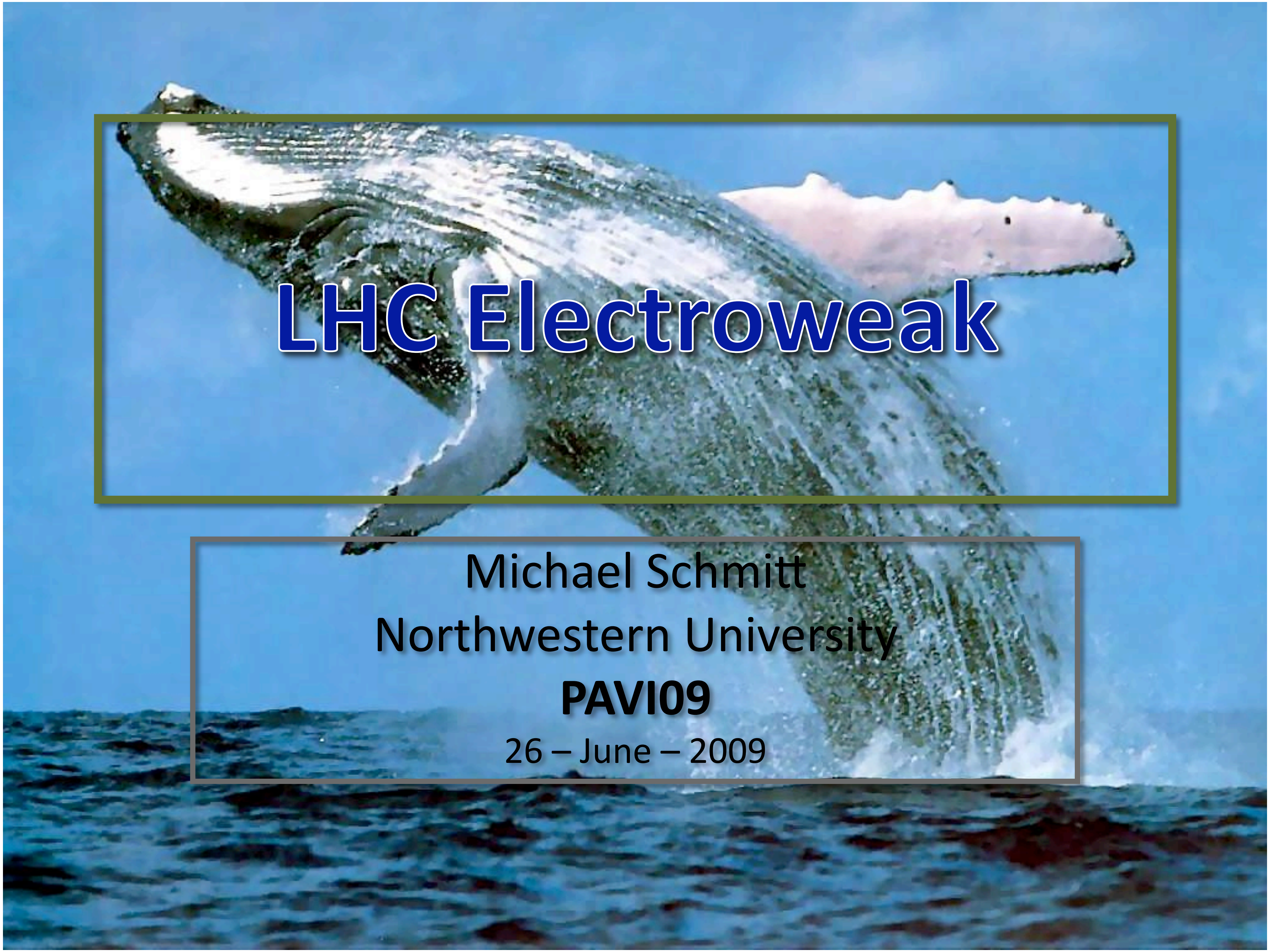


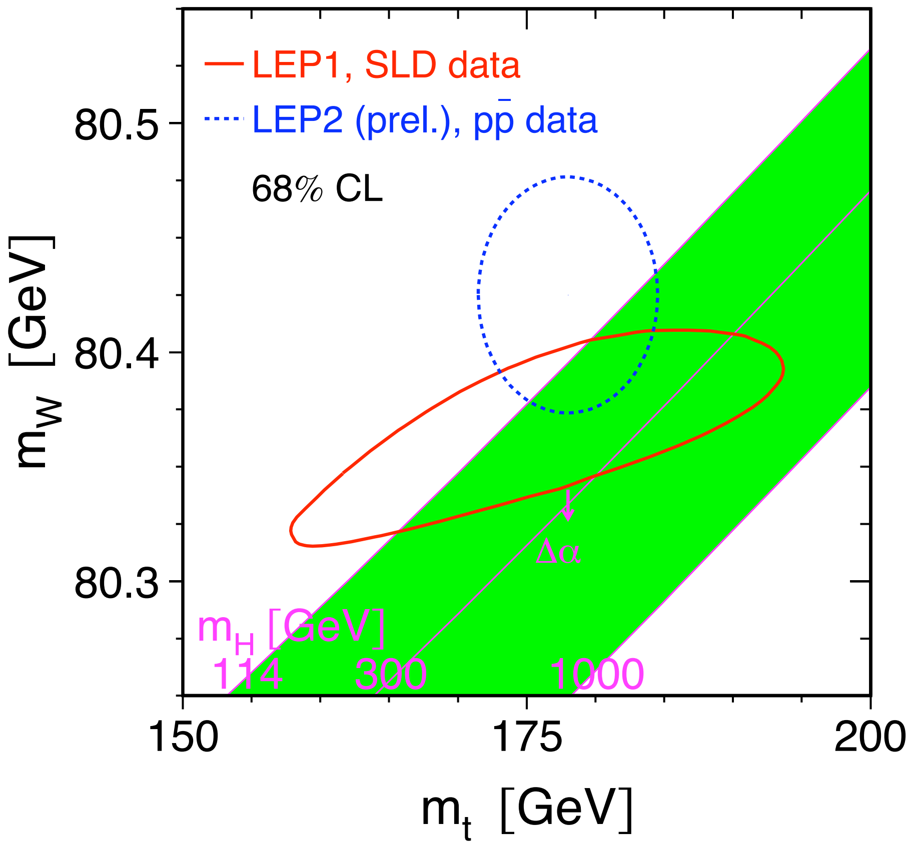
LHC Electroweak

Michael Schmitt
Northwestern University

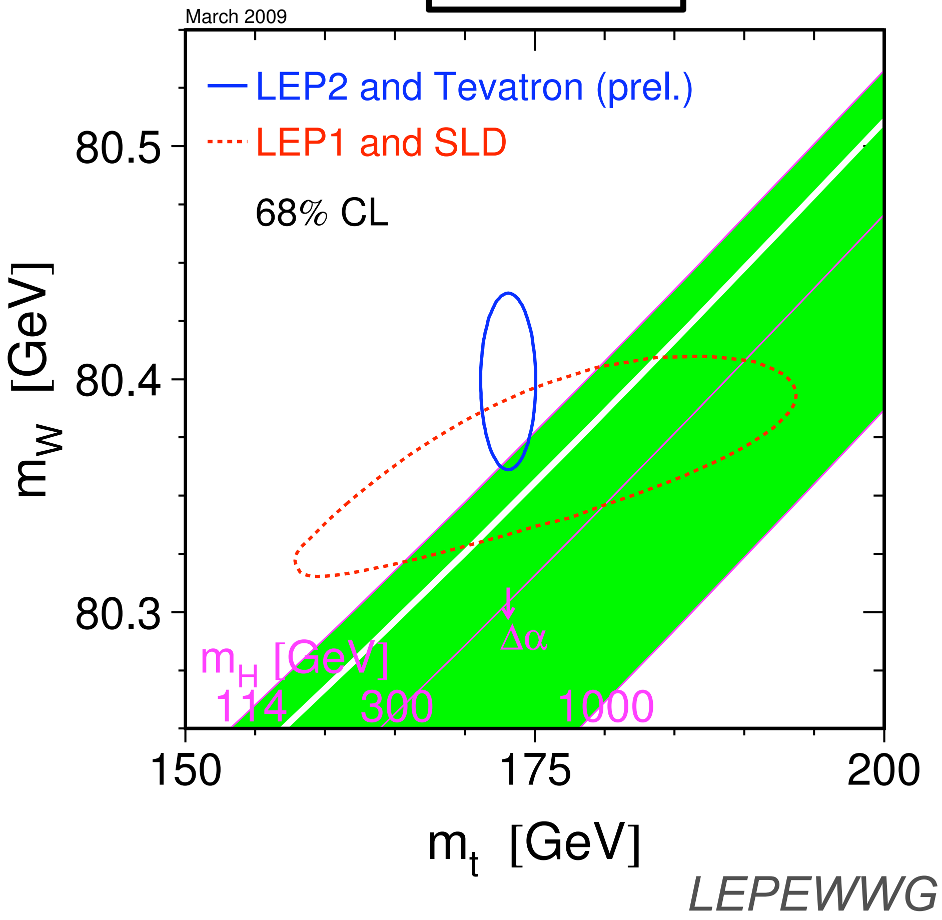
PAVI09

26 – June – 2009

2005



2009



How might the LHC change this picture?

topics

- **the LHC and the LHC experiments**
- **what to expect (hope for) this coming year**
- **top quark mass measurements**
- **W mass measurements**
- **Z forward-backward asymmetries**
- **closing**

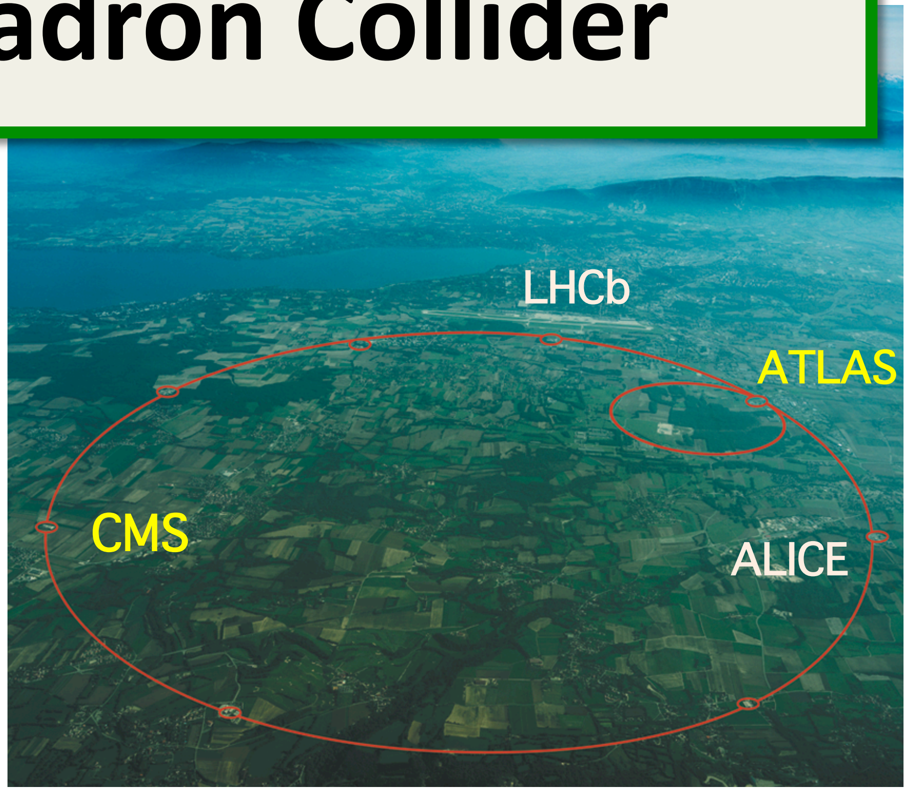
many other electroweak topics left out:

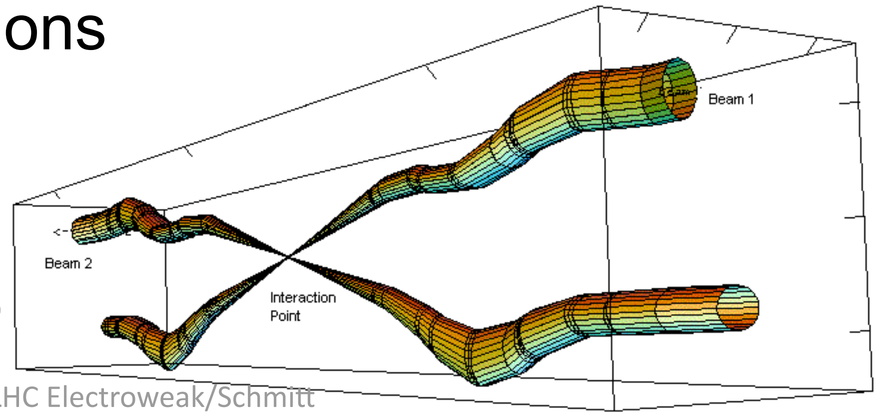
- W, Z cross sections
- di-boson production / tri-linear couplings
- W polarization in top decays
- the Higgs boson

The LHC and the LHC Detectors

LHC : Large Hadron Collider

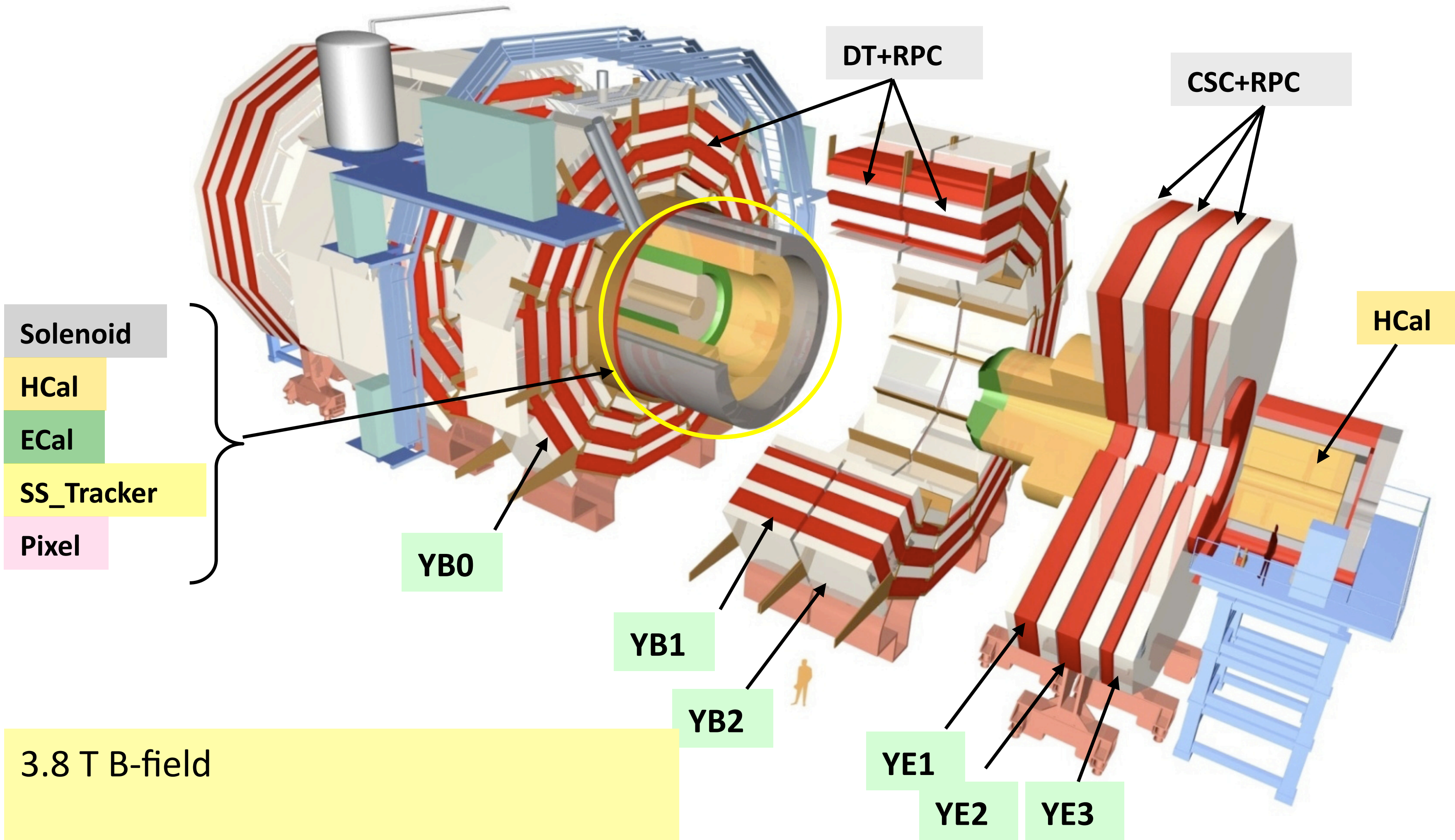
- two colliding proton beams
- up to 7 TeV per beam
- multiple acceleration stages
- most collisions are initiated by *gluons*, not quarks
- for W production, $X_{Bj} \approx 10^{-3}$
- heavy ion program runs alternately with pp collisions
- beams cross every 25 ns
- $O(10^8)$ collisions per sec
- transverse size $O(10\ \mu m)$





