Electroweak physics at LHC
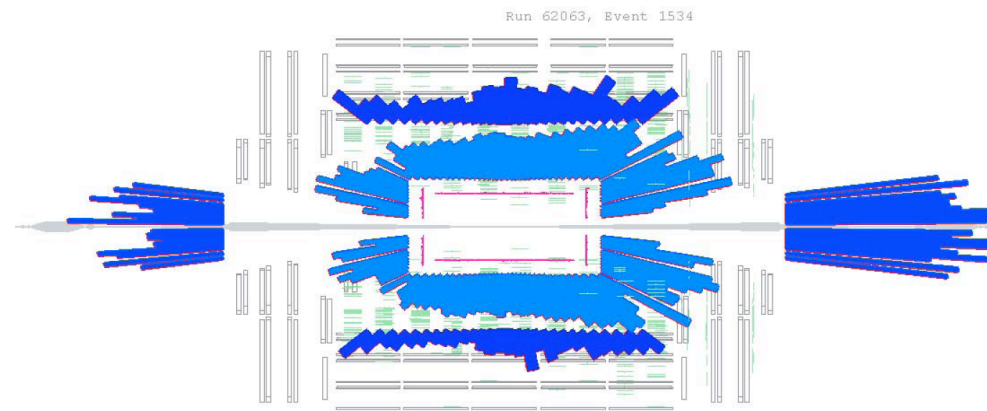
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On behalf of the ATLAS & CMS Collaborations

Physics @ LHC - 2008

Split, Croatia

first beam event seen in ATLAS

first beam event seen in CMS
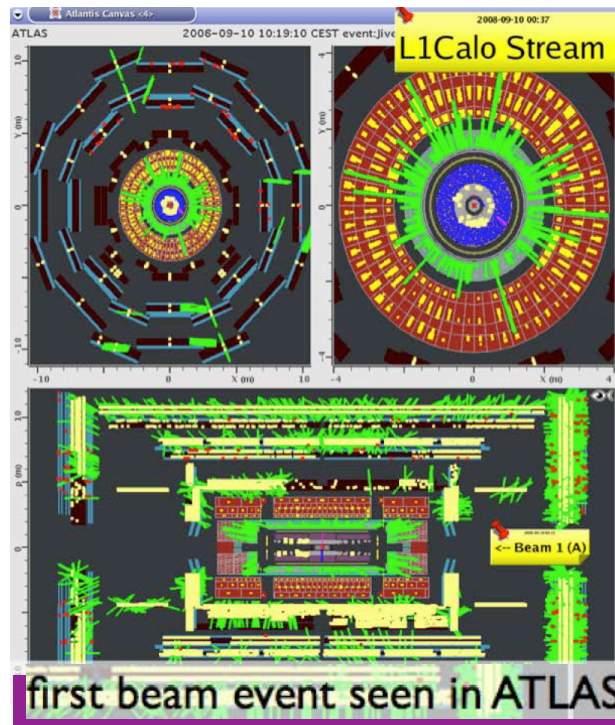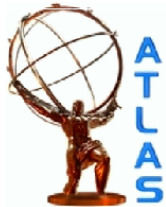
ElectroWeak physics at LHC

Large number of topics --> need to make a (personal) choice :

Outline

- **W mass**

- **Top mass**

- **Forward Backward asymmetry in Z decay**

- **Associated production of Gauge Bosons**

**Current EW theory successfully tested at present energies**

Aim @ LHC : deeper understanding in view of :

  * **tightening indirect constraints (M_W, M_{top})**
  * **search for deviations (couplings)**
  * **understanding and calibrating detectors(i.e. see**
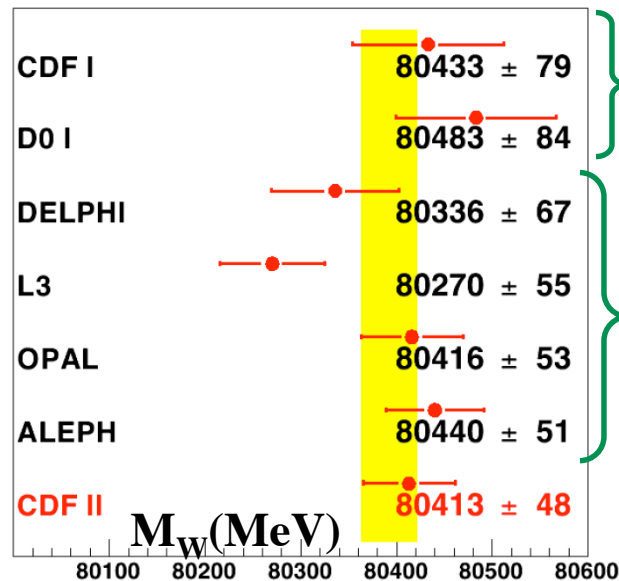
  K. Lohwasser talk)

Each experiment @ LHC: 'Low' lumi 10 fb^{-1}/y
'High' lumi 100 fb^{-1}/y
TeVatron has collected so far ≈ 4.5 fb^{-1}

W &Top masses

❖ **M_W: fundamental parameter of the theory linked to M_{top} & to Higgs mass:**
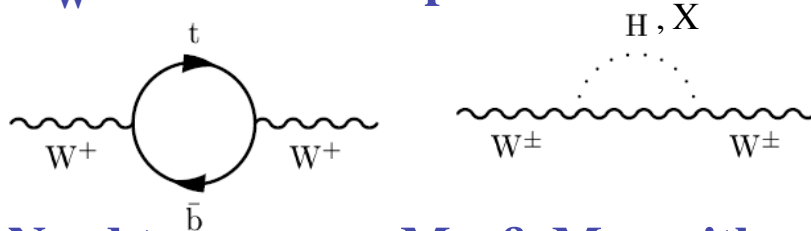
$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}}\frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

❖ **Need to measure M_W & M_{top} with greatest precision**

$f(M_{top}^2, \ln M_H) \sim$ few %

$\Delta M_W^{TeV\ I} = 59$ MeV

$\Delta M_W^{LEP} = 33$ MeV

0. 3‰

World average(ICHEP08):$M_W = 80399 \pm 25$ MeV

Great job !! Still LHC could improve it :

❖ **W(&Z) cross-sections an order of magnitude more than TeVatron**

$\sigma_{Wl\nu}^{NNLO\ 14\ TeV} \sim 20$ nb --> 1 fb^{-1} gives ~ 4 000 000 W events (ε_{sel}~20%)

