H→WW and the Discovery of the Higgs Boson at ATLAS

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Introduction

Projects on ATLAS

Basic Tracking / Commissioning with Cosmic-Rays
TRT Performance
Inner Detector Alignment (TRT)
Electron Identification
- Designing HLT Trigger / Offline Electron Definitions

Electron Efficiency
Multivariate Electron Identification

Physics on ATLAS

W/Z Cross section (300/nb, 35/pb)
WW Cross section (35/pb, 1/fb)
Search for $H \rightarrow WW$
- W+jet Background
- Observation of Higgs.

Outline

The Higgs: Introduction/Motivation

Why H$\rightarrow$WW.

H$\rightarrow$WW$\rightarrow$ lνlν (WW$\rightarrow$lνlν)

Results in broader context

Standard Model and the Higgs

- Simple/Accurate description elementary particles and their interactions

Matter Particles

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix} \qquad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

- Quantum Field Theory. Gauge Invariance $SU(3) \times SU(2) \times U(1)$

Standard Model and the Higgs

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Gauge Bosons

$$g \qquad W \qquad Z \qquad \gamma$$

- Consistent theory strong, weak, and electromagnetic forces.
- Gauge Invariance implies massless Matter Particles and Gauge Bosons

Standard Model and the Higgs

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Higgs boson:

"Spontaneously Symmetry Breaking"
Allows for Massive fermions, Massive Weak bosons and Gauge Invariance
Additional particle predicted by the theory.

Standard Model and the Higgs

- Simple/Accurate description elementary particles and their interactions

Matter Particles

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g W Z γ

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Higgs boson:

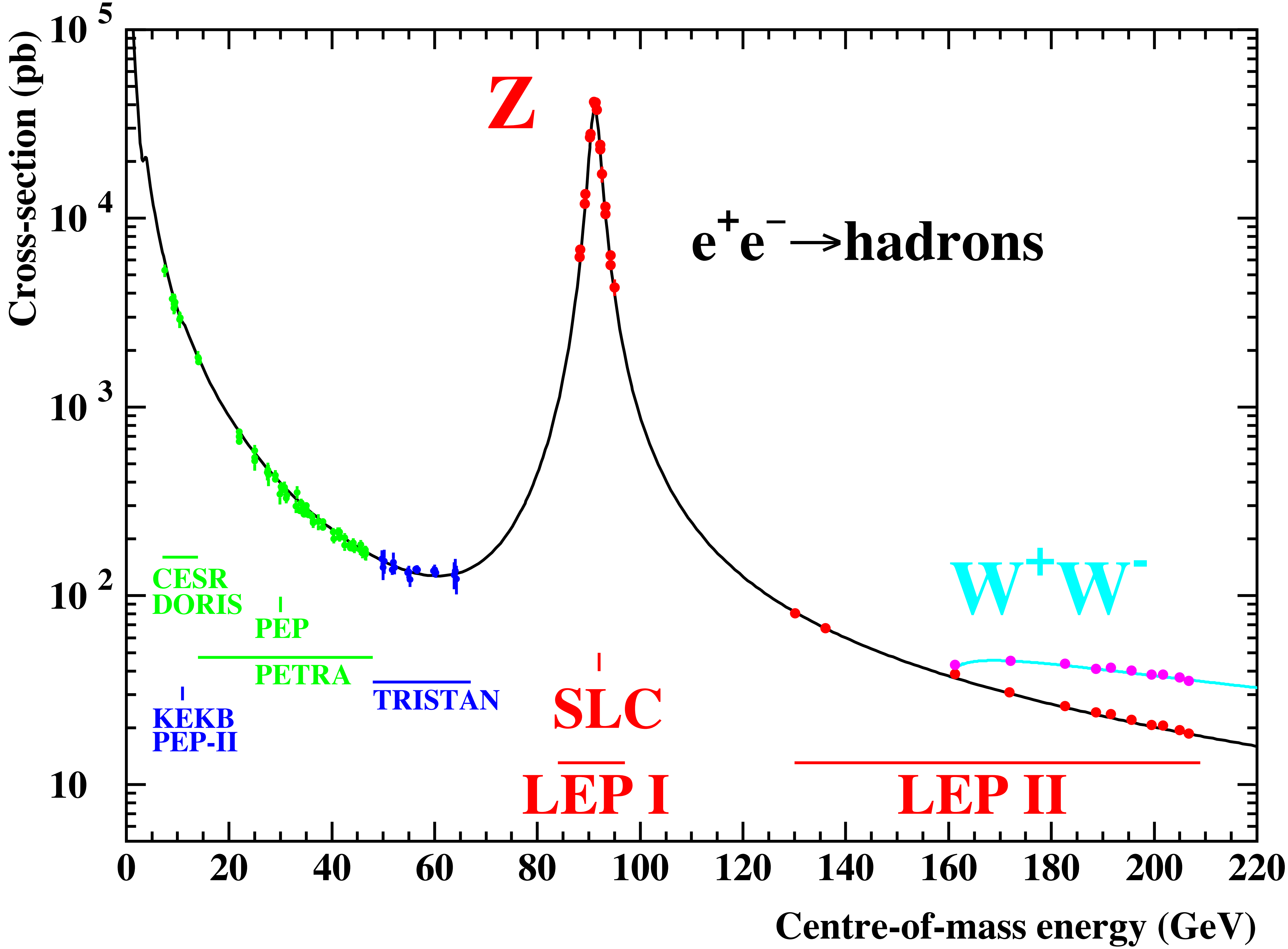
“Sponta

Allows

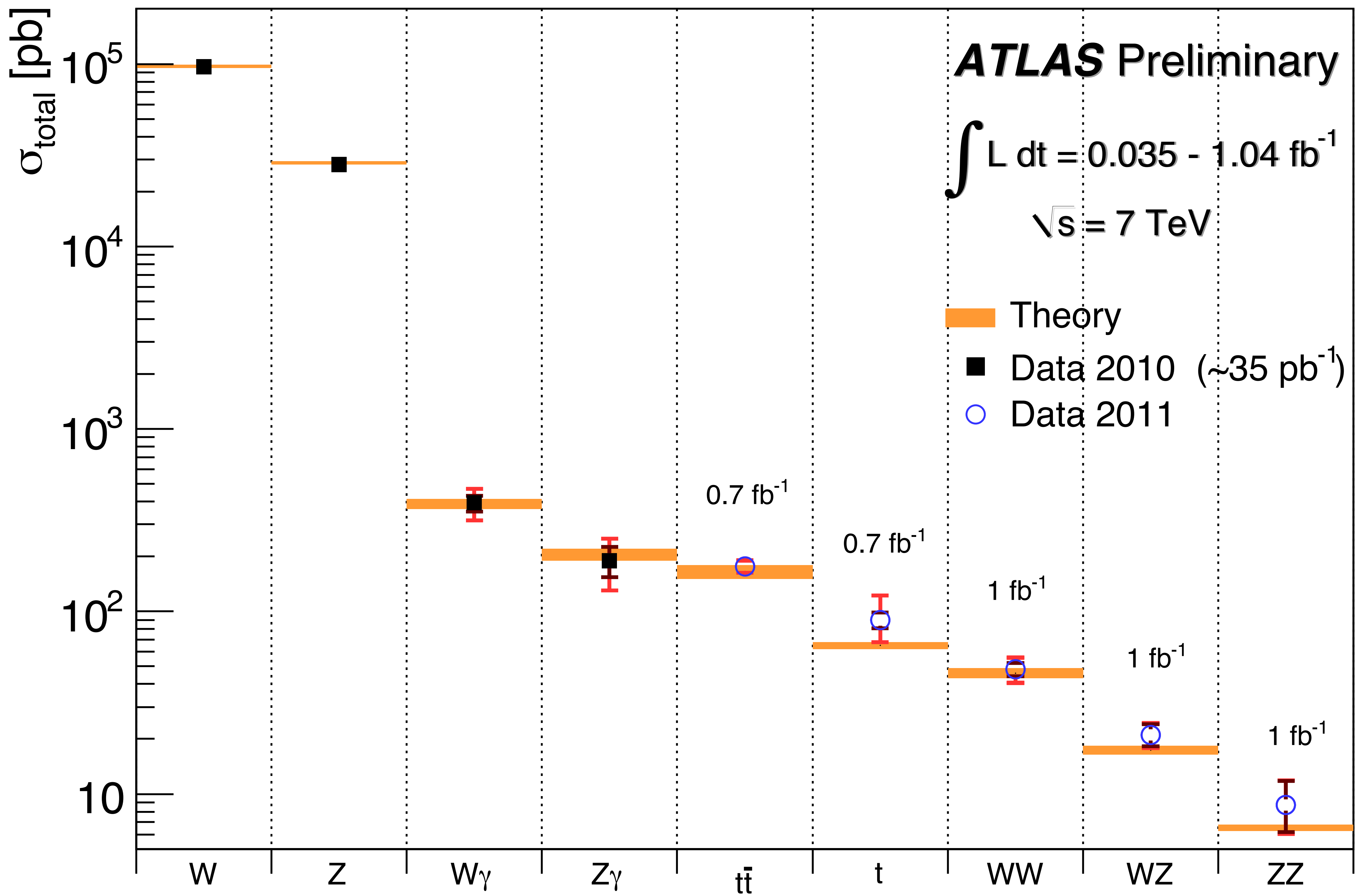
Additio

Prior to LHC, only element of theory not directly confirmed by experiment.

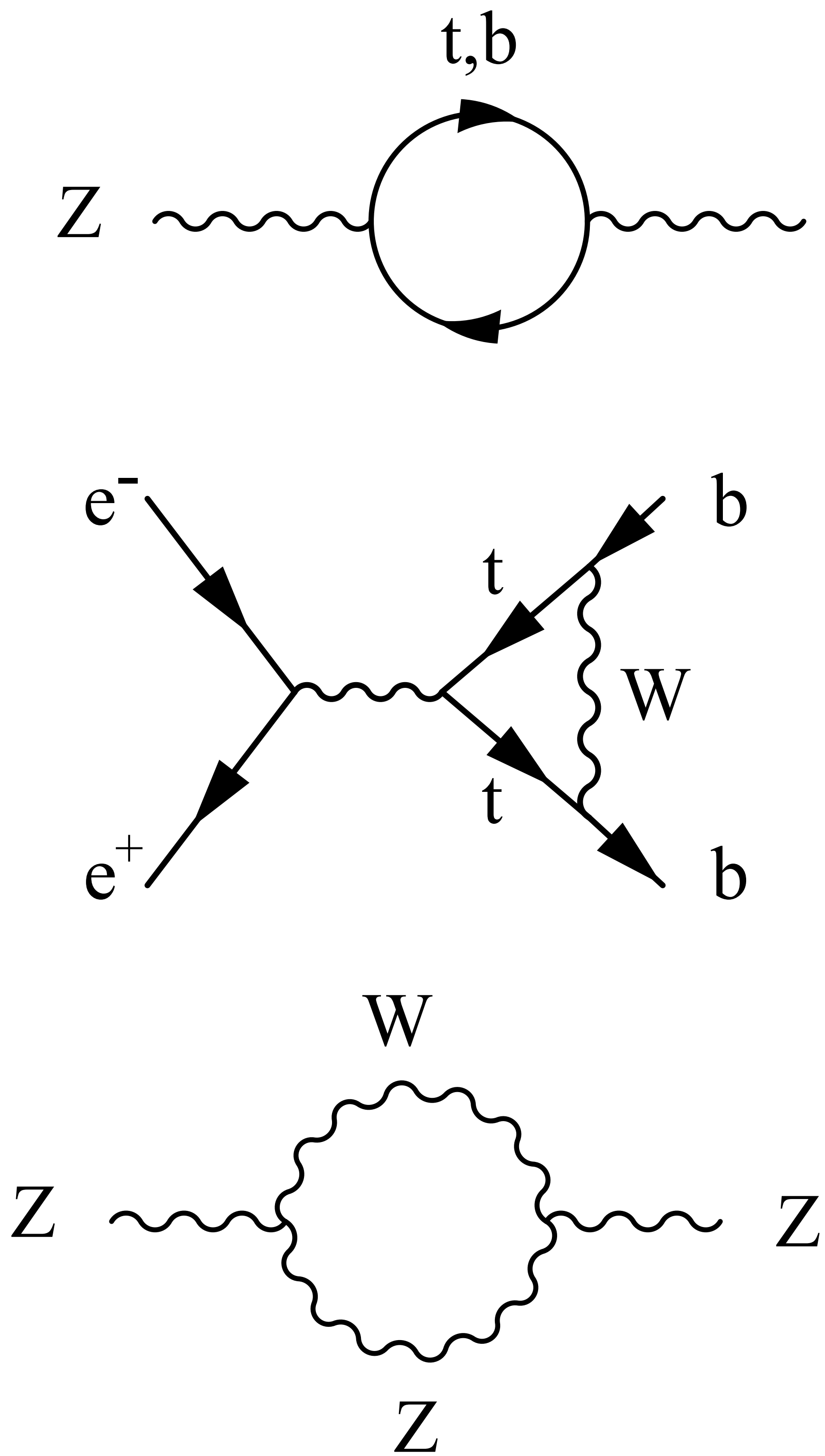
e^+e^- Collisions

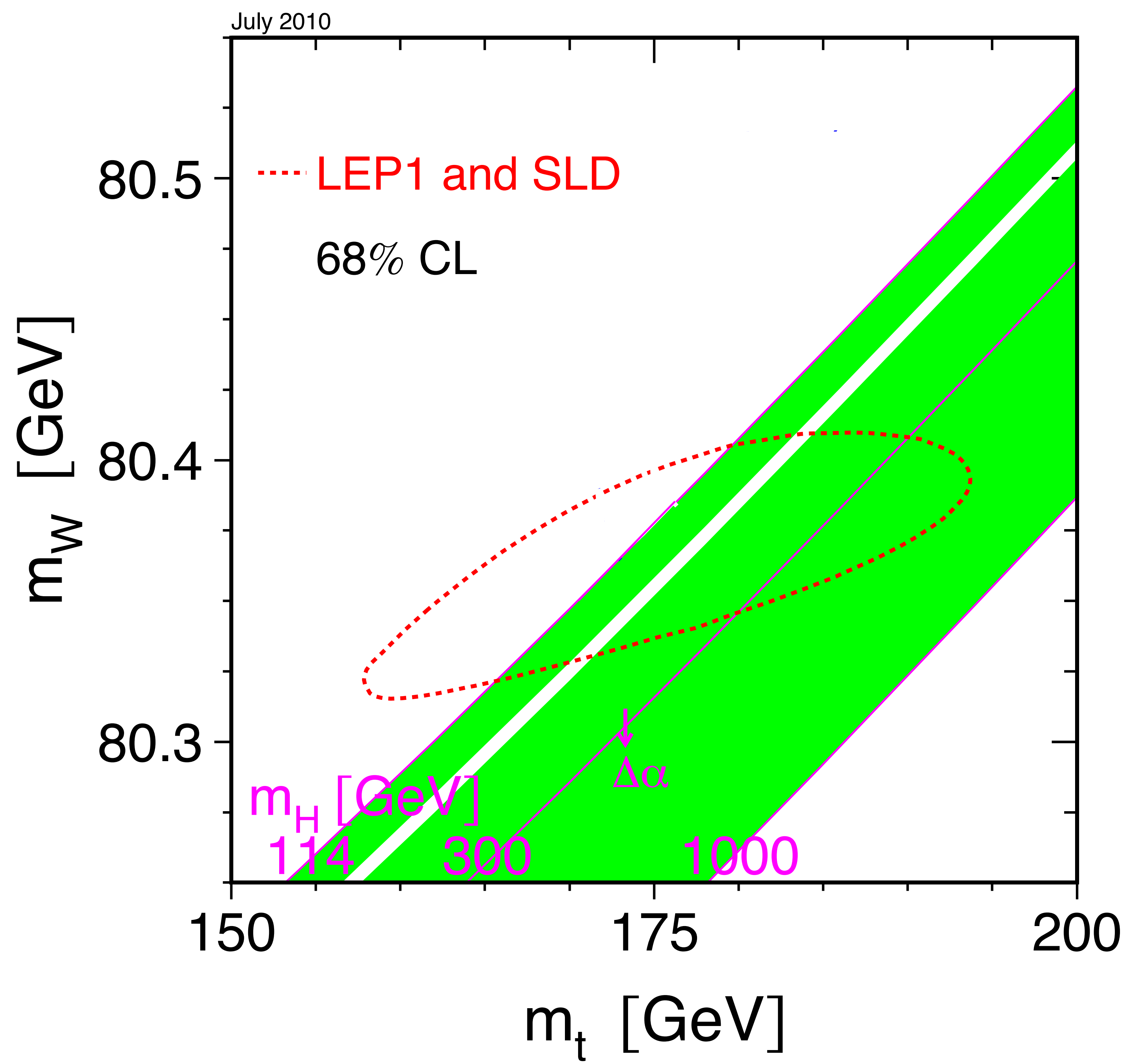


Hadron Collisions



Predicting the Mass of the Top Quark





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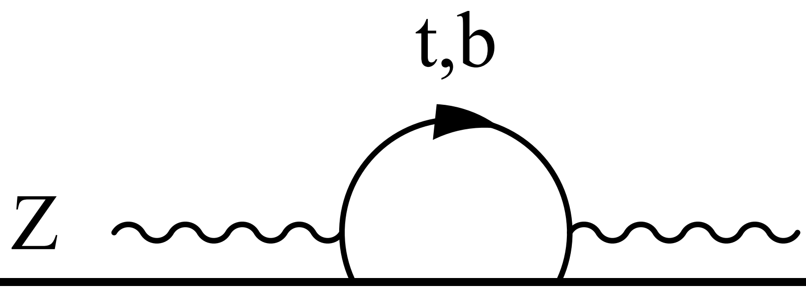
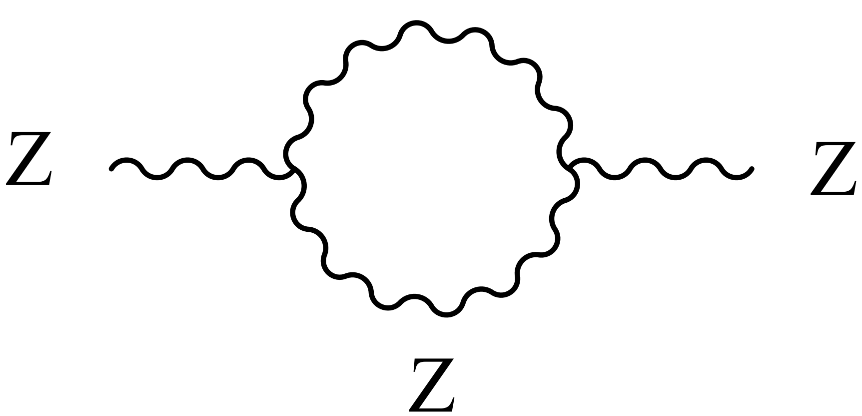
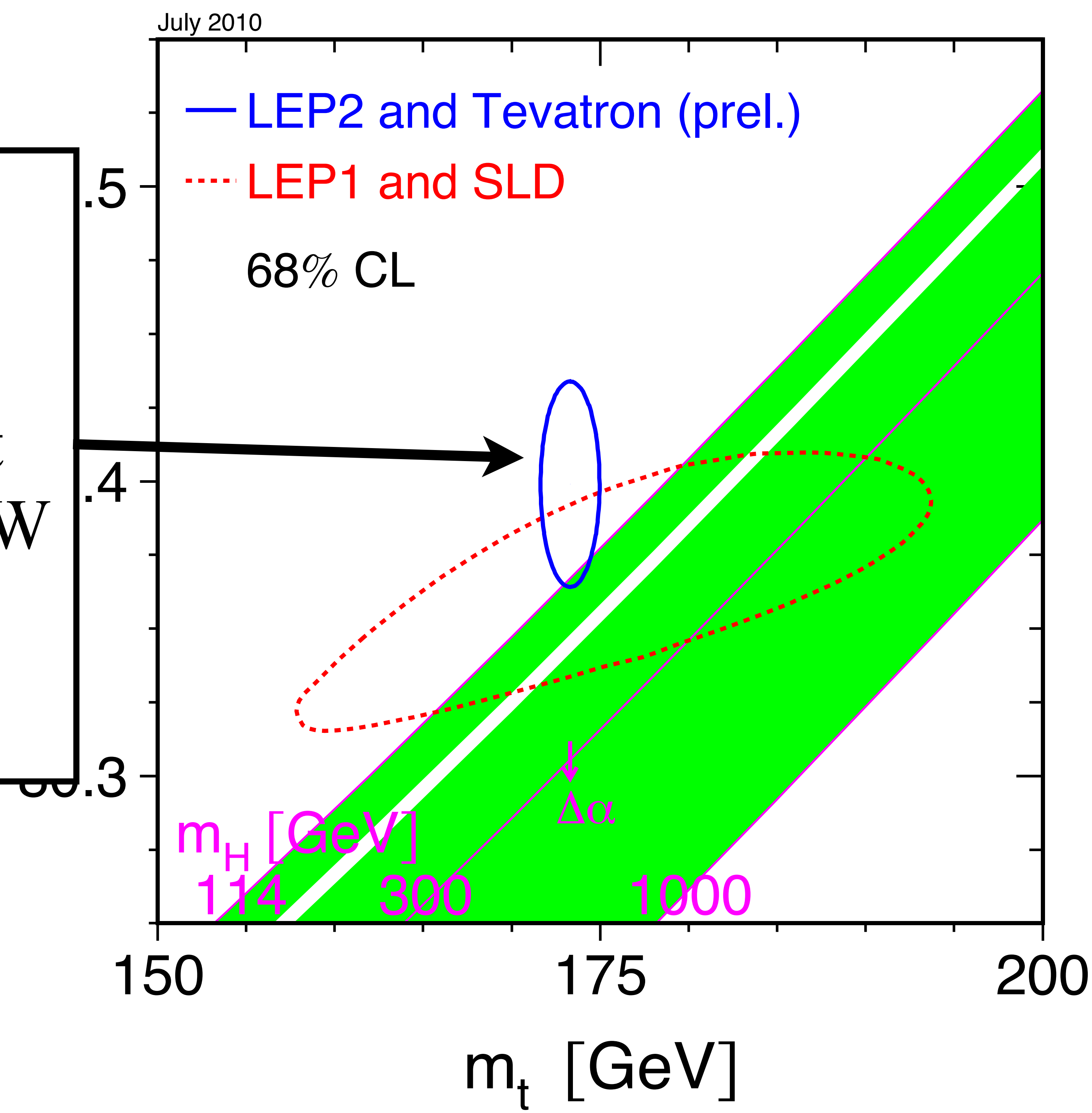


Fermilab

- Discovered Top Quark
- Precise measurement of mt
- Precise measurement of mW

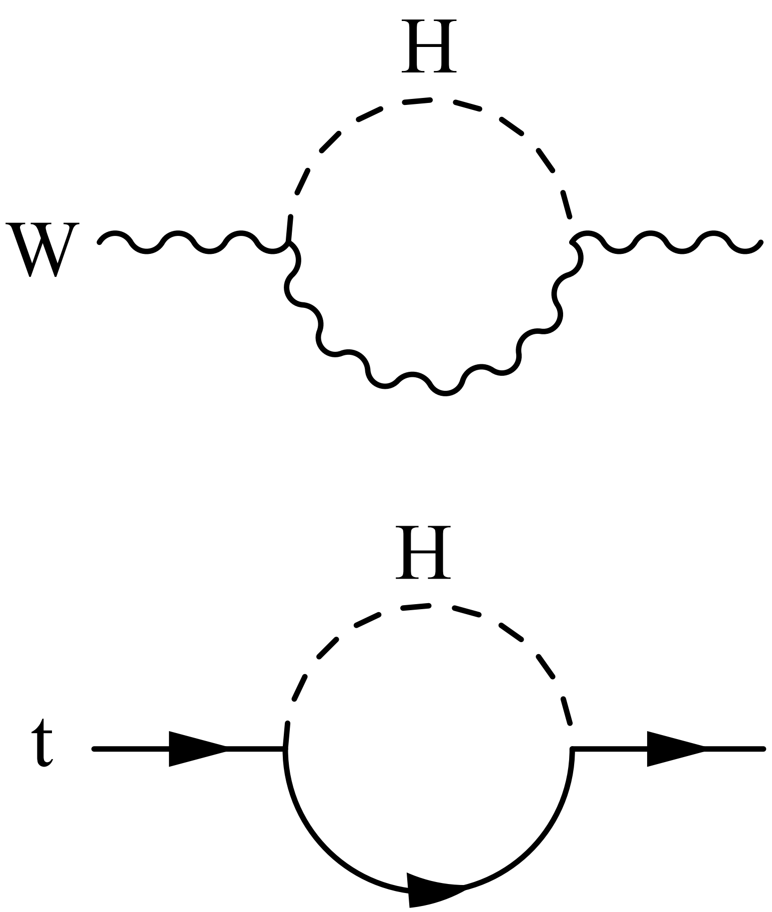
Validation of SM radiative corrections

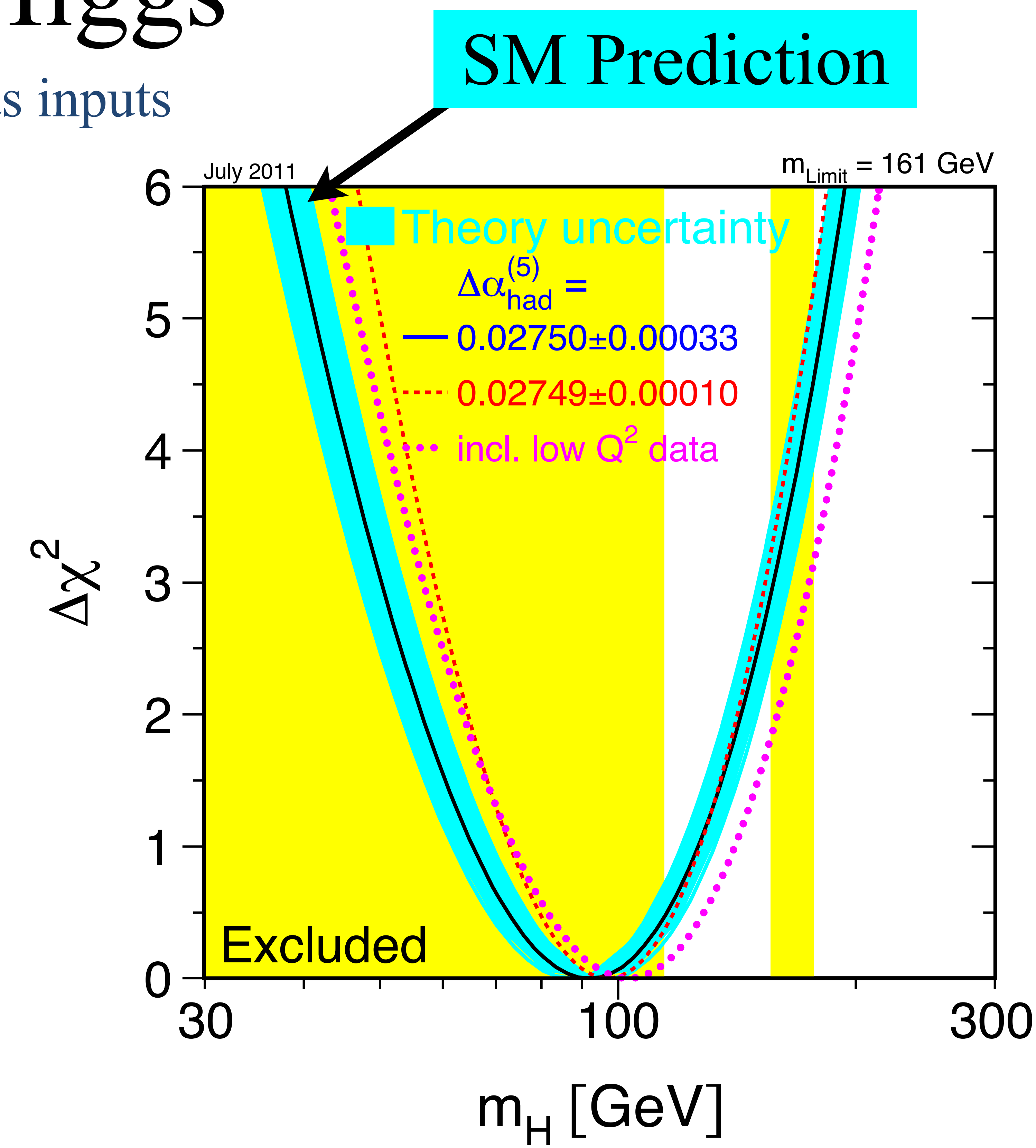




Same Game for Higgs

Now use measured mt and mW as inputs





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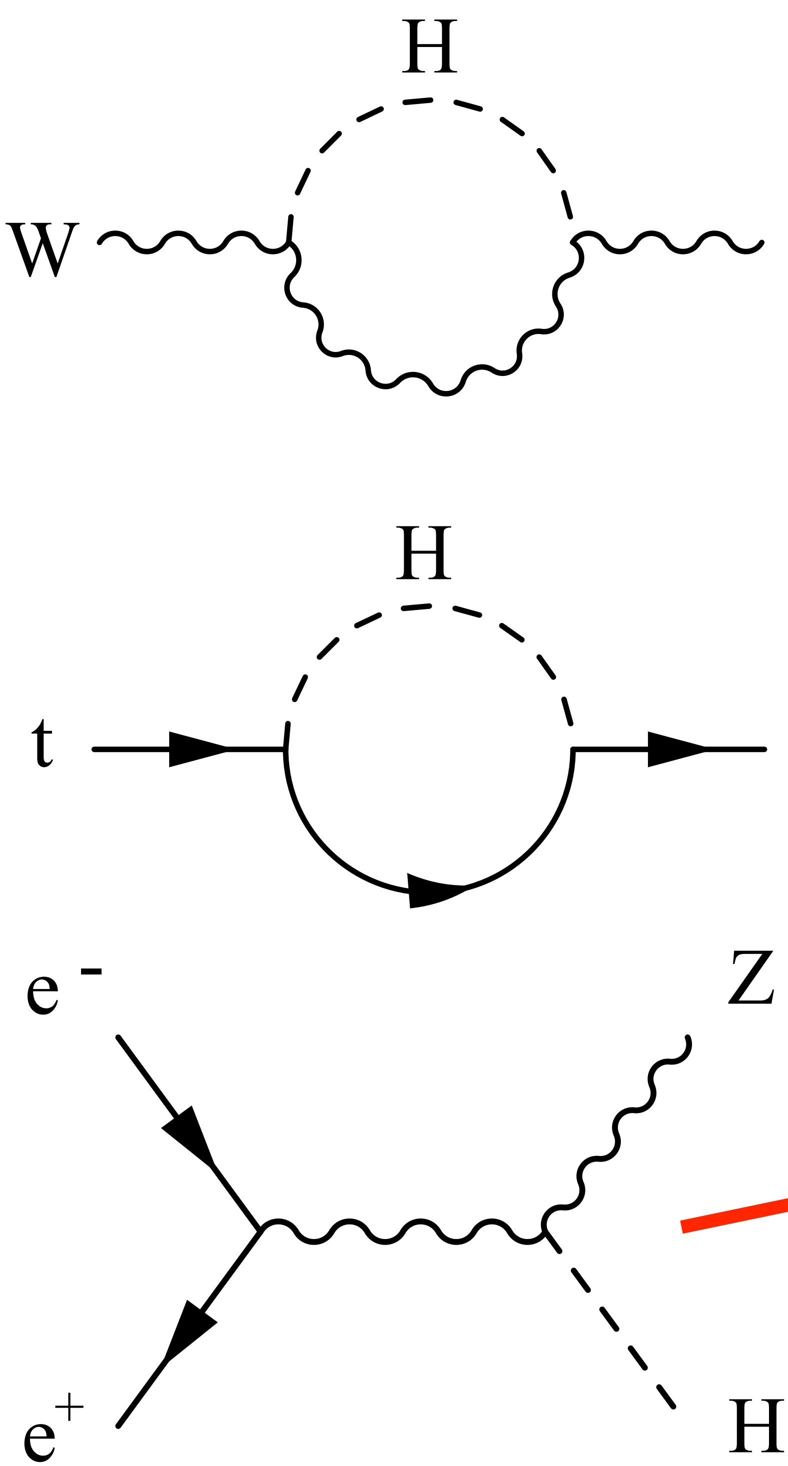
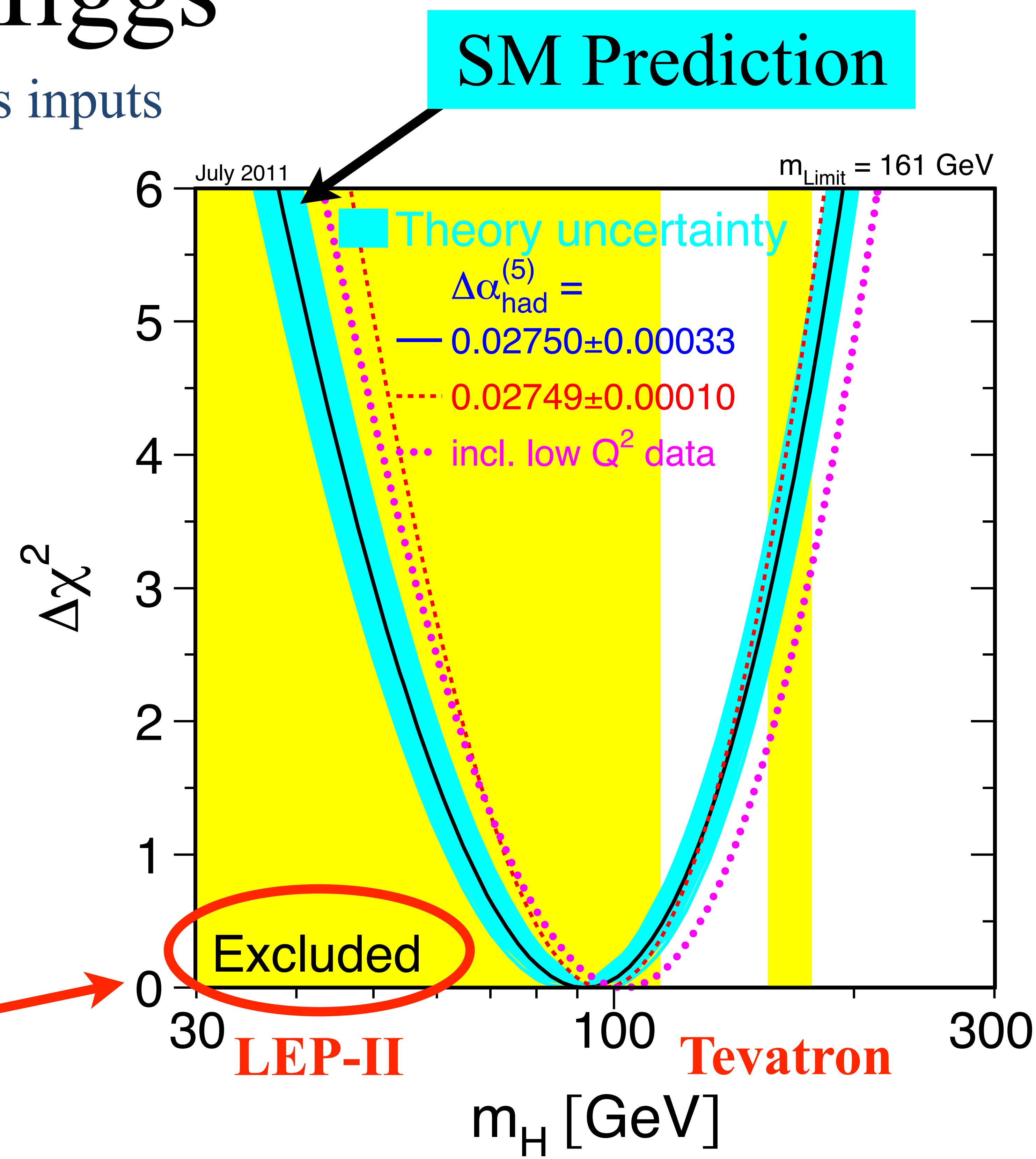
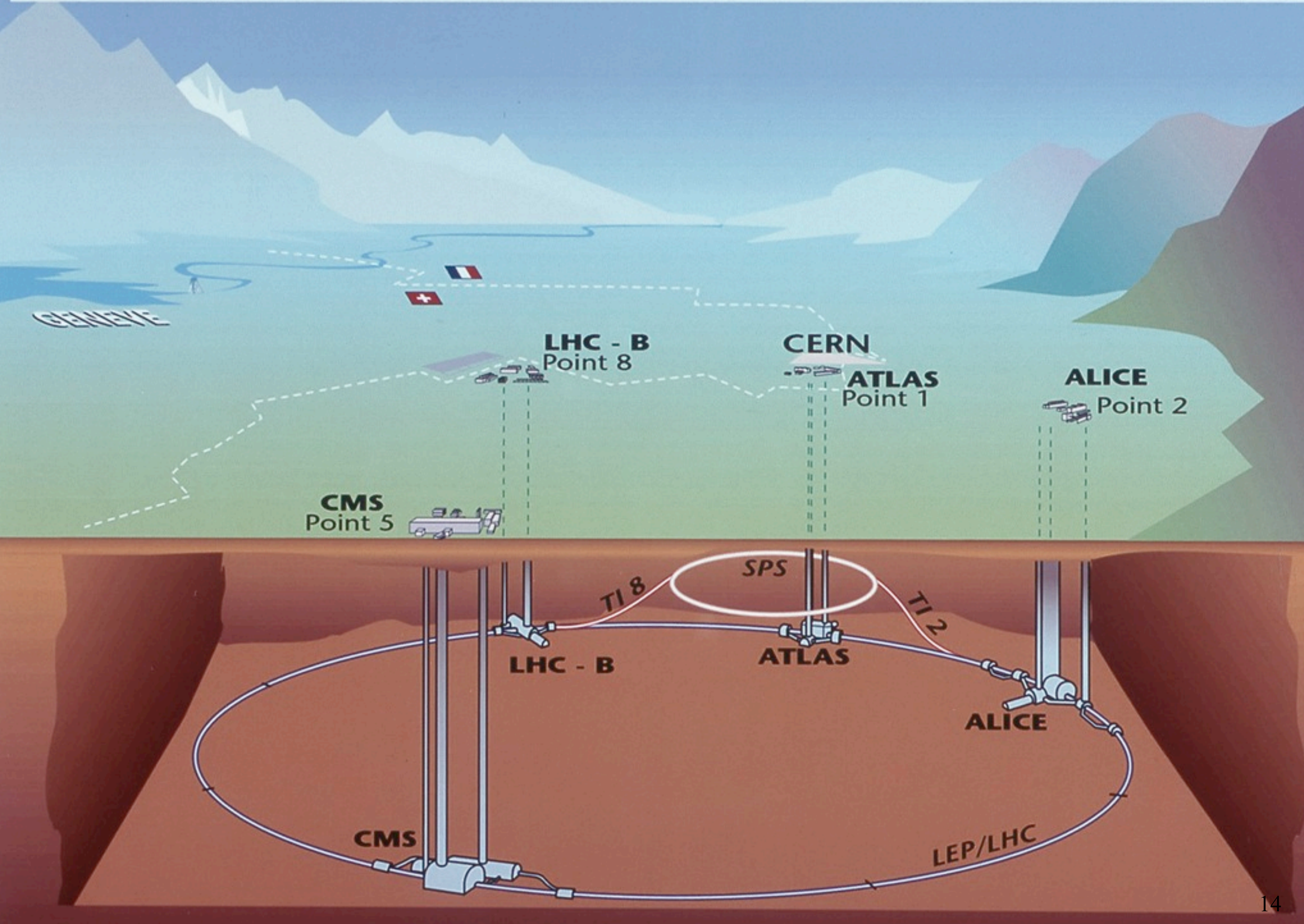
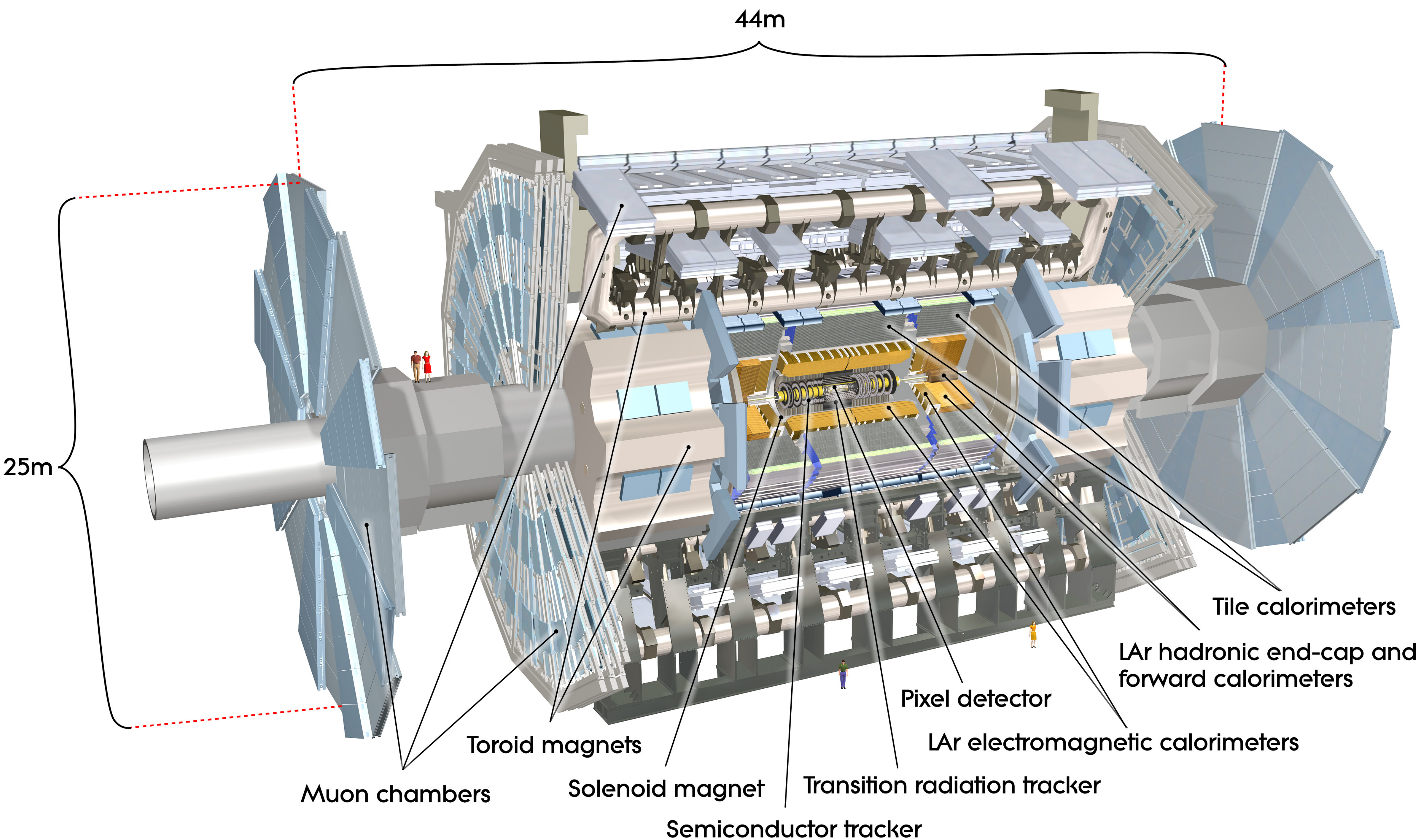




