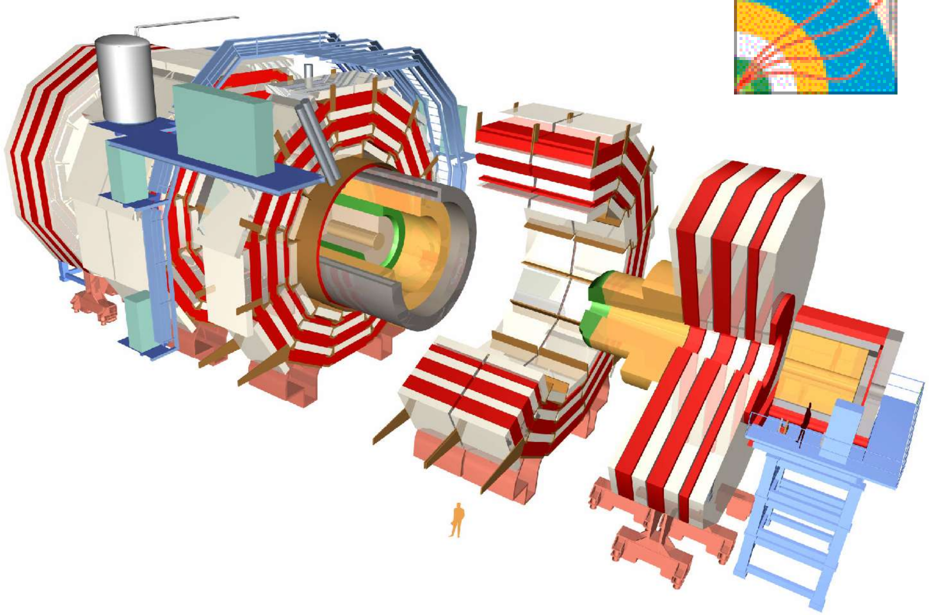
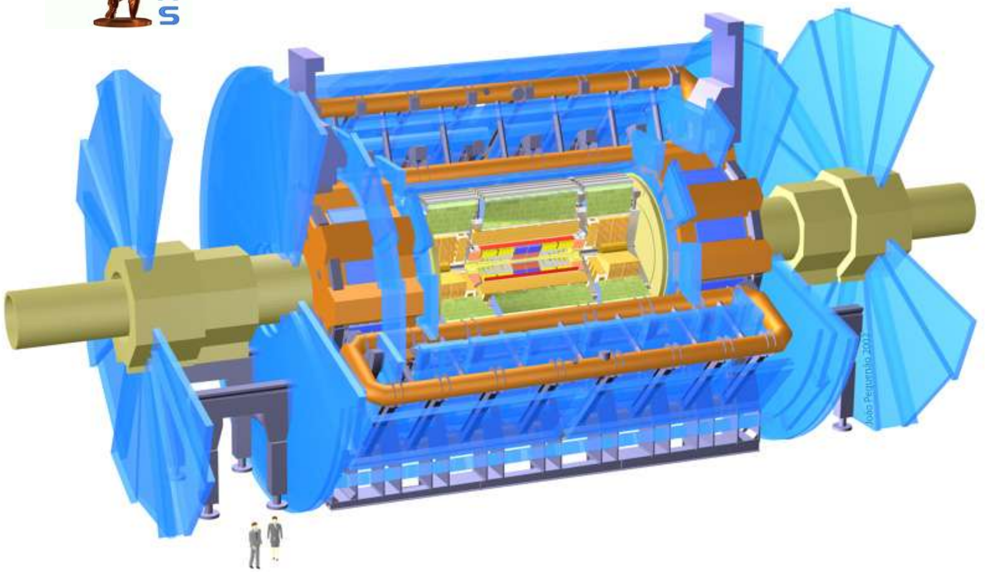
Ludwig-Maximilians-Universität München

Top Physics at the Startup of the LHC

Frank Fiedler, Munich University

on behalf of the ATLAS and CMS collaborations

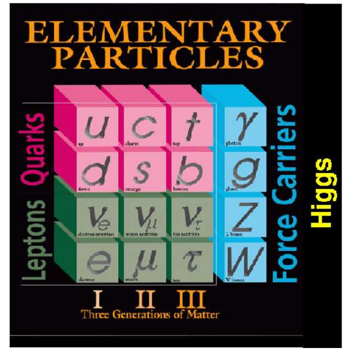


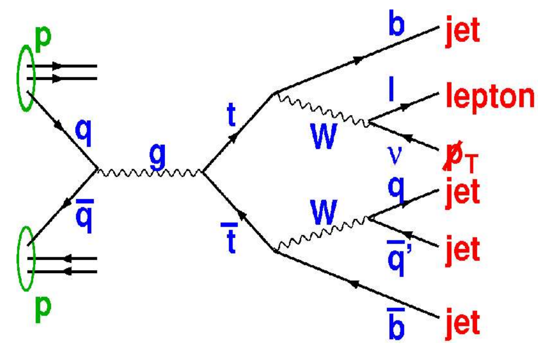


DPF 2006, October 29 – November 3rd, 2006, Honolulu/HI/USA

Overview

- Top quark production and decay at the LHC

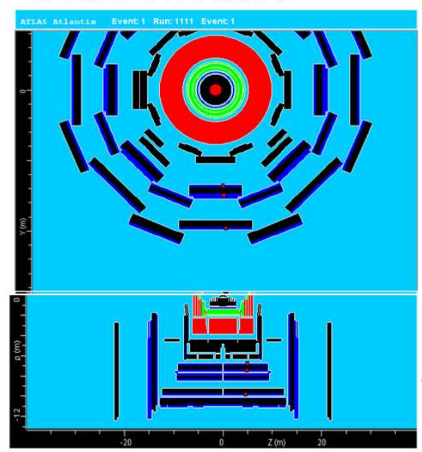




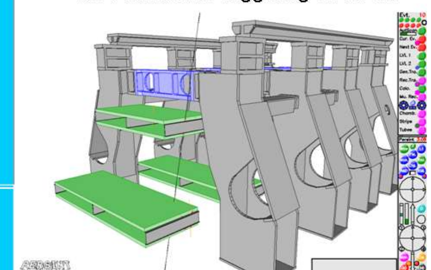
(our picture of reality)

- Commissioning the LHC detectors

RPC run # 1111 of sector 13

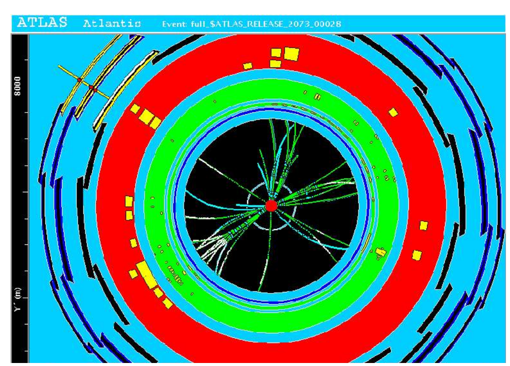


MDT run #1068 triggering on RPCs



(already reality)

- First LHC top physics results
  -> example studies



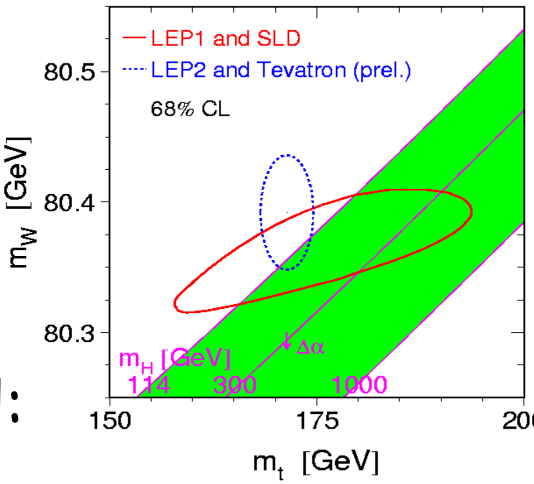
(reality soon)

Motivation

2.) Measurements:

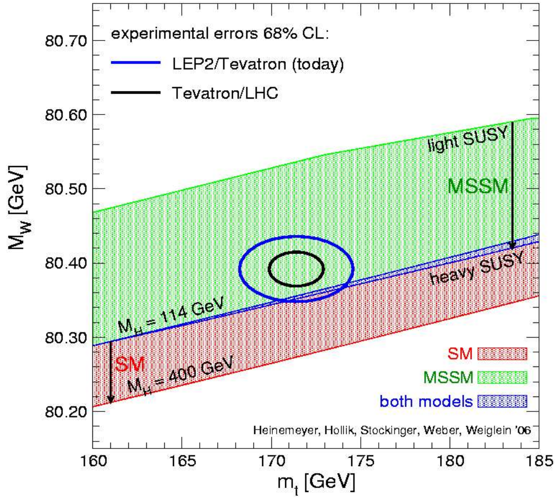
- in the Standard Model:

  constrain Higgs mass →



- beyond the Standard Model:

  SM consistency test →



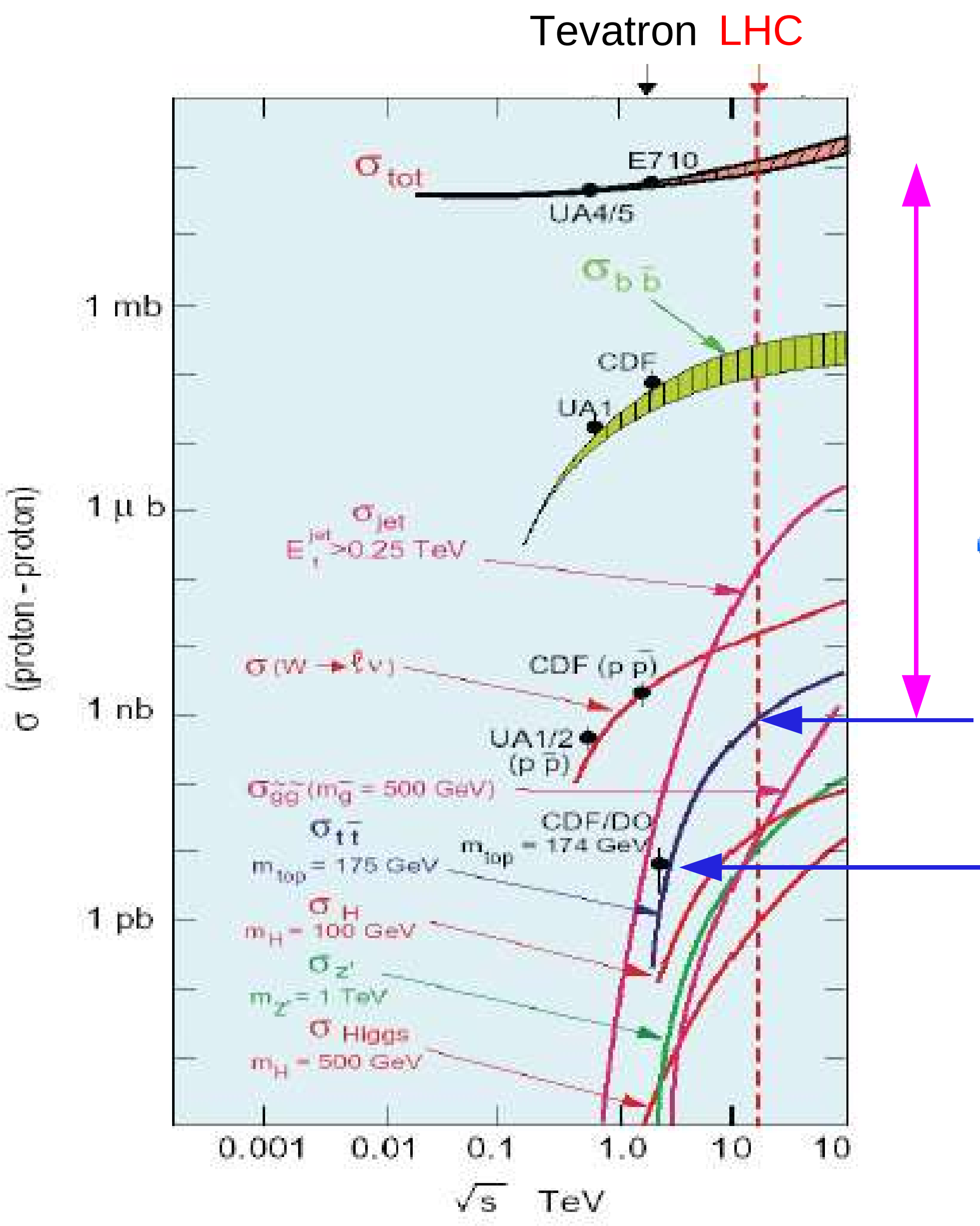
- search for new physics in top events:

  ttbar production, single top production

  top quark decays
- top as background to other searches

1.) Detector Calibration:

- need all detector components to measure top
- have lots of top events
- can use top to commission/calibrate the detector

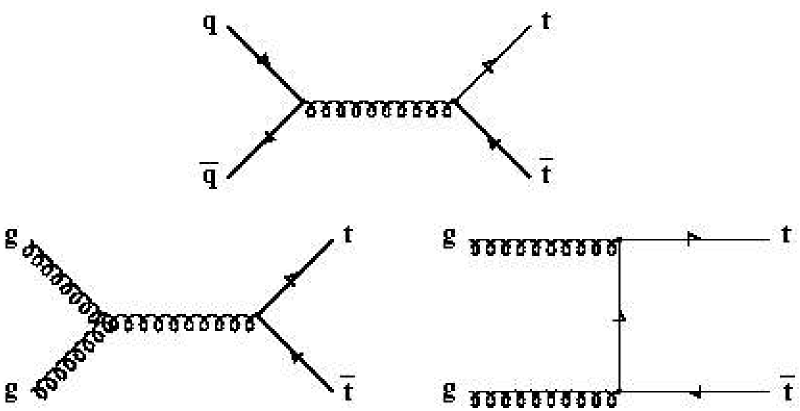


- 8 orders of magnitude...
- cross sections for ttbar production:
  ~830 pb (LHC)
  ~6.7 pb (Tevatron)

Top Quark Production (I)

Top/antitop pair production (strong interaction)

Feynman diagrams (LO):



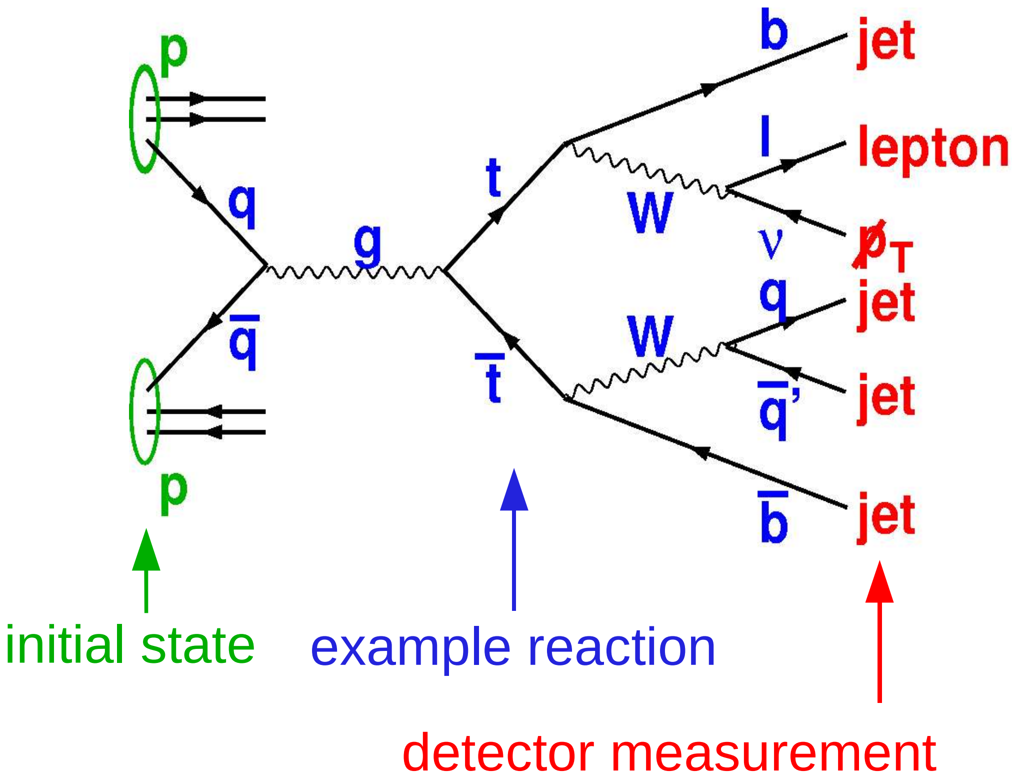
production cross section:

Tevatron Run II $p\bar{p}$, 1.96 TeV	LHC pp, 14 TeV
85 %	5 %
15 %	95 %
6.7 pb	830 pb
7000 events (per fb^{-1})	8000000 events (per 10 fb^{-1})

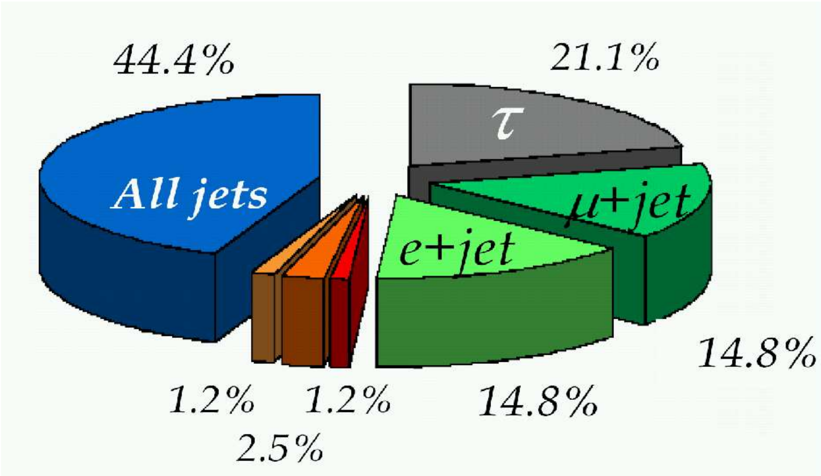
-> Detector commissioning, top quark properties

$t\bar{t}$ Event Topologies

- Top quarks... do not hadronize (τ = 4·10^{-25}s)
  decay almost(!) always via t->Wb
- W decays determine experimental signature



Classification:

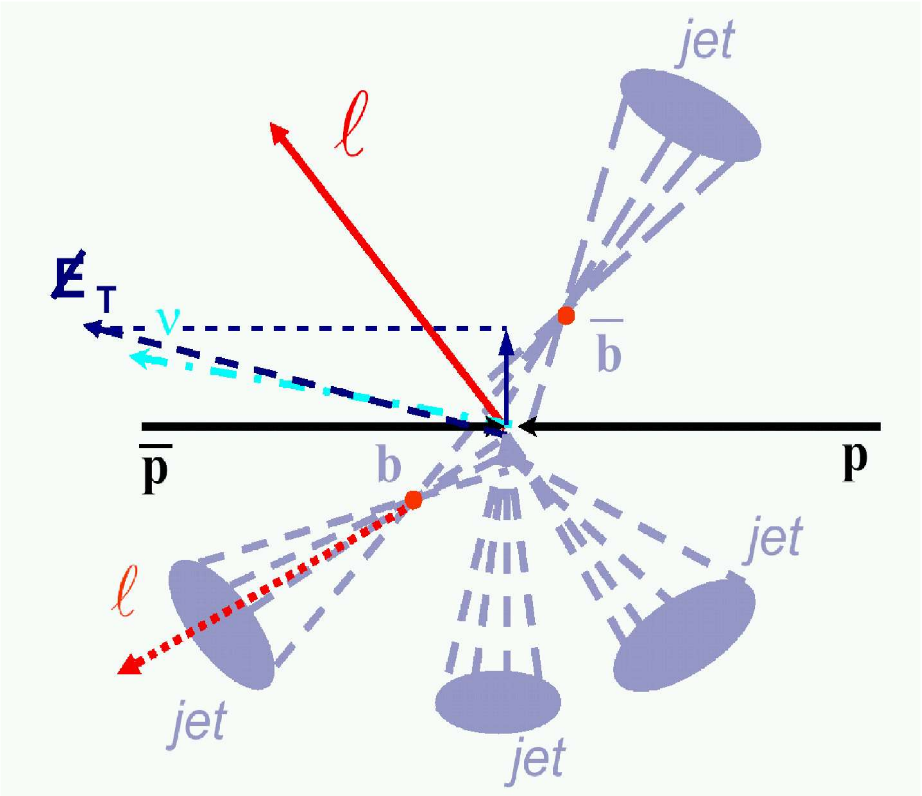


- 5% "dilepton"
- 30% "lepton+jets"
- 44% "all-hadronic"
- 21% "with τ decays"

$t\bar{t}$ Event Topologies

30% lepton+jets events:

- 1 energetic, isolated lepton
- 4 energetic jets (of which 2 b jets)
- missing transverse energy



"gold-plated" channel: event selection

- easy to trigger (lepton!)
- large event yield
- relatively small backgrounds

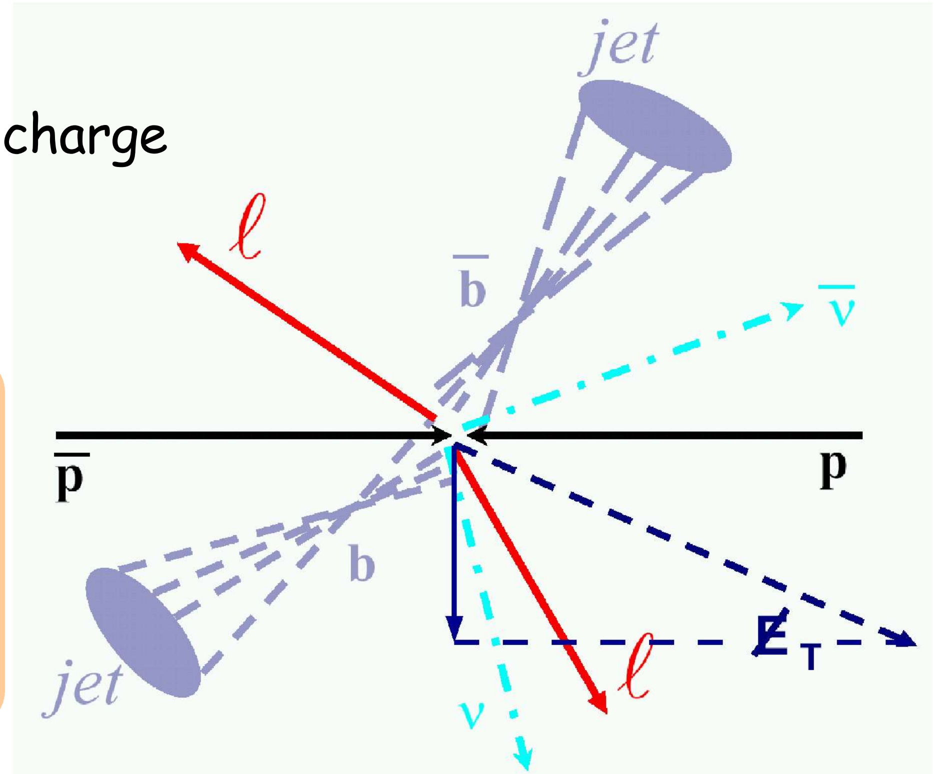
"gold-plated" channel: kinematic information

- full kinematic event reconstruction possible (W, top mass constraints)
  => top mass measurement
  => trigger and b-tagging efficiency studies
  => jet energy scale calibration (W->jj), jet resolution studies

$t\bar{t}$ Event Topologies

5% dilepton events:

- 2 energetic, isolated leptons of opposite charge
- 2 energetic b jets
- missing transverse energy



- easy to trigger (leptons!)
- small backgrounds (especially eμ channel)
- small BR not an issue(?) at the LHC
- **but:** no obvious top or W mass peaks (two neutrinos…)

44% all-hadronic events:

- 6 energetic jets (of which 2 b jets)
- no charged leptons
- no missing transverse energy

- large backgrounds (multijet events!)

21% events with τ decays:

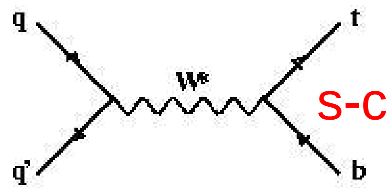
- various topologies
- additional neutrinos from τ decay

- studies of τ identification

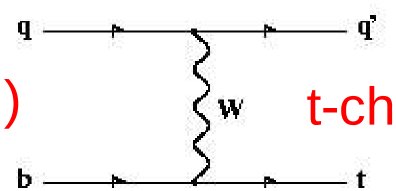
Top Quark Production (II)

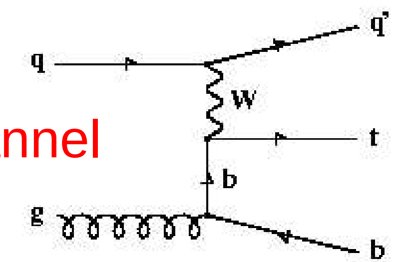
Single top (or antitop) production (weak interaction)

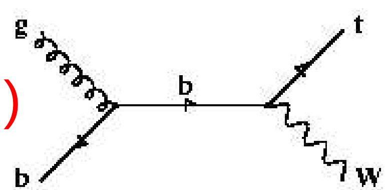
Feynman diagrams (LO):

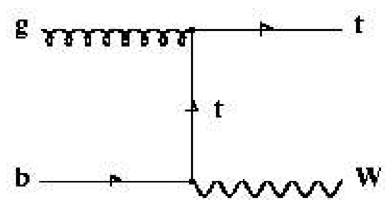
1.) 

s-channel

2.) 

t-channel


3.) 



t+W associated production

-> top polarization, $|V_{tb}|$

production cross section:

	Tevatron Run II $p\bar{p}$, 1.96 TeV	LHC pp, 14 TeV
1.)	0.9 pb	10 pb
2.)	2.4 pb	240 pb
3.)	0.12 pb	60 pb

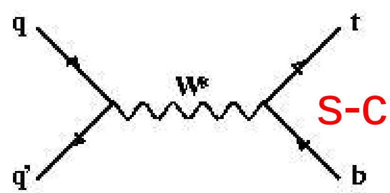
smaller cross section
larger backgrounds
=> not yet seen

Single Top Event Topologies

Single top (or antitop) production (weak interaction)

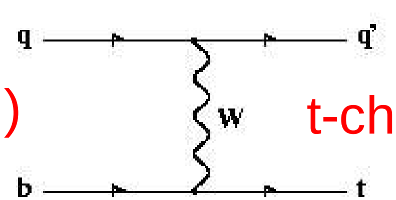
Feynman diagrams (LO):

1.)

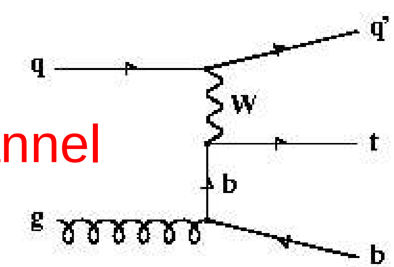


s-channel

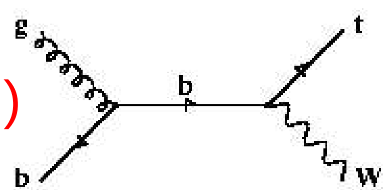
2.)

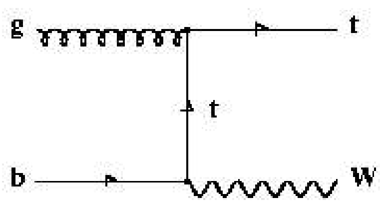


t-channel



3.)





t+W associated production

-> top polarization, $|V_{tb}|$

require ≥1 leptonic W decay:

- **s-channel:** 1 lepton,
  2 b jets,
  missing transverse energy
- **t-channel:** 1 lepton,
  1 b jet (+forward jets),
  missing transverse energy
- **associated production:**
  either 1 lepton,
  1 b jet, 2 light jets,
  missing transverse energy
  or 2 leptons (opposite charge),
  1 b jet,
  missing transverse energy

History of the Top Quark

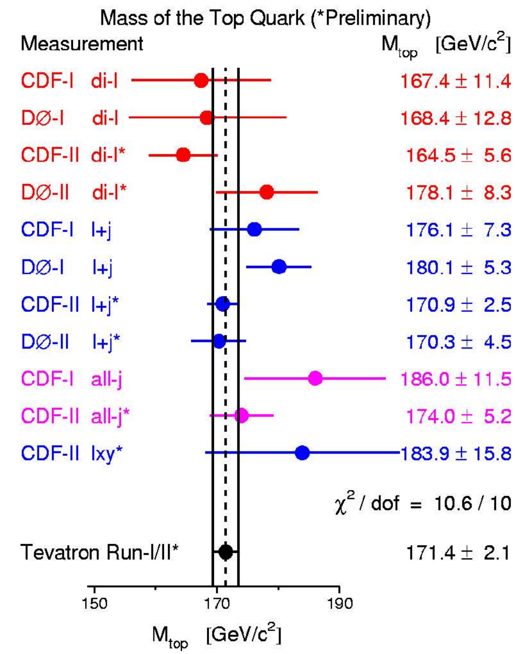
1977-1995: indirect predictions (existence, mass)

1992-1996: Tevatron Run I, ppbar collisions at 1.8 TeV

- 1995: discovery at the Tevatron (ttbar production)
- basic properties (σ(ttbar), decay channels, mass)
- 2004: last Run I top mass measurement ready

2002-today: Tevatron Run II, ppbar collisions at 1.96 TeV

- ttbar "rediscovery"
- improved cross section
- improved properties measurements (Δm_{top}=2.1GeV)
- working on single top



soon: LHC, pp collisions at 14 TeV

- Tevatron lessons: commissioning!, analyses
- precision measurements of top properties
- search for new physics with top quarks

Tevatron Lessons

Lesson 1:

- We know what the top quark looks like

Lesson 2:

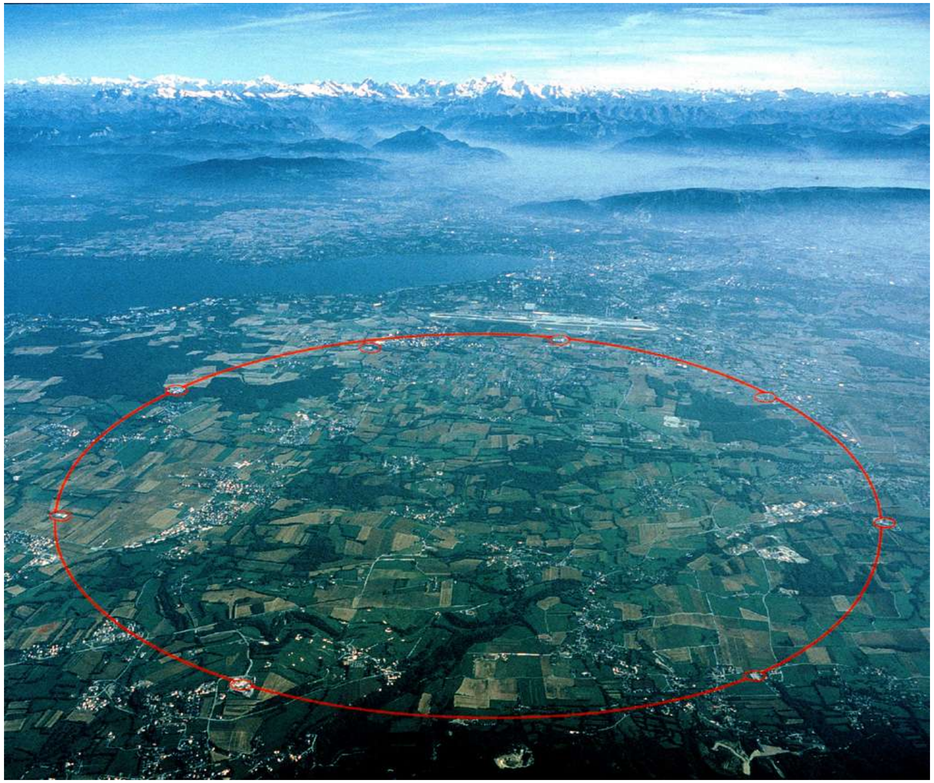
- We will **not** observe the top quark in n minutes

