Standard Model Physics with CMS

in the first year of LHC

Joachim Mnich

CMS Myon Meeting

April 29th, 2004

Aachen

Status of SM Physics with CSM

- not much SM studies done so far in CMS
- mostly generator with smearing
- all and much more needs to be redone
- stagged DAQ increased muon p_T thresholds

 much work to be done for the Physics TDR

 SM physics particularly important in the initial low luminosity phase of LHC

 Muons are the key to many interesting SM analyses

Physics Reconstruction & Selection
Standard Model Group

CMS PRS SM Group

- **Top physics**
- **B-physics**
- **Electroweak physics (W/Z)**
- **QCD**
- **Forward physics**
  (total pp x-section, elastic scattering, diffraction, luminosity) together with TOTEM

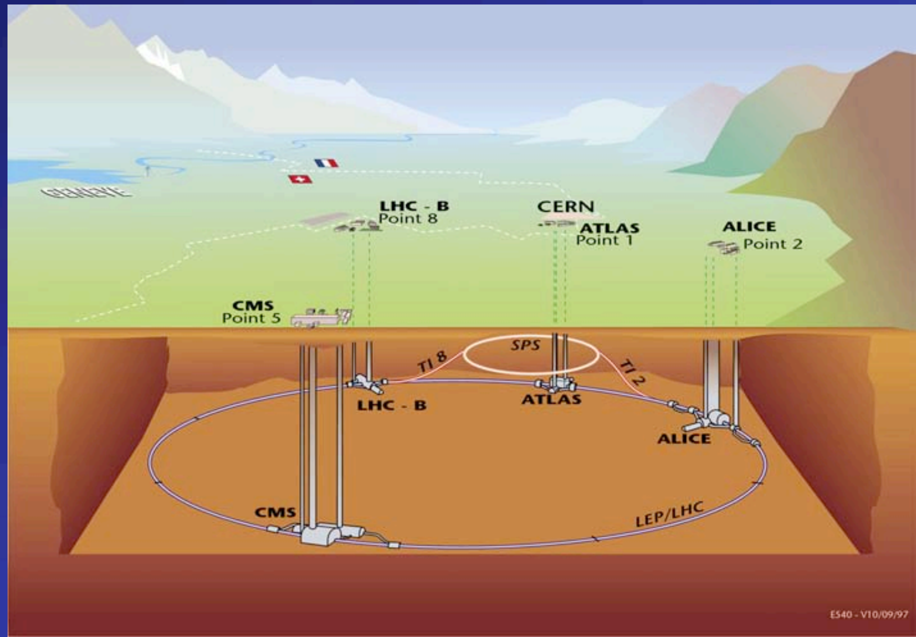
Alternative title of the talk:

A Commercial for SM Physics with CMS

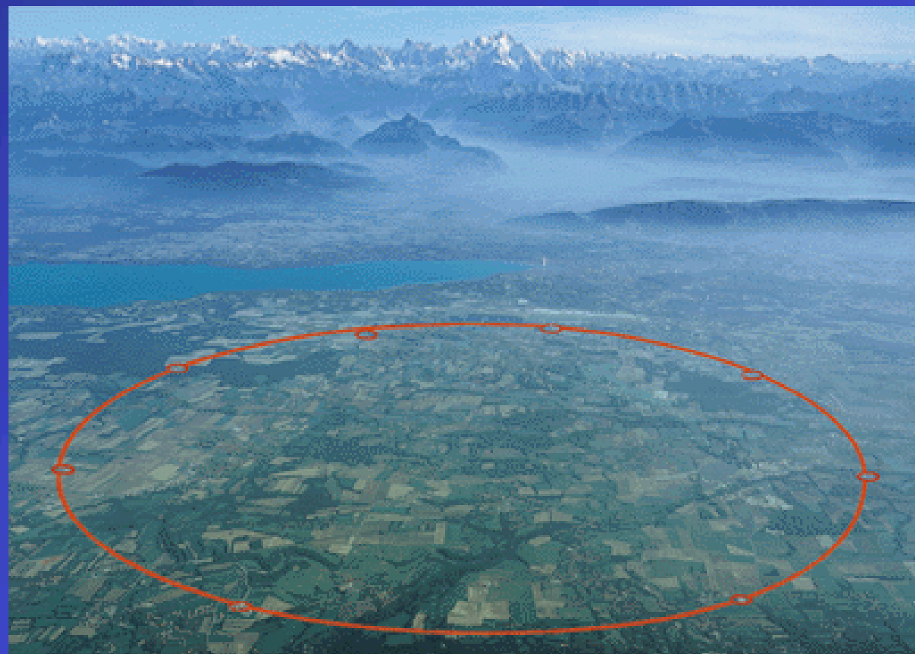
General Remarks on the LHC

The LHC uniquely combines the two most important features for HEP experiments:

1. High energy 14 TeV
2. and high luminosity $10^{33} - 10^{34}/cm^2/s$



Physics programme:
- Higgs
- SUSY and other searches
- Test of the SM



Cross Section of some SM processes:

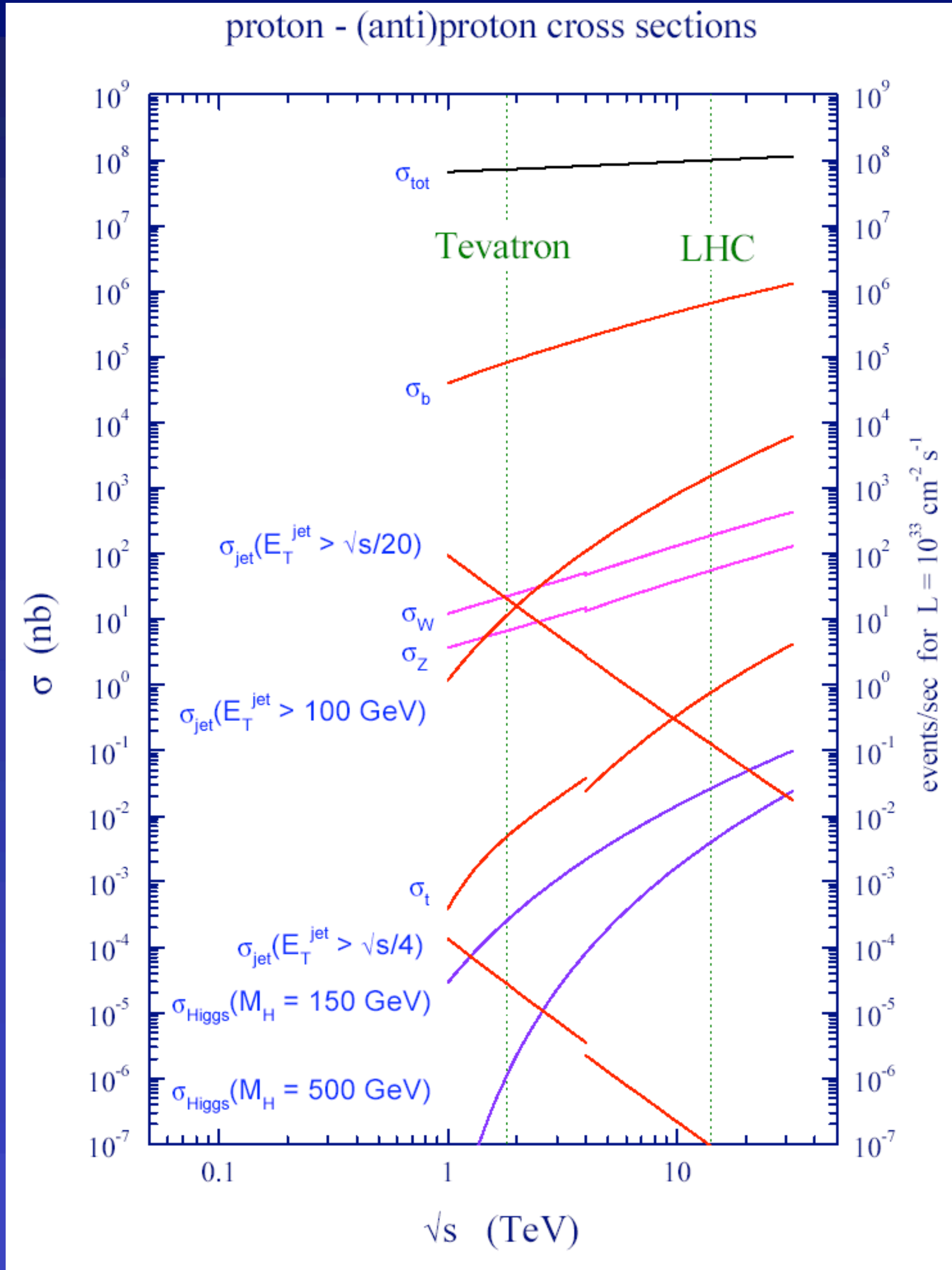
Low luminosity phase:

10^{33}/cm^2/s = 1/nb/s

Per second approx.

- o **200 W-bosons**
- o **50 Z-bosons**
- o **1 $t\bar{t}$-pair**

will be produced!



Initial SM Physics at the LHC

I) 1 fb^{-1} i.e. a couple of months after start

W & Z, Drell-Yan

First top results (cross section, mass)

QCD & jet physics

Forward physics

II) 10 fb^{-1} i.e. the generic first year at $10^{33}/cm^2/s$

sufficient for many SM analyses

Here in this talk: emphasis on muons

For further reading:

CERN Yellow Report 2000-004

Workshop on Standard Model Physics (and More) at the LHC

Parton Distribution Functions (pdf)

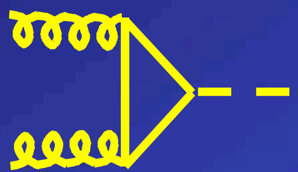
LHC is a proton-proton collider

But fundamental processes are the scattering of

- quark – antiquark
- quark – gluon
- gluon – gluon

Examples:

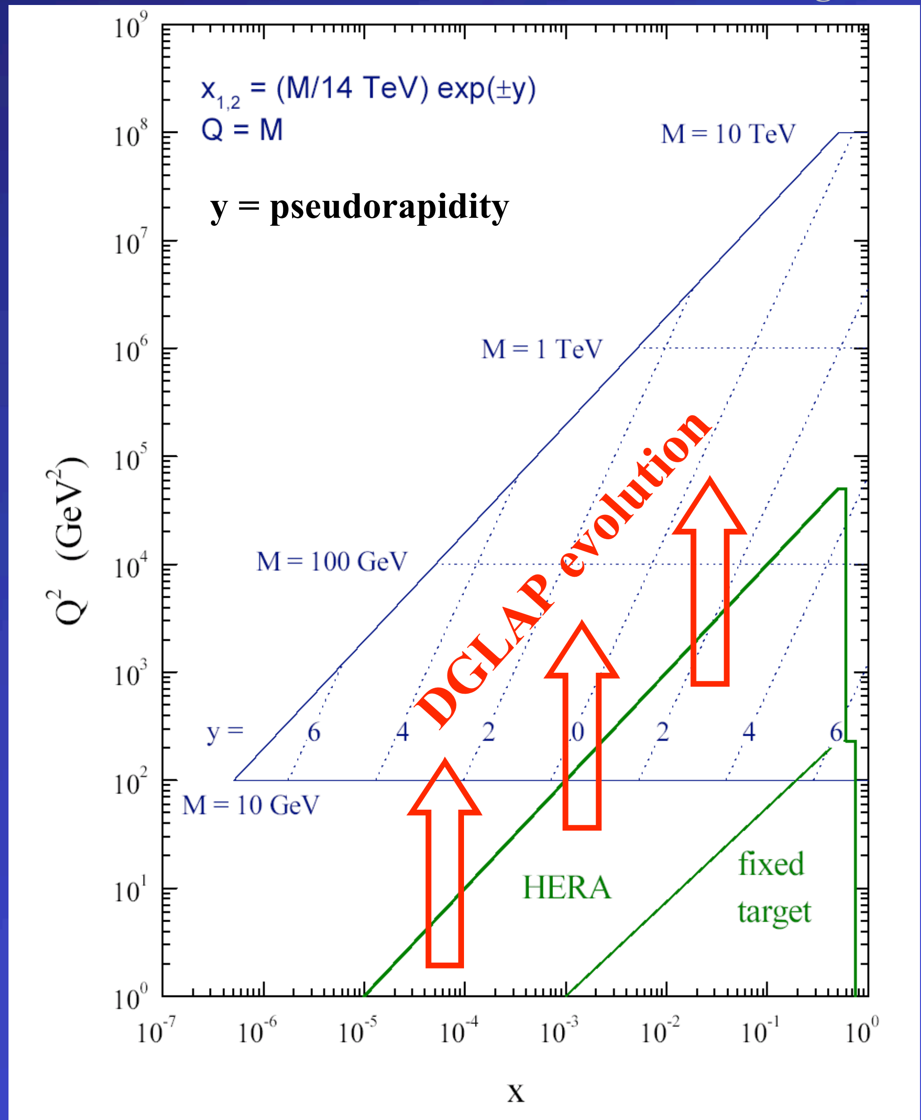
$q\bar{q} \rightarrow W \rightarrow l\nu$



