p_T imbalance

ATLAS VBF + E_T^{miss} (+γ)

vector boson fusion photon

University of Pittsburgh

Tae Min Hong

ATLAS EXPERIMENT

APS DPF 2021

July 14, 2021

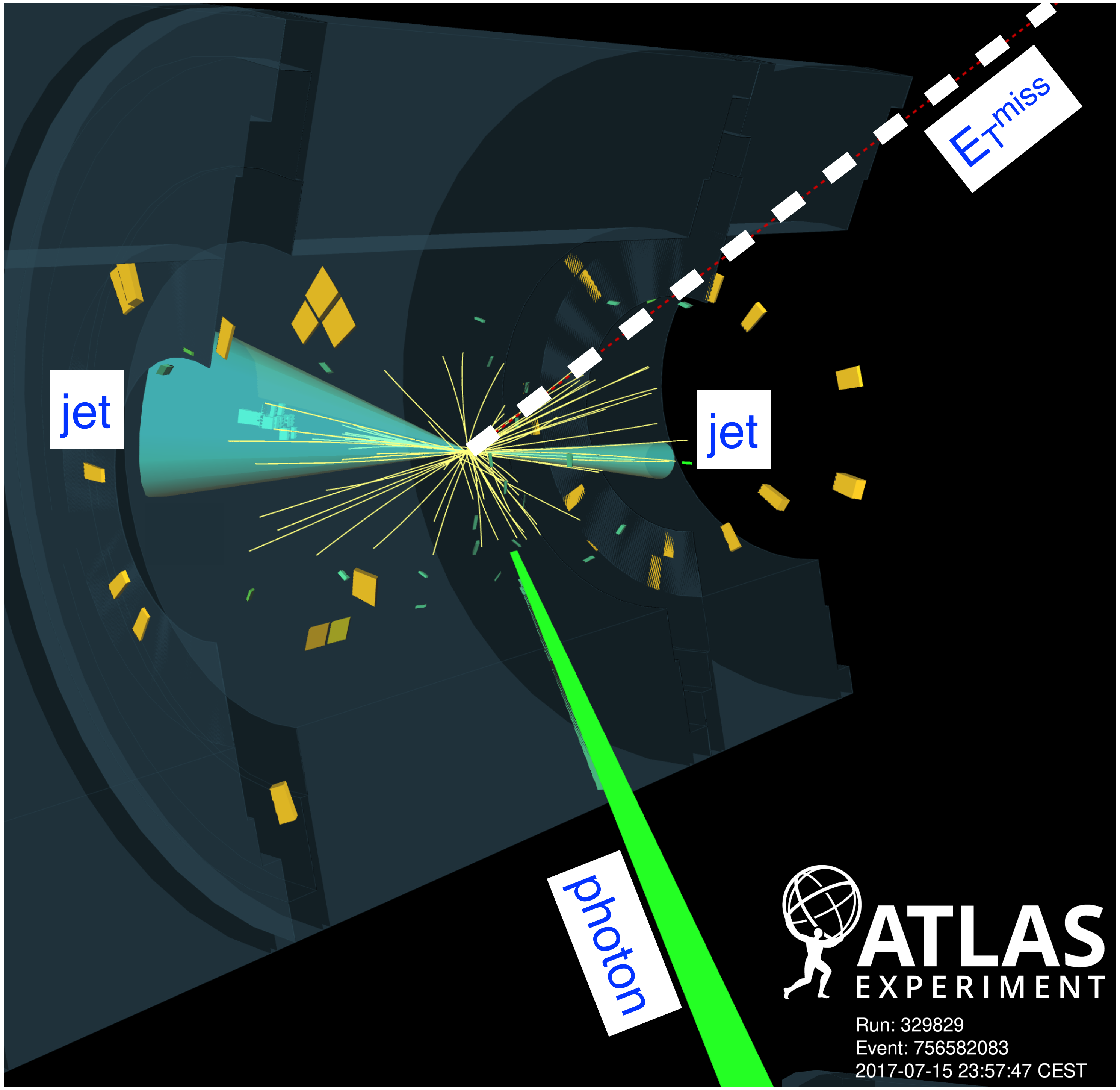
https://indico.cern.ch/event/1034469/contributions/4430545/

- Intro
  - Detector signature
  - Motivation
- Analysis
  - Signal models
  - Dominant backgrounds
  - Event selection
  - Systematics
- Results
  - Higgs to "invisible"
  - Higgs to "dark photon" +γ

- VBF + E_T^{miss}
  - ATLAS-CONF-2020-008 (April 2020)
  - https://cds.cern.ch/record/2715447
- VBF + E_T^{miss} +γ
  - ATLAS-CONF-2021-004 (March 2021)
  - https://cds.cern.ch/record/2758212

focus today

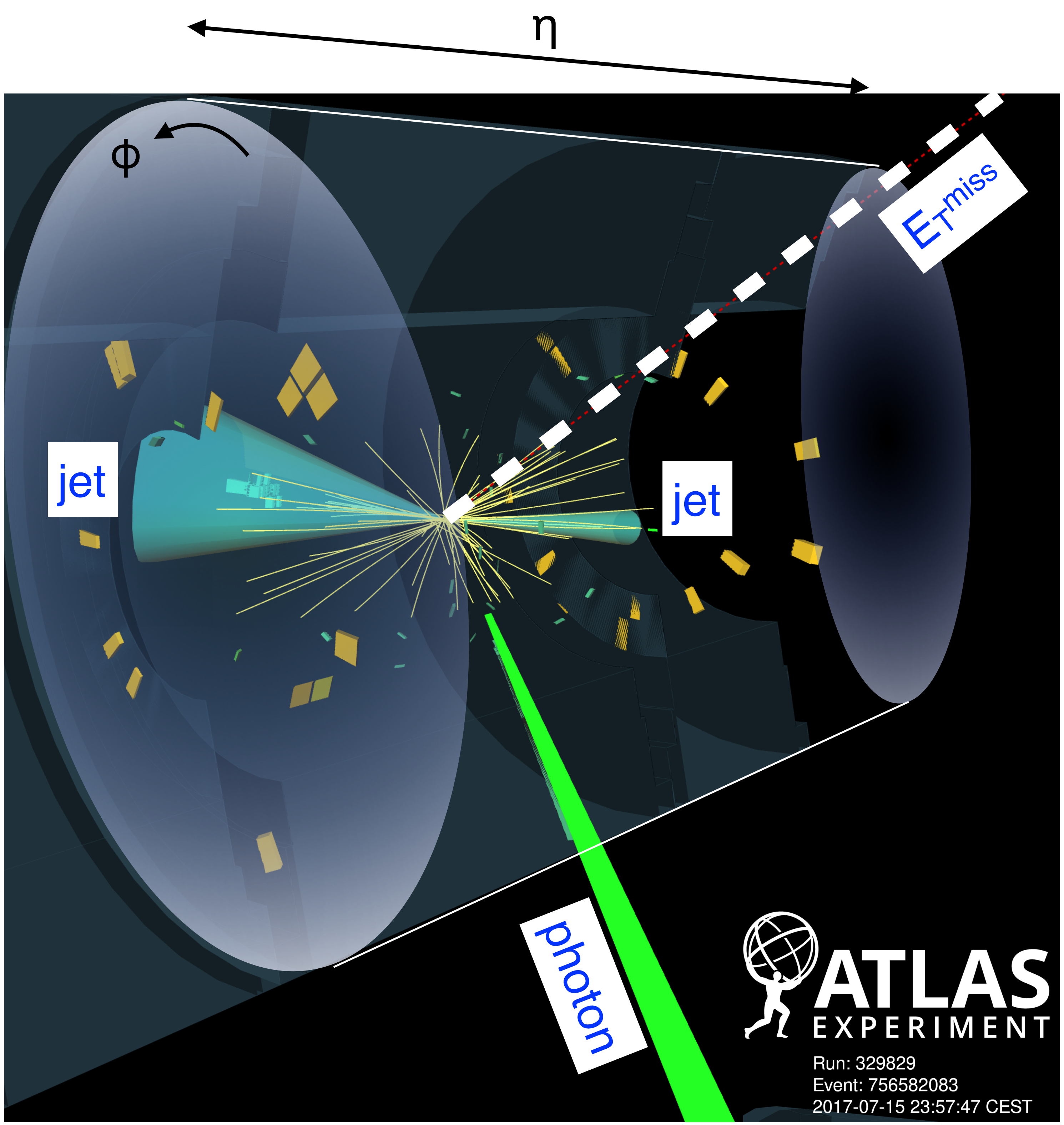
- ATLAS geometry
  - η along the beam direction
  - ϕ azimuthal angle
- VBF jet pair
  - High p_T
  - Wide gap in η
  - Not back-to-back in ϕ
  - Large $m_{jet\text{-}jet}$ 2 TeV →
  - Low hadronic activity in between
- E_T^{miss}
  - p_T imbalance 840 GeV →
- For $+\gamma$
  - High-p_T photon 540 GeV →
  - $m_T(E_T^{miss}, \gamma)$ 1.1 TeV →
  - Its η in between jets



