Dark Higgs and Exotic Higgs Decay Searches at Colliders

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Dark Sectors Workshop
SLAC
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https://indico.cern.ch/event/507783/

BaBar Dark Higgs Search

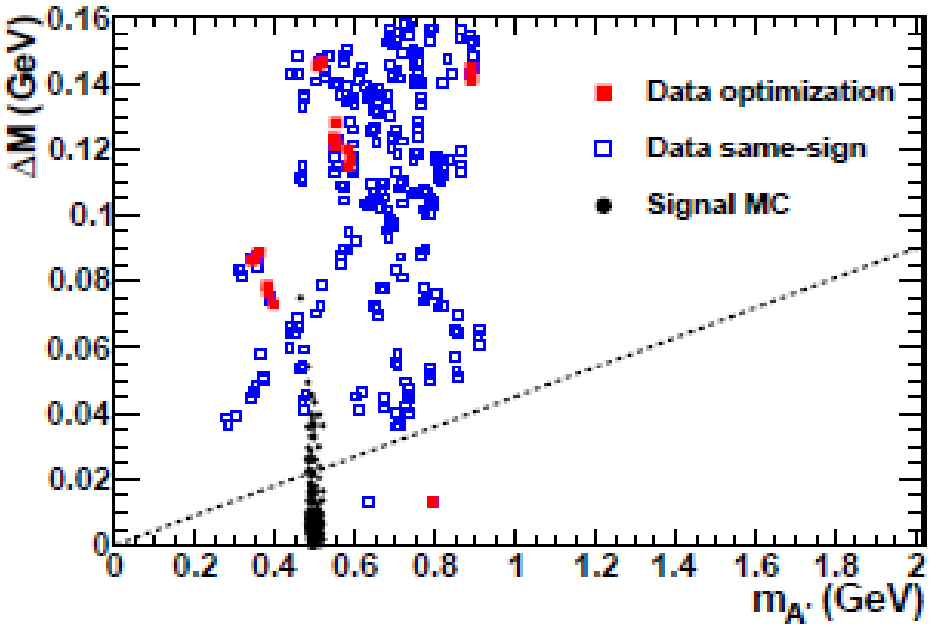
arXiv:1202.1313 [hep-ex]

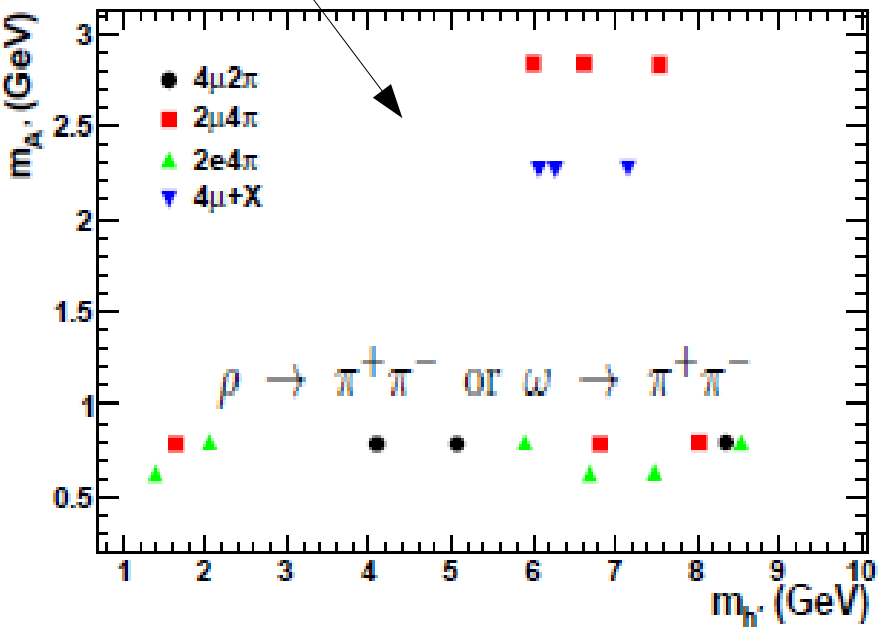
- New possible channel with dark Higgs and dark photons

$$\text{Higgs-strahlung process, } e^+e^- \rightarrow A'h', h' \rightarrow A'A'$$

- A' decays to lepton pairs, pion pairs, or other (less pure)

- Backgrounds determined from same-sign data
- 6 events observed, consistent with backgrounds
  (3 possible pairings of h' → A'A' per event)





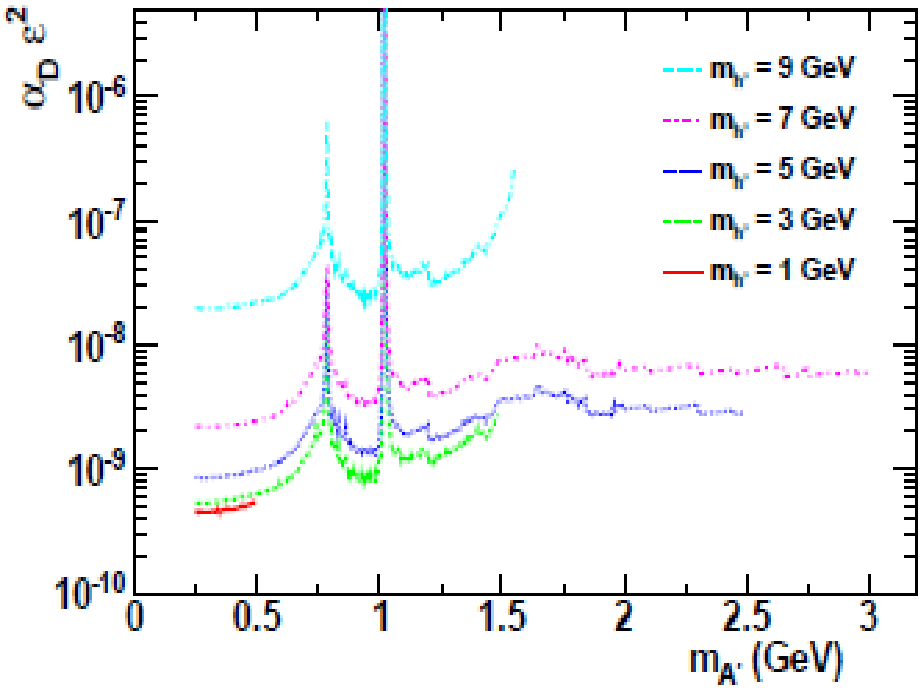
BaBar Dark Higgs Search

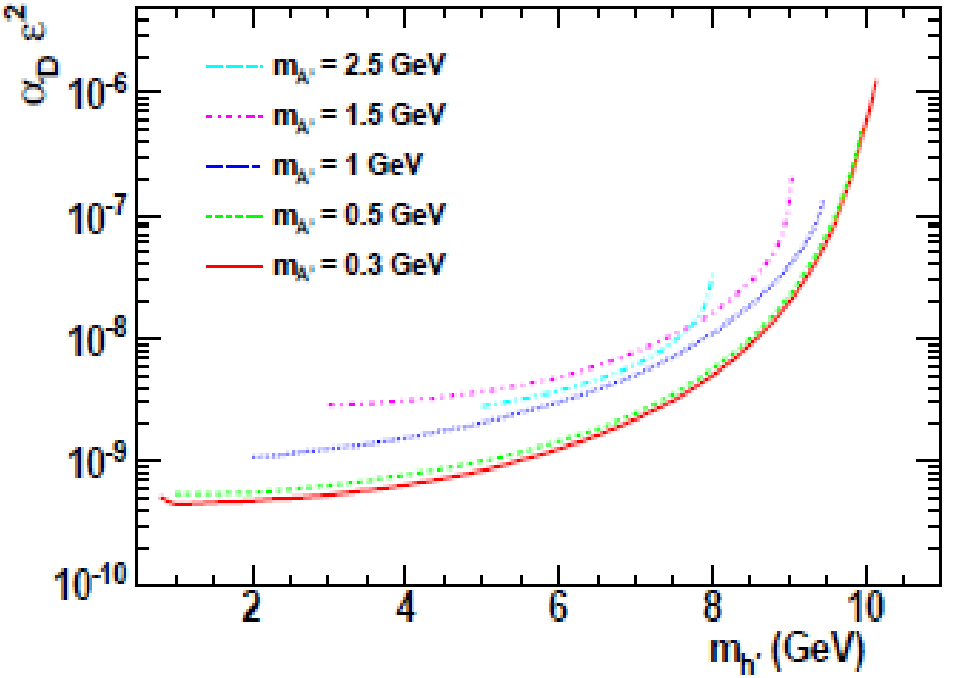
- New possible channel with dark Higgs and dark photons

$$\text{Higgs-strahlung process, } e^+e^- \rightarrow A'h', h' \rightarrow A'A'$$

- A' decays to lepton pairs, pion pairs, or other (less pure)

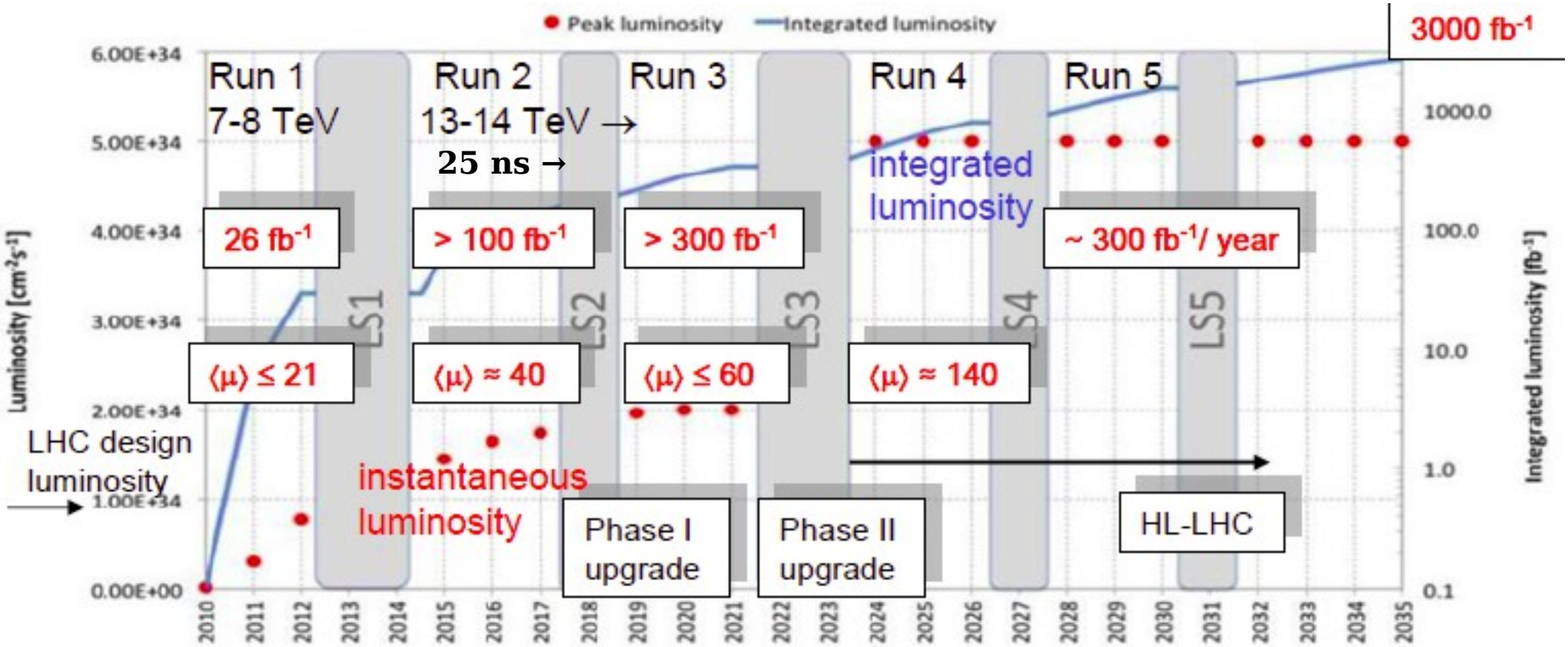
- Set limits on the dark gauge couplings, vs. h', A' masses



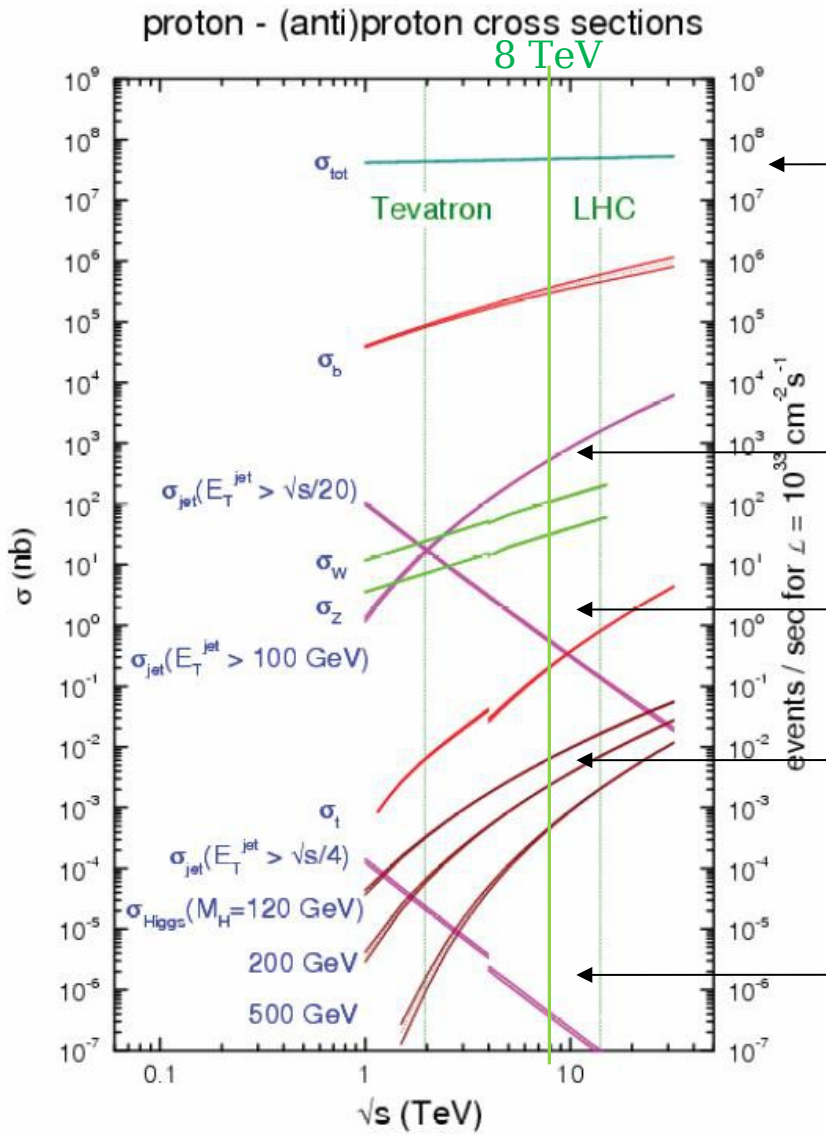


LHC era is just starting!

- 7 TeV in 2010/11, ~5/fb … **8 TeV in 2012, ~21/fb**
- 13 TeV in 2015, ~3/fb … 2016, *just restarted data taking*



LHC: The intense energy frontier



40 million p-p collisions / second !

