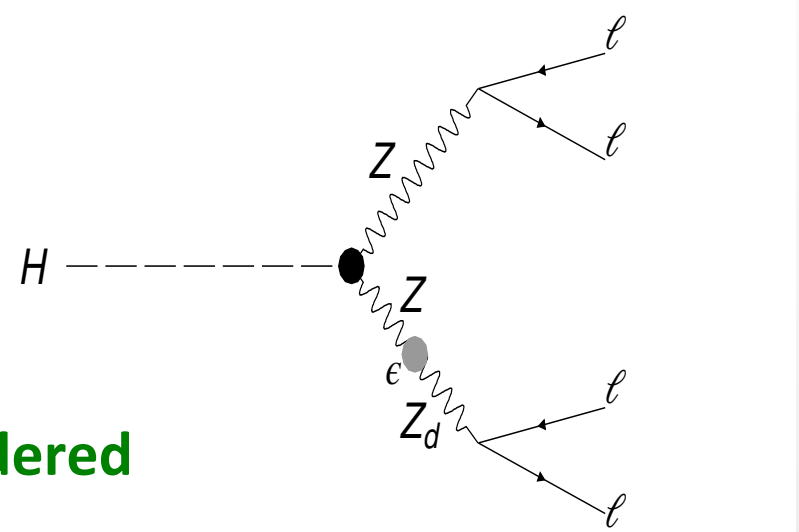
$$\mathcal{L} \subset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}m_{D,0}^2\hat{Z}_D^{\mu}\hat{Z}_{D\mu}\,.$$

$$V_0(H,S) = -\mu^2|H|^2 + \lambda|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|H|^2\,.$$

Search for Hidden Sector at LHC

- pp → Z_d → ll
  - To measure ε
- H → ZZ_d → 4l
  - To measure ε and δ
- H → Z_dZ_d → 4l
  - To measure κ



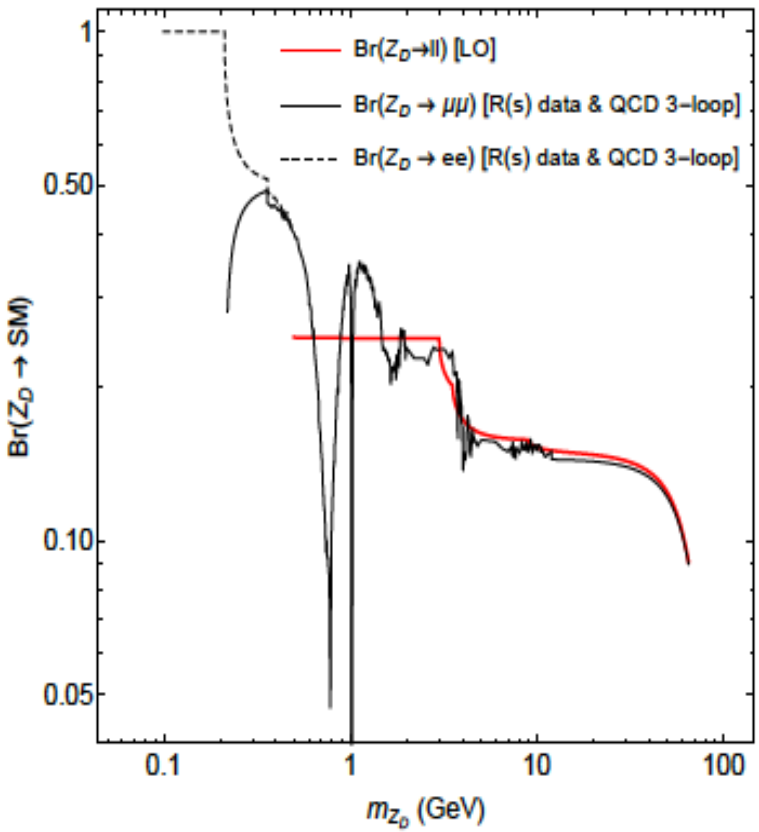


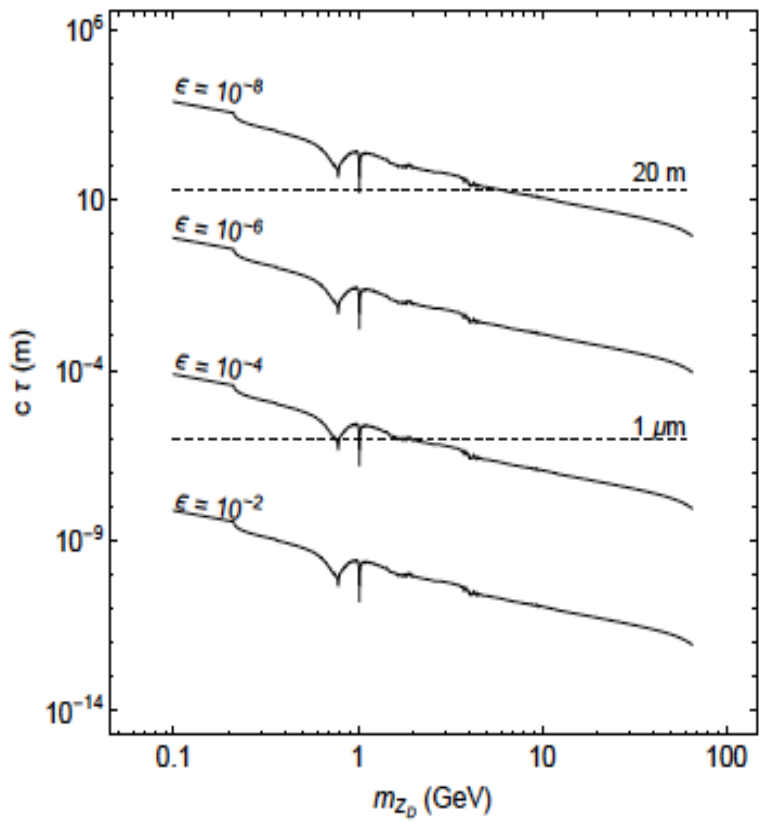
In this talk, only prompt Z_d considered

