# The 125 GeV boson: experimental status and plans

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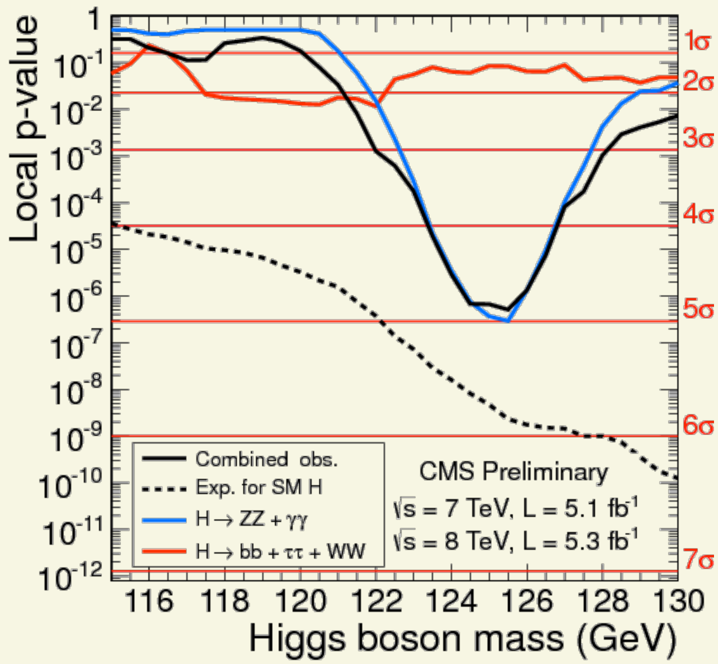
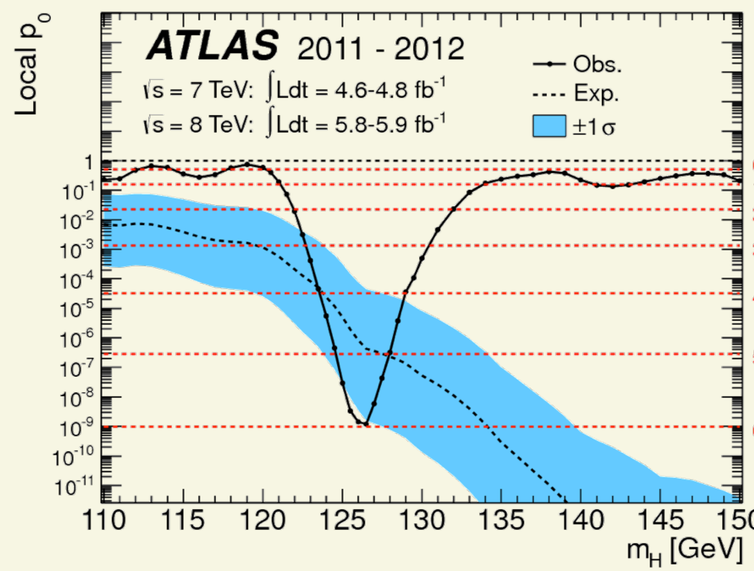
Duke University

Lattice Meets Experiment 2012 * Boulder, CO

# Outline

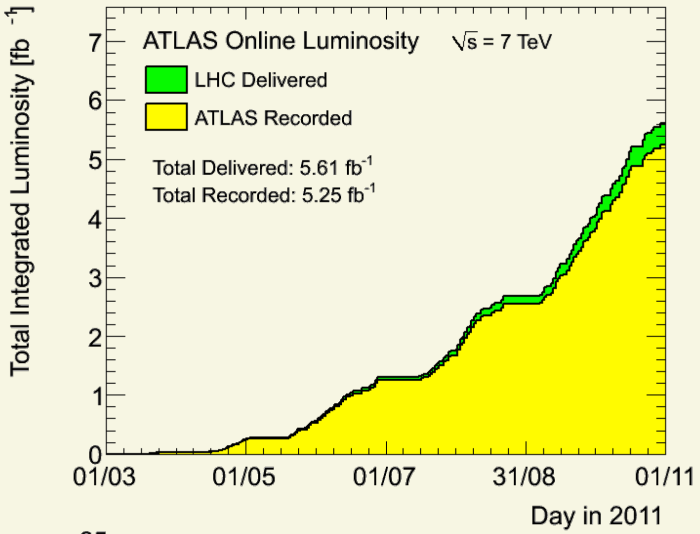


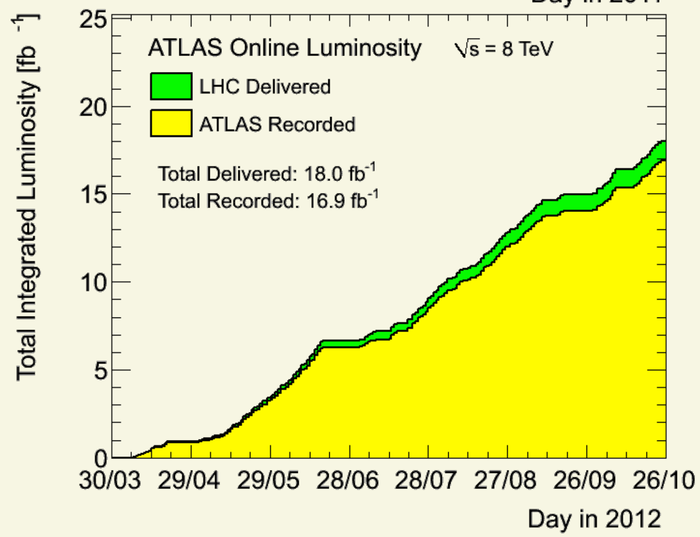




1. What experimental tools do we have to study this new particle's properties?
2. What do the current datasets tell us?
3. Recent results on couplings, and prospects for future measurements

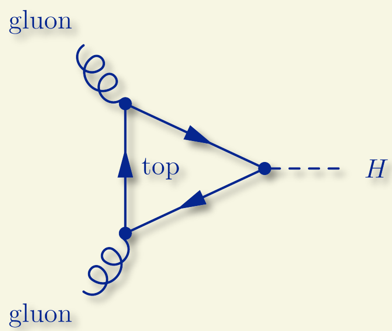
# Higgs production

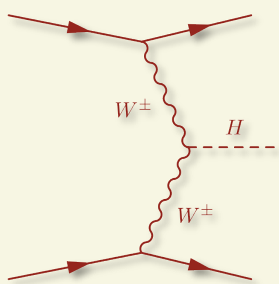
- Thanks to LHC:
  - Results today use 5 $fb^{-1}$ (7 TeV) + 6 $fb^{-1}$ (8 TeV)
  - Expect an *additional* 20 $fb^{-1}$ this year
- Luminosity uncertainty:
  - 1.8%/3.6% (2011/2012, ATLAS)
  - 4.4% (2011/2012, CMS)

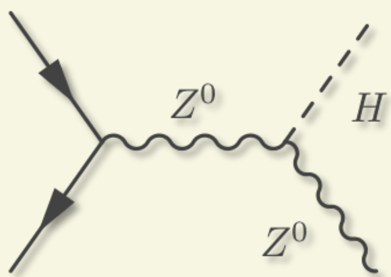


# Higgs production



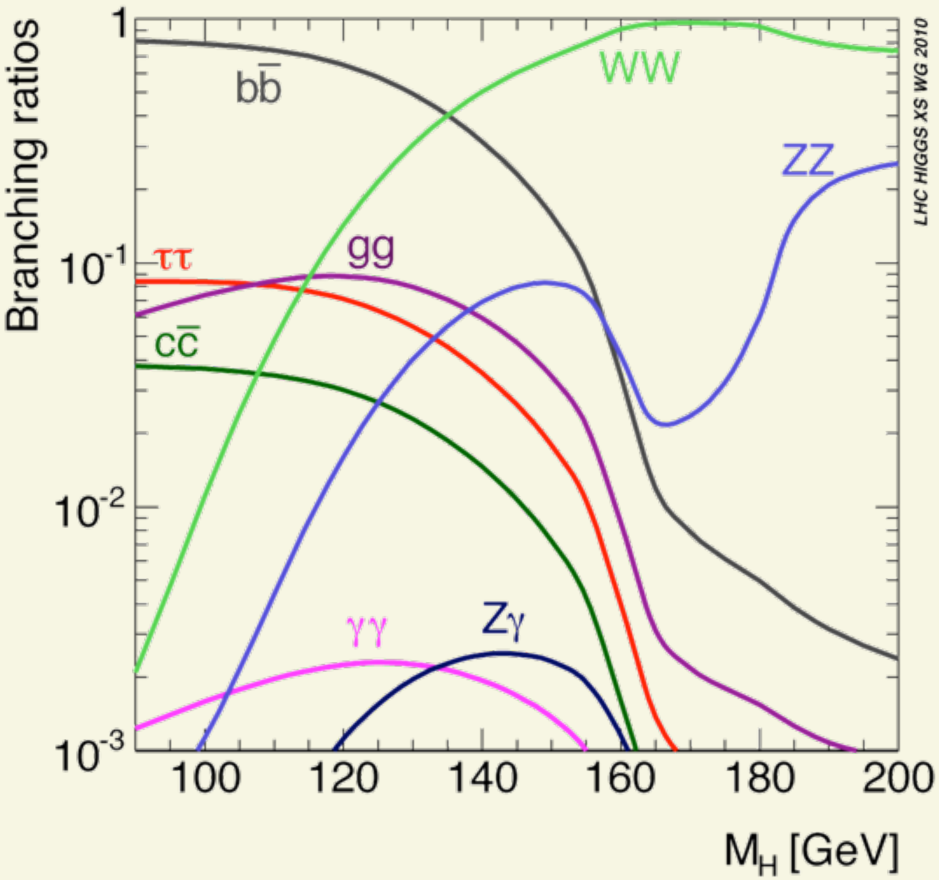




- Gluon fusion
  - 15 pb (7 TeV)
  - 14% uncertainty (scale + PDF)
  - 30% higher at 8 TeV
- Vector boson fusion
  - 1.22 pb (7 TeV)
  - 3% uncertainty
- Associated production
  - WH: 0. 57 pb (7 TeV) +/- 3%
  - 20% higher at 8 TeV

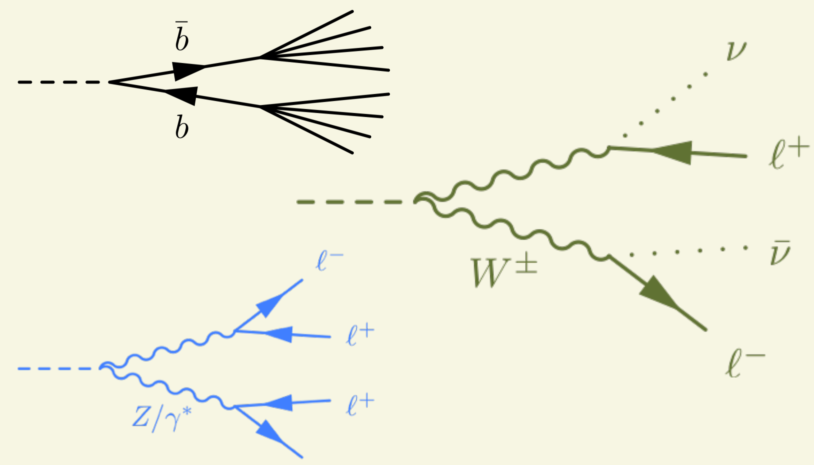
# Higgs decay

**Higgs decay probabilities**

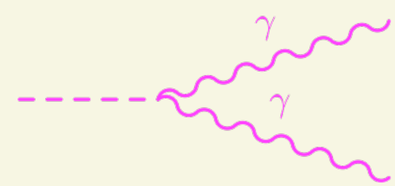



**Observable final states**

Unstable particles

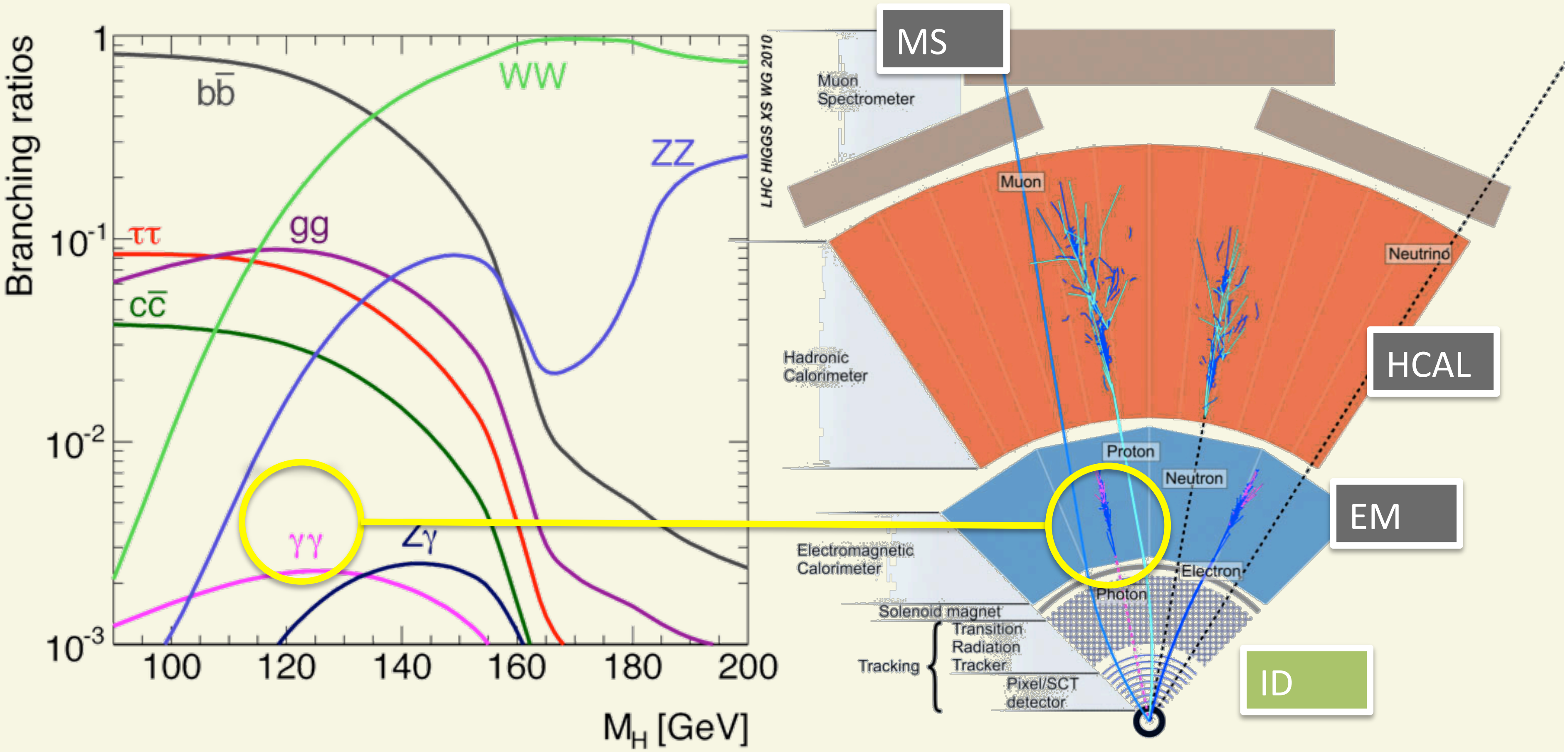



Stable particles



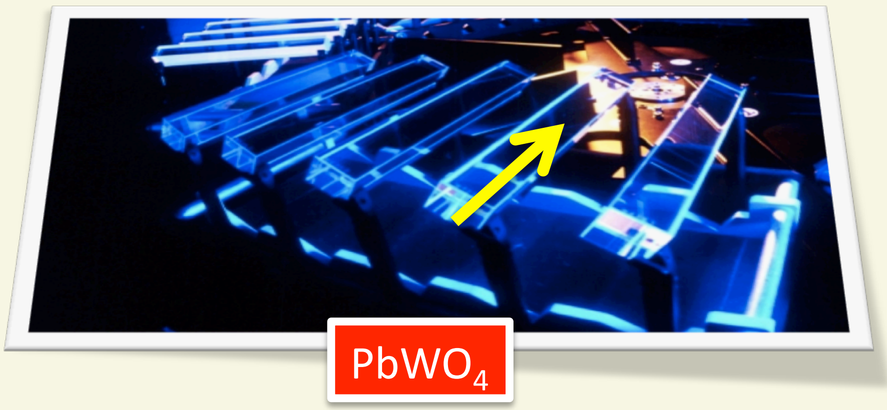
# Higgs reconstruction

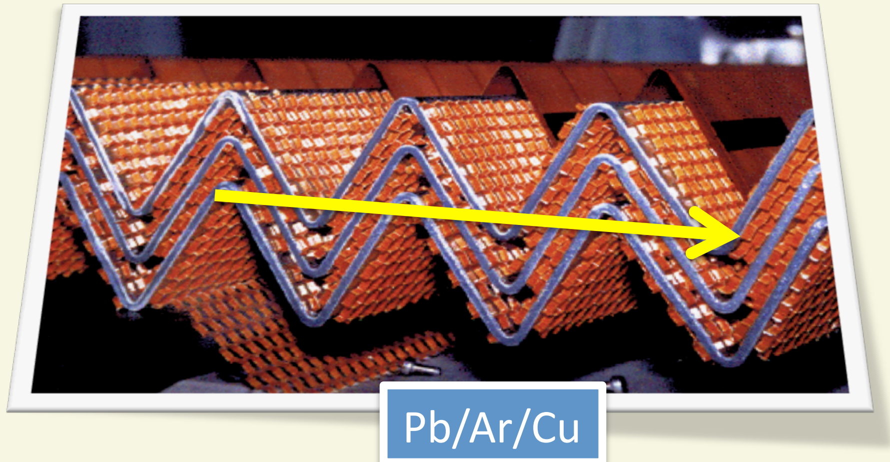
**Higgs decay probabilities**




"golden channel"

