Searching for New Physics in Di-Tau Final States with ATLAS

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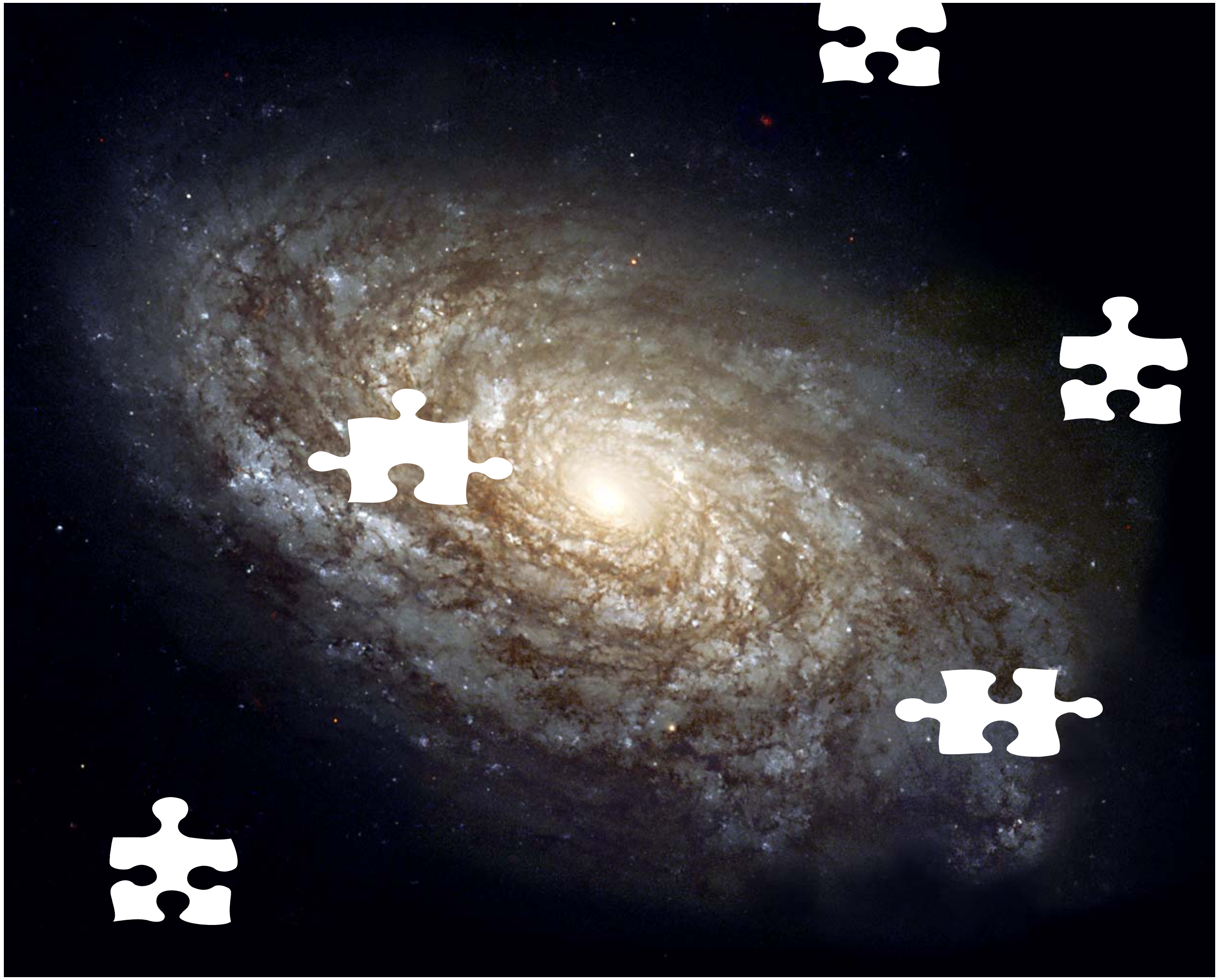
University of Pennsylvania
Experimental High-Energy Physics Seminar

A Beautiful Picture of Nature

We have an extremely successful Standard Model (SM) of particle physics

However a number of significant pieces are still missing…



Just to name a few:

Dark Matter

Dark Energy

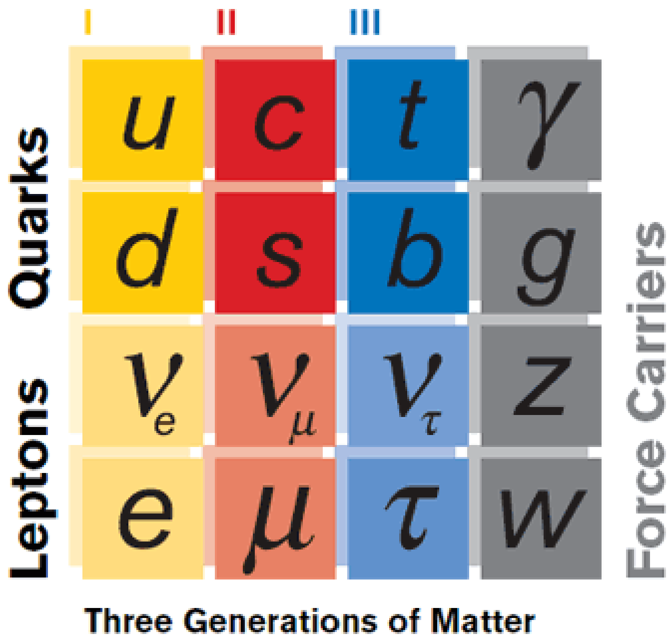
Electroweak Symmetry Breaking

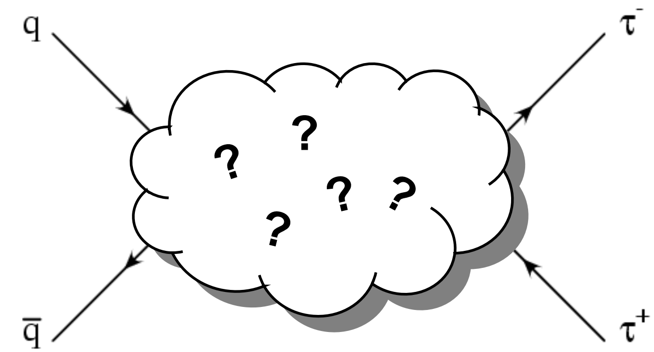
Quantum Gravity

Searches at High-Energy Colliders

Could find some answers by looking in di-tau final states

- **Many theories beyond the SM predict new physics here**





The tau lepton is kind of a heavy cousin of the electron (third generation)

- **Massive ~1.78 GeV/c²**
- **Measurable lifetime cτ ~87 μm**
- **Decays hadronically ~65% of the time**

Decay modes	TAUOLA-CLEO
$\tau \to e\nu_e\ \nu_\tau$,	17.8 %
$\tau \to \mu\nu_\mu\ \nu_\tau$	17.4 %
$\tau \to h^\pm neutr.\nu_\tau$	49.5 %
$\tau \to \pi^\pm\nu_\tau$	11.1 %
$\tau \to \pi^0\pi^\pm\nu_\tau$	25.4 %
$\tau \to \pi^0\pi^0\pi^\pm\nu_\tau$	9.19 %
$\tau \to \pi^0\pi^0\pi^0\pi^\pm\nu_\tau$	1.08 %
$\tau \to K^\pm neutr.\nu_\tau$	1.56 %
$\tau \to h^\pm h^\pm h^\pm neutr.\nu_\tau$	14.57 %
$\tau \to \pi^\pm\pi^\pm\pi^\pm\nu_\tau$	8.98 %
$\tau \to \pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	4.30 %
$\tau \to \pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.50 %
$\tau \to \pi^0\pi^0\pi^0\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.11 %
$\tau \to K^0_S X^\pm\nu_\tau$	0.90 %
$\tau \to (\pi^0)\pi^\pm\pi^\pm\pi^\pm\pi^\pm\pi^\pm\nu_\tau$	0.10 %
other modes with K	1.30 %
others	0.03 %

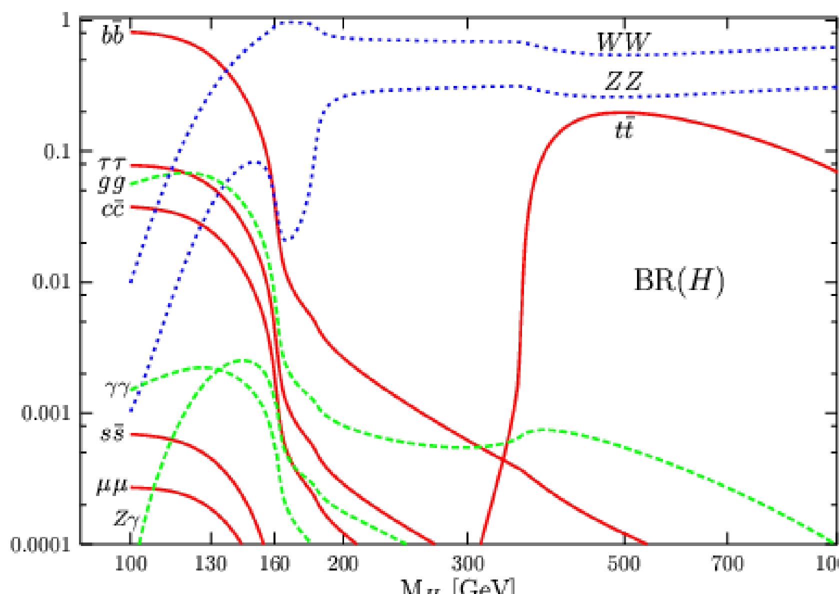
Electroweak Symmetry Breaking

Higgs Mechanism believed to be responsible for electroweak symmetry breaking

- **The Higgs boson has eluded experimentalists for decades**
- **A key objective for the CERN Large Hadron Collider**

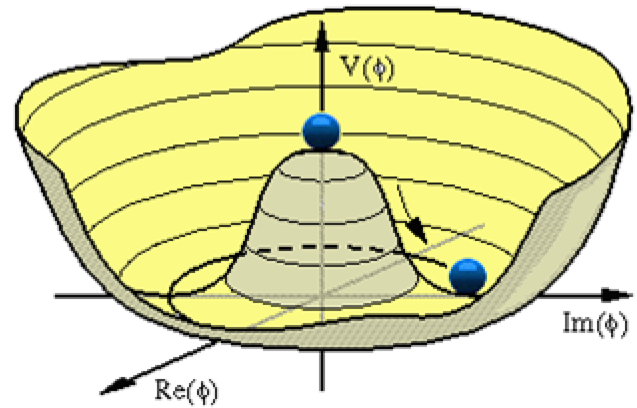
For low Higgs masses, tau lepton final states have an advantage over bb

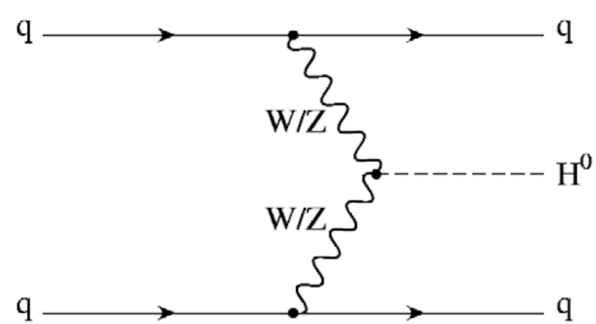
- **Good discovery sensitivity in ~30 fb^{-1} of 14 TeV LHC data**



A. Djouadi hep-ph/0503172

Origin of mass?





Vector Boson Fusion

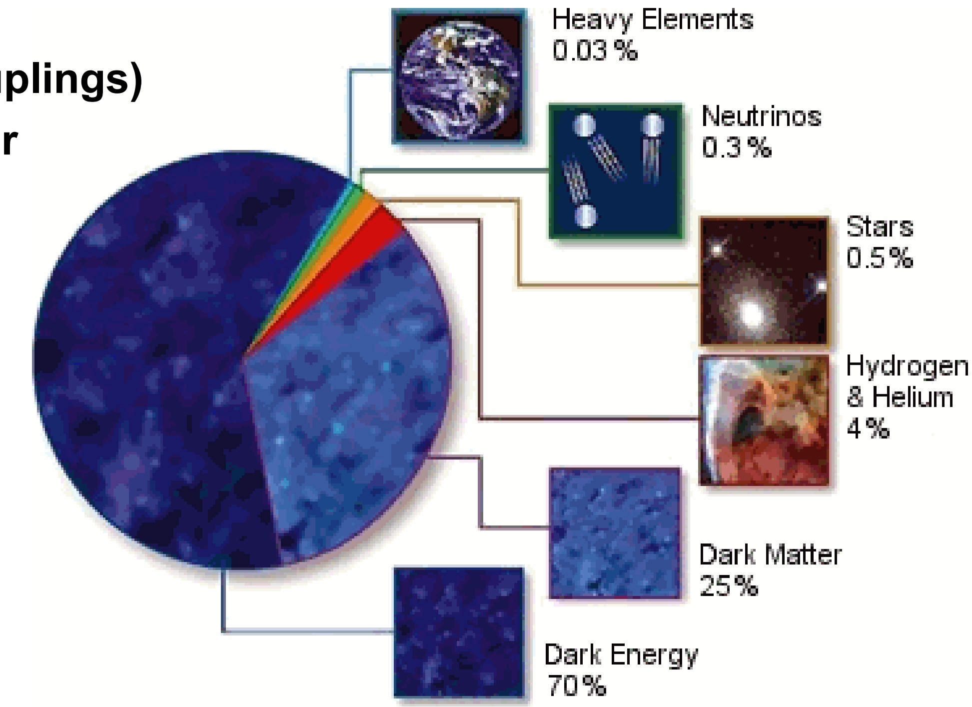
Supersymmetry?

Every particle has a "super-partner" particle

- Fermion ↔ Boson

Motivation for Supersymmetry

- Naturalness (Hierarchy Problem)
- Unification of the forces (gauge couplings)
- Provides a candidate for Dark Matter



Minimal Supersymmetric extension to the SM: a two Higgs doublet model (h, A, H, $H^{\pm}$)

- Coupling to the tau could be significantly enhanced over the SM
- Some Higgses could be quite massive ~500 GeV

Extra Dimensions? Grand Unification?

Some models predict an extra gauge boson, referred to as the Z'

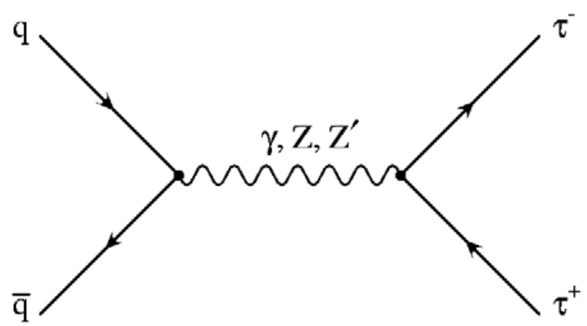
Would appear as a high mass resonance

- **Z' could couple equally to all generations (inclusiveness)**
- **Or preferentially to the third (exclusiveness)**

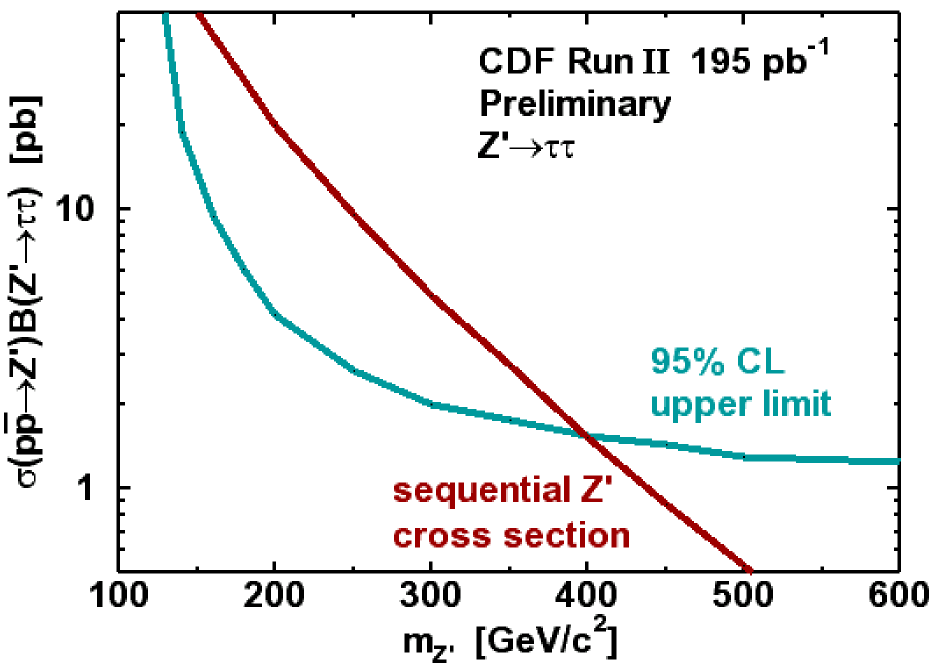
The current limit on Z'→tau tau searches comes from the Tevatron

- **From CDF > ~400 GeV/c^2 @ 95% CL**
- **Reference:** D. Acosta et al., Phys. Rev. Lett. 94, 091803 (2005)

A massive graviton could be another source of di-tau resonances



The main focus of this talk



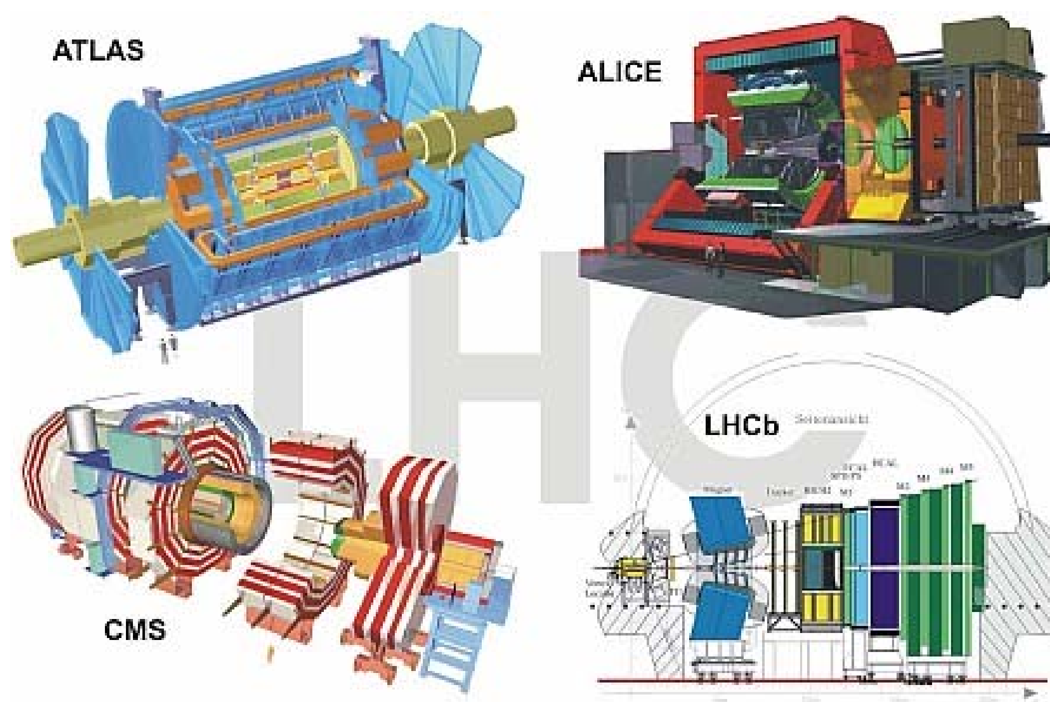
The Large Hadron Collider (LHC)

One Primary Objective of the LHC

Elucidate the mechanism responsible for Electroweak Symmetry Breaking

- **Particle accelerator located at CERN (Geneva, Switzerland)**
- **26.7 km circumference**
- **pp collider at $\sqrt{s} = 14$ TeV**
- **Instantaneous luminosity of $\sim 10^{33} - 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$**
- **40 MHz bunch-crossings with a "pile-up" of 2-20 inelastic collisions per crossing**
- **First circulating beam September 10, 2008 / First collisions in 2009 (?)**

High p_T **Heavy Ion**

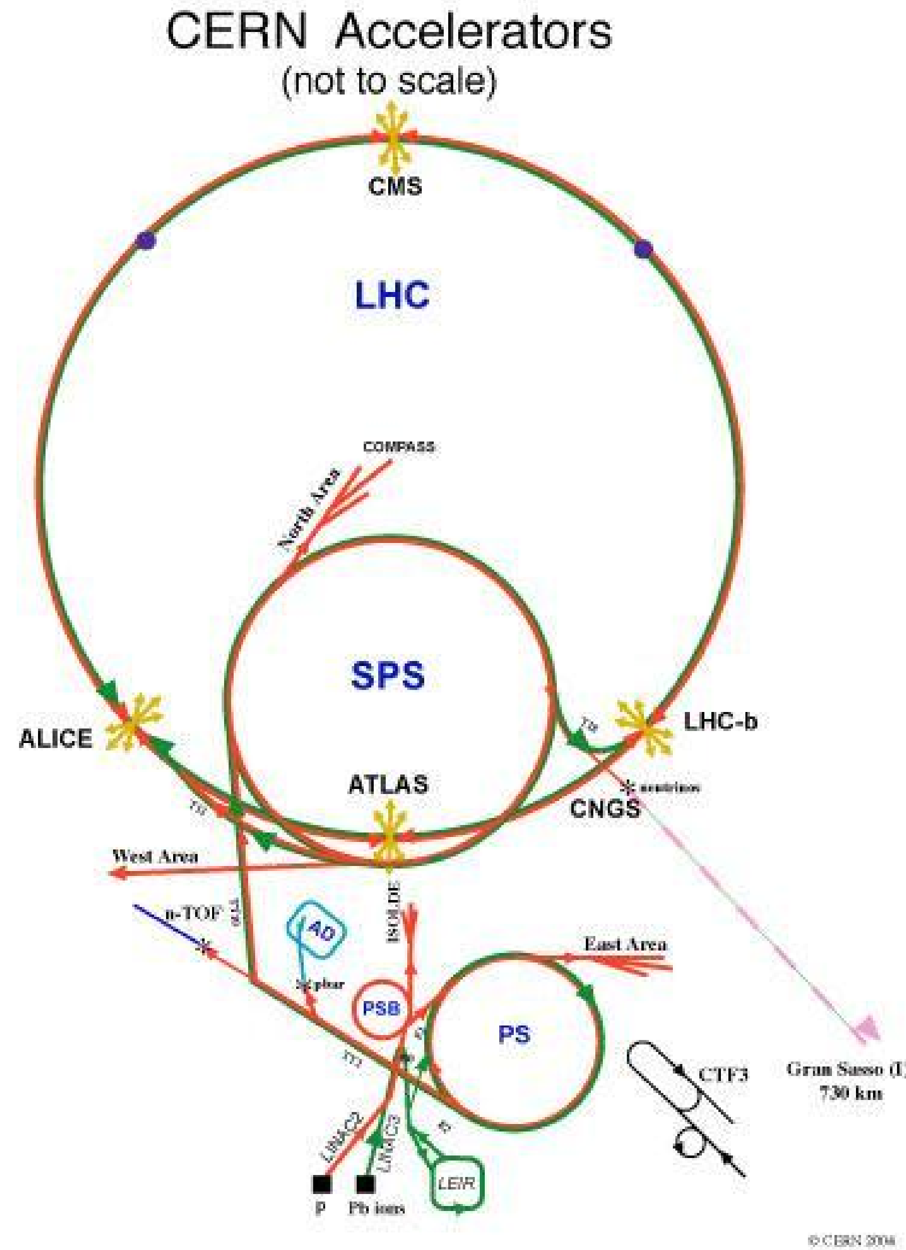


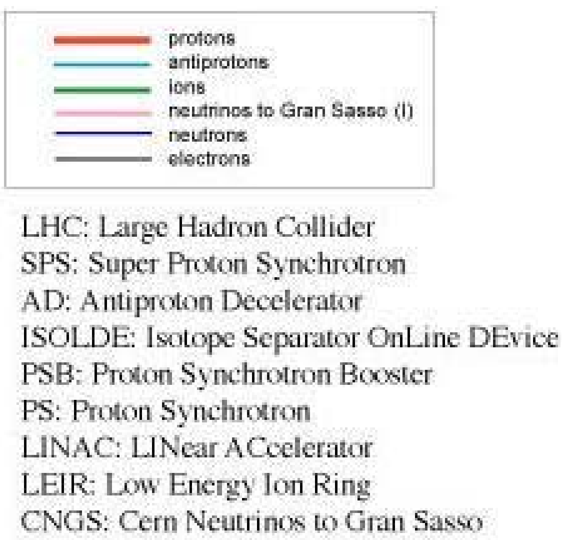
High p_T **b Physics**

The Large Hadron Collider

Housed in the former LEP tunnel

- **Dipole field at 7 TeV is 8.33 T**
- **~350 MJ per beam!**
- **Ultimately ~2800 bunches**
- **Vacuum 10^{-13} atm (~6500 m^3 pumped)**
- **1232 Dipoles (operate at 1.9 K)**
- **858 Quadrupoles**
- **Typical store lasts ~10 hours**
- **Can also be used for ion running (Pb)**
- **Final price tag estimated at 4G EUR**

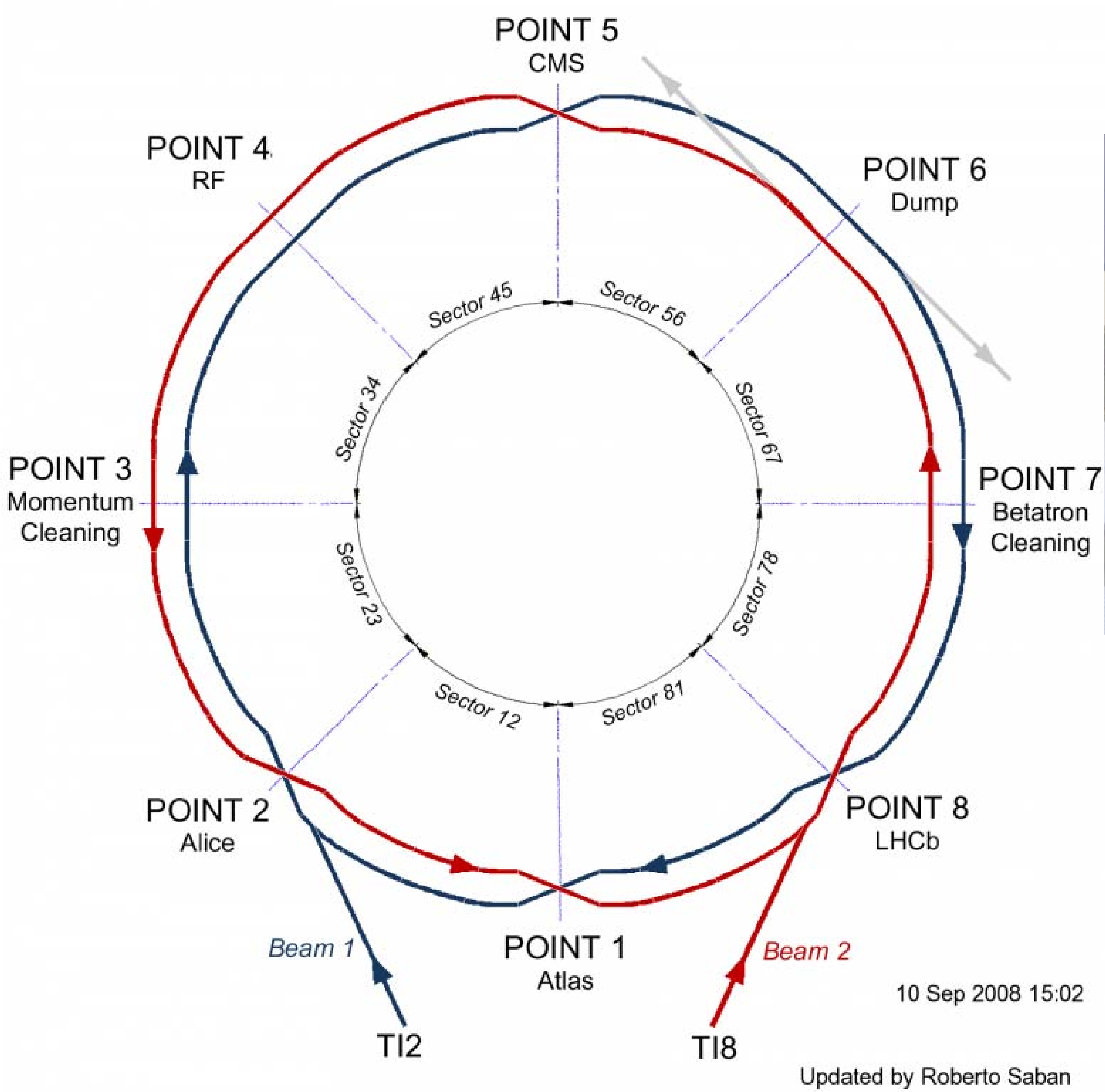


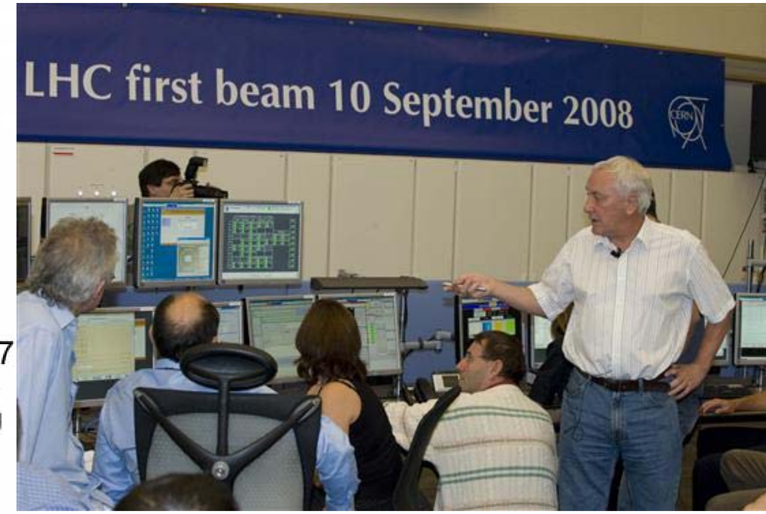


September 10, 2008

First circulating beam!