http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_19.pdf

Detector signature

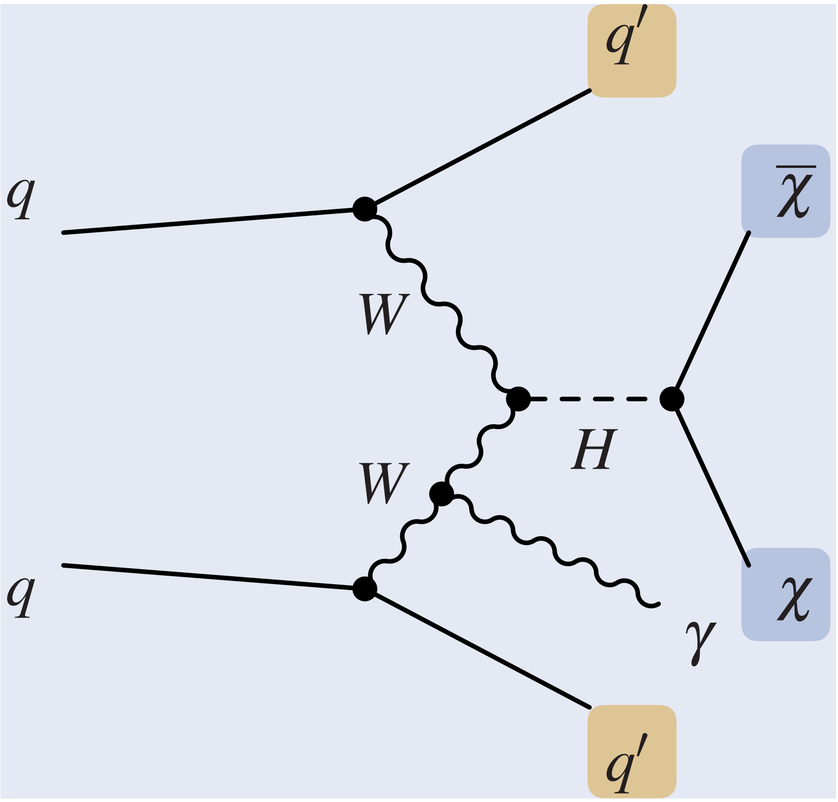
- ATLAS geometry
  - η along the beam direction
  - ϕ azimuthal angle
- VBF jet pair
  - High p_T
  - Wide gap in η
  - Not back-to-back in ϕ
  - Large $m_{jet\text{-}jet}$ 2 TeV →
  - Low hadronic activity in between
- E_T^{miss}
  - p_T imbalance 840 GeV →
- For +γ
  - High-p_T photon 540 GeV →
  - $m_T(E_T^{miss}, \gamma)$ 1.1 TeV →
  - Its η in between jets



http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_19.pdf

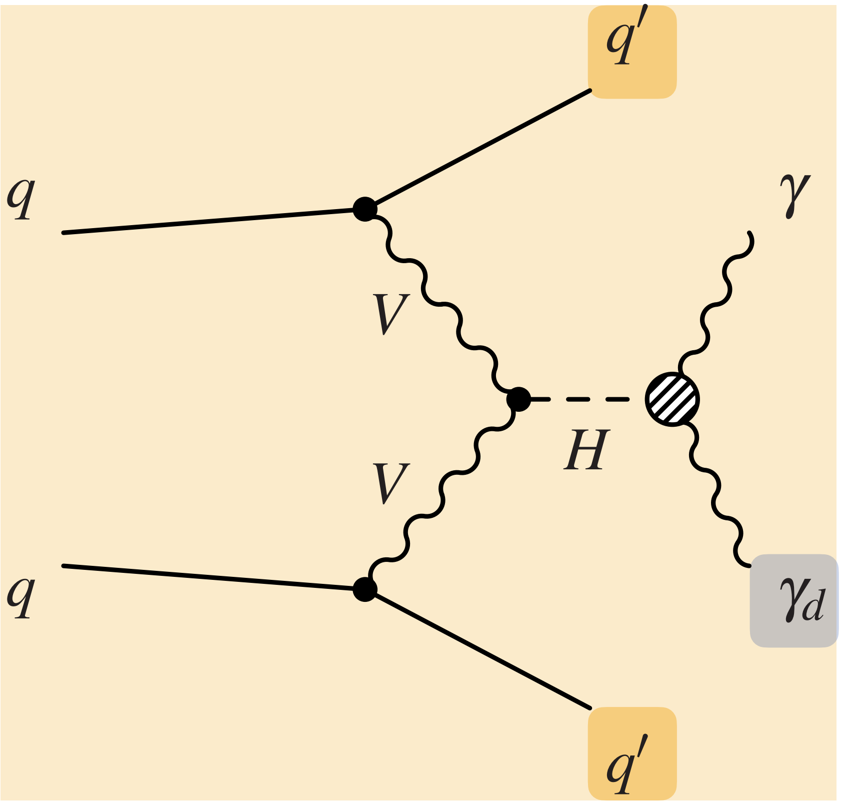
Motivation

- Higgs portal to Dark Matter (χ)
  - Without γ: Most sensitive production channel in VBF
  - With ISR γ: Powerful reduction of strong backgrounds
  - Also scan m_{scalar} for Higgs-like scalar production



http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_01a.pdf

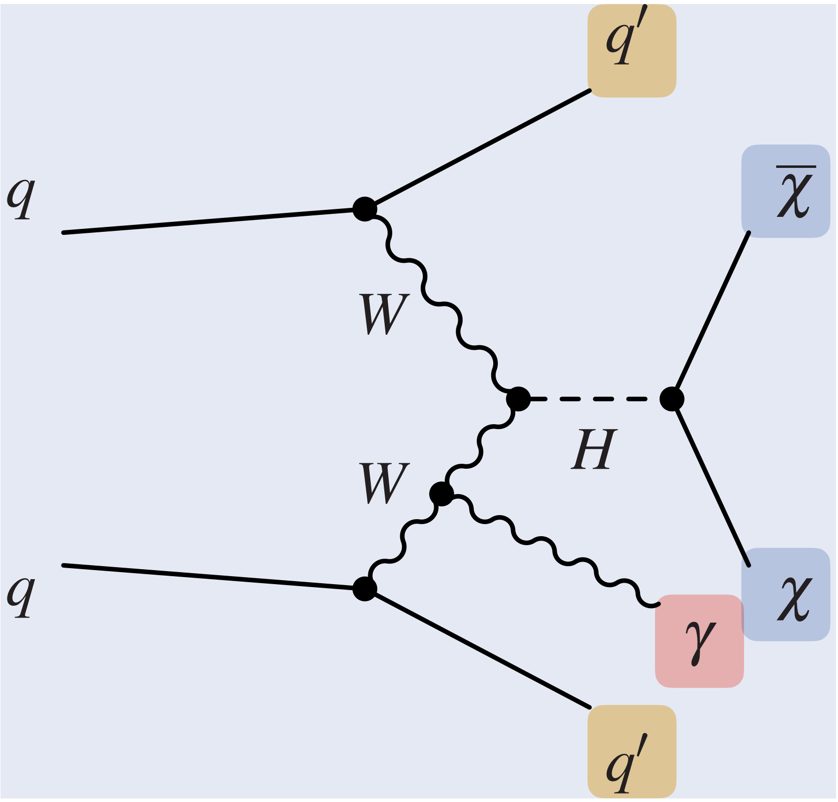
- Higgs portal to Dark Photon (γ_d)
  - Can probe H → γ γ_{dark}
  - Also scan m_{scalar} for Higgs-like scalar production



