Searches Exploiting the Higgs Boson as a Dark/Hidden Sector Portal at the LHC

Run 1 Results and Run 2 Prospects

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Outline

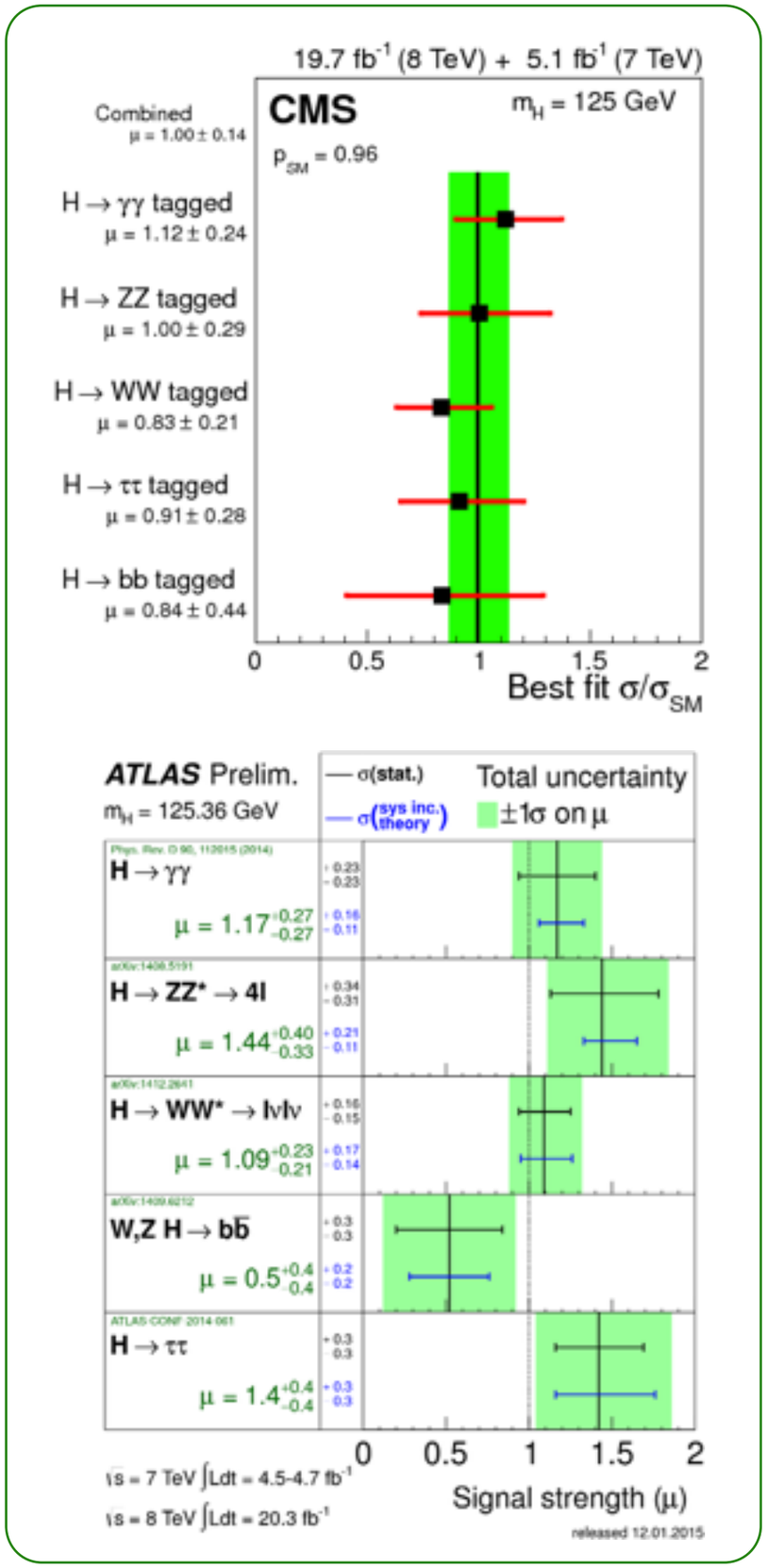
The Higgs

The Higgs as a dark/hidden sector portal

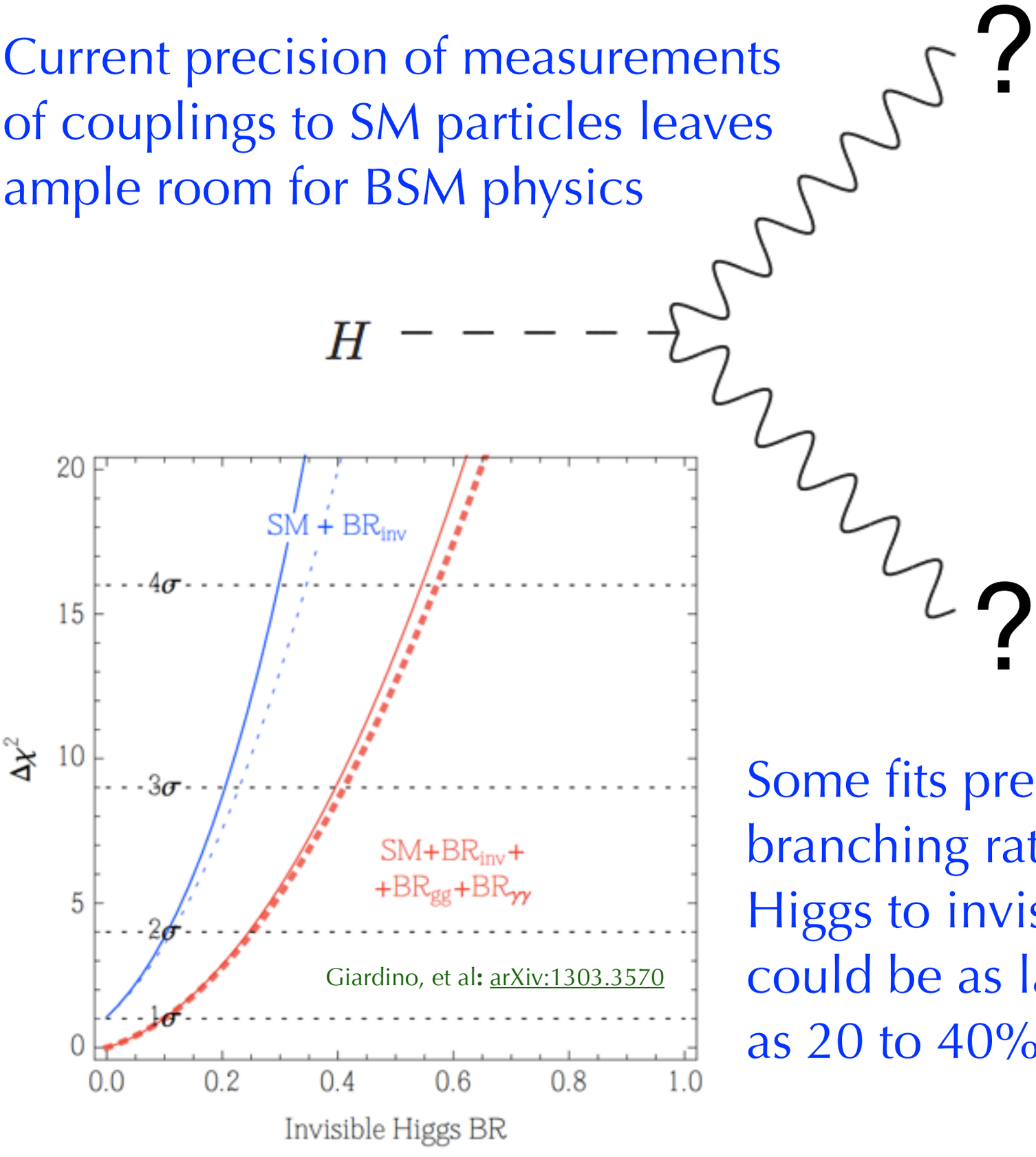
Dark sector Higgs-related searches at ATLAS/CMS

Run 2 prospects

How Standard is the Higgs?



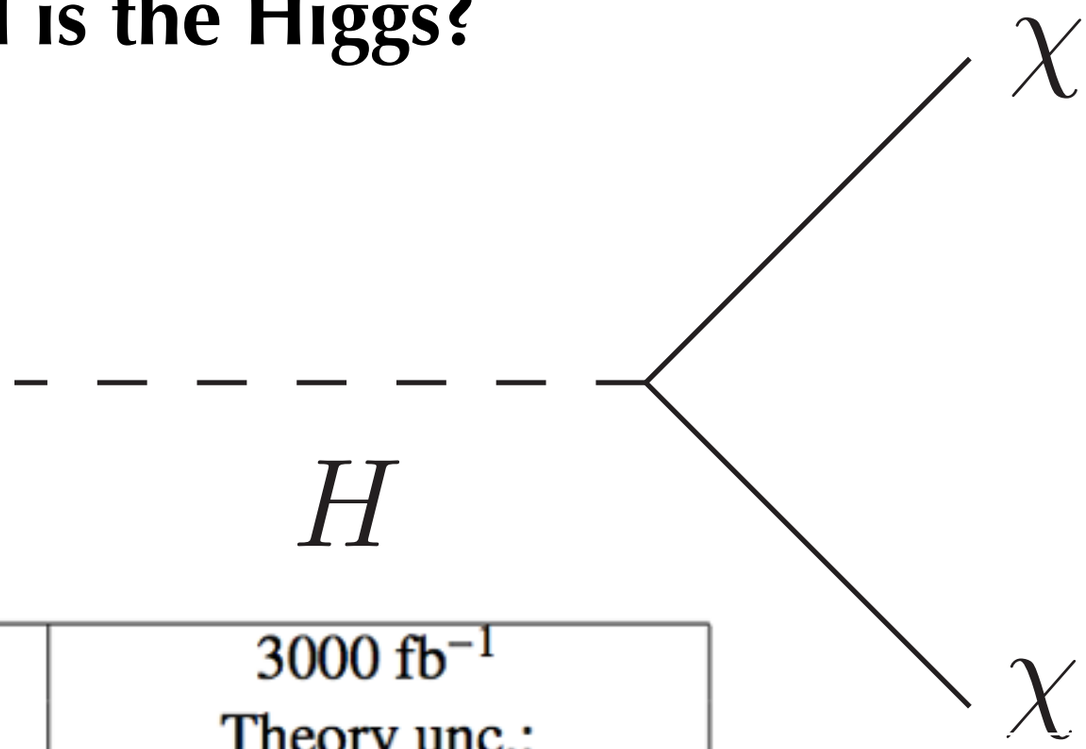
Current precision of measurements of couplings to SM particles leaves ample room for BSM physics



Some fits predict branching ratio of Higgs to invisible could be as large as 20 to 40%

How Standard is the Higgs?

Even with 3000/fb at 14 TeV LHC, ~10% of Higgs width could be invisible



Nr.	Parameter	300 fb^{-1} Theory unc.: All	Half	None	3000 fb^{-1} Theory unc.: All	Half	None
9	κ_g	8.9%	7.1%	6.3%	6.7%	4.1%	2.8%
	κ_γ	4.9%	4.8%	4.7%	2.1%	1.8%	1.7%
	$\kappa_{Z\gamma}$	23%	23%	23%	14%	14%	14%
	$BR_{i,u}$	<22%	<20%	<20%	<14%	<11%	<10%

ATL-PHYS-PUB-2014-016

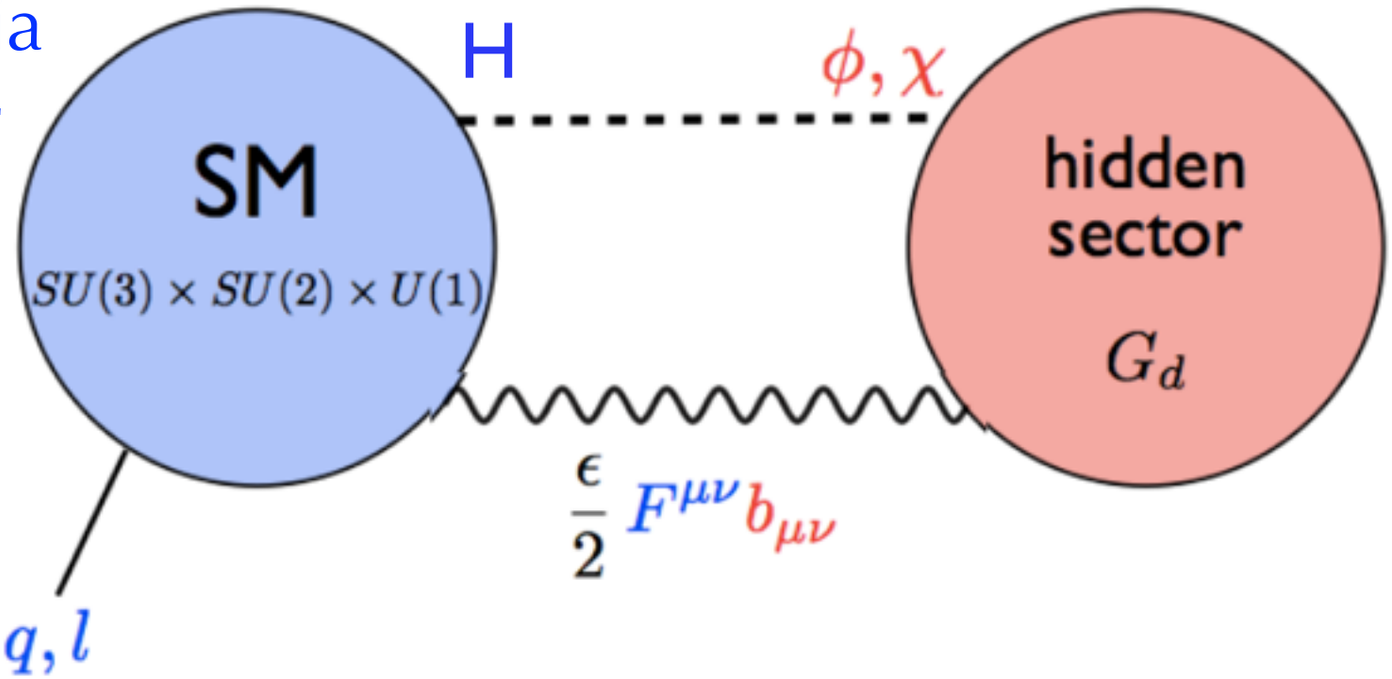
CMS projection for 3000/fb:
$BR_{inv} < 11\%$
< 7% if theory uncertainties scaled by 0.5, other systematic uncertainties scaled by $1/L^{1/2}$

H125 is an excellent opportunity for new physics at the LHC

The Higgs as a dark/hidden sector portal

Many extensions of the SM postulate new states readily accessible via the SM scalar sector

See *Exotic Decays of the 125 GeV Higgs Boson* for an exhuastive roundup: arXiv:1312.4992



The small total width of the Higgs (~4 MeV) means that even a small BSM coupling can translate into a detectable signature

- H125 could be our **best** window into a dark sector
- In addition to the generic interest in discovering evidence of a dark sector, most extensions feature a viable dark matter candidate
- Hadron collider results complement DM direct detection experiments

Here highlighting both dedicated searches for invisible Higgs decays (resulting in E_T^{miss}) and searches where the Higgs plays an initial or intermediate role:

H —> invisible

Mono-H

H —> mono-X (+)

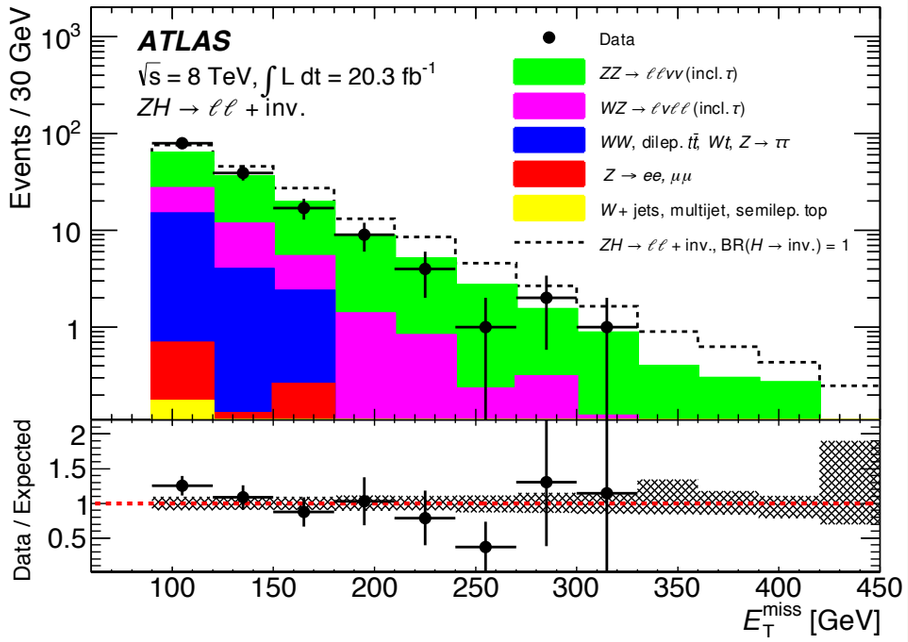
H —> hidden valley —> unique exp. objects

H —> 2X —> 2P2Q, resonant X

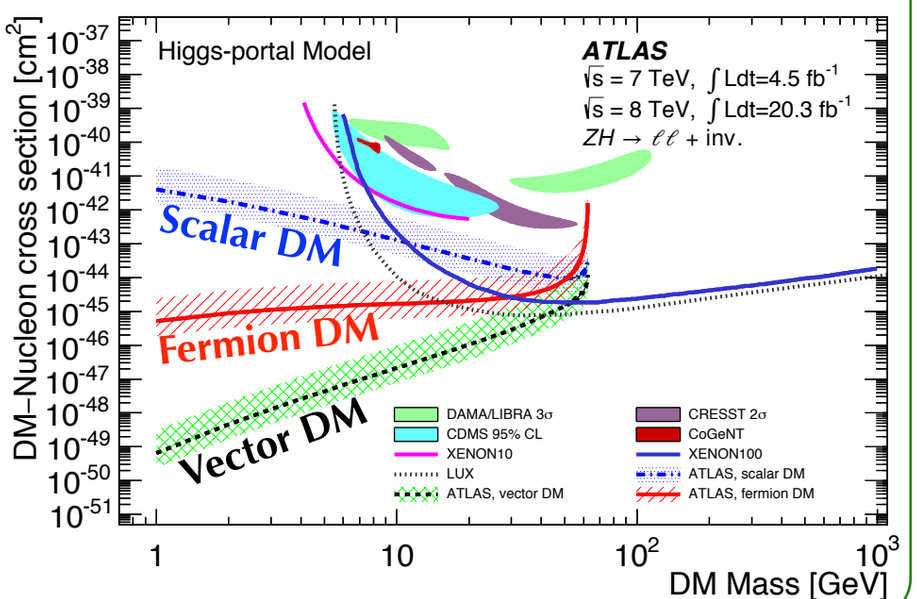
VH ⟶ (ll or jj) + invisible / VBF H ⟶ invisible

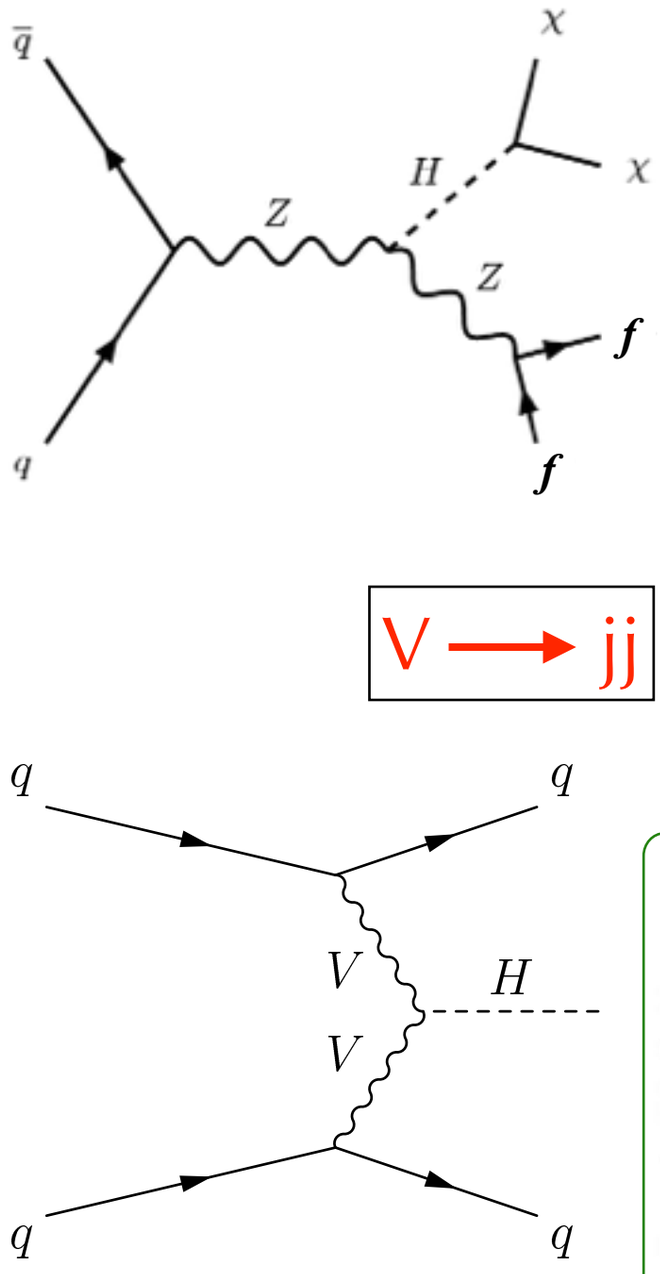
ATLAS: PRL 112.201802
arXiv:1504.04324 (Submitted to EPJC)
ATLAS-CONF-2015-004

Z ⟶ ll (l = e,μ)