- **450 GeV Beam 1 (clockwise) ~10:30**
- **450 GeV Beam 2 (counter-clockwise) ~15:00**

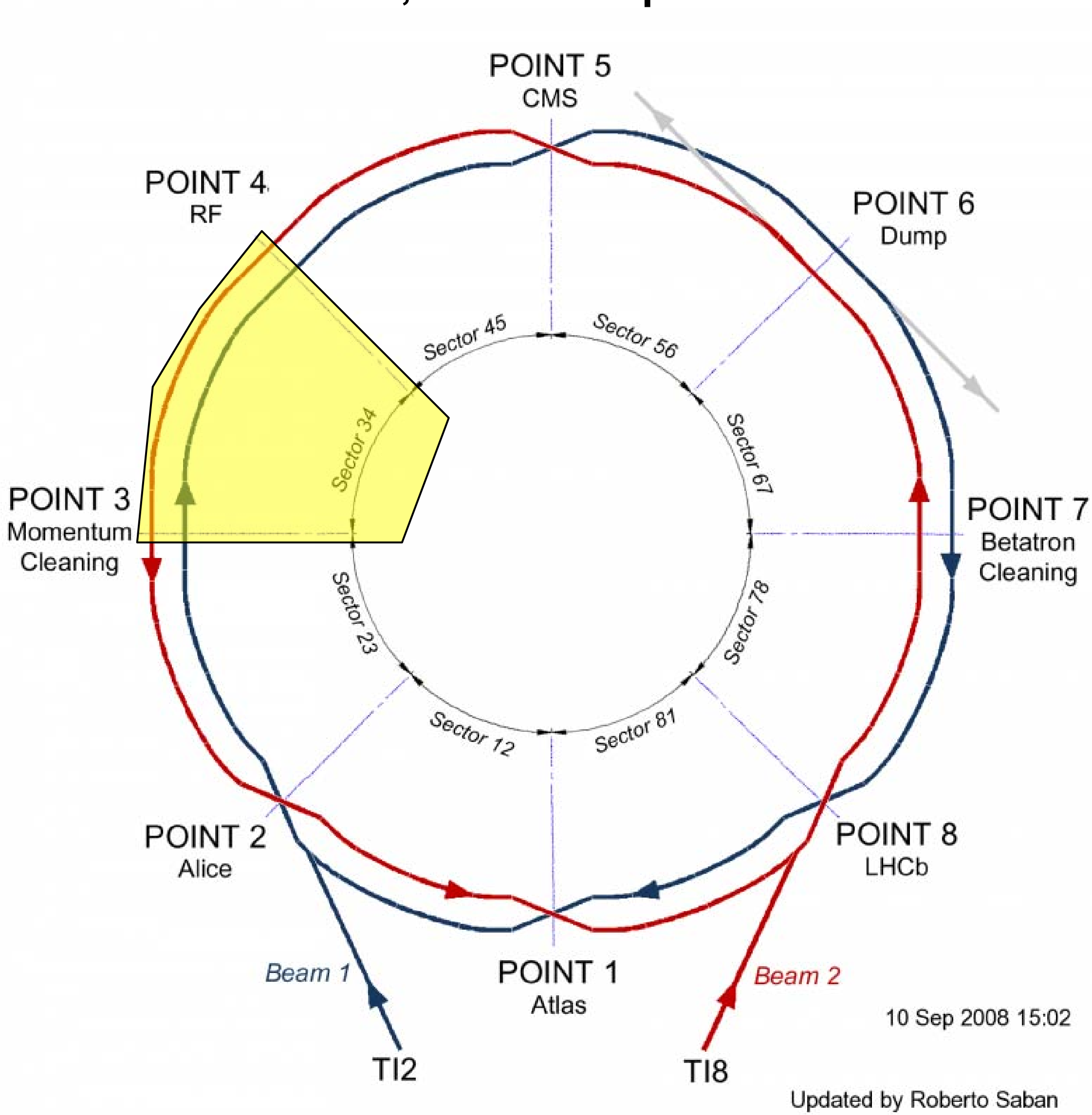


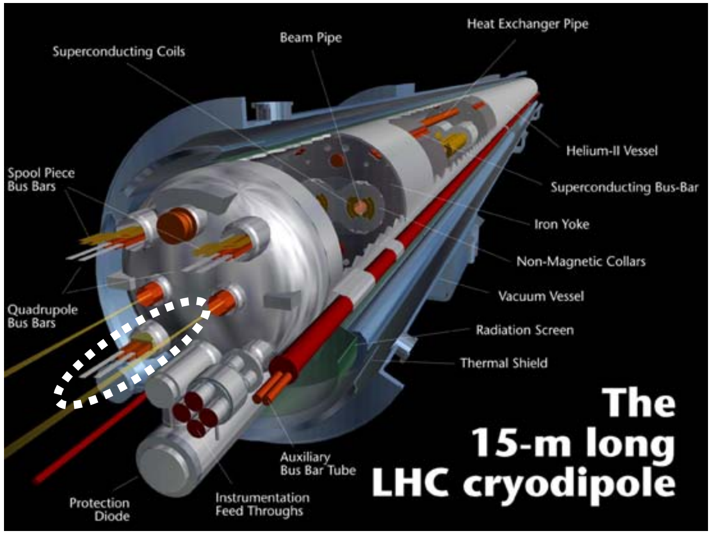


September 19, 2008

Electrical fault during powering tests of the main dipole circuit in Sector 3-4

- **Resulted in magnet displacements and damage to super-insulating blankets**
- **Afterwards, it became quite clear that collisions during 2008 would not occur**





Dipole bus-bar

The ATLAS Experiment

The ATLAS Experiment

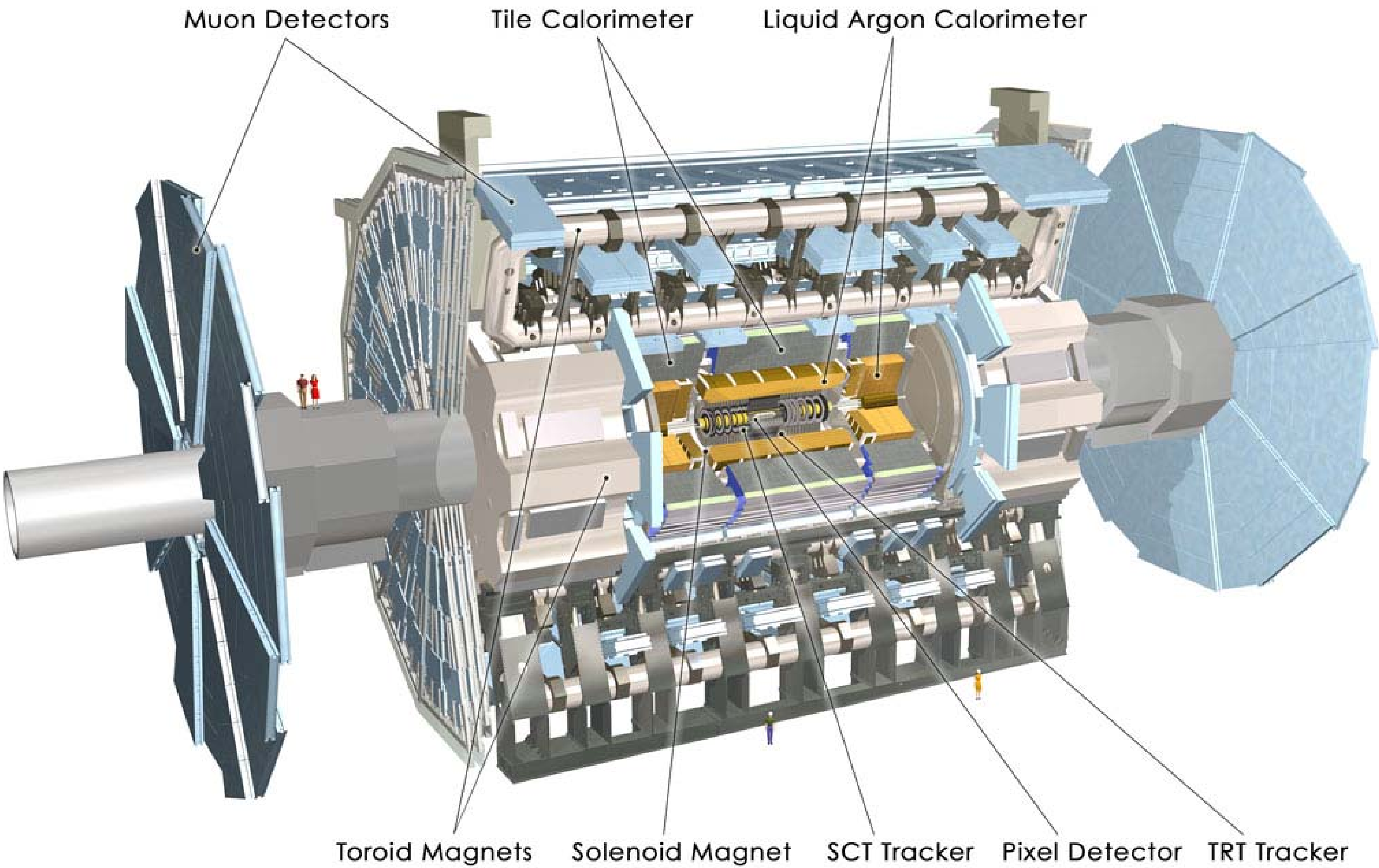
A Toroidal LHC ApparatuS (ATLAS)

- **Collaboration formed in 1992**
- **As of April 2007: 37 Countries, 167 Institutions, ~2000 Members**
- **The largest collider detector ever built**

The ATLAS Experiment

General purpose experiment at the LHC

- **Not just poised for finding and studying Higgs: Top, Exotics, SUSY, etc.**
- **Length ~40 m, Radius ~10 m, Weight ~7k tons, Channels ~10^8**



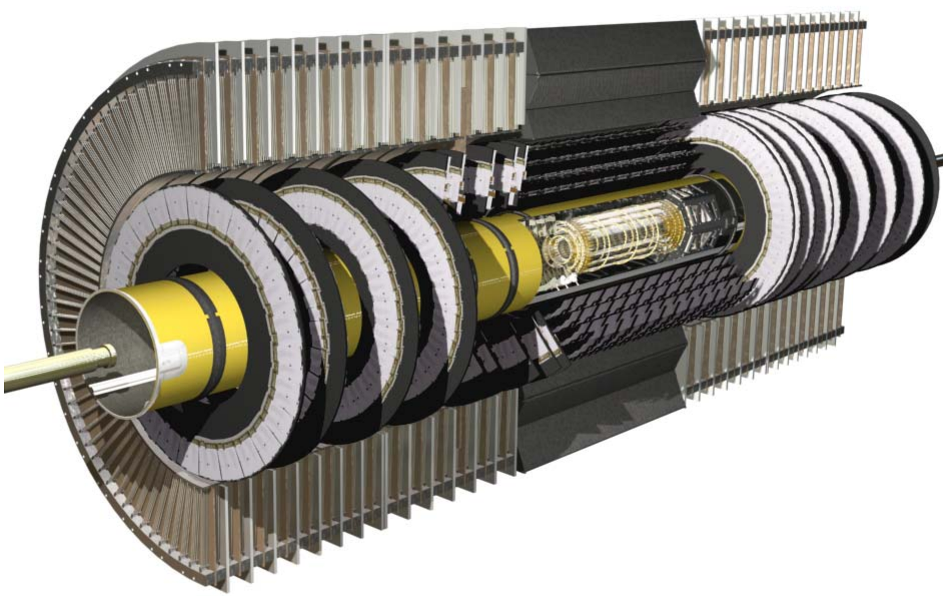
The ATLAS Experiment

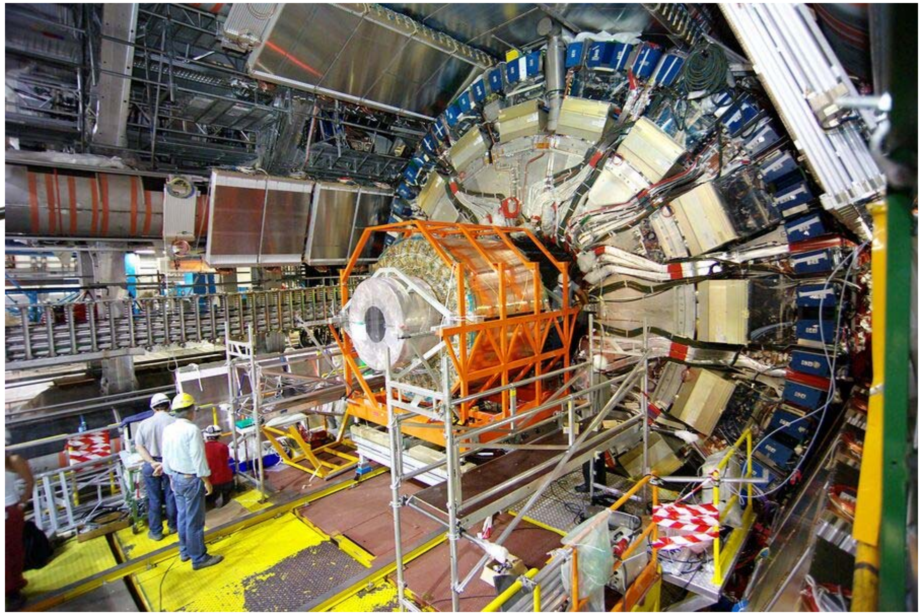
The Inner Tracker

- **Comprised of the silicon Pixel Detector (50 x 400 µm), Semiconductor Tracker (silicon strips 80 µm pitch), Transition Radiation Tracker (straw tracker)**
- **Resides inside of the central solenoid (magnetic field of 2 Tesla)**

$$\frac{\delta p_T}{p_T} \simeq 5 \times 10^{-4} \oplus 0.01$$

Silicon ROD





The ATLAS Experiment

Electromagnetic Calorimeter

- **Pb and liquid Ar**

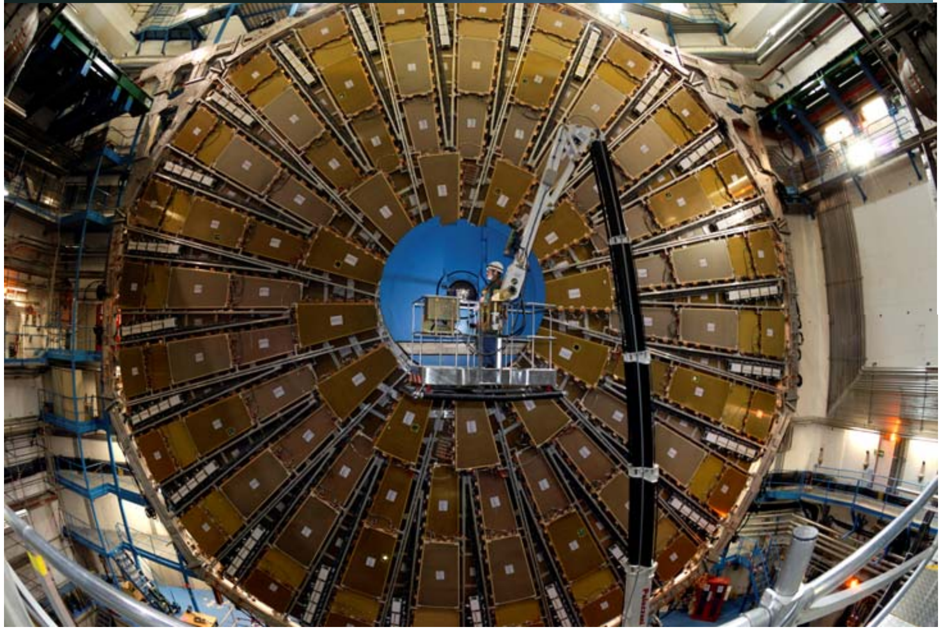
$$\frac{\delta E}{E} = \frac{0.1}{\sqrt{E}}$$

Hadronic Calorimeter

- **Fe + scintillator and Cu + liquid Ar**

$$\frac{\delta E}{E} = \frac{0.5}{\sqrt{E}} \oplus 0.03 \quad |\eta| < 3$$

$$\frac{\delta E}{E} = \frac{1}{\sqrt{E}} \oplus 0.07 \quad |\eta| \geq 3$$



Muons

- **Monitored Drift-Tube chambers**
- **Cathode Strip Chambers**
- **Resistive Plate Chambers**
- **Thin Gap Chambers**

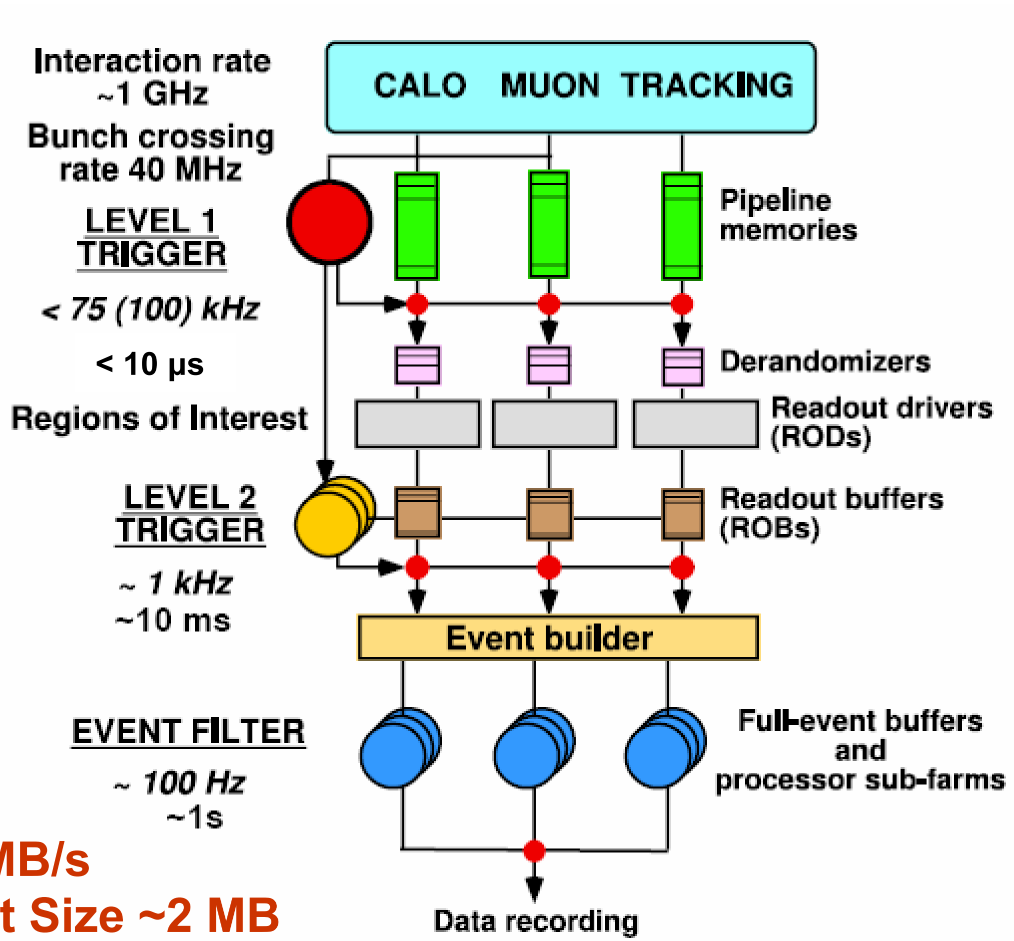
$$\frac{\delta p_T}{p_T} \simeq 0.1 \text{ at } 1 \text{ TeV}$$

The ATLAS Experiment

Trigger and Data Acquisition System:

- **Level-1 is hardware, Level-2 confined to "Regions of Interest", Event Filter has the ability to access the entire event**

High-Level Trigger



Level 1

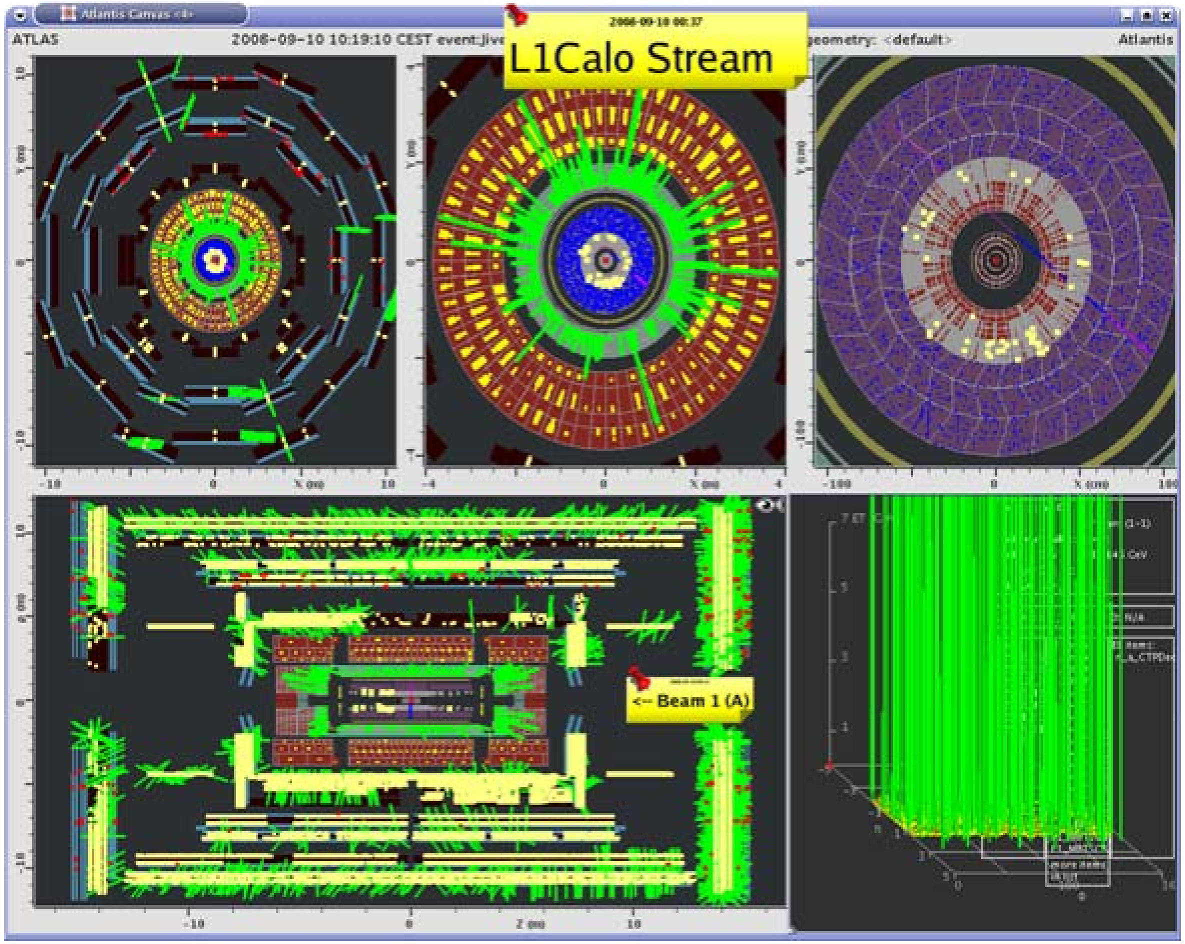
Level 2

Level 3
(Event Filter)

~100 MB/s
Average Event Size ~2 MB
~1 PB/year (petabyte = 10^{15} bytes!)

September 10, 2008

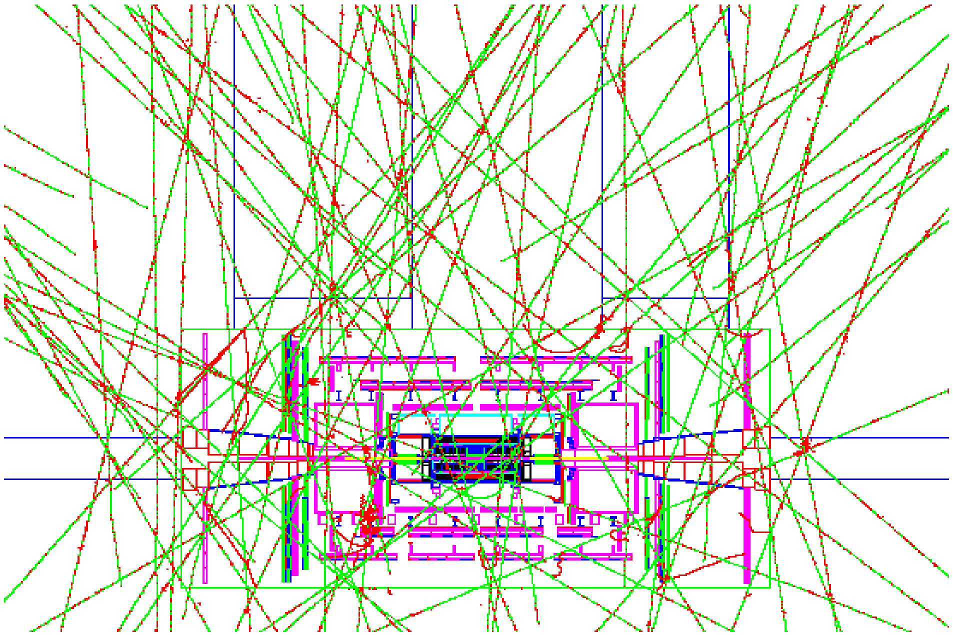
First beam event in ATLAS!

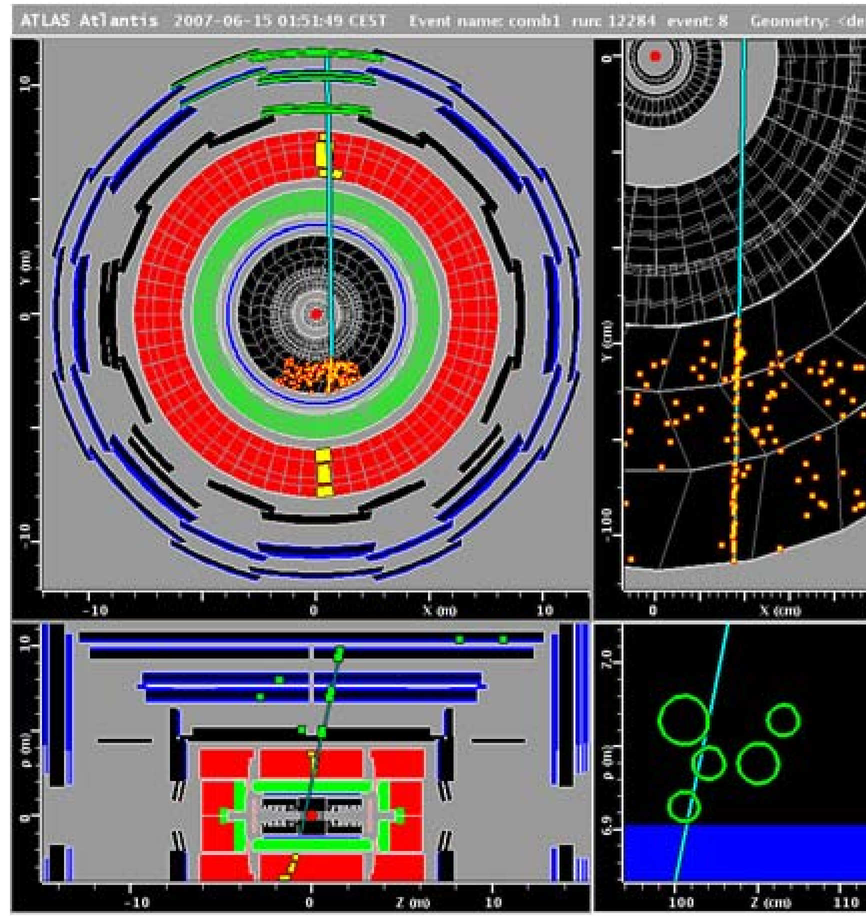


After September 19, 2008

ATLAS continues taking valuable cosmics data…

- **We get a constant delivery of cosmic rays for free**
- **Typical trigger rate is 1 – 200 Hz**
- **Useful for alignment studies**
- **Debug DAQ**
- **Exercise data-taking chain…**





Strategy and Start-up

The LHC has ushered in a new era…

- Collisions in 2009 (?)
- Few ~100 pb^{-1} by the year's end?
- Both ATLAS and CMS have already recorded beam data!

Understand the detectors…

- Diagnose hot or dead channels
- Tally up dead material
- Tracking detector alignment
- Tune the detector simulations to better match ATLAS and CMS

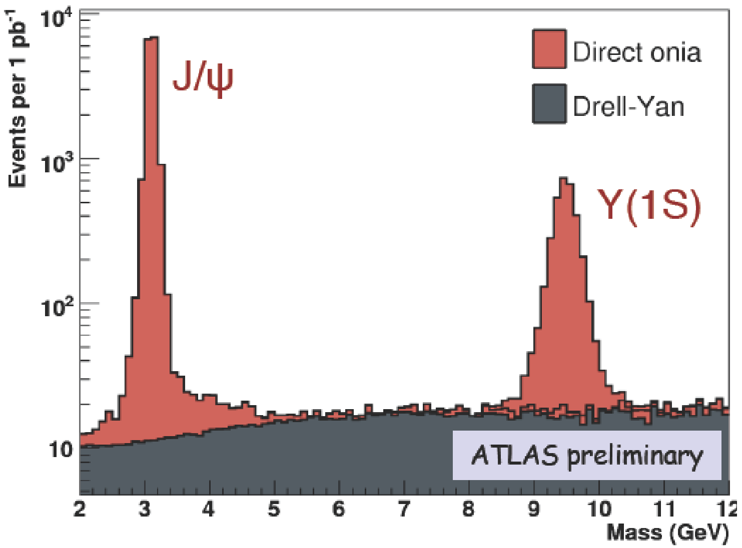
…do Standard Model measurements

- Examine our standard candles
- Demonstrate the ability to measure Ws, Zs and top quarks (b-jet identification)

…then search for the Higgs and New Physics

LHC The first five years?

2009	~100 pb^{-1}	10^{31} cm^{-2} s^{-1}
2010	~1 fb^{-1}	10^{32} cm^{-2} s^{-1}
2011	~10 fb^{-1}	2 x 10^{33} cm^{-2} s^{-1}
2012	~30 fb^{-1}	2 x 10^{33} cm^{-2} s^{-1}
2013	~100 fb^{-1}	2 x 10^{34} cm^{-2} s^{-1}



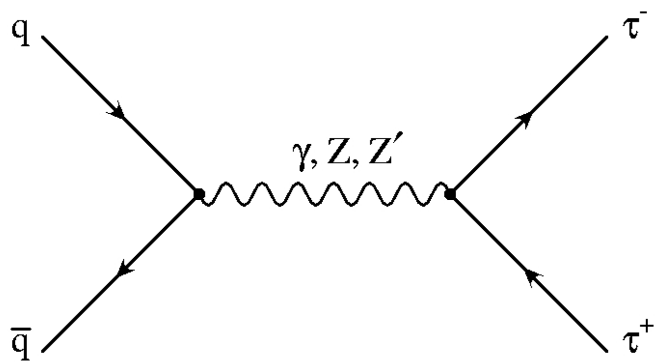
1 pb^{-1} = 3 days at 10^{31} cm^{-2} s^{-1}

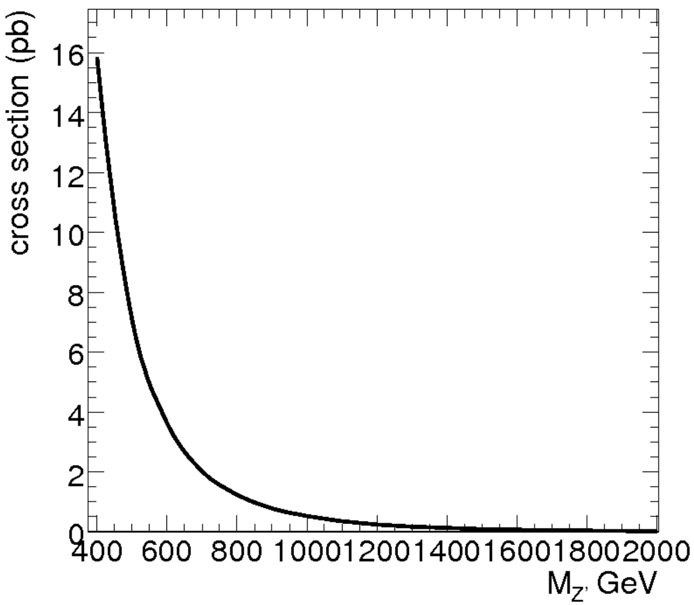
ATLAS Z’ Studies

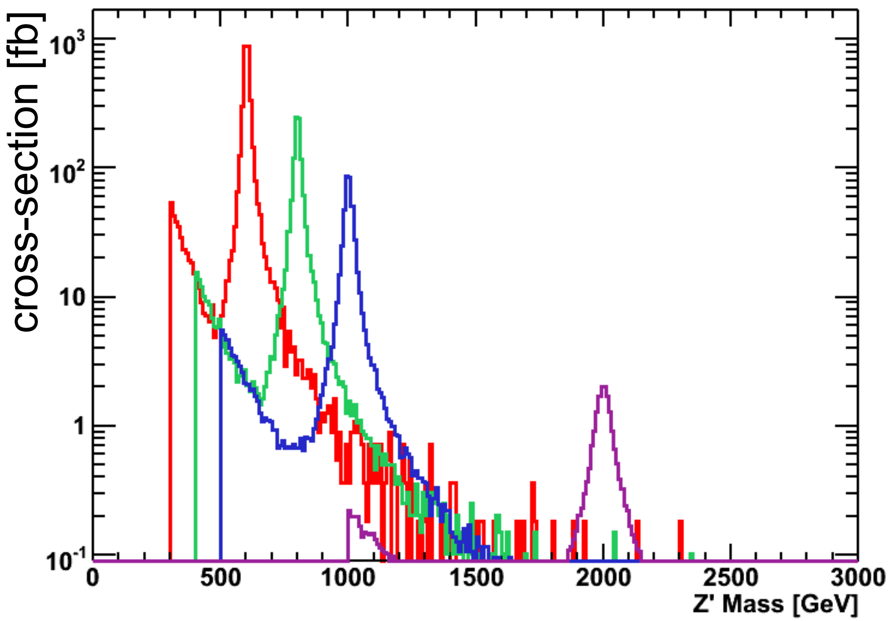
Three Final States Considered

Considered four signal mass points (all three di-tau final states: ll, lh, hh)

- **600, 800, 1000 and 2000 GeV**
- **Used cross-sections from the Sequential Standard Model ("SSM")**
- **Backgrounds considered: Drell-Yan, QCD di-jets, W+jets, Z+jets, ttbar**







Mass distribution from MC Truth

Event Selection (lh final-state)

(a) Trigger

- **Trig_EF_e25i || Trig_EF_e60 || Trig_EF_mu20i**
- **Hadronic tau trigger not yet explored (could be used in combination with MET trigger)**

(b) Lepton Selection

- **Good electrons and muons as selected by the offline software**
- **Must have at least one electron or muon for the lh channel**
- **|eta| < 2.5; pT > 27 (e); pT > 22 (mu)**

(c) Hadronic Tau

- **Good hadronic taus has selected by the offline software**
- **Require number of tracks to be 1 || 3**
- **Tau pT > 60**
- **Cut on a likelihood variable (derived from a handful of discriminants) as a function of the tau transverse energy (enhances QCD rejection)**

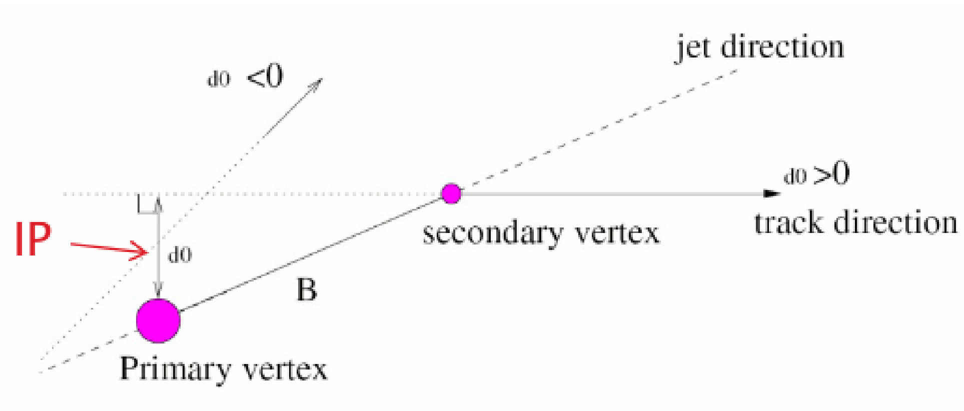
Hadronic Tau ID in ATLAS

Hadronic tau identification at a hadron collider is a difficult task

- **Complicated by the need to distinguish from QCD multi-jets**
- **Tau jets have lower track multiplicities contained in a narrow cone**
- **Characteristics of the track system and the calorimetric showers also help to distinguish against QCD jets (fakes)**