http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_01b.pdf

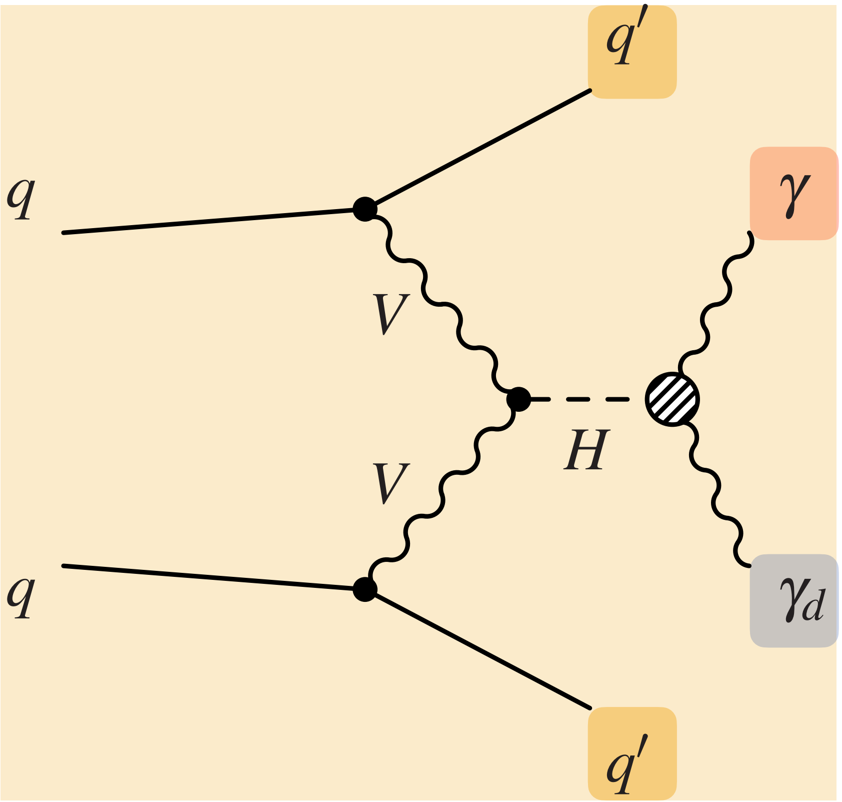
Motivation

- Higgs portal to Dark Matter (χ)
  - Without γ: Most sensitive production channel in VBF
  - With ISR γ: Powerful reduction of strong backgrounds
  - Also scan m_{scalar} for Higgs-like scalar production



http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_01a.pdf

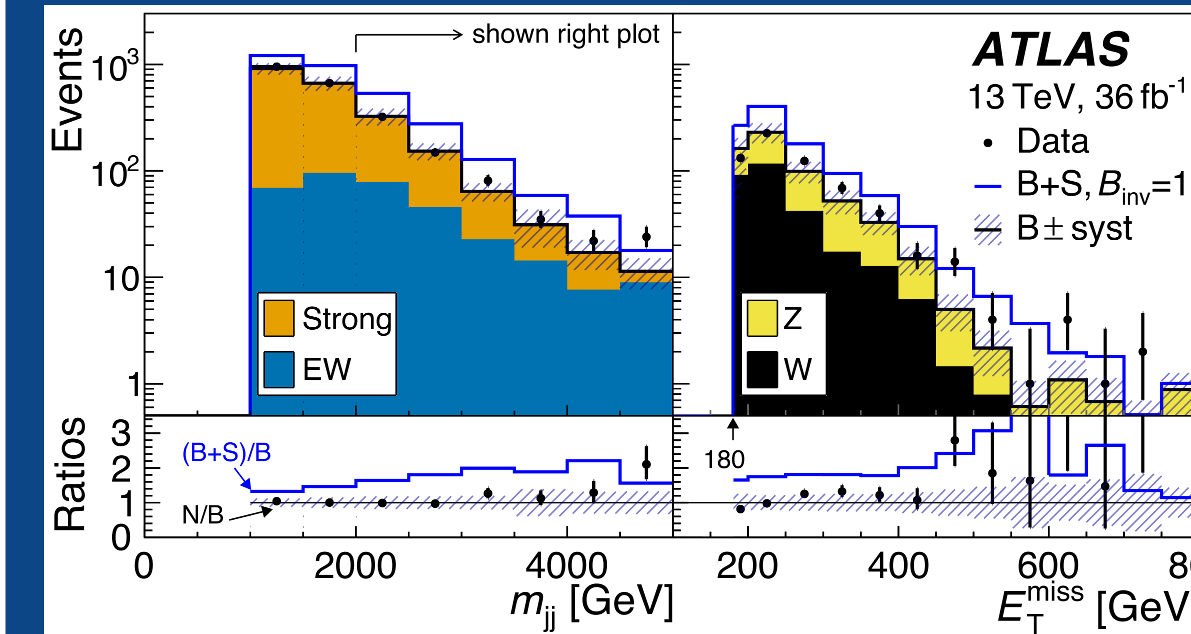
- Higgs portal to Dark Photon (γ_d)
  - Can probe H → γ γ_{dark}
  - Also scan m_{scalar} for Higgs-like scalar production



http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_01b.pdf

Signal models

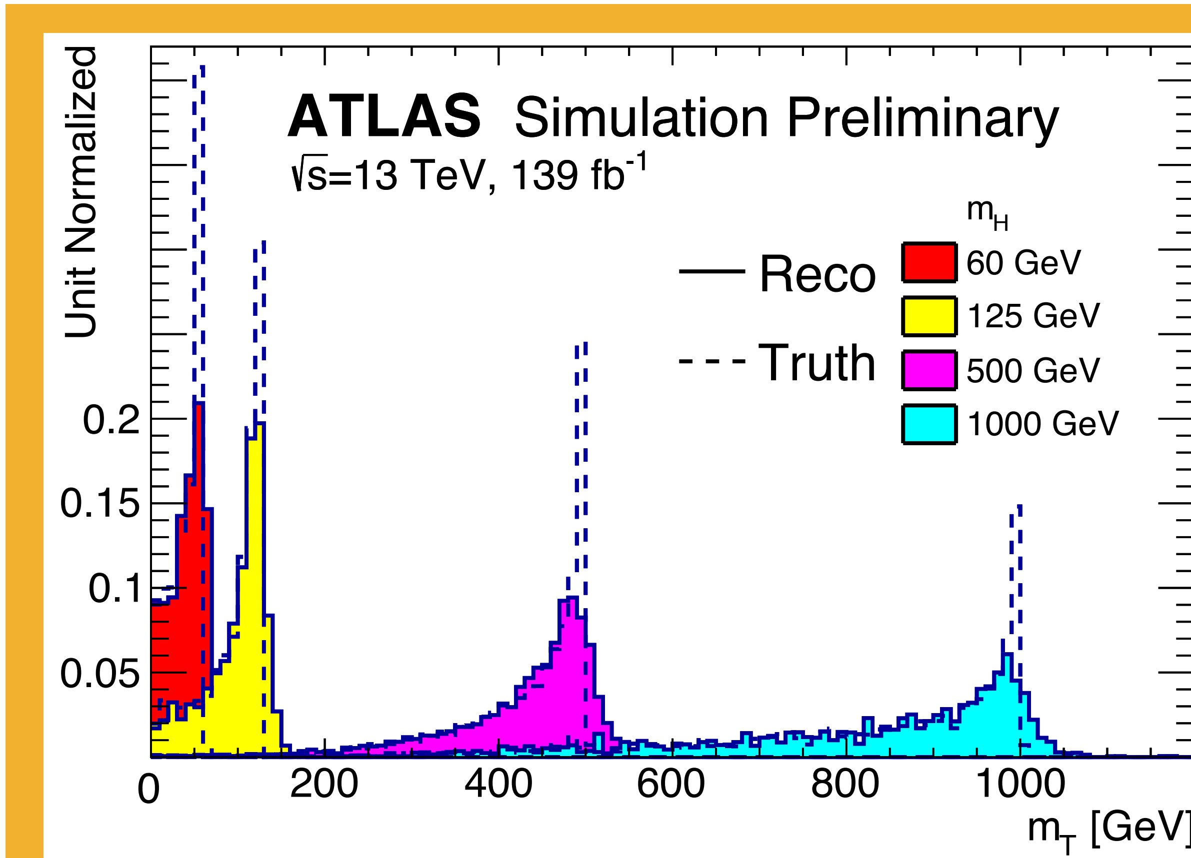
- H portal to χ
  - VBF H_{125} w/ POWHEG NLO
  - VBF H_{125} + γ_{ISR} w/ MG5_aMC@NLO
  - S-to-B is higher with m_{jj}, E_T^{miss}, see →