BR($Z_d \rightarrow ll$) and Z_d decay length

- Z_d could be long-lived depending of kinetic mixing parameter ε

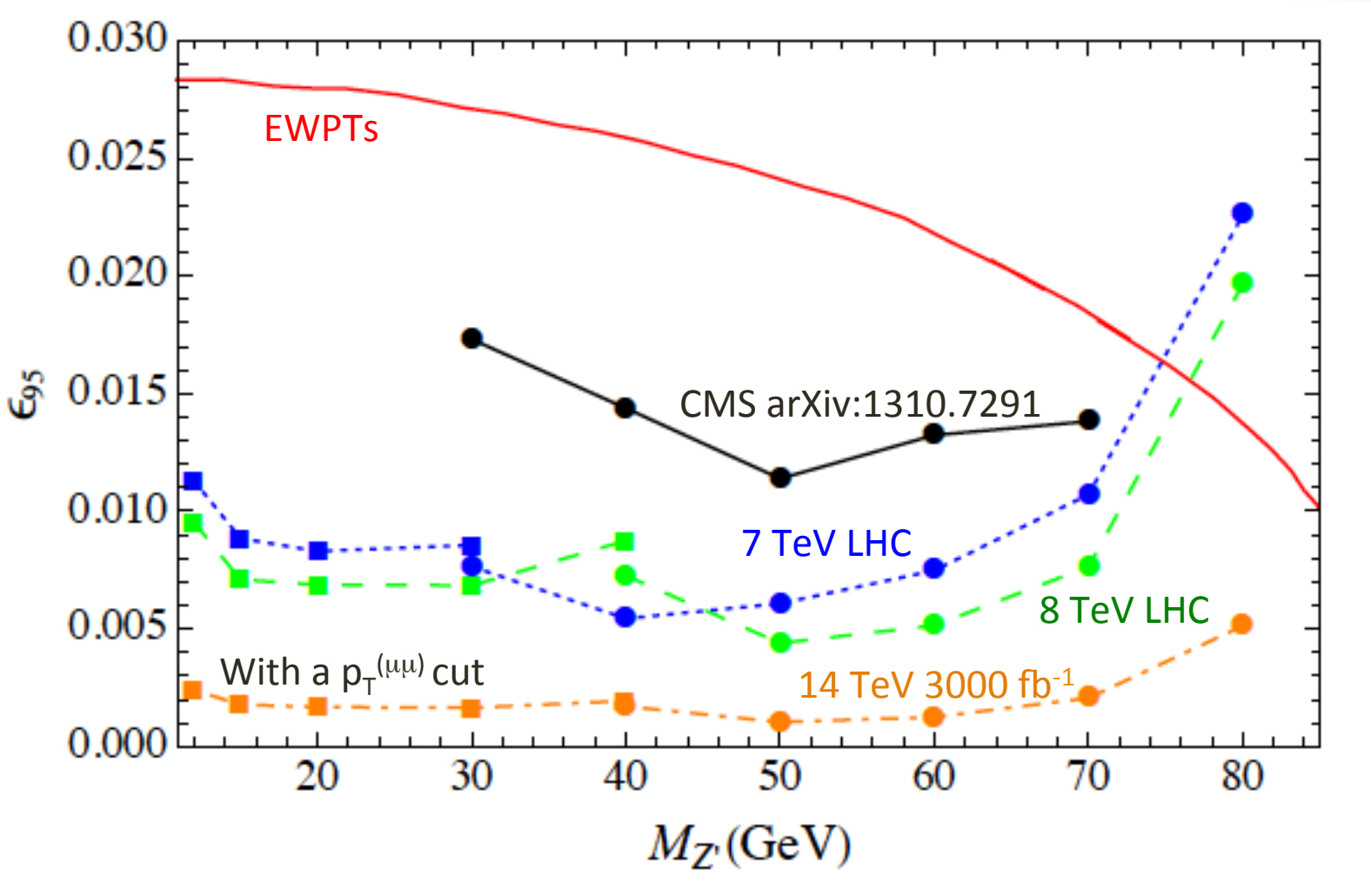
Curtin et al, arXiv: 1412.0018, arXiv: 1312.4992





BR ($Z_d \rightarrow ll$) is independent of ε under the assumption that $Z_d \not\rightarrow$ dark Sector States

