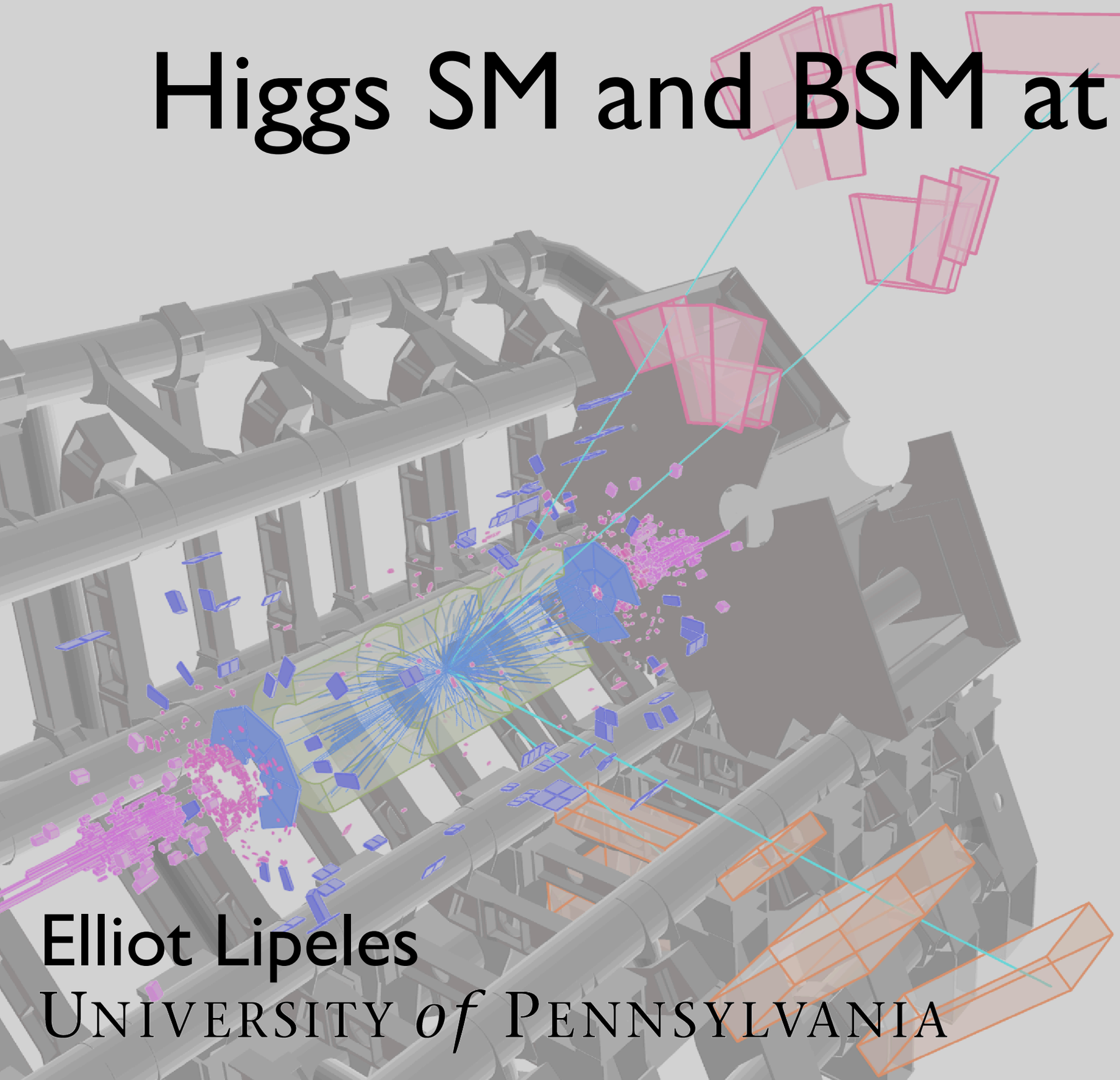
Higgs SM and BSM at ATLAS



Elliot Lipeles
University of Pennsylvania

Introduction

Standard Model Channels @ 125 GeV
- Rates ~ coupling strengths
- Higgs Properties (mass, spin)
- Differential distributions

BSM decays @ 125 GeV

Still dominated by Run 1 results...

Run 1 produced more 125 GeV Higgs Bosons than Run 2 so far...

Still some new results in more modes and combinations

Searching for more Higgs Bosons

Pair Production

2015 Run 2 13 TeV results competitive with Run 1

Outlook

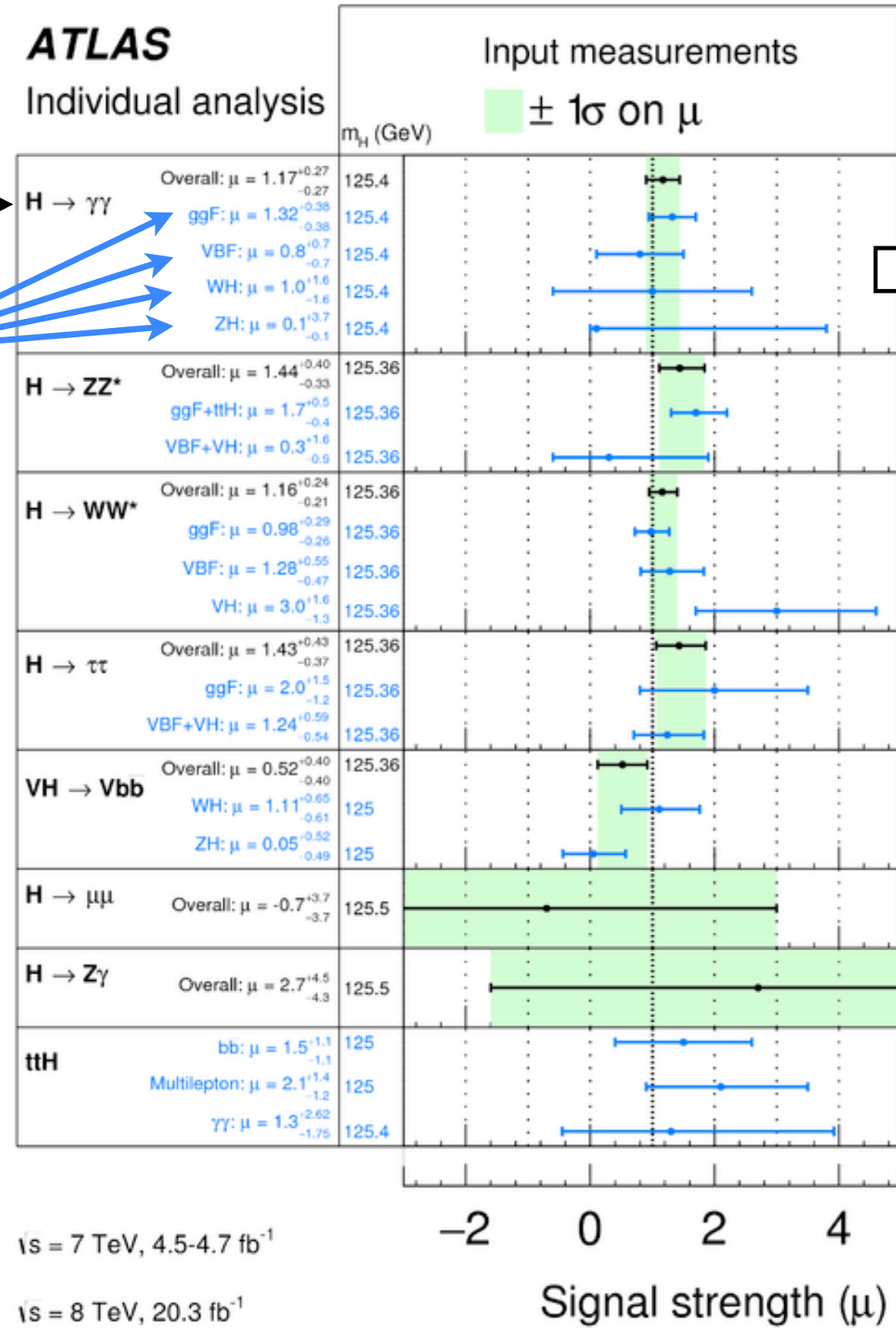
Rates → Coupling Strengths @ 125 GeV

Decay Mode

Production Channels

Each entry uses a sample of events selected to target the specific combination of production and decay mode

See talks by Carlo Enrico Pandini, Peter Kluit, and Ricardo Goncalo



Eur. Phys. J. C76 (2016) 6

Combined Fit(s)

➡ Coupling Strengths
➡ Test the Mass Generation Hypothesis
➡ BSM constraints

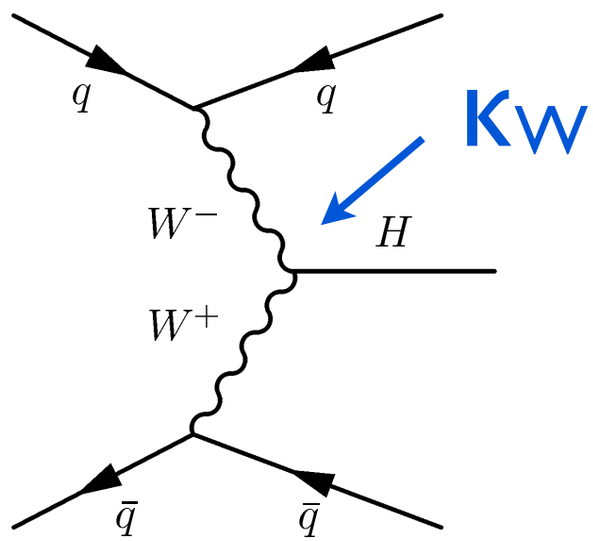
I'll show a set of ATLAS plots...

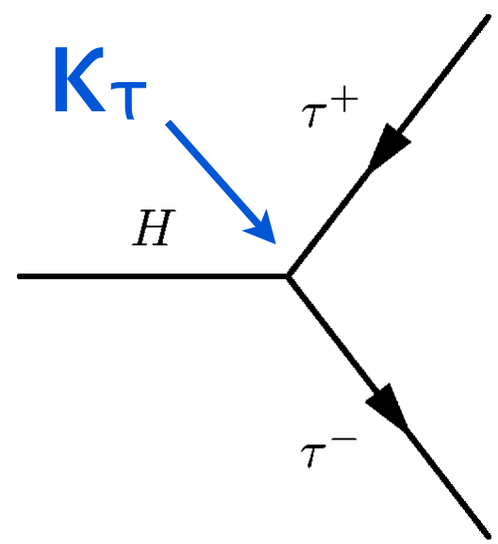
There is now an ATLAS + CMS combination, see talk by Eric Feng

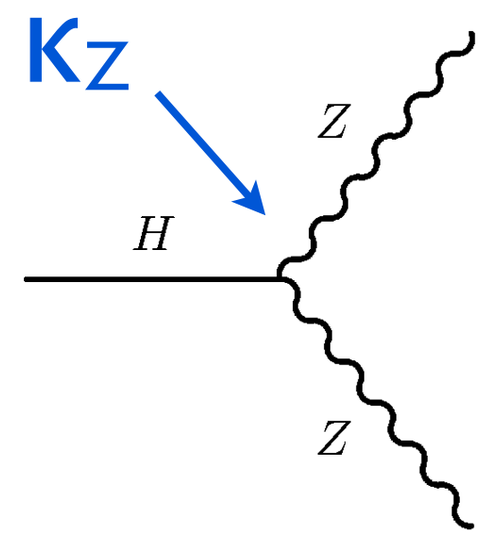
Coupling Interpretation

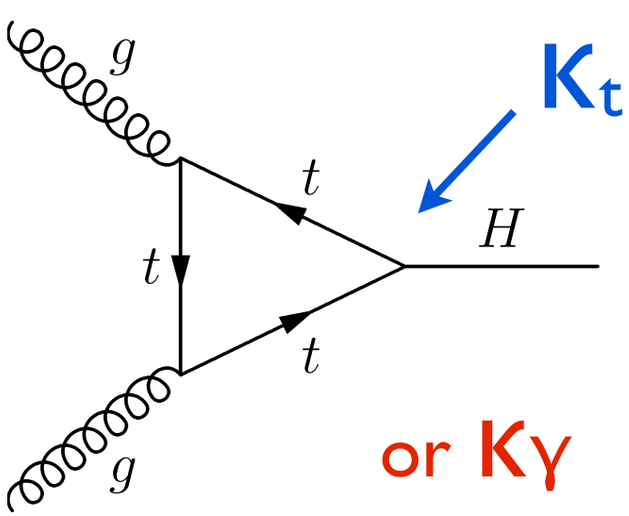
Simple model: assign a multiplicative factor to each kind of vertex

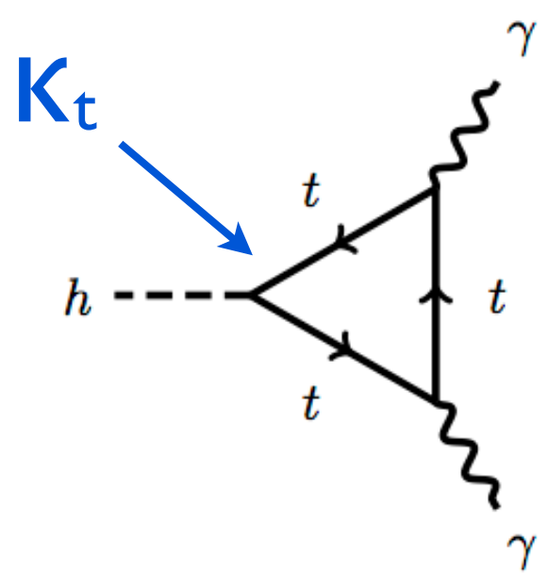
- $\kappa_i = 1$ is SM, $\kappa_i \neq 1$ is BSM
- Caveat: doesn't account for shape changes with BSM physics

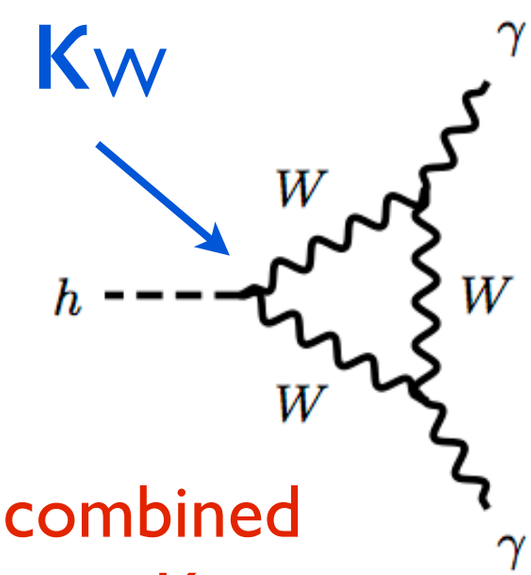










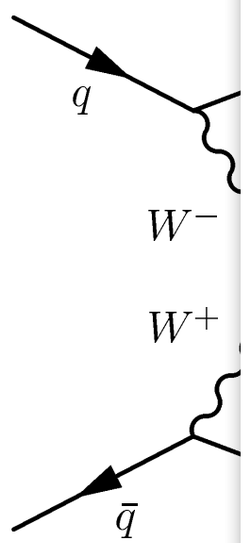


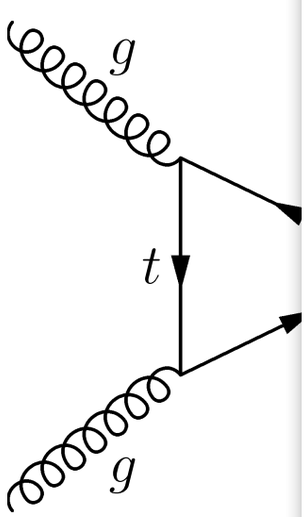
Both combined in a single κ_γ

Coupling Interpretation

Simple n

- $\kappa_i = 1$
- Cave





No BSM particles fit

$\kappa_W = 0.91 \pm 0.14$

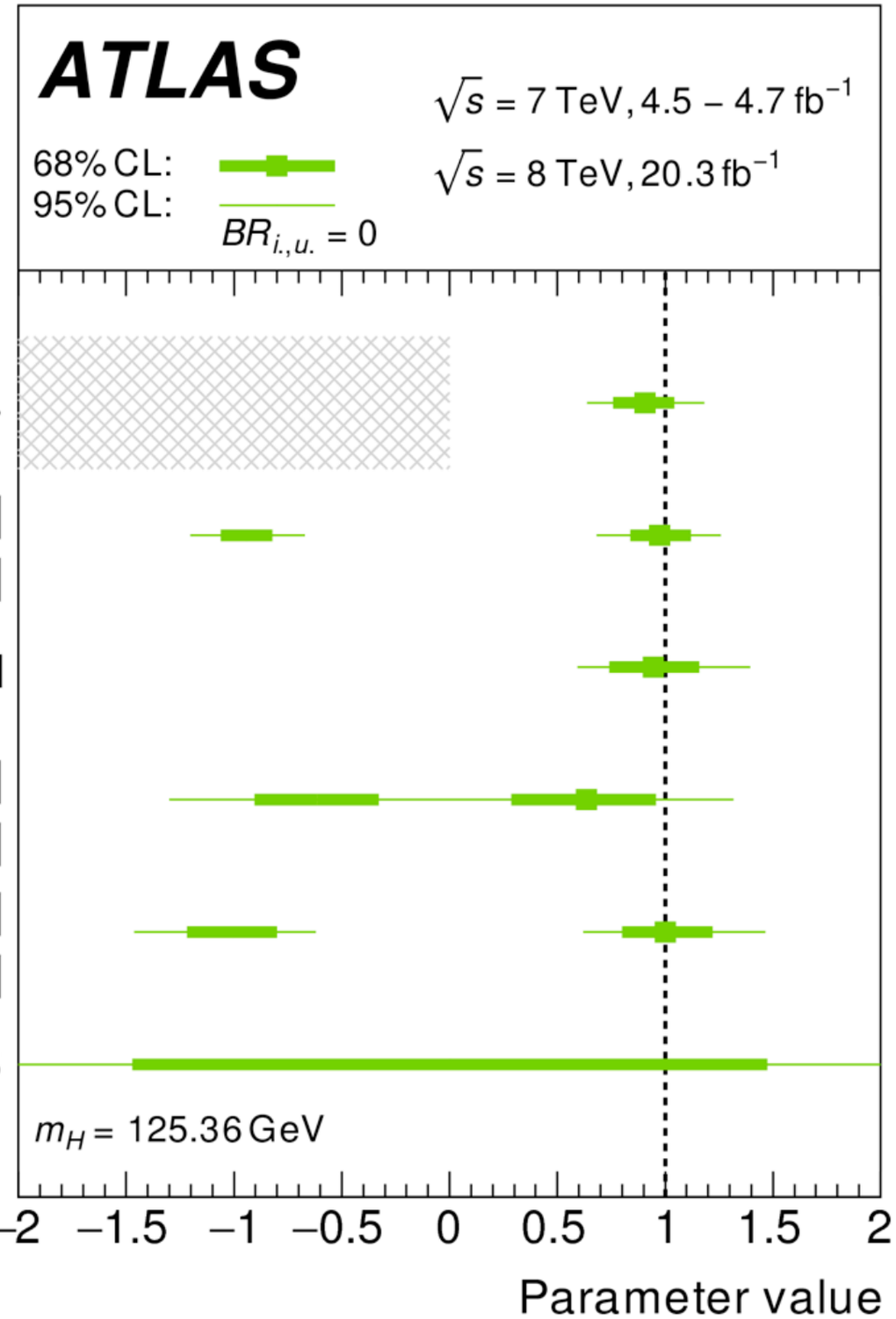
$\kappa_Z \in [-1.06, -0.82] \cup [0.84, 1.12]$