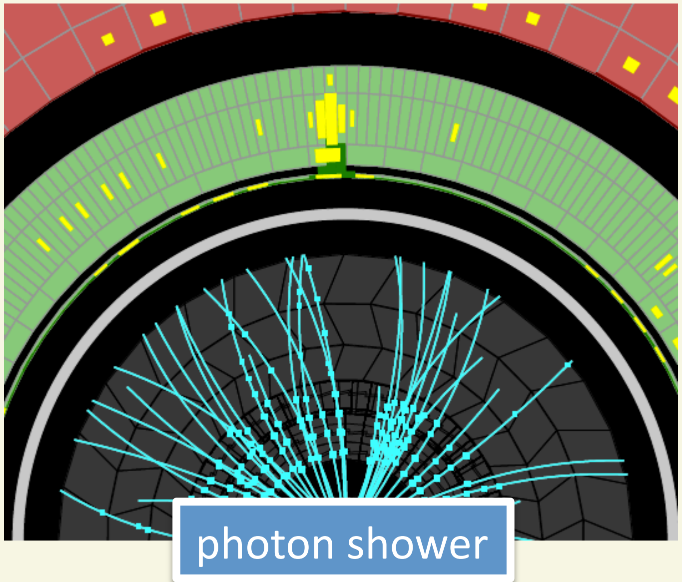
# photon reconstruction

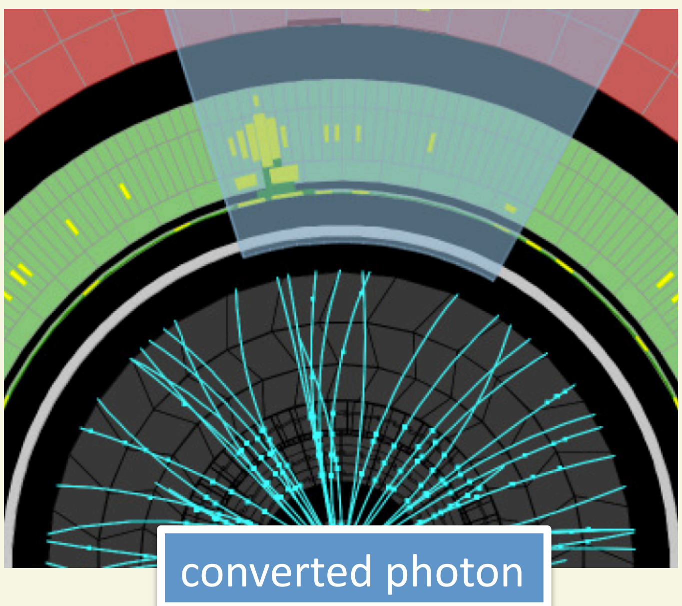



| CMS | ATLAS |
| --- | --- |
| energy resolution: ~ 0.5% (constant term) for high-$E_T$ photons | energy resolution: 10%/√E (1% constant term in barrel) |
| angular resolution improved by "likely" collision vertex | "pointing:" resolution ~15 mm (pileup-robust) |
| identification and energy corrections: BDT | neural-net or cut-based identification |

# photon reconstruction

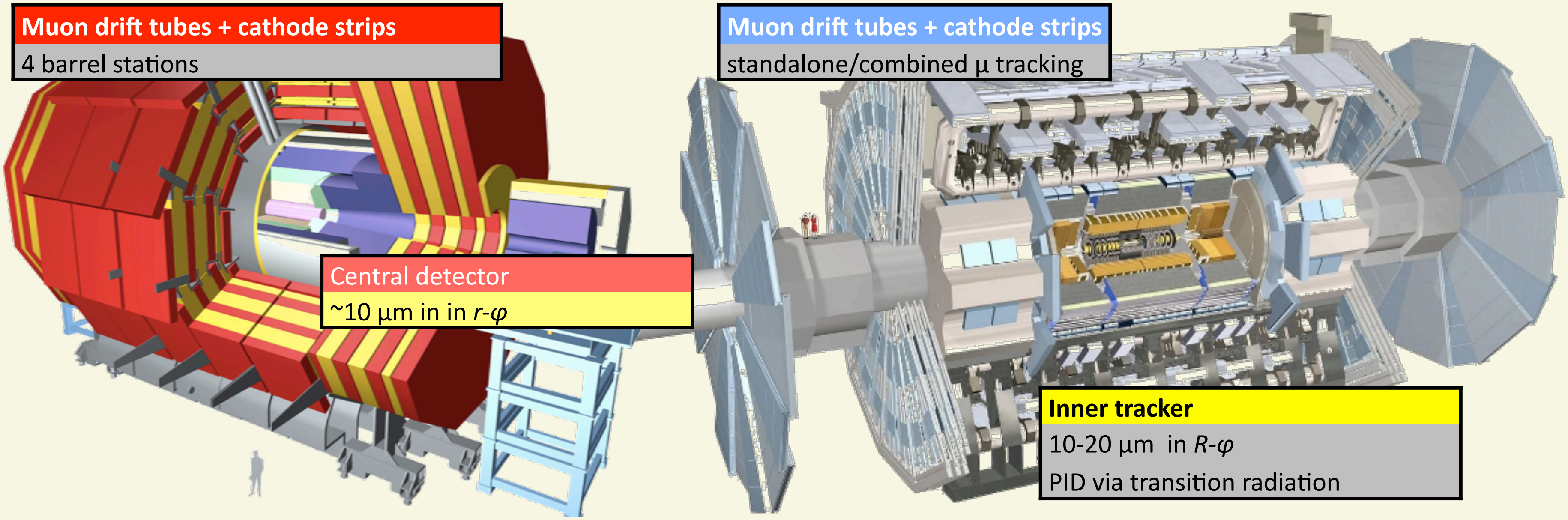



- ~40% of Higgs candidates reconstructed as converted photons
  - ATLAS: Z vertex resolution improves

    …but overall $m_H$ resolution degrades (3.2 GeV → 4.5 GeV)
  - CMS: improves mass resolution

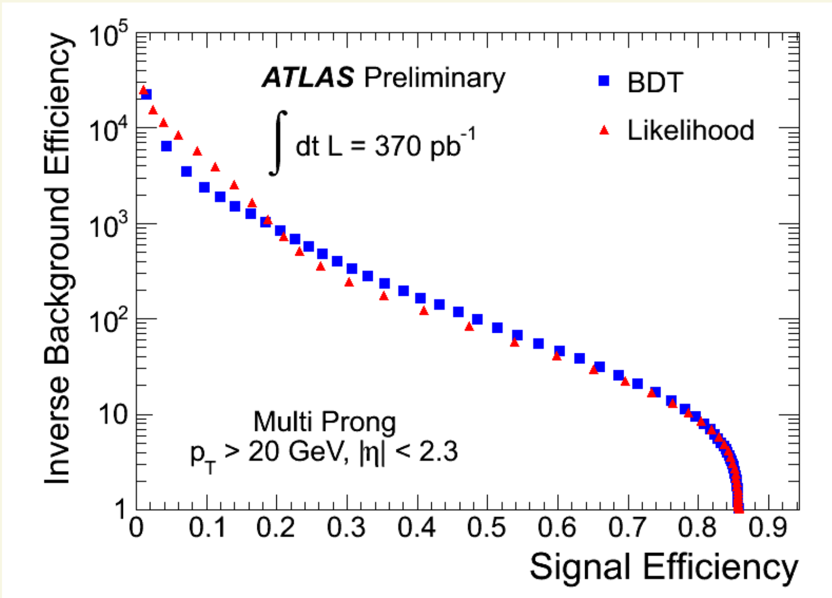
# lepton reconstruction




| CMS |
|---|
| electrons: > 7 GeV, \|η\| < 2.37 |
| muons: $E_T$ > 6 GeV, \|η\| < 2.7 |
| missing $E_T \gtrsim$ 25 GeV |

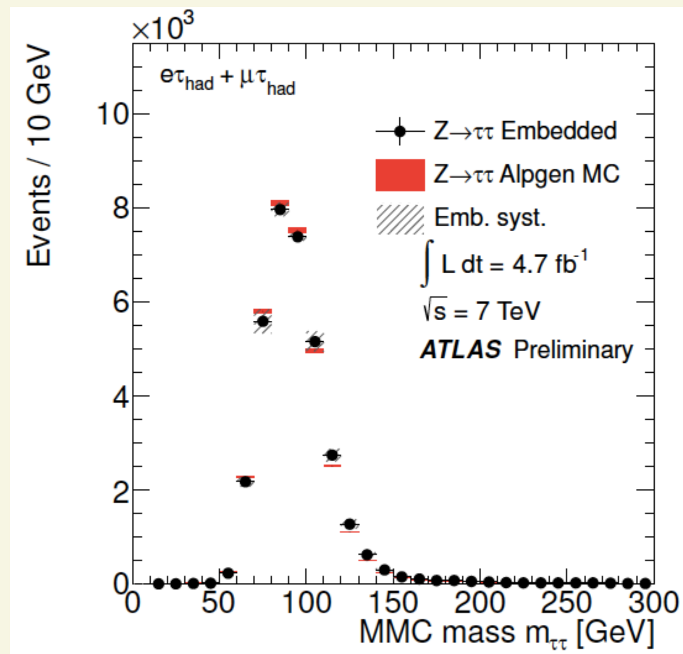
| ATLAS |
|---|
| electrons: : ET > 7 GeV, \|η\| < 2.5 |
| muons: $E_T$ > 5 GeV, \|η\| < 2.5 |
| missing $E_T \gtrsim$ 25 GeV |

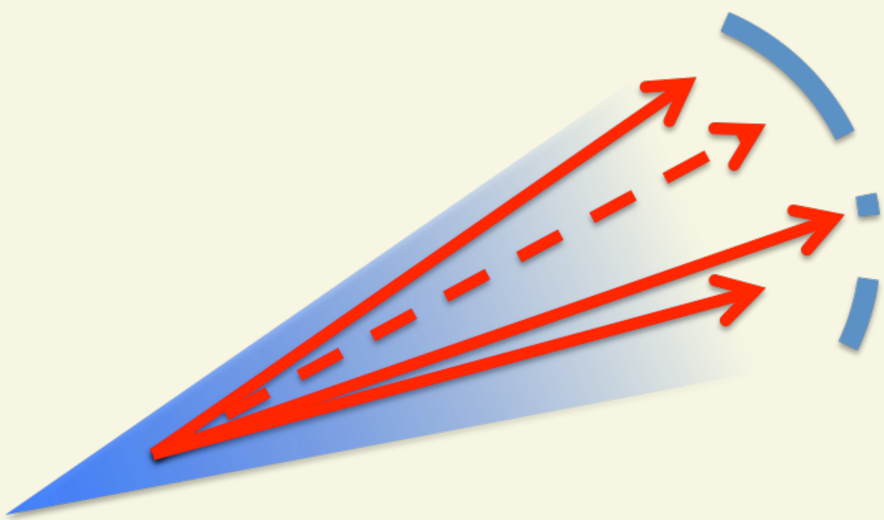
# hadronic tau reconstruction



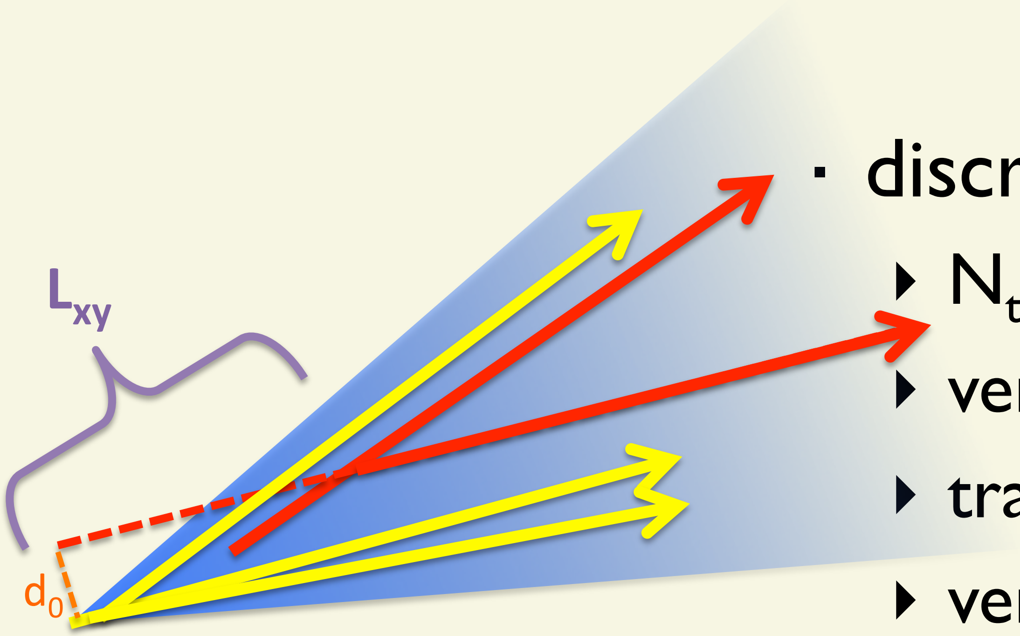

uncertainties:

- $\tau_H$ identification: < 4%
- $\tau_H$ energy scale: 2-5%



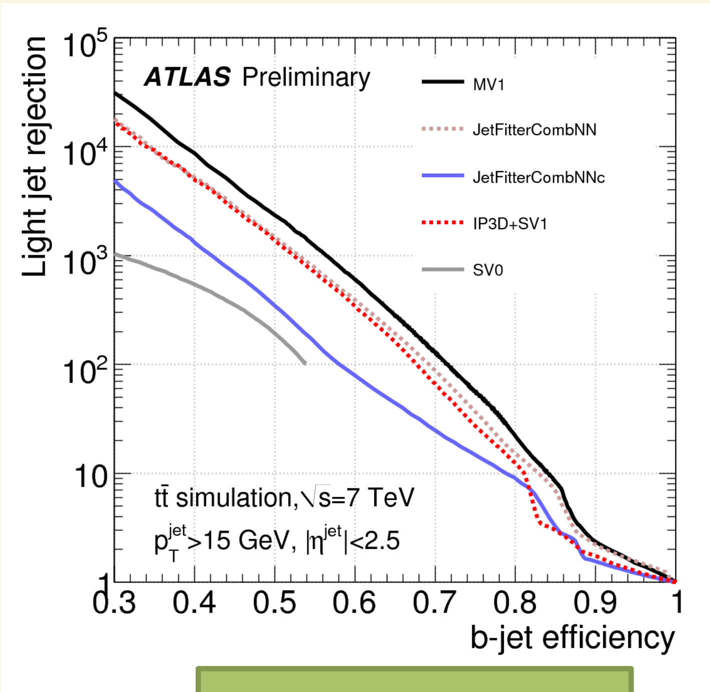
# b-jet tagging

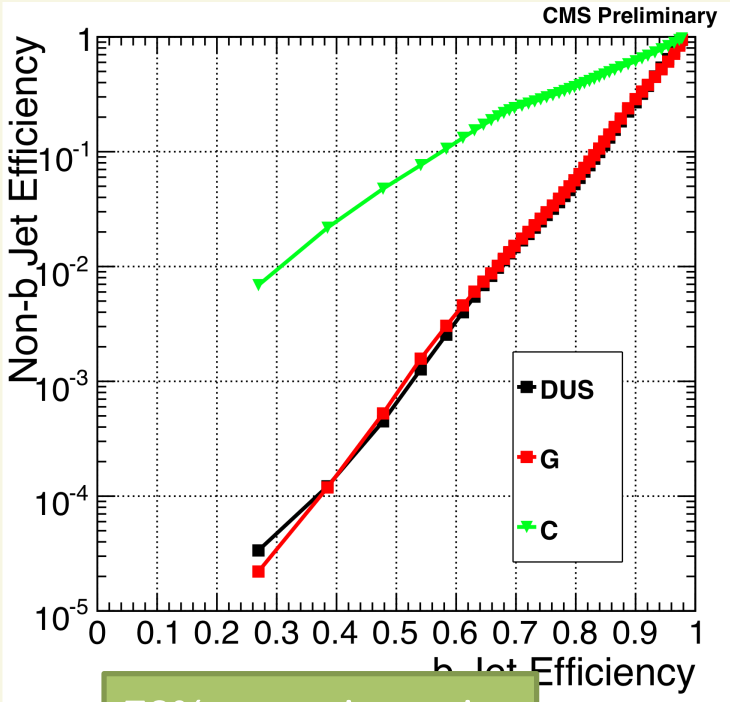



- discriminating variables:
  - $N_{tracks}$, $m_{vertex}$
  - vertex $L_{xy}$ significance
  - track impact parameter $d_0$
  - vertex $p_T$ ratio

