A search for MSSM Higgs bosons in the $\tau_{lep}\,\tau_{had}$ decay mode with the ATLAS detector at the LHC

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Final Exam

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ATLAS

Outline

- Motivation
- The ATLAS Experiment
- Selecting MSSM Higgs events
- Estimating the backgrounds
- Systematics & statistics
- Results
- Summary

Disclaimer: the following analysis was produced with data from the ATLAS detector, but is not an official or approved ATLAS result.

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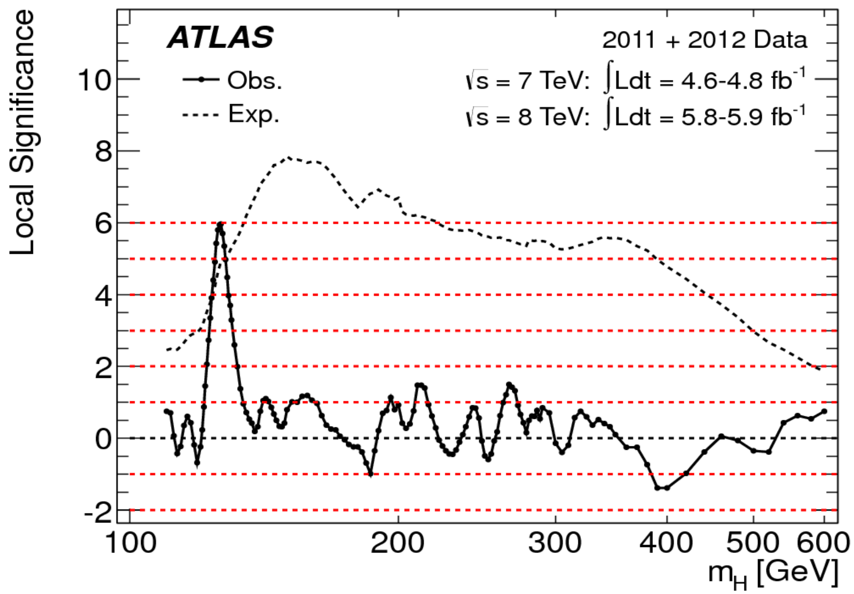
We have a Higgs!



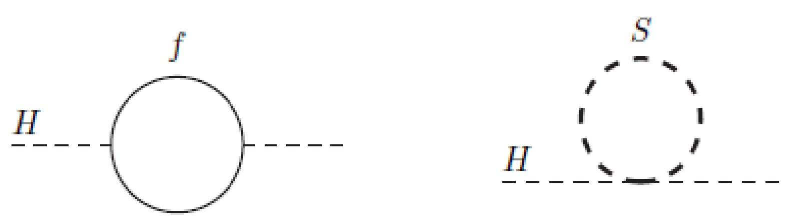
Fireworks in Seattle, July 4 2012
Celebrating announcement of Higgs discovery

- On July 4, 2012, the ATLAS and CMS experiments announced the discovery of a new boson decaying to ZZ, WW, and γγ, with a mass around 125 GeV.
- Subsequent measurements have confirmed: if it is not the long-sought Higgs boson, it is a darn good imposter.

We have a Higgs!

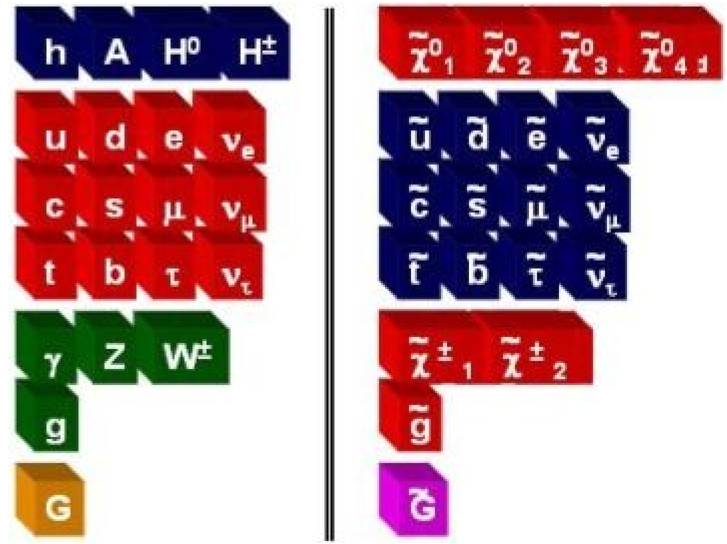
We have a Higgs! So what next?

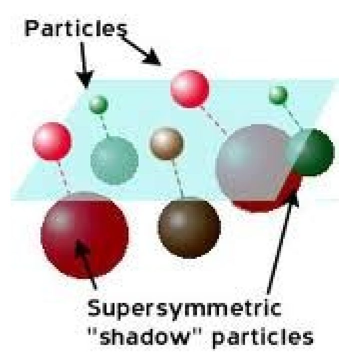
- Certainly a nice accomplishment, and a valid pretext for opening up some champagne.
- But let's not get ahead of ourselves: The interesting work is just getting started.
- Is this thing alone? Can it completely explain why our particles have mass? And above all: Why the heck is it so darn light?



Supersymmetry

- SUSY rescues the Higgs boson from out-of-control quantum corrections via a symmetry between fermions and bosons.
- Requires a new particle for all of the known SM particles.
  - Searches for these things turning up empty so far.
- Many other interesting features, including an extended Higgs sector.



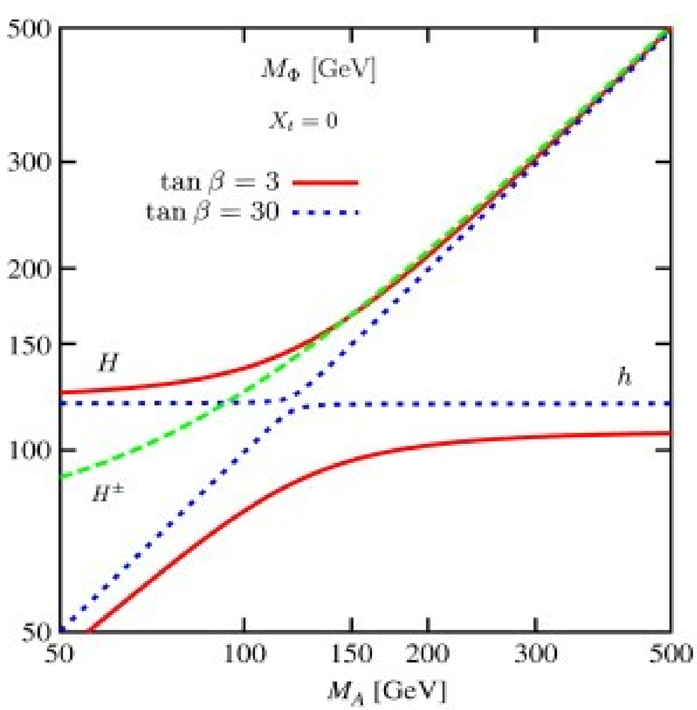


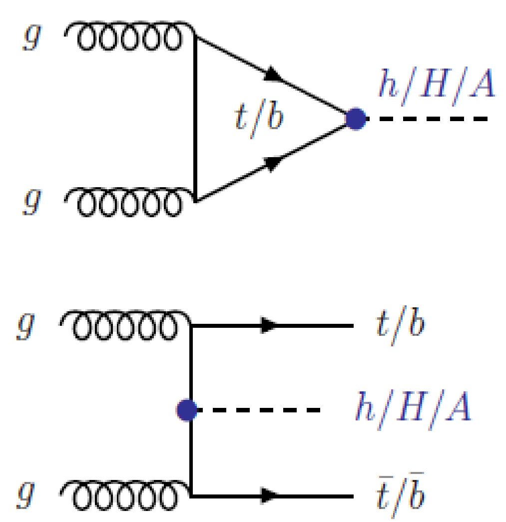
The MSSM Higgs Sector

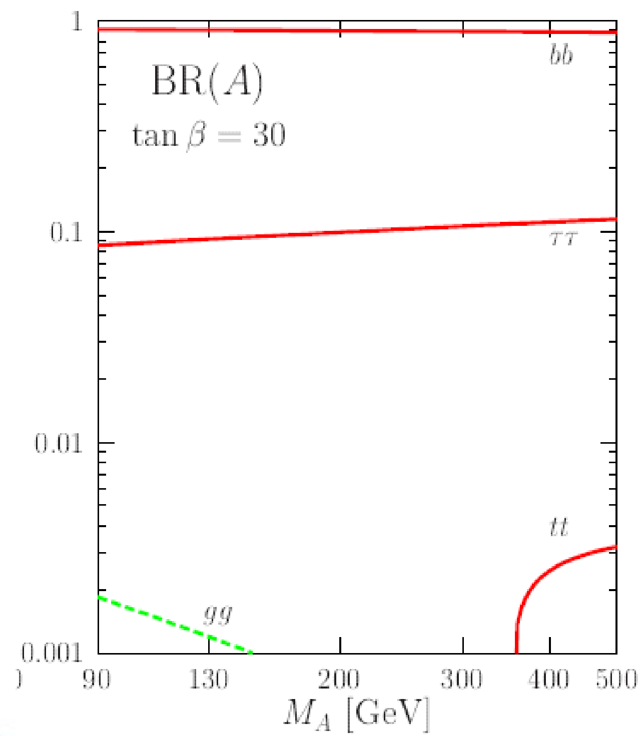
- SUSY requires two Higgs doublets, $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$ & $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$, to generate mass separately for opposite-isospin fermions.
- Now eight degrees of freedom; 3 are still eaten by generating the W & Z masses → 5 physical Higgs bosons.
  - Two charged: H^+, H^- from real part of H_1^-, H_2^+
  - Two neutral, CP-even: H, h from real part of H_1^0, H_2^0
  - One neutral, CP-odd: A from "un-eaten" imaginary part of H_1^0, H_2^0
- Determined (before quantum corrections) by two free parameters: m_A and $\tan\beta = v_2/v_1$

The MSSM Higgs Sector (II)

- Either *h* or *H* has a mass ~degenerate with *A*, the other must be near 125 GeV.
- At high tanβ, couplings to down-type fermions (especially b, τ) are enhanced.
- Couplings to W, Z are absent or suppressed.

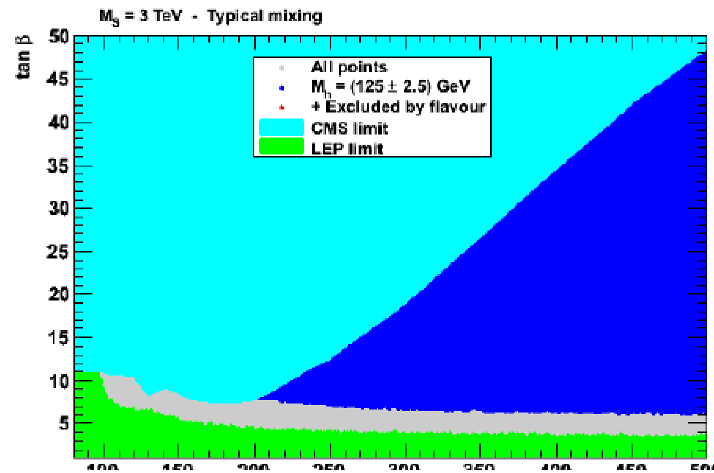




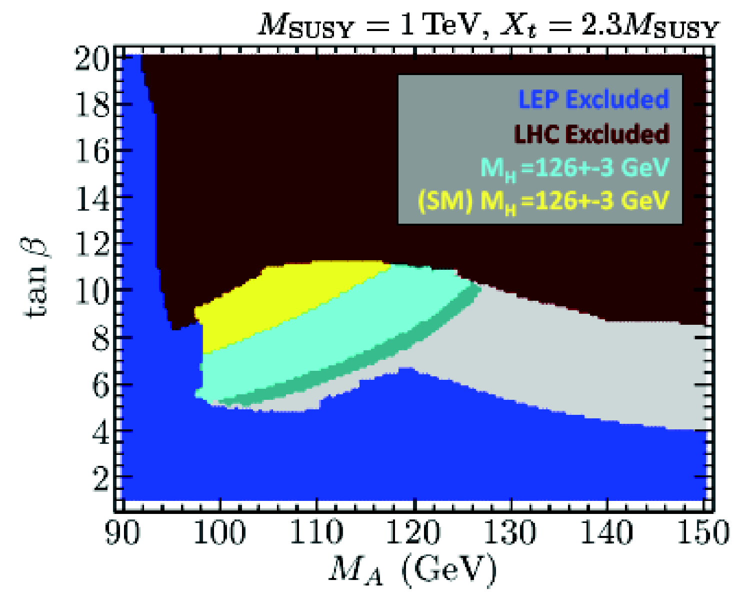


The MSSM and the Higgs discovery

- The 125 GeV boson must be accounted for as either *h* or *H*.
- *h* is the most likely: by adjusting the SUSY parameters almost any m_A-tanβ point is consistent with m_h ~ 125 GeV.
  - Can even adjust the decay rates as needed.
- The possibility of *H* at 125 is more constrained but still viable.



Djouadi *et al*



Heinemeyer, Stal, Weiglin

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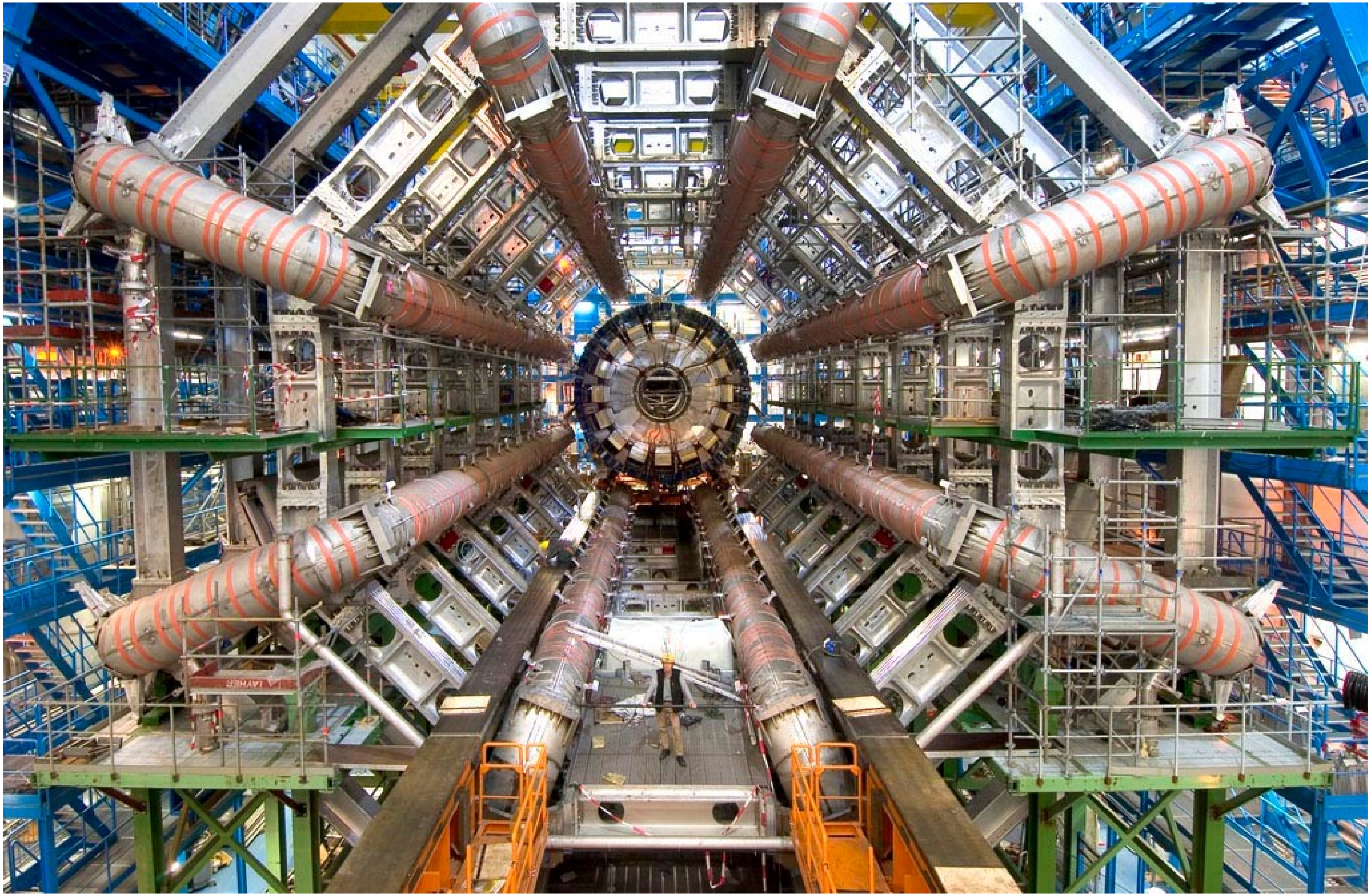
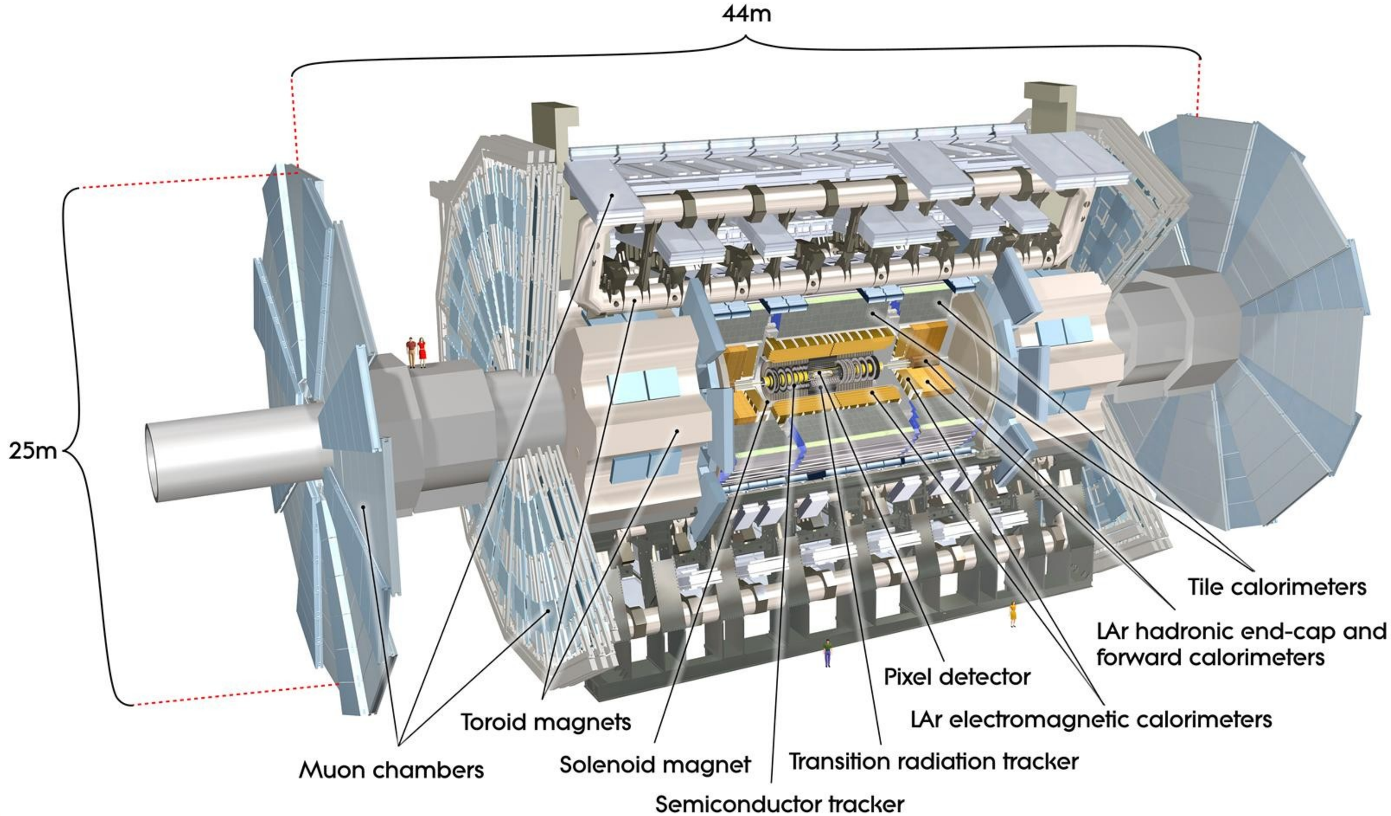
The ATLAS Detector