$gg \rightarrow H$

⇒ need precise pdf(x,Q^2) + QCD corrections (scale)

J. Stirling



Synergy HERA & LHC:

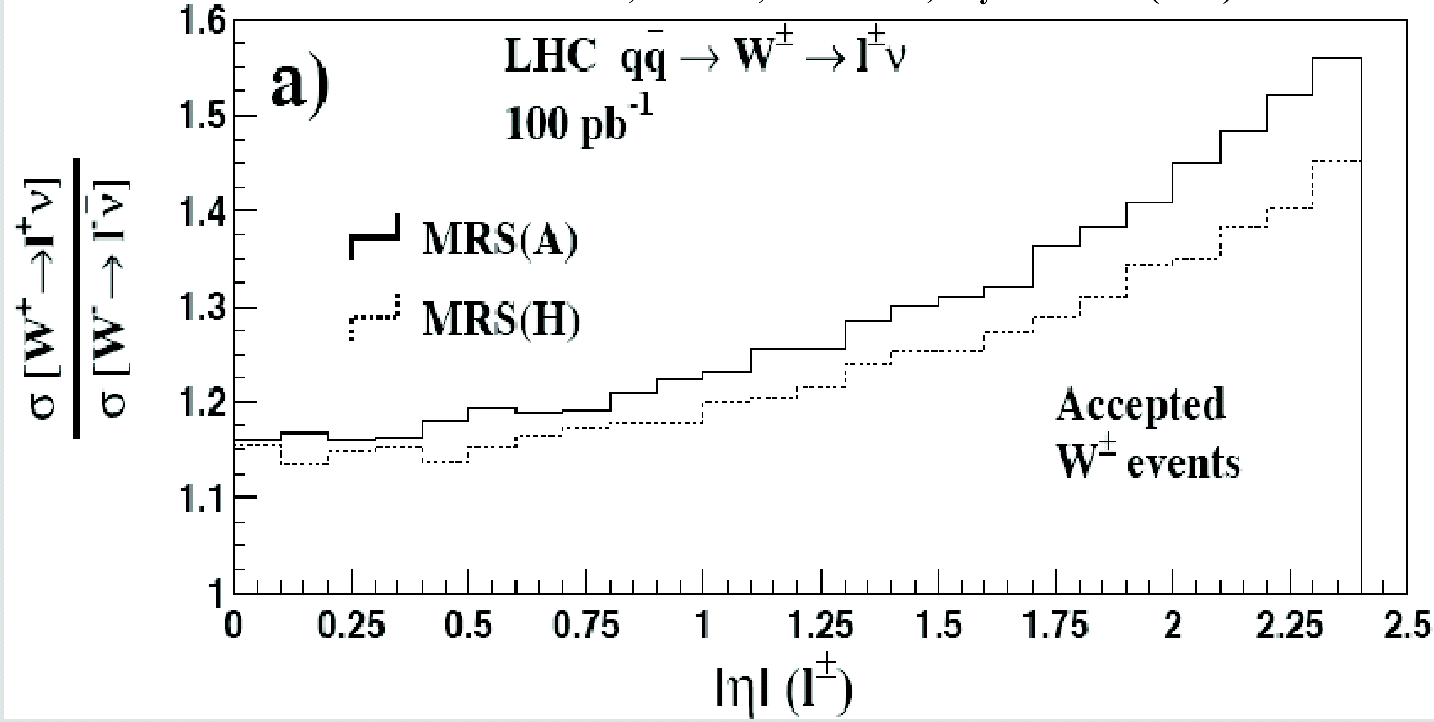
- make pdf measured at HERA useable for the LHC
- transfer of methods & knowledge to determine pdf at the LHC

W/Z production

- p_T and rapidity distributions are very sensitive to pdf
- particularly sensitive variable:
  ratio of W^+/W^- cross section measures u(x)/d(x)

Example: study for 0.1 fb^{-1}, i.e. $2\cdot10^6$ W produced

M. Dittmar, F. Pauss, D. Zürcher, Phys. Rev D56 (1997) 7284



Sensitive to small differences in sea quark distribution

Luminosity Measurement

- **Determine proton-proton luminosity L_{pp} from W & Z**

$$N^{pp\to Z} = L^{pp} \cdot PDF(x_1, x_2, Q^2) \cdot \sigma^{q,\bar{q}\to Z}(+HO)$$

pp → W

theory

more accurate than L_{pp} from pp → pp?

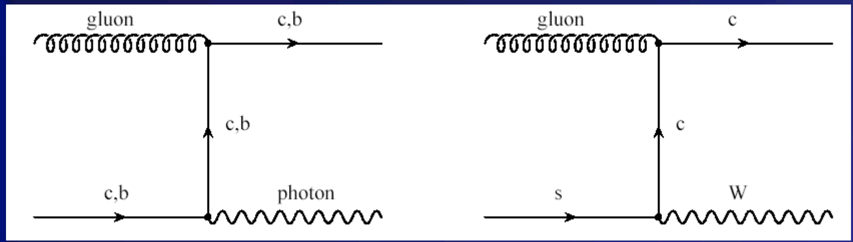
- **Parton-parton luminosity (at least for $q\bar{q}$)**

$L_{q\bar{q}} = L_{pp} \cdot pdf(x_1,x_2,,Q^2)$

- **or use pp → W/Z for normalisation**

$$N_{pp\to WW} = N_{pp\to Z} \cdot \frac{\sigma_{q,\bar{q}\to WW}}{\sigma_{q,\bar{q}\to Z}} \cdot \frac{PDF(x_1', x_2', Q'^2)}{PDF(x_1, x_2, Q^2)}$$

PDF of s, c and b quarks



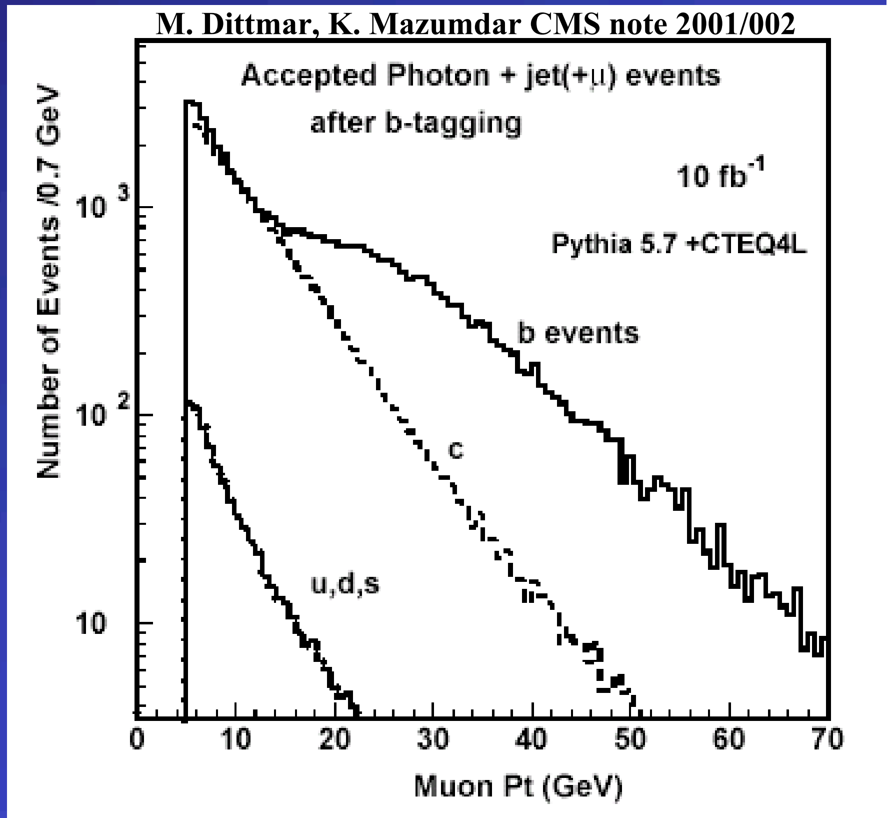
Isolated high p_T + jet with incl.

Isolated high p_T e/ + jet with incl.

Estimate 5-10% accuracy on pdf
Limited by fragmentation functions

Analyses only suited for
low luminosity phase

„Generator level“ study done for YR



NB: increased p_T threshold after DAQ stagging not taken into account

W Mass Measurement

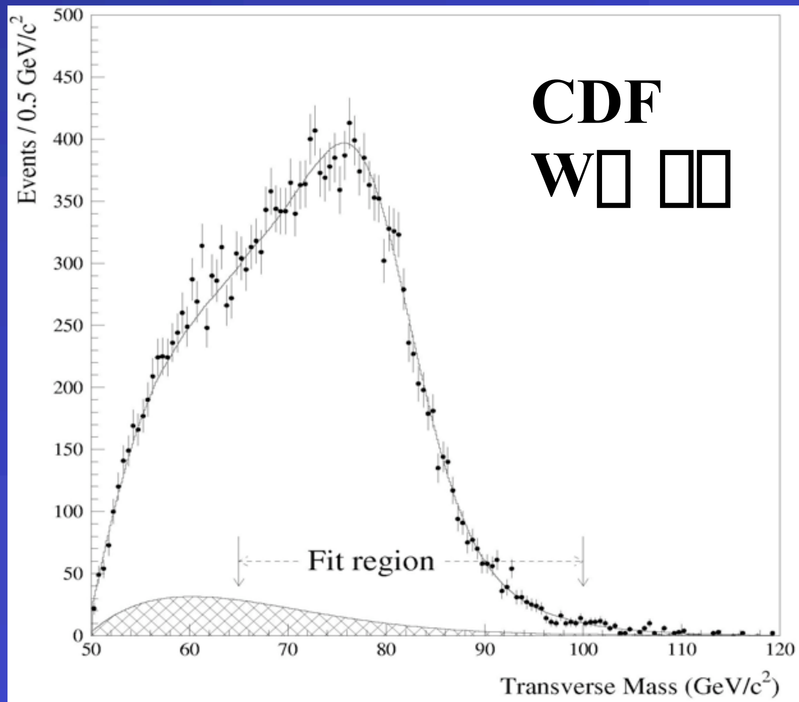
2004: m_W = 80 412 ± 42 MeV — LEP & Tevatron Run I

2007: m_W □ 80 ... ± 20 MeV (2.5 ·10^{-4}) from Tevatron Run II

Improvement at the LHC to ± 10 MeV envisaged
requires control of systematic error to 10^{-4} level

m_W from
e.g. transverse mass distribution

$$M_T = \sqrt{(E_T^{\mu} + E_T^{\nu})^2 - (\vec{P}_T^{\mu} + \vec{P}_T^{\nu})^2}$$



General idea at LHC:

- take Z □ □□ events
- remove one □ to fake Z □ □ "□"
- fix m_Z = 91 187.5 ± 2.1 MeV

