A search for dark matter through invisible decays of the Higgs boson

Josh Kunkle

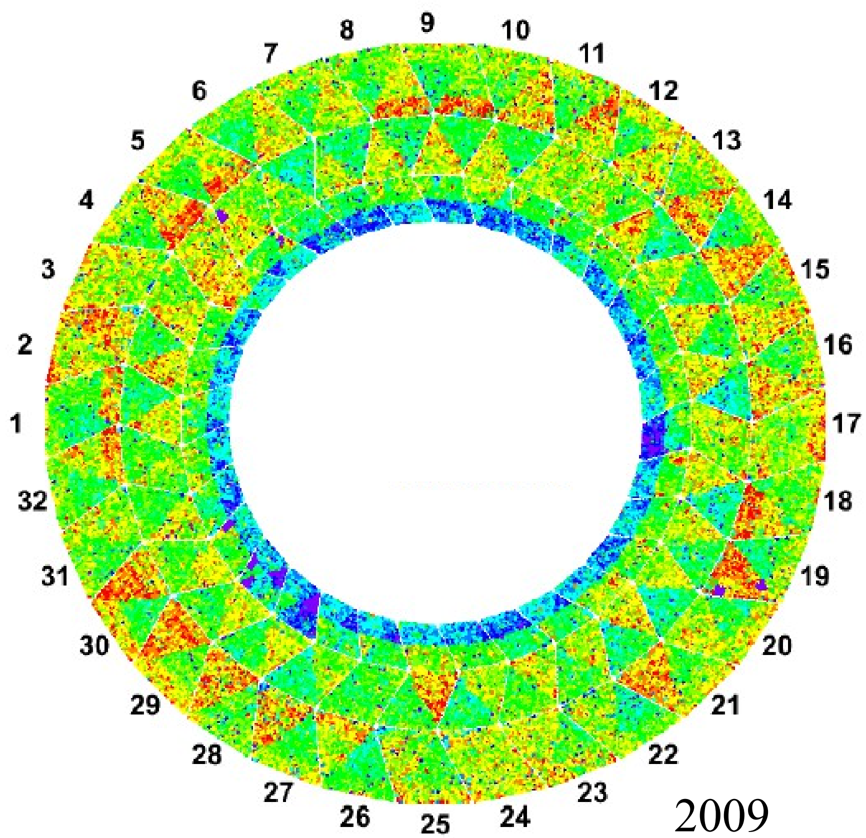
Advisor : Elliot Lipeles

PhD Thesis defense
July 11, 2013

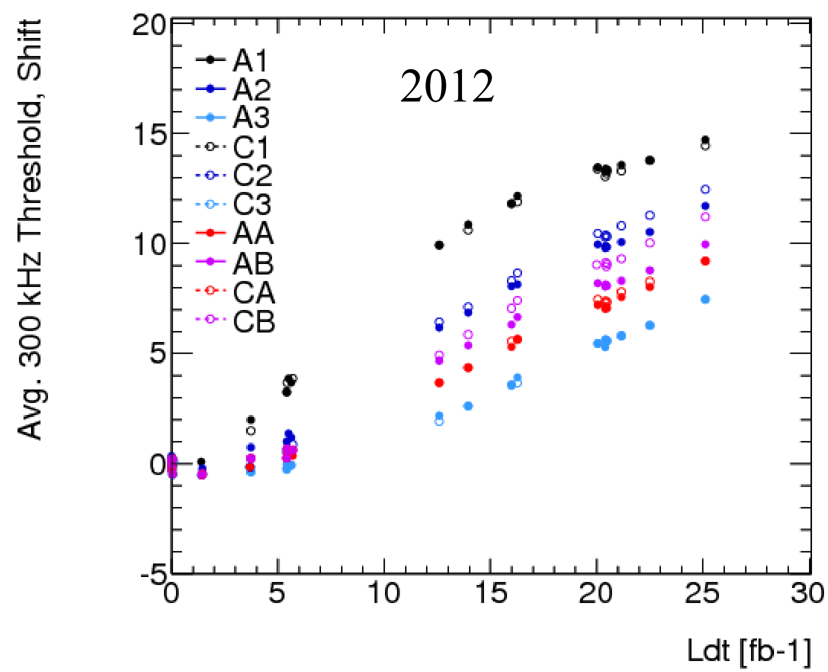
My work with Penn on ATLAS

- Modification and installation of TRT readout electronics
- Developed software to analyze scans of the TRT

2008

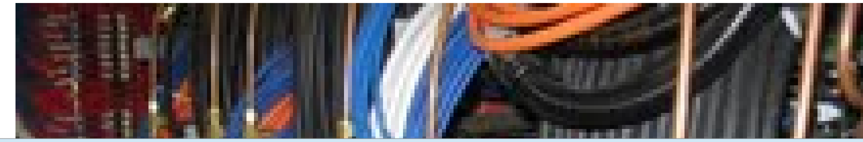


2009



My work with Penn on ATLAS

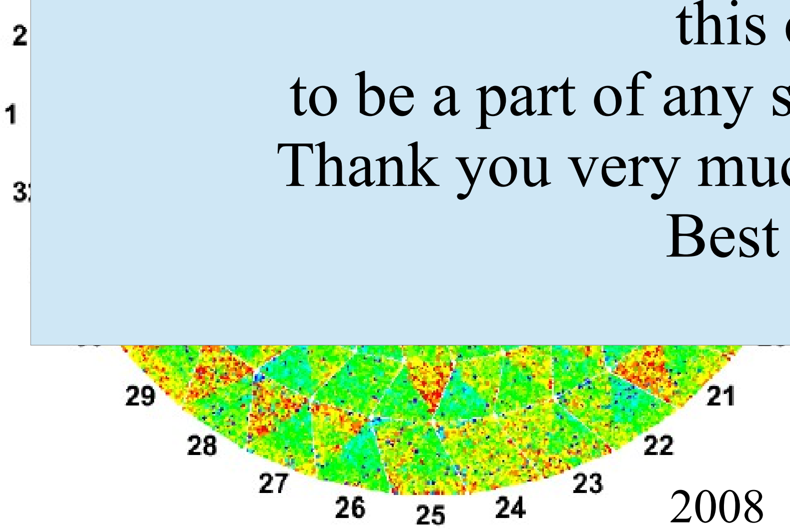
2008



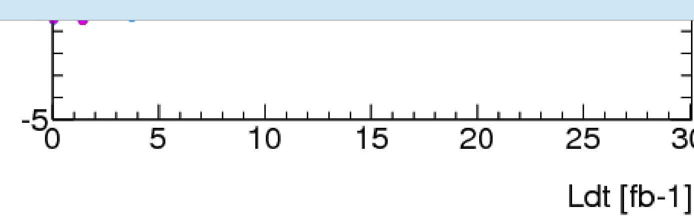
- Modification and installation of TRT readout
-

2011-07-26

Dear Colleagues,
I would like to thank our expert crew, which fixed the problem with the low voltage cable in the pit. Now we are fully back.
This work was done in a very difficult conditions without space, cooling, light and air
but with magnetic field of 1.5 T and residual radiation.
…
Taking in to account environmental conditions I would think that this crew is qualified
to be a part of any submarine of shuttle expedition.
Thank you very much Liz, Dominick, Jon and Josh!
Best regards Anatoli



2008

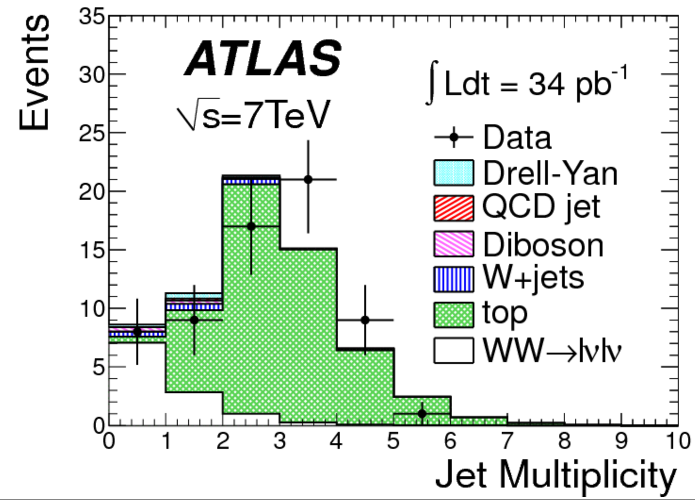


My work with Penn on ATLAS

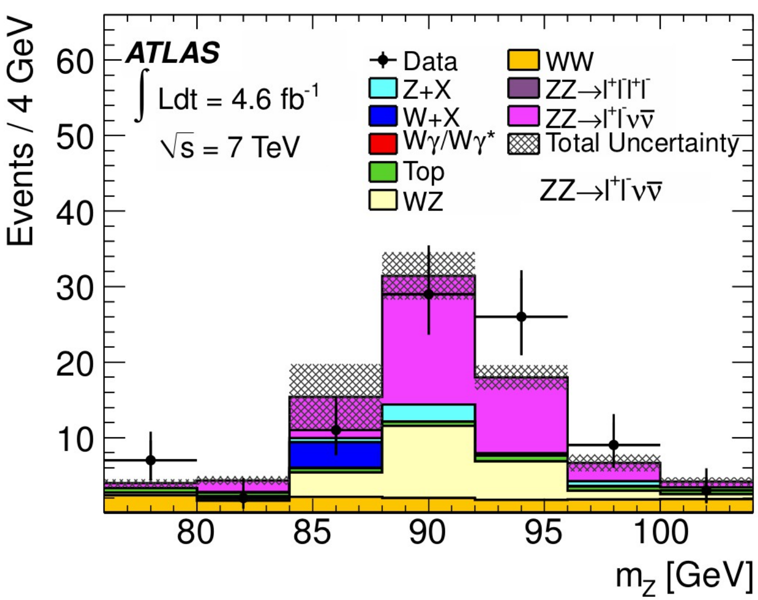
Trigger rates

- Predicted trigger rates for the first data
- Helped to develop an enhanced bias trigger for predicting rates at higher luminosity

Physics in 2010 – WW cross section

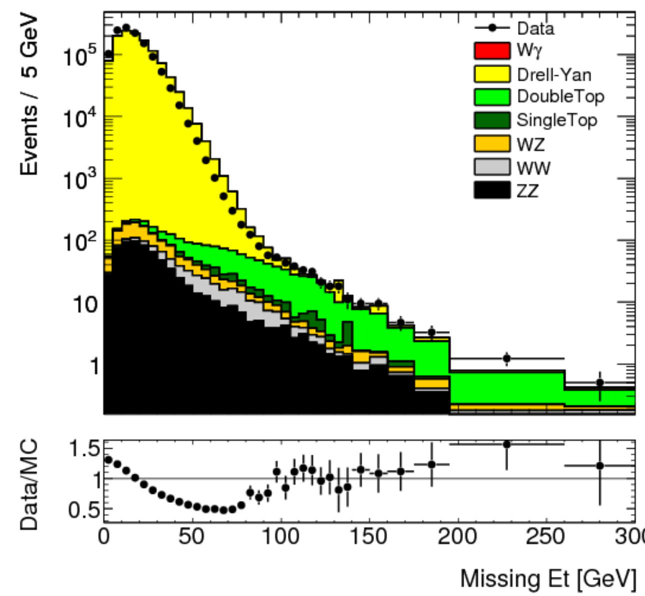


Physics in 2011 – ZZ cross section



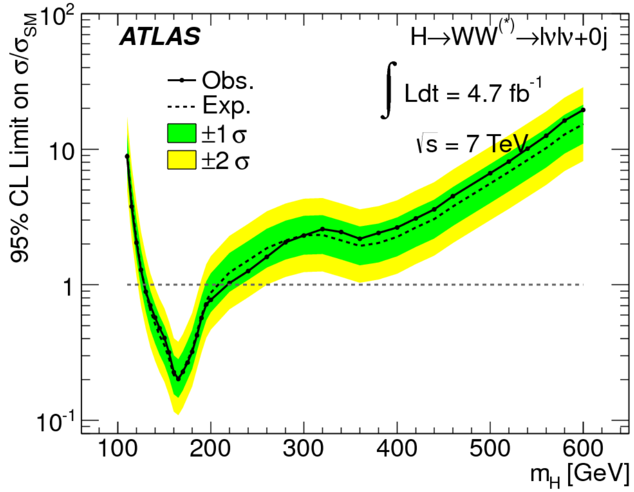
Studies of missing transverse momentum

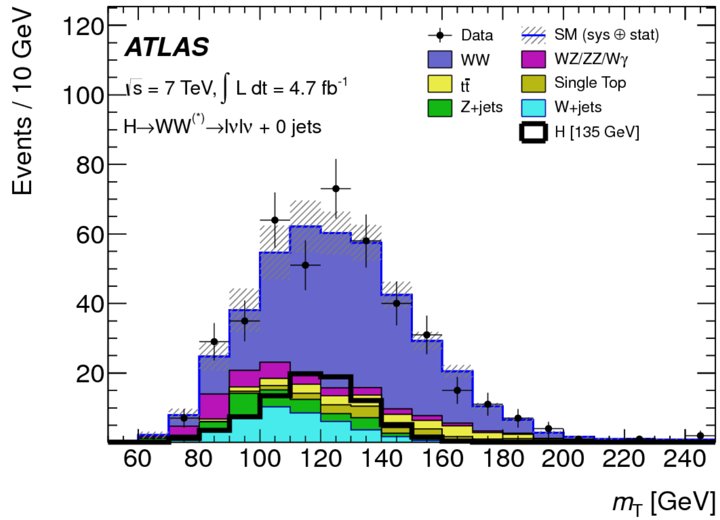
2010 - 2012



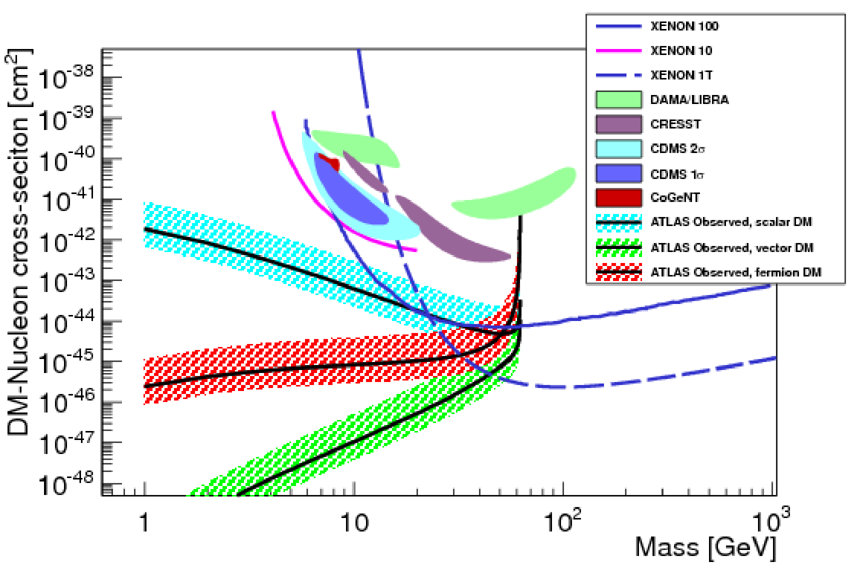
My work with Penn on ATLAS

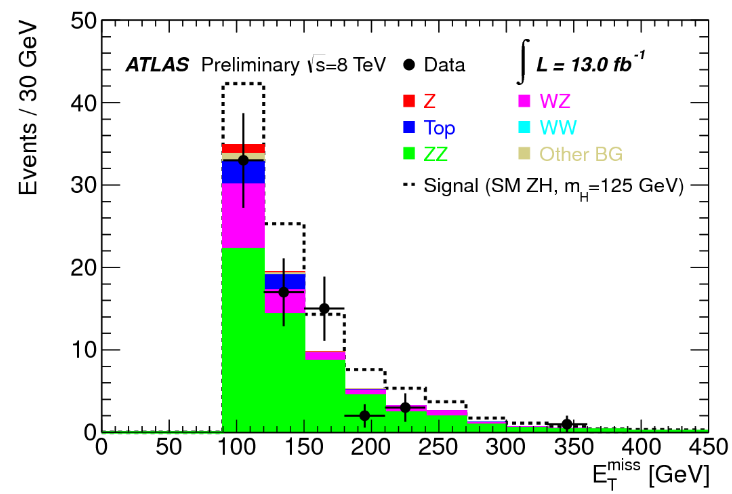
Physics in 2011 – Search for H → WW





Physics in 2012 – Invisible Higgs





Outline

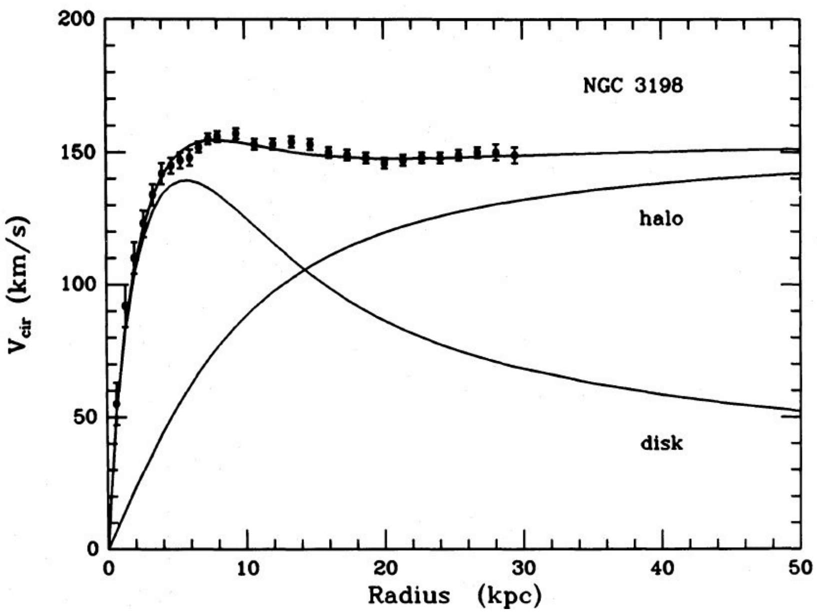
- Dark matter
- The Higgs
- The Higgs and dark matter – Higgs portal models
- The LHC
- The ATLAS experiment
- Standard Model measurements
- Search for $H \rightarrow WW$
- Search for ZH, $H \rightarrow$ invisible
- Single photon method
- Dark matter results

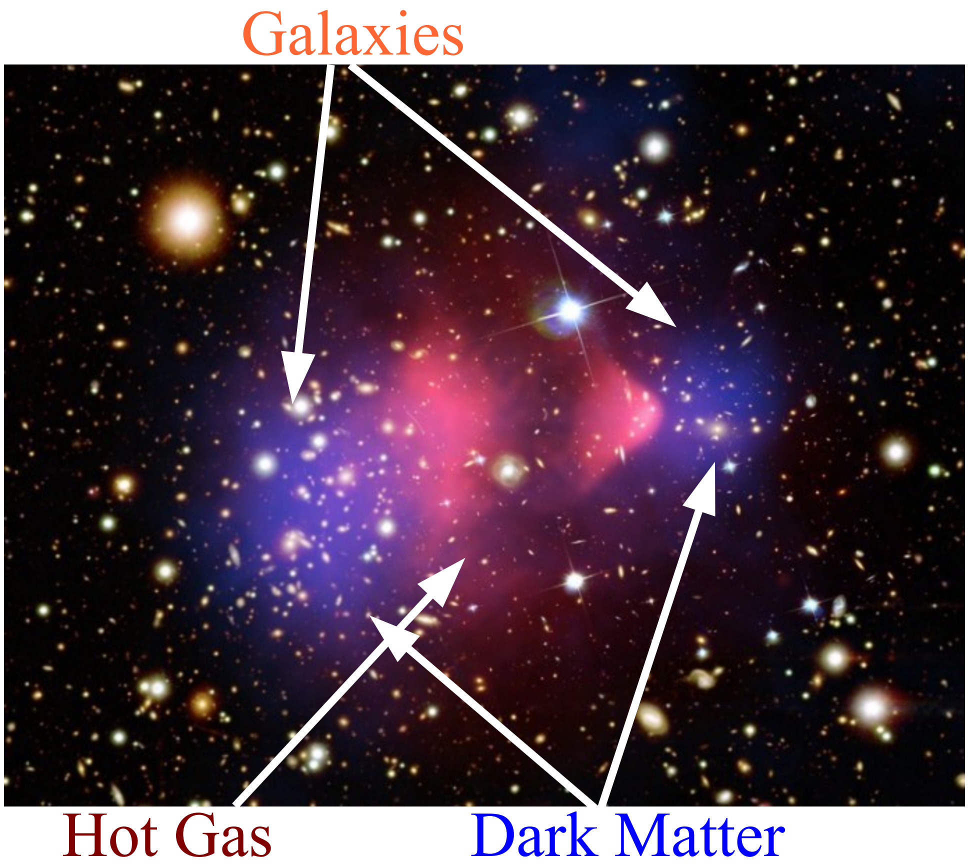
Dark matter

The existence of dark matter is our most concrete evidence for physics beyond the Standard Model

Dark matter has only been observed through its gravitational interaction

- Galaxy rotation curves
- Weak lensing – Bullet cluster
- Cosmic Microwave Background





Is there hope of seeing dark matter at the particle level?
We think so!

