Standard Model Physics at the LHC

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Standard Model Physics at the LHC

Outline:

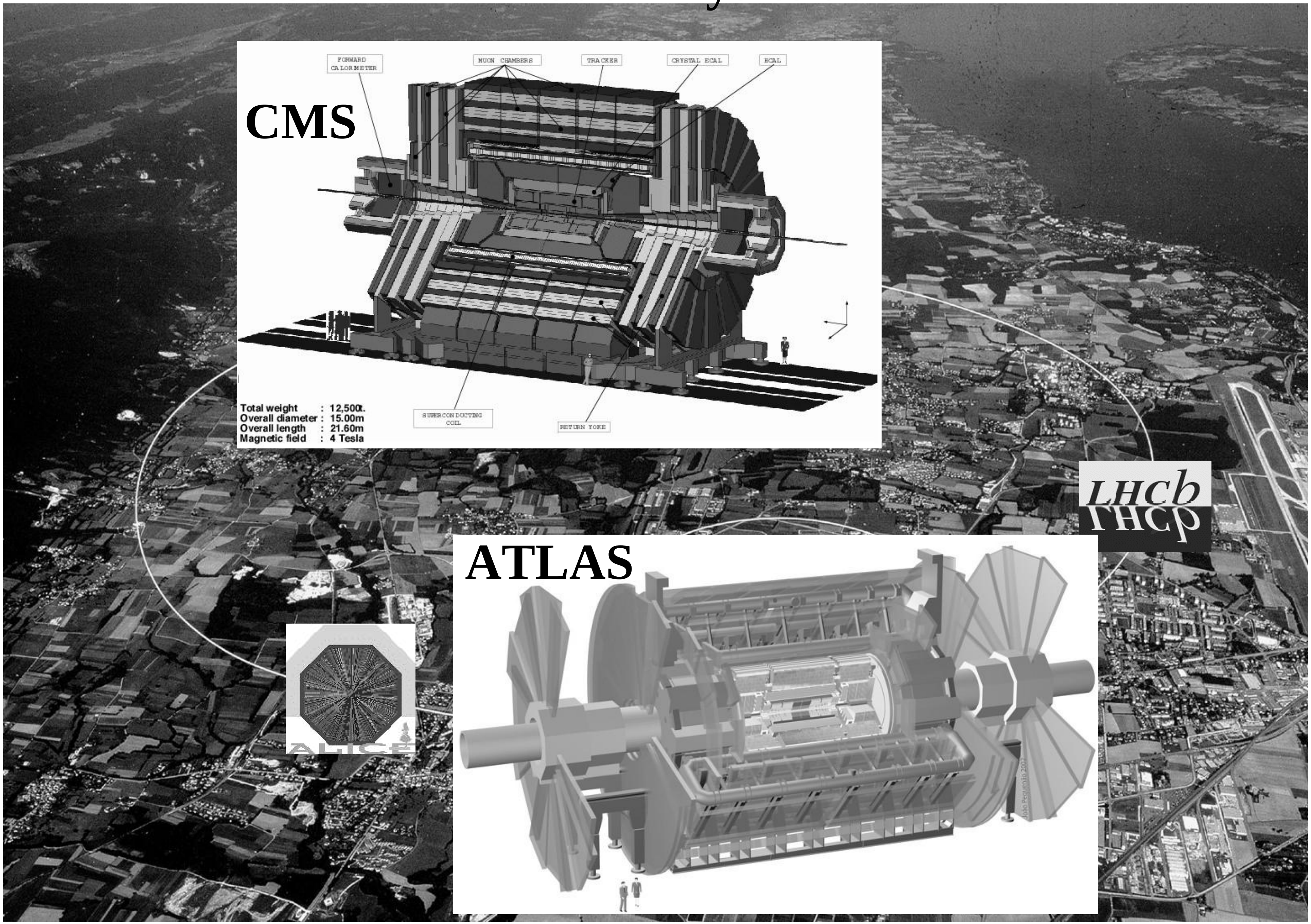
Perspectives on

- **Parton distribution functions**
- **QCD + jet physics**
- **Electroweak physics (Z/W bosons)**
- **Top physics**

Will not cover other SM physics topics, e.g.

- **Higgs**
- **B-physics**
- **Tau physics**
- **Diffraction, luminosity, ...**

Standard Model Physics at the LHC



Cross Section of Various SM Processes

The LHC <u>uniquely</u> combines the two most important virtues of HEP experiments:

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

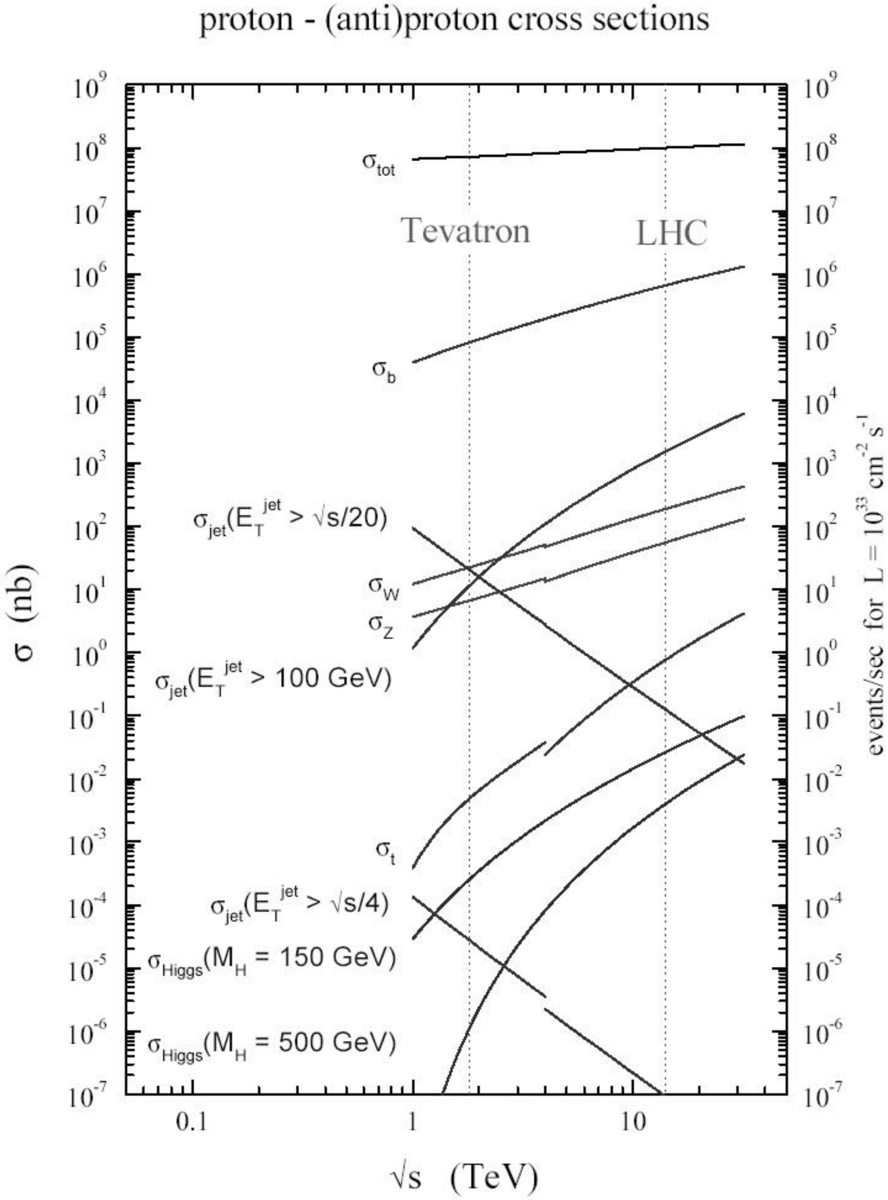
⇒ Low luminosity phase

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

approximately

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

will be produced per second!

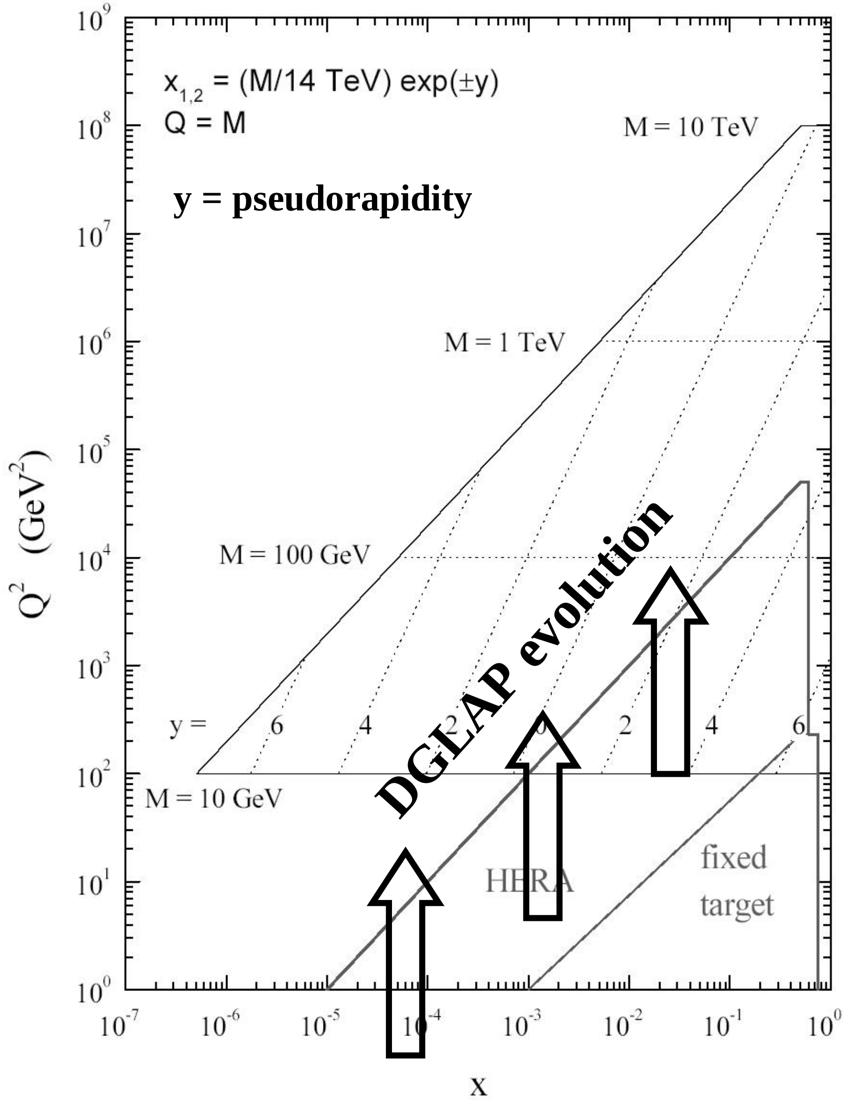


Parton Distribution Functions (PDF)