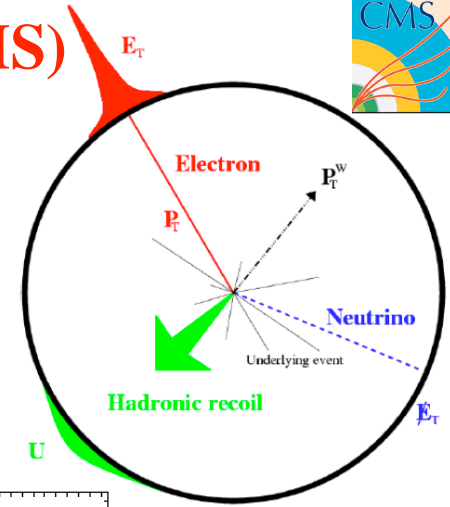❖ **Design peak luminosity ~ an order of magnitude more than TeVatron**
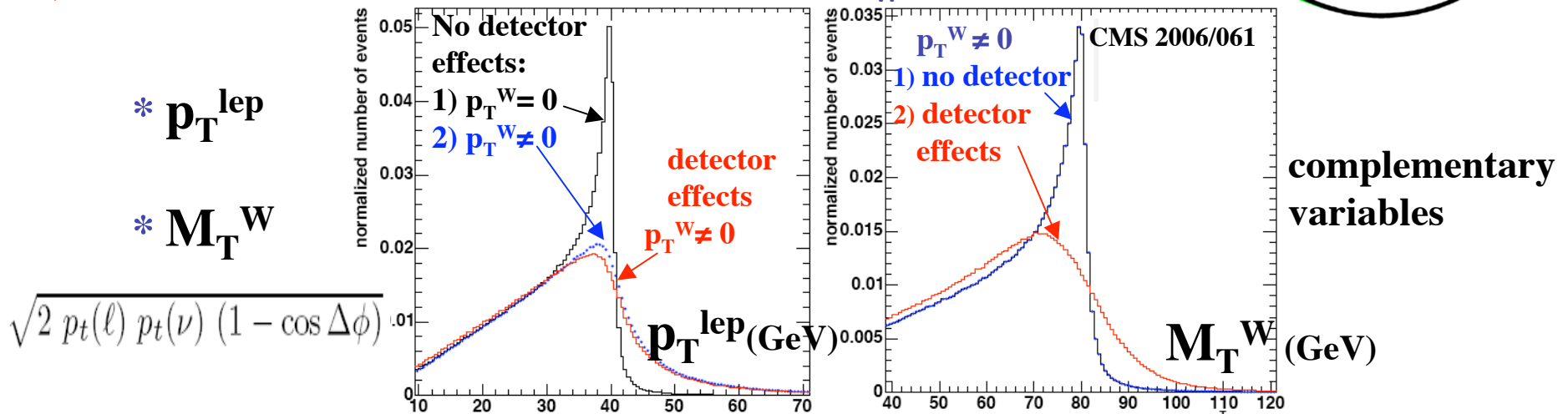
Mass of W boson: analysis steps (ATLAS & CMS)

1) Select candidate W's

(in leptonic channel)

Isolated lepton $p_T^{lep} > 25$ GeV ,
$|\eta| < 2.4$

$E_T^{Miss} > 25$ GeV

No jets with $p_T > 30$ GeV

Recoil < 20 GeV

2) Plot the two main variables sensitive to M_W :

* p_T^{lep}

* M_T^W

$$\sqrt{2\, p_t(\ell)\, p_t(\nu)\, (1 - \cos \Delta\phi)}$$

No detector effects:
1) $p_T^W = 0$
2) $p_T^W \neq 0$

detector effects $p_T^W \neq 0$

p_T^{lep}(GeV)

$p_T^W \neq 0$
1) no detector
2) detector effects

CMS 2006/061

detector effects

M_T^W (GeV)

complementary variables

3) Build templates (i.e. expected distributions of p_T^{lep} & $M_T^W = f(M_W)$)

4) χ^2 fit to find the template matching best the data ⟹ M_W)

❖ **Z events play a crucial role: reduce experimental & theoretical uncertainties**

* Z events 'modified' and used to build templates (**CMS**)
* Z events used to tune W MC (**ATLAS**)

Mass of W boson: build templates (CMS)

Method 1: Scaled observable method

$$R'(X) = corr * R(X)$$

$$\frac{d\sigma^W}{dp_T^{lep}} = \frac{M_Z}{M_W} R'(X) \frac{d\sigma^Z}{dp_T^{lep}}$$

$$R(X) = \frac{d\sigma^W}{d(p_T^{lep}/M_W)} \bigg/ \frac{d\sigma^Z}{d(p_T^{lep}/M_Z)}$$

predicted   ~ from theory   measured

$R(X)$: calculable using perturbative QCD

$corr$: W/Z acceptance and exp. resolution -> understanding detector response

mainly lepton scale linearity

1 fb⁻¹ : ΔM_W = 40 (stat.) $\oplus$ 40 (exp.) $\oplus$ 40 (theo.) MeV

mainly p_T^W spectrum

Method 2: Morphing (scaling the Z events rathen then the Z observables)

'Correction factor'
transformed Z events / # W events

- no cuts
- p_t cuts
- η cut on muon(s)
- recoil cut
- all cuts on FAMOS level

CMS 2006/061 M_T^W (GeV)
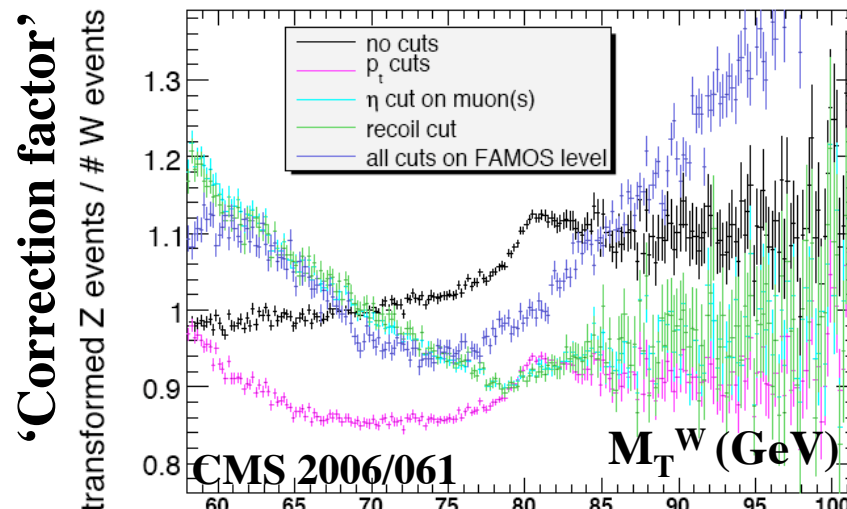
1 fb⁻¹ :

mainly PDF

ΔM_W = 40 (stat.) $\oplus$
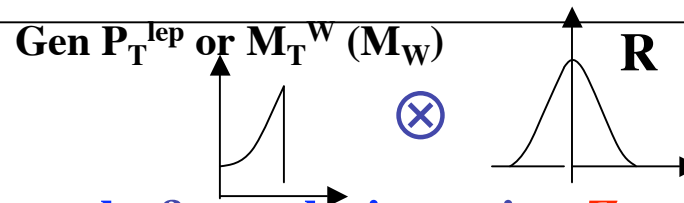
64 (exp.) $\oplus \geq$ 20 (theo.) MeV

mainly E_T^{Miss} scale

⚠ Data driven methods developed by CMS in recent cross-section analyses will decrease the experimental systematic error

Mass of W boson: build templates (ATLAS)

Gen P_T^{lep} or M_T^W (M_W) $\otimes$ **R**

❖ **Templates for p_T^{lep} :**

- **Get the energy/momentum scale & resolution using Z-->ll events:**

  Fit Z-->ll data with Templates = [f(lept. scale, lept. resolution)]

- **Tag and Probe to determine the lepton efficiency(Z-->ll events)**

❖ **Templates for M_T^W :**

- **Model missing momentum response by looking at Z-->ll events**

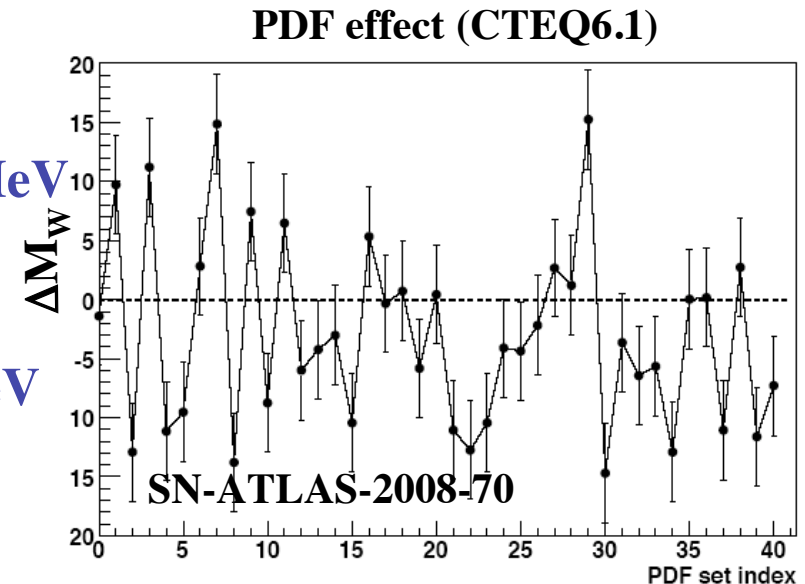**control of experimental systematics**

❖ **Results for** (**15 pb^{-1}** :)

W-> e ν   with p_T^{lep}
   $\Delta M_W = 120$ (stat) $\oplus$ 114 (exp.) $\oplus$ 25 (PDF) MeV

W-> μ ν   with M_T^W
   $\Delta M_W = 57$ (stat) $\oplus$ 230 (exp.) $\oplus$ 25 (PDF) MeV

How to control the theoretical uncertainties?

