# Higgs to Invisible at ATLAS

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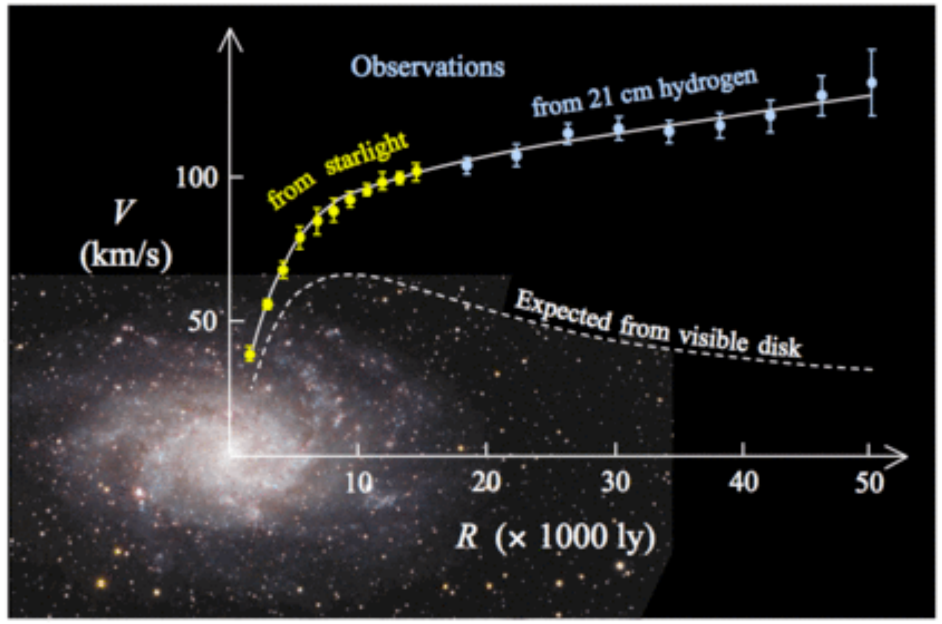
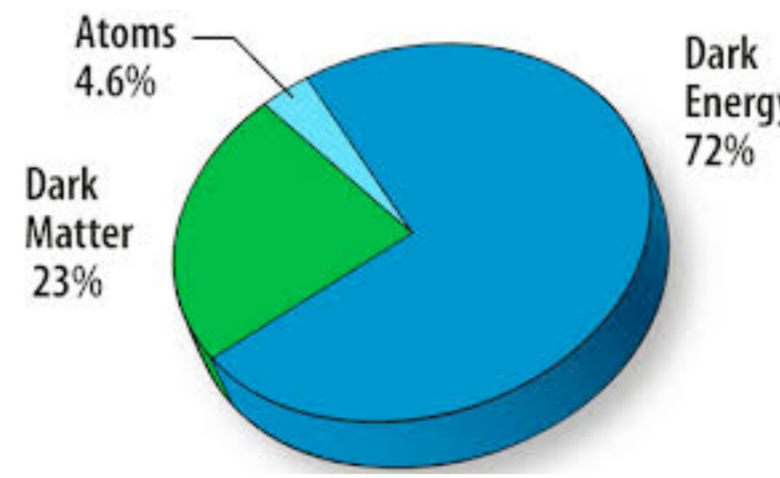
# Outline

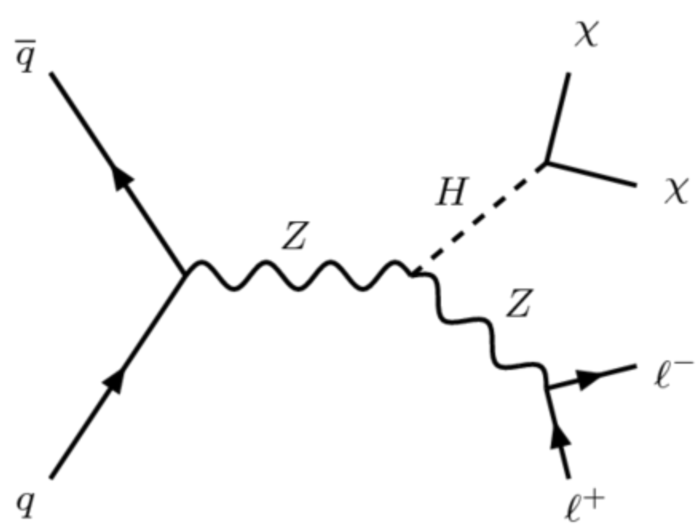
## Physics Motivation



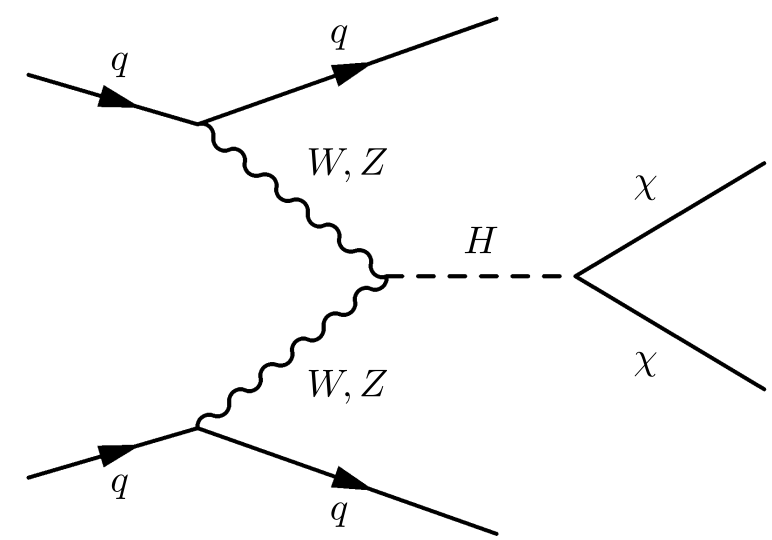




## Data Analyses

ZH, H→invisible




Vector Boson Fusion (VBF), H→invisible




## Summary: Other measurements, constraints, and interpretation

# Higgs = Special Probe for Dark Matter

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## *Unique in SM*

$HH^\dagger$ is a dimension two operator with no quantum numbers

It is the only gauge invariant and Lorentz invariant operator than can couple to SU(3)xSU(2)xU(1) singlets at tree level

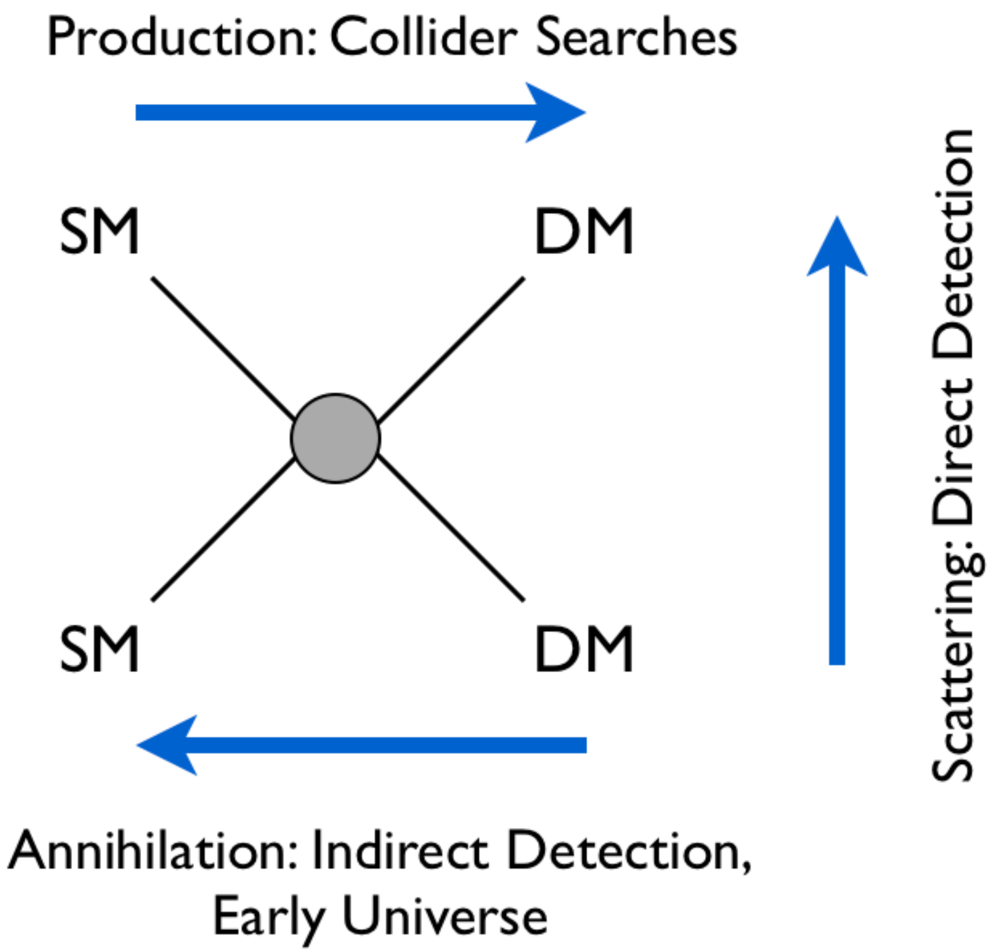
I.e. coupling to fermions or the gauge bosons would require a larger than dim 4 operator, which not renormalizable and must have a cut-off scale

## *Higgs Portal Concept*

General Idea: DM only couples to SM via Higgs

- Simplest one DM particle with WIMP miracle and no other particles already excluded
- Higgs would have been mostly invisible
  - Still order 50 papers with "Higgs Portal" in the title since the Higgs discovery with many variations

# Relation to other DM searches



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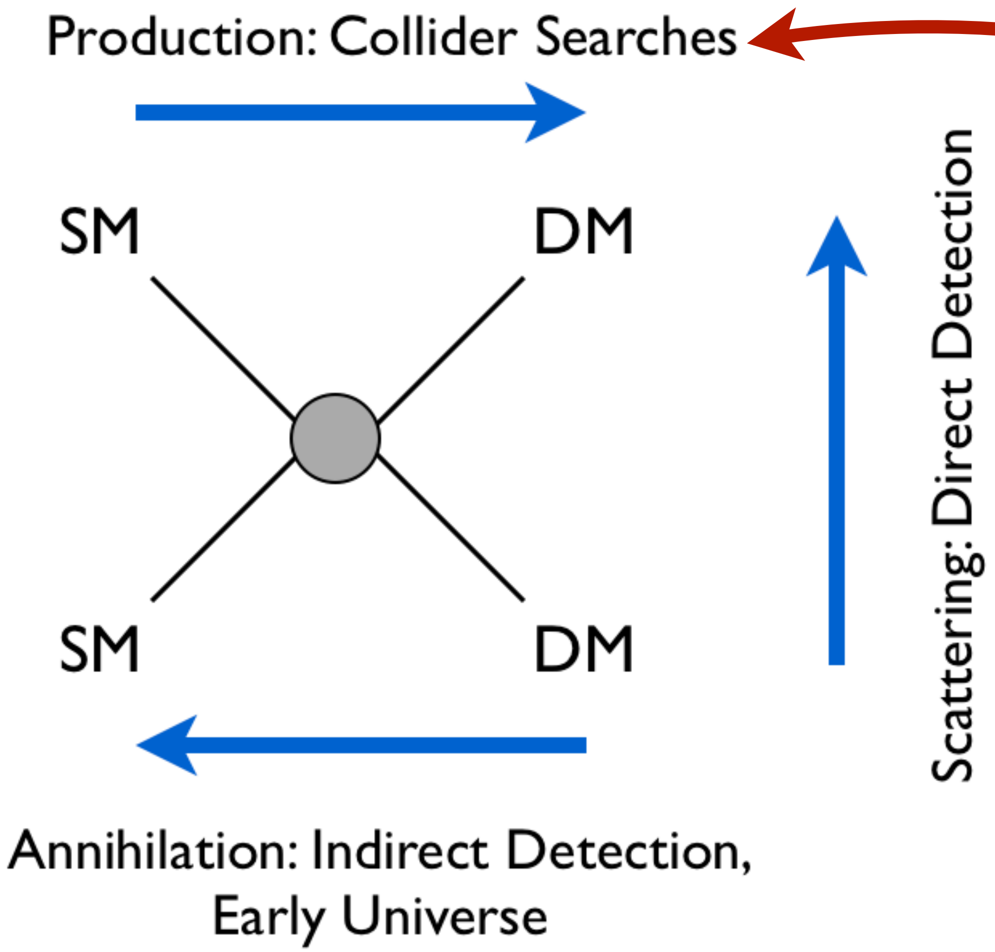
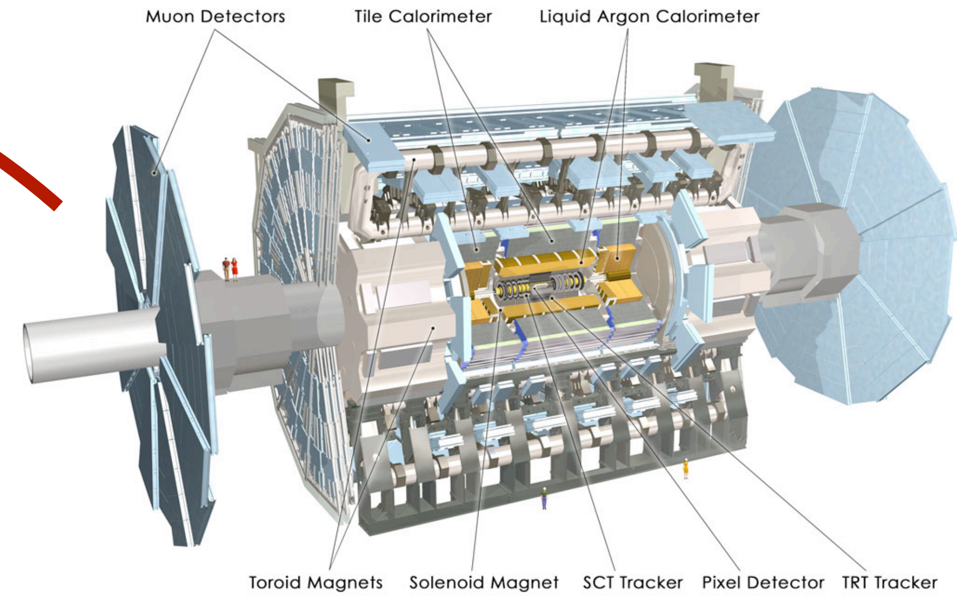
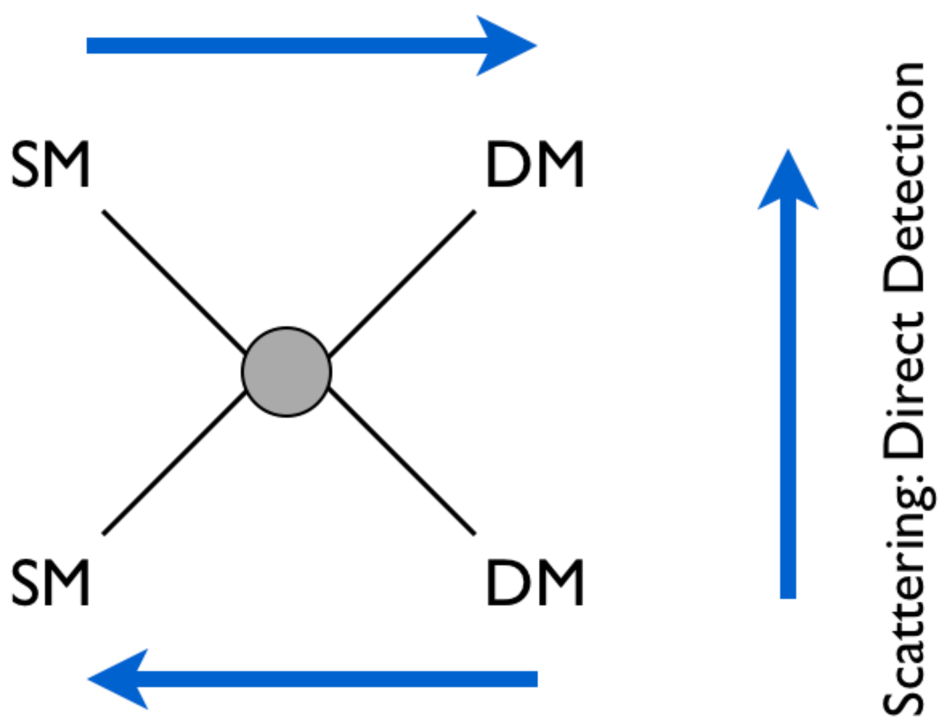



The rest of the talk is about this



# Relation to other DM searches

Production: Collider Searches




Annihilation: Indirect Detection,
Early Universe

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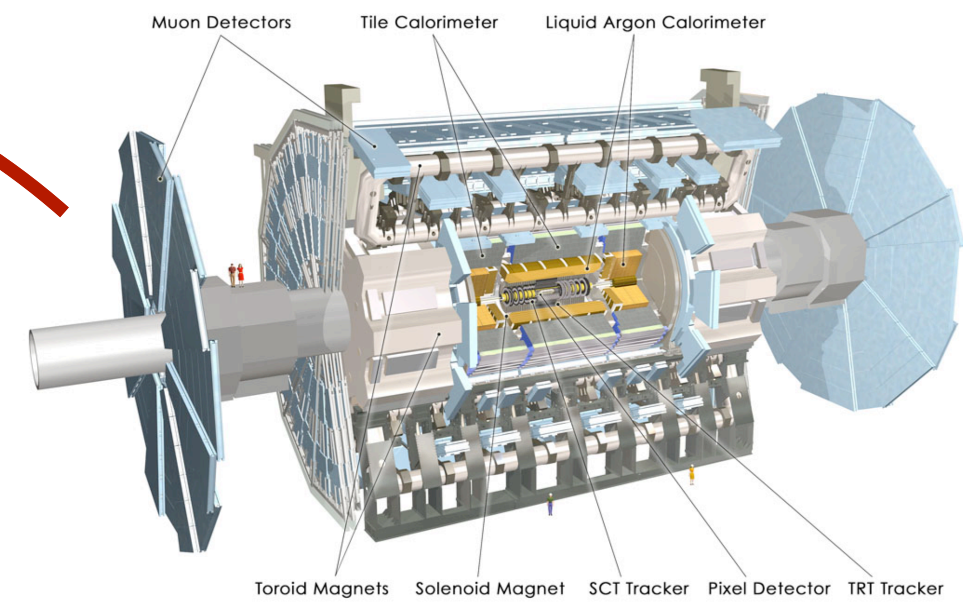
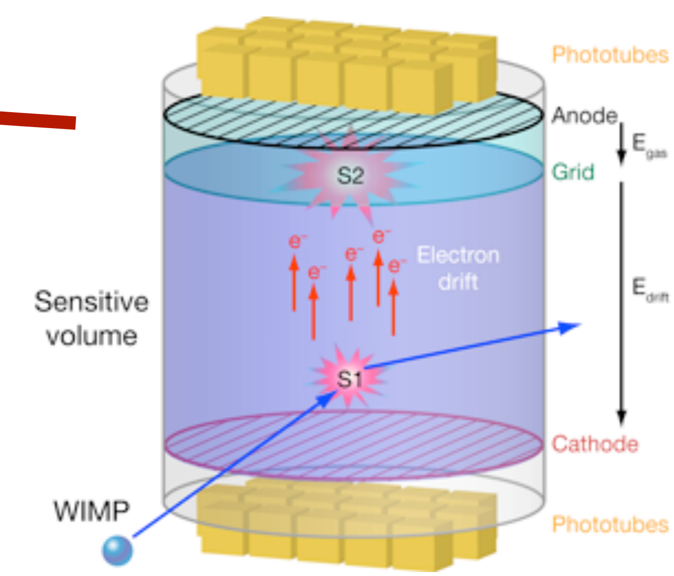



Variety of Underground Experiments



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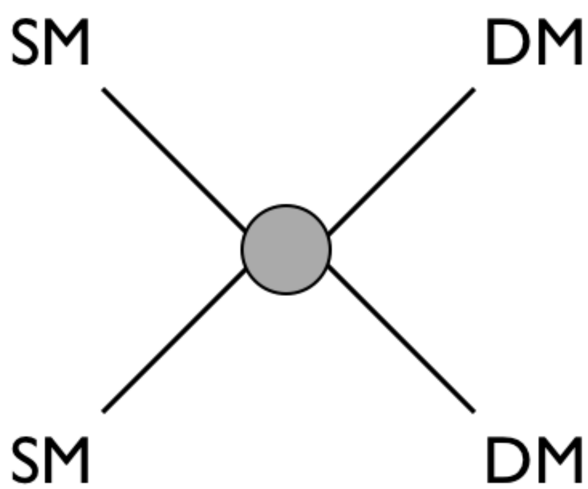
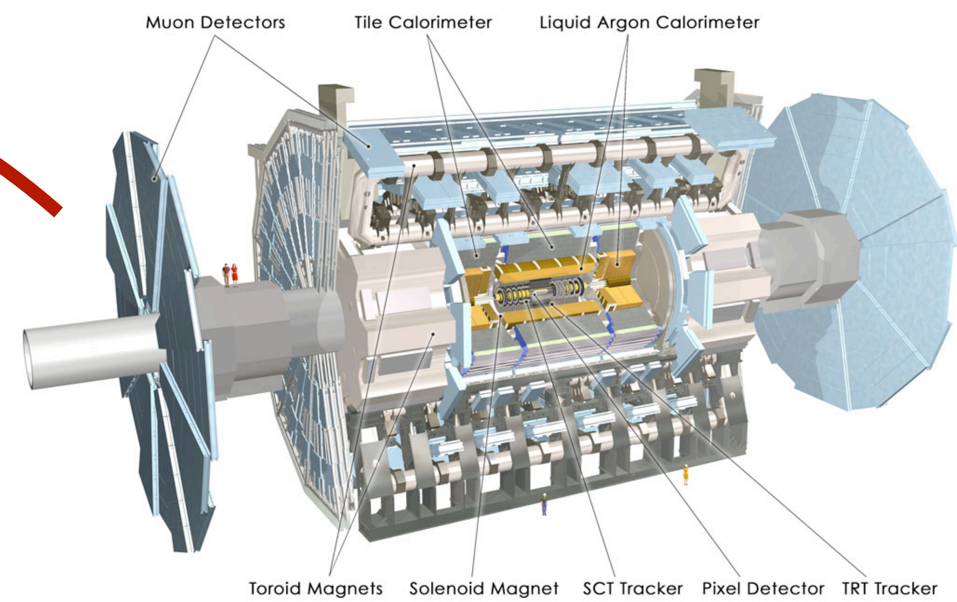



Annihilation: Indirect Detection, Early Universe

Scattering: Direct Detection

The rest of the talk is about this

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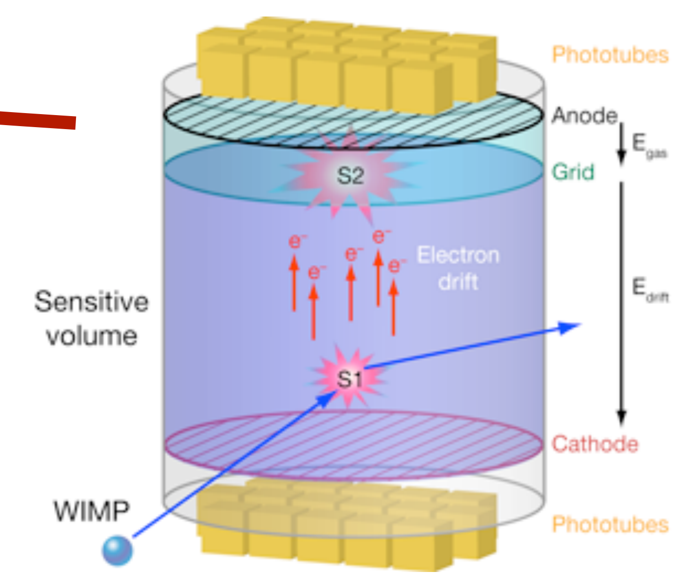
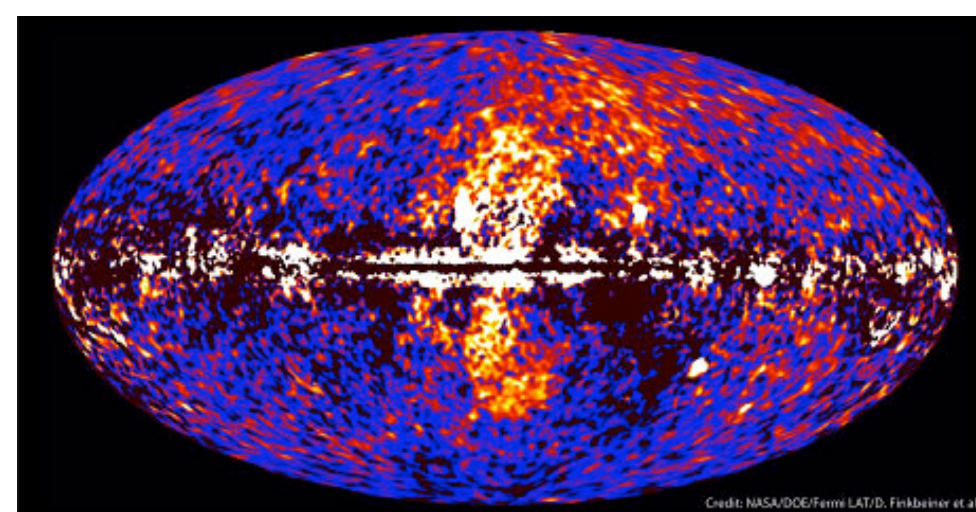