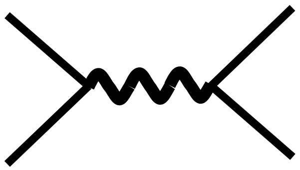
LHC is a proton-proton collider

But fundamental processes are the scattering of

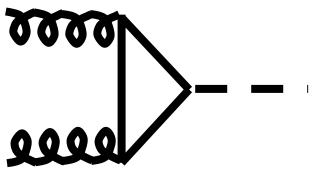
- **Quark – Antiquark**
- **Quark – Gluon**
- **Gluon – Gluon**



<u>Examples:</u>



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



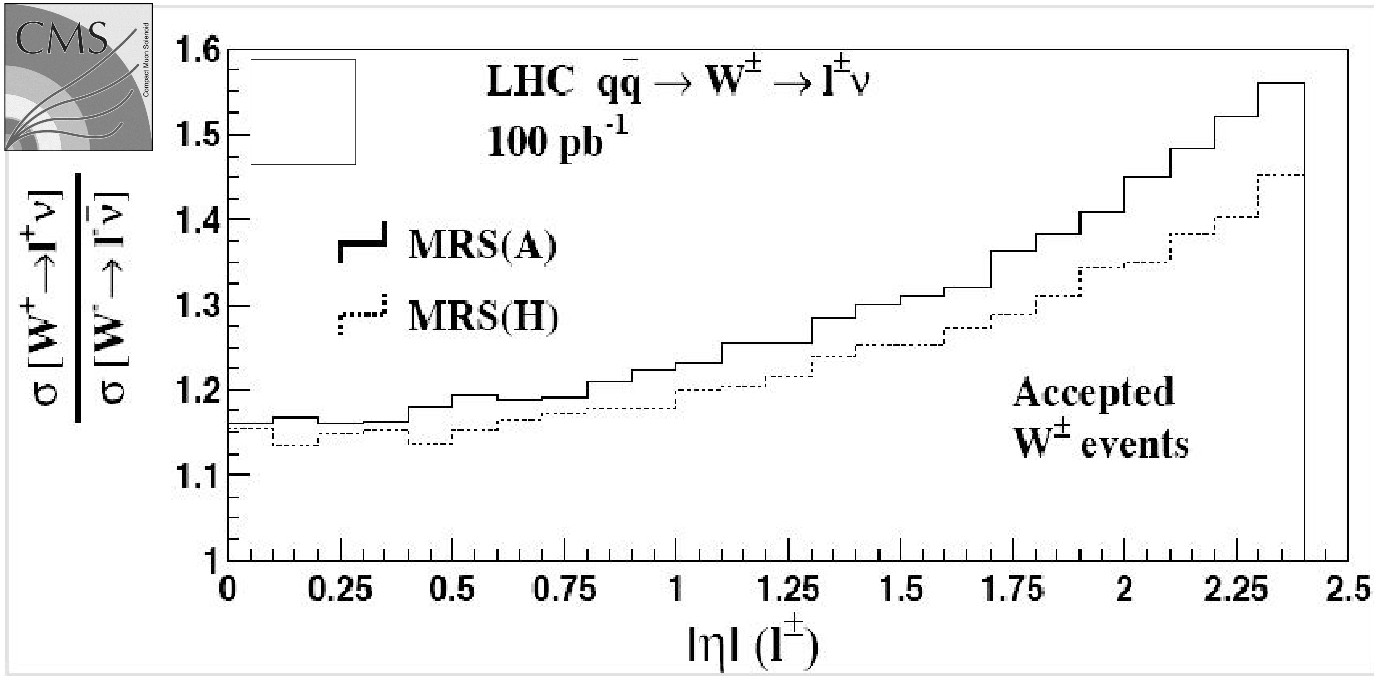
$gg \rightarrow H$

$\Rightarrow$ **need precise pdf(x,Q^2)**
+ QCD corrections (scale)

PDF from W/Z production

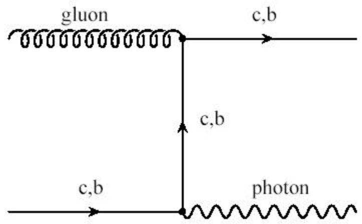
- p_T and rapidity distributions are very sensitive to pdf
- particularly sensitive variable:
  ratio of W^+/W^- cross section measures u(x)/d(x)

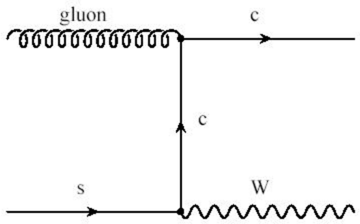
Example: study for 0.1 fb^{-1}, i.e. $2\cdot10^6$ $W\rightarrow\mu\nu$ produced



Sensitive to small differences in sea quark distribution

PDF of s, c and b quarks

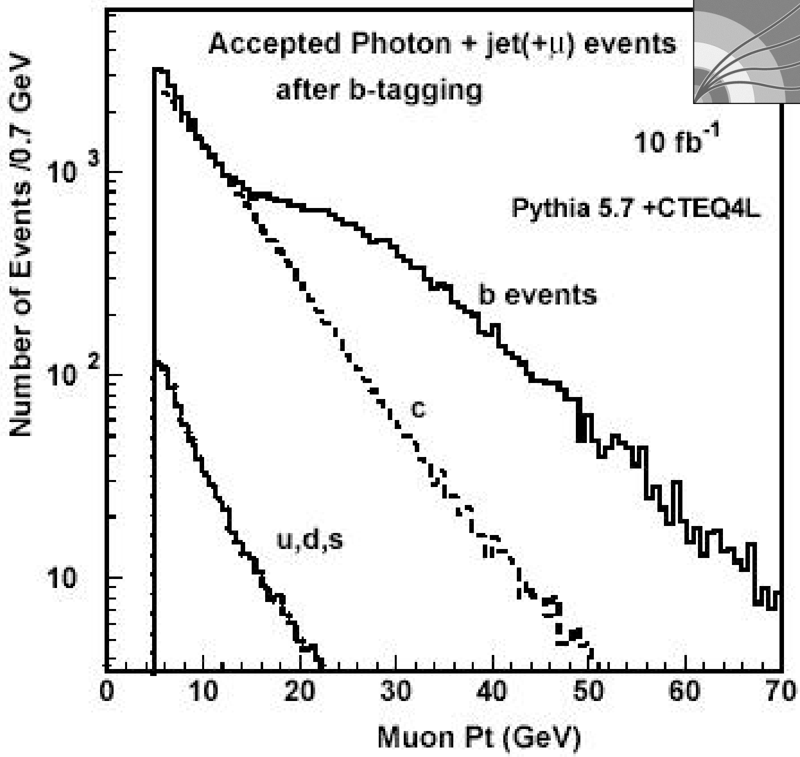




Isolated high p_T γ + jet with incl. μ

Isolated high p_T e/ μ + jet with incl. μ

Generator level study:



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

Analyses only suited for
low luminosity phase

Parton Distribution Functions (PDF)

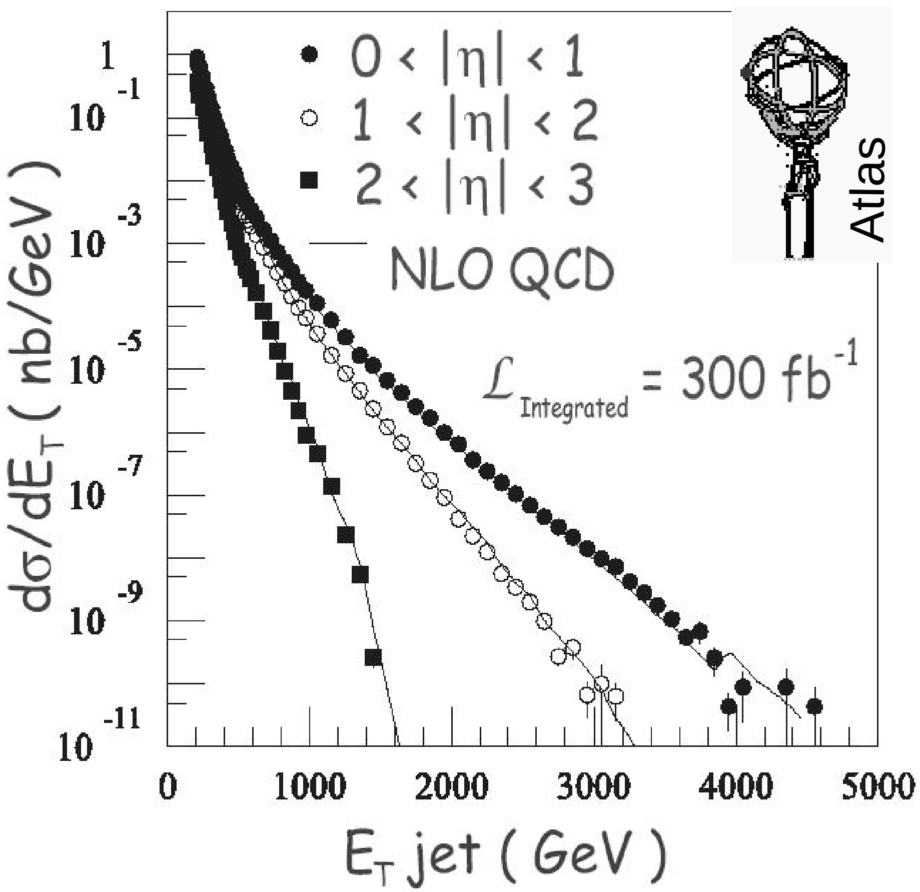
Recipe for measurements of PDFs from SM processes:

Process:	Constraning PDF of:
Di-jets	Quarks and Gluons
Jet + photon(s)	Quarks and Gluons
Jet + W	Quarks and Gluons
W and Z	Quarks
Drell-Yan	Quarks

Advertisement for the ongoing HERA/LHC workshop:

Jet Physics

- **Measure jet E_T spectrum, rate varies over 11 orders of magnitude**
- **Test QCD at the multi-TeV scale**



Inclusive jet rates for 300 fb^{-1}:

E_T of jet	Events
> 1 TeV	$4 \cdot 10^6$
> 2 TeV	$3 \cdot 10^4$
> 3 TeV	400

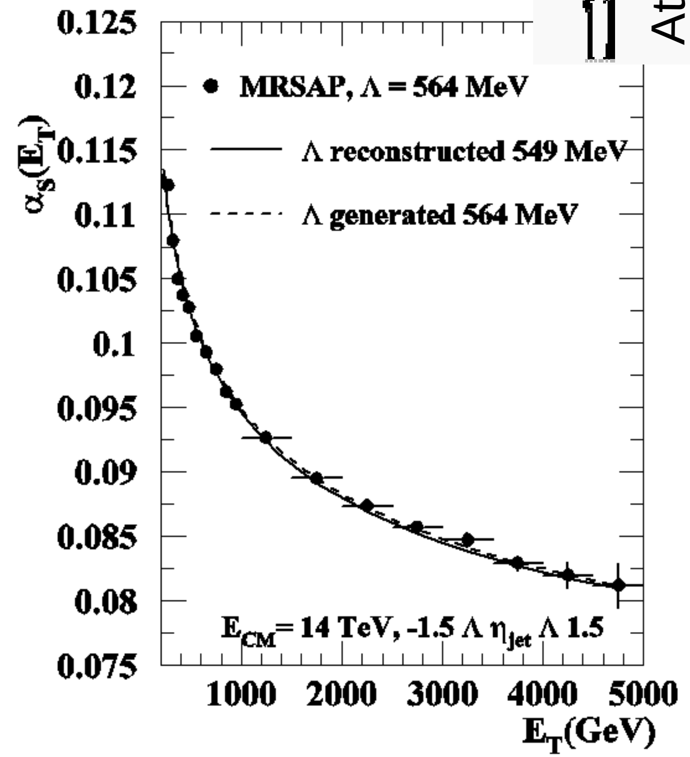
QCD

Measurement of α_s at LHC limited by

- **PDF (3%)**
- **Renormalisation & factorisation scale (7%)**
- **Parametrisaton (A,B)**

$$\frac{d\sigma}{dE_T} \sim \alpha_S^2(\mu_R)A(E_T) + \alpha_S^3(\mu_R)B(E_T)$$

- **10% accuracy $\alpha_s(m_Z)$ from incl. jets**
- **Improvement from 3-jet to 2-jet rate?**