Relative beam sizes around IP1 (Atlas) in collision

The CMS Detector

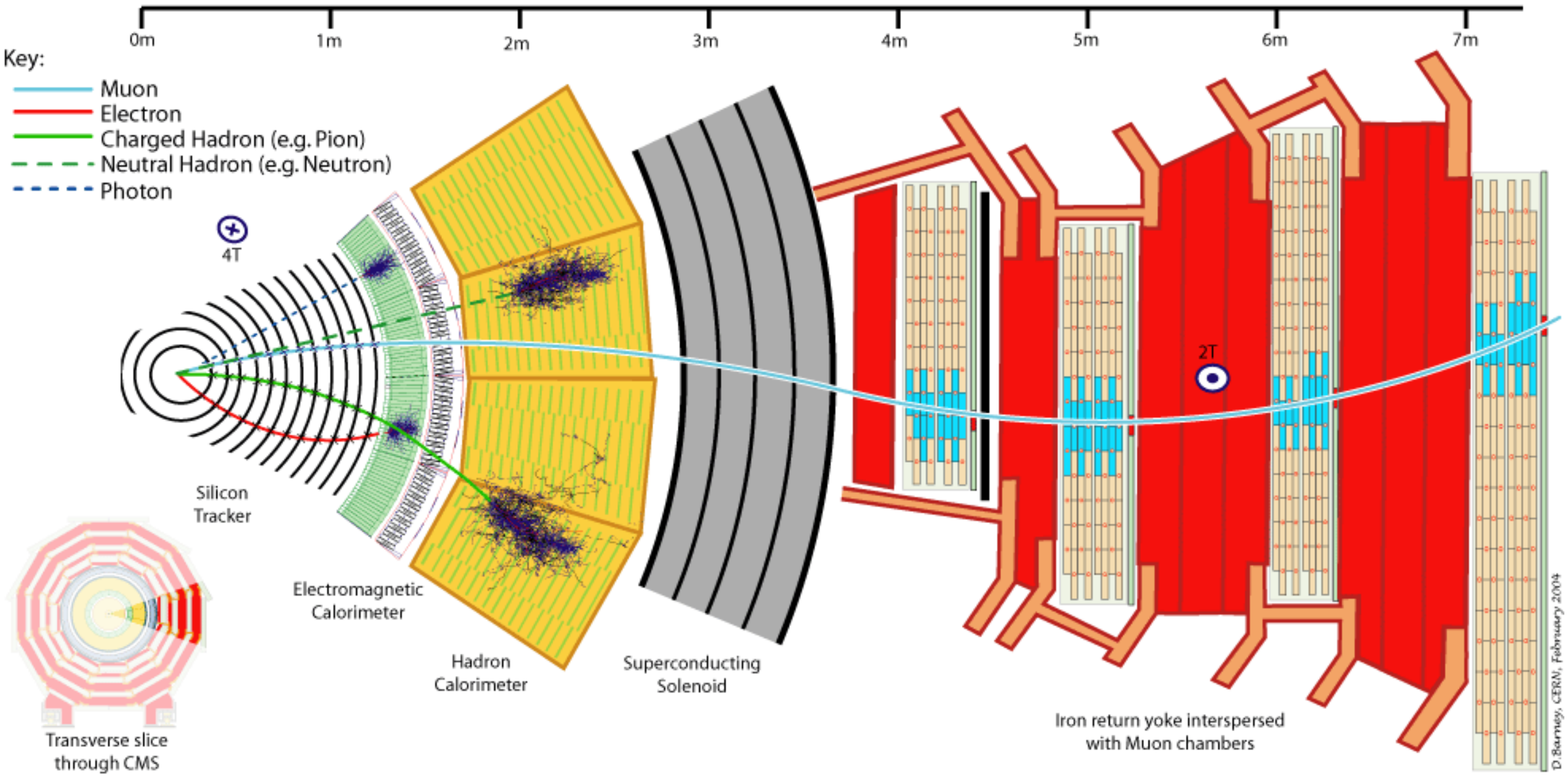


3.8 T B-field

DAQ/Trigger: 10^7 reduction in rate

22m long / 15m diameter / 12,500 tons

CMS


0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

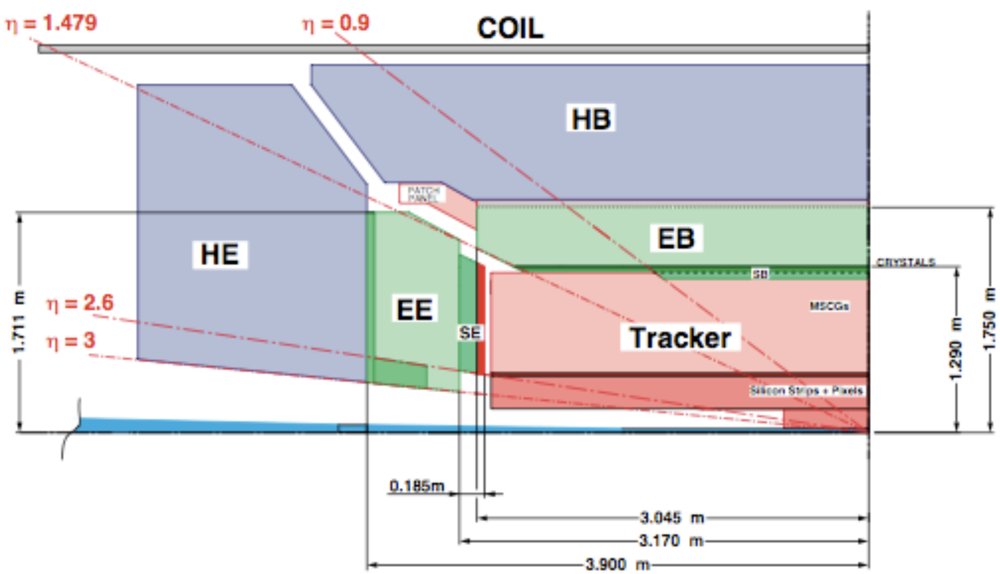
CMS

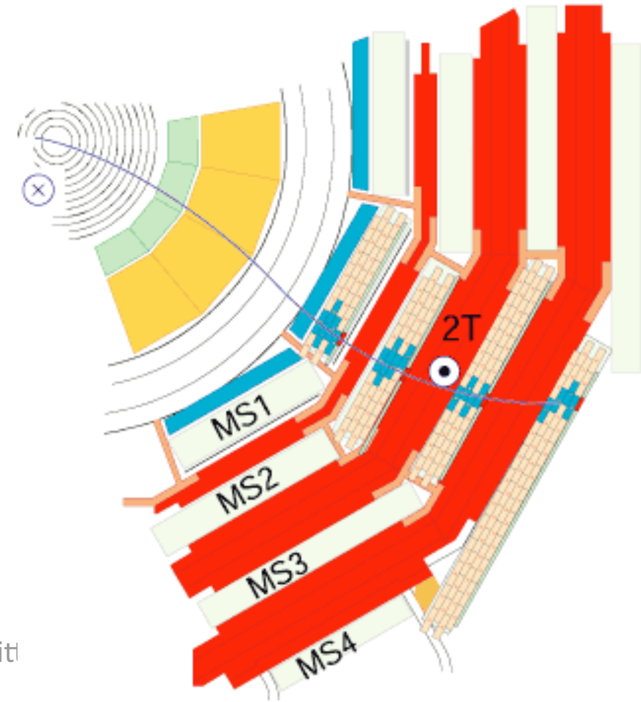
ELECTONS

- 80k lead-tungstate crystals
- granularity 0.0175 x 0.0175
- cover barrel & end caps
- no cracks
- 26 X_0 thick
- avalanche photodiodes
- $\sigma(E) / E = 0.006$ at 100 GeV

MUONS

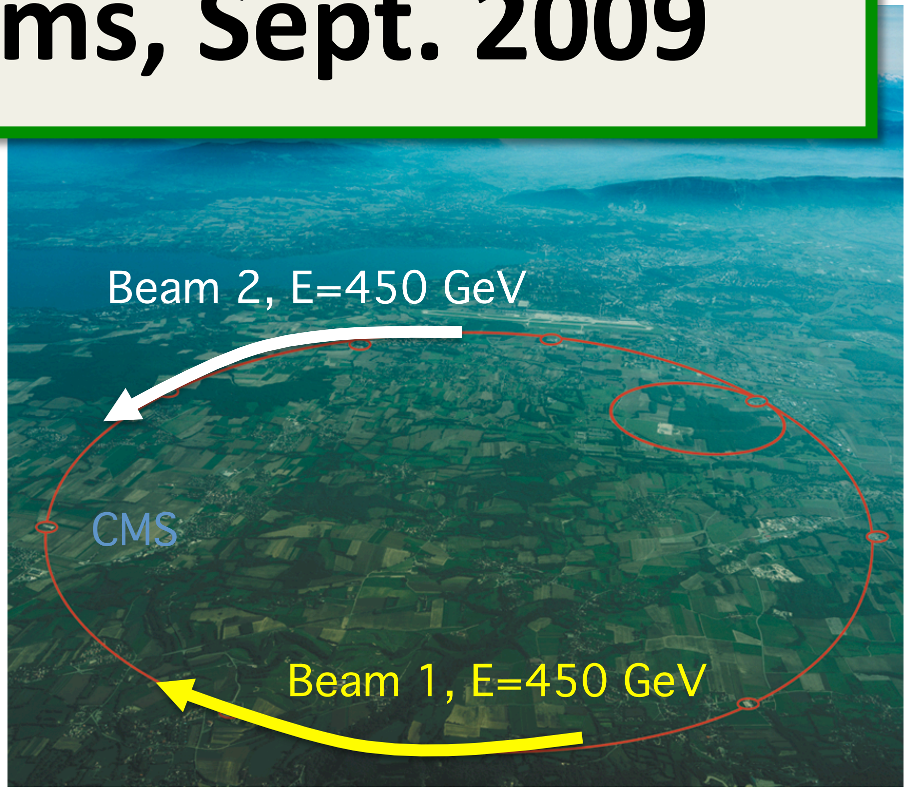
- four “stations” provide four segments
  - drift tubes in barrel
  - cathode strip chambers in end caps
  - resistive plate chambers for trigger
- fields up to 2 T allow p measurement
- combined with tracks in tracker:
  $\sigma(p_T) / p_T = 0.015$ at 100 GeV



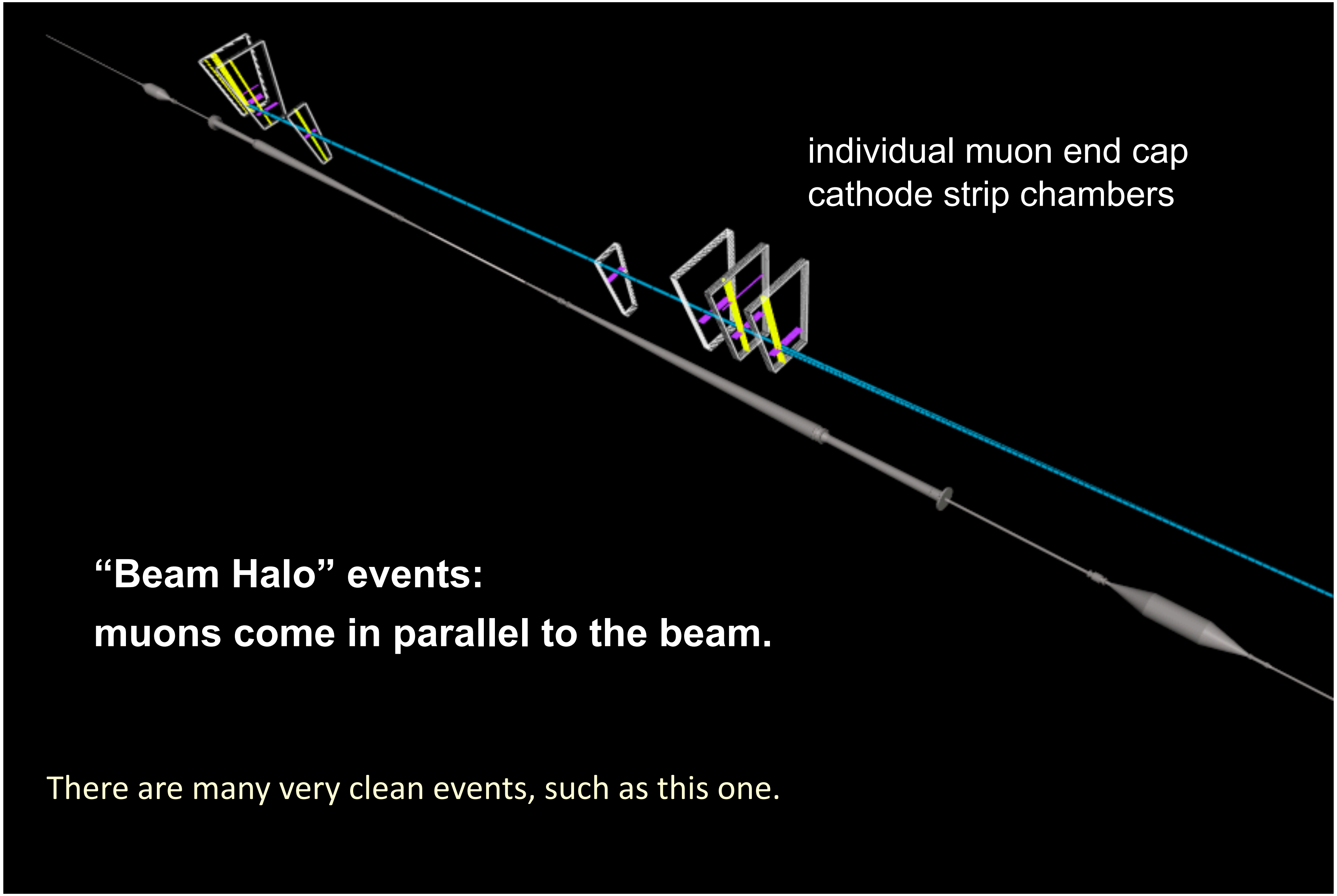


LHC : First Beams, Sept. 2009

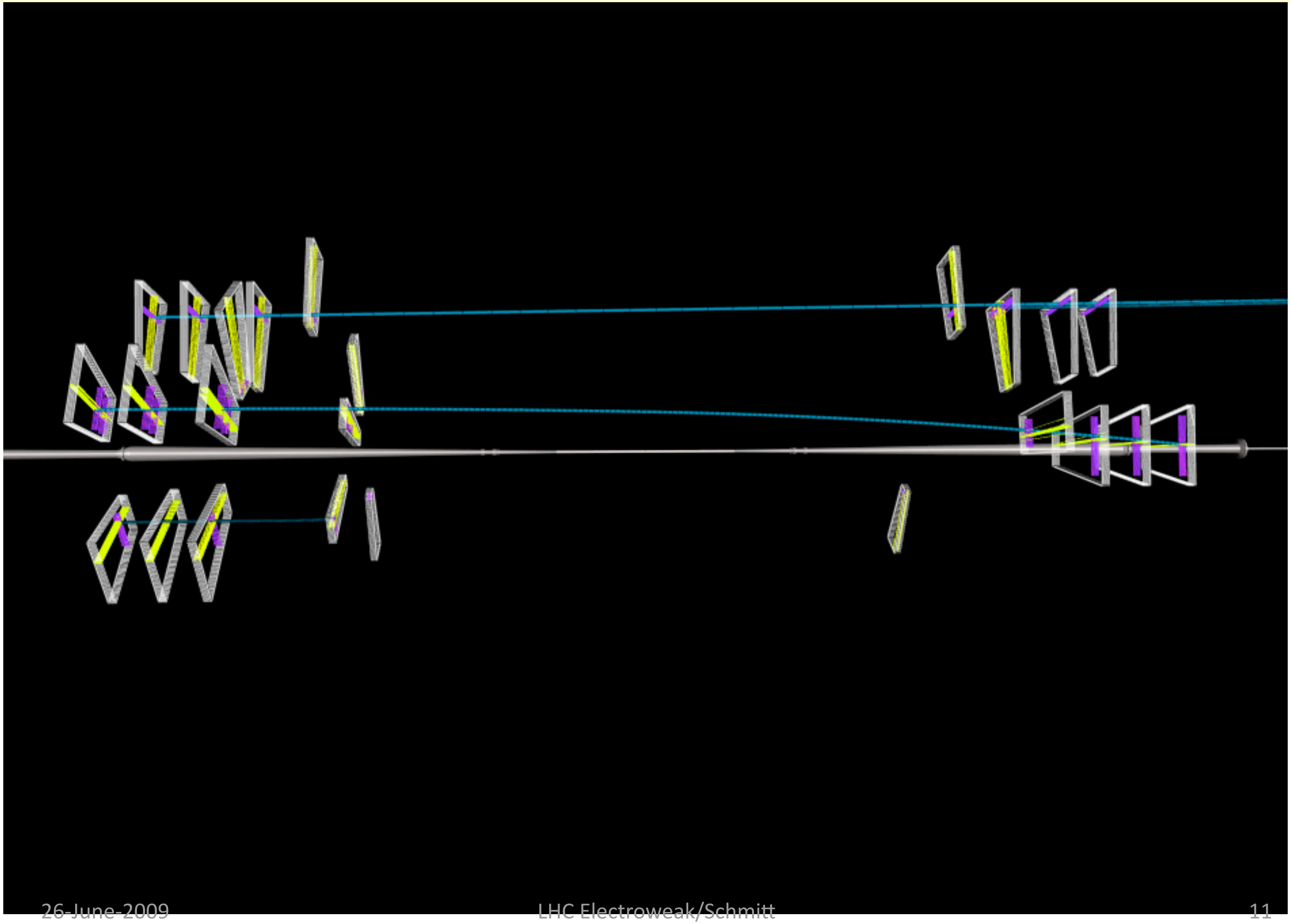
- **7-8 September**
  - Single shots of beam 1 onto closed collimator 150m upstream of CMS
- **9 September**
  - Additional single shots of beam 1 onto collimator 150m upstream
- **10 September (Media Day!)**
  - Beam 1 circulated in the morning, 3 turns by 10:40am (in 1 hour!)
  - Beam 2 circulated by 3:00pm, 300 turns by 11:15pm
- **11 September**
  - RF system captures beam at 10:30pm (millions of orbits)
- **19 September**
  - magnetic incident