PDF effect (CTEQ6.1)

SN-ATLAS-2008-70

Mass of W boson: main theoretical uncertainties

❖ **Transverse momentum distribution p_T^W affects p_T^{lep}**

Study $p_T(l^+l^-)$ vs M_{l+l-} in γ^*/Z events

10 fb^{-1}, $\Delta M_W \approx 3$ MeV

SN-ATLAS-2008-70

$p_T(l^+l^-)$ GeV
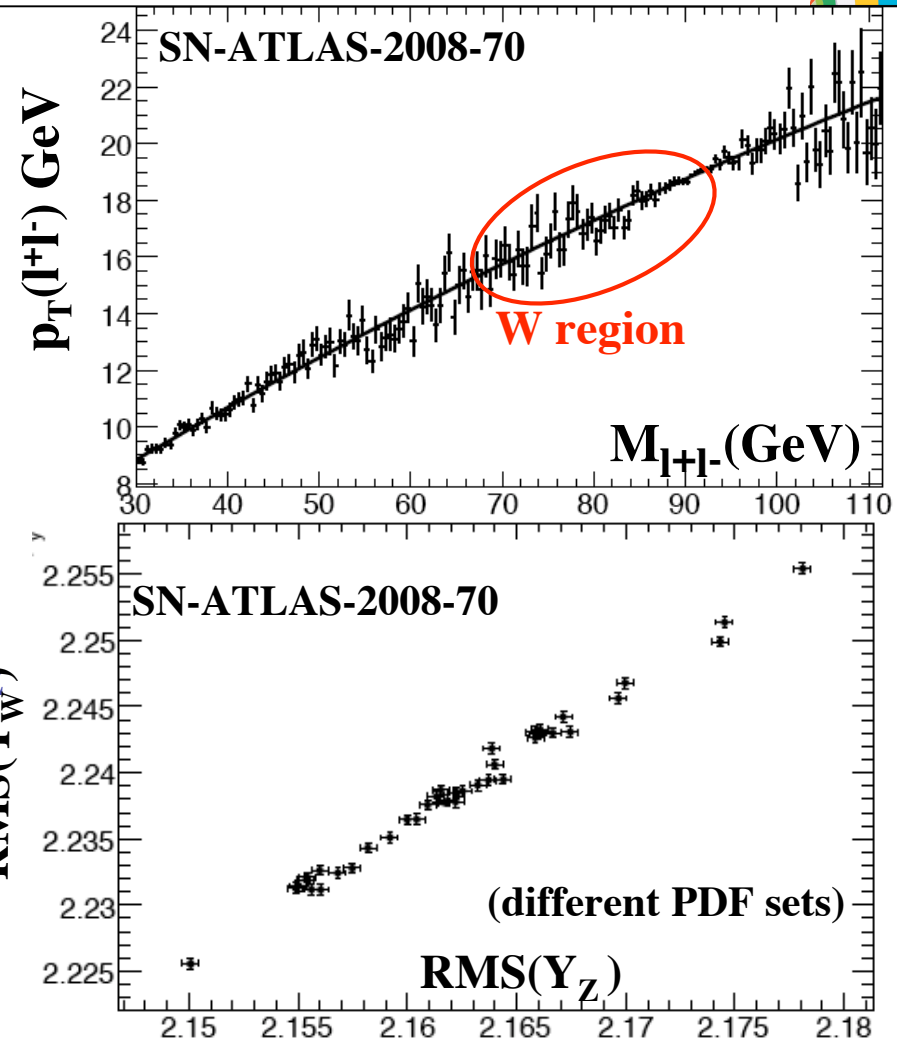
W region

M_{l+l-}(GeV)

❖ **PDF affect rapidity of $W(Y_W) \rightarrow M_W$**

Strong correlation between Y_W and Y_Z when varying PDF

10 fb^{-1}, $\Delta M_W \approx 1$ MeV

SN-ATLAS-2008-70

RMS(Y_W)

(different PDF sets)

RMS(Y_Z)

10 fb^{-1} Total systematics $\Delta M_W < 10$ MeV (1 analysis)

● **For equal contribution to M_H (indirect) uncertainty :**
   if $\Delta M_W < 10$ MeV --> $\Delta M_{top} < 1.5$ GeV
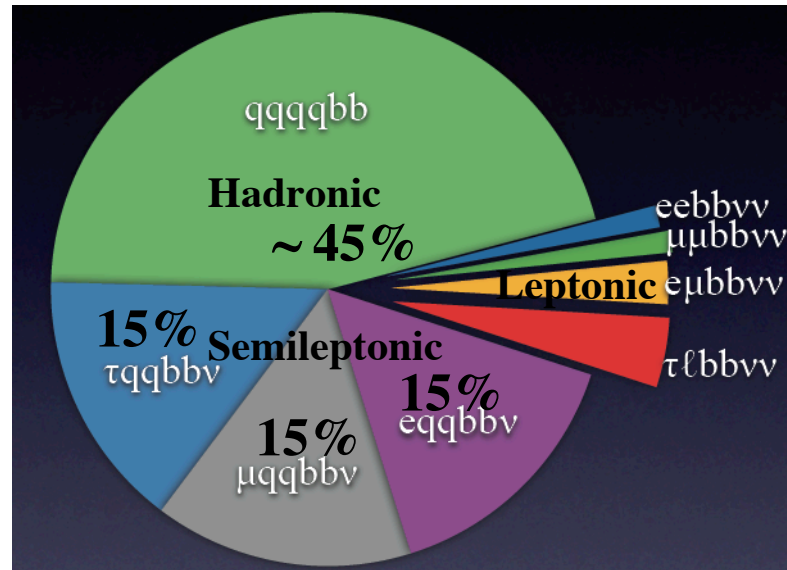
Top Mass measurement

- **Accurate measurement of M_{top} important :** * consistency check of SM
  * constrain Higgs mass within SM

- **Top abundantly produced @ LHC:** $\sigma_{tt}^{NLO} \sim$ 830 pb $\Rightarrow$ ~10^7 $t\bar{t}$ pairs/y @ 10^{33}cm s^{-1}

  (x 100 TeVatron !!)

