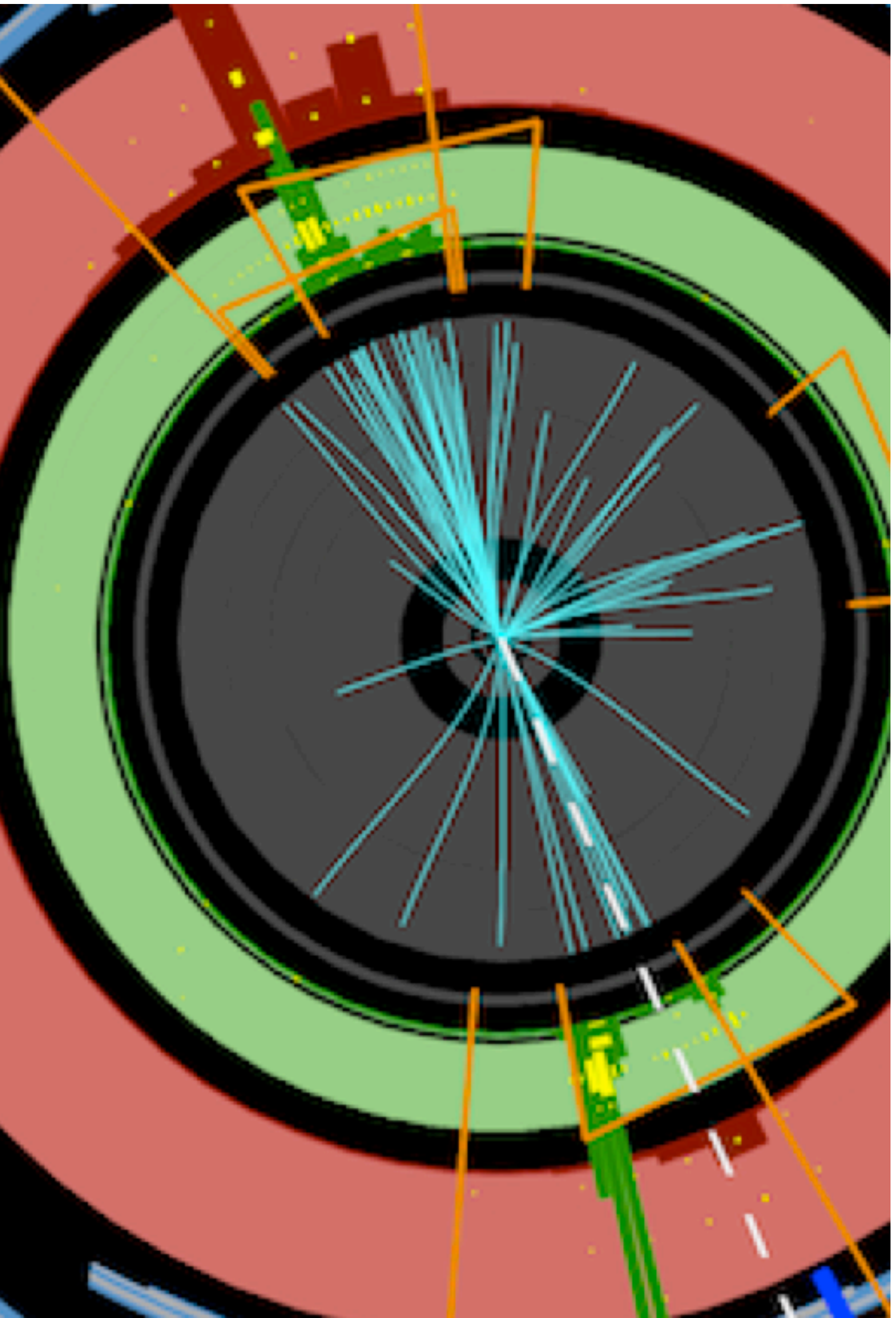
The Top Quark



Yes, it is Large.
But, is it Essential?

M. E. Peskin
October 2015

Quarks are known to be the constituents of all strongly-interacting particles, including the proton and neutron, the pions and kaons, and and the heavy D and B mesons.

It seems that life needs only 2 of these quarks, u and d.

However, in reality, there are 6.

The last, most elusive and mysterious, is the top quark.

light and heavy quarks

$$\begin{matrix} u & c & t \\ d & s & b \end{matrix}$$

light and heavy leptons

$$\begin{matrix} \nu_e & \nu_\mu & \nu_\tau \\ e & \mu & \tau \end{matrix}$$

and, for every particle, an antiparticle masses of the quarks and leptons, in GeV

e	0.00051	d	0.0048	u	0.0023
μ	0.106	s	0.095	c	1.28
τ	1.777	b	4.18	t	173.

What is the evidence that this heavy quark exists ?

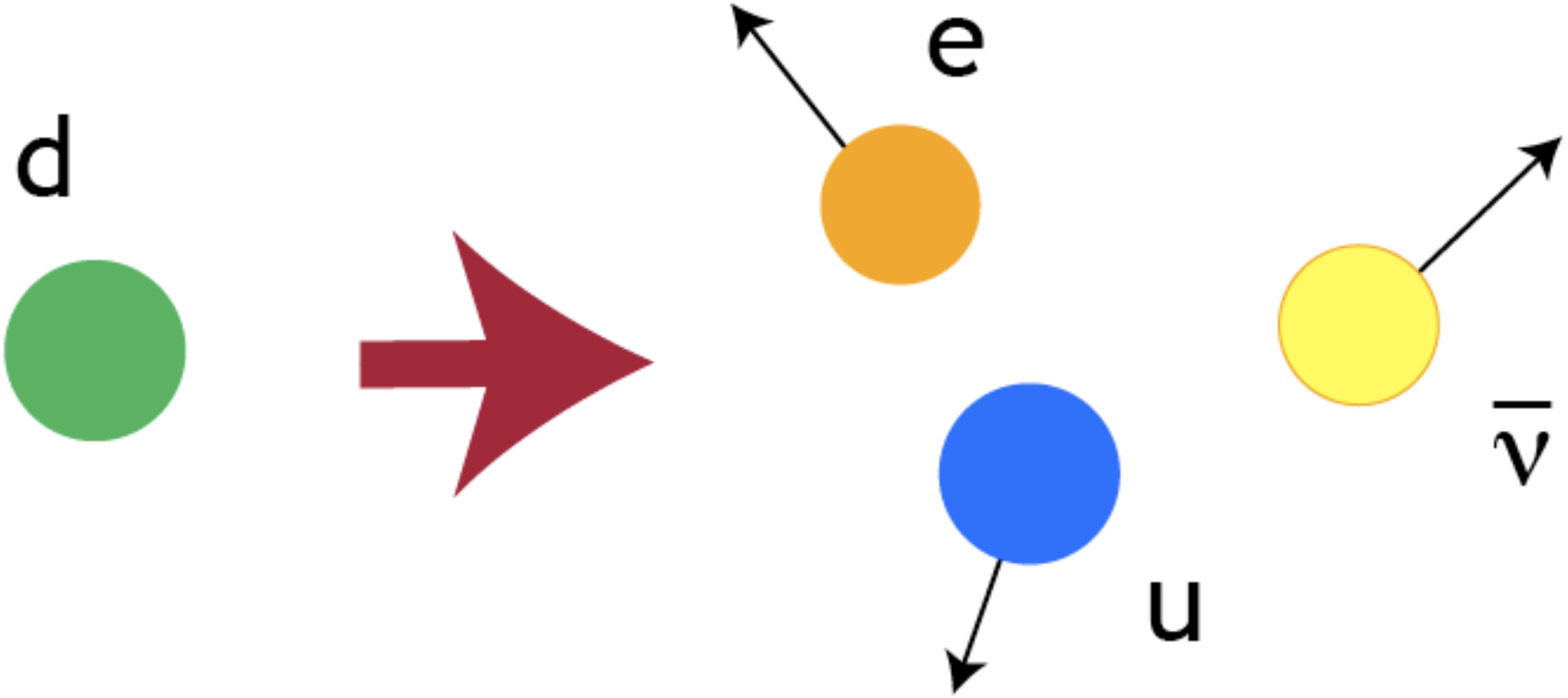
As I explain this, it will also become clear why particle physicists are so obsessed by this particle.

What does a quark look like in an experimental display ?

Except for u and d, all quarks are unstable with respect to decay through the weak interactions.

The weak interactions are mediated by the W boson, a particle with spin 1 and mass 80.4 GeV. In an ordinary weak interaction decay, the W boson is barely visible.

Fermi's famous theory of beta decay contracted its presence to an instant.

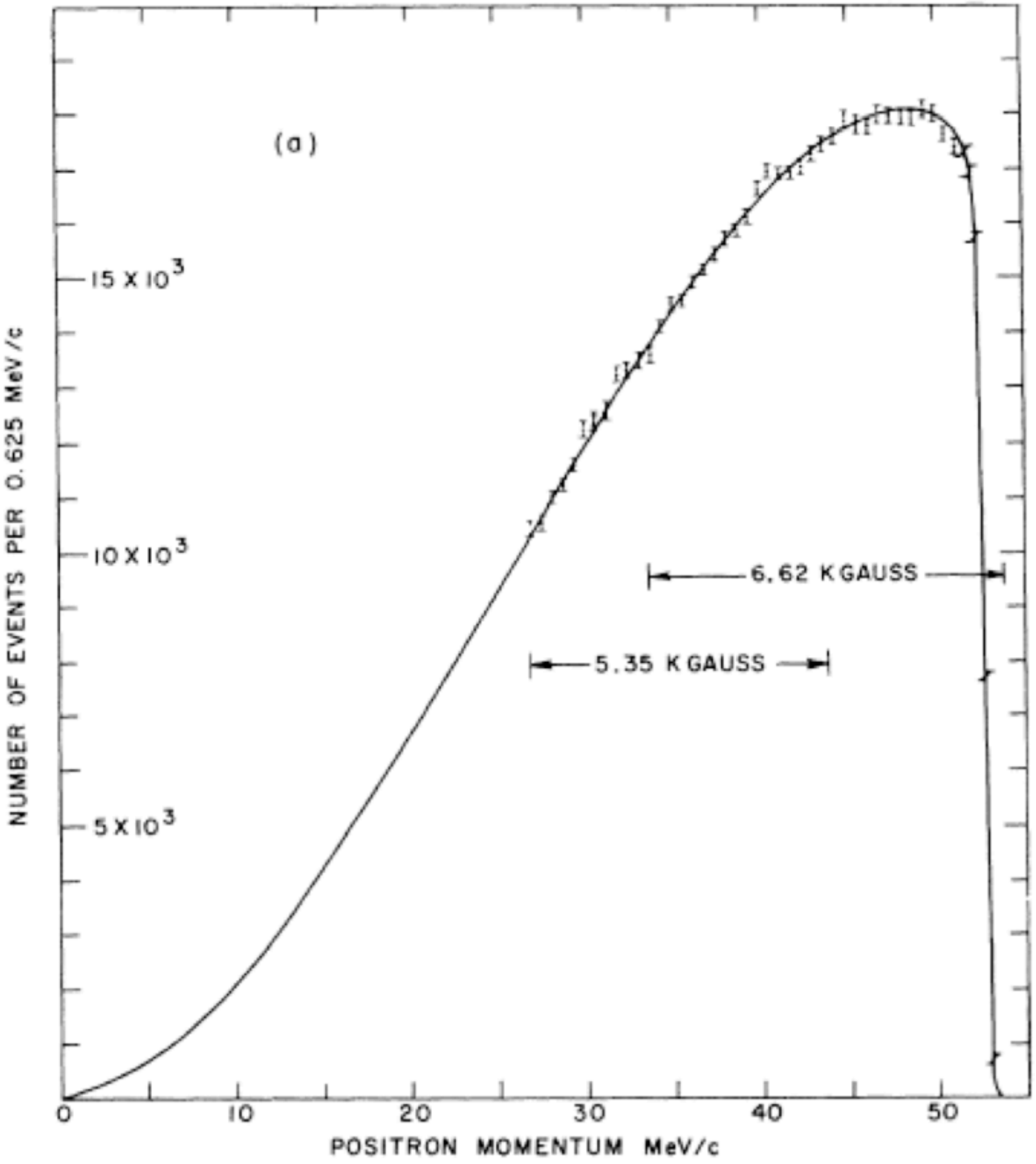

d
e
u
$\bar{\nu}$

In fact, no progress could be made in the theory of beta decay for another 25 years, until the discovery that the weak interactions violate parity.

Bruno Touschek

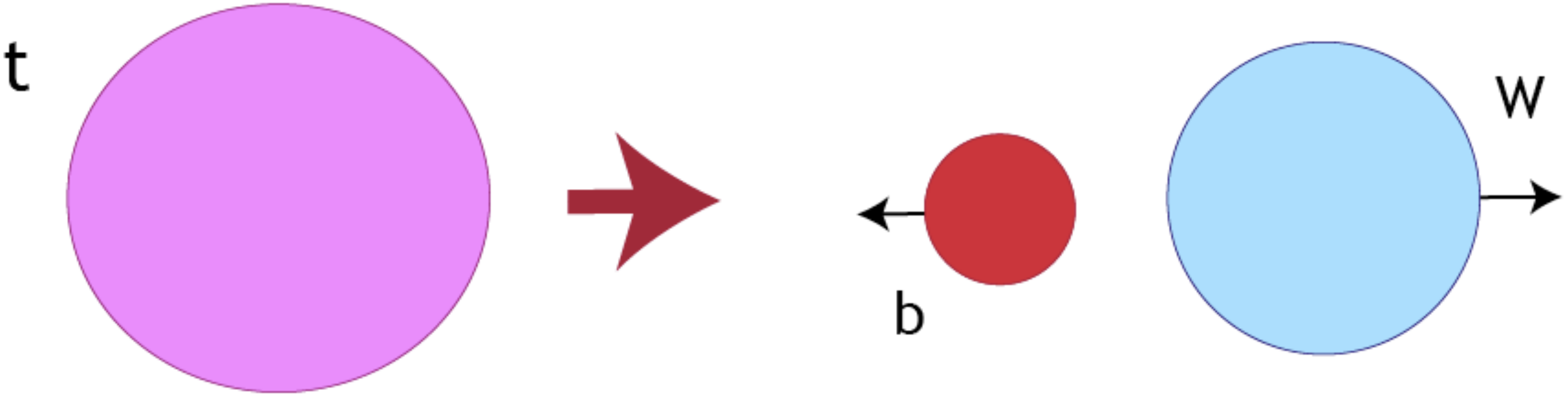
Bruno Touschek

electron energy spectrum in $\mu \to e\,\overline{\nu}_e\,\nu_\mu$

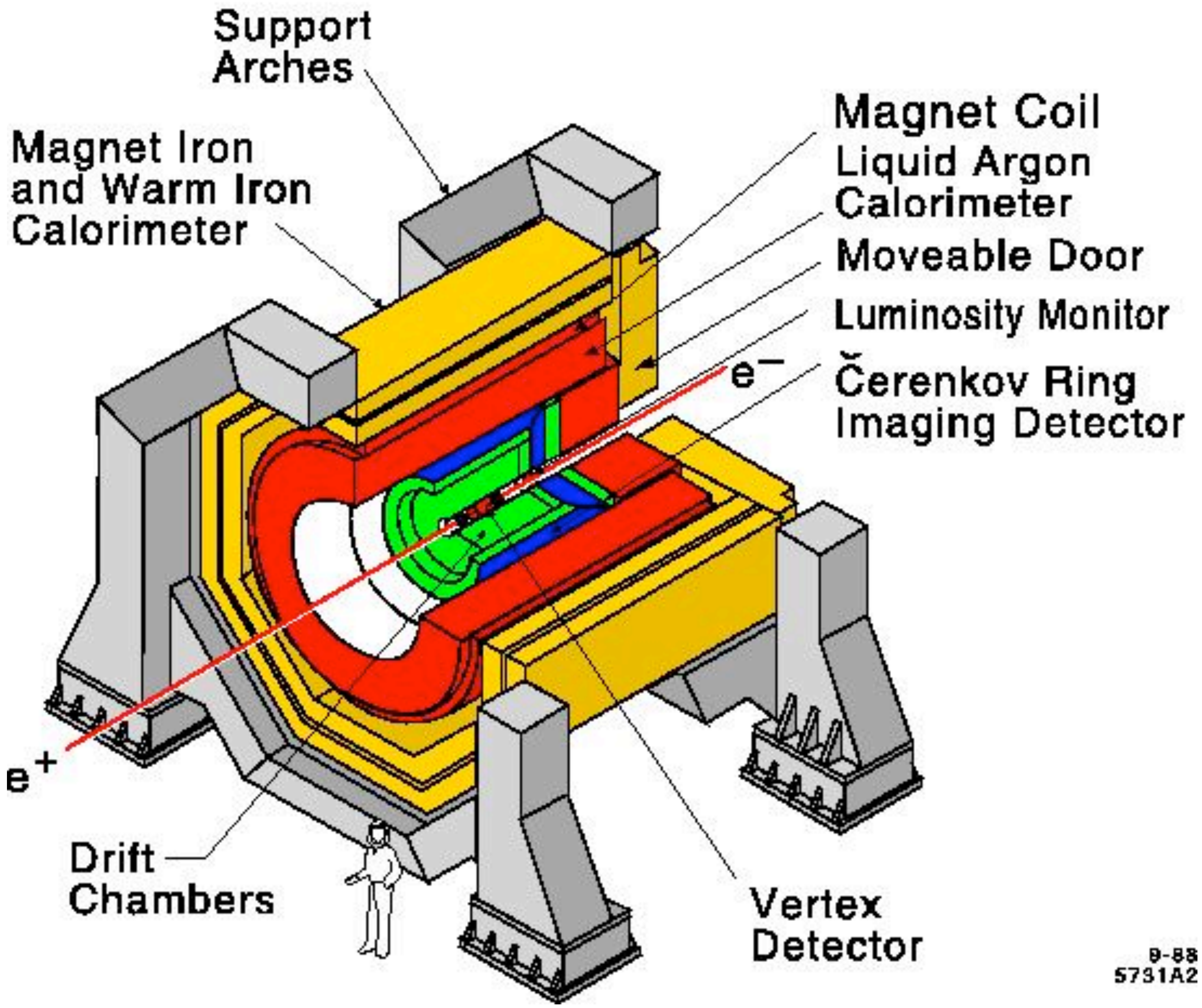


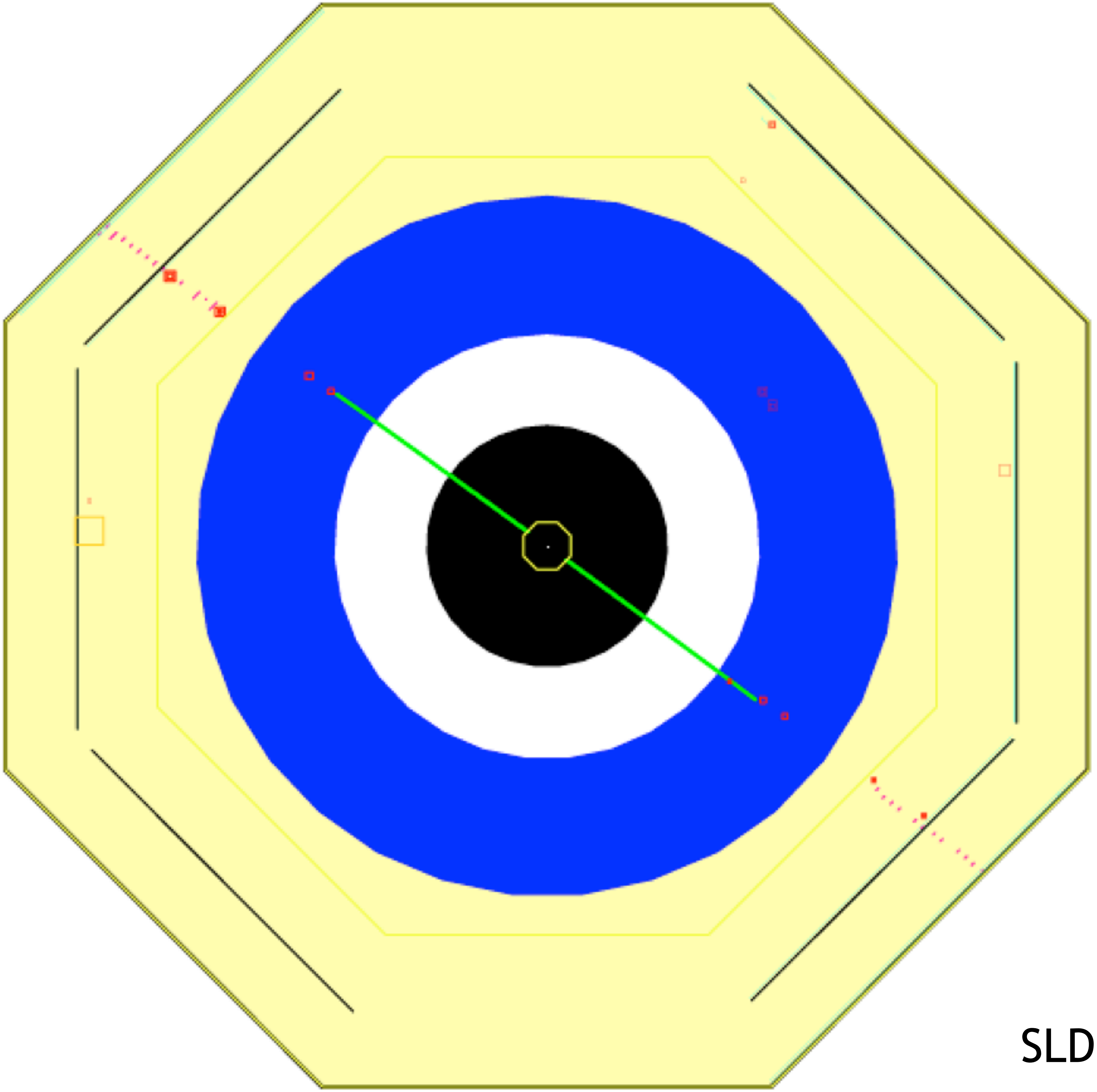
M.Bardon, et al.

The top quark, if it is as heavy as I say, defies these expectations. It is sufficiently heavy that it can decay to a physical W boson, which is then directly visible.