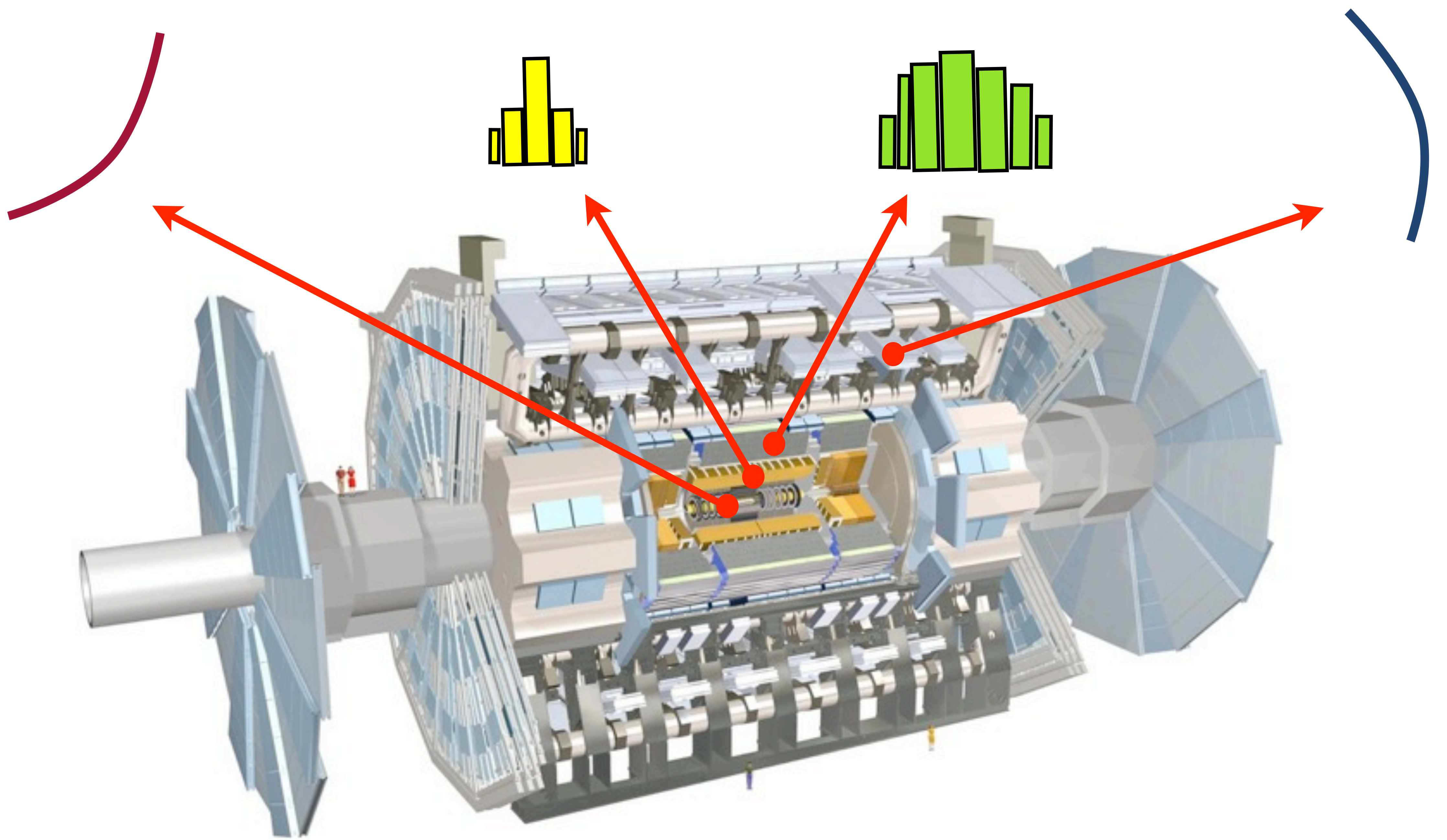
Overall view of the LHC experiments.



A Toroidal LHC ApparatuS



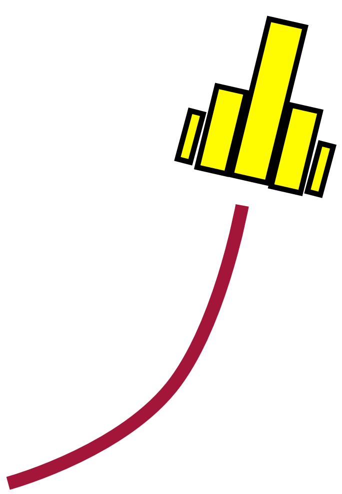
The Basic Outputs:



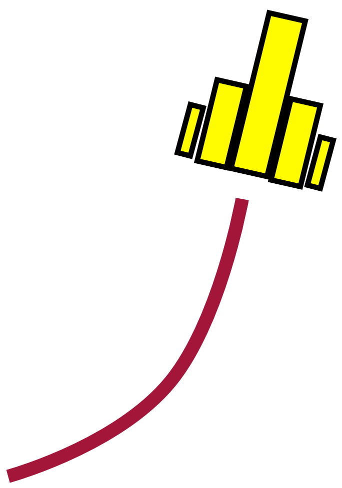
A lot of work goes into making/understanding these basic outputs. Chapter 4-7

ν_e	ν_μ	ν_τ	u	c	t
e	μ	τ	d	s	b

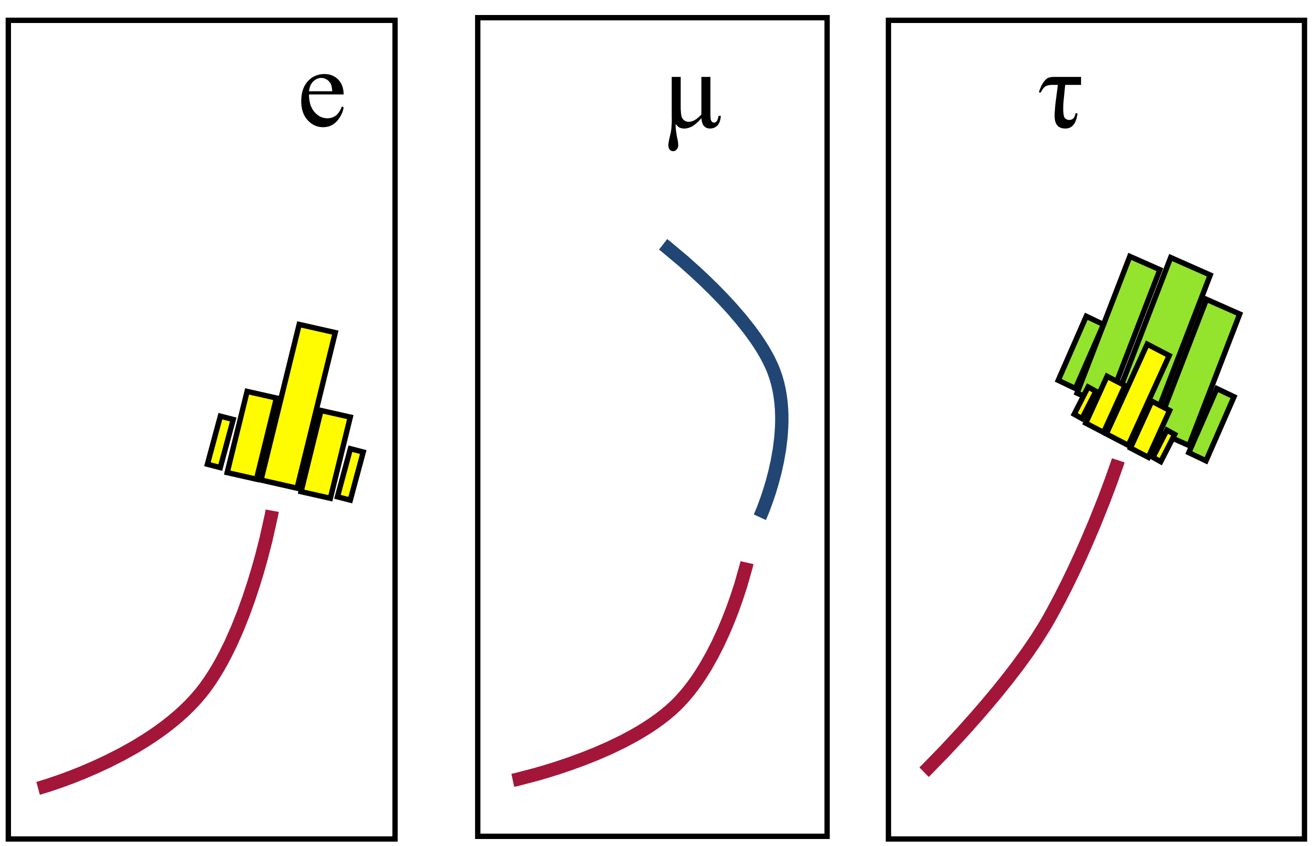
ν_e	ν_μ	ν_τ	u	c	t
e	μ	τ	d	s	b



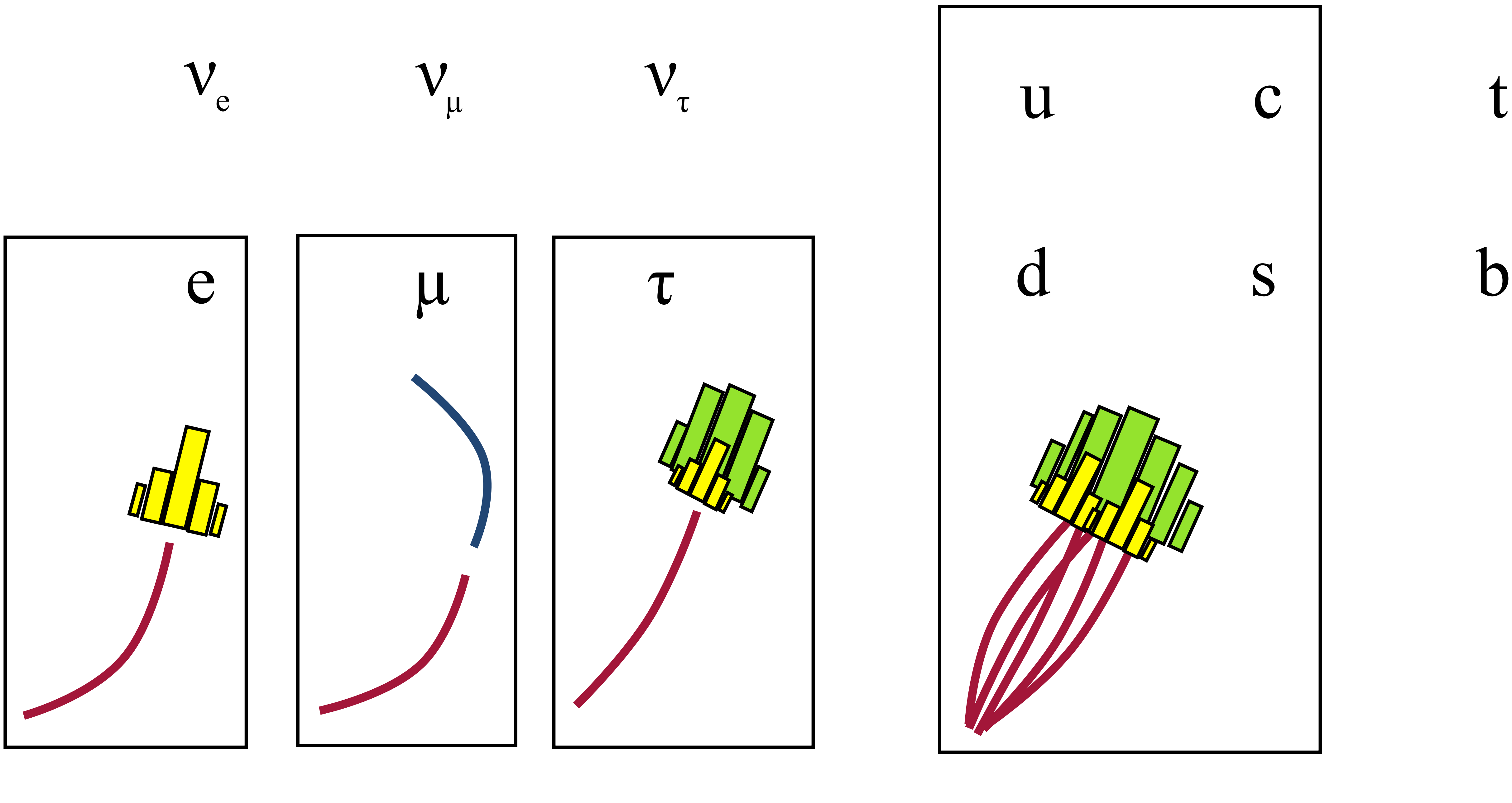
ν_e	ν_μ	ν_τ	u	c	t
e	μ	τ	d	s	b



ν_e	ν_μ	ν_τ



u	c	t
d	s	b


ν_e
ν_μ
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u
c
t
e
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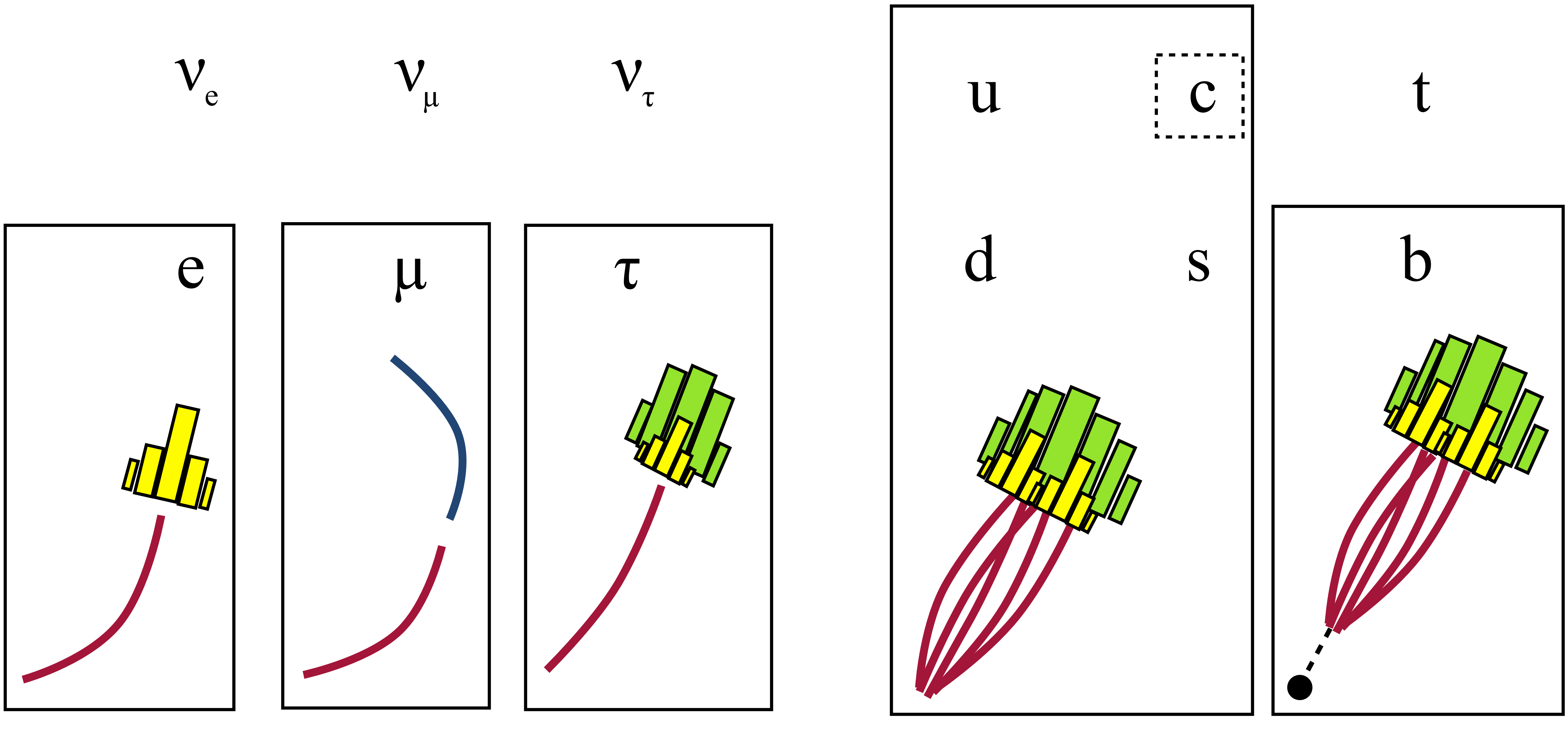
d
s
b



ν_e
ν_μ
ν_τ
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c
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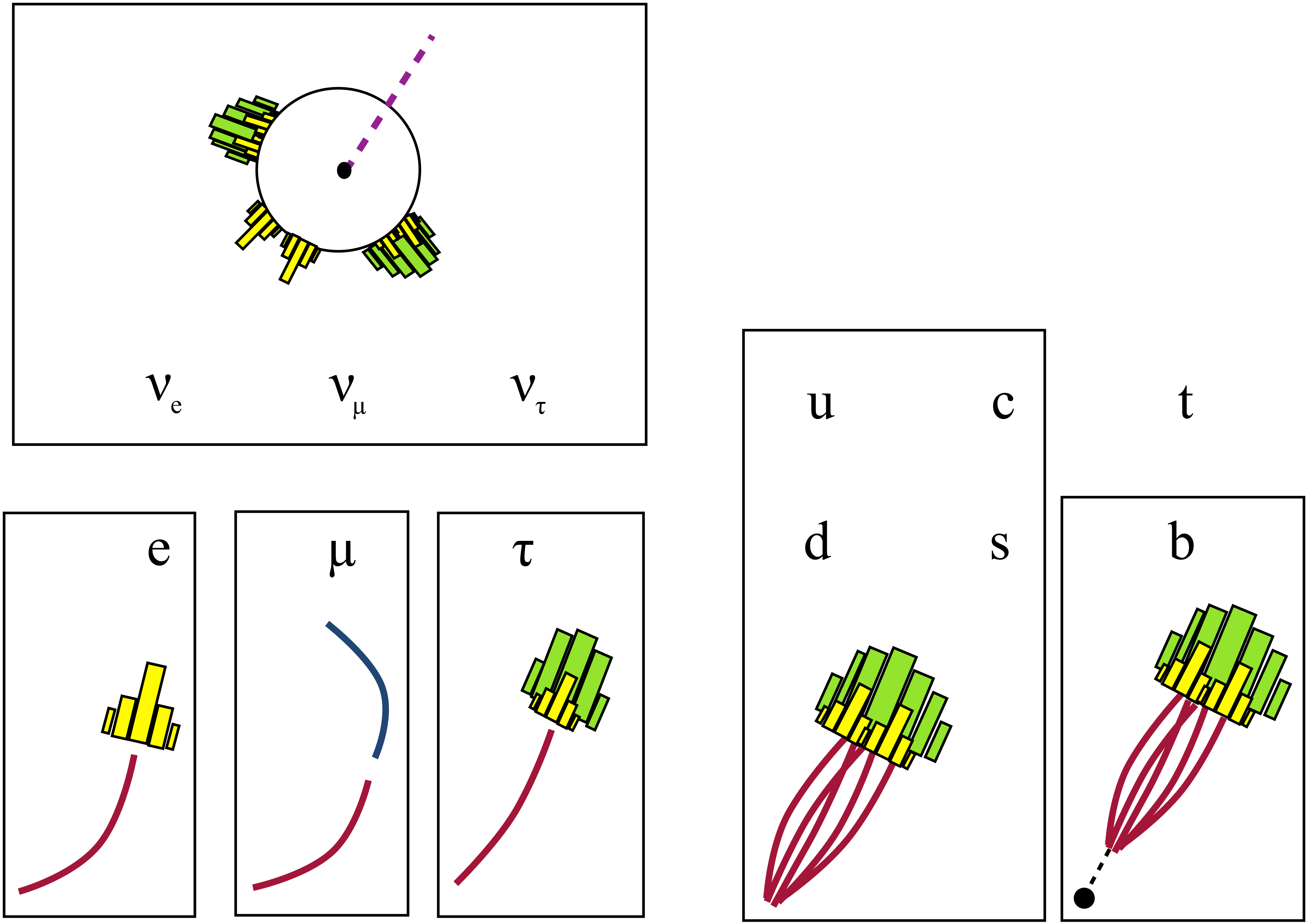
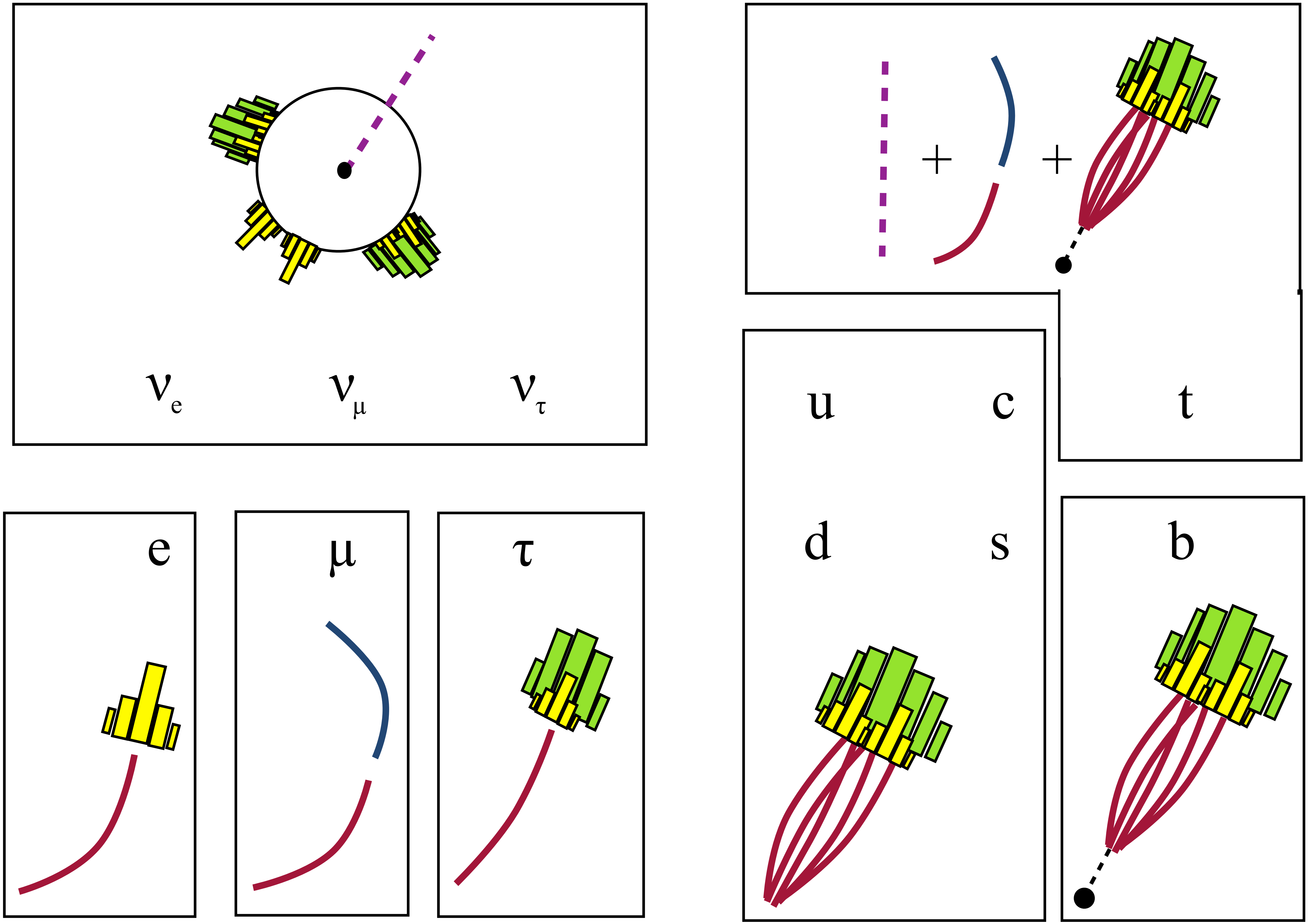
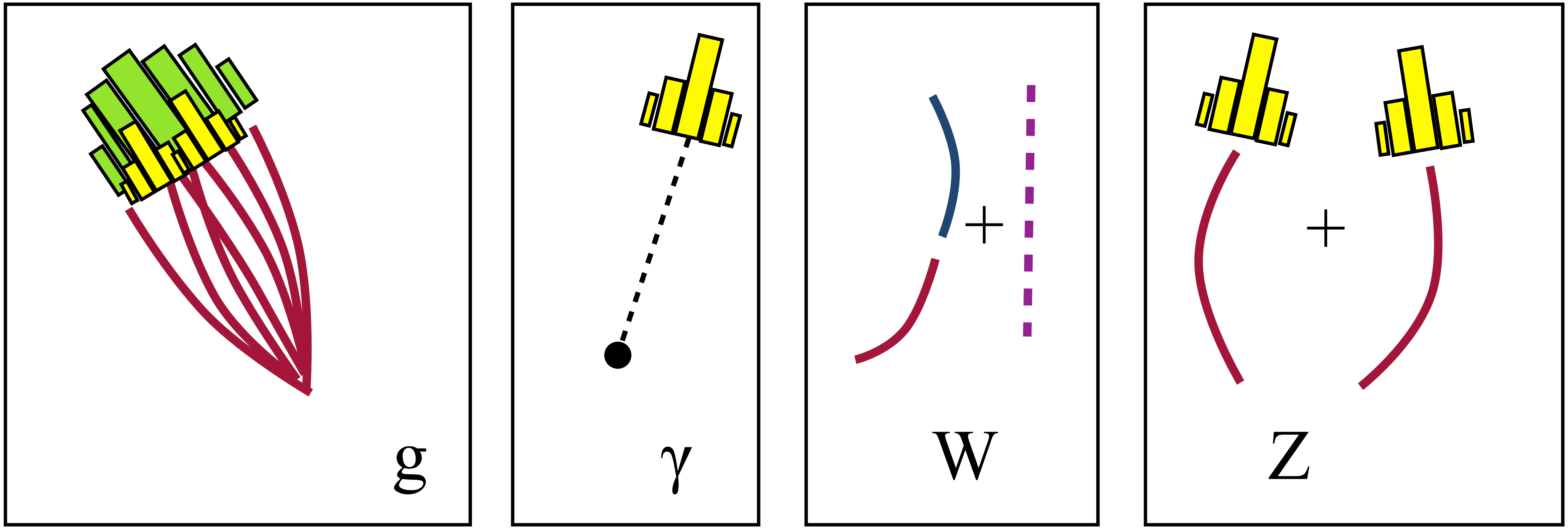
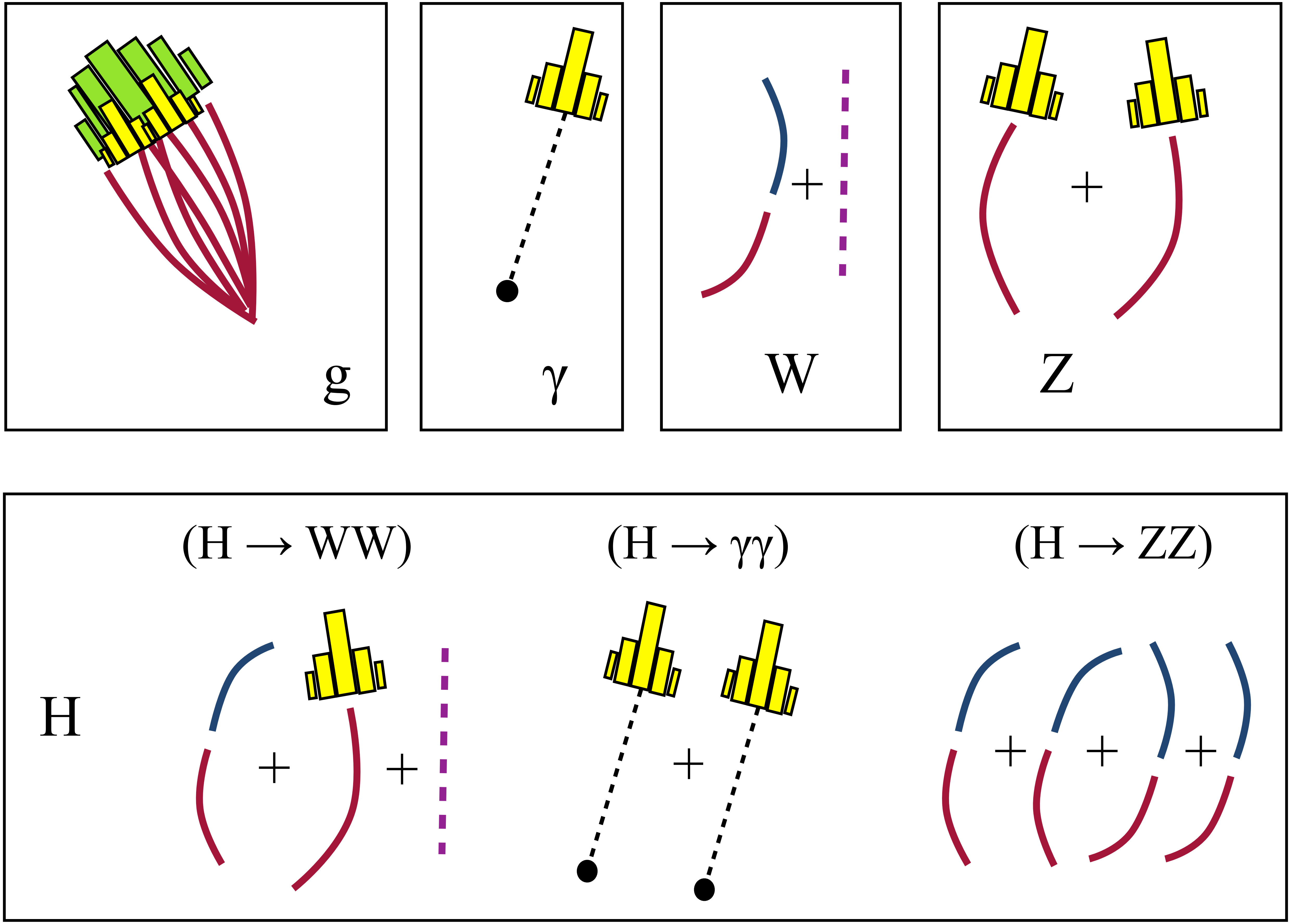


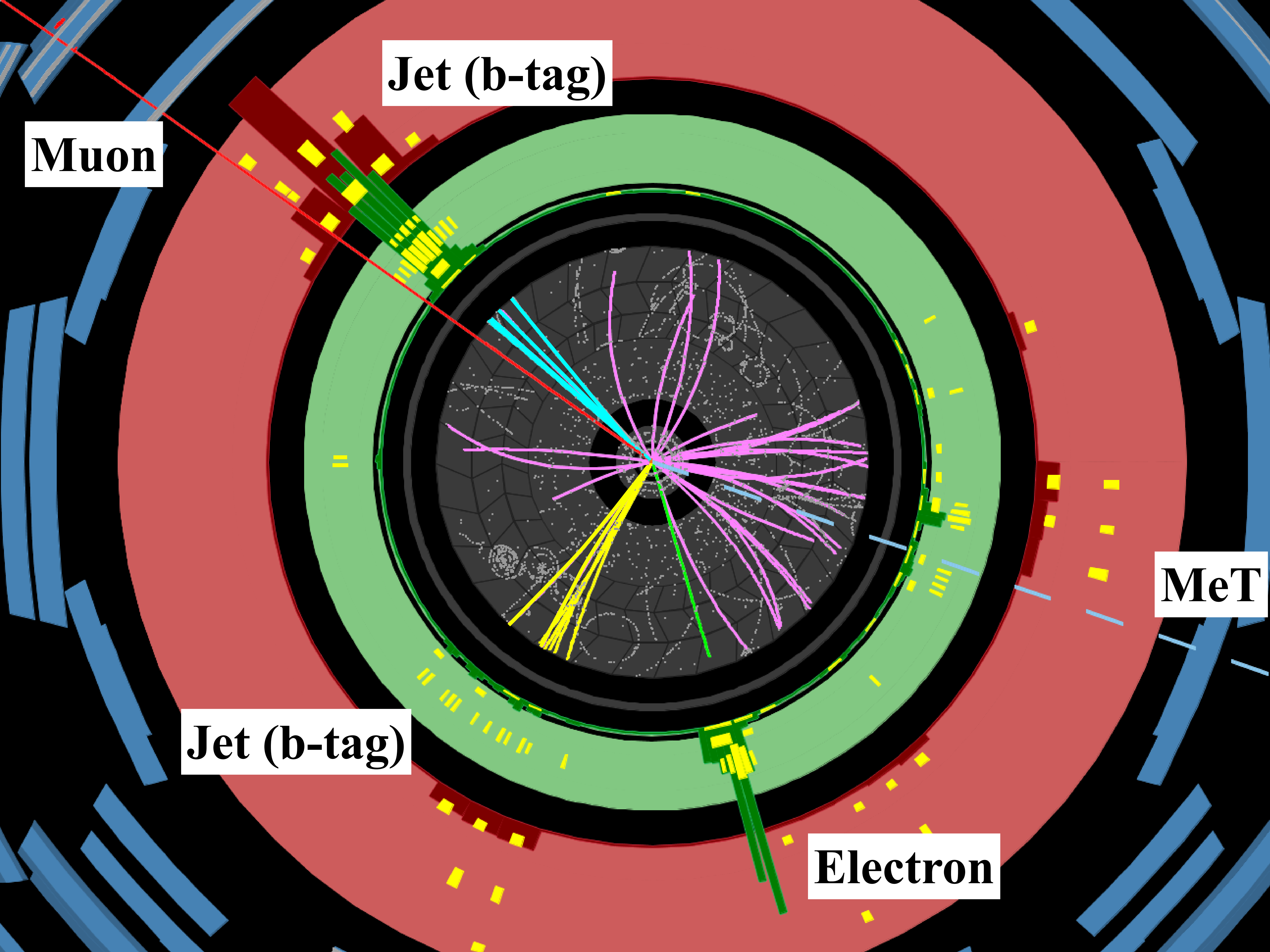
ν_e ν_μ ν_τ
u c t
d s b
e μ τ



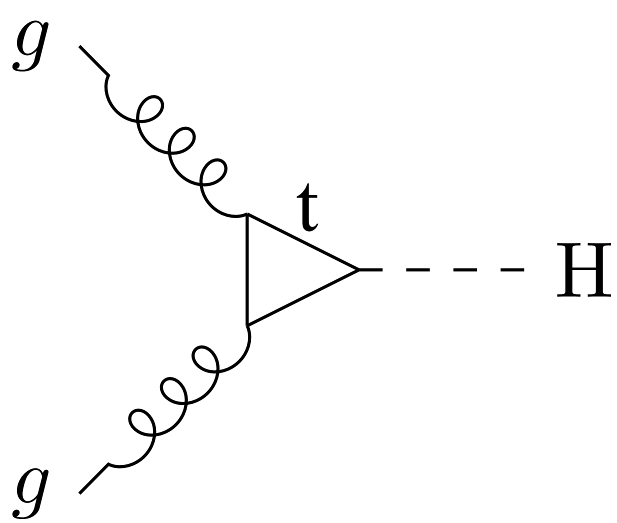
ν_e
ν_μ
ν_τ
+
+
u
c
t
d
s
b
e
μ
τ

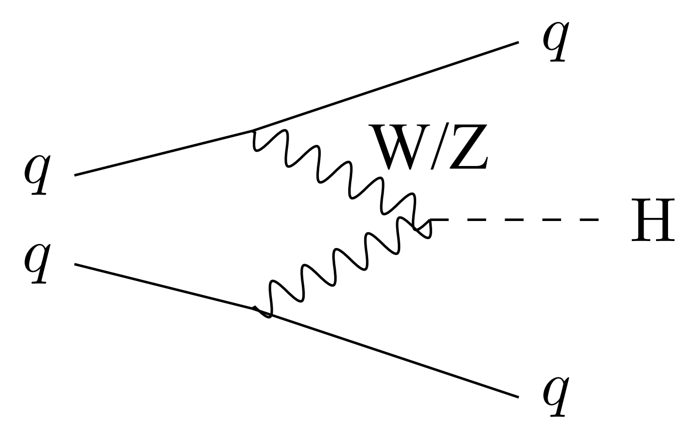

g
γ
W
+
Z
+

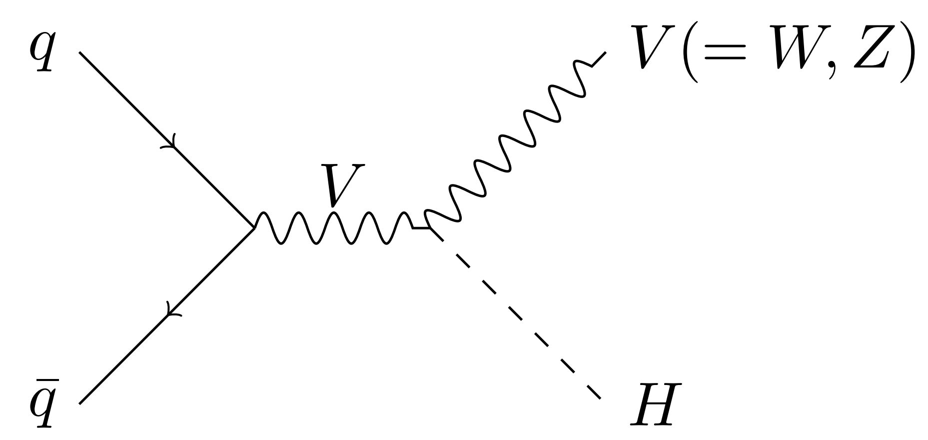

g
γ
W
Z
H
(H → WW)
(H → γγ)
(H → ZZ)

