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ATLAS collaboration

- The data now
- 2013+

Royal Holloway
9th April 2010

How to make the Big Discovery

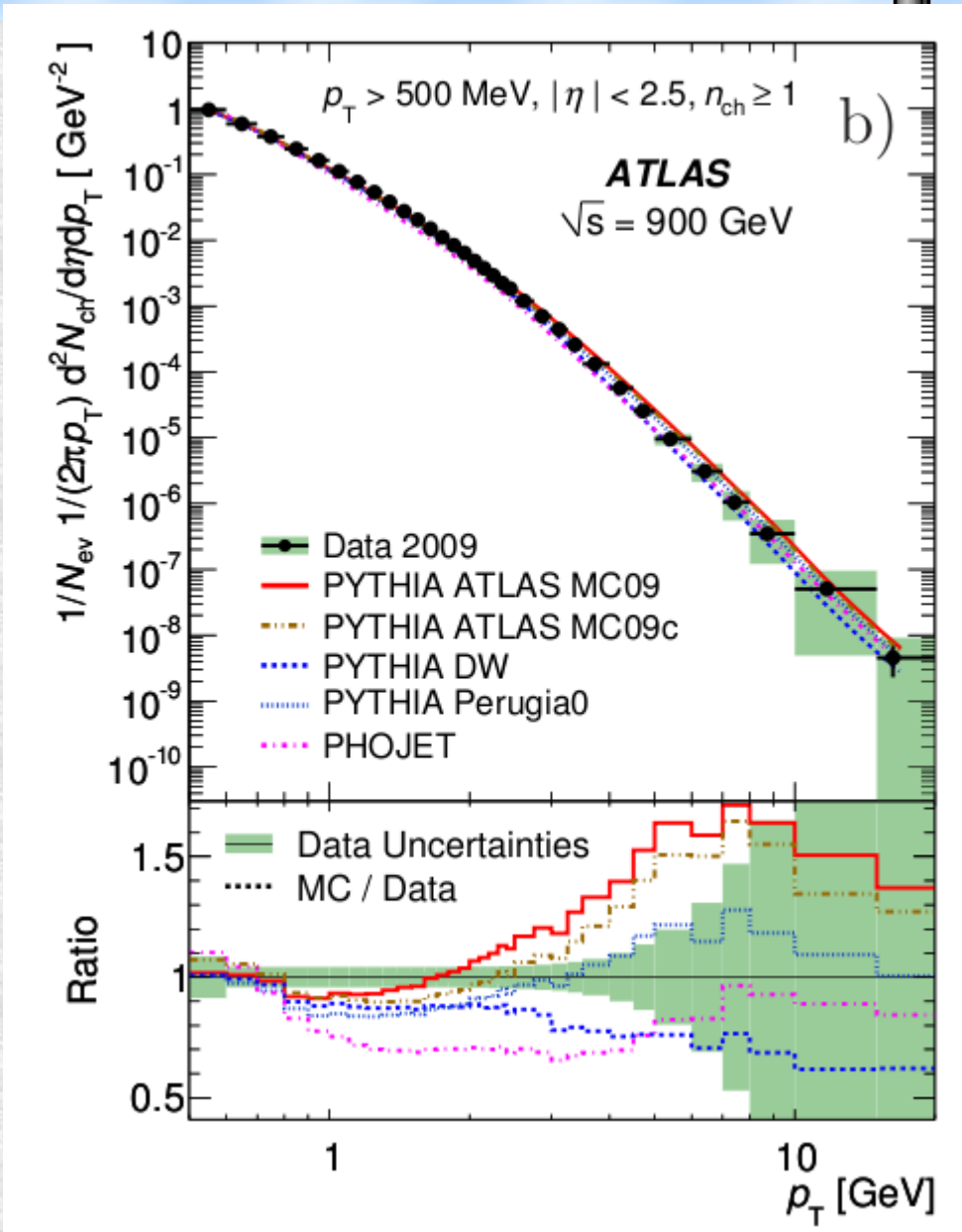
Outline

- Tease Frank
- The background
  - Where is this Higgs
- Higgs discovery for
  - (low mass) Standard Model Higgs
  - √s=14TeV
- ~~Omitted for 2010/11~~
  - ~~nMSSM~~
  - ~~H+~~
  - ~~Lepto-genic SUSY~~
  - ~~Any other theory with discovery potential~~
- ~~Omitted for 2013+~~
  - ~~More models than I can remember~~

Data

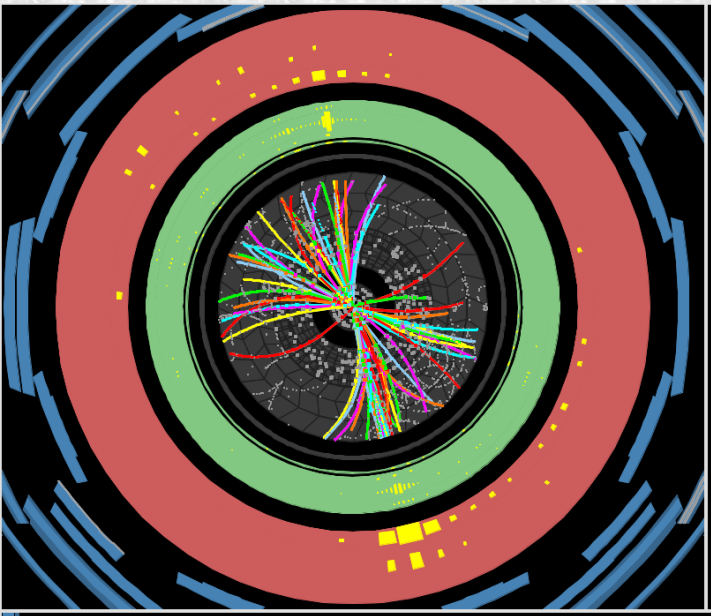
900GeV min bias

- The p_T spectrum around 4GeV looks an excellent place to distinguish models
- Where is the Sherpa curve for 7TeV?
- Data will be coming very soon.....



Data

Di-jet event

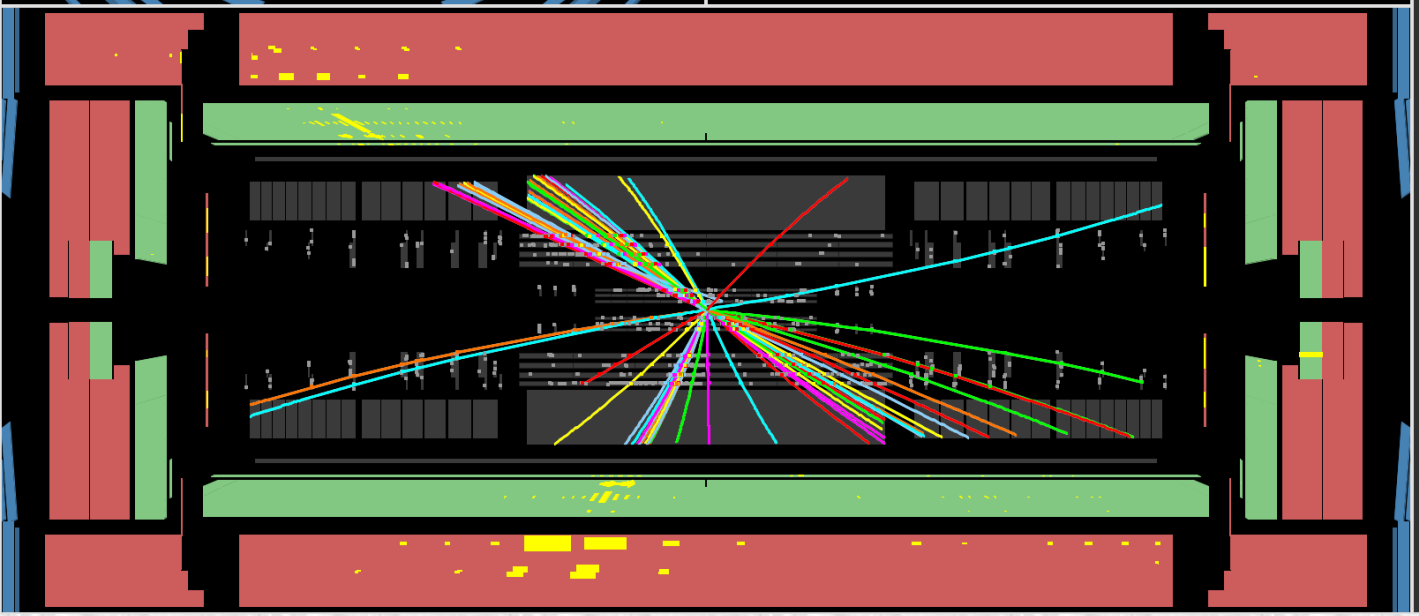


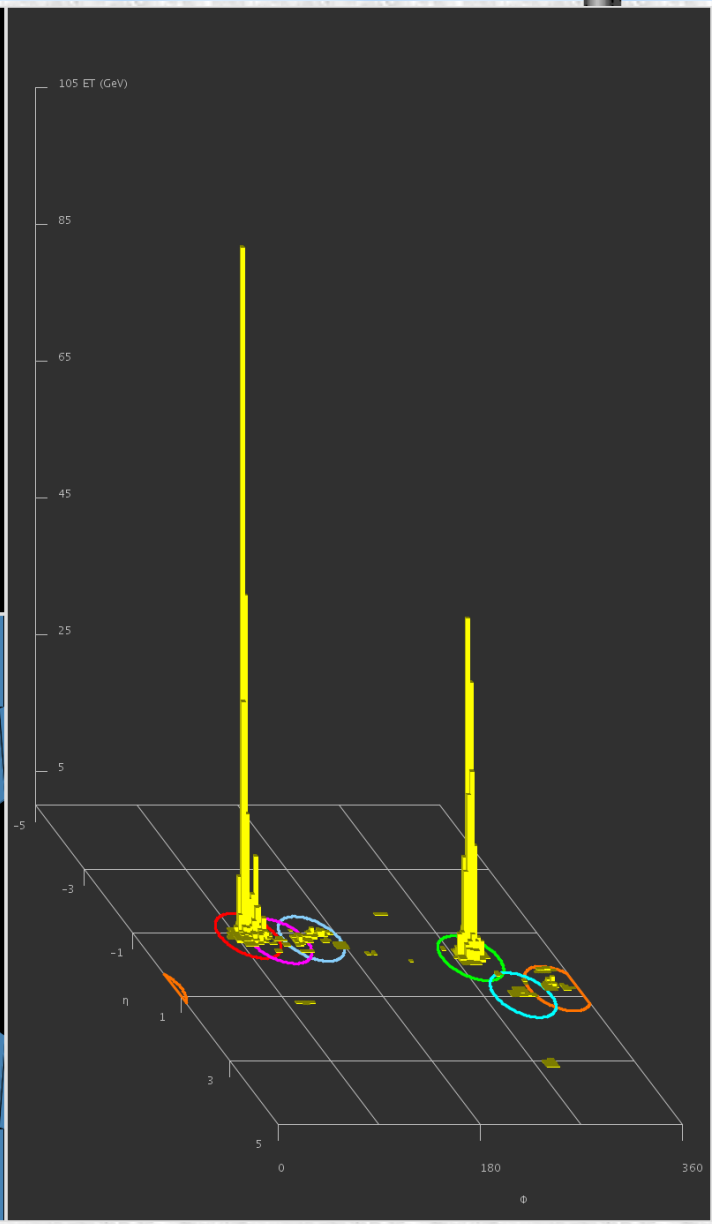
ATLAS EXPERIMENT

Run Number: 152166, Event Number: 810258

Date: 2010-03-30 14:56:29 CEST

Di-jet Event at 7 TeV



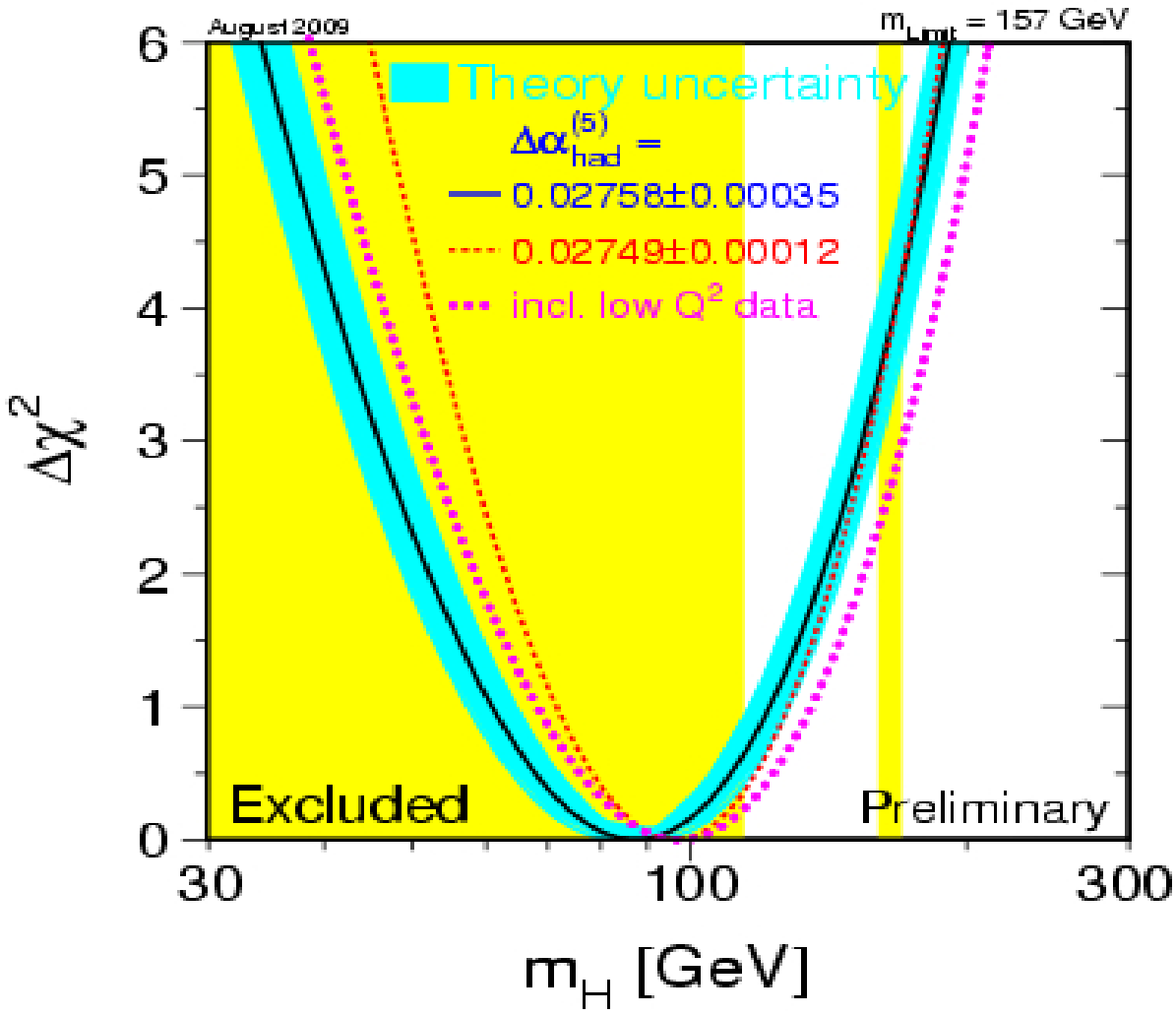


Why believe in a light Higgs?

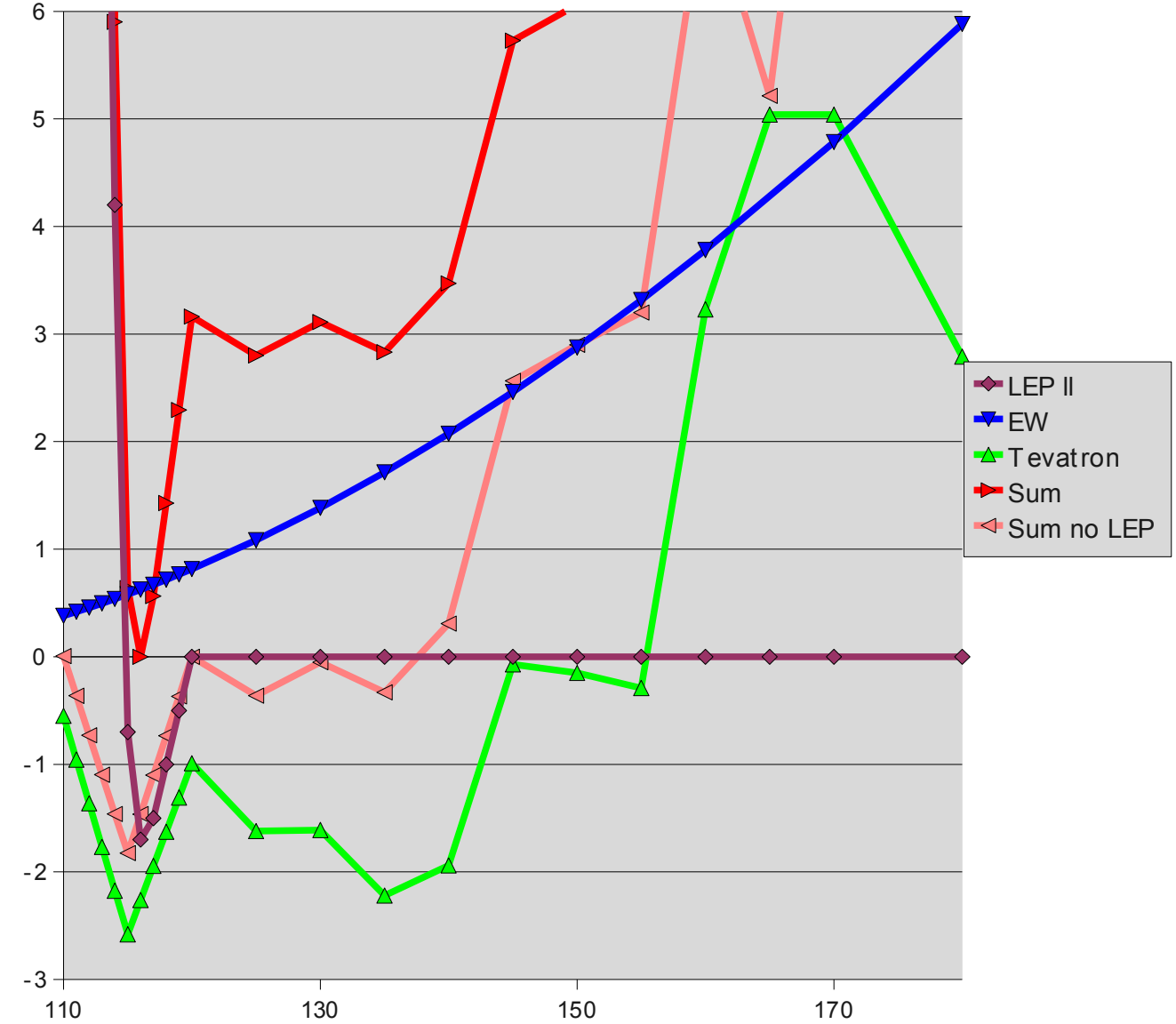
- Electroweak fit (Z properties, W and top mass) give at 95%:

M_H<157GeV/c²

M_H<186GeV/c²
(with search bound)*

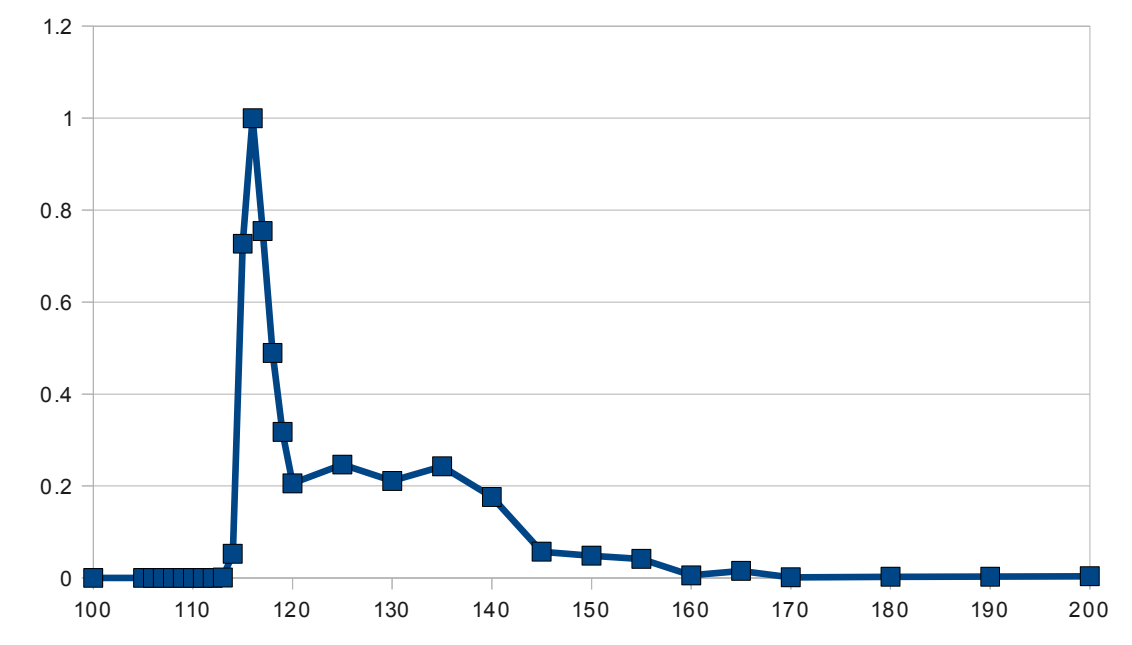


Likelihoods from EW/LEP/TeV



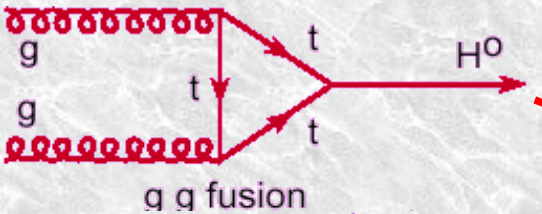
- Assumes SM Higgs is it
- Sum of likelihoods: crude but instructive
  - Higgs mass 115 to 120 (145)GeV
- Of course we all hope there is more to life..

