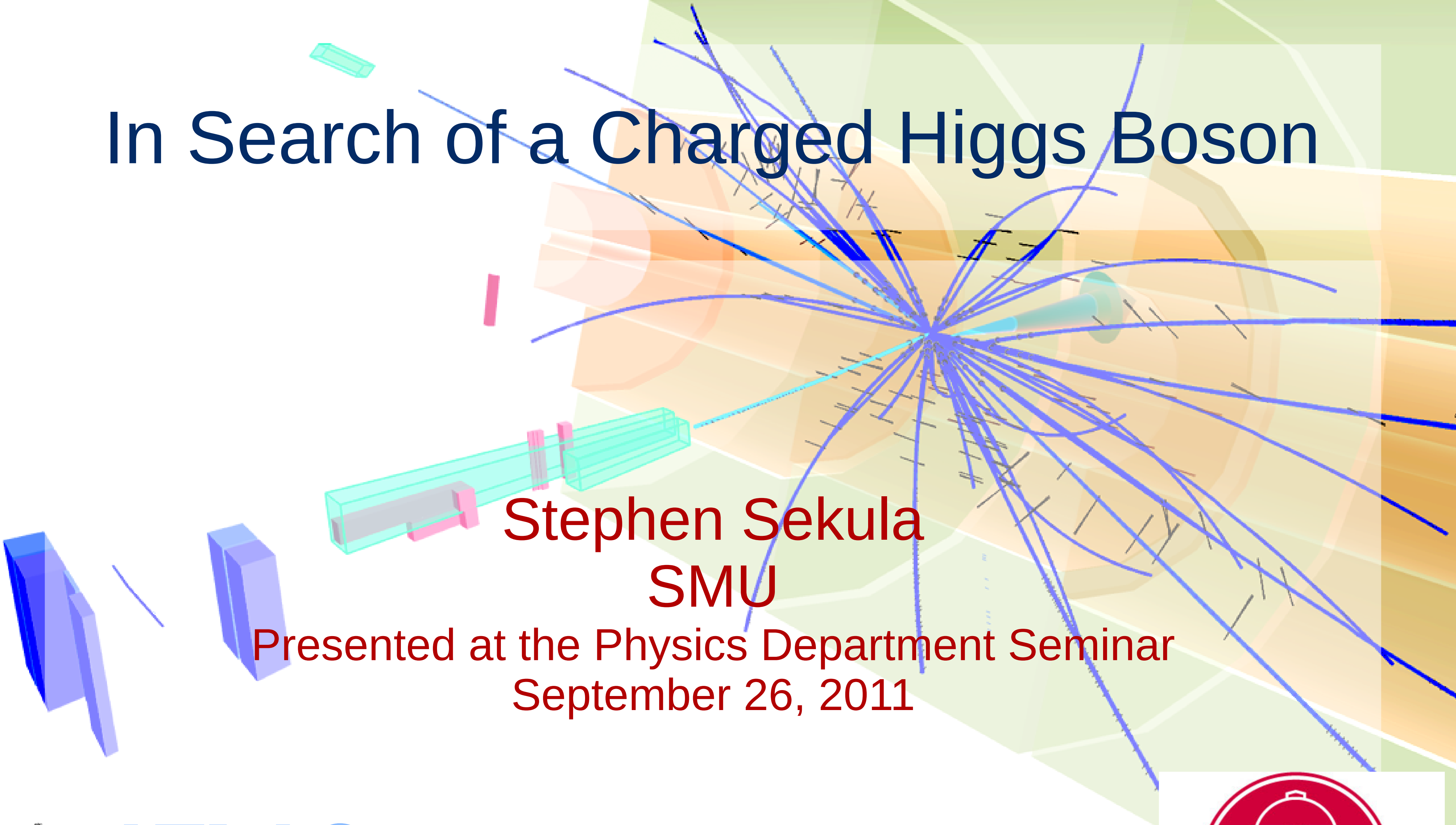


In Search of a Charged Higgs Boson

Stephen Sekula
SMU

Presented at the Physics Department Seminar
September 26, 2011

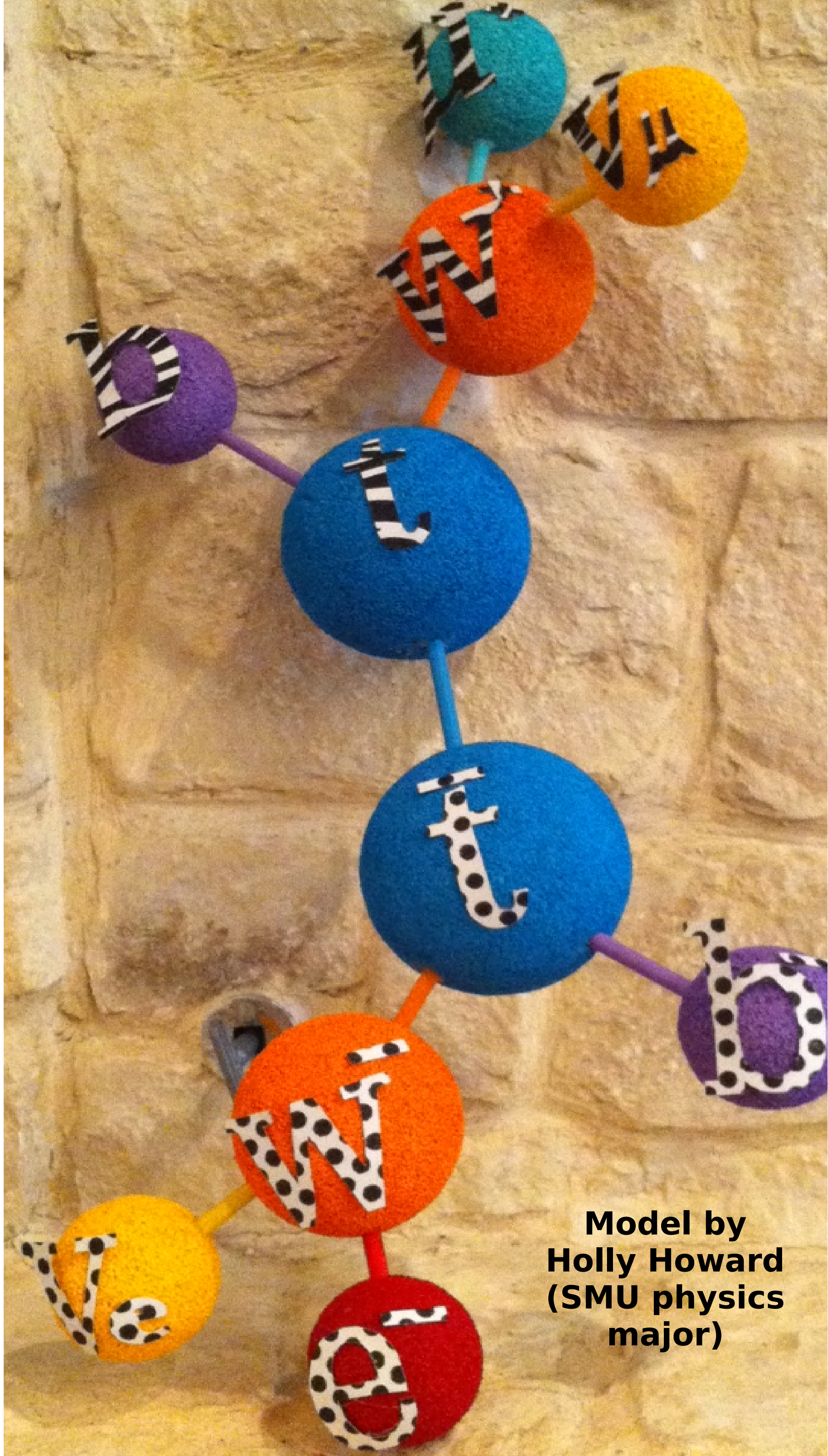
ATLAS EXPERIMENT
http://atlas.ch

BABAR

SMU

Programme

- Theoretical Motivation
  - Standard Model (SM)
  - Beyond the SM
  - Supersymmetry (SUSY) and the MSSM Higgs scenario(s)
- Low-energy implications
  - how does a charged Higgs affect precision physics at low energy?
- The direct test at high energy
  - The Large Hadron Collider and the ATLAS Experiment
  - Direct search for a “low mass” H+



Model by Holly Howard (SMU physics major)

The Standard Model Higgs

Mass is introduced in the Standard Model by introducing a complex isodoublet, Φ, whose self-interactions provide a mechanism for spontaneous symmetry breaking and gives rise to fermion and boson masses

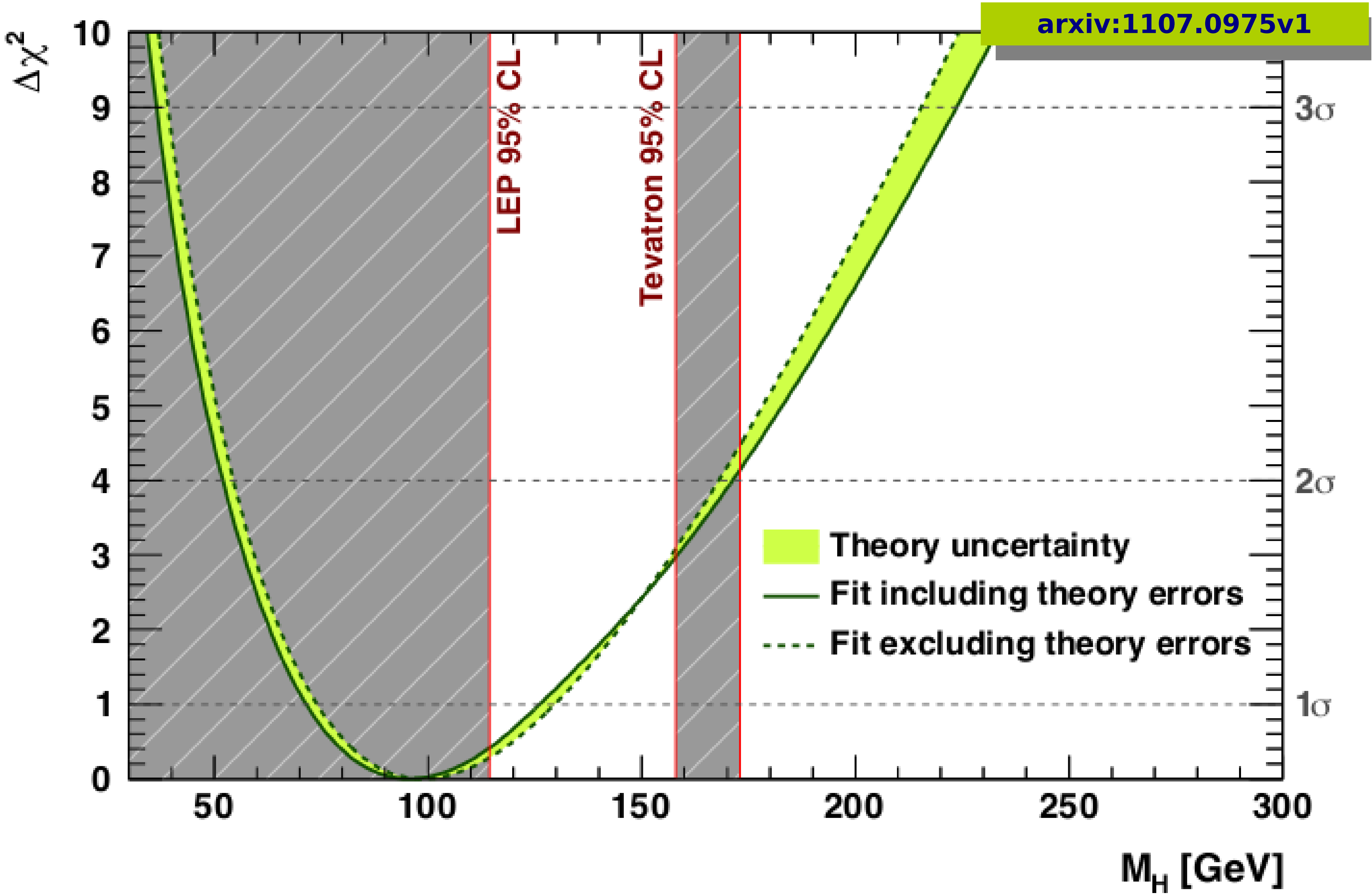
$$\Phi = \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix} \longrightarrow$$

Adds 4 degrees of freedom to the Standard Model, which by a clever gauge transformation can be made to appear at the three longitudinal polarizations of the W^+, W^-, and Z^0 bosons and in the mass of a new scalar boson, the Higgs.

$$V(\Phi) = \mu^2 |\Phi|^2 + \lambda |\Phi|^4 \longrightarrow m_H = \sqrt{-2\mu^2}$$

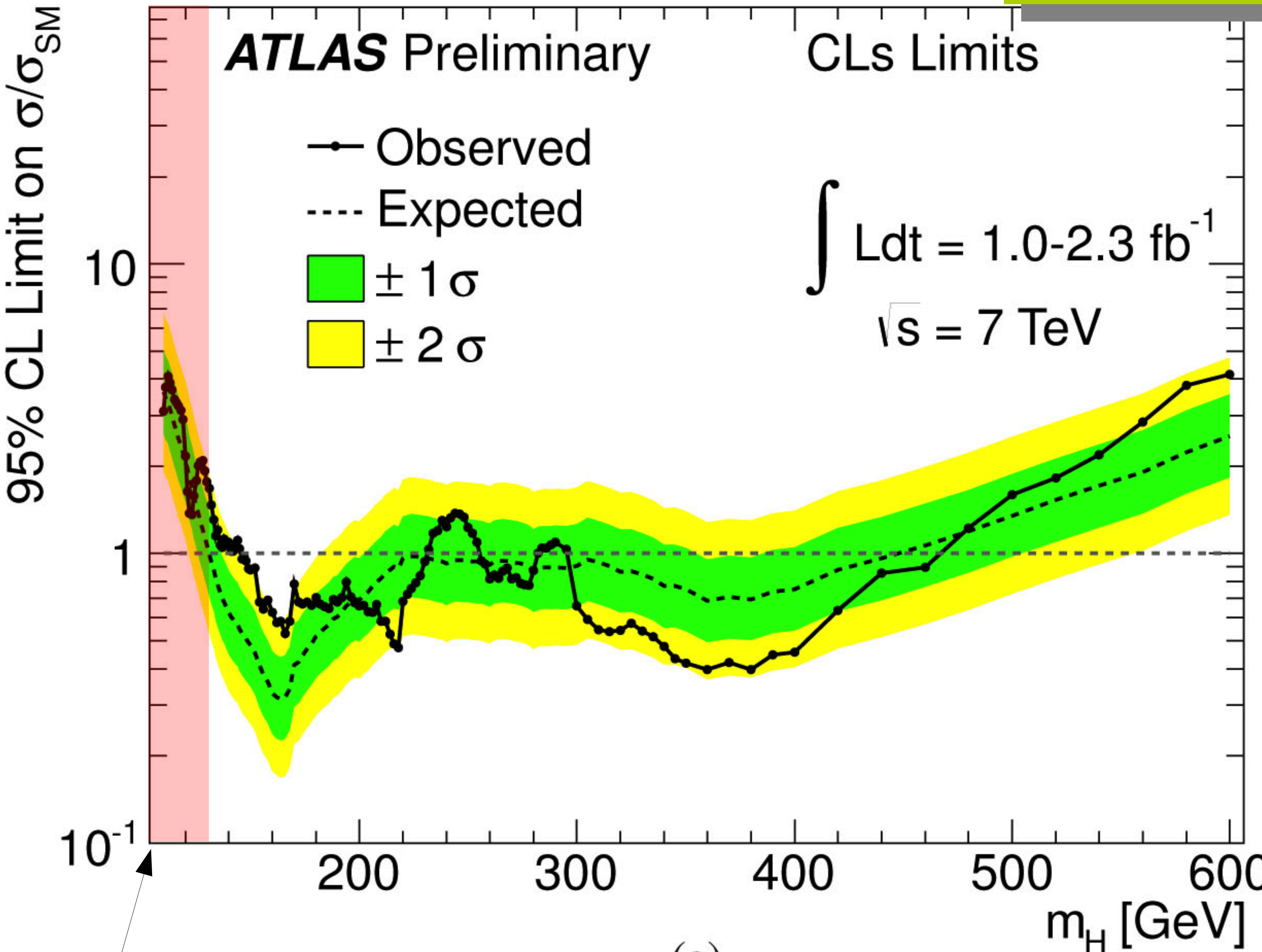
$$m_H = \sqrt{-2\lambda v^2} \longrightarrow$$

Vacuum Expectation Value (VEV) of the Higgs Field, v = 246 GeV



arxiv:1107.0975v1
$\Delta\chi^2$
10
9
8
7
6
5
4
3
2
1
0
LEP 95% CL
Tevatron 95% CL
3σ
2σ
1σ
Theory uncertainty
Fit including theory errors
Fit excluding theory errors
50
100
150
200
250
300
M_H [GeV]

ATLAS-CONF-2011-135



(a)

Red region indicates central value + 1σ for indirect prediction of Higgs mass.