Verification of running of α_s and test of QCD at the smallest distance scale

- **α_s = 0.118 at m_Z**
- **$\alpha_s \approx$ 0.082 at 4 TeV (QCD expectation)**

Electroweak Physics: Properties of W and Z bosons

Measurement of the W mass at the LHC

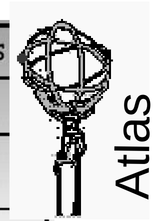
m_W is important parameter in precision tests of the SM

2004: $m_W = 80\,425 \pm 34$ MeV LEP & Tevatron Run I

2007: $m_W \approx 80\ \ldots\ \pm 20$ MeV ($2.5 \cdot 10^{-4}$) incl. Tevatron Run II

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

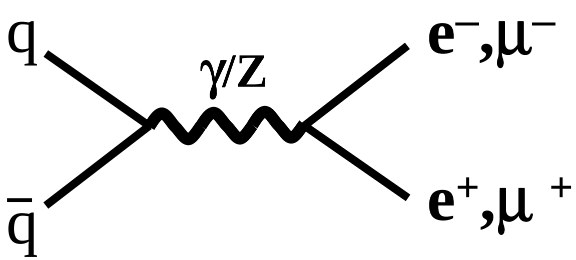
Source	CDF Run Ib	ATLAS or CMS	$W \to l\nu$, one lepton species
	30K evts, 84 pb^{-1}	60M evts, 10fb^{-1}	
Statistics	65 MeV	< 2 MeV	
Lepton scale	75 MeV	15 MeV	most serious challenge
Energy resolution	25 MeV	5 MeV	known to 1.5% from Z peak
Recoil model	33 MeV	5 MeV	scales with Z statistics
W width	10 MeV	7 MeV	$\Delta\Gamma_W \approx 30$ MeV (Run II)
PDF	15 MeV	10 MeV	
Radiative decays	20 MeV	<10 MeV	(improved Theory calc)
$P_T(W)$	45 MeV	5 MeV	$P_T(Z)$ from data, $P_T(W)/P_T(Z)$ from theory
Background	5 MeV	5 MeV	
TOTAL	113 MeV	≤ 25MeV	Per expt, per lepton species



- **Take advantage from large statistics $Z \to e^+e^-, \mu^+\mu^-$**
- **Combine channels & experiments**

$\Rightarrow \Delta m_W \leq 15$ MeV

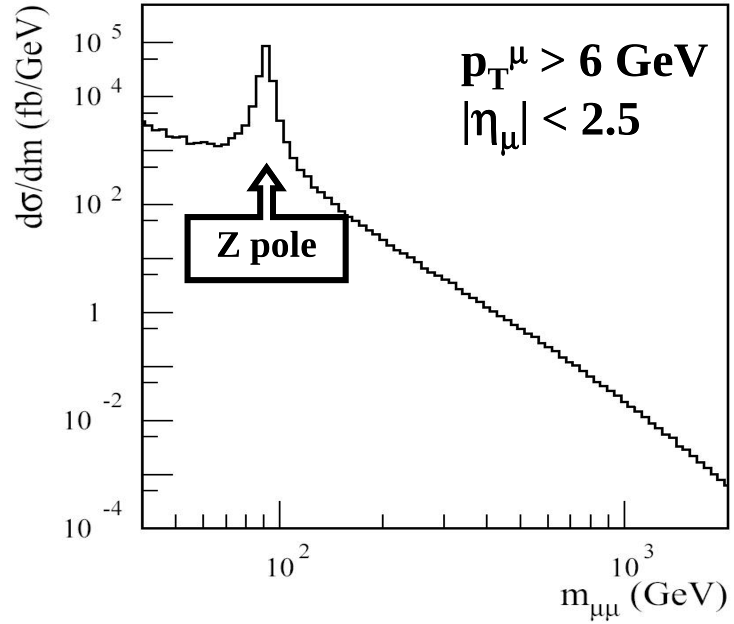
Drell-Yan Lepton-Pair Production

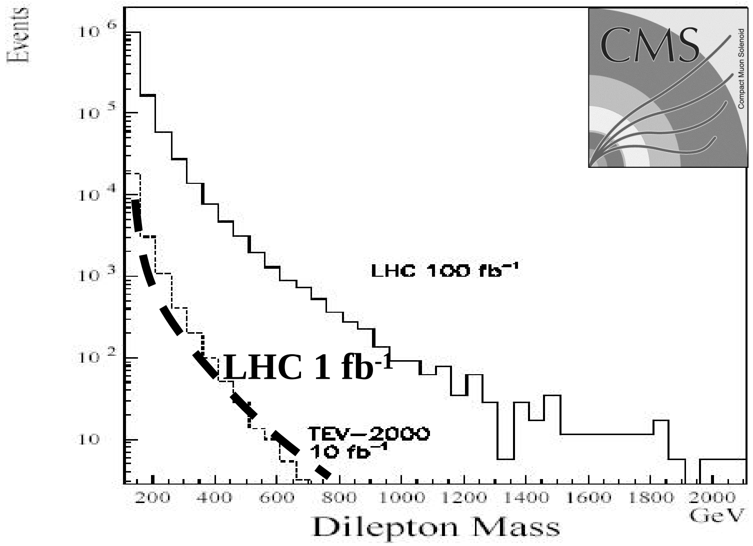


Inversion of $e^+e^- \to q\bar{q}$ at LEP

- **Total cross section**
  pdf
  parton lumi
  search for Z′, extra dim. , ...

Much higher mass reach as compared to Tevatron



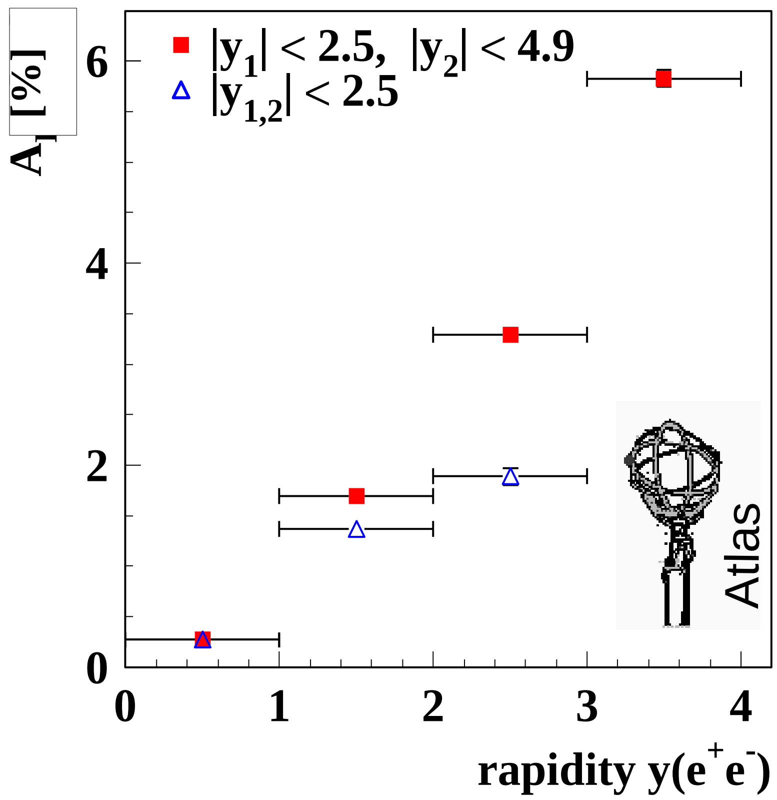


Drell-Yan Lepton-Pair Production

- **Forward-backward asymmetry**
  estimate quark direction
  assuming $x_q > x_{\bar{q}}$
- **Measurement of $\sin^2\vartheta_W$ effective**
  - **2004: LEP & SLD**
    $\sin^2\vartheta_W = 0.23150 \pm 0.00016$
- **A_{FB} around Z-pole**
  - **large cross section at the LHC**

    $\sigma(Z \to e^+e^-) \approx 1.5$ nb
  - **stat. error in 100 fb^{-1}**
    incl. forward electron tagging
    (per channel & expt.)

    $\Delta\sin^2\vartheta_W \approx 0.00014$
- **Systematics (probably larger)**
  - **PDF**
  - **Lepton acceptance**
  - **Radiative corrections**



Di-Boson Production

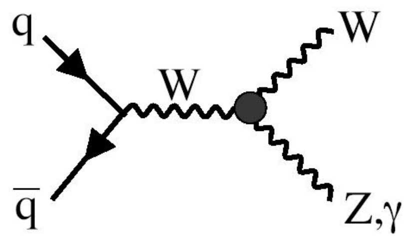
Measuring Triple Gauge Couplings (TGC)
& testing the gauge boson self couplings of the SM

➢ **$WW\gamma$ and WWZ vertices do exist in the SM**

Requiring C,P and
elm. gauge invariance

$\Rightarrow$ 5 coupling parameters

$\kappa_{\gamma,Z}$	1	Dim4, $\propto \sqrt{s}$
$\lambda_{\gamma,Z}$	0	Dim6, $\propto s$
g_1^Z	1	Dim4, $\propto \sqrt{s}$



➢ **$ZZ\gamma$ and ZZZ vertices do NOT exist in the SM**

Requiring Lorentz & elm.
gauge invariance
& Bose symmetry

$\Rightarrow$ 12 coupling parameters

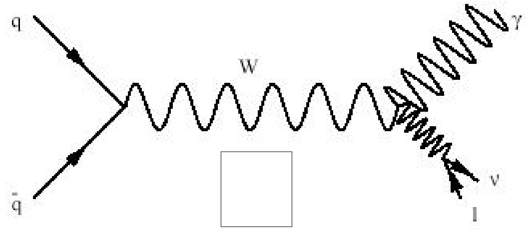
h_i^V, f_i^V (V= γ,Z)

h_1	dim6, $\propto s^{3/2}$	~~CP~~
h_2	dim8, $\propto s^{5/2}$	~~CP~~
h_3	dim6, $\propto s^{3/2}$	CP
h_4	dim8, $\propto s^{5/2}$	CP
f_4	dim6, $\propto s^{3/2}$	~~CP~~
f_5	dim6, $\propto s^{3/2}$	CP

Deviations from SM
amplified by
high energies!