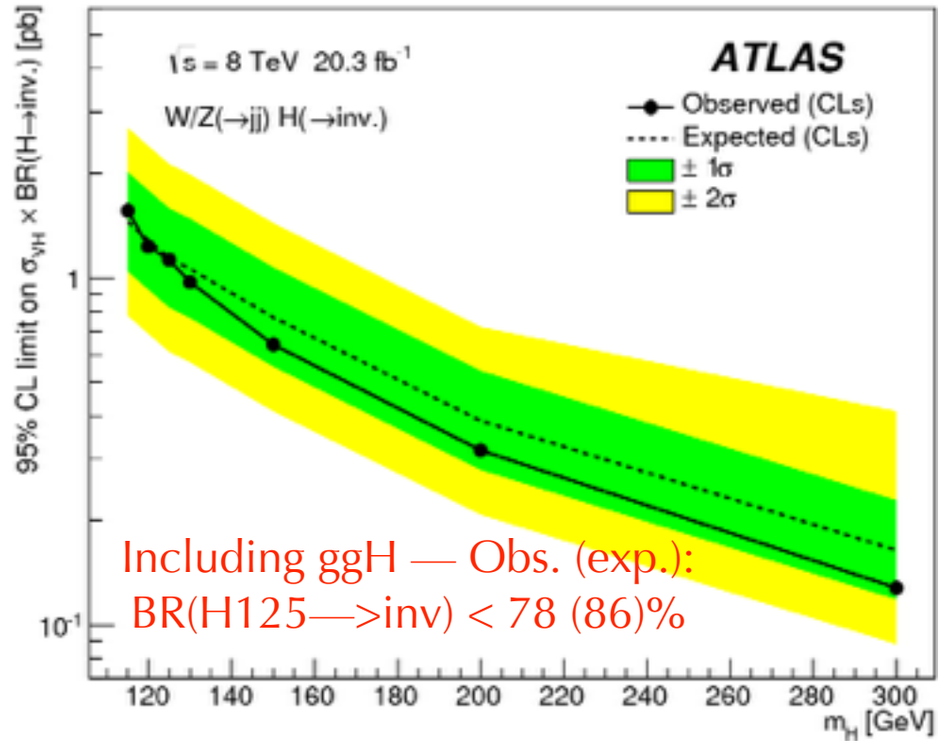
ZH — Obs. (exp.):
BR(H125—>inv) < 75 (62)%





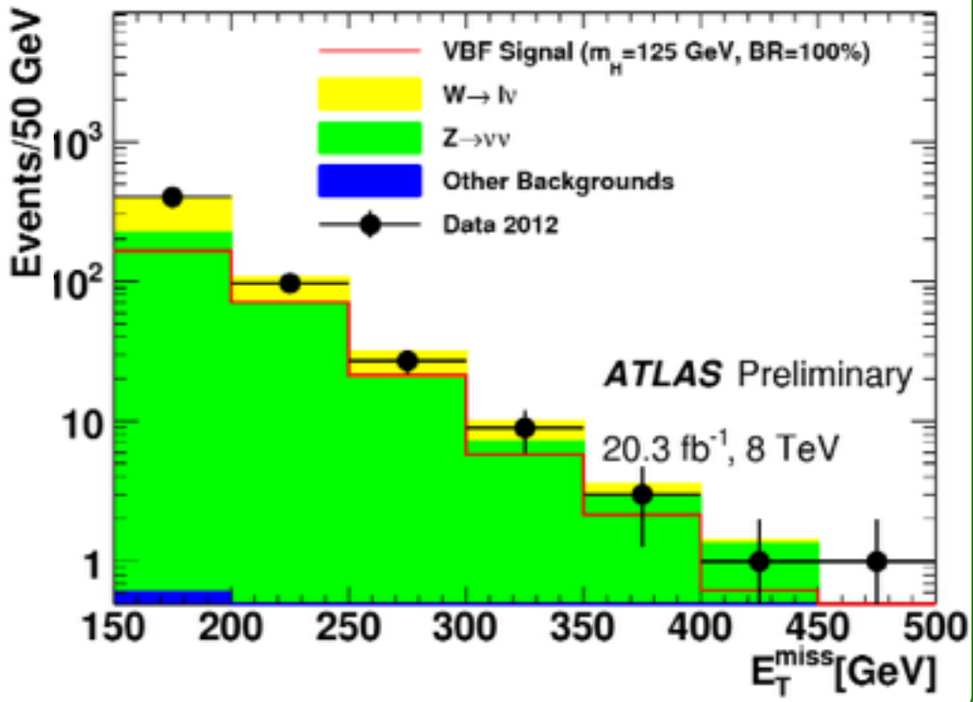
V ⟶ jj

Collider results interpreted in model-dependent way to complement dark matter direct-detection experiments



Including ggH — Obs. (exp.):
BR(H125—>inv) < 78 (86)%

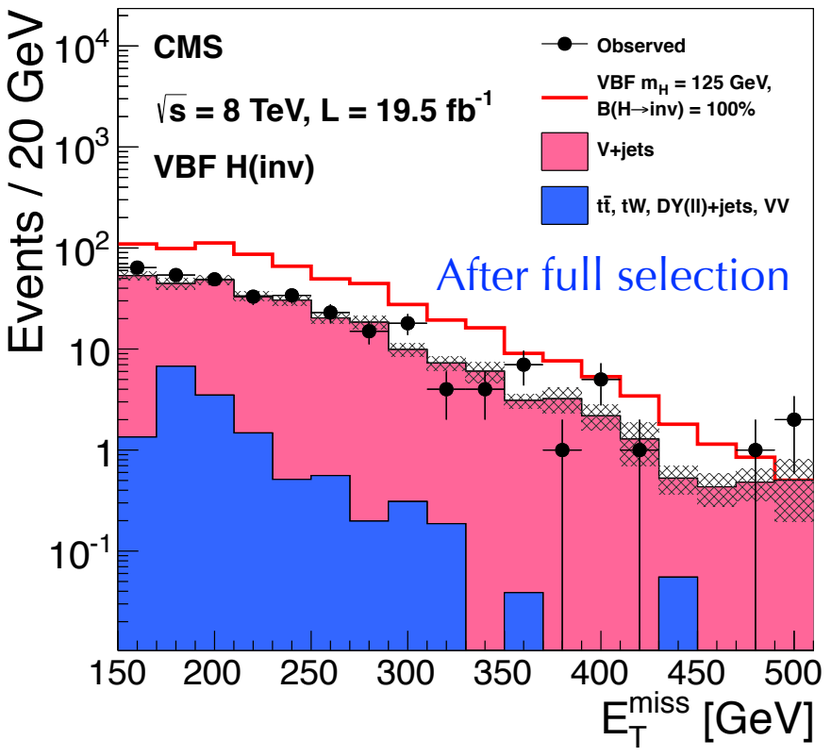
Strongest limit from VBF — Obs. (exp.):
BR(H125—>inv) < 29 (35)%

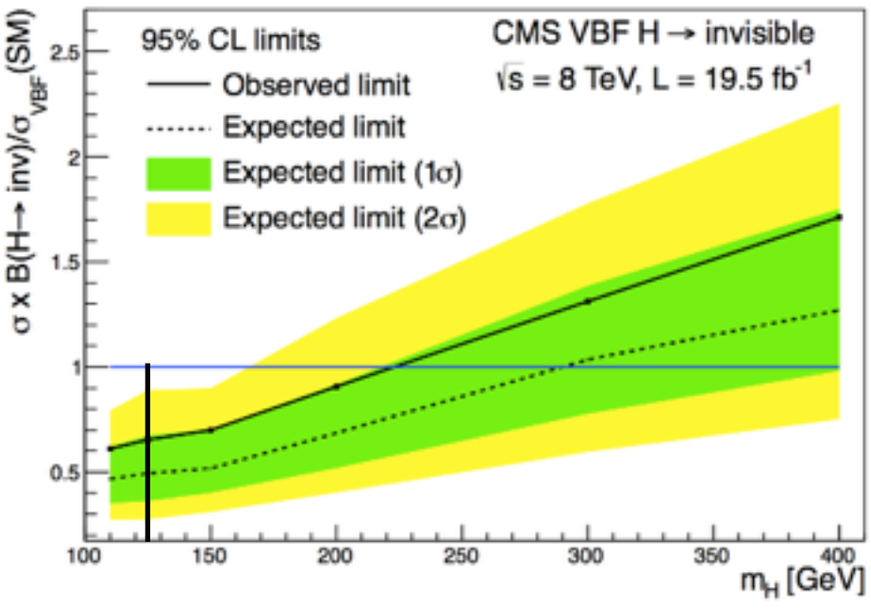


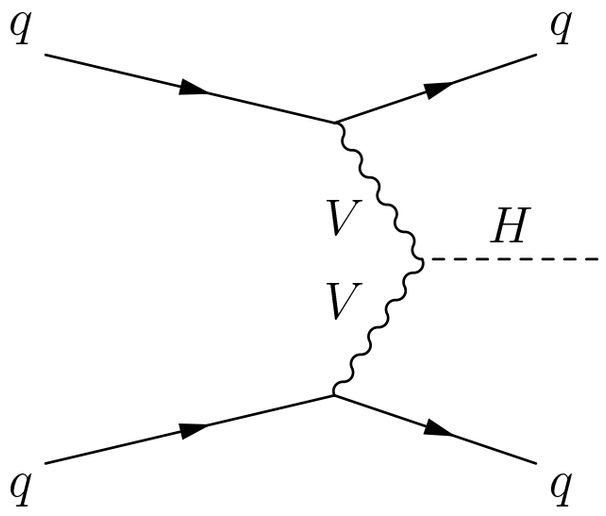
VH ⟶ (ll or jj) + invisible / VBF H ⟶ invisible

CMS: EPJC 74 (2014) 2980

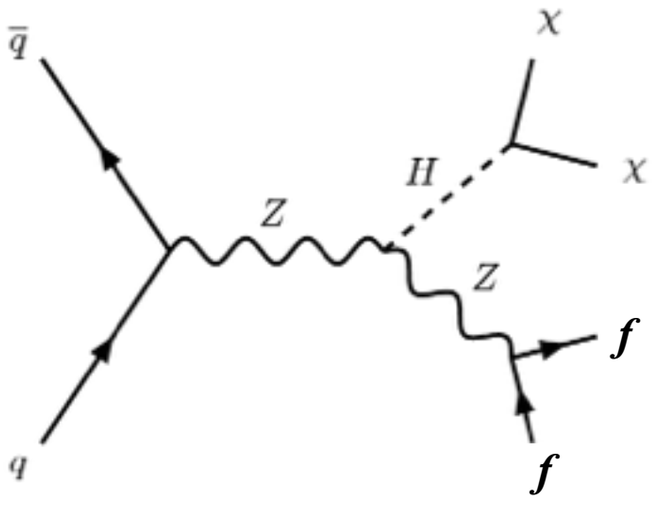
VBF



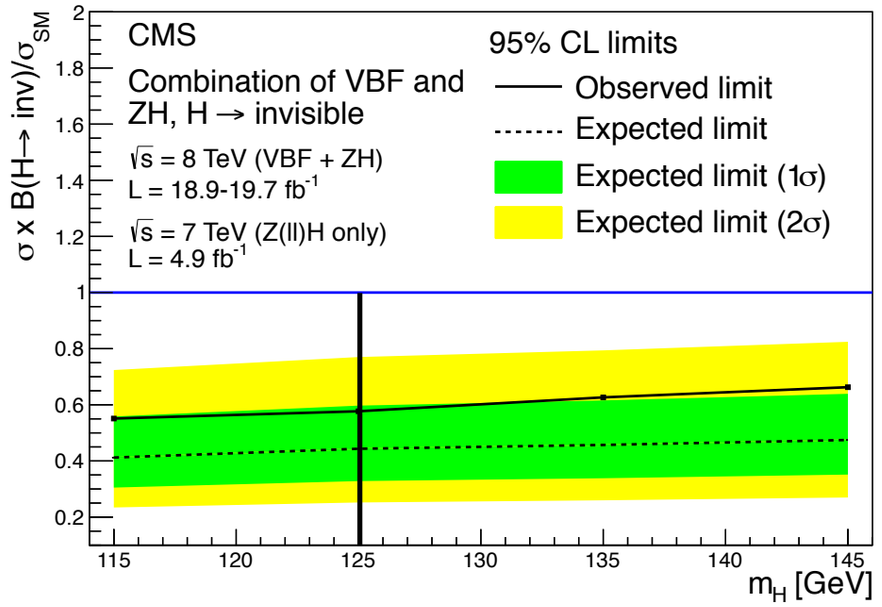


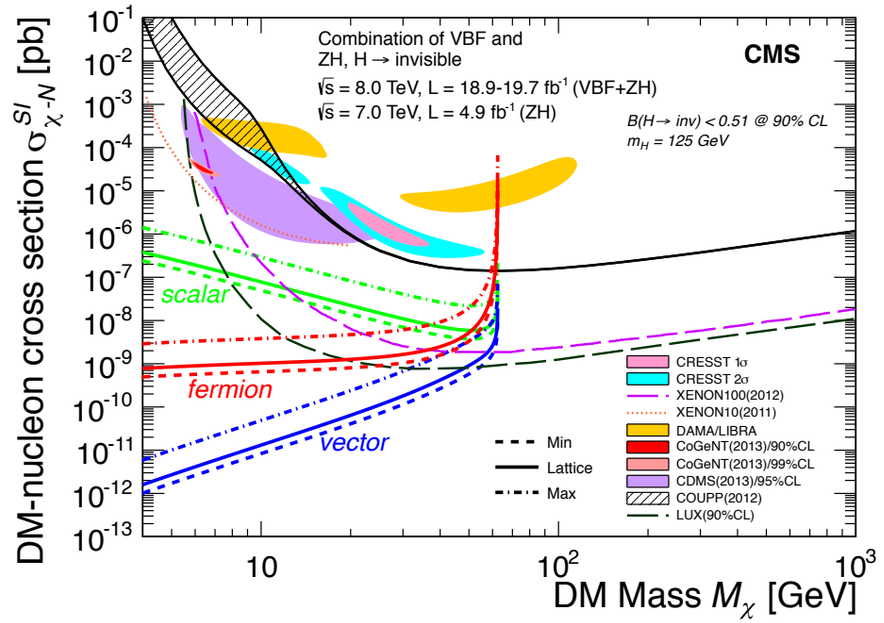


All channels combined
Obs. (exp.):
BR(H125—>inv) < 58 (44)%



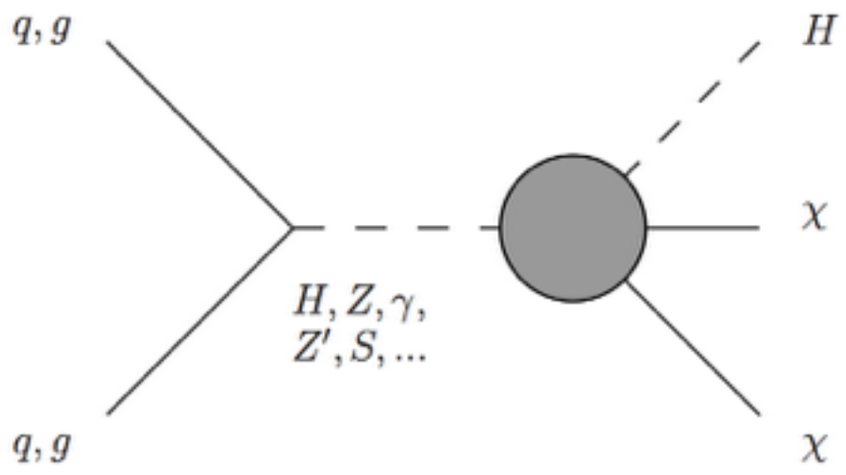
Combination VBF and ZH





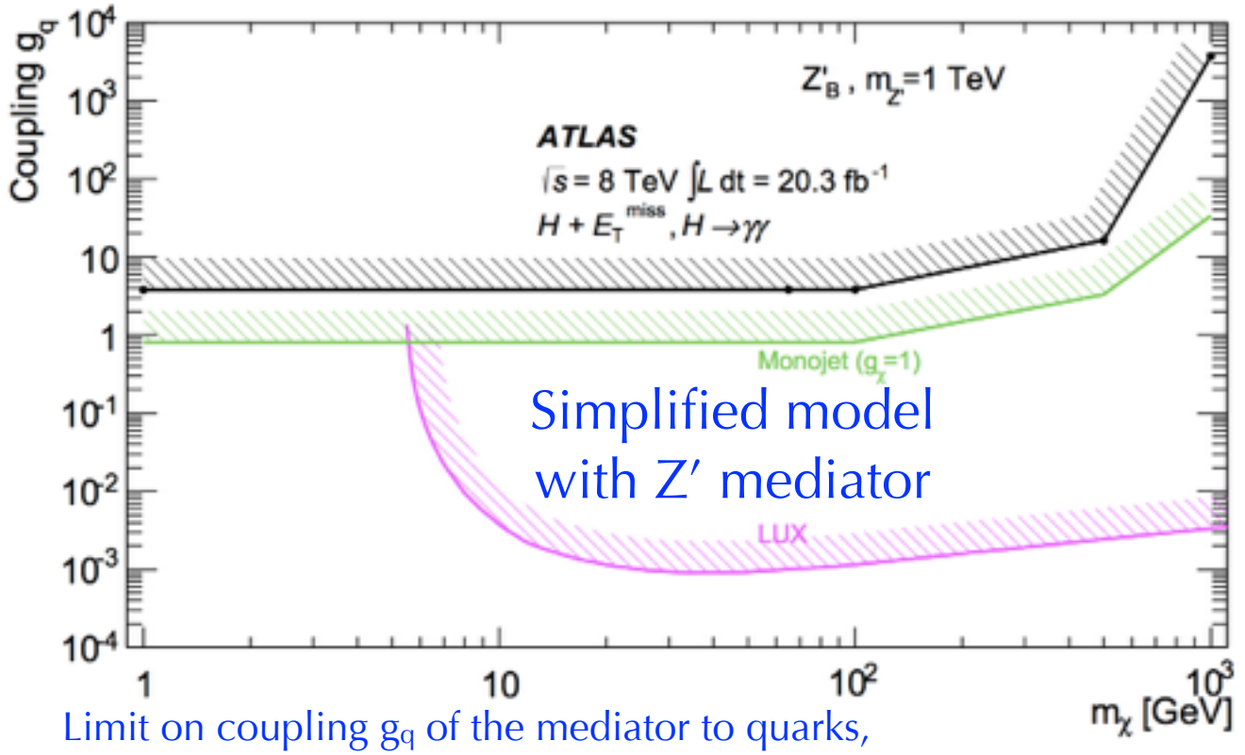
$H \longrightarrow 2\gamma + E_T^{miss}$

ATLAS: arXiv:1506.01081
Submitted to PRL

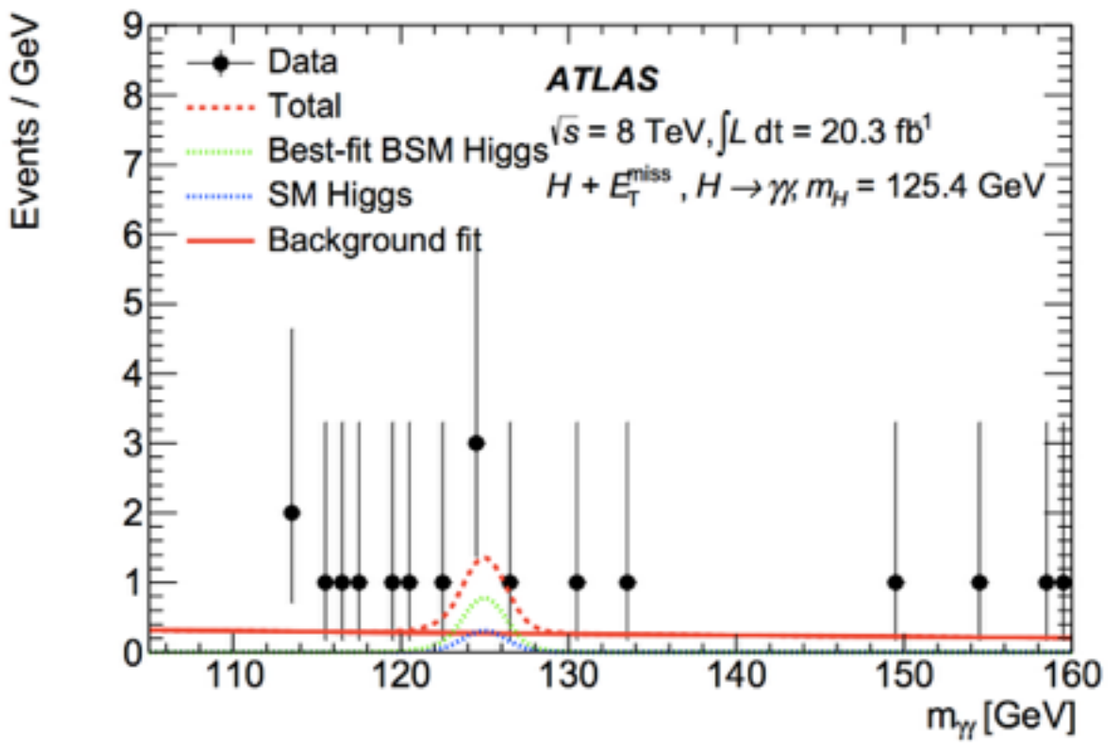


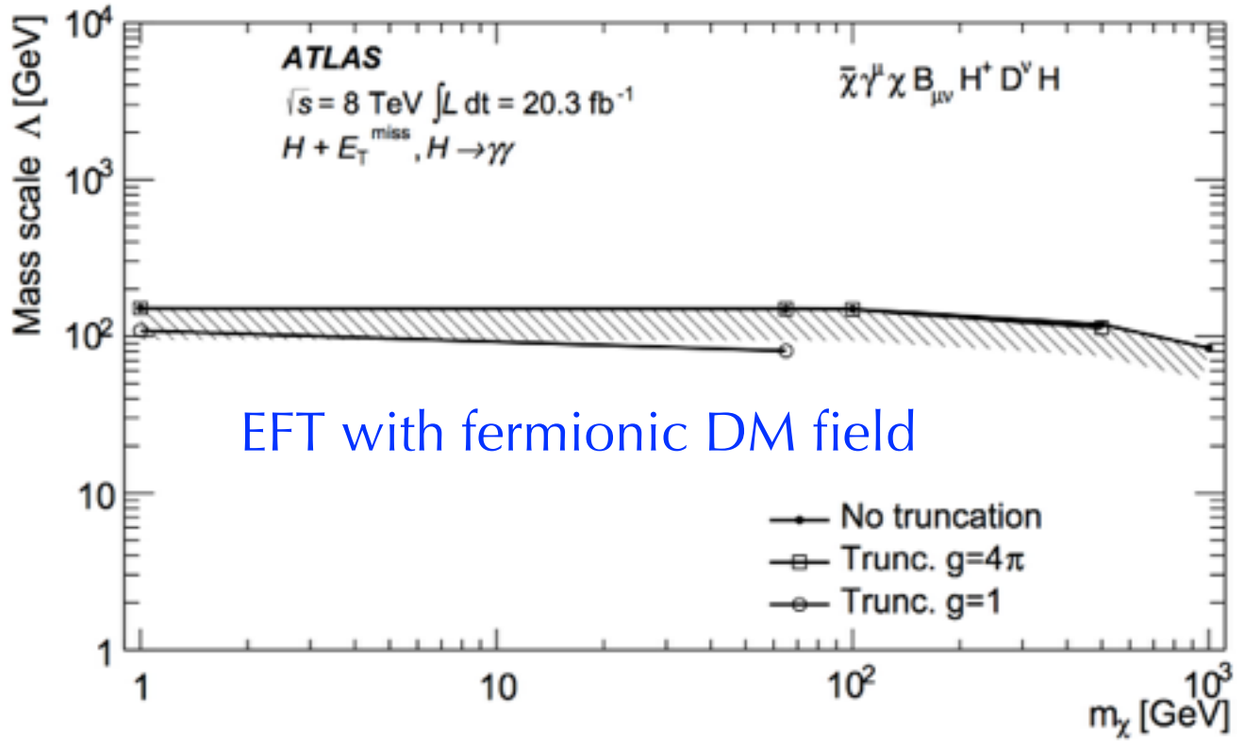
Directly probes the structure of the effective DM-SM coupling