Dark matter – the WIMP hypothesis

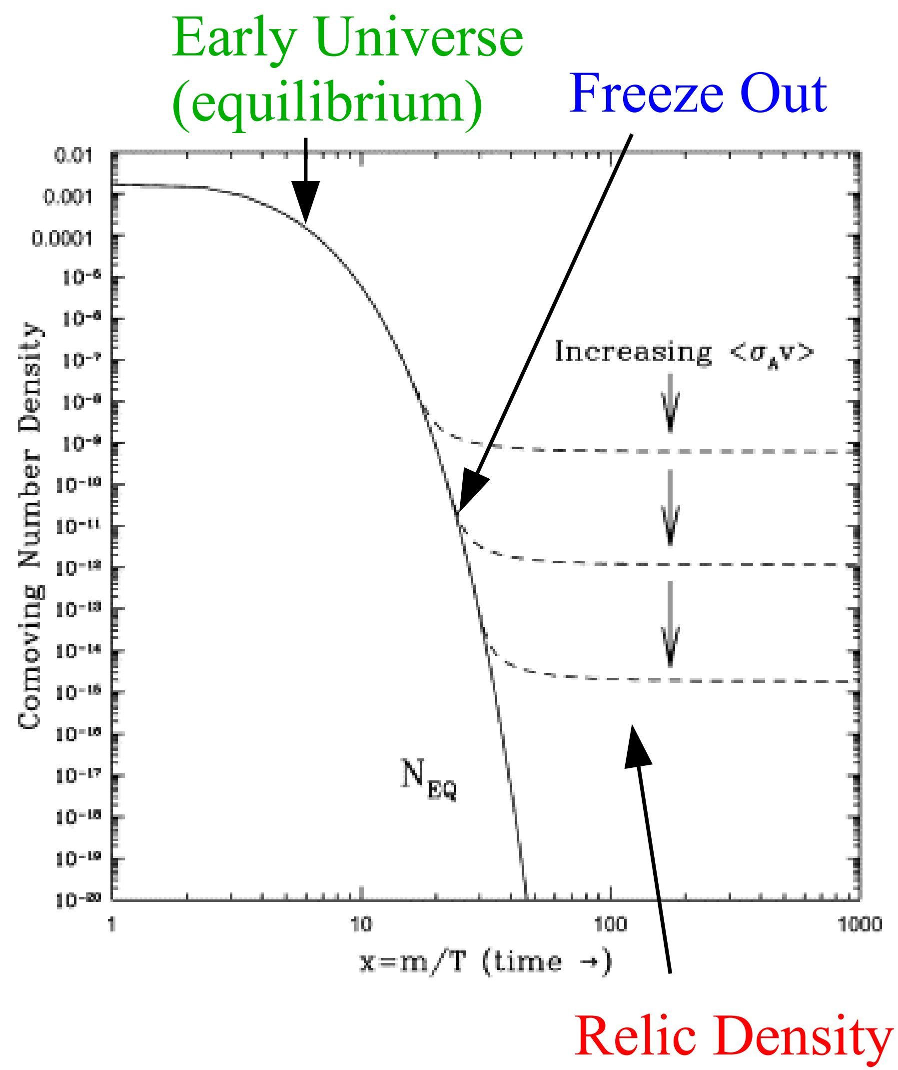
In early universe, dark matter annihilation is in equilibrium, followed by "freeze out"

We know how much dark matter existed in the early universe (CMB), and we measure the current "relic" density

Weak scale cross section is required to produce observed relic density

Experimental limits indicate that the dark matter particle has a mass between a few GeV and a TeV
[Phys. Rev. Lett. 107, 241303 (2011)]

Possibly has large coupling to the Higgs



Searches for dark matter

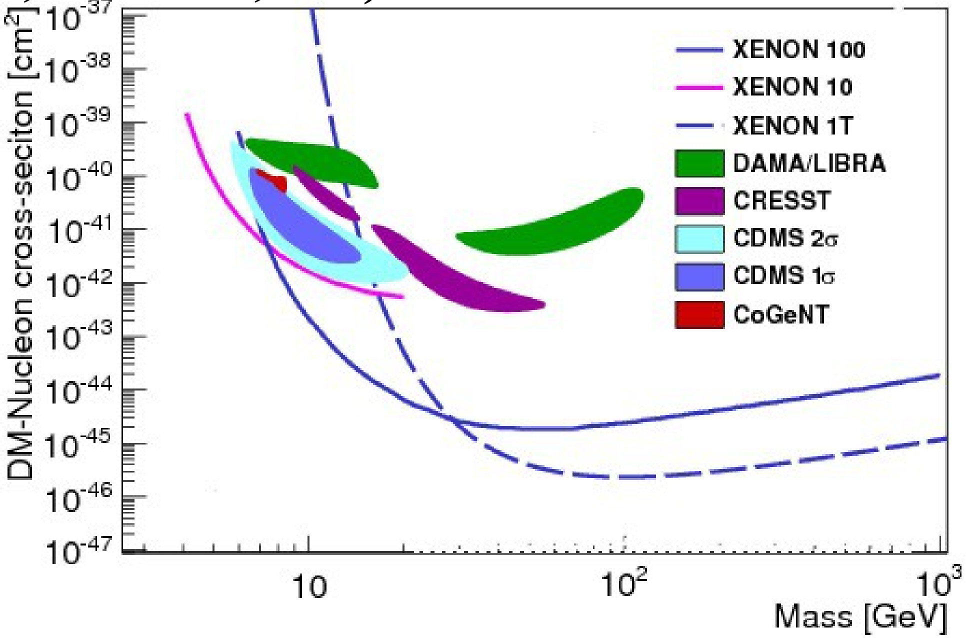
Scattering detectors (XENON, CDMS, DAMA, …)

Earth moves through the dark matter halo

Design low noise detectors to detect dark matter scatters

Limits + observations (some conflicting!)

CDMS – M_{DM} = 8.6 GeV (2013)



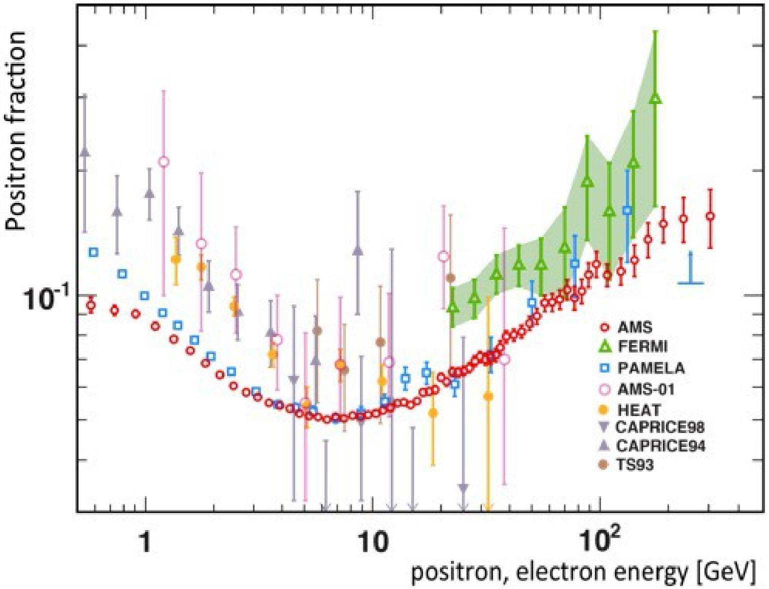
Colliders (LHC)

Search for dark matter production in proton collisions

Form of interaction is unknown – parametrize with an effective theory

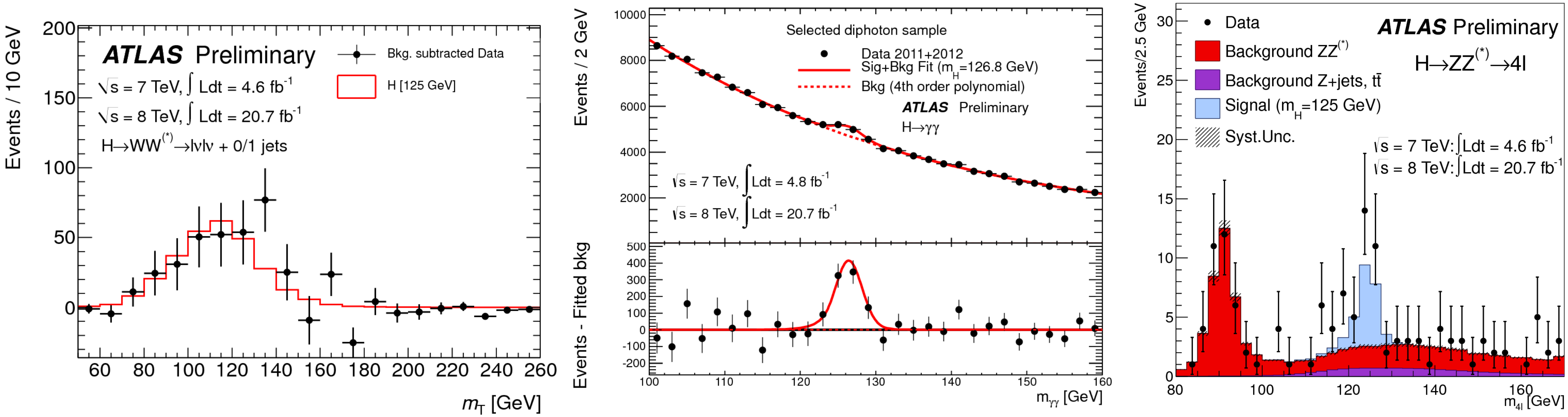
Must be produced with some other object (photon, jet, Z, W) to be visible

Cosmic rays (AMS, PAMELA, …)



The Higgs boson

We found it!



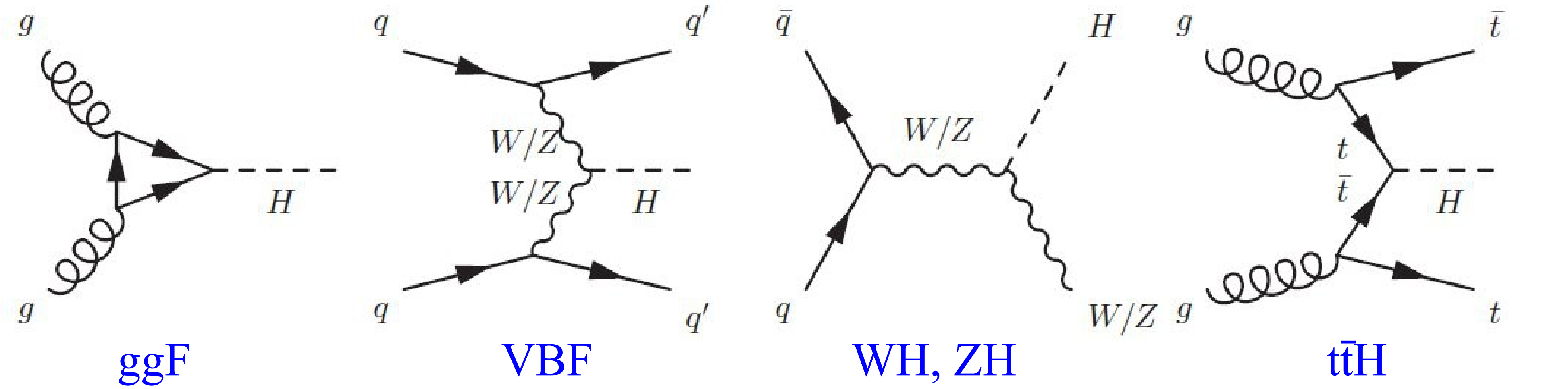
Generates masses for the W and Z bosons during electroweak symmetry breaking

Mechanism of mass generation extended to all other massive particles through Yukawa couplings

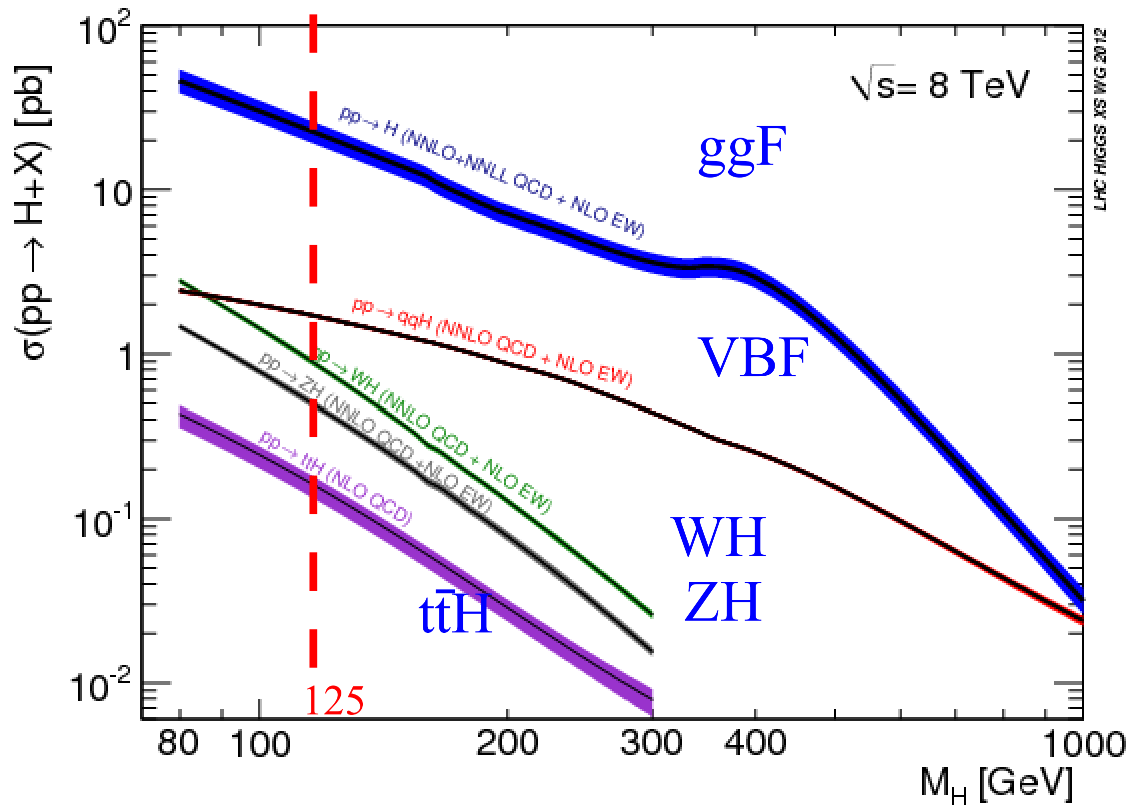
Spectrum of decay products depends on Higgs mass.

- We are fortunate to have M_H=125 where the decay phenomenology is rich

The Higgs at the LHC



- Main production through gluon fusion (Higgs coupling to light quarks is too small – proceeds through a top loop)
- VBF and associated production at the edge of sensitivity
- Invisible Higgs search in ZH channel

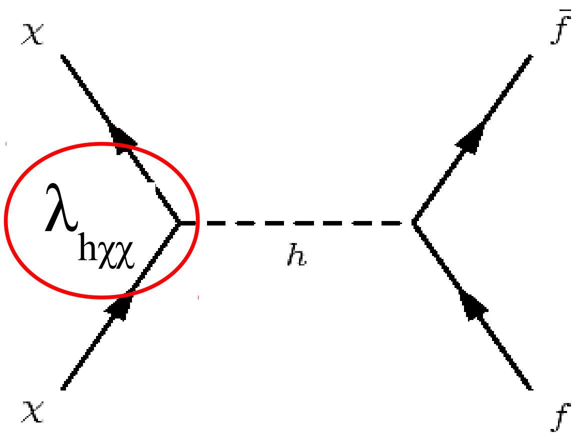
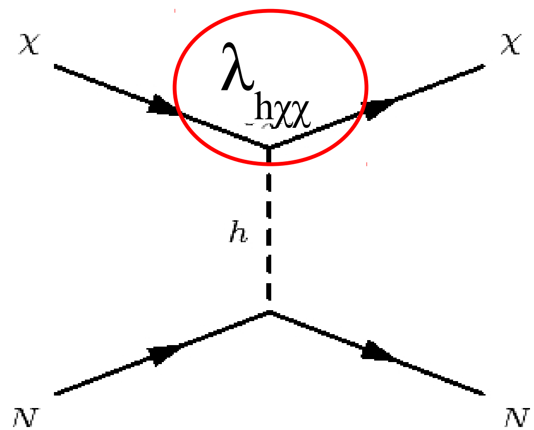
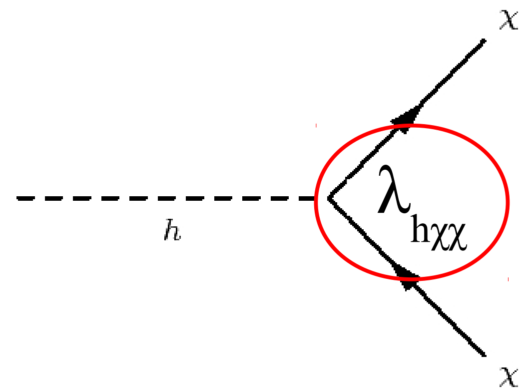


Higgs portal models

- Simple assumption – Dark matter interacts with the Standard Model only through the Higgs
  - Introduce one coupling constant $\lambda_{h\chi\chi}$
- Well motivated – What *can* Dark matter couple to?
  - Cannot couple to photons (dark)
  - Cannot couple to Z bosons (already excluded)
  - DM is massive – could couple to the Higgs
- Generic – Subsumes a detailed model such as SUSY
- Facilitates comparisons to other dark matter experiments

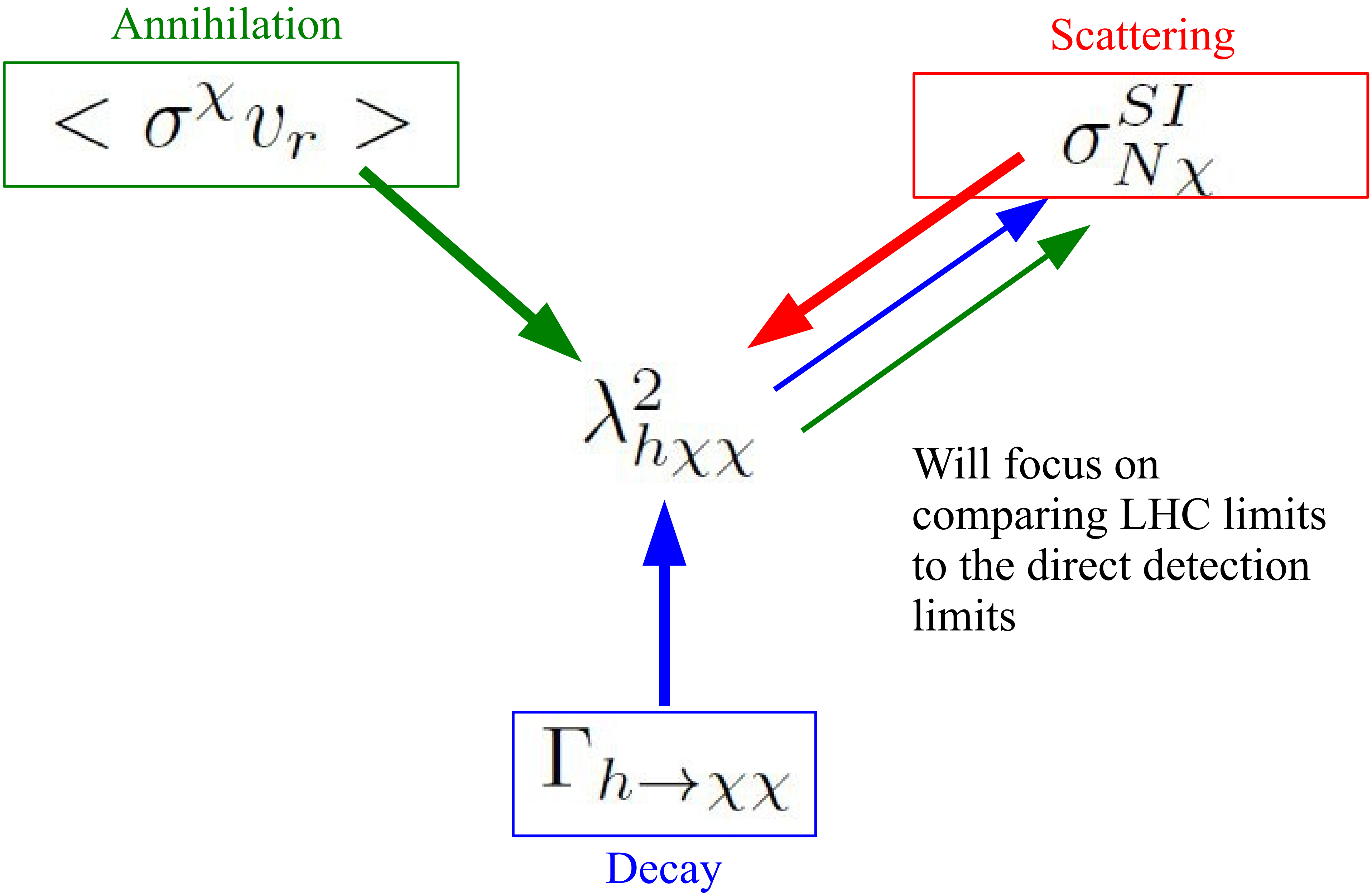
Higgs portal models

- Three modes of DM detection

Annihilation WMAP, Planck	Scattering XENON, CDMS etc…	Decay LHC
		

- The coupling vertex allows us to compare results from these three modes on the same footing