Gamma Ray (and Neutrino) Astronomy



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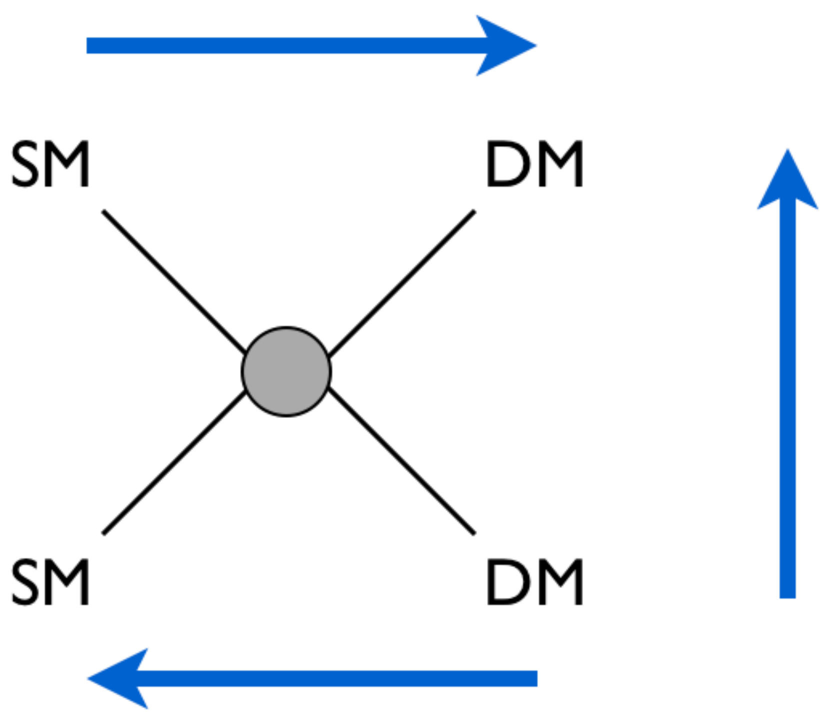


Scattering: Direct Detection

Annihilation: Indirect Detection, Early Universe

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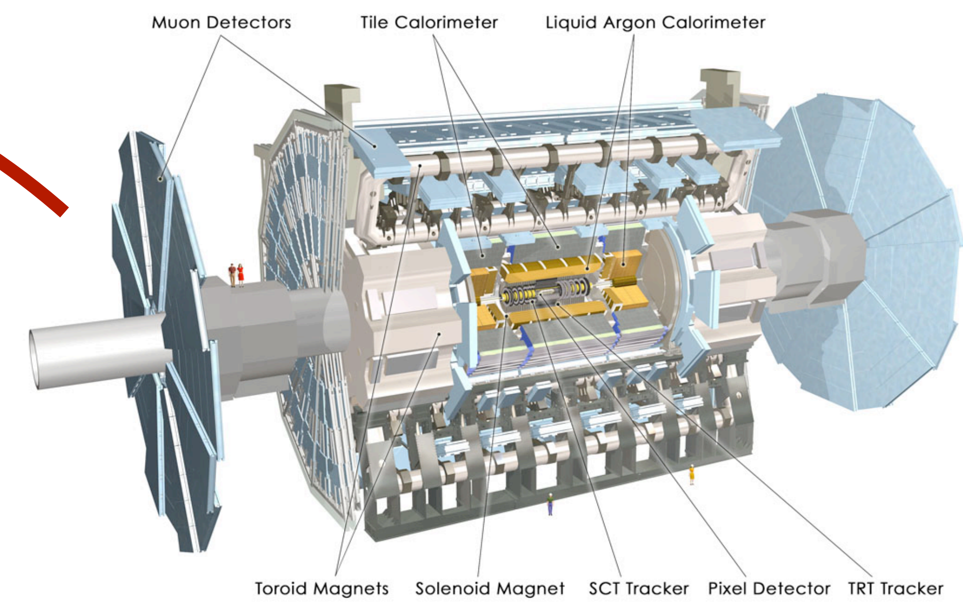


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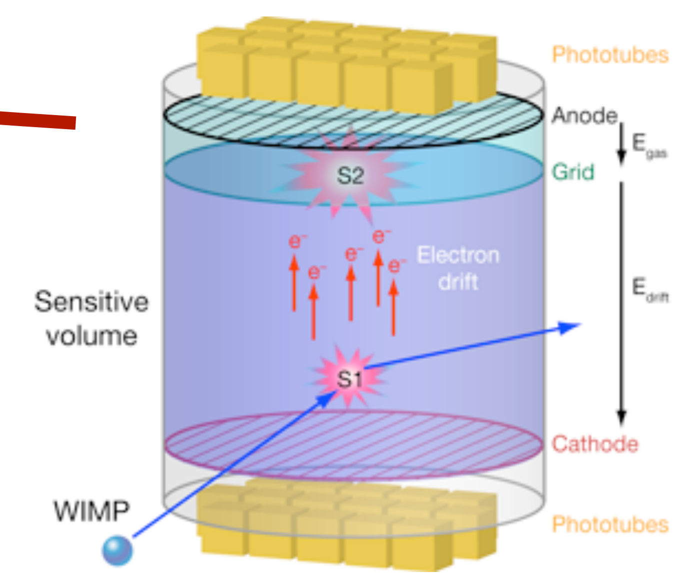
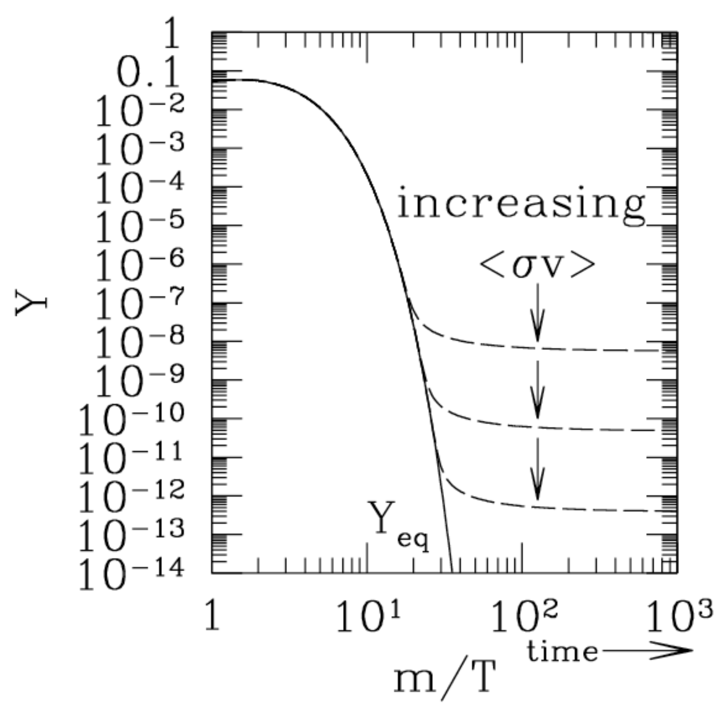



WIMP miracle

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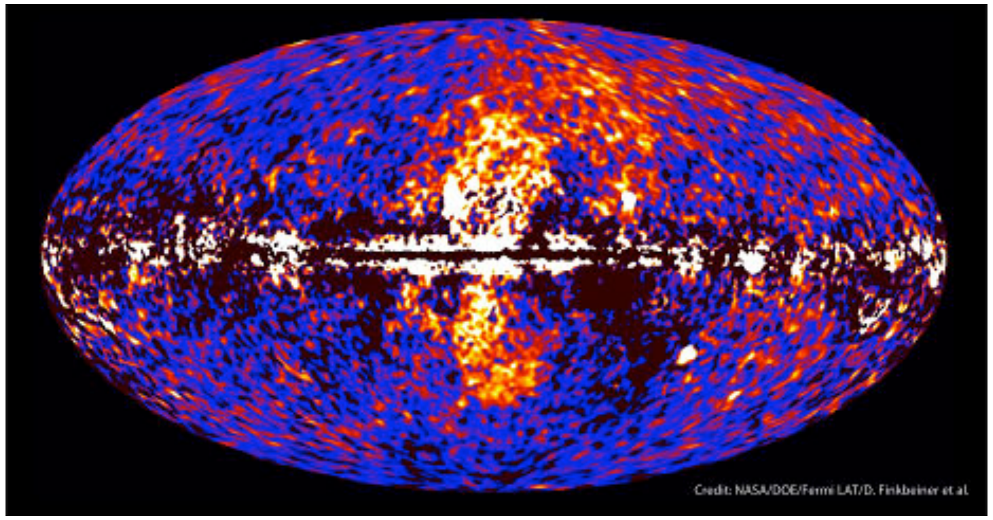

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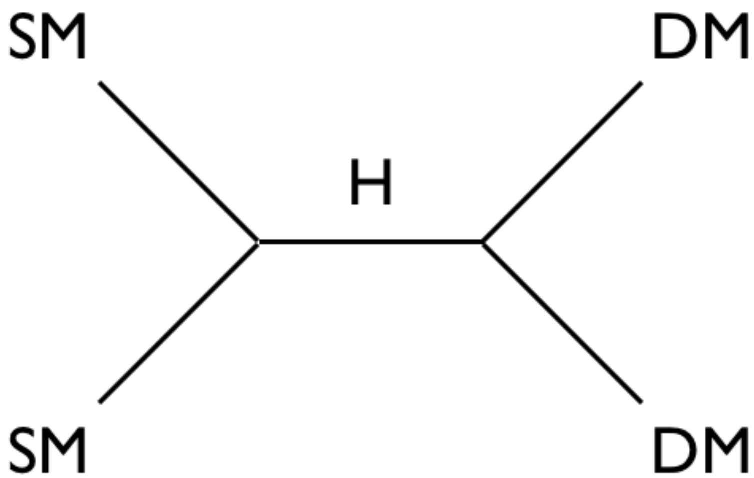


Scattering: Direct Detection

Annihilation: Indirect Detection, Early Universe

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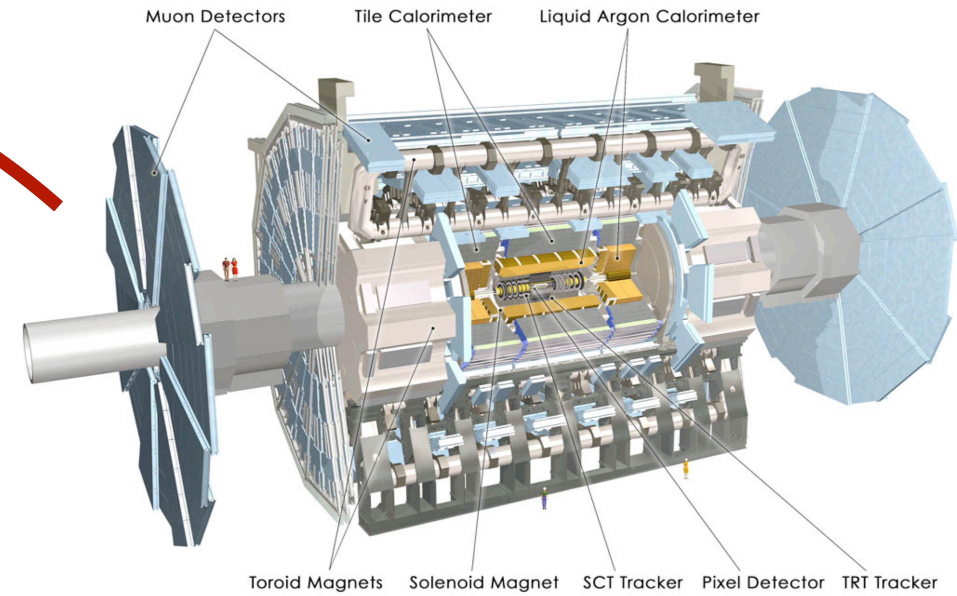


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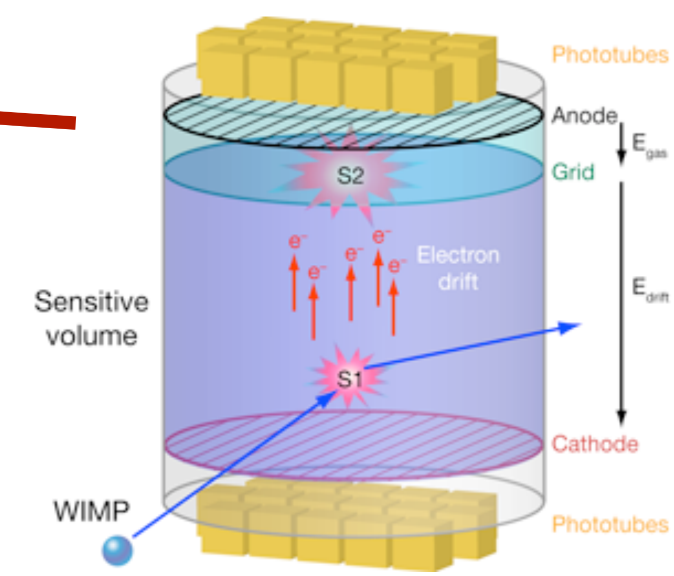


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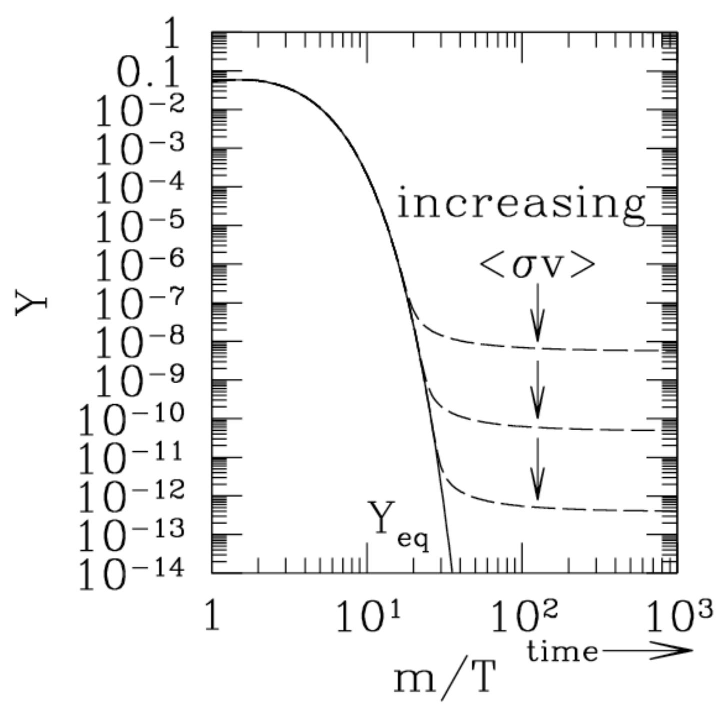


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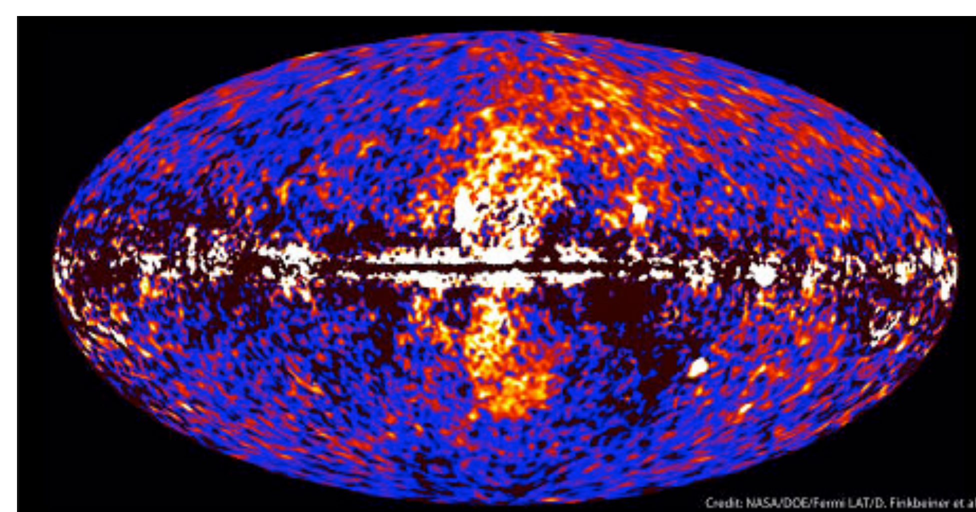
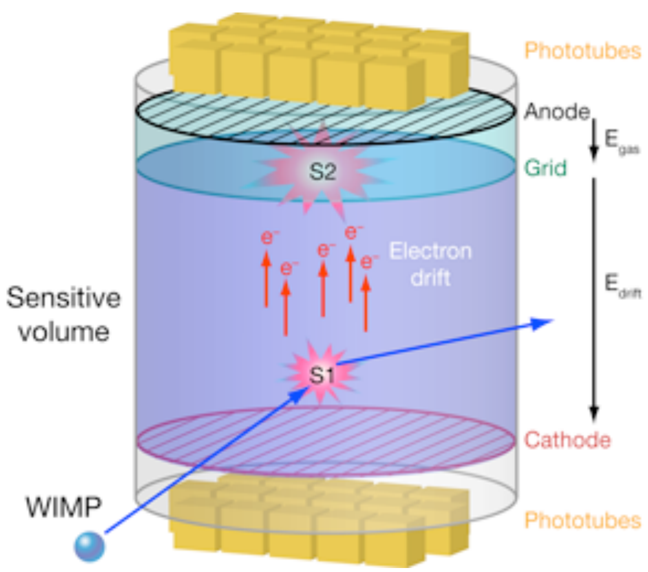


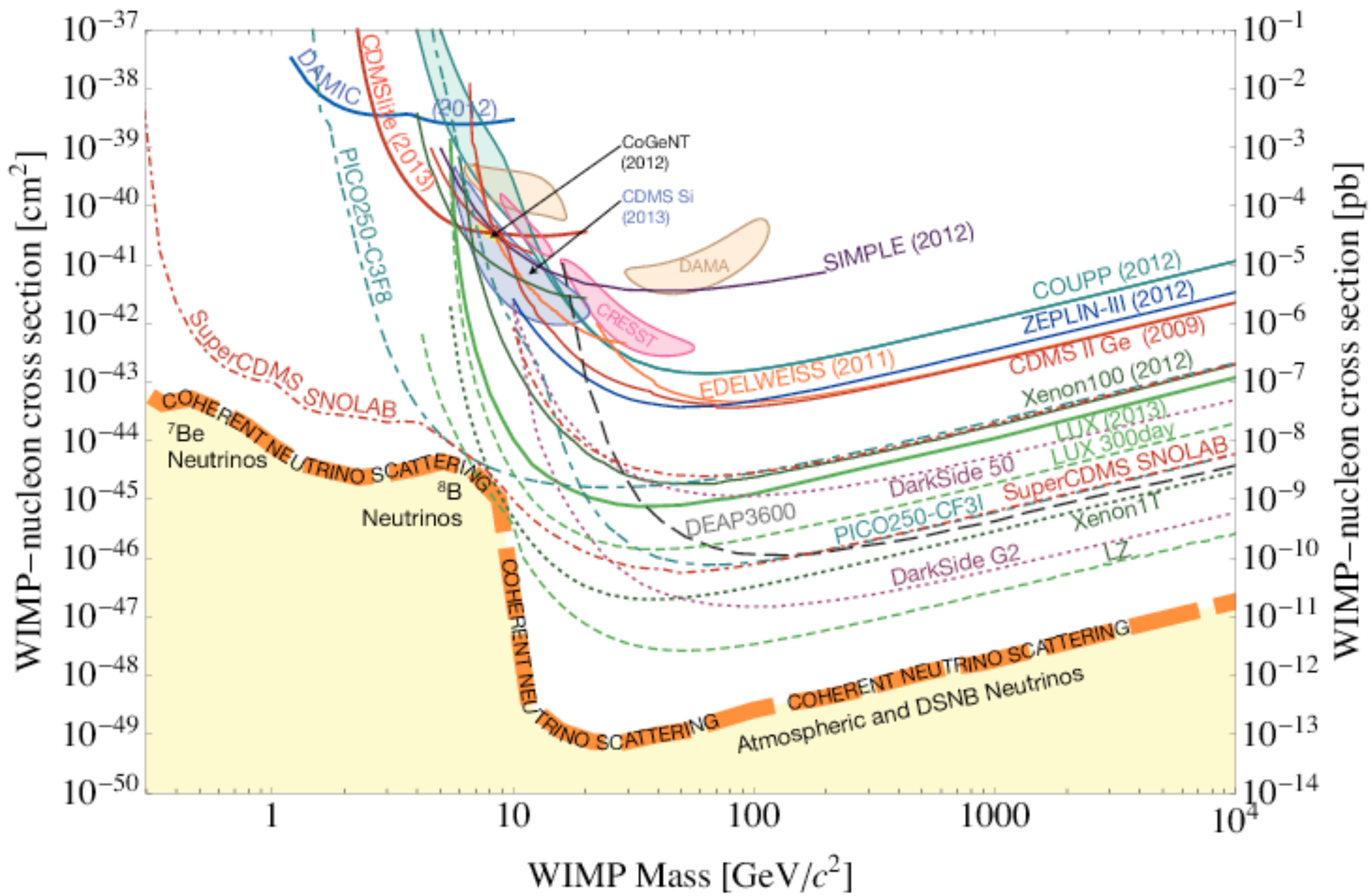
# Relation to Direct Searches

Solid Lines are actual results

Dashed Lines are proposed experiments




Variety of Underground Experiments

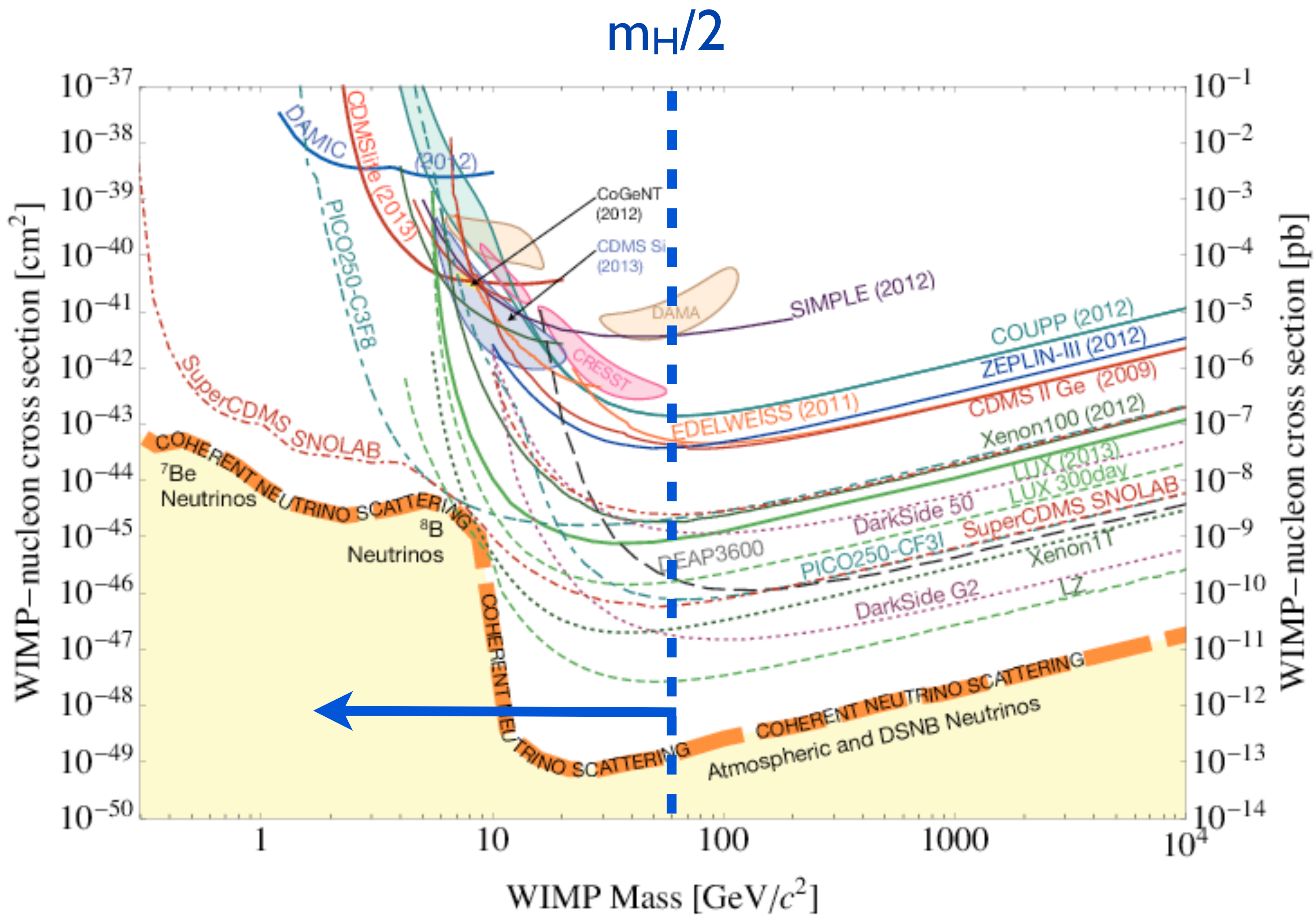



We will be able to put a line on this plot *under the assumptions that the DM couples to the nucleon via Higgs* (and some other caveats)