1000 Hz of jets, pT>100 GeV

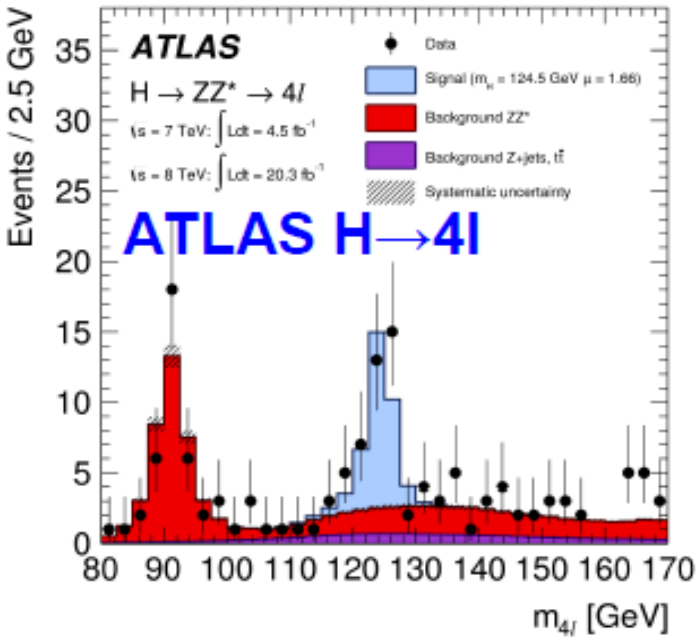
2 Hz of Z->ee or μμ

1 Higgs / minute

1 Higgs->ZZ->eeμμ / week !

Billions of Z bosons per year
Millions of H bosons per year

Higgs, finally!



NEW

to be submitted to PRL

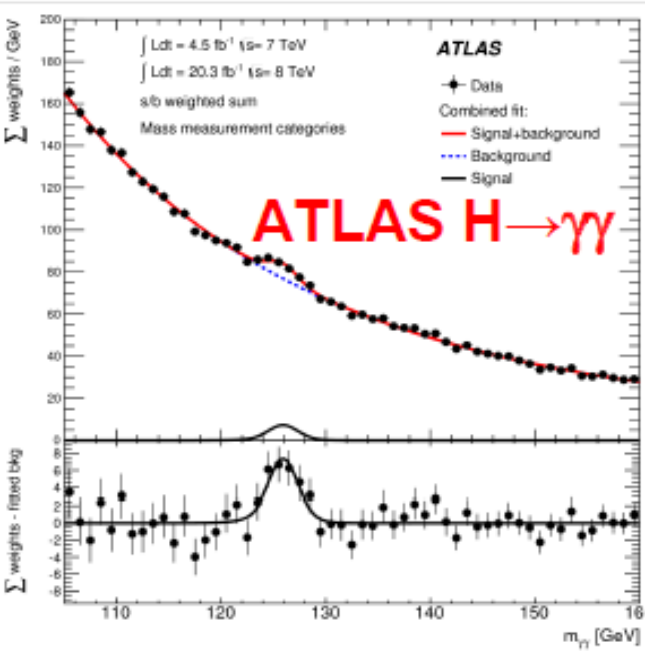
Combination of ATLAS+CMS mass measurements in

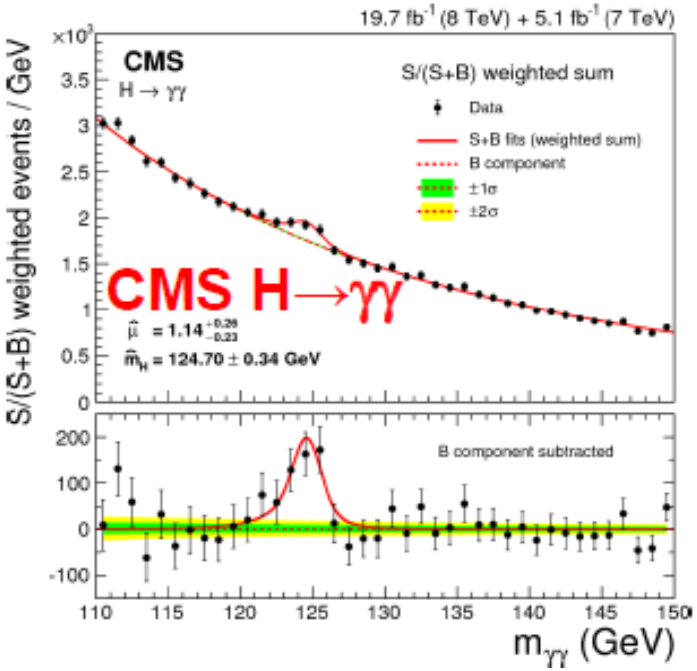
- **H → γγ**
- **H → 4l**

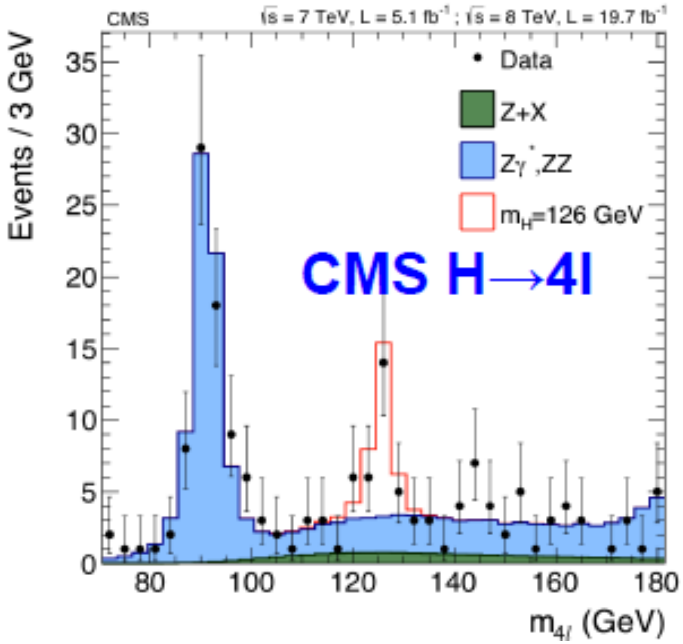
Aim to be agnostic to the signal yields: 3 signal strength parameter μ for

- **gg → H → γγ**
- **VBF H → γγ**
- **H → 4l**

simultaneously determined from data (profiled)



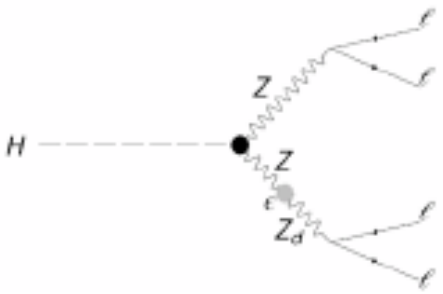




$H \rightarrow Z_{(d)}Z_d \rightarrow 4l$ (ATLAS) New

ATLAS (8 TeV)
arXiv:1505.07645
Submitted to PRD

Higgs as a portal to the hidden/dark sector

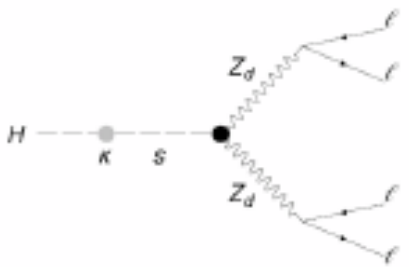


Light exotic gauge boson Z_d: $m_{Zd}<m_Z$

Based on SM Higgs to 4l analysis

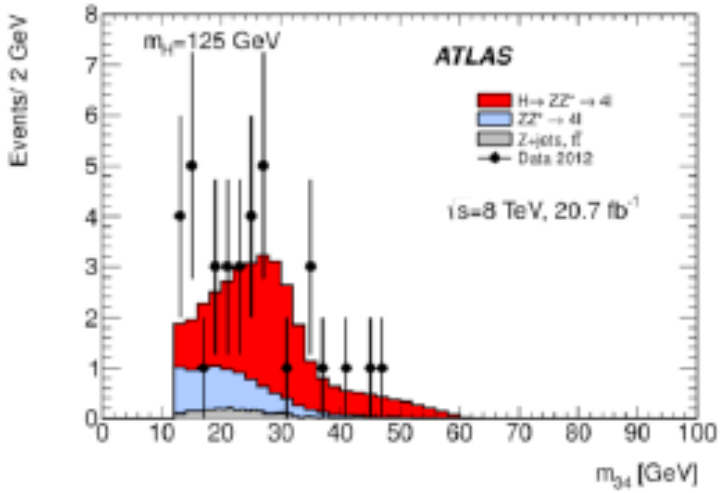
Model independent analysis

115 GeV $<m_{4l}<$130 GeV



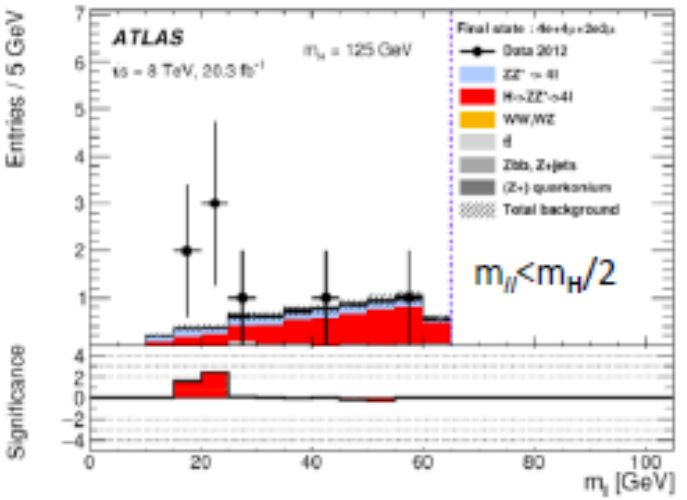
Look for excess in m_{34}

m_{12} closest to m_Z



Look for excess in m_{ll}

$|m_{12}-m_{34}|$=min



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

BGs: H→ZZ*→4l determined from data, ZZ* (MC), tt̄, Z+jets (DD)

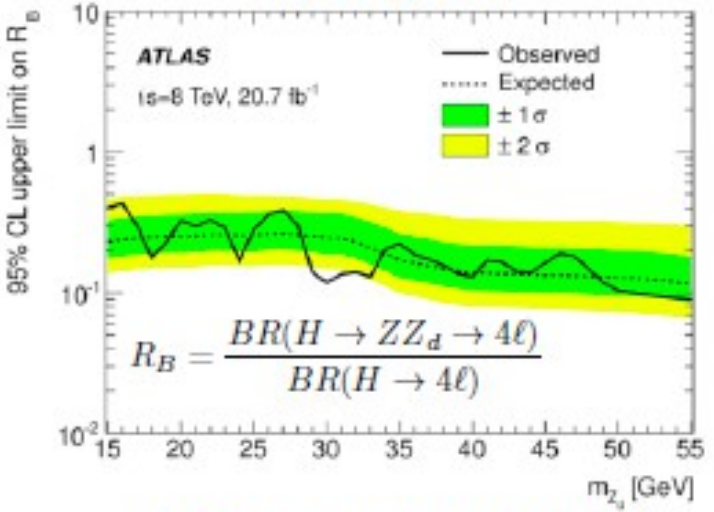
BGs: (MC) H→ZZ*→4l, ZZ*→4l

$m_{Zd}-m_{ll}<\delta m$= 5/3/4.5 GeV - 4e/4μ/2e2μ

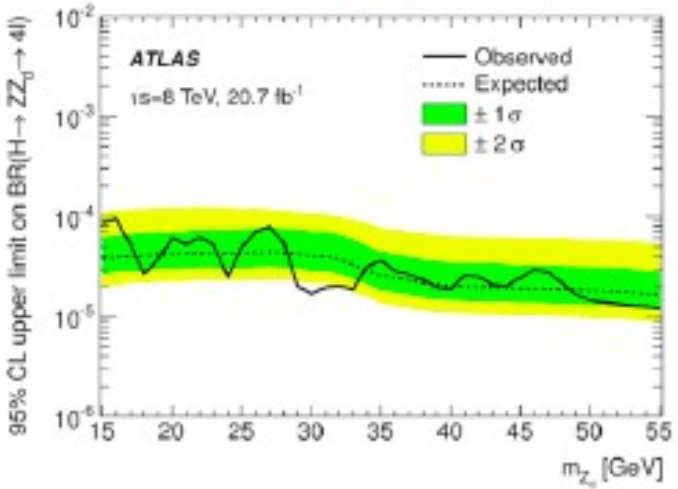
$H \to Z_{(d)} Z_d \to 4l$ (ATLAS)

Observed data well described by SM expectation=>Upper limits set

$H \to Z Z_d \to 4l$

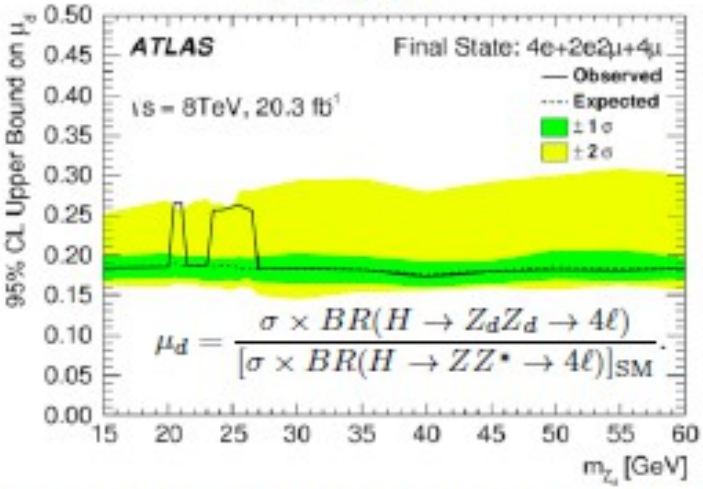


95% CL limits: $R_B < 0.4$ (0.2)

