Search for dark interactions at the LHC

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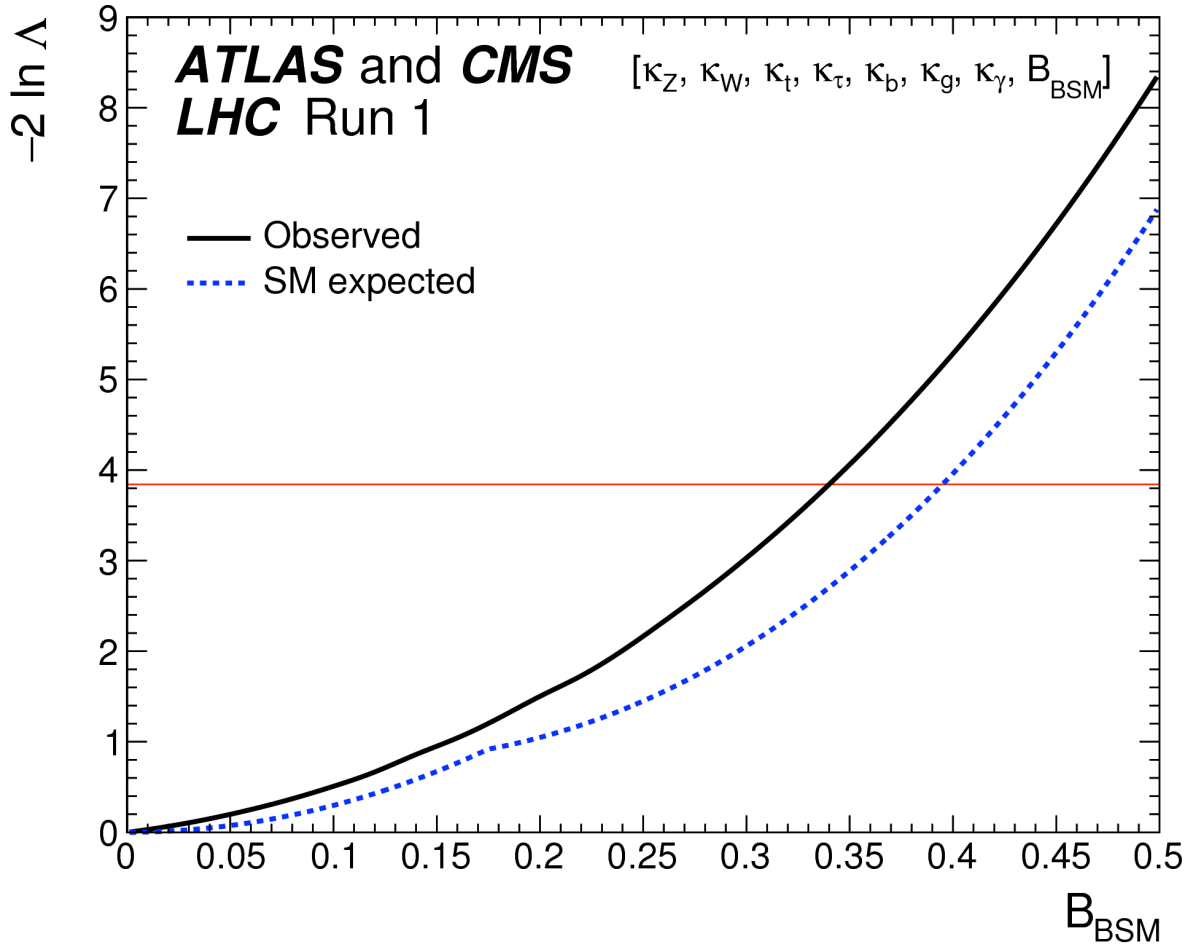
BNL

On the behalf of the ATLAS and CMS Collaborations

Searching for dark interactions in the decays of h125

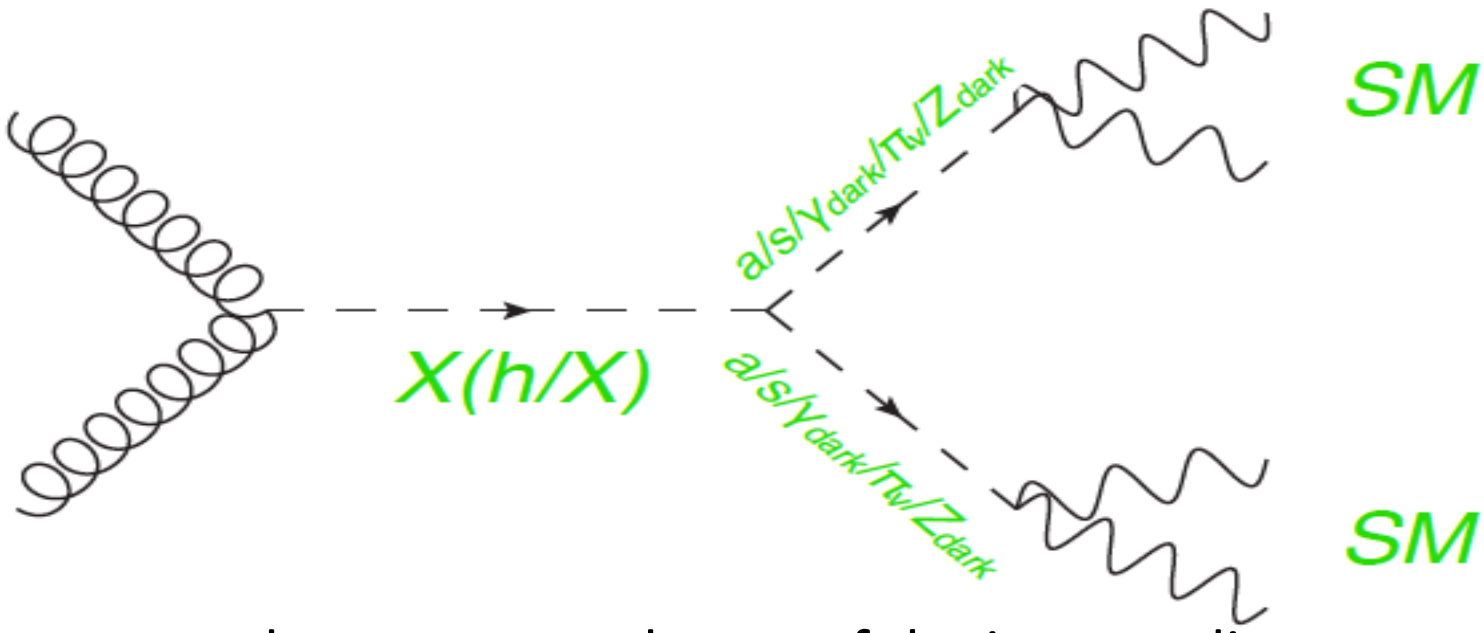
JHEP 08 (2016) 045



- BR (h125 → BSM) < 34% at 95% CL

Searching for dark interactions in the decays of h125

- It could be h → WIMP (invisible/undetected)
- Or it could be



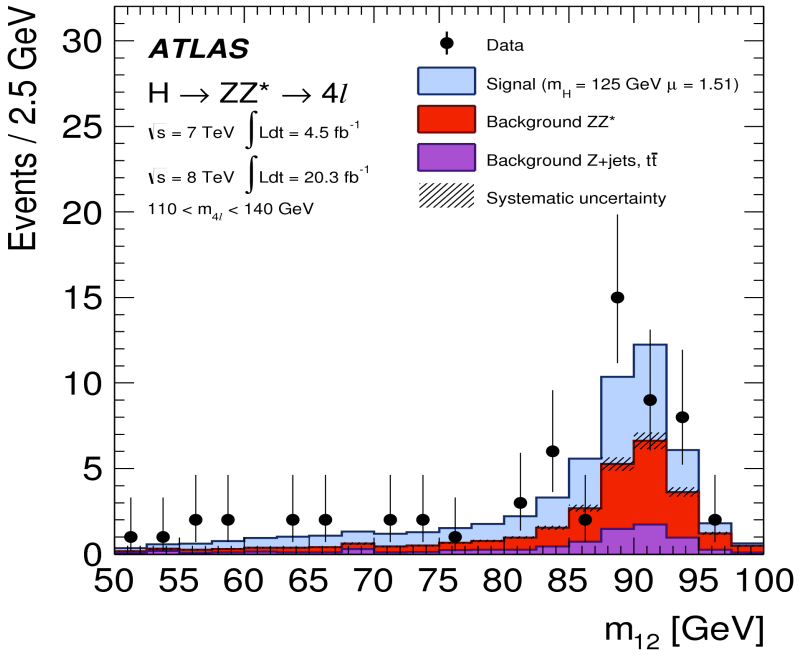
Prompt and non-prompt decays of the intermediate state

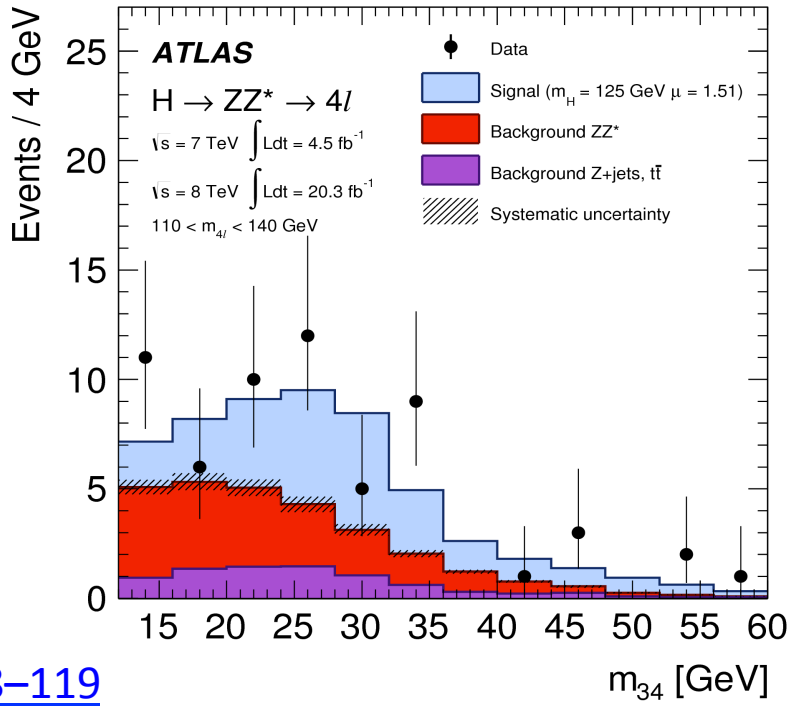
LHC Searches

- H → aa → fermions
  - 4b
  - 2b2τ
  - 2b2μ
  - 2μ2τ
  - 4τ
- H → aa → 4γ
- H → aa → 2b+Missing Energy
- H → Z (Zdark) Zdark → 4l
  - Zdark = Z_d
- H → invisible
- H → lepton-jets
- H → Long-lived particles → Displaced hadronic jets
- H → …
- …

H→ZZ*→4l (SM)

- 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} (2^{nd} 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