Converting between modes

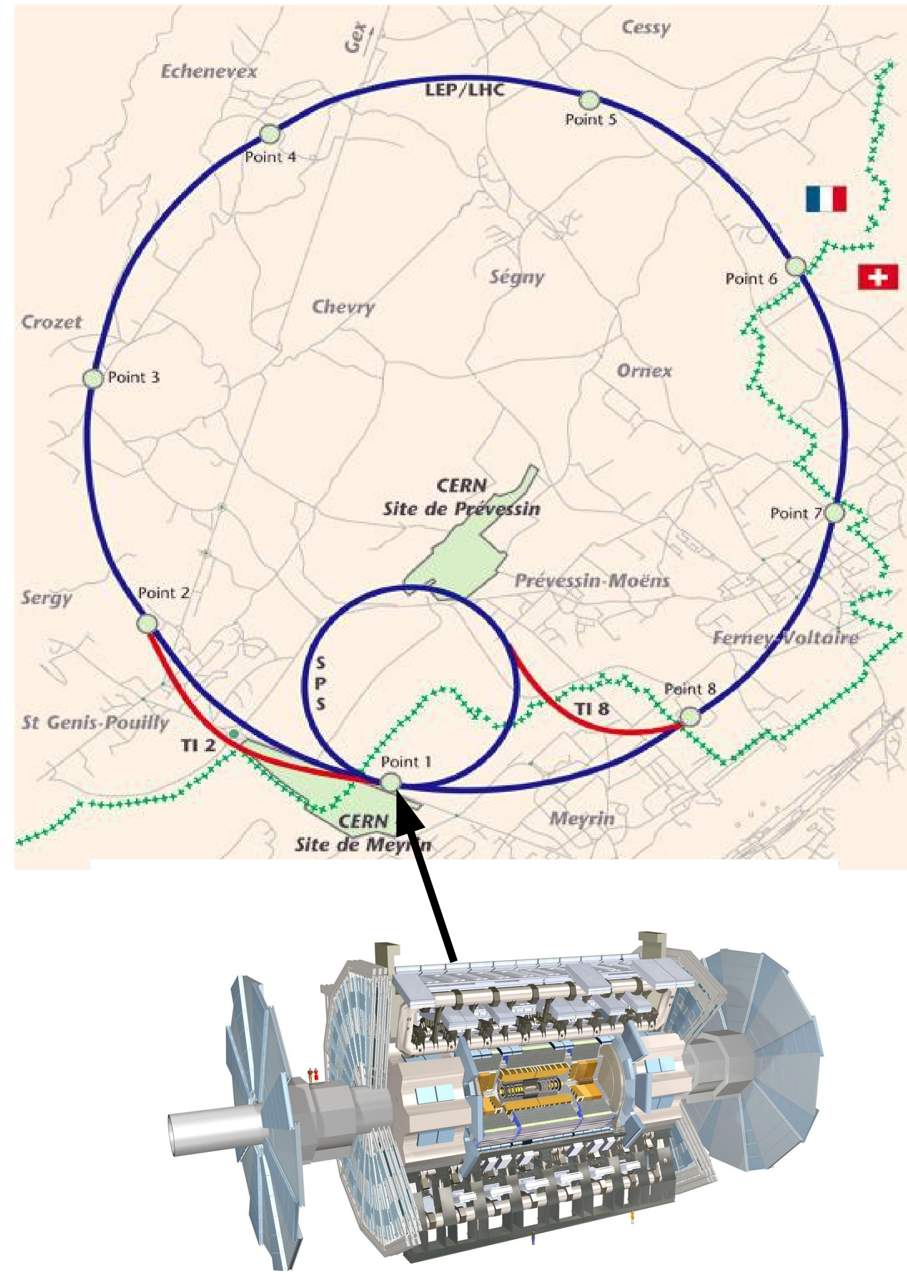


Will focus on comparing LHC limits to the direct detection limits

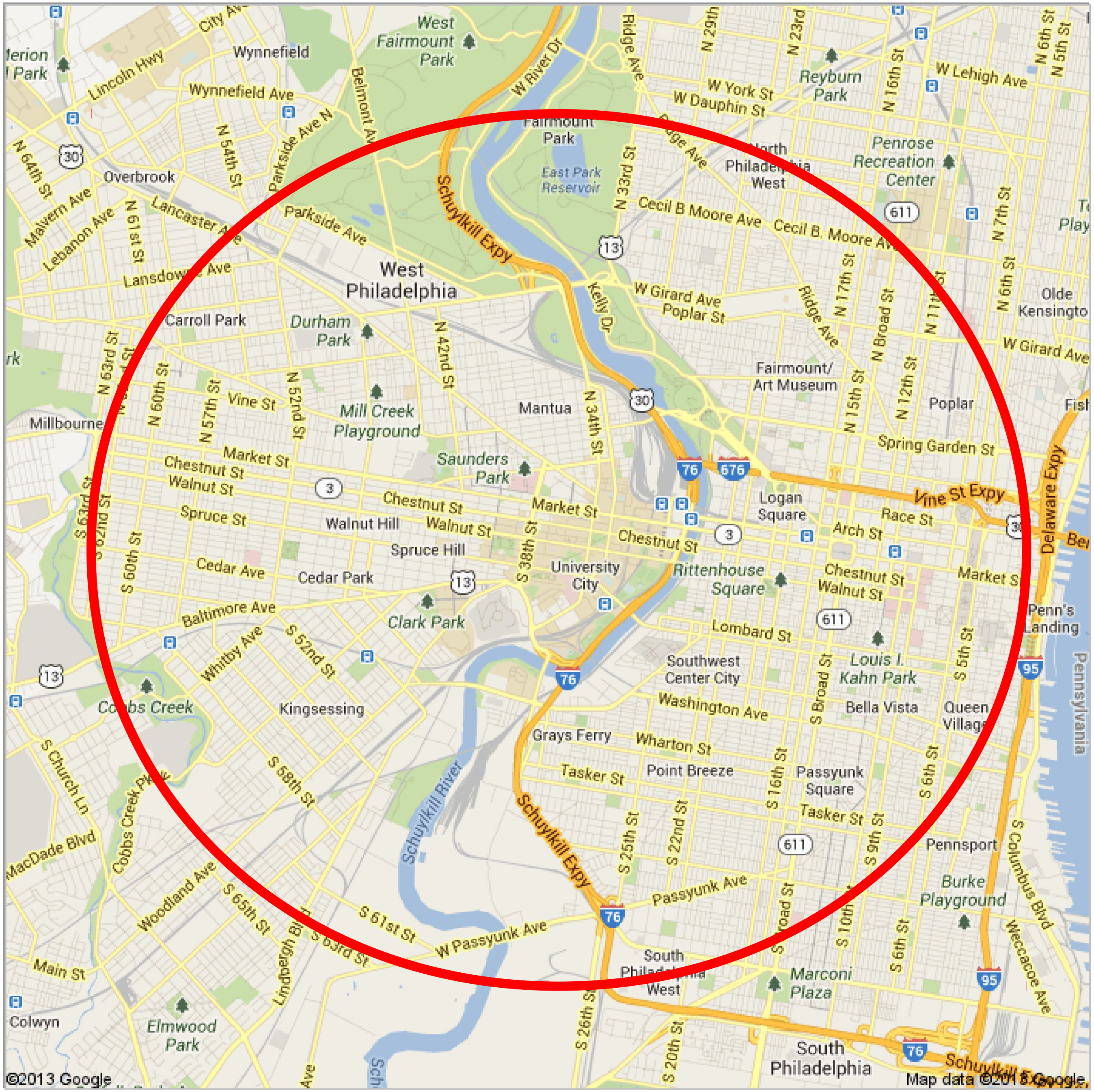
The LHC

<u>"Largest and most complex scientific instrument ever built"</u>

- 27 km long circular tunnel 100 m underground with 1232 superconducting dipole magnets cooled to 1.9 K plus over 5000 focusing and correction magnets
- Two counter-rotating beams of protons colliding at four points (ATLAS, LHC-b, CMS, ALICE)
- Proton-proton collisions at COM energy of 7 TeV and 8 TeV (upgrading to 13-14 TeV)
- Nominally in 2012 : $1.5\text{x}10^{11}$ protons per bunch x 1380 bunches per beam colliding at 20 MHz
- Beam is squeezed to 16µm at collision
- 400 million collisions per second in ATLAS



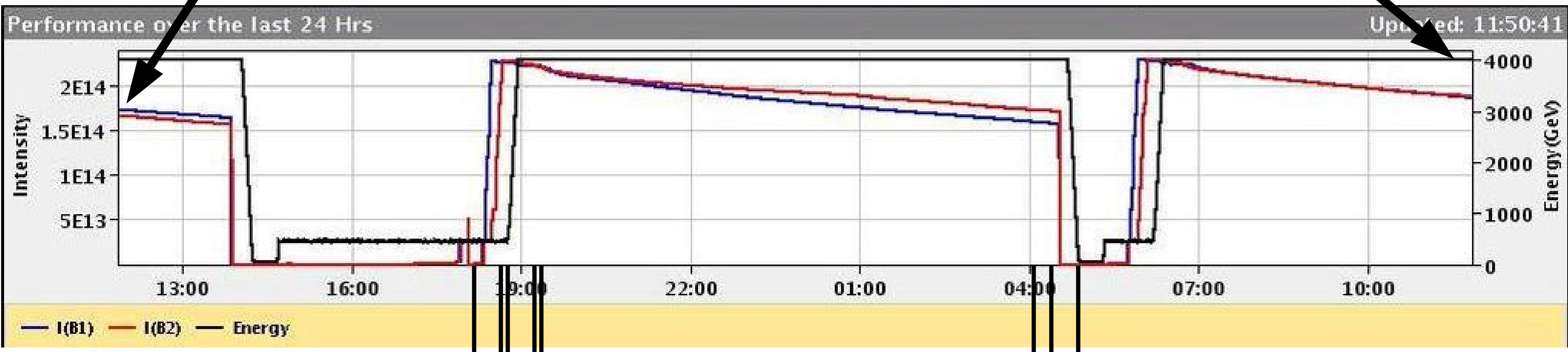
If the LHC was in Philly ...



An LHC fill

Beam intensity (each beam)

Magnet current (beam energy equivalent)



Filling :
The protons travel through 6 separate accelerators before injection into the LHC

Ramp : Beam energy is increased from 450 GeV to 4 TeV

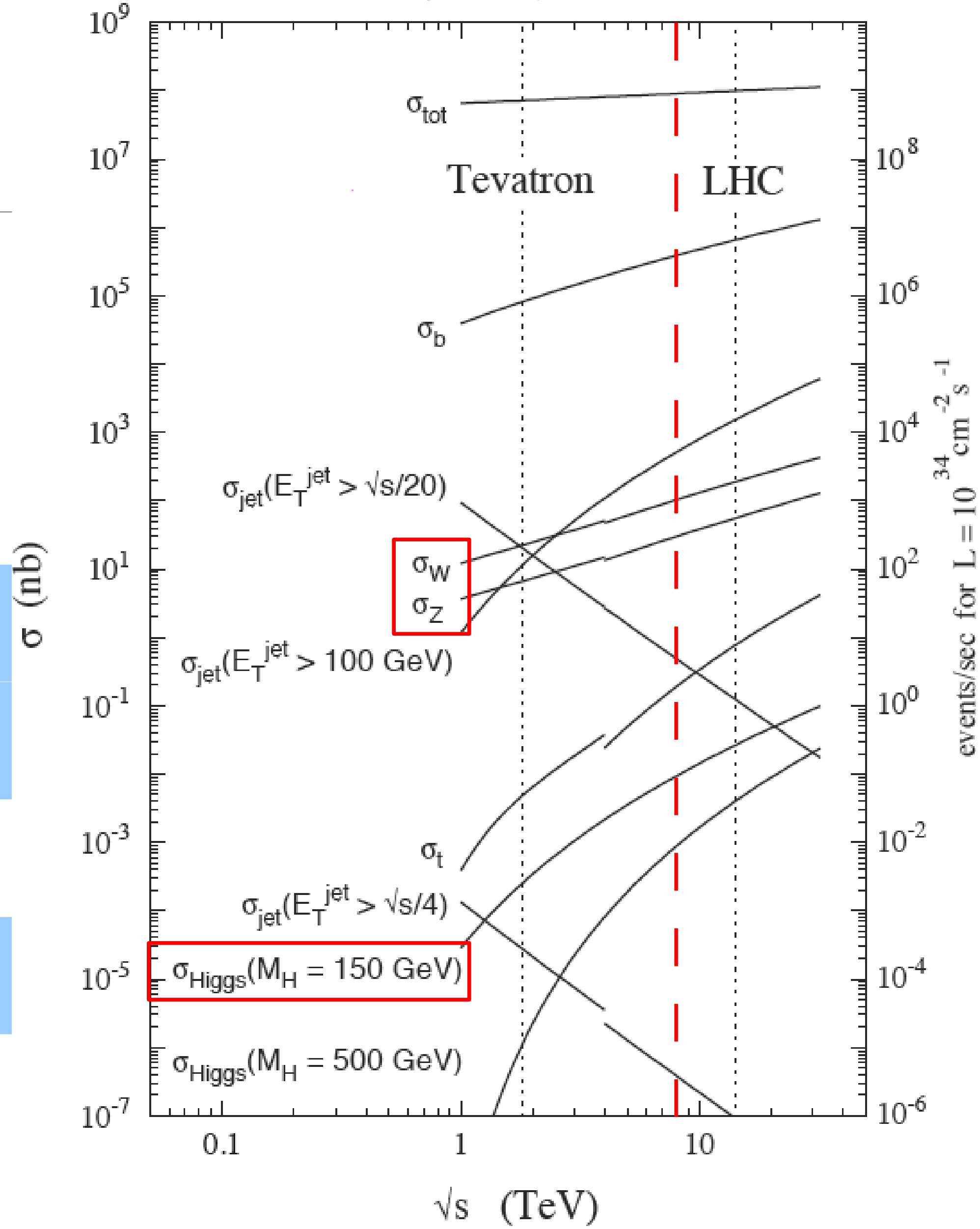
Stable beams :
<u>Data taking</u>
Main beam loss is from collisions!
Record : 22.8 hours, 0.24 fb^{-1}

Beam dump :
Many causes –
The beam is sensitive

Event rates at the LHC

Channel	Total rate (Hz)	Selected rate (Hz)	Selected Average Δt
bb	4×10^{6}	4×10^{6}	0.23 μs
W (lν)	1000	300	3.3 ms
Z (ll)	300	30	33 ms
WW (lνlν)	0.4	0.04	25 s
ZZ (llνν)	0.08	2×10^{-3}	8.3 min
H	0.2		5 s (total)
H → WW	0.04	4×10^{-3}	4.2 min
H → γγ	4×10^{-4}	4×10^{-4}	42 min
H → ZZ (4l)	5×10^{-3}	5×10^{-5}	5.5 hr

1 nb = 10 Hz

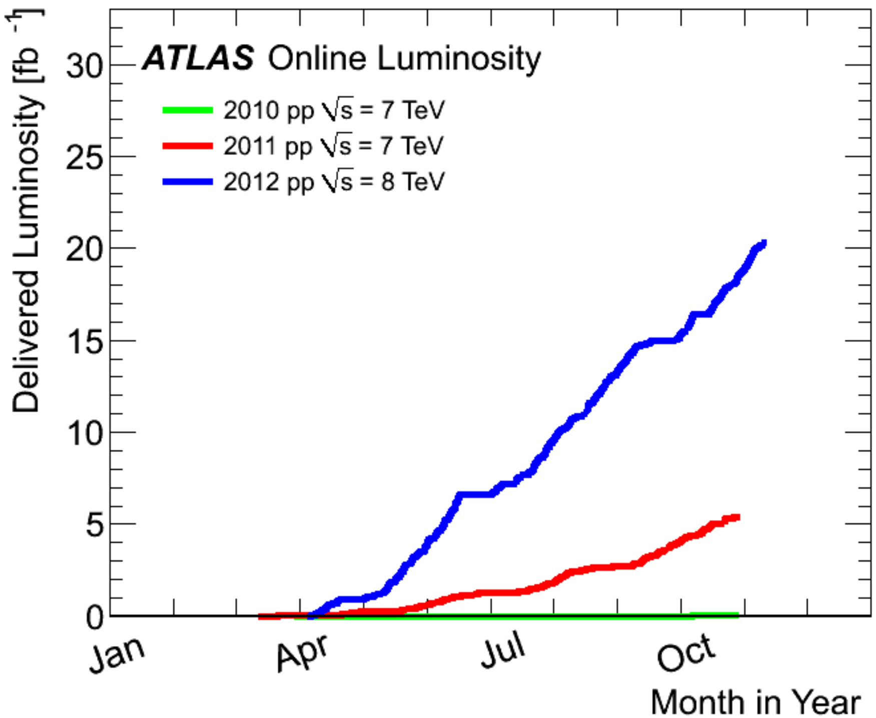


Why we need 400 million collisions per second!

LHC Performance

The LHC ran in 2010-2012 producing more data each year

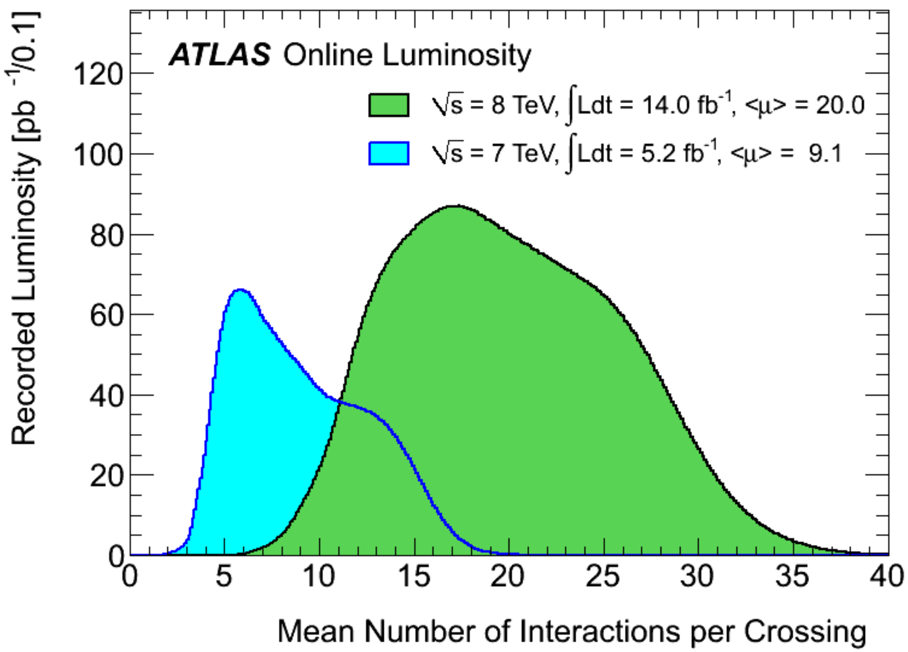
- 2010 – 34 pb^{-1}
- 2011 – 4.6 fb^{-1}
- 2012 – 21 fb^{-1}



1 fb^{-1} is approximately 100 trillion proton-proton collisions

To achieve the highest luminosities, must have multiple proton-proton collisions per bunch crossing – Pileup

An interesting event is accompanied by multiple "noise" events



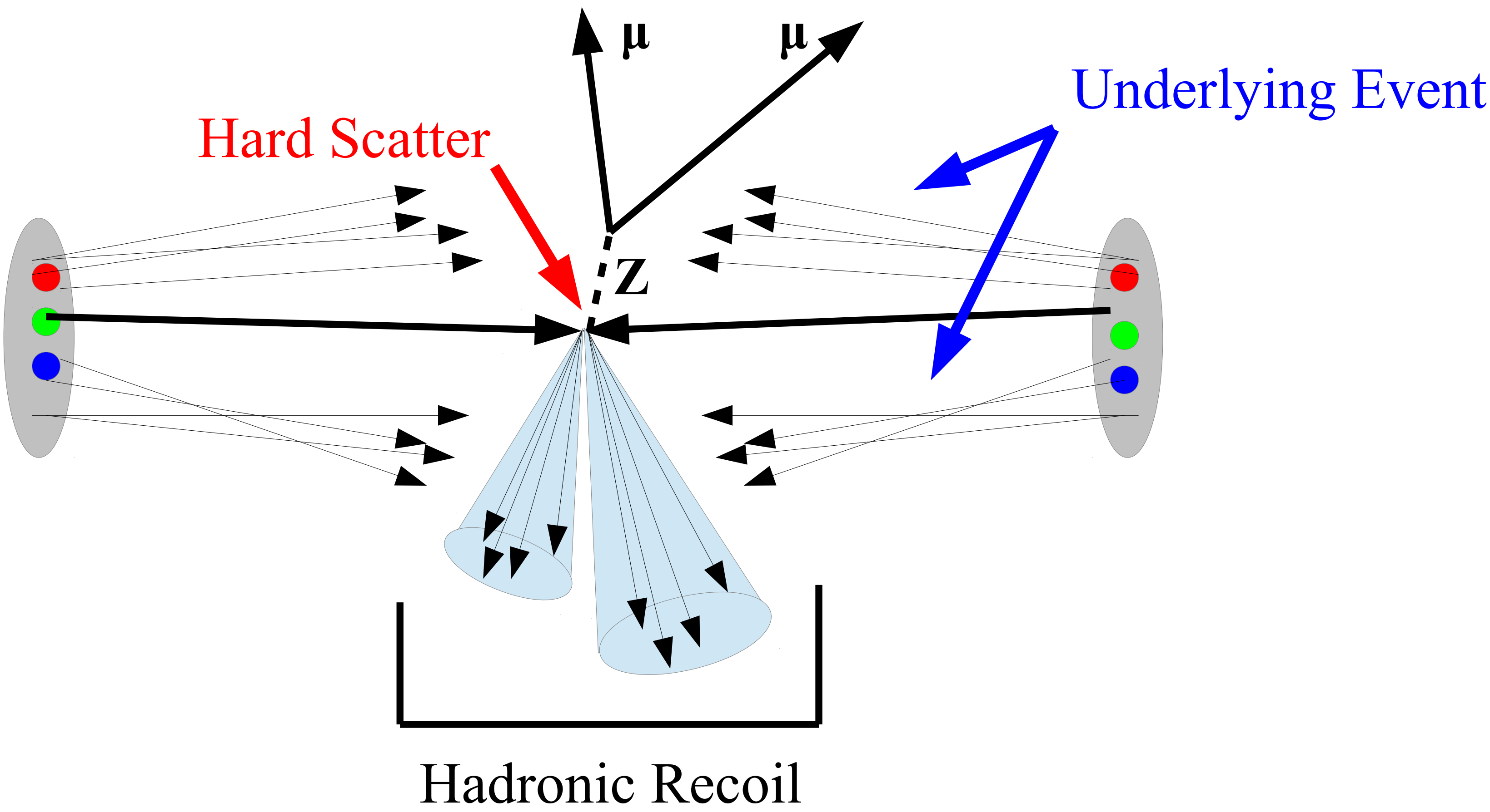
Proton-Proton collisions

Use Z production as example

Hard Scatter – parton-parton collision producing high p_T particles

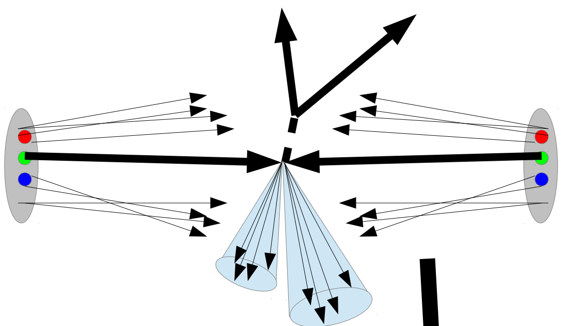
Hadronic Recoil – hadrons recoiling against Z boson p_T, usually identified as jets