# Direct Dark Matter "Signals"

Shaded Areas at "Signals"

Obviously the signals are hotly debated

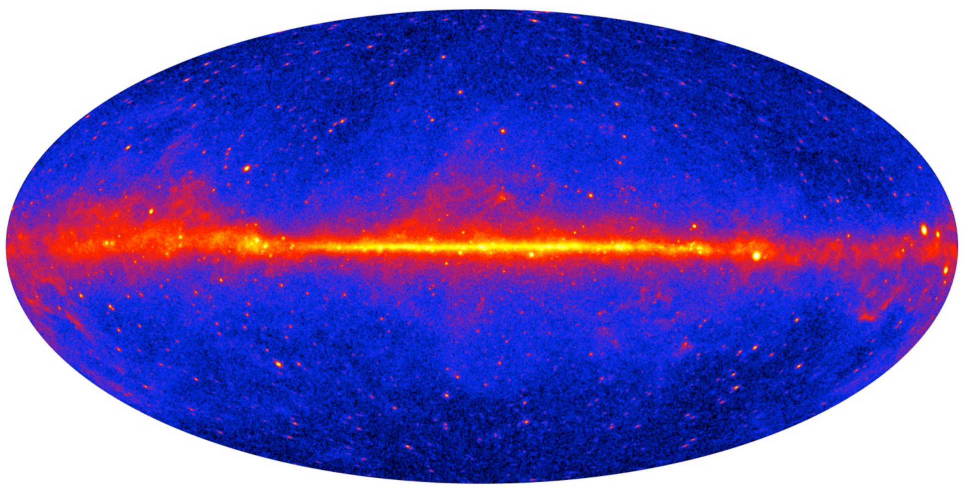



Higgs to Invisible will limit the potential coupling of candidate models with masses below $m_H/2$

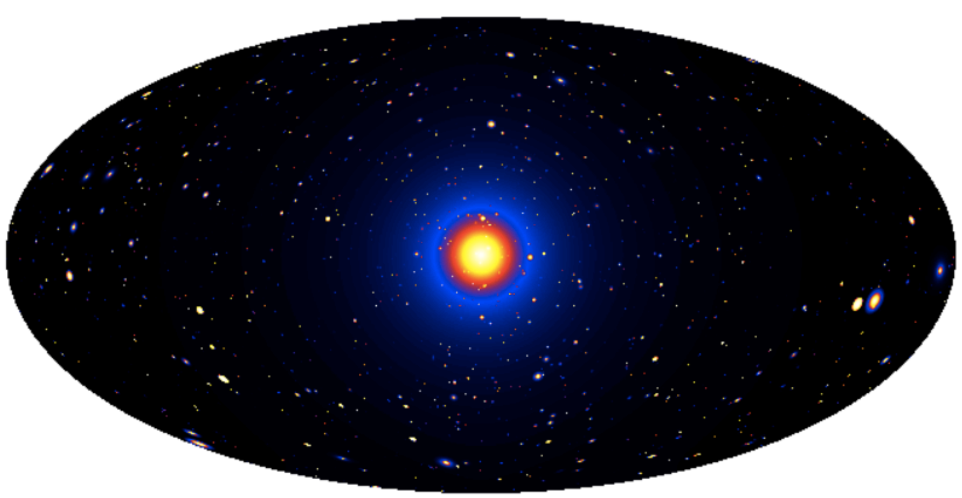
# Indirect Dark Matter "Signals"

Indirect searches = looking for particles from DM annihilation in Galaxy or Galaxy Halos

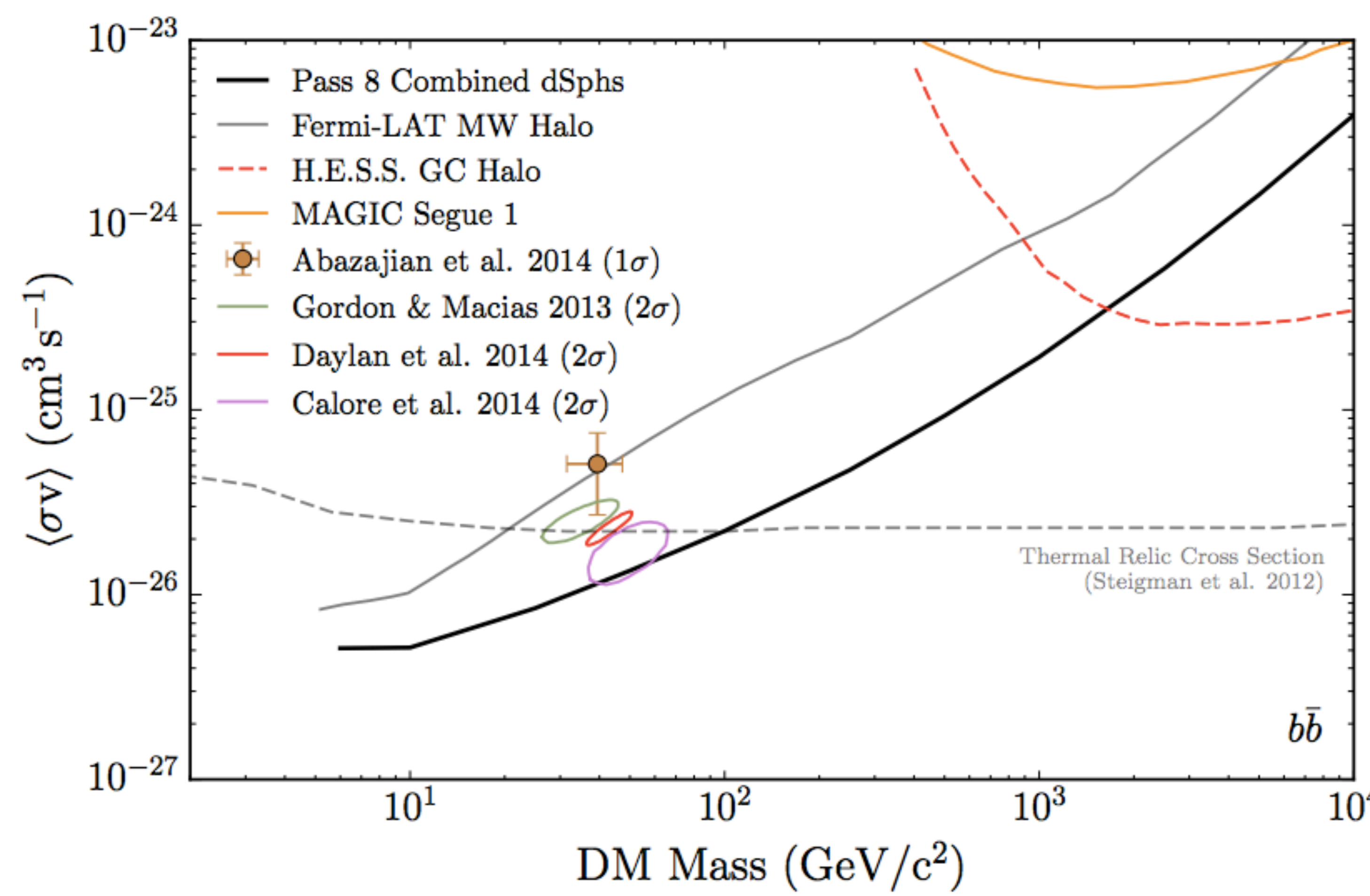
Gamma Ray Sky (~300 MeV to 50 GeV)



Simulated DM addition to Gamma Ray Sky



Here again there are hotly debated signals



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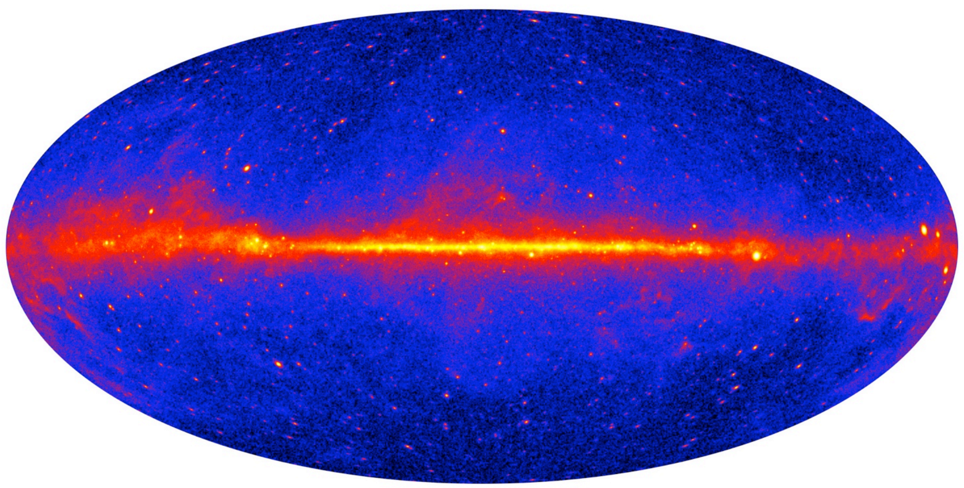

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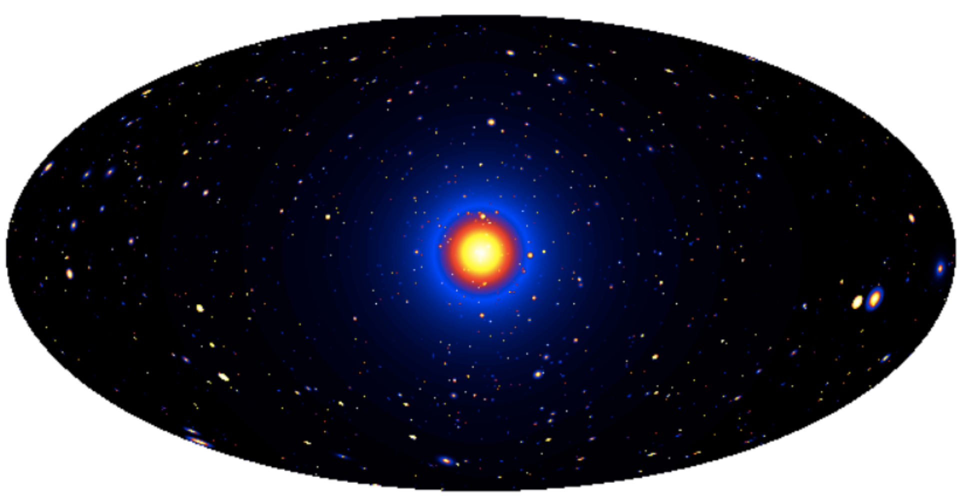

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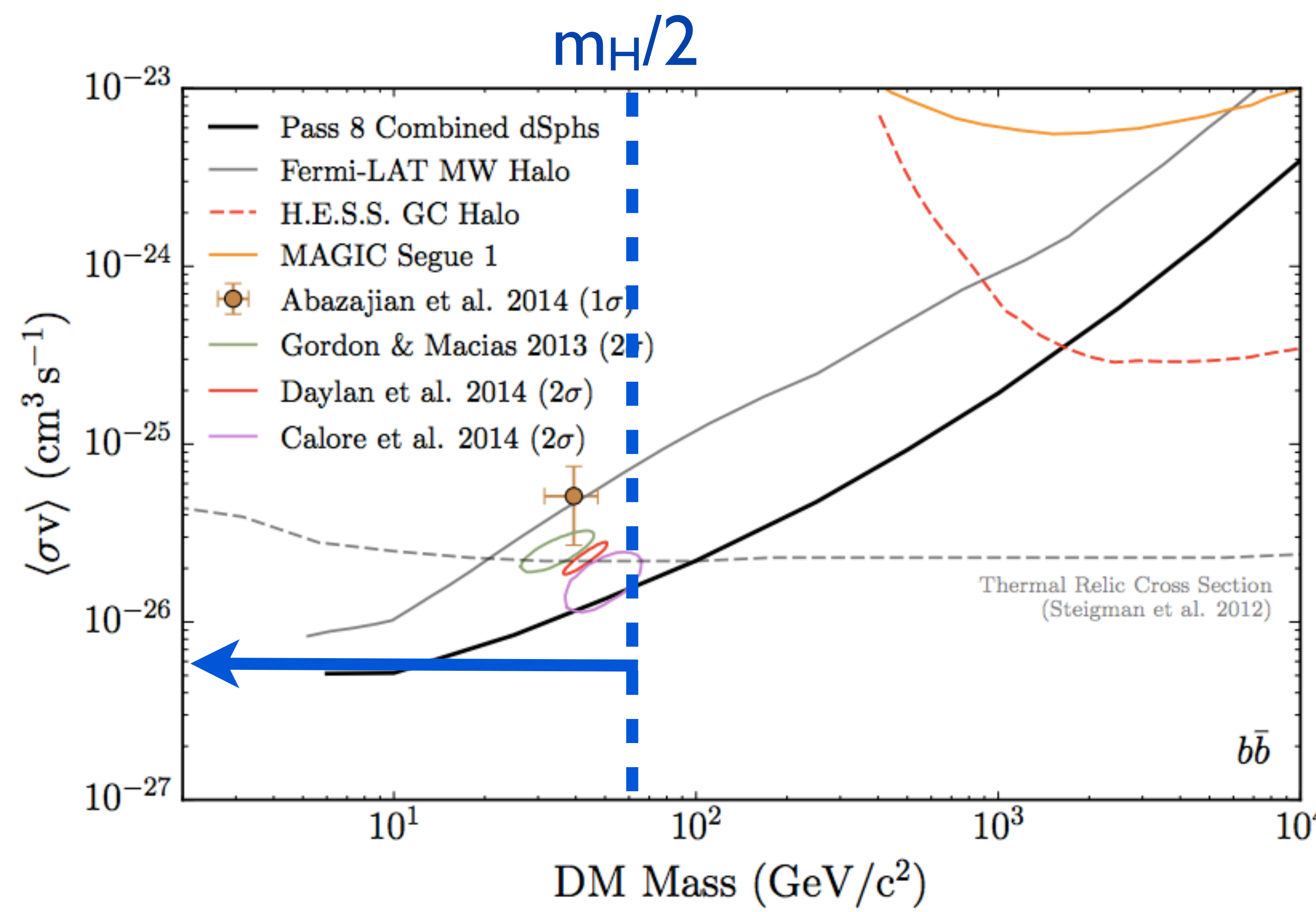
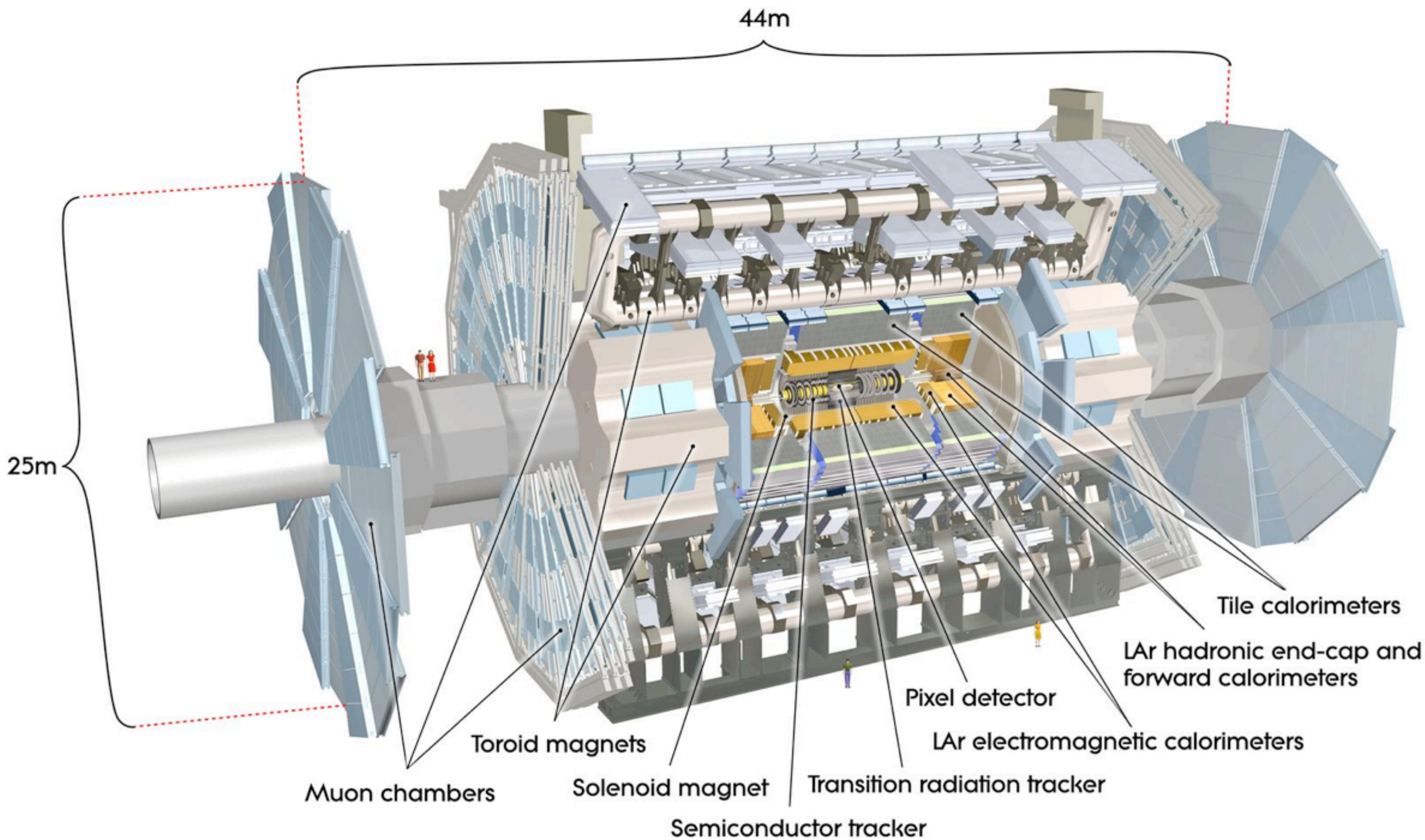


# ATLAS stuff...

pp collisions

Results are with Run 1 Data: 7 Tev (4.5 $fb^{-1}$) and 8 TeV (20.3 $fb^{-1}$)

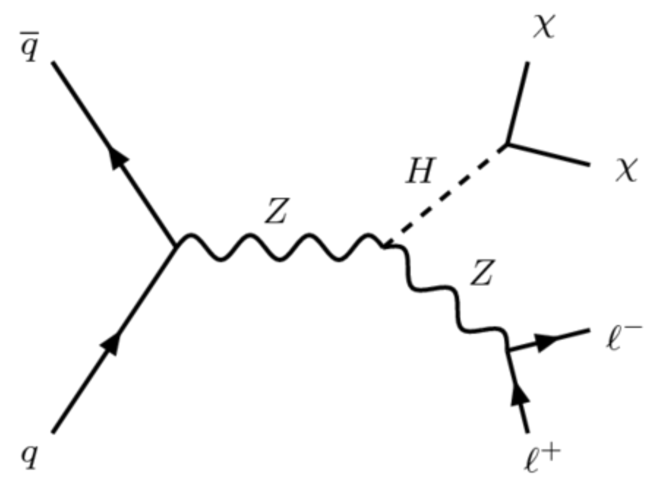
I won't further describe the ATLAS detector and data set



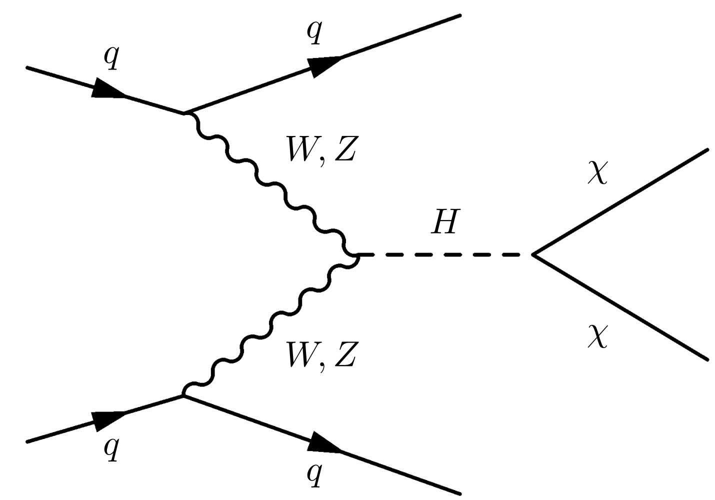
# Higgs to Invisible

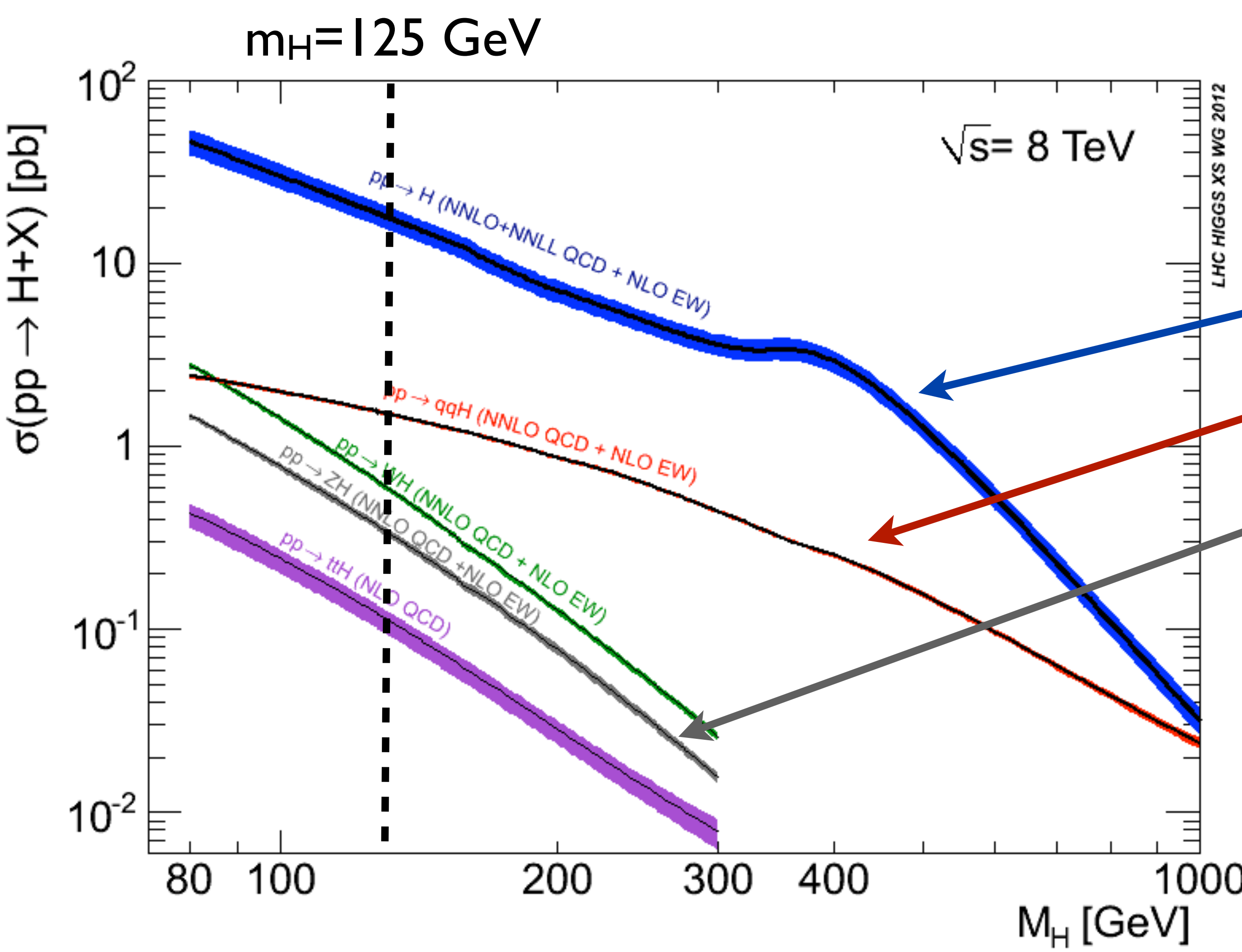
I'll discuss these searches

ZH, H→invisible




VBF, H→invisible



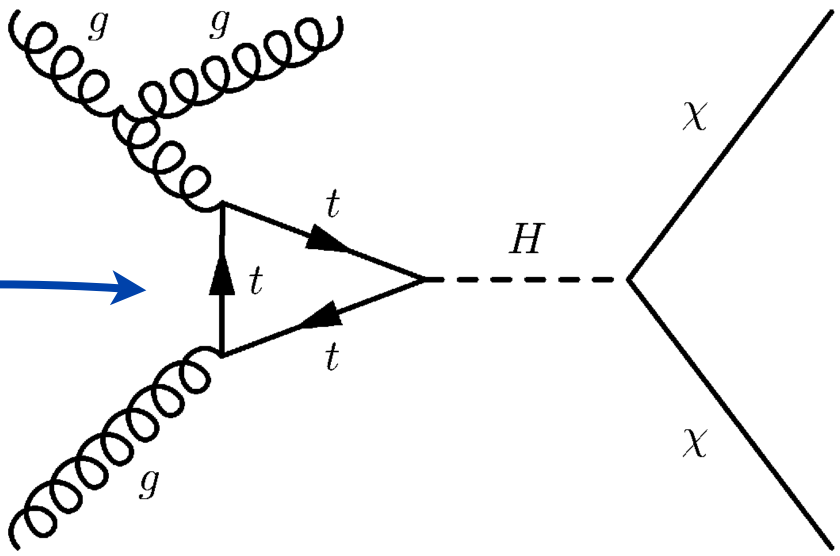

But everyone knows that ggH is much larger than VBF or ZH production

**Why not use ggH?**

# Higgs to Invisible: Why not ggH?

ggH would need need to be boosted by an extra gluon in the event

- VBF and ZH have some natural boost, but not that much




The real reason is over here

- Gluons and quarks in the proton don't couple well to the Higgs
- qq→Z→νν background is much larger than ggH production

$$\frac{\sigma(ggH)}{\sigma(Z) \times BR(Z \to \nu\nu)} = \frac{\approx 19 \text{ pb}}{\approx 6000 \text{ pb}}$$

- Need to focus on processes where signal is on a more equal footing with background
- I.e. things that already have a W or Z in them (top also works ...see later...)