Dijet invariant mass ***p_T imbalance***

http://cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-37/fig_05.pdf

- H portal to γ_d
  - VBF H_{125} → $\gamma\gamma_{dark}$ w/ POWHEG v2
  - $m_T(E_T^{miss}, \gamma)$ as proxy for m_H, see →



Transverse mass of E_T^{miss} and γ

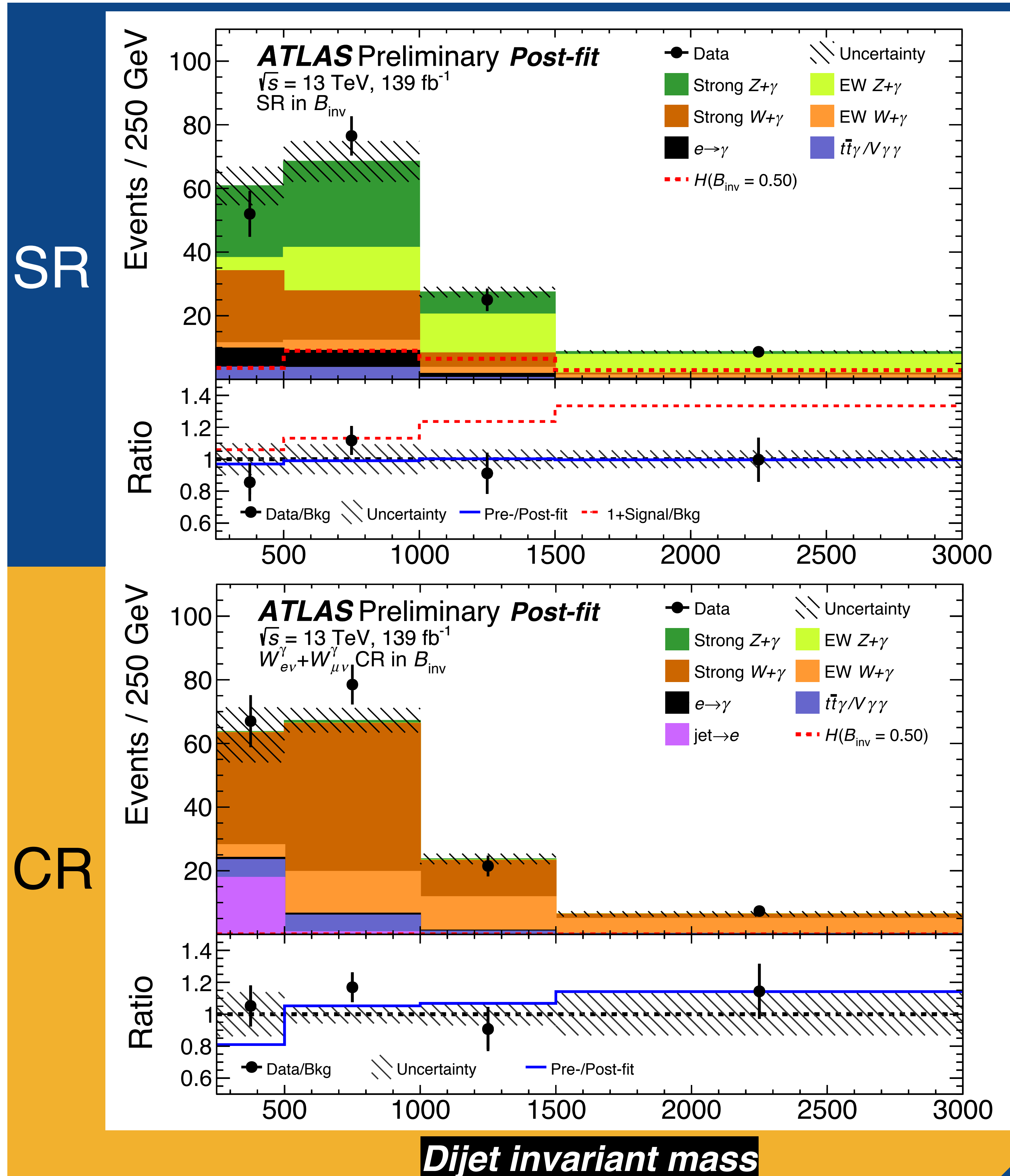
http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_13.pdf

Backgrounds, for +γ

- Weak boson bkg'd
  - Z → νν — No leptons
  - W → ℓν — Loses a lepton

- Signal Region
  - E_T^{miss} trigger, > 150 GeV
  - "Centrality" of γ, 3rd jet
  - For $+\gamma_{ISR}$, $15 < p_T^{\gamma} < 110$ GeV
  - For $+\gamma_{dark}$, max(110,0.7 m_T)

- Control Region
  - For W → ℓν, Require a lepton
  - Lepton trigger, > 30 GeV
  - Reverse γ centrality cut