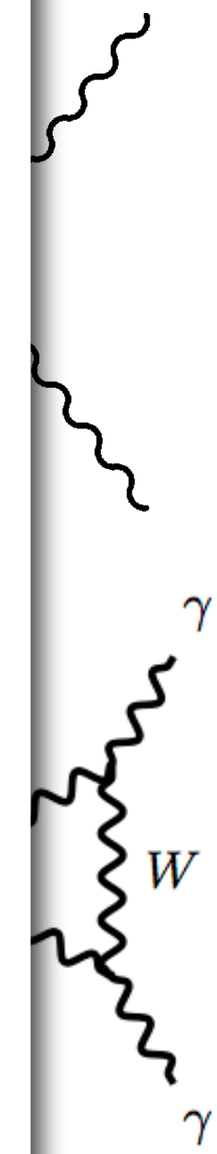
$\kappa_t = 0.94 \pm 0.21$

$\kappa_b \in [-0.90, -0.33] \cup [0.28, 0.96]$

$\kappa_\tau \in [-1.22, -0.80] \cup [0.80, 1.22]$

$(95\%\,CL) \quad |\kappa_\mu| < 2.28$





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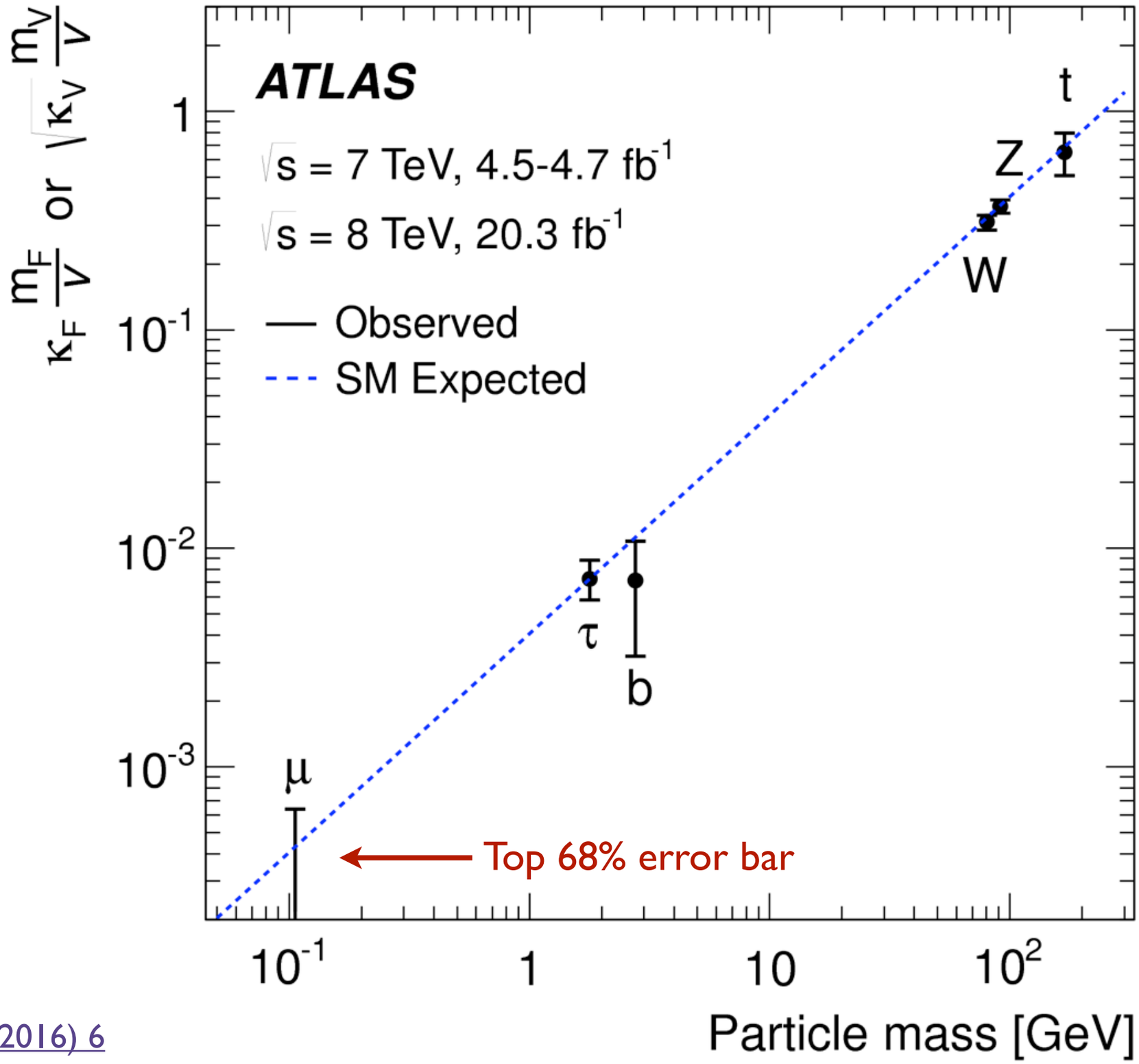
Testing the mass generation hypothesis



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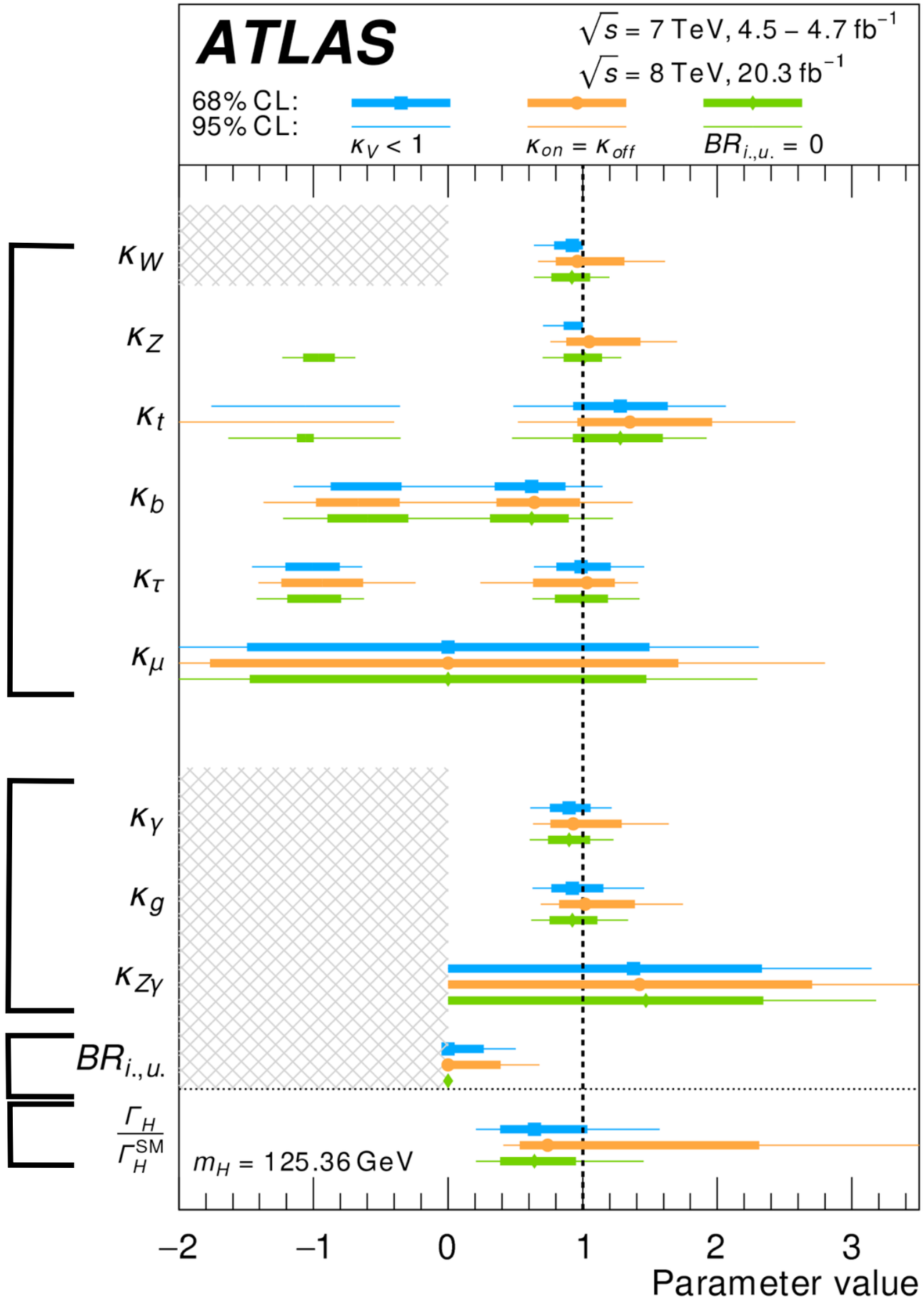
A General BSM fit



Tree Level

New Physics in Loops

"Invisible" decays

Non-SM width

Eur. Phys. J. C76 (2016) 6

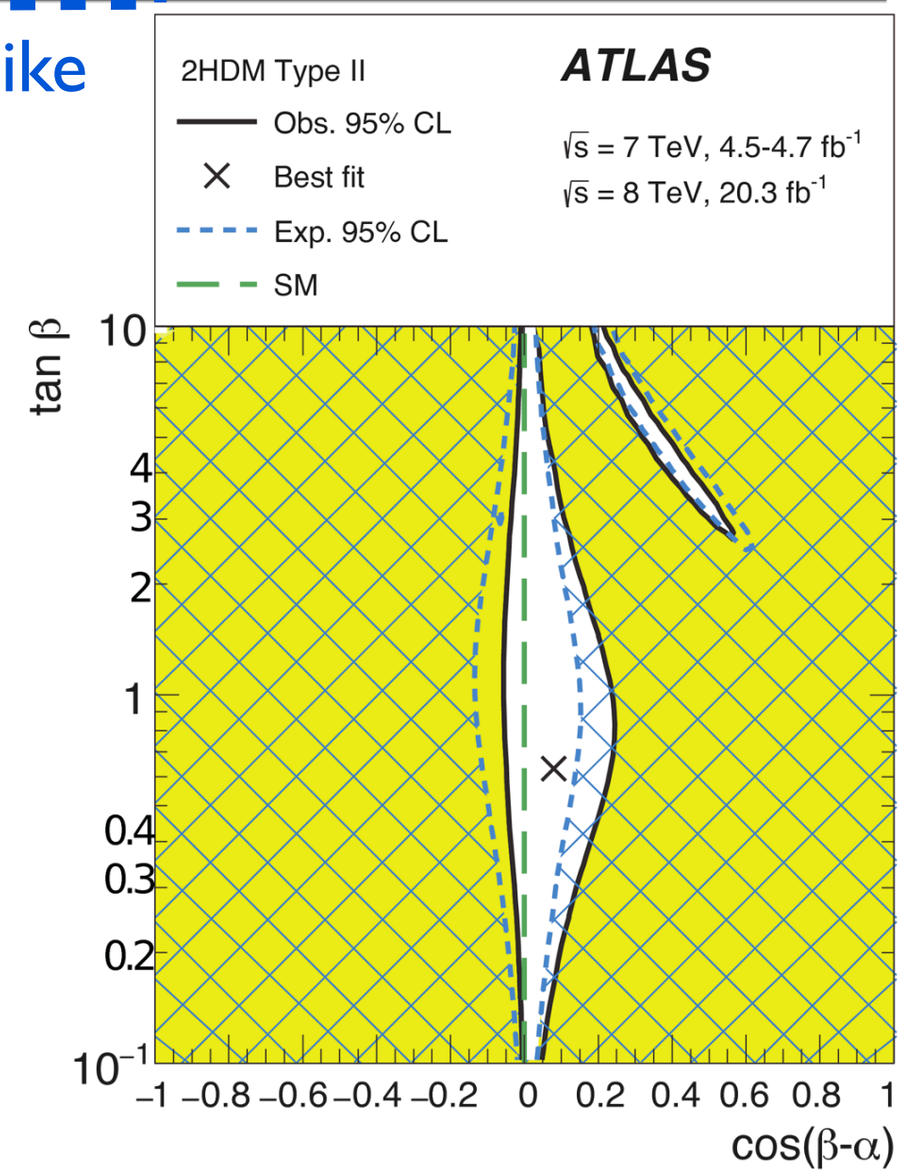
A BSM fit

← Various 2 Higgs Doublet Models →

Coupling scale factor	Type I	Type II	Lepton-specific	Flipped
κ_V	$\sin(\beta-\alpha)$			
κ_u	$\cos(\alpha)/\sin(\beta)$			
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_ℓ	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

SUSY-like

Set limits on BSM specific models



JHEP11(2015)206

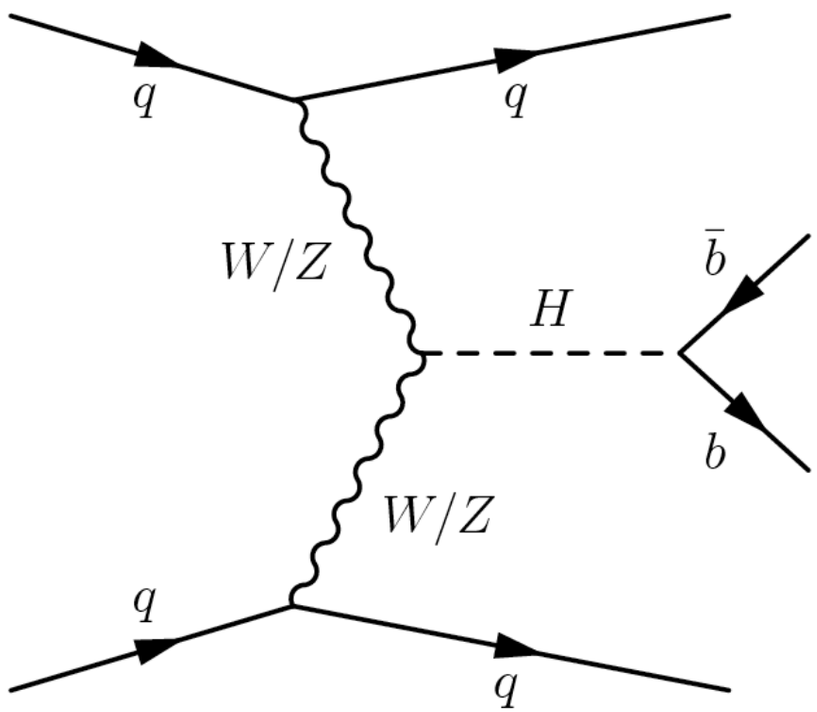
New constraints on H→bb (Run 1 data)

WH or ZH with H→bb is the main constraint on the H→bb decay rate

$\mu = 0.52 \pm 0.4$ (observed)

Now other options are being explored:

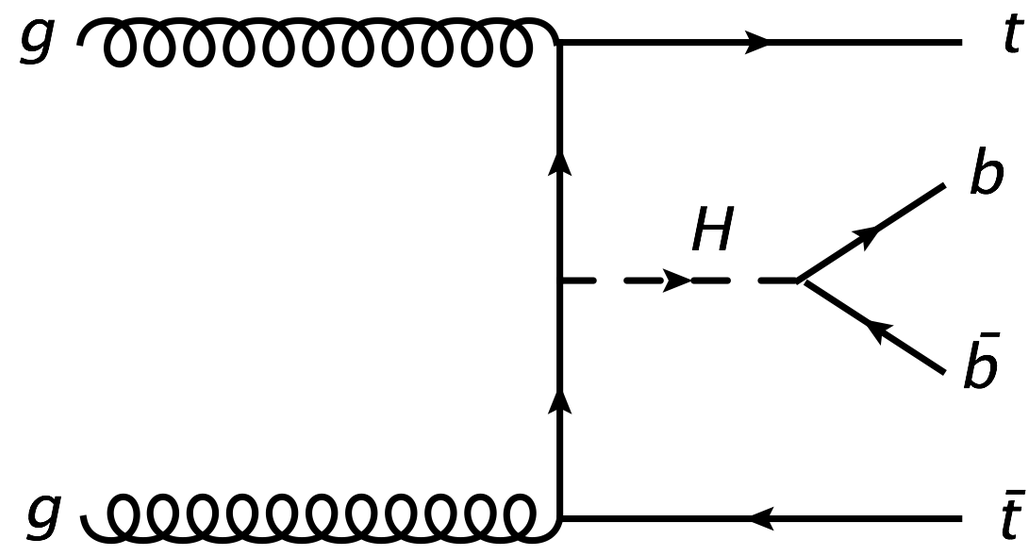
VBF with H→bb



$\mu = -0.8 \pm 2.3$ (observed)

arXiv:1606.02181

ttH decaying hadronically with H→bb



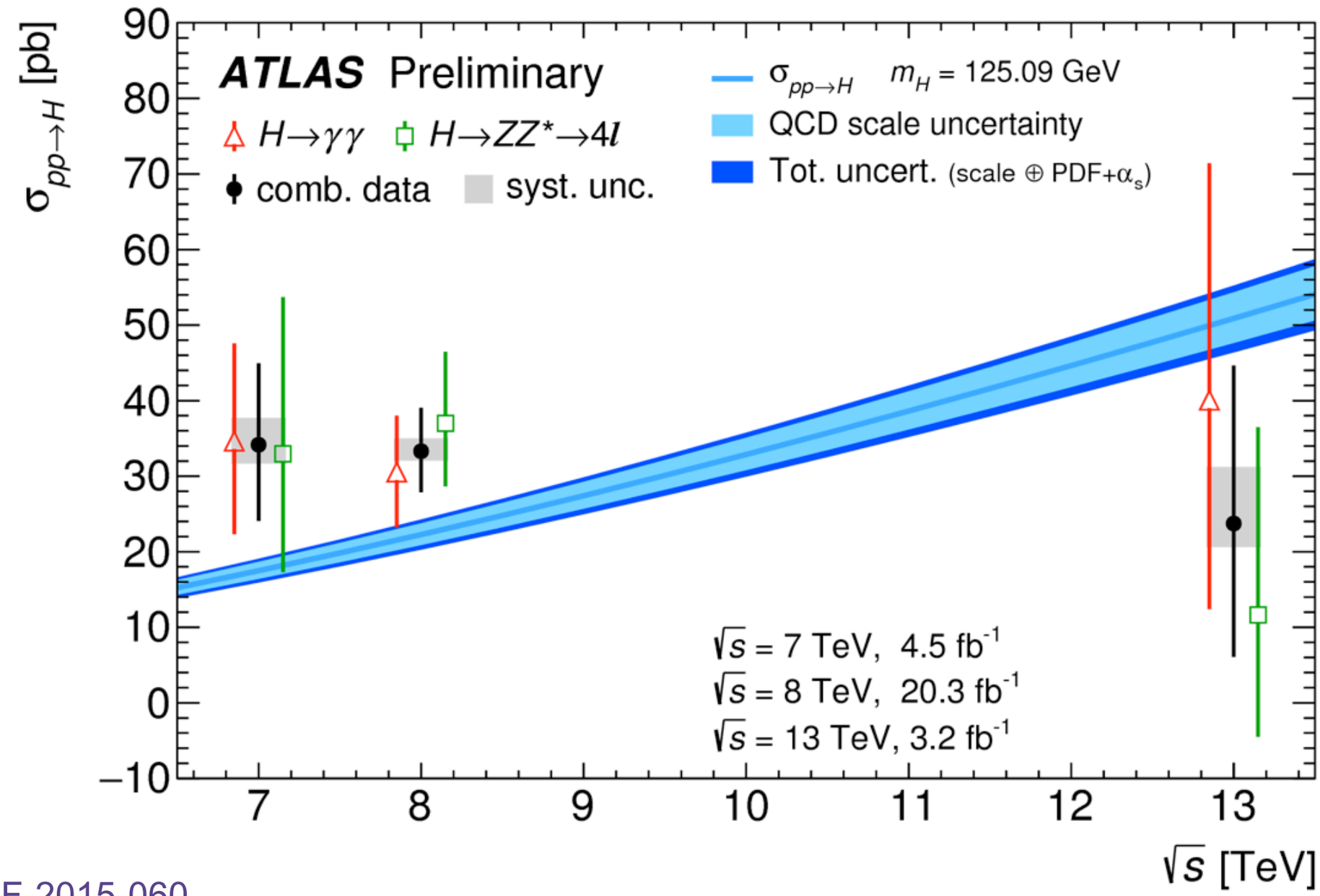
$\mu = 1.7 \pm 0.8$ (observed)

JHEP 05 (2016) 160

Rates Measurements at 13 TeV

Sensitivity has not yet reached 7+8 TeV sensitivity

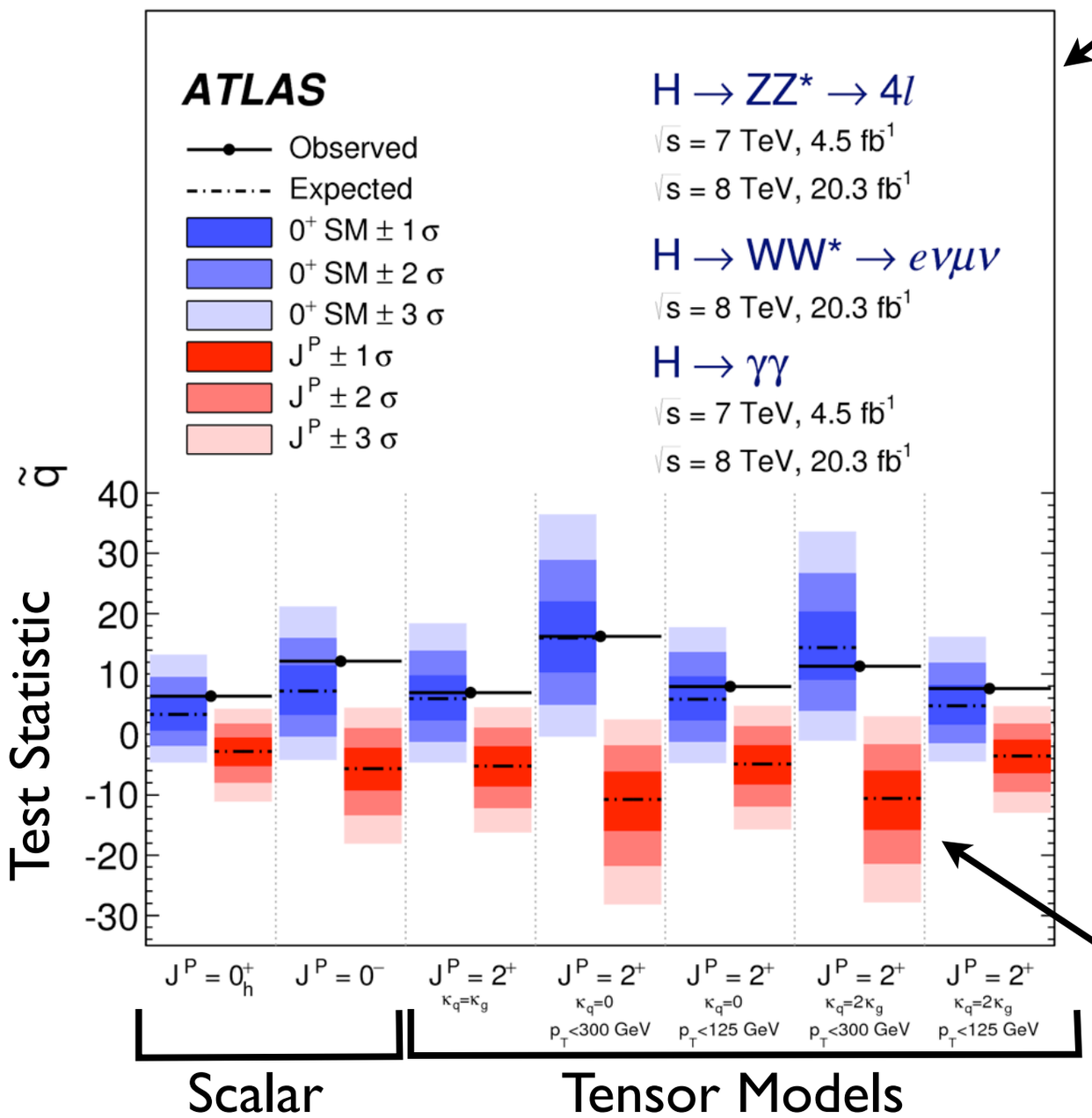
Yields consistent with expectations



ATLAS-CONF-2015-060

Spin, Parity, and Mass @ 125 GeV

Spin and Parity constraints using angular distributions in H→γγ, H→ZZ, and H→WW



- Effective field theory modifications of tensor structure in diboson production
  - Eur. Phys. J. C75 (2015) 476
- Test of CP structure in VBF H→ττ
  - arXiv:1602.04516
- Mass measurement (combines ZZ and γγ)

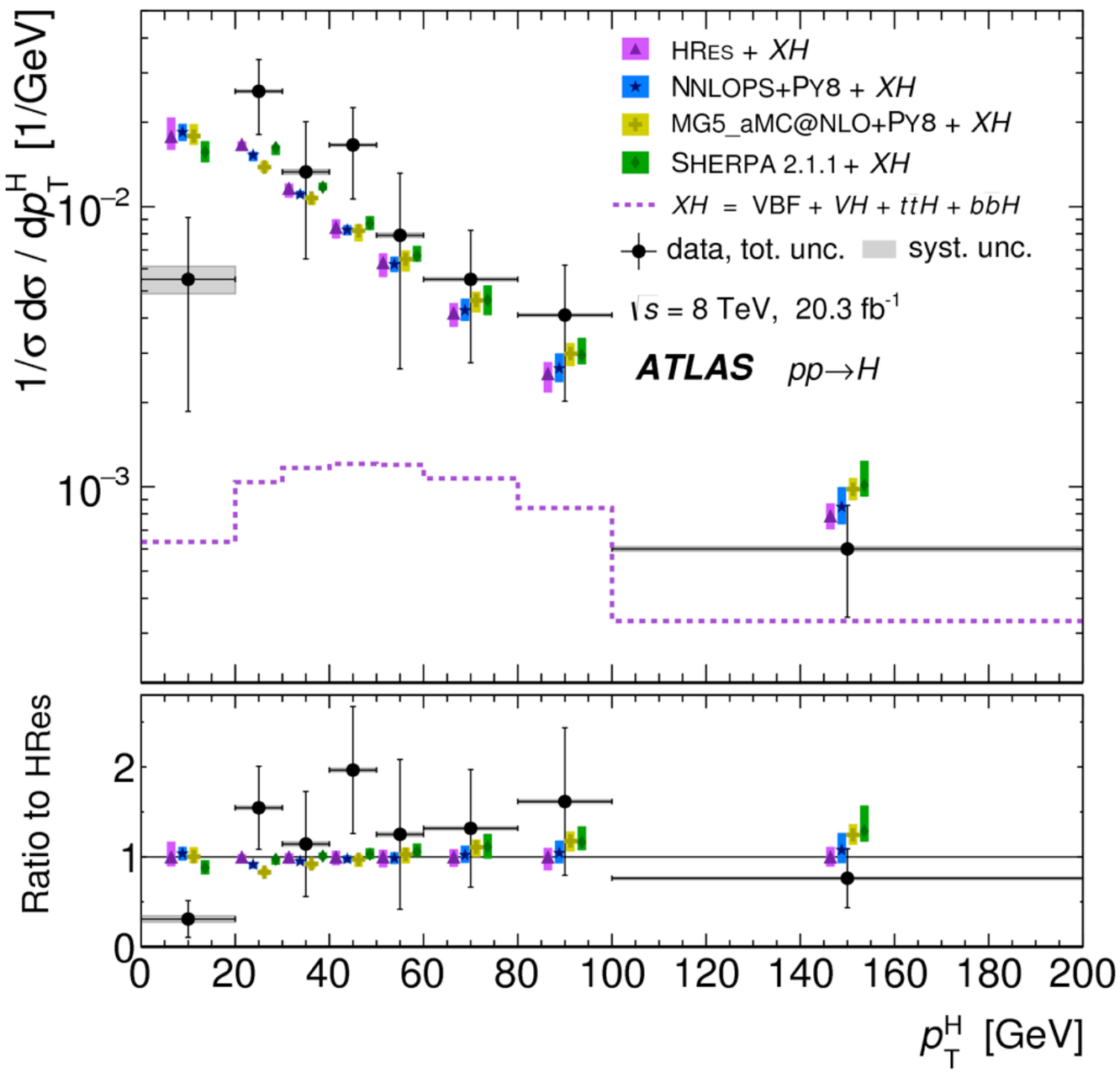
m_H = 125.36 ± 0.37(stat) ± 0.18(syst) GeV

  - Phys. Rev. D. 90, 052004 (2014)

Distributions of test statistic expectations for SM and non-SM

Differential Distributions @ 125 GeV

- Different distributions are sensitive to different modeling aspects...
  - Perturbative QCD: N_{jets}, Higgs p_T, leading-jet p_T,
  - Soft Gluon Resummations: Higgs p_T
  - PDFs: Higgs rapidity
- ... or sensitive to new physics
- Tests agreement of shapes with theoretical predictions
- First Example: ZZ and γγ combined



Phys. Rev. Lett. 115 (2015) 091801

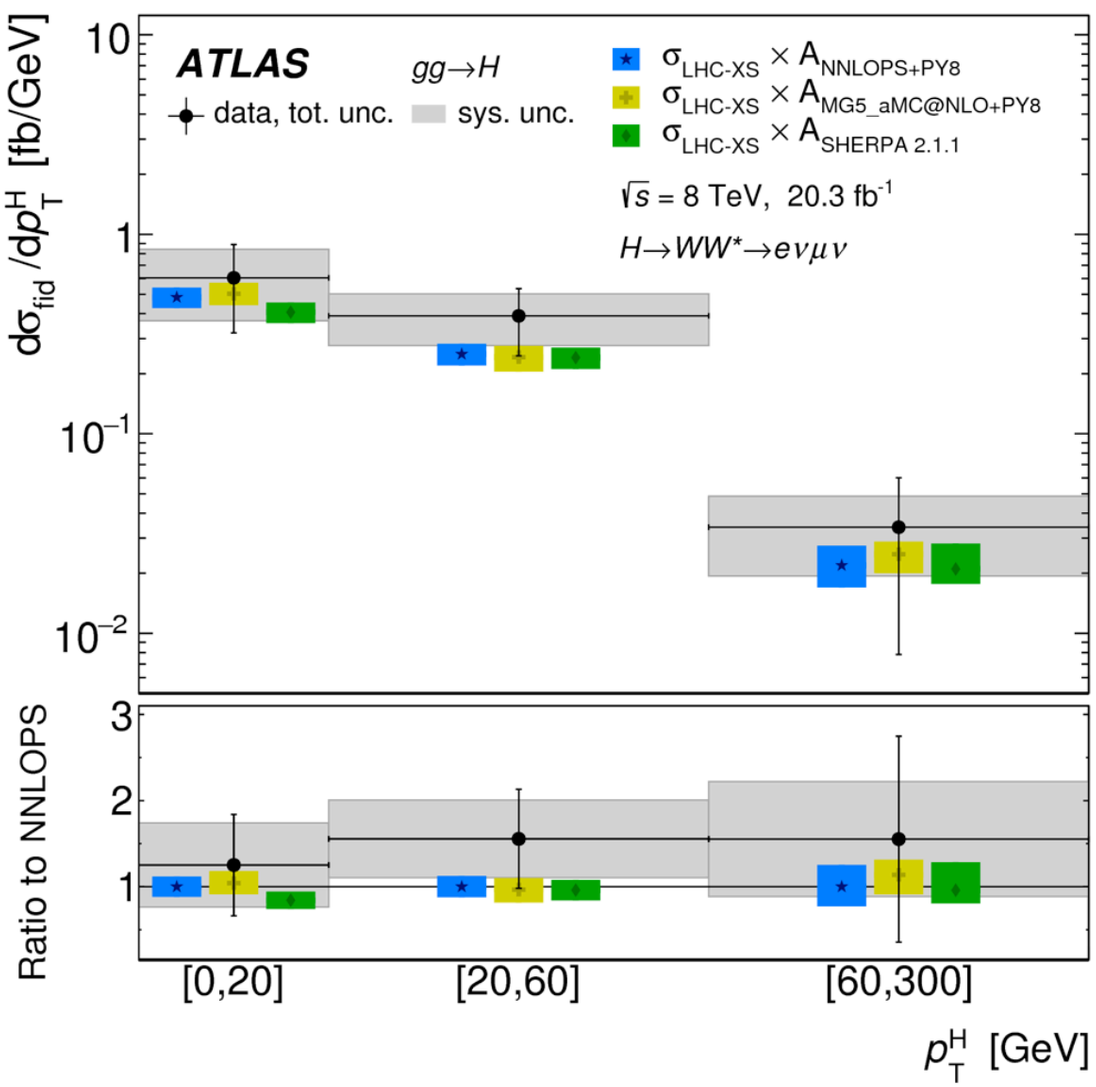
Quantify Agreement = p-values

	p_T^H	$\|y^H\|$	p_T^{j1}
HRes	15%	64%	-
NNLOPS	10%	64%	64%
SHERPA 2.1.1	22%	63%	88%
MG5_aMC@NLO	8%	60%	88%