WWγ Couplings

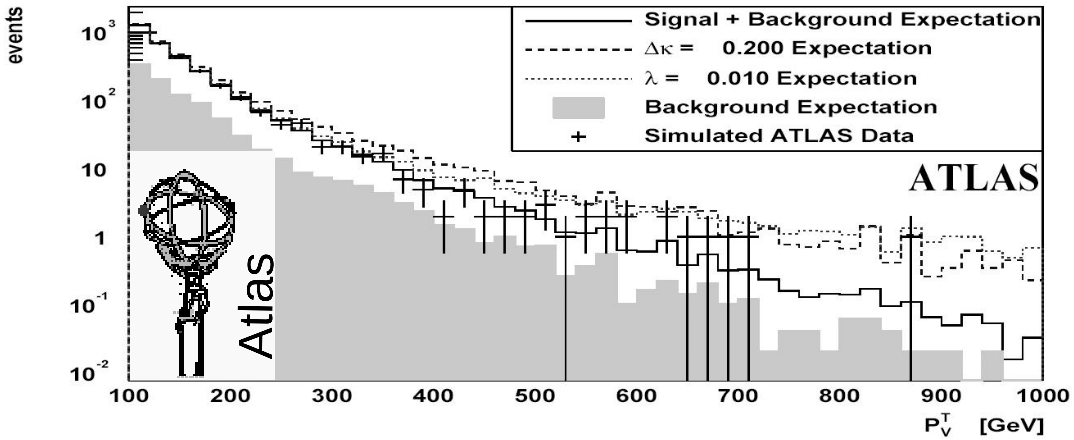
Test CP conserving anomalous couplings at the WWγ vertex Δκ and λ

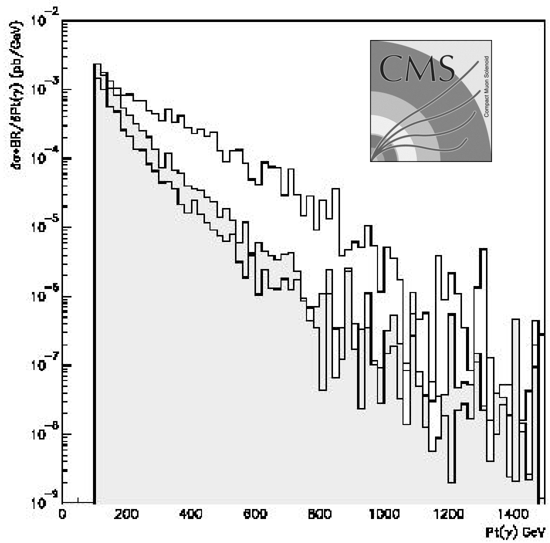


- **Wγ final states**
- **W → eν and μν**
- **p_T spectrum of bosons**

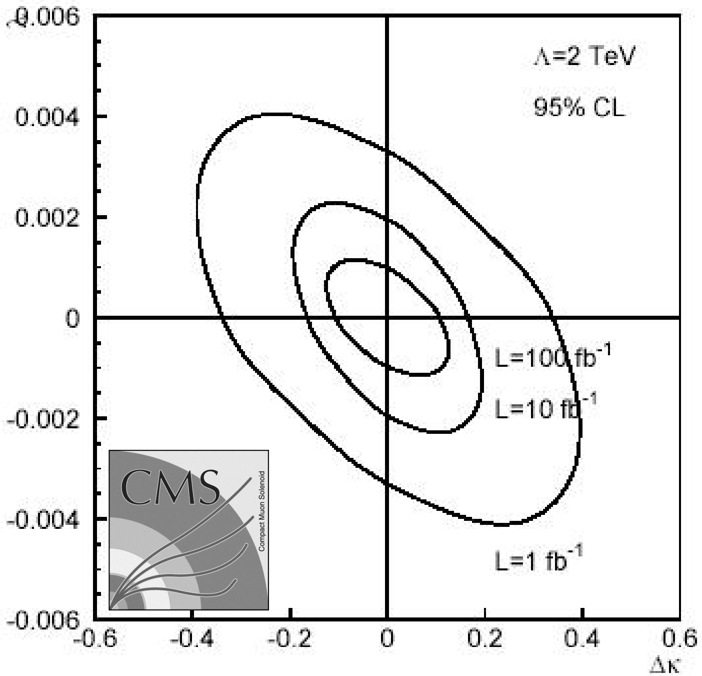
p_T (γ) spectrum for SM couplings & current limits Δκ, λ at 1.5 TeV

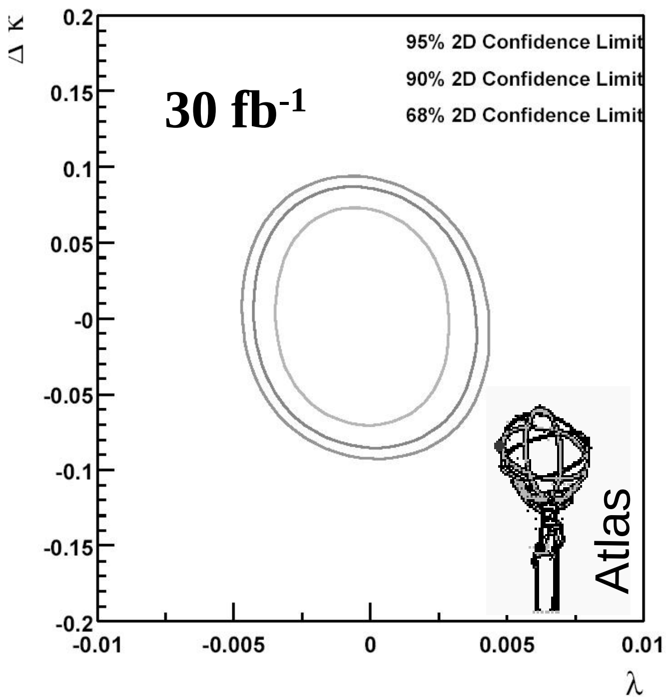
Sensitivity to anomalous couplings from high end of the p_T spectrum

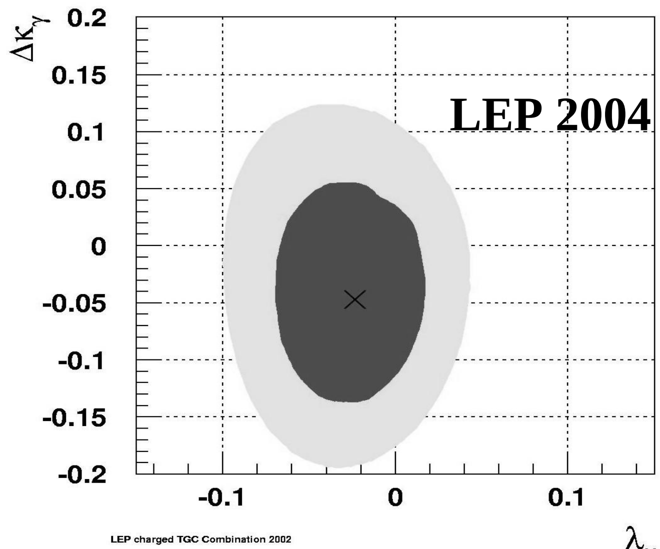




Sensitivity to WWγ Couplings





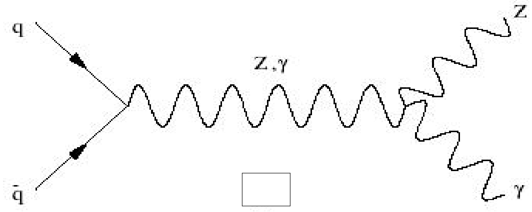


- At LHC limits depend on energy scale Λ
- Large improvement wrt LEP in particular on λ due to higher energy

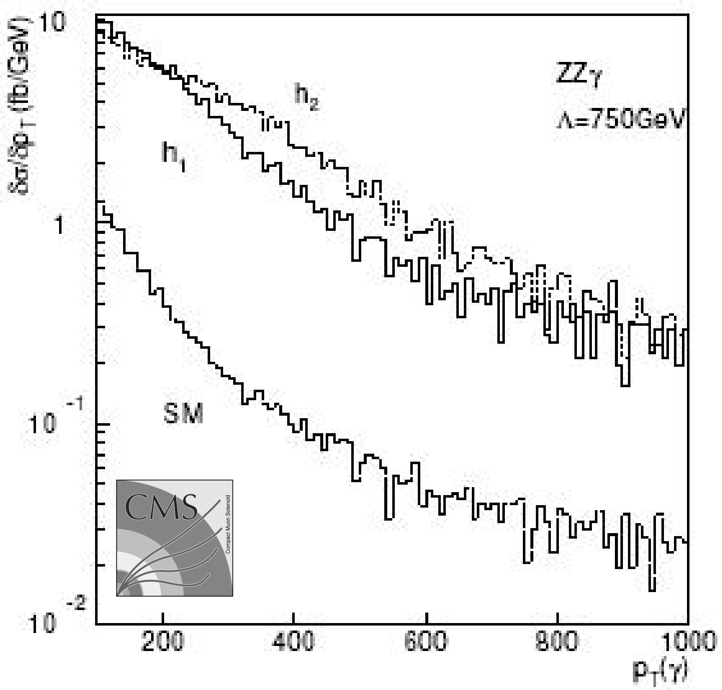
ZZγ Couplings

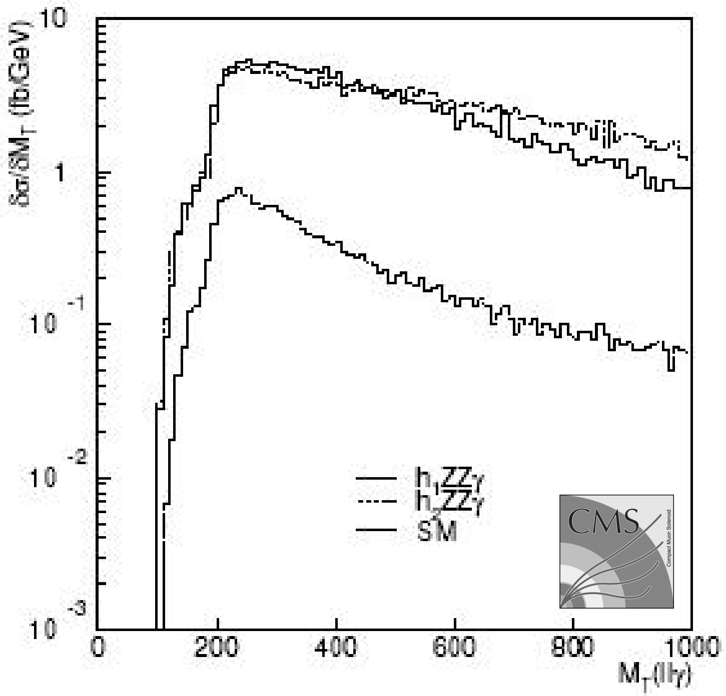
Example: Couplings at the ZZγ vertex h_i^γ

- **Zγ final states**
- **Z → e^+e^- and $\mu^+\mu^-$**
- **p_T spectrum of photons and $m_T(ll\gamma)$**