- Sensitive to $m_\chi > m_H/2$
- Consider both EFT and simplified models



Limit on coupling g_q of the mediator to quarks, assuming maximal coupling g_χ to DM



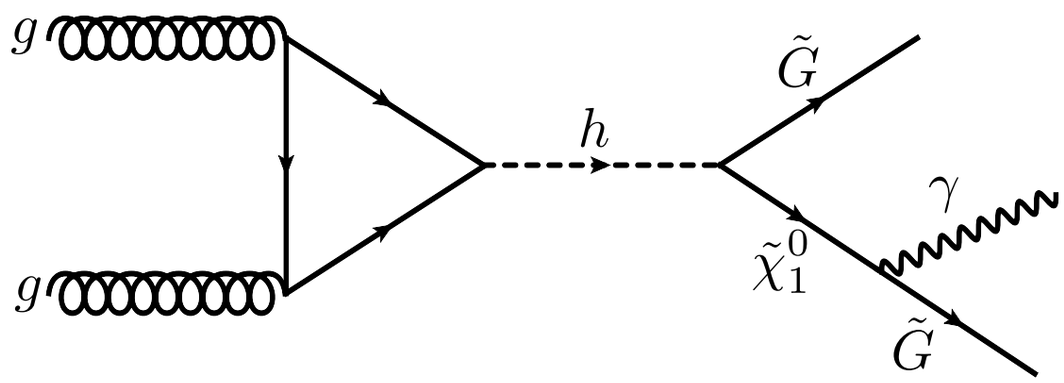


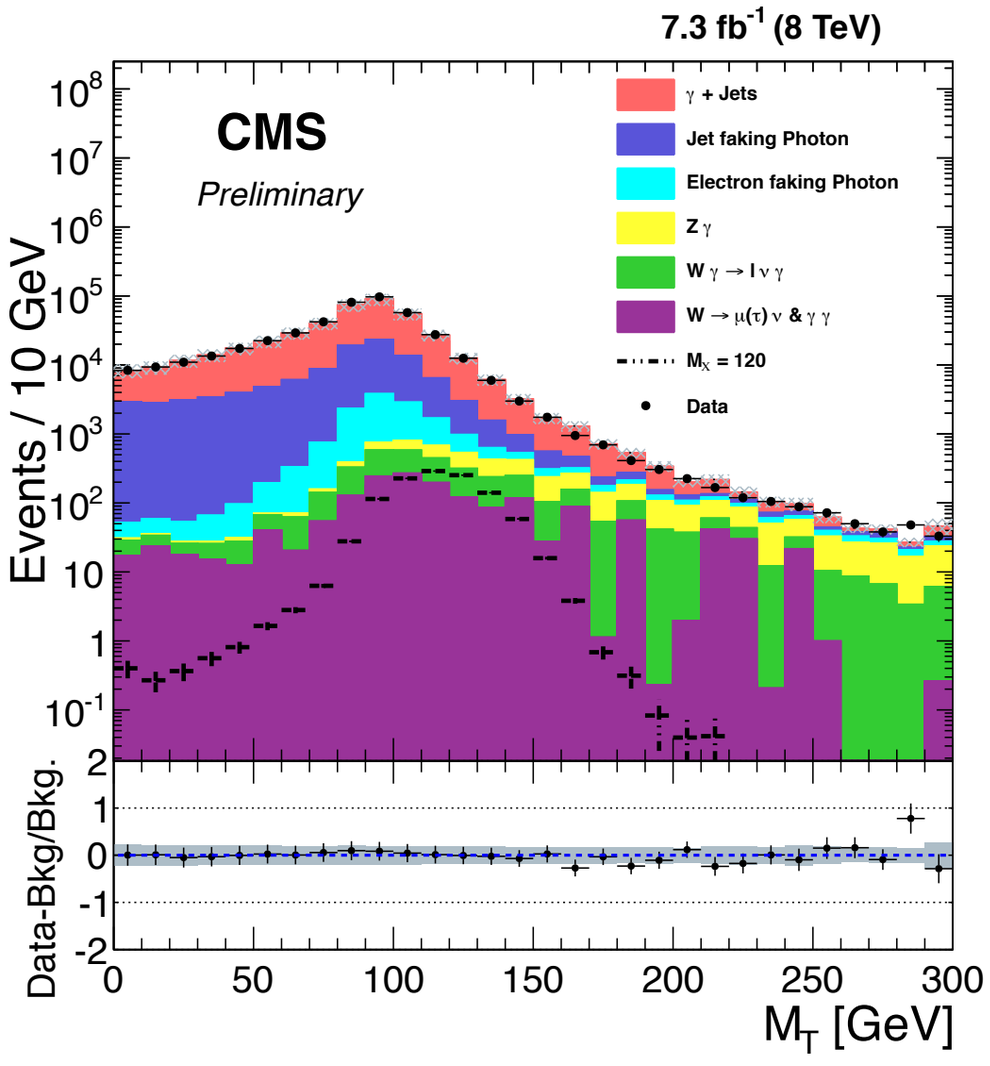
$H \longrightarrow$ mono-γ + E_T^{miss}

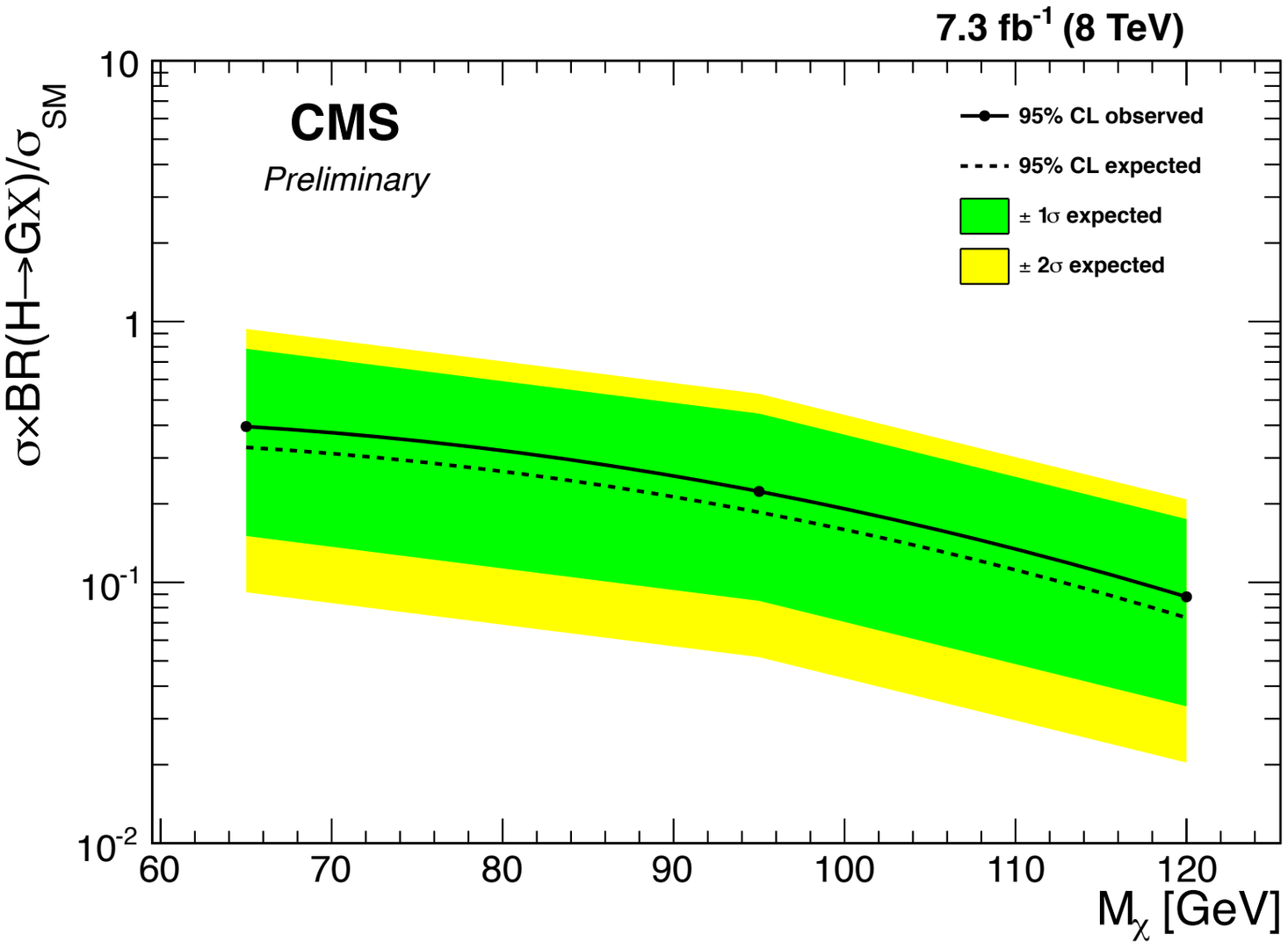
CMS: CMS-PAS-HIG-14-024

Exotic Higgs decay in low-scale SUSY breaking scenario entailing additional optimizations from model-independent search for new physics

- Irreducible background from $Z\gamma$
- Others from γ+jet and mono-e and mono-jet faking γ
- Require $M_T > 100$ GeV





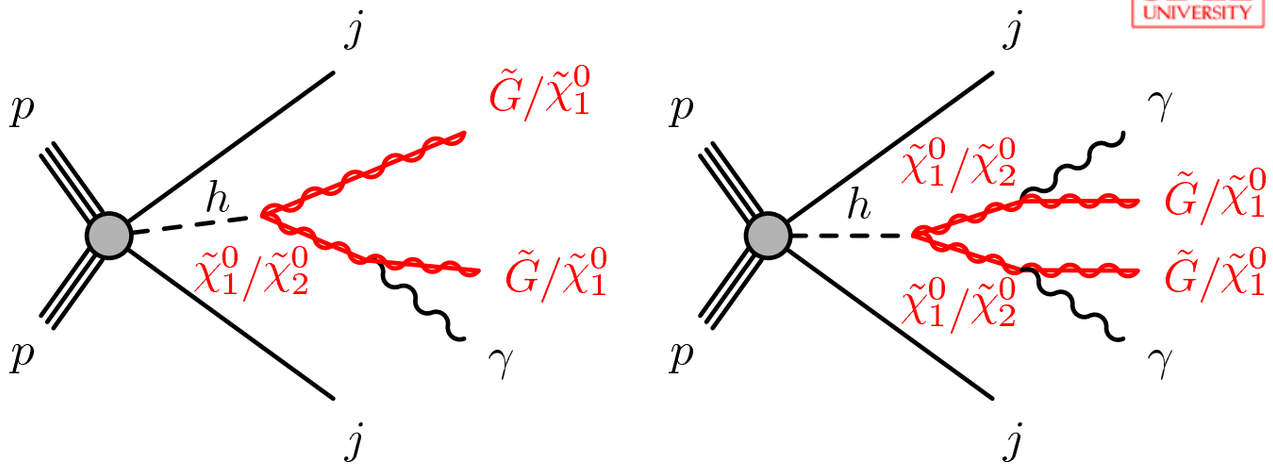


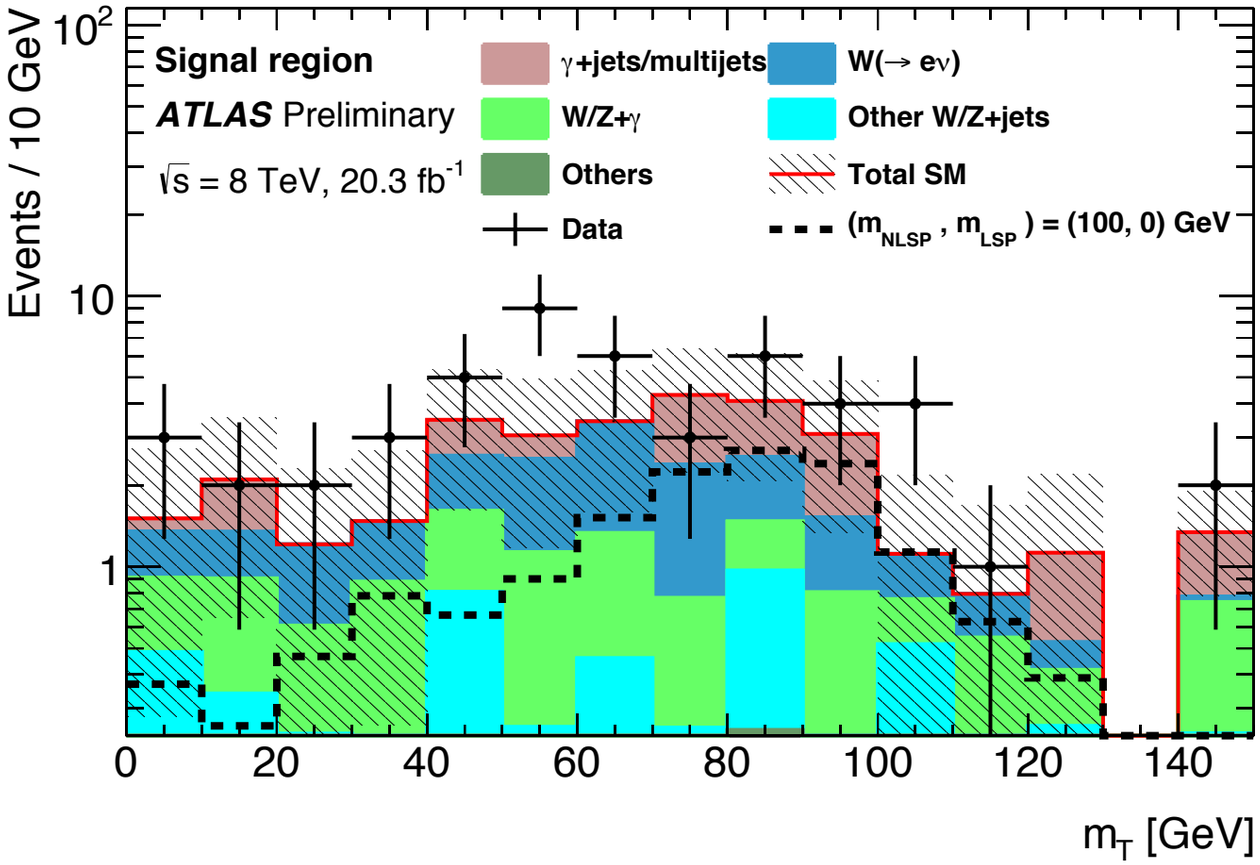
(VBF) H ⟶ {mono-γ or 2γ} + E_T^{miss}

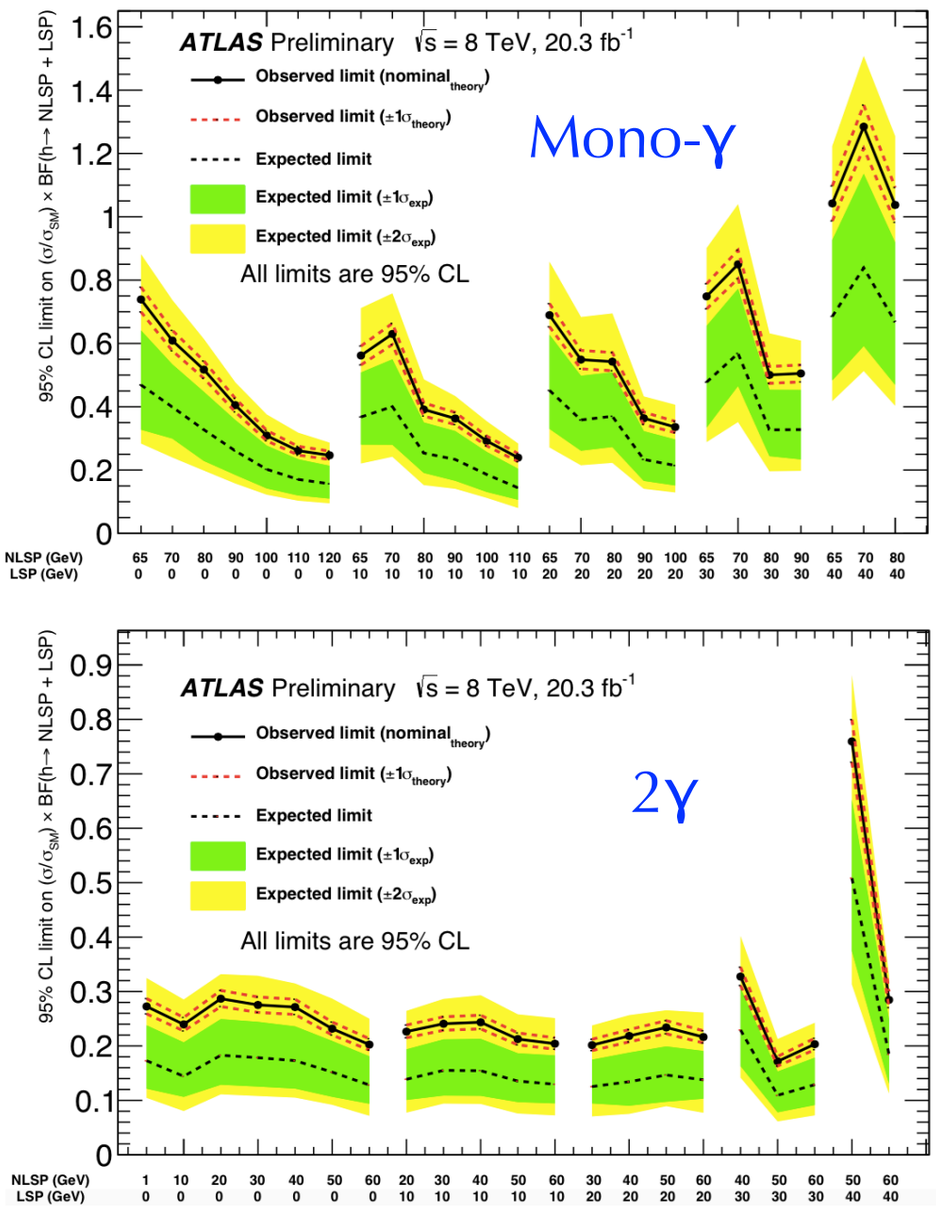
ATLAS: ATLAS-CONF-2015-001

Exotic Higgs decay in GMSB and NMSSM-type scenarios

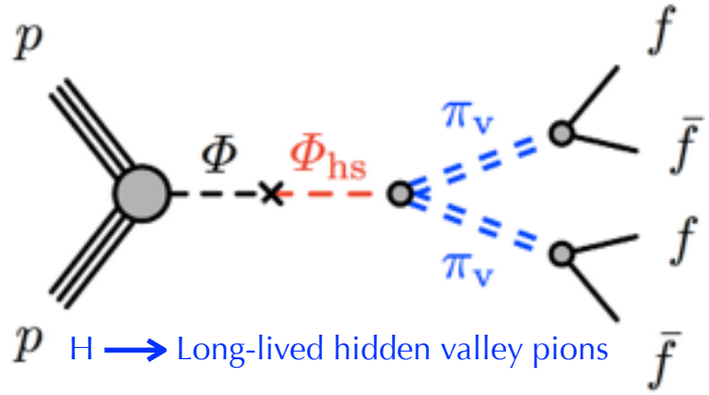
- VBF production facilitates better data-driven γ+jets and multi-jet background estimates than ggH
- VBF ==> Higgs boosted in transverse plane ==> γ and E_T^{miss} not necessarily back-to-back ==> use angles to define control regions