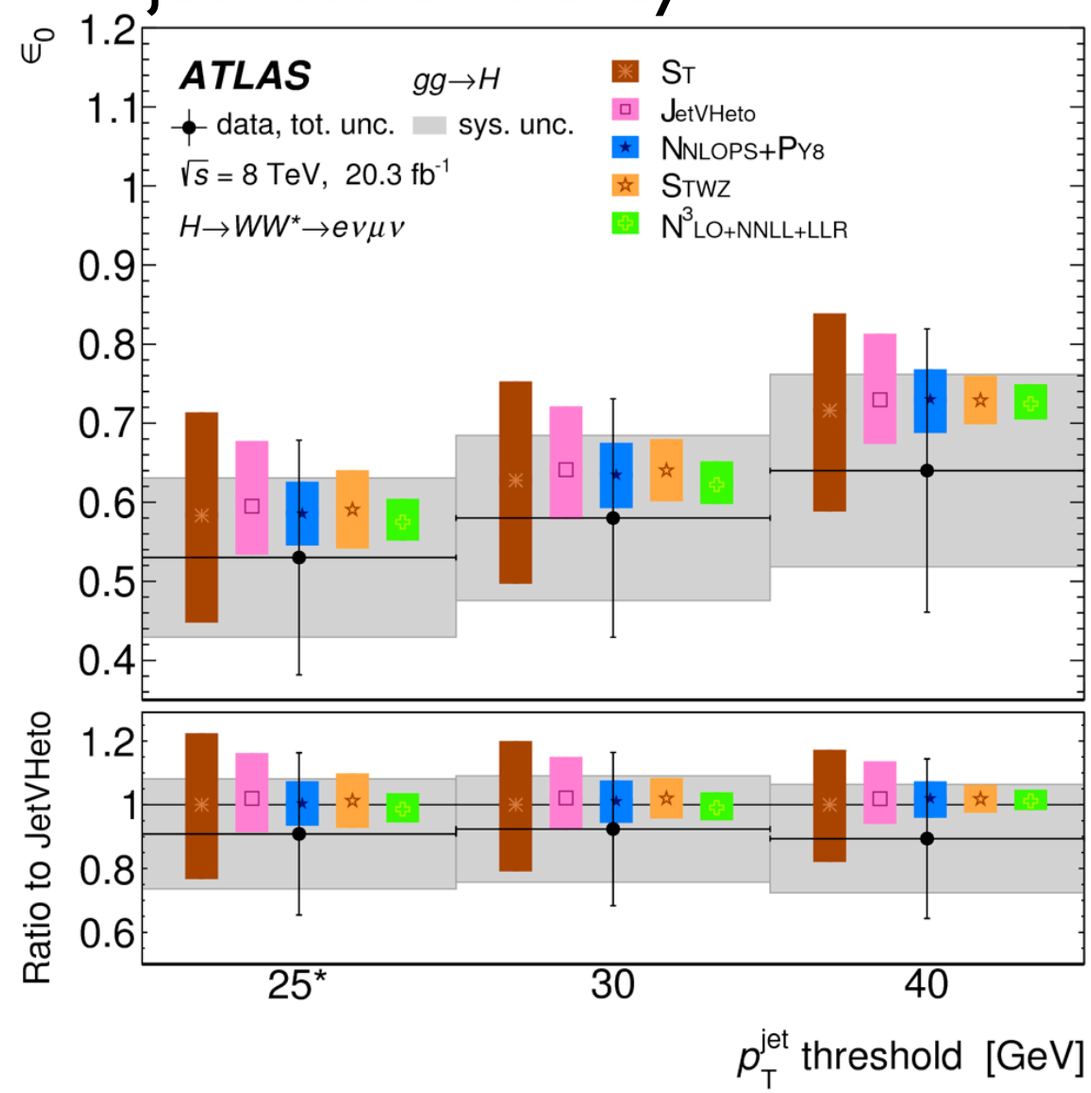
Differential Distributions @ 125 GeV

Recently extend to used H→WW also

Complicated because of need for a jet veto to suppress large top background



Dedicated measurement of jet-veto efficiency



arXiv:1604.02997

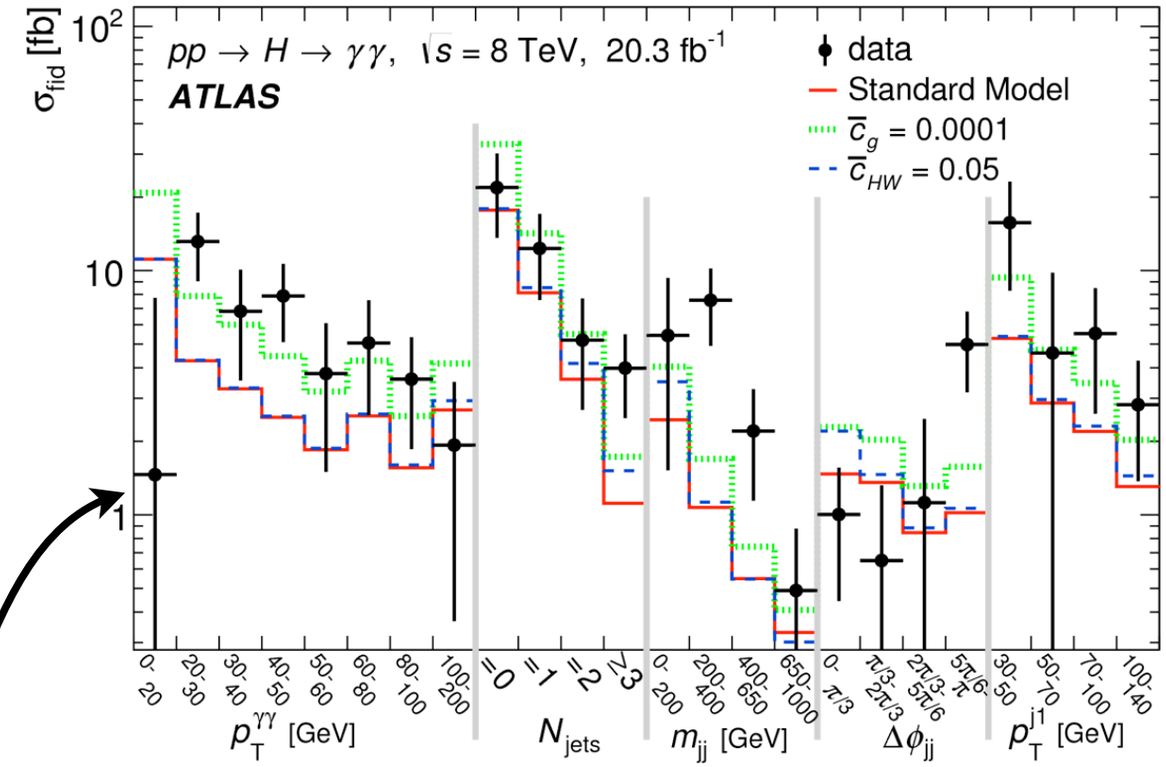
Differential Distributions @ 125 GeV

Differential distributions can also be used to limit BSM contributions

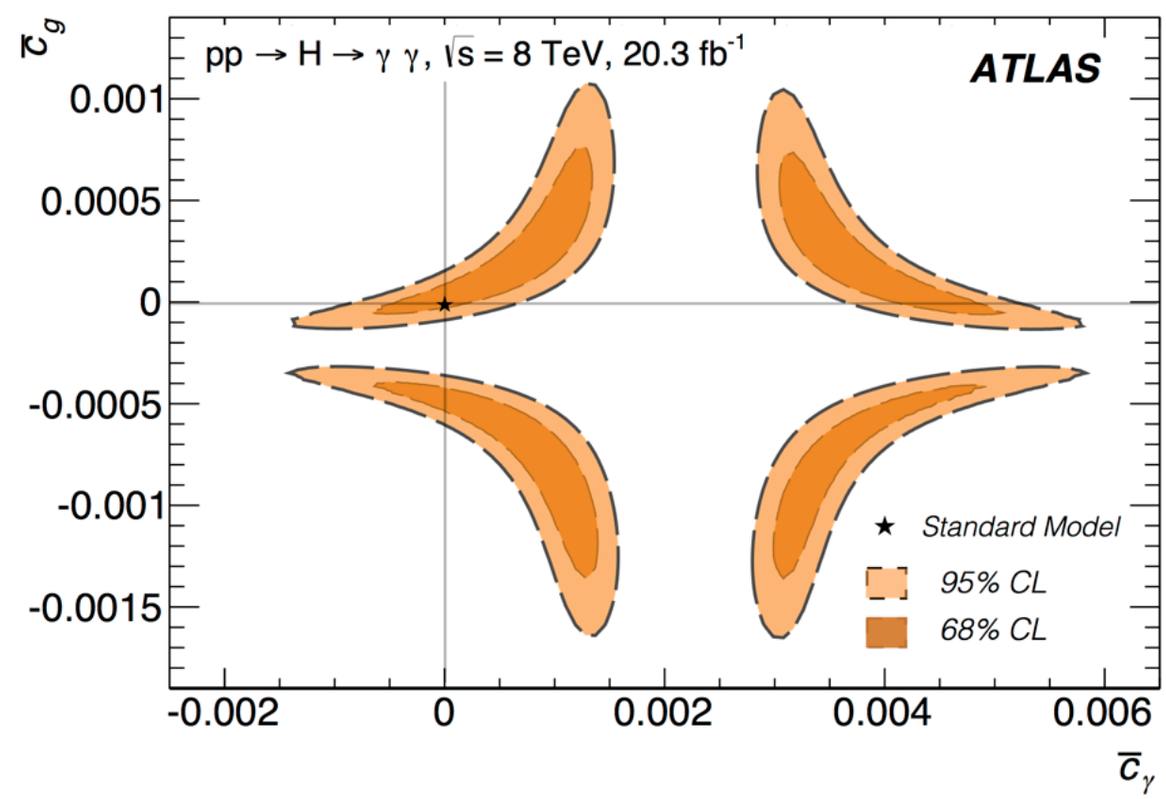
For example, limits on an extended Effective Lagrangian using H→γγ

$$\mathcal{L}_{\text{eff}} = \bar{c}_\gamma O_\gamma + \bar{c}_g O_g + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_\gamma \tilde{O}_\gamma + \tilde{c}_g \tilde{O}_g + \tilde{c}_{HW} \tilde{O}_{HW} + \tilde{c}_{HB} \tilde{O}_{HB},$$

Changes in differential distributions



Limits on Wilson coefficients



Physics Letters B 753 (2016) 69-85

BSM decays @ 125 GeV

Higgs is a narrow resonance

- all decay modes are suppressed by
  - small Yukawa couplings (bb, ττ, cc)
  - off-shell vector bosons (WW*, ZZ*)
  - loop couplings (γγ, gg)

See talk by Philip Chang: Search for non-standard and rare decays of the Higgs boson

This makes Higgs decay especially sensitive to potential BSM decay modes

- Also easy to couple Higgs to new physics for model building (Higgs "portal")

Example ATLAS searches:

- Lepton Flavor Violating decays (hep-ex/1604.07730)
- Additional light weakly coupled scalars (a) or vectors (Z_d)
  - H to aa to 4 gamma (hep-ex/1509.05051)
  - H to aa to μμττ (Phys. Rev. D92 (2015) 052002)
  - H to aa to 4b (hep-ex/1606.08391)
  - H to Z_dZ_d to 4 e/μ leptons (Phys. Rev. D 92 (2015) 092001)
- Decay to SUSY particles (ATLAS-CONF-2015-001)
- Direct coupling to dark matter (aka Higgs to Invisible)

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Lepton Flavor Violating Decays

Various models exists in which lepton flavor violation could happen

- Multiple Higgs doublets, composite Higgs, and many more...
- $H \to e\mu$ tightly constrained from $\mu \to e\gamma$, but $H \to \mu\tau$ allowed

CMS has a small excess in $H \to \mu\tau$:

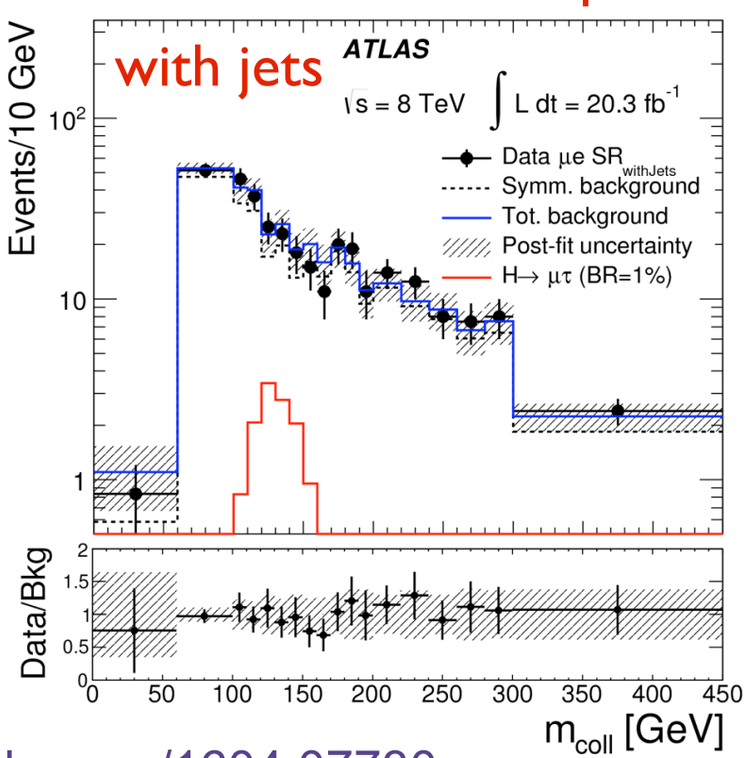
- 2.4σ significance
- $BR(H \to \mu\tau) = 0.84^{+0.39}_{-0.37}\,\%$
- CMS Limit $BR(H \to \mu\tau) < 1.51\%$

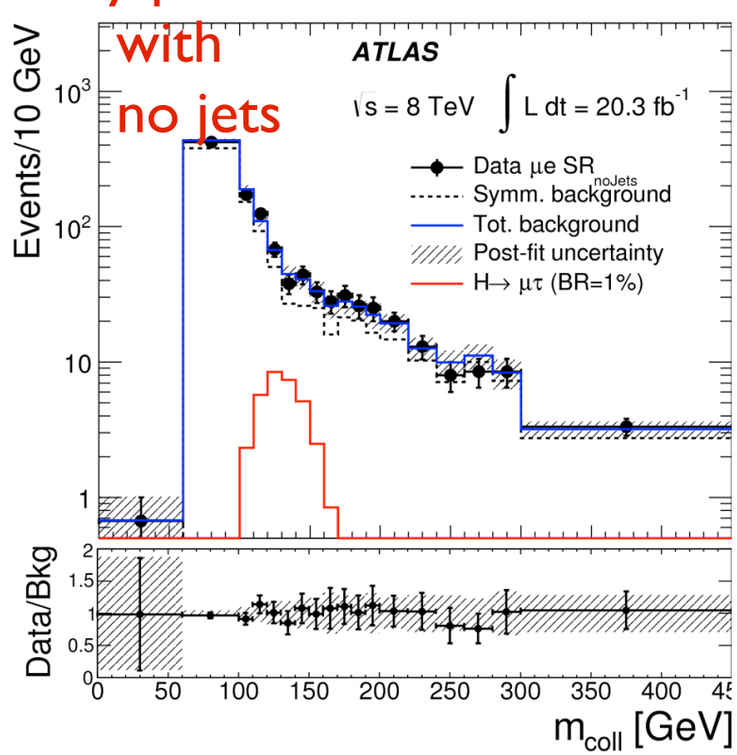
ATLAS search combines

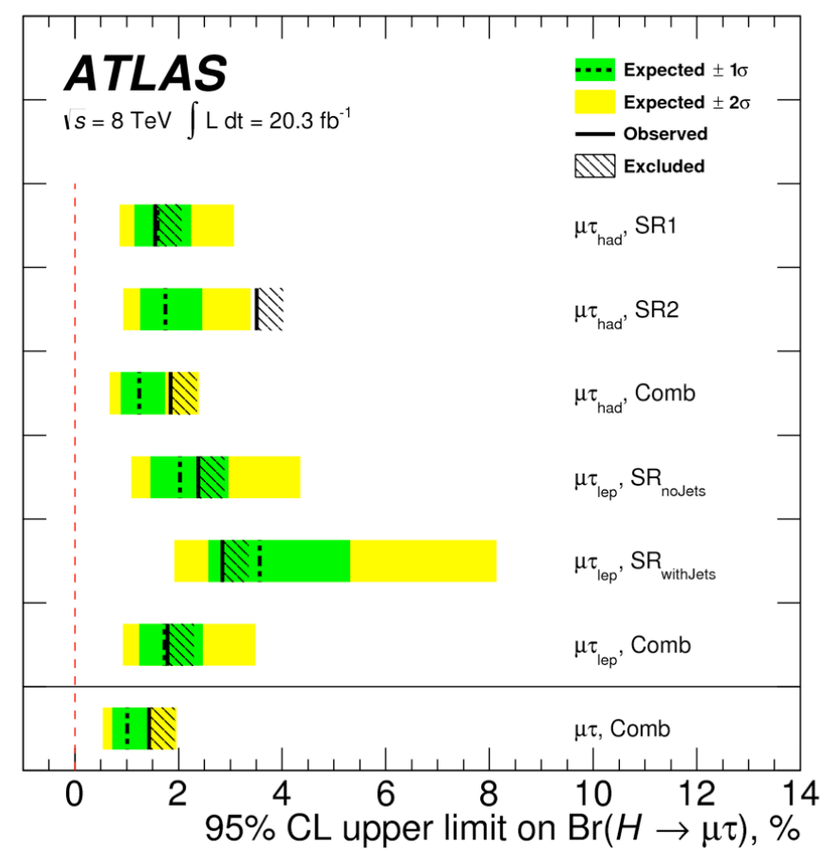
- leptonic τ decay (focus on $e\mu$)
- hadronic τ decay ("τ_{had}")