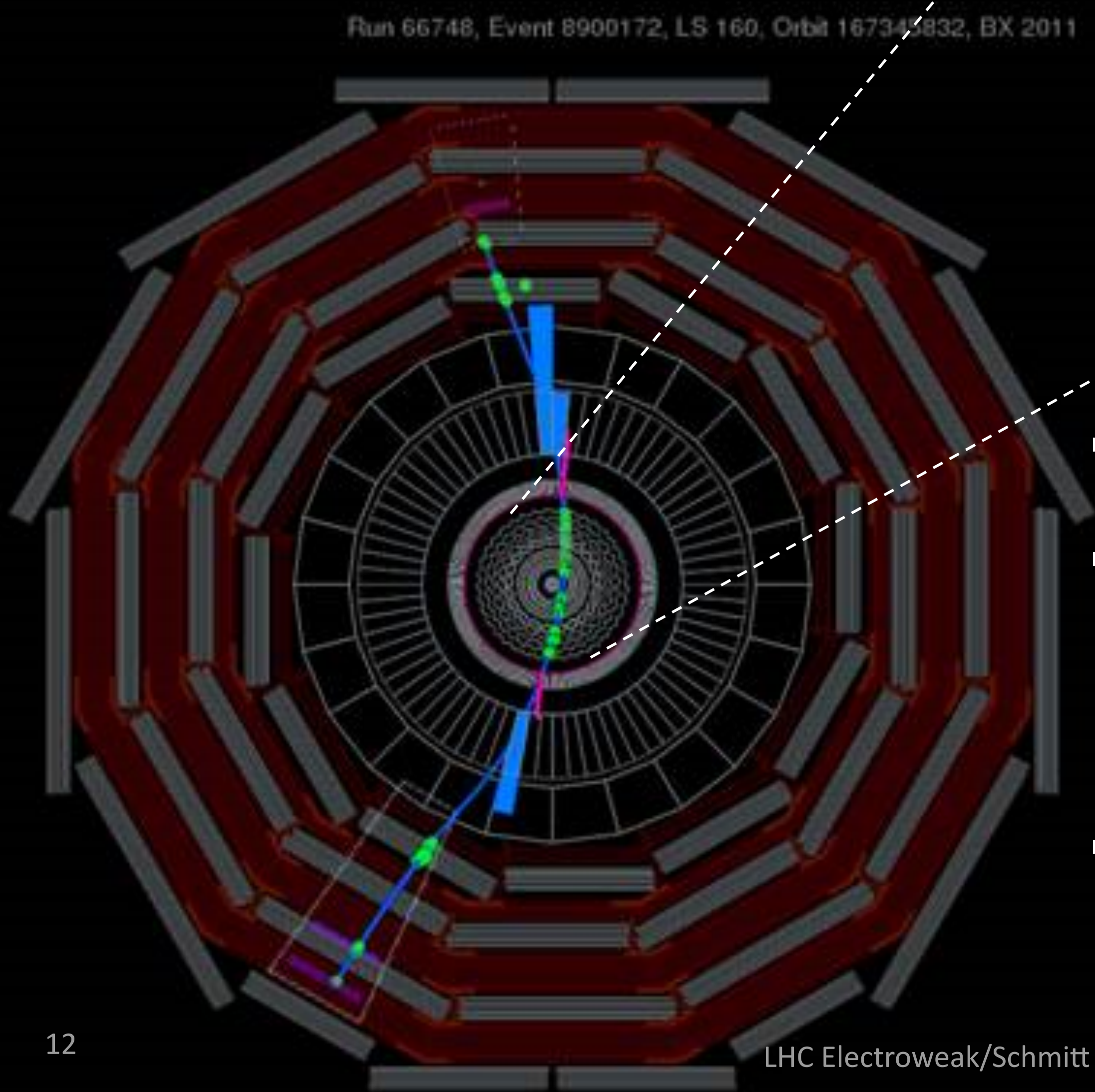
- **During all of these activities, CMS triggered and recorded data**
  - ~40 hours of beam to CMS
  - All systems on, except for Tracker and Solenoid

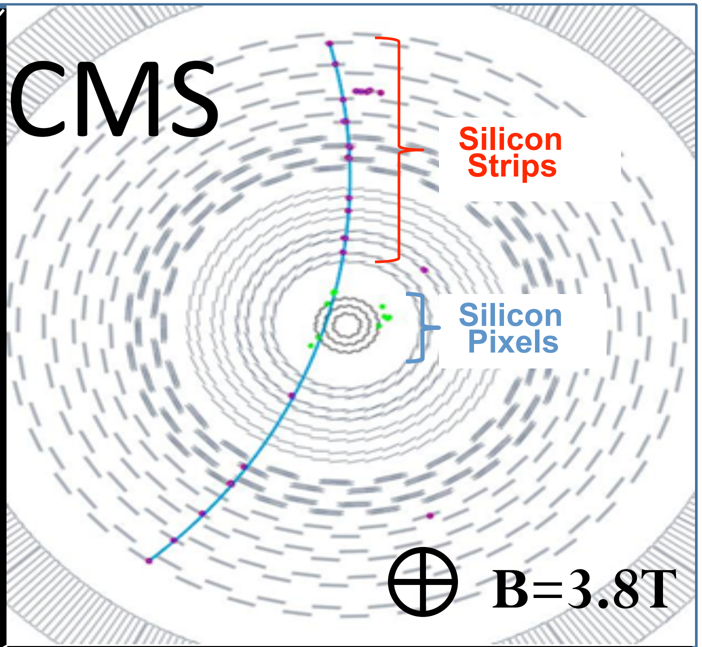

individual muon end cap
cathode strip chambers
“Beam Halo” events:
muons come in parallel to the beam.
There are many very clean events, such as this one.

Sometimes we reconstruct stand-alone muons across 20m !



Cosmic Rays in CMS





- We carried out a serious cosmic ray data taking exercise (Oct 08)
- The data have allowed us to commission the hardware to an unprecedented degree.
  - tracker & muon alignment
  - calorimeter uniformity
- Several publications will come out this fall.

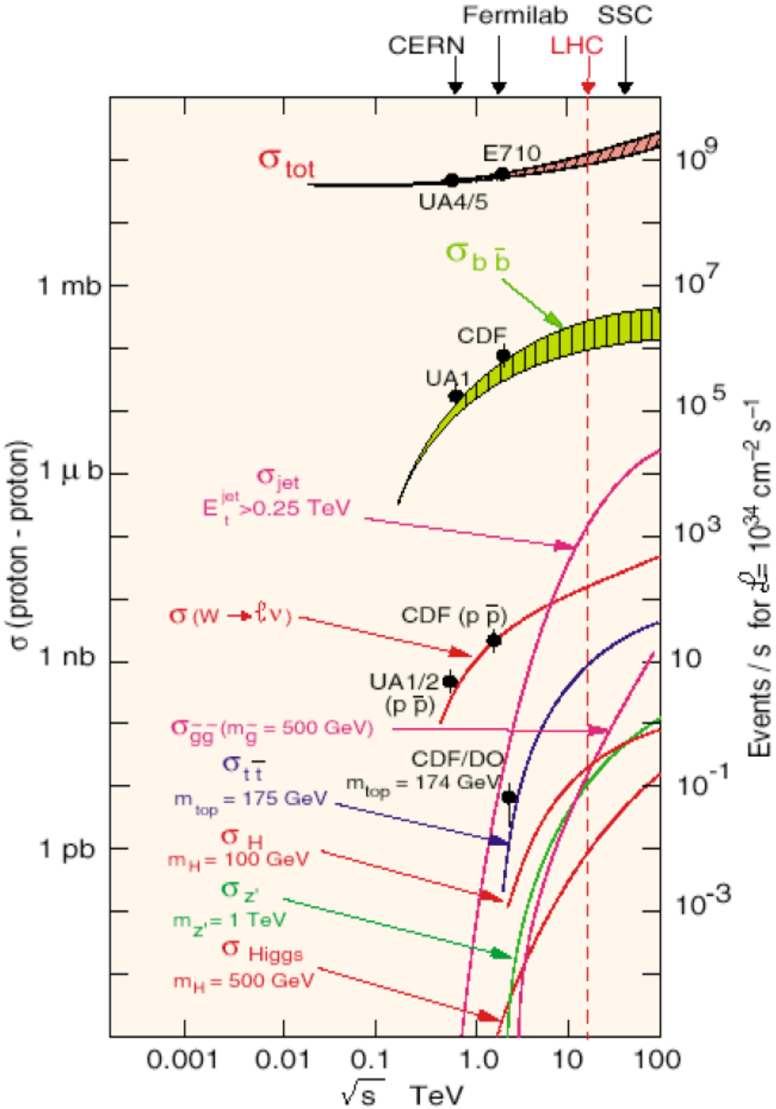
The First Run: 2009-2010

Prospects for Beam

The LHC run will be long, and should deliver at least 200 pb^{-1} per experiment.

Month	Comment	Turn around time	Availability	Max number bunches	Protons/Bunch	Min beta*	Peak Luminosity $cm^{-2}s^{-1}$	Integrated Luminosity
1	Beam commissioning							First collisions
2	Pilot physics, partial squeeze, gentle increase in bunch intensity, 40%	Long	Low	43	3×10^{10}	4 m	1.2×10^{30}	100 - 200 nb^{-1}
3		5	40%	43	5×10^{10}	4 m	3.4×10^{30}	~ 2 pb^{-1}
4	2.5% nominal beam intensity	5	40%	156	5×10^{10}	2 m	2.5×10^{31}	~13 pb^{-1}
5		5	40%	156	7×10^{10}	2 m	4.9×10^{31}	~25 pb^{-1}
6	9% nominal beam intensity, 75 ns	5	40%	936	3×10^{10}	2 m	5.1×10^{31}	~30 pb^{-1}
7	15% nominal beam intensity, 75 ns	5	40%	936	5×10^{10}	2 m	1.4×10^{32}	~75 pb^{-1}
8	15% nominal beam intensity, 75 ns*	5	40%	936	5×10^{10}	2 m	1.4×10^{32}	~75 pb^{-1}
9	15% nominal beam intensity, 75 ns*	5	40%	936	5×10^{10}	2 m	1.4×10^{32}	~75 pb^{-1}
10	Ions							
							TOTAL	**~300 pb^{-1}**

What can we expect to do with first collisions?



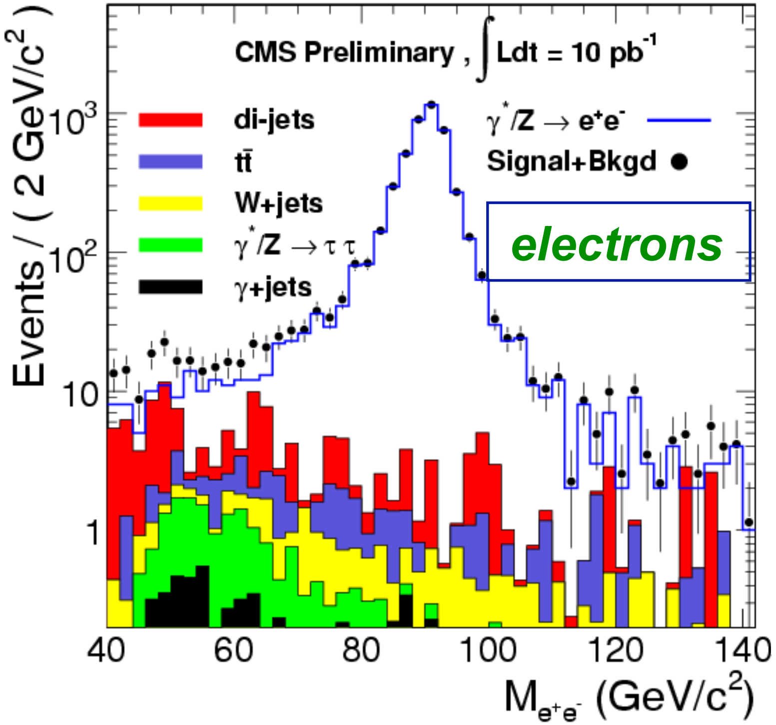
Typical Standard Model processes

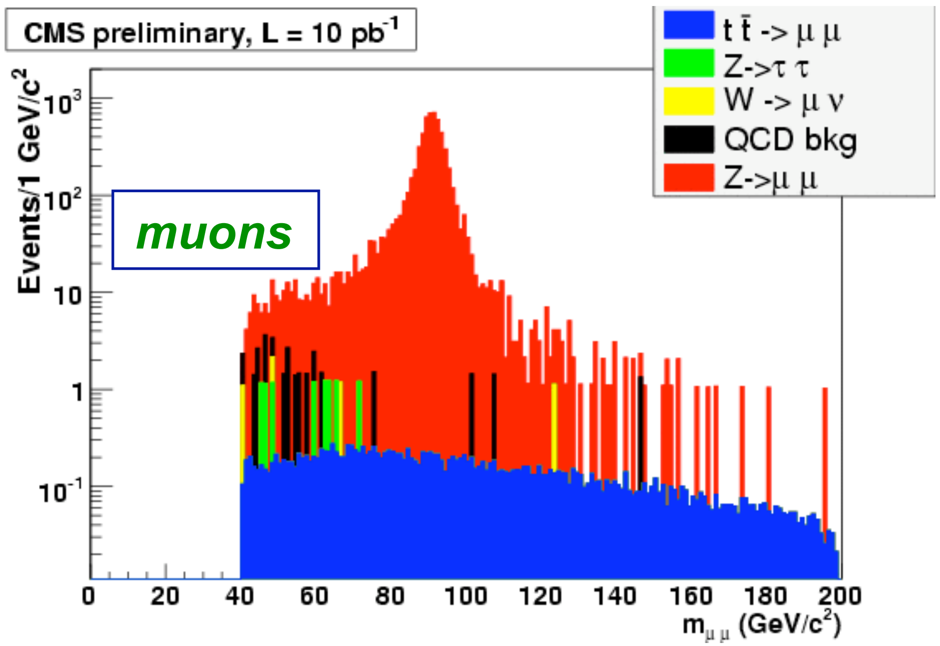
Process	σ (nb)	Events (∫Ldt = 100 pb^{-1})
Min bias	10^8	$\sim10^{13}$
bb	5×10^5	$\sim10^{12}$
Inclusive jets $p_T > 200$ GeV	100	$\sim10^7$
W → eν, μν	15	$\sim10^6$
Z → ee, μμ	1.5	$\sim10^5$
tt	0.8	$\sim10^4$

Yields are very high compared to the Tevatron

Benchmark: Z boson signal with the first 10 pb^{-1}

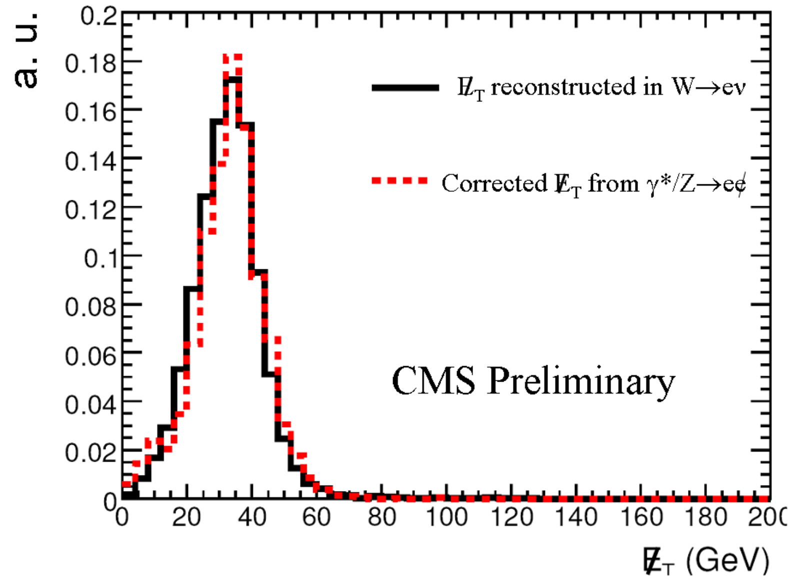
- select pairs of electrons or muons
- about 5k events selected in each channel
- Z peak is prominent over backgrounds from top, W+jets, tau pairs
- backgrounds estimated from data, efficiencies measured from data
- signal yield will be better known than the luminosity