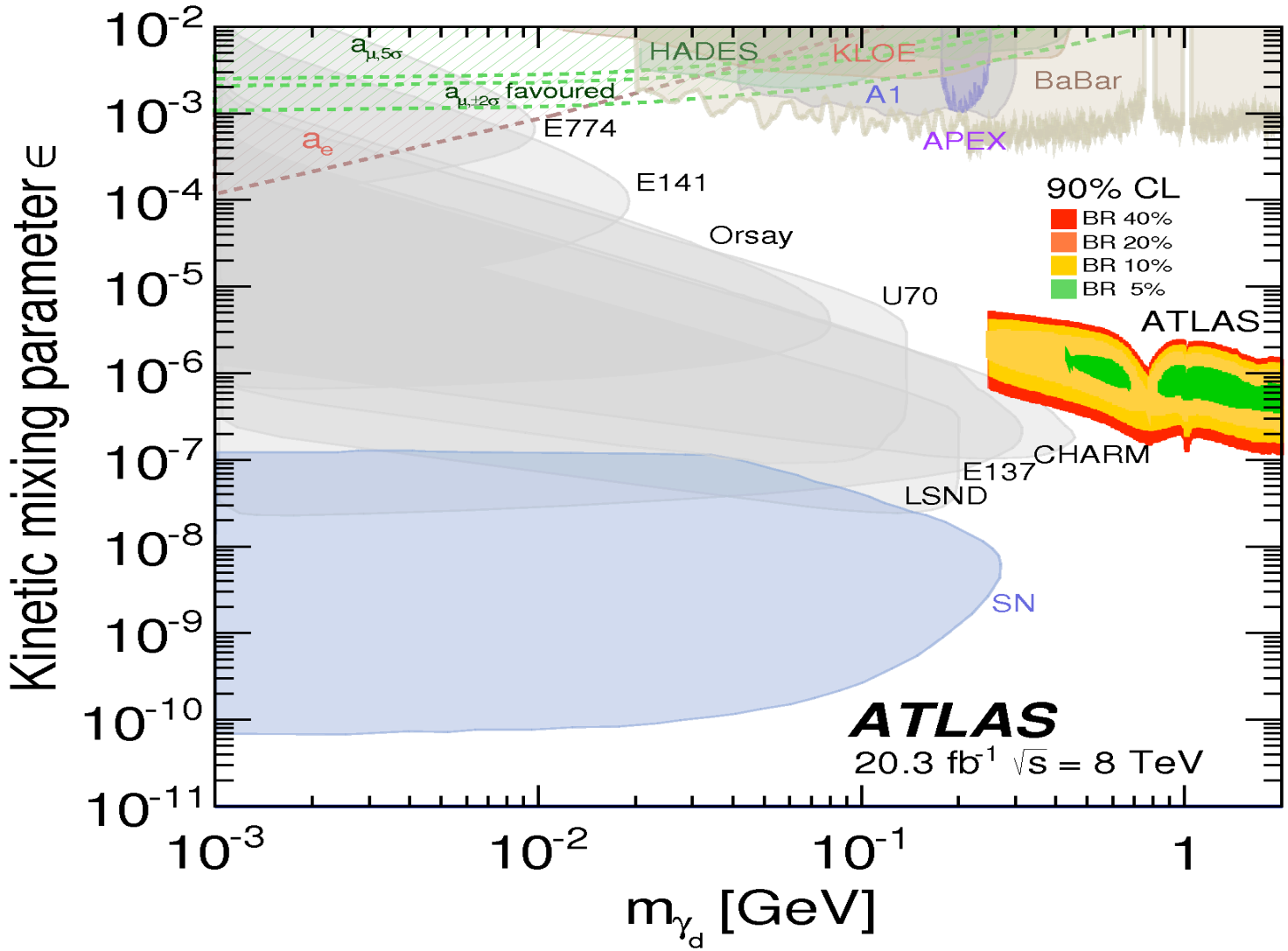
Bounds on kinetic mixing parameter ε



1408.1075v2

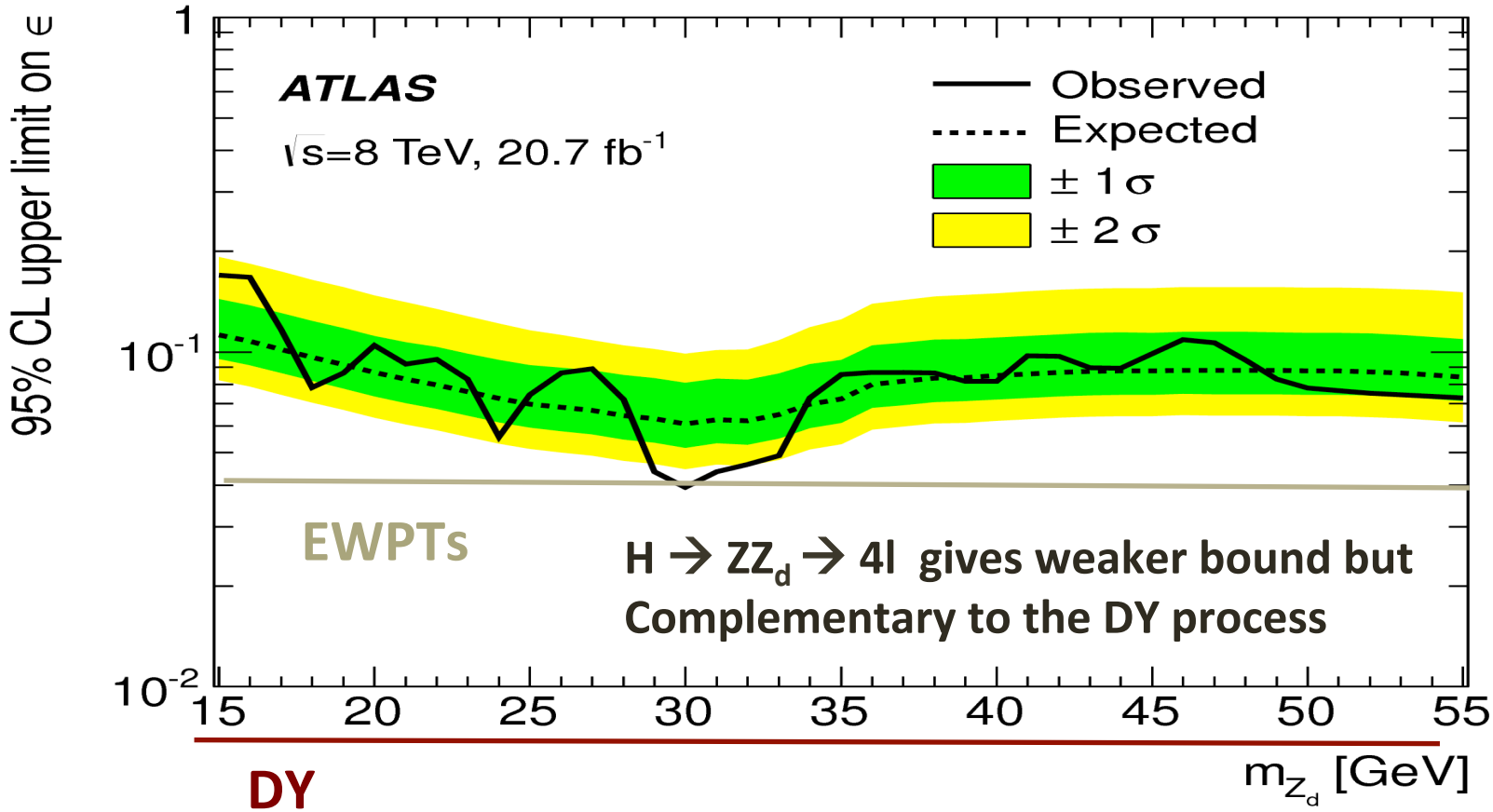
Bounds on kinetic mixing parameter ε

- ATLAS, *JHEP11(2014)088*



ε from BR (H → ZZ_d → 4l) measurement

