Early Electroweak and Top Quark Physics with CMS

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BMBF-Forschungsschwerpunkt
"Elementarteilchenphysik mit dem CMS-Experiment"

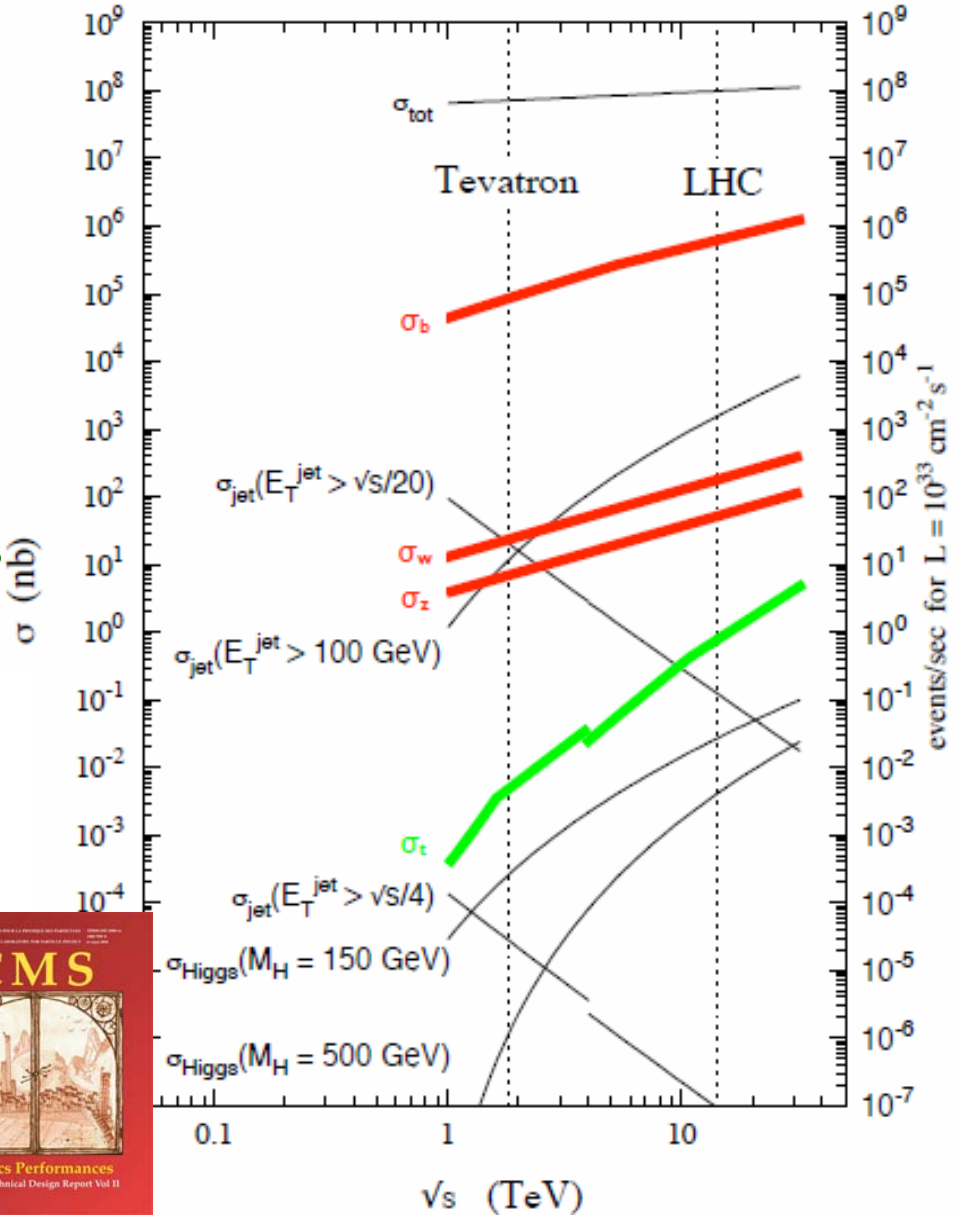
Physik an der TeV-Skala mit dem Large Hadron Collider

Compact Muon Solenoid

FSP102

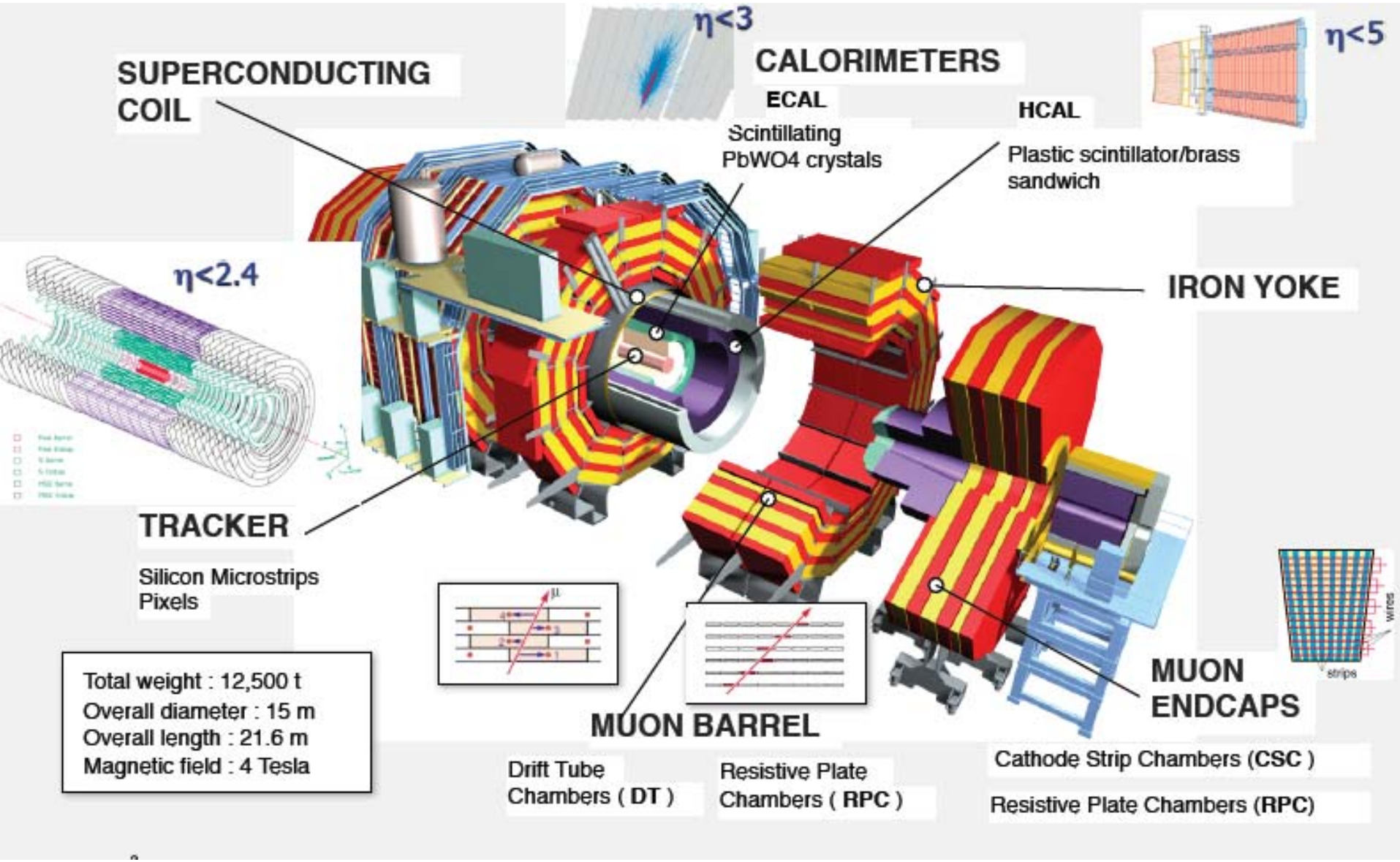
Introduction

- **From Tevatron to LHC**
  - W,Z,top cross sections much increased w.r.t. Tevatron
  - Large event samples already early
- **Top and EW Physics at the LHC**
  - Precision measurements
    - m_W, m_t, $|V_{tb}|$ etc.
  - Sensitivity to new physics
  - Background to Higgs,BSM searches
- **Use as commissioning tool:**
  - W,Z: ECAL calibration; Tracker+muon alignment
  - Ttbar: jet energy scale, btagging