- leptons, neutrinos in jet lower b-jet: mass scale ~5% low
- b-jet energy resolution: ~10% (CMS), 13% (ATLAS)

# b-jet tagging



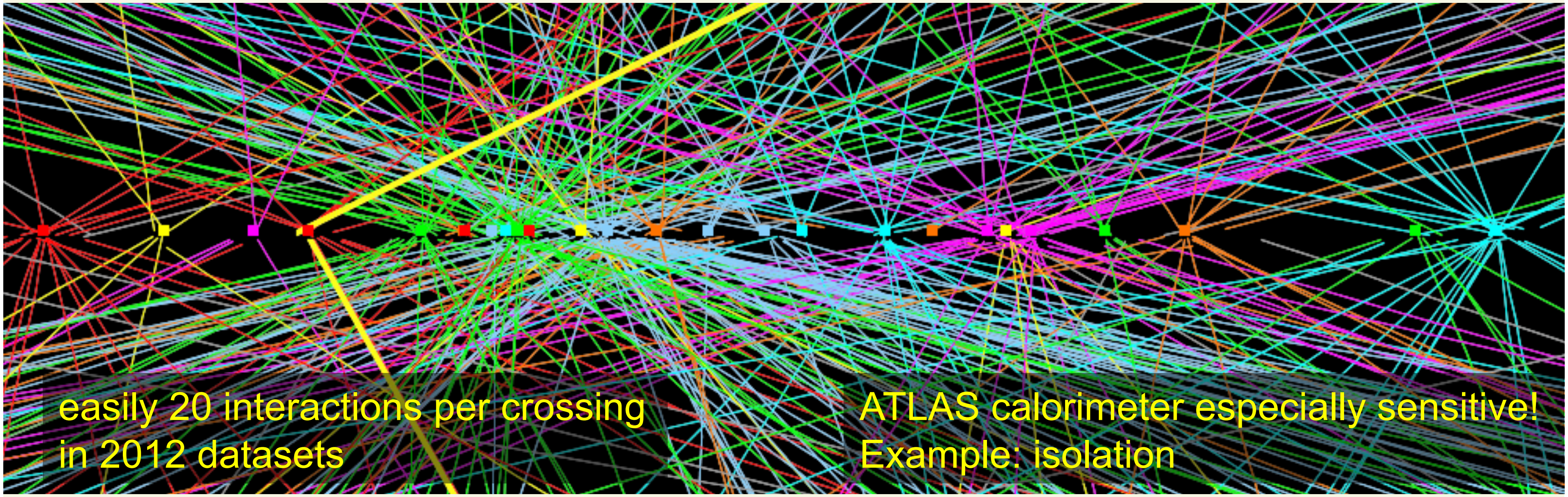




70% operating point
<1 % background

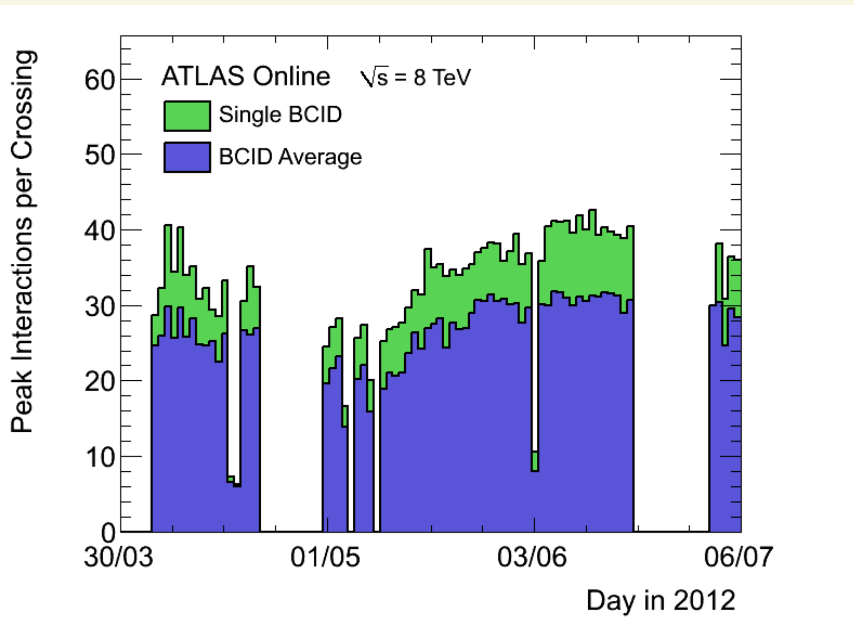
70% operating point
2% background

- ATLAS MV1:
  - 3-d impact parameters + vertex reconstruction → neural network
- CMS CSV:
  - vertex significance and energy-based likelihood ratio

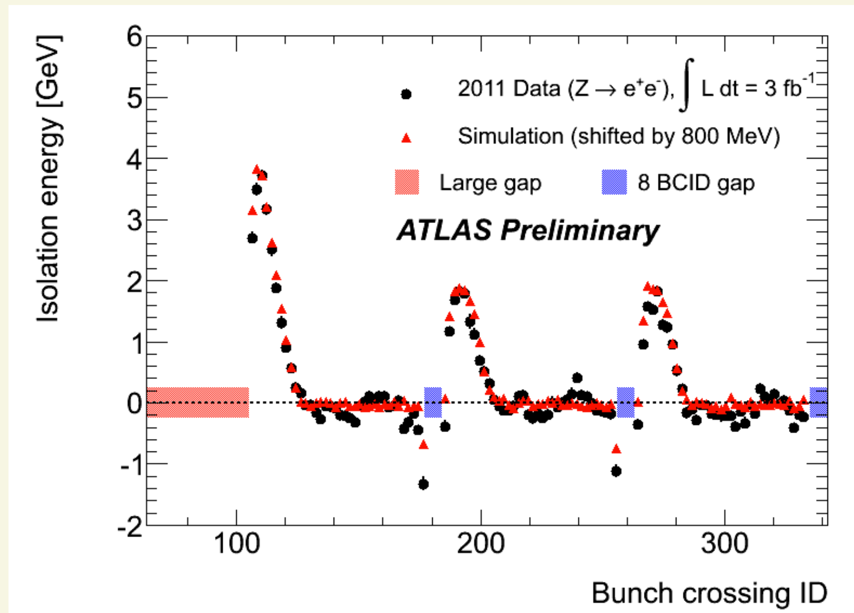
# pileup



easily 20 interactions per crossing
in 2012 datasets
ATLAS calorimeter especially sensitive!
Example: isolation

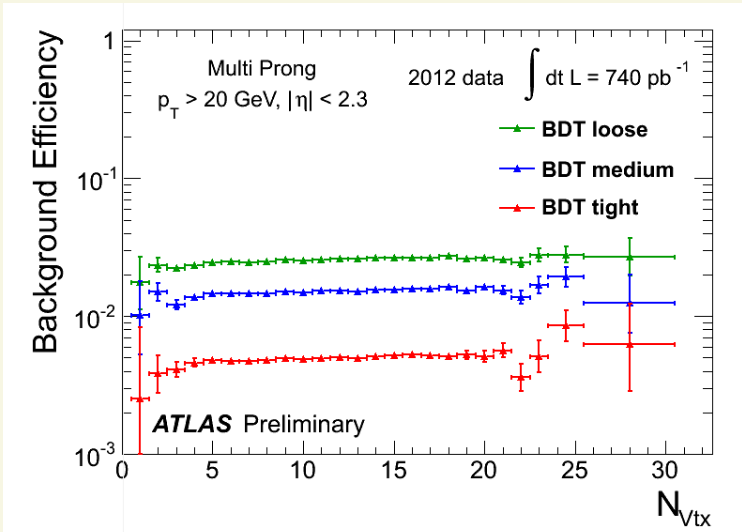



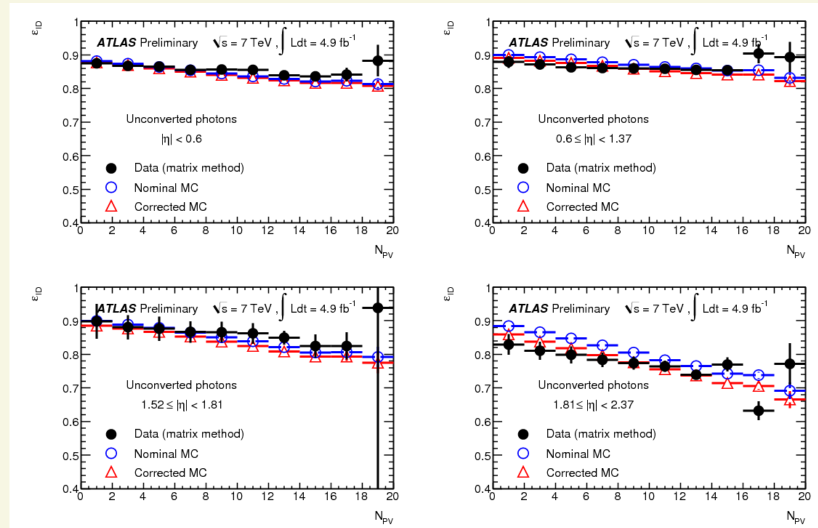
ATLAS Online √s = 8 TeV
Single BCID
BCID Average
Peak Interactions per Crossing
Day in 2012
30/03
01/05
03/06
06/07

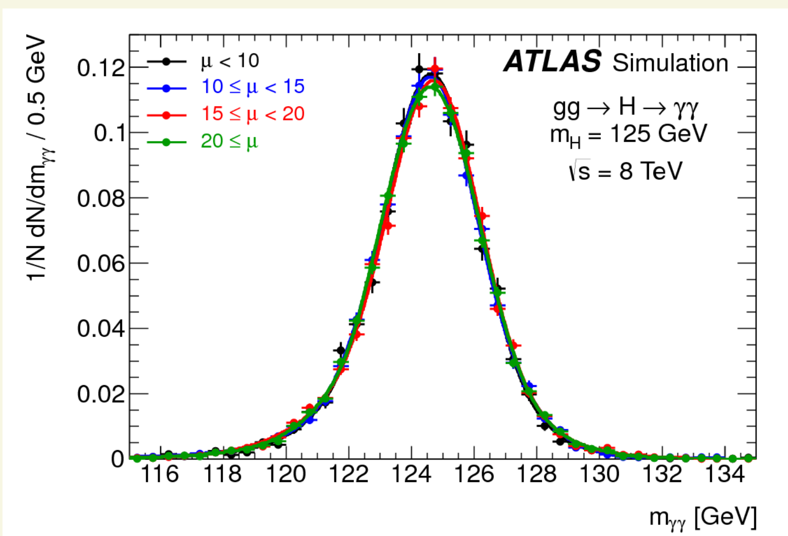



2011 Data (Z → e+e-), ∫ L dt = 3 fb-1
Simulation (shifted by 800 MeV)
Large gap
8 BCID gap
ATLAS Preliminary
Isolation energy [GeV]
Bunch crossing ID