Extending the Standard Model

- We have good reason to believe the SM is incomplete
  - e.g. neutrino mass/mixing, divergence of corrections to Higgs mass, dark matter, dark energy, that pesky gravity problem . . .
- Extending the SM to solve some of these problems typically means adding more fermions and bosons
  - if the Higgs mechanism is the origin of mass, you need more Higgs bosons to give mass to all the new particles in any extension

Minimal Supersymmetric Standard Model

- Extend the SM with Supersymmetry
  - adds a fermion for every boson, a boson for every fermion
- Requires the addition of at least one more Higgs field doublet
  - adds 4 more degrees of freedom (read: more unknowns that must be measured)
  - leads to 5 physical Higgs boson states:
    - H^0,h^0, A^0,H^+,H^-
  - The MSSM requires that up-type fermions couple to one doublet and down-type fermions couple to the other ("Type-II two-Higgs-doublet Model" or "Type-II 2HDM")

The Charged Higgs Boson

- Two of the new states are spin-0 and carry electric charge: $H^{\pm}$
- General statement:
  - there is no such “beast” in the Standard Model
  - observation of a charged scalar gauge boson would be unambiguous evidence of physics beyond the SM!
- Decay/Production Rates
  - depend on charged Higgs mass and the parameter tan β:

$$\tan\beta \equiv \frac{v_2}{v_1}$$

v_2: VEV for doublet that couples to down-type fermions (d,s,b,e,μ,τ)

v_1: VEV for doublet that couples to up-type fermions (u,c,t, ν)

Charged Higgs Decay

- Decay modes
  - $H^{\pm} \rightarrow \tau\,\nu$: dominates for large tanβ
    - this mode can be used to constrain tan β from above
  - $H^{\pm} \rightarrow c\,\bar{s}$: higher rate at low tanβ
    - can be used to constrain tanβ from below
  - $H^{\pm} \rightarrow t^{(*)}\bar{b}$:
    - also useful at low tanβ
    - difficult due to off-shell top at low H mass and in general due to top decay to many jets/leptons + MET

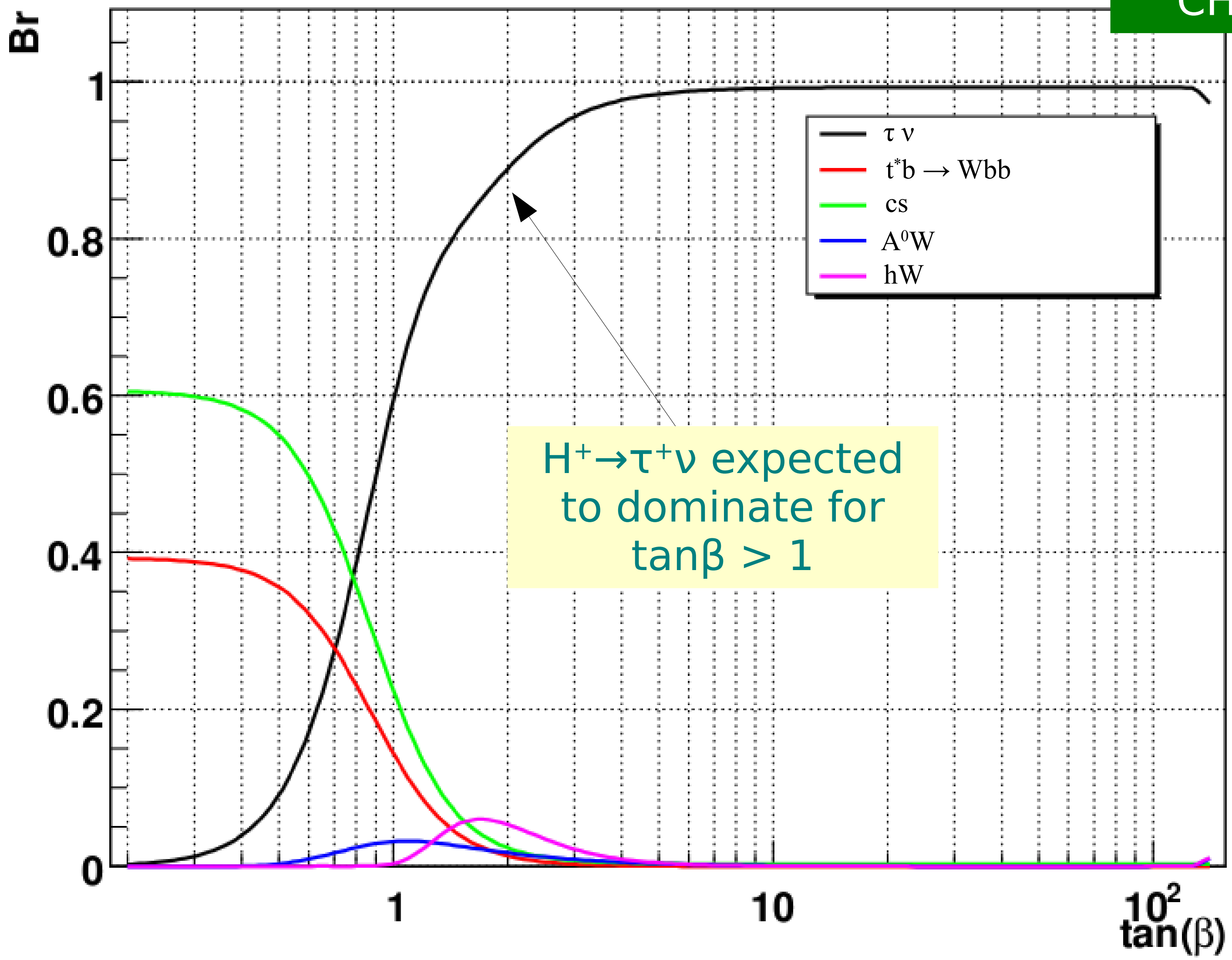
“m_h-max Scenario”

- One of the “benchmark points” in SUSY space for LHC searches
  - chosen to obtain the largest possible Higgs boson mass as a function of tanβ (e.g. m_h up to ~140GeV)

$$m_t = 174.3 \text{ GeV}, \quad M_{SUSY} = 1 \text{ TeV}, \quad \mu = 200 \text{ GeV}, \quad M_2 = 200 \text{ GeV},$$
$$X_t^{\text{OS}} = 2\, M_{SUSY} \text{ (FD calculation)}, \quad X_t^{\overline{\text{MS}}} = \sqrt{6}\, M_{SUSY} \text{ (RG calculation)}$$
$$A_b = A_t, \quad m_{\tilde{g}} = 0.8\, M_{SUSY} \ .$$

arXiv:hep-ph/0202167
(Eur.Phys.J.C26:601-607,2003)
and arXiv:hep-ph/9812472
(Eur.Phys.J.C9:343-366,1999)

P. Gutierrez, CHARGED2010

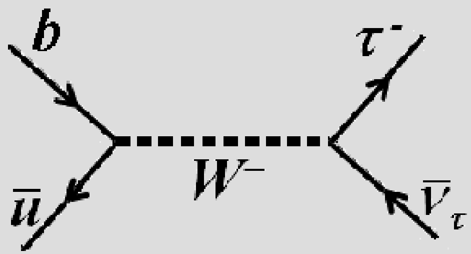


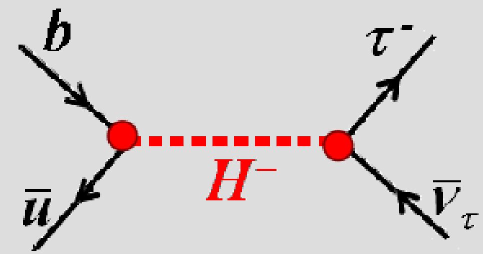
Trends in the decay branching fractions of H+ for m_{H+}=120GeV (computed using FeynHiggs in the m_h-max scenario of the MSSM)

Low-Energy Implications

leptonic

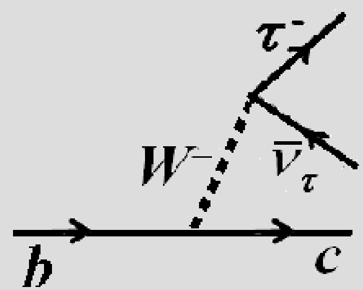
- $B \to \tau \nu_\tau$

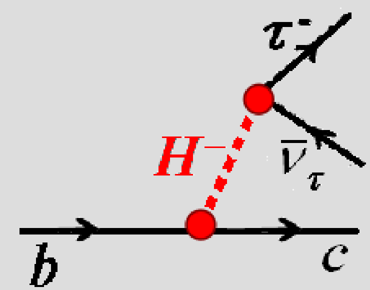




semileptonic

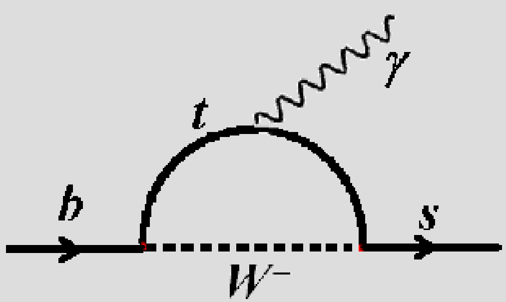
- $B \to D^{(*)} \tau \nu_\tau$

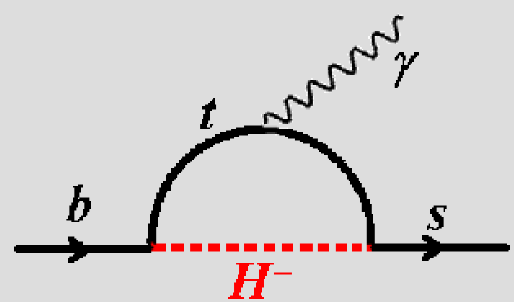




inclusive radiative

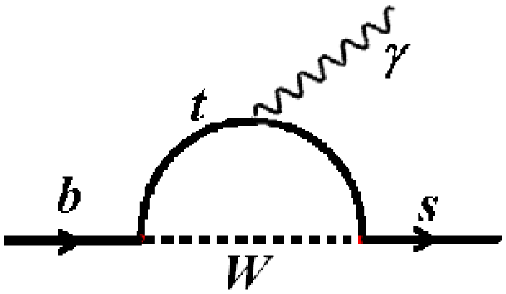
- $B \to X_s \gamma$



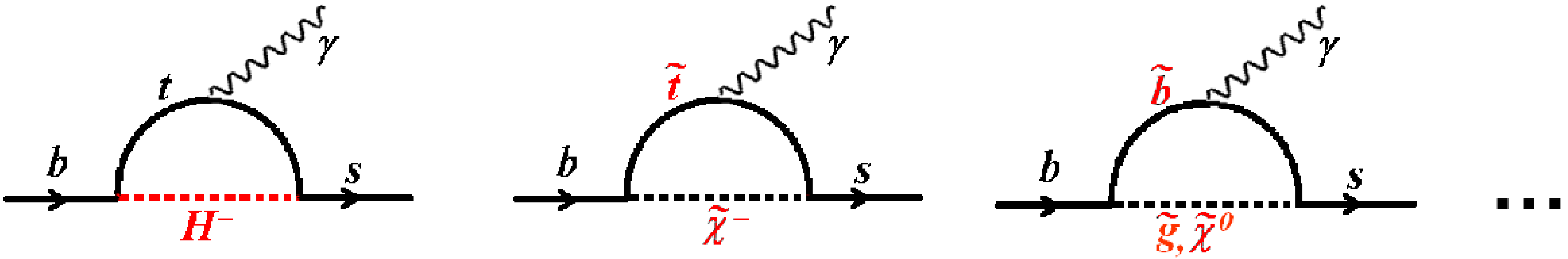


From Maria Różańska, CHARGED 2010

FCNC process
in SM occurs via loop diagram



new physics can enter with size comparable to SM contributions

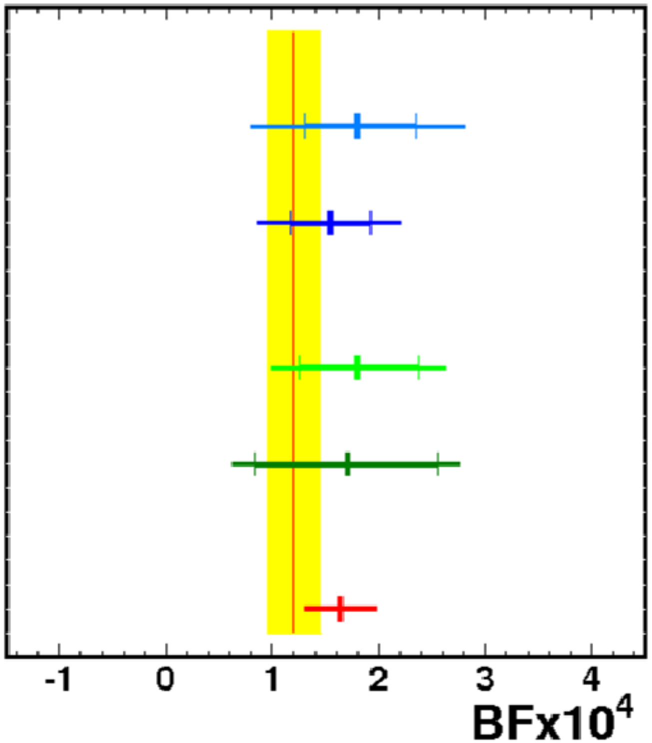


☺ *BF*-enhancement due to the amplitudes with *$H^{\pm}$* depends on $m_{H^{\pm}}$ but is almost independent of tanβ

☹ more NP processes complicate the interpretation…

From Maria Różańska, CHARGED 2010

$BF(B^{+} \to \tau^{+}\nu_{\tau})$



stat. syst.

$[1.79^{+0.56}_{-0.49}(stat)^{+0.46}_{-0.51}(syst)] \times 10^{-4}$ — hadronic tags

$[1.54^{+0.38}_{-0.37}(stat)^{+0.35}_{-0.37}(syst)] \times 10^{-4}$ — semileptonic tags

$[1.80^{+0.57}_{-0.54}(stat) \pm 0.26(syst)] \times 10^{-4}$ — hadronic tags

$[1.7 \pm 0.8(stat) \pm 0.2(syst)] \times 10^{-4}$ — semileptonic tags

$[1.64 \pm 0.34] \times 10^{-4}$ — **HFAG** Aug. 2010 — average[1]

Standard Model[2]