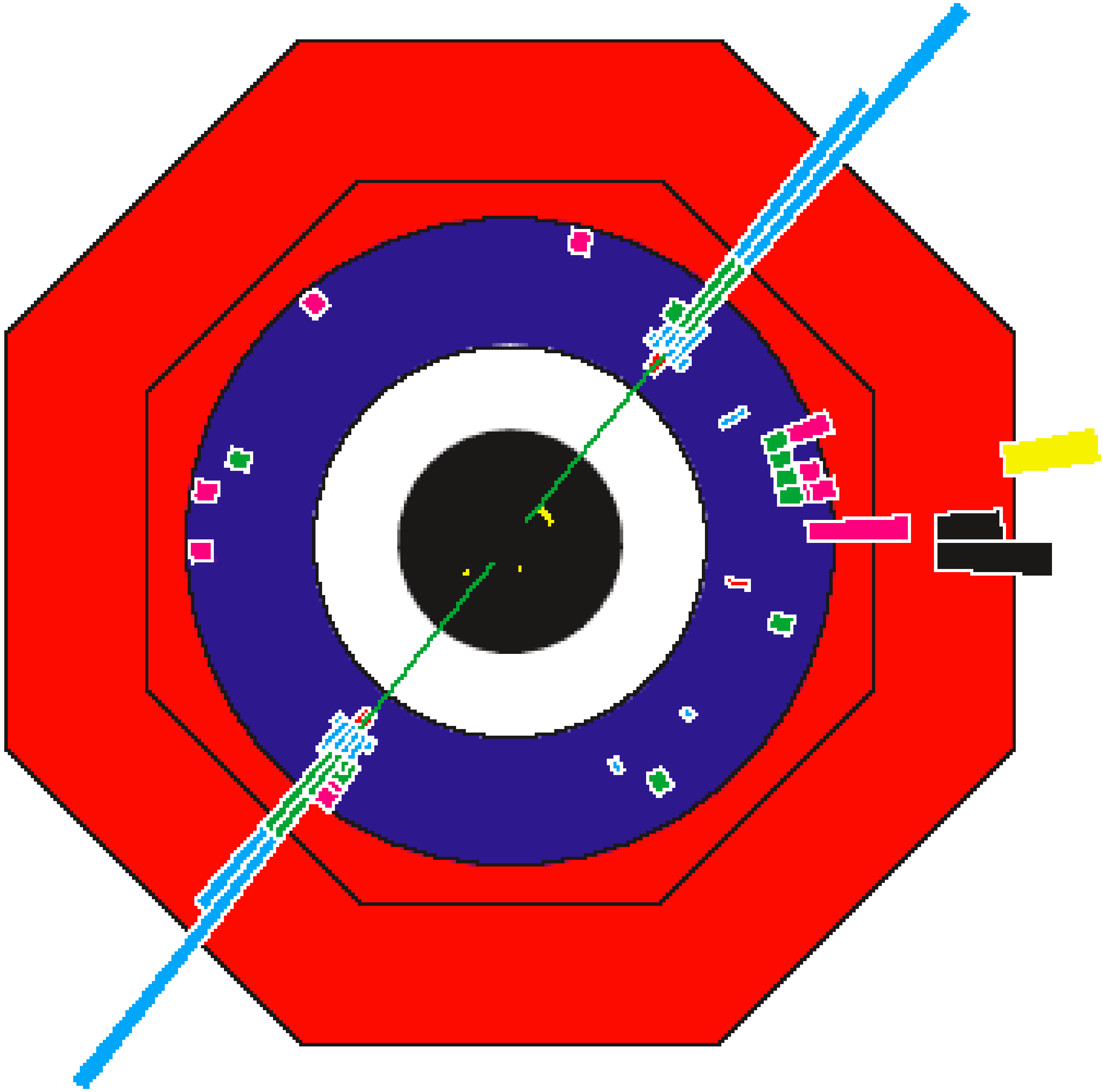


SLD

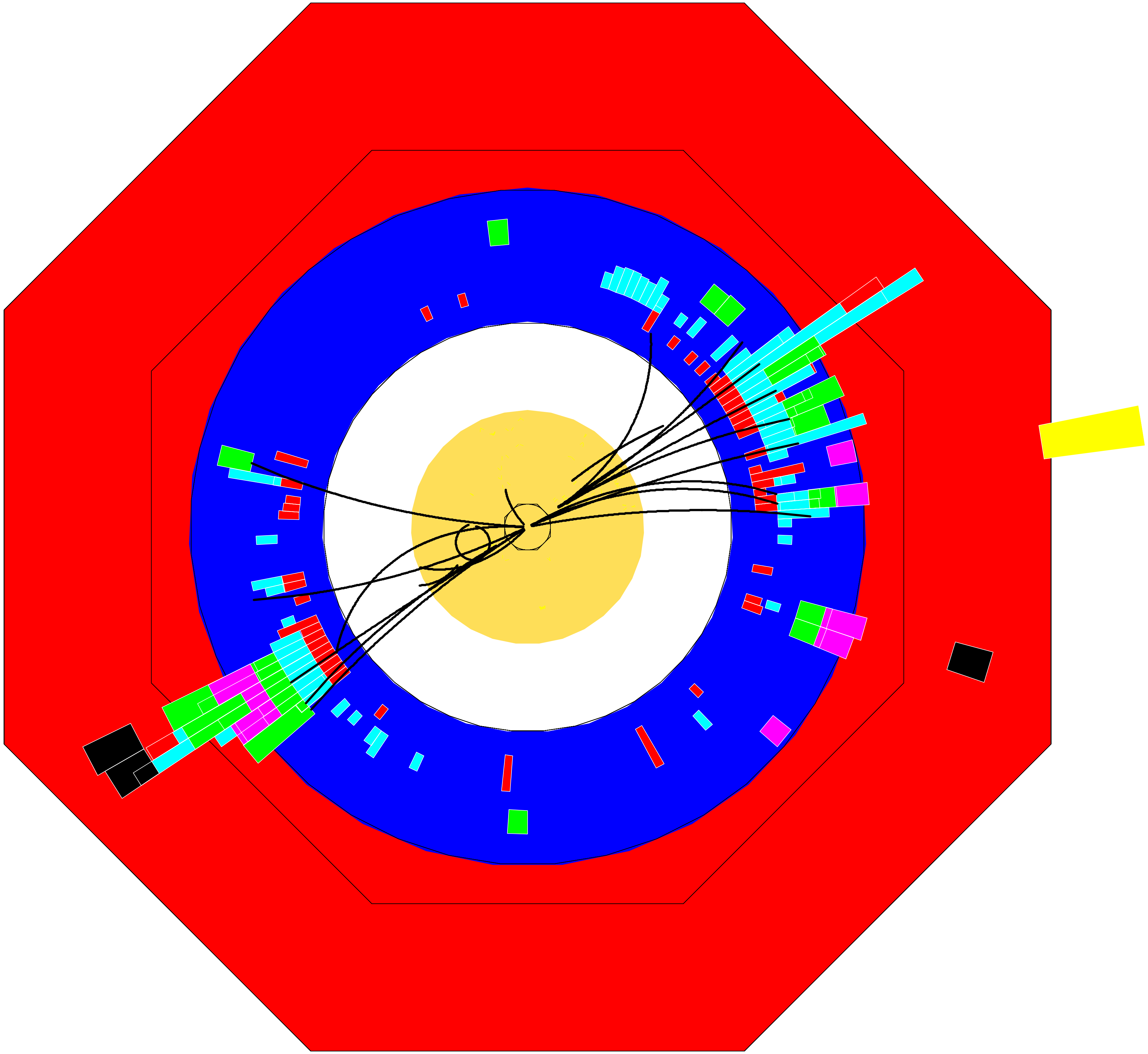

Support Arches
Magnet Iron and Warm Iron Calorimeter
Magnet Coil
Liquid Argon Calorimeter
Moveable Door
Luminosity Monitor
Čerenkov Ring Imaging Detector
e^-
e^+
Drift Chambers
Vertex Detector
9-88
5731A2



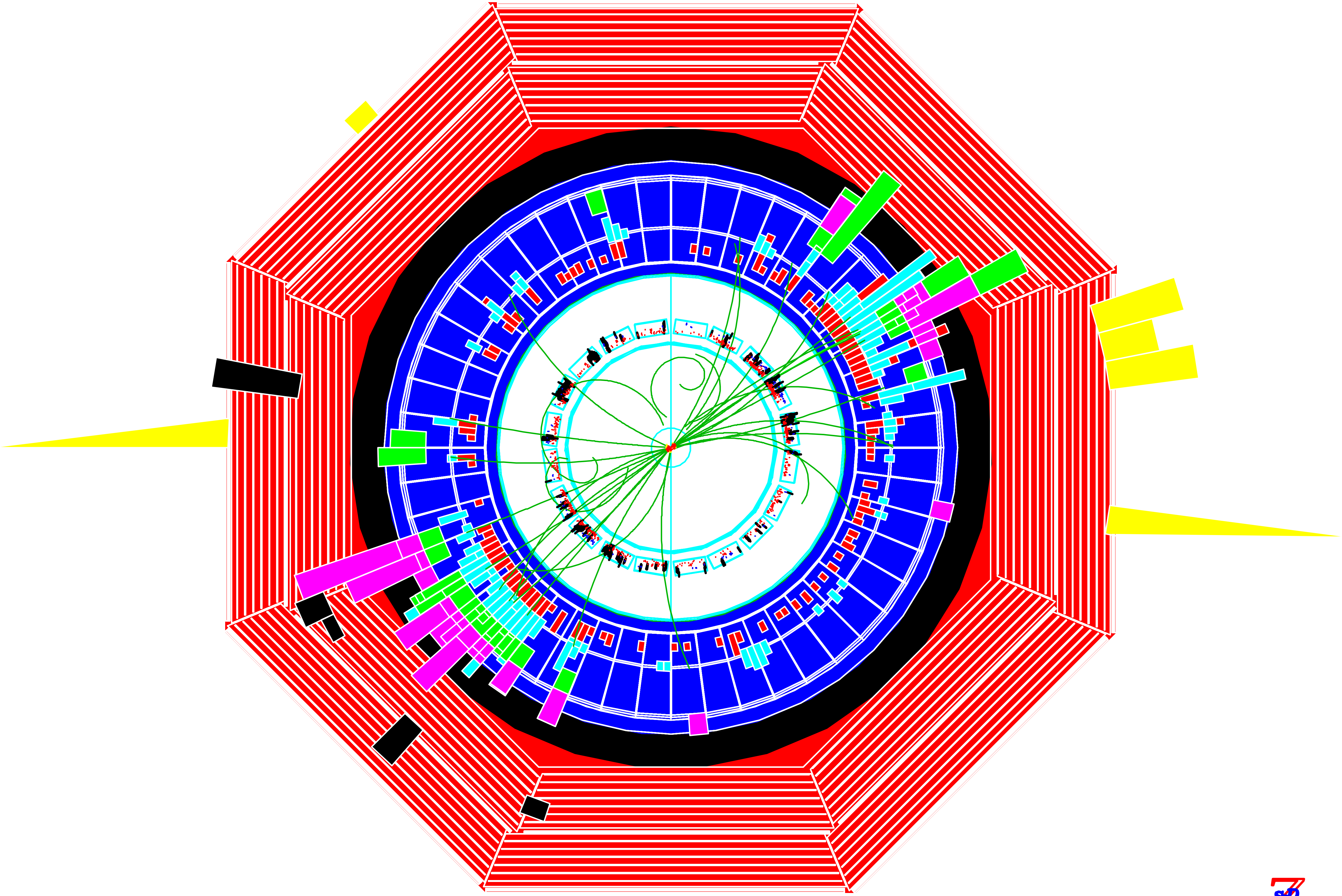
SLD



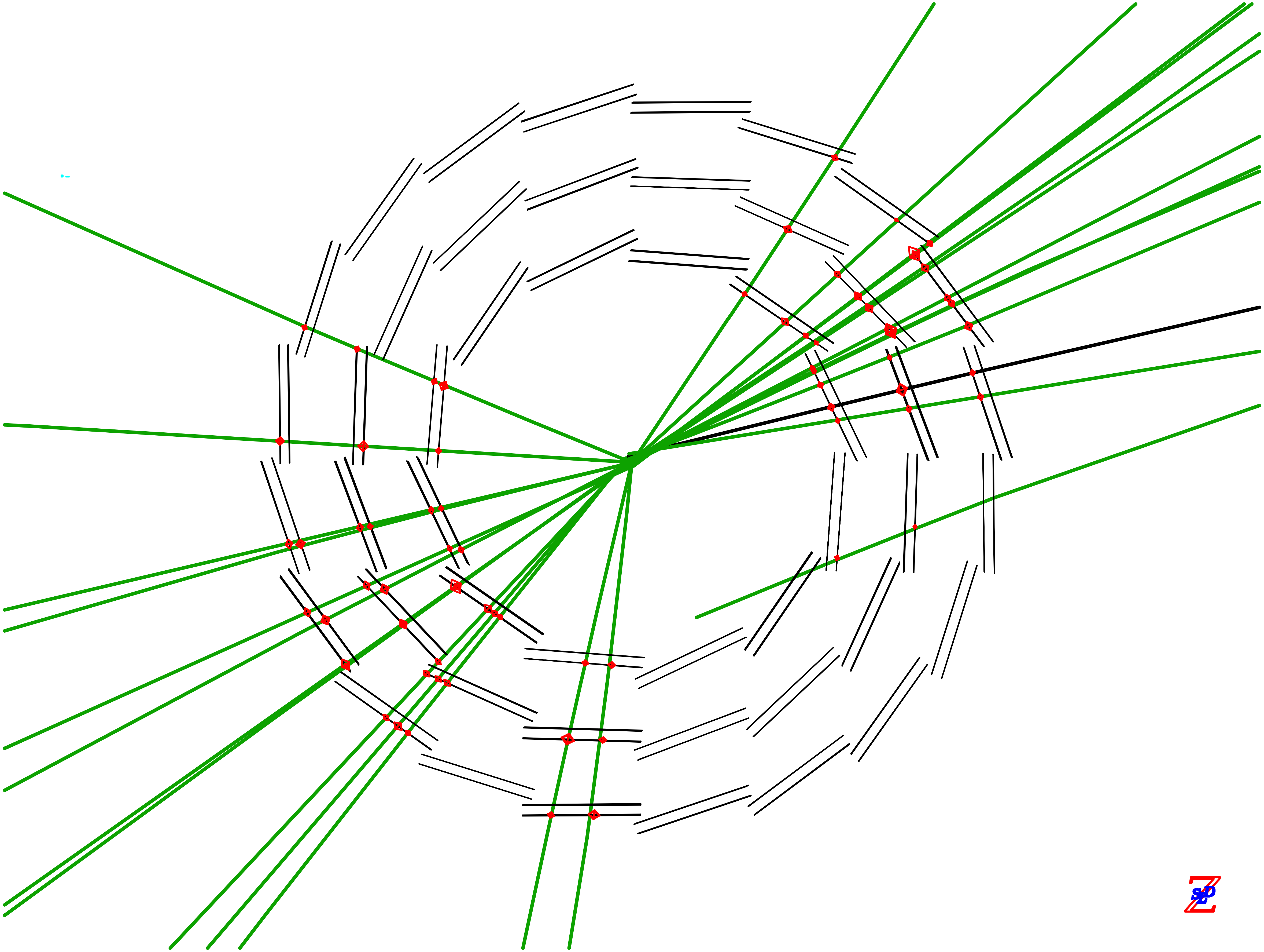
SLD

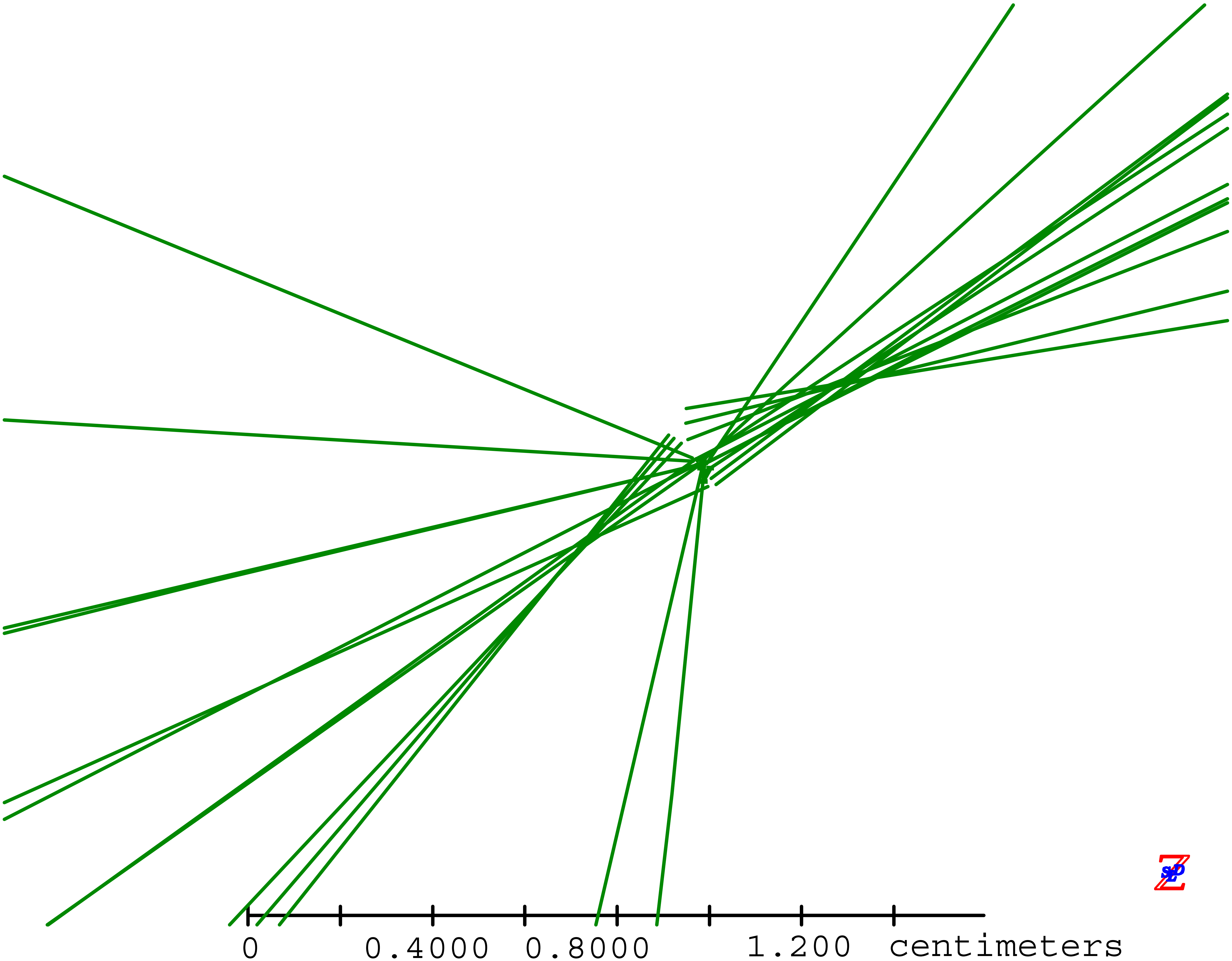


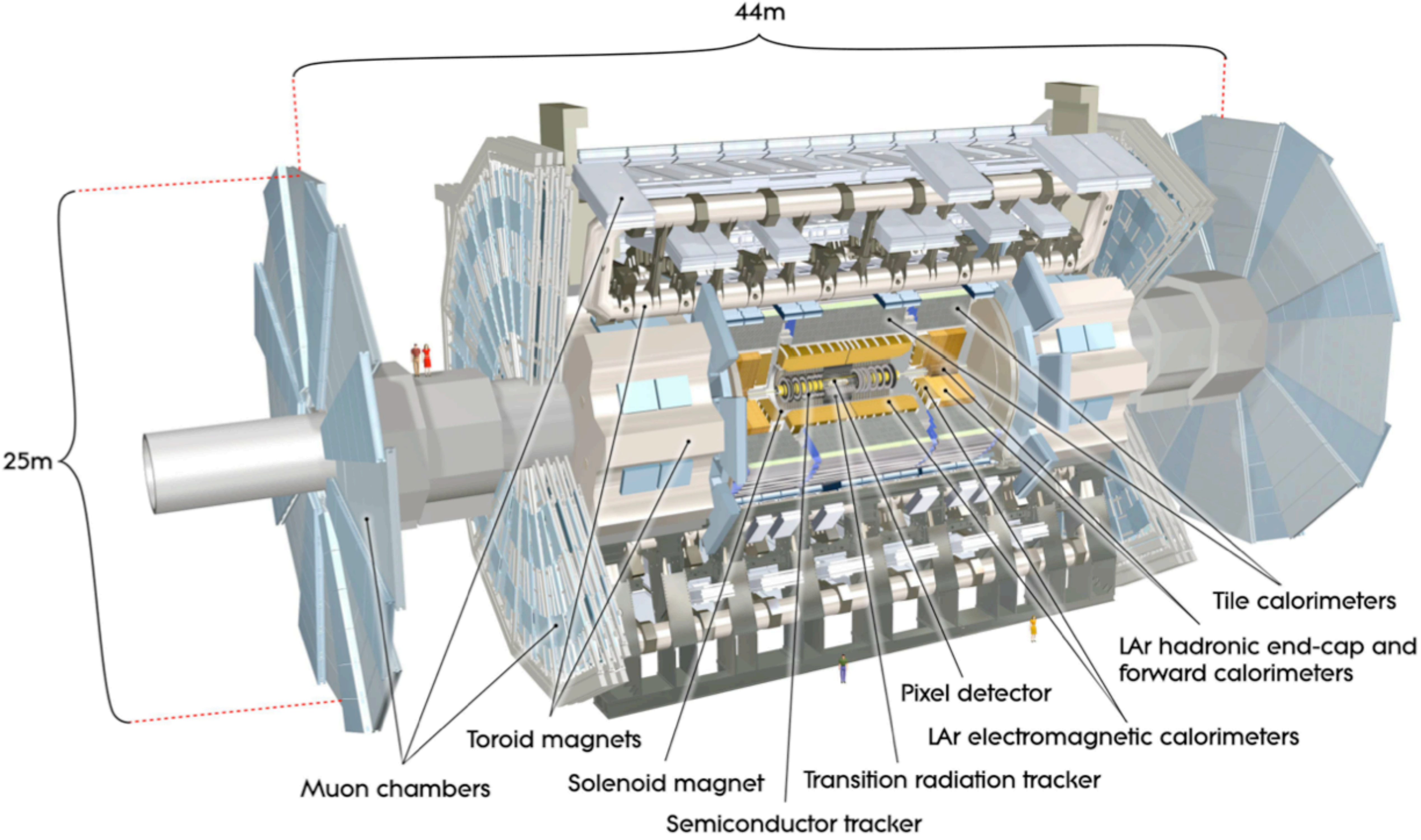
SLD

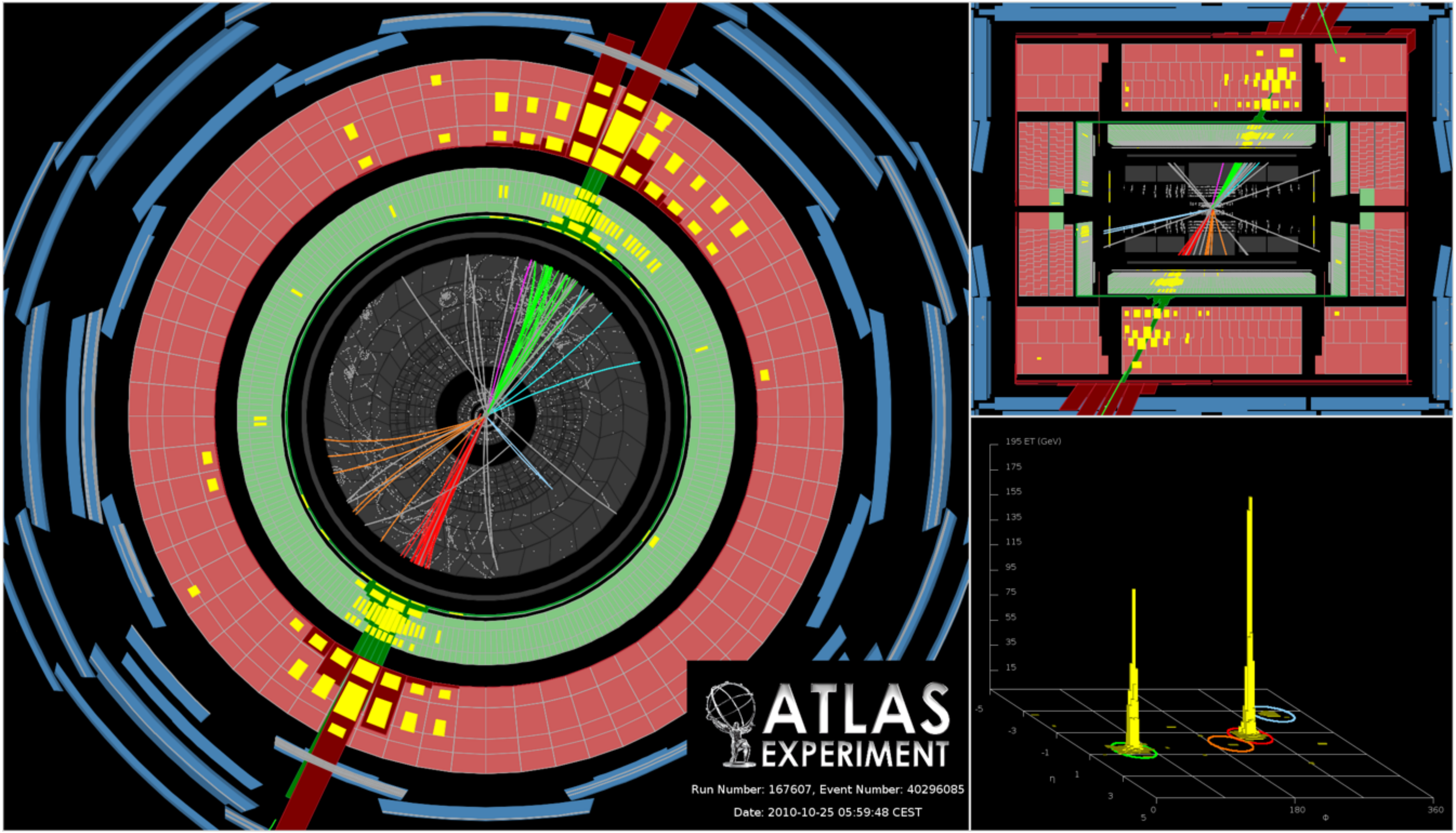


SLD




0
0.4000
0.8000
1.200
centimeters

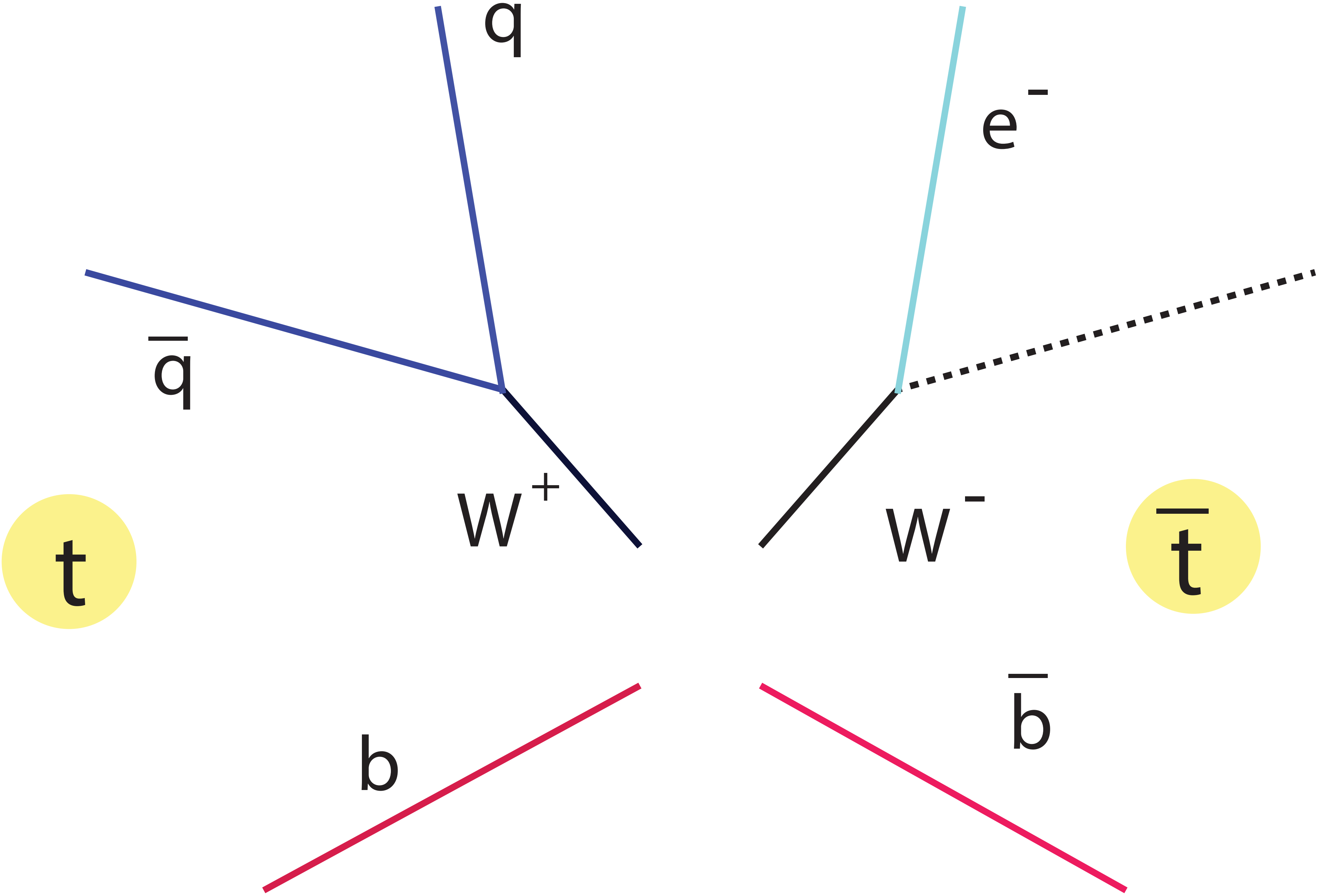

44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker


ATLAS
EXPERIMENT
Run Number: 167607, Event Number: 40296085
Date: 2010-10-25 05:59:48 CEST
195 ET (GeV)
175
155
135
115
95
75
55
35
15
-5
-3
-1
1
3
5
η
0
180
360
Φ

top ⇨ b + W

⇨ b + q + $\bar{q}$

⇨ b + e + $\bar{\nu}$


q
$\bar{q}$
W^+
t
b
e^-
W^-
$\bar{t}$
$\bar{b}$

Significant samples of the various types of top quark events were first discovered by the CDF and DO experiments at the Fermilab Tevatron in 1995,