gg-> $t\bar{t}$ ~ 90%   **$q\bar{q}$ -> $t\bar{t}$ ~ 10%**
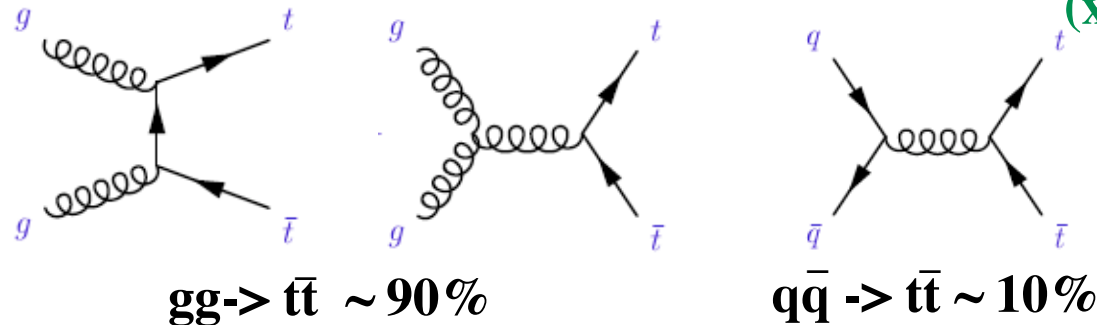
- **Br(t->Wb) ≈ 100%).**   **Decays :**

- **Hadronic :**
  - **+ high Br**
  - **+ possible to reconstruct whole event**
  - **- high bkg and combinatorics**
- **Leptonic :**
  - **+ lower bkg & combinatorics**
  - **- low Br,**
  - **- final state difficult to reconstruct**

- **Semileptonic: good compromise ('golden')**

Top Mass in semileptonic decays: analysis steps

1) Event selection:

1 isolated high p_T lept+E_t^{miss}+ $\geq$ 4 jets of high p_T (2 b-jets)

$\varepsilon \approx 5\%$, S/B $\approx$ 10, $\varepsilon_b \approx 60\%$

2) Hadronic W mass reconstruction M_{jj}: several methods

Ex: first select jet pairs in a mass range then get M_{jj}, $\alpha_{1,2}$:

$$\chi^2 = \frac{\left(M_{jj} - M_W^{PDG}\right)^2}{\Gamma_W^2} + \frac{\left(E_{j1}(1-\alpha_1)\right)^2}{\sigma_1^2} + \frac{\left(E_{j2}(1-\alpha_2)\right)^2}{\sigma_2^2}$$

$\alpha_{1,2}$ & $\sigma_{1,2}$ = light jet energy scale & resolution

3) Top quark reconstruction: several methods

Ex: choose b jet closest to W->jj + further cuts

4) Leptonic W mass recostruction $M_{l\nu}$
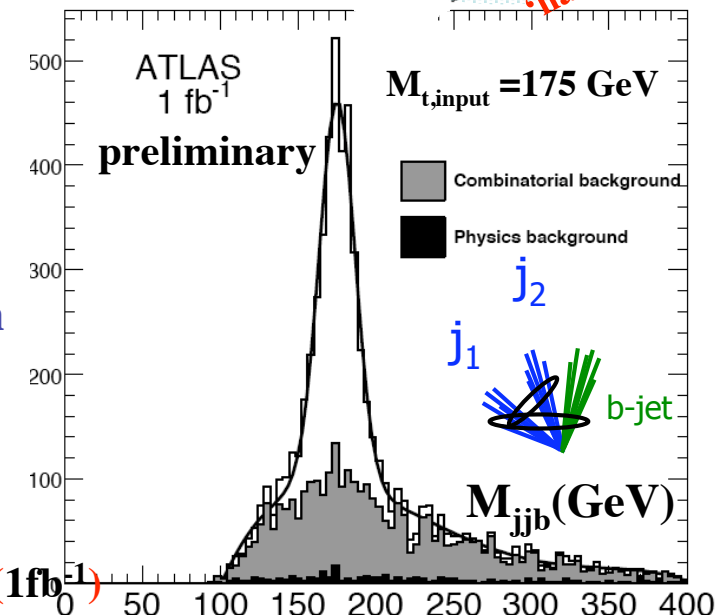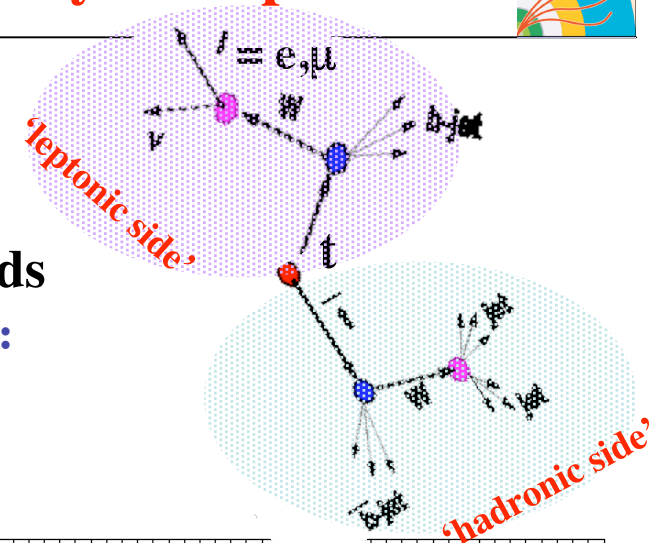
Using known W mass and 4-momentum conservation (then select solution such that | $M_{l\nu b}$-M_{jjb}| is minimum after step **4**)

5) Top quark mass

Gaussian+polynomial fit M_{top}= 175.0 ± 0.2$_{stat}$ GeV (1fb^{-1})

Kinematic fit to the full event (less sensitivity to **F**inal**S**tate**R**adiation)

$M_{top}^{fit}(\chi^2=0) = 174.8 \pm 0.4_{stat}$ GeV

ATLAS 1 fb^{-1} preliminary

$M_{t,input}$ =175 GeV

Combinatorial background

Physics background

j_2

j_1

b-jet

M_{jjb}(GeV)

Top Mass in semileptonic decays: systematics

Systematic uncertainty	χ^2 minimization method
Light jet energy scale	0.2 GeV/%
b jet energy scale	0.7 GeV/%
ISR/FSR	$\simeq$ 0.3 GeV
b quark fragmentation	$\leq$ 0.1 GeV
Background	negligible
Method	0.1 to 0.2 GeV

**Most important systematics :
jet enegy scale (JES) of
* b-jet (1 fb^{-1} ΔM_{top}(b-JES) ≈ 1-3.5 GeV
depending on b-JES ≈ 1-5%)**

**@LHC (1 fb^{-1}, 1 analysis) : M_{top}= 175.0 ± 0.2$_{stat}$ ± 1.0$_{syst}$ GeV
Current value (TeV ICHEP2008): M_{top}= 172.4 ± 0.7$_{stat}$ ± 1.0$_{sys}$ GeV**

● **If no use of b-tag ('early data')**
   * higher combinatorics
      ---> additional cuts
   $\varepsilon \approx 1.6\%$, purity ≈ 50%
   * issue: constraint bkg shape with data

