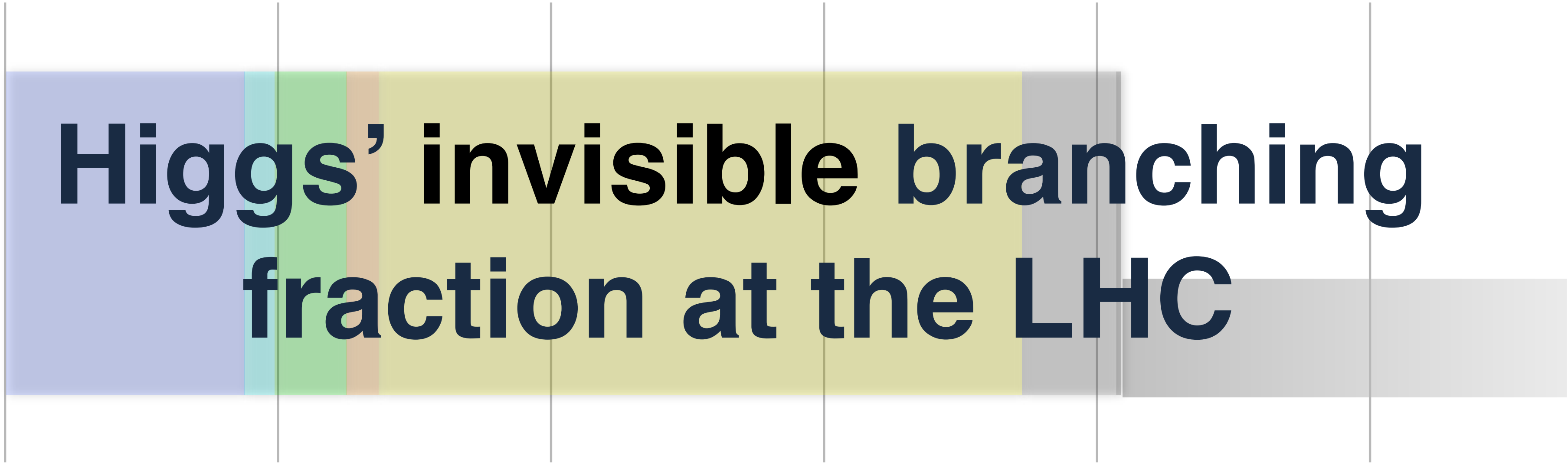


Higgs’ invisible branching fraction at the LHC

BNL HEP Seminar

April 28, 2016

University of
Pittsburgh

Tae Min
Hong

ATLAS
Experiment

Thanks

Institutional

I thank U.S. ATLAS for the funds to be a U.S.A. Scholar at BNL.

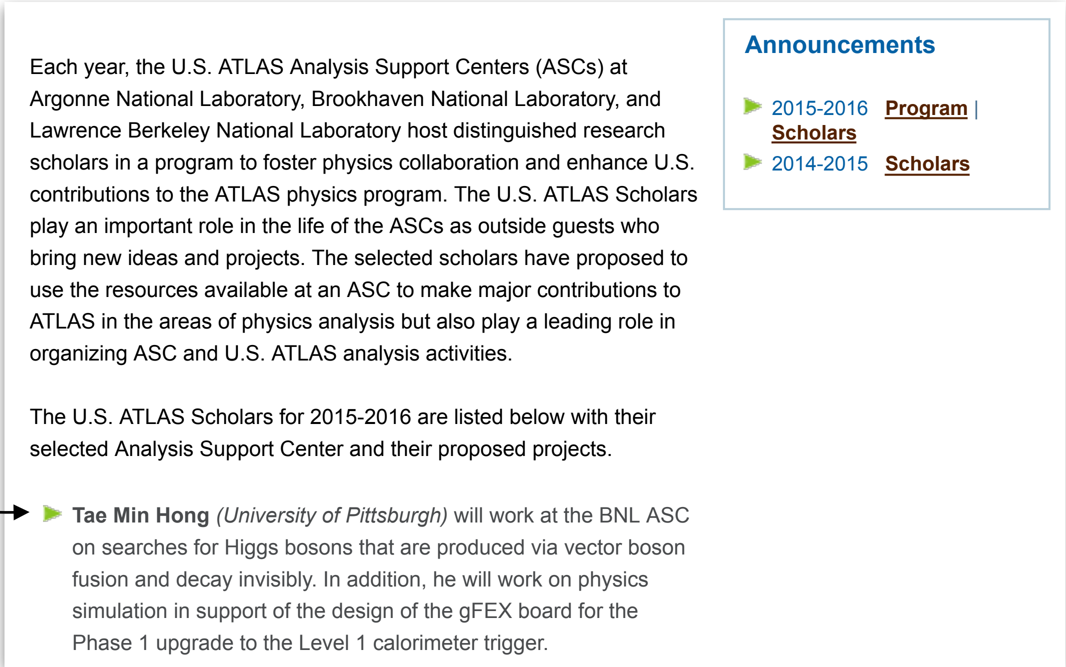
Individual

I thank Michael and Kétévi for their collaboration on projects.

I thank Philip for talk content, preparation, and discussion.

More thanked in aux. slides.

Announcement of 2015-2016 U.S. ATLAS Scholars



Each year, the U.S. ATLAS Analysis Support Centers (ASCs) at Argonne National Laboratory, Brookhaven National Laboratory, and Lawrence Berkeley National Laboratory host distinguished research scholars in a program to foster physics collaboration and enhance U.S. contributions to the ATLAS physics program. The U.S. ATLAS Scholars play an important role in the life of the ASCs as outside guests who bring new ideas and projects. The selected scholars have proposed to use the resources available at an ASC to make major contributions to ATLAS in the areas of physics analysis but also play a leading role in organizing ASC and U.S. ATLAS analysis activities.

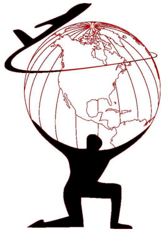
The U.S. ATLAS Scholars for 2015-2016 are listed below with their selected Analysis Support Center and their proposed projects.

- **Tae Min Hong** *(University of Pittsburgh)* will work at the BNL ASC on searches for Higgs bosons that are produced via vector boson fusion and decay invisibly. In addition, he will work on physics simulation in support of the design of the gFEX board for the Phase 1 upgrade to the Level 1 calorimeter trigger.

Announcements

- 2015-2016 **Program** | **Scholars**
- 2014-2015 **Scholars**

- and 5 other scholars listed on the webpage http://www.usatlas.bnl.gov/programoffice/scholars.php



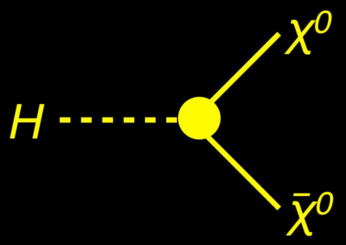
M. Begel
BNL, L1 calo

K. Assamagan
BNL, H invisible

P. Chang
U Illinois-UC

Topics covered

Higgs → invisible



Why *Higgs width*

Overview *Indirect via couplings* *Direct via searches*

Key analysis VBF $H \to WW^*$ VBF $H \to$ *invisible*

I worked on this in Run 1

I'm working on this for Run 2

Key background $t\bar{t} \to WbW\bar{b}$ $Z \to \nu\bar{\nu}$

Future

ATLAS-centric talk (will point out v. CMS)

Warning → measurement

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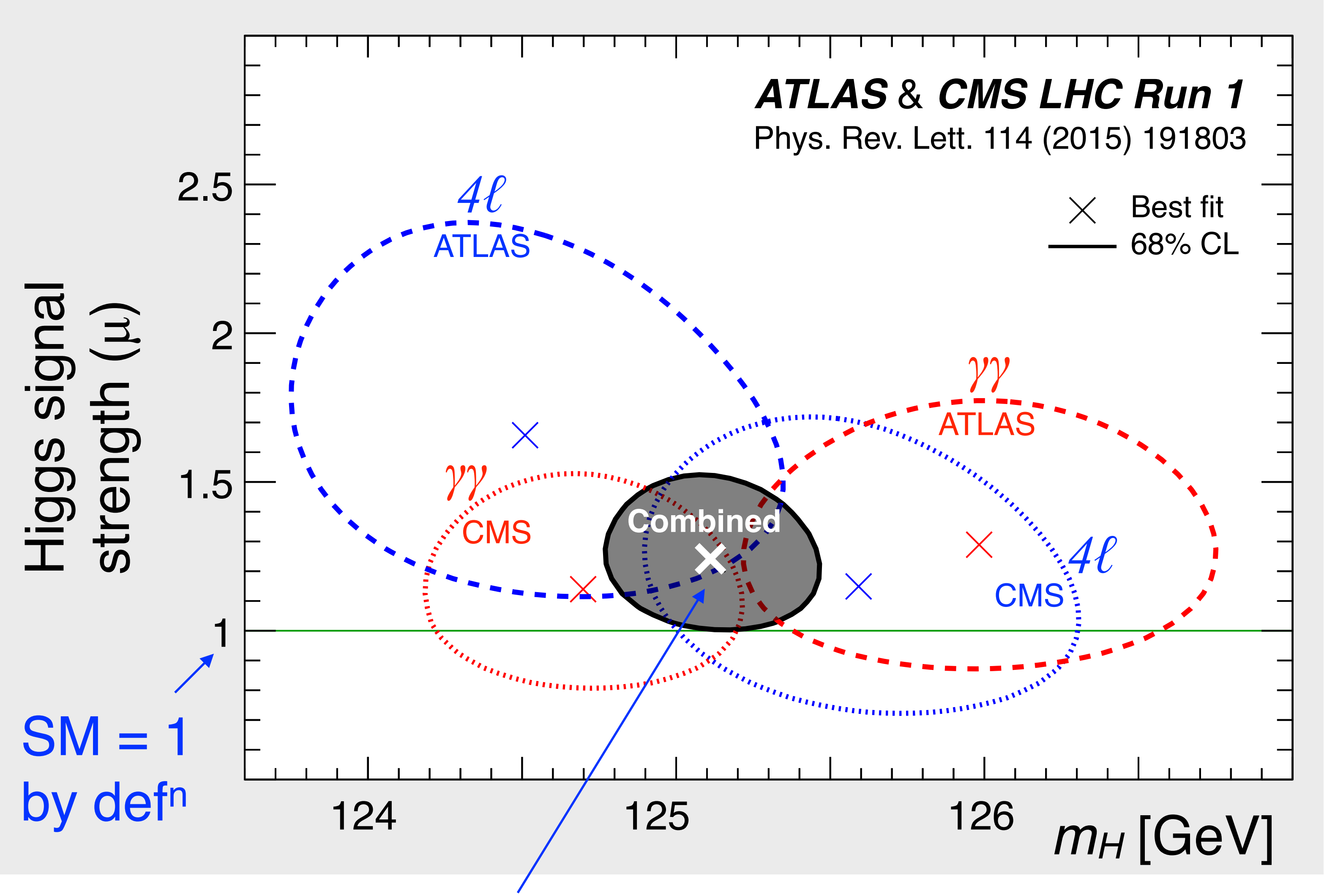
“We apologize… for having no idea what is [m_H]… For these reasons we do not want to encourage big experimental searches for the Higgs…”

Nucl. Phys. B 106 (1976) 292



SM = 1 by def^n

125.1± 0.2 fixes width & SM branching ratios

Is large $H_{125} \to$ *invisible* motivated?

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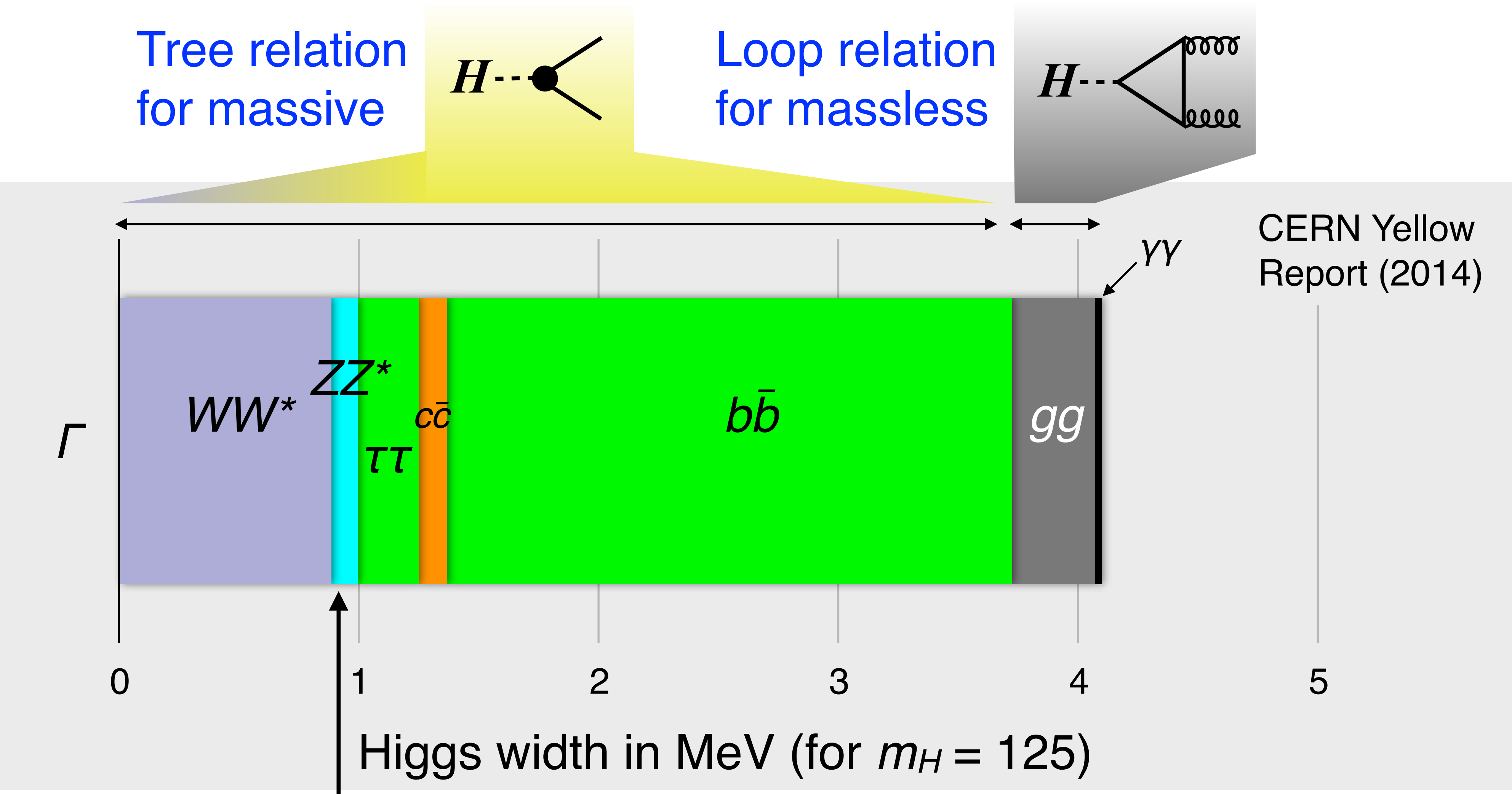
Let's review the Higgs width


Tree relation for massive

Loop relation for massless

CERN Yellow Report (2014)

Higgs width in MeV (for $m_H = 125$)

$H_{125} \to 4\nu$ is tiny at 0.1% B.R.

Higgs is so narrow because 125

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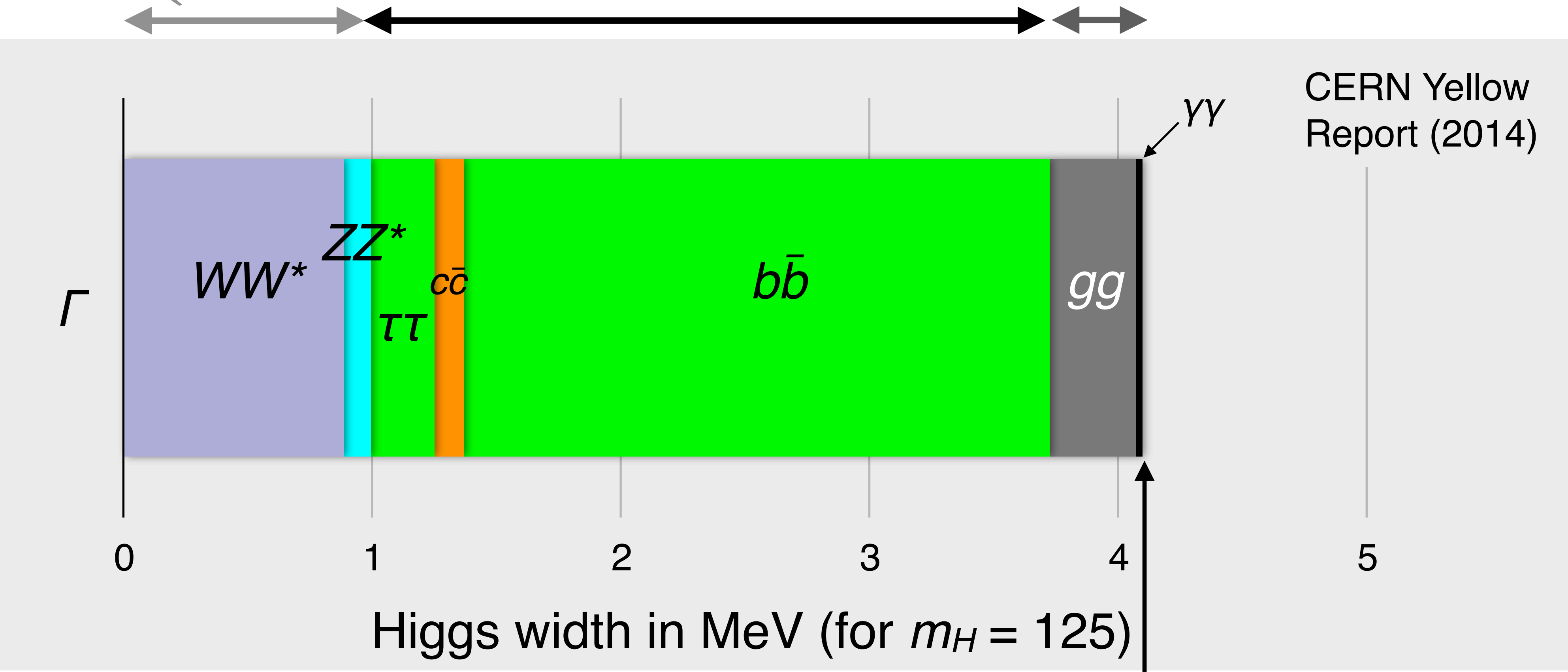
Massive bosons
p.s. suppressed
($m_H \ll 2 \cdot m_{W,Z}$)

Fermion m_F mean tiny
Yukawa couplings
($t\bar{t}$ large, but $m_H \ll 2 \cdot m_{top}$)

Massless bosons
loop suppressed



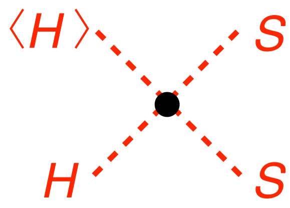
CERN Yellow Report (2014)

Higgs width is tiny!
1000x smaller than W/Z at ~2 GeV

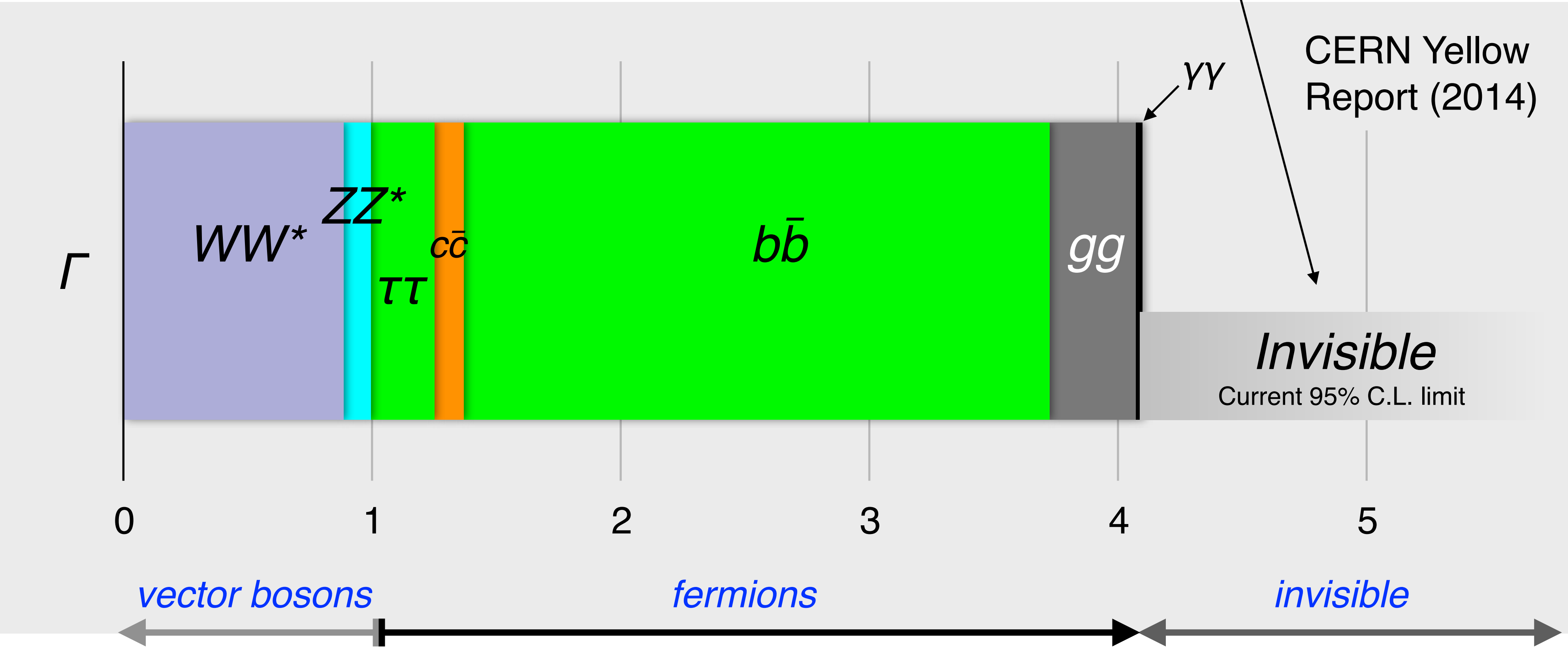
$\mathcal{O}$(MeV) is ~~not un~~reasonable

Curtin, Essig, Zhong, 1412.4779 (2015)
Curtin +12 others, 1312.4992 (2014)
Chang +3 others, 0801.4554 (2008)
Silveira & Zee, PL B161,136 (1985)
and many many more papers
including by Hooman & Tao

Terms $\frac{\zeta}{2} H^2 S^2$ are allowed



- H^2 is SM singlet, dim.-2 op.
- Fully renormalizable
- $\mathcal{O}$(0.01) coupling = $\mathcal{O}$(MeV) width



CERN Yellow Report (2014)

Measure these branching ratios
to **indirectly** limit invisible

Search for this
to **directly** limit invisible

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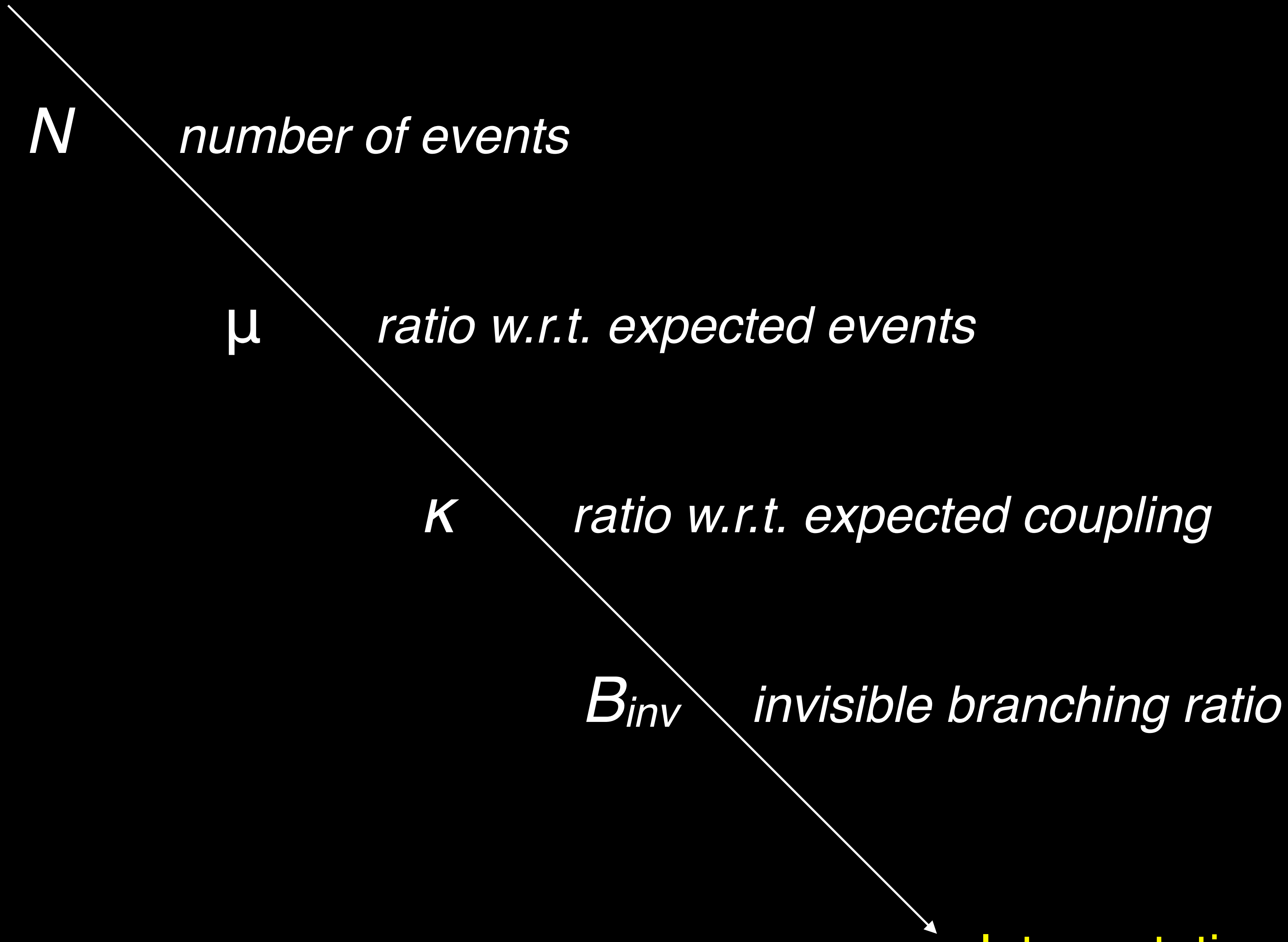
Hiding in the couplings