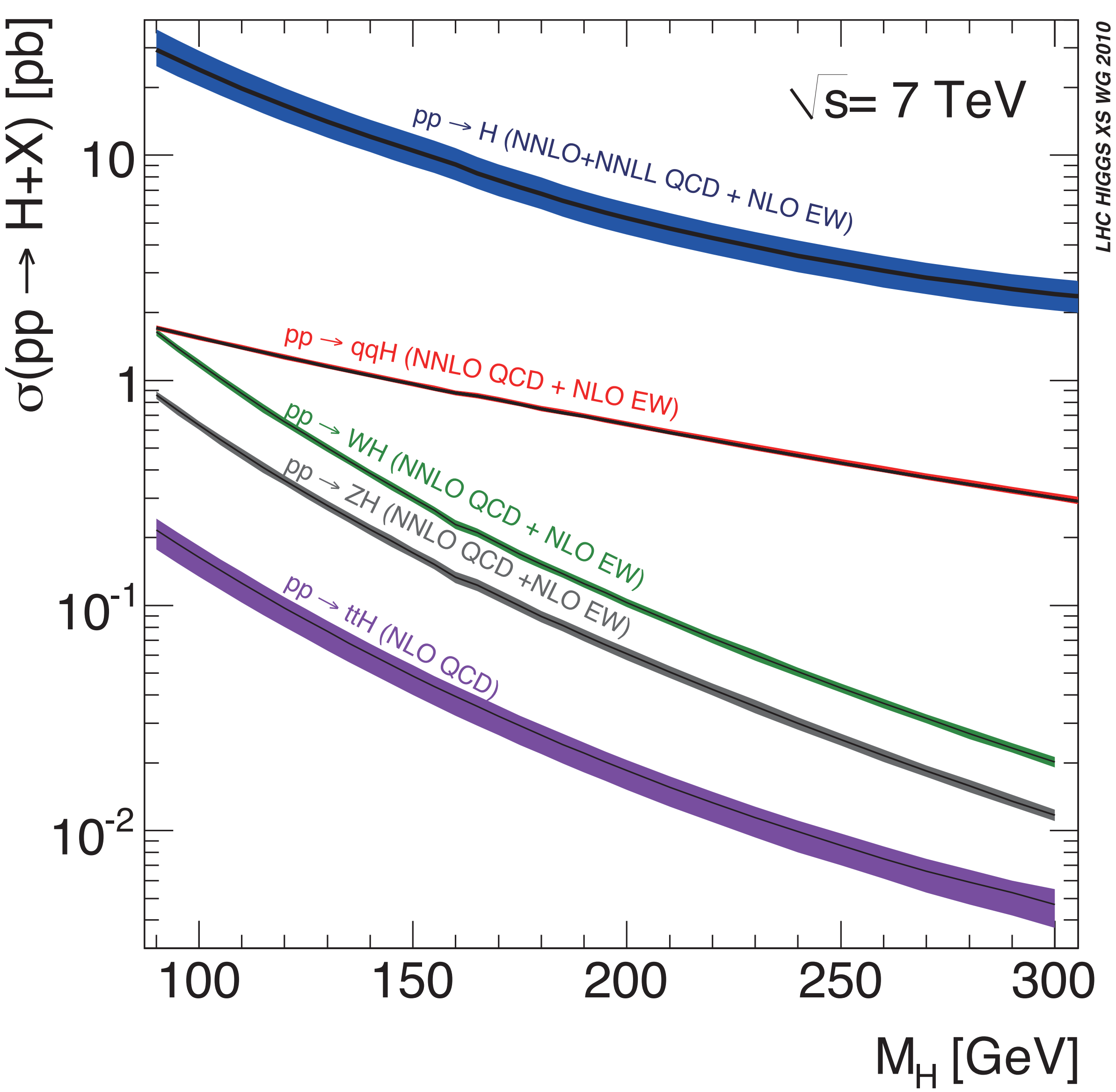

Jet (b-tag)
Muon
MeT
Jet (b-tag)
Electron

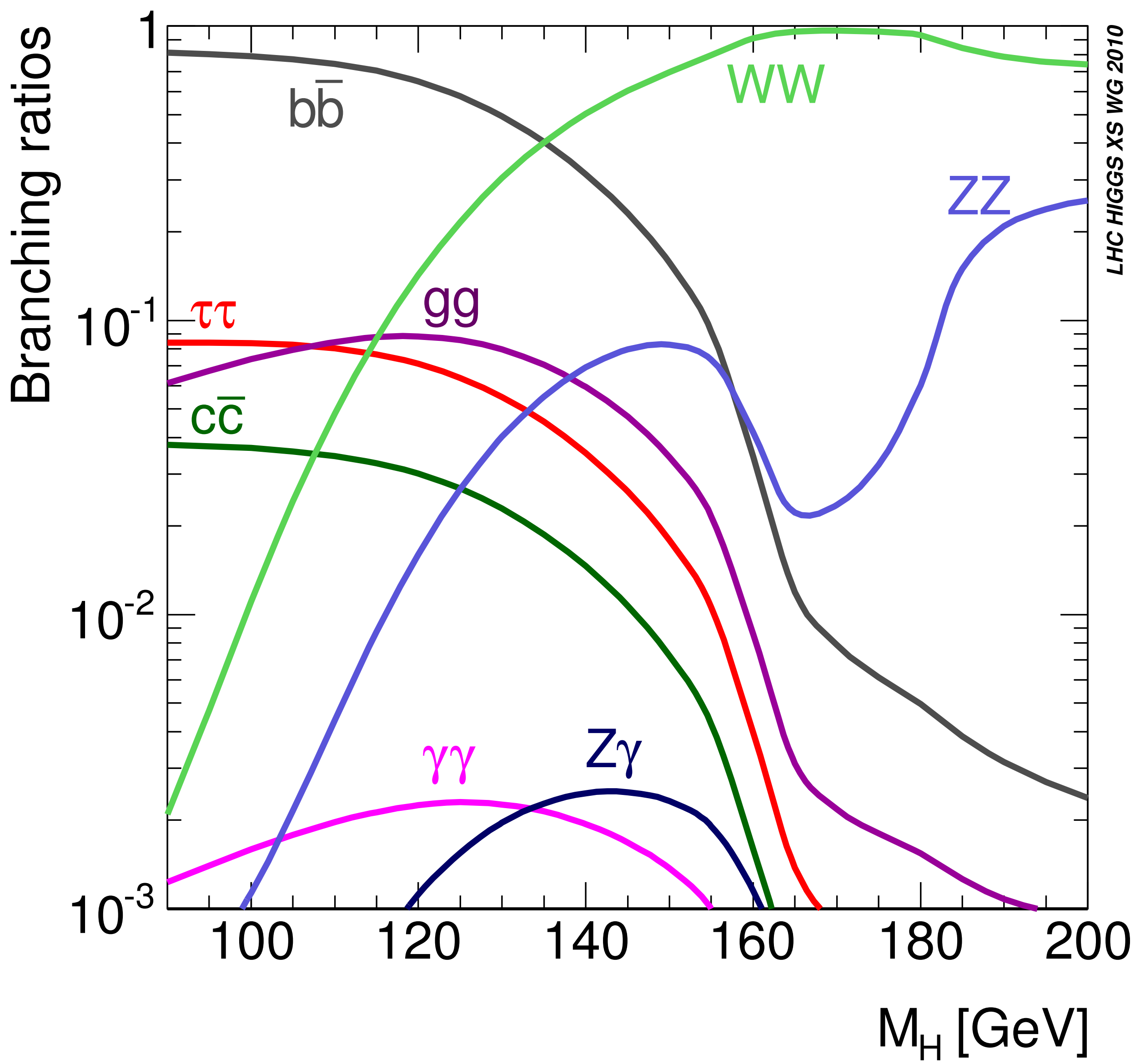
Higgs at the LHC



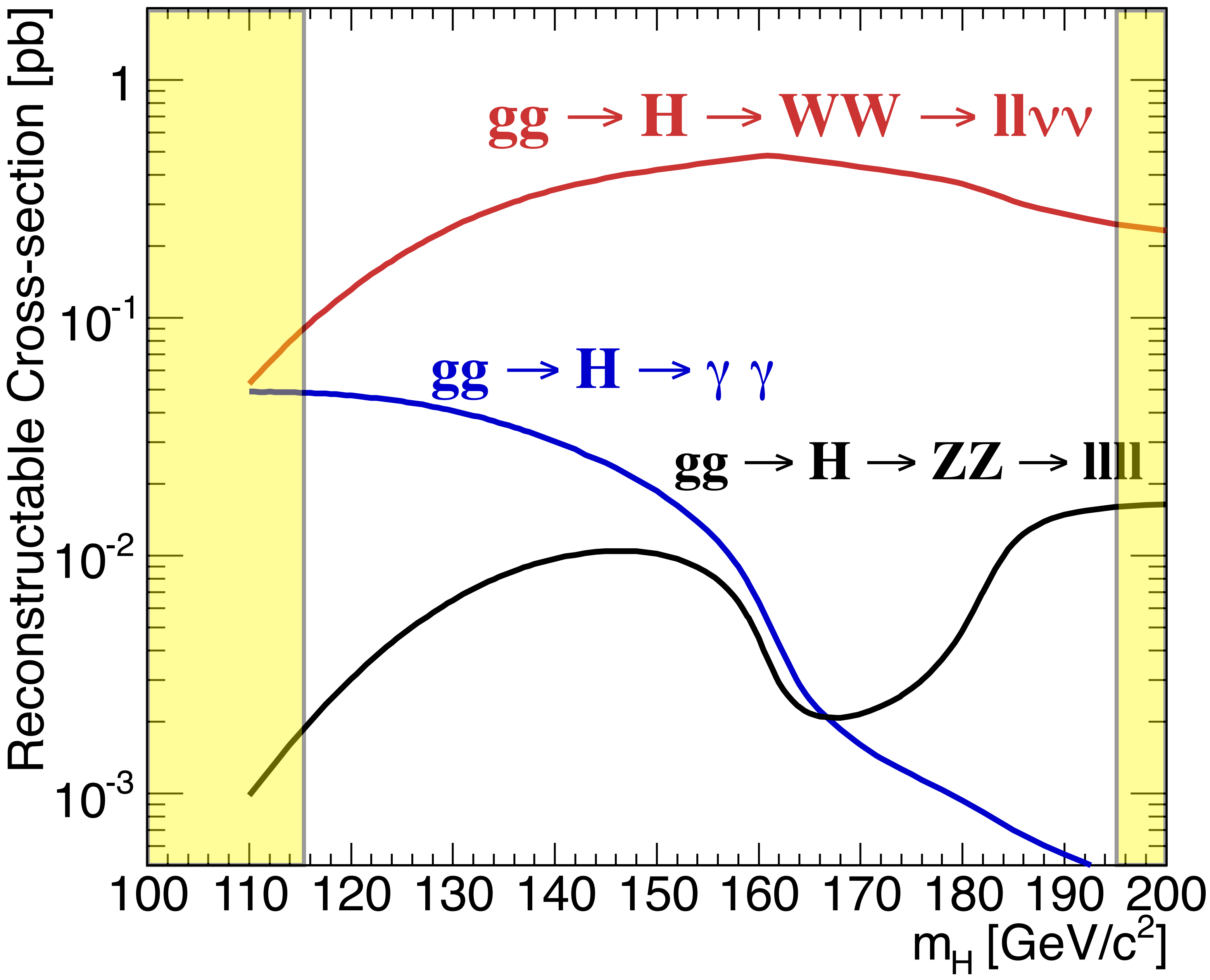








How to look for the Higgs.



WW→lνlν has Strongest sensitivity over broad range of m(H)

Critical in the region between LEP and SM prediction

Mediator of EWK symmetry breaking must couple to the W and Z

lνlν Final State

Tools needed for lνlν final state have wide applicability.

- Lepton ID

  ...Tracking/ Electron ID / Trigger

- W+jets background (ubiquitous)

  ...Data Driven W+jet modeling

- MeT modeling.

Broad range of physics lνlν final state has wide applicability.

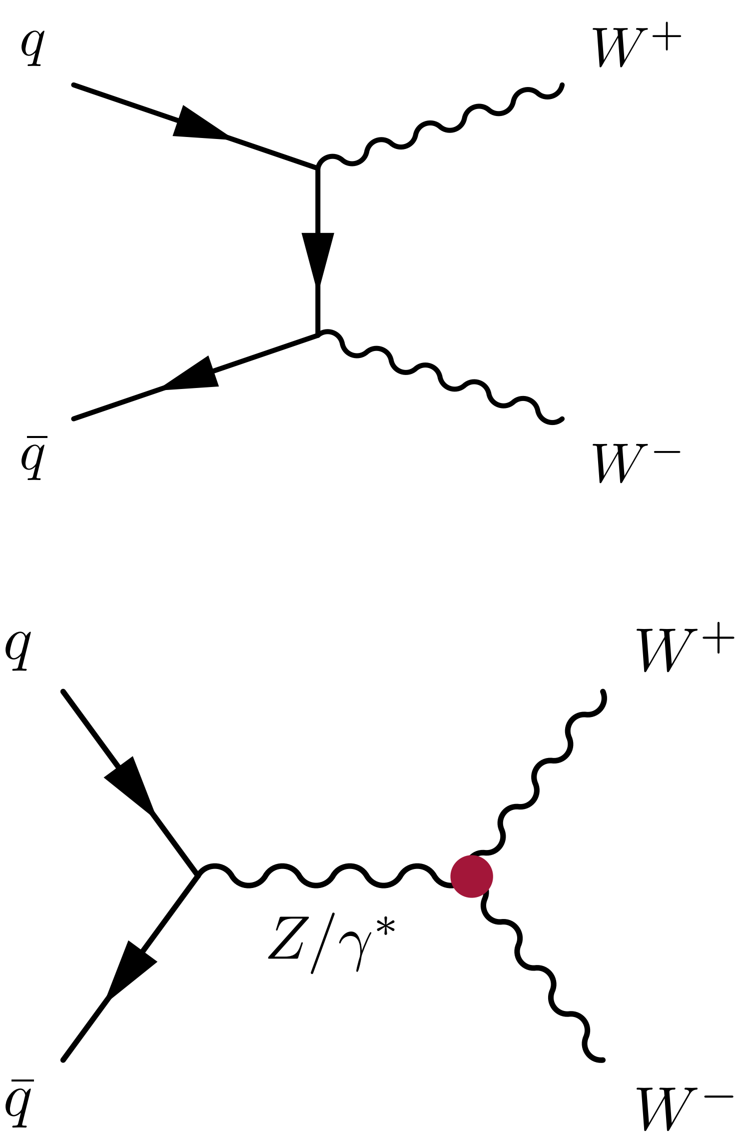
- Higgs Physics.
- SM measurements.

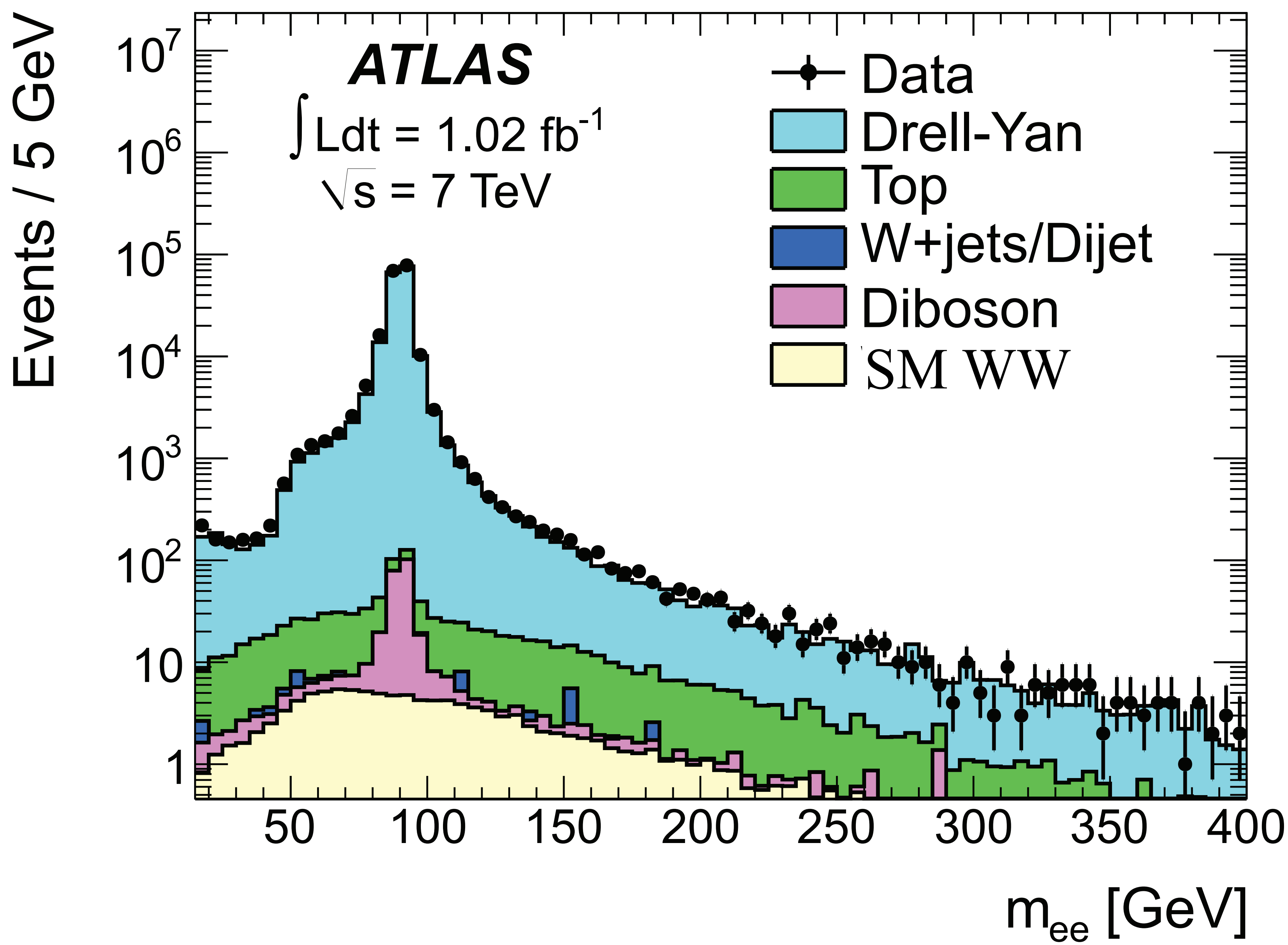
  ...SM WW cross section, 35/pb, 1/fb

- SUSY / Exotic extensions to the SM.

Finding the Haystack

Continuum Standard Model WW production major background.





Finding WW→lνlν

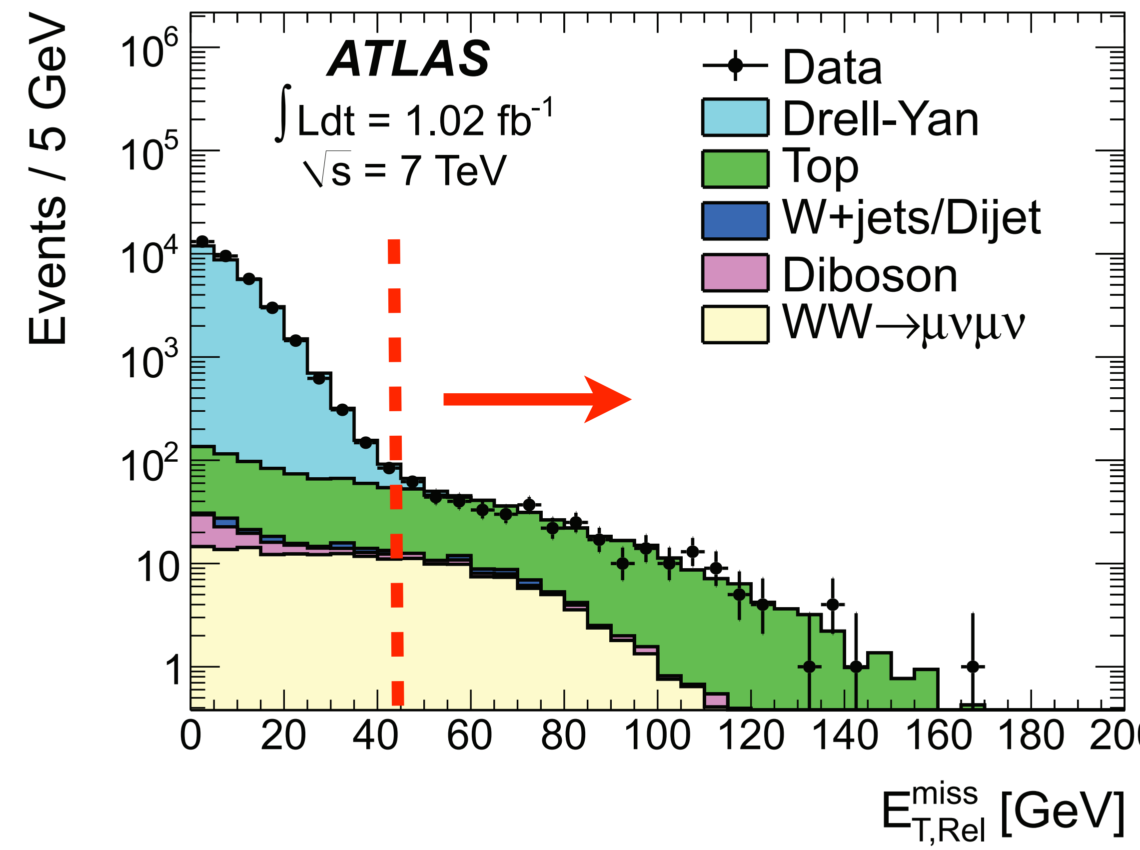
Backgrounds:

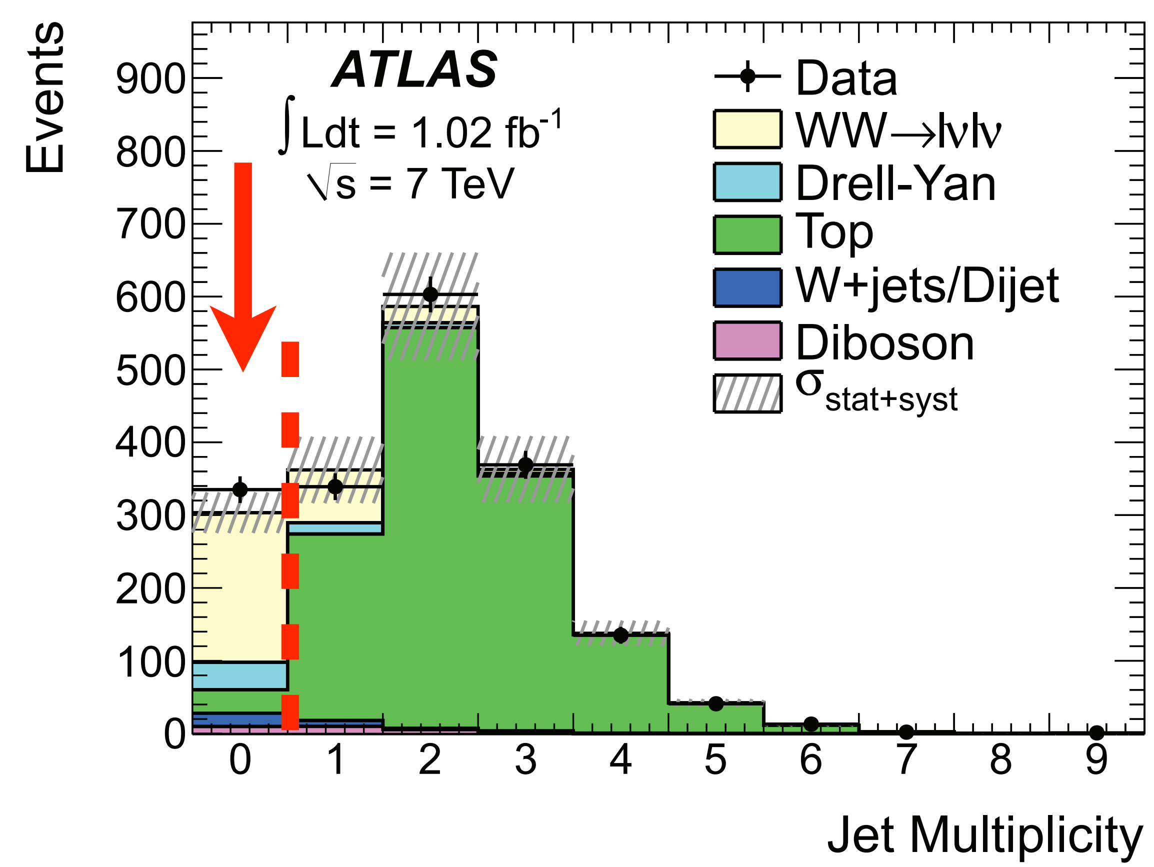
Drell-Yan: (lepton pair + 'fake' MeT)
- Require Large Missing Energy
- Reject events consistent w/Z mass

Top: (WW produced w/2 b-jets)
- Jet Veto

W+Jets: (lepton w/MeT + 'fake' lepton)
- Isolation / lepton Identification

Other Diboson: (WZ, ZZ, Wγ)
- remove events w/ > 2 leptons.





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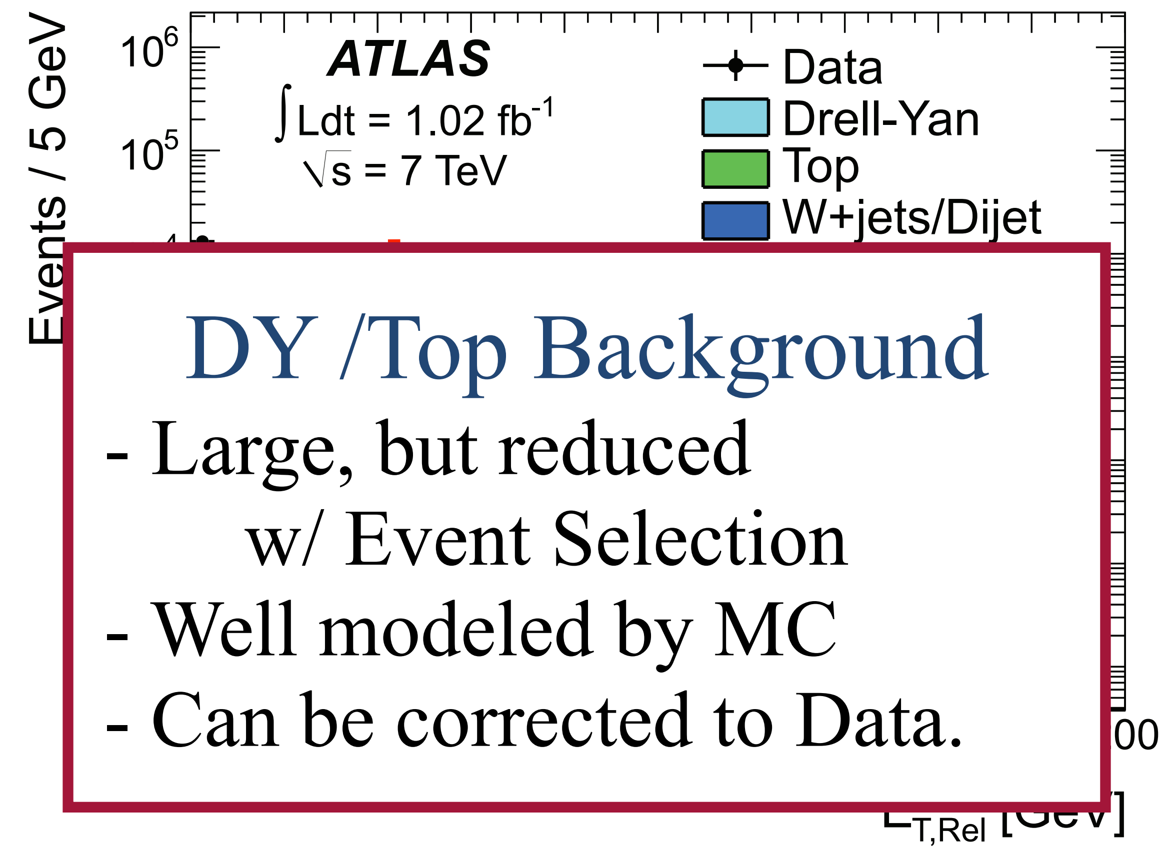
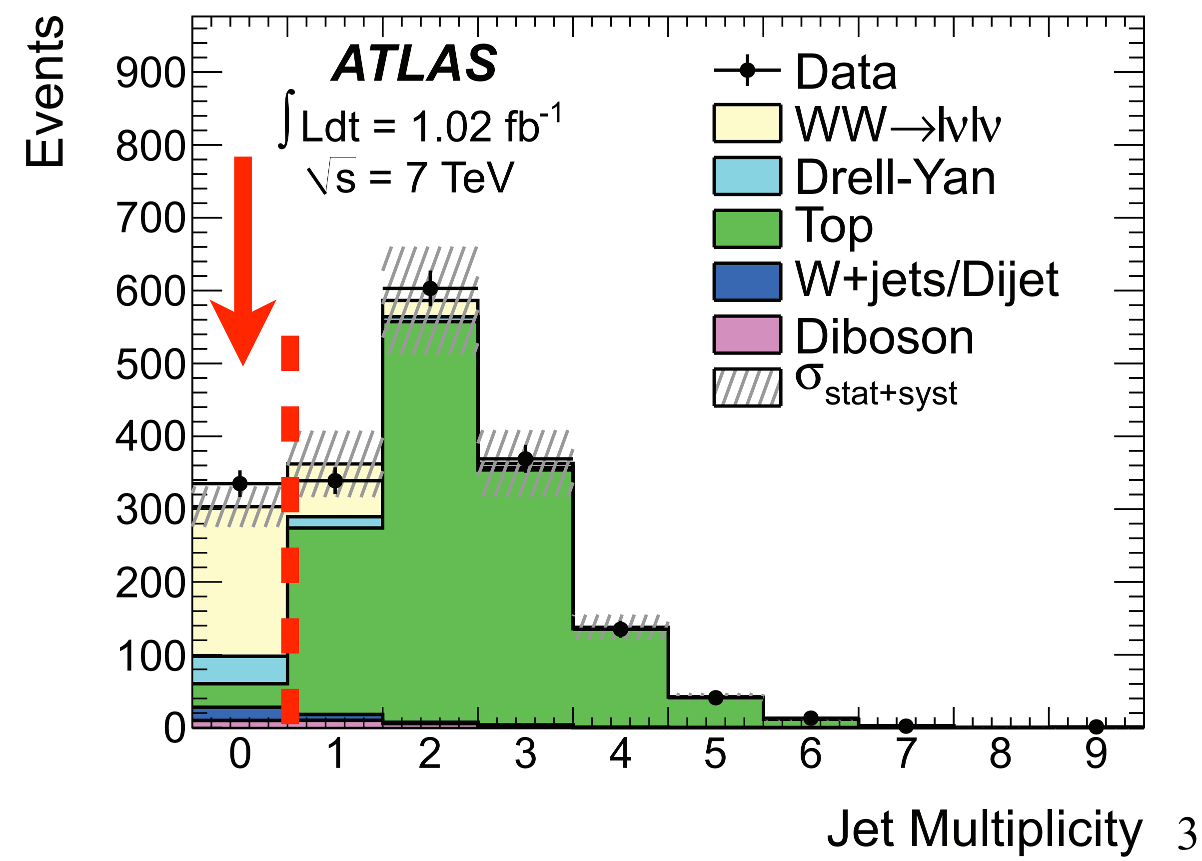


DY /Top Background
- Large, but reduced w/ Event Selection
- Well modeled by MC
- Can be corrected to Data.



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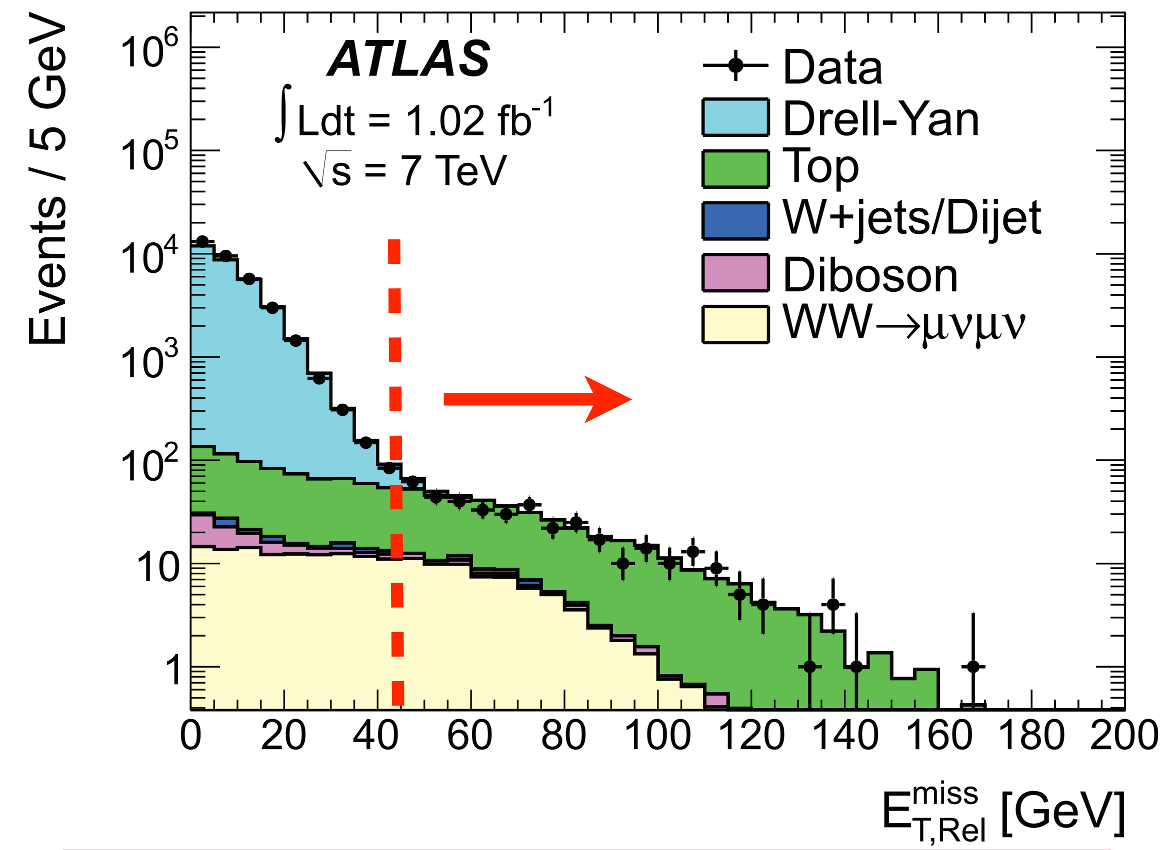
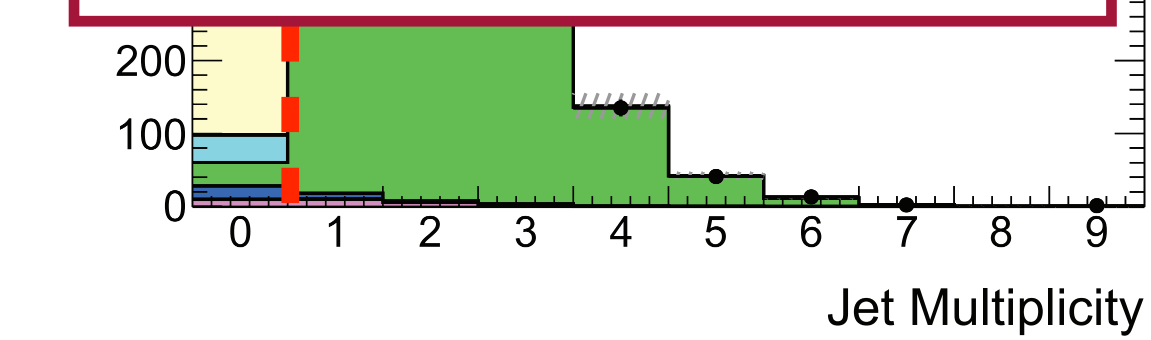


W+Jet Background
- Small, but not suppressed w/ Event Selection
- Difficult to model in MC
- Important at Low Pt.