H ⟶ displaced jets

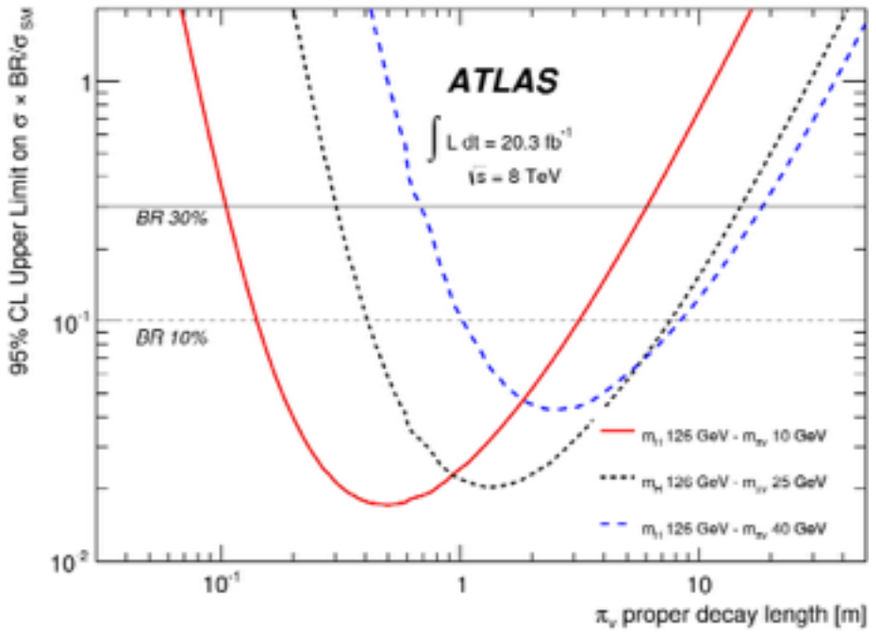


H ⟶ Long-lived hidden valley pions

ATLAS: PLB 743 (2015) 15-34

DJs in the hadronic calorimeter

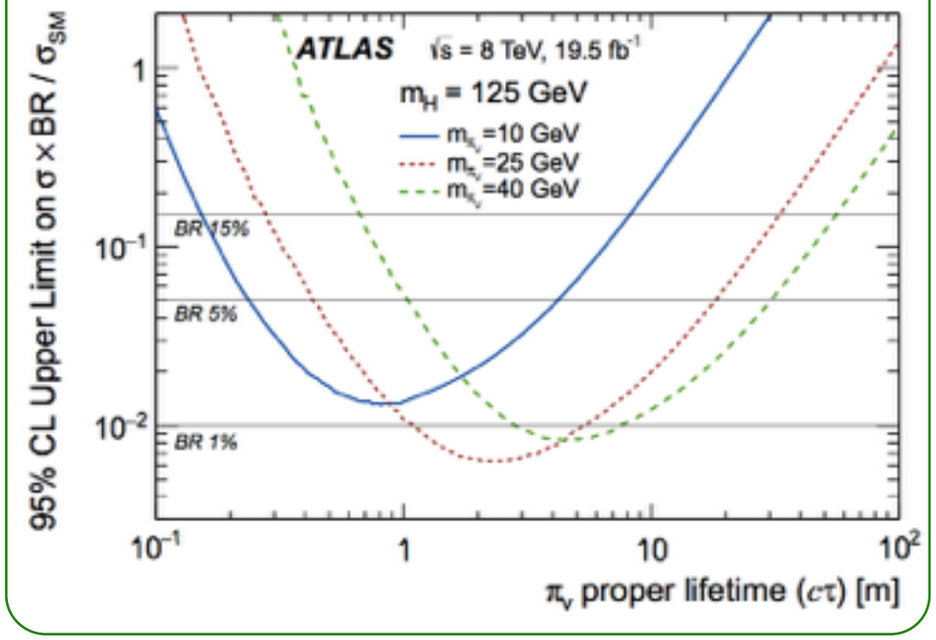
Pair of jets decaying in the HCal, no ID tracks pointing towards the jet



ATLAS: arXiv1504.03634
Submitted to PRD

DJs in the ID or muon spectrometer

Five topologies defined by combinations of muon and jet + E_T^{miss} triggers

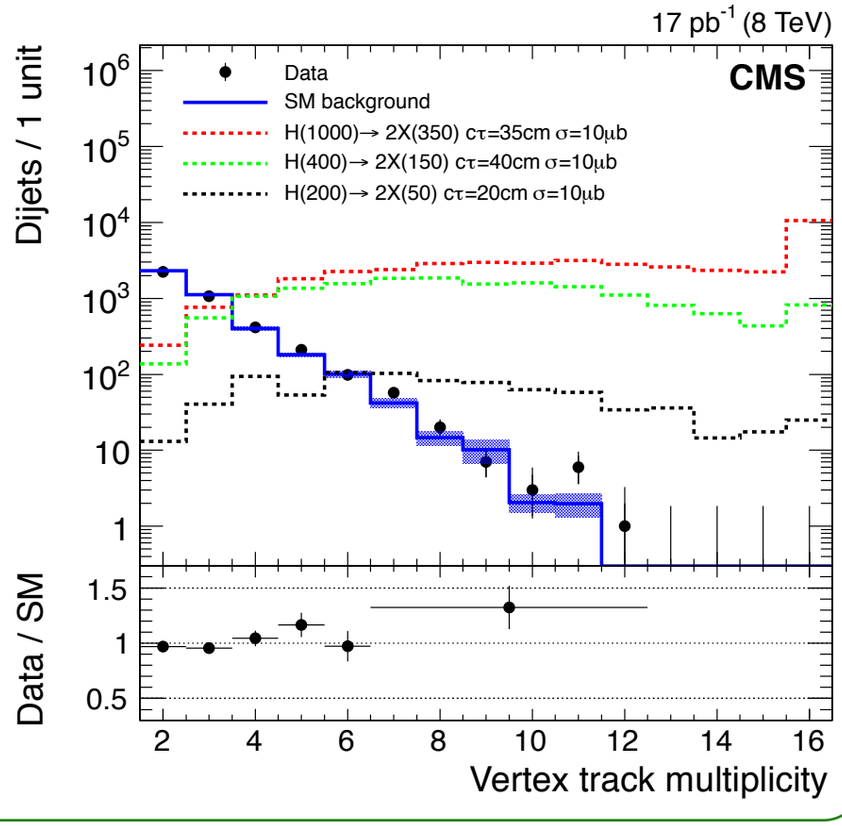


CMS: PRD.91.012007

DJs in the inner detector

Two sets of displaced tracks are fitted for finding a common secondary vertex

Signal events should have higher number of tracks associated to the secondary vertex

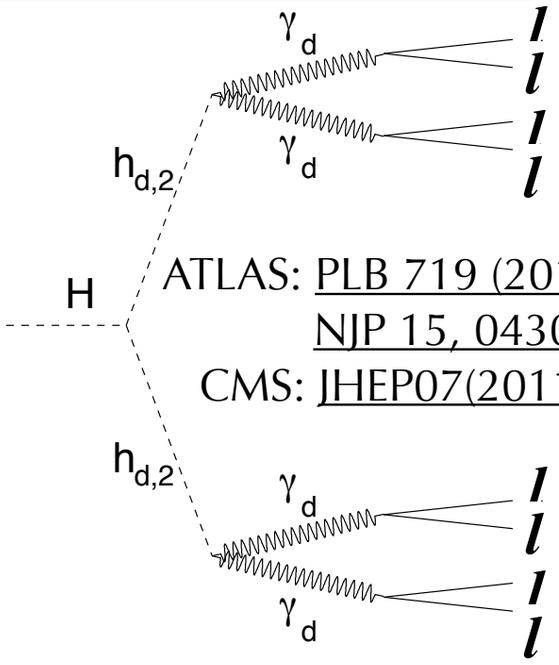


H ⟶ lepton-jets (via dark fermions/scalars/photons)

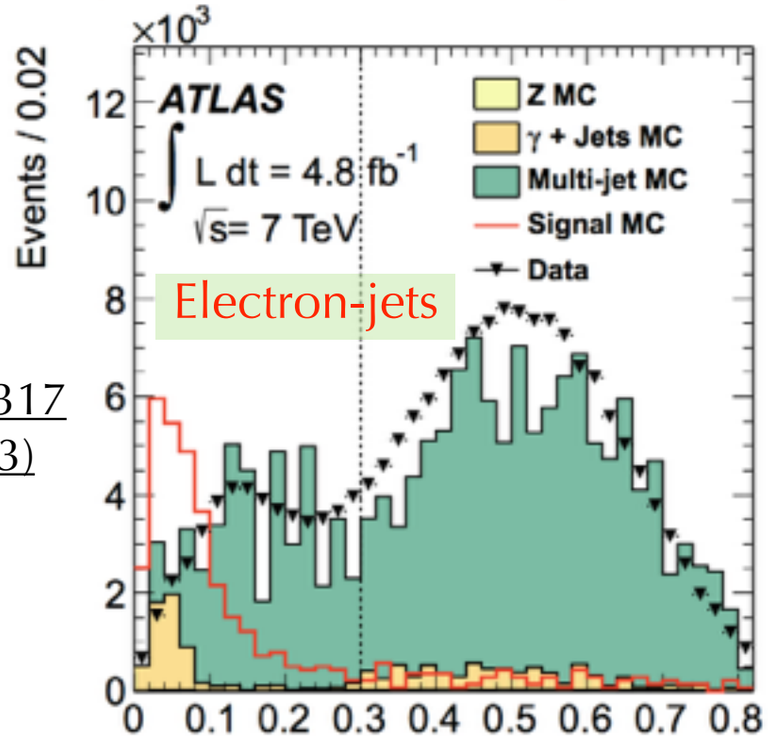
Dark/hidden sector coupled to SM Higgs and leptons via very light dark sector particles

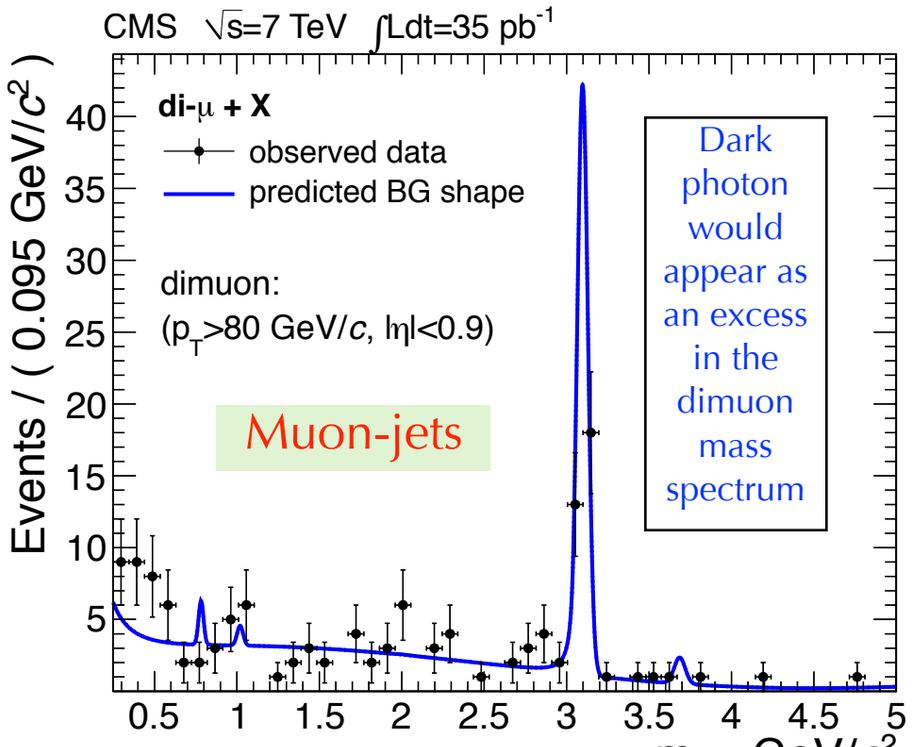
- Highly collimated groupings of leptons: **lepton-jets;** distinct LHC signature

Prompt — 7 TeV



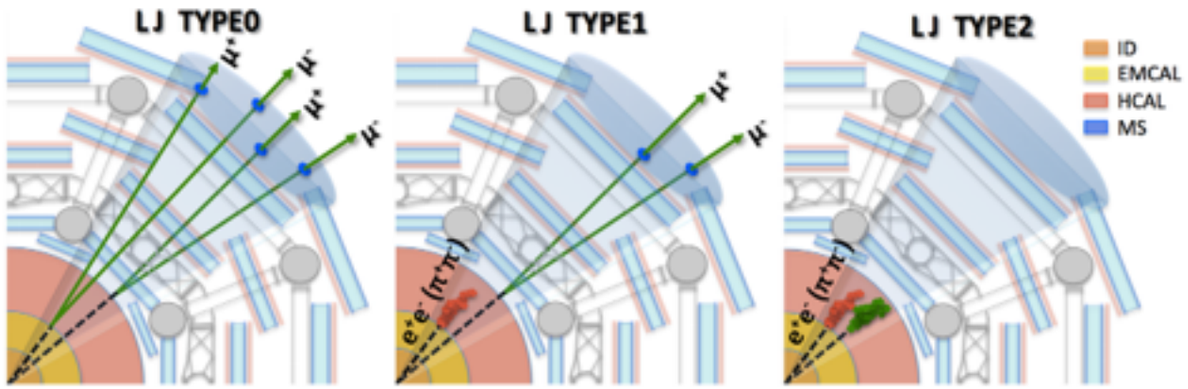
ATLAS: PLB 719 (2013) 299-317
NJP 15, 043009 (2013)
CMS: JHEP07(2011)098





Displaced — 8 TeV

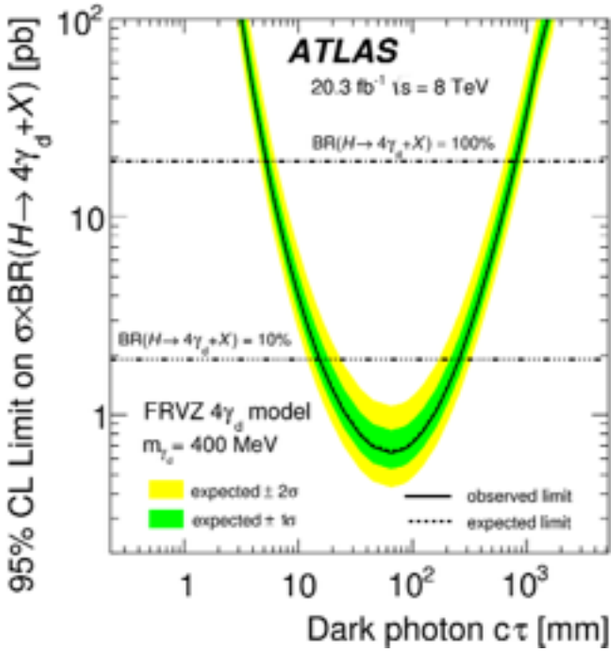
ATLAS: JHEP11(2014)088

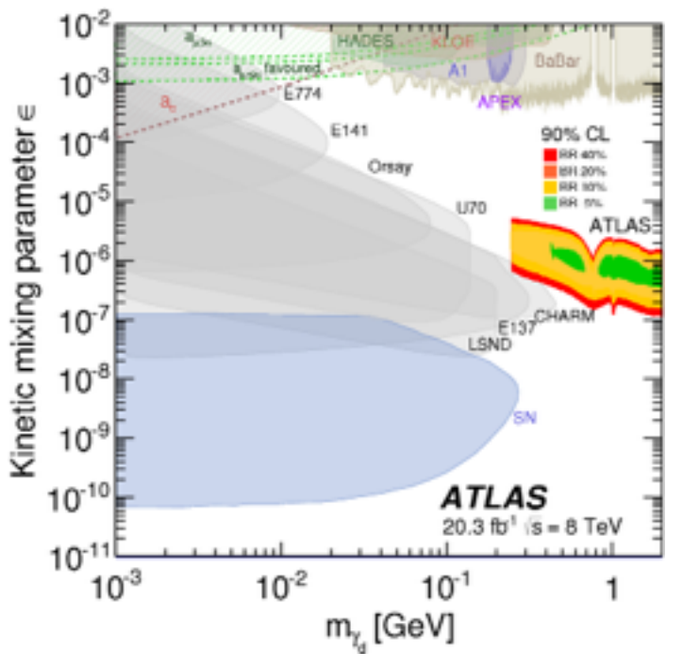


Three separate types of lepton-jet definitions considered

Cosmic backgrounds important here

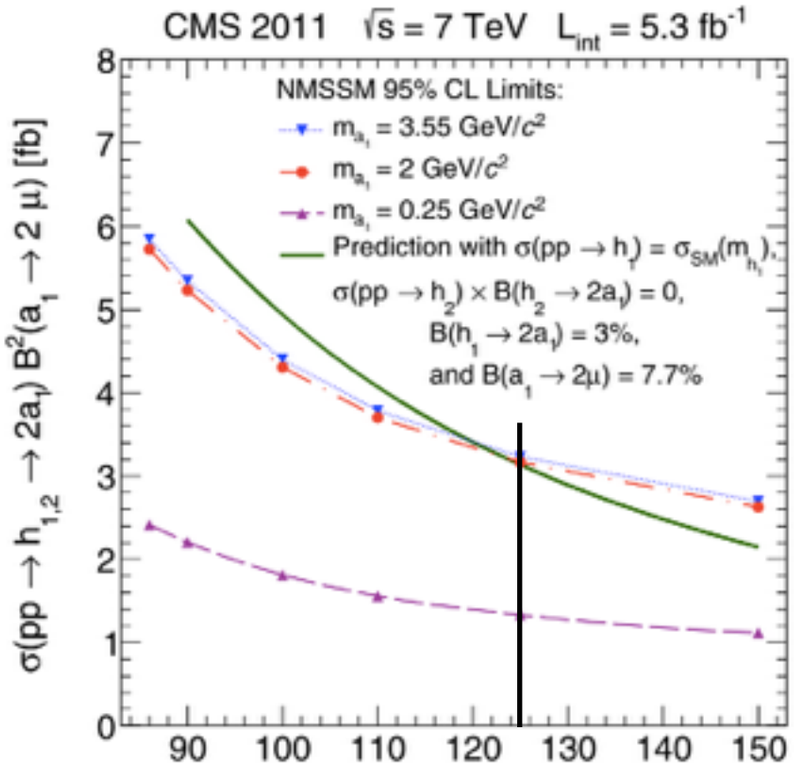
Weak interaction ==> non-negligible dark photon lifetime



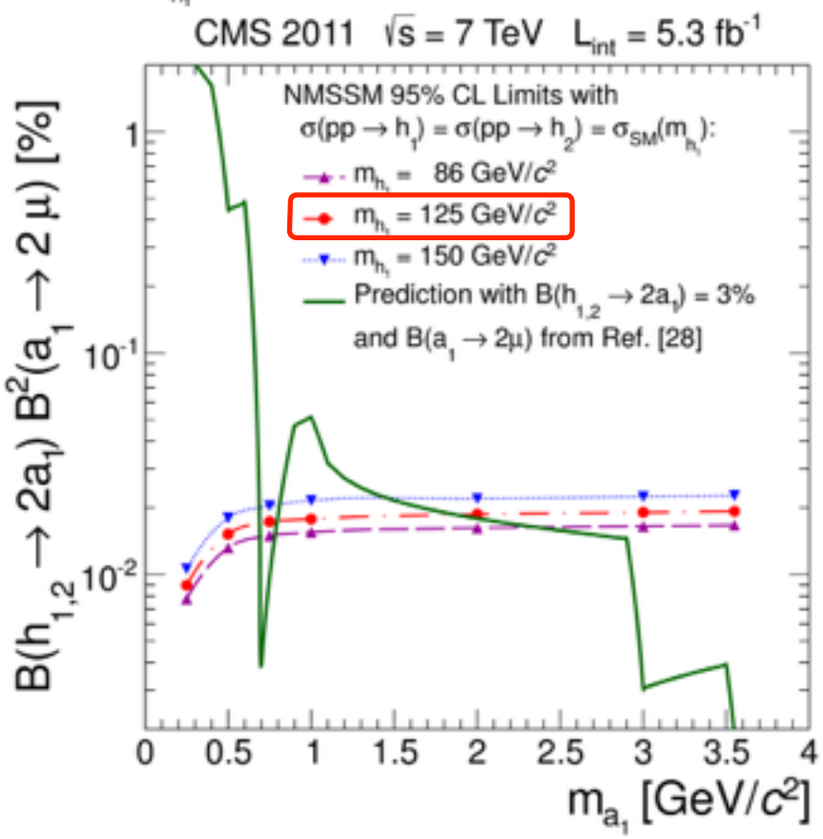


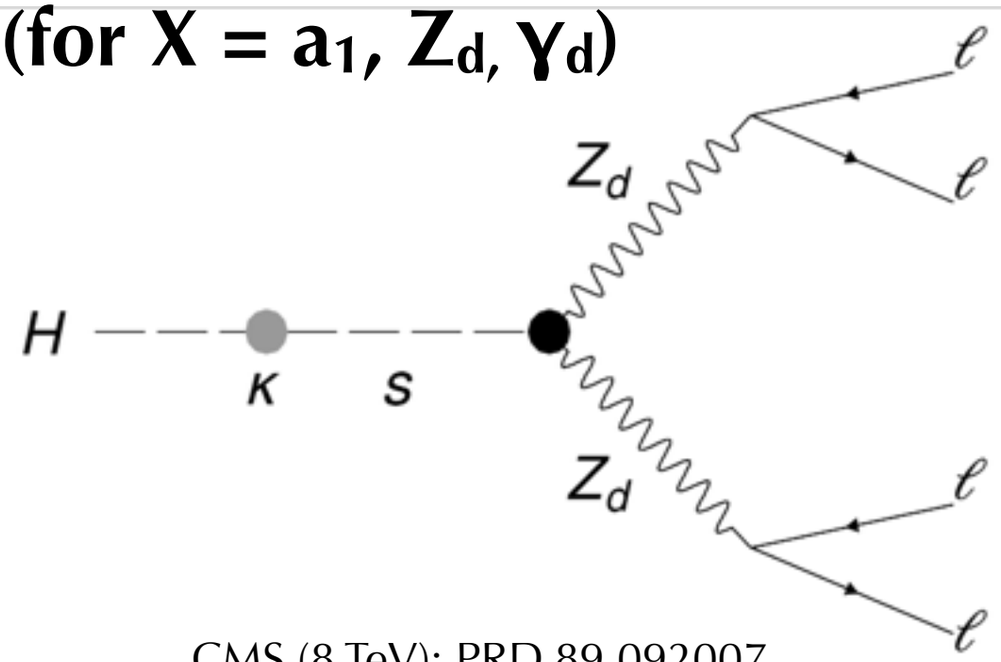
$H \longrightarrow XX \longrightarrow 4l$ (for $X = a_1, Z_d, \gamma_d$)