Two algorithms in ATLAS: calorimetry-based and track-based:

- **Calorimetry-based: Exploit collimated energy deposition, isolation region, EM Radius and Fraction**
- **Track-based: Exploit track multiplicity, isolation region, impact parameter, invariant mass**



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other modes with K	1.30 %
others	0.03 %

In this study the calorimetry-based algorithm was used

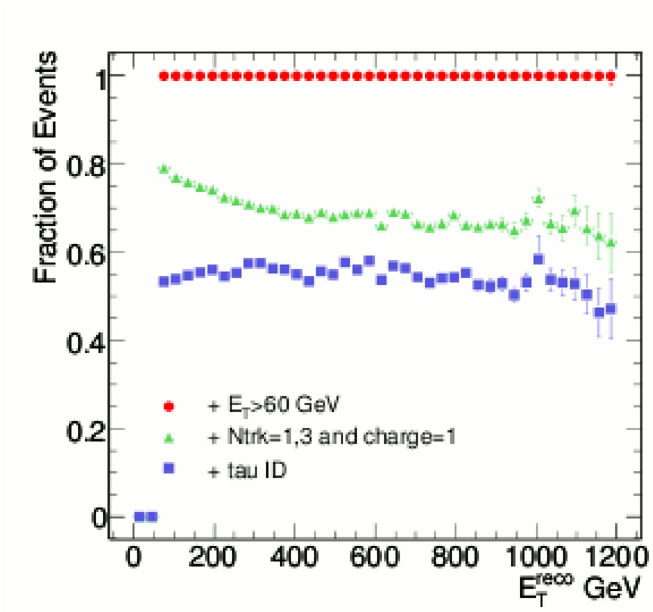
Hadronic Tau ID in ATLAS

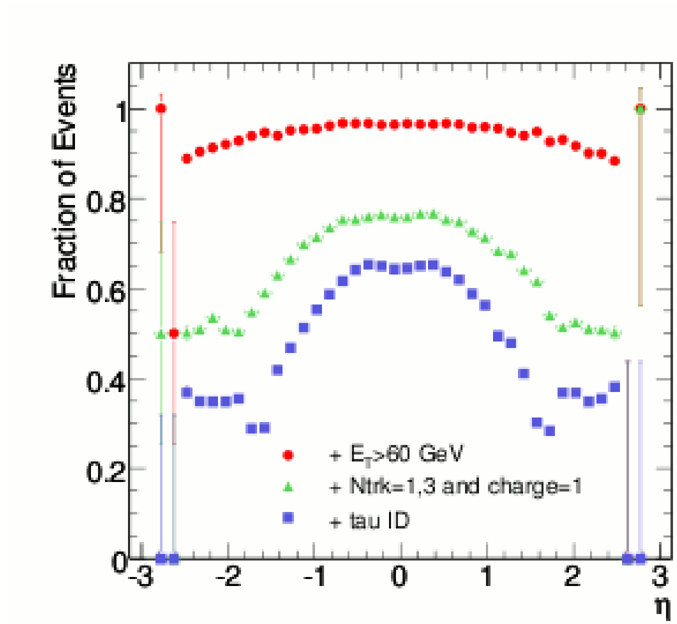
A one-dimensional likelihood ratio is built from multiple discriminating variables

- **Includes discrete variables like number of tracks or tau charge, as well as continuous variables such as the radius of the cluster in the EM calorimeter**

We cut on the value of the log of this likelihood ratio (LLH) as a function of E_T

- **A fixed cut would not be optimal for jet rejection, nor flat as a function of energy**





Event Selection (lh final-state)

(d) Opposite Charge

- **Require that the product of the tau and lepton charges be <= 0**

(e) Missing Transverse Energy

- **Require MET > 30**

(f) Transverse Mass

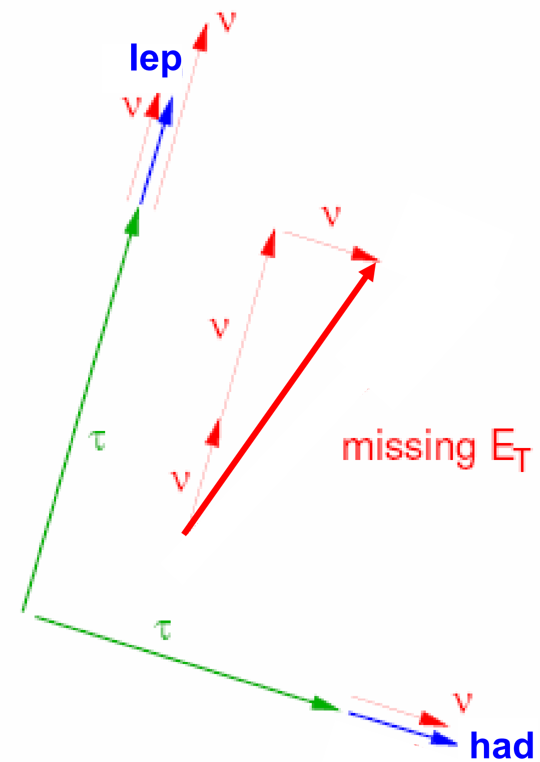
- **Build the transverse mass using the lepton and MET**
- **Require MT < 20**

(g) Total Event pT (vector sum)

- **Require pT TOT < 50**

(h) Visible Mass

- **Build the visible mass using the lepton, tau and MET four-vector (Pz = 0)**
- **Use cuts on Mvis like a mass window, but only with a lower bound**



(i) Mass Reconstruction (collinear approximation)

- **Check that the two taus are not back-to-back in the lab frame**
- **Cut on the fractions of the visible tau momentum carried by the decay daughters**

Results for the lh final-state

Analysis for the lh final-state

Includes all four Z’ signal masses

- **Assume 14 TeV running**
- **ATLAS full detector simulation**

	Z’ Signal σ [fb]				Background σ [fb]			
Cut	m = 600 GeV	m = 800 GeV	m = 1000 GeV	m = 2000 GeV	$t\bar{t}$	$W+$ jets	$Z+$ jets	QCD
Trigger	1356.0	516.8	223.6	11.6	213494.2	12358210.0	2062080.5	3369127.5
Lepton	905.1	336.2	139.8	6.6	151010.4	9028033.0	1062146.4	121617.1
Tau	367.6	153.2	67.0	3.6	7808.2	74818.4	39573.5	3354.1
Charge	314.8	132.1	58.4	3.1	2487.0	3502.8	23097.7	831.4
MET > 30	269.7	115.7	53.4	2.9	2034.6	$2343.8^{\dagger}$	707.7	$181.8^{\dagger}$
$M_{TR} < 20$	186.7	77.9	35.0	1.7	164.5	$182.6^{\dagger}$	245.4	$86.4^{\dagger}$
P_T TOT < 50	165.2	68.0	30.5	1.4	44.6	$149.7^{\dagger}$	175.7	$16.2^{\dagger}$
$M_{vis} > 300$	144.7	–	–	–	17.1	$44.5^{\dagger}$	18.8	$8.9^{\dagger}$
M_{col}	23.5	–	–	–	5.7	$5.8^{\dagger}$	5.0	$1.5^{\dagger}$
$M_{vis} > 400$	–	59.1	–	–	6.9	$20.1^{\dagger}$	5.0	$3.1^{\dagger}$
M_{col}	–	7.8	–	–	2.3	$0.0^{\dagger}$	$0.4^{\dagger}$	$0.0^{\dagger}$
$M_{vis} > 500$	–	–	25.4	–	3.4	$11.7^{\dagger}$	1.3	$0.1^{\dagger}$
M_{col}	–	–	2.4	–	$0.1^{\dagger}$	$0.0^{\dagger}$	$0.0^{\dagger}$	$0.0^{\dagger}$
$M_{vis} > 700$	–	–	–	1.2	2.3	$2.8^{\dagger}$	$0.4^{\dagger}$	$0.0^{\dagger}$

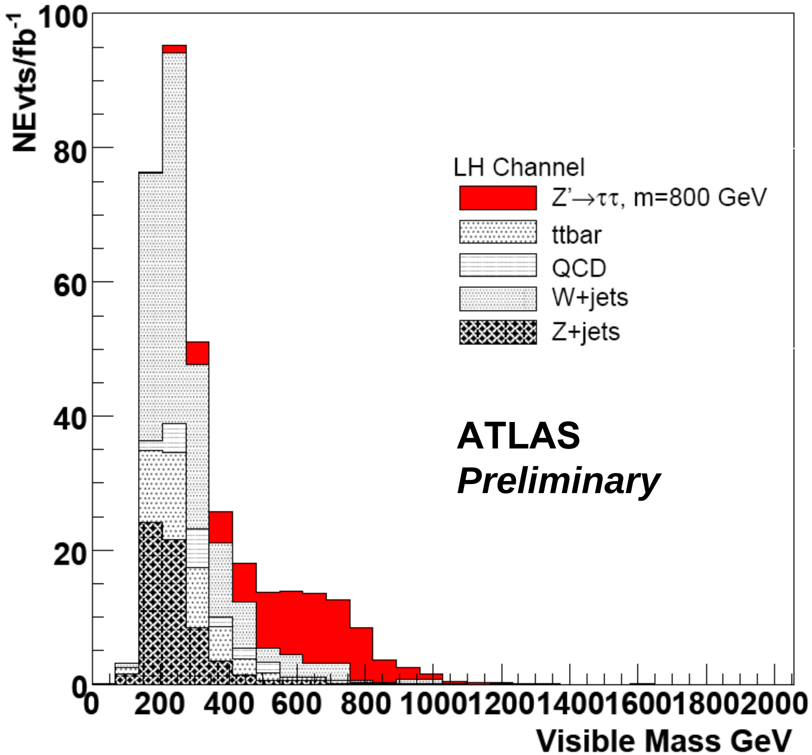
ATLAS
Preliminary

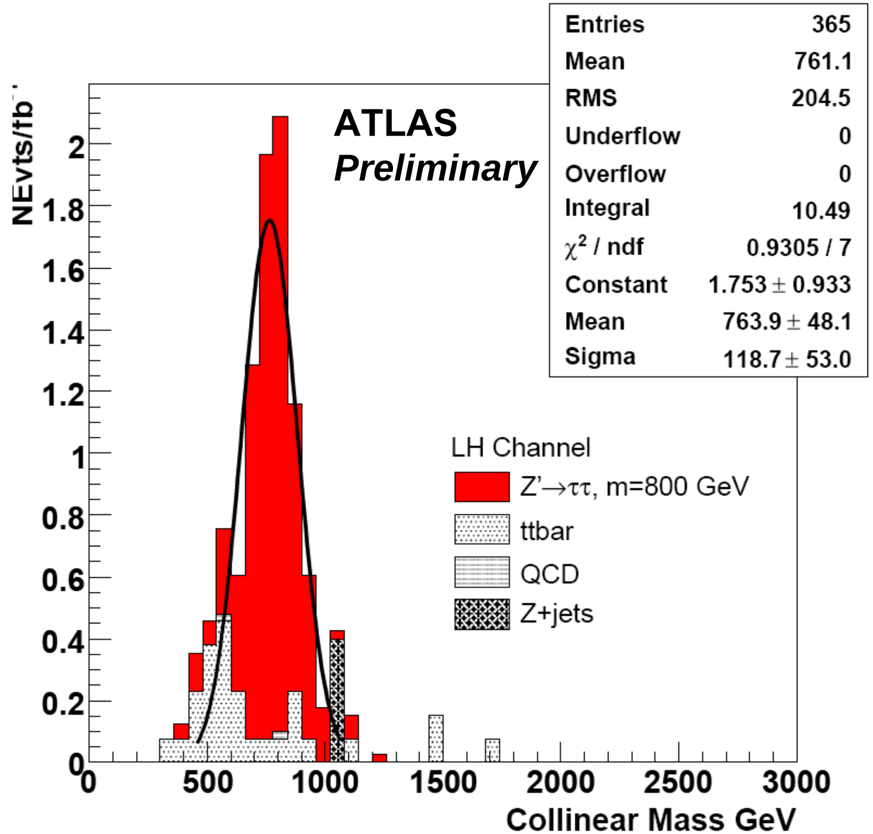
All cross-sections here are given in fb

Plots for the lh final-state

Both the Visible and the Collinear masses are shown

- **Plotted for an 800 GeV Z'**
- **Assuming 1 fb^{-1} of data at 14 TeV**





Results for the hh final-state

Analysis for the hh final-state

Large similarities with the lh selection, but:

- **Use hadronic tau trigger in combination with MET (Preliminary)**
- **Increase the minimum MET requirement to 40 GeV**
- **Different MT and pT TOT cuts than the lh channel; < 35 and < 50, respectively**

Turns out to be our most powerful final-state

- **Note that the primary trigger for this channel is the hadronic tau trigger**
- **Studies are currently underway to further explore the trigger for this channel**

	Z' Signal σ [fb]				Background σ [fb]			
Cut	$m = 600$ GeV	$m = 800$ GeV	$m = 1000$ GeV	$m = 2000$ GeV	$t\bar{t}$	$W+$ jets	$Z+$ jets	QCD
Trigger	1475.3	567.8	245.9	12.2	70531.8	1668621.5	404922.8	1833543.8
2 Taus	204.0	102.2	47.8	3.1	211.3	250.7	710.0	831.5
Charge	197.1	98.5	46.1	2.9	195.3	183.4	649.9	829.1
MET > 40	168.1	86.2	40.8	2.7	177.1	$128.6^{\dagger}$	73.2	$79.9^{\dagger}$
$M_{TR} < 35$	146.5	72.6	34.7	2.1	42.3	$29.0^{\dagger}$	49.4	$38.8^{\dagger}$
P_T TOT < 50	129.9	65.0	30.3	1.7	12.6	$21.2^{\dagger}$	40.3	$27.6^{\dagger}$
$M_{vis} > 400$	116.6	–	–	–	1.1	$9.7^{\dagger}$	13.8	$16.8^{\dagger}$
M_{col}	18.6	–	–	–	$0.4^{\dagger}$	$0.0^{\dagger}$	0.8	$1.8^{\dagger}$
$M_{vis} > 500$	–	55.9	–	–	1.1	$4.6^{\dagger}$	10.8	$6.1^{\dagger}$
M_{col}	–	6.8	–	–	$0.1^{\dagger}$	$0.0^{\dagger}$	0.8	$0.0^{\dagger}$
$M_{vis} > 600$	–	–	24.6	–	$0.7^{\dagger}$	$3.0^{\dagger}$	3.0	$4.3^{\dagger}$
M_{col}	–	–	2.5	–	$0.02^{\dagger}$	$0.00^{\dagger}$	$0.04^{\dagger}$	$0.00^{\dagger}$
$M_{vis} > 800$	–	–	–	1.6	$0.2^{\dagger}$	$0.5^{\dagger}$	0.8	$0.3^{\dagger}$

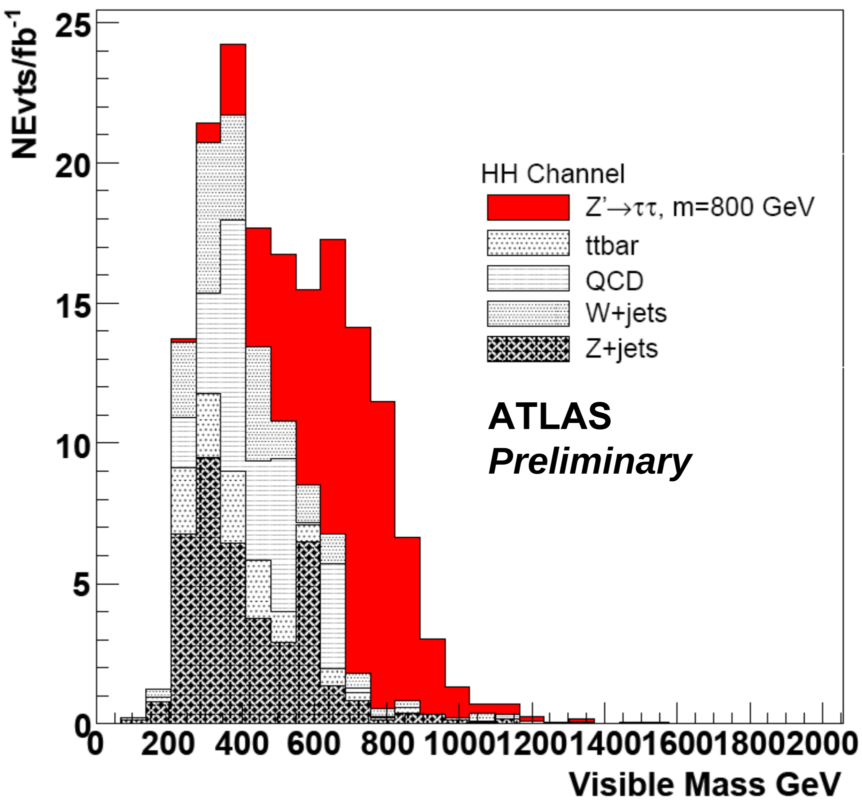
ATLAS
Preliminary

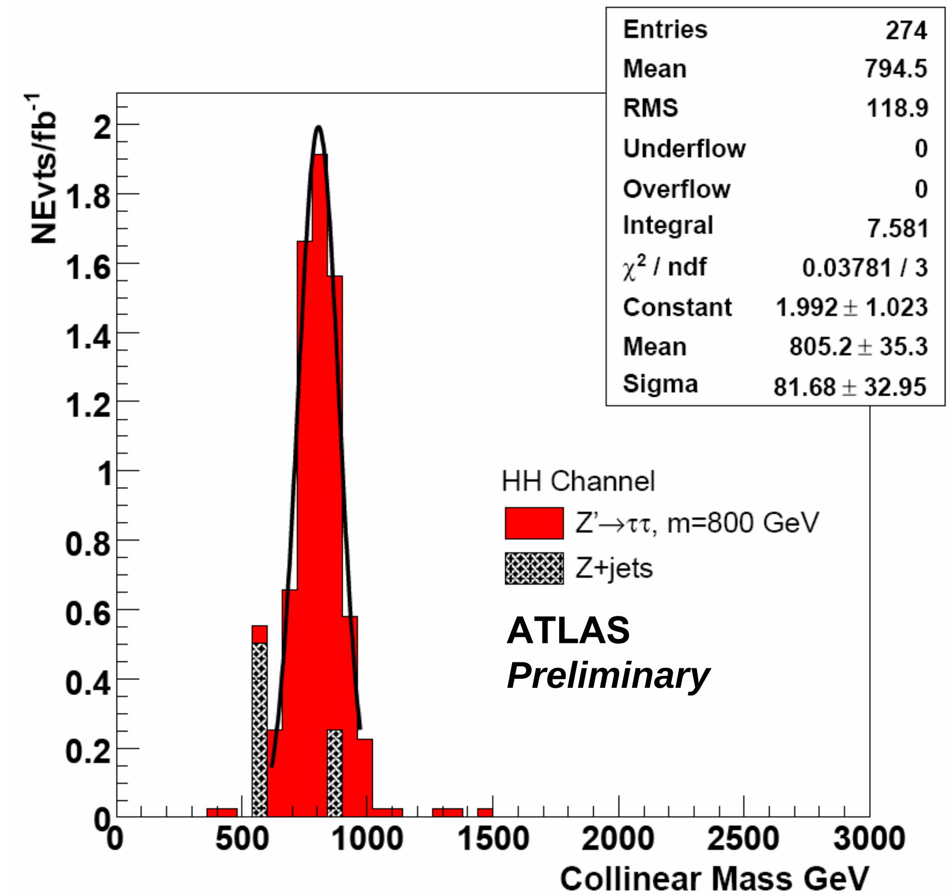
All cross-sections here are given in fb

Plots for the hh final-state

Both the Visible and the Collinear masses are shown

- **Plotted for an 800 GeV Z'**
- **Assuming 1 fb^{-1} of data**





Excellent Mass Resolution

Results for the ll final-state

Analysis for the ll final-state

Large similarities with the lh selection, but:

- **Obviously no hadronic tau selection**
- **MET requirement at 40 GeV**
- **MT and pT TOT cuts are < 35 and < 50, respectively**
- **Added a b-tag veto (displaced vertex) to help with background rejection**

	Z' Signal σ [fb]				Background σ [fb]		
Cut	$m = 600$ GeV	$m = 800$ GeV	$m = 1000$ GeV	$m = 2000$ GeV	$t\bar{t}$	$W+$ jets	$Z+$ jets
Trigger	1355.9	516.8	223.7	11.6	213494.2	12365976.0	2050989.6
2 Leptons	132.3	55.2	25.7	1.1	13861.8	2250.3	640457.2
Charge	131.0	54.8	25.3	1.1	13219.4	1591.0	638777.9
MET > 40	92.2	41.9	20.7	1.0	9964.5	$641.9^{\dagger}$	1205.9
$M_{TR} < 35$	69.3	31.9	16.0	0.7	1602.6	$82.5^{\dagger}$	331.9
P_T TOT < 70	52.2	24.5	12.3	0.5	551.6	$52.7^{\dagger}$	192.7
b Veto	52.0	24.2	12.0	0.5	130.1	$52.0^{\dagger}$	162.0
$M_{vis} > 300$	38.6	–	–	–	29.7	$5.0^{\dagger}$	18.4
M_{col}	2.5	–	–	–	0.9	$1.8^{\dagger}$	1.5
$M_{vis} > 400$	–	14.9	–	–	8.7	$1.8^{\dagger}$	7.7
M_{col}	–	0.6	–	–	$1.3^{\dagger}$	$0.9^{\dagger}$	$0.0^{\dagger}$
$M_{vis} > 500$	–	–	6.8	–	2.6	$0.9^{\dagger}$	4.6
M_{col}	–	–	0.2	–	$0.4^{\dagger}$	$0.0^{\dagger}$	$0.0^{\dagger}$
$M_{vis} > 700$	–	–	–	0.3	$1.7^{\dagger}$	$0.0^{\dagger}$	4.6

ATLAS
Preliminary

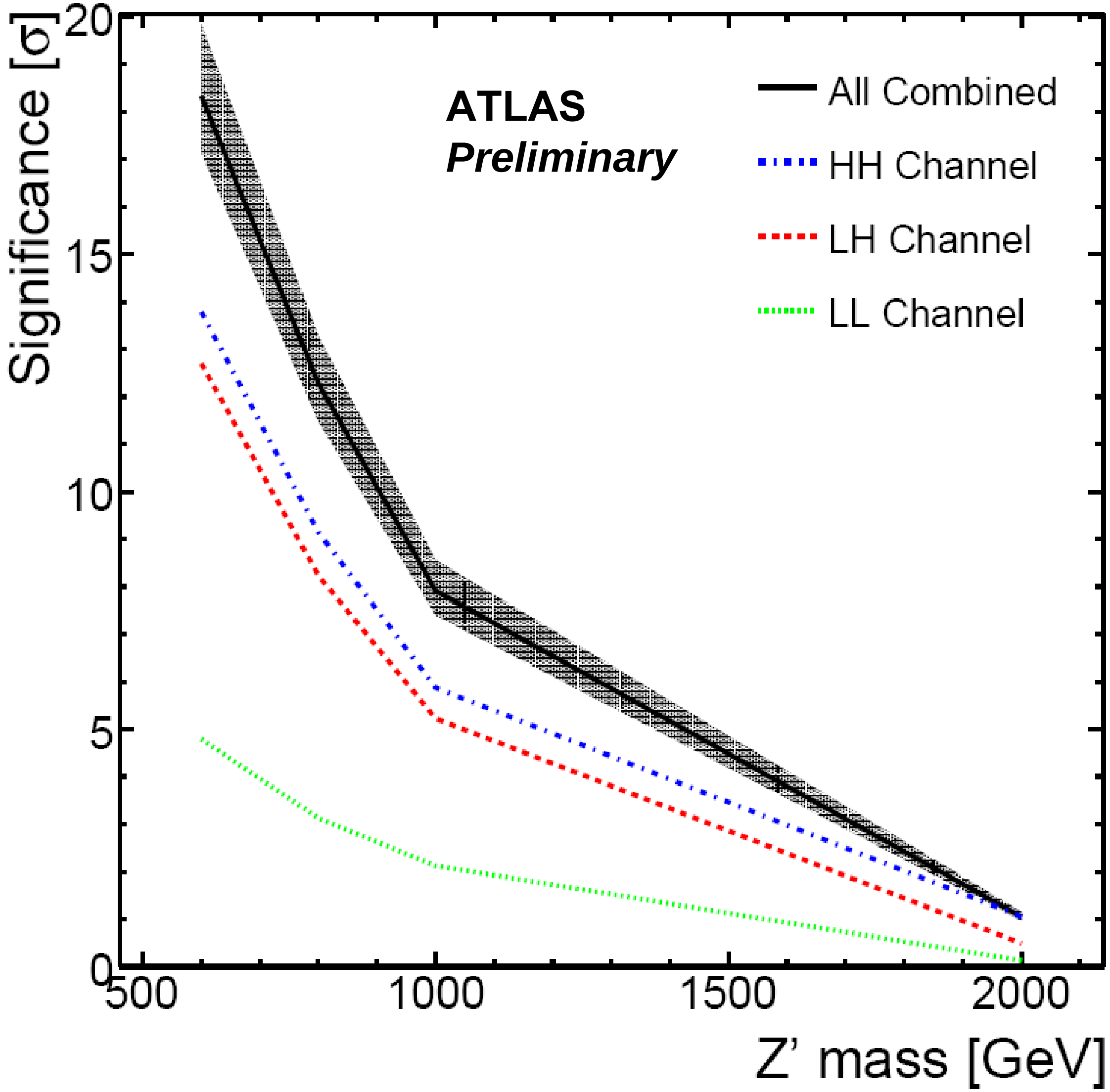
All cross-sections here are given in fb

Results for combination

Combination of all final-states

At the level of the Visible Mass cut

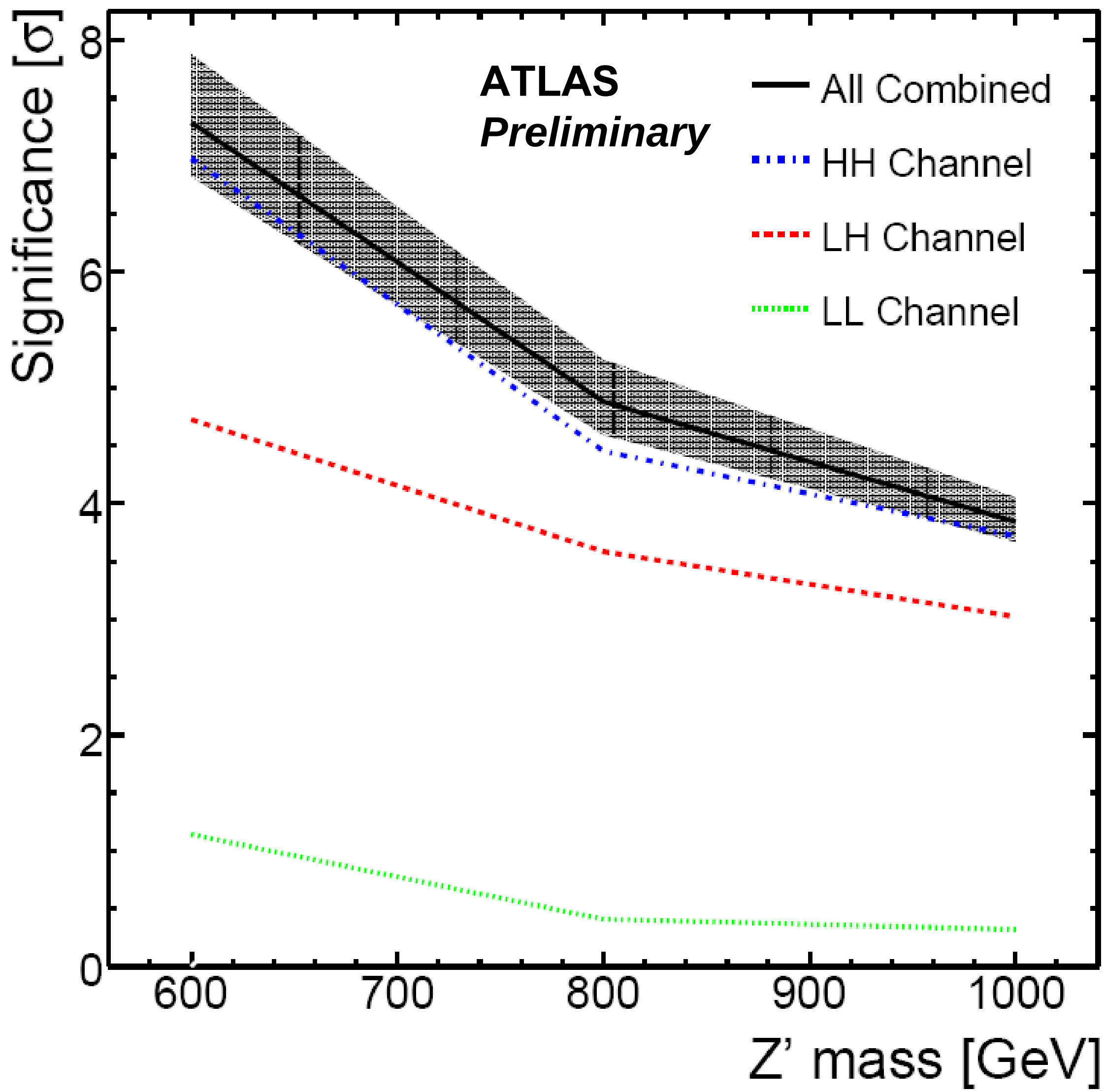
- **With and without inclusion of the systematics (assume 20%) estimates**



Combination of all final-states

At the level of the Collinear Mass cut

- **With and without inclusion of the systematics (assume 20%) estimates**

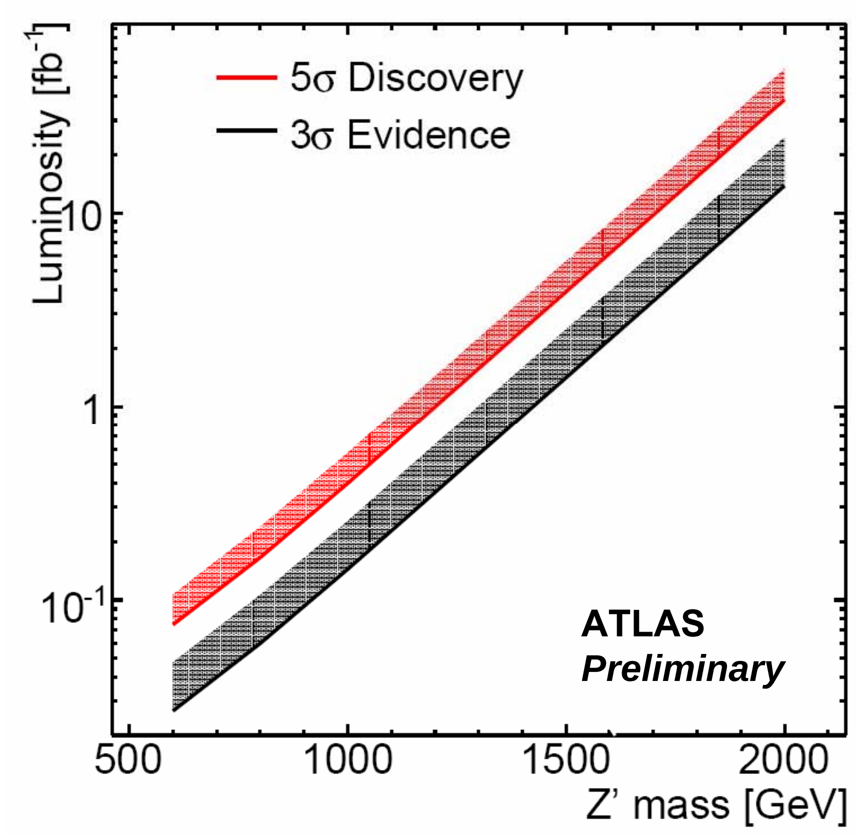


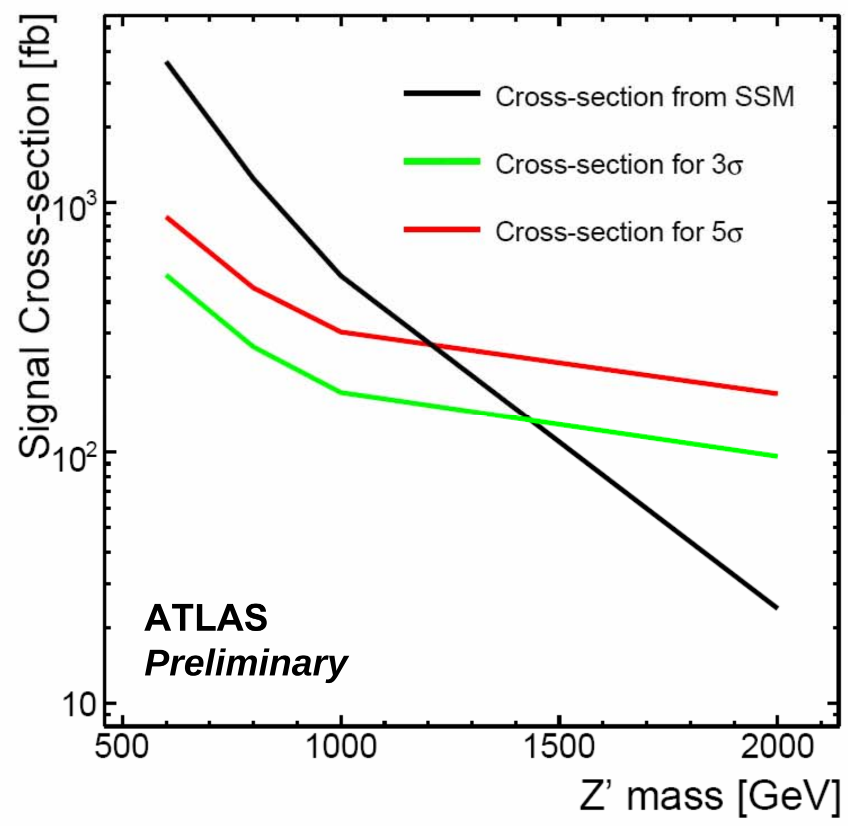
What if it is not the SSM?