**M_{top}=172.4 ± 1.5$_{stat}$ GeV
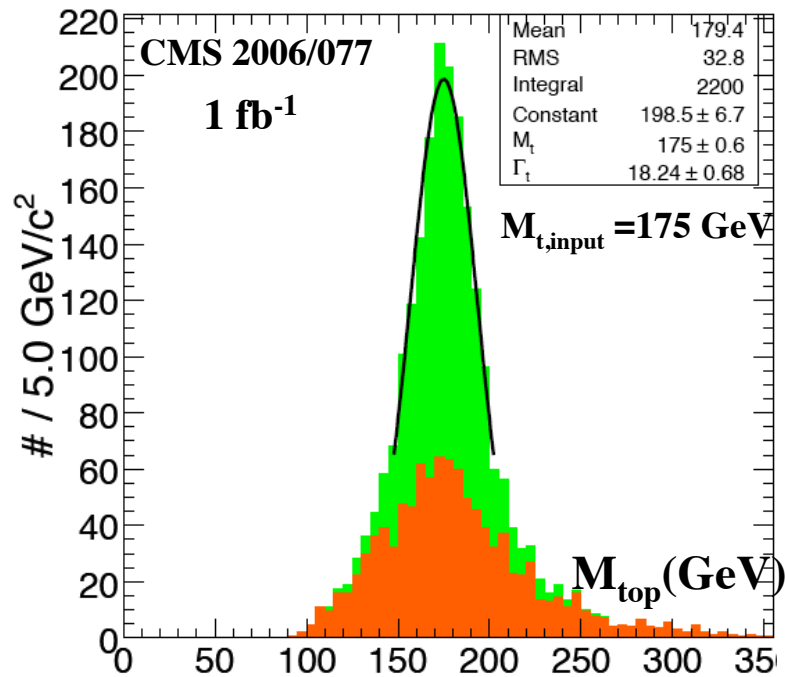Systematics ≈ as above except from
ΔM_{top}(bkg) which goes to ~1 GeV**
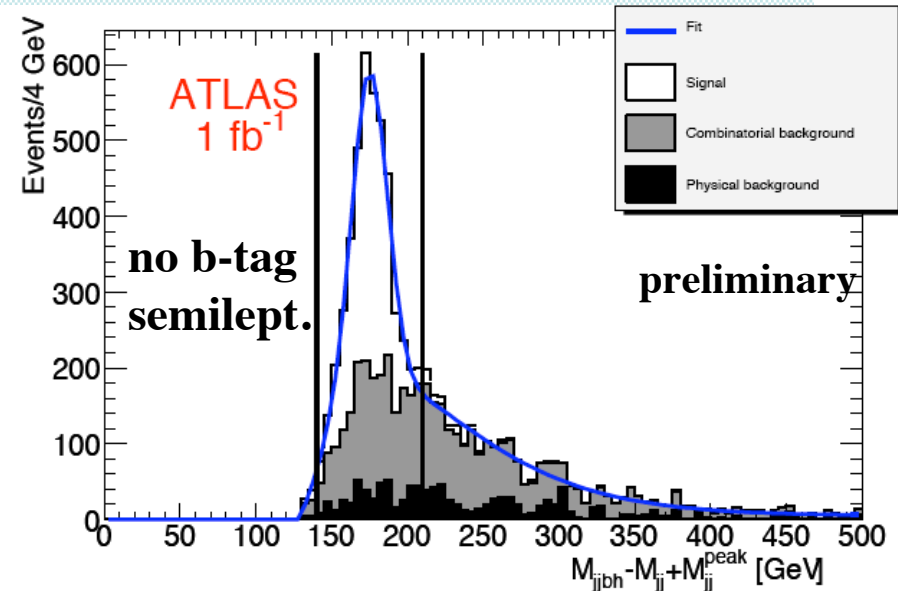
Top Mass fully hadronic & Top Mass di-leptonic decays

Starting S/B < 10^{-6}

Selection S/B ≈ 1/9   ε = 2.7%

Likelihood on masses and angles
to perform the pairing + top choice

Starting S/B ≈ 5*10^{-3}

Kinematical reconstruction of event
pairing with likelihood

S/B ≈ 12   ε = 1.2%

CMS 2006/077

1 fb^{-1}

Mean	179.4
RMS	32.8
Integral	2200
Constant	198.5 ± 6.7
M_t	175 ± 0.6
Γ_t	18.24 ± 0.68

$M_{t,input}$ =175 GeV

M_{top}(GeV)

CMS 2006/077

1 fb^{-1}

Legend
- Signal
- Zjets
- Diboson
- ttbar non dilepton

$M_{t,input}$ =175 GeV

M_{top}(GeV)

M_{top}=175.0 ± 0.6(stat) ± 4.2(syst) GeV

Systematics: JES & ISR/FSR
QCD background
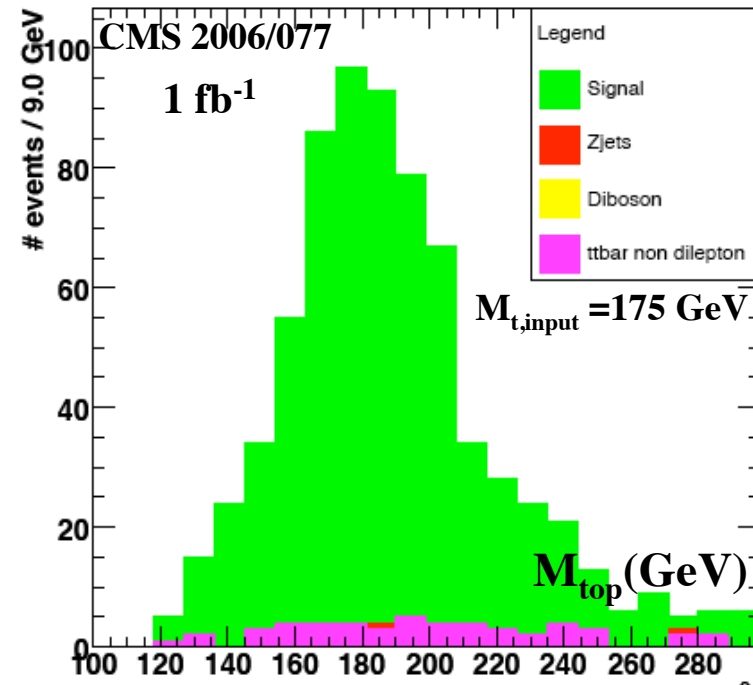
M_{top}=178.5 ± 1.5 (stat) ± 2.9(syst) GeV

Main systematics: JES, ISR/FSR

❖ **Final states with J/ψ (100 fb⁻¹) :**
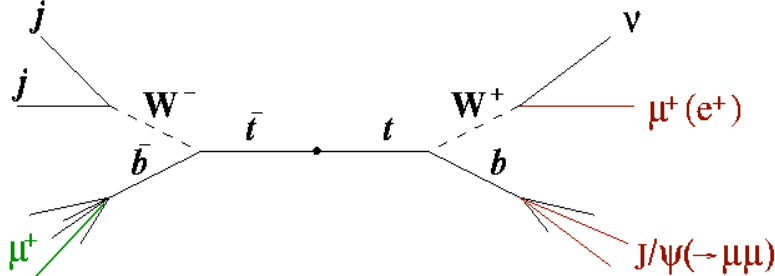
• **Correlation between $M_{lep\,J/\psi}$ and M_{top}**

  --> No systematics on b-jet scale !

• **~ 1000 evts/100 fb⁻¹ --> ΔM_top ~ 1 GeV (main syst. b-fragmentation)**

$m_{J/\Psi-l} = a\, m_t + b$

a = 0.56 +/- 0.05
b = (-25.3 +/- 8.3) GeV/c²

CMS 2006/058

M_top (GeV)

❖ **M_top from the measured t̄t production cross section**

• **Uncertainty ΔM_top ≥ 2 GeV from theory calculation**

• **Can be reduced with computation of higher order, resummation of NLL corrections, PDF measurement.**

A lot of theoretical activity. Many recent results ('08)

pp → tt, √S=14 TeV
σ (pb) (σ_ref) at NLO + NLL QCD
MRST, α_s(M_Z)=0.1175, k_T=0.4 GeV
A=0,   μ=m_t

Lower inset:
σ(param)/σ(ref)
Solid: param=(NLO+NLL A=2)
Dots: param=(NLO+NLL A=0)
Dashes: param=(NLO)
Upper: μ=m_t/2
Lower: μ=2m_t