Probability Density

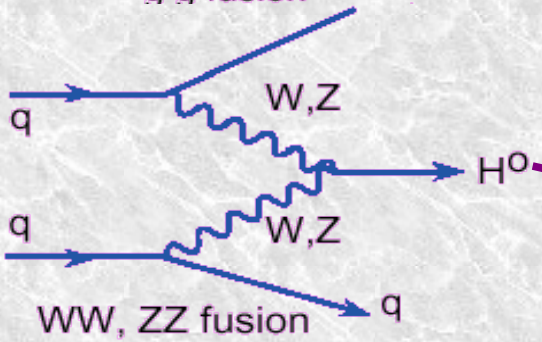


- Prior flat in m_H yields above curve
- H to WW will reach upper side of this
- ⇉Higgs will not be found without serious luminosity
  - Or a lepton collider

Higgs production

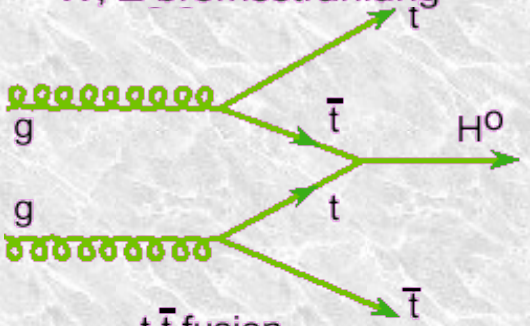


g g fusion

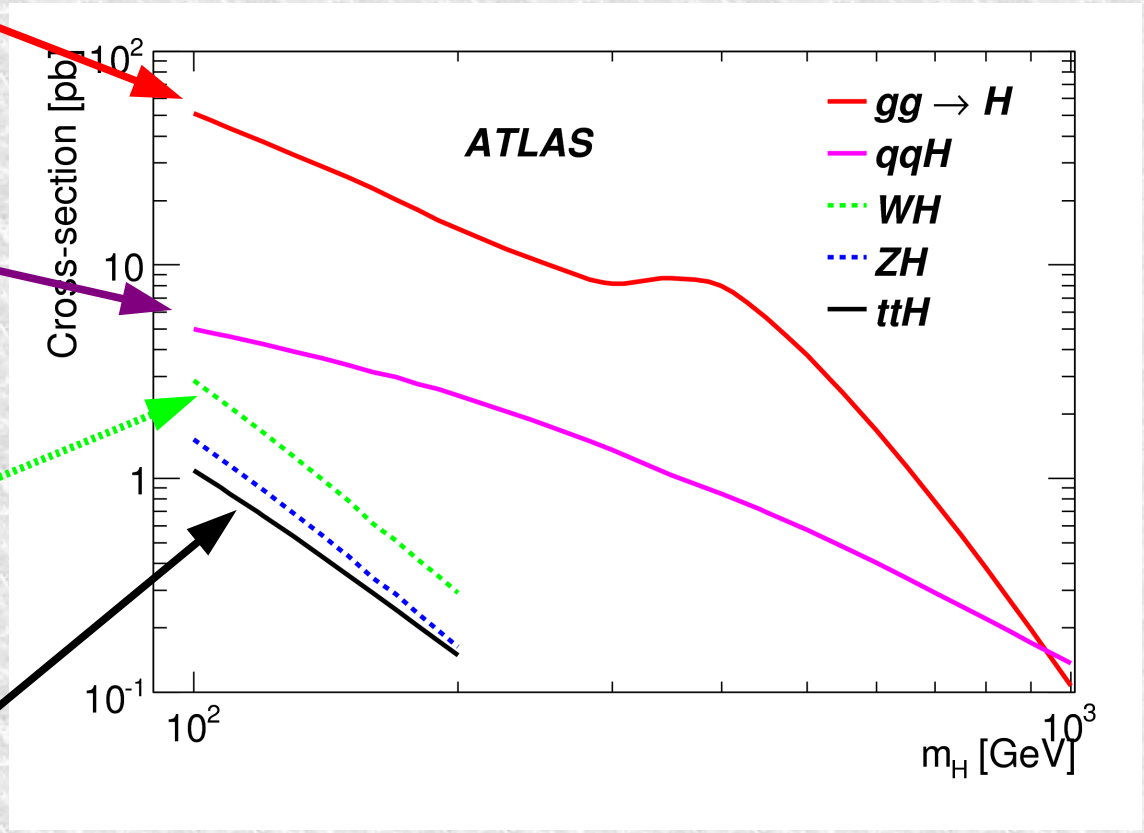


WW, ZZ fusion

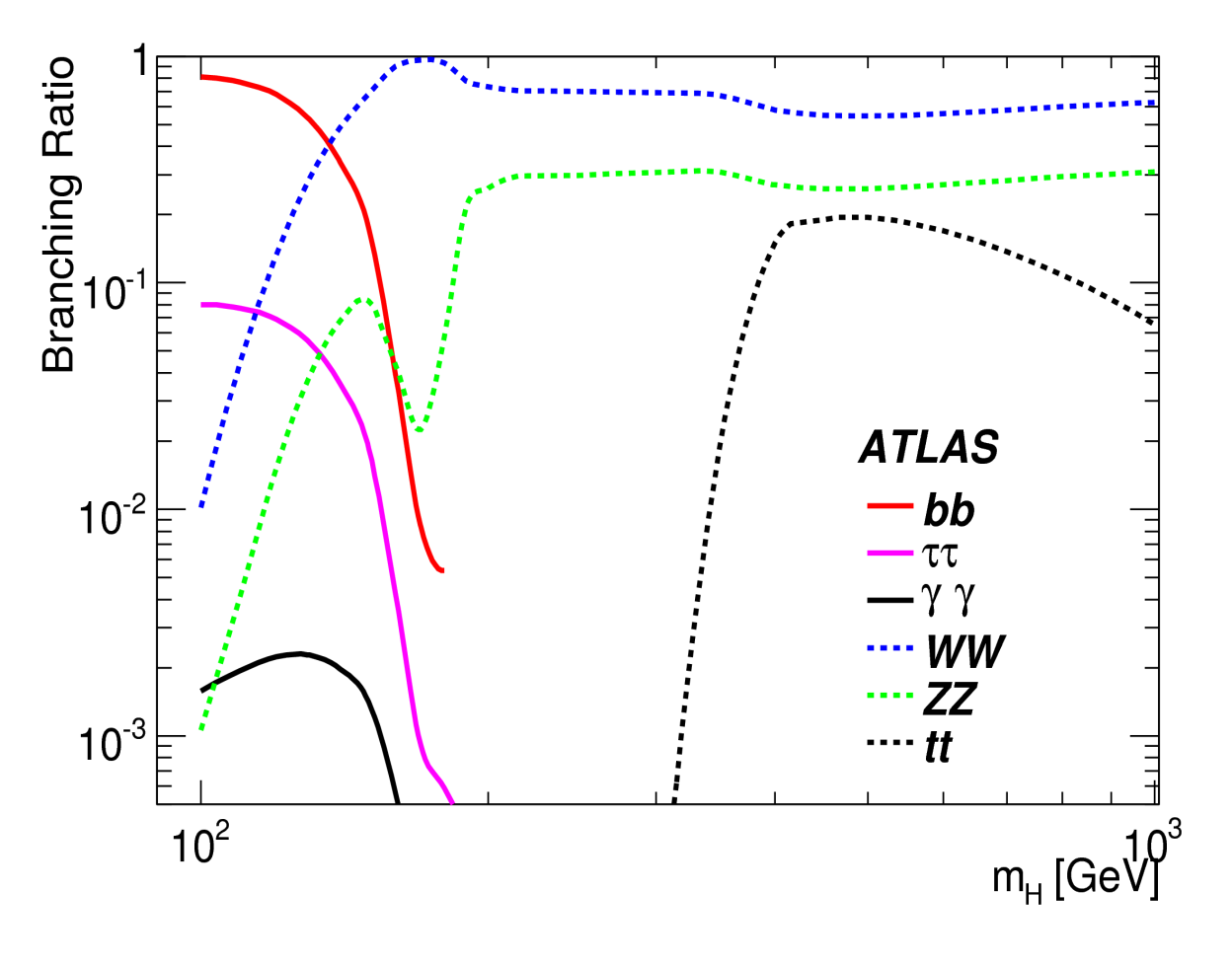
W, Z bremsstrahlung



t t̄ fusion



Higgs Decay



- Only decays considered for analysis are shown

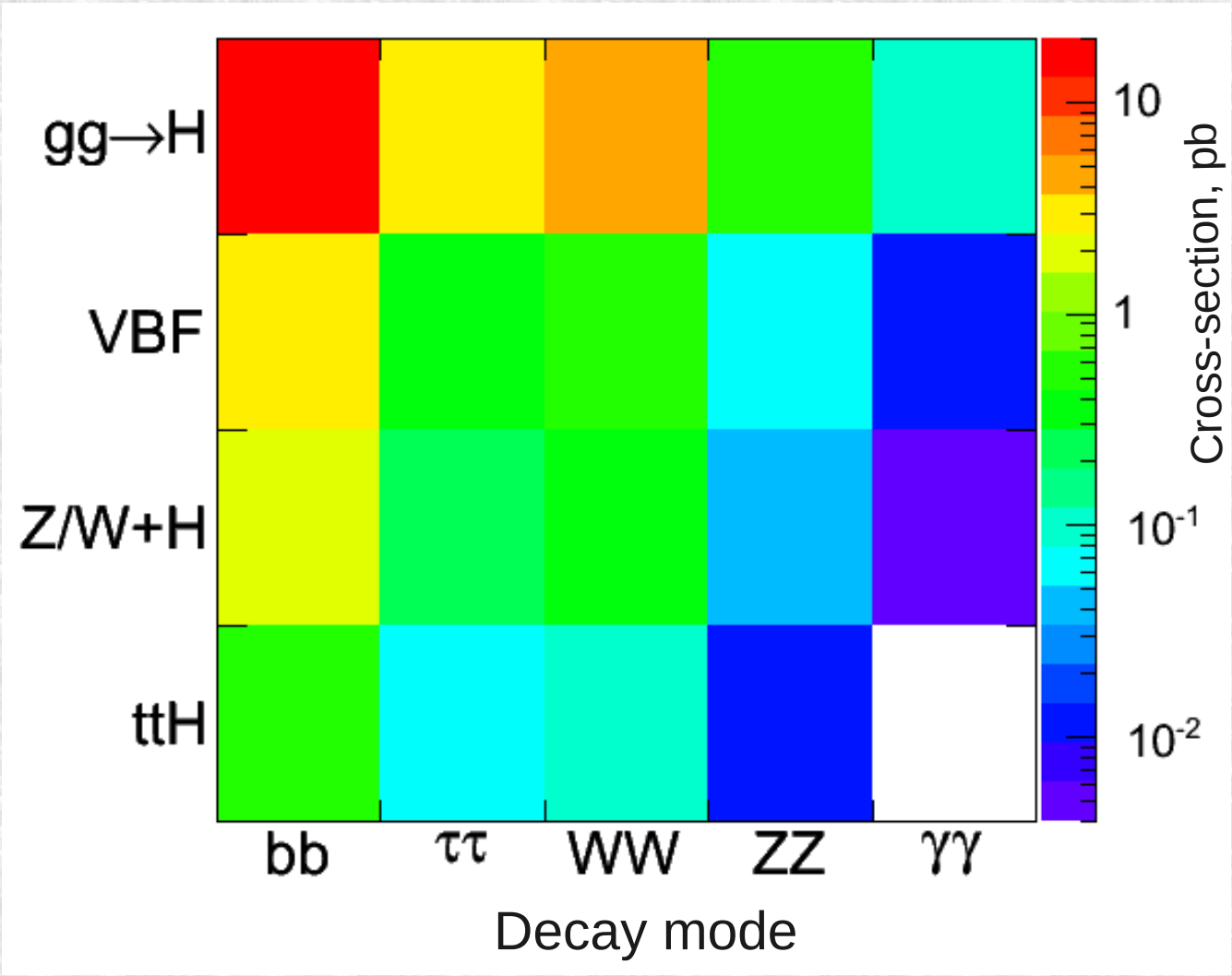
Observables

- LHC cannot observe the Higgs
- We can only look for e.g. jets + l^+ + l^- + E_T^{miss}
  - VBF H to WW
  - VBF H to ZZ to llvv
  - Countless backgrounds (tt, WW plus jets etc)
- Interference is a real issue for high mass
  - Small for SM Higgs ranges
  - Little studied
- Defining the process considered at NLO is not trivial
  - 'VBF' is not an easy concept to all orders

The Higgs Discovery

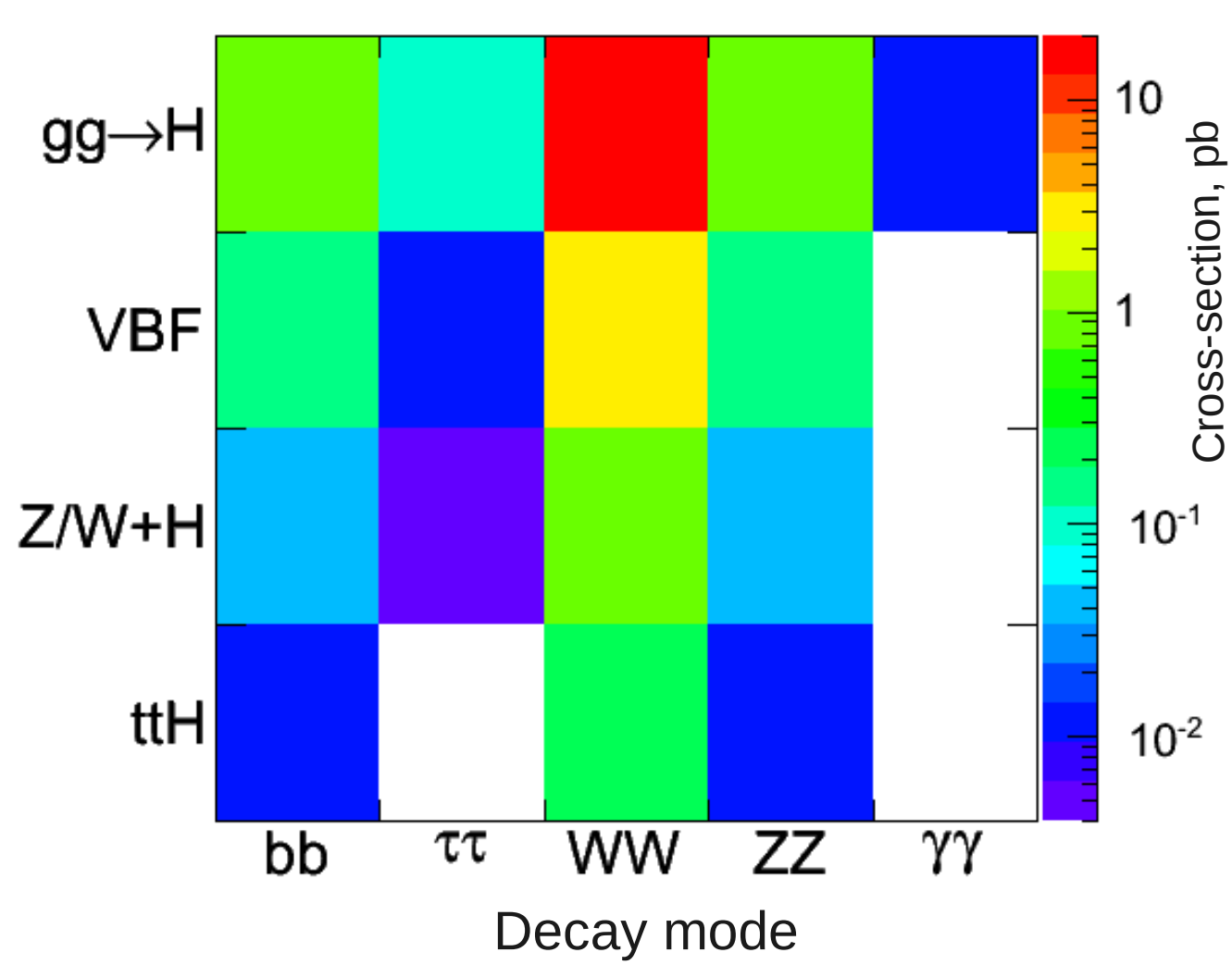
- If Higgs boson is heavy (>130GeV/c^2)
  - Significant decays to $WW^{(*)}$, $ZZ^{(*)}$
  - Clear leptonic decay modes
  - $ZZ \rightarrow 4l$ is frankly nicer, but $WW \rightarrow l\nu l\nu$ more common
  - Relative sensitivity depends upon m_H
  - The discovery is statistically promising
- As Higgs boson is light (<130GeV/c^2)
  - Use rare $H \rightarrow \gamma\gamma$
  - Or VBF $H \rightarrow \tau\tau$
  - Associated Higgs decays to $b\bar{b}$
  - WW and ZZ search way off-shell

Higgs rates: m_H=120GeV



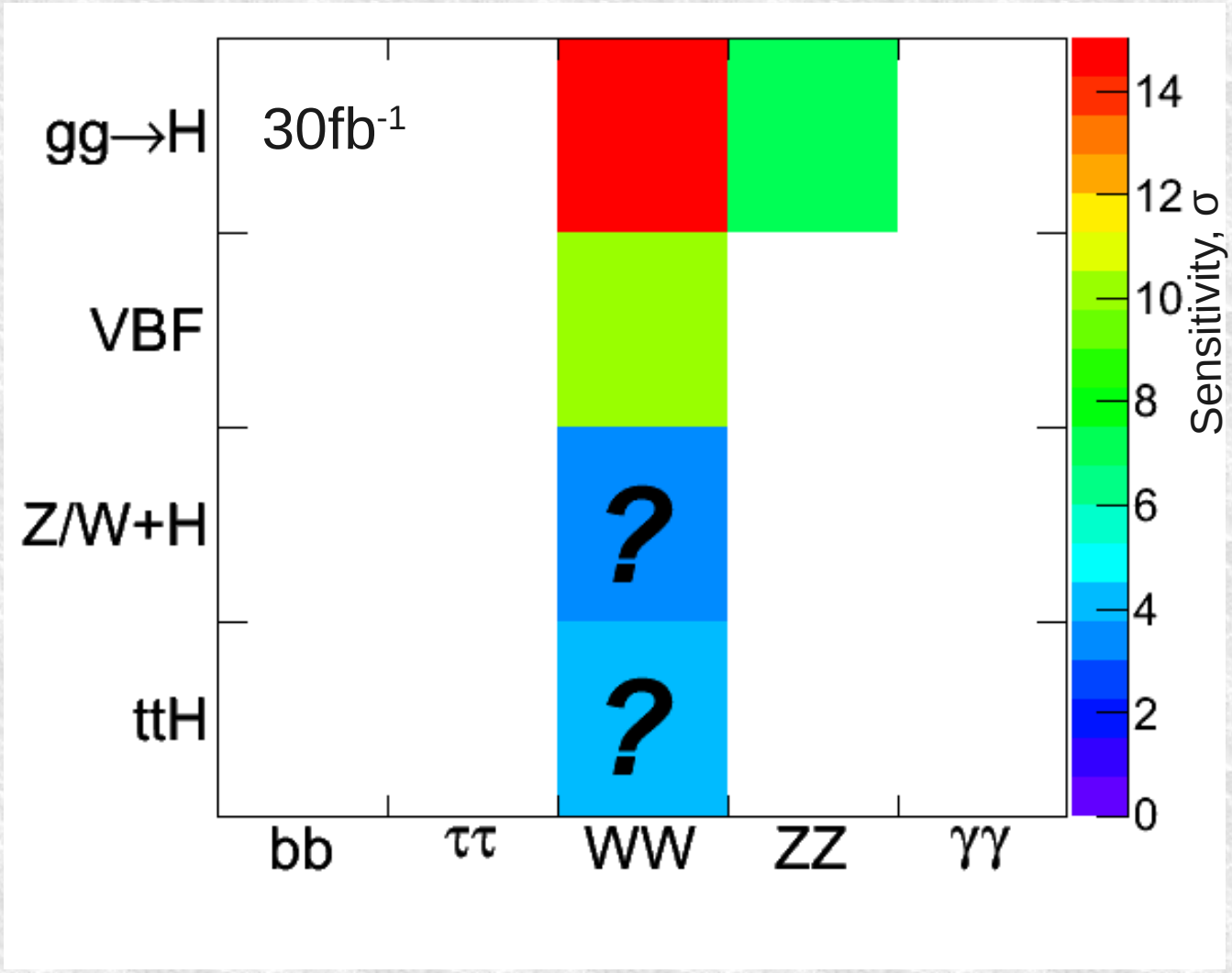
- Cross-section times branching ratio in channels examined