For Evidence or Discovery

Left: Assuming the SSM cross-section, luminosity for evidence or discovery

Right: Minimum CS needed for evidence or discovery in 1 fb^{-1} of data





Conclusions

First LHC Collisions expected ~late Summer of 2009

The ATLAS and CMS Experiments are ready for collision data-taking

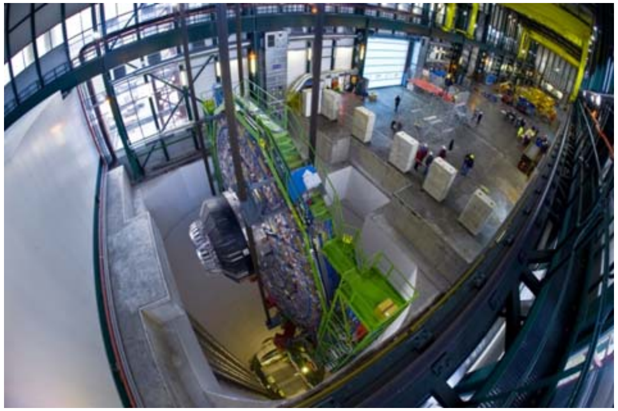
- **Both experiments have already taken extensive amounts of cosmics data**
- **This data has already helped to gain understanding about the detectors**
- **Calibration of the subsytems and refinement of the software continues**

At the right mass and cross-section, a Z' discovery could come very early

- **~1 fb^{-1} at 14 TeV**
- **Analysis is easily extended into a massive graviton or MSSM Higgs Search**

Use tau polarization to determine the spin of any observed resonance

- **Can distinguish between left and right-handed taus on a statistical basis**

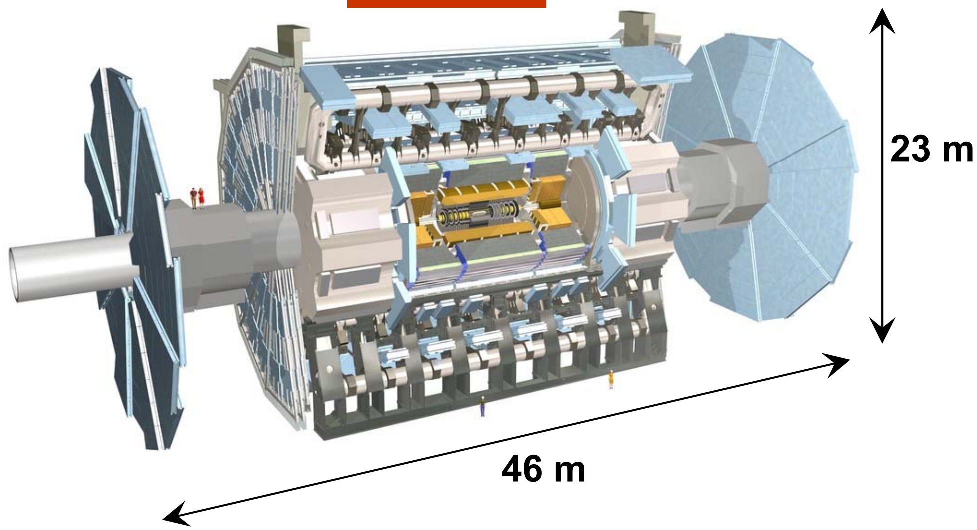


Backup Slides

The ATLAS Experiment

Designed to search for the Higgs and New Physics over a wide mass range

ATLAS



Hermetic calorimetry

- **Exceptional measurement of missing transverse energy, jets to high eta**

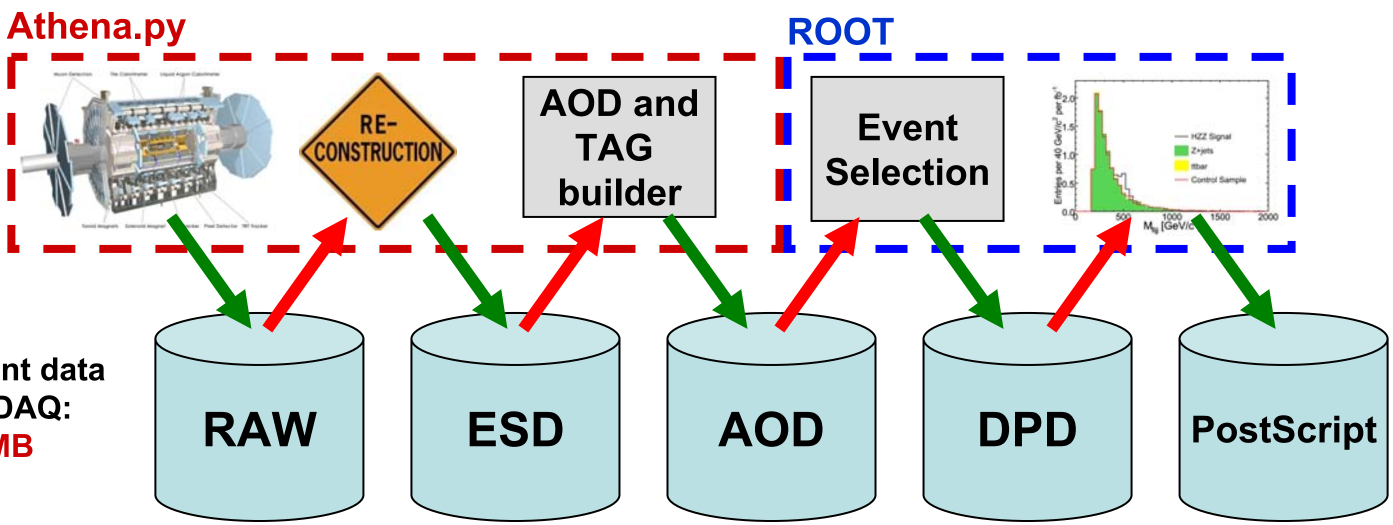
Exceptional particle identification

• **Muons**	**Efficiency ~90%**	**Jet Rejection ~10^5**
• **Electrons**	**Efficiency ~80%**	**Jet Rejection ~10^5**
• **Photons**	**Efficiency ~80%**	**Jet Rejection ~10^3**
• **b-Jet ID**	**Efficiency ~60%**	**Light Jet Rejection ~10^2**
• **Tau ID**	**Efficiency ~50%**	**Jet Rejection ~10^2**

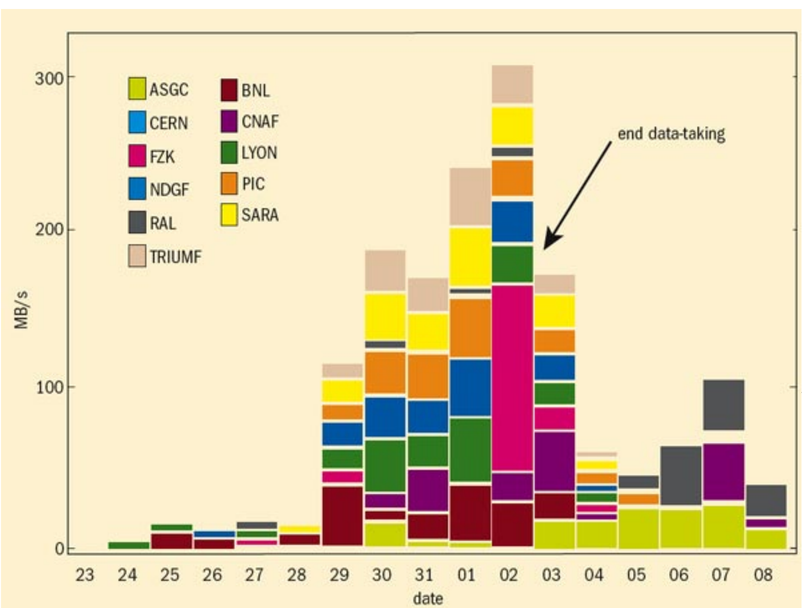
Electron, muon and photon energy and momentum resolution of ~2-3%

ATLAS Data-taking Chain

First test of the end-to-end data-taking chain took place in September 2007



RAW Event data from TDAQ: ~2 MB



ESD (Event Summary Data):
output of reconstruction (calo cells, track hits, ..): ~1 MB

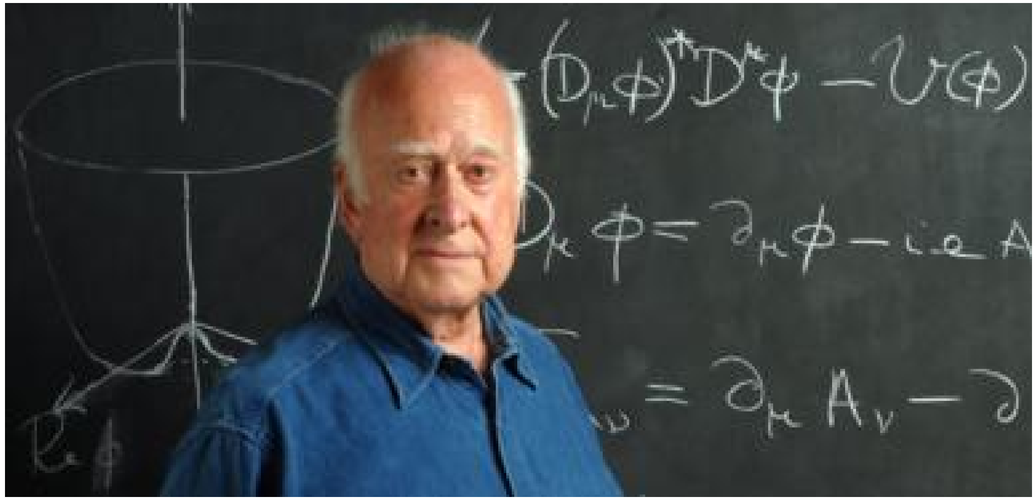
AOD (Analysis Object Data):
physics objects for analysis (e,γ,m,jets, …): ~100 kB

TAG (Event Level Metadata):
Reduced set of information for event selection: ~1 kB

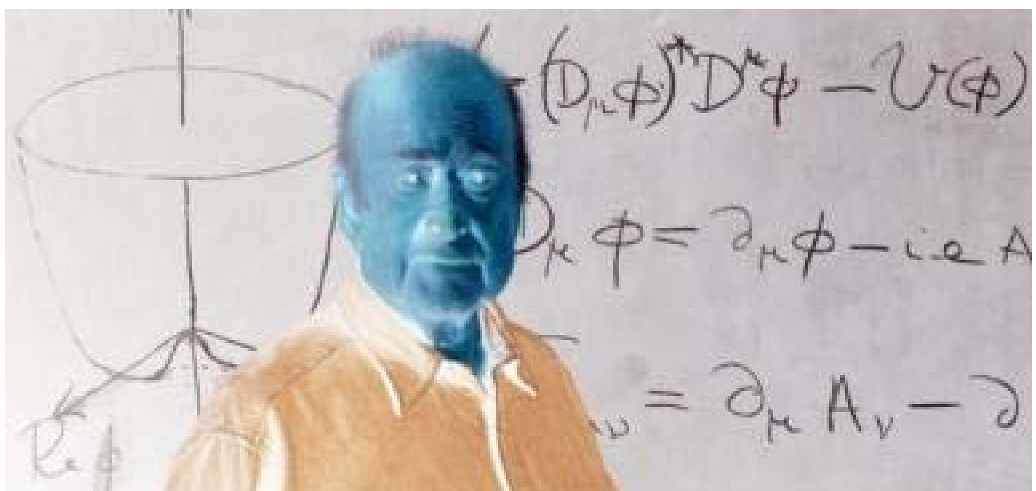
DPD (Derived Physics Data): equivalent of old ntuples: ~10 kB

Flow of data from CERN Tier 0 to Tier 1 sites all over the world.

For data processing and analysis, the GRID is an absolute necessity



Supersymmetric Higgs(es)

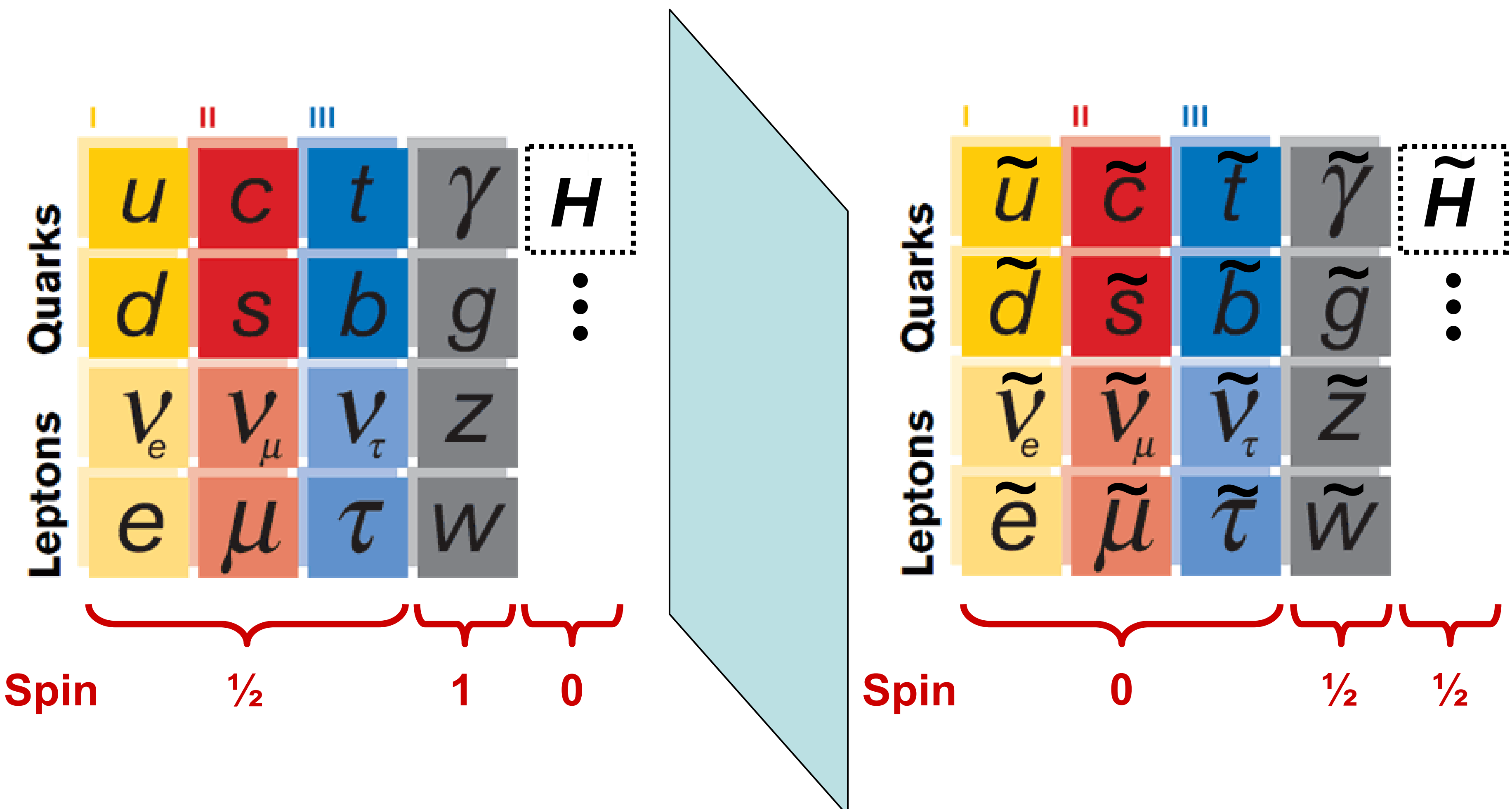


Supersymmetry

Every particle has a “super-partner” particle

Fermions ⟷ Bosons

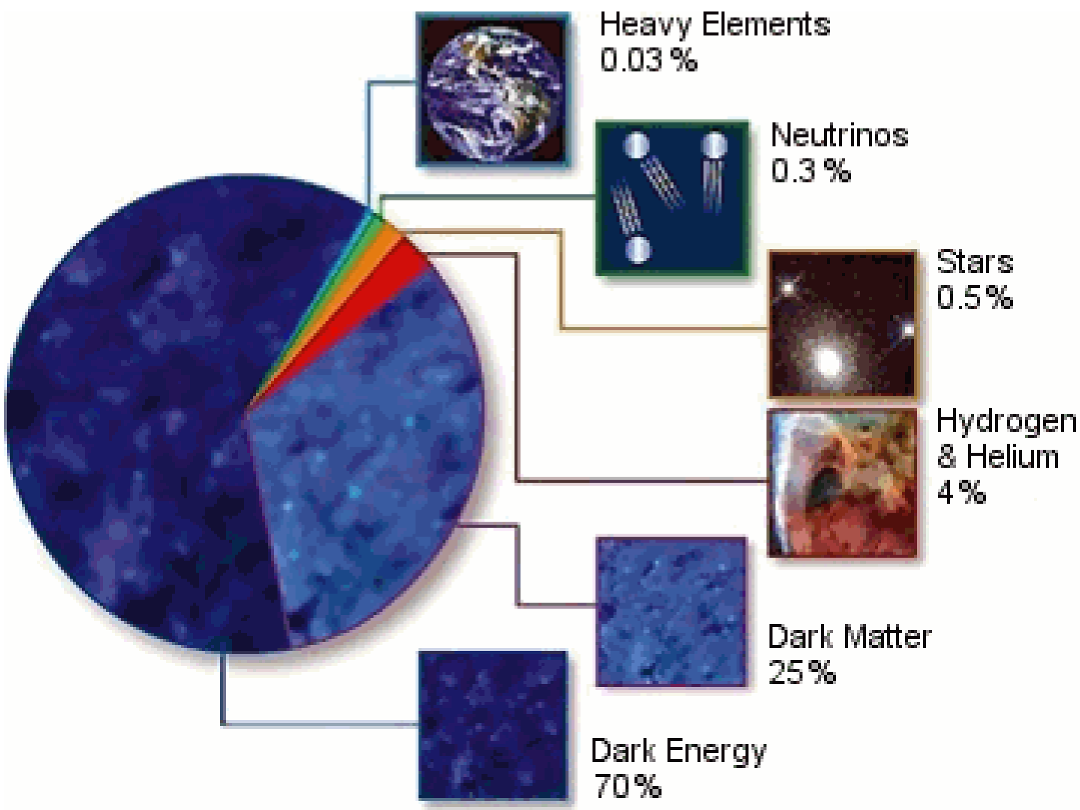
Half-Integer Spin: ½, ³⁄₂, … | **Integer Spin: 0, 1, …**

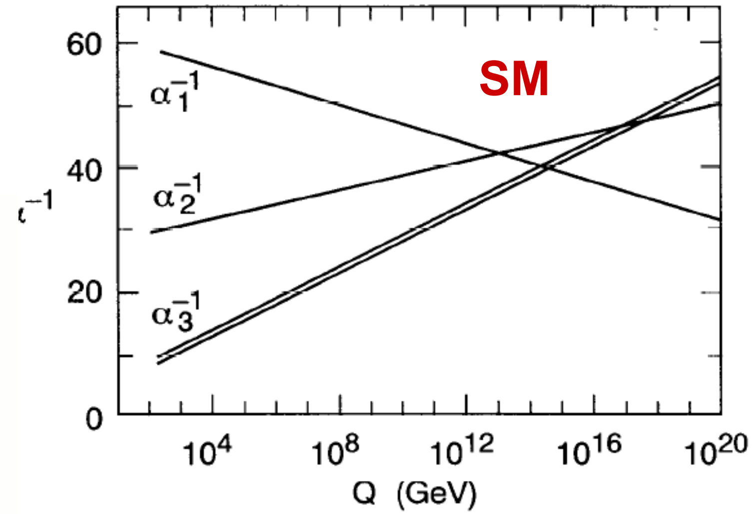


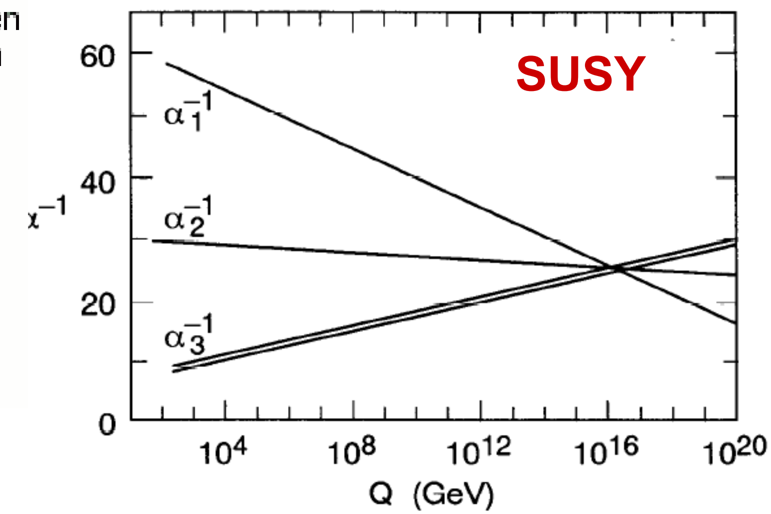
Motivation for SUSY

Motivation for Supersymmetry

- **Naturalness (Hierarchy Problem)**
- **Unification of the forces (gauge couplings)**
- **Provides a candidate for Dark Matter**





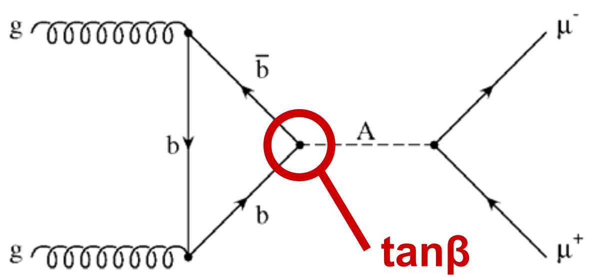


MSSM Higgs at the LHC

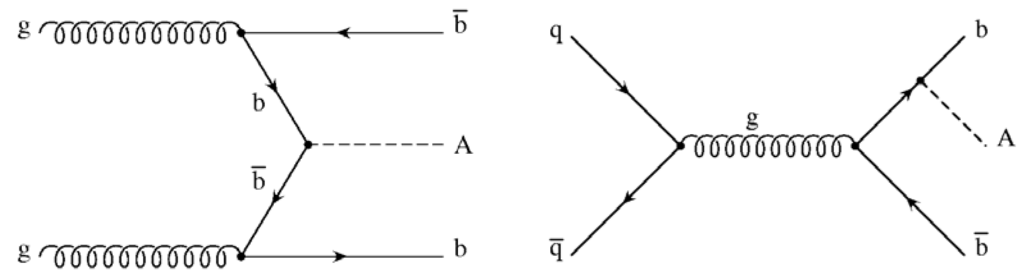
Minimal Supersymmetric extension to the SM: (A, H, h, H±)

- As one example here, consider A / H →μμ
- Not visible in the SM
- Enhanced in the MSSM by ~tan²β; excellent mass resolution as opposed to ττ

Direct and associated production



Enhanced for large tanβ



Divide μμ analysis into two uncorrelated channels

Initial event selection:

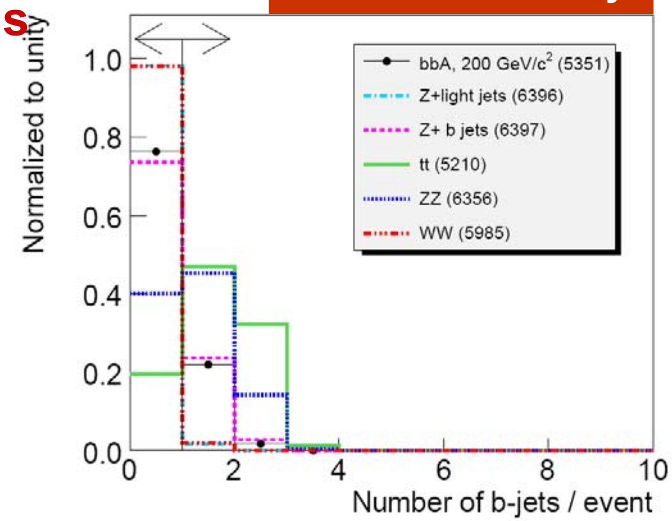
- Di-muon selection, low event MET, b-tag

0 b-jet

≥1 b-jet

- Acoplanarity, sum pT of all jets

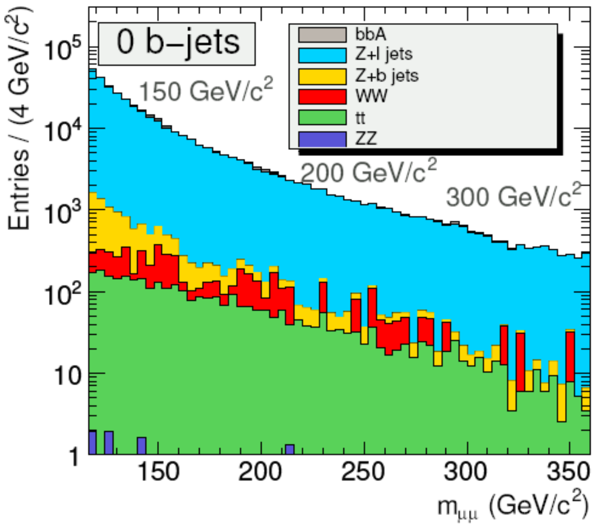
ATLAS Preliminary

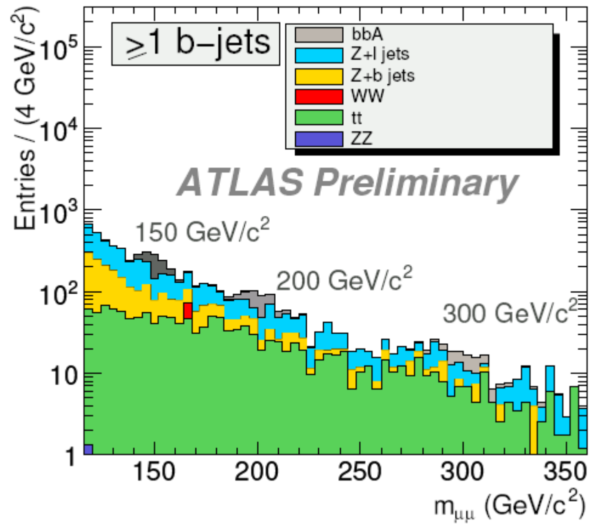


MSSM Higgs at the LHC

Combine the 0 and ≥ 1 b-jet analyses to increase the significance

- **A very similar analysis has been explored for the ττ channel**

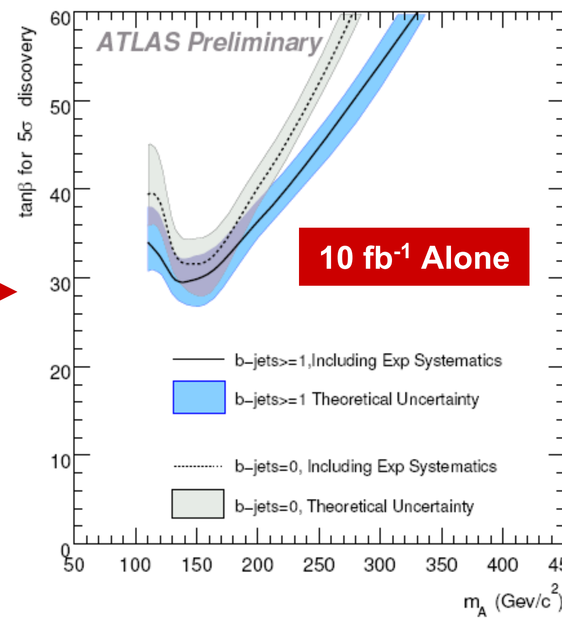


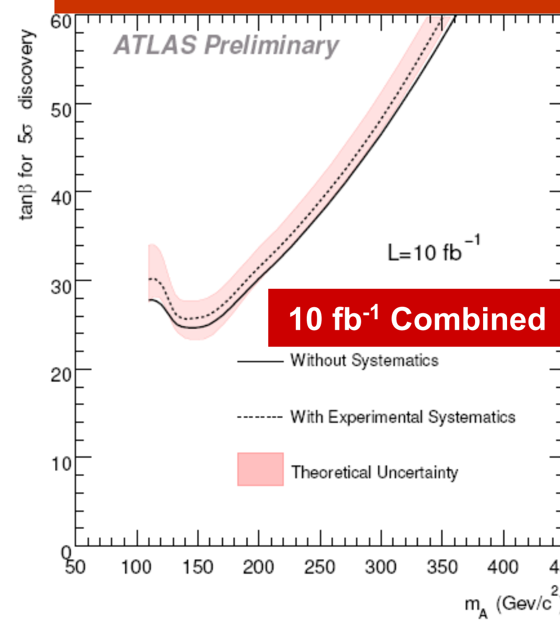


Reconstructed Invariant mass

ATLAS CSC 2008 10 fb^{-1}

tanβ for a 5σ Discovery

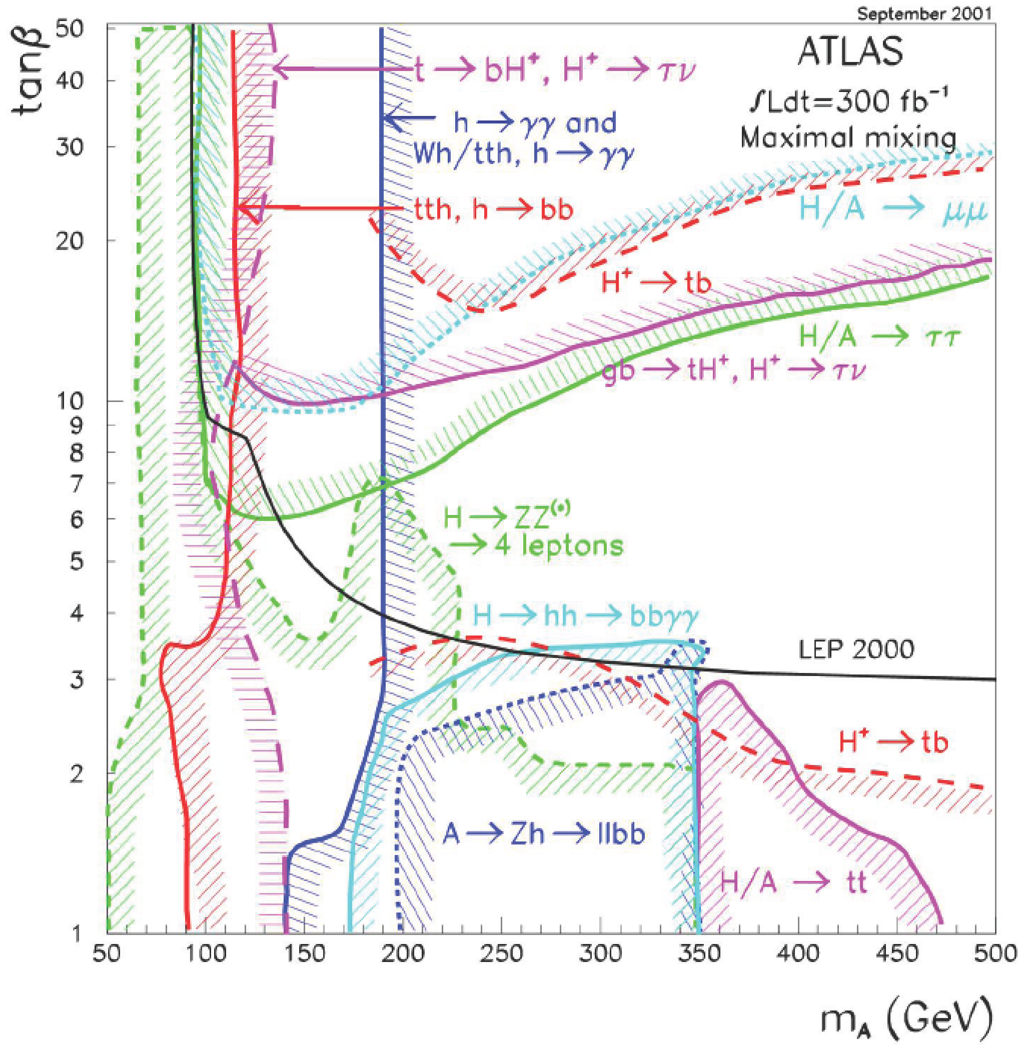




MSSM Higgses with ATLAS

The complete region of the m_A – tanβ parameter space should be accessible to ATLAS

- **mA = 50 – 500 GeV**
- **Tanβ = 1 - 50**

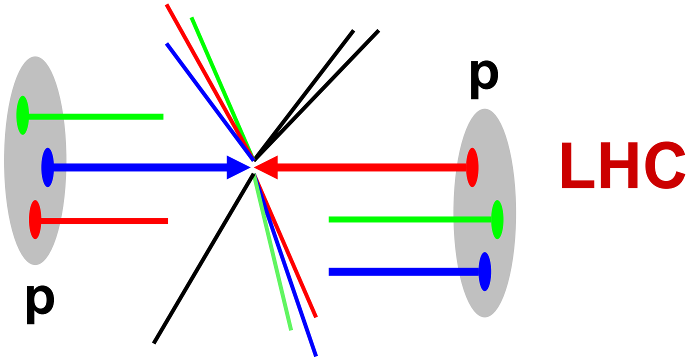


ILC Specific

Is it really the Higgs?

