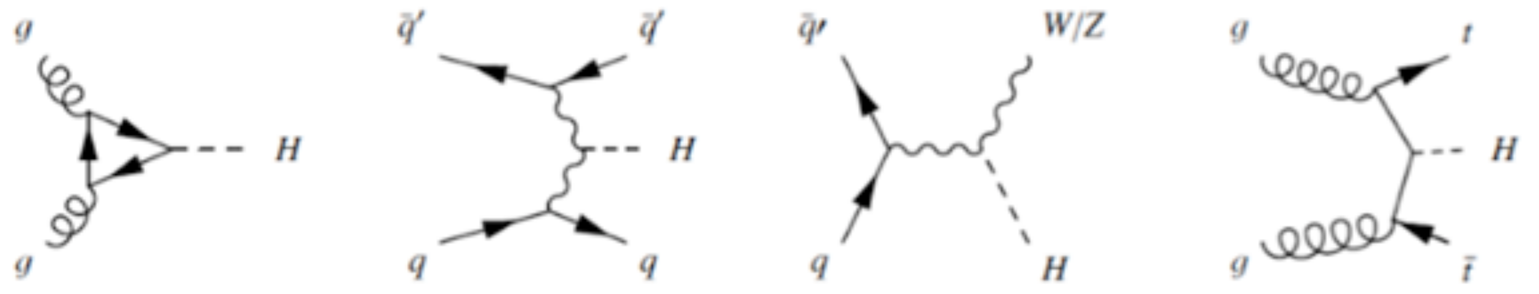
Searching for Invisibly Decaying Higgs Boson at the LHC

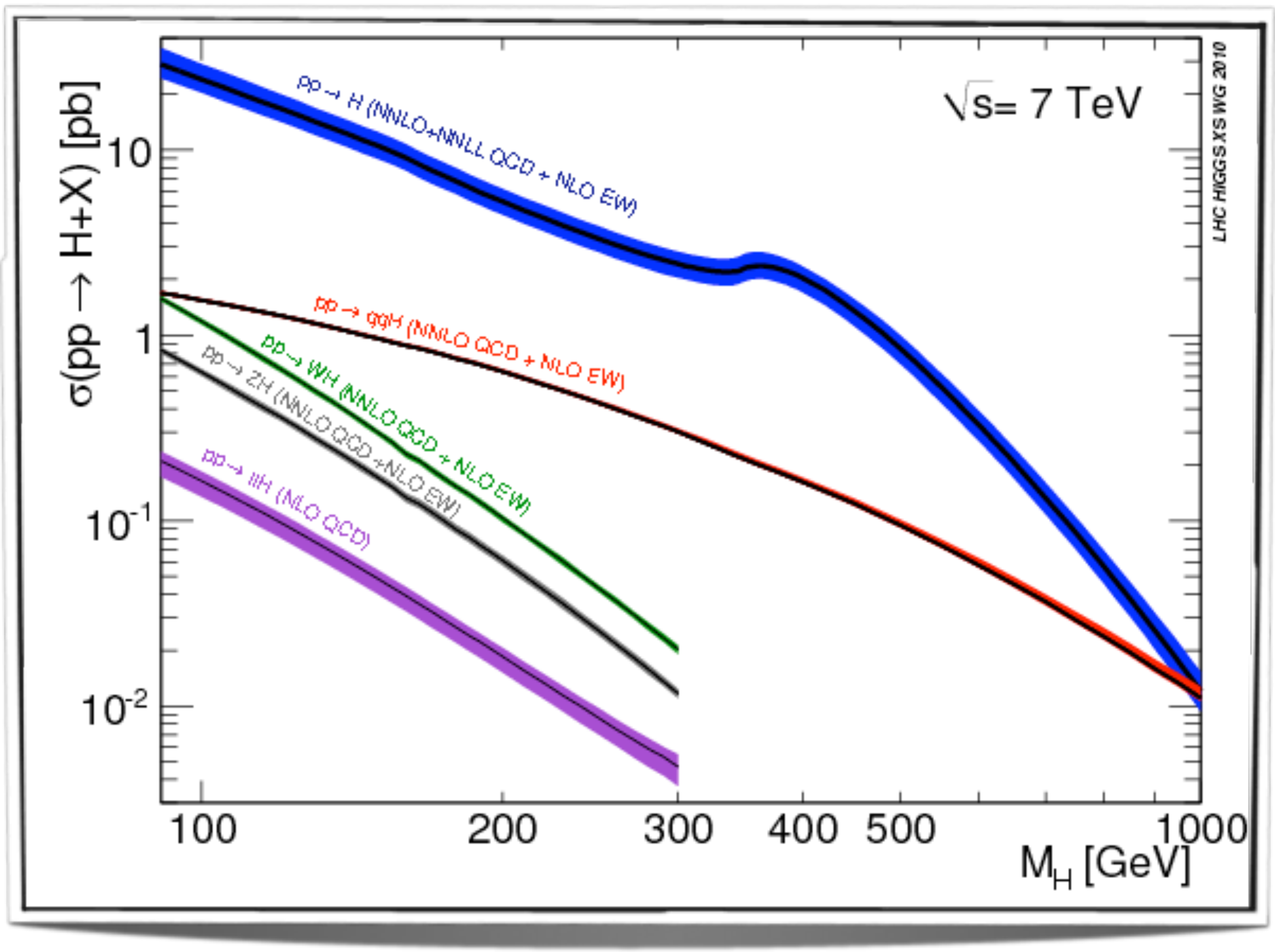
David Šálek
GRAPPA
http://grappa.science.uva.nl/

Dark Matter at the LHC
KICP workshop, Chicago

September 19-21, 2013

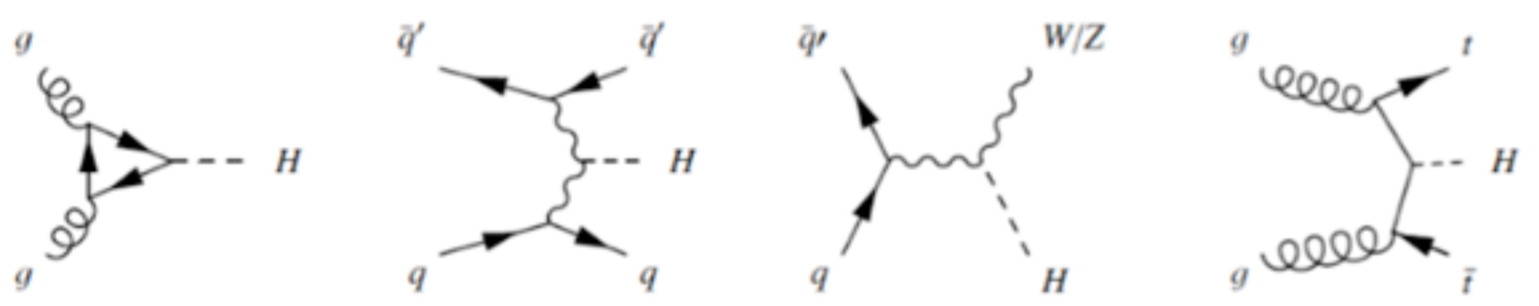
Invisibly decaying Higgs boson

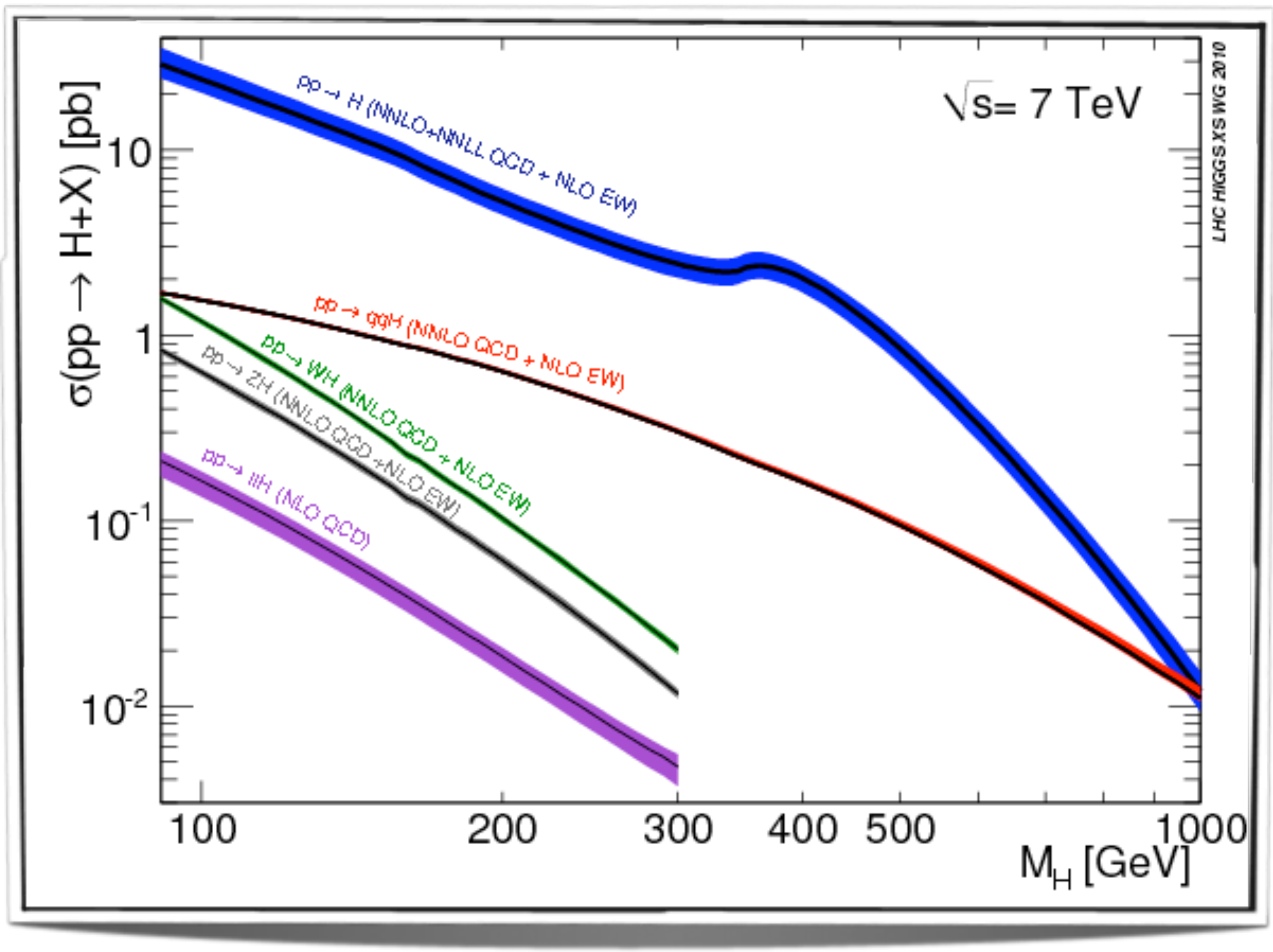




× BR(H→invisible)

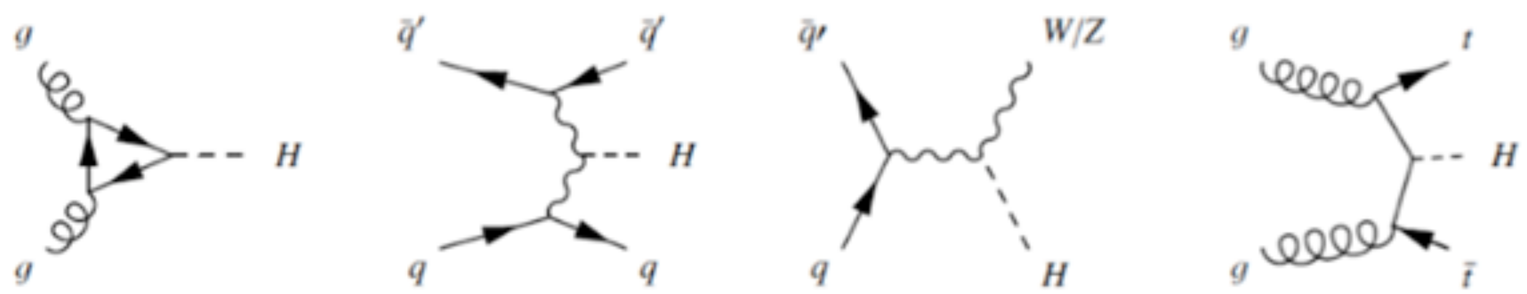
Invisibly decaying Higgs boson

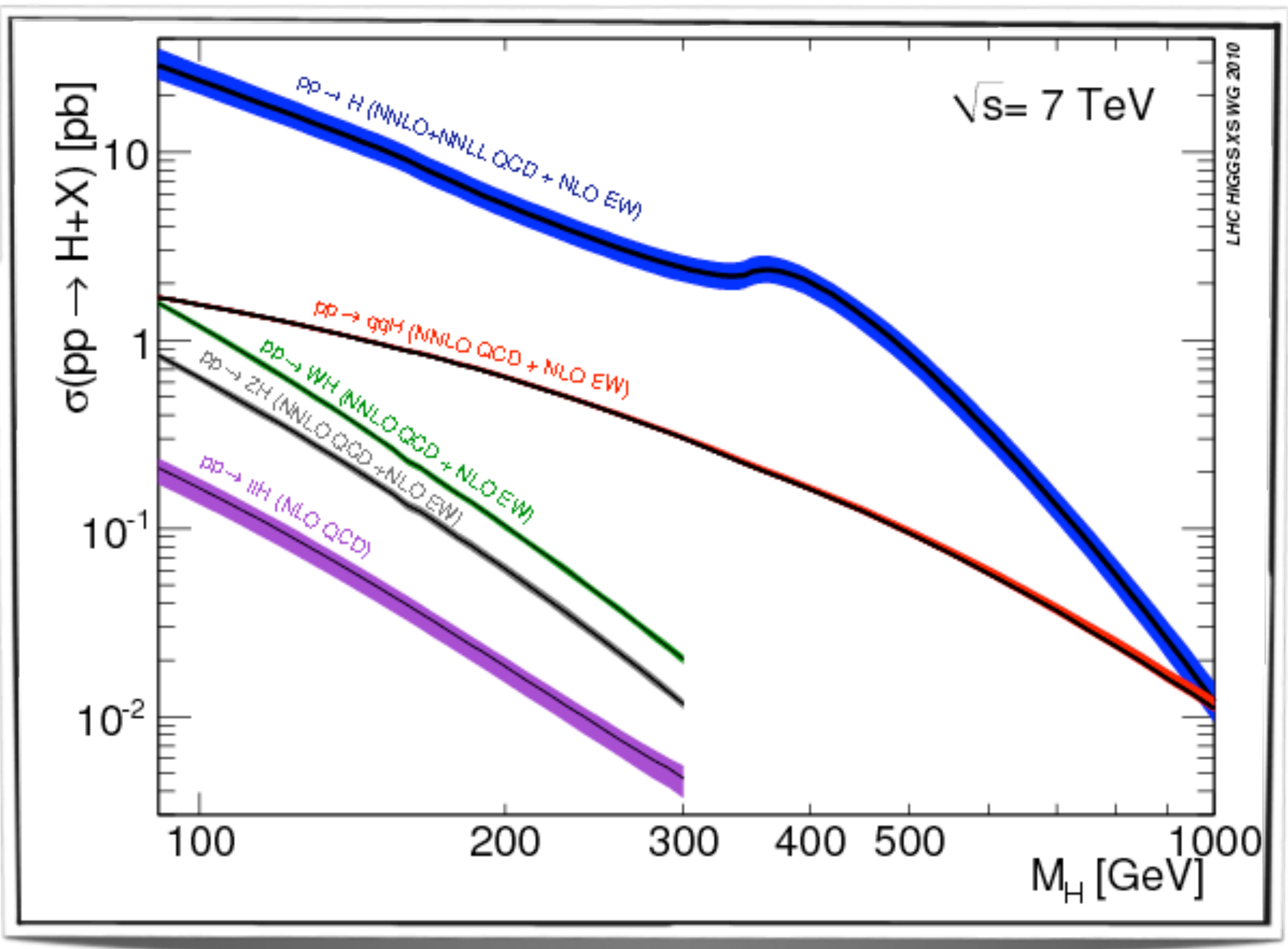




× BR(H→ZZ→νννν)