CMS (7 TeV): PLB 726 (2013) 564-586

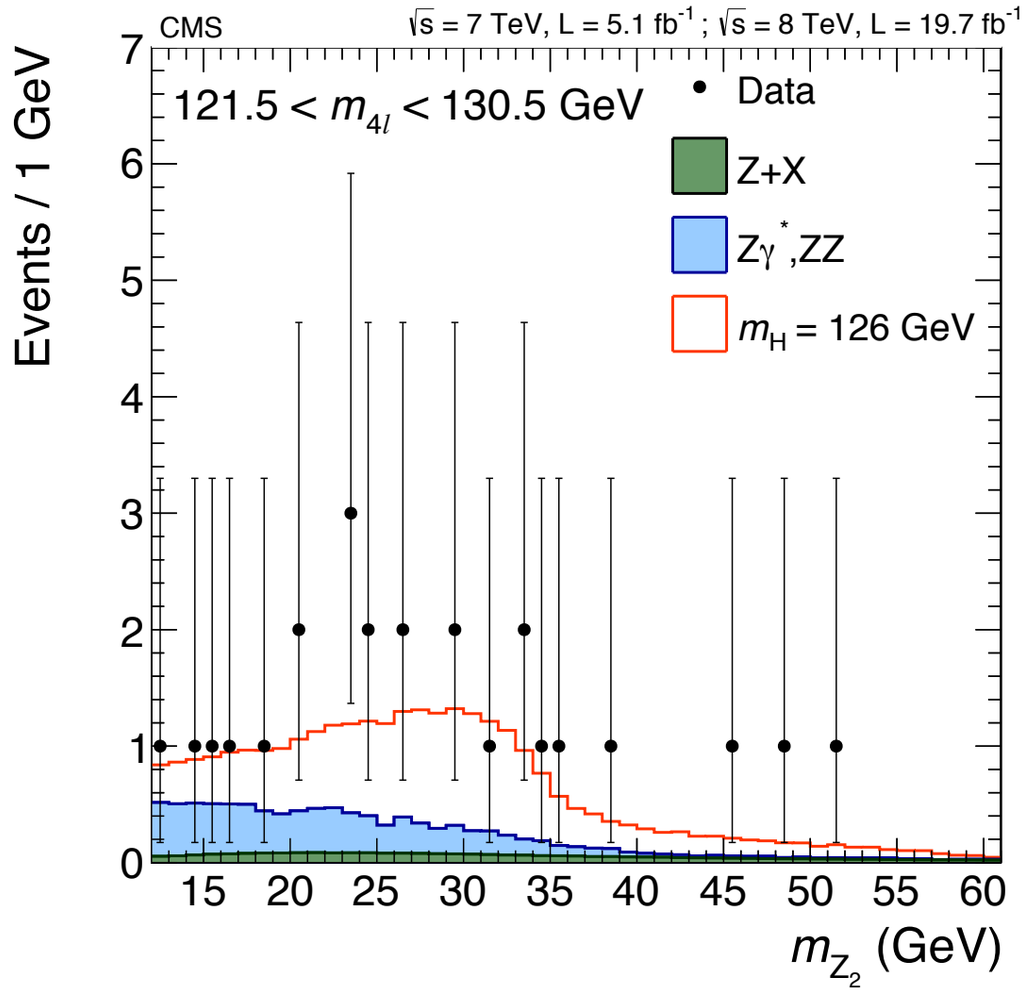


Focus on
low m_X range:
0.25-3.5 GeV





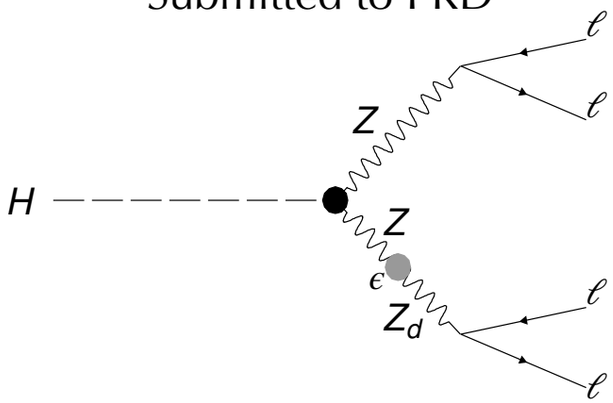
CMS (8 TeV): PRD.89.092007

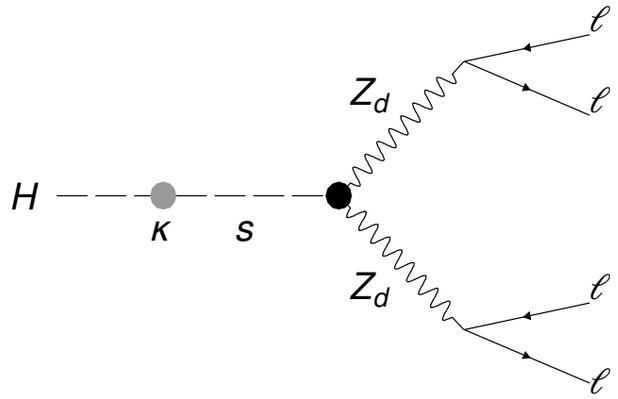


mZ2 spectrum from SM h —> ZZ* —> 4l measurement

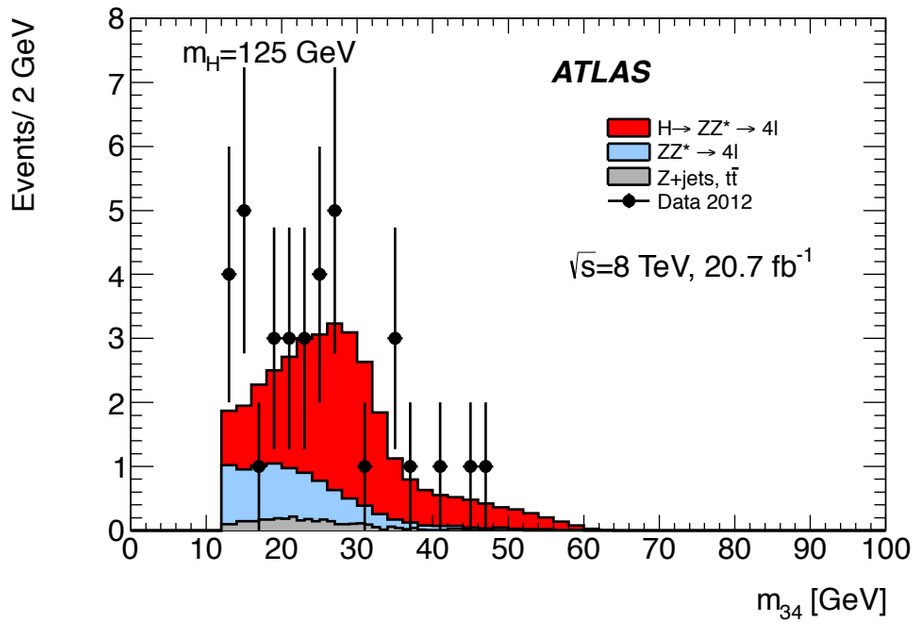
ATLAS (8 TeV): arXiv:1505.07645
Submitted to PRD

$H \longrightarrow Z_{(d)}Z_d \longrightarrow 4l$

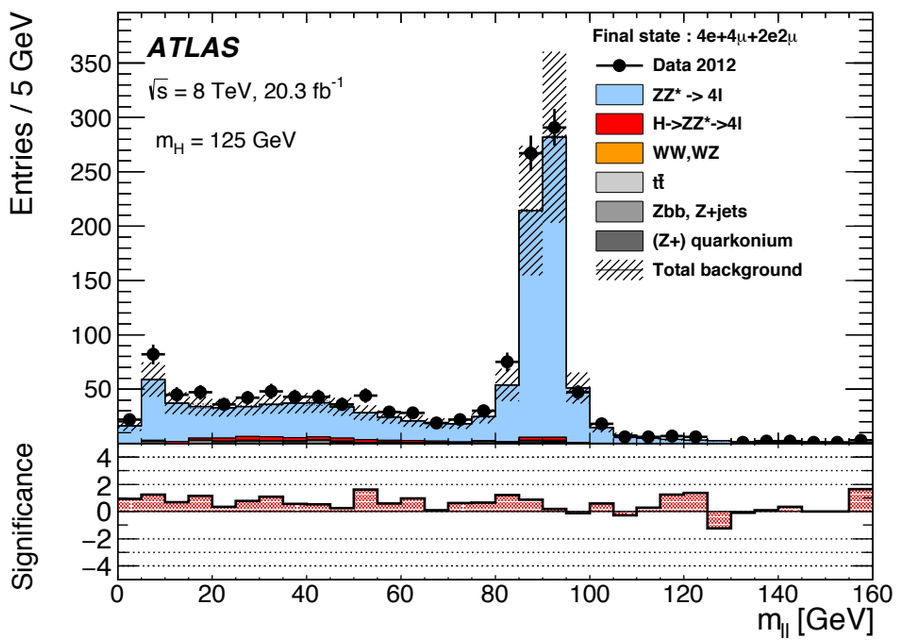




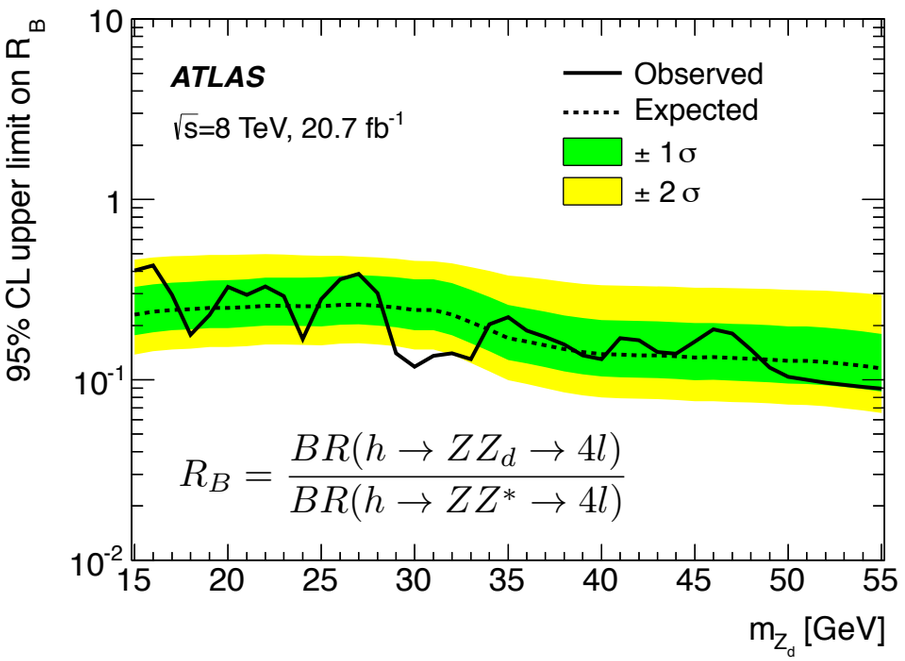
Dedicated search in ATLAS Higgs-to-four-leptons events

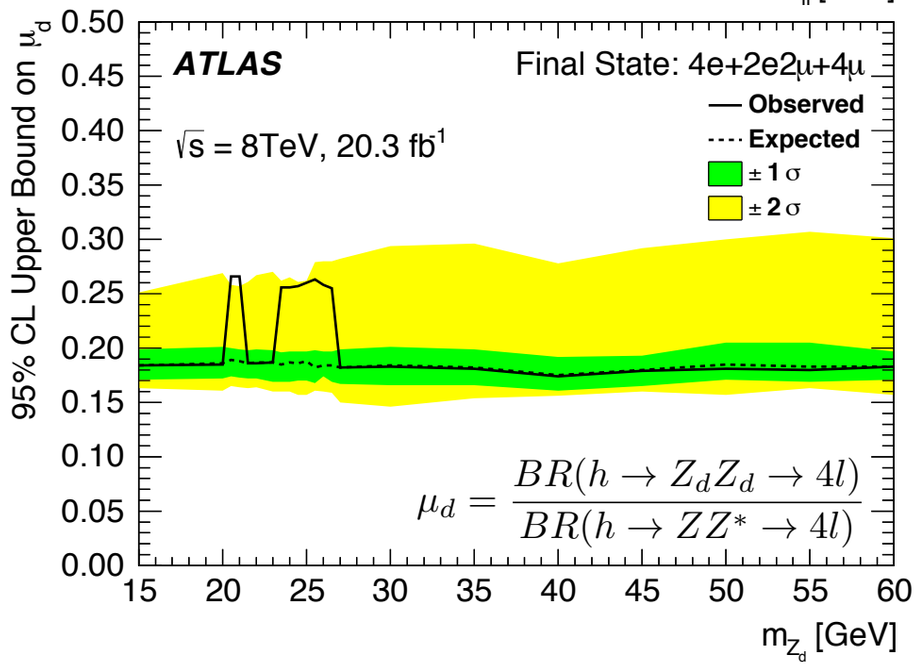


ZZ_d: Look for excesses in m_{34} spectrum (where m_{12} is closest to m_Z)



Z_dZ_d: keep events with a unique quadruplet where the mass difference between the 2 dilepton system $|m_{12}-m_{34}|$ is minimal; then apply a Z-veto and a J/ψ and ϒ veto





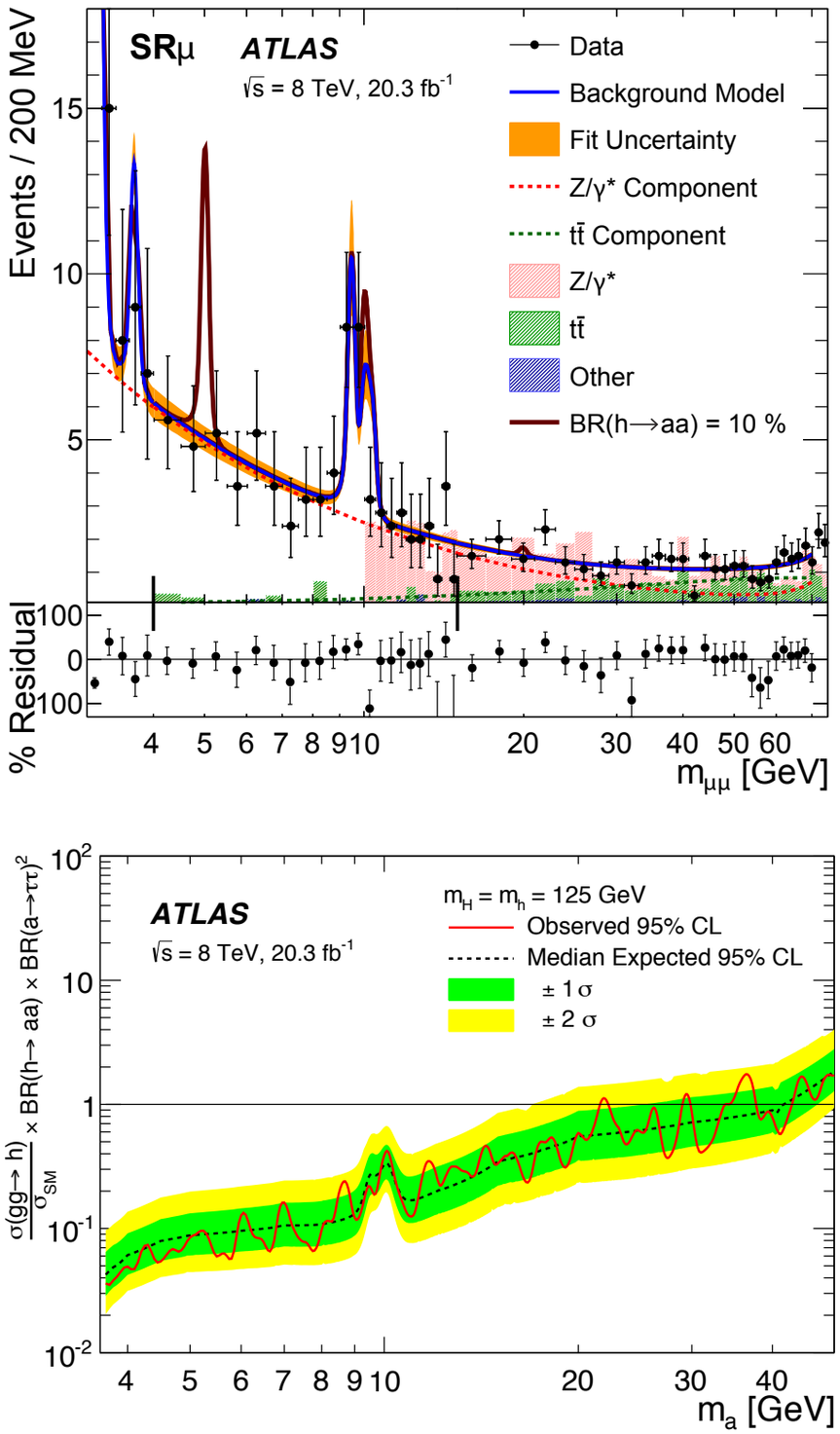
ATLAS: arXiv:1505.01609
Submitted to PRD

H ⟶ aa(ss) ⟶ {2μ2τ or 4μ}

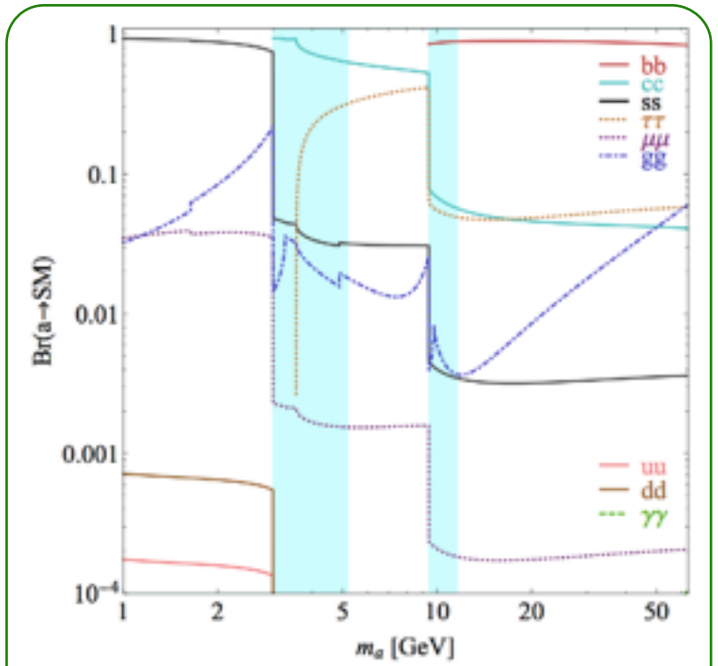
CMS: arXiv:1506.00424
Submitted to PLB

THE OHIO STATE UNIVERSITY

H —> aa —> 2μ2τ



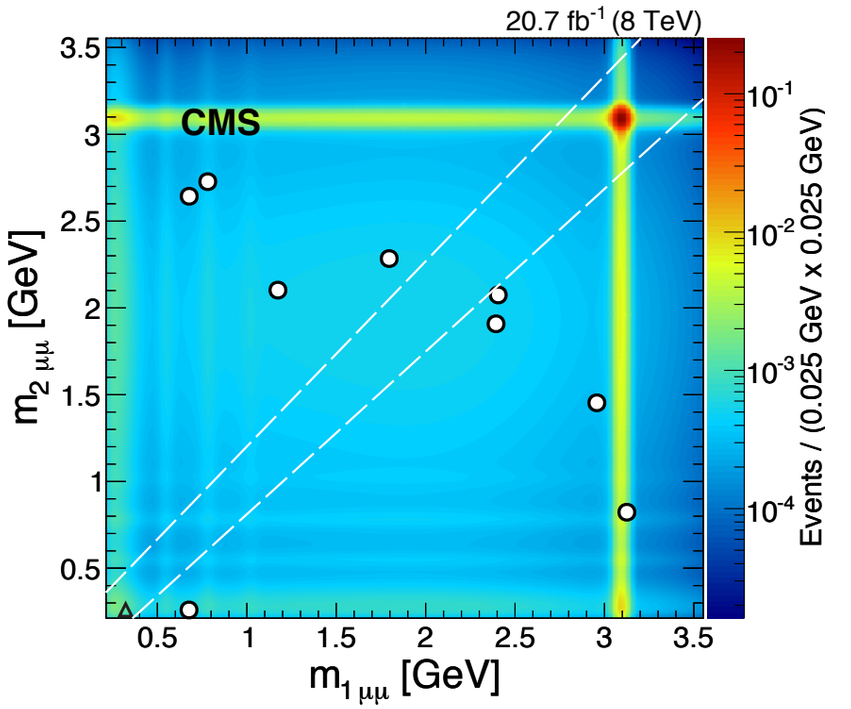
Extended Higgs sectors with relatively light (pseudo)scalars (*a*)*s* from hidden sectors

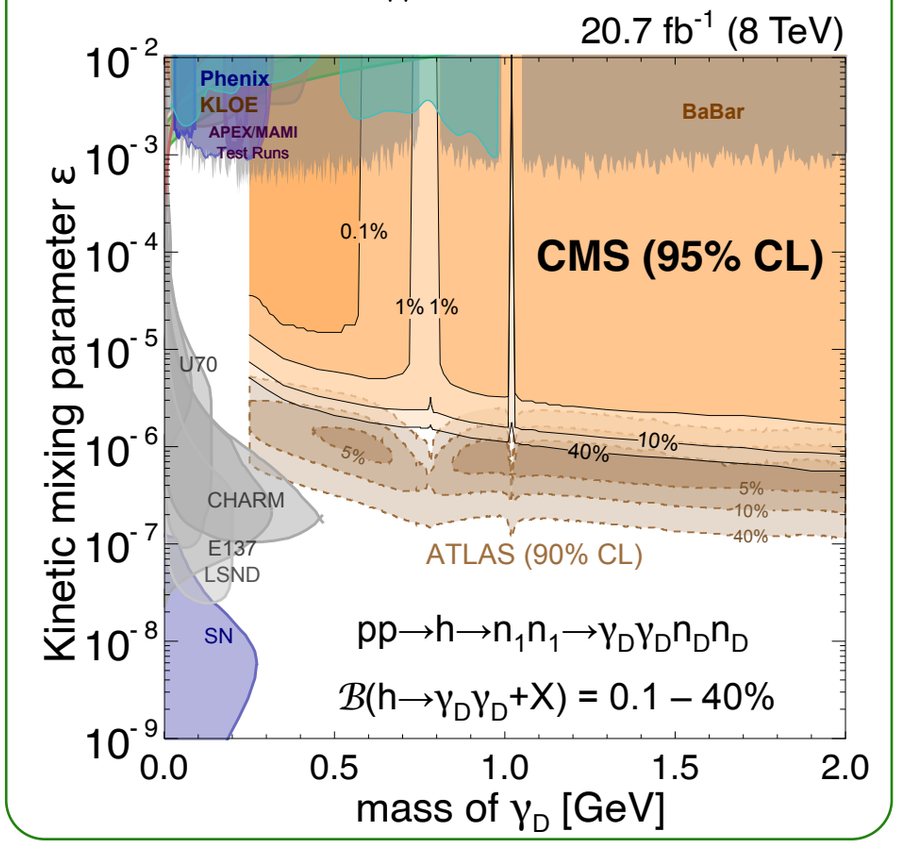


Example:
2HDM+S with
Type 1 Yukawa couplings

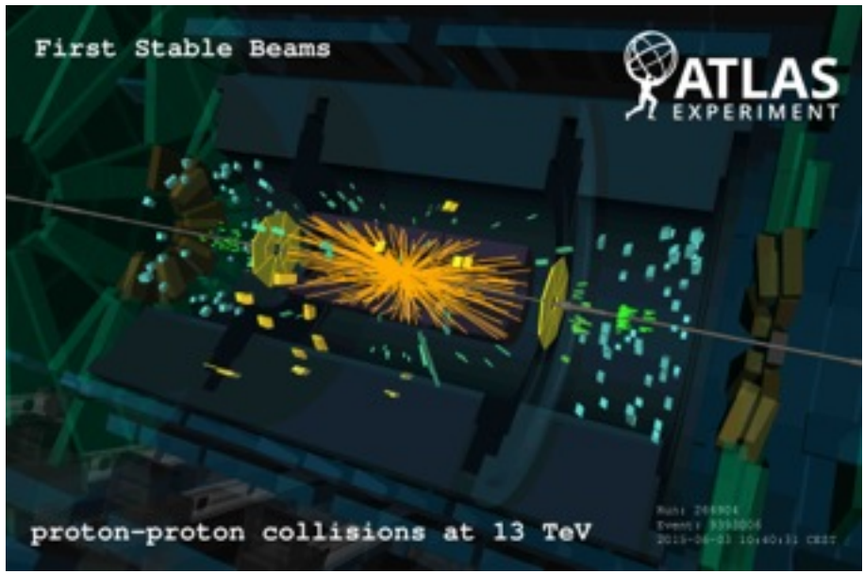
Interpreted in kinetic mixing parameter / dark photon mass plane