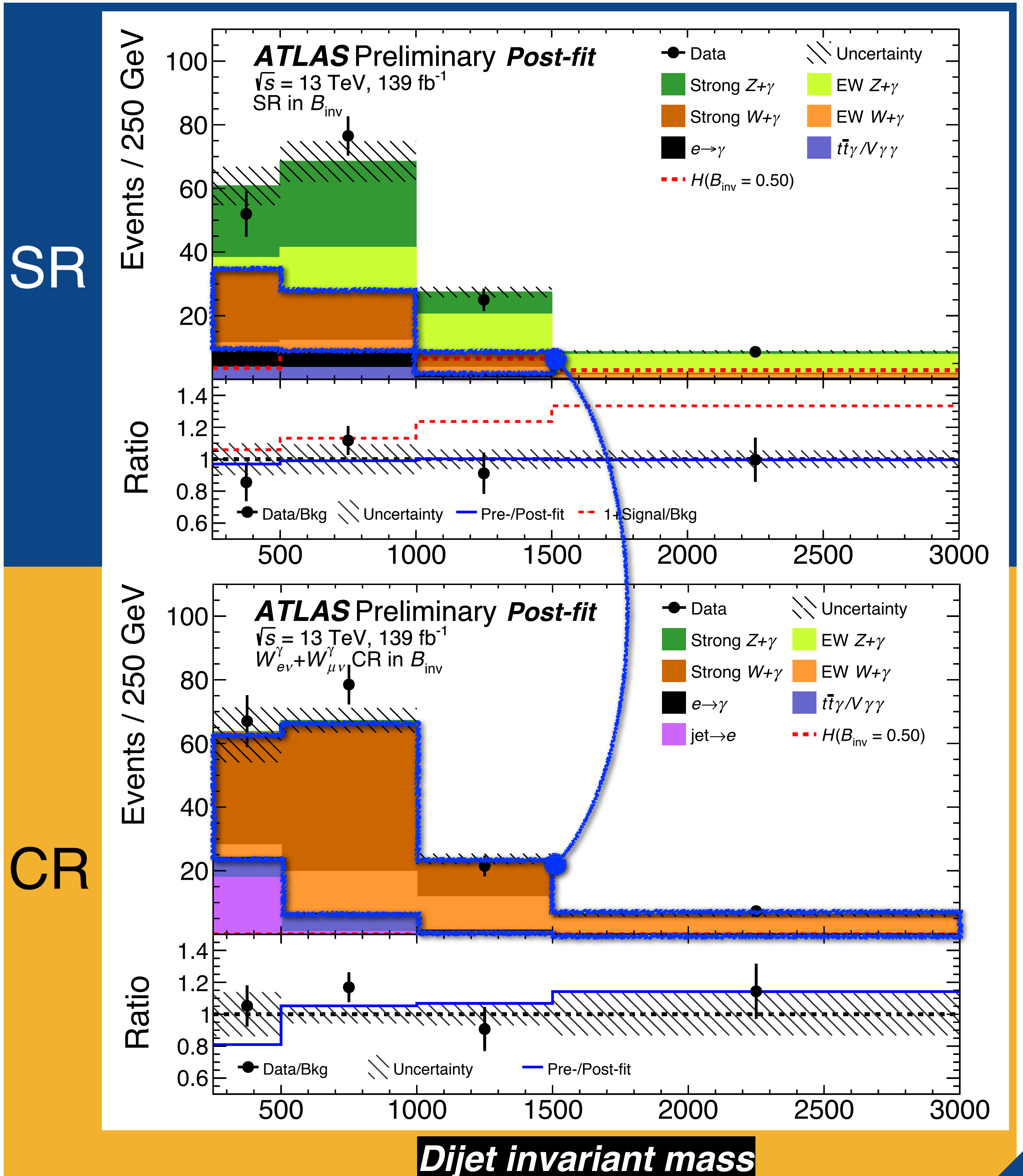


http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_04a.pdf, fig_04b.pdf

Backgrounds, for +γ

TM Hong

- Weak boson bkg'd
  - Z → νν No leptons
  - W → ℓν Loses a lepton
- Signal Region
  - E_T^{miss} trigger, > 150 GeV
  - "Centrality" of γ, 3rd jet
  - For +γ_{ISR}, 15 < p_T^γ < 110 GeV
  - For +γ_{dark}, max(110,0.7 m_T)
- Control Region
  - For W → ℓν, Require a lepton
  - Lepton trigger, > 30 GeV
  - Reverse γ centrality cut



http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_04a.pdf, fig_04b.pdf

Uncertainties, for +γ

- Statistical
  - √N
  - MC
- Theoretical
  - Wγ, Zγ theory
- Experimental
  - JES, JER

	1σ Uncertainty on $\mathcal{B}_{\rm inv}$	on $\mathcal{B}(H \to \gamma\gamma_{\rm d})$
Data stats.	0.106	0.0051
$V\gamma$+ jets theory	0.056	0.0028
MC stats.	0.045	0.0026
Jet Scale and Resolution	0.045	0.0011
Photon	0.032	0.0011
$e \to \gamma$, jet$\to e, \gamma$ Bkg.	0.026	0.0024
Pileup	0.025	0.0004
$W\gamma$+ jets/$Z\gamma$+ jets Norm.	0.021	0.0005
$E_{\rm T}^{\rm miss}$	0.012	0.0003
Signal theory	0.004	0.0010
Lepton	0.002	0.0008
Total	0.148	0.0071

http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/tab_05.pdf

Evaluated by fixing parameters to their best-fit values and quadratically subtracting from the total nominal systematic uncertainty