Invisibly decaying Higgs boson





× BR(H→DM+DM)

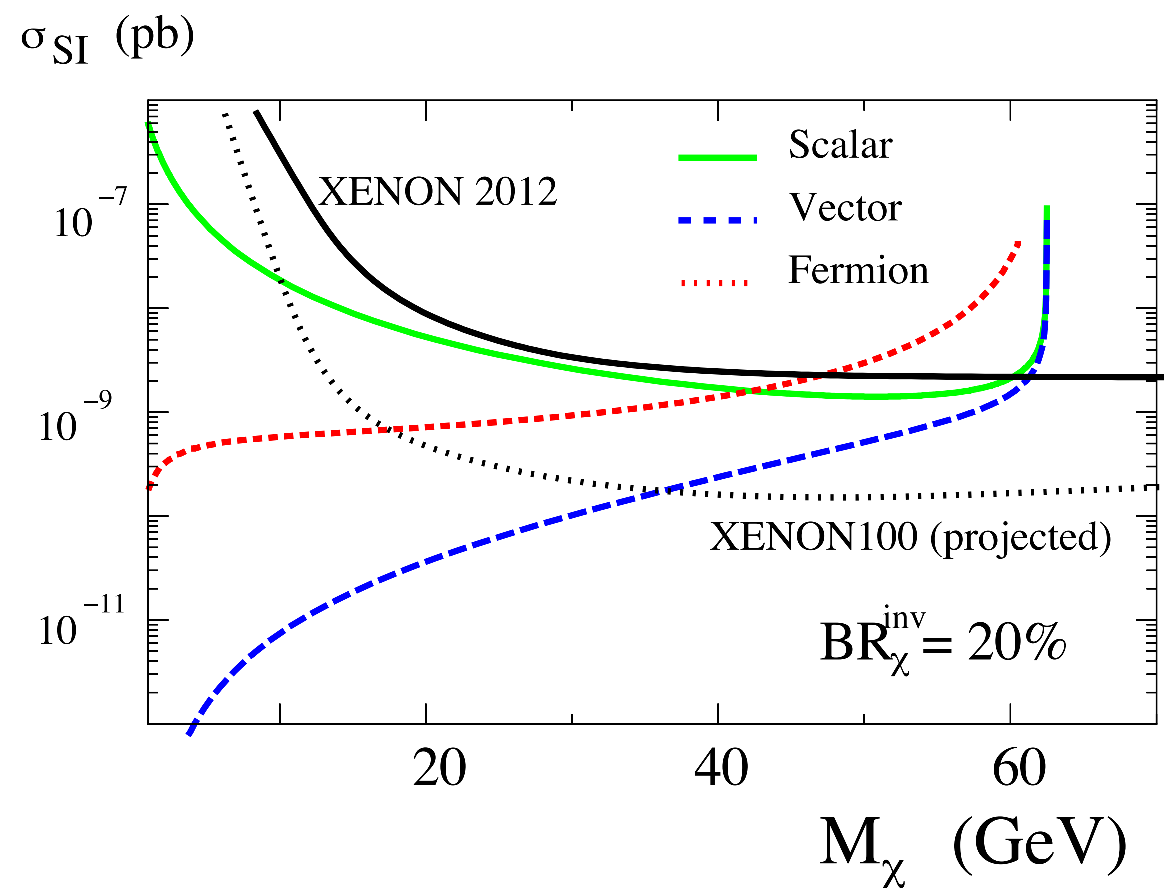
Higgs portal Dark Matter

arxiv:1205.3169

$$\Delta\mathcal{L}_S = -\frac{1}{2}m_S^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{4}\lambda_{hSS} H^\dagger H S^2 \,,$$

$$\Delta\mathcal{L}_V = \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \frac{1}{4}\lambda_{hVV} H^\dagger H V_\mu V^\mu,$$

$$\Delta\mathcal{L}_f = -\frac{1}{2}m_f f f - \frac{1}{4}\frac{\lambda_{hff}}{\Lambda} H^\dagger H f f + \text{h.c.}\,. \quad (2)$$



- Limit on the invisible Higgs decay rate from the LHC can be translated into limits on the DM cross section on nucleons and compared with direct detection experiments.

Where can we look for H → invisible at the LHC?

- LHC results do not exclude the possibility of a sizable branching ratio to invisible particles of the SM Higgs boson candidate at mH ~ 125 GeV.

➡ interpretation in terms of BR(H→inv) for mH = 125 GeV

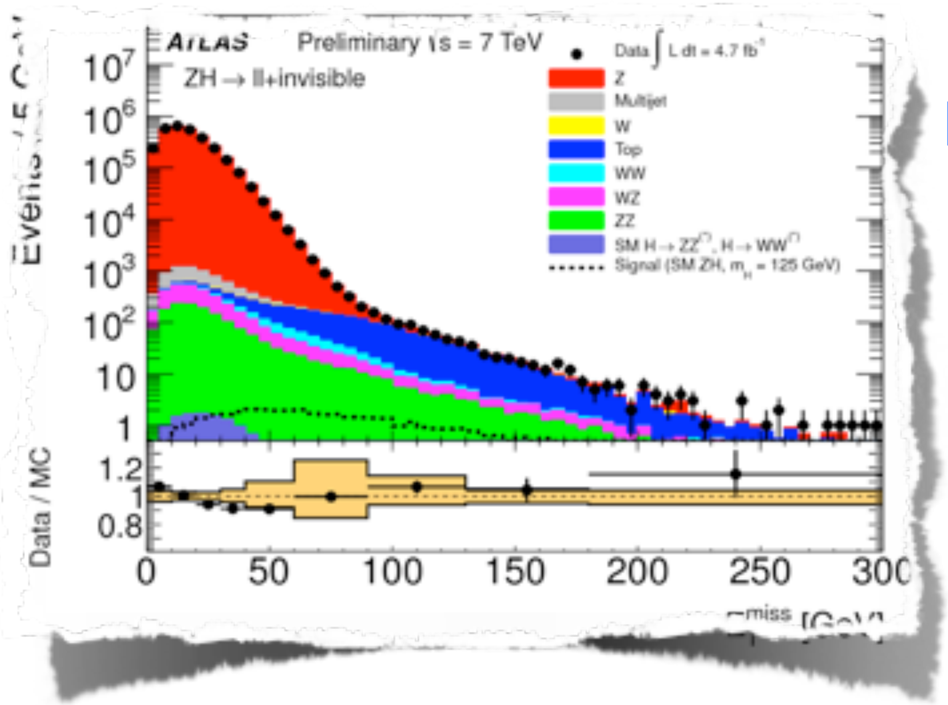
- LEP excluded invisibly decaying Higgs boson for mH < 114.4 GeV assuming it is produced in association with Z and that it decays predominantly to invisible particles.

➡ search for a narrow scalar boson decaying to invisible particles over a mass range between 115 and 300 GeV