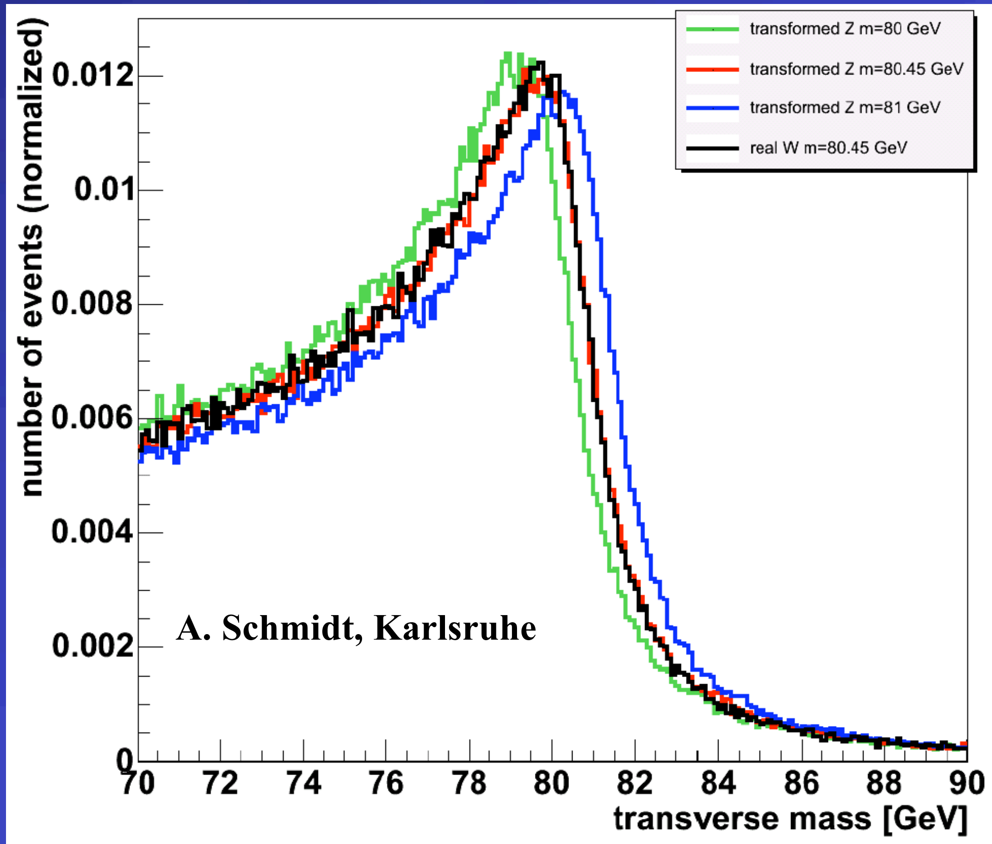
One possible strategy:

- use both muons to reconstruct the Z
- boost into Z rest frame
- set Z mass to arbitray new value M^X and width to □$_W$
- remove one muon
- boost back to dectector frame
- calculate new transverse mass M^X_T and compare to W data

Other clever ideas?

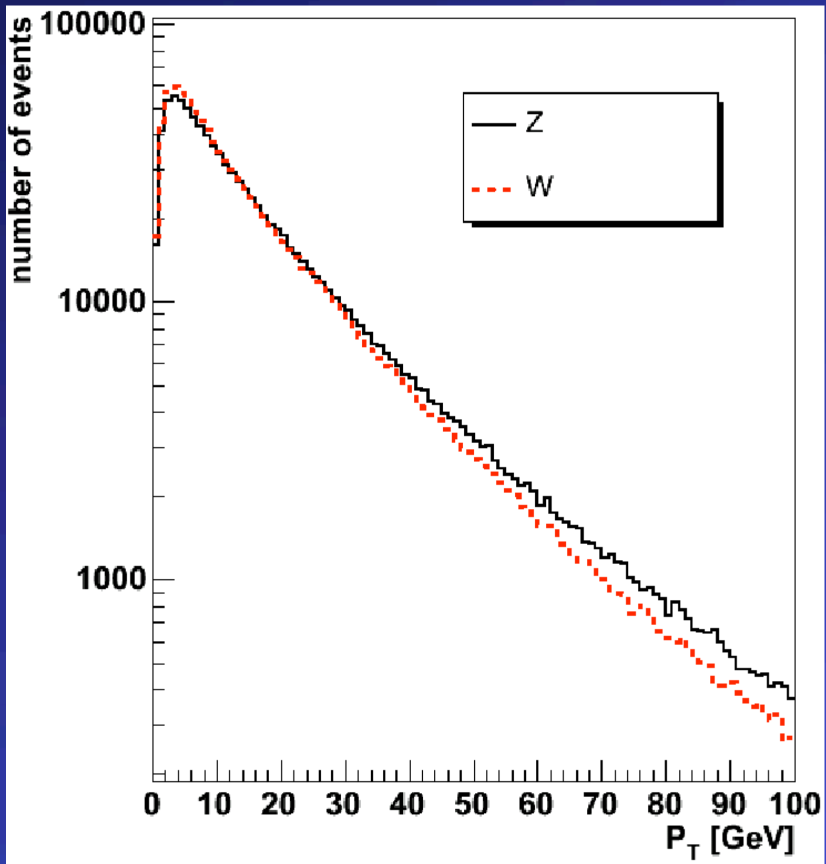
Distributions obtained from 10^6 generated Z □ □□

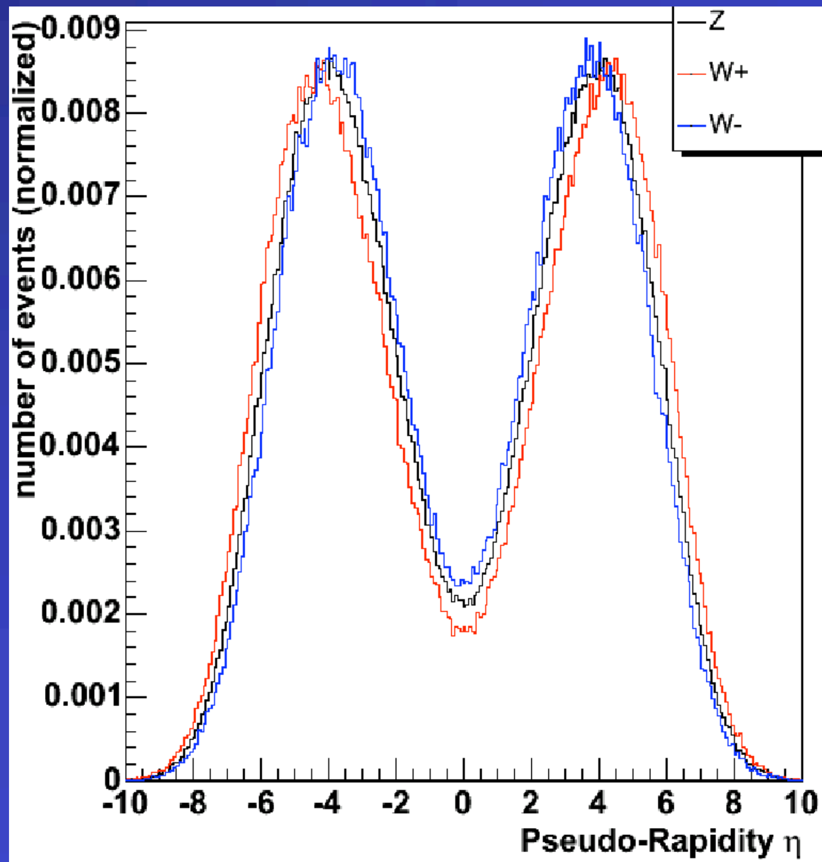
- corresponding to □ 1 fb^{-1}
- stat. error □ 20 MeV



Small differences between W and Z:

- production: p_T & □ distribution
- final state radiation
  (□ doesn‘t radiate!)
- background





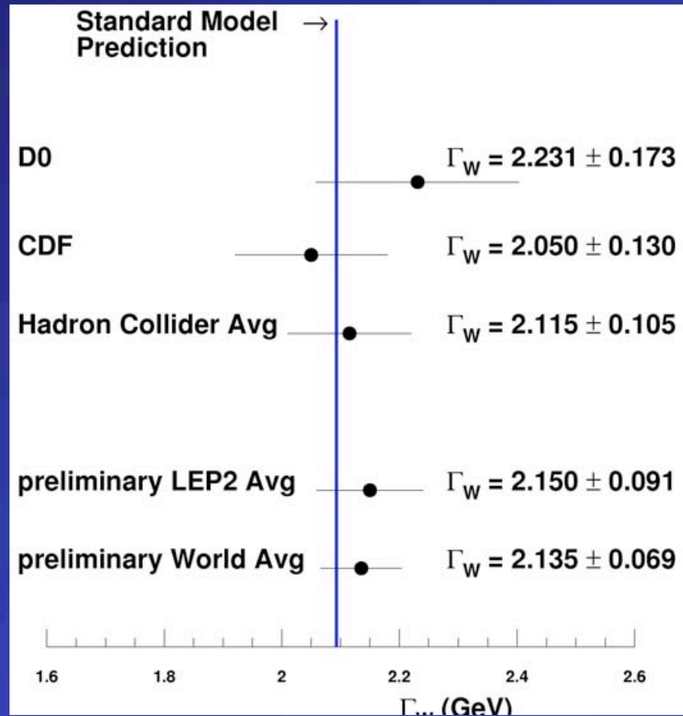
Measurement of the W Width

- **from m_T spectrum:**

  high end is sensitive to Γ_W

  Tevatron: Γ_W = 2.115 ± 0.105 GeV

  LEP: Γ_W = 2.150 ± 0.091 GeV



- **from ratio of W/Z cross section:**

$$R = \frac{\sigma(p\bar{p} \to W + X) \cdot BR(W \to l\nu)}{\sigma(p\bar{p} \to Z + X) \cdot BR(Z \to ll)} = \frac{\sigma(W)}{\sigma(Z)} \cdot \frac{\Gamma_Z}{\Gamma_{Z \to ll}} \cdot \frac{\Gamma(W \to l\nu)}{\Gamma_W}$$

theory (↑ $\sigma(W)/\sigma(Z)$) LEP (↑ $\Gamma_Z/\Gamma_{Z \to ll}$)

→ limit on non-SM W decays

Tevatron:

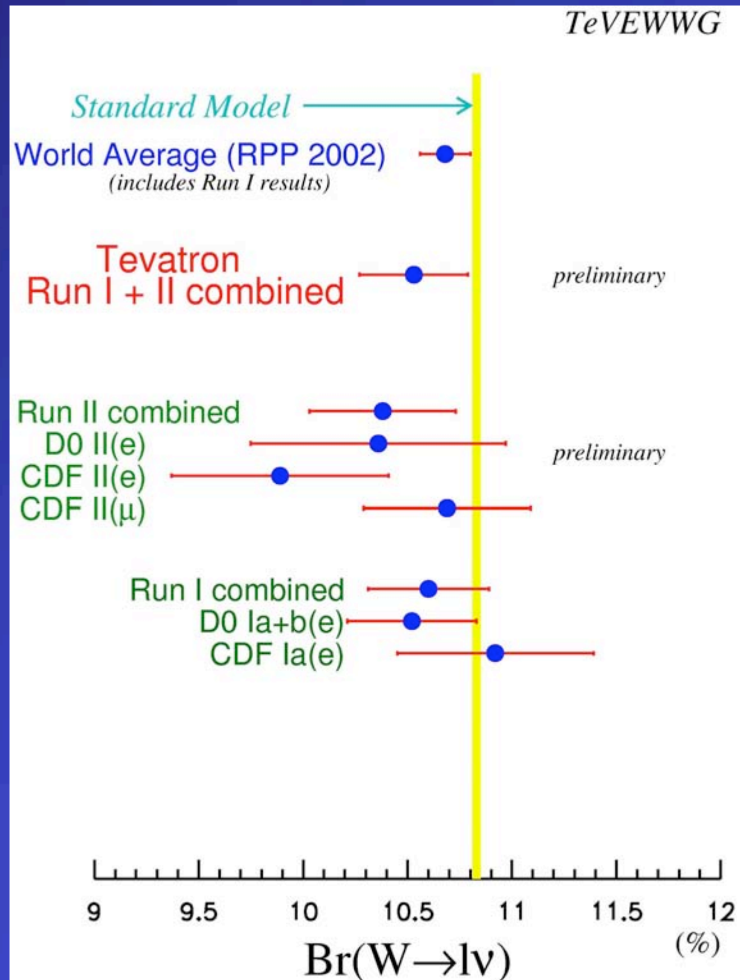
Γ_W = 2.171 ± 0.051 GeV

Lepton Universality in Charged Currents

e.g. Tevatron
approx 50k events/expt. in Run I

measure branching ratios

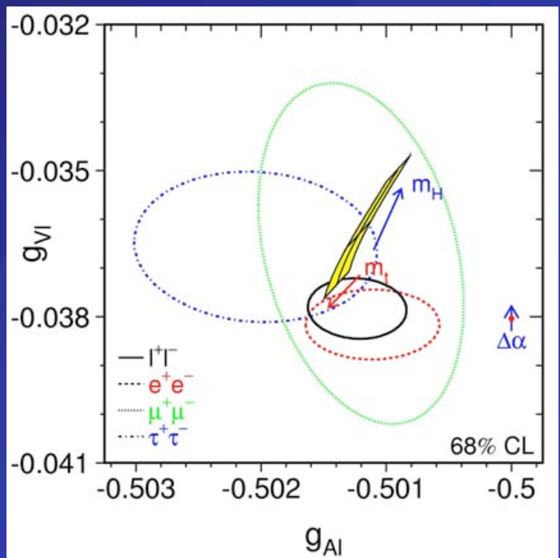
BR(W□□□) / BR(W□e□)