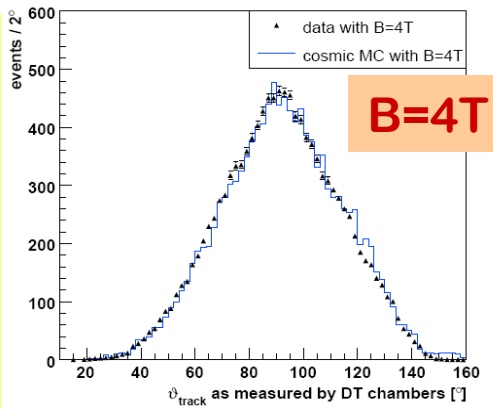
- All results presented here from CMS Physics TDR, Vol. 2 (2006) http://cmsdoc.cern.ch/cms/cpt/tdr/
  - Full GEANT-4 detector simulation
  - Systematic error evaluation

The CMS Detector

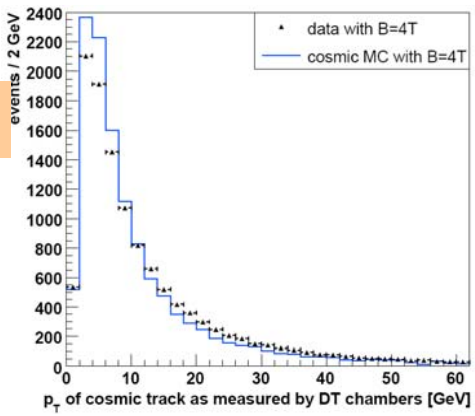


Commissoning on the surface: Magnet Test and Cosmic Challenge (MTCC) – Summer 2006

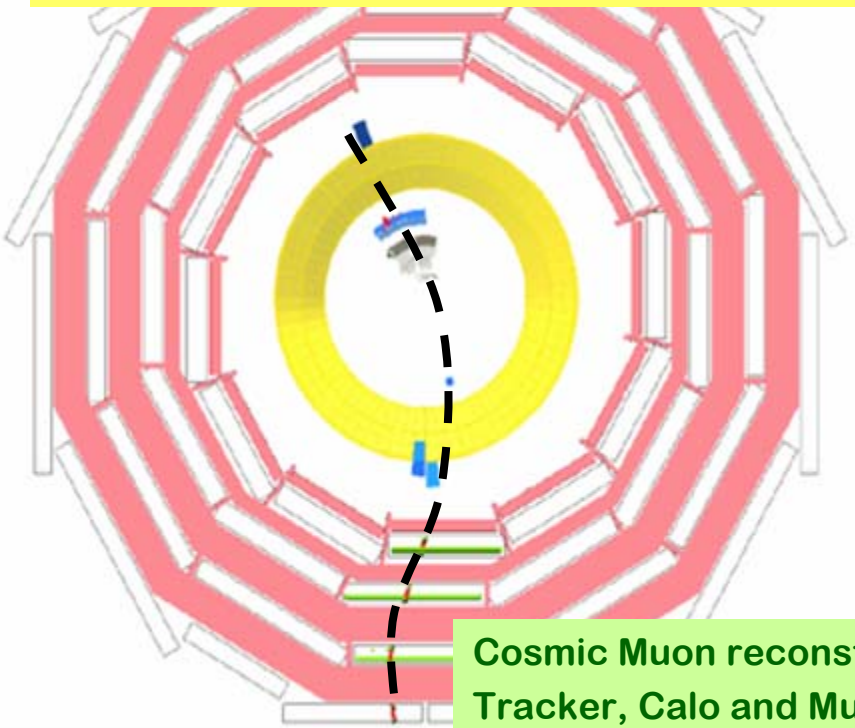
- **Experiment closed first time**
- **Magnet commissioning and field mapping**
- **Combined operation of full chain: Detector – Electronics – DAQ – Trigger – Software**
- **Establish timing, calibration, operation procedures**



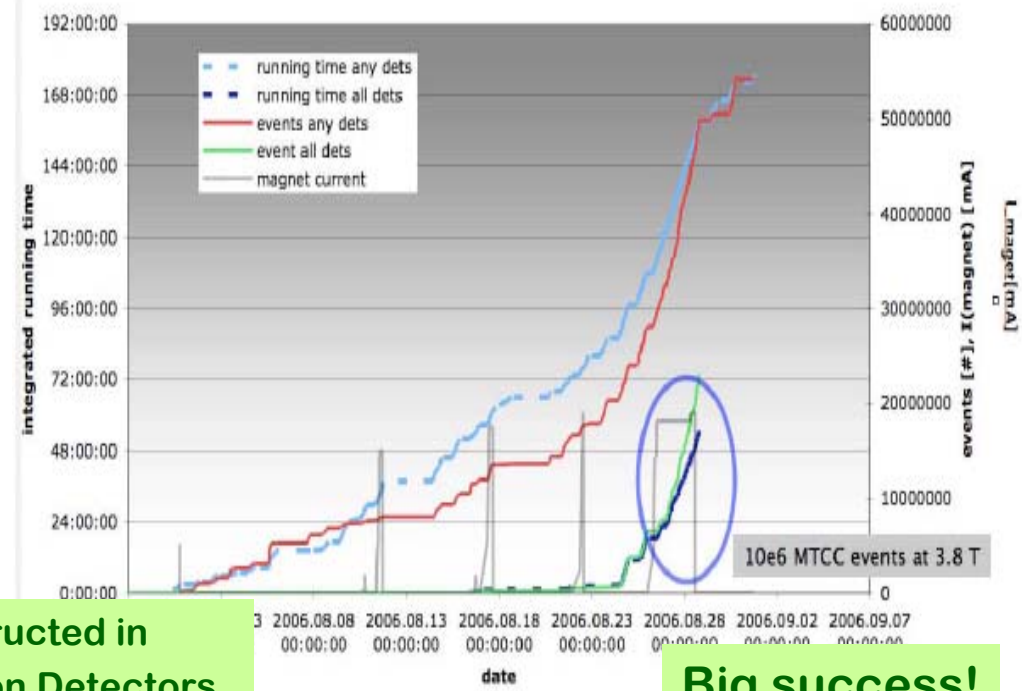
B=4T



- **Muon θ, Pt compared with MC**



Cosmic Muon reconstructed in Tracker, Calo and Muon Detectors

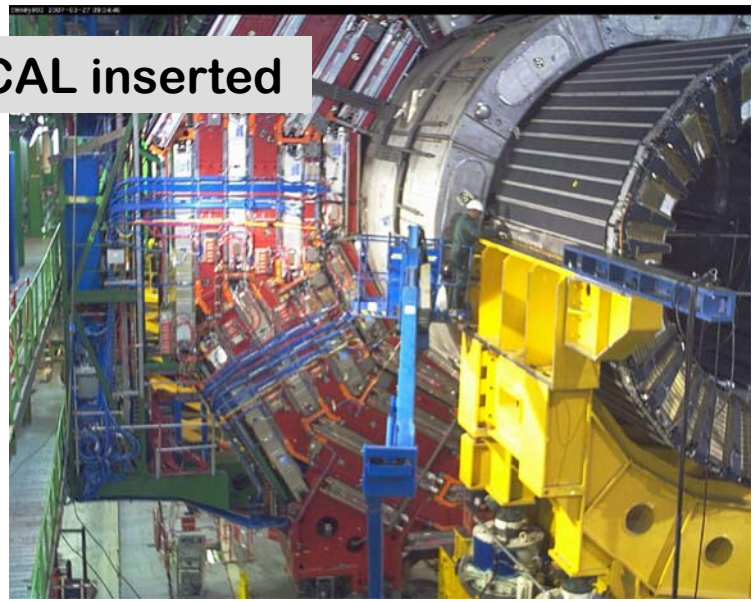


Big success!