LHC searches for H → invisible

ATLAS ZH

ATLAS-CONF-2013-011

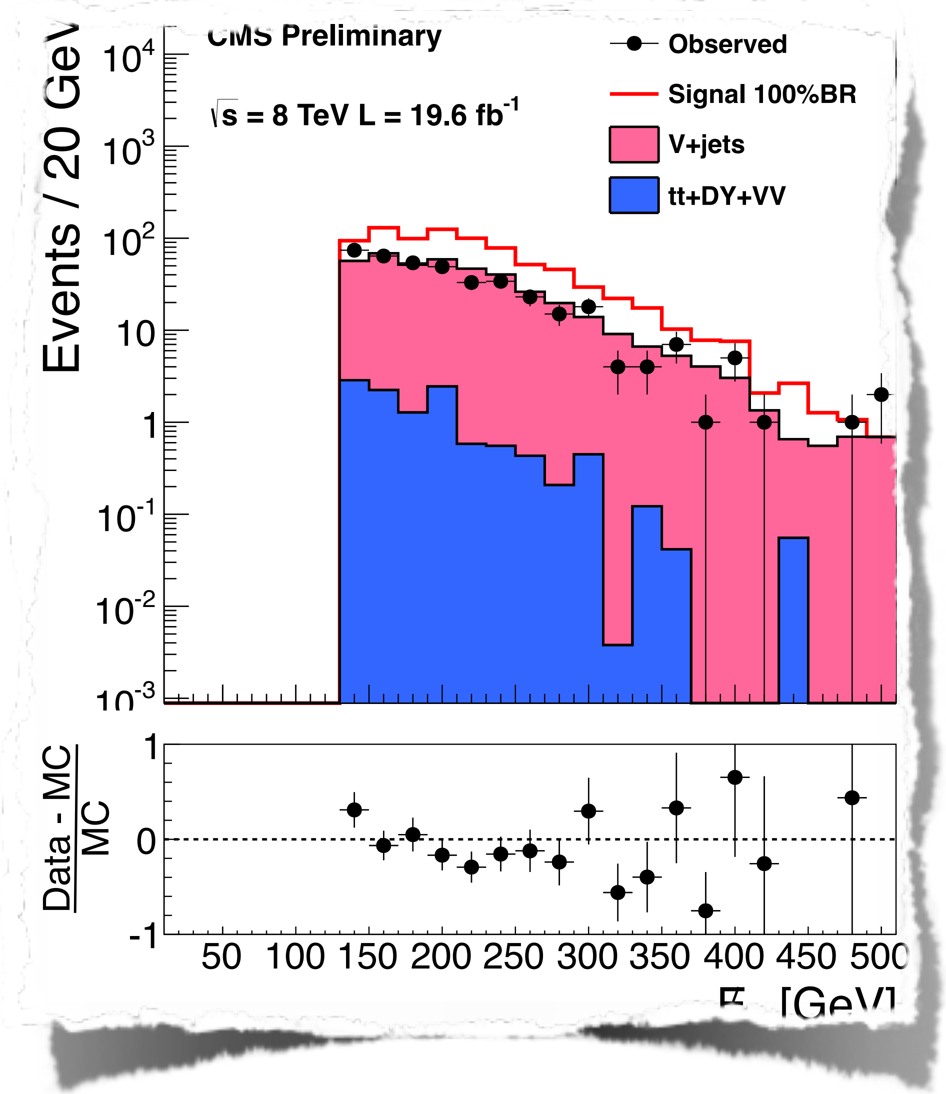


4.7 fb-1 2011
13.0 fb-1 2012

CMS VBF

CMS-HIG-13-013

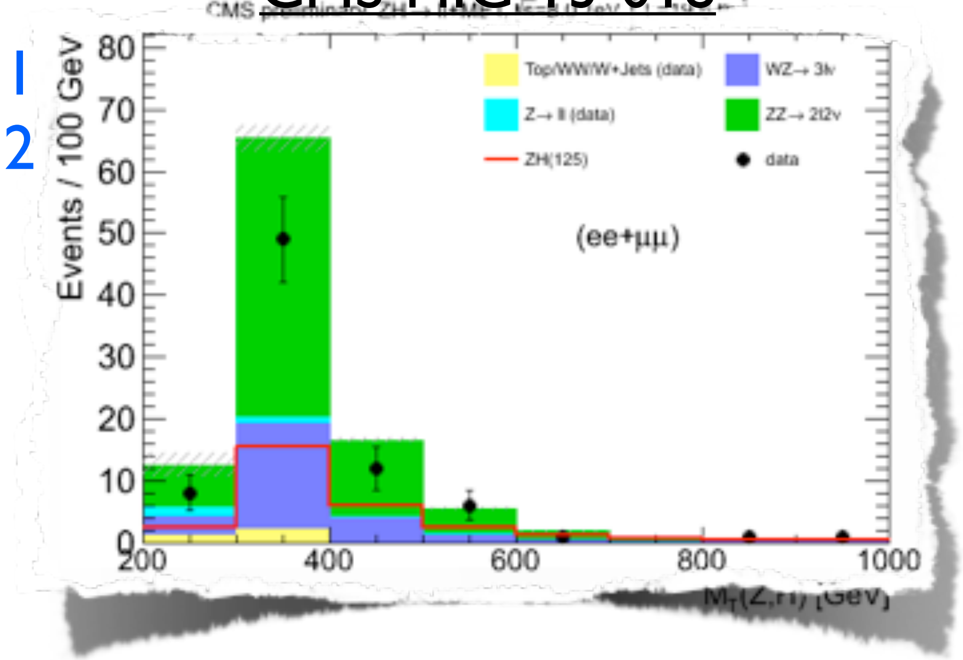
19.6 fb-1 2012



CMS ZH

CMS-HIG-13-018

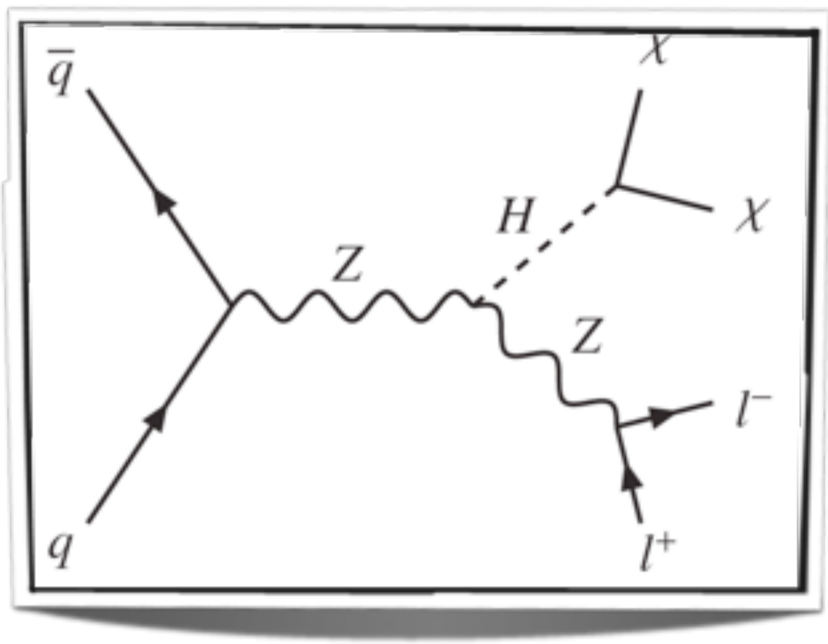
5.1 fb-1 2011
19.6 fb-1 2012



Invisible decays of a Higgs boson produced in association with a Z boson

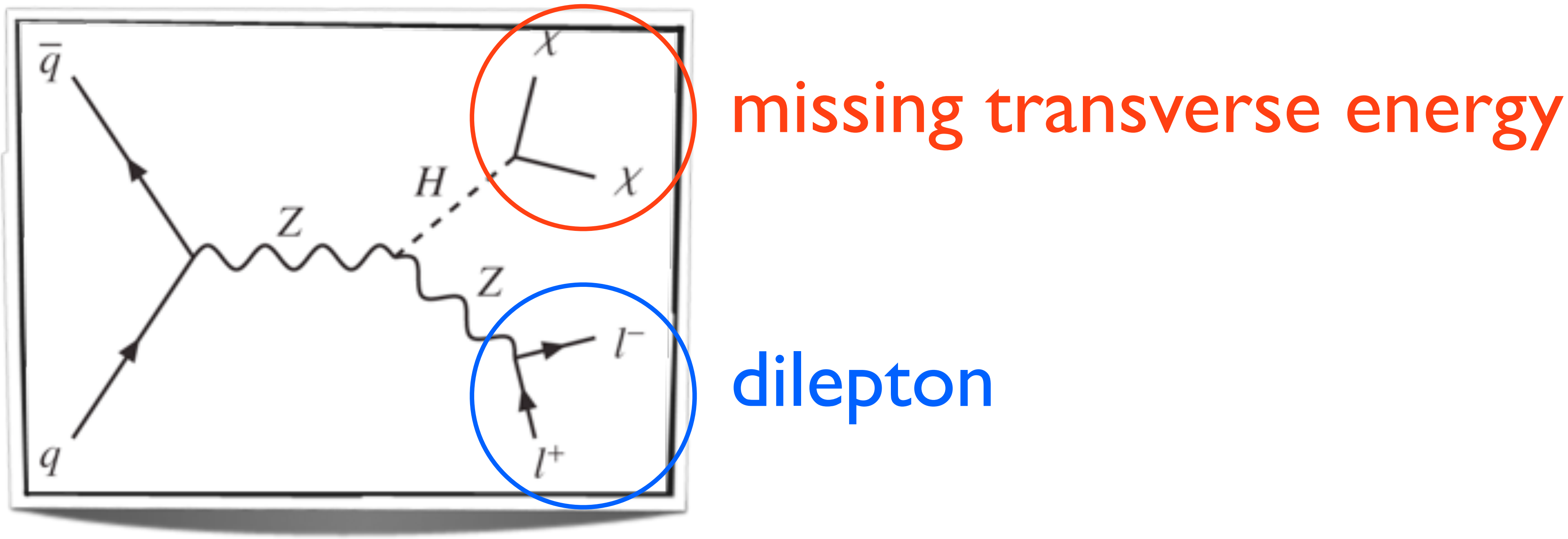
ATLAS ZH
ATLAS-CONF-2013-011

4.7 fb-1 2011
13.0 fb-1 2012



mH = 125 GeV	$\sqrt{s}$ = 7 TeV	$\sqrt{s}$ = 8 TeV
σ(ZH)	316 fb	394 fb
$\sigma(Z(\rightarrow ll)H(\rightarrow inv))$	31.9 fb	39.8 fb
$\sigma(Z(\rightarrow ll)H(\rightarrow ZZ\rightarrow \nu\nu\nu\nu))$	0.034 fb	0.042 fb

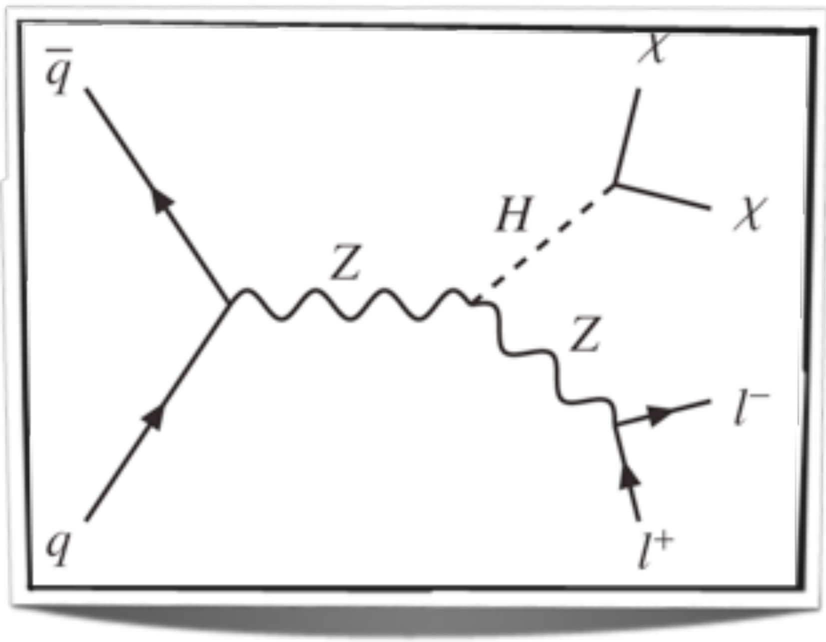
Event selection (i)

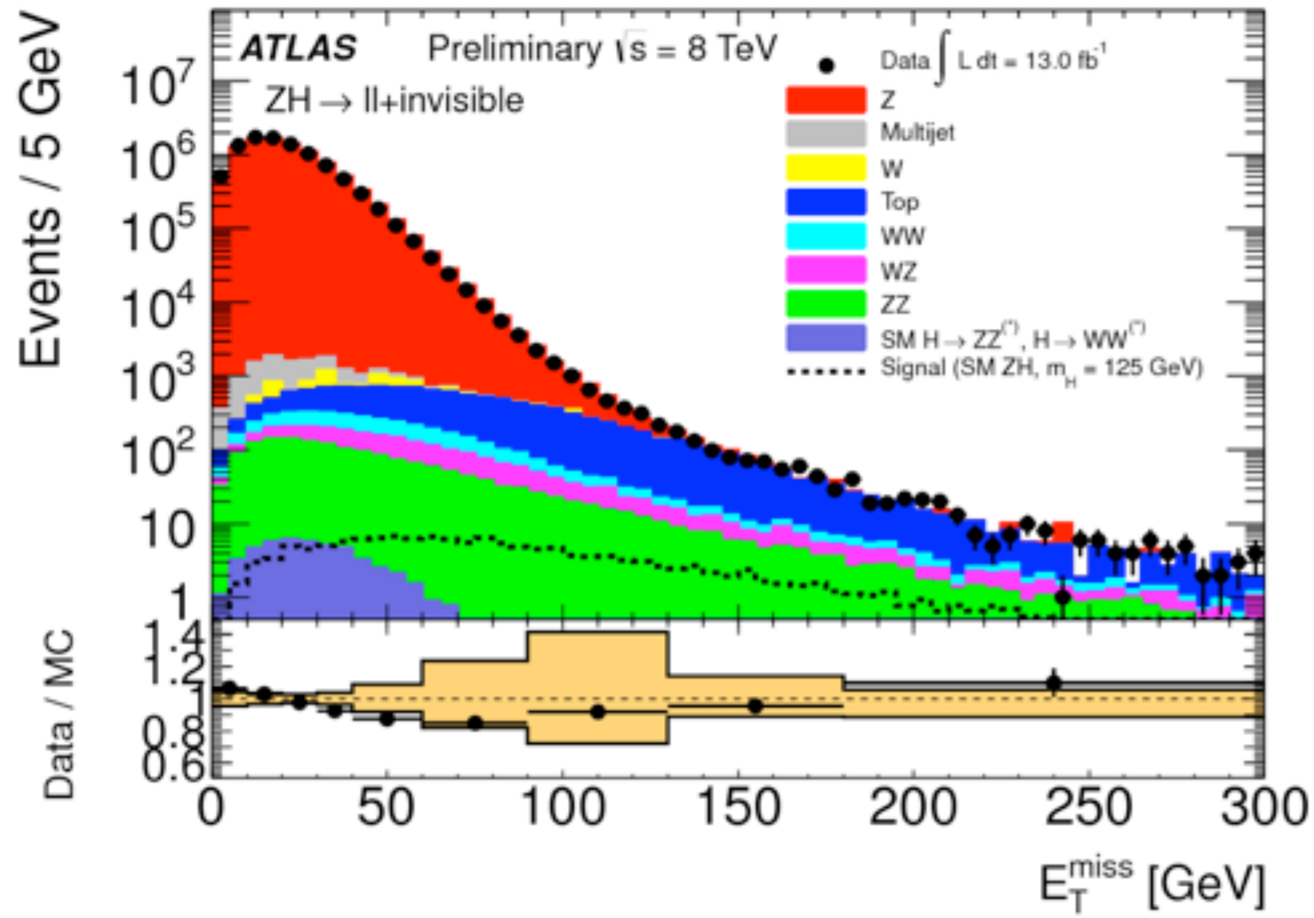


- primary vertex
- 2 opposite charged electrons or muons having pT > 20 GeV
- veto on any other electron or muon with pT > 7 GeV
- invariant mass of the dilepton system consistent with the Z mass

➡ 76 GeV < m_{ll} < 106 GeV

Event selection (i)





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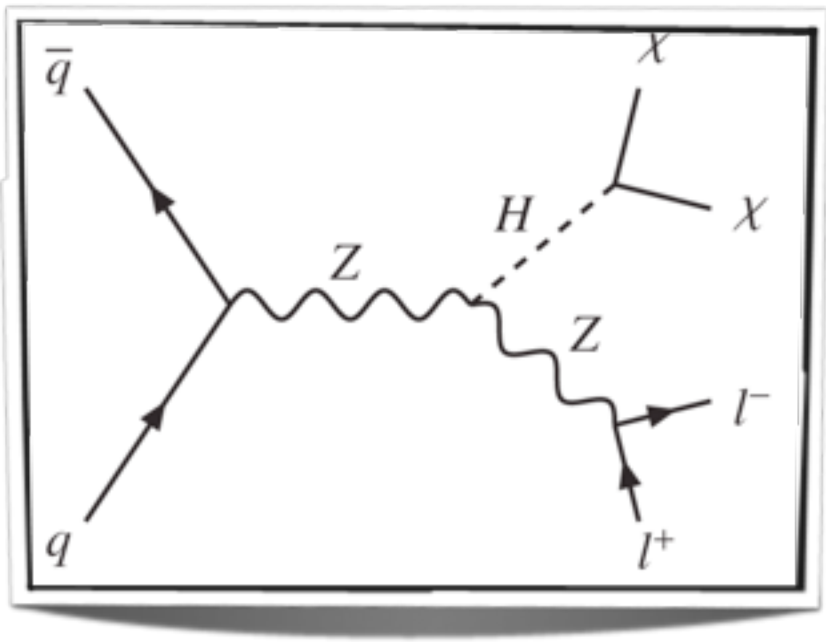
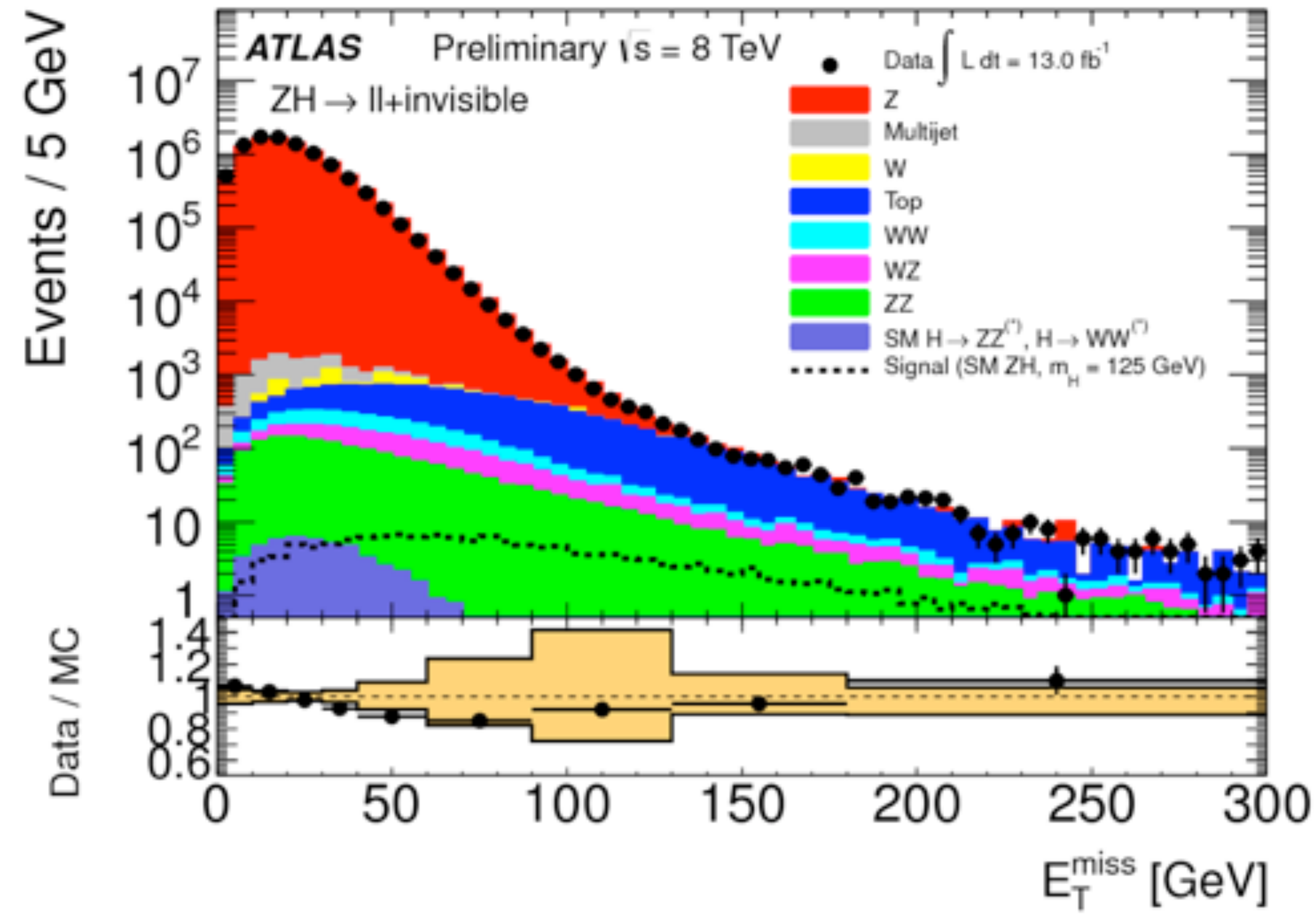