Measurements



N *number of events*

μ *ratio w.r.t. expected events*

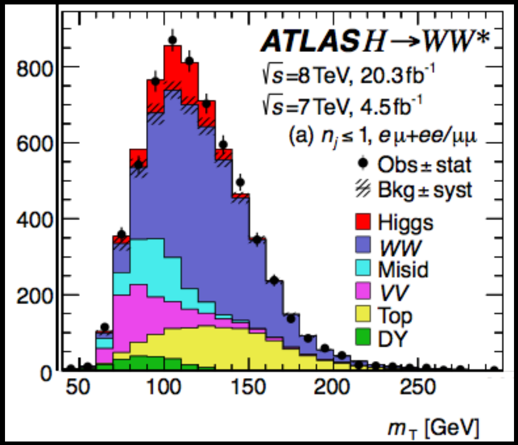
κ *ratio w.r.t. expected coupling*

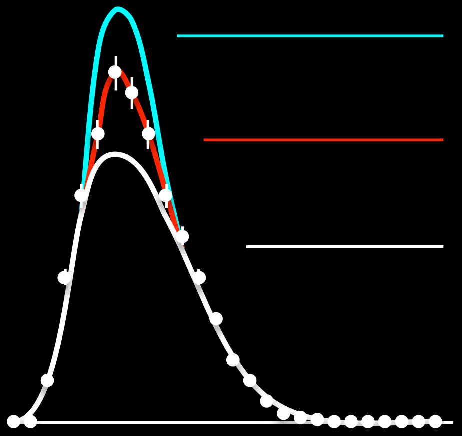
B_{inv} *invisible branching ratio*

Interpretations

Hiding in the couplings

Relating $N \to \mu$



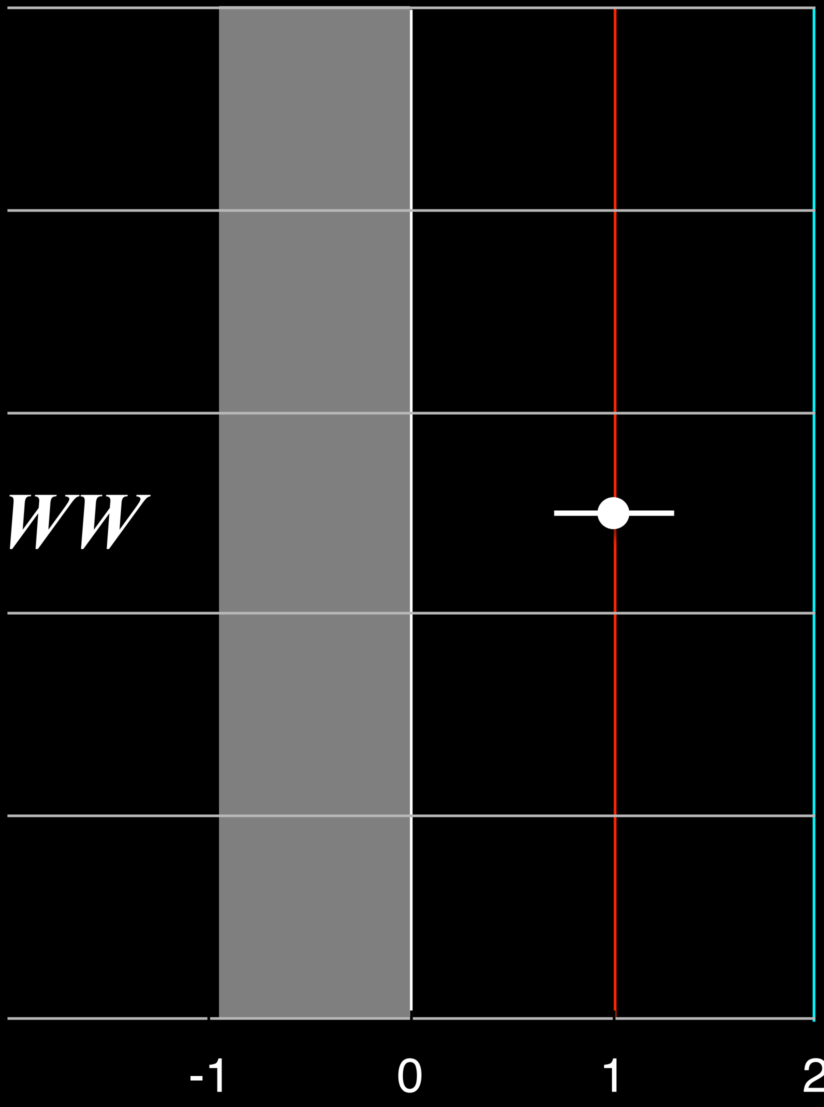


$2 \cdot N_{\text{expected}}$

$1 \cdot N_{\text{expected}}$

$0 \cdot N_{\text{expected}}$

Summary table



Signal strength (μ)

N event yields

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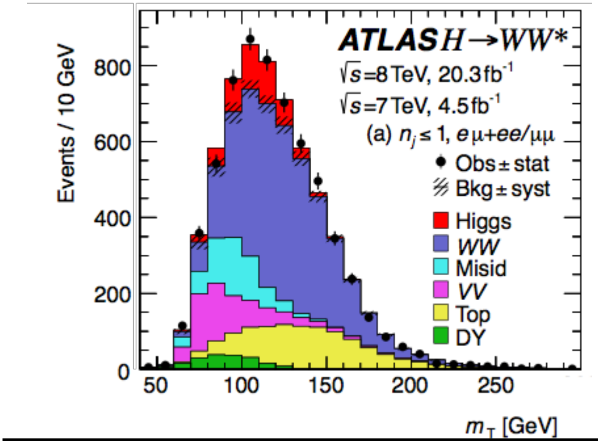
My rough estimate of events in the peak (don't read plots!)

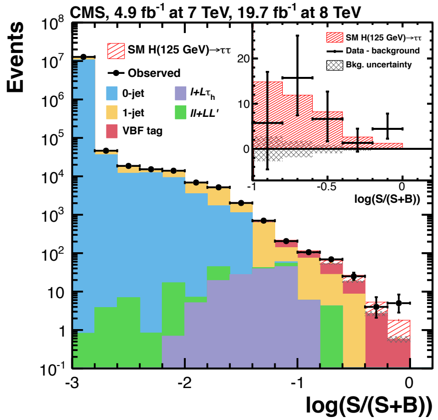


WW

$5 - 6\sigma$

$N_\text{bkg} \approx 7\text{k}$

$N_\text{sig} \approx 500$

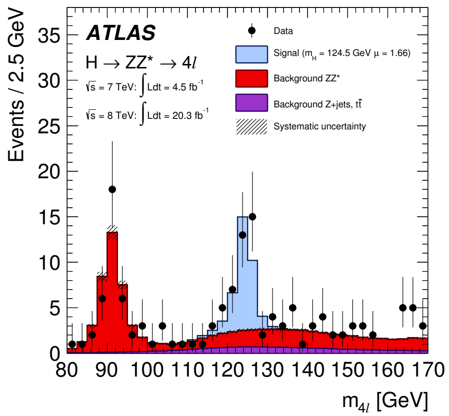


$\tau\tau$

$3 - 4\sigma$

$N_\text{bkg} \approx 200\text{k}$

$N_\text{sig} \approx 650$

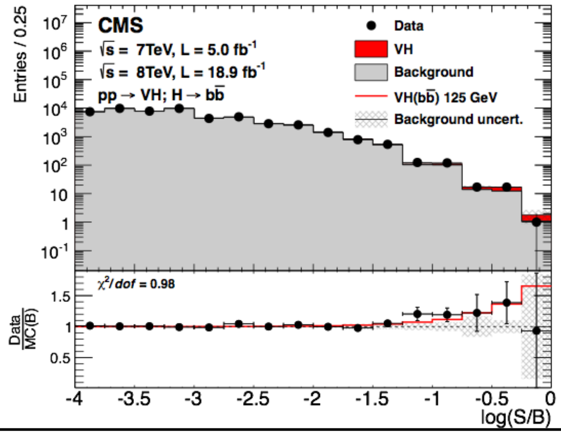


ZZ

$6 - 7\sigma$

$N_\text{bkg} \approx 10$

$N_\text{sig} \approx 16$

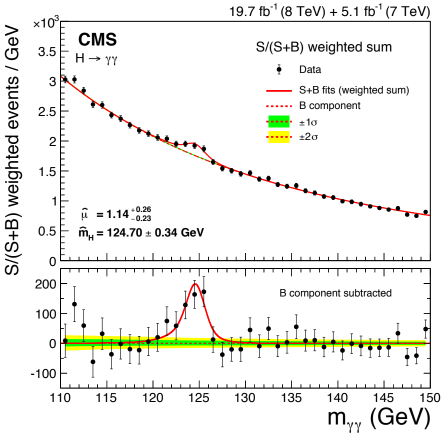


$b\bar{b}$

2σ

$N_\text{bkg} \approx 2\text{k}$

$N_\text{sig} \approx 60$

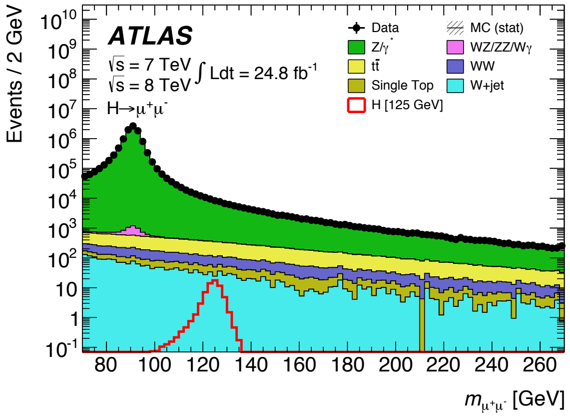


$\gamma\gamma$

$5 - 6\sigma$

$N_\text{bkg} \approx 5\text{k}$

$N_\text{sig} \approx 170$



$\mu\mu$

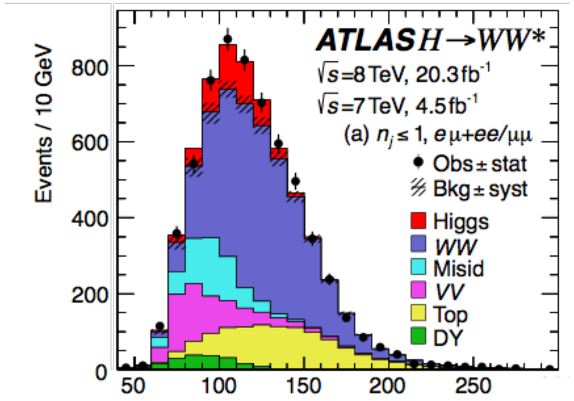
0.2σ (exp)

$N_\text{bkg} \approx 20\text{k}$

$N_\text{sig} \approx 30$

From $N \rightarrow \mu$

Combine all channels



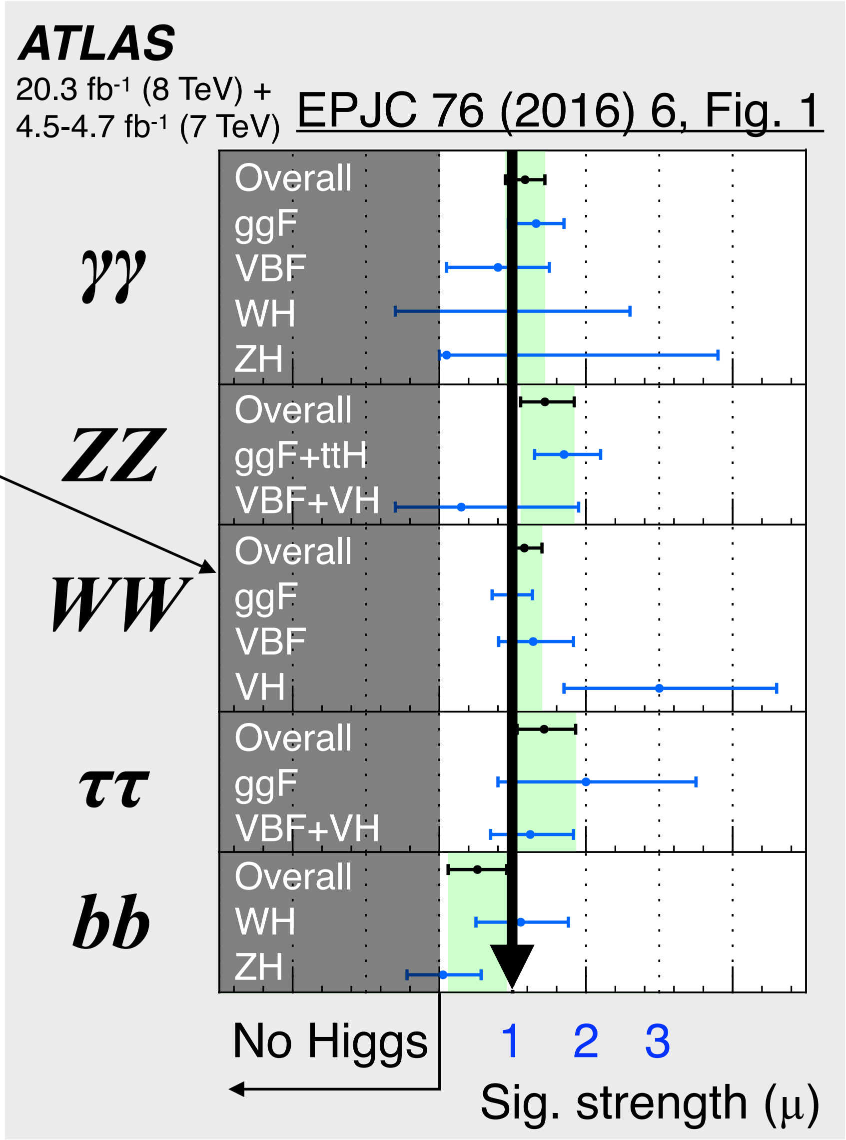
WW

5 - 6σ

$N_{\mathrm{bkg}} \approx$ 7k

$N_{\mathrm{sig}} \approx$ 500

Summary table –($\mu\mu$, $Z\gamma$, $t\bar{t}H$)



EPJC 76 (2016) 6, Fig. 1

Combination

μ_{ATLAS} = 1.18 ±0.15

μ_{CMS} = 1.00 ±0.14

Breakdown

Statistical	0.09
Systematic	0.07
Higgs theory	0.07

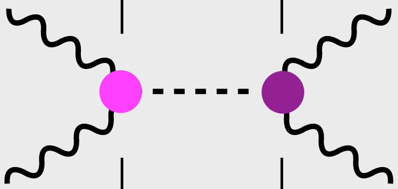
15%
Run 1
per exp't

From $N \to \mu \to \kappa$

Example of VBF ***WW***

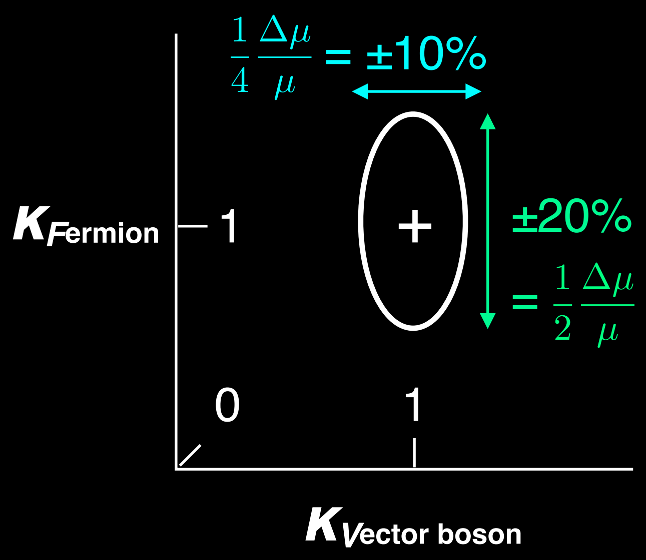
$N \propto \sigma_{VBF} \cdot \Gamma_{WW} / \Gamma_H$ — $\sim\Gamma_F$

$$\mu = \frac{N_{obs}}{N_{exp}} = \frac{\sigma_{obs}}{\sigma_{exp}} \cdot \frac{\Gamma_{obs}}{\Gamma_{exp}} \bigg/ \frac{\Gamma_{obs}}{\Gamma_{exp}}$$

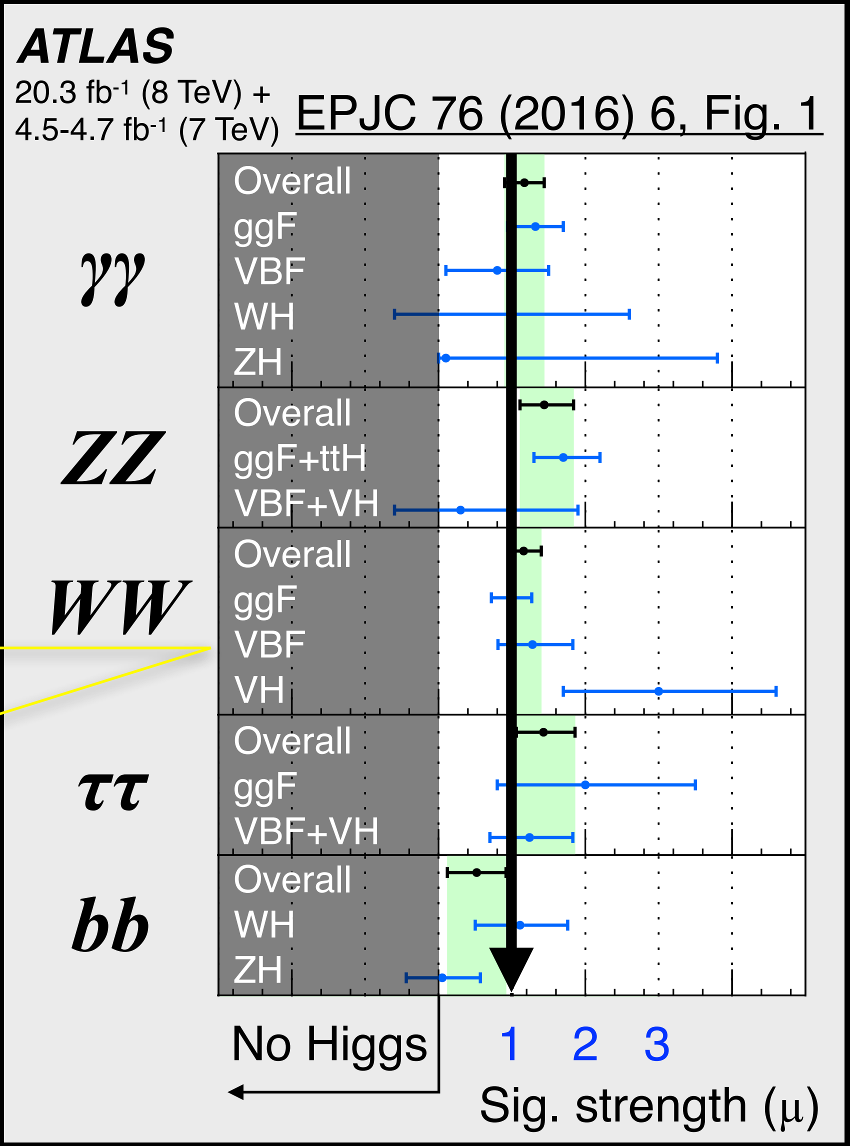


$$\approx \kappa_V{}^2 \cdot \kappa_V{}^2 \;/\; \kappa_H{}^2 \approx \frac{\kappa_V{}^4}{\kappa_F{}^2}$$

$\frac{\Delta\mu}{\mu} = \pm 40\%$



Summary table –($\mu\mu$, $Z\gamma$, $t\bar{t}H$)



EPJC 76 (2016) 6, Fig. 1

From $N \to \mu \to \kappa \to B_{inv}$

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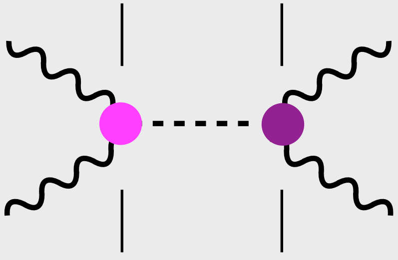
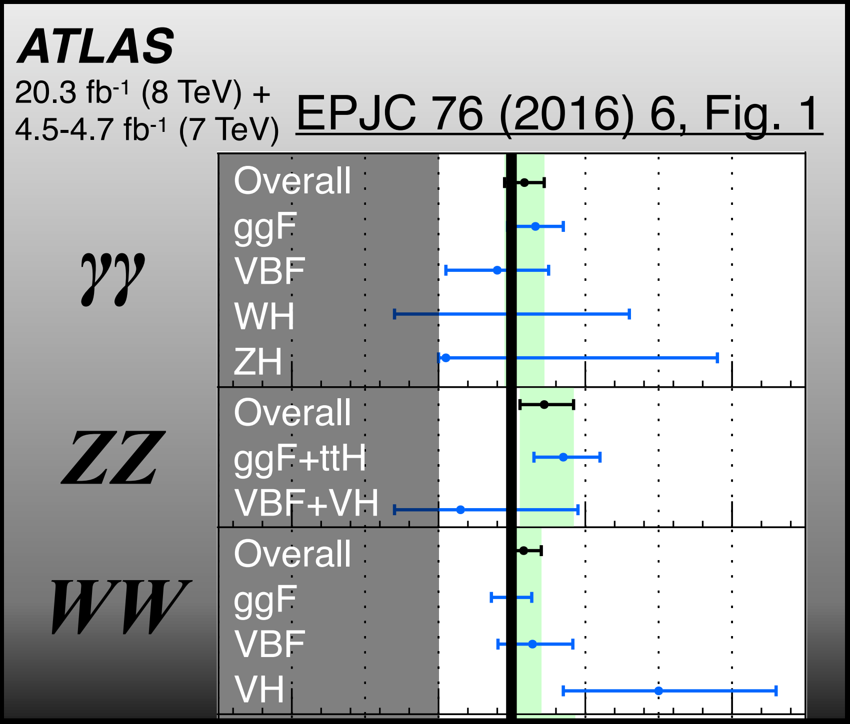
Add a term to the full width



$$N \propto \sigma_{VBF} \cdot \Gamma_{WW} / \Gamma_H$$

$$\underbrace{\mu}_{\text{1 d.o.f.}} = \underbrace{\kappa_V^2 \cdot \kappa_W^2 / \kappa_H^2}_{\text{many d.o.f.}} \cdot \underbrace{(1-B_{inv})}_{\text{1 d.o.f.}}$$

Summary table $-(\mu\mu, Z\gamma, t\bar{t}H)$



EPJC 76 (2016) 6, Fig. 1

You can approx. $\mu \to B_{inv}$ by hand

① Write down 1σ

② Rewrite 1σ as 68% limit for 1 d.o.f.

③ Rescale • 2 as 95% limit for 1 d.o.f.

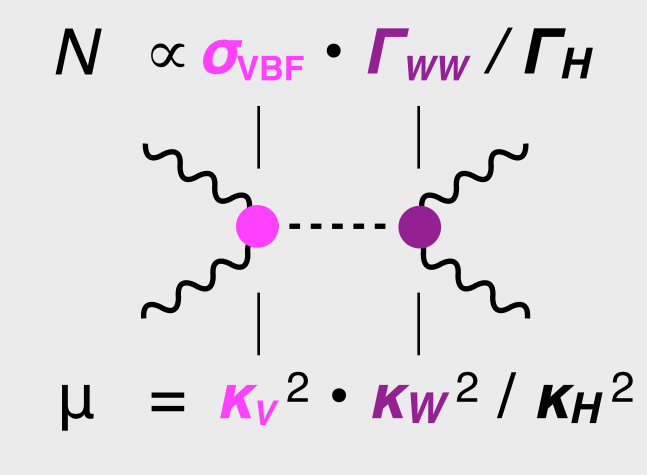
④ Rescale by $\sqrt{p(\chi^2, dof)} \approx 2$ for 8 d.o.f.

⑤ Compare with ATLAS full fit result

Value	*CL*	N_{dof}
$\Delta\mu/\mu = 0.127$	1σ	1
$B_{inv} < 0.127$	68%	1
$B_{inv} < 0.254$	95%	1
$B_{inv} < 0.508$ my est.	95%	8
$B_{inv} < 0.49$ (0.48)	95%	8

From $N \to \mu \to \kappa \to B_{inv}$

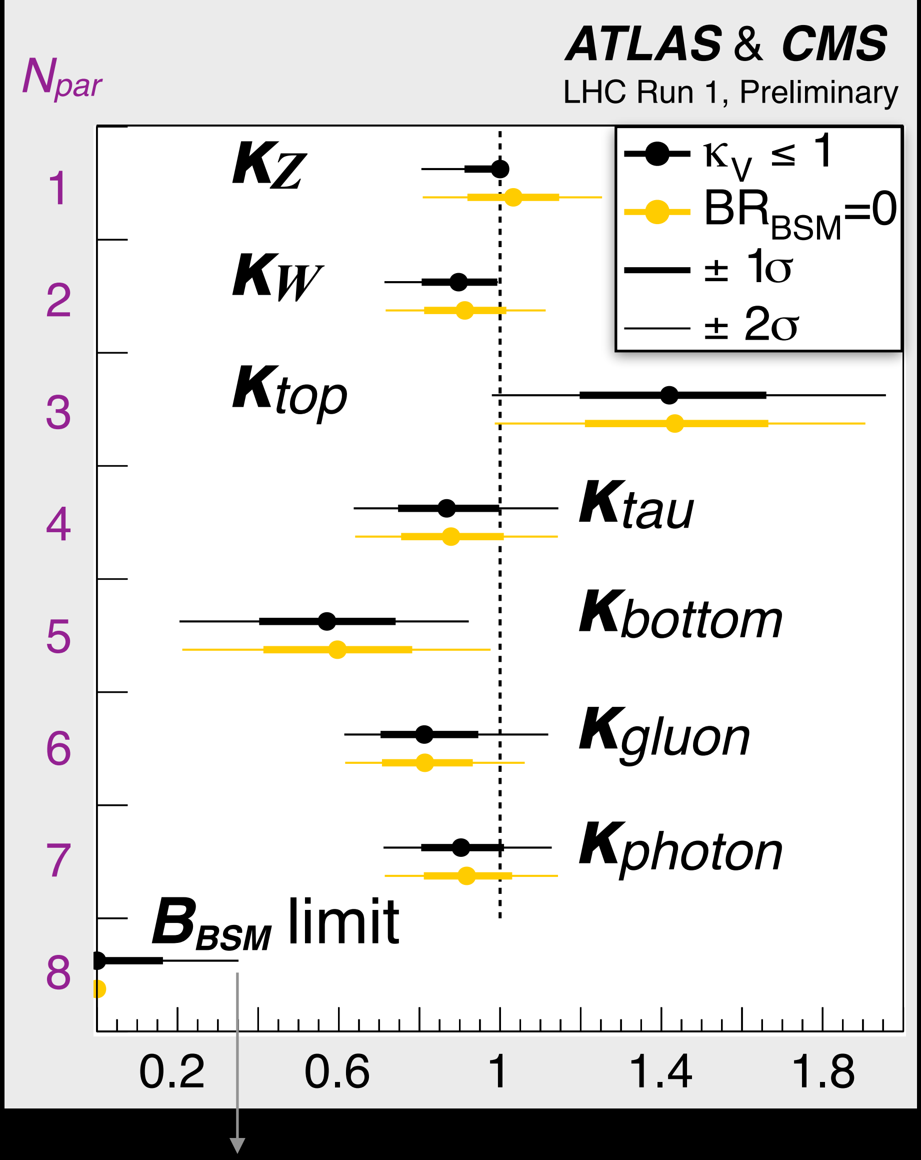
8 parameter fit with “invisible”



$$N \propto \sigma_{VBF} \cdot \Gamma_{WW} / \Gamma_H$$

$$\mu = \kappa_V^2 \cdot \kappa_W^2 / \kappa_H^2 \cdot (1-B_{inv})$$

κ fit with BSM



Why do we say “BSM”?