A Toroidal Lhc ApparatuS

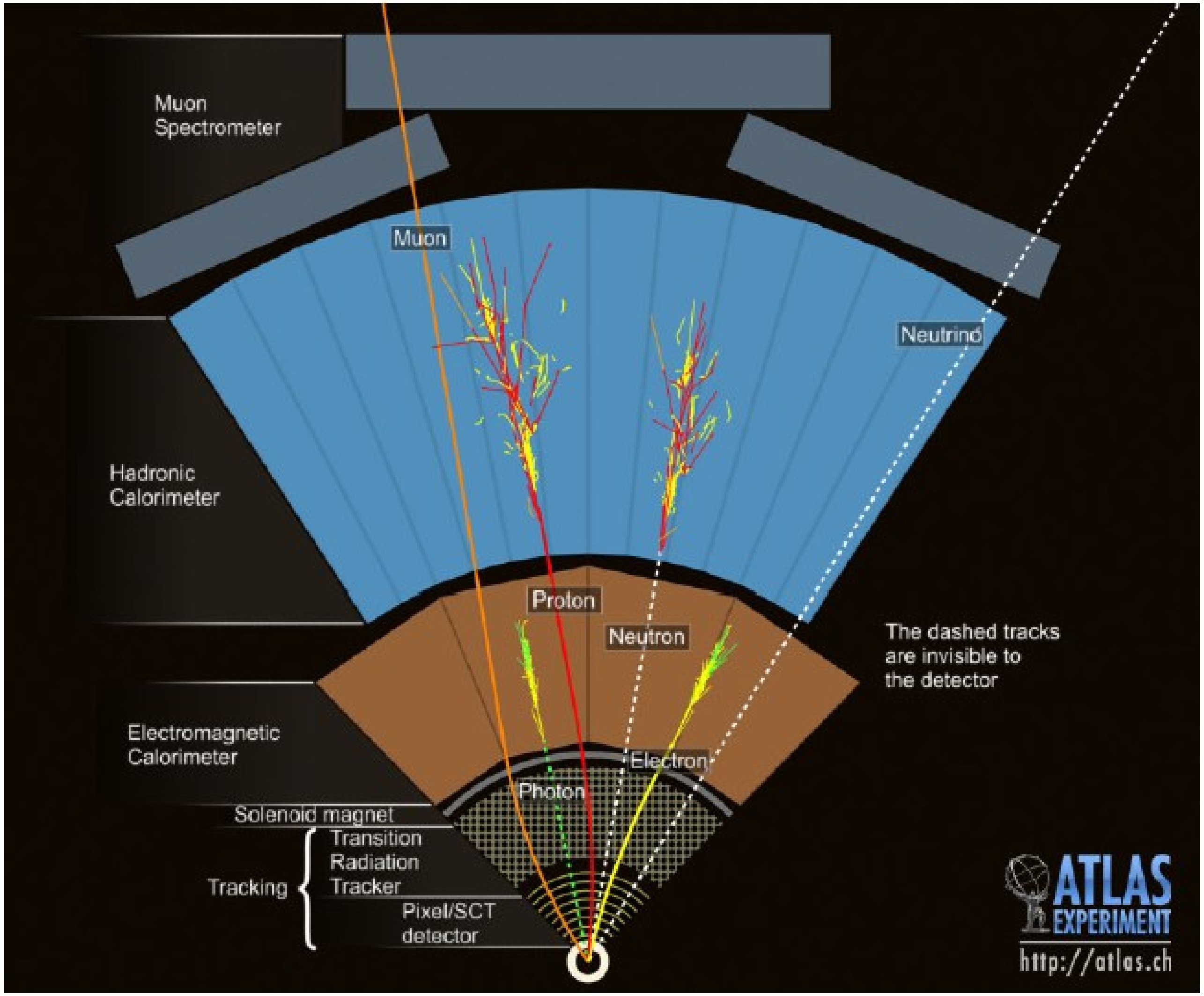


ATLAS

- Inner detector for precise tracking of charged particles.
- Calorimeter for charged & neutral energy measurements.
- Muon detector immersed in toroidal magnetic field.
- Events selected with 3-level trigger system to reduce rate.



Particle identification



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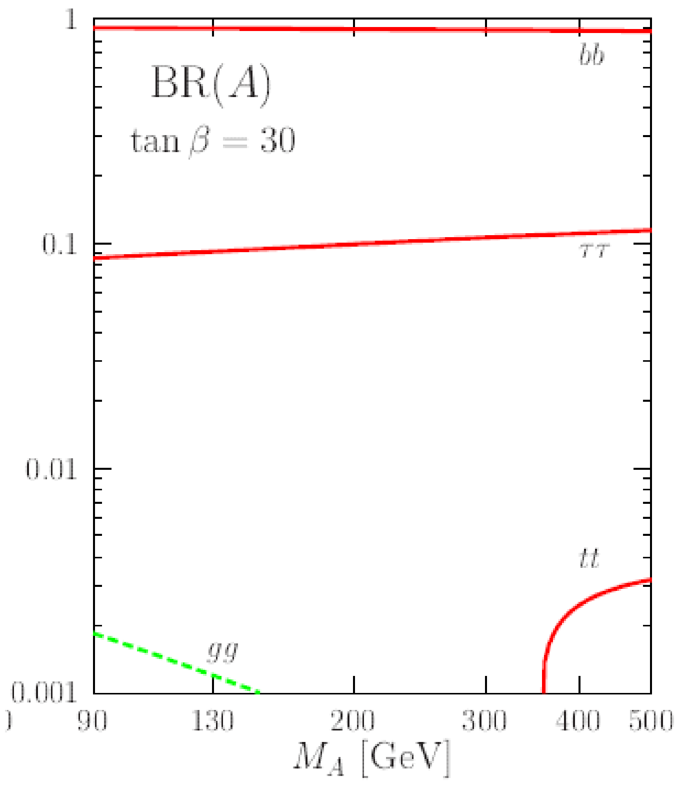
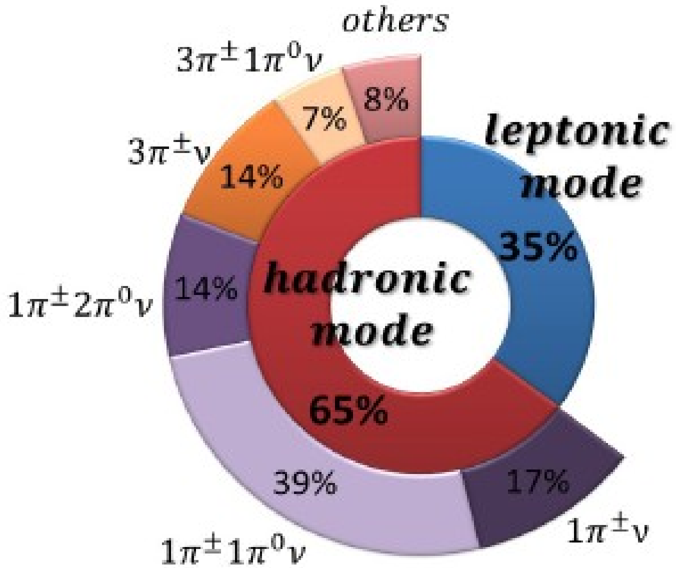
MSSM Higgs Decays

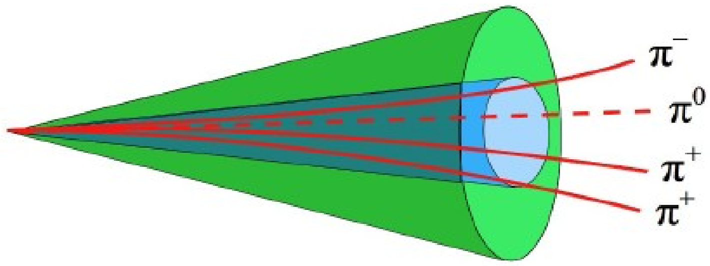


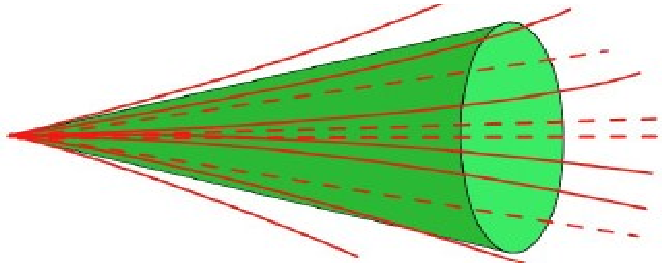
- The most promising region for discovery is at high tanβ.
- In this case the Higgs bosons decay almost exclusively to b quarks or tau leptons.
- b quarks are difficult to trigger on, and have large backgrounds.
- Taus offer a cleaner signature, especially in the case of decays into electrons or muons.
- The decay mode with one hadronic and one leptonic tau offers a good compromise of cleanliness and branching ratio.

Tau leptons

- Mass = 1.777 GeV
- Decay length = 87 µm.
- 35% leptonic decays; 65% hadronic
  - Leptonic case: only reconstruct electron or muon, no way to tell it came from a tau.
- Challenge: distinguish hadronic tau from much more common QCD jet.
- Take advantage of the low track multiplicity, low m/p (→ highly collimated decay products).

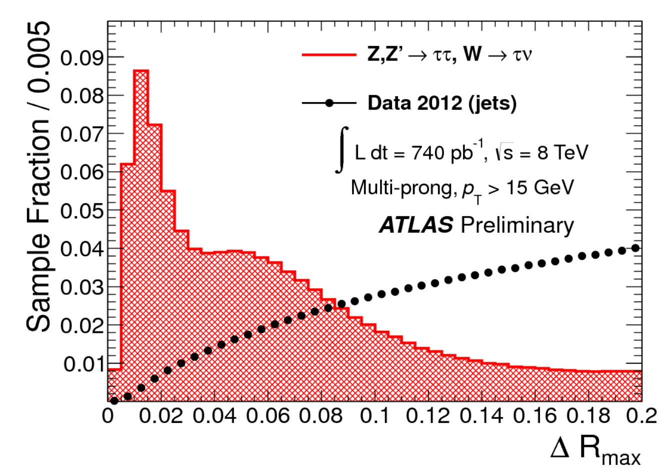


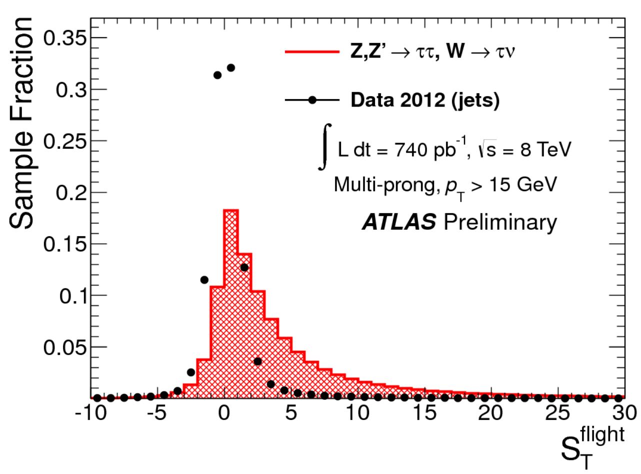


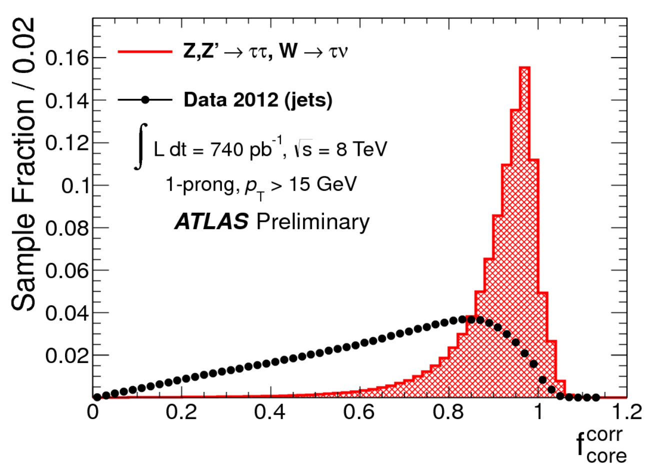


Tau Identification

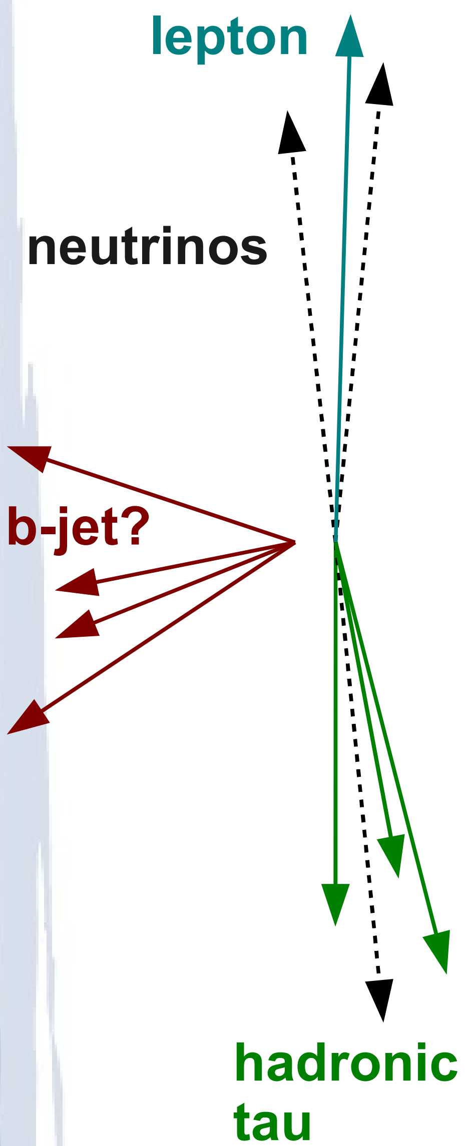
- Taus are reconstructed from energy clusters in the calorimeter, just like jets.
- Tracks are counted in a cone of 0.2 around the jet axis.
- Variables are defined based on collimation, isolation from nearby activity, and reconstructed flight length.
- These variables are used to create Boosted Decision Tree and Projective Likelihood discriminants.



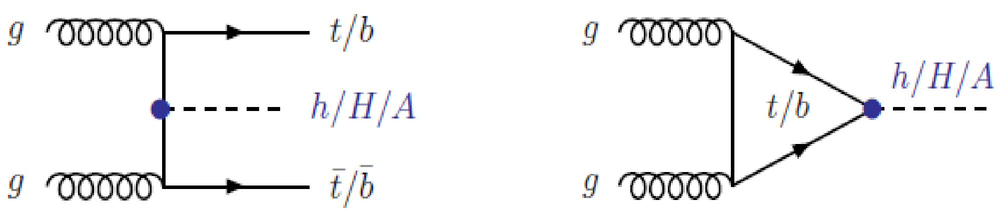




The MSSM Higgs signature

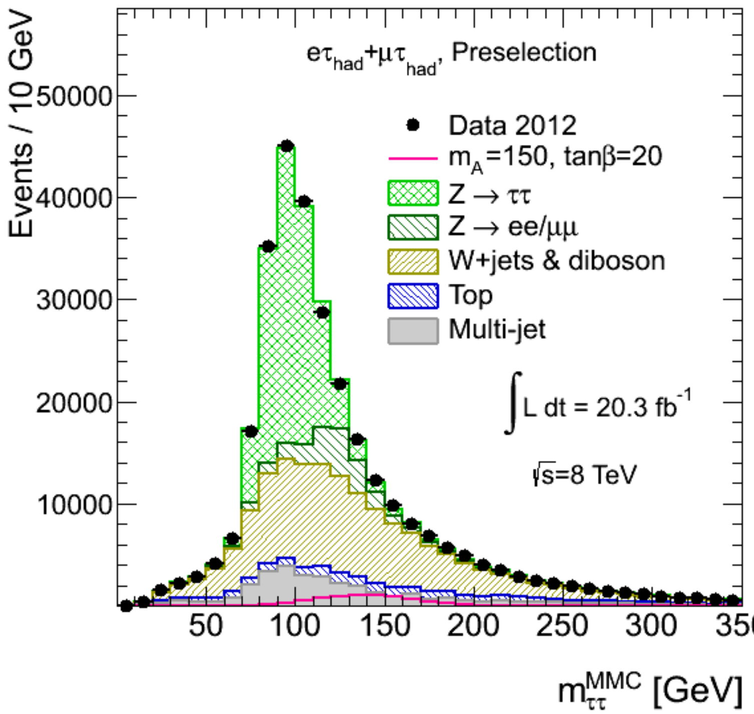


- The final state for signal events contains one lepton (electron or muon), and one hadronic tau, with opposite charge.
- In the case of b-associated production, there may also be an identified b-jet(s).
- Presence of neutrinos may lead to significant missing energy.
- Tau leptons tend to be back-to-back, especially for high mass Higgs bosons.



Analysis strategy

- Events are considered in the analysis which pass a single-electron or single-muon trigger, and have exactly one opposite-sign lepton & hadronic tau.
- At this point, significant backgrounds from $Z\rightarrow\tau\tau$, $W\rightarrow l\nu$, QCD multi-jets, $Z\rightarrow ee/\mu\mu$, and top quarks.

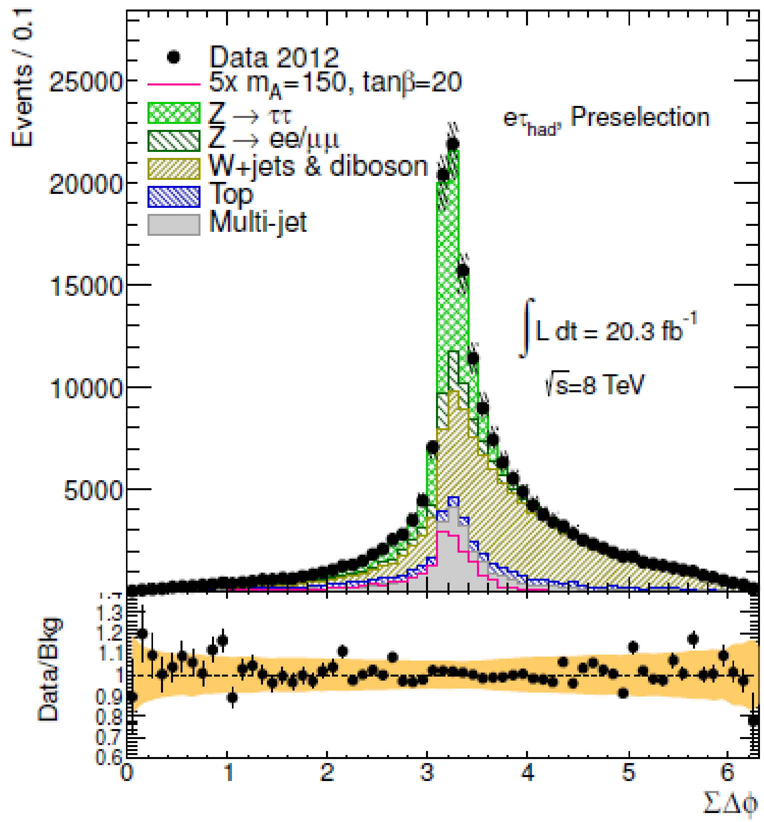


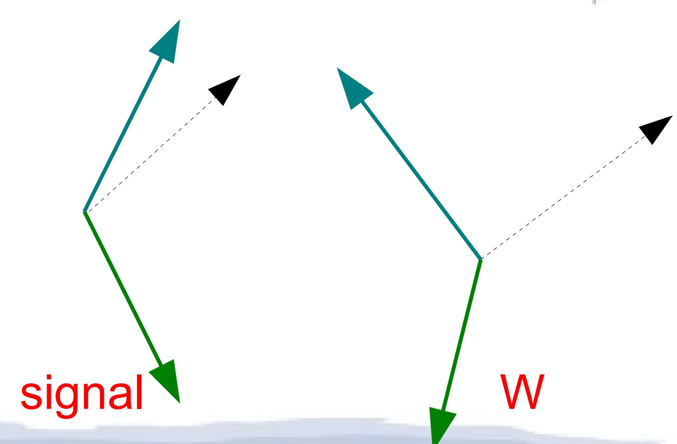
- The amount of background, the background composition, and the signal kinematics differ significantly between low-mass and high-mass Higgs bosons.
- We therefore use separate analysis cutflows targeting the low- and high-mass regions.