H —> aa —> 4μ



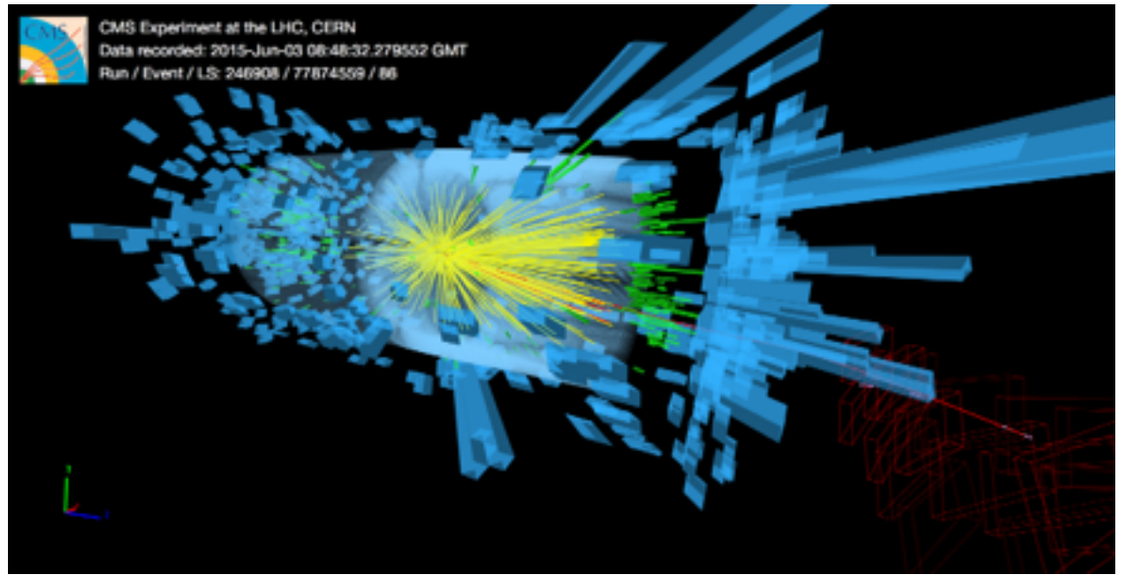


Prospects in Run 2



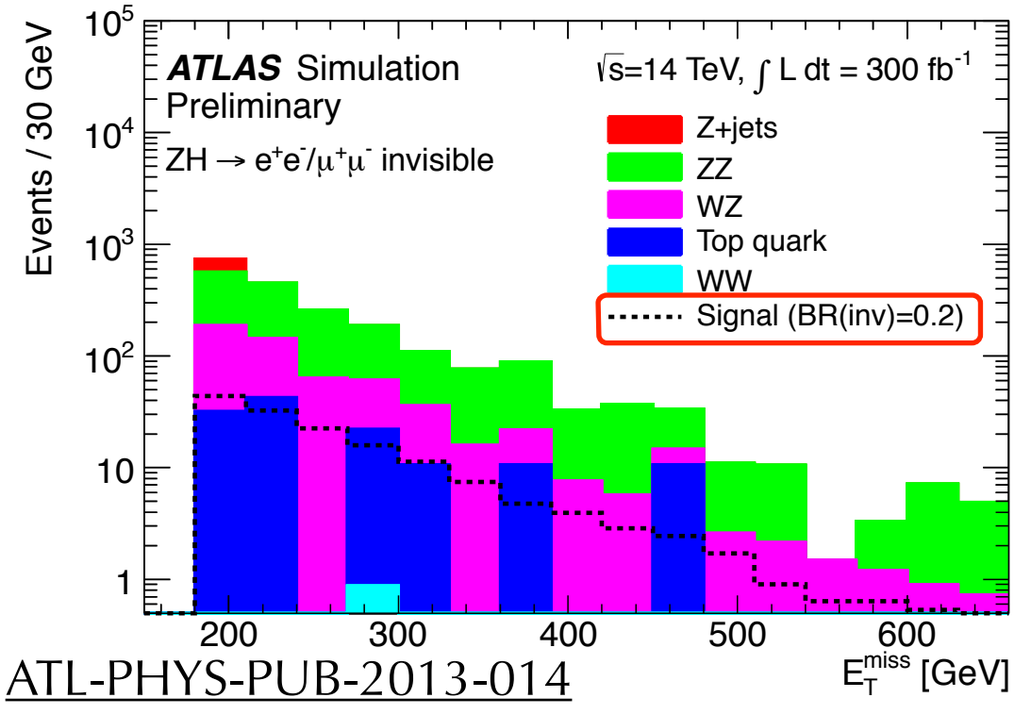
Run 2
is upon us!

Most Higgs-related dark sector searches improve in sensitivity and reach in Run 2



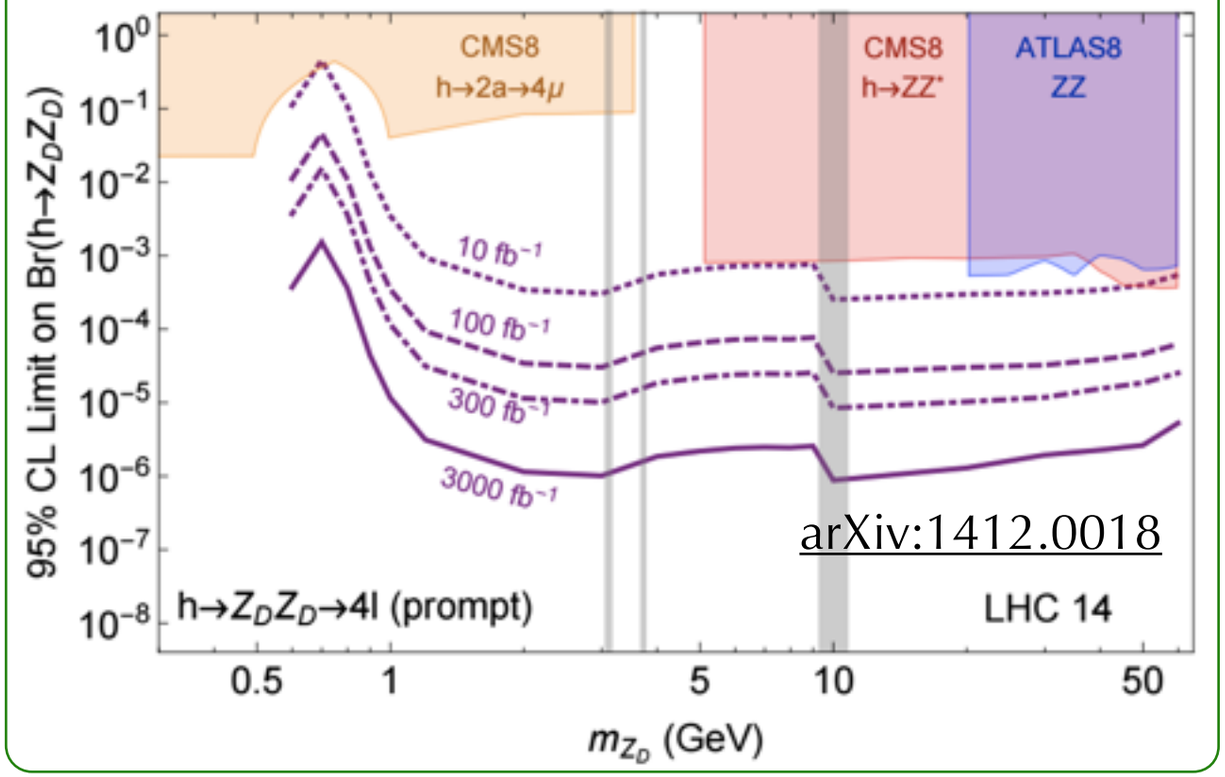
Example: ZH —> ll + invisible

BR(H →inv.) limits at 95% (90%) CL	300 fb^{-1}	3000 fb^{-1}
Realistic scenario	23% (19%)	8.0% (6.7%)
Conservative scenario	32% (27%)	16% (13%)



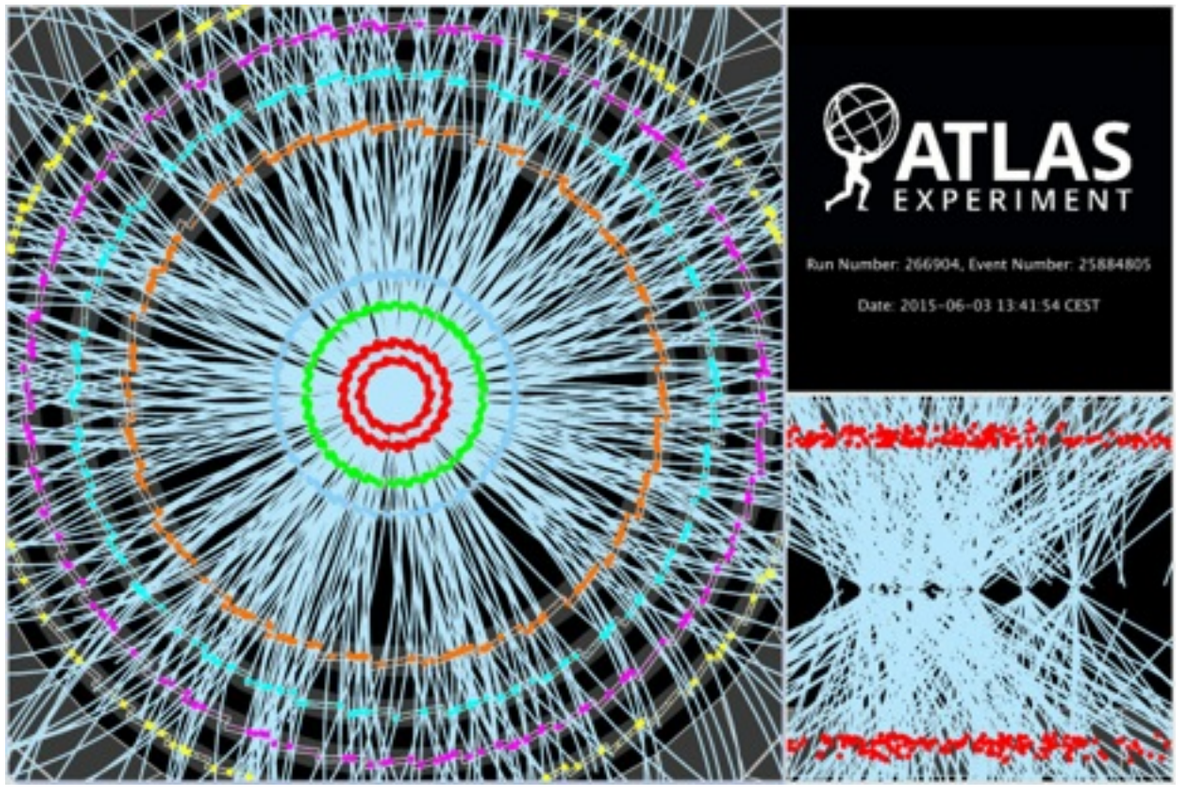
ATL-PHYS-PUB-2013-014

Example: H —> $Z_{(d)}Z_d$ —> 4l



arXiv:1412.0018

Conclusions



Impressive legacy of Run 1 CMS and ATLAS searches using the Higgs as a window into dark/hidden sectors

Run 2 is here!

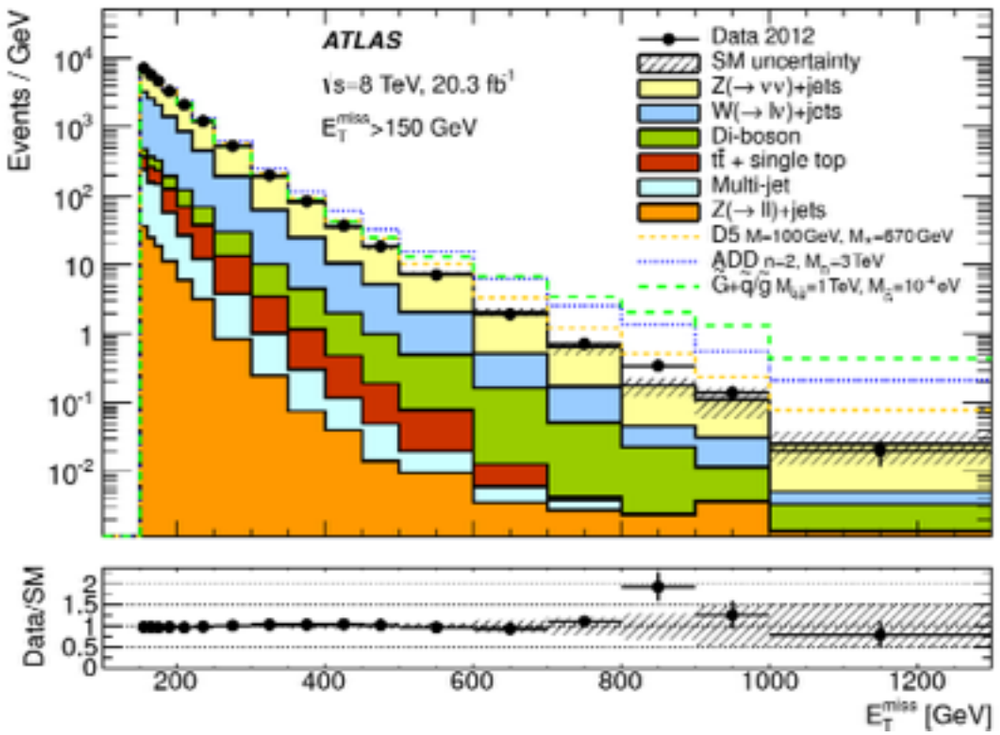
- Dedicated Higgs-related dark sector searches will be a very hot topic
- The properties of H125 at the LHC nicely allow for invisible/dark sector couplings and decays, and our prospects only improve at 13 TeV

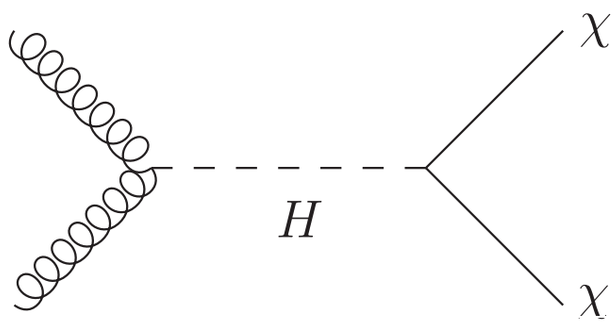
Dark matter, dark photons, hidden valley pions may be right around the corner, and the Higgs may guide us to them

Additional material

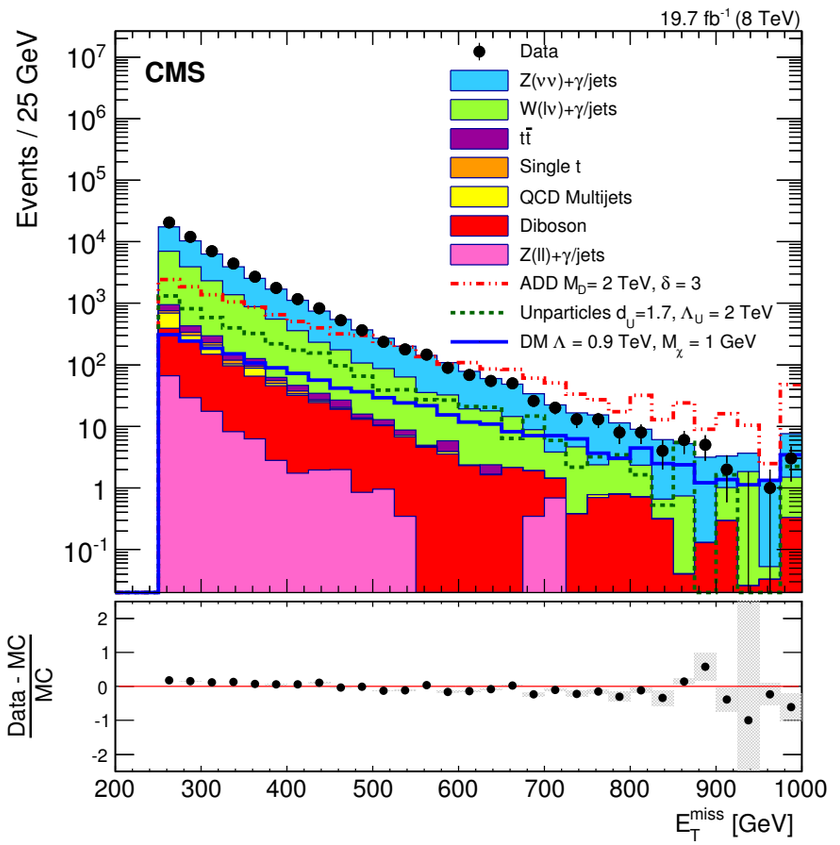
Monojet + H ⟶ invisible

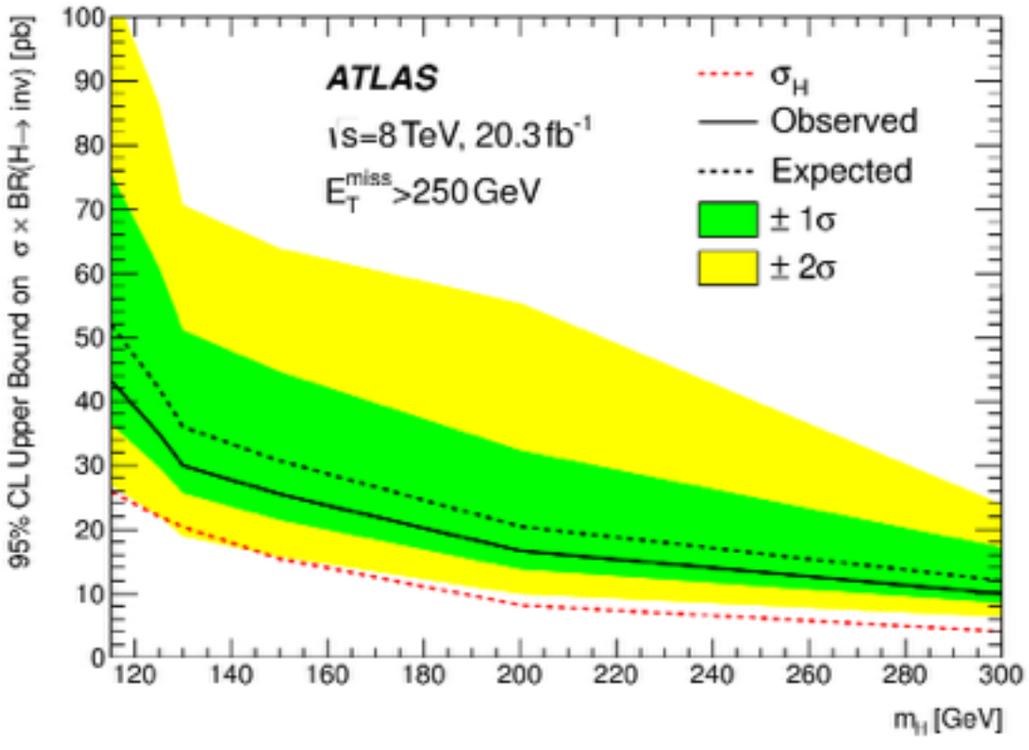
ATLAS: arXiv:1502.01518
CMS: arXiv:1408.3583



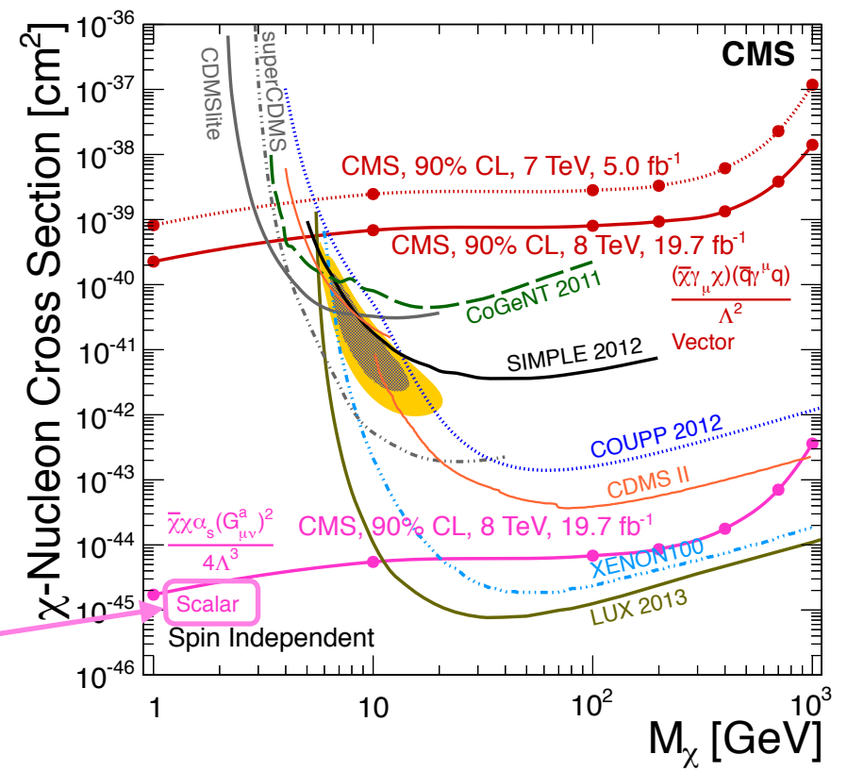


Look for excesses in tails of E_T^{miss}





Collider results interpreted in model-dependent way to complement dark matter direct-detection experiments