Technically includes “undetected.”

Examples are $H \to$ *soft jets.*

If assume zero, then = invisible.

Using couplings alone, indirectly limit $B_{BSM} < 0.34$ ATLAS+CMS
(0.35)

Closer look at μ_{ggF} v. μ_{VBF}

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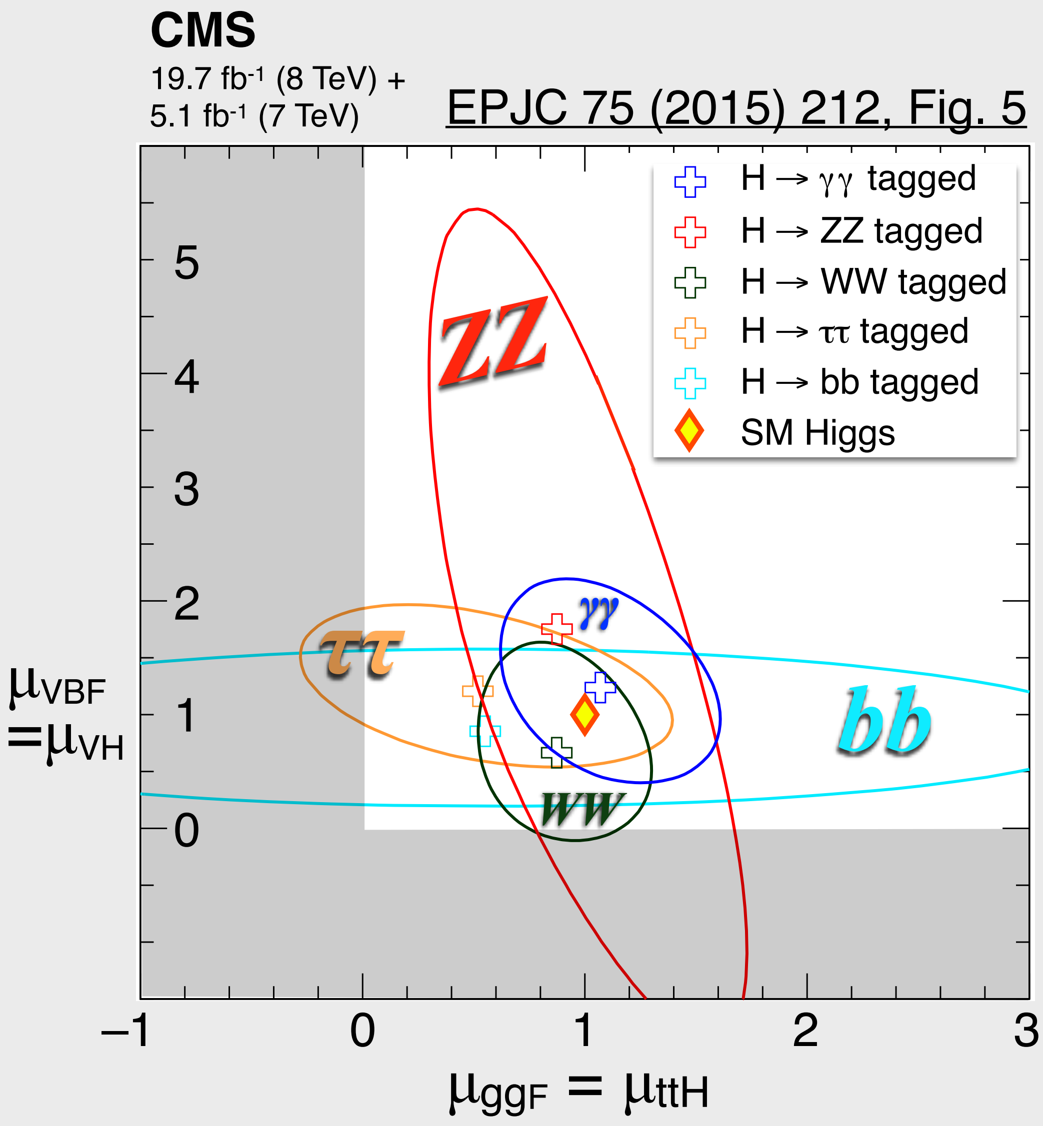
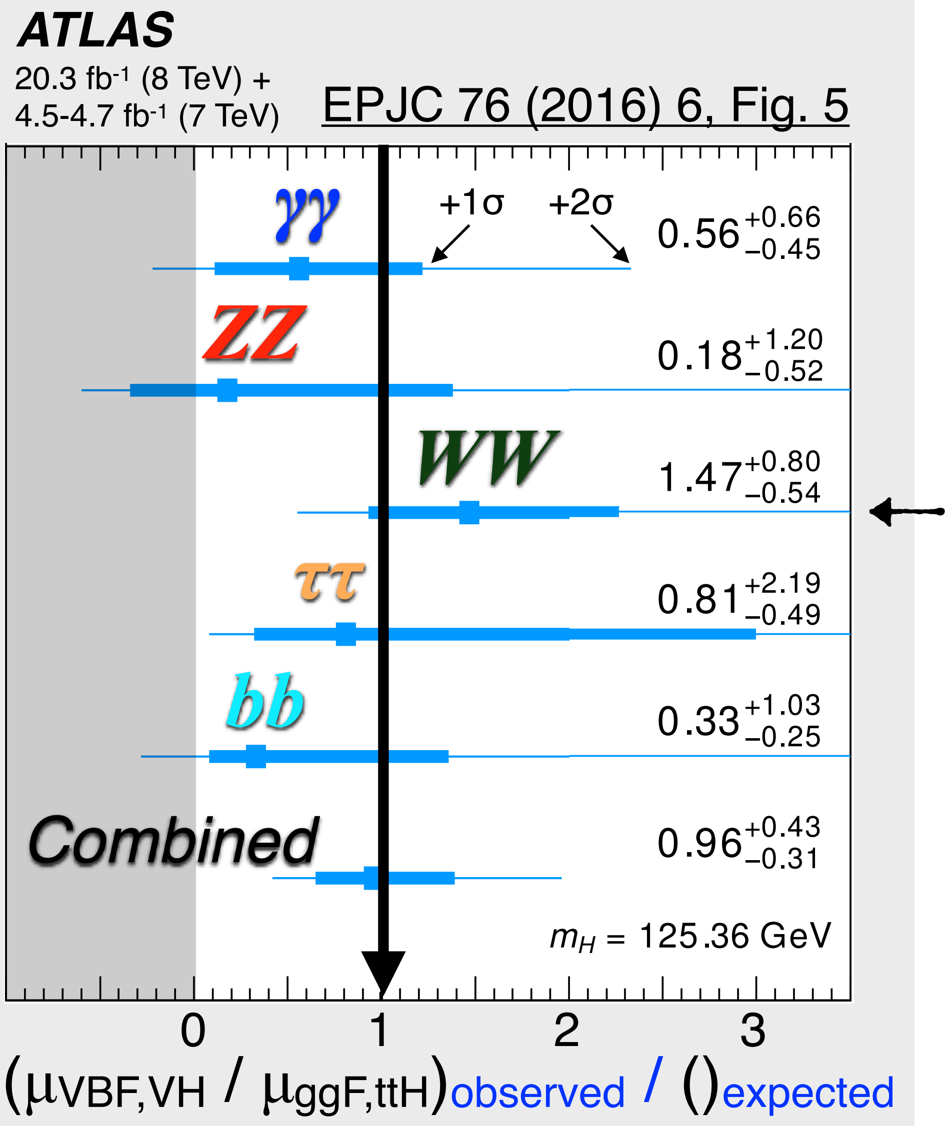
Pittsburgh

WW and ***γγ*** are similar size circles in μ



EPJC 75 (2015) 212, Fig. 5



EPJC 76 (2016) 6, Fig. 5

W strongest input, establishes VBF production

Closer look at $\kappa_{\text{Vector boson}}$ v. κ_{Fermion}

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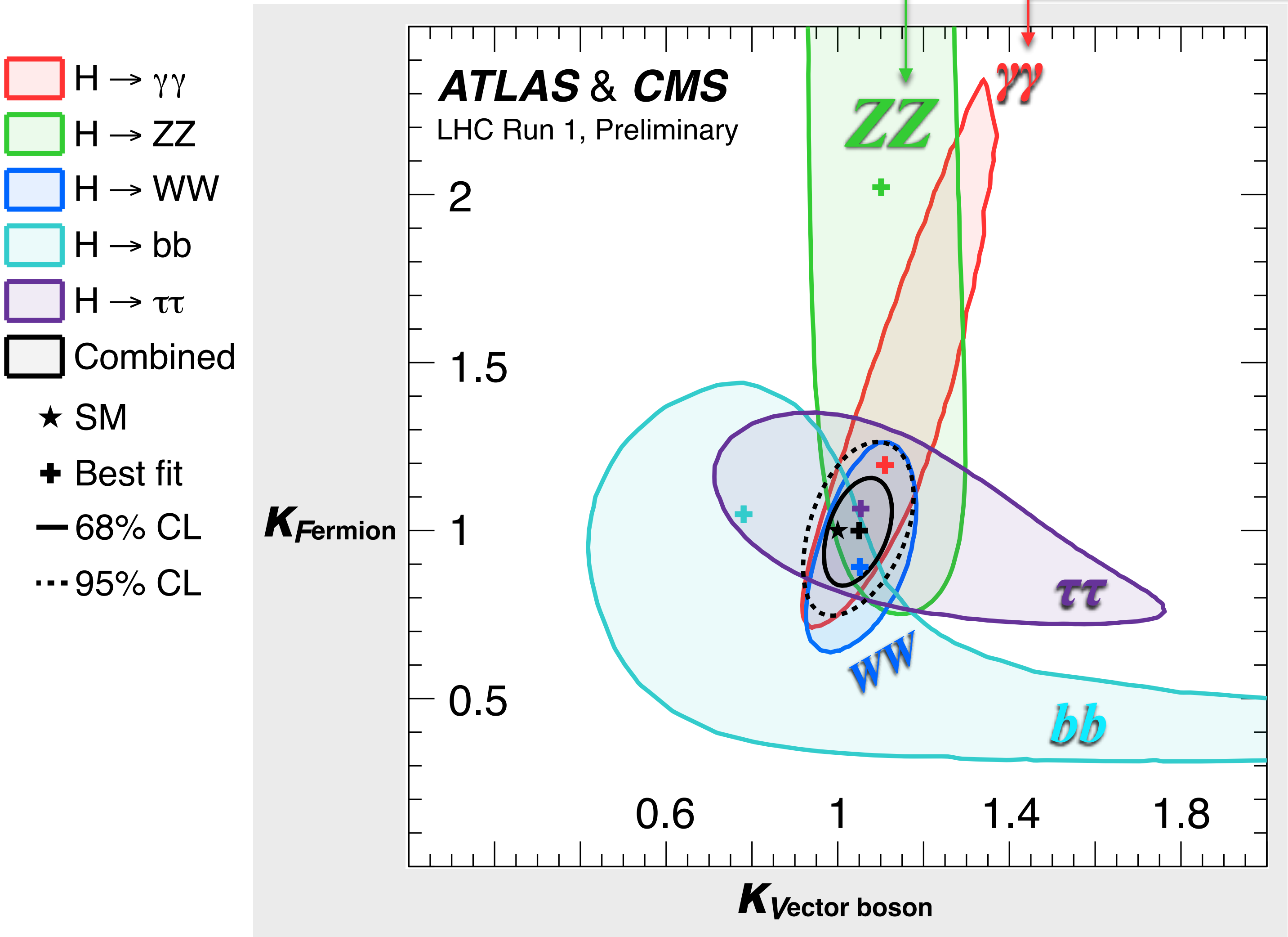
Pittsburgh

“The most precise determination of κ_V and κ_F is obtained from ***WW***.”

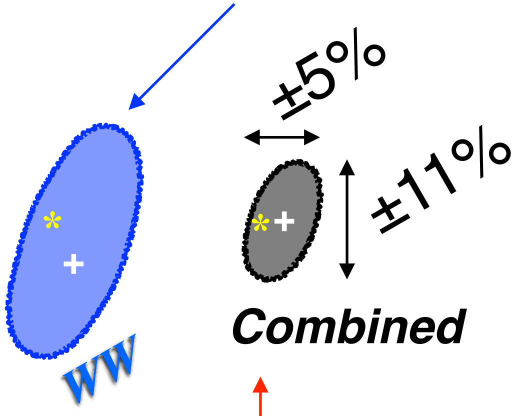
CONF-2015-044 / HIG-15-002 (2015)



No VBF *ZZ* → not bounded above

Loop & interference

Upper bound for ***WW***, but not ***ZZ***, ***γγ***?
Answer VBF ***WW***.



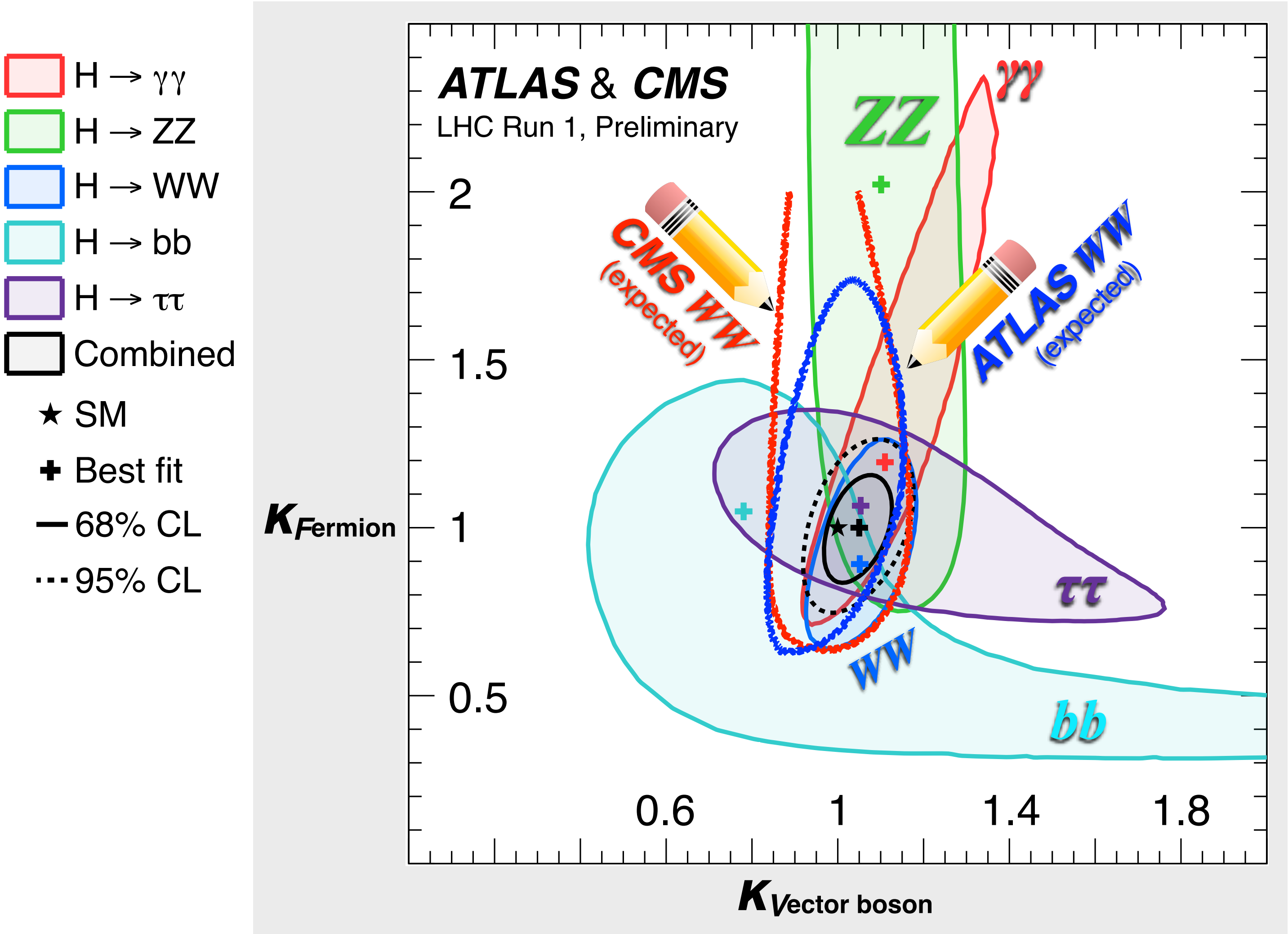
Combined

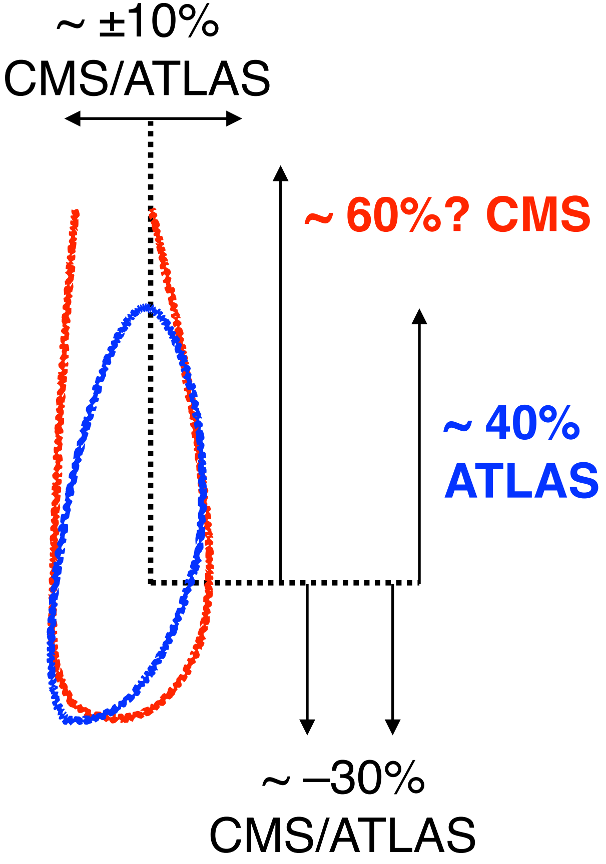
“At first look, the LHC is unlikely to <u>ever</u> get to 6% sensitivity.”

PRD 86 (2012) 095001, received 18 July 2012

ATLAS v. CMS

Compare the expected contour. Here I overlay them by hand.





~ ±10%
CMS/ATLAS

~ 60%? CMS

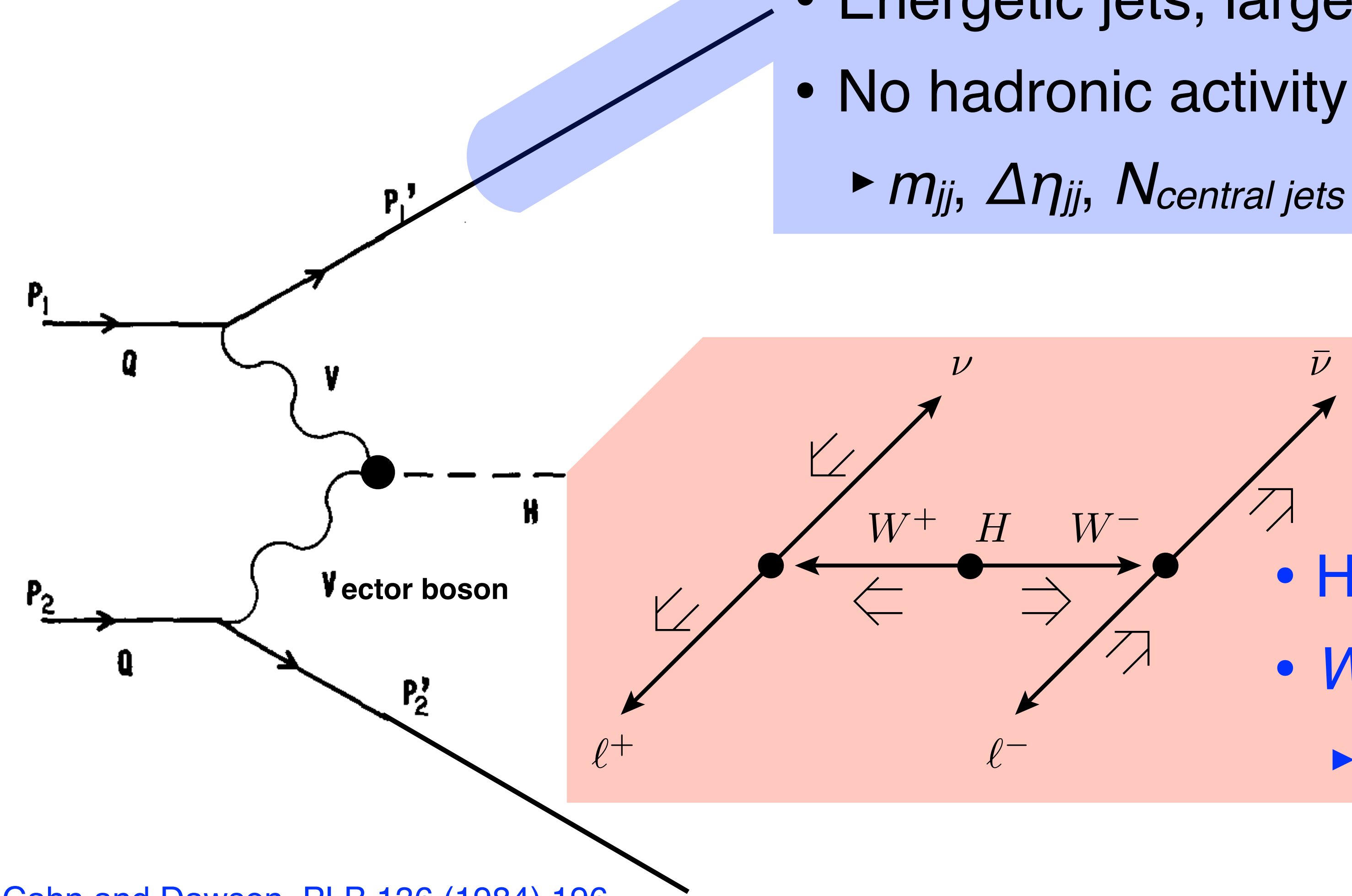
**~ 40%
ATLAS**

~ –30%
CMS/ATLAS

Difference in the upper bound in $\kappa_{Fermion}$ is due to VBF *WW*.

Physics of VBF $H \to WW^* \to e\nu\mu\nu$

LHC is a vector boson collider



- Energetic jets, large η gap
- No hadronic activity
  - m_{jj}, $\Delta\eta_{jj}$, $N_{central\ jets}$

- $t\bar{t}$ rejection
  - $m_{\ell j}$, Σp_T

- Higgs spinless
- *W* violates parity
  - m_T, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$

Cahn and Dawson, PLB 136 (1984) 196

Fig. 1. Higgs boson production from virtual vector boson pairs (V = W or Z).