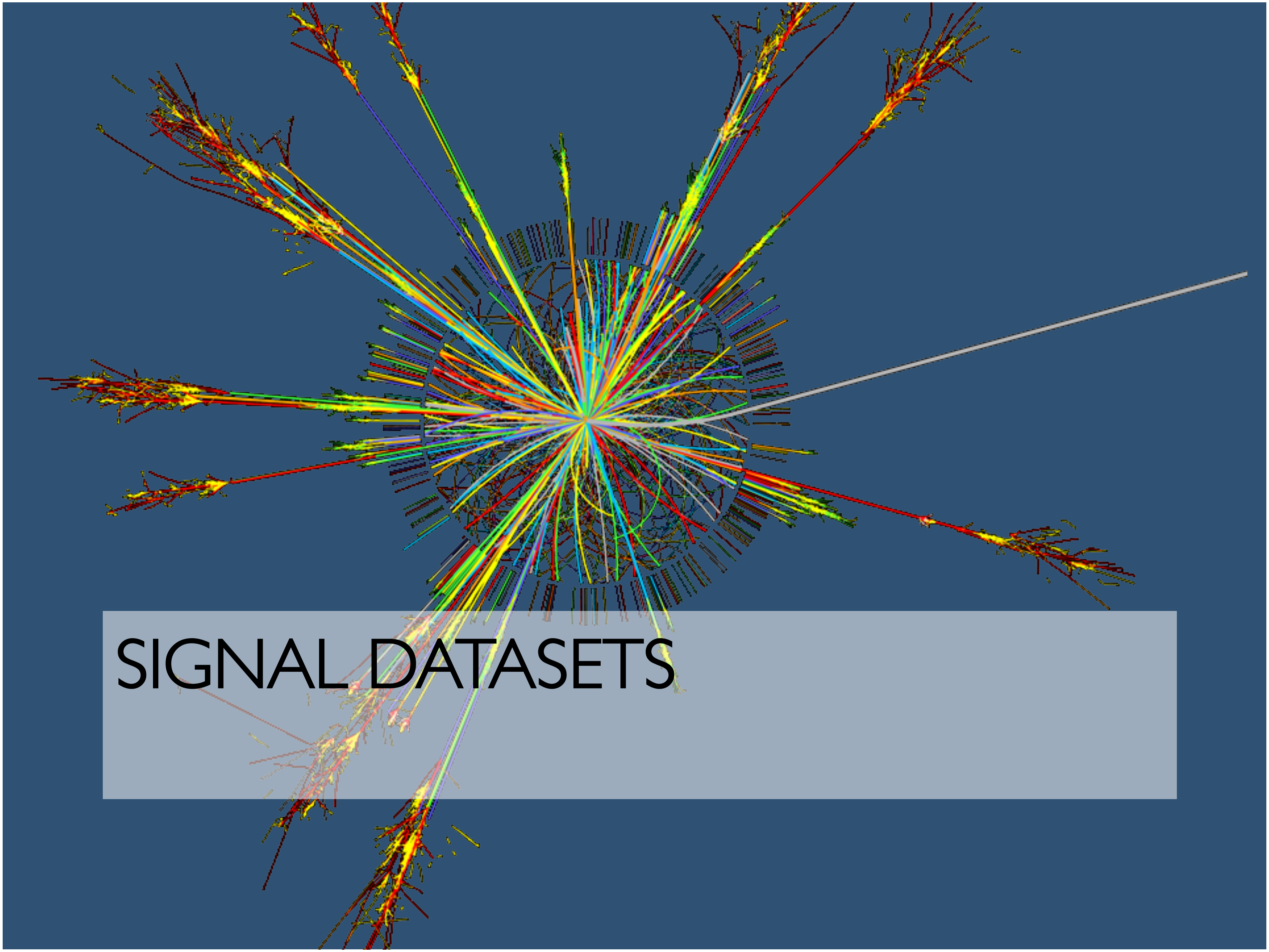
# pileup performance



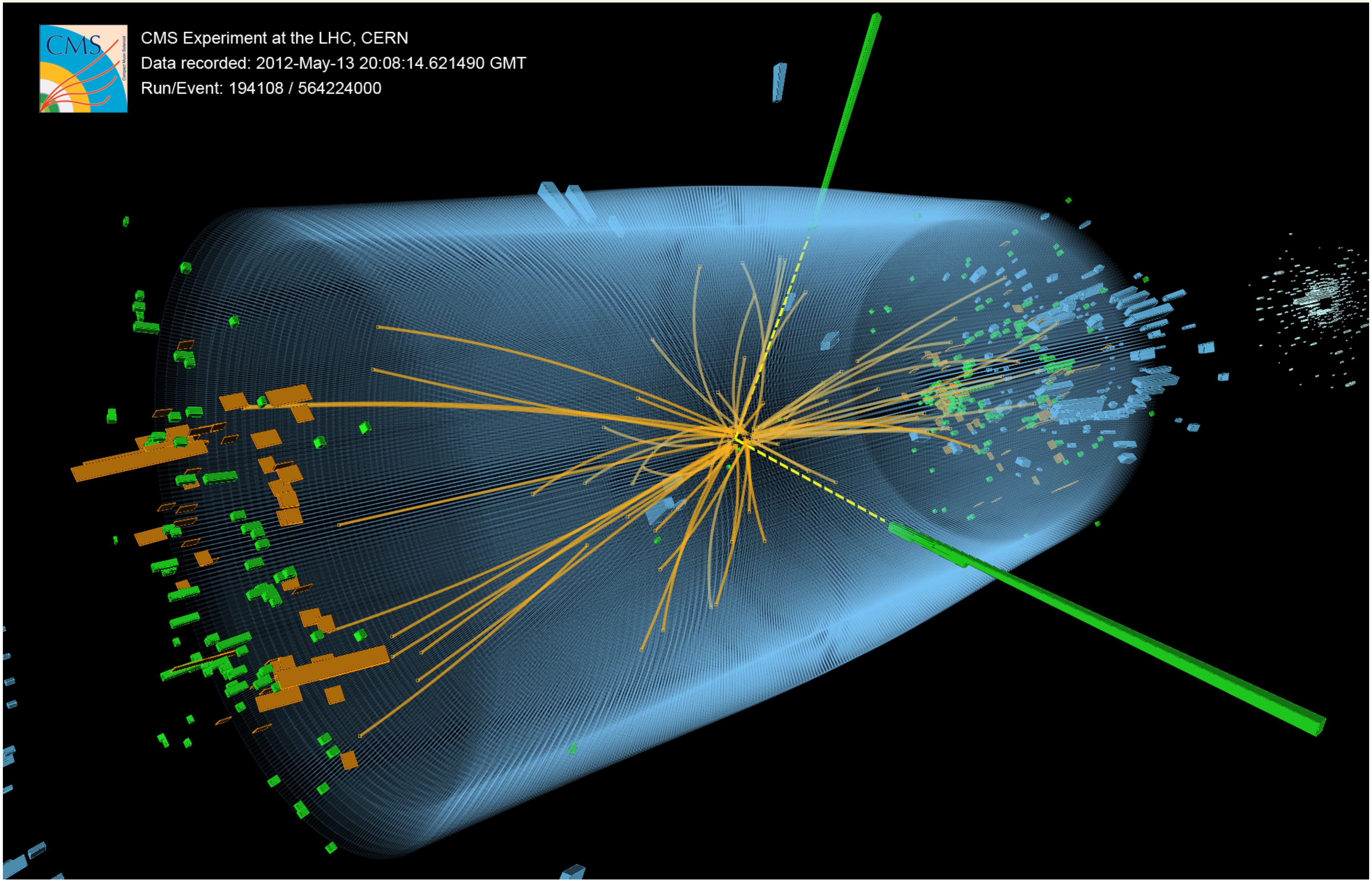




current techniques control pileup effects for at least 20 interactions

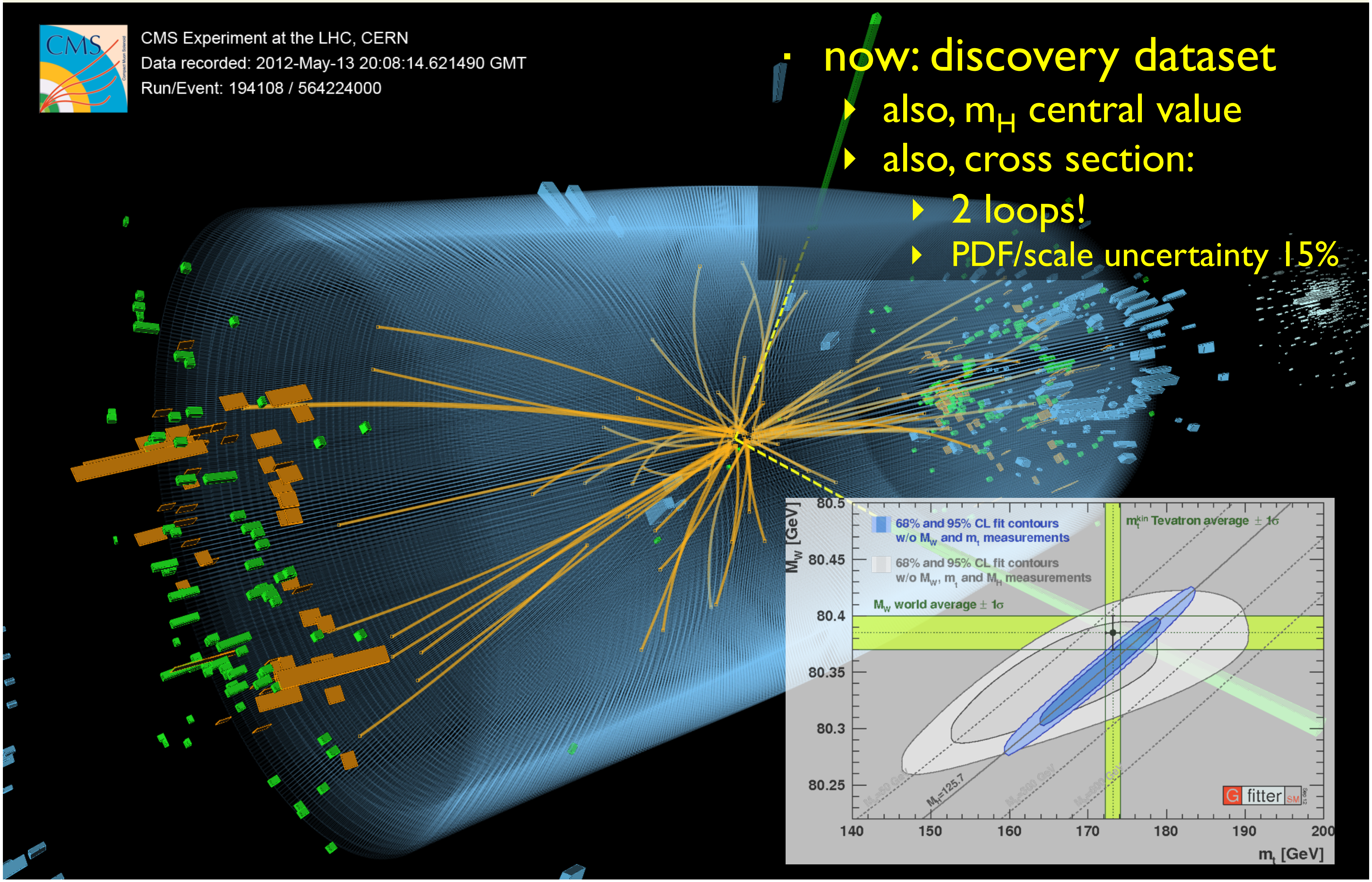


# SIGNAL DATASETS

# Diphoton channel

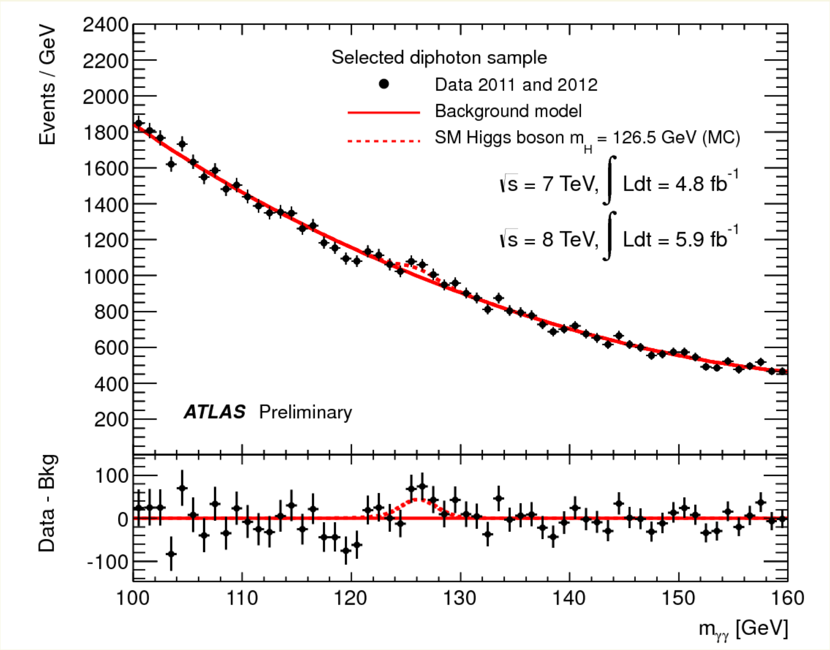


# Diphoton channel



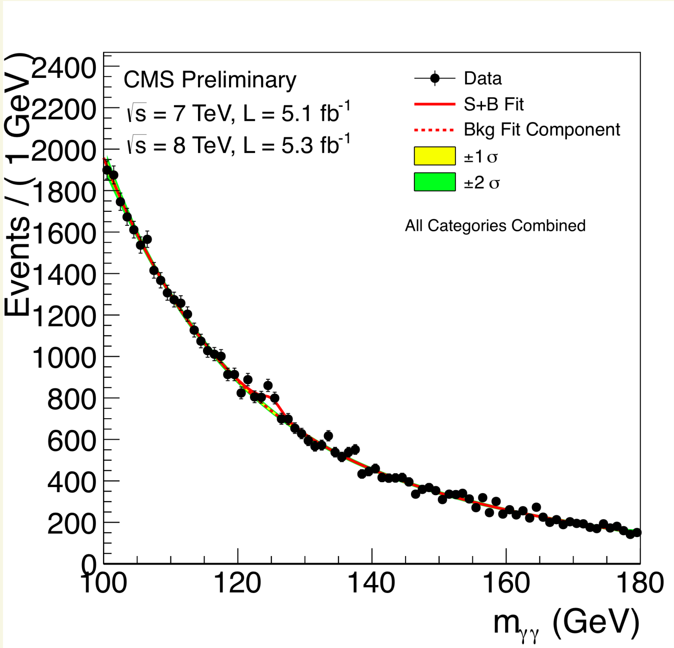

- now: discovery dataset
  - also, $m_H$ central value
  - also, cross section:
    - 2 loops!
    - PDF/scale uncertainty 15%

# Diphoton channel




- ATLAS
  - photon $E_T$ thresholds: > (40,35)
  - background mostly irreducible:
    - about 20% *fake* photons
    - fit with 4th degree polynomial

- CMS
  - tighter cuts at high mass:
    - photon $E_T$ > (m/3,m/4)
  - MVA event selection
    - removes additional 76% of photon background



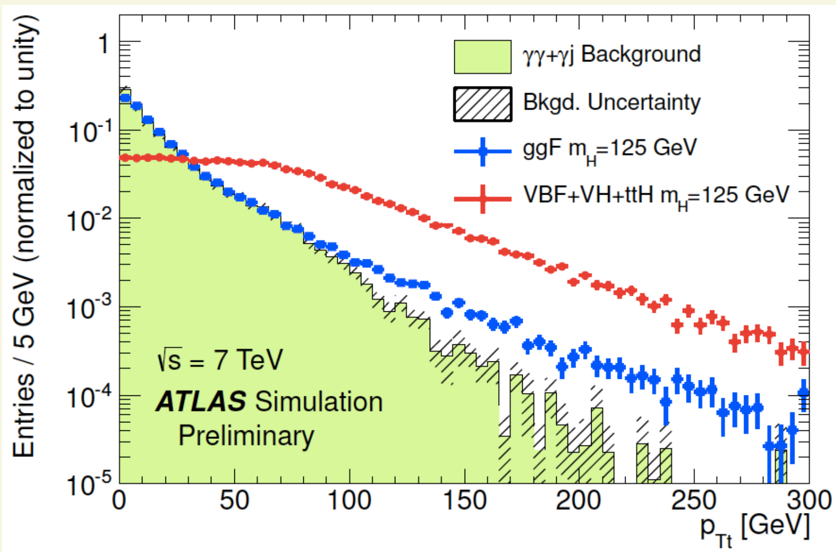

***expect***: *~110-140 GeV exclusion*

***Observe***: *excess! 4.5 (4.1) σ **local** significance.*

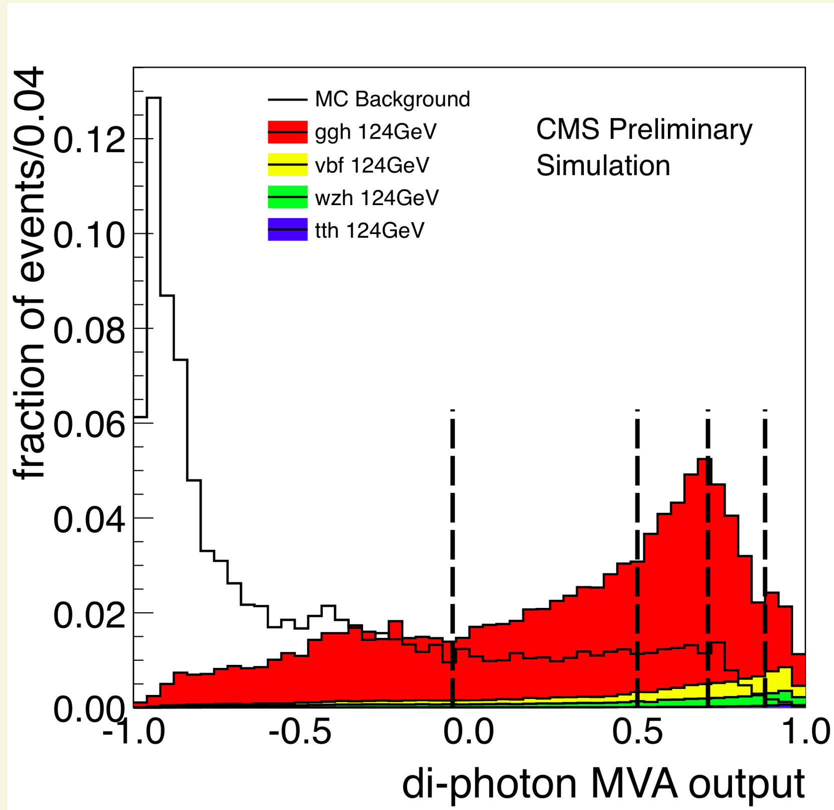
# Diphoton event weights

$$p_{Tt} = \frac{2\vec{p_T}_1 \times \vec{p_T}_2}{|\vec{p_T}_1 - \vec{p_T}_2|}$$

(correlated to diphoton $p_T$)

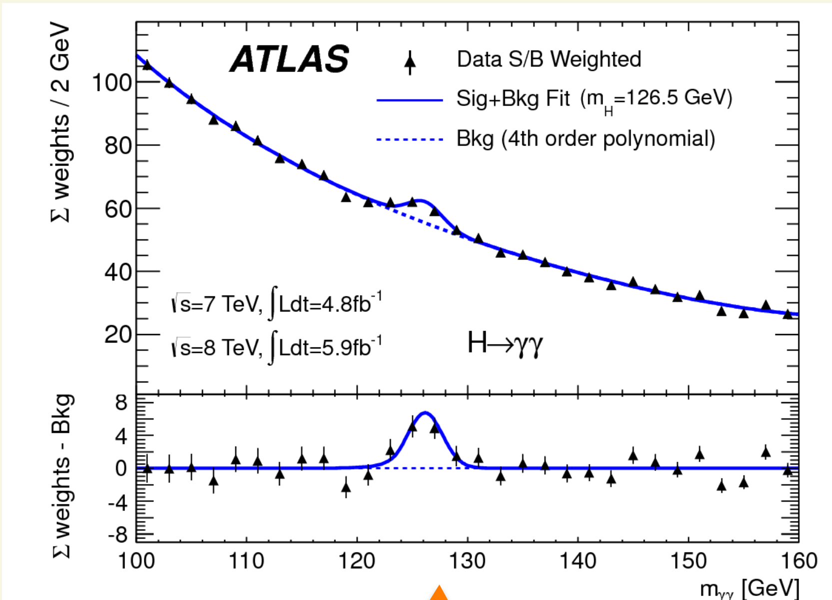



$$w_i = S_i / B_i$$



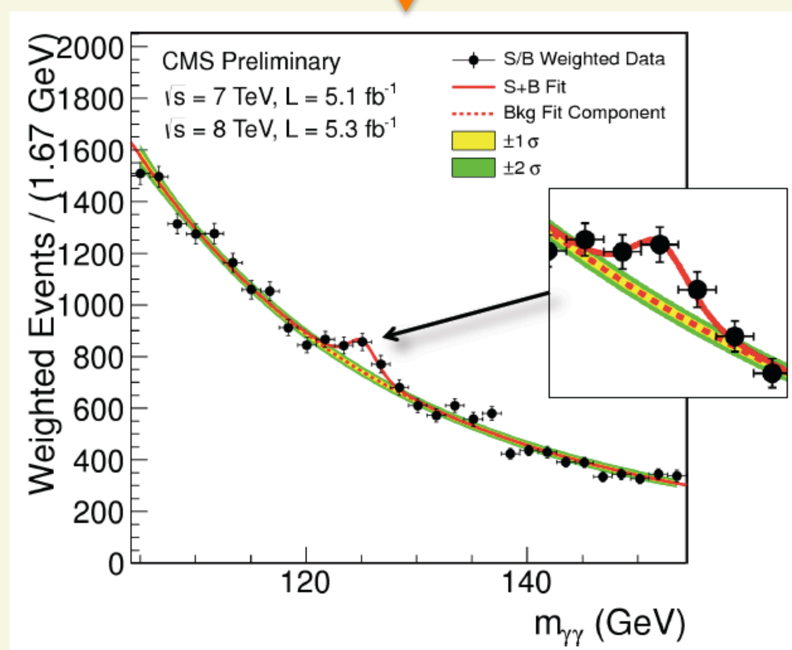

decision tree output:
photon ID quality, angles, energy ratios.