The low-mass analysis

- First, we've got to do something about all that W.
- For signal events, neutrinos are aligned with taus, so MET is usually aligned with one or between the two.
- W events more often form a “triad” with the MET, lepton, and “tau” well-separated.
- Sum-delta-phi offers good rejection without much signal loss:

$$\Sigma\Delta\phi = \Delta\phi(E_T^{miss}, \tau_h) + \Delta\phi(E_T^{miss}, lepton)$$



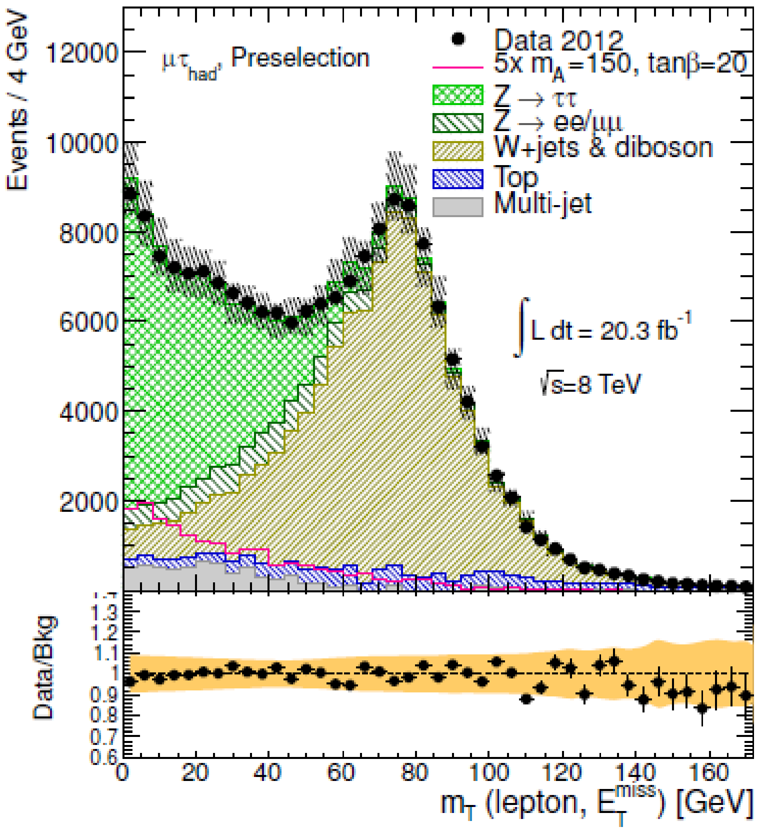


The low-mass analysis (II)

- For a similar reason as sum-delta-phi, the transverse mass between the lepton and MET offers good separation from W:

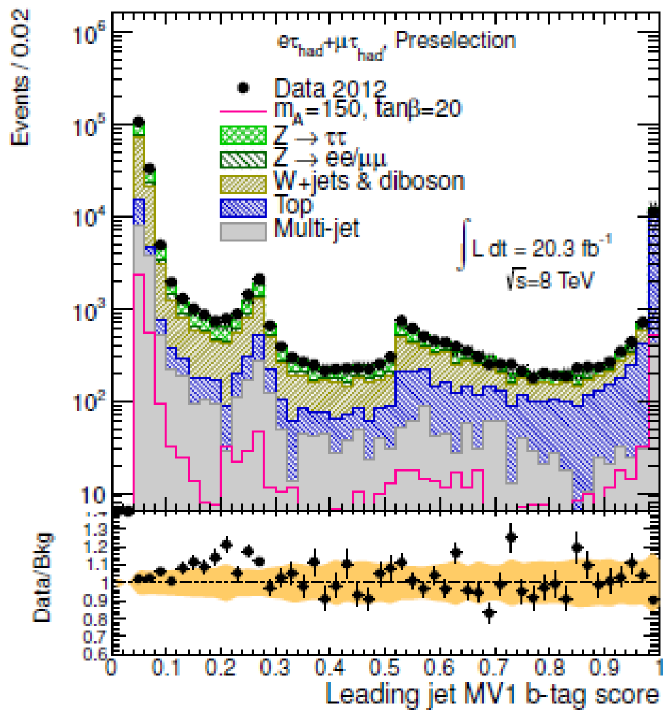
$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\mathrm{lep}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)}$$

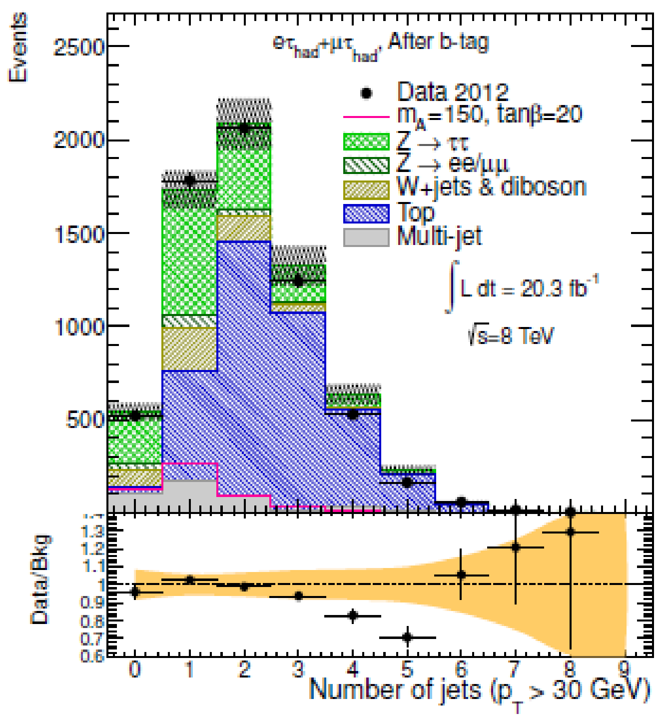
- W peaks close to the W mass.
- Signal usually has MET close to lepton (because of extra neutrino), or else very small, and so tends to low values.



b-jet categorization

- Can gain sensitivity to b-associated production by requiring a b-tagged jet.
- This is not very efficient and ignores gluon fusion, so we keep events failing this cut in a separate b-veto category.
- Top is now a huge problem: reduce by vetoing on a 2nd jet.





Low-mass: summary of cuts

- Pre-selection: Single-lepton trigger, 1 isolated lepton, 1 opposite-sign hadronic tau.

b-tag sub-channel

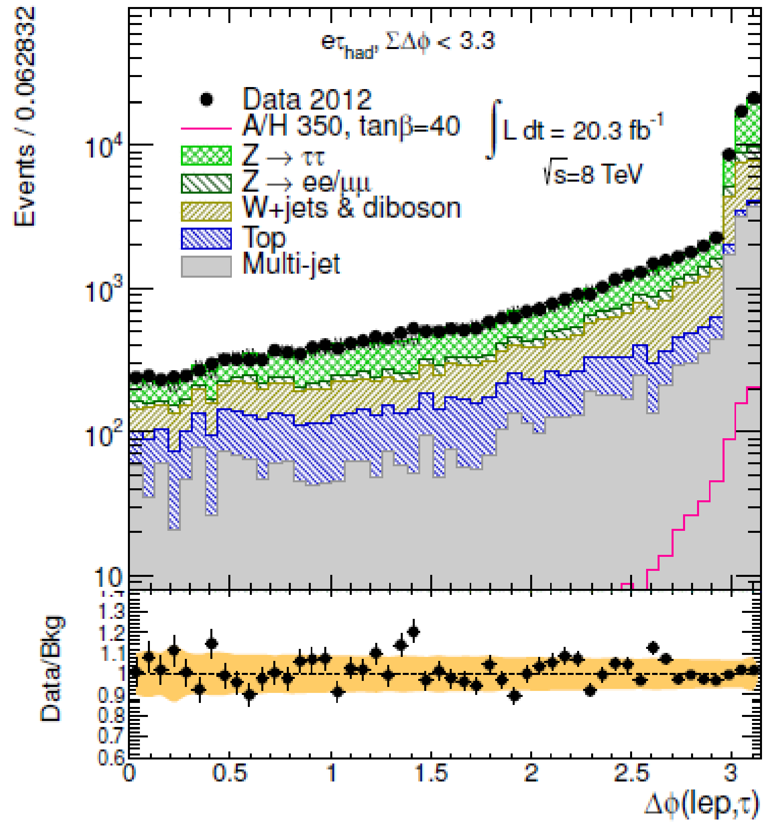
- 1 b-jet, p_T > 20 GeV.
- Transverse mass < 45 GeV
- No second jet with p_T > 30 GeV

b-veto sub-channel

- No b-tagged jets.
- Sum-delta-phi < 3.3
- Transverse mass < 60 GeV

The high-mass analysis

- W is still a major background at high mass: we apply the same cut on sum-delta-phi as before.
- The boost of the Higgs bosons is now much smaller relative to the momentum of the decay products: taus will be back-to-back.
- We require the azimuthal angle between the tau and lepton to be at least 2.4.

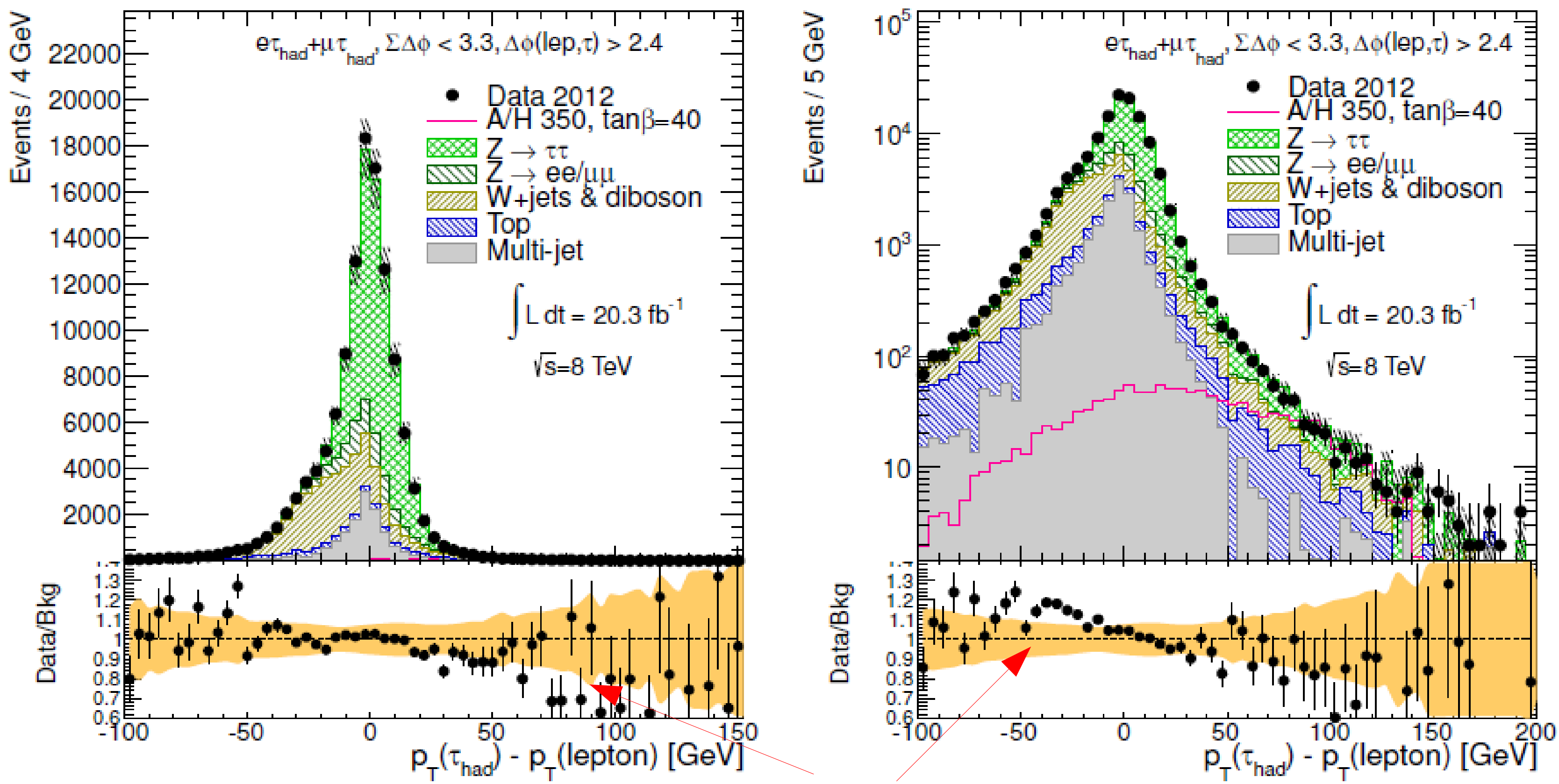


Delta-p_T

- Hadronic taus usually have a higher fraction of visible vs. invisible energy as compared to leptonic taus.
- Motivates a new variable: $\Delta p_T = p_T(\text{tau}) - p_T(\text{lepton})$.
- Expect positive, sometimes large values for signal, but small or negative values for all major backgrounds:
  - W: Lepton receives boost from W mass, while “tau” jet does not.
  - top: Lepton and tau both come from W, but tau loses some momentum to neutrino.
  - $Z \rightarrow \tau\tau$: Same as signal, but imbalance smaller.
  - $Z \rightarrow ee/\mu\mu$: No great imbalance expected.
  - QCD: No great imbalance expected.

Delta-p_T

- We apply a cut at 45 GeV.
- Kills a lot of our signal, but also 99% of background, and roughly doubles the sensitivity at high mass.



*Do not worry about the modelling, it will be explained later

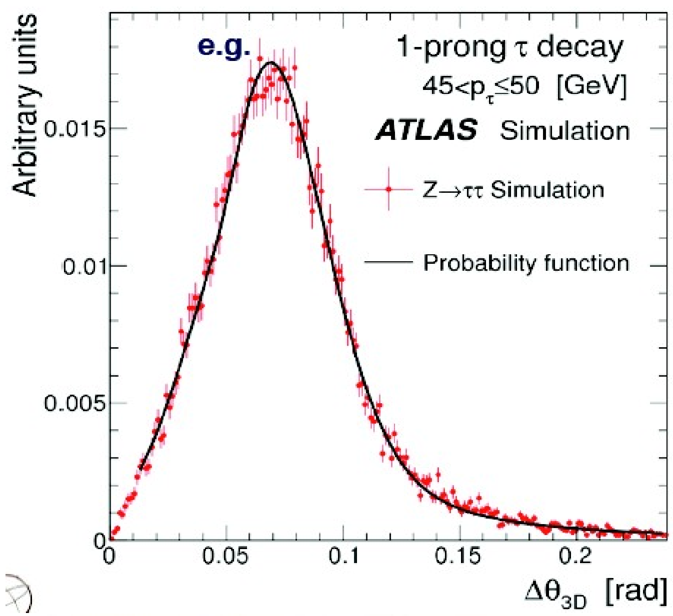
High-mass: summary of cuts

- Preselection: Same as the low-mass analysis.
- Sum-Delta-phi < 3.3
- Delta-phi (lepton, tau) > 2.4
- Delta-p_T > 45 GeV.

- No b-jet categorization is applied, as the kinematic information at high mass is better at separating signal from background.

Mass reconstruction

- After the event selection, we want to use the invariant mass of the two taus to check for a Higgs resonance.
- Calculating the mass exactly is impossible: no way to know how the missing energy came from the various neutrinos.
- Instead we scan the possible solutions, and weight each one based on what it says about the tau decays: the Missing Mass Calculator (MMC).



$$
\begin{aligned}
E_x^{\mathrm{miss}} &= p_{\mathrm{miss}_1} \sin\theta_{\mathrm{miss}_1} \cos\phi_{\mathrm{miss}_1} + p_{\mathrm{miss}_2} \sin\theta_{\mathrm{miss}_2} \cos\phi_{\mathrm{miss}_2}, \\
E_y^{\mathrm{miss}} &= p_{\mathrm{miss}_1} \sin\theta_{\mathrm{miss}_1} \sin\phi_{\mathrm{miss}_1} + p_{\mathrm{miss}_2} \sin\theta_{\mathrm{miss}_2} \sin\phi_{\mathrm{miss}_2}, \\
m_\tau^2 &= m^2_{\mathrm{miss}_1} + m^2_{\mathrm{vis}_1} + 2\sqrt{p^2_{\mathrm{vis}_1} + m^2_{\mathrm{vis}_1}}\sqrt{p^2_{\mathrm{miss}_1} + m^2_{\mathrm{miss}_1}} \\
&\quad -2 p_{\mathrm{vis}_1} p_{\mathrm{miss}_1} \cos\Delta\theta_{\mathrm{vm}_1}, \\
m_\tau^2 &= m^2_{\mathrm{vis}_2} + 2\sqrt{p^2_{\mathrm{vis}_2} + m^2_{\mathrm{vis}_2}} \cdot p_{\mathrm{miss}_2} \\
&\quad -2 p_{\mathrm{vis}_2} p_{\mathrm{miss}_2} \cos\Delta\theta_{\mathrm{vm}_2}
\end{aligned}
$$

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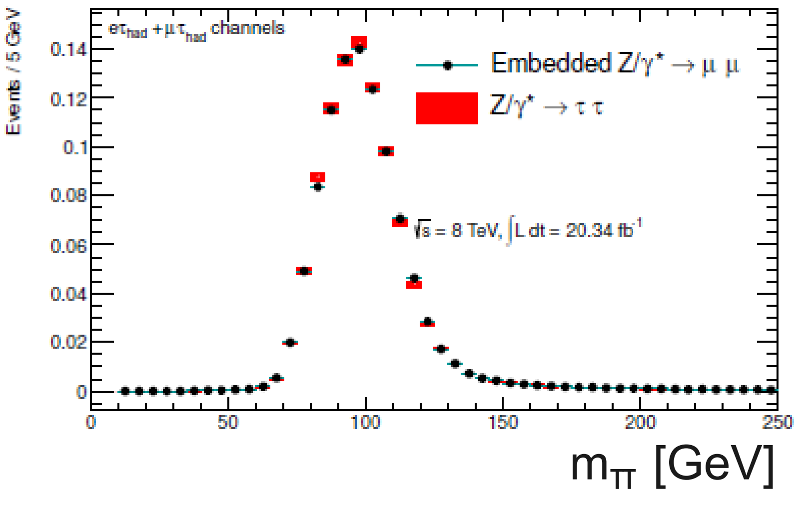
Background estimation

- The simplest way to predict the backgrounds is using Monte Carlo simulation.
- However, simulating proton collisions is difficult and unreliable. If you ever observed a signal, people would just say the simulation is off.
- To really prove something, backgrounds must be estimated or validated directly from the data.
- This usually involves changing around cuts to find control regions with background but no signal.

$Z \to \tau\tau$ with "embedding"

- $Z\to\tau\tau$ is the #1 background: important to get it right!
- No way to define a control region in data that is rich in $Z\to\tau\tau$ but doesn't contain signal.
- Instead, $Z\to\mu\mu$ events are selected in data, and transformed into tau events as follows:
  - Muons removed from the event.
  - Taus are simulated with the same kinematics.
  - "Mini" tau event passed through detector simulation.
  - This is "embedded" into original event.



QCD Multijets

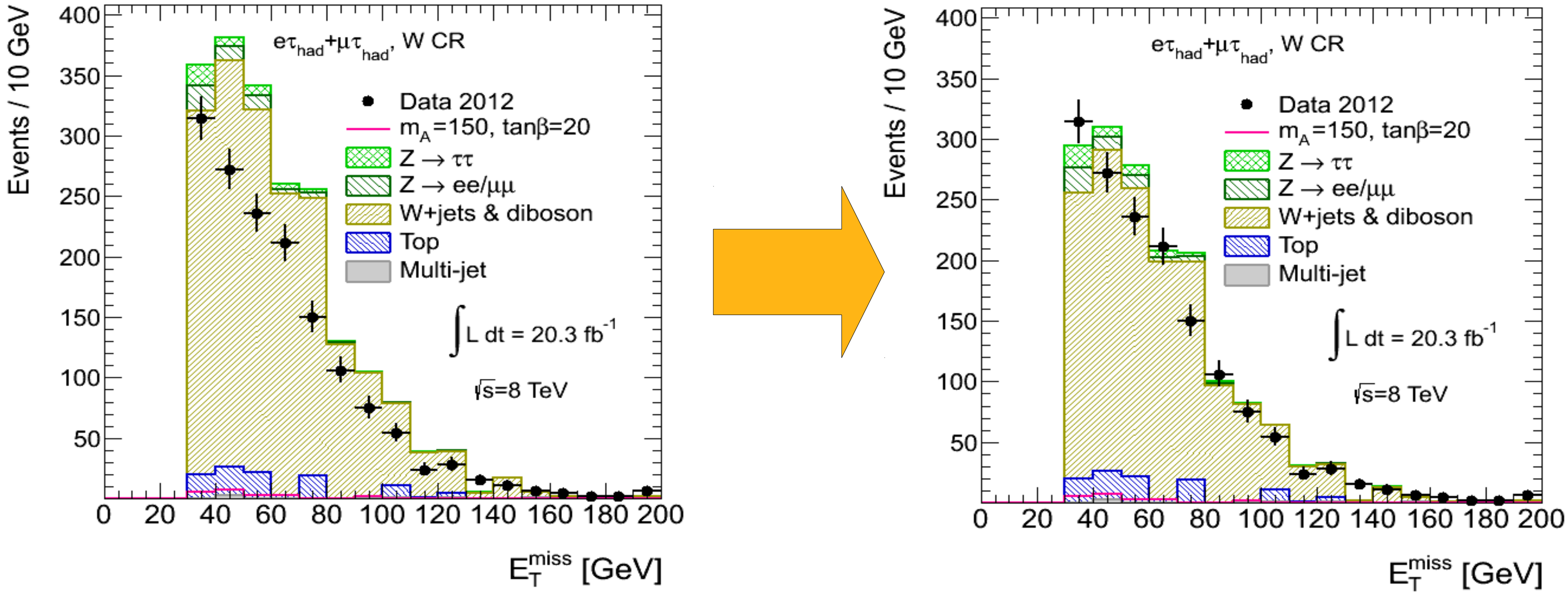
- For these events to pass our cuts, one jet must be mis-identified as a lepton and another as a tau. It's rare, but the cross-section is so huge that the rate isn't too small.
- QCD events do not necessarily have opposite-sign lepton and tau: use same-sign events as the estimate.
- This prediction must be scaled by the OS/SS ratio for QCD; we measure this by defining two more regions with non-isolated leptons.
- Non-QCD events must be subtracted from the SS region.

	Isolation	Inverted Isolation
OS	A (Signal)	B
SS	C	D

$$n_A^{QCD} = n_C \frac{n_B}{n_D} \equiv r_{B/D} n_C$$

Backgrounds with jet→τ fakes

- The rate at which jets are mis-identified as taus is very poorly modelled by MC.
- This affects W, top, and Z→ee/μμ.
- We correct for this by scaling the MC in control regions.