- Use the calculations of Curtin et al, arXiv: 1412.0018 to extract ε from the BR (H → ZZd → 4l). ε >> κ



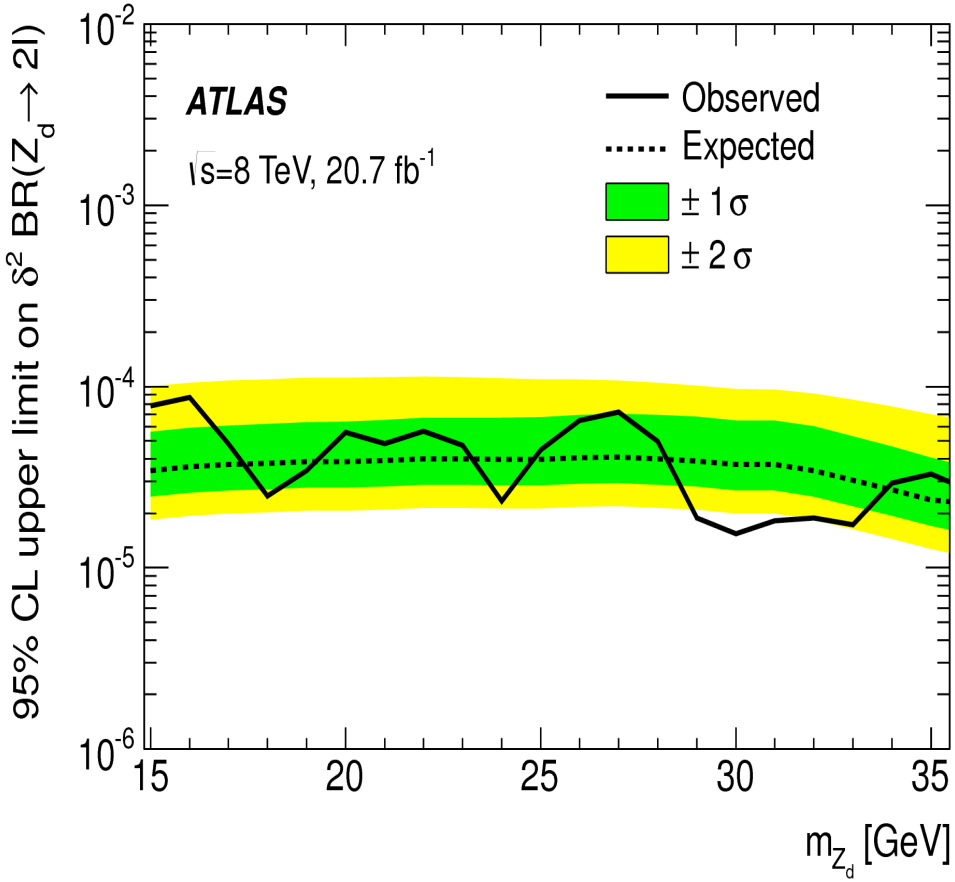
δ from BR (H → ZZ_d → 4l) measurement

- One can show that in the limit of $m_{Zd}^2 << (m_H^2 - m_Z^2)$:

Davoudiasl et al, arXiv: 1304.4935, arXiv: 1203.2947

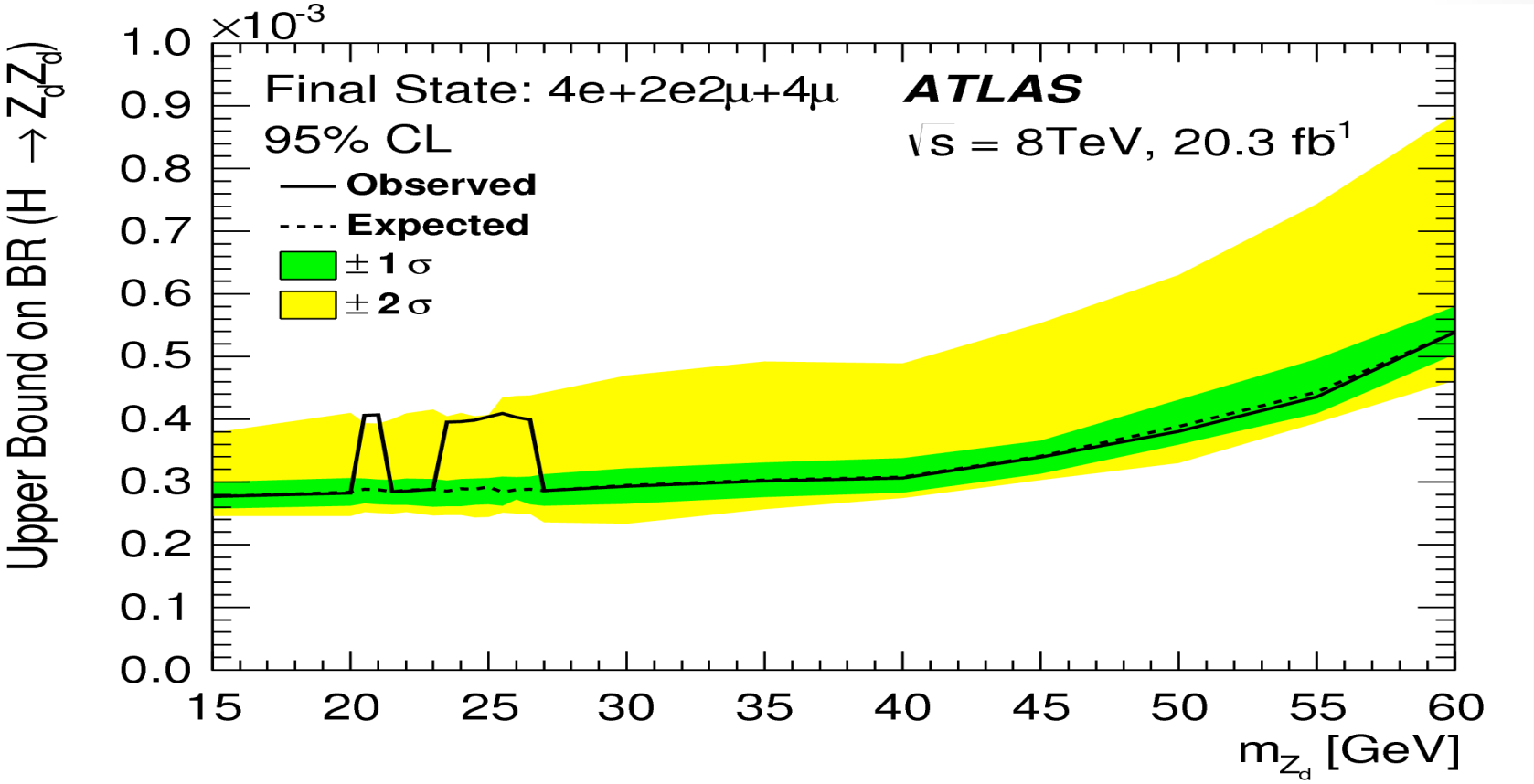
$$\frac{R_B}{(1-R_B)} \simeq \delta^2 \times \mathrm{BR}(Z_d \to 2\ell) \times \frac{\mathrm{BR}(Z^* \to 2\ell)}{\mathrm{BR}(H \to ZZ^* \to 4\ell)} \times \frac{f(m_{Z_d})}{\Gamma_{SM}},$$

$$f(m_{Z_d}) = \frac{1}{16\pi} \frac{(m_H^2 - m_Z^2)^3}{v^2 m_H^3}.$$



BR(H → $Z_d Z_d$)

- Our upper bound on the signal md of H → $Z_d Z_d$ → 4l can be transformed into up bound on BR (H → $Z_d Z_d$). But you need a model for BR (Z_d → ll)
- Use the calculations of BR (Z_d → ll) from of Curtin et al, arXiv: 1412.0018