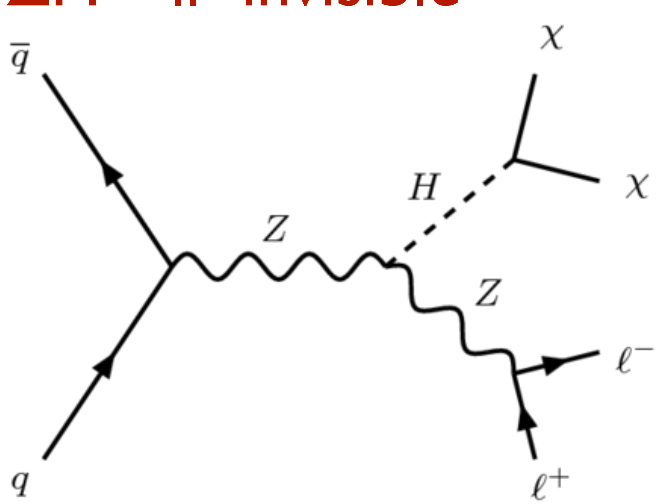
$$\frac{\sigma(VBFH)}{\sigma(VBF - like\ Z) \times BR(Z \to \nu\nu)} = \frac{\approx 1.6 \text{ pb}}{\approx 0.6 \text{ pb}}$$

# Higgs to Invisible in ZH with Z→ll

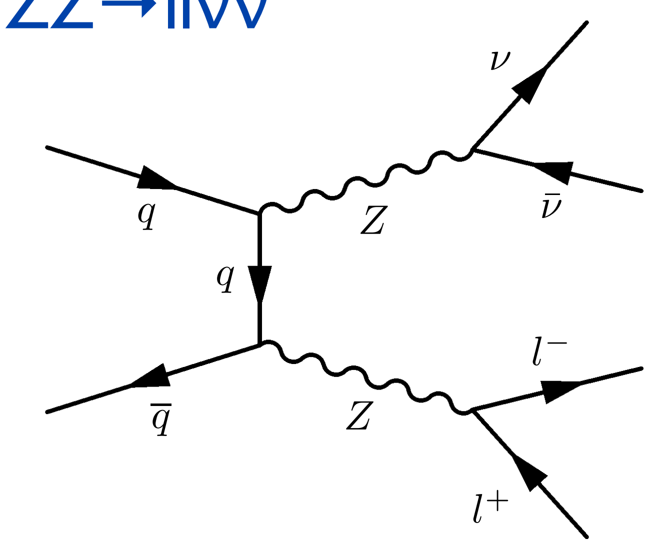
## Signal and Background Summary

**Basic Selection:** Exactly two charged leptons (e or μ, only same-flavor combinations)
"Missing Transverse Energy" ($E_T^{miss}$) (actually momentum)

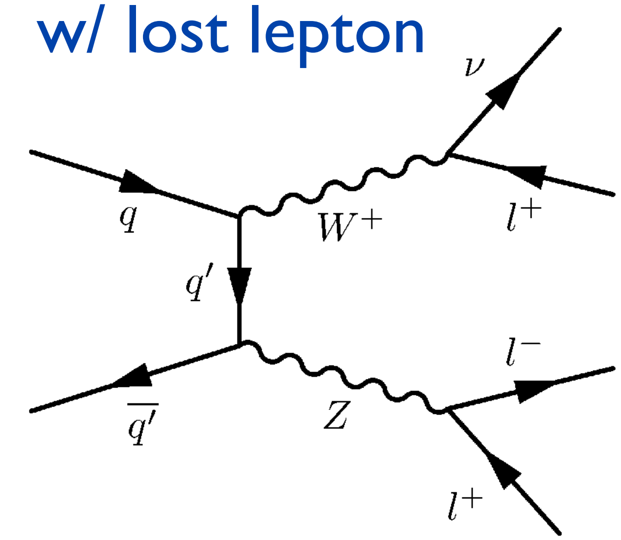
**Signal:**
**ZH→ll+invisible**



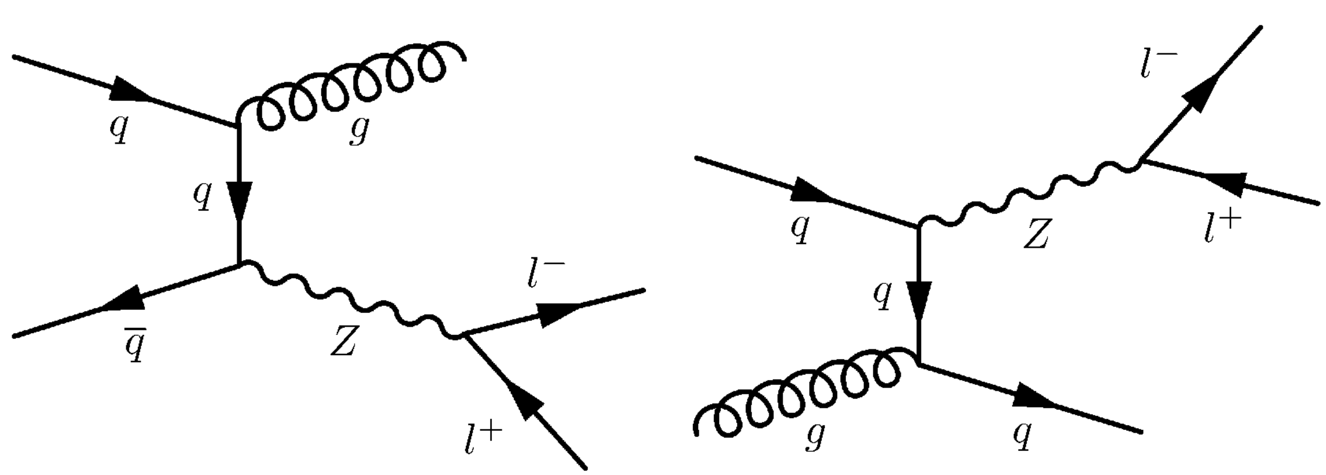

**"Irreducible" Background**
**ZZ→llνν**




**WZ→lllν**
**w/ lost lepton**



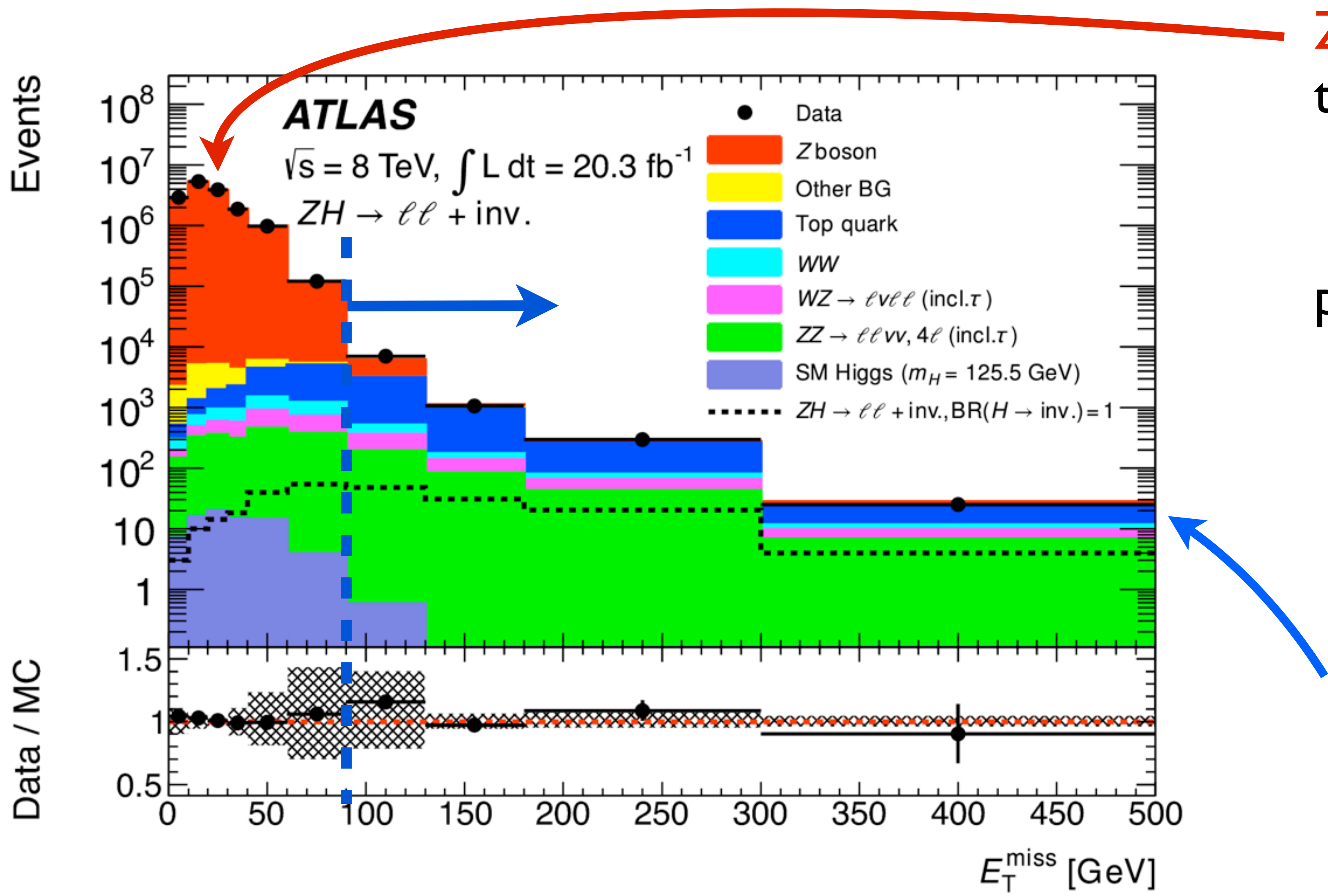

**Z→ll + fake Missing Energy**




**Additional Backgrounds:**
$t\bar{t}$ ,WW→llνν,
single top, Z→ττ

# Higgs to Invisible in ZH with Z→ll

## Selection and Resulting Composition




Z+jets is much much larger than signal

$$E_T^{miss} > 90 \text{ GeV}$$

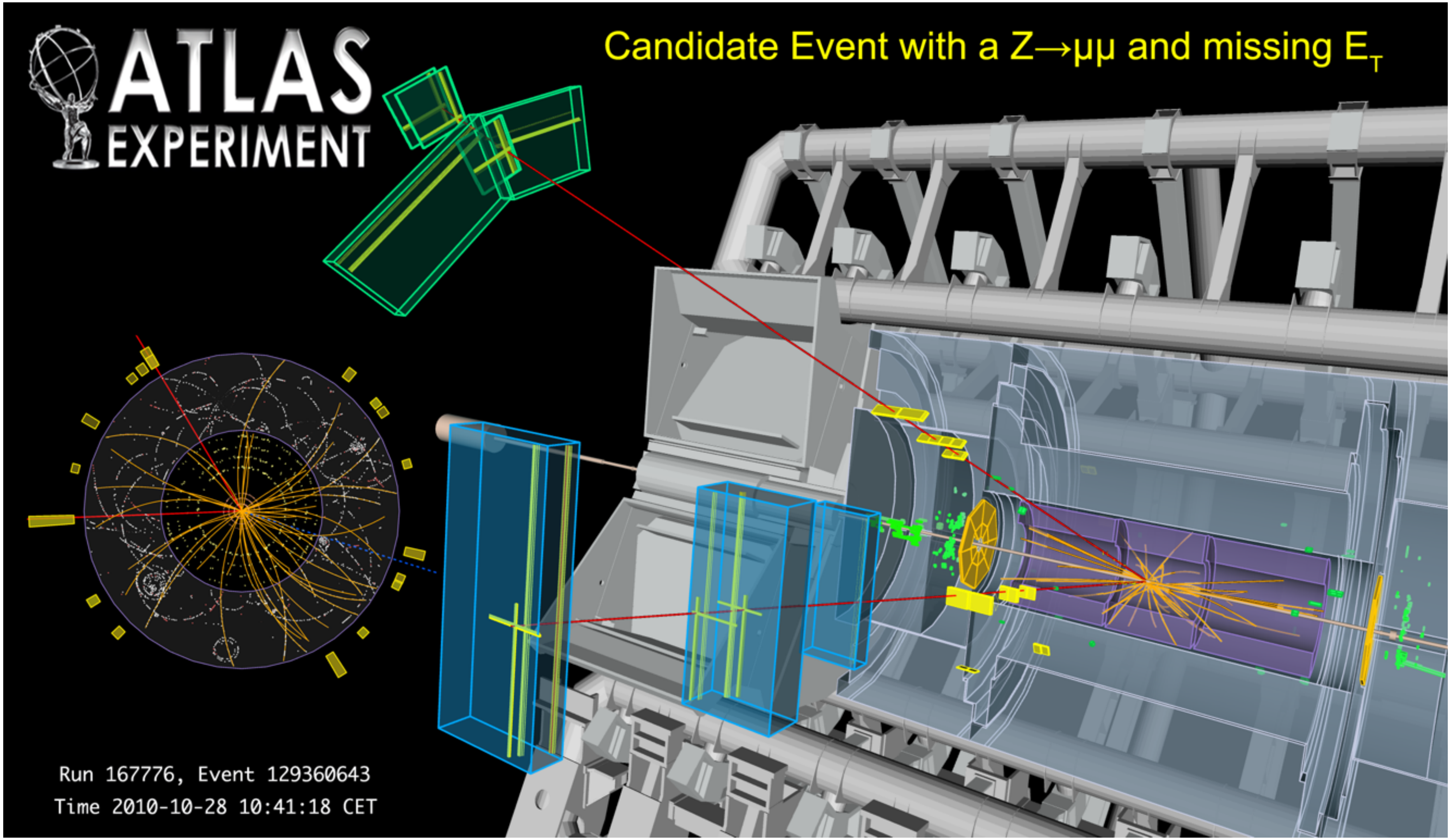
plus additional "cleaning"

$$\begin{aligned} \phi(\vec{E}_T^{miss}, \vec{p}_T^{ll}) &> 2.6 \\ \phi(l,l) &< 1.7 \\ |E_T^{miss} - p_T^{ll}|/p_T^{ll} &< 0.2 \end{aligned}$$

$t\bar{t} \to WWbb \to \ell\nu\ell\nu bb$
also larger than signal, so veto jets with $p_T$ > 25 GeV

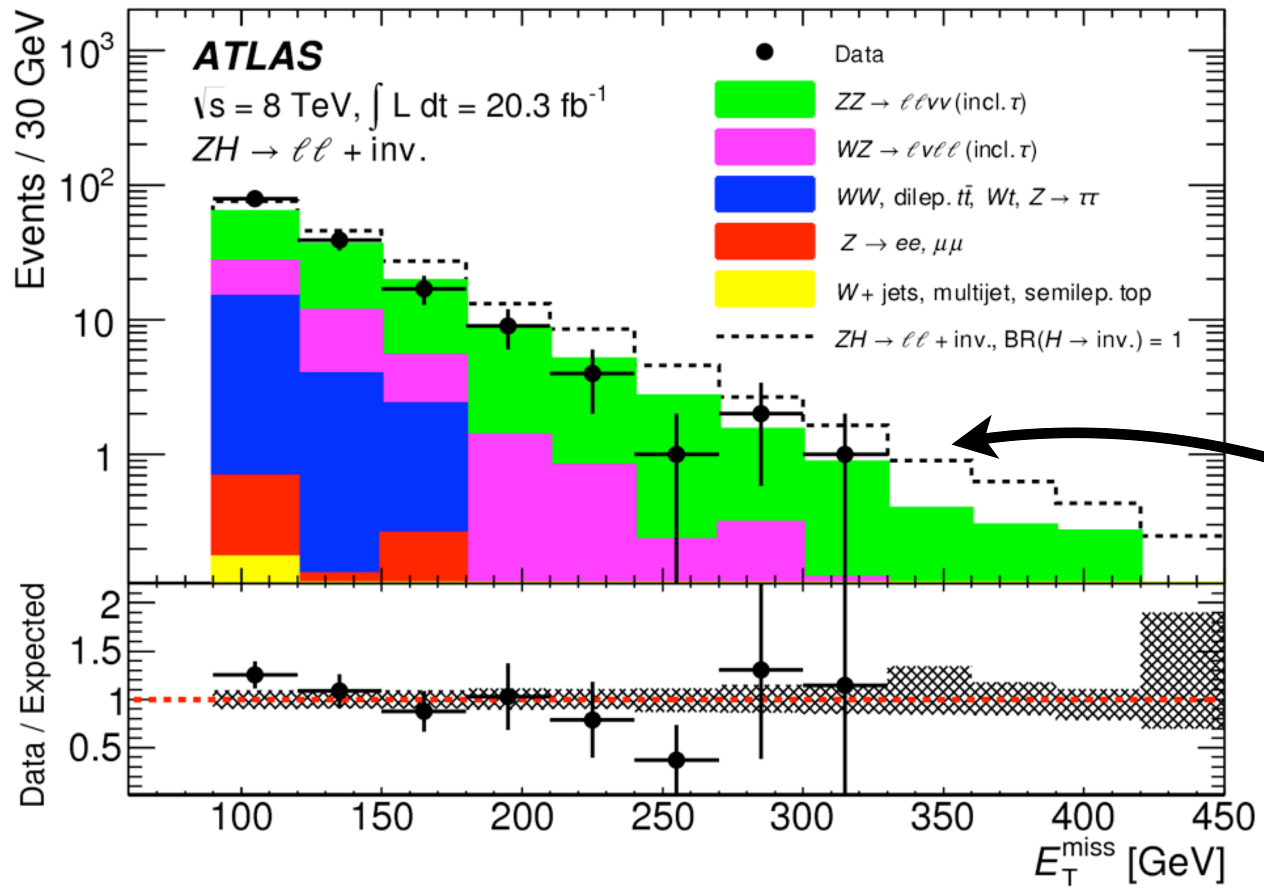
Signal here is normalized to a 100% Higgs branching fraction... limits will be a bit below this

# Z + MET Event Topology



# Higgs to Invisible in ZH with Z→ll

## Selection and Resulting Composition




After all cuts 100% BR signal would be comparable to total background (signal is stack on backgrounds)

Slightly better S/B at high $E_T^{miss}$

Signal is extracted from fit to this $E_T^{miss}$ distribution

| Data period | 2011 (7 TeV) | 2012 (8 TeV) |
|---|---|---|
| $ZZ \rightarrow \ell\ell\nu\nu$ | $20.0 \pm 0.7 \pm 1.6$ | $91 \pm 1 \pm 7$ |
| $WZ \rightarrow \ell\nu\ell\ell$ | $4.8 \pm 0.3 \pm 0.5$ | $26 \pm 1 \pm 3$ |
| Dileptonic $t\bar{t}$, $Wt$, $WW$, $Z \rightarrow \tau\tau$ | $0.5 \pm 0.4 \pm 0.1$ | $20 \pm 3 \pm 5$ |
| $Z \rightarrow ee$, $Z \rightarrow \mu\mu$ | $0.13 \pm 0.12 \pm 0.07$ | $0.9 \pm 0.3 \pm 0.5$ |
| $W$ + jets, multijet, semileptonic top | $0.020 \pm 0.005 \pm 0.008$ | $0.29 \pm 0.02 \pm 0.06$ |
| Total background | $25.4 \pm 0.8 \pm 1.7$ | $138 \pm 4 \pm 9$ |
| Signal ($m_H = 125.5$ GeV, $\sigma_{ZH,SM}$, BR($H \rightarrow$ inv.) = 1) | $8.9 \pm 0.1 \pm 0.5$ | $44 \pm 1 \pm 3$ |
| Observed | 28 | 152 |

# Higgs to Invisible in ZH with Z→ll

Background Modeling and Systematics

Dominant ZZ background is modeled with MC simulation

| | |
|---|---|
| Systematics included PDFs and scale ($q^2$) variations | 5% |
| Specified parton shower model uncertainty for jet-veto | 6% |
| Many detector response systematics (generally small)<br>Largest is jet energy scale for jet-veto | 6% |

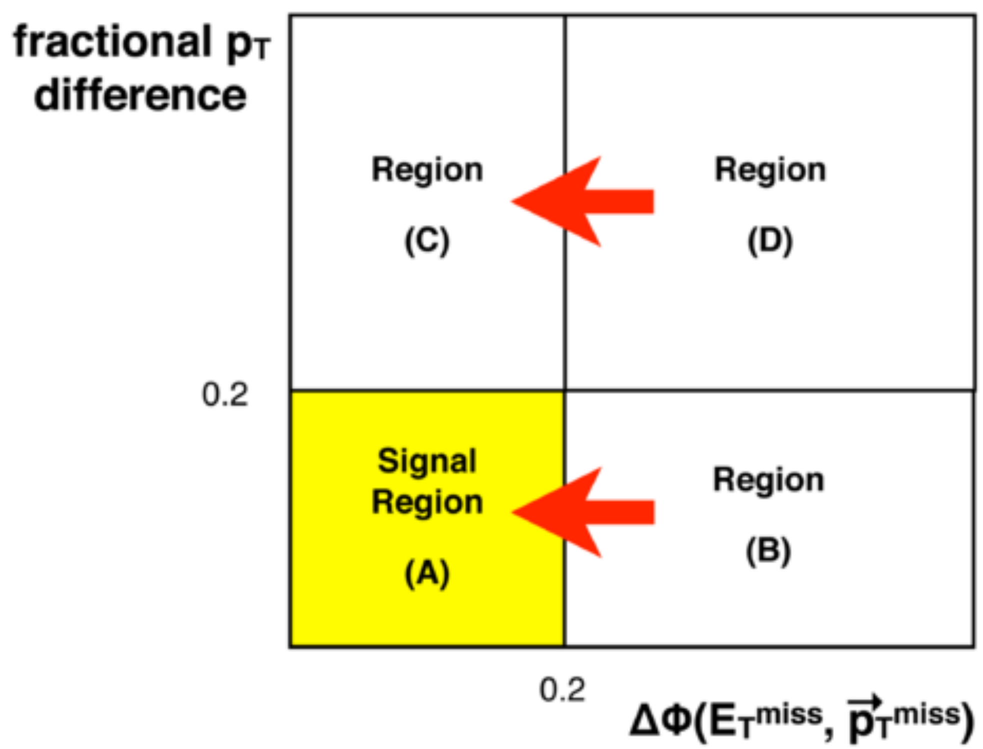
WZ background and Signal (ZH) similar to ZZ