Higgs rates: m_H=160GeV

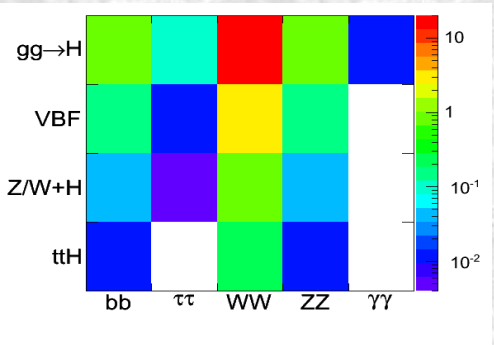


- Cross-section times branching ratio in channels examined
  - WW dominates
  - ZZ similar
  - Others fall

Higgs sensitivity: m_H=160GeV

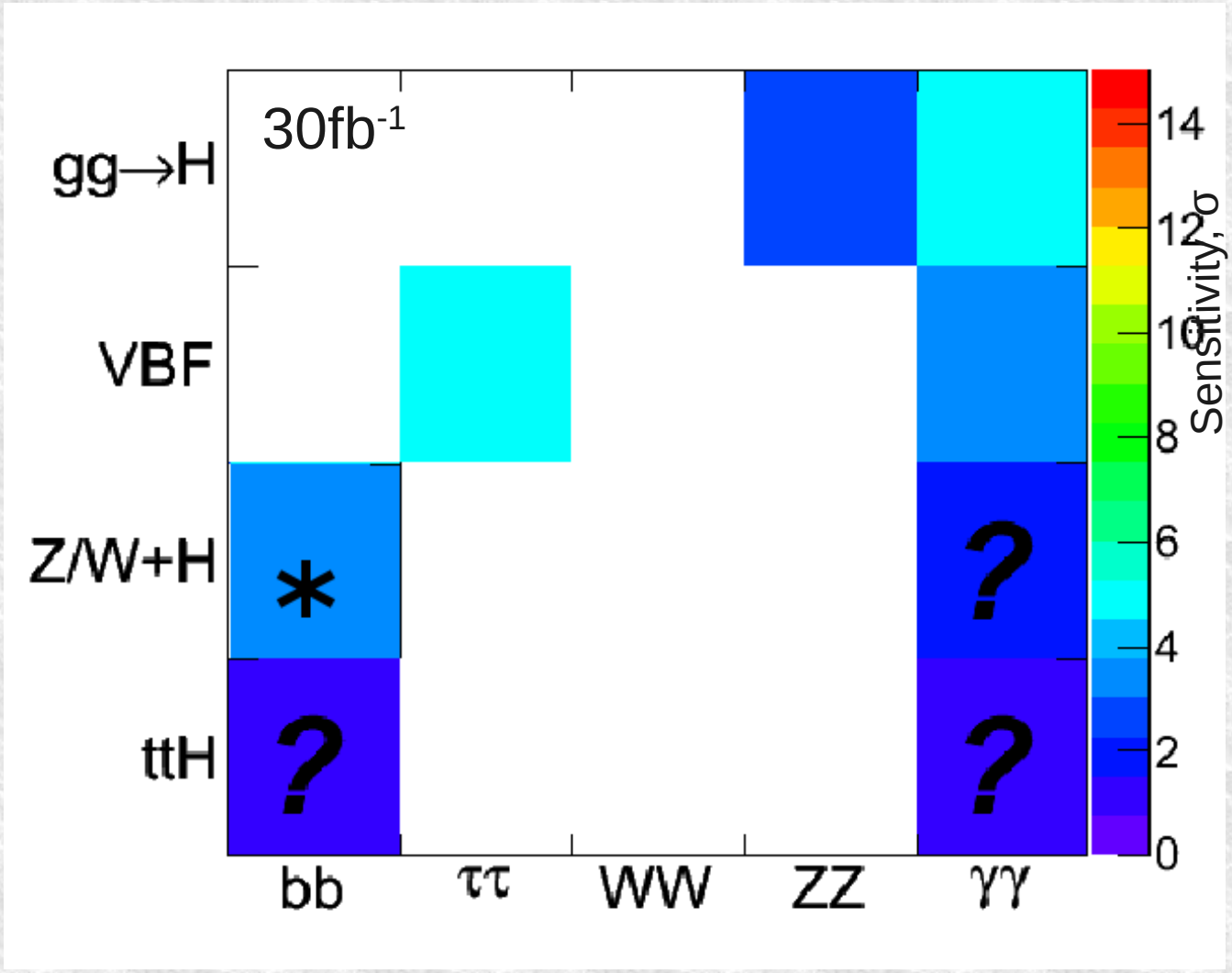


- '?': my estimate.
- ZZ VBF surely possible too
- Cross-sections mimic sensitivity

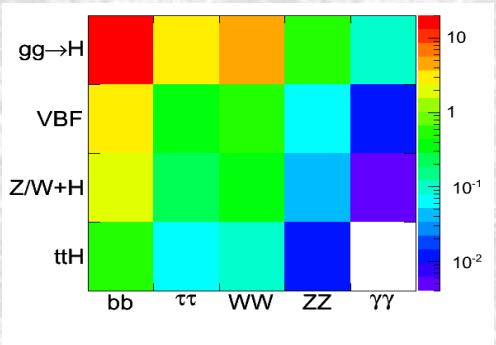


From CERN-OPEN-2008-020

Higgs sensitivity: m_H=120GeV



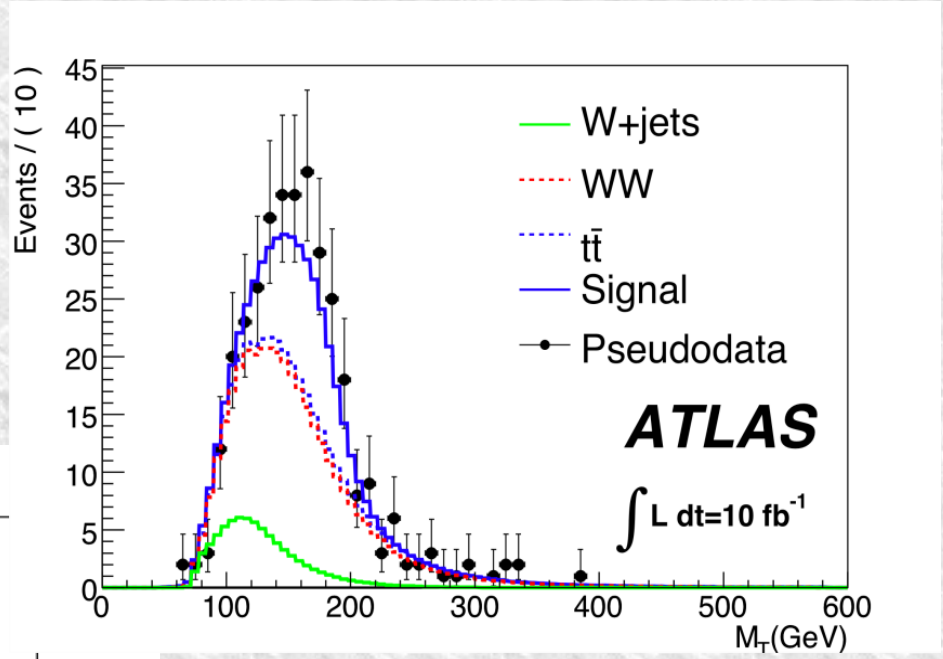
- '?': my estimate.
- ττ VBF isolated
- Several **weak** channels
- **Several** weak chanels

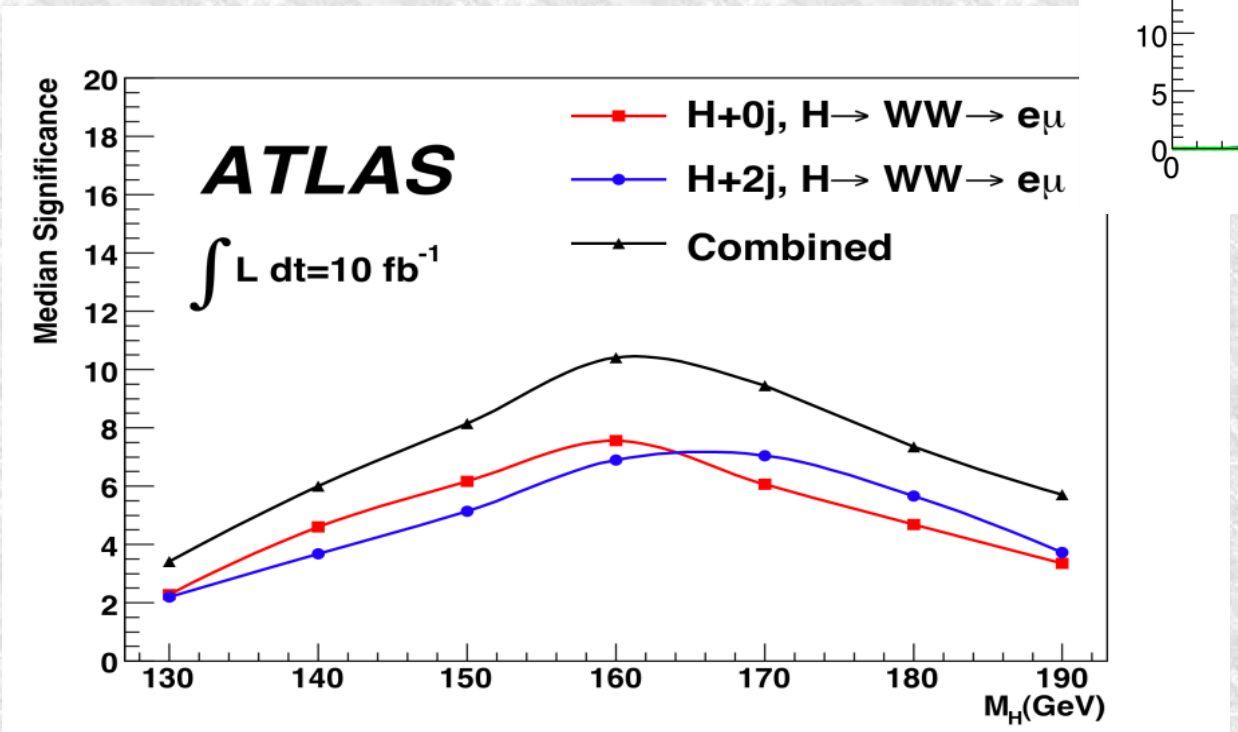


From CERN-OPEN-2008-020 (* later)

H to WW(*)

- High rate esp. near 160GeV
- I had assumed Bruce would discuss this.



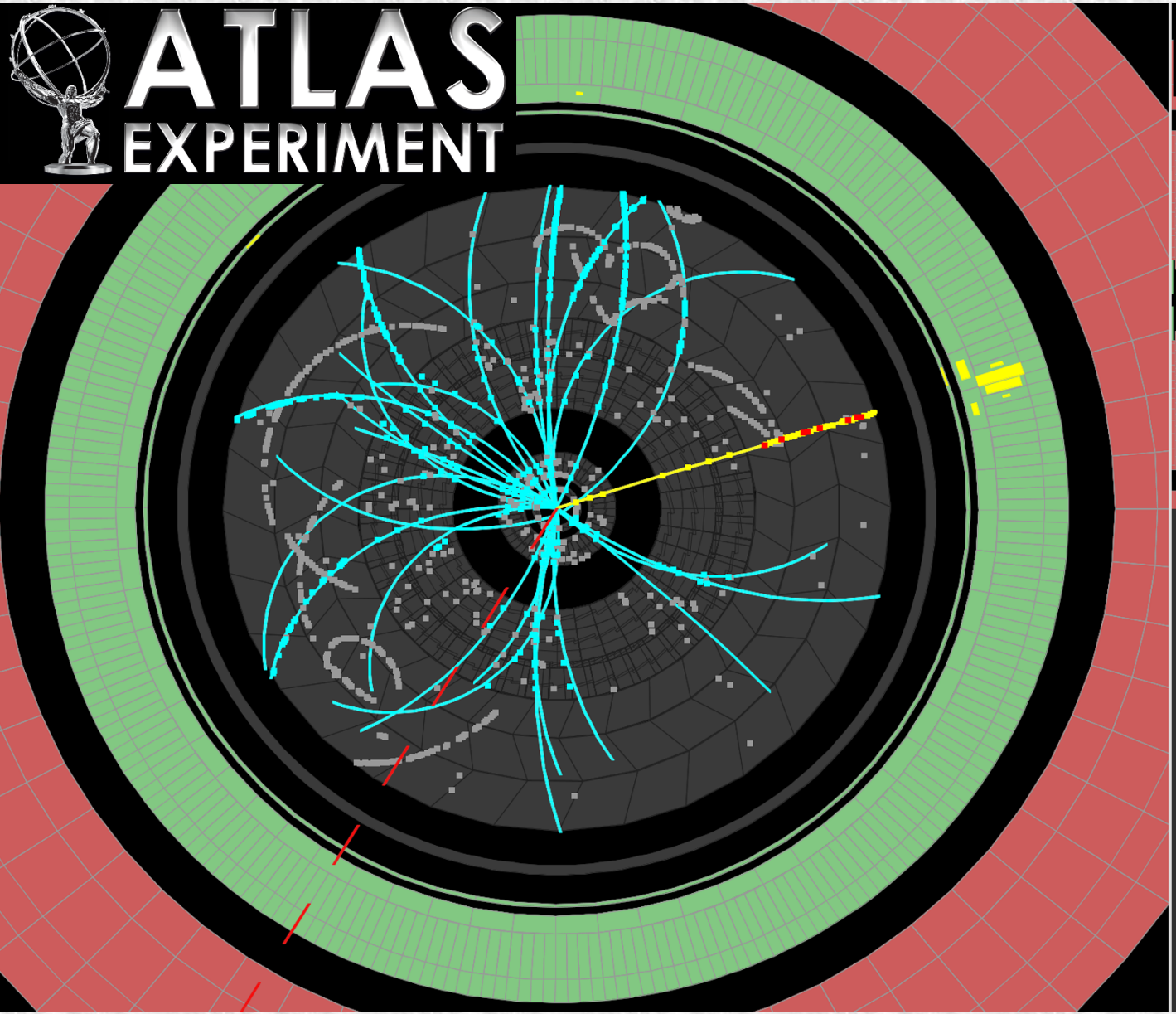


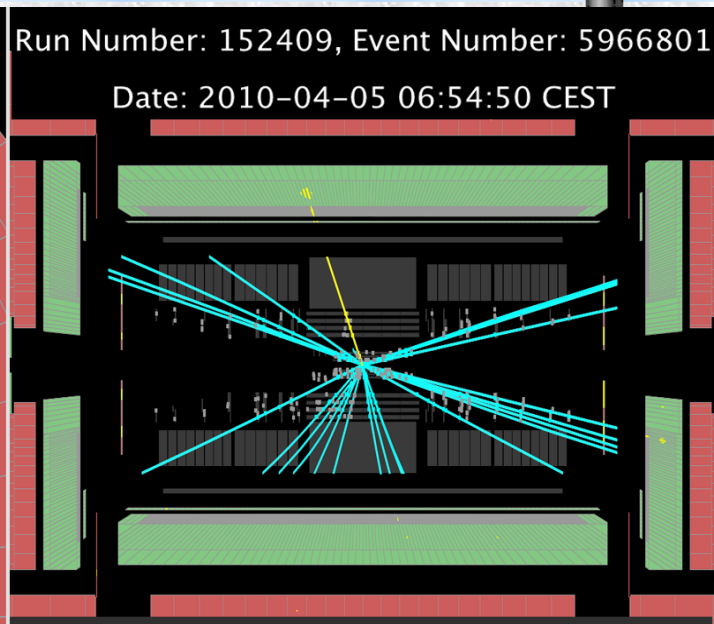
Controls

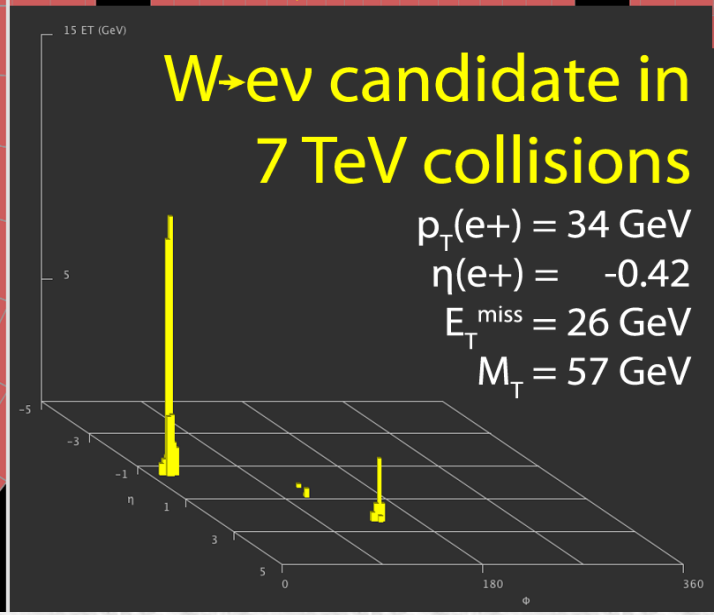
- WW bkd from ll angle
- W+jets from fake rate study

