Invisible Higgs decays in Vector Boson Fusion

Othmane Rifki

LHC discussion on Dark Matter

23. Sep 2018

Outline

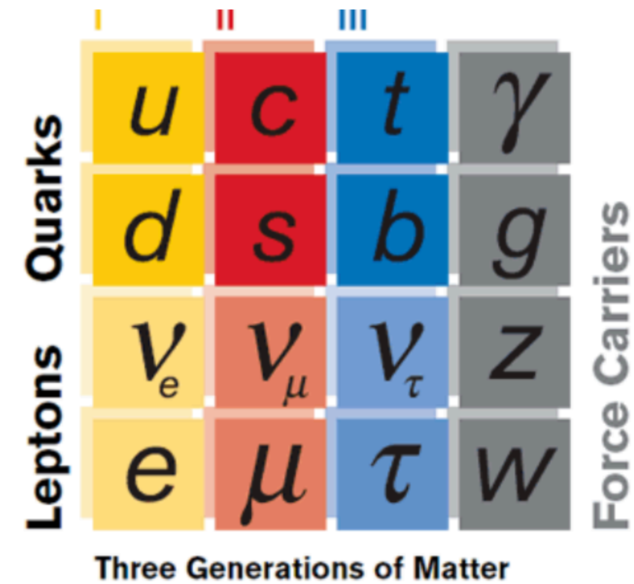
- Why search for Higgs to Invisible?
- Vector boson fusion channel (VBF)
- Other Higgs to invisible limits
- Global fits from visible decays
- Higgs portal interpretation

Motivation

Higgs (H) is a special probe for **Dark Matter** (**DM**)

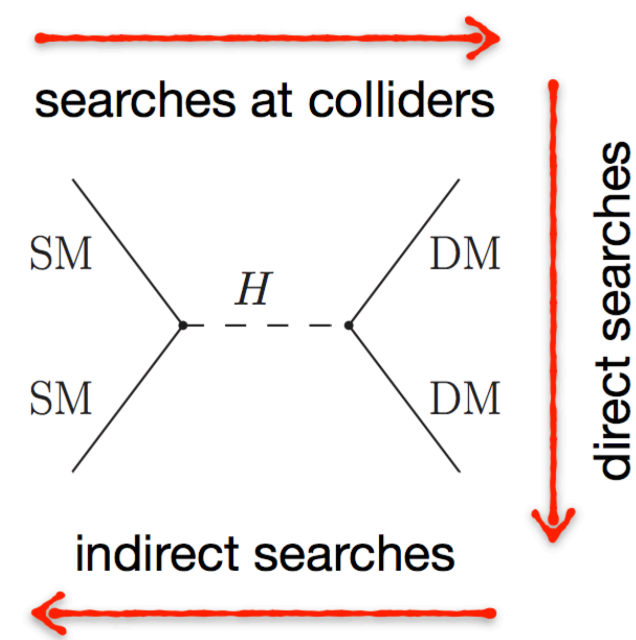
Dark Sector

Higgs



- DM may "live" in some Dark Sector and not charged under gauge groups of the SM
- Higgs could have some coupling to the Dark Sector, i.e "Higgs Portal"
- Higgs acting as mediator between SM and DM

➡**Direct production at the LHC**



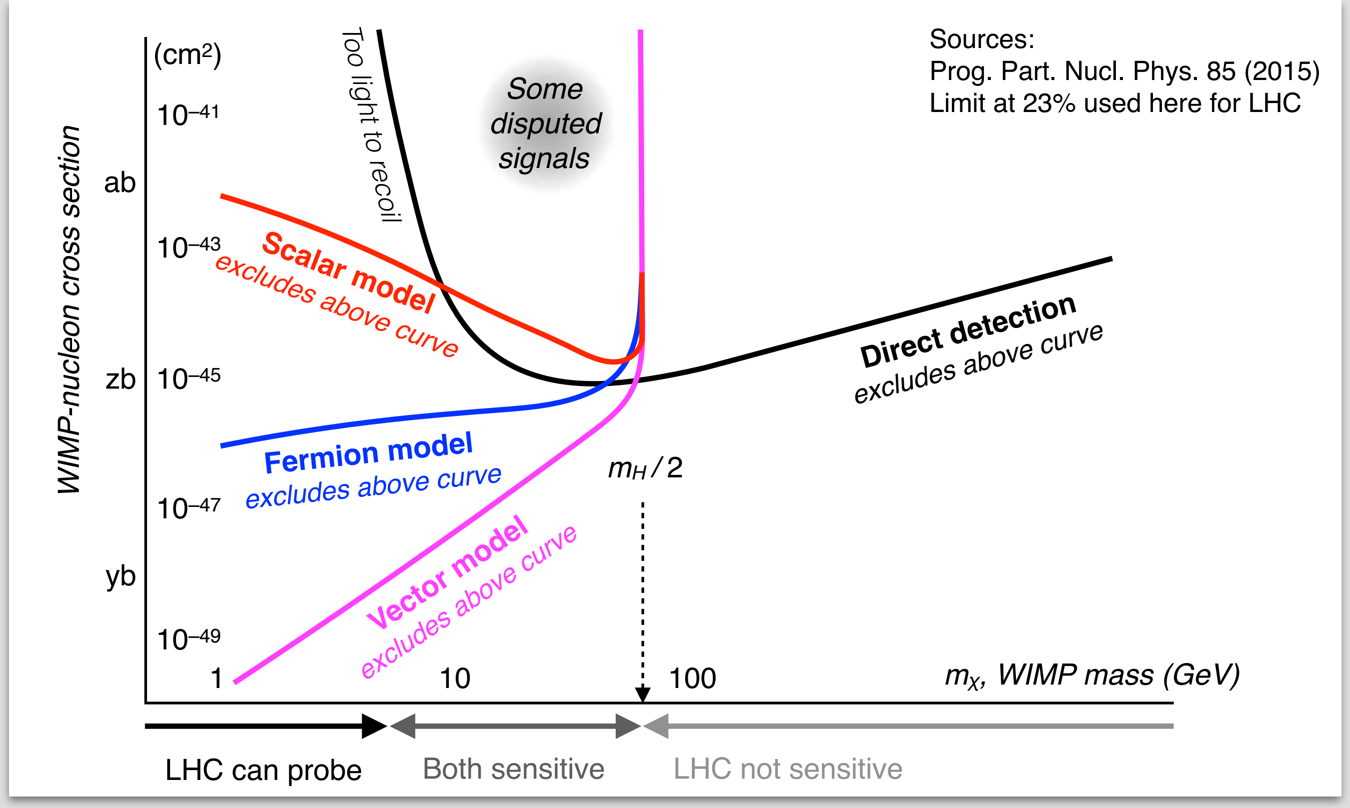
Motivation

- In the SM, H > Invisible only from H > ZZ > νννν with B(H > inv) = 0.026 x 0.20^2 = 0.1 %

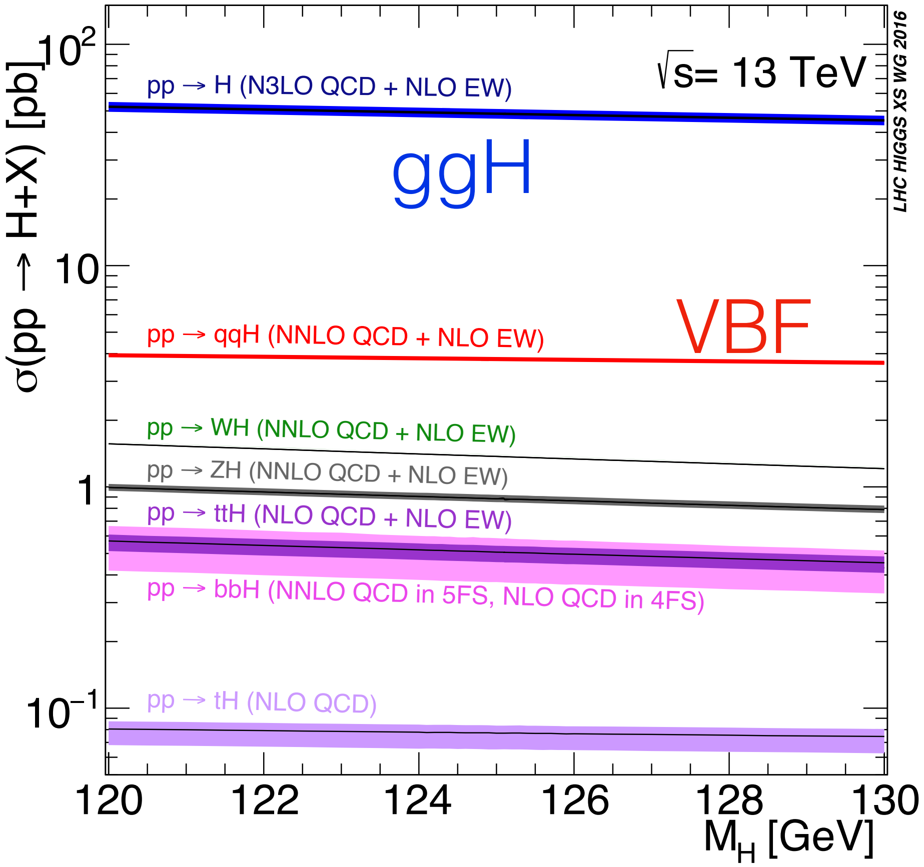
  Any deviation would indicate BSM physics!
- Higgs to Invisible searches are powerful for $m_{DM} \leq m_H/2$

Dark matter interpretation of invisible Higgs

Limit on *B(H → invisible)* with Higgs-DM portal results in colored exclusion curves.

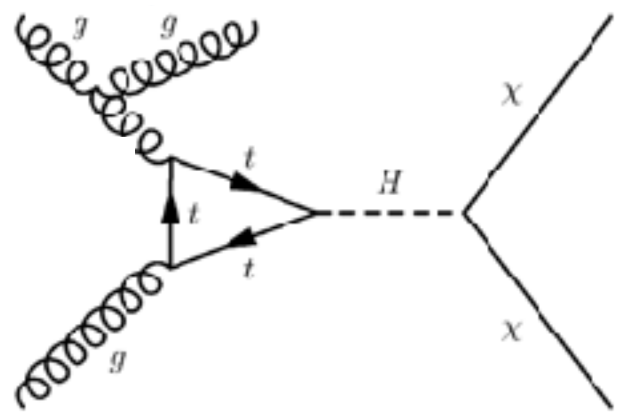


Why VBF?



ggH production is much larger than VBF

Why not use ggH?



1. ggH would need to be boosted by an extra gluon in the event
   VBF has some natural boost
2. qq > Z > vv background is much larger than ggH production

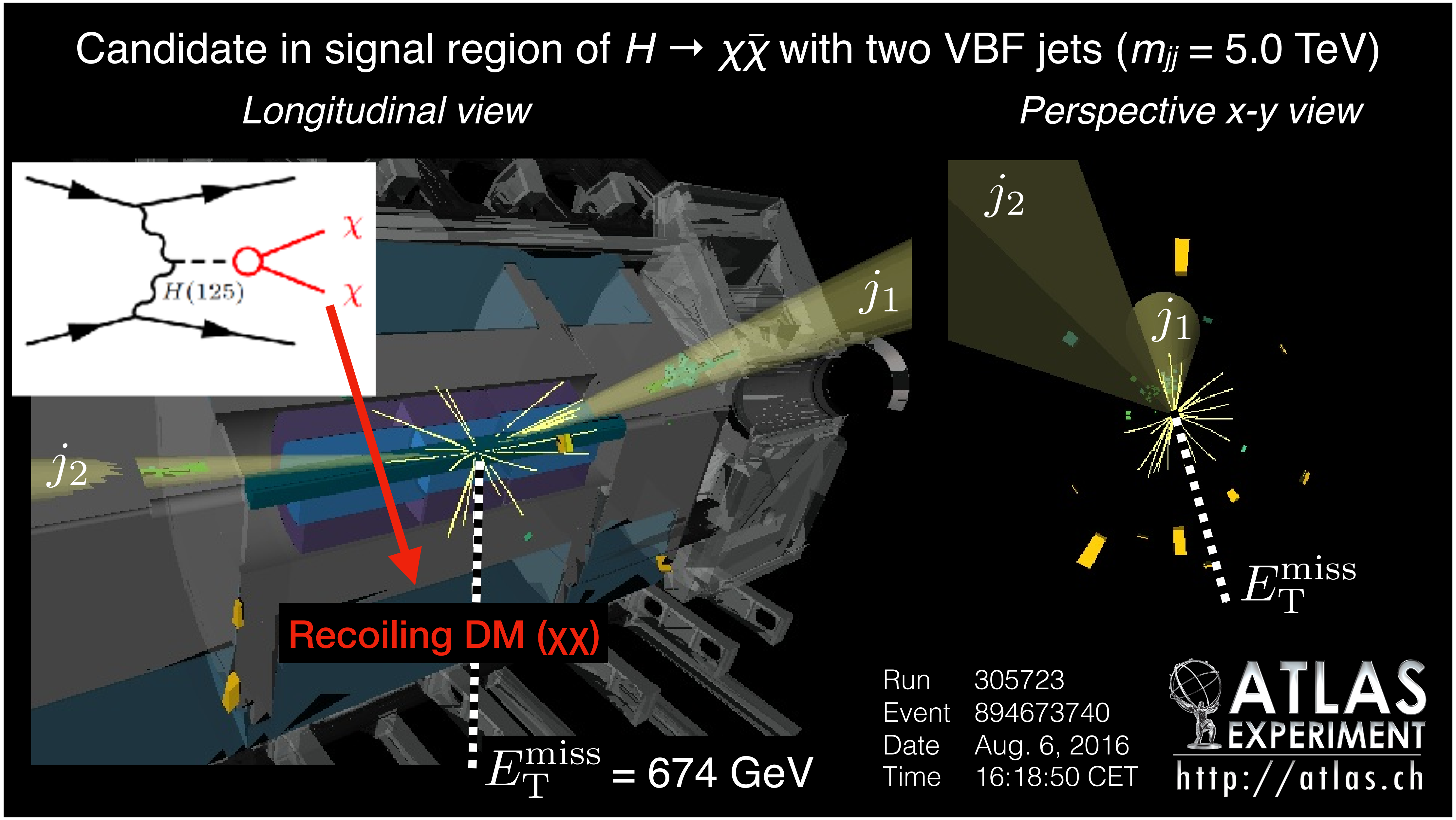
$$\frac{\sigma(\text{ggH})}{\sigma(Z)\times BR(Z\rightarrow \nu\nu)} = \frac{\approx 45pb}{\approx 8422pb}$$

$$\frac{\sigma(\text{VBF H})}{\sigma(\text{VBF } Z)\times BR(Z\rightarrow \nu\nu)} = \frac{\approx 3.8pb}{\approx 2.9pb}$$