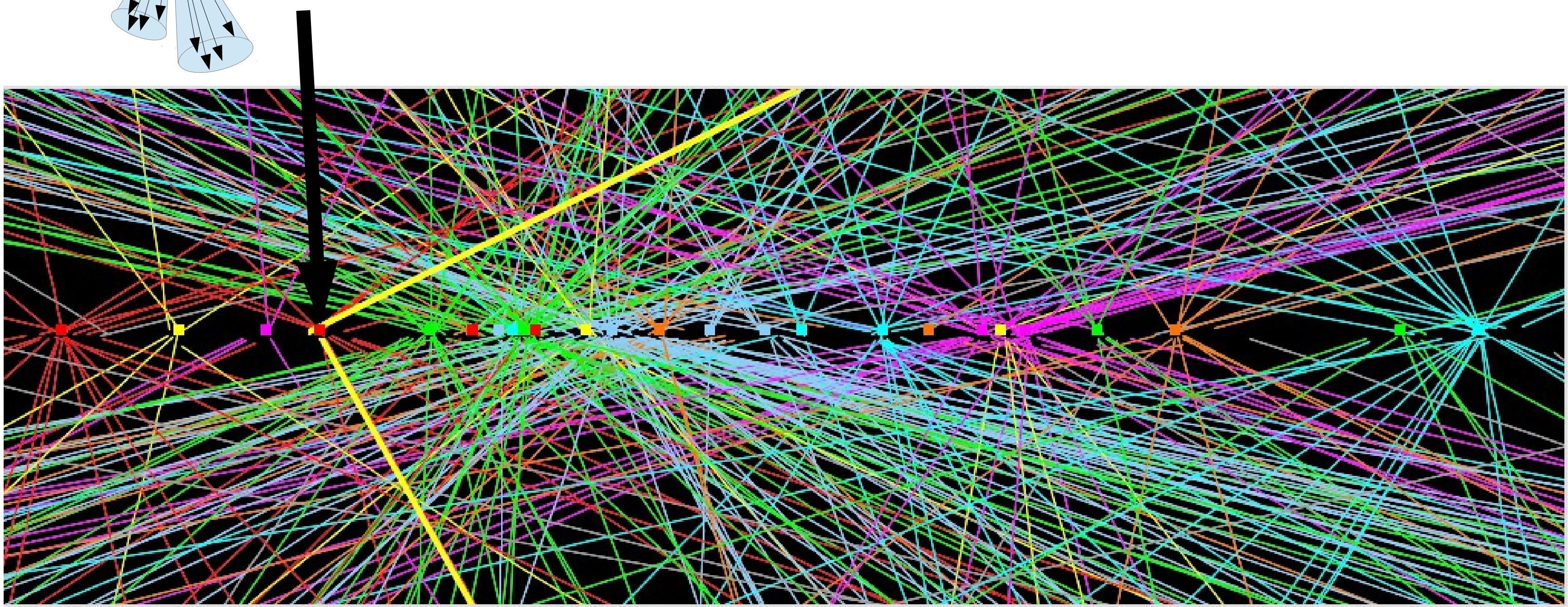
Underlying Event – Remnants of the proton not involved in hard scatter



Proton-Proton collisions

Hard Scatter – parton-parton collison producing high pT particles
Hadronic Recoil – hadrons recoiling against Z boson pT, usually identified as jets
Underlying Event – Remnants of the proton not involved in hard scatter
Pileup – Additional proton-proton interactions





The ATLAS detector

ATLAS – General purpose detector

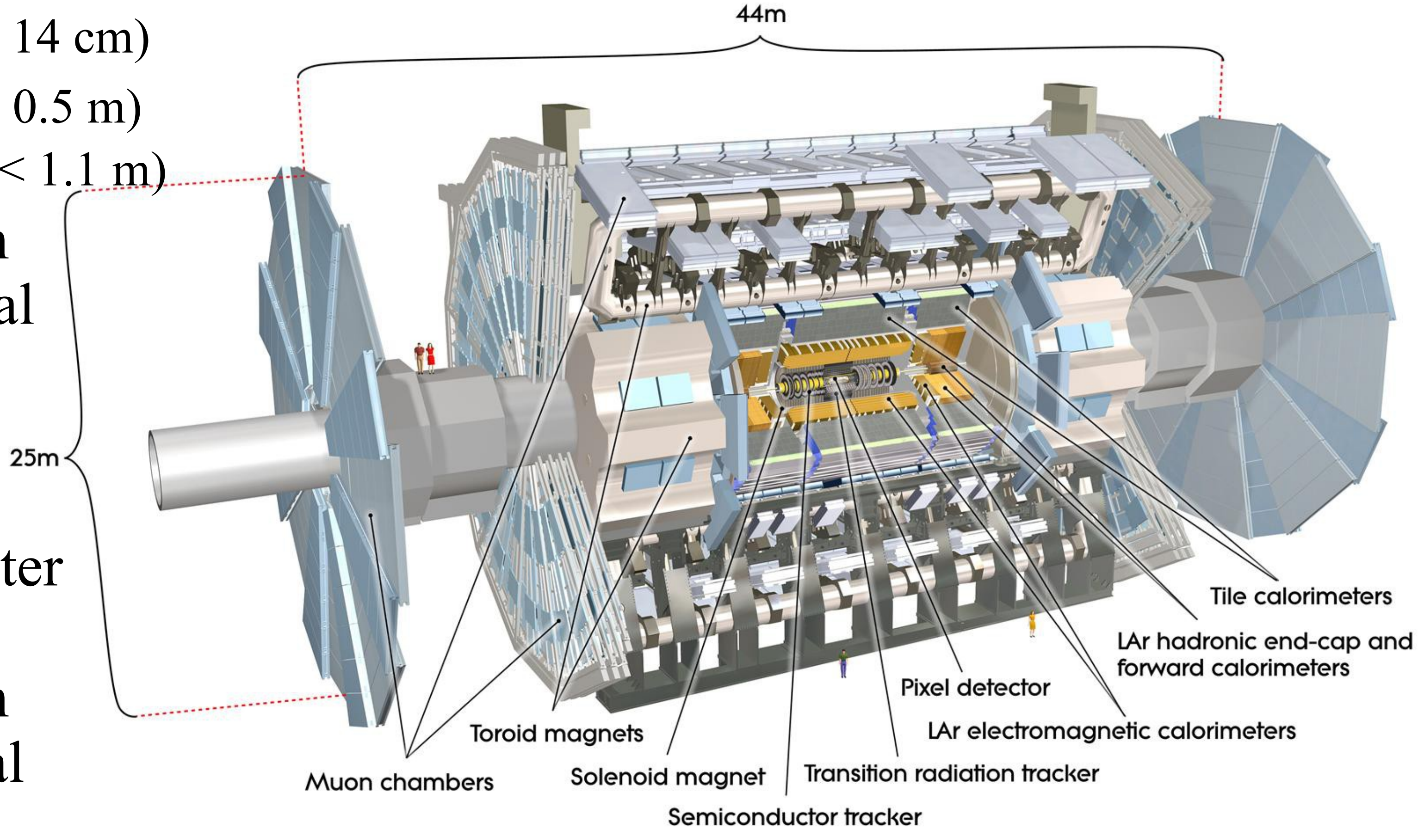
- Fully reconstruct event kinematics
- Record as many events as possible

Sub detectors

- Tracker
  - Pixel (4 cm < r < 14 cm)
  - SCT (0.3 m < r < 0.5 m)
  - TRT (0.55 m < r < 1.1 m)
  - Contained within 2 Tesla Solenoidal B-field
- Electromagnetic (EM) calorimeter
- Hadronic calorimeter
- Muon system
  - Contained within 0.5 Tesla Toroidal B-field

Trigger

Level	Output rate
1 (hardware)	75 kHz
2	3 kHz
3 (Event Filter)	400 Hz



Objects

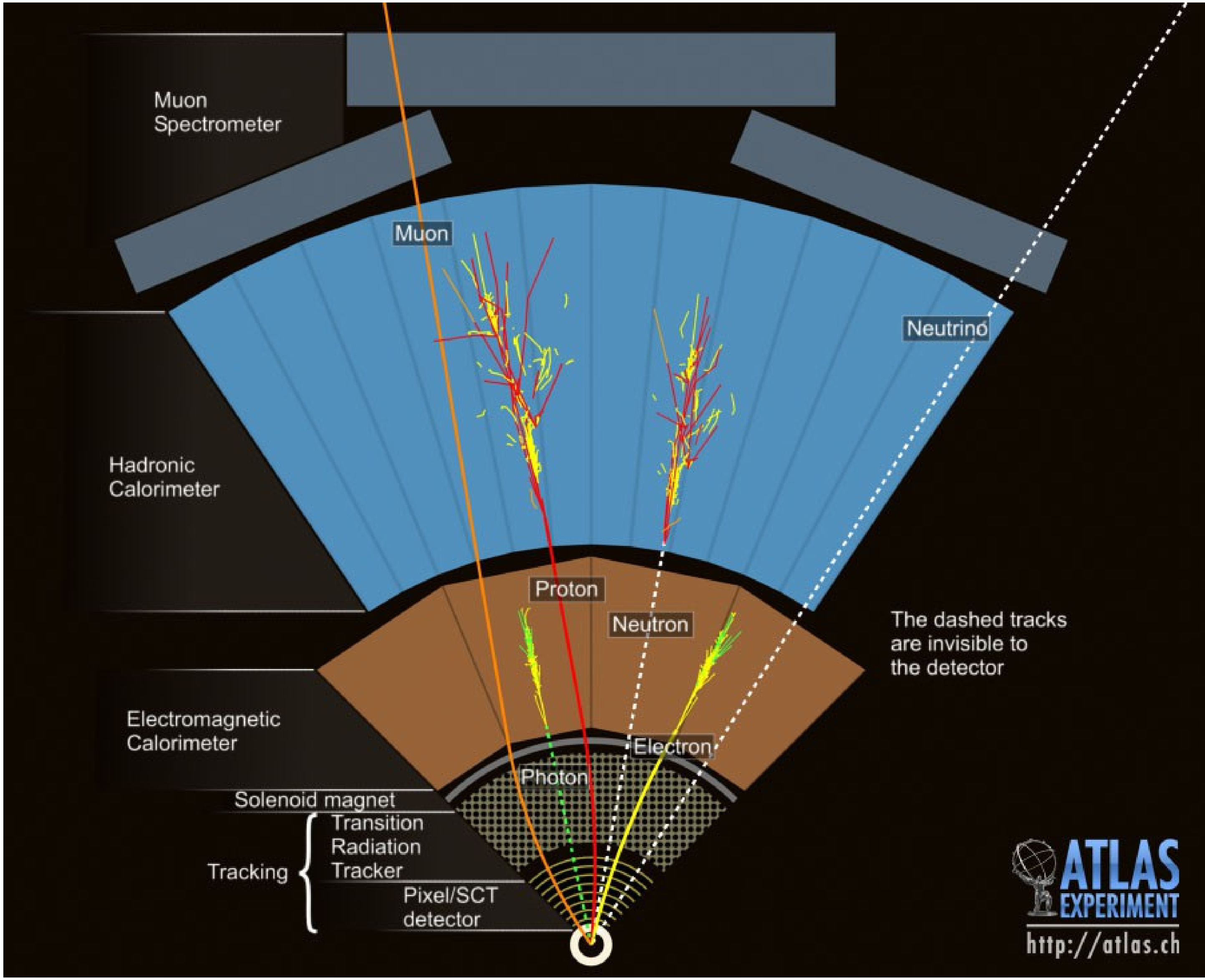
Electrons :
Narrow shower in EM calorimeter + track

Photons :
Narrow shower in EM calorimeter + no track (or + conversion tracks)

Jets :
Collections of boosted hadrons. Wide shower in hadronic calorimeter

Muons :
Pass through calorimeters, track in Muon Spectrometer

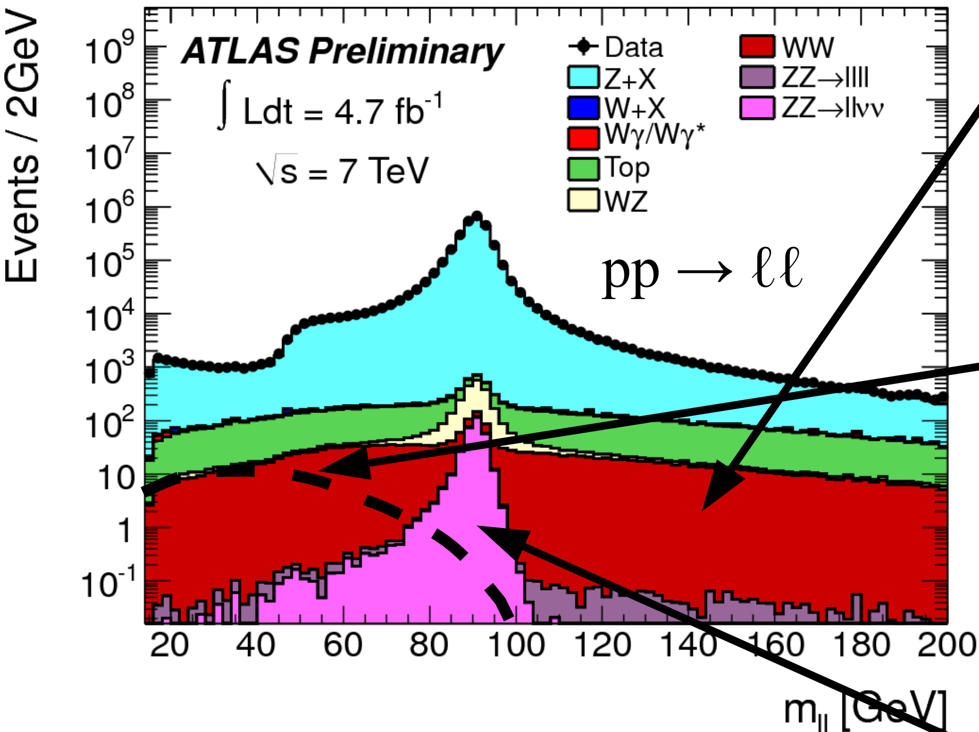
Neutrinos : Undetected – infer presence from transverse momentum imbalance



Diboson physics

I have had the opportunity to work on a number of diboson analyses

Common theme : ℓℓ+ Met final state



- WW → lνlν
  - Phys.Rev.Lett. 107 (2011) 041802
    (34 pb^{-1}, 7 TeV)
  - Physics Letters B 712 (2012) 289-308
    (1.0 fb^{-1}, 7 TeV)
- H → WW → lνlν
  - Phys. Rev. Lett. 108 (2012) 111802
    (2.1 fb^{-1}, 7 TeV)
  - Phys.Lett. B716 (2012) 62-81
    (4.7 fb^{-1}, 7TeV)
  - ATLAS-CONF-2012-158 (HCP)
    (13.0 fb^{-1}, 8 TeV)
- ZZ → llνν
  - JHEP 03 (2013) 128
    (4.7 fb^{-1}, 7 TeV)
- ZH → ll + invisible
  - ATLAS-CONF-2013-011
    (4.7 fb^{-1}, 7 TeV + 13.0 fb^{-1}, 8 TeV)

I have developed methods to estimate the Drell-Yan background for these analyses – Missing Et modeling

Also have contributed to Missing Et performance studies

Missing transverse momentum

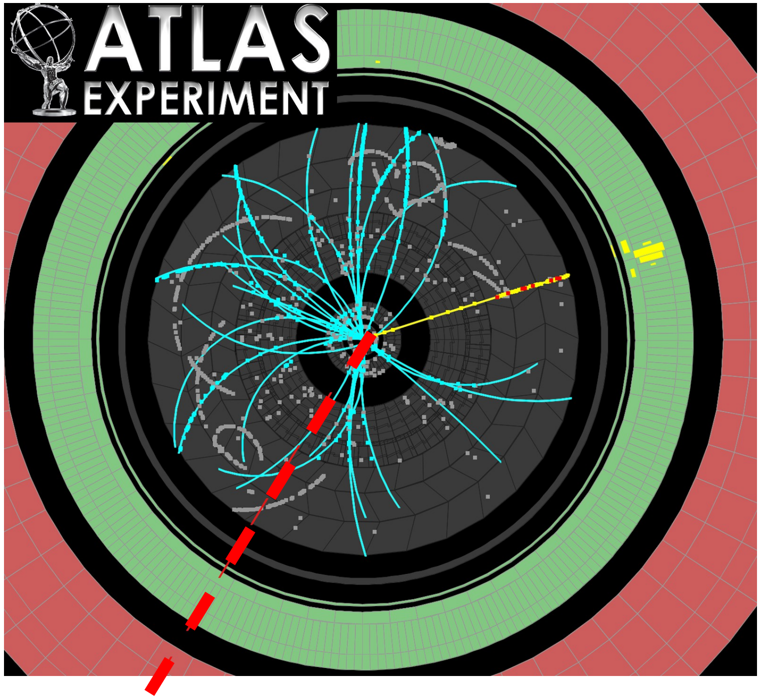
Often shortened to Missing Et or Met

- **Use momentum conservation in the transverse plane to identify undetected particles**

$$\vec{E}_T^{miss} = -\sum_i \vec{p}_T^{\,i}$$

- Simple version
  - Vector sum of p_T of all calorimeter deposits
  - Include p_T of muons that escape the calorimeter
- Refined version
  - Use identified objects and their calibrated momenta (electrons, muons, jets, photons)
  - Include soft energy not associated to any object
- Track Missing Et
  - Sum all tracks associated to primary vertex
  - Replace electron track with cluster

W → e ν



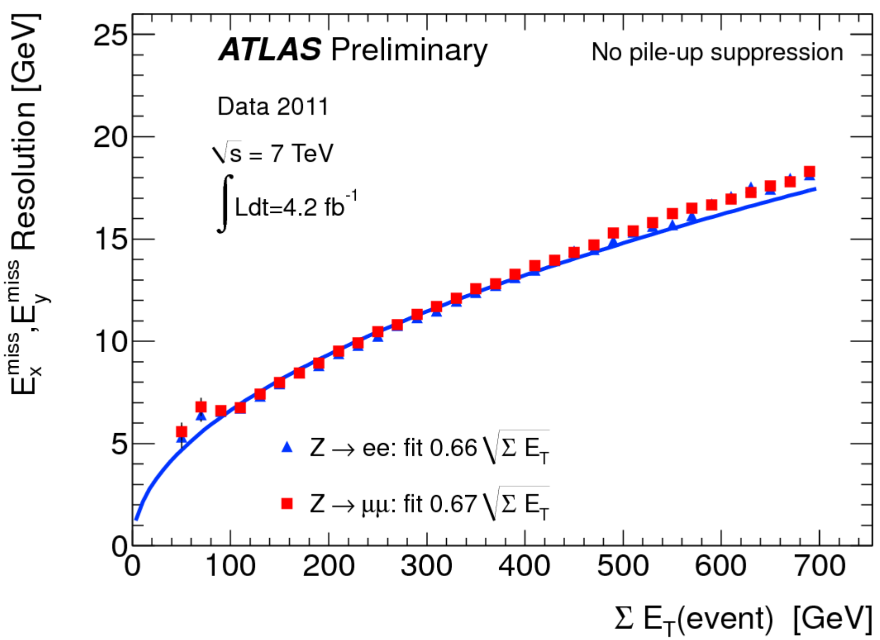
Infer neutrino direction, momentum

Missing Et resolution

Fake Missing Et

In events with no true Missing Et, measured Missing Et is dominated by detector resolution

Resolution ~ $\sqrt{\text{SumEt}}$ (Pileup dependence)