20 years ago.

e + 4 jet event

40758_44414

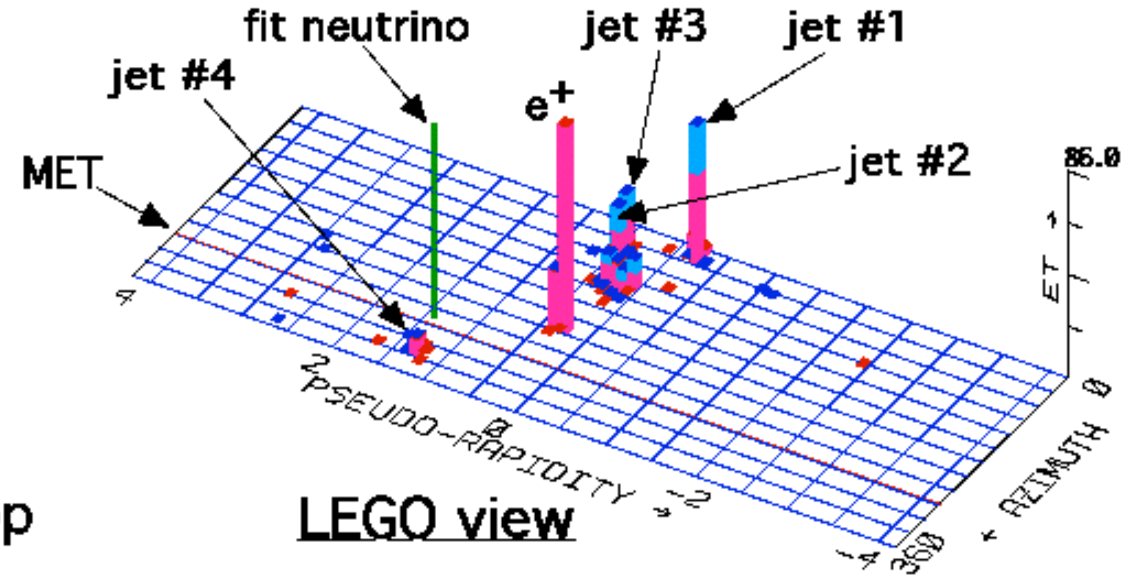
24-September, 1992

TWO jets tagged by SVX

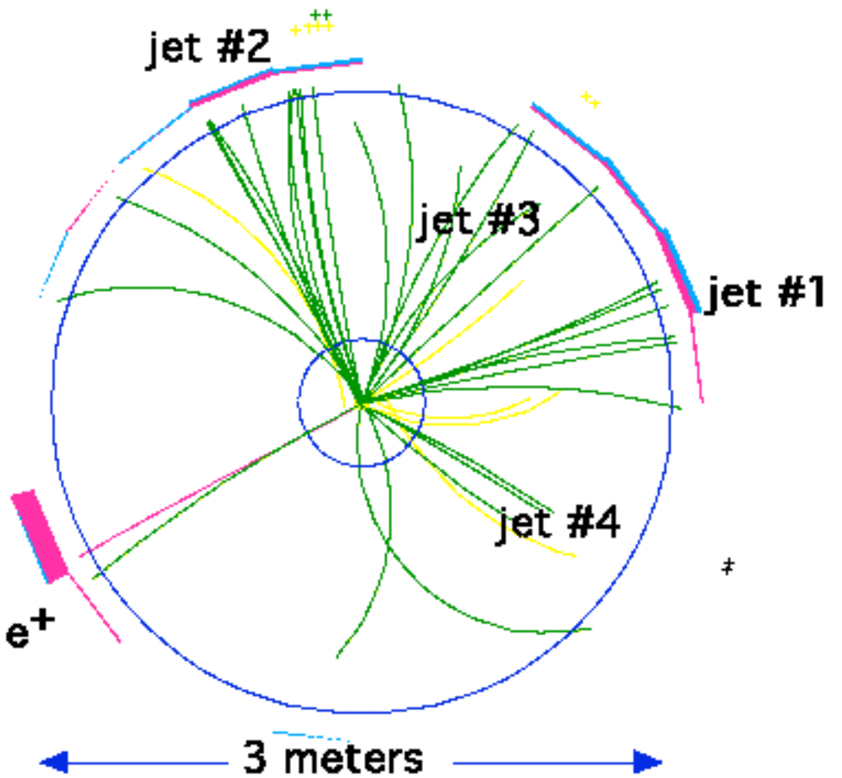
fit top mass is 170 +- 10 GeV

e^+, Missing E_t, jet #4 from top

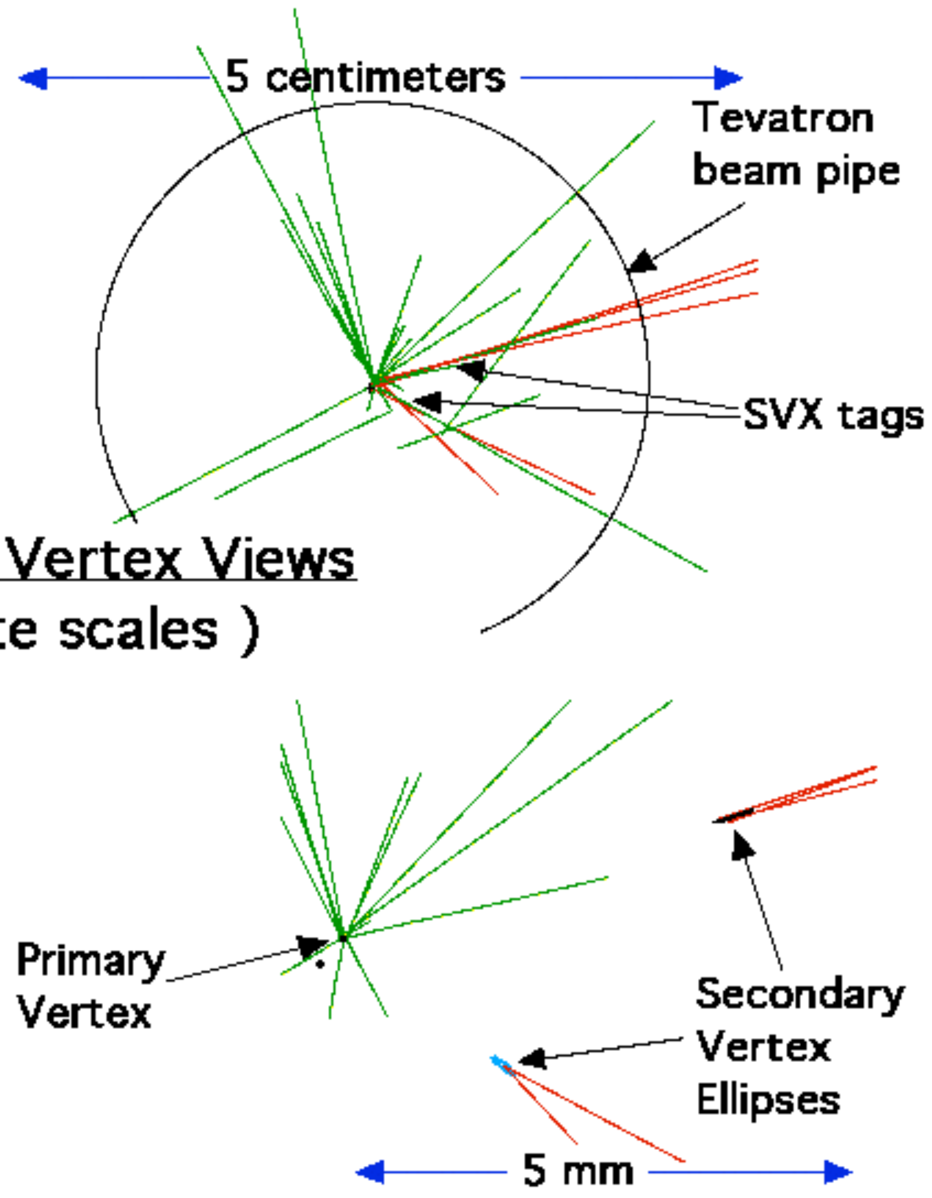
jets 1,2,3 from top (2&3 from W)



LEGO view



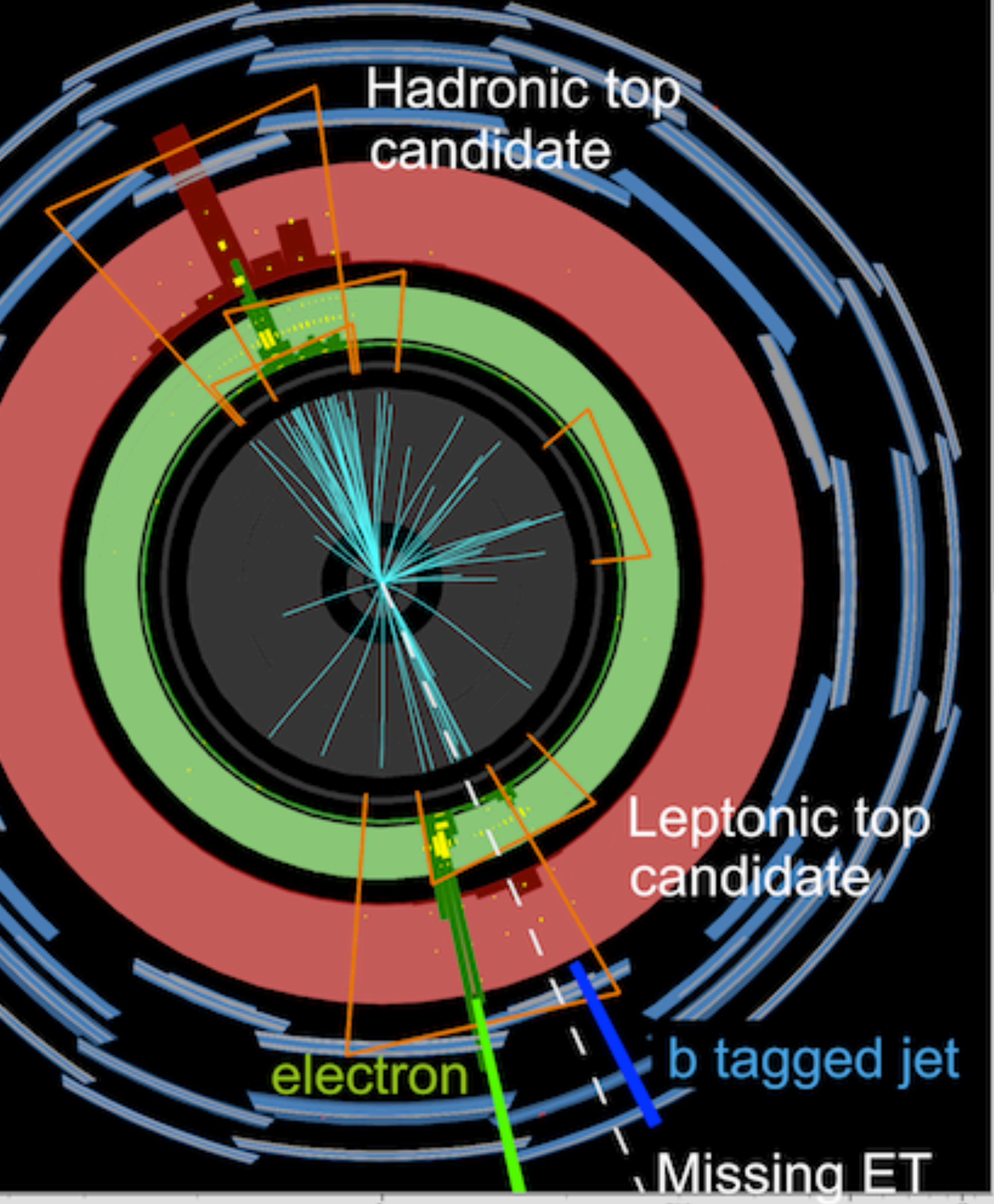
Tracking View



Two Vertex Views

(note scales)

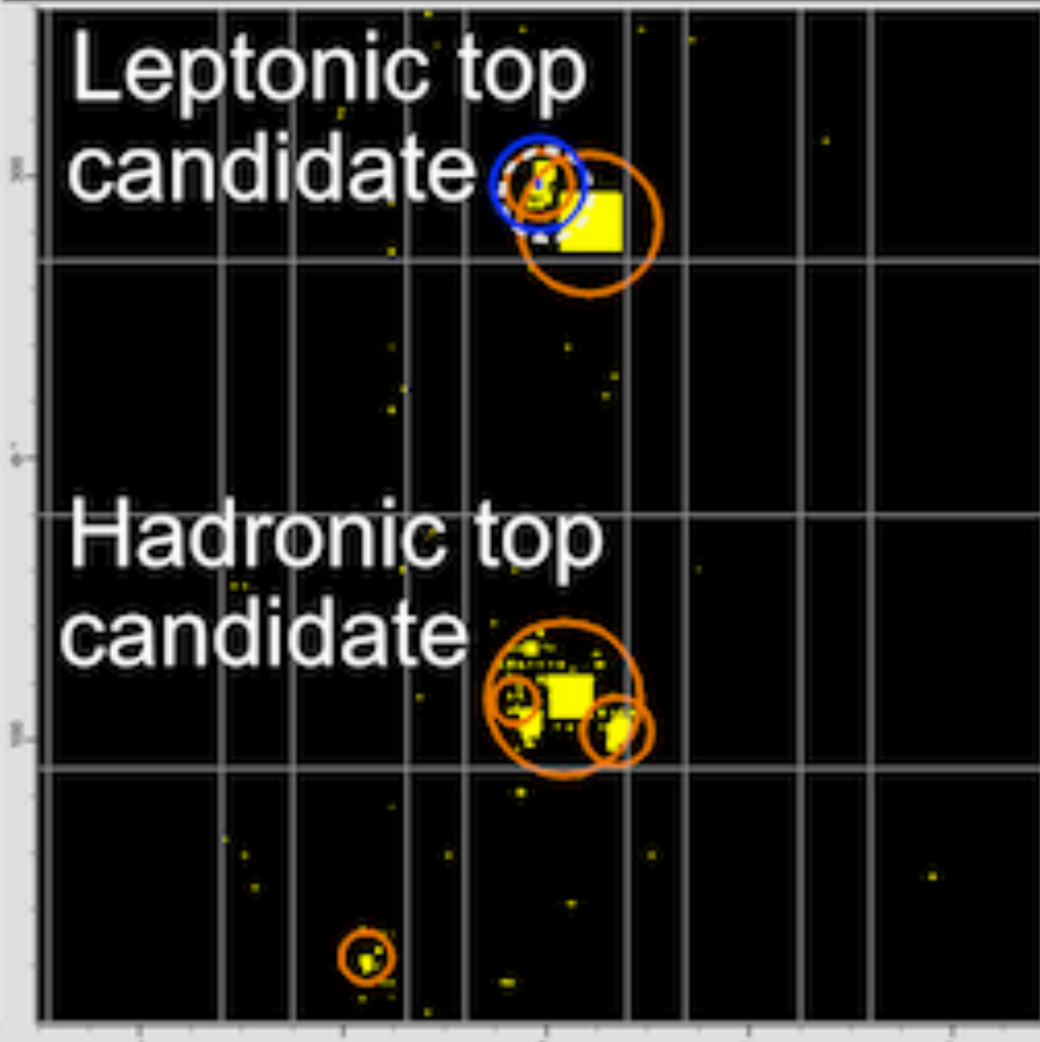
CDF



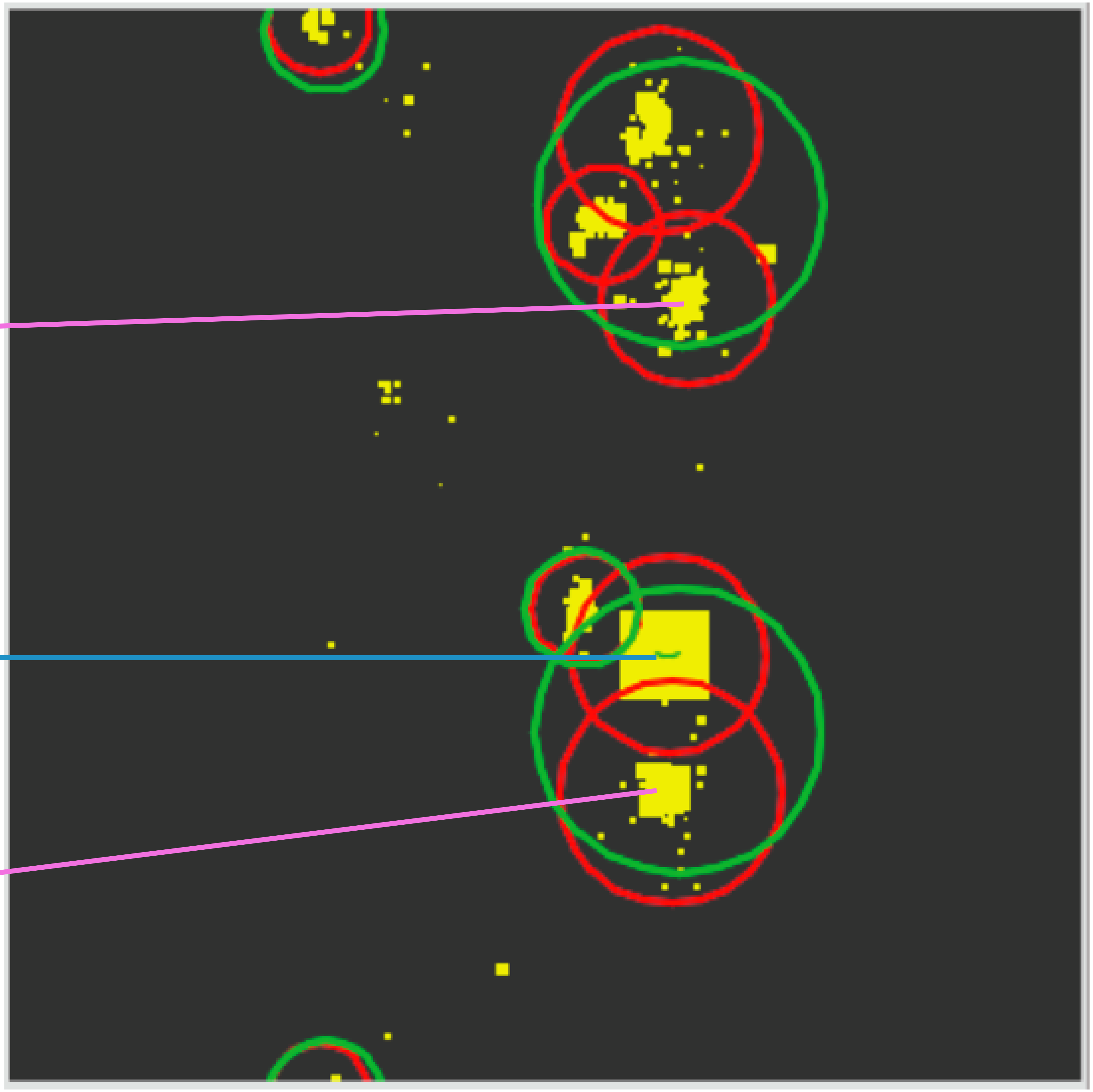
ATLAS EXPERIMENT

Run Number: 180400, Event Number: 54251178

Date: 2011-04-28 03:33:58 CEST



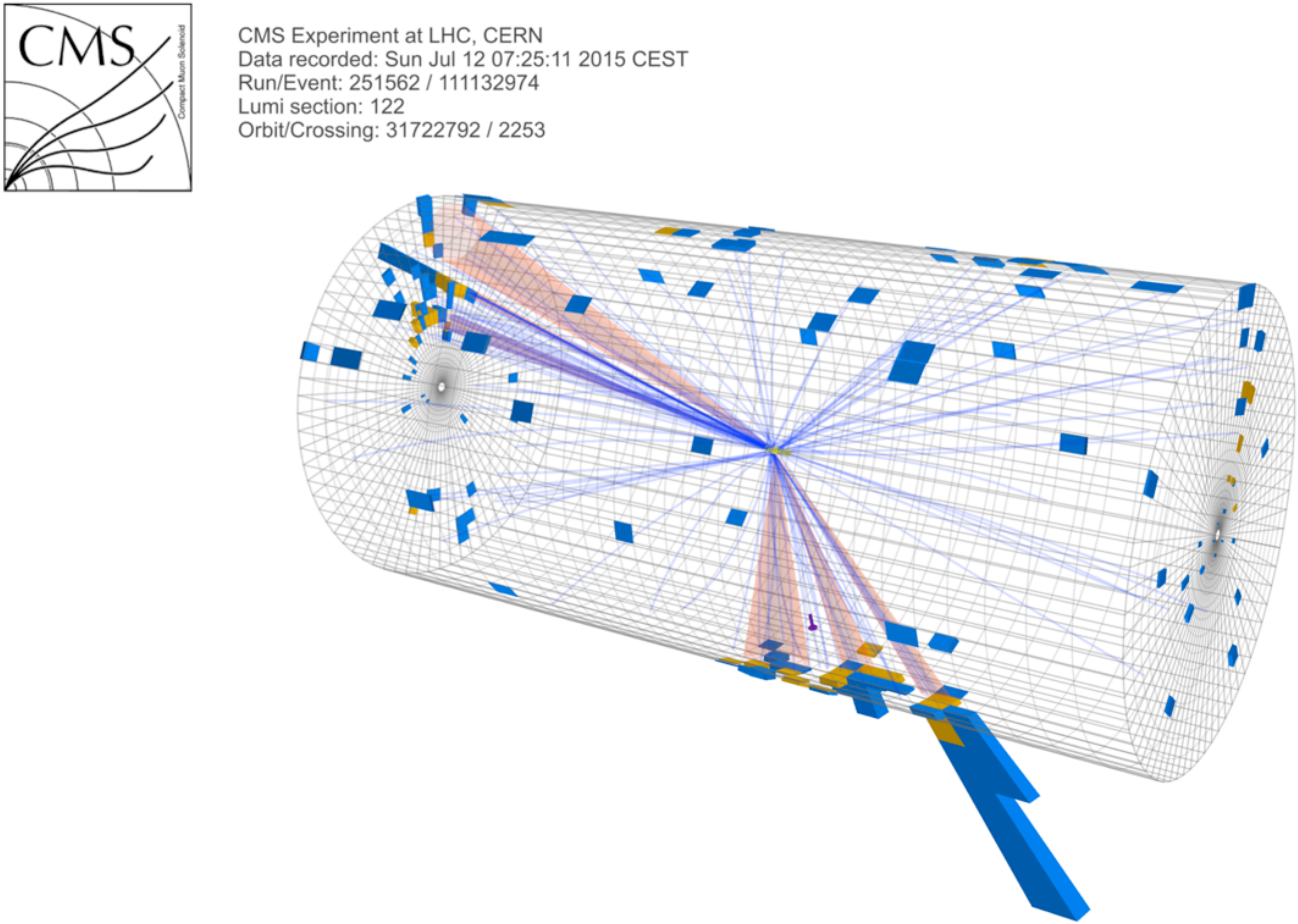
ATLAS boosted top-antitop event



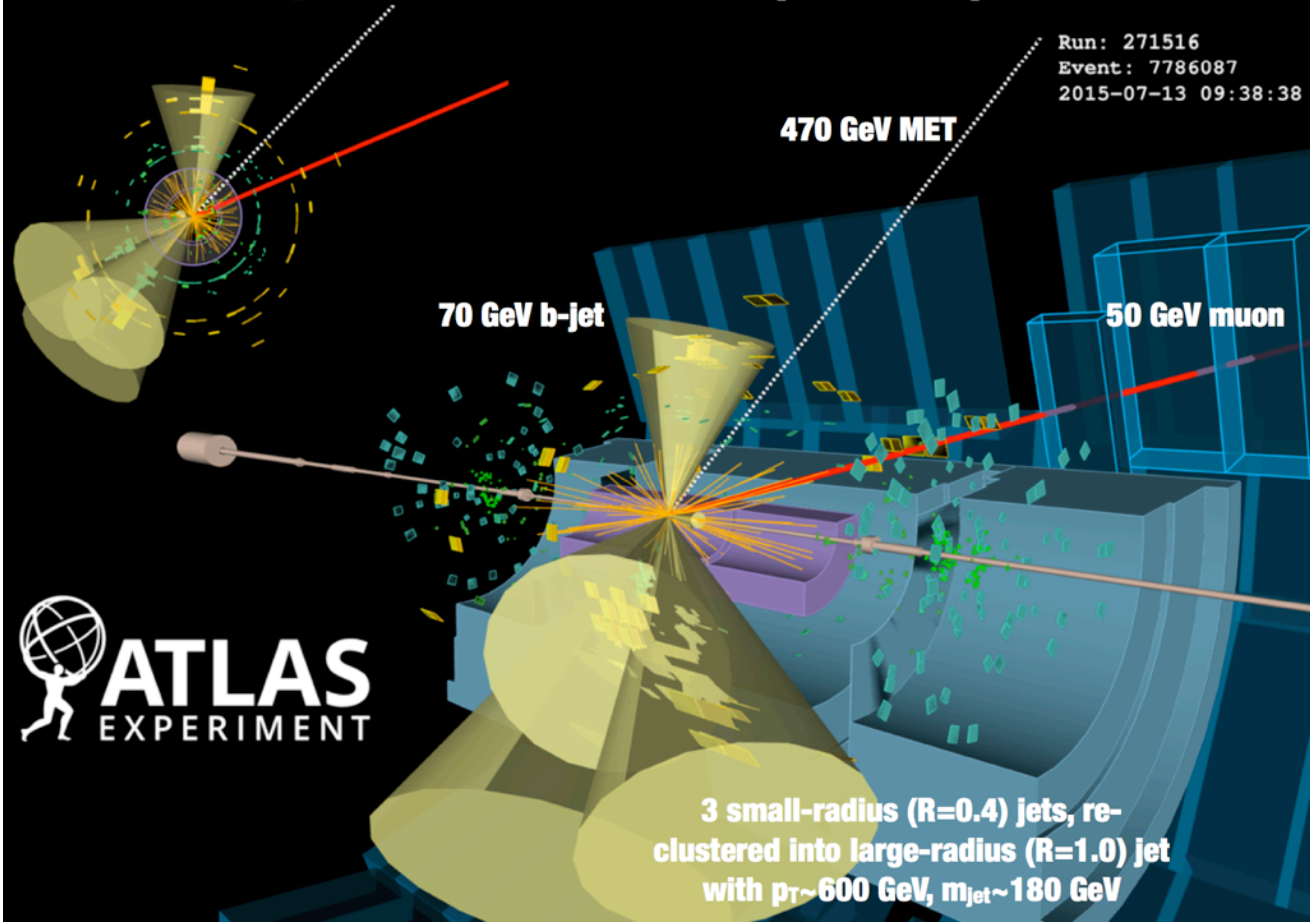
b-tagged jet

electron

b-tagged jet


CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253

Run-2 Top Jet Candidate (ATLAS)