Focus on processes where signal ~ background

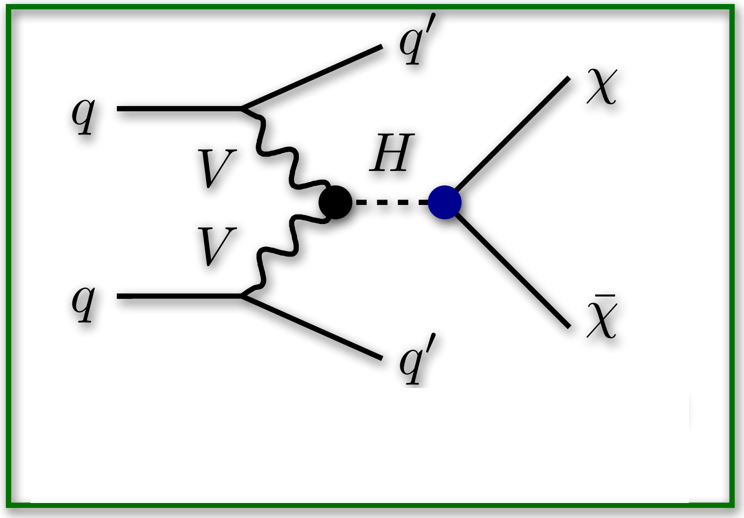
VBF Topology

- 2 well-separated jets
- Large missing transverse momentum

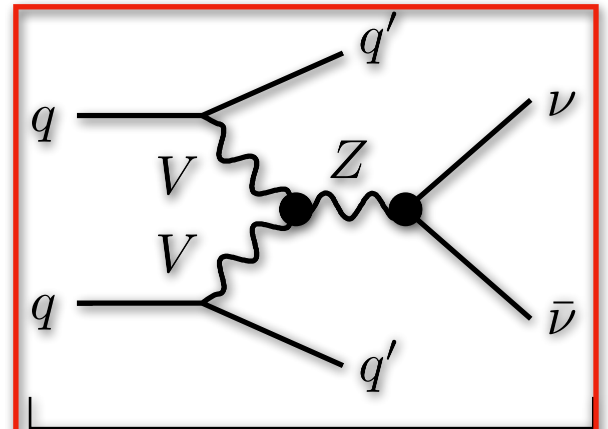


Signal and Background

Signal

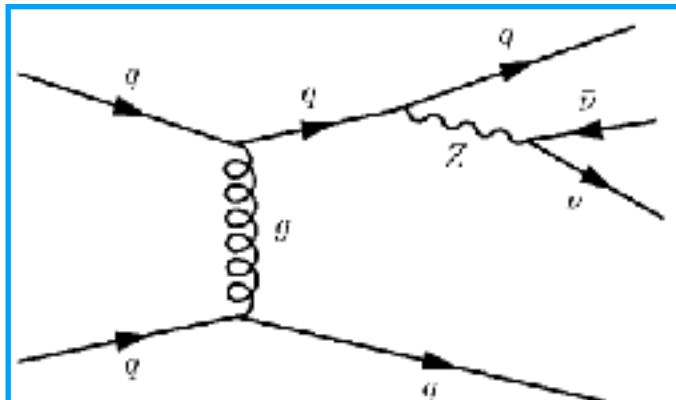


Irreducible Background

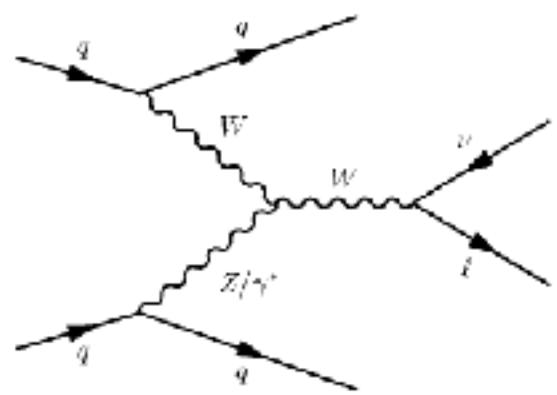


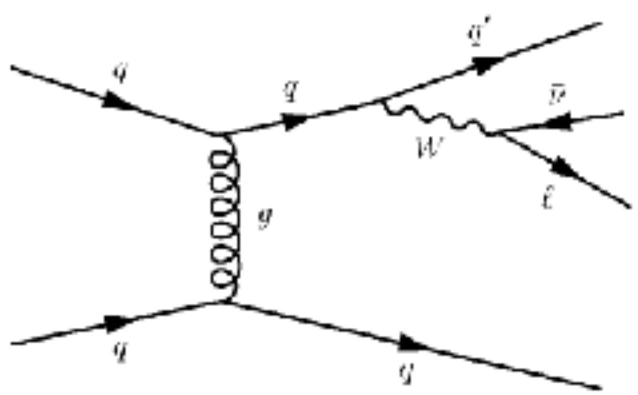
$Z + 2j$ *via weak process*

Reducible Background



+ many other diagrams





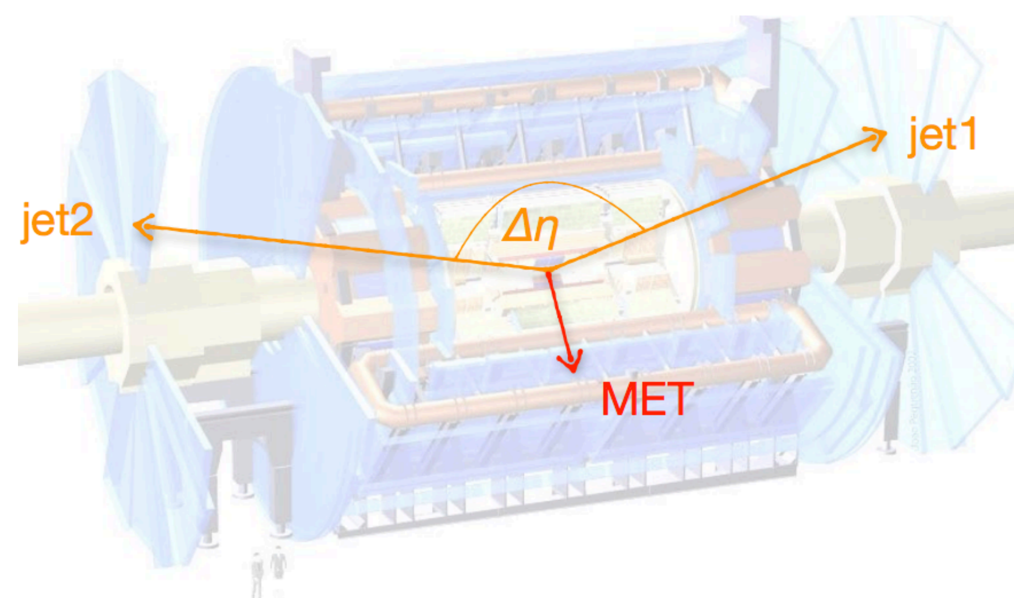
Z+2j via strong process

Both strong and weak W > lv (lost lepton)

Selection

Basic 2-jet+MET Selection

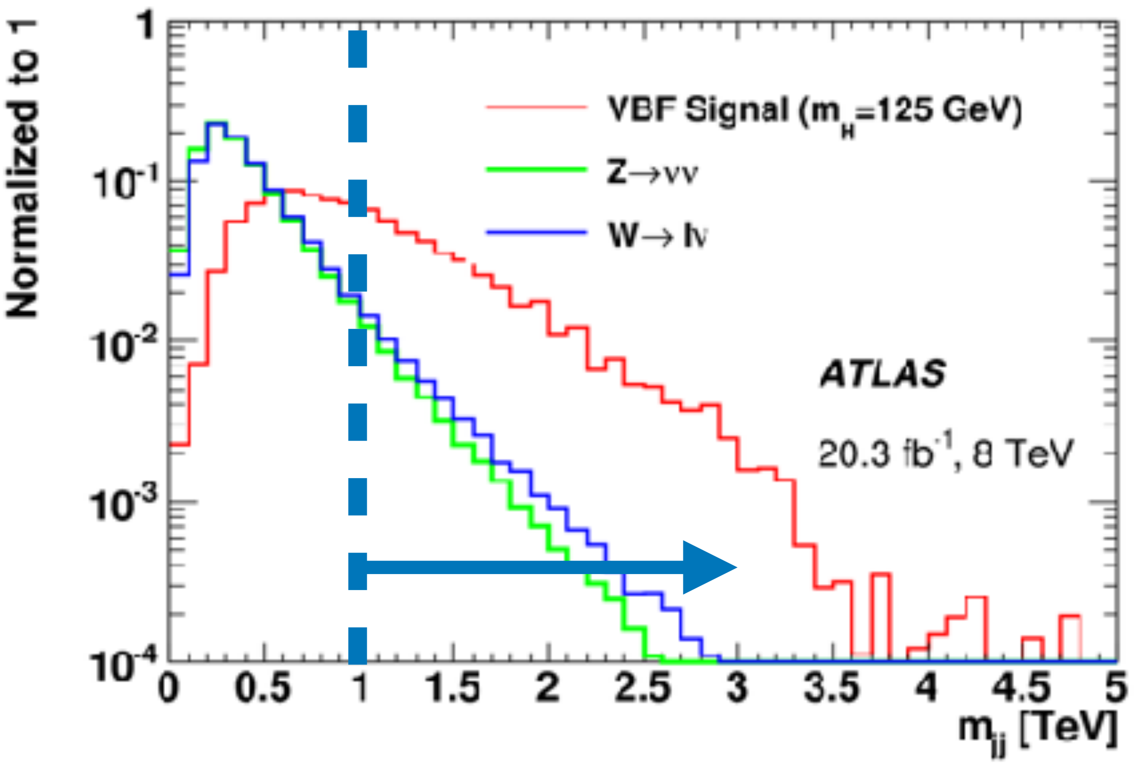
- Jet 1: pT > 80 GeV
- Jet 2: pT > 50 GeV
- Veto 3rd jet above 25 GeV
- MET > 180 GeV (determined by trigger)