Lesson 3:

- We know what we have to do to observe it

The LHC

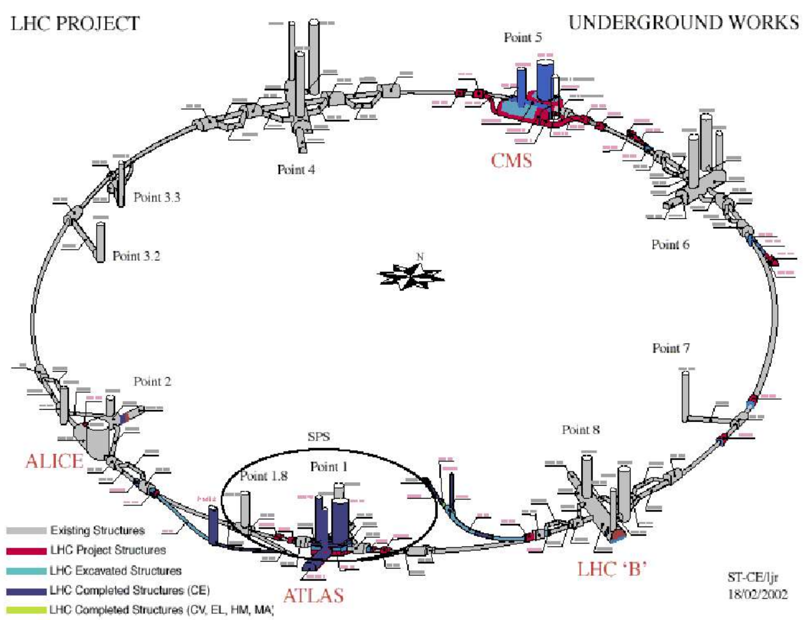
- pp collisions at E_{CM} = 14 TeV (+heavy ion collisions)
- low luminosity phase: L ~ few x $10^{33}cm^{-2}s^{-1}$ (until 2009)
- high luminosity phase: L ~ $10^{34}cm^{-2}s^{-1}$ (from 2009)
  (compare Tevatron: L ~ $10^{32}cm^{-2}s^{-1}$)

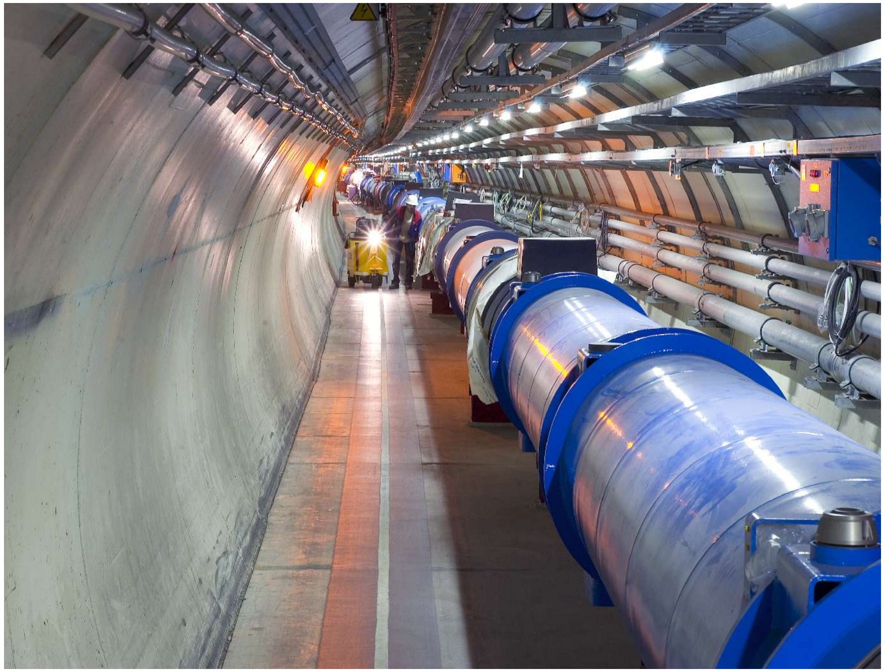


The LHC

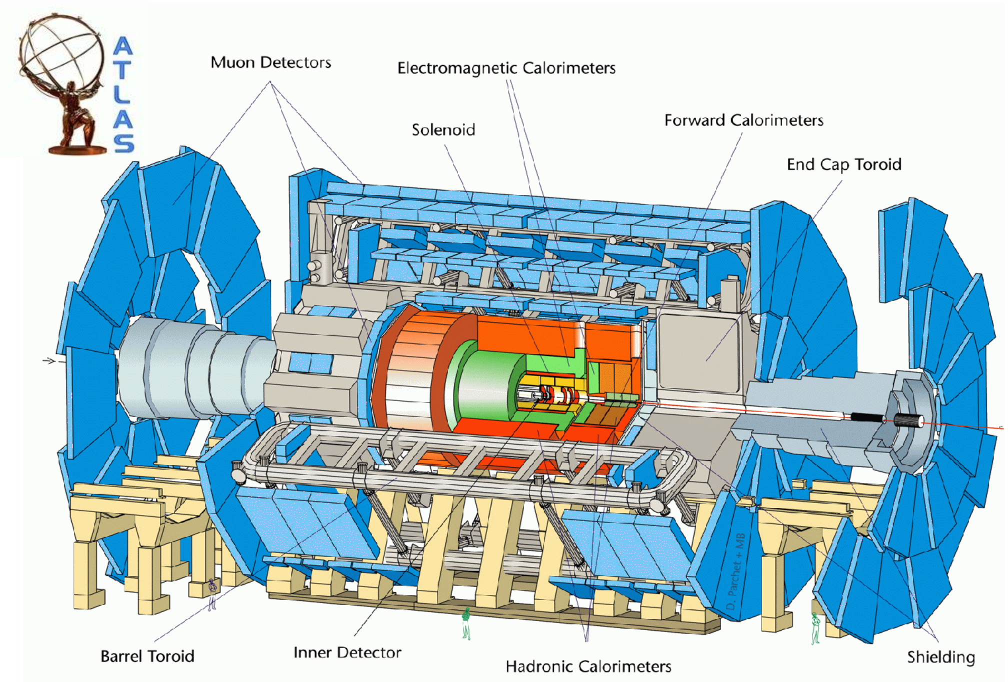
Experiments:

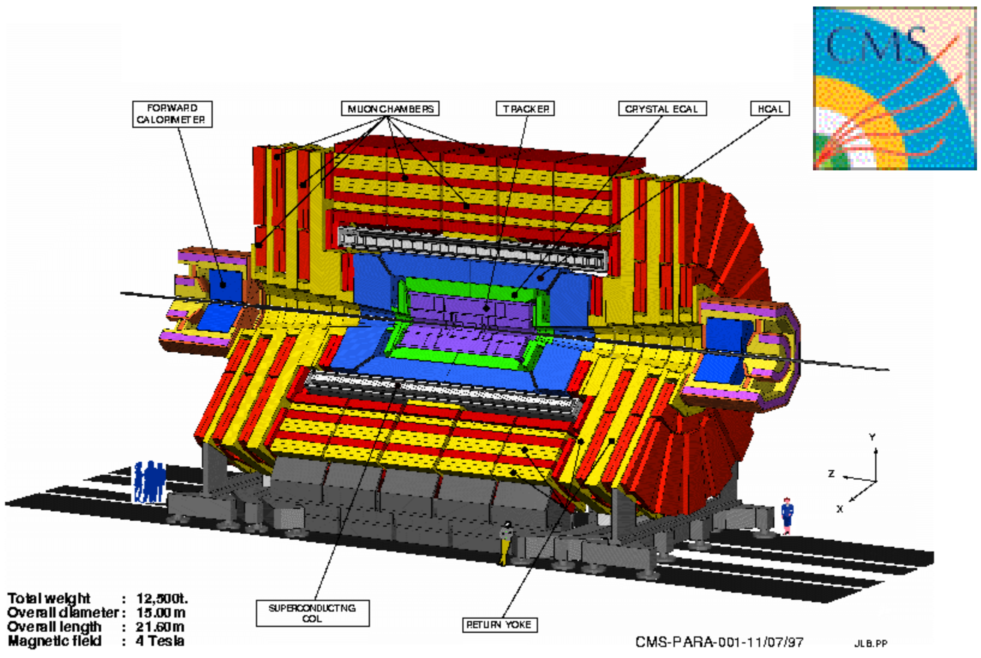
- ATLAS & CMS => general-purpose => top physics => this talk
- LHCb => b physics
- ALICE => heavy ion physics
- TOTEM => pp cross section, diffractive physics





ATLAS and CMS

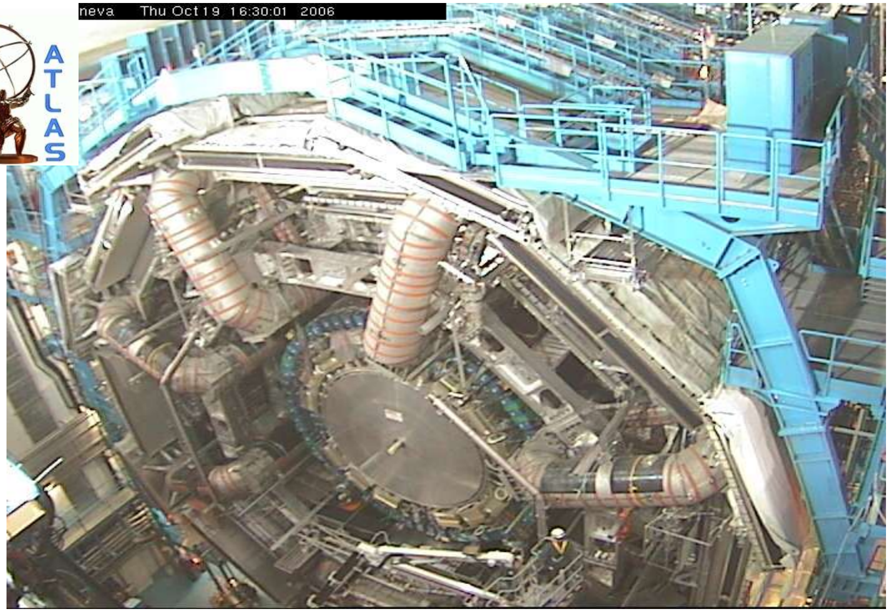




- Tracking ($|\eta|<2.5$, B=2T) :
  - Si pixels and strips
  - Transition Radiation Detector (e/π separation)
- Calorimetry ($|\eta|<5$) :
  - EM : Pb-LAr with Accordion shape
  - HAD: Fe/scintillator (central), Cu/W-LAr (fwd)
- Muon Spectrometer ($|\eta|<2.7$) :
  - air-core toroids with muon chambers

- Tracking ($|\eta|<2.5$, B=4T) :
  - Si pixels / strips
- Calorimetry ($|\eta|<5$) :
  - EM : $PbWO_4$ crystals
  - HAD: brass/scintillator (central, end-cap), Fe/Quartz (fwd)
- Muon Spectrometer ($|\eta|<2.5$) :
  - return yoke of solenoid instrumented with muon chambers

ATLAS and CMS



ATLAS cavern (webcam)

- Tracking (|η|<2.5, B=2T) :
  - Si pixels and strips
  - Transition Radiation Detector (e/π separation)
- Calorimetry (|η|<5) :
  - EM : Pb-LAr with Accordion shape
  - HAD: Fe/scintillator (central), Cu/W-LAr (fwd)
- Muon Spectrometer (|η|<2.7) :
  - air-core toroids with muon chambers

CMS magnet test preparation

- Tracking (|η|<2.5, B=4T) :
  - Si pixels / strips
- Calorimetry (|η|<5) :
  - EM : $PbWO_4$ crystals
  - HAD: brass/scintillator (central, end-cap), Fe/Quartz (fwd)
- Muon Spectrometer (|η|<2.5) :
  - return yoke of solenoid instrumented with muon chambers

Schedule

LHC Machine:

Installation:
- last magnet installed: March 2007
- machine closed: August 31, 2007

Commissioning Run:
- first collisions: November 2007
  - at injection energy: E_{CM} = 900 GeV
  - luminosity: $L \sim 10^{29} cm^{-2} s^{-1}$
- shutdown: end of 2007

Full energy:
- first physics run: Spring 2008
  - at energy: E_{CM} = 14 TeV
  - integrated luminosity: a few fb^{-1} by end of 2008

Detectors:

"Phase I": cosmic rays
- functioning of detectors
- alignment

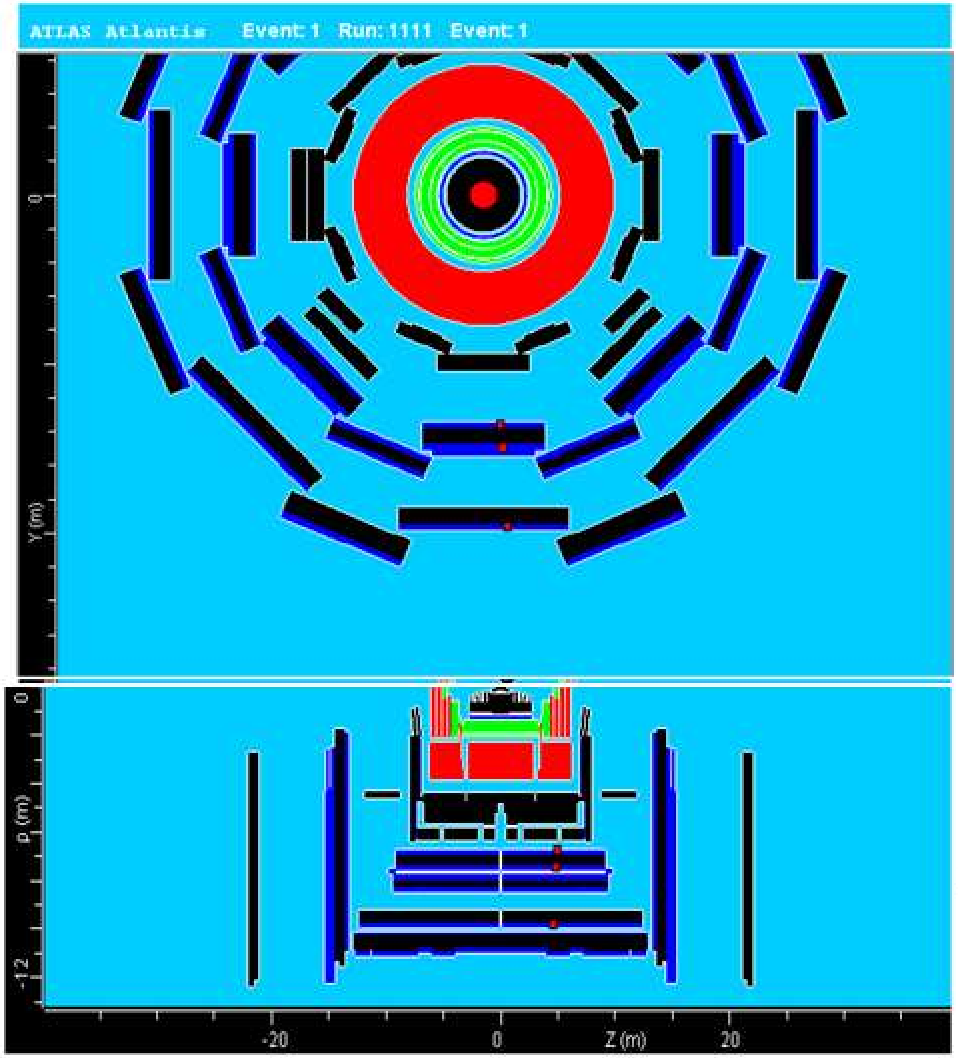
"Phase II": commissioning data
- tracking momentum scale
- inter-calibration of calorimeter