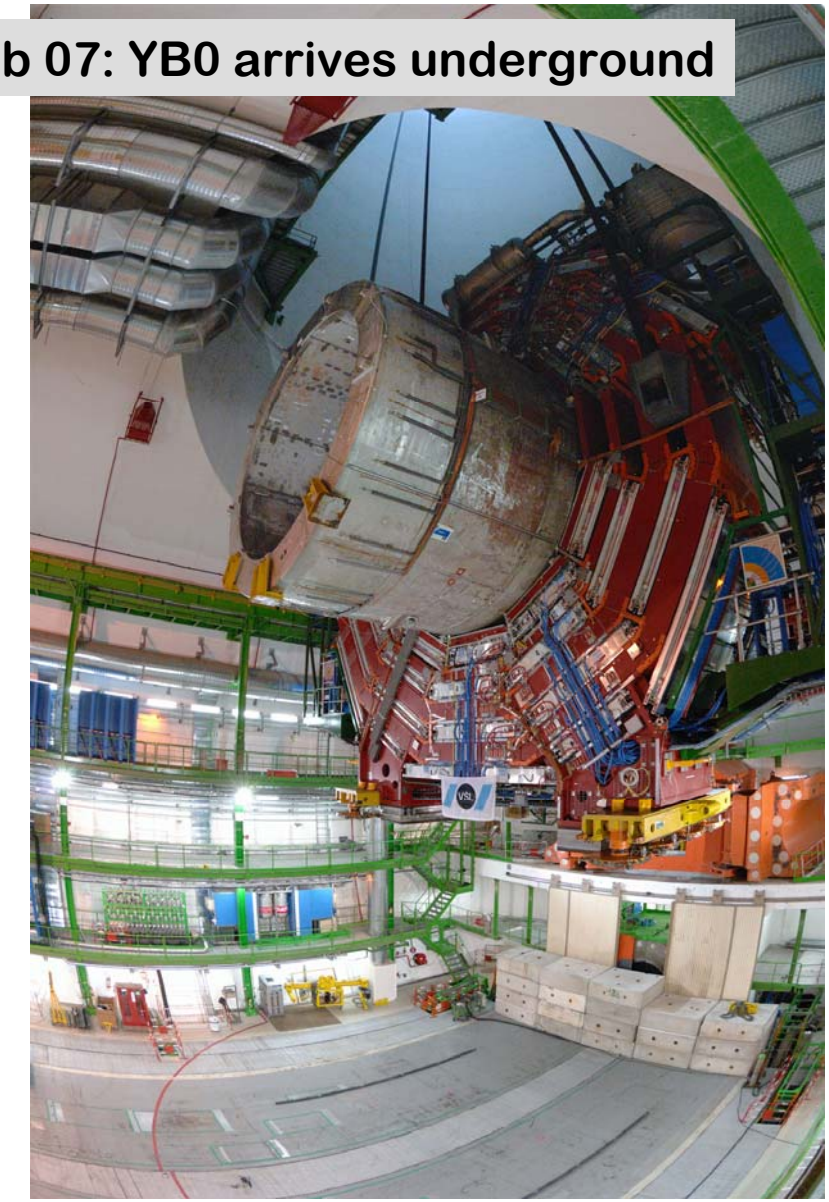
Now: Going Underground

Dec 06: YE+2 Endcap Disk

Mar 07: HCAL inserted



Feb 07: YB0 arrives underground

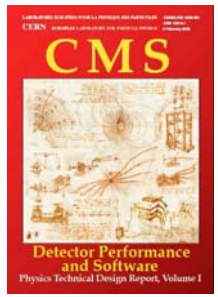


Detector Performance

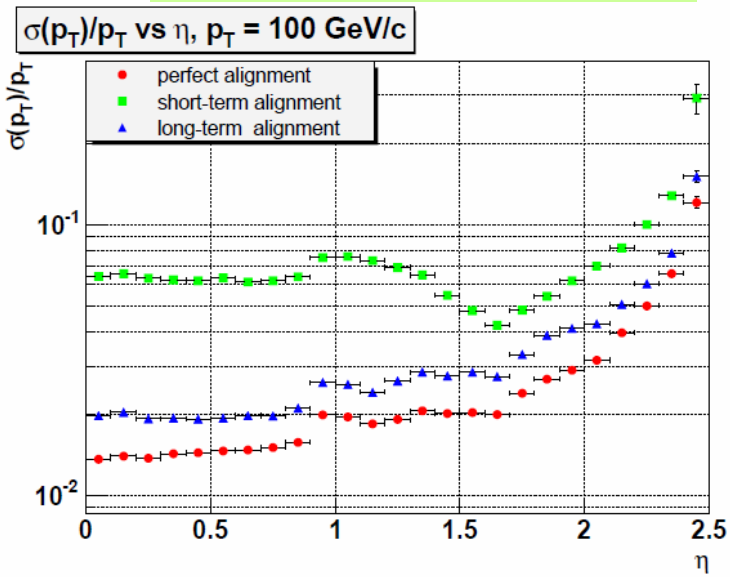
Physics TDR Vol. 1: Detector Performance and Software (2006)

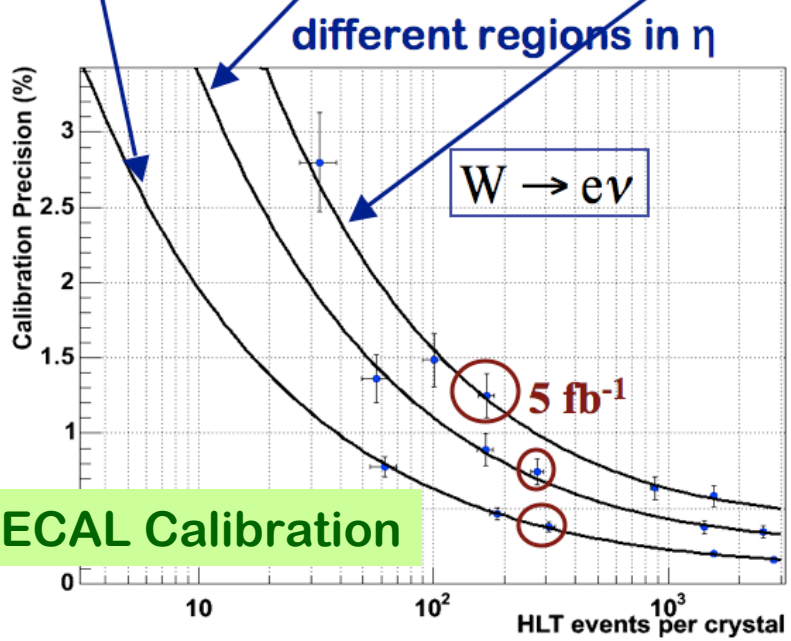
http://cmsdoc.cern.ch/cms/cpt/tdr/

- **Physics Objects reconstruction**
  - Electrons, Photons, Muons, jets and missing ET, b- and tau-tagging
- **Calibration and Alignment Procedures**

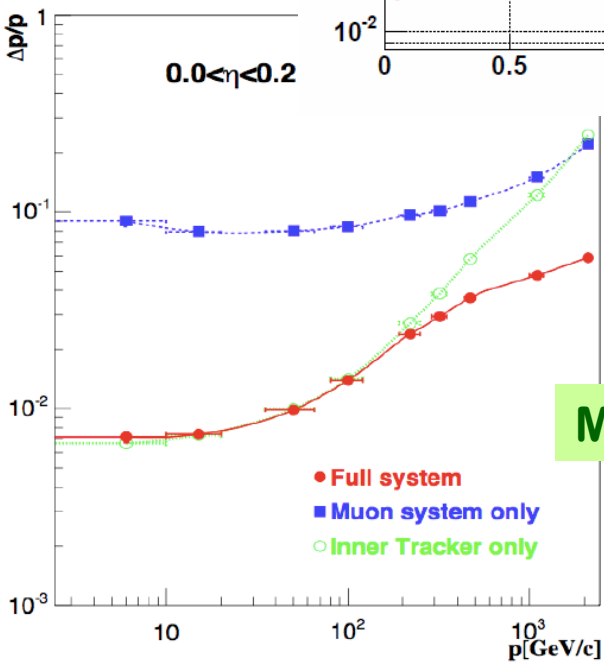


Tracker Misalignment





ECAL Calibration



Muon Resolution

$W^{\pm}/Z^0$ Production

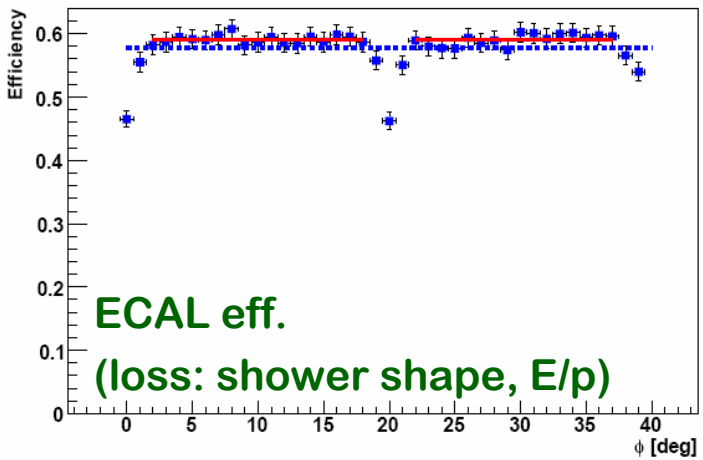
CMS Note 2006/082
CMS Note 2006/124

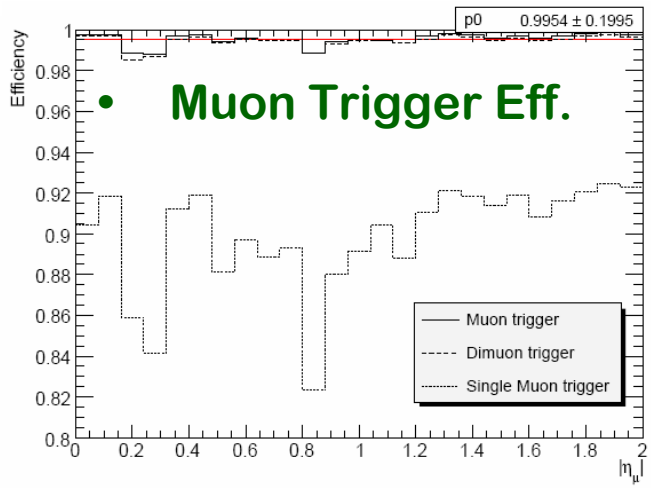
Luminosity	10^{32} cm^{-2}s^{-1}		$2 * 10^{33}$ cm^{-2}s^{-1}		
Time	few weeks	6 months	1 day	few weeks	one year
Int. Luminosity	100 pb^{-1}	1 fb^{-1}		1 fb^{-1}	10 fb^{-1}
$W^{\pm} \to \mu^{\pm}\nu$	700K	7M	100K	7M	70M
$Z^0 \to \mu^+\mu^-$	100K	1M	20K	1M	10M