Backgrounds with jet→τ fakes

- Z CR's involve 2 leptons; W CR's involve high sum-delta-phi, and top CR's involve a high-p_T b-jet.
- Control regions defined separately for each of the final states, to account for extra b-jet, high tau p_T at high mass.

	b-veto	b-tag	high-mass
Z→ll (jet-fake)	2 SF, OS leptons 70 < m < 110	same as veto, plus: 1+ b-jet, pT < 60	same as veto, plus: tau pT > 85 GeV
W + jets	Sum-dphi > 3.6 MET > 30 GeV no b-jets	Sum-dphi > 3.6 MET > 30 GeV 1 b-jet, pT < 60 Sum(jet pt) < 100	Sum-dphi > 3.4 tau pT > 100 GeV MET > 40 GeV no b-jets
top	1 b-jet, pT > 60 GeV Sum(jet pt) > 150 MET > 20 GeV mT < 60 GeV (OS)	same as veto	1 b-jet, pT > 60 GeV MET > 20 GeV tau pT > 85 GeV

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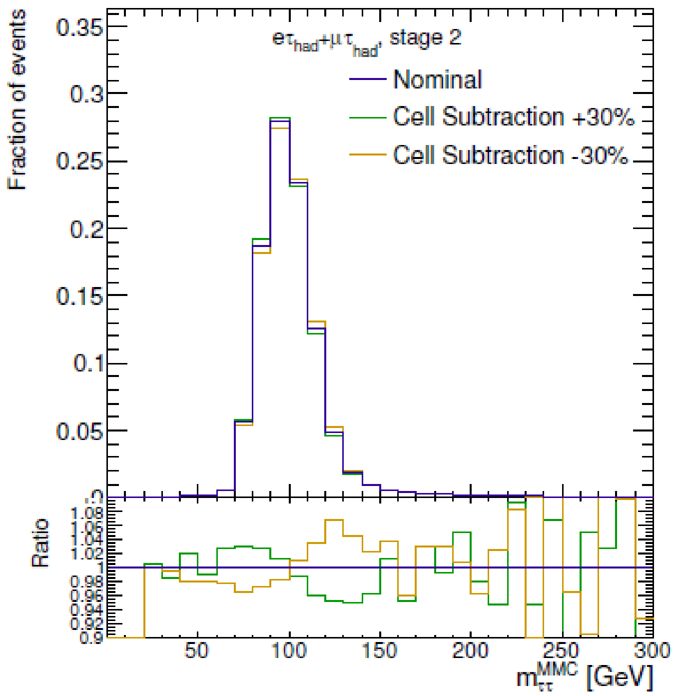
Background estimation systematics

- The embedding procedure has two systematic sources:
  - The isolation criteria applied in selecting the original muons
  - The procedure for subtracting the muon energy deposits in the calorimeter.



- Systematics are applied on the fake jet control regions by varying the criteria to judge the validity of extrapolation.
- The systematic on the QCD estimate comes from the stability of the OS/SS ratio with mass, and the extrapolation from the non-isolated regions.

Theory-related systematics

- Uncertainties on the cross-sections are applied for signal and backgrounds which are not scaled to data.
- We also consider the effect of MC uncertainties on the cutflow efficiencies.
  - Analysis cuts performed at truth-level with MC samples using alternative tuning parameters.

Sample	Uncertainty
Background Samples	
$Z \to ee/\mu\mu/\tau\tau$	$\pm$ 5 %
Diboson	$\pm$ 6 %
Signal Samples($\tan\beta = 20$)	
$ggA/h/H$ ($m_A \leq 300$ GeV)	$< 15\%$
$bbA/h/H$ ($m_A \geq 120$ GeV)	$-(< 20)\%, +(< 9)$ %
$bbA/h/H$ ($m_A = 110$ GeV)	$-(< 25)\%, +(< 9)$ %
$bbA/h/H$ ($m_A = 100$ GeV)	$-(< 28)\%, +(< 9)$ %
$bbA/h/H$ ($m_A = 90$ GeV)	$-(< 30)\%, +(< 9)$ %

Event yields	b-tag deviation [%]	b-veto deviation [%]
CKKW down	-4.5 ± 0.8	0.2 ± 0.4
CKKW up	-10.0 ± 0.8	0.9 ± 0.4
Fac. scale up	-22.2 ± 0.7	3.3 ± 0.4
Fac. scale down	14.6 ± 0.9	-3.5 ± 0.4
Ren. scale down	0.2 ± 0.8	-0.6 ± 0.4
Ren. scale up	-0.9 ± 0.8	-0.5 ± 0.4
PDF	± 0.1	± 0.2
Total (up)	14.6 ± 1.2	3.4 ± 0.7
Total (down)	-24.7 ± 1.6	-3.6 ± 0.7

Detector-related systematics

	Signal	Embedding $Z \to \tau\tau$	QCD	W+jets	$Z \to ll$	Top	Diboson
	b-tag selection, electron						
JES B-Jets	1.0	-	0.5	4.8	0.2	2.6	1.2
JES Eta Modelling	1.9	-	0.4	7.5	2.3	5.8	4.3
JES Flavor Composition	1.9	-	1.3	8.5	5.0	3.7	5.8
JES Flavor Response	1.9	-	2.2	7.9	3.8	3.0	5.8
JES Modelling	1.4	-	1.6	14.0	3.5	8.0	7.0
JES Pileup	1.0	-	1.9	6.6	3.1	4.4	7.0
TES	4.1	4.6	2.5	1.5	7.2	0.3	4.1
MET Scale/Resolution	0.7	-	1.7	1.1	0.0	0.4	0.0
JER	0.9	-	0.2	12.4	4.7	1.5	2.1
JVF	6.1	-	7.2	8.5	1.6	5.8	2.2
Tau ID	3.4	3.4	0.1	0.9	0.0	0.5	1.7
Lepton to tau fake rate	0.0	0.0	0.0	0.1	5.1	0.0	0.0
Electron ID and energy	2.1	2.1	0.8	1.4	2.5	1.6	2.4
Muon ID and momentum	0.0	0.0	0.7	1.3	0.8	1.1	0.0
Pileup	1.2	0.1	0.4	1.5	0.8	0.5	1.2
b-jet tagging efficiency	5.5	-	0.2	1.9	0.4	3.7	0.7
c and light jet tagging rate	0.3	-	2.9	5.8	4.9	1.0	9.4
Luminosity	2.8	2.8	-	-	2.8	-	2.8

- For every variation, the entire analysis procedure is repeated to get the uncertainties.

Statistical procedure (I)

- The ditau MMC mass distributions after all cuts is used as the final discriminating variable.
- To exploit full information, we count events in each mass bin.
- The agreement of a given hypothesis with the observed data is quantified using a Likelihood Function:

$$\mathcal{L}(\mu, \theta) = \prod_{\substack{\text{j=bin and} \\ \text{category}}} \text{Poisson}(N_j \mid \mu \cdot s_j + b_j) \prod_{\theta_i} \text{Gaussian}(\theta_i \mid 0, 1) .$$

  - μ is the signal strength: $\mu = 0$ implies background only; $\mu = 1$ is the nominal signal model we're testing.
  - $\vec{\theta}$ are the nuisance parameters, which quantify how the expected signal & background depend on systematics.
  - N is observed, s and b are expected signal and background

Statistical procedure (II)

- For each μ hypothesis, we maximize the likelihood function by scanning over the θ; $\hat{\mu}$ is the global maximum point.
- To decide if μ is excluded, we use the following test statistic:

$$\tilde{q}_\mu = \begin{cases} -2\ln\left(\frac{\mathcal{L}(\mu,\hat{\hat{\boldsymbol{\theta}}}_\mu)}{\mathcal{L}(0,\hat{\hat{\boldsymbol{\theta}}}_0)}\right) & \text{if } \hat{\mu} < 0, \\ -2\ln\left(\frac{\mathcal{L}(\mu,\hat{\hat{\boldsymbol{\theta}}}_\mu)}{\mathcal{L}(\hat{\mu},\hat{\boldsymbol{\theta}})}\right) & \text{if } 0 \le \hat{\mu} \le \mu, \\ 0 & \text{if } \hat{\mu} > \mu, \end{cases}$$

Compare to 0 if $\hat{\mu}$ is negative (unphysical)

How unlikely is my μ compared to the most likely point?

No penalty if the best-fit signal is stronger

- If $\tilde{q}_\mu$ is too high, then μ is excluded at 95% Confidence Level; if μ = 1 is excluded, then the signal hypothesis is excluded.
- We can estimate expected exclusion limits using the “Asimov dataset” (pretending the data is exactly what we expect).

Outline

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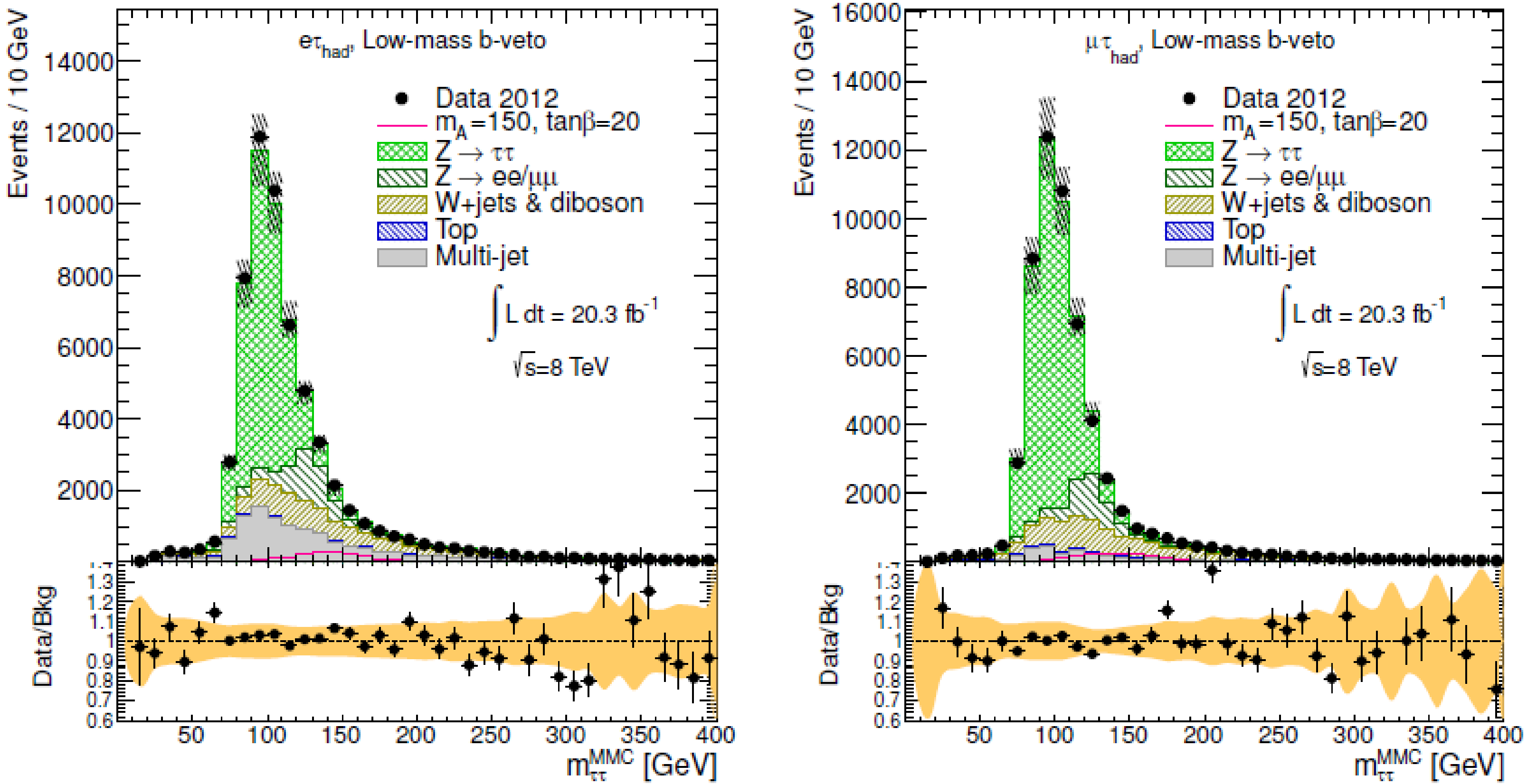
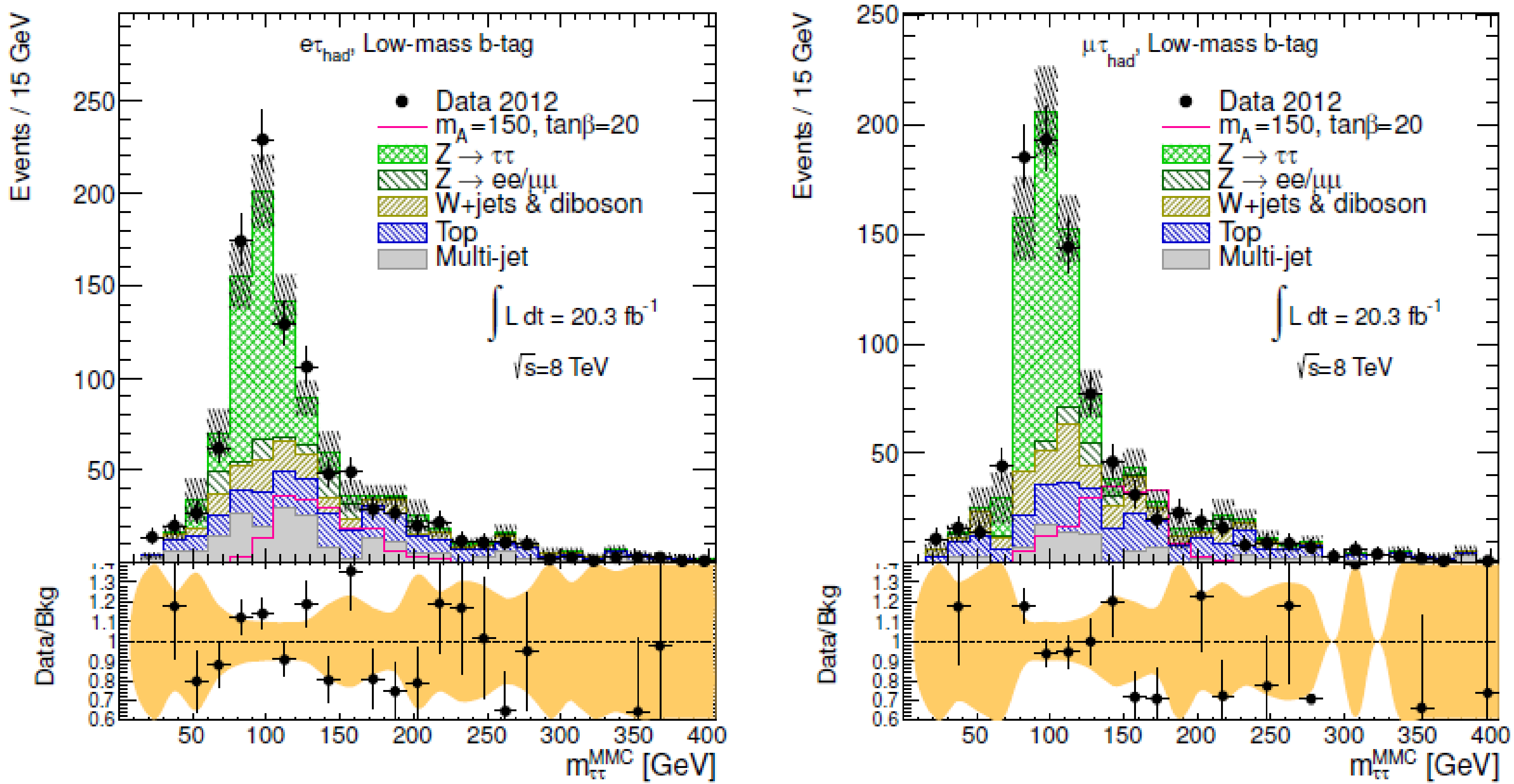
Anyone wishing to remain blinded to the results should leave at this point.

Low-mass b-veto



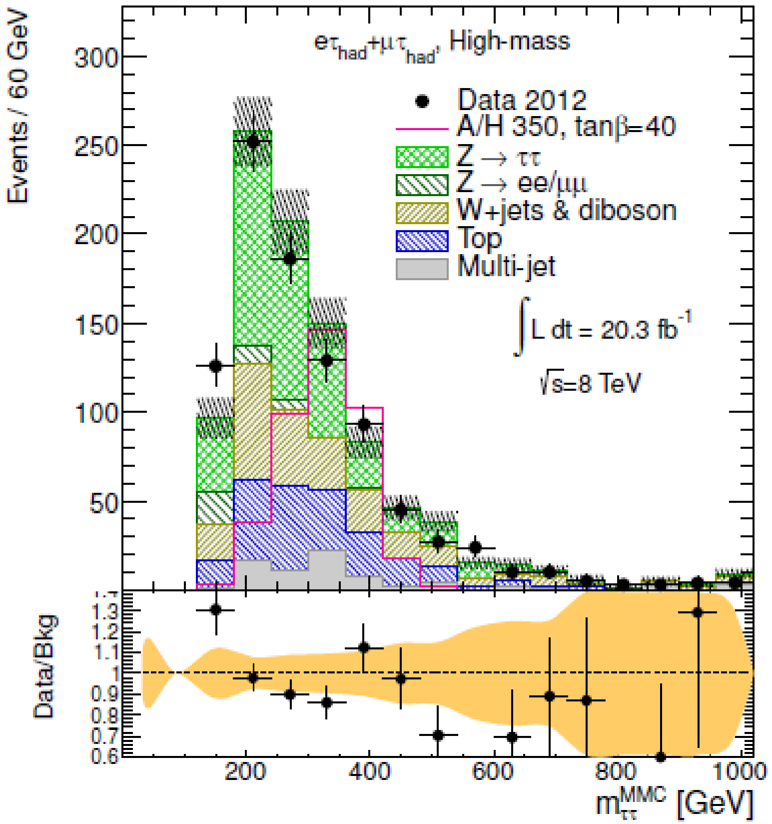
- No significant excess is observed.

Low-mass b-tag



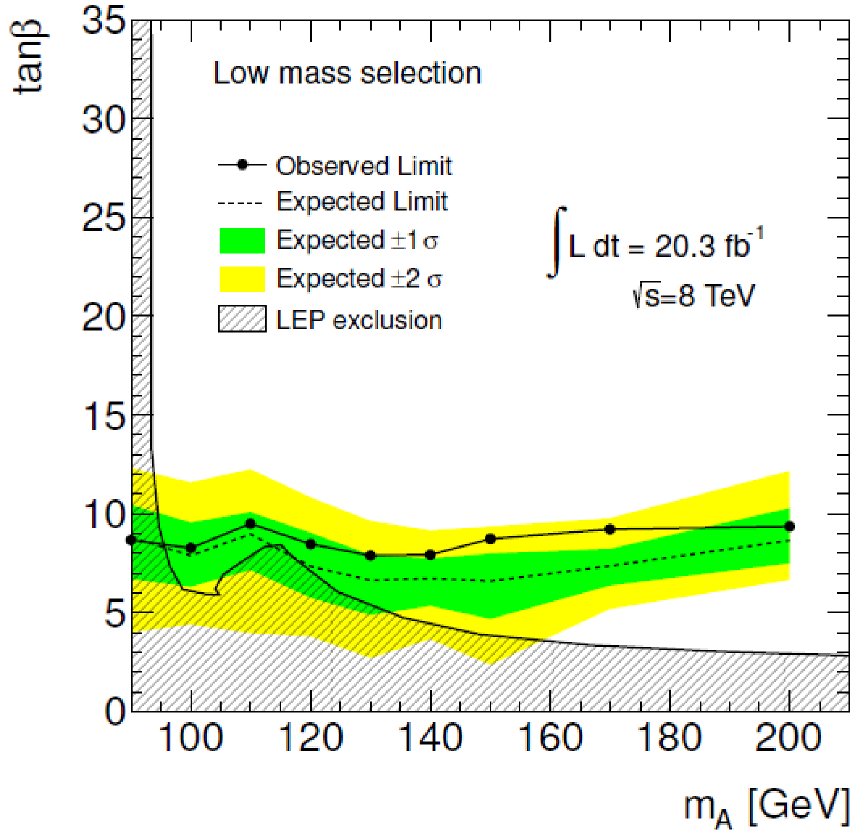
- No significant excess is observed.