- primary vertex
- 2 opposite charged electrons or muons having pT > 20 GeV
- veto on any other electron or muon with pT > 7 GeV
- invariant mass of the dilepton system consistent with the Z mass

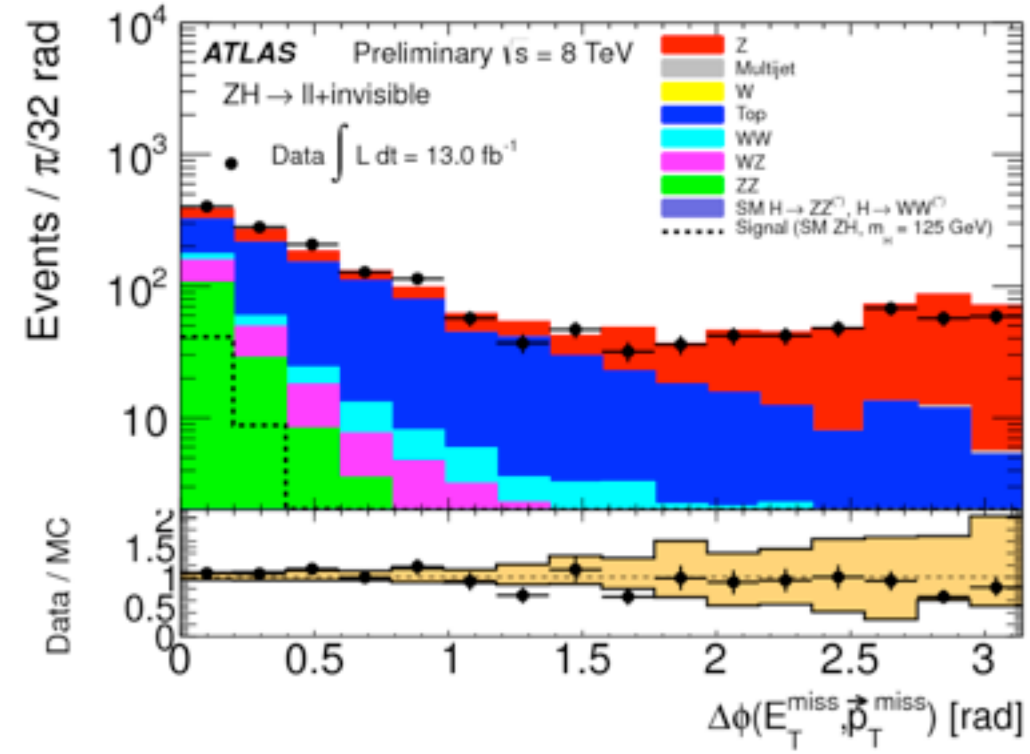
➡ 76 GeV < m_{ll} < 106 GeV

➡ missing transverse energy > 90 GeV to reject Z background

Event selection (ii)

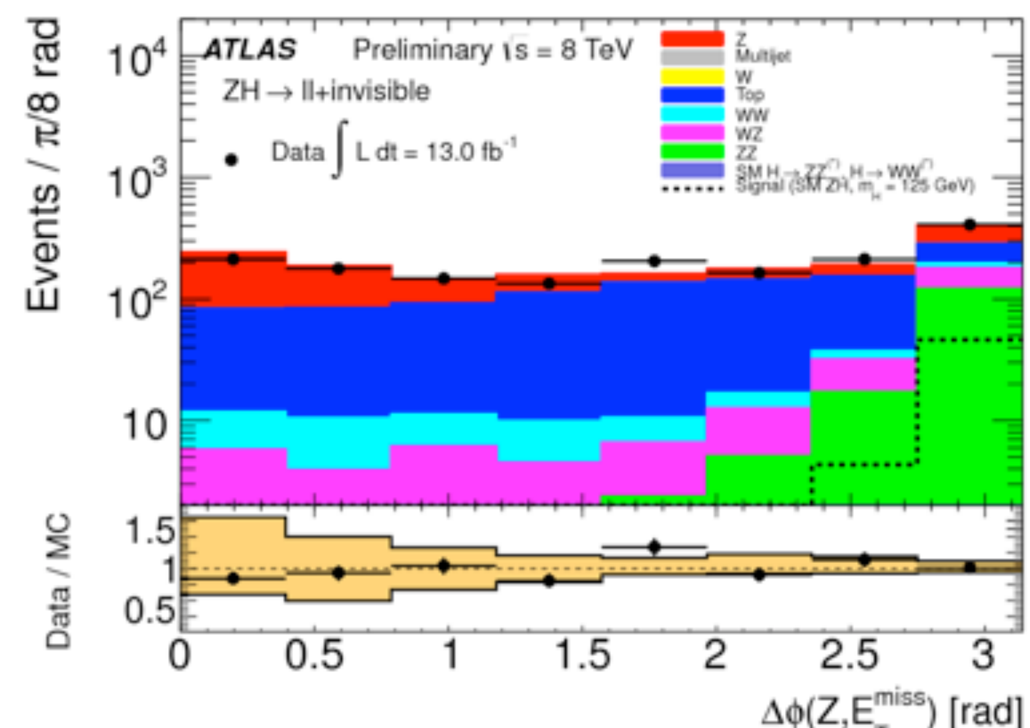
- In events with true E_T^{miss} from "invisible" particles, p_T^{miss} has the same azimuthal angle as E_T^{miss}.

➡ $\Delta\varphi(E_T^{miss}, p_T^{miss}) < 0.2$



- Z boson is balanced by the invisibly decaying Higgs boson.

➡ $\Delta\varphi(Z, E_T^{miss}) > 2.6$



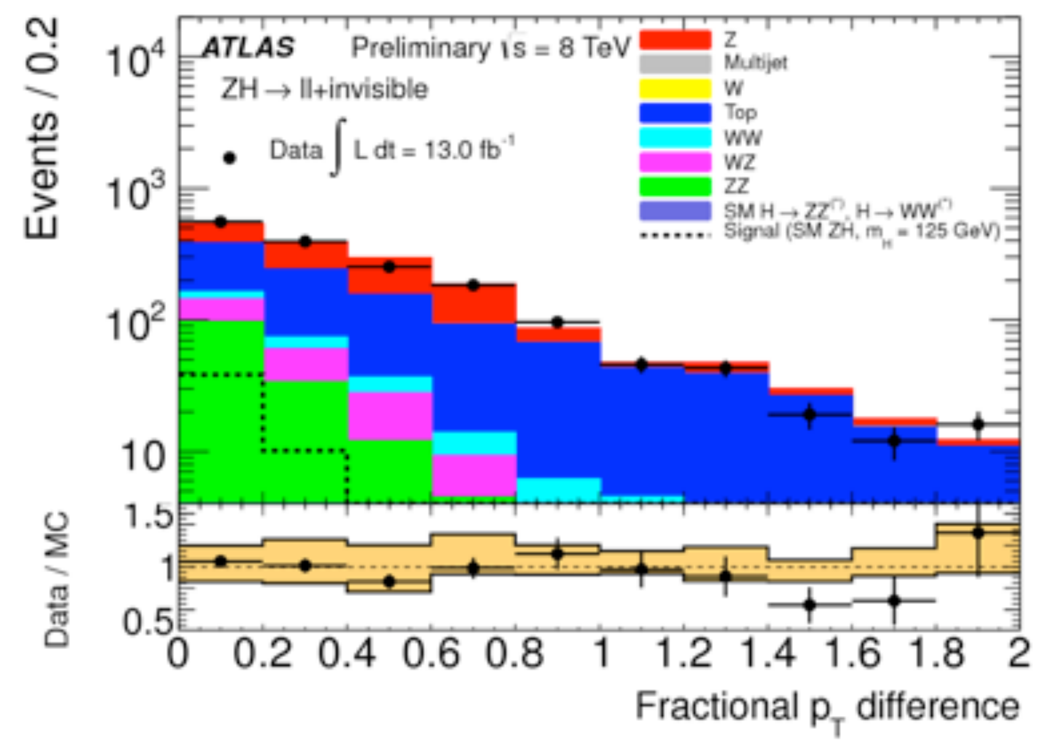
Event selection (iii)

- In order to produce the required large E_T^{miss}, the Higgs boson must be boosted.
- Therefore, the recoiling Z boson must also have large pT.
- This causes the decay leptons to be close in azimuth.

➡ $\Delta\varphi(ll) < 1.7$

- Magnitude of p_T^{ll} and E_T^{miss} should be compatible.

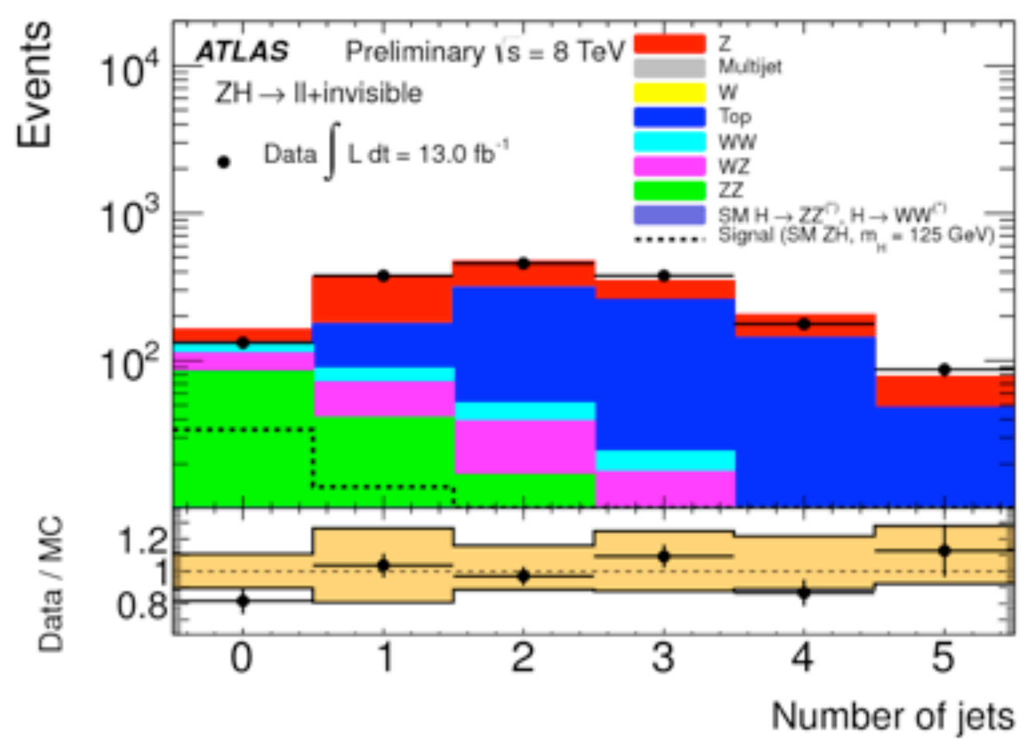
➡ $|E_T^{miss} - p_T^{ll}| / p_T^{ll} < 0.2$



Event selection (iv)

- Majority of signal is produced in association with no high pT jet whereas backgrounds from boosted Z or tt pairs tend to have high pT jets.