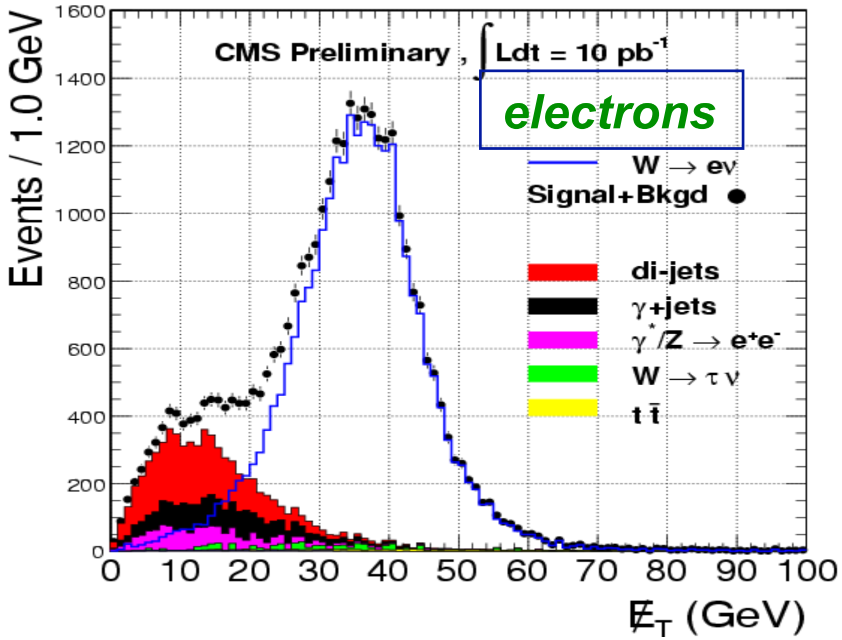


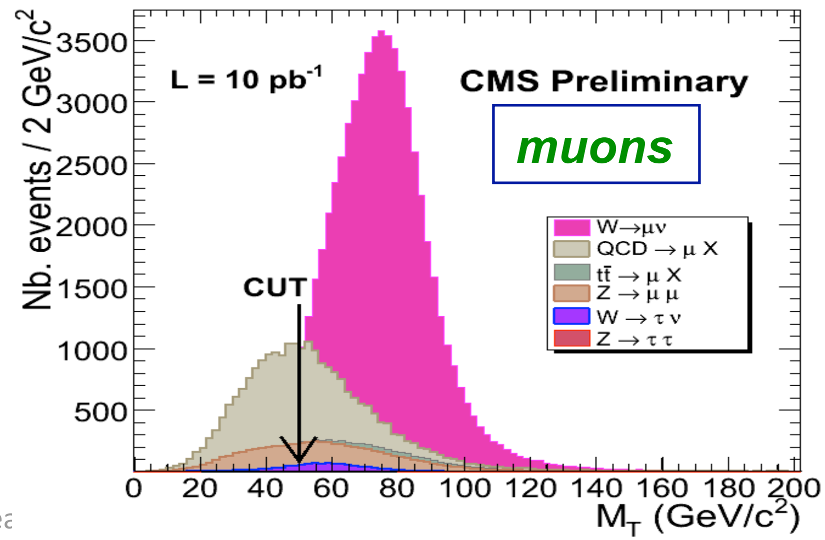


Benchmark: W boson signal with the first 10 pb^{-1}

- select electron or muon and significant missing energy, MET (for the neutrino)
- about 30k electron, 60k muon events
- missing energy distribution calibrated from the Z di-lepton events
- multi-jet backgrounds estimated from data
    - “isolation” of lepton is the key

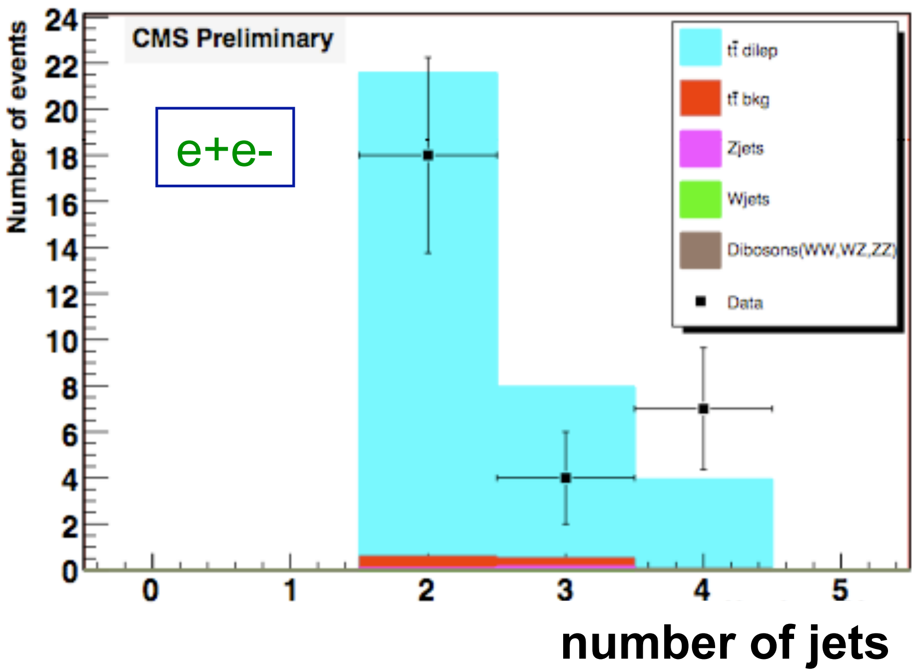


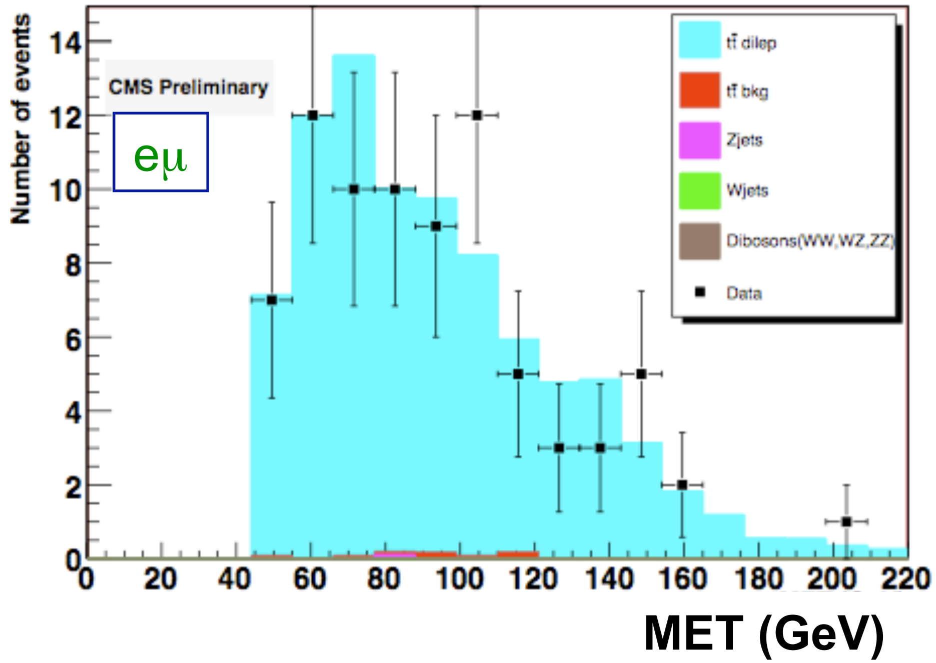




Benchmark: top quark signal with first 200 pb^{-1}

- cleanest topology: both W's decay to leptons (e or μ)
- demand missing energy as expected from the neutrinos
- apply a loose b-tag to greatly reduce multi-jet backgrounds
- signal-to-background is tremendous!
- cross section at 10 TeV is about 55% lower than at 14 TeV
- statistical uncertainty on cross section measurement would be roughly 10%





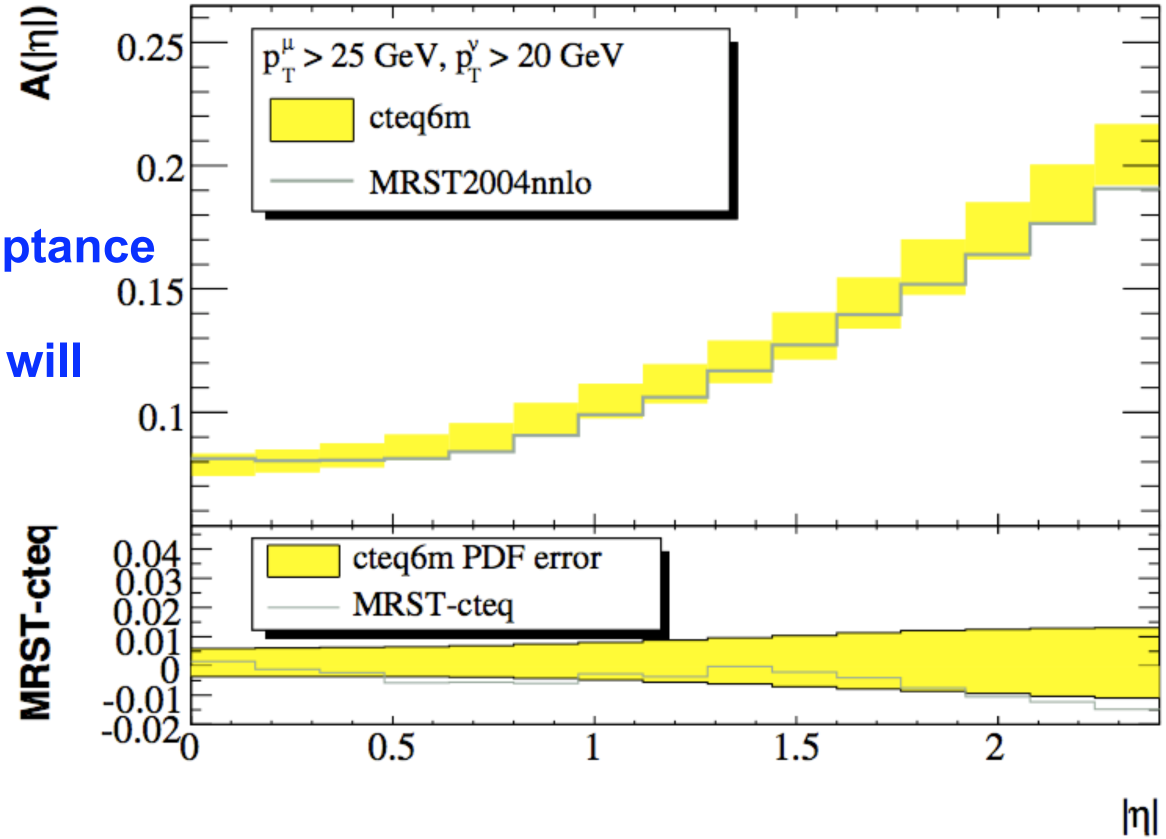
Benchmark: W charge asymmetry with 100 pb^{-1}

parity violation!

$$A(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\bar{\nu}_\mu) - \frac{d\sigma}{d\eta}(W^- \to \mu^-\nu_\mu)}{\frac{d\sigma}{d\eta}(W^+ \to \mu^+\bar{\nu}_\mu) + \frac{d\sigma}{d\eta}(W^- \to \mu^-\nu_\mu)}$$

Variation of W+/W- ratio with angle (rapidity) depends on u/d ratio.

- asymmetry varies from 0.1 to 0.2, even for leptons in the acceptance
- a precision of 1% or better will discriminate PDF's

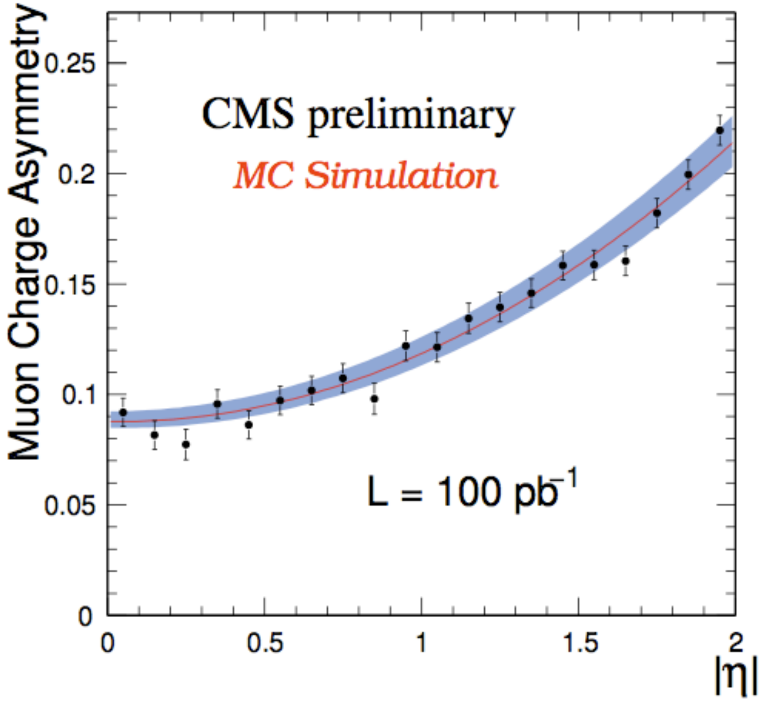


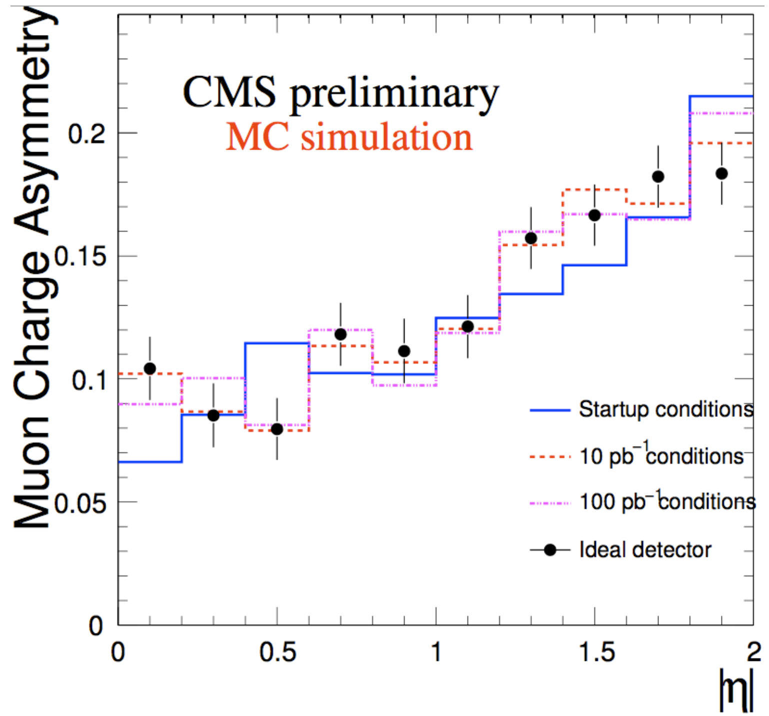
Remember: initial state has Q = +2.

prospective measurement with 100 pb^{-1}

- select muons following the W cross section measurement:
  $p_T > 20$ GeV $|\eta| < 2.0$

- Z sample will allow all efficiencies to be measured to better than 1%
- near-ideal alignment achievable with 100 pb-1
- backgrounds are small with essentially no intrinsic asymmetry