Run: 271516
Event: 7786087
2015-07-13 09:38:38

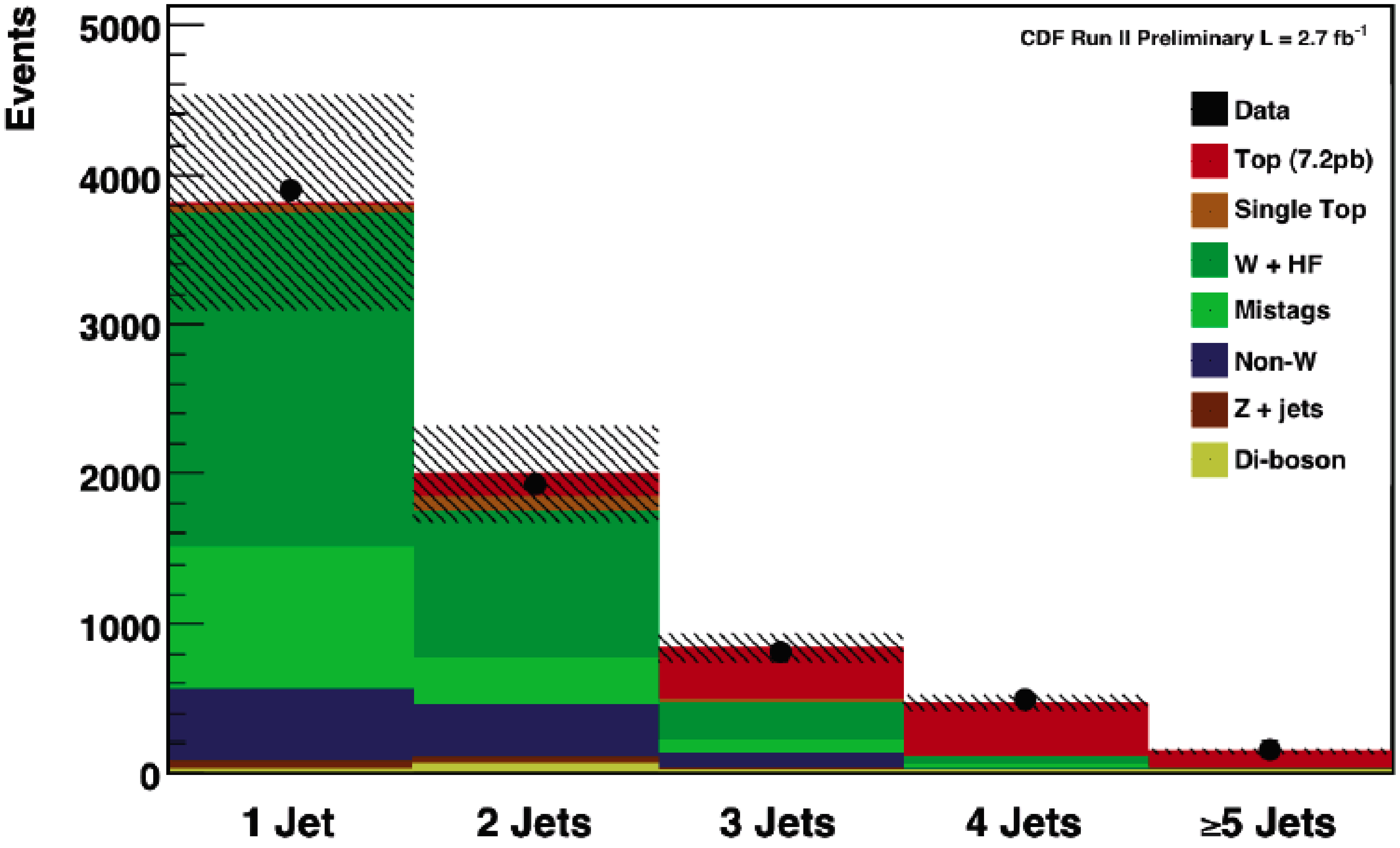
470 GeV MET

70 GeV b-jet

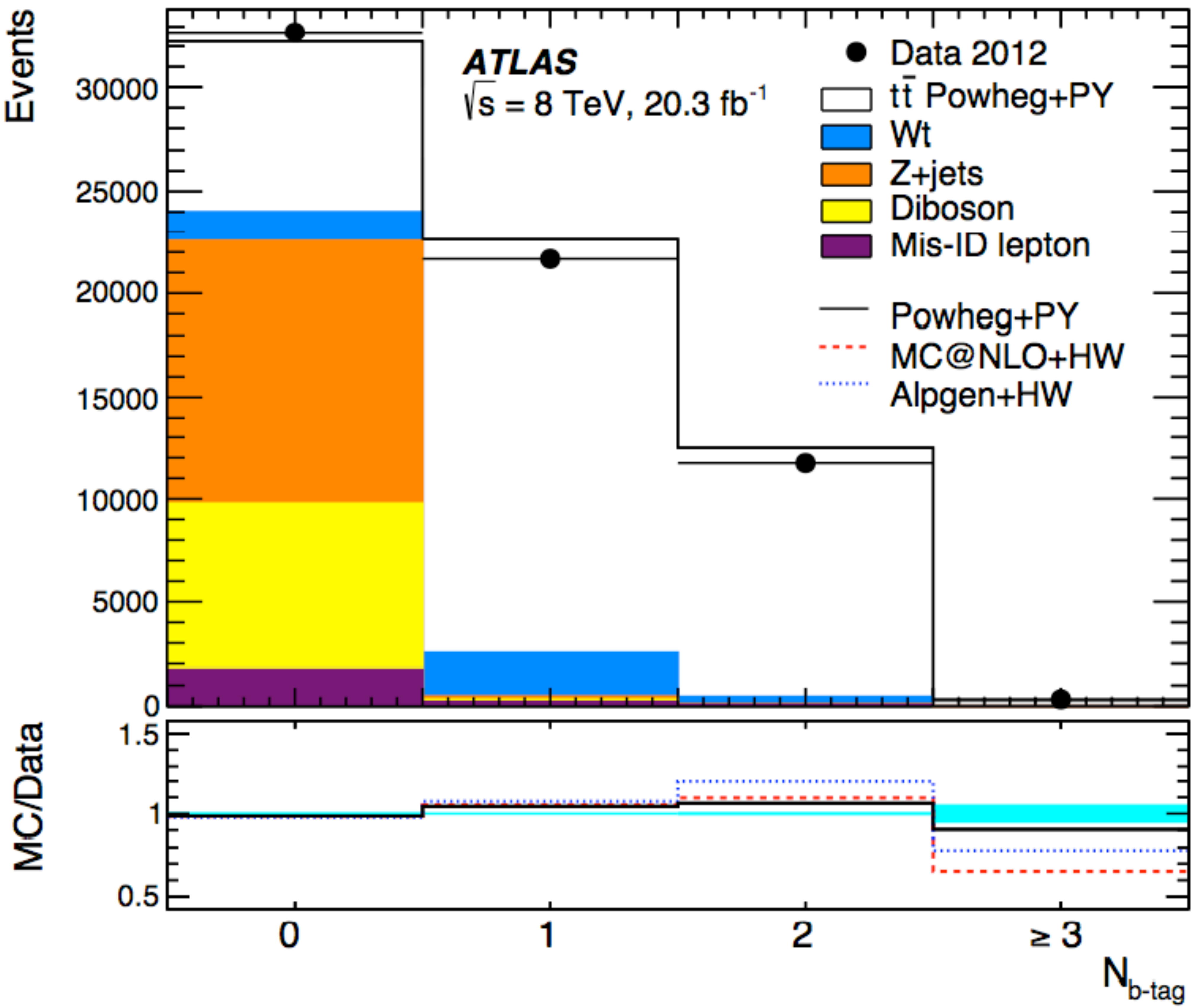
50 GeV muon

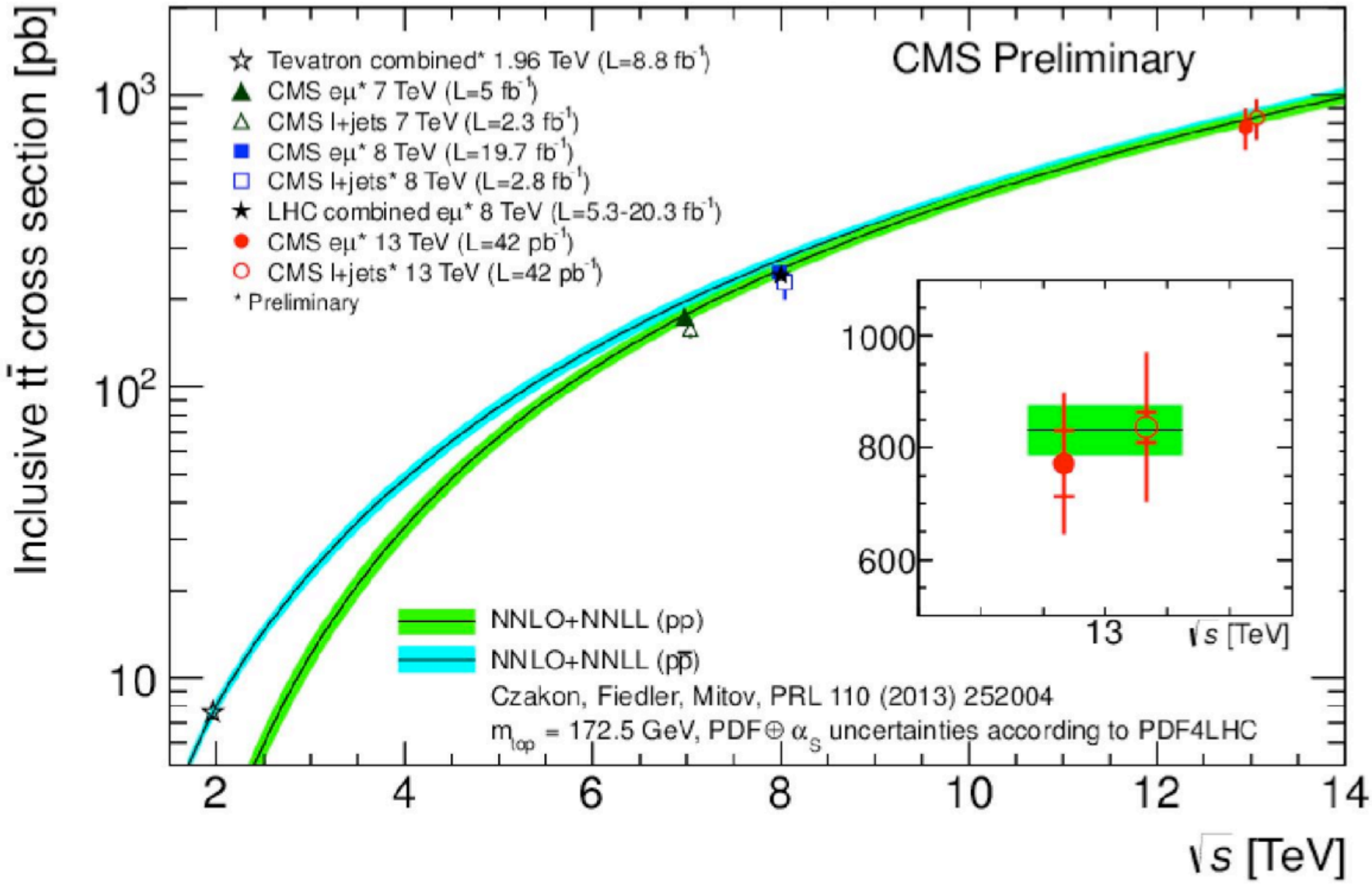
3 small-radius (R=0.4) jets, re-clustered into large-radius (R=1.0) jet with p_T~600 GeV, m_{jet}~180 GeV

CDF 1-lepton + missing ET + b-tagged jet

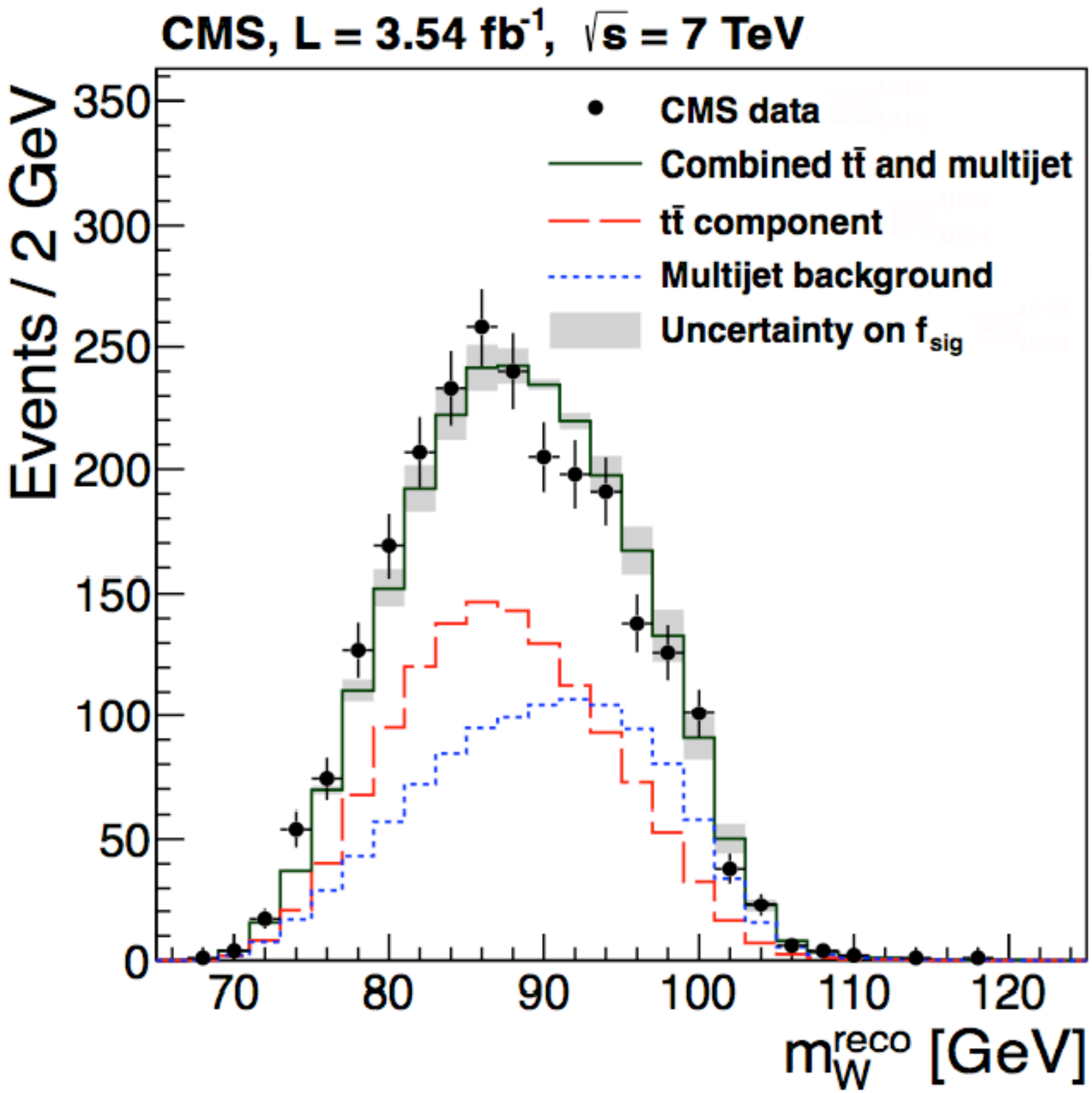


ATLAS analysis of e + μ events

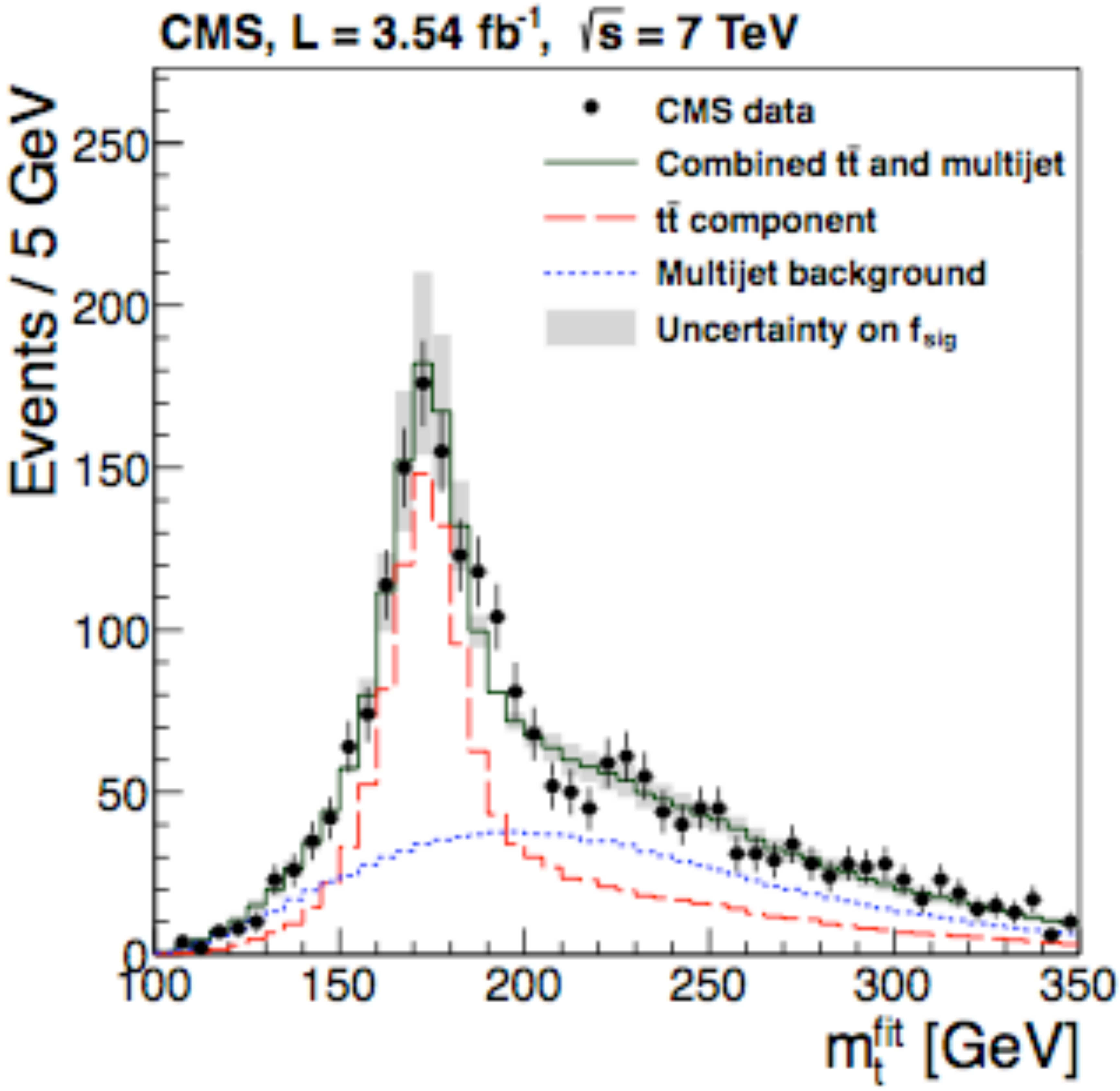


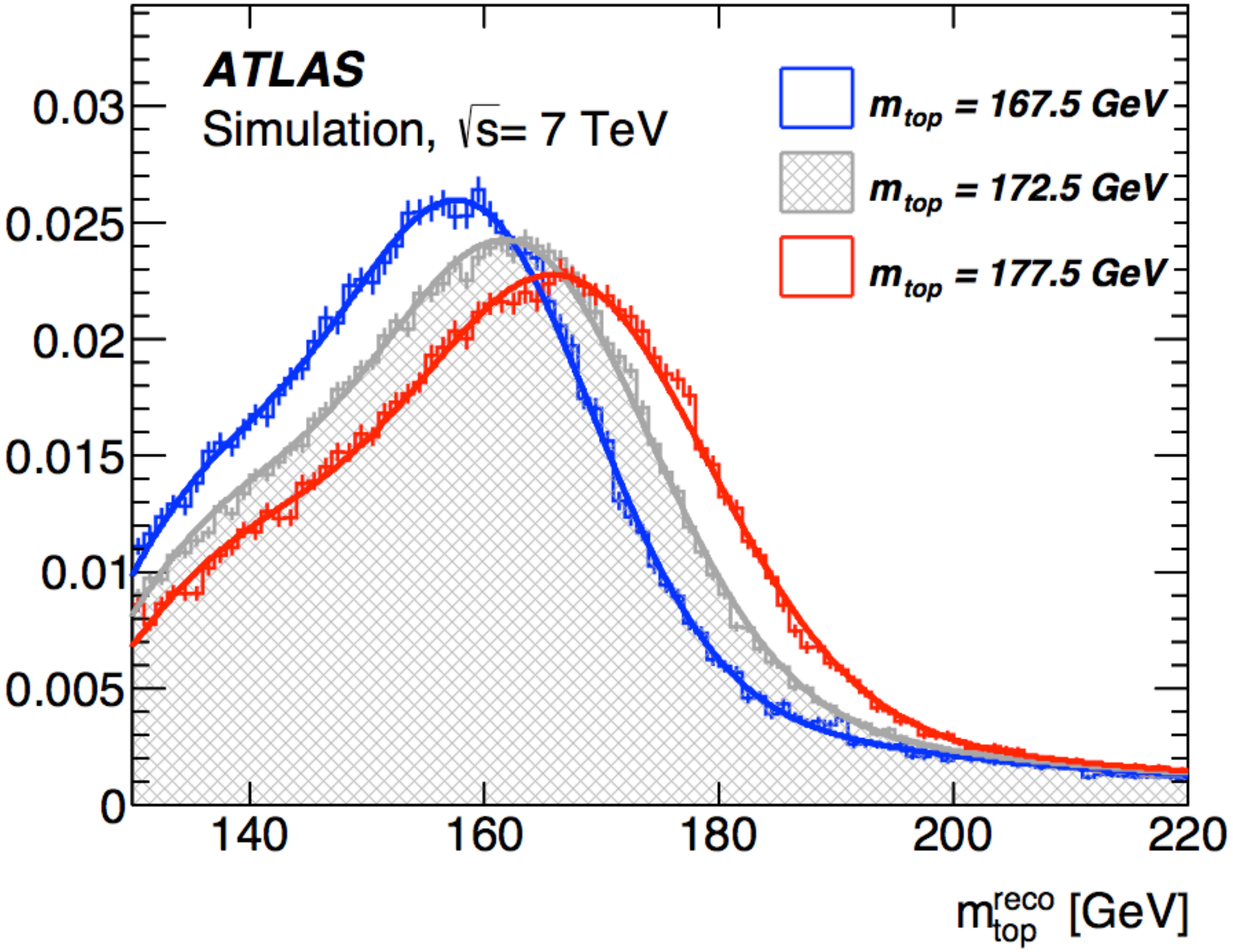

CMS Preliminary
☆ Tevatron combined* 1.96 TeV (L=8.8 fb⁻¹)
▲ CMS eμ* 7 TeV (L=5 fb⁻¹)
△ CMS l+jets 7 TeV (L=2.3 fb⁻¹)
■ CMS eμ* 8 TeV (L=19.7 fb⁻¹)
□ CMS l+jets* 8 TeV (L=2.8 fb⁻¹)
★ LHC combined eμ* 8 TeV (L=5.3-20.3 fb⁻¹)
● CMS eμ* 13 TeV (L=42 pb⁻¹)
○ CMS l+jets* 13 TeV (L=42 pb⁻¹)
* Preliminary
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
m_top = 172.5 GeV, PDF⊕α_S uncertainties according to PDF4LHC
Inclusive tt̄ cross section [pb]
10³
10²
10
2
4
6
8
10
12
14
√s [TeV]
1000
800
600
13
√s [TeV]