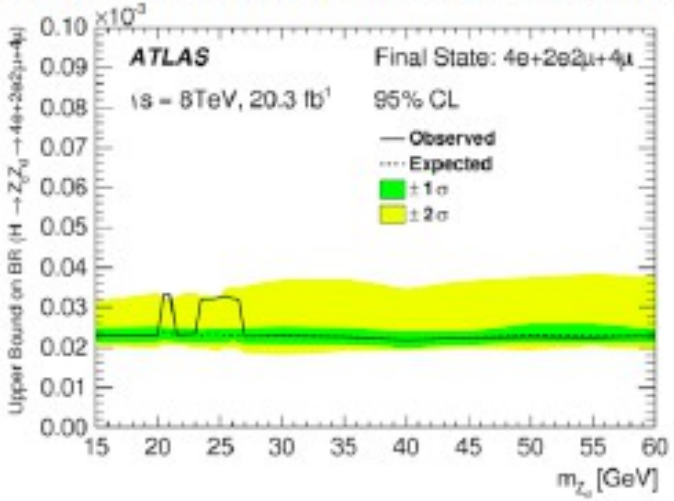


95% CL limits: $BR(H \to ZZ_d \to 4l) < (1\text{-}9) \times 10^{-5}$

$H \to Z_d Z_d \to 4l$



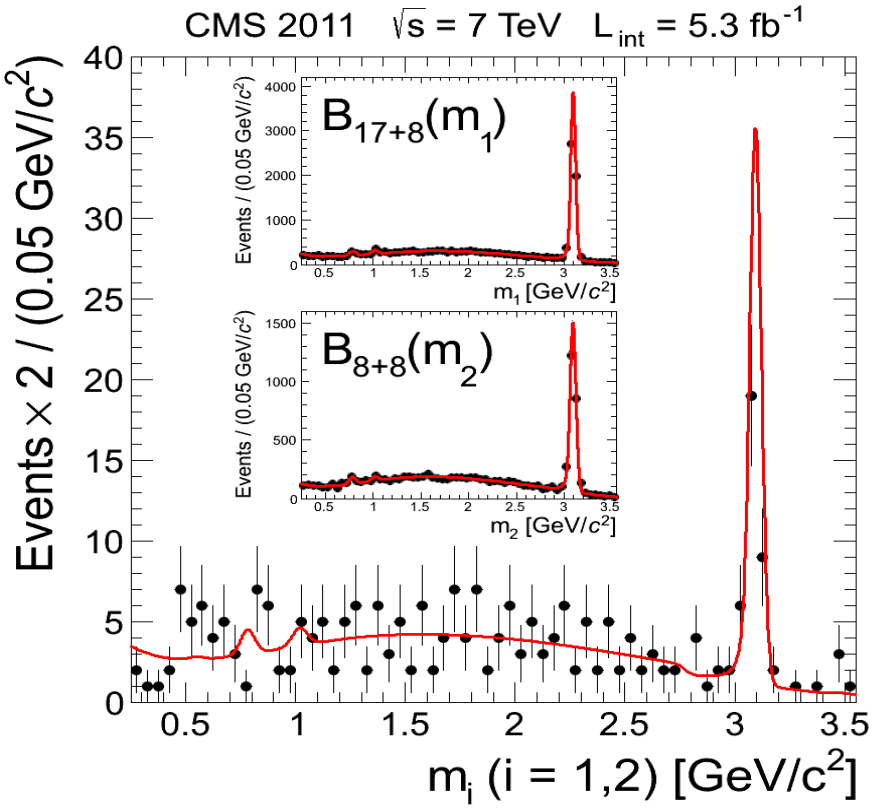
2 (4e, 4μ) observed events with significance 1.7 σ

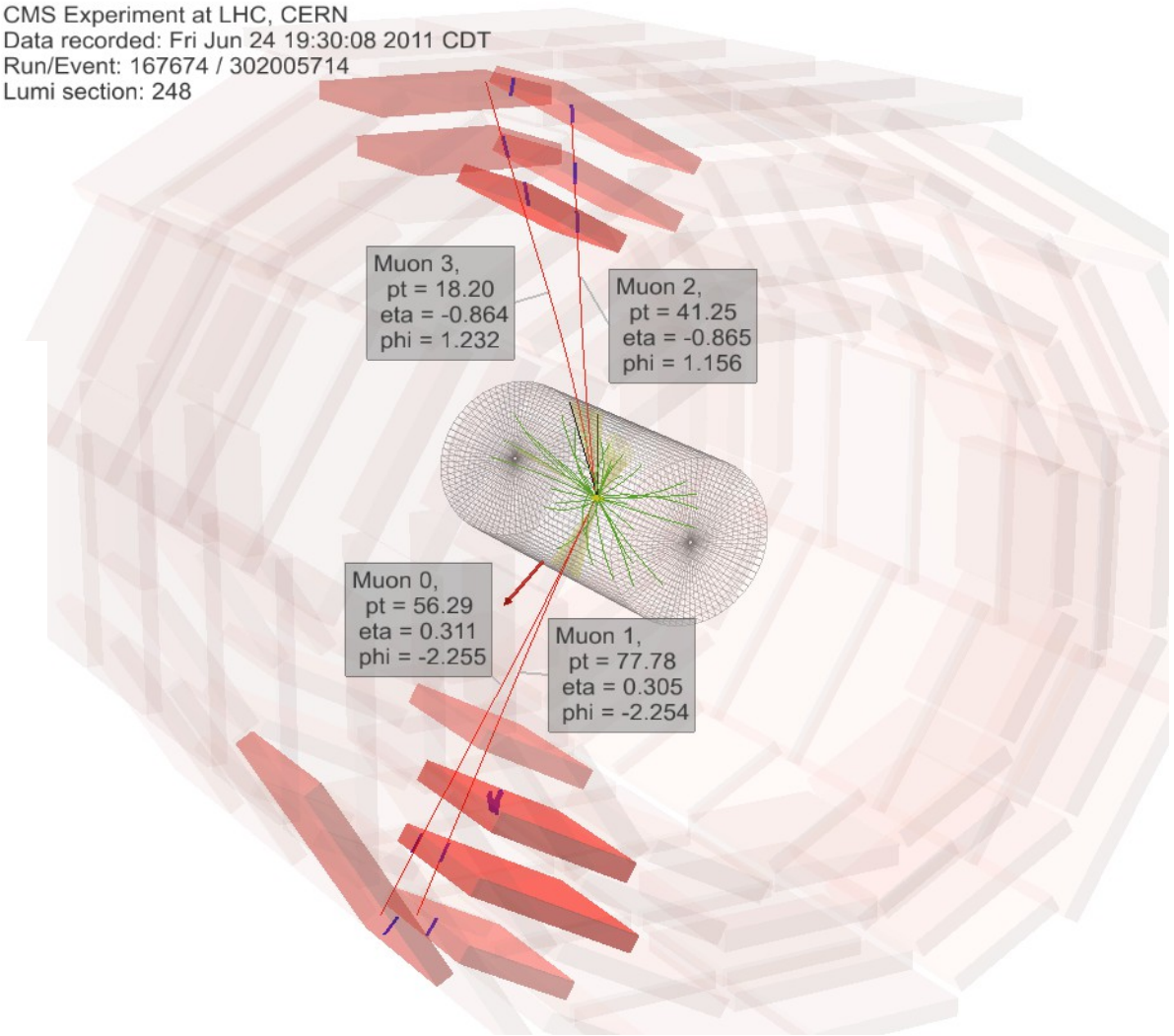


95% CL limits $BR(H \to Z_d Z_d \to 4l)$: $(2\text{-}3) \times 10^{-5}$

CMS search for H → muon-jets

- Select 4-muon events
- Look for di-muon invariant mass bump at low mass in *isolated* muon pairs

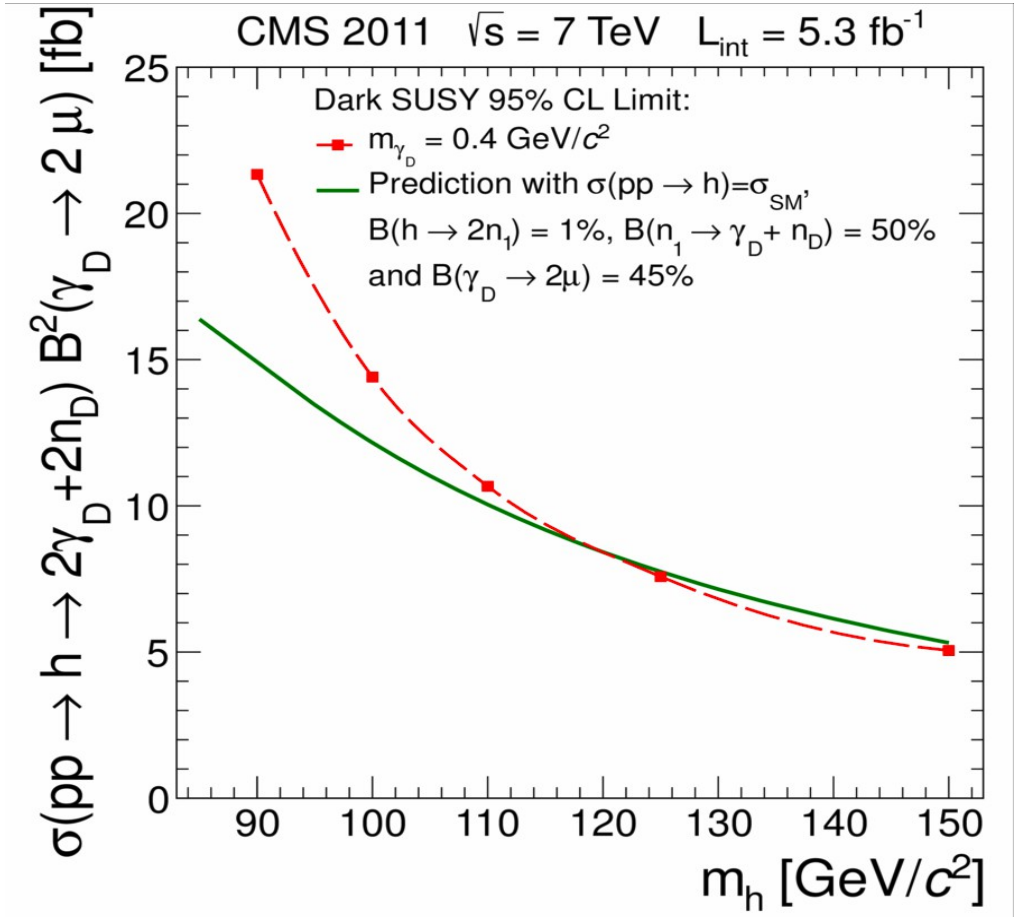


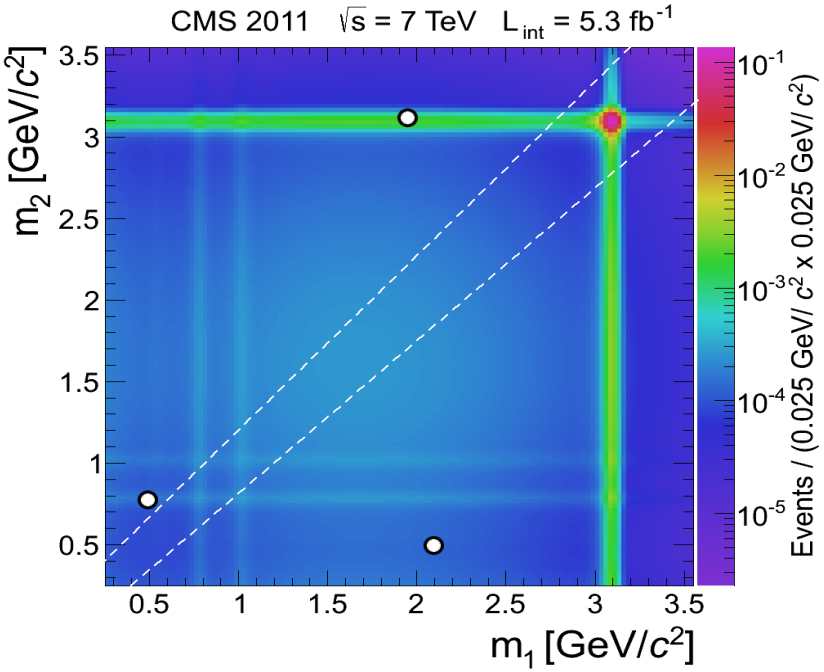


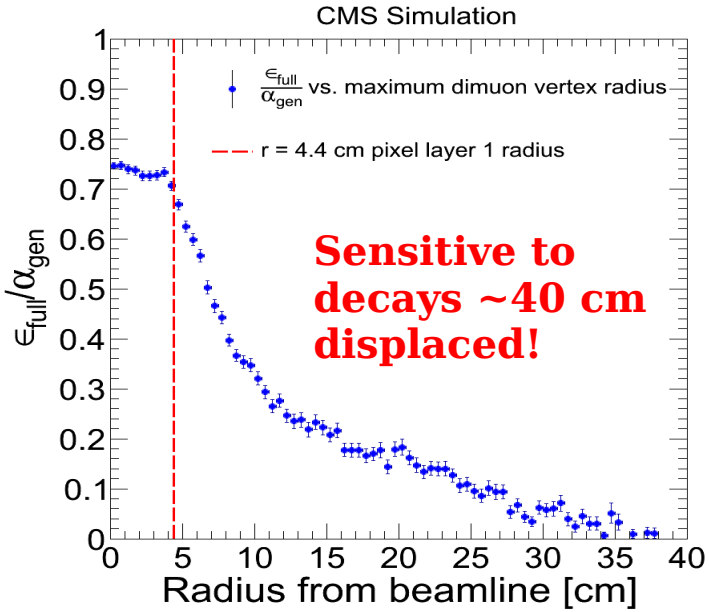
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO12012

CMS search for H → muon-jets

- Look for two mu+ mu- pairs to have the same mass
- Exclude SM H decays with <1% BR to muon-jets





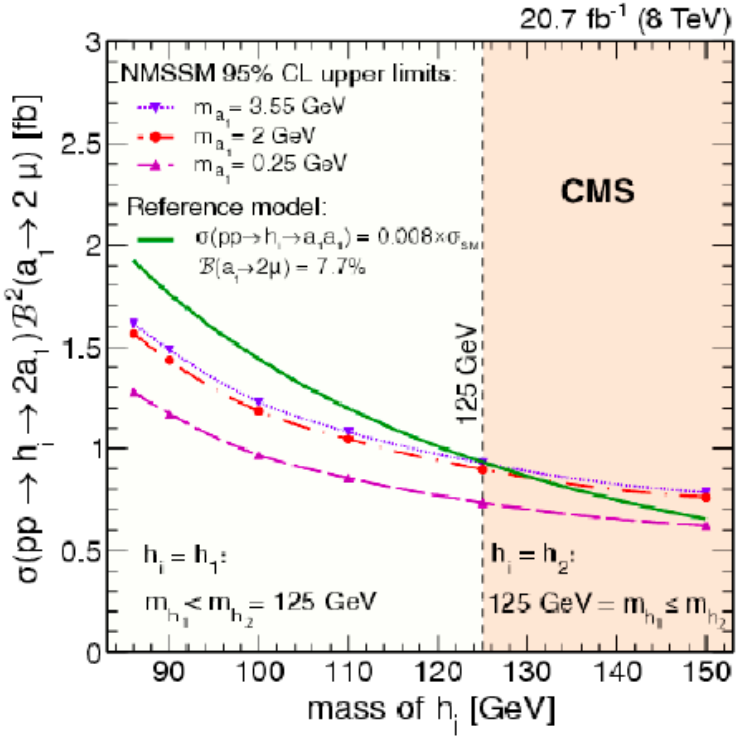


CMS search for H → dimuon-jets

- ***Recently updated with 8 TeV dataset!***
  - NMSSM Higgs sector: 3 CP-even neutral Higgs bosons $h_{1,2,3,}$ 2 CP-odd neutral Higgs bosons a and a pair of charged Higgs bosons $h^{\pm}$
  - $h_{1,2} \rightarrow 2\alpha_1$, h_1 or h_2 can be the boson observed at 125 GeV
  - $\alpha_1 \rightarrow 2\mu$, 2 pairs of isolated muons (di-muons), $m_{1\mu\mu} \approx m_{2\mu\mu}$ within detector resolution

Light boson masses in the range $2m_\mu < m_\alpha < 2m_\tau$ (0.25-3.55 GeV)

1 event obs. 2.2±0.7 SM exp.