- **Abundantly produced, clean leptonic signatures, σ(NLO) known to 4-5%**
- **Already for 1fb^{-1}, the measurement of $W^{\pm}/Z^0$'s is dom. by systematics:**

$$\Delta\sigma/\sigma(pp \to Z+X \to \mu\mu+X) \approx (0.13(stat.) + 2.3(syst.) + 10(lumi.))\%$$
$$\Delta\sigma/\sigma(pp \to W+X \to \mu\nu+X) \approx (0.04(stat.) + 3.3(syst.) + 10(lumi.))\%$$

- **Luminosity measurement!**
- **If L known, constrain PDFs!**





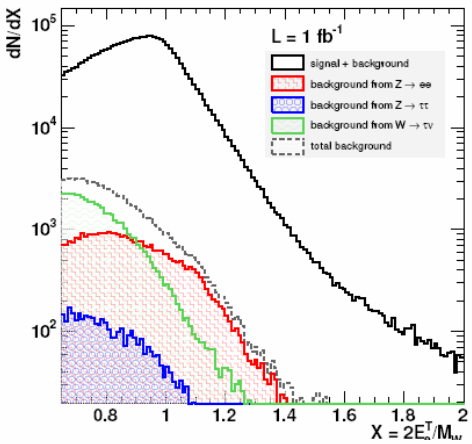
Large samples of $e^{\pm}$,$\mu^{\pm}$ to calibrate and commission detector and trigger!

m_W Measurement

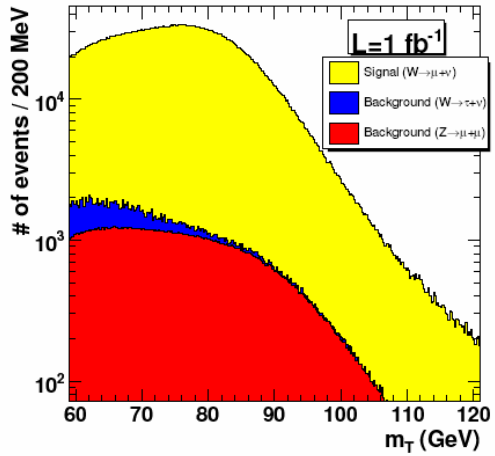
- **Important SM parameter (m_H constraint)**
- **New methods using W/Z ratios and large Z^0 statistics at LHC**
  - ❑ **"scaled observables"**
    - o Giele, Keller PRD 57 (1998)
    - o Treat Z as W, rescale according to mass ratio, use R(W/Z) from theory
  - ❑ **"morphing"**
    - o Kinematic transformation Z→ W