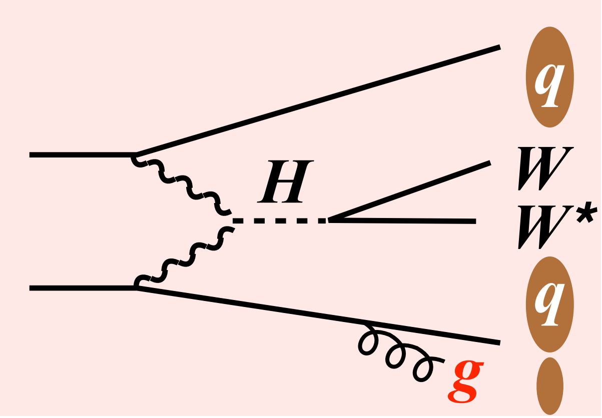
ATLAS uses BDT & reject ggF Higgs
CMS uses $m_{\ell\ell}$ & keep ggF Higgs

VBF topology

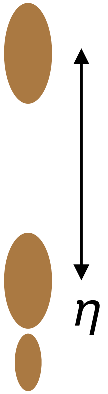
Activity

Jets

VBF Higgs

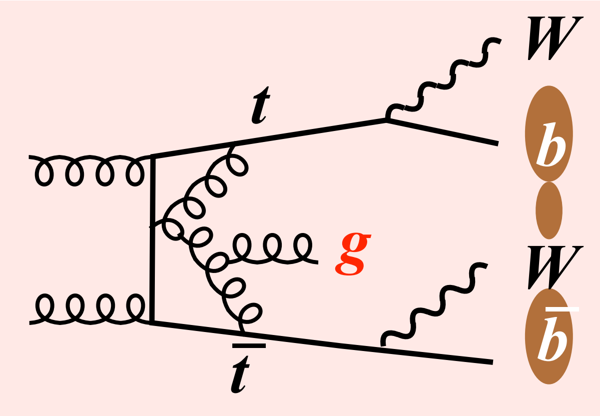


No color near H
No extra jets inside

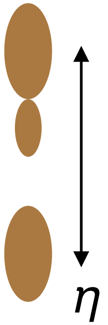


Jets widely separated

$t\bar{t} \to WbW\bar{b}$

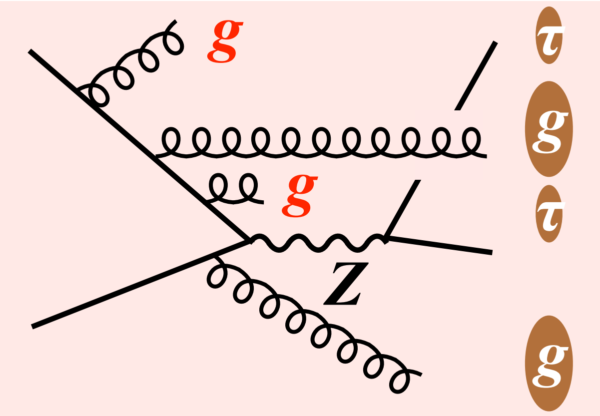


Hadronic activity

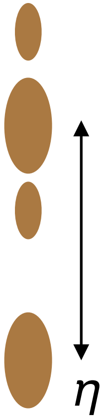


Jets not as separated

$Z + jets$



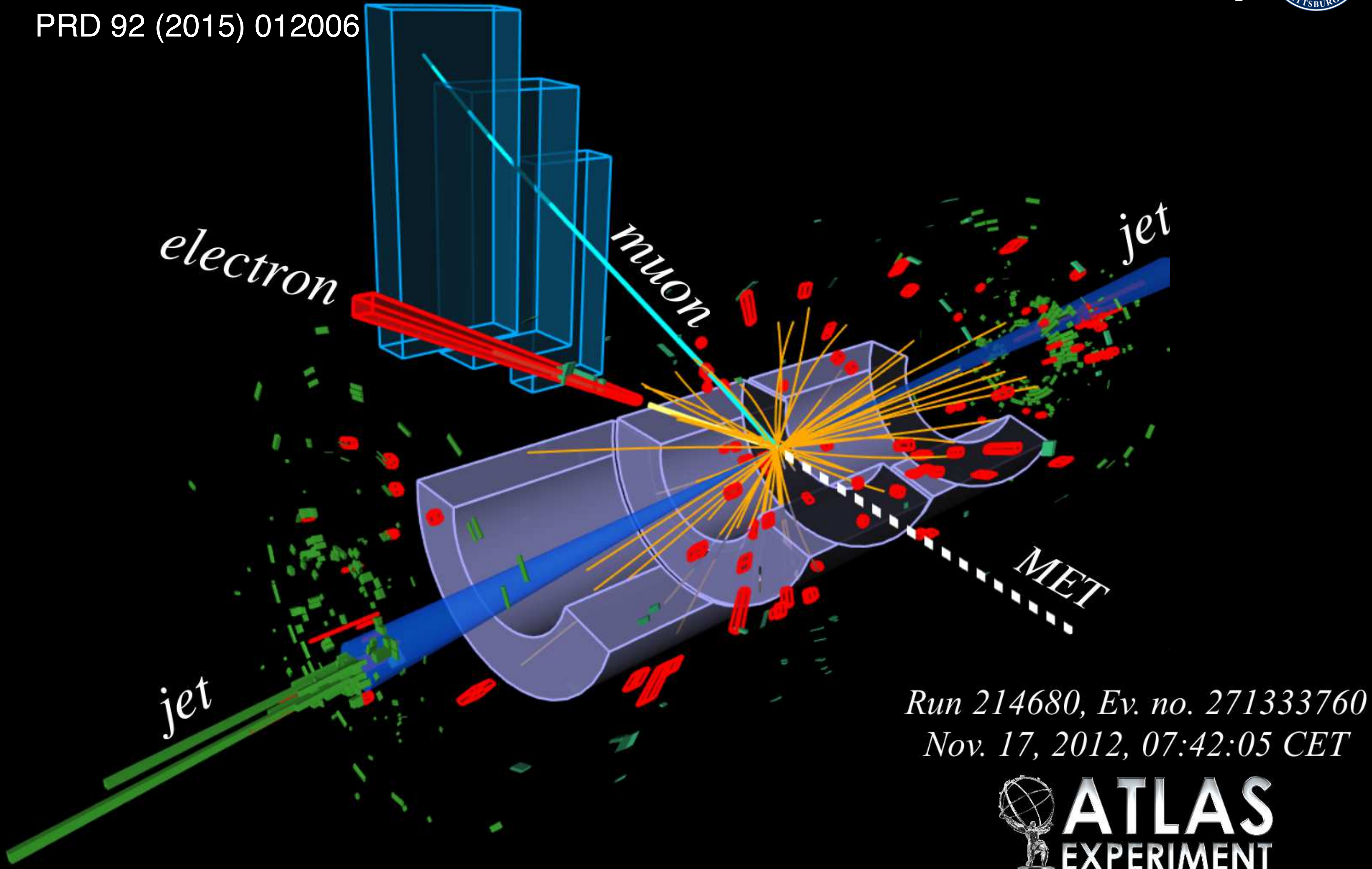
Hadronic activity



Jets not as separated

VBF → *H* → *WW** → *eνμν*

PRD 92 (2015) 012006

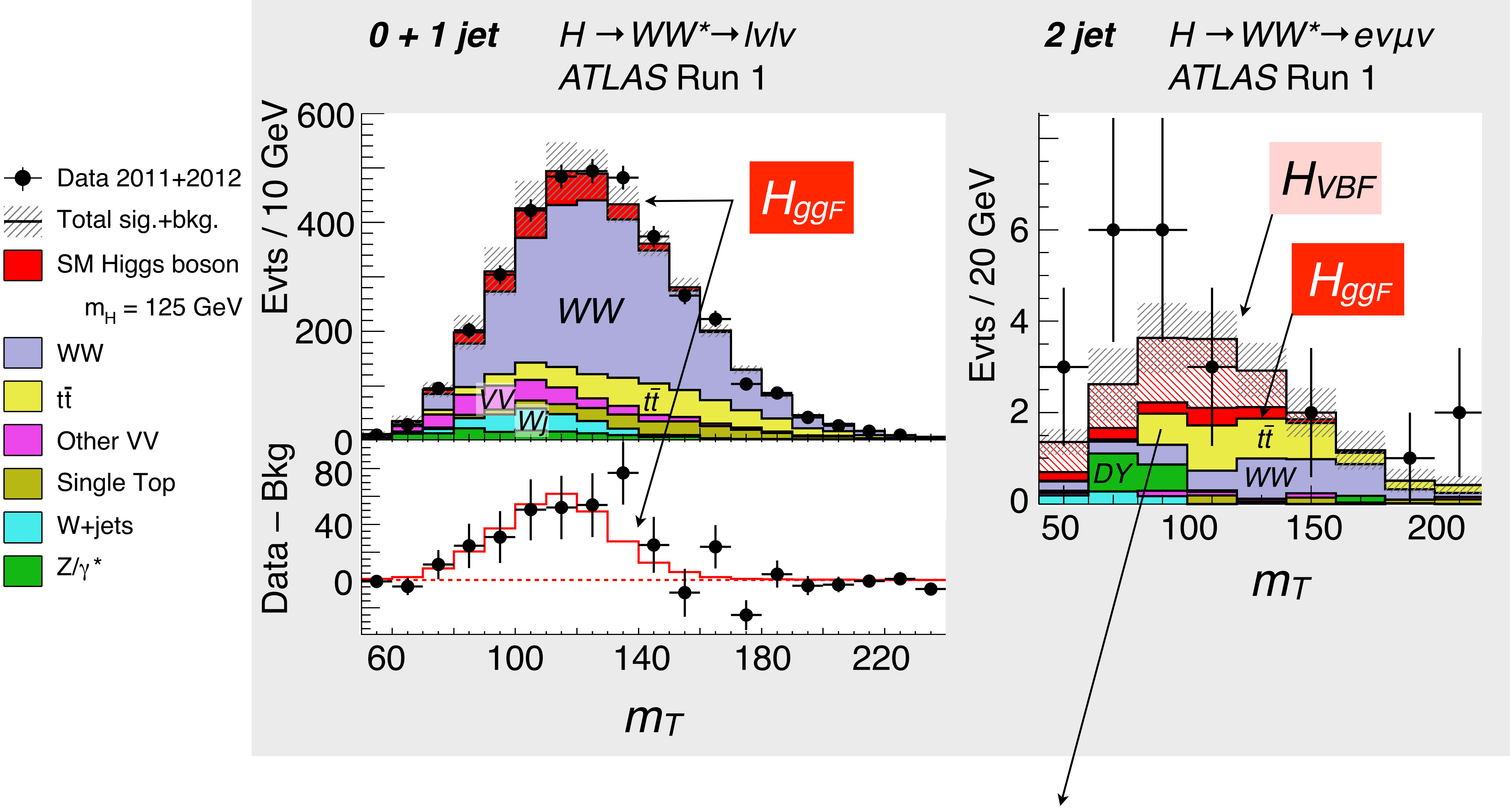


Run 214680, Ev. no. 271333760
Nov. 17, 2012, 07:42:05 CET

ATLAS EXPERIMENT
http://atlas.ch

Transverse mass

You can see with your eyes a broad peak for signal



Difficulty estimating $t\bar{t}$, leading systematic

Variables for VBF $H \to WW^* \to e\nu\mu\nu$

Three groups of variables

Higgs decay

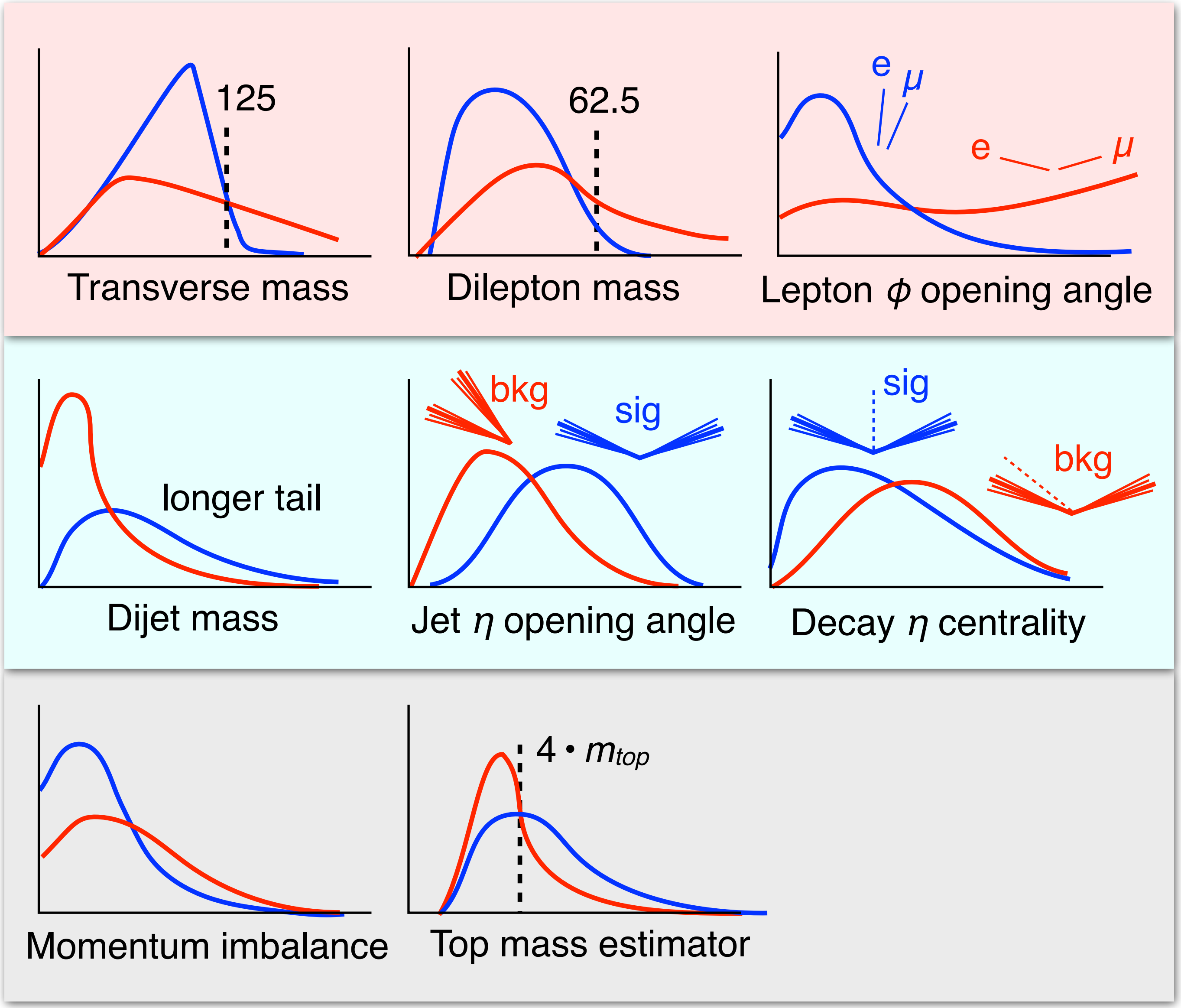
- $m_T \lesssim m_H$
- $m_{\ell\ell}$ small
- $\Delta\phi_{\ell\ell}$ small

VBF configuration

- m_{jj} large
- Δy_{jj} large
- centrality of $\ell\ell$

Top quark

- $\boldsymbol{\Sigma p_T}$
- $\boldsymbol{\Sigma} m_{\ell j}$ of lep-jet



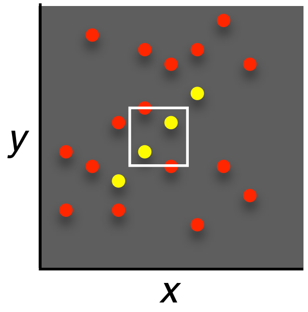
We tried $\mathcal{O}$(1k) variable combinations & matrix element methods

Multivariate analysis

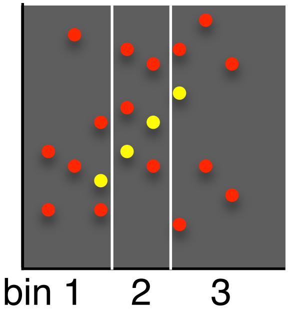
BDT can be thought of as an *S/B* grouping of cut-and-count bins

Cartoon of methods

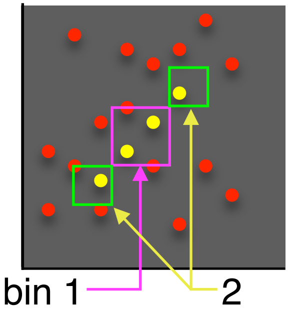
Cut/count



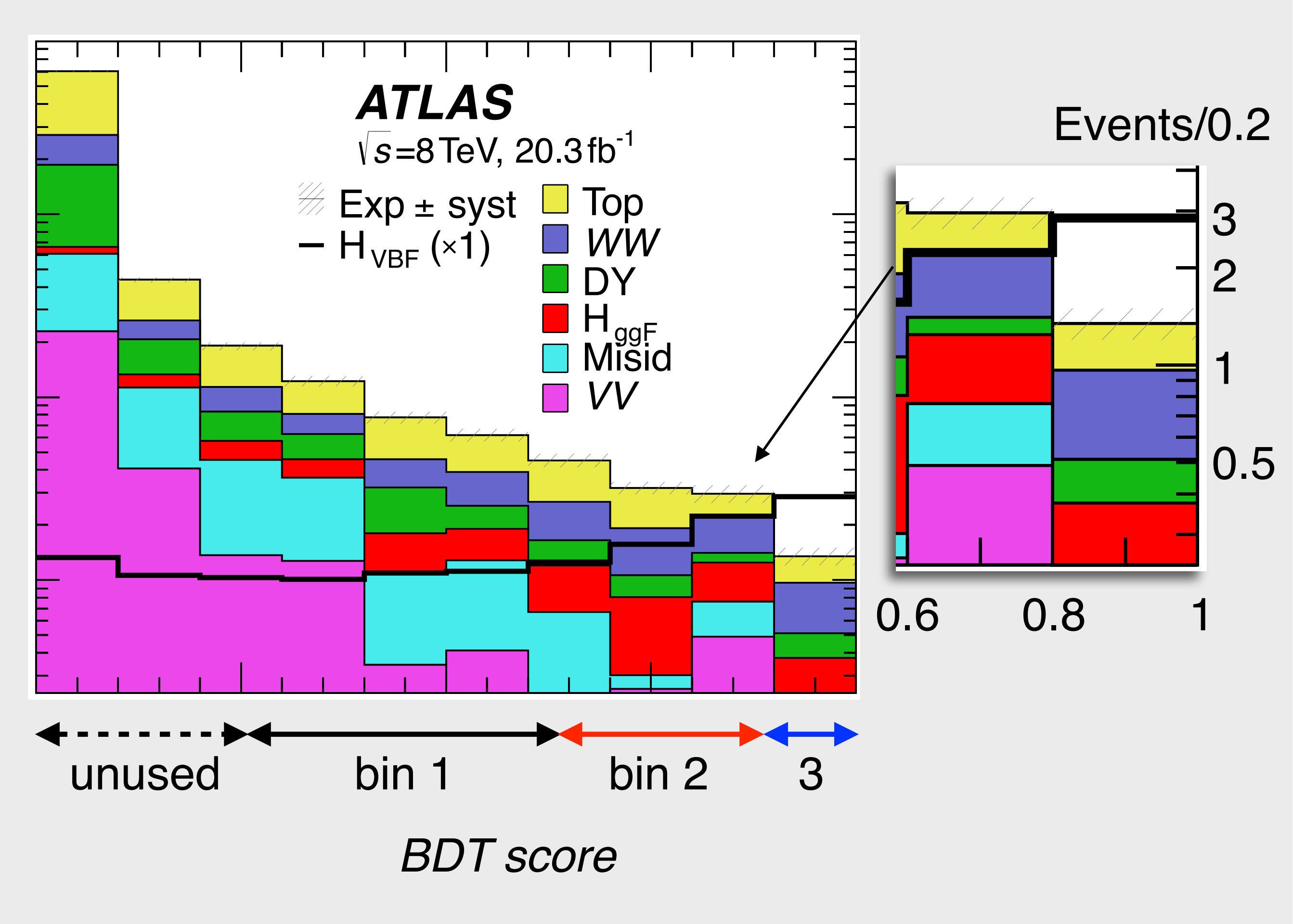
“Cut-based”



BDT



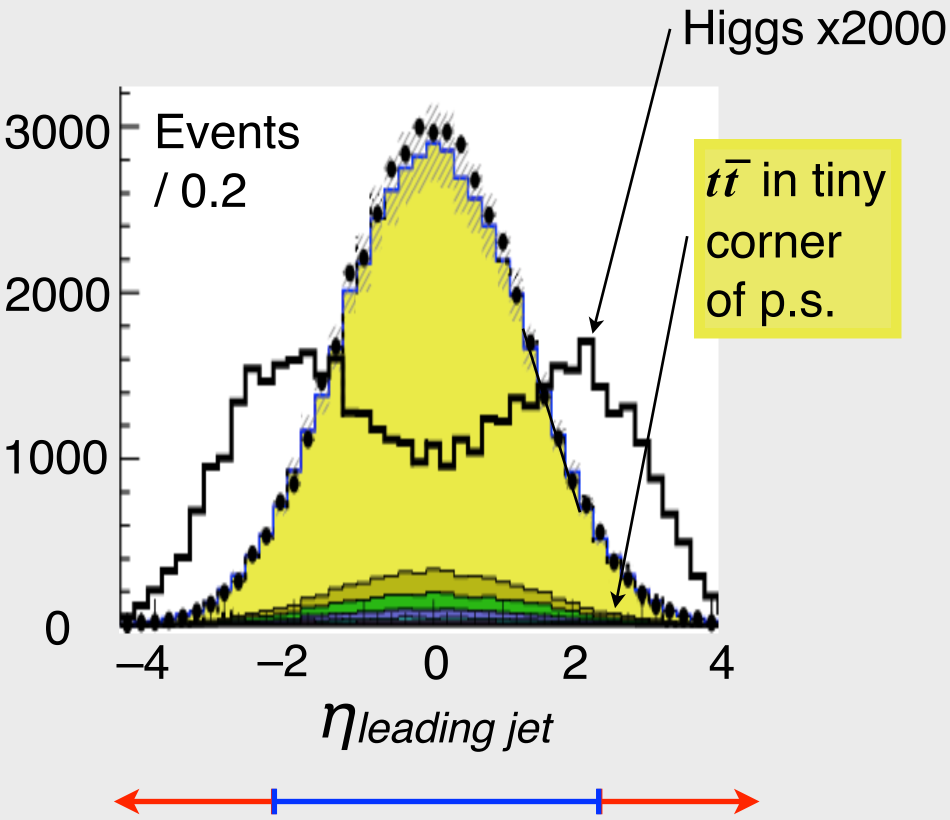
Resulting distribution



Achieved 2-to-1 ratio of *S*-to-*B*

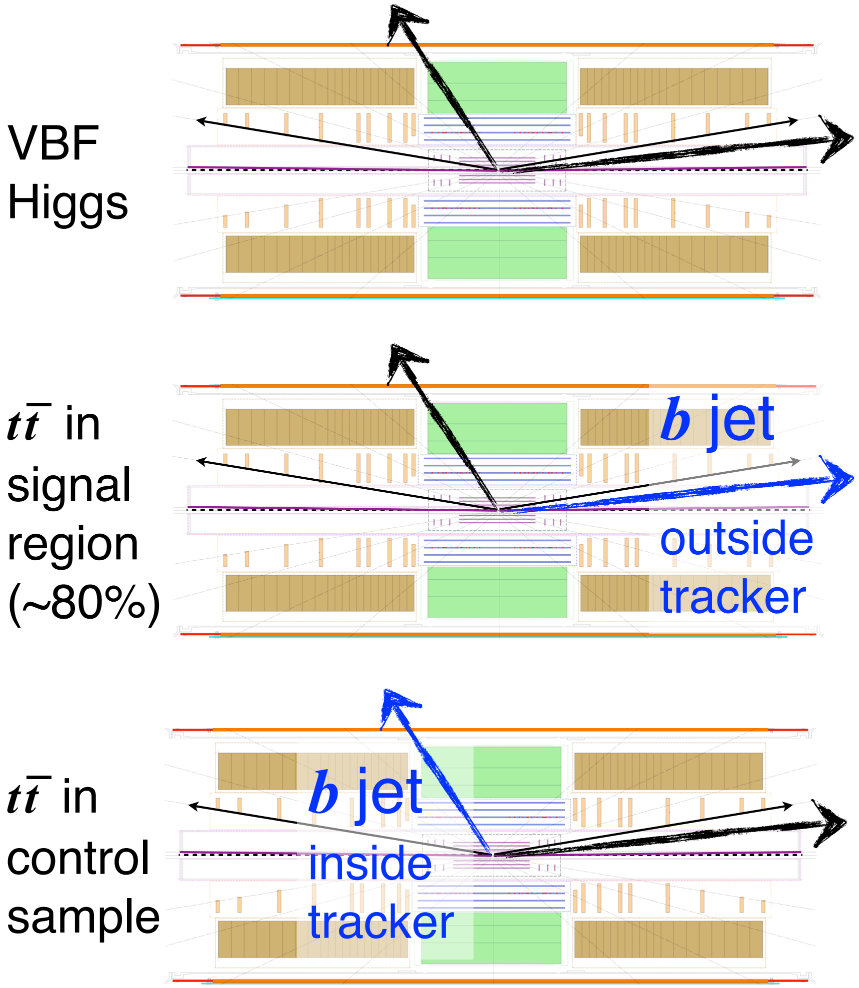
Difficulty estimating $t\bar{t} \to WbW\bar{b}$

Can't reject *b* jets where there is no tracker



tracker, can veto

can't *b*-tag outside tracker



VBF Higgs

$t\bar{t}$ in signal region (~80%)

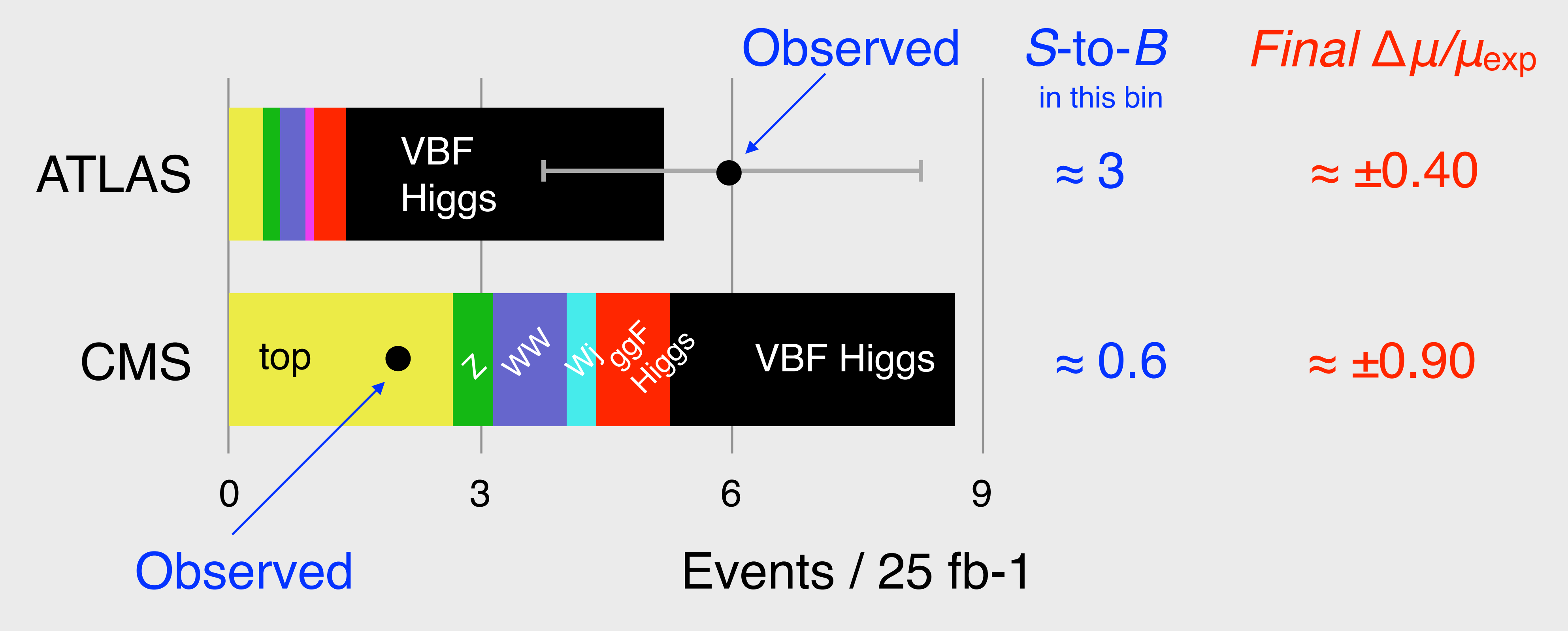
$t\bar{t}$ in control sample

Only $N_{b\text{-}tag} = 1$ faithful, extrapolation good to 30%

ATLAS v. CMS

Comparison of a sensitive eμ bin in Run 1

Not the fit distributions, but representative samples.