Finding WW→lνlν

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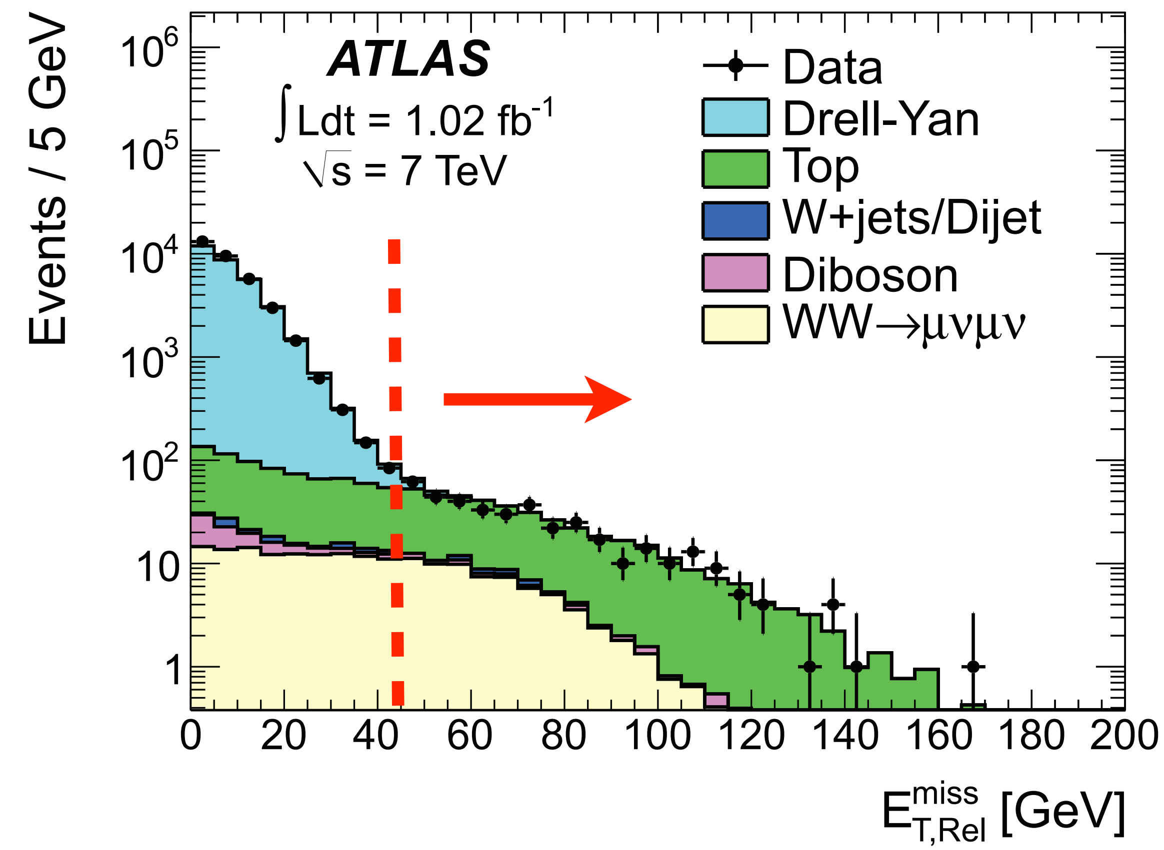
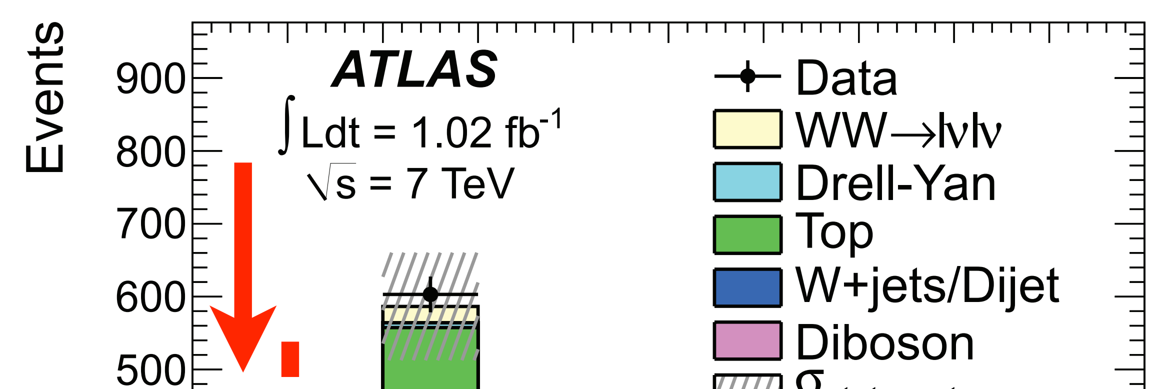
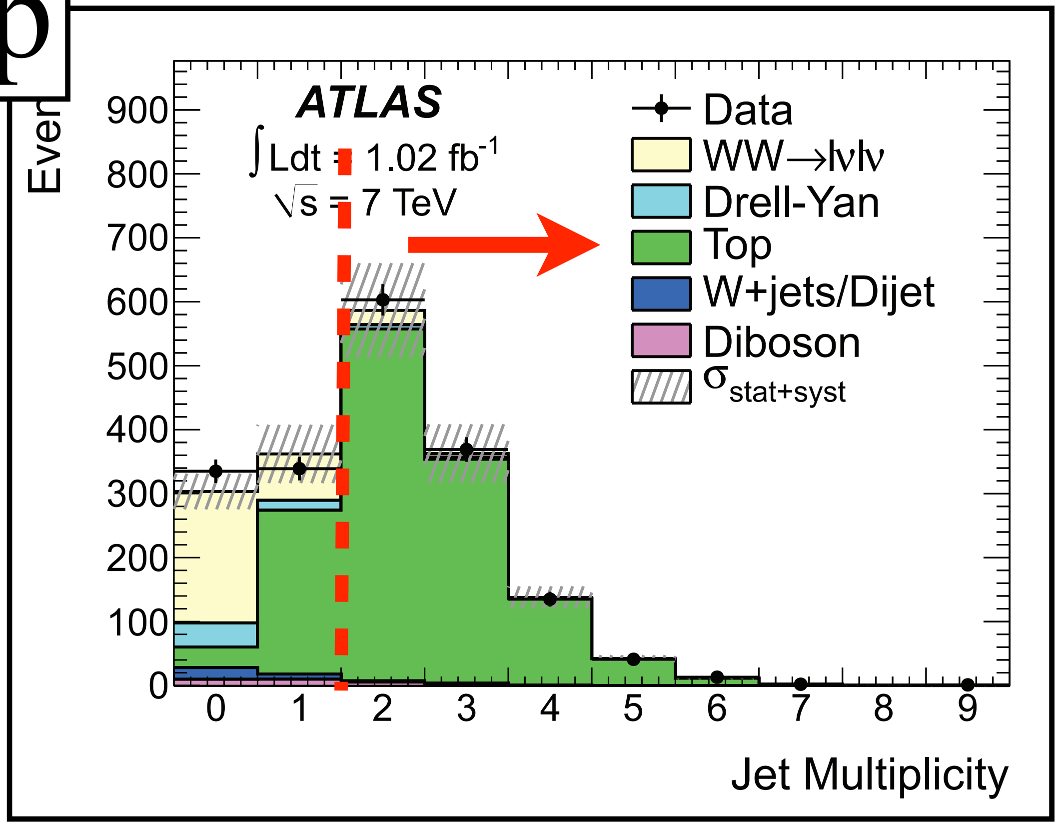




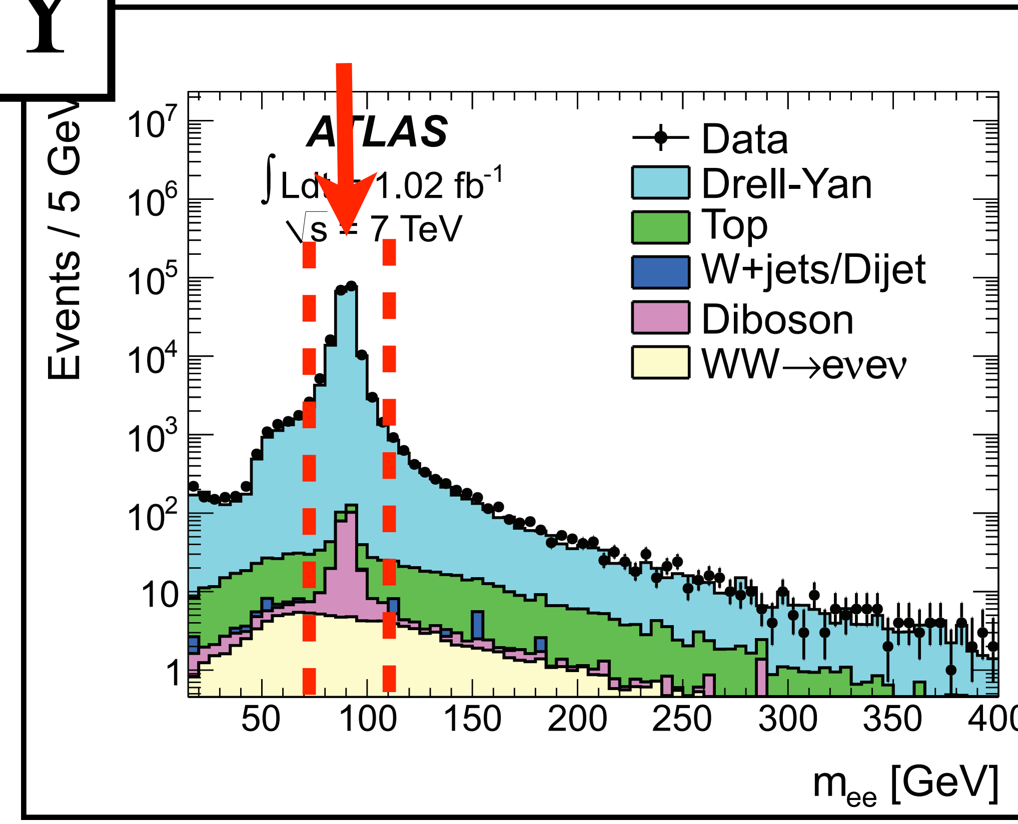
Diboson Background
- Small, and suppressed w/ Event Selection
- Well modeled by MC.

Background Estimation

Top



DY



W+jet

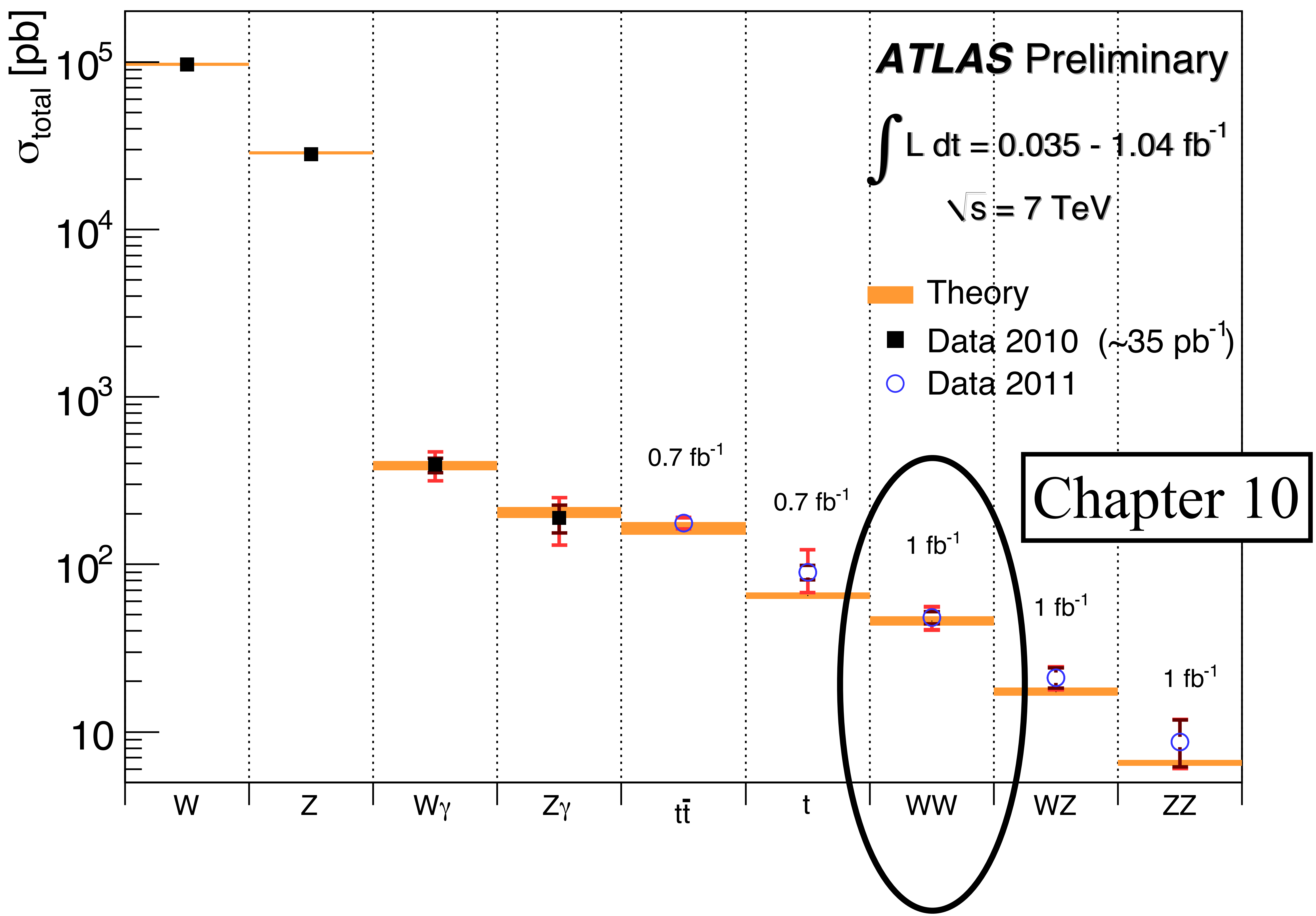
$$N_{\rm Bkg}^{\rm W+Jet} = f \times N_{\rm (Lepton+Denm)}$$

Observed Lepton-Denm. pairs passing event selection.

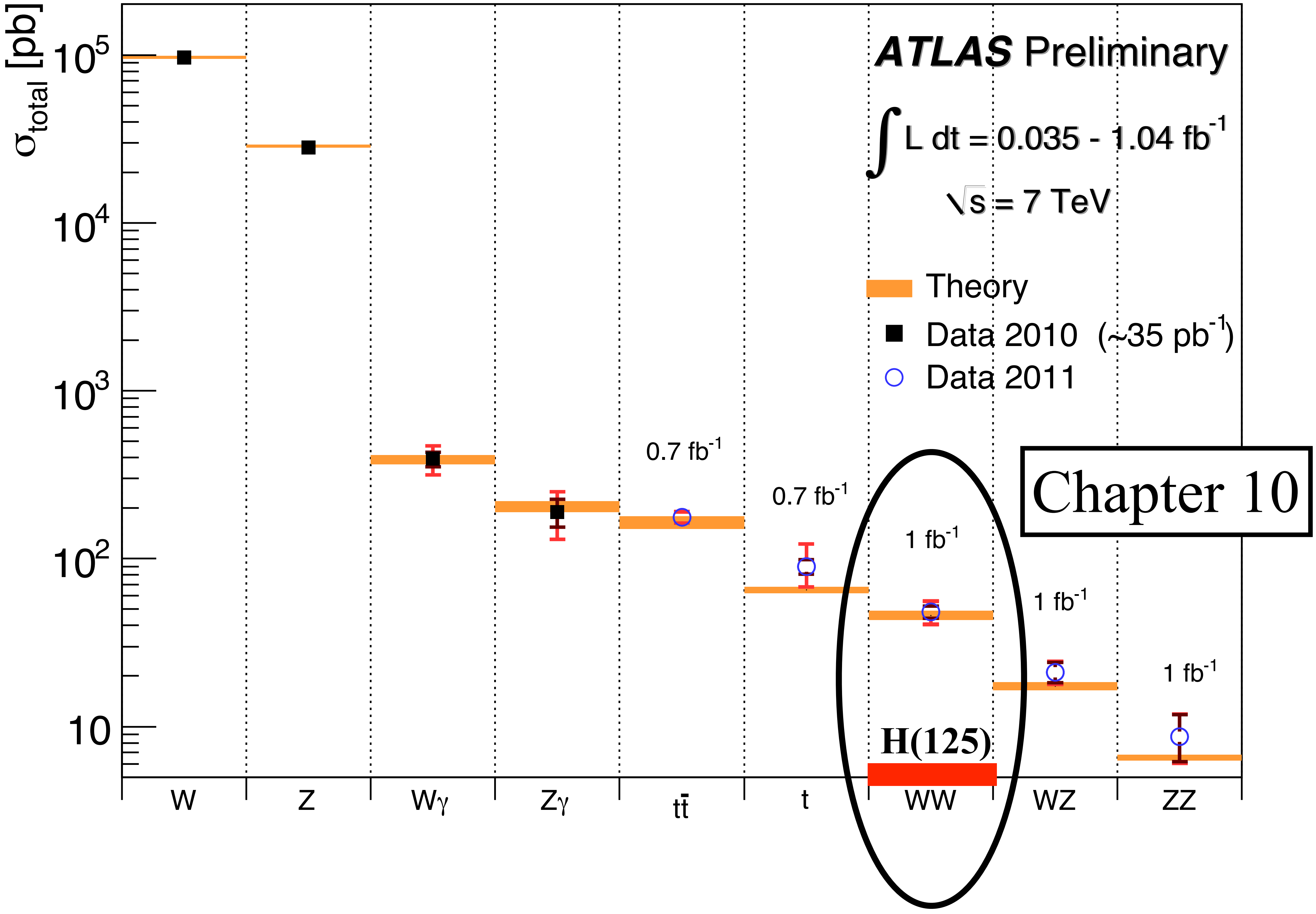
Measured in a di-jet sample

A lot of work goes into making/understanding bkg. prediction. Chapter 9-11

SM WW Cross Section Measurement



SM WW Cross Section Measurement

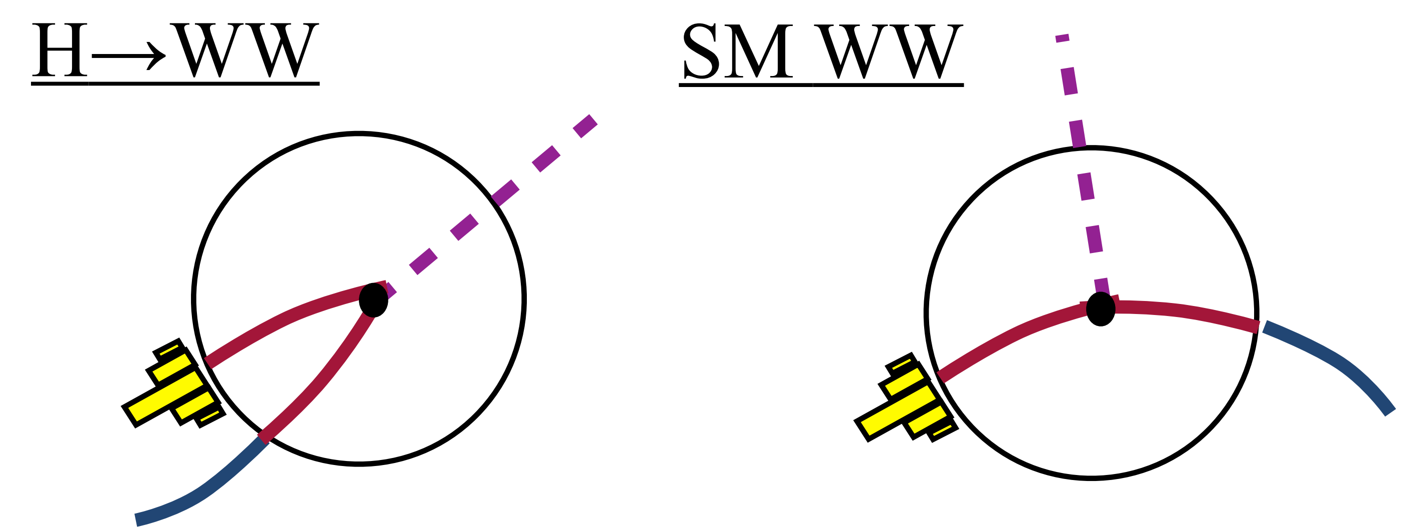


Finding the Needle

H→WW analysis

- Basic WW Selection.
  (Dominated by SM WW)
- Small opening angle.
- Fit mT

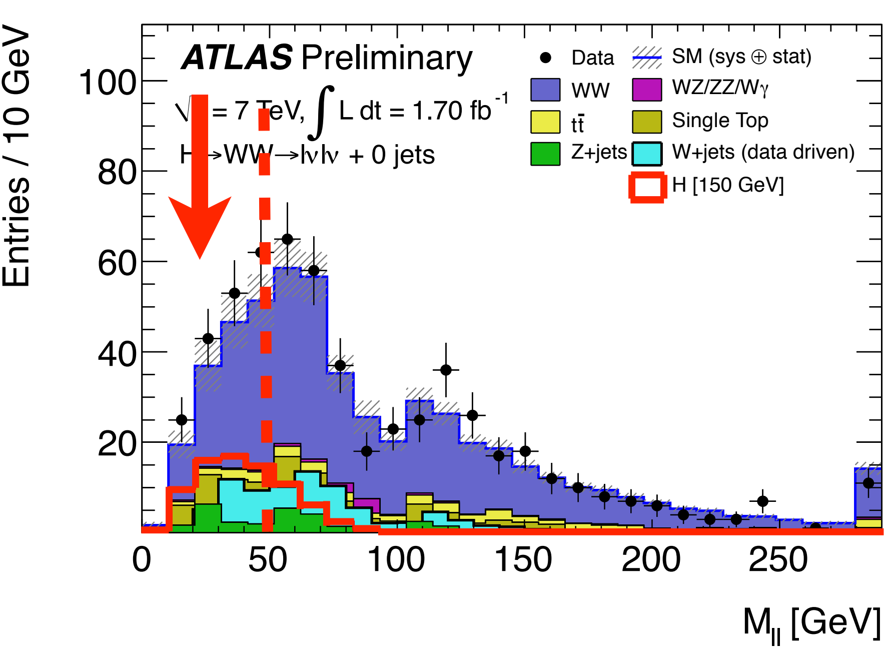
Exploit spin-0 nature of Higgs.

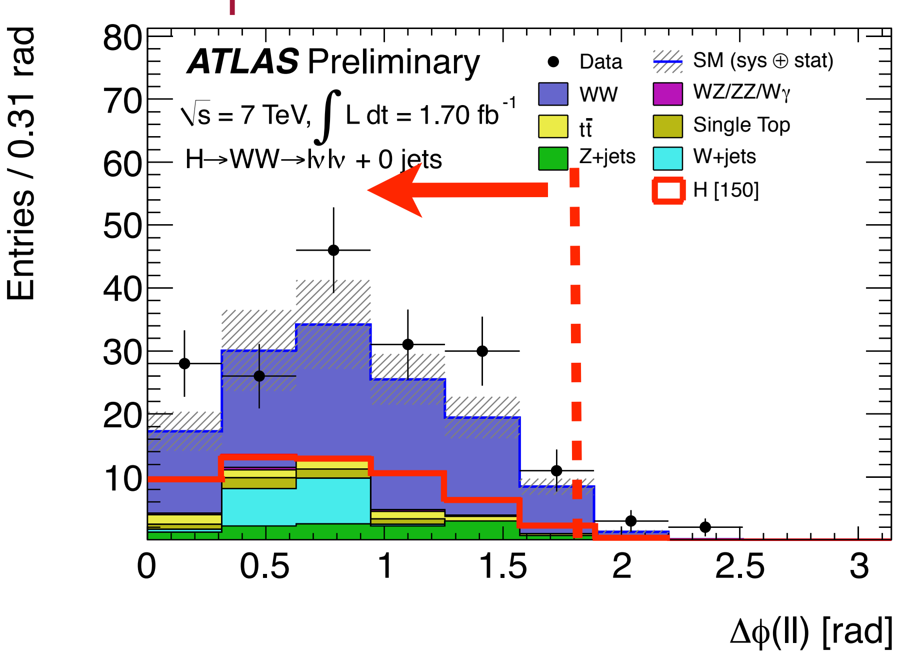


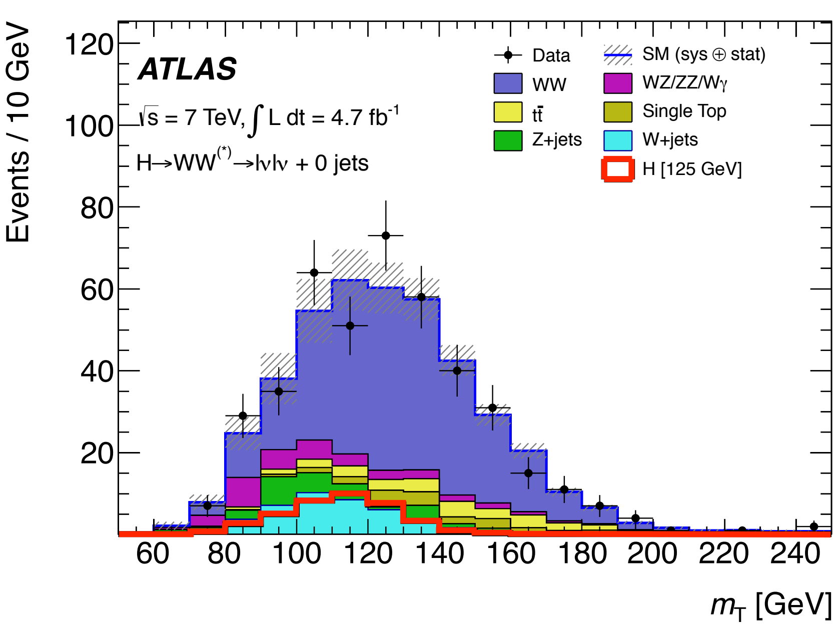
Mll

Δϕll

mT

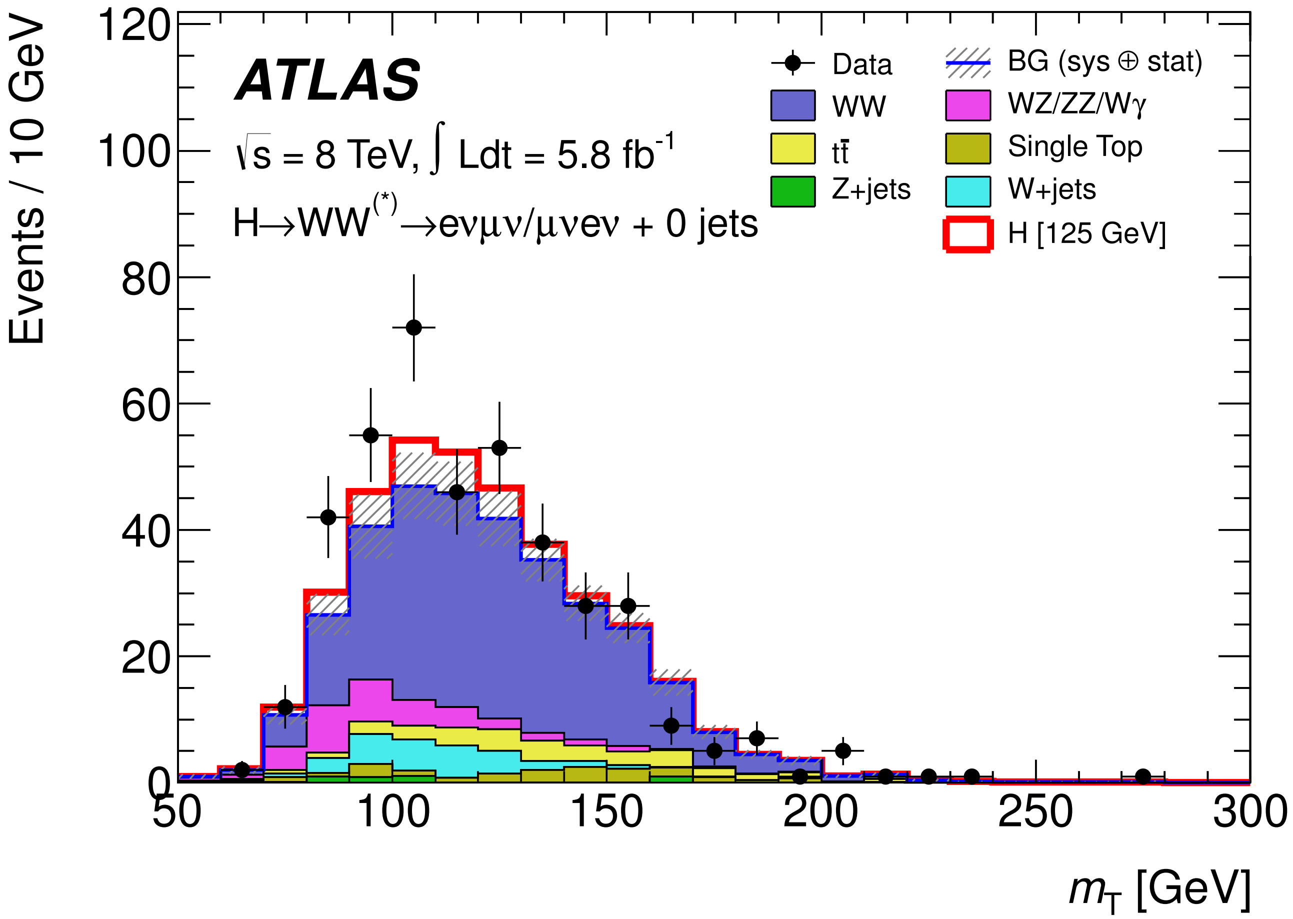


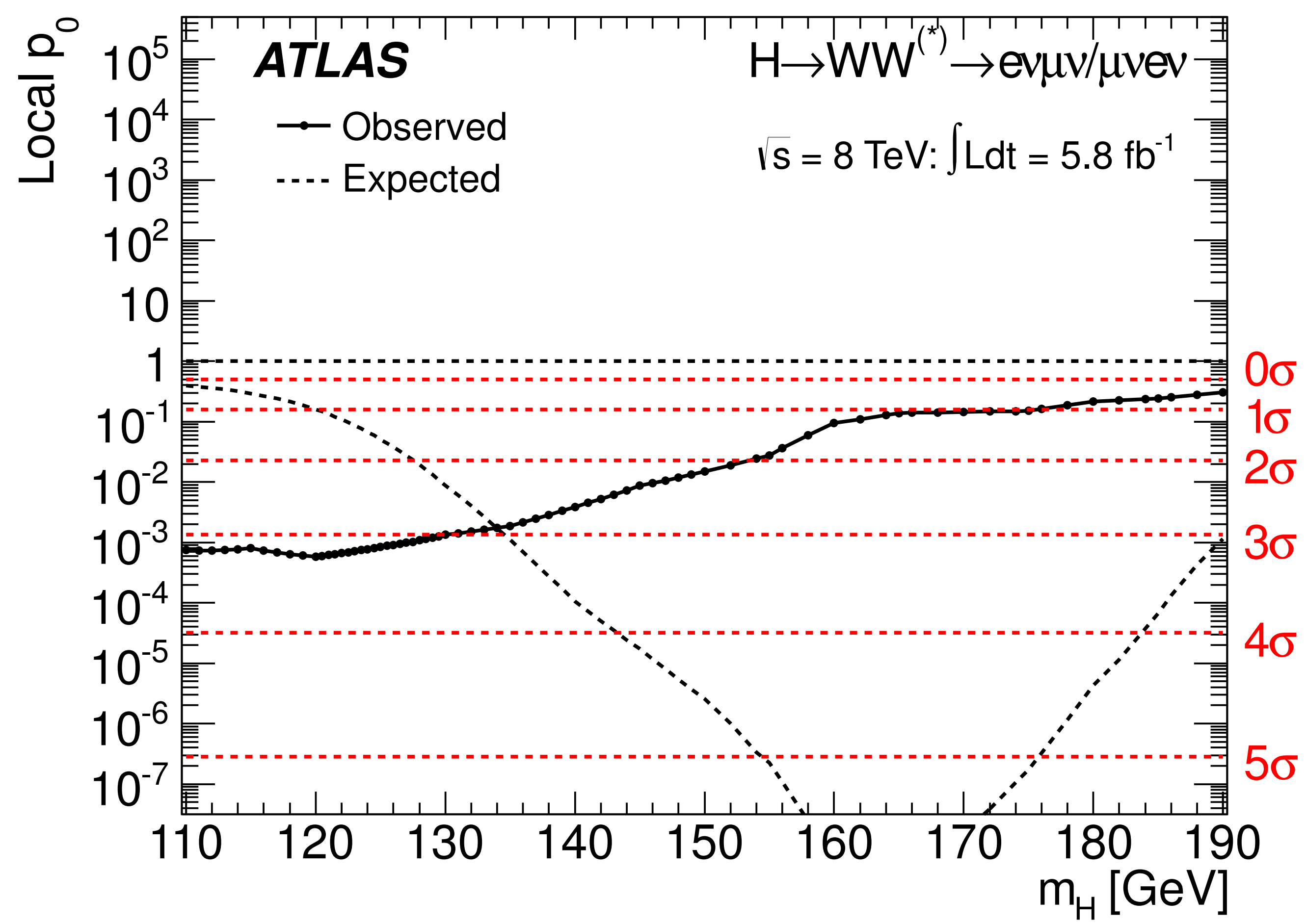




Results H→WW

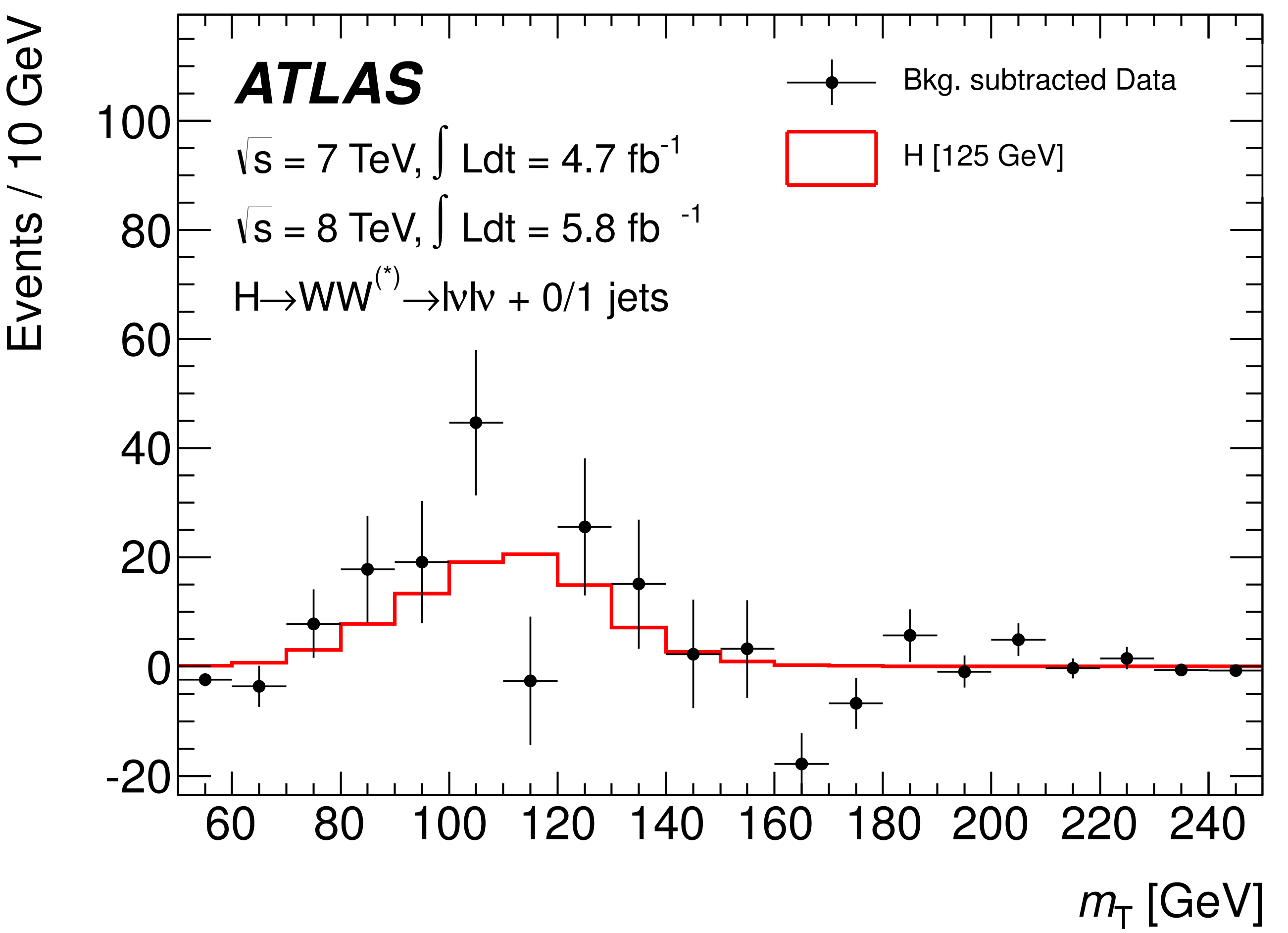
2012 Results (5.8/fb 8 TeV)

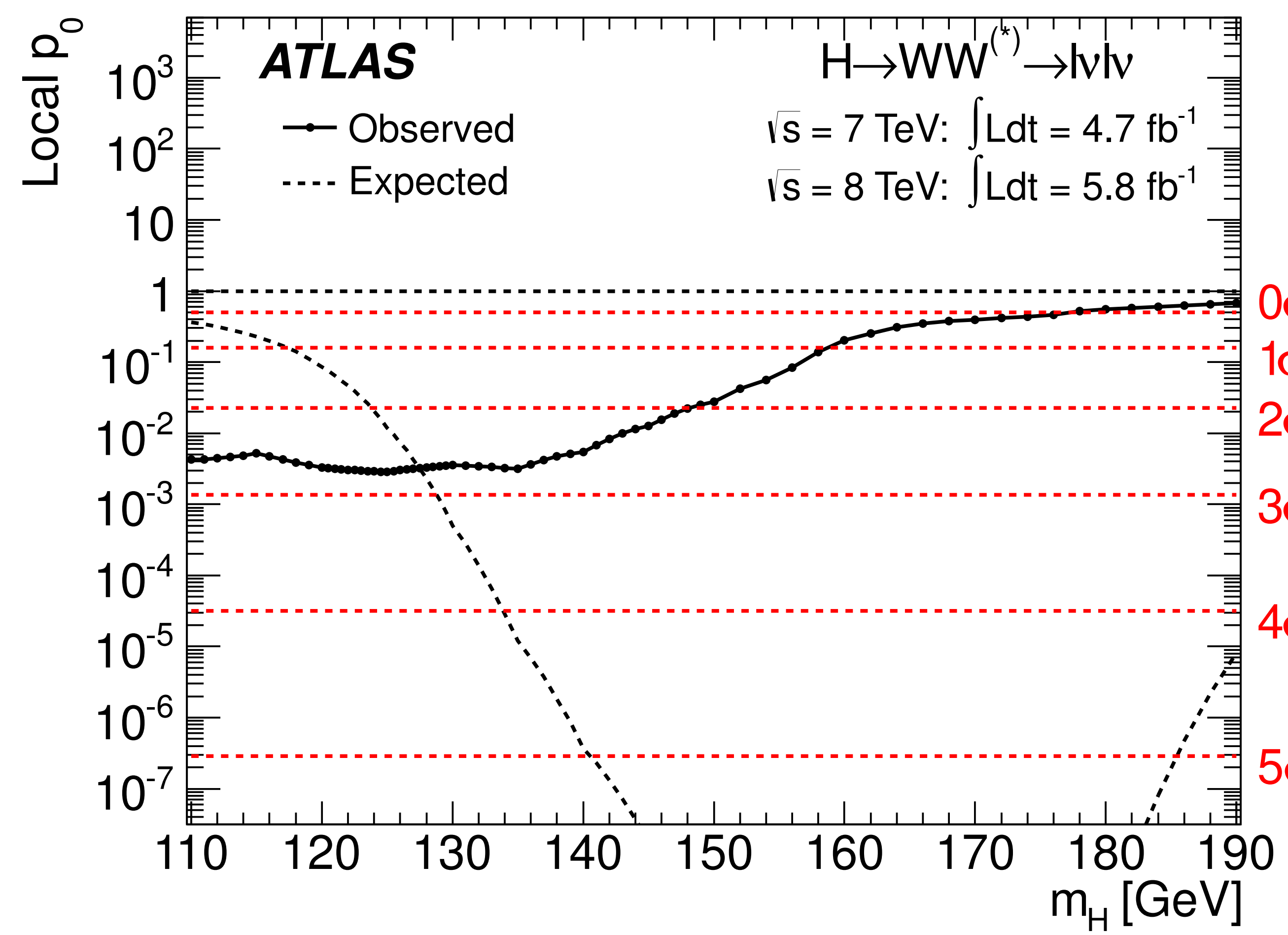




Results H→WW

Combined Results (5.8/fb 8 TeV + 4.7/fb 7 TeV)