$\delta m/m = 0.21\ \delta\sigma/\sigma$

hep-ph/00033
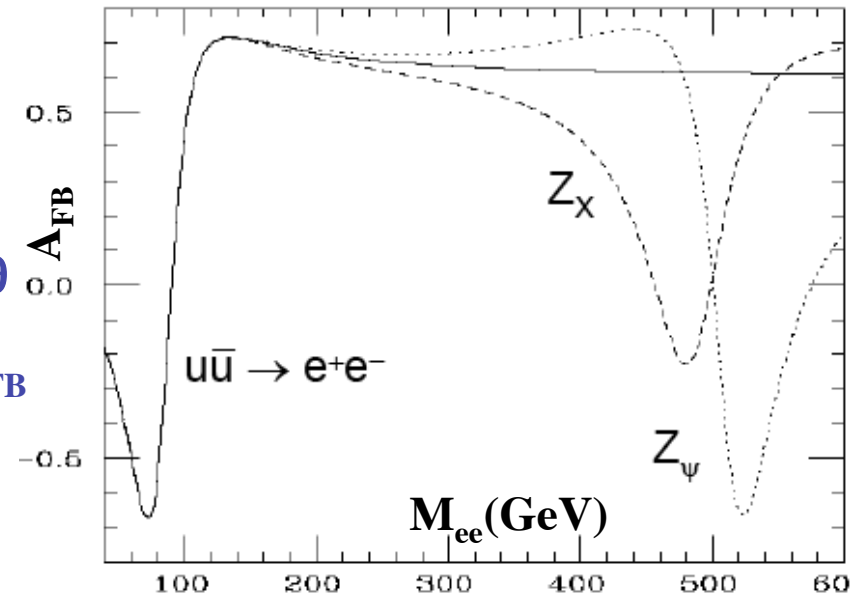
M_top (GeV)
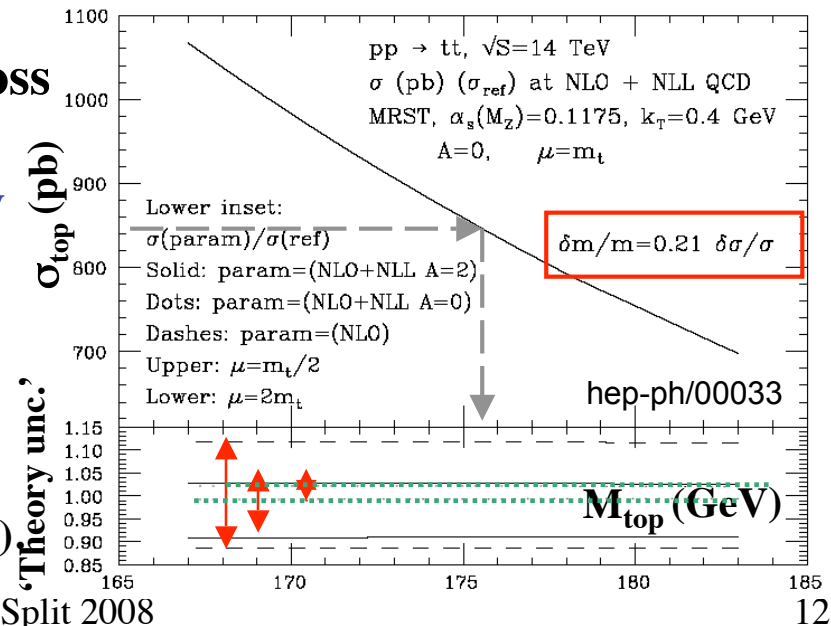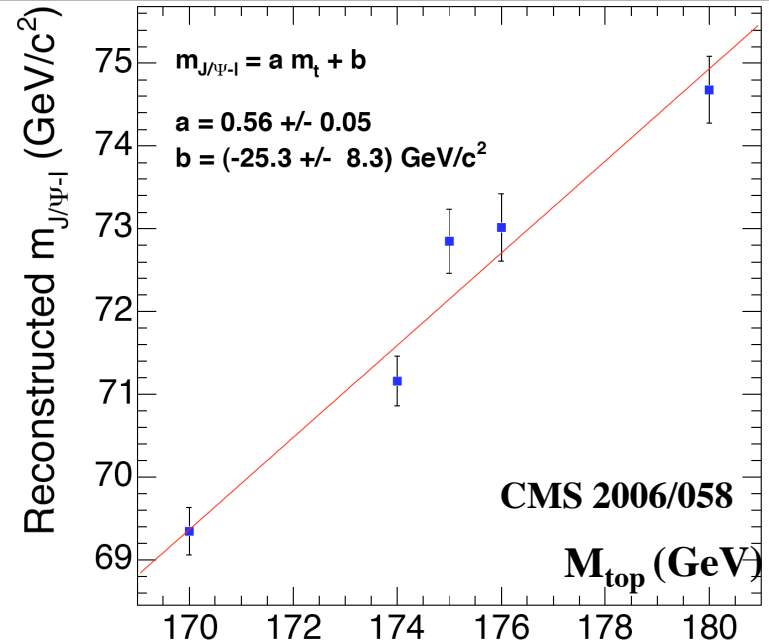
Forward-backward Asymmetry in γ*/Z decay
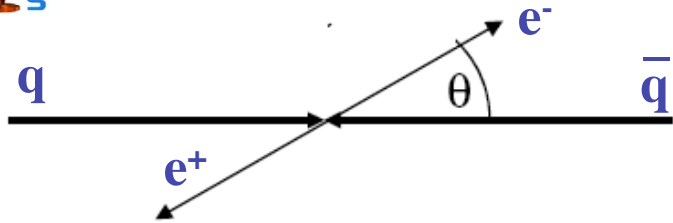
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta} = \left[\frac{3}{8}(1+\cos^2\theta) + A_{FB}(s)\cos\theta\right]$$

- **Parity violation in neutral current --> asymmetry in the angular distribution of leptons**

$$A_{FB}(s) = \frac{1}{\sigma}[\sigma(\cos\theta > 0) - \sigma(\cos\theta < 0)]$$

- **$A_{FB}(s)$ depends on $g_V^{q,l}$, $g_A^{q,l}$, $Q_{q,l}$**

  --> probes V-A
  extraction weak mixing angle $\sin^2\theta$
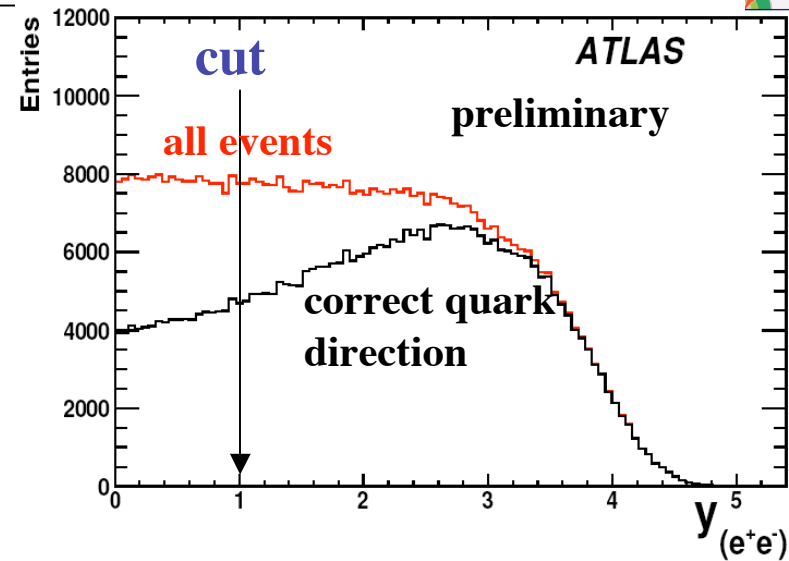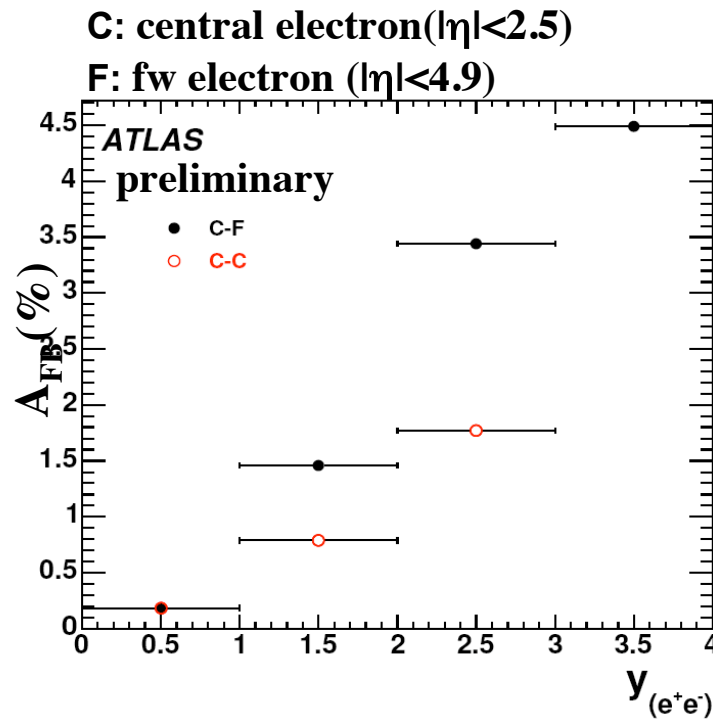
- **Exchange of new particles would alter A_{FB}**