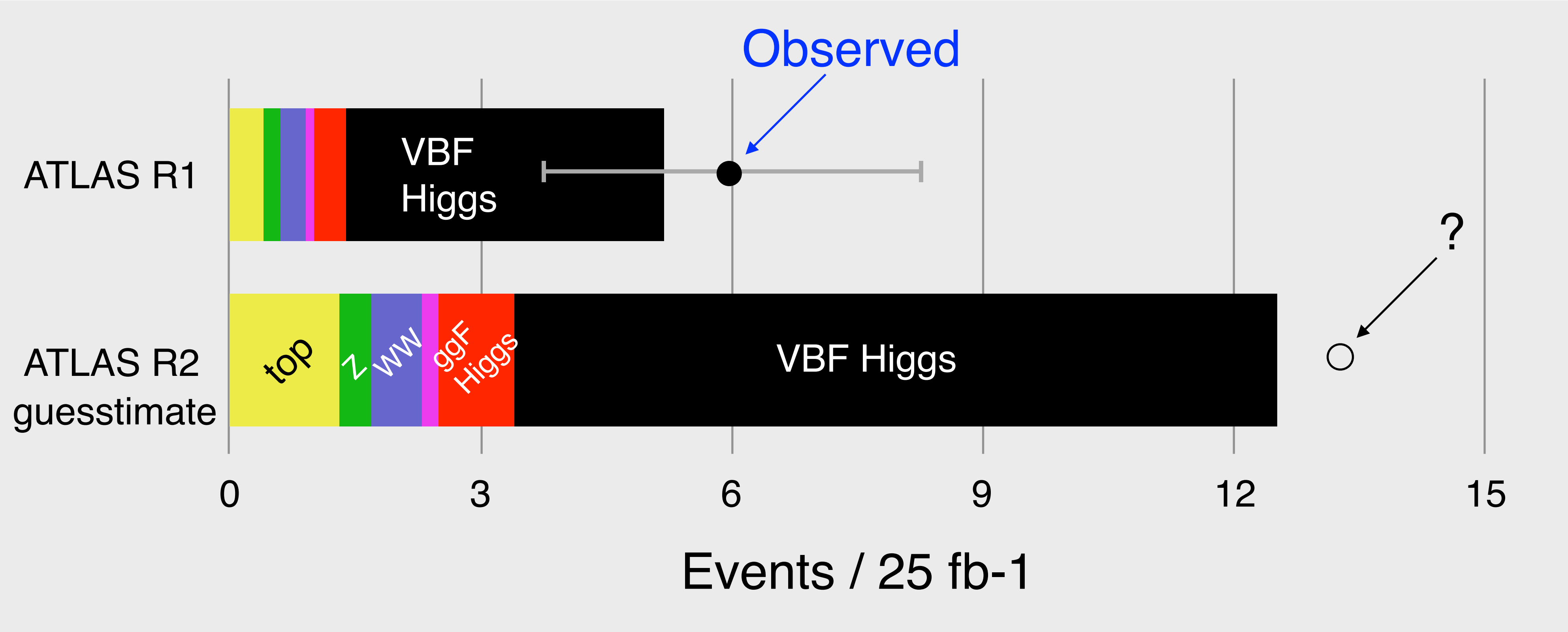


Small statistics, room for improvement in Run 2

The future

Back-of-the-envelope using the most sensitive eμ bin with 25 fb^{-1}

All contributions scale up by a factor of 2-3 for Run 2

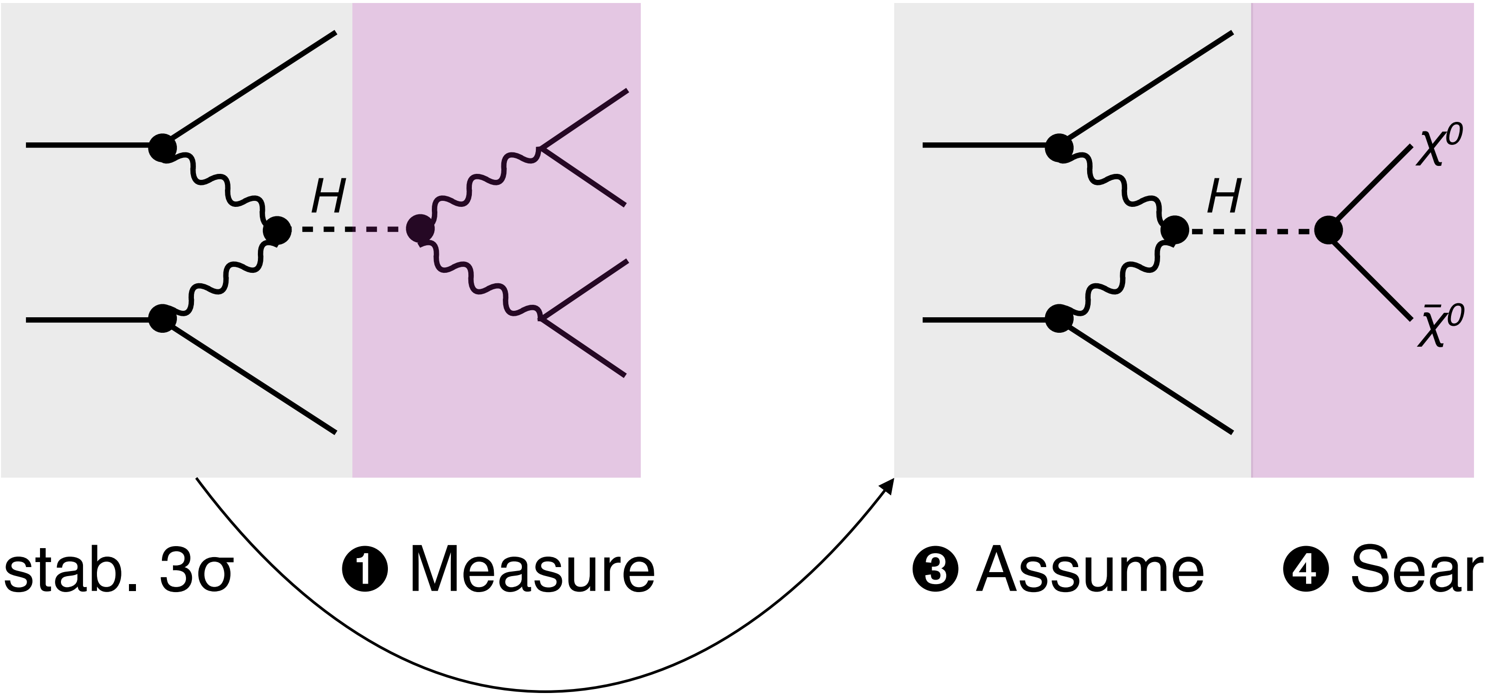


Have 3σ in Run 1, will likely approach 5σ in Run 2

VBF Higgs established

VBF $H \rightarrow WW^*$

VBF $H \rightarrow$ *invisible*



❷ Estab. 3σ

❶ Measure

❸ Assume

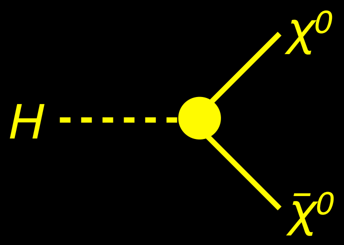
❹ Search

Many similarities

- Higgs p_T theory
- VBF jets
- MET

Topics covered

Higgs → invisible



~~*Why*~~ ~~*Higgs width*~~

Overview ~~*Indirect via couplings*~~ ***Direct via searches*** Run 1 ≲ 30%

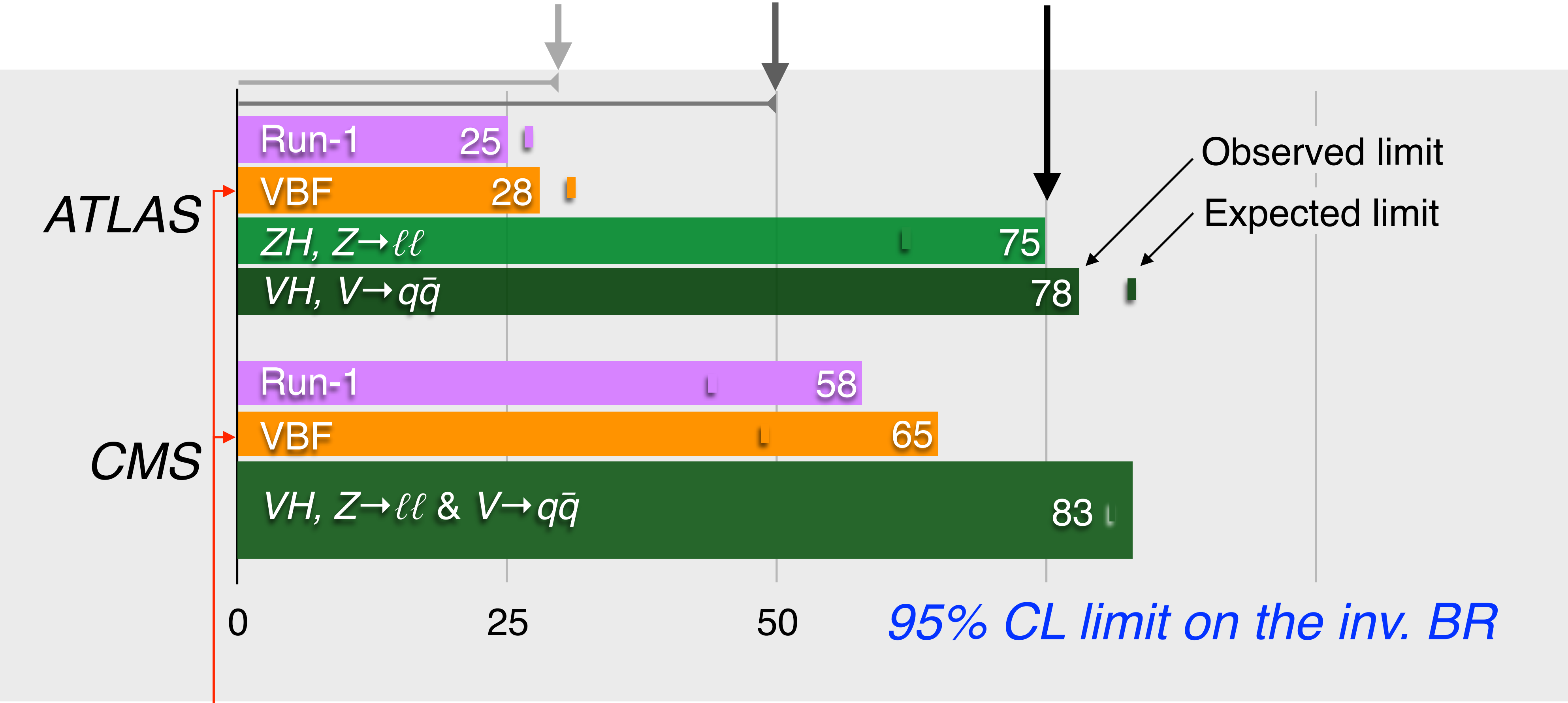
Key analysis ~~VBF $H \to WW^*$~~ **VBF $H \to$ *inv*** VBF *WW* best for κ

Key background ~~$t\bar{t} \to WbW\bar{b}$~~ $Z \to \nu\bar{\nu}$

ATLAS-centric talk (will point out v. CMS) *Future*

Direct searches

VBF is dominant, not comprehensive



~30% w/ ATLAS +CMS couplings

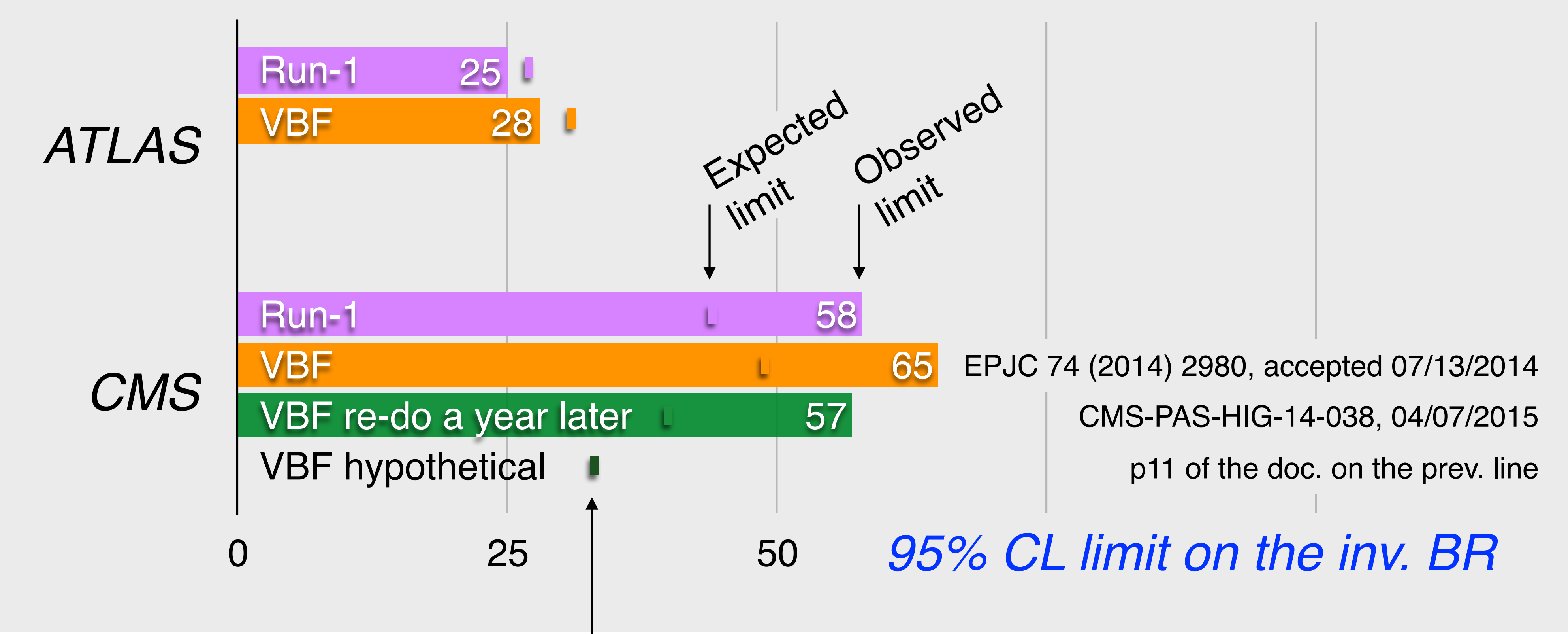
~50% w/ ATLAS couplings

Z→ℓℓ considered best prospect for a while

Why are the two VBF results so different?

VBF history

The crux of all these differences is on estimating $Z \to \nu\bar{\nu}$



EPJC 74 (2014) 2980, accepted 07/13/2014

CMS-PAS-HIG-14-038, 04/07/2015

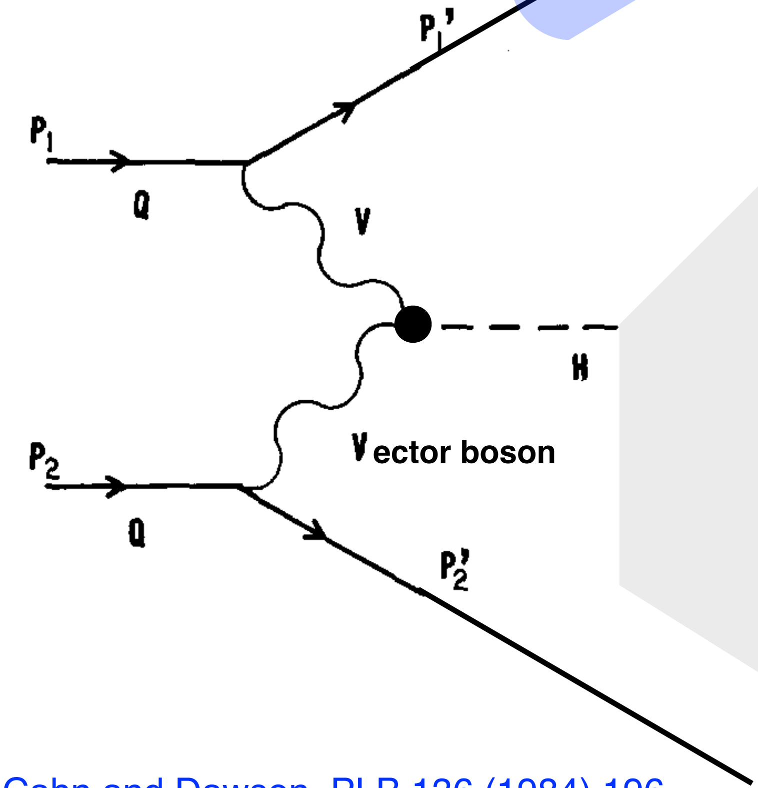
p11 of the doc. on the prev. line

“If (CMS normalized *Z* using *W* similar to ATLAS) it would be … 33%.”

Physics of VBF *H* → *invisible*

Production established by *WW**

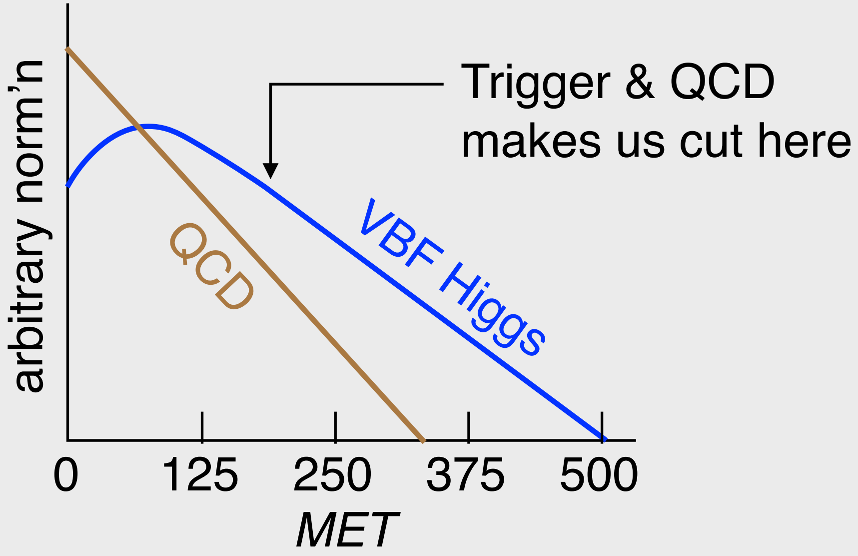
- Energetic jets with large η gap
- No hadronic activity
- m_{jj}, $\Delta\eta_{jj}$, $N_{\text{central jets}}$



Cahn and Dawson, PLB 136 (1984) 196

Fig. 1. Higgs boson production from virtual vector boson pairs (V = W or Z).

- *MET* = Higgs P_T



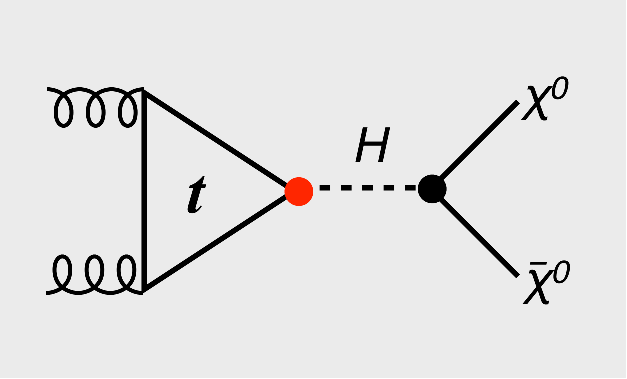
Not as many handles, background est. crucial

Why not ggF?

The problem is invisible

Disappears

- Can only measure recoil
- Decay products conserve momentum



There is nothing to measure

Wait, why not ggF + 1 jet?

The problem is the $Z \to v\bar{v}$

Invisible

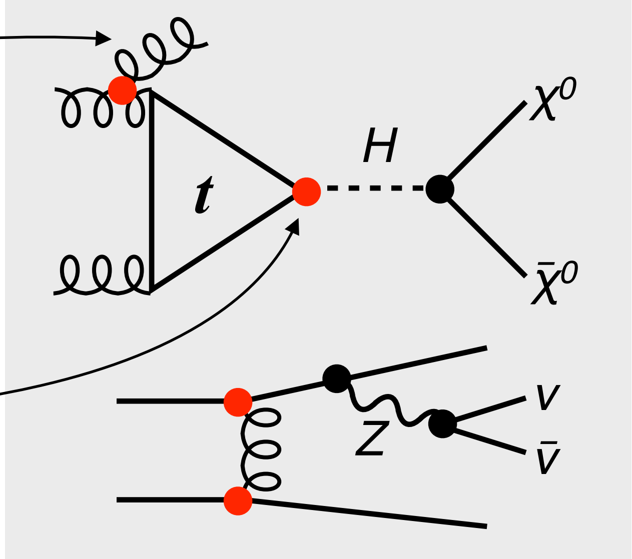
- Measure the mono-jet
- Need some boost for *MET*

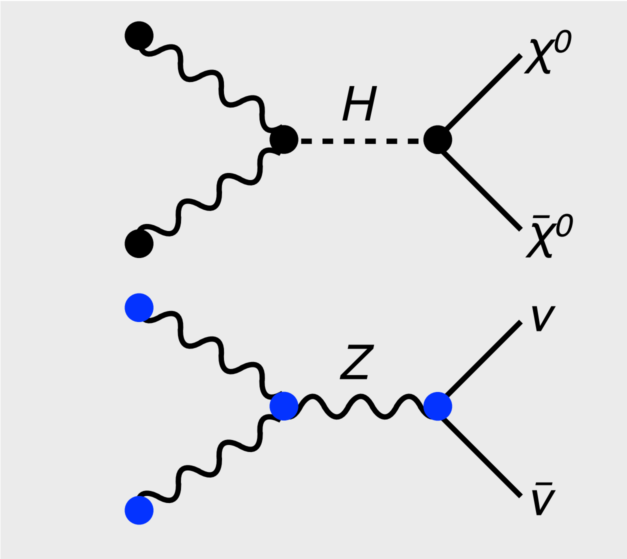
ggF is loop suppressed

- *Z+jet* abundant however
- Ratio $\frac{\sigma_{qqZ} \cdot B_{Zvv}}{\sigma_{H+1j}} \approx \frac{6000\text{ pb}}{19\text{ pb}} = \frac{300}{1}$

VBF is tree level

- *Z+jet* is $(\alpha_W)^{4+}$ suppressed
- Ratio $\frac{\sigma_{VBF\text{-}Z} \cdot B_{Zvv}}{\sigma_{VBF}} \approx \frac{0.6\text{ pb}}{1.6\text{ pb}} = \frac{1}{2}$



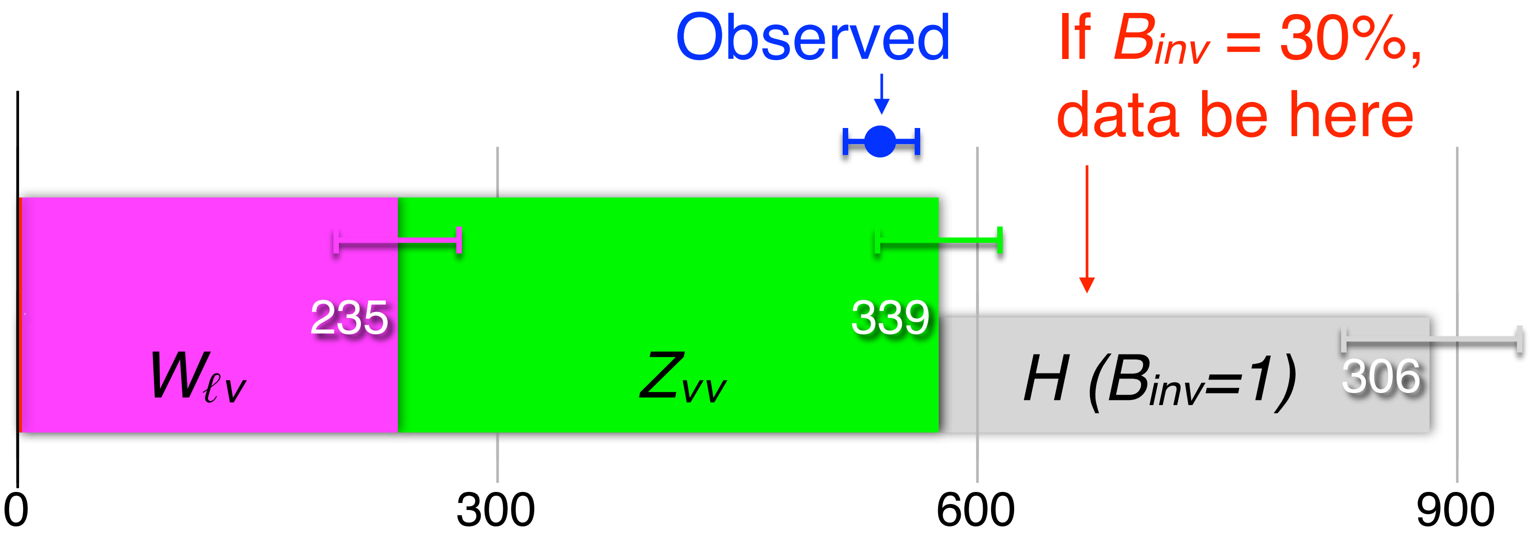


Not worth the trouble for ggF

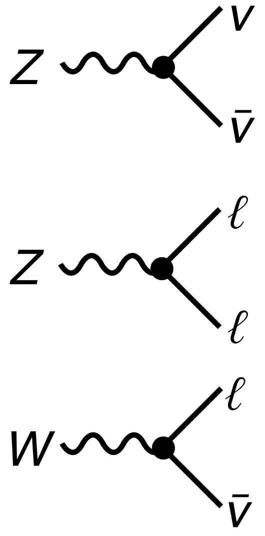
VBF analysis

ATLAS Run 1

- $B_{inv} < 28\%$ (31%)