to next slide

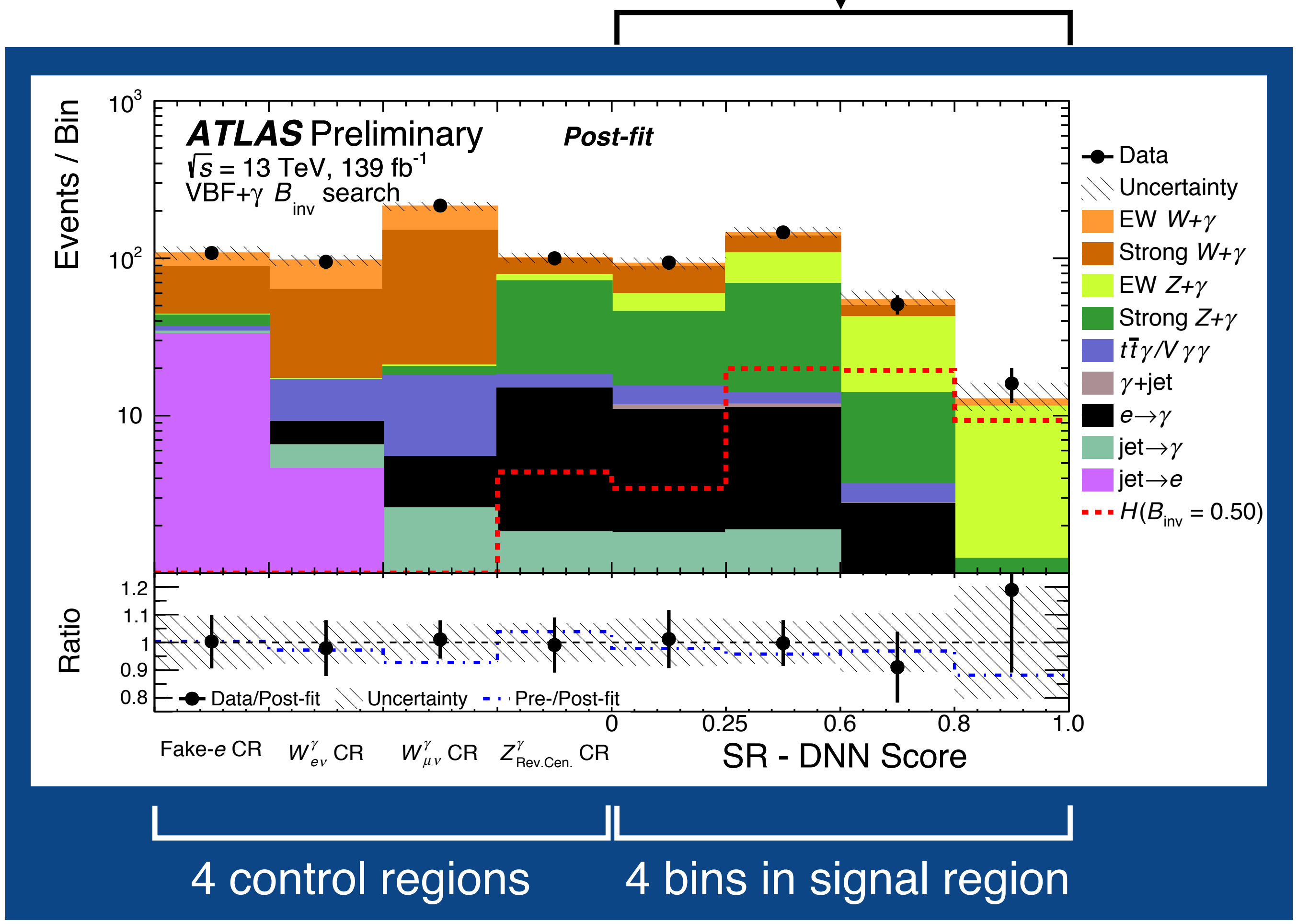
Result: Higgs to "invisible" +γ

TM Hong

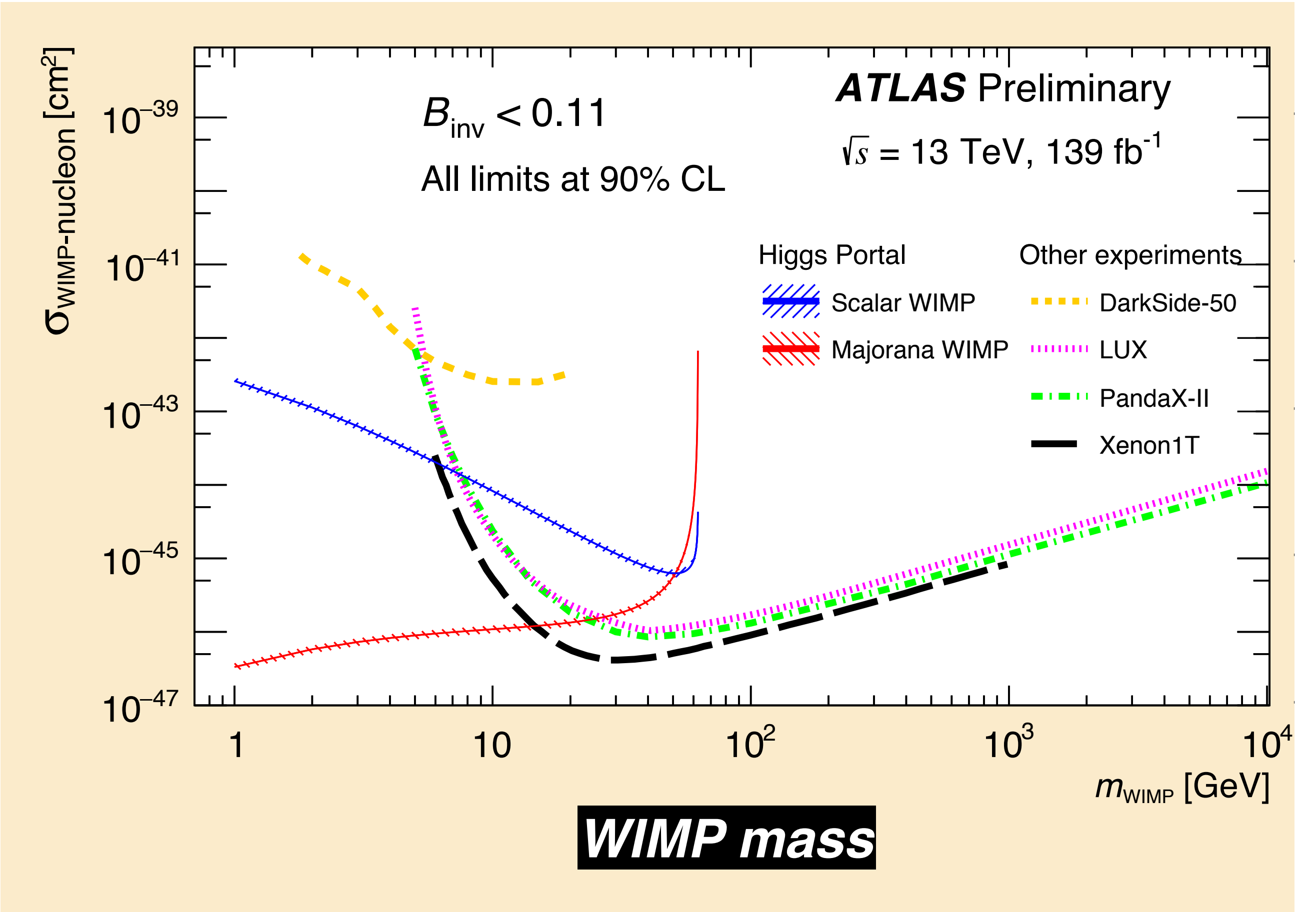
- Analysis strategy
  - Dense Neural Network w/ Keras+Tensorflow
  - 3 blocks of 384 neurons with ReLU activation
  - 4 signal region bins in output score

- Result for +γ
  - Observed limit B_{inv} of 0.37
  - Expected limit B_{inv} of 0.34 ± 0.13
  - Compare with **no** γ 0.37 (36 fb^{-1})
  - Updated (below) 0.13 (139 fb^{-1})

from prev. slide



http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_03.pdf

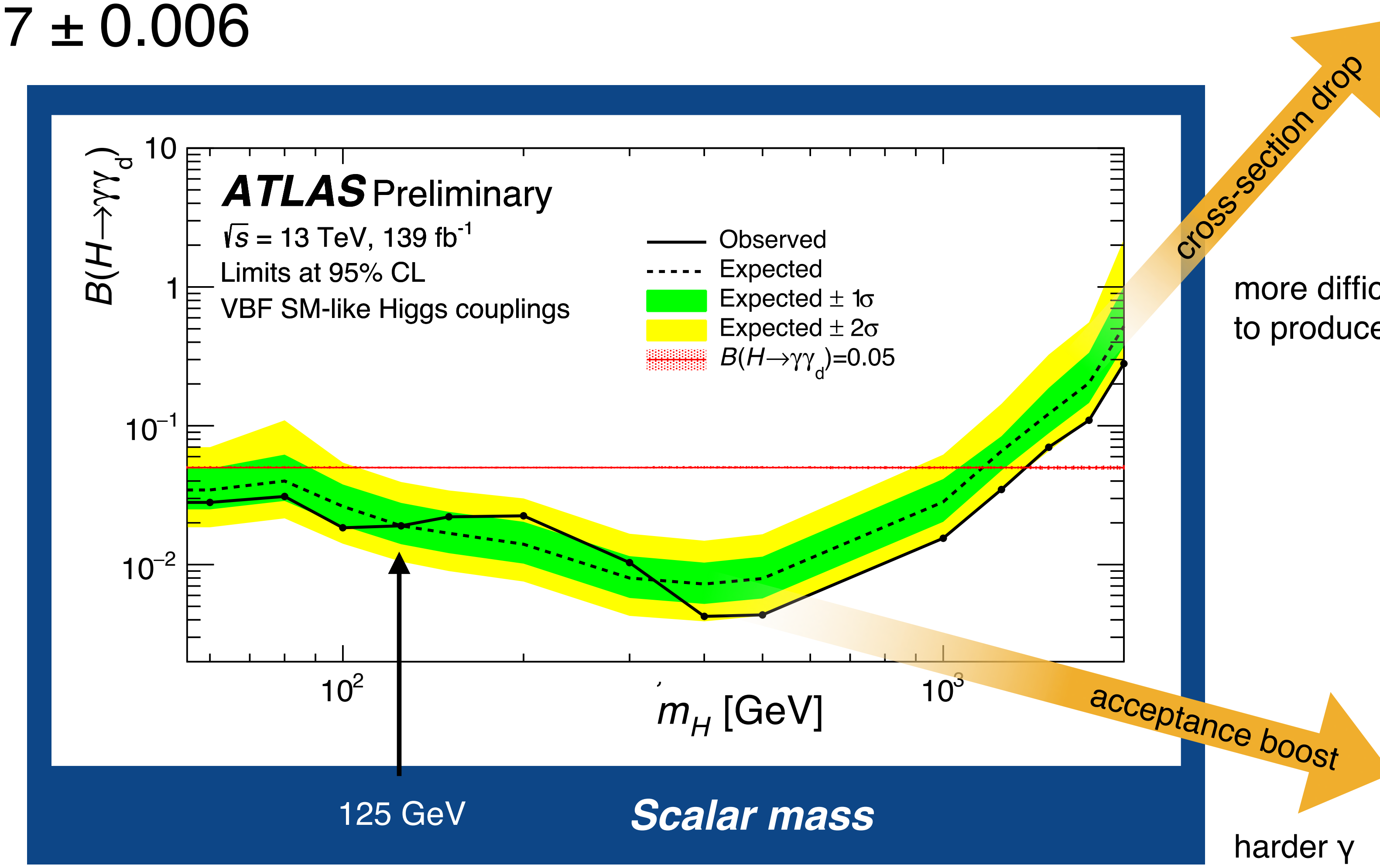


http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2020-008/fig_10.pdf

Result: Higgs to $\gamma\gamma_{dark}$

TM Hong

- Dark photon
  - Analysis strategy: m_T bins (not DNN)
  - Observed limit B_{dark} of 0.014
  - Expected limit B_{dark} of 0.017 ± 0.006
  - Scalar mass scan (NWA)