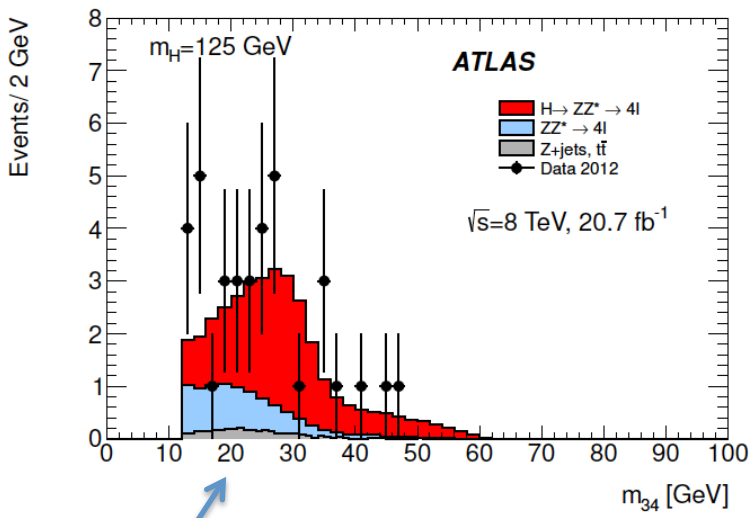


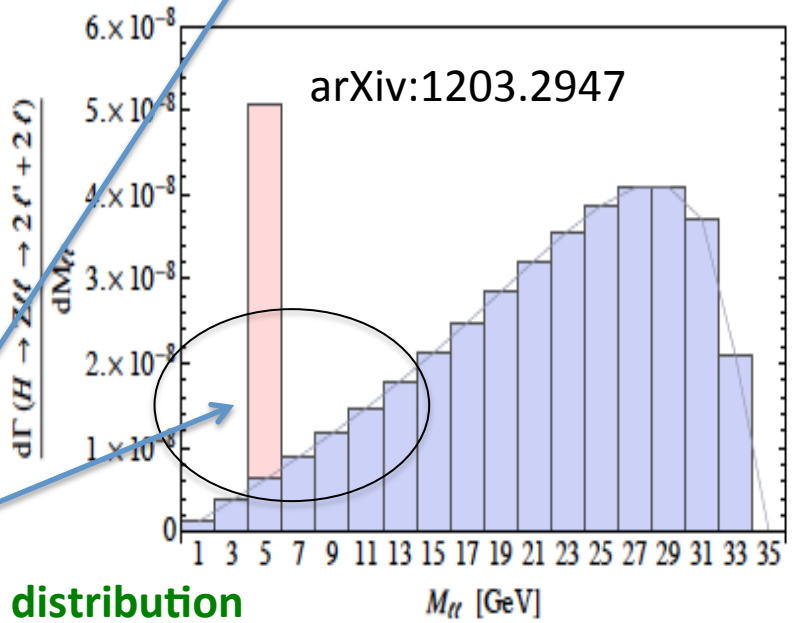
Physics Letters B 726 (2013) 88–119

ATLAS H → ZZ_d → 4l

[PRD 92 (2015) 092001]

- Same as in the standard H → ZZ* → 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 → 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 → ZZ_d → 4l in $15 < m_{2l} < 55$ GeV**



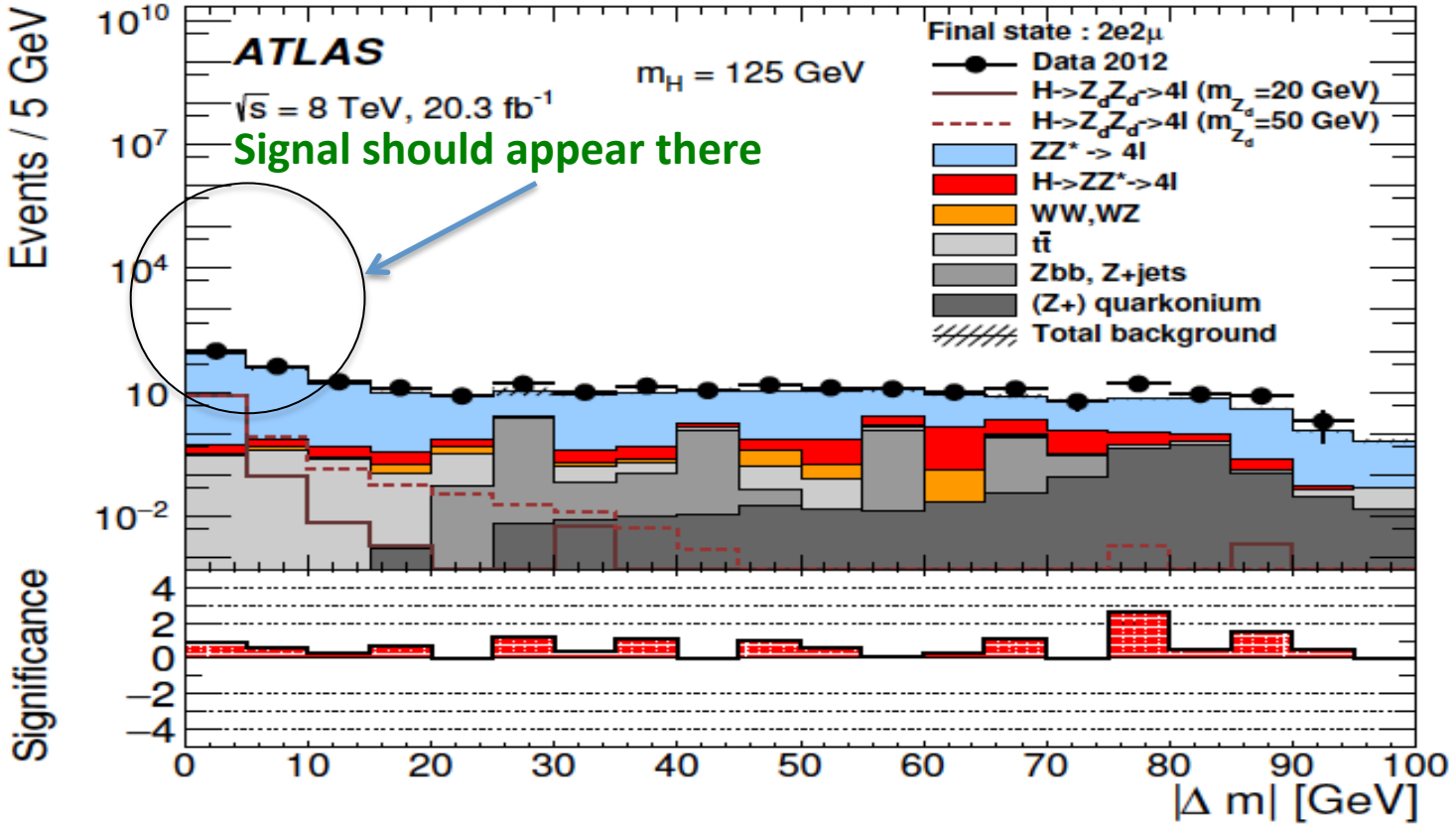


Signal should appear as a narrow peak in m_{34} distribution

ATLAS H → Z_dZ_d → 4l

- Start with the identification of 4 leptons as in H → ZZ* →4l, and the formation of 4l quadruplets with SFOS
- Select the unique quadruplet by exploiting the mass difference **$\Delta m = |m_{12}-m_{34}|$ minimal**
- $115 < m_{4l} < 130$ GeV
- **Apply a Z-veto and J/Psi and Upsilon-Veto**