Properties that we will want to measure to confirm a Higgs discovery:

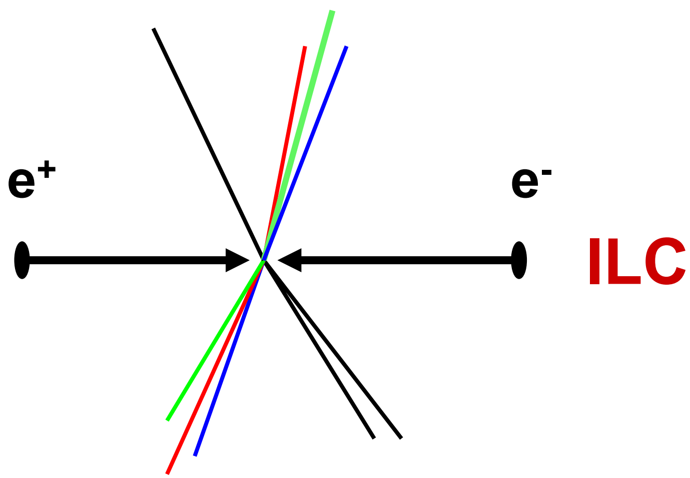
- **What is the mass and width?**
- **Does it have charge?**
- **What are the production processes and cross-sections?**
- **What are the branching-ratios?**
- **What are the couplings?**
- **What is its spin?**



Reasonably good precision from the LHC ~10-20% level
Get precise measurements from a high-energy e+e- collider ~1% level

The advantages of an e+e- collider:

- **They're elementary particles**
- **Able to collide them with well defined energy and angular momentum**
- **Collisions at the full center-of-mass energy**
- **"Democratic" particle production**
- **Possible to fully reconstruct the events**



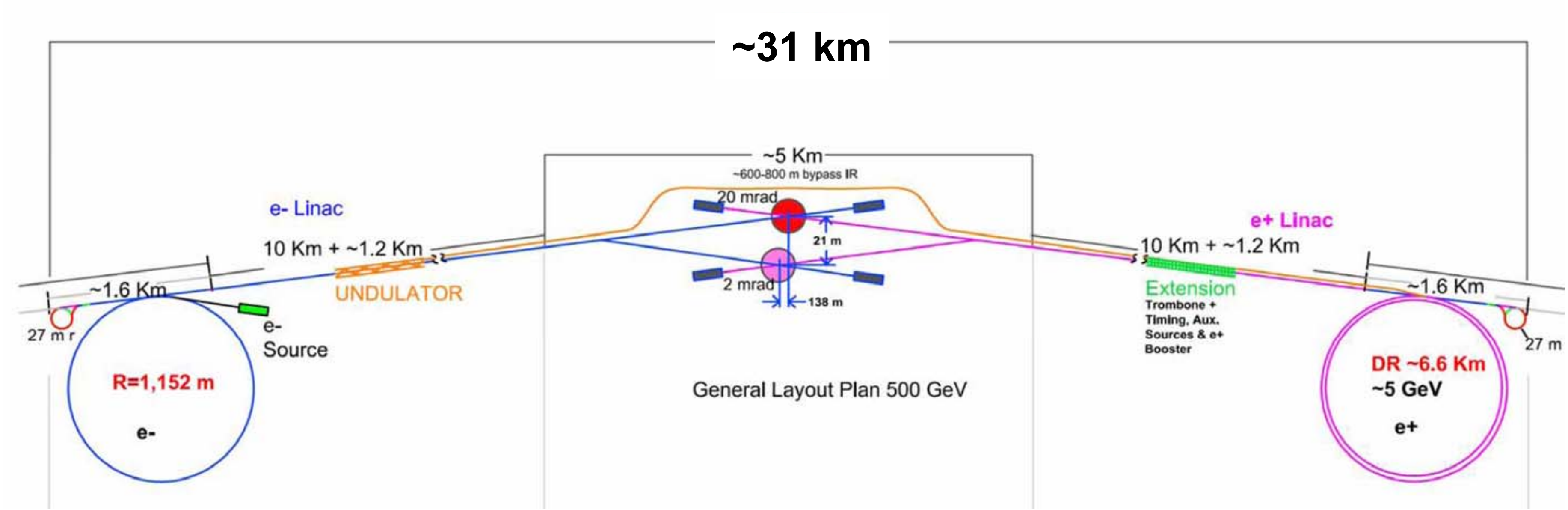
The International Linear Collider (ILC)

Already a huge international effort of R&D on this accelerator

- Global design effort well underway

Parameters for the ILC (derived from the scientific goals)

- Center-of-mass energy adjustable from 200 – 500 GeV (extendible to 1 TeV)
- Total integrated luminosity of 500 fb^{-1} in 4 years
- Energy stability and precision below 0.1%
- Electron polarization of at least 80%



Cost: ~6.6 Billion USD

Location: One of three possible sites

- Locations in the Americas, Europe and Asia: Fermilab, CERN and Japan

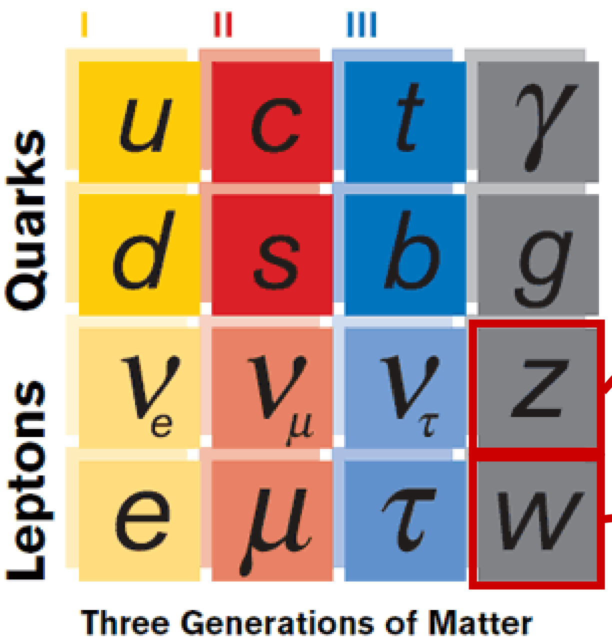
Timescale: Commissioning sometime beyond 2020?

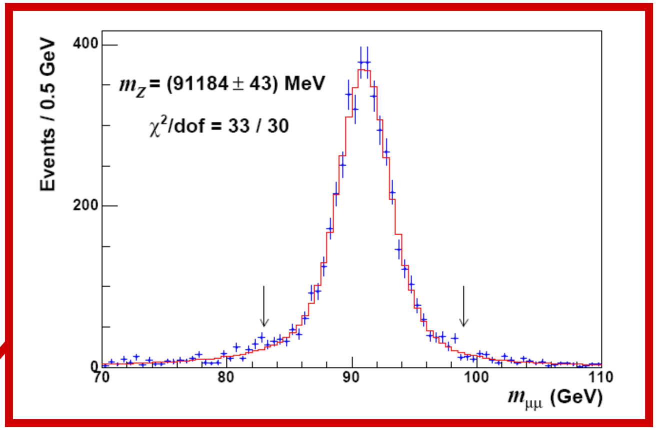
Higgs Specific

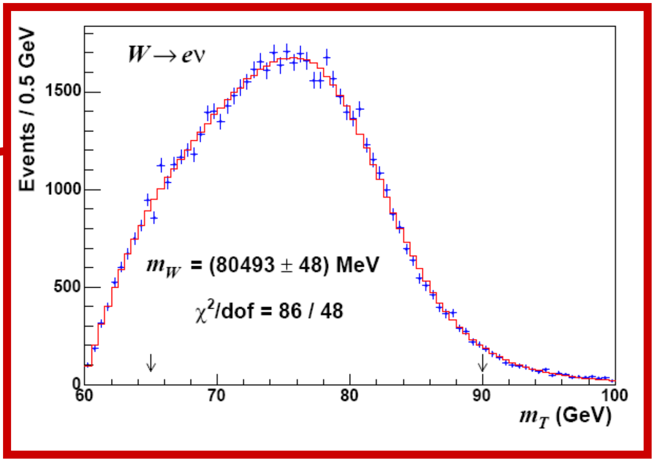
The Origin of Mass

The SM says that all of the carriers of the Electromagnetic and Weak forces must have the same "symmetric" mass, of zero

- **These force carriers are the γ and $W^{\pm}/Z$, respectively**
- **We know from experiment that the Weak force carriers have a non-zero mass**
- **The symmetry is broken**







Discovered by the UA1 and UA2 Experiments at CERN in 1983

T. Aaltonen *et al.* arXiv:0708.3642

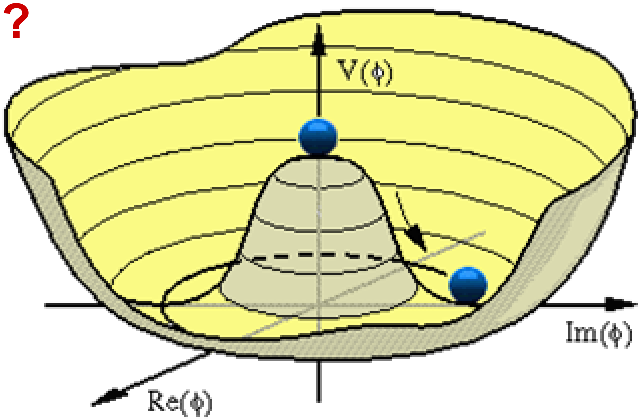
The Origin of Mass

What breaks the symmetry of the Weak Interactions?

- **In the theory, postulate a Higgs Field ϕ**
  and a potential energy function:

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

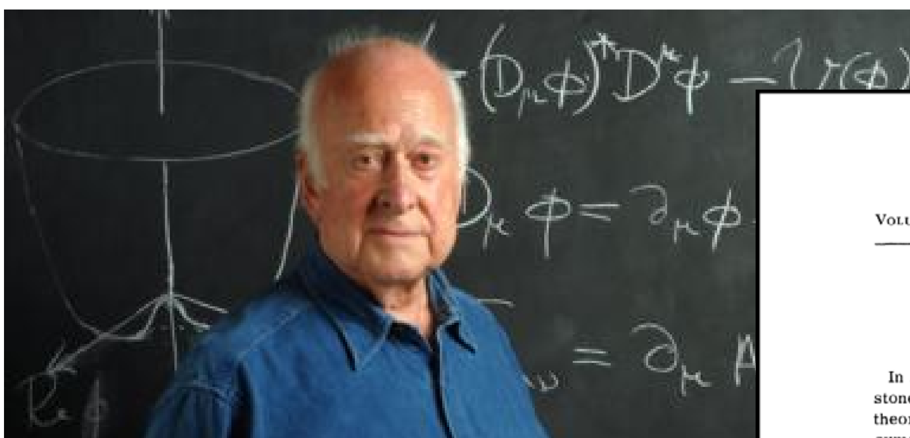
- **Assume minimum is not at $\phi = 0$ but,**
  some non-zero value: ϕ_0



Analogy to a ball rolling down a hill

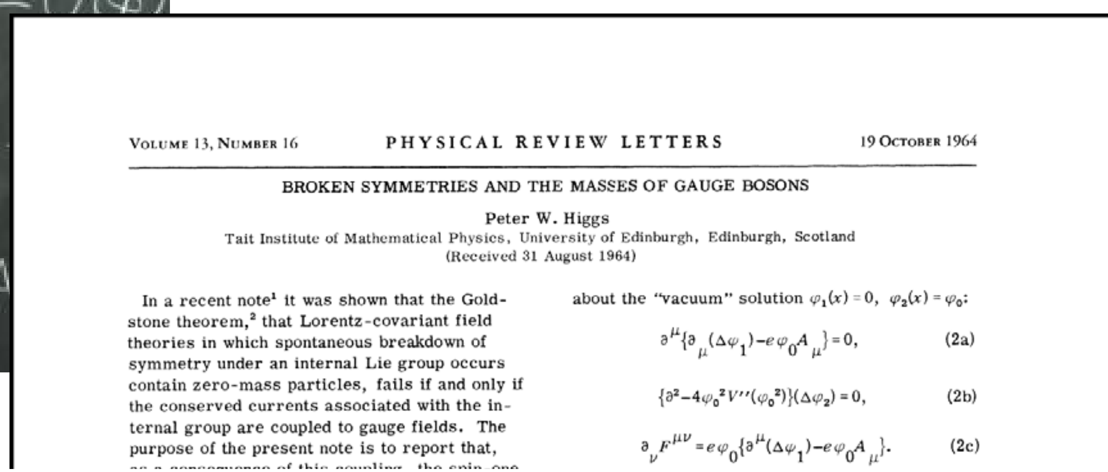
- **Direction that the ball rolled down has now been singled out from all other directions; the symmetry has been spontaneously broken**

Through the Higgs Mechanism, particles obtain an "effective mass"



Peter Higgs

1964



VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that,

about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \qquad (2a)$$

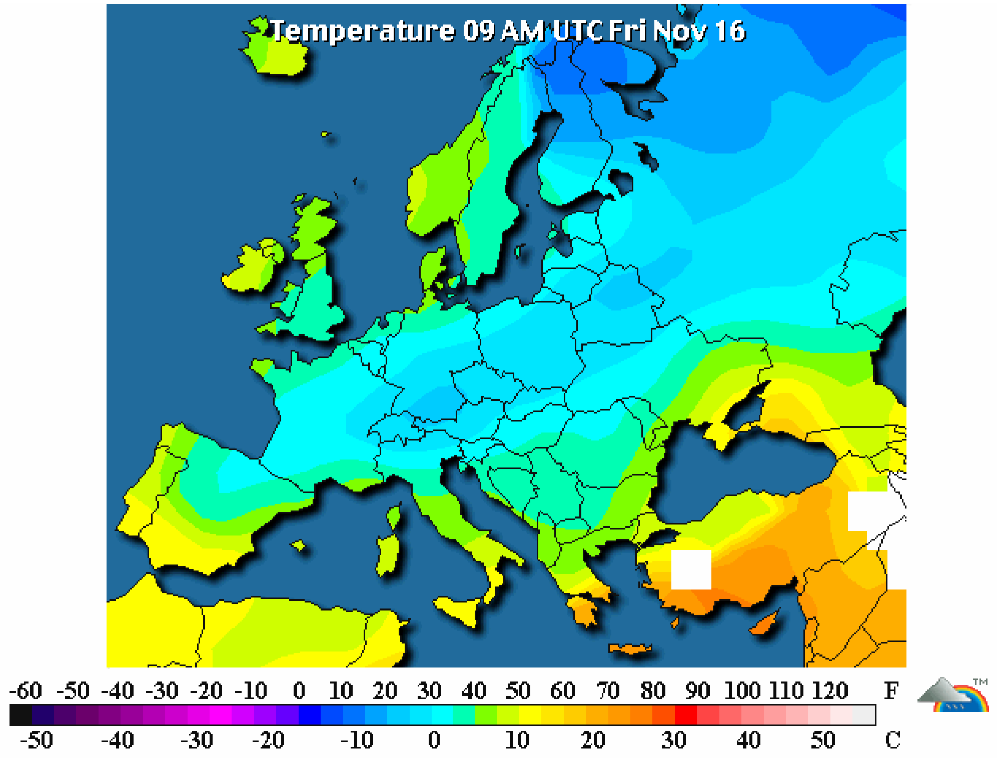
$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \qquad (2b)$$

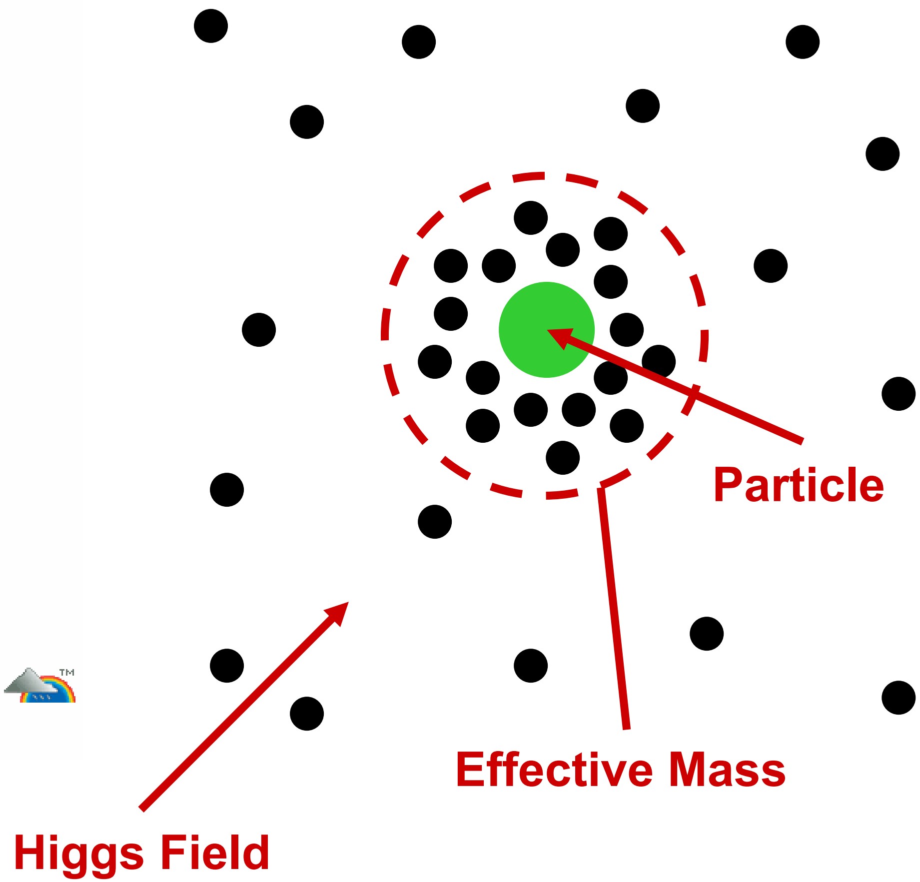
$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu(\Delta\varphi_1) - e\varphi_0 A_\mu\}. \qquad (2c)$$

The Higgs Field

The Higgs Field is a scalar field (think of a temperature map)

- **Particles obtain an "effective mass" by interacting with the Higgs field of empty space**





What we know about the Higgs

From Theory… the exact Higgs mass is unknown

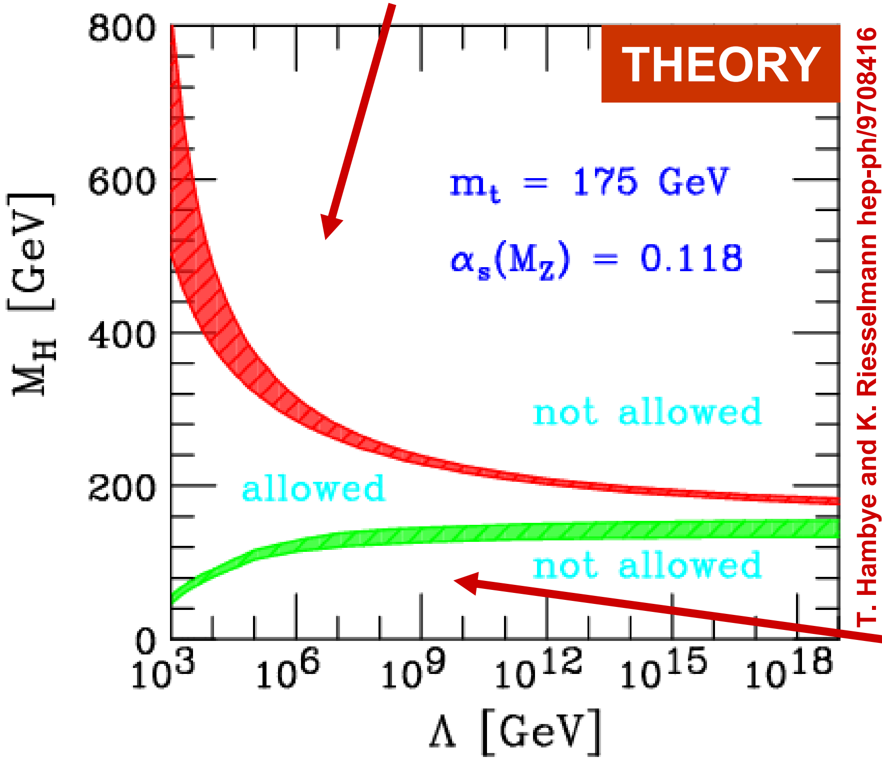
- **If SM is valid up to the Plank Scale ~10^{19} GeV then M_H is in a limited range:**

$$130\ \mathrm{GeV/c^2} \lesssim M_H \lesssim 180\ \mathrm{GeV/c^2}$$

- **If there is new physics ~10^3 GeV:**

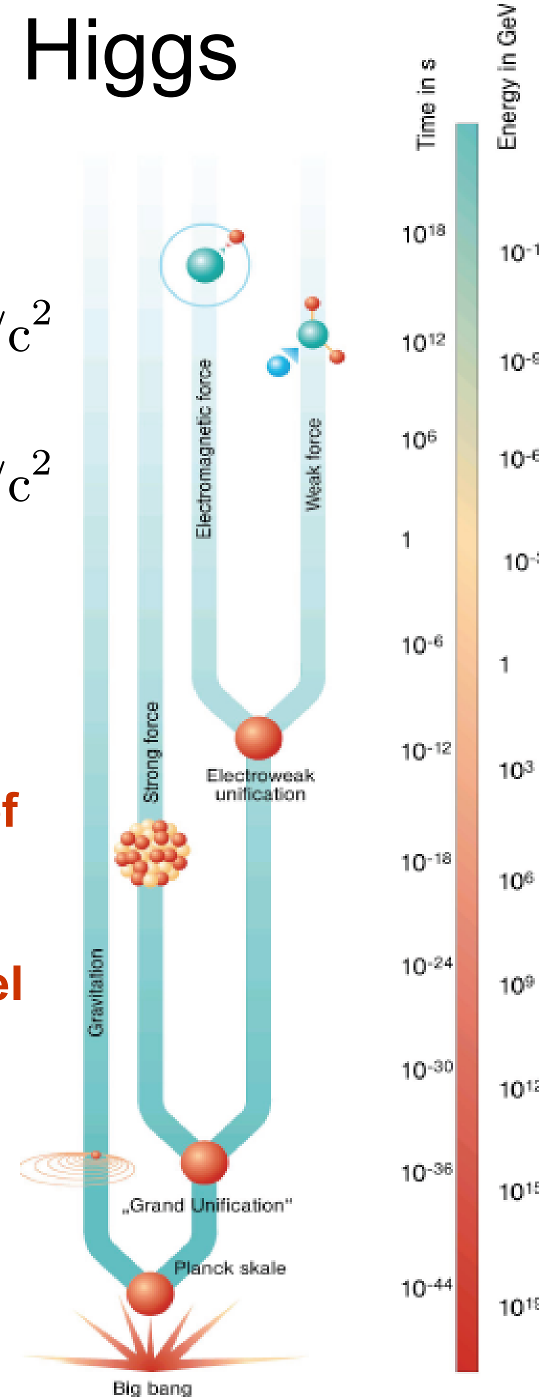
$$50\ \mathrm{GeV/c^2} \lesssim M_H \lesssim 800\ \mathrm{GeV/c^2}$$

SM Higgs Sector no longer meaningful for this Λ



Λ is the scale of new physics beyond the Standard Model

Vacuum stability



What we know about the Higgs

From Experiments of the past…

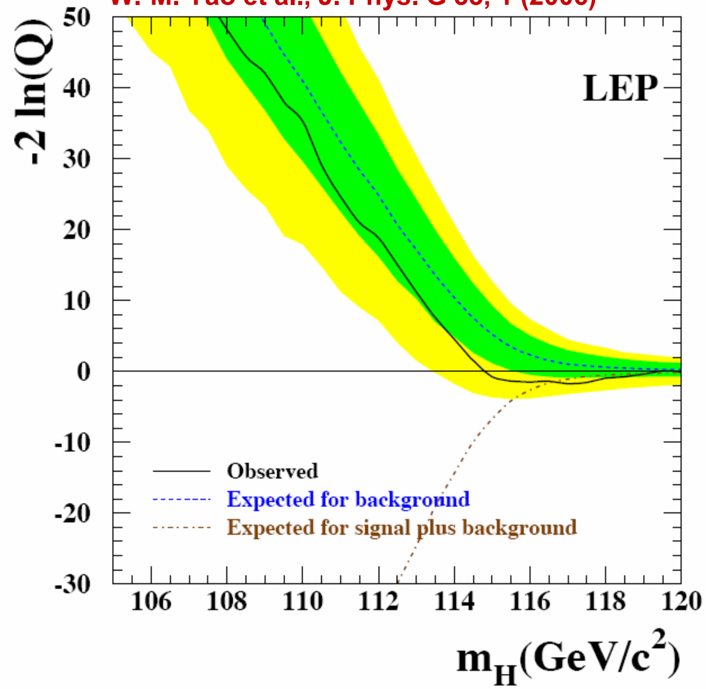
Higgs searches at the Large Electron-Positron Collider (LEP) at CERN

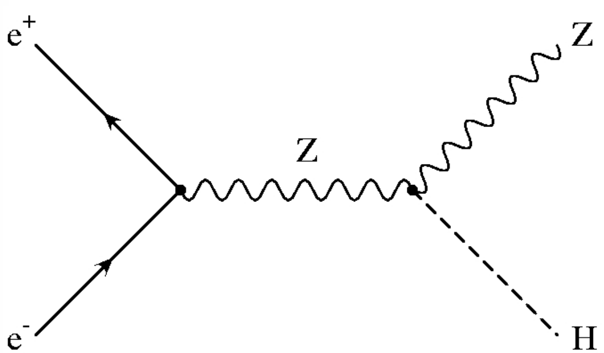
- **Collider ran from 1989 through 2000**
- **In 2000, center-of-mass energy was 200 - 210 GeV**
- **Four detectors: ALEPH, DELPHI, L3 and OPAL**

Present Limit from direct searches at LEP:

$$M_H > 114.4\ \mathrm{GeV/c^2}, \mathrm{CL} = 95\%$$

W.-M. Yao et al., J. Phys. G 33, 1 (2006)





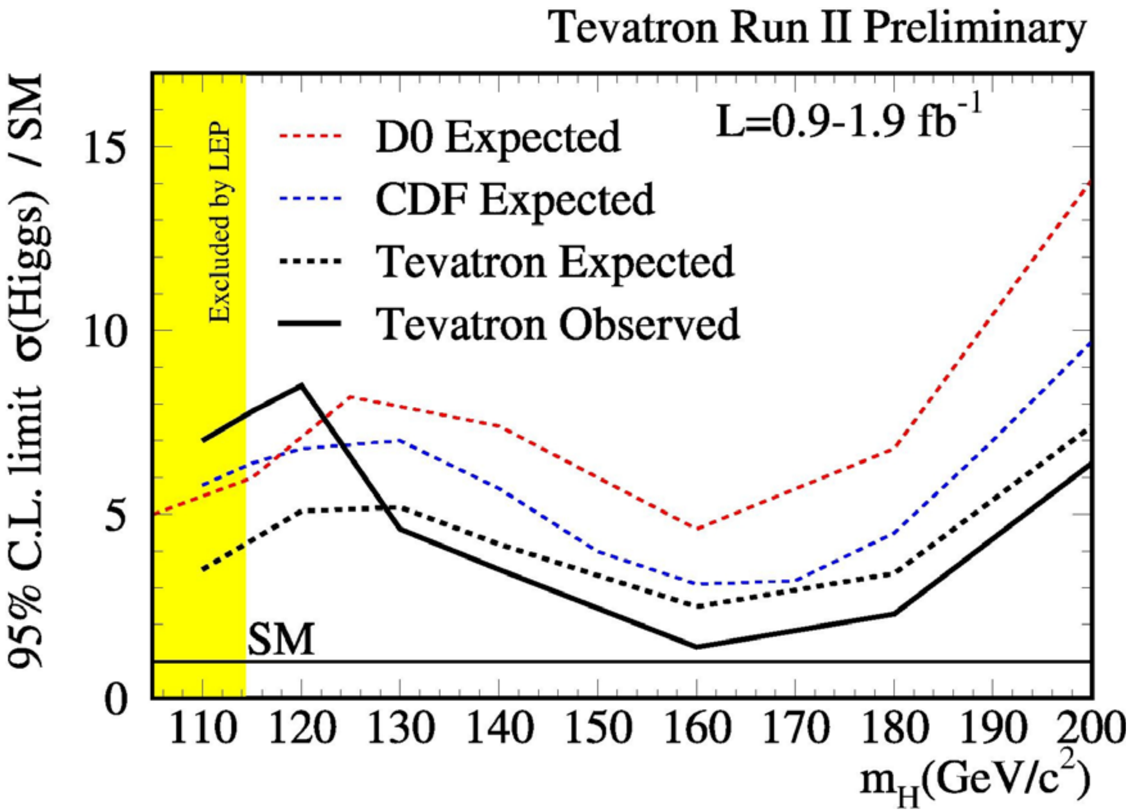
What we know about the Higgs

From Experiments of the present…

Very aggressive searches at the CDF and D-Zero Experiments

- **Proton anti-proton collider near Chicago, USA**
- **Running with a center-of-mass energy of 1.96 TeV**
- **Now looking into roughly 3 fb^{-1} of data, but no sign of the Higgs yet**
- **Running through 2010 is on the table; could provide a total of 8 – 10 fb^{-1}**

Fermilab

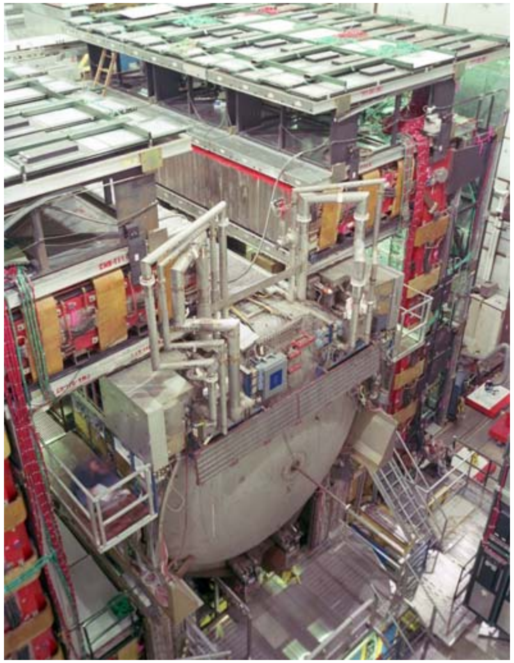


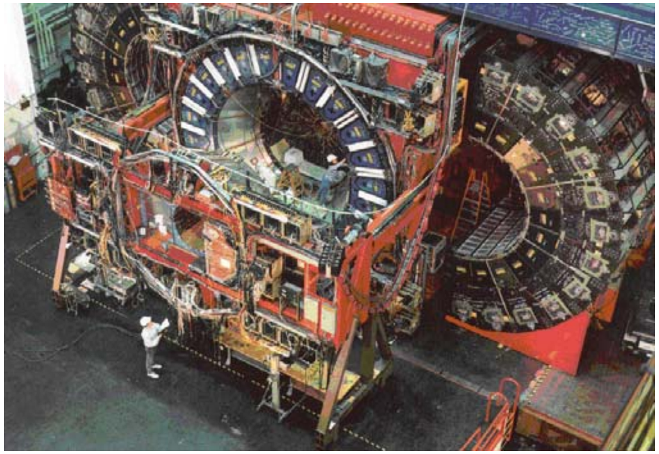
*Note: 1 barn (b) = 10^{-28} m^2

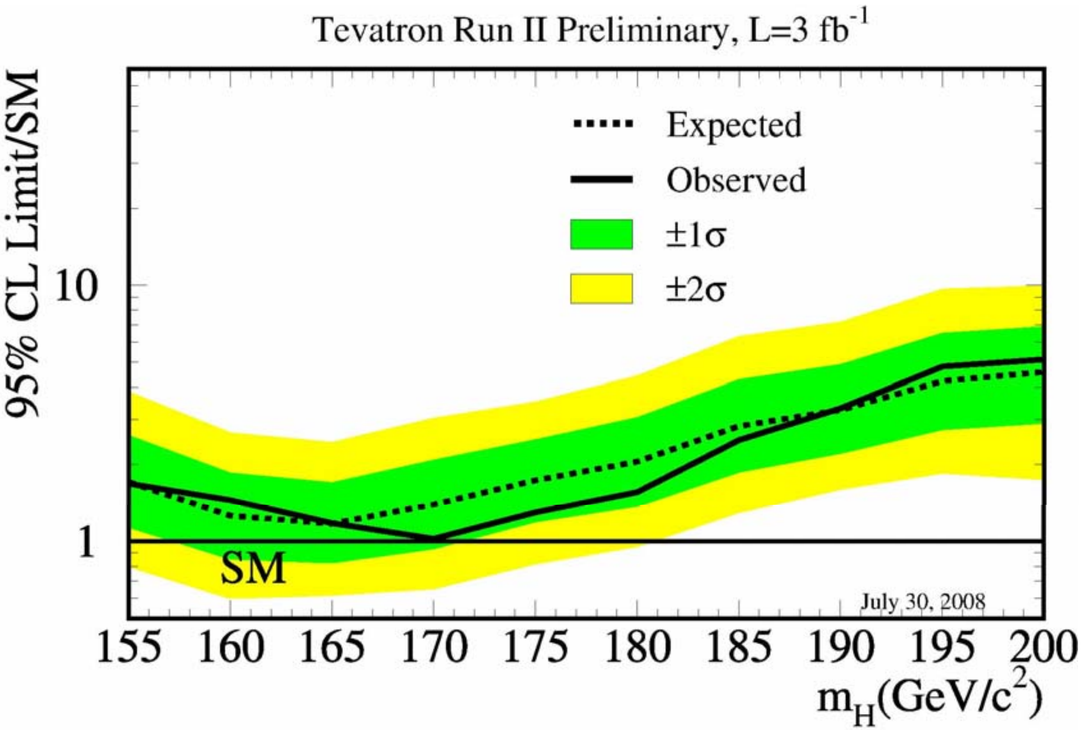
What we know about the Higgs

ICHEP 2008 combined result from CDF and D-Zero [155, 200 GeV]