"Phase III": physics data
- full detector calibration:
  - Z->ll events
  - ttbar events => this talk
- measurements
  - first top results => this talk

Detector Commissioning

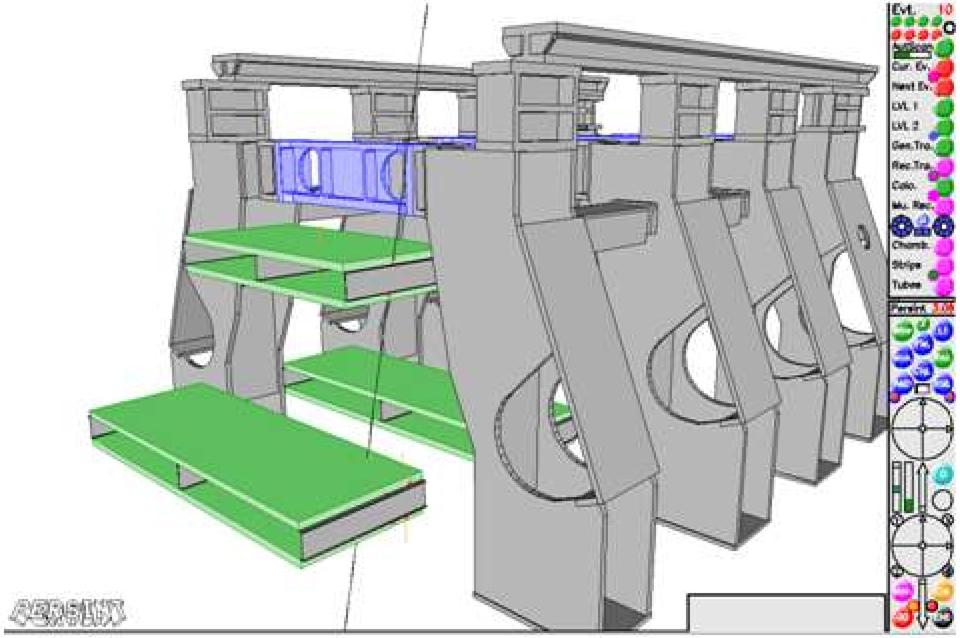
- "Phase I" has already started:

RPC run # 1111 of sector 13



- Taking cosmic muons with L1 μ trigger
- Efficiency, noise, alignment studies of muon chambers

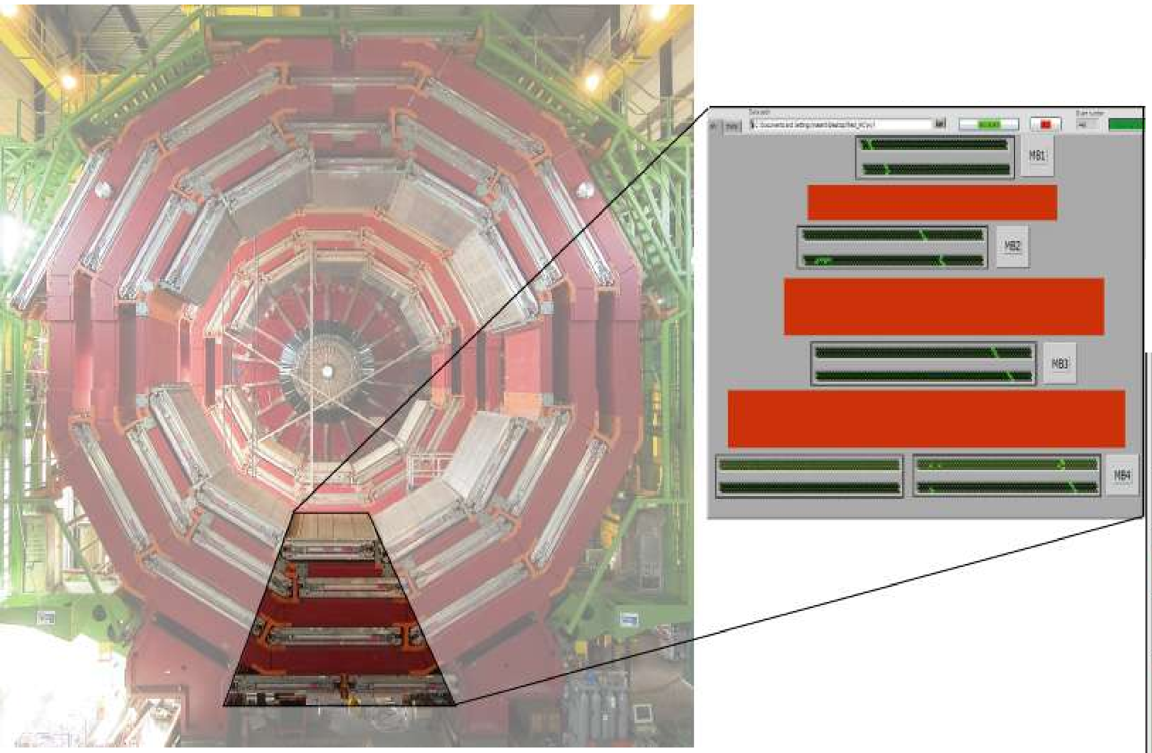
MDT run #1068 triggering on RPCs



ATLAS

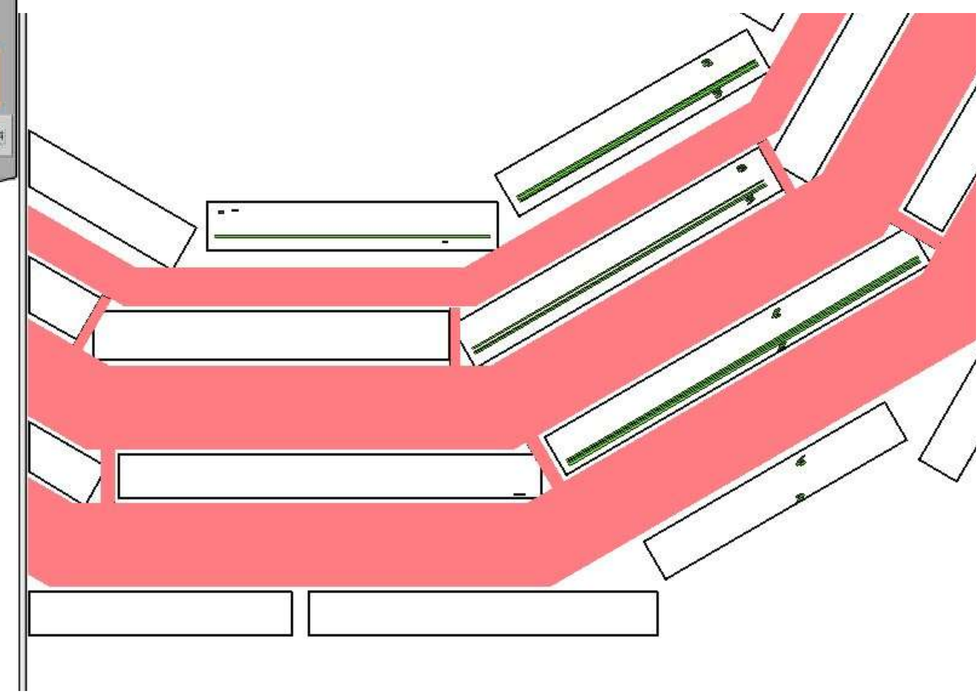
Detector Commissioning

- "Phase I" has already started:



CMS

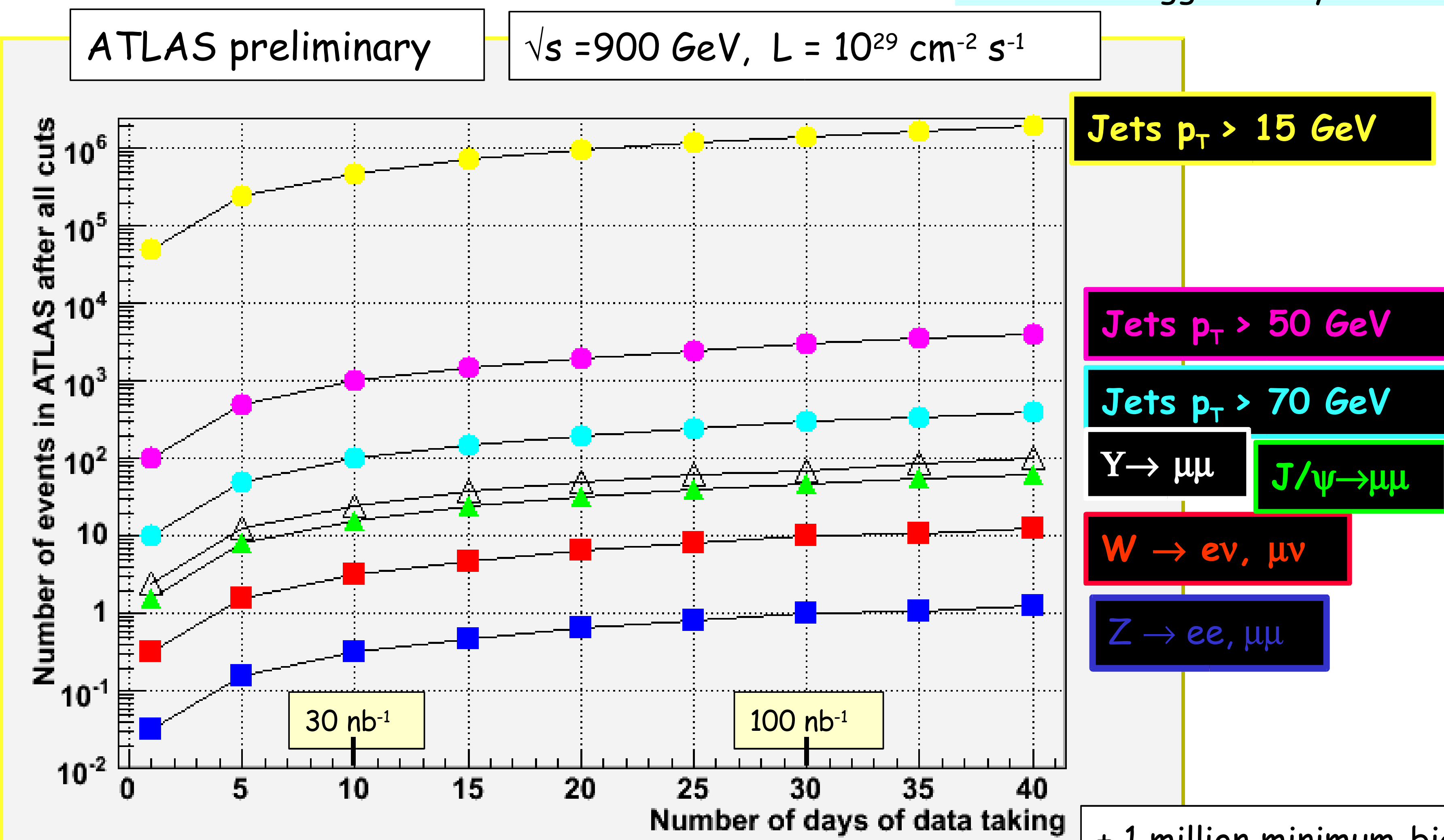
- Cosmic muon traversing the solenoid field



- Commissioning with cosmic muons

- "Phase II": data to expect...

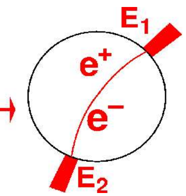
included: 30% data taking efficiency
trigger/analysis efficiencies

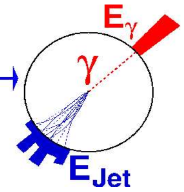


+ 1 million minimum-bias/day

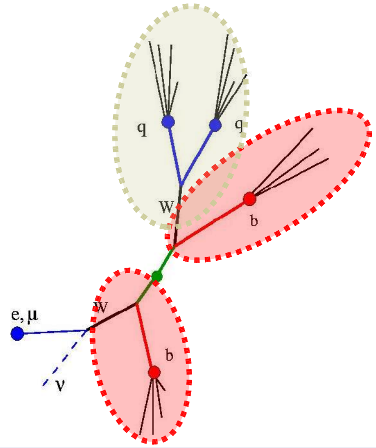
Physics Commissioning

- "Phase III":
- use Z->μμ decays to calibrate muon chambers
  tracking momentum scale
  Z->ee decays to calibrate electromagnetic calorimeter
- but: hadronic calorimeter? -> jet energies? -> missing E_T?
  b tagging? -> b-jet ID?
- => indirect method for jet energies:
  1.) calibrate ECAL with Z->ee
  2.) calibrate HCAL with γ+jet events
  (or use Z+jet events)





- => alternative: lepton+jets
  ttbar events!



Physics Commissioning

- "Normal" selection in the lepton+jets channel (example cut values):
  - 1 energetic isolated lepton — E_T > 20 GeV
  - ≥4 energetic jets (e.g. 0.4 cone jets) — E_T > 40 GeV, $|\eta|<2.5$
  - ≥2 b-tagged jets
  - significant missing E_T — E_T^{miss} > 20 GeV
- works great for a perfect detector
- Scientific honesty: no detector is perfect from the start
  => educated guess on what may be wrong:
  - "perfect" lepton reconstruction (calibrated with Z->ll)
    note: will require a lot of work on alignment, energy calibration, etc.!
  - no b tagging
  - imperfect jet energy calibration
- => demonstrate we can still find&calibrate ttbar events!

ttbar without b tagging

- assume a perfect detector except for b tagging
- purely kinematic selection:

ATL-PHYS-PUB-2005-024

1 isolated lepton	$E_T > 20$ GeV	Selection efficiency = 5.3%
exactly 4 jets (R=0.4)	$E_T > 40$ GeV	
missing E_T	$E_T^{miss} > 20$ GeV	

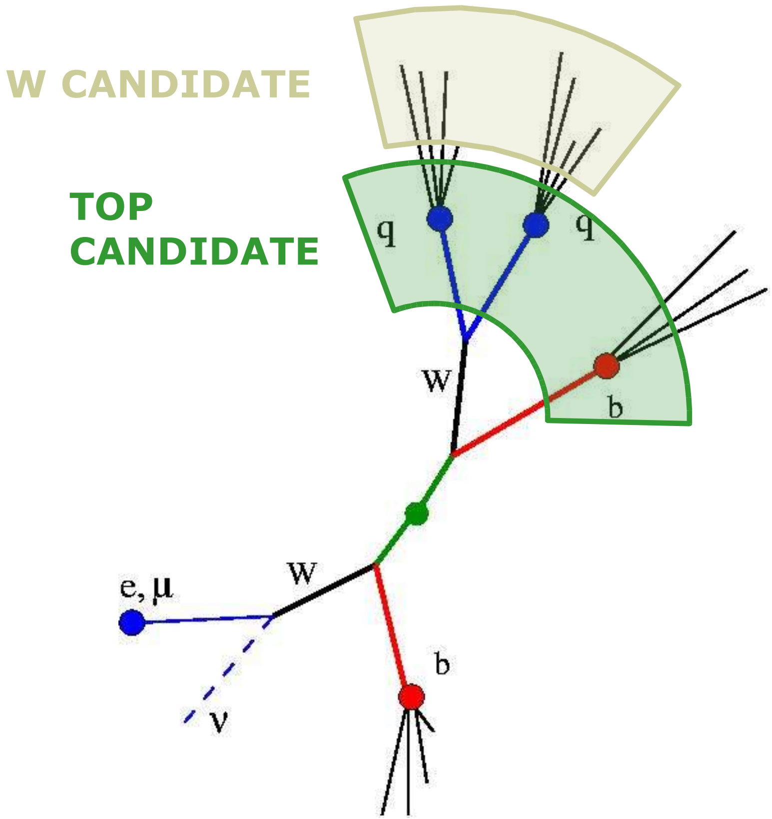
- assign jets to top and W decays:

1.) hadronic top:

Three jets with highest vector-sum p_T as the decay products of the top

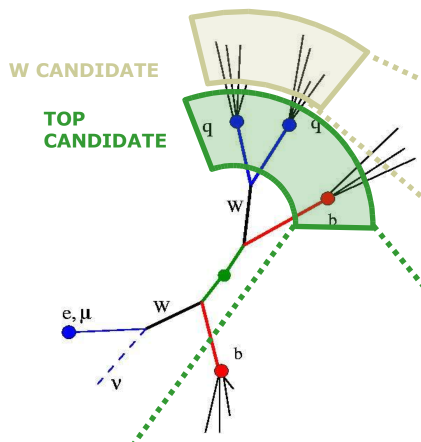
2.) W boson:

Two jets in hadronic top with highest momentum in reconstructed jjj C.M. frame
(do not use reconstructed jj mass to avoid biasing background spectrum)



ttbar without b tagging

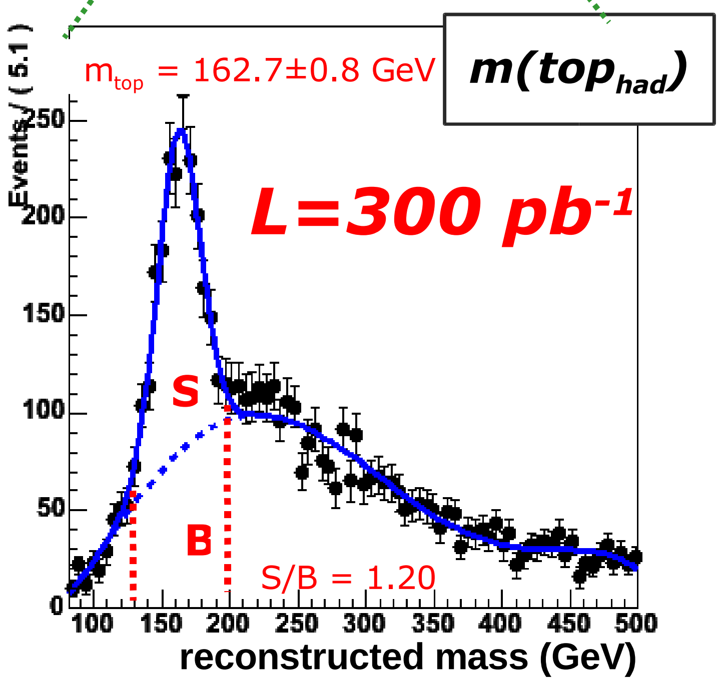
- reconstructed mass distributions, signal only: ATL-PHYS-PUB-2005-024

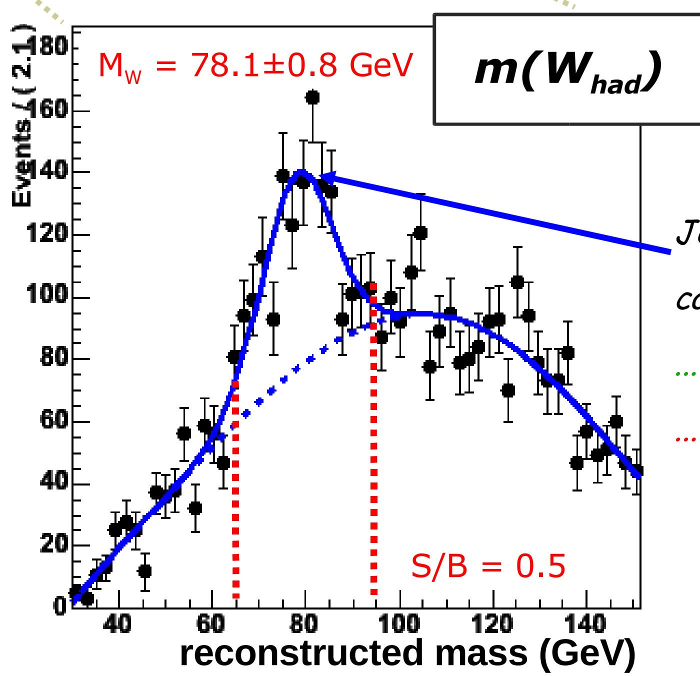


- top, W mass peaks clearly visible
- but remember!

signal only -> already have large combinatorial background

perfect detector calibration -> already see mass shifts (energy sharing between jets)





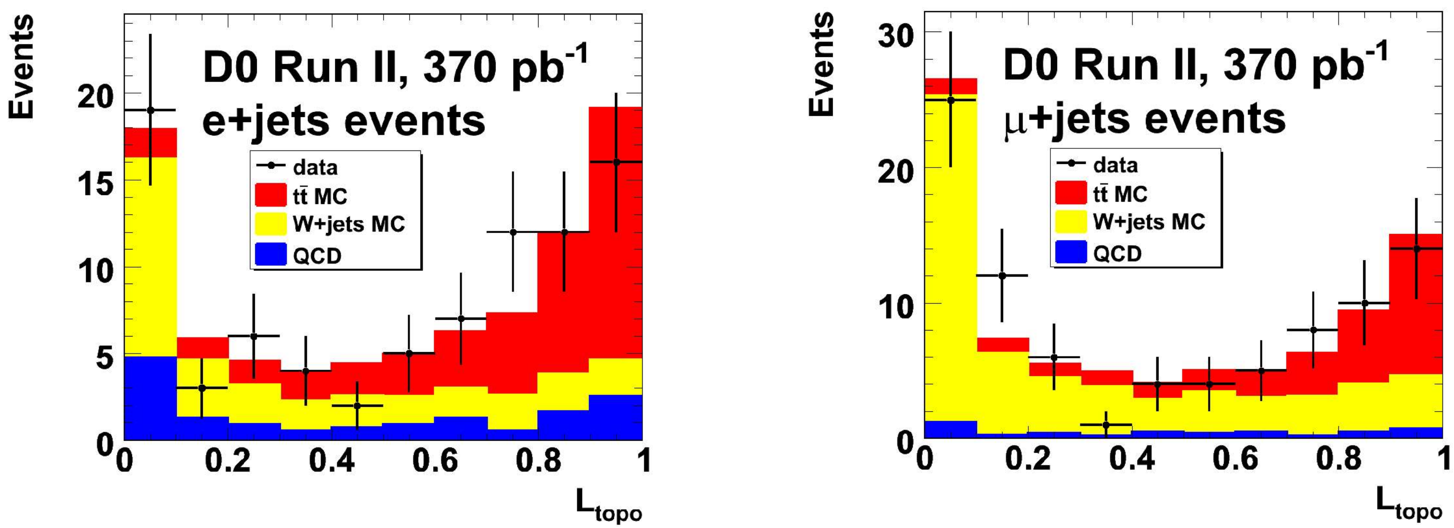
Jet energy scale calibration...

... possible from m(W) peak

... and necessary!

Backgrounds: look at Tevatron experience

- example: topological ttbar likelihood used by DØ



hep-ex/0609053

Dominant physics backgrounds:

- W+jets events ← generate with ALPGEN
- multijet (QCD) events (fake/non-isolated lepton) -> detector performance?

Additional backgrounds:

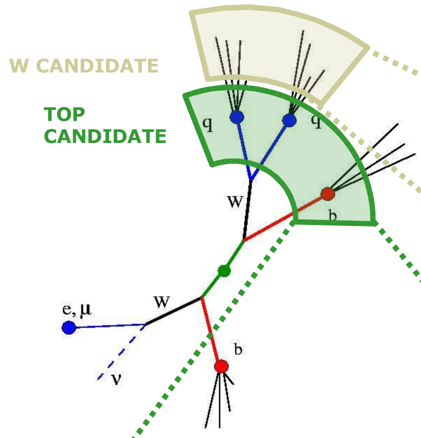
- multiple interactions
- underlying event

reliable studies only with data

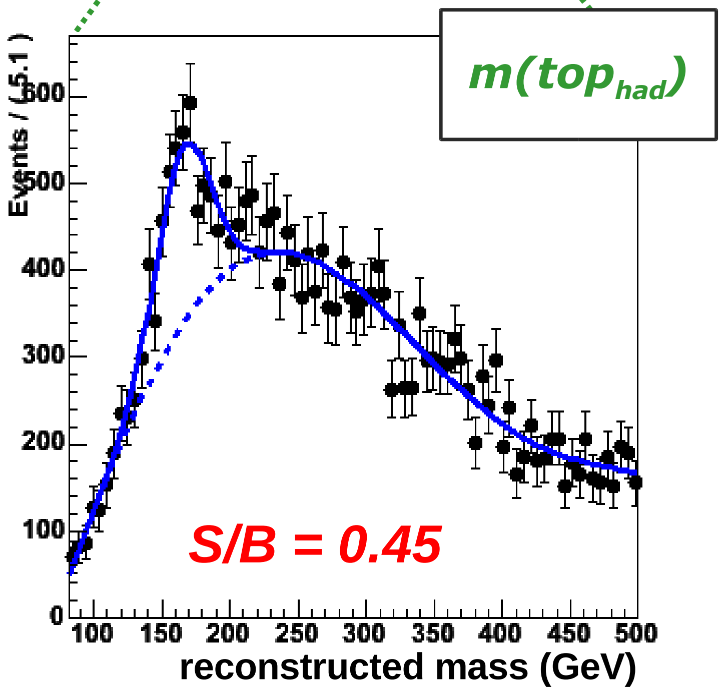
ttbar without b tagging

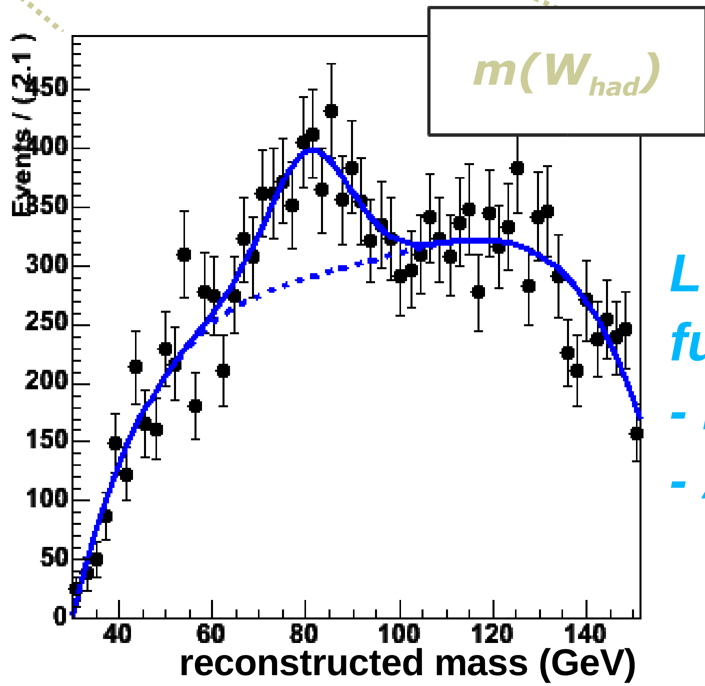
- including W+jets background:

ATL-PHYS-PUB-2005-024



- ~ 3 times as much background
- top, W mass peaks still clearly visible
- but remember!
  no QCD background yet
  perfect detector calibration



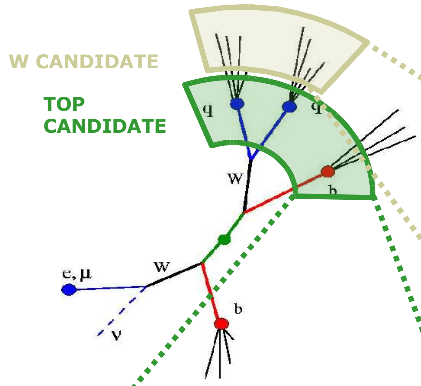


$L = 300 pb^{-1}$
full simulation:
- MC@NLO ttbar,
- ALPGEN W+jets

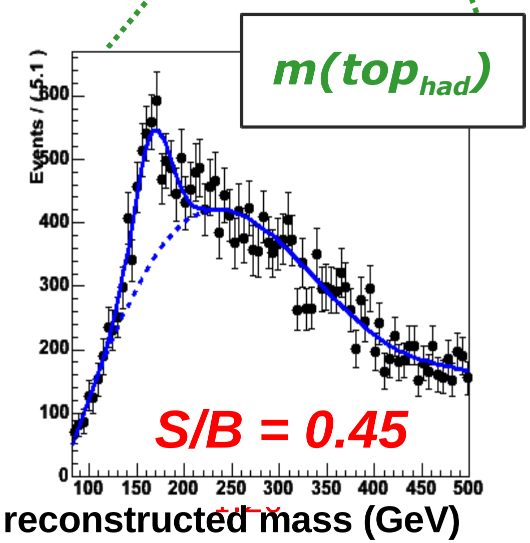
ttbar without b tagging

- signal/background enhancement possible:

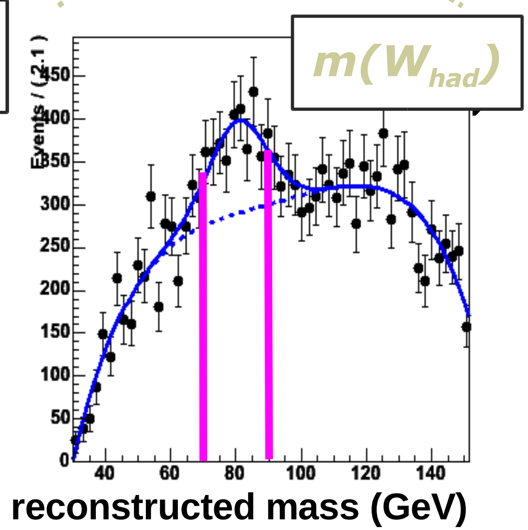
ATL-PHYS-PUB-2005-024



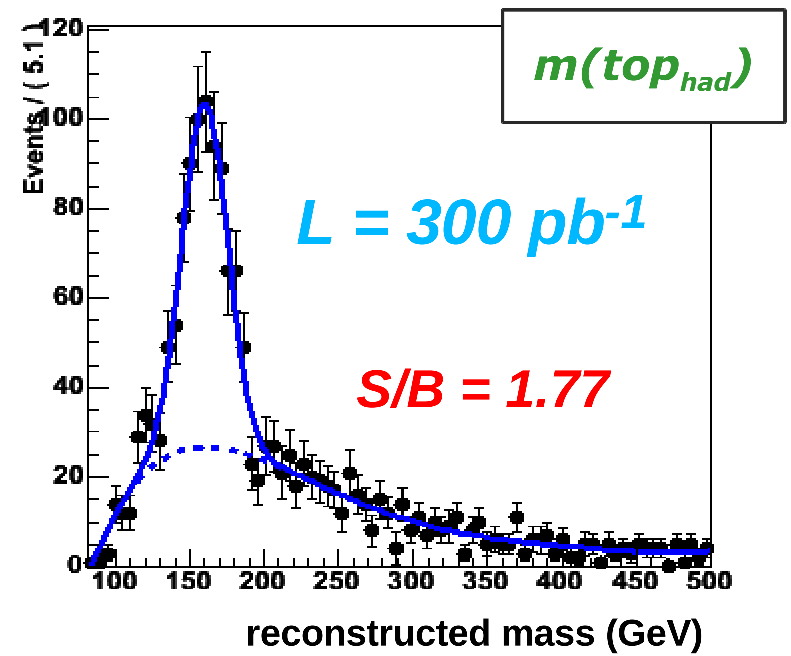
- can exploit reconstructed hadronic W mass to clean up signal
- if W mass well-reconstructed