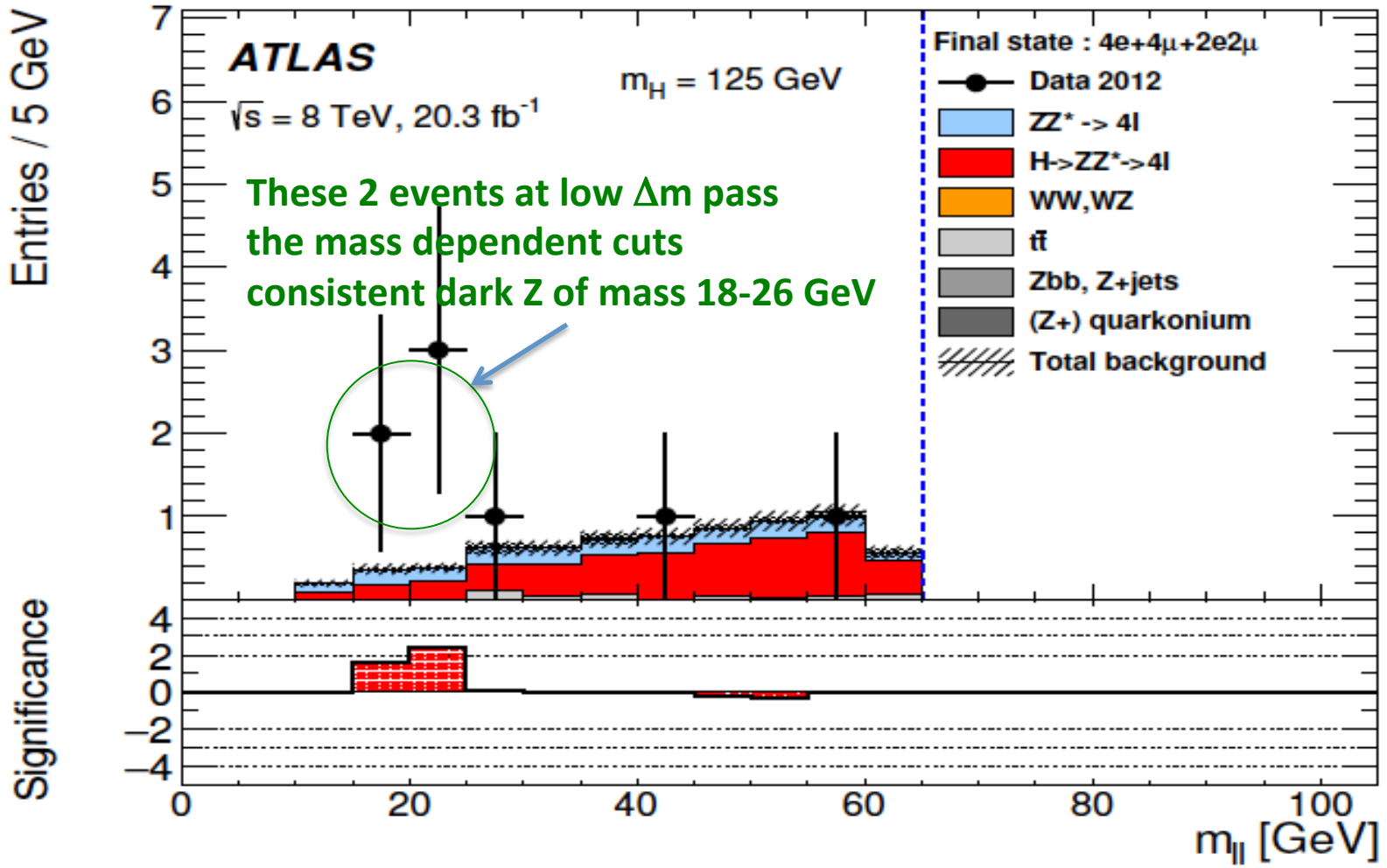
PRD 92 (2015) 092001



ATLAS H → Z_dZ_d → 4l

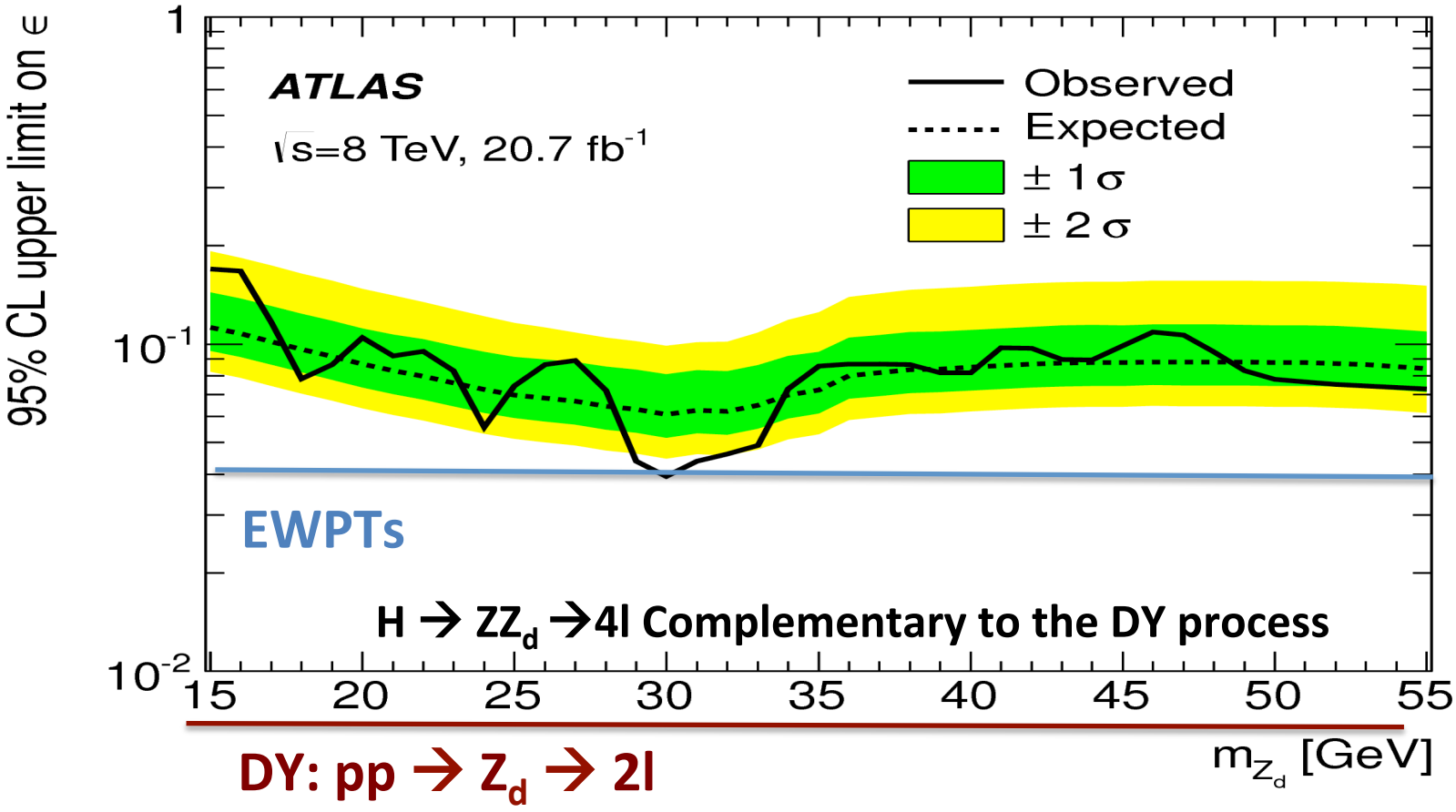
- No significant excess. 1.7σ(4e) and 1.7σ(4μ). 0 event in 2e2μ

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



Kinetic mixing parameter ε from BR ($H \rightarrow ZZ_d \rightarrow 4l$) measurement

- Use the calculations of Curtin et al, arXiv: 1412.0018 to extract ε from the R_B=BR ($H \rightarrow ZZ_d \rightarrow 4l$) / BR ($H \rightarrow 4l$)



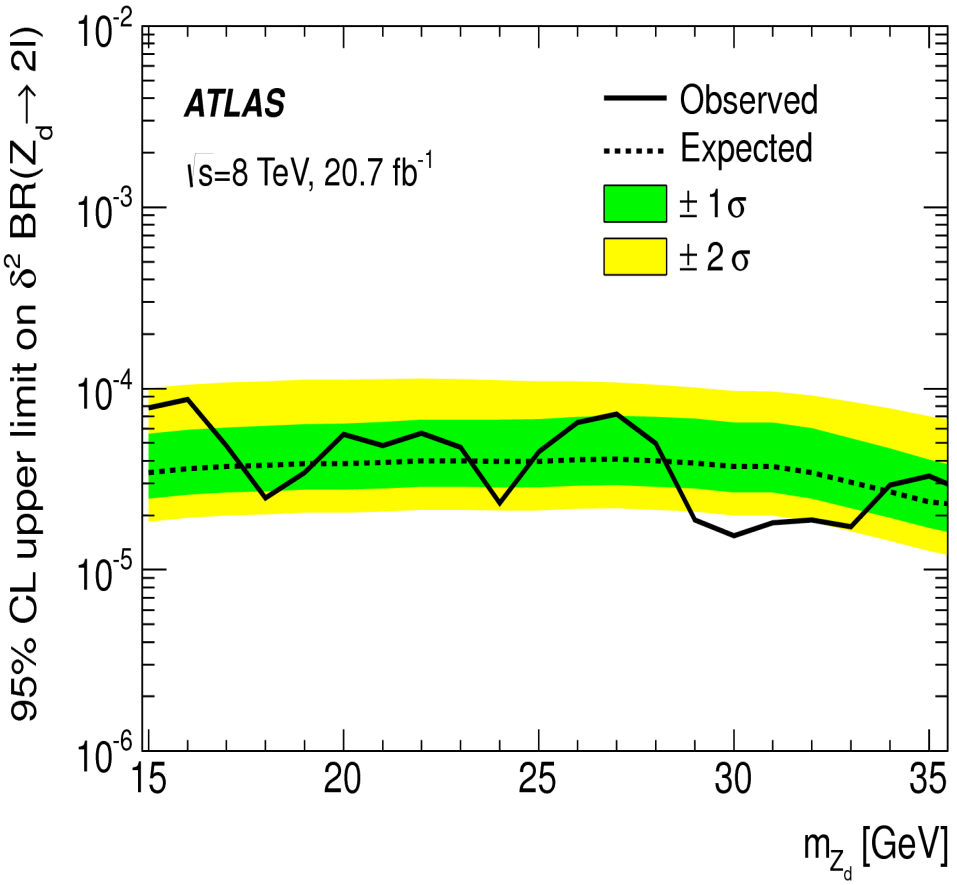
Upper bound on the Z-Z_d mass mixing parameter δ from BR ($H \rightarrow ZZ_d \rightarrow 4l$) measurement

- In the limit of $m_{Zd}^2 << (m_H^2 - m_Z^2)$:

Davoudiasl et al, arXiv: 1304.4935, arXiv: 1203.2947

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

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



Upper bound on Higgs mixing parameter κ from $H \rightarrow Z_d Z_d \rightarrow 4l$

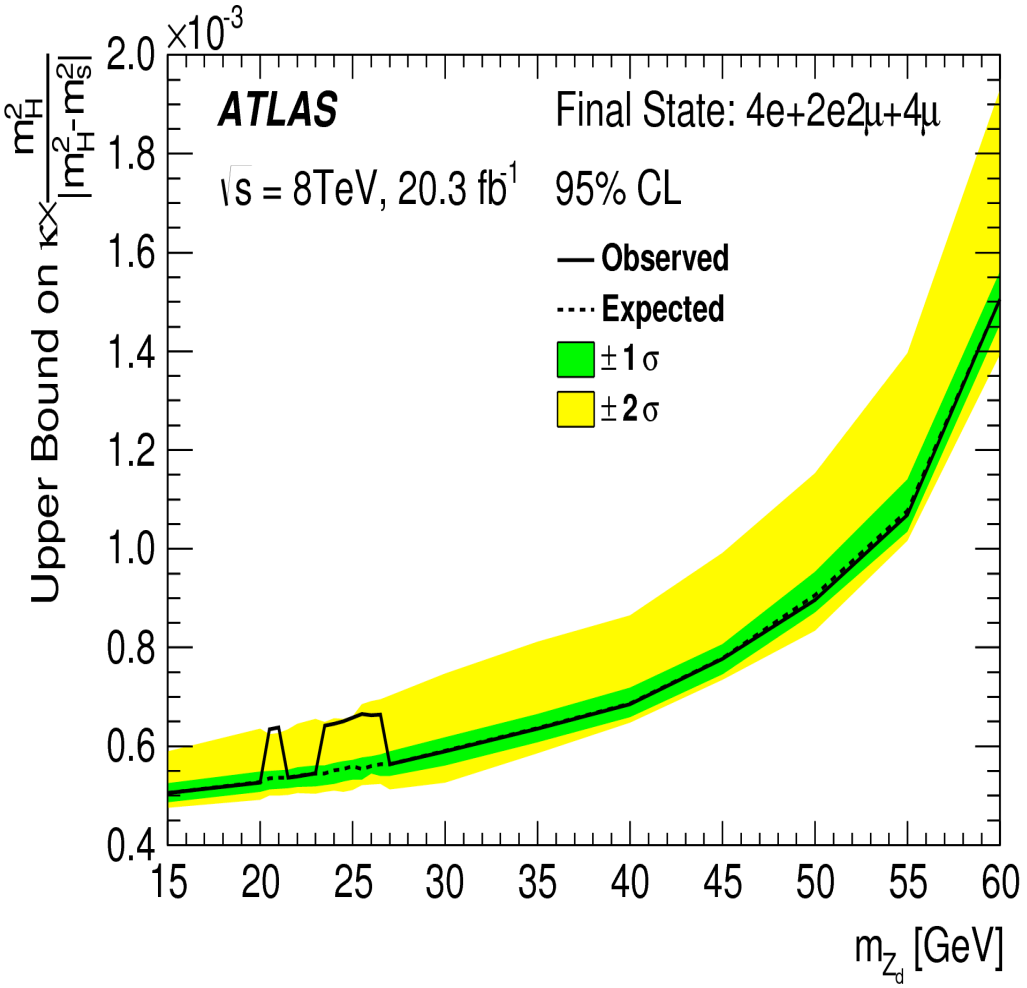
- From Curtin et al, arXiv: 1412.0018, κ relates to our measurement as follows:

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

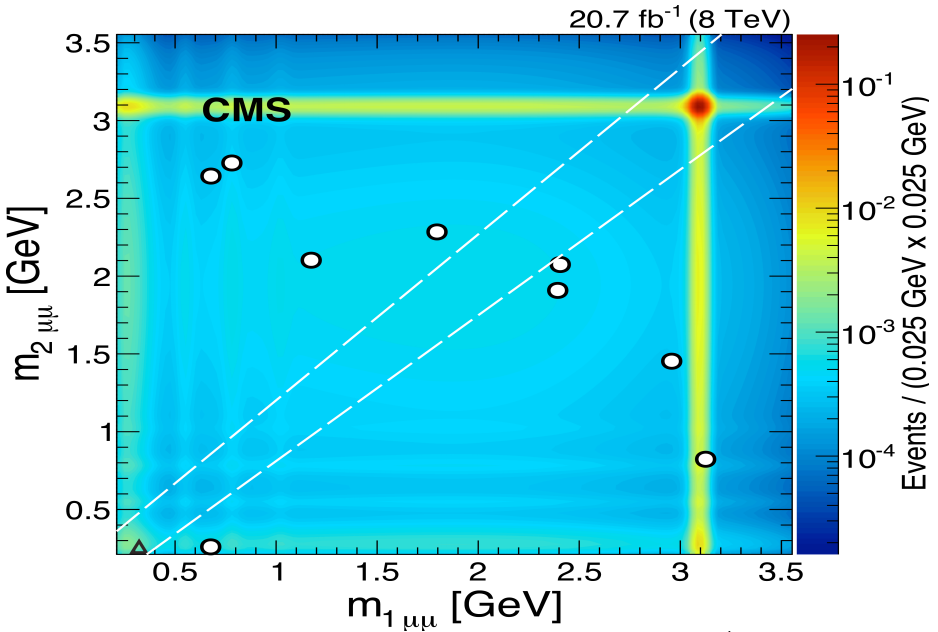
$$f(m_{Z_d}) = \frac{v^2}{32\pi m_H} \times \sqrt{1 - \frac{4m_{Z_d}^2}{m_H^2}} \times \frac{\left(m_H^2 + 2m_{Z_d}^2\right)^2 - 8\left(m_H^2 - m_{Z_d}^2\right)m_{Z_d}^2}{\left(m_H^2 - m_S^2\right)^2}.$$