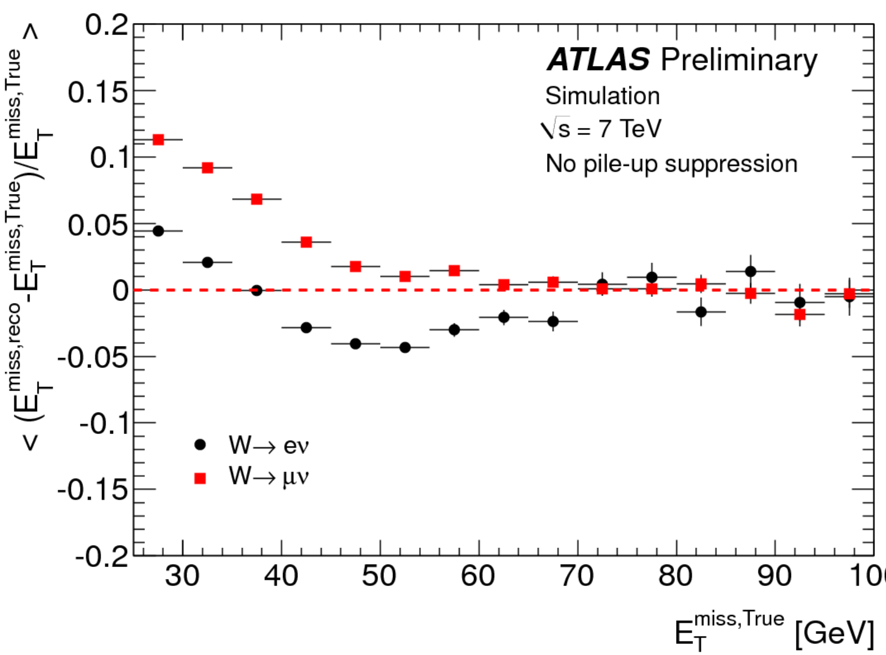
Mean of Missing Et distribution is directly related to the resolution

True Missing Et

Generally well measured

Better than 5% for Met > 40 GeV

Challenge is to reject events that have Fake Missing Et



Simulating pileup

How to include pileup modeling in MC :

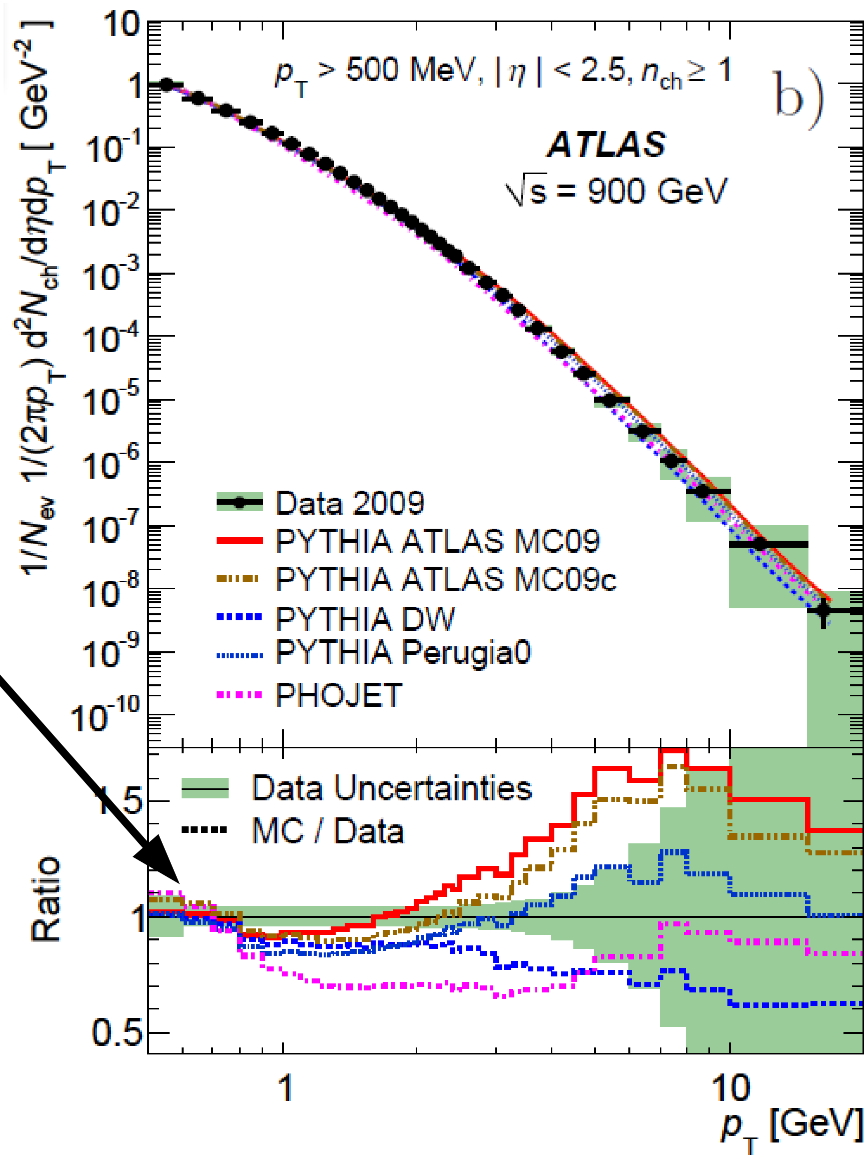
- Generate hard scatter with your favorite program
- Overlay min-bias events generated with Pythia to simulate pileup
- Run detector simulation

Despite tuning efforts, still difficult to model all low-level event kinematics

Modeling is propagated to the Missing Et and amplified by the number of pileup interactions (~ 25)

Fake Missing Et is difficult to model and has large systematic uncertainties

Prefer data-driven estimates



Scaling pileup in simulation

I contributed to early studies of Missing Et mismodeling

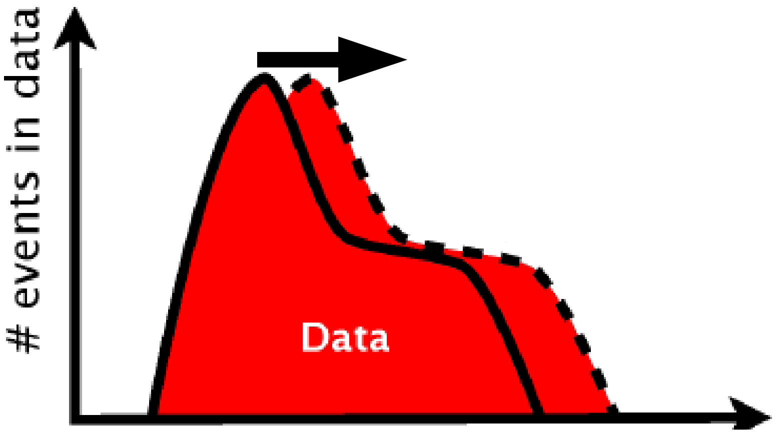
- First became a problem in early 2011 when pileup increased
- Traced the problem back to the track multiplicity and p_T modeling in the pileup collisions
- Contributed to developing a scaling procedure that tunes the number of pileup interactions

We weight the simulated number of pileup interactions to match data

Shift the distribution in data before reweighting to simulate more or less pileup

Now is used by nearly every analysis

Shift higher to simulate more pileup

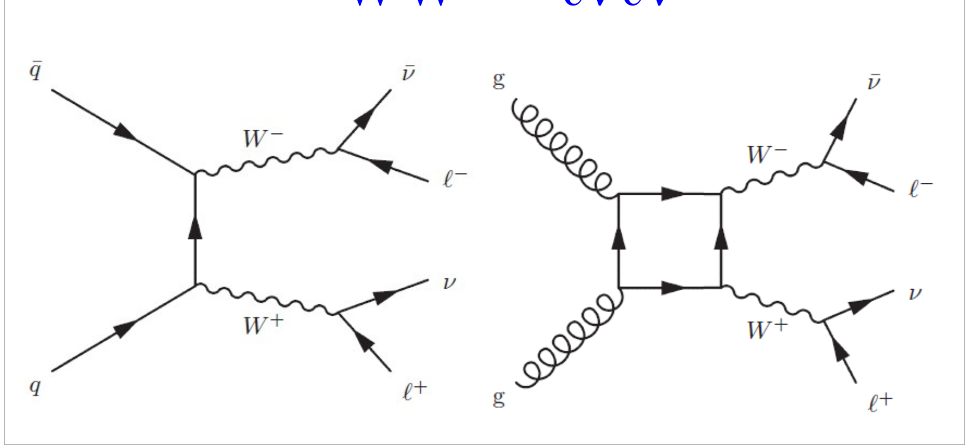


Number of pileup interactions

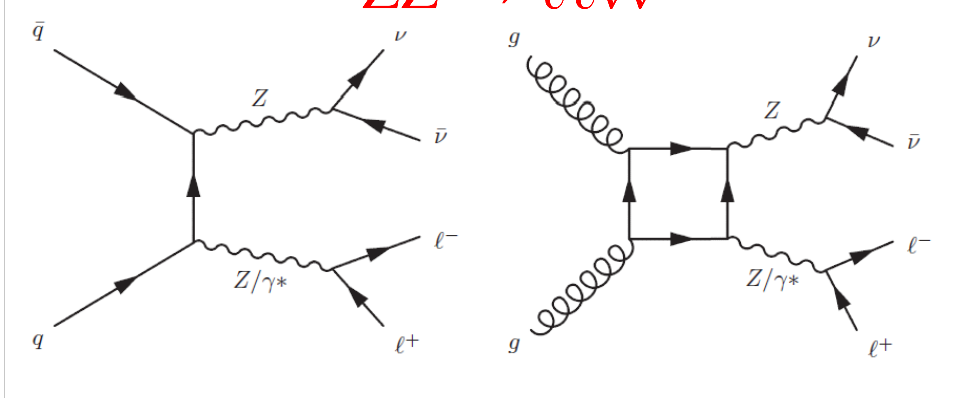
Standard model measurements

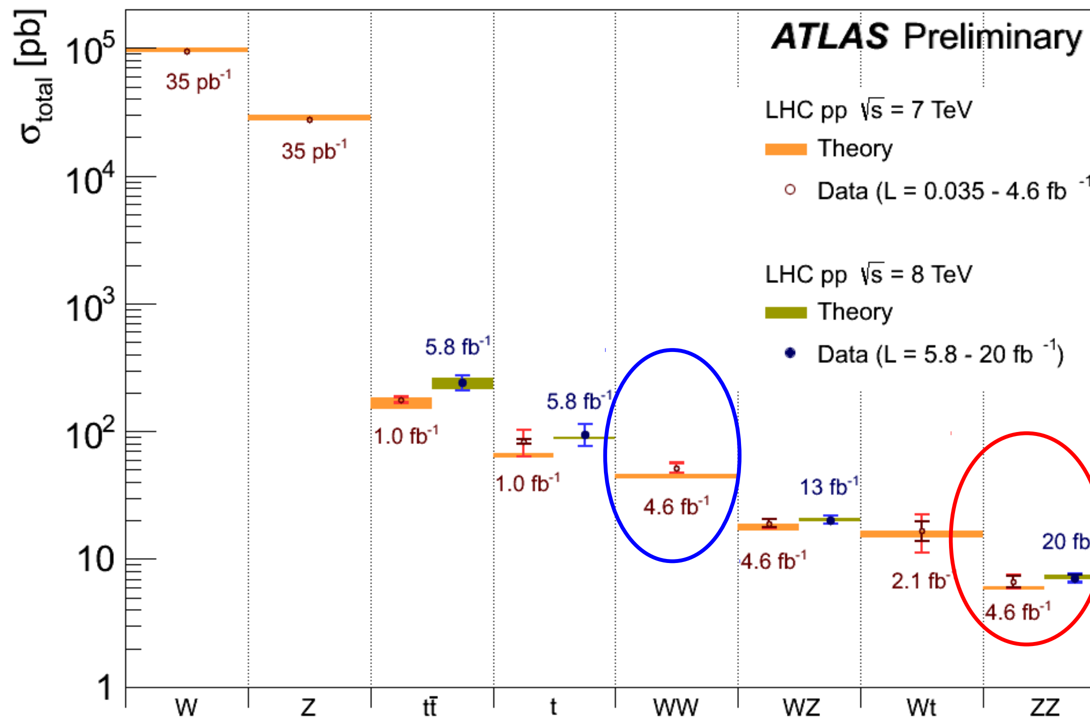
- Must understand Standard Model in order to search for new physics
- Calibrate objects on Standard Model processes
- Standard Model is a testbed for experimental techniques

$WW \to \ell\nu\ell\nu$



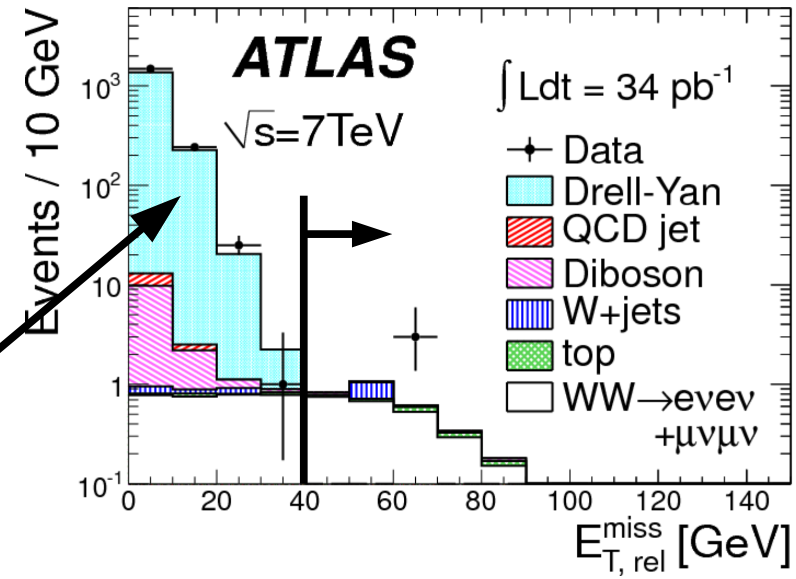
$ZZ \to \ell\ell\nu\nu$



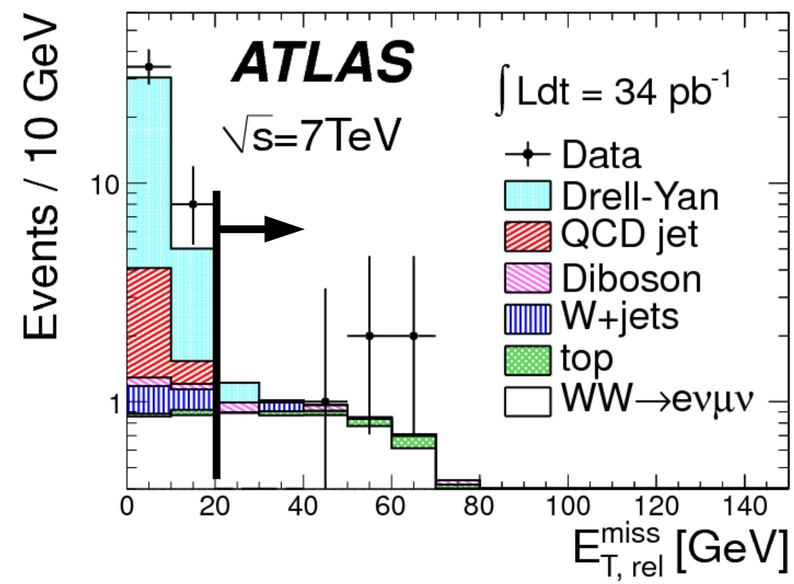


WW cross section measurement

- Three channels – ee, μμ, eμ
- Veto Z mass peak – $|M_Z - M_{\ell\ell}| > 15$ GeV (ee, μμ)
- Veto Z/γ* – Met > 40 (ee, μμ),
  Met > 20 (eμ)
- Veto $t\bar{t}$ – Zero reconstructed jets



<u>I estimated the Drell-Yan background</u> : Use simulation to estimate the number of background events and derive the systematic uncertainty by validating the simulation in the Z mass peak



8 events were observed in 34 pb⁻¹ of data

$$\sigma^{WW} = 40^{+20}_{-16}(\text{stat.}) \pm 7(\text{syst.})\text{pb}$$

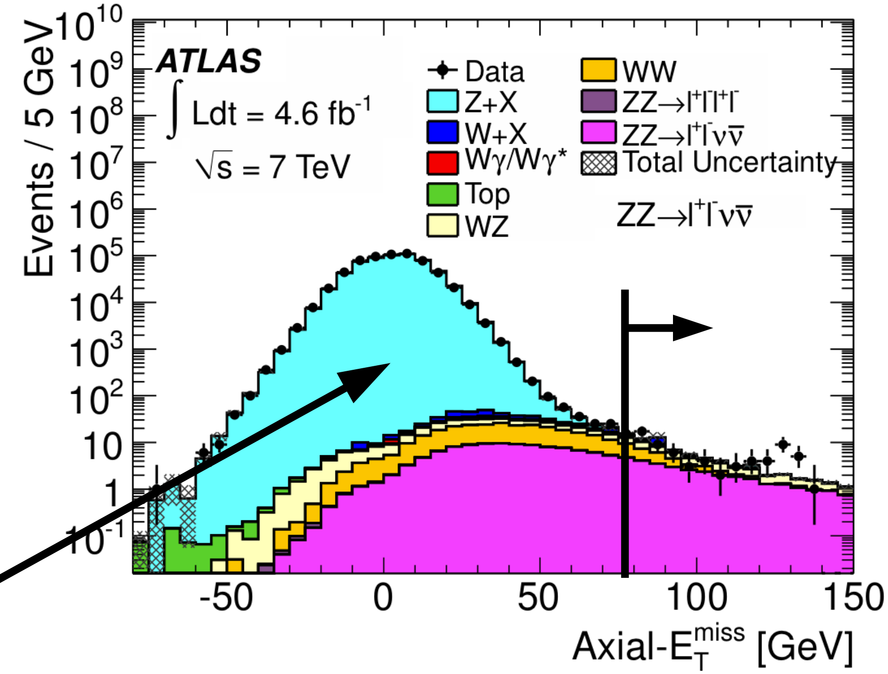
Theory : 46 pb

ZZ cross section measurement

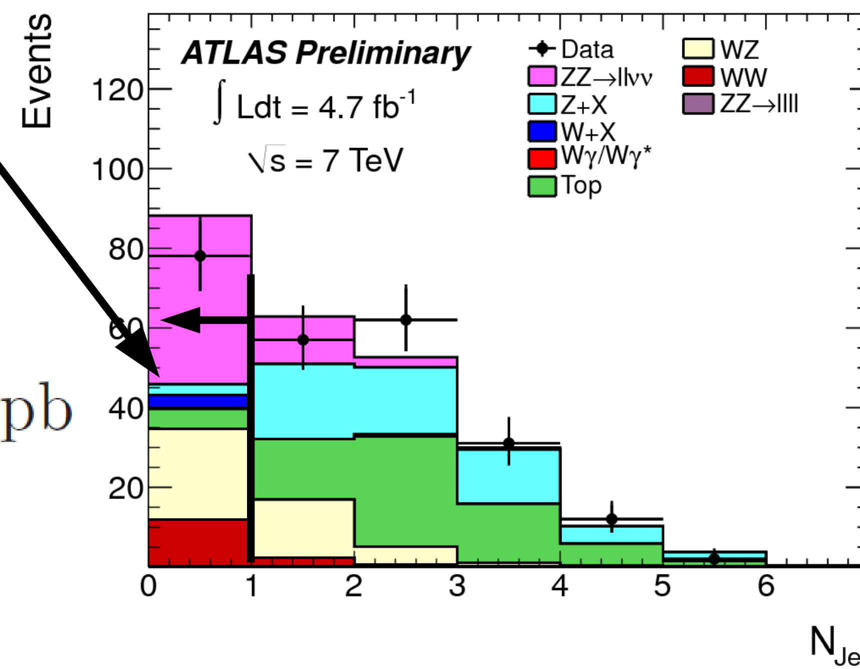
- Two channels – ee, μμ
- Require Z bosons --

  $|M_Z - M_{\ell\ell}| < 15$ GeV
- Veto single Z – Axial Met > 80 GeV
- Require momentum balance –

  $|p_T^{\ell\ell} - \text{Met}|/p_T^{\ell\ell} < 0.4$
- Veto $t\bar{t}$ – Zero reconstructed jets



<u>I estimated the Z+X background</u> : Use single photon events to model Met in Z + X events. More on this later



$$\sigma^{ZZ} =$$

$$5.7^{+1.4}_{-1.3}(\text{stat.})^{+0.7}_{-0.6}(\text{syst.}) \pm 0.1(\text{lumi})\ \text{pb}$$