Results consistent within uncertainties, but all above the SM prediction

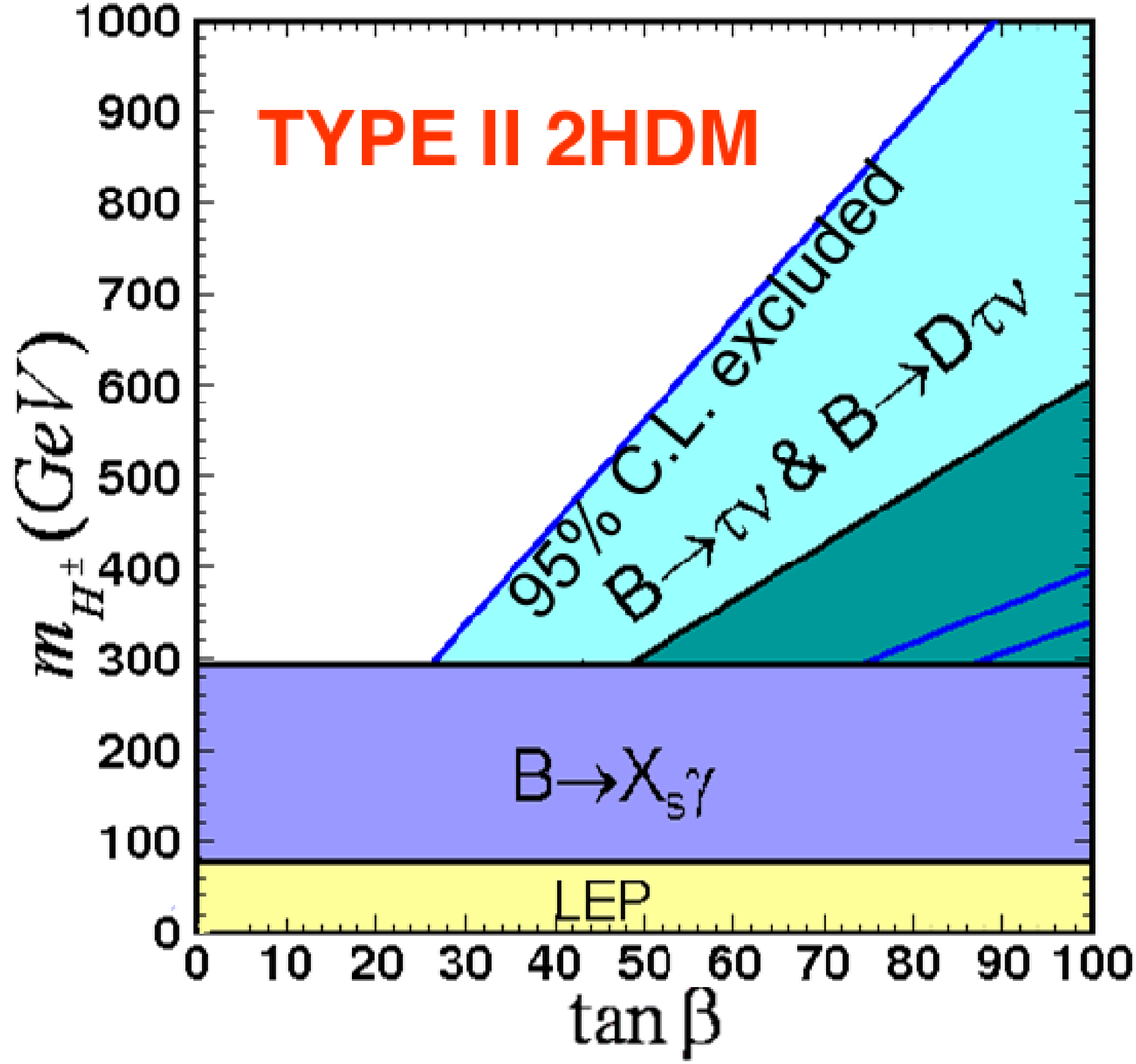
$r_H = 1.37 \pm 0.39$

[1] HFAG, http://www.slac.stanford.edu/xorg/hfag

[2] $|V_{ub}| = (4.32 \pm 0.16 \pm 0.29) \times 10^{-3}$ HFAG ICHEP08

$f_B = 190 \pm 13\,\text{MeV}$ HPQCD arXiv:0902.1815

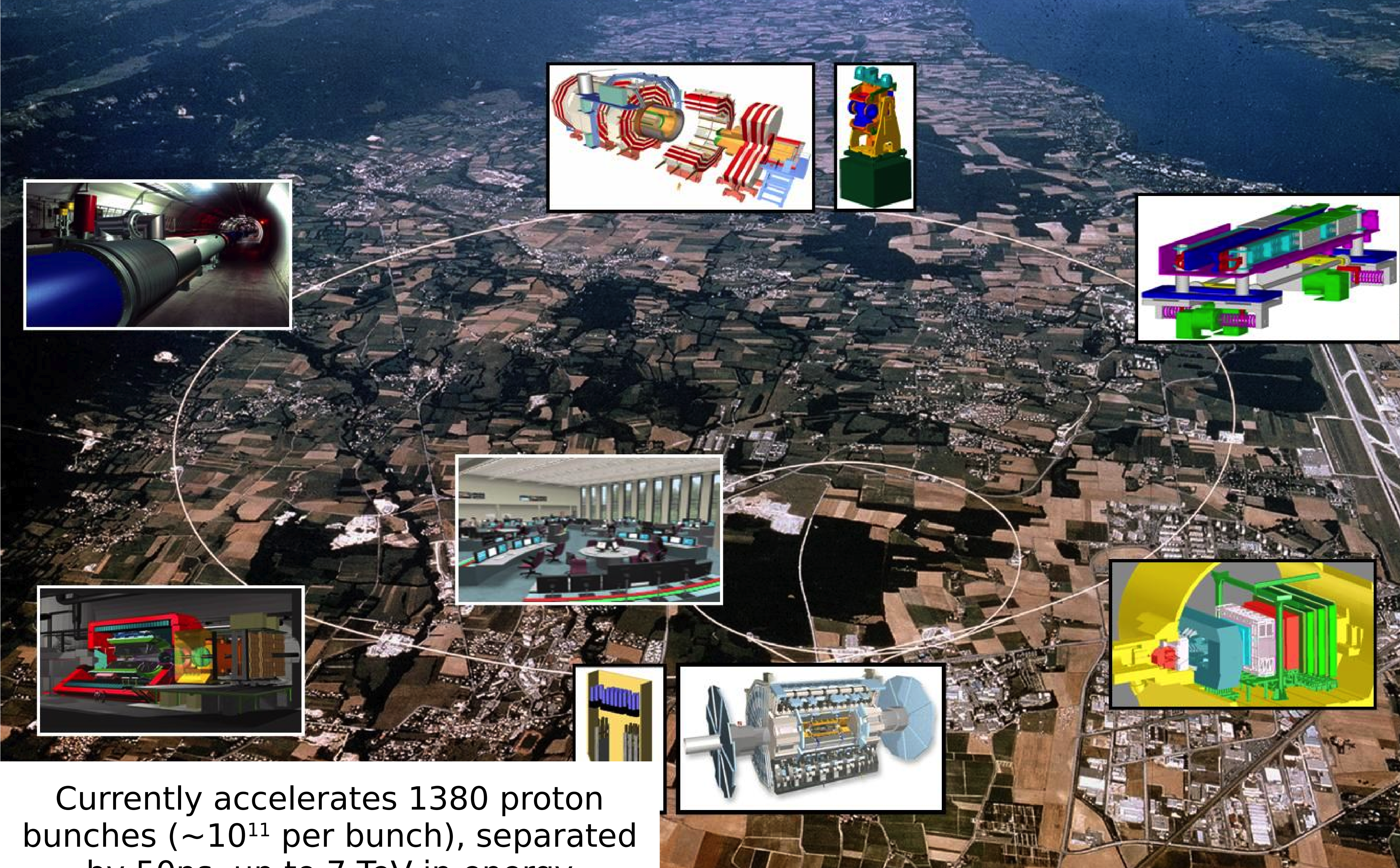
From Maria Różańska, CHARGED 2010



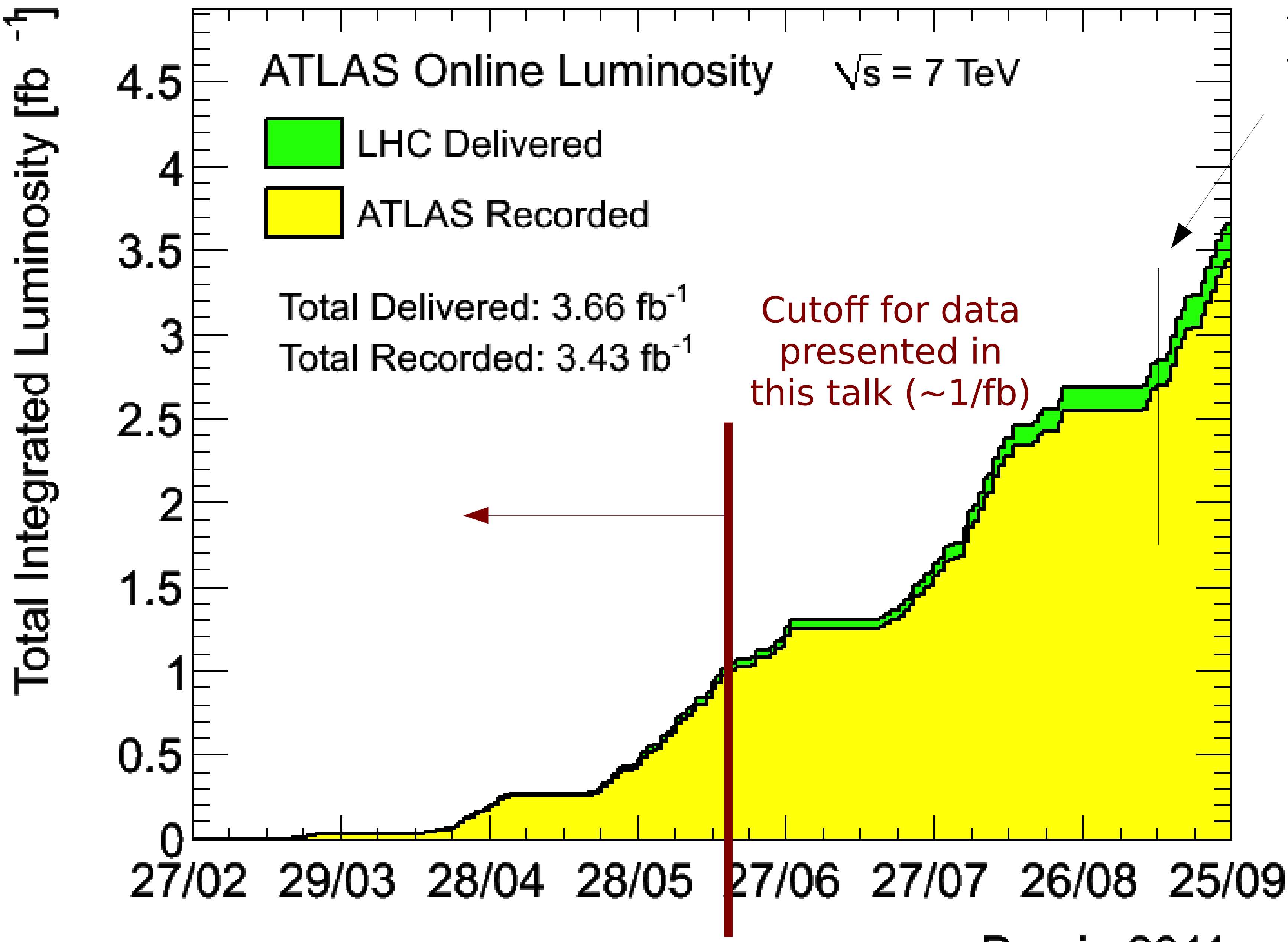
Indirect constraints would suggest that a charged Higgs is excluded whose mass is <300 GeV (tan β < 25) or whose mass is less than [300,1000] GeV for tanβ>25 . . .

But one must always be careful with indirect constraints. We have an unprecedented data sample for direct search, and we should use it!

The Large Hadron Collider @ CERN in Geneva, Switzerland



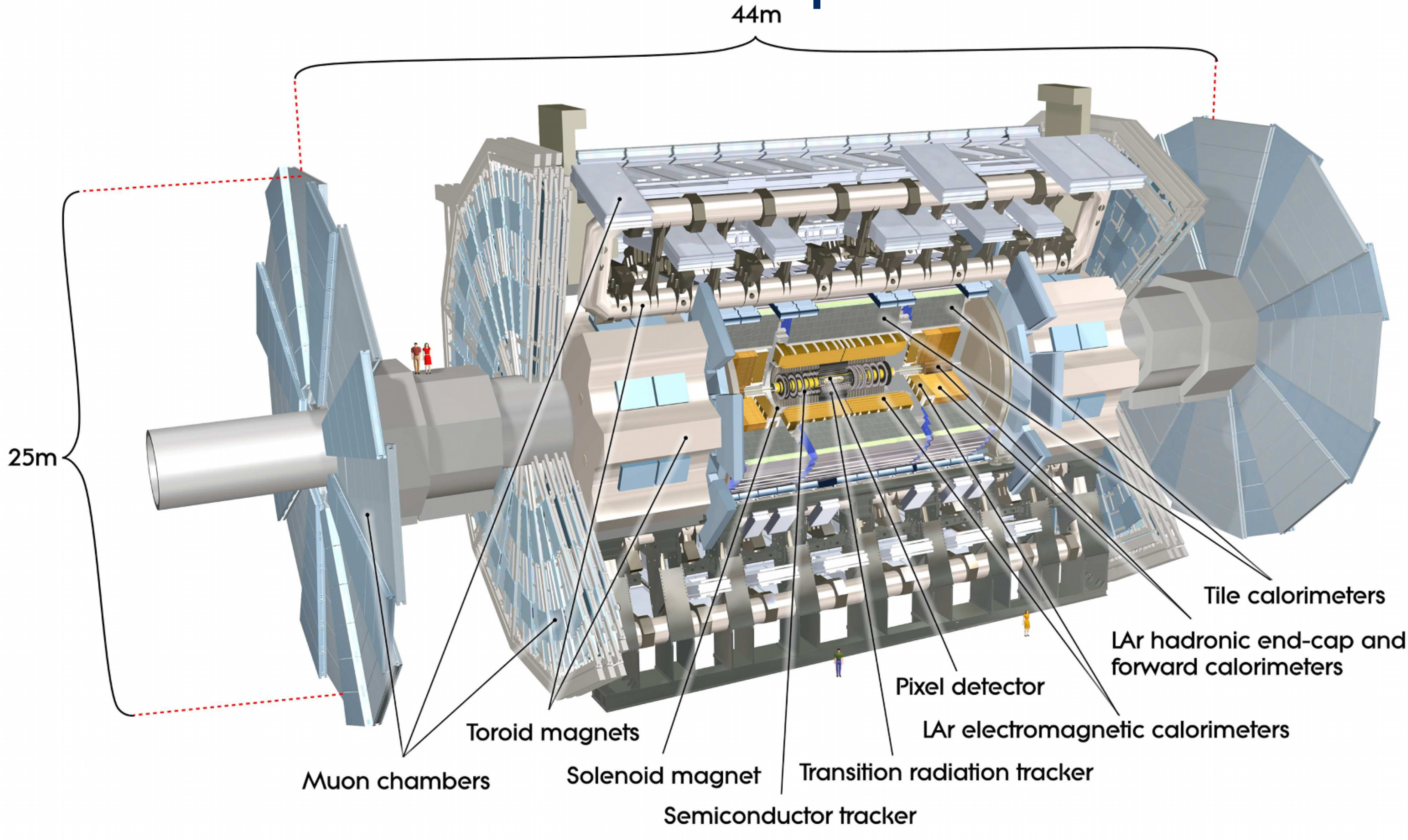
Currently accelerates 1380 proton bunches (~10^{11} per bunch), separated by 50ns, up to 7 TeV in energy (designed for 14 TeV)

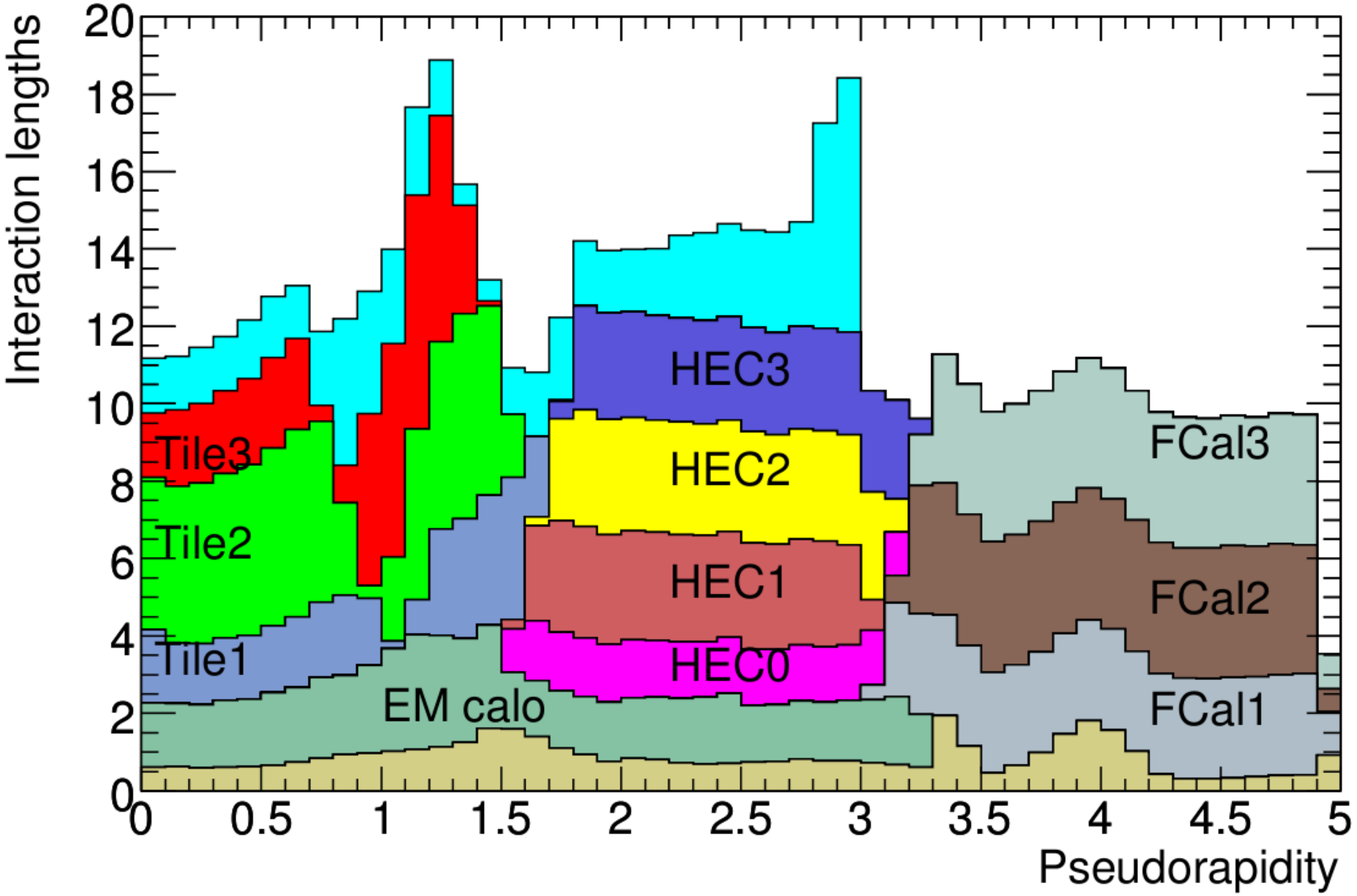


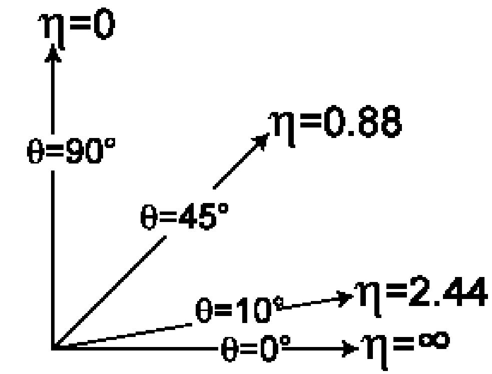
This marks the date of Ryszard's seminar two weeks ago!

Remember: $L \cdot \sigma = N$

The ATLAS Experiment



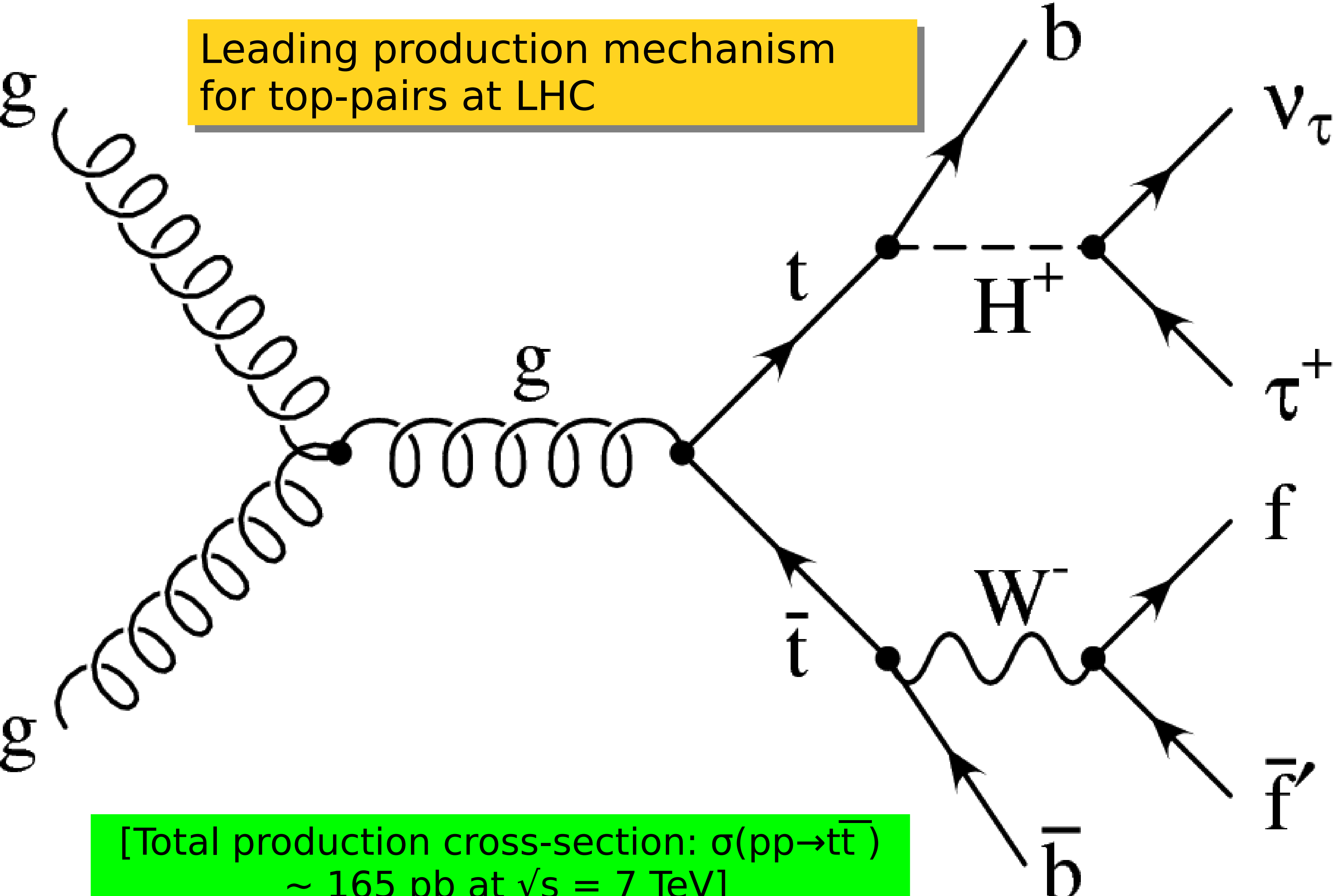




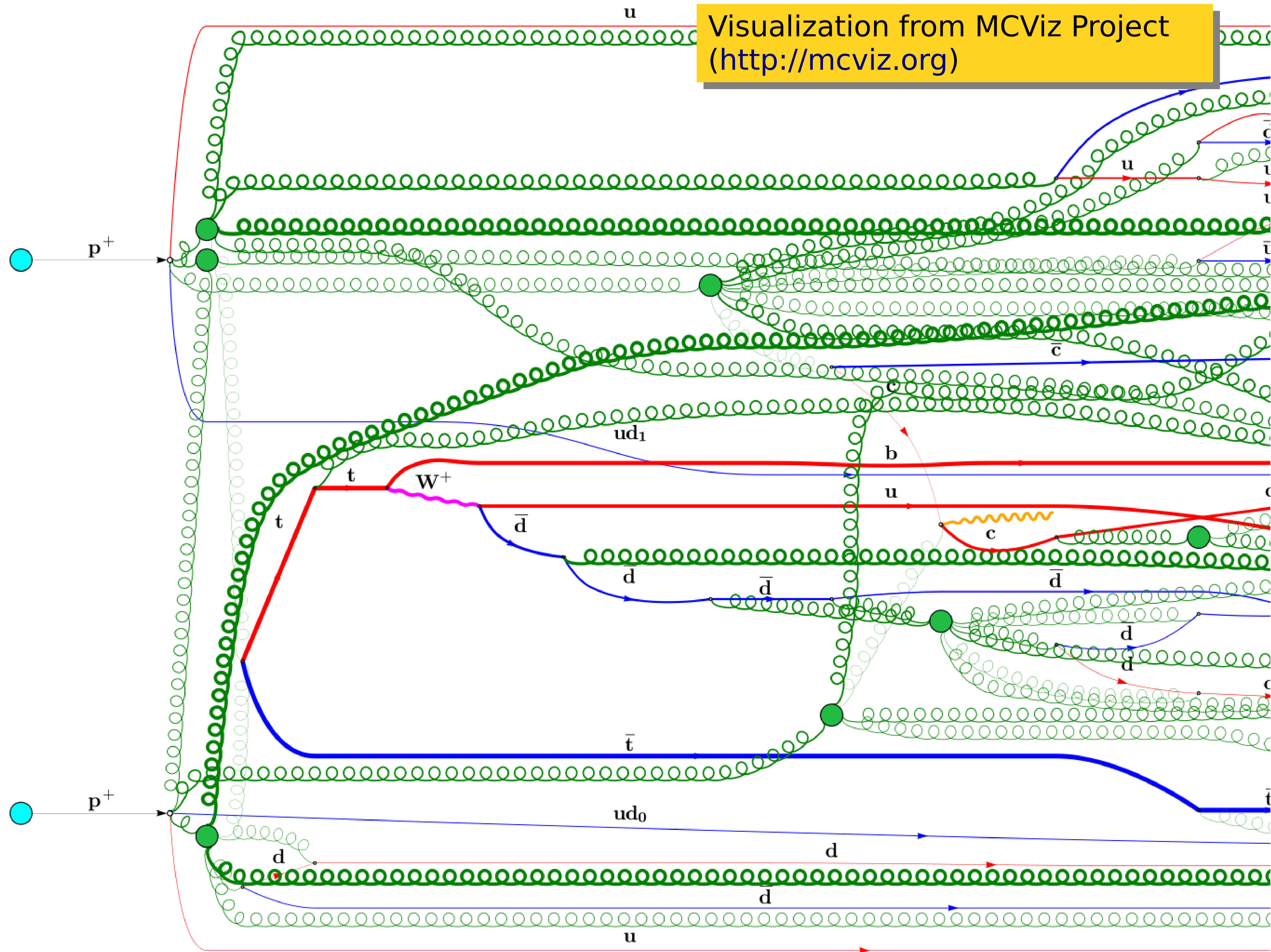
$$\eta = -\log\left(\tan\left(\frac{\theta}{2}\right)\right)$$