$K >> \varepsilon$

$m_S > m_H/2$

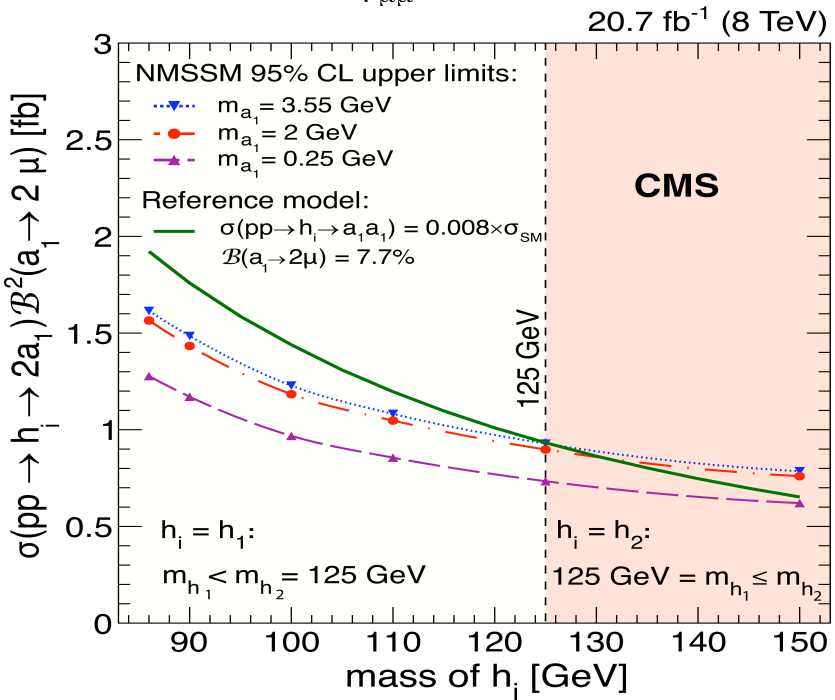


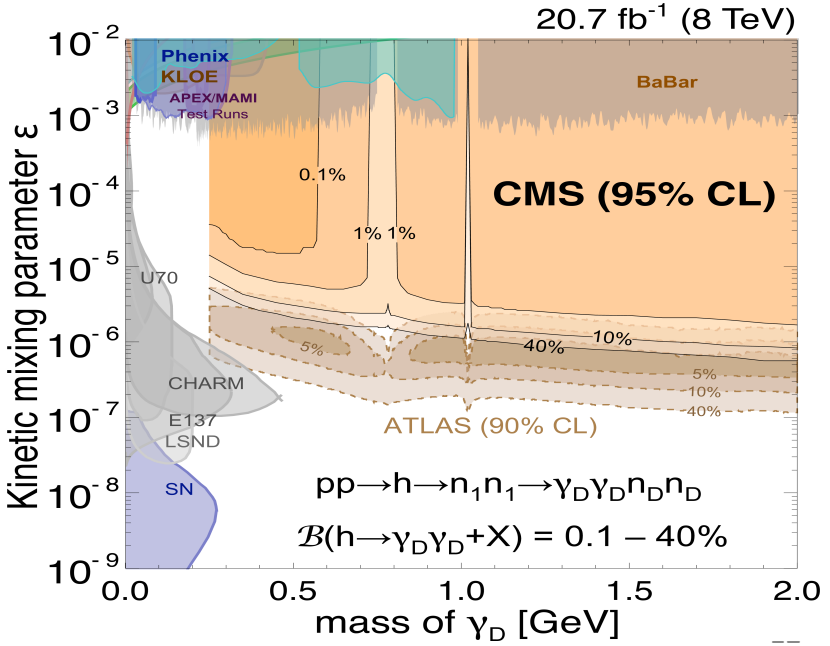
CMS h → aa → 4μ



Phys. Lett. B 752 (2016) 146

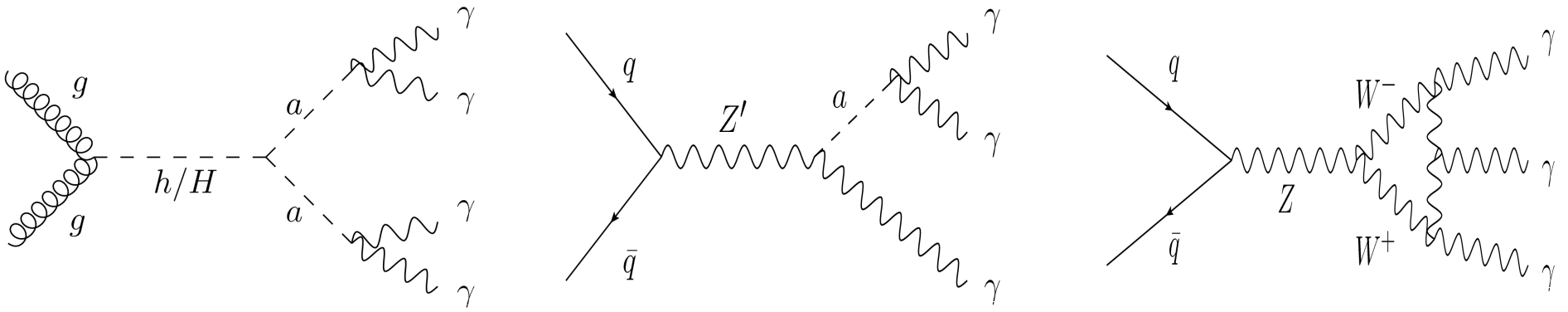
CMS searched for pair production of new light bosons decaying into muons interpreted in 2 benchmark models



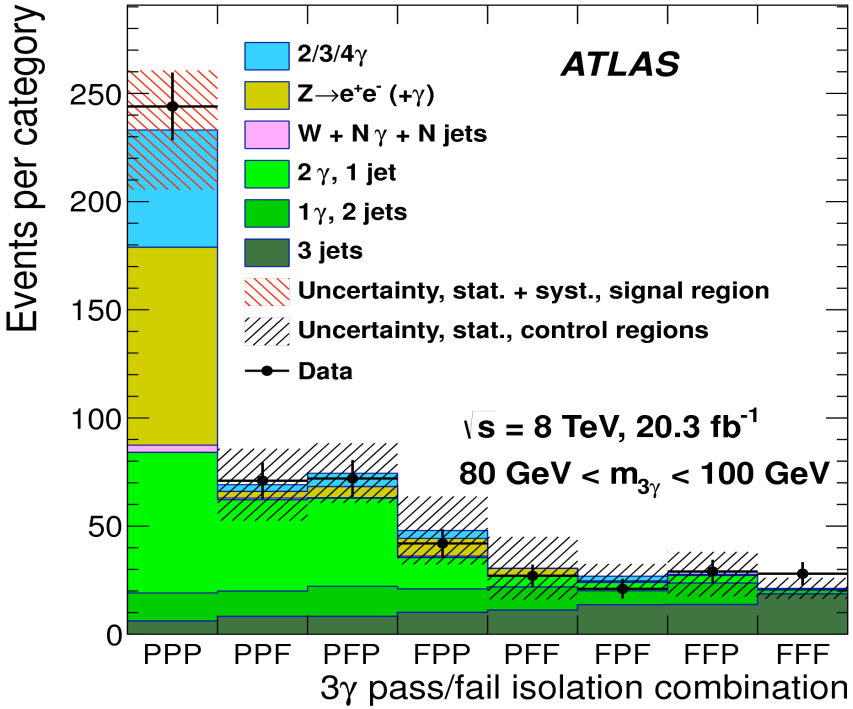


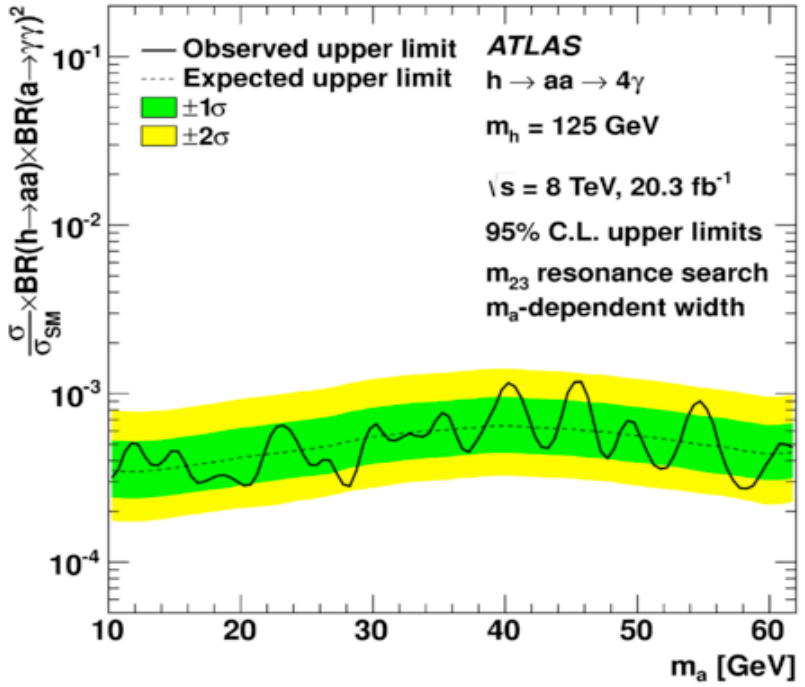
h → aa → 4γ

Eur. Phys. J. C 76(4) , 1-26 (2016)



- No excess. Limits for SM h → 4γ, H→4γ and Z'→3γ





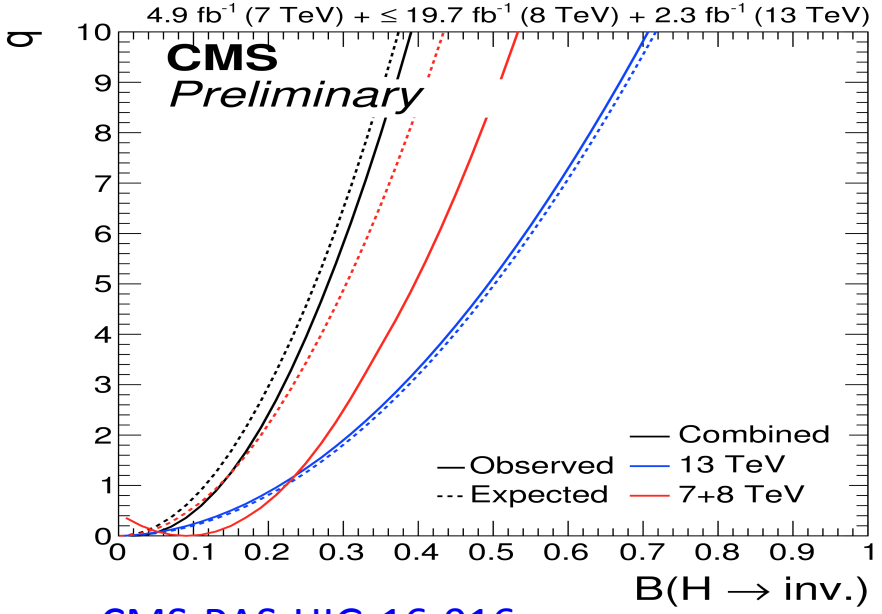
CMS H → invisible Results

- **ZH, Z → ll (l=e, μ) and H → invisible**
  - CMS-PAS-EXO-16-038
  - 12.19 fb^{-1} @ 13 TeV
  - Upper bound on BR (H → invisible): Obs (Exp) 0.86 (0.70)
- **ZH, Z → bb and H → invisible**
  - **8 TeV analysis**
  - **Upper bound on σ x BR / σ_{SM}:** Obs (Exp) 1.82 (1.99)
- **VH, V → jj and H → invisible**
  - EXO-16-013, 12.19 fb^{-1} @13 TeV
  - Upper bound on BR (H → invisible): Obs (Exp) 1.17 (0.72)
- **Monojet search with H → invisible interpretation**
  - CMS-PAS-EXO-16-037
  - 12.19 fb^{-1} @ 13 TeV
  - Upper bound on BR (H → invisible): Obs (Exp) 0.48 (0.85)
- **VBF H → invisible**
  - CMS-PAS-HIG-16-009
  - 2.3 fb^{-1} @ 13 TeV
  - Upper bound on BR (H → invisible): Obs (Exp) 0.69 (0.62)
- **Combination of H → invisible measurements**
  - CMS-PAS-HIG-16-016
  - 7+8+13 TeV Combination of direct searches
  - Obs (Exp) 0.24 (0.23)