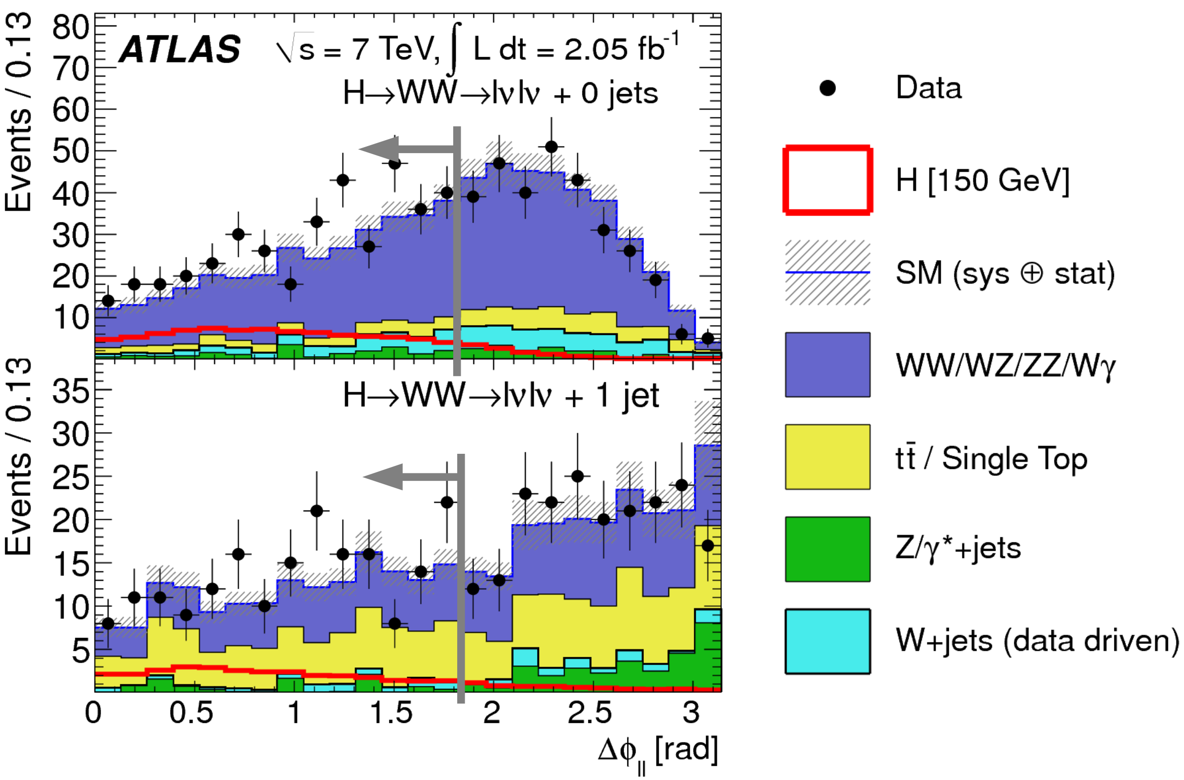
Theory : 5.9 pb

Search for H → WW

- Opposite-sign lepton pairs – ee μμ eμ
- Large missing transverse momentum from neutrinos
- Use 0 and 1 jet final states + 2 jet VBF (tag forward jets)

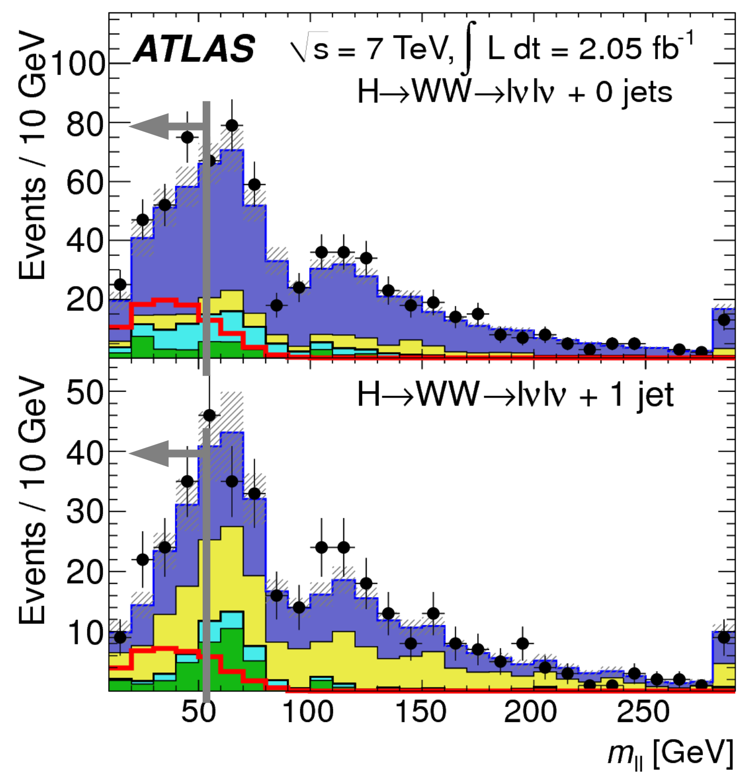
WW Spin correlation :

Require small $\Delta\varphi(l^+, l^-)$



Low m_H :

Require low $m(l^+, l^-)$



Background Estimates

Use data-driven estimates for main backgrounds

W + jets	Z/γ* + jets
Reject with isolation, PID	Reject with met cut
10 % of Background	5% of Background
Extrapolate from inverted lepton PID control region	Normalize MC using Z control region
Top	**WW**
Reject with jet cuts	Reject with $\Delta\varphi(l,l)$, $m(l,l)$ cut
5% of Background	65 % of Background
Jet veto efficiency derived in b-tag control region	Normalize MC using high $m(l^+,l^-)$ control region

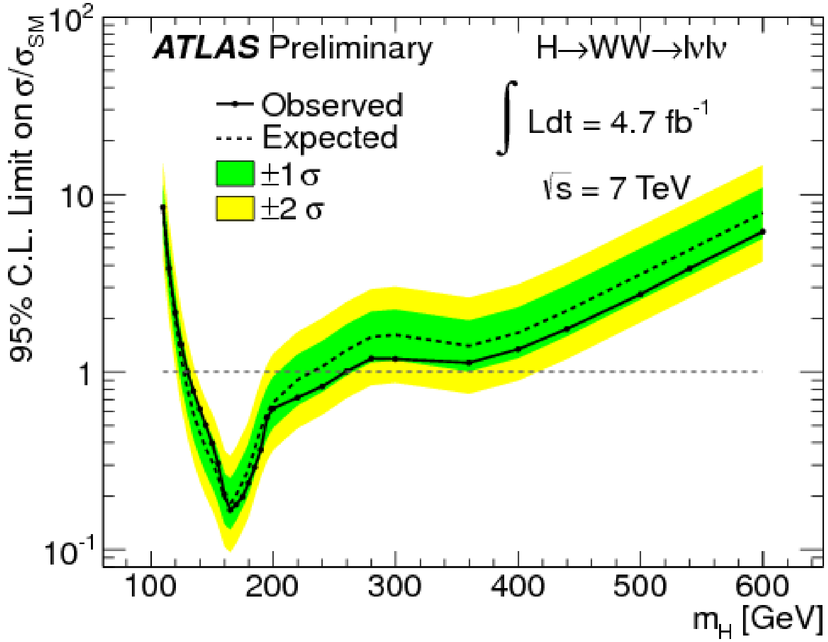
Remaining backgrounds from Di-Bosons are estimated using simulation

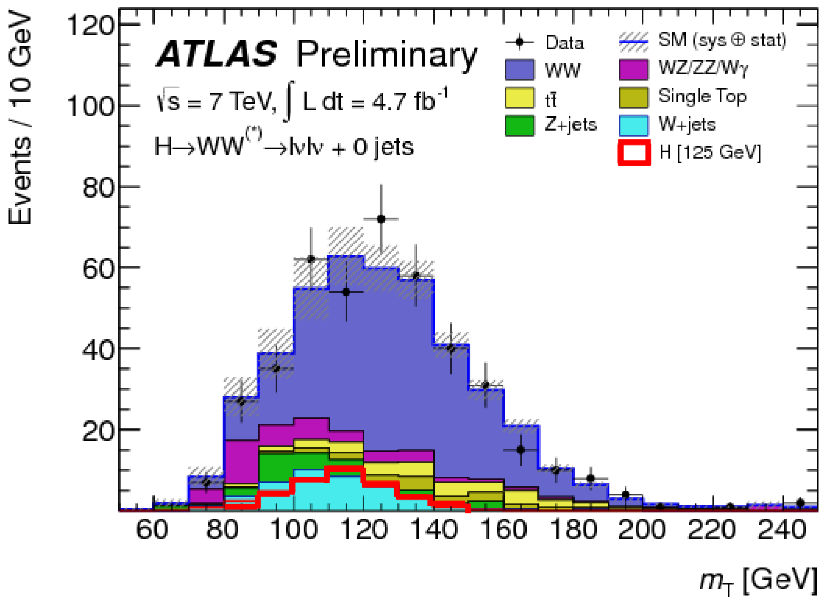
Results

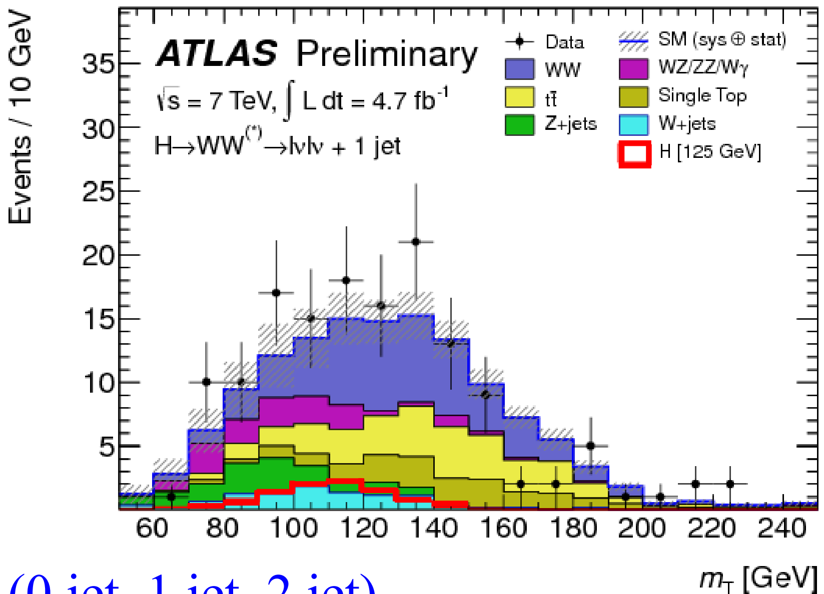
Transverse Mass (m_T) is a proxy for Higgs mass for WW channel

No significant excess observed

Fit m_T shape to extract limits





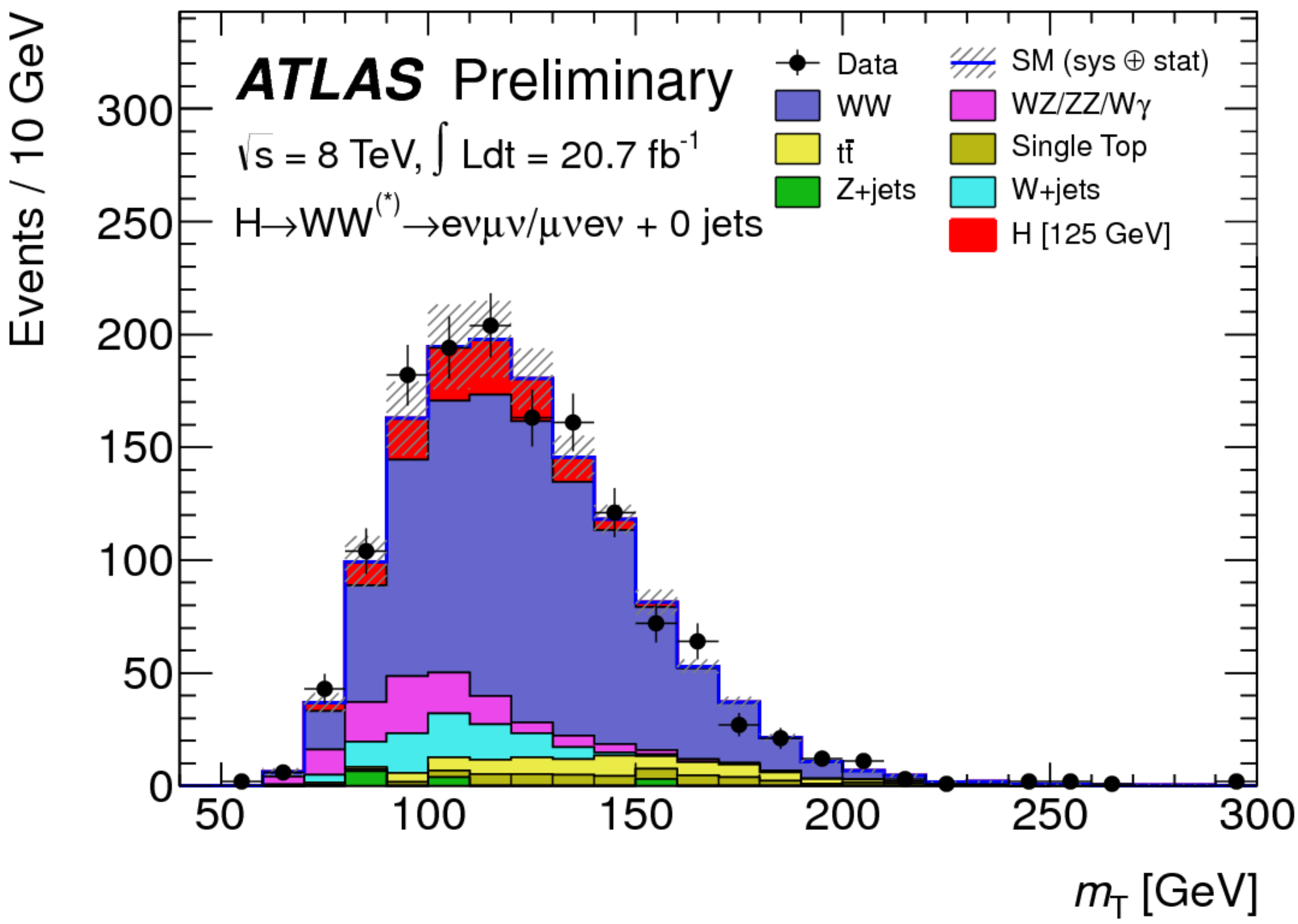


Likelihood for each M_H in 9 channels (ee, mm, em) x (0 jet, 1 jet, 2 jet)

Expected 95% C.L. Exclusion : 127 GeV < m_H < 234 GeV

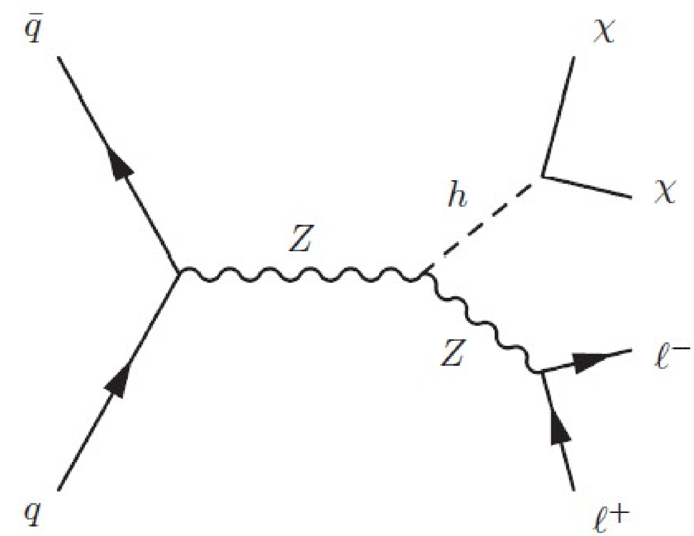
Observed 95% C.L. Exclusion : 130 GeV < m_H < 260 GeV

H → WW With full data



Search for invisible decays of the Higgs boson

Higgs to invisible branching ratio is very small – search for anomalous enhancements of the invisible rate



Many BSM models enhance invisible rate. Decays to dark matter are most compelling

Signature : Boosted leptonically decaying Z + large Met

Very similar to ZZ → $\ell\ell\nu\nu$ (Replace invisible Z with invisible Higgs)

Place limit on

- Invisible BR of 125 GeV Higgs boson
- Cross section of another Higgs boson that decays only to invisible particles

Event Selection

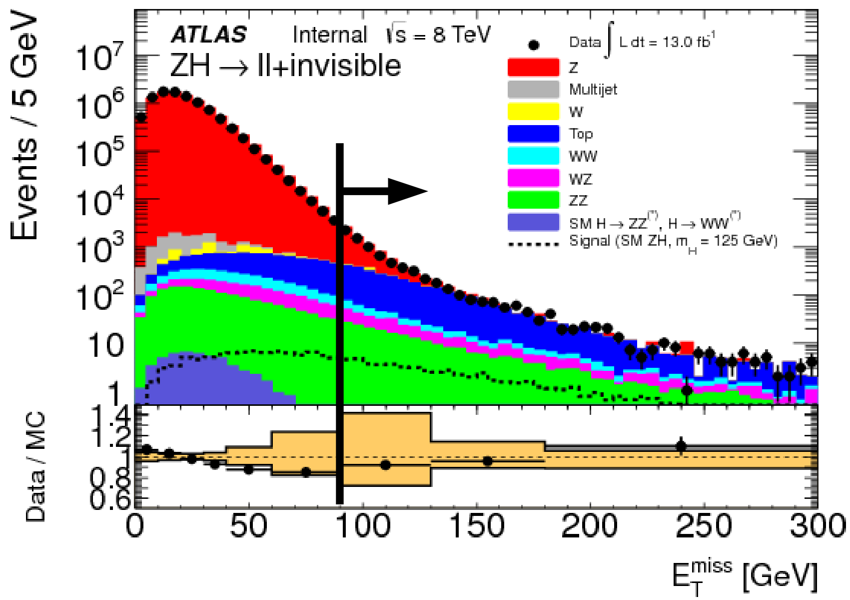
- Two channels – ee, μμ
- Require Z bosons --

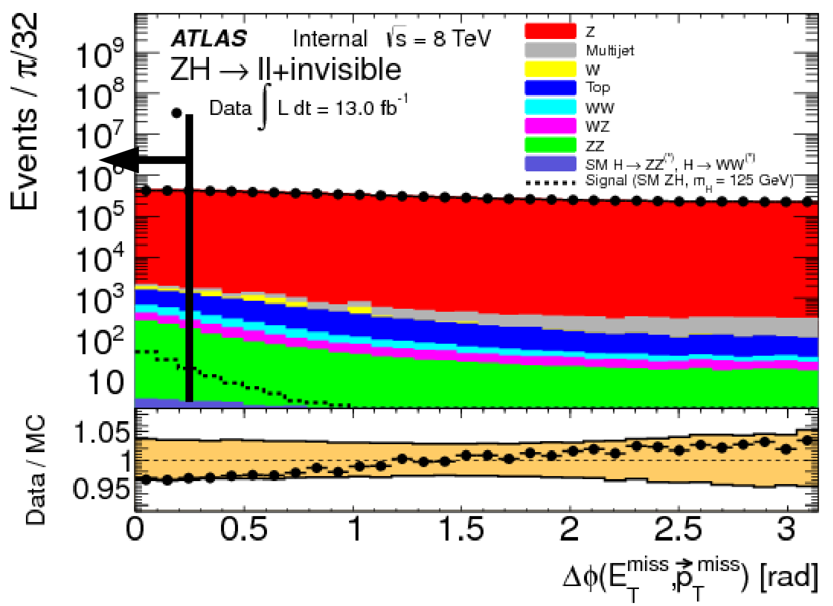
  $|M_Z - M_{\ell\ell}| < 15$ GeV
- Veto single Z – Met > 90 GeV
- Use track based Met as confirmation –

  Δφ(Met, Track Met) < 0.2
- Z back-to-back with Met –

  Δφ(Z, Met) > 2.6
- Boosed Z – $\Delta\phi(\ell,\ell) < 1.7$
- Require momentum balance –

  $|p_T^{\ell\ell} - \text{Met}|/p_T^{\ell\ell} < 0.4$
- Veto $t\bar{t}$ – Zero reconstructed jets





Single photon method

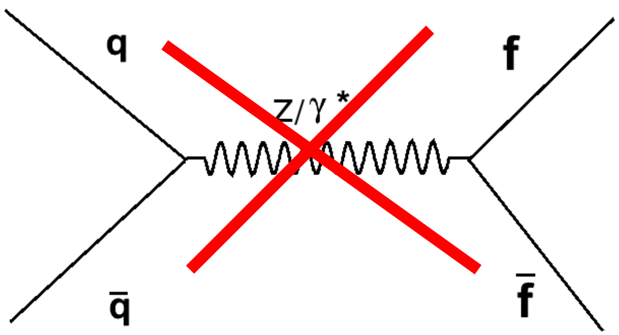
- Use single photon events as a proxy to Z + jet events
- Model Pileup, Underlying Event, hadronic recoil
- Provides modeling of Missing Et, jet multiplicity, recoil, etc.
- p_T distributions differ – weight photon p_T distribution to match Z p_T distribution

Procedure

1. Select a sample of single photon events
2. Select a sample of Z + jet events
3. Normalize single photon sample to Z sample
4. Weight the photon pT distribution to match Z pT distribution
5. Subtract real Met backgrounds from single photon sample
6. Results – Apply analysis cuts to single photon sample

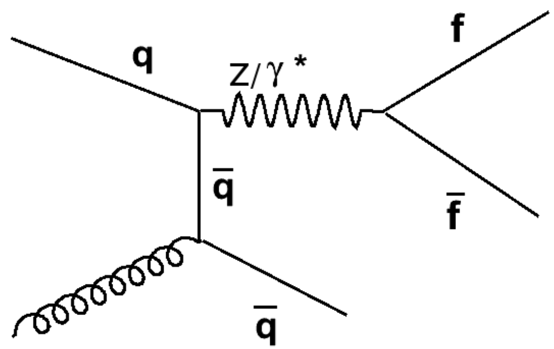
Why does this work?