High mass



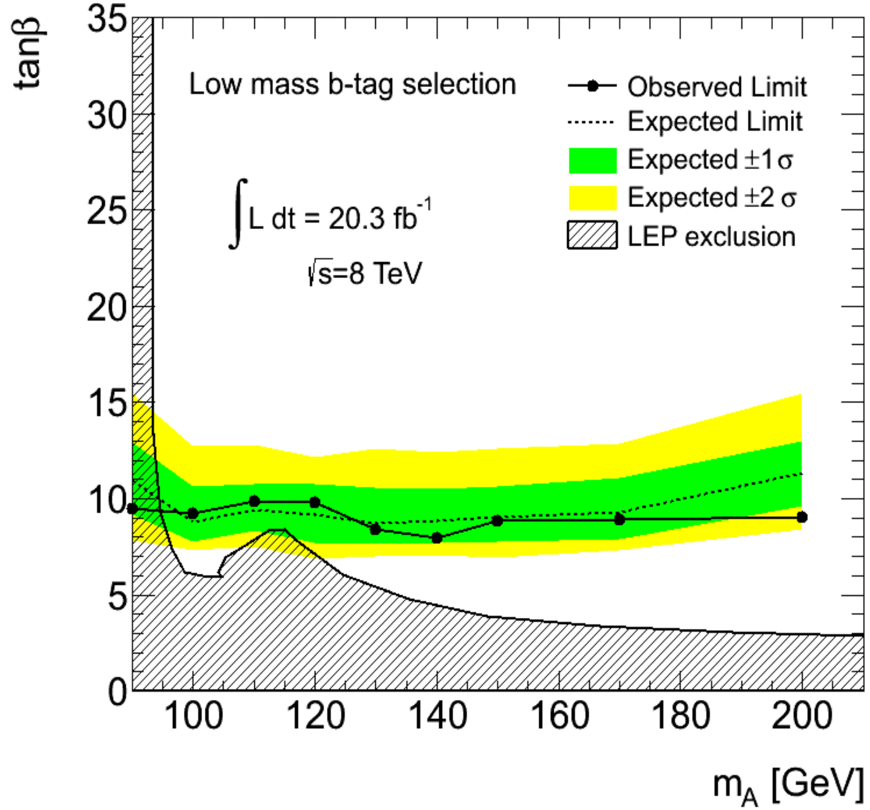
- Electron and muon channels are combined at high mass.
- No significant excess is observed.

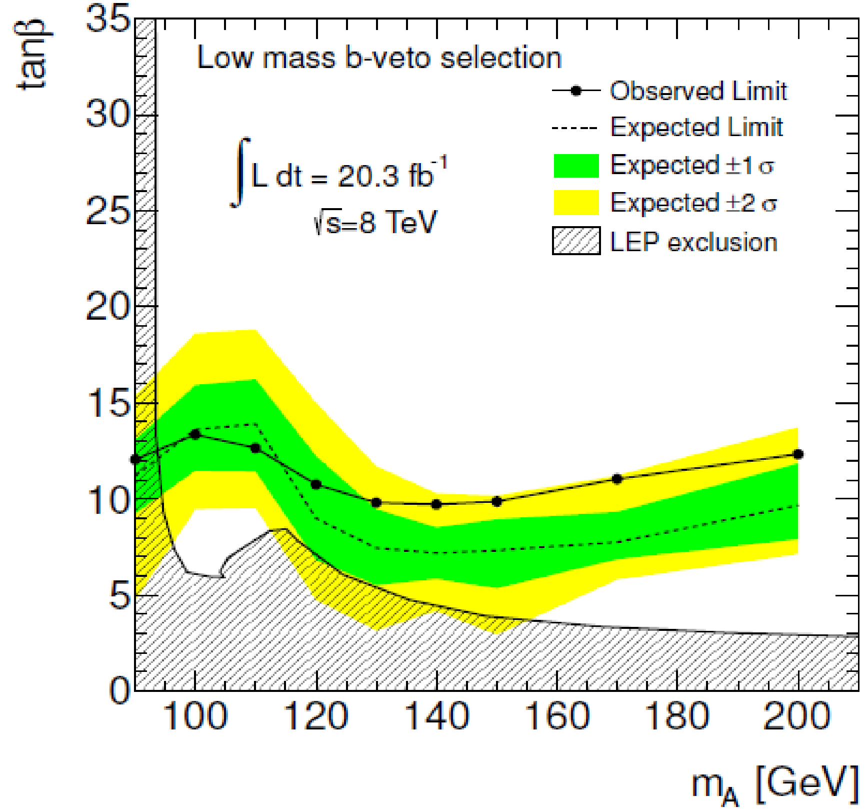
Limits: Low mass



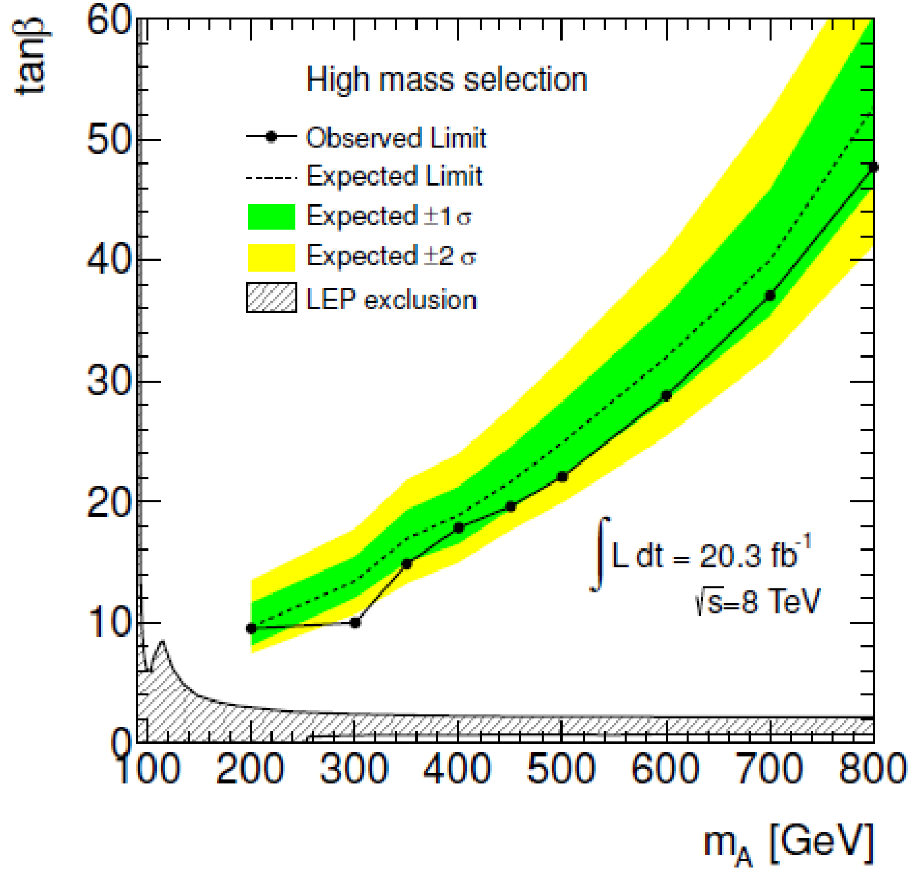
- Values of tanβ above the lines are excluded at 95% CL.
- The low tanβ region is becoming very tightly constrained.

Limits: b-tag and b-veto

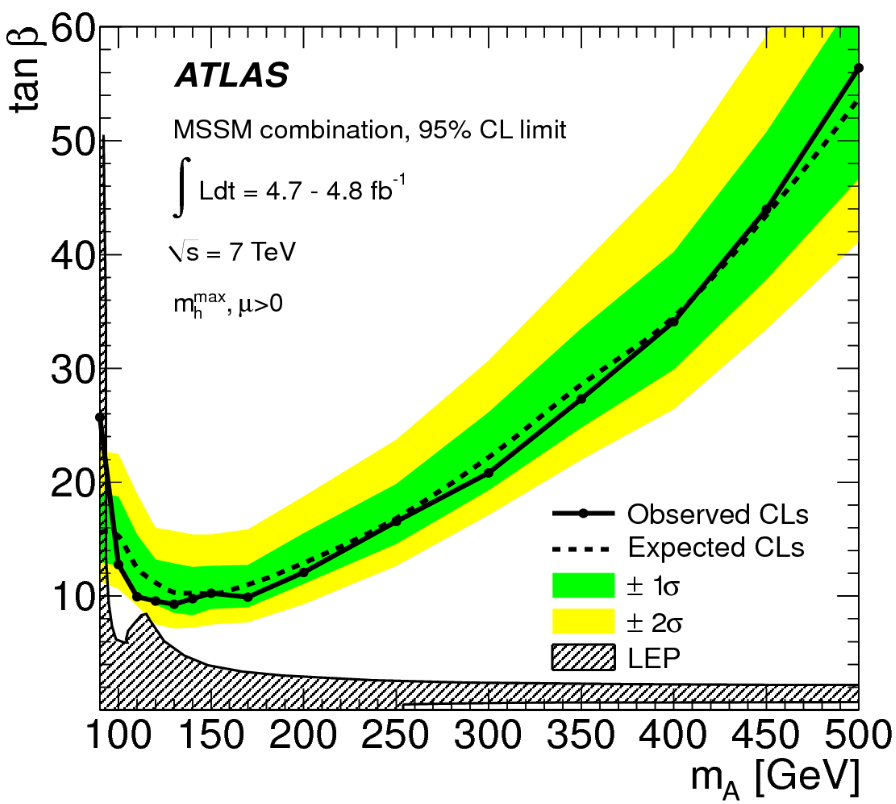


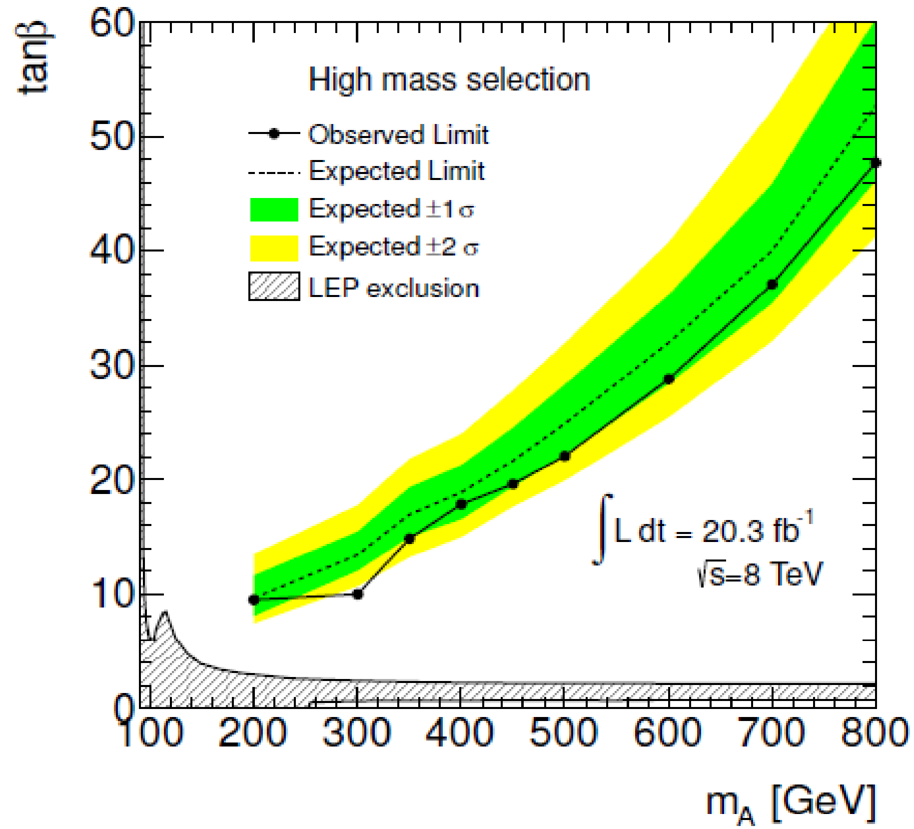


Limits: High-mass



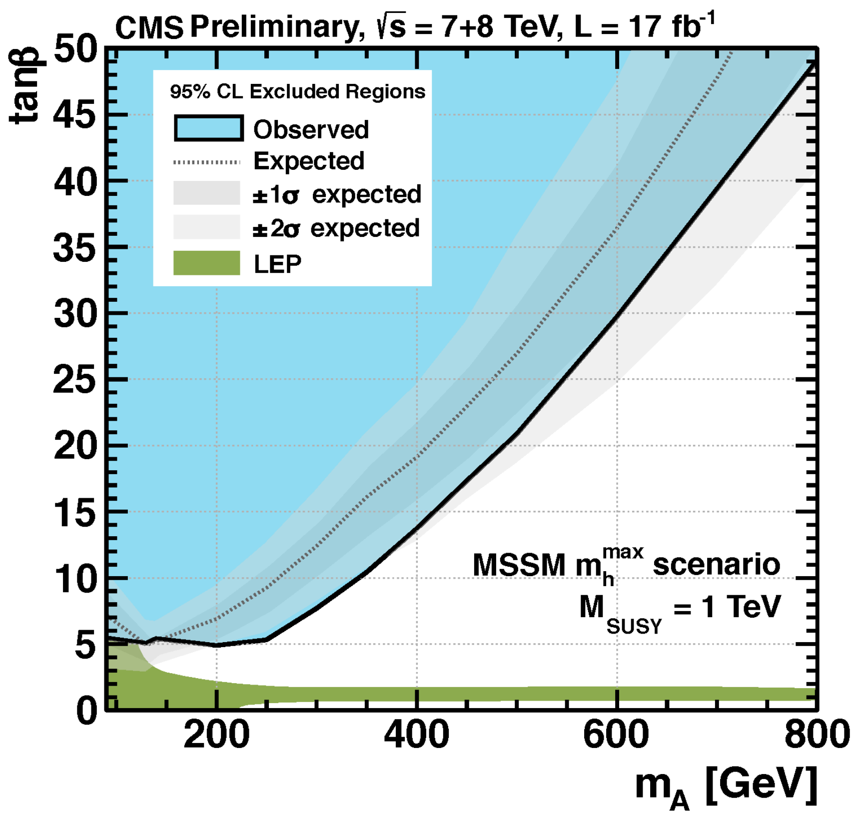
Comparison with previous result

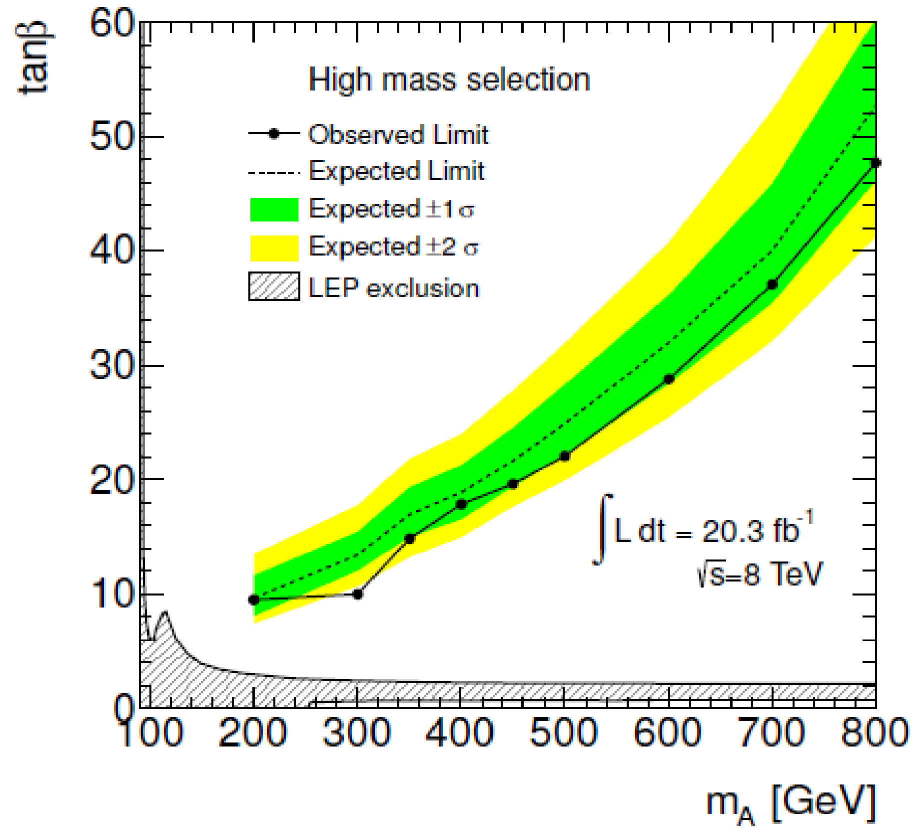




- Very significant improvement with respect to the previous ATLAS results (from 2011 data).
- Especially strong at high mass, much larger than expected simply from luminosity increase.

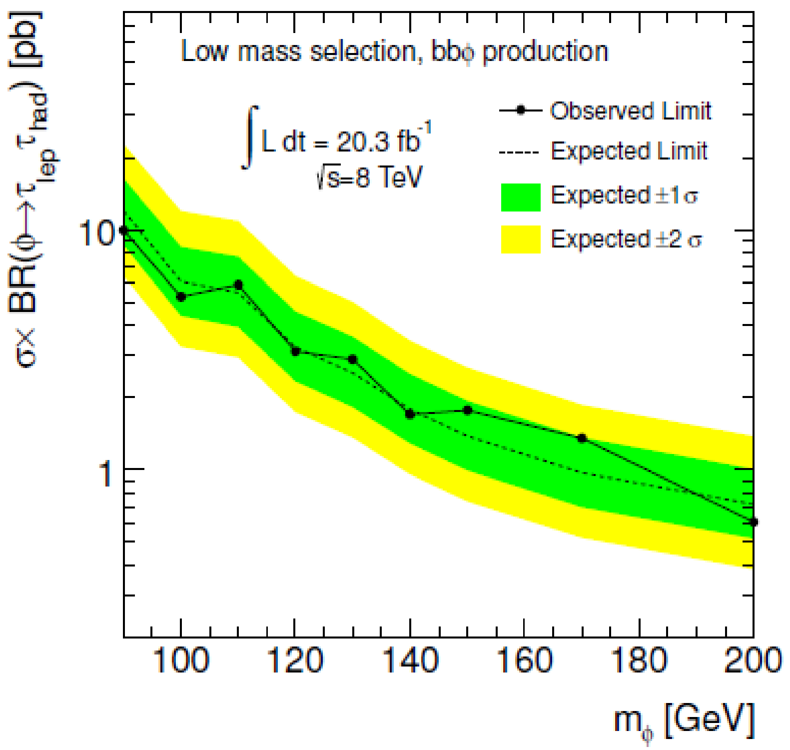
Comparison with CMS

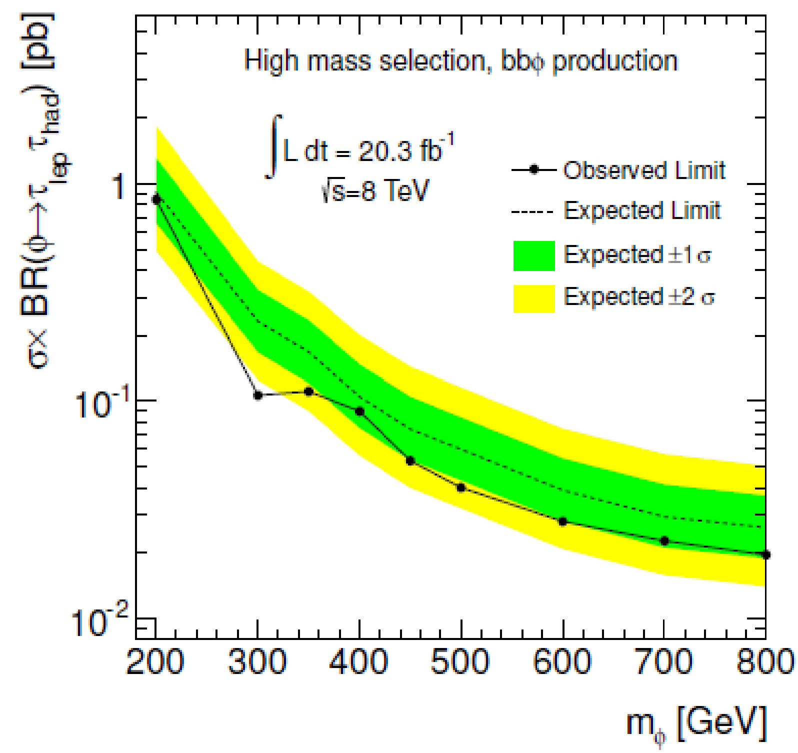




- CMS result with 12 fb^{-1} at 8 TeV + 5 fb^{-1} at 7 TeV, lh + ll.
- ATLAS setting world's best limits for all masses above 500 GeV.
- ATLAS most sensitive experiment for all masses above 350 GeV.

Cross-section limits





- We also set limits on the cross-section * branching ratio for generic scalar bosons, for both production processes.
- Useful for theorists to extend the analysis to other models.

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Conclusions

- A search for the neutral MSSM Higgs bosons has been presented.
- Significant improvements from previous analyses achieved by introducing new categorization, new variables, and improved background estimation.
- No evidence of additional Higgs states has been seen.
- Sensitivity has been extended into regions of phase space never before explored.

Acknowledgements

- Many thanks to my colleagues at CERN who assisted with this analysis.
  - Especially Matt & Nikos.
- Thanks to all of my friends in Geneva and Seattle.
- Thanks to everyone on my committee,
- And of course...

Thank you Anna!