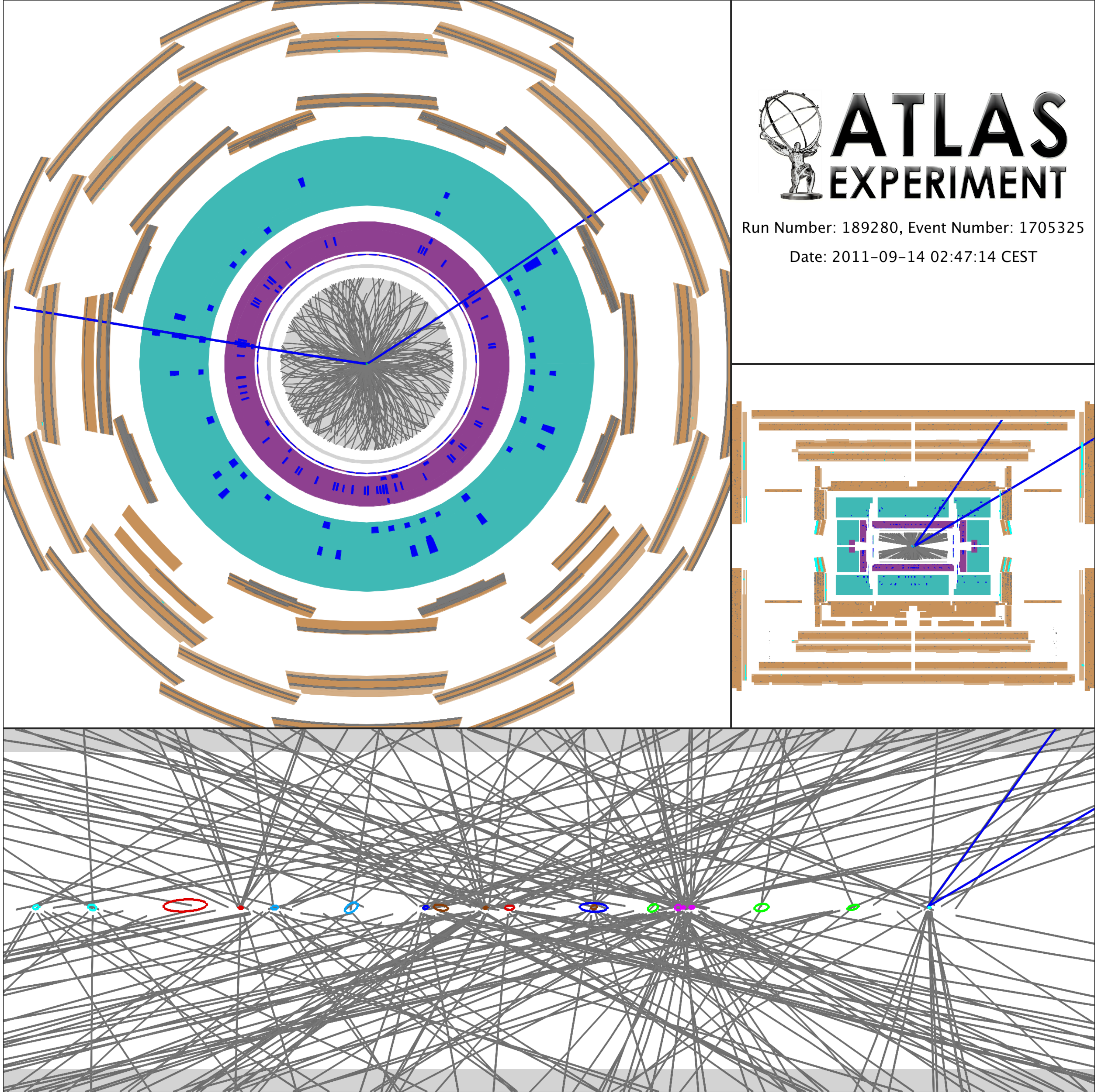
Since much of what I will be talking about today is based on jet reconstruction, it's useful to note that using jets with |η|>2.5 means risking incomplete containment of the jets in the EM and Hadronic Calorimeters.

Leading production mechanism
for top-pairs at LHC

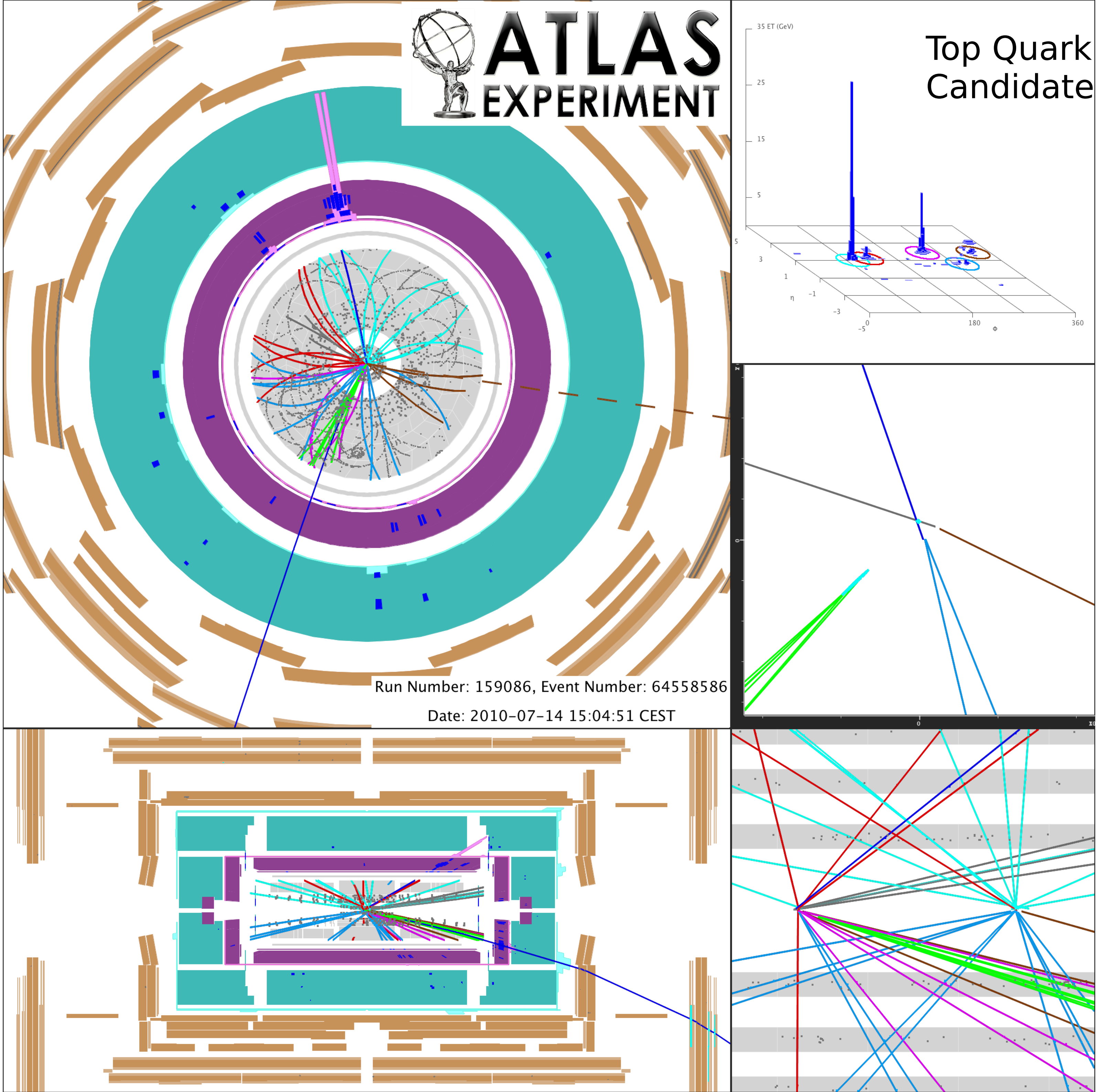


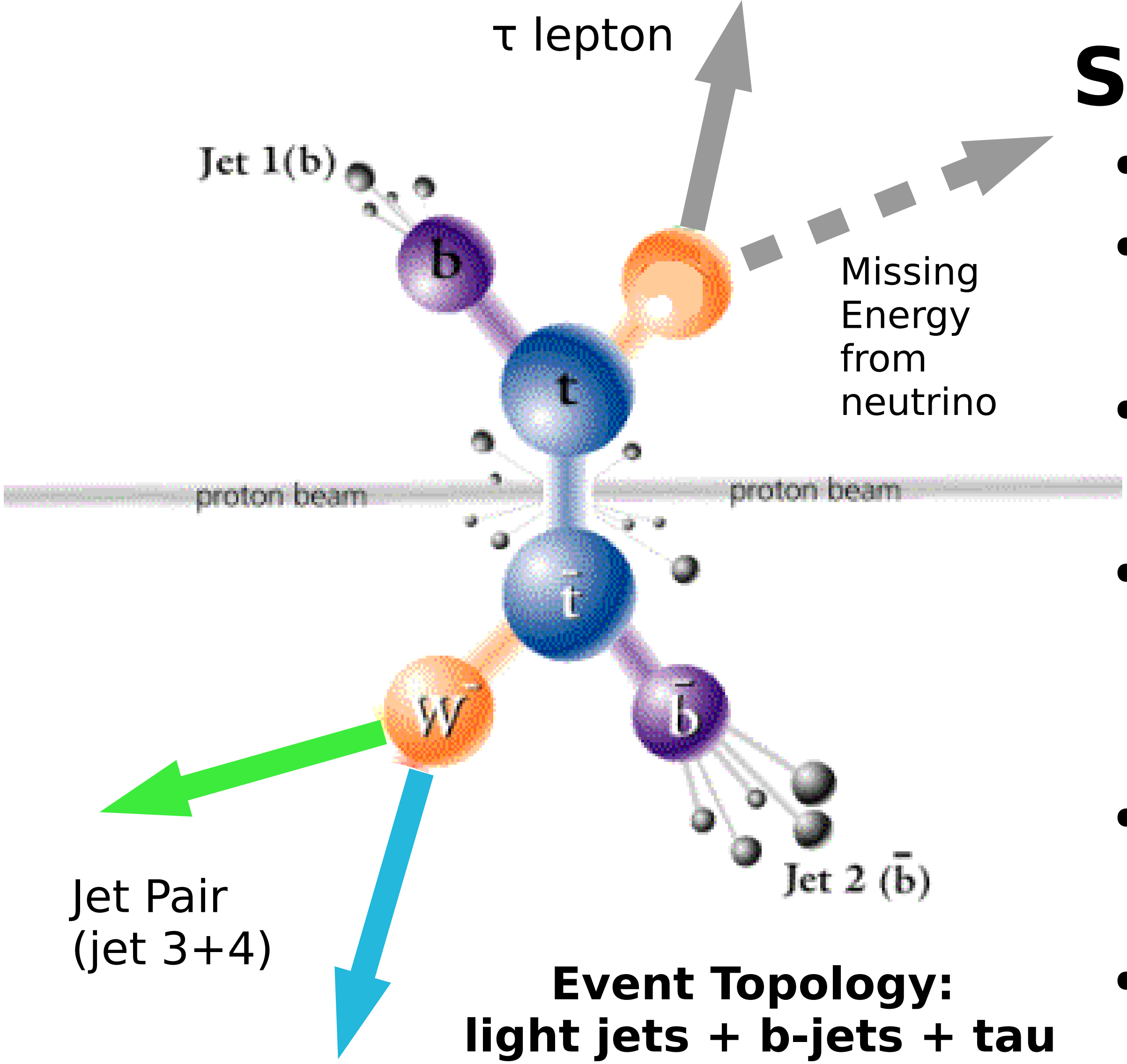
[Total production cross-section: $\sigma(pp \to t\bar{t})$
~ 165 pb at $\sqrt{s}$ = 7 TeV]


Visualization from MCViz Project
(http://mcviz.org)
u
p$^+$
p$^+$
t
t
W$^+$
b
u
$\overline{d}$
$\overline{d}$
$\overline{d}$
$\overline{d}$
d
d
c
$\overline{c}$
c
ud$_1$
$\overline{t}$
ud$_0$
d
d
$\overline{d}$
u


ATLAS EXPERIMENT
Run Number: 189280, Event Number: 1705325
Date: 2011-09-14 02:47:14 CEST

Top Quark Pair Candidate Event





Event Topology: light jets + b-jets + tau + MET

STRATEGY

- Require >= 4 jets
- Require >= 1 b-tagged jet
- Require a well-identified tau lepton
- Require significant missing transverse energy (MET)
- Combine (jj)b into a top quark candidate
- Study the tau+MET system

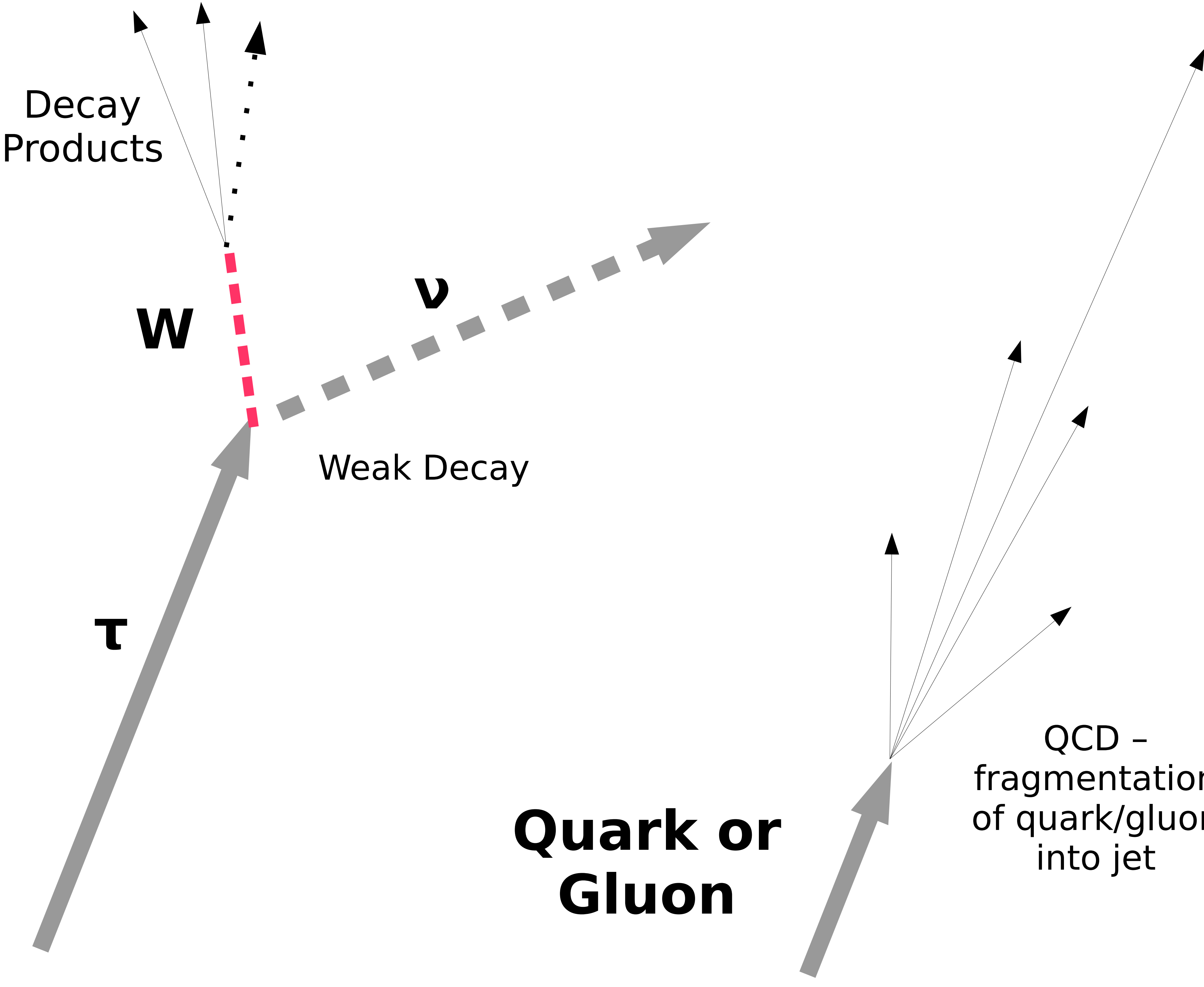
In the next part of the talk I'll focus in on a few key features of the reconstruction: tau identification and background rejection/estimation.