- **Exclude 170 GeV/c² @ 95% CL**



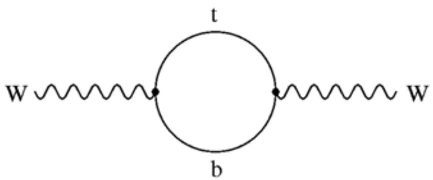




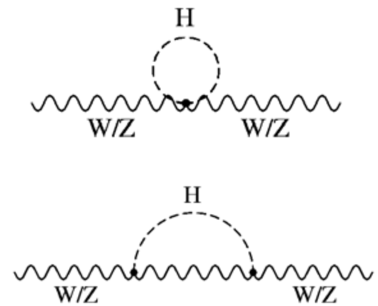
What we know about the Higgs

From other experimental measurements…

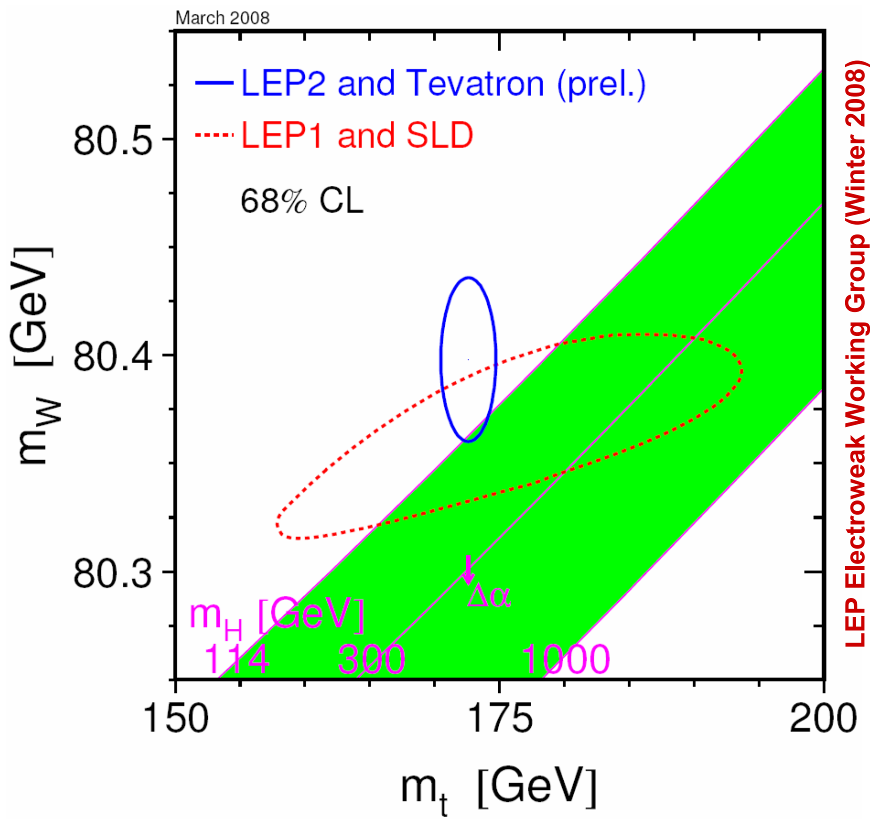
- **Precision Electroweak measurements are indirectly sensitive to the Higgs mass through radiative corrections**



$$\delta_t \propto M_t^2$$



$$\delta_H \propto \ln\left(\frac{M_H}{M_W}\right)$$



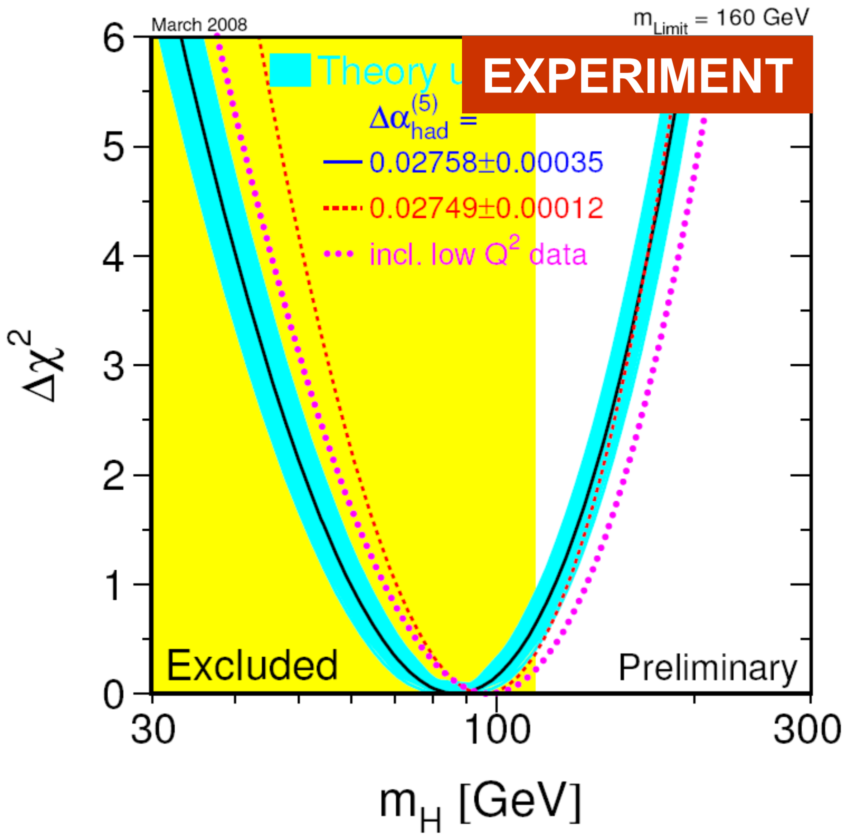
m_W = 80.398 +/- 0.025 GeV

m_t = 172.8 +/- 1.4 GeV

What we know about the Higgs

All experimental data to date favors a light Higgs

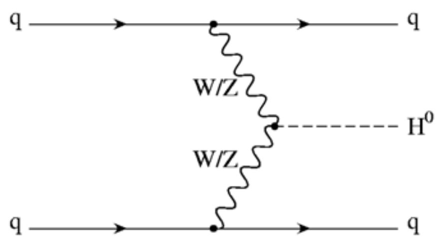
- **SM: $M_H = 87^{+36}_{-27}$ GeV; $M_H < 160$ GeV @ 95% CL**
- **LEP Direct Limit: $M_H > 114.4$ GeV @ 95% CL**



Fit to Electroweak data performed by the LEP Electroweak Working Group (Winter 2008)

Higgs production at the LHC

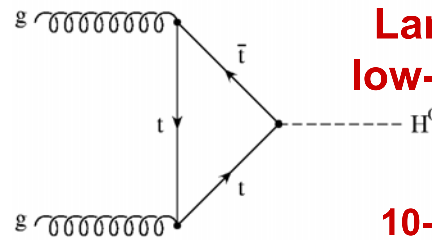
Vector Boson Fusion



The two "spectator" quarks make for a very distinct final state

<10% unc. NLO

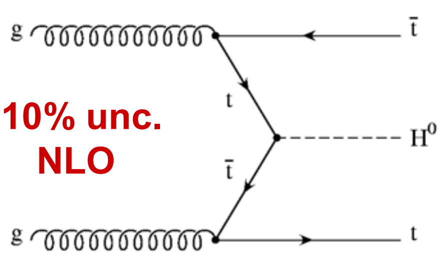
Gluon-gluon Fusion



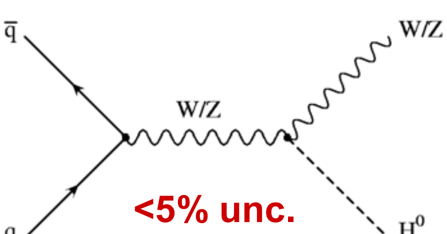
Large backgrounds for low-mass Higgs searches

10-20% unc. NNLO

Associated Production

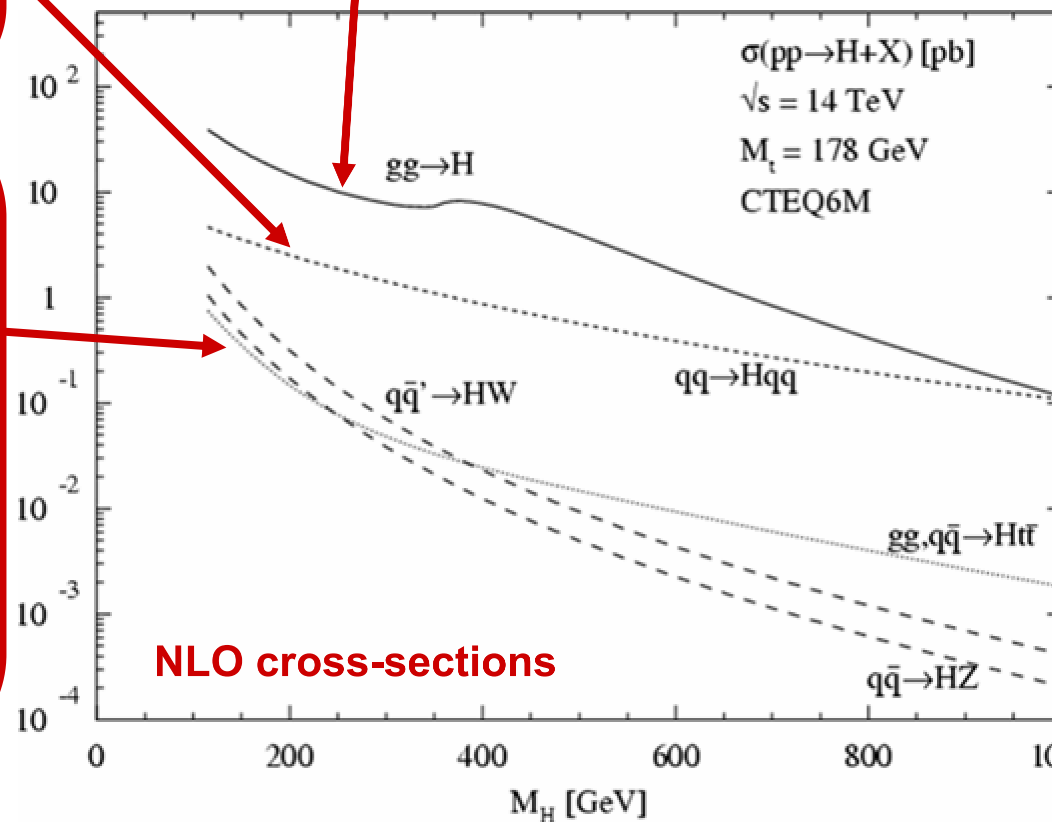


~10% unc. NLO



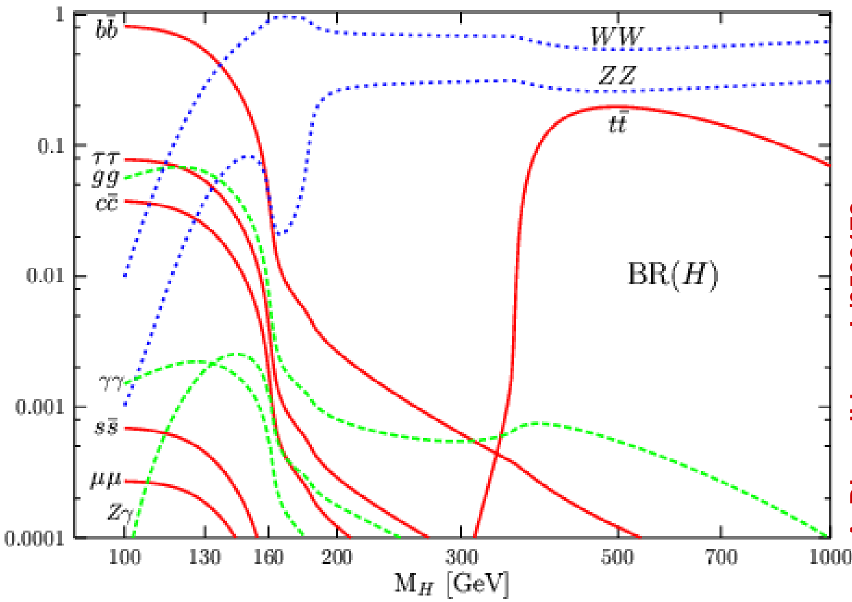
<5% unc. NNLO

Allows for triggering regardless of Higgs decay mode



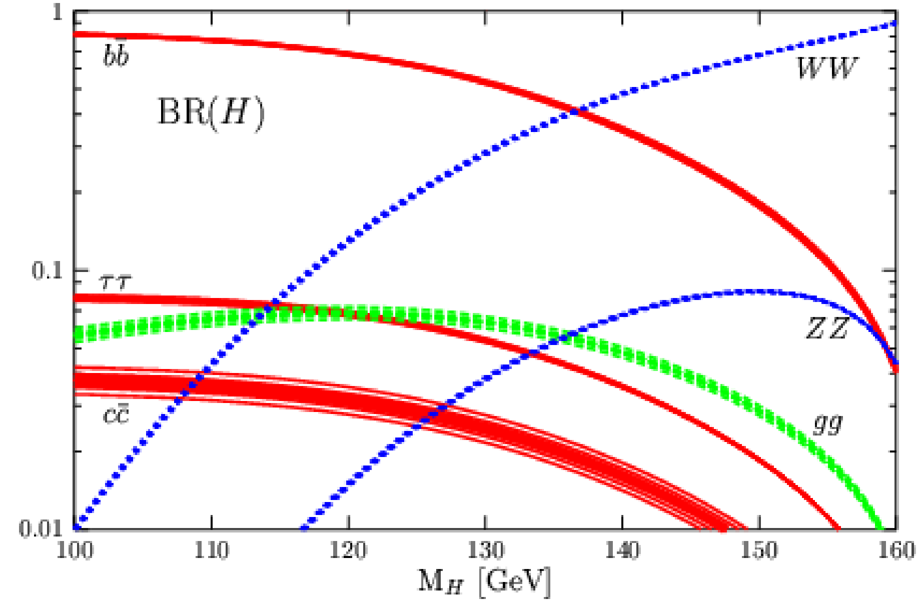
M.Spira, Fortsch. Phys. 46 203-284 (1998)

SM Higgs discovery final states



A. Djouadi hep-ph/0503172

Includes quark mass uncertainties (t, b, c) and $\alpha_s(M_Z)$



At low mass ($M_H < 2M_Z$)

- Dominant decay through bb; enormous QCD background, suppressed in ttH
- $H\rightarrow\tau\tau$ accessible through Vector Boson Fusion (VBF)
- $H\rightarrow WW^{(*)}$ accessible through gluon-gluon fusion and VBF
- $H\rightarrow\gamma\gamma$ has a low BR (decays through top and W loops); but due to excellent γ/jet separation and γ resolution is still very significant
- $H \rightarrow ZZ^* \rightarrow 4l$ also accessible

For higher masses

- $H\rightarrow WW$ and $H\rightarrow ZZ\rightarrow 4l$ final-states

Forward Jet Tagging and the Central Jet Veto

We can get the upper-hand in the VBF channels

Forward Jet Tagging

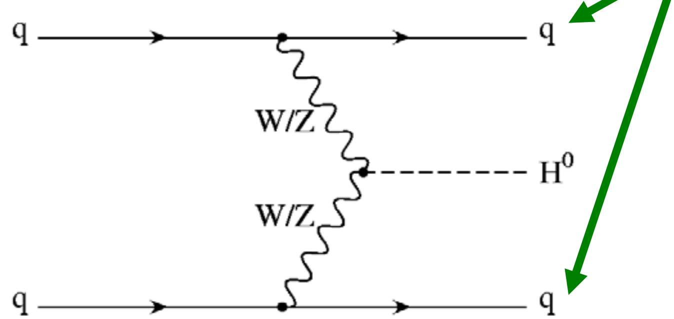
- **D. Rainwater, D. Zeppenfeld, et al.**

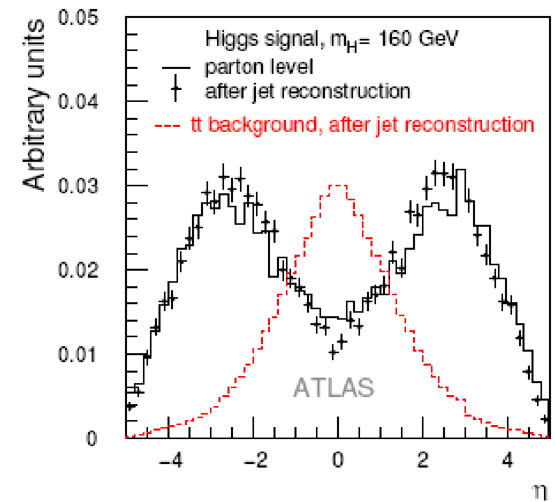
$$\eta_{j1} \cdot \eta_{j2} < 0$$

$$|\Delta\eta_{jj}| > 3.5 - 4$$

$$m_{jj} > 500 - 700 \text{ GeV}$$

Tagging Jets



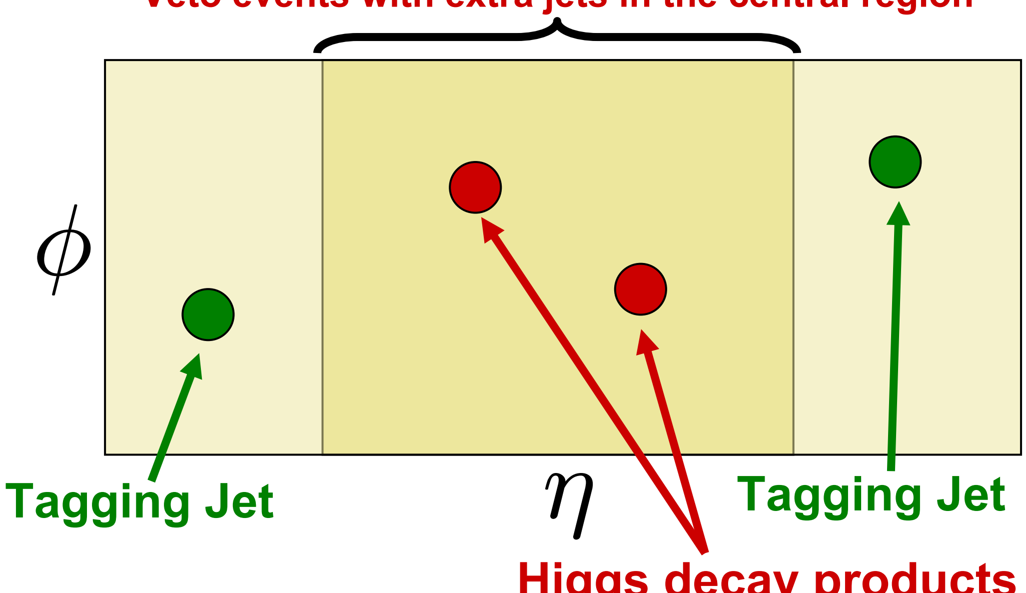


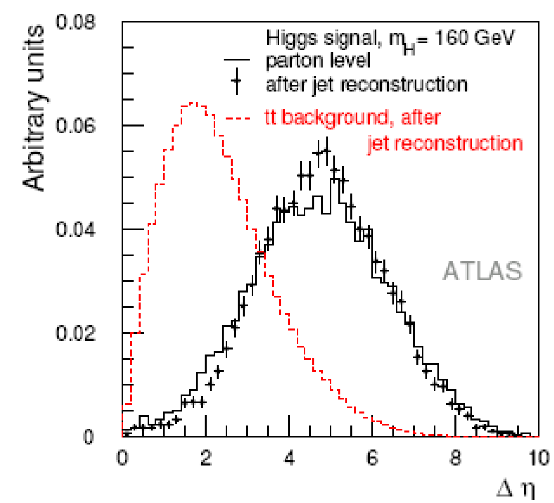
S. Asai et al., ATL-PHYS-2003-005

Central Jet Veto

- **V.Barger, K.Cheung and T.Han in PRD 42 3052 (1990)**

Veto events with extra jets in the central region





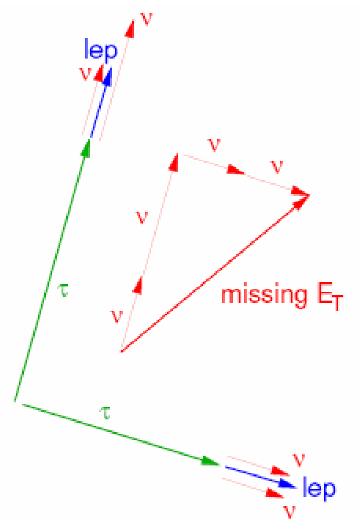
VBF H → ττ

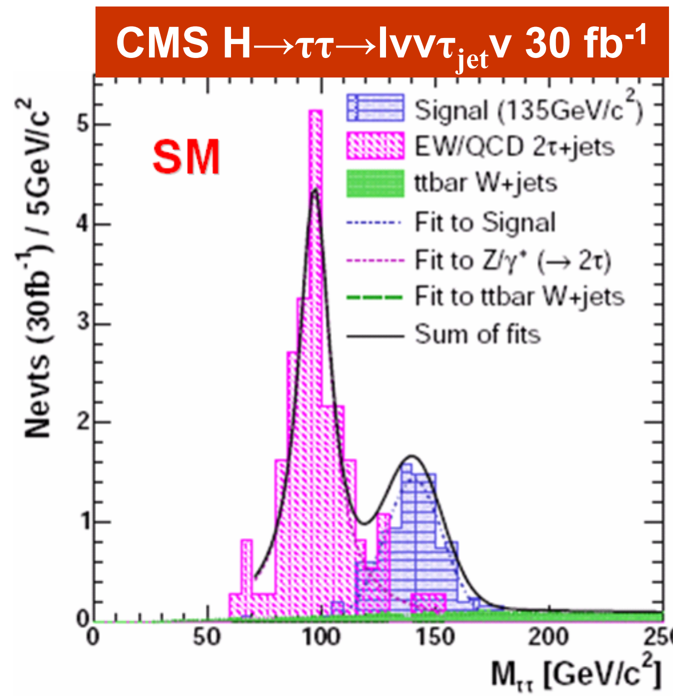
A very significant channel for low masses

- Important for studying the coupling of Higgs to leptons
- Three final states lepton-lepton, lepton-hadron, hadron-hadron
- Triggers for the fully hadronic mode are under investigation

Mass reconstruction via the collinear approximation

- Approximation breaks down when the two taus are back-to-back
- Mass resolution limited by missing transverse energy (~8 – 10 GeV)





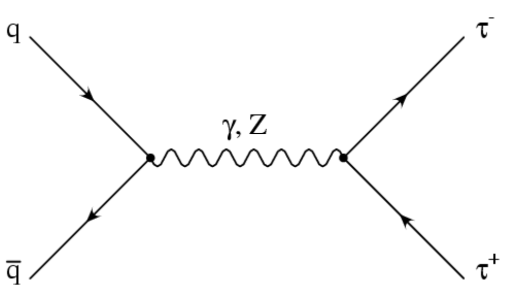
Experimental issues:

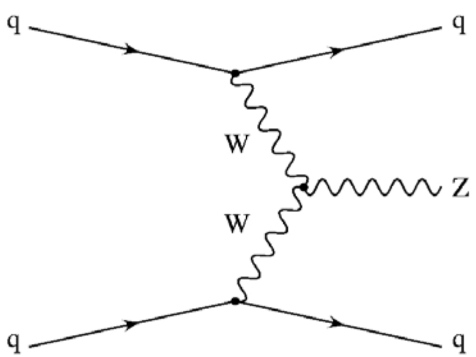
- Tau tagging (Likelihood, Neural Net methods)
- Z+jets background (especially for low masses)
- tt rejection (b-jet ID and veto for lepton-lepton)

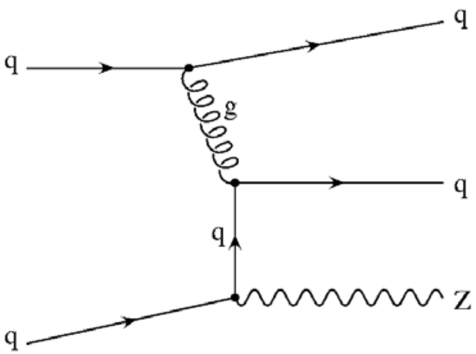
VBF H → ττ

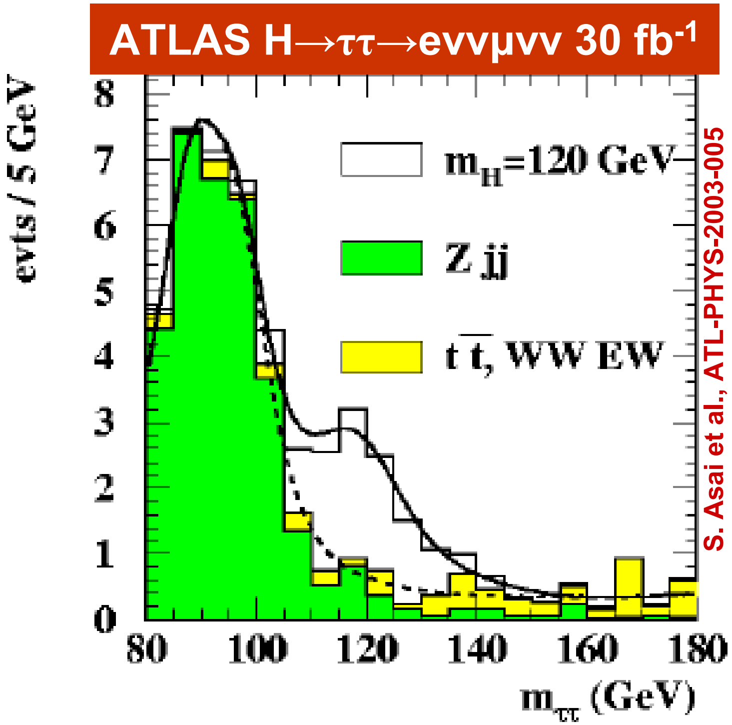
Data-driven control samples are being explored for many backgrounds

- **The relative contributions from different jet multiplicities are not known**
- **Unknowns related to critical analysis cut-specific variables exist**







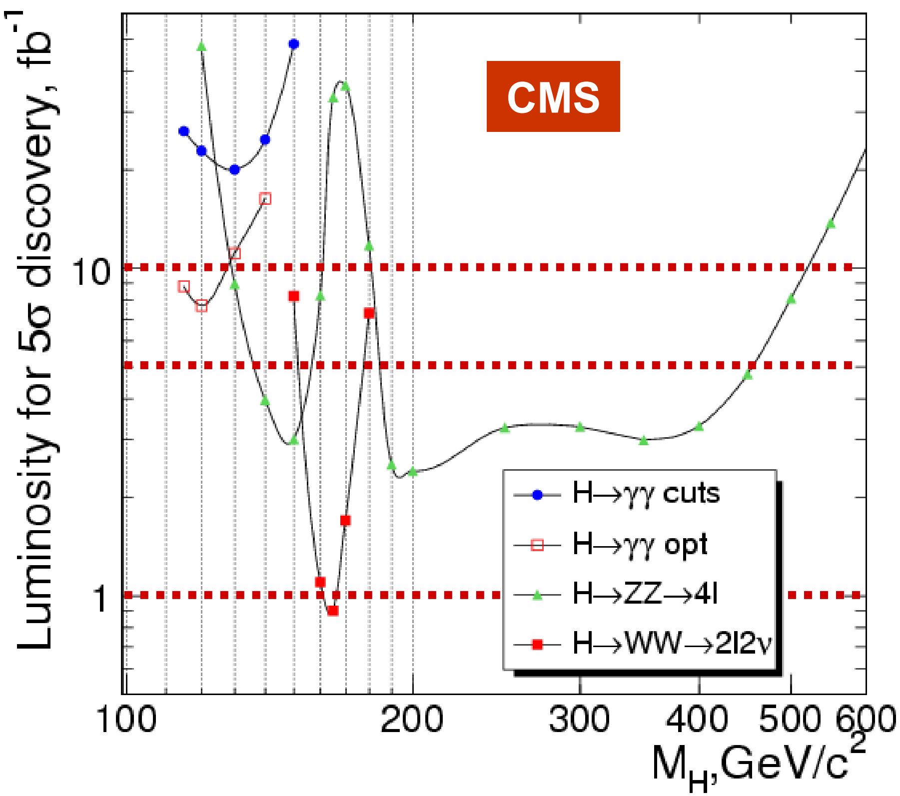


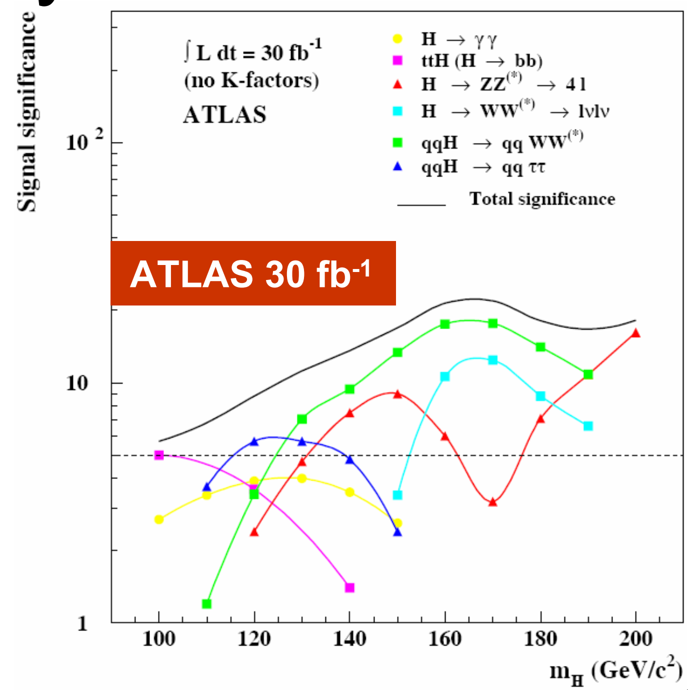
For the dominant background, collect Z→μμ and Z→ee events from data and use TAUOLA to decay the leptons to taus

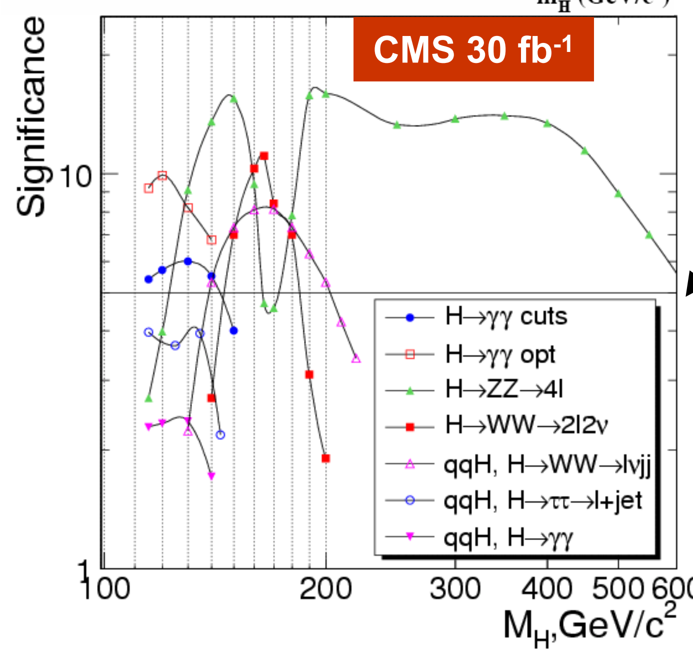
In this way we can emulate each of the lepton-lepton, lepton-hadron and hadron-hadron final states

Obtain both the background shape and normalization from data

SM Higgs Discovery Potential







Luminosity for SM Higgs discovery or exclusion

- **~few 100 pb^{-1}, some exclusion @ 95% CL**
- **~1 fb^{-1}, 5σ discovery if M_H ~160 - 170 GeV**
- **~10 fb^{-1}, discovery over a broad mass range**