IN THE NEWS: Boeing | Traffic alert | Arena proposal | Home prices | Ma

UW physicists helped discover 'God particle'

ALAN BERNER / THE SEATTLE TIMES

UW physicists Gordon Watts and Anna Goussiou have been working on Higgs physics theories for more than a decade. Though scientists predicted the existence of the Higgs boson, also known as the "God particle," for half a century, they found convincing evidence of its existence only recently.

backup

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- “Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in pp collisions at sqrt(s)=7 TeV with the ATLAS detector”, JHEP02(2013)095, arXiv: 1211.6956
- “Search for Neutral MSSM Higgs Bosons Decaying to Tau Pairs in pp Collisions”, CMS-PAS-HIG-12-050

The Higgs Mechanism (I)

- All known particles & interactions described by the Standard Model, which obeys an SU(3) x SU(2) x U(1) symmetry.

$$\mathcal{L}_{\mathrm{SM}} = \boxed{-\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a} - \boxed{\frac{1}{4}W^a_{\mu\nu}W^{\mu\nu}_a} - \boxed{\frac{1}{4}B_{\mu\nu}B^{\mu\nu}} \qquad (1.11)$$
$$+\underline{\bar{L}_i\, iD_\mu\gamma^\mu\, L_i} + \underline{\bar{e}_{Ri}\, iD_\mu\gamma^\mu\, e_{R_i}} + \underline{\bar{Q}_i\, iD_\mu\gamma^\mu\, Q_i} + \underline{\bar{u}_{Ri}\, iD_\mu\gamma^\mu\, u_{R_i}} + \underline{\bar{d}_{Ri}\, iD_\mu\gamma^\mu\, d_{R_i}}$$

- This requires 8 gluon fields ($G^{1\text{-}8}$), 3 W fields, and 1 B field, all of which *must be massless*, or the symmetry is violated:

$$\frac{1}{2}M_A^2 A_\mu A^\mu \to \frac{1}{2}M_A^2(A_\mu - \frac{1}{e}\partial_\mu\alpha)(A^\mu - \frac{1}{e}\partial^\mu\alpha) \neq \frac{1}{2}M_A^2 A_\mu A^\mu$$

- Moreover, left- and right-handed fermions are treated differently under SU(2), as either a doublet or a singlet.
- Adding a mass term there would likewise break the symmetry:

$$-m_e(\bar{e}_R e_L + \bar{e}_L e_R)$$

The Higgs Mechanism (II)

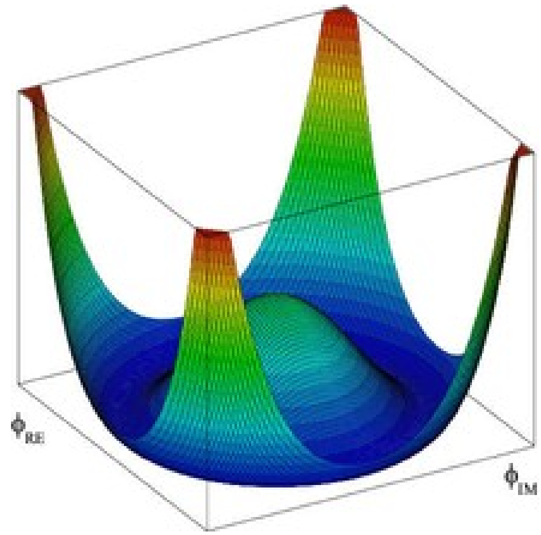
- To solve this, we introduce a new SU(2) doublet: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$,

  with a lagrangian:

$$\mathcal{L}_S = \left|\left(\partial_\mu - ig_2\frac{\tau_a}{2}W_\mu^a - ig_1\frac{1}{2}B_\mu\right)\Phi\right|^2 - \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

- If $\mu^2 < 0$, Φ obtains a non-zero vacuum expectation value: by default it exists everywhere in the universe!

- Particles may become massive by coupling to this field, *without messing up the symmetries*.



The Higgs Mechanism (III)

- Apply a gauge transformation to write $\Phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$

  then expand the Lagrangian: $\left| \left(\partial_\mu - i g_2 \frac{\tau_a}{2} W_\mu^a - i g_1 \frac{1}{2} B_\mu \right) \Phi \right|^2$

  $$= \frac{1}{2}(\partial_\mu H)^2 + \frac{1}{8} g_2^2 (v+H)^2 |W_\mu^1 + i W_\mu^2|^2 + \frac{1}{8}(v+H)^2 |g_2 W_\mu^3 - g_1 B_\mu|^2$$

- Defining: $W^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp i W_\mu^2)\ ,\ Z_\mu = \frac{g_2 W_\mu^3 - g_1 B_\mu}{\sqrt{g_2^2 + g_1^2}}\ ,\ A_\mu = \frac{g_2 W_\mu^3 + g_1 B_\mu}{\sqrt{g_2^2 + g_1^2}}$

  we obtain: $M_W = \frac{1}{2} v g_2\ ,\ M_Z = \frac{1}{2} v \sqrt{g_2^2 + g_1^2}\ ,\ M_A = 0$

  the three electroweak gauge fields we know from experiment.

- Fermion masses come from adding Yukawa terms:

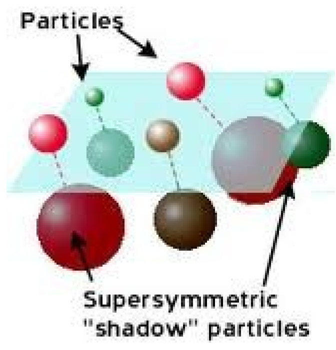
$$\mathcal{L}_F = -\lambda_e \bar{L} \Phi e_R = -\frac{1}{\sqrt{2}} \lambda_e (v + H) \bar{e}_L e_R$$

Supersymmetry (I)

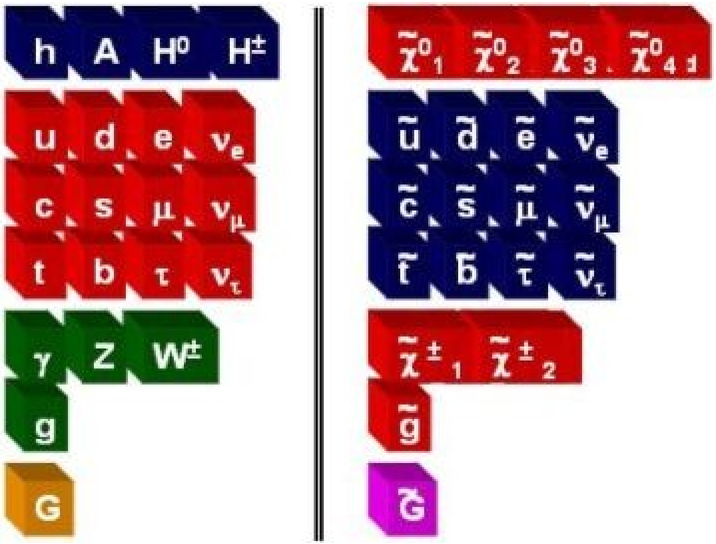
- So the Standard Model is saved! Still, no one believes it.
  - No dark matter.
  - Quantum corrections to μ^2.

- Supersymmetry kills both these birds (and several others) with one stone: a spinor-valued spacetime symmetry.
- To satisfy this, a system must have equal numbers of fermionic and bosonic degrees of freedom.
  - Every particle has a partner "super-particle".

$$\{Q_\alpha, Q^\dagger_{\dot\alpha}\} = -2\sigma^\mu_{\alpha\dot\alpha}P_\mu,$$
$$\{Q_\alpha, Q_\beta\} = 0, \qquad \{Q^\dagger_{\dot\alpha}, Q^\dagger_{\dot\beta}\} = 0$$



Supersymmetry (II)

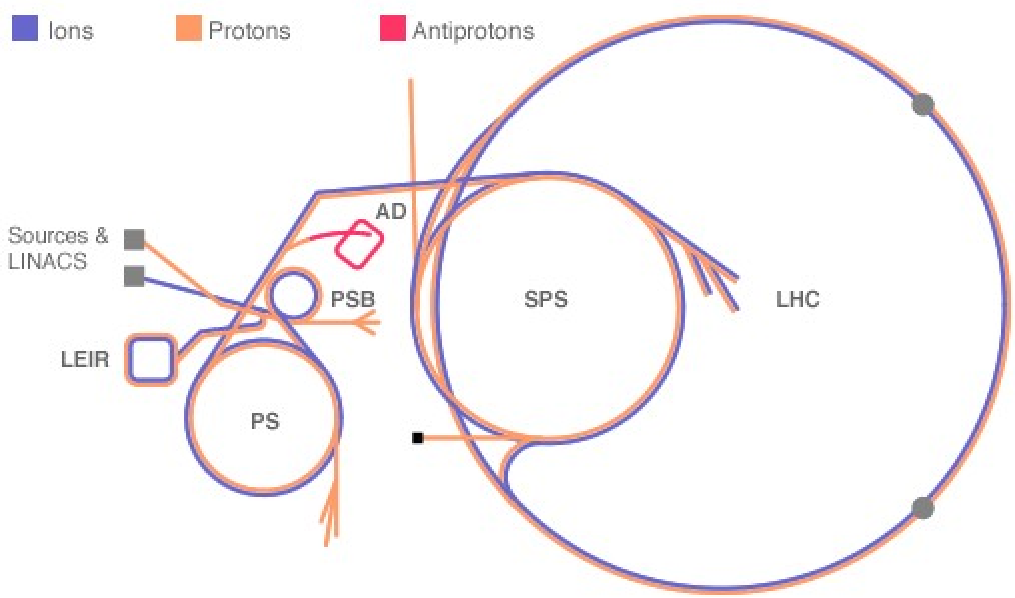


- Each fermion has a spin-0 *sfermion* partner.
- Gauge and Higgs bosons have *gaugino*, *higgsino* partners.
  - These mix, to form *charginos* and *neutralinos*.

- SUSY generator Q commutes with SM gauge symmetries → super-partners must have same charge, mass, etc.
- No SUSY particles have been observed: supersymmetry must be broken!

The LHC accelerator complex

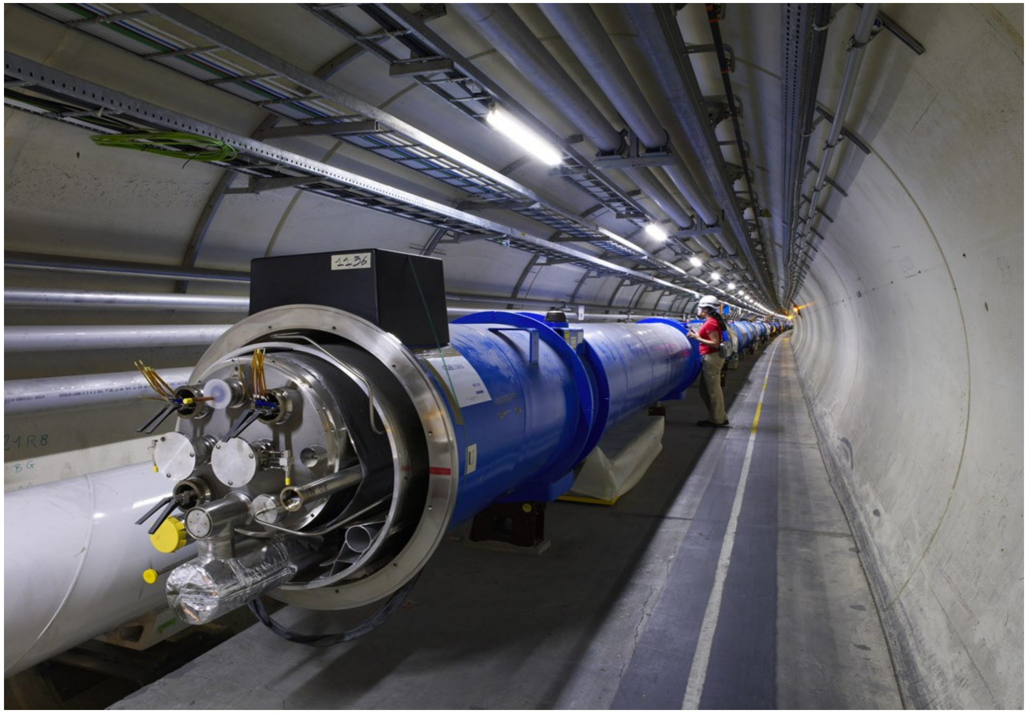
- Protons obtained by removing electrons from hydrogen atoms.
- Accelerated by LINAC2 to 50 MeV
- Proton Synchrotron Booster raises energy to 1.4 GeV.
- Proton Synchrotron increases that to 26 GeV.
- Super Proton Synchrotron accelerates them to 450 GeV.



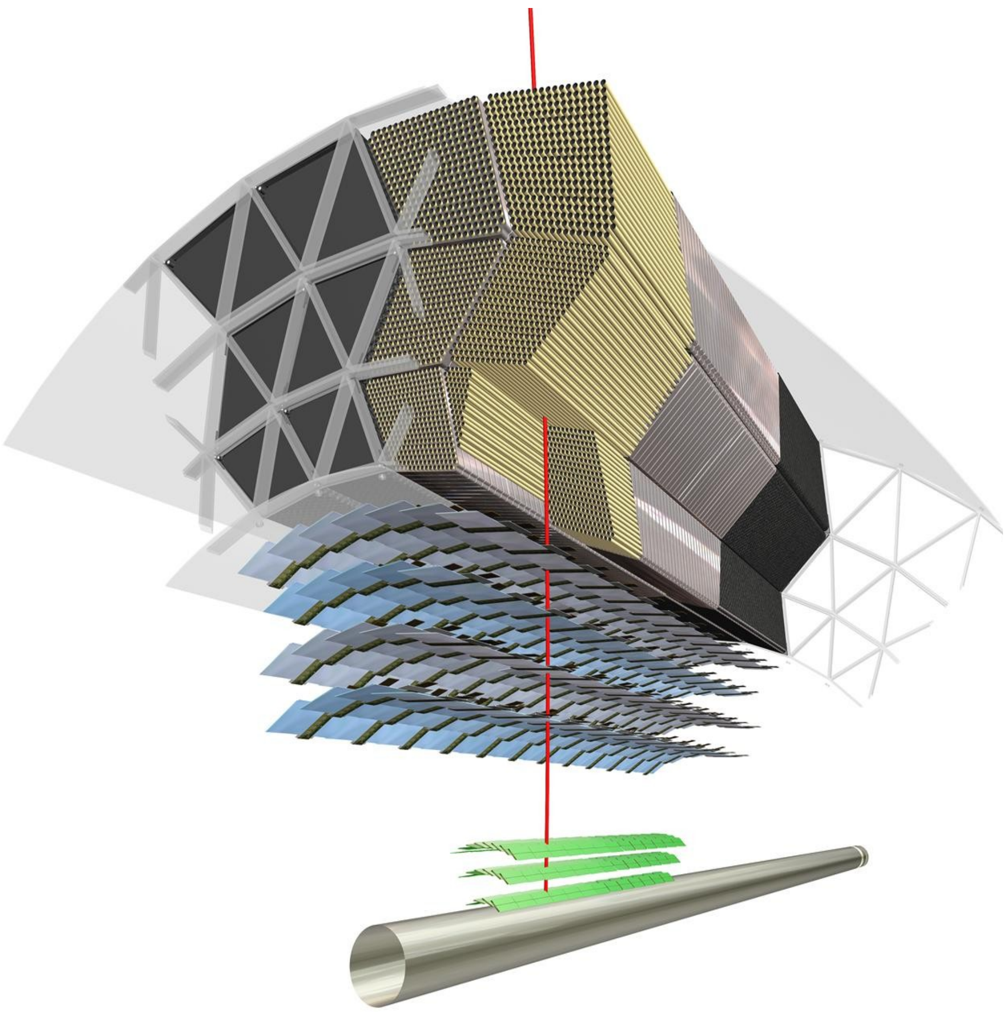
- Finally they are injected into the LHC, which raises them up to 4 TeV.

The LHC

- Acceleration & bunching via radiofrequency cavities.
- Bending from 1232 superconducting dipole magnets at 4.8T
- 392 quadrupole magnets for beam squeezing.
- Protons grouped in 1374 bunches of ~$2*10^{14}$ protons each.
- Bunches cross every 50 ns in 4 spots along the beamline.
- Maximum instantaneous luminosity: $7.7*10^{33}$ cm^{-2} s^{-1}
- Design parameters:
  - 2080 bunches
  - 25 ns
  - 7 TeV/beam
  - 10^{34} cm^{-2} s^{-1}



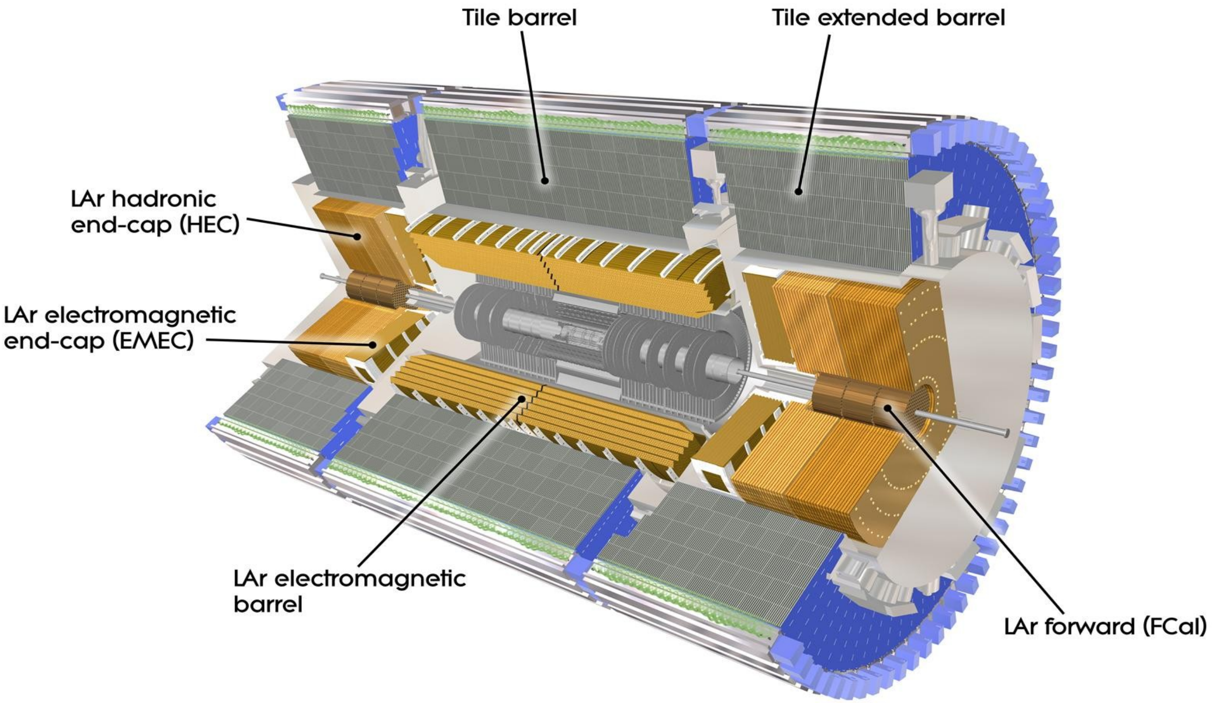
Inner Detector



- Pixel Detector provides 3 measurements for vertexing and tracking.
- Semi-Conductor Tracker useful for precise momentum measurement.
- Transition Radiation Tracker aides in tracking and particle identification.
- All immersed in 2T magnetic field.

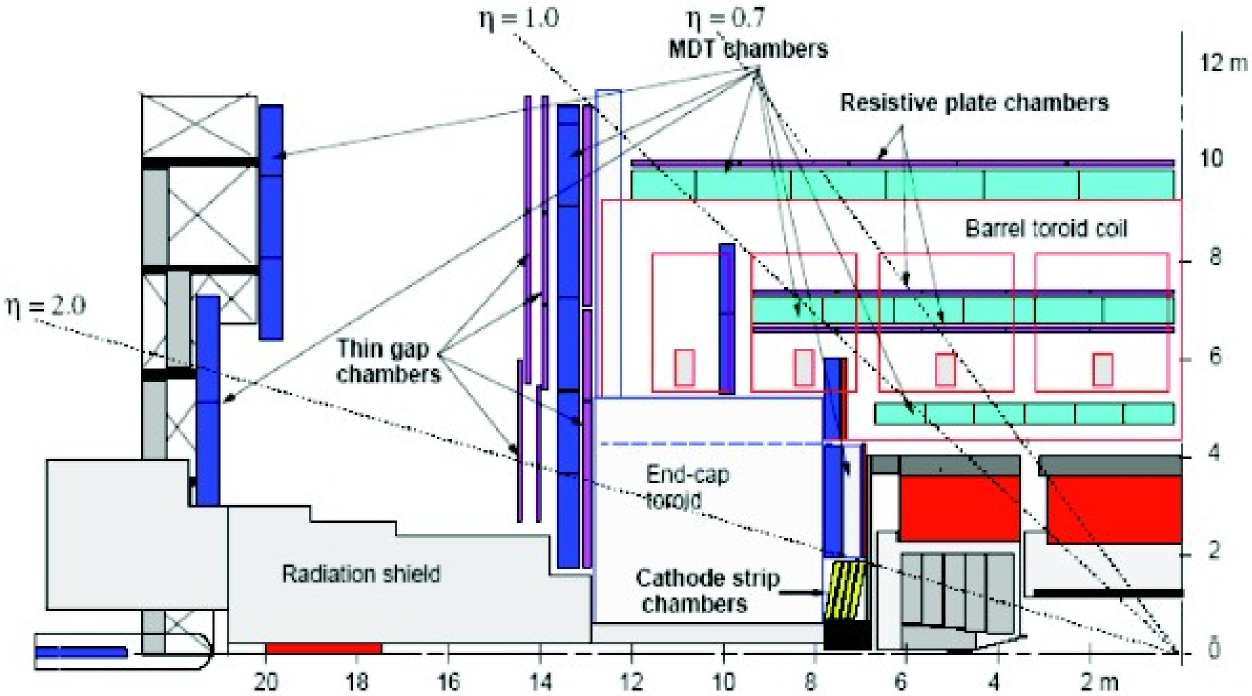
Calorimeters

- Electromagnetic calorimeter uses layers of lead absorbers and Liquid argon.
- Hadronic calorimeter uses LAr (endcap) or plastic scintillator tiles (barrel).
- Fine segmentation and layers for pointing.
- 23 radiation lengths for e/γ, 11 for hadrons



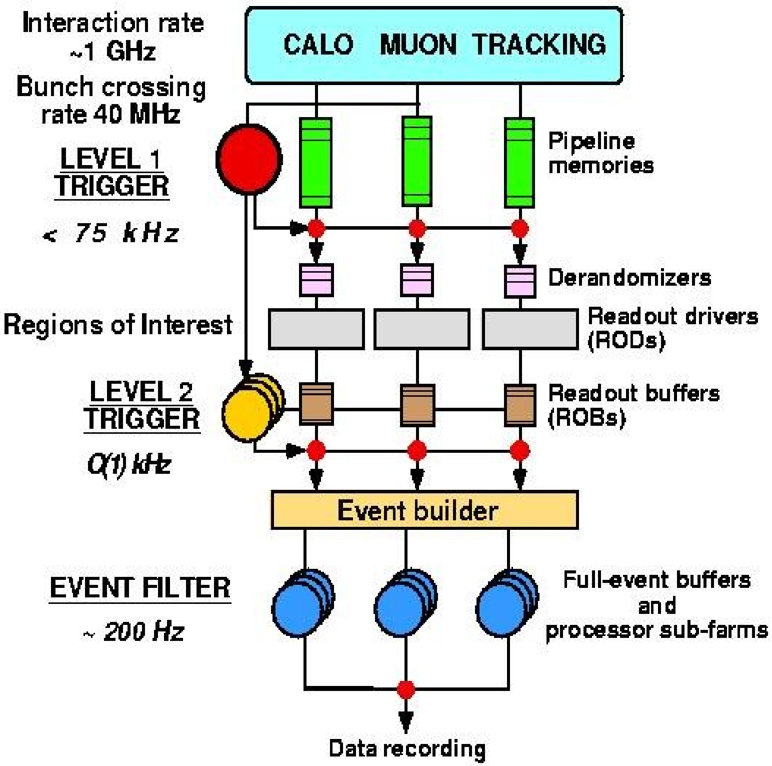
Muon Spectrometer

- Muon tracking done by 3 layers of Monitored Drift Tubes (MDT's) or Cathode Strip Chambers.
  - > 32 000 MDT's constructed at UW!
- High-speed triggering provided by Resistive Plate Chambers and Thin Gap Chambers.