Data

e-ν candidate event

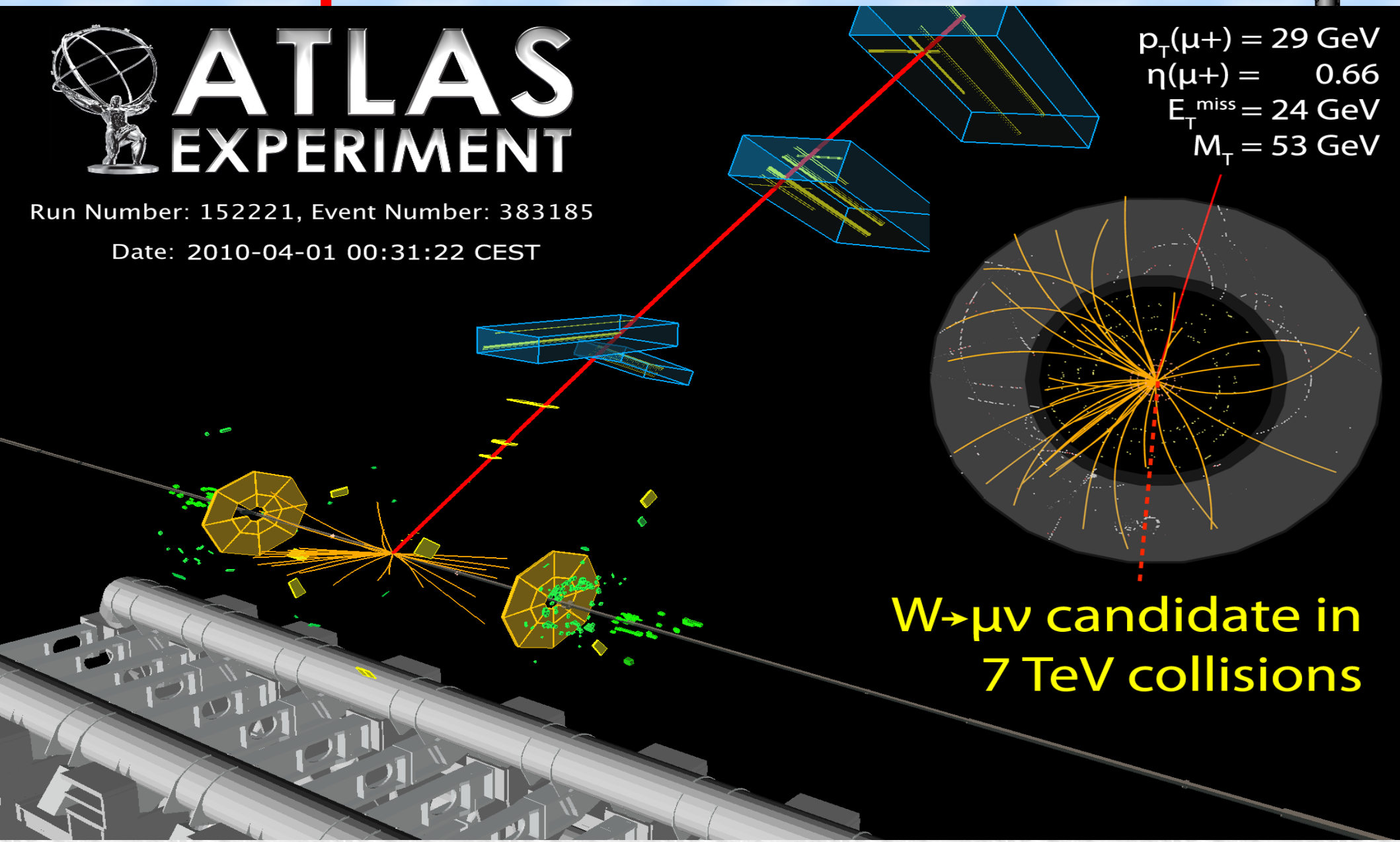




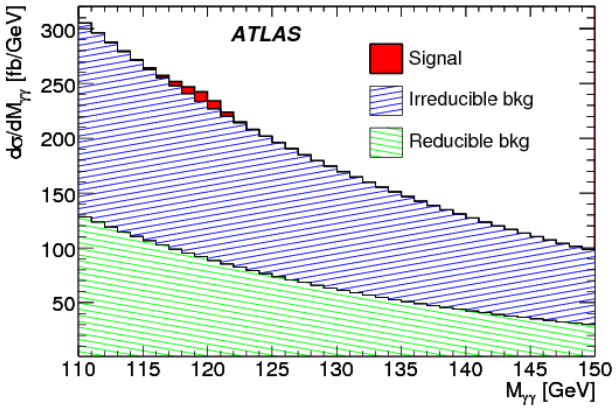


Data

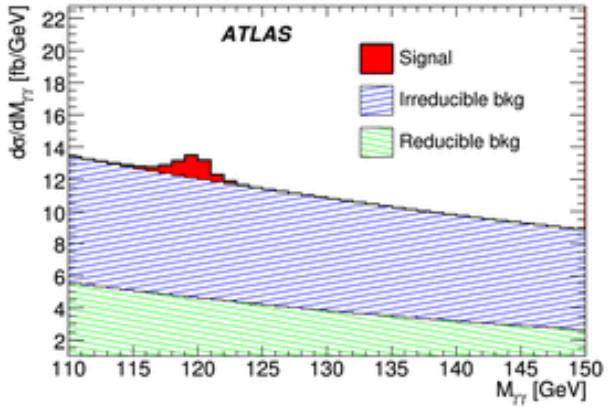
μ-ν candidate event



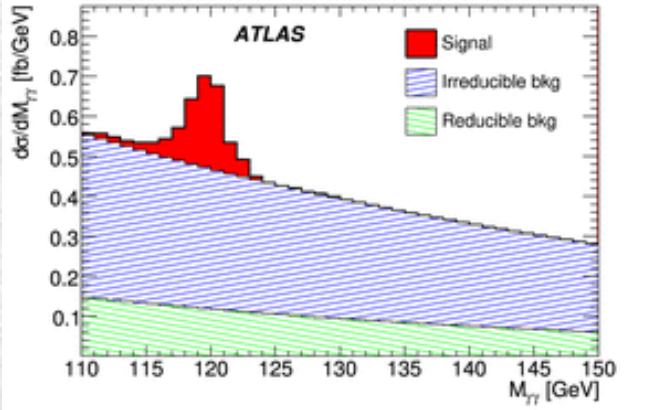
Higgs to γγ



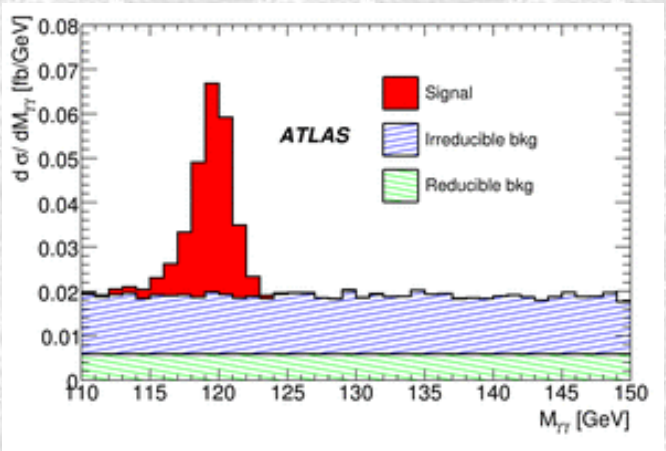
Inclusive analysis (gluon fusion)



Higgs plus 1 jet analysis (gluon fusion + VBF)

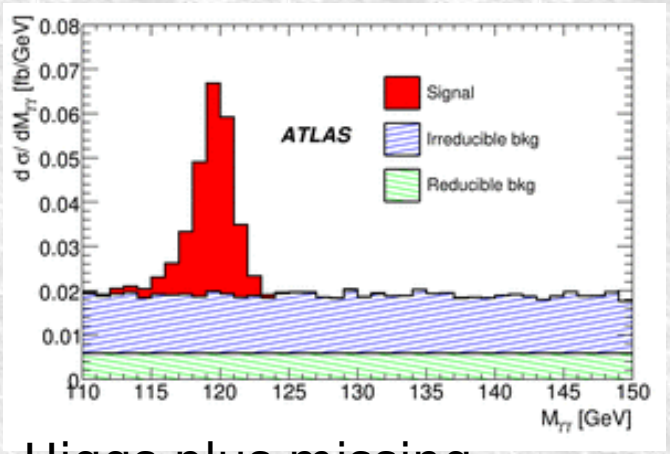


Higgs plus 2 jet analysis (80% VBF, 20% gluon)



Higgs plus 1 lepton. (ttH + WH)

- Sensitive to all production processes!
- Exploit s/b if reliable models

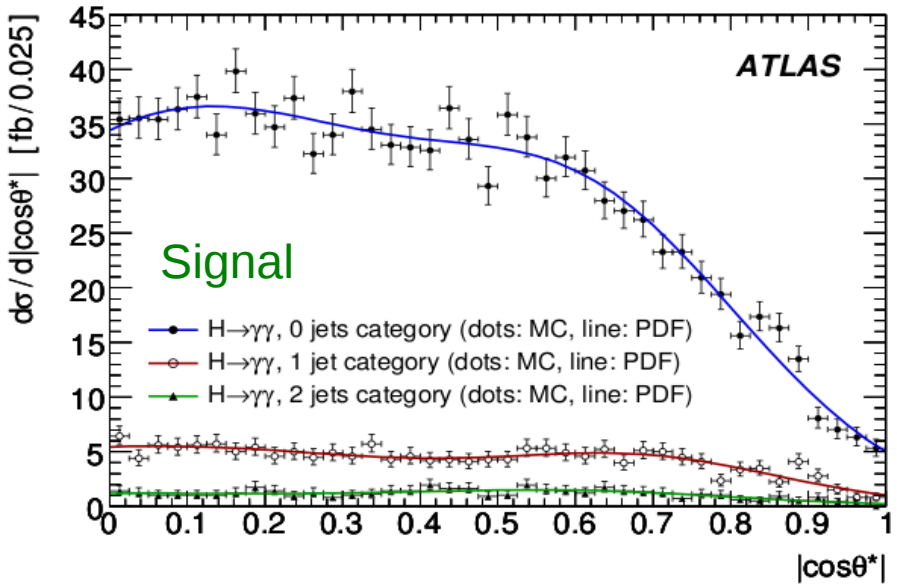


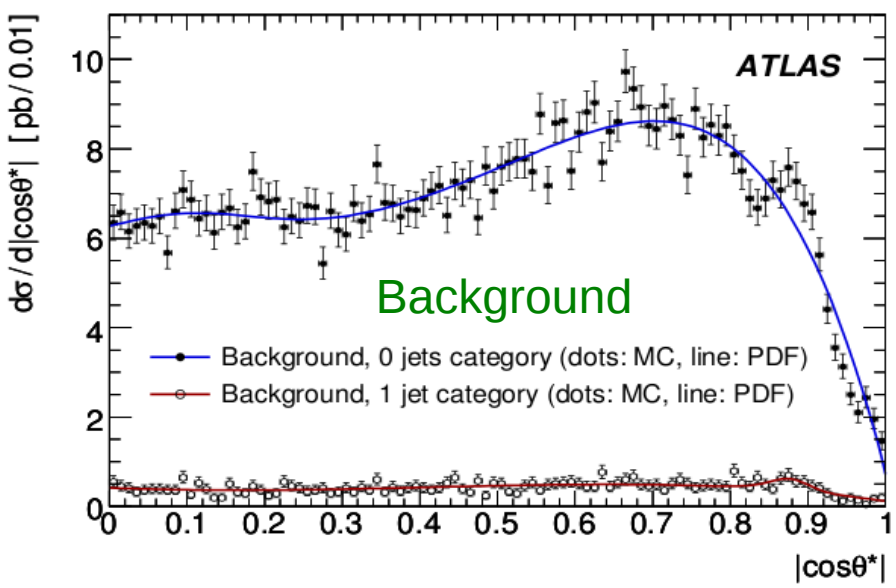
Higgs plus missing energy (ZH+WH)

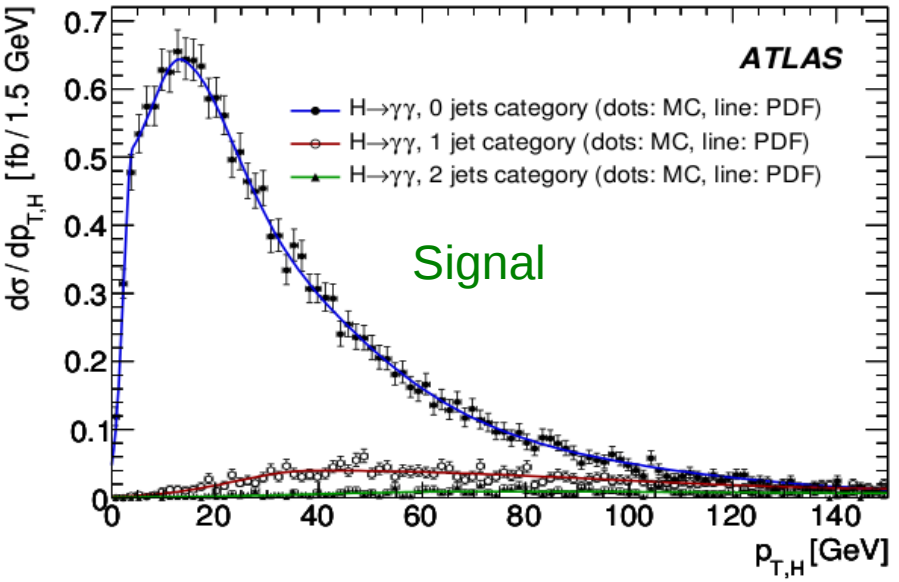
Higgs to γγ

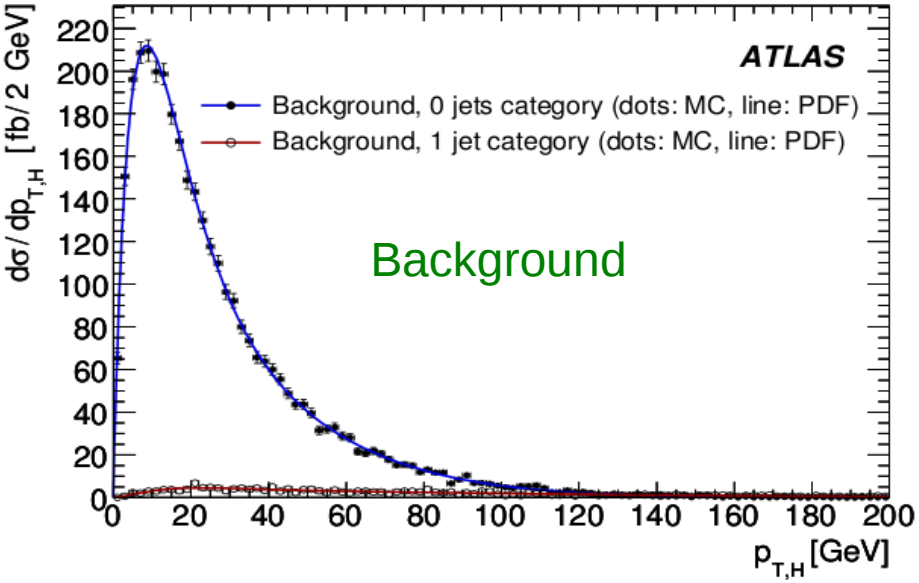
- Large and slowly-evolving backgrounds
- Good mass resolution
- Can extract background shape from data
  - As outlined by Glen Cowan: add parameters
    - But limit dσ/dM so peak is not explained away
  - Even in multi-dimensions
- Signal description required to good accuracy
  - p_T, η, $\cos\theta^*$ dependence
  - Variation with jet characteristics
    - Such as Jet veto survival probability.
  - Mass resolution – mostly experimental problem
    - Primary vertex charged multiplicity for 0 jets?
- Want predictions allowing coupling variation

Kinematic Distributions



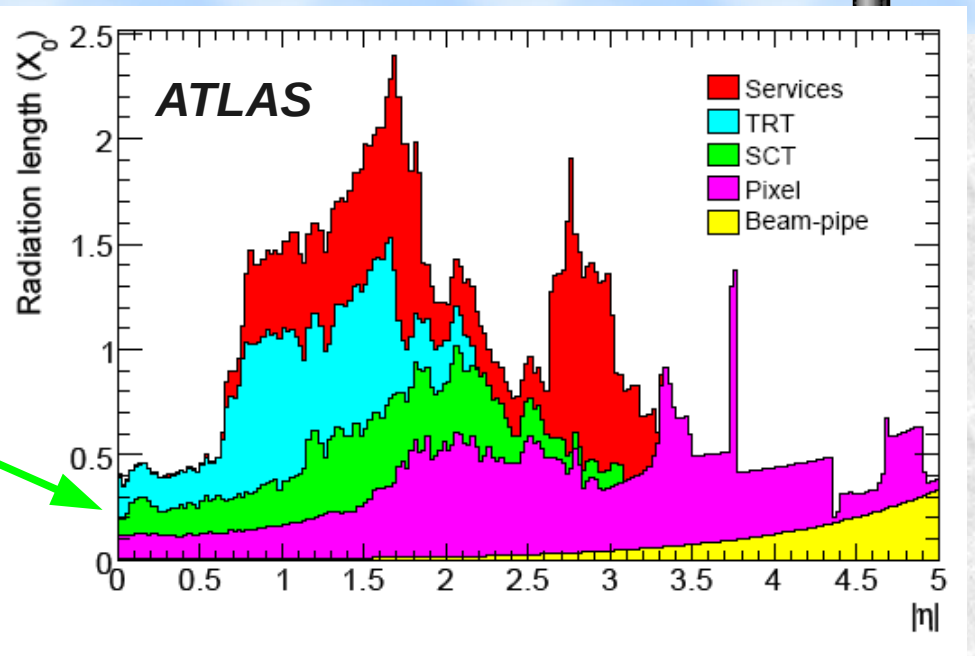


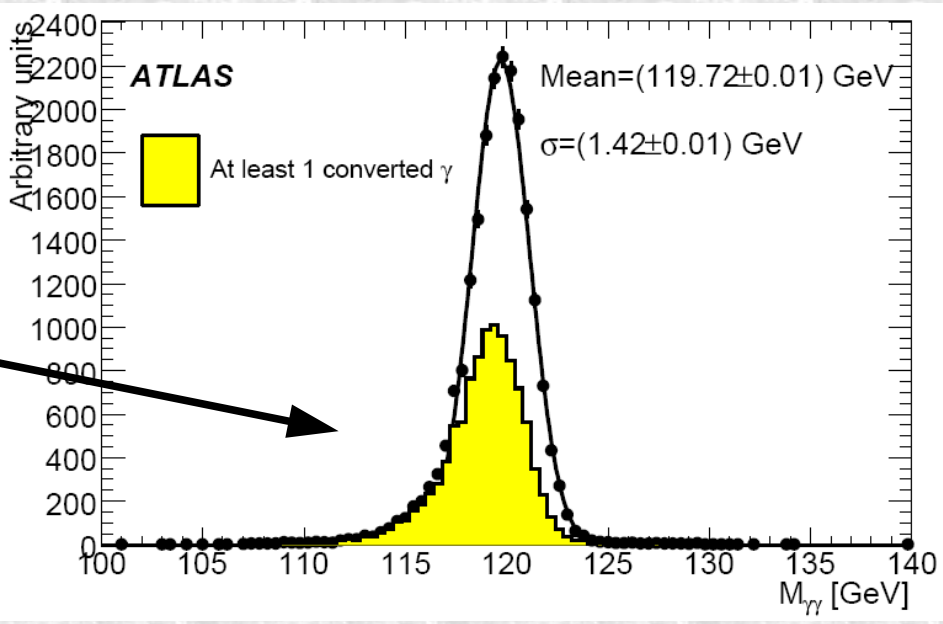




Material Distributions

- Material distribution makes electron/photon energy scale harder
  - CDF 0.2 X_0 in silicon
  - D0 4X_0 before calorimeter
- Needs to be understood for photon reconstruction
- Electron/photon scale difference from MC
- Effect on 120GeV H→γγ