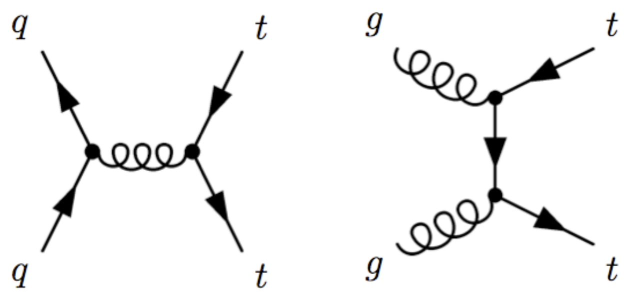


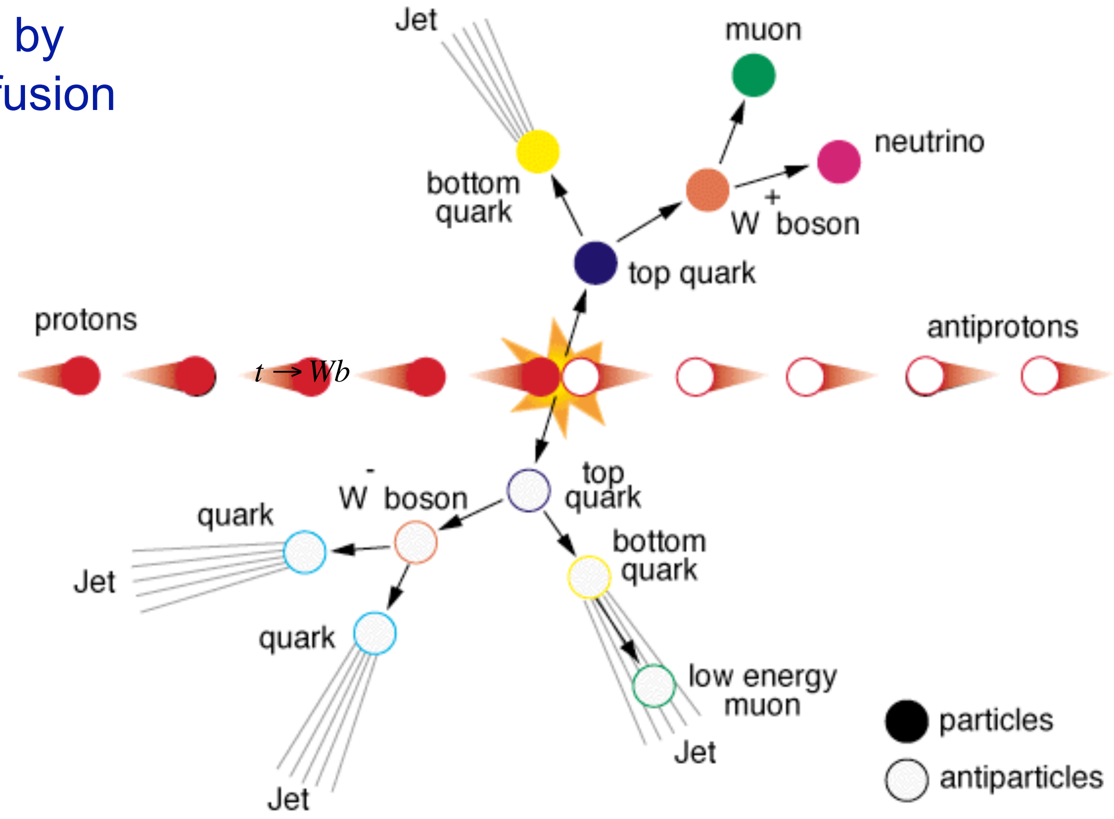


top quark mass

top quark signals

top quarks are produced by
quark annihilation + gluon fusion





A Top Antitop Quark Event from the
D-Zero Detector at Fermilab

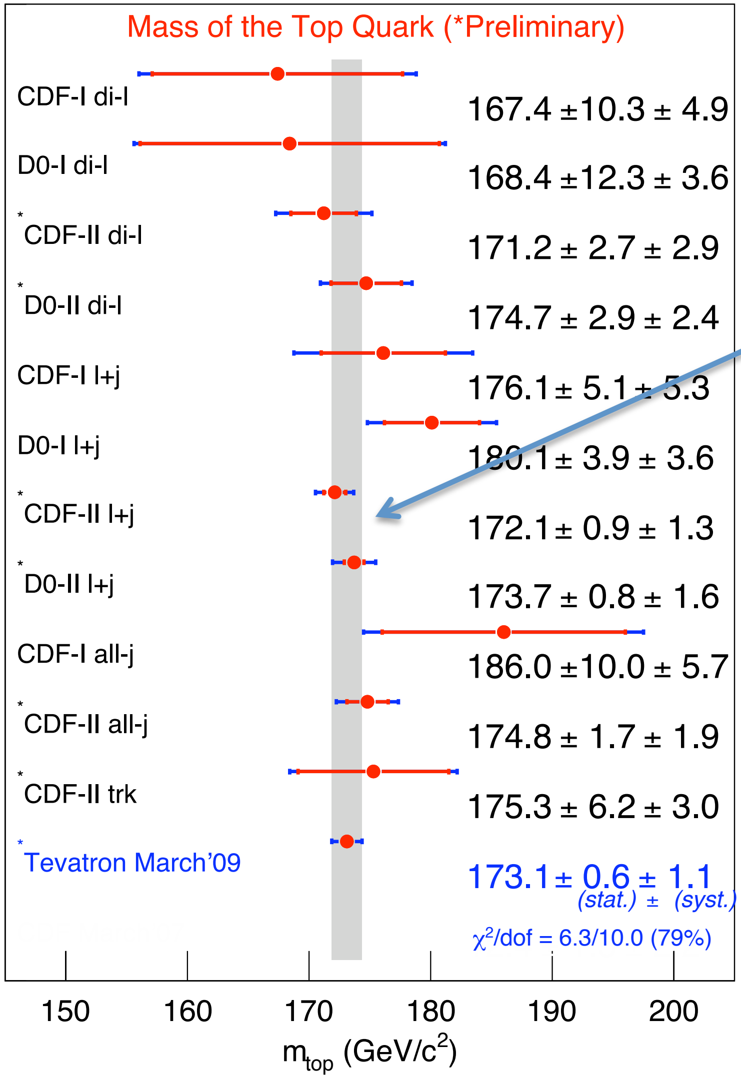
top quark decays:

t → Wb

followed by:

W → qq' or lν

reminder: Tevatron Results



- many measurements combined
- overall consistency is good
- best measurements are in the "semi-leptonic" channel
- result is now systematics limited
  main systematic is the jet energy scale, which is constrained by the W peak
- much better than anticipated in 1998…

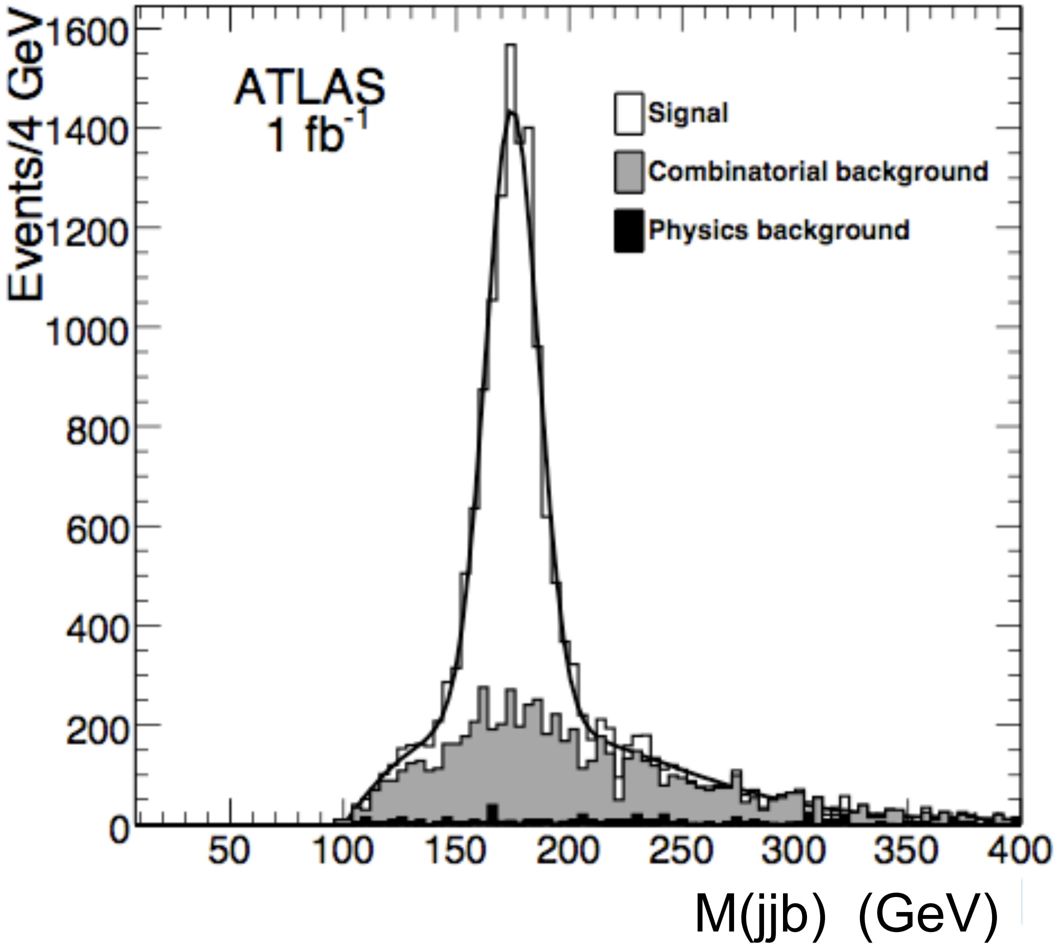
M_t = 173.1 ± 0.6 (stat) ± 1.1 (syst) GeV

Run I: M_t = 174.3 ± 3.2 (stat) ± 4.0 (syst) GeV

top mass at the LHC

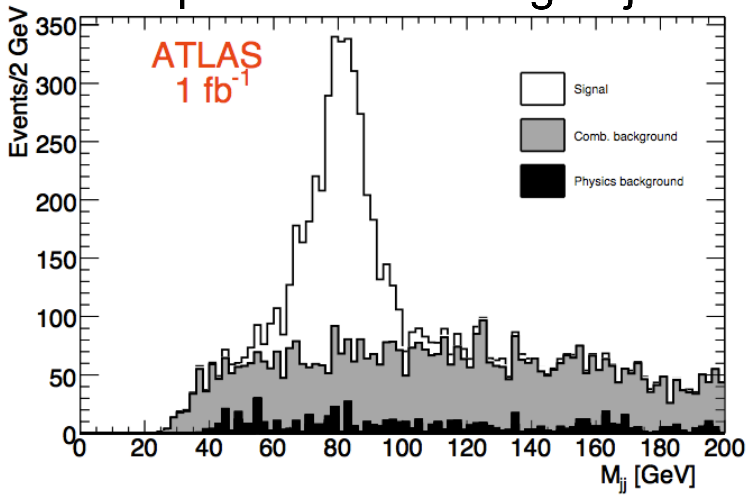
- follow the methods developed at the Tevatron
- focus mainly on the "semi-leptonic" channel
- the cross section is 100 times larger
  - 10^8 top quark pairs produced in 1 fb^{-1}
- CMS, 10 fb^{-1}:
  - fit the kinematics of each event
  - event-by-event likelihood as function of M_t
  - ΔM = 0.2 GeV (stat), 1.1 GeV (syst)
- ATLAS, 1 fb^{-1}:
  - ΔM = 0.4 GeV for calorimeter calibration of 1%
  - ΔM = 0.7 GeV for b-jet energy scale uncertainty of 1%
  - ΔM = 0.3 GeV for initial/final state radiation

ATLAS: top->3 jets



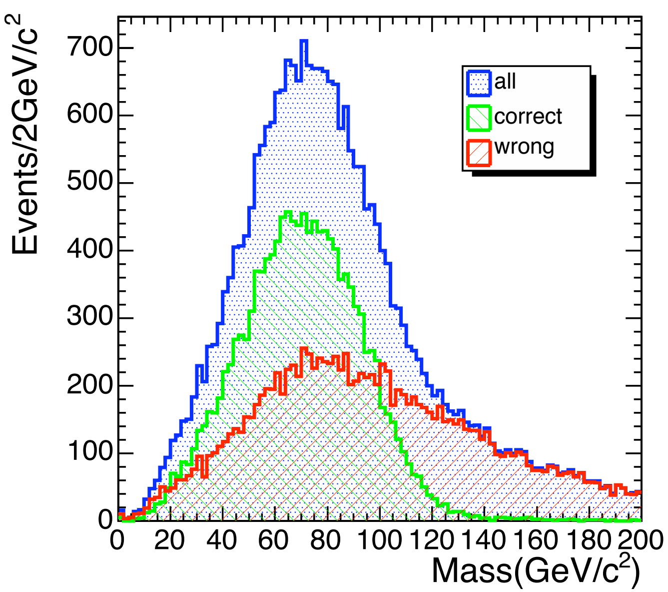
- use the leptonic W decay to trigger & select the event
- reconstruct the top which decays to 3 jets
- two of those jets make the W
- use the W mass to fix the calorimeter energy scale
- b-jet energy scale still somewhat uncertain

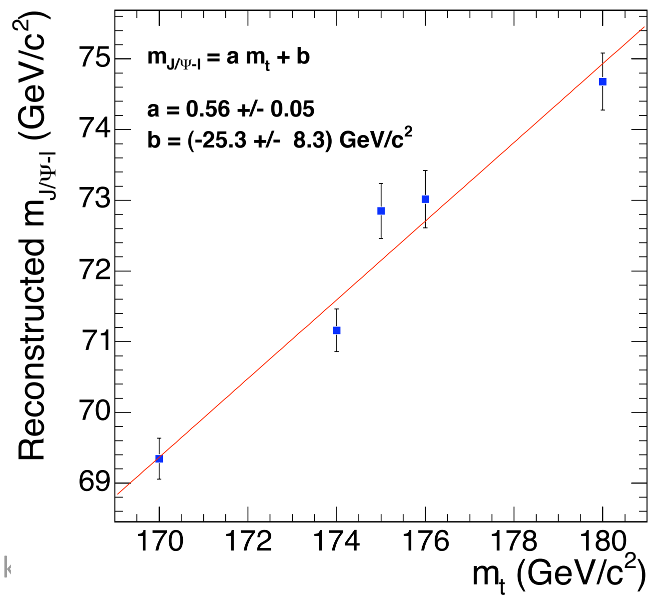
W peak from two “light” jets



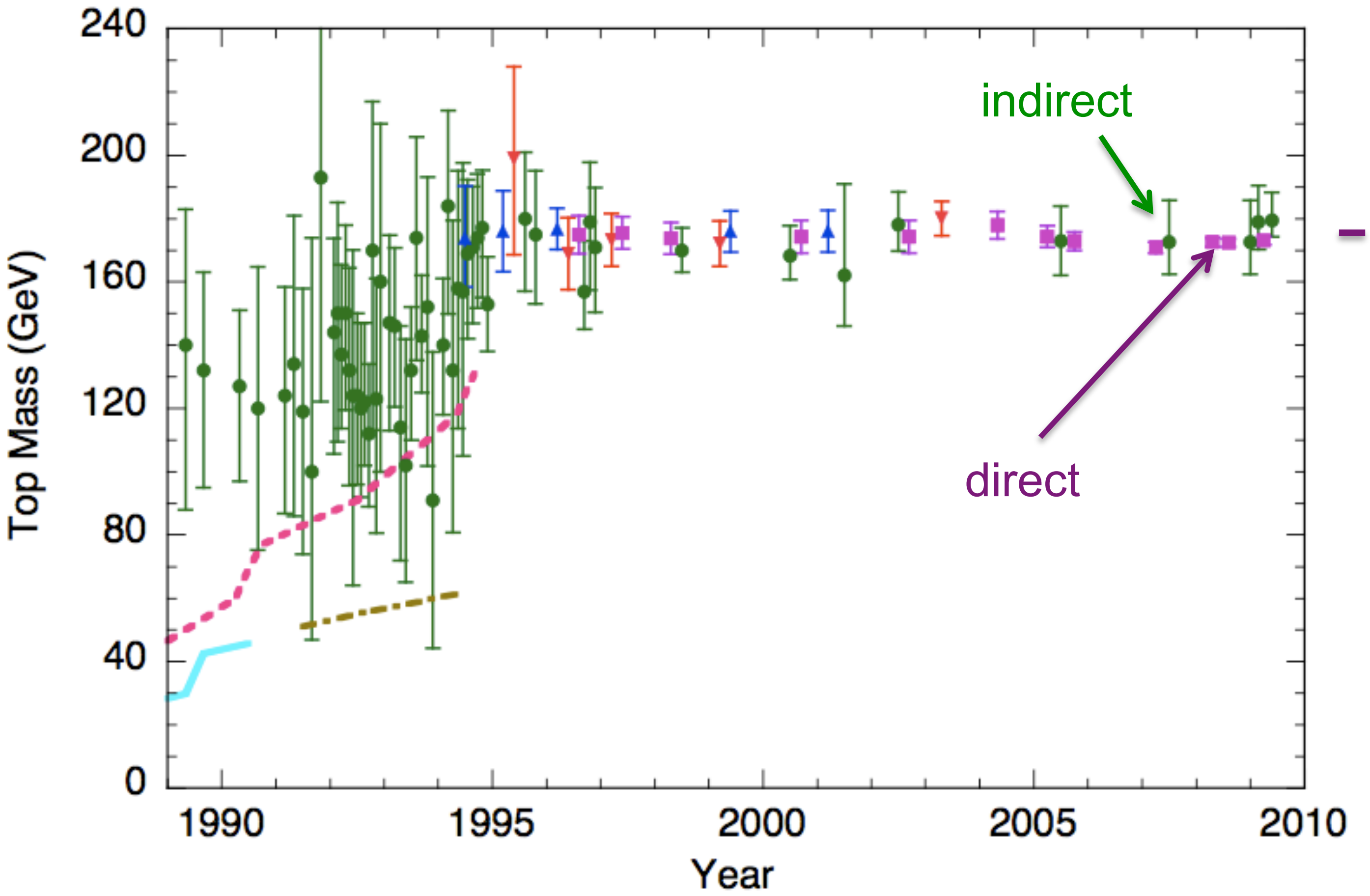
CMS: novel approach using J/ψ and μ

- let one b hadron decay to an energetic J/ψ (to a muon pair)
- let one W boson decay leptonically (again, to a muon)
- the energies of the muons from the J/ψ indirectly reflect M_t
- use the invariant mass of the J/ψ + μ as the observable
- absolutely no systematic from calorimeter energy scales
- There are so many events, this actually works!
  - ΔM = 1 GeV (stat), 1.5 GeV (syst) given 20 fb^{-1}





what will the future be?



LHC era

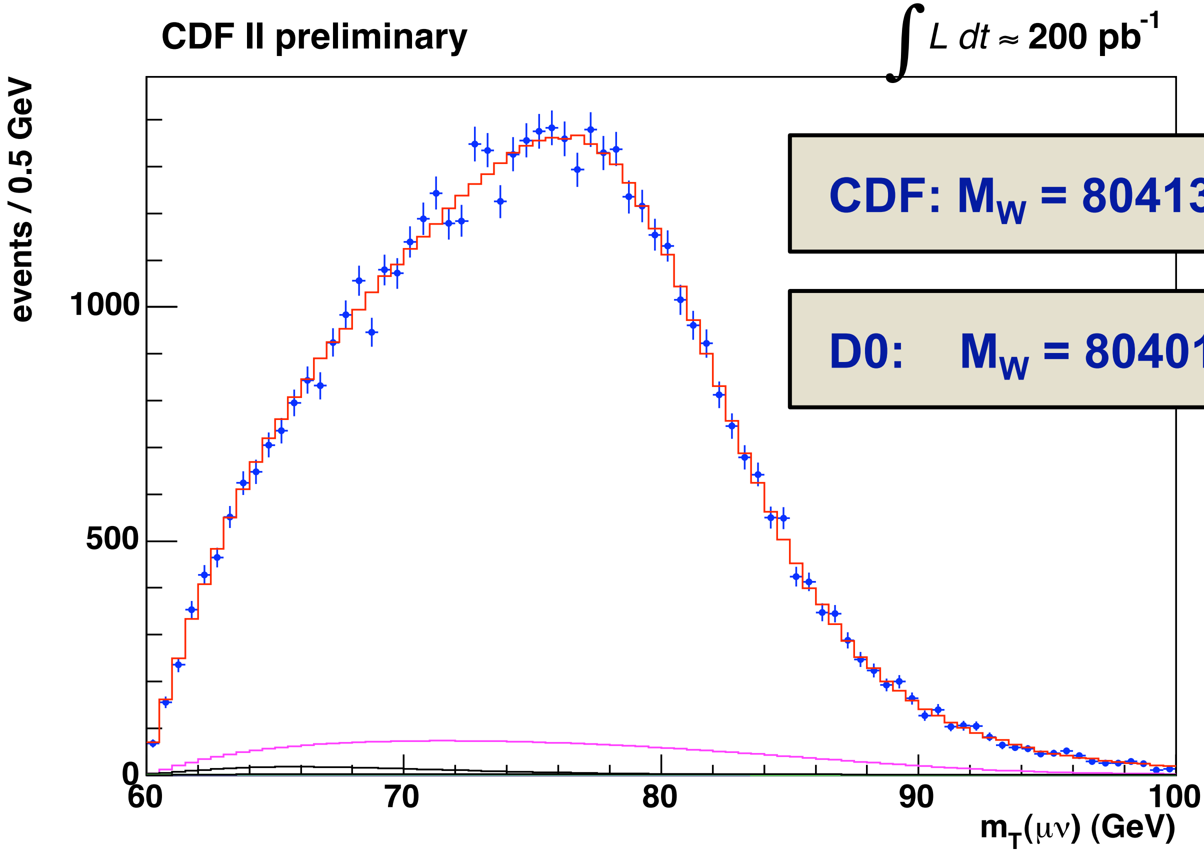
ΔM_t = 1 GeV?

less?