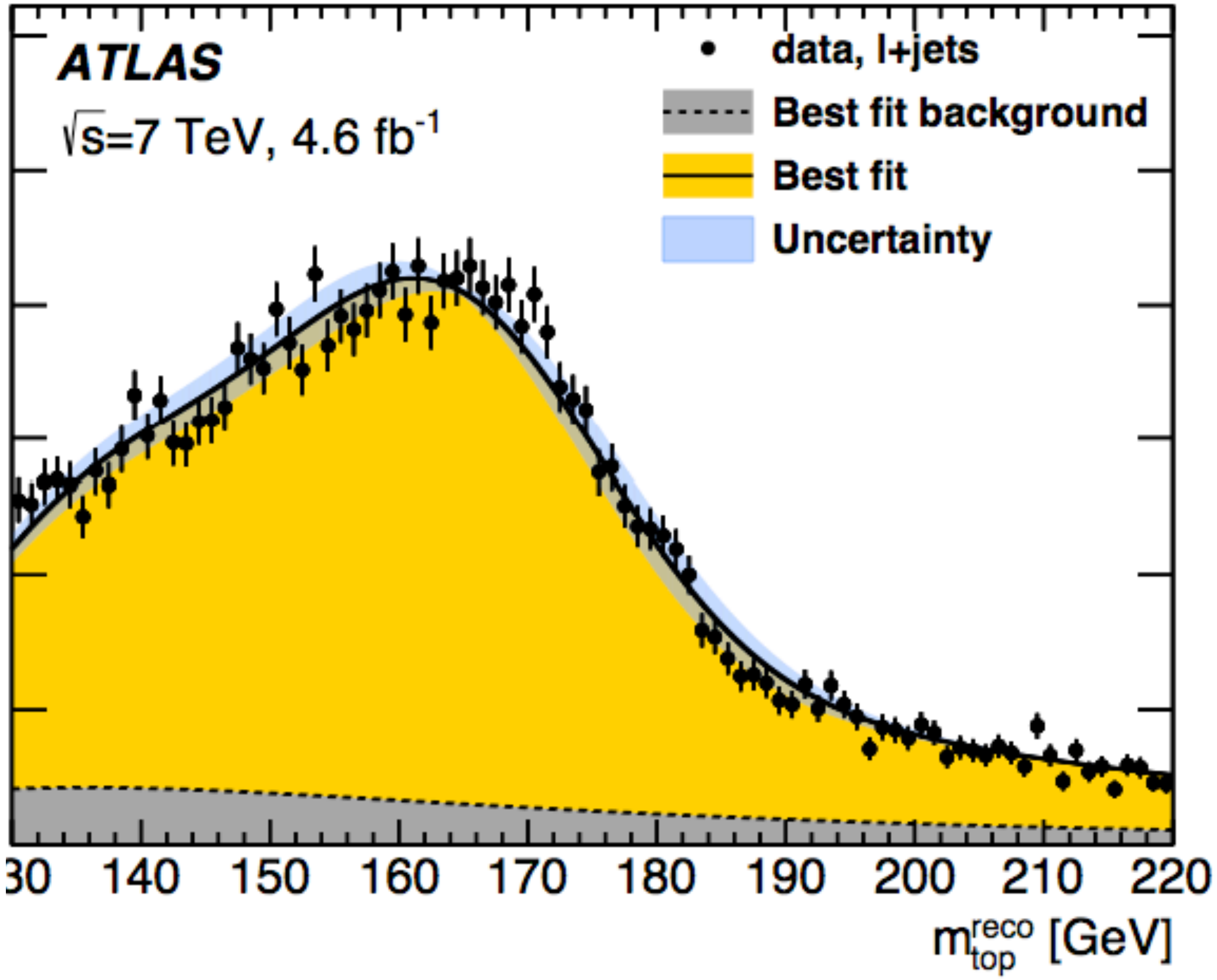
CMS events w. 6 jets, 2 b-tags



CMS events w. 6 jets, 2 b-tags

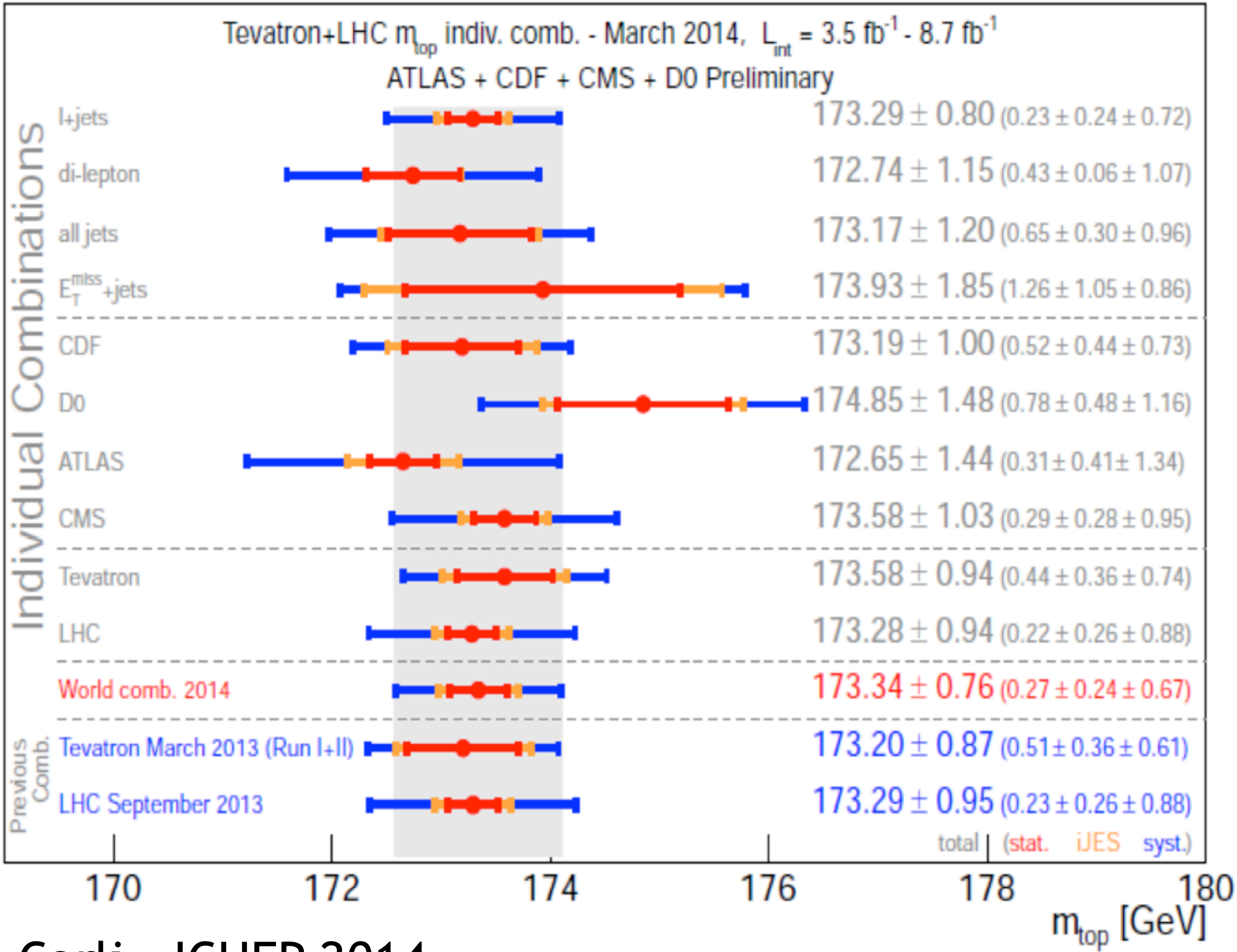




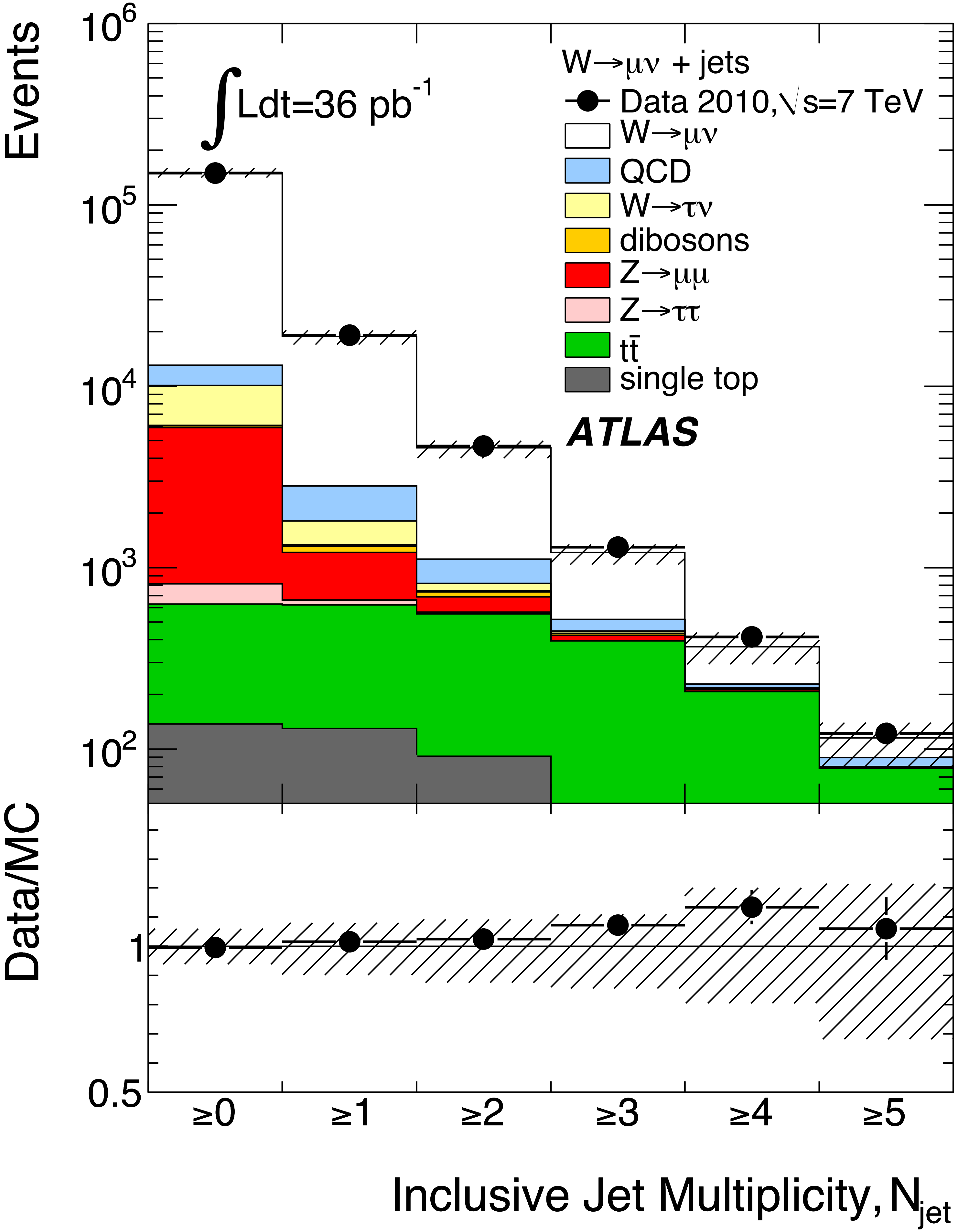


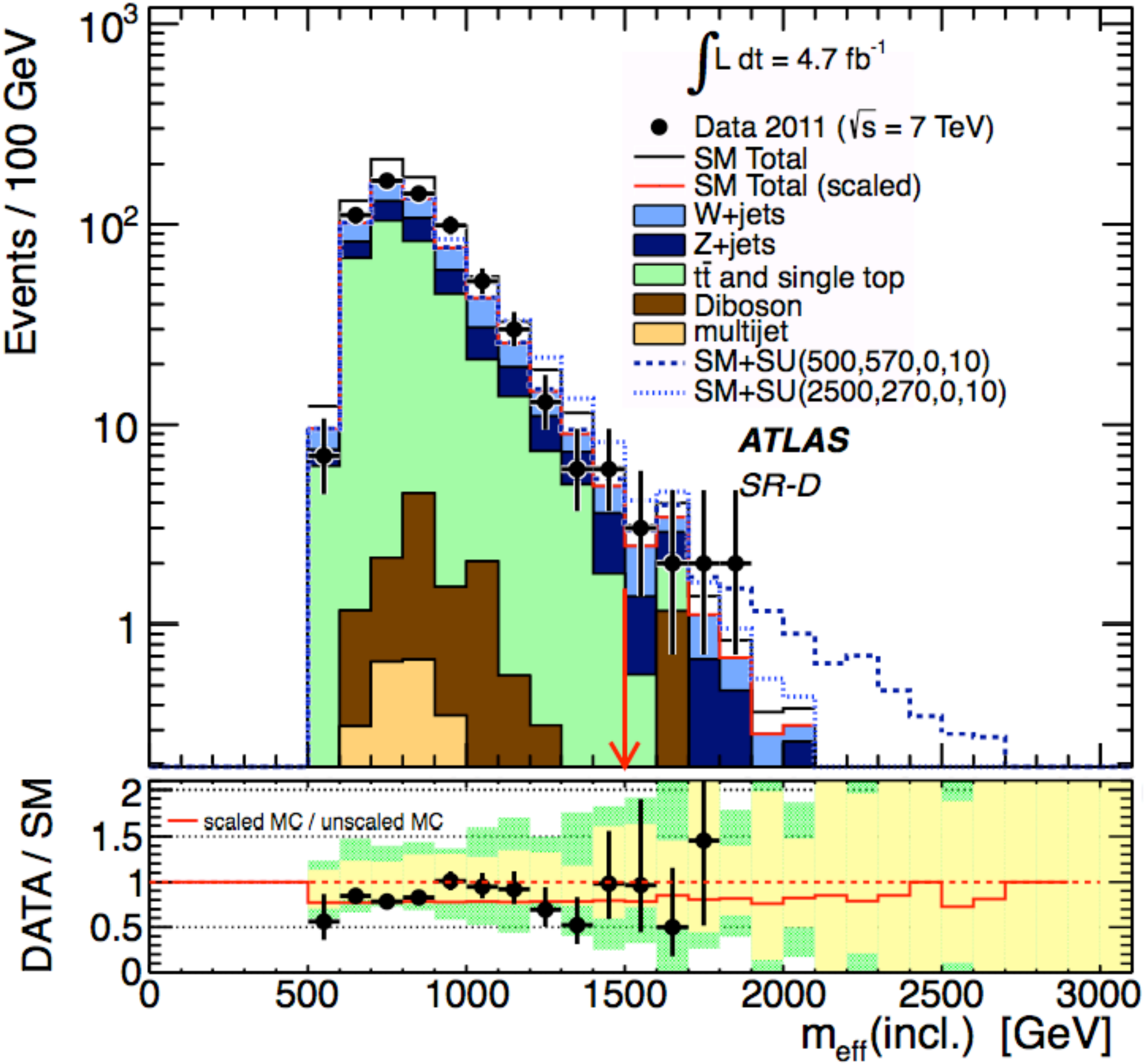
events with at least 2 b-tagged jets

$$m_t = 172.33 \pm 0.75(\mathrm{stat.}) \pm 1.02(\mathrm{syst.})$$



Carli - ICHEP 2014


Events
$\int Ldt = 36\ pb^{-1}$
$W \rightarrow \mu\nu$ + jets
Data 2010, $\sqrt{s}$=7 TeV
$W \rightarrow \mu\nu$
QCD
$W \rightarrow \tau\nu$
dibosons
$Z \rightarrow \mu\mu$
$Z \rightarrow \tau\tau$
$t\bar{t}$
single top
ATLAS
10^6
10^5
10^4
10^3
10^2
Data/MC
1
0.5
≥0
≥1
≥2
≥3
≥4
≥5
Inclusive Jet Multiplicity, N_{jet}


$\int L\,dt = 4.7\ \mathrm{fb}^{-1}$
Data 2011 ($\sqrt{s}$ = 7 TeV)
SM Total
SM Total (scaled)
W+jets
Z+jets
$t\bar{t}$ and single top
Diboson
multijet
SM+SU(500,570,0,10)
SM+SU(2500,270,0,10)
ATLAS
SR-D
Events / 100 GeV
10^3
10^2
10
1
DATA / SM
scaled MC / unscaled MC
2
1.5
1
0.5
0
0
500
1000
1500
2000
2500
3000
m_{eff}(incl.) [GeV]

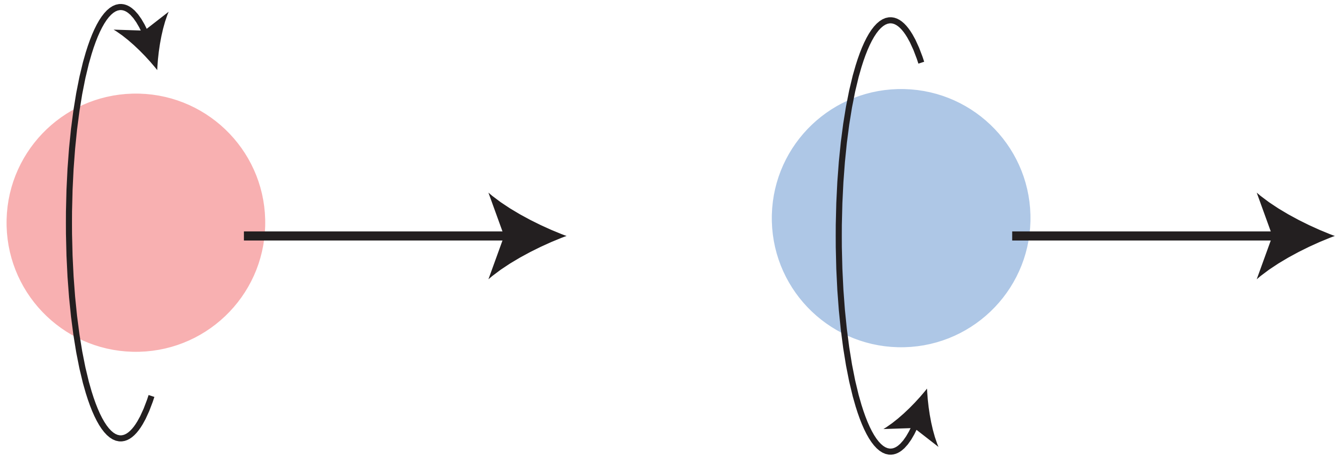
So far, I have explained why the top quark is odd, and maybe why it is interesting, but not why it is important.

Its importance comes from its connection to the Higgs field, the field responsible for those interactions of quarks and leptons that are most poorly understood.

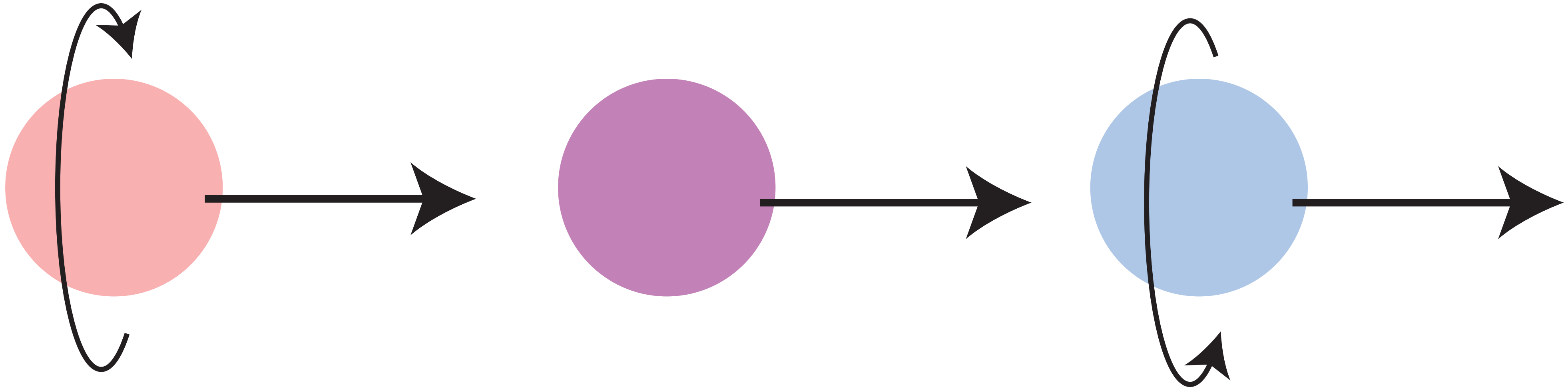
The Higgs field is supposed to be responsible for generating the masses of quarks and leptons.

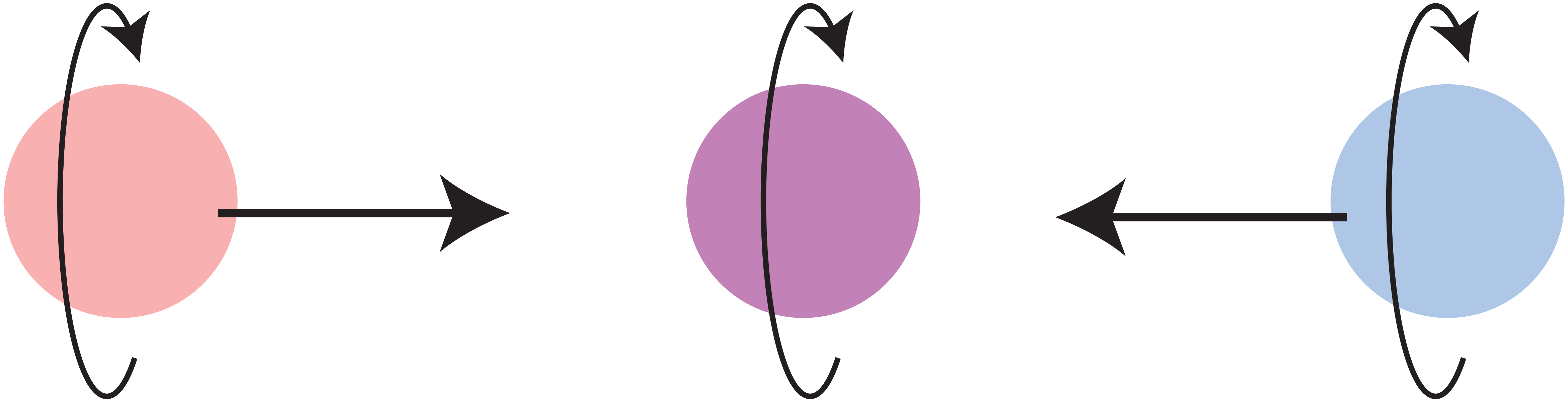
Before continuing, I must explain why something is needed to give mass to these particles.

spin 1/2



spin 1





So,

mass implies mixing of the L and R states

to permit this, these states should have
the same quantum numbers

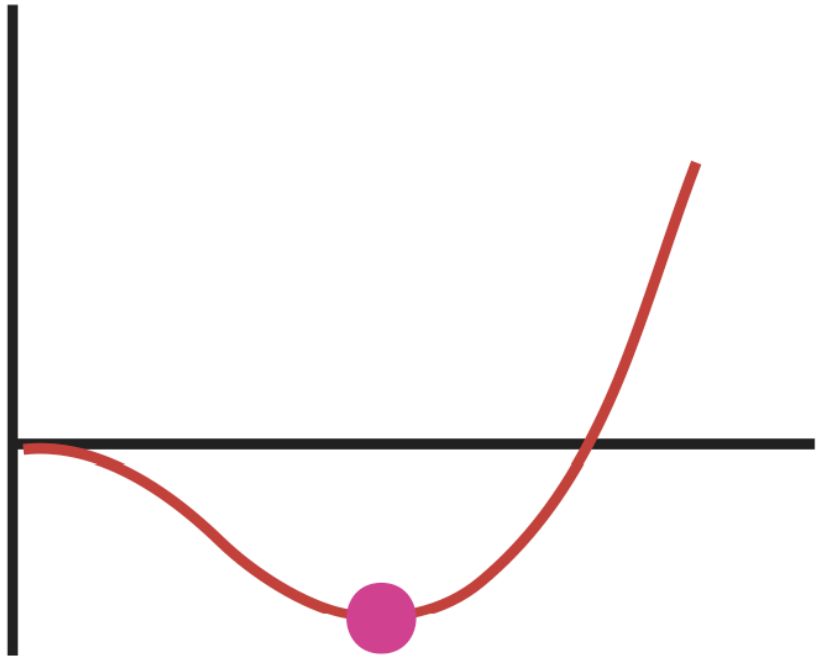
but, they do not ! The W couples to L but not to R

this is the essence of the parity violation of
the weak interactions

solution: (Weinberg, Salam)

The charge associated with the W boson is not conserved because the associated symmetry is spontaneously broken.

The order parameter of this spontaneous symmetry breaking is called the Higgs field.



L and R fermions mix through their couping to this field. Larger masses come from larger couplings.

We now see that the top quark is heavy because it has a large coupling to the Higgs field.

This coupling is the largest among all known elementary particles.