Simulations

Process	Generator	Cross section [pb]
$t\bar{t}$ with $\geq 1\ell$	MC@NLO	89.4
single-top (s, t, Wt channel)	MC@NLO	21.4, 1.41, 14.6
$W \to \ell\nu$+jets	ALPGEN	$3.1 \cdot 10^4$
$Z/\gamma^* \to \ell\ell$+jets	ALPGEN	$3.2 \cdot 10^3$
$t\bar{t} \to bH^\pm bW$ with $H^\pm \to \tau\nu$	PYTHIA	29.6

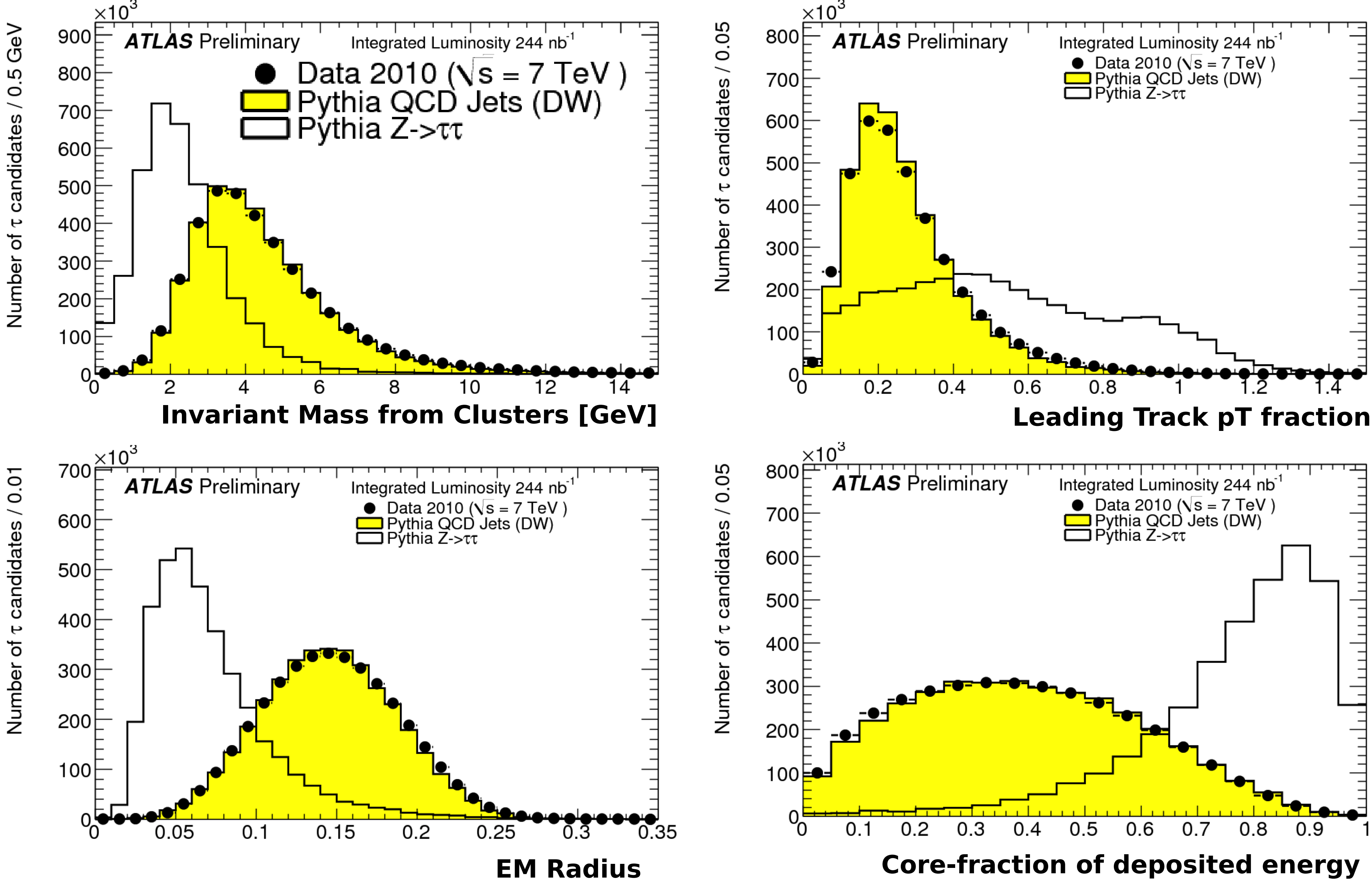
After all our selection criteria are applied (see next several slides), we find this dominates over all other backgrounds.

One notable omission from this table: ***generic multi-jet QCD***! More on that in a few slides . . .


Decay
Products
W
ν
Weak Decay
τ
Quark or
Gluon
QCD –
fragmentation
of quark/gluon
into jet

Tau Reconstruction

- Tau Decay
  - mass: 1.777 GeV/c^2, with electric charge (either ±e)
  - 35% leptonic final states ($e^+ \nu\ \nu$, $\mu^+ \nu\ \nu$),
    65% hadronic final states (e.g. $\pi^+ \nu$, $\pi^+\pi^0\nu$, $\pi^+\pi^-\pi^+ \nu$)
    - hadronic final states will superficially resemble jets → jet background expected to be the largest problem
- Tau Reconstruction
  - seeded from either a track (trajectory left by a charged particle), a calorimeter jet candidate, or both
  - identification uses additional variables
    - e.g. mass (tracks, clusters), momentum of the leading (highest-pT) track, size and distribution of energy in calorimeters (EM and hadronic)



These and other variables are combined using multivariate algorithms (e.g. boosted decision trees or likelihood ratios) to define a final selector output.

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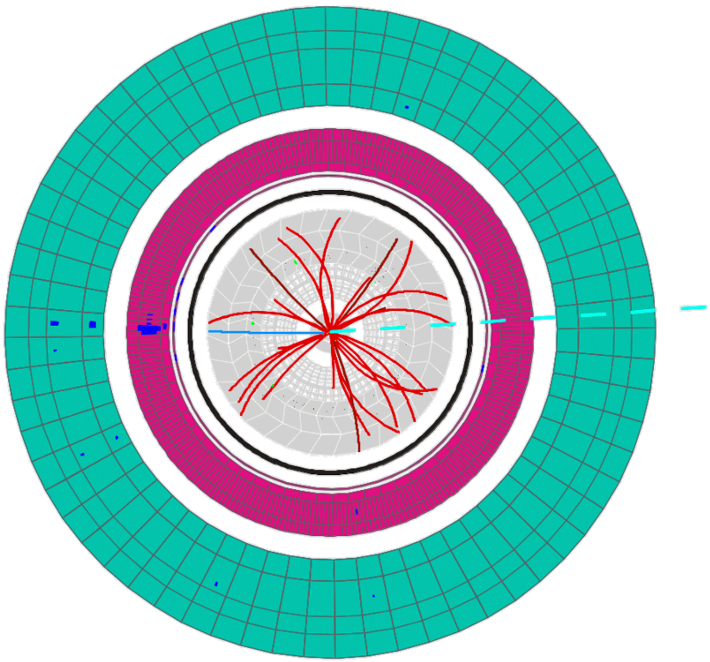
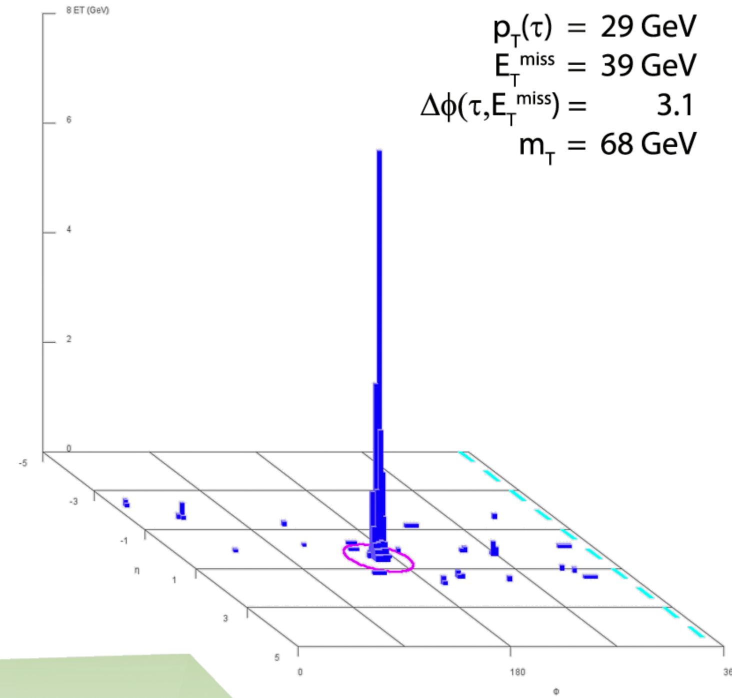
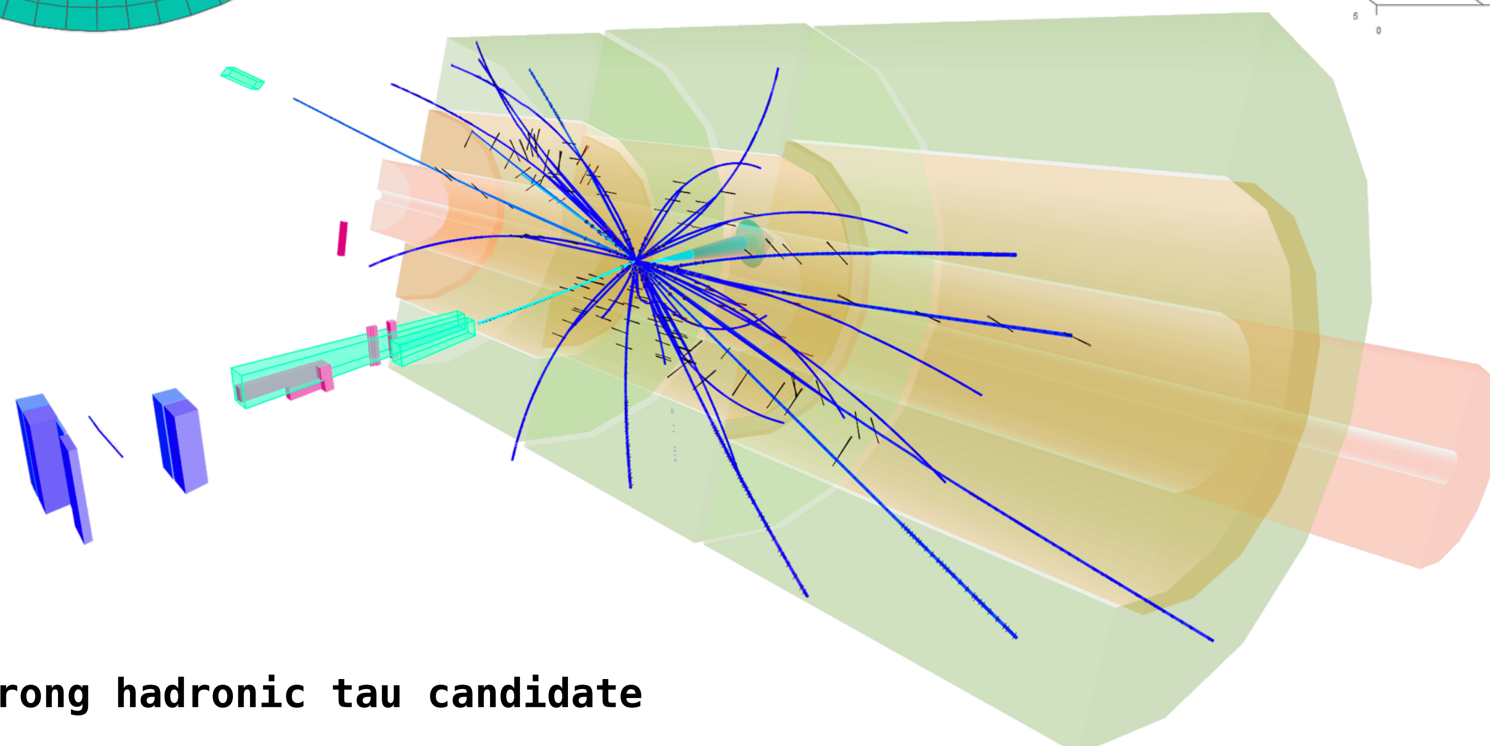


ATLAS EXPERIMENT

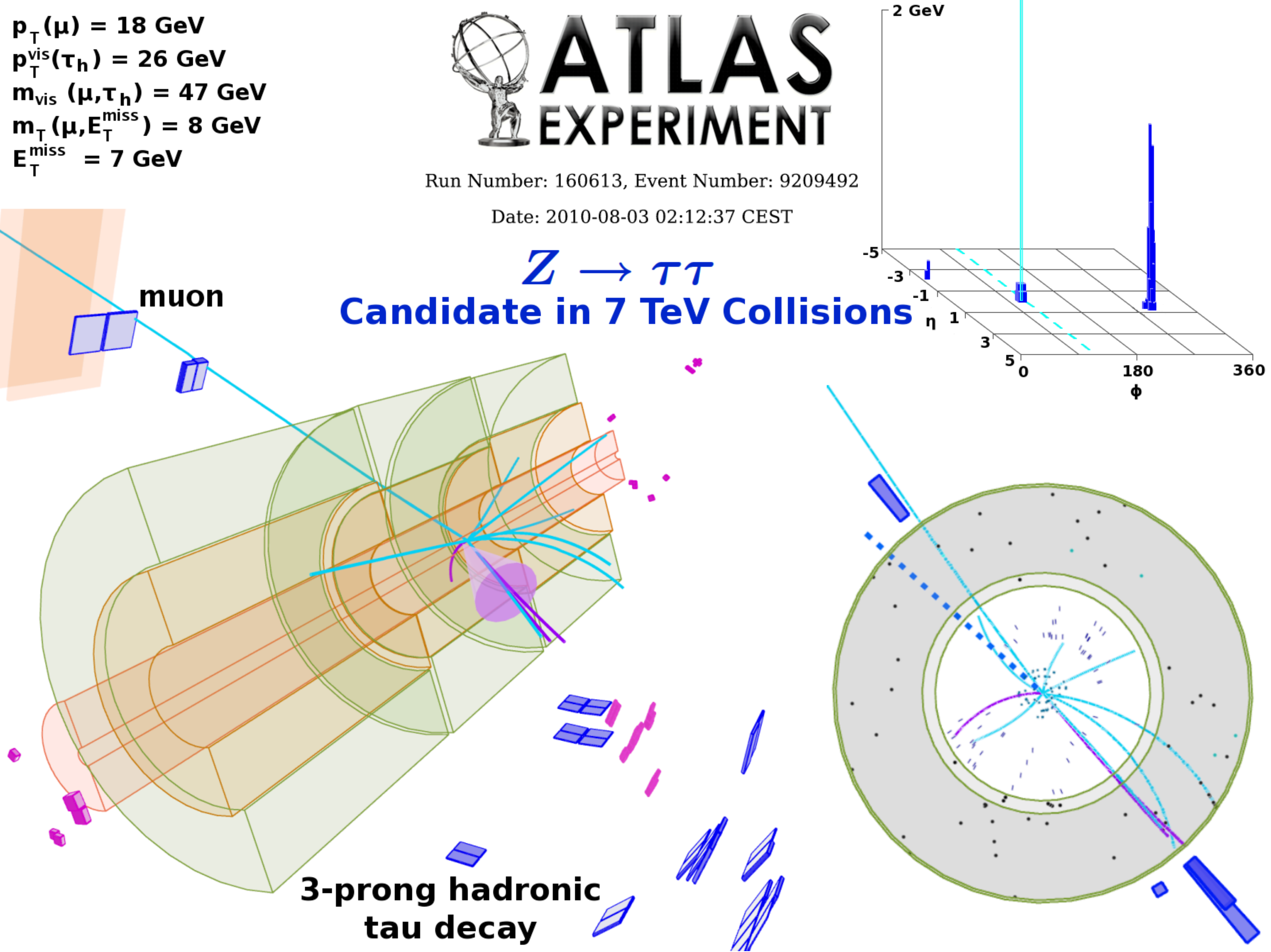
Run 155697, Event 6769403
Time 2010-05-24, 17:38 CEST

W→τν candidate in 7 TeV collisions

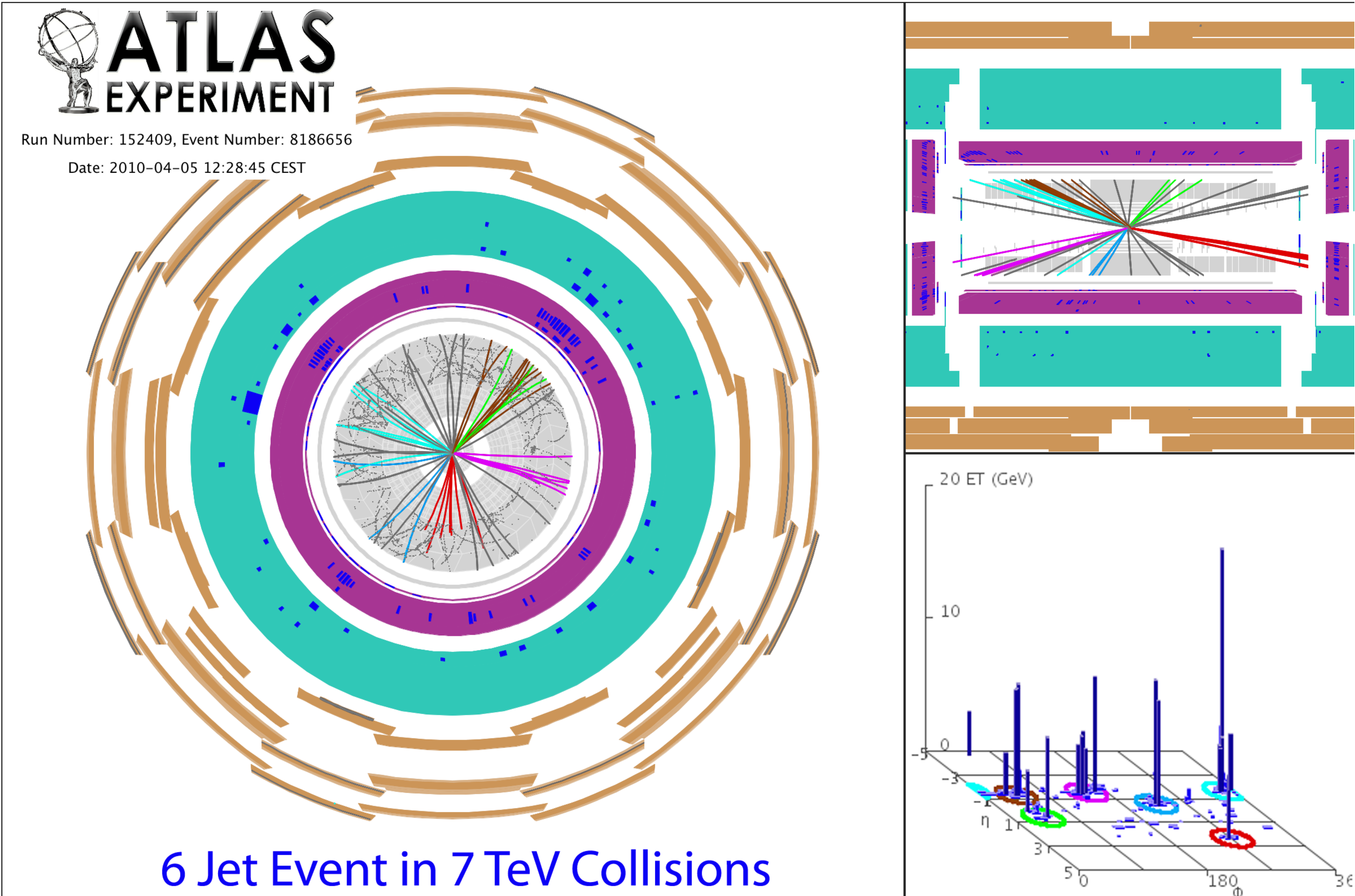




Single-prong hadronic tau candidate

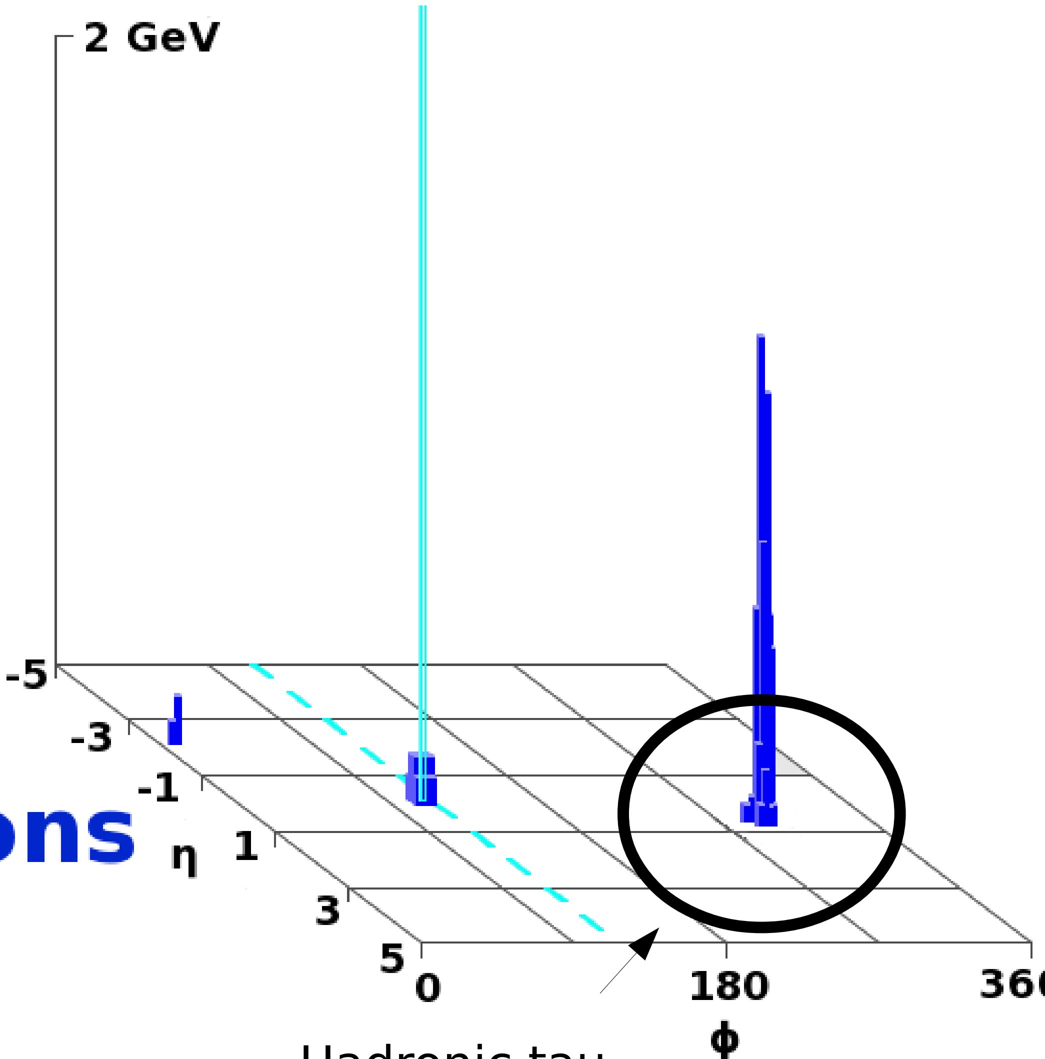


$p_T(\mu)$ = 18 GeV
$p_T^{vis}(\tau_h)$ = 26 GeV
m_{vis} (μ,τ_h) = 47 GeV
$m_T(\mu,E_T^{miss})$ = 8 GeV
E_T^{miss} = 7 GeV
ATLAS EXPERIMENT
Run Number: 160613, Event Number: 9209492
Date: 2010-08-03 02:12:37 CEST
$Z \rightarrow \tau\tau$
Candidate in 7 TeV Collisions
2 GeV
-5
-3
-1
1
3
5
η
0
180
360
φ
muon
3-prong hadronic tau decay