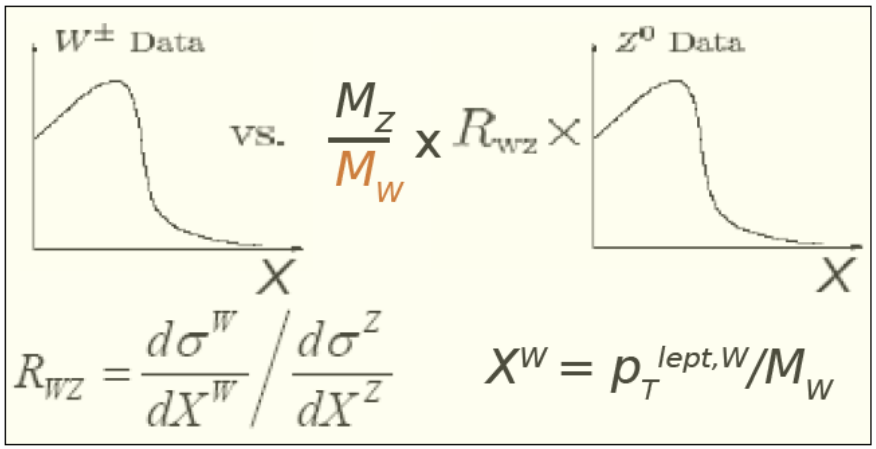
CMS Note 2006/061

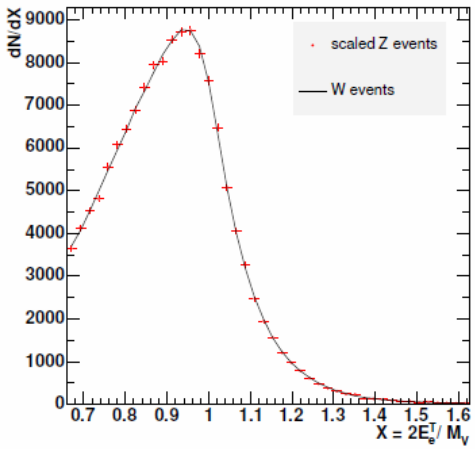
- **Electron ch.**

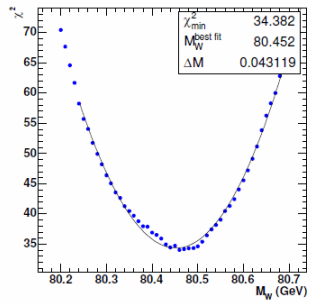


- **Muon ch.**







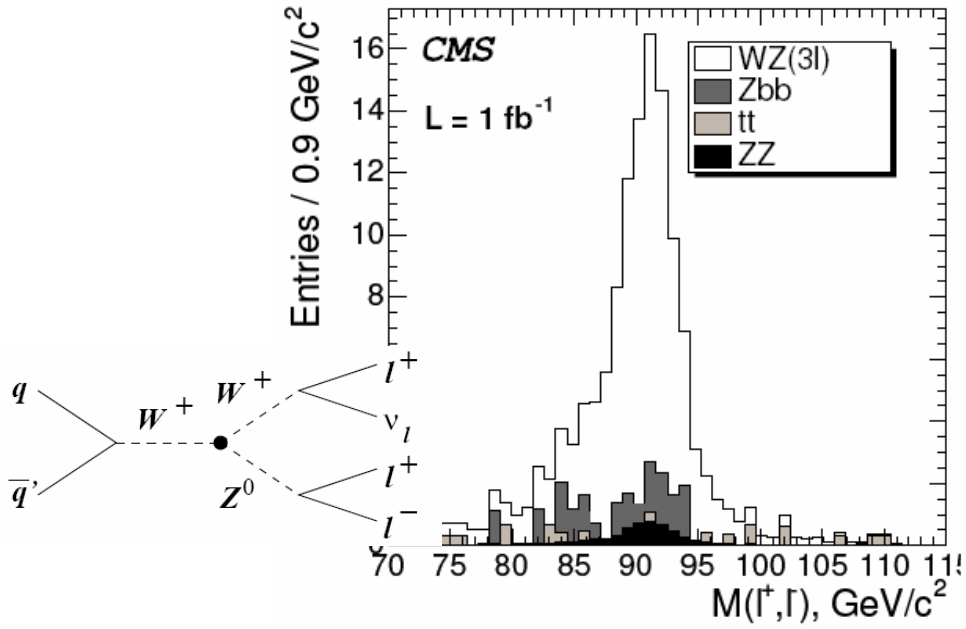


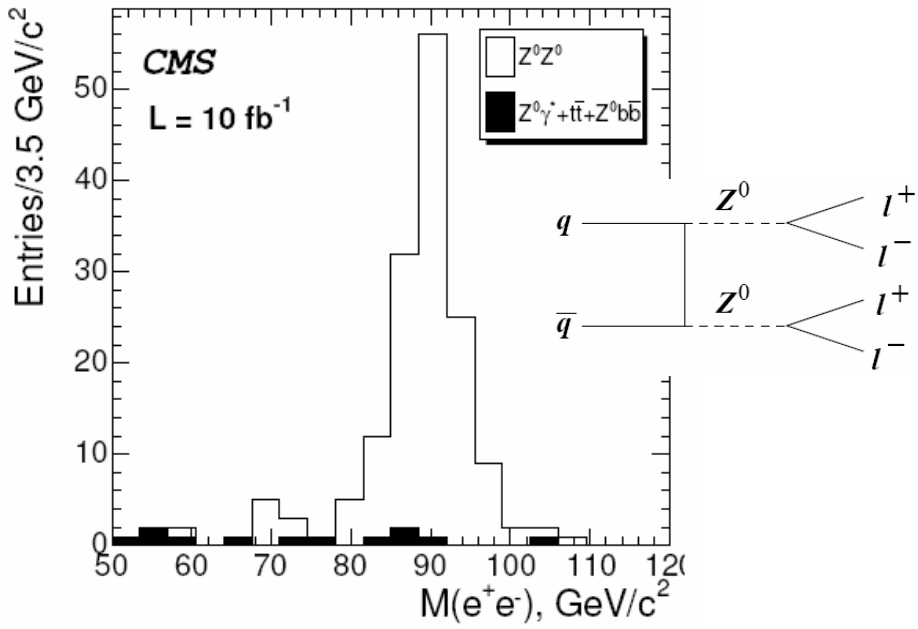
- **Scaled pt (e channel): Δm_W ~ 40 (15) (stat) + 40 (20) (syst) MeV @ 1 (10) fb^{-1}**
- **Theor. error dominated by p_T(W): 30 MeV, to be improved with NNLO**

Multiboson Production $W^{\pm}Z^0$, Z^0Z^0

- Probes triple gauge boson couplings (non-abelian gauge symmetry)
- Large LHC cross sections: $\sigma(WZ)\sim 50pb$, $\sigma(ZZ)\sim 20pb$
  - Observable with early LHC data
- Sensitive to new physics

CMS Note 2006/108





- WZ(e or μ): 97 events @ 1fb^{-1} (5σ with 150 pb^{-1}!)
- ZZ (4e): 71 events @ 10 fb^{-1}

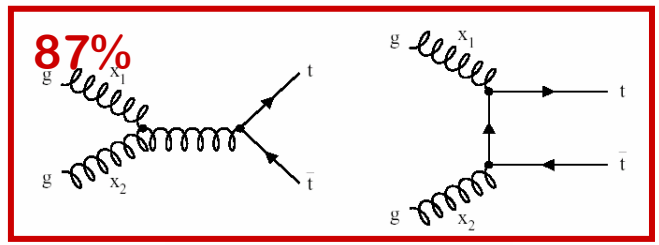
Large S/B: useful to contrain Higgs backgrounds!

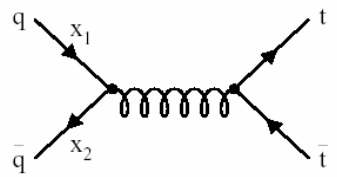
Early Top Quark Physics

- **Tevatron: 10 ttbar / day (85% qq→tt)**
- **LHC: 1 ttbar / sec (87% gg→tt)**

	1.96 TeV	14 TeV	
ttbar pairs	$5.06^{+0.13}_{-0.36}$ pb	833^{+52}_{-39} pb	(x170)
Wjj (*)	~1200 pb	~7500 pb	(x6)
bb+other jets (*)	~2.4×10^5 pb	~5×10^5 pb	(x2)

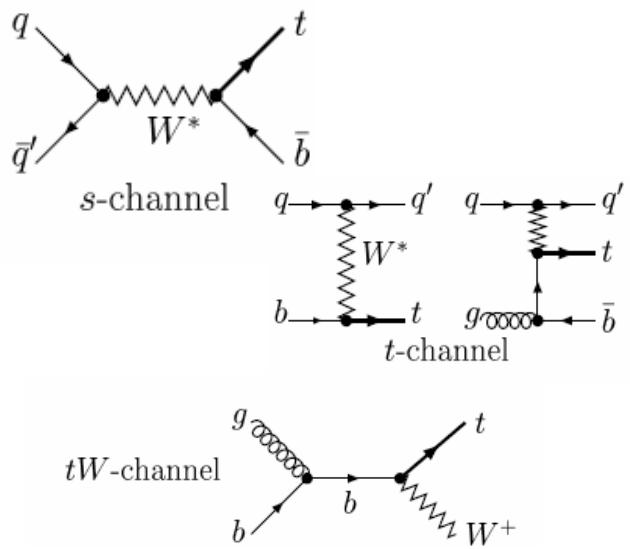
(*) with kinematic cuts in order to better mimic signal
Belyaev, Boos, and Dudko [hep-ph/9806332]





- **LHC: 30 single top / min**

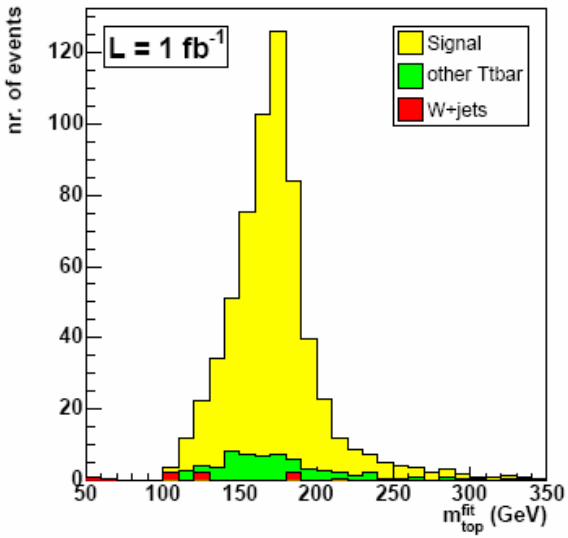
Single top (s-channel)	0.88±0.12 pb	10±1 pb	(x10)
Single top (t-channel)	1.98±0.22 pb	245±17 pb	(x120)
Single top (Wt channel)	0.15±0.04 pb	60±10 pb	(x400)



800k ttbar and 350k single-top produced in 1 fb^{-1}

Top Cross Section

- **Due to high S/B after selection, cross section can be measured in a counting experiment**
- **Semi-leptonic channel**
  - **Event Selection:**
    - p_T(Lepton) > 20 GeV
    - p_T(Jet) > 30 GeV
    - b-tags > 1
    - Kinematic fit
  - **S/B ~ 27**
  - **Eff. ~ 6.3%**



CMS Note 2006/064

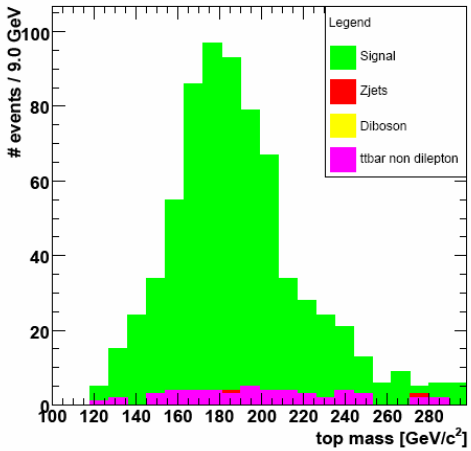
	$\Delta\hat{\sigma}_{t\bar{t}(\mu)}/\hat{\sigma}_{t\bar{t}(\mu)}$
Statistical Uncertainty ($1fb^{-1}$)	1.2%
Statistical Uncertainty ($5fb^{-1}$)	0.6%
Statistical Uncertainty ($10fb^{-1}$)	0.4%
Simulation samples (ϵ_{sim})	0.6%
Simulation samples (F_{sim})	0.2%
Pile-Up	3.2%
Underlying Event	0.8%
Jet Energy Scale (light quarks)	1.6%
Jet Energy Scale (heavy quarks)	1.6%
Radiation	2.6%
Fragmentation	1.0%
b-tagging (conservative)	7.0%
Parton Density Functions	3.4%
Background level	0.9%
Total Systematic Uncertainty	9.2%
Integrated luminosity ($1fb^{-1}$)	10%
Integrated luminosity ($5fb^{-1}$)	5%
Integrated luminosity ($10fb^{-1}$)	3%
Total Uncertainty ($1fb^{-1}$)	13.7%
Total Uncertainty ($5fb^{-1}$)	10.5%
Total Uncertainty ($10fb^{-1}$)	9.7%

- $\Delta\sigma/\sigma$ ~ 1.2% (stat.) $\pm$ 9.2% (syst.) $\pm$ 10% (lumi) @ 1 fb^{-1}
- $\Delta\sigma/\sigma$ ~ 0.4% (stat.) $\pm$ 9.2% (syst.) $\pm$ 3% (lumi) @ 10 fb-1

If b-tag unc. reduced to 2%, total error down to 7% (10 fb^{-1}) 2-3 GeV on m_t from xs!