Hierarchy of coupings in nature:

$$\alpha = e^2/4\pi = 1/137 \qquad \text{at} \qquad Q = 0$$

$$\alpha = e^2/4\pi = 1/128 \qquad \text{at} \qquad Q = 90 \text{ GeV}$$

$$\alpha_w = g^2/4\pi = 1/29.6 \qquad \text{at} \qquad Q = 90 \text{ GeV}$$

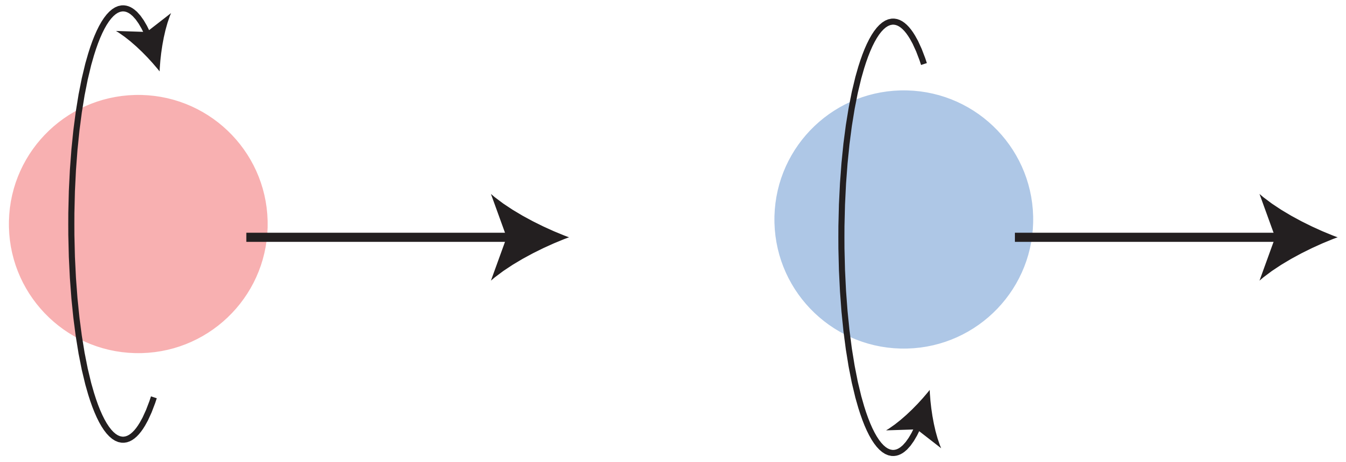
$$\alpha_s = g_s^2/4\pi = 1/8.5 \qquad \text{at} \qquad Q = 90 \text{ GeV}$$

$$\alpha_t = y_t^2/4\pi = 1/12.7 \qquad \text{at} \qquad Q = 90 \text{ GeV}$$

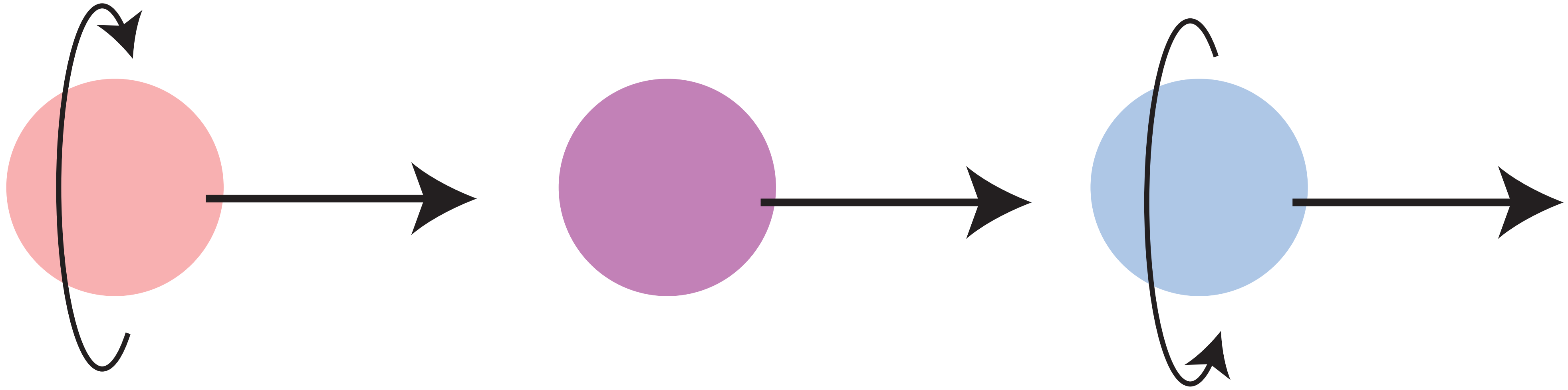
$$\alpha_b = y_b^2/4\pi = 1/42,000 \qquad \text{at} \qquad Q = 90 \text{ GeV}$$

In fact, the large coupling of the top quark to the Higgs field is directly visible in experiment.

massless spin 1 (photon)



massive spin 1 (W)



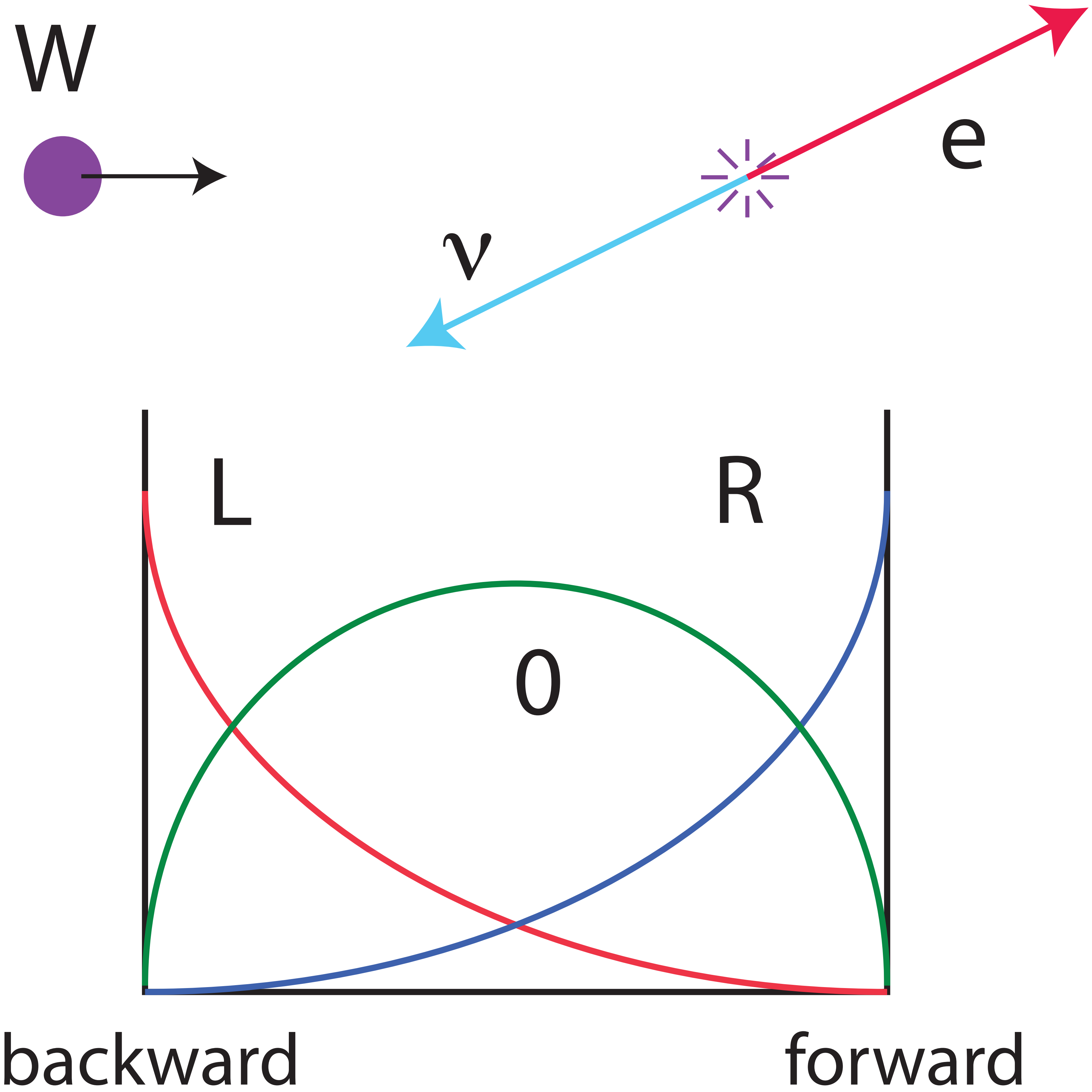
The W(0) comes from the Higgs field !

So, we expect

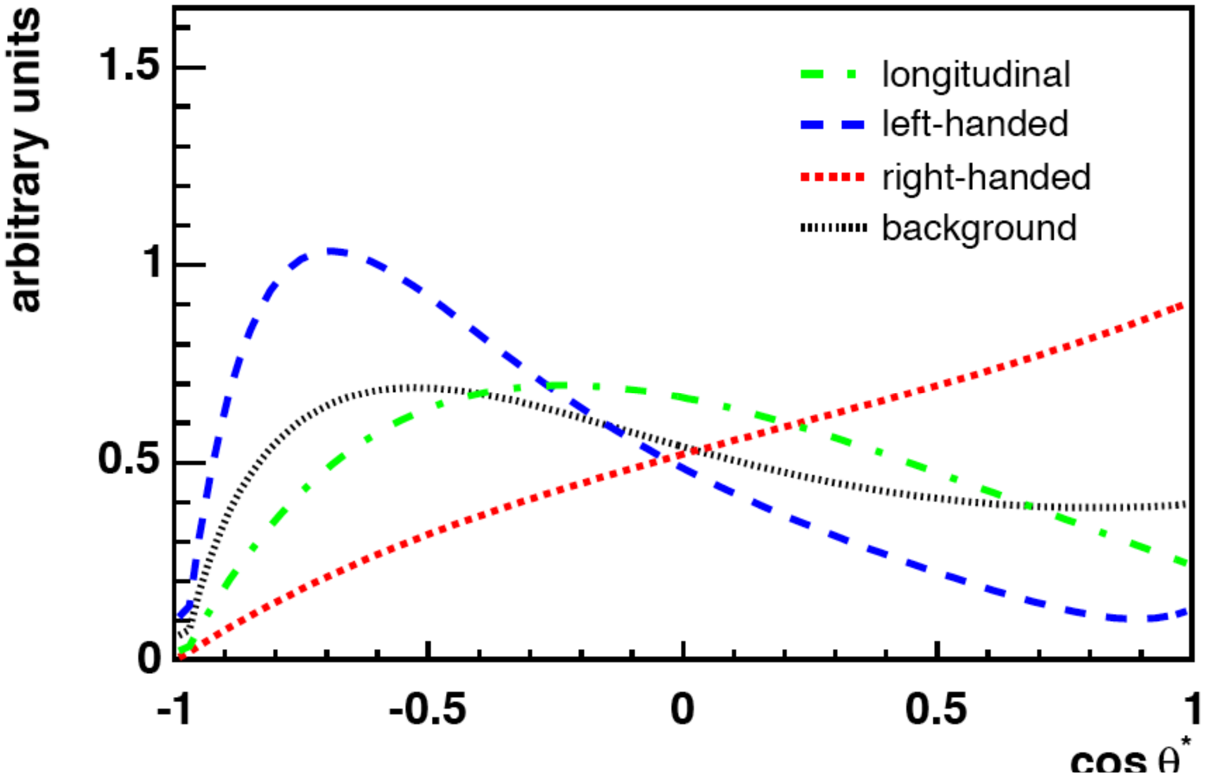
$$\frac{\Gamma(t \to W_0\, b)}{\Gamma_t \to W_L\, b)} = \frac{\alpha_t}{\alpha_w} = 2.3$$

or,

70% of top quark decays are to W(0).

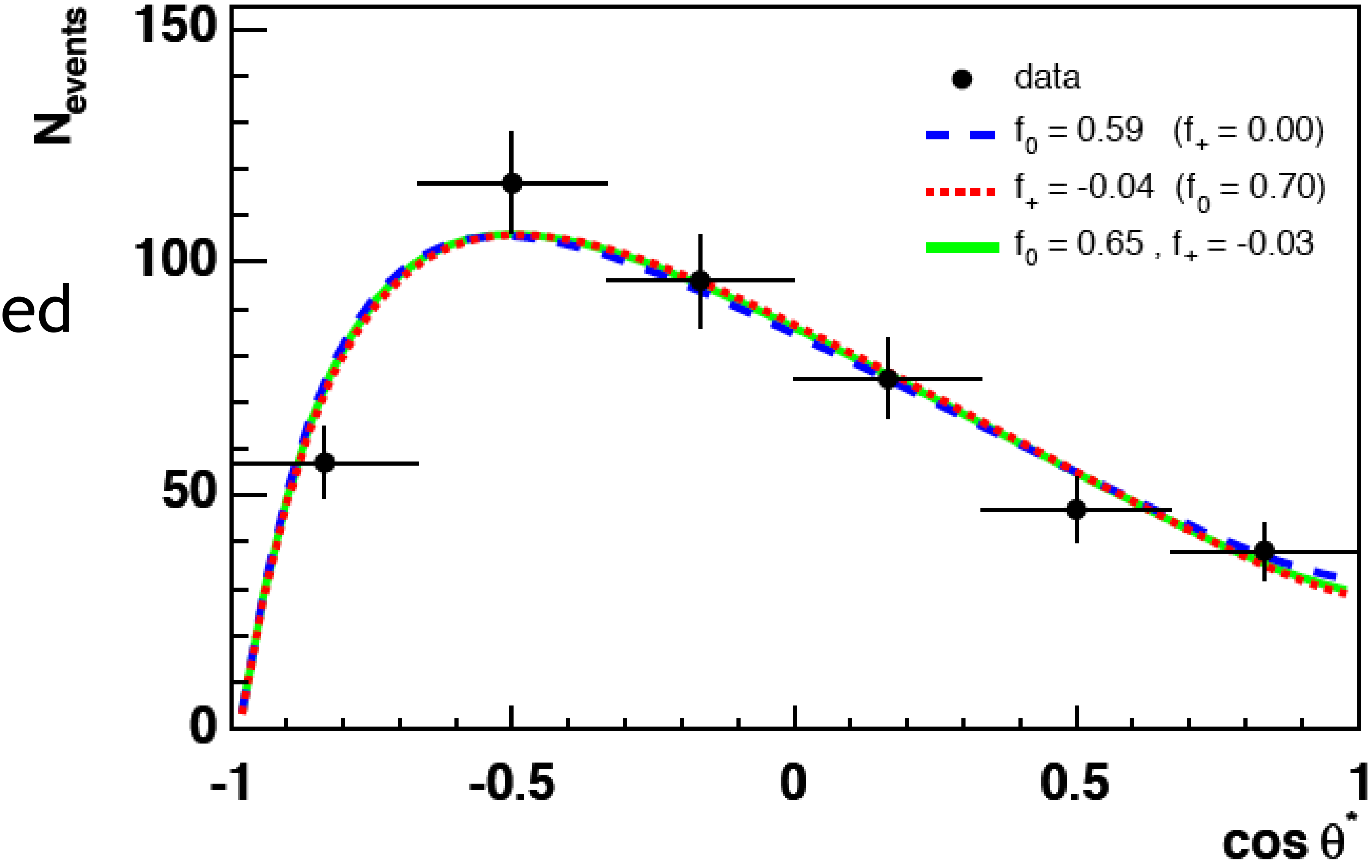

W
e
ν
L
R
0
backward
forward

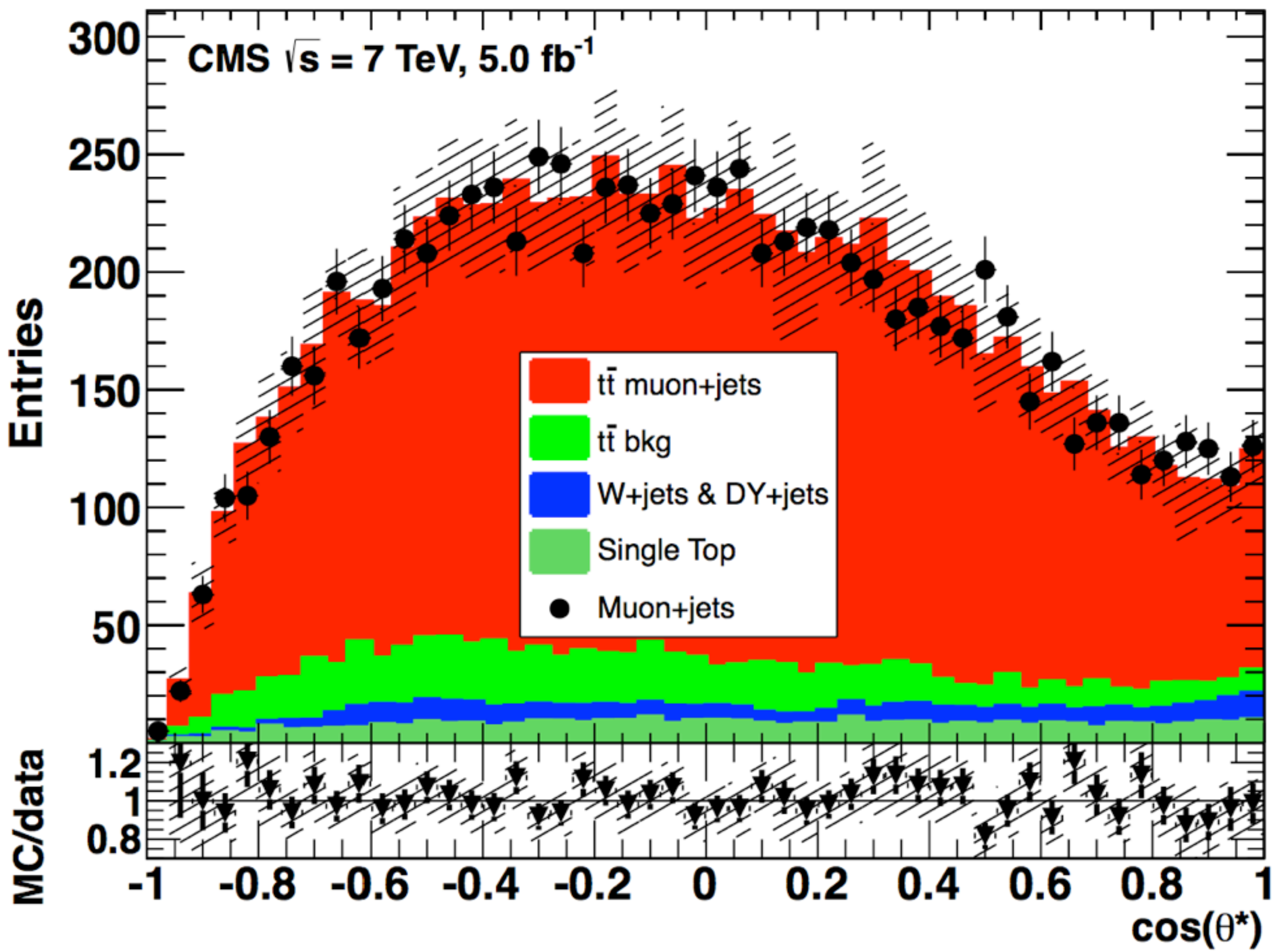
templates



CDF
experiment

observed




CMS √s = 7 TeV, 5.0 fb^{-1}
Entries
300
250
200
150
100
50
MC/data
1.2
1
0.8
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
cos(θ*)
$t\bar{t}$ muon+jets
$t\bar{t}$ bkg
W+jets & DY+jets
Single Top
Muon+jets

Even before the discovery of the Higgs boson,

this could be cited as evidence that the mass of the top quark is the result of spontaneous symmetry breaking.

Now we must address the interpretation of the value of α_t .

Is this a large value, signifying that the top quark has a special role in the theory of the Higgs field ?

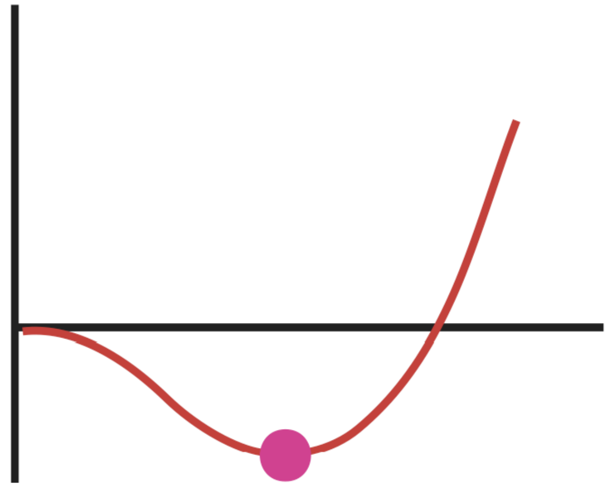
Or is it a small value, signifying that the top quark is no way special dynamically ?

In the latter view, the top quark is “ordinary” and the other quarks and leptons are “puny”. (This point of view might be helpful to those particle physicists who are concerned about the physics of flavor.)

If α_t were large enough to be important in the dynamics of spontaneous symmetry breaking, the physics of the top quark could give us a clue as to why this symmetry breaking occurs.

At the present time, our understanding of this transition is on the same footing at the Landau-Ginzburg theory of superconductivity.

We postulate a scalar field, assign it a potential unstable at the origin, and fit its properties to experiment.



In the theory of superconductivity, this attitude was always considered provisional.

Eventually, Bardeen, Cooper, and Schrieffer developed their fascinating theory of electron pairing at the Fermi surface.   This gave a clear explanation of why superconductivity occurs and allowed the calculation of the superconducting properties of metals and alloys.

Shouldn’t we expect this level of explanation also for the symmetry breaking in the weak interactions ?

Here is a first try at such a theory:

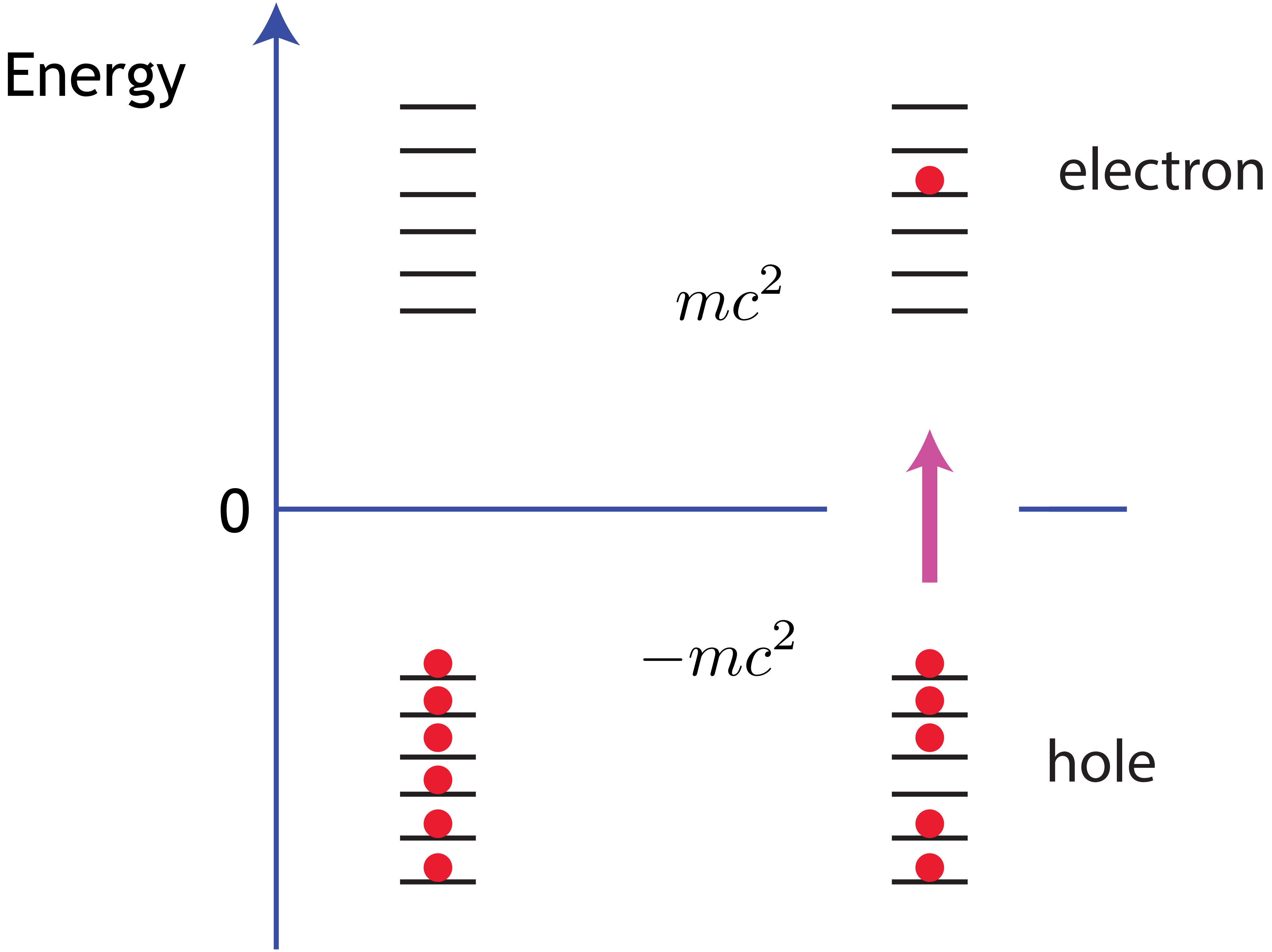
Introduce a Higgs scalar field, and couple top quarks to it. At this level, the top quark is massless.