BGs dominated by $b\bar{b}$ and J/ψ pair production

- 95% CL upper limits for NMSSM on $\sigma(pp \rightarrow h_{1/2} \rightarrow 2\alpha_1)B^2(\alpha_1 \rightarrow 2\mu)$ as a function of
  - m_{h1} ($86 < m_{h1} < 125$ GeV) and
  - m_{h2} ($m_{h2} > 125$ GeV)
- Limits compared to predicted rate (solid curve), with simplified scenario
  - $\sigma(pp \rightarrow h_i \rightarrow 2\alpha_1) = 0.008\ \sigma_{SM}$

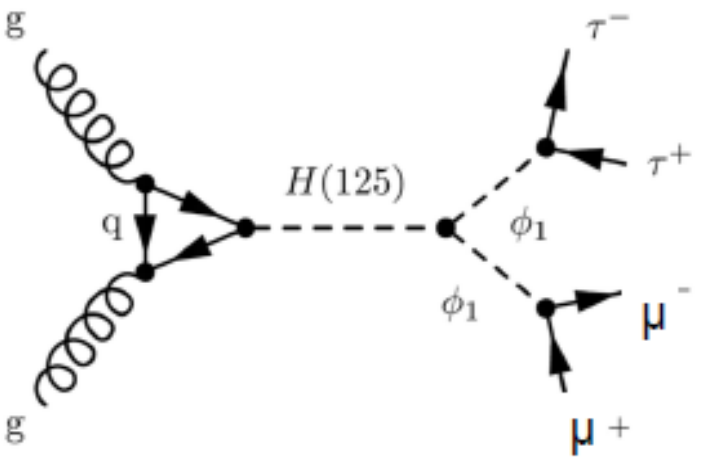
ATLAS Search for H → ditau-jets

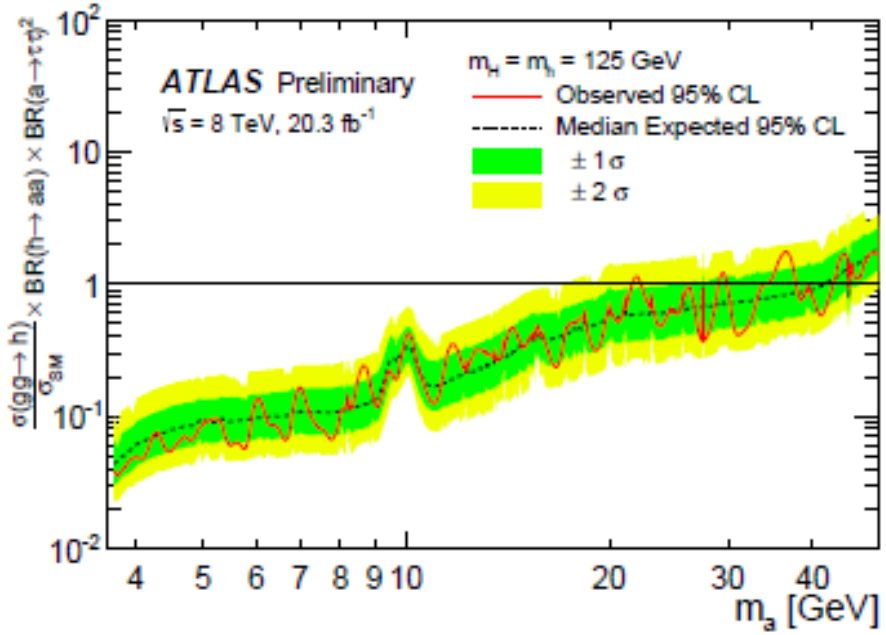
NMSSM CP-odd scalar
assumed to be light

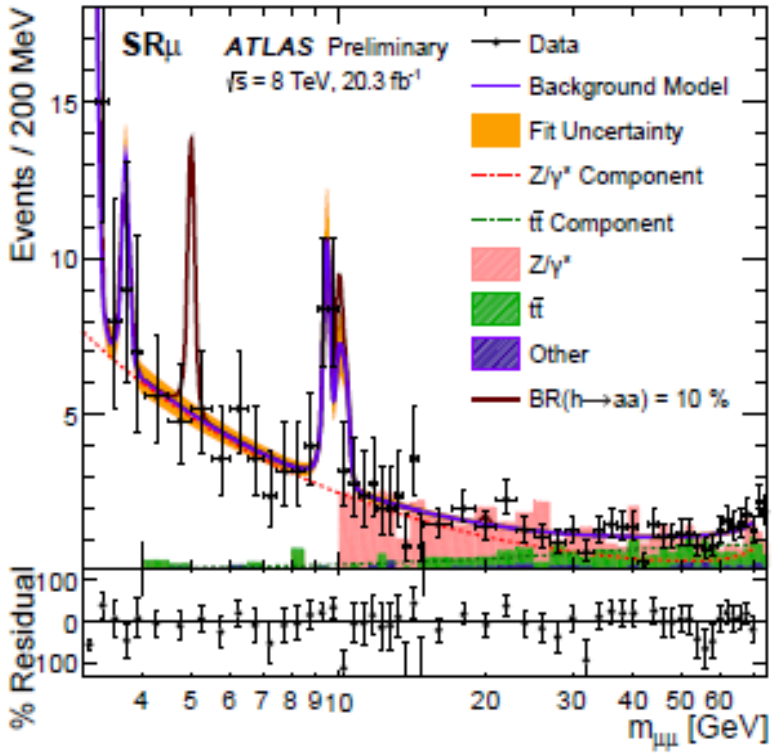
$H \to a_1 a_1 \to 2\mu 2\tau$ offers advantages wrt 4τ despite the smaller BR
use $m_{\mu\mu}$ as final observable

τ_{lep} decay
Boosted a_1 decays: special τ_{had} ID

search performed in range
$2m_\tau < m_{a1} < 50$ GeV





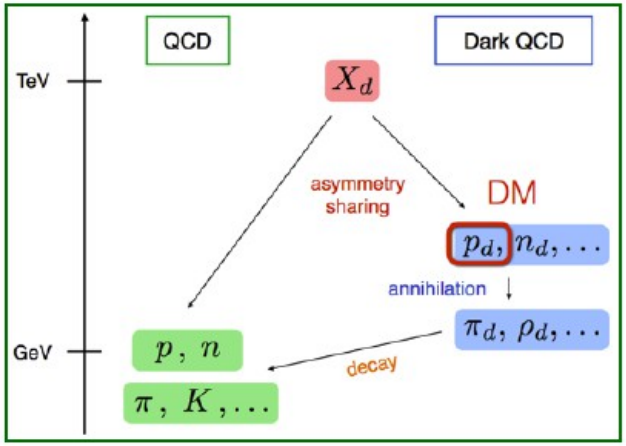


Other LHC Rich Hidden Sector Searches

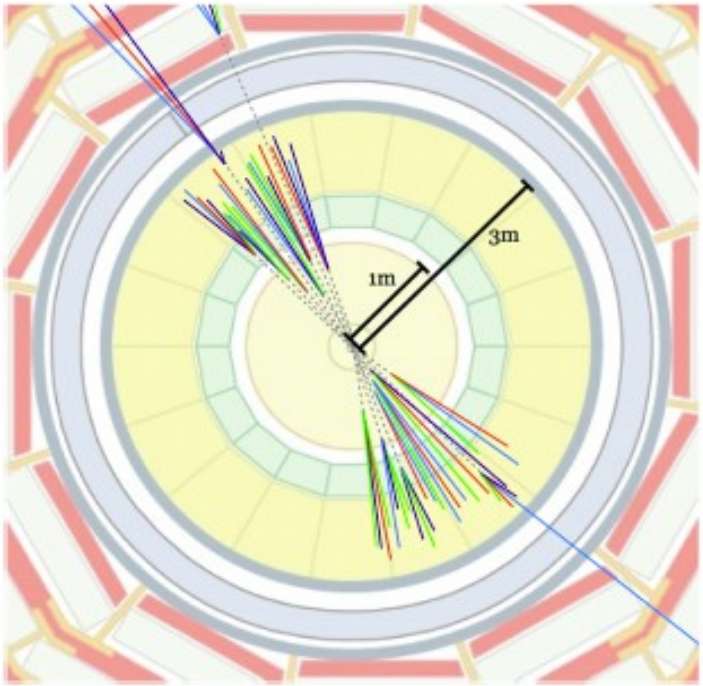
- Rich dark sector with long-lived dark-pions … **Emerging Jets**

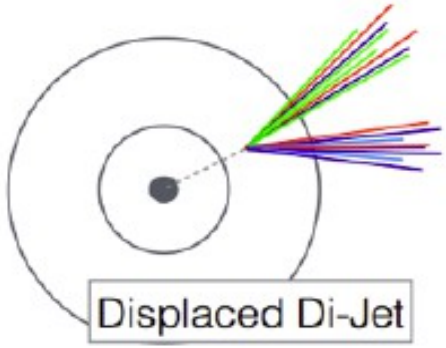
What are emerging jets?

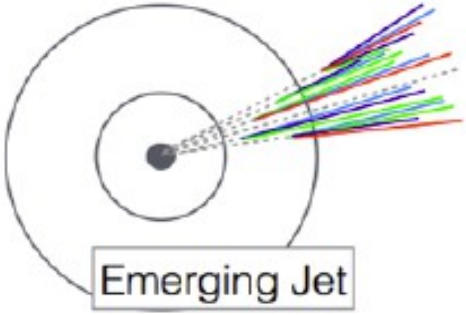
A novel LHC signature where dark or hidden sector quarks decay to the visible sector via multiple displaced vertices of varying displacements within the same jet object. Pair-produced dark quarks then give rise to **neither prompt jets nor a pair of displaced jets** pointing to the same displaced vertex, but to **emerging jets**.



arXiv:1502.05409





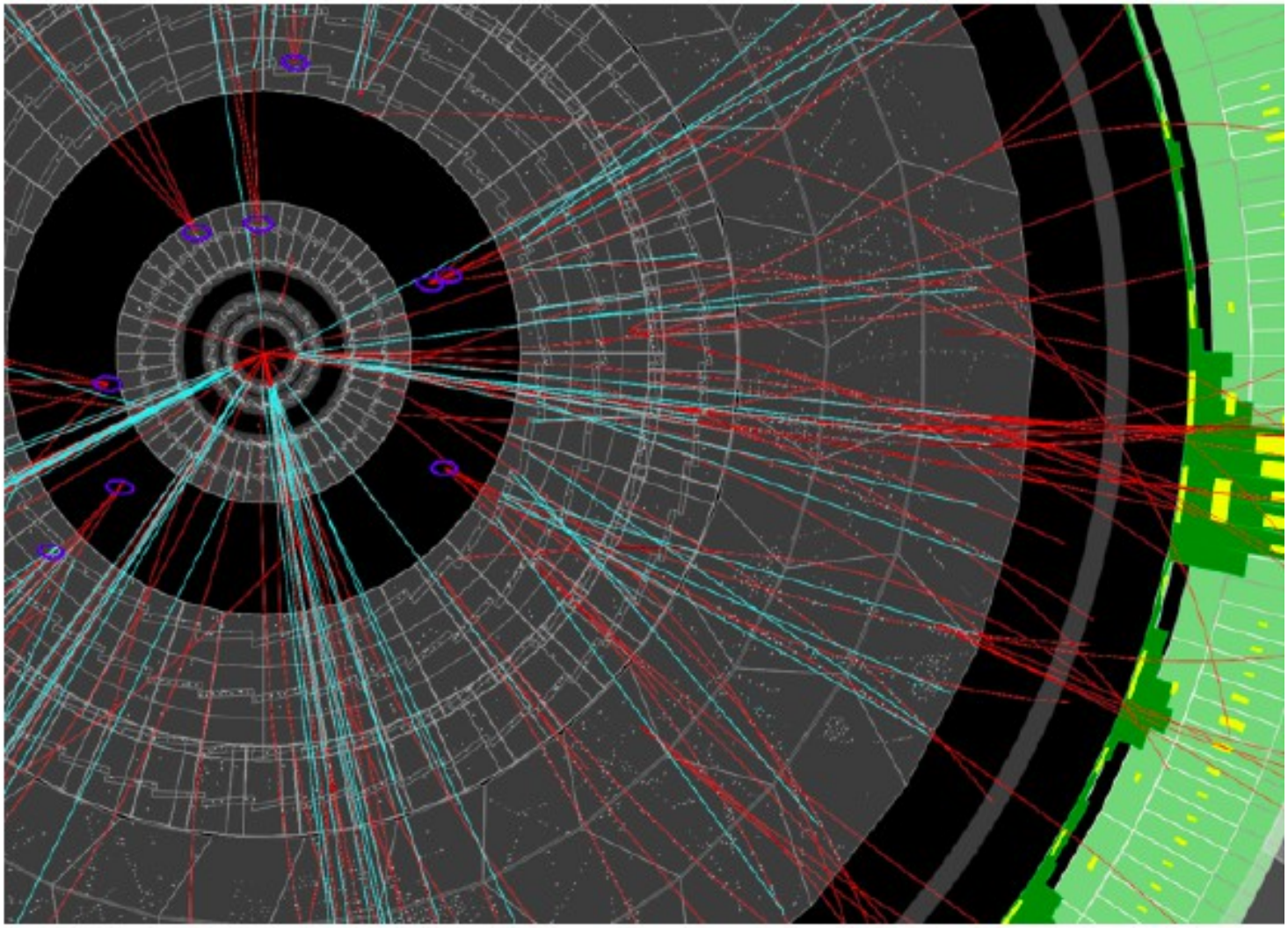


arXiv:1502.05409

Other LHC Rich Hidden Sector Searches

Tracks

- Red: Truth
- Blue: Reconstructed



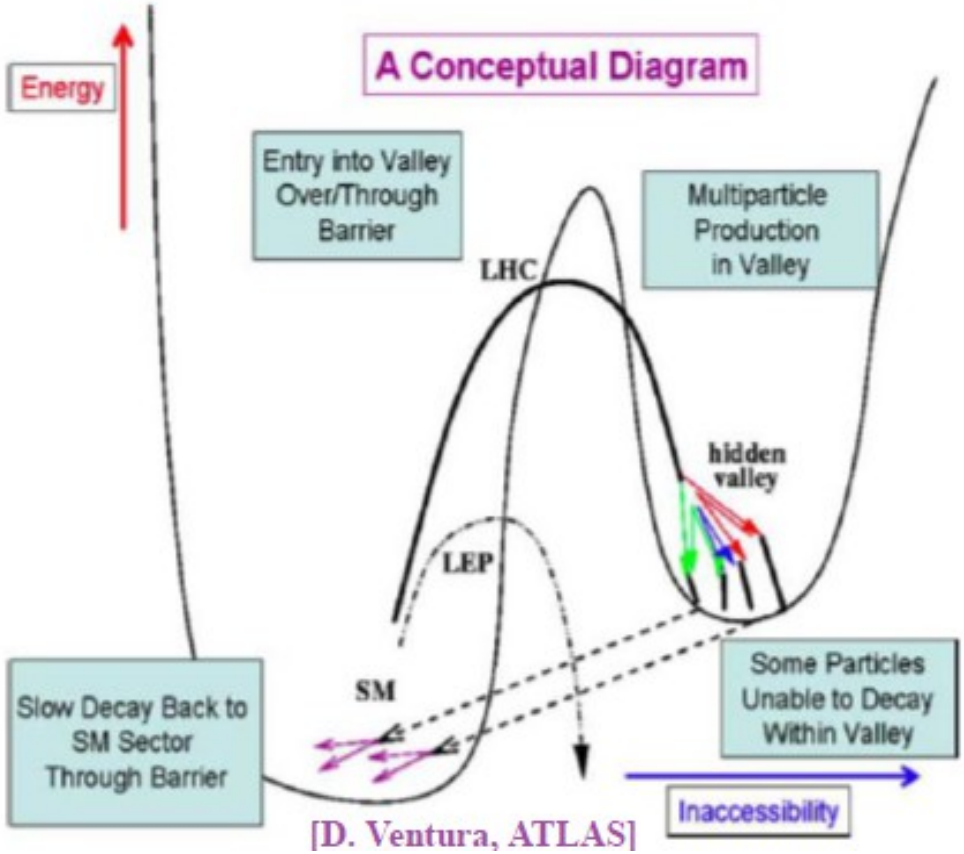
Clearly some challenges by-eye: "Where" is the emerging jet? Is some measure of "emergingness" of a standard jet possible if the displaced vertices are so broadly distributed?