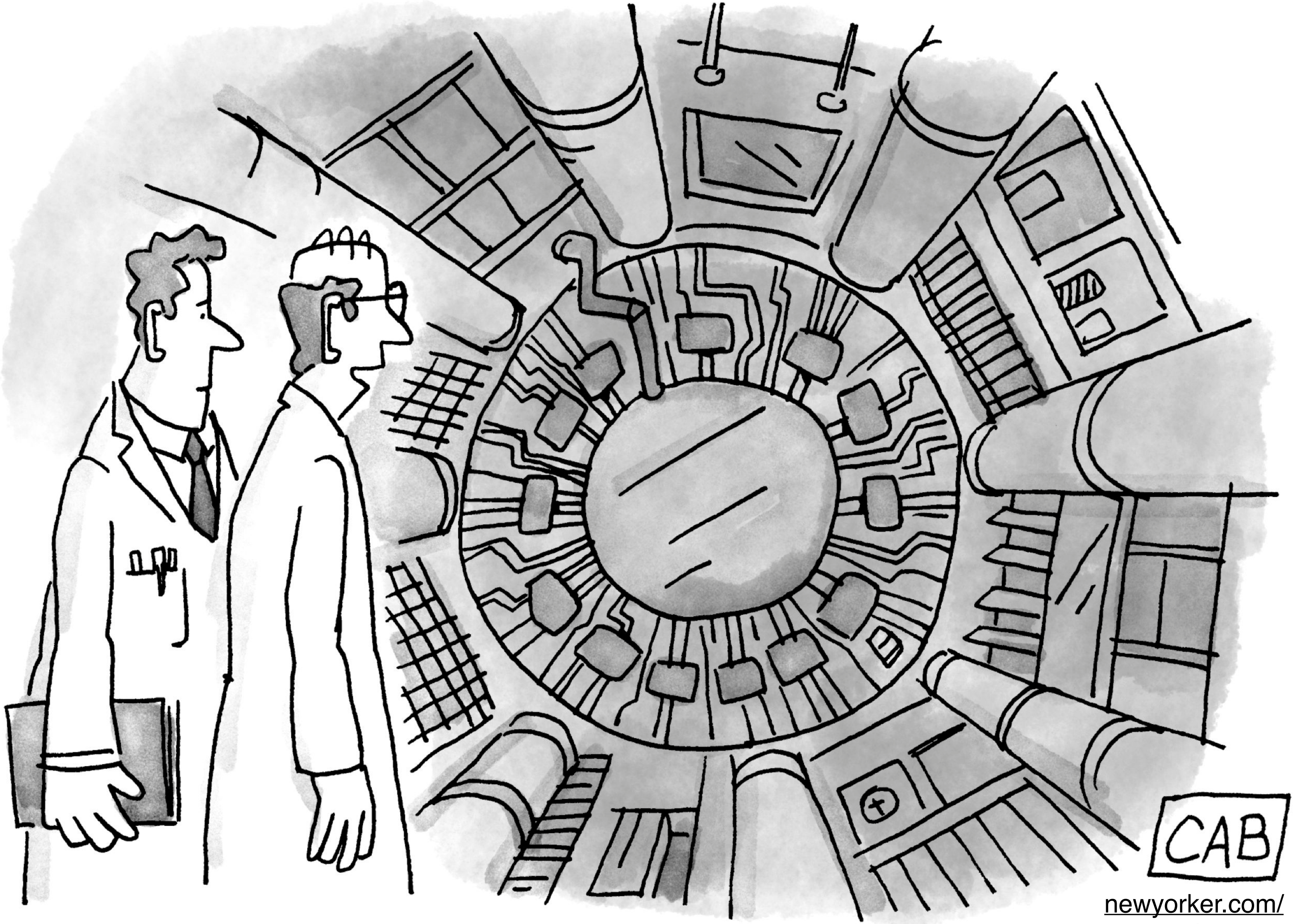
$Z_{\nu\nu}$ estimates



Method	*Who*	*Pro*	*Con*	*Precision*
N_{MC}	-	WYSIWYG	Jet energy, QCD scale	± 50%
$N_{Z\ell\ell}$	CMS Run 1 $\mu\mu$ only (?)	$Z_{\ell\ell} = Z_{\nu\nu}$	Low stats (~20 evts)	± 40%
$N_{MC} \cdot R_{W\ell\nu}$	ATLAS R1, CMS Run 2	Large stats (~600 evts)	$W_{\ell\nu} \neq Z_{\nu\nu}$	± 10%

Reduce even more in Run 2? Maybe $\gamma_{\ell\ell} \sim Z_{\ell\ell}$

Dark matter interpretation



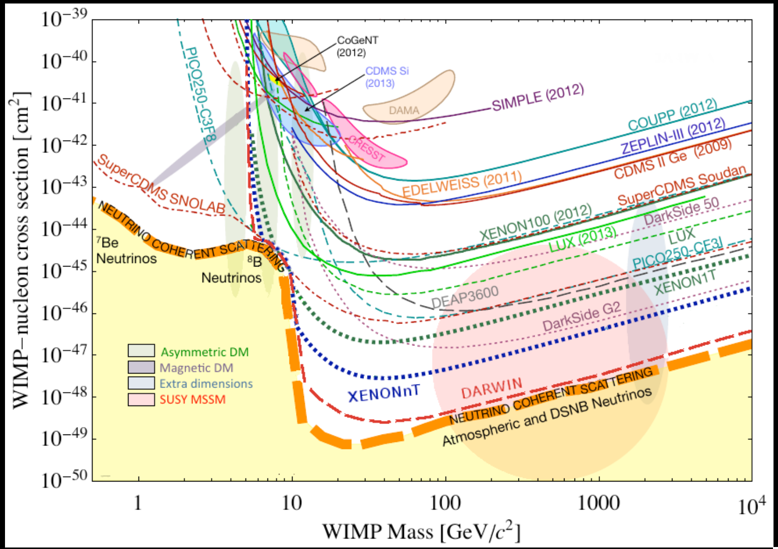
newyorker.com/
cartoons/a18624

Once you ~~have a collider~~, every problem starts to look like ~~a particle~~.

look for invisible

dark matter

Dark matter interpretation



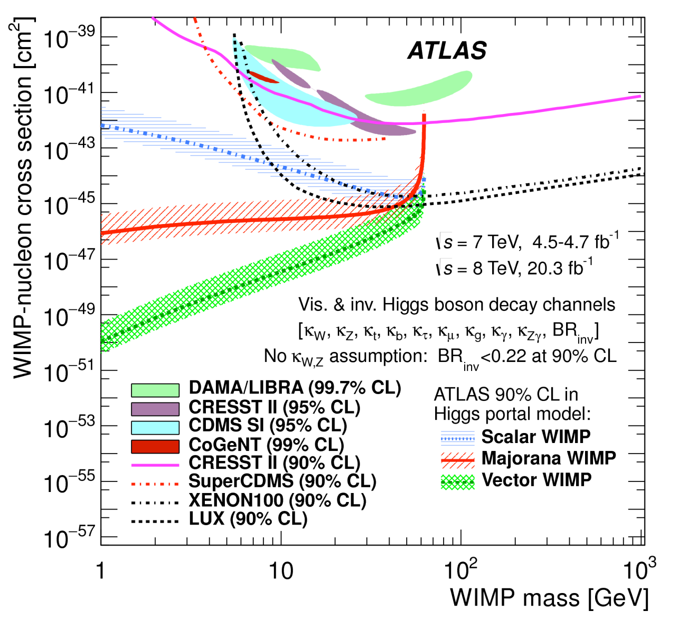
Many direct detection results

LHC measurement

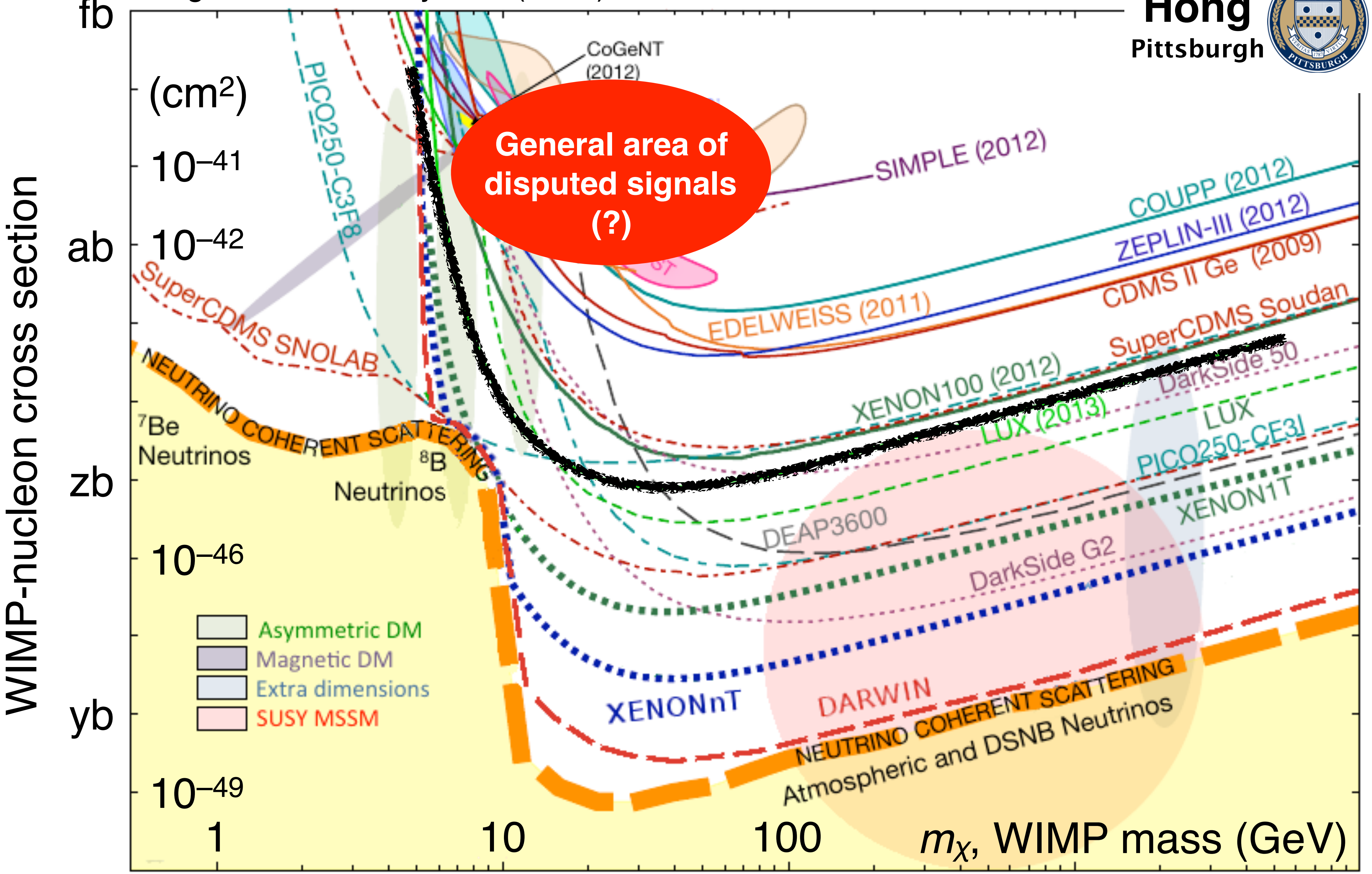
$$\sigma \sim \Gamma_{inv} \cdot \begin{cases} (m_\chi)^2 \\ (m_\chi)^0 \\ (m_\chi)^{-2} \end{cases}$$

DM interpretation

DM model



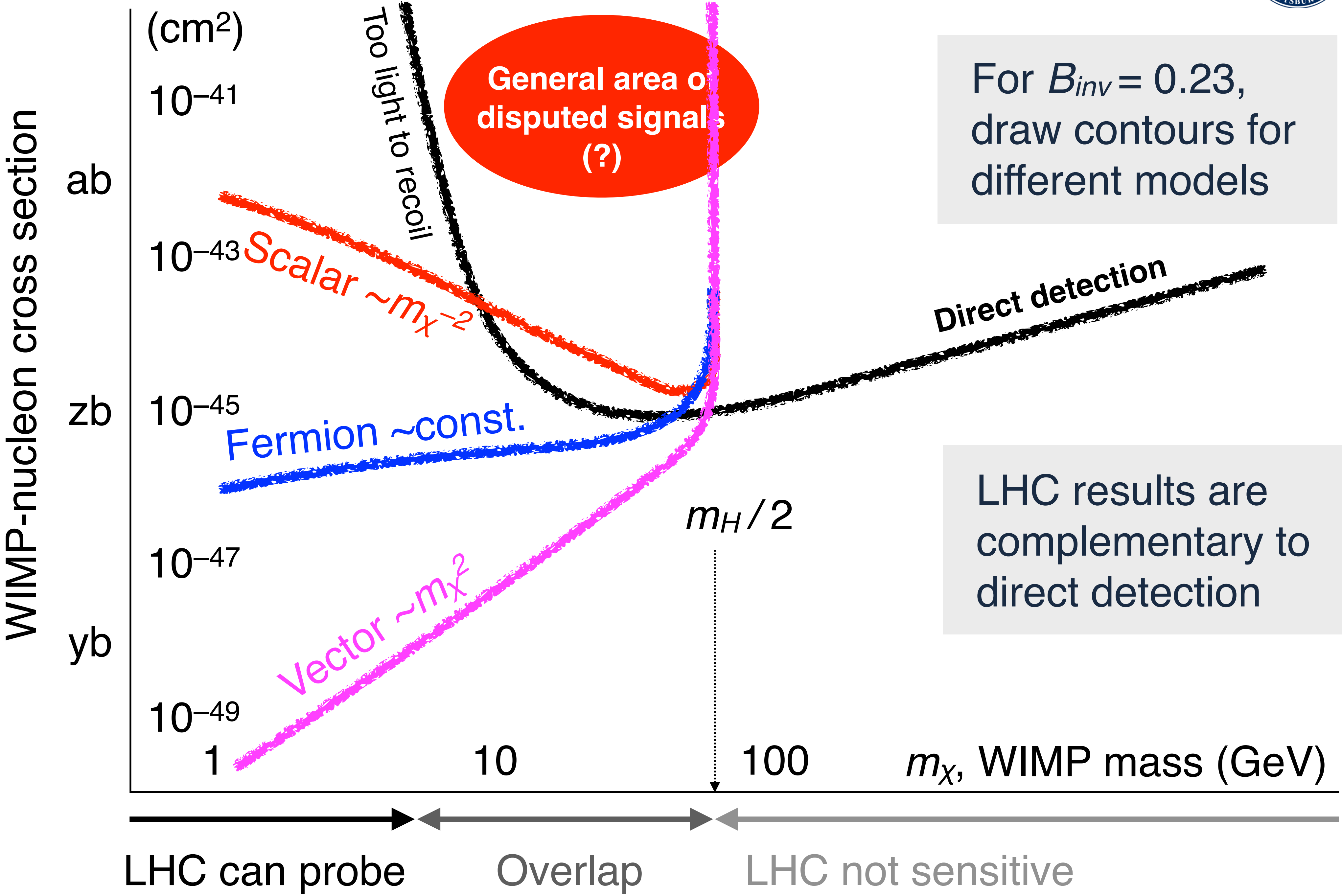
Prog. Part. Nucl. Phys. 85 (2015)



General area of disputed signals (?)

Direct detection exclude to $m_\chi \sim 5$ GeV of $\sigma \sim$ ab-zb range

LHC overlay

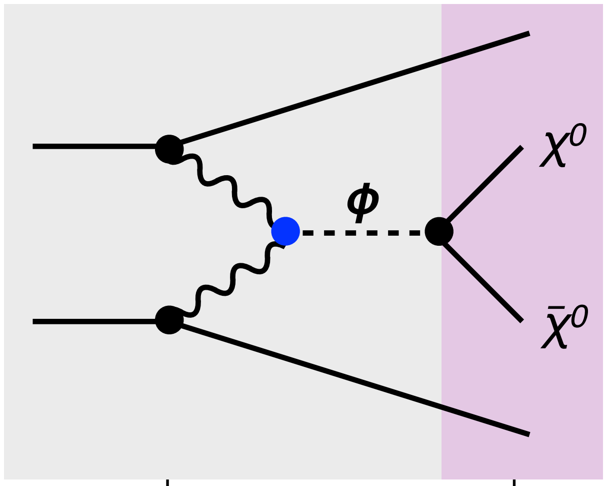


For $B_{inv} = 0.23$, draw contours for different models

LHC results are complementary to direct detection

<u>Reinterpret</u> VBF → *invisible*?

VBF *any* → *invisible*



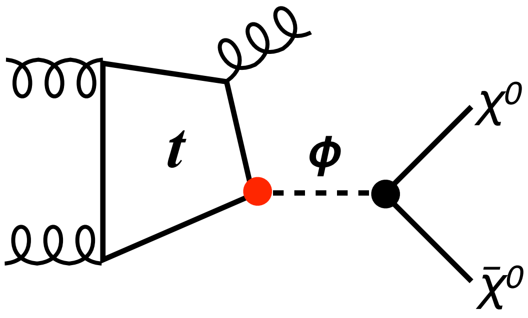
model

<u>same</u> measurement

on σ_{any}, e.g.,

- *Fermiophobic scalars coupling to electroweak bosons*, 1604.07975 (yesterday)
- *Electrowk SUSY sector with compressed sleptons*, PRD 87 (2013) 035029, 91 (2015) 055025

Mono-jet search for DM

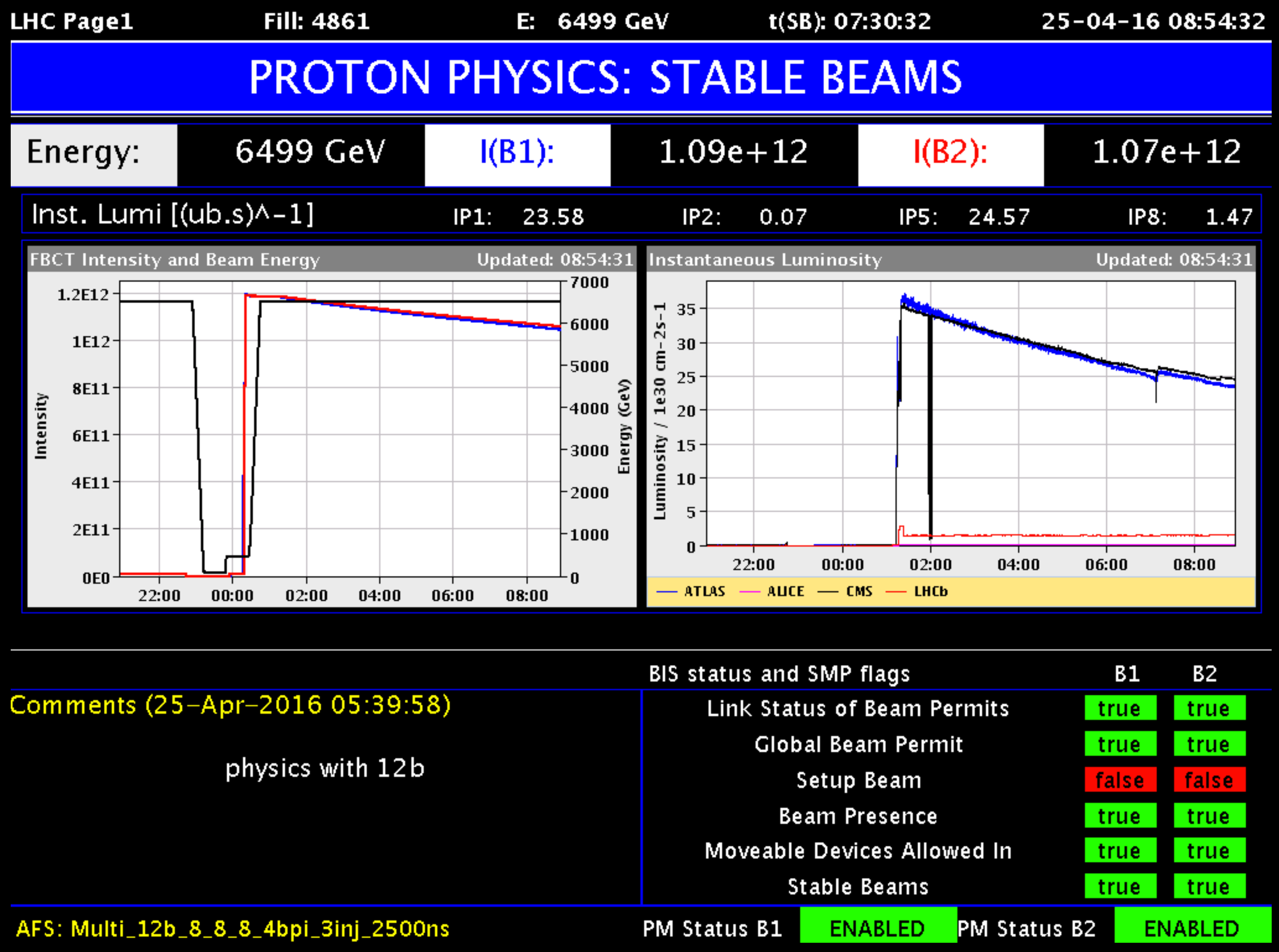


If DM is fermiophobic, mono-jet not sensitive

Tell us your favorite model!

The future is now

Collisions started this week, ATLAS collected $\mathcal{O}(1)$ pb^{-1}



LHC Page1 Fill: 4861 E: 6499 GeV t(SB): 07:30:32 25-04-16 08:54:32

PROTON PHYSICS: STABLE BEAMS

Energy:	6499 GeV	I(B1):	1.09e+12	I(B2):	1.07e+12

Inst. Lumi [(ub.s)^-1]	IP1:	23.58	IP2:	0.07	IP5:	24.57	IP8:	1.47

Comments (25-Apr-2016 05:39:58)

physics with 12b

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	true	true
Global Beam Permit	true	true
Setup Beam	false	false
Beam Presence	true	true
Moveable Devices Allowed In	true	true
Stable Beams	true	true

AFS: Multi_12b_8_8_8_4bpi_3inj_2500ns

PM Status B1 ENABLED PM Status B2 ENABLED

← Monday

← Nice decay

Hope to have $\mathcal{O}(10)$ fb^{-1} of data this calendar year

The future

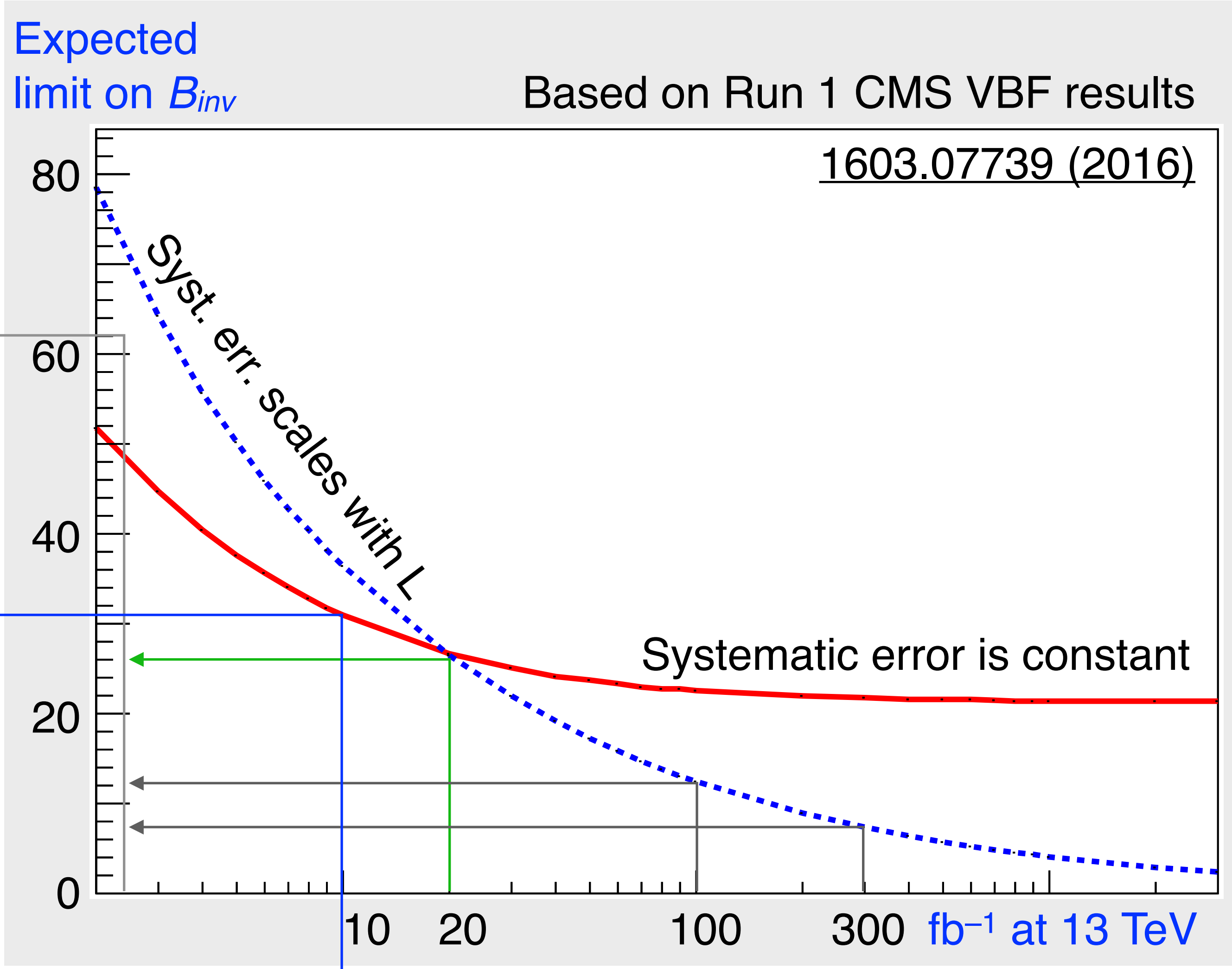
Luminosity projections

CMS Run-2 VBF results with 2.3 fb^{-1}

- Limit 69% (62%)
- *Z* norm'd w/ *W*

ATLAS Run-1 VBF

- Limit 28% (31%)
- *Z* norm'd w/ *W*



Run 2 target

Run 3+ target

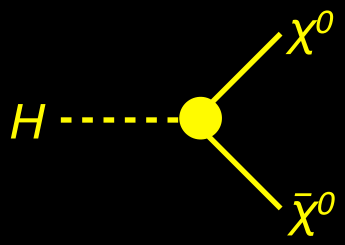
Need 10 fb^{-1} of 13 TeV reach Run 1

We'll try for < 20% in Run 2

Maybe possible? < 10% in Run 3

Summary

Higgs → invisible



Why *Higgs width*

Discovery =
Revolutionary

Overview *Indirect via couplings* *Direct via searches*

Run 1 ≲ 30%
both approaches

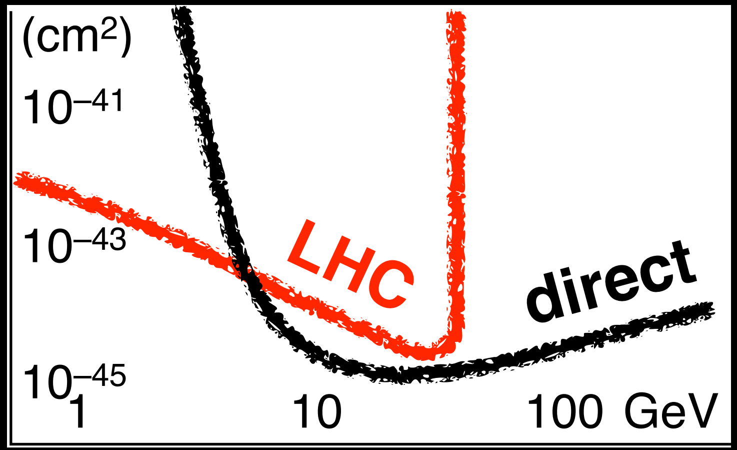
Key analysis VBF $H \rightarrow WW^*$ VBF $H \rightarrow inv$

VBF is best (for me)

Interpretations

LHC is better than many thought

Will get better



My future

I need a PeV collider!

Auxiliary material

More thanks

I thank Elliot for his clear slides on VBF invisible at a PITT workshop.
https://indico.cern.ch/event/460471/contributions/1132574/attachments/1199947/1745600/HInvis_PittPacc.pdf

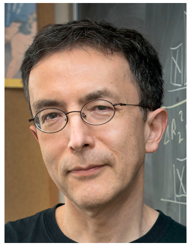
I thank George for the SUSY chat.
It turns out I knew about the compressed scenario for my job talk & forgot it until our chat!

I thank Ben for slides feedback.
Especially on the details of VBF *invisible.*

I thank Alex for the talk rehearsal.
Especially on the prospects for VBF $H \to WW^*$.

I thank Josh for discussions.
Especially on going from Γ_{inv} to σ_{DM}.