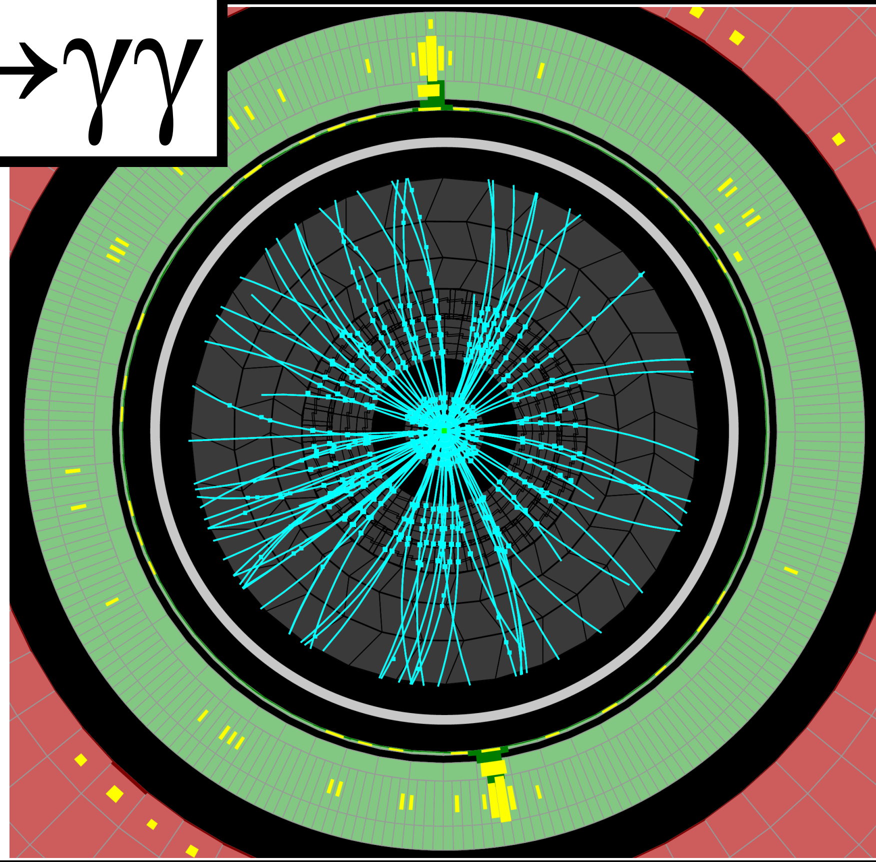


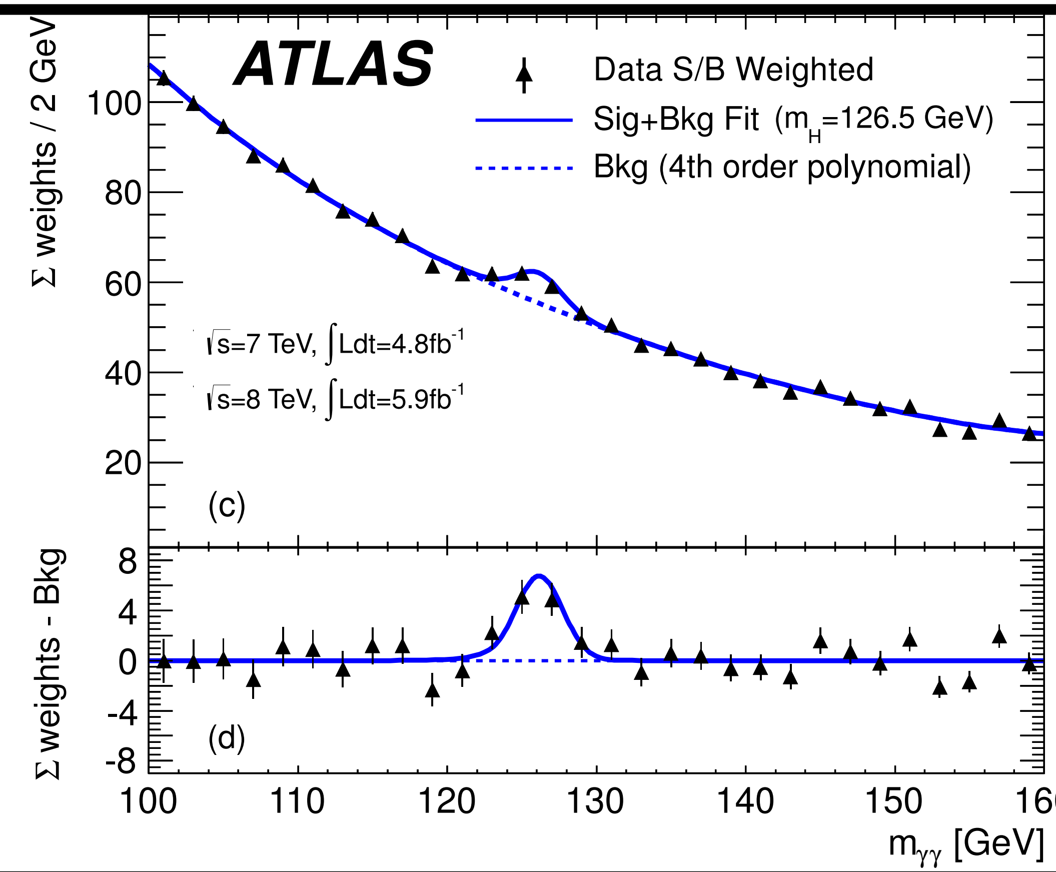


Background Subtracted

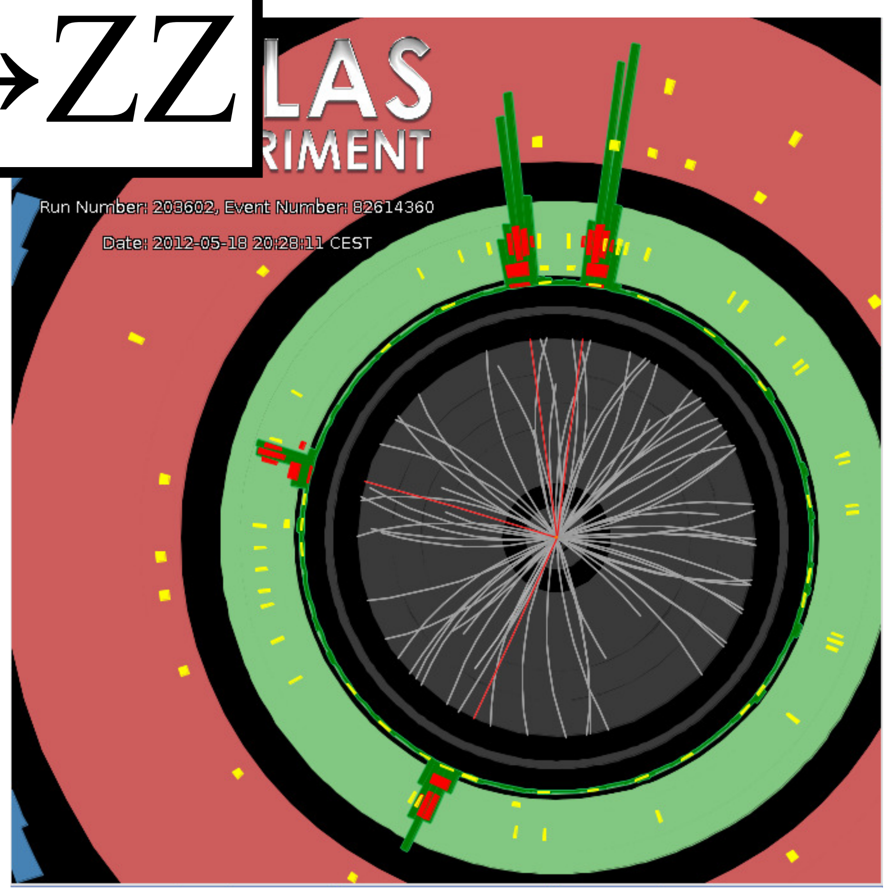
Other Higgs Searches

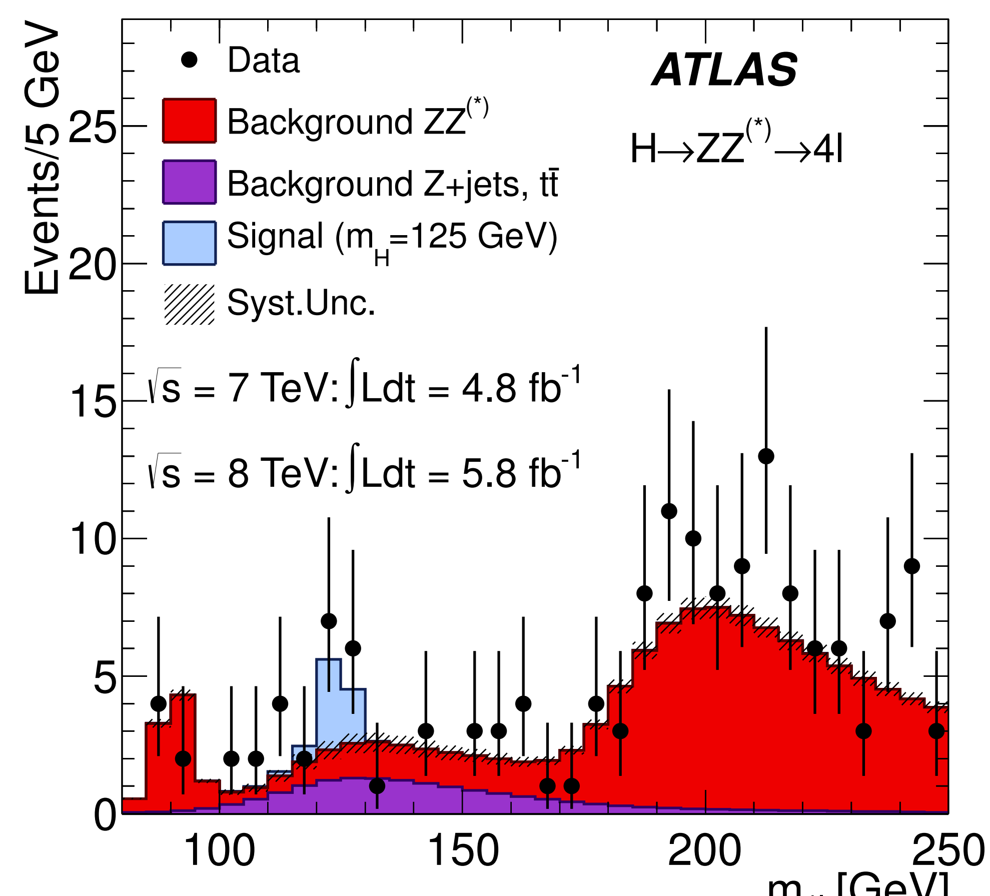
H→γγ

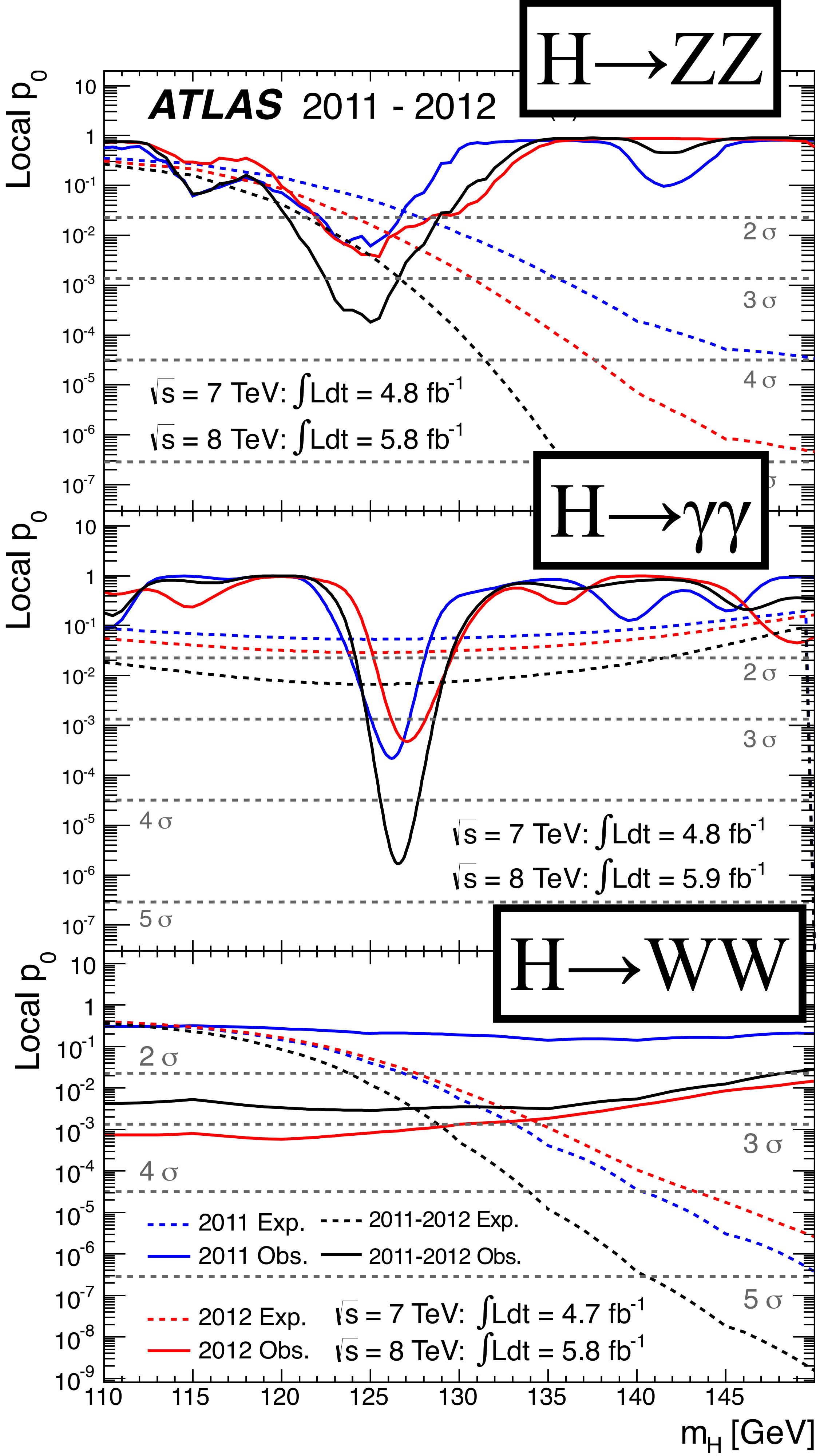


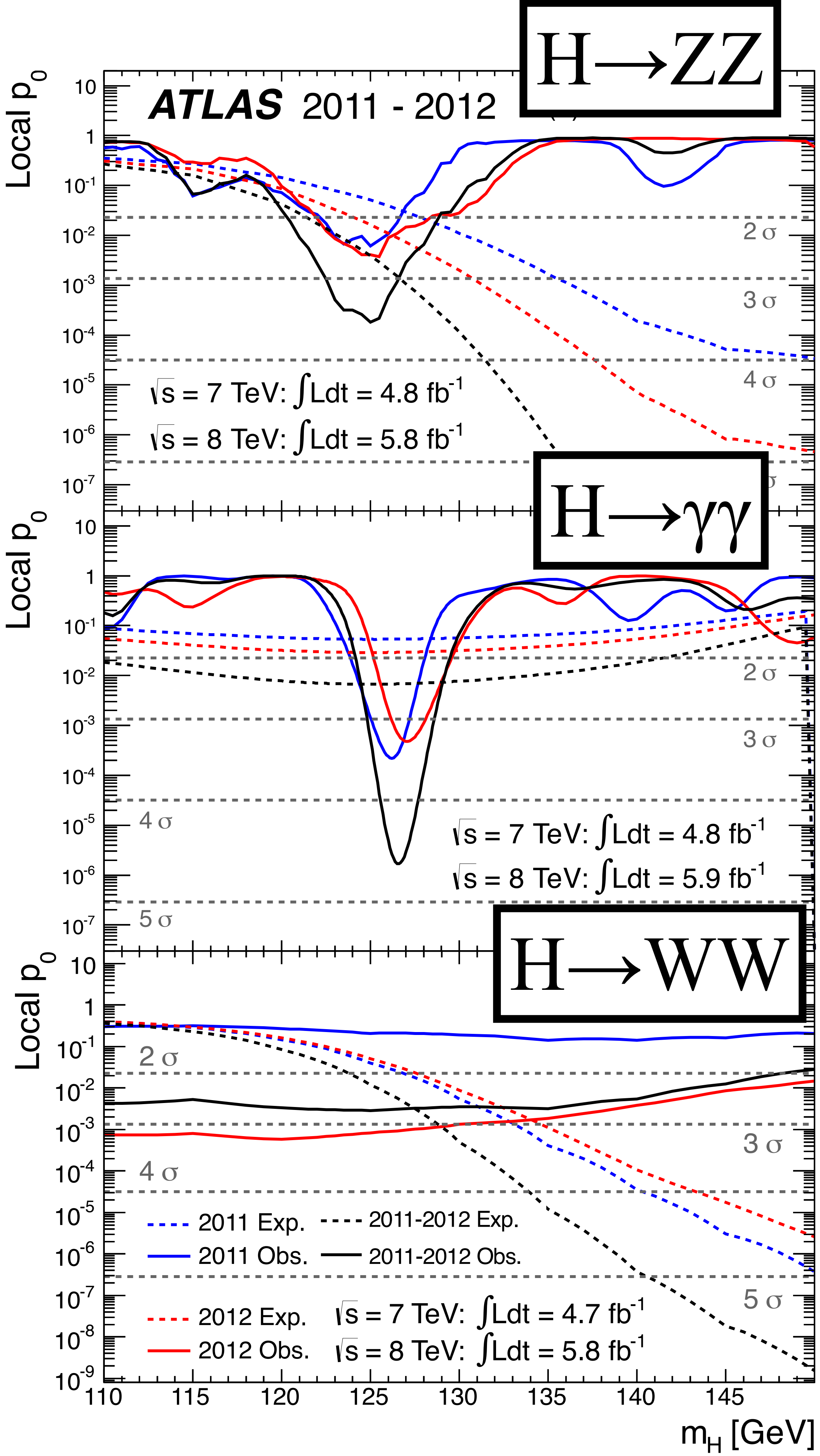


H→ZZ

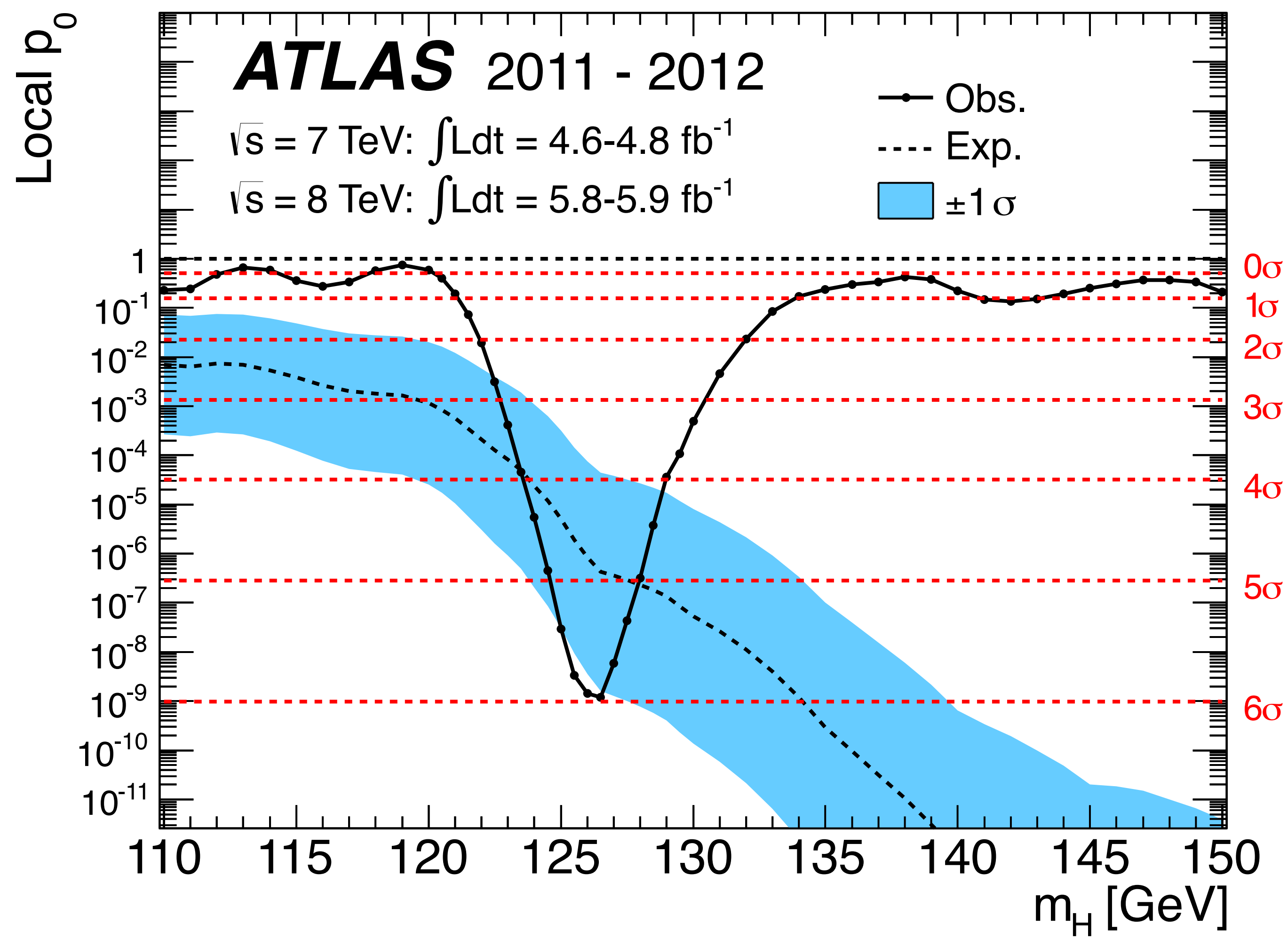


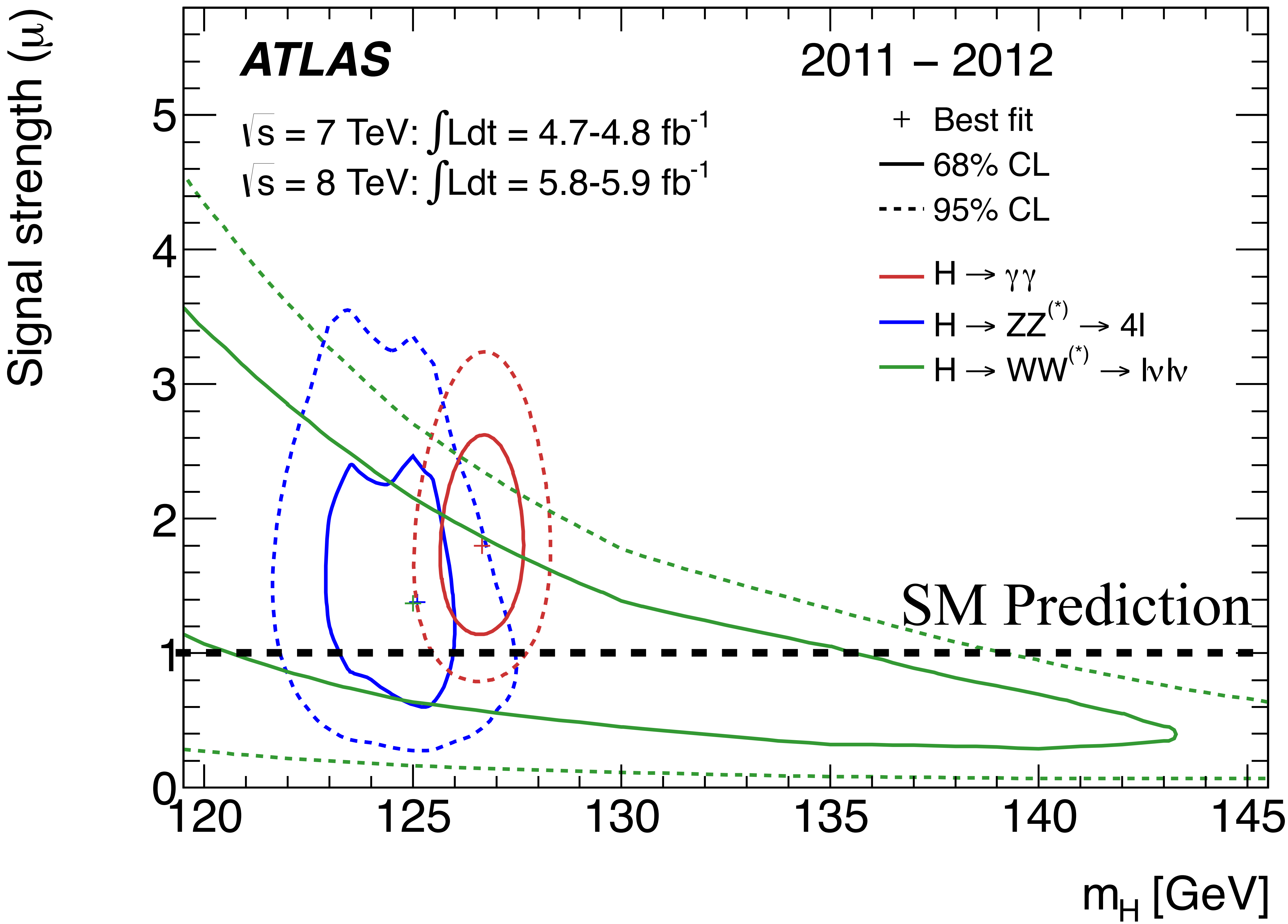


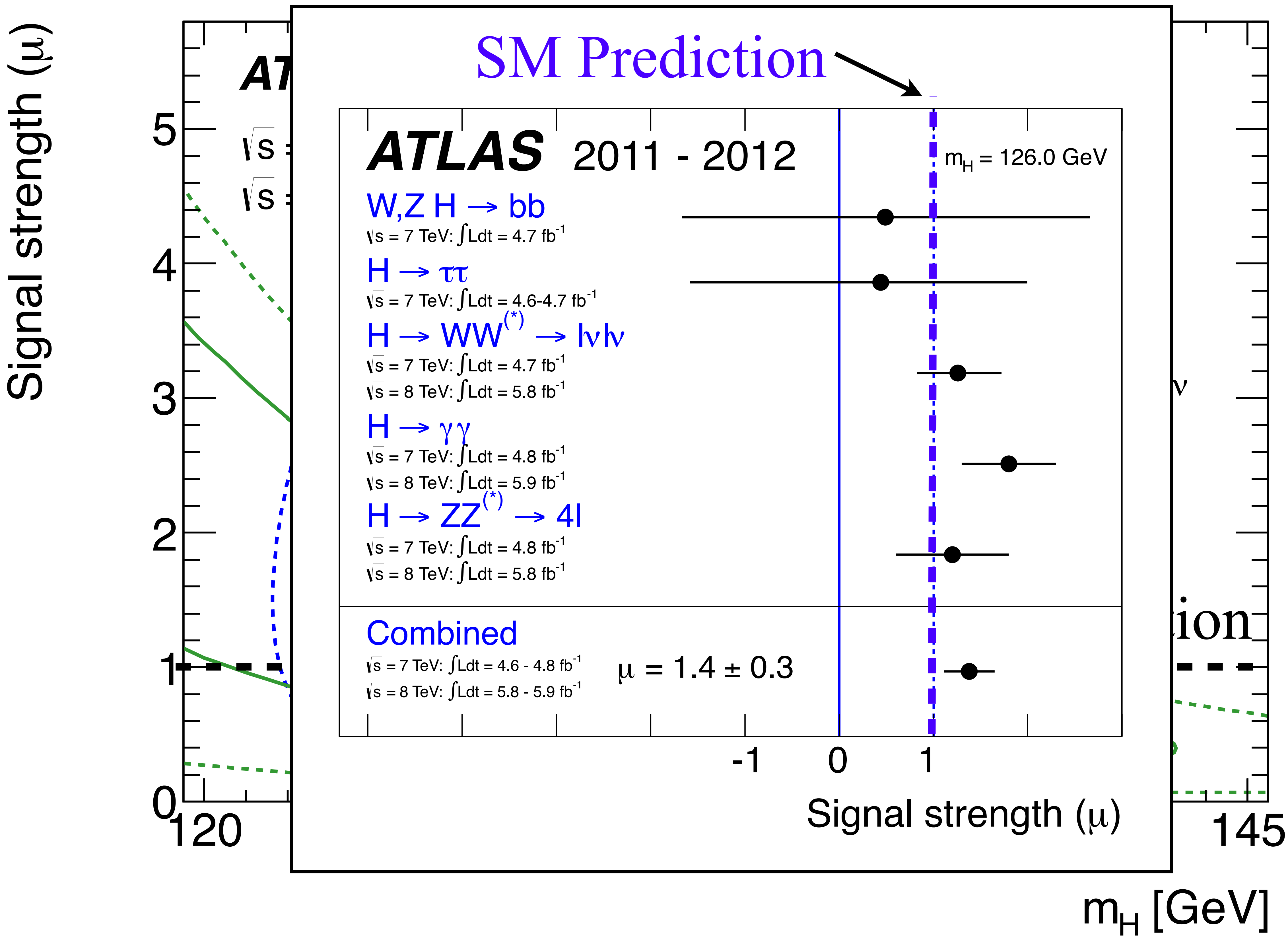

H→ZZ
ATLAS 2011 - 2012
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
H→γγ
√s = 7 TeV: ∫Ldt = 4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.9 fb-1
H→WW
2011 Exp.
2011 Obs.
2011-2012 Exp.
2011-2012 Obs.
2012 Exp.
2012 Obs.
√s = 7 TeV: ∫Ldt = 4.7 fb-1
√s = 8 TeV: ∫Ldt = 5.8 fb-1
Local p0
mH [GeV]



Combined Results




ATLAS
2011 – 2012
$\sqrt{s}$ = 7 TeV: $\int Ldt$ = 4.7-4.8 fb^{-1}
$\sqrt{s}$ = 8 TeV: $\int Ldt$ = 5.8-5.9 fb^{-1}
Best fit
68% CL
95% CL
$H \rightarrow \gamma\gamma$
$H \rightarrow ZZ^{(*)} \rightarrow 4l$
$H \rightarrow WW^{(*)} \rightarrow l\nu l\nu$
SM Prediction
Signal strength (μ)
m_H [GeV]
0
1
2
3
4
5
120
125
130
135
140
145


SM Prediction
ATLAS 2011 - 2012
m_H = 126.0 GeV
W,Z H → bb
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
H → ττ
√s = 7 TeV: ∫Ldt = 4.6-4.7 fb⁻¹
H → WW(*) → lνlν
√s = 7 TeV: ∫Ldt = 4.7 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8 fb⁻¹
H → γγ
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.9 fb⁻¹
H → ZZ(*) → 4l
√s = 7 TeV: ∫Ldt = 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8 fb⁻¹
Combined
√s = 7 TeV: ∫Ldt = 4.6 - 4.8 fb⁻¹
√s = 8 TeV: ∫Ldt = 5.8 - 5.9 fb⁻¹
μ = 1.4 ± 0.3
-1
0
1
Signal strength (μ)
Signal strength (μ)
0
1
2
3
4
5
120
145
m_H [GeV]

The New York Times

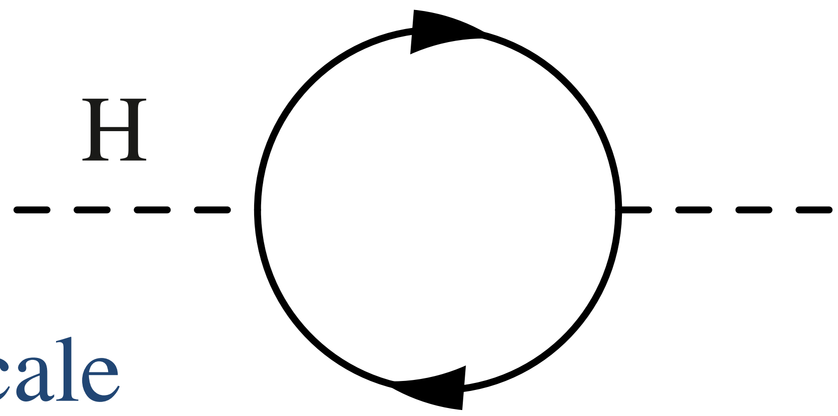
Physicists Find Elusive Particle Seen as Key to Universe

Problem with the Higgs Mass

Loop Corrections to Higgs Mass

$$m_h^2 = {m_h^0}^2 - \Lambda^2$$

cut-off scale



The Standard Model is incomplete.

- GUT, Gravity ...

$$\Lambda^2 \sim 10^{36}\ \mathrm{GeV}^2$$

implausible cancelation from ${m_h^0}^2$

Problem with the Higgs Mass

Loop Corrections to Higgs Mass

$$m_h^2 = {m_h^0}^2 - \Lambda^2$$

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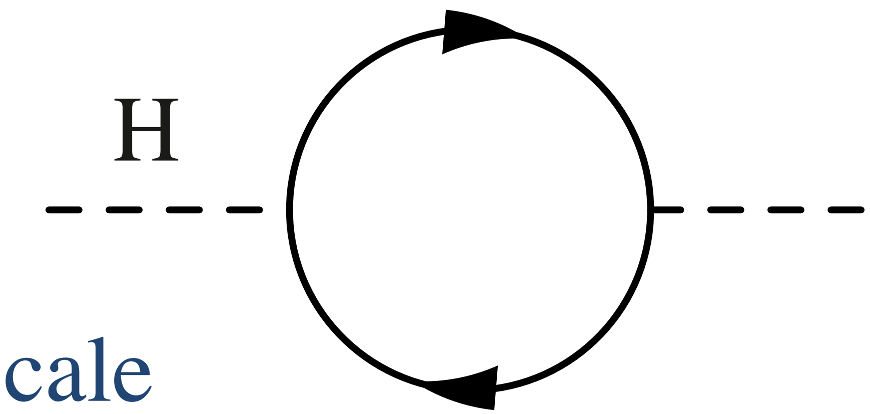


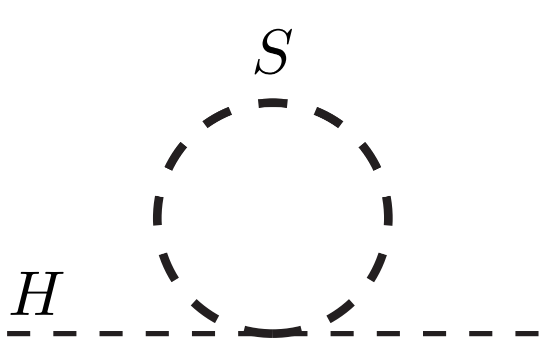
The Standard Model is incomplete.

- GUT, Gravity ...

$$\Lambda^2 \sim 10^{36}\ \mathrm{GeV}^2$$

implausible cancelation from ${m_h^0}^2$

<u>Super Symmetry</u>



$\mathcal{L} = \mathcal{L}_{\mathrm{SUSY}} + \mathcal{L}_{\mathrm{soft}},$ $m_{\mathrm{soft}} \sim$ TeV scale

$$\Delta m_H^2 = m_{\mathrm{soft}}^2 \left[\frac{\lambda}{16\pi^2} \ln(\Lambda_{\mathrm{UV}}/m_{\mathrm{soft}}) + \ldots \right]$$

Conclusions

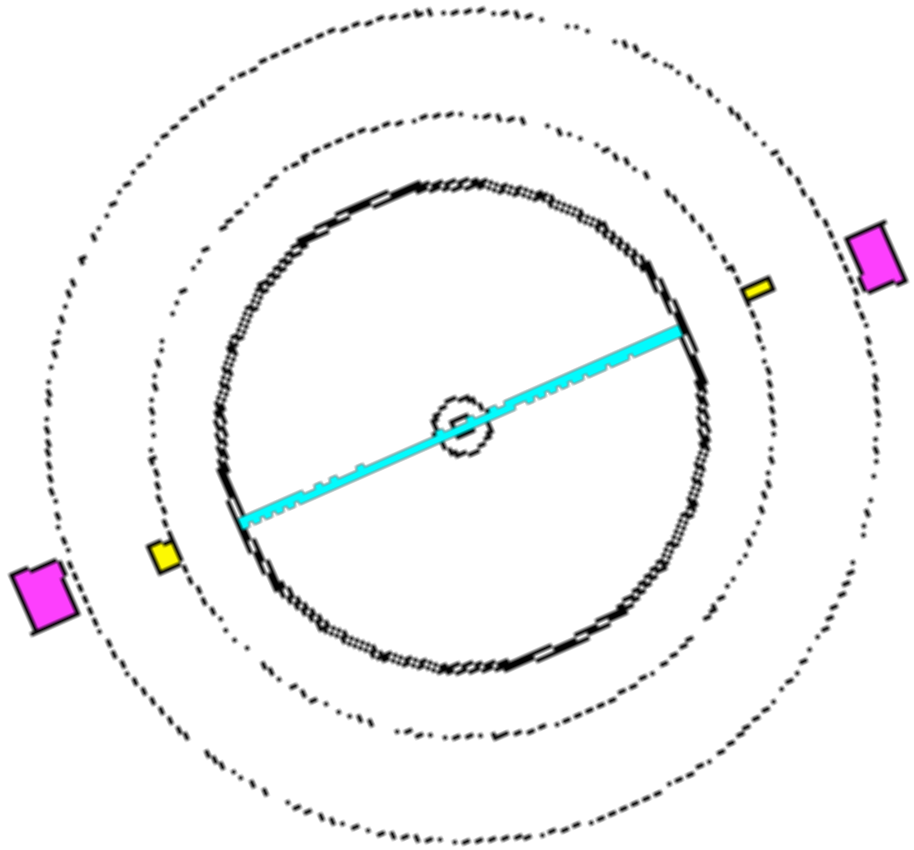
"We are, I think, in the right road of improvement,
for we are making experiments."

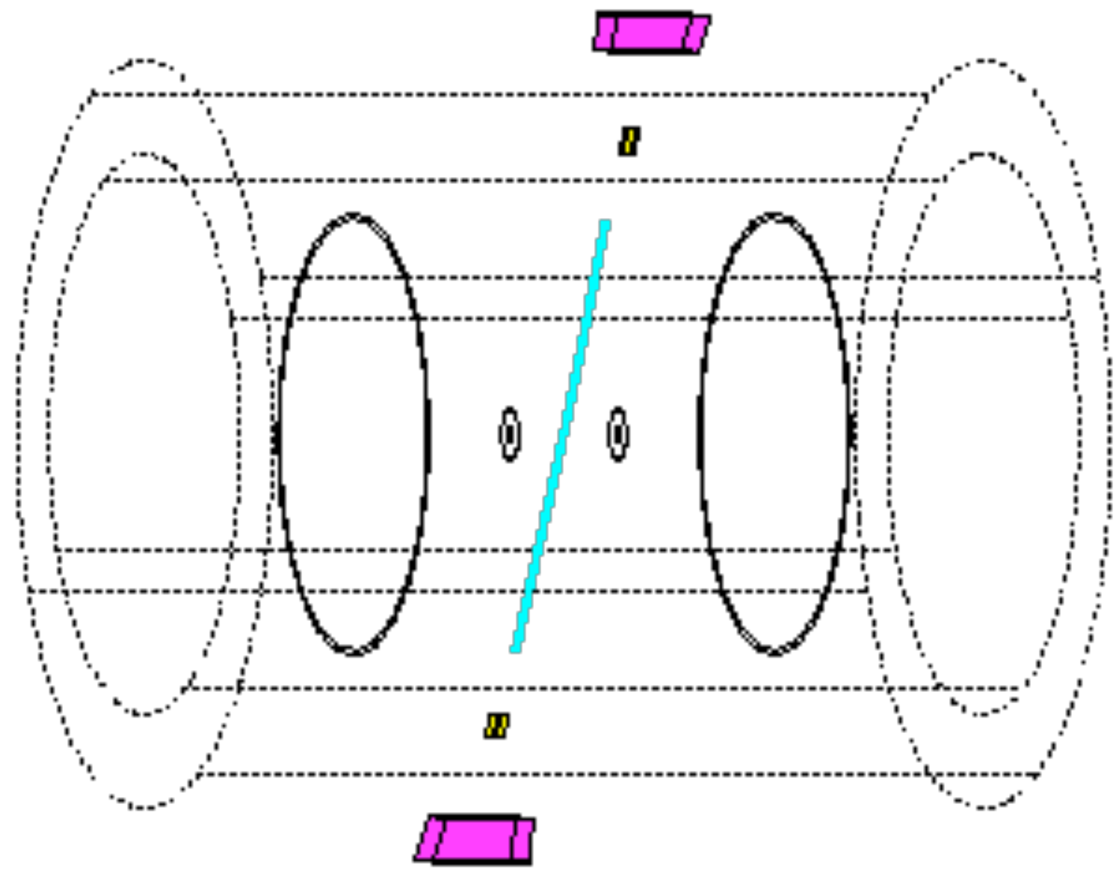
– Benjamin Franklin

Its a great time to be doing particle physics !