Tau Specific

Hadronic Tau Selection

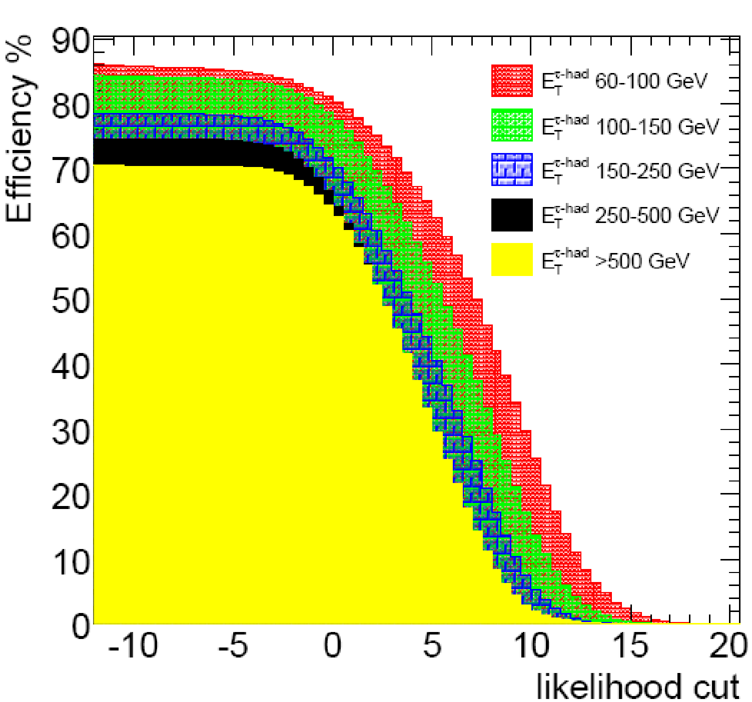
Zofia has already given a number of talks on high-pT tau selection:

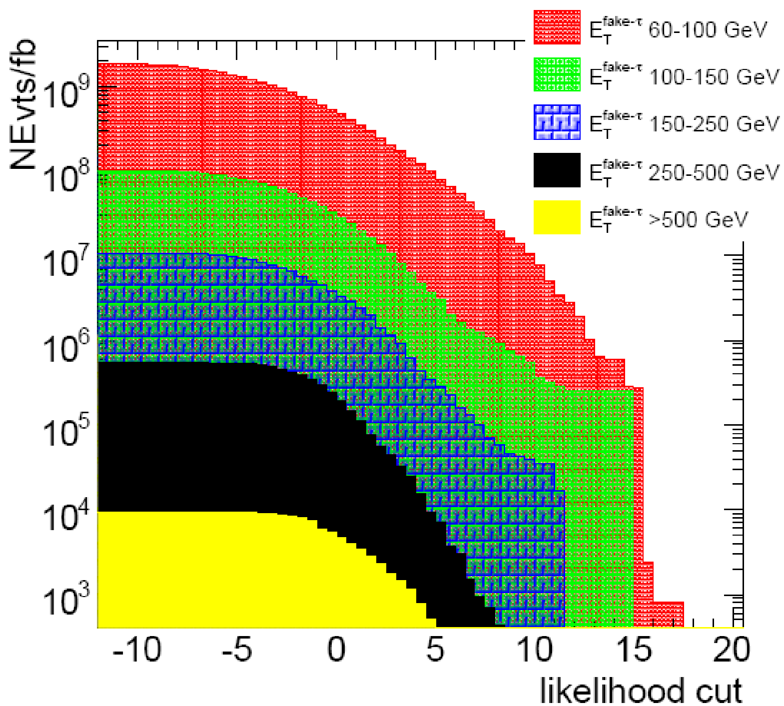
http://indico.cern.ch/getFile.py/access?contribId=1&resId=1&materialId=slides&confId=18959

http://indico.cern.ch/getFile.py/access?contribId=3&resId=0&materialId=slides&confId=17392

Her studies have sculpted the hadronic tau selection criteria for Z'

- **e.g., cut on the tau likelihood as a function of the tau ET (see next few slides)**





Efficiency	35-70	70-140	140-280	280-560	560-1120	1120-2240
$E_T > 60$ GeV	8.06±0.05	80.18±0.07	99.30±0.01	99.97±0.00	100.00±0.00	100.00±0.00
$+N_{trk}1,3$	1.48±0.02	13.09±0.06	10.84±0.05	8.13±0.04	6.88±0.04	6.08±0.06
$+ \lvert charge \rvert = 1$	1.39±0.02	12.19±0.05	10.12±0.05	7.58±0.04	6.40±0.04	5.64±0.06
$+llh$ cut	0.05±0.00	0.27±0.01	0.44±0.01	0.69±0.01	0.91±0.01	0.69±0.02
N Events for 1 fb^{-1}	$4{\cdot}10^7$	$4{\cdot}10^6$	$1{\cdot}10^6$	$9{\cdot}10^5$	$3{\cdot}10^3$	40

Tau ID in ATLAS

- **two algorithms:** calorimetry-based (*tauRec*) and track-based (*tau1p3p*)
- **Calorimetry:** collimated energy deposition, π^0s produced, isolation region, EM radius, EM fraction
- **Tracking:** low track multiplicity, isolation region, positive impact parameter, invariant mass and width of track system (3-prong)
- **Highlights from Data Preparation Perspective:**
  - τ-specific calibrations need to be understood
  - tracking objects associated with calo objects: good sensitivity to detector performance

Tau ID in ATLAS

Track based approach

identify "good quality" hadronic track, $p_T > 9$ GeV,
find nearby "good quality" tracks with $p_T > 2$ GeV in $\Delta R<0.2$

τ_{1P}

no nearby-track
(ϕ,η) from track at vertex

build E_T^{eflow}, use $\Delta R < 0.2$

build discrimination variables
use $\Delta R < 0.2$ as a "core",
$0.2 < \Delta R < 0.4$ for isolation only

τ_{1P} - single-prong candidates

τ_{3P}

2 nearby tracks
(ϕ,η) from bary centre of tracks
Σcharge = +-1

build E_T^{eflow}, use $\Delta R < 0.2$

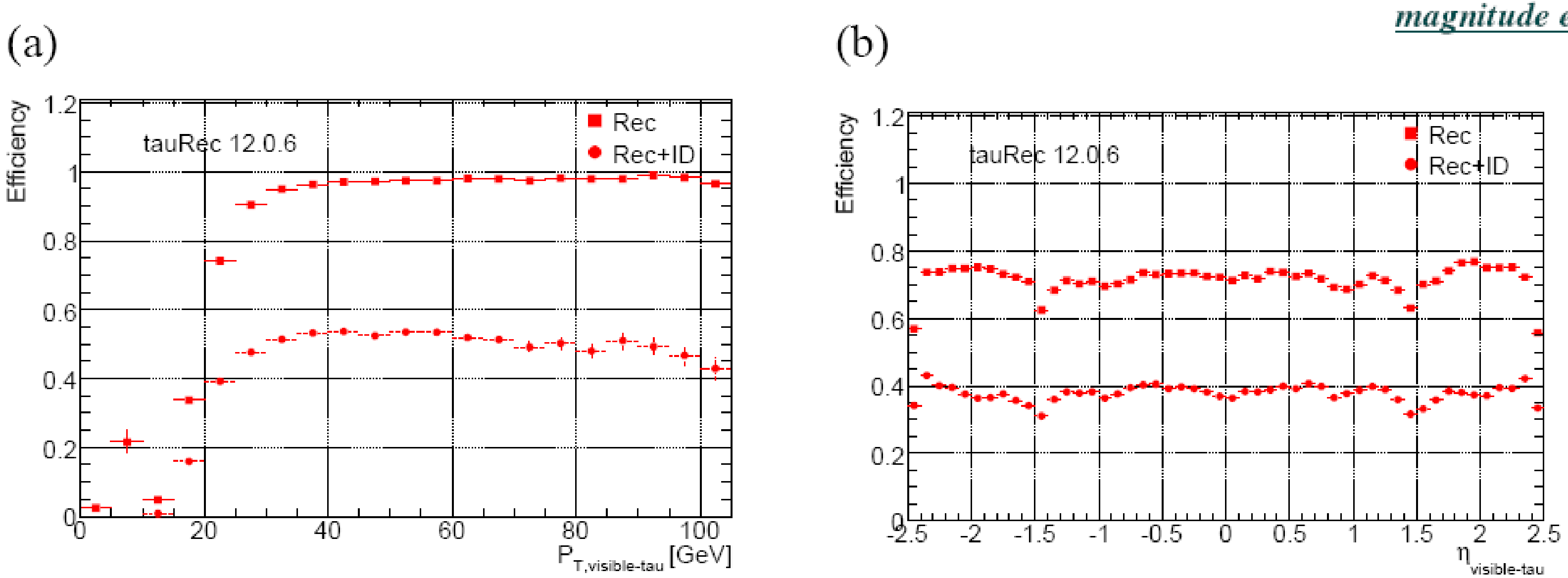
build discrimination variables
use $\Delta R < 0.2$ as a "core",
$0.2 < \Delta R < 0.4$ for isolation only

τ_{3P} - three-prong candidates

Tau Efficiency

faking tau	**estimated** FR
electrons	~2%
muons	~0.5%
jets	~0.1%

FR depends on event activity and tau ID requirements, so this table just gives a rough order of magnitude estimate



Efficiency of reconstruction and rec/id with *tauRec* as a function of (a) Pt and (b) η in *Z* sample.

Tau Identification and QCD rejection (2)

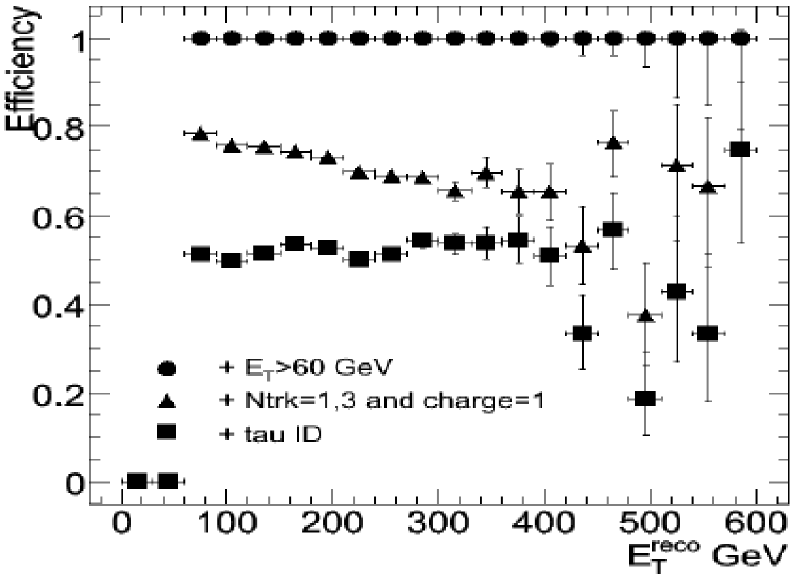
To Identify taus:

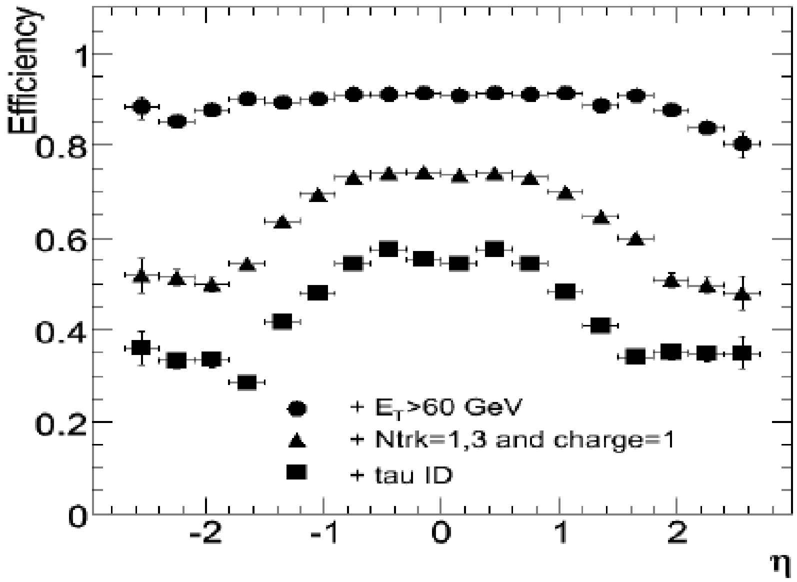
- Overlap removal: remove muons and tight electrons if within R=0.2
- Require N_{trk}==1,3 and charge=1
- Cut on llh variable as a function of E_T:

llh>6 (E_T<100); llh>4 (100<E_T<150); llh >2 (150<E_T<250); llh>0 (E_T>250)

- Tau Pt>60 GeV

Cut	Efficiency %
E_T >60 GeV	89.1 %
+N $_{trk}$ + |charge|=1	65.5 %
+ llh cut	46.6 %





Tau energy resolution

Resolution extracted from gaussian fit in 2 sigma to $E_T^{calib}/E_t^{vis,true}$

H1 style calibrated taus:

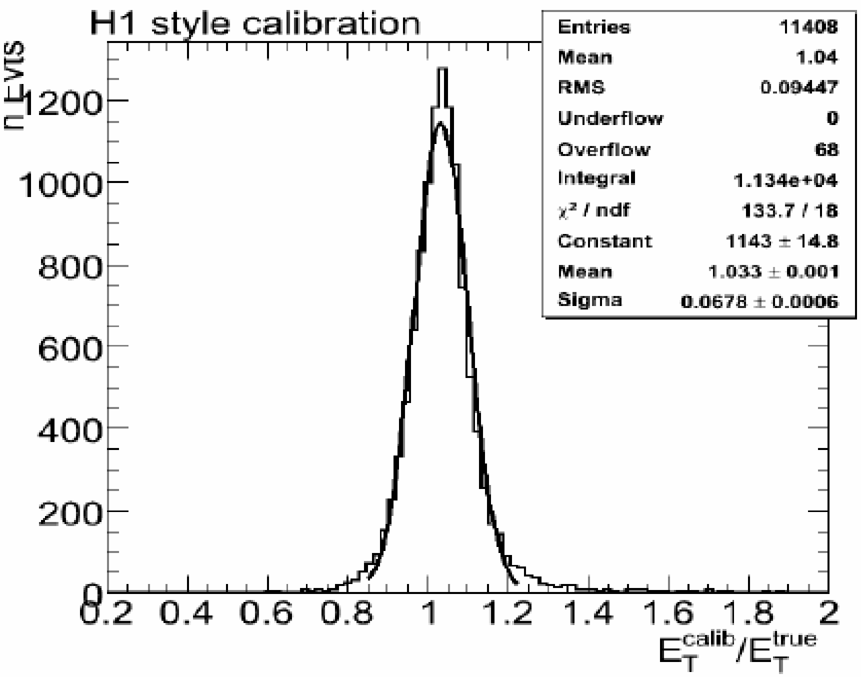
Resolution: 6.78 %;

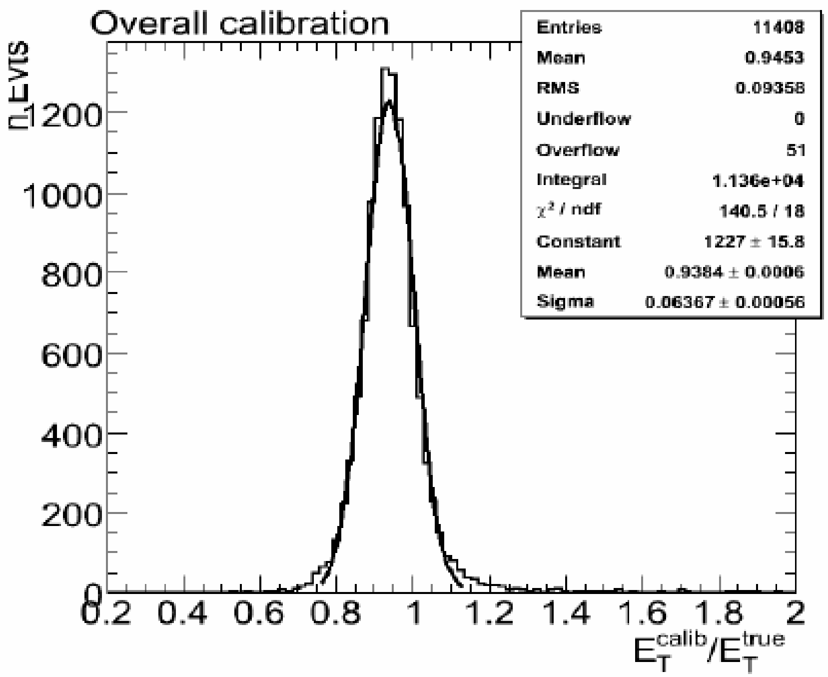
Relative resolution (mean/sigma)= 6.56%

Overall calibrated taus:

Resolution: 6.36 %;

Relative resolution (mean/sigma)= 6.78%





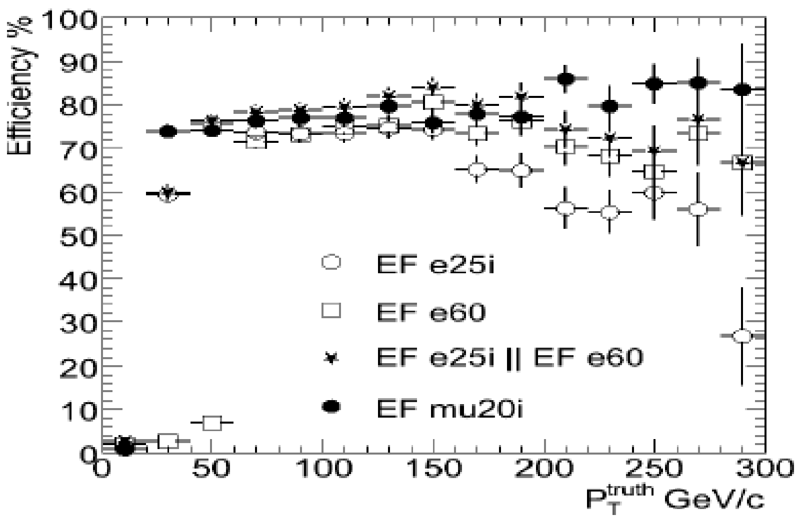
Trigger for ll and lh channels

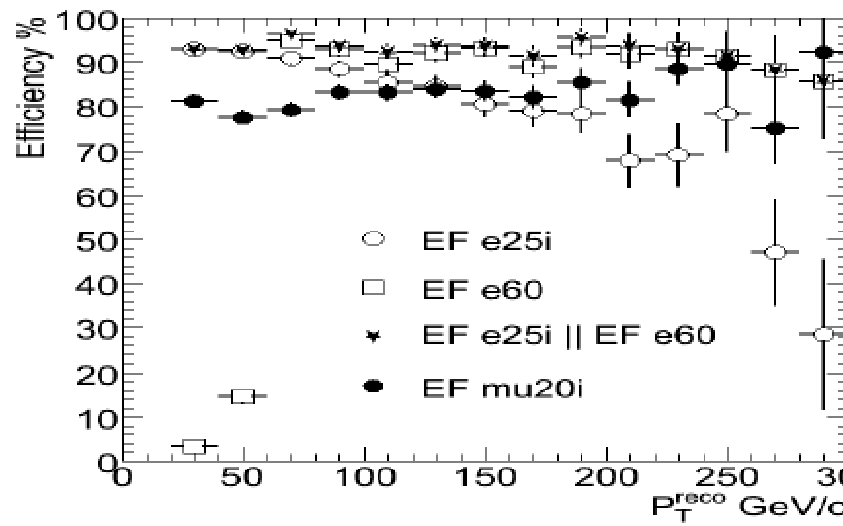
Non optimal, looking forward to samples with Release 13 to study tau+e and tau+μ menu items

- **Electron trigger: e25i || e60**
  - Used for eh, ee, and eμ final states
  - At high P_T e25i non optimal due to isolation-> use combination of e25i || e60
- **Muon trigger : mu20**
  - Used for μh, $\mu\mu$, μe final states

Trigger menu	e25i	e60	e25i || e60	mu20
		$e\tau_h$		$\mu\tau_h$
Efficiency wrt to truth	70.5%	73.4%	77.1%	75.5%
Efficiency wrt offline	85.8%	92.1%	93.4%	80.6 %
		ee		$\mu\mu$
Efficiency wrt to truth	83.5%	78.9%	87.3%	87.6%
Efficiency wrt offline	91.8%	94.2%	95.5%	90.3%
		$e\mu$		$e\mu$
Efficiency wrt to truth	67.4%	70.1%	73.0%	73.7%
Efficiency wrt offline	84.5%	91.2%	92.4%	79.6%

- Trigger studies performed using trigger decision after EF, efficiency shown wrt to highet Pt lepton



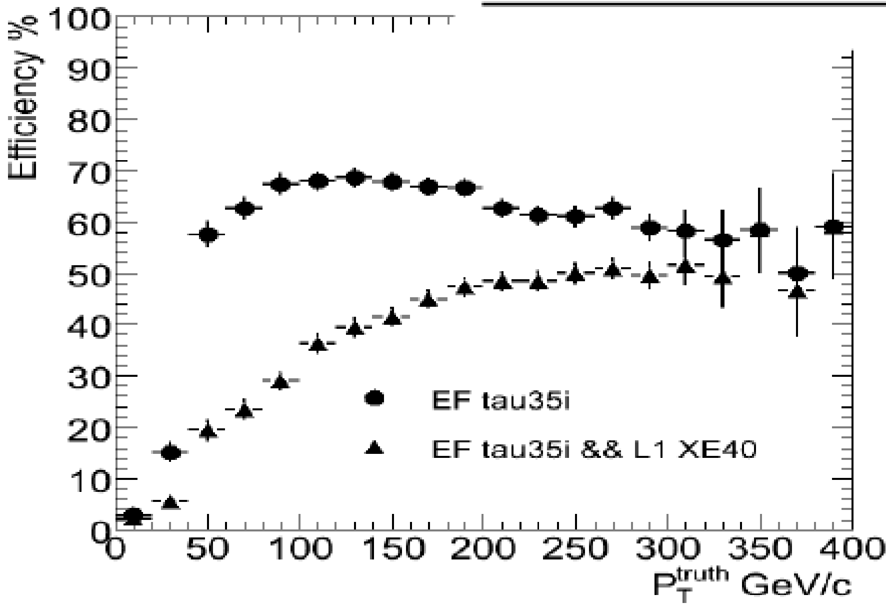


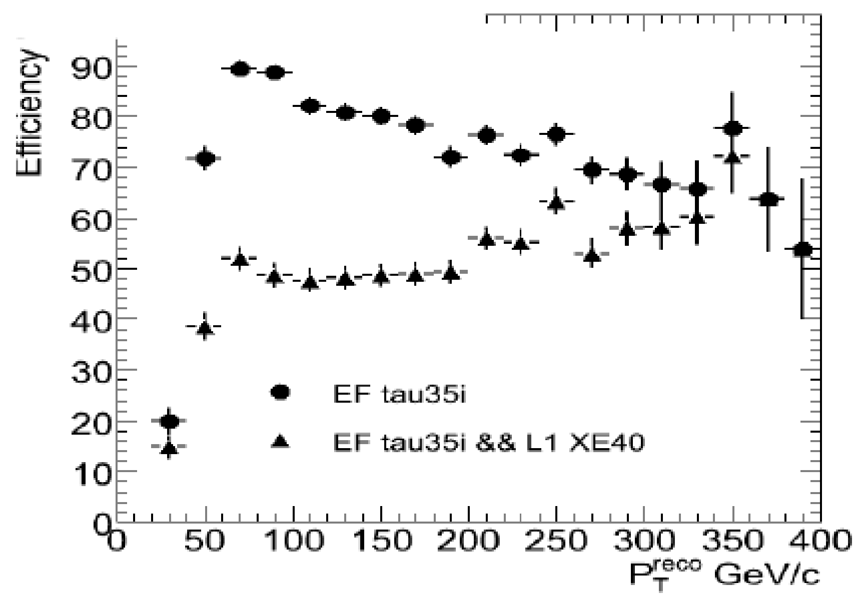
Trigger for hh channel

Non optimal, looking forward to samples with Release 13 to study tau60, tau100

- Use tau35i+XE40 to trigger events with hh final state.
- Total rate of such item is 4Hz, predicted unprescaled at 10^{32} lumi.
  See Marc-Andre Dufour's talk on Trigger Open meeting (Menus), the 17 of Jan
- http://indico.cern.ch/getFile.py/access?contribId=1&resId=0&materialId=slides&confId=24859
- Trigger studies performed using trigger decision after EF, efficiency shown wrt to highet Pt hadronic tau.

Trigger menu	tau35i	tau35i + XE40
Efficiency wrt to truth	63.6 %	41.4%
Efficiency wrt offline	77.0%	51.1 %





Tau Polarization

We can distinguish between left- and right-handed taus on a statistical basis

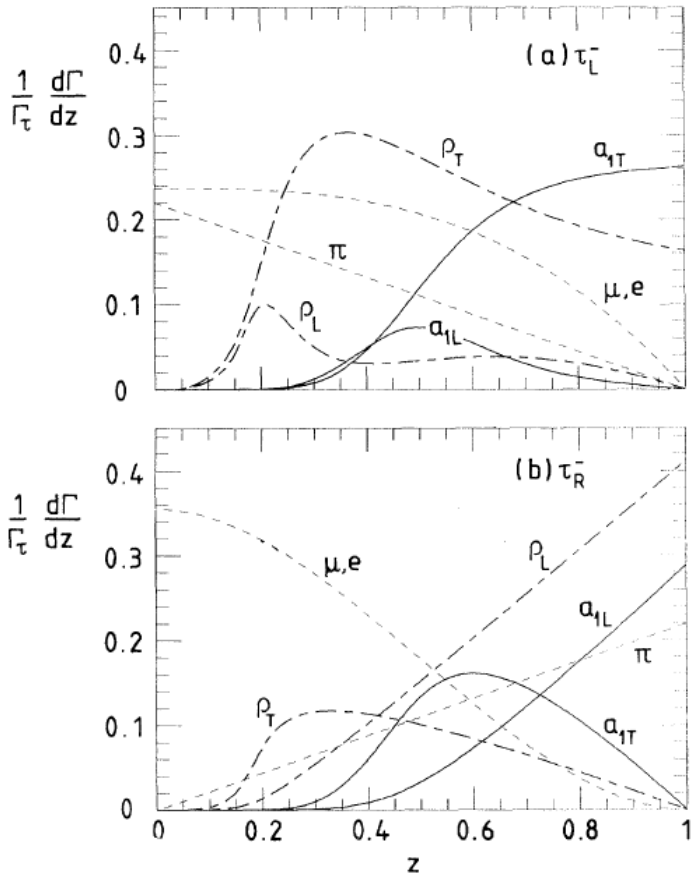


FIG. 1. The fractional energy distributions of particle A^- arising from (a) left-handed and (b) right-handed τ^- decays, i.e., $\tau^- \to A^- +$ missing energy where $z = E_A/E_\tau$, and where it is assumed that $E_\tau \gg m_\tau$. The T,L subscripts refer to transversely, longitudinally polarized vector mesons. The effects of the finite widths of the ρ and a_1 are included. Distributions (a) and (b) characterize W^- and H^- decays, respectively.

Plots of the fractional energy distributions are taken from:

B.K. Bullock, K. Hagiwara and A.D. Martin, Phys. Rev. Lett. **67**, 3055 (1991)

Z' Specific

Systematics

"Official" CSC systematic sources were considered:

Source	Relative uncertainty	Z' Mass 600 GeV	800 GeV	1000 GeV	2000 GeV
Electron Energy Scale	$\pm 0.5\%$	0.4	0.4	0.3	0.1 %
Electron Energy Resolution	$\sigma(E_T) \oplus 0.012 E_T$	0.3	0.2	0.2	0.2 %
Electron ID Efficiency	$\pm 1\%$	0.4	0.4	0.4	0.3 %
Muon Energy Scale	$\pm 1\%$	0.2	0.2	0.1	0.1 %
Muon Energy Resolution	$\sigma(p_T) \oplus 0.011 p_T \oplus 1.710^{-4} p_T^2$	0.4	0.2	0.1	0.0 %
Muon ID Efficiency	$\pm 5\%$	1.8	1.8	1.8	1.6 %
Tau Energy Scale	$\pm 5\%$	10.1	6.0	5.0	3.0 %
Tau Energy Resolution	$\sigma(E) \oplus 0.45\sqrt{E}$	0.8	0.2	0.1	0.1 %
Tau ID Efficiency	$\pm 5\%$	6.4	6.5	6.5	7.0 %
Jet Energy Scale	$\pm 7\%$	1.2	1.0	1.1	1.2 %
Jet Energy Resolution	$\sigma(E) \oplus 0.45\sqrt{E}$	0.3	0.4	0.5	0.3 %
Total		12.2	9.1	8.5	7.8 %

Unc

A conservative sum in quadrature gives a total of ~20%

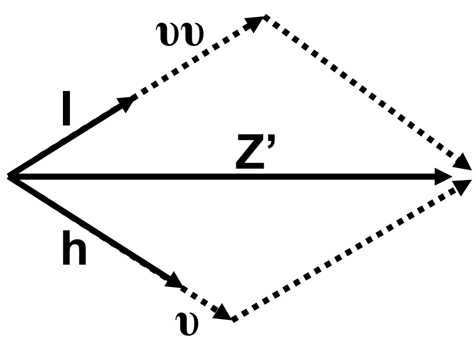
Large systematics for backgrounds due to poor MC statistics

- **Assume systematics on background will be the same as the signal (~20%)**

Mass Reconstruction

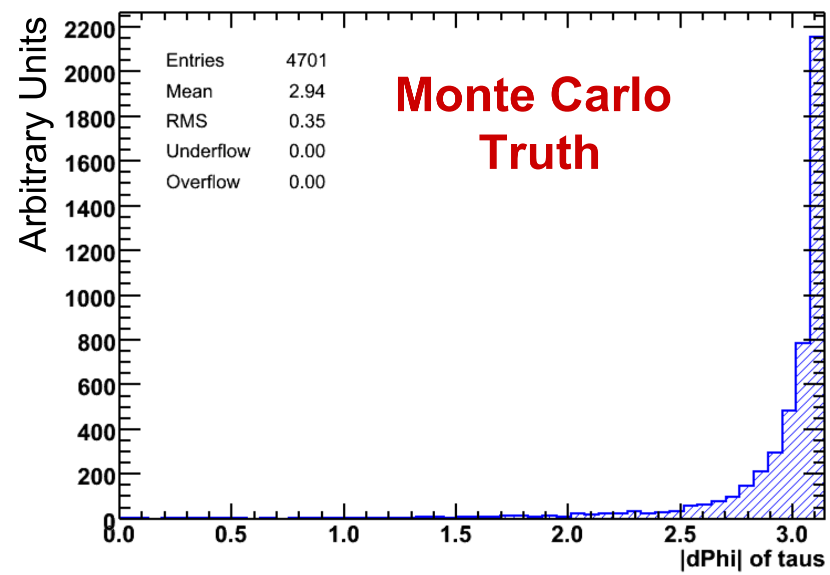
Full di-tau mass reconstruction is possible

- Use the collinear approximation when the parent particle is heavily boosted
- Approximation breaks down when the decay daughters are back-to-back
  - A heavy Z' is more or less generated at rest in the lab-frame
  - Two taus are most often quite nearly back-to-back
  - Could consider cutting on high $\Delta\phi_{lh}$, but high $\Delta\phi_{lh}$ helps to reject background
- A large statistics sample will be important for any asymmetry measurement



$$p_{T,\tau 1} + p_{T,\tau 2} = \frac{p_{T,1}}{x_1} + \frac{p_{T,2}}{x_2}$$
$$= p_{T,1} + p_{T,2} + p_{T,\mathrm{miss}}$$

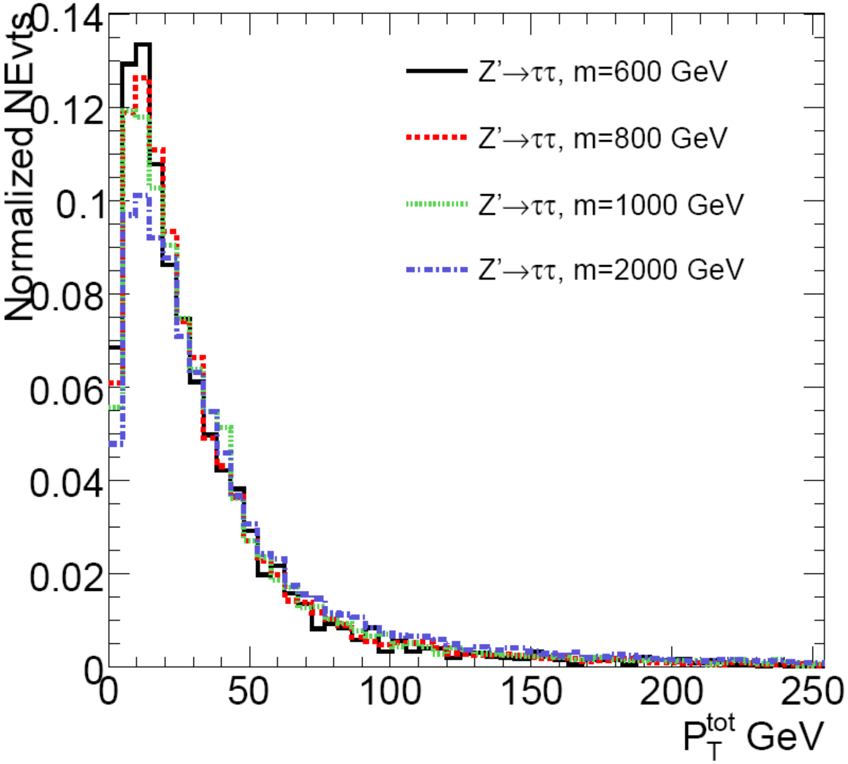
$$m_{\tau\tau}^2 = (p_{\tau 1} + p_{\tau 2})^2 = \frac{2 p_1 \cdot p_2}{x_1 x_2} + 2 m_\tau^2$$
$$\approx \frac{2 p_1 \cdot p_2}{x_1 x_2}$$