E. Lipeles
U Pennsylvania



G. Redlinger
BNL

B. Carlson
U Pittsburgh

A. Tuna
Harvard U

J. Kunkle
U Maryland

Abstract for this seminar

https://indico.bnl.gov/conferenceDisplay.py?confId=1765

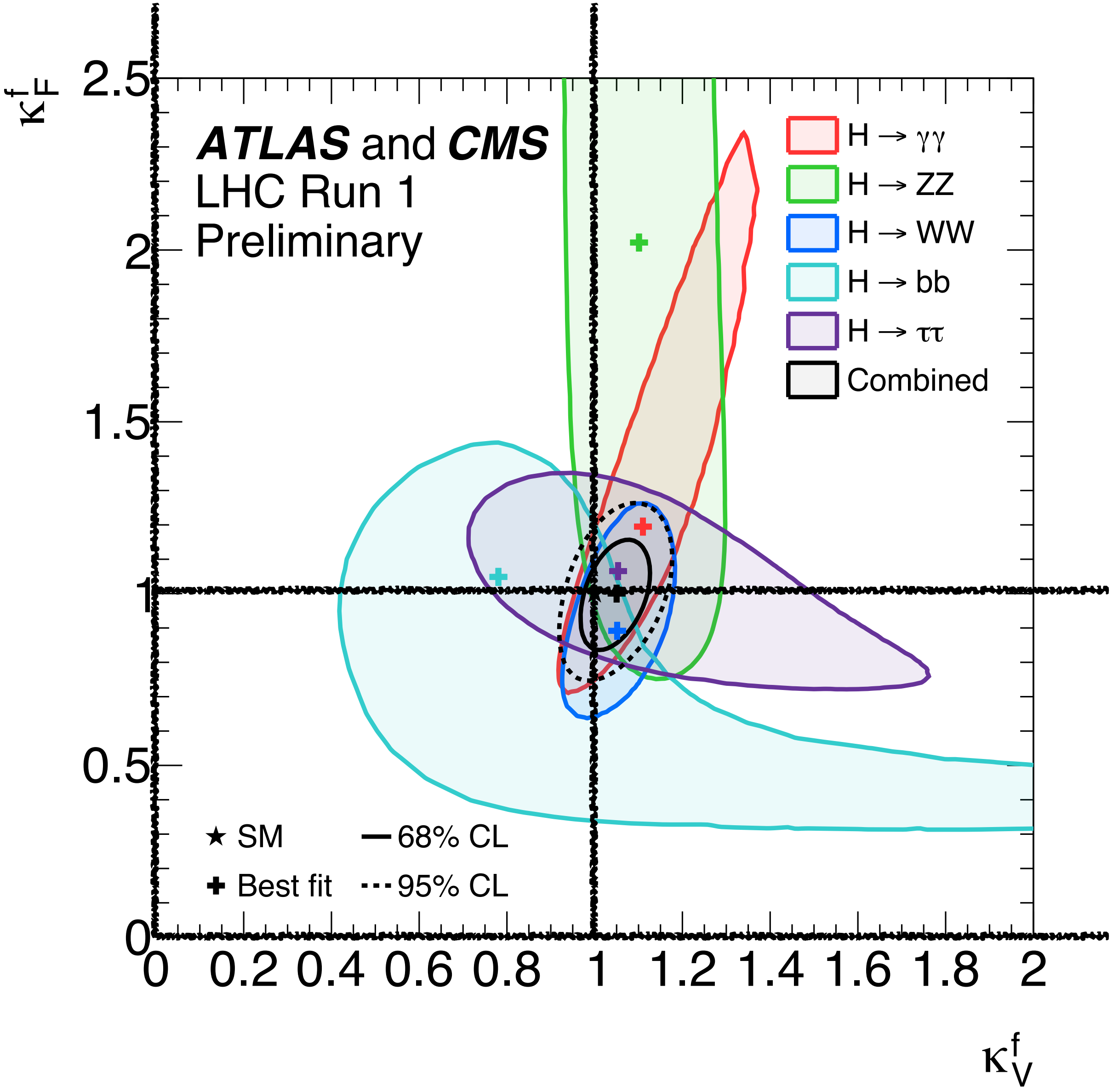
Does the Higgs have a large invisible branching fraction? Two approaches are presented. The first is an indirect constraint of the invisible branching fraction using precision Higgs couplings measurements. The second is a direct search of invisible decays. In particular, I will discuss in detail two of ATLAS's results: the $H \rightarrow WW$ in VBF, which is one of the strongest inputs for the couplings and the evidence for VBF Higgs production, and the $H \rightarrow$ *invisible* in VBF, which gives the strongest direct limit. Comparisons with CMS's results are made.

No idea on Higgs mass

Nucl. Phys. B 106 (1976) 292

"We should perhaps finish with an apology and a caution. We apologize to the experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm, and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up."

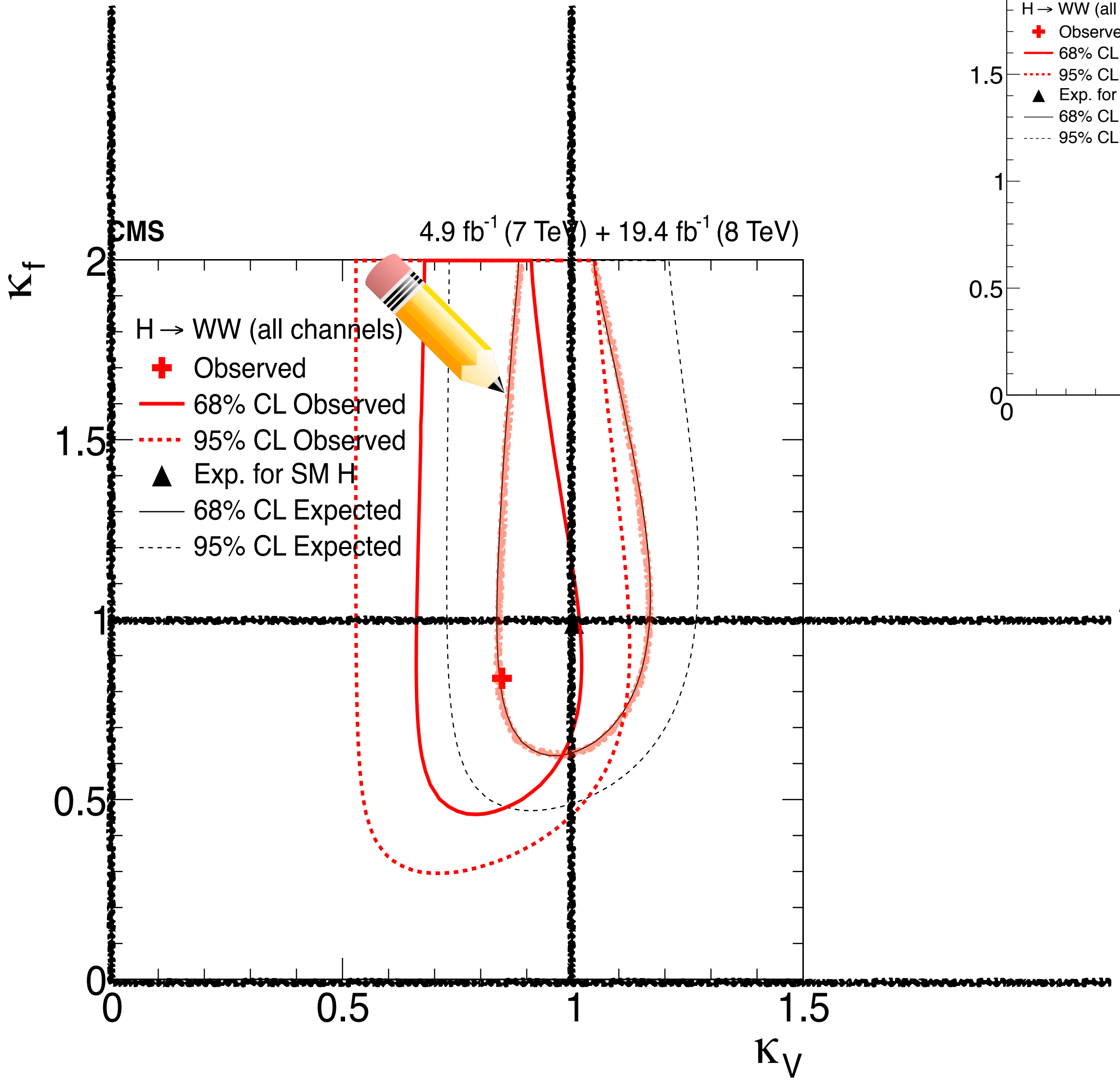
Guidelines for the next 2 slides

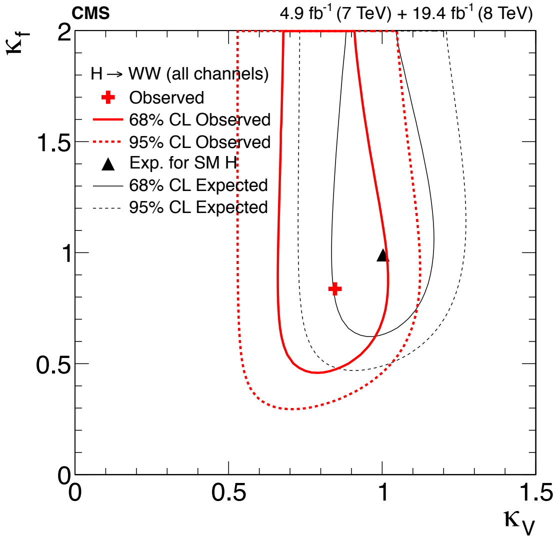


Guidelines

CMS overlay

CMS-HIG-13-023

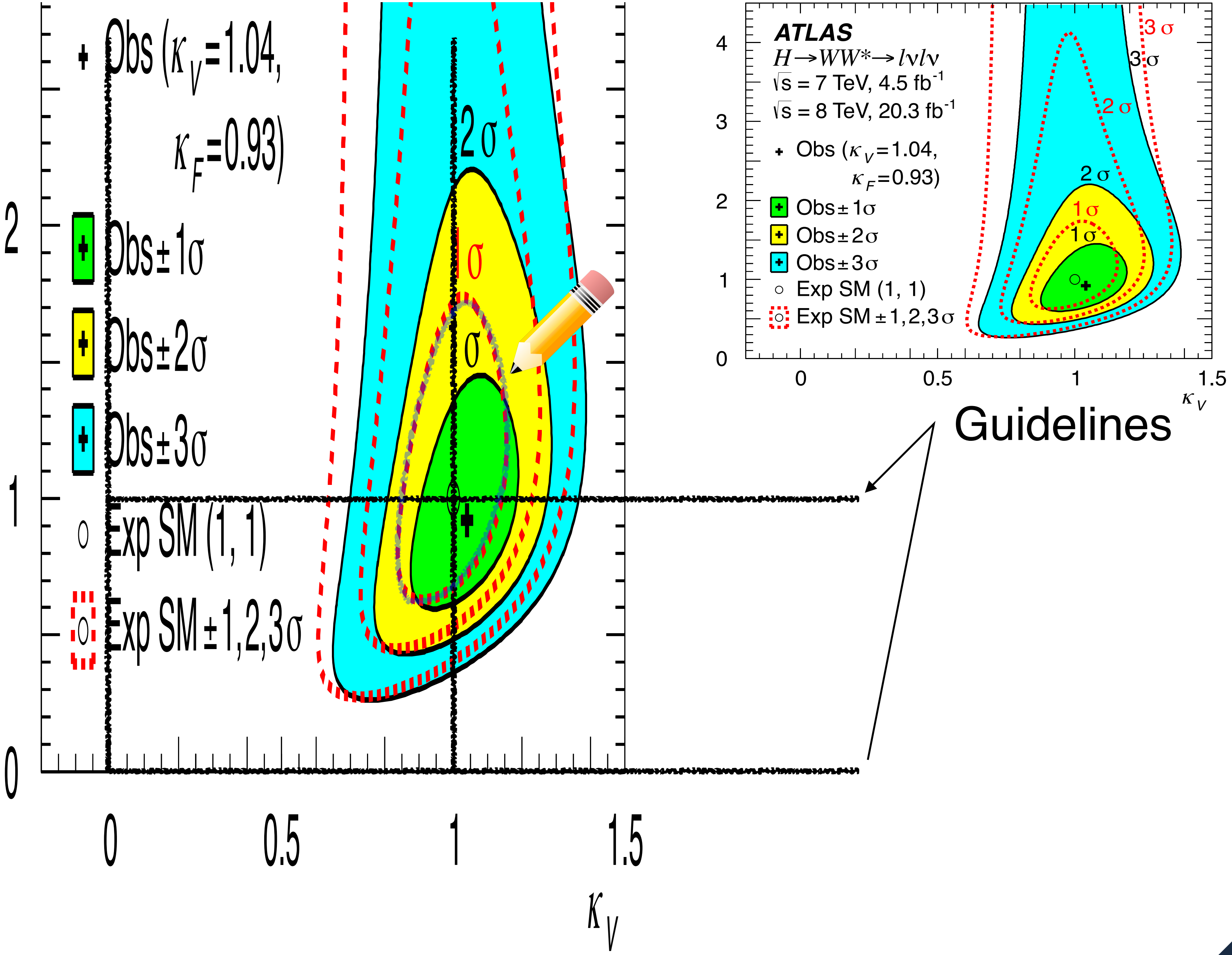




Guidelines

ATLAS overlay

ATLAS-HIGG-2013-13



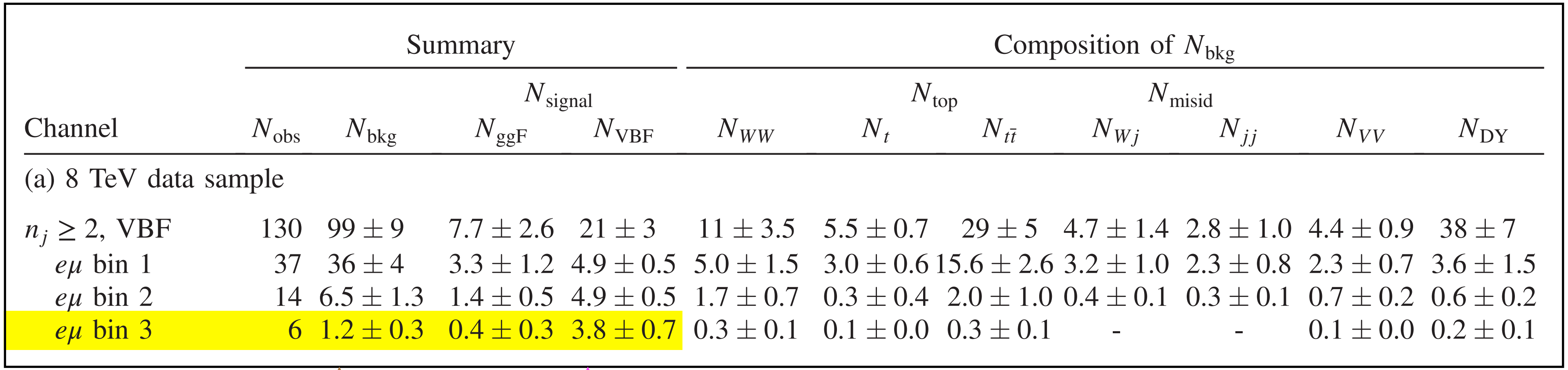
Guidelines

VBF WW^* comparison

Hong
Pittsburgh

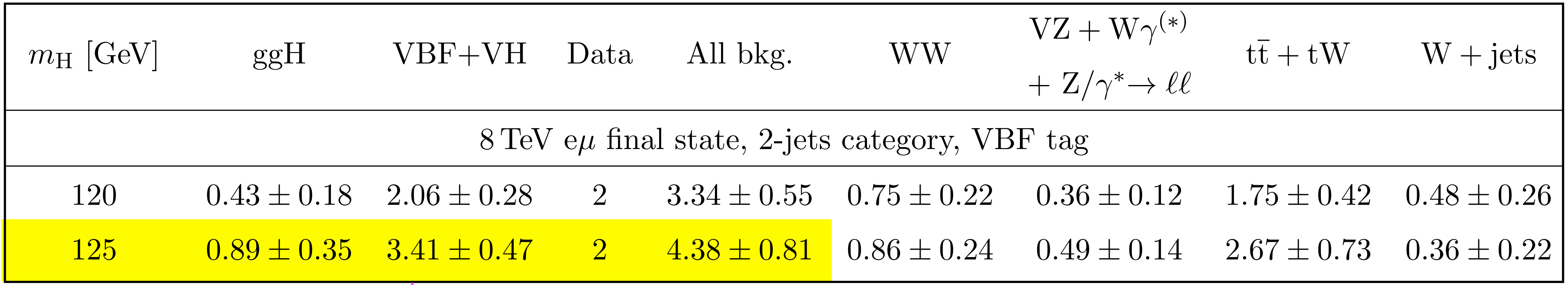
PRD 92 (2015) 012006 v. JHEP 01 (2014) 096

ATLAS



	Summary				Composition of N_{bkg}						
			N_{signal}			N_{top}		N_{misid}			
Channel	N_{obs}	N_{bkg}	N_{ggF}	N_{VBF}	N_{WW}	N_t	$N_{t\bar{t}}$	N_{Wj}	N_{jj}	N_{VV}	N_{DY}
(a) 8 TeV data sample											
$n_j \geq 2$, VBF	130	99 ± 9	7.7 ± 2.6	21 ± 3	11 ± 3.5	5.5 ± 0.7	29 ± 5	4.7 ± 1.4	2.8 ± 1.0	4.4 ± 0.9	38 ± 7
$e\mu$ bin 1	37	36 ± 4	3.3 ± 1.2	4.9 ± 0.5	5.0 ± 1.5	3.0 ± 0.6	15.6 ± 2.6	3.2 ± 1.0	2.3 ± 0.8	2.3 ± 0.7	3.6 ± 1.5
$e\mu$ bin 2	14	6.5 ± 1.3	1.4 ± 0.5	4.9 ± 0.5	1.7 ± 0.7	0.3 ± 0.4	2.0 ± 1.0	0.4 ± 0.1	0.3 ± 0.1	0.7 ± 0.2	0.6 ± 0.2
$e\mu$ bin 3	6	1.2 ± 0.3	0.4 ± 0.3	3.8 ± 0.7	0.3 ± 0.1	0.1 ± 0.0	0.3 ± 0.1	-	-	0.1 ± 0.0	0.2 ± 0.1

CMS

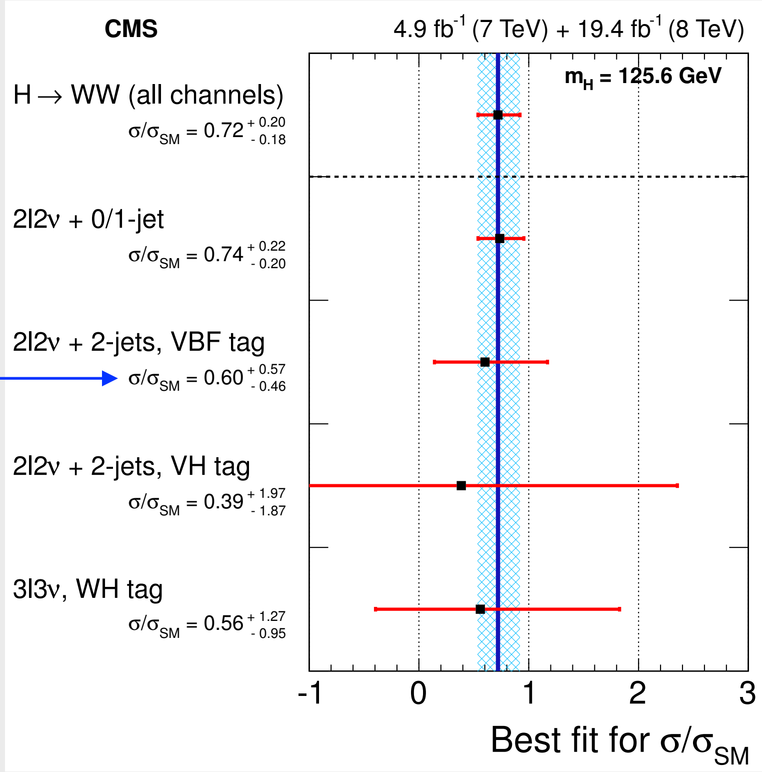


m_{H} [GeV]	ggH	VBF+VH	Data	All bkg.	WW	$\mathrm{VZ} + \mathrm{W}\gamma^{(*)}$ $+\ \mathrm{Z}/\gamma^* \to \ell\ell$	$\mathrm{t\bar{t}} + \mathrm{tW}$	$\mathrm{W} + \mathrm{jets}$
8 TeV $e\mu$ final state, 2-jets category, VBF tag								
120	0.43 ± 0.18	2.06 ± 0.28	2	3.34 ± 0.55	0.75 ± 0.22	0.36 ± 0.12	1.75 ± 0.42	0.48 ± 0.26
125	0.89 ± 0.35	3.41 ± 0.47	2	4.38 ± 0.81	0.86 ± 0.24	0.49 ± 0.14	2.67 ± 0.73	0.36 ± 0.22

VBF *WW** comparison

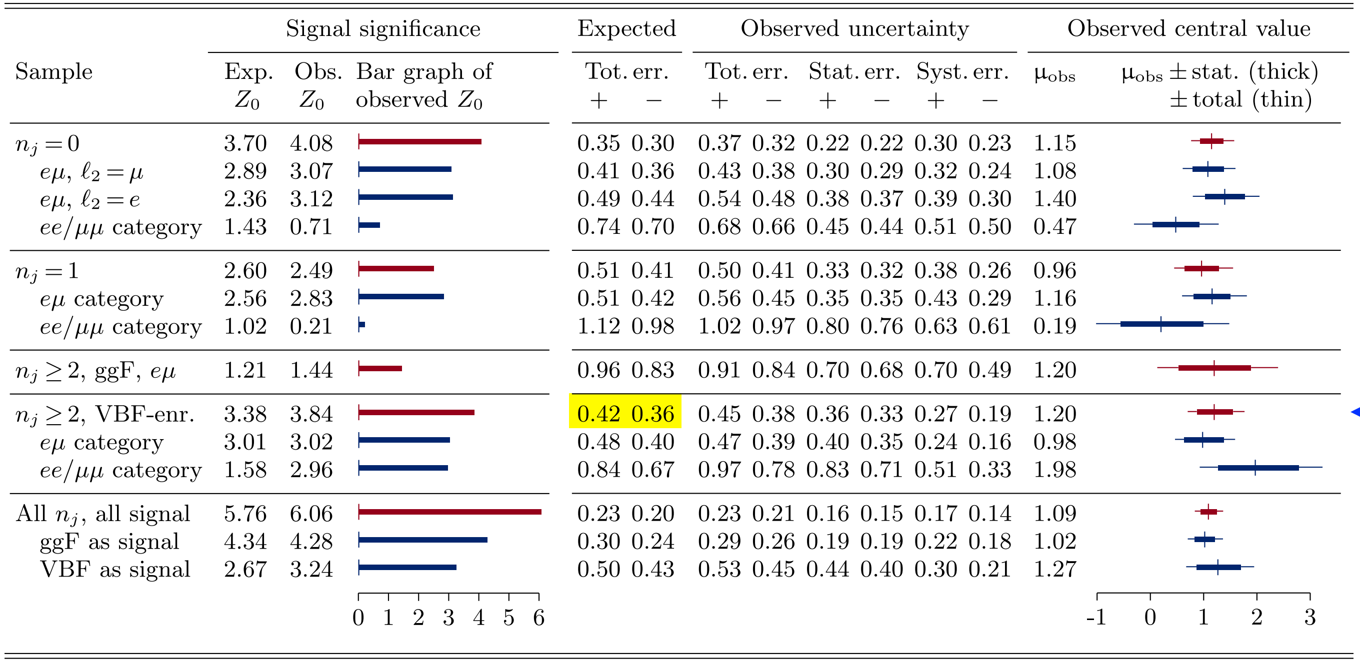
PRD 92 (2015) 012006 v. JHEP 01 (2014) 096