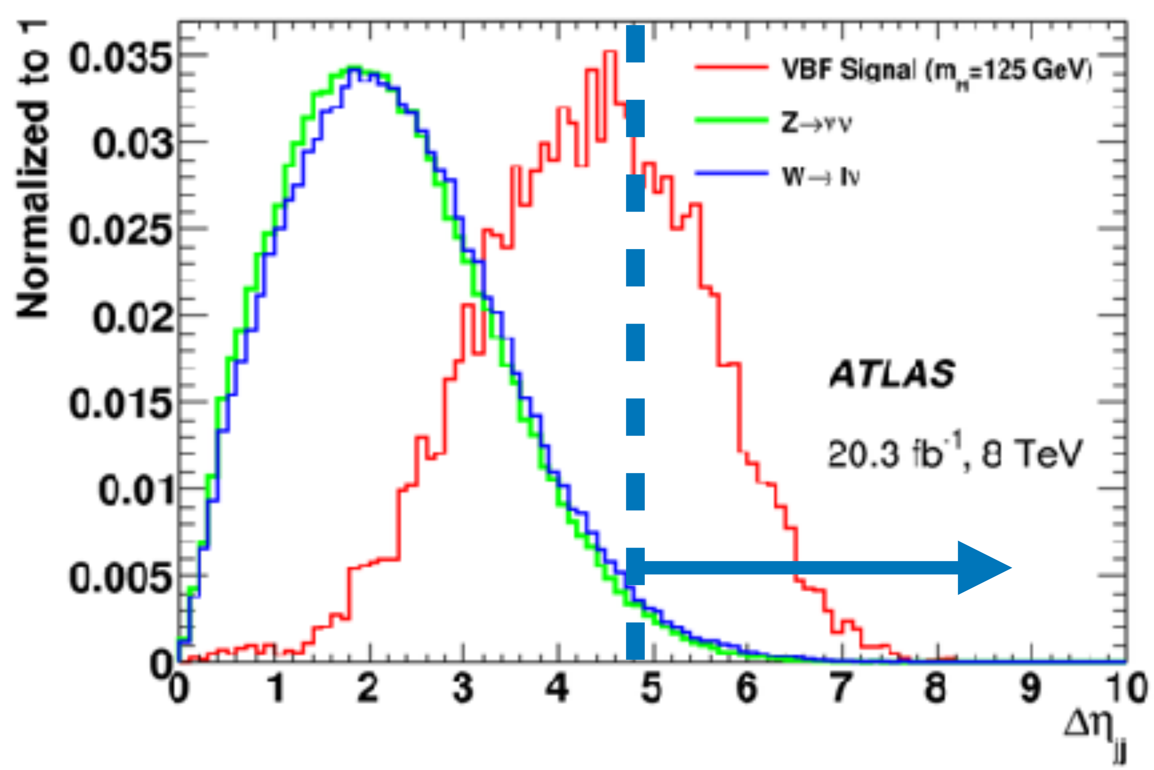
MET cleaning

- |DPhi(j,MET)| > 1
- |DPhi(j,j)| < 1.8

m_{jj} > 1 TeV

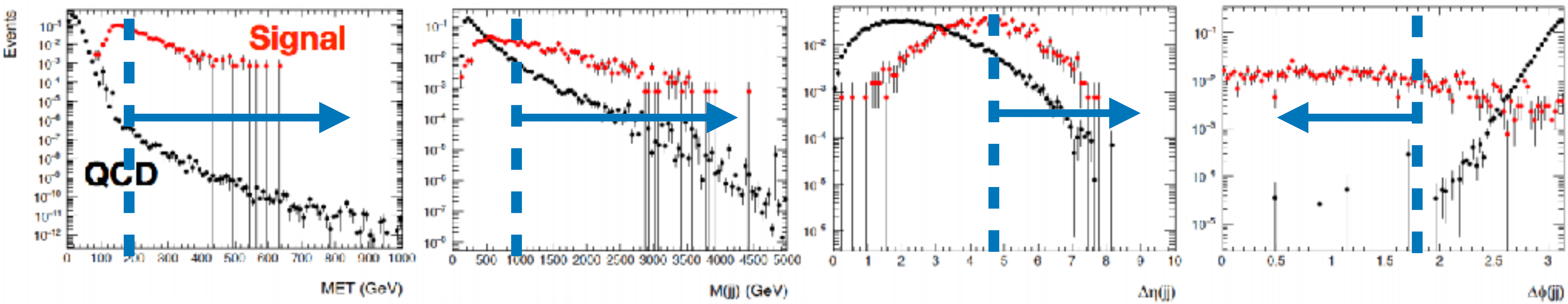


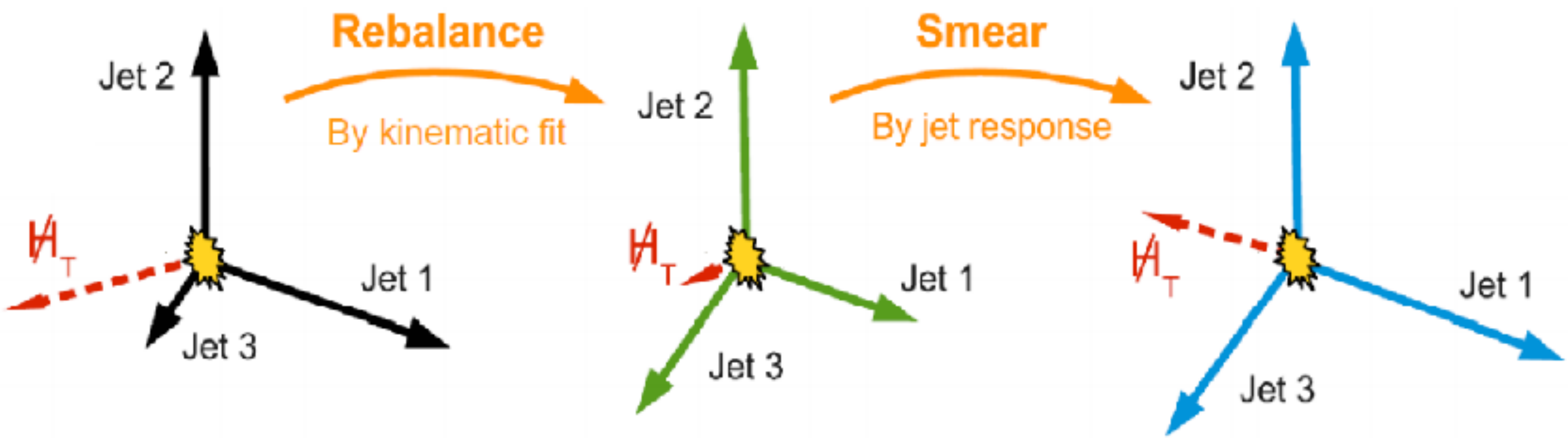
$\Delta\eta_{jj}$ > 4.8



Multijet Background

QCD multijet background is small for analysis selection
Difficult to estimate since it is due to instrumental effect





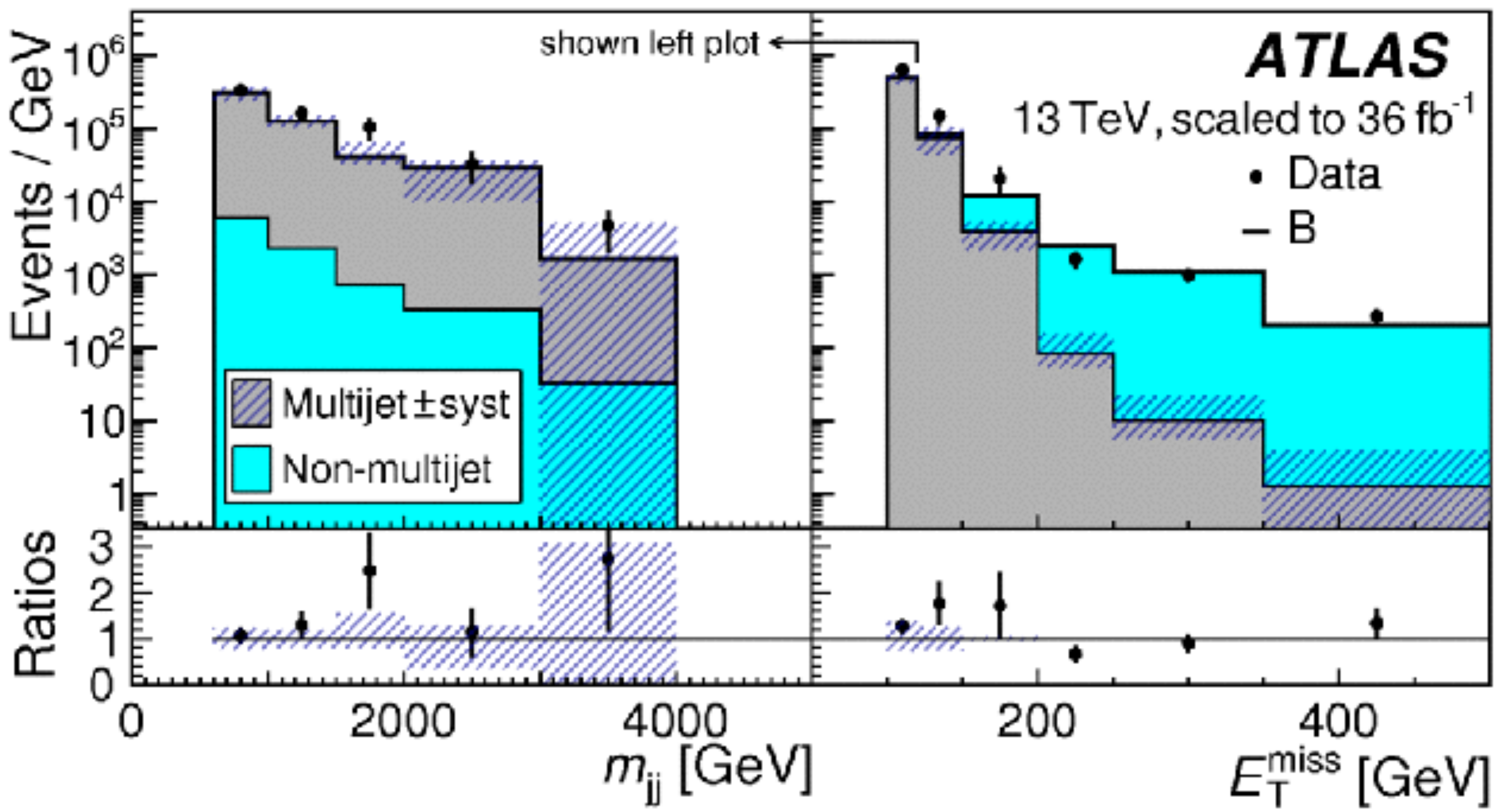
Seed: Single jet triggers

Vary jet pT, minimize MET
Based on jet resolution
Sample of events with no MET

Randomly vary jet pT according to known resolution

Multijet Background

Multijet background under control



~10 events in SR

Multijet events also contribute to regions with electrons if one jet is mis-identified as electron

- Additional MET significance requirement (high and low MET sig. used in fit)

$$E_T^{miss}\text{ sig.} = \frac{E_T^{miss}}{\sqrt{p_T(j1) + p_T(j2) + p_T(el)}}$$

Backgrounds

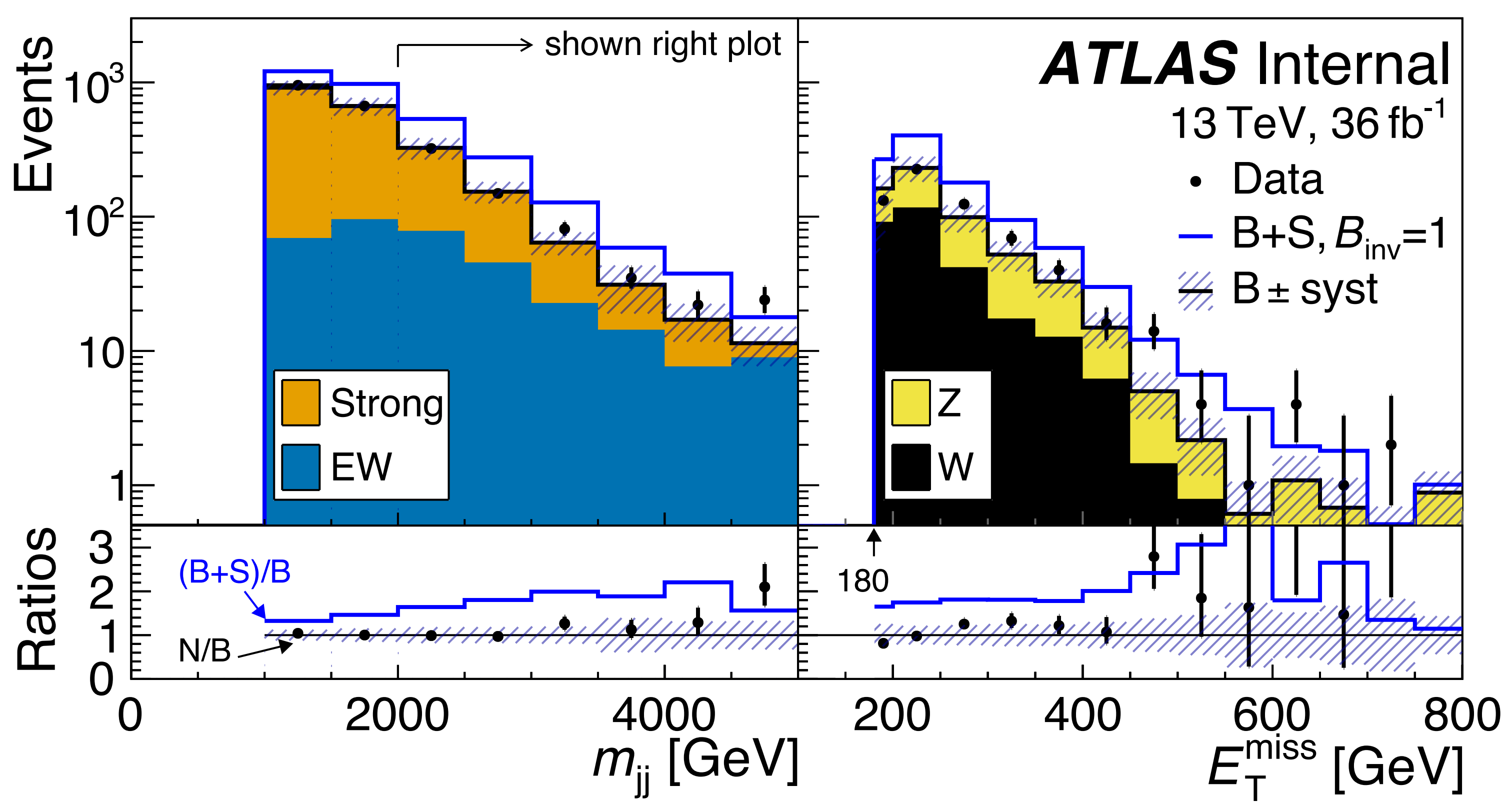
W and Z backgrounds are ~50/50

Small top and diboson background from MC
Multijet reduced by SR cuts
Background estimation next…

Description	SR Yield [EW]
N, observed	2252
B, expected	2243
$Z \to \nu\nu$	1111 [18%]
$Z \to ee, \mu\mu$	12 [9%]
$Z \to \tau\tau$	10 [16%]
$W \to e\nu, \mu\nu$	540 [16%]
$W \to \tau\nu$	533 [20%]
Other	36
S, signal	1070
VBF	930
Gluon fusion	140

Signal for 100% branching fraction

Larger EW fraction at higher Mjj



Background Modelling

Statical uncertainty: 1/sqrt(2252) ~ 2%

Systematic uncertainty: ~20%

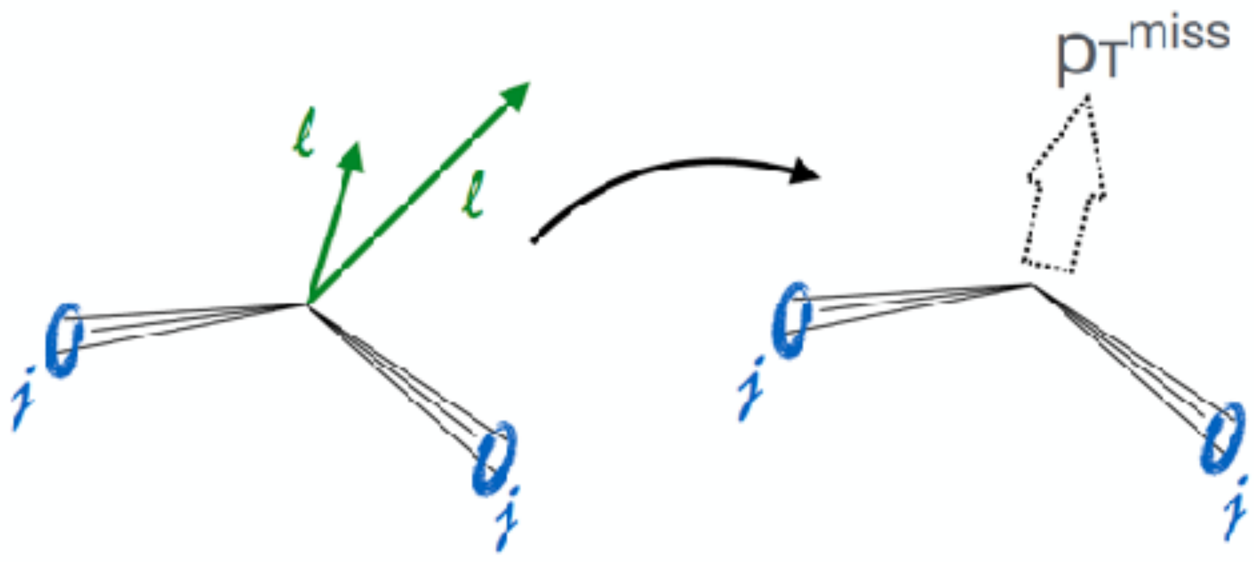
- Modelling of underlying physics of W or Z + 2 jets
- Jet uncertainties (forward jets, jet veto)

MC systematics are too large to exploit the full statistics!