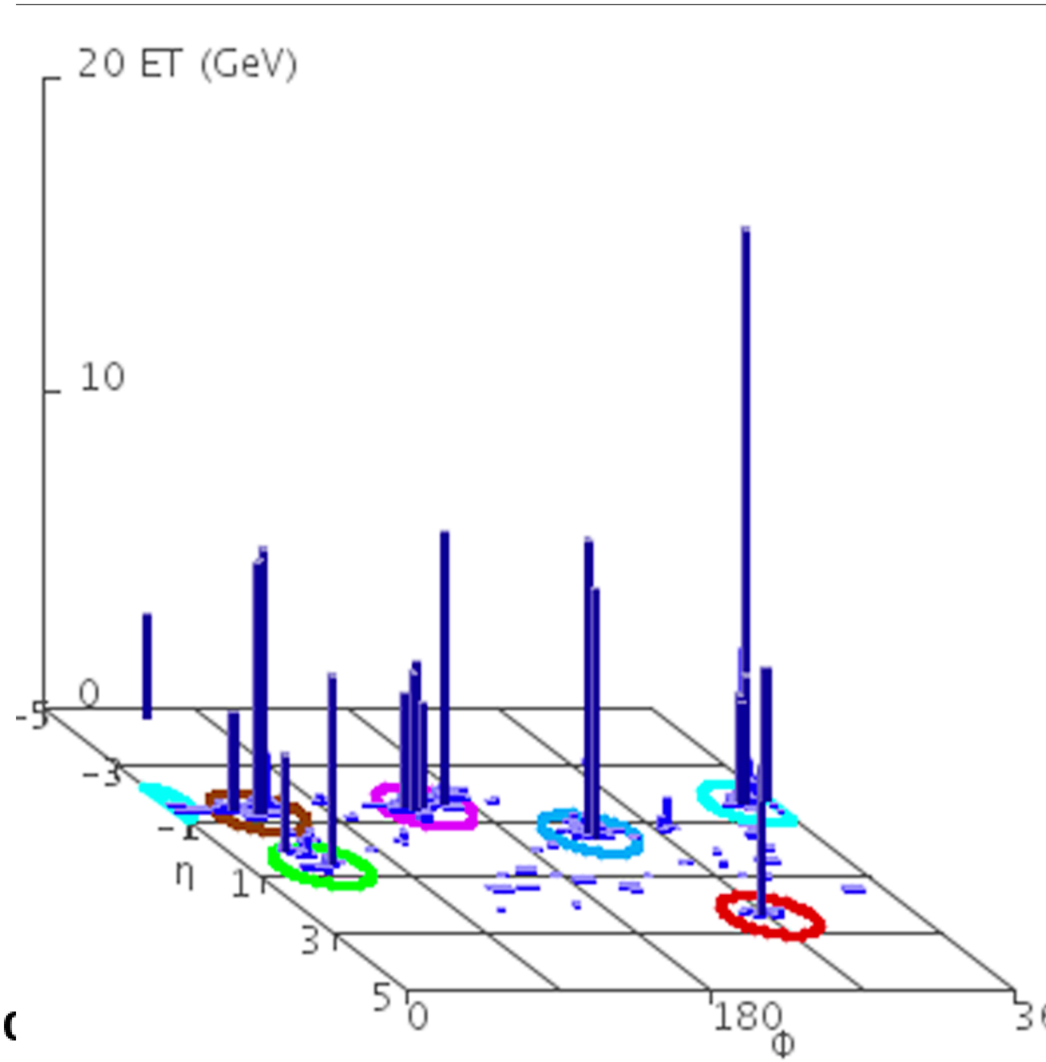


6 Jet Event in 7 TeV Collisions

ons

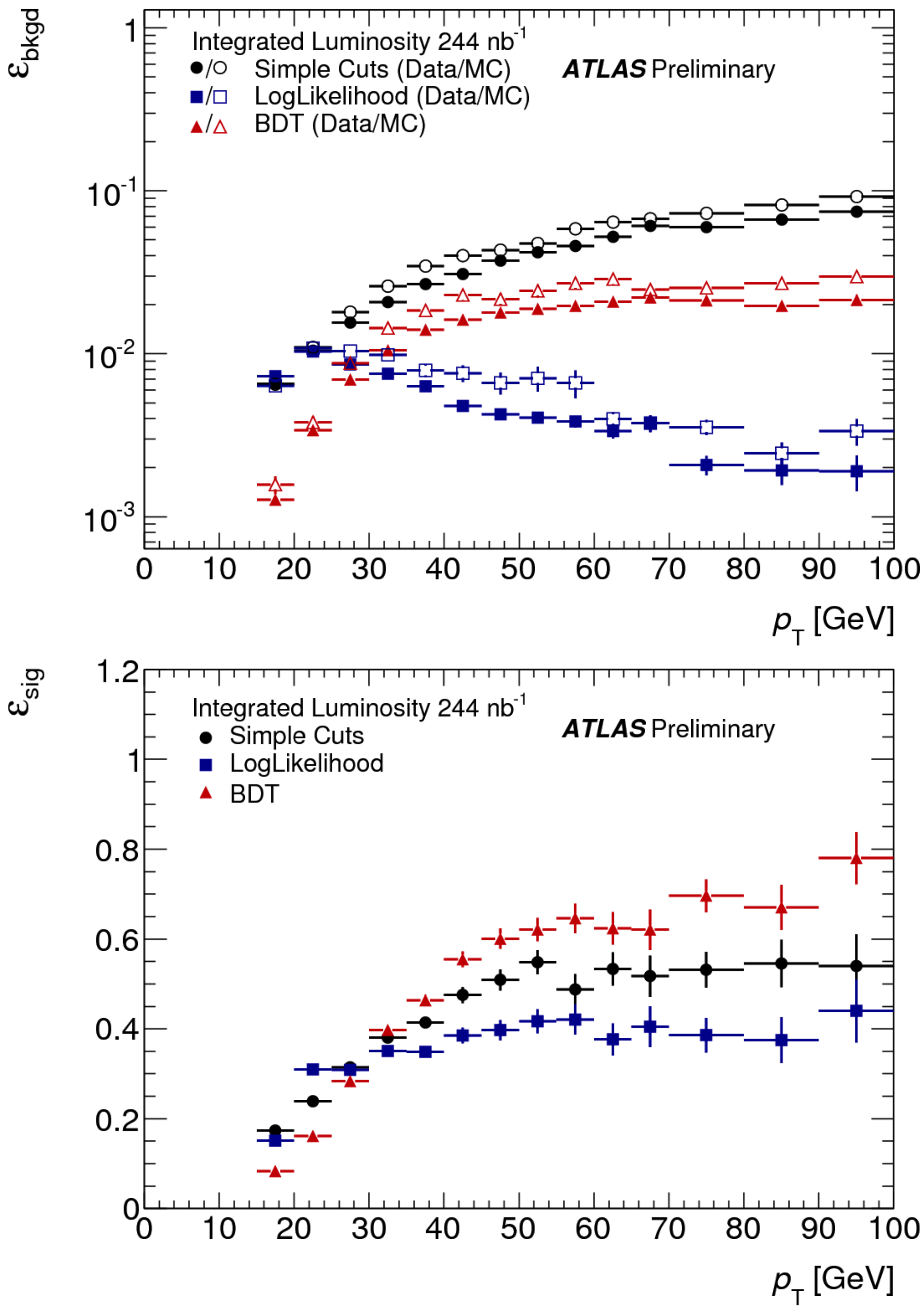


Hadronic tau



Multi-jet QCD event

Tau Selection for $H^+ \to \tau^+ \nu$



- We use the likelihood-based selector for the charged Higgs search
- Improves on background efficiency by ~order of magnitude while maintaining an acceptable signal efficiency
- We measure our τ signal efficiency using $Z \to \tau\tau$ events in data and find ~30% efficiency

Baseline Event Selection

- Trigger:
  - require at least 1 tau object (pT>29 GeV) and MET>35 GeV
- Event refinement
  - >= 4 jets (excluding tau jets) with pT>20 GeV and |η|<2.5
  - 1 tight-identified tau jet, 1 or 3 prongs, pT>35GeV and |η|<2.3
  - veto events containing identified electrons or muons
  - MET>40 GeV
  - Large fluctuations in the absolute measured MET are possible, event-by-event, due to the limited energy resolution on jets, etc. We reject large METs due to this effect by requiring

$$\frac{MET}{(1/2)\sqrt{\sum E_T^{\text{visible}}}} > 8\,\text{GeV}^{1/2}$$

  - Top mass, the mass of the highest-pT (jj)b system, must satisfy [120,240]GeV
  - Use transverse mass of the tau+MET system to finalize the analysis

Transverse Mass

From Phys. Rev. Lett. 50, 1738-1740 (1983)

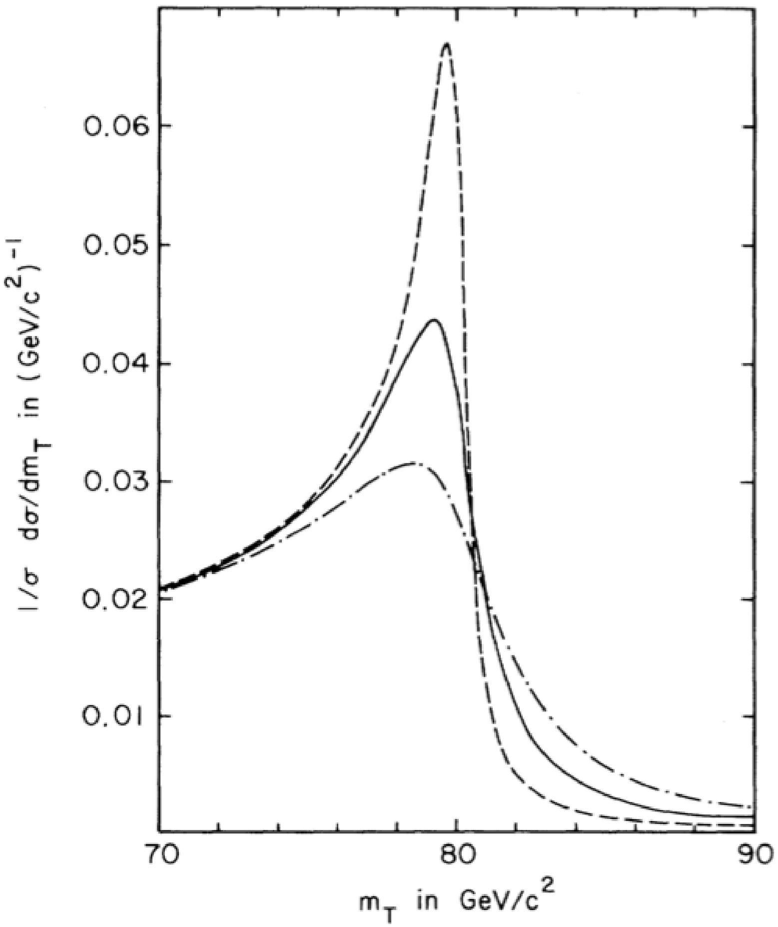


FIG. 2. $\sigma^{-1} d\sigma/m_T$ for $M = 80$ GeV/c^2 and $p_T^W = 0$ GeV/c^2. The dashed, solid, and dot-dashed lines refer to $\Gamma = 1$, 2.5, and 5 GeV/c^2, respectively.

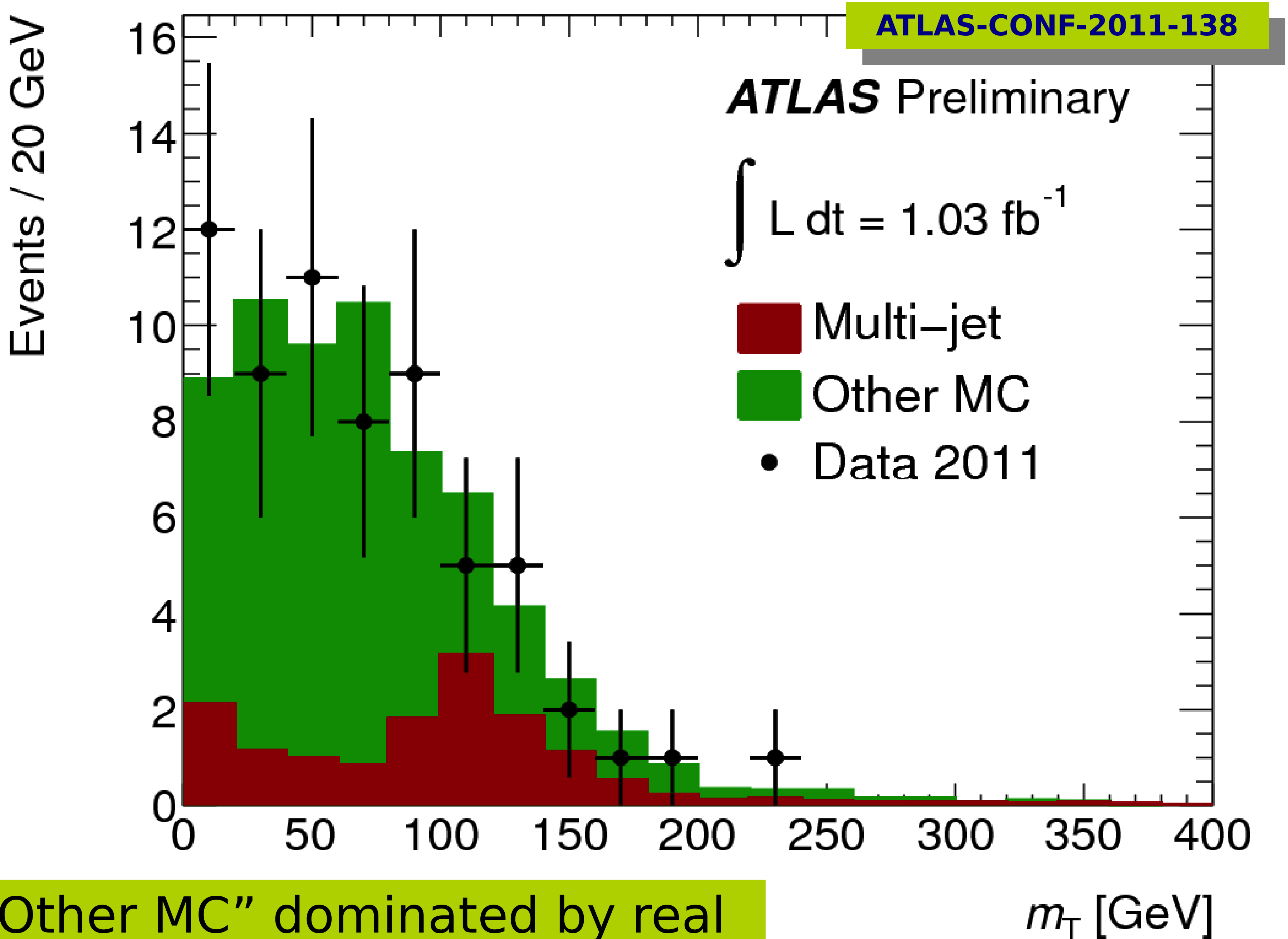
General Definition:

$$M_T^2 \equiv \left(E_T^l + E_T^\nu\right)^2 - \left(\vec{p}_T^{\,l} + \vec{p}_T^{\,\nu}\right)^2$$