Spectra for SM couplings compared to current limits on anomalous couplings (Λ = 1.5 TeV):

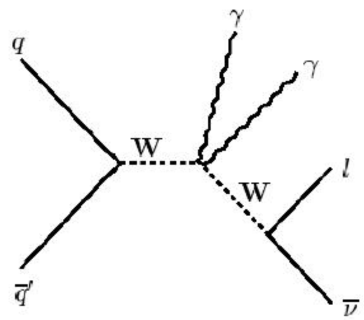




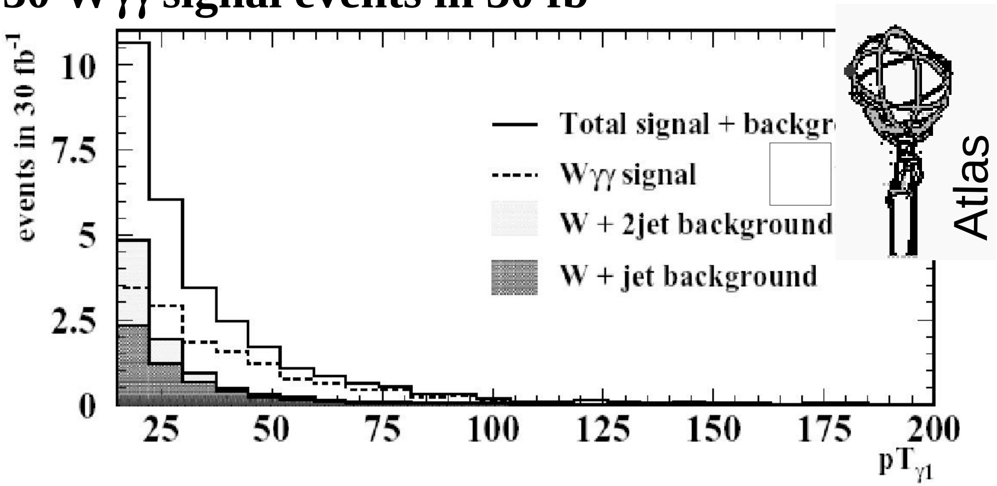
Triple-Boson Production

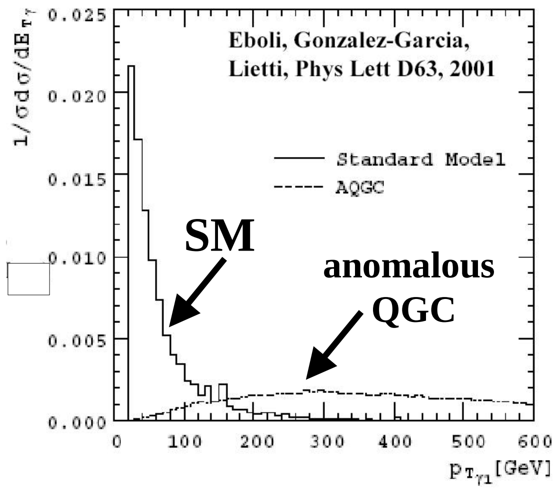
Sensitive to quartic gauge boson couplings (QGC)

Events for 100 fb^{-1} (m_H = 200 GeV)	Produced (no cuts,no BR)	Selected (leptons, p_T>20 GeV, $\|\eta\|$ < 3)
pp → WWW (3 ν´s)	31925	180
pp → WWZ (2 ν´s)	20915	32
pp → ZZW	6378	2.7
pp → ZZZ	4883	0.6
pp → Wγγ	best channel for analysis	



30 Wγγ signal events in 30 fb^{-1}

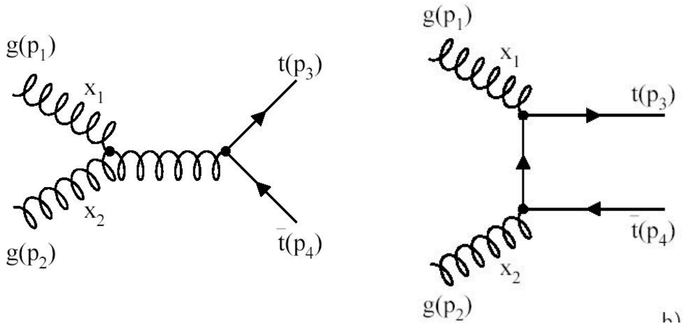


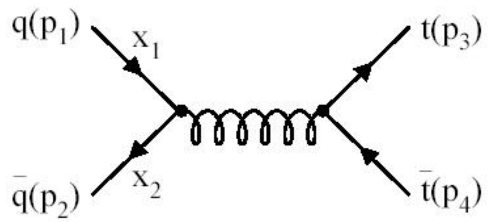


Top Physics

- $t\bar{t}$ production

87% gluon fusion **13% quark annihilation**

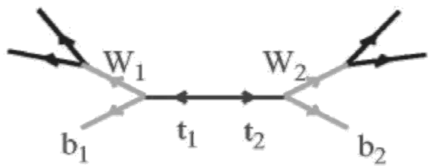




Inverse ratio of production mechanism as compared to Tevatron

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

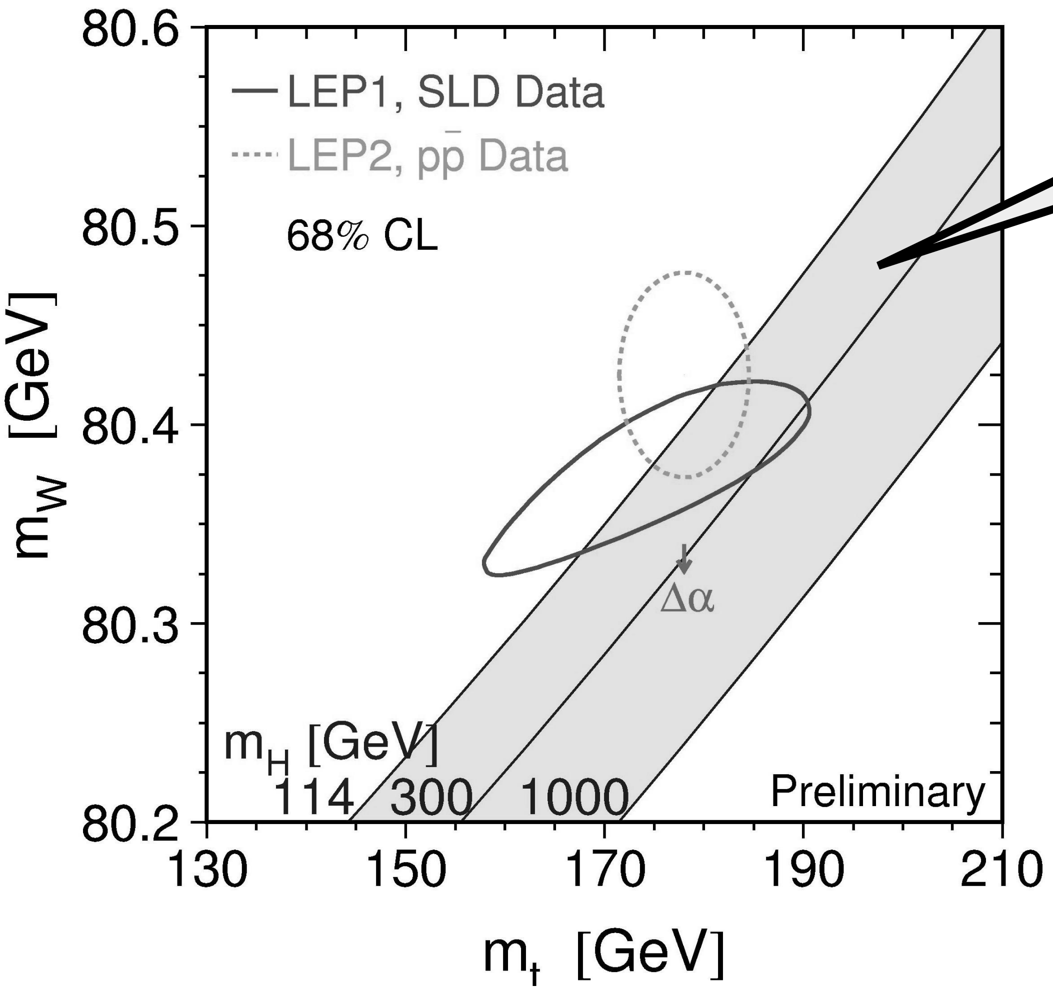
LHC is a top factory!



- **Top decay: ≈ 100% t → bW**
- **Other rare SM decays:**
  - **CKM suppressed t → sW, dW: 10^{-3} –10^{-4} level**
  - **t→bWZ: $O(10^{-6})$**

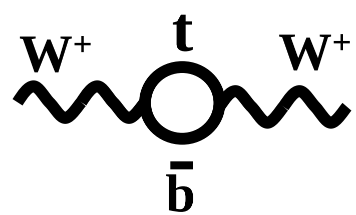
    difficult, but since $m_t \approx m_b+m_W+m_Z$ sensitive to m_t
- **& non-SM decays, e.g. t → bH^+**

Measurement of the Top Mass: Motivation



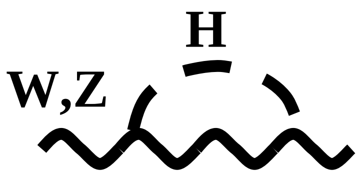
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2} \frac{1}{m_W^2 \sin^2\theta_W} \frac{1}{1-\Delta r}$$