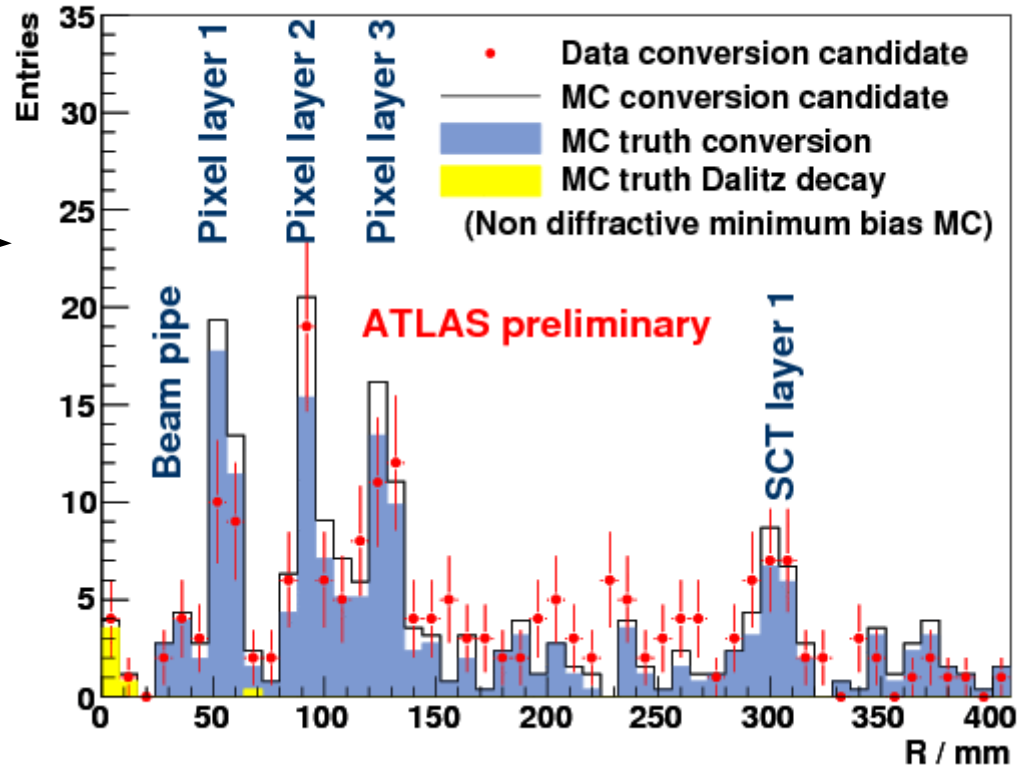


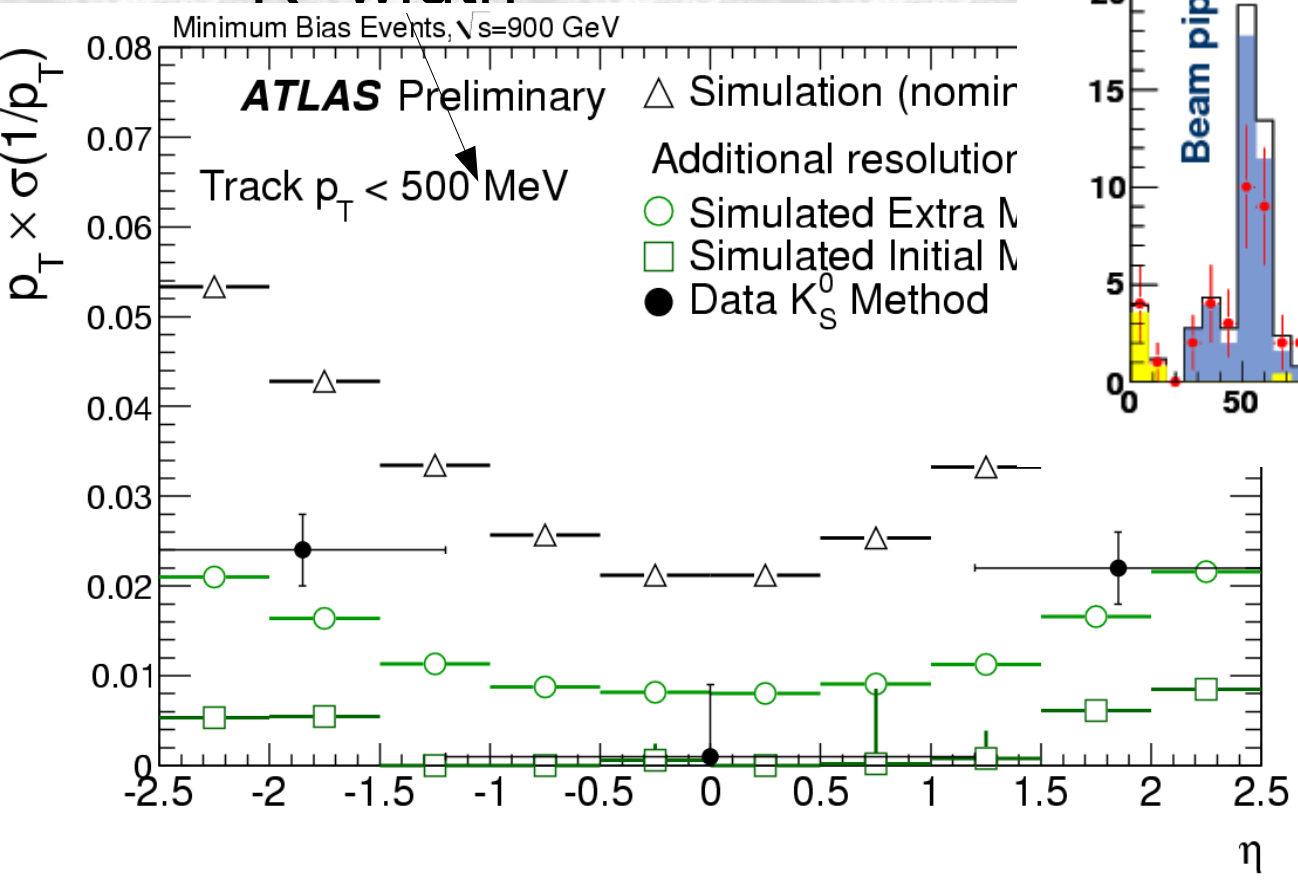


Data

In situ material testing

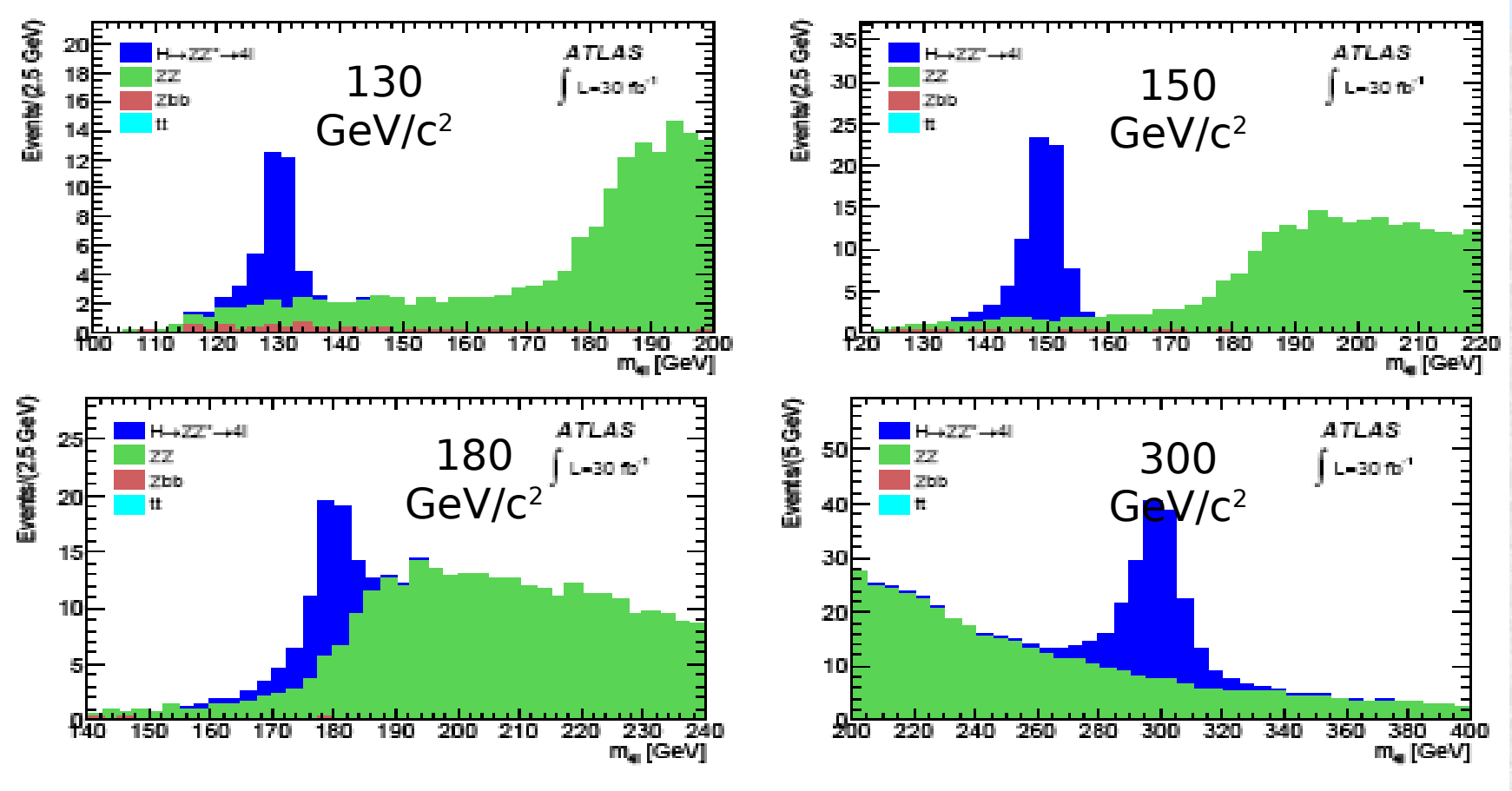
- 6 different methods used so far, e.g.
  - γ conversions
  - K^0 width





- Some extra K^0 width at high eta
- Otherwise <few % X_0 missing

$H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$

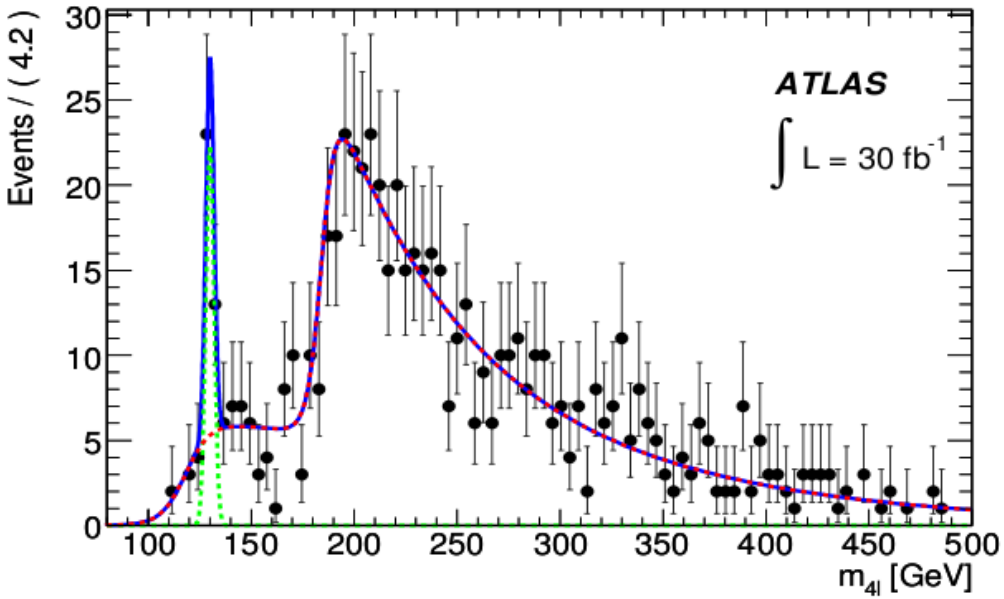


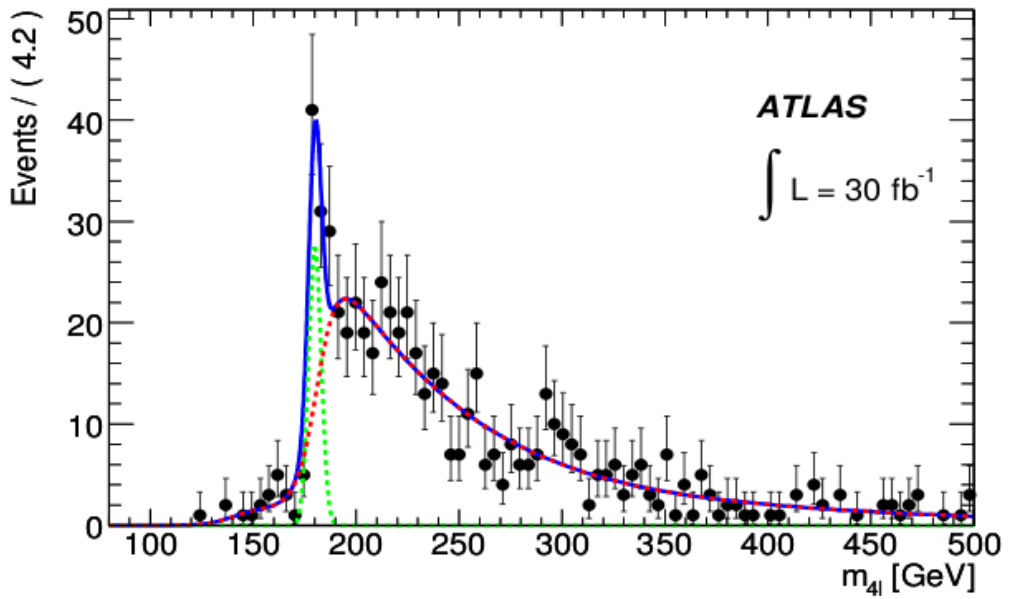
- ZZ dominates 200-400GeV
- Dominant backgrounds
  - ZZ – well predicted
  - Zbb – contributes at low mass

$H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$

- Narrow mass peaks like gg
  - Same questions about signal p_T, η, jet structure
- Z decays allow more spin analysis
  - Matrix element style analysis possible?
    - But how do we control backgrounds here?
    - Impact of detector systematics non-trivial
- Public analysis does not separate VBF
  - Not needed(?) for discovery, but useful later
- Low mass Higgs strains channel
  - lepton ID at low p_T
  - Heavy flavour backgrounds
    - Need $Zb\bar{b}$ background: data plus theory?

Fitting the mass spectrum





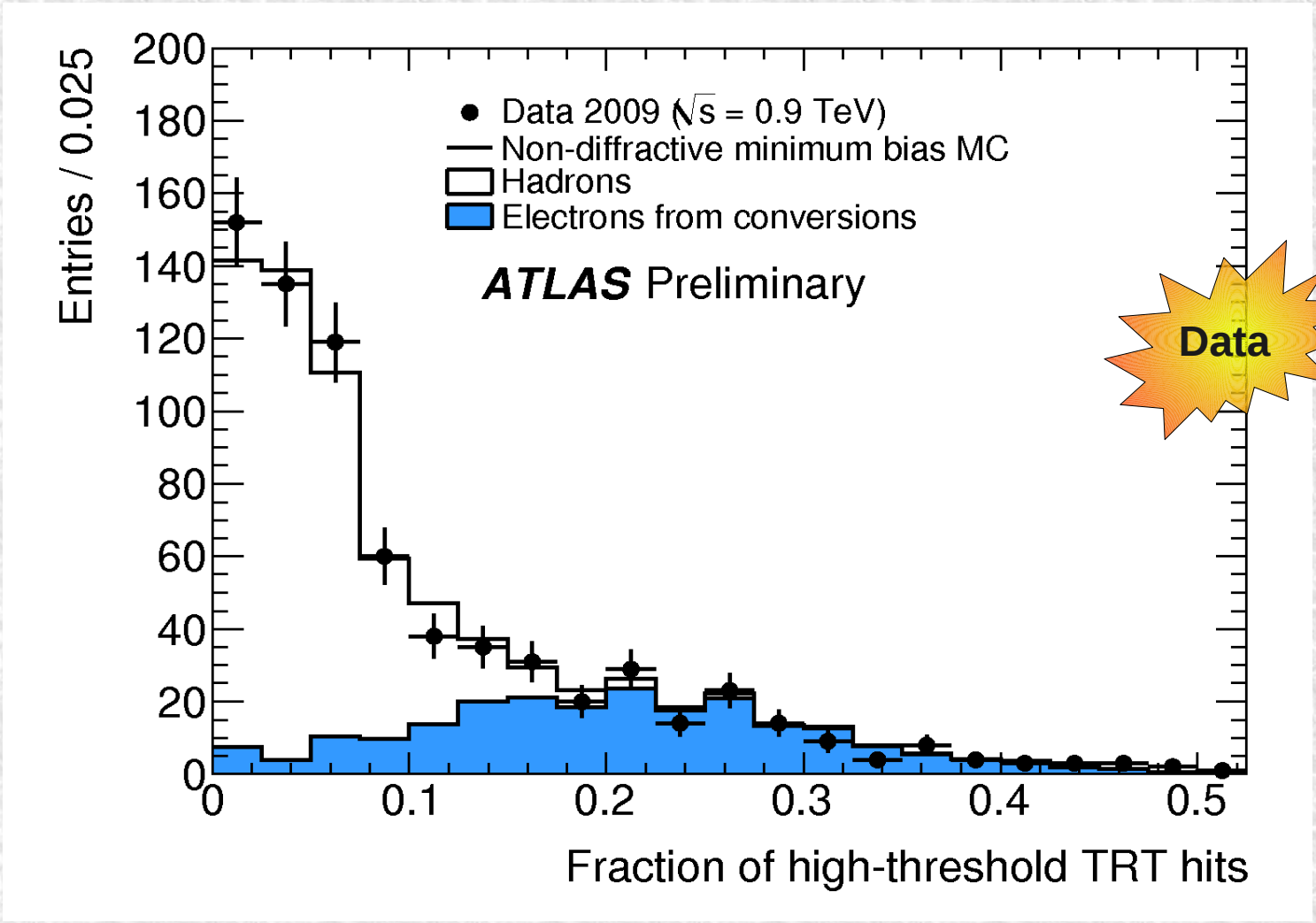
$$f(m_{ZZ}) = \frac{p0}{(1+e^{\frac{p6-m_{ZZ}}{p7}})(1+e^{\frac{m_{ZZ}-p8}{p9}})} + \frac{p1}{(1+e^{\frac{p2-m_{ZZ}}{p3}})(1+e^{\frac{p4-m_{ZZ}}{p5}})}$$

- Two fermi functions for background
  - Note the way the way the first changes with selection
  - Is this a good approach?

Electron/jet rejection

- See ATLAS Conf 2010-005
  https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2010-005/
- Tight electrons eff. 71.5%
- Jet rejection: $1.38 \pm 0.06 \times 10^5$
- Background surviving:
  - 29.6% e from Z, W
  - 44.8% b, c
  - 11.5% photon conversions, π^0 Dalitz decays
  - 14.1% hadrons

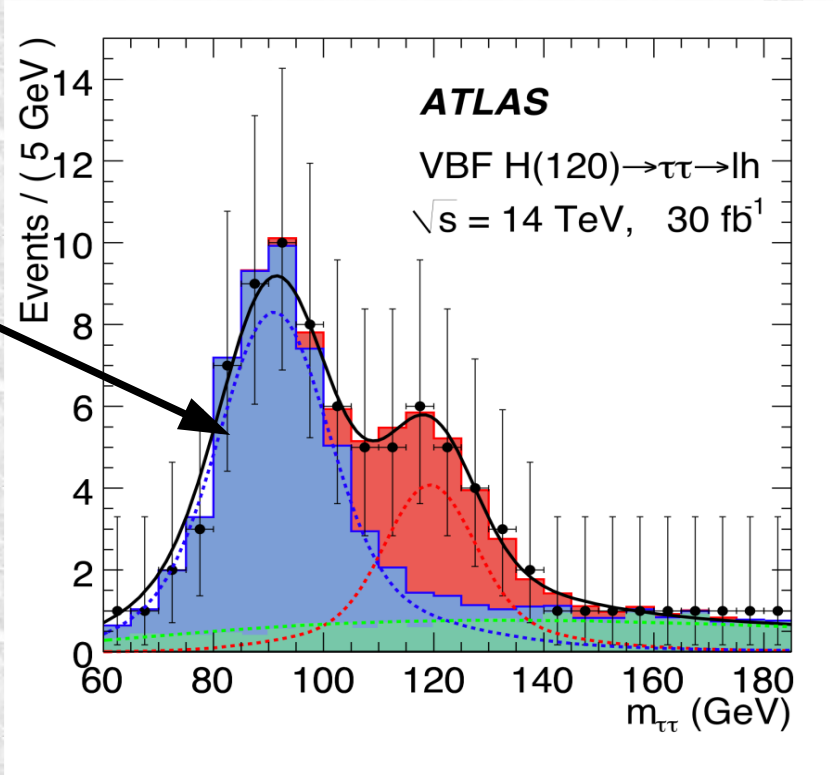
TRT electron ID

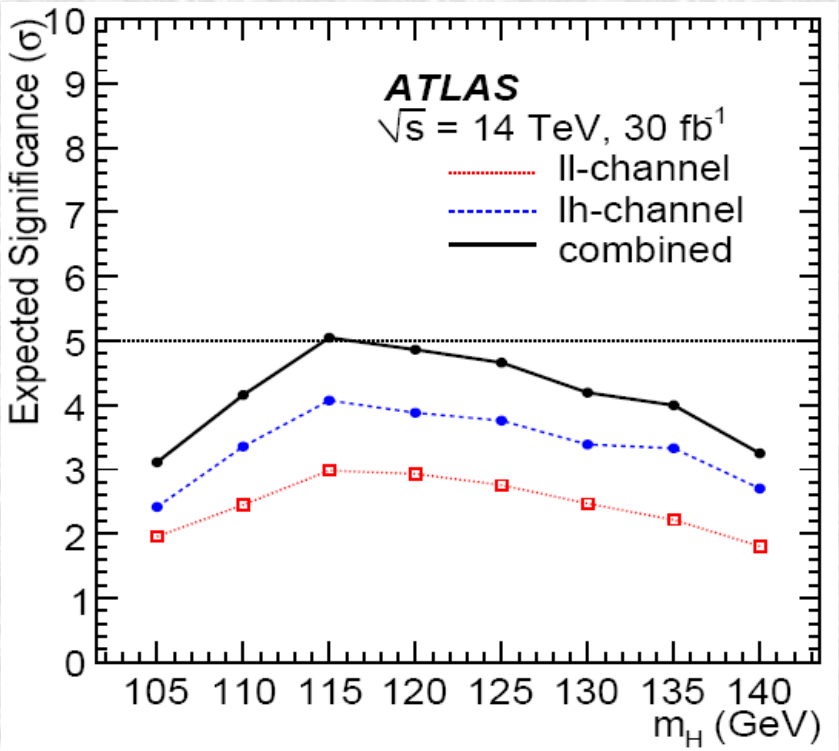


- Soft electron candidates from minimum bias

H → tau tau

- Should give good s/b if:
  - jet veto works and is understood
  - Also good modelling of Z background – as Bruce said