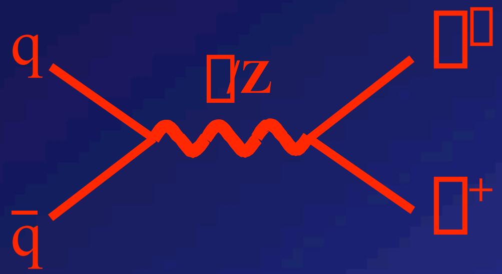
for comparison:

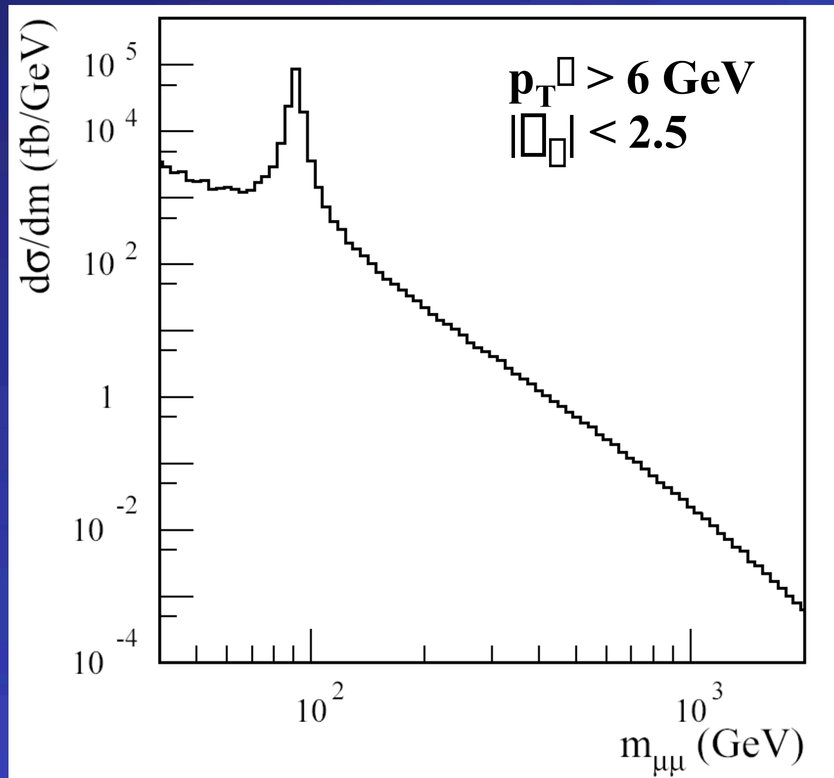
- LEP result: 0.997 + 0.021
- tau decays: 0.2% precision (at low Q^2)

- lepton universality in neutral currents:



Drell-Yan process: $q\bar{q} \rightarrow \mu^+\mu^-$

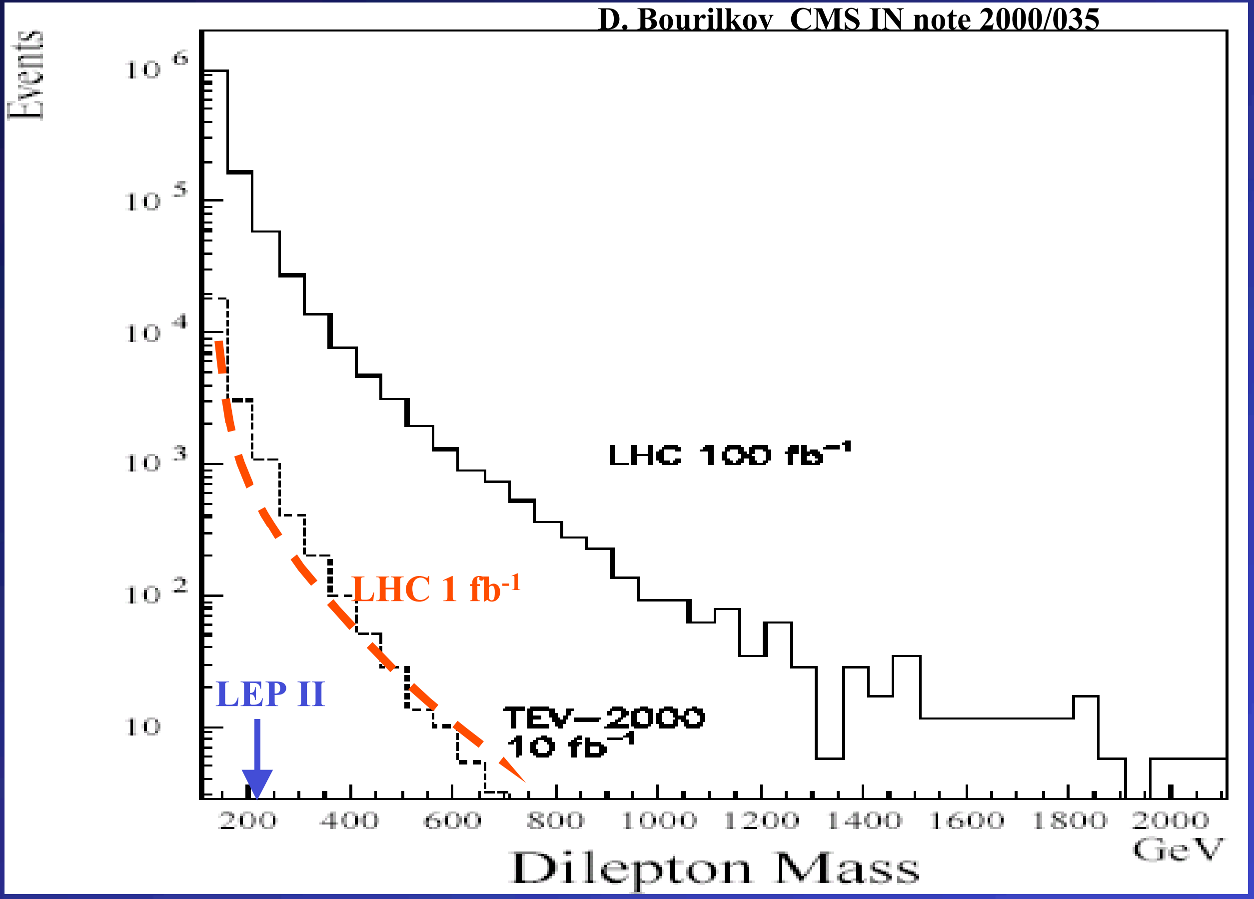




- **total cross section**
  - pdf
  - parton lumi
  - search for Z'
- **forward-backward asymmetry**
  - estimate quark direction
  - assuming $x_q > x_{\bar{q}}$
  - measurement of $\sin^2\theta_W$

Inversion of $e^+e^- \rightarrow q\bar{q}$ at LEP

Mass reach at the LHC:

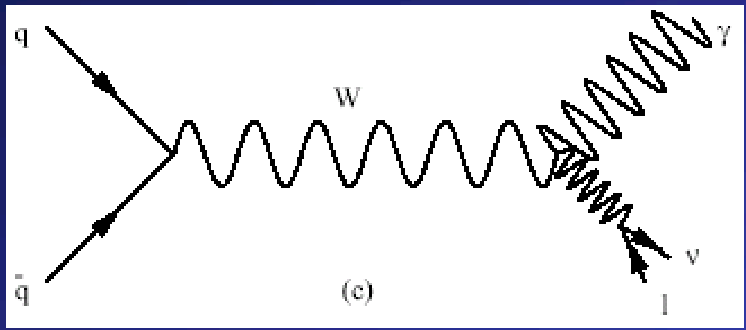


- 1 fb^{-1} at LHC comparable to 10 fb^{-1} at the Tevatron due to higher energy

CMS: So far only generator level studies done!

Triple Gauge Boson Couplings

Test CP conserving anomalous couplings at the WW□vertex □□ and □

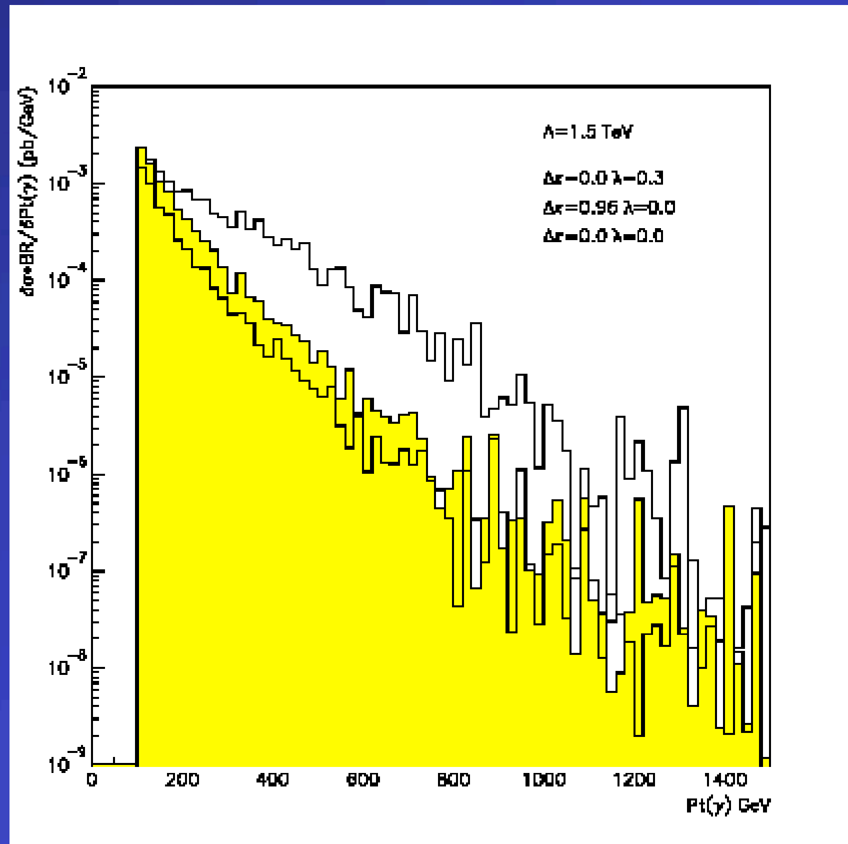


Method:

- W□final states
- W □e□ and □□
- p_T spectrum of photon

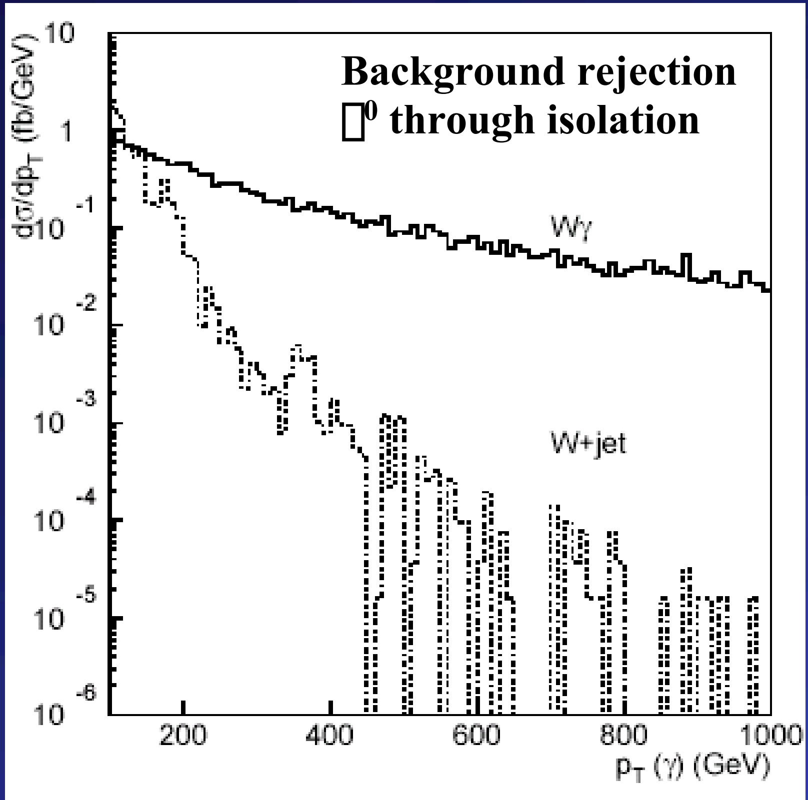
Sensitivity:

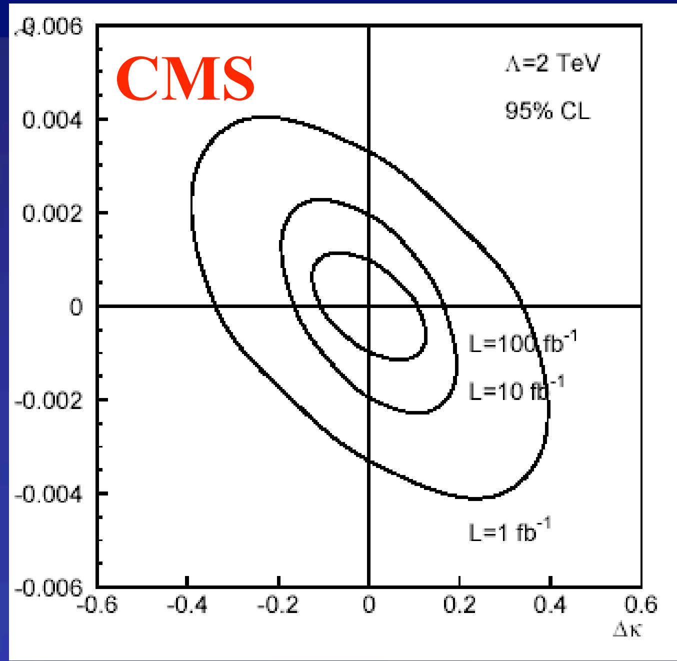
p_T spectrum SM couplings vs current limits at 1.5 TeV

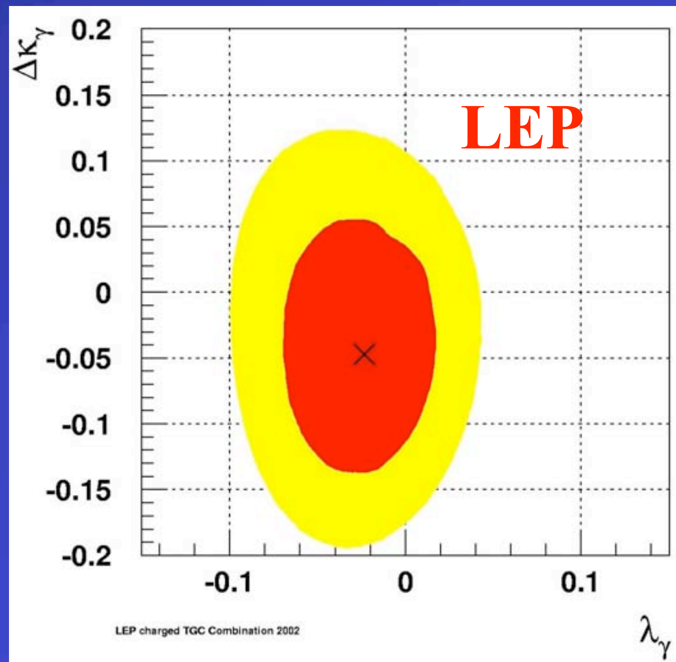


C.K. Mackay, P. R. Hobson,
CMS note 2001/052 & 2001/056

WWγ couplings







- **Result of the study:**

95% CL limits from 100 fb^{-1}

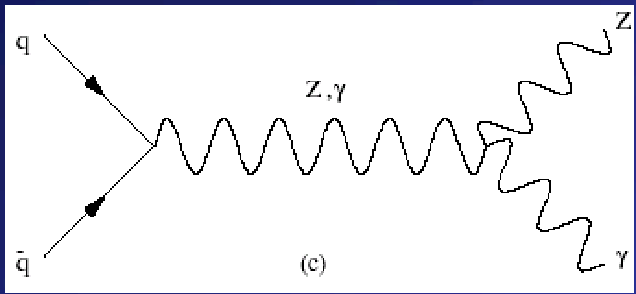
$\Delta\kappa < 0.1$

$\lambda < 0.0009$

(2 TeV)

Triple Gauge Boson Couplings

Z□□and ZZ□vertices



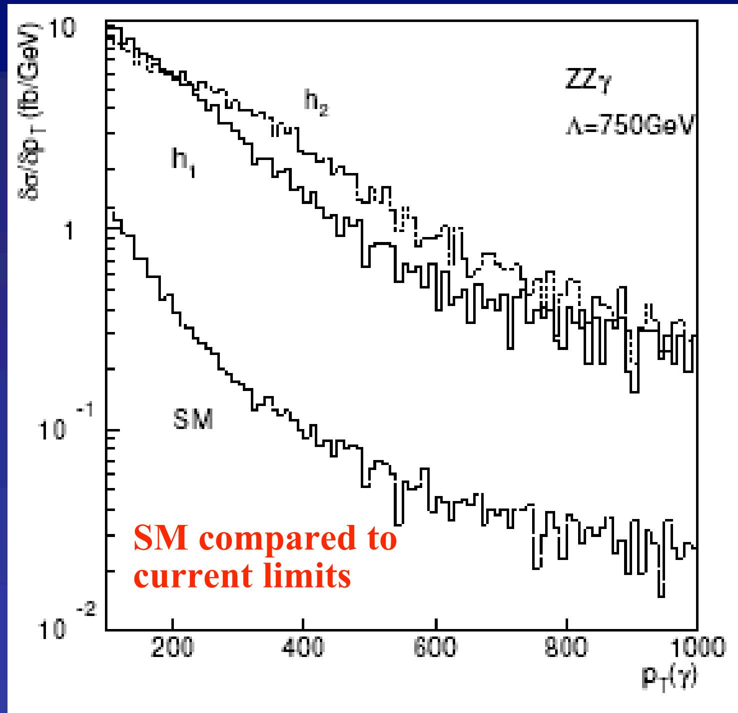
h_1^V, h_2^V, h_3^V and h_4^V (V=Z,γ),

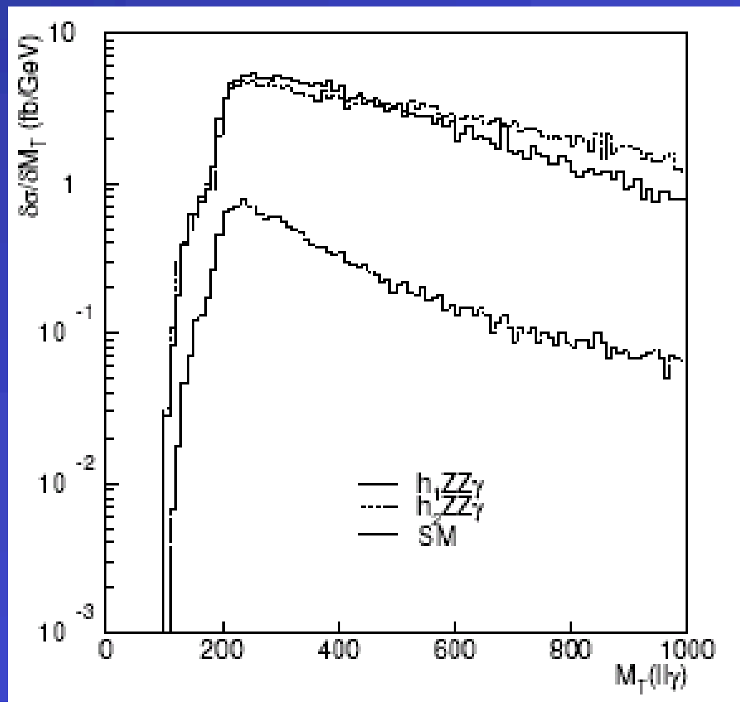
Z□final states

Z □ee and □□

p_T spectrum of photon

and m_T(ll□)



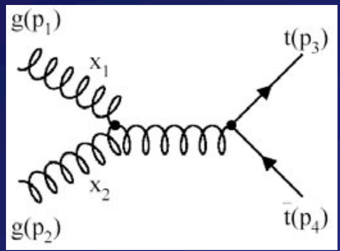


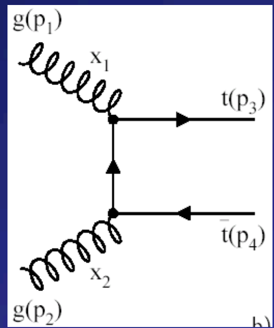
C.K. Mackay, P. R. Hobson,
CMS note 2002/028

Top Physics

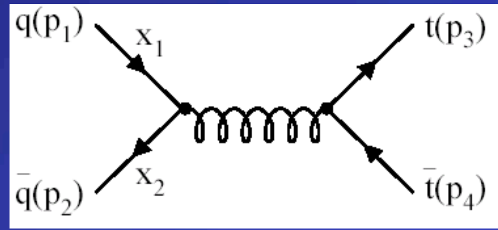
- $t\bar{t}$ production

87% gluon fusion





13% quark annihilation



(opposite to Tevatron)

- approx. 1 $t\bar{t}$-pair per second at $10^{33}/cm^2/s$

LHC is a top factory!