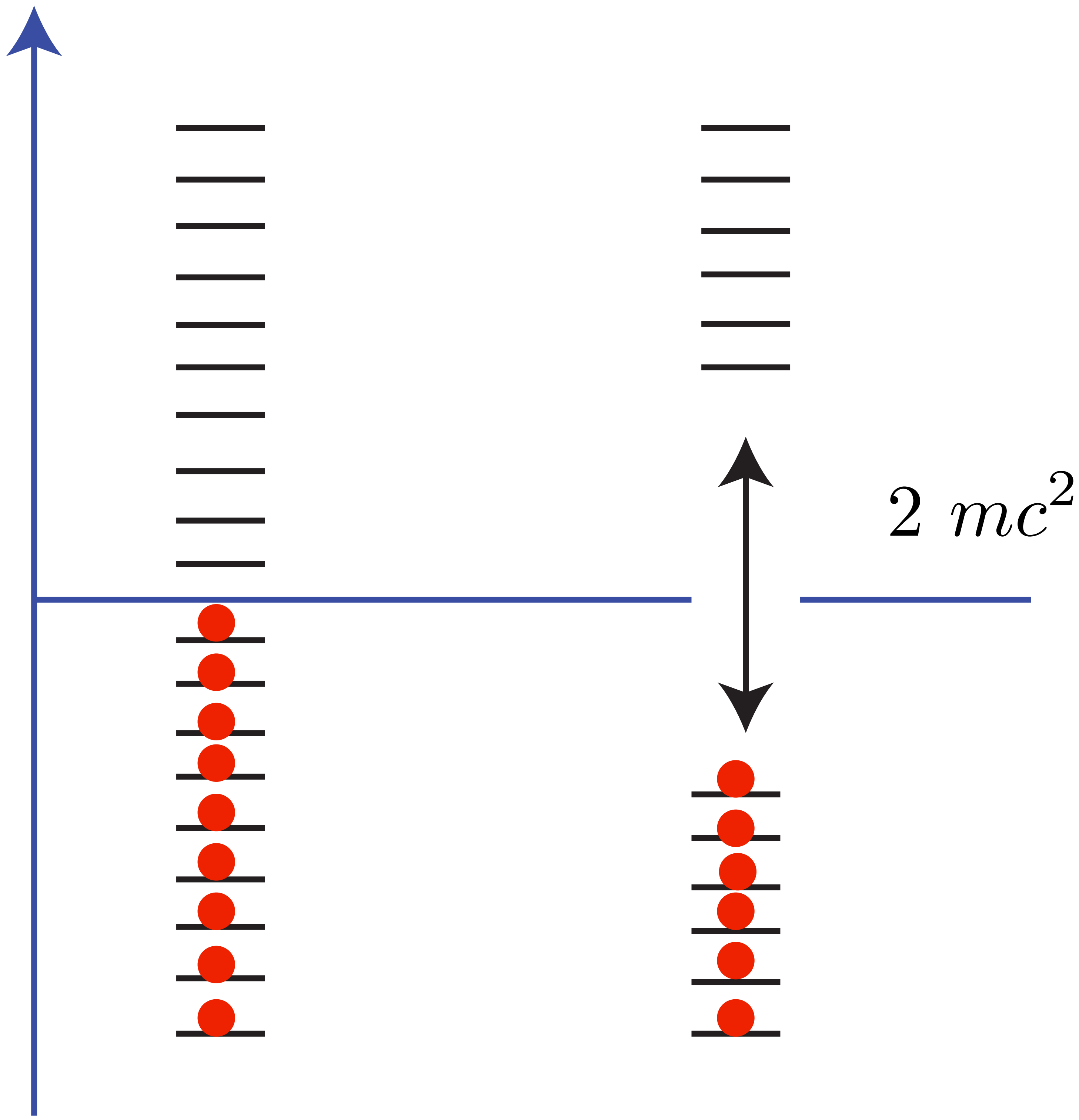
Give the Higgs field a potential energy that is neutral between

$\langle\varphi\rangle = 0$ and $\langle\varphi\rangle \neq 0$

Then, I claim, there is an effect that drives the Higgs field to nonzero values.

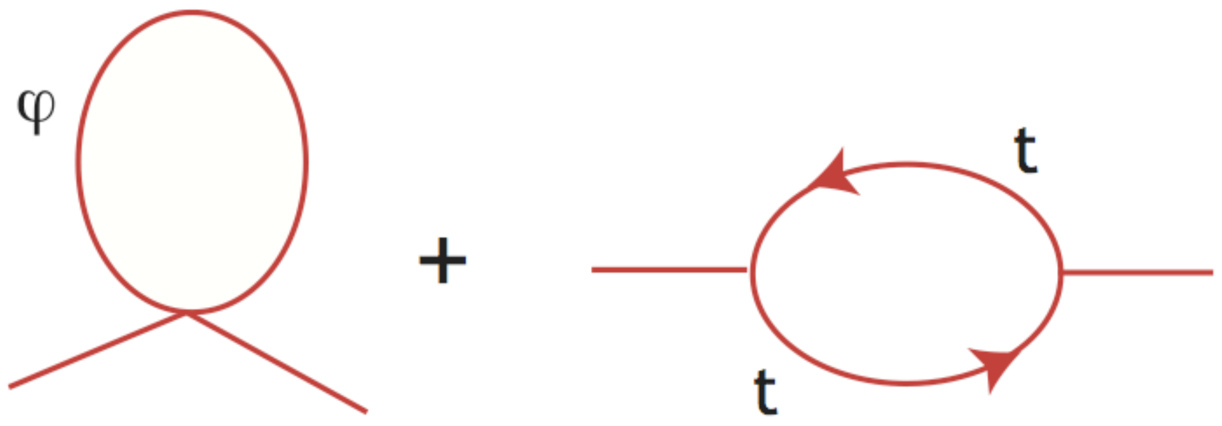
This comes from the physics of the Dirac sea.




$2\ mc^2$

The problem is that the formation of a mass gap does not stabilize at a fixed value.   As we make the gap larger, the energy of the vacuum continue to decrease.

The problem here is actually a problem with the view of the Higgs boson as a scalar field.   If start with a scalalr field of small mass, and we compute the correction to this mass from Feynman diagrams, we find



$$\mu^2 = \mu^2_{\text{bare}} + \frac{3\lambda}{8\pi^2}\Lambda^2 - \frac{3y_t^2}{8\pi^2}\Lambda^2 + \cdots$$

So, to make sense of this calculation, we need a framework in which the Higgs field is not a simple scalar field but, rather, has more structure. Here are some of the solutions proposed:

1.

The Higgs field is a bound state of fermions, like the scalar field of the Landau-Ginzburg theory. This solution is called "technicolor".

This approach necessarily leads to a large mass for the scalar bound state. The discovery of the Higgs boson as a resonance at 125 GeV -- which is a small value on the relevant scale -- eliminates this class of models.

2.

The Higgs field is a scalar field, but a symmetry forbids it from acquiring mass. When the symmetry is broken, the mass correction can be finite.

The most successful theory along this line is called “supersymmetry”. In this theory, there is a new scalar particle that is the partner of each quark and lepton. In particular, there is a scalar top quark that balances the vacuum energy of the massive top quark.

3.

The Higgs field can be composite, but not an ordinary bound state. Instead, it is a Goldstone boson resulting from spontaneous breaking of a new symmetry at very short distances. A Goldstone boson naturally has zero mass.

However, if the symmetry was not perfect, a small correction can give a mass to the Goldstone boson, and this mass term can be negative and give the Higgs instability.

I will now discuss the current status of these latter two ideas.

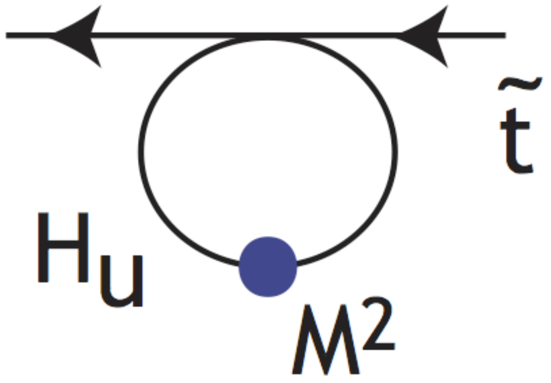
In each case, there is a beautiful theory in which the top quark plays an essential role in generating a finite and negative mass parameter μ^2 for the Higgs field.

In each case, the mechanism requires new elementary particles that ought to be found at the LHC.

Supersymmetry is not an manifest symmetry; the symmetry must be broken at some high energy.

Assume that the Higgs mass term is positive. Also, positive masses are generated for the scalar quarks including the partners of t_L and t_R.

These mass terms are corrected by the diagrams



The corrections are negative !

They are multiplicative and modify the values of the masses as a function of distance scale.

In fact, the masses of the three scalar particles are coupled, in the following set of differential equations.

The three mass terms race toward negative values as the energy scale Q decreases:

$$\frac{dM_{tL}^2}{d\log Q} = 1 \cdot \frac{\alpha_t}{2\pi}[M_{tL}^2 + M_{tR}^2 + M_\varphi^2 + A_t^2] - \frac{8\alpha_s}{3\pi} m_{\tilde{g}}^2 + \cdots$$

$$\frac{dM_{tR}^2}{d\log Q} = 2 \cdot \frac{\alpha_t}{2\pi}[M_{tL}^2 + M_{tR}^2 + M_\varphi^2 + A_t^2] - \frac{8\alpha_s}{3\pi} m_{\tilde{g}}^2 + \cdots$$

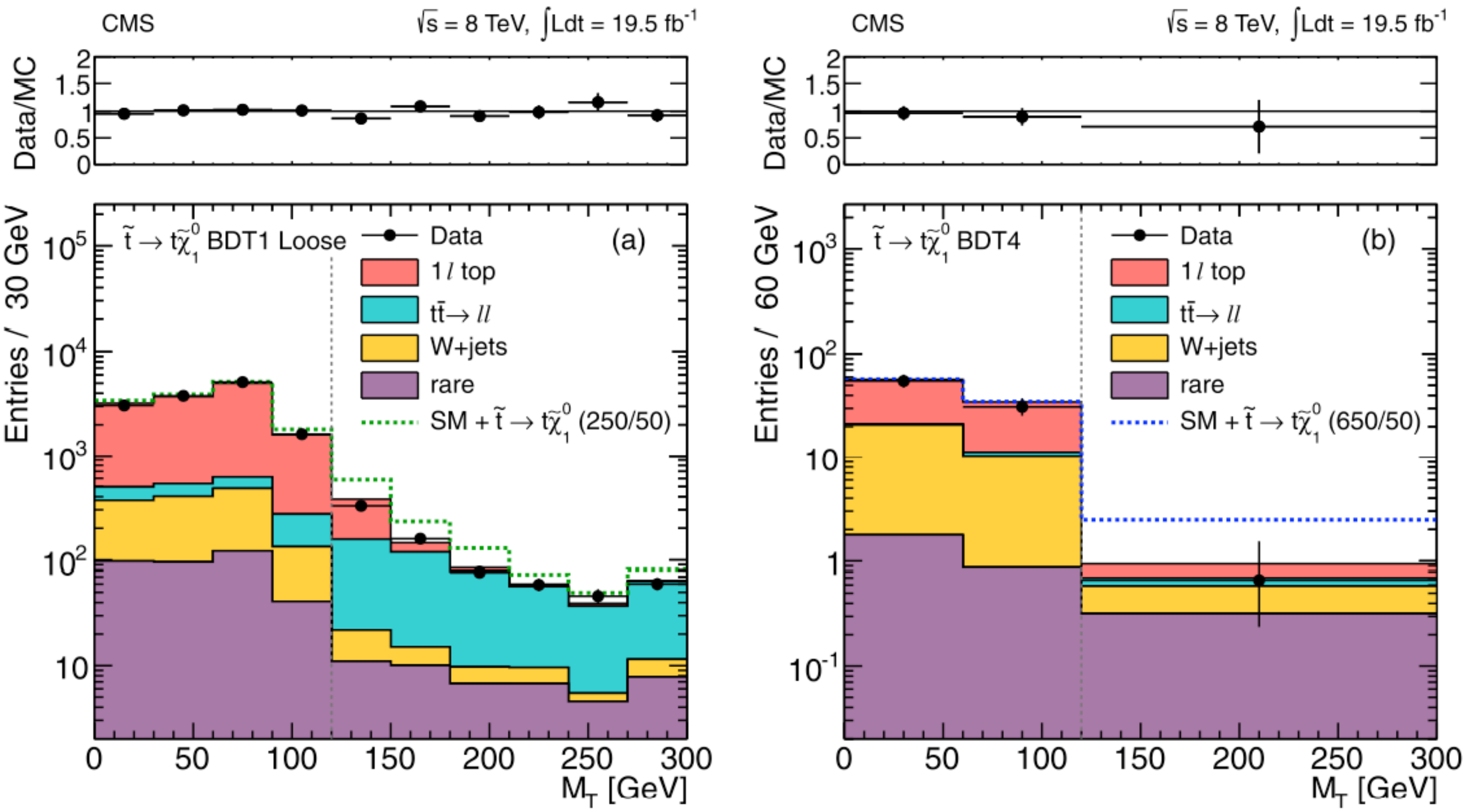
$$\frac{dM_\varphi^2}{d\log Q} = 3 \cdot \frac{\alpha_t}{2\pi}[M_{tL}^2 + M_{tR}^2 + M_\varphi^2 + A_t^2] + \cdots$$

The winner is the Higgs boson. The pattern of symmetry breaking predicted is then the one observed in nature.

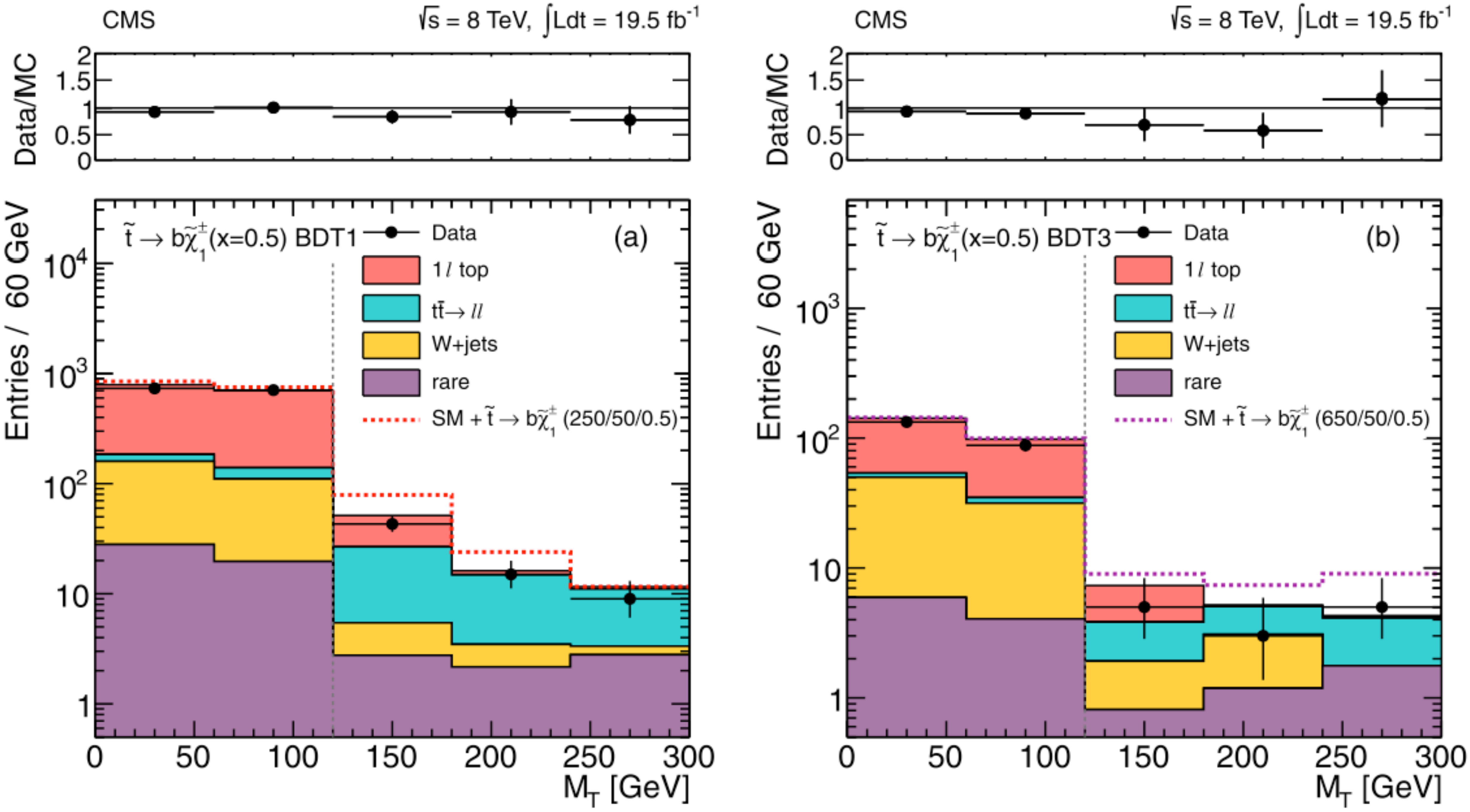
The mechanism is beautiful, but to make it work the scalar partners of the top quark must exist, and at values of the mass not so far from

$$\langle \varphi \rangle = 250 \text{ GeV}$$

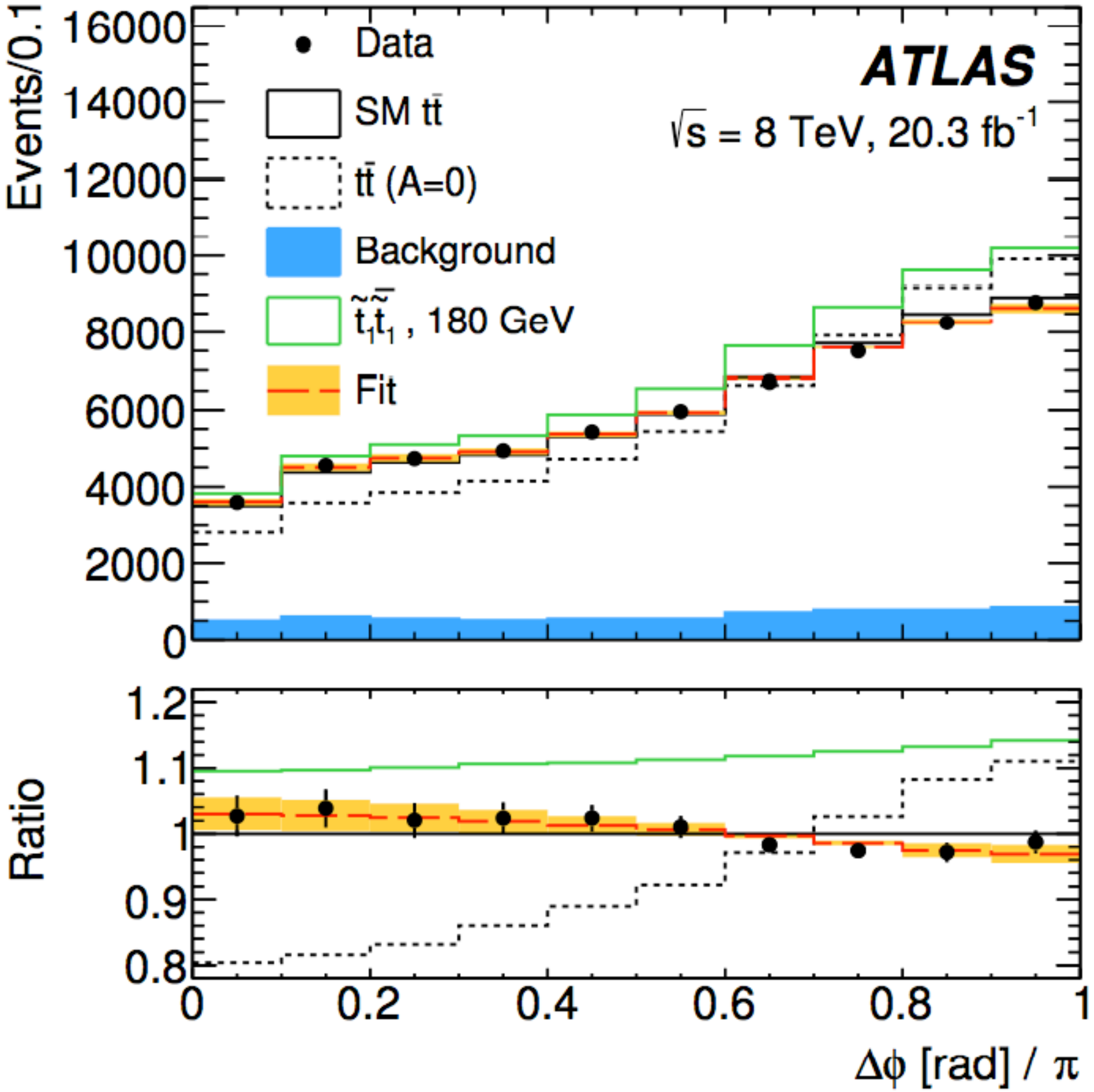
CMS search for pair production of $\tilde{t} \to t\chi \to Wb\chi$

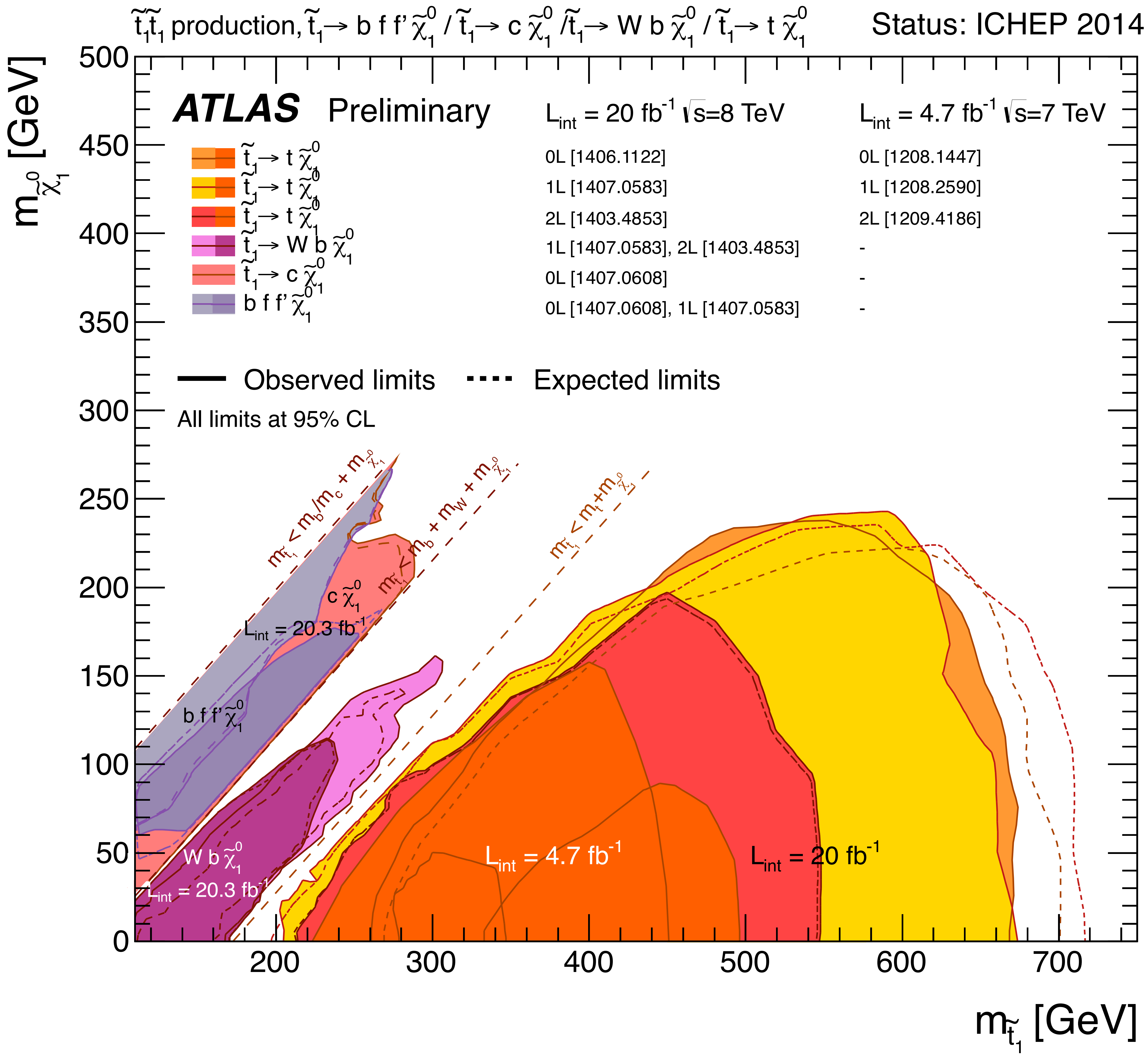


CMS search for pair production of $\tilde{t} \to W\tilde{b} \to Wb\chi$



ATLAS direct search for production of spin 0 particles along with $t\bar{t}$:




$\tilde{t}_1\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b f f' \tilde{\chi}^0_1$ / $\tilde{t}_1 \rightarrow c \tilde{\chi}^0_1$ / $\tilde{t}_1 \rightarrow W b \tilde{\chi}^0_1$ / $\tilde{t}_1 \rightarrow t \tilde{\chi}^0_1$
Status: ICHEP 2014
ATLAS Preliminary
L_{int} = 20 fb^{-1} $\sqrt{s}$=8 TeV
L_{int} = 4.7 fb^{-1} $\sqrt{s}$=7 TeV
$\tilde{t}_1 \rightarrow t \tilde{\chi}^0_1$ 0L [1406.1122] 0L [1208.1447]
$\tilde{t}_1 \rightarrow t \tilde{\chi}^0_1$ 1L [1407.0583] 1L [1208.2590]
$\tilde{t}_1 \rightarrow t \tilde{\chi}^0_1$ 2L [1403.4853] 2L [1209.4186]
$\tilde{t}_1 \rightarrow W b \tilde{\chi}^0_1$ 1L [1407.0583], 2L [1403.4853] -
$\tilde{t}_1 \rightarrow c \tilde{\chi}^0_1$ 0L [1407.0608] -
b f f' $\tilde{\chi}^0_1$ 0L [1407.0608], 1L [1407.0583] -
Observed limits
Expected limits
All limits at 95% CL
$m_{\tilde{t}_1} < m_b/m_c + m_{\tilde{\chi}^0_1}$
$m_{\tilde{t}_1} < m_b + m_W + m_{\tilde{\chi}^0_1}$
$m_{\tilde{t}_1} < m_t + m_{\tilde{\chi}^0_1}$
c $\tilde{\chi}^0_1$
L_{int} = 20.3 fb^{-1}
b f f' $\tilde{\chi}^0_1$
W b $\tilde{\chi}^0_1$
L_{int} = 20.3 fb^{-1}
L_{int} = 4.7 fb^{-1}
L_{int} = 20 fb^{-1}
$m_{\tilde{\chi}^0_1}$ [GeV]
0
50
100
150
200
250
300
350
400
450
500
$m_{\tilde{t}_1}$ [GeV]
200
300
400
500
600
700

If the Higgs particles are composite and Goldstone bosons, they arise from spontaneous symmetry breaking among some unknown, heavy particles.