signal+background



W mass window →



final reconstructed top mass spectrum

- to also use leptonic top -> need $\not{E}_T$ -> need jet energy calibration

b Tagging Calibration

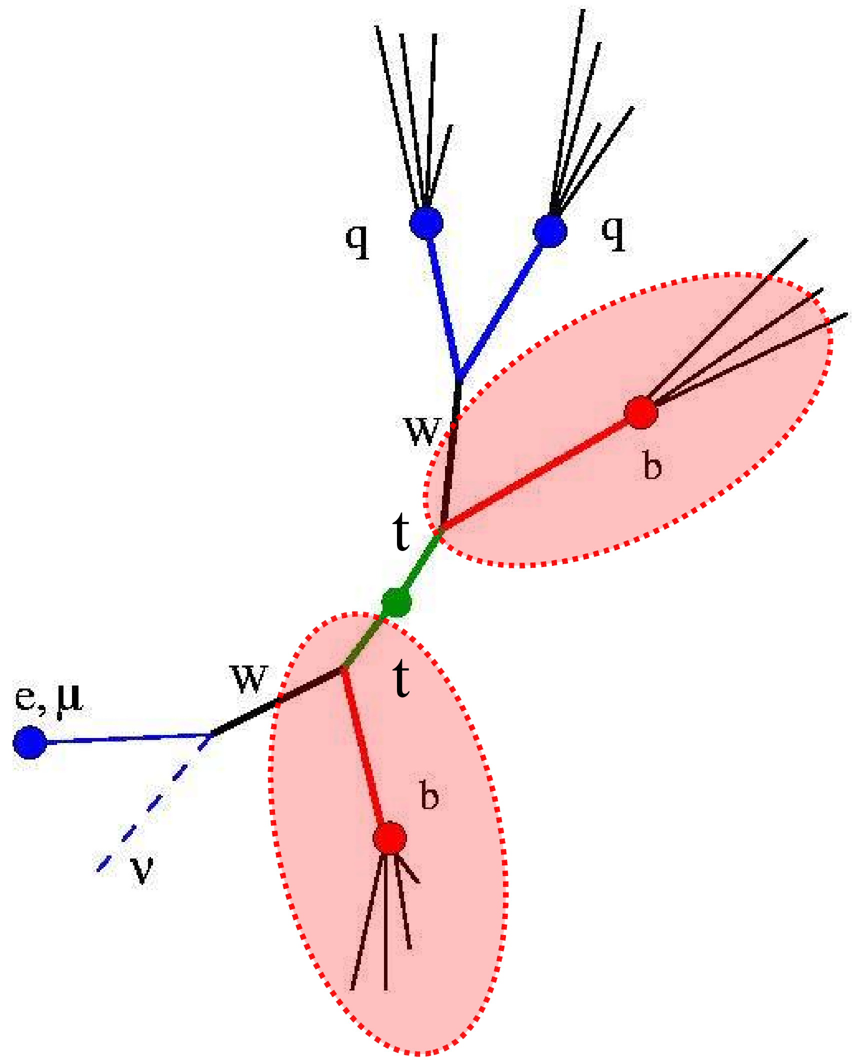
- Select ttbar events without using b tagging
  => calibrate b tagging efficiency

Lepton+jets events:

- S/B ratio (b jets / flavor mixture) = 1.77 with simple selection
- possible further S/B improvements (e.g., cut also on leptonic top mass)
- verification of S/B with mass peaks!

Dilepton events:

- only 2 b jets, clean sample
- careful with ISR/FSR!
- no mass peak for verification
- sample smaller
- => for cross-checks



Jet Energy Calibration

- Effect of mis-calibration of...

hep-ex/0403021

jet energy: $\Delta E/E=1\%$ -> Δm_{top} = 1.6 GeV

jet-jet opening angle: $\Delta\cos(\theta)=1\%$ -> Δm_{top} = 1.2 GeV

- problem: a priori knowledge of jet energy calibration: O(10%)

detector effects: detector commissioning

physics effects: isr/fsr, underlying event

- Jet energy calibration with Z(->ll)+jet events:

-> light and b jet energy scales to 1%

- problem: energy sharing between jets

systematic effect on jet-jet opening angle θ

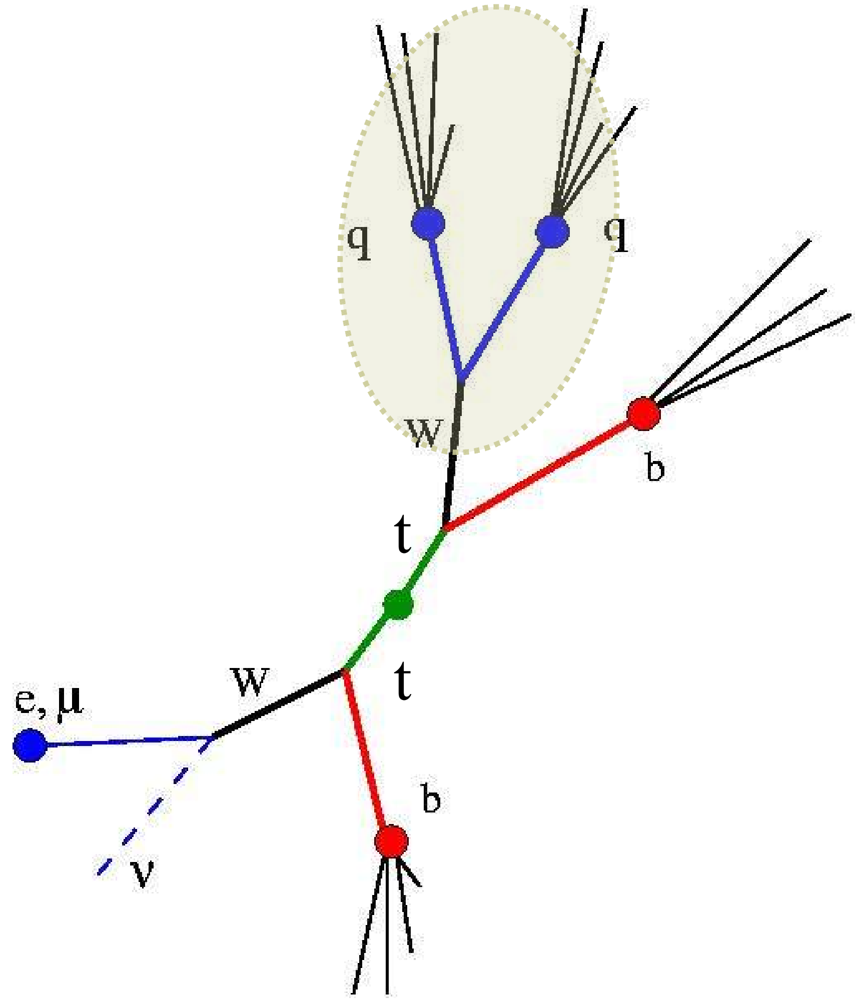
=> W mass in ttbar events shifted downwards

- => in-situ calibration using W decays in ttbar events

(still have to extrapolate from light jets to b jets)

Jet Energy Calibration

- ttbar events: source of identifiable hadronic W decays (->light quark jets)
- invariant mass of jets should yield well known W mass
- => calibrate light jet energy scale directly within ttbar events
- caution: do not use W mass for jet assignment to avoid bias
- reduction of combinatorics using b-tagging when possible



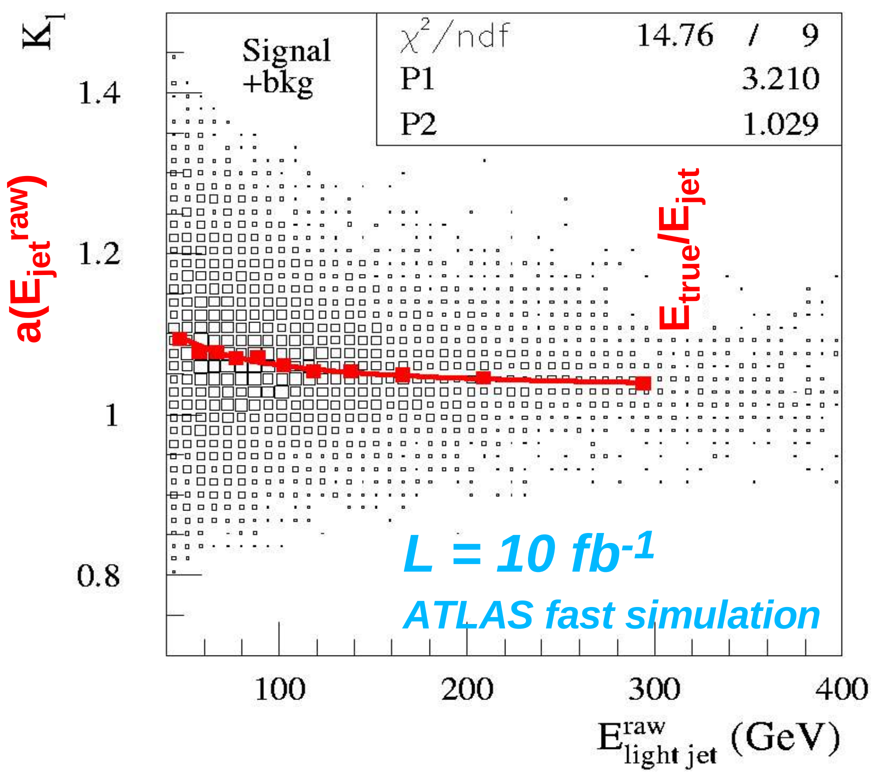
In Situ Jet Calibration

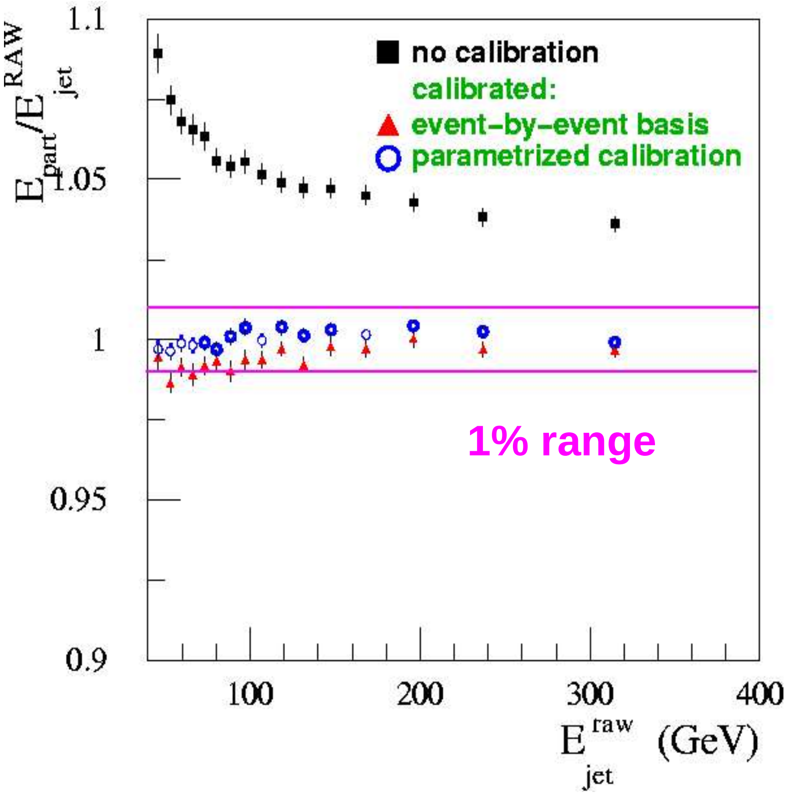
- calibrate energy scale:

  rescale jet energies with a factor a

  => $m_W^2 = 2\ a_1 E_{jet1}\ a_2 E_{jet2}\ (1-\cos\theta)$
- fit for a as a function of raw jet energy

hep-ex/0403021

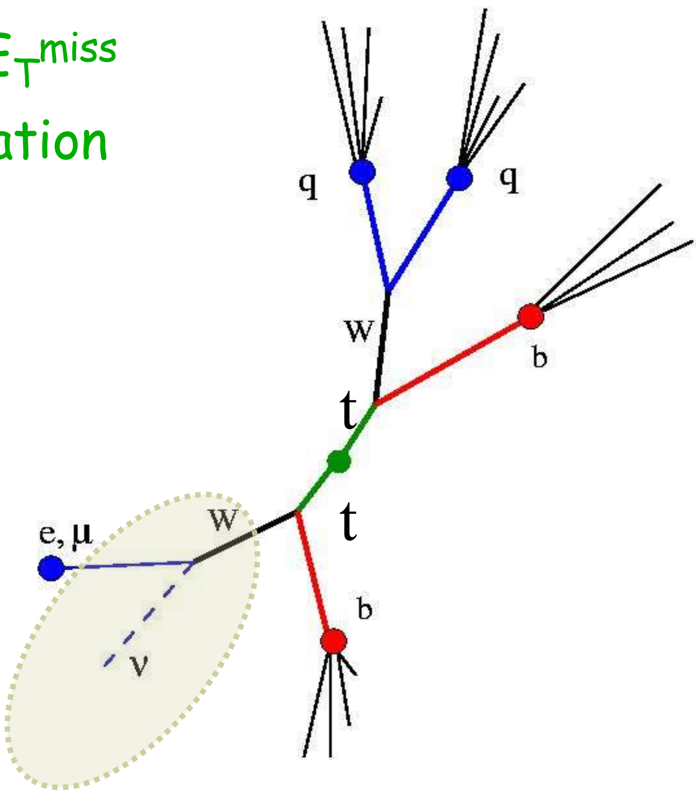




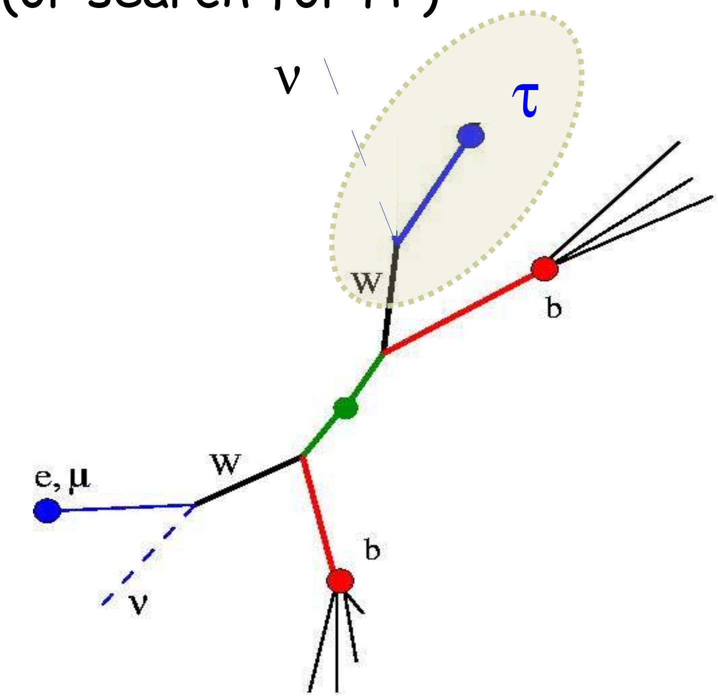
More Calibration

- Essential ingredients for many searches: neutrinos, τ leptons
- => Calibrate E_T^{miss} and τ ID with ttbar events!