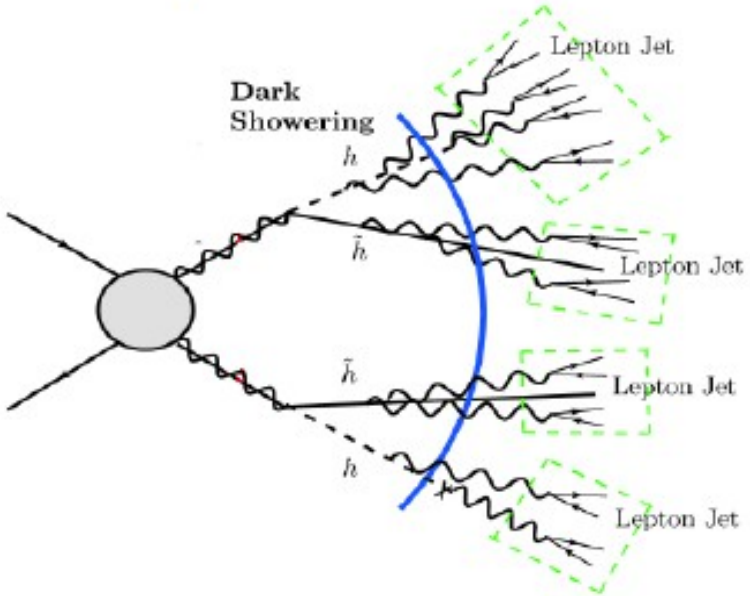
Event-level quantity possibly more manageable and powerful enough (TBD — still running)

New Displaced Dark Photon Searches

Hidden Sector

- γ_d accompanied by zoo of other "hidden" particles?
- G_{dark} bigger than U'(1)?





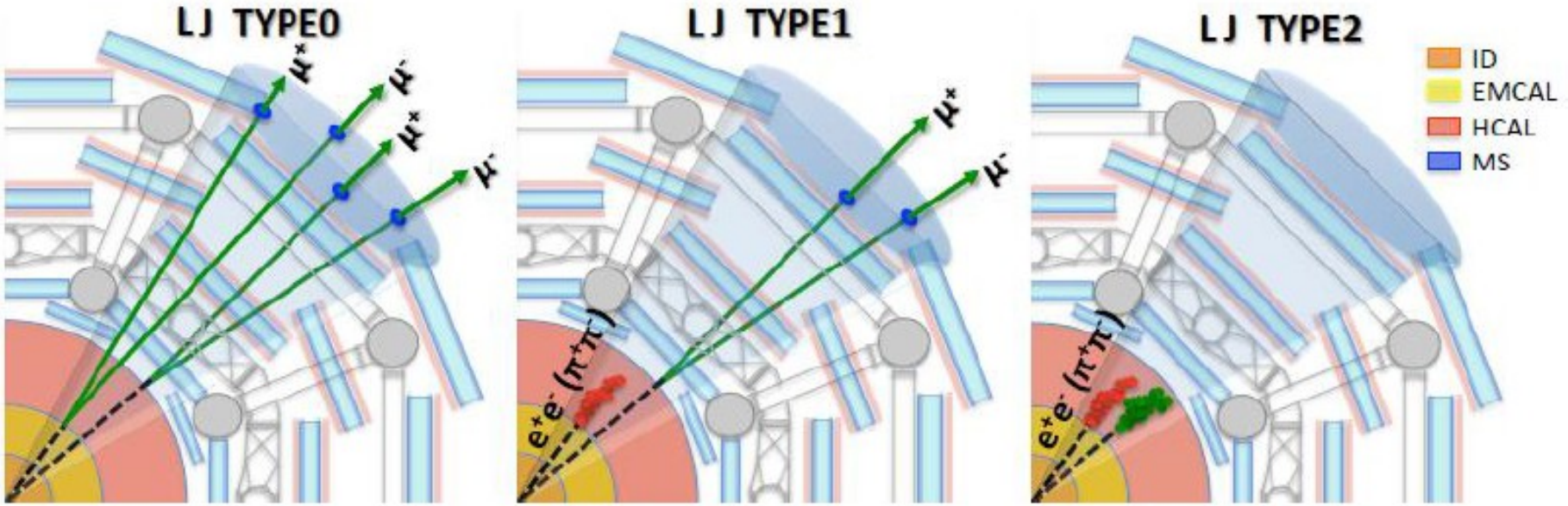
- Production of multiple boosted γ_d from long decay chains → multiple displaced LJs

Run 1 Results: ATLAS

Targets γ_d decays beyond pixel detector, up to muon spectrometer

- Muon pairs: have only spectrometer information
- Electron / pion pairs: appear as jets in calorimeters
- LJ categorization:

[arXiv:1409.0746]



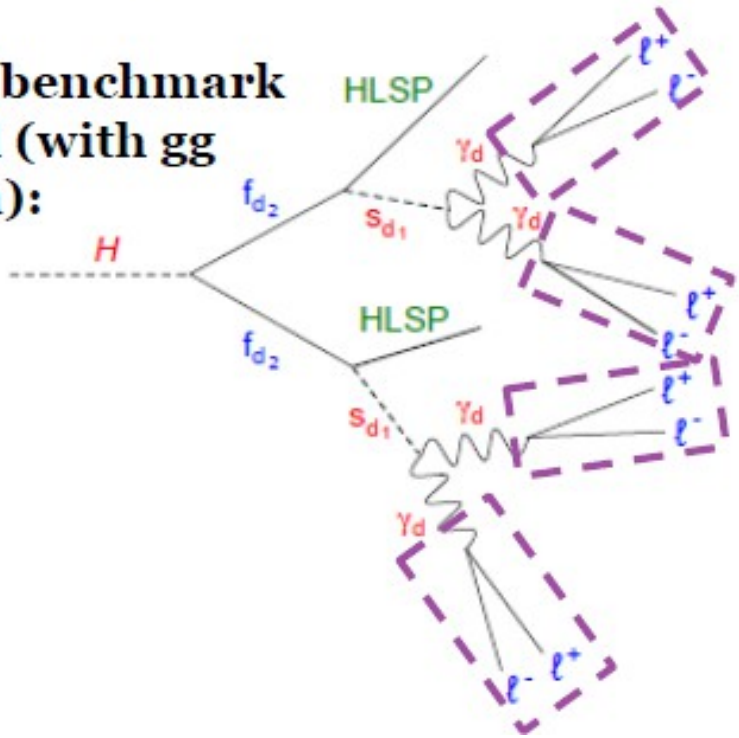
New Displaced Dark Photon Searches

Run 1 Results: ATLAS

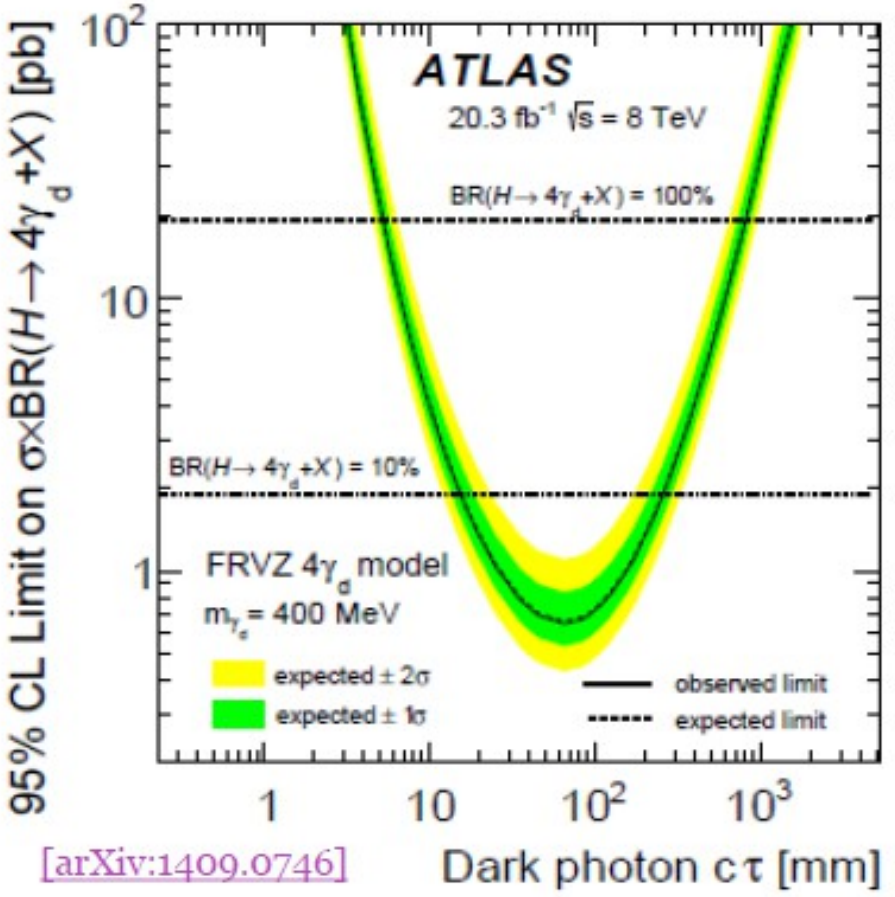
Events (+/- stat. +/- sys.)

Data	119
Cosmic rays	$40 \pm 11 \pm 9$
Multi-jets (ABCD)	$70 \pm 58 \pm 11$
Total background	$110 \pm 59 \pm 14$

FRVZ benchmark model (with gg fusion):



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



[arXiv:1409.0746]

New Displaced Dark Photon Searches

Run 1 Results: CMS

Targets γ_d decays within the pixel detector, into muon LJs only

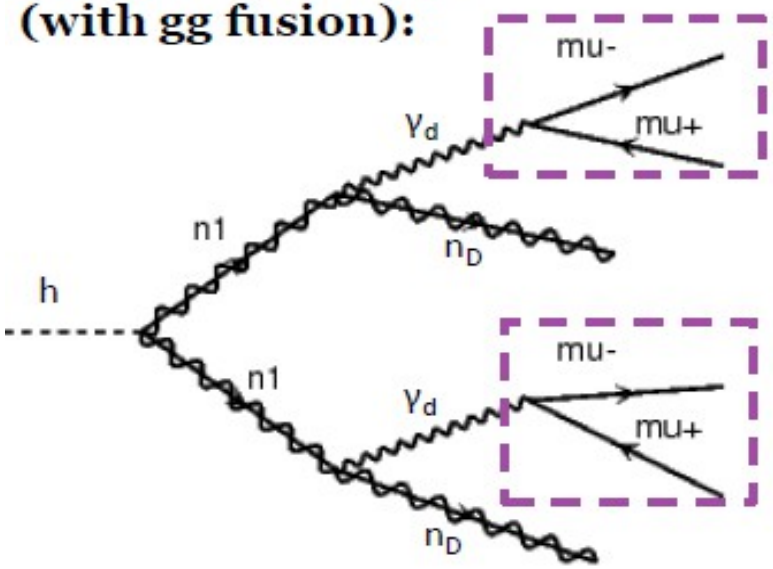
- Trigger: dimuon, p_T > 17 GeV (leading), p_T > 8 GeV (subleading)
- Selection criteria:

[arXiv:1506.00424]

Model-independent 95% CL:

$$\sigma(pp \to 2a + X)\,\mathcal{B}^2(a \to 2\mu)\,\alpha_{gen} \leq 0.24 + 0.09 \exp\left(-\frac{(m_{\mu\mu} - 0.32)^2}{2 \times 0.03^2}\right)$$
$$= \bar{N}(m_{\mu\mu}) / (\mathcal{L}\bar{r})$$

Dark SUSY benchmark model (with gg fusion):



α = kinematic & geometrical acceptance
ε = selection efficiency
$r = \varepsilon_{data} / \alpha_{gen}$

m_{γ_D} [GeV]		0.25	
$c\tau_{\gamma_D}$ [mm]	0	0.5	2
ϵ_{sim} [%]	8.85 ± 0.12	1.76 ± 0.05	0.23 ± 0.03
α_{gen} [%]	14.32 ± 0.14	2.7 ± 0.06	0.31 ± 0.03
$\epsilon_{sim}/\alpha_{gen}$	0.62 ± 0.01	0.65 ± 0.02	0.74 ± 0.13

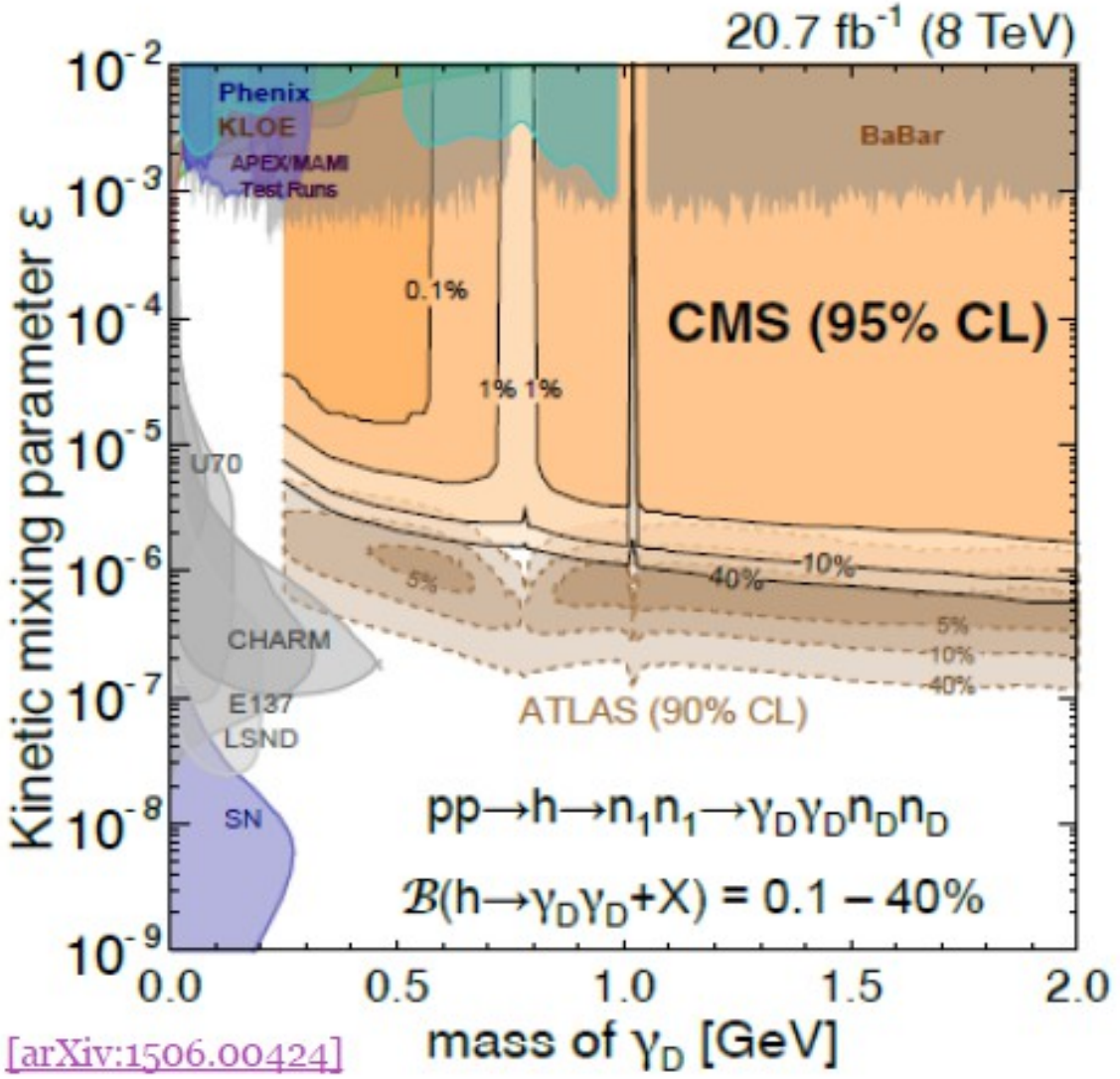
m_{γ_D} [GeV]		1.0	
$c\tau_{\gamma_D}$ [mm]	0	0.5	2
ϵ_{sim} [%]	6.13 ± 0.23	4.73 ± 0.07	1.15 ± 0.04
α_{gen} [%]	8.89 ± 0.28	6.98 ± 0.09	1.68 ± 0.05
$\epsilon_{sim}/\alpha_{gen}$	0.69 ± 0.03	0.68 ± 0.01	0.68 ± 0.03