➡ veto on jets with pT > 20 GeV and |η| < 2.5



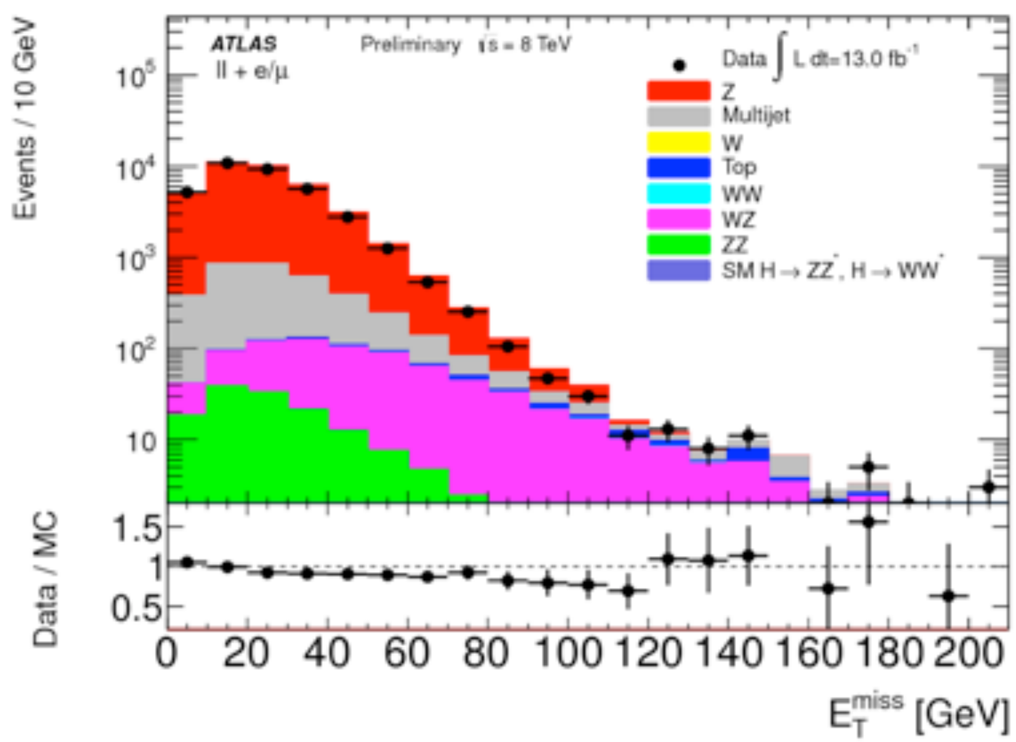
Backgrounds

- dibosons
  - ZZ → llνν (irreducible, ~70%)
  - WZ → lνll where W decay lepton is not identified
  - WW → lνlν where the leptons mimic a Z boson
- tt and Wt where leptons mimic a Z boson
- inclusive Z → ll
- inclusive W → lν and dijet events where jets are mis-reconstructed as leptons

Backgrounds from MC

- ZZ and WZ backgrounds are taken from MC.

- WZ simulation is validated in a trilepton control region.



Flavor symmetry

- WW, tt, Wt, Z→ττ are estimated using flavor symmetry in the final states.

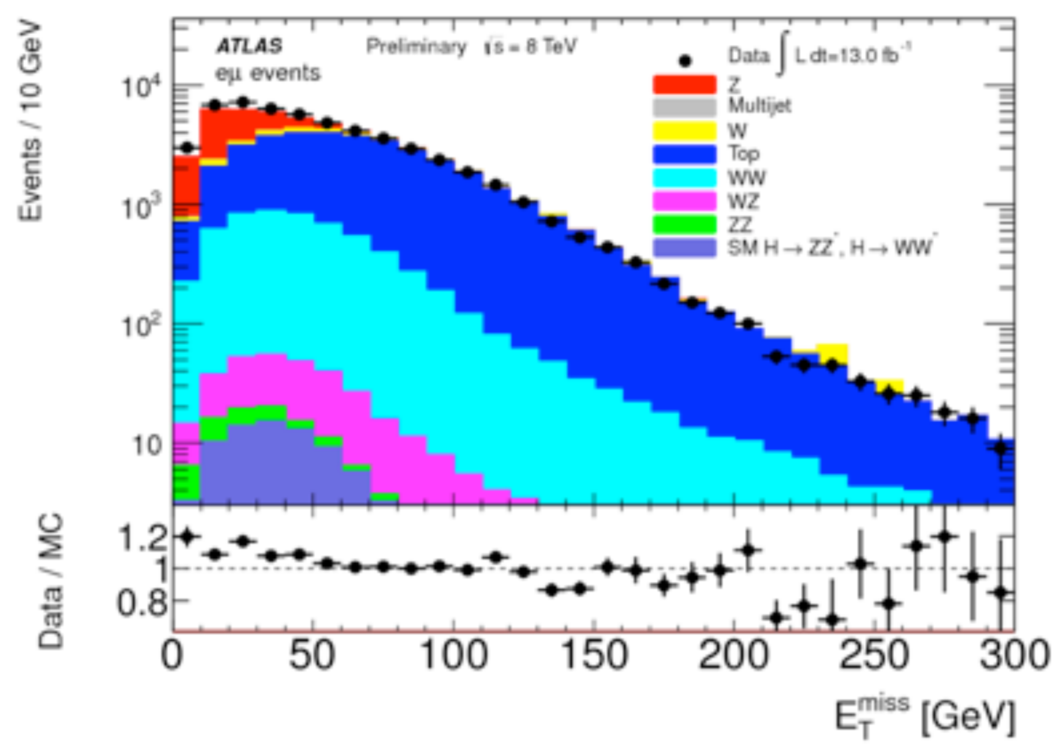
  BR(eμ) = 2 × BR(ee) or BR(μμ)

➡ eμ control region is defined (signal free).

$$N_{ee}^{\mathrm{bkg}} = \frac{1}{2} \times N_{e\mu}^{\mathrm{data,sub}} \times k$$

$$N_{\mu\mu}^{\mathrm{bkg}} = \frac{1}{2} \times N_{e\mu}^{\mathrm{data,sub}} \times \frac{1}{k}$$

$$k = \sqrt{\frac{N_{ee}^{\mathrm{data}}}{N_{\mu\mu}^{\mathrm{data}}}}$$

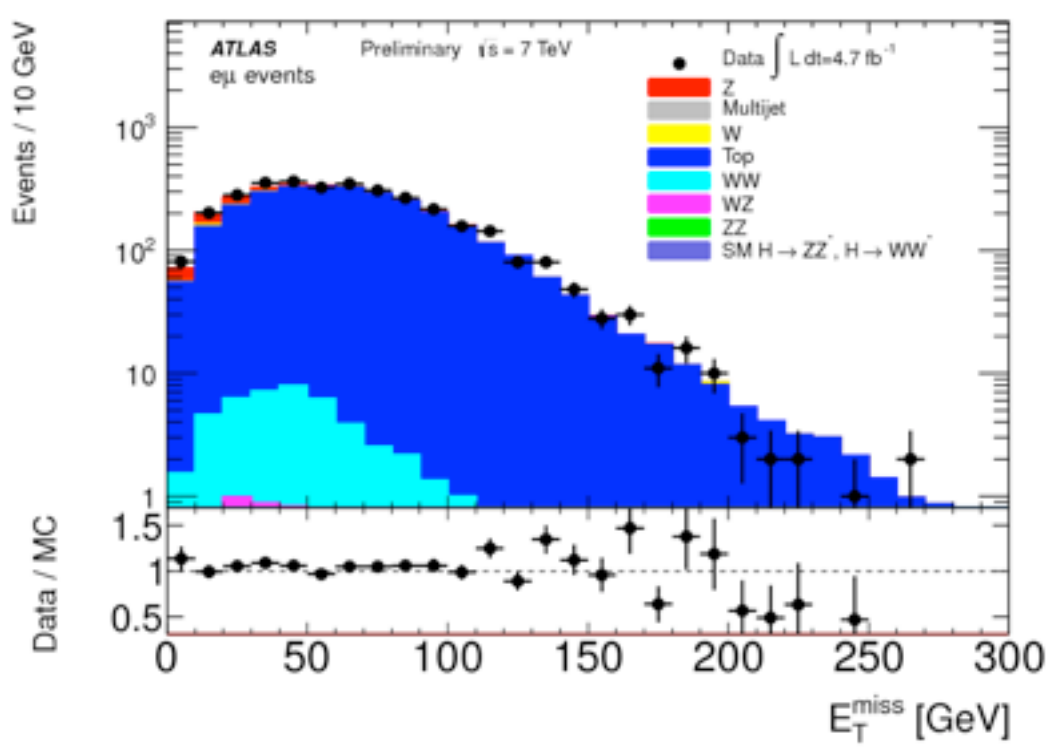


Flavor symmetry

- For 2011 data, this method gives consistent results as MC but larger uncertainty.

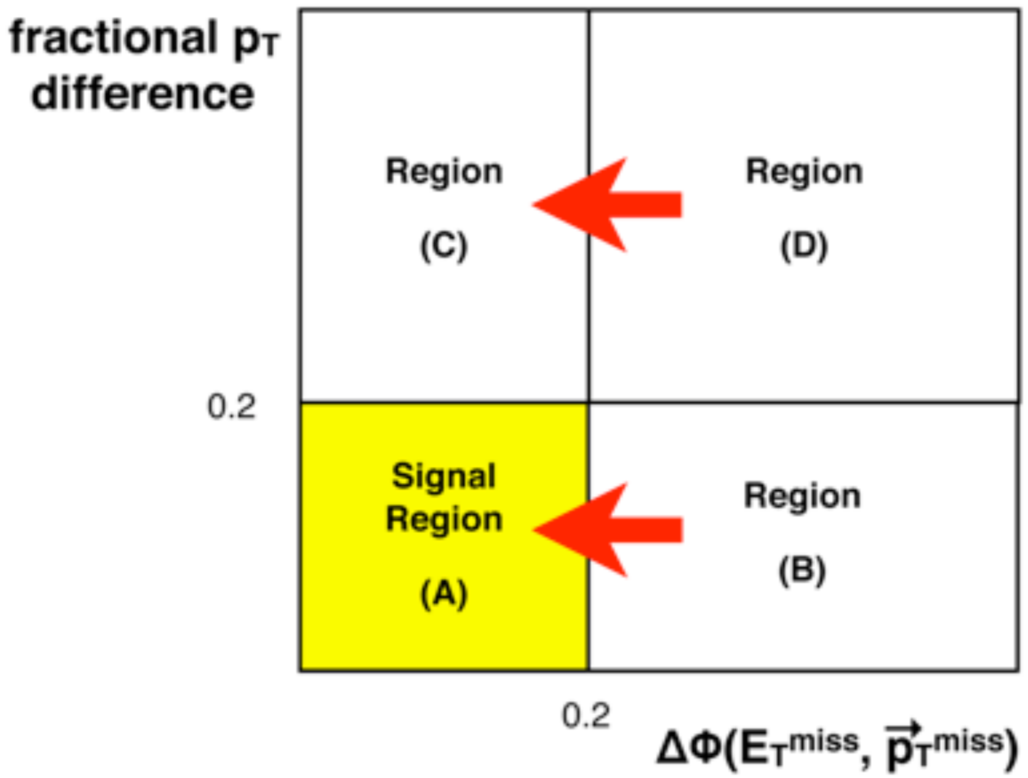
➡ MC estimates are used for WW, tt and single top events.

- Top quark MC samples are validated in the eμ events with a b-tagged jet.



ABCD method

- Background from inclusive Z boson production is estimated with ABCD method.
- two uncorrelated variables: $\Delta\varphi(E_T^{miss}, p_T^{miss})$, $|E_T^{miss} - p_T^{ll}| / p_T^{ll}$



$$N_A^{est} = N_B^{obs} \times \frac{N_C^{obs}}{N_D^{obs}} \times \alpha$$

- Correction factor α, accounting for the correlation between the two variables, is derived from MC.

Matrix method

- Background from inclusive W production and multijet events is estimated using the Matrix method.

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{bmatrix} \times \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}.$$

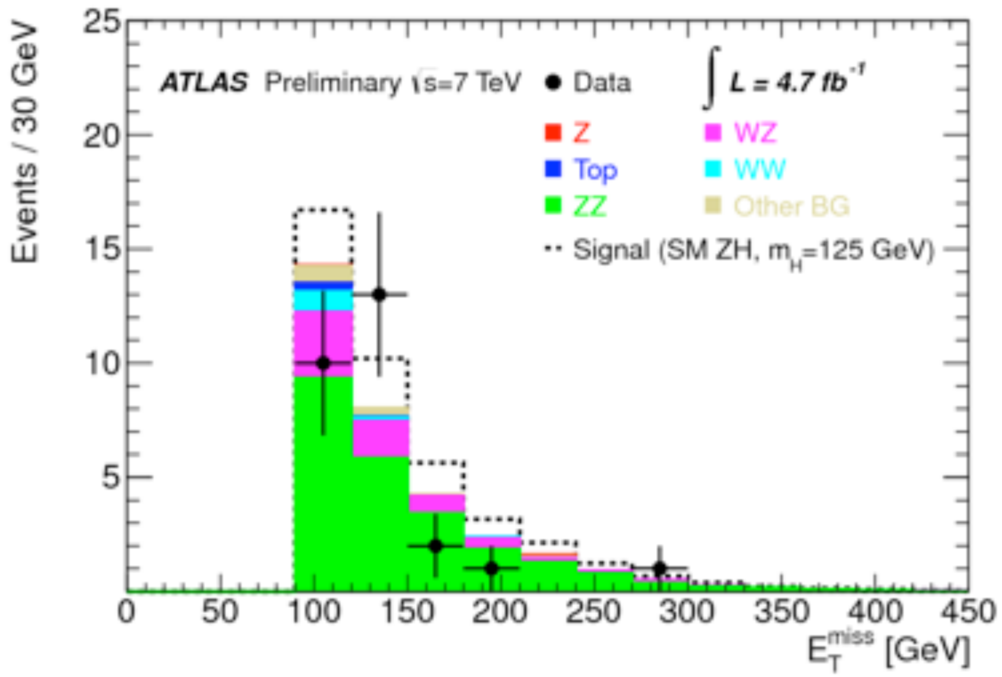
- Two selection criteria for leptons are used: tight (T) and loose (L).
- Reconstruction efficiencies (r) and fake rates (f) have to be known.
- By inverting the matrix, we can calculate the backgrounds:

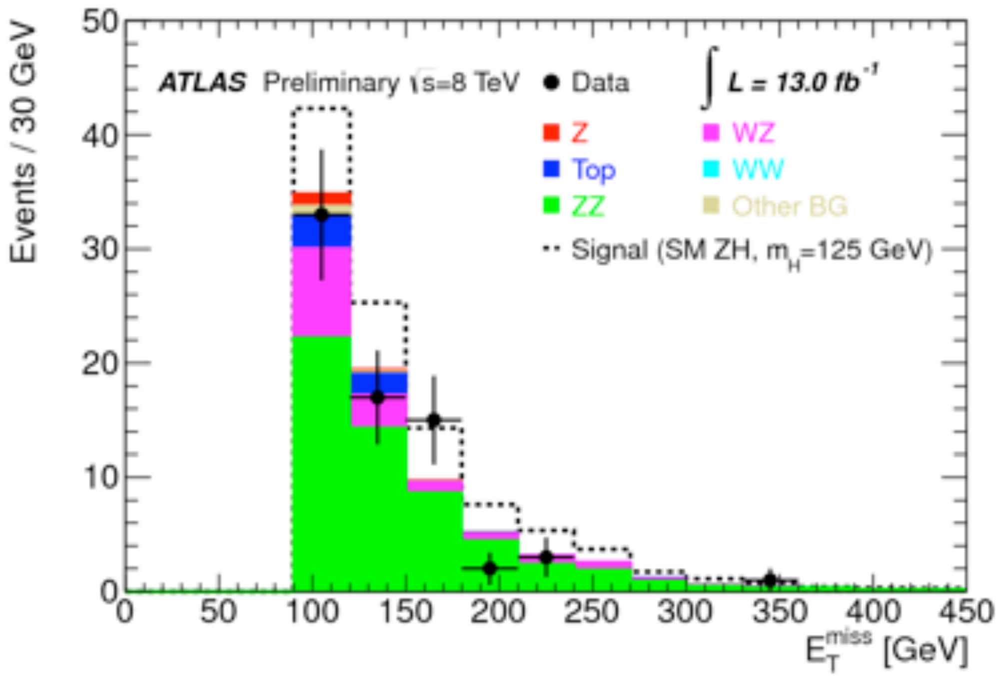
$$N_{W+\text{jets}} = \sum_{i}^{N_{\text{events}}} N_{RF}^{i} \times r_1^i \times f_2^i + N_{FR}^{i} \times f_1^i \times r_2^i,$$

$$N_{\text{multijet}} = \sum_{i}^{N_{\text{events}}} N_{FF}^{i} \times f_1^i \times f_2^i.$$

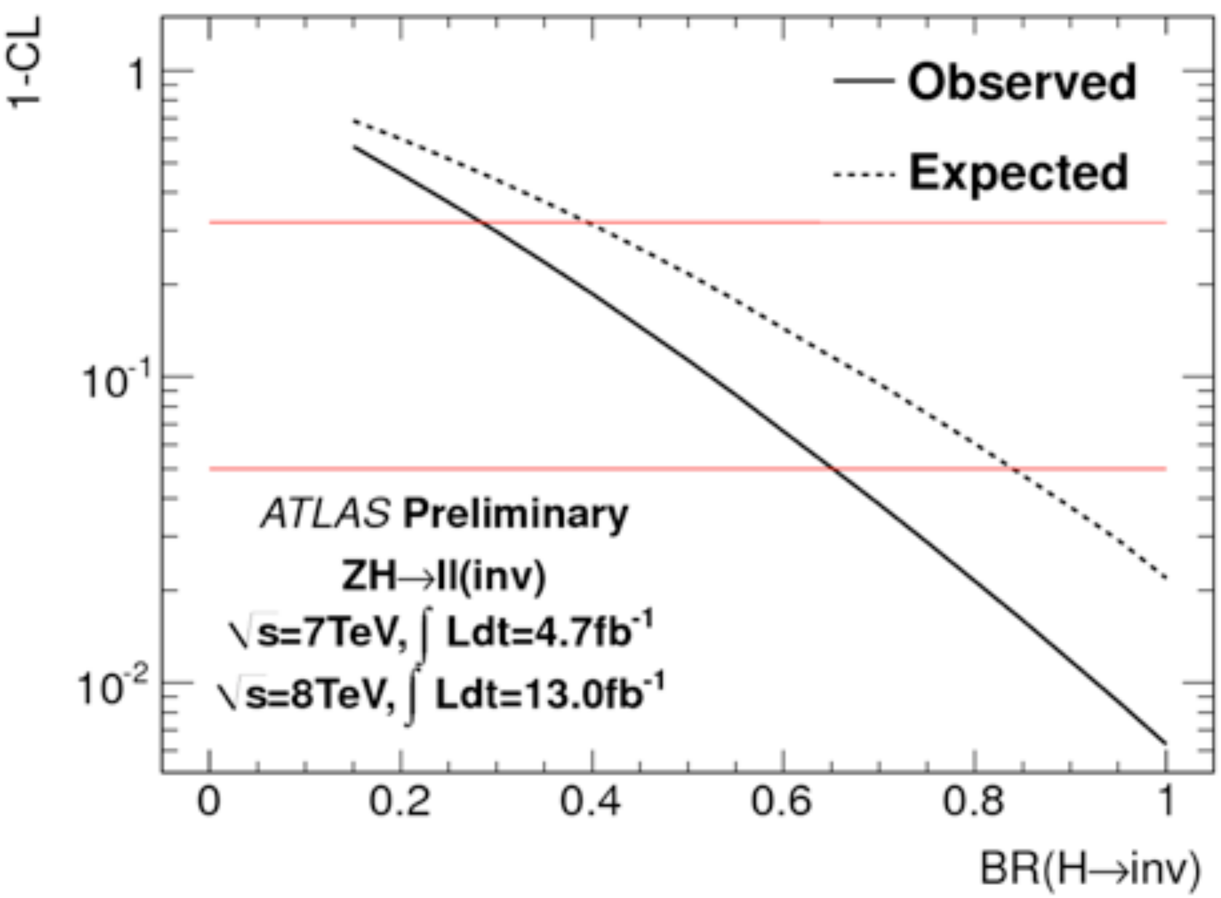
Results

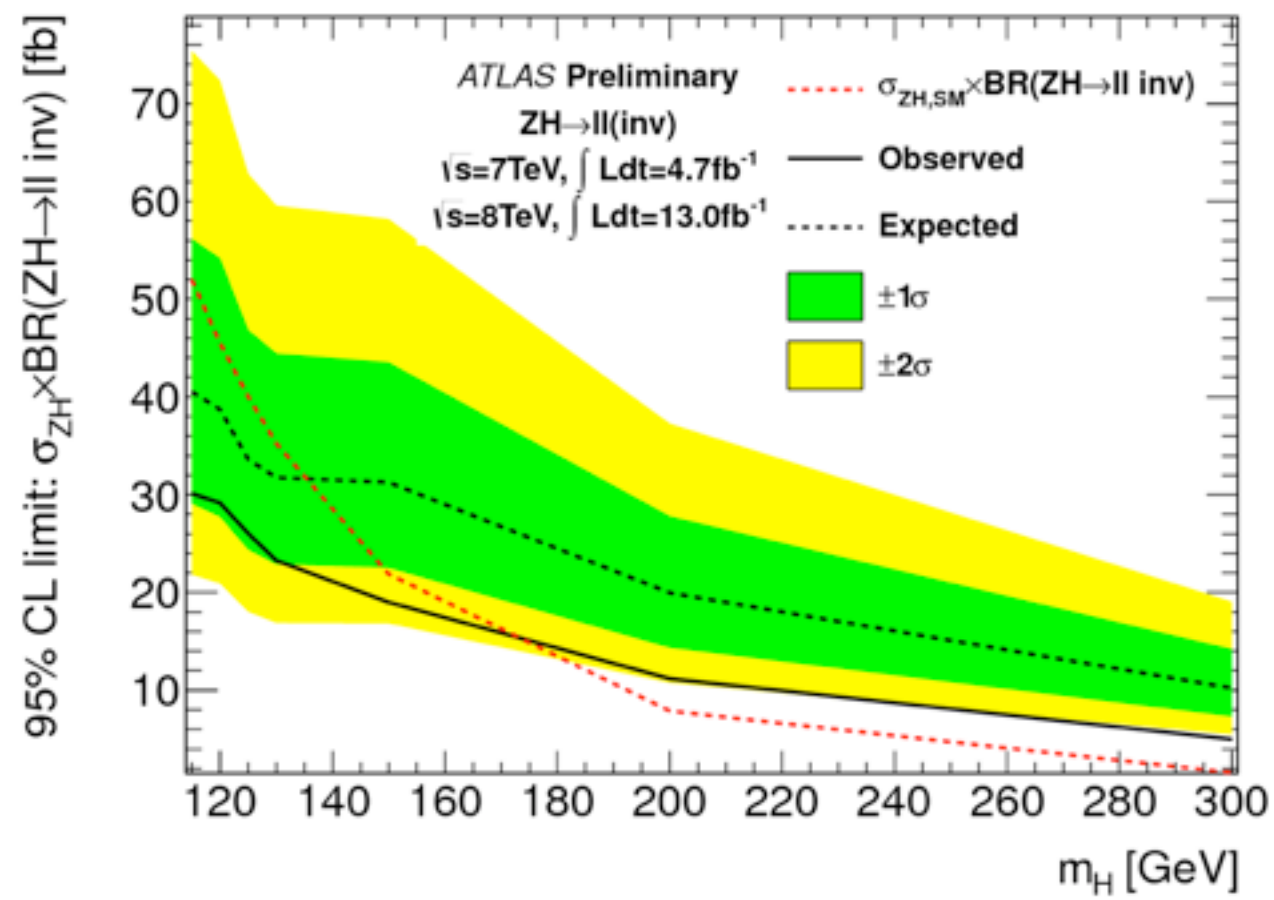
Data Period	2011 (7 TeV)	2012 (8 TeV)
ZZ	23.5 ± 0.8 ± 2.5	56.5 ± 1.2 ± 5.7
WZ	6.2 ± 0.4 ± 0.7	13.9 ± 1.2 ± 2.1
WW	1.1 ± 0.2 ± 0.2	used $e\mu$ data-driven
Top quark	0.4 ± 0.1 ± 0.4	used $e\mu$ data-driven
Top quark, WW and $Z \to \tau\tau$ ($e\mu$ data-driven)	used MC	4.9 ± 0.9 ± 0.2
Z	0.16 ± 0.13 ± 0.09	1.4 ± 0.4 ± 0.7
W + jets, multijet	1.3 ± 0.3 ± 0.2	1.4 ± 0.4 ± 0.3
Total BG	32.7 ± 1.0 ± 2.6	78.0 ± 2.0 ± 6.5
Observed	27	71





Limit on BR(H → invisible)





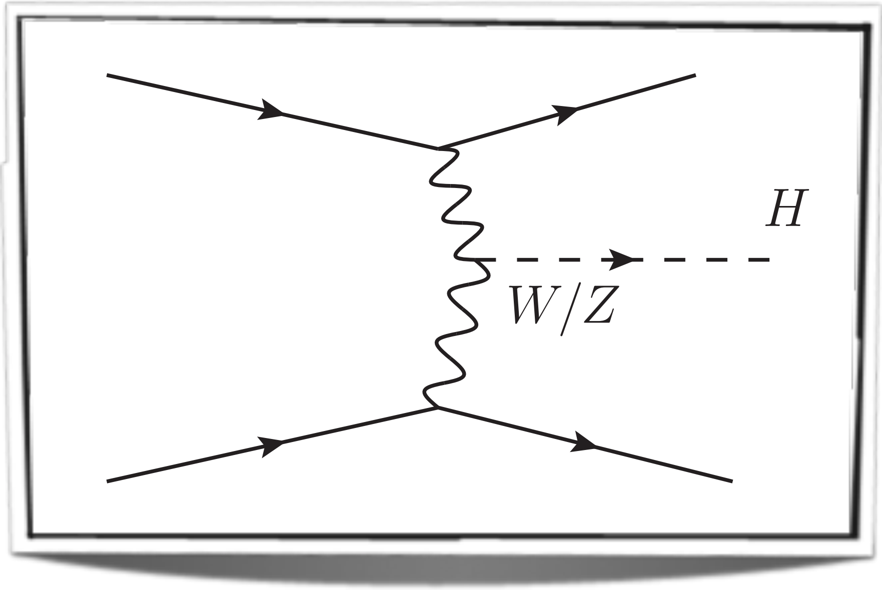
- Assuming the ZH production rate for a 125 GeV SM Higgs boson, limits are set on the invisible branching fraction at 95% confidence level.
- BR(H → invisible) = 65% (84% expected)
- Limits are also set on σ × BR(H → invisible) of a possible additional Higgs-like boson over the mass range 115 < m_H < 300 GeV.

Search for invisible Higgs decays in the VBF channel

CMS VBF

CMS-HIG-13-013

19.6 fb-1 2012



two jets separated by a large rapidity gap with high invariant mass

+

missing transverse energy

Event selection

- primary vertex
- veto electrons and muons with $p_T > 10$ GeV
- two jets with $p_T > 50$ GeV, $|\eta| < 4.7$, $\eta_1\eta_2 < 0$, $\Delta\eta_{jj} > 4.2$, $m_{jj} > 1100$ GeV
- $E_T^{miss} > 130$ GeV
- veto on jets with $p_T > 30$ at $\eta_1 < \eta < \eta_2$
- small azimuthal separation between the jets ($\Delta\varphi_{jj} < 1.0$) is required in order to suppress QCD multijet background

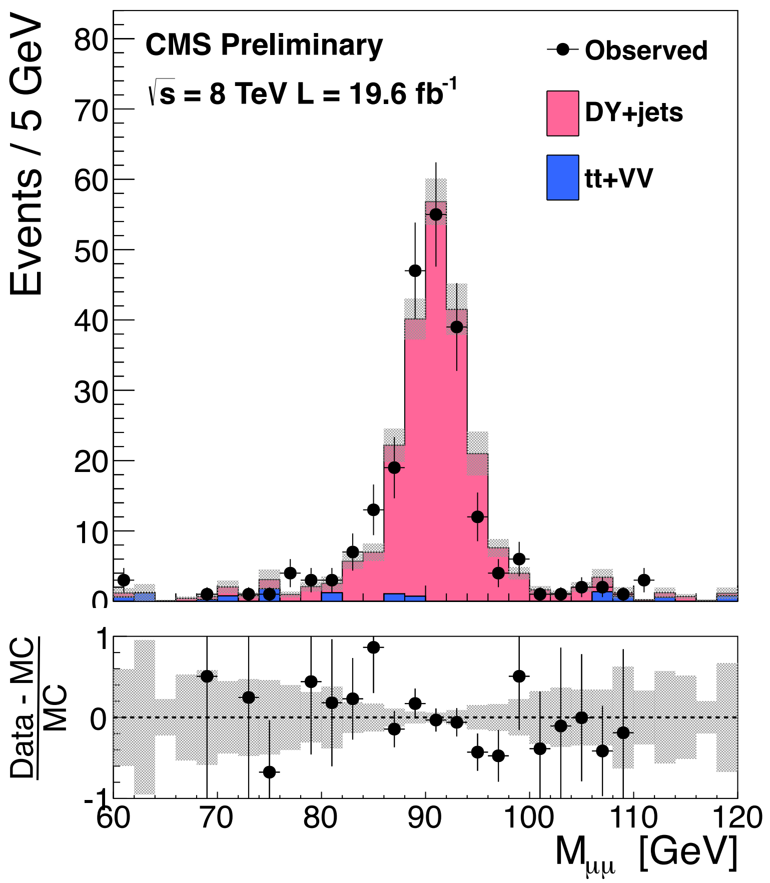
Backgrounds

- electroweak backgrounds from $Z(\to\nu\nu)$+jets and $W(\to l\nu)$+jets (estimated in a data-driven way)
- QCD multijets (estimated using ABCD method with E_T^{miss} and central jet veto)
- tt, single top, diboson, DY+jets (estimated from Monte Carlo)