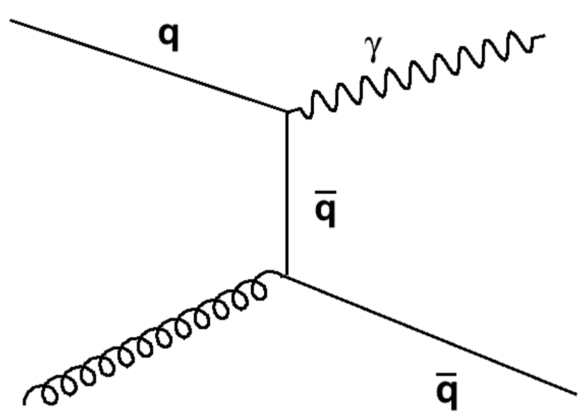
- No true Missing Et – measured Missing Et is “fake”
- In-situ sampling of underlying event and pileup
- Same production diagrams



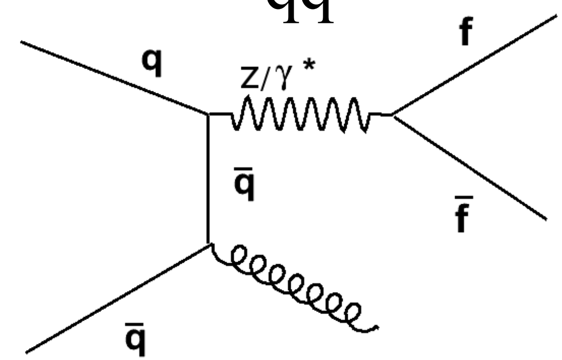
Produces Zs with 0 p_T – not accessible to this method, (photon trigger threshold) Analysis must reject these events

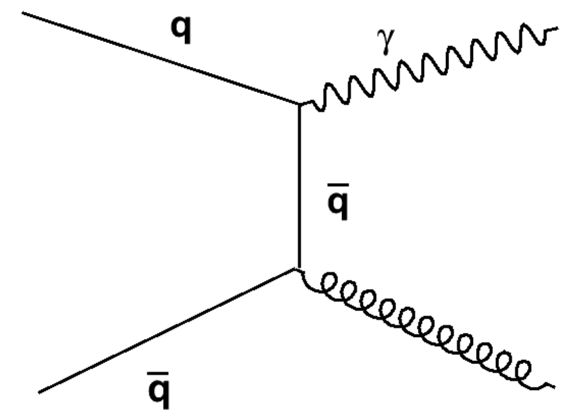
qg





$q\bar{q}$





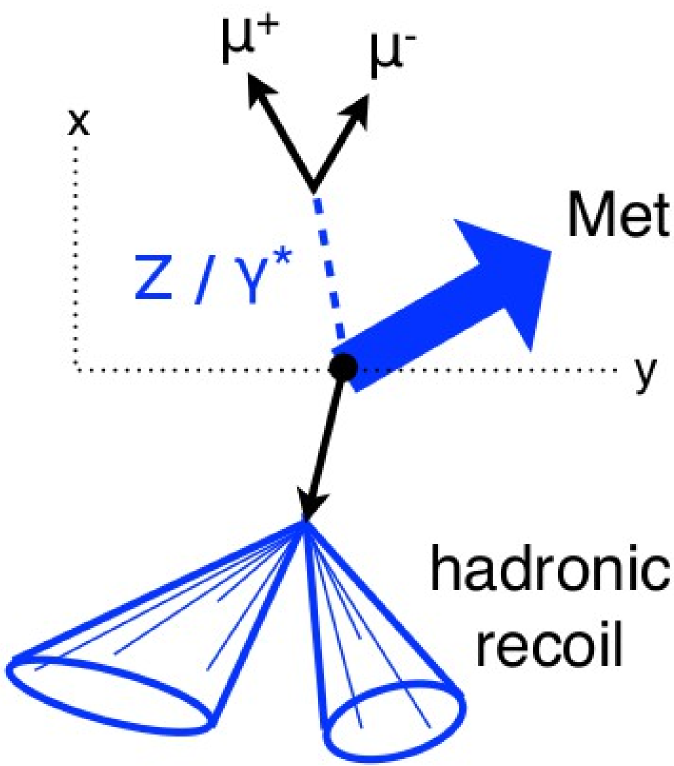
Why does this work?

What we want to estimate

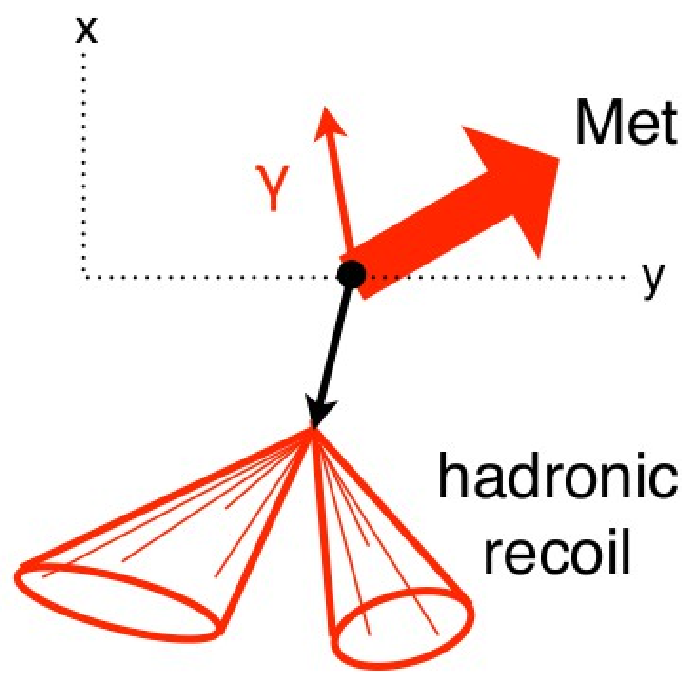
Use this high-stat sample

Main difference is in the lepton system

Otherwise similar contributions to Missing Et



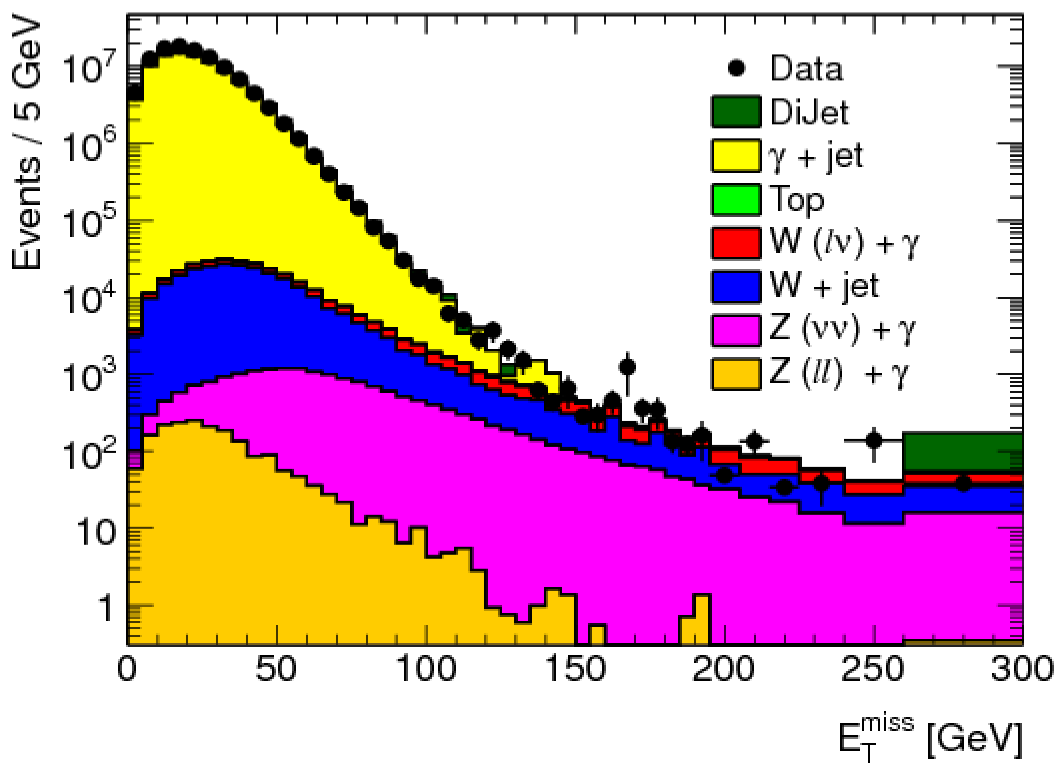
- Pileup
- Underlying Event
- Hadronic Recoil



Single Photon Events

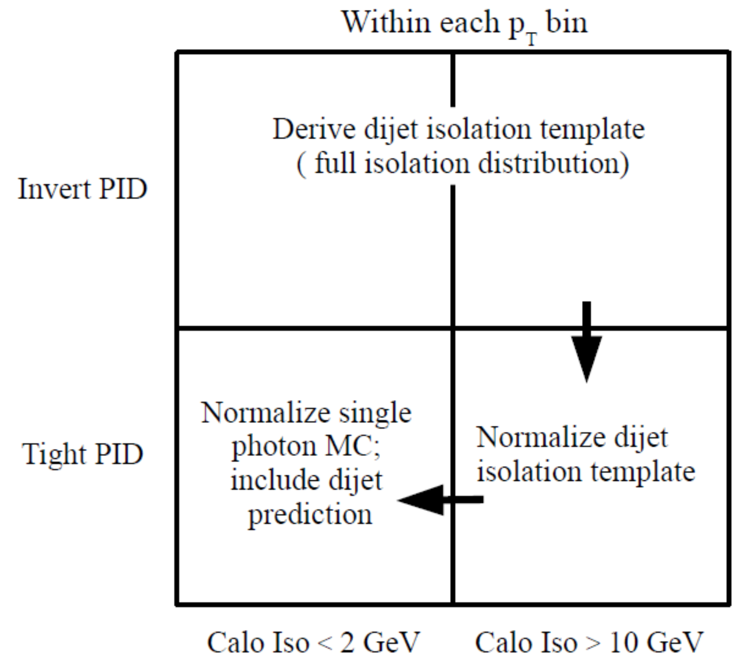
Selection dominated by single photon events, but some backgrounds are present

- Single Photon : Dominant contribution at low Missing Et
- Dijets : ~15% contribution at low Missing Et
- $W \rightarrow e\nu$: Real Missing Et background when the electron fakes a photon
- $W\gamma \rightarrow l\,\nu\,\gamma$: Real Missing Et background when lepton is lost
- $Z\gamma \rightarrow \nu\nu\gamma$: Real Missing Et background, irreducible



Dijet background estimate

- Too few statistics in dijet simulation
- Single photon simulation does not correctly model the isolation cut

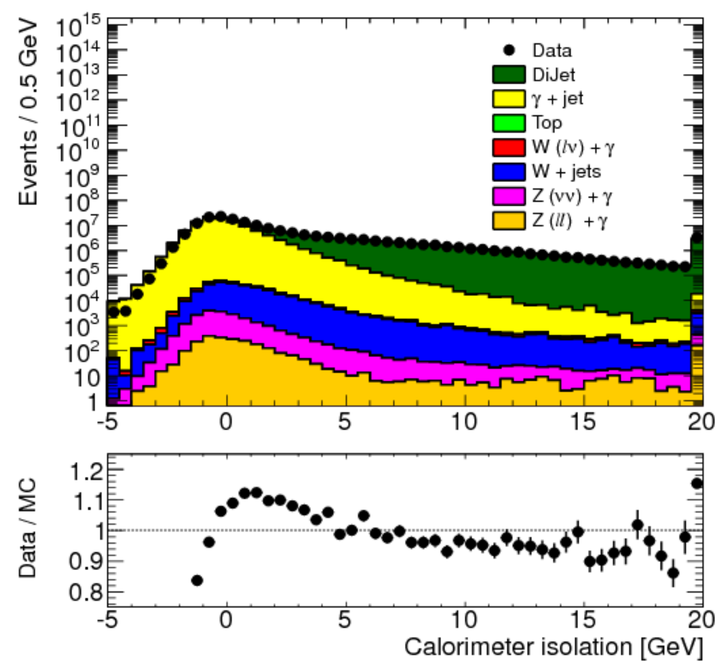


<u>Procedure</u>

Derive an isolation template in a dijet rich control region by inverting selected photon identification cuts

Normalize the isolation template in the non-isolated region of fully identified photons (p_T dependent)

Apply the isolation cut. Normalize the single photon simulation to match the data (p_T dependent)

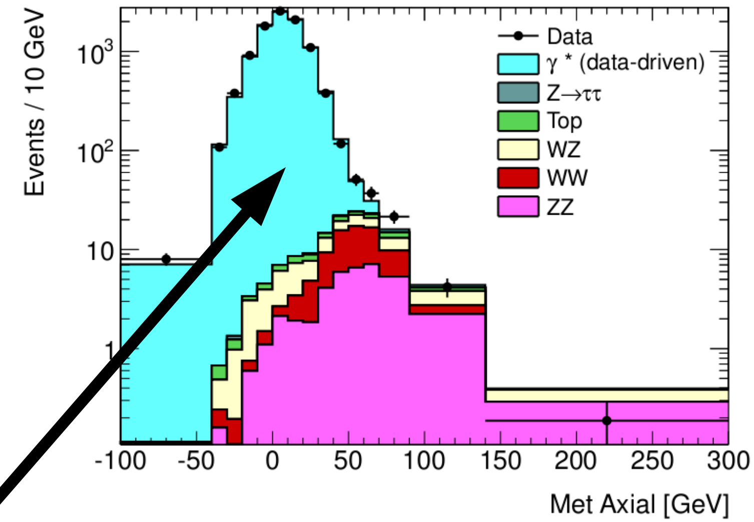


Systematics

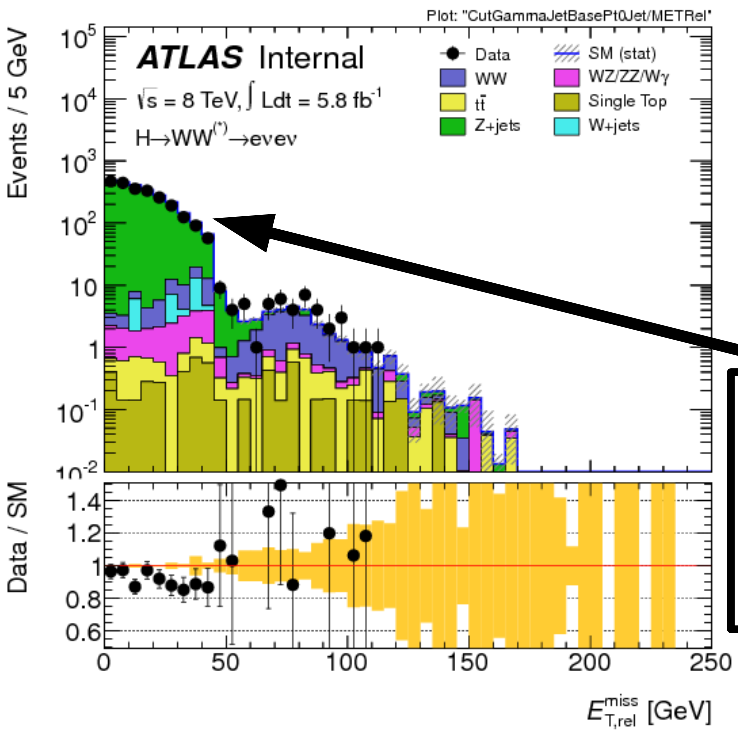
- Dijet contamination – remove PID and isolation cuts to enhance dijet contamination. Use difference in estimate as systematic
- Monte Carlo subtraction – Vary the monte carlo by cross section uncertainties and repeat the procedure. Variation from nominal is systematic
- Level of agreement in low Missing Et control region (small compared to others)
- Total systematic uncertainty is 30% - 40%

Single photon results

2011 Z → ℓℓνν



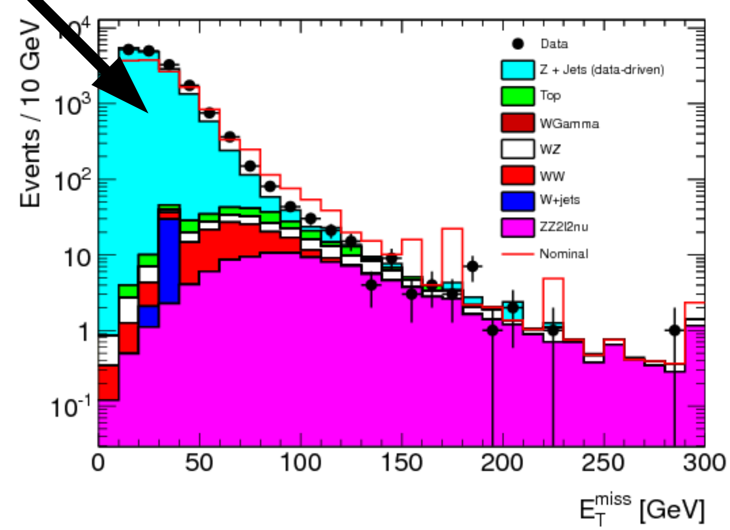
2012 H → WW



Extended Method!

Predictions from single photon estimate

2013 ZH, H → invisible

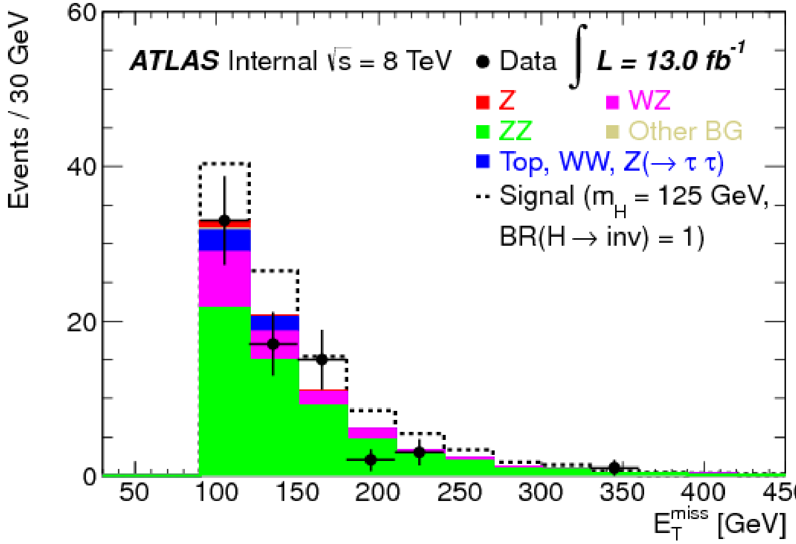


ZH, H → invisible Results

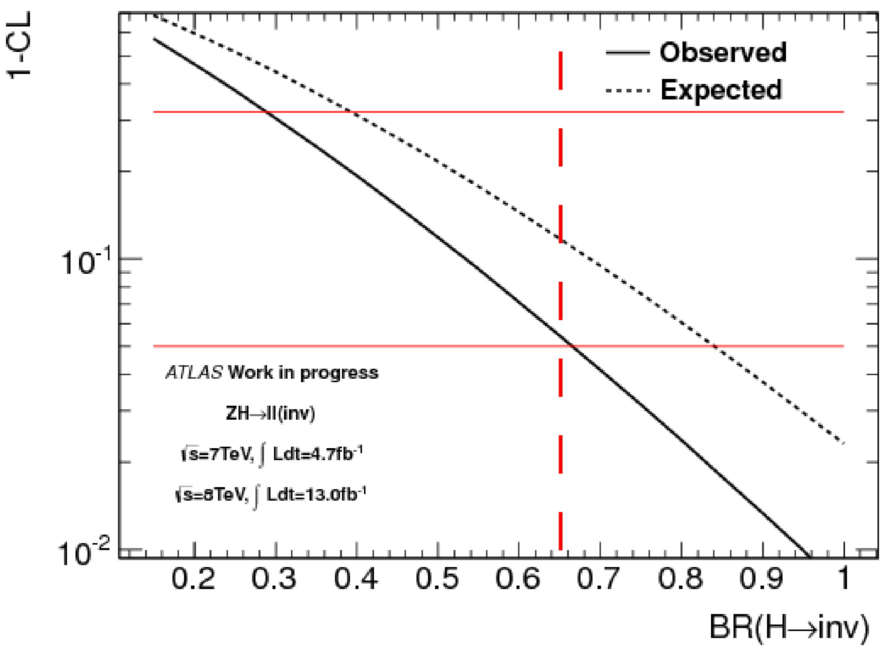
We observe no excess of events – set a limit

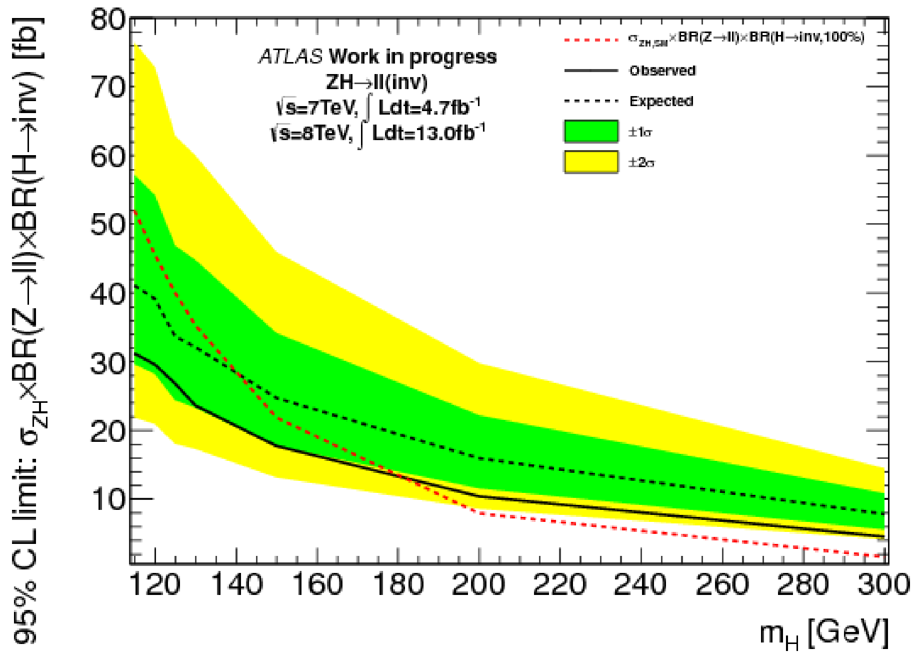
BR (H → invisible)
- Expected < 84%
- Observed < 65% (68 % confidence)