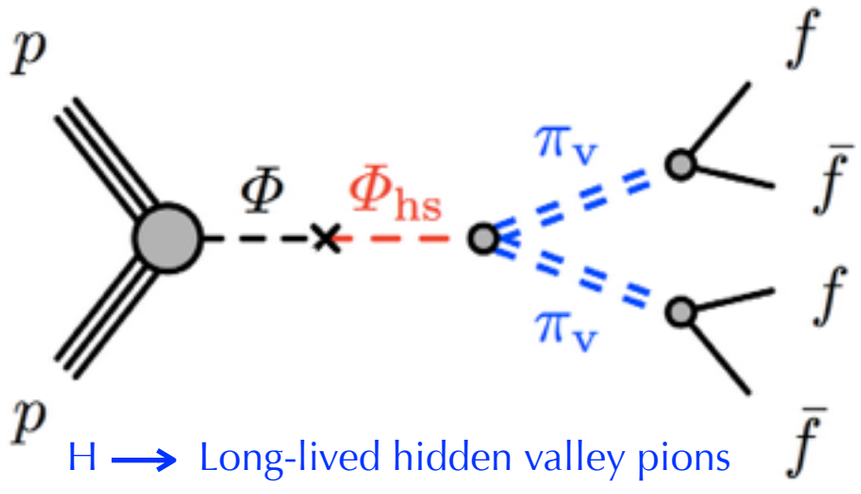
H ⟶ displaced jets

ATLAS: PLB 743 (2015) 15-34

Displaced jets in the hadronic calorimeter

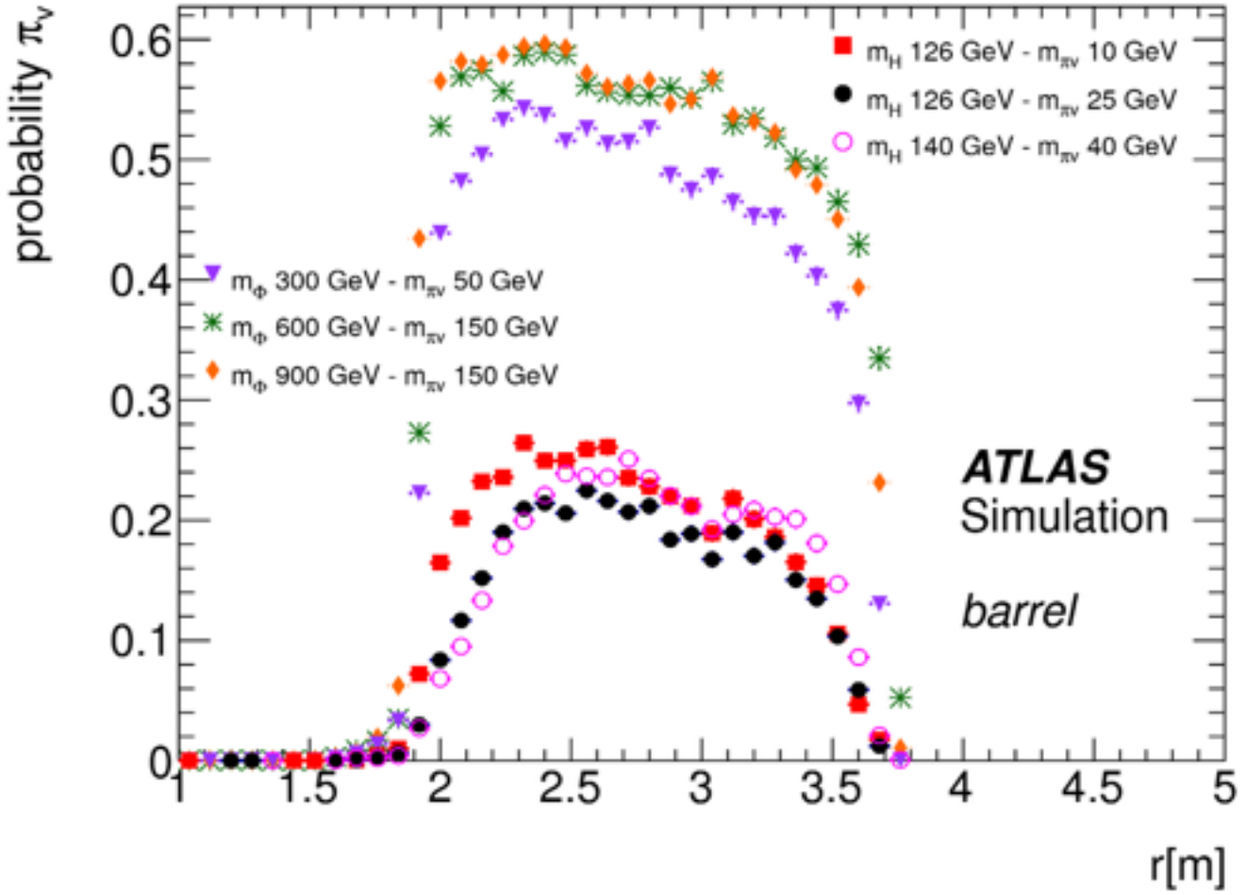
Pair of jets decaying in the HCal

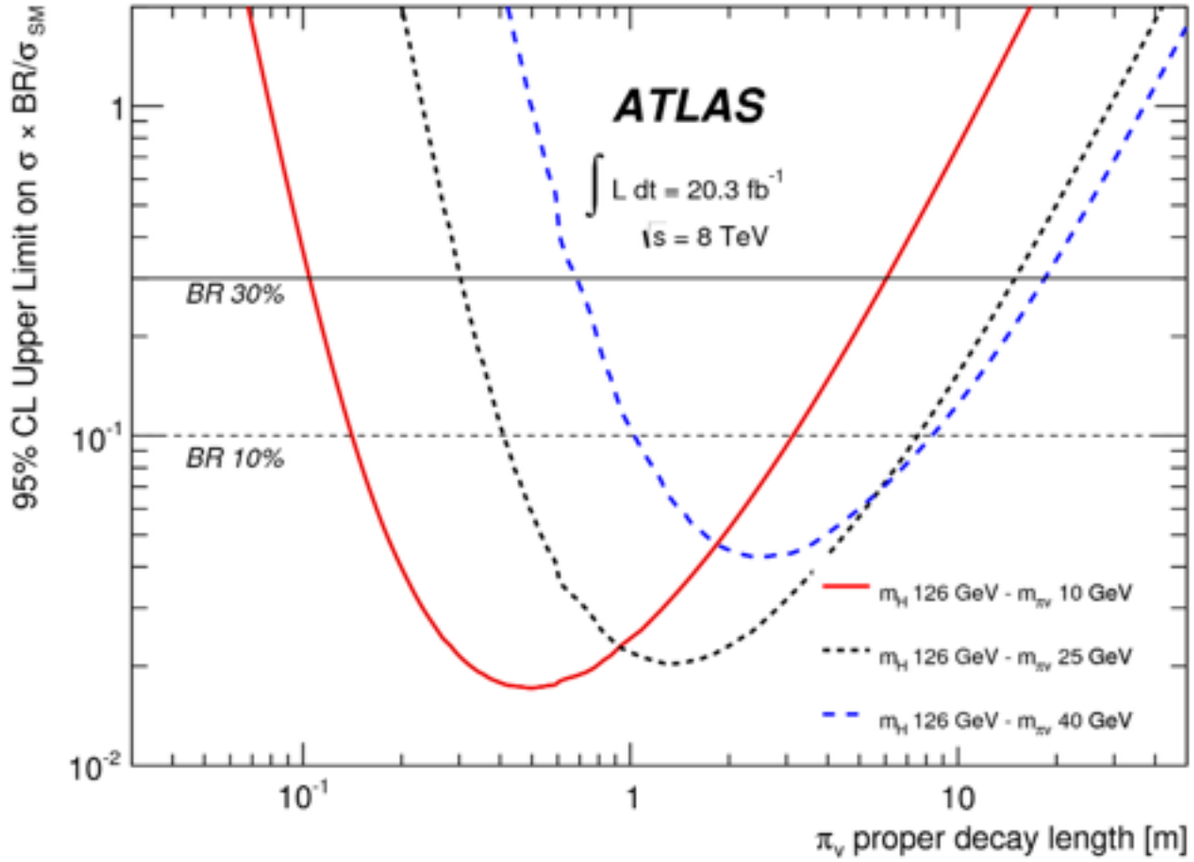
- A narrow radius
- No ID tracks pointing towards the jet
- Large energy deposit in the HCal with little to no energy in the ECal
- Primary background from SM multijets



H ⟶ Long-lived hidden valley pions

Probability that a single π_v passes the trigger, as a function of radial decay length in the barrel





H ⟶ displaced jets

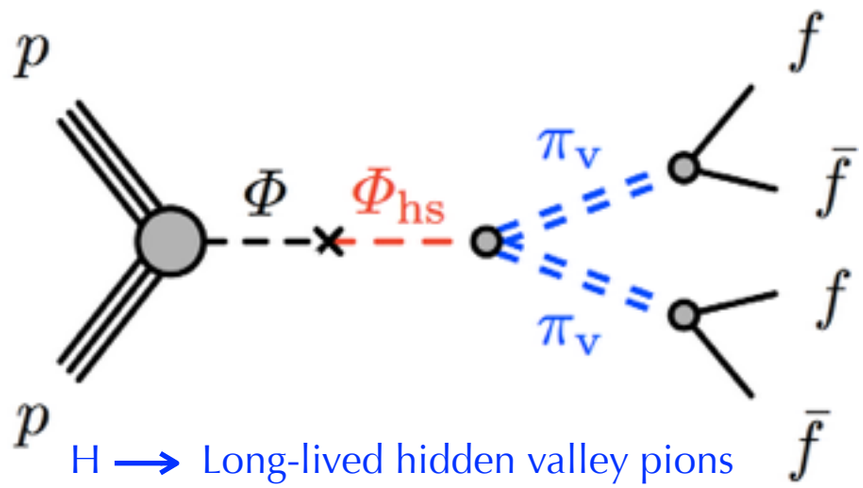
CMS: PRD.91.012007

Displaced jets in the inner detector

Displaced decays in the CMS tracker associated to jet pairs

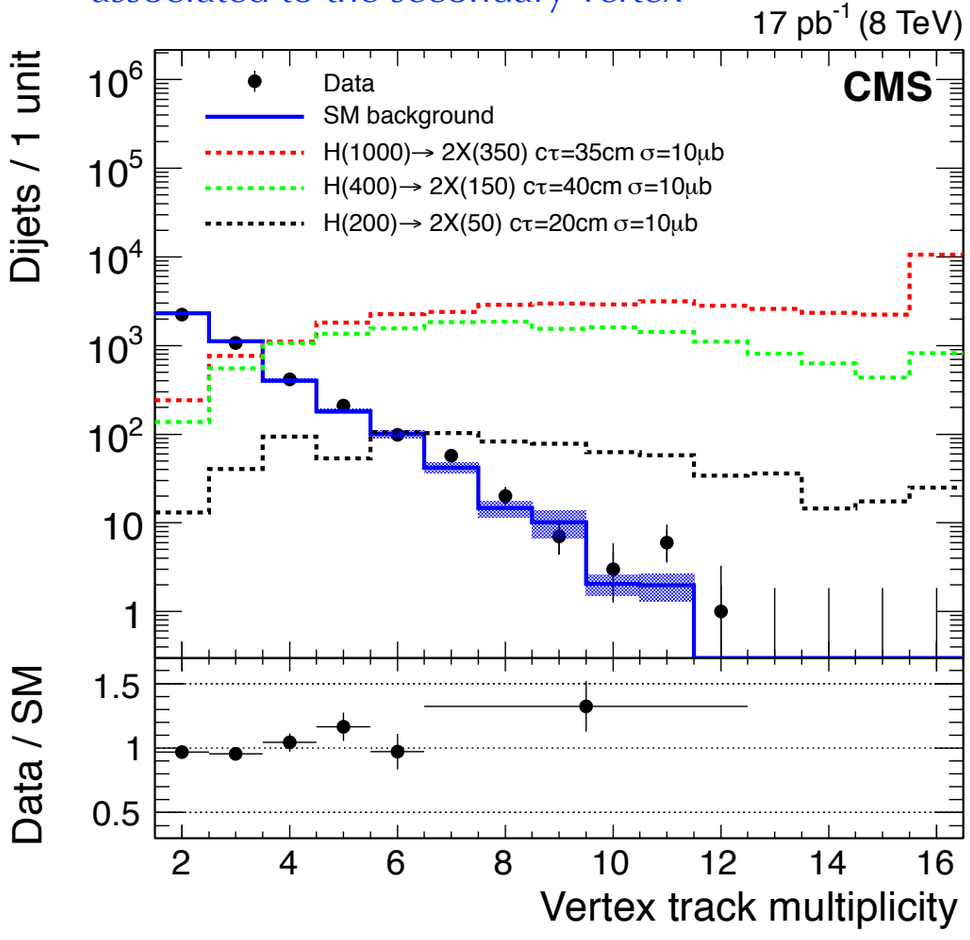
Challenge: Keep displacements, reject huge QCD background

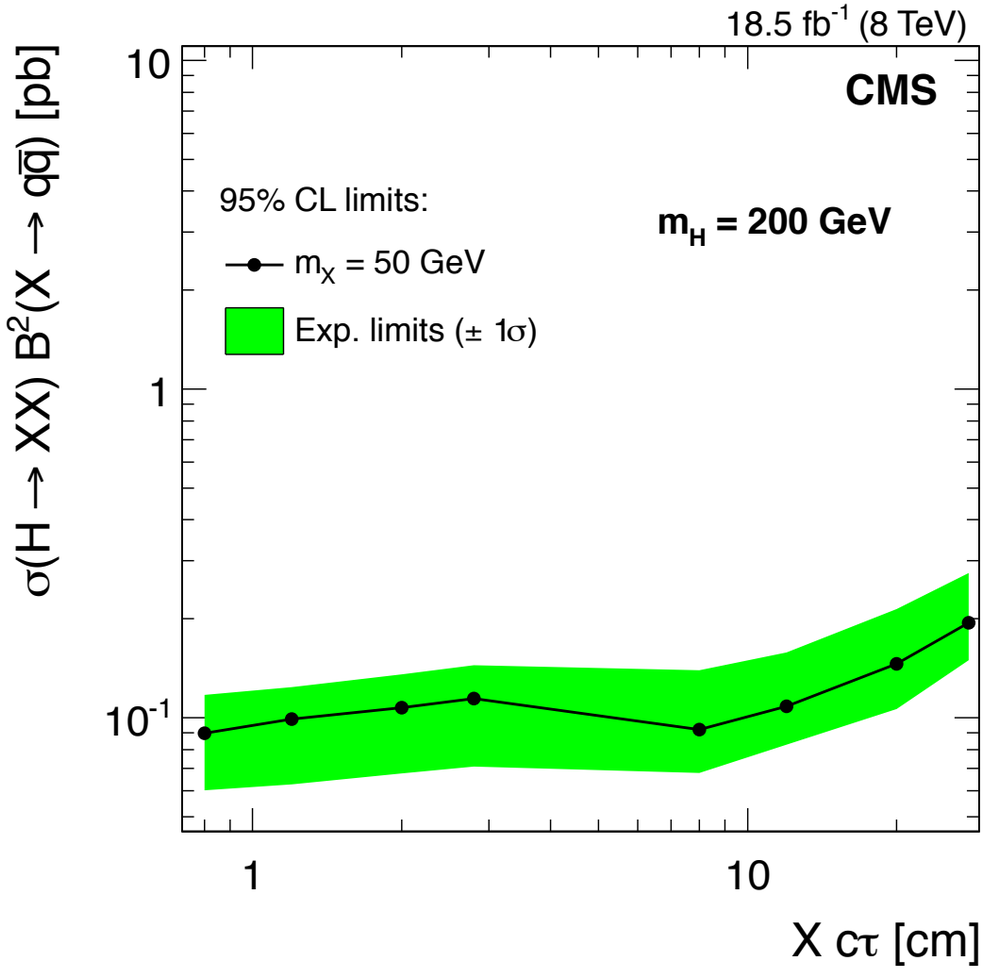
- Cuts on 3D impact parameters and on the fraction of jet's total energy associated to tracks
- Two sets of displaced tracks are fitted for finding a common secondary vertex
- Further likelihood discriminant with four ingredients



H ⟶ Long-lived hidden valley pions

Signal events should have higher number of tracks associated to the secondary vertex



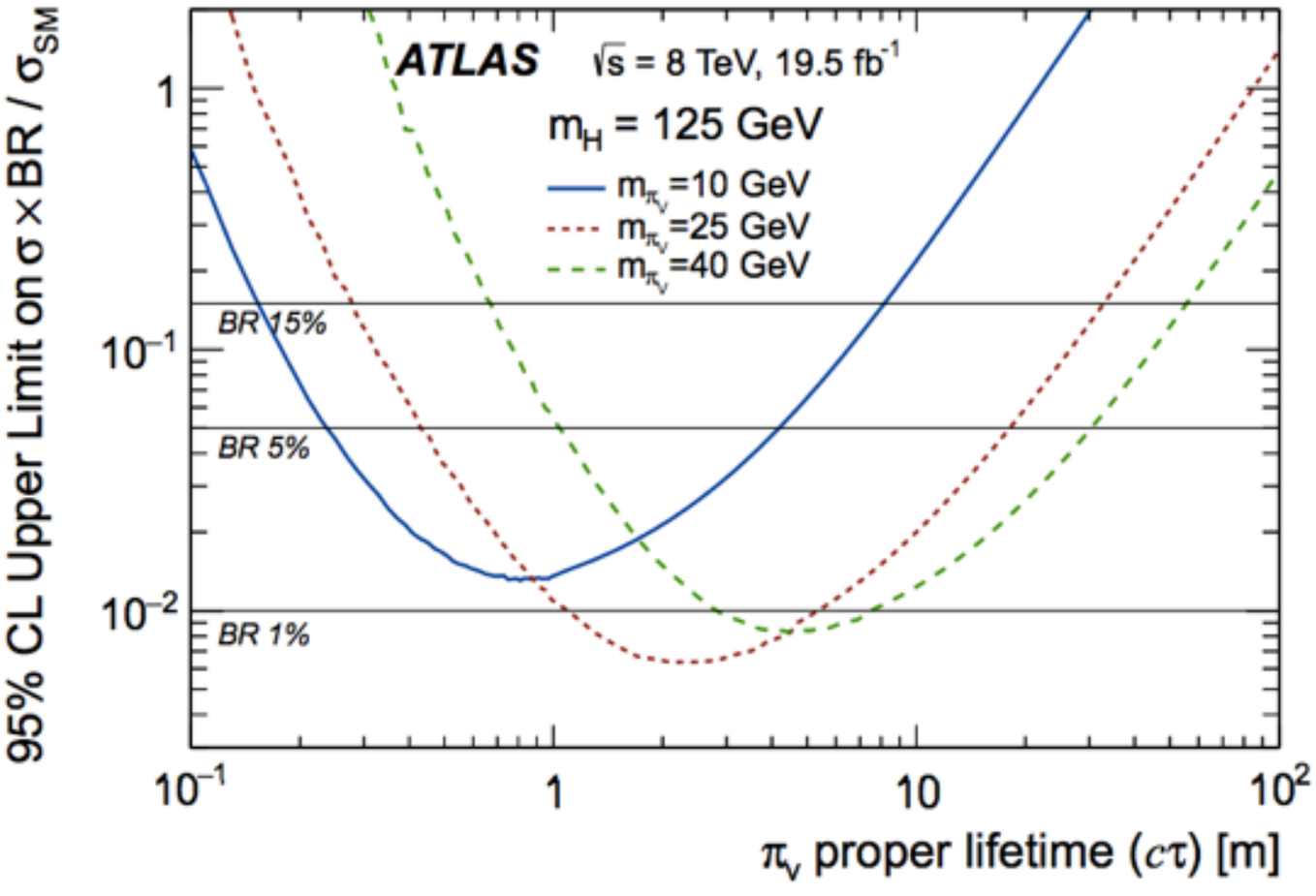


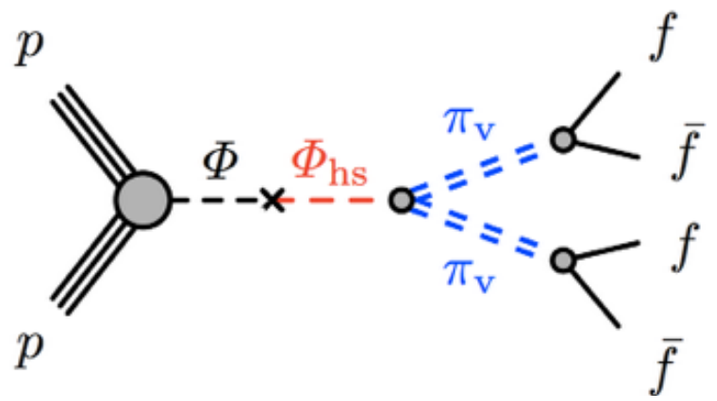
H ⟶ displaced jets

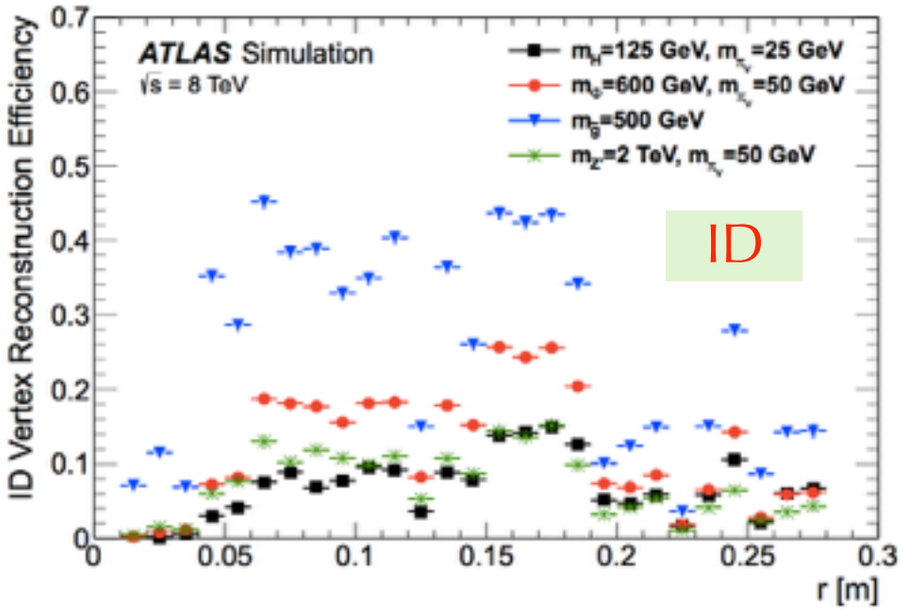
ATLAS: arXiv1504.03634
Submitted to PRD

Displaced jets in the inner detector or muon spectrometer

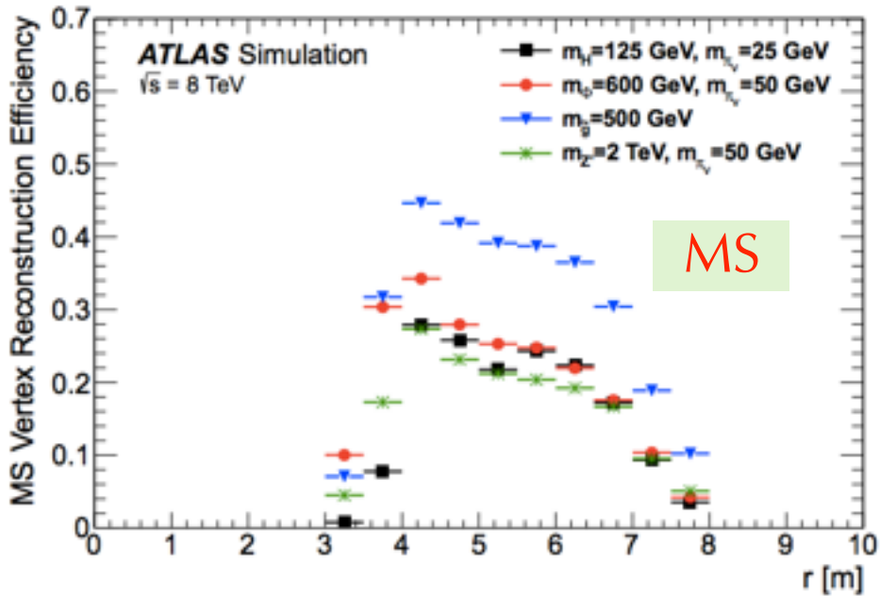
- Two or more jets originating in the ID and/or MS
- Five topologies defined by combinations of muon and jet + E_T^{miss} triggers
- Jet backgrounds dominant: QCD jets in the ID and punch-through jets in the MS