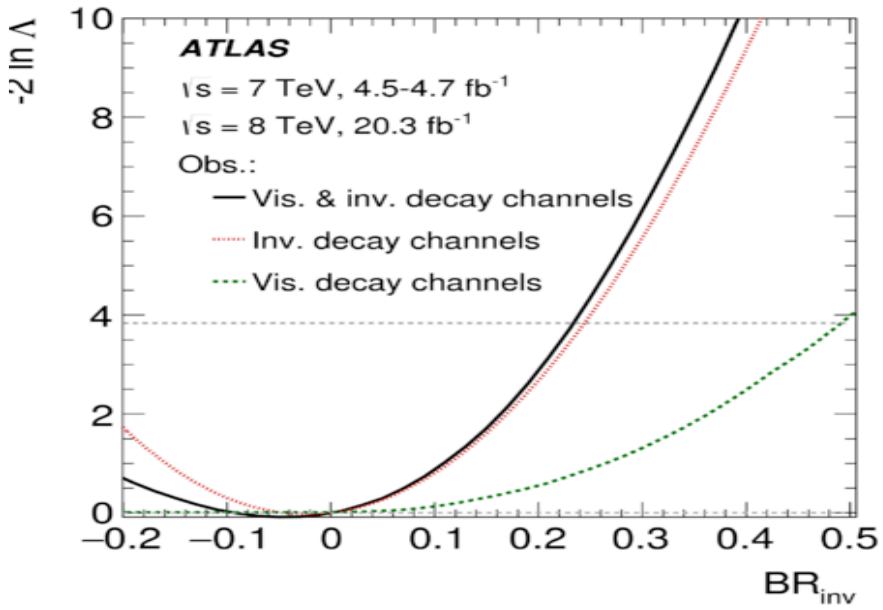
ATLAS H → invisible Results

- **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)
  - ATLAS-CONF-2016-056, 13 TeV Run 2,13.3 fb^{-1} : Obs (Exp) 0.98 (0.65)
- **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**
  - JHEP 01 (2016) 172, 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)
- **Combination of H → invisible measurements @ 8 TeV**
  - JHEP 11 (2015) 206, arXiv:1509.00672
  - Combination of direct searches in Z(→ll), V(→jj), and VBF
  - Obs (Exp) 0.25 (0.27)
  - From Coupling fits and combination of visible and invisible decays: Obs (Exp) 0.23(0.24)

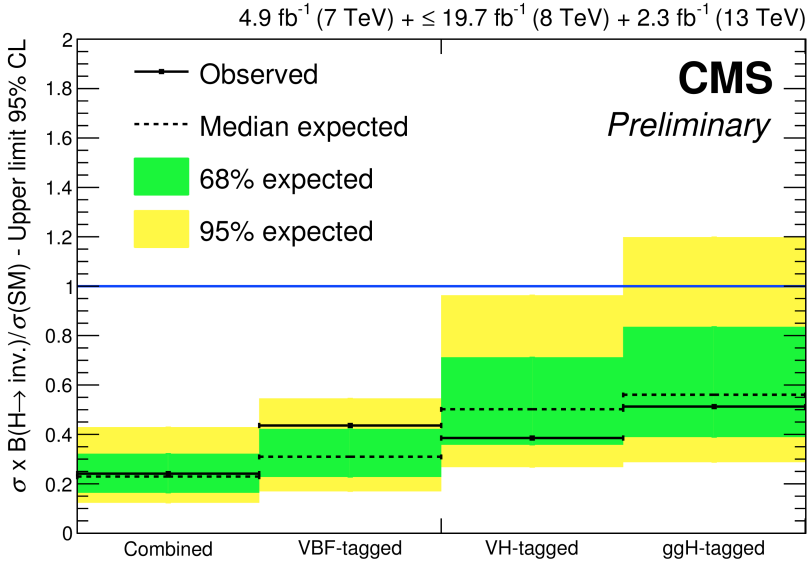
Combined H → invisible Results



CMS-PAS-HIG-16-016



JHEP11(2015)206

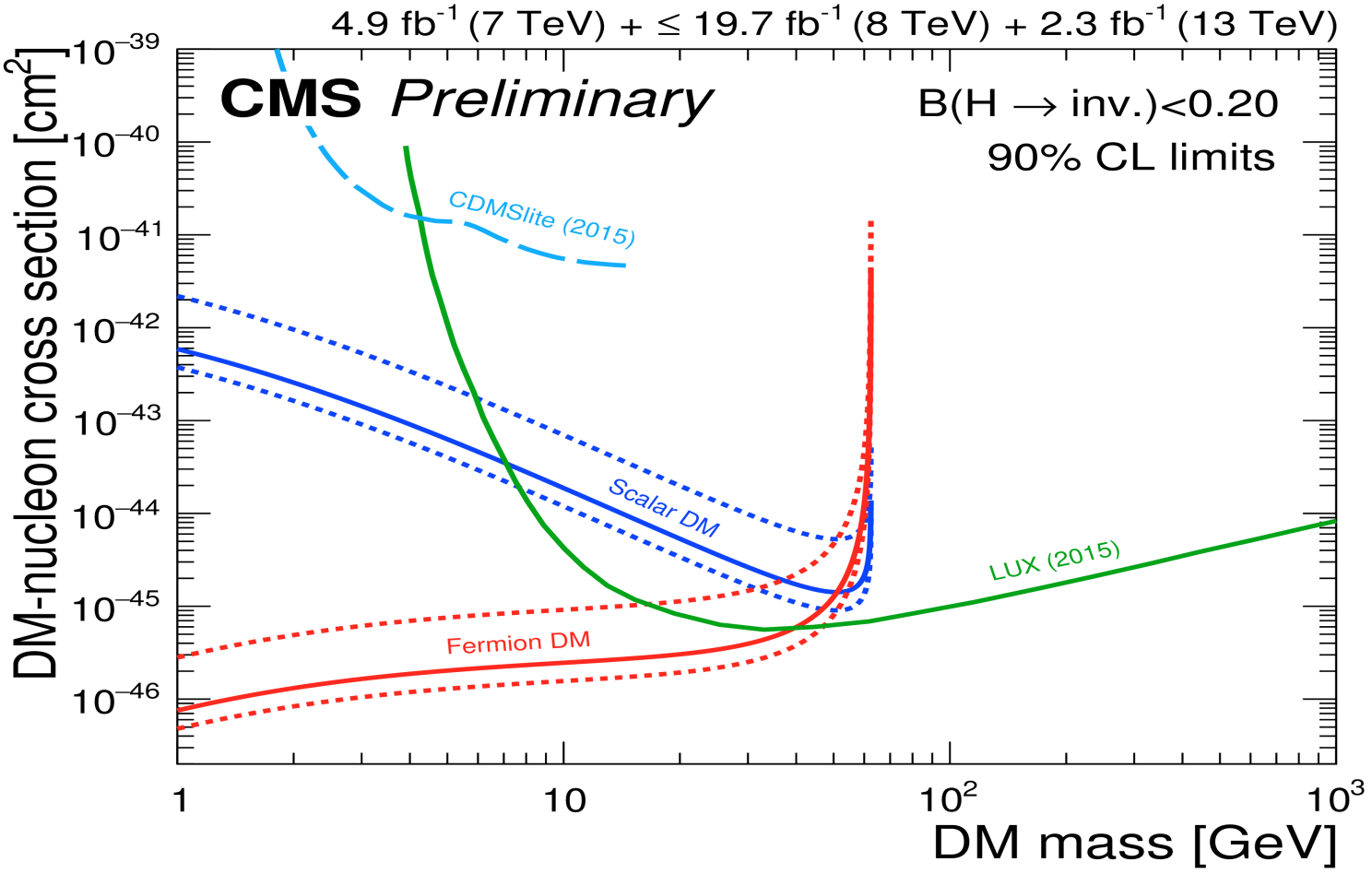


Decay channels	Coupling parameterisation	κ_i assumption	Upper limit on BR$_{inv}$ Obs.	Exp.
Invisible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR_{inv}}]$	$\kappa_{W,Z,g} = 1$	0.25	0.27
Visible decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR_{inv}}]$	$\kappa_{W,Z} \leq 1$	0.49	0.48
Inv. & vis. decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR_{inv}}]$	**None**	**0.23**	**0.24**
Inv. & vis. decays	$[\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau, \kappa_\mu, \kappa_g\ \kappa_\gamma, \kappa_{Z\gamma}, \mathrm{BR_{inv}}]$	$\kappa_{W,Z} \leq 1$	0.23	0.23

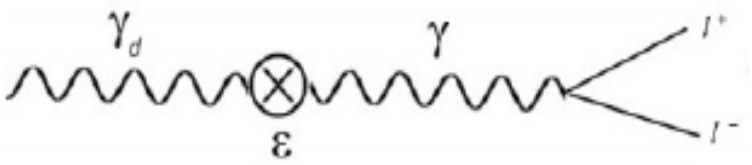
Higgs Portal Dark Matter

- The upper bound on the BR (H → invisible) can be used to constrain WIMP-Nucleon scattering cross section and compare to direct dark matter detection experiments

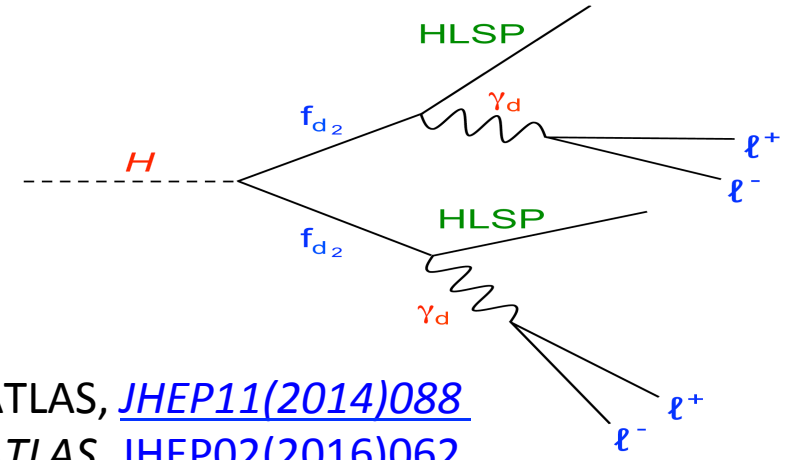
CMS-PAS-HIG-16-016



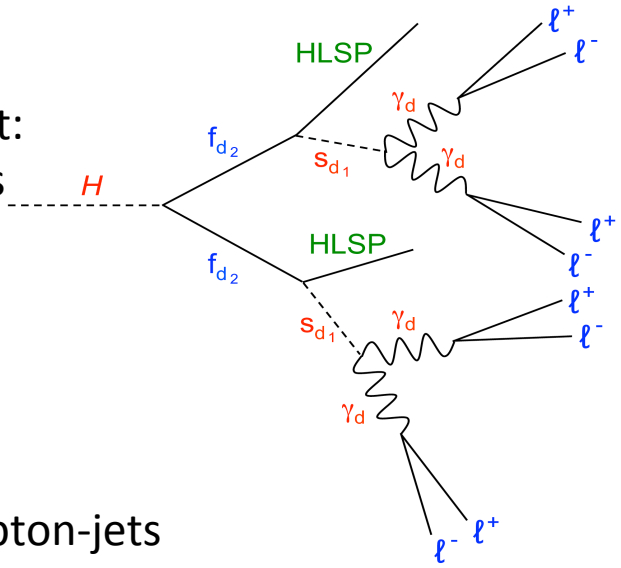
H → lepton-jets + X



Kinetic mixing ε between dark photon and SM photon
Signature: collimated pairs of leptons (lepton-jets)



Parameter of interest:
- Dark photon mass
- ε
- Dark photon cτ



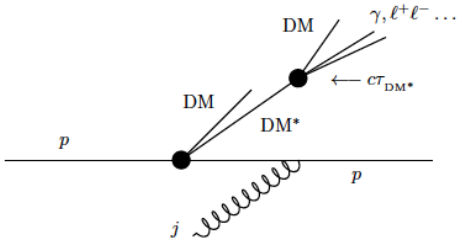
ATLAS, *JHEP11(2014)088*
ATLAS, JHEP02(2016)062
CMS, PRD 91 (2015) 052012