Specific to W → l ν (where final-state particles are essentially "massless" on these energy scales):

$$M_T^2 \equiv 2\, p_T^l\, E_T^{miss} \left(1 - \cos \Delta\phi\right)$$

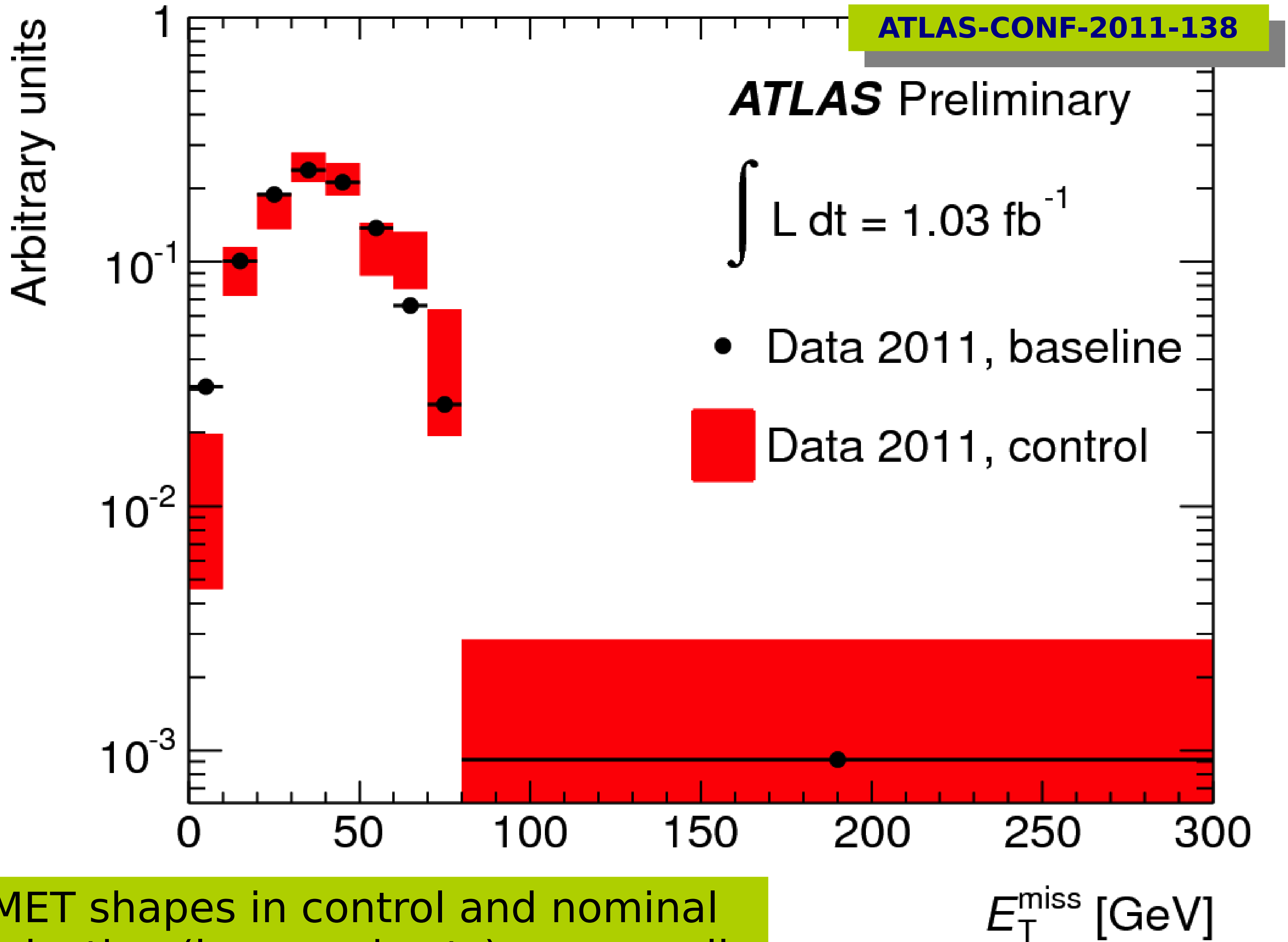
Transverse mass of the tau+MET system in tau + jets + MET events



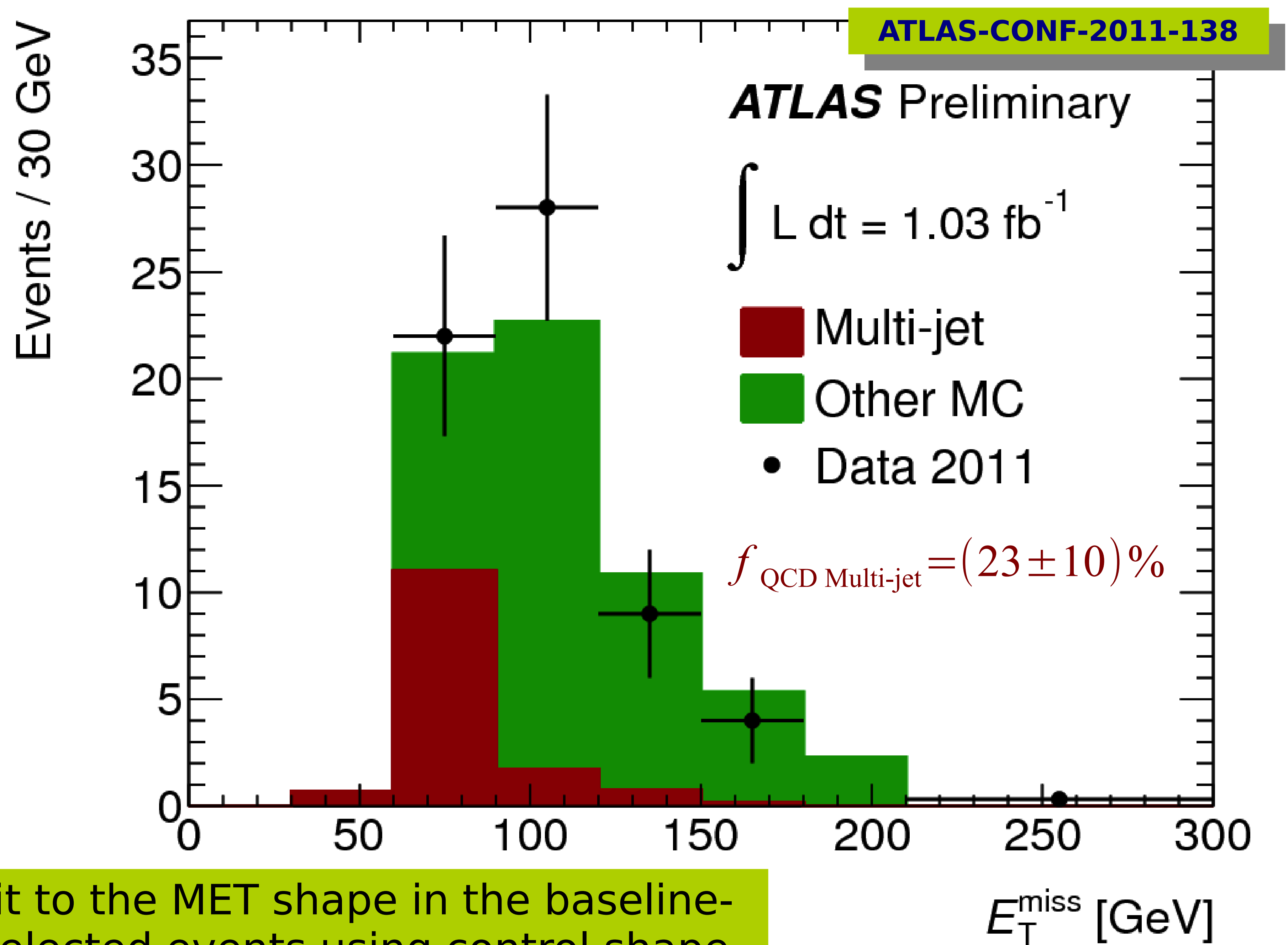
"Other MC" dominated by real Standard Model $t\bar{t}$ events

QCD Background Estimate

- MC Simulations of the QCD background are insufficient to understand this background
  - too few events are generated for a precision study – few/none survive all of our selection criteria
  - variable shapes not in great agreement at early stages of the selection when there is more QCD MC available
  - use data-driven method to study this background
- Method – define a “control sample” [A. Randle-Conde]
  - invert the b-tagging and tau selection cuts
    - No b-tagged jet AND no tau candidate passing the nominal criteria
    - subtract tt and other well-modeled MC shapes from MET distribution
    - Look at MET in these control events and develop a template to fit the MET shape in baseline-selection events



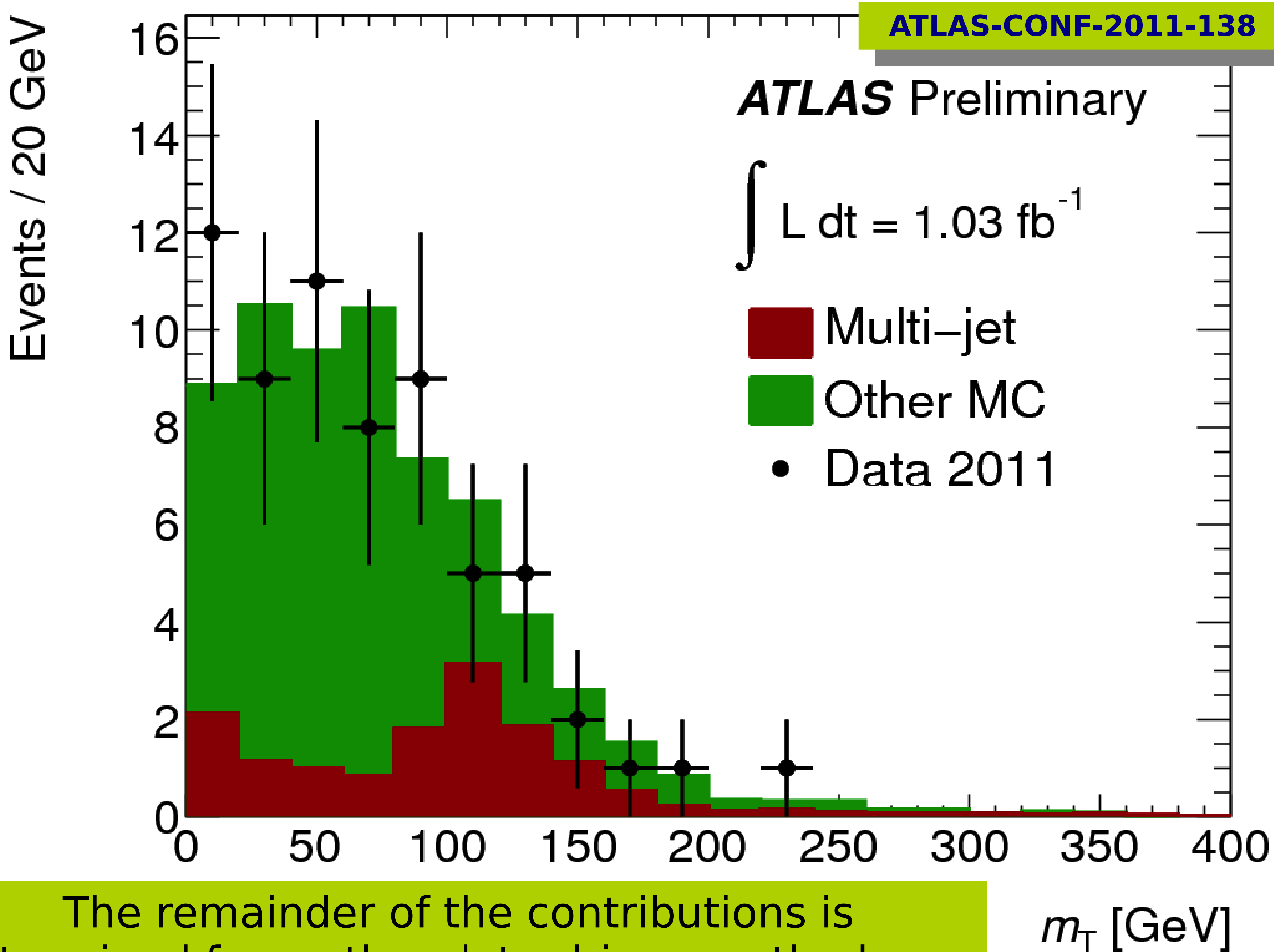
MET shapes in control and nominal selection (loosened cuts) agree well



Fit to the MET shape in the baseline-selected events using control shape and MC (e.g. SM $t\bar{t}$).

Transverse mass of the tau+MET system in tau + jets + MET events

ATLAS-CONF-2011-138



The remainder of the contributions is determined from other data-driven methods . . .

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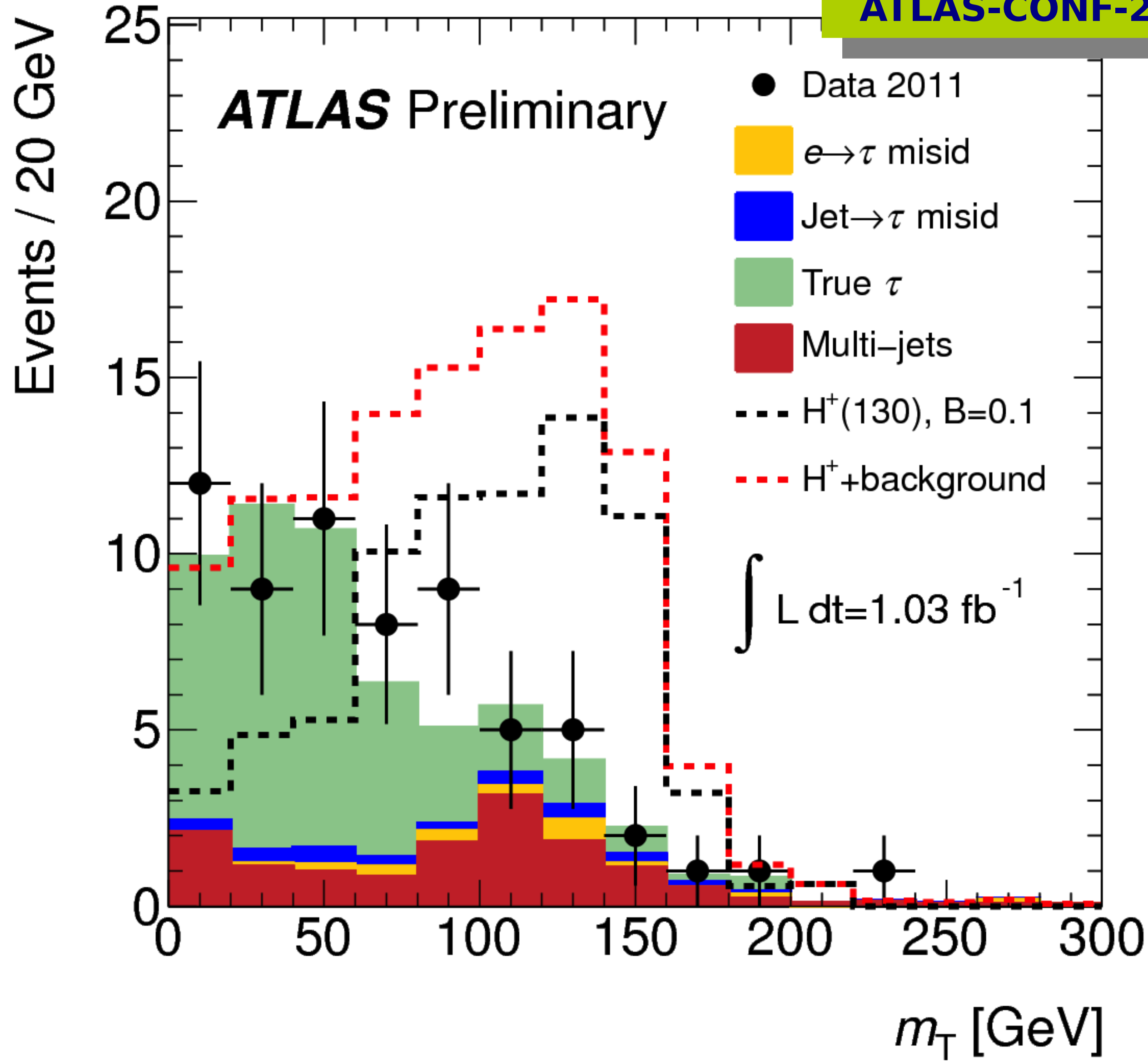
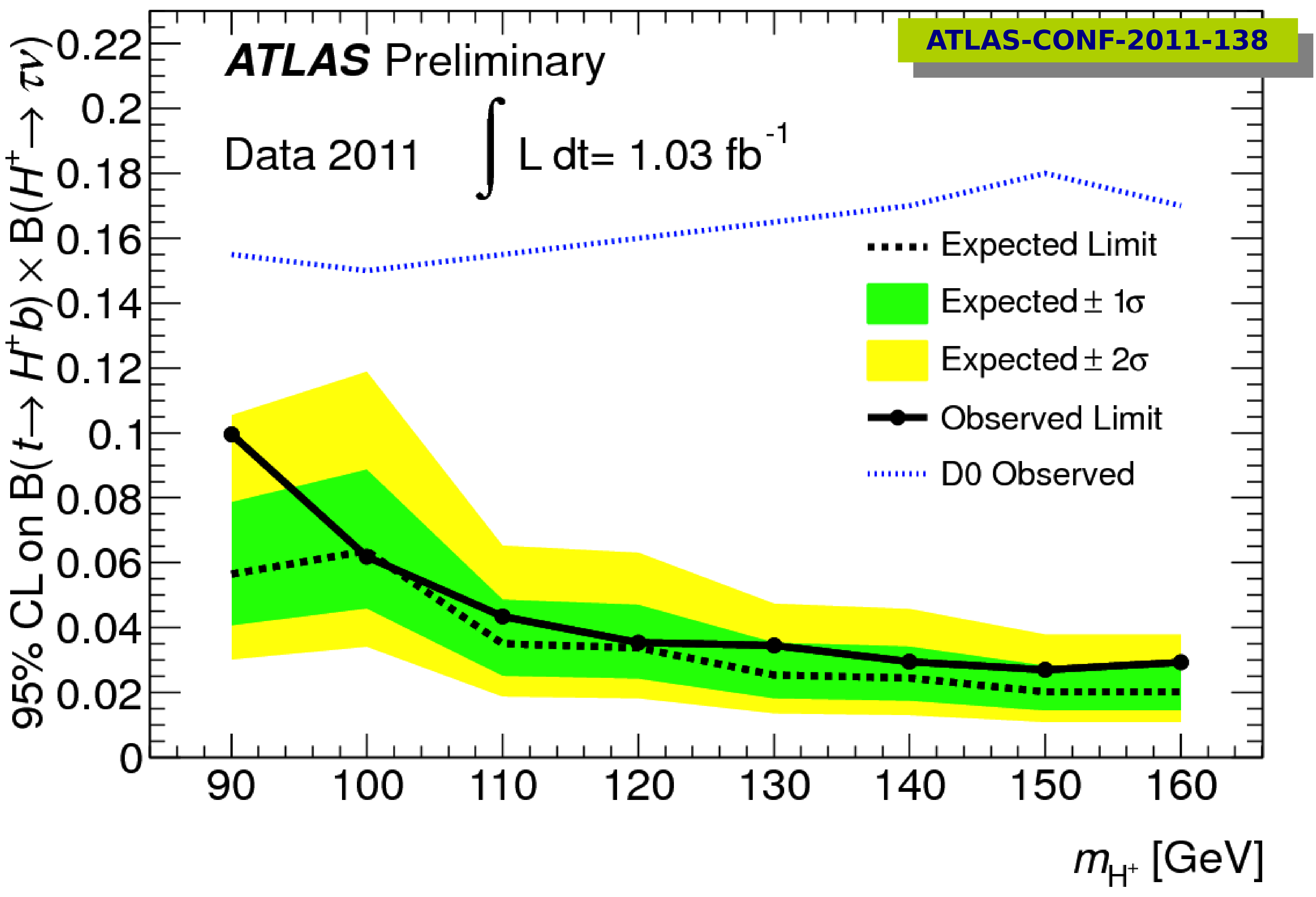


	Events with/from					
	true τ jets	jet $\rightarrow \tau$ mis-id	$e \rightarrow \tau$ mis-id	multi-jet	expected (sum)	data
$m_T > 40$ GeV	21 ± 5	2.4 ± 0.7	1.9 ± 0.2	12 ± 5	37 ± 7	43