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



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

$\oplus$

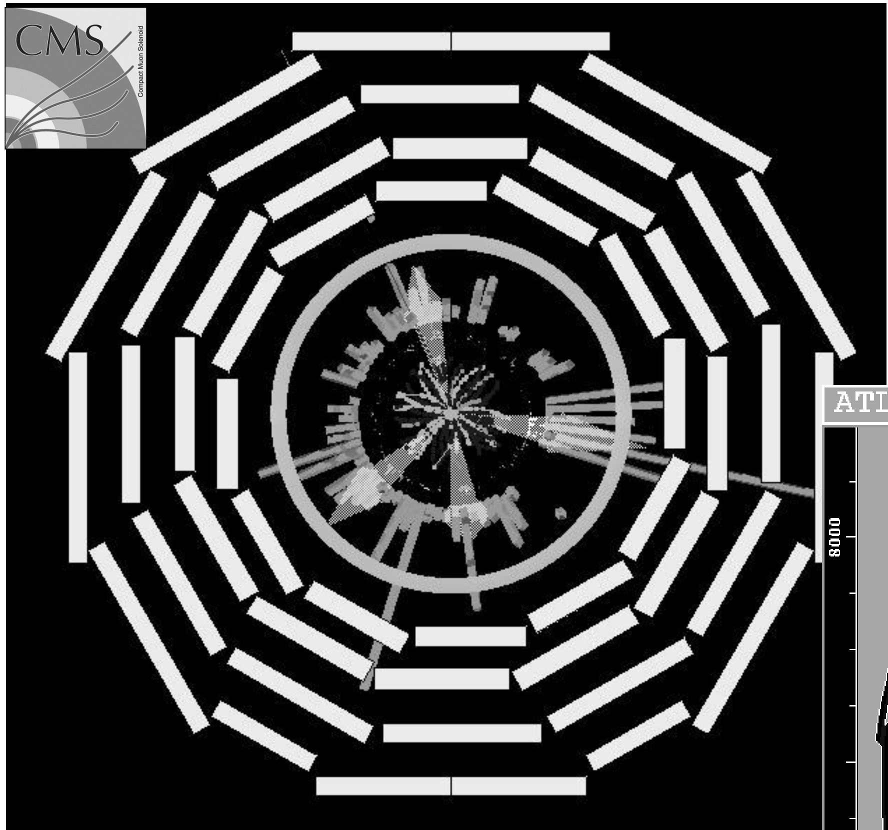


$\Delta r_W \propto \log m_H$

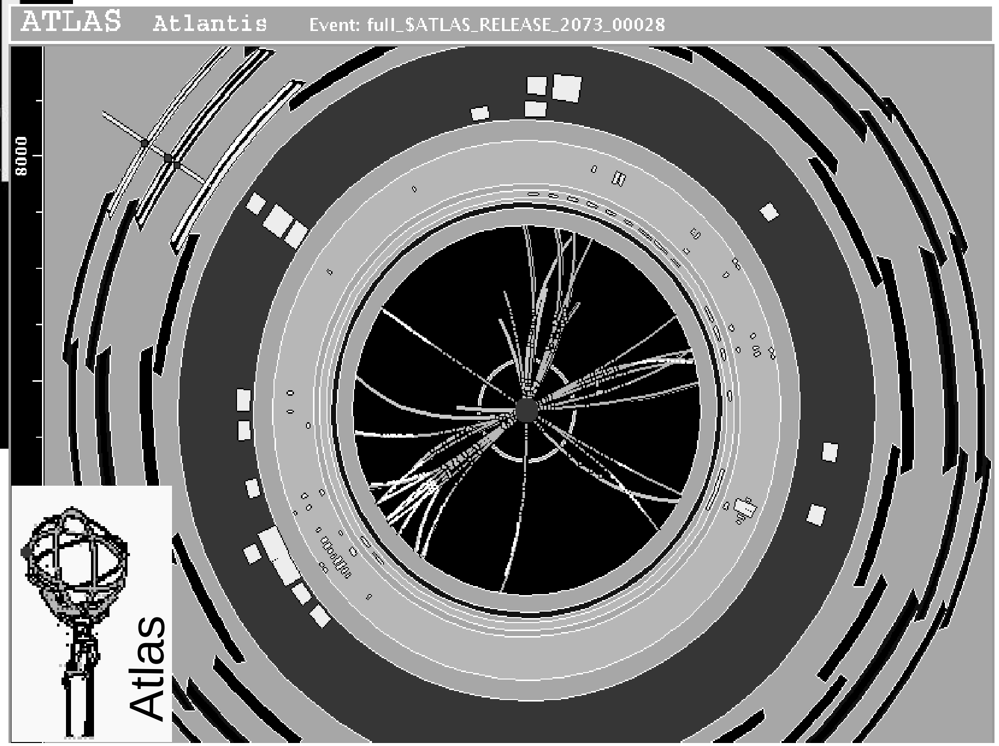
Top mass from Tevatron:

$m_t =$ [illegible] $\pm$ [illegible] GeV

Top Mass from Semi-Leptonic Events



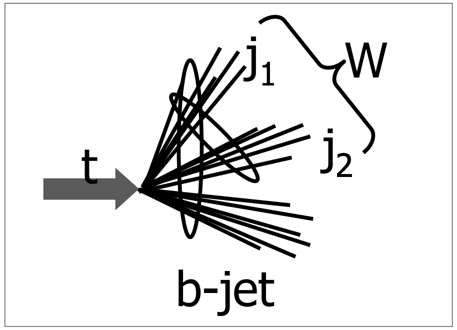
Easiest channel tt $\rightarrow$ bb qq lν
- Large branching ratio
- Easy to select

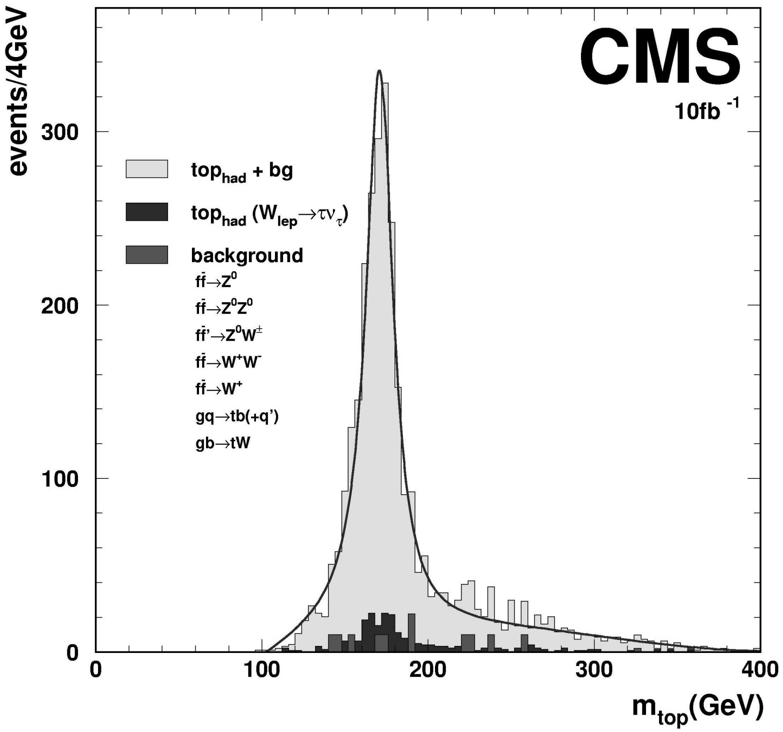


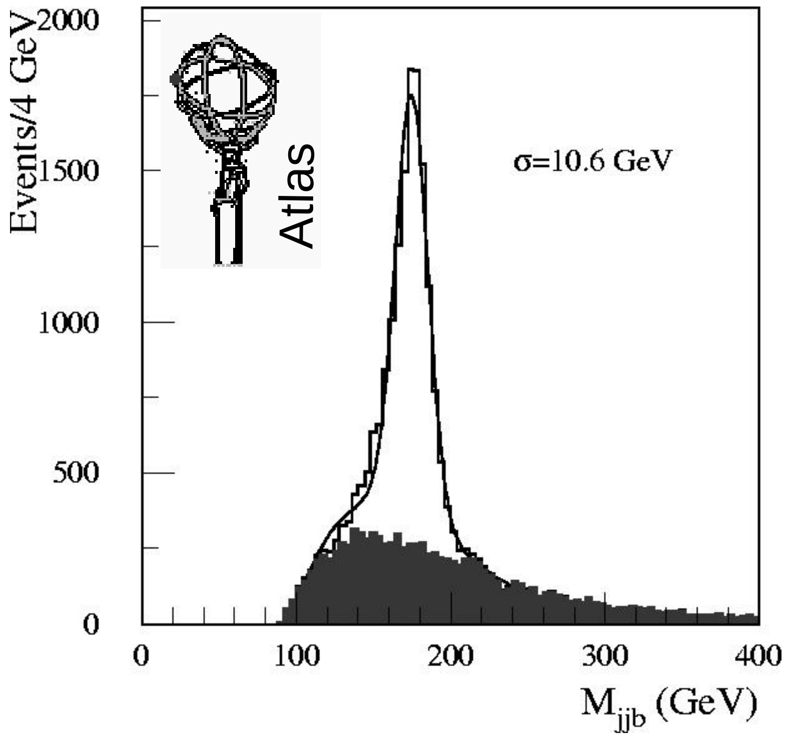
tt $\rightarrow$ bb qq $\mu\nu$ events from CMS & ATLAS

Top Mass from Semi-Leptonic Events

Reconstruct m_t from hadronic W decay
Constrain two light quark jets to m_W







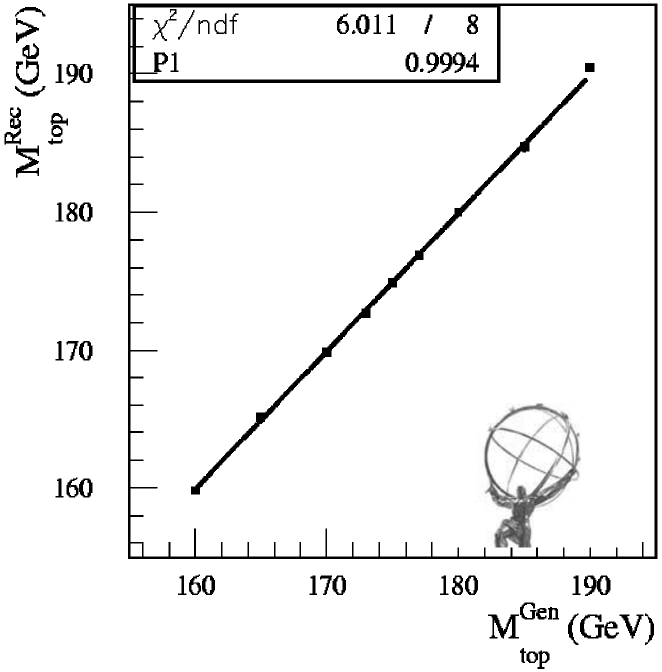
Top Mass from Semi-Leptonic Events

- **3.5 million semileptonic events in 10 fb^{-1} (first year of LHC operation)**

⇒ Error on $m_t \approx \pm 1 - 2$ GeV

Dominated by

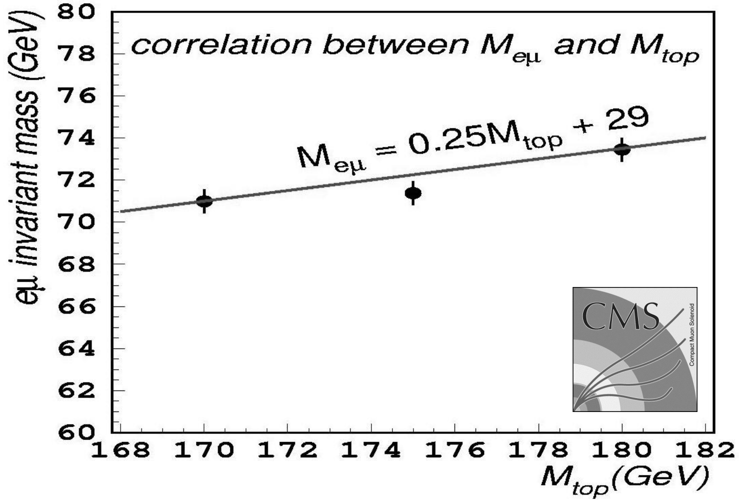
- **Jet energy scale (b-jets)**
- **Final state radiation**