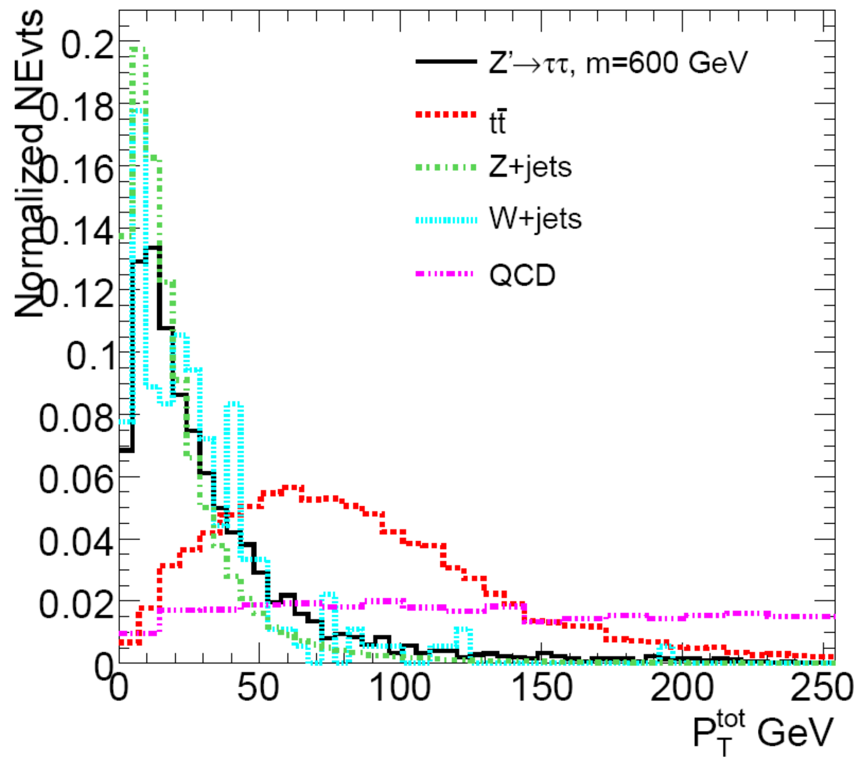


Event pT Total

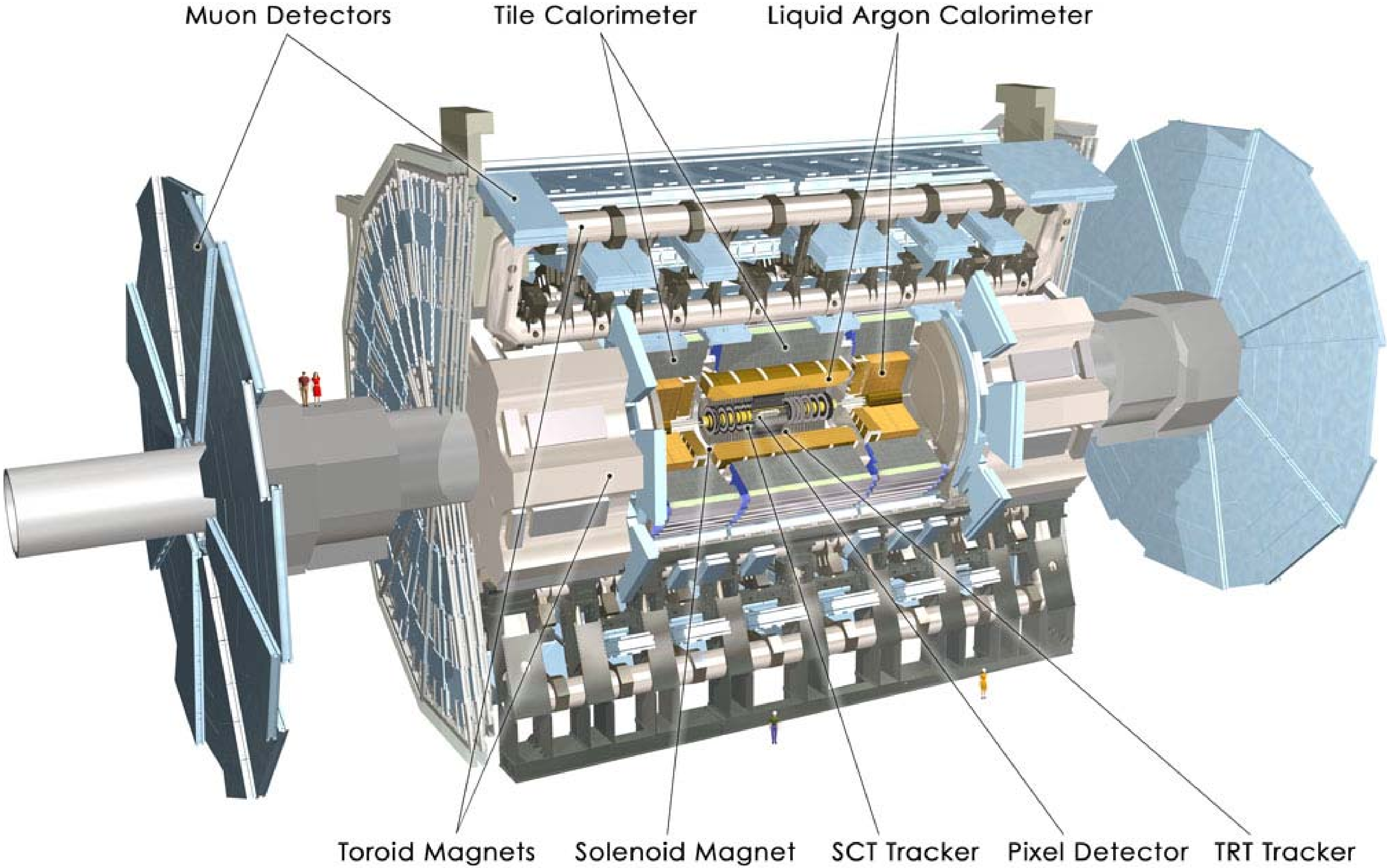
Another cut that we use is the total pT of the event

- **Use the hadronic tau, lepton, MET and leading-jet**

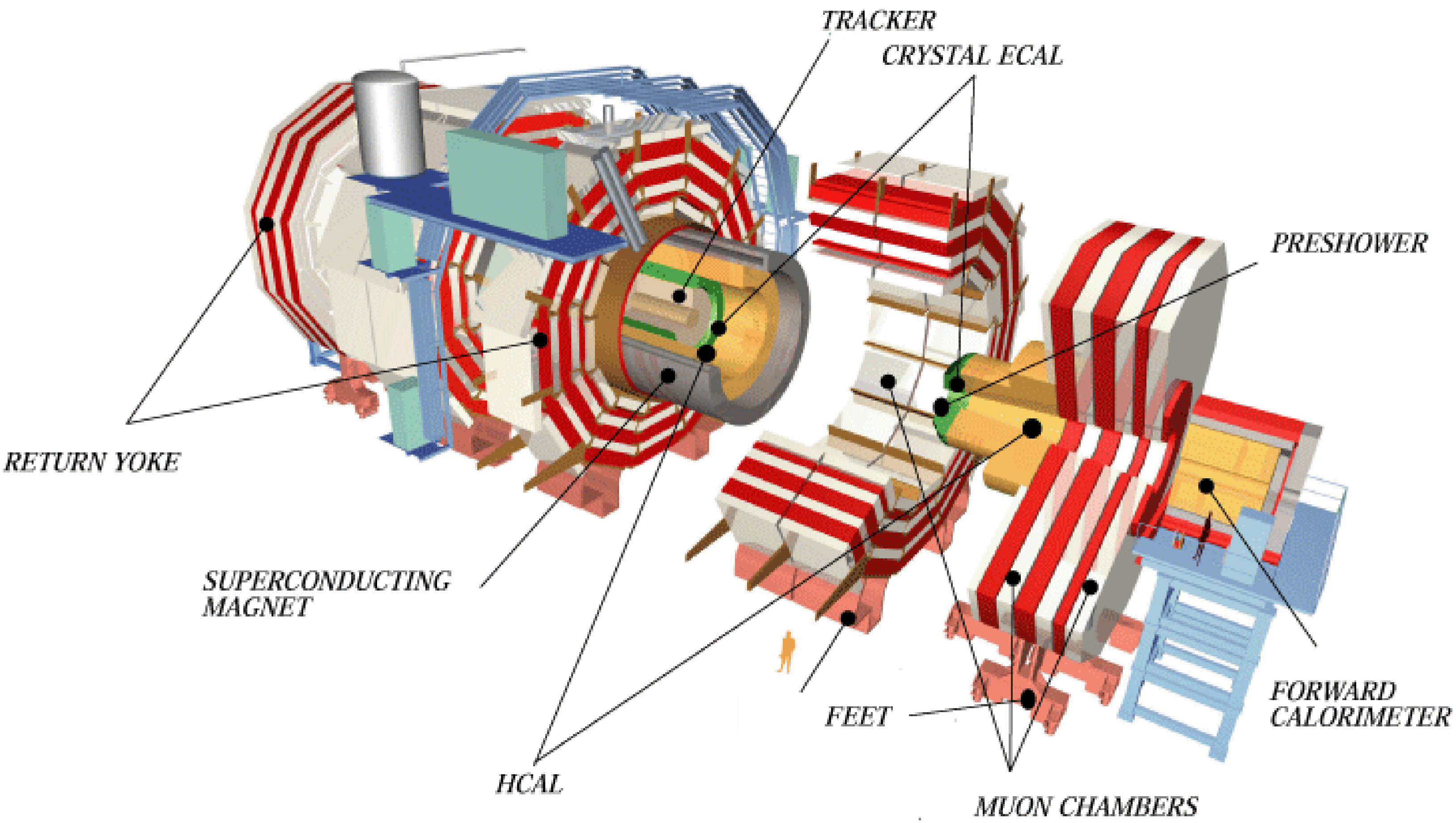




The ATLAS Experiment



The CMS Experiment

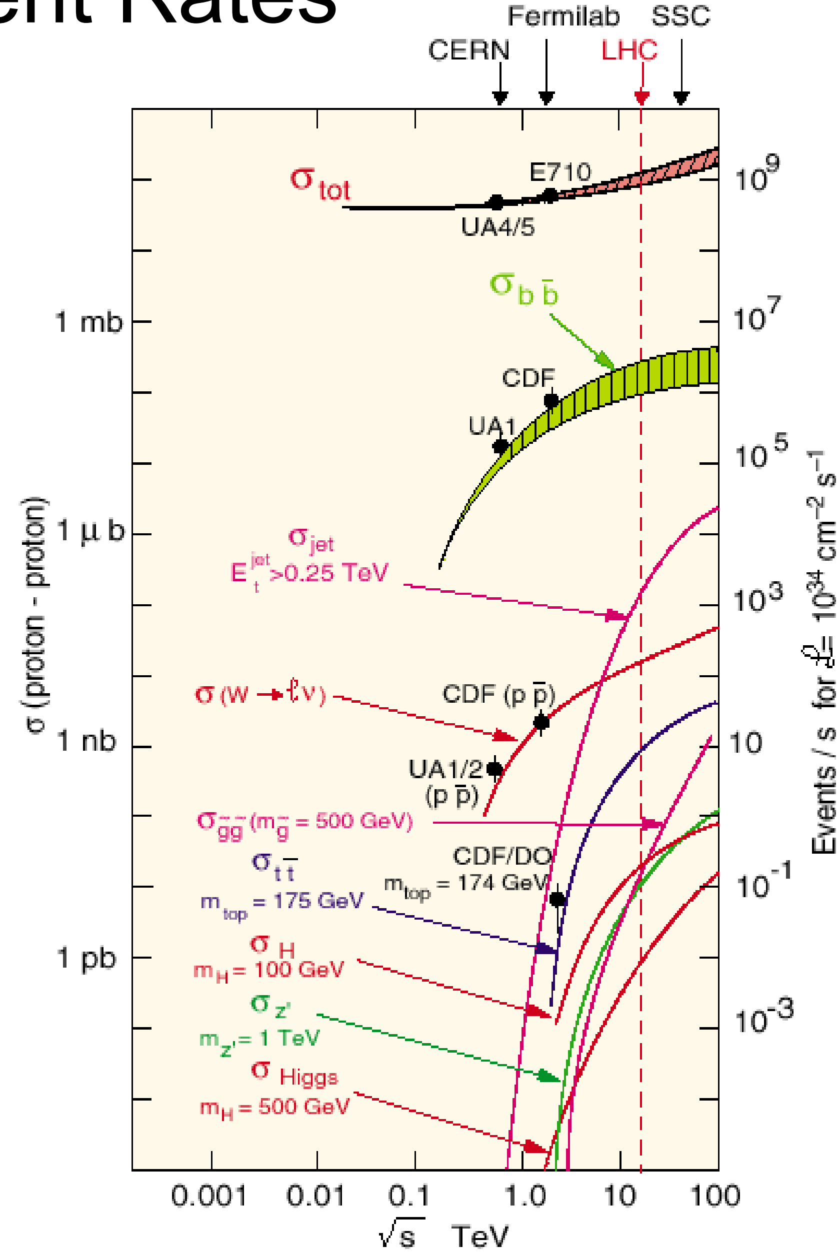


Expected Event Rates

ATLAS with LHC at $\mathcal{L} = 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Process	Events / s	Events in 10 fb^{-1}
W→eν	15	10^8
Z→ee	1.5	10^7
ttbar	1	10^6
bbbar	10^6	10^{12}-10^{13}
H (m=130)	0.02	10^5

Many of these processes become backgrounds to New Physics searches… …more on this later

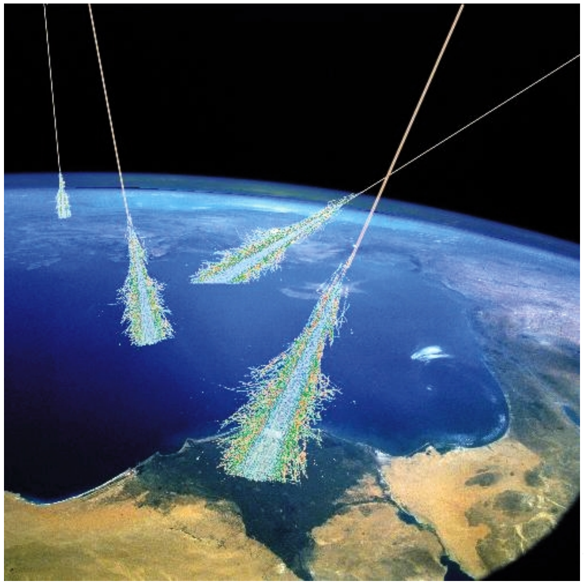


Center of mass energy

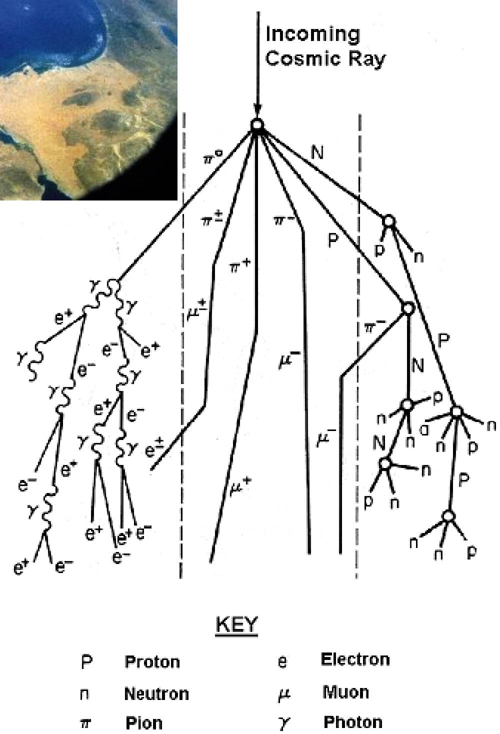
An Unexpected Event?

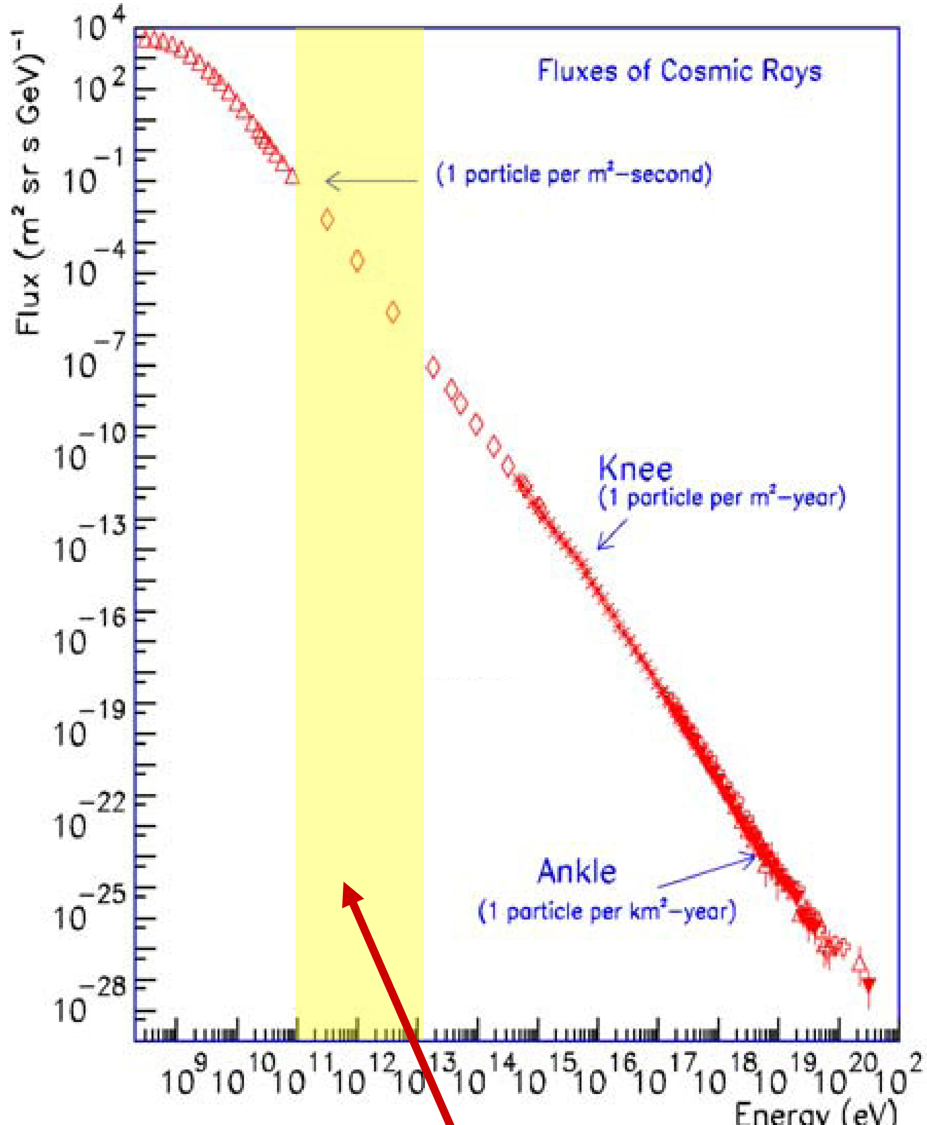
The media likes to get carried away… Will a Black Hole swallow the Earth?

I think we're safe…



~4.5 Billion Years

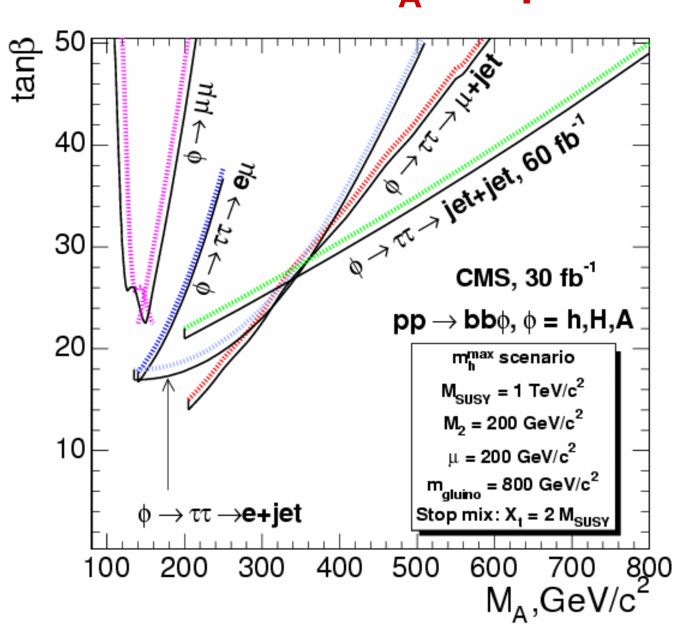


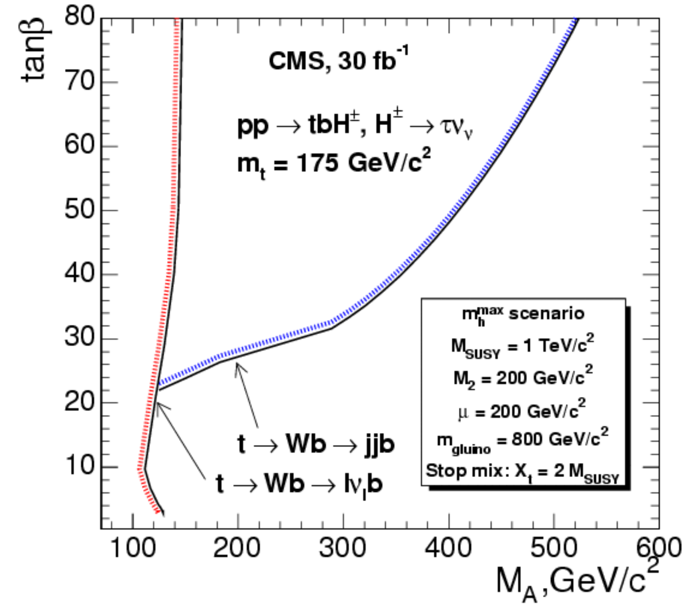


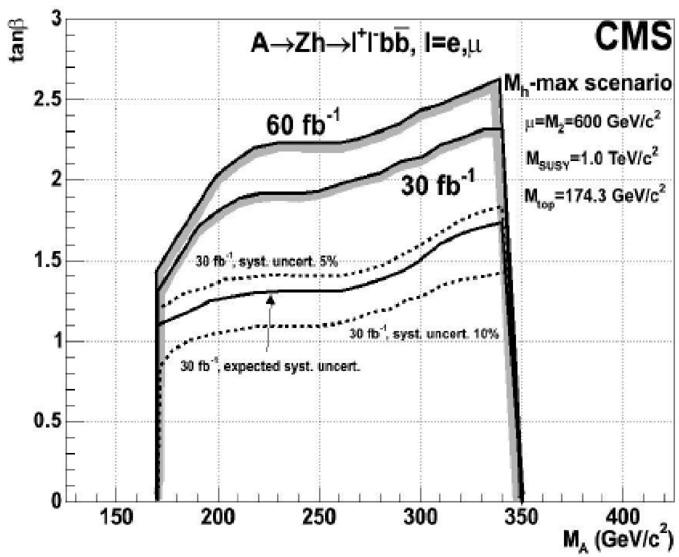
Earth-based Accelerators

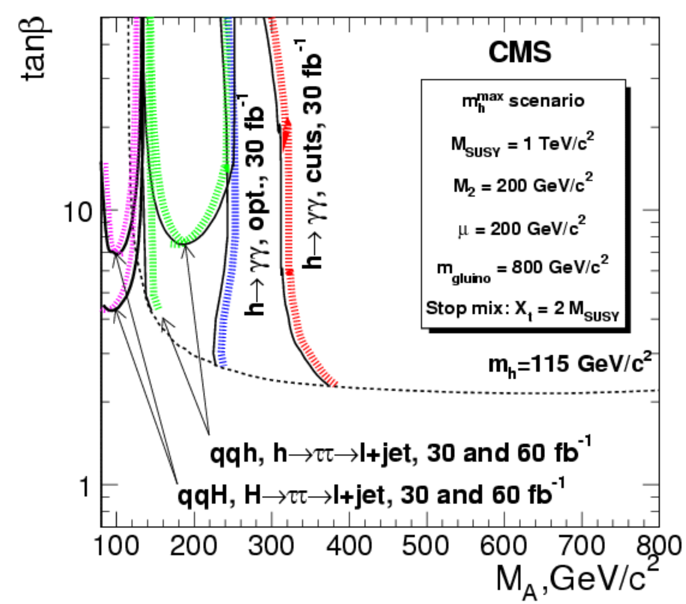
MSSM Higgs at the LHC

Summary of CMS reach in M_A tan β









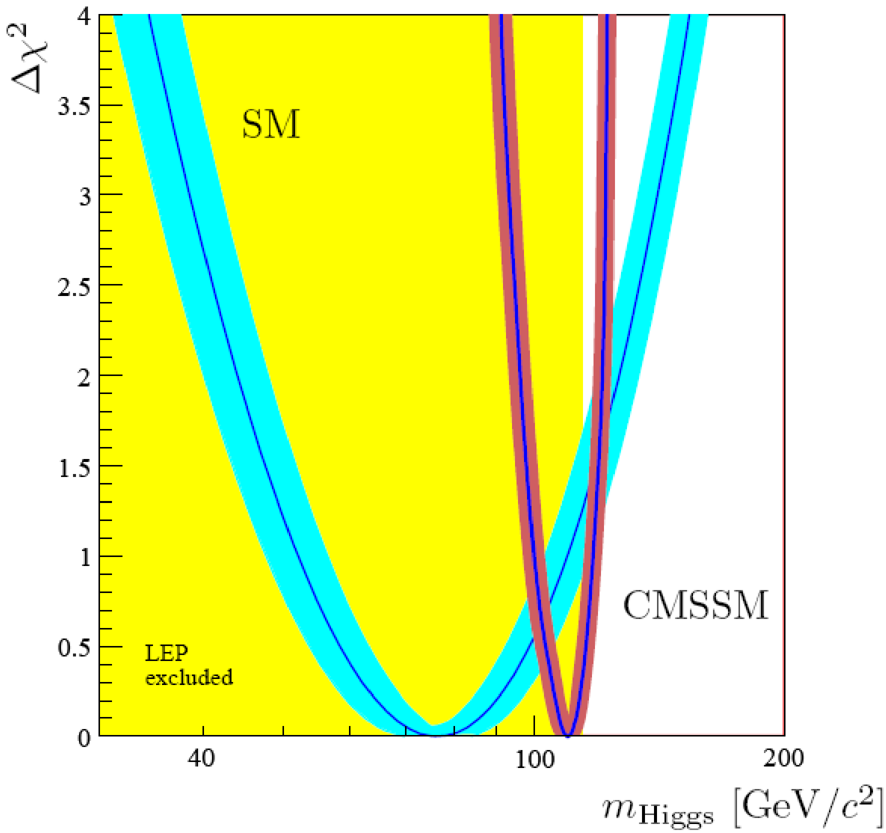
CMSSM

Constrained MSSM

- **O. Buchmueller et al., arXiv:0707.3447v2 [hep-ph]**
- **CMSSM: M_h = 110 (+8)(-10) ± 3 (theo.) GeV**
- **Includes CDM, flavor physics and a_μ experimental data**

CMSSM parameter	Preferred value
M_0	(85^{+40}_{-25}) GeV/c^2
$M_{1/2}$	(280^{+140}_{-30}) GeV/c^2
A_0	(-360^{+300}_{-140}) GeV/c^2
$\tan\beta$	10^{+9}_{-4}
sgn(μ)	+1 (fixed)

Table 2
Values of the CMSSM parameters at the globally preferred χ^2 minimum, and corresponding 1-sigma errors. The lower limit of Eq. 2 is included.



chi² / ndf = 17.34 / 14

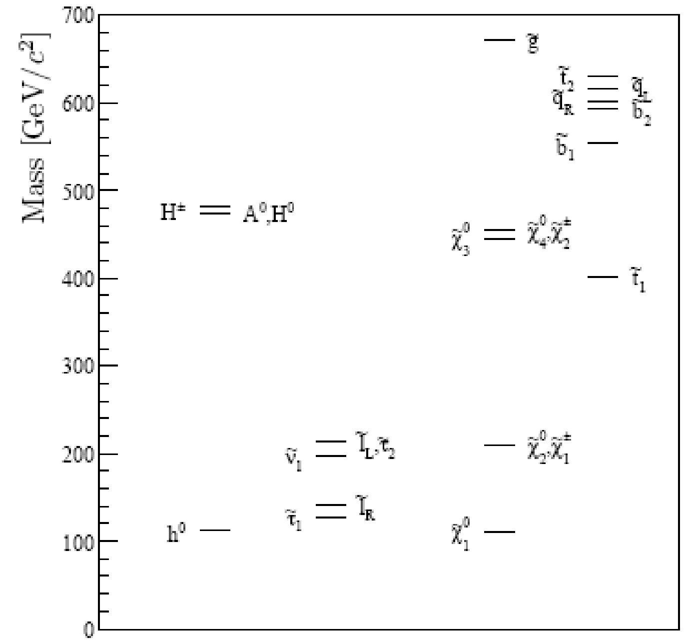


Figure 2. Mass spectrum of super-symmetric particles at the globally preferred χ^2 minimum. Particles with mass difference smaller than 5 GeV/c^2 have been grouped together.

Impact Parameter

Displaced vertices present

in Zbb and tt

Impact Parameter Significance ≡ d_0/σ_{d0}

Transverse impact parameter resolution

~15 μm for P_T = 20 GeV

Transverse primary vertex spread

~15 μm, taken into account

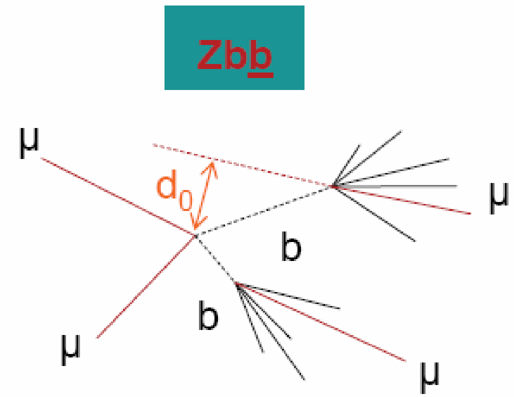
Isolation + Impact Parameter Criteria

O(10^2) Rejection for Zbb

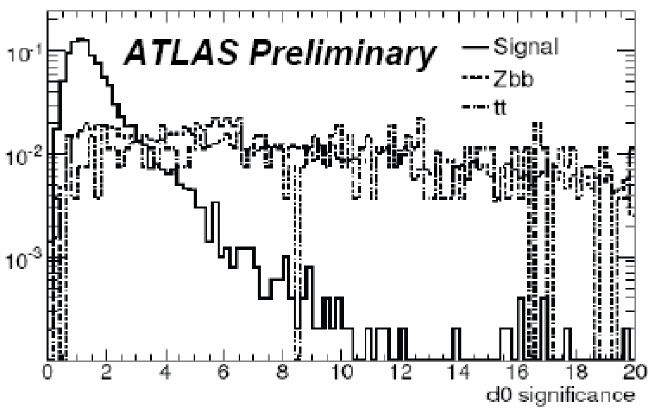
O(10^3) Rejection for tt

for signal efficiency O(80%)

Effect of pile-up on signal significance ≤5% *preliminary*

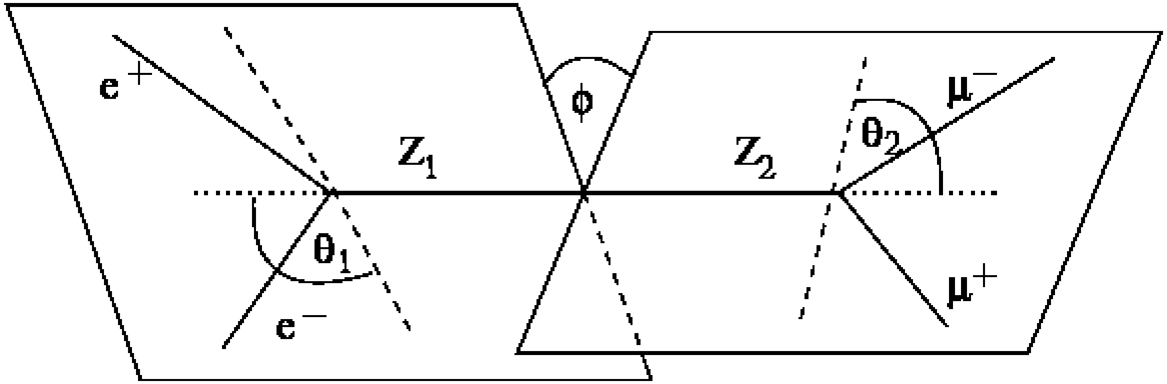


H(130 GeV) → ZZ* → 4μ



Higgs Properties

Higgs Properties: CP



Azimutal angle ϕ between decay planes in the rest frame of Higgs

$$F(\phi) = 1 + \alpha \cos(\phi) + \beta \cos(2\phi)$$

Polar angle θ between lepton and the Z momentum in Z rest frame

$$G(\theta) = L \sin^2(\theta) + T(1+\cos^2(\theta)),\ R=(L-T)/(L+T)$$

M_{Z*} distribution for $M_H < 2\ M_Z$, $d\Gamma_H/dM_{Z*}^2 \sim \beta^n$ near threshold (n=1 in SM)

$$\beta^2=[1-(M_Z+M_{Z*})^2/M_H^2][1-(M_Z-M_{Z*})^2/M_H^2]$$

Resent ATLAS fast simulation study on sensitivity to $F(\phi)$ and $G(\theta)$ for exclusion of 0^-, 1^+, 1^- for $M_H > 2M_Z$: SN-ATLAS-2003-025