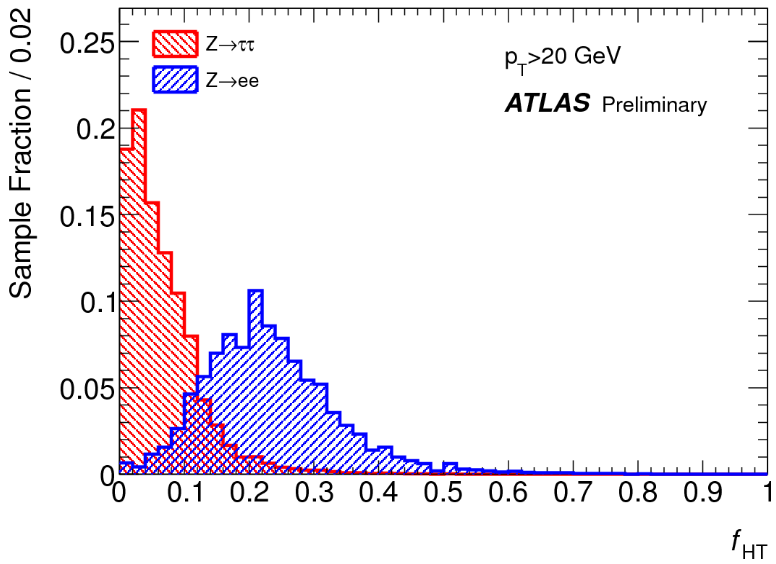
Trigger System

- Events occur every 50 ns and are about 1.5 MB of data each.
- Can only record ~400 events/sec → Use trigger to ensure we choose the right ones!

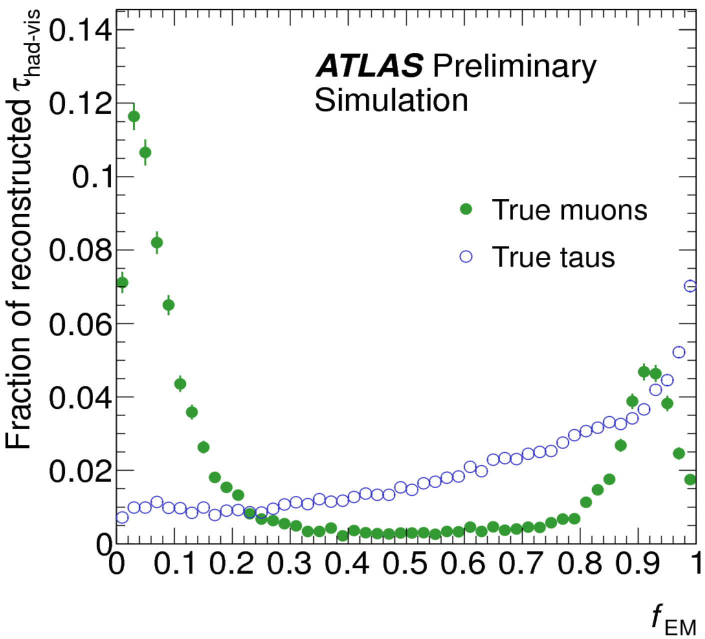


- L1 is hardware-based and reduces rate to ~ 64 kHz.
- L2 is software-based, combines information from L1 ROI's to reduce rate to ~ 5 kHz
- Event Filter performs simplified event reconstruction, reduces rate to 400 Hz.

Leptons faking taus



- Although jets are the main problem, electrons and even muons can also fake the signature of a hadronic tau.
- Information from the TRT and calorimeters are combined in a BDT to reject electrons.



- Muons are rejected by combining information on the calorimeter shower profile, with the ratio of measurements from the tracker & calorimeter.

Why 2 higgs doublets?

- SUSY demands that only superfields, and not their conjugate fields, appear in the superpotential.
  - In SM, Φ and its conjugate $\tilde{\Phi} = (i\Phi^*\sigma_2)/2$ (with opposite hypercharge) generate mass for opposite isospin fermions
  - In MSSM, need 2 fields with opposite hypercharge.
- Anomalies occur in the SM unless the hypercharges of all the fermions add up to zero.
  - Happily, they do.
  - Introducing a single charged higgsino would spoil this.
  - With two charged higgsinos, we're okay.

MSSM relations

$$M_{h,H}^2 = \frac{1}{2}\left[M_A^2 + M_Z^2 \mp \sqrt{(M_A^2+M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta}\right]$$

$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

$$\alpha = \frac{1}{2}\arctan\left(\tan 2\beta \, \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}\right)$$

Φ	$g_{\Phi\bar{u}u}$	$g_{\Phi\bar{d}d}$	$g_{\Phi VV}$	$g_{\Phi AZ}$	$g_{\Phi H^\pm W^\mp}$
H_{SM}	1	1	1	0	0
h	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\mp\cos(\beta-\alpha)$
H	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$	$-\sin(\beta-\alpha)$	$\pm\sin(\beta-\alpha)$
A	$\cot\beta$	$\tan\beta$	0	0	1

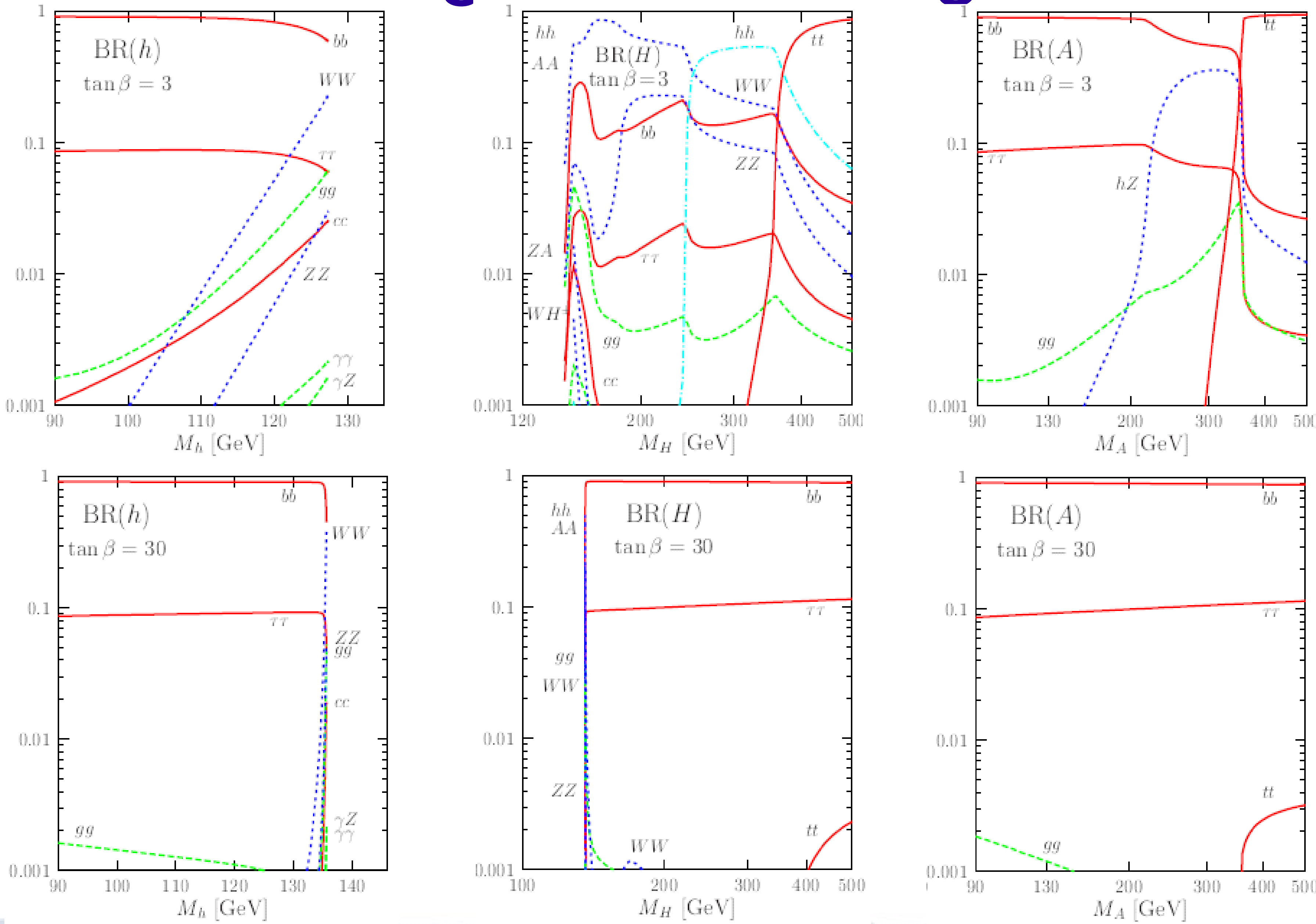
m_h-max scenario

- Relationships on the previous page hold at tree-level.
- Quantum corrections can be important: must specify values of other SUSY parameters.
- We use the "m_h-max" scenario: this leaves the maximum possible space open from LEP.

  M_S = 1 TeV
  X_t = 2 TeV
  M_2 = 200 GeV
  mu = 200 GeV
  M_3 = 800 GeV

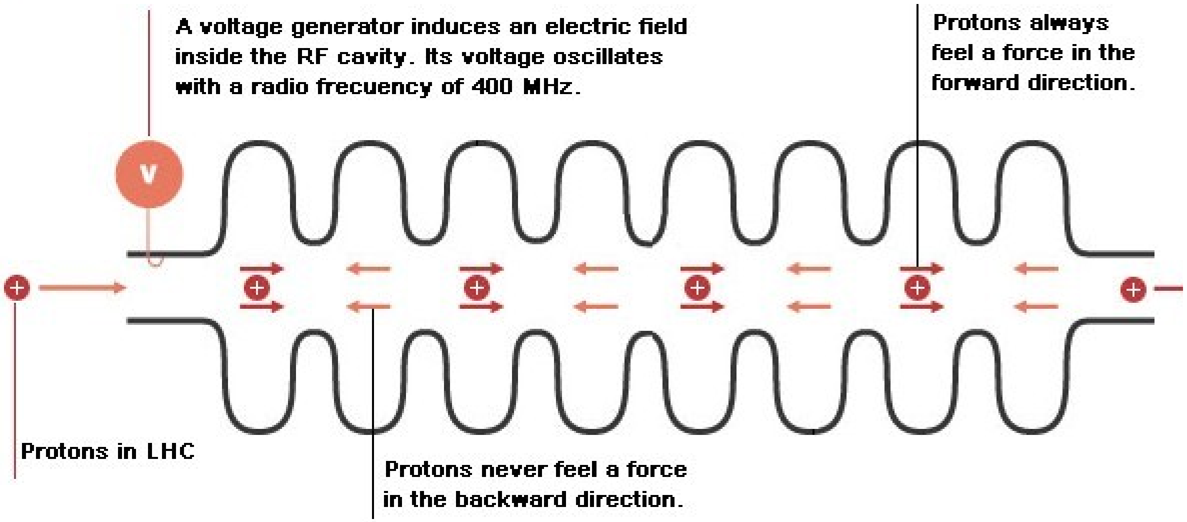
- By coincidence, the cross-section * branching ratio for higgs to tau decays depends very little on these parameters.

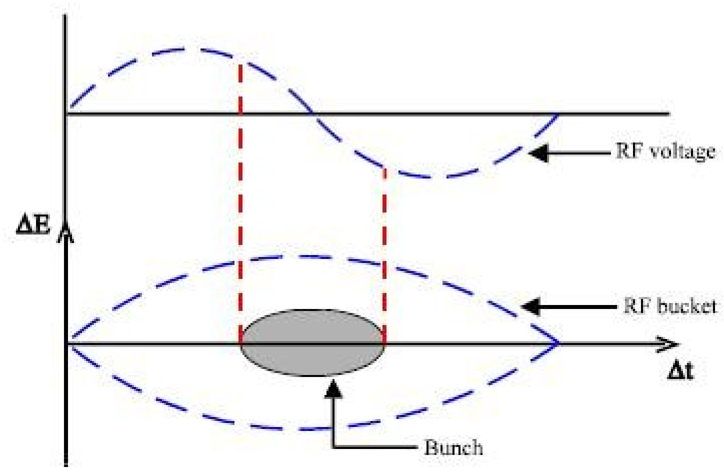
MSSM Higgs branching ratios



RF Cavities

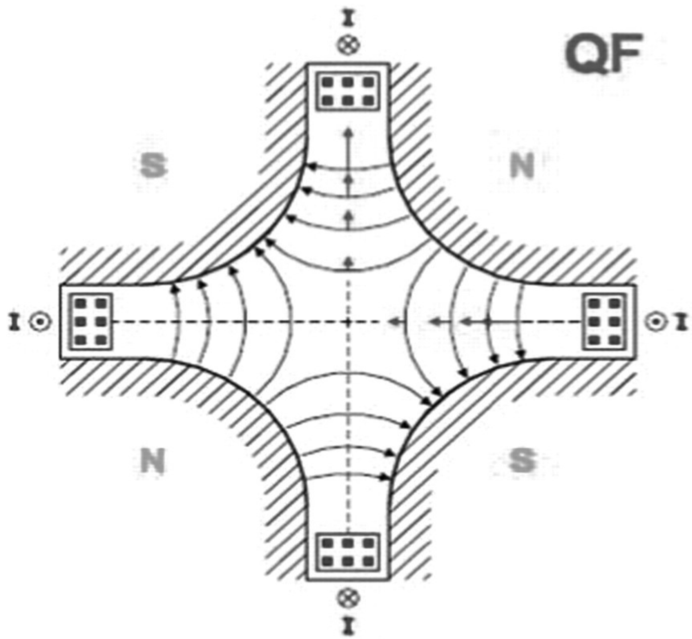
- RF cavities accelerate the beam to the top energy, and keep the protons in tightly-spaced bunches.



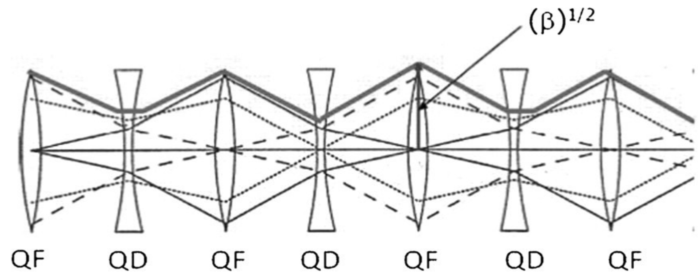


Quadrupole squeezing

- Must squeeze the beams tightly to get maximum luminosity
- Cannot simultaneously do this in two directions.
- Instead use sequence of magnets aligned to successively squeeze in the x & y directions, and defocus in the other

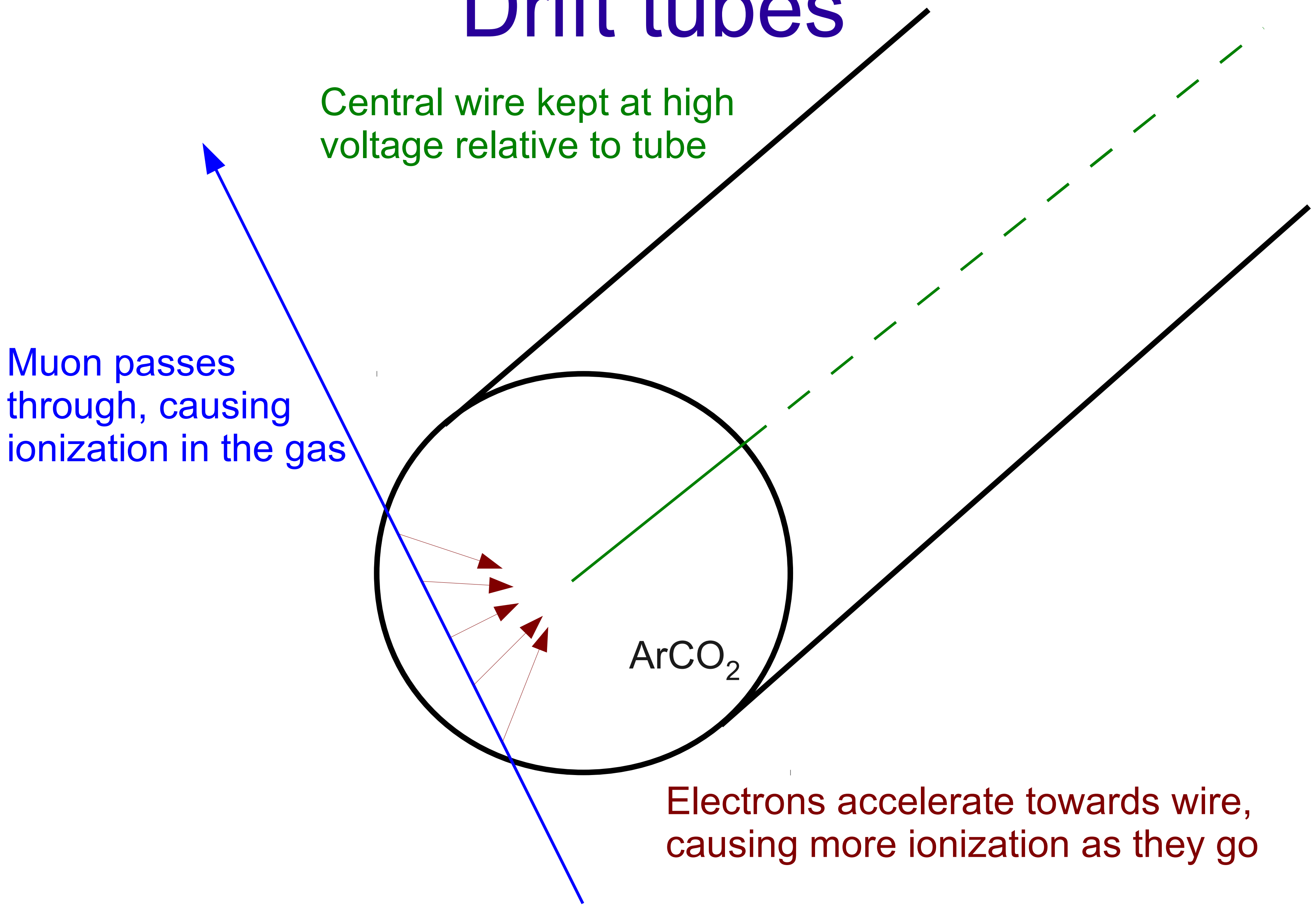


(a)



(b)