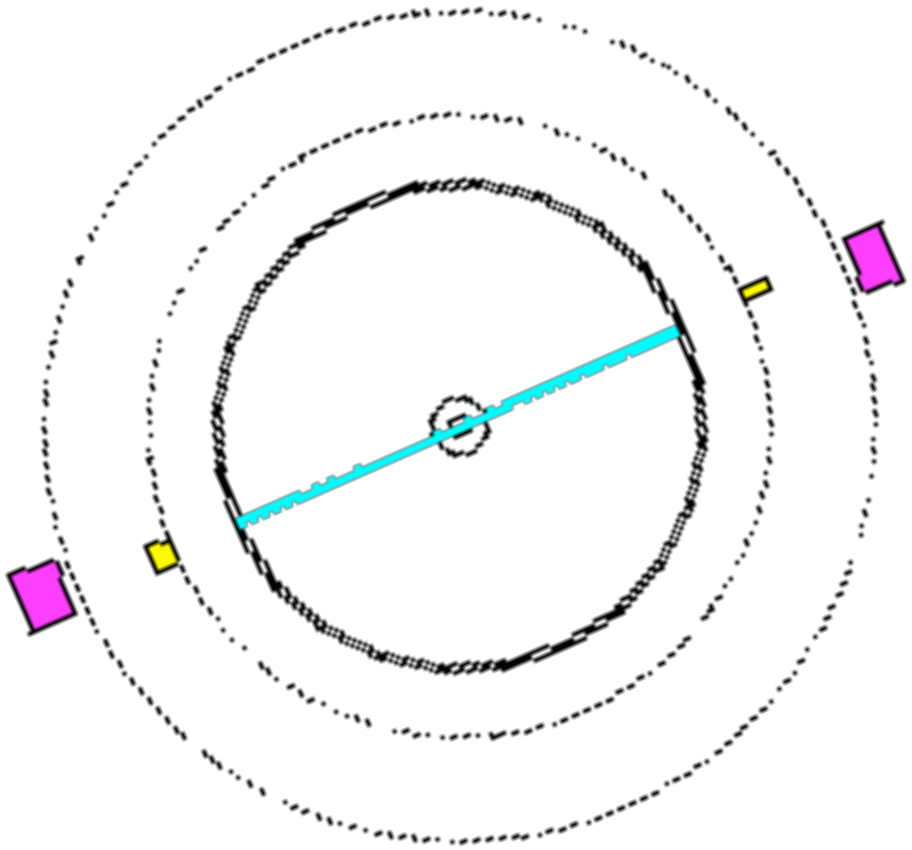
Supporting Material

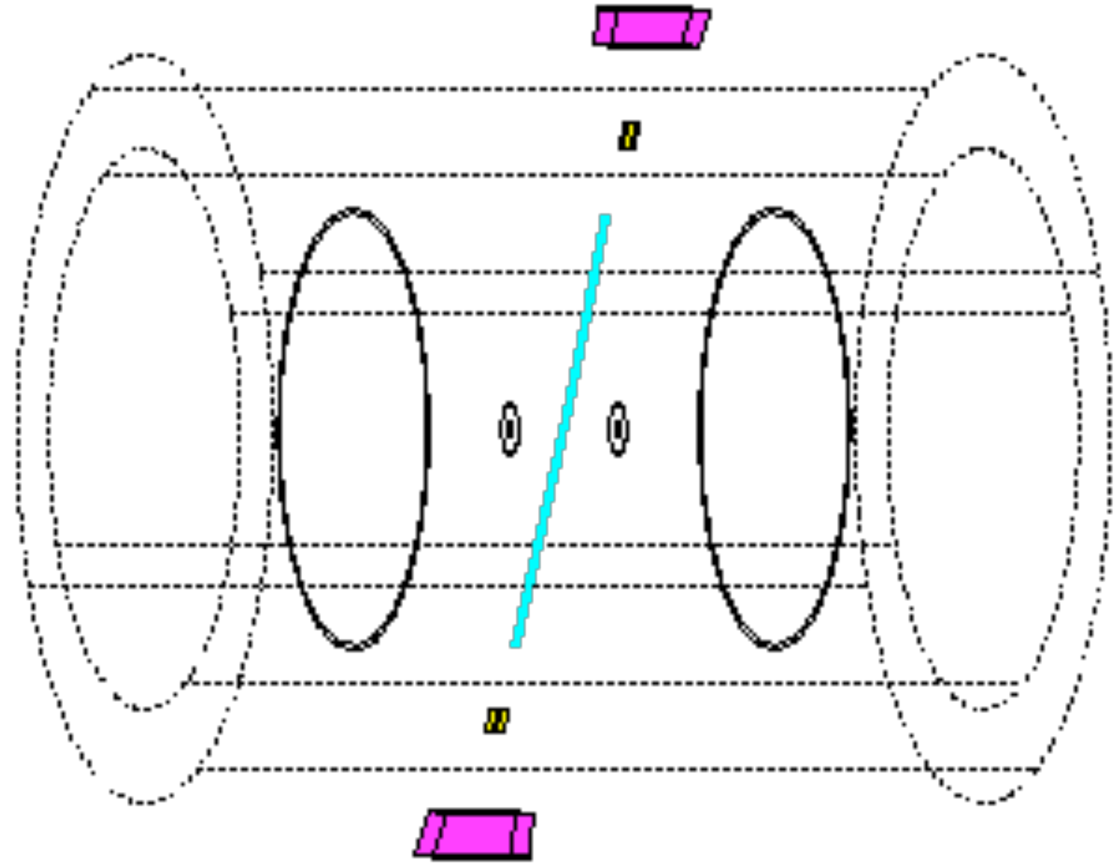
Z→μμ at LEP (Opal)



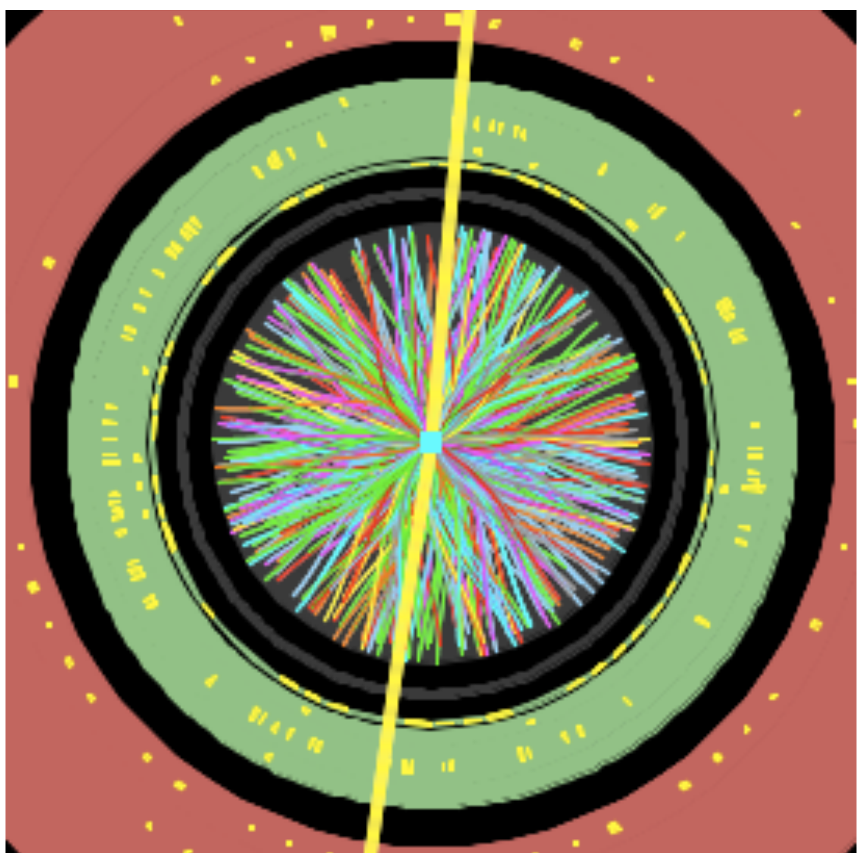


$Z \rightarrow \mu\mu$ at LEP (Opal)

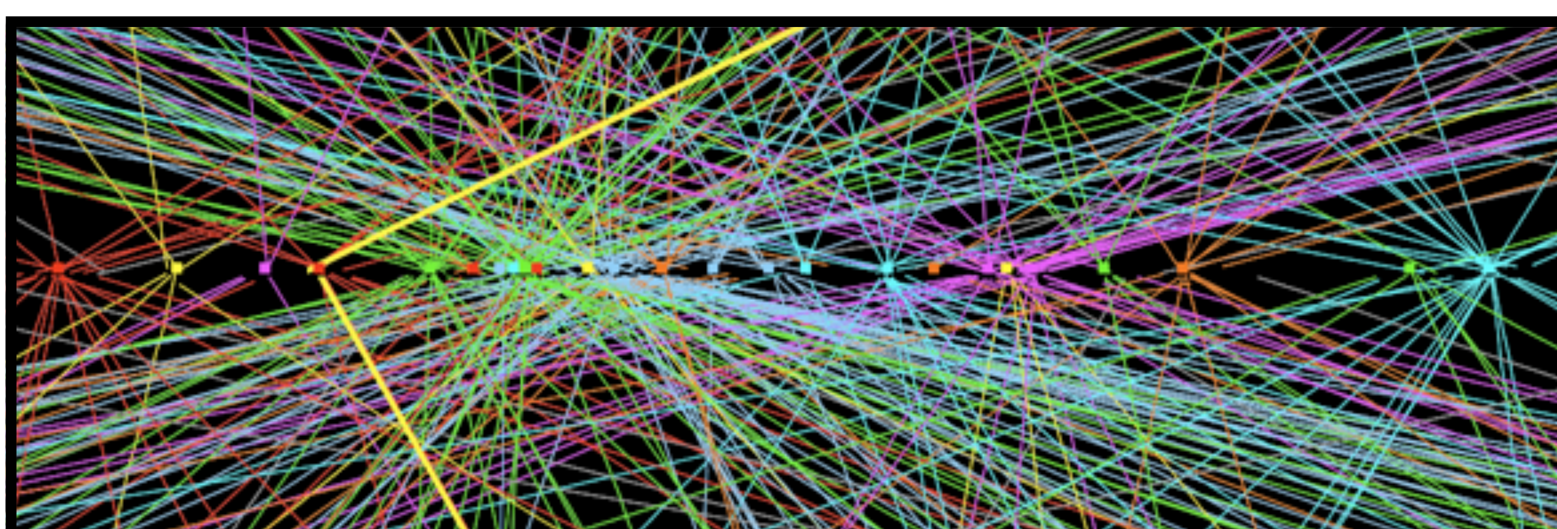




$Z \rightarrow \mu\mu$ at the LHC (ATLAS)



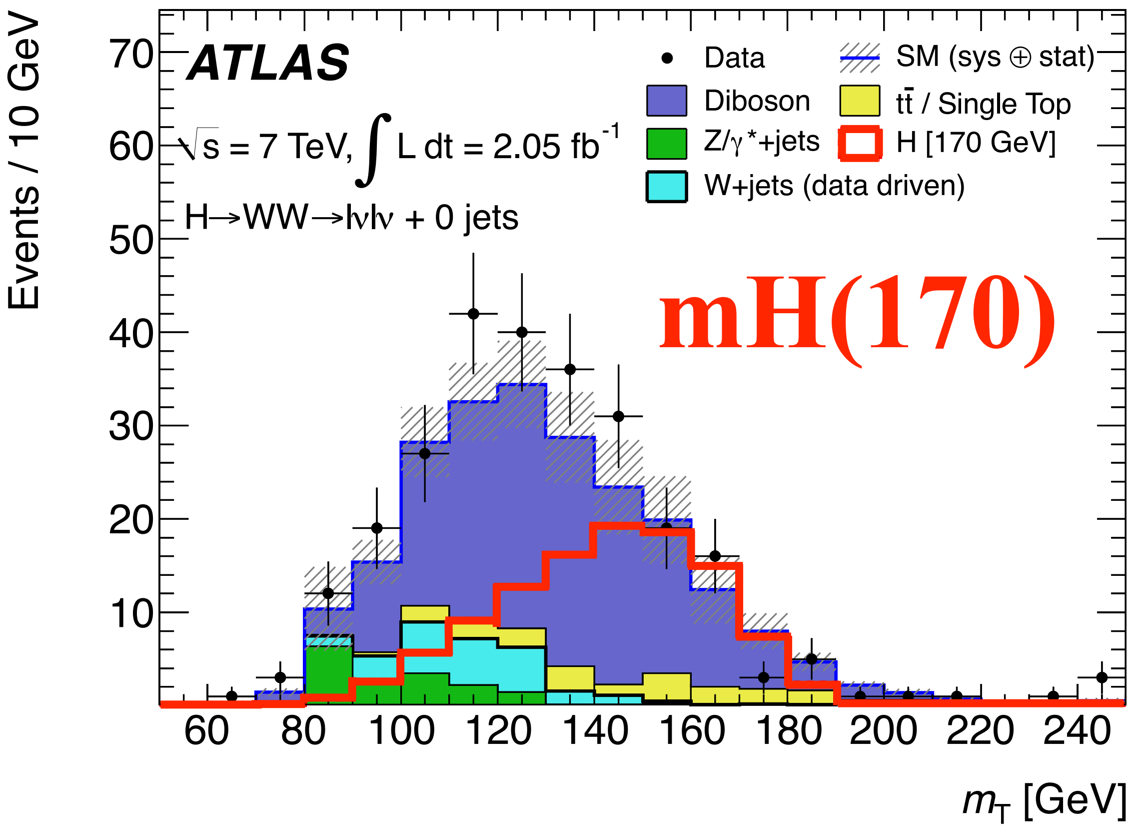
"Pile-up"

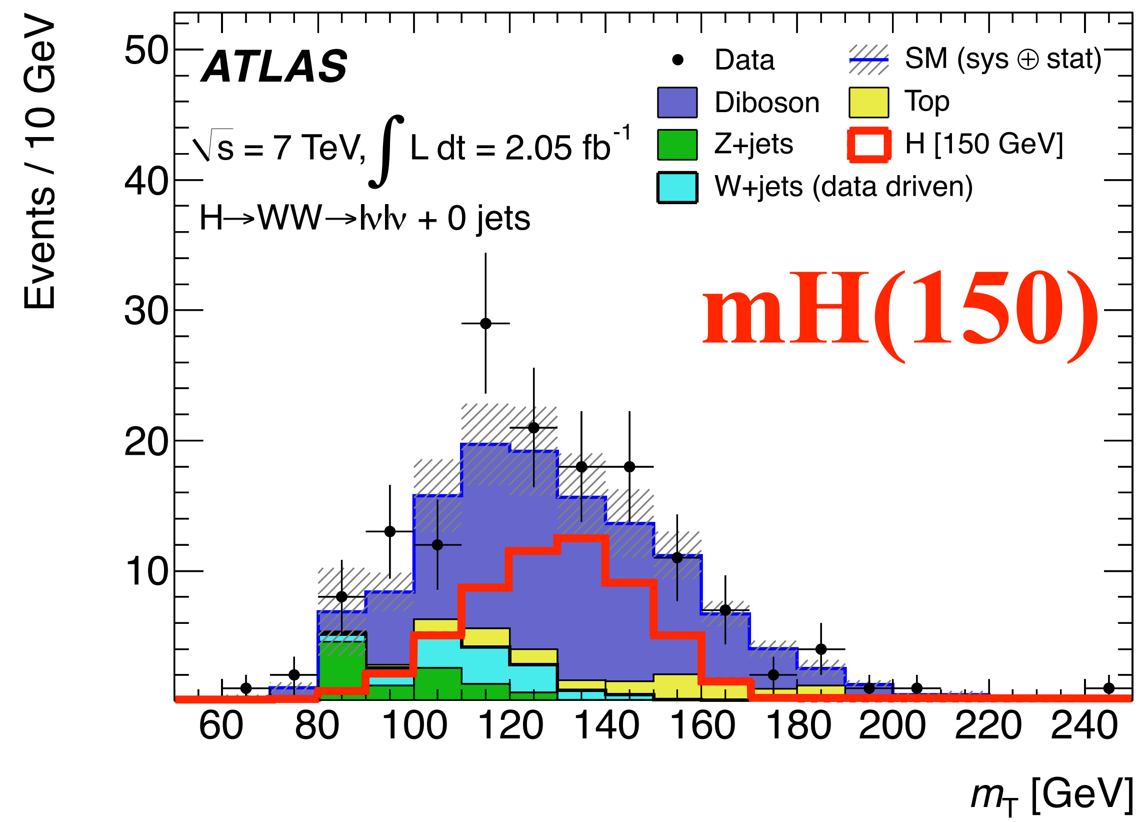


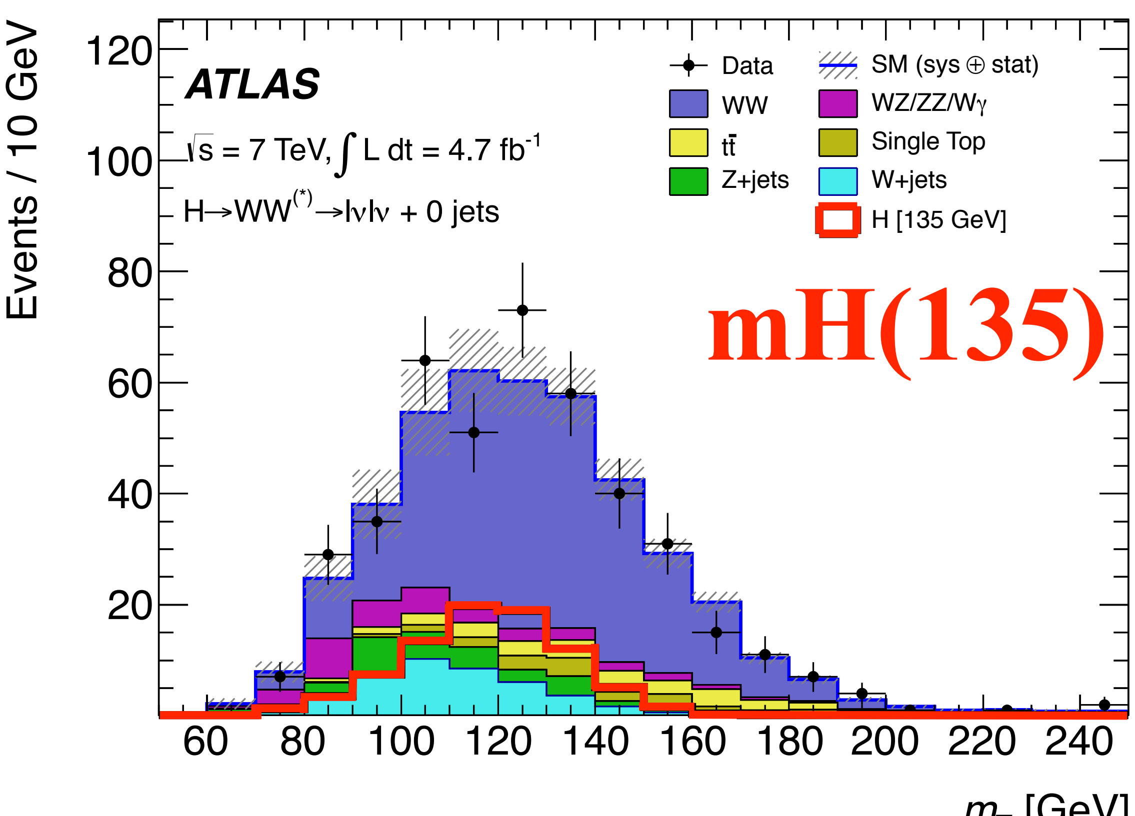
~10 cm

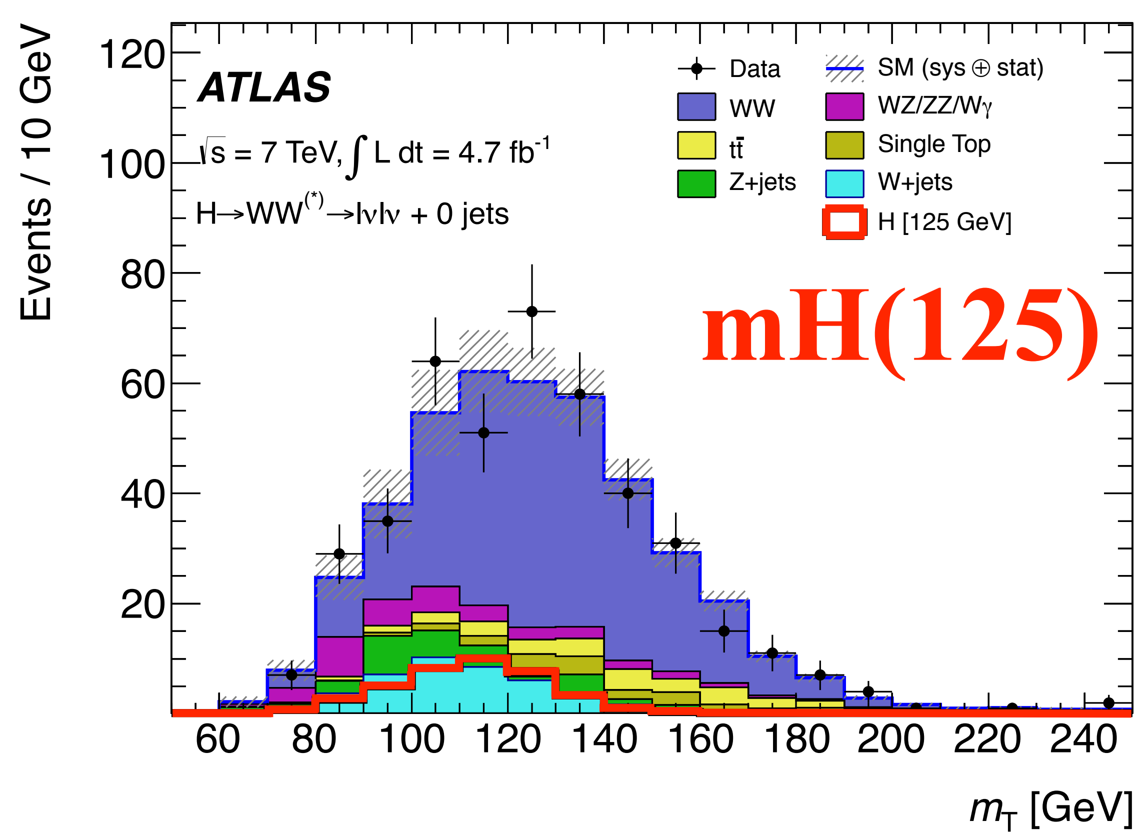
Transverse Mass

$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{ll} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left|\mathbf{p}_{\mathrm{T}}^{ll} + \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}\right|^2},$$

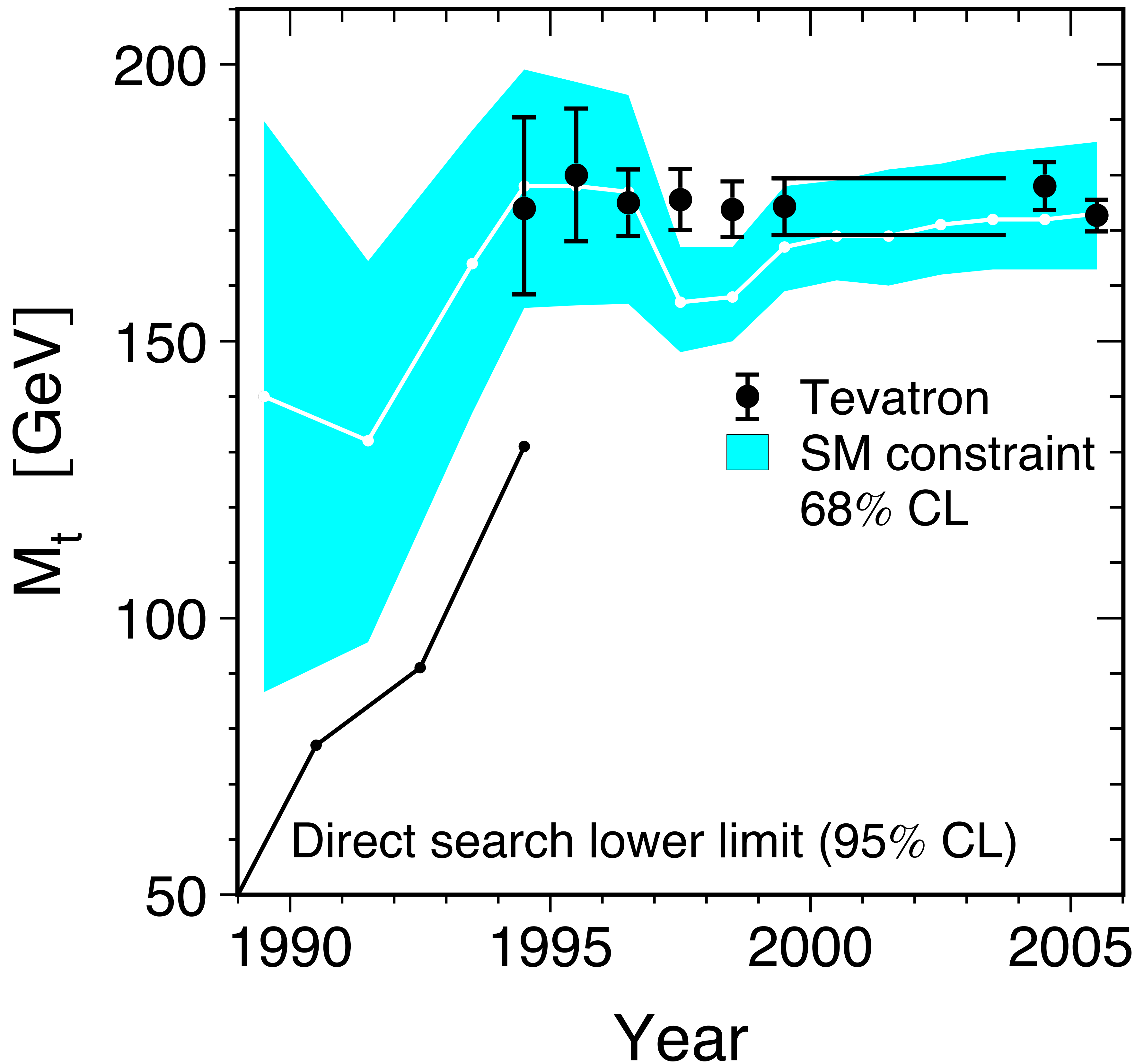








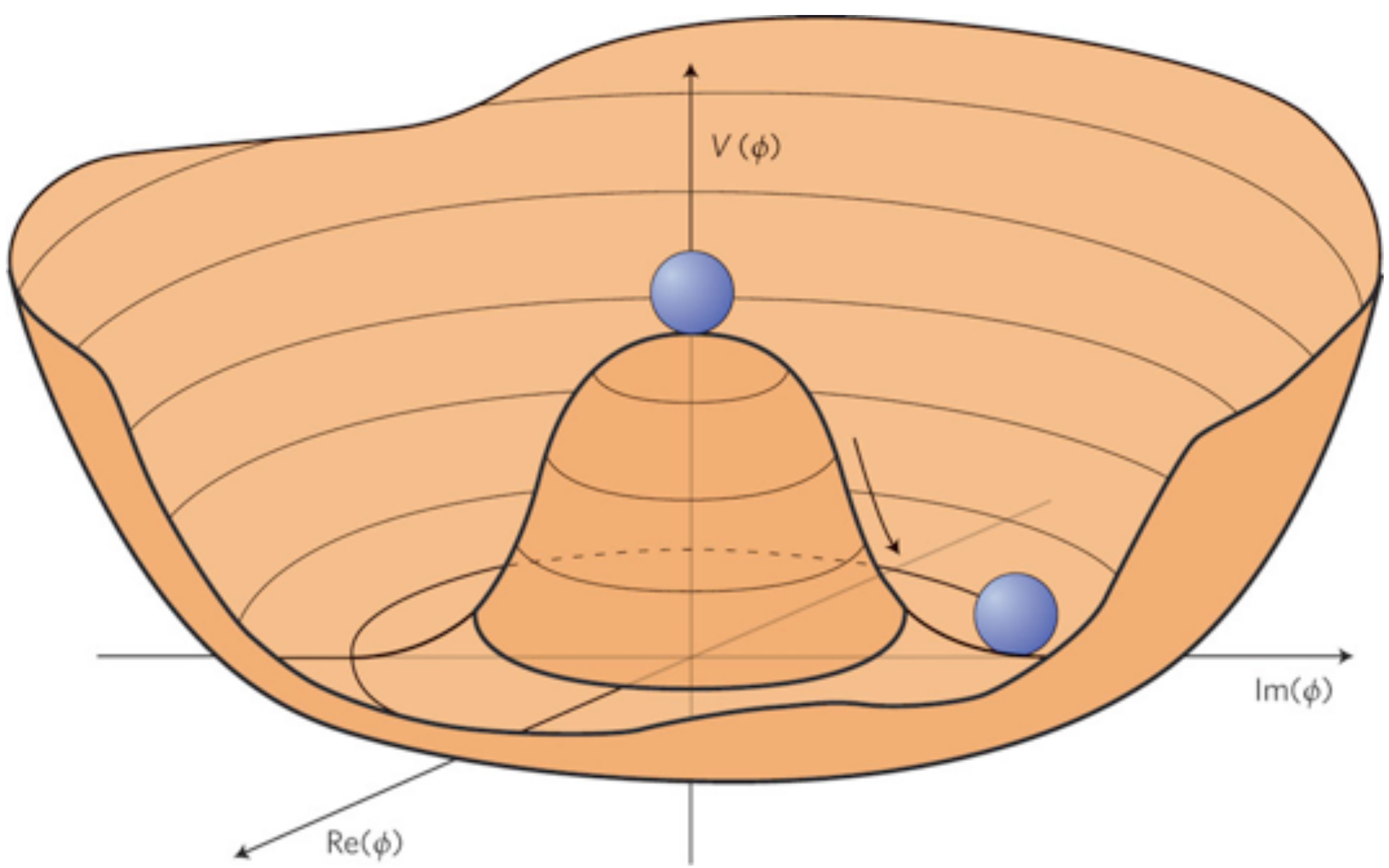
Top Mass Vs Time



Spontaneous Symmetry Breaking

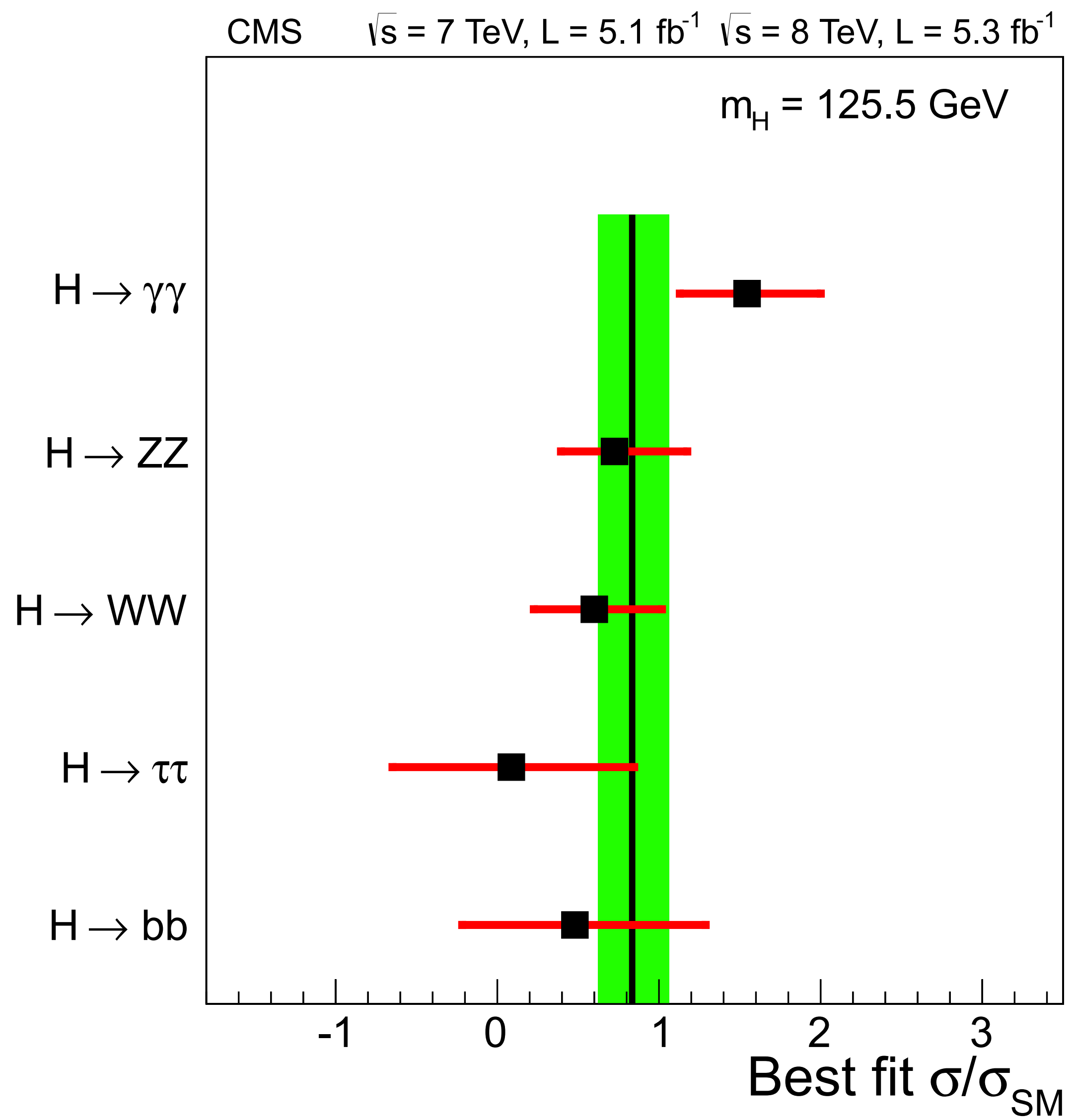
Add scalar field that couple to $SU(2) \times U(1)$ gauge fields:

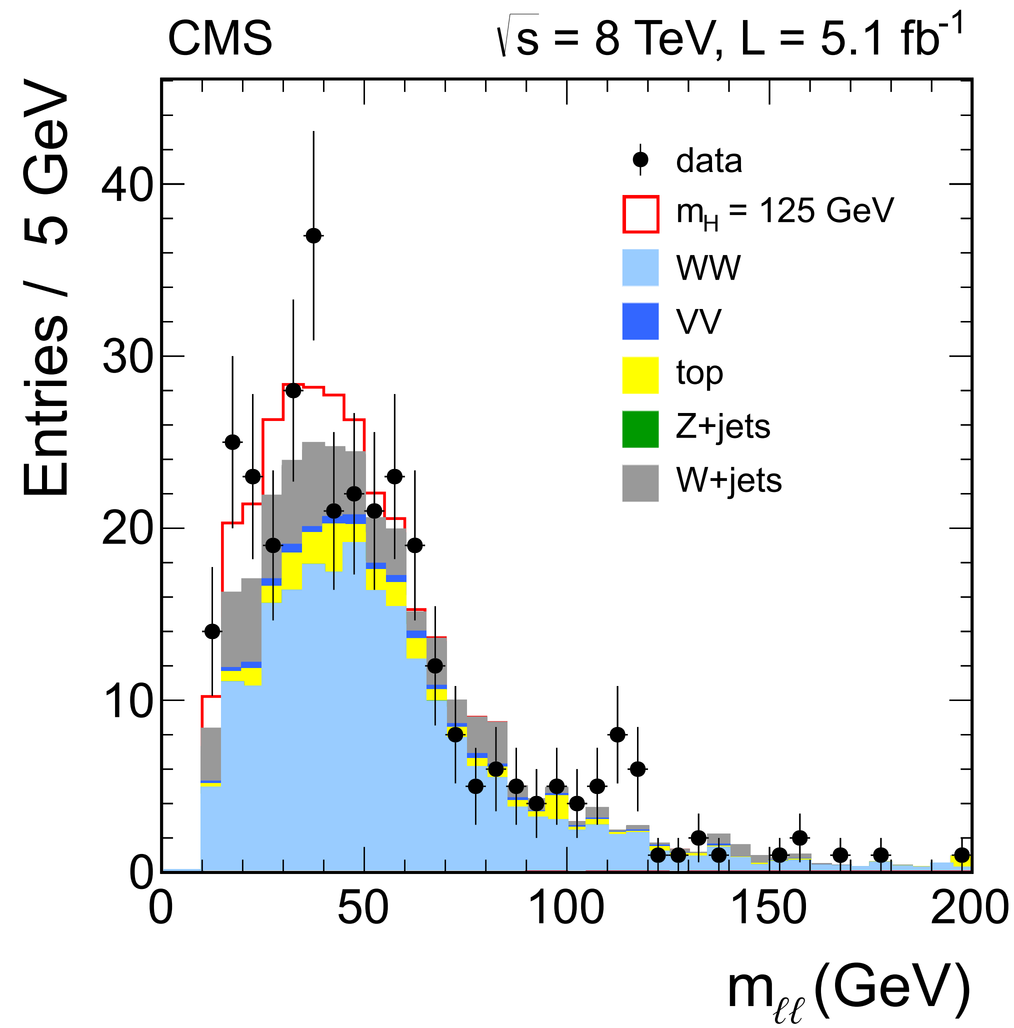
Lagrangian preserve symmetry, but the state that describe reality does not

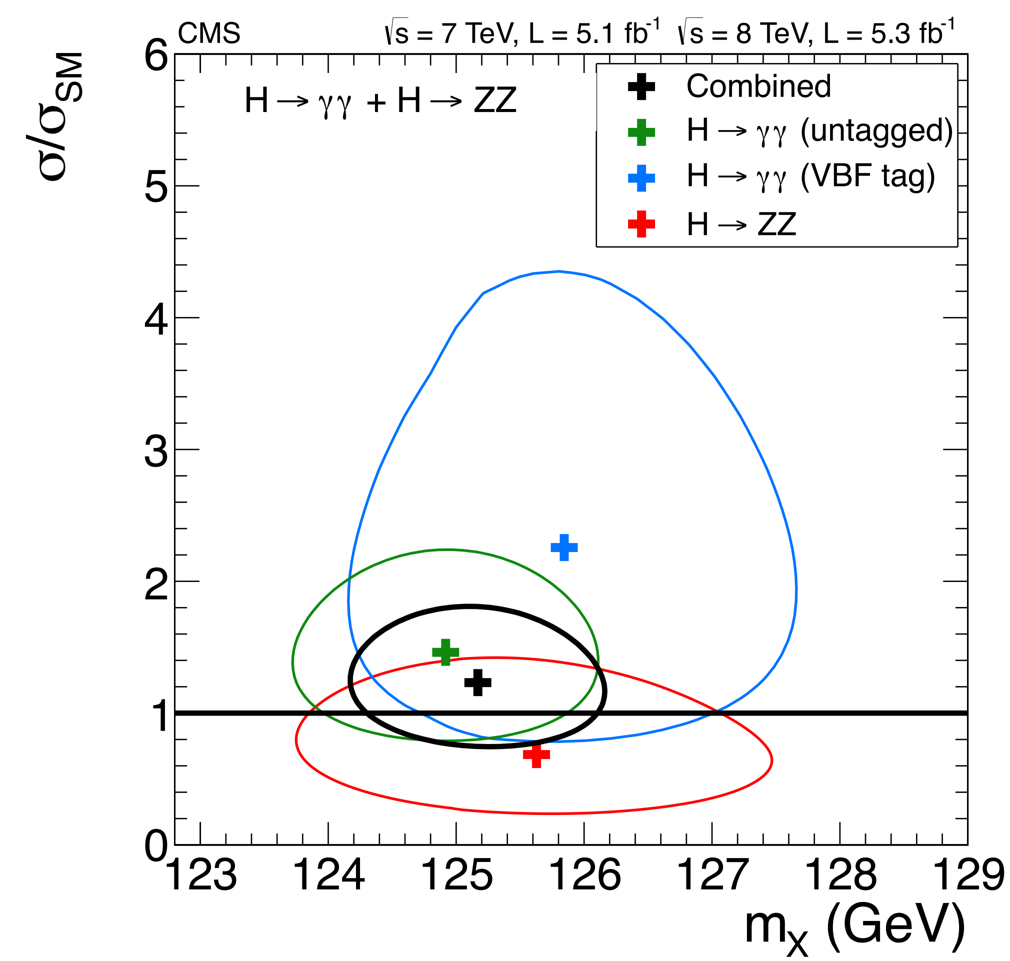


Higgs in CMS

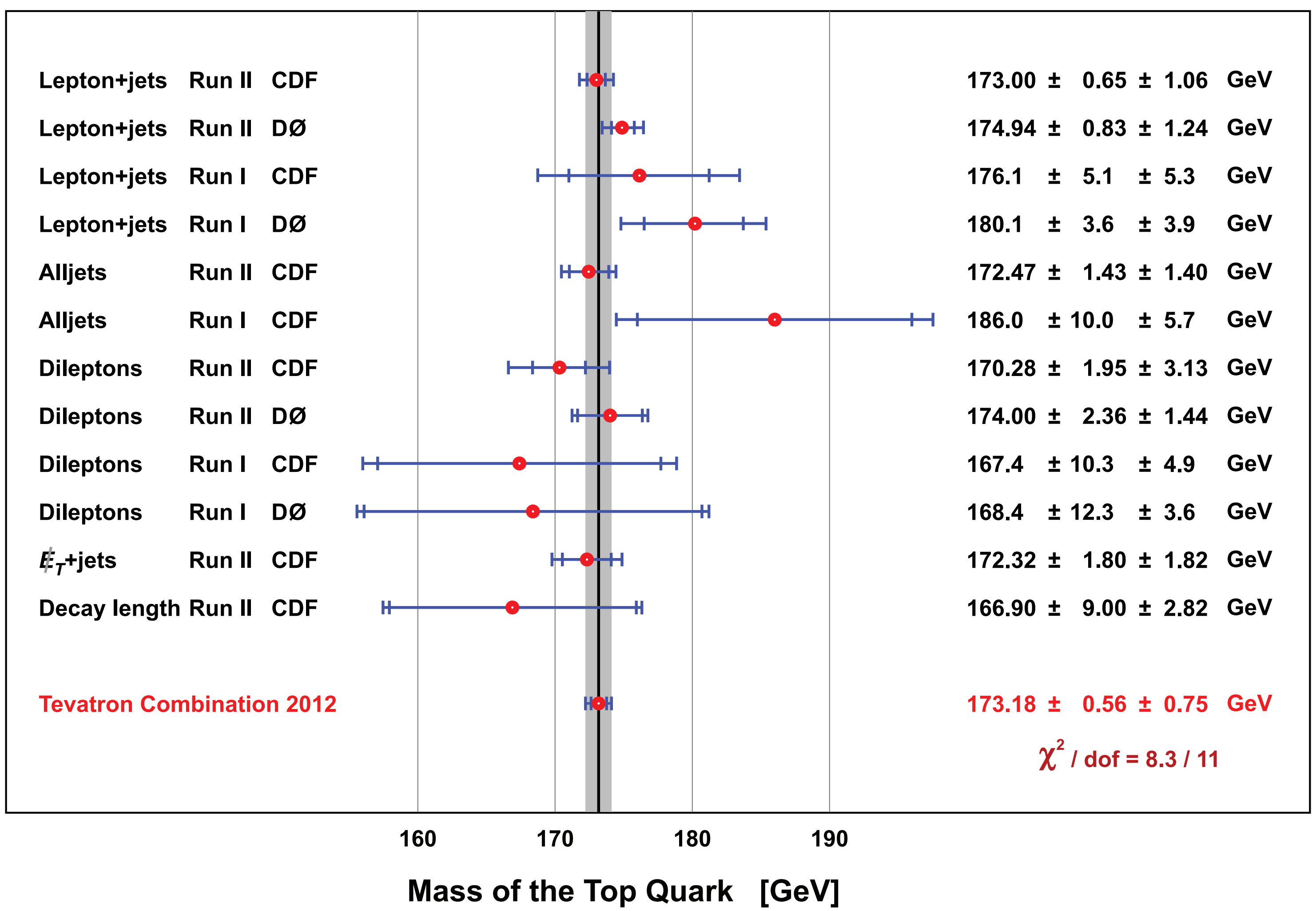
The other guys see it too.