Top Mass from Other Channels

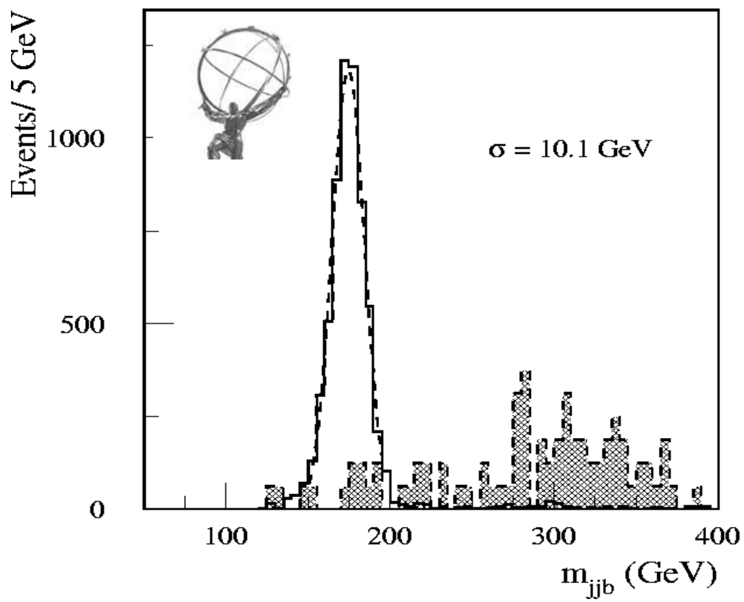
Di-lepton events:
- **BR ≈ 5%**
- **low background**
- **but two neutrinos in final state**

⇒ $\Delta m_t \approx \pm 1.7$ GeV

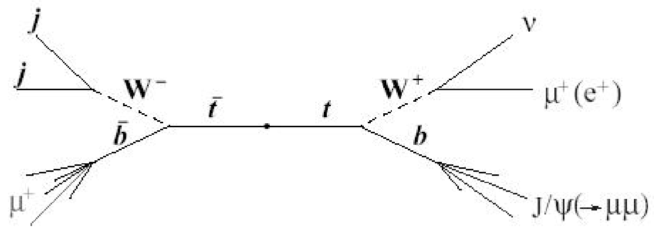


Fully hadronic events:
- **BR ≈ 45%**
- **difficult jet enviroment**

⇒ $\Delta m_t \approx \pm 3$ GeV



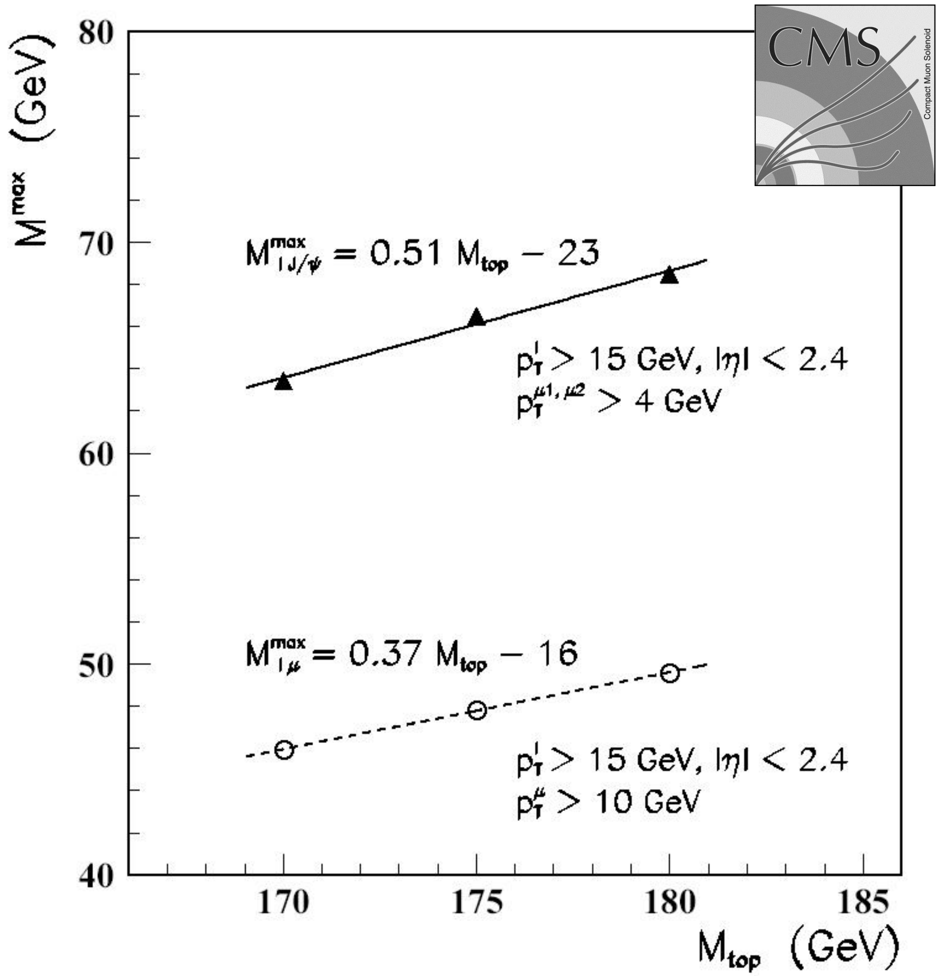
Top Mass from J/Ψ channel



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:**

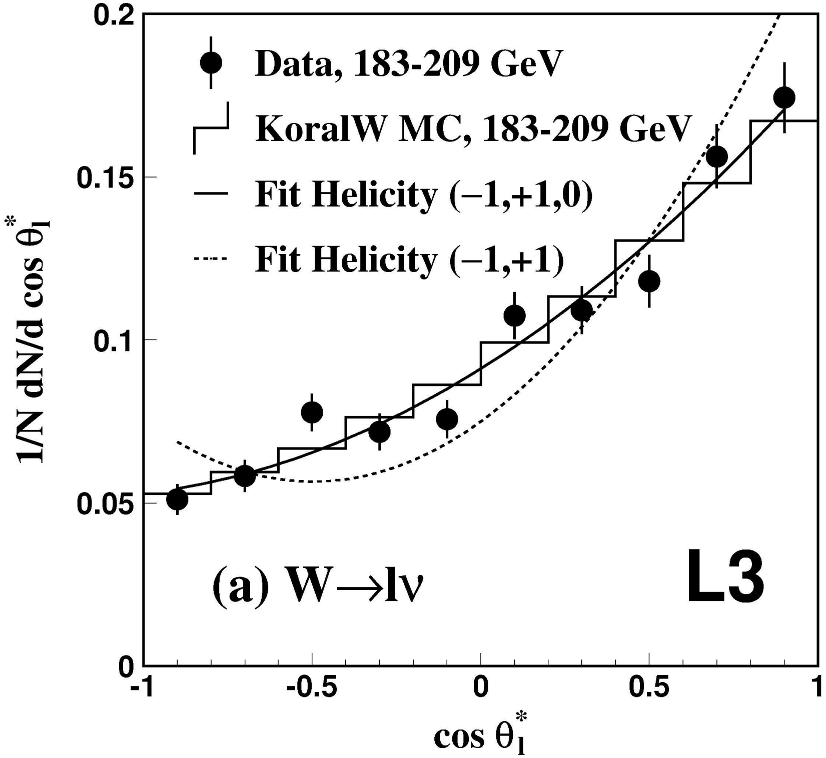
  $\Delta m_t \approx 1$ **GeV**

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^*

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



$\Rightarrow$

- **Fraction of longitudinal W in $e^+e^- \rightarrow W^+W^-$**

  0.218 ± 0.031

  SM: 0.24

- **Tevatron:**
  Longitudinal W in top decays

  0.91 ± 0.52 CDF

  0.56 ± 0.31 D0

  SM: 0.7

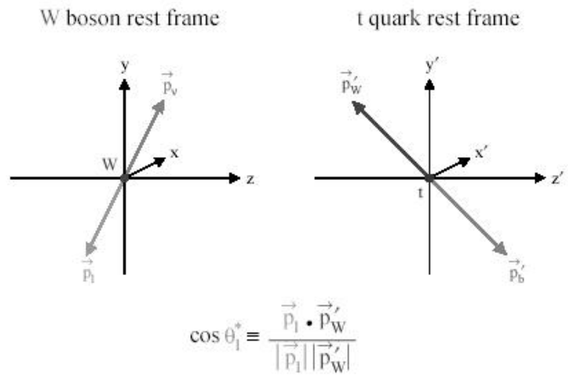
W Polarization in Top Decays

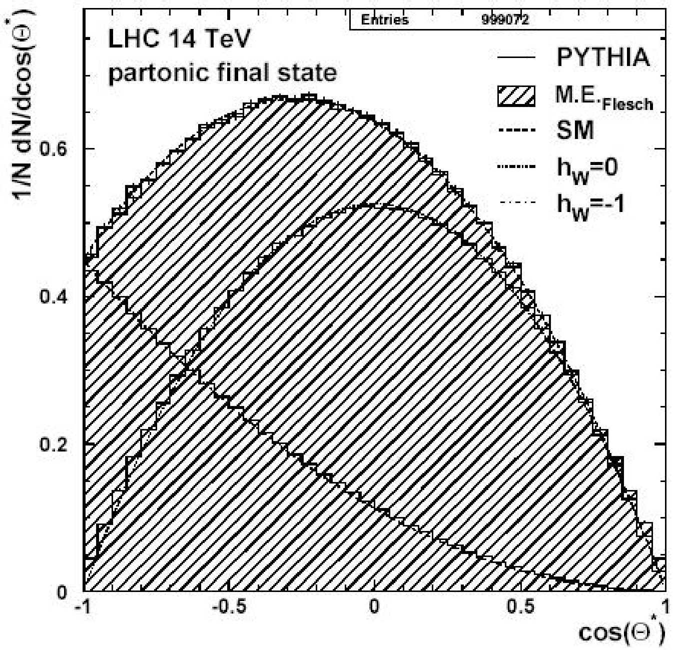
Standard Model prediction:

$$\frac{\Gamma(h_W = -1)}{\Gamma_{tot}} = 02 \qquad \frac{\Gamma(h_W = 0)}{\Gamma(h_W = -1)} = \frac{1}{2}\left(\frac{m_t}{m_W}\right)^2 = 3$$

$$\frac{\Gamma(h_W = 0)}{\Gamma_{tot}} = 003$$

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

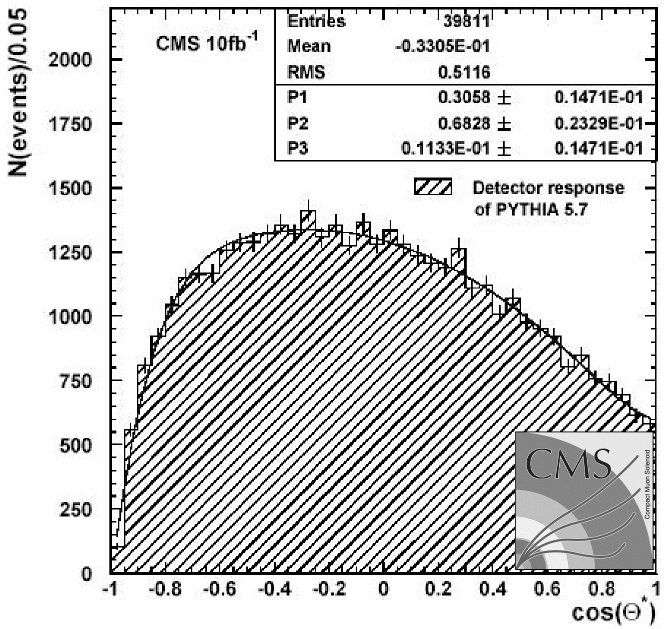




detector simulation

→

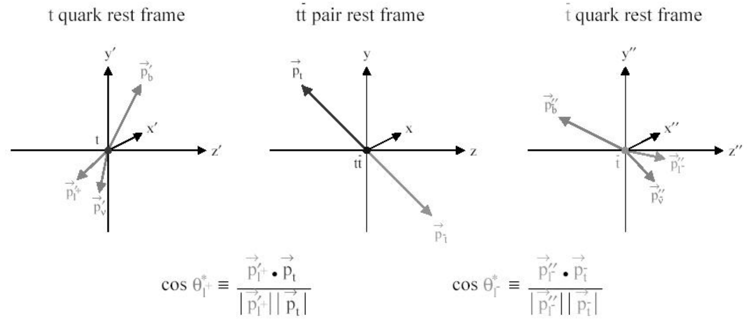
& acceptance



⇒ precision on fraction of long. pol. W:
± 0.023 (stat) ± 0.022 (sys)