Electroweak backgrounds

- $Z \to \nu\nu$
  - $Z \to \mu\mu$ control region requiring a pair of well reconstructed muons with pT > 20 GeV and invariant mass $60 < m_{\mu\mu} < 120$ GeV

$$N(Z \to \nu\nu) = \frac{(N^c_{obs} - N^c_{bkg})}{\varepsilon_{\mu\mu}\varepsilon^C_{VBF}} \cdot \frac{\sigma(Z \to \nu\nu)}{\sigma(Z/\gamma^* \to \mu\mu)} \cdot \varepsilon^S_{VBF}$$



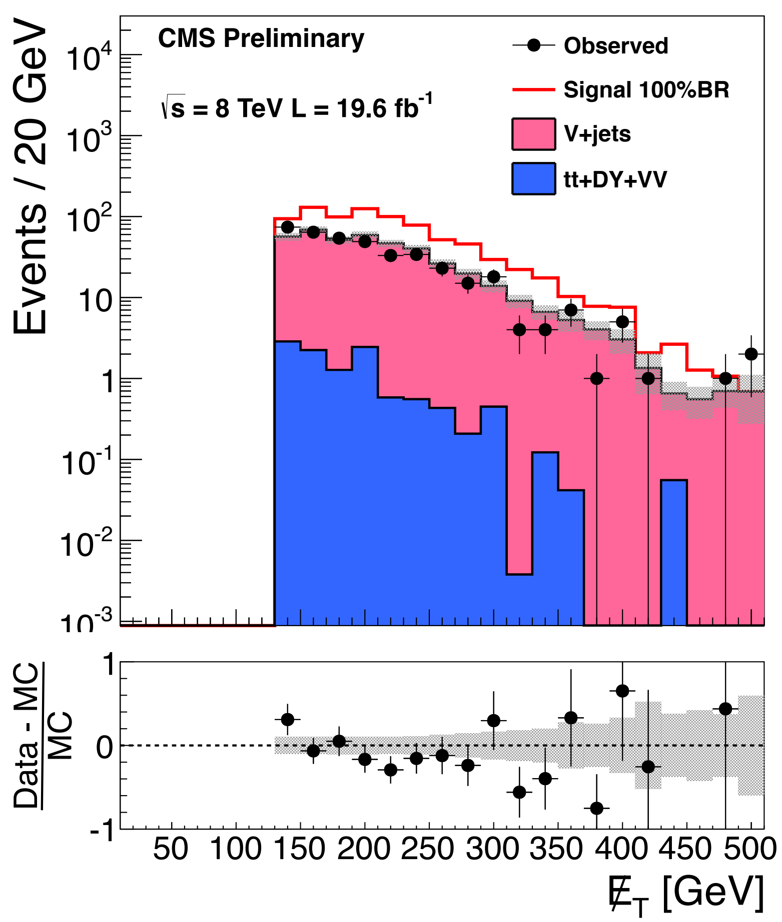
- $W \to e\nu$ and $W \to \mu\nu$
  - single lepton control regions

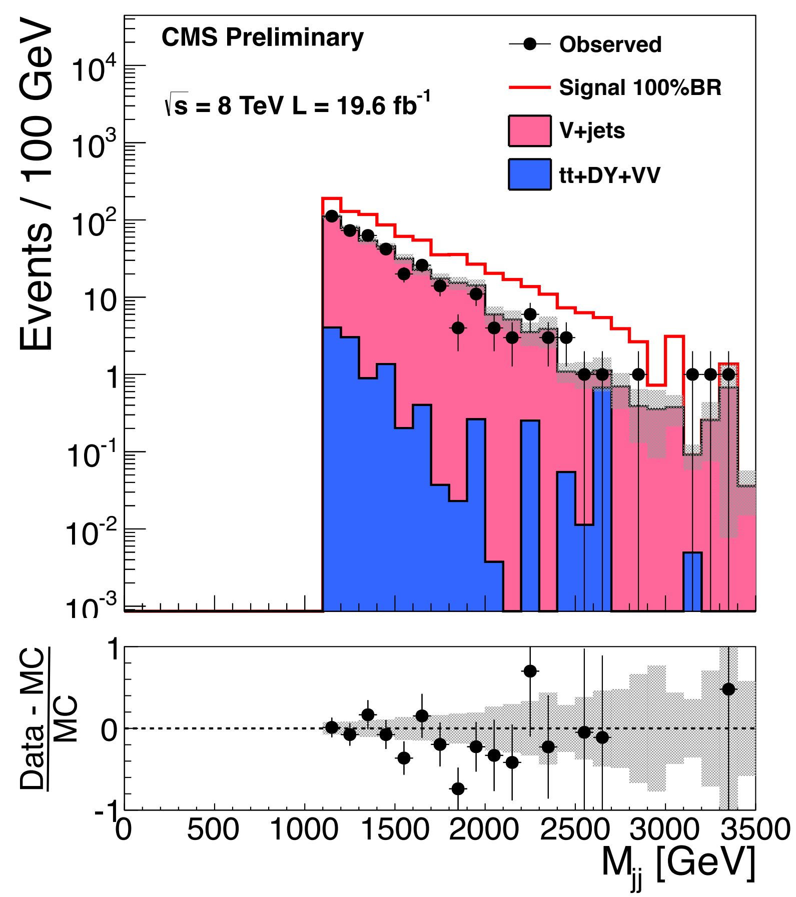
$$N^s_\ell = (N^c_{obs} - N^c_{bkg}) \cdot \frac{N^s_{WMC}}{N^c_{WMC}}$$

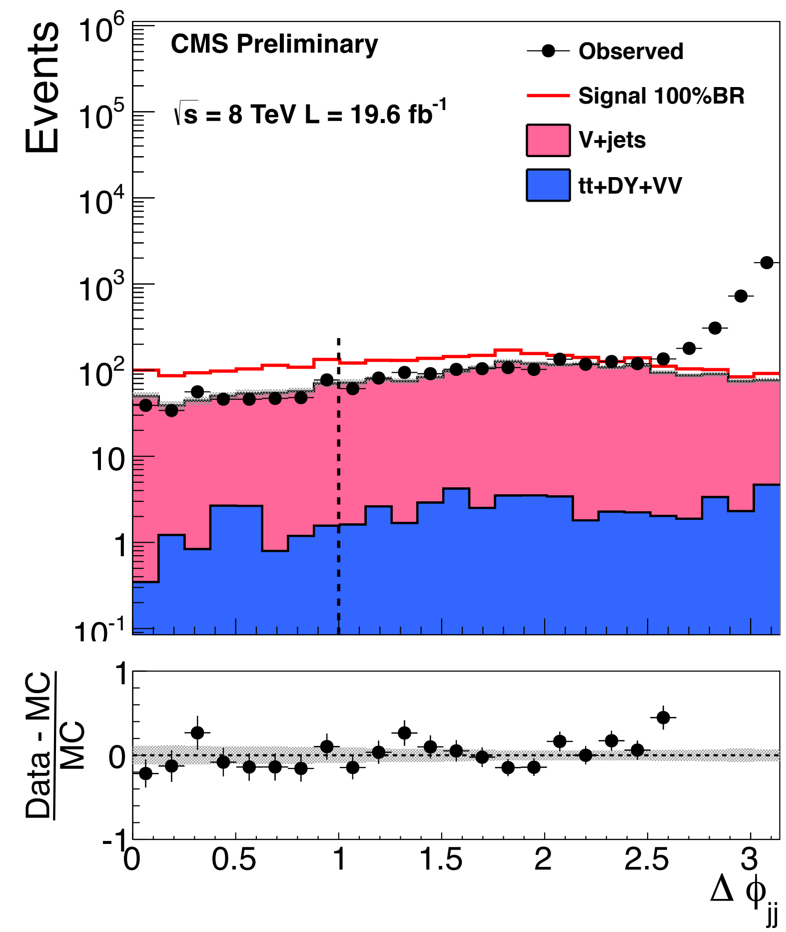
- $W \to \tau\nu$
  - control region with one hadronic tau (and without the central jet veto in order to increase statistics)

Results

Background	N_{est}
$Z \to \nu\nu$	$102 \pm 30\,(\mathrm{stat.}) \pm 26\,(\mathrm{syst.})$
$W \to \mu\nu$	$67.2 \pm 5.0\,(\mathrm{stat.}) \pm 15.1\,(\mathrm{syst.})$
$W \to rme\nu$	$68.2 \pm 9.2\,(\mathrm{stat.}) \pm 18.1\,(\mathrm{syst.})$
$W \to \tau\nu$	$54 \pm 16\,(\mathrm{stat.}) \pm 18\,(\mathrm{syst.})$
QCD multijet	$36.8 \pm 5.6\,(\mathrm{stat.}) \pm 30.6\,(\mathrm{syst.})$
Other SM	$10.4 \pm 3.1\,(\mathrm{syst.})$
Total background	$339 \pm 36\,(\mathrm{stat.}) \pm 50\,(\mathrm{syst.})$
Observed	390