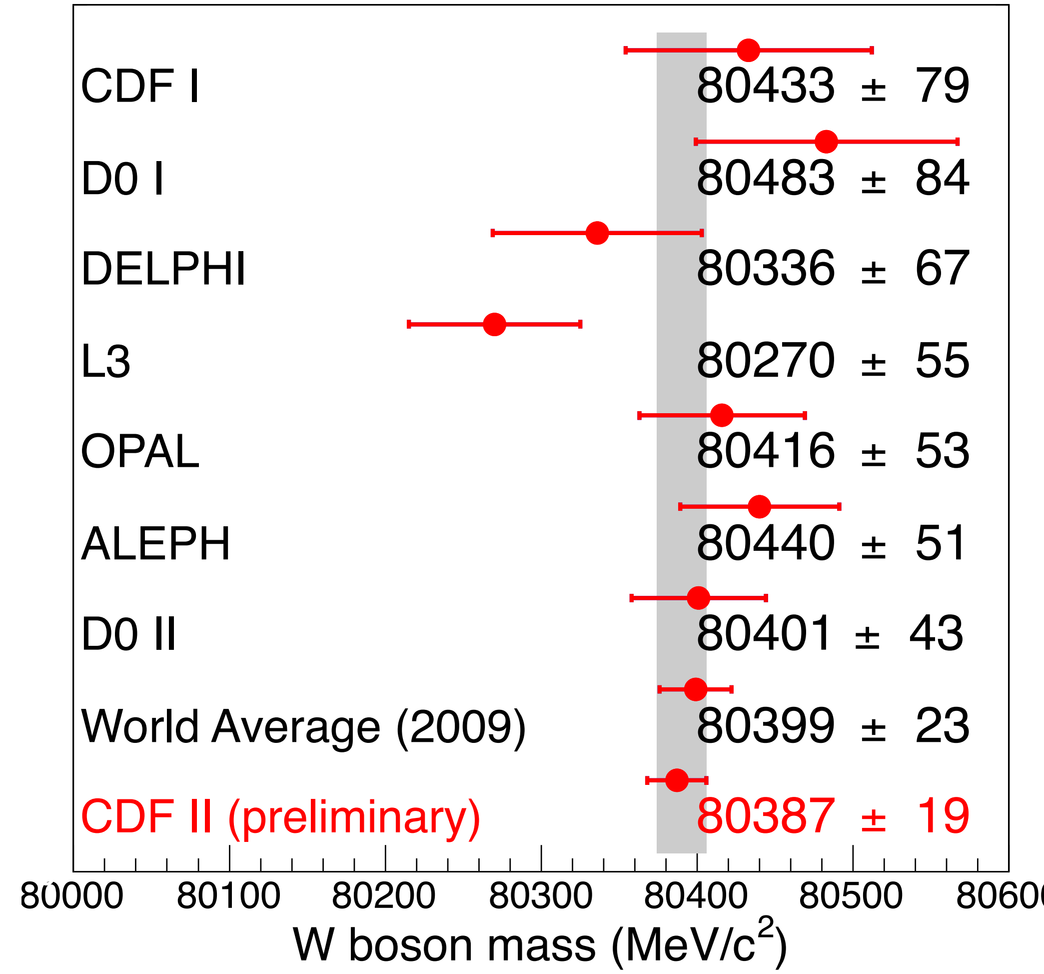




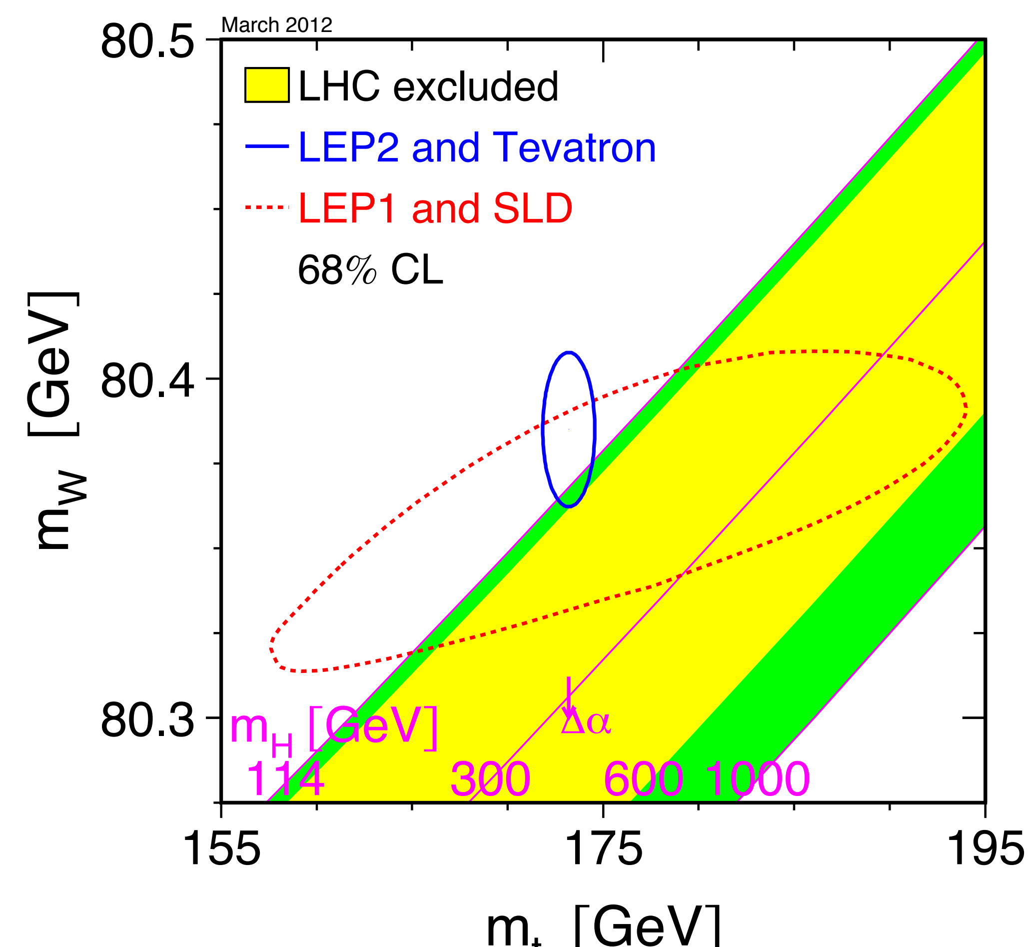
mT and mW



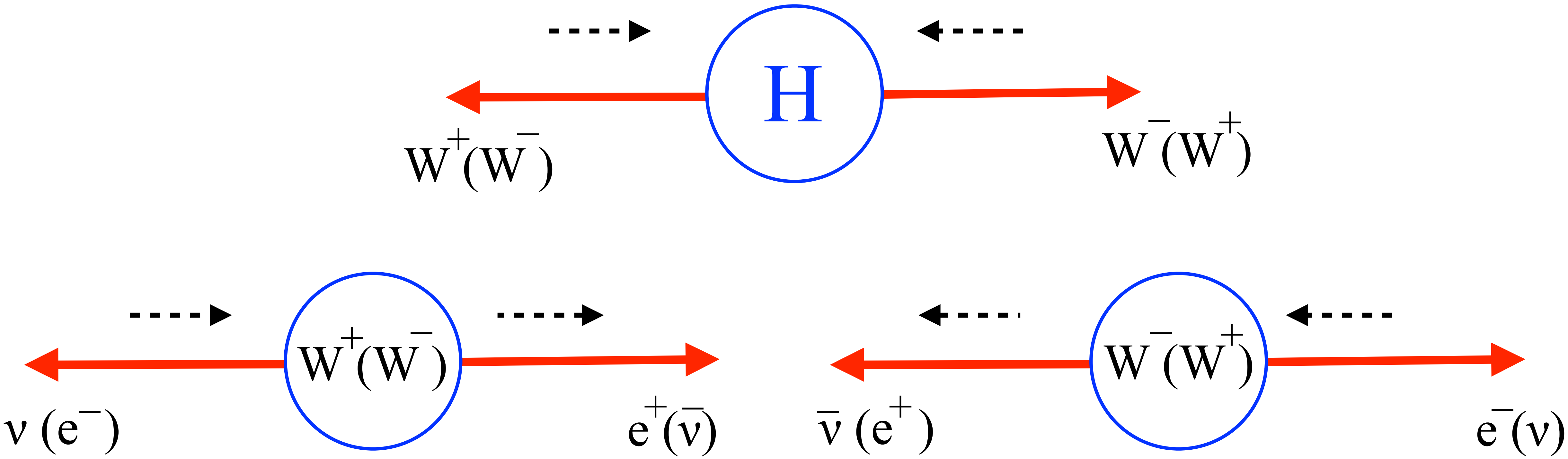
Lepton+jets Run II CDF 173.00 ± 0.65 ± 1.06 GeV
Lepton+jets Run II DØ 174.94 ± 0.83 ± 1.24 GeV
Lepton+jets Run I CDF 176.1 ± 5.1 ± 5.3 GeV
Lepton+jets Run I DØ 180.1 ± 3.6 ± 3.9 GeV
Alljets Run II CDF 172.47 ± 1.43 ± 1.40 GeV
Alljets Run I CDF 186.0 ± 10.0 ± 5.7 GeV
Dileptons Run II CDF 170.28 ± 1.95 ± 3.13 GeV
Dileptons Run II DØ 174.00 ± 2.36 ± 1.44 GeV
Dileptons Run I CDF 167.4 ± 10.3 ± 4.9 GeV
Dileptons Run I DØ 168.4 ± 12.3 ± 3.6 GeV
$\not{E}_T$+jets Run II CDF 172.32 ± 1.80 ± 1.82 GeV
Decay length Run II CDF 166.90 ± 9.00 ± 2.82 GeV
Tevatron Combination 2012 173.18 ± 0.56 ± 0.75 GeV
χ^2 / dof = 8.3 / 11
160
170
180
190
Mass of the Top Quark [GeV]

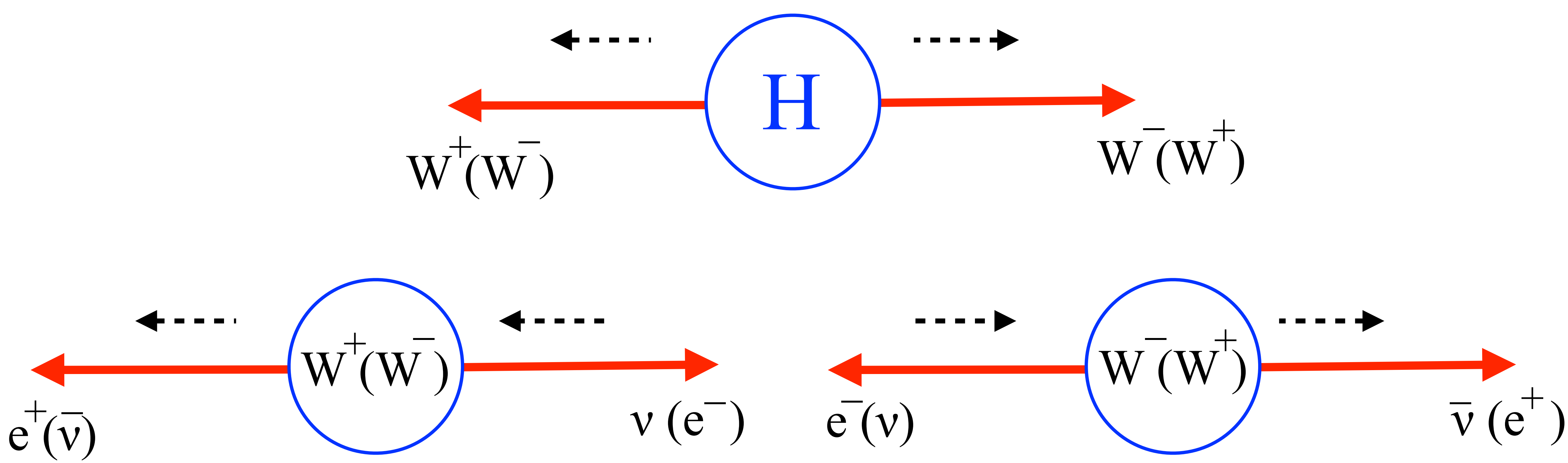


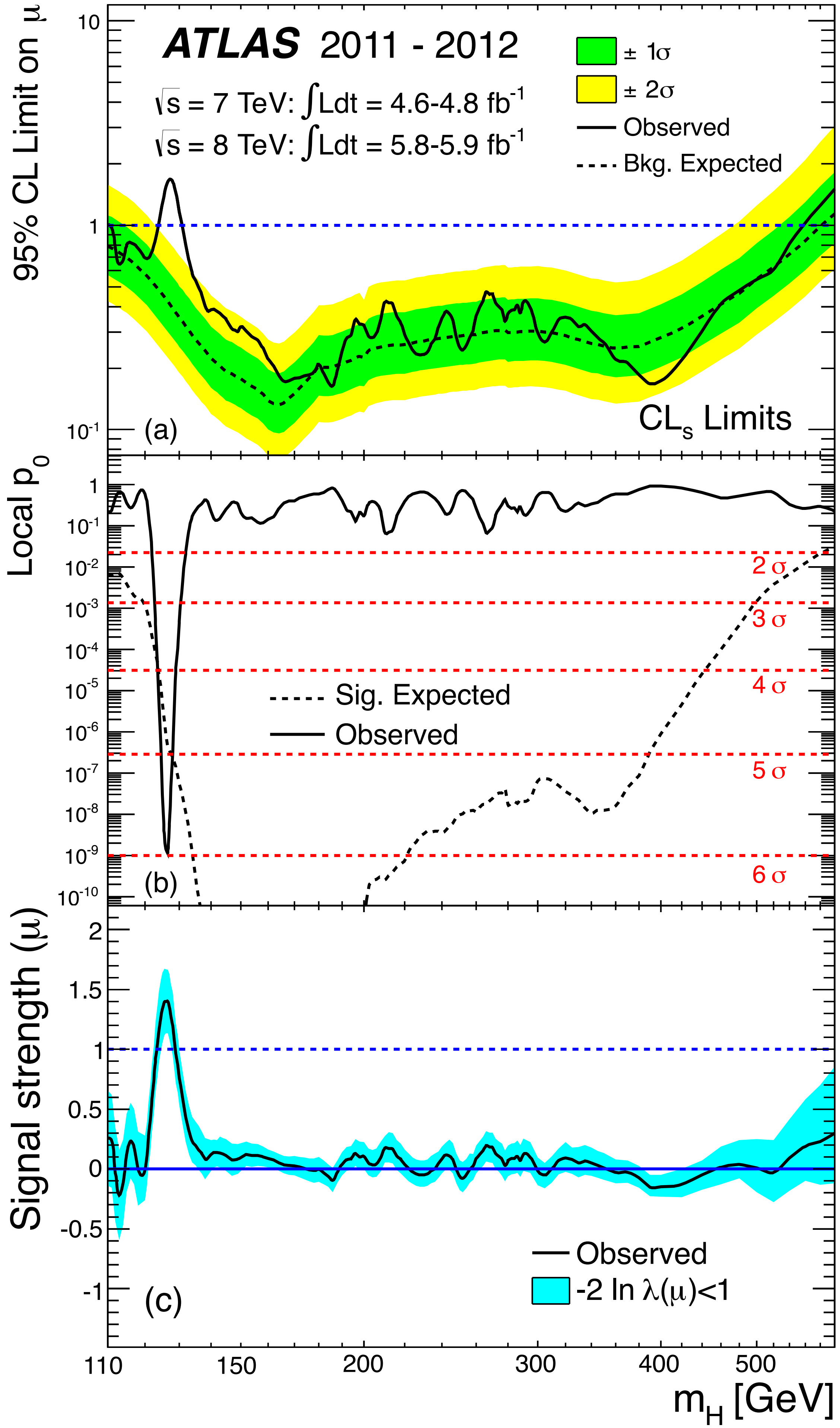
CDF I 80433 ± 79
D0 I 80483 ± 84
DELPHI 80336 ± 67
L3 80270 ± 55
OPAL 80416 ± 53
ALEPH 80440 ± 51
D0 II 80401 ± 43
World Average (2009) 80399 ± 23
CDF II (preliminary) 80387 ± 19
80000
80100
80200
80300
80400
80500
80600
W boson mass (MeV/c^2)



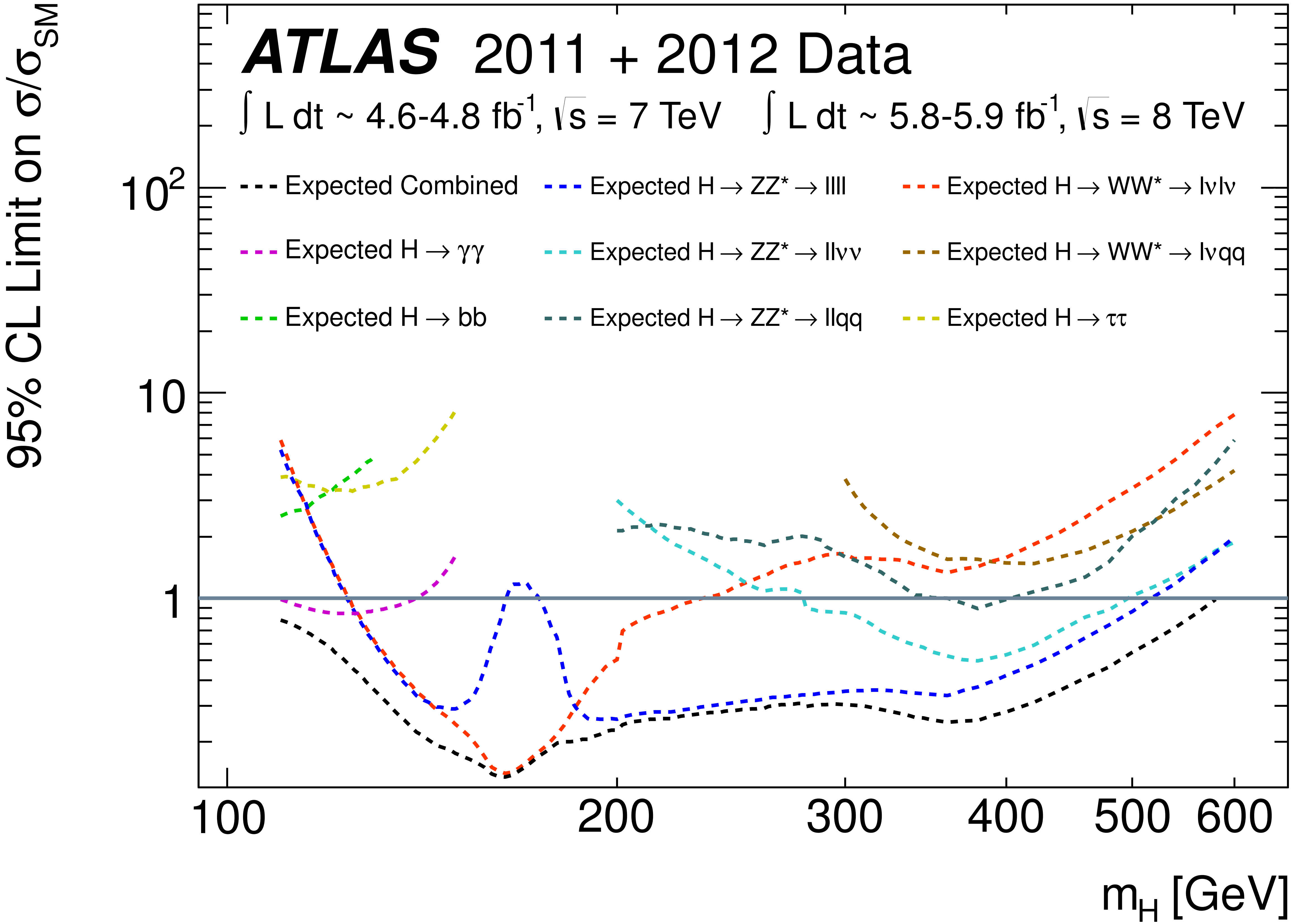
March 2012
LHC excluded
LEP2 and Tevatron
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
600
1000
$\Delta\alpha$
155
175
195
m_t [GeV]


H
$W^+(W^-)$
$W^-(W^+)$
$W^+(W^-)$
$\nu\ (e^-)$
$e^+(\bar{\nu})$
$W^-(W^+)$
$\bar{\nu}\ (e^+)$
$e^-(\nu)$

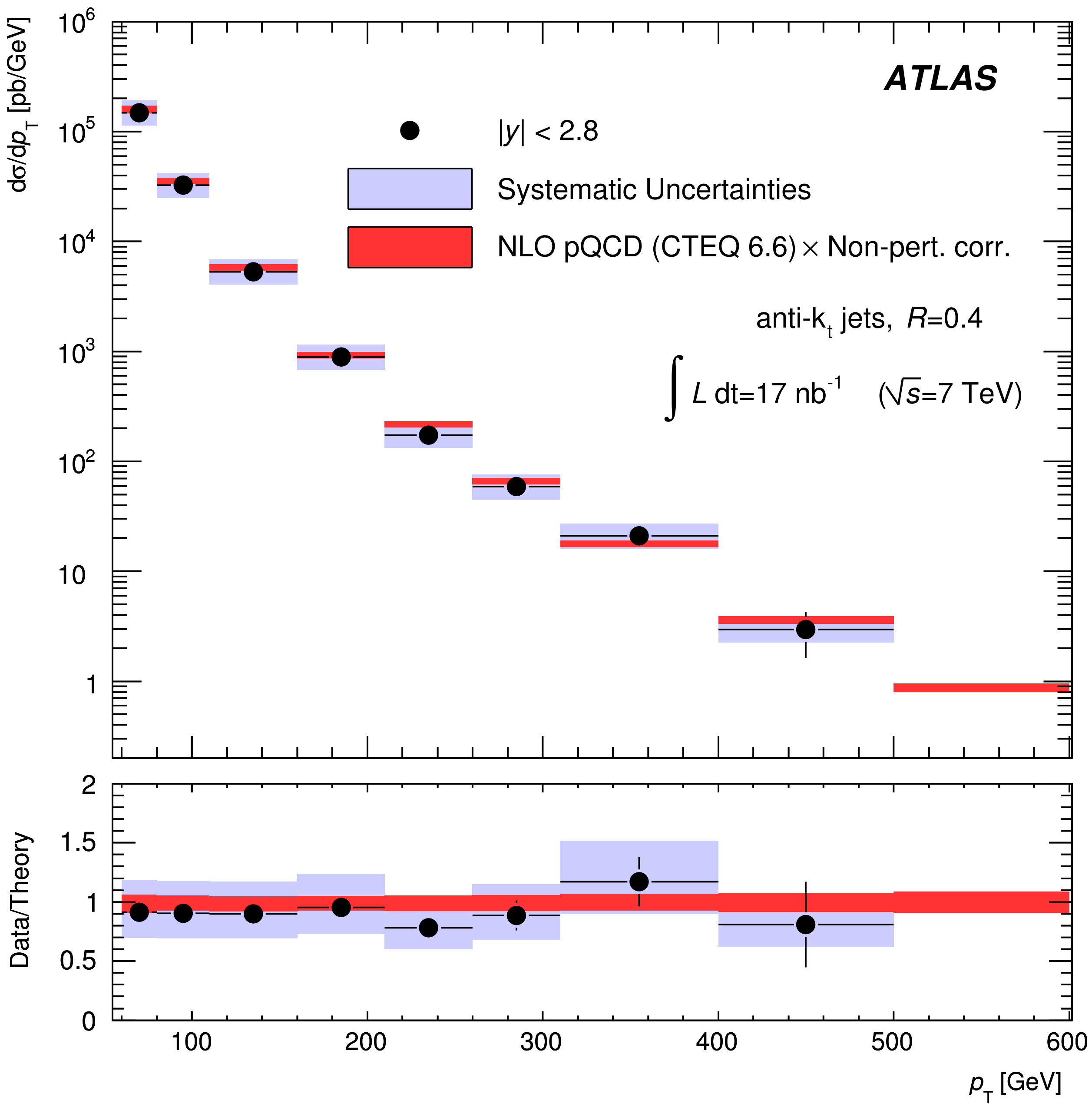

H
$W^+(W^-)$
$W^-(W^+)$
$W^+(W^-)$
$e^+(\bar{\nu})$
$\nu\ (e^-)$
$W^-(W^+)$
$e^-(\nu)$
$\bar{\nu}\ (e^+)$

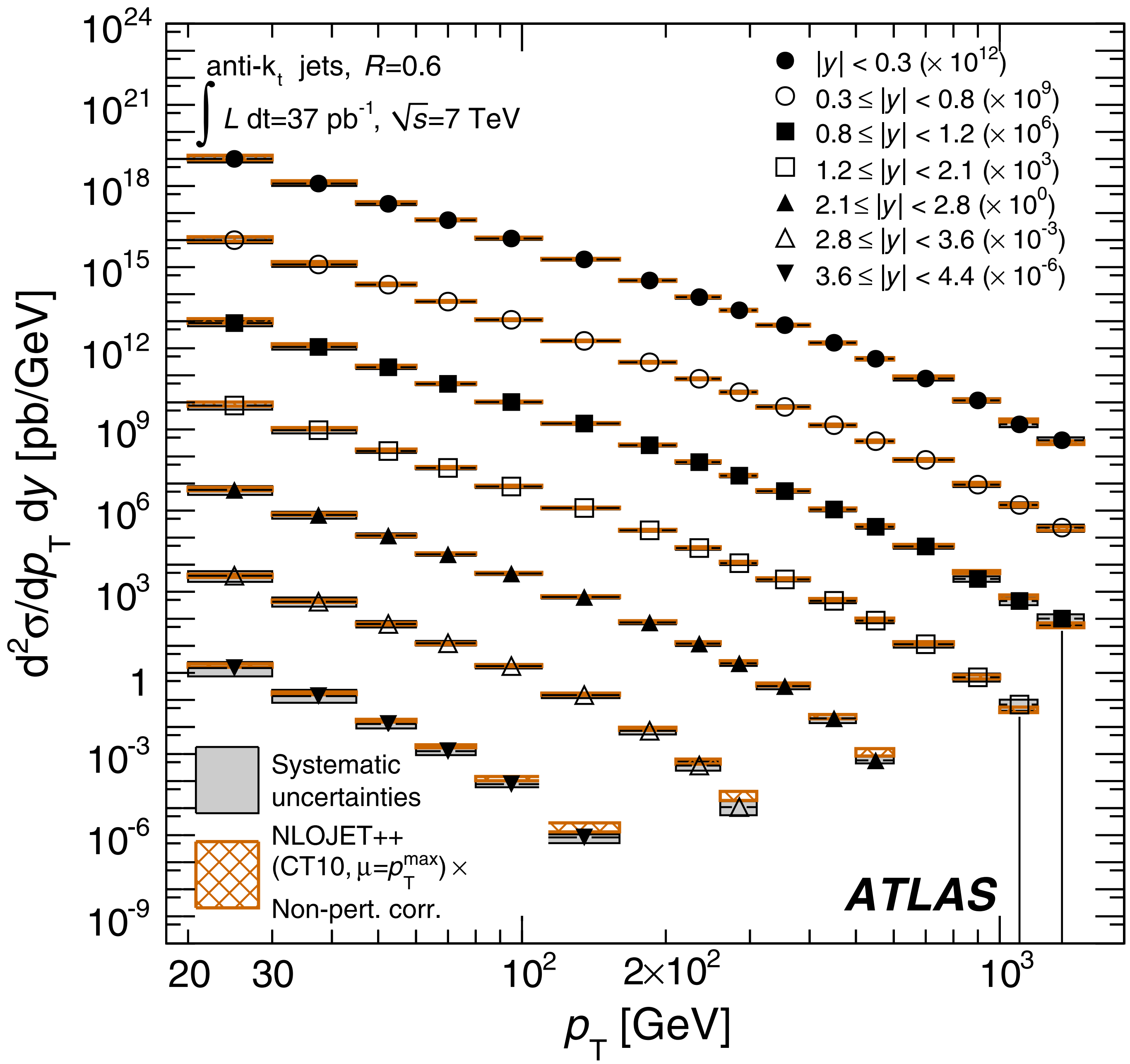


ATLAS 2011 - 2012
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb-1
± 1σ
± 2σ
Observed
Bkg. Expected
95% CL Limit on μ
CLs Limits
(a)
Local p0
Sig. Expected
Observed
2 σ
3 σ
4 σ
5 σ
6 σ
(b)
Signal strength (μ)
Observed
-2 ln λ(μ)<1
(c)
110
150
200
300
400
500
mH [GeV]

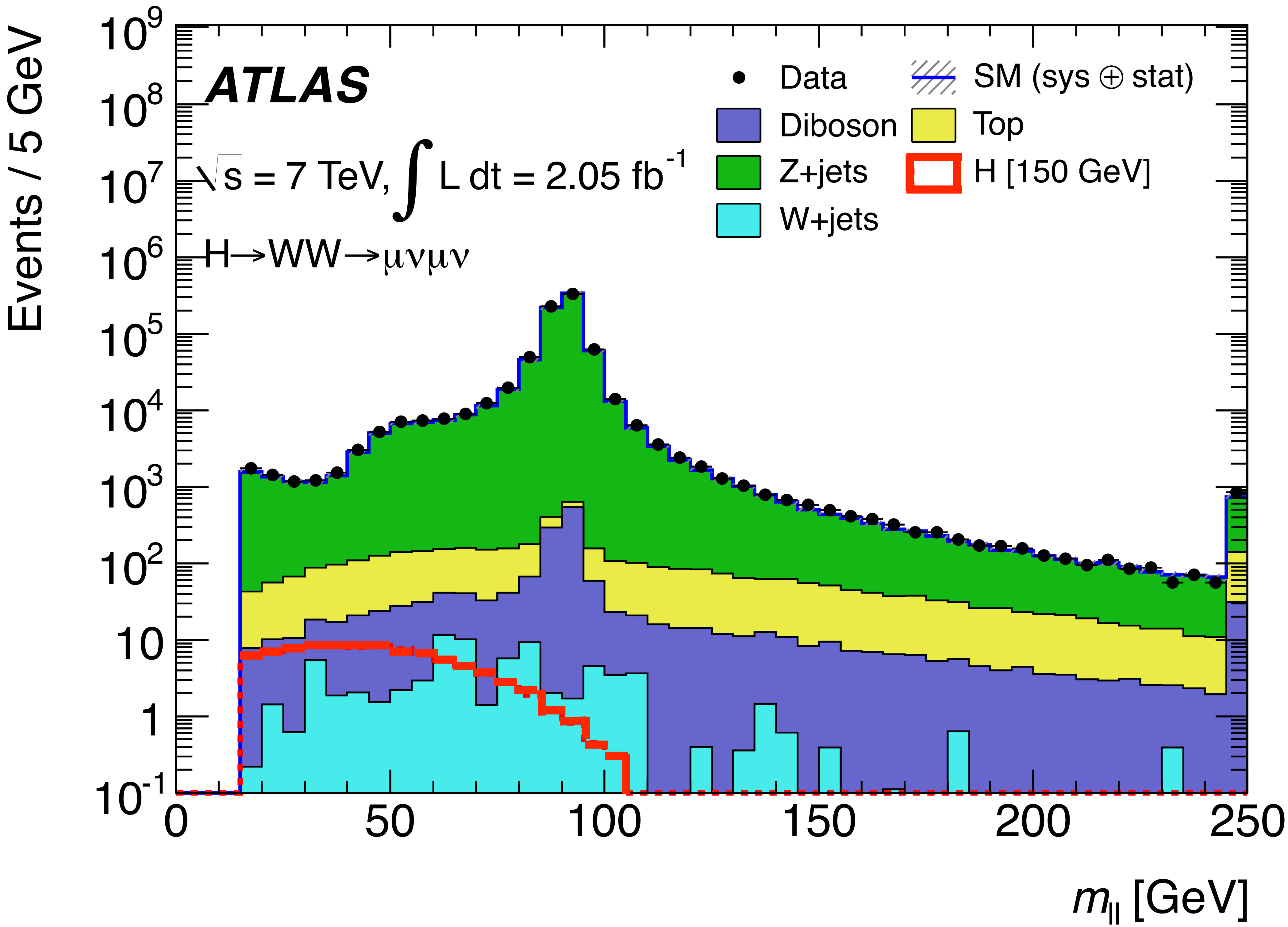

ATLAS 2011 + 2012 Data
∫ L dt ~ 4.6-4.8 fb^{-1}, $\sqrt{s}$ = 7 TeV ∫ L dt ~ 5.8-5.9 fb^{-1}, $\sqrt{s}$ = 8 TeV
Expected Combined
Expected H → ZZ* → llll
Expected H → WW* → lνlν
Expected H → γγ
Expected H → ZZ* → llνν
Expected H → WW* → lνqq
Expected H → bb
Expected H → ZZ* → llqq
Expected H → ττ
95% CL Limit on σ/σ$_{SM}$
10^2
10
1
100
200
300
400
500
600
m_H [GeV]

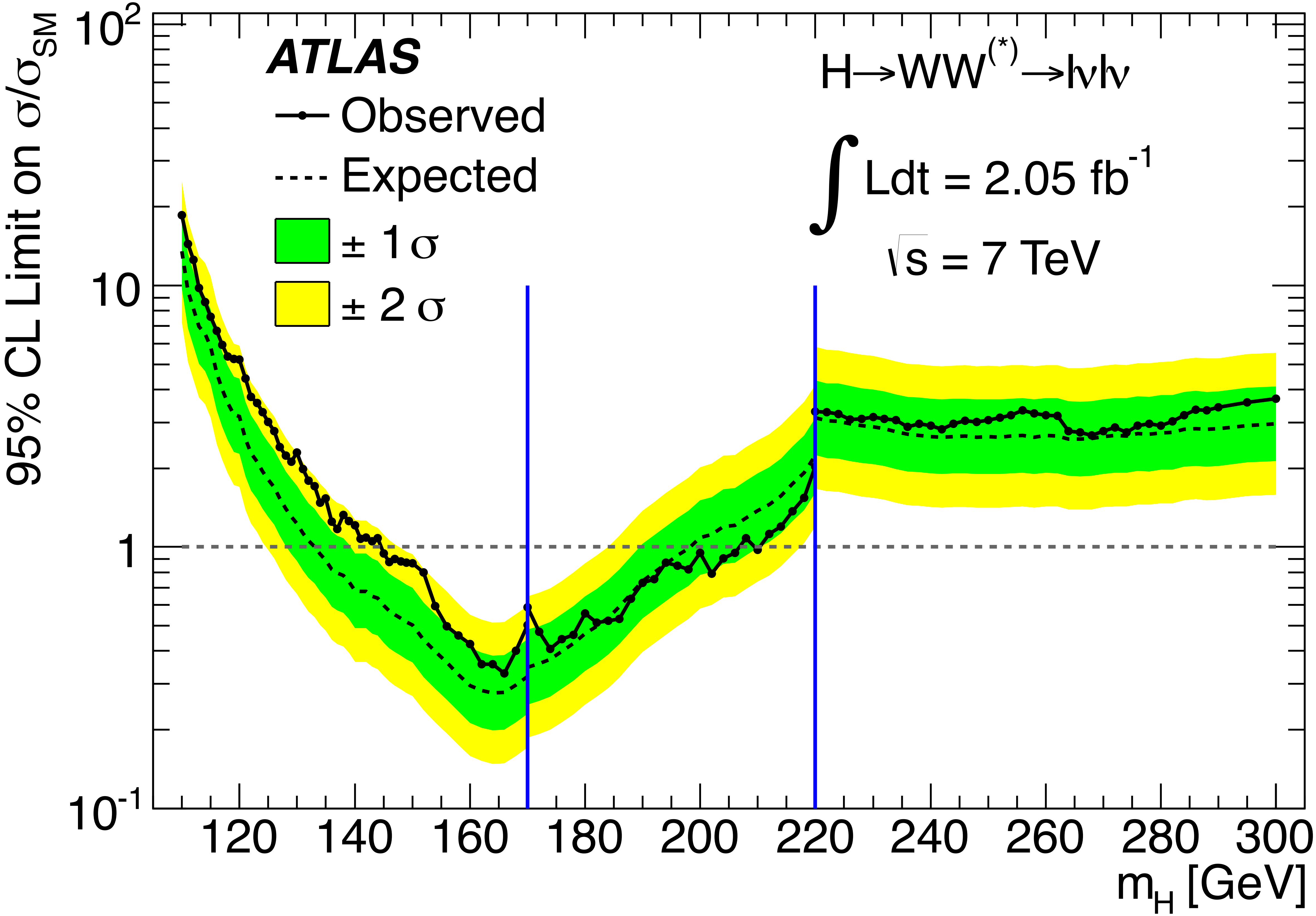
Jet Measurements



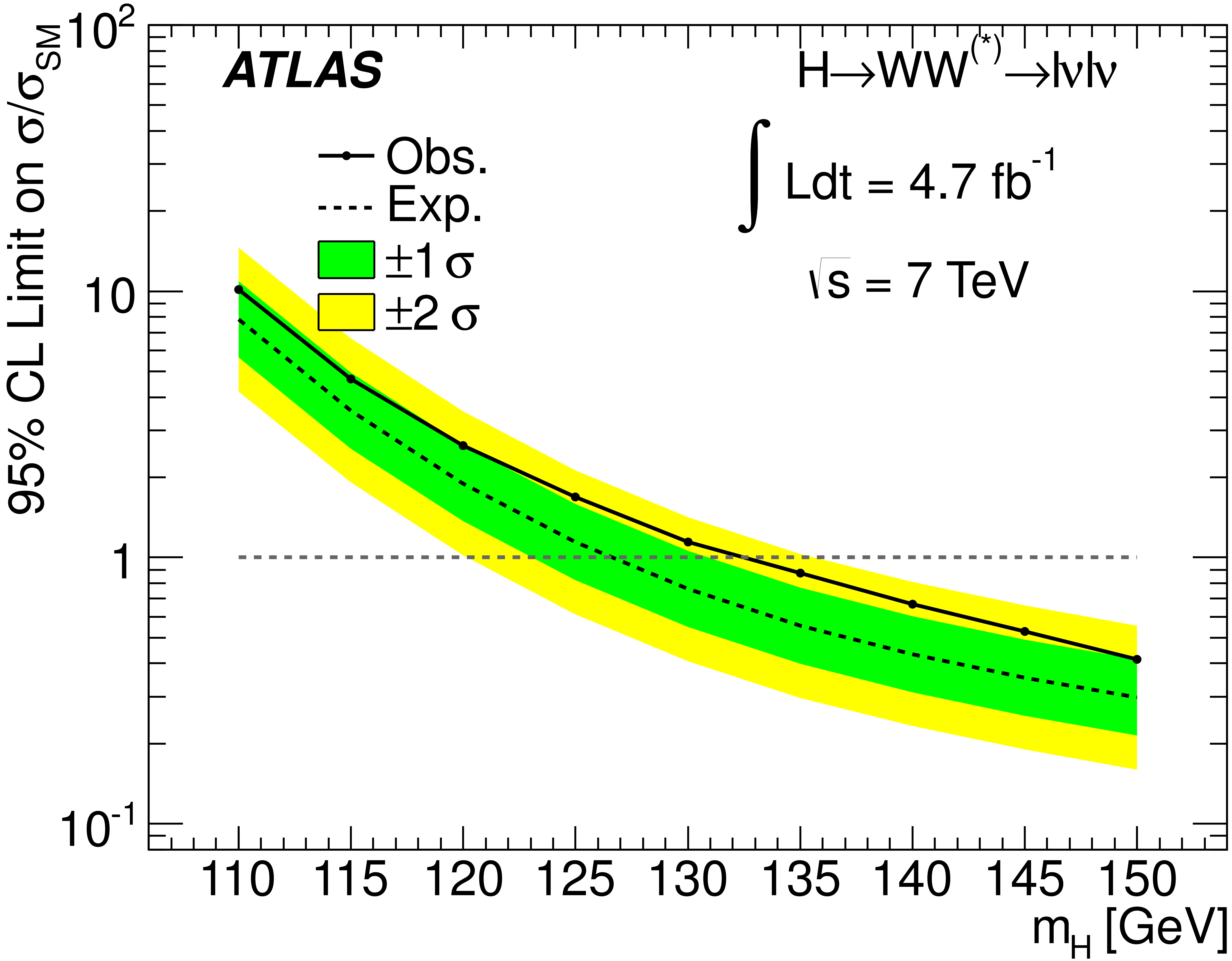


Finding the Needle



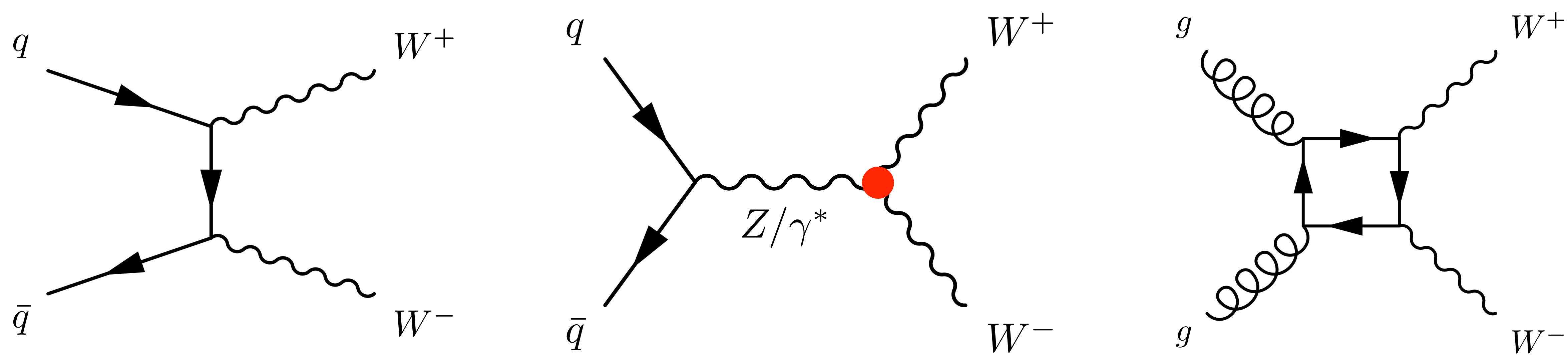


ATLAS
Observed
Expected
± 1 σ
± 2 σ
H→WW(*)→lνlν
∫Ldt = 2.05 fb-1
√s = 7 TeV
95% CL Limit on σ/σSM
10-1
1
10
102
120
140
160
180
200
220
240
260
280
300
mH [GeV]