CMS



$+100_{-80}\%$ →

ATLAS



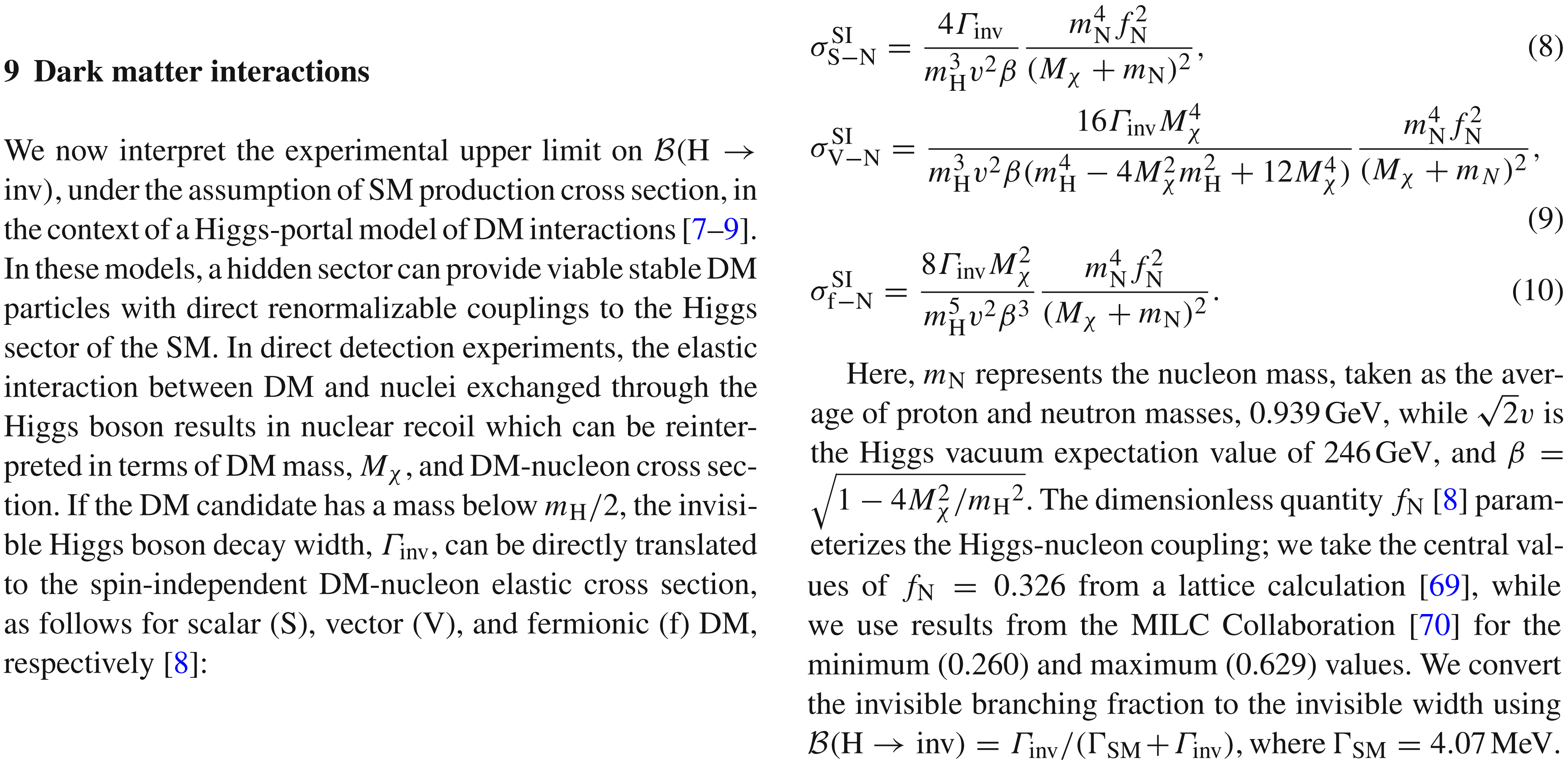
Sample	Signal significance			Expected		Observed uncertainty						Observed central value	
	Exp. Z_0	Obs. Z_0	Bar graph of observed Z_0	Tot. err. +	Tot. err. −	Tot. err. +	Tot. err. −	Stat. err. +	Stat. err. −	Syst. err. +	Syst. err. −	μ_{obs}	μ_{obs} ± stat. (thick) ± total (thin)
$n_j = 0$	3.70	4.08		0.35	0.30	0.37	0.32	0.22	0.22	0.30	0.23	1.15	
$e\mu$, $\ell_2 = \mu$	2.89	3.07		0.41	0.36	0.43	0.38	0.30	0.29	0.32	0.24	1.08	
$e\mu$, $\ell_2 = e$	2.36	3.12		0.49	0.44	0.54	0.48	0.38	0.37	0.39	0.30	1.40	
$ee/\mu\mu$ category	1.43	0.71		0.74	0.70	0.68	0.66	0.45	0.44	0.51	0.50	0.47	
$n_j = 1$	2.60	2.49		0.51	0.41	0.50	0.41	0.33	0.32	0.38	0.26	0.96	
$e\mu$ category	2.56	2.83		0.51	0.42	0.56	0.45	0.35	0.35	0.43	0.29	1.16	
$ee/\mu\mu$ category	1.02	0.21		1.12	0.98	1.02	0.97	0.80	0.76	0.63	0.61	0.19	
$n_j \geq 2$, ggF, $e\mu$	1.21	1.44		0.96	0.83	0.91	0.84	0.70	0.68	0.70	0.49	1.20	
$n_j \geq 2$, VBF-enr.	3.38	3.84		0.42	0.36	0.45	0.38	0.36	0.33	0.27	0.19	1.20	
$e\mu$ category	3.01	3.02		0.48	0.40	0.47	0.39	0.40	0.35	0.24	0.16	0.98	
$ee/\mu\mu$ category	1.58	2.96		0.84	0.67	0.97	0.78	0.83	0.71	0.51	0.33	1.98	
All n_j, all signal	5.76	6.06		0.23	0.20	0.23	0.21	0.16	0.15	0.17	0.14	1.09	
ggF as signal	4.34	4.28		0.30	0.24	0.29	0.26	0.19	0.19	0.22	0.18	1.02	
VBF as signal	2.67	3.24		0.50	0.43	0.53	0.45	0.44	0.40	0.30	0.21	1.27	

← ±40%

Hong
Pittsburgh

Higgs-DM models

CMS Run-1 paper on VBF and *ZH*, EPJC 74 (2014) 2980



9 Dark matter interactions

We now interpret the experimental upper limit on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$, under the assumption of SM production cross section, in the context of a Higgs-portal model of DM interactions [7–9]. In these models, a hidden sector can provide viable stable DM particles with direct renormalizable couplings to the Higgs sector of the SM. In direct detection experiments, the elastic interaction between DM and nuclei exchanged through the Higgs boson results in nuclear recoil which can be reinterpreted in terms of DM mass, M_χ, and DM-nucleon cross section. If the DM candidate has a mass below $m_\mathrm{H}/2$, the invisible Higgs boson decay width, Γ_inv, can be directly translated to the spin-independent DM-nucleon elastic cross section, as follows for scalar (S), vector (V), and fermionic (f) DM, respectively [8]:

$$\sigma^\mathrm{SI}_\mathrm{S-N} = \frac{4\Gamma_\mathrm{inv}}{m_\mathrm{H}^3 v^2 \beta} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_\mathrm{N})^2}, \tag{8}$$

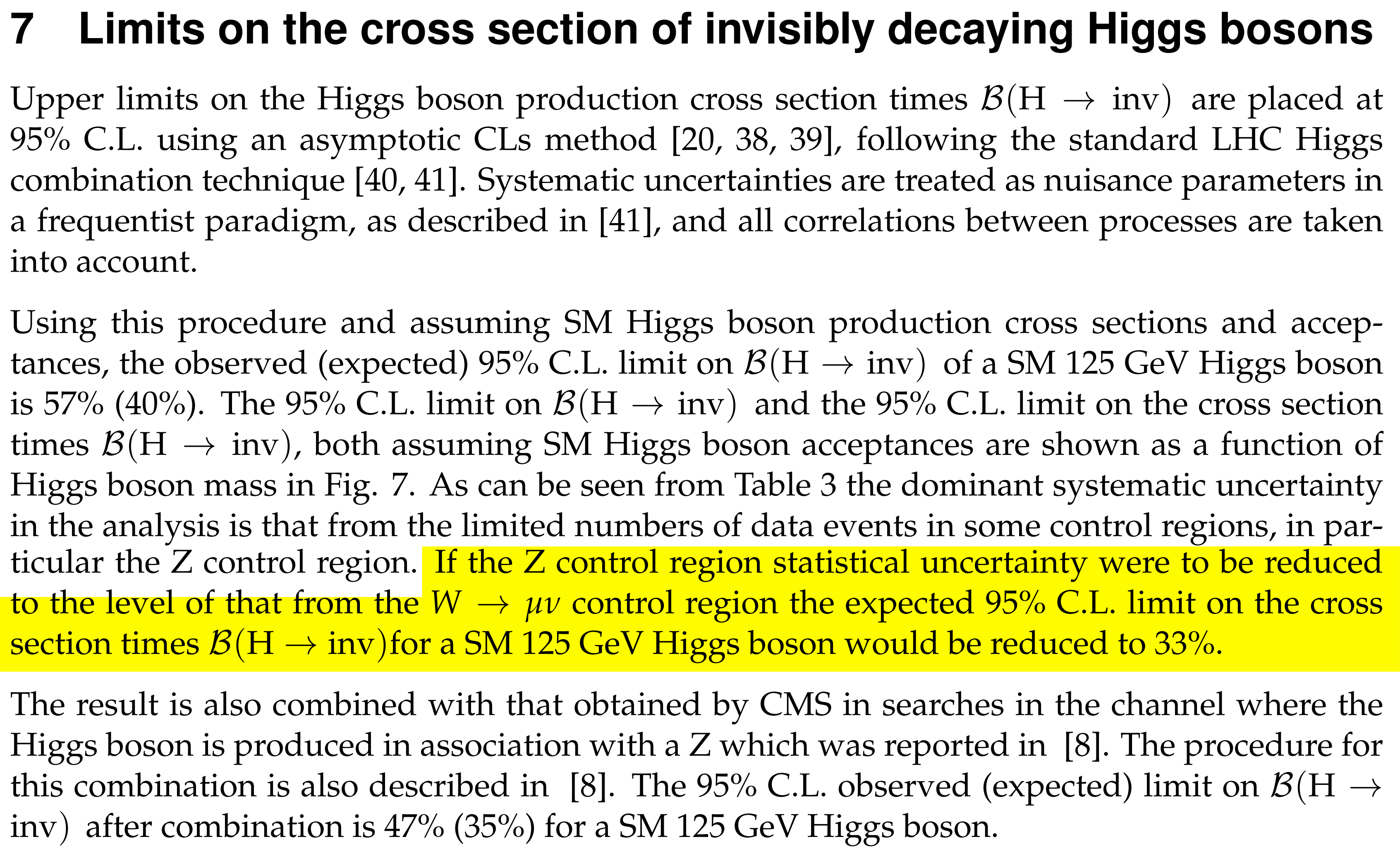
$$\sigma^\mathrm{SI}_\mathrm{V-N} = \frac{16\Gamma_\mathrm{inv} M_\chi^4}{m_\mathrm{H}^3 v^2 \beta (m_\mathrm{H}^4 - 4M_\chi^2 m_\mathrm{H}^2 + 12M_\chi^4)} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_N)^2}, \tag{9}$$

$$\sigma^\mathrm{SI}_\mathrm{f-N} = \frac{8\Gamma_\mathrm{inv} M_\chi^2}{m_\mathrm{H}^5 v^2 \beta^3} \frac{m_\mathrm{N}^4 f_\mathrm{N}^2}{(M_\chi + m_\mathrm{N})^2}. \tag{10}$$

Here, m_N represents the nucleon mass, taken as the average of proton and neutron masses, 0.939 GeV, while $\sqrt{2}v$ is the Higgs vacuum expectation value of 246 GeV, and $\beta = \sqrt{1 - 4M_\chi^2/m_\mathrm{H}{}^2}$. The dimensionless quantity f_N [8] parameterizes the Higgs-nucleon coupling; we take the central values of $f_\mathrm{N} = 0.326$ from a lattice calculation [69], while we use results from the MILC Collaboration [70] for the minimum (0.260) and maximum (0.629) values. We convert the invisible branching fraction to the invisible width using $\mathcal{B}(\mathrm{H} \to \mathrm{inv}) = \Gamma_\mathrm{inv}/(\Gamma_\mathrm{SM} + \Gamma_\mathrm{inv})$, where $\Gamma_\mathrm{SM} = 4.07\,\mathrm{MeV}$.

VBF invisible results CMS Run 1

CMS PAS HIG-14-038



7 Limits on the cross section of invisibly decaying Higgs bosons

Upper limits on the Higgs boson production cross section times $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$ are placed at 95% C.L. using an asymptotic CLs method [20, 38, 39], following the standard LHC Higgs combination technique [40, 41]. Systematic uncertainties are treated as nuisance parameters in a frequentist paradigm, as described in [41], and all correlations between processes are taken into account.

Using this procedure and assuming SM Higgs boson production cross sections and acceptances, the observed (expected) 95% C.L. limit on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$ of a SM 125 GeV Higgs boson is 57% (40%). The 95% C.L. limit on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$ and the 95% C.L. limit on the cross section times $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$, both assuming SM Higgs boson acceptances are shown as a function of Higgs boson mass in Fig. 7. As can be seen from Table 3 the dominant systematic uncertainty in the analysis is that from the limited numbers of data events in some control regions, in particular the Z control region. If the Z control region statistical uncertainty were to be reduced to the level of that from the $W \to \mu\nu$ control region the expected 95% C.L. limit on the cross section times $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$for a SM 125 GeV Higgs boson would be reduced to 33%.

The result is also combined with that obtained by CMS in searches in the channel where the Higgs boson is produced in association with a Z which was reported in [8]. The procedure for this combination is also described in [8]. The 95% C.L. observed (expected) limit on $\mathcal{B}(\mathrm{H} \to \mathrm{inv})$ after combination is 47% (35%) for a SM 125 GeV Higgs boson.

VBF invisible syst. for ATLAS Run 1

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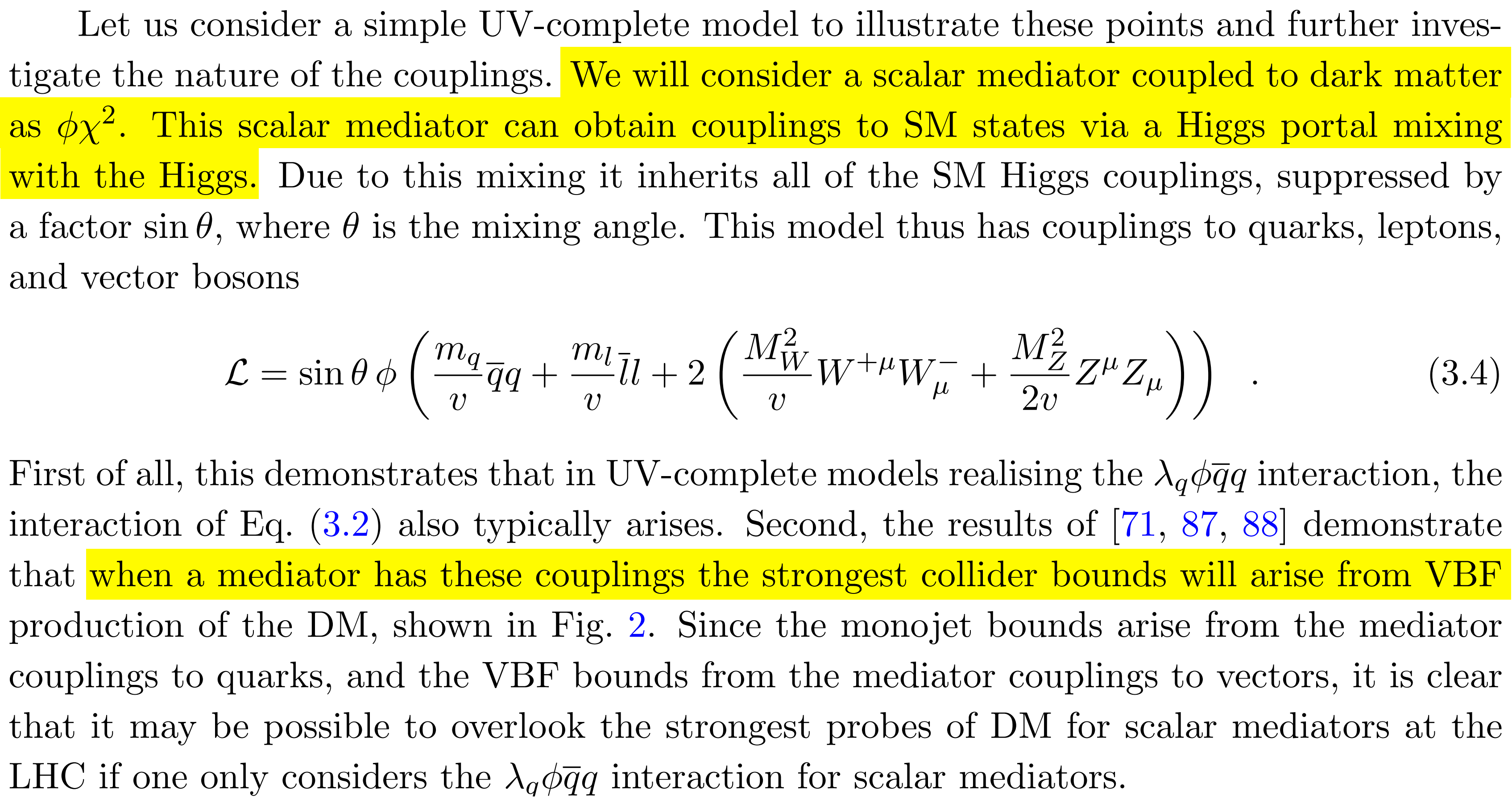
Uncertainty	VBF	ggF	Z or W	$Z_{\mathrm{SR}}/W_{\mathrm{CR}}$ or $W_{\mathrm{SR}}/W_{\mathrm{CR}}$
Jet energy scale	16 9	43 12	17–33 0–11	3–5 1–4
Jet energy resolution	Negligible 3.1	Negligible 3.2	Negligible 0.2–7.6	Negligible 0.5–5.8
Luminosity	2.8	2.8	2.8	Irrelevant
QCD scale	0.2	7.8	5–36 7.5–21	7.8–12 1–2
PDF	2.3 2.8	7.5	3–5 0.1–2.6	1–2
Parton shower	4.4	41 29	9–10	5
Veto on third jet			Negligible	Negligible
Higgs boson p_{T}	Negligible	9.7	Irrelevant	Irrelevant
MC statistics	2 0.6	46 13	2.3–6.4 0.8–4.5	3.3–6.6

Table 7. Detector and theory uncertainties (%) after all SR or CR selections. For each source of uncertainty, where relevant, the first and second rows correspond to the uncertainties in SR1 and SR2 respectively. The ranges of uncertainties in the Z or W column correspond to uncertainties in the Z+jets and W+jets MC yields in the SR or CR. The search uses the uncertainties in the ratios of SR to CR yields shown in the last column.

Fermiophobic scalars

https://arxiv.org/abs/1604.07975 (27 April 2016)



Let us consider a simple UV-complete model to illustrate these points and further investigate the nature of the couplings. We will consider a scalar mediator coupled to dark matter as $\phi\chi^2$. This scalar mediator can obtain couplings to SM states via a Higgs portal mixing with the Higgs. Due to this mixing it inherits all of the SM Higgs couplings, suppressed by a factor $\sin\theta$, where θ is the mixing angle. This model thus has couplings to quarks, leptons, and vector bosons

$$\mathcal{L} = \sin\theta\,\phi\left(\frac{m_q}{v}\bar{q}q + \frac{m_l}{v}\bar{l}l + 2\left(\frac{M_W^2}{v}W^{+\mu}W_\mu^- + \frac{M_Z^2}{2v}Z^\mu Z_\mu\right)\right) \quad . \tag{3.4}$$

First of all, this demonstrates that in UV-complete models realising the $\lambda_q\phi\bar{q}q$ interaction, the interaction of Eq. (3.2) also typically arises. Second, the results of [71, 87, 88] demonstrate that when a mediator has these couplings the strongest collider bounds will arise from VBF production of the DM, shown in Fig. 2. Since the monojet bounds arise from the mediator couplings to quarks, and the VBF bounds from the mediator couplings to vectors, it is clear that it may be possible to overlook the strongest probes of DM for scalar mediators at the LHC if one only considers the $\lambda_q\phi\bar{q}q$ interaction for scalar mediators.

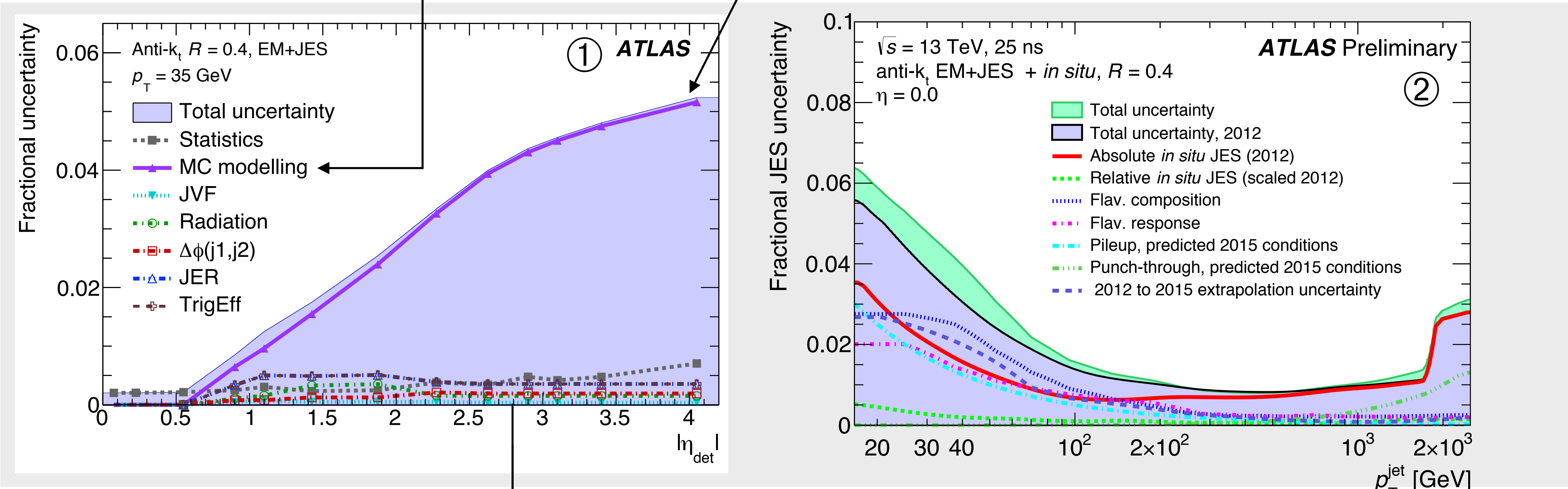
If ϕ is fermiophobic, mono-jet isn't the best (VBF may be).

Jet energy uncertainties

ATLAS performance

Extra parton radiation altering the p_T balance. Pythia v. Herwig++

- 5% for 35 GeV
- 3% for 350 GeV



use jets < 0.8

value at 2.8
dijet balance

v. $Z_{\ell\ell}$

v. photon

v. Σ(calib. jets)

1 particle

① *Jet energy measurement and its systematic uncertainty in proton-proton collisions at √s = 7 TeV with the ATLAS detector*, EPJC 75 (2015) 17.

② *Jet calibration and systematic uncertainties for jets reconstructed in the ATLAS detector at √s=13 TeV*, ATL-PHYS-PUB-2015-015 (24 July 2015).

LUX latest results this week

PRL 116 (2016) 161301, 161302

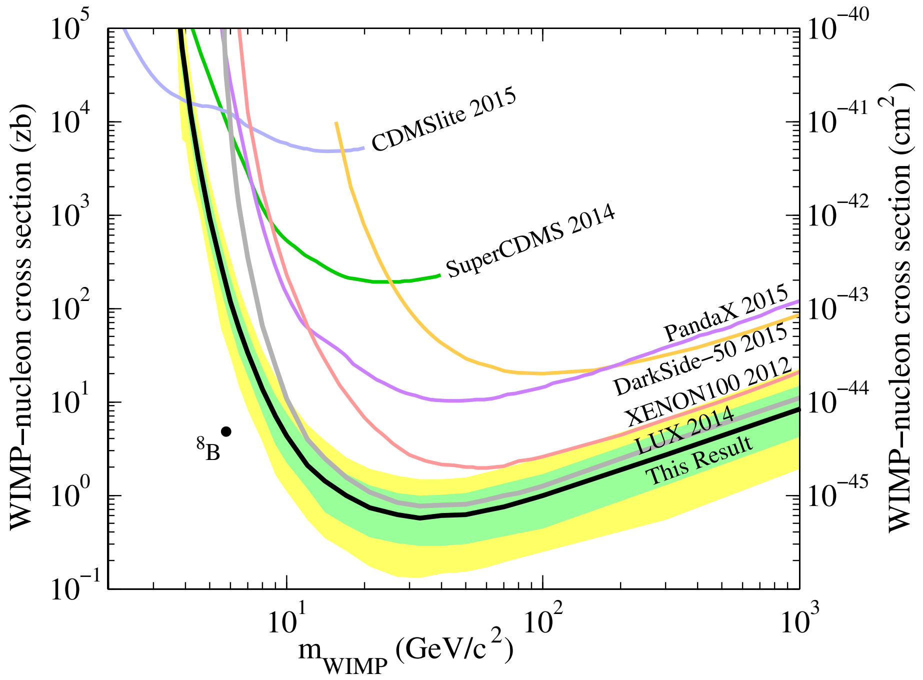


FIG. 3. Upper limits on the spin-independent elastic WIMP-nucleon cross section at 90% C.L. Observed limit in black, with the 1- and 2-σ ranges of background-only trials shaded green and yellow. Also shown are limits from the first LUX analysis [6] (gray), SuperCDMS [40] (green), CDMSlite [41] (light blue), XENON100 [42] (red), DarkSide-50 [43] (orange), and PandaX [44] (purple). The expected spectrum of coherent neutrino-nucleus scattering by ^{8}B solar neutrinos can be fit by a WIMP model as in [45], plotted here as a black dot.

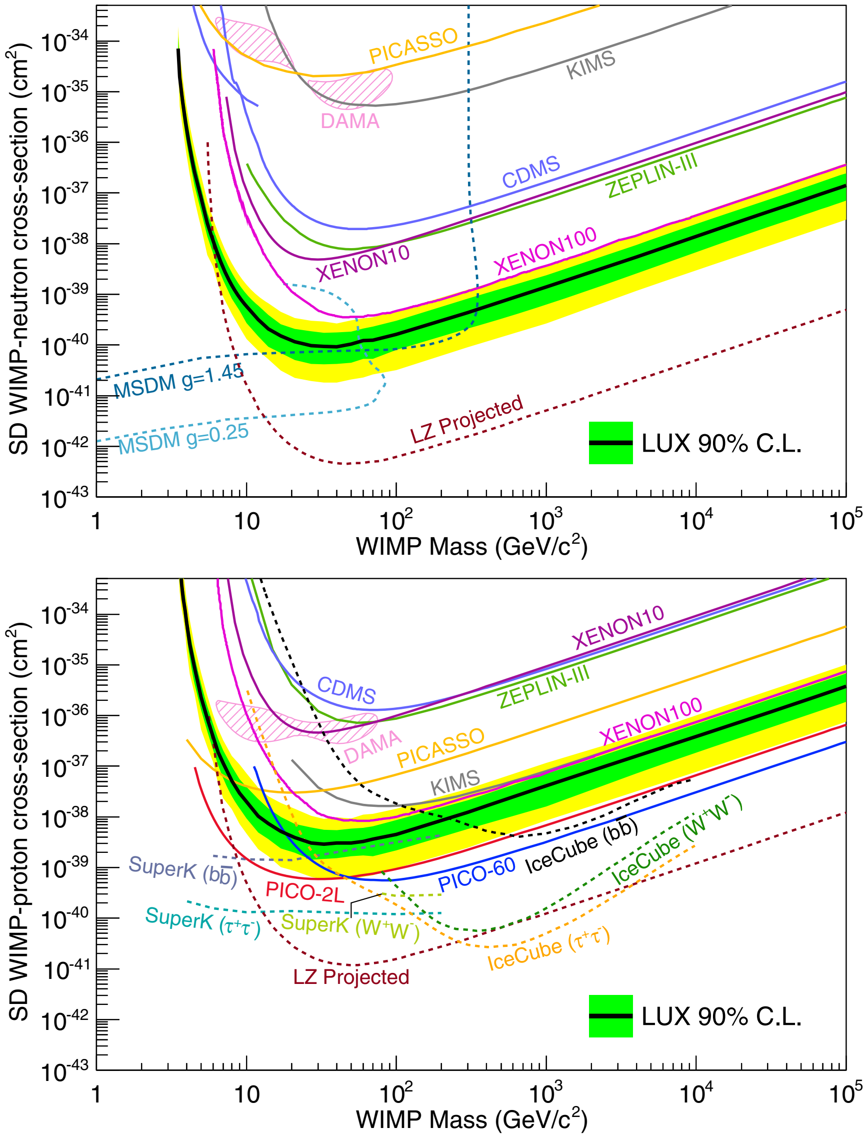


FIG. 1. LUX upper limits on the WIMP-neutron (top) and -proton (bottom) elastic SD cross sections at 90% C.L. The observed limit is shown in black with the $\pm1\sigma$ ($\pm2\sigma$) band from simulated background-only trials in green (yellow). Also shown