# Diphoton results, weighted

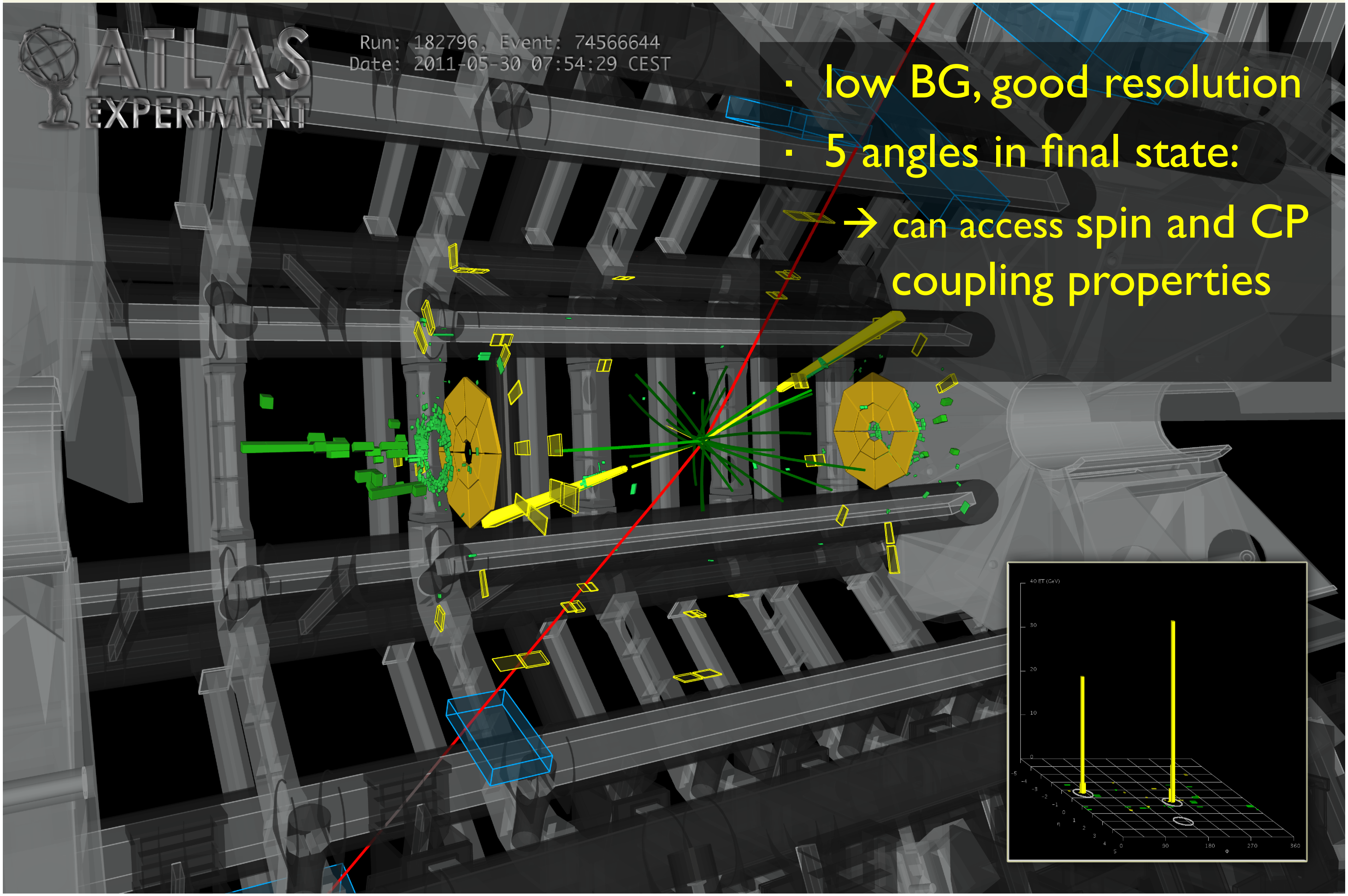



- local significance
  - 4.6 σ (→3.6 σ, look-elsewhere)
- signal shape represents 1.6 GeV diphoton mass resolution

- local significance
  - 4.1 σ (→3.2 σ, look-elsewhere)
- fitted width 1.2 GeV (best category)



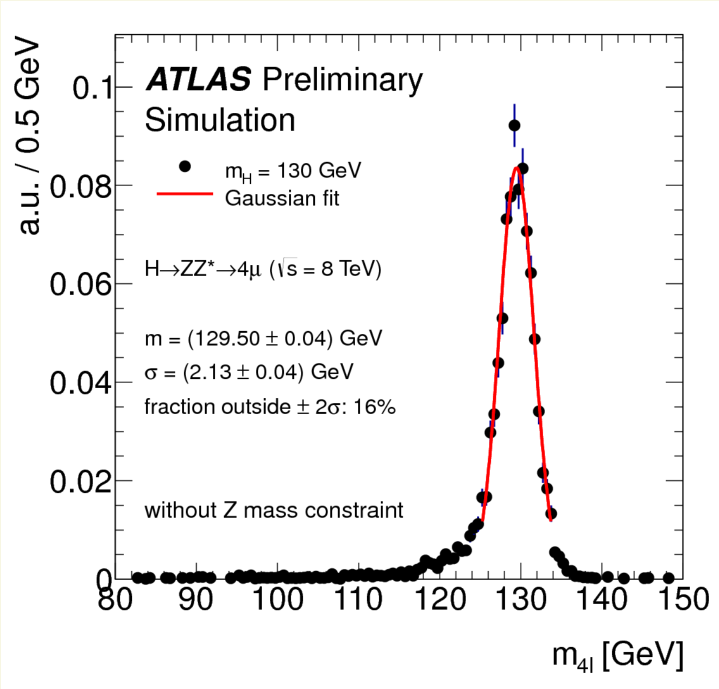
# ZZ* channel




- low BG, good resolution
- 5 angles in final state:
  - → can access spin and CP coupling properties

# ZZ* channel: selection

- Virtual! mZ* ≳12 GeV
  - requires soft lepton thresholds!
  - reject hadron resonances: mass > 5 GeV
- CMS
  - Z1:40-120 GeV, Z2: 12-120 GeV
  - matrix element analysis
- ATLAS
  - $Z_1$: 50-106 GeV, $Z_2$: 17.5-115 GeV (mass dependent)




- Z-mass constraints applied when reasonable:
  - Expected resolution 1.8-2.5 GeV after constraint

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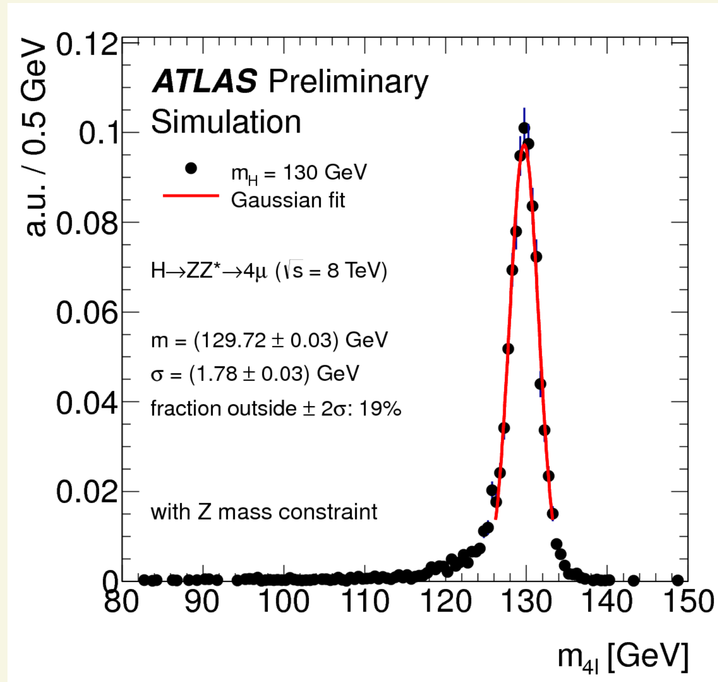


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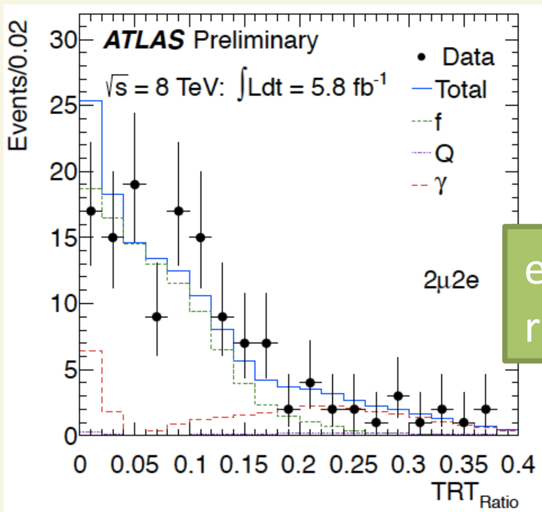
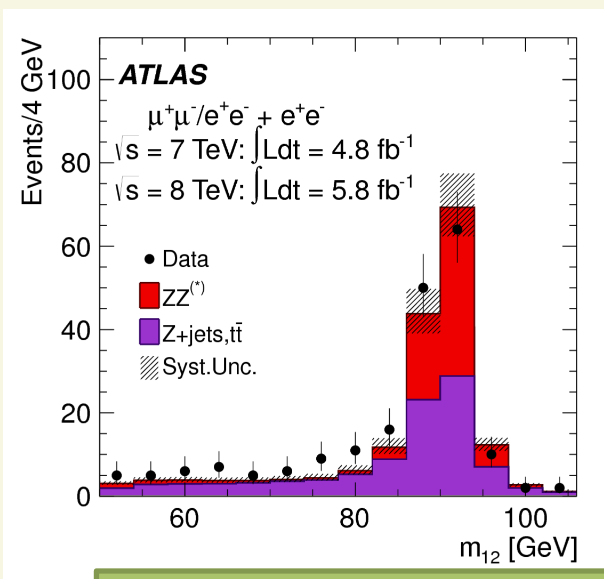
# ZZ* channel: backgrounds

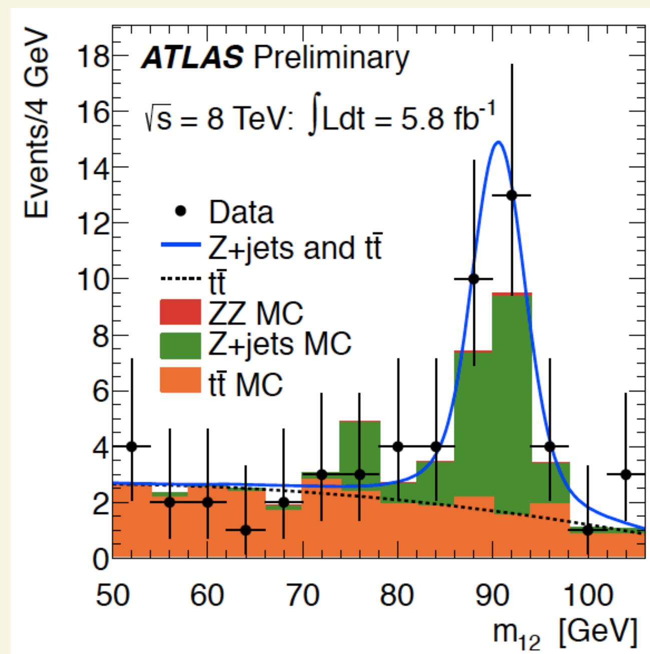
- Continuum ZZ*
- Z+jets (fake leptons)
- top-antitop (dilepton+ fakes)