$WW,\ t\bar{t},\ Wt,$ and $Z \rightarrow \tau\tau$: Use eμ combinations and extrapolate to ee/μμ

Z+jets with fake $E_T^{miss}$ is modeled with "ABCD" method using $\phi(\vec{E}_T^{miss}, \vec{p}_T^{ll})$ and $|E_T^{miss} - p_T^{ll}|/p_T^{ll}$

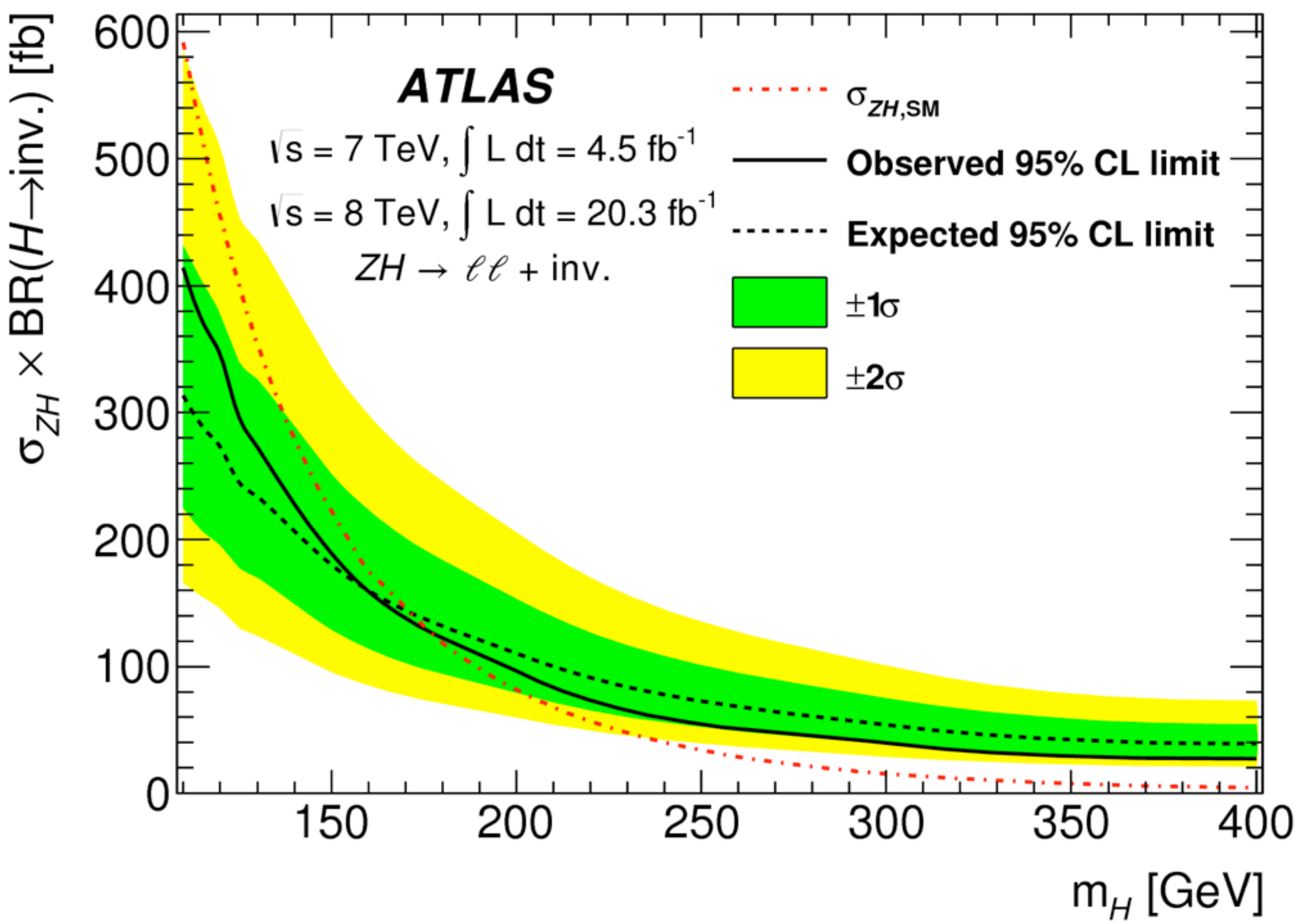
$$N_A = N_C \times \frac{N_C}{N_D}$$

A 7% correlation between these variables is found in MC



# Higgs to Invisible in ZH with Z→ll

Statistical Interpretation and Results




Scan a variety of Higgs masses

At $m_H$ = 125 GeV

Observed BR limit
75% at 95% C.L.

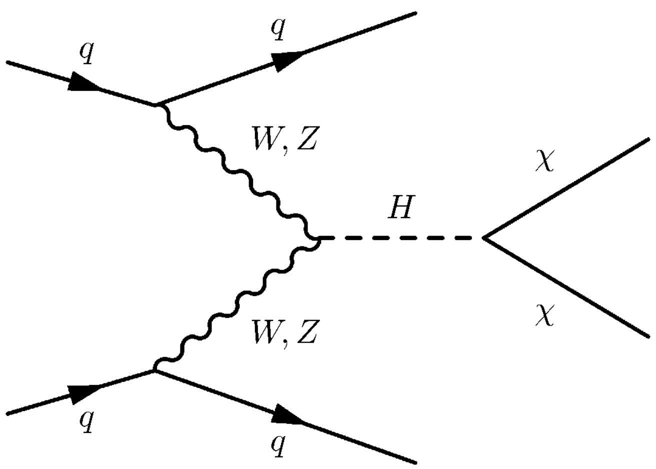
Expected BR limit
62% at 95% C.L.

# VBF Higgs to Invisible

## Signal and Background Summary

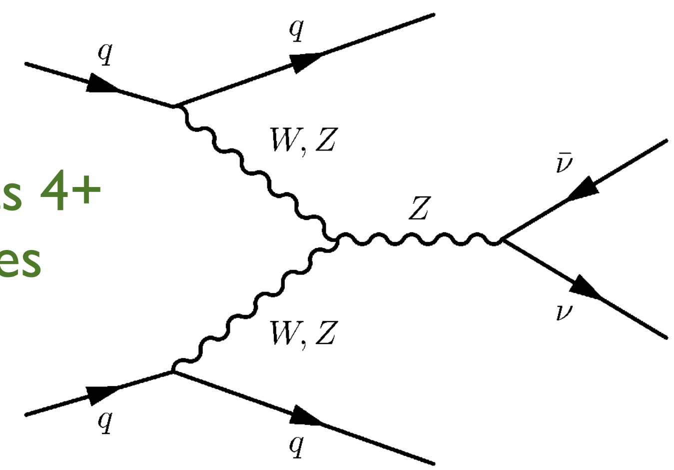
VBF = vector boson fusion

Signal: VBF, H→invisible



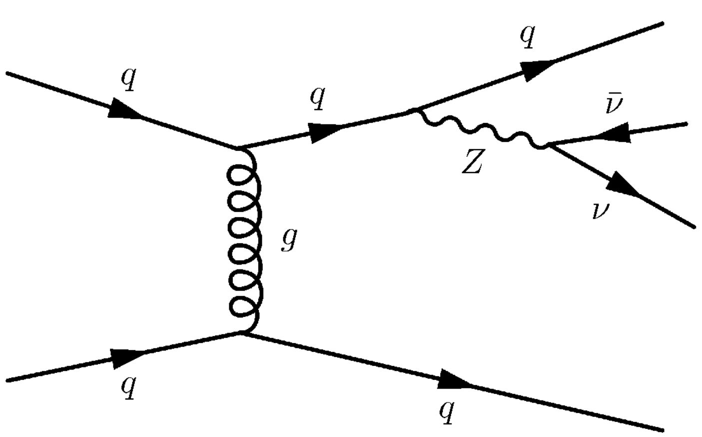

Irreducible Z→νν background:
VBF, Z→νν ~ "Weak", Z→νν

"Weak" has 4+ ewk vertices




Plus "multijet QCD" (i.e. no actual weak bosons)

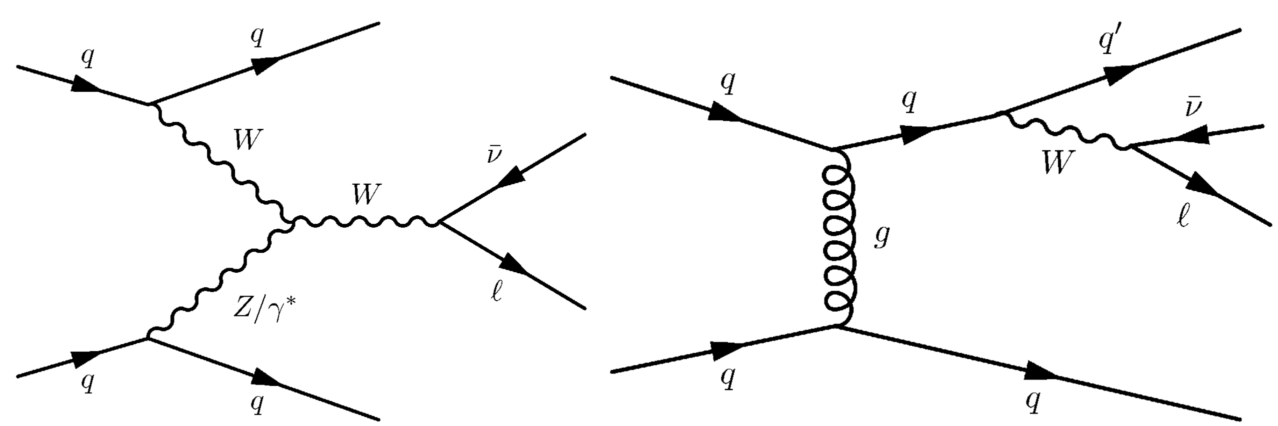
"Reducible" Z→νν background:
"Strong" Z→νν




\+ many other diagrams

"Strong" has 2 ewk vertices

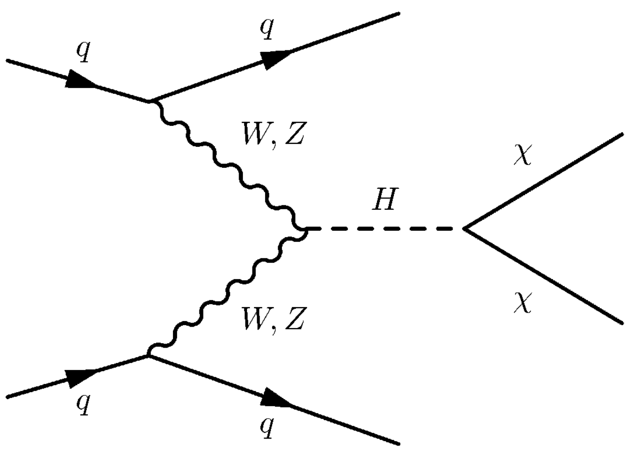
W background:
Both Strong and Weak W→lν (with lost lepton)