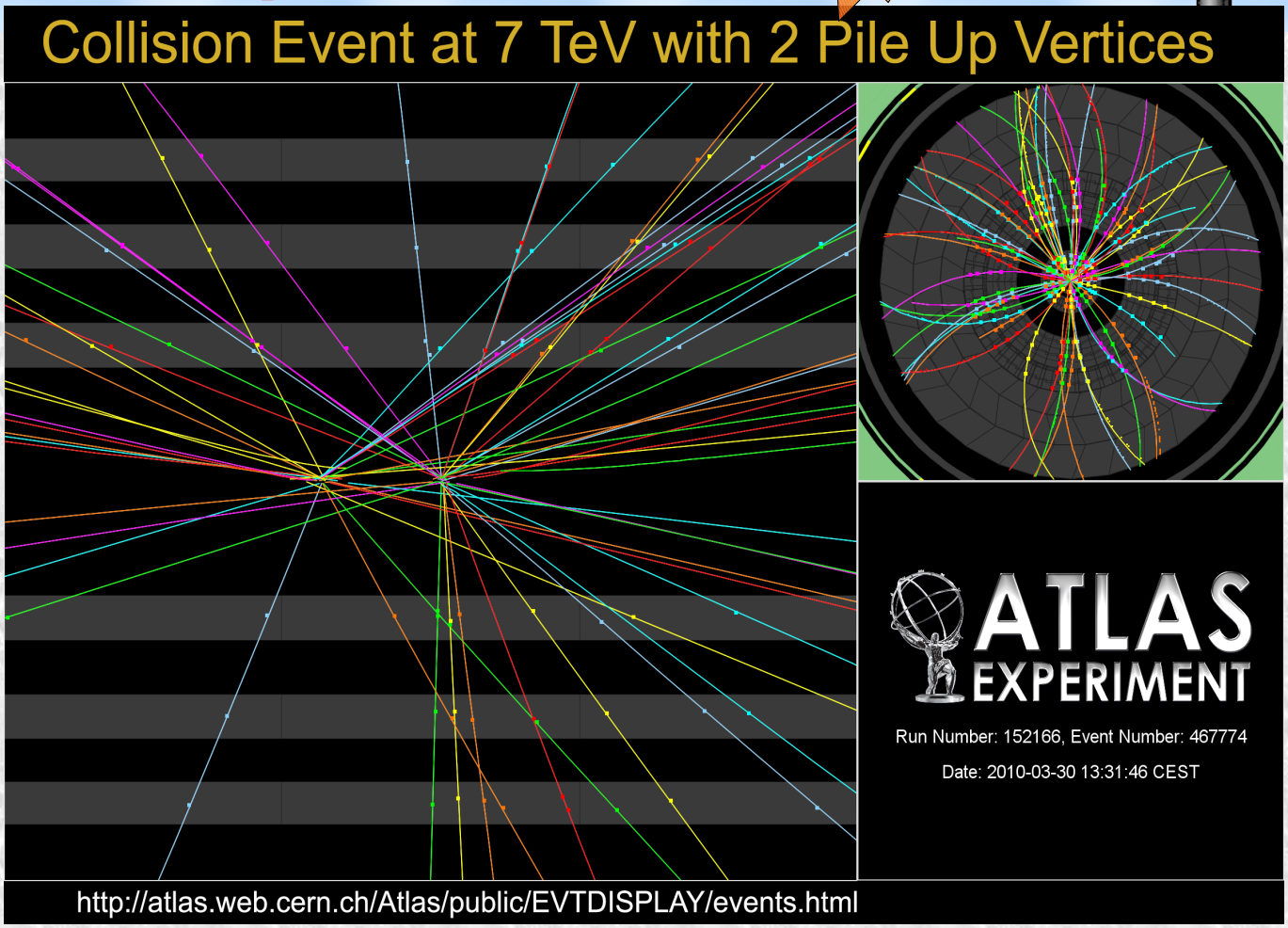




$H \rightarrow \tau\tau$ jet veto

Data

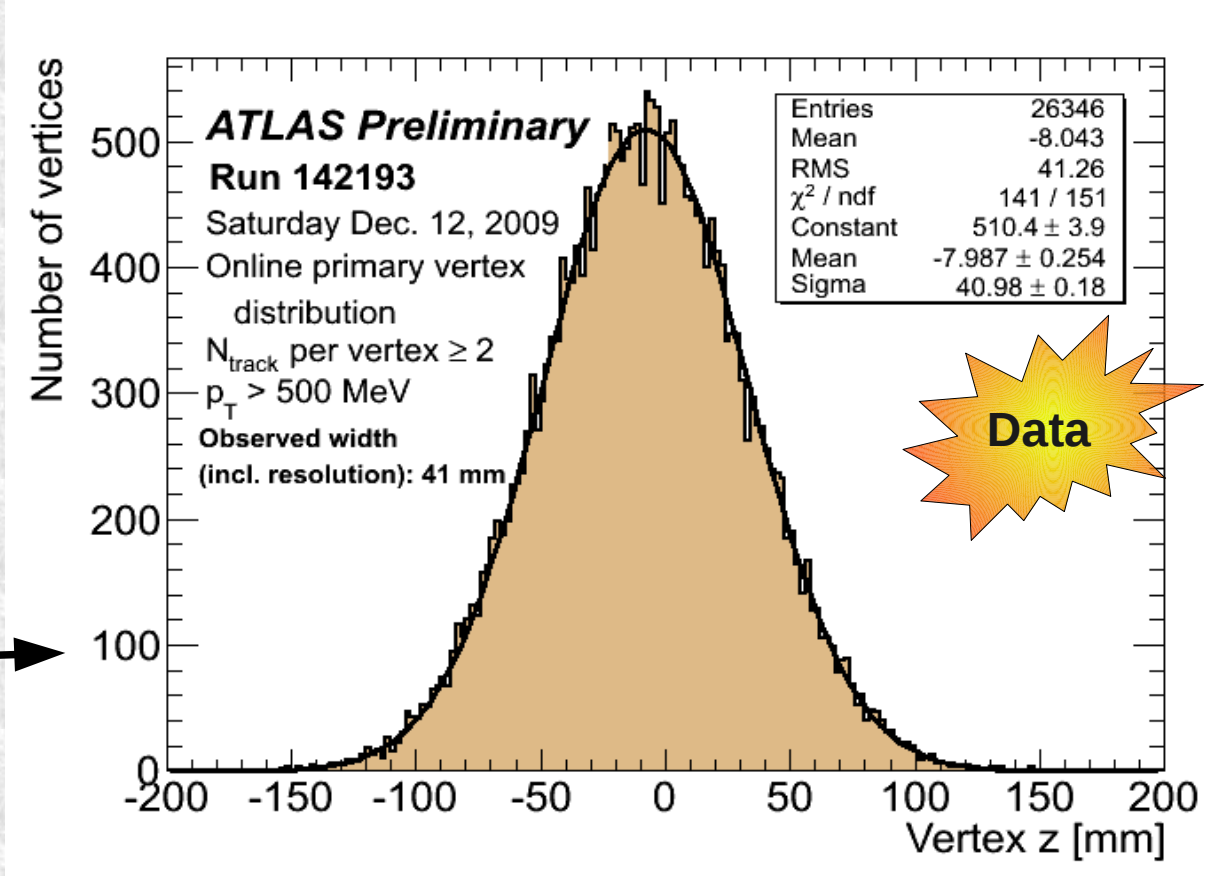
- Requires VBF
  - The jet veto survival is debatable
    - Underlying event?
    - Multiple-interactions ?
    - pile-up



- Need to measure this
  - Can VBF Z provide enough?

H → ττ and beamspot

- Track jets have less pileup problems
  - Long beamspot allows event separation
  - But beamspot is half length expected
  - But will beamspot stay short?



Mass resolution depends upon missing energy

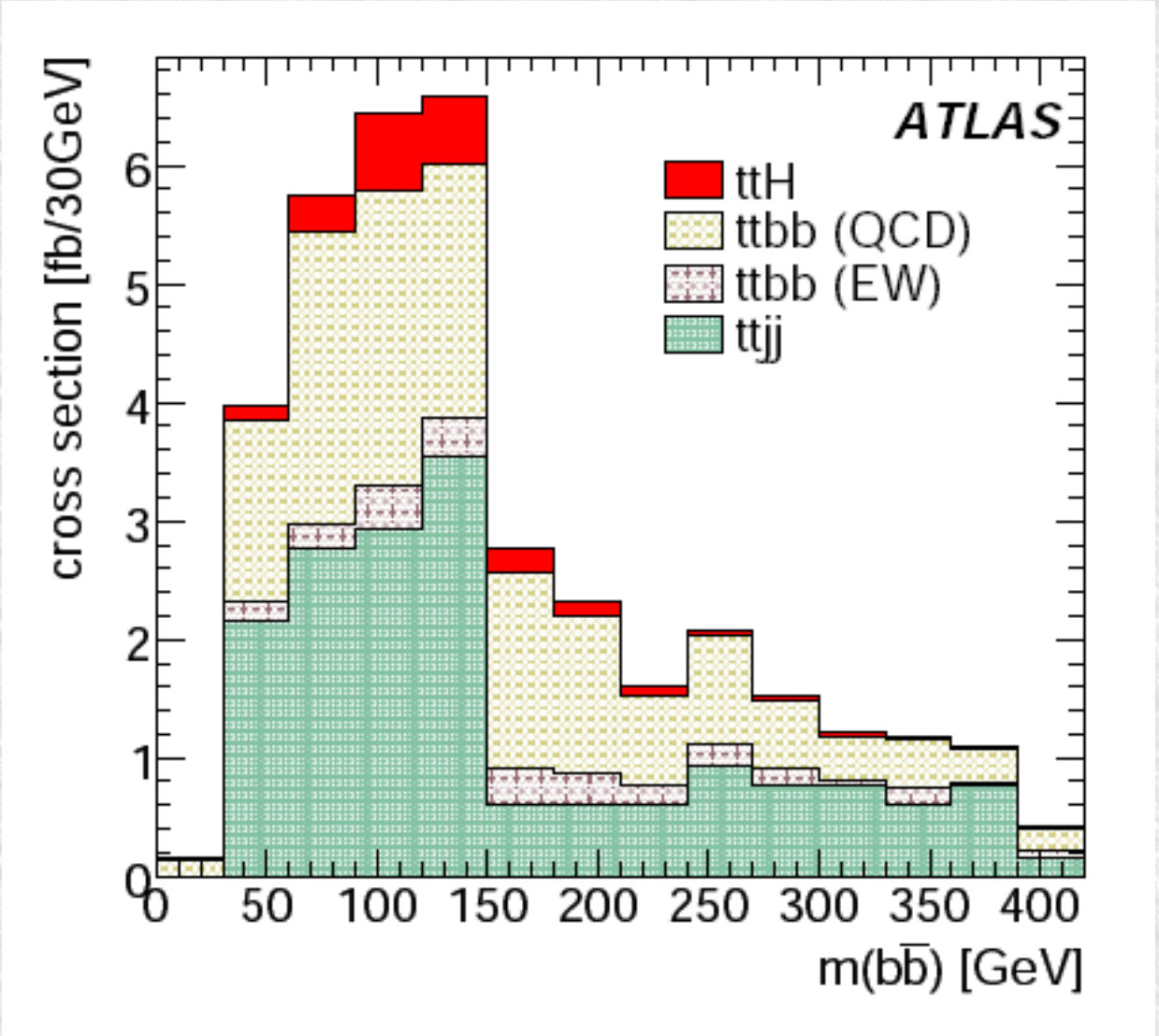
- Underlying event must be well known
- Z production also measures this.

ttH, H to bb

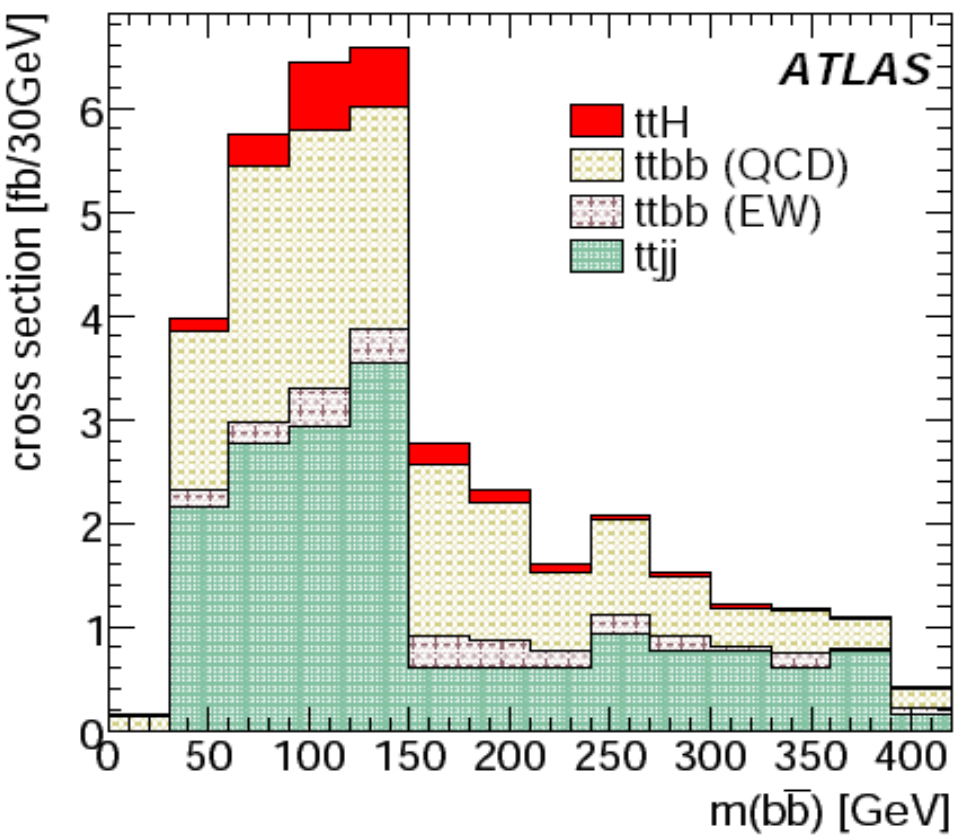
- s/b poor
  - Improving simulations always seems to add complication

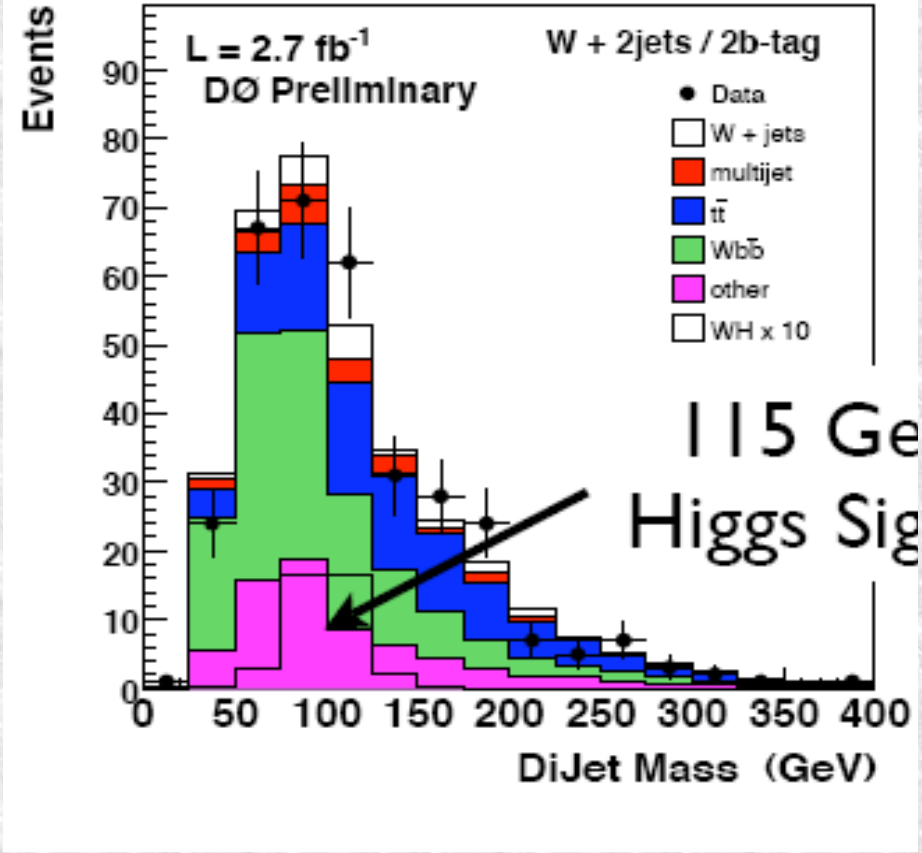
'Dead';
S. Heinemeyer, Seattle, Jan 2009

ArXiV: 0905:0110
ttbb k-factor 1.8
Increases the background
[Signal too, by 1.25]



ttH, H to bb: Doesn't lie down

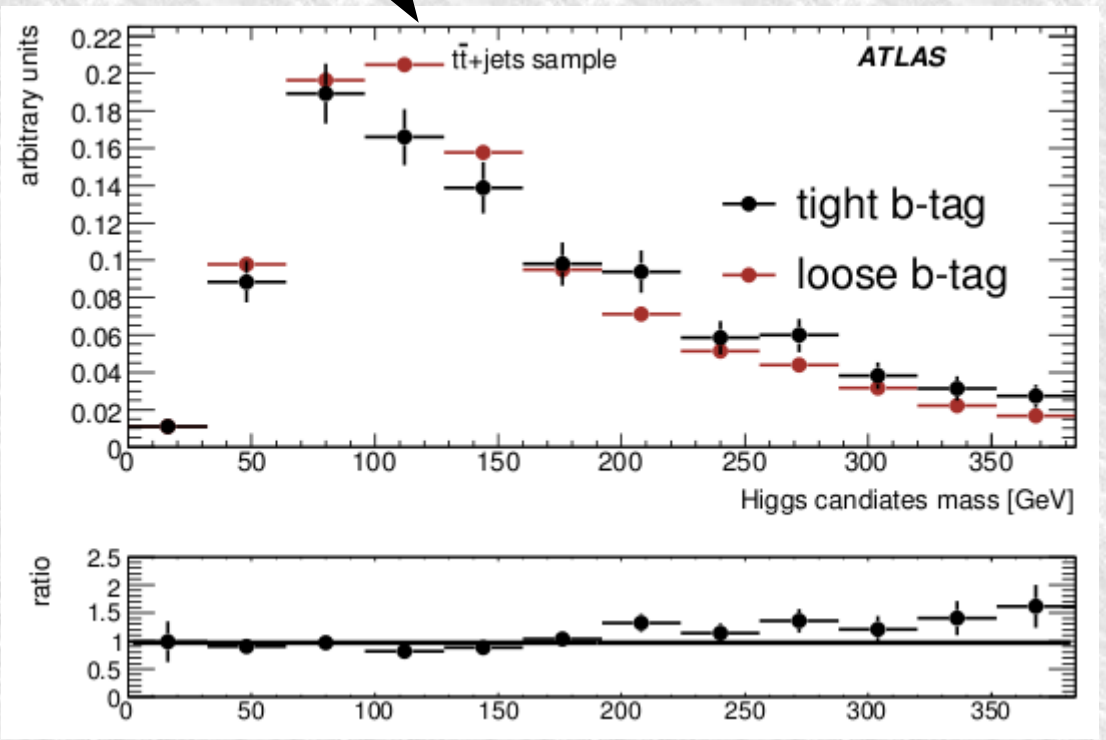




- Looks not much worse than Wbb at D0 to me
- Wait – TeVatron plot has signal shown times 10!