[arXiv:1506.00424] $m_{n_1} = 10\,\text{GeV}$, $m_{n_D} = 1\,\text{GeV}$

Run 1 Results: ATLAS + CMS

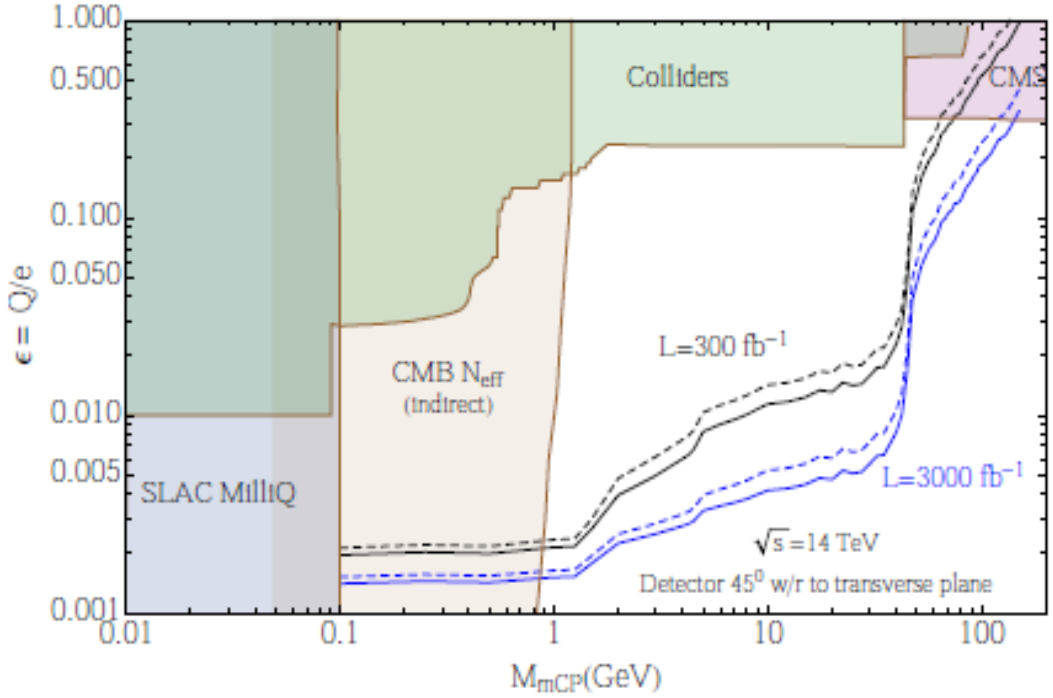
Combined results for γ_d interpretation:

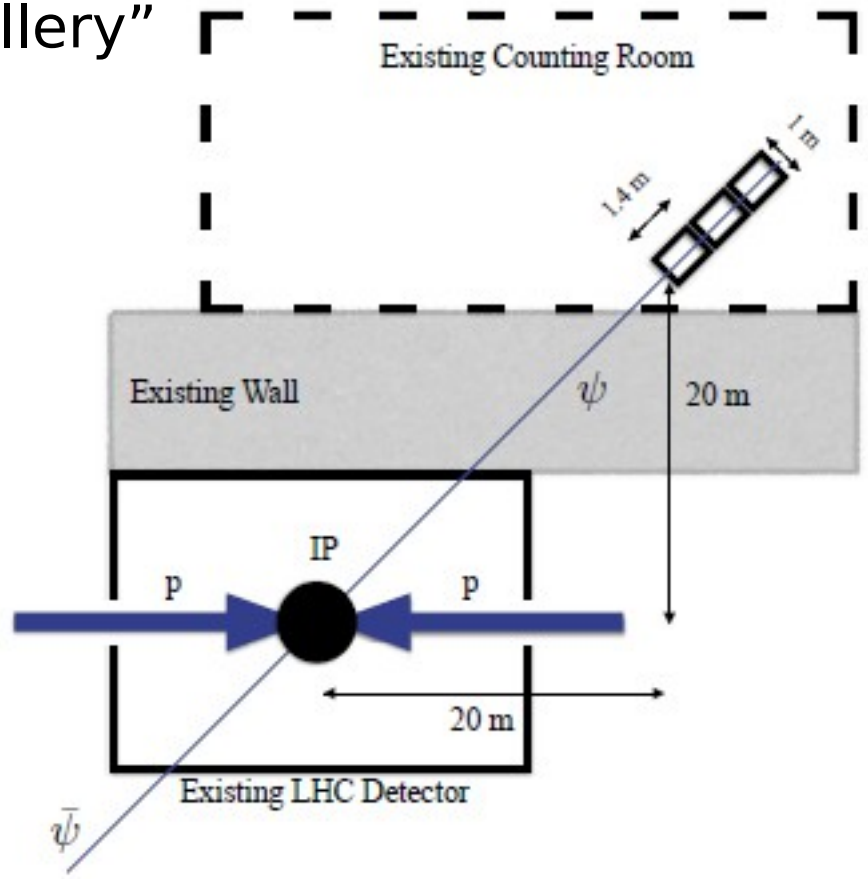
- Complementary coverage in γ_d parameter space
- In regions other experiments were unable to reach!
  - ATLAS & CMS limits have extra parameter (BR for h → hidden)



New LHC Experiment: MilliQan

- Milli-charged particles → massive, with electric charge ~10^{-3} e
- Easy to add to SM: “dark U(1)” (with massless dark photon) kinetic mixing → dark fermion milli-charged under SM
- Currently weak direct limits for fermion mass > 100 MeV
- ~1 photo-electron observed per 1m long scintillator
- Require triple-incidence in time window
- Moving forward in CMS “drainage gallery”



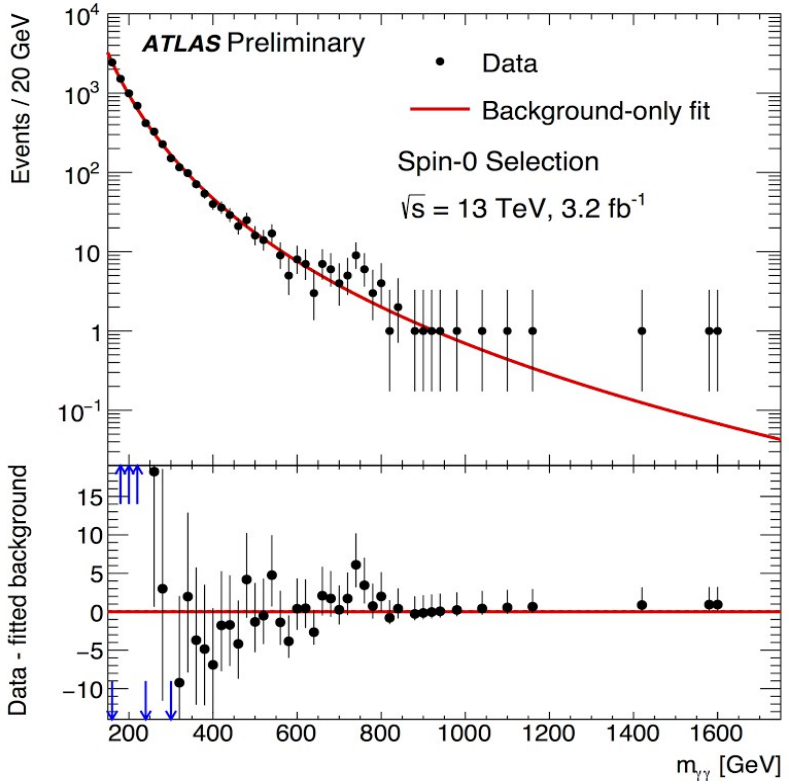


750 Pound Elephant in the Room

- Let's not forget the ~3σ diphoton excess *at both ATLAS and CMS*
- We'll have enough data by ~July to either confirm or refute
- What if it is real?
- Rich dark sector connections? Analyses we should plan?

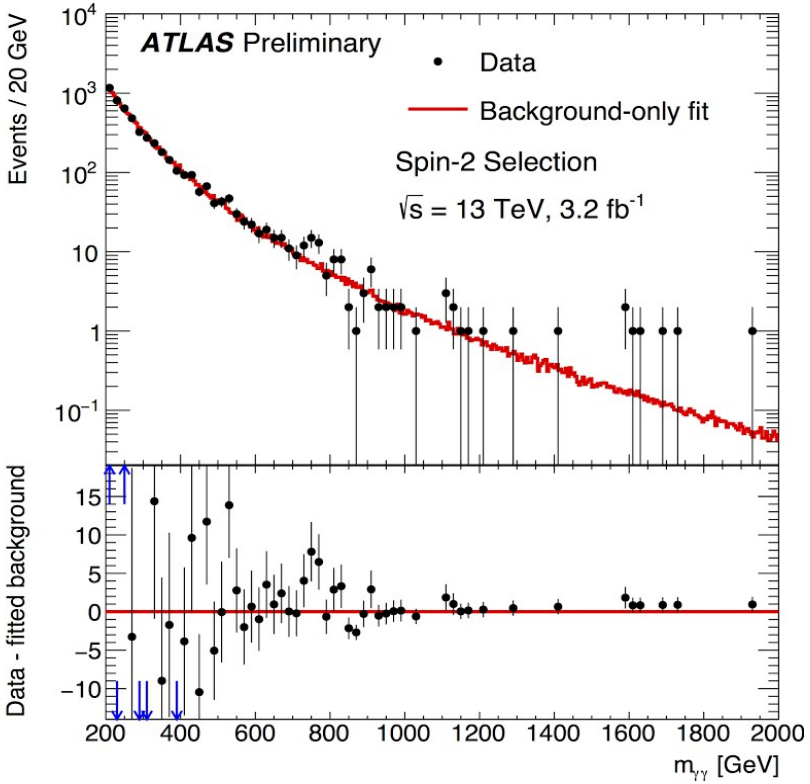
SPIN-0 ANALYSIS

background-only fit



SPIN-2 ANALYSIS

background-only fit

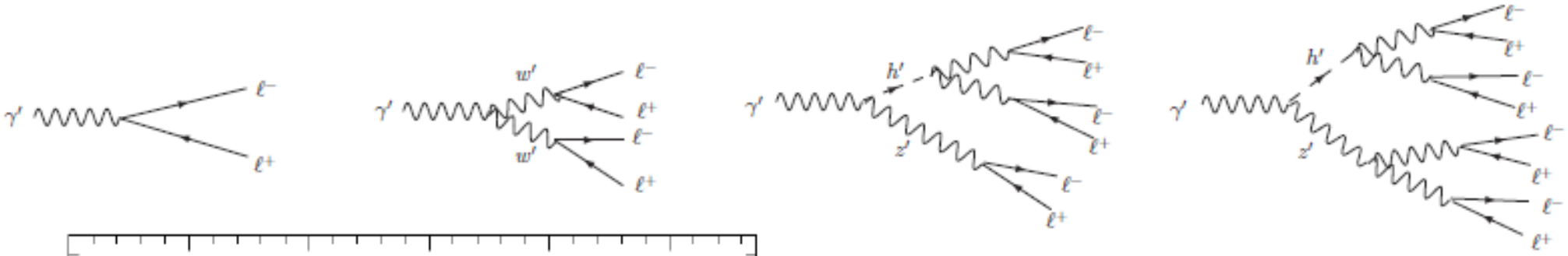


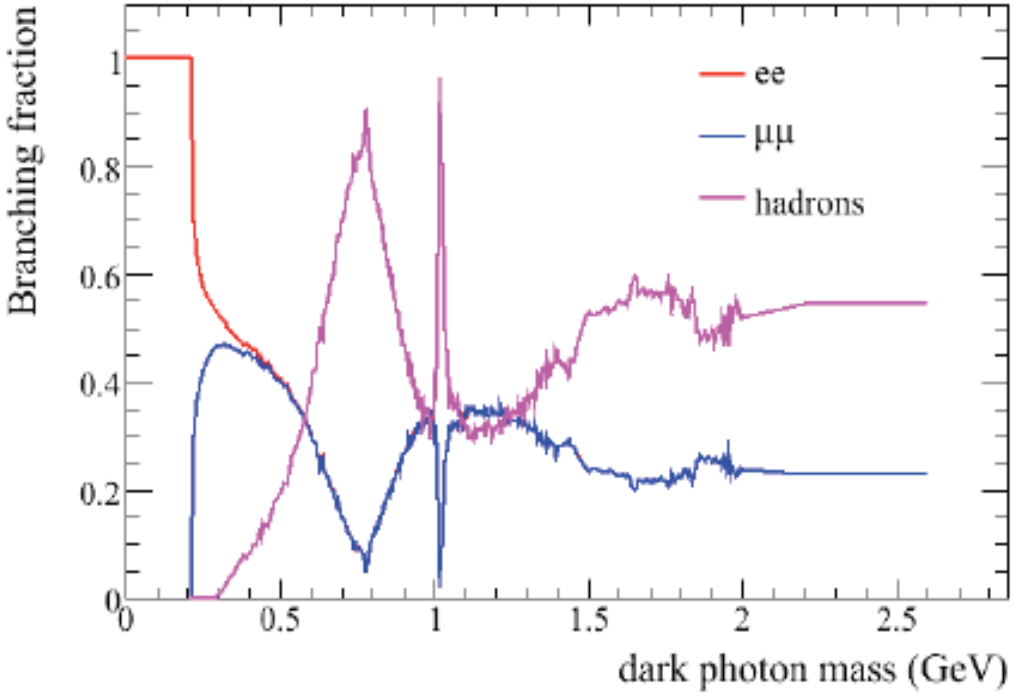
Backup

Lepton jets

- **Dark photons are *boosted***

  Create “lepton jets”:
  pairs of collinear electrons or muons





Probably prompt decays,
but maybe not…

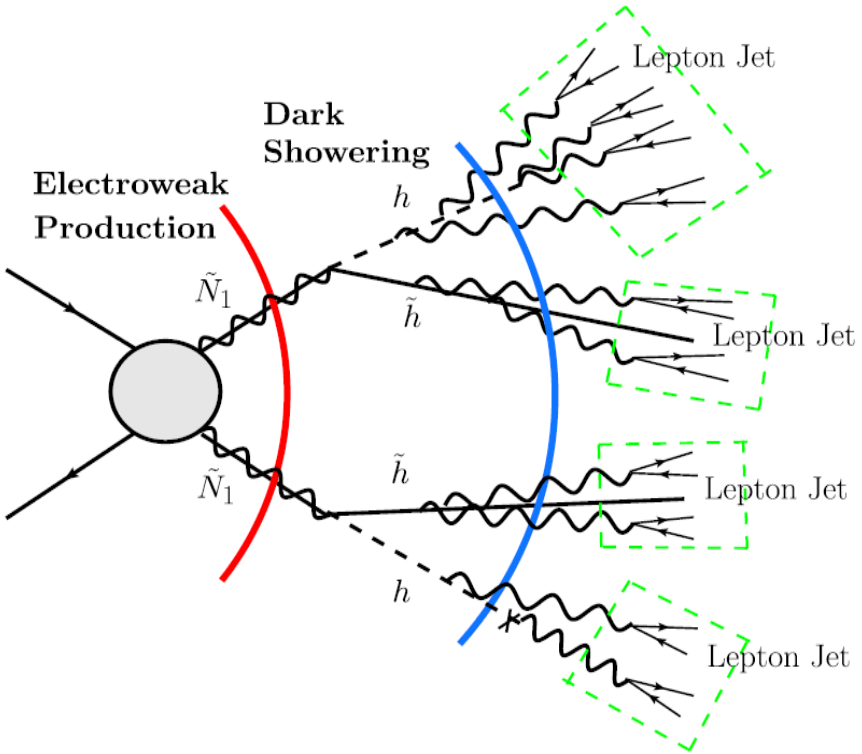
$$c\tau^{\gamma' \to n\ell}_{2-\text{body}} \sim \frac{1}{\alpha \epsilon^2 m_{\gamma'}} = 2.7 \times 10^{-6}\ \text{cm} \left(\frac{\text{GeV}}{m_{\gamma'}}\right)\left(\frac{10^{-3}}{\epsilon}\right)^2$$