Top Cross Section (cont.)

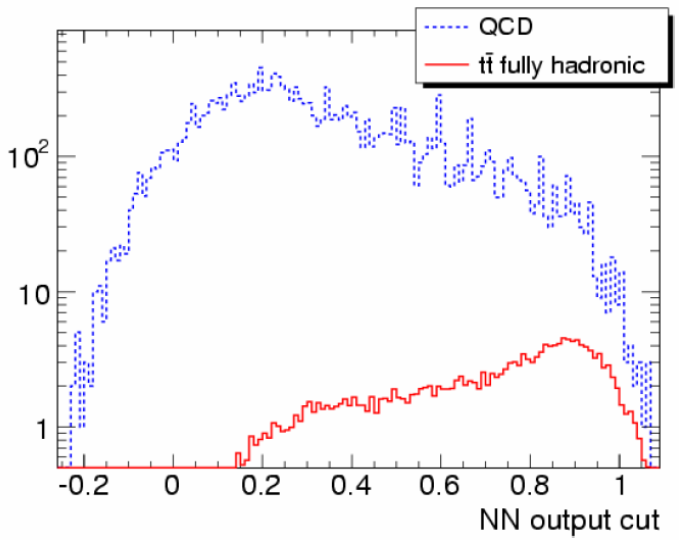
- **Dilepton channel:**
  - Event Selection
    - P_T(Lepton) > 20 GeV
    - 2 b-jets > 30 GeV
    - MET > 40 GeV
    - Kinematic fit
  - N=660 in 1 fb^{-1}



Effect	$\Delta\sigma_{t\bar{t}\ dil\ e/\mu}/\sigma_{t\bar{t}\ dil\ e/\mu}$
ISR and FSR	2.5%
Jet Energy Scale	3.6%
b-tag efficiency	3.8%
lepton reconstruction	1.6%
$\not{E}_T$	1.1%
Pile-Up	3.6%
Underlying Event	4.1%
heavy quark fragmentation	5.1%
PDF uncertainties	5.2%
Statistical uncertainty	0.9%
Integrated luminosity	3%

$\Delta\sigma/\sigma$ ~ 0.9% (stat.) $\pm$ 11% (syst.) $\pm$ 3% (lumi) @ 10 fb^{-1}

- **Fully hadronic channel:**
  - Selection:
    - Dedicated b-tag multijet trigger
    - >5 Jets, E_T>30 GeV
    - Topology
    - 2 b-tags
  - N=8000 events in 1 fb^{-1}
  - S/B improvement with Neural Net event selection



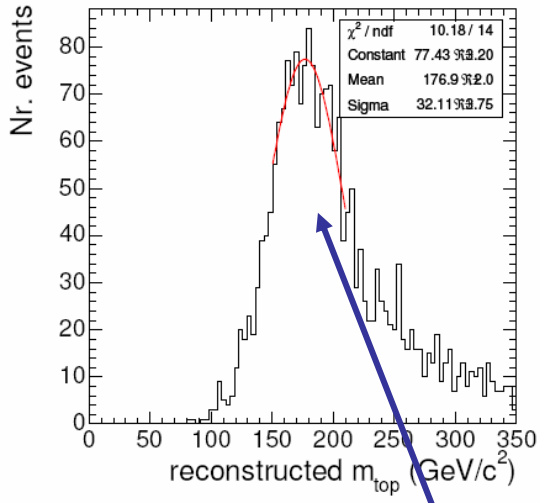
$\Delta\sigma/\sigma$ ~ 3% (stat.) $\pm$ 20% (syst.) $\pm$ 3% (lumi) @ 10 fb^{-1}

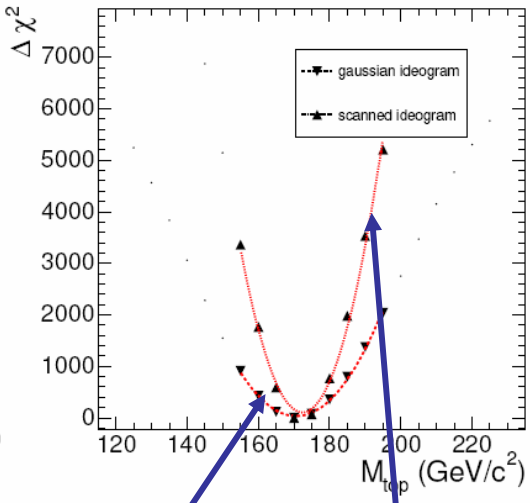
CMS Note 2006/077

Top Mass Measurement

- m_t fundamental SM param.
- Related to m_h

- **Semileptonic channel:**
  - A simple gaussian fit is compared with more sophisticated "ideogram method", also employing kinematic constraints
  - Clear gain in precision when using the fitted ideogram
  - 1 GeV uncertainty reachable with good detector understanding
    (JES 1.5%, btag 2% etc.)





	Standard Selection		
	Gaussian Fit Δm_t (GeV/c^2)	Gaussian Ideogram Δm_t (GeV/c^2)	Full Scan Ideogram Δm_t (GeV/c^2)
Pile-Up (5%)	0.32	0.23	0.21
Underlying Event	0.50	0.35	0.25
Jet Energy Scale (1.5%)	2.90	1.05	0.96
Radiation (Λ_{QCD}, Q_0^2)	0.80	0.27	0.22
Fragmentation (Lund b, σ_q)	0.40	0.40	0.30
b-tagging (2%)	0.80	0.20	0.18
Background	0.30	0.25	0.25
Parton Density Functions	0.12	0.10	0.08
Total Systematical uncertainty	3.21	1.27	1.13
Statistical Uncertainty (10 fb^{-1})	0.32	0.36	0.21
Total Uncertainty	3.23	1.32	1.15

Δm_t = 0.21 (stat.) $\pm$ 1.13 (syst.) GeV @ 10 fb^{-1}

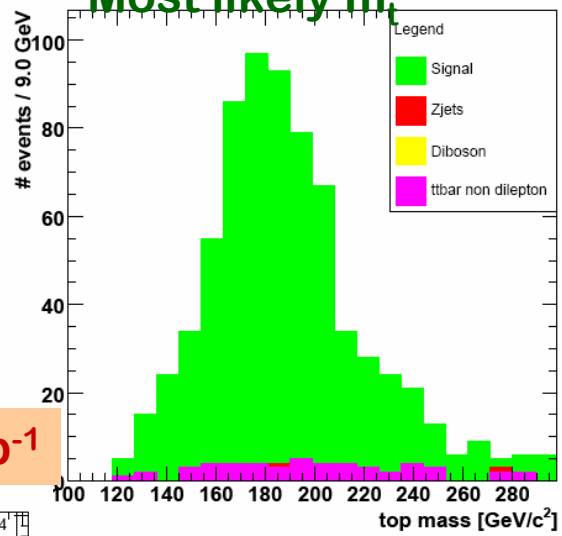
CMS Note 2006/066

Top Mass Measurement (cont.)

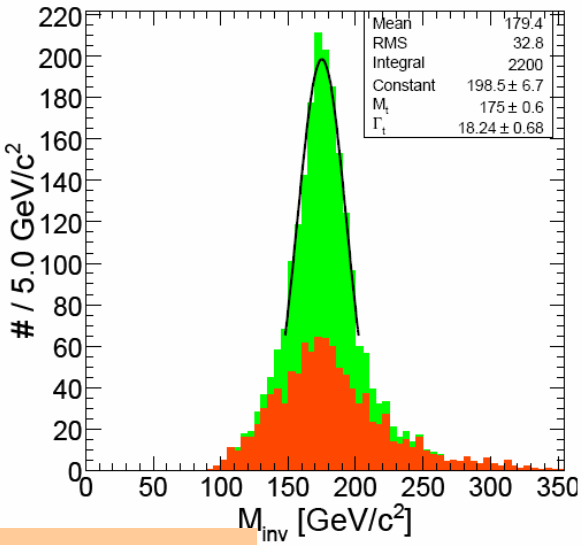
- **Dilepton channel**
  - ❑ Experimental error dominated by jet energy scale, known to
    - o 15% at 1 fb^{-1}: $\Delta m \sim 4.2$ GeV
    - o 10…3.0% for 1…10 fb^{-1} $\Delta m \sim 2.9$ GeV
    - o 1.5% longer term: $\Delta m \sim 1.0$ GeV