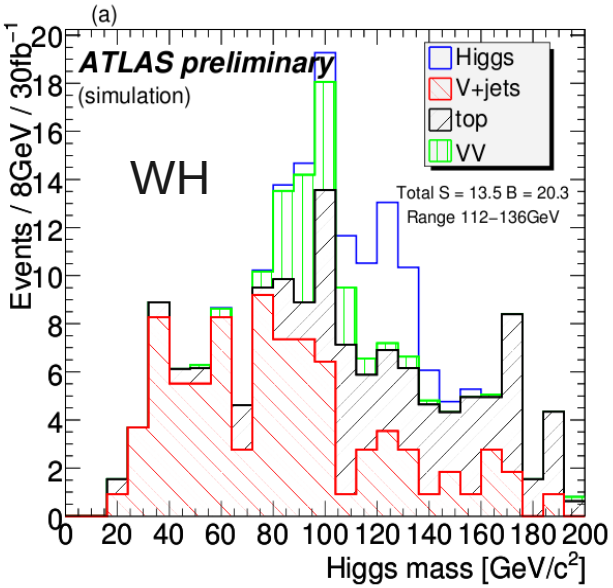
$t\bar{t}H$, $H \rightarrow b\bar{b}$

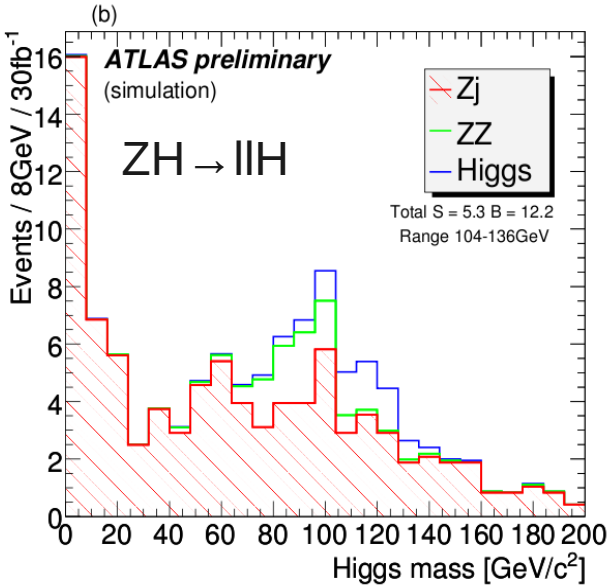
- Control of the background at 5% level required
  - Impossible to calculate
  - Can we fit it?
- Relating $t\bar{t}j\bar{j}$ to $t\bar{t}b\bar{b}$ backgrounds will help
  - ttjj has very similar jj mass distribution, no signal
- Is there more? e.g.
  - Does jjbb teach anything??

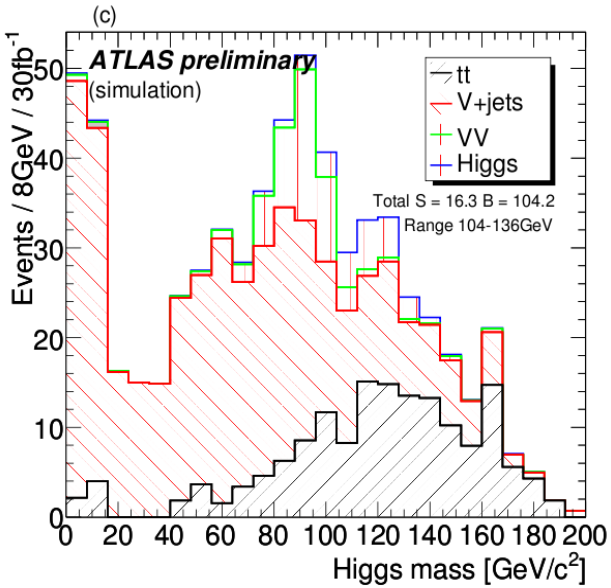


W/Z+H→bb:

- WH/ZH at LHC via subjets
  - Use boosted (p_T>200GeV) Higgs
  - Decompose merged jets
- Combined significance like γγ or ττ







ZH → ννH

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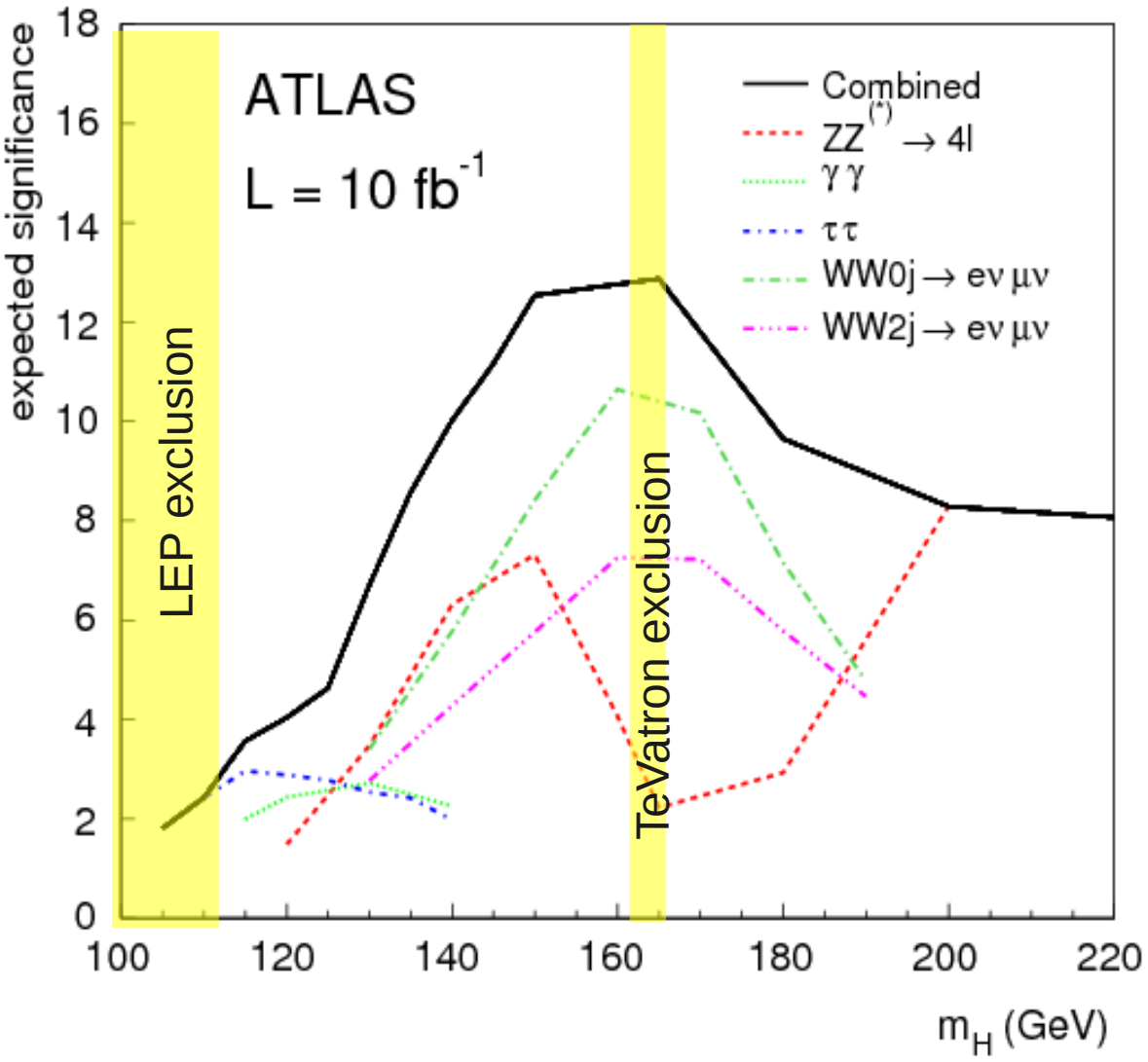
W/Z+H→$b\bar{b}$

- This was written off for years
  - The subjets revivied it
  - There must be other such tricks for other channels
    - Experience with data will bring them out
    - But theoretical suggestions are welcome
- Background level needs to be controlled
  - γbb is like Zbb but with no Higgs contribution
    - Can we get around the mass for background shape
      - Maybe use $\sqrt{(p_{T,jj}^2 + m_{jj}^2)}$
    - Or just verify simulation – which regime?

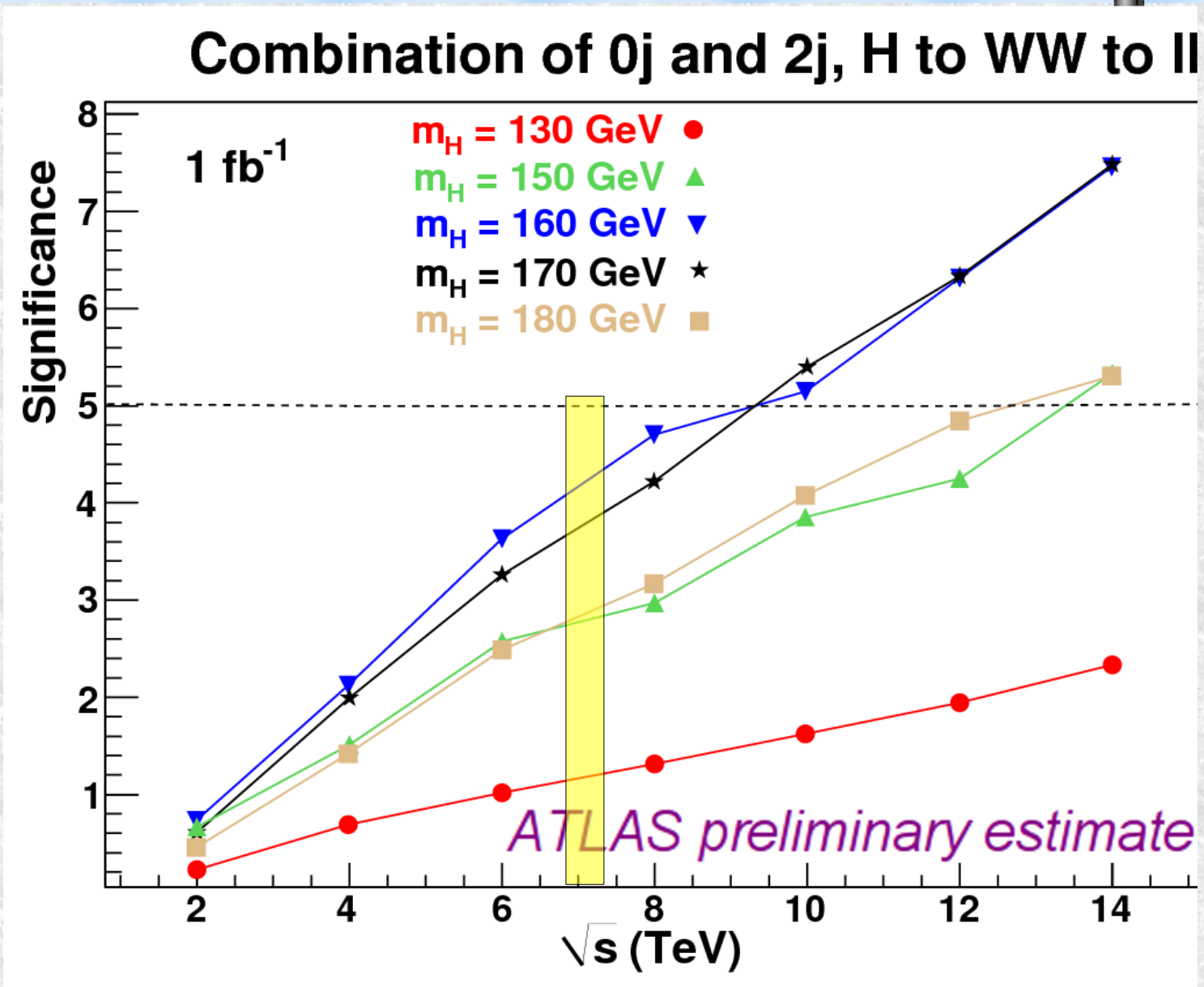
Higgs combination at 14TeV

- At full energy, 10fb^{-1} gives good discovery sensitivity
  - Except below 130GeV
  - No ZH, WH
    - add ~3σ at 120
- Nb: ZZ channels comparable to WW at 150 and 190GeV



$H \rightarrow W^+W^-$ $1fb^{-1}$ v $\sqrt{s}$

- Rough estimates
- 4σ for best mass range
  - Systematic treatment
- ZZ channel will add at 150/180
- May even let CMS help out

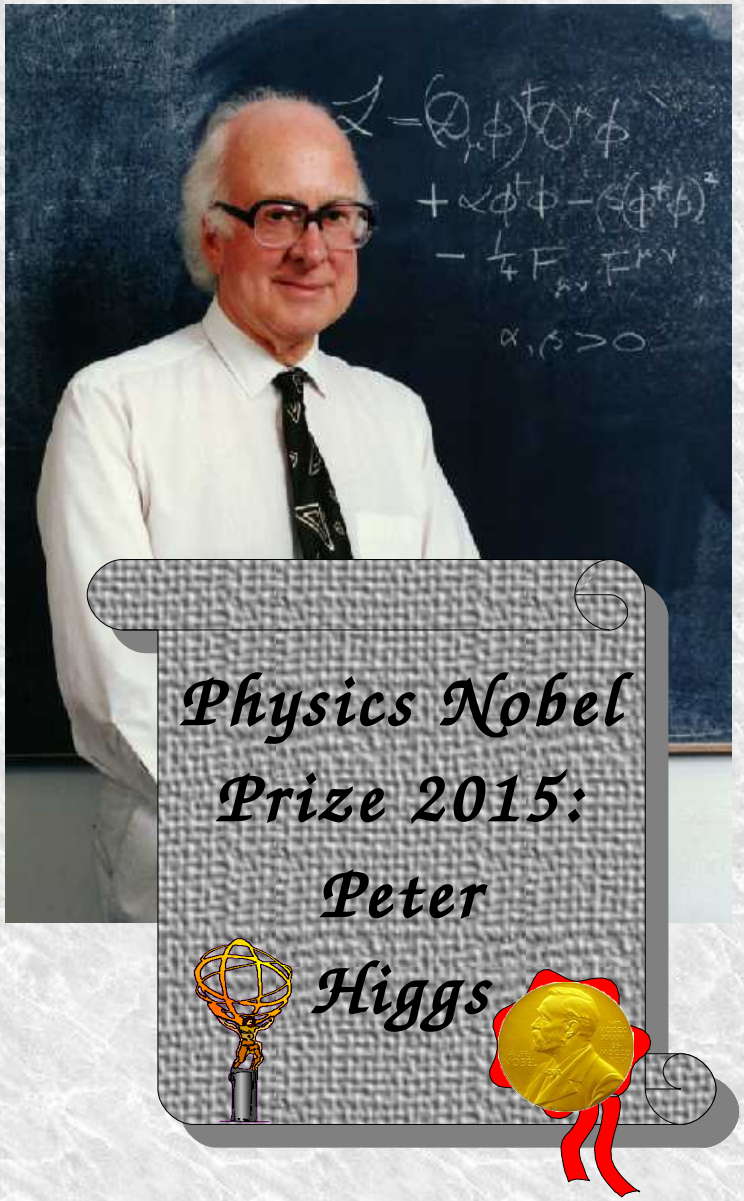


ATLAS options for 2010/11

- What would you like us to do?
  - Real searches in all channels ASAP?
  - Real searches in all SM channels ASAP?
  - Search in WW for 200pb^{-1}
  - SM Sensitivity at 7TeV ASAP?
  - SM Sensitivity at 7TeV after data cross-checks?
  - Combined SM studies at 1000pb^{-1}
  - MSSM plane sensitivity:
    - At 7TeV? 14TeV?
  - MSSM plane limits/discoveries:
    - 200pb^{-1}? 1000pb^{-1}?
  - Something else?

Conclusions

- We are ringing Peter's doorbell
- It will be ~2014 before we know who answers



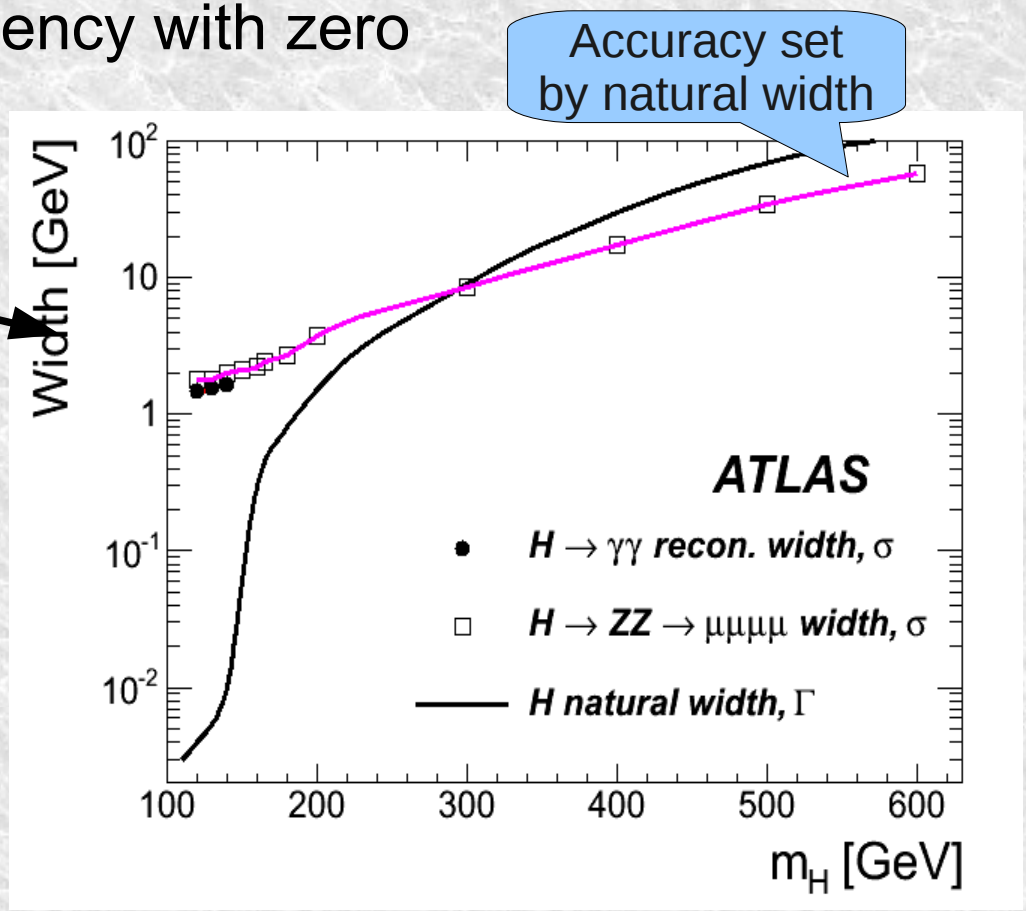
Backup

Higgs mass

- 120GeV
  - Higgs to γγ dominates
  - Statistical precision 1.4-1.7GeV per event
  - ⇒Dominated by photon scale, O(0.5%) or better
  - Assumes luminosity ~$10^{33}cm^2s^{-1}$; pileup degrades vertex reconstruction
- 160GeV
  - Measured by H→ZZ→llll
  - Resolution 2-2.5GeV per event
  - ⇒Dominated by lepton scale O(0.5-0.2%) or better
- Non-SM Higgs may suppress bosonic decays
  - ττ has best measurement – outside this scope