- **@ TeVatron : statistics dominated.**
  Major uncertainties : PDF, detector resolution

Forward-backward Asymmetry in Z decay@LHC

• **@ LHC : the quark direction is not known**
--> take the Z direction
cut on Y_Z improves this assumption

C: central electron($|\eta|$<2.5)
F: fw electron ($|\eta|$<4.9)

☀ **Forward electron identification important !!**
($\varepsilon_{fw\ ele} \sim 50\%$ R_{ject} = 100 --> ΔA_{FB}(stat) = 1.5 10^{-4})

• **Electron channel favoured wrt to μ channel**
due to higher angular acceptance
($|\eta|$ < 4.9)

• **Extraction of weak mixing angle $\sin^2\vartheta$ around the Z pole (85 <M_{ee}< 97 GeV) :**

$$A_{FB} = b \{ a - \sin^2\vartheta_{eff}^{lept} \}$$ **with a and b from MC** (a = 0.23±0.03   b = 1.8 ±0.3)

ATLAS preliminary : 100 fb^{-1}

Uncertainties	$\delta \sin^2_{eff}$
Energy scale	1.5×10^{-5}
Reco. Efficiency	1.9×10^{-5}
Energy resolution	1.1×10^{-6}
Charge ID	1.4×10^{-5}
Bkg. subtraction	$<10^{-5}$
Theory(PDF)	2.4×10^{-4}
a and b parameters	3×10^{-5}
Statistical error	1.5×10^{-4}

Main uncertainty PDF.
Conversely can be used to constrain PDF

The weak mixing angle very well measured at LEP & SLD

3.2 σ
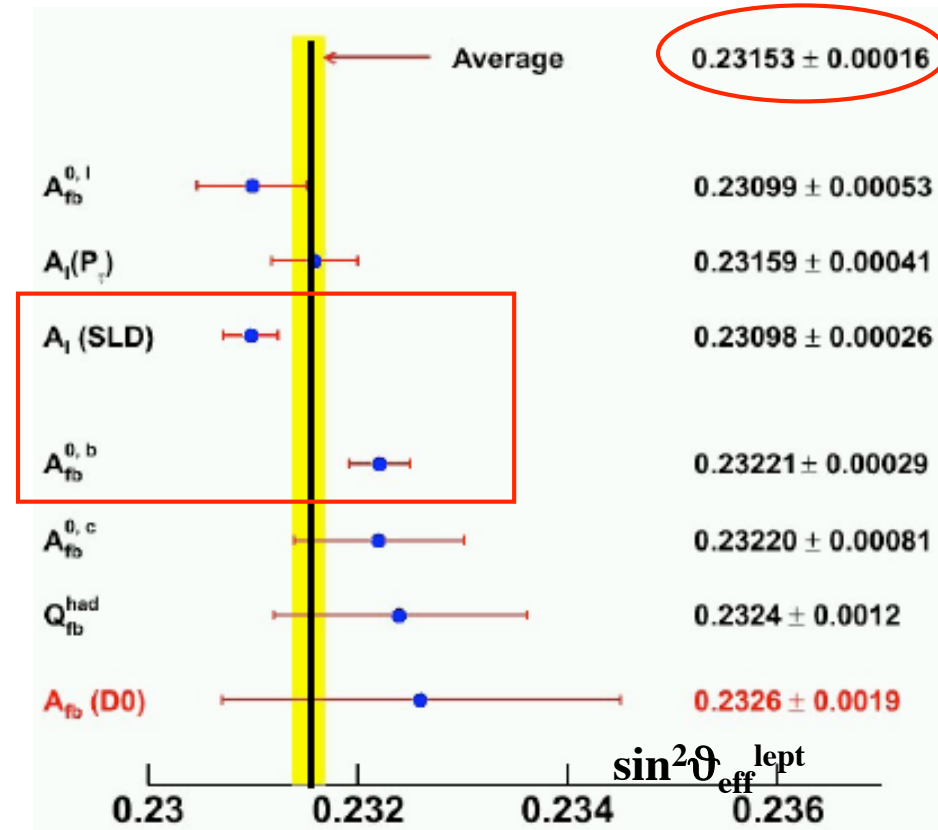
Diboson LO SM diagrams:
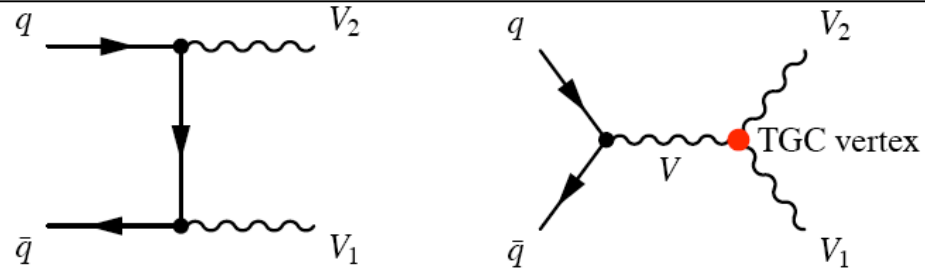
TGC = Triple Gauge Coupling = Self interaction among 3 gauge bosons (V)

- **Direct test of non-Abelian structure of SM** (**demonstrated @ LEP**) at the highest energy
- **If no Higgs found -> dibosons important in understanding EWSB**
- **Background for Higgs & New Physics**

$$q\bar{q}' \to W^{(*)} \quad \to W\gamma : WW\gamma$$
$$q\bar{q}' \to W^{(*)} \quad \to WZ : WWZ$$
$$q\bar{q} \to Z/\gamma^{(*)} \to WW : WW\gamma, WWZ$$
$$q\bar{q} \to Z/\gamma^{(*)} \to Z\gamma : \boxed{ZZ\gamma, Z\gamma\gamma}$$
$$q\bar{q} \to Z/\gamma^{(*)} \to ZZ : \boxed{ZZ\gamma, ZZZ}$$

Not permitted in SM

- **'Anomalies' appear as enhanced rates** at **high p_T^V or M_T (VV)** & changes in **angular distributions**

- **All diboson processes already measured @ TeVatron (in leptonic channels), improvements expected @ LHC:**
  1) **cross-sections a factor ~ 10 higher**
  2) **higher energy allows to explore the most favorable kinematic region**