$t\bar{t}$ Spin Correlation

Very short lifetime,
no top bound states
⇒ Spin info not diluted
by hadron formation

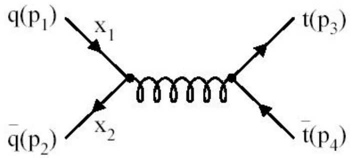


$$\mathcal{A} = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}$$

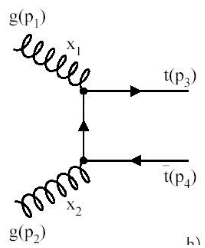
$$\frac{1}{N}\frac{d^2N}{d\cos\theta^*_{\ell+}\, d\cos\theta^*_{\ell-}} = \frac{1}{4}(1 - \mathcal{A}\cos\theta^*_{\ell+}\cos\theta^*_{\ell-})$$

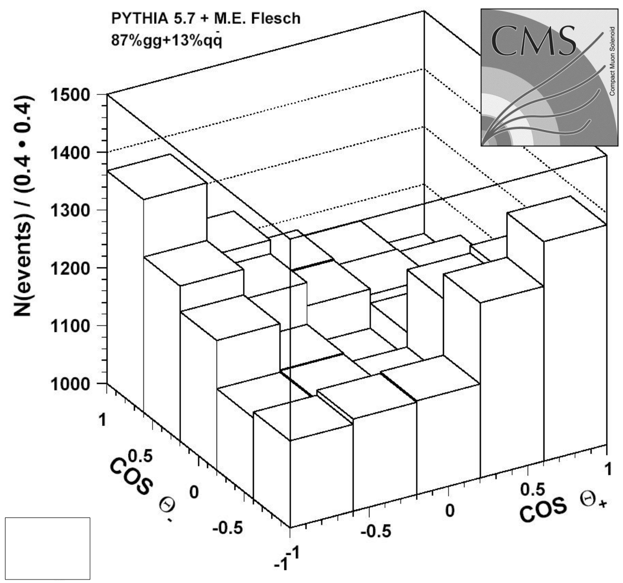
Distinguishes between

- **quark annihilation**
  A = -0.469



- **and gluon fusion**
  A = +0.431



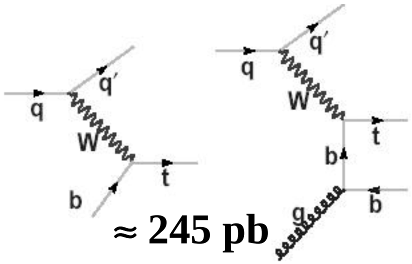


Use double leptonic decays
tt → bb lν lν

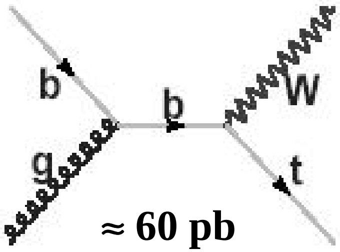
A= 0.311 ± 0.035 ± 0.028 (using 30 fb^{-1})

Single Top Production

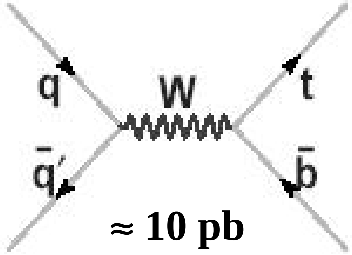
Production mechanisms and cross sections:



≈ 245 pb



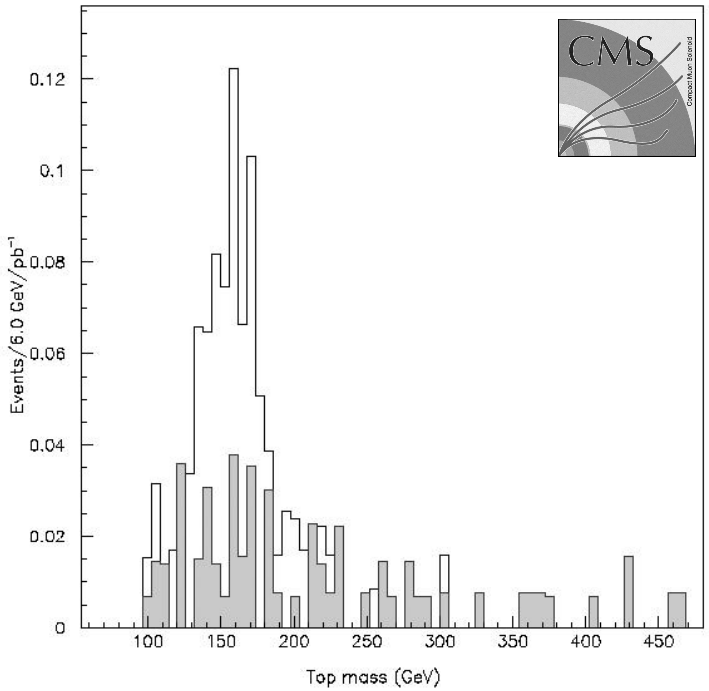
≈ 60 pb



≈ 10 pb

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

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



experimental determination of V_{tb} to percent level (with 30 fb^{-1})

Determination of Top Charge

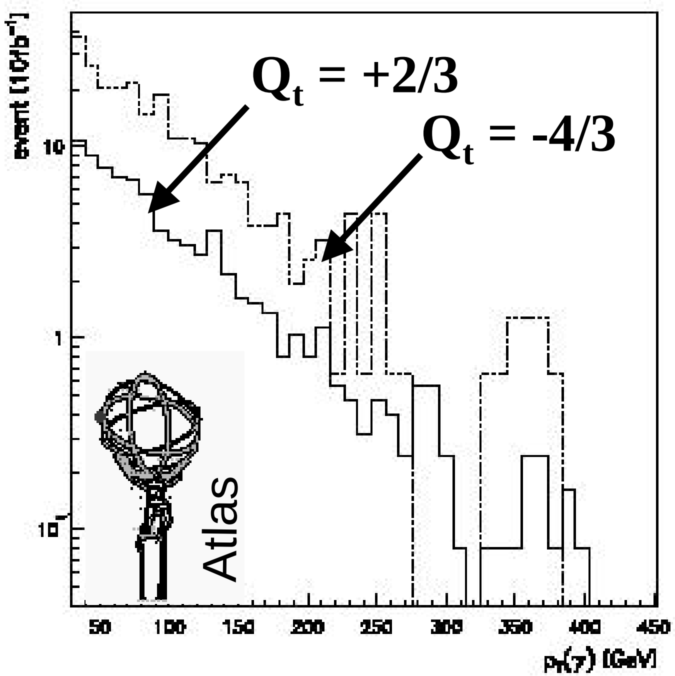
Top charge:

- **Q_t = +2/3 not yet established** $t \rightarrow W^{+}b$
- **Q_t = -4/3 not yet excluded** $t \rightarrow W^{-}b$

LHC:

Determine charge from rate of radiative ttγ events

p_T spectrum of photons for 10 fb^{-1}:



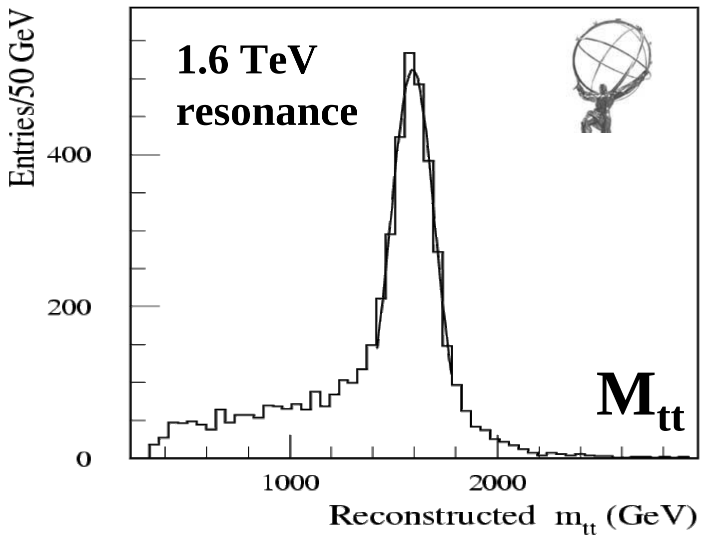
Measurement of tt cross section

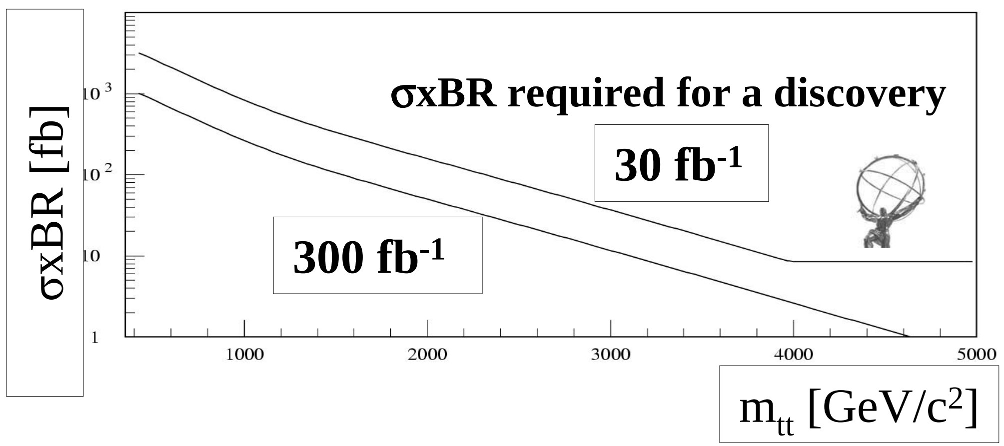
Total cross section:

- **At 14 TeV interesting in itself**
- **Sensitive to top mass $\sigma_{tt} \propto 1/m_t^2$**

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 decaying to top-pairs $X \rightarrow tt$**





Summary & Conclusions

SM physics at the LHC

- **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**

Credits:
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