$\Delta m_t = 1.5\ (0.5)\ (\text{stat.}) \pm 2.9\ (1.1)\ (\text{syst.})$ GeV @ 1 (10) fb^{-1}

Most likely m_t



- **Fully hadronic channel**
  - •Jet pairing likelihood improves S/B from 1/9 to 1/3 at same efficiency



	Δm_t[GeV/c^2]
Pile Up	0.4
Underlying Event	0.6
PDF	1.4
IS/FS Radiation	2.3
Fragmentation	0.9
Jet Energy Scale	2.3
b-Tagging	0.3
Background	2.0

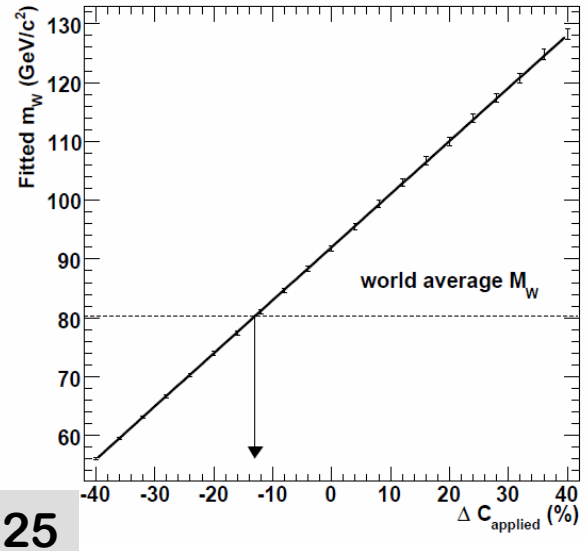
$\Delta m_t = 0.6\ (\text{stat.}) \pm 4.2\ (\text{syst.})$ GeV @ 1 fb^{-1}

CMS Note 2006/077

N.B. mass measurement also studied in t $\rightarrow$ l + J/Ψ +X decays, see CMS Note 2006/058

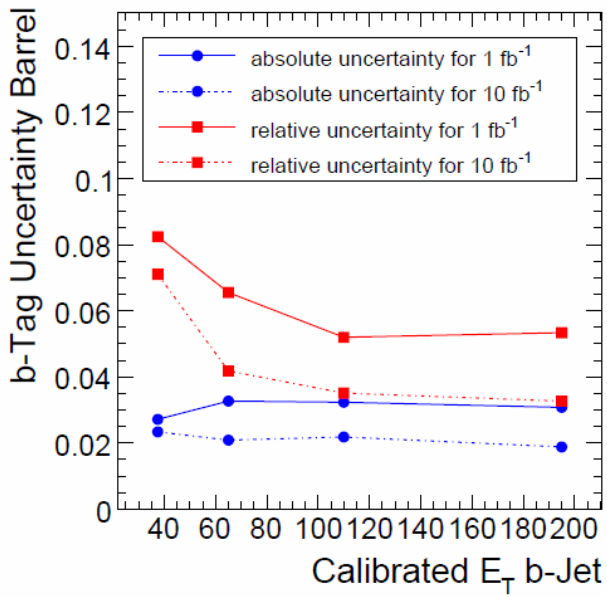
Top as commissioning tool

- **Light quark jet energy scale from m_W constraint in W→ jj in ttbar**
  - Adapt jet energy scale until correct m_W is fitted
  - No btag in start-up scenario
  - Result:
    - ΔE_{jet} (stat.) ~ 1% (for 1 fb^{-1})
    - ΔE_{jet} (syst.) ~ 3% (pileup)



CMS Note 2006/025

- **B-tagging efficiency determination in ttbar events**
  - Selection of high-purity dilepton ttbar events
  - Purity of b-content in selected sample: 44% ± 1.6% (stat.) ± 1.9% (syst.)
  - Rel. uncertainty on btag eff.
    - 1 fb^{-1}: 6%
    - 10 fb^{-1}: 4%



CMS Note 2006/013

Single Top Production

- **Sensitive to new physics**
- **Measurement of $|V_{tb}|$**

$$R = \frac{\Gamma(t \to Wb)}{\Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

- **NLO Cross section ~370 pb**
  - **3.7M events in 10 fb^{-1}**
- **t-channel results for 10 fb^{-1}:**
  - **Optimized event selection (S/N~1.34)**
    - **MET > 40 GeV**
    - **Light jet p_T>40 GeV, $|\eta|$>2.5**
    - **B-jet p_T>35 GeV, $|\eta|$<2.5**
    - **Topological cuts** **N_{evt}=2400**

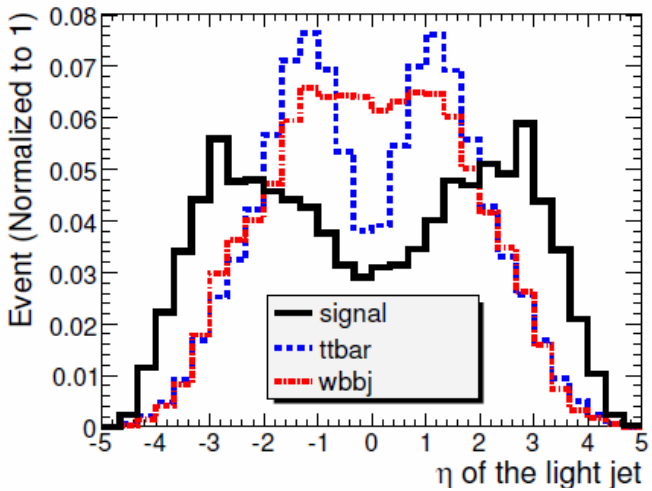
$\Delta\sigma/\sigma$ = 2.7 (stat.) $\pm$ 8.1 (syst.) $\pm$ 3 (lumi) %

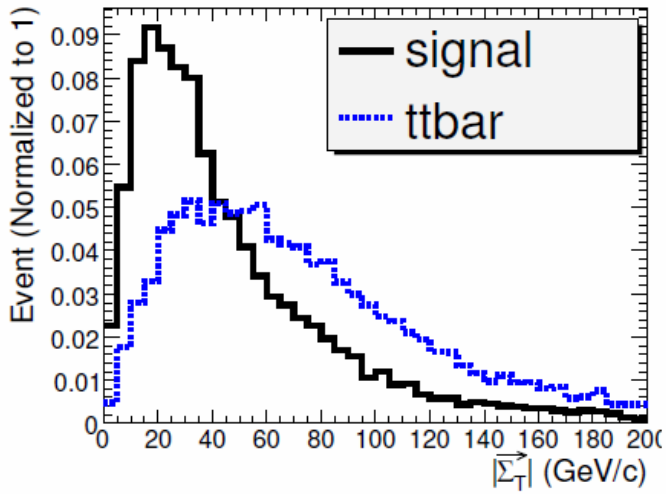
- **Other channels:**
  - **s-channel**

$\Delta\sigma/\sigma$ = 18 (stat.) $\pm$ 31 (syst.) $\pm$ 3 (lumi) %

  - **tW-channel**

$\Delta\sigma/\sigma$ = 7.4 (stat.) $\pm$ 18 (syst.) $\pm$ 3 (lumi) %





CMS Note 2006/084

CMS Note 2006/086

Conclusions

- **Exciting prospects already for 1 fb^{-1} of LHC data**
  - **Electroweak: Large samples of W,Z events in early phase**
    - Calibration and monitoring
    - Luminosity / PDF measurements
    - Combined W-mass measurement with $\Delta m_W \sim 50$ MeV
    - Measurements of W+Jets, Z+Jets, Diboson production
  - **Top Quarks**
    - First cross section and mass measurements in all decay channels
    - Use for calibration (JES) and commissioning (btag)

- **Promising precision measurements**
  - **W-mass: $\Delta m_W \sim 15$ MeV feasible when combining channels**
  - **Top-mass: $\Delta m_t < 1$ GeV (with combination of J/Ψ channel)**
  - **Single top cross sections**

Many more results to be found in PTDR I+II and ~150 accompanying (public) CMS Notes!

The CMS Detector will be ready to face these challenges when LHC turns on!