Chris Quigg, 2009

W Mass

reminder: Tevatron Results



(2007, 0.2 fb^{-1})

CDF: M_W = 80413 ± 34 (stat) ± 34 (syst) MeV

D0: M_W = 80401 ± 21 (stat) ± 38 (syst) MeV

(2009, 1 fb^{-1})

- use both e and μ channels
- fit templates to M_T, p_T spectra
- largest systematic is the lepton energy scale
- more precise measurements are still possible…

Current World Average error is about 23 MeV.

W mass at the LHC

ΔM_W = 8 MeV has the same impact as ΔM_t = 1 GeV.

- number of events is semi-infinite: $O(10^8)$ for 10 fb^{-1}
- this measurement is all about systematic uncertainties
- develop some of the data-driven approaches from Tevatron
- key: **Z's are like W's** except:
  - they give two charged leptons and no neutrino
  - their mass and width is slightly different
- use Z's to build "templates" for the fit
- after a lot of tuning, leading uncertainties will be:
  - linearity of energy response, calorimeter calibration
  - PDF uncertainties, boson p_T model

Method 1: "Scaled Observables"

The W distribution is proportional to the Z position modified by a known function R:

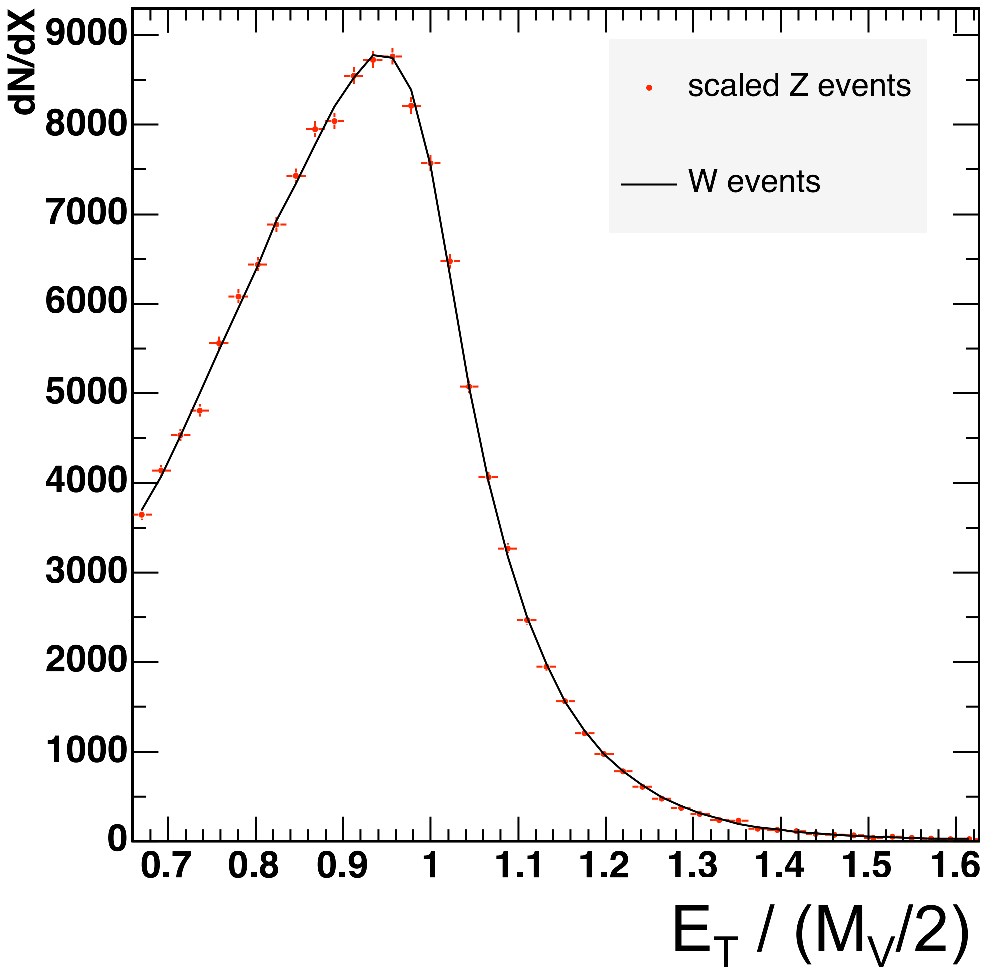
$$\left.\frac{d\sigma^W}{dO^W}\right|_{pred} = \frac{M_Z}{M_W} R(X) \frac{d\sigma^Z}{dO^Z}\left(O^Z = \frac{M_Z}{M_W} O^W\right)\Bigg|_{meas}$$

$$R(X) = \frac{d\sigma^W}{dX^W} \Big/ \frac{d\sigma^Z}{dX^Z} \qquad X^V = \frac{O^V}{M^V}$$

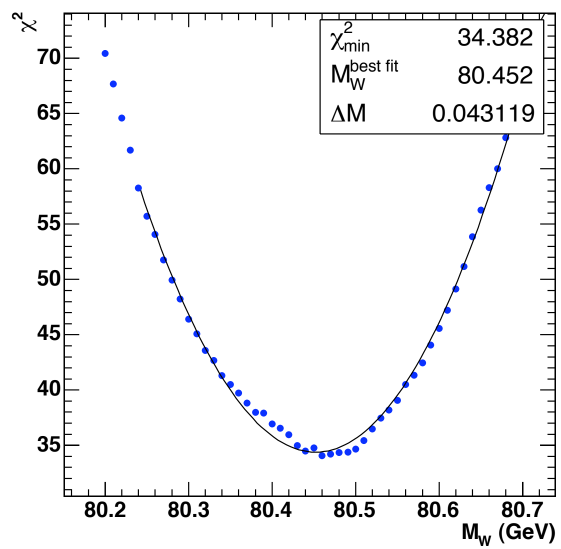
- "O" is an observable, such as lepton p_T or transverse mass M_T.
- "X" is simply "O" scaled by the boson mass (M_W or M_Z, as appropriate).
- R(X) can be calculated accurately from theory – it is a ratio.
- Compare the predicted distribution to the observed one;
  vary M_W to get the best agreement.

(red points) (black curve)

example: compare the scaled **Z** events to the actual **W** events, for electron E_T



- this simulation corresponds to about 1 fb-1
- statistical error would be about 45 MeV

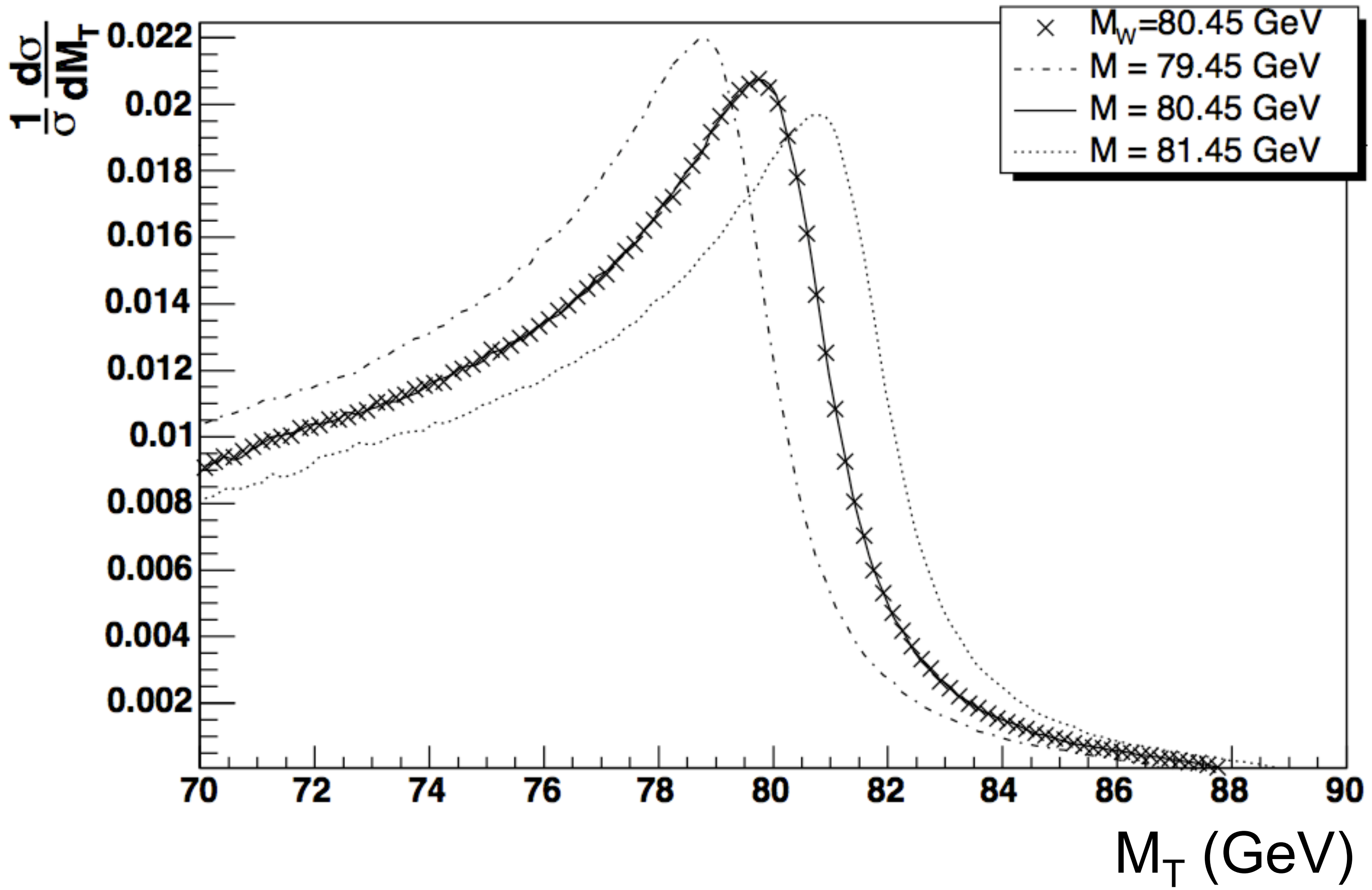


Method 2: "Morphing Events"

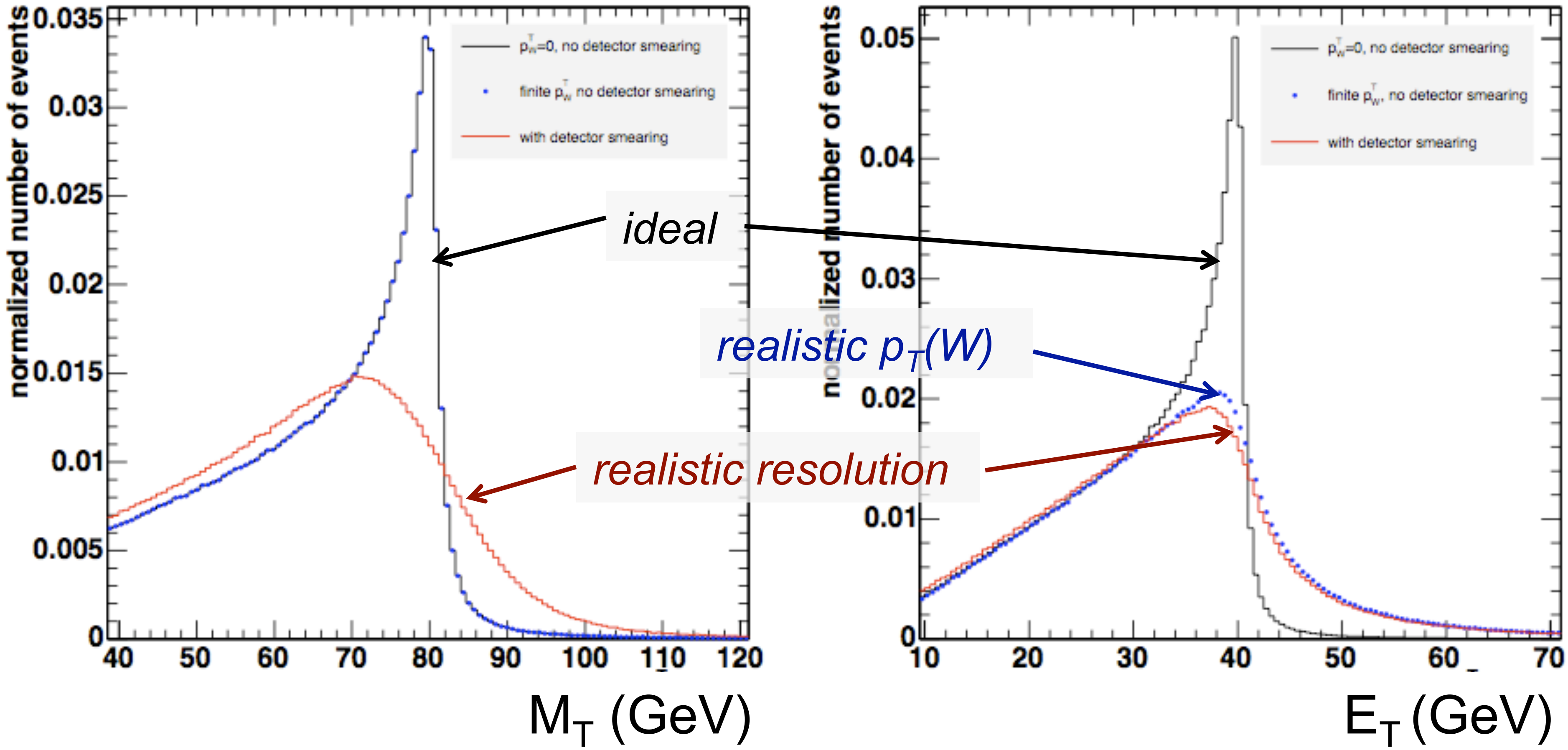
- Take a reconstructed Z event and turn it into a W boson event:
  1. Identify a Z boson through its decay to two muons (or electrons).
  2. Boost to the di-muon center-of-mass frame.
  3. Rescale the muon momenta according to the Z and W masses (and a small correction for the Z width).
  4. Boost back to the lab frame.
  5. Simulate the neutrino by throwing out one of the muons.
  6. Analyze the event as if it were a W event.
- Compare the M_T distribution from these "morphed" Z events to the M_T distribution of the actual W events.
- Vary the assumed M_W in the Z-morphing part until the best agreement is obtained.

illustration:

- curves represent "morphed" Z distributions for 3 different M_W
- points represent the true M_T distribution for W's



Systematic uncertainties are "orthogonal" for E_T and M_T fits:



susceptible to detector resolution

susceptible to boson p_T model

Systematic Uncertainties:

- using real Z's reduces all instrumental uncertainties
- not so easy: linearity of energy response
  - electrons from Z's and from W's have slightly different energies
  - average energy scale is set using Z's as templates
  - excursions to higher or lower energies difficult to control
  - benchmarks from Ψ and J/ψ decays are problematic
- not so easy: calorimeter scale, needed for MET
  - earlier studies perhaps too pessimistic (2% assumed)
  - Tevatron experience shows that this is very hard
- not so easy: PDF uncertainties
  - they enter through acceptance effects (longitudinal boost)
  - perhaps much better after LHC measurements taken into account?

bottom line:

given 10 fb^{-1}, combining *e* and μ channels:

$$\Delta M_W = \begin{array}{l} 10 \text{ MeV (stat)} \\ 20 \text{ MeV (syst)} \end{array}$$