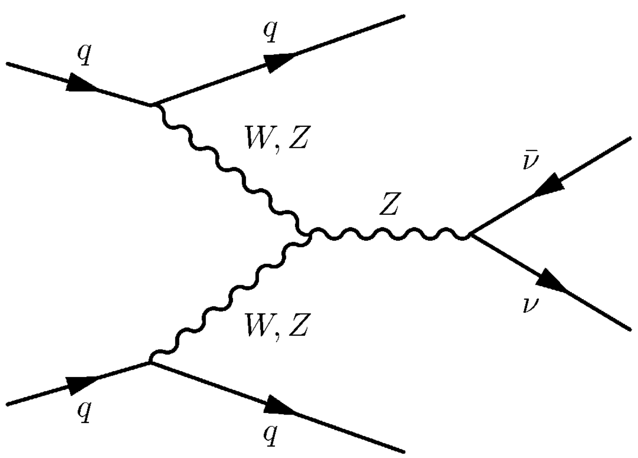
# VBF Higgs to Invisible

## How do you tell VBF from non-VBF?

Signal: VBF, H→invisible



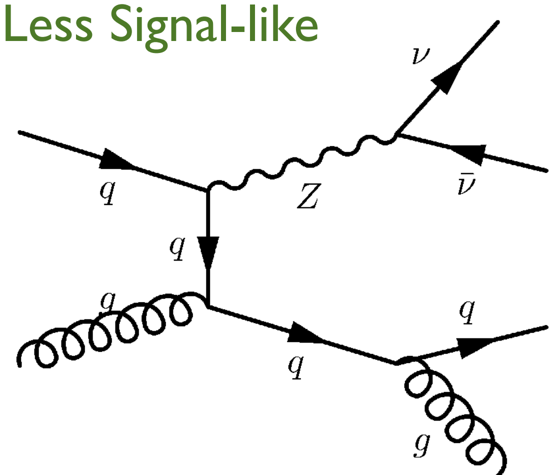

Irreducible background:
“Weak”, Z→νν

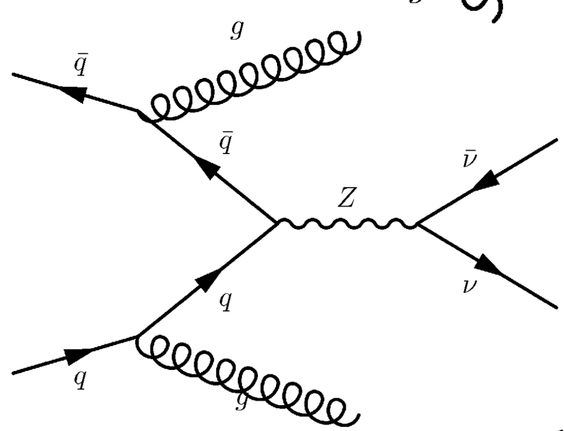


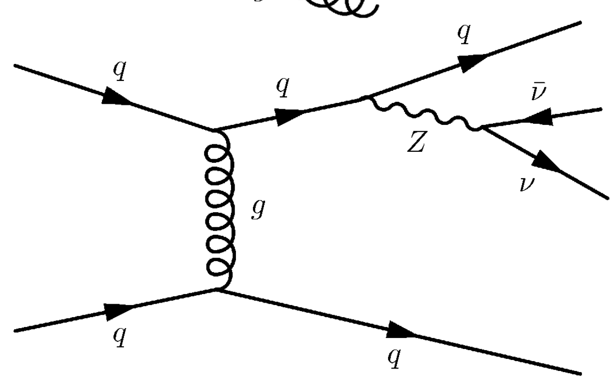

VBF has two jets separated in aligned along the beam directions

“Reducible” background:
“Strong” Z→νν

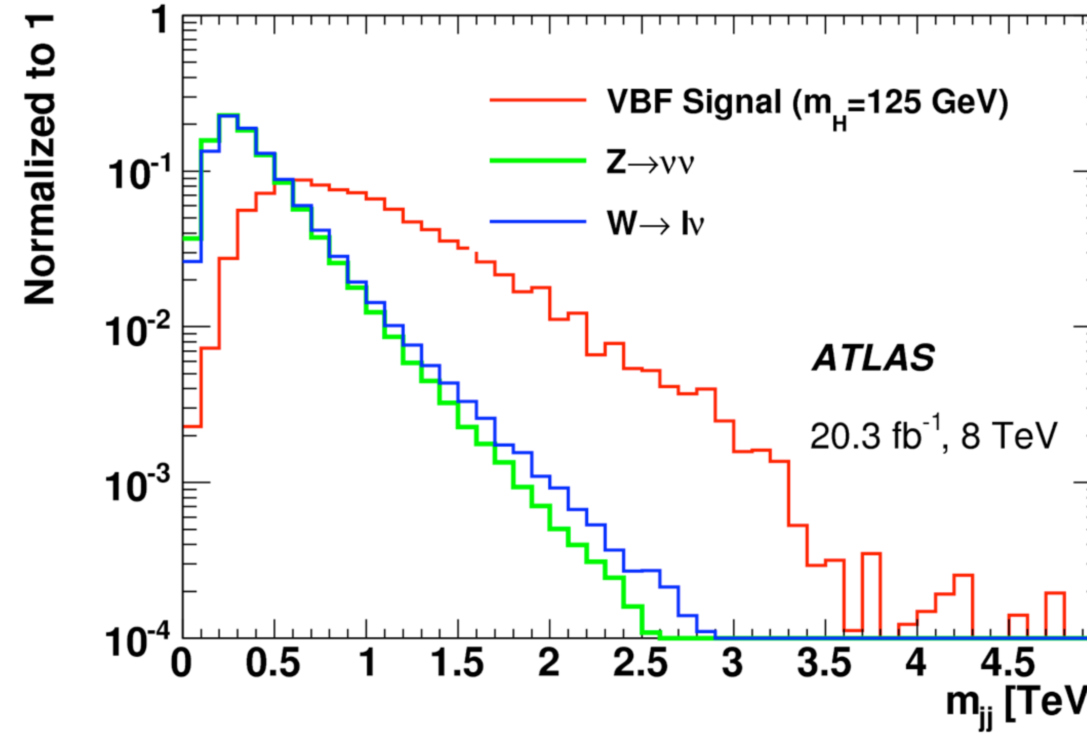
Less Signal-like

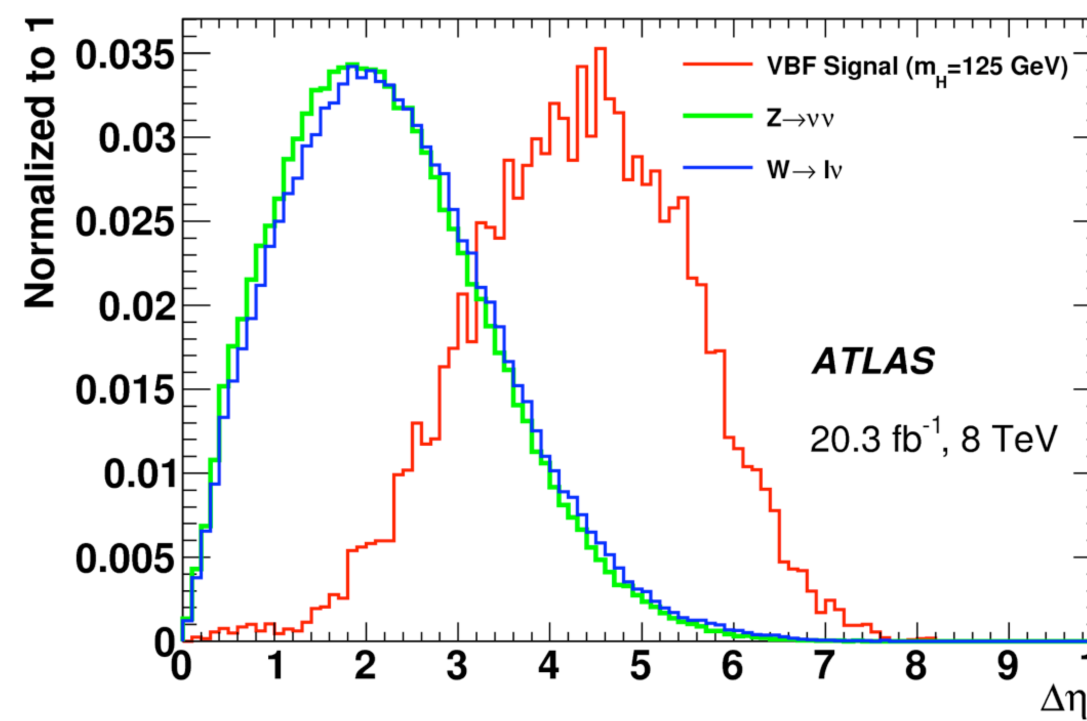


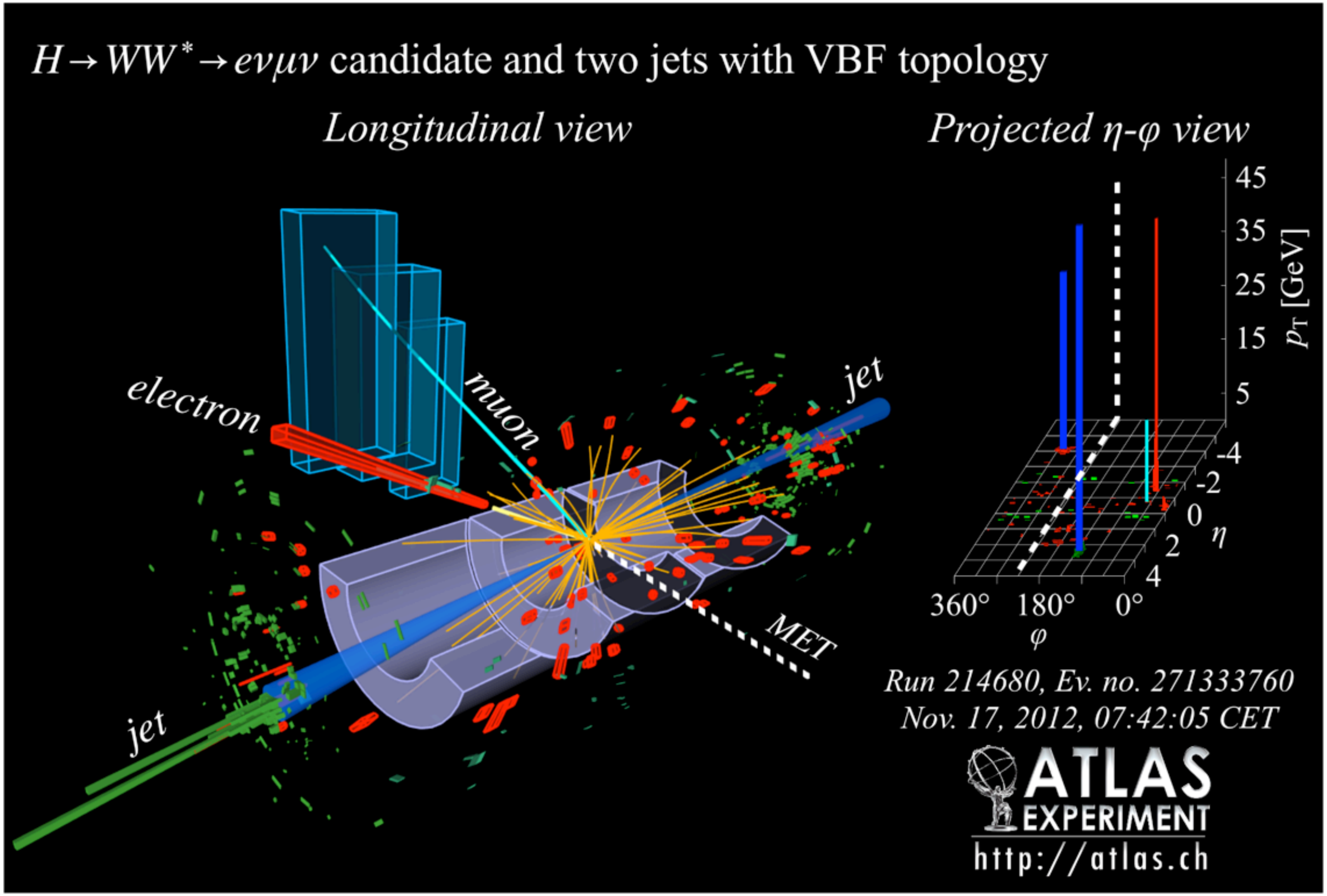

More Signal-like



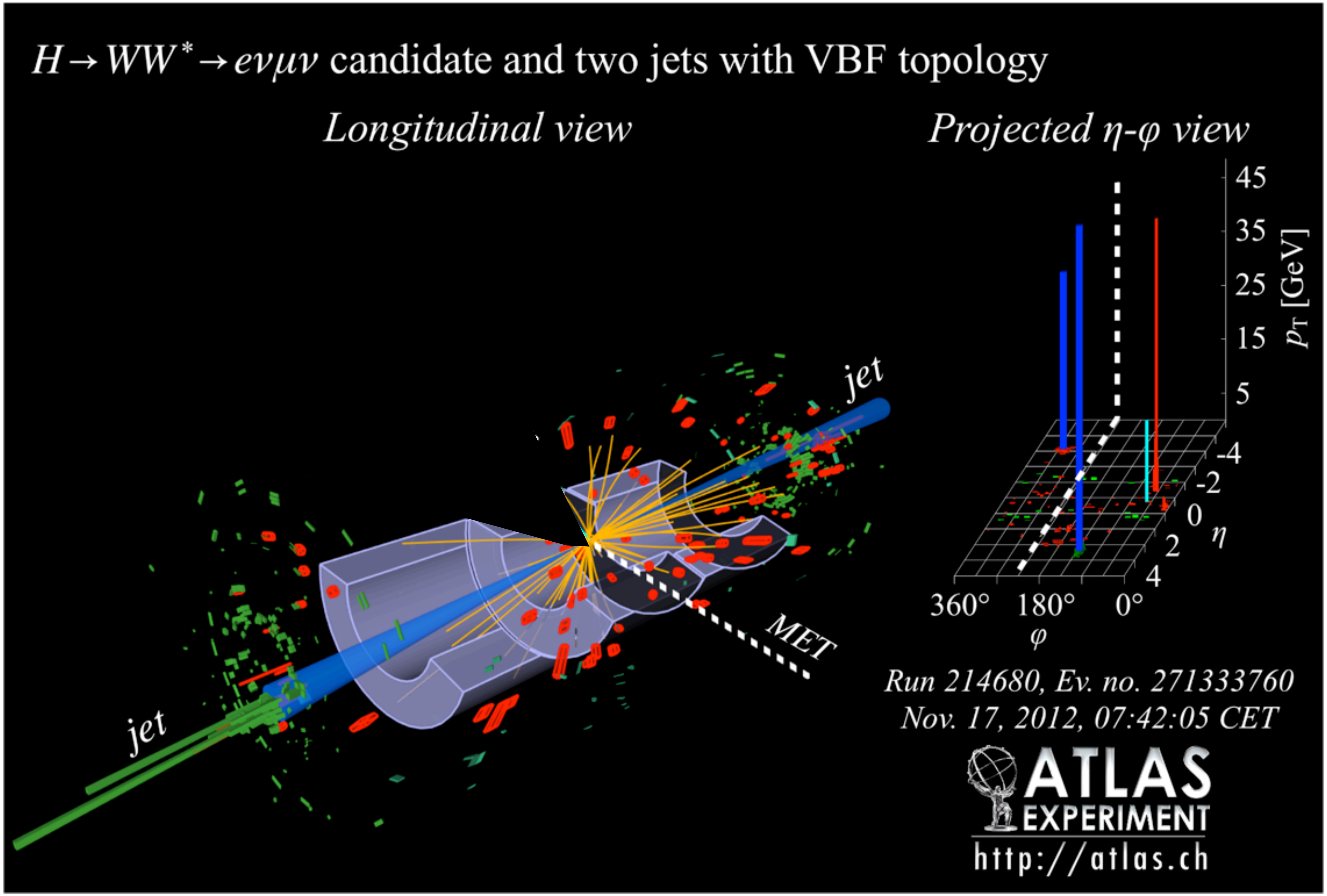
# VBF Event Display

Actually H→WW→llνν but illustrative anyway



# VBF Event Display

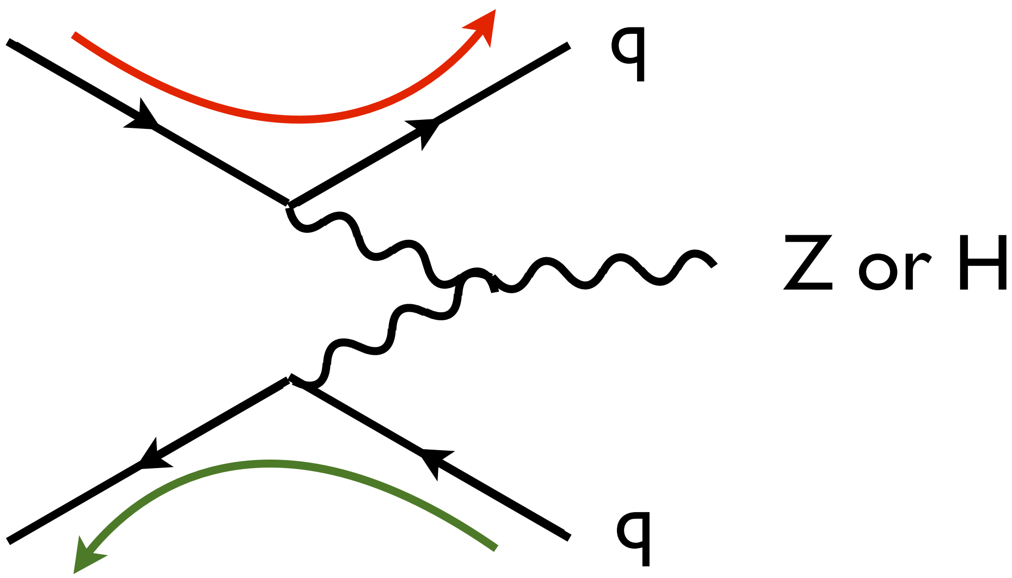
Actually H→WW→llνν but illustrative anyway

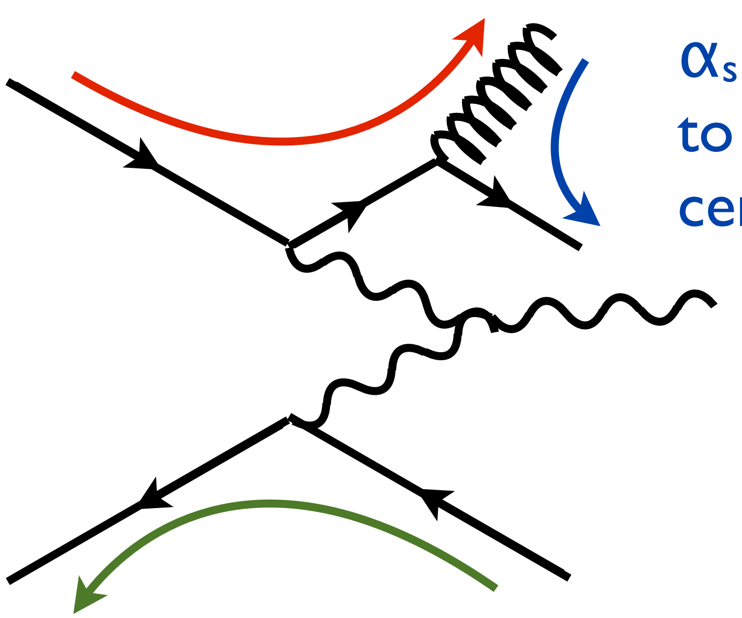


# VBF Higgs to Invisible

## Second handle for VBF: Central Jet Veto

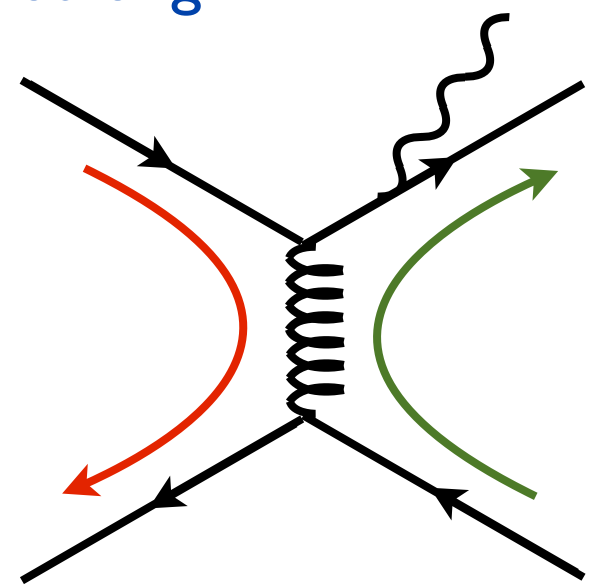
VBF-like topologies:
Signal and Weak $Z \rightarrow \nu\nu$ background



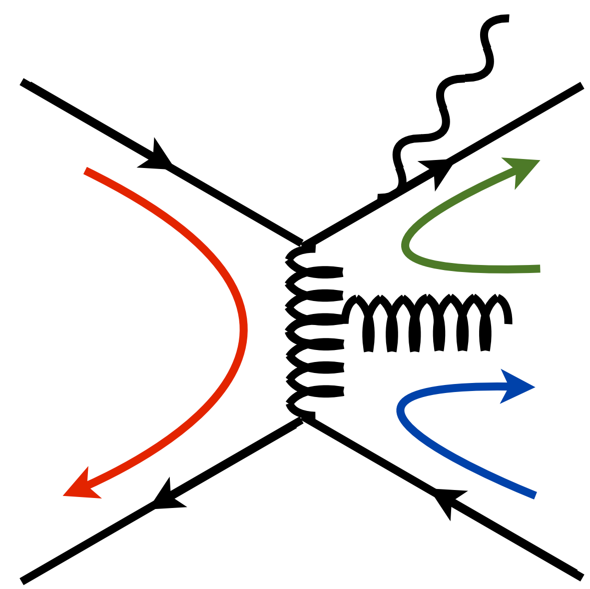



$\alpha_s$ at hard scale
to get to
central region

"Reducible" background:
"Strong" $Z \rightarrow \nu\nu$



$\alpha_s$ already at
hard scale

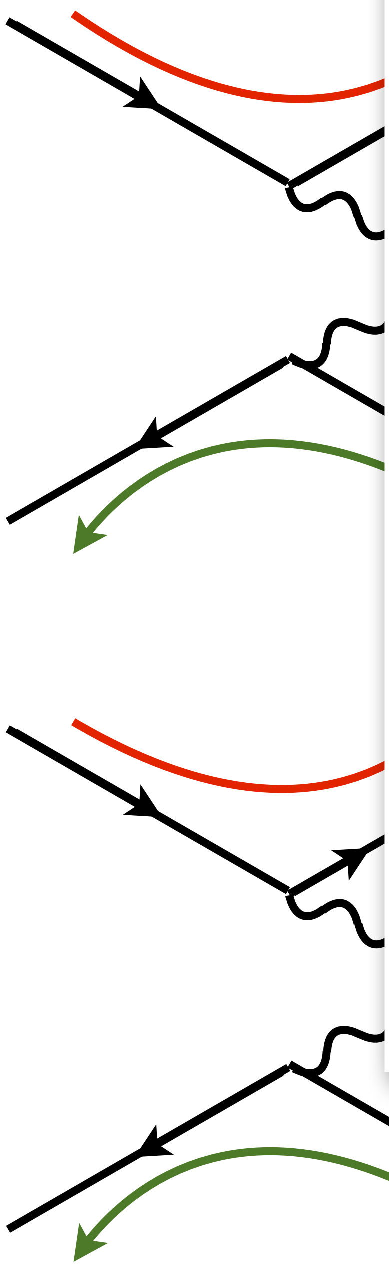


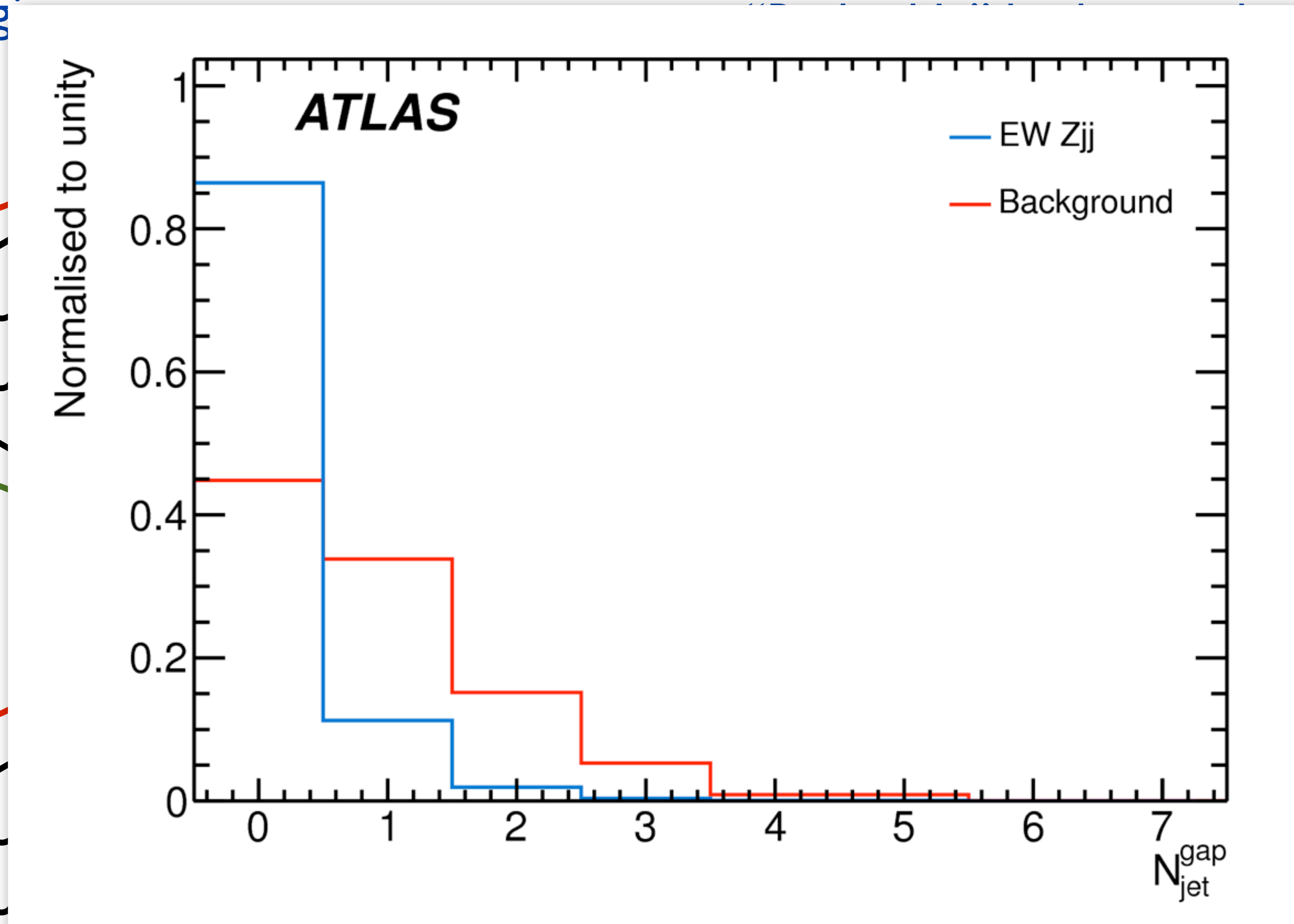
now two $\alpha_s$
both at lower
scales

# VBF Higgs to Invisible

## Second handle for VBF: Central Jet Veto

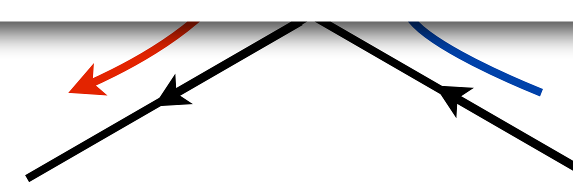
VBF-like topolog
Signal and Weak






eady at
cale

wo $\alpha_s$
at lower



# VBF Higgs to Invisible

## Selection

### Basic 2-jet+MET Selection

Jet 1: pT > 75 GeV
Jet 2: pT > 50 GeV
$E_T^{miss}$ > 150 GeV

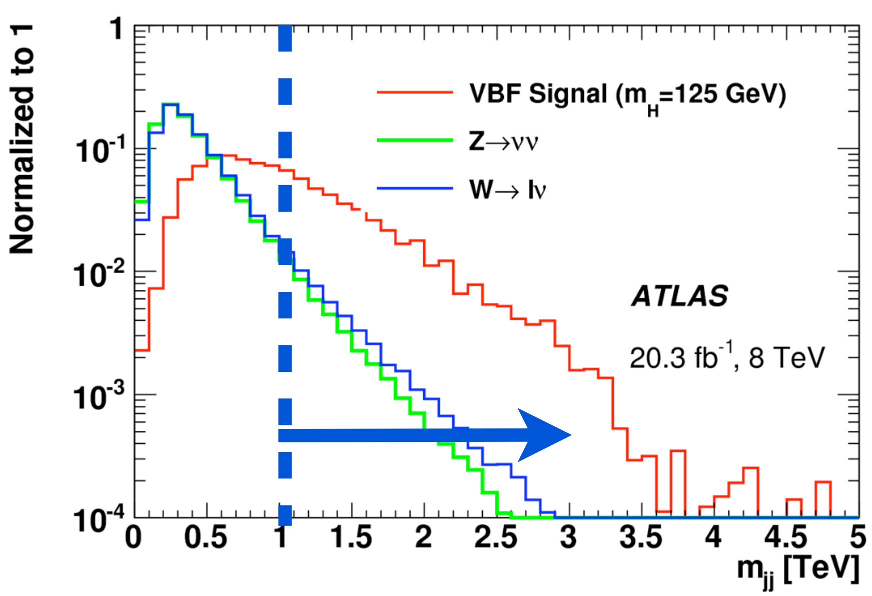
Mostly determined by the trigger

### MET Cleaning

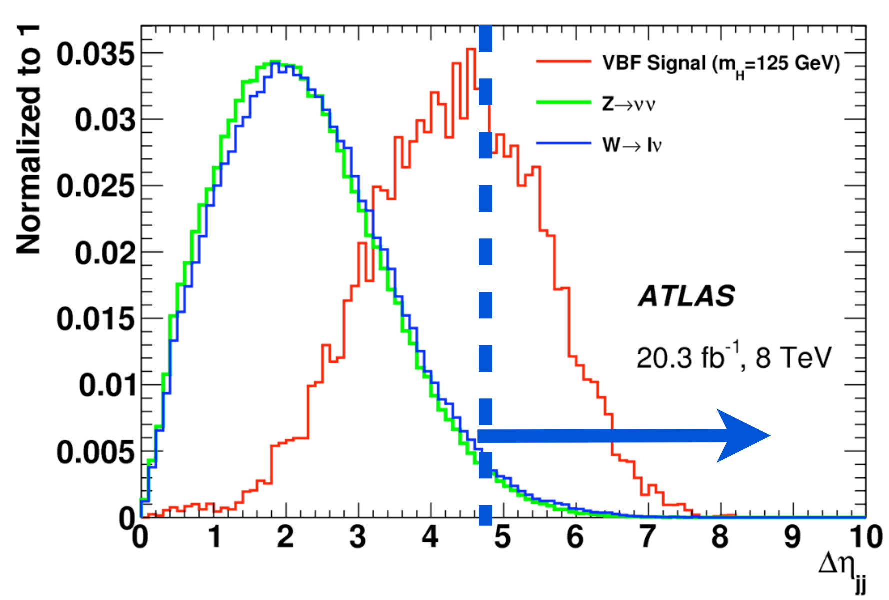
$|\Delta\varphi(j, E_T^{miss})|$ > 1.6 for jet 1
> 1.0 otherwise

$|\Delta\varphi(j,j)|$ < 2.5

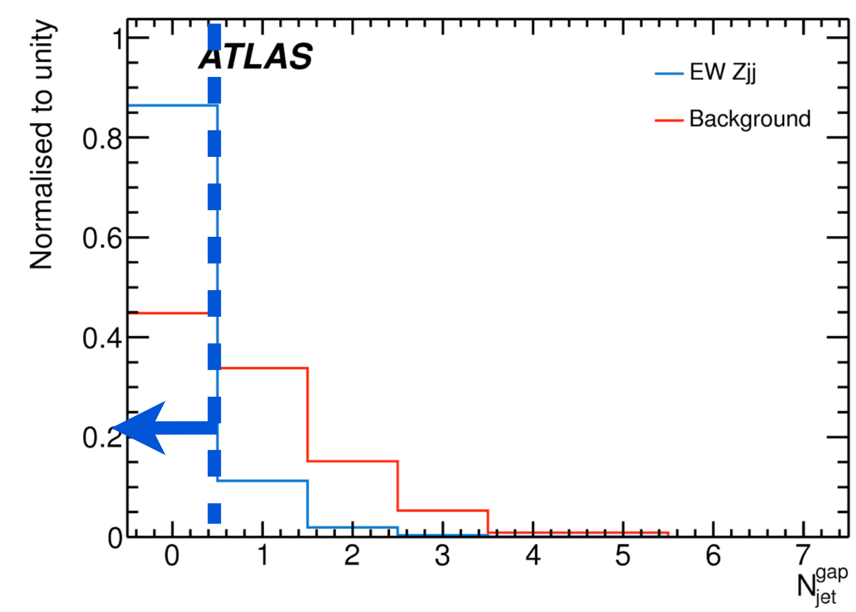
### VBF Selection




$m_{jj}$ > 1 TeV




$\Delta\eta_{jj}$ > 4.8




No addition jets, $p_T$ > 30 GeV

# VBF Higgs to Invisible

## Selection

Paper actually has three signal regions

| Requirement | SR1 | SR2a | SR2b |
|---|---|---|---|
| Leading Jet $p_T$ | >75 GeV | >120 GeV | >120 GeV |
| Leading Jet Charge Fraction | N/A | >10% | >10% |
| Second Jet $p_T$ | >50 GeV | >35 GeV | >35 GeV |
| $m_{jj}$ | >1 TeV | $0.5 < m_{jj} < 1$ TeV | > 1 TeV |
| $\eta_{j1} \times \eta_{j2}$ | <0 | | |
| $\lvert\Delta\eta_{jj}\rvert$ | >4.8 | >3 | $3 < \lvert\Delta\eta_{jj}\rvert < 4.8$ |
| $\lvert\Delta\phi_{jj}\rvert$ | <2.5 | N/A | |
| Third Jet Veto $p_T$ Threshold | 30 GeV | | |
| $\lvert\Delta\phi_{j,E_T^{miss}}\rvert$ | >1.6 for $j_1$, >1 otherwise | >0.5 | |
| $E_T^{miss}$ | >150 GeV | >200 GeV | |

Almost all the sensitivity comes from SR1 which is what I described

$m_{jj}$ > 1 TeV

$\Delta\eta_{jj}$ > 4.8

No addition jets, $p_T$ > 30 GeV

# VBF Higgs to Invisible

## Resulting Selection

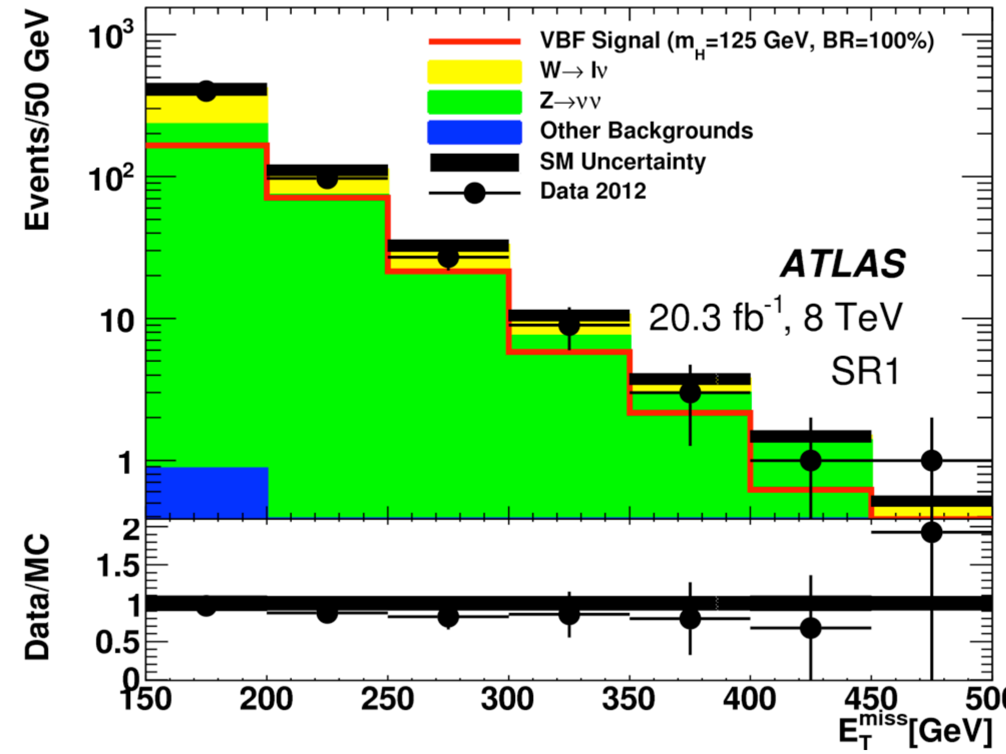
Signal for 100% Branching Fraction, (Yields from MC)

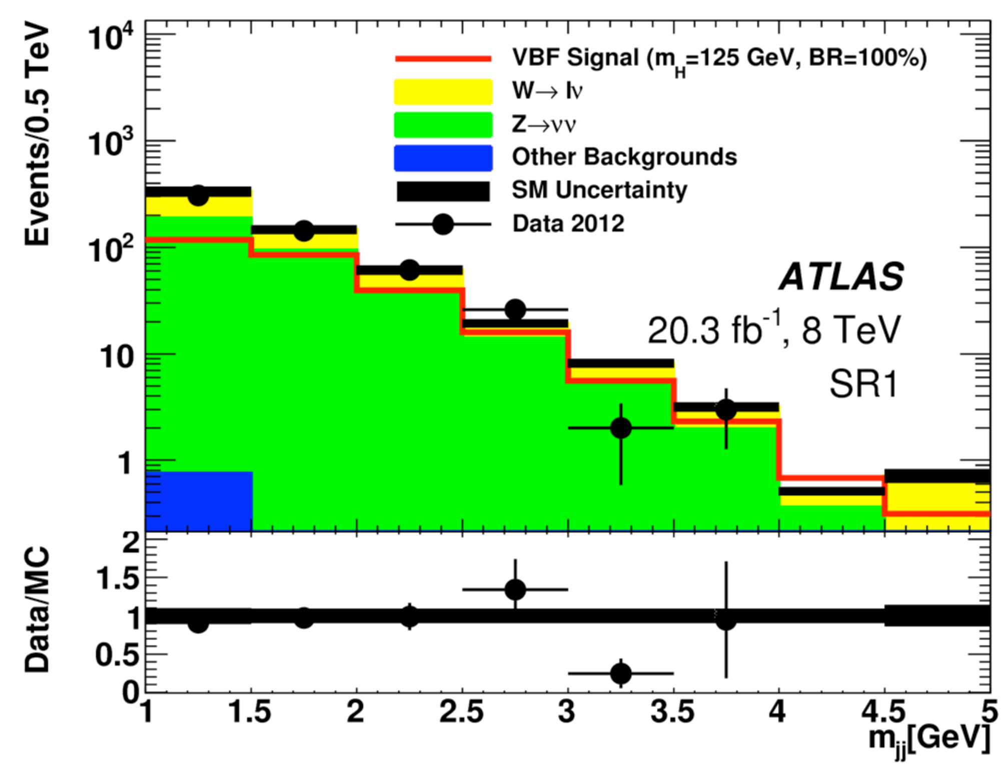
| Signal region | SR1 |
|---|---|
| Process | |
| ggF signal | 20± 15 |
| VBF signal | 286± 57 |
| $Z(\to \nu\nu)$+jets | 339± 37 |
| $W(\to \ell\nu)$+jets | 235± 42 |
| Multijet | 2± 2 |
| Other backgrounds | 1±0.4 |
| Total background | 577± 62 |
| Data | 539 |

W and Z backgrounds are ~50/50 strong and weak production (background estimation next slide...)