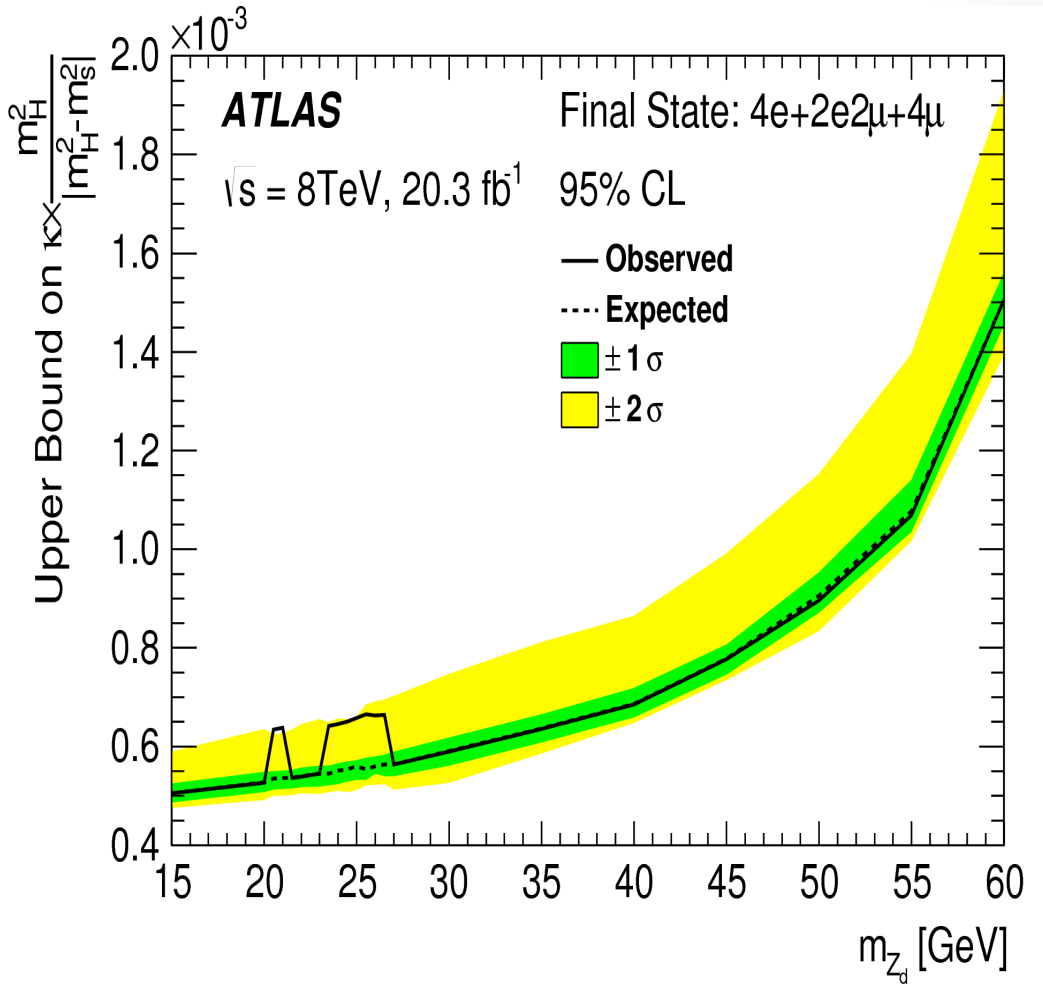


κ from H → $Z_d Z_d$ → 4l

- From Curtin et al, arXiv: 1412.0018, one can show that k relates to our measurement as follows:

$$\kappa^2 = \frac{\Gamma_{SM}}{f(m_{Z_d})} \frac{BR(H \to Z_d Z_d)}{1 - BR(H \to Z_d Z_d)},$$

$$f(m_{Z_d}) = \frac{v^2}{32\pi m_H} \times \sqrt{1 - \frac{4m_{Z_d}^2}{m_H^2}} \times \frac{\left(m_H^2 + 2m_{Z_d}^2\right)^2 - 8\left(m_H^2 - m_{Z_d}^2\right)m_{Z_d}^2}{\left(m_H^2 - m_S^2\right)^2}.$$



K >> ε

$m_S > m_H/2$

Higgs Portal Dark Matter

- The upper bound on the BR (H → invisible) can be used to constrain WIMP-Nucleon scattering cross section and compare to Direct Dark Mark Matter Detection Experiments

$$\Gamma_H^{\rm inv} = \frac{\mathrm{BF}(H \to \text{ invisible})}{1 - \mathrm{BF}(H \to \text{ invisible})} \times \Gamma_H,$$

$$\Gamma_{H\to SS}^{\rm inv} = \frac{\lambda_{HSS}^2 v^2 \beta_S}{64\pi m_H},$$

$$\Gamma_{H\to VV}^{\rm inv} = \frac{\lambda_{HVV}^2 v^2 m_H^3 \beta_V}{256\pi m_V^4}\left(1 - 4\frac{m_V^2}{m_H^2} + 12\frac{m_V^4}{m_H^4}\right),$$

$$\Gamma_{H\to ff}^{\rm inv} = \frac{\lambda_{Hff}^2 v^2 m_H \beta_f^3}{32\pi\Lambda^2},$$

$$\sigma_{SN}^{\rm SI} = \frac{\lambda_{HSS}^2}{16\pi m_H^4}\frac{m_N^4 f_N^2}{(m_S + m_N)^2},$$

$$\sigma_{VN}^{\rm SI} = \frac{\lambda_{HVV}^2}{16\pi m_H^4}\frac{m_N^4 f_N^2}{(m_V + m_N)^2},$$

$$\sigma_{fN}^{\rm SI} = \frac{\lambda_{Hff}^2}{4\pi\Lambda^2 m_H^4}\frac{m_N^4 m_f^2 f_N^2}{(m_f + m_N)^2},$$