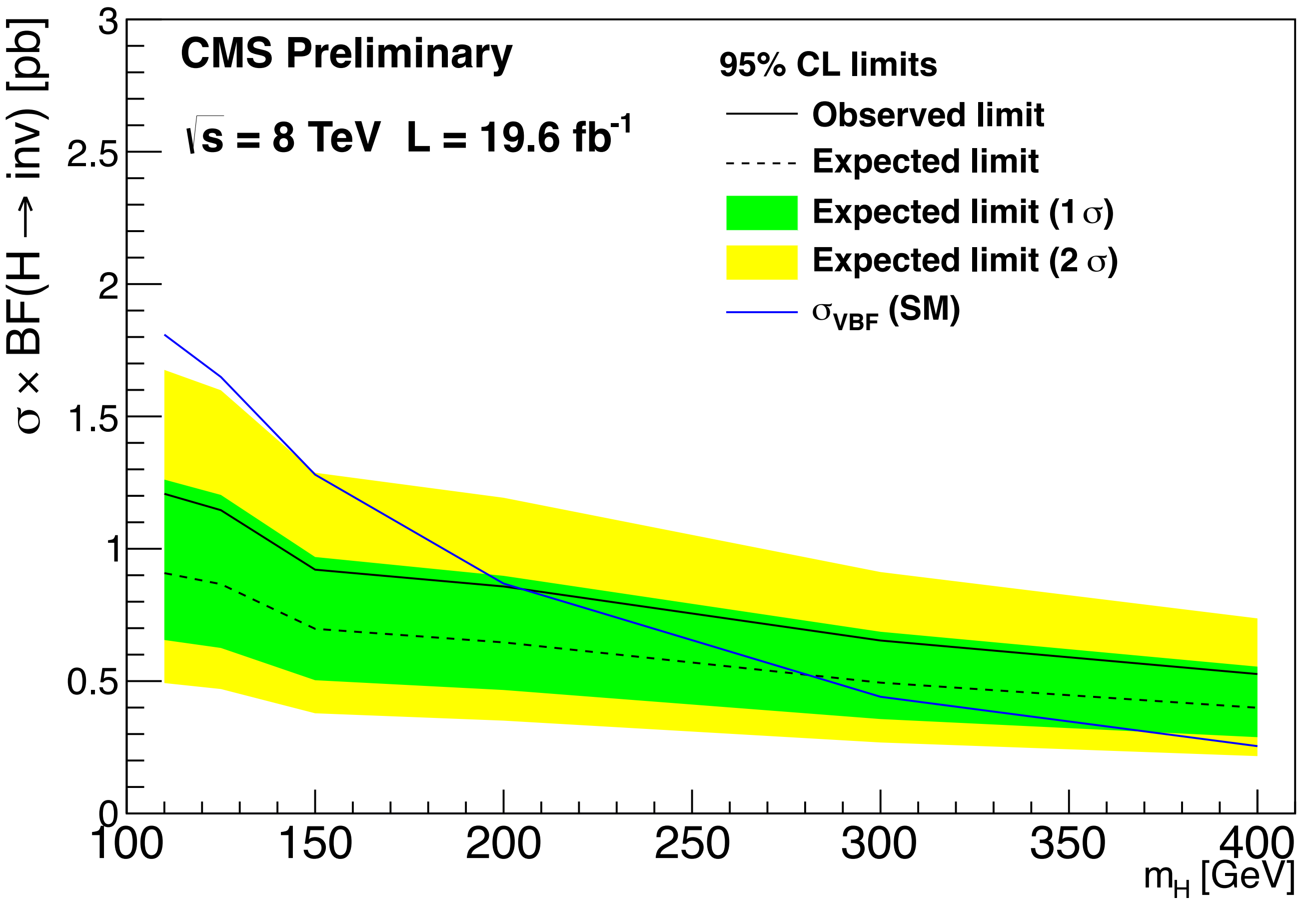


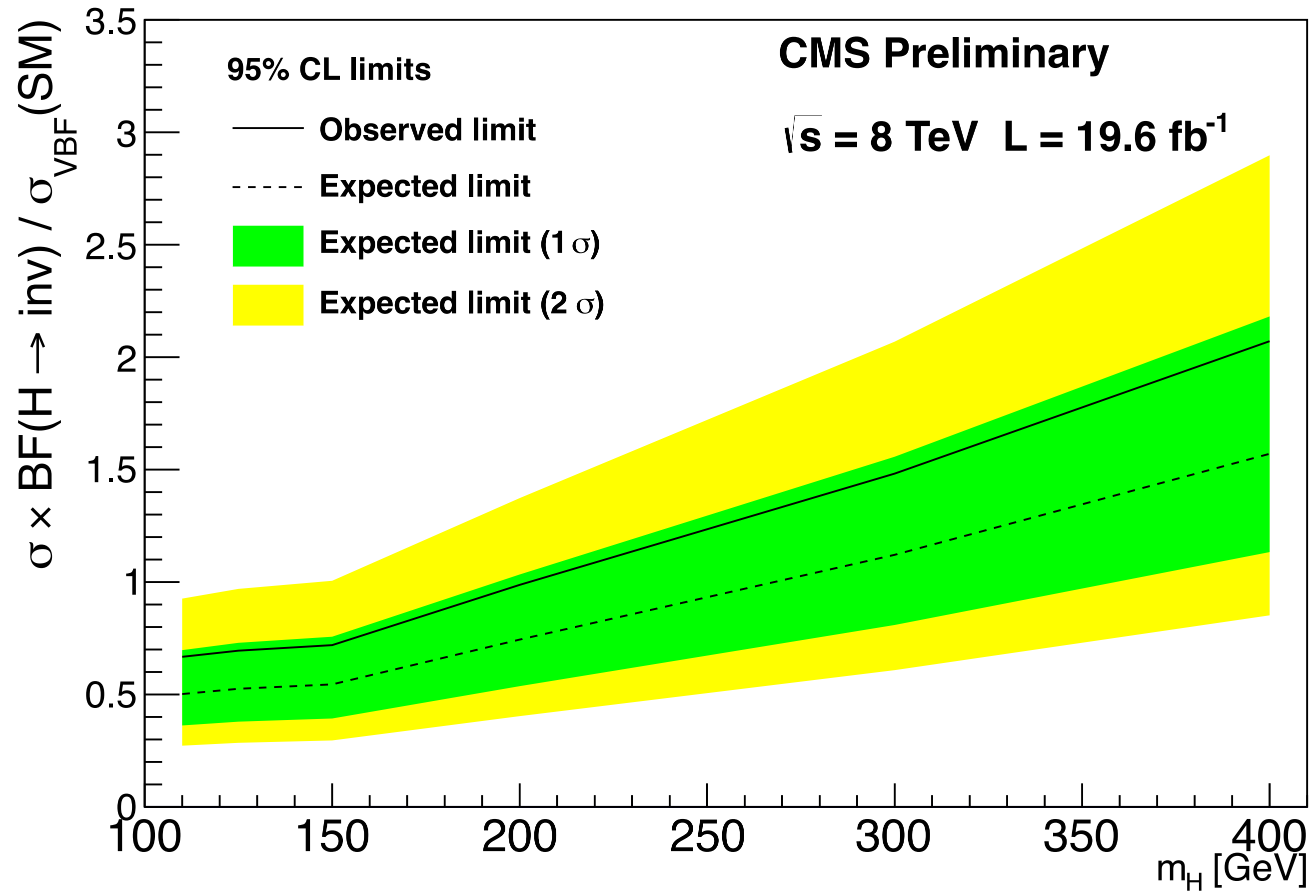




Limit on BR(H → invisible)

- Assuming the VBF production rate for a 125 GeV SM Higgs boson, limits are set on the invisible branching fraction at 95% confidence level.
- BR(H → invisible) = 69% (53% expected)



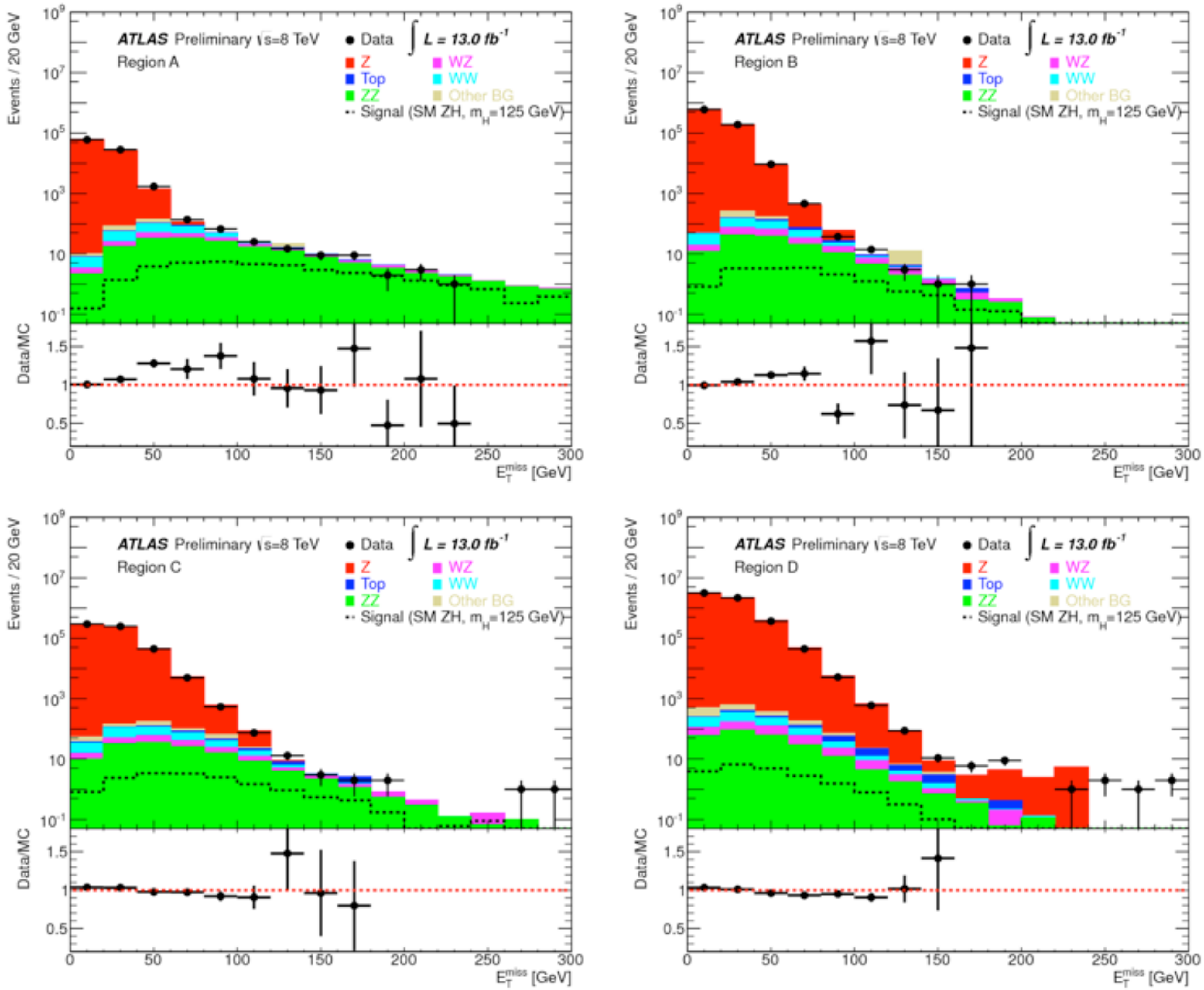


Summary of H → invisible results

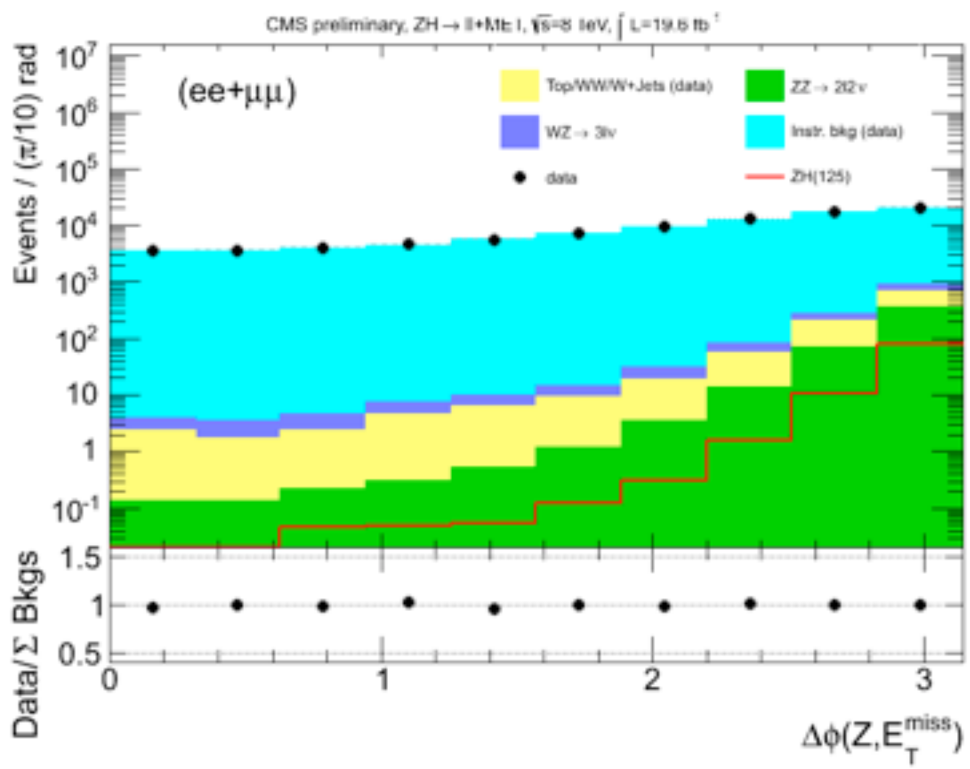
- ATLAS ZH
  - BR(H → invisible) = 65% (84% expected)
- CMS ZH
  - BR(H → invisible) = 75% (91% expected)
- CMS VBF
  - BR(H → invisible) = 69% (53% expected)

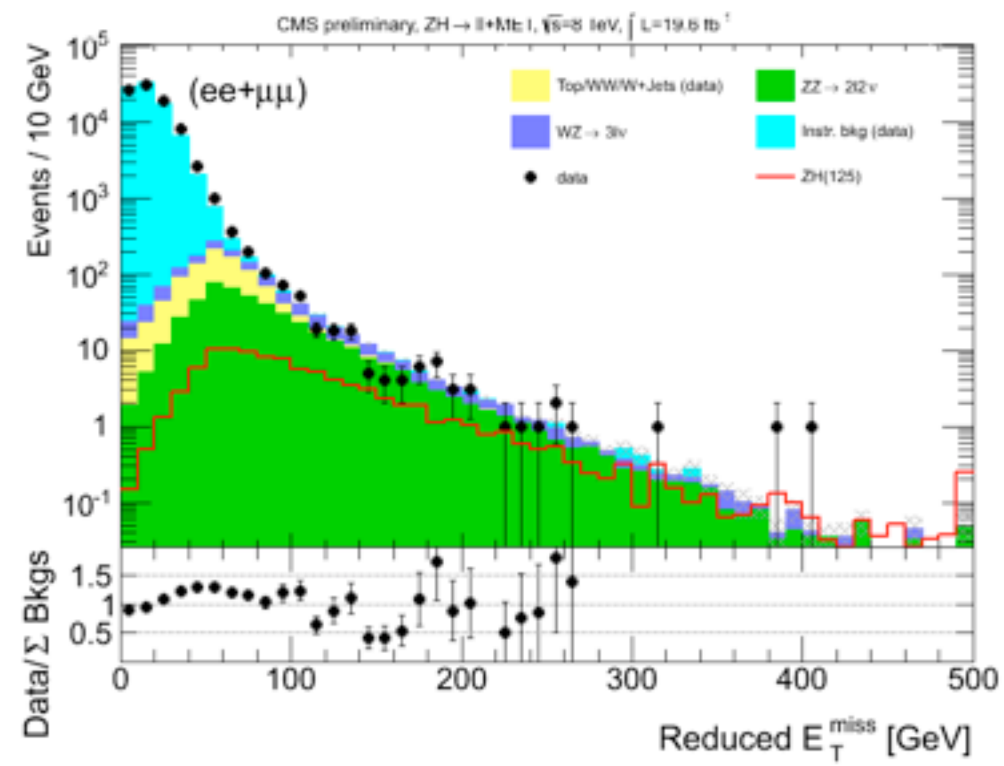
extra material

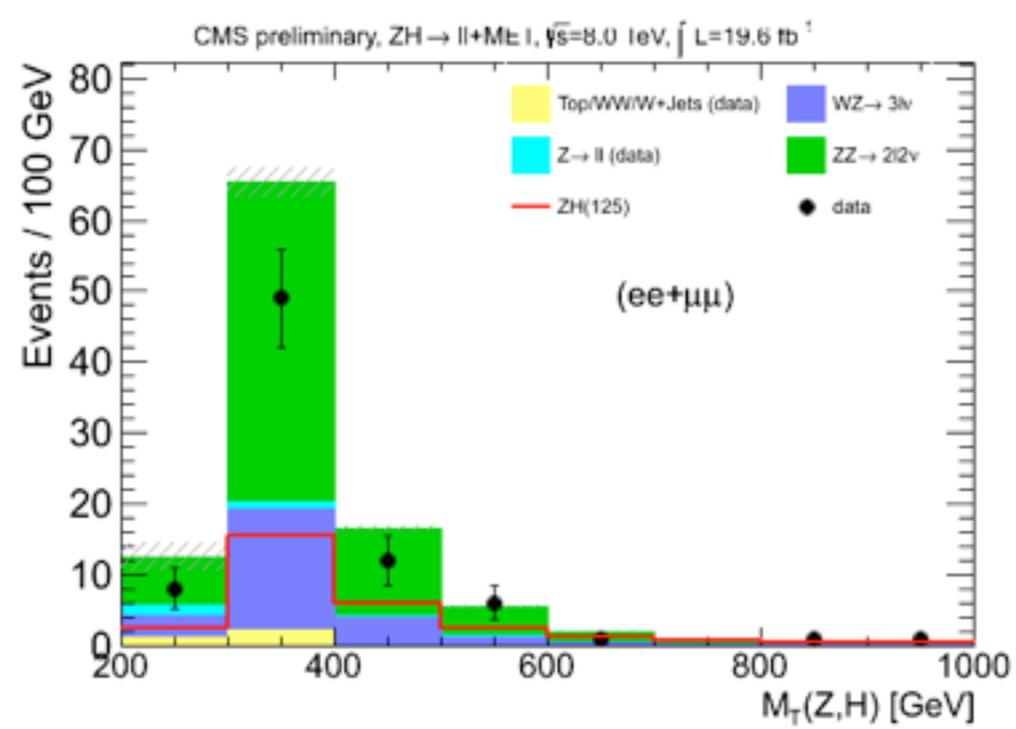
ABCD method for the Z background determination in the ZH analysis



Invisible decays of a Higgs boson produced in association with a Z boson







Invisible decays of a Higgs boson produced in association with a Z boson