Small top and diboson backgrounds from MC

Mulitjet from similar procedure to ZH analysis: $|\Delta\varphi(j,j)|$ and $|\Delta\varphi(j, E_T^{miss})|$



# VBF Higgs to Invisible

## Background Modeling

MC systematics are just too large to exploit the full statistics!

W and Z systematics from MC modeling

| Uncertainty | | *Z* or *W* |
|---|---|---|
| Jet energy scale | SR1<br>SR2 | 17–33<br>0–11 |
| Jet energy resolution | | Negligible<br>0.2–7.6 |
| Luminosity | | 2.8 |
| QCD scale | | 5–36<br>7.5–21 |
| PDF | | 3–5<br>0.1-2.6 |
| Parton shower | | 9–10 |

Numbers at in %

Detector Response to Jets: How well does a generator level jet energy agree with a reconstructed jet energy. (Forward jets are less well calibrated)

Modeling of Underlying Physics of the Z or W + 2-jet process

Structure of Proton

How partons (gluon or quark) hadronize

Background yield will have a 1/sqrt(577 events) ~ 4% statistical error

Systematic Uncertainty on W and Z MC yield ~50%

# VBF Higgs to Invisible

## Background Modeling

Solution: Use Z→ll and W→lν data with found leptons to model Z→νν and W→lν (with a lost lepton)

Define Control Regions:

- Z CR = 2-leptons, use ll-system in place of $E_T^{miss}$ wherever it occurs
- W CR = 1-lepton+MET and use l+MET-system in place of $E_T^{miss}$ wherever it occurs

There are two yields to predict in the signal region:

- Z→νν
- W→lν where the lepton is lost

| | SR1 $Z$ Control Regions | |
|---|---|---|
| Background | $Z(\to ee)$+jets | $Z(\to \mu\mu)$+jets |
| QCD $Z \to \ell\ell$ | 10.4 ± 1.5 | 14.0 ± 1.5 |
| EW $Z \to \ell\ell$ | 7.4 ± 0.8 | 8.2 ± 0.8 |
| Other Backgrounds | 0.3 ± 0.2 | 0.2 ± 0.1 |
| Total | 18.1 ± 1.7 | 22.4 ± 1.7 |
| Data | 22 | 25 |

Naively you would use W to model W and Z to model Z, but there is a problem

- Z→ll statistics is really poor b/c small Z→ll branching fraction
- BR(Z→ee+μμ) ~0.066
- BR(Z→νν) ~0.2

**We don't want to use ~50 Z→ll events to model ~340 Z→νν events**

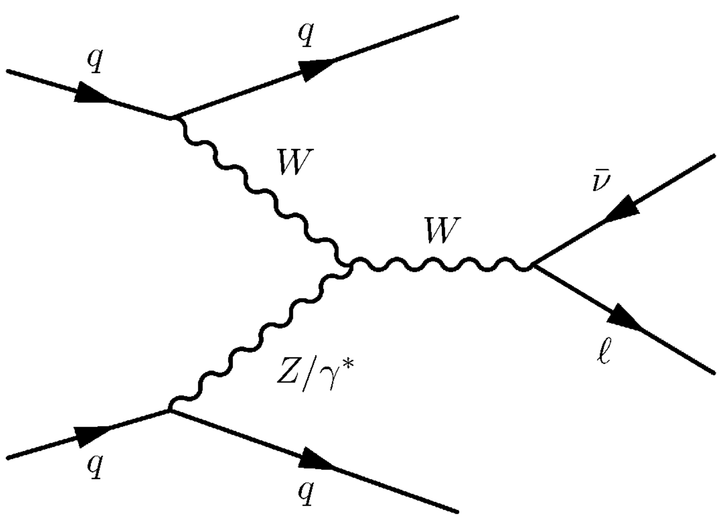
# VBF Higgs to Invisible

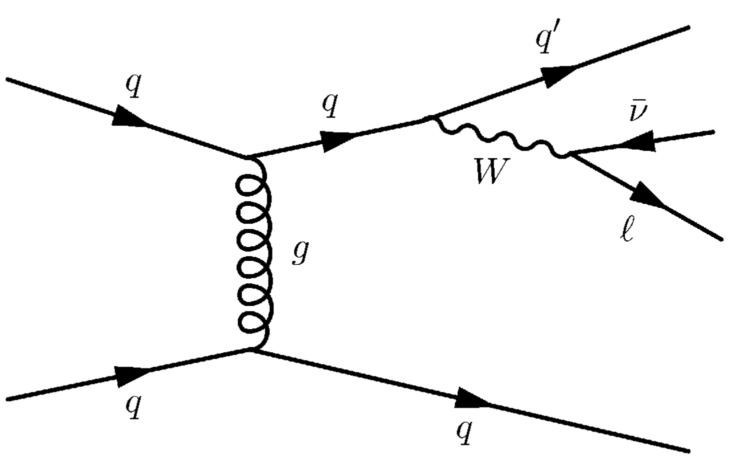
## Background Modeling

**Solution: Allow W→lν to model Z→νν**

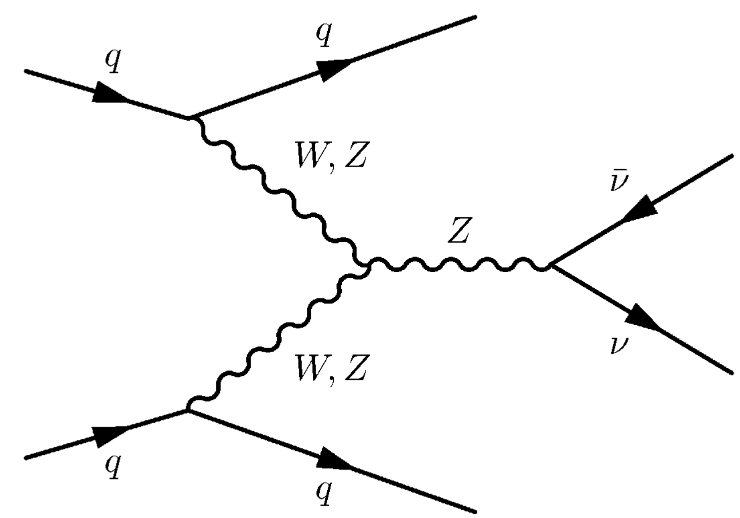
- processes are similar enough to account for difference with MC

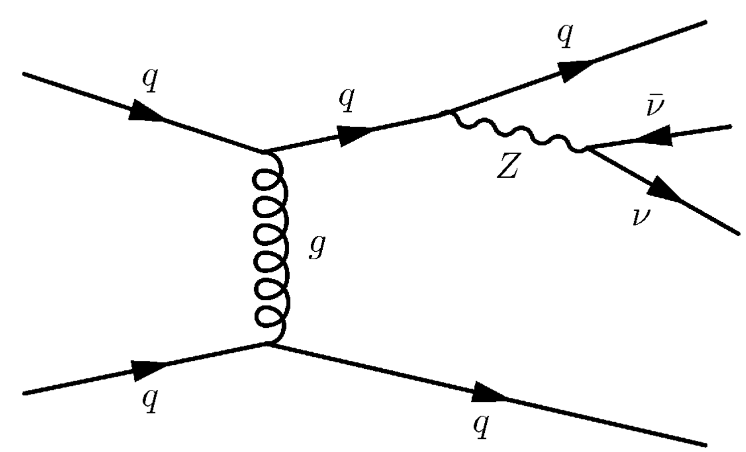
W→lν




Z→νν




Caveats to similarity

- Mass
- V and A structure of coupling different
- Flavor Differences in couplings
  - Quark flavors are symmetric except for mass
  - Big effect if top is involved in a diagram, but that is rare

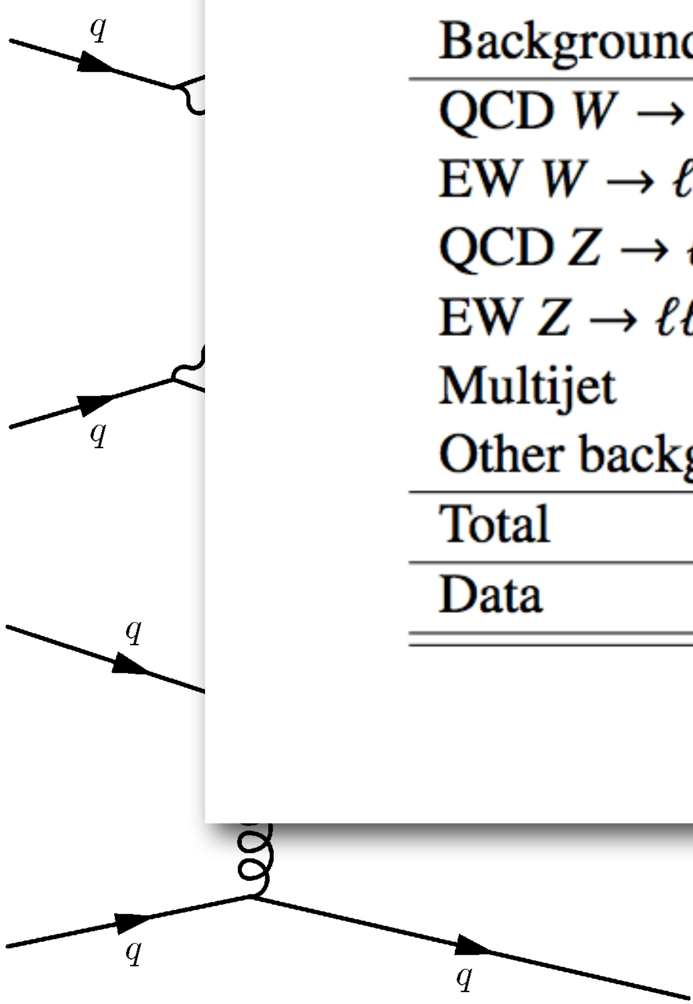
***Use MC to model all these***

# VBF Higgs to Invisible

## Background Modeling

**Solutio**

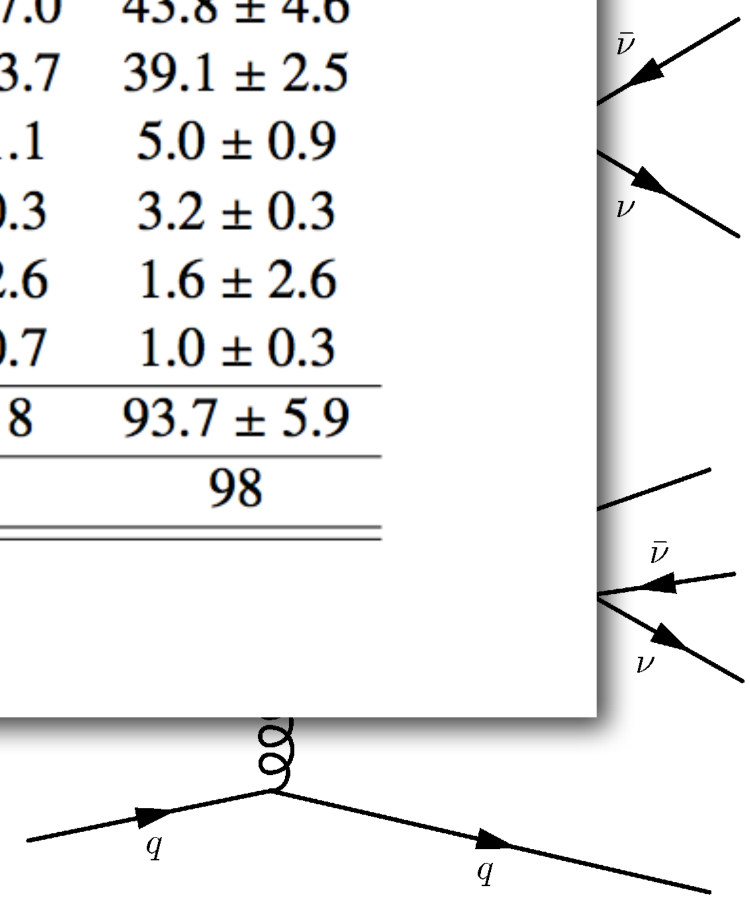
- proce




But we now have ~650 $W \to l\nu$ events to model ~340 $Z \to \nu\nu$ events... no longer the limiting factor in the analysis

| Background | SR1 $W$ Control Regions | | | |
|---|---|---|---|---|
| | $W^+ \to e\nu$ | $W^- \to e\nu$ | $W^+ \to \mu\nu$ | $W^- \to \mu\nu$ |
| QCD $W \to \ell\nu$ | 92.3 ± 7.2 | 55.1 ± 5.3 | 85.5 ± 7.0 | 43.8 ± 4.6 |
| EW $W \to \ell\nu$ | 99.4 ± 4.0 | 52.5 ± 2.9 | 81.9 ± 3.7 | 39.1 ± 2.5 |
| QCD $Z \to \ell\ell$ | 3.4 ± 0.6 | 4.4 ± 0.9 | 6.4 ± 1.1 | 5.0 ± 0.9 |
| EW $Z \to \ell\ell$ | 2.5 ± 0.3 | 2.9 ± 0.3 | 2.7 ± 0.3 | 3.2 ± 0.3 |
| Multijet | 28.0 ± 6.8 | 28.0 ± 6.8 | 1.6 ± 2.6 | 1.6 ± 2.6 |
| Other backgrounds | 4.0 ± 0.7 | 1.8 ± 0.4 | 3.2 ± 0.7 | 1.0 ± 0.3 |
| Total | 230 ± 11 | 145 ± 9 | 181 ± 8 | 93.7 ± 5.9 |
| Data | 225 | 141 | 182 | 98 |

involved in a diagram,
but that is rare




***Use MC to model all these***

# VBF Higgs to Invisible

## Systematics Reduction with Ratio Method

| Uncertainty | *Z* or *W* | $Z_{SR}/W_{CR}$ or $W_{SR}/W_{CR}$ |
|---|---|---|
| Jet energy scale | 17–33<br>0–11 | 3–5<br>1–4 |
| Jet energy resolution | Negligible<br>0.2–7.6 | Negligible<br>0.5–5.8 |
| Luminosity | 2.8 | Irrelevant |
| QCD scale | 5–36<br>7.5–21 | 7.8–12<br>1–2 |
| PDF | 3–5<br>0.1-2.6 | 1–2 |
| Parton shower | 9–10 | 5 |

QCD scale variations are treated as correlated for W and Z processes

Assumption validated using $Z\to ll/W\to l\nu$ in a sample with loosened VBF selection

Effect of Systematics Significantly Reduced

- Uncertainty on absolute yields is order 30-50% total
- Uncertainty on ratios is order 10%
  - many uncertainties are actually now MC stat limited :(

# VBF Higgs to Invisible

## Statistical Interpretation and Results

Postfit yields and uncertainties

| Signal region<br>Process | SR1 |
|---|---|
| ggF signal | 20± 15 |
| VBF signal | 286± 57 |
| $Z(\to \nu\nu)$+jets | 339± 37 |
| $W(\to \ell\nu)$+jets | 235± 42 |
| Multijet | 2± 2 |
| Other backgrounds | 1±0.4 |
| Total background | 577± 62 |
| Data | 539 |

Global likelihood fit using 1-bin for each SR and CR

- Total 9 bins (SR, W-CR, Z-CR) x (SR1, SR2a, SR2b)
- Free parameters are
  - 3 scale factors for the W and Z in each of (SR1, SR2a, SR2b)
  - 1 signal yield correlated across all bins
- Systematics implemented as correlated Gaussian constrained nuisance parameters

**Final Results = Limits on Invisible Higgs BR !!!**

| Results | Expected | $+1\sigma$ | $-1\sigma$ | $+2\sigma$ | $-2\sigma$ | Observed |
|---|---|---|---|---|---|---|
| SR1 | 0.35 | 0.49 | 0.25 | 0.67 | 0.19 | 0.30 |
| SR2 | 0.60 | 0.85 | 0.43 | 1.18 | 0.32 | 0.83 |
| Combined Results | 0.31 | 0.44 | 0.23 | 0.60 | 0.17 | 0.28 |

Recall ZH, $Z\to ll$ limit was 75% observed with 65% expected

# Other Higgs to Invisible Limits

| | ATLAS | | CMS | |
|---|---|---|---|---|
| | Observed | Expected | Observed | Expected |
| ZH, Z→ll | 75% | 62% | 83% | 86% |
| VBF H | 28% | 31% | 57% | 40% |
| WH+ZH with W/Z→jj | 78% | 86% | 53% | 62% |
| ZH with W/Z→bb | | | 182% | 199% |

These signals will all largely systematics limited,
If a signal is observed then it will have to be multiple places to be believed

Interestingly a CMS search for tt+MET can be reinterpreted as a ttH, H→invisible limit giving 40% observed (65% expected) PRL 113, 151801 (2014)

# Limits from Global Fits

There is an entirely different way to constrain Higgs to Invisible

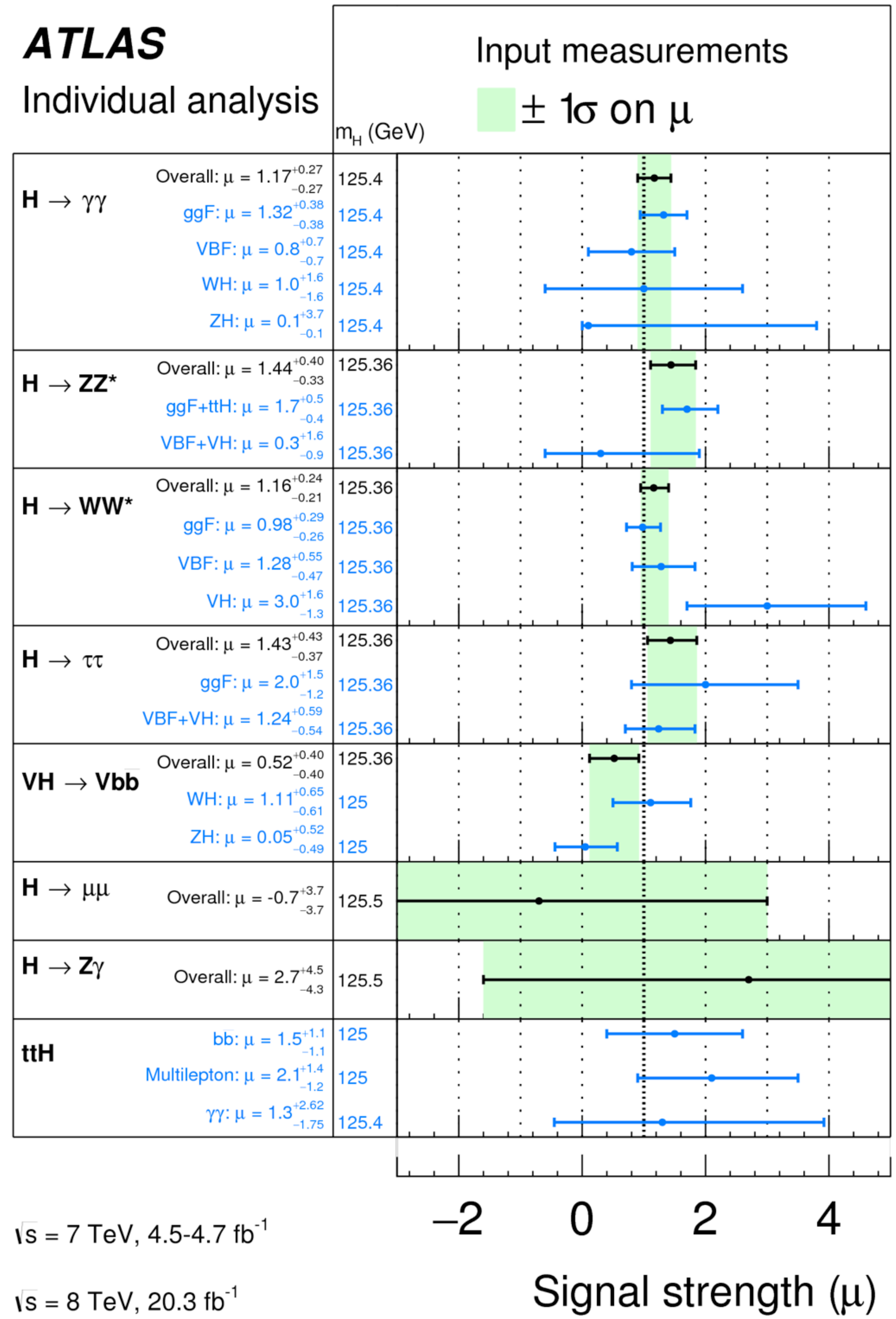
We have a huge array of measurements of visible Higgs decays

***All*** of these would be suppressed if the Higgs had an additional decay mode

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

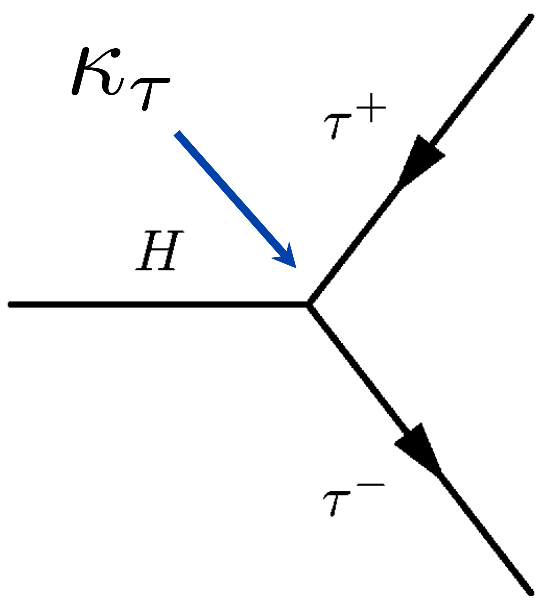
$$\Gamma_{\text{total}} = \Gamma_{\text{bb}} + \Gamma_{\text{WW}} + \Gamma_{\text{ZZ}} + \ldots + \Gamma_{\text{BSM}}$$

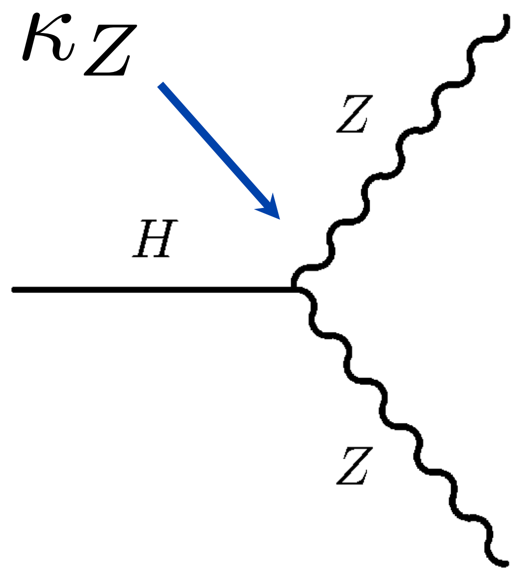
Of course there can be conspiracies where e.g. an extra $\Gamma_{\text{BSM}}$ is hidden by a suppressed $\Gamma_{\text{bb}}$ ... until H→bb is well measured