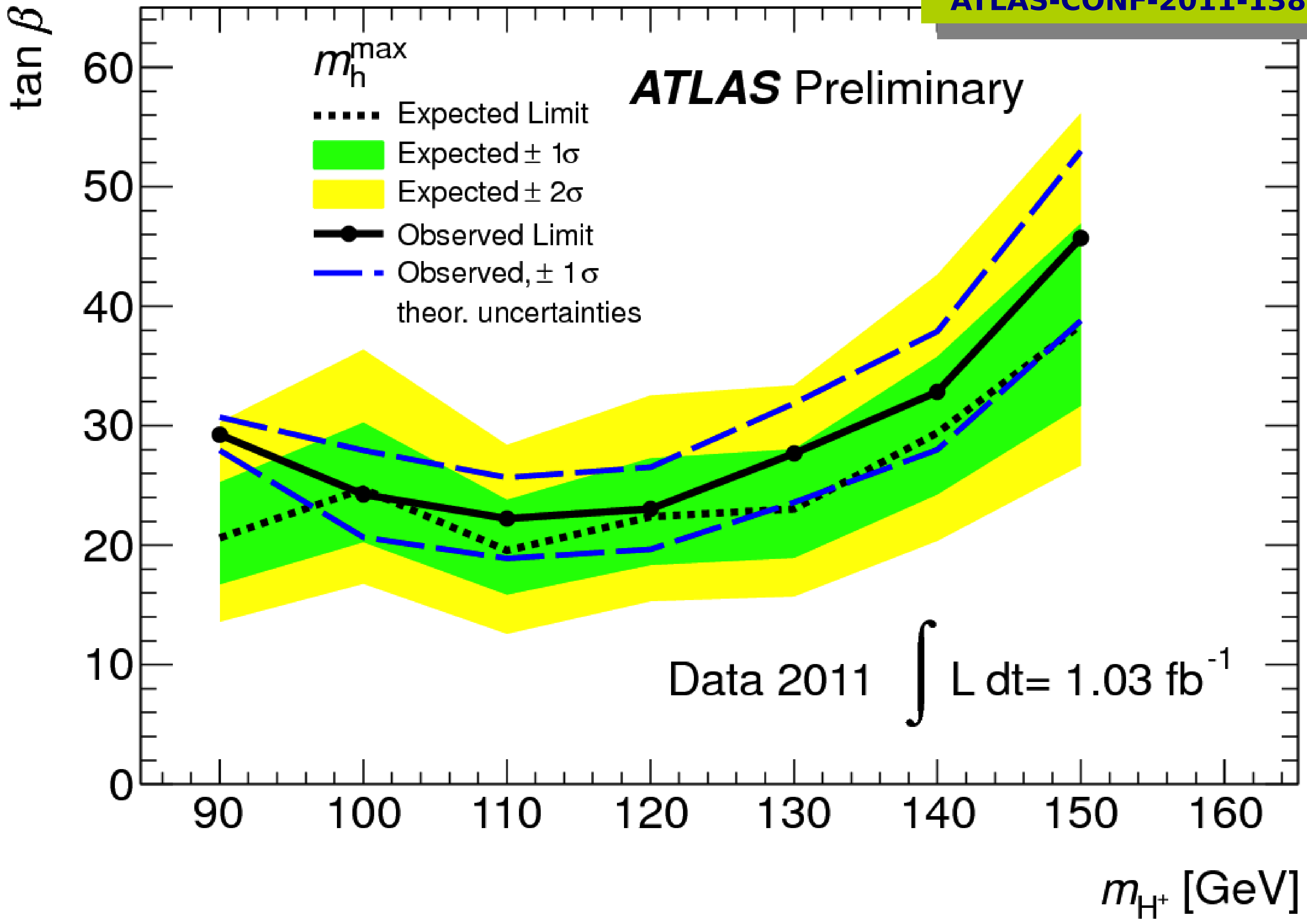
Systematics

Quantity	Uncertainty
Luminosity [36]	$\pm 3.7\%$
Jet energy resolution (JER)	$\pm(10 - 30)\%$, depending on p_T and η
Jet energy scale (JES)	$\pm(2.5 - 14)\%$, depending on p_T and η
E_T^{miss}	Uncertainty due to scale/resolution uncertainties (e.g. JES); additional 10% of pile-up-related uncertainty
b-tagging efficiency SF unc.	$\pm(0.05 - 0.15)$, depending on p_T and η
b-tagging mistag rate	$\pm(0.16 - 0.39)$, depending on p_T and η
b jets JES uncertainty	an additional $\pm 2.5\%$ on top of the standard JES
τ identification efficiency	$\pm(8.5 - 9.9)\%$, depending on p_T
τ energy scale	$\pm(4.5 - 6.5)\%$, depending on p_T, η, number of associated tracks
τ electron mis-id correction factors	$\pm(23 - 100)\%$, depending on η; for one-prong only
$\tau+E_T^{miss}$ trigger	$\pm 9\%$
e reco. efficiency SF	$\pm(0.7 - 1.8)\%$, depending on η
e identification efficiency SF	$\pm(2.2 - 3.8)\%$, depending on E_T and η
e energy scale	$\pm(0.3 - 1.8)\%$, depending on p_T and η
e energy resolution	$\pm(0.5 - 2.4)\%$ (additional constant term), depending on p_T and η
μ reco. efficiency SF	$\pm(0.25 - 0.55)\%$, depending on the data-taking period
μ momentum scale and resolution	$\pm(0.4 - 0.7)\%$, depending on η
Initial/final state radiation modelling	-16% / +19% ($t\bar{t}$ signal and background)
Acceptance	$\pm$ 4% (background), $\pm$ 10% (signal)
$t\bar{t}$ cross section	165^{+4}_{-9}(scale) $^{+7}_{-7}$(pdf) pb



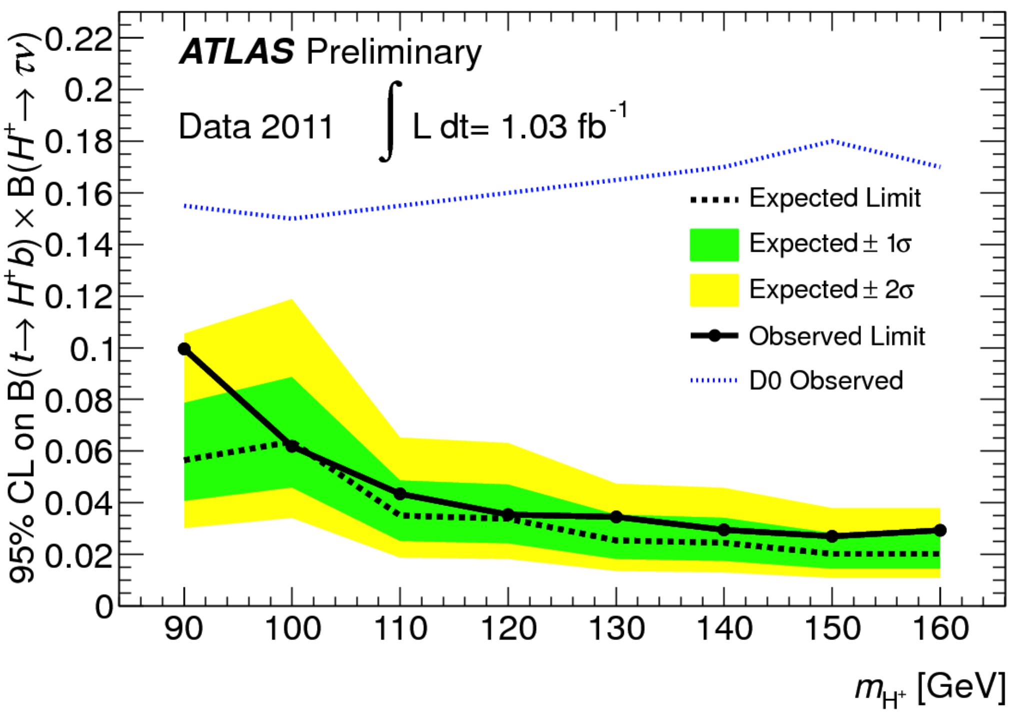
ATLAS-CONF-2011-138
ATLAS Preliminary
Data 2011 ∫ L dt= 1.03 fb-1
Expected Limit
Expected ± 1σ
Expected ± 2σ
Observed Limit
D0 Observed
95% CL on B(t→H+b) × B(H+→τν)
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
90
100
110
120
130
140
150
160
mH+ [GeV]

ATLAS-CONF-2011-138



Comparison to other measurements

hadronic tau + jets



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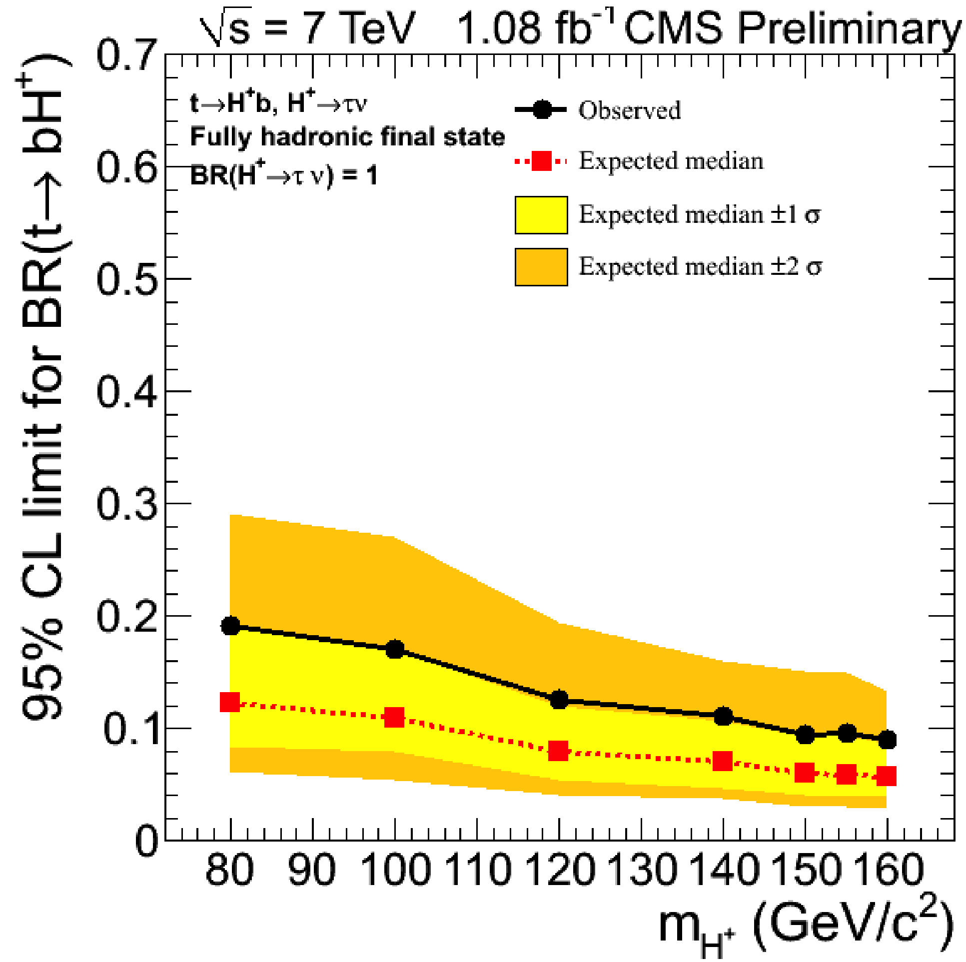
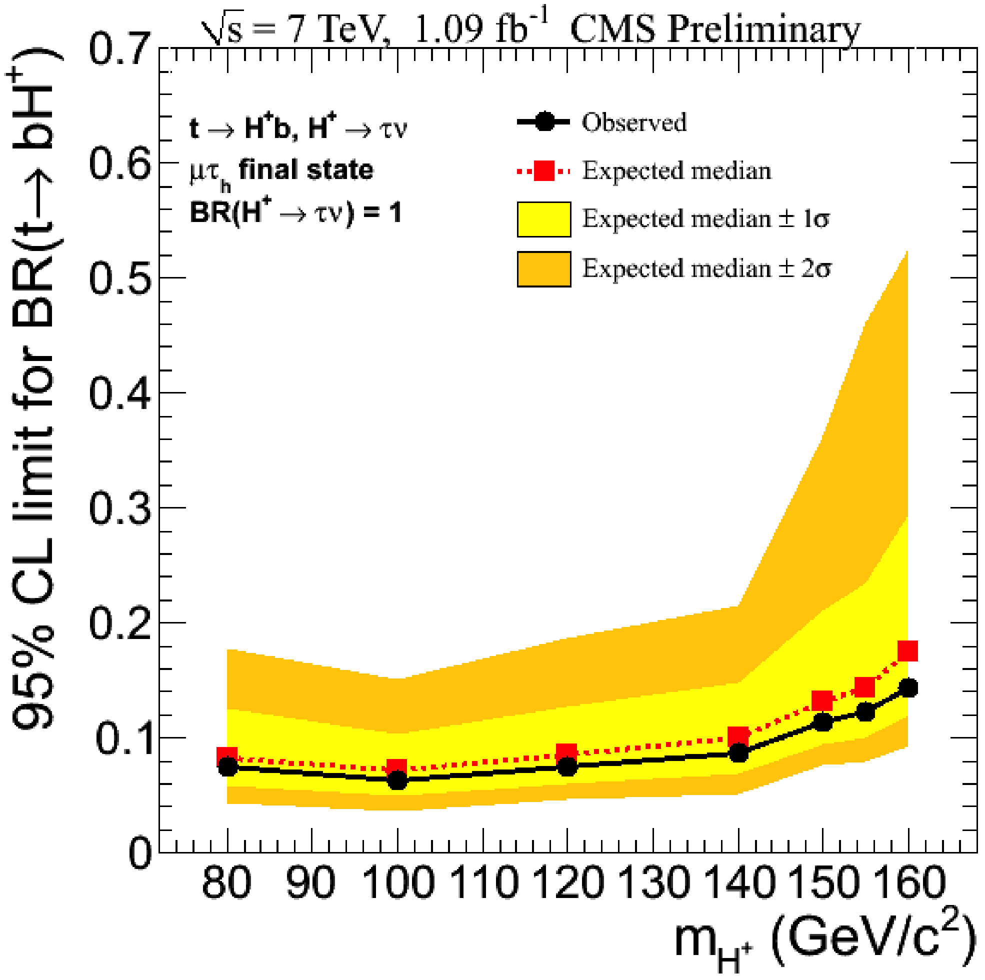


CMS-PAS-HIG-11-008

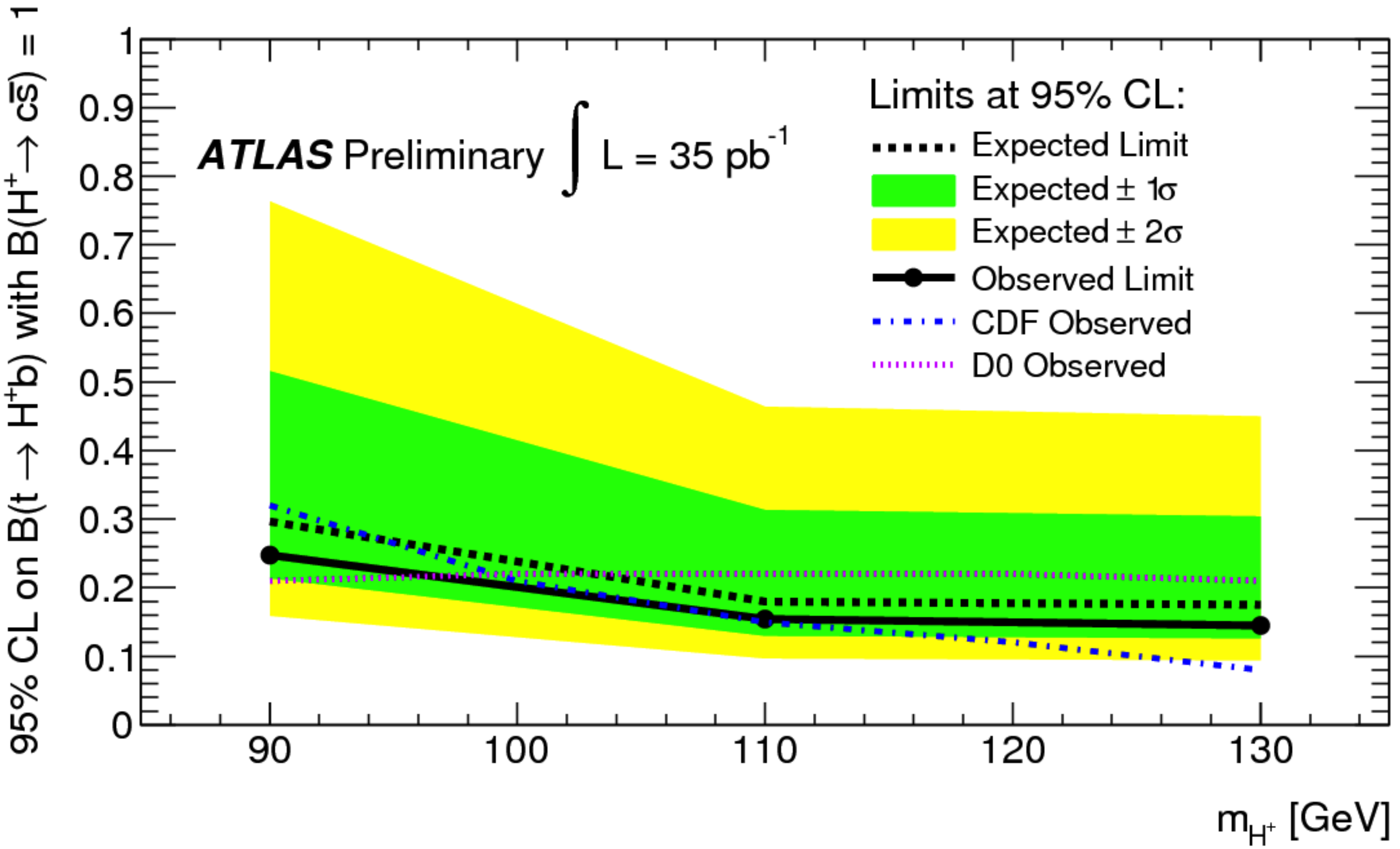
Comparison (continued)



ATLAS tau+lepton search was not ready in time for summer conferences but will be ready for our publication on this topic.

Comparison (cont.)

ATLAS-CONF-2011-094



ATLAS is pursuing other final states besides τν

Future Directions/Issues

- Increased Pileup Collisions
  - we are already at $L = 3.3 \times 10^{33}\ cm^{-2}\ s^{-1}$
    - corresponds to $\langle\mu\rangle \sim$ 11 per crossing
  - at $L = 2 \times 10^{34}\ cm^{-2}s^{-1}$ (~2016), $\langle\mu\rangle \sim 46$
  - Impact on MET, tau, and jet triggers
  - Impact on offline reconstruction of MET, etc.
  - We are involved in trigger rates and object triggering studies for these conditions
- New methods for searching
  - $H+ \rightarrow W^+Z^0$
  - $H^+ \rightarrow tb$
  - $H^+ \rightarrow$ SUSY???

Conclusions

- An exciting time for discovery-oriented physics
  - when keeping up with the data becomes your biggest problem, you're living in a golden age
- Direct tests of SUSY/MSSM hypothesis are possible at the target energy scales
  - SUSY is supposed to be interesting once you get to around 1 TeV
  - Here we are – where are you, SUSY?
- Testing the Higgs Mechanism
  - The race to discover a SM Higgs is hotter than ever
  - If the Higgs is the mechanism for the attainment of mass, and there are more particles out there (SUSY or no), then we need more Higgses
- Unprecedented sensitivity to $t \rightarrow Hb$
  - We're approaching the 1% level in sensitivity – precision tests are coming
  - Need to open up the space for higher-mass charged Higgs searches