Custom re-tracking to recover hits omitted from standard track-finding algorithm



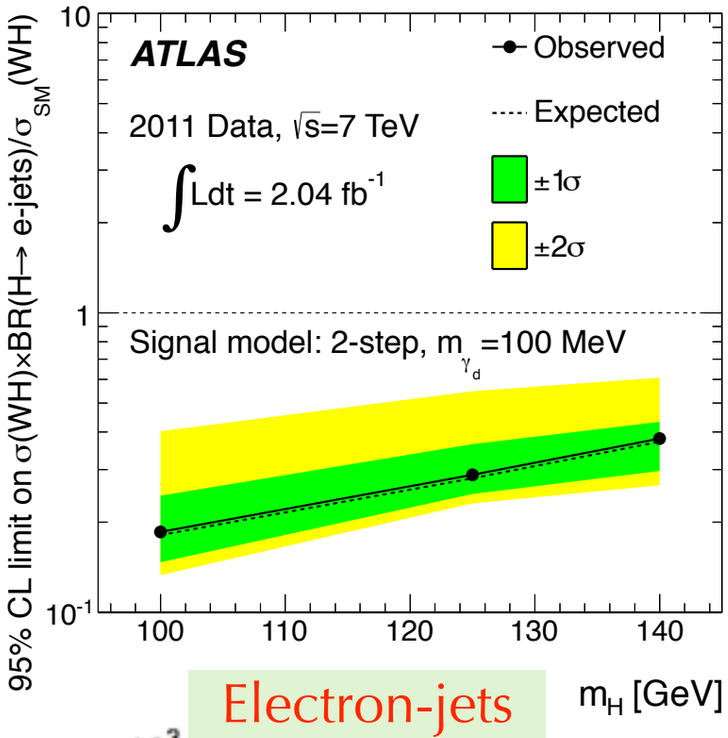
H ⟶ lepton-jets (via dark fermions/scalars/photons)

ATLAS: PLB 719 (2013) 299-317
NJP 15, 043009 (2013)
CMS: JHEP07(2011)098

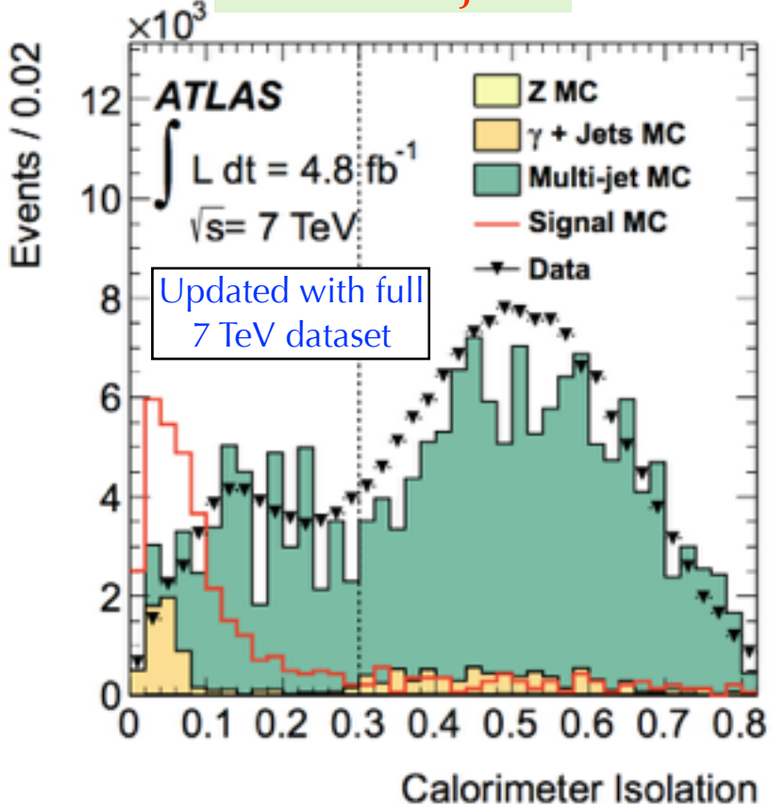
Prompt — 7 TeV

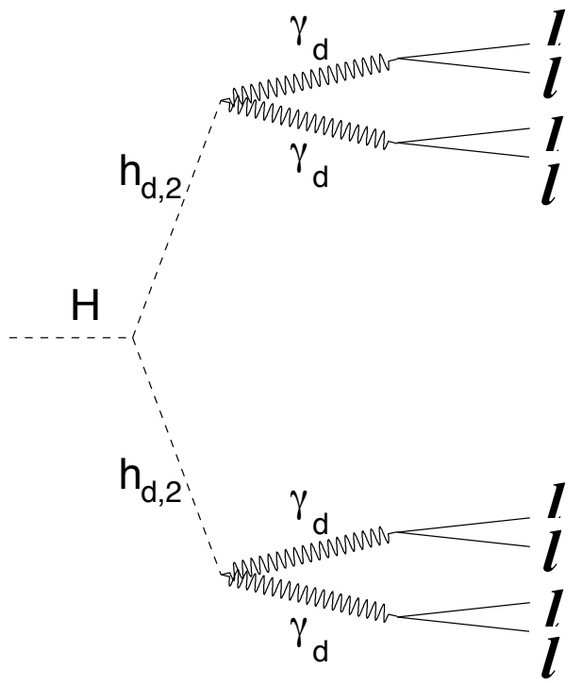
Dark/hidden sector coupled to SM Higgs and leptons via very light dark sector particles

- Highly collimated groupings of leptons: **lepton-jets**
- Distinct LHC signature



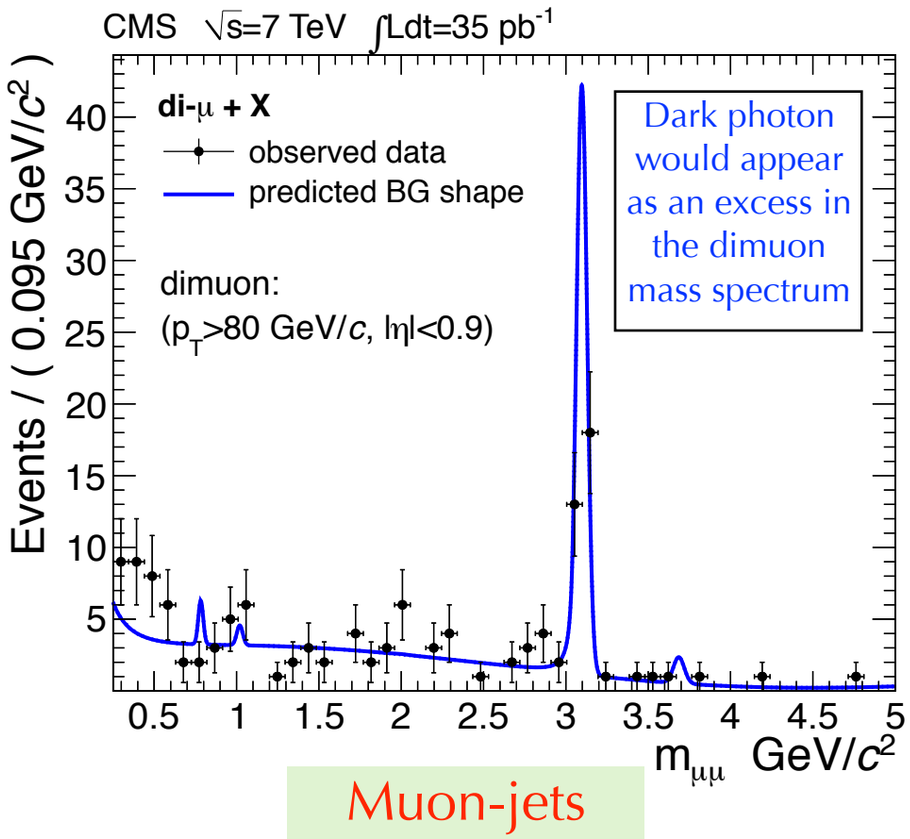
Electron-jets



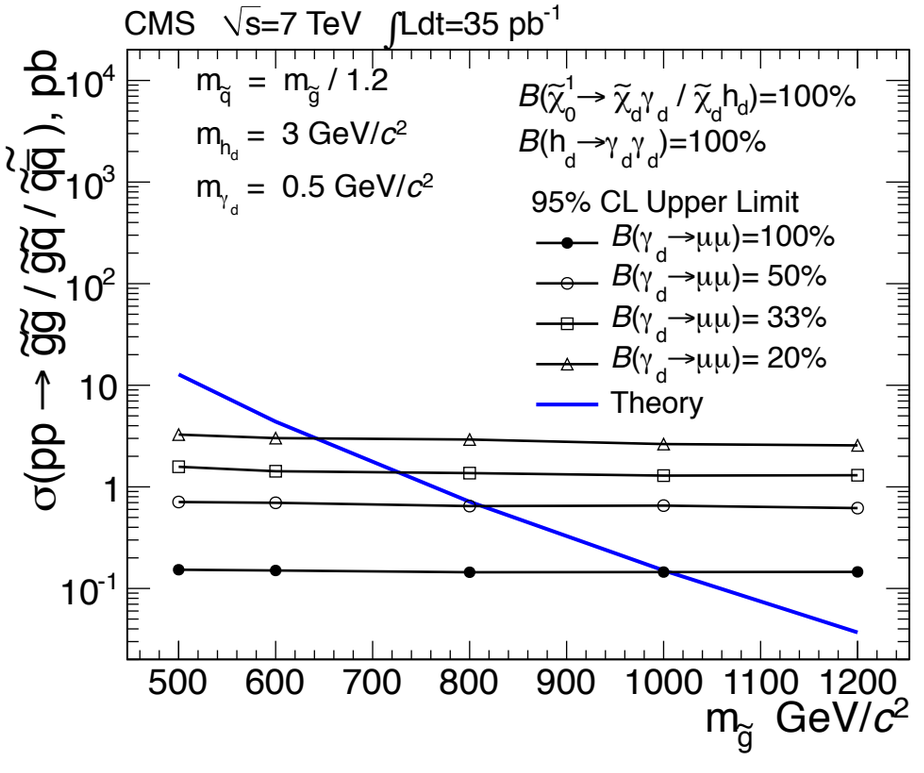


WH associated production for electron-jets

- Main background from W+jets
- QCD estimated with data-driven methods



Muon-jets

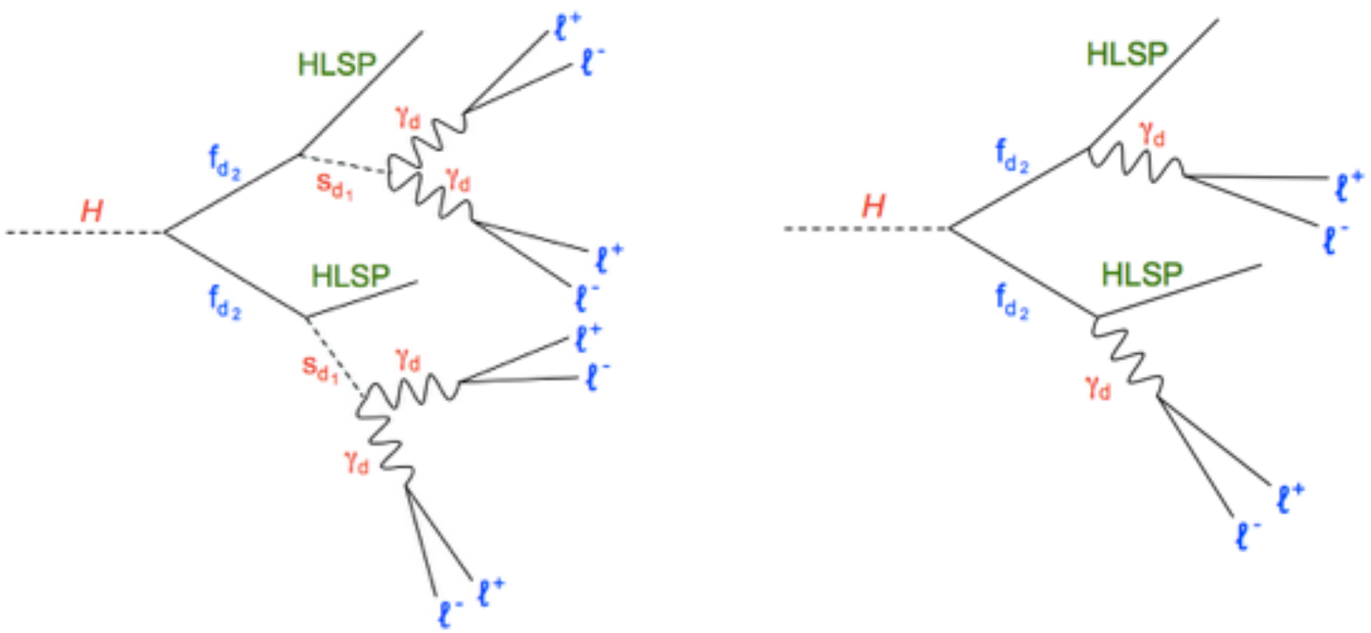


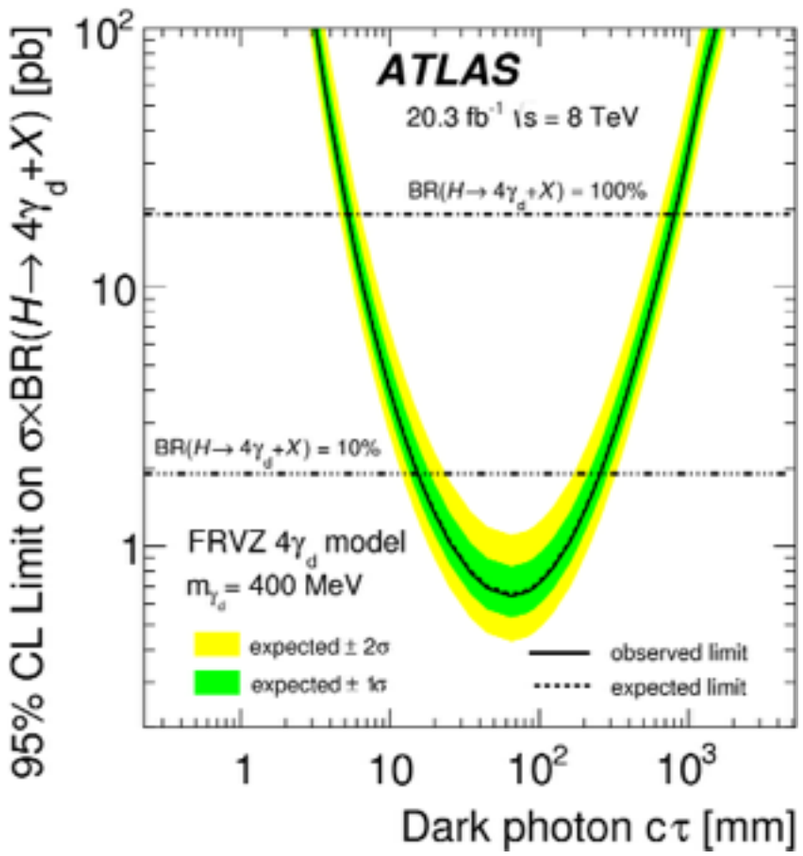
H ⟶ lepton-jets (via dark fermions/scalars/photons)

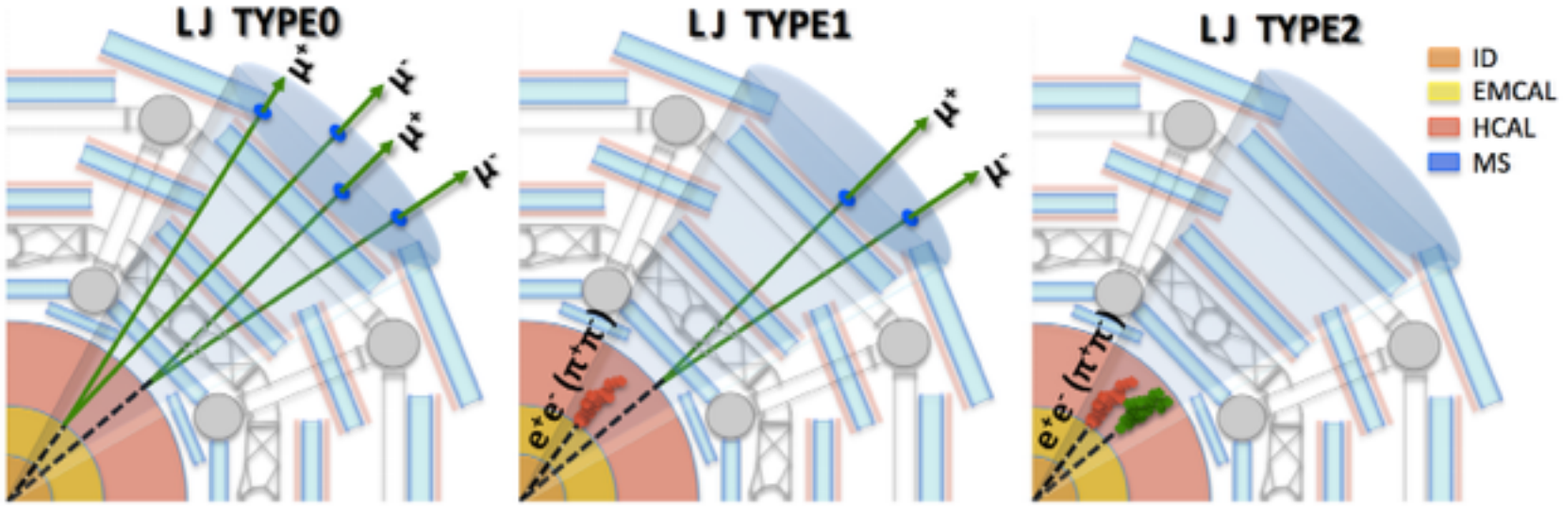
ATLAS: JHEP11(2014)088

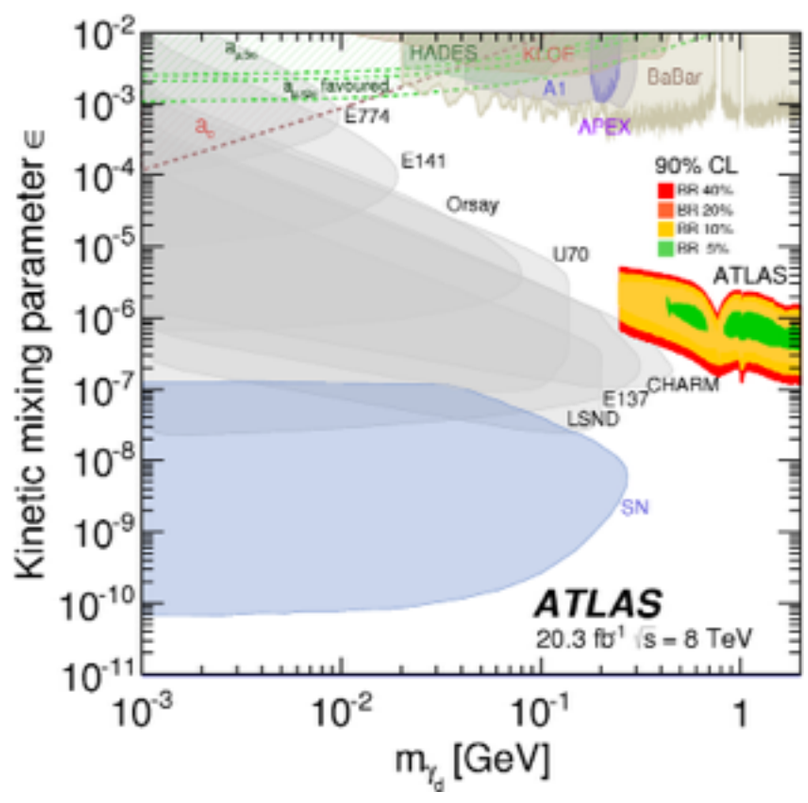
Displaced — 8 TeV

Weak interaction ==> non-negligible dark photon lifetime









Three separate types of lepton-jet definitions considered

Cosmic backgrounds important here