Solution: Use Z>ll and W>lv data with found leptons to model Z>vv and W>lv (with lost lepton)

Define control regions:

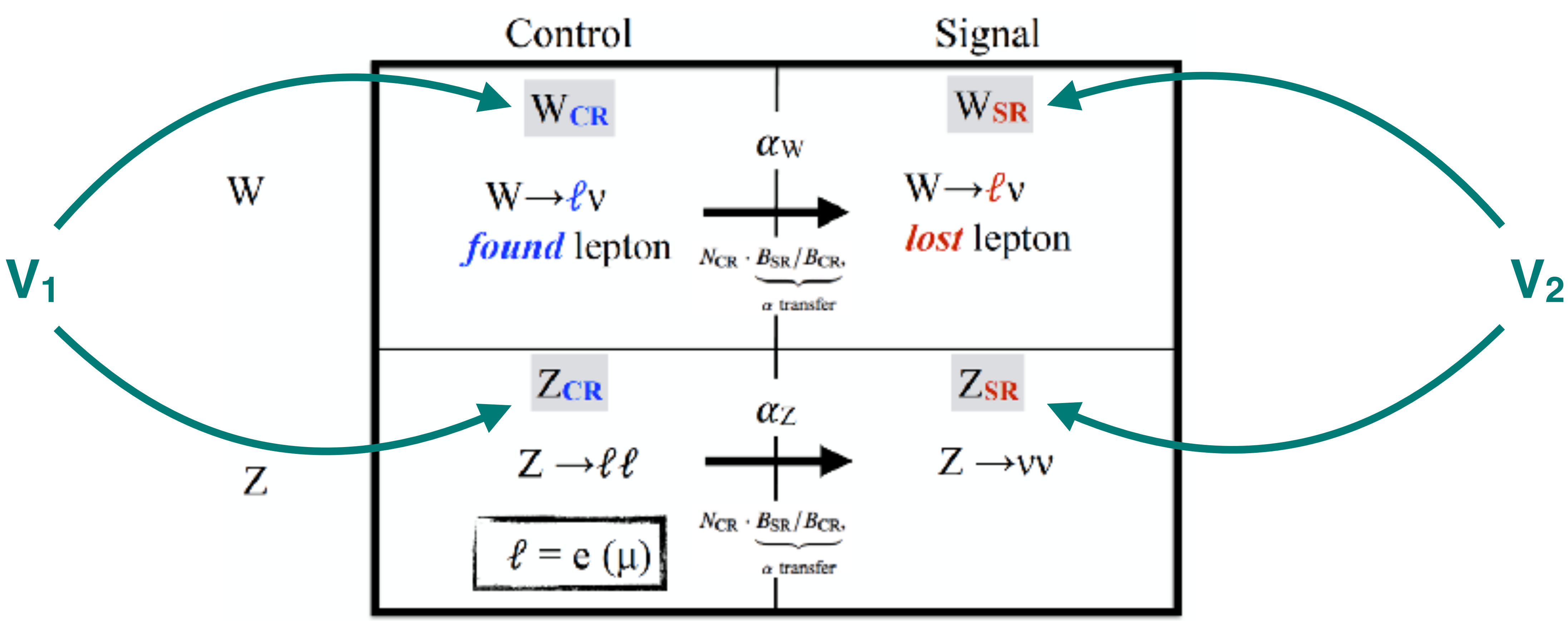
- Z CR: 2-leptons, use **ll-system** instead of **MET**
- W CR: 1-lepton, add **1-lepton** pT to the **MET**



Background Modelling

Use precise measurement of V1 to get an improved prediction for V2:

$$\frac{d\sigma(V_2)}{dx} = \left[\frac{d\sigma(V_2)/dx}{d\sigma(V_1)/dx}\right]_{\text{theory}} \times \left[\frac{d\sigma(V_1)}{dx}\right]_{\text{measured}}$$



Simultaneous fit to **signal region** and **Z and W control regions** leads to cancellation of important theory uncertainties

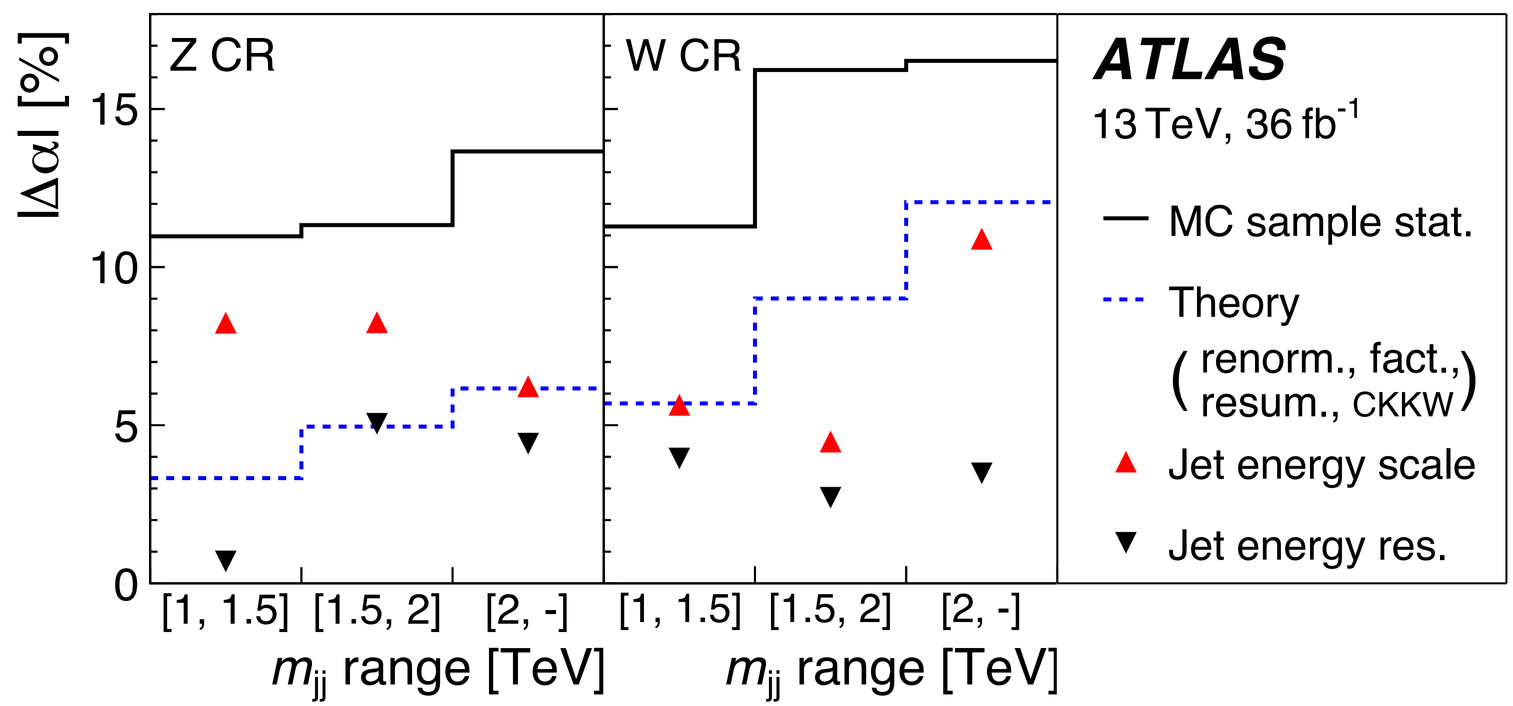
Uncertainties

Systematics reduction with ratio method:

Source	$\mathcal{B}_{\text{inv}}$ improve. [%] using all m_{jj} bins: Δ	visual	Yields, α changes (%) in $1<m_{jj}<1.5$ TeV: S	B^Z_{SR}	B^Z_{CR}	α_Z	α_W
Experimental (†)							
Jet energy scale	10		12	7	8	8	6
Jet energy resol.	2		2	0	1	1	4
E_T^{miss} soft term	1		2	2	2	2	2
Lepton id., veto	2		-	-	-	-	4
Pileup distrib.	1		3	1	2	3	1
Luminosity	0		2	2	2	-	-
Theoretical (‡)							
Resum. scale	1		-	2	3	0	2
Renorm., fact.	2		-	20	19	1	2
CKKW matching	4		-	2	3	1	5
PDF	0		1	1	2	1	1
3rd jet veto	2		7	-	-	-	-
Statistical							
MC sample (⋆)	12		4	5	9	10	9
Data sample	21		6	5	12	12	6
Combined							
All † sources	17						
All ‡ sources	10						
Combine †, ‡	28						
Combine †, ‡, ⋆	42						

QCD scale variations are treated as correlated

Many uncertainties due to MC stat!



$$B_{SR}^{est} = B_{SR}\cdot \underbrace{N_{CR}/B_{CR}}_{k\ \text{normalization}} = N_{CR}\cdot \underbrace{B_{SR}/B_{CR}}_{\alpha\ \text{factor}}$$

Fit Model

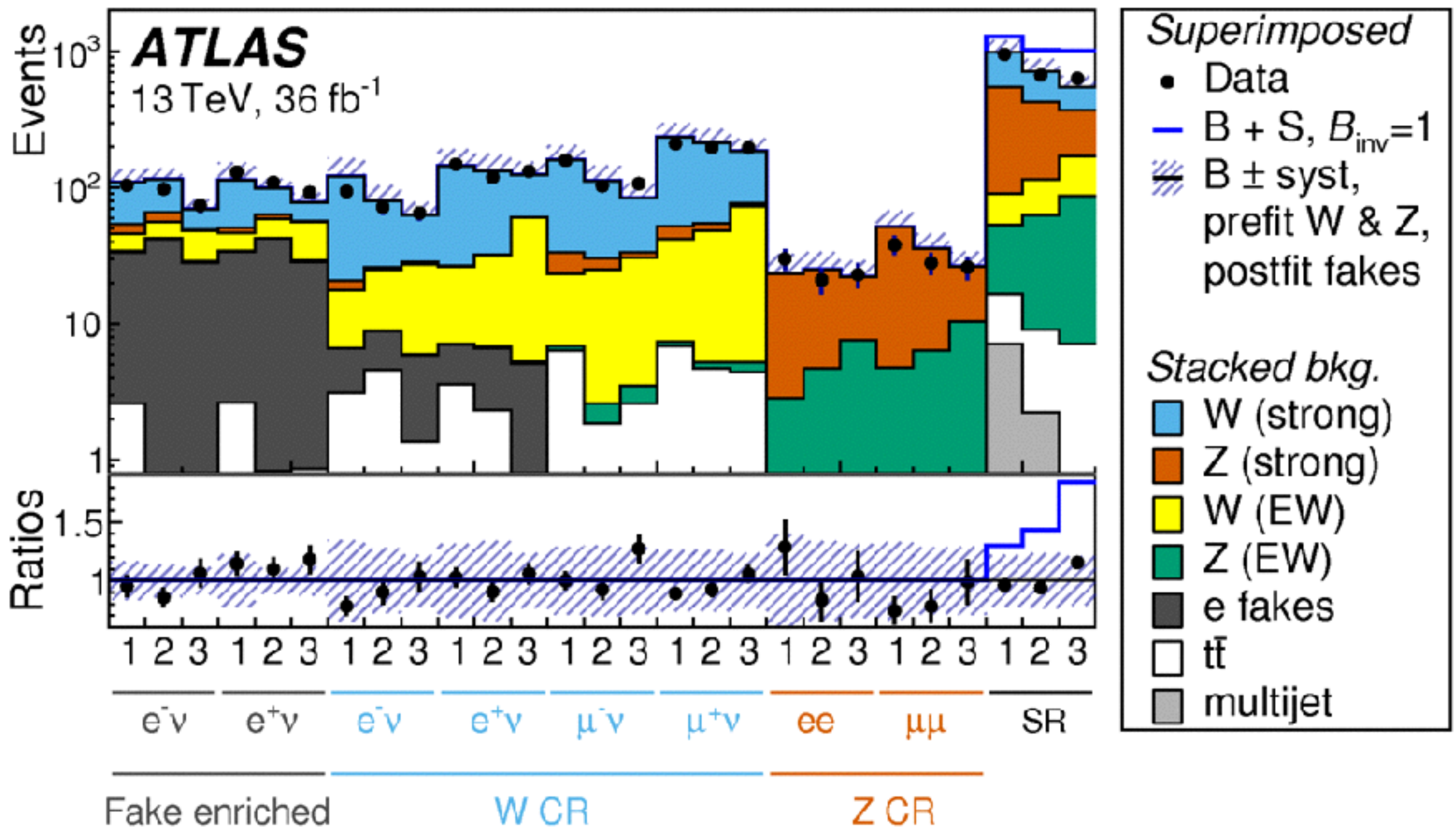
Global likelihood fit using **8 control region bins** for each **signal region bin**