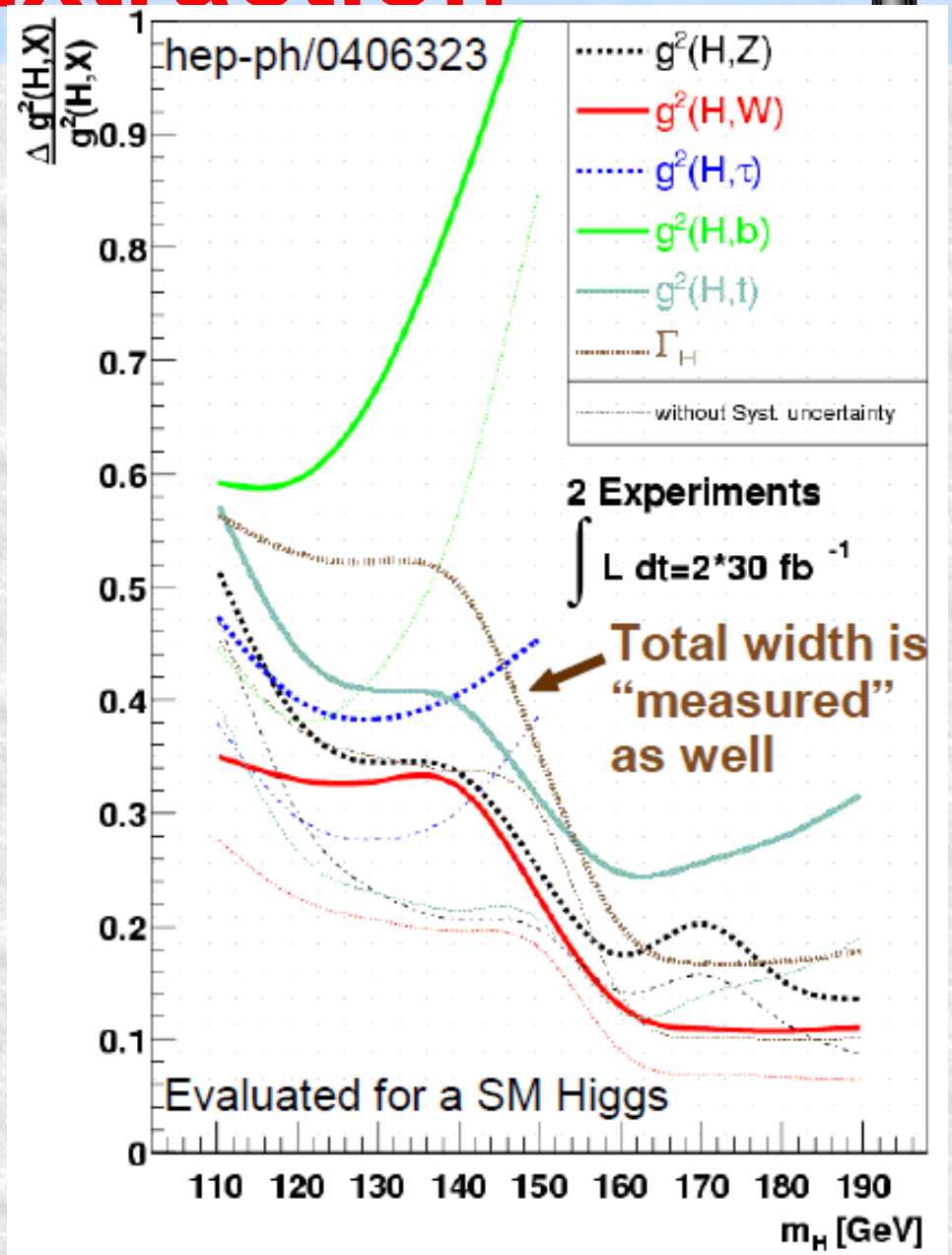
Higgs Couplings

- Lifetime/Width:
  - Standard Model Higgs < 200GeV
  - Lifetime ~ 10^{-22}s – decay length not measurable
    - But we must check consistency with zero
  - Width rises with mass
  - <10MeV below 140GeV
  - Measurable from ~200 GeV
- Branching Ratios:
  - Much more promising...
  - But without total rate
  - Only relative BR's



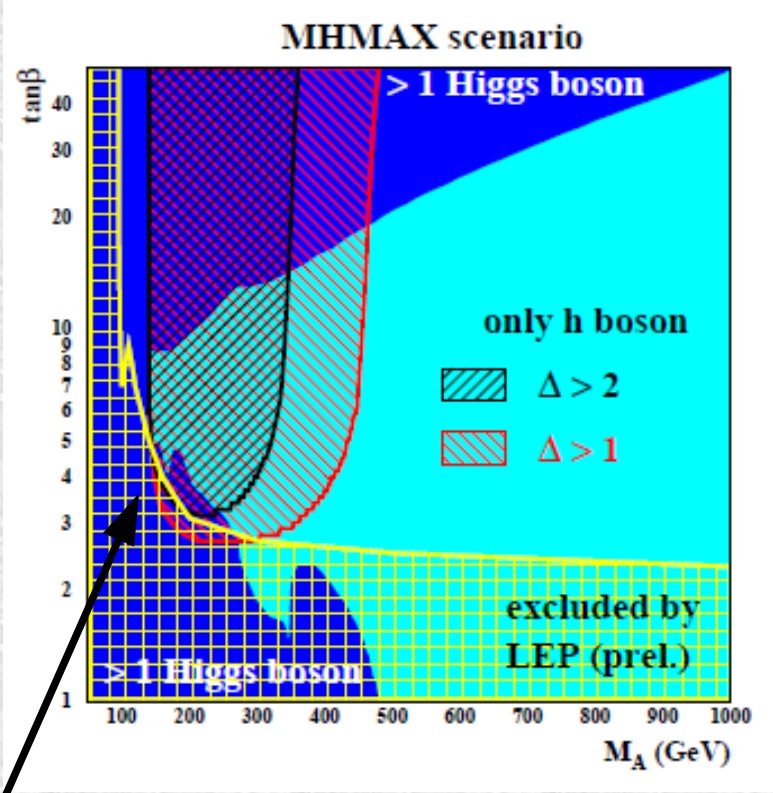
Couplings Extraction

- Only relative rates can be measured
  - More assumptions needed
  - Here HWW/HZZ couplings forced <= SM values
- Find couplings squared for 30fb^{-1}, 2 expts, to:
  - 40% W, Z, τ, and t
  - 60% for b
- Will improve with more data



Discrimination from MSSM

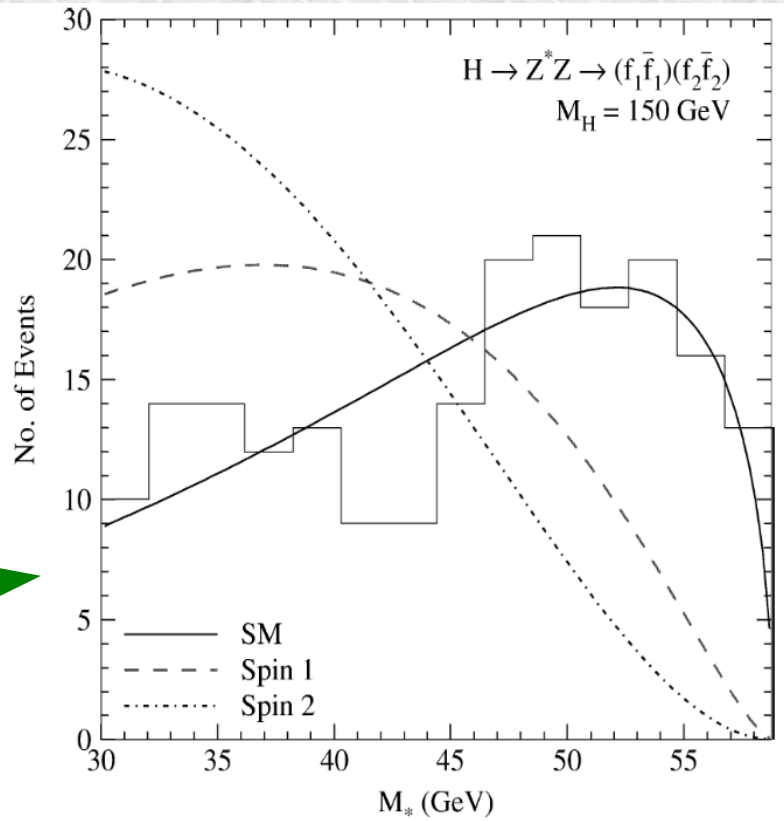
- In many cases several MSSM Higgs bosons can be found
- If only one, can we distinguish from SM?
- Use Br. h→ττ/h→WW in VBF production, c/f SM→ Δ
- Ratio cancels production effects
- Δ>2 in black region is two-sigma separation

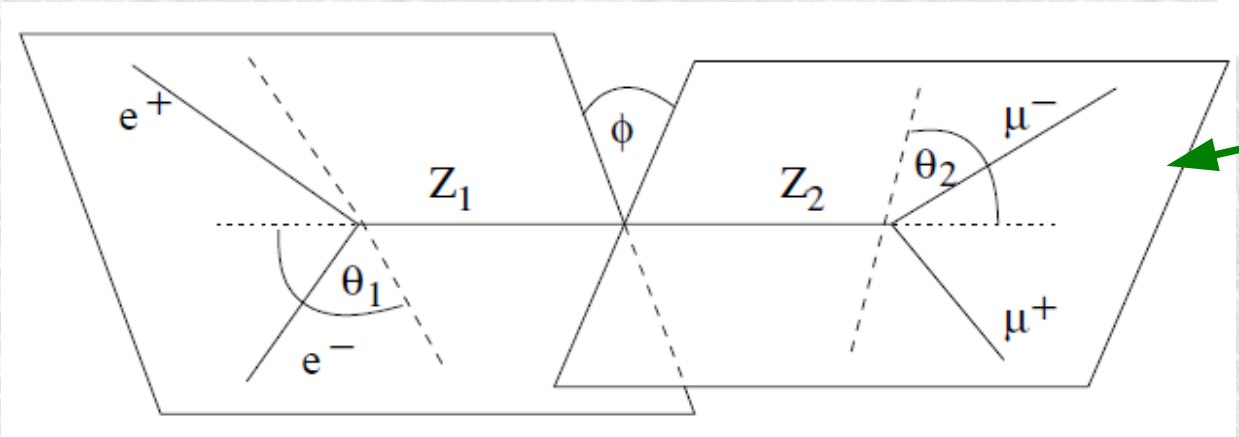


arXiv:hep-ph/0410112

Spin Measurement

- All channels naturally exclude fermionic source
- H to γγ observation excludes spin 1.
- ZZ angular distributions will confirm spin 0
  - Low mass: Z* mass distribution





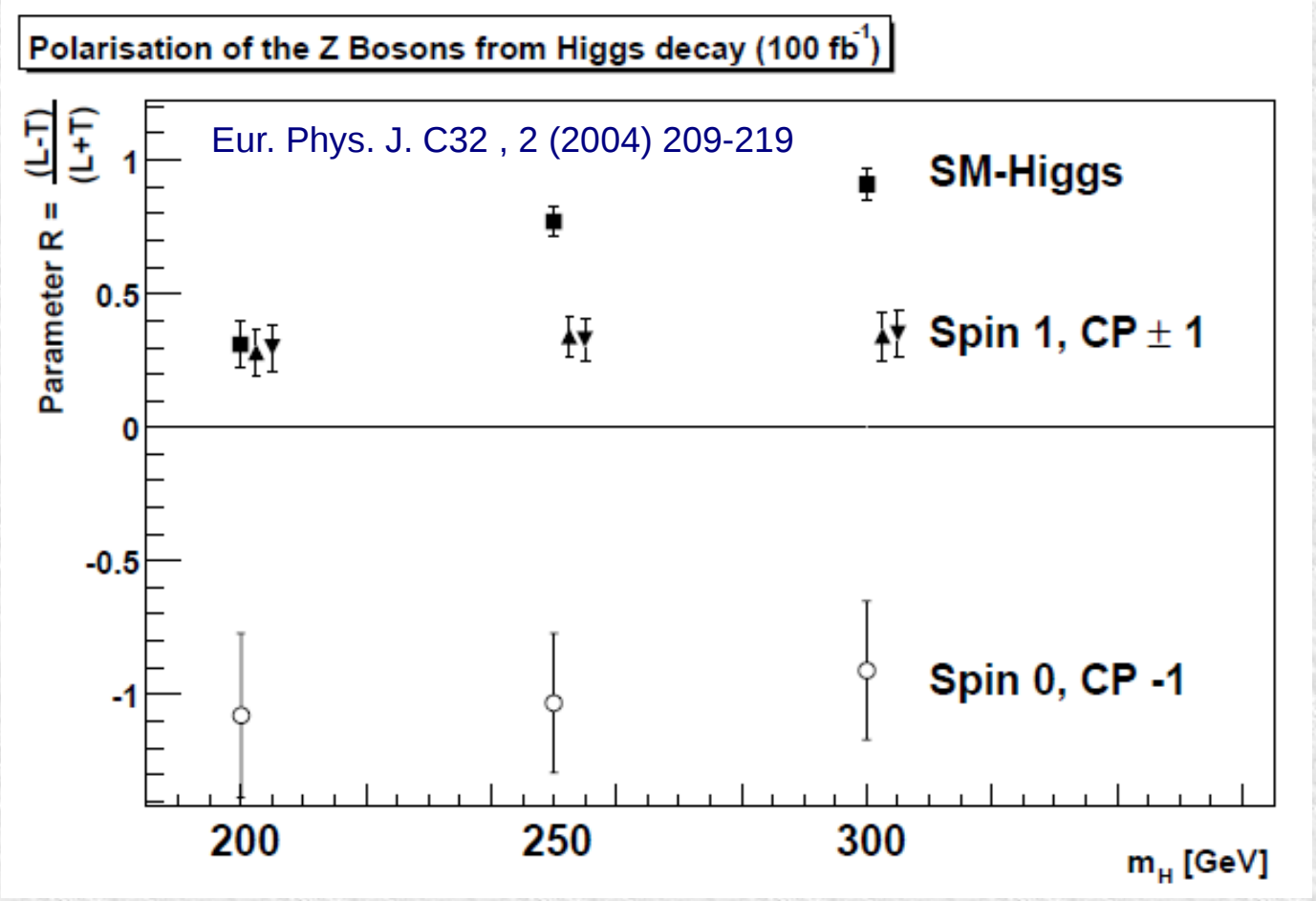
- High mass: ZZ decay correlations
- Also H→WW l-l mass

Parity Extraction

- Using ZZ angles above, extract

$$R = \frac{L_{Longitudinal} - T_{Transverse}}{L_{Longitudinal} + T_{Transverse}}$$

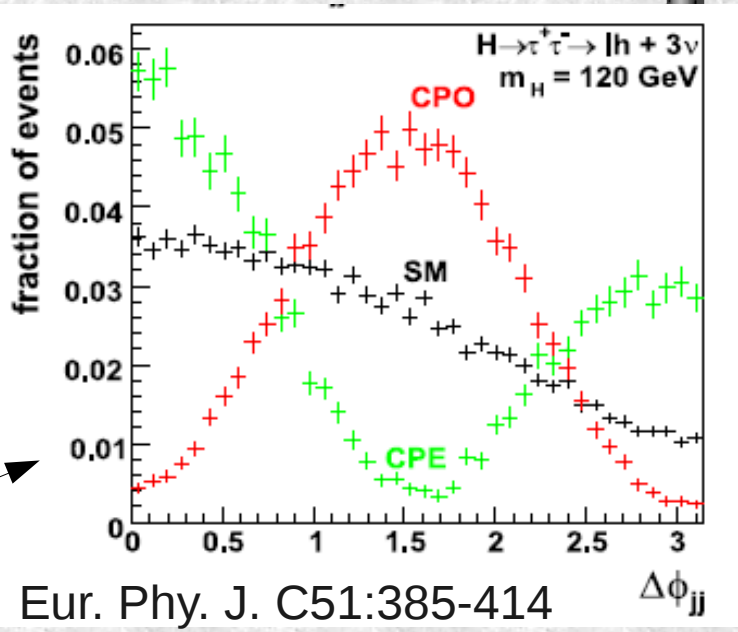
  - $100fb^{-1}$ clearly gives parity



- VBF angles also sensitive.

Anomalous couplings

- CPO (odd) and CPE (even) anomalous WWH couplings could exist in addition to SM ones.
- H to WW decay gives a test
- The VBF H→ττ also:
  - Interjet angle
    - High statistics
    - 10fb^{-1} in ATLAS
    - CPE ~ distinguishable with this dataset



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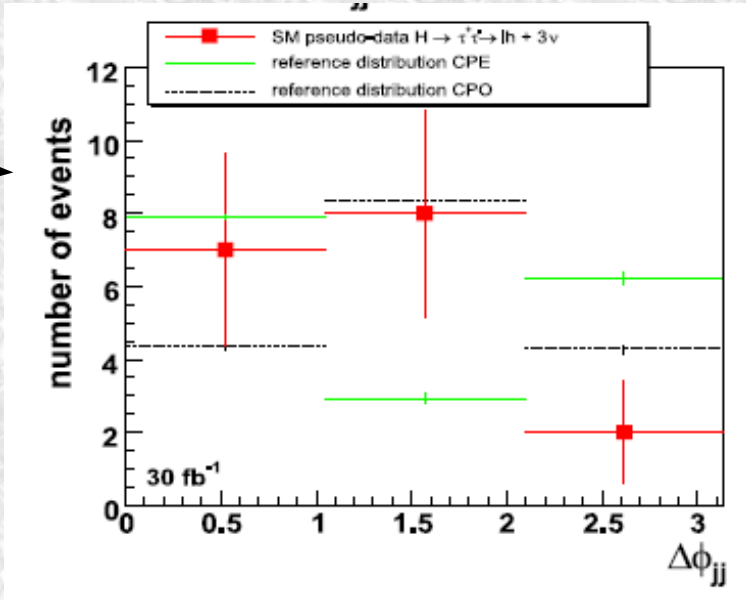
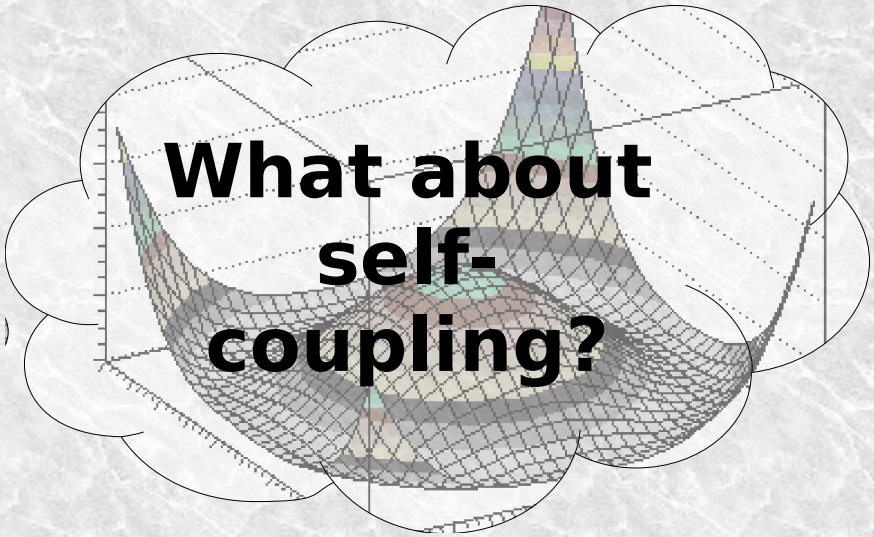
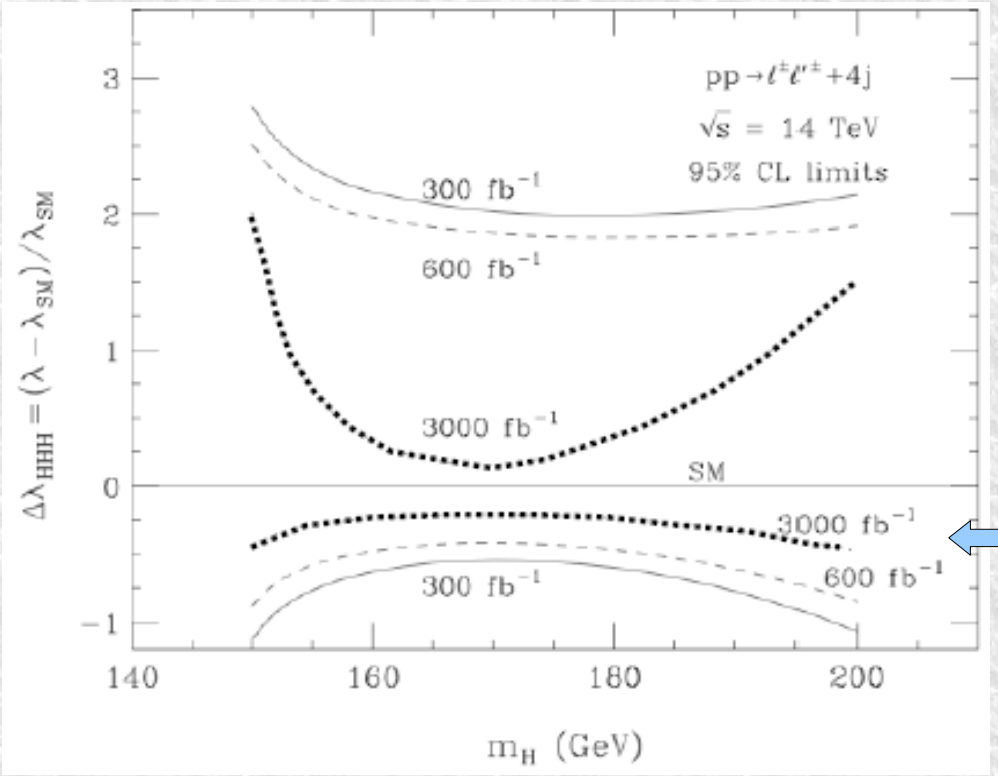


Higgs self-coupling

- Very desirable test of the theory
  - Quartic self-coupling drives VeV





- Extremely challenging
  - SLHC required, plus luck
- hep-ph/0304015 finds 160-180GeV plausible
  - No pileup, fast-sim, backgrounds look low
  - Now ~ excluded!