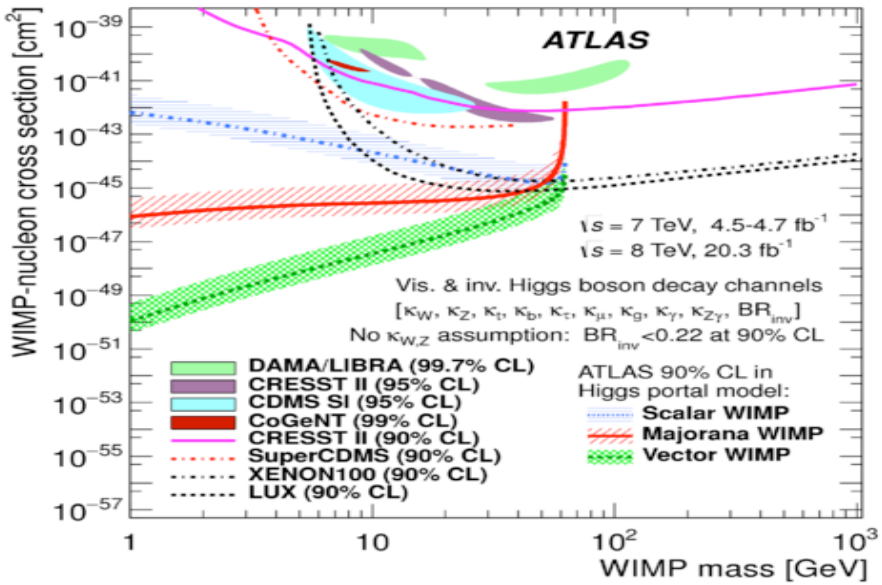
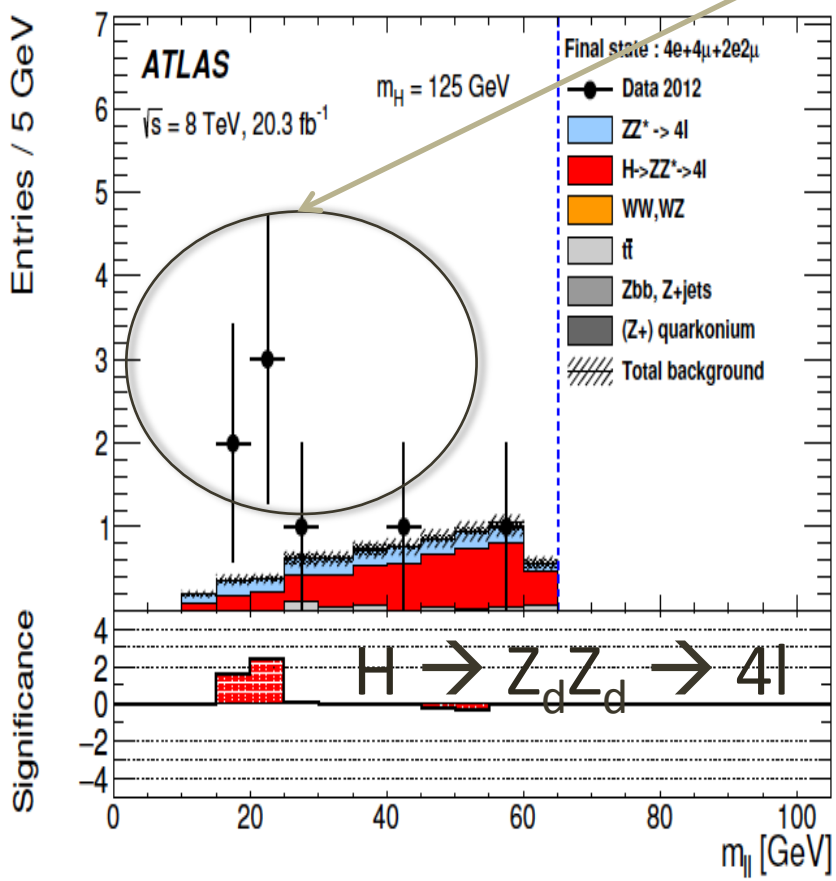


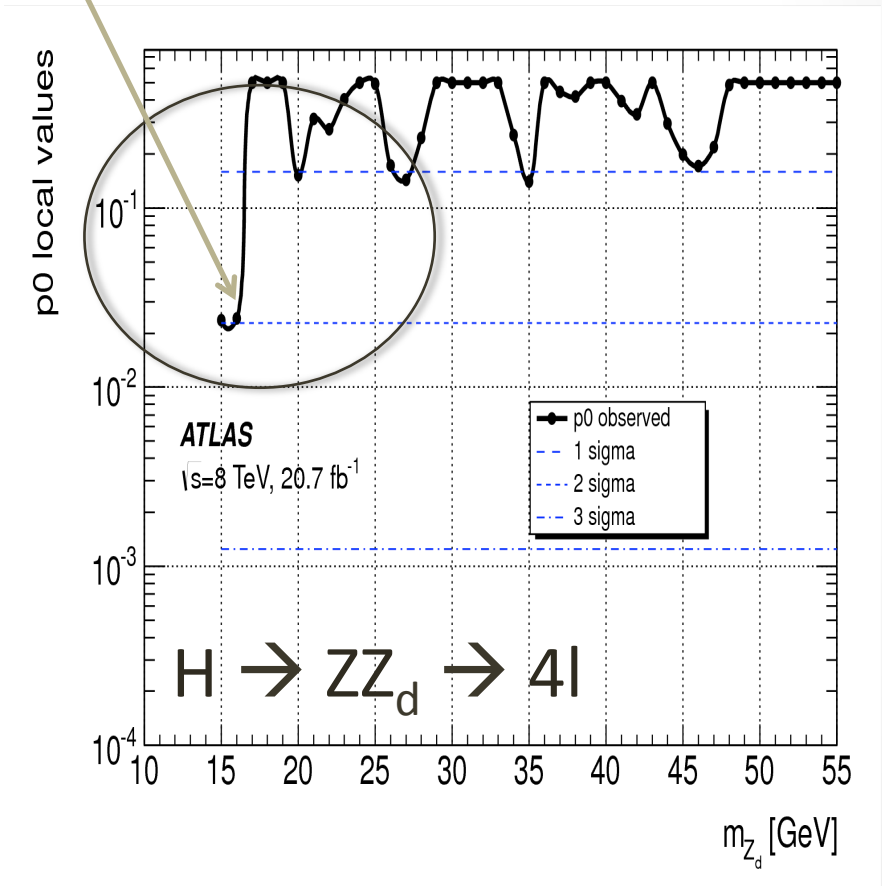
Table 11: Parameters in the Higgs-portal dark-matter model.