- Signal region bins defined in Mjj: **1-1.5TeV, 1.5 - 2TeV, > 2TeV**
- Each **Mjj bin is treated independently**
- **Separate normalisation factors for W and Z processes**: 3x2 factors
- 1 normalisation factor for mis-identified electrons
- 1 signal yield correlated across all bins
- Systematics implemented as correlated Gaussian constrained nuisance parameters

27 bins, 9 free parameters, 1 signal yield

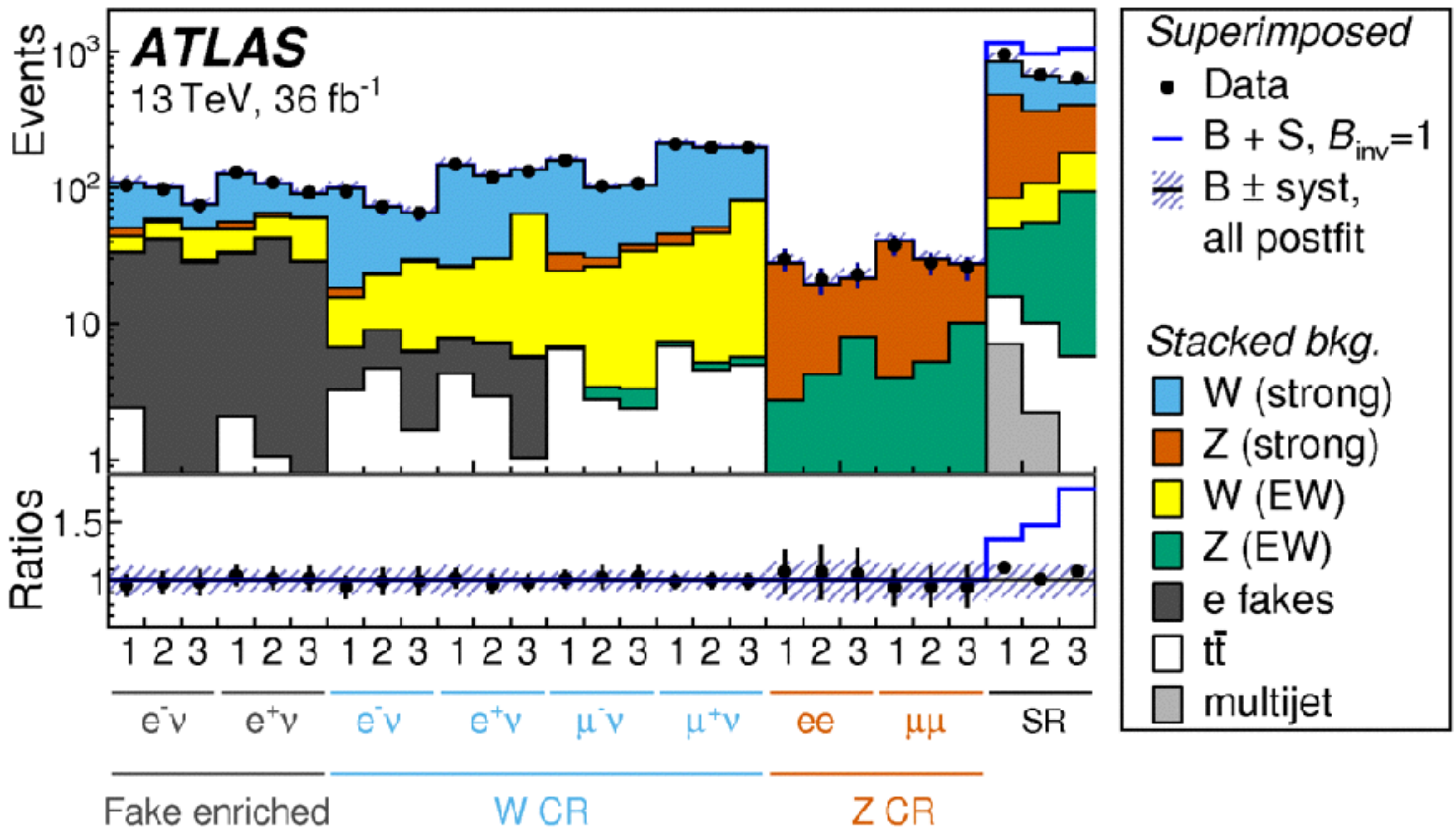
Pre-fit

Global likelihood fit with 27 bins, 9 free parameters, 1 signal yield



Post-fit

Global likelihood fit with 27 bins, 9 free parameters, 1 signal yield

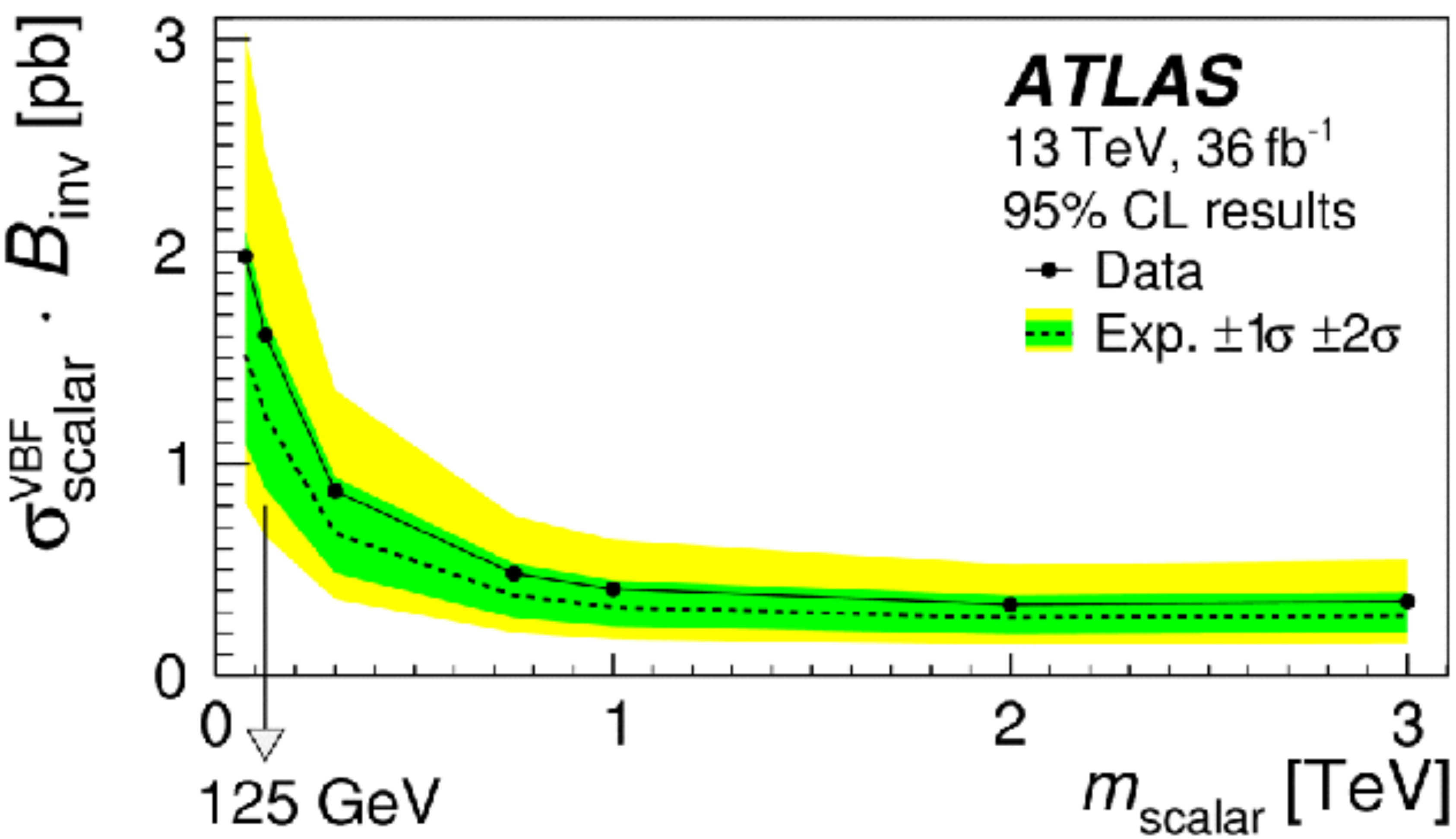


Result

Upper bound on branching fraction of Higgs to Invisible at 95% CL:

Observed = 0.37

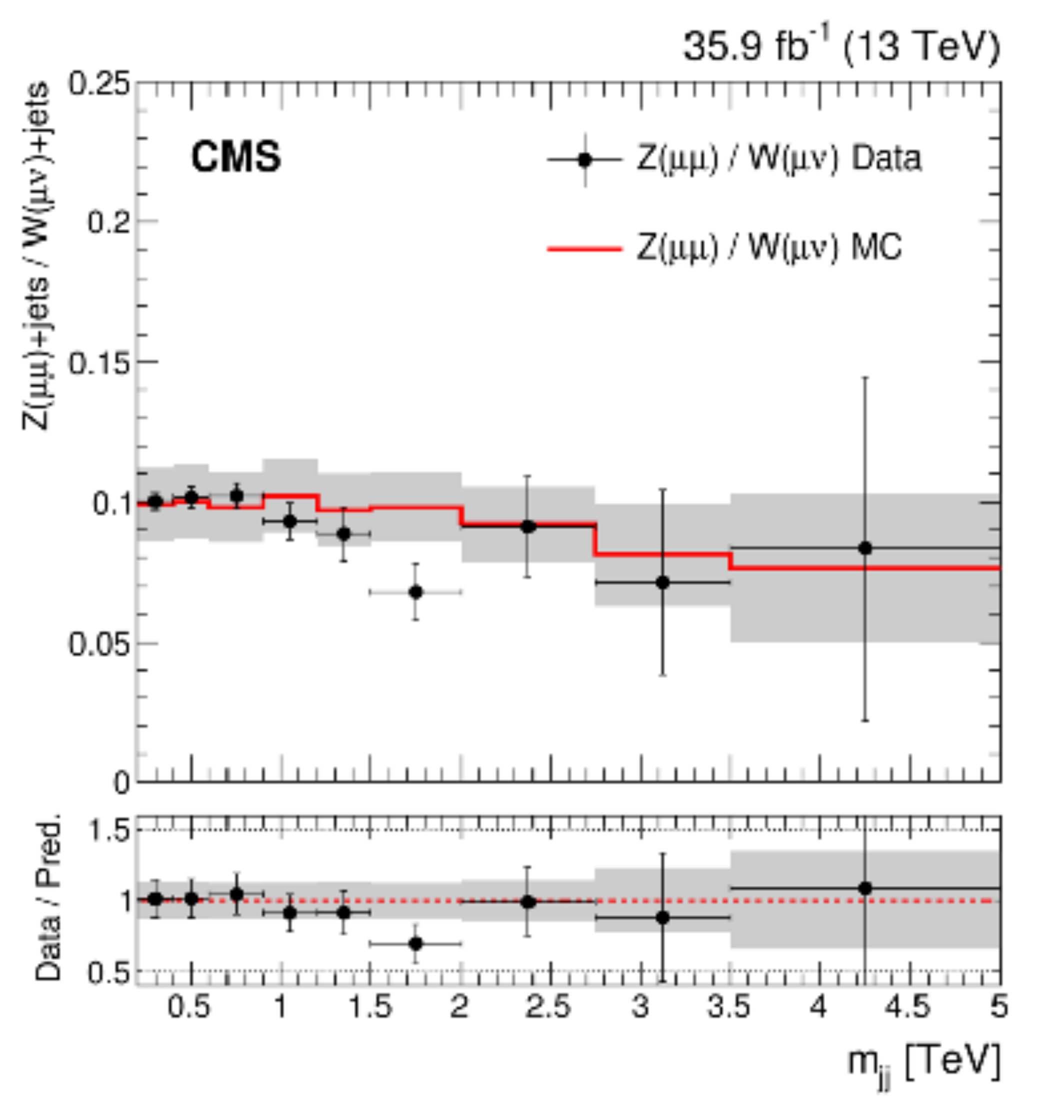
Expected = 0.28



CMS Result

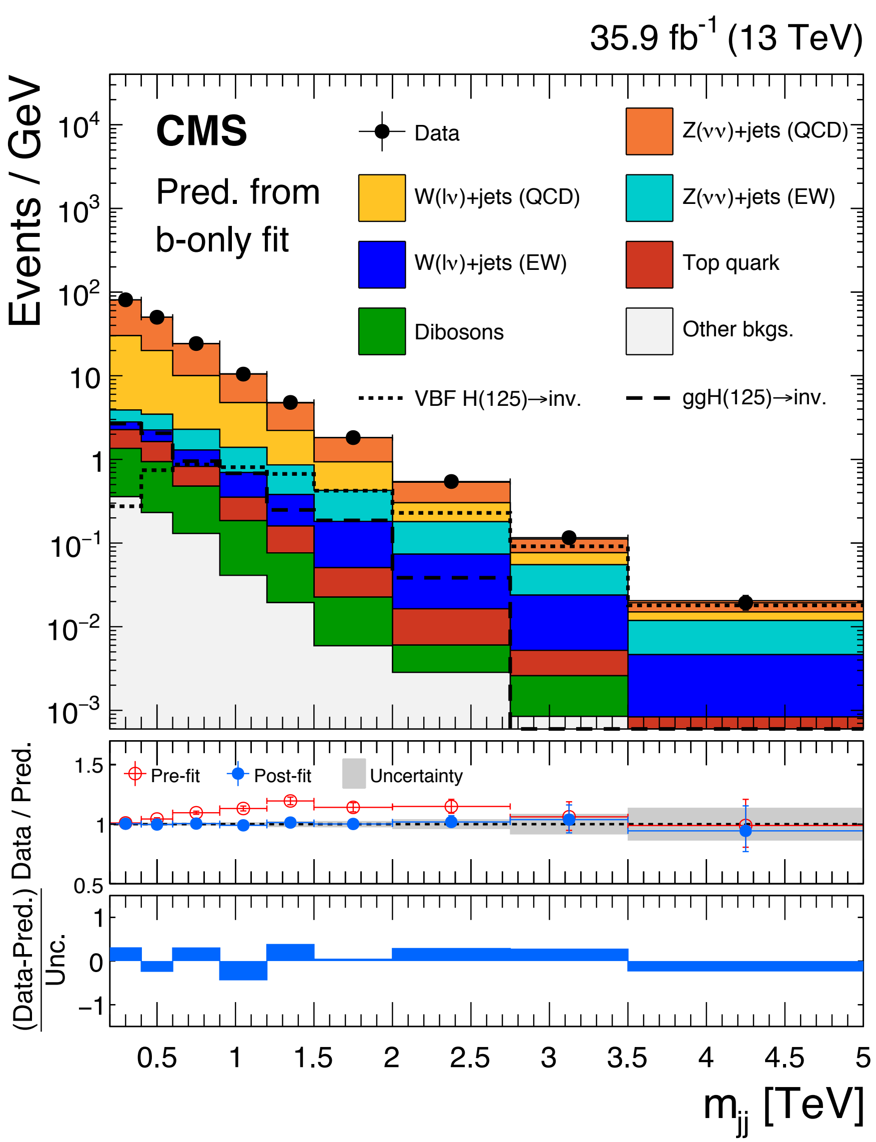
Cut-and-Count

Observed = 0.58
Expected = 0.30



Shape-fit MC

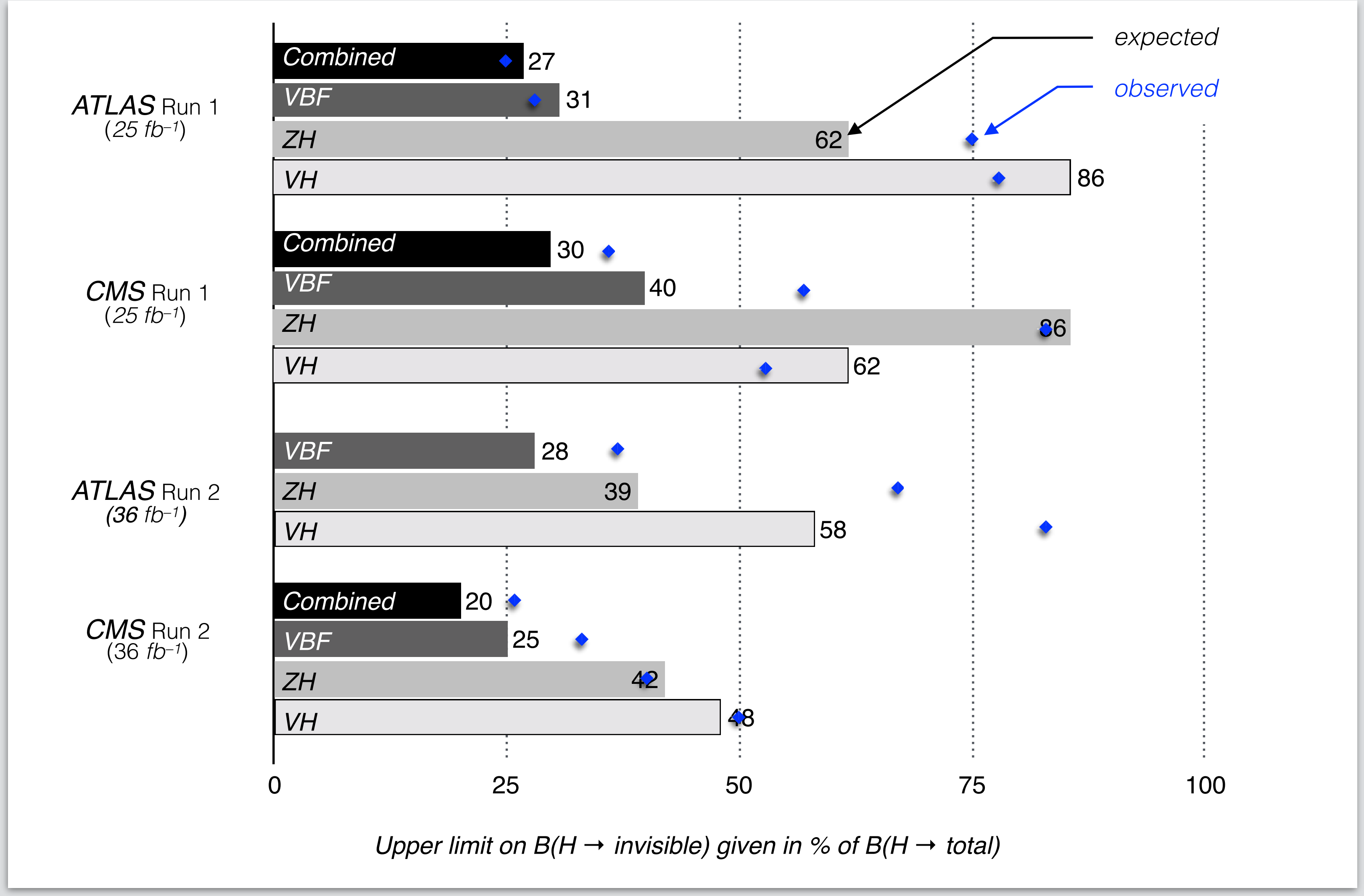
Observed = 0.33
Expected = 0.25



Other Higgs to Invisible

Invisible Higgs decays comparisons

For upper limits, smaller is better. 95% conf. level. Selected competitive results are shown.



Sources:

J. High Energy Phys.

11 (2015) 206

01 (2016) 172

02 (2017) 135

Phys. Letters B

776(2018)318–337

arXiv

1809.06682

1809.05937

If a signal is observed, then it will have to be in multiple places!

Global Higgs fits

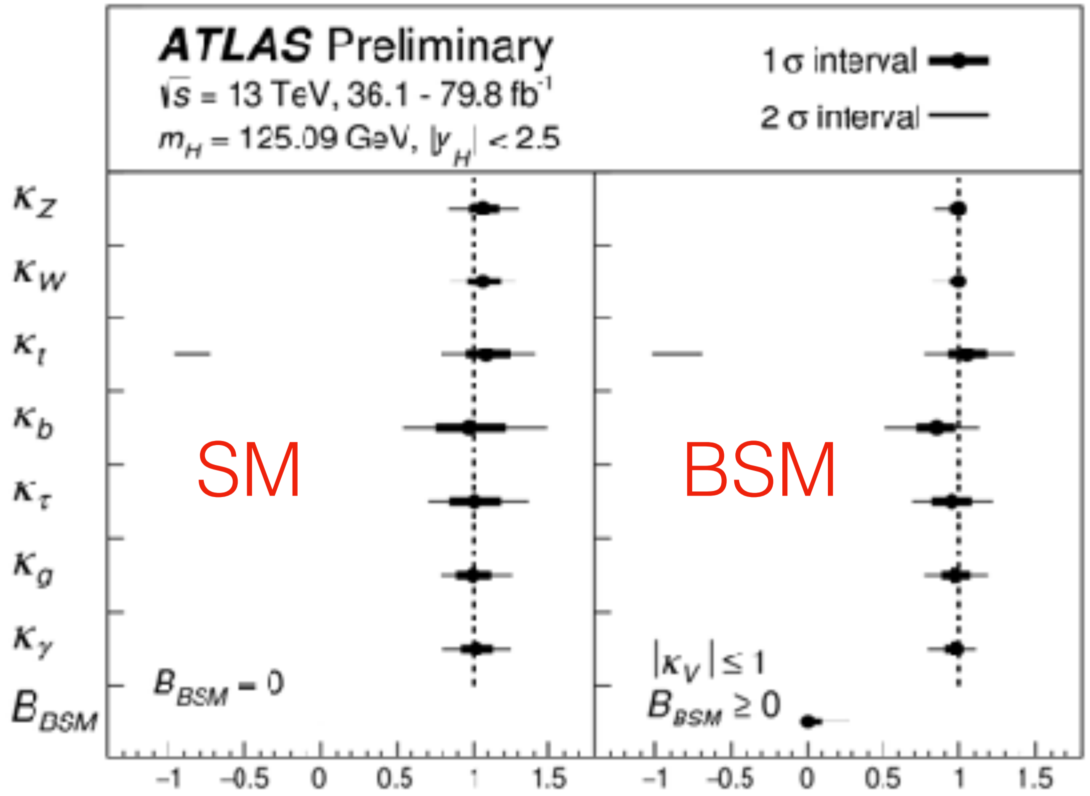
There is another way to constrain Higgs to invisible…

Use the higgs visible decays!

Higgs decays would be suppressed if the Higgs have an additional decay mode

$$\sigma(\mathrm{ggH}) \times BR(H \to WW) = \sigma(\mathrm{ggH}) \frac{\Gamma_{WW}}{\Gamma_{\mathrm{total}}}$$

$$\Gamma_{\mathrm{total}} = \Gamma_{\mathrm{bb}} + \Gamma_{\mathrm{WW}} + \Gamma_{\mathrm{ZZ}} + \ldots + \Gamma_{\mathrm{BSM}}$$



Do a global fit using all the measurements to get limits on the k_X parameters

Decay channels	κ_i assumption	Upper limit on $\mathrm{BR}_{\mathrm{inv}}$ Obs.	Exp.
Invisible decays	$\kappa_{W,Z,g} = 1$	0.25	0.27
Visible decays	$\kappa_{W,Z} \leq 1$	0.49	0.48
Inv. & vis. decays	**None**	**0.23**	**0.24**
Inv. & vis. decays	$\kappa_{W,Z} \leq 1$	0.23	0.23

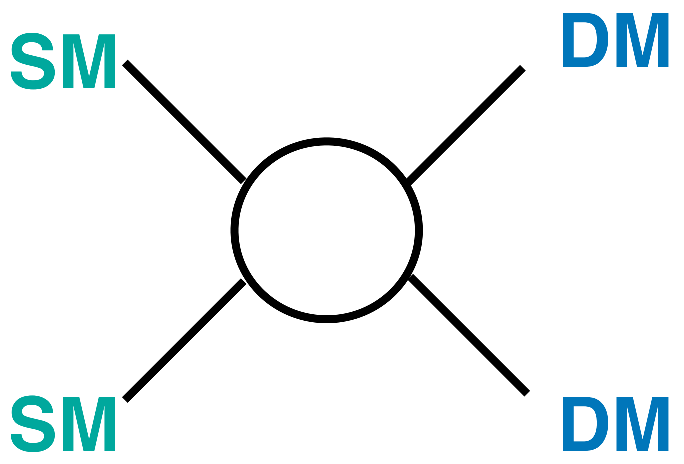
Combination of direct searches

Indirect limit from visible processes

Combination of everything under two assumptions

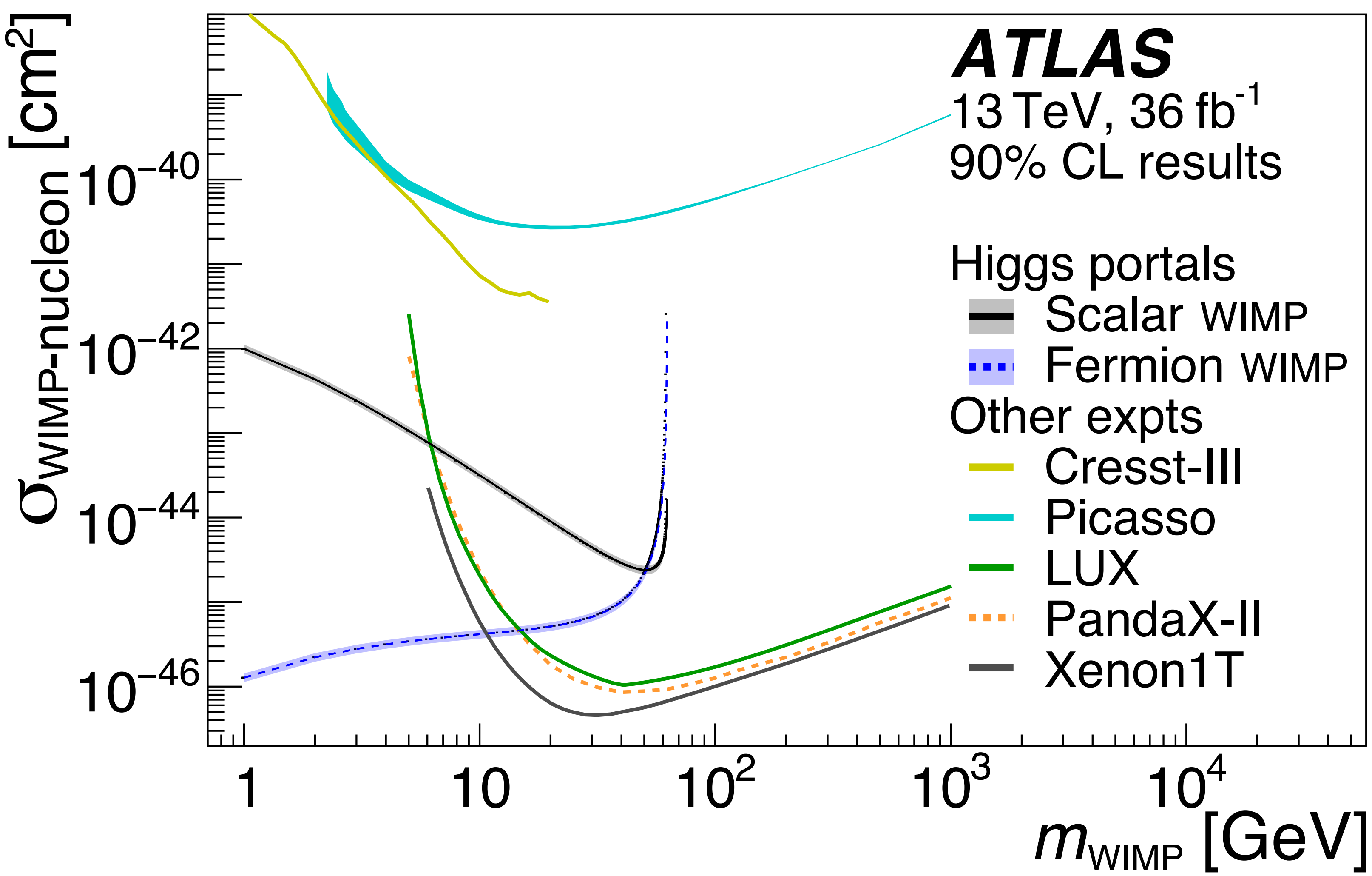
Higgs Portal Interpretation

Higgs to invisible provides strong constraint on DM for $m_{DM} < m_H/2$



Strong complementarity with direct dark matter searches:

- H to invisible not sensitive above mH/2
- Direct DM not sensitive below m_{DM} ~ 10 GeV
- Overlap in 10 - 60 GeV



Assuming DM couples to SM via Higgs only…

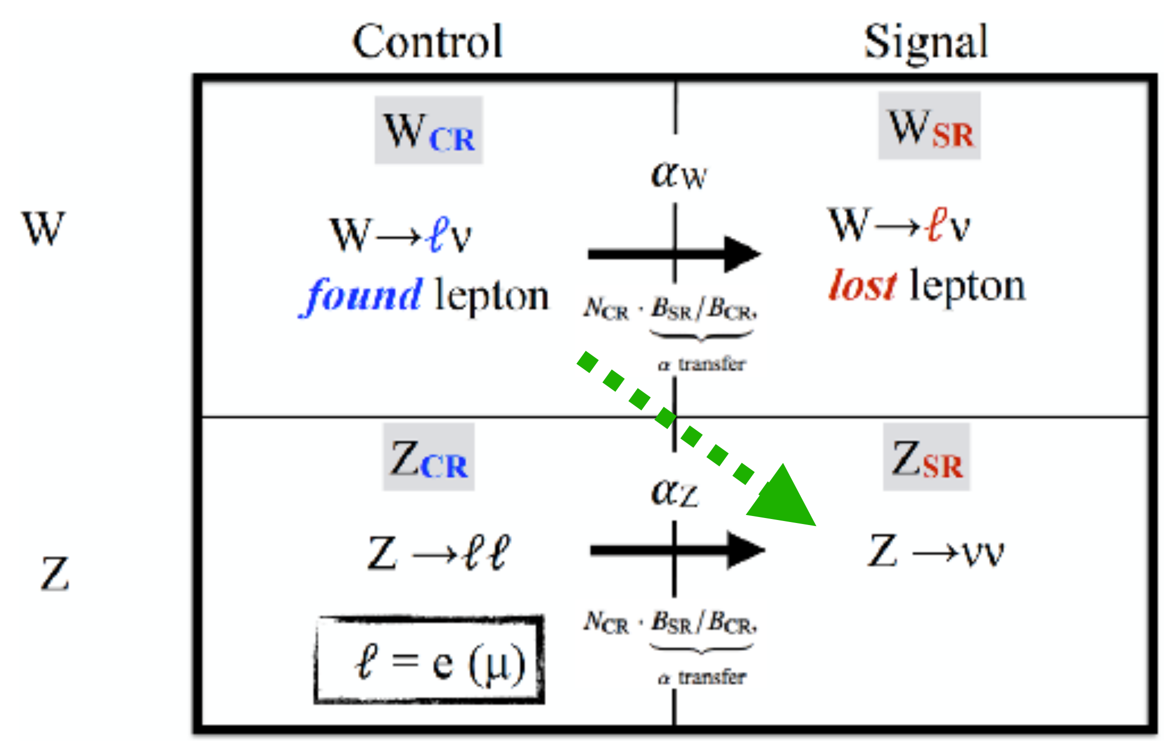
Extrapolating between W and Z

- Z > ll statistics is really poor due to small branching ratio (ll:7% vs. νν:20%)
- Using 166 Z > ll events to model 1111 Z > νν events!
- W events give x10 more stats.

Why don't we use W's?

We do not know how to correlate theory uncertainties when extrapolating between EWK+QCD W and Z in the presence of non-trivial VBF selection

Description	SR Yield [EW]	W CR Yield [EW]	Z CR Yield [EW]
N, observed	2252	1602	166
B, expected	2243	1648	183
$Z \to \nu\nu$	1111 [18%]	-	-



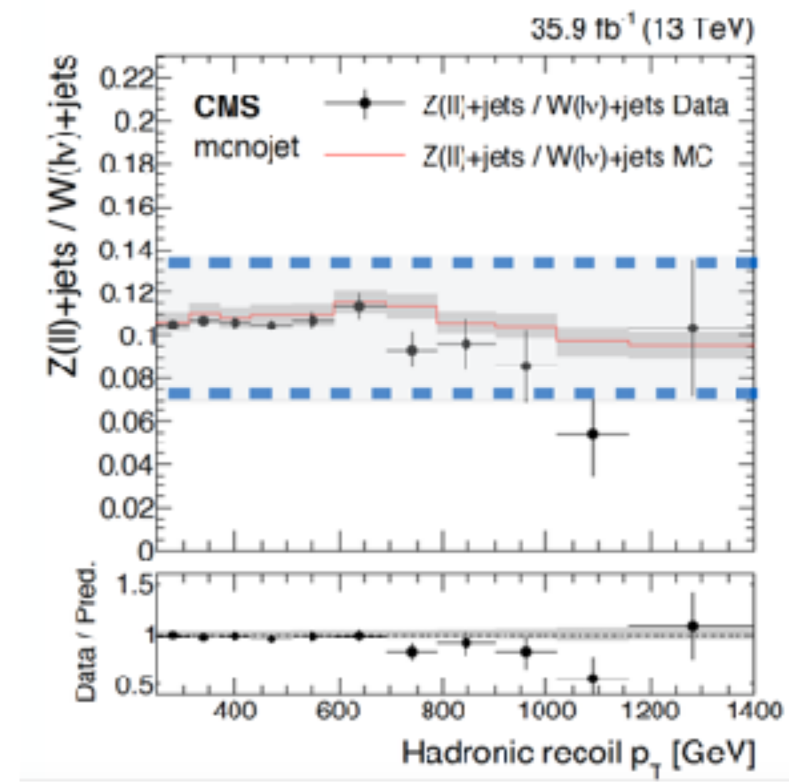
Theorist of the month

[arXiv:1705.04664](https://arxiv.org/abs/1705.04664)

Precise predictions for V+jets dark matter backgrounds

J. M. Lindert[1], S. Pozzorini[2], R. Boughezal[3], J. M. Campbell[4], A. Denner[5], . . .

Combination of state-of-the-art predictions (N)NLO QCD+(N)NLO EW in order to match (future) experimental sensitivities (1-10% accuracy in the few hundred GeV-TeV range)



Jonas Lindert

Theorist of the month of October

At DESY the week of October 22nd

We would be happy to welcome you to our

Symposium at DESY

- Combination and comparisons of Dark Matter searches at **colliders, direct and indirect experiments**
- Including input from **theory**
- Exciting line-up of talks and topics
- Young Scientist Forum
- Dark Matter show at the planetarium (outreach)
- Registration deadline October 10th

Backup

Fit model

$$B_{\mathrm{SR}}^{\mathrm{est}} = B_{\mathrm{SR}} \cdot \underbrace{N_{\mathrm{CR}}/B_{\mathrm{CR}}}_{k \text{ normalization}} = N_{\mathrm{CR}} \cdot \underbrace{B_{\mathrm{SR}}/B_{\mathrm{CR}}}_{\alpha \text{ factor}}$$

Summary of fit model, each bin of m(jj) is treated separately according to the model shown here.

Actually binned in charge

	SR	ee	μμ	e MET sig. > 4	e MET sig. < 4	μ
Signal	μ x S					
Z	k_Z x B_Z	k_Z x B_Z	k_Z x B_Z	k_Z x B_Z	k_Z x B_Z	k_Z x B_Z
W+jets	k_W x B_W	k_W x B_W	k_W x B_W	k_W x B_W	k_W x B_W	k_W x B_W
mis-ID				β	R x β	

$B_{W(Z)}$: prediction from MC

R: ratio from loose not tight

β: normalization of mis-ID component

m_{jj}	k_W	k_Z	β
1.0 – 1.5 TeV	0.91 ± 0.18	1.10 ± 0.27	3.63 ± 1.76
1.5 – 2.0 TeV	0.94 ± 0.18	0.98 ± 0.23	4.0 ± 1.47
> 2.0 TeV	1.07 ± 0.19	1.13 ± 0.27	6.8 ± 2.13

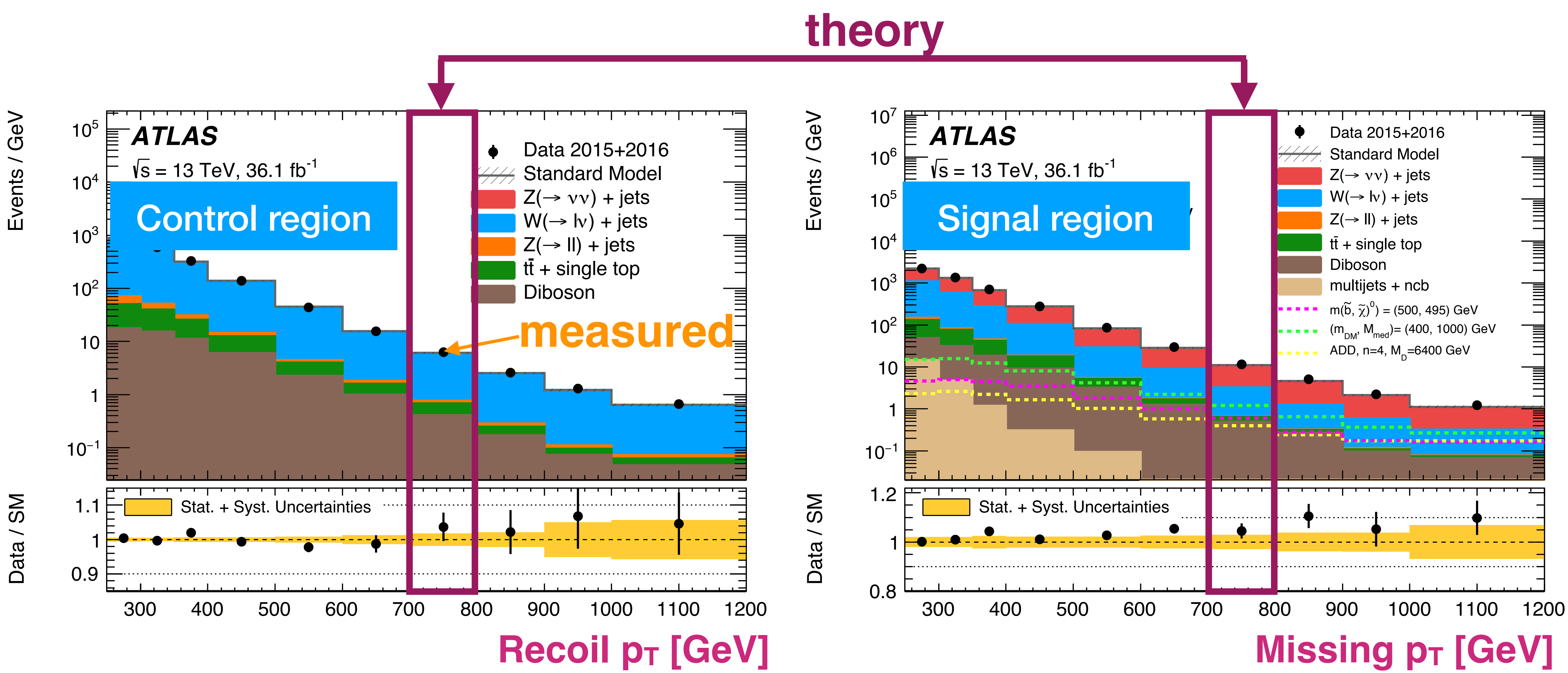
Yields

Description	SR		W CR		Z CR	
	Yield	[EW]	Yield	[EW]	Yield	[EW]
N, observed	2252		1602		166	
B, expected	2243		1648		183	
$Z \to \nu\nu$	1111	[18%]	-		-	
$Z \to ee, \mu\mu$	12	[9%]	38	[9%]	181	[23%]
$Z \to \tau\tau$	10	[16%]	11	[16%]	-	
$W \to e\nu, \mu\nu$	540	[16%]	1400	[30%]	-	
$W \to \tau\nu$	533	[20%]	130	[34%]	-	
Other	36		67		2	
S, signal	1070		-		-	
VBF	930		-		-	
Gluon fusion	140		-		-	

	1 - 1.5TeV	1.5 - 2TeV	> 2TeV
Observed	952	667	633
Background	850 ± 113	660 ± 90	590 ± 81
Signal	300	310	460
S/B	0.4	0.5	0.8