more difficult to produce

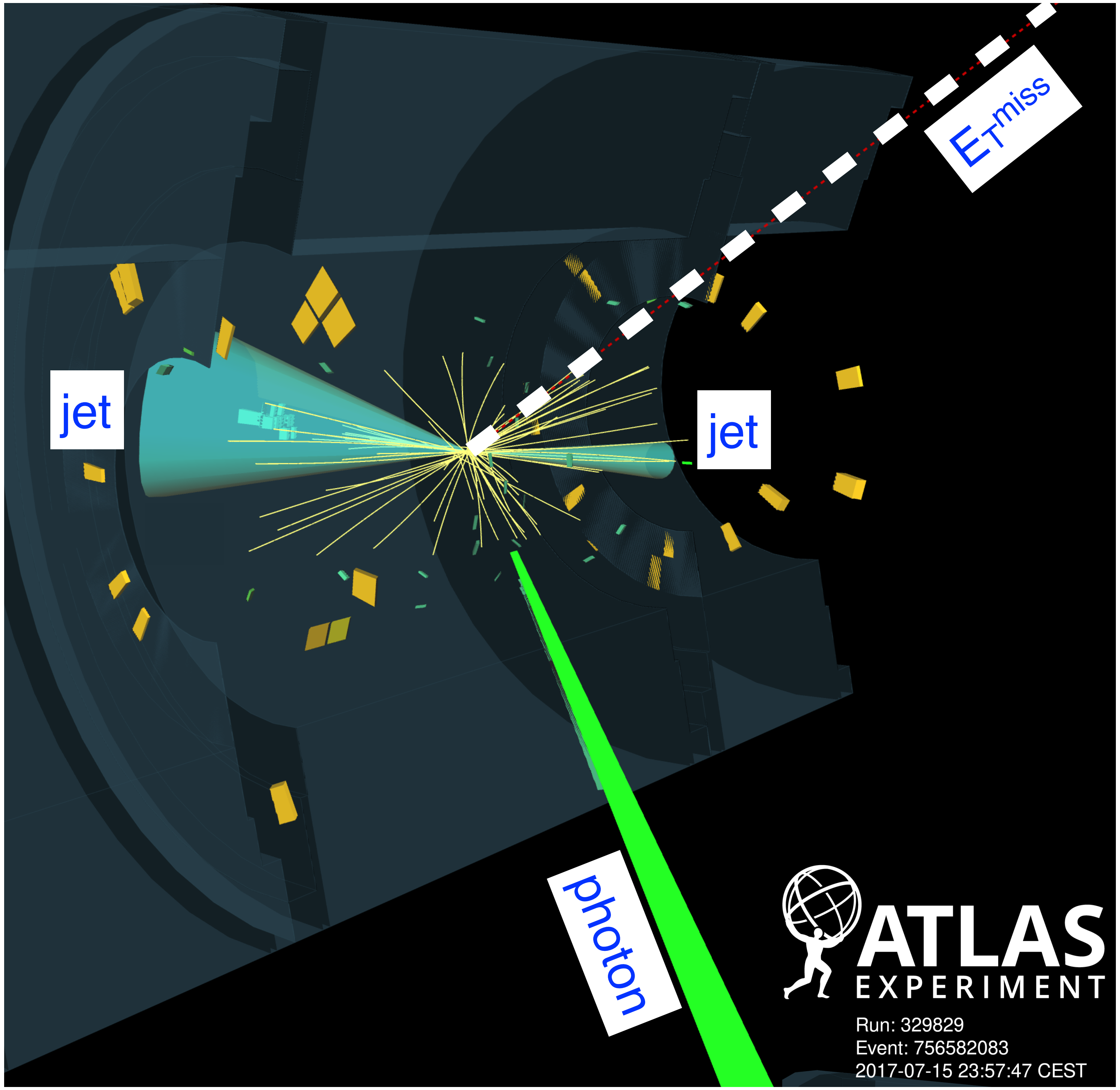
harder γ
larger E_T^{miss}

http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_12.png

- Previous results
  - CMS limit B_{dark} of 0.029 observed
    0.021 expected

Conclusions

- VBF + E_T^{miss} (+γ)
  - Probes Higgs coupling to DM
  - Probes Higgs coupling to γ_{dark}
  - Consider other scalar masses



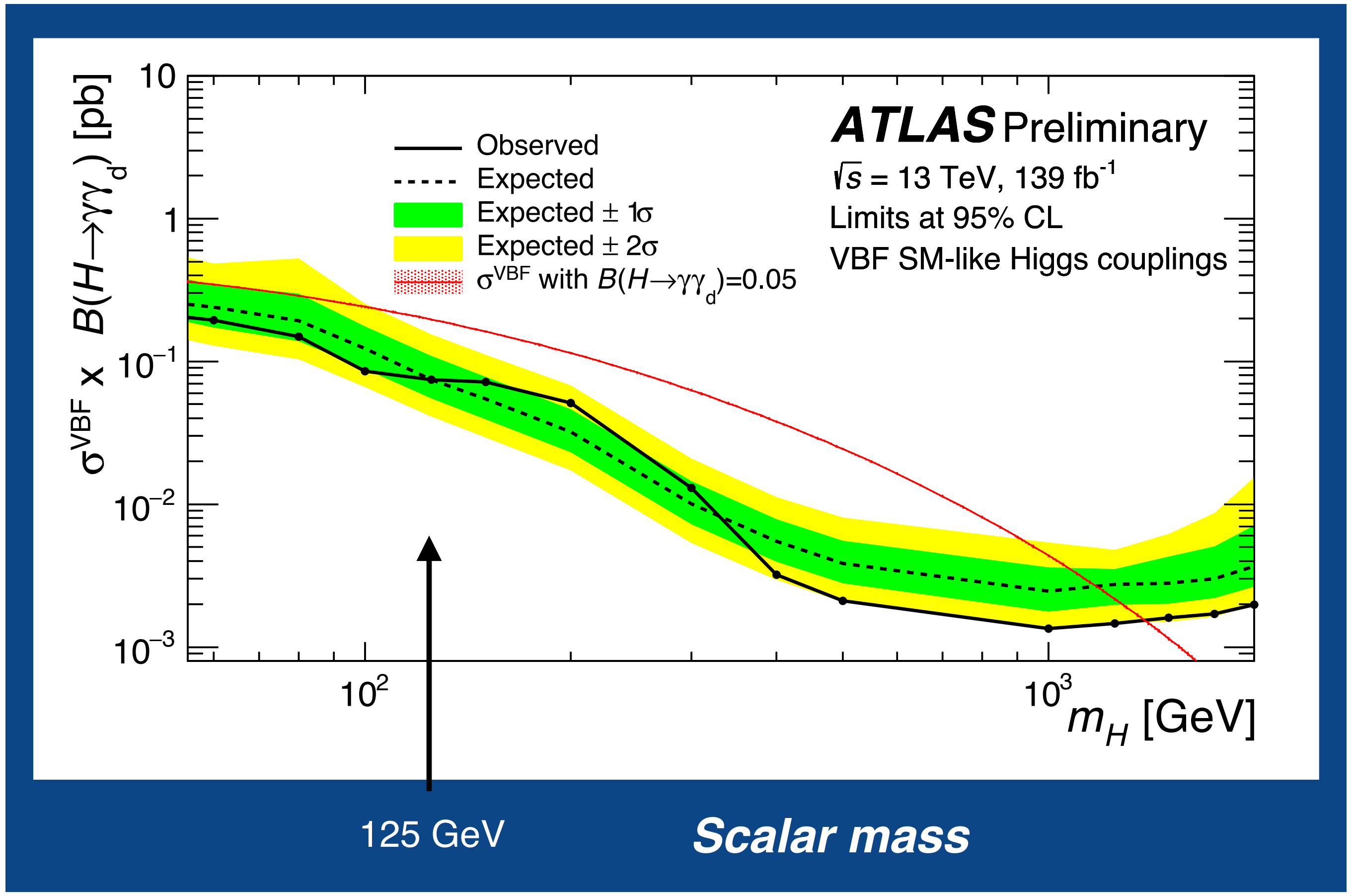
http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_19.pdf

- Results
  - Limit B_{inv} of 37% (for +γ 139 fb^{-1})
    13% (139 fb^{-1})
  - Limit B_{dark} of 1.4%
  - Scanned m_{scalar} up to 5 TeV