Mass dependent limit for Higgs like particle



Submitting a paper soon using the full dataset





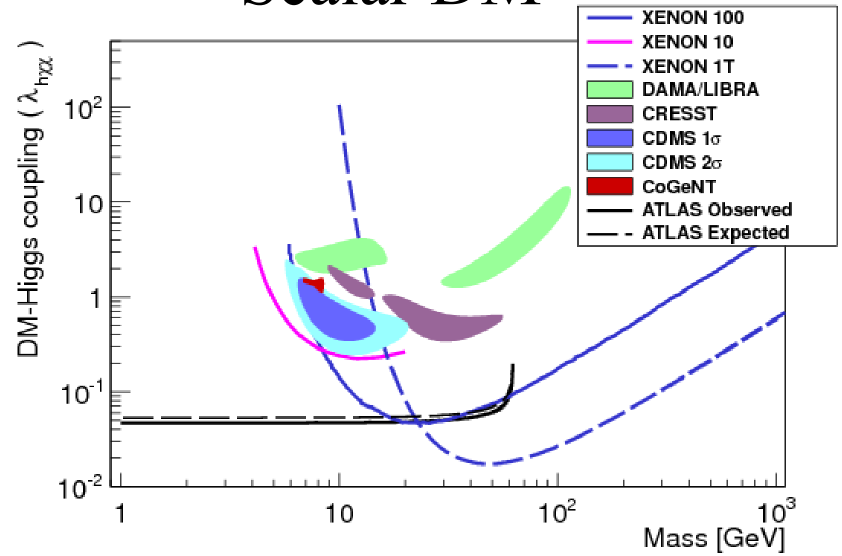
Dark matter limits

Interpret invisible branching ratio limit in terms of
Compare to current direct detection limits / observations converted to

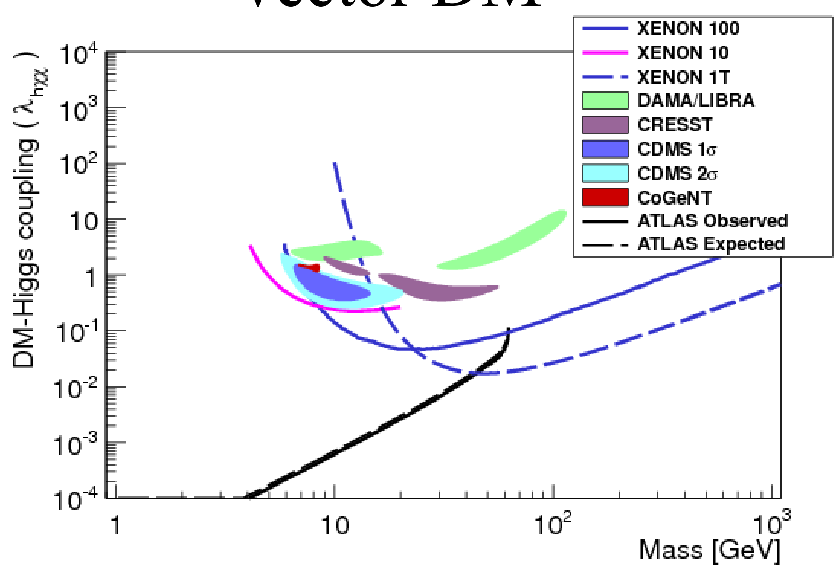
Only sensitive below $M_{DM} < M_H/2$

Provides significant exclusion at low mass where direct detection does not reach

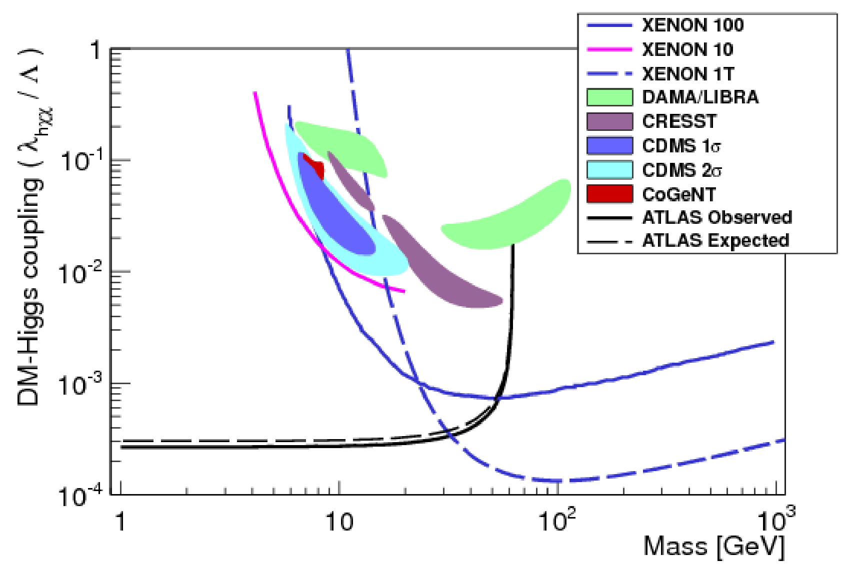
Scalar DM



Vector DM



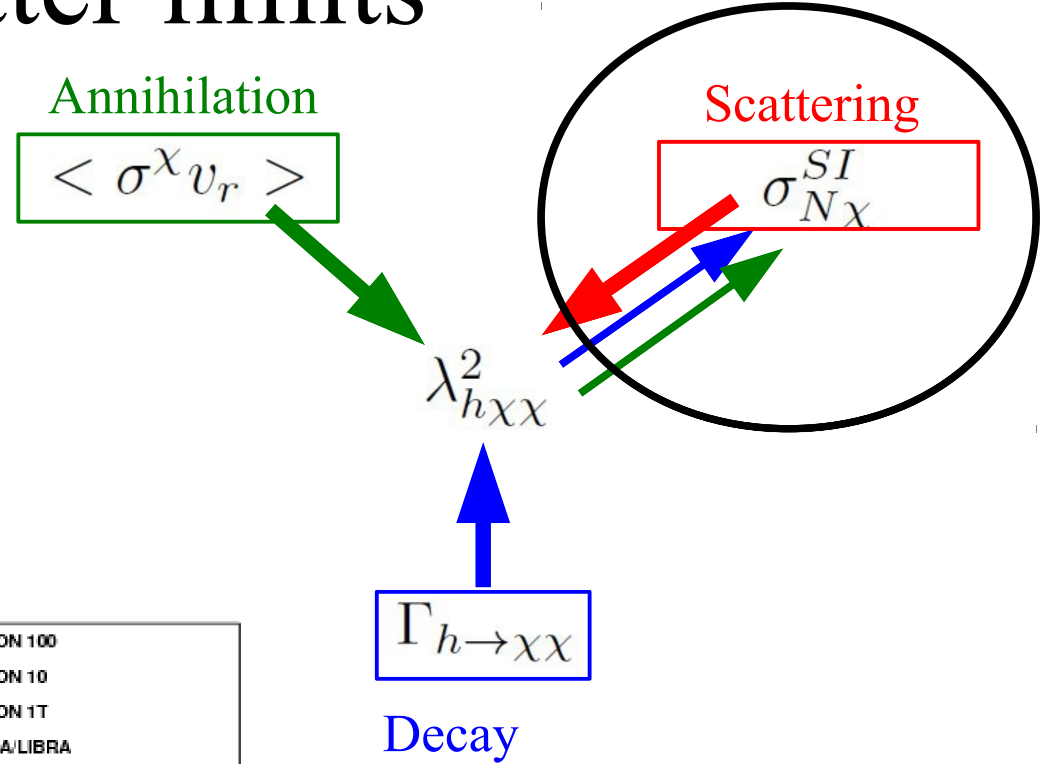
Majorana DM

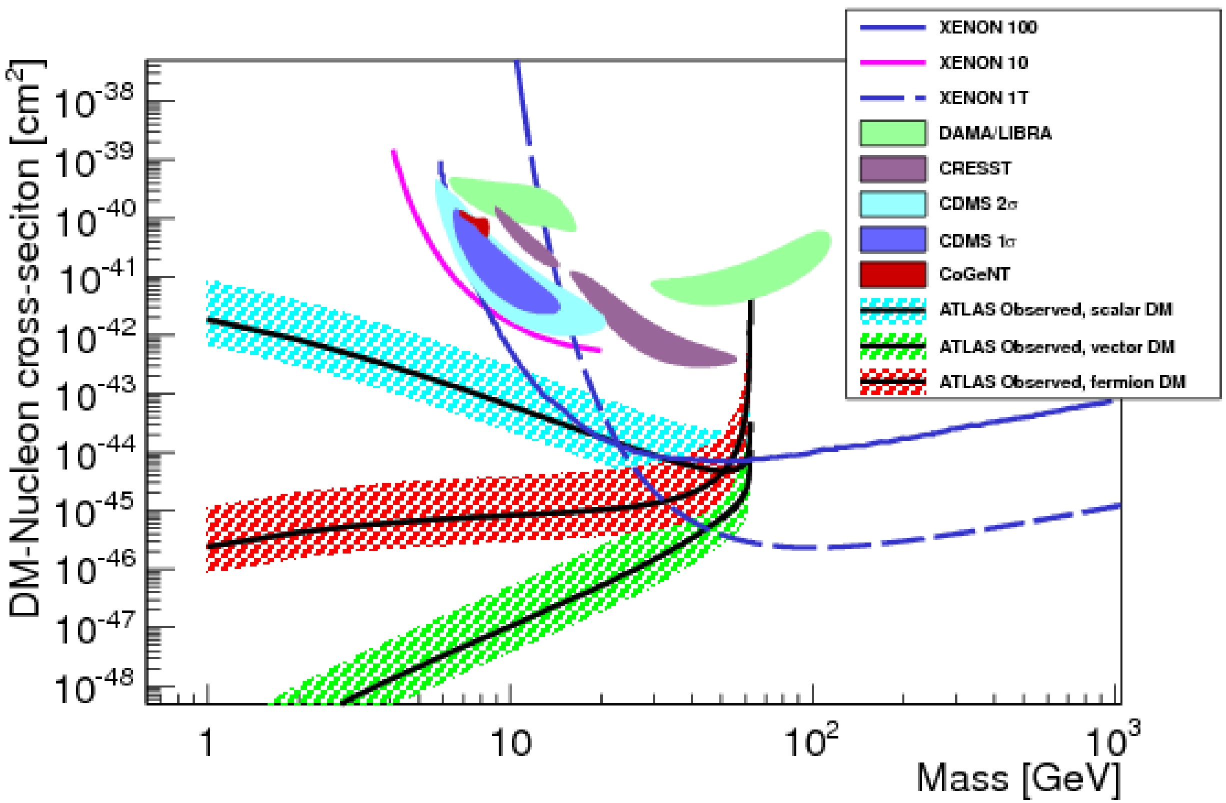


Dark matter limits

Interpret the limit as a limit on the scattering DM-Nucleon cross section

Compare direct detection with Higgs portal scalar, vector, and majorana DM





Conclusion :
Over full mass range, DM cannot have a strong coupling to the Higgs

If CDMS is correct *and* DM couples only to the Higgs, we would not have discovered it!

Summary

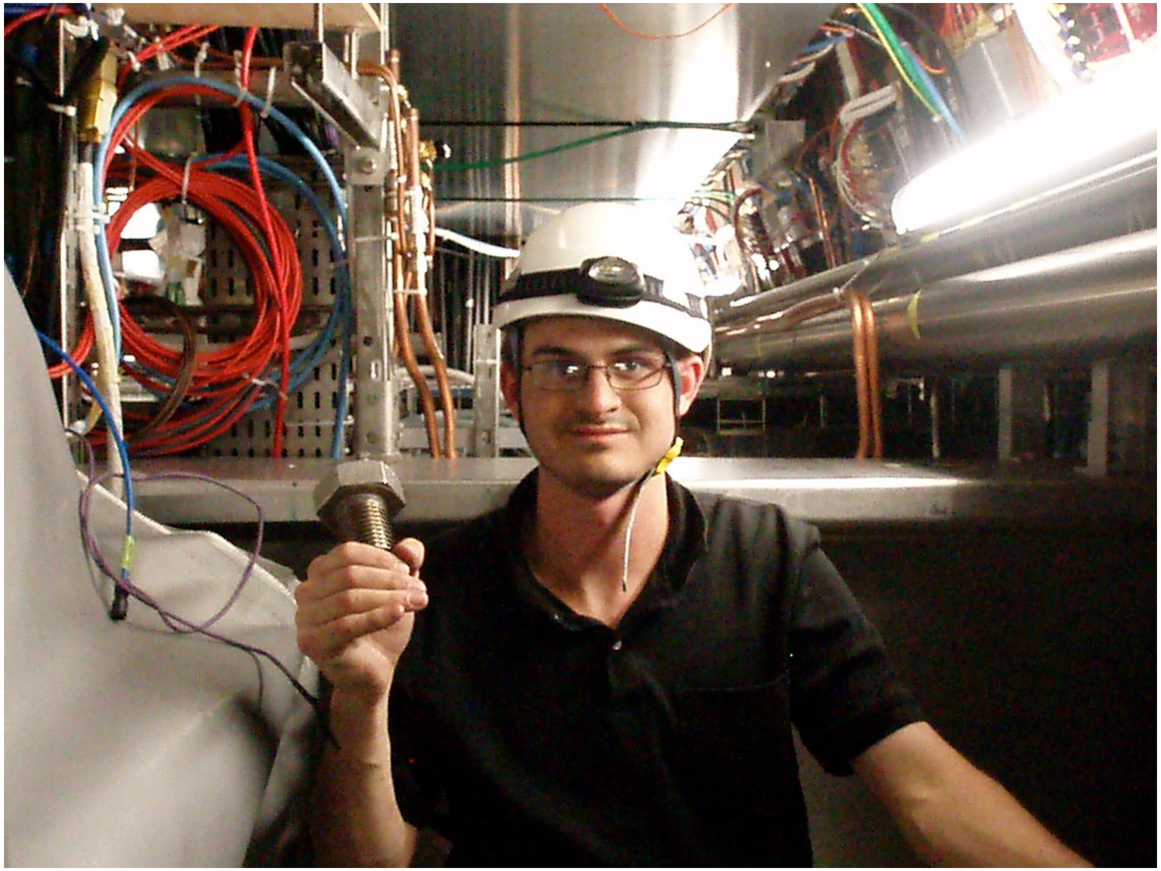
We did not find dark matter!
It's up to you now, Rami!

But, we learned more about it
If dark matter is lighter than half the Higgs mass then it cannot couple strongly to the Higgs

The scientific community is closing in on dark matter!

The first run of the LHC was amazing. Looking forward to more amazing achievements out of the machine!

Thanks to everybody for making these six years a wonderful and unforgettable experience!

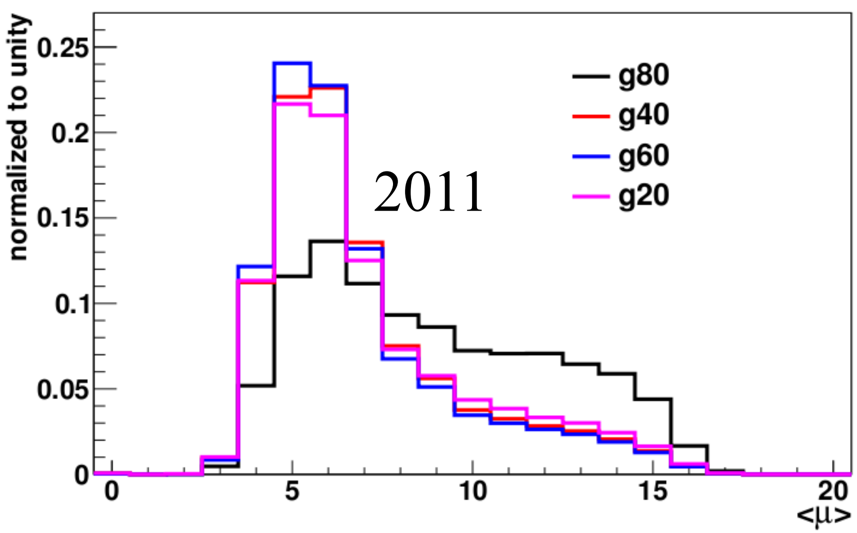


Backup

Photon Selection

- E_T > 25 GeV (trigger)
- Tight ID (shower shapes)
- Isolation
- Not converted (more on conversions later)
- No electrons or muons

- Select an OR of loose photon triggers
- Low threshold triggers are highly prescaled
- prescaled triggers are biased to lower pileup
- Reweight pileup distribution to match unprescaled trigger



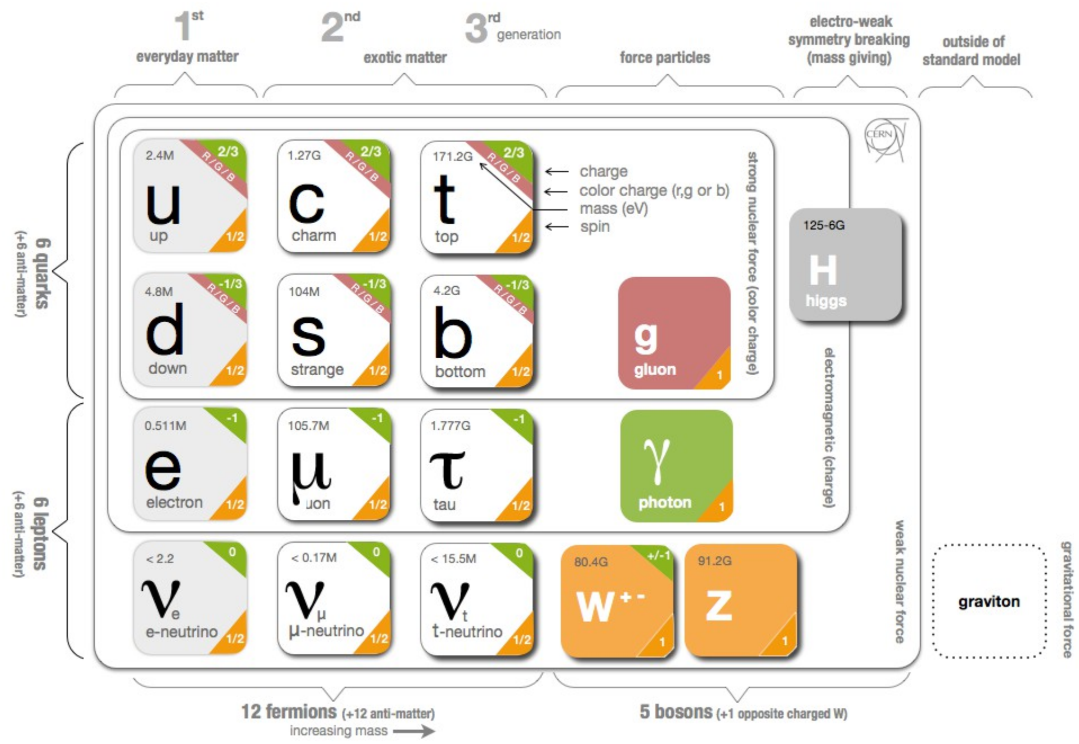
The Standard Model

Unifies three forces of nature (strong, electromagnetic, weak) under a single theory

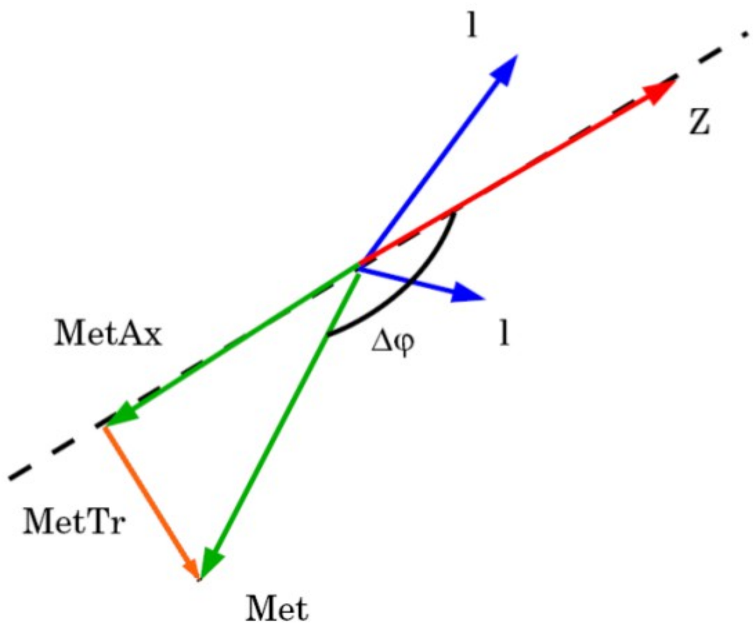
Transformations between particles are written in terms of gauge groups

The Standard Model is broken! Particle masses range between 0.0005 GeV to 175 GeV (and neutrinos are even lighter)

Introduce the Higgs mechanism to accomplish symmetry breaking



Axial Met



ZH, H → inv Background Estimation

ZZ, WZ

- The two largest backgrounds
- Estimate using simulation
  - No good control regions for a data driven estimate
  - Dominant source of systematics Improvements needed in the future to improve BR limit

WW, tt, Z → tt

- Use the em control region
- All exhibit BR(emu) = 2BR(ee) = 2BR(mm)
- Derive cut efficiencies in emu events
- Correct for lepton efficiencies using Z mass peak

W + jet

- Jet must fake a lepton
- Use "Matrix method"
- Measure jet fake probability relative to a loose lepton (jet enhanced) definition
- Extract number of real + fake events from identified tight + loose events using jet fake probability and lepton identification efficiency

Z + jet

- Use ABCD method
- Extrapolate number of events in the signal region by extrapolating the a signal cut efficiency from an uncorrelated sample
- Validate with single photon method