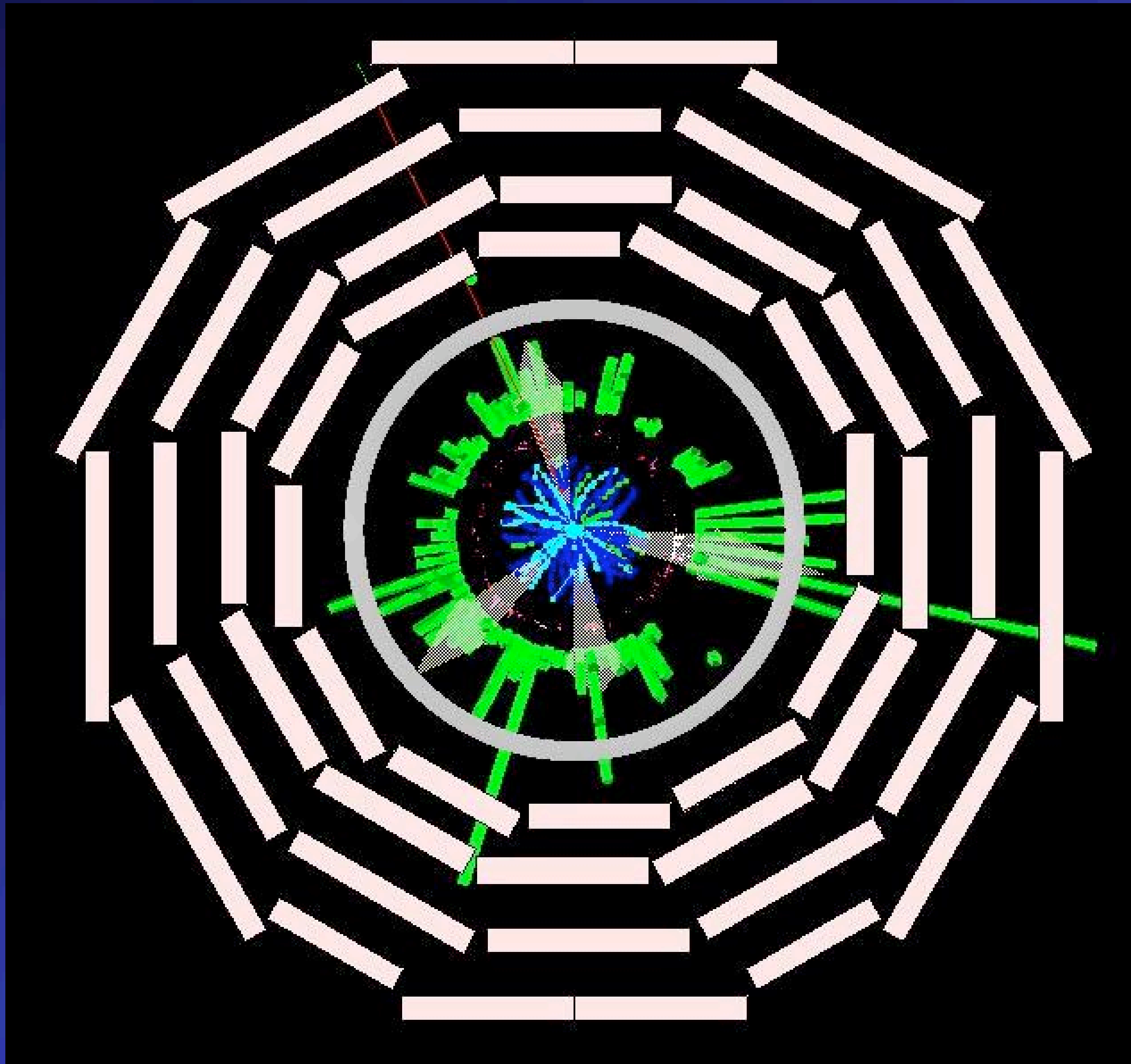
- top decay: ≈100% $t \rightarrow bW$

other rare SM decays:

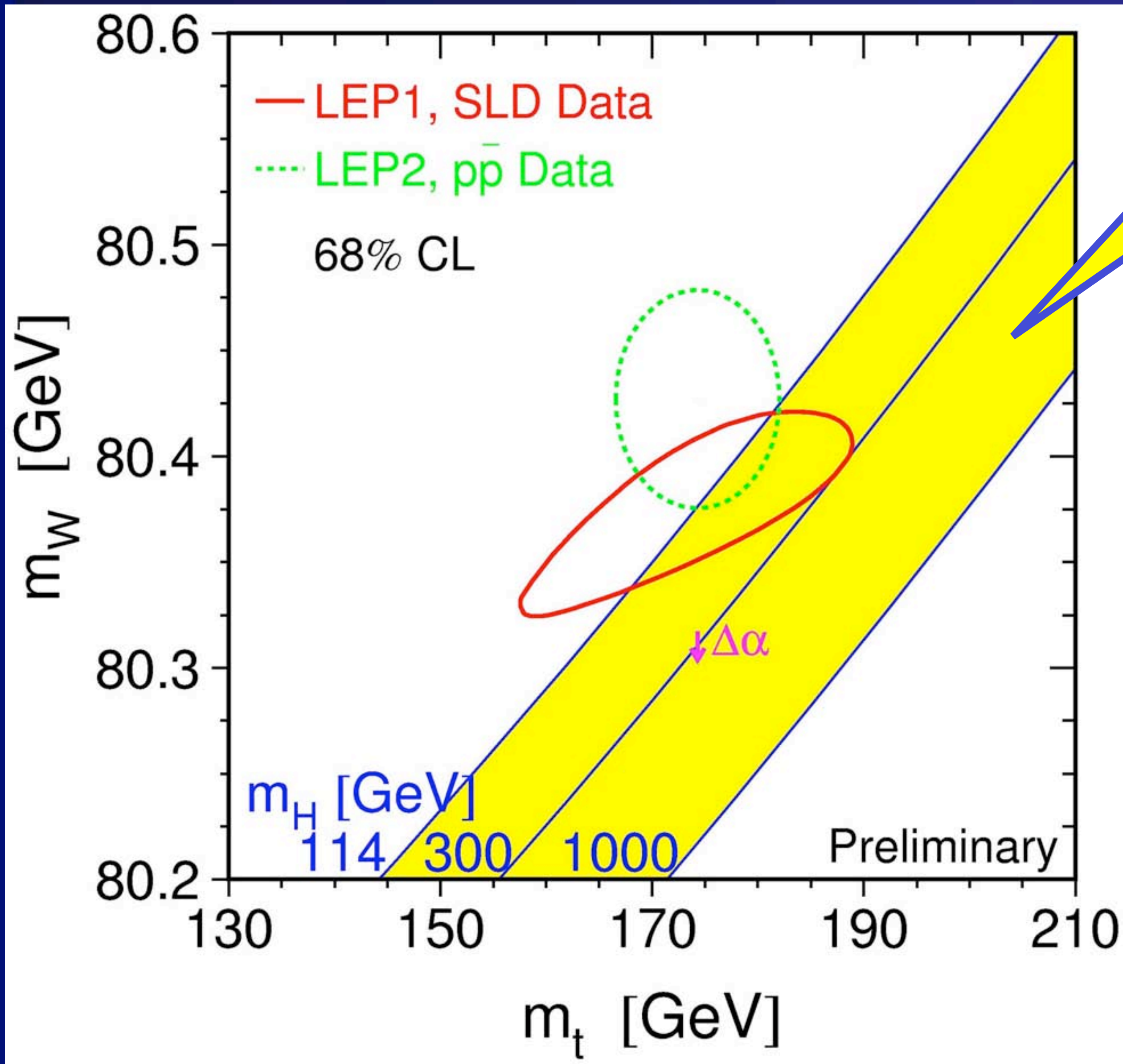
- CKM suppressed $t \rightarrow sW$, dW: 10^{-3} –10^{-4} level
- $t \rightarrow bWZ$: $O(10^{-6})$

Note: $m_t \approx m_b+m_W+m_Z$ sensitive to m_t

tt □bb qq □□ event:

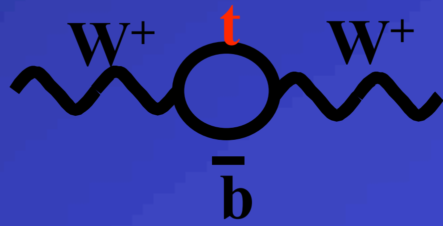


Measurement of the Top Mass: Motivation



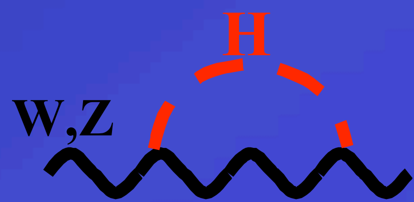
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2 m_W^2 \sin^2\theta_W} \frac{1}{1-\Delta r}$$

$1-\Delta r \cong$
$(1-\Delta\alpha)(1-\Delta r_W)$



$\Delta r_W \propto (m_t^2 - m_b^2)$

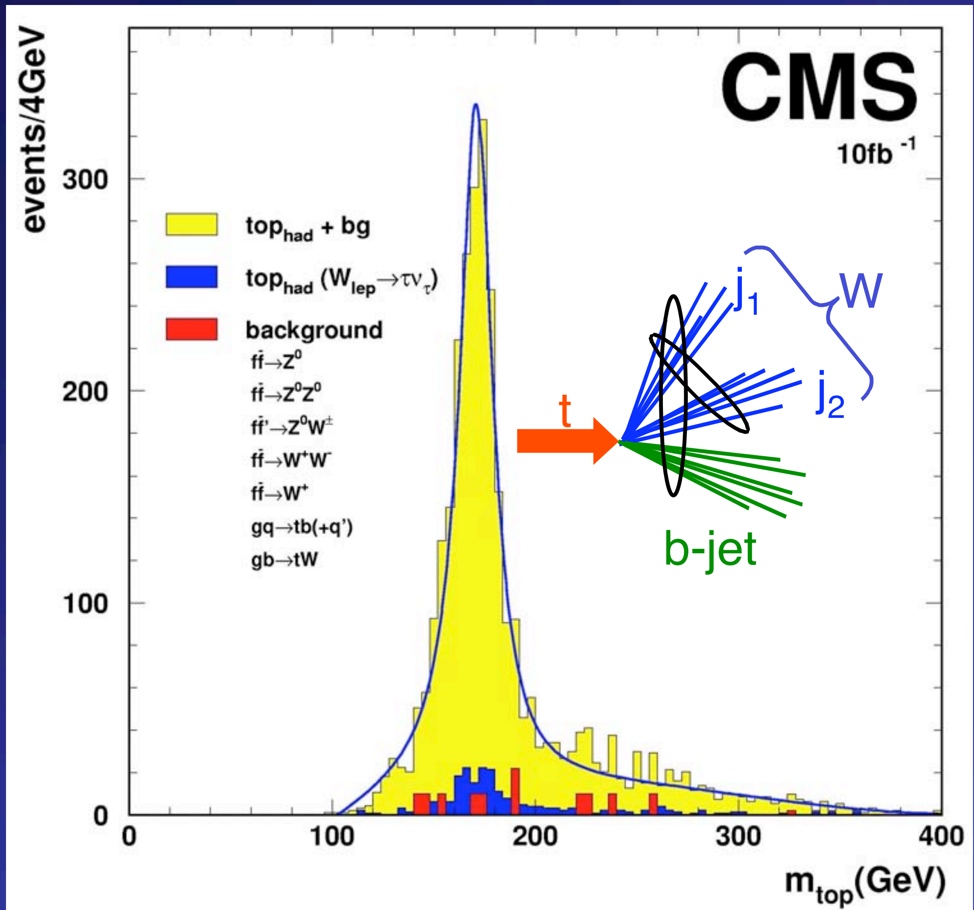
+



$\Delta r_W \propto \log m_H$

Top Mass

- „easiest“ channel tt □bb qq l□
- but measurement possible in other channels



- 3.5 million semileptonic events corresponding to 10 fb^{-1}
- CMS analysis with hard cuts: 0.14% of the events kept (!!!)

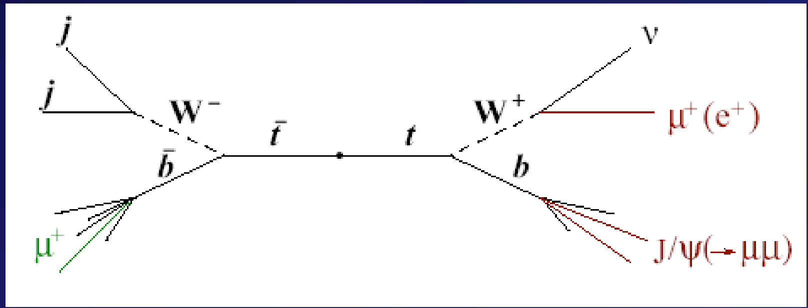
□ Error on m_t □ ± 1 GeV

statistical error	250 MeV
largest sys. errors:	
p_T spectrum	400 MeV
b-jet energy scale	?