Back-up

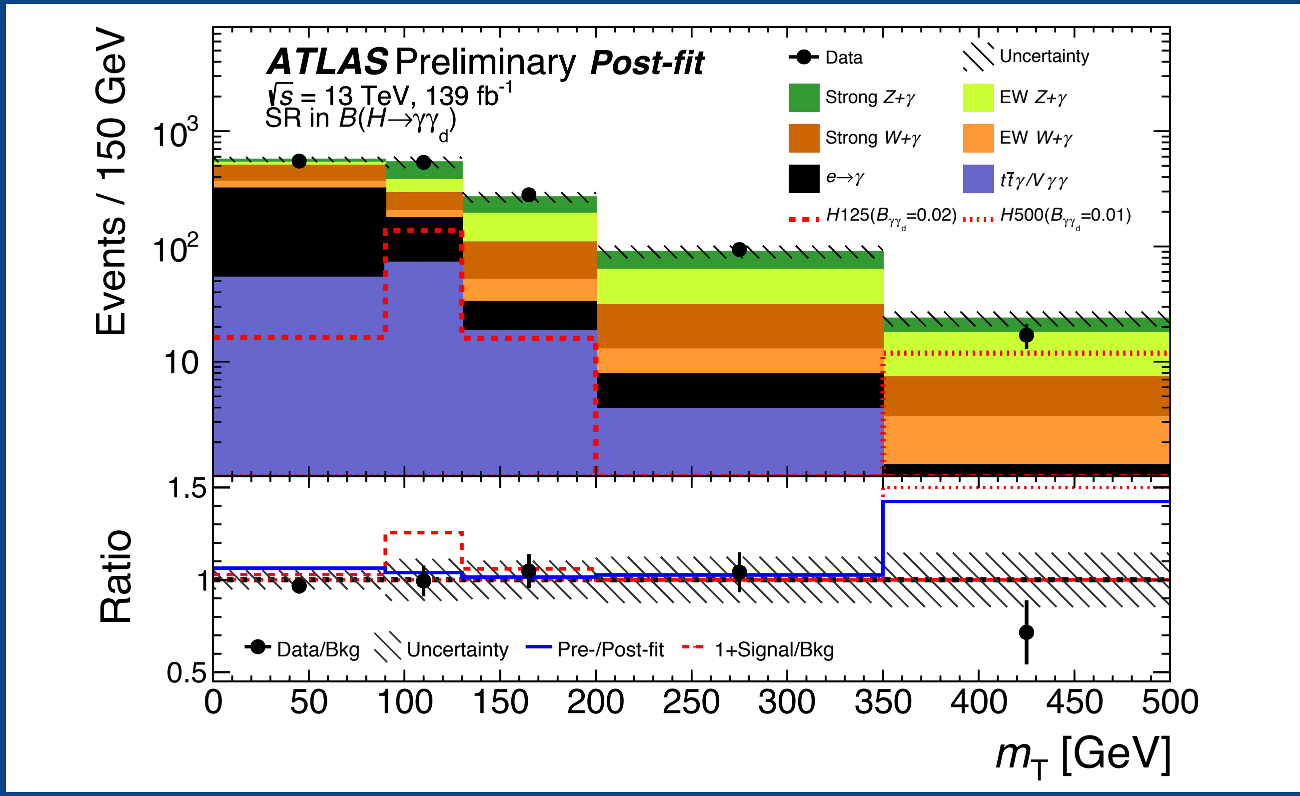
Result: Higgs to $\gamma\gamma_{dark}$

- Dark photon
  - Scalar mass scan (NWA)



http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_07.png

- Dark photon
  - m_T bin fit



Transverse mass of E_T^{miss} and γ

http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/fig_06.pdf

MC samples for +γ

Table 1: Summary of generators used for simulation. The details and the corresponding references are provided in the body of the text. The V in V+jets represents either a W or a Z boson.

Process	Generator	ME Order	PDF	Parton Shower	Tune
		Signal Samples			
ggF Higgs	Powheg v2 NNLOPS	NNLO	PDF4LHC15	Pythia8.230	AZNLO
VBF Higgs+γ	MadGraph5_aMC@NLO 2.6.2	NLO	PDF4LHC15	Herwig 7.1.3p1	A14
ggF Higgs$\to \gamma\gamma_{\mathrm{d}}$	Powheg v2 NNLOPS	NNLO	PDF4LHC15	Pythia8.244p3	AZNLO
VBF Higgs$\to \gamma\gamma_{\mathrm{d}}$	Powheg v2	NLO	CTEQ6L1	Pythia8.244p3	AZNLO
		Background Samples			
Strong $V\gamma$+ jets	Sherpa v2.2.8	NLO (up to 1-jets), LO (up to 3-jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
EW $V\gamma$+ jets	MadGraph5_aMC@NLO 2.6.5	LO	NNPDF3.1lo	Pythia8.240	A14
EW VV+jets	Sherpa v2.2.1 or Sherpa v2.2.2	LO	NNPDF3.0nnlo	Sherpa MEPS@LO	Sherpa
VV+jets	Sherpa v2.2.1 or Sherpa v2.2.2	NLO (up to 1-jet), LO (up to 3-jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
EW V+ jets	Herwig 7.1.3 or Herwig 7.2.0	NLO	MMHT2014nlo68cl	Herwig 7.1.3	Herwig 7
Strong $W(\to \mu\nu)$ + jets/ $W(\to \tau\nu)$ + jets	Sherpa v2.2.8	NLO (up to 2-jets), LO (up to 4-jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
$t\bar{t}\gamma$	MadGraph5_aMC@NLO 2.2.3	NLO	NNPDF2.3lo	Pythia8.186	A14
$t\bar{t}$	PowhegBox v2	NLO	NNPDF3.0nlo	Pythia8.230	A14
γ + jet	Sherpa v2.2.2	NLO (up to 2-jets), LO (up to 4-jets)	NNPDF3.0nnlo	Sherpa MEPS@NLO	Sherpa
		Systematic Samples			
$V\gamma$+ jets α^4 interference	MadGraph5_aMC@NLO 2.6.2	LO	NNPDF3.1lo	Pythia8.240	AZNLO

http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/tab_01.pdf

Table 3: Summary of the requirements defining the different regions considered in this analysis. Where present, the values in squared brackets are referring to the regions defined in the search for $H \to \gamma\gamma_d$ signal. The leading and subleading jets must satisfying the fJVT requirements mentioned in Sec. 5. In the SR and $Z^{\gamma}_{\text{Rev.Cen.}}$ CR definitions $E_T^{\text{miss,lep-rm}} \equiv E_T^{\text{miss}}$ since no lepton is present.

Variable	SR	$W^{\gamma}_{\mu\nu}$ CR	$W^{\gamma}_{e\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	Fake−e CR
$p_T(j_1)$ [GeV]	> 60				
$p_T(j_2)$ [GeV]	> 50				
N_{jet}	2,3				
$N_{\text{b-jet}}$	< 2				
$\Delta\phi_{jj}$	< 2.5 [2.0]				
$\lvert\Delta\eta_{jj}\rvert$	> 3.0				
$\eta(j_1) \times \eta(j_2)$	< 0				
C_3	< 0.7				
m_{jj} [TeV]	> 0.25				
E_T^{miss} [GeV]	> 150	–	> 80	> 150	< 80
$E_T^{\text{miss,lep-rm}}$ [GeV]	–	> 150	> 150	–	> 150
$E_T^{\text{jets,no-jvt}}$ [GeV]	> 130				
$\Delta\phi(j_i, E_T^{\text{miss,lep-rm}})$	> 1.0				
N_{γ}	1				
$p_T(\gamma)$ [GeV]	$> 15, < 110$ [$> 15, <\max(110, 0.733 \times m_T)$]				
C_{γ}	> 0.4	> 0.4	> 0.4	< 0.4	> 0.4
$\Delta\phi(\gamma, E_T^{\text{miss,lep-rm}})$	> 1.8 [–]				
N_{ℓ}	0	1 μ	1 e	0	1 e
$p_T(\ell)$ [GeV]	> 30				

η_{γ}, η_{j2}

http://cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2021-004/tab_03.pdf

8 variables fed to DNN

centrality C_{γ} [102] is defined as

$$C_{\gamma} = \exp\left(-\frac{4}{(\eta_1 - \eta_2)^2}\left(\eta_{\gamma} - \frac{\eta_1 + \eta_2}{2}\right)^2\right), \quad (1)$$