ATLAS Limit $BR(H \to \mu\tau) < 1.43\%$

leptonic τ decay plots







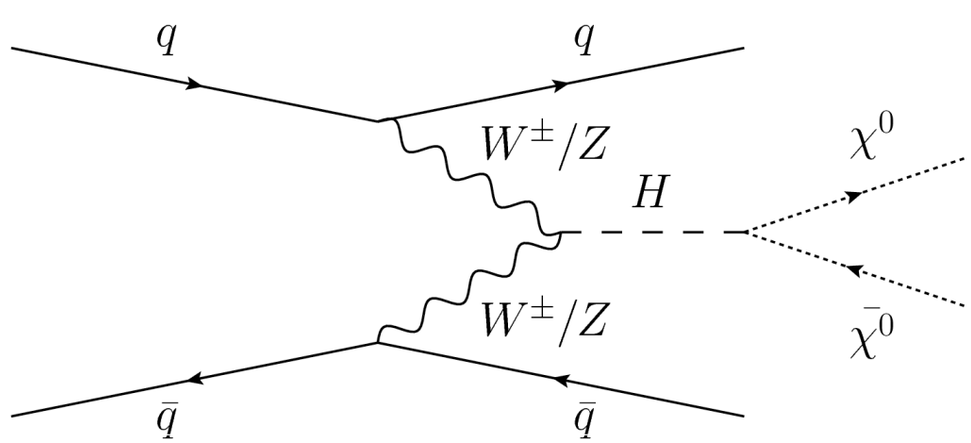
hep-ex/1604.07730

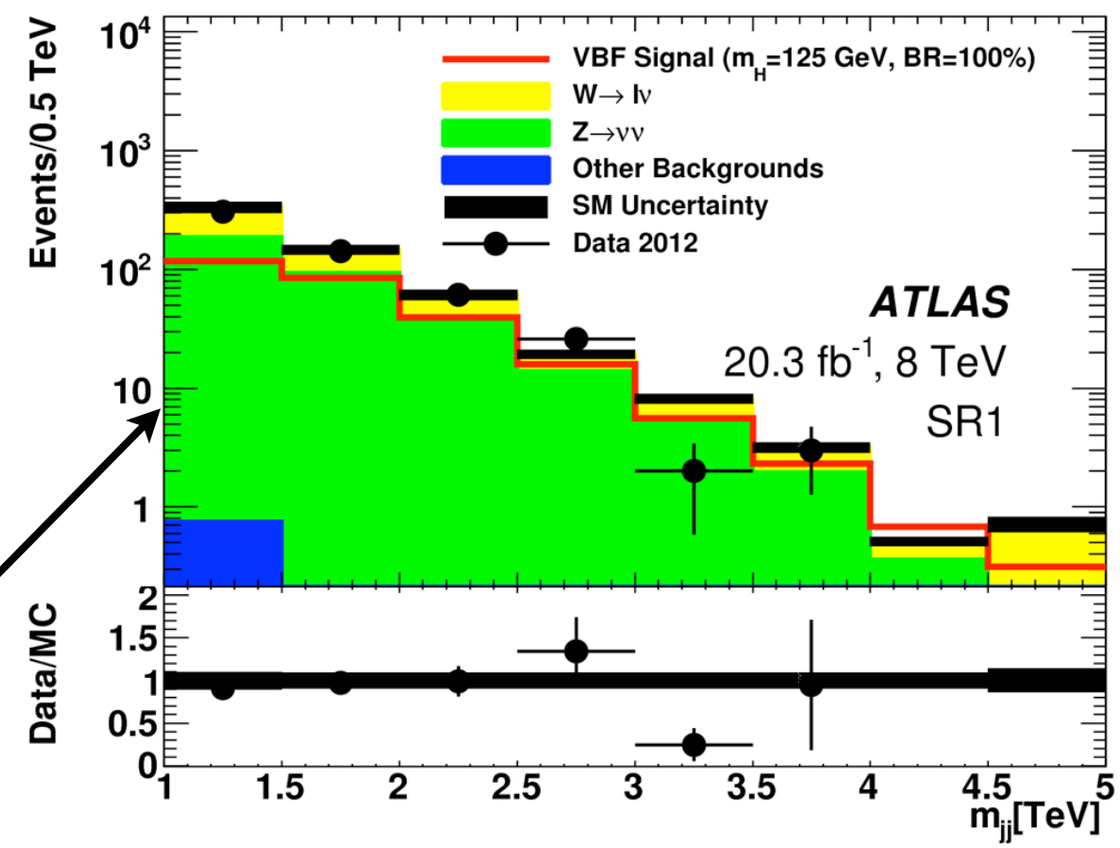
Higgs to Invisible: Direct Searches

Assume SM production rate

Channel	Branching Fraction Limit	
	Expected	Observed
ZH with Z→ll Phys. Rev. Lett. 112, 201802 (2014)	0.62	0.75
WH or ZH with W/Z→jj Eur. Phys. J. C (2015) 75:337	0.86	0.78
Vector Boson Fusion JHEP 01 (2016) 172	0.31	0.28

Example signal diagram (for VBF)





Modeling Z→νν is the key challenge

VBF analysis uses W→lν as constraint

Higgs to Invisible: Indirect Constraints

Higgs to invisible can also be limited by indirect constraints from the coupling fit

Limits are then model dependent, results below are least model dependent option

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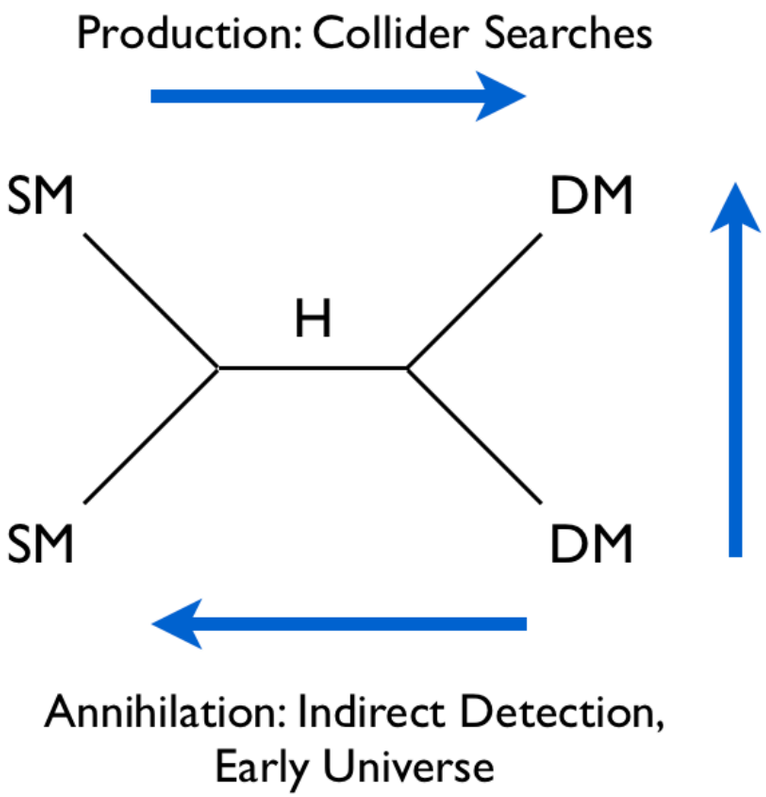
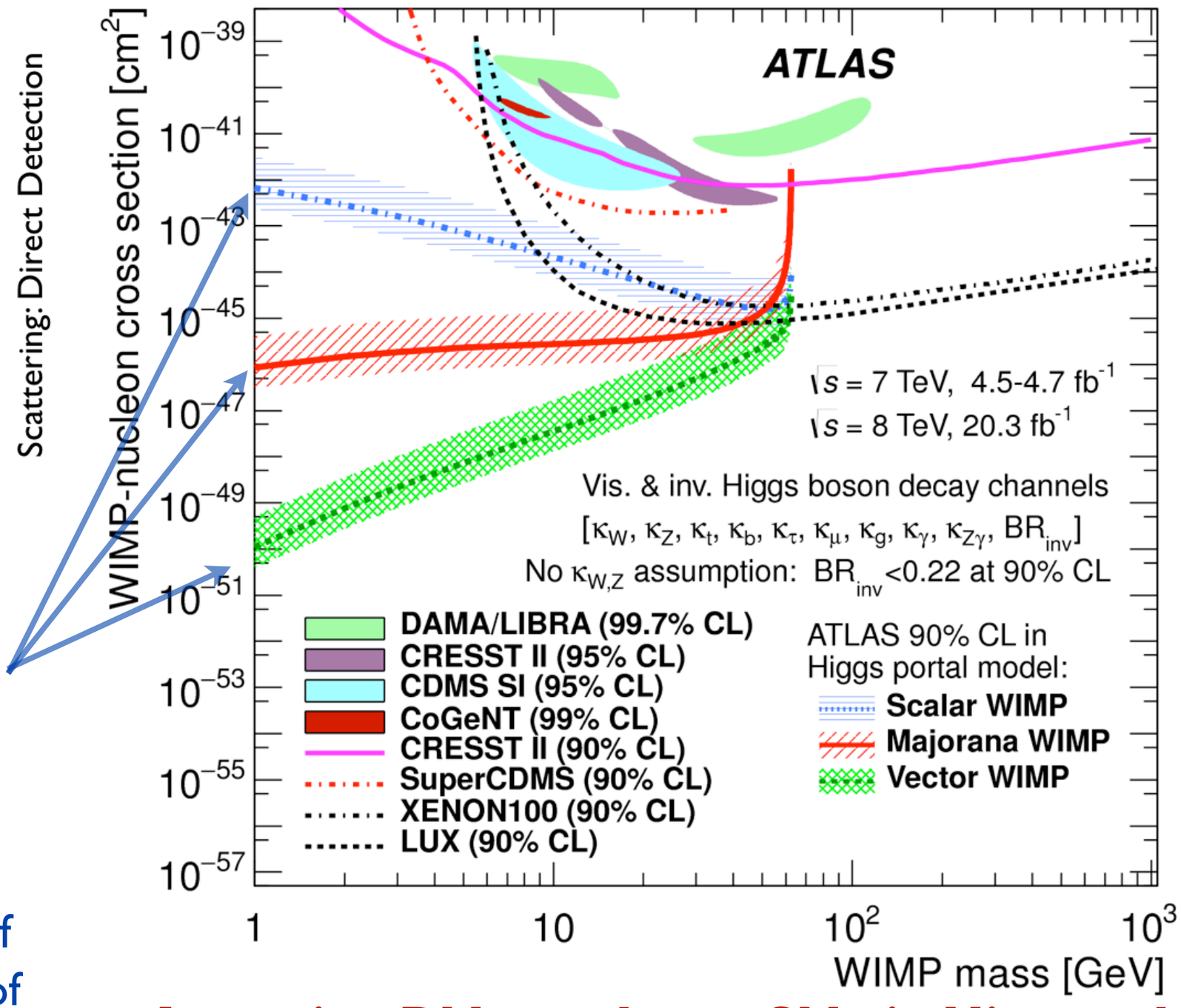
Vector Boson Fusion	0.31	0.28
Combination of Direct Limits	0.27	0.25
Indirect limit from fit to visible rates	0.48	0.49
Combination of Direct and Indirect Limits	0.23	0.23

JHEP11(2015)206

Higgs Portal Interpretation





Limits depend on the particle assumption (scalar, Majorana fermion, vector)

Comparable sensitivity to direct dark matter searches (if $m_X < m_H/2$) without the loss of sensitivity at low WIMP mass

JHEP11(2015)206

Assuming DM couples to SM via Higgs only and other caveats.... (in back-up)

More Higgses

Numerous models introduce additional Higgses (MSSM and beyond)

- Heavy Higgs (H),
- Charged Higgs ($H^{\pm}$),
- Pseudo-scalar Higgs (A)

Wide variety of ATLAS searches

13 TeV results for items in red

- Heavy Higgs (H)
  - Heavy dibosons (WW, ZZ) : llqq, ννqq,lνqq, qqqq,
    - ZZ→ 4l ,ZZ→ ννll,WW→lνlν
  - Diphoton
  - Dihiggs: 4b, bbγγ, bbττ, γγWW
  - A/H → ττ
- Charged Higgs ($H^{\pm}$)
  - tH^+ with $H^+ \rightarrow \tau\nu$ and hadronic top decay
  - $H^+ \rightarrow tb$, $H^+ \rightarrow WZ$, $H^+ \rightarrow cs$, $H^+ \rightarrow \tau\nu$ in top decay
- Pseudo-scalar Higgs (A)
  - A → Zγ → llγ, A→ ZH → llbb or ννbb, A → ττ