electron fakes:
relax electron-ID cuts



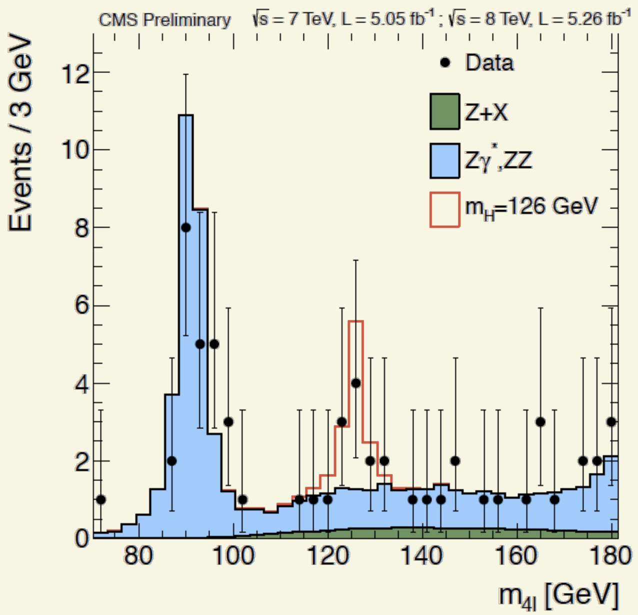

top events: fit leading “Z” mass

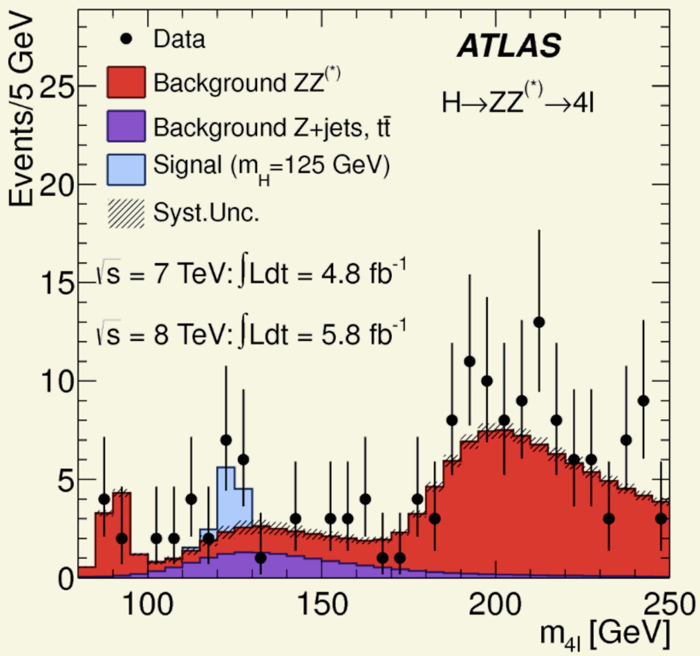


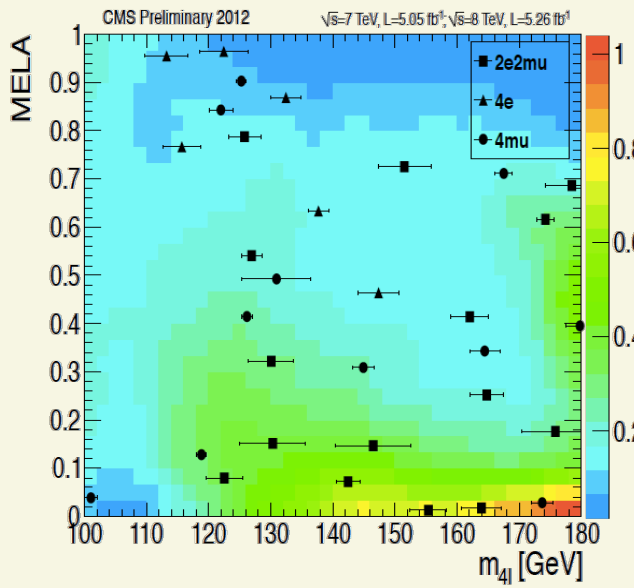

muon fakes: invert “prompt” cut

# ZZ channel: results

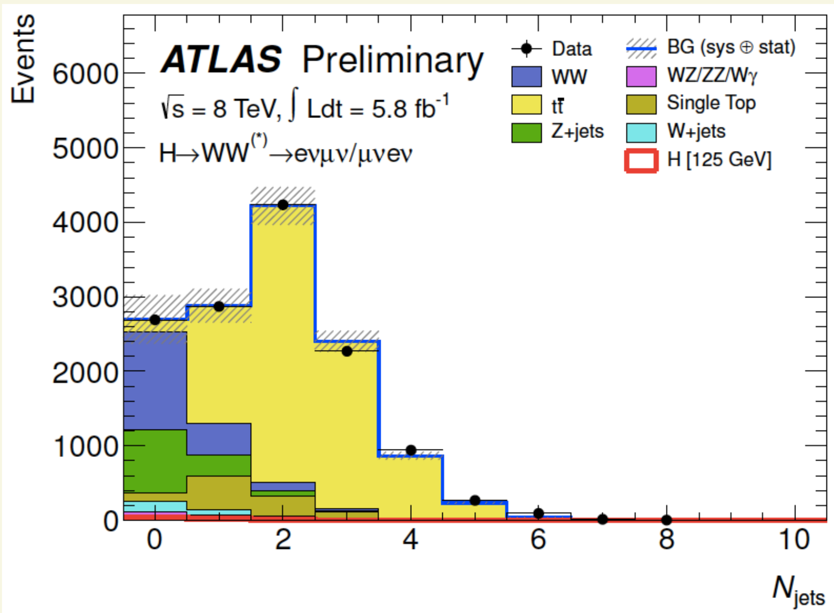
- local significance:
  - $3.4\,\sigma \rightarrow 2.5\,\sigma$ (ATLAS)
  - $3.2\,\sigma$ CMS
    - note: CP odd could be distinguished at $1.6\,\sigma$



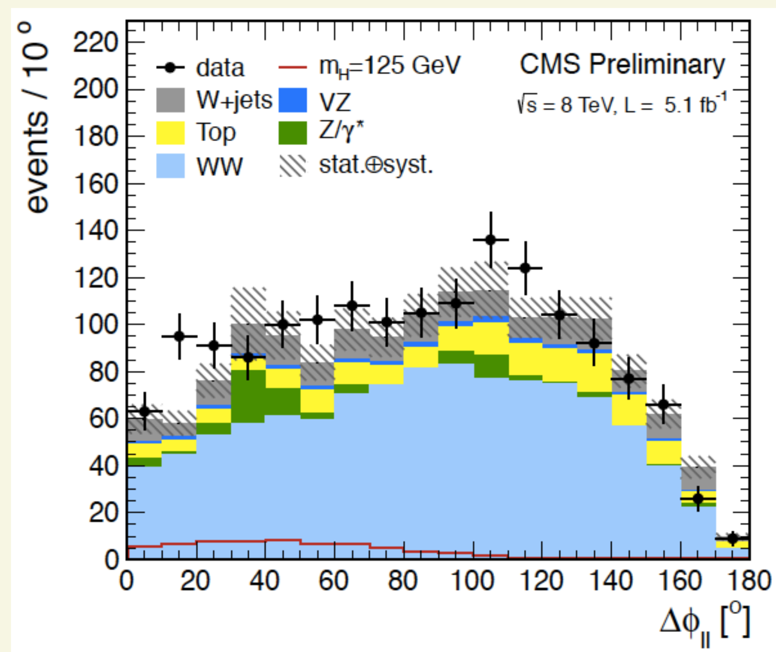



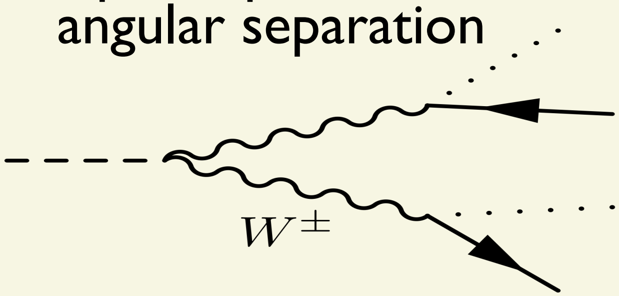
# WW*




- Large backgrounds, poor mass resolution:
  - b-tagging, kinematics for $t\bar{t}$
  - wrong-sign for W+jets
  - high-$m_{ll}$, large $\phi_{ll}$ for WW
  - Remainder: pure simulation

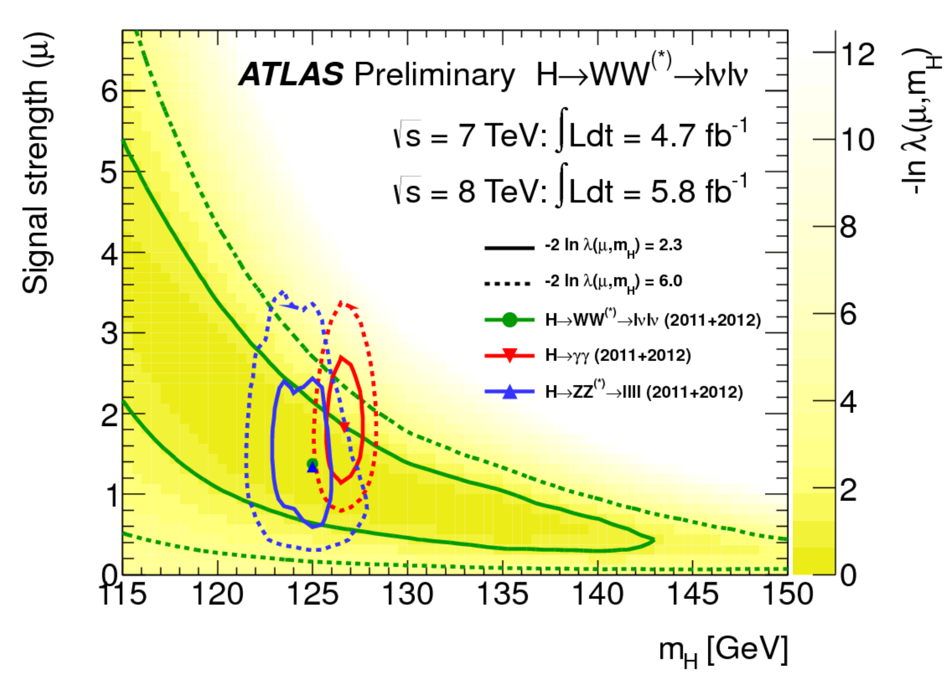


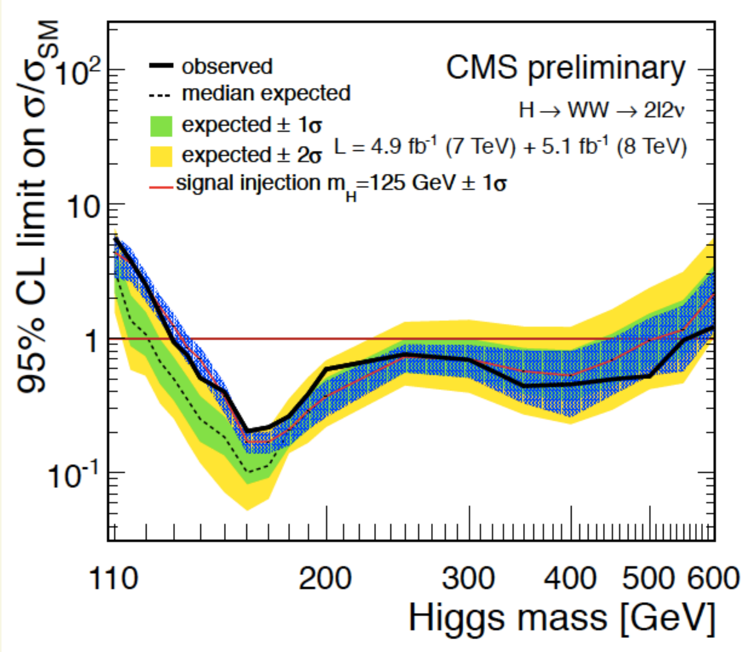

- W as spin analyzer:
  - leptons produced at small angular separation



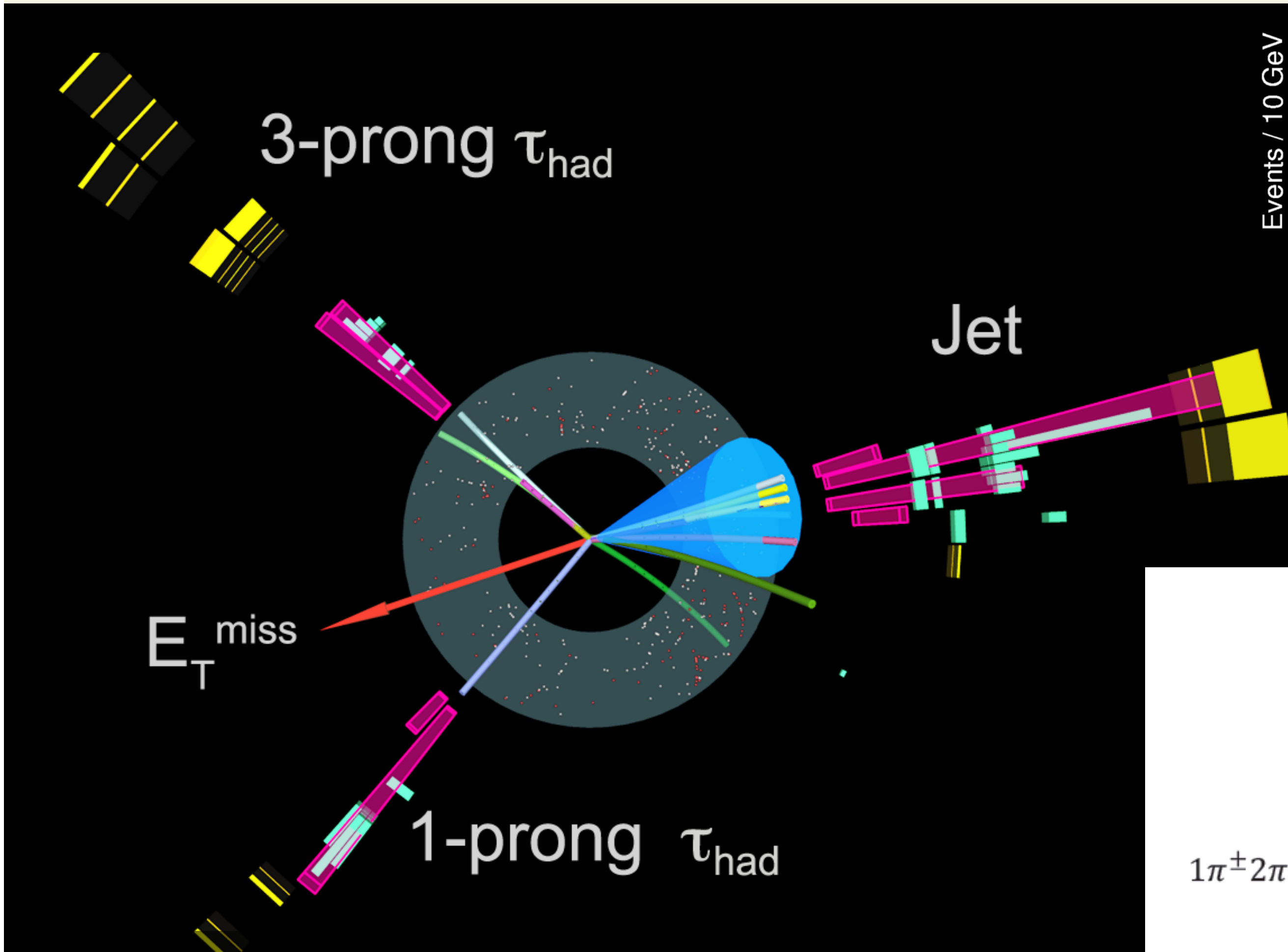
# WW*

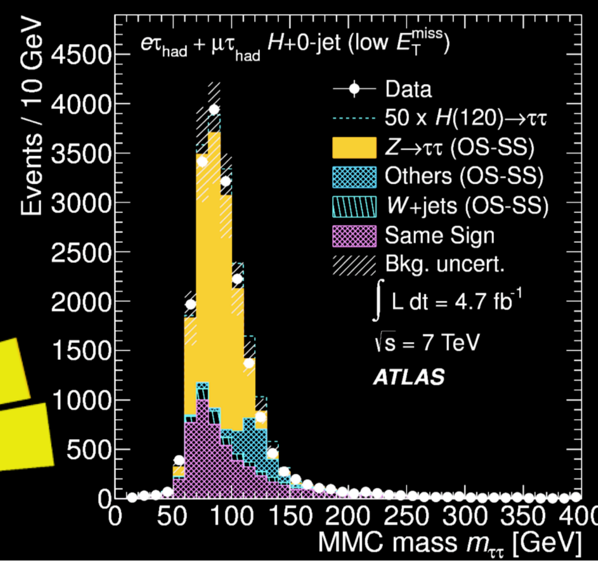
- ATLAS: Require *relative* $E_T$miss > 25 GeV:
  - transverse component to nearest lepton or jet (within d$\phi$ < $\pi$/2)
- Fit $m_T$ distribution: $m_T = \sqrt{(E_T(\ell\ell) + E_T(\text{miss}))^2 - |\vec{p}_T(\ell\ell) + \vec{p}_T(\text{miss})|^2}$