Vacuum expectation value	$v/\sqrt{2}$	174 GeV
Higgs boson mass	m_H	125 GeV
Higgs boson width	Γ_H	4.07 MeV
Nucleon mass	m_N	939 MeV
Higgs–nucleon coupling form factor	f_N	$0.33^{+0.30}_{-0.07}$

Conclusions

- **In the LHC Run 2**
  - We continue the searches for H → invisible
  - We push the H → $Z_{(d)}Z_d$ → 4l searches to low mass, below 15 GeV
  - We will see whether our current excesses get stronger or disappear



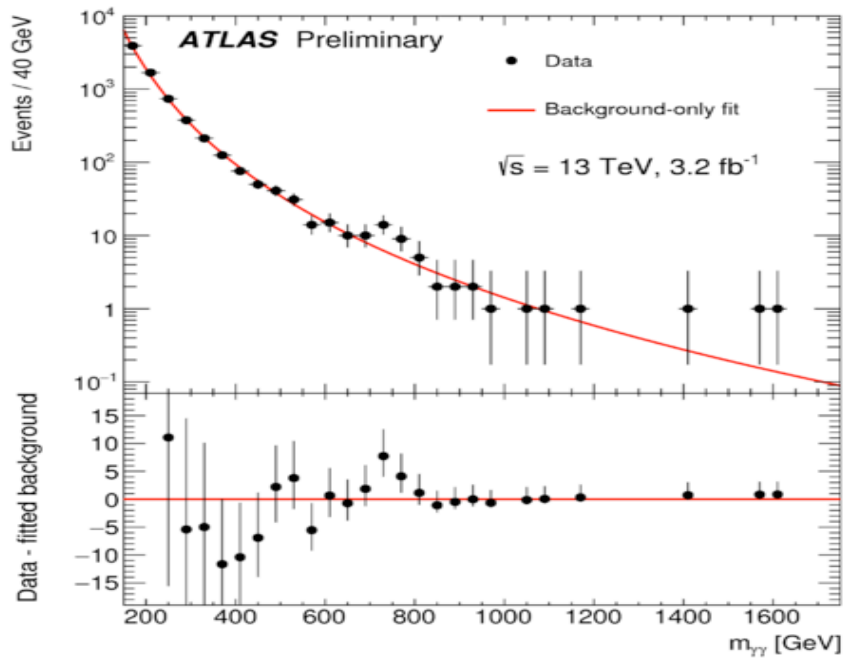


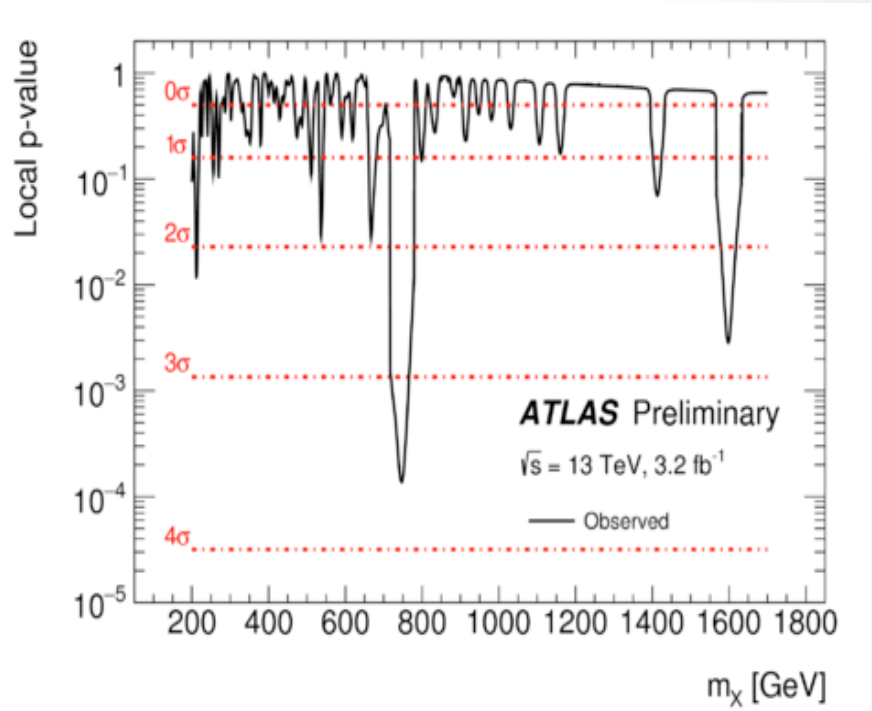
2nd Dark Interactions Workshop

- Here at BNL on 4-7 October 2016
- https://www.bnl.gov/di2016/

Additional Slides

Search for 2-photon resonance





- **Signal Model**
  - Narrow Width Approximation. Using Double Sided Crystal Ball (DSCB) function. **3.6σ local excess. 2.0σ with Look-Elsewhere Effect (LEE)**
  - Large Natural Width. Using DSCB fitted with simulated samples with different widths up to 25% of the resonance mass. **3.9σ local excess, 2.3σ excess with LEE included**