Measurements at 1 fb^{-1}

- initial mass determination
- total & diff. cross sections

Top Mass from J/ψ channel:



1000 events/y @ 10^{34}

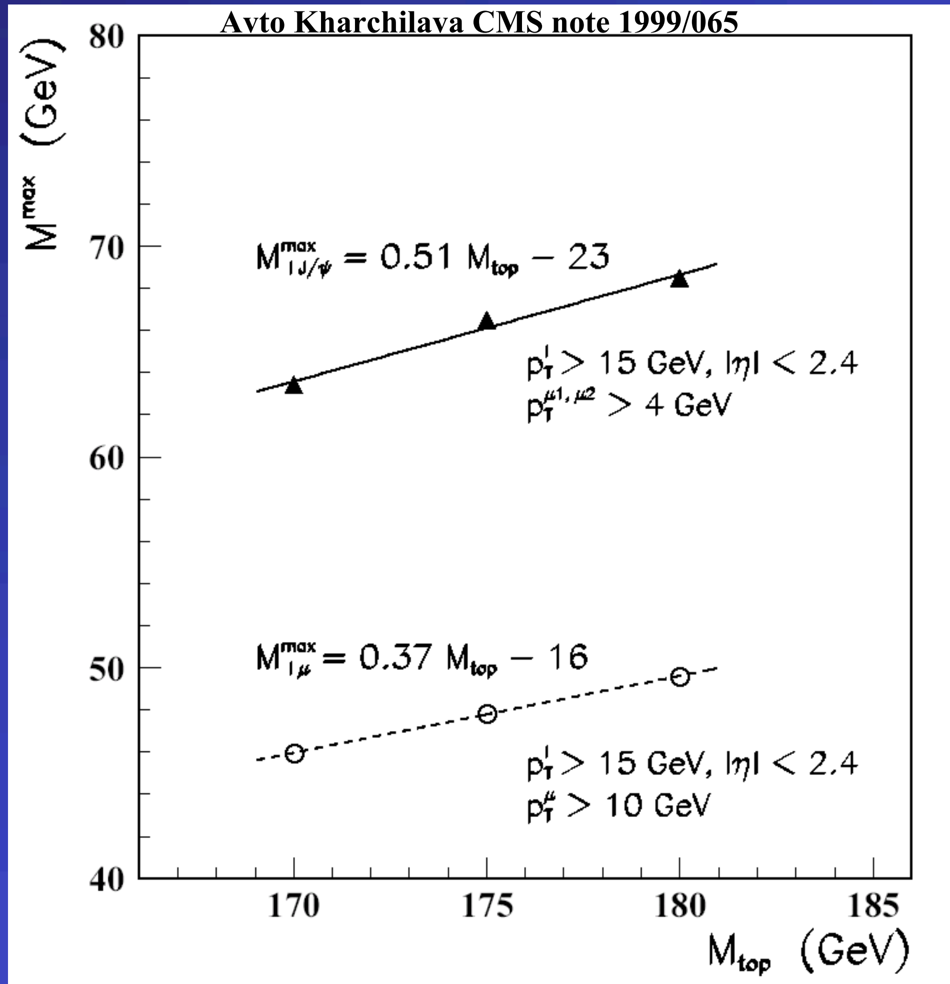
- **Method:**
  Partial reconstruction of top:
  J/ψ + lepton

☺ **independent of jet energy scale**

☹ **limited by b fragmentation & needs high luminosity**

- **Estimated ultimate precision:**

  $\Delta m_t < \sim 1$ **GeV**

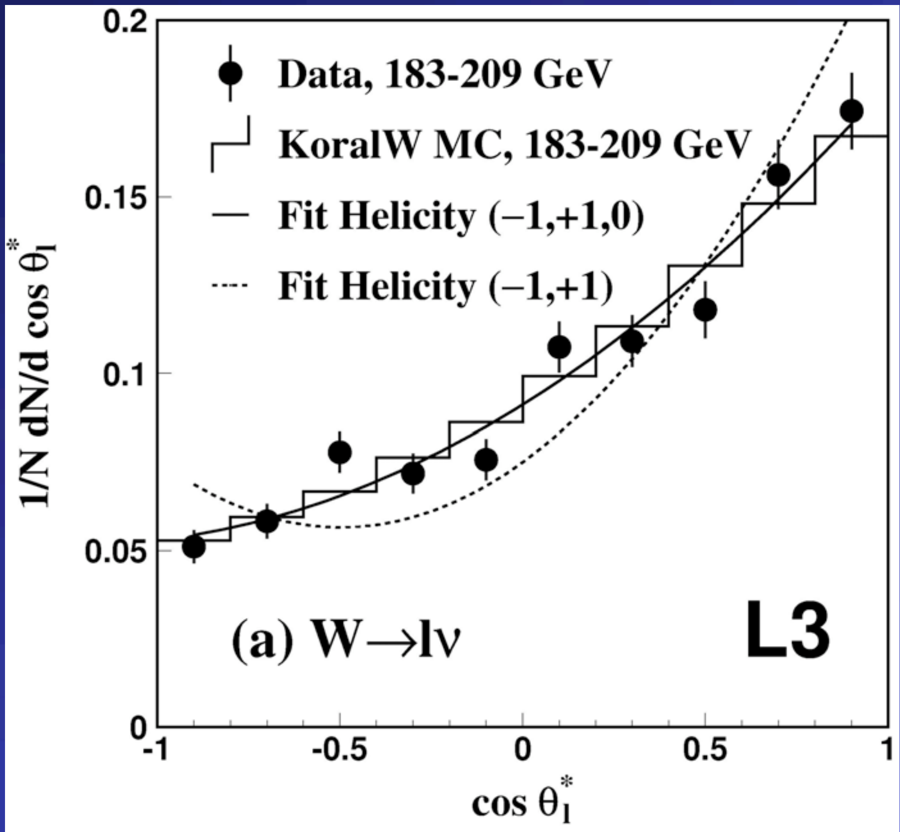


W Polarization

Massive gauge bosons have three polarization states

At LEP in $e^+e^- \rightarrow W^+W^-$:
determine W helicity from lepton (quark) decay angle in W rest frame θ^*

- o $(1 \pm \cos \theta^*)^2$ transverse
- o $\sin^2\theta^*$ longitudinal



⇒

Fraction of long. W
in $e^+e^- \rightarrow W^+W^-$

0.218 ± 0.031

(SM pred.: 0.24)

Tevatron (CDF):
Long. W in top decays

0.91 ± 0.52

(SM pred.: 0.7)

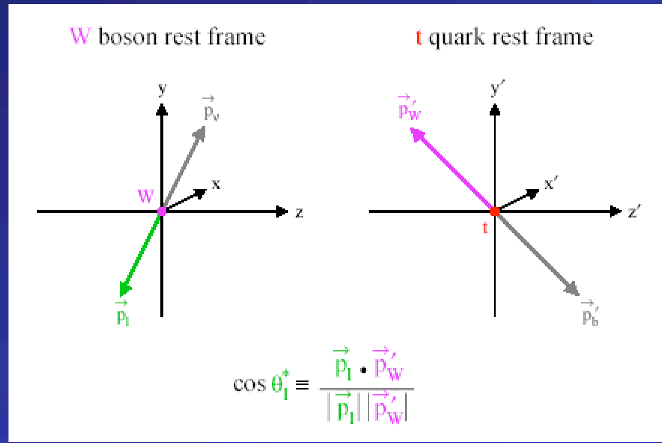
W Polarization in Top Decays

Standard Model prediction:

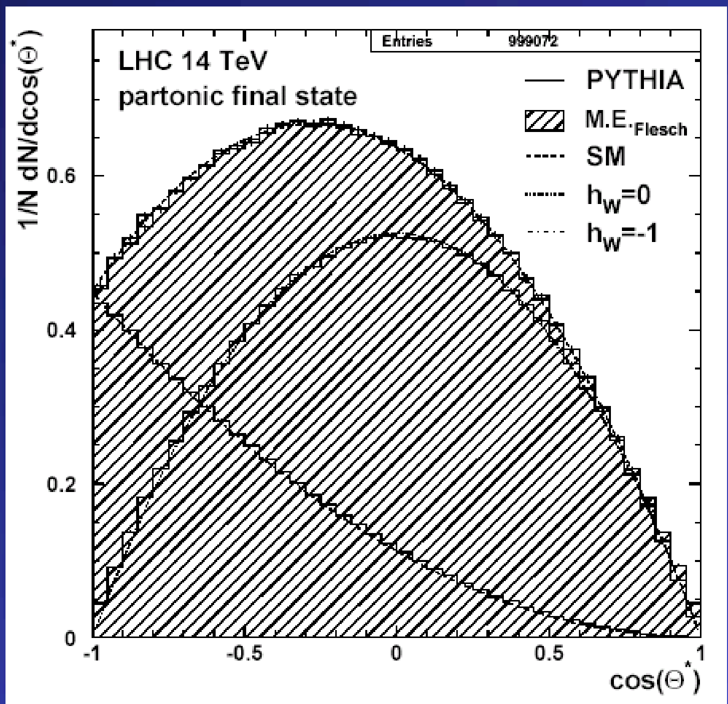
$$\frac{\Gamma(h_W=-1)}{\Gamma_{tot}} \approx 0.297 \qquad \frac{\Gamma(h_W=0)}{\Gamma(h_W=-1)} = \frac{1}{2}\left(\frac{m_t}{m_W}\right)^2 \approx 2.37$$

$$\frac{\Gamma(h_W=0)}{\Gamma_{tot}} \approx 0.703$$

$$\frac{\Gamma(h_W=+1)}{\Gamma_{tot}} \approx 0$$

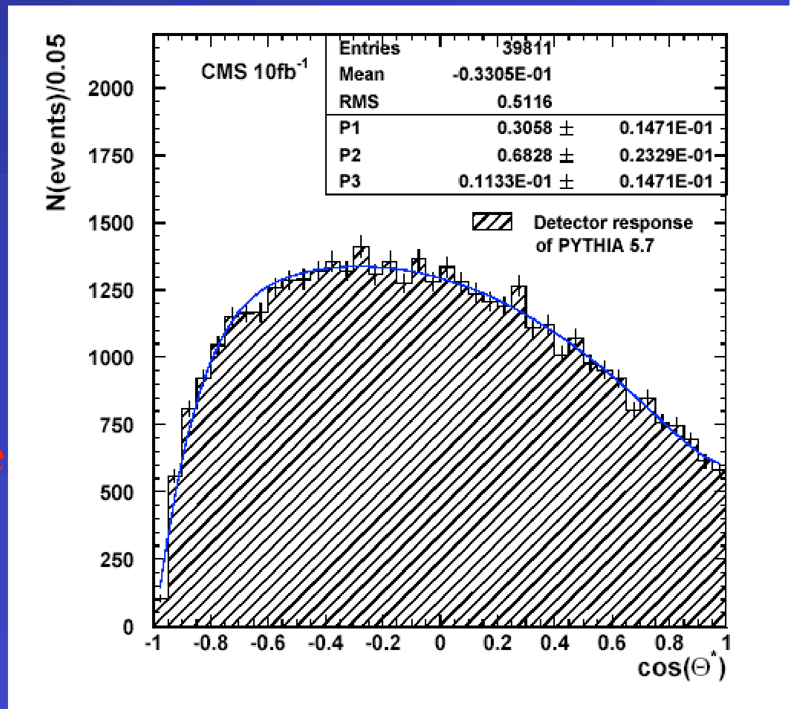


L. Sonnenschein thesis



detector simulation

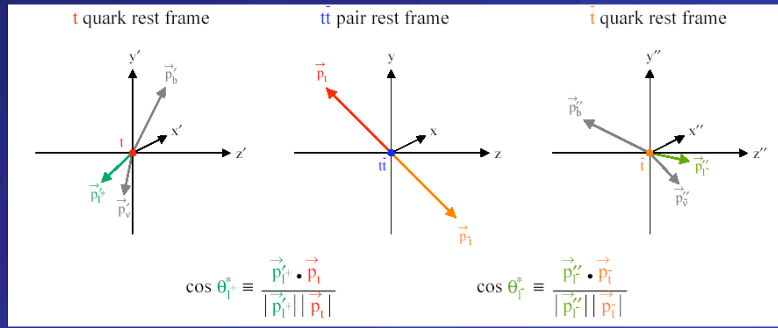
& acceptance



→ fraction of long. pol. W: 68.3 ± 2.3 (stat) ± 2.2 (sys) %

$t\bar{t}$ Spin Correlation

L. Sonnenschein thesis



Very short lifetime,
no top bound states

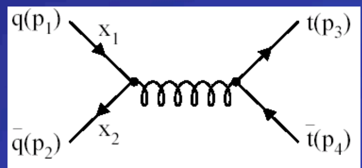
⇒ Spin info not diluted
by hadron formation

$$\mathcal{A} = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}$$

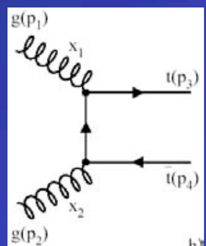
$$\frac{1}{N}\frac{d^2N}{d\cos\theta^*_{\ell+}\, d\cos\theta^*_{\ell-}} = \frac{1}{4}(1 - \mathcal{A}\cos\theta^*_{\ell+}\cos\theta^*_{\ell-})$$