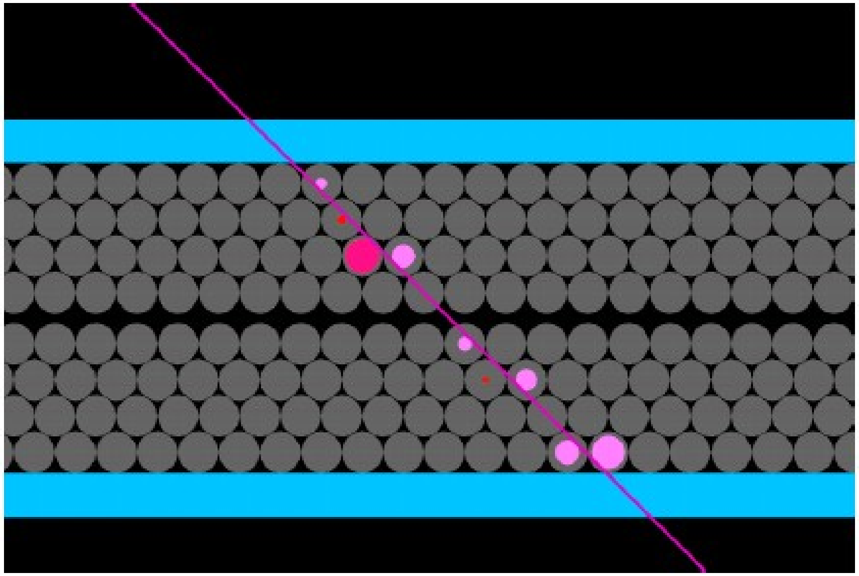
Drift tubes



Central wire kept at high voltage relative to tube
Muon passes through, causing ionization in the gas
$ArCO_2$
Electrons accelerate towards wire, causing more ionization as they go

ATLAS MDT's

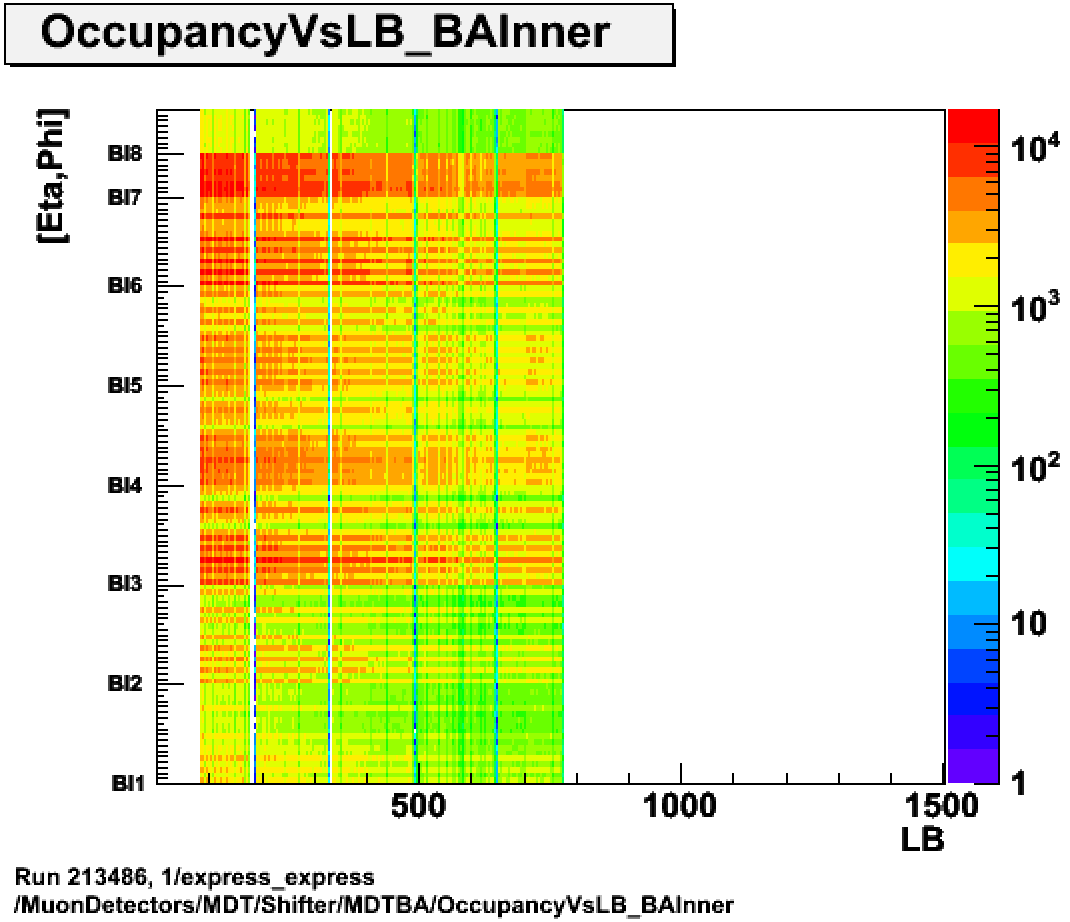
- MDT's are arranged in 3 layers of chambers; each chamber has 2 multi-layers, and each multi-layer is 3-4 tubes thick.
- Using precise timing, we deduce the radius for each tube traversed.
- Connecting the edges we can form a straight-line segment.



- Matching segments across the chambers gives us a track, with momentum determined by the curvature.

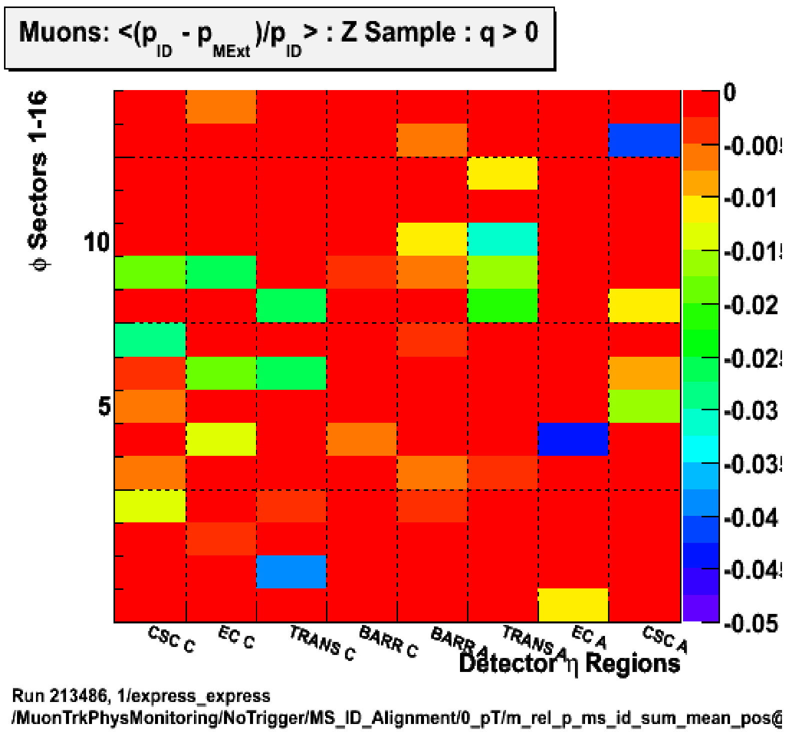
MDT Data Quality

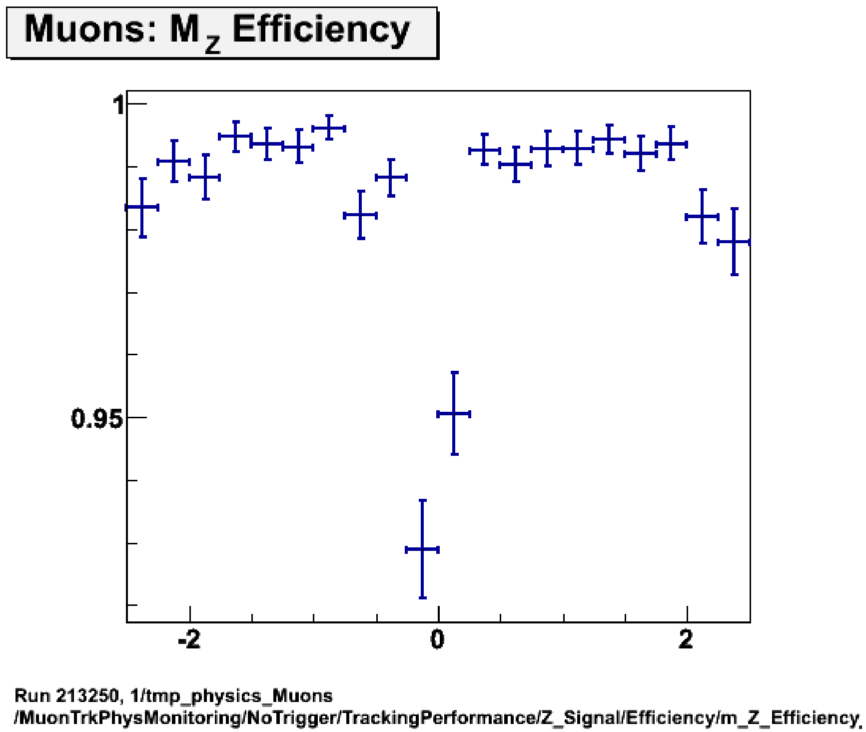
- I am responsible for MDT data quality monitoring tools.
- Focus has been on new techniques to identify the duration of hardware problems within a run.



Muon data quality

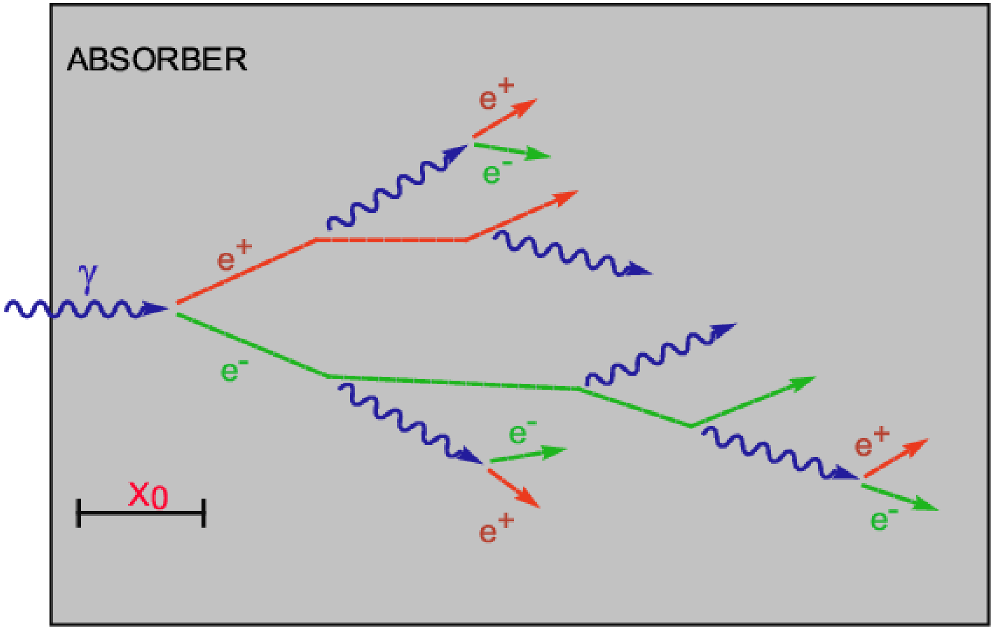
- I have also helped to create a new package that looks at muon data quality from a broader perspective.
- Allows us to spot problems in alignment, tracking efficiency, B-field mapping, etc.





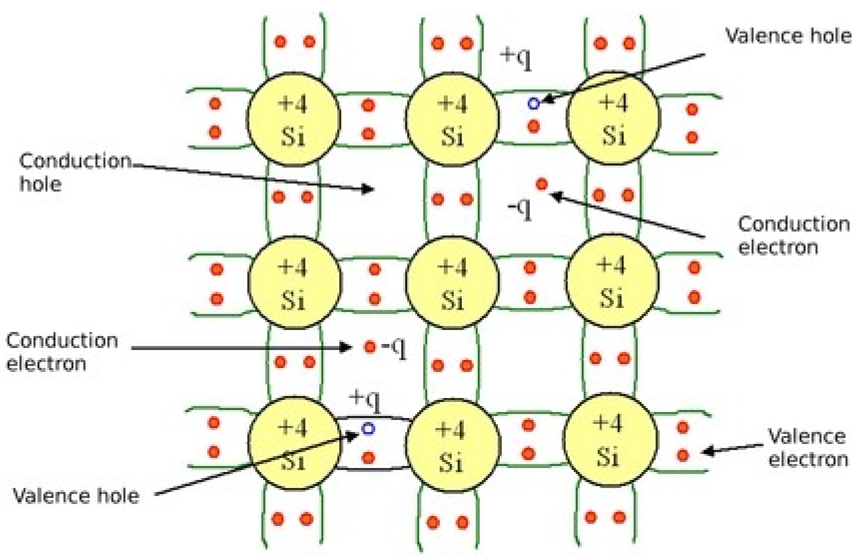
Calorimeters

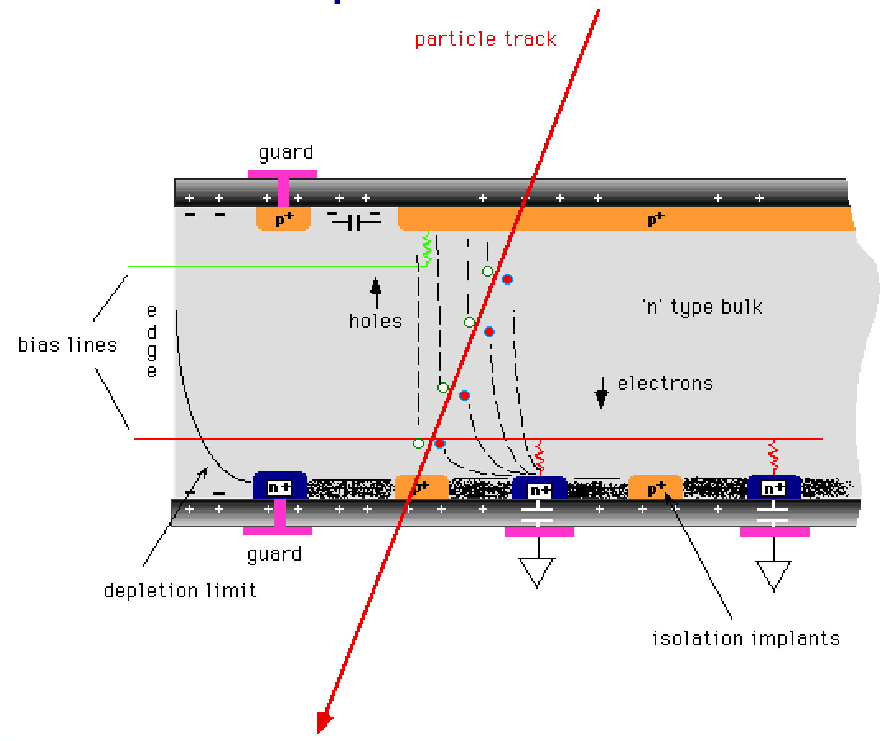
- High-energy photons in a dense medium will pair-produce into electrons and positrons; electrons and positrons will emit photons via brehmstrahlung.
- This continues until all “shower” particles are low-energy and collected by the scintillators.
- ATLAS uses “sampling” calorimeter: scintillator layers mixed with lead absorbers.



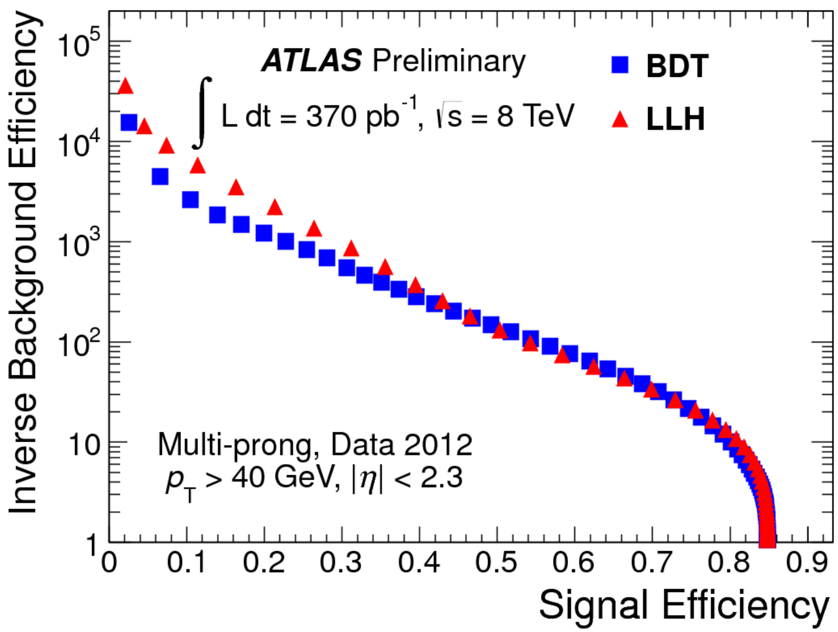
Semiconductor trackers

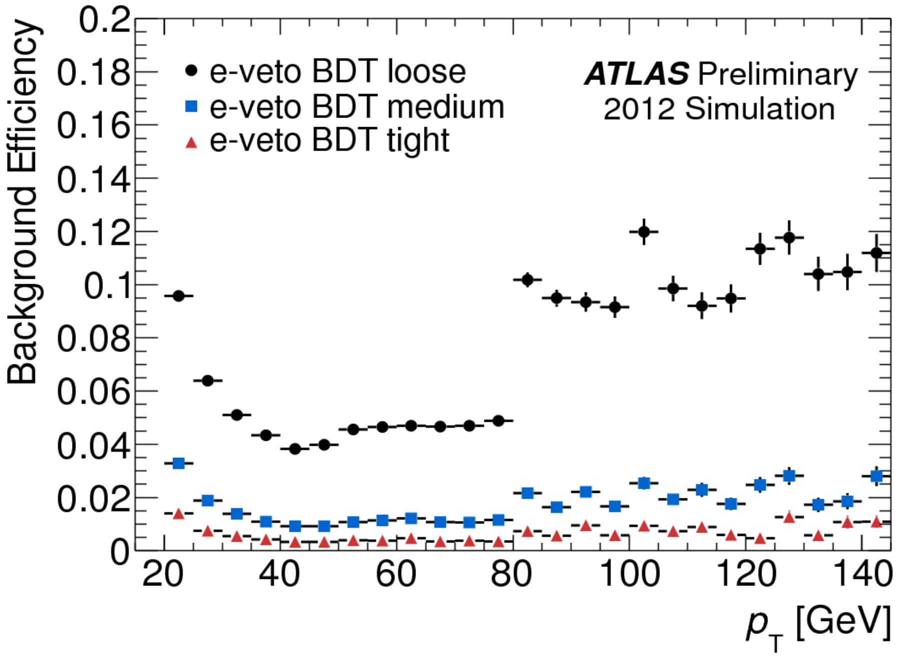
- Similar to drift tube: charged particle creates free electron-hole pairs in solid semi-conductor.
- Electrons are attracted to n+ strips used to read out the signal.
- Thinness of n+ strips results in excellent position resolution





Tau Performance





- Additionally, efficiency for true taus know to within 4% (measured with $Z\rightarrow\tau\tau$ tag-and-probe).
- Energy scale known to within ~3% (from a hybrid data-MC estimation).

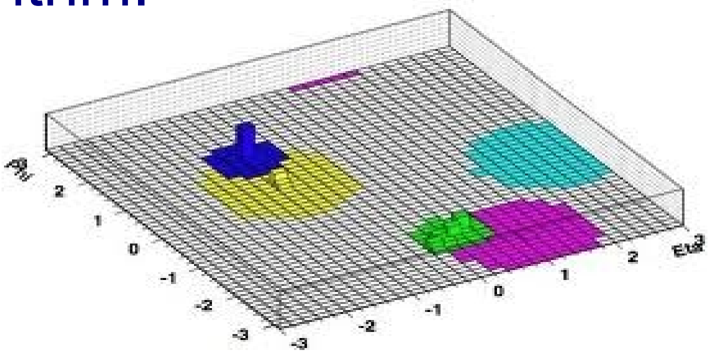
Electron & Muon reconstruction

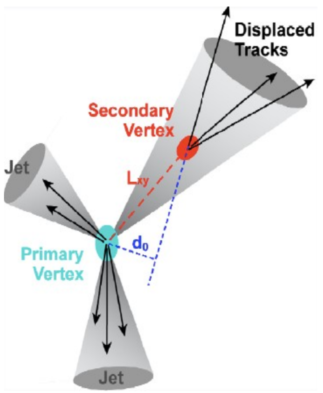
- Clusters are formed corresponding to local maxima in the 2nd layer of the ECAL.
- Electrons are formed as clusters matched to ID tracks.
- Additional quality criteria are applied to reject pions.

- Muons are formed by matching tracks in the muon spectrometer to ID tracks, and performing a statistical combination to get the combined momentum measurement

Jets and b-tagging

- Jets start from calorimeter clusters, which are re-calibrated to account for the different hadronic calorimeter response.
- These are combined into jets using the anti-kt recombination algorithm.





- Due to weak mixing of the 3rd generation, b-hadrons travel a significant distance before decaying.
- Jets may be tagged as coming from a b-quark by looking for a secondary vertex, or high impact-parameter tracks.
  - Information combined using a neural network.

Missing transverse energy

- The presence of neutrinos or other non-interacting particles can be inferred from the conservation of momentum.
  - Only valid in the transverse plane, since interacting partons may have different momentum
- For best resolution, every physics object must be calibrated separately.