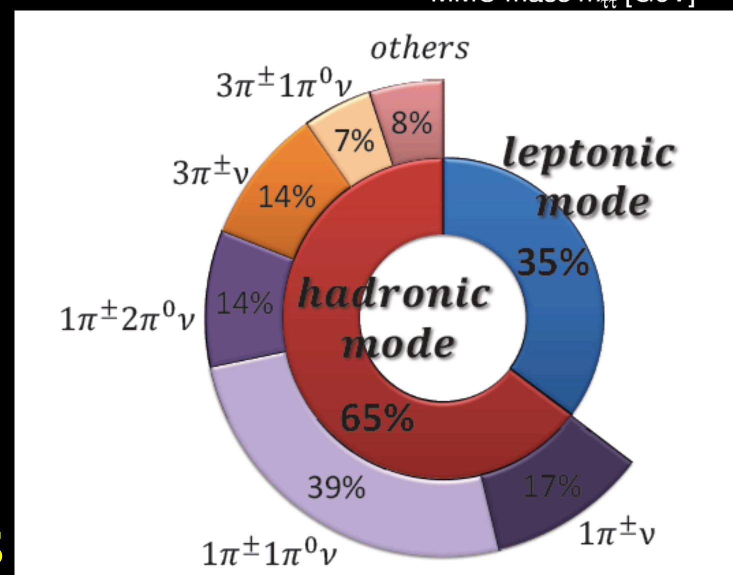


# $H \rightarrow \tau\tau$



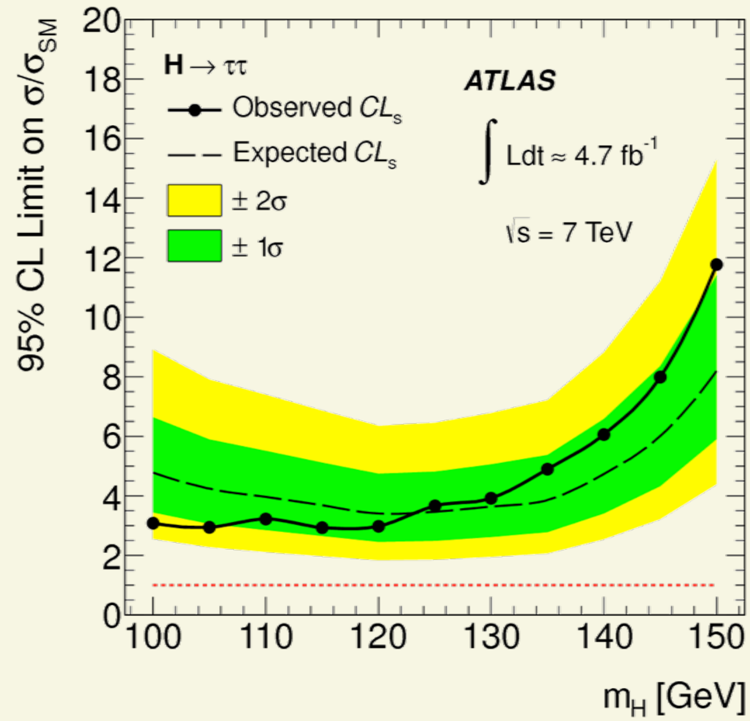




- verify fermion coupling!
- access many production channels

# $H \rightarrow \tau\tau$

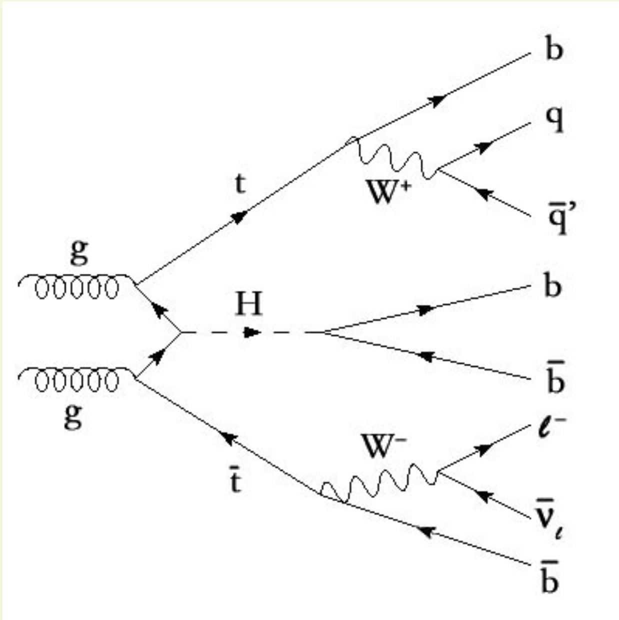
- lots of categories:
  - (3 tau-pair decays) x (gluon fusion, boosted, VBF, VH)
- most sensitive: "boosted" $\tau_h\tau_h$, but all < 0.03 S/B
- $Z\tau\tau$ is the largest background:
  - modeled by *embedding*

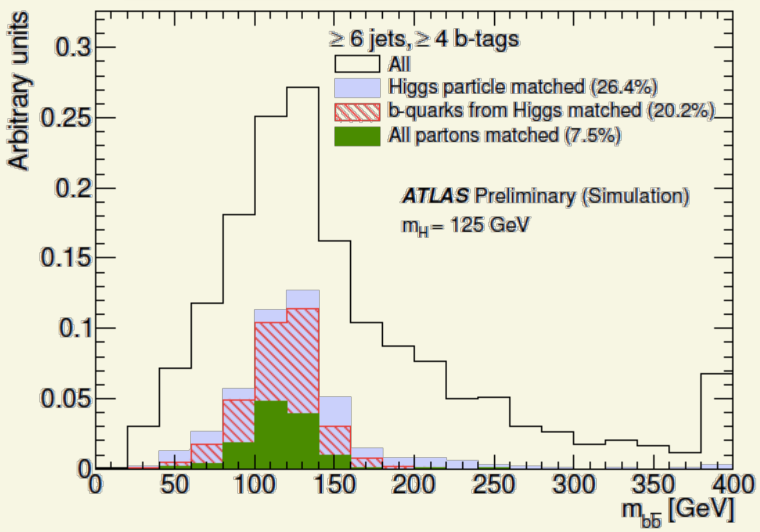


# top-associated production

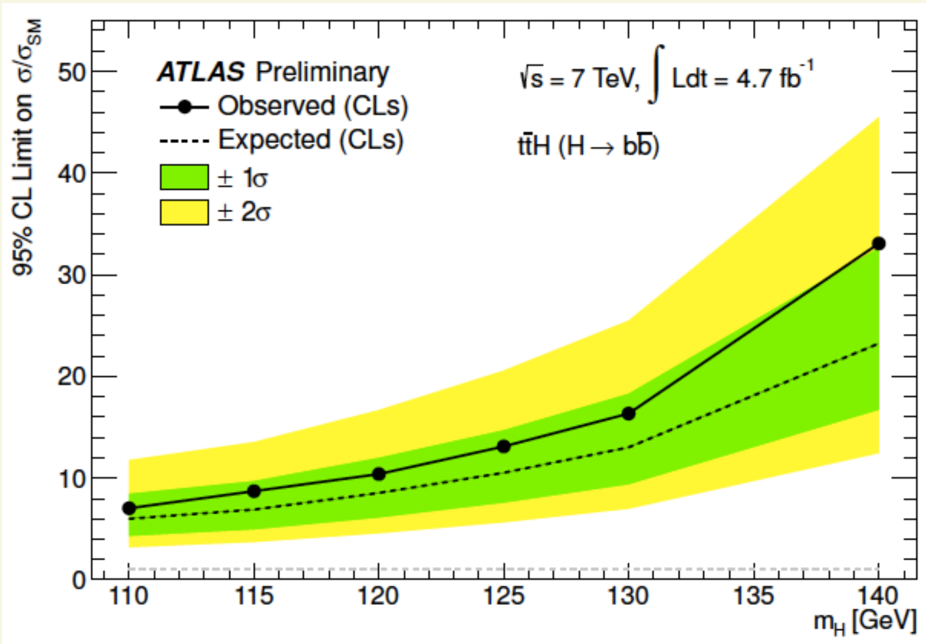
*direct* test of large top-Higgs coupling

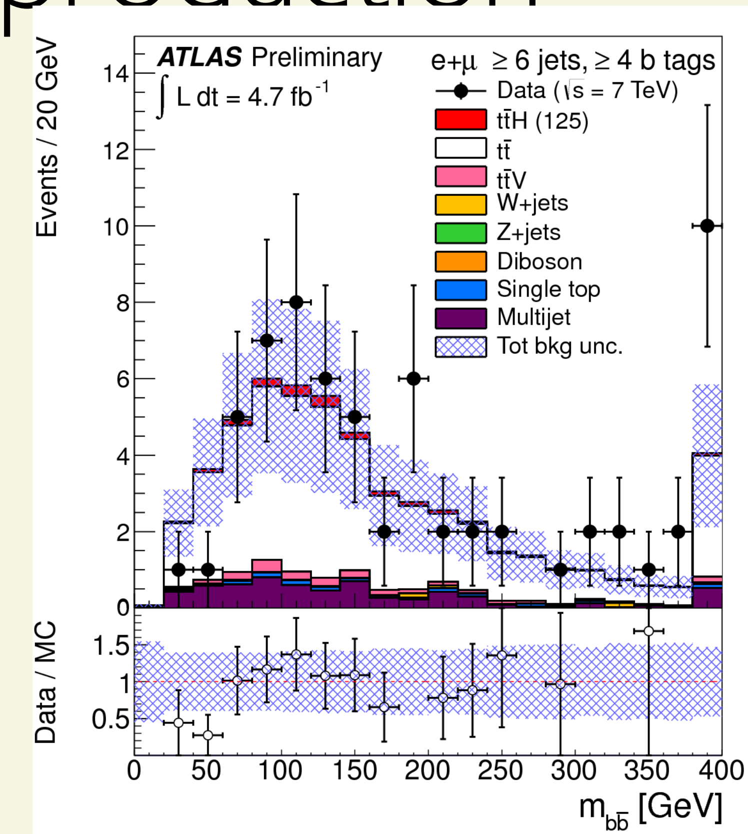
- combinatorial challenge:
  - correct pair among 4 b-tagged jets
  - ATLAS kinematic likelihood fit gets correct daughters in 20% of events
- acceptance: allow fewer jets/tags
  - use $H_T$ instead of $m_{bb}$



# top-associated production




- ATLAS (lepton+jets): KL classification, then fit distribution
  - loose limits (< 13 x SM) at 125 GeV
- CMS (lepton+jets + dilepton; ANN):
  - < 3.8 x SM at 125 GeV
  - ANN doubles expected sensitivity w.r.t ATLAS

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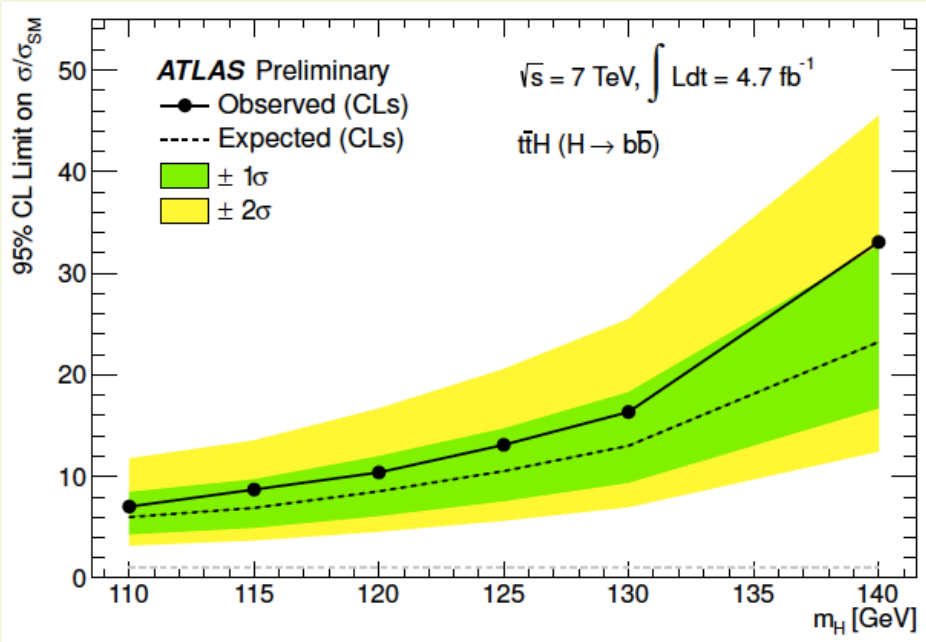


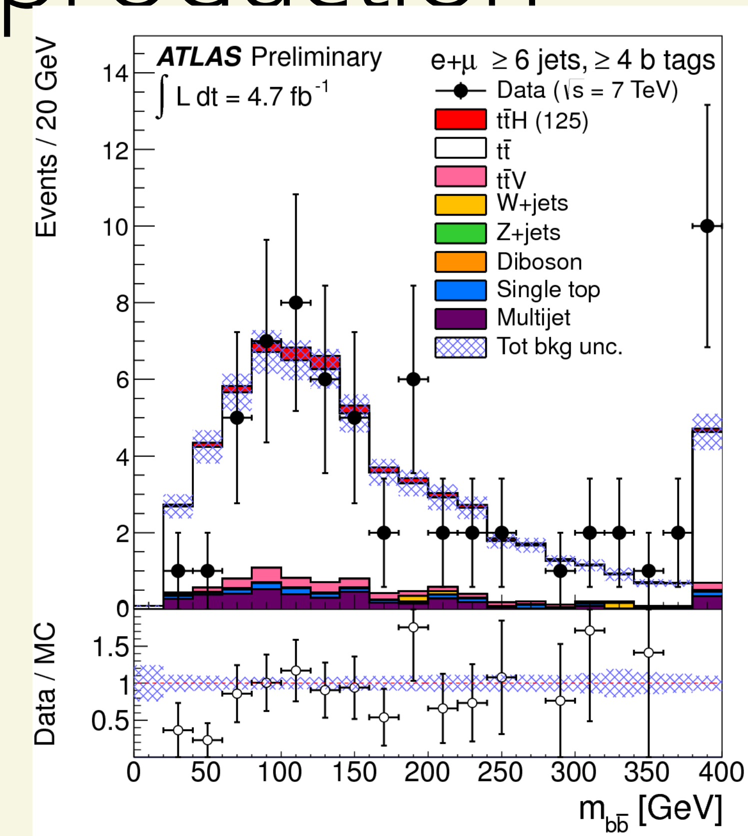


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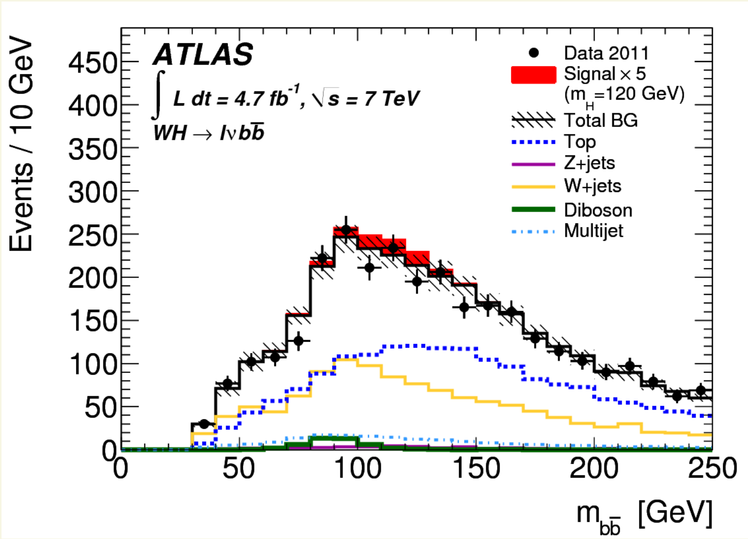
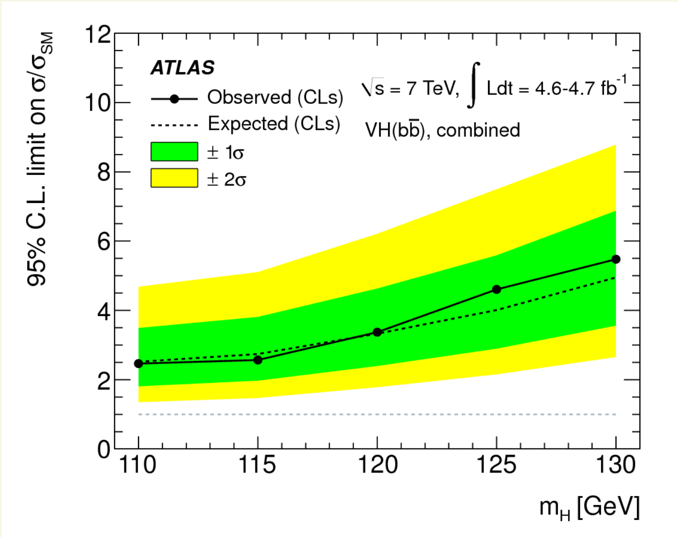
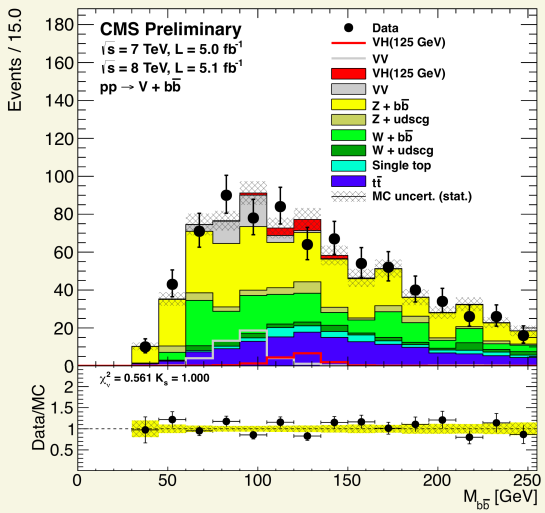
# VH with H→bb