SUSY lepton jets

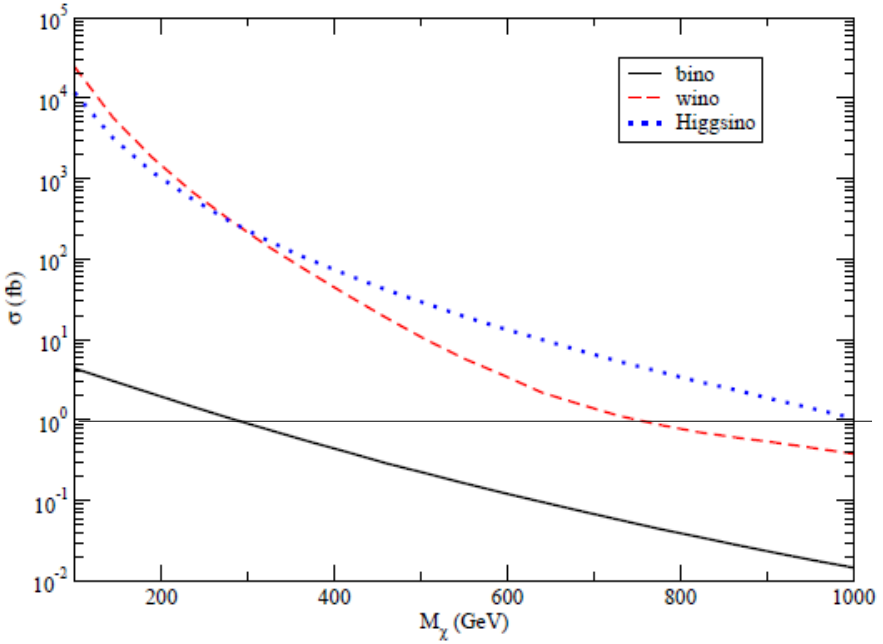
- **LSP decays to dark sector?!** BR = 1! Prompt:

$$\tau_{\mathrm{LSP}\to h+\tilde{h}} \sim \left(\alpha_y^{\mathrm{dark}} f_{\tilde{B}}^2 \epsilon^2 M_{\mathrm{LSP}}\right)^{-1}$$
$$= 7\times 10^{-19}\ \mathrm{s}\left(\frac{100\ \mathrm{GeV}}{M_{\mathrm{LSP}}}\right)^2\left(\frac{0.01}{\alpha_y^{\mathrm{dark}}}\right)\left(\frac{1.0}{f_{\tilde{B}}}\right)^2\left(\frac{10^{-3}}{\epsilon}\right)^2$$

- **Changes signature of SUSY**
  - Less MET
  - Two *dark* photons (lepton jets)

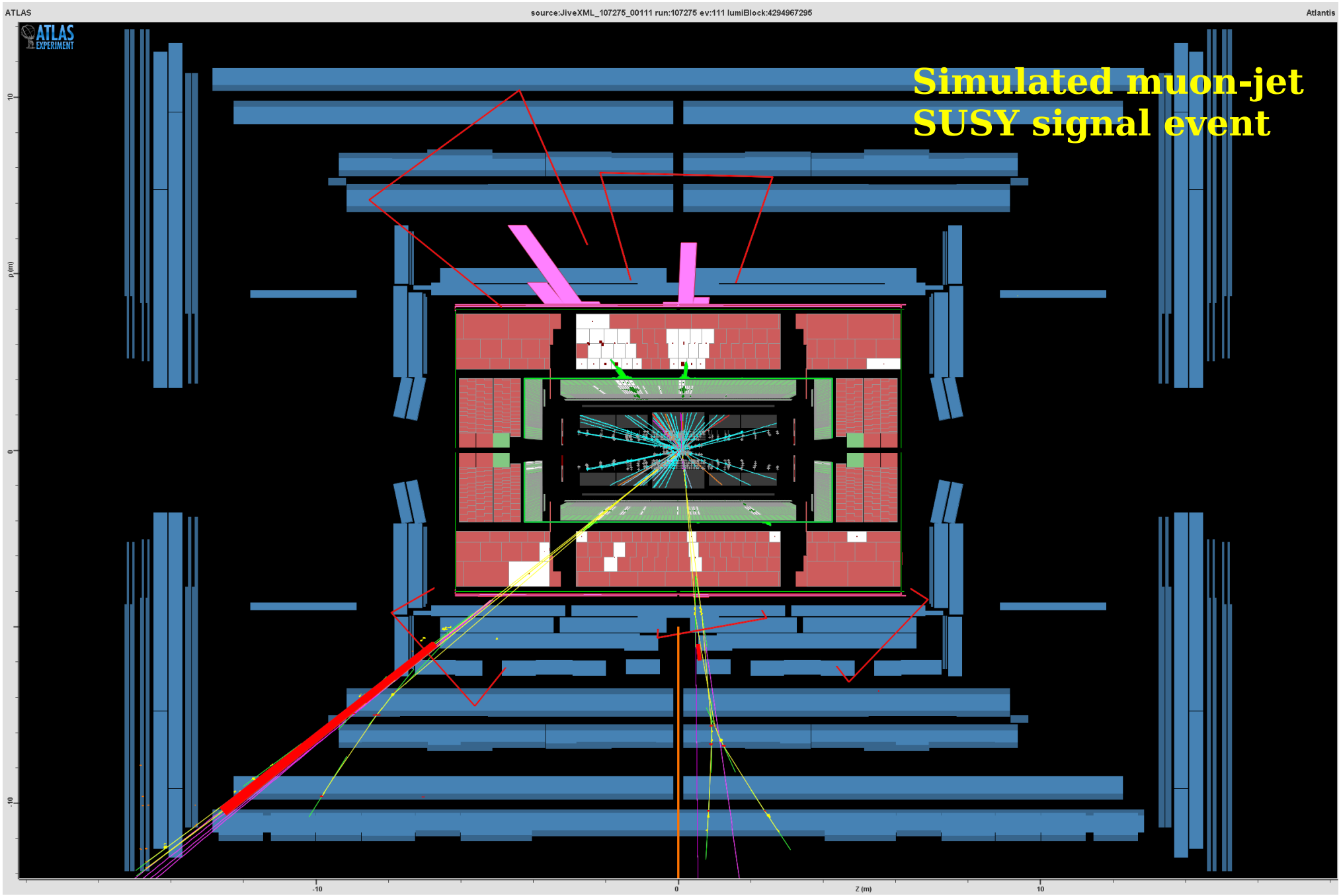


Electroweak production is small but still observable



Possibly large production rate for colored SUSY particles...

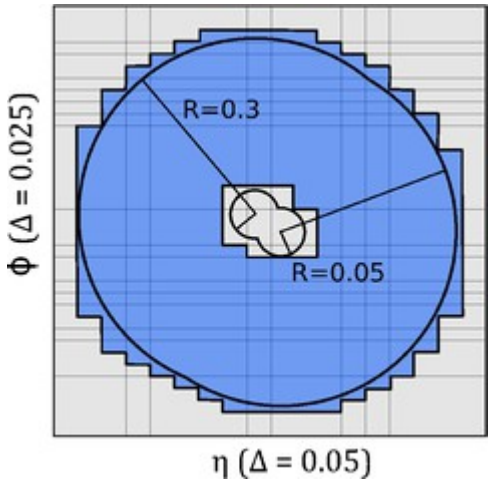
SUSY lepton jets at ATLAS



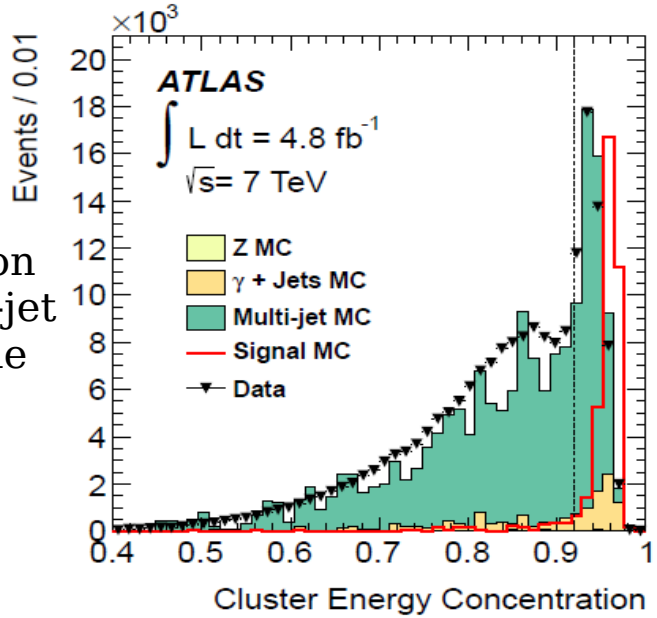
SUSY lepton jets at ATLAS

- Search for events with:
  - 2 prompt muon lepton-jets
  - 2 prompt electron lepton-jets
  - 1 prompt 4-muon lepton-jet
- Custom lepton-jet identification to separate from QCD jets
- Backgrounds measured in control regions
- Dark photon also *could* give peak at dark photon mass
- No excess observed

Muon isolation definition



Electron lepton-jet variable



	Electron LJ	1 Muon LJ	2 Muon LJ
Data	15	7	3
All background	15.2±2.7	3.0 ± 1.0	0.5 ± 0.3

Jet prob bkgd method: $14.55^{+0.23}_{-0.04}$ 2.2 ± 0.9 events

SUSY lepton jets at ATLAS

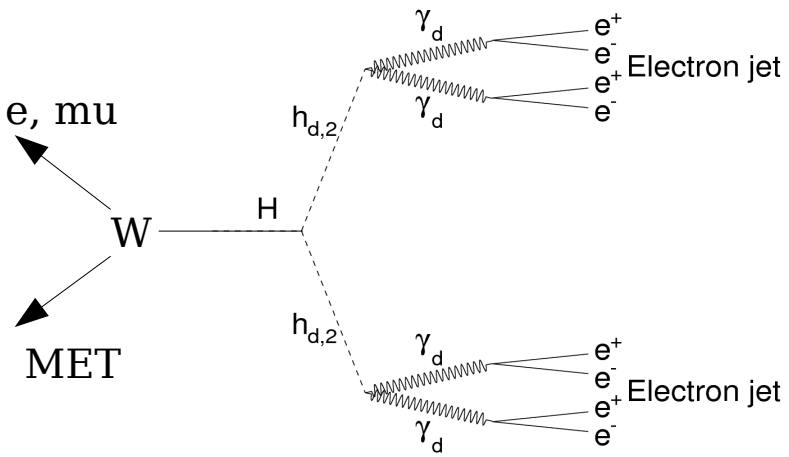
- Cross-sections excluded for various dark-photon masses and radiation parameters <~ 0.02 – 0.1 pb
- Constrains strong-production up to ~TeV and even weak-production up to ~400 GeV (assuming LSP → lepton-jet)
- **Update to 2012 data**
- **Study *long-lived* decays to electron (or muon?) lepton-jets in the tracker (~0.1 – 10 cm)**

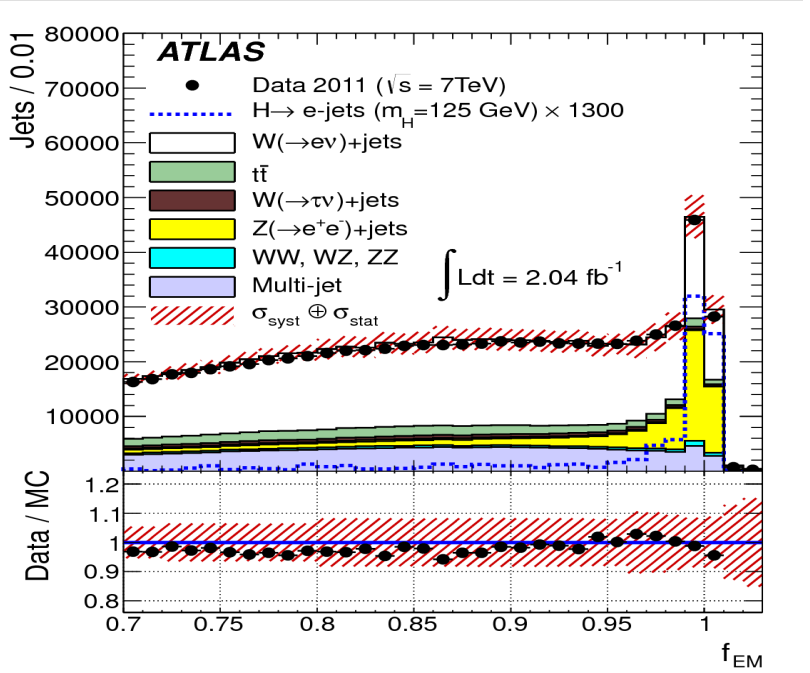
Cross-section limits for various decays

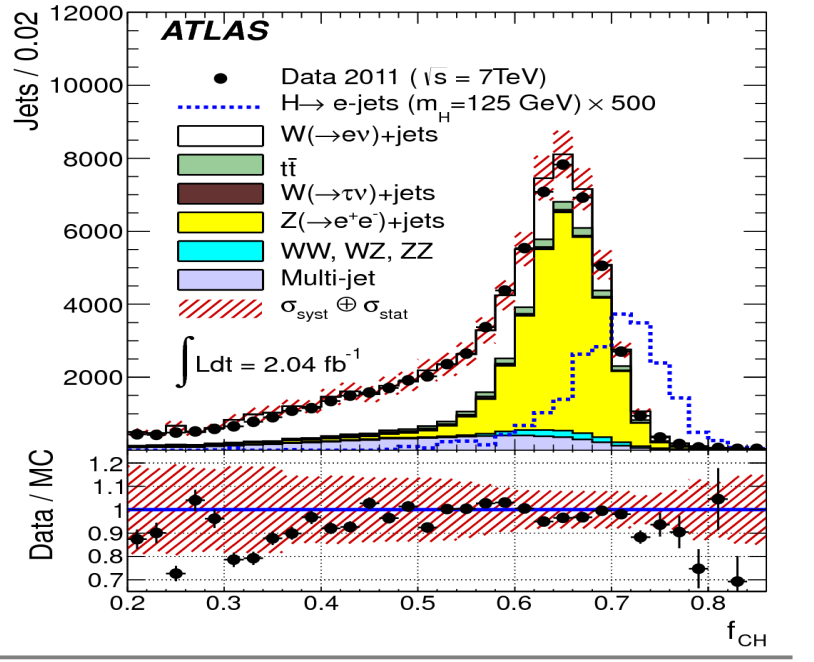
Signal Parameters		Electron LJ	1 Muon LJ	2 Muon LJ
α_d	m_{γ_D} [MeV]	Obs (Exp) pb	Obs (Exp) pb	Obs (Exp) pb
0.0	150	0.082 (0.082)	-	-
0.0	300	0.11 (0.11)	0.060 (0.035)	0.017 (0.011)
0.0	500	0.20 (0.21)	0.15 (0.090)	0.019 (0.012)
0.10	150	0.096 (0.10)	-	-
0.10	300	0.37 (0.37)	0.064 (0.036)	0.018 (0.011)
0.10	500	0.39 (0.39)	0.053 (0.035)	0.018 (0.011)
0.30	150	0.11 (0.11)	-	-
0.30	300	0.40 (0.40)	0.099 (0.055)	0.020 (0.012)
0.30	500	1.2 (1.2)	0.066 (0.043)	0.022 (0.015)