Also see talks by Dmitri Tsybychev and Blake Burghgrave

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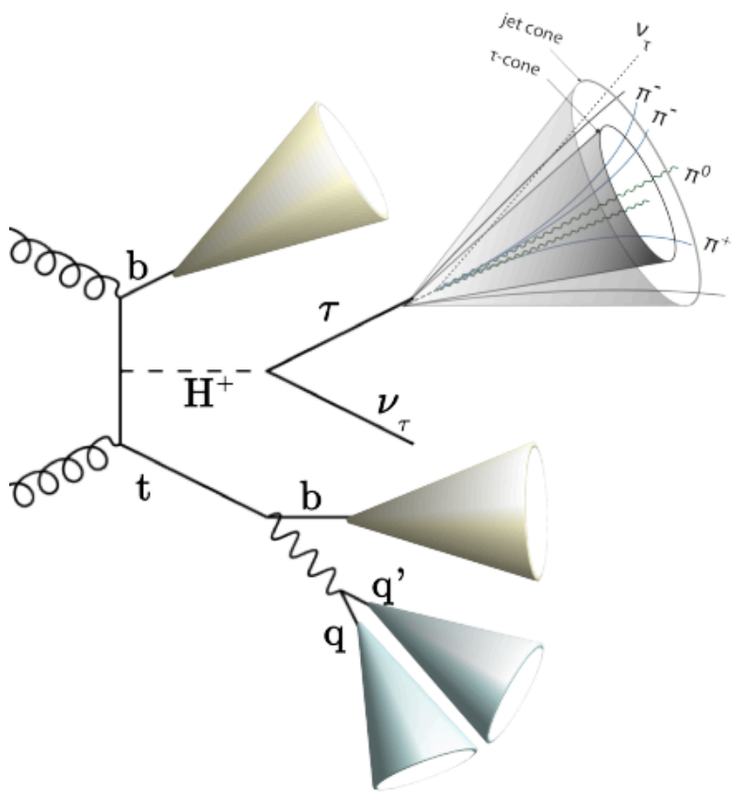
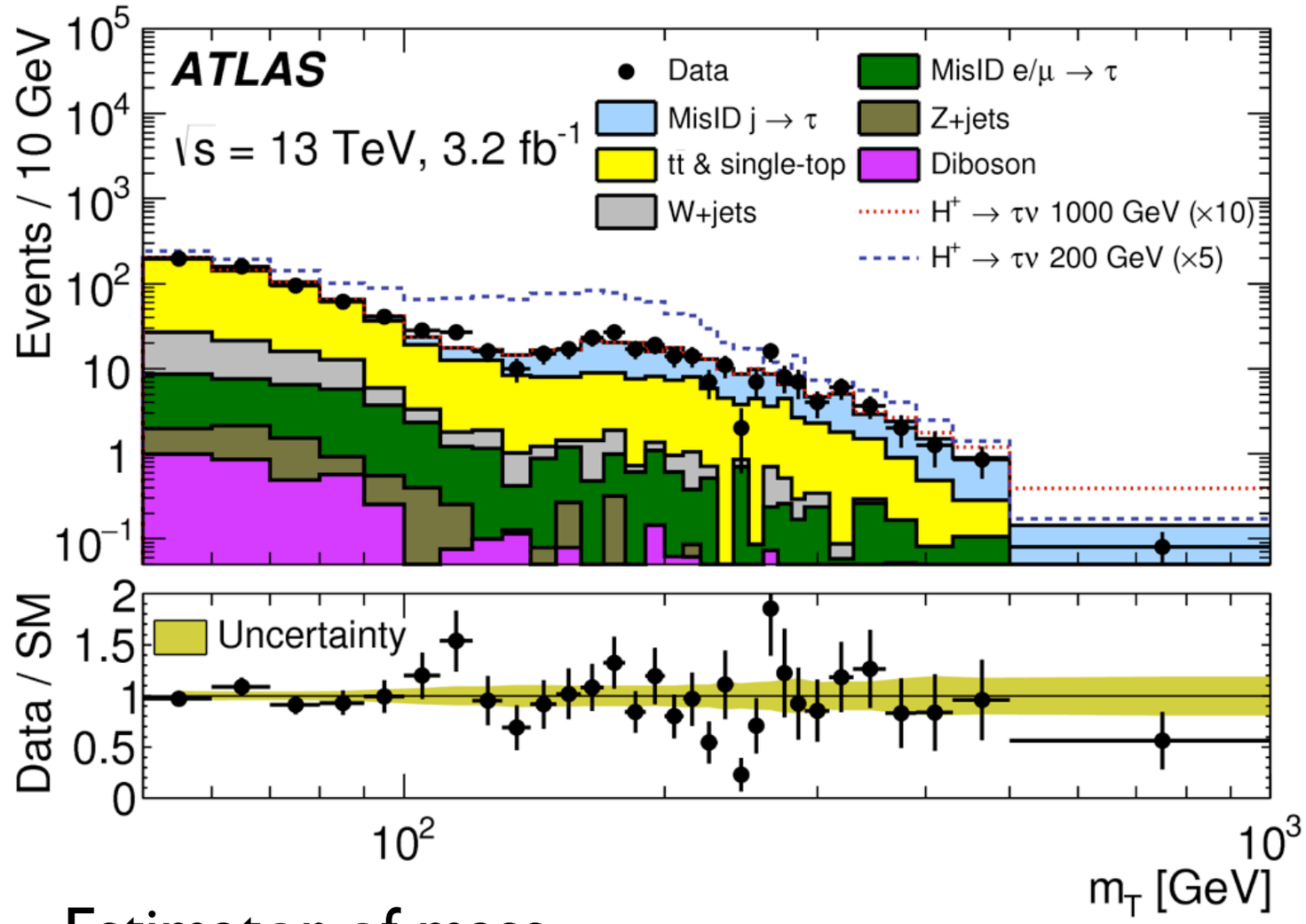
$H^+ \to \tau\nu$ in tH^+ with hadronic top

New 13 TeV result!

Targets $m_{H^+} > m_{top}$





Estimator of mass...

$$m_T = \sqrt{p_T^\tau E_T^{miss}(1 - \cos\Delta\phi_{p_T^\tau, E_T^{miss}})}$$

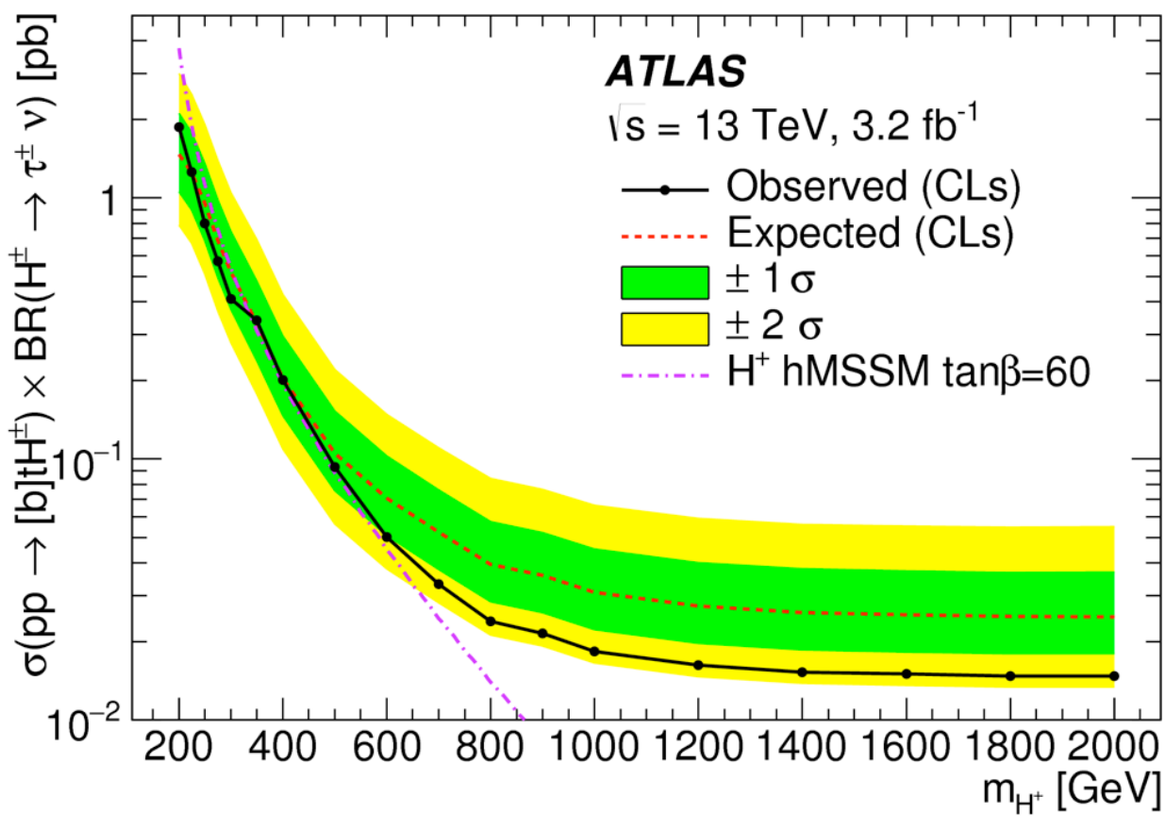
- Select 3 jets, at least one b-tagged
- Hadronic τ candidate
- Large E_T^{miss} (> 150 GeV)

Phys.Lett. B759 (2016) 555

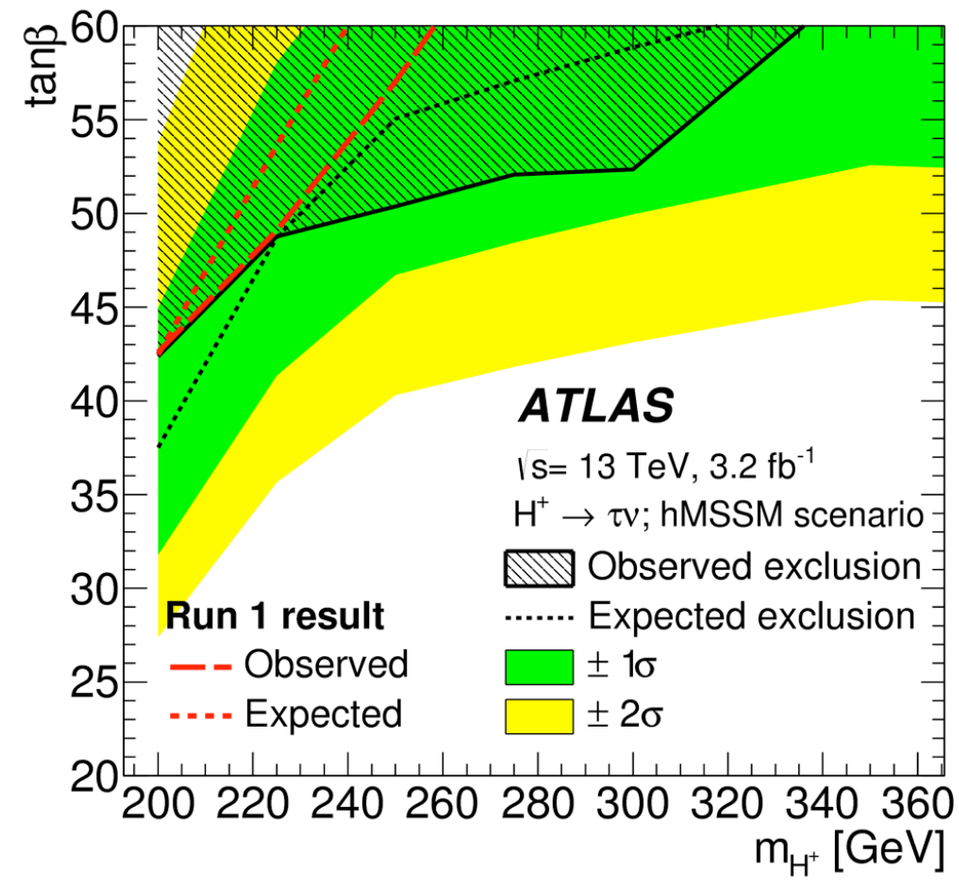
$H^+ \to \tau\nu$ in tH^+ with hadronic top

New 13 TeV result!

Resulting Limits



σ x BR limit vs mass



In hMSSM parameter space

b-tagged

- Hadronic τ candidate
- Large E_T^{miss} (> 150 GeV)

$$m_T = \sqrt{p_T^\tau E_T^{miss}(1 - \cos\Delta\phi_{p_T^\tau, E_T^{miss}})}$$

Phys.Lett. B759 (2016) 555

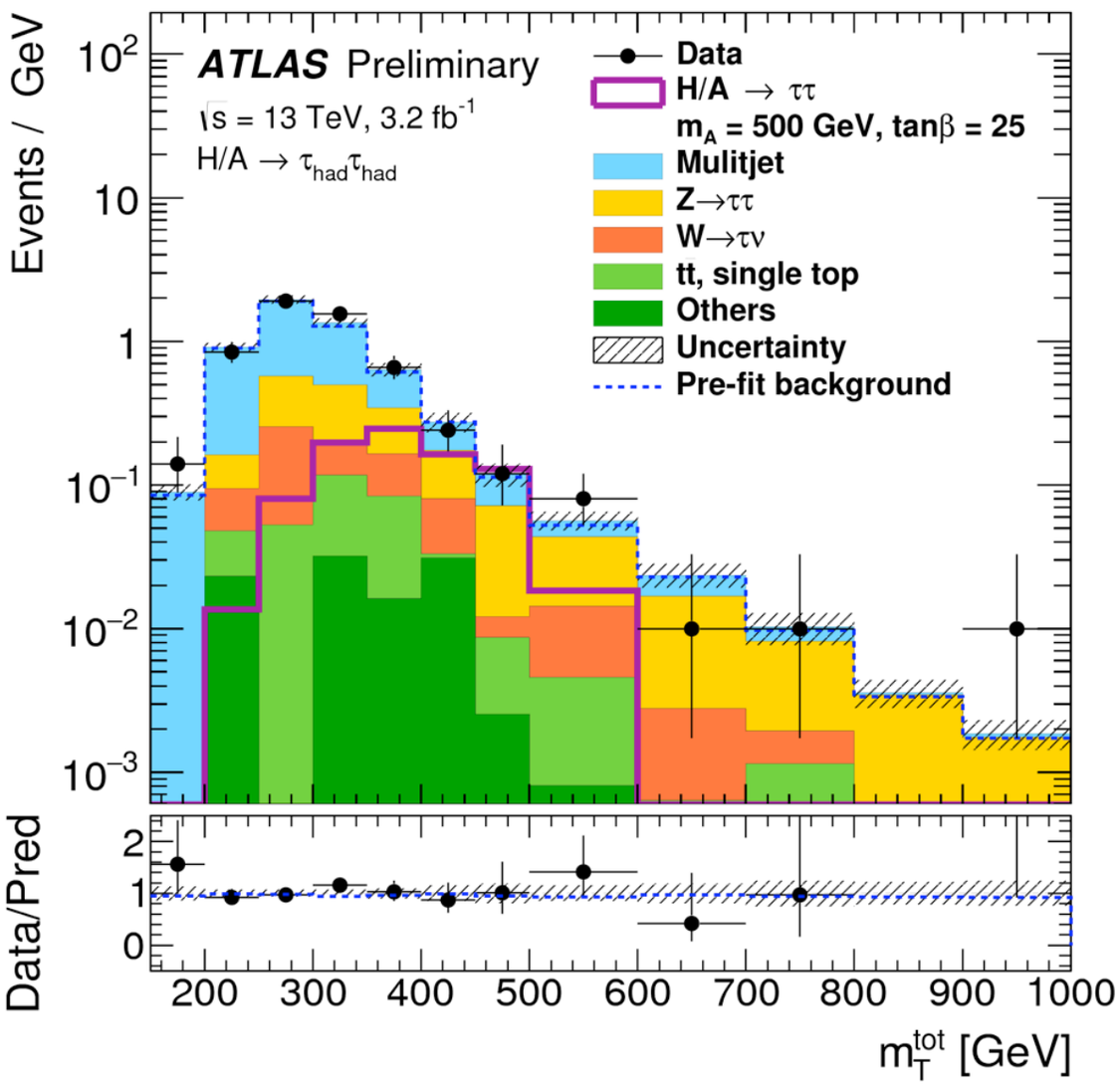
H/A →ττ

Another example of Run 2 vs Run 1

ATLAS-CONF-2015-061

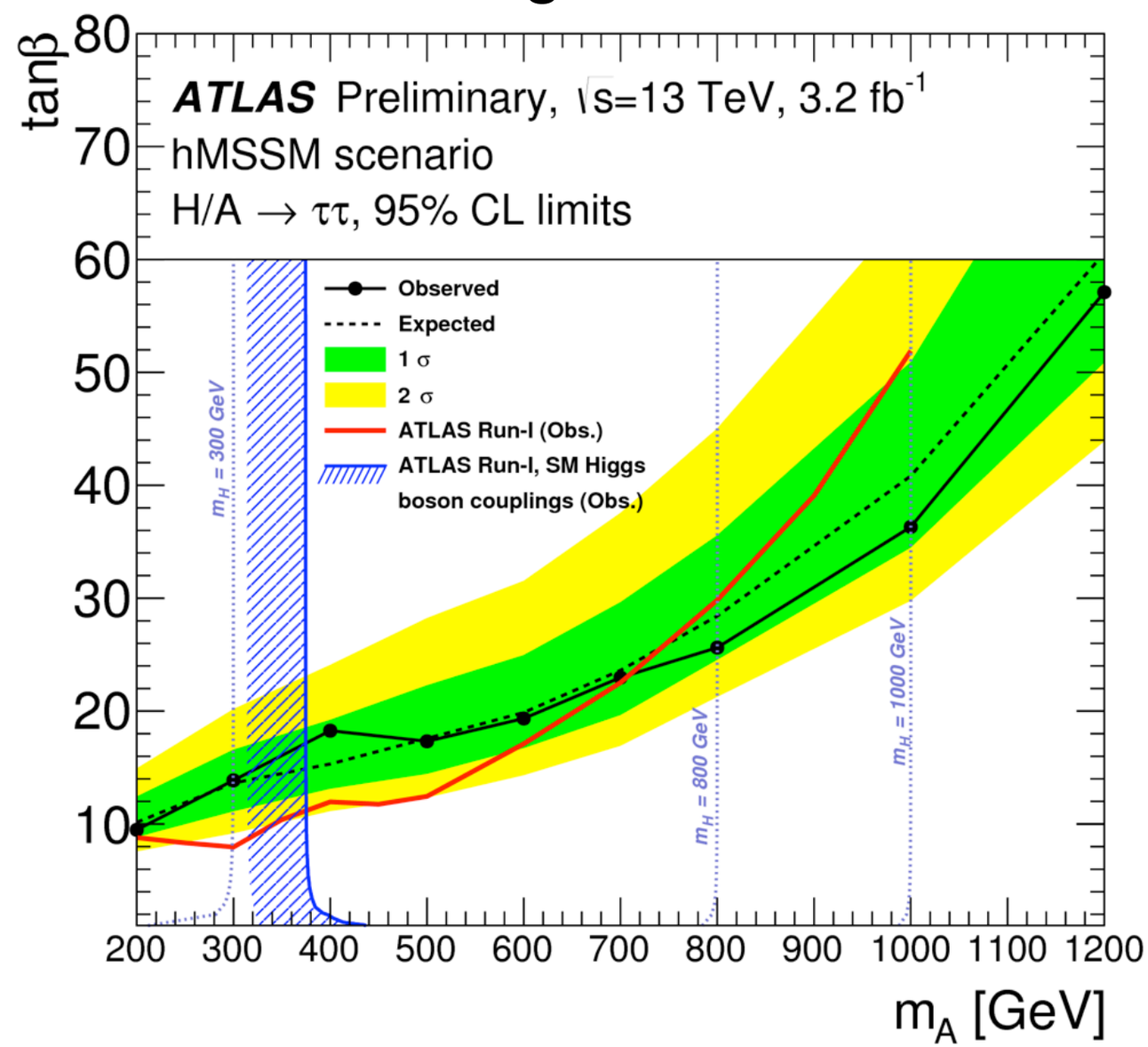
Combination of τ_{lep} τ_{had} and τ_{had} τ_{had}