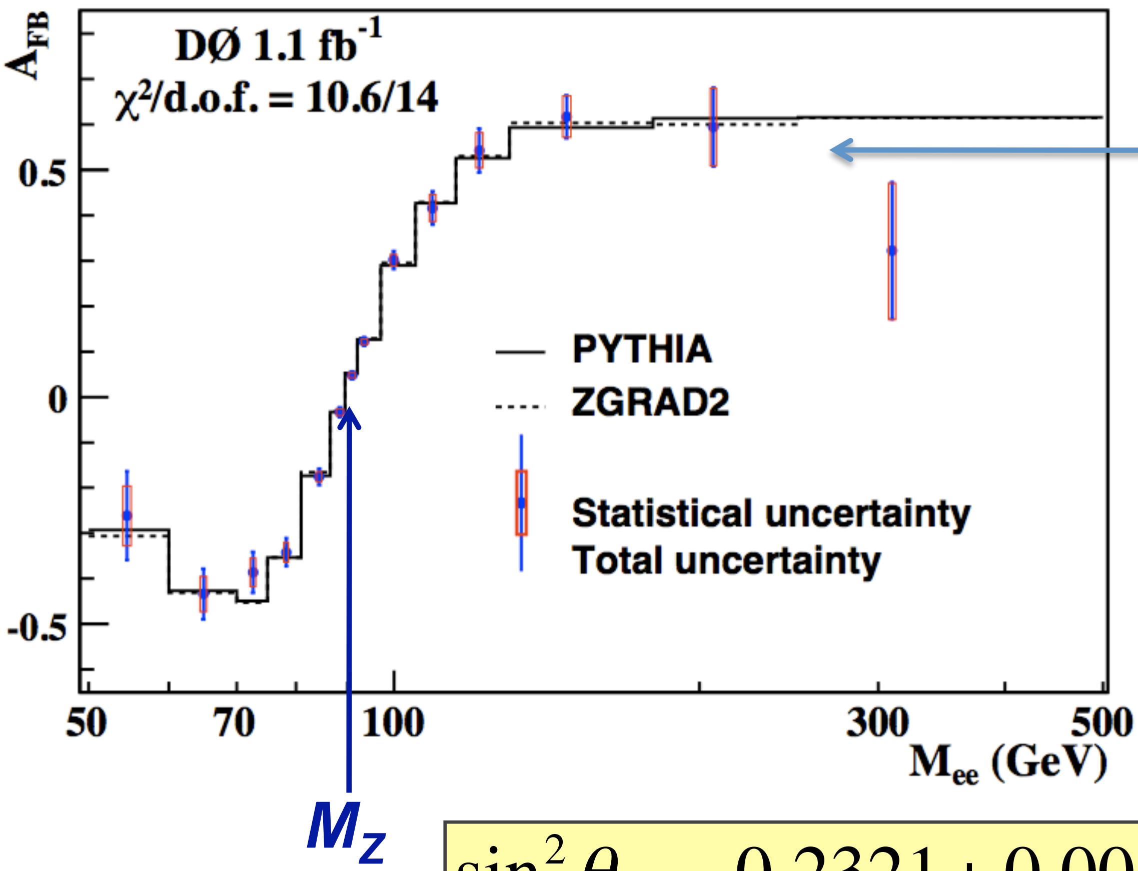
Z FB Asymmetry

A_{FB} and SM-EWK

$$q\bar{q} \rightarrow Z/\gamma^{*} \rightarrow e^{+}e^{-}$$

- parity violation in the weak neutral current
- asymmetry of e^{+} direction w.r.t. quark direction
- governed by weak mixing angle θ_W
- interference of Z* and γ^* plays key role – varies strongly with M_{ee}
- A_{FB} goes through zero at (near) the Z peak
- measurement errors on M_{ee} are a major issue

reminder: Tevatron Results



notice large A_{FB} when far from M_Z

CDF attempted to extract the u and d couplings to Z.

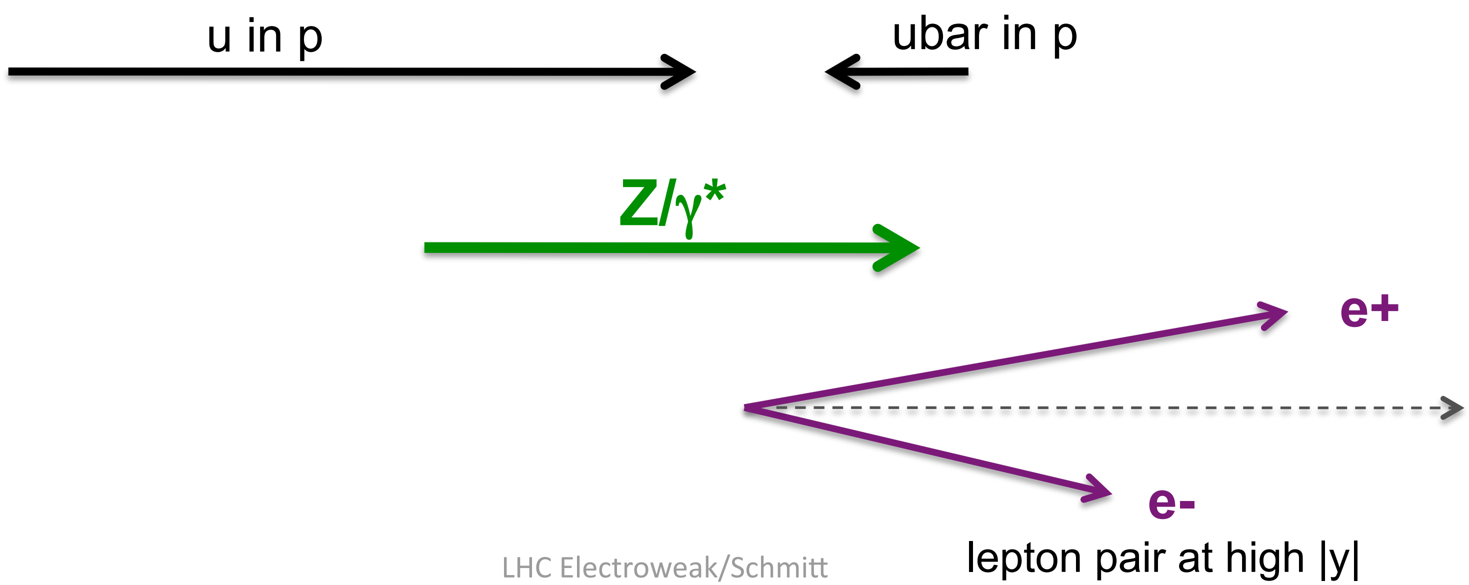
from 1.1 fb^{-1}, D0 measures

$$\sin^2\theta_W = 0.2321 \pm 0.0018(stat) \pm 0.0006(syst)$$

(J. Erler's fit value is 10x better.)

A_{FB} at the LHC

- big problem: which way is the quark going?
- partial answer:
  - **if the Z is boosted in one direction – that's the direction of q**
- only boosted Z's are sufficiently unambiguous
- makes the measurement much harder



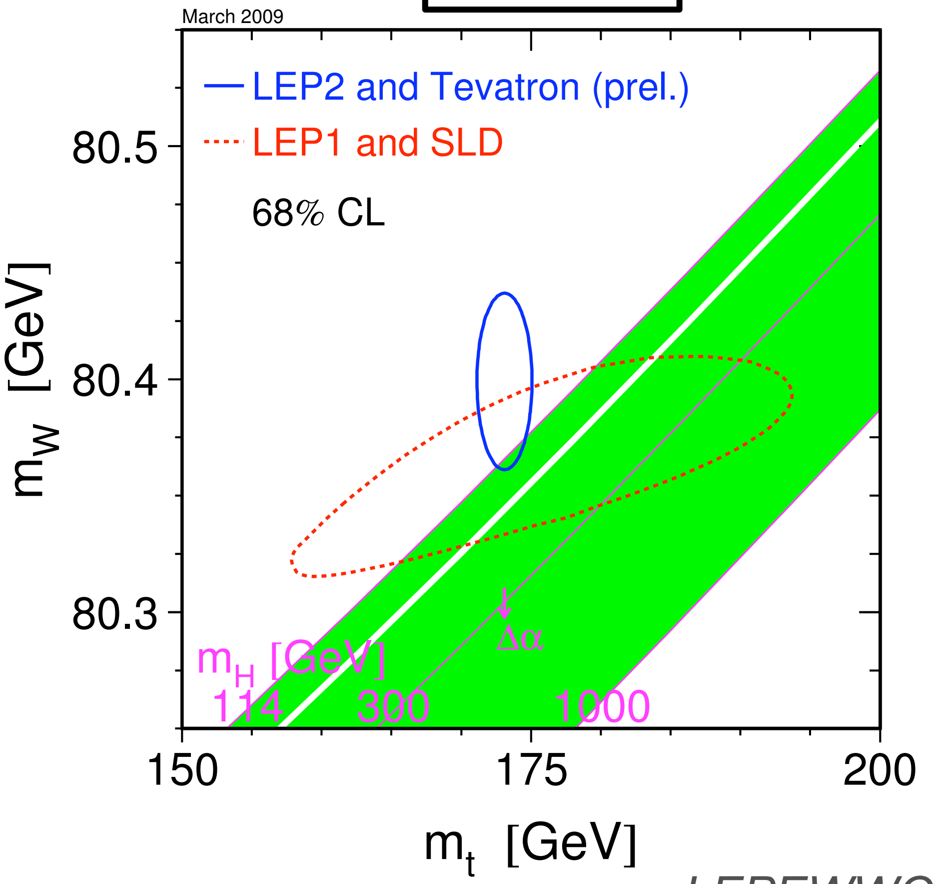
- This is perhaps the most difficult measurement at the LHC.
- Neither ATLAS nor CMS have published detailed studies.
- problems:
  - PDF uncertainties are important at large |y|
  - electro-weak corrections, too
  - energy/momentum measurements are less good in end caps
  - charge confusion will be a problem – dilutes A_{FB}
  - jet backgrounds are more severe at high |y|
- bottom line:
  - statistical uncertainty on $\sin^2\theta_W$: approx 2×10^{-4} (2 expt's)
  - PDF's & EWK correction might be the dominant uncertainty
  - mass scale & resolution is challenging (need 10x smaller than CDF)
  - a hopeful guess:

$$\Delta\sin^2\theta_W \text{ : approx } 3 \times 10^{-4}$$

(which is somewhat worse than current world average)

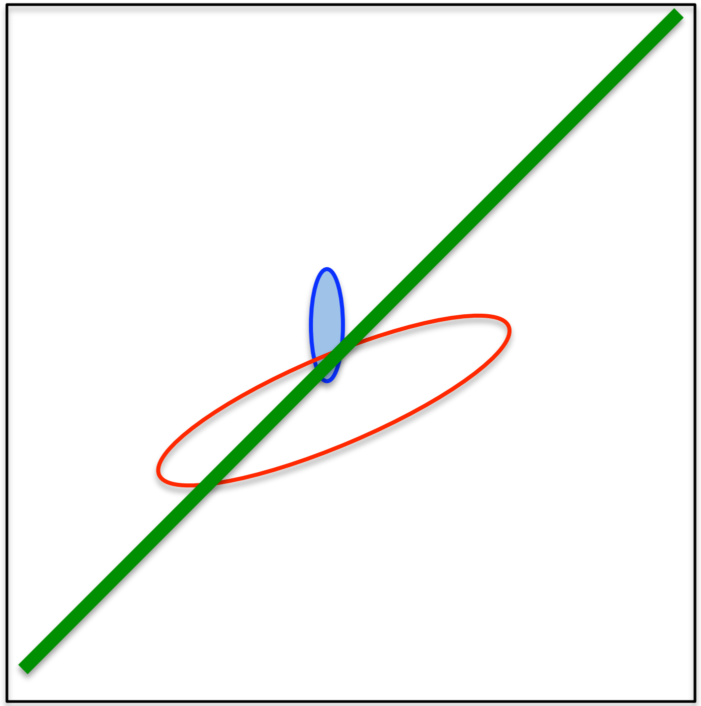
CLOSING

2009



LEPEWWG

2012



How might the LHC <u>and low-energy experiments</u> change this picture?

- **Recall: the main point of the LHC is to discover direct signals for new physics – not to do precision measurements such as M_W, M_t, etc.**

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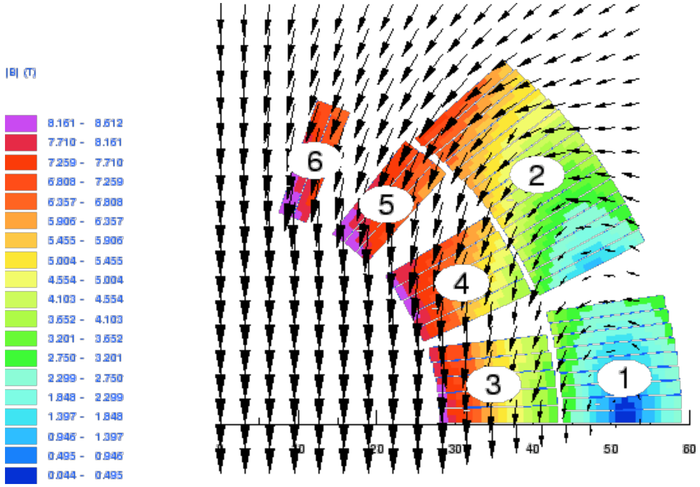
- It may well turn out that precision measurements at low energies will play a key role in elucidating the theory that explains the new physics.
- I predict the future will bring together the people at the "precision" and the "high energy" frontiers.

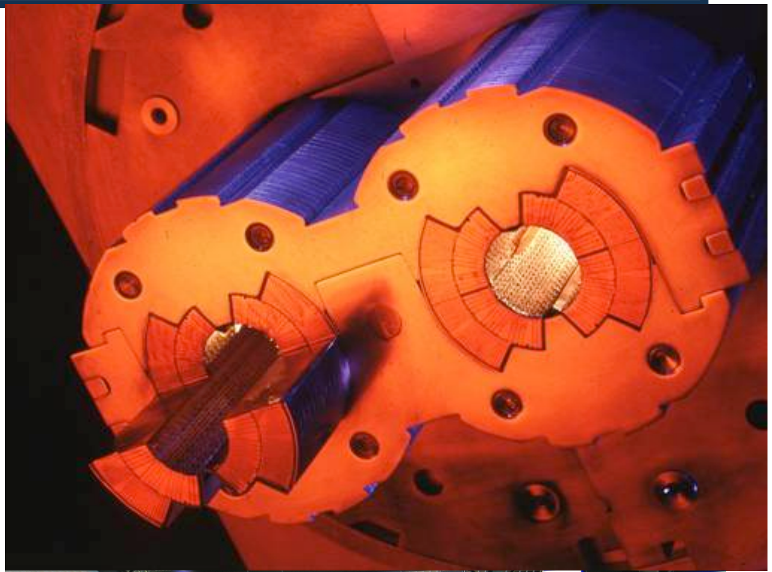
thank you!

EXTRAS

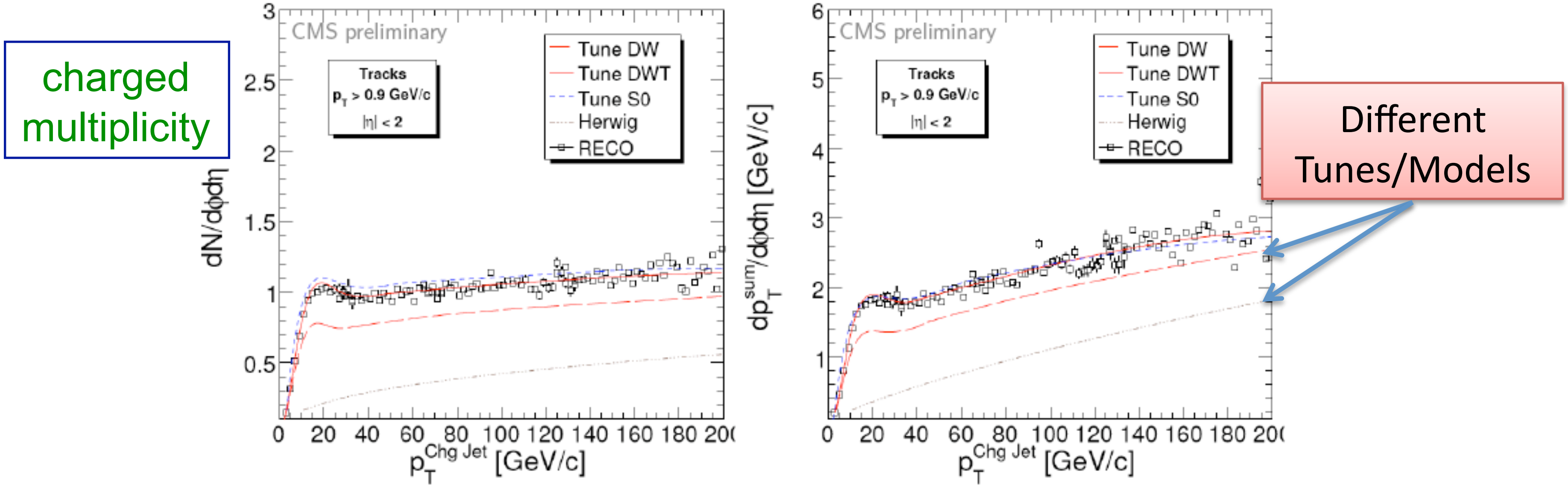
LHC dipoles

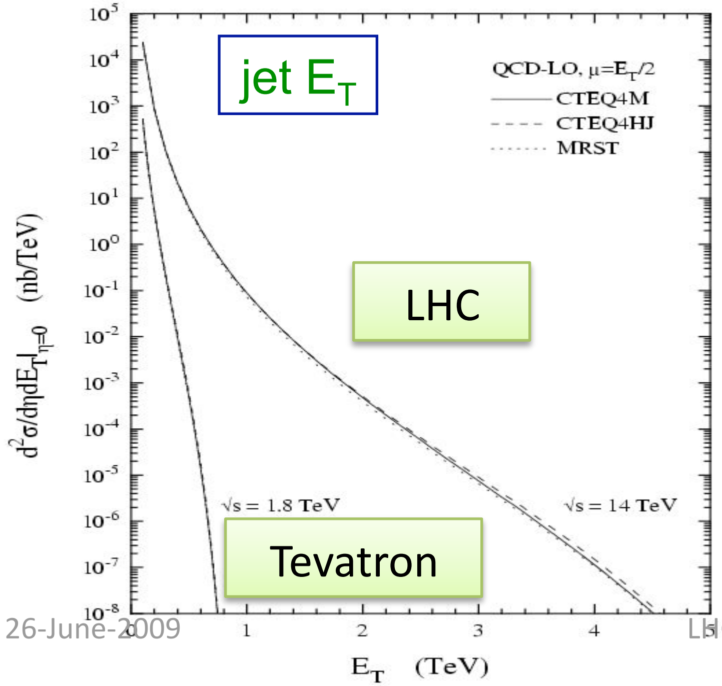
- 8.4 T field
- two bores – unique
- 11.7 kA current
- superconducting   (1.9 deg K, sf He)
- force loading is 400 tonnes per meter
- 14.3 m long
- weight: 35 tonnes
- cost about CHF 500k
- 1232 dipoles around the ring (27 km)