http://arxiv.org/abs/1212.5409

ATLAS Search for WH → prompt electron-jets





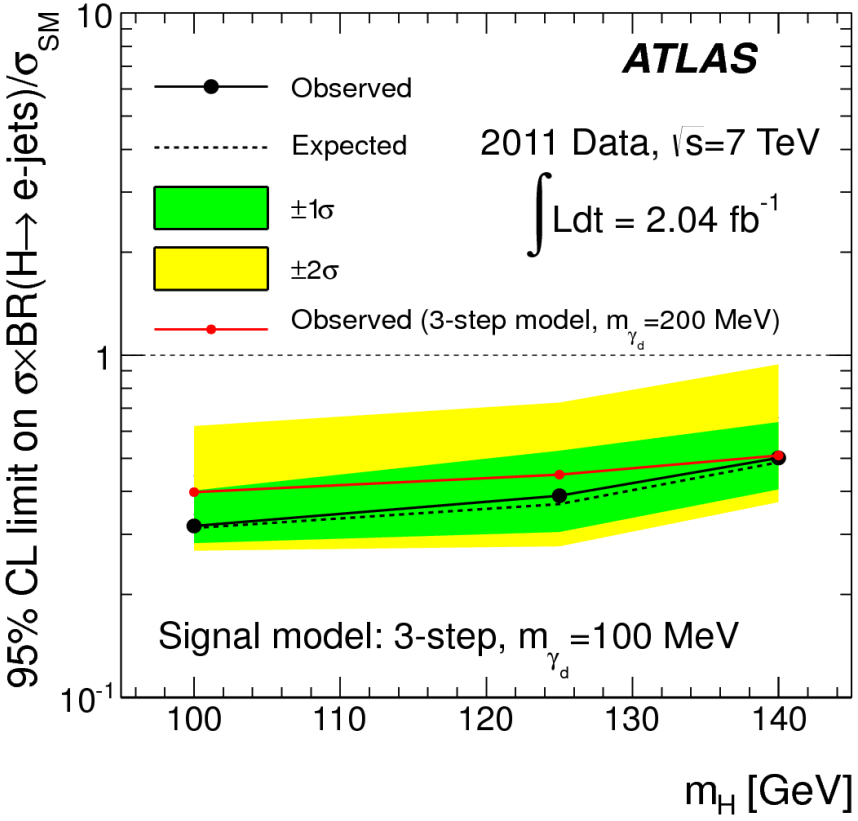


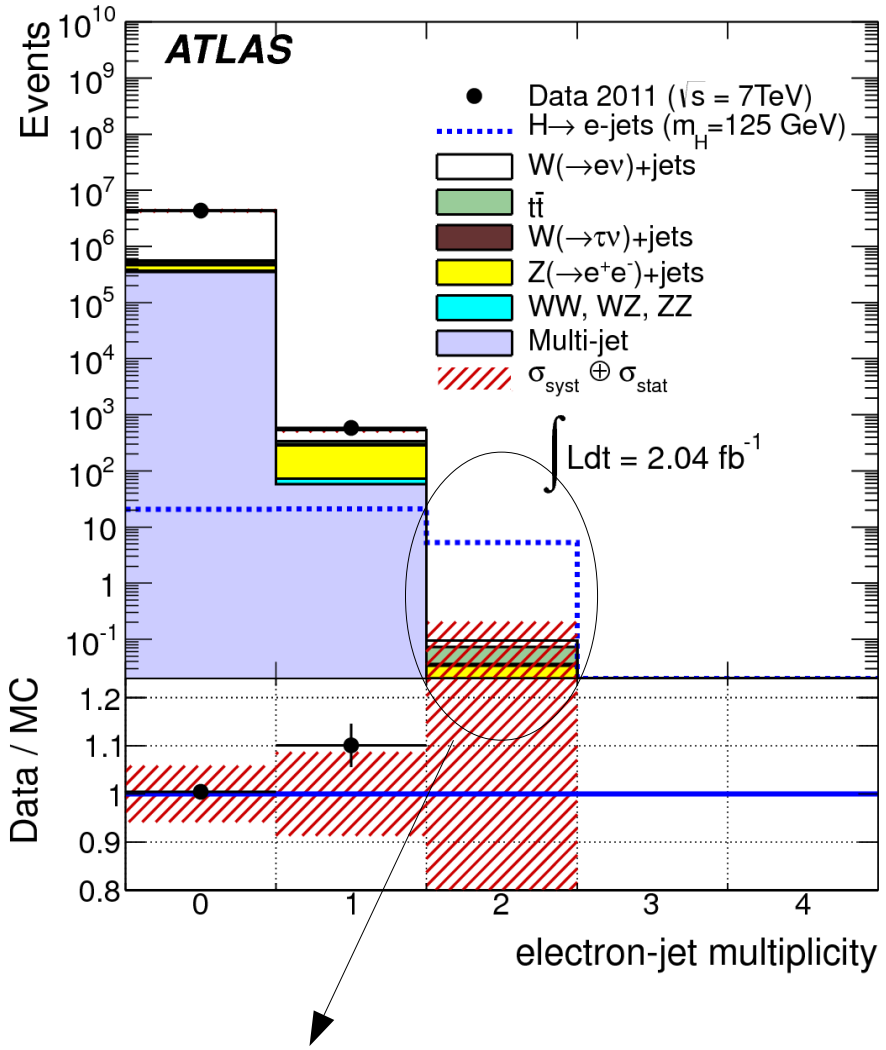
- Electron lepton-jets would have:
  - Large EM energy fraction
  - Large charged particle pT fraction
  - Large number of tracks
- Separate signal from other backgrounds with QCD jets

ATLAS Search for WH → prompt electron-jets

- No excess observed with 2 electron-jets
- **BR(h → electron-jets) < ~50%**

http://arxiv.org/abs/1302.4403





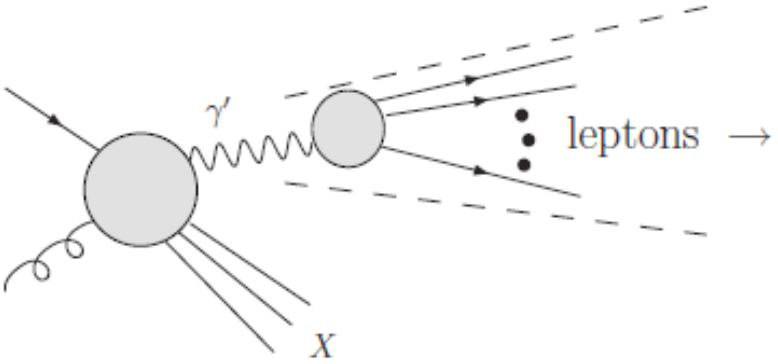
Backgrounds are small:
20 fb^{-1} at 8 TeV → BR < ~5%!

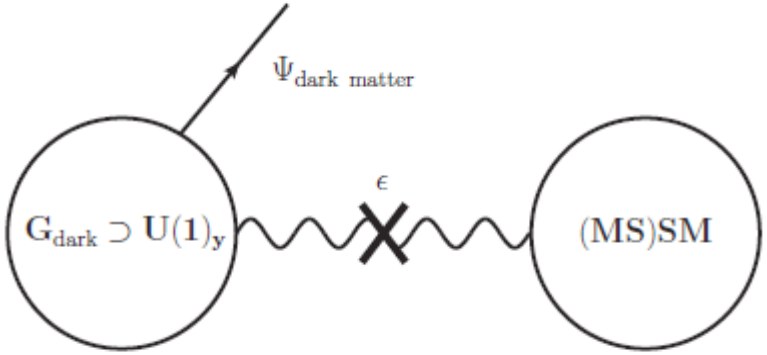
Dark-photon production

- **Jet + dark-photon**

New, kinetically coupled U(1)

$$\mathcal{L}_{\text{gauge mix}} = -\frac{1}{2}\epsilon_1 b_{\mu\nu} A^{\mu\nu} - \frac{1}{2}\epsilon_2 b_{\mu\nu} Z^{\mu\nu}$$

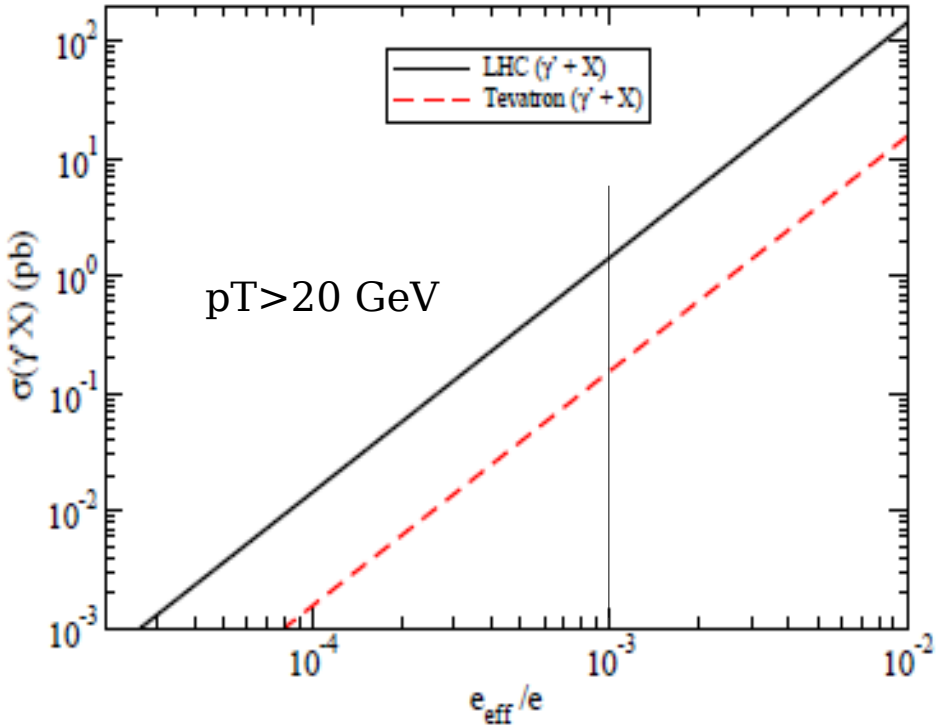




$\sigma \approx (\alpha_{EM}\, \varepsilon)^2$

Large jet background

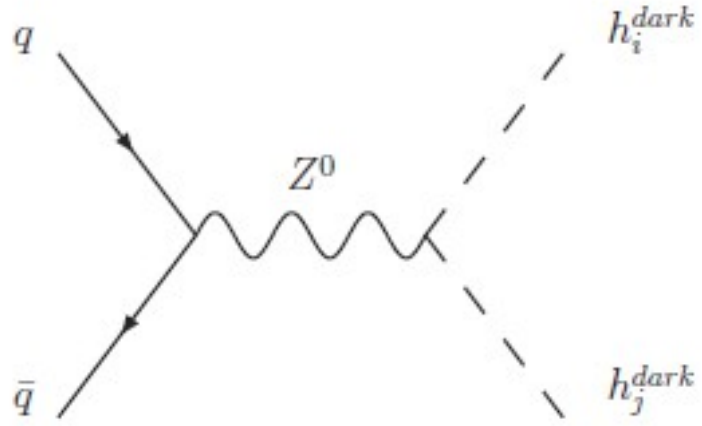
$\sigma \approx (\alpha_s)^2$

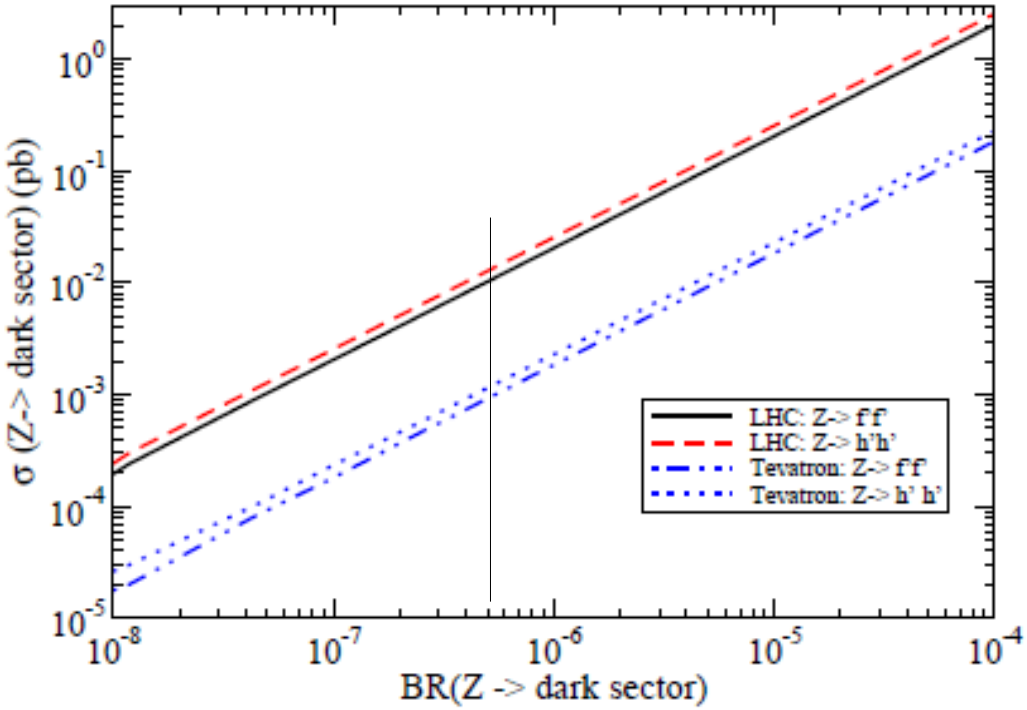


Rare Z decays

- **Z decays to dark sector**

$$\mathrm{BR}(Z^0 \to d_i d_i) = \frac{c_{d_i}}{\Gamma_Z^0} \frac{\epsilon^2 g_y^2 y_{d_i}^2 \sin^2\theta_W}{48\pi} M_{Z^0}$$





Factor ~200 smaller cross-section

But *two* dark-things in each event

Much less background from jets