Mass estimator for τ_{had} τ_{had}



Run 2 more sensitive at high mass,

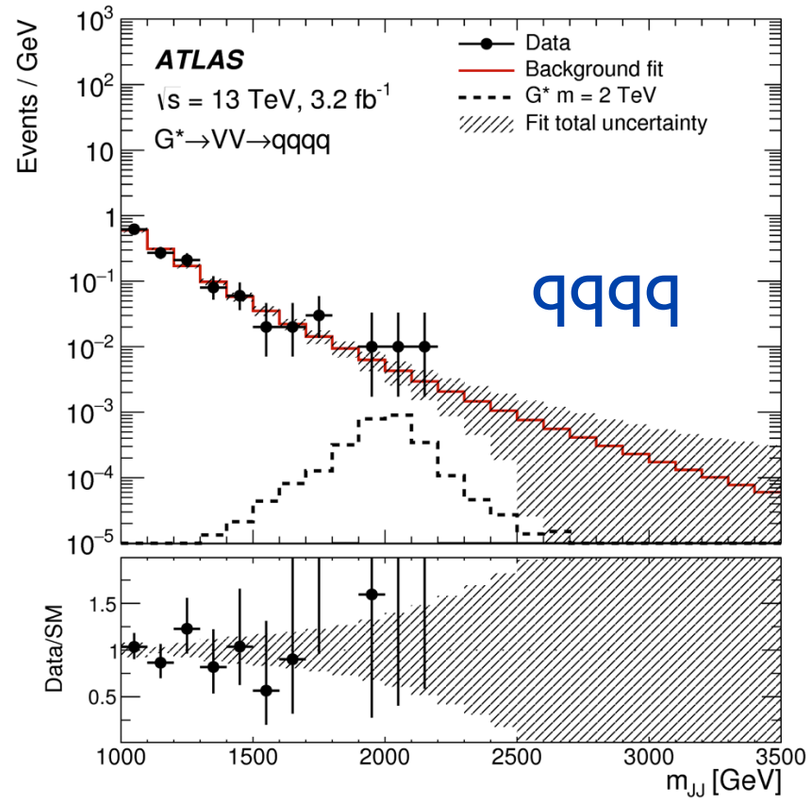
- But not yet at low mass
- That will change soon

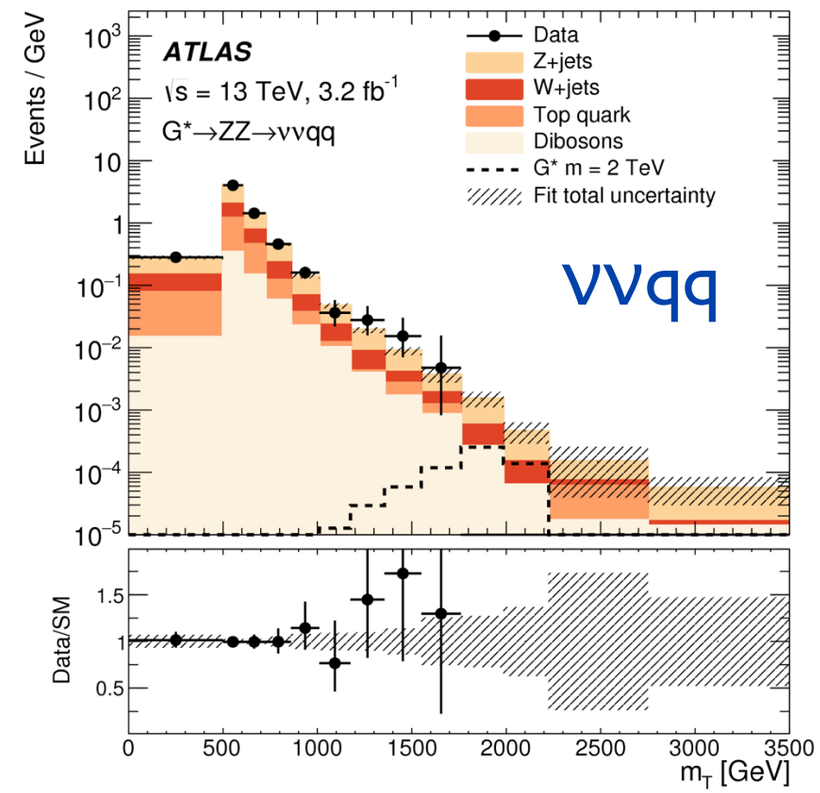


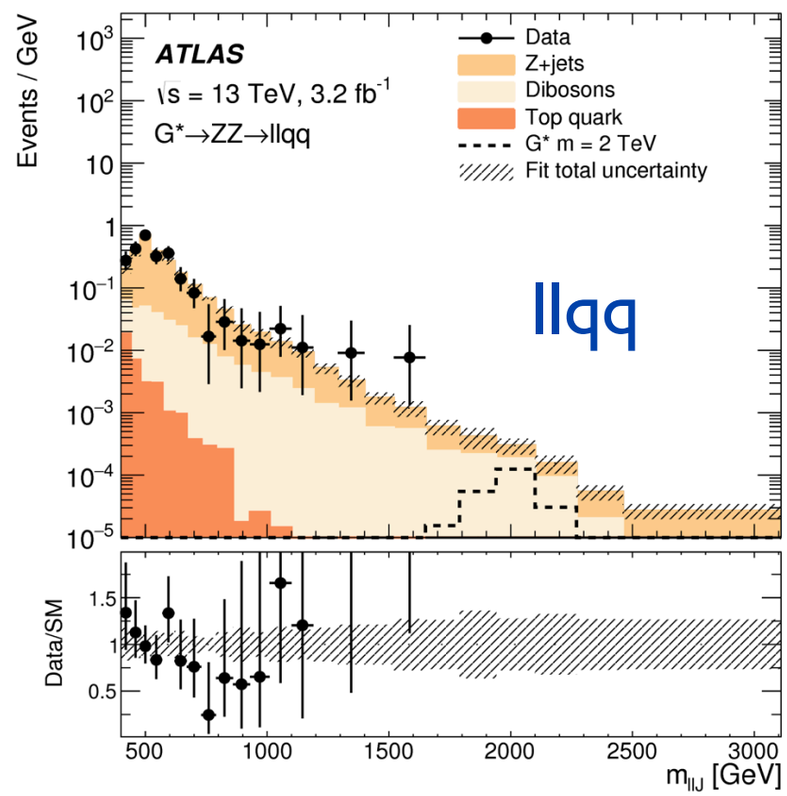
Heavy Scalars Decaying to WW and ZZ

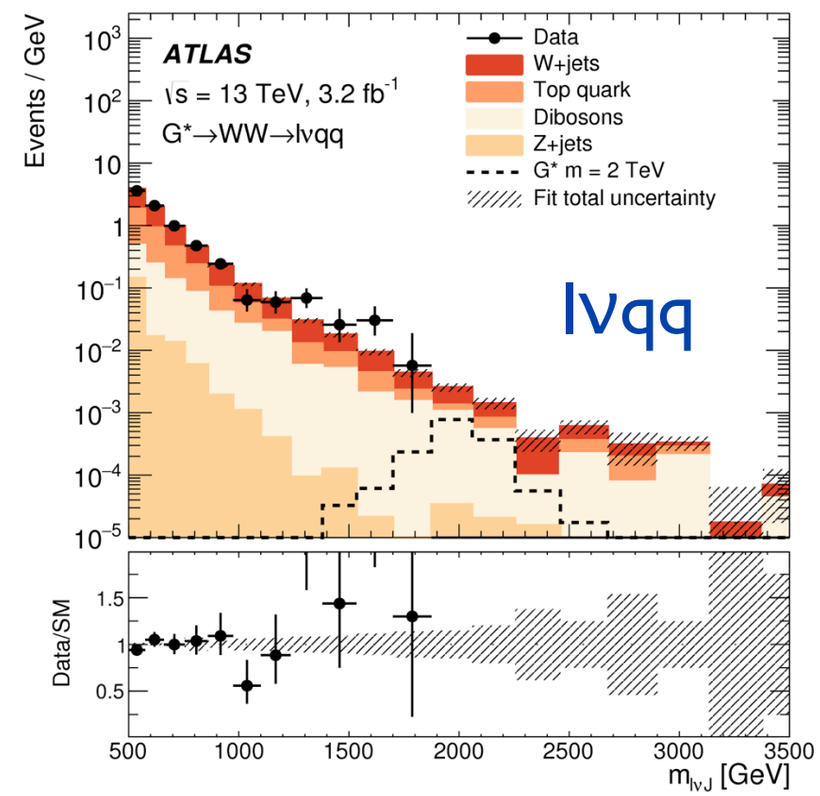
Moving to higher mass

- Complete search for llqq, ννqq, lνqq, qqqq with Z or W→qq merged into one large-R jet
- Each final state has a resonance mass estimator
- Same analysis used to constrain
  - Heavy Scalar
  - Graviton
  - W′ and Z′









Heavy Scalars Decaying to WW and ZZ

Moving to higher mass

- Comp
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large-R

- Each f
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- Same
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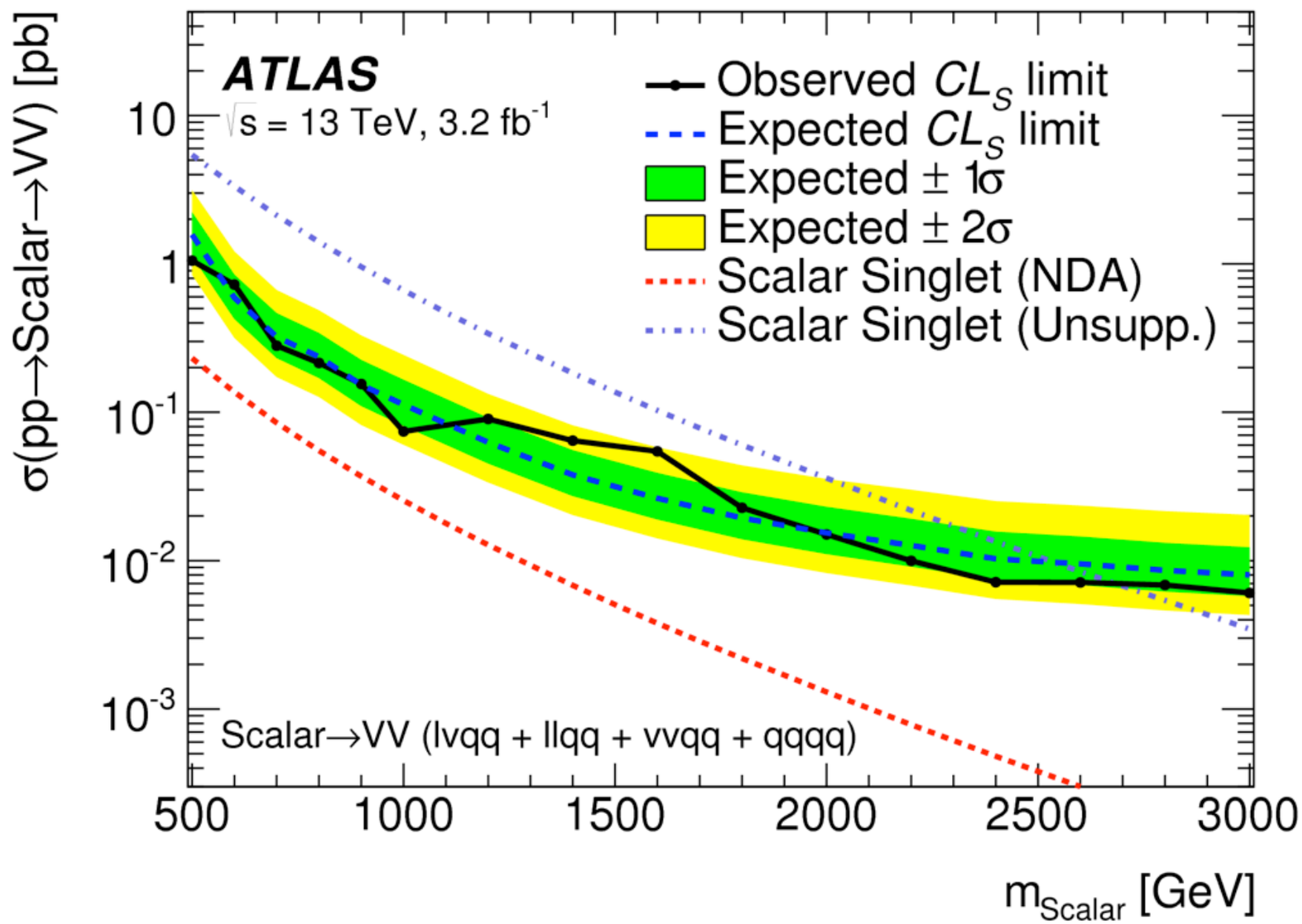
  - W