Early studies of event properties

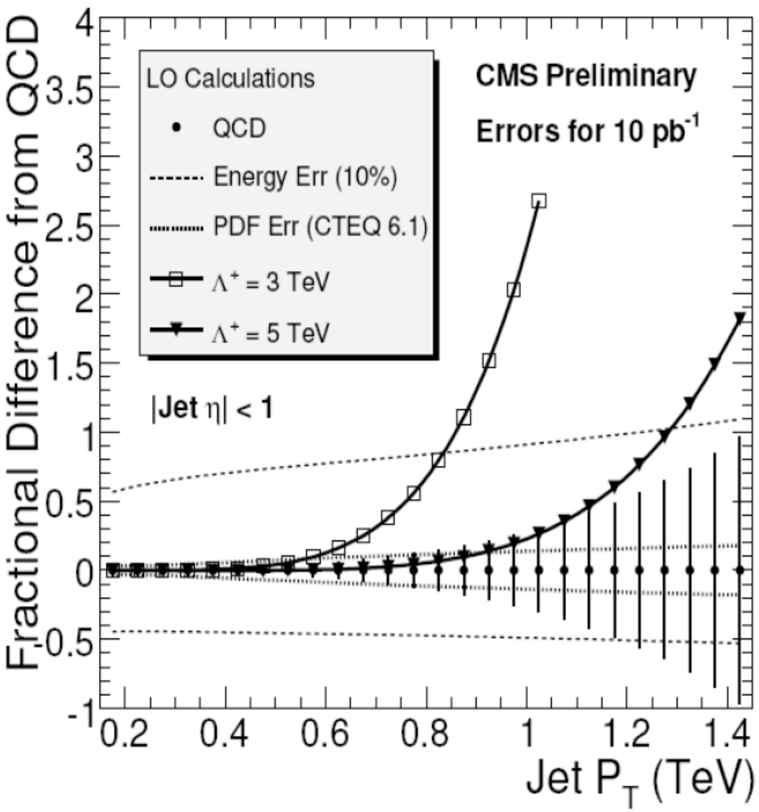


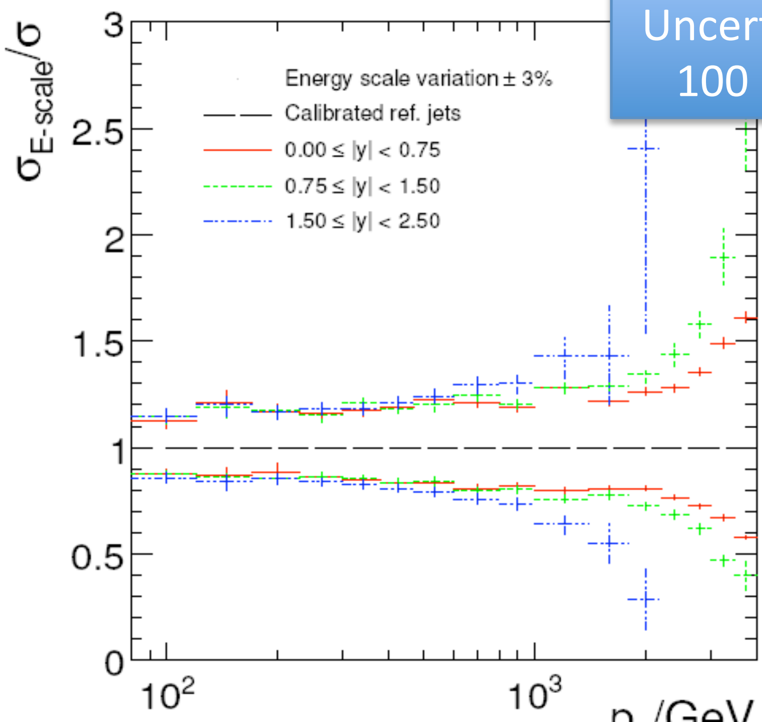


- Enormous QCD Cross section
  - New territory in terms of Jet E_T
- Underlying event measured with very first data
  - Understand environment at 14 TeV
  - Tune MC models
  - Observables N_{ch}, P_T^{Sum}
    - In Transverse region

Jets/QCD

- Measurement of Inclusive Jet Cross Section
  - Understanding of Jet Energy scales, resolutions
  - PDF Uncertainties



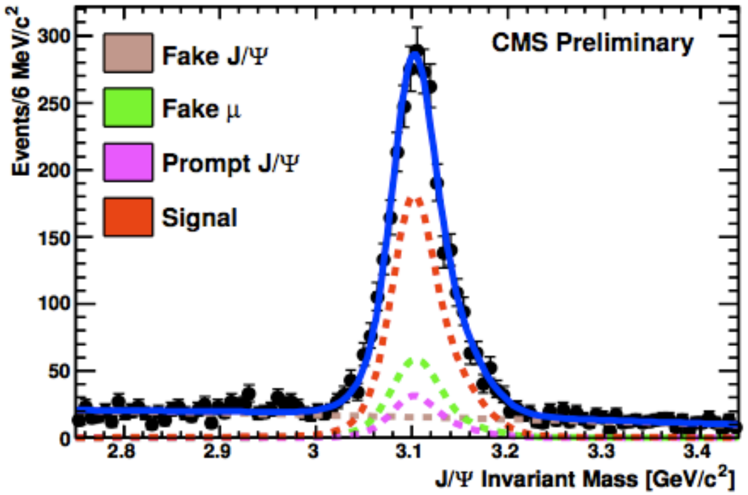


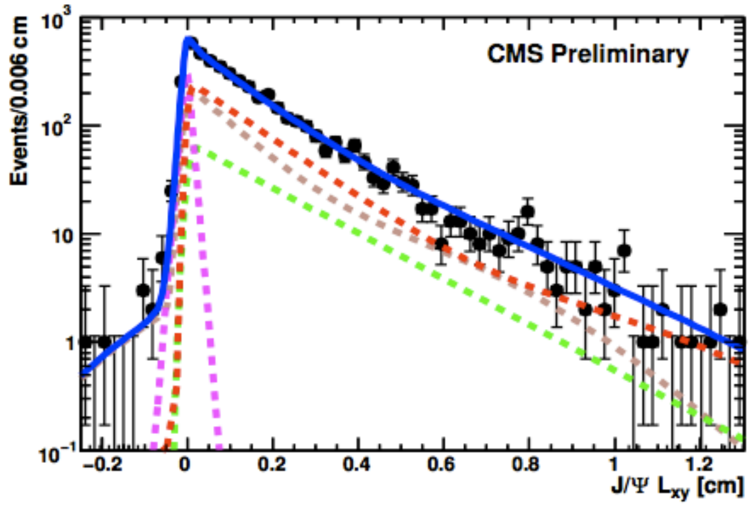
Energy Scale Uncertainty 100 pb^{-1}

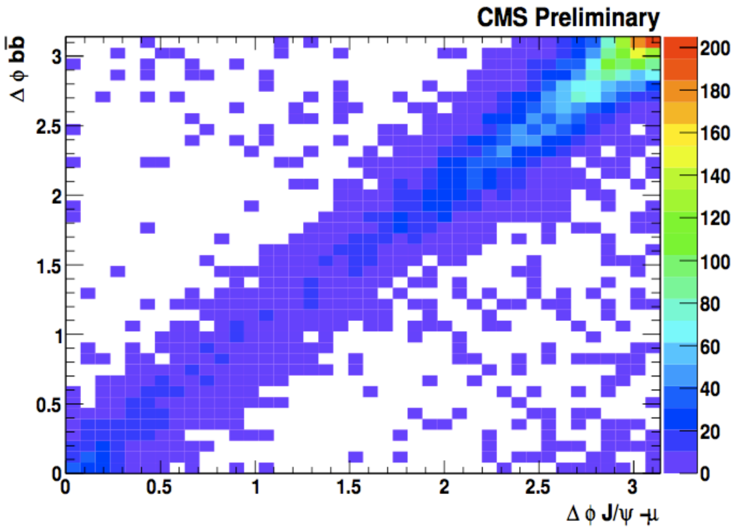
- Potential for discovery of Contact interactions in Dijets,
  - 4 TeV for 10 pb^{-1}
  - 7 TeV for 100 pb^{-1}
  - 10 TeV for 1 fb^{-1}

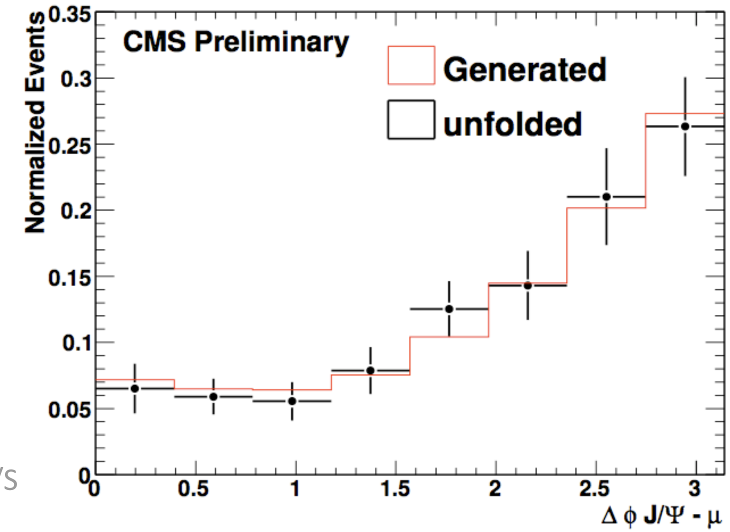
bb angular correlations

- bb angular correlations reflect three underlying QCD processes
- provide a good test NLO QCD
- measure angular correlation between J/psi and b->μ (50 pb^{-1})

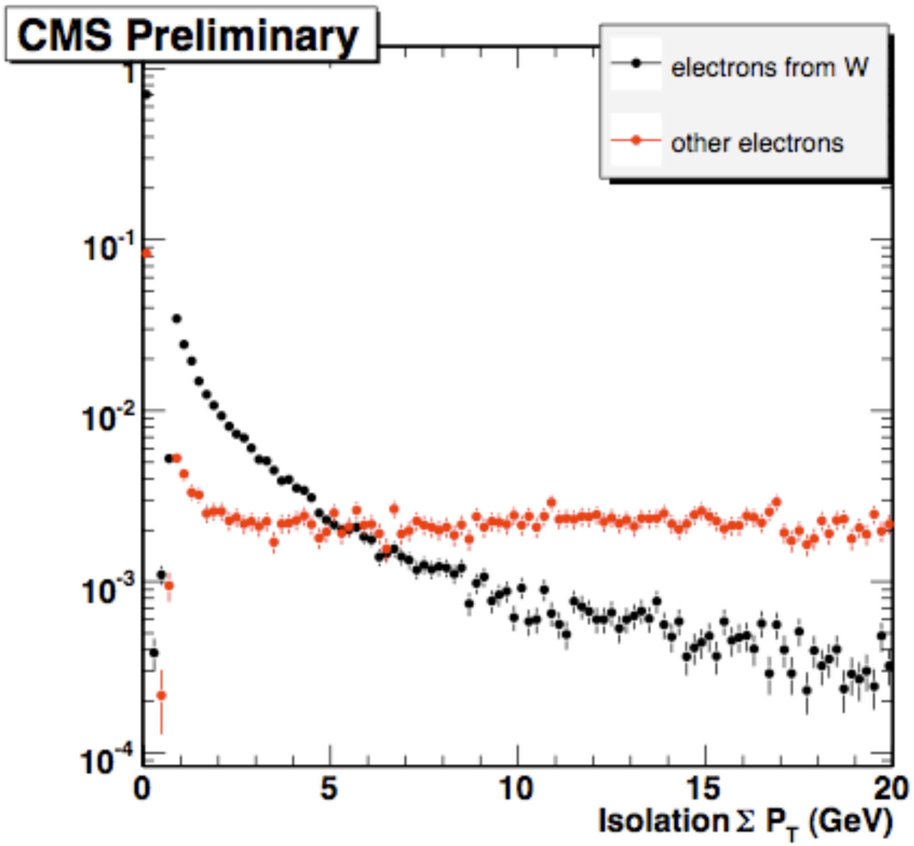


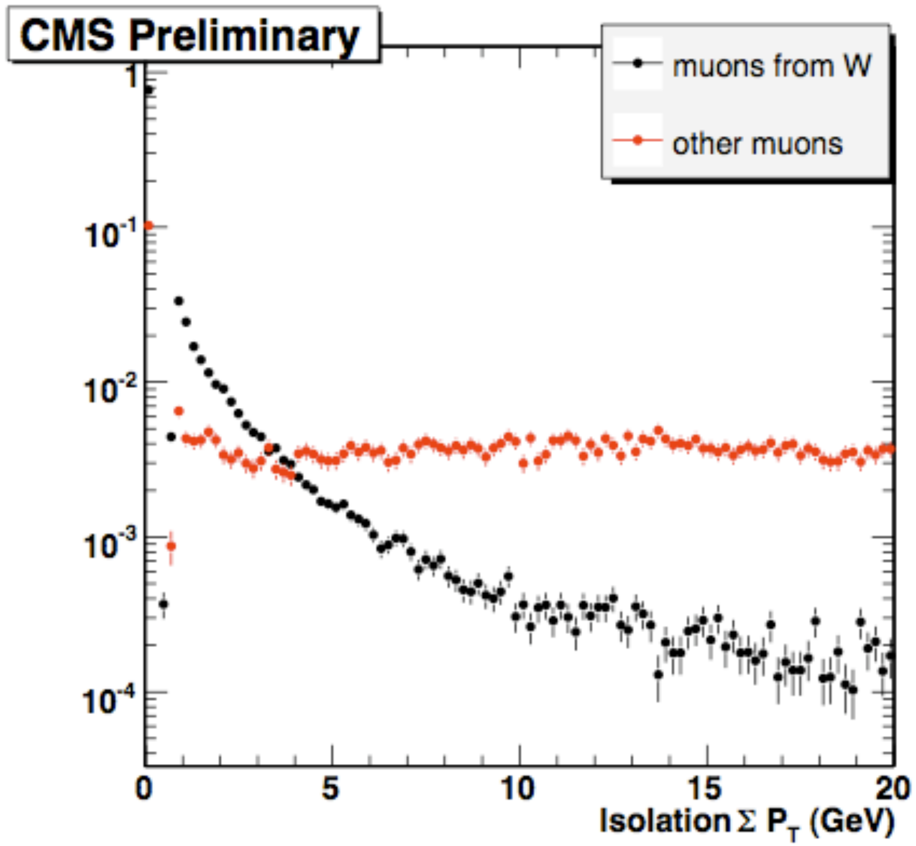






lepton isolation: sum of tracks within a cone





systematic uncertainties on the W mass measurement

CDF

Systematic	$W \to e\nu$	$W \to \mu\nu$	Common
$p_T(W)$ model	3	3	3
QED radiation	11	12	11
Parton distributions	11	11	11
Lepton energy scale	30	17	17
Lepton energy resolution	9	3	0
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
$u_{\|\|}$ efficiency	3	1	0
Lepton removal	8	5	5
Backgrounds	8	9	0
Total systematic	39	27	26
Total uncertainty	62	60	26

TABLE II: Systematic and total uncertaint
the m_T fits, which are the most precise.
shows the correlated uncertainties.

D0

Source	$\sigma(m_W)$ MeV m_T	$\sigma(m_W)$ MeV p_T^e	$\sigma(m_W)$ MeV $\not{E}_T$
Experimental			
Electron Energy Scale	34	34	34
Electron Energy Resolution Model	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences	4	4	4
Recoil Model	6	12	20
Electron Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Total	35	37	41
W production and decay model			
PDF	9	11	14
QED	7	7	9
Boson p_T	2	5	2
W model Total	12	14	17
Total	37	40	44

Source of uncertainty	uncertainty with 1 fb^{-1}	ΔM_W [MeV/c^2] with 1 fb^{-1}	uncertainty with 10 fb^{-1}	ΔM_W [MeV/c^2] with 10 fb^{-1}
scaled lepton-p_T method applied to W→ $e\nu$				
statistics		**40**		15
background	10%	10	2%	2
electron energy scale	0.25%	10	0.05%	2
scale linearity	0.00006/ GeV	30	<0.00002/ GeV	<10
energy resolution	8%	5	3%	2
MET scale	2%	15	<1.5%	<10
MET resolution	5%	9	<2.5%	< 5
recoil system	2%	15	<1.5%	<10
total instrumental		**40**		**<20**
PDF uncertainties		20		<10
Γ_W		15		<15
p_T^W		30		30 (or NNLO)
transformation method applied to W→ $\mu\nu$				
statistics		**40**		15
background	10%	4	2%	negligible
momentum scale	0.1%	14	<0.1%	<10
$1/p^T$ resolution	10%	30	<3%	<10
acceptance definition	η-resol.	19	$< \sigma_\eta$	<10
calorimeter E_T^{miss}, scale	2%	38	≤1%	<20
calorimeter E_T^{miss}, resolution	5%	30	<3%	<18
detector alignment		12	–	negligible
total instrumental		**64**		**<30**
PDF uncertainties		≈20		<10
Γ_W		10		< 10