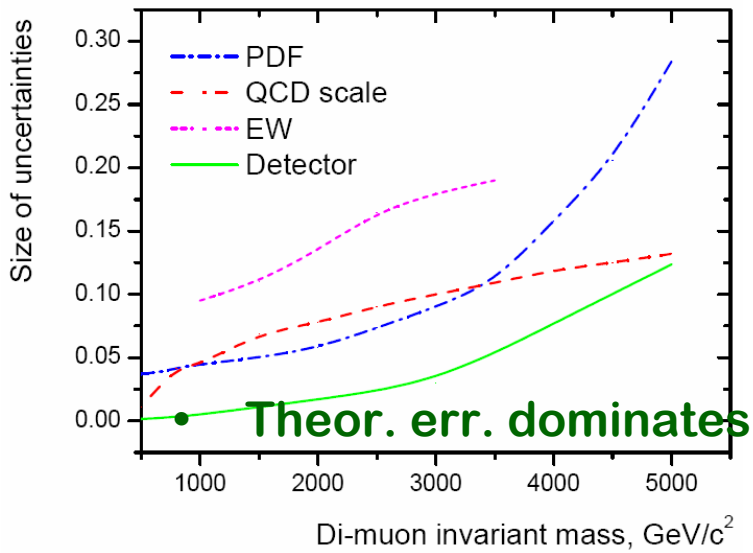
Backup

Drell-Yan Muon Pairs

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}M_{ll}\mathrm{d}y}[pp \to l_1 l_2 + X] \approx \sum_{ij} \left(f_{i/p}(x_1) f_{j/p}(x_2) + (i \leftrightarrow j)\right) \hat{\sigma}$$

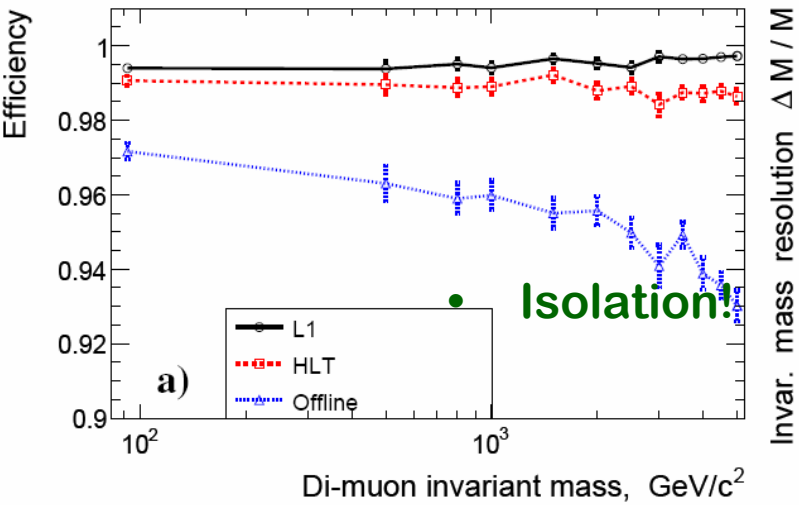
- **s-channel γ^*/Z^0 exchange**
- **Sensitivity to PDFs**
- **Measurement of A_{FB} at high luminosity**
- **High mass region sensitive to new physics**

CMS Note 2006/123

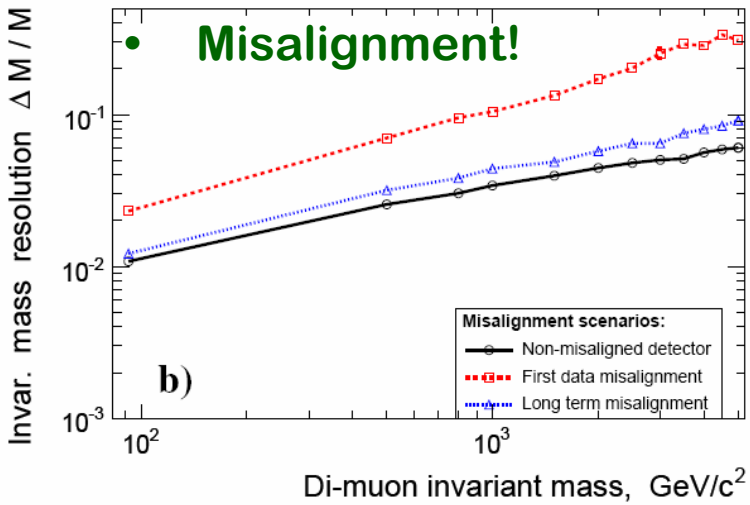


- **Theor. err. dominates**

- **Cross section calculated for 11 samples with $M_{inv.}$ > 0.2 … 5 TeV**



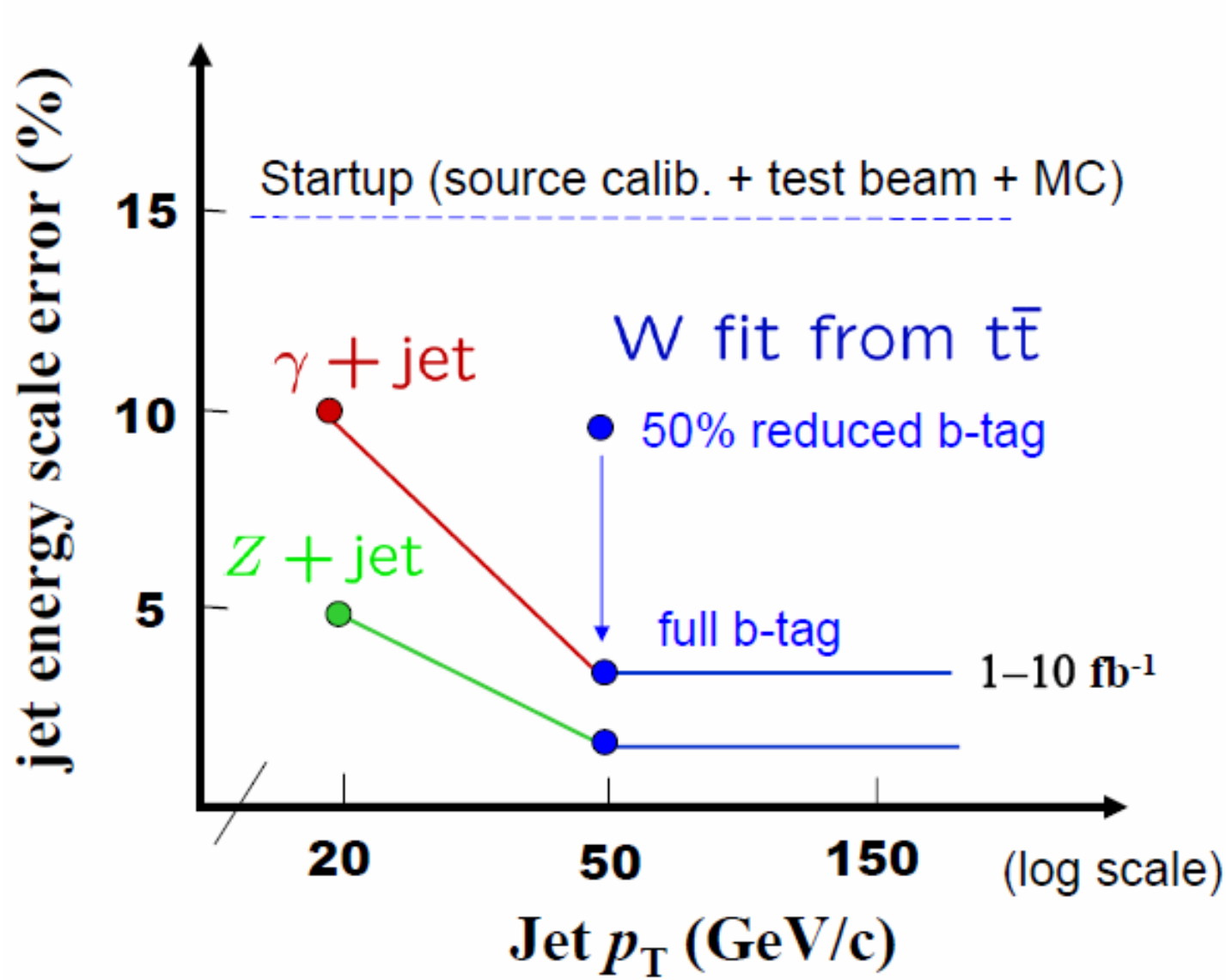
- **Isolation!**



- **Misalignment!**

- **With 1fb^{-1}, XS can be measured up to M~1 TeV**

Jet Energy Scale Uncertainty



Ideogram method

event-by-event likelihood approach

- probability or ideogram of an event
  $P(y|m_t) \sim \exp\left(-\frac{1}{2} \cdot \chi^2(y|m_t)\right)$ with
  $\chi^2(y|m_t) = \left(\frac{m_t - m_t^{fit}}{\sigma_{m_t}^{fit}}\right)^2$
- convolution with th. expected probability density $P(m_t|M_t)$
  $\mathcal{L}_i(M_t) = \int P(y|m_t) \cdot P(m_t|M_t) dm_t$

  $P(m_t|M_t)$ includes Breit-Wigner shape of signal, combinatorial and process background; with M_t as the true value of the top mass
- maximum likelihood method on combination of all convoluted ideograms