Resulting Limits

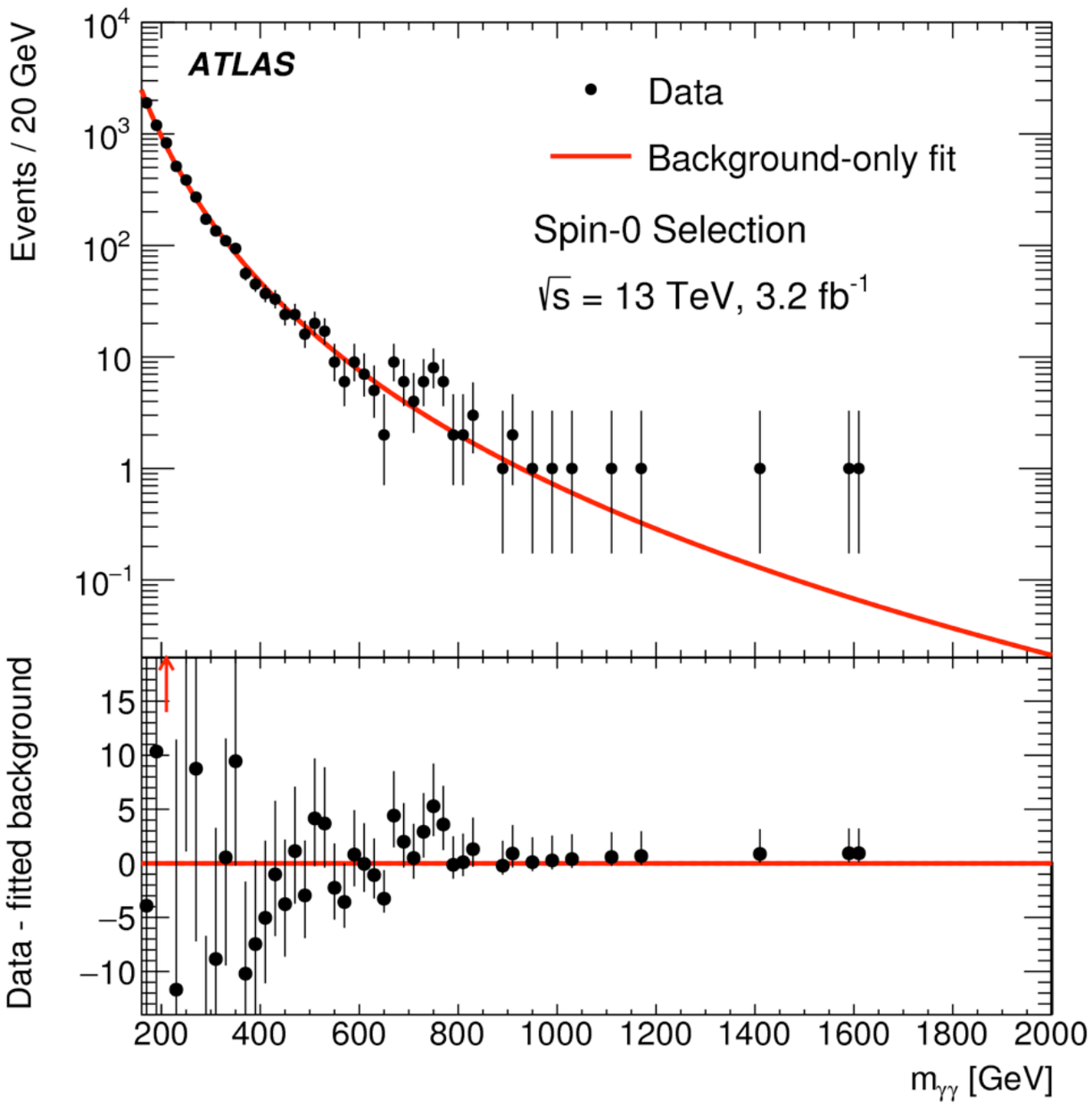


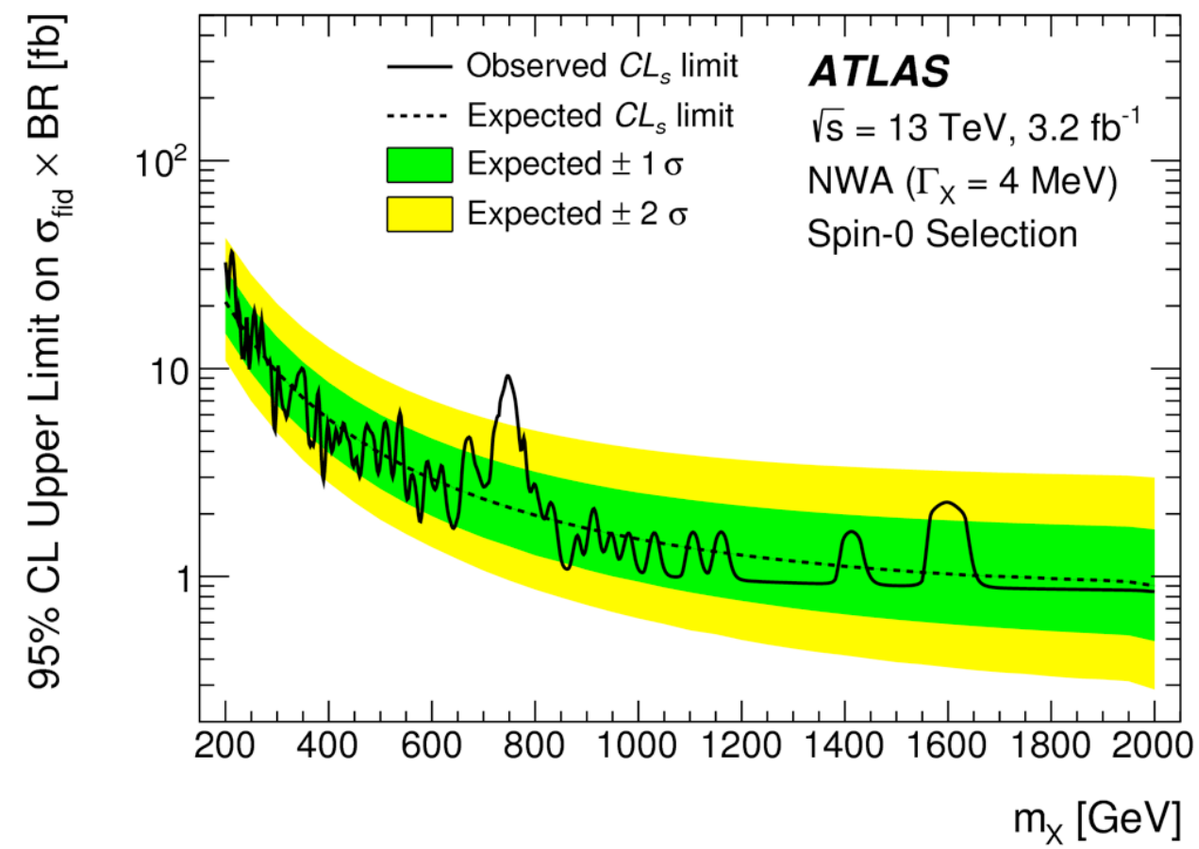
Search for Heavy Higgs to Diphoton

Obviously important

You've probably heard about the result

See talk by Eilam Gross: Search for a high mass diphoton resonance using the ATLAS detector





Local Significance: 3.9 σ

Global Significance: 2.1 σ

Needs more data to know one way or the other

Higgs Pair Production

Higgs pair production is a direct probe of the Higgs self-coupling (i.e. the Higgs potential)

Analyses generally combine heavy resonance and non-resonant searches

SM non-resonant challenging

8 TeV analyses in 4b, bbττ, bbγγ, WWττ

Combination expected limit is 48 x SM non-resonant cross-section

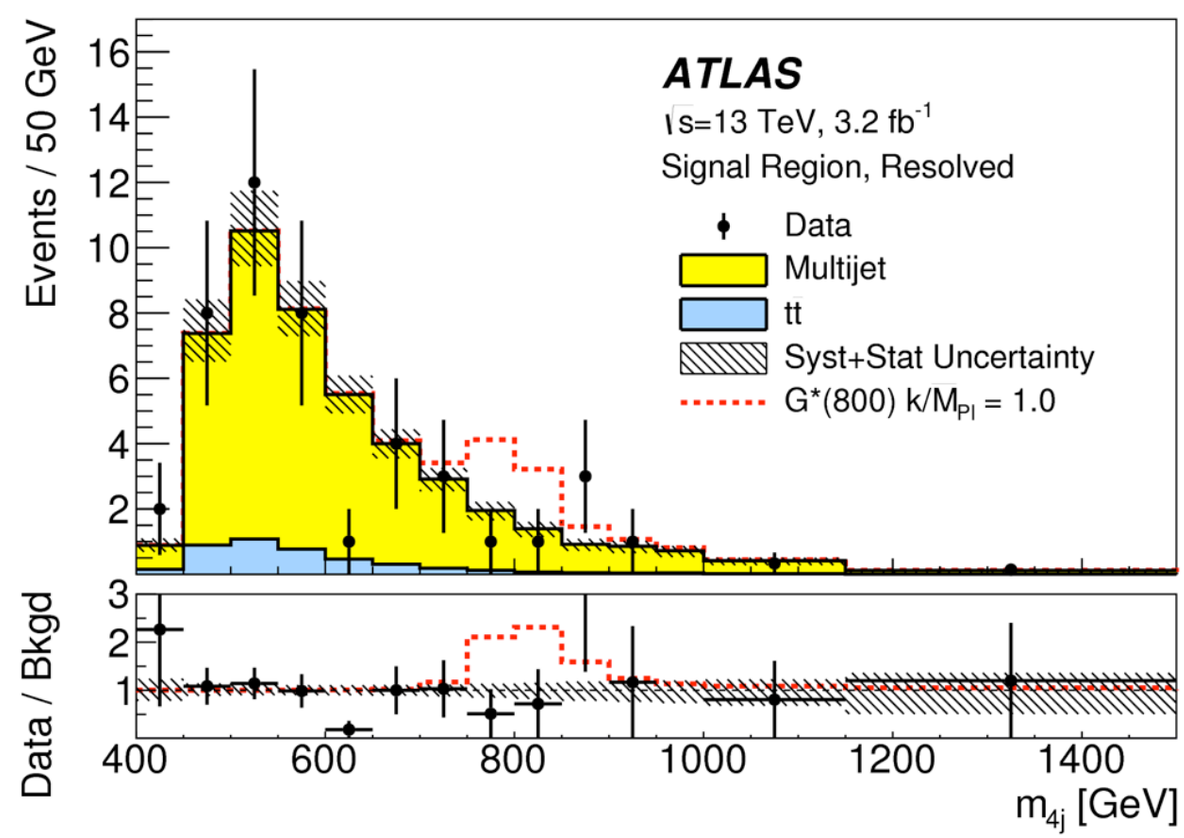
BSM sensitivity comes sooner...

Example HH→4b analysis (13 TeV analysis)

Analysis divided into resolved (lower dihiggs mass) and boosted jet regimes

Yields in resolved region

Sample	Signal Region Yield
Multijet	43.3 ± 2.3
$t\bar{t}$	4.3 ± 3.0
Z+jets	–
Total	47.6 ± 3.8
Data	46
SM hh	0.22 ± 0.05
G^*_{KK} (800 GeV), $k/\bar{M}_{Pl} = 1$	5.7 ± 1.5



The Future

Run 1: 5 fb^{-1} 7 TeV + 20 fb^{-1} 8 TeV

Run 2 (until end 2018):
- ~3 fb^{-1} 13 TeV from 2015
- ~7 fb^{-1} 13 TeV so far in 2016
- ~100 fb^{-1} expected

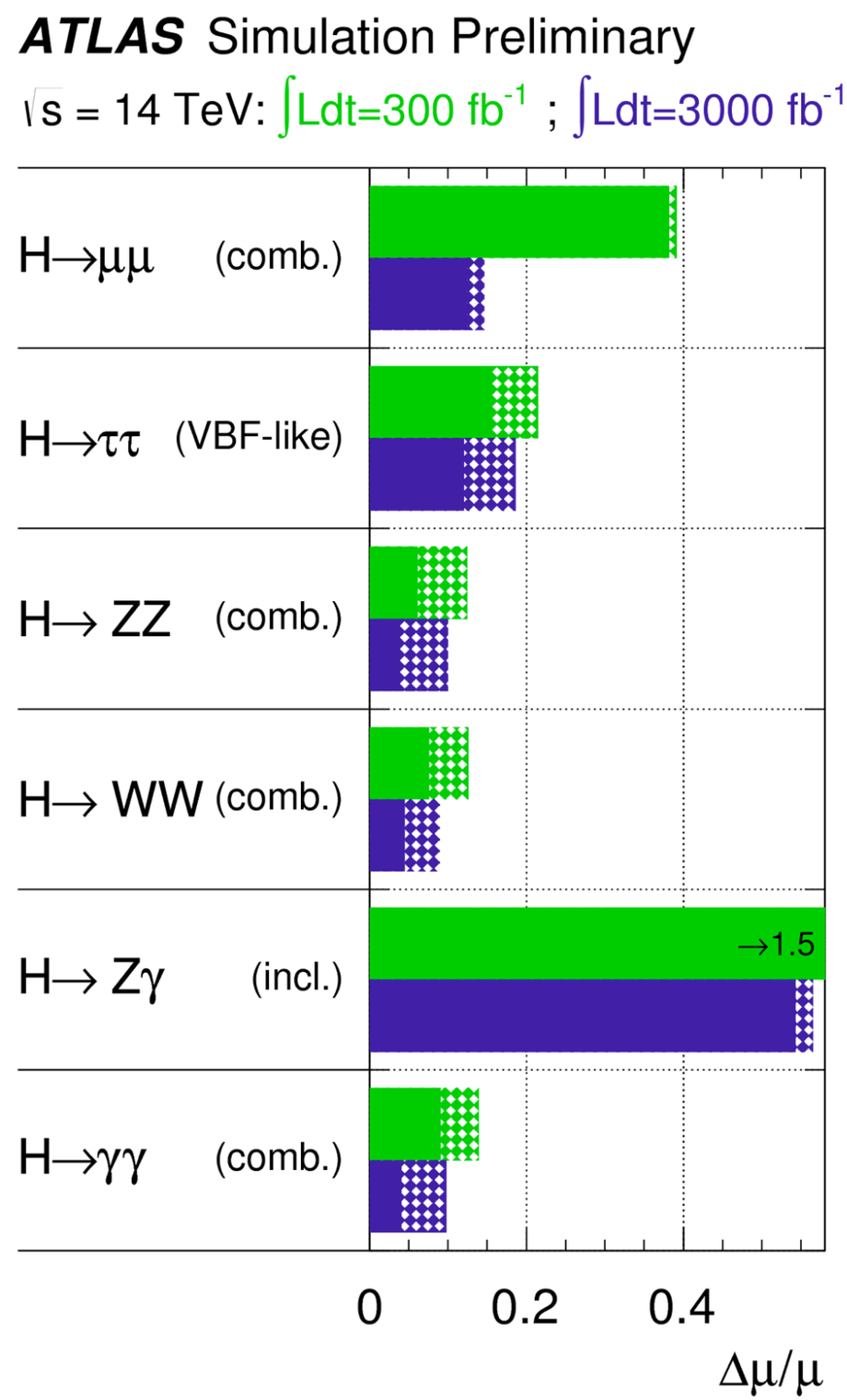
Run 3 (2020-2023): ~ 300 fb^{-1}

HL-LHC (2026-2035): ~ 3000 fb^{-1}

Precision Higgs Measurement is a big part of that program
- ~5% achievable in several channels
- Great theory program to match this, e.g. N^3LO ggH prediction

Big reach on rare decays (e.g. $H\to\mu\mu$)
- and possible BSM decays

Challenging goal to observe Higgs self-coupling



hashed area indicates theory uncertainty

Summary

Four years ago today, a particle discovery was announced by ATLAS and CMS

We now know this particle strongly resembles the SM Higgs boson

But there are still many things to test and possibilities to explore

- Precision rates and shapes, BSM decays, more Higgses, pair production

And much more data to come!

- LHC performance in 2016 is great so far, with 7 fb^{-1} already recorded

Back-up

Caveats on the Portal Models

Complete instead of effective field theory can move result...

Example: Add an additional scalar to generate fermion and vector masses (and couple the fermion to the Higgs) http://arxiv.org/abs/1405.3530 (Baek, Park)

Fermion | Vector

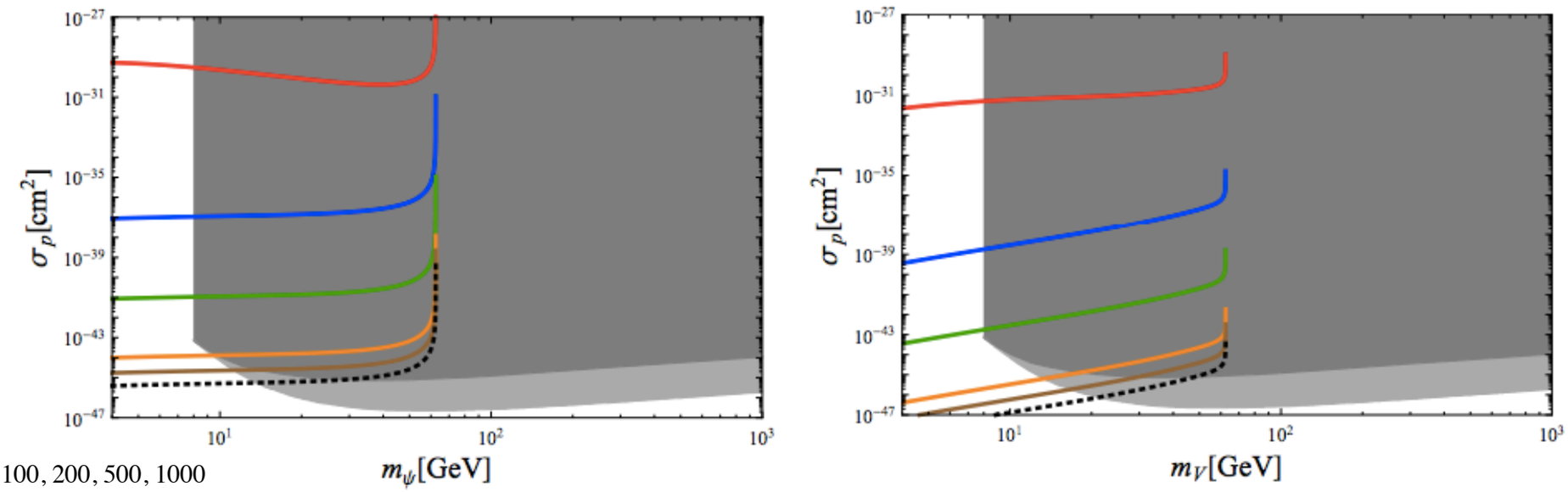
$m_s = 10^{-2}$ GeV

$m_s = 1$ GeV

$m_s = 10$ GeV

$m_s = 50$ GeV

$m_s = 70$ GeV



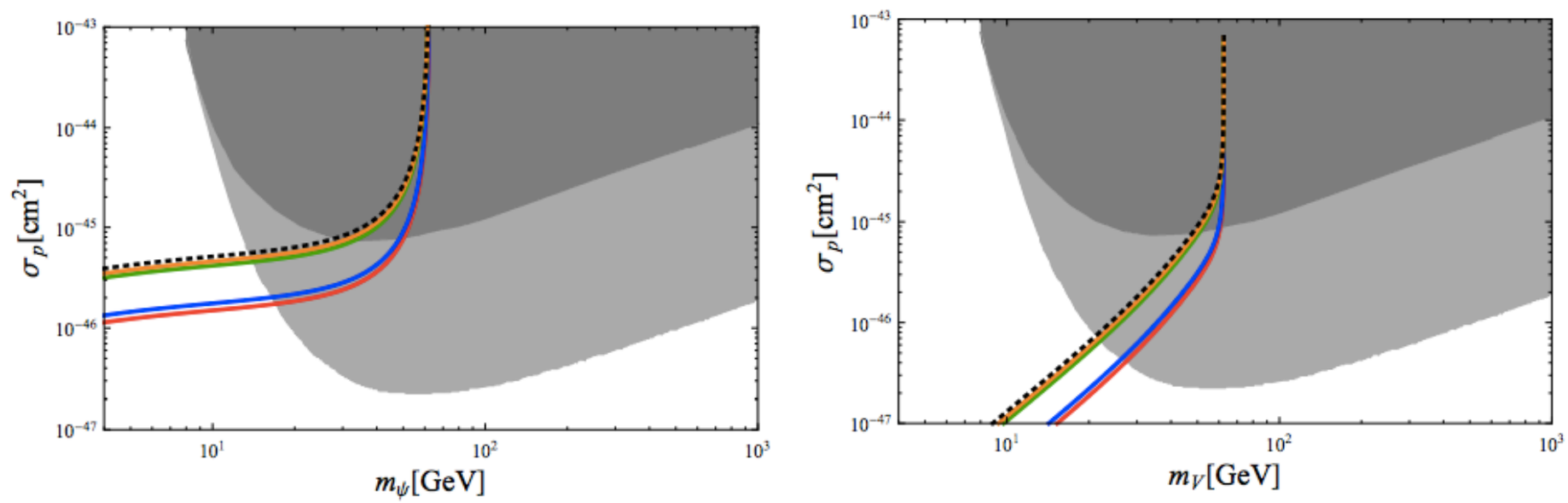
100, 200, 500, 1000

$m_s = 1000$ GeV

$m_s = 500$ GeV

$m_s = 200$ GeV

$m_s = 100$ GeV



Dashed line is the simple Higgs Portal model result