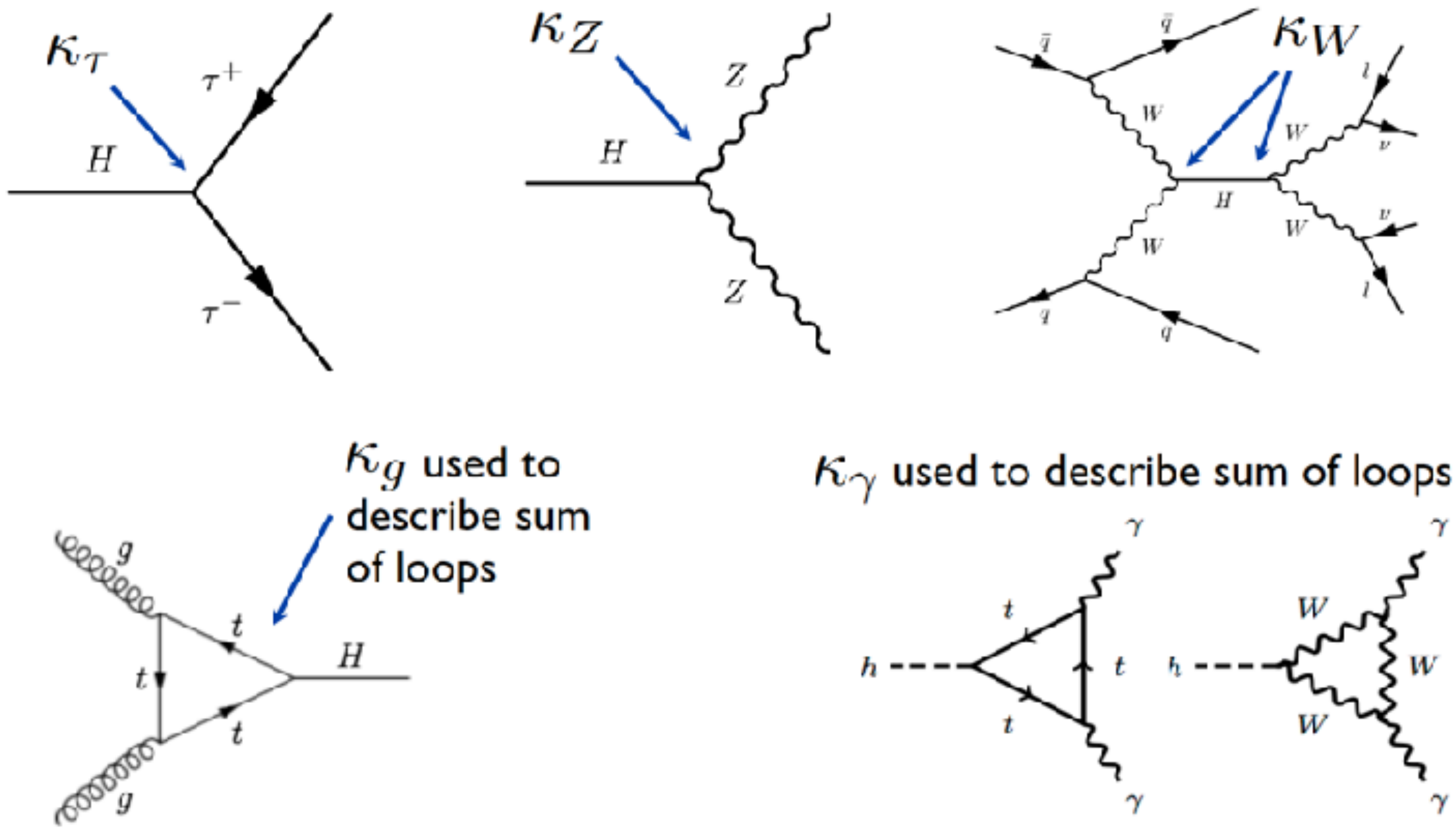
Background Modelling

$$\frac{d\sigma\left(V_2\right)}{dx} = \left[\frac{d\sigma\left(V_2\right)/dx}{d\sigma\left(V_1\right)/dx}\right]_{\text{theory}} \times \left[\frac{d\sigma\left(V_1\right)}{dx}\right]_{\text{measured}}$$



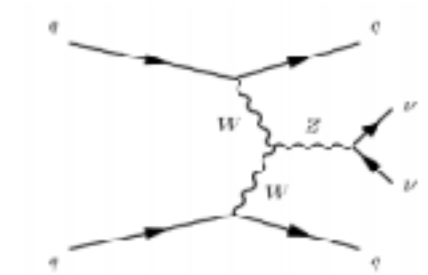
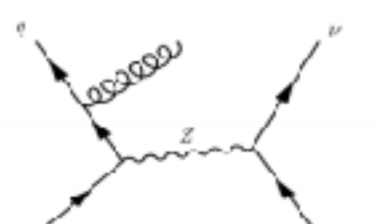
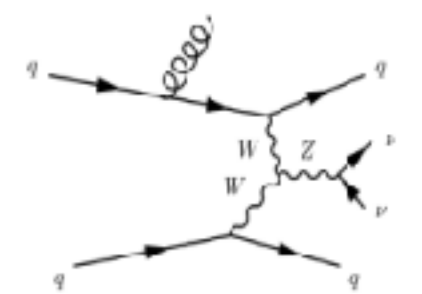
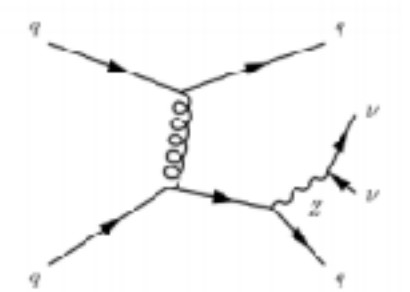
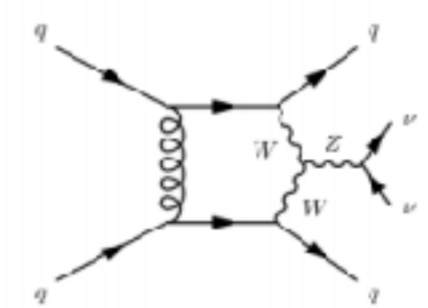
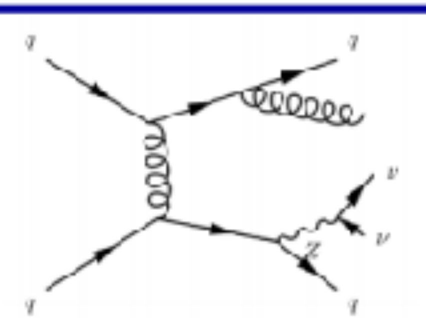
Global Higgs fits

For each Higgs coupling add a parameter κ which describes its deviation from the SM (SM when κ_X=1)

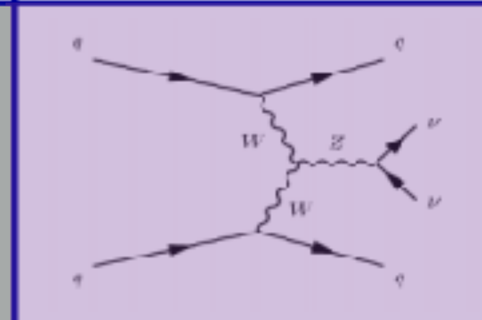
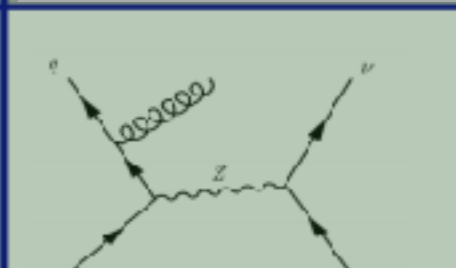
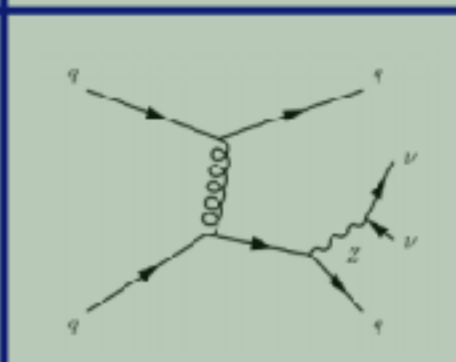
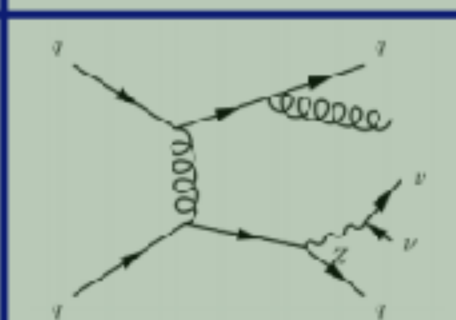


$$k_h^2 = \Gamma_h / \Gamma_{h,SM} = \Sigma_j k_j^2 BR_j / (1 - BR_{inv})$$

W/Z + Jets

Order	QCD α_{EW}^2	α_{EW}^3	EWK α_{EW}^4	α_{EW}^5
α_s^0	Negligible in our SR/CR	Doesn't Exist		Interference Only
α_s^1	 + pileup jet	Interference Only		Interference Only
α_s^2		Interference Only		Higher Order
α_s^3		Interference Only	Higher Order	

W/Z + Jets

Order	Sherpa 2.2.1 α_{EW}^2	Madgraph5 α_{EW}^3	Sherpa 2.2.1 α_{EW}^4	α_{EW}^5
α_s^0				
α_s^1	 + pileup jet	Interference Only		
α_s^2				Higher Order
α_s^3			Higher Order	

Simulation

CMS

QCD(α_{EW}^2): MG5_aMC@NLO at LO in α_s for up to 4 partons
EWK(α_{EW}^4):MG5_aMC@NLO at LO in α_s for up to 2 partons
Corrections: apply pT-mjj dependent NLO corrections to the V+jets NLO and EWK

ATLAS

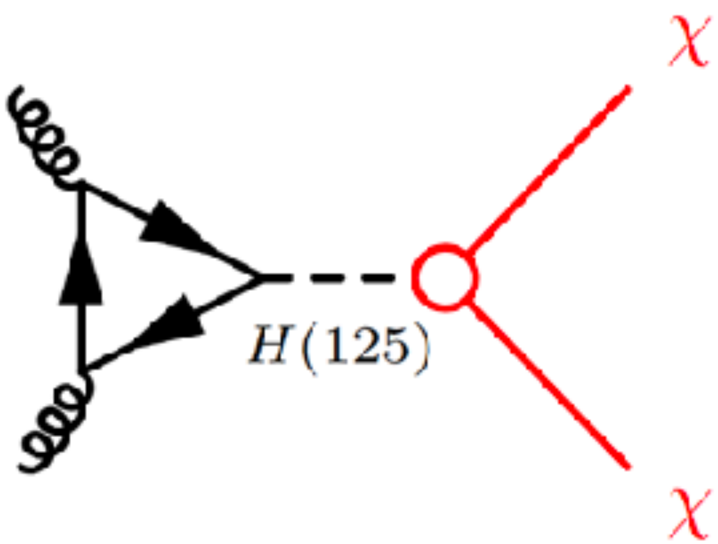
QCD(α_{EW}^2): Sherpa NLO in α_s for the first 2 partons, LO for up to 4 partons
EWK(α_{EW}^4): Sherpa LO in α_s for up to 3 partons
Interference(α_{EW}^3): modelled with MG5_aMC@NLO

Comparisons with CMS

Requirement	CMS cut-and-count	CMS Shape	ATLAS	Background
e(μ)(τ)	< 10 (10) (18) GeV		< 7 (7) (-) Gev	Z(ll), W(lv)
Jet p_T	> 80 (40) GeV		> 80 (50) GeV	All
Jet Pileup Removal	PFlow		JVT > 0.59	QCD multijet
Third Jet Veto	—		< 25 GeV	ggH
MET	> 250 GeV		> 180 GeV	QCD, tt, W+jets
MHT	—		> 150 GeV	QCD multijet
Δϕ(jj)	< 1.5		< 1.8	Z(vv), W(lv)
Δϕ(j,MET)	0.5		1.0	QCD multijet
m(jj)	> 1300 GeV	> 200 GeV	1-1.15, 1.5-2, >2 TeV	Z(vv), W(lv)
Δη(jj)	> 4	> 1	> 4.8	Z(vv), W(lv)
γ, b-jet	Veto		—	top, γ, Vγ

Search Channels

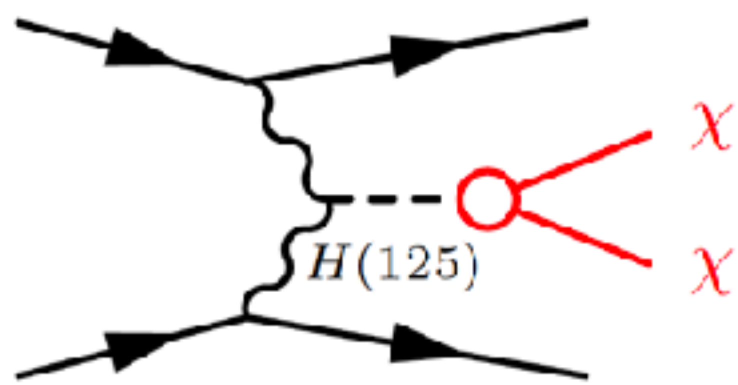
Gluon fusion: 49 pb



- Use an ISR jet for triggering
- Looked for by Mono-jet

Least sensitive

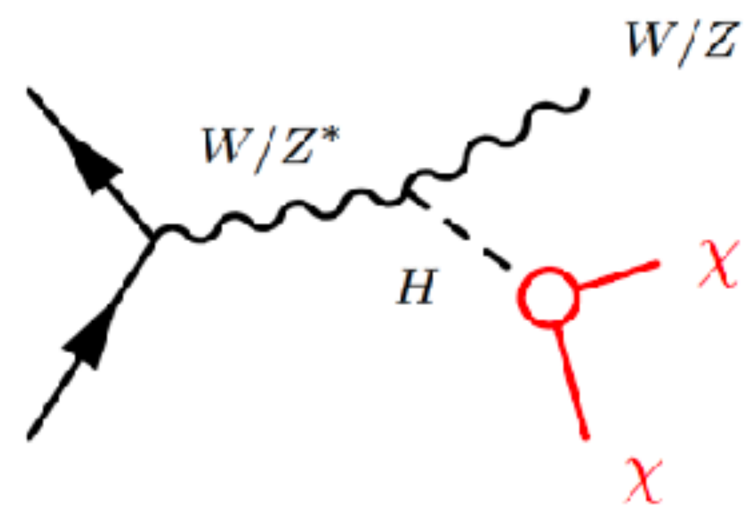
VBF: 3.8 pb



- Tag using forward jets with large Δη(jj)
- Dedicated analysis

Most sensitive

VH: 2.3 pb



- Tag using Z(ll) or jet from V(had)
- Looked for by V + MET

Intermediate