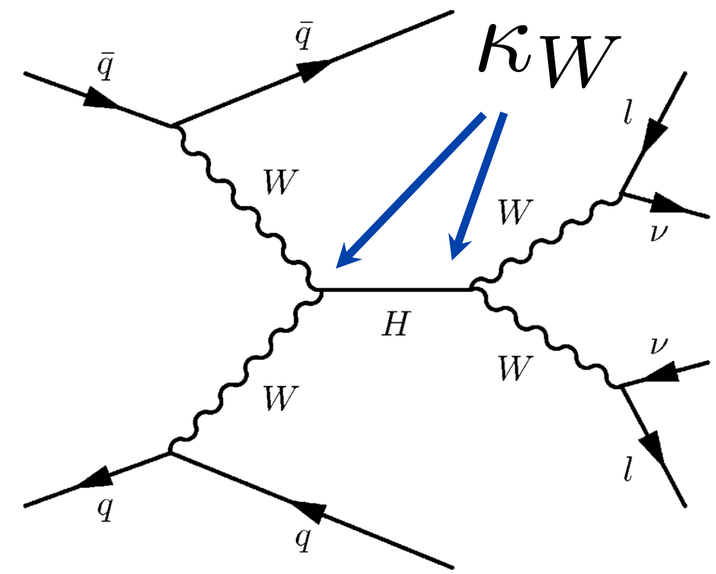


# Global Higgs Fits

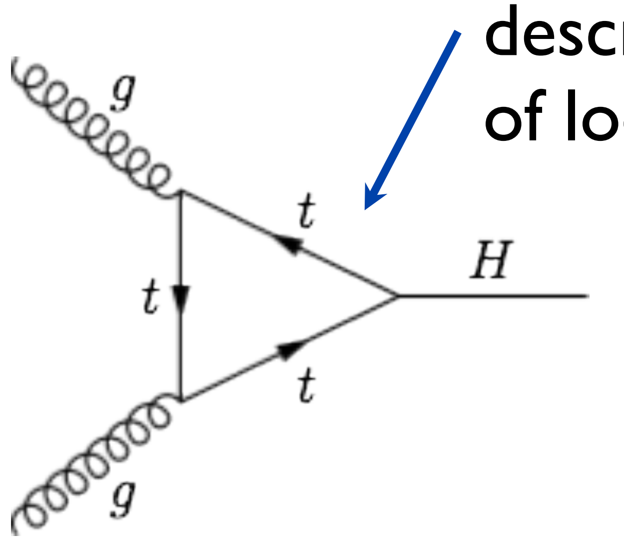
General Idea: for each Higgs coupling add a parameter κ which describes it's deviation from the SM (SM is when all $\kappa_x = 1$)



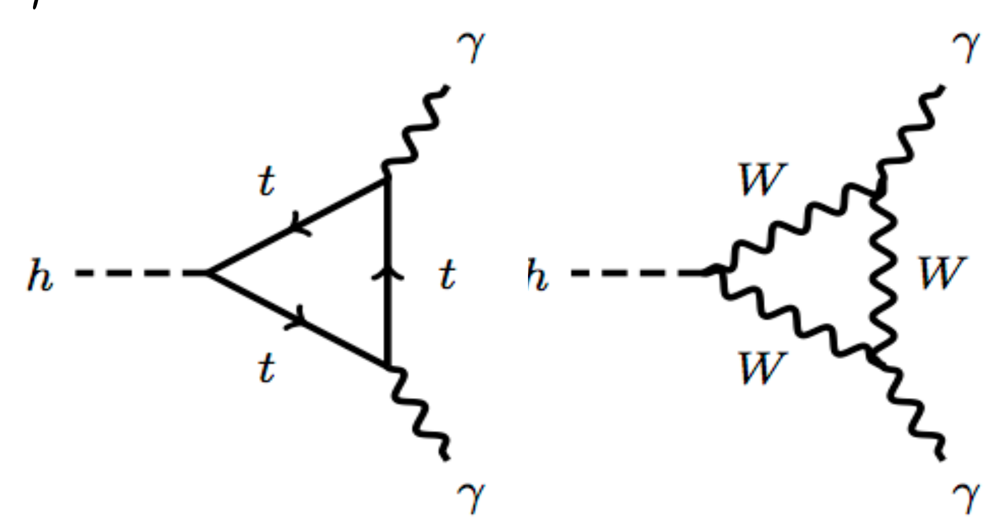




$\kappa_g$ used to describe sum of loops




$\kappa_\gamma$ used to describe sum of loops



# Limits from Global Fits

Each measurement here can then be described in terms of this model....

$$\mu = \frac{\sigma \times \mathrm{BR}}{\sigma_{\mathrm{SM}} \times \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_g^2 \cdot \kappa_Z^2}{\kappa_h^2}$$

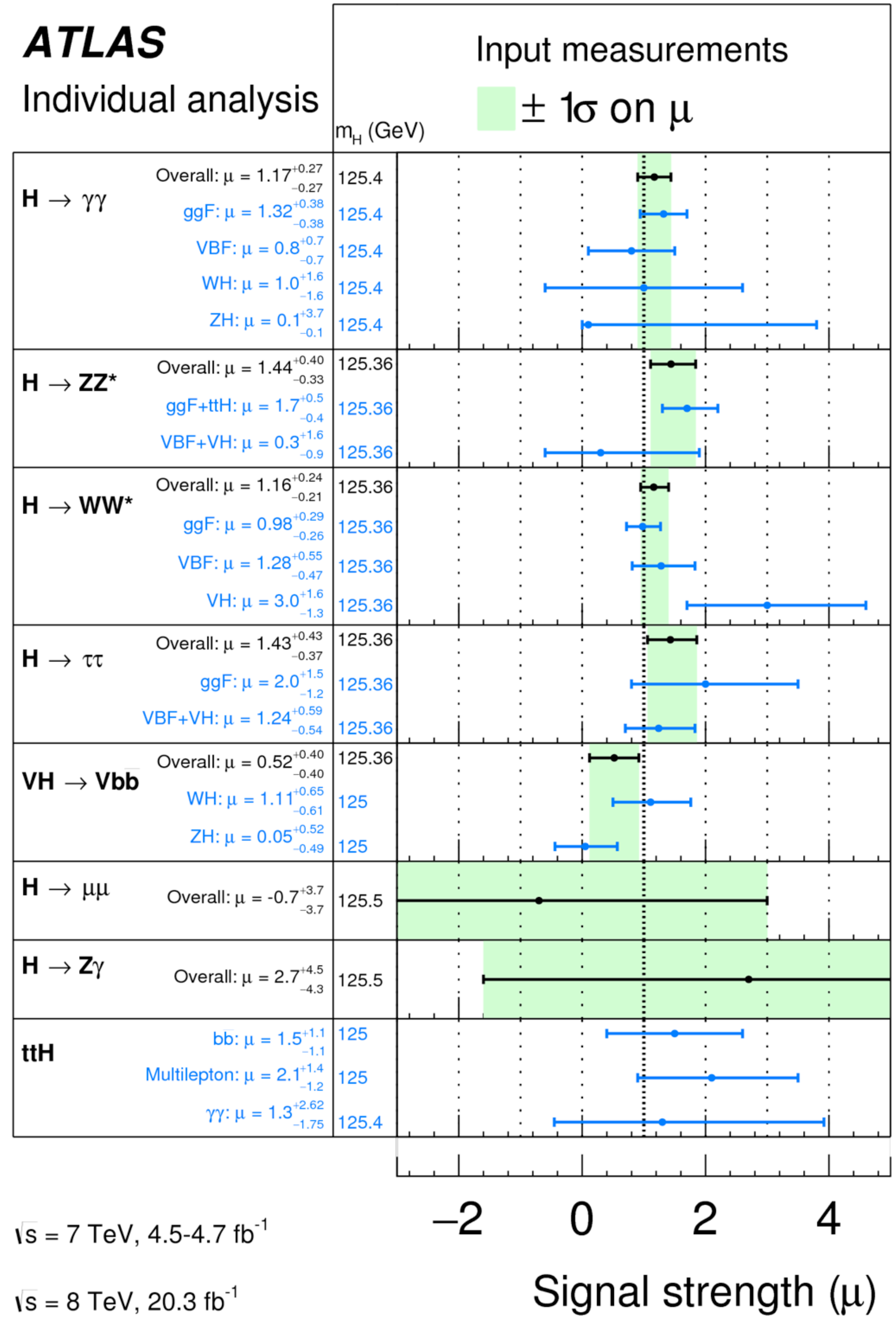
where

$$\kappa_h^2 = \sum_{jj} \frac{\kappa_j^2 \Gamma_{jj}^{\mathrm{SM}}}{\Gamma_h^{\mathrm{SM}}}$$

Numerator here is calculation this:

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

Then do a global fit using all the measurements to get limits on the $\kappa_x$ parameters



# Global Higgs Fits

## Invisible Limits

Here is the set parameters included in the fit

| | | | |
|---|---|---|---|
| Higgs portal (Baseline config. of vis. & inv. Higgs boson decay channels: general coupling param., no assumption about $\kappa_{W,Z}$) | $\kappa_Z$ | $Z$ boson coupling s.f. | $0.99 \pm 0.15$ |
| | $\kappa_W$ | $W$ boson coupling s.f. | $0.92 \pm 0.14$ |
| | $\kappa_t$ | $t$-quark coupling s.f. | $1.26^{+0.32}_{-0.34}$ |
| | $\kappa_b$ | $b$-quark coupling s.f. | $0.61 \pm 0.28$ |
| | $\kappa_\tau$ | Tau lepton coupling s.f. | $0.98^{+0.20}_{-0.18}$ |
| | $\kappa_\mu$ | Muon coupling s.f. | $< 2.25$ at 95% CL |
| | $\kappa_g$ | Gluon coupling s.f. | $0.92^{+0.18}_{-0.15}$ |
| | $\kappa_\gamma$ | Photon coupling s.f. | $0.90^{+0.16}_{-0.14}$ |
| | $\kappa_{Z\gamma}$ | $Z\gamma$ coupling s.f. | $< 3.15$ at 95% CL |

+ $BR_{inv}$ which is the key parameter for Higgs to invisible limits!

| Decay channels | $\kappa_i$ assumption | Upper limit on $BR_{inv}$ 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 |

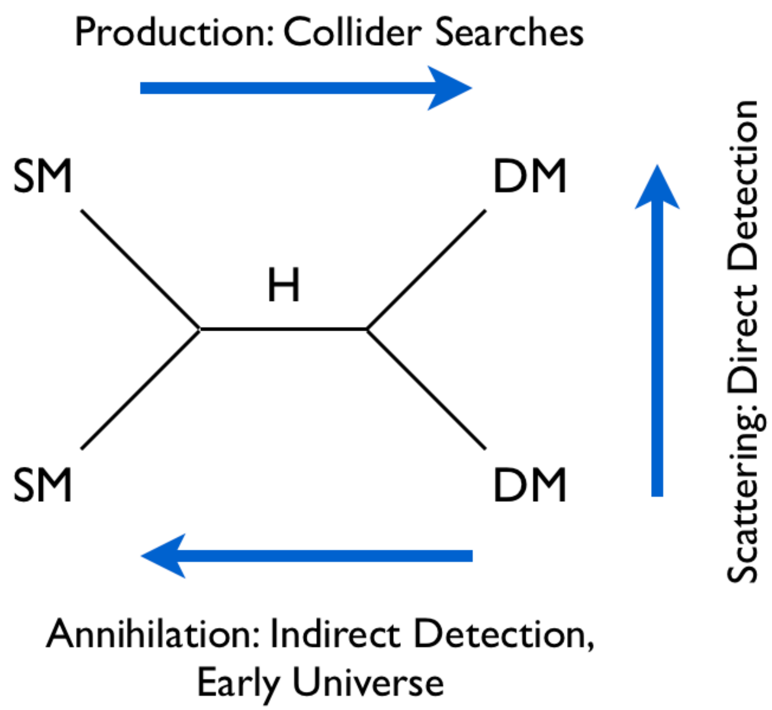
Combination of direct limits

Indirect limit from visible processes

Combination of everything under two assumptions

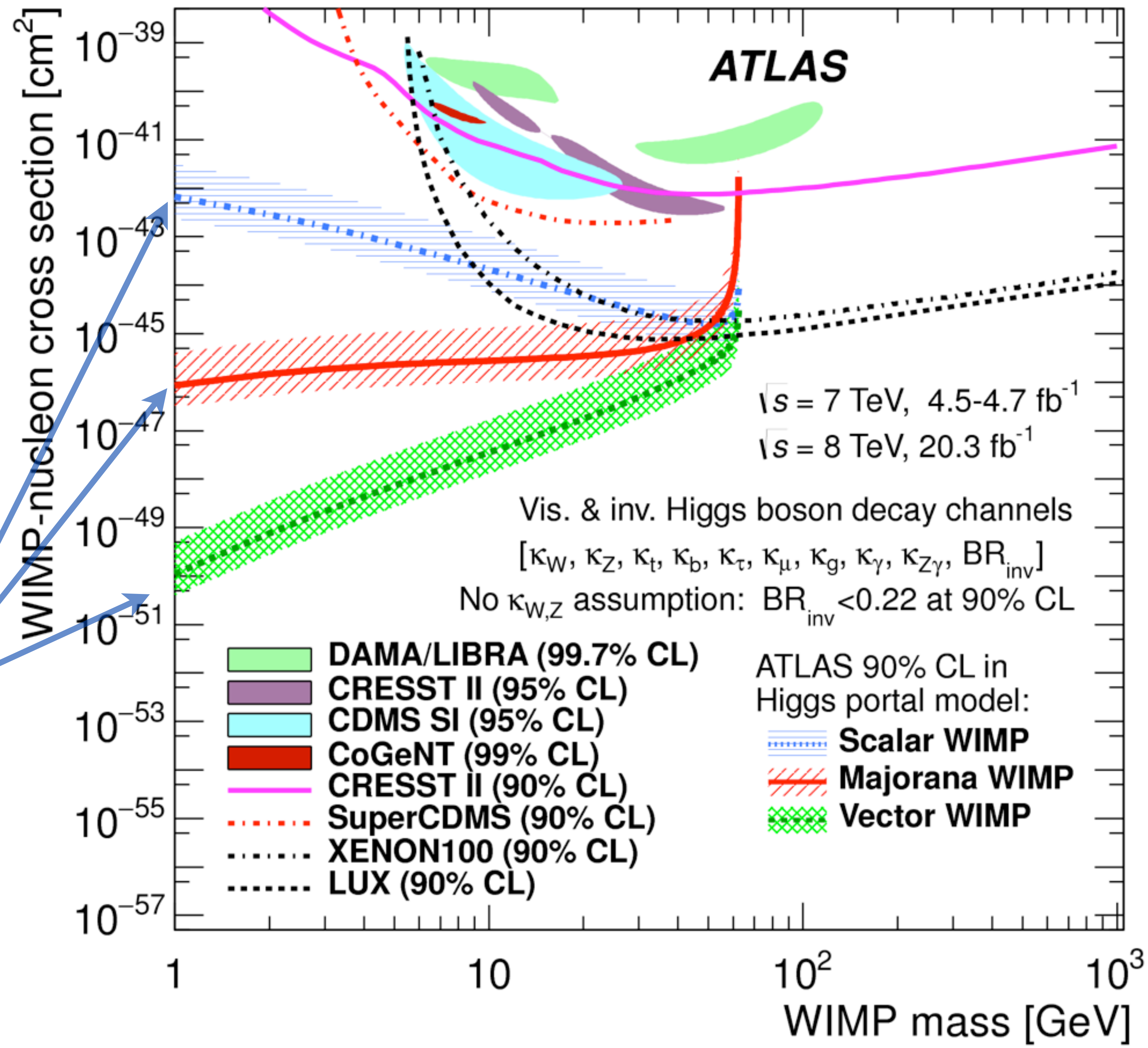
# Higgs Portal Interpretation

Remember this relation...




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

Comparable sensitivity to direct dark matter searches without the loss of sensitivity at low WIMP mass




**Assuming DM couples to SM via Higgs only and other caveats.... (next slide)**

# Caveats on the Portal Models

Here are the Lagrangians…

$$\mathcal{L}_{\rm SSDM} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_S}{4!}S^4 - \frac{\lambda_{HS}}{2}S^2 H^\dagger H$$

$$\mathcal{L}_{\rm SFDM} = \overline{\psi}(i\partial - m_\psi)\psi - \frac{\lambda_{\psi H}}{\Lambda}\overline{\psi}\psi H^\dagger H$$

$$\mathcal{L}_{\rm VDM} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \frac{\lambda_{VH}}{2}V_\mu V^\mu H^\dagger H - \frac{\lambda_V}{4}(V_\mu V^\mu)^2$$

Problems

- Masses inserted by hand
- Vector mass given by hand is not renormalizable
- Fermion is an effective field theory and if the mediator that has been integrated out is too light it can effect the relationship between scattering cross-section and $BR_{inv}$

On going theory work on this topic

- Next slide example impact of fixing these problems in the context of a model

# Caveats on the Portal Models

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

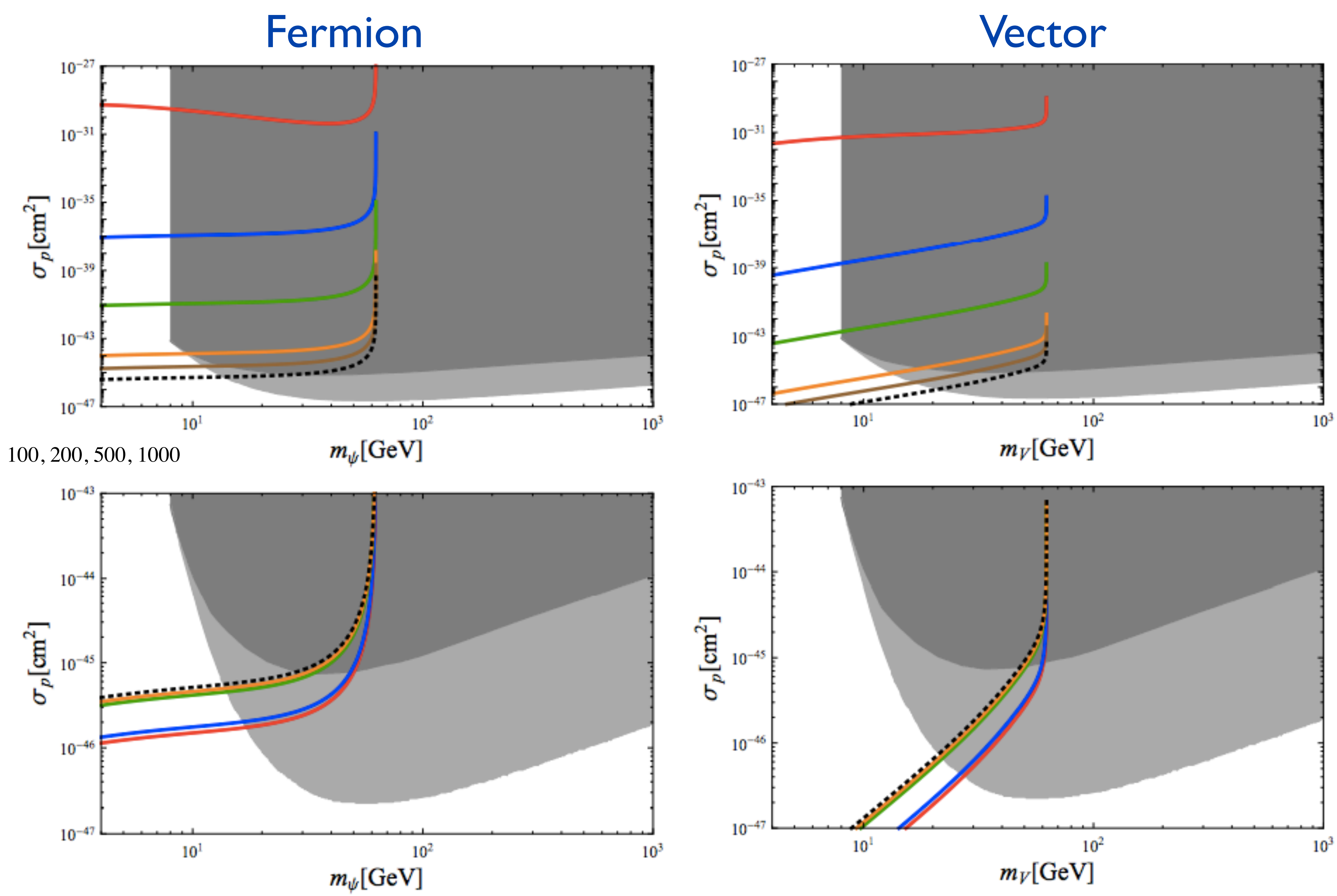
$m_s$ = $10^{-2}$ GeV

$m_s$ = 1 GeV

$m_s$ = 10 GeV

$m_s$ = 50 GeV

$m_s$ = 70 GeV




$m_s$ = 1000 GeV

$m_s$ = 500 GeV

$m_s$ = 200 GeV

$m_s$ = 100 GeV

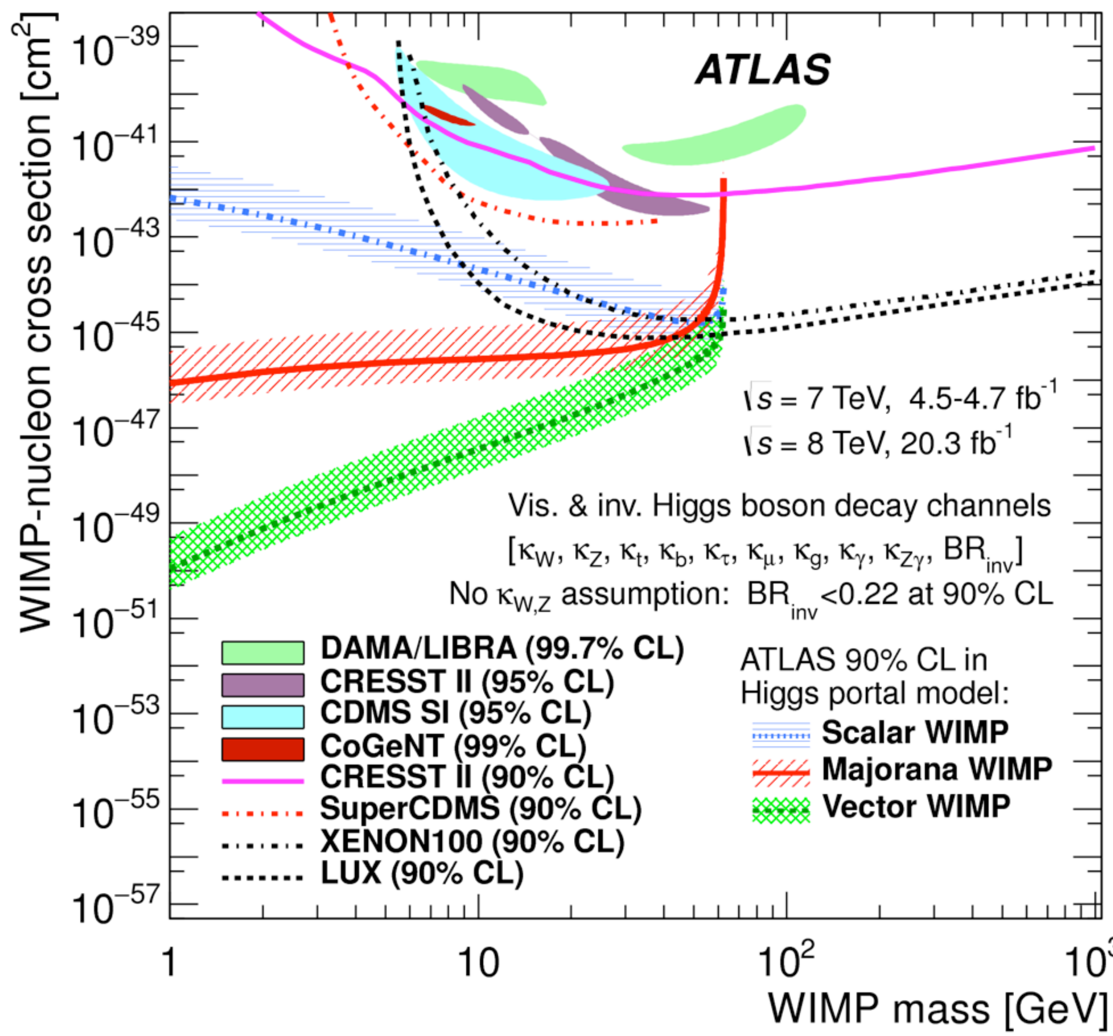
Dashed line is the simple Higgs Portal model result

# Higgs to Invisible Summary

Provides strong constraint on Dark Matter model building for $m_{DM} < m_H/2$

Strongly complementary to the direct dark matter searches

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




Various hints in direct and indirect searches are in the overlap range

Getting ready for Run 2 VBF Higgs to Invisible

My other work you can ask me about later...

- H to WW (Run 1 only)
- SUSY compressed spectra trilepton (Run 2 only)
- ATLAS Phase-1/2 trigger (jets, track trigger, and menus/architecture)
- ATLAS Upgrade strips tracker readout
- Fast timing detectors (just starting)