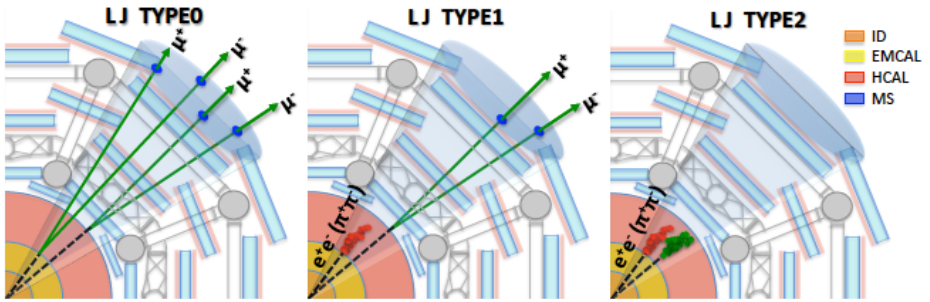
Prompt or displaced lepton-jets

Falkowski, Ruderman, Volanski and Zupan
http://arxiv.org/abs/1007.3496

FRVZ signal models with ggF Higgs production

Izaguirre, Krnjaic, Shuve
http://arxiv.org/abs/1508.03050





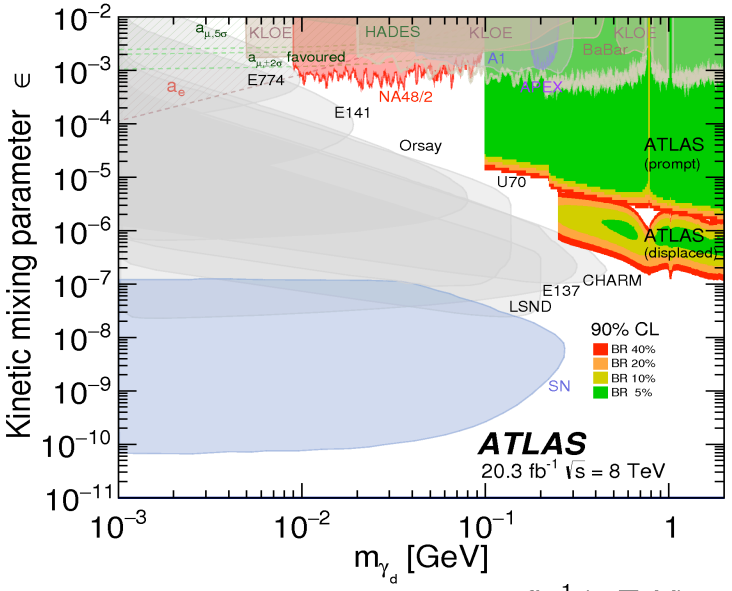
H → lepton-jets + X

- ATLAS

JHEP02(2016)062

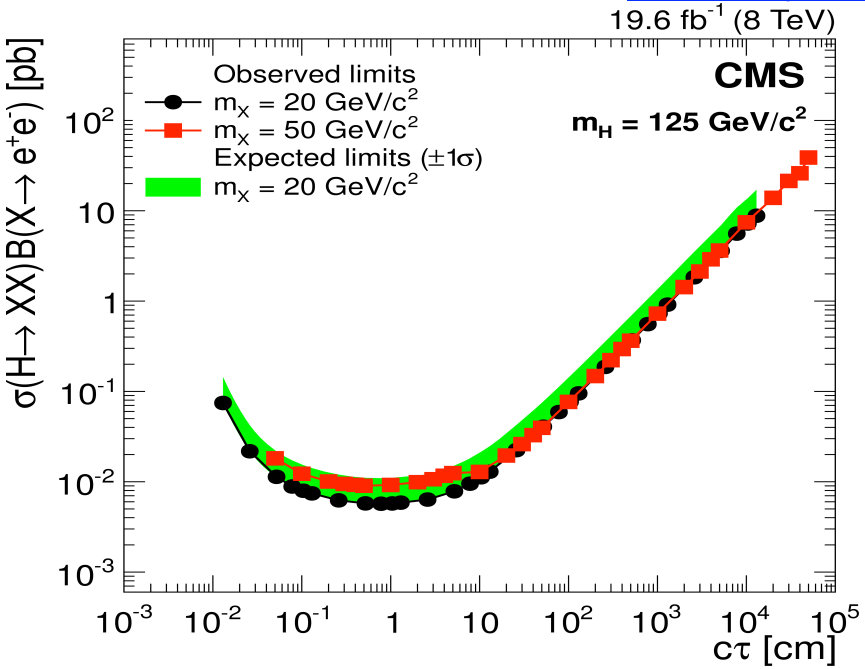
FRVZ model	Excluded $c\tau$ [mm] BR(10%)
$H \to 2\gamma_d + X$	$14 \leq c\tau \leq 140$
$H \to 4\gamma_d + X$	$15 \leq c\tau \leq 260$

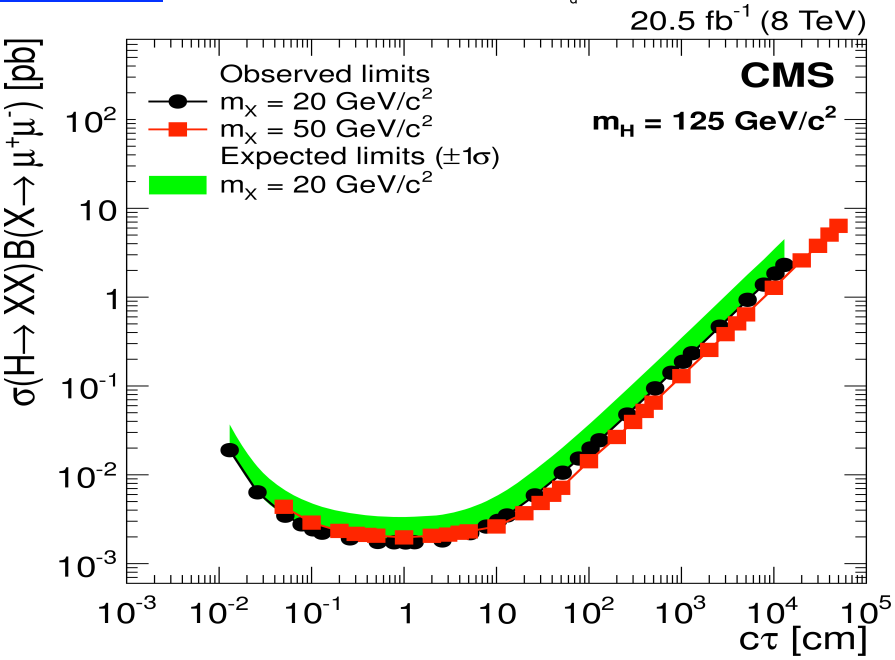
Prompt for BR=10%, cτ<3.2 excluded



- CMS

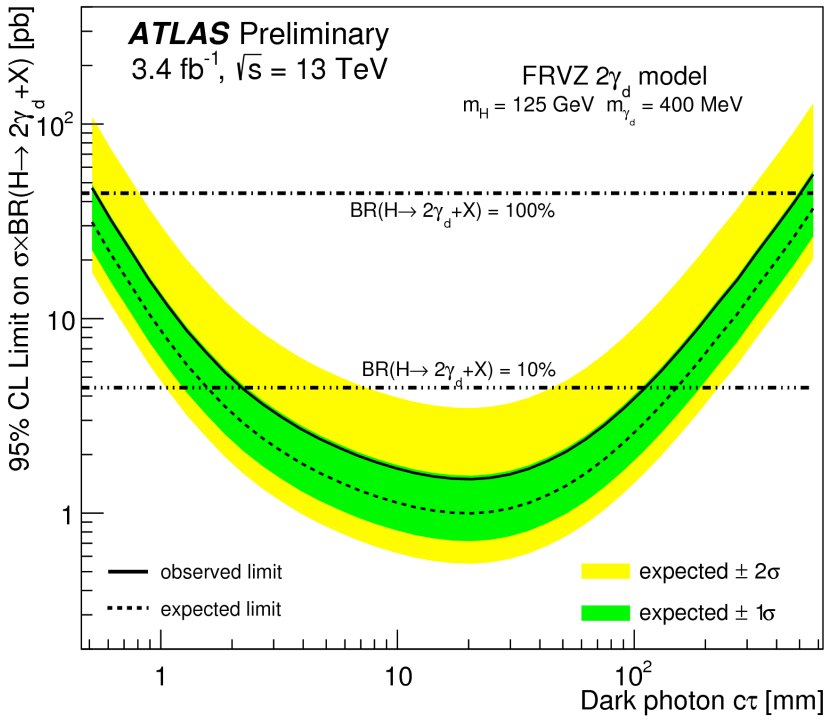
PRD 91 (2015) 052012

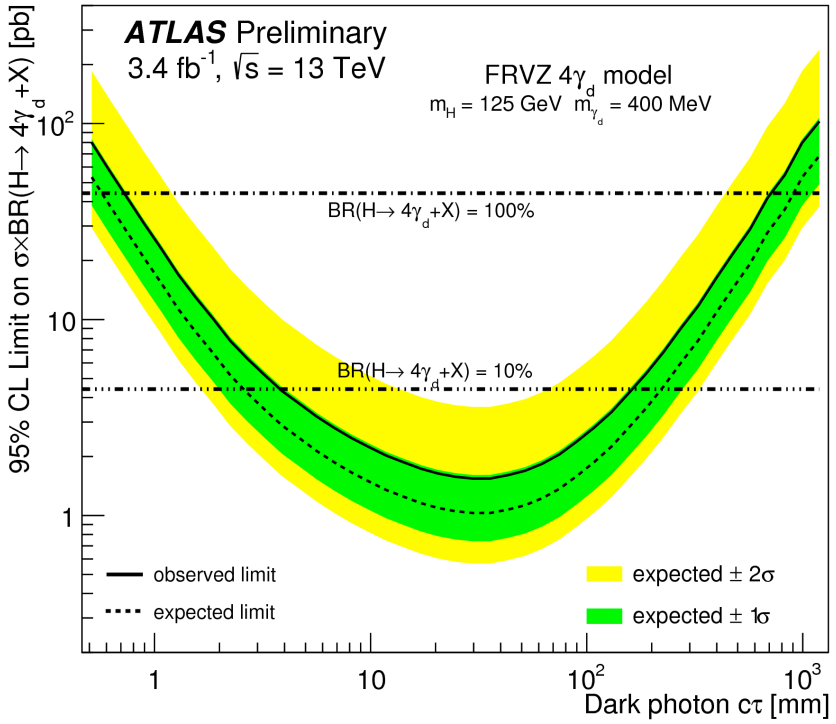




ATLAS Run2 H →lepton-jets + X

ATLAS-CONF-2016-042



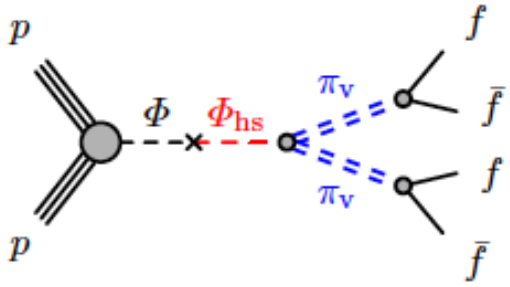


FRVZ model	m_{H} (GeV)	Excluded $c\tau$ [mm]
Higgs $\rightarrow$ $2\gamma_{\mathrm{d}} + X$	125	$2.2 \leq c\tau \leq 111.3$
Higgs $\rightarrow$ $4\gamma_{\mathrm{d}} + X$	800	$3.8 \leq c\tau \leq 163.0$
Higgs $\rightarrow$ $2\gamma_{\mathrm{d}} + X$	125	$0.6 \leq c\tau \leq 63$
Higgs $\rightarrow$ $4\gamma_{\mathrm{d}} + X$	800	$0.8 \leq c\tau \leq 186$