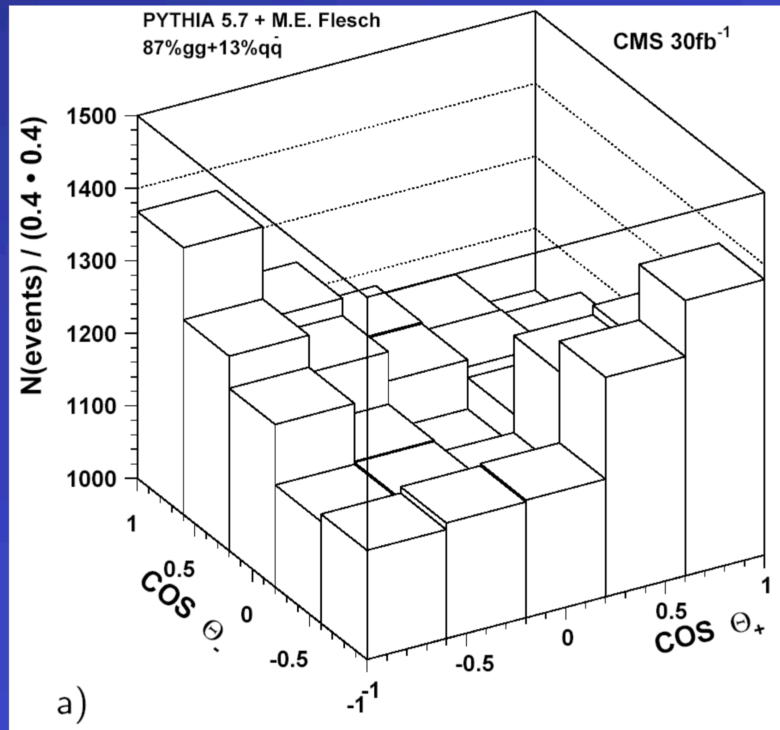
Distinguishes between

- quark annihilation
  A = -0.469



- and gluon fusion
  A = +0.431



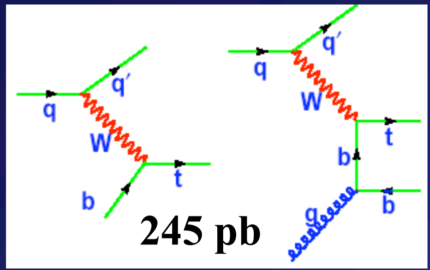


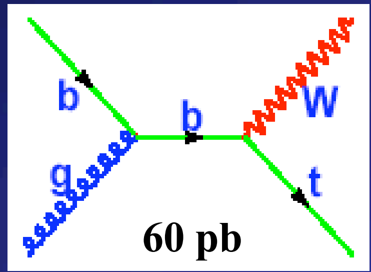
uses double leptonic decays
tt → bb lν lν

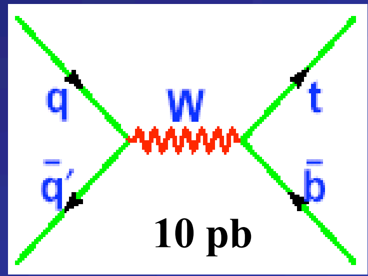
A= 0.311 ± 0.035 ± 0.028 (using 30 fb^{-1})

Single Top Production

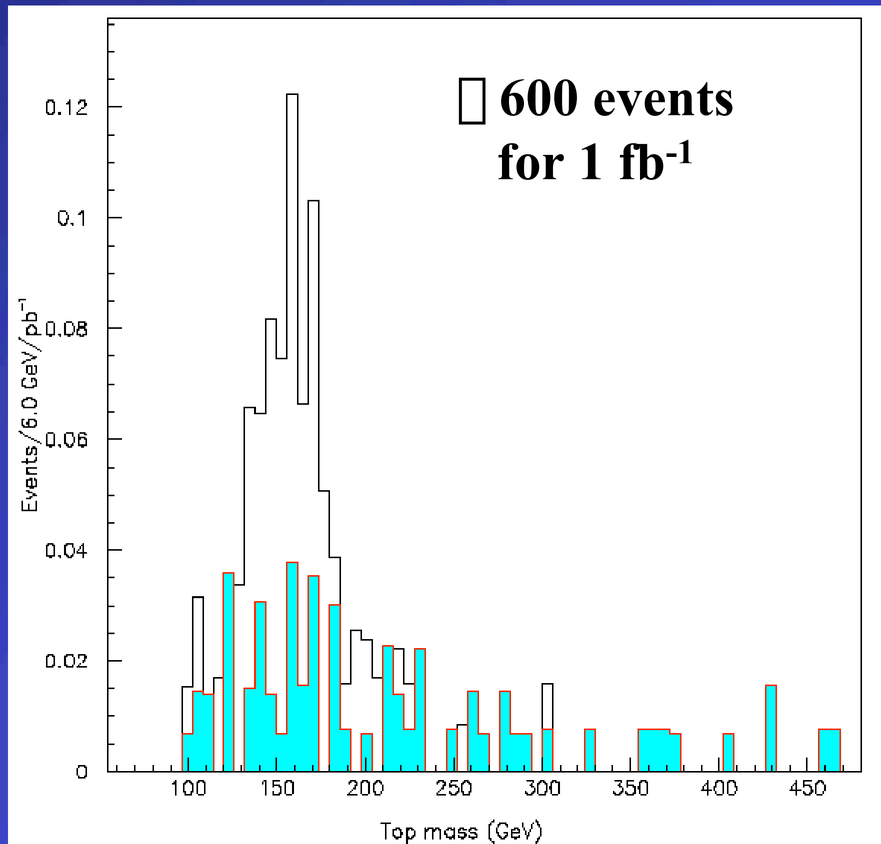
Production mechanisms and cross sections:







- Selection:
  $t \to bW \to b\, e\nu\ (\mu\nu)$
  b-jet + high p_T lepton
  reconstruction of top mass
- Background from $t\bar{t}$
  signal to bkgd. 3.5 : 1



- direct measurement of V_{tb}
- observable by Tevatron in Run II
- LHC $\sigma_t \approx 1.5\ \sigma_{\bar{t}}$

Dan Green et. al. CMS note 1999/048

Other top quark measurements at low luminosity:

- total $t\bar{t}$ cross section   sensitive to mass
- differential cross sections
  - → $d\sigma/dp_T$ checks pdf
  - → $d\sigma/d\eta$ checks pdf
  - → $d\sigma/dm_{tt}$ sensitive to production of heavy object $X \rightarrow t\bar{t}$
- $t\bar{t}$ + photon   sensitive to top charge

Nothing done so far in CMS...

Other Possible SM Physics with Muons

- **b-physics**
  - inclusive b-production
    measurement of total & diff. cross sections
    $d\sigma/dp_T$, $d\sigma/d\eta$
  - Mesurement of BR($b \rightarrow J/\psi + X$)
  - CP violation in $B^0_s \rightarrow J/\psi + \phi$

  all to be revisited in light of stagged DAQ

- **Tau physics**
  - measurement of lifetime
  - search for rare decays

- **Other ideas ?**

Summary & Conclusions

SM physics with CMS

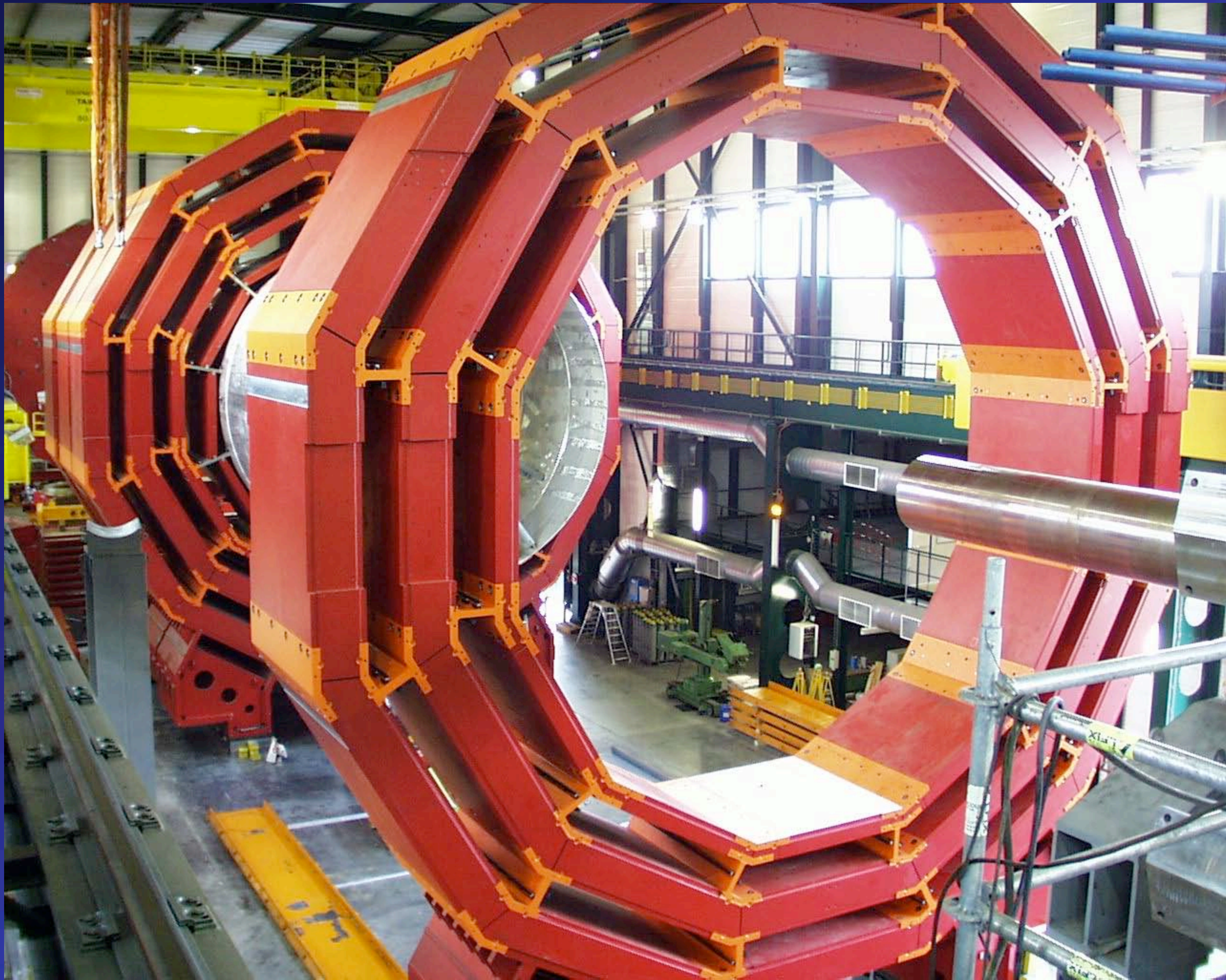
- very important in initial phase
  - to check detector
  - to check generators (pdf)
  - to prepare discoveries

- large potential for precision measurements
  - large cross sections
  - precision limited by systematics
  - use as many different strategies as possible

- Work for Physics TDR has started

Join in NOW!

Complete the missing parts ...



... to make very interesting (SM) physics at the LHC