1.) calibrate e/μ energy/momentum scales
2.) calibrate light and b jet energy scales
m_{top} from Tevatron
=> first E_T^{miss} calibration

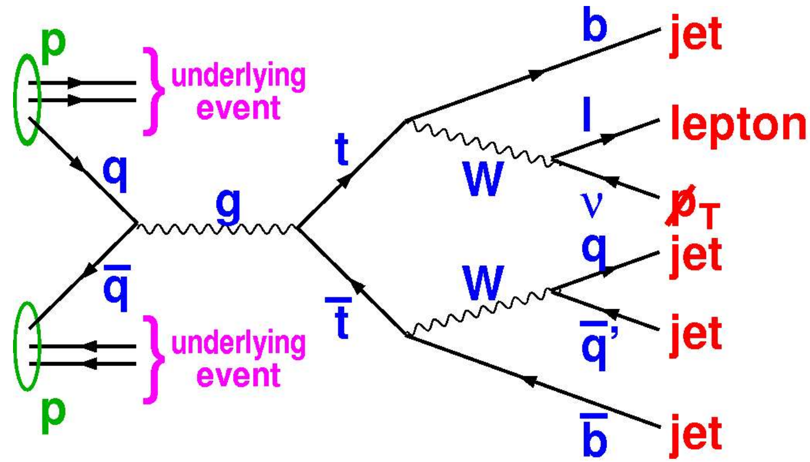


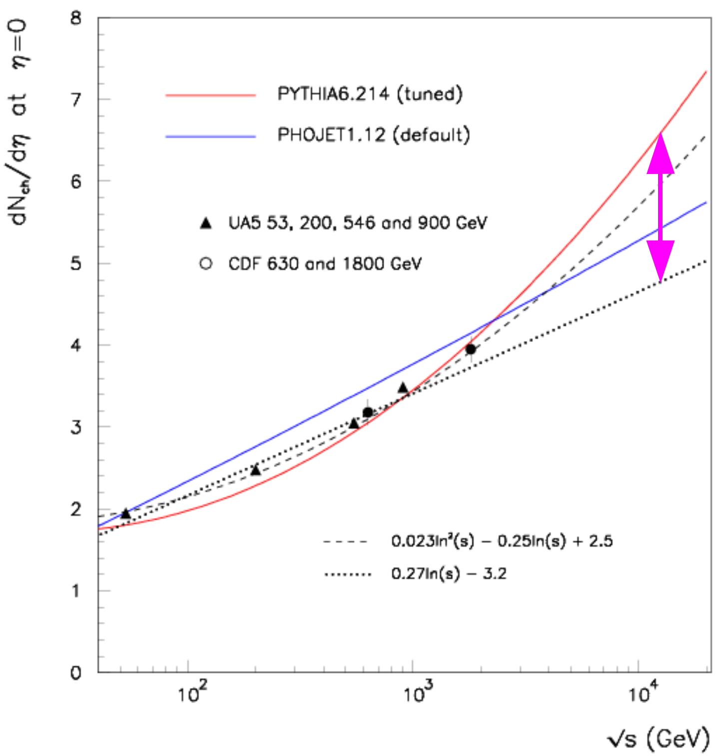
measure number of ttbar events in other channels
=> known number of events with τ
(or search for H±)



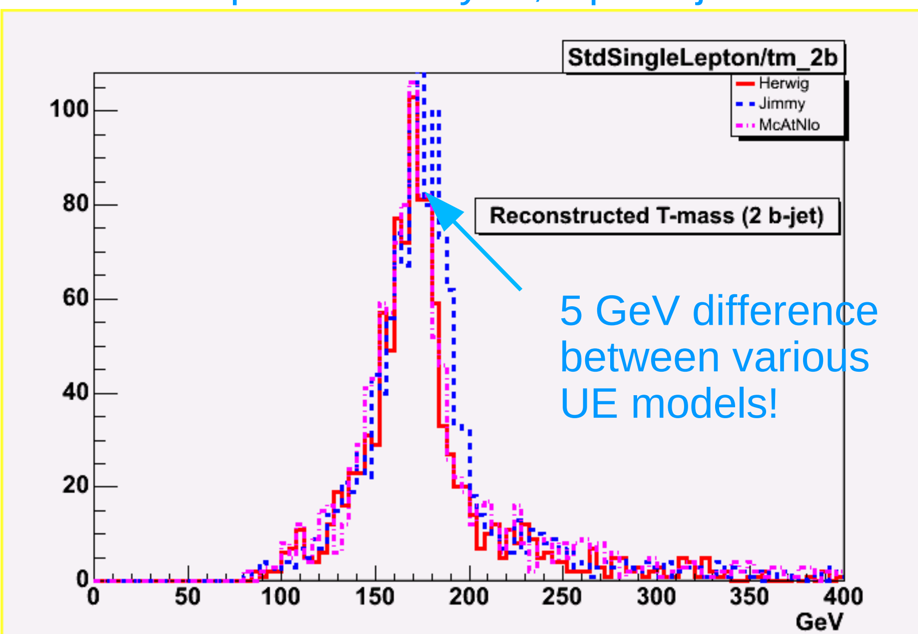
More Backgrounds

Effects of underlying event
- hard to predict for LHC
- large effects
- need LHC data to study (only few events needed)





standard top mass analysis, lepton+jets channel



ATL-PHYS-PUB-2005-024

Commissioning Summary

Inputs needed for ttbar events:

- jet reconstruction efficiency (offline) (dijet events)
- jet energy (HCAL) inter-calibration (dijet events)
- underlying event studies (from min. bias events)
- charged lepton ID efficiency (trigger & offline) (from Z->ll)
- charged lepton energy/momentum scale (from Z->ll)

Calibration information ttbar events can provide:

- b-tagging efficiency
- light jet energy scale, jet-jet opening angle calibration
- E_T^{miss} calibration
- τ ID efficiency

=> First physics measurements:

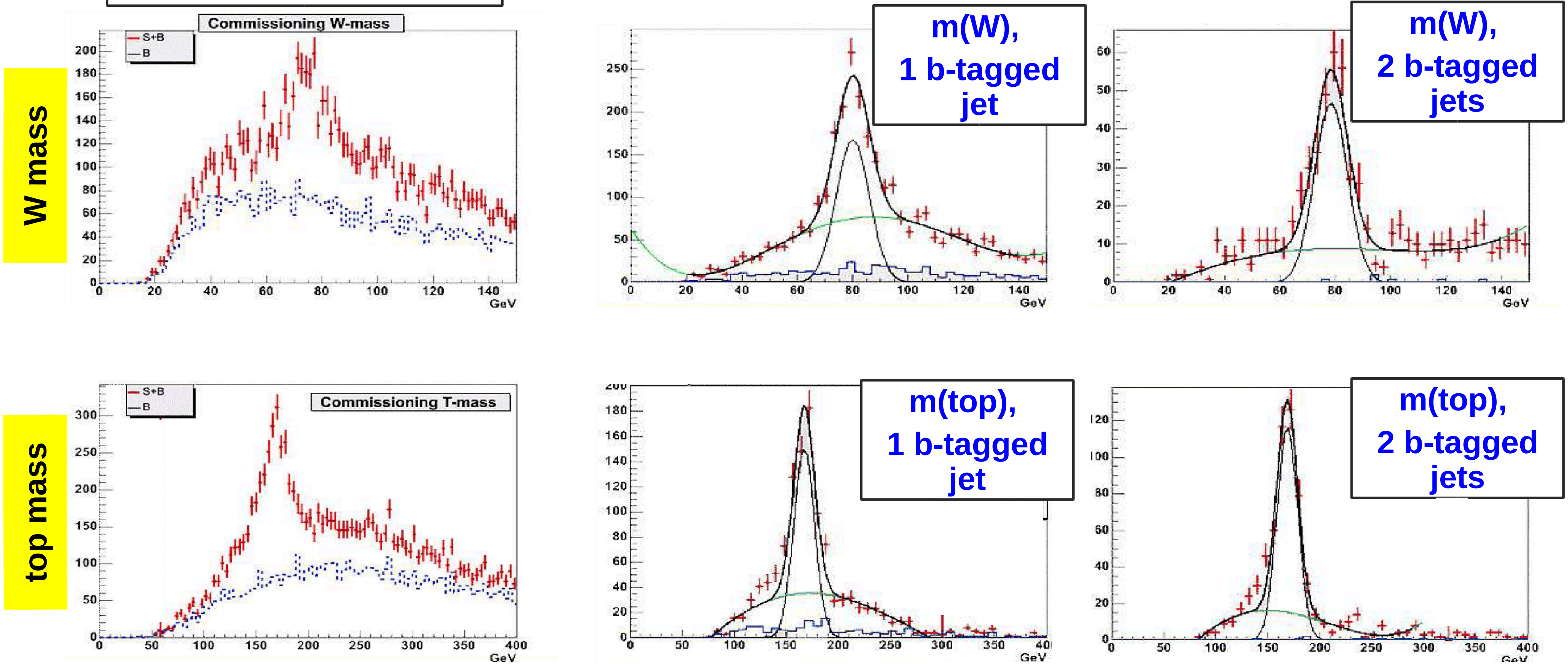
- relative cross-section σ(ttbar)/σ(W)
- top quark mass (will take time to beat the Tevatron) -> this talk
- single top discovery/confirmation

First Top Measurements

- Top mass measurement with a calibrated detector
- Effect of b tagging:

no b tagging *(commissioning)*

with b tagging



Top Quark Mass

Lepton+jets channel:

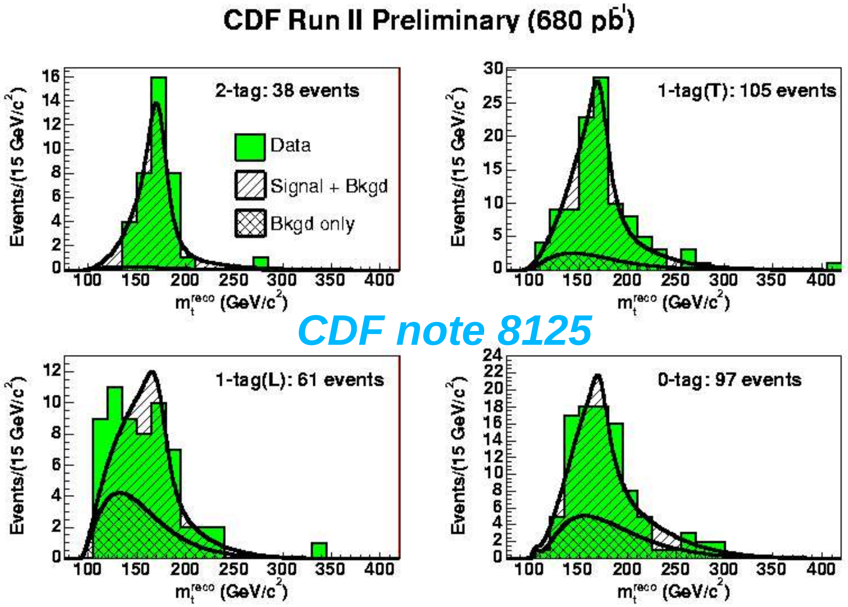
- hadronic top mass:

  most straightforward technique
- kinematic fit:

  also use leptonic side

  -> reduced statistical error

  -> Tevatron



- Matrix Element / Dynamical Likelihood:

  integrate over all possible final states

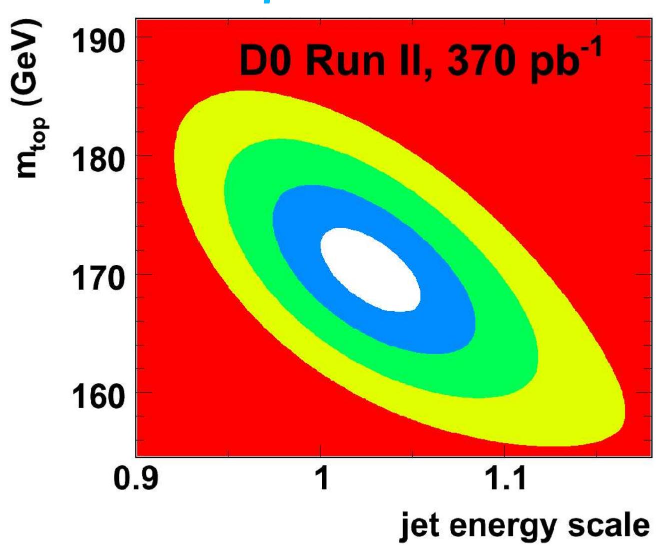
  best possible statistical error

  -> Tevatron

  -> too computing intensive for m_{top} @ LHC (?)

  => Ideogram technique (CMS)

hep-ex/0609053



- events with large p_T(top)

  independent systematics

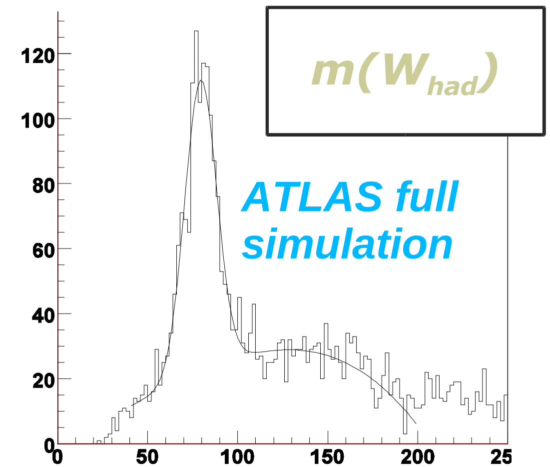
Top Quark Mass

- Measurement based on the hadronic top mass:
  - 0.) event selection (including 2 b-tagged jets)
  - 1.) find W->jj decay and jet energy rescaling parameters

$$\chi^2 = \frac{\left(M_{jj}(\alpha_1, \alpha 2) - M_W\right)^2}{\Gamma_W^2} + \left(\frac{E_{j1}(1-\alpha_1)}{\sigma_{j1}}\right)^2 + \left(\frac{E_{j2}(1-\alpha_2)}{\sigma_{j2}}\right)^2$$

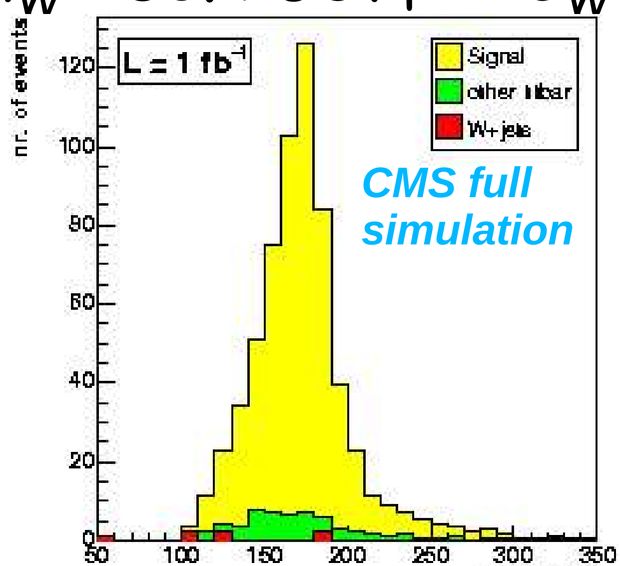
W mass — jet energy

contributions to χ^2

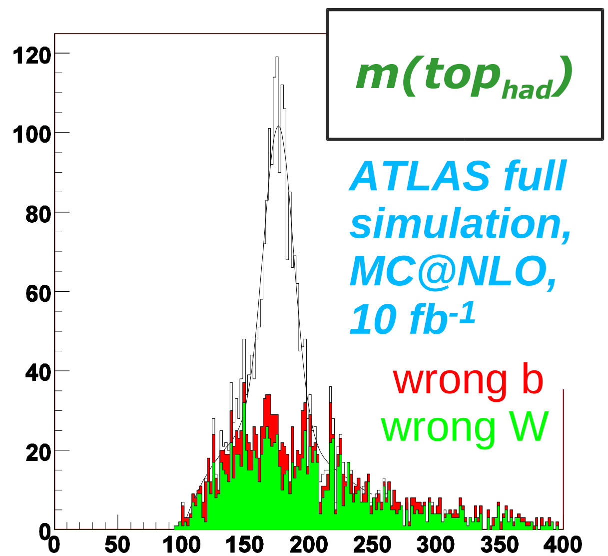


W mass before rescaling (GeV)

  - 2.) select events if $|m_W - 80.4 \text{ GeV}| < 2\sigma_W$
  - 3.) choose b jet to give largest top p_T



top quark mass



top quark mass

Top Quark Mass

- statistical error: 0.05-0.25 GeV with 10 fb^{-1} -> not dominant!