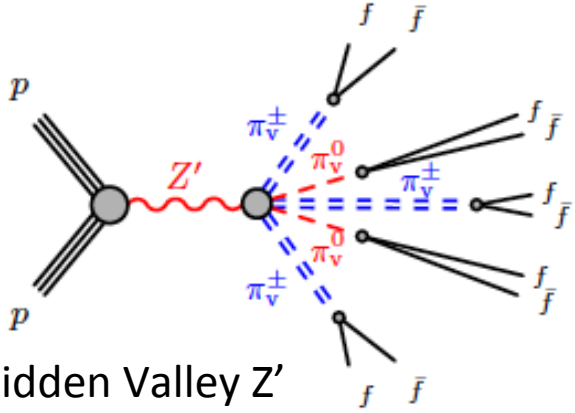
Long-lived, weakly-interacting particles → displaced hadronic jets

- Benchmark models

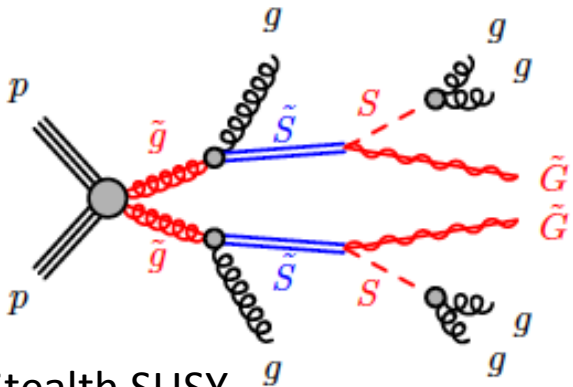
ATLAS, PRD 92, 012010 (2015)
CMS, PRD 91 012007 *(2015)*



Higgs decays



Hidden Valley Z'



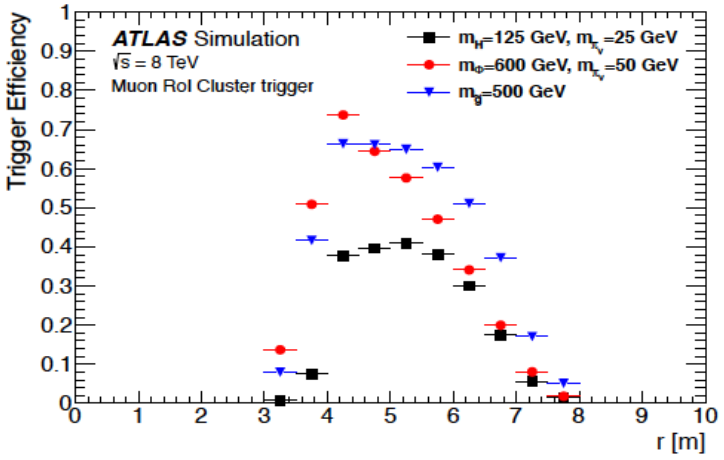
Stealth SUSY

(a) (b)

LLPs decays to hadronic jets far from the IP
Search for displaced vertices in the ID and MS

Muon RoI Cluster Trigger to select hadronic decays in the outer radius of HCal to middle of MS

Single jet + Met Trigger also used for the Z' search



Long-lived, weakly-interacting particles → displaced hadronic jets

PRD 92, 012010 (2015)

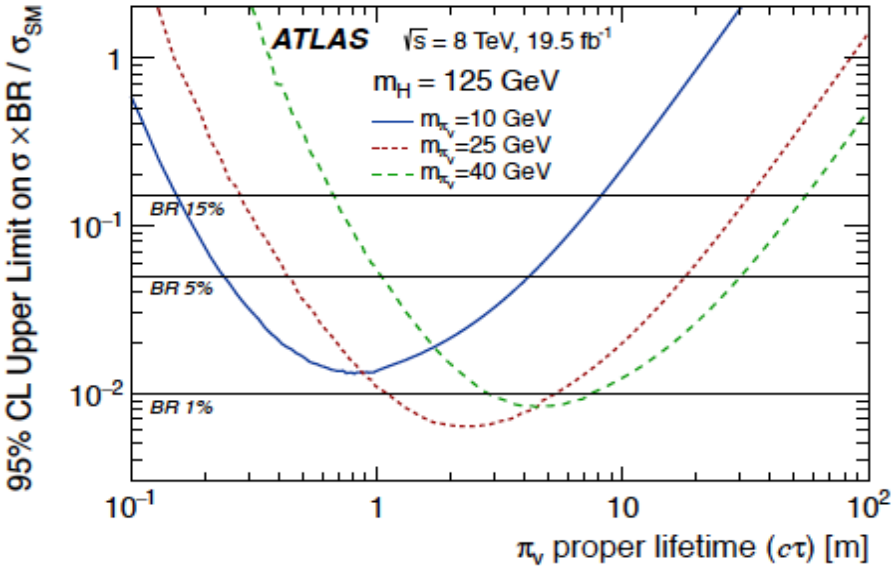
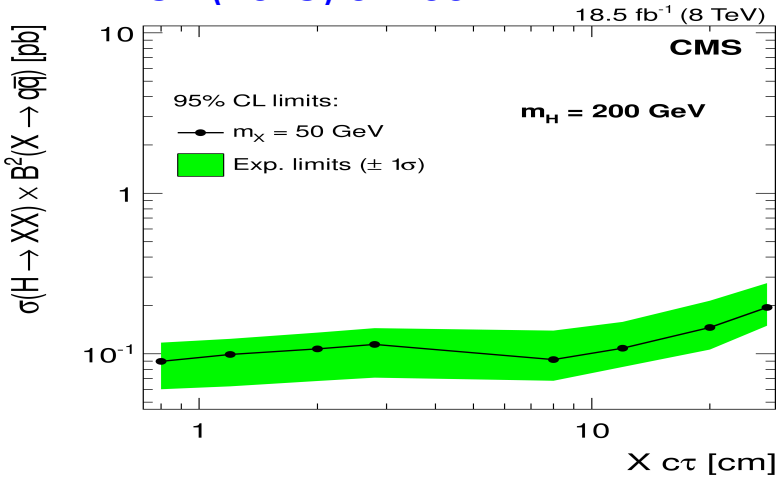
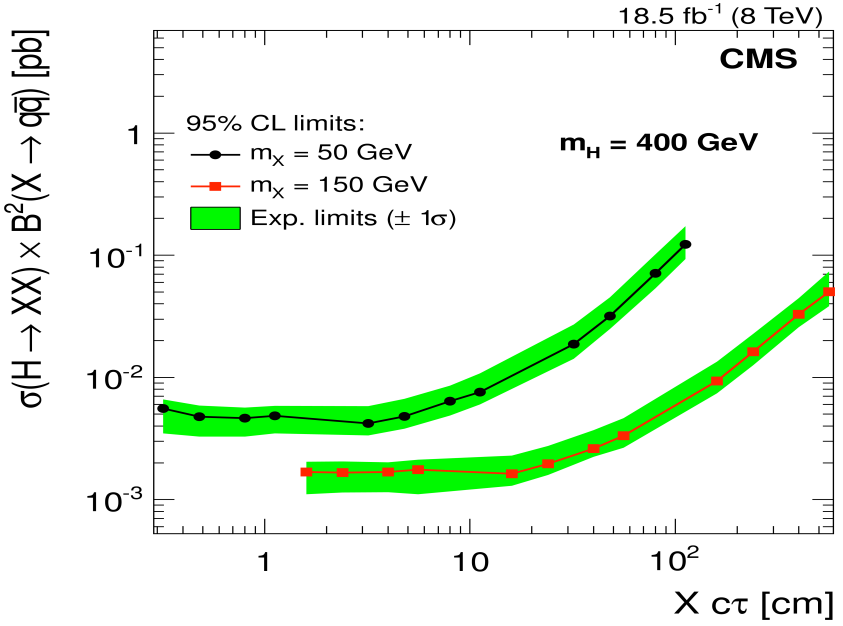


TABLE XI. Ranges of π_v proper decay lengths excluded at 95% CL assuming a 30%, 15%, 5%, or 1% BR for $m_H = 125$ GeV.

m_{π_v}	Excluded $c\tau$ range [m]			
[GeV]	1% BR	5% BR	15% BR	30 % BR
10	no limit	0.24–4.2	0.16–8.1	0.12–11.8
25	1.10–5.35	0.43–18.1	0.28–32.8	0.22–46.7
40	2.82–7.45	1.04–30.4	0.68–55.5	0.52–79.2