ATLAS
H→WW(*)→lνlν
∫Ldt = 4.7 fb-1
√s = 7 TeV
Obs.
Exp.
±1 σ
±2 σ
95% CL Limit on σ/σSM
m_H [GeV]
10^2
10
1
10^-1
110
115
120
125
130
135
140
145
150

WW Cross Section



Motivation:

- Dominant Background to H→WW search
- Test EWK model, Sensitive to Triple Gauge Couplings

Signature:

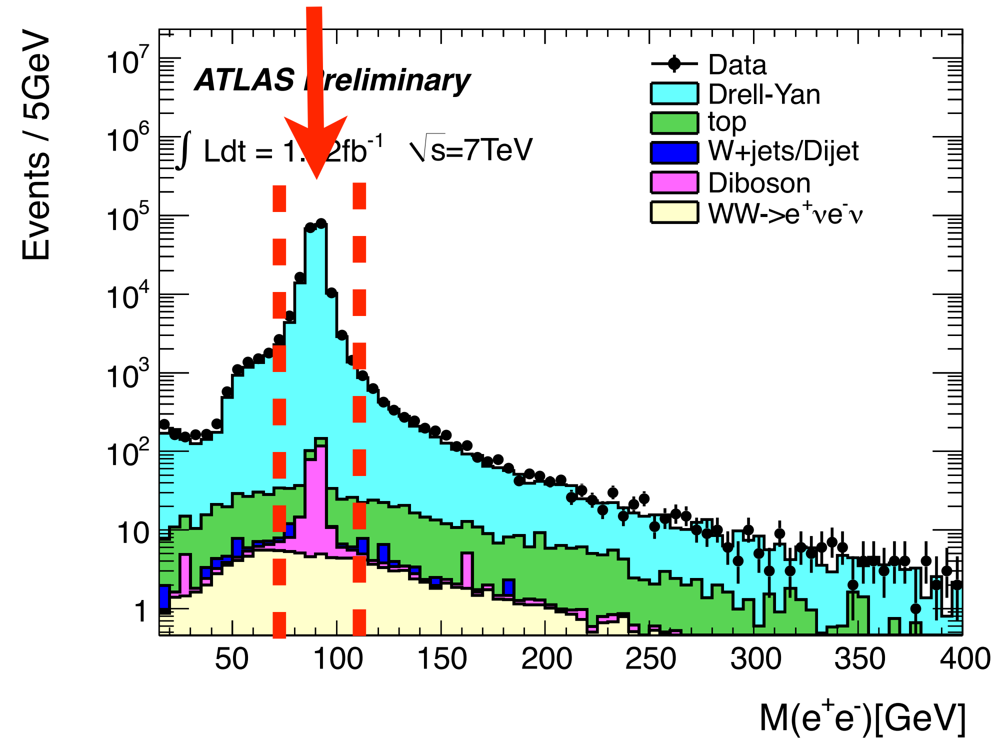
- Performed Fully Leptonic Decays.
- 2 Opposite-Sign Leptons (e,μ)
- Large Missing Energy

$$\sigma_{WW} = \frac{N - N_{Bkg}}{\epsilon \times A \times L}$$

Drell-Yan Background

Background from DY if "fake" MeT

Observed momentum imbalance that is not due to the presence of neutrinos.

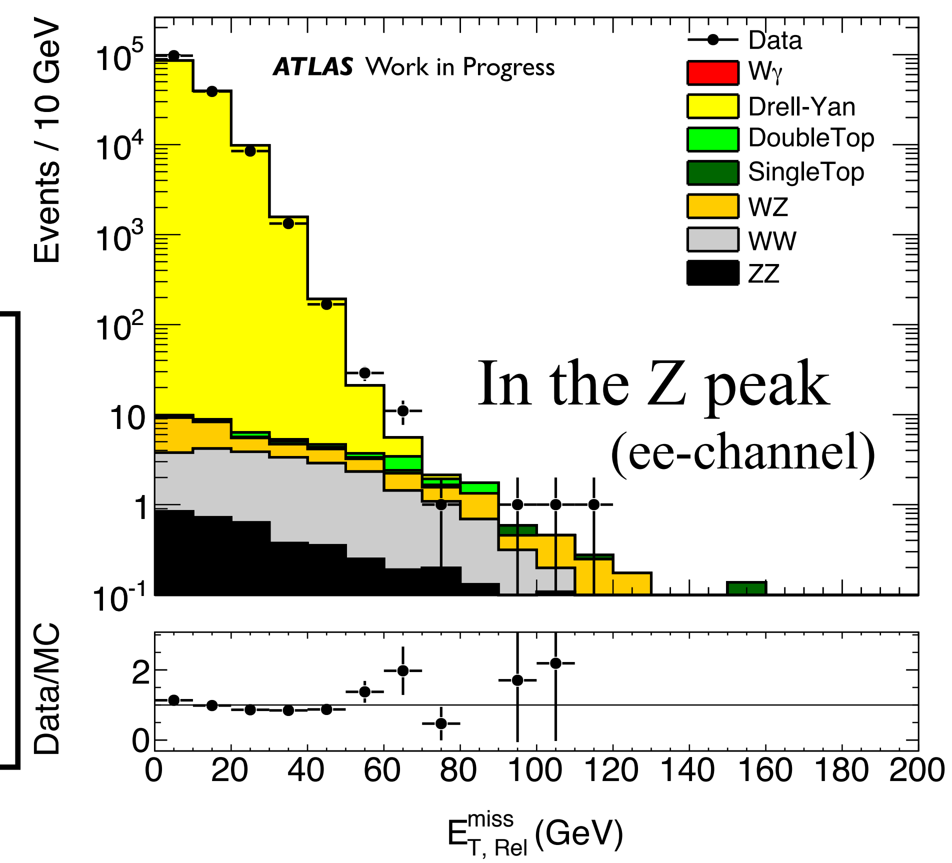


Causes of fake MeT not necessarily expected to be reproduced by MC.

Use Data Events in the Z peak:

Quantify modeling of MeT in DY Events with:

$$S(E_T^{miss,Rel}) = \frac{N_{Data} - N_{MC}}{N_{DY}}$$



Measurement:

Channel	*S*
ee	0.06 ± 0.08
mm	0.05 ± 0.10

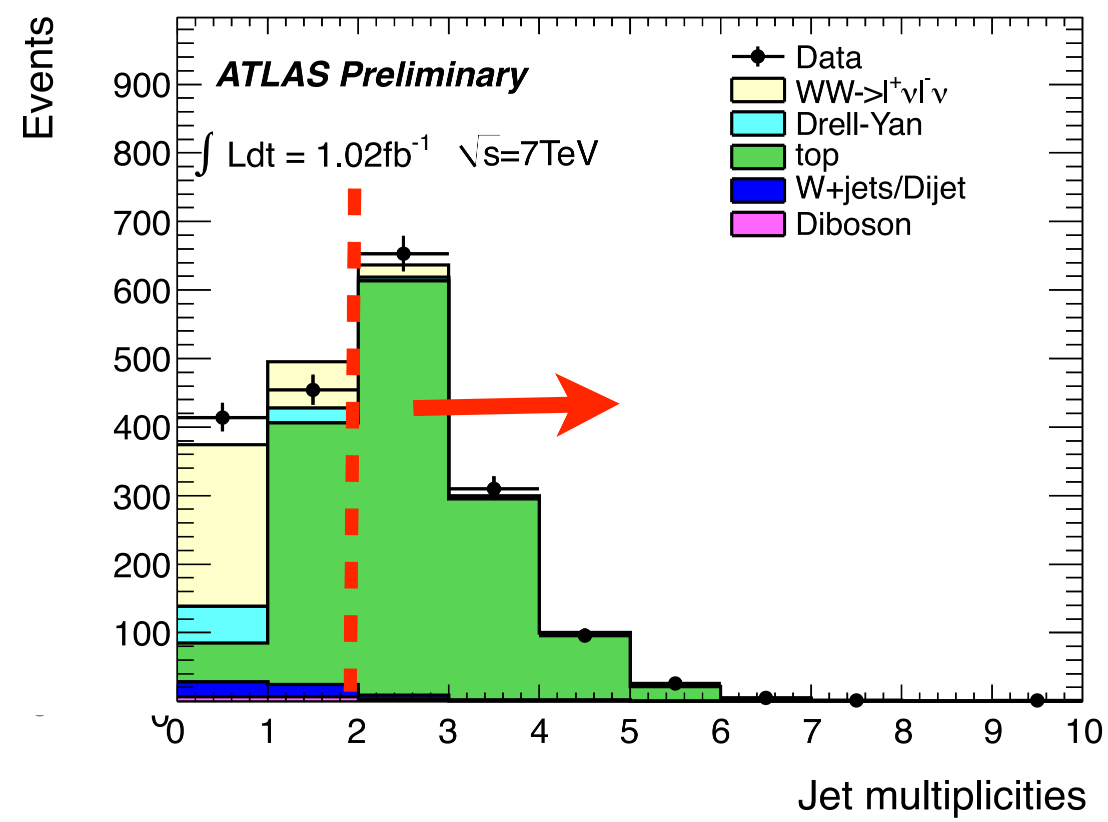
- Given Data/MC consistency do not correct prediction.
- *S* to assign systematic.

Top Background

Background from Top from lost Jets

Use Top control region in data

$$N^{\text{Bkg}}_{\text{Top}}(\text{0-jet}) = N^{\text{Data-CR}}_{\text{Top}} \times \frac{N^{\text{MC}}_{\text{Top}}(\text{0-jet})}{N^{\text{MC-CR}}_{\text{Top}}}$$



Reduce systematics by applying SF measured in Tag sample.

$$N^{\text{Bkg}}_{\text{Top}}(\text{0-jet}) = N^{Data}_{\text{Top}} \times \text{SF} \times \frac{N^{\text{MC}}_{\text{Top}}(\text{0-jet})}{N^{\text{MC}}_{\text{Top}}}$$

SF - scale factor from tag sample

Leads to cancelation of some of the JES uncertainty in jet-veto .
~20 % systematic vs ~40 % without SF.

Fake Factor Method

Observed Lepton-Denm. pairs passing event selection.

$$N_{\rm Bkg}^{\rm W+Jet} = f \times N_{\rm (Lepton+Denm)}$$

Measured in a di-jet sample

1) Define Denominator Definition
2) Measure f and its uncertainty in di-jet control sample
3) Select (Lepton-Denm.) pairs passing the Event selection
4) Subtract non-W+jet contribution to (Lep-Denm) pairs, with MC
5) Scale by f to predict W+jet event yields / kinematics.

WW Cross Section Results

Background Process	$e\mu$-channel	ee-channel	$\mu\mu$-channel
DY	$13.0 \pm 2.1 \pm 1.6$	$12.5 \pm 2.3 \pm 1.4$	$10.9 \pm 2.5 \pm 1.4$
Top	$11.9 \pm 1.8 \pm 2.4$	$3.1 \pm 0.5 \pm 0.6$	$3.8 \pm 0.6 \pm 0.8$
W+jet	$10.0 \pm 1.6 \pm 2.1$	$4.1 \pm 1.3 \pm 0.9$	$4.2 \pm 1.1 \pm 1.3$
Di-boson	$5.1 \pm 1.0 \pm 0.7$	$2.1 \pm 0.8 \pm 0.3$	$2.9 \pm 0.4 \pm 0.4$
Total background	$40.0 \pm 3.3 \pm 3.6$	$21.7 \pm 2.8 \pm 1.8$	$21.8 \pm 2.8 \pm 2.1$
(Data Yields)	(202)	(59)	(64)

$$\sigma(pp \to WW) = 54.4 \pm 4.0(\text{stat}) \pm 3.9(\text{syst}) \pm 2.0(\text{lumi}) \text{ pb},$$

NLO SM prediction of $\sigma(pp \to WW) = 44.4 \pm 2.8$ pb.

Source	**Uncertainty**
Luminosity	3.7%
Background	9.6%
Acceptance	7.4%
Systematic	**13.1%**
Statistical	**8.3%**

Hww Cut Flows

2011

0-jet	Signal	WW	Di-boson	$t\bar{t}$	Single Top	Z/γ^*	$W+$jets	Total Bkg.	Obs.
Jet Veto	56.7 ± 0.2	1273 ± 79	97 ± 4	174 ± 12	95 ± 7	1039 ± 28	217 ± 4	2893 ± 115	2849
$m_{\ell\ell} < 50$ GeV	45.2 ± 0.2	312 ± 20	41 ± 3	29 ± 2	19 ± 2	168 ± 10	70 ± 2	639 ± 28	645
$p_{\mathrm{T}}^{\ell\ell}$ cut	40.1 ± 0.2	282 ± 18	35 ± 3	28 ± 2	18 ± 2	28 ± 6	49 ± 2	439 ± 26	443
$\Delta\phi_{\ell\ell} < 1.8$	39.0 ± 0.2	276 ± 17	33 ± 2	27 ± 2	18 ± 2	28 ± 6	44 ± 1	425 ± 26	429

1-Jet	Signal	WW	Di-boson	$t\bar{t}$	Single Top	Z/γ^*	$W+$jets	Total Bkg.	Obs.
1 jet	22.7 ± 0.1	343 ± 54	56 ± 3	1438 ± 60	436 ± 19	357 ± 17	85 ± 3	2715 ± 142	2706
b-jet veto	20.9 ± 0.1	319 ± 50	52 ± 3	412 ± 18	139 ± 7	332 ± 16	76 ± 3	1330 ± 84	1369
$\lvert\mathbf{p}_{\mathrm{T}}^{tot}\rvert < 30$ GeV	14.0 ± 0.1	226 ± 35	34 ± 2	181 ± 8	80 ± 4	108 ± 8	37 ± 2	666 ± 51	684
$Z \to \tau\tau$ veto	14.0 ± 0.1	220 ± 34	34 ± 2	173 ± 8	77 ± 4	85 ± 7	37 ± 2	627 ± 50	644
$m_{\ell\ell} < 50$ GeV	10.9 ± 0.1	49 ± 8	14 ± 2	33 ± 2	18 ± 1	24 ± 3	12 ± 1	148 ± 12	170
$\Delta\phi_{\ell\ell} < 1.8$	10.1 ± 0.1	44 ± 7	13 ± 2	31 ± 2	17 ± 1	10 ± 2	10 ± 1	126 ± 10	145

2012

0-jet	Signal	WW	Di-boson	$t\bar{t}$	Single Top	Z/γ^*	$W+$jets	Total Bkg.	Obs.
Jet Veto	47.5 ± 0.4	1308 ± 9	125 ± 4	184 ± 4	109 ± 6	850 ± 32	138 ± 4	2714 ± 34	2691
$p_{\mathrm{T}}^{\ell\ell} > 30$ GeV	43.4 ± 0.4	1077 ± 8	99 ± 4	165 ± 4	98 ± 5	47 ± 8	102 ± 2	1589 ± 14	1664
$m_{\ell\ell} < 50$ GeV	34.9 ± 0.4	244 ± 4	33 ± 2	28 ± 2	17 ± 2	5 ± 2	29 ± 1	356 ± 6	421
$\Delta\phi_{\ell\ell} < 1.8$	33.6 ± 0.4	234 ± 4	32 ± 2	27 ± 2	17 ± 2	4 ± 2	25 ± 1	339 ± 6	407

1-Jet	Signal	WW	Di-boson	$t\bar{t}$	Single Top	Z/γ^*	$W+$jets	Total Bkg.	Obs.
1 jet	24.9 ± 0.3	396 ± 5	74 ± 3	1652 ± 12	479 ± 12	283 ± 20	68 ± 3	2953 ± 27	2874
b-jet veto	21.1 ± 0.3	334 ± 4	56 ± 2	349 ± 6	115 ± 6	236 ± 18	53 ± 2	1144 ± 21	1115
$\lvert\mathbf{p}_{\mathrm{T}}^{tot}\rvert < 30$ GeV	12.2 ± 0.2	210 ± 3	30 ± 2	139 ± 4	63 ± 5	124 ± 14	23 ± 2	590 ± 15	611
$Z \to \tau\tau$ veto	12.2 ± 0.2	204 ± 3	29 ± 2	133 ± 3	61 ± 5	98 ± 12	23 ± 2	547 ± 14	580
$m_{\ell\ell} < 50$ GeV	9.2 ± 0.2	37 ± 1	10 ± 1	21 ± 1	12 ± 2	16 ± 5	8.0 ± 0.9	104 ± 6	122
$\Delta\phi_{\ell\ell} < 1.8$	8.6 ± 0.2	34 ± 1	9 ± 1	20 ± 1	11 ± 2	3 ± 2	6.4 ± 0.7	84 ± 4	106

Hww Systematics

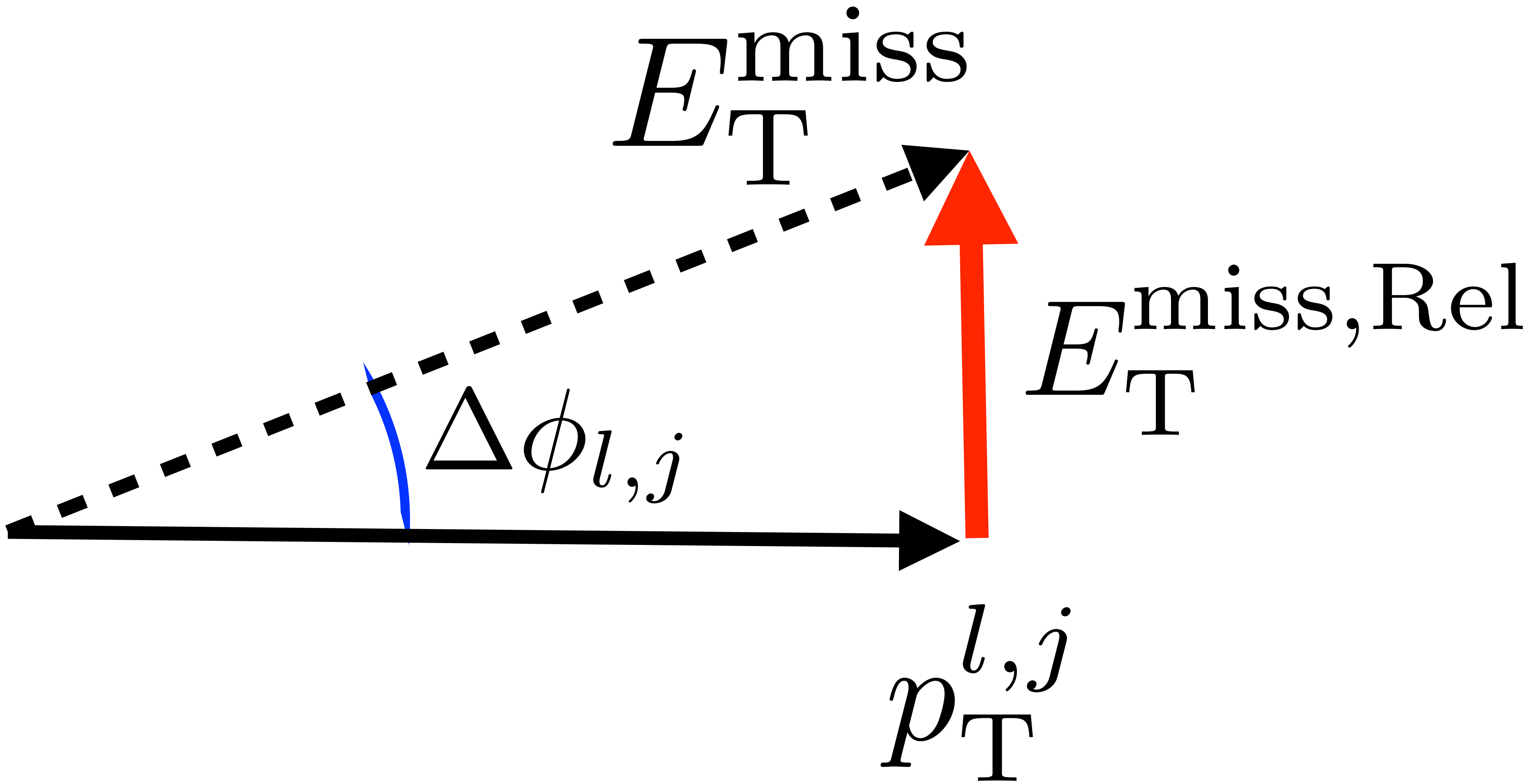
2011

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	19	-
1-jet incl. ggF signal ren./fact. scale	10	-
W+jets fake factor	-	10
Parton distribution functions	8	2
WW normalization	-	6
Jet energy scale	6	-
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	27	-
2-jet incl. ggF signal ren./fact. scale	15	-
E_T^{miss} modeling	8	3
W+jets fake factor	-	7
b-tagging efficiency	-	7
Parton distribution functions	7	1

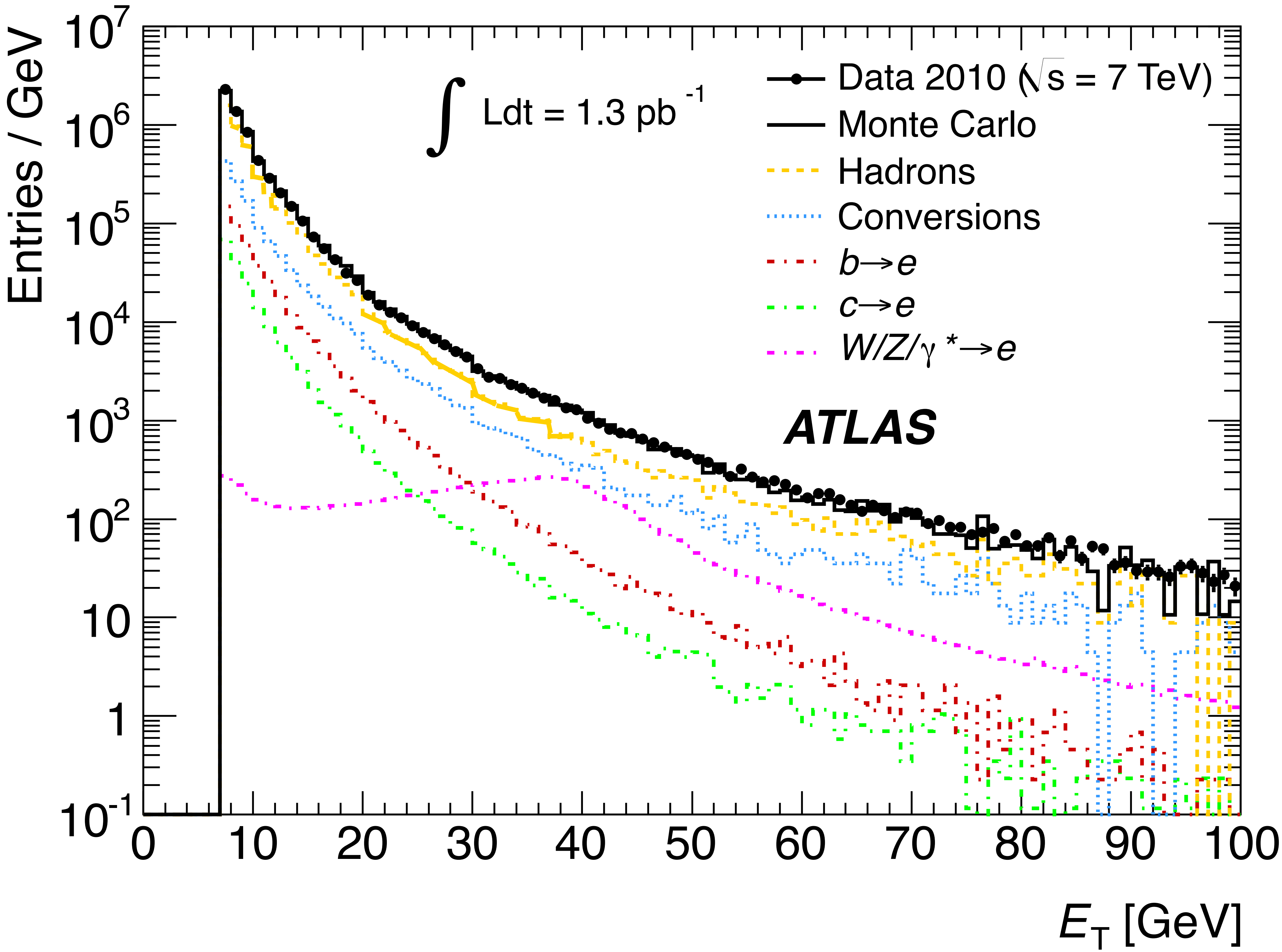
2012

Source (0-jet)	Signal (%)	Bkg. (%)
Inclusive ggF signal ren./fact. scale	13	-
1-jet incl. ggF signal ren./fact. scale	10	-
Parton distribution functions	8	2
Jet energy scale	7	4
WW normalization	-	7
WW modeling and shape	-	5
W+jets fake factor	-	5
QCD scale acceptance	4	2
Source (1-jet)	**Signal (%)**	**Bkg. (%)**
1-jet incl. ggF signal ren./fact. scale	28	-
WW normalization	-	25
2-jet incl. ggF signal ren./fact. scale	16	-
b-tagging efficiency	-	10
Parton distribution functions	7	1
W+jets fake factor	-	5

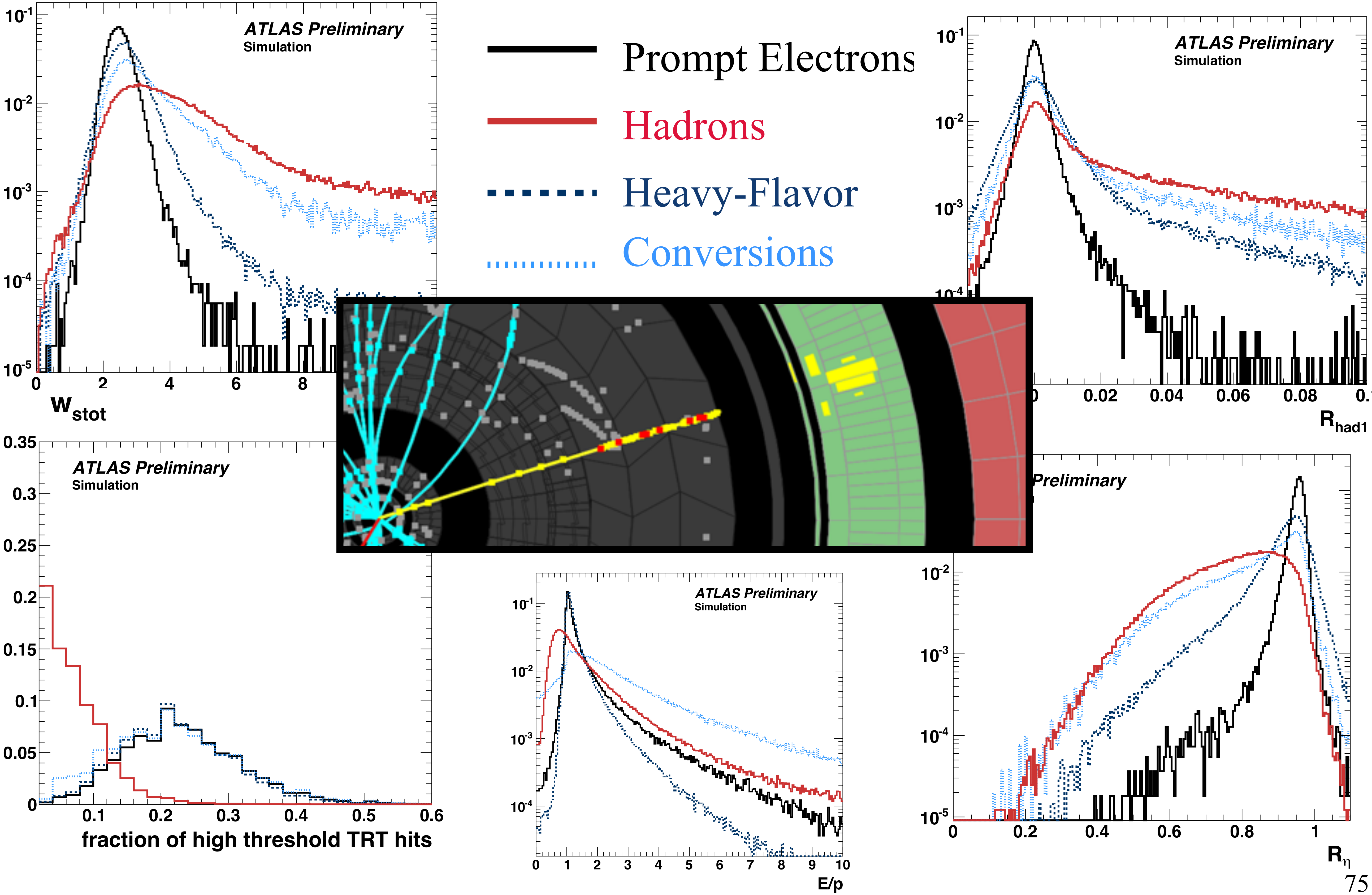
Relative Missing Energy



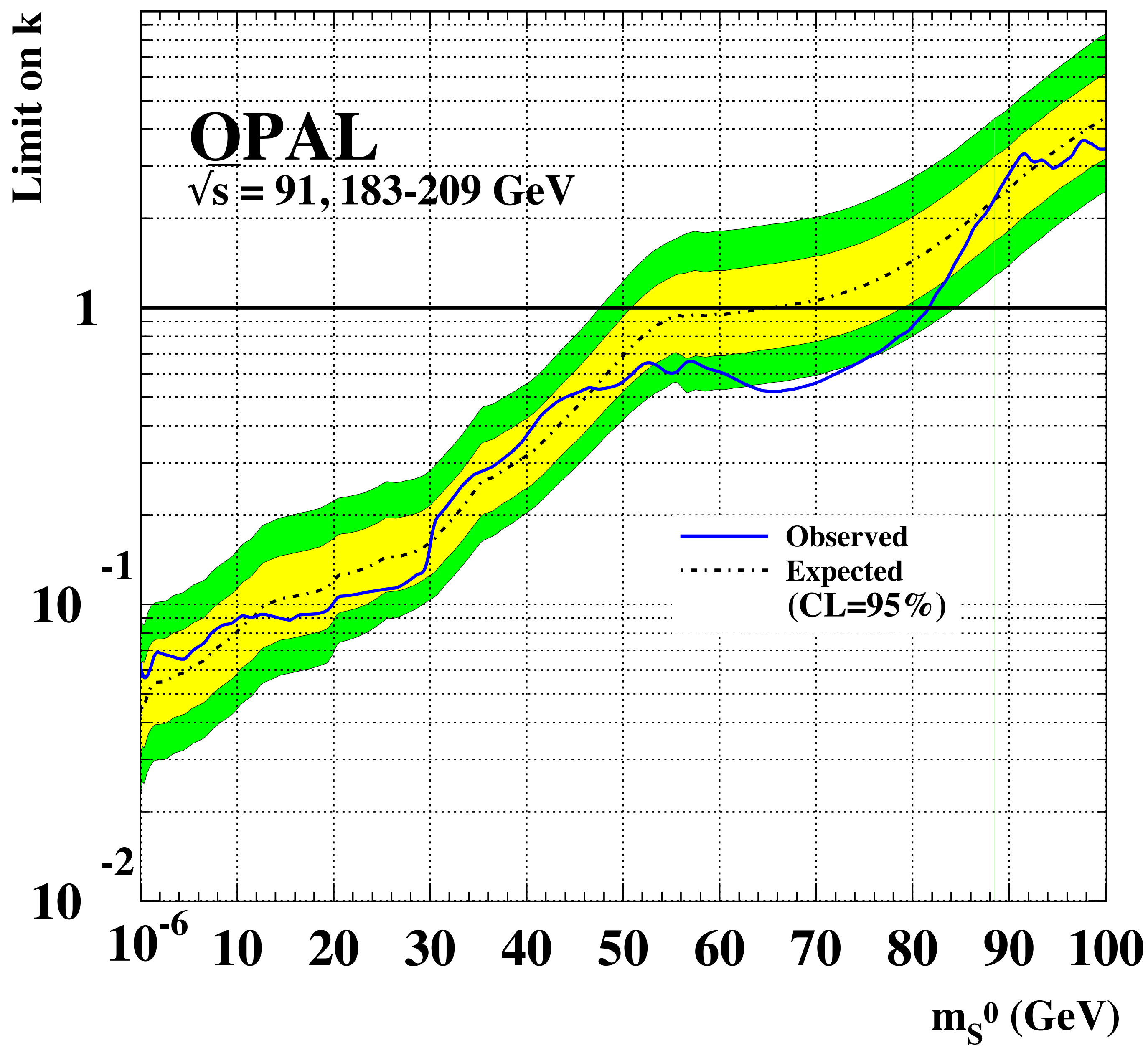
Electron Candidates in ATLAS



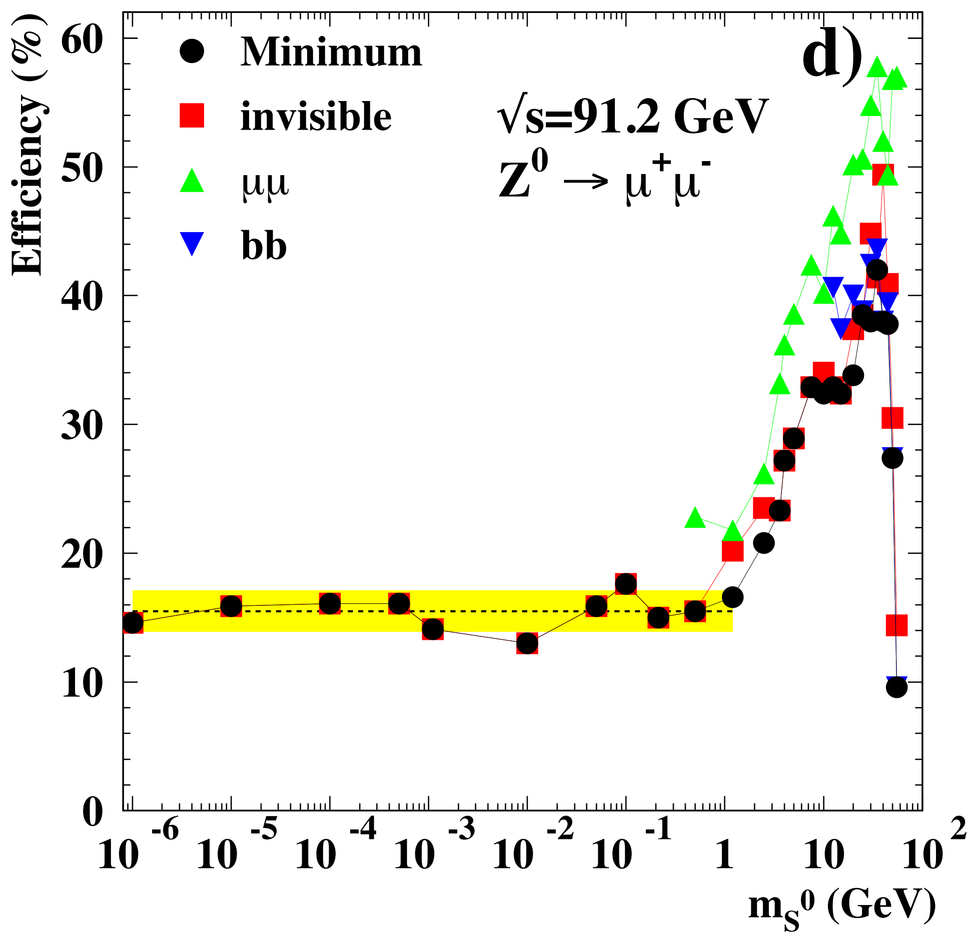
Electron Identification



Low Low Mass



Limit on k
OPAL
√s = 91, 183-209 GeV
Observed
Expected
(CL=95%)
1
10 -1
10 -2
10-6
10
20
30
40
50
60
70
80
90
100
mS0 (GeV)



Efficiency (%)
Minimum
invisible
μμ
bb
d)
√s=91.2 GeV
Z0 → μ+μ-
0
10
20
30
40
50
60
10 -6
10 -5
10 -4
10 -3
10 -2
10 -1
1
10
10 2
mS0 (GeV)