  => study (and reduce) systematic errors; other measurement techniques
- Kinematic fit for the top quark mass:

  => reduced uncertainty from fsr modeling
- Selection of high p_T top quarks:

  => independent systematic errors => combination

uncertainty	hadronic top	kinematic fit	high-p_T top
light-jet energy scale (1%)	0.2	0.2	
b-jet energy scale (1%)	0.7	0.7	
final state radiation	1.0	0.5	0.1
mass rescaling			0.9
underlying event			1.3
CR, m_{top} definition	$O(\Lambda_{QCD})$	$O(\Lambda_{QCD})$	$O(\Lambda_{QCD})$
total	**1.3**	**0.9**	**1.6**

-> studies needed

Dilepton channel:

very clean channel

but 2 neutrinos: no direct m_{top} measurement possible

- Weighting technique:

  assume m_{top} value

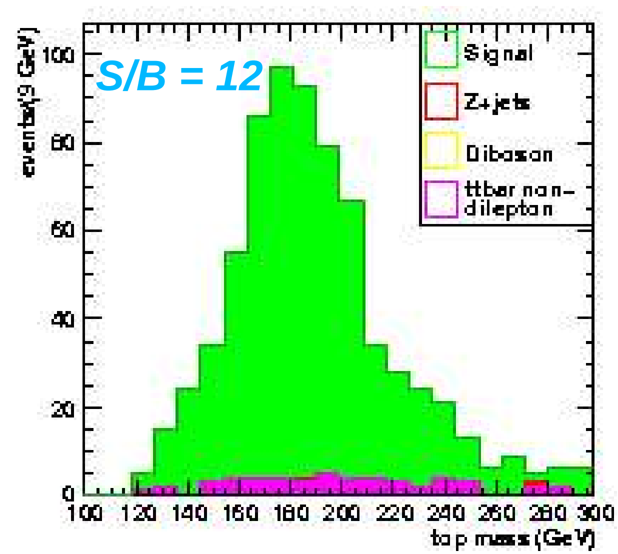
  reconstruct event kinematics

  assign event weight according to MC distributions

  evaluate weights for different m_{top} hypotheses

  -> largest systematics: PDF modeling (1.2 GeV, ATLAS), JES (1 GeV, CMS)

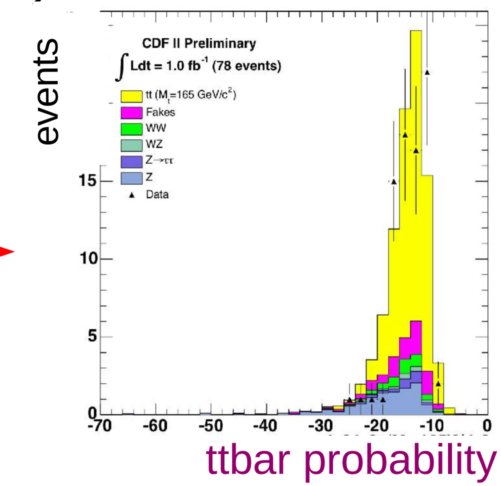
CMS Physics TDR Vol II



- Matrix Element technique:

  integrate over all possible final states

  -> Tevatron



All-hadronic channel:

very large multijet background

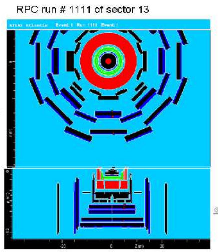
~3 GeV systematic error from FSR modeling

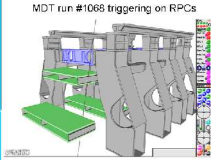
hep-ex/0403021

Summary and Outlook

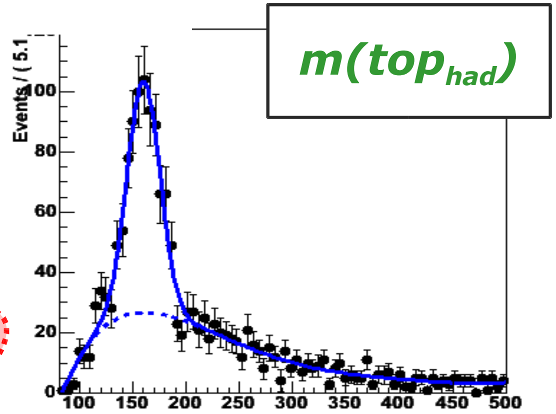
- While the Tevatron is producing results...
  see the many talks here at DPF2006!

- ...LHC detector commissioning has begun:
  cosmic ray events

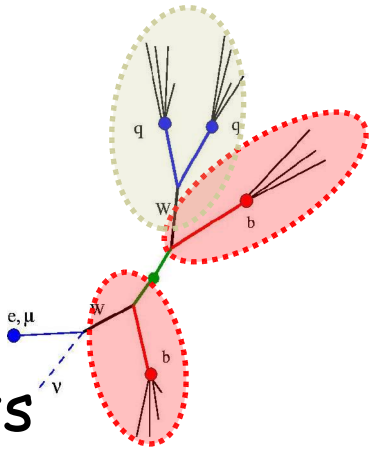




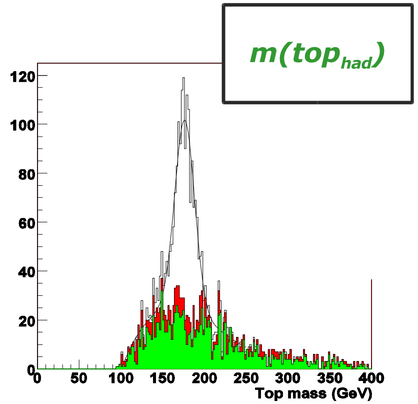
- 2008: first data at ECM = 14 TeV
  ttbar signal easy to find



- Top events crucial for calibration:
  b-tagging efficiency
  jet energy scale
  missing transverse energy



- Preparations for ttbar measurements
  top quark mass ("benchmark measurement")
  other measurements: talk by Mohsen Khakzad (Wednesday)



Backup Slides

ATLAS and CMS

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity 4 magnets Calorimeters in field-free region	Solenoid Only 1 magnet Calorimeters inside field
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\ p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segm.
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → $\sigma/p_T \sim 7$ % at 1 TeV standalone	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

ATLAS and CMS

- Completion of the detectors:

Detectors will not be complete in 2007

- ATLAS because of staging TRT coverage over $|\eta|<2$ instead of 2.4
- CMS pixel and end-cap ECAL installed during first shutdown
- BOTH reduced trigger bandwidth due to deferrals on HLT processors (~50% of full capability)

Small impact on performances at low L (except for B physics)

- Detector performance:

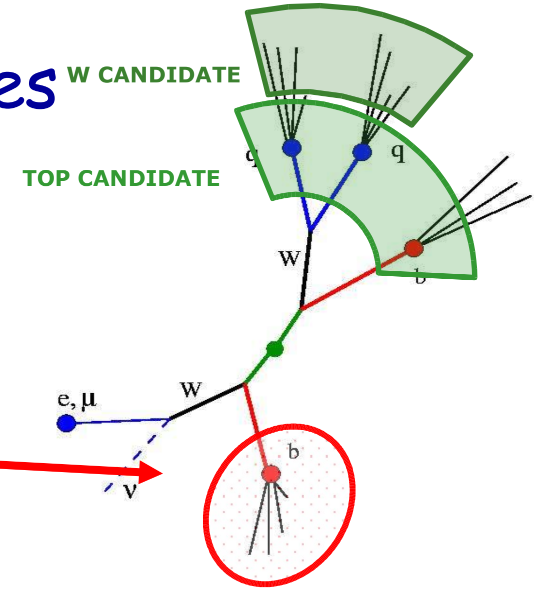
	Expected performance day 1	Physics samples to improve (examples)
ECAL uniformity e/γ scale	~ 1% (ATLAS), 4% (CMS) 1-2 % ?	Minimum-bias, $Z \rightarrow ee$ $Z \rightarrow ee$
HCAL uniformity Jet scale	2-3 % < 10%	Single pions, QCD jets $Z (\rightarrow ll)$ +1j, $W \rightarrow jj$ in $t\bar{t}$ events
Tracking alignment	20-500 μm in $R\phi$?	Generic tracks, isolated μ, $Z \rightarrow \mu\mu$

Ultimate statistical precision achievable after few days of operation. Then face systematics ....

E.g. : tracker alignment : 100 μm (1 month) $\rightarrow$ 20μm (4 months) $\rightarrow$ 5 μm (1 year) ?

b-Tagging Studies

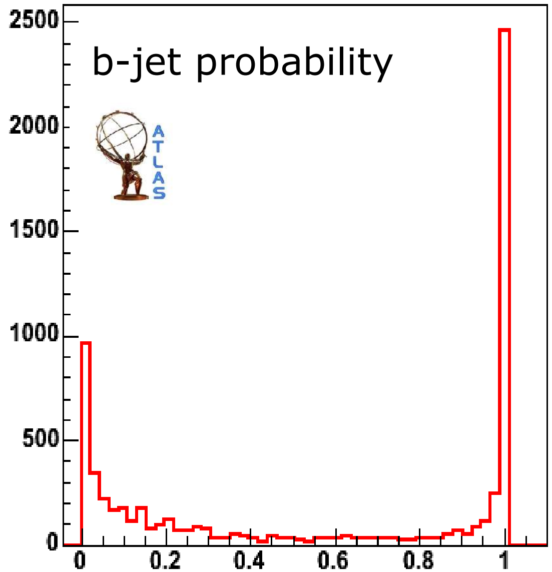
- Exploiting ttbar signal : b-tagging studies
  - An enriched sample of b-jets can be extracted from L+jets Top events
  - Cut on $m(W_{had})$ and $m(top_{had})$ masses
  - Look at b-jet probability of 4[th] jet (must be b jet if all assignments are correct)

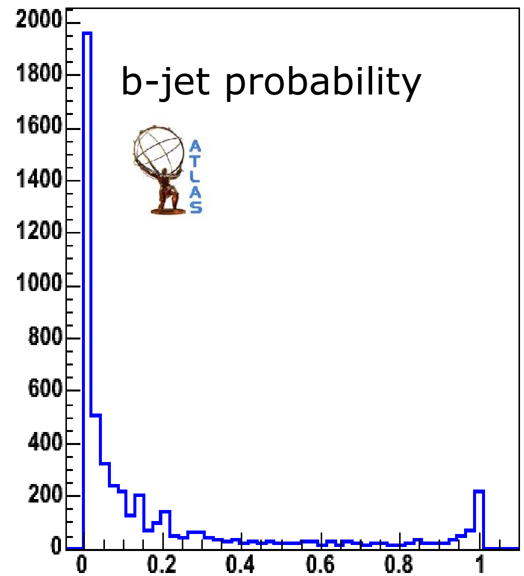


ttbar (signal)

'always b jet if all jet assignment are OK'

b enrichment expected and observed





W+jets (background)

'random jet', few b jets expected

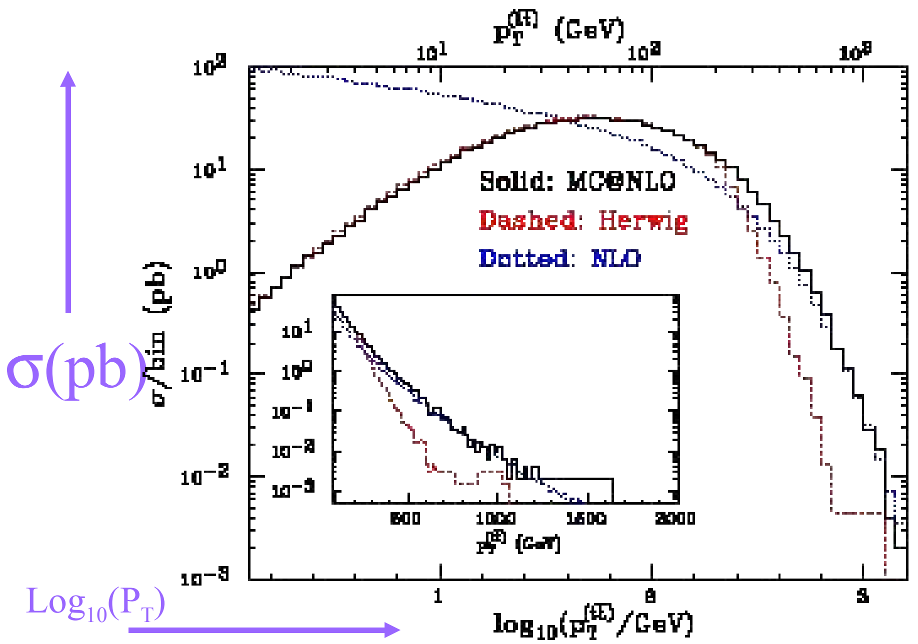
$t\bar{t}$ Cross Section

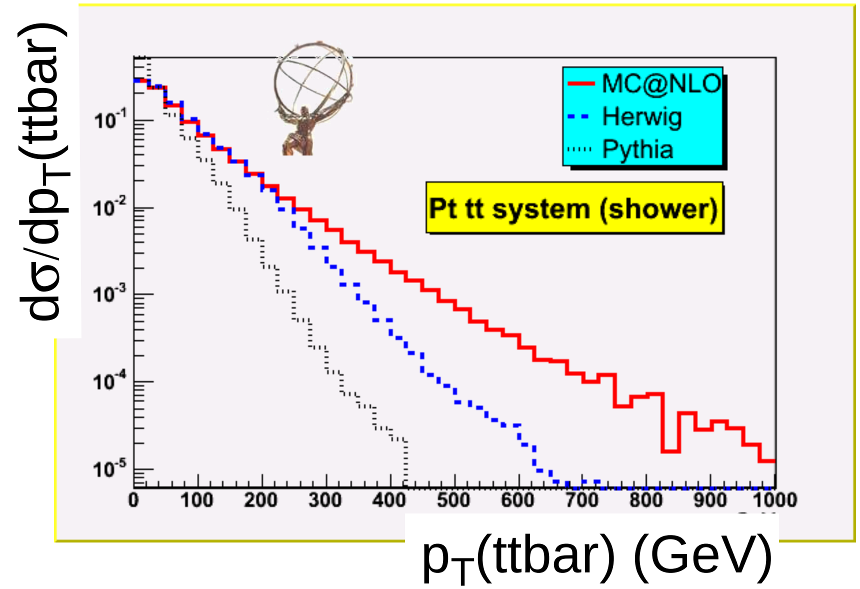
- Systematic errors on the ttbar cross section measurement with 10 fb^{-1}: (largest contributions)

Uncertainty	lepton+jets	dilepton
light jet energy scale	1.6%	--
b jet energy scale	1.6%	3.6%
b tagging (conservative)	7.0%	3.8%
pileup	3.2%	3.6%
underlying event	0.8%	4.1%
b fragmentation	1.0%	5.1%
PDF uncertainties	3.4%	5.2%
integrated luminosity	3%	3%

CMS Physics TDR Vol II

- MC@NLO: NLO Monte Carlo
  - Matching NLO calculations of QCD process with parton shower MC
    - Total rates are accurate to NLO
    - Hard emissions treated as in NLO computations
    - Soft/collinear emissions handled by MC shower
    - No 'double counting' between these
  - Interfaced to Herwig





p_T(ttbar):

- Herwig and MC@NLO agree at low p_T
- MC@NLO harder at large p_T