PRD 91 (2015) 012007



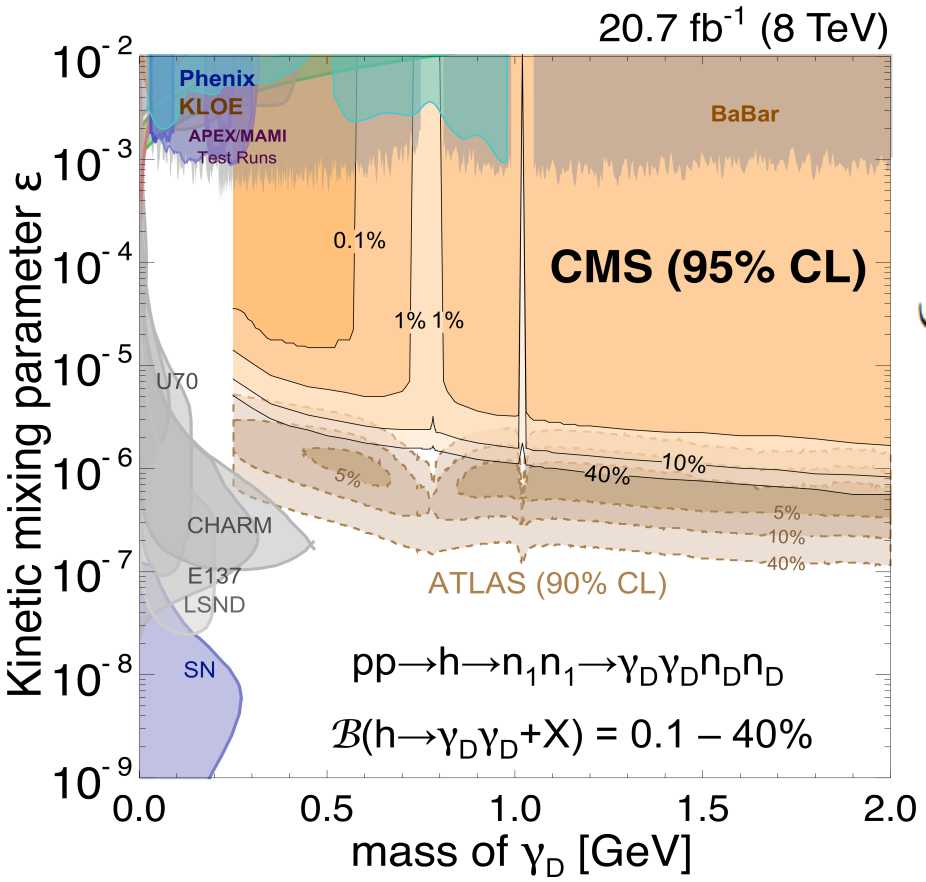


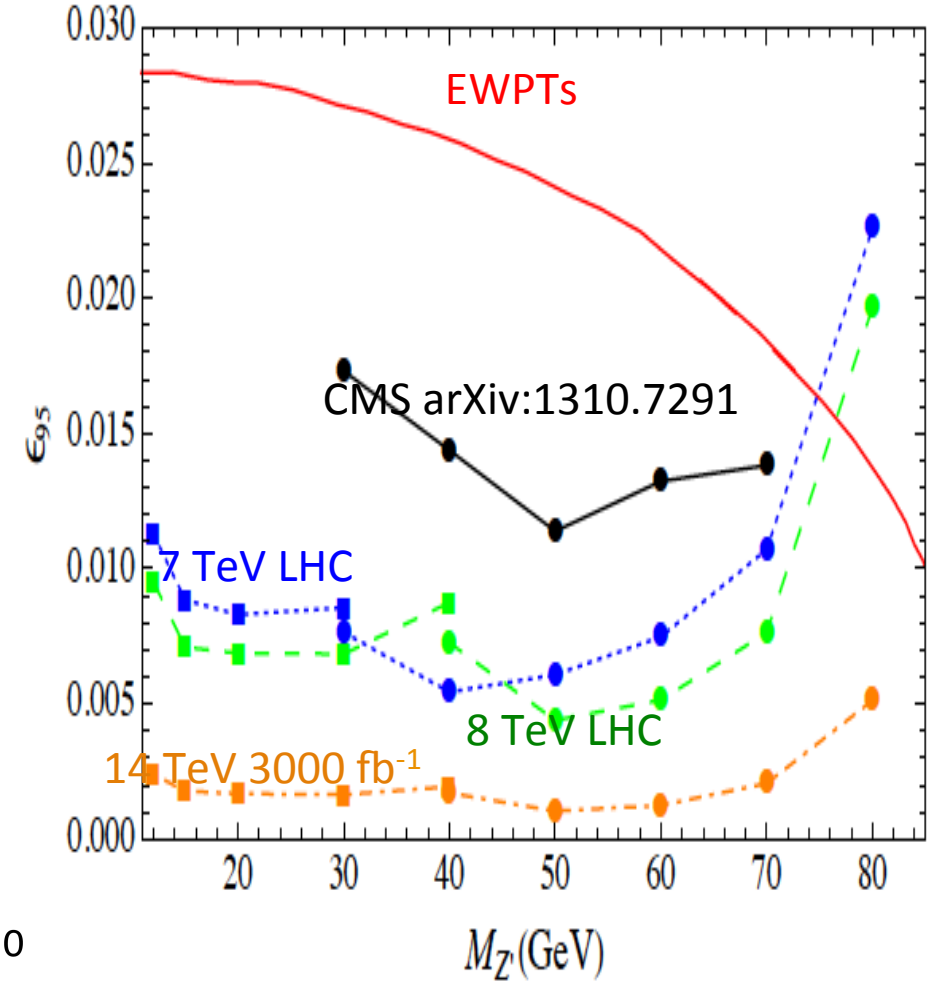
Bounds on kinetic mixing parameter ε

1408.1075v2

ATLAS, JHEP02(2016)062

CMS, Phys. Lett. B 752 (2016) 146

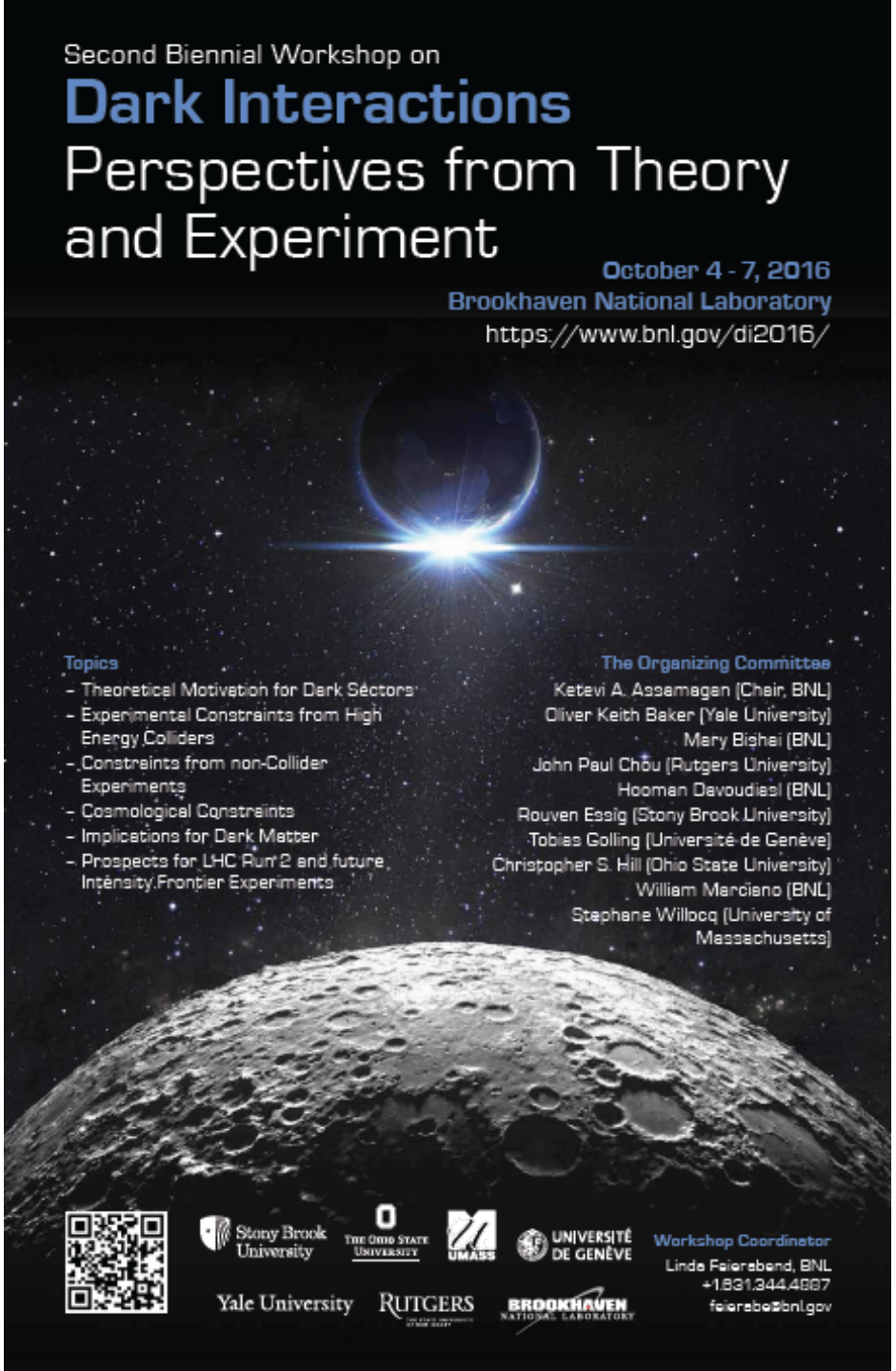




Conclusions

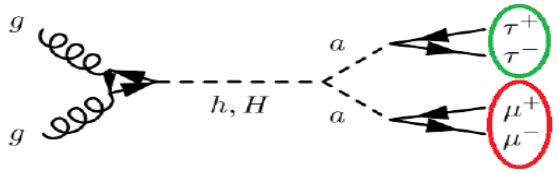
- Many searches for dark interactions at LHC
  - Dark vector bosons in H → 4l events
  - H → invisible particles
  - H → lepton-jets
  - H → LLPs
  - H → aa → fermions, photons
- No excess found
- Run 2 might yield exciting discoveries
- For more information
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic
  - http://cms.web.cern.ch/news/cms-physics-results

- **Dark Interactions workshop at BNL 4-7 October 2016**
  - www.bnl.gov/di2016



ATLAS h → aa → μμττ

- Single μ and di-μ triggers used
- 2 signal regions, SRμ and SRe
- No significant excess in 3.7 < $m_{\mu\mu}$ (GeV) < 50
- Upper bound on h → aa production relative to the SM gg→h production

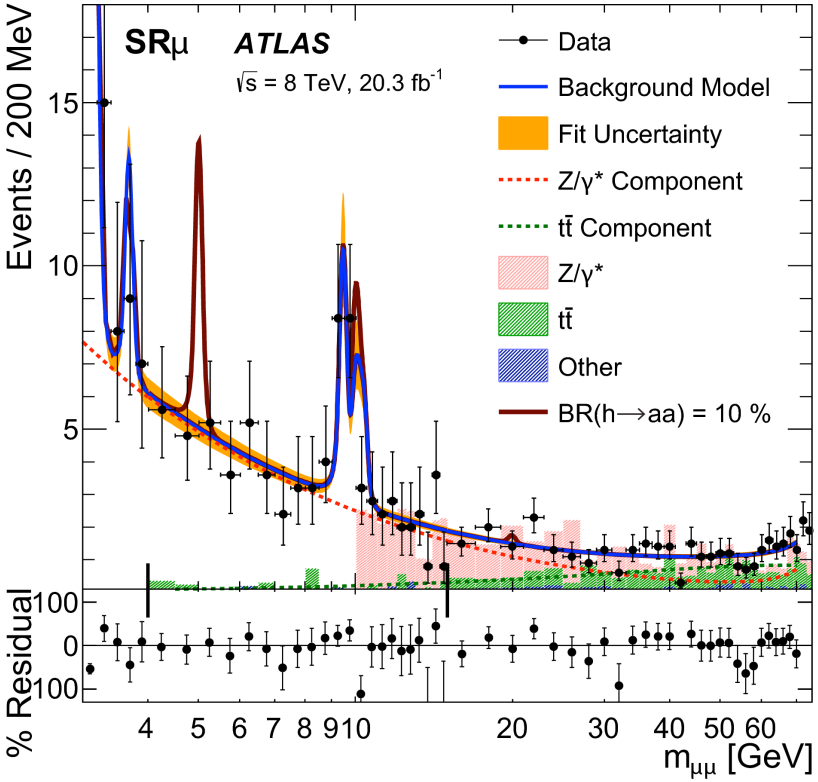


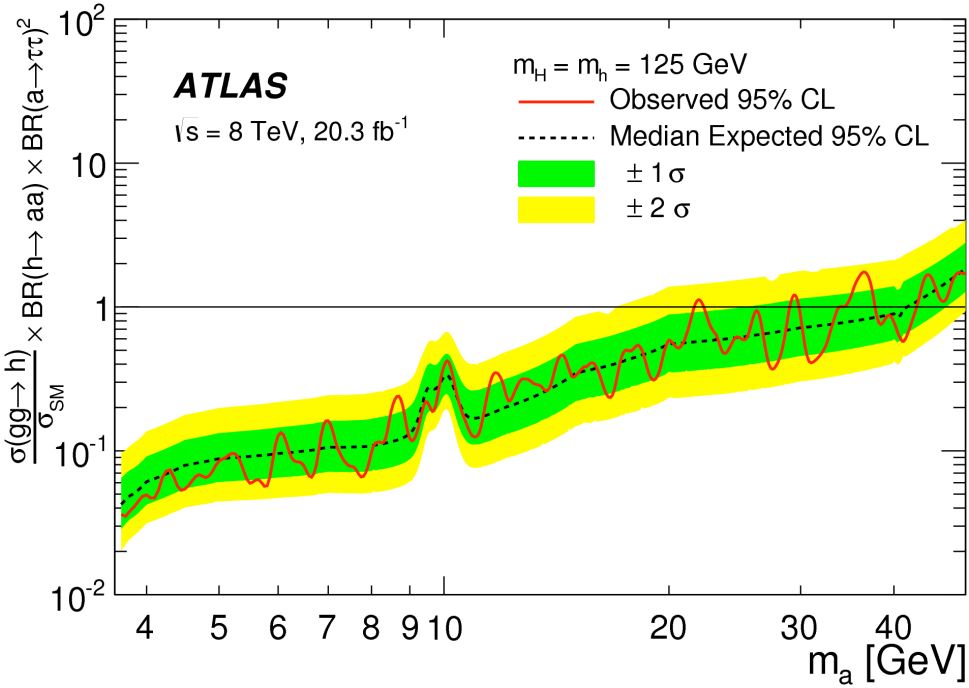
Pre-select $\mu^{\pm}\mu^{\mp}$ events

Signal Selection: $\mu^{\pm}\mu^{\mp}+\ell^{\pm}\mathrm{trk}^{\mp}$

Validation: $\mu^{\pm}\mu^{\mp}+\ell^{\pm}\mathrm{trk}^{\pm}$

Control: $\mu^{\pm}\mu^{\mp}$+(b-)jets





PRD 92 (2015) 052002