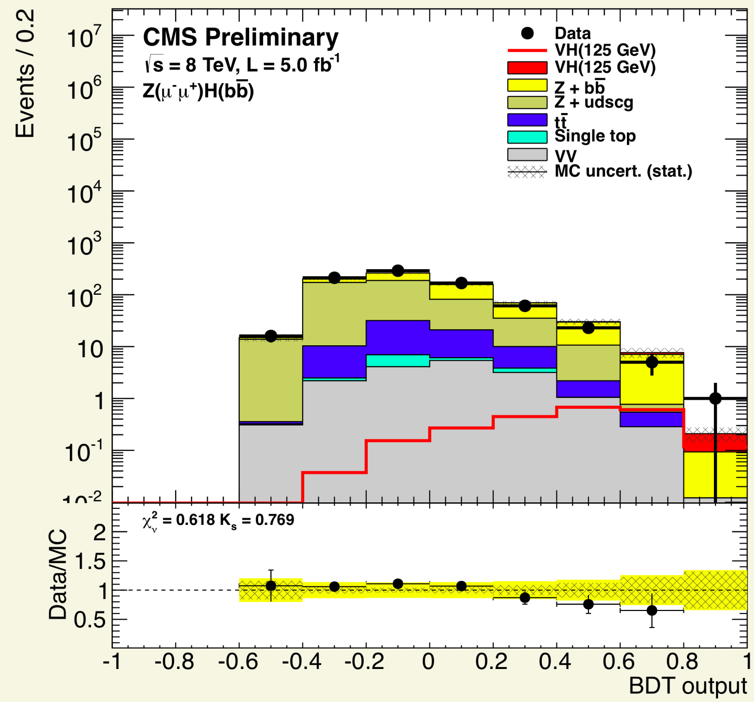
- Best way to observe key leptonic coupling
  - Tevatron evidence channel
- Simple reconstruction:
  - “standard” weak boson finding ($\ell\nu, \nu\nu, \ell\ell$)
  - 2 MV1 b-tagged jets $p_T$ > 25 GeV
- boson $p_T$ cut improves S/B
  - varies from 1/100 to 1/10
  - CMS exploits high $p_T$ region…
- highly-boosted analysis favored for 13 TeV
  - requires alternative Higgs reconstruction

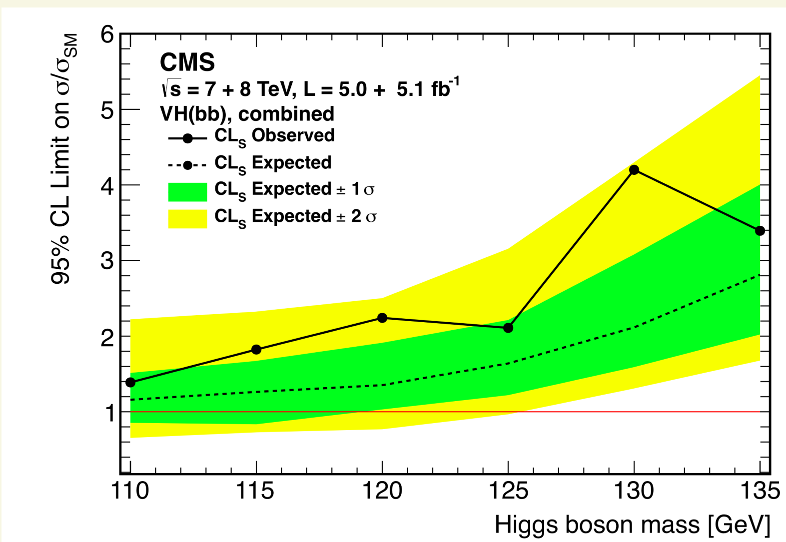


# boosted H→bb



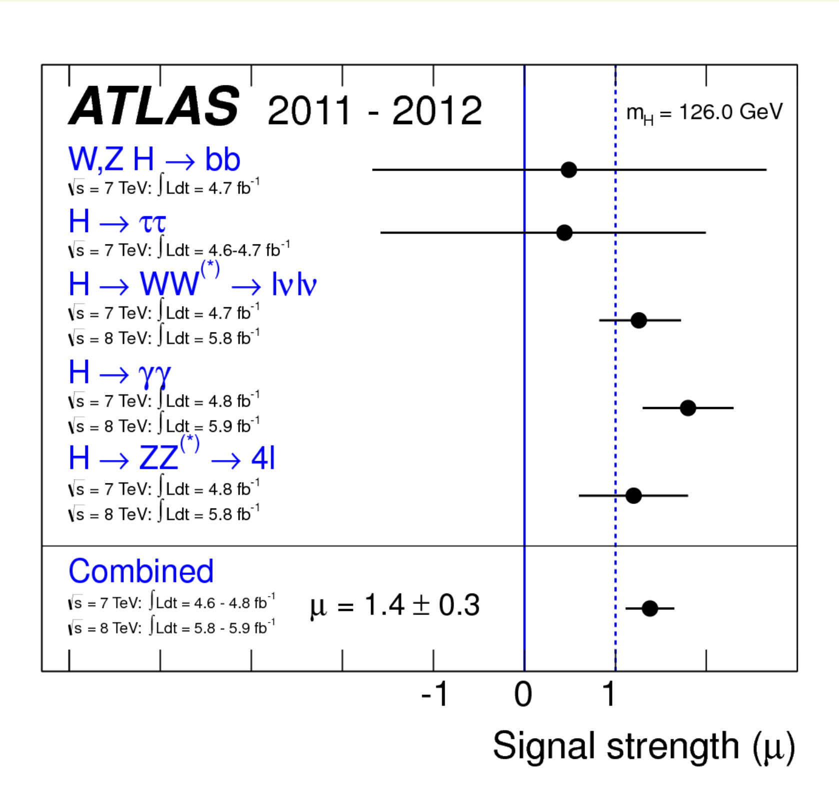



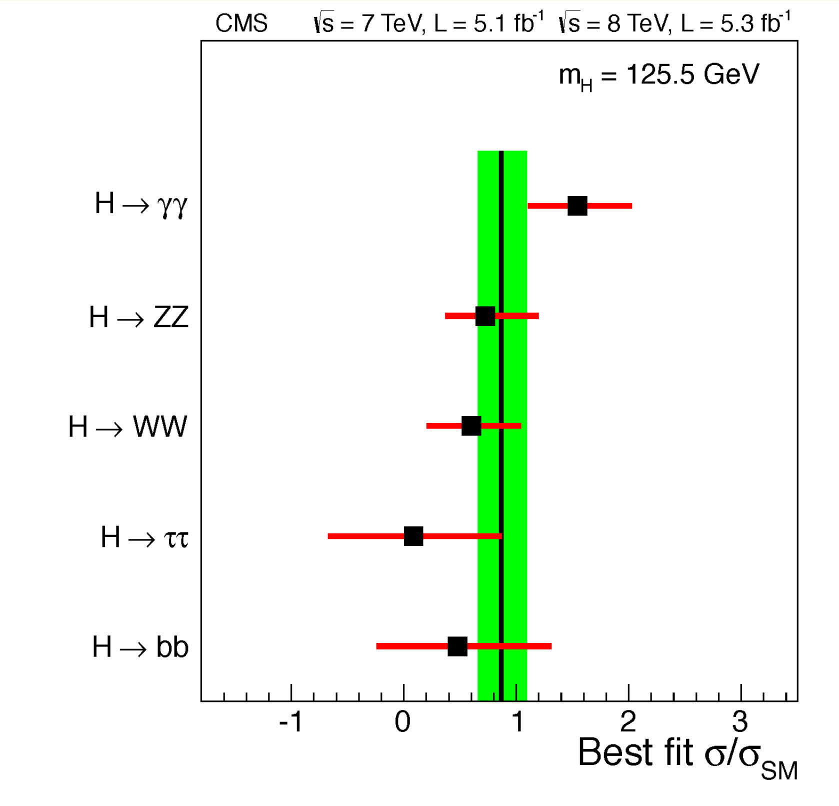

CMS:

merged jet categories not considered

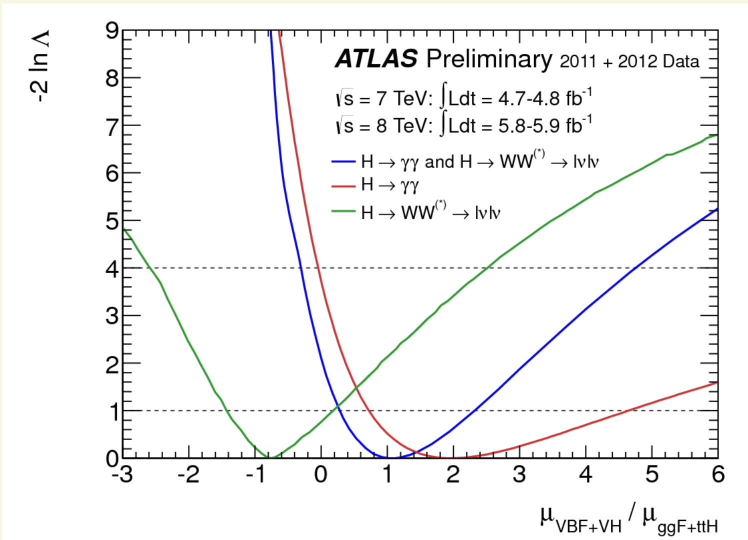
boosted decision tree includes
kinematics, jets, and *color flow*

# Summary: status of signal strength

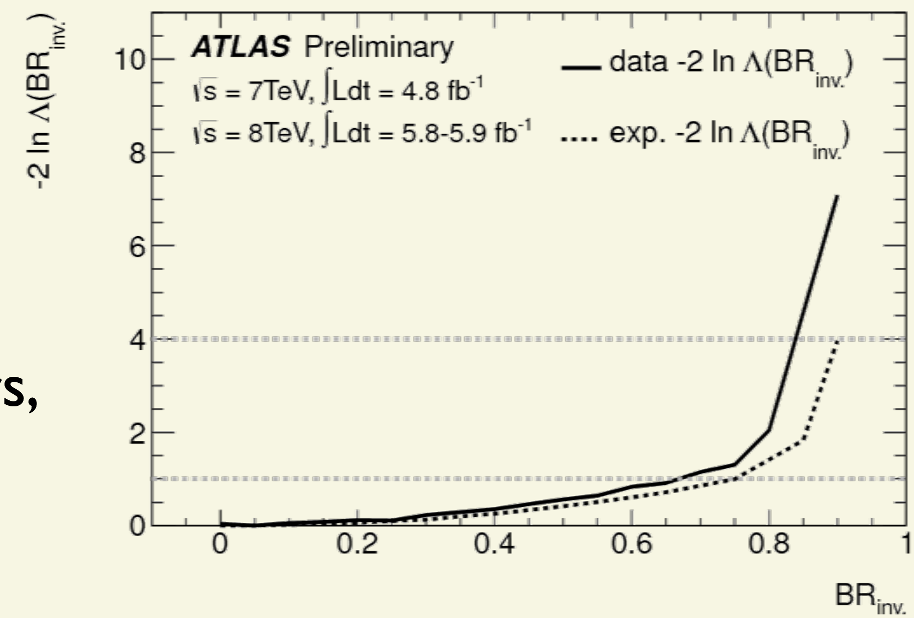


# SM properties




- very first *comparisons* of signal strength of different processes:
  - no significant deviation from SM

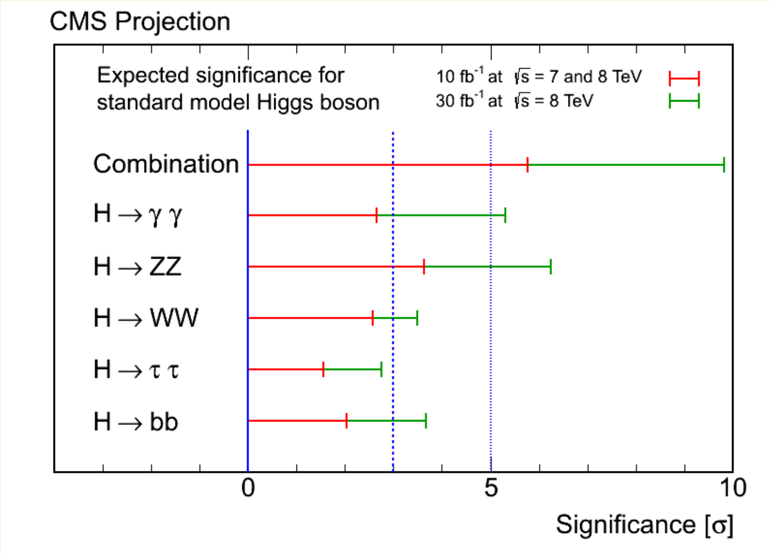



- Invisible particles?
  - float gg, $\gamma\gamma$ vertex factors, fixing other couplings
  - BR < 0.84 at 95% CL

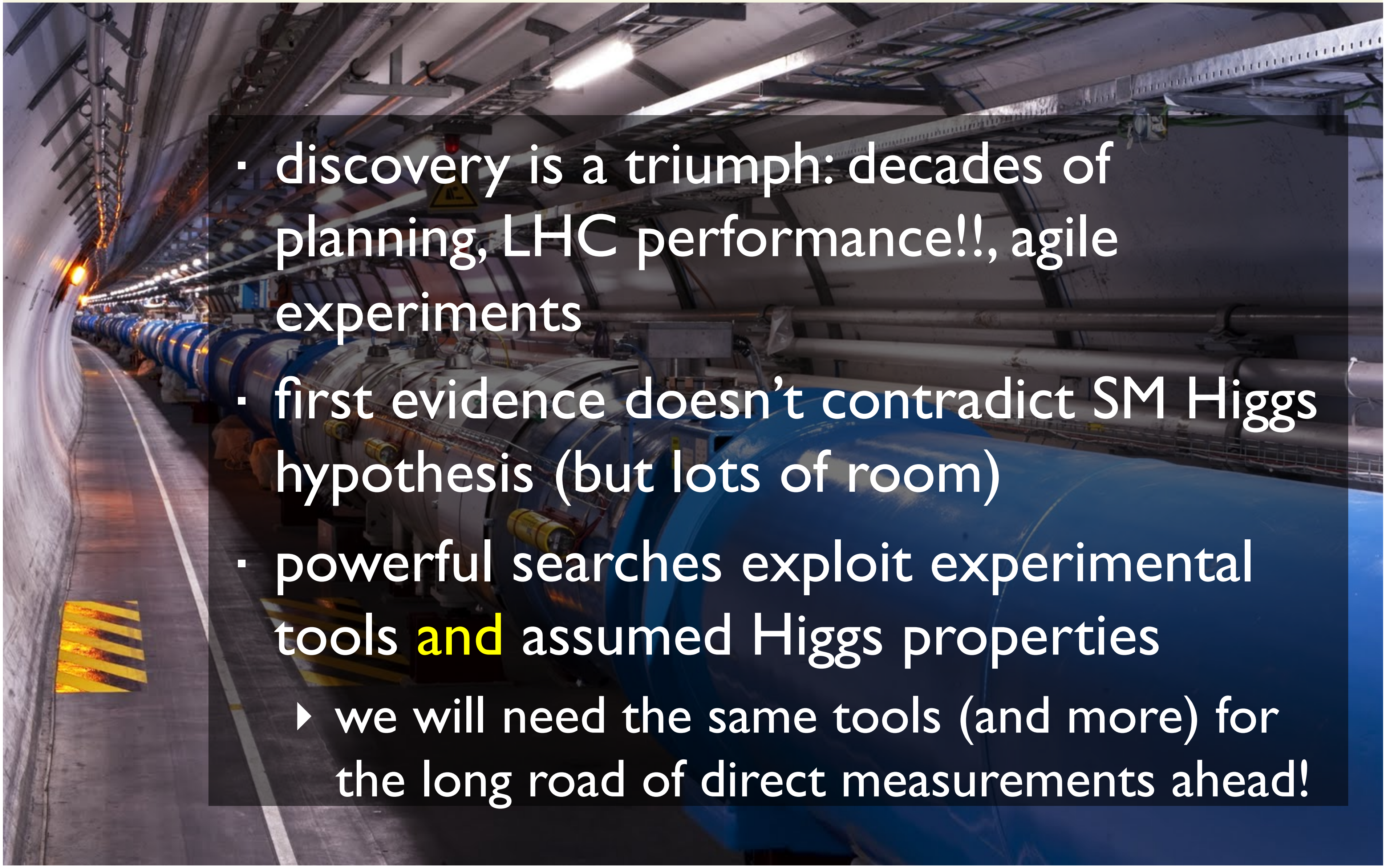
# near-term prospects

| ATLAS best signal categories (today) | | |
|---|---|---|
| **Process** | **exp. signal** | **background (90% mass window)** |
| H→$\gamma\gamma$ | 150 | 6820 |
| H→$\gamma\gamma$ (VBF) | 5 | 24 |
| H→ZZ→4ℓ | 6 | 5 |
| H→WW | 77 | 667 |
| H→$\tau\tau$ (VBF) | 1.2 | 22 |
| ZH→Zbb | 4 | 321 |
| ttH (best) | 2 | 62 |

- Hints of lepton couplings with 2012 data: likely
  - MVA would help
- CMS: near 3 $\sigma$ CP determination in ZZ* channel?



# conclusions



- discovery is a triumph: decades of planning, LHC performance!!, agile experiments
- first evidence doesn't contradict SM Higgs hypothesis (but lots of room)
- powerful searches exploit experimental tools and assumed Higgs properties
  - we will need the same tools (and more) for the long road of direct measurements ahead!