If the symmetries among these particles are not exact, that can generate corrections that drive the Higgs mass term to be nonzero.

Such corrections can be generated when we try to incorporate the large value of the top quark mass into the framework.

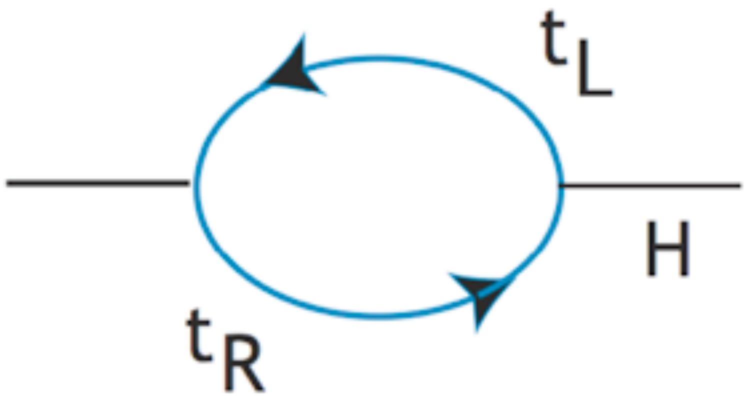
For example, in the scheme of Arkani-Hamed, Cohen, Katz, and Nelson, the massless quark multiplets

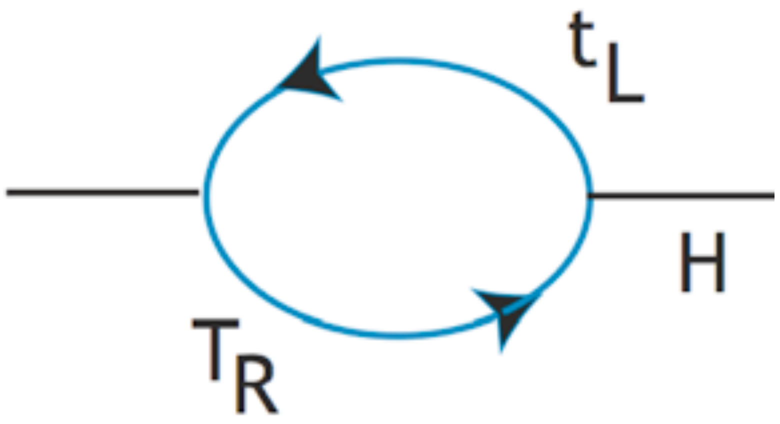
$$(t_L, b_L) \ , \ t_R$$

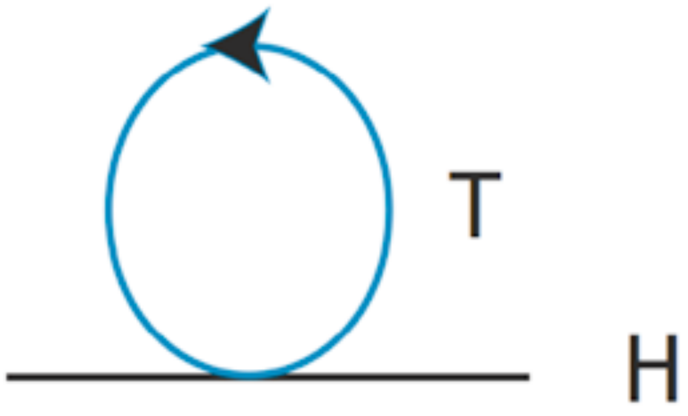
mix with a massive fermion

$$T_L \ , \ T_R$$

The Higgs mass is generated by diagrams







which are automatically free of quadratic divergences.

One finds

$$\mu^2 = -3\frac{\alpha_T}{2\pi} m_T^2 \log \frac{M^2}{m_T^2}$$

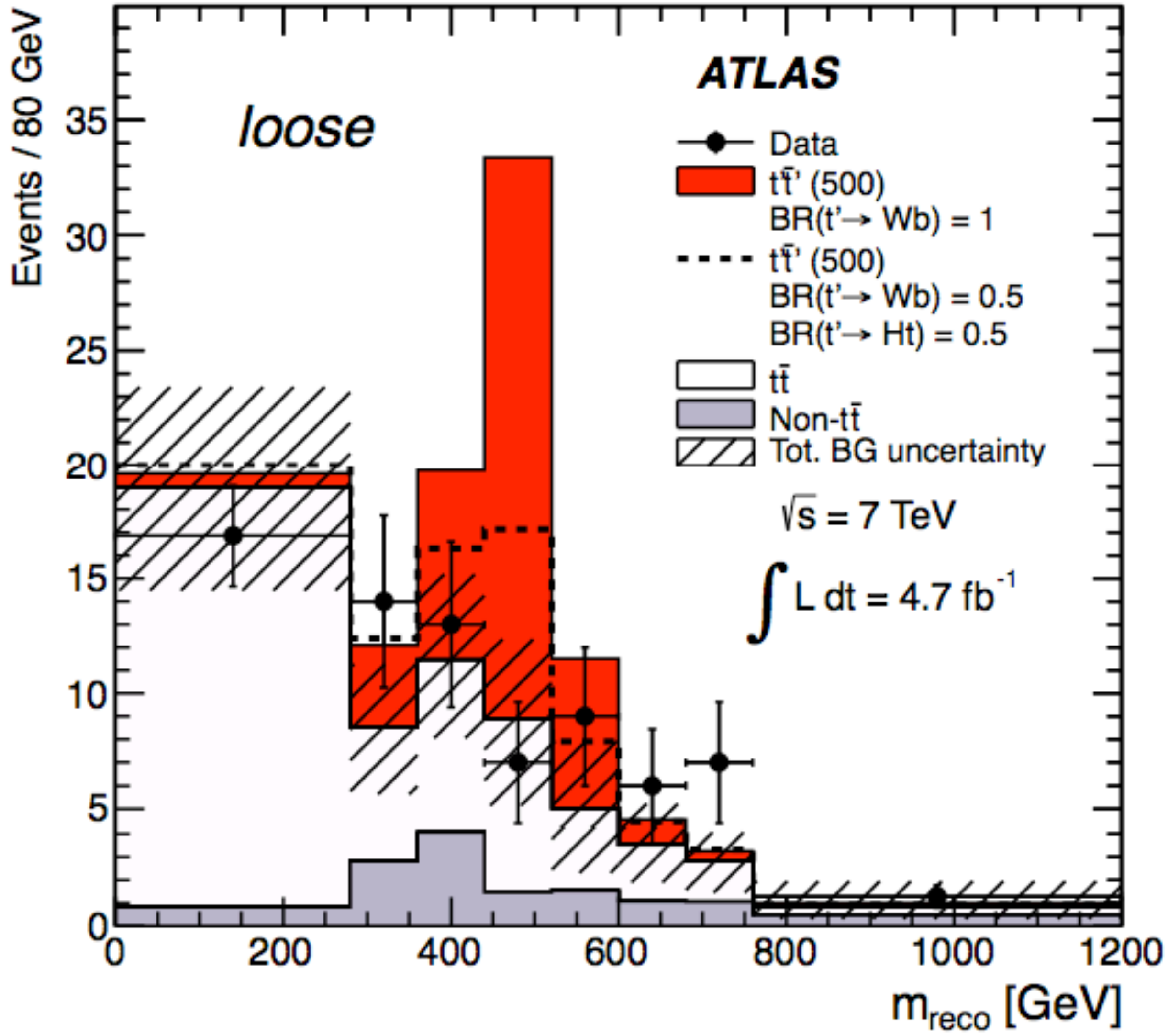
where M is the compositeness scale and α_T is a quark-Higgs couplings related to α_t .

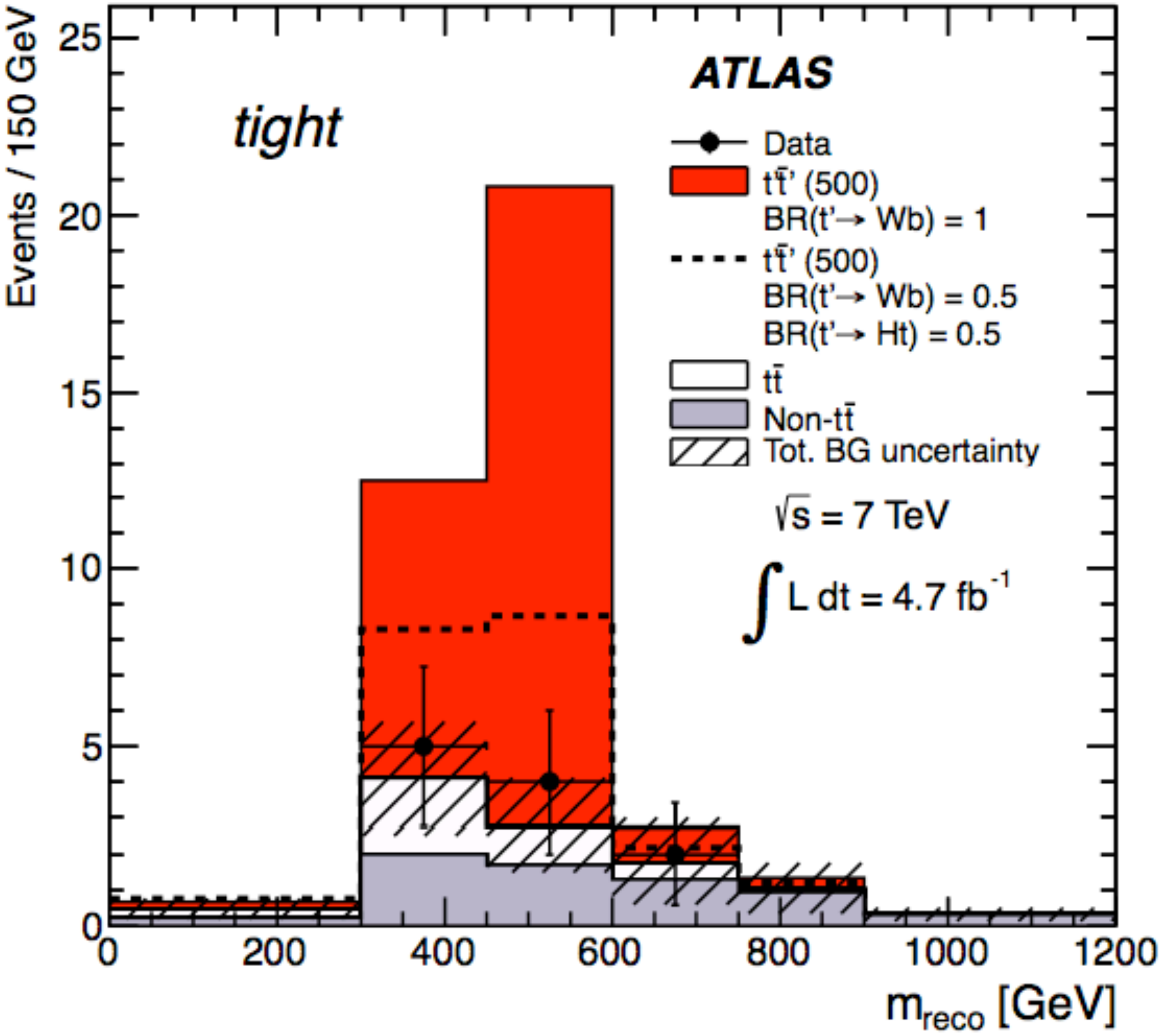
The negative sign here ultimately derives from the negative sign in the top quark loop diagram, but scale of the effect is set by the properties of the T .

The mechanism is beautiful, but to make it work the heavy partners of the top quark must exist, and at values of the mass not so far from

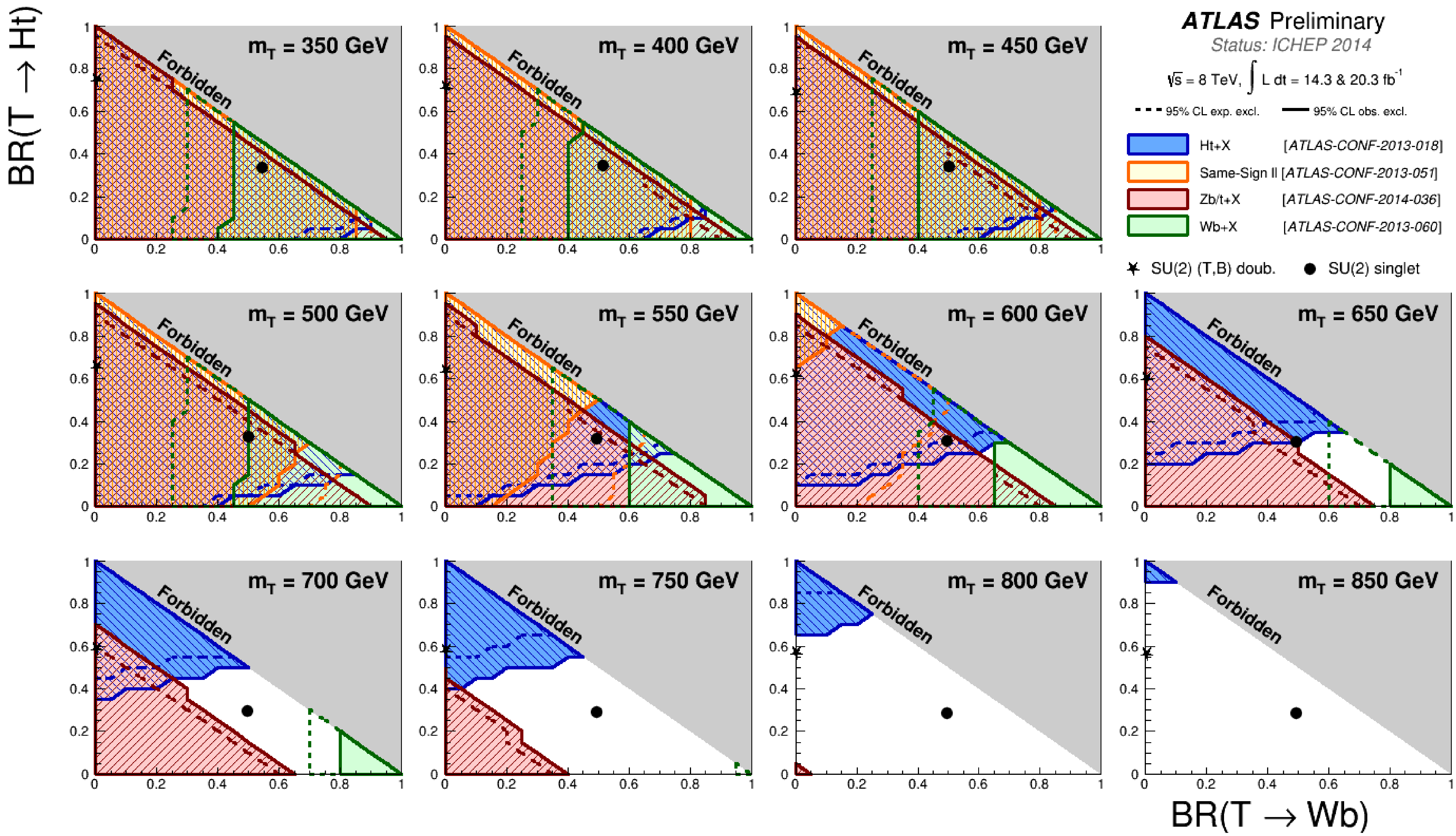
$$\langle \varphi \rangle = 250 \text{ GeV}$$

ATLAS search for pair production of $T \to W\, b$





ATLAS constraints on $T \rightarrow W\,b\;,\;\; Z\,t\;,\;\; h\,t$

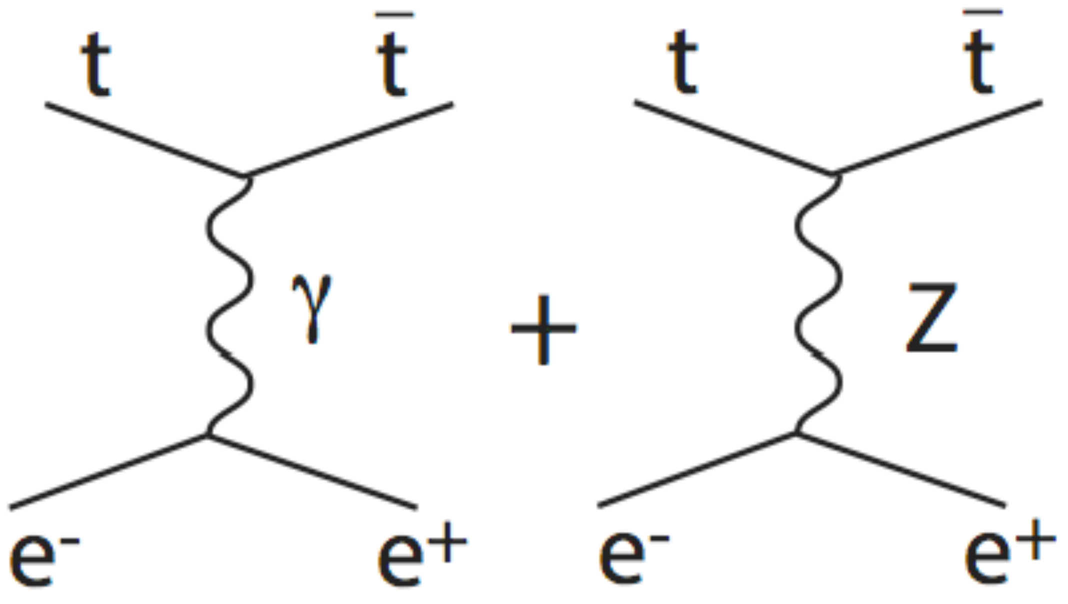


Models with composite Higgs bosons and top quark partners have another interesting consequence, that the

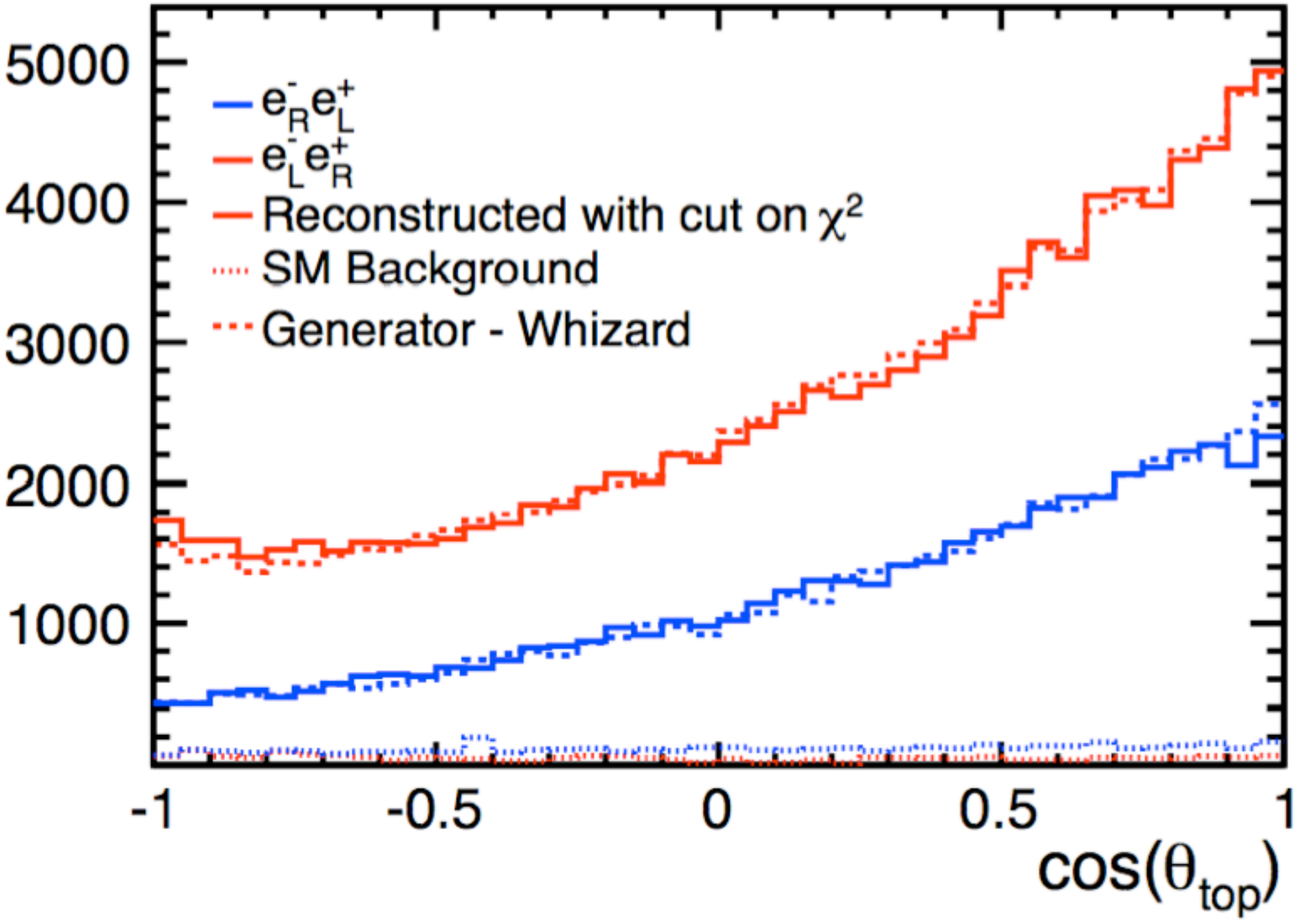
$$t\bar{t}Z$$

may receive small but measurable corrections.

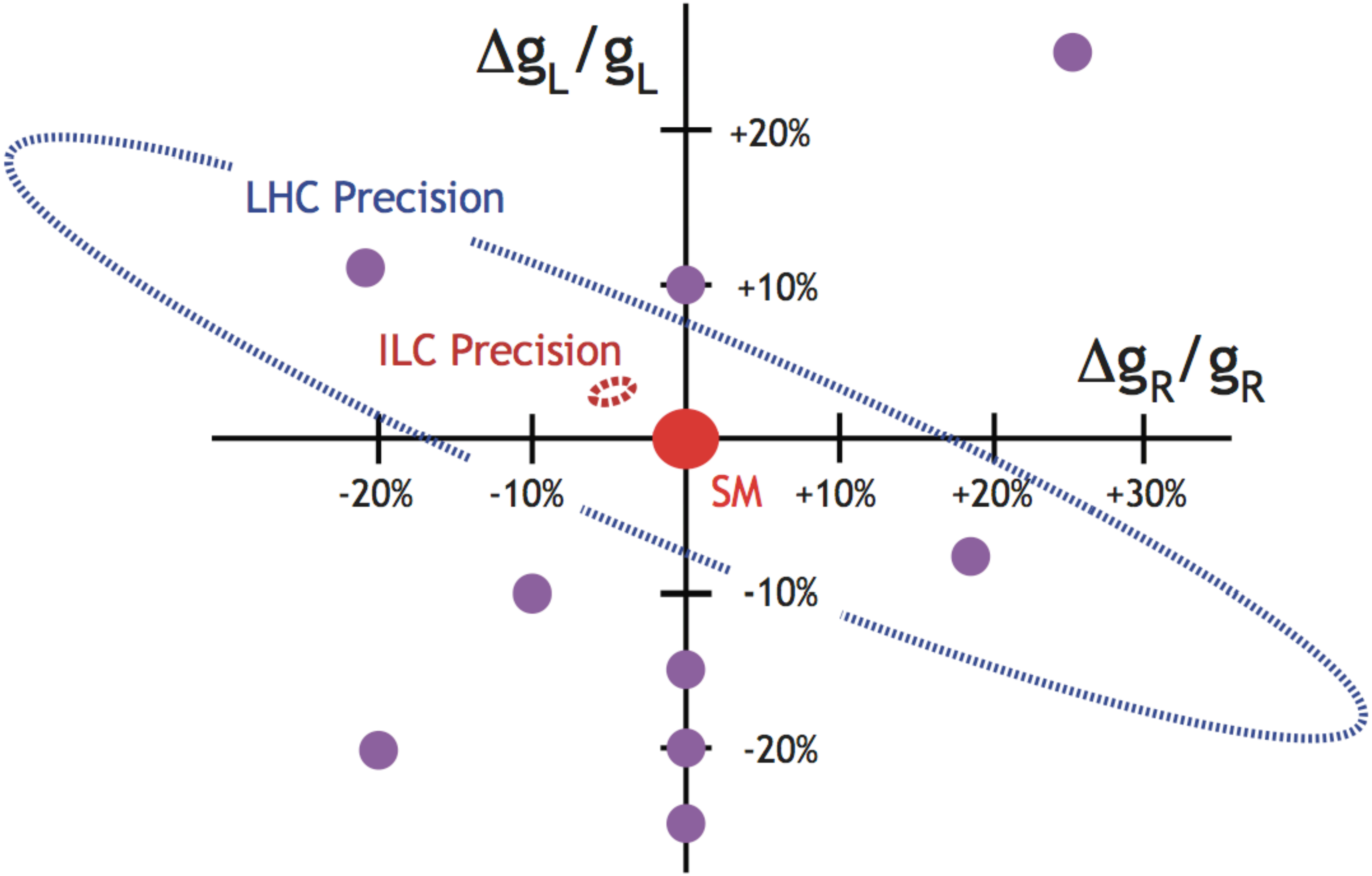
The ideal tool to measure these couplings would be an electron-positron collider, for which the $t\bar{t}Z$ couplings are an intrinsic part of the top quark production mechanism.



simulated angular distribution of $e^+e^- \to t\bar{t}$ at the International Linear Collider with polarized beams



expected LHC and ILC measurements vs predictions of composite Higgs models



We still do not know the role of the top quark in a broader picture of the fundamental interactions.

Is the top quark ordinary, but just somewhat oversized ?

Does it play an essential role in the physics of the Higgs field ?

Either answer is possible.   The coming run of the LHC, and future experiments at e+e- colliders, will test these possibilities.