Associated production of Gauge Bosons : WZ

$\sigma(SM)^{NLO} \approx 55$ pb

$l = e, \mu$

W

ν

q

W

q'

Z

$l^+ = e, \mu$

$l^- = e, \mu$
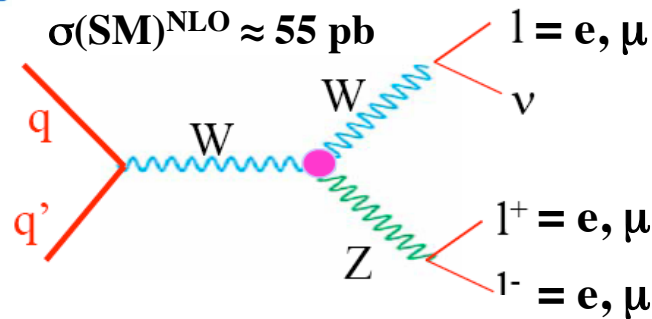
- $\epsilon_{trigger} = 98\%$

- ≥ 3 high p_T isolated leptons (e, μ) + cuts on $M_{Z\ candidate}$ and on $M_{TW\ candidate}$

- --> 300 pb^{-1}: $N_{signal}^{MC} = 34.9 \pm 0.5$

  $N_{signal} / N_{bkg} = 2.6$

- ZZ&Zγ bkg (31% of bkg)
  tt,W+jets bkg(20% of bkg) } from MC

- Data driven method to estimate
  Z+jet (main bkg) $N_{signal}^{Pseudo-data} = 33.0 \pm 3.5$

- Main syst.: lumi (10%), M_{TW} cut (10%)
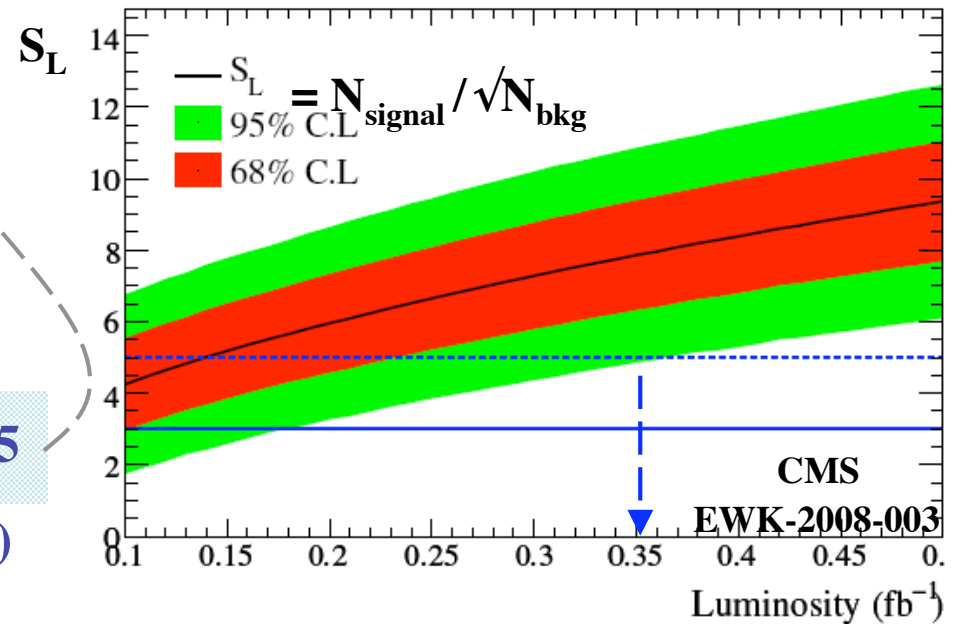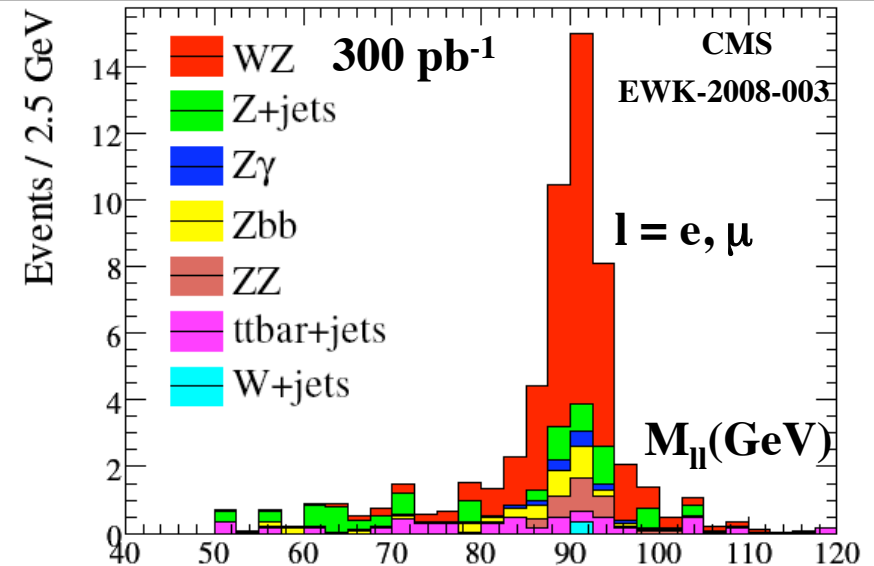
- **14 possible WWZ and WWγ couplings; usually use 5 independent, CP conserving, EM gauge invariance preserving couplings:** g_1^Z, k_γ, k_Z, λ_γ, λ_Z

- **5 'Anomalous Couplings' (AC) :**

$$\Delta g_1^Z \equiv g_1^Z - 1, \quad \Delta \kappa_\gamma \equiv \kappa_\gamma - 1, \quad \Delta \kappa_Z \equiv \kappa_Z - 1, \quad \lambda_\gamma, \quad \text{and} \quad \lambda_Z.$$

in SM : $\Delta g_1^Z = 0$, $\Delta k_\gamma = \Delta k_Z = 0$, $\lambda_\gamma = \lambda_Z = 0$

λ_V grow as $\hat{s}$ ($\equiv$ invariant diboson mass) --> enhanced sensitivity @ LHC

WW more sensitive to Δk_V (grows as $\hat{s}$) than **WZ & Wγ** (grows as $\sqrt{\hat{s}}$)

WZ more sensitive to Δg_1^Z than **WW** --> complementarity

- **To avoid unitarity violation @ high energy --> introduce a cutoff scale Λ**
  replacing $\alpha \to \dfrac{\alpha}{(1 + \hat{s}/\Lambda^2)^{\mathbf{n}}}$ **n = 2** ($\alpha \equiv \Delta g_1^Z$, $\Delta k_{\gamma/Z}$, $\lambda_{\gamma/Z}$)
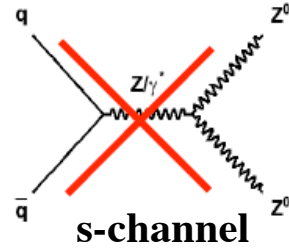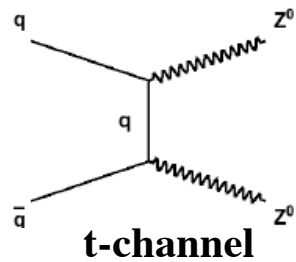
- **To extract AC :**
  fits to total cross-sections and differential distributions (i.e. E_T^γ, p_T^Z, M_T^{VV}, sensitivity at high values)

⚠ **Angular distribution have additional resolving power - not used here**

Neutral TGC

$$V = Z,\gamma$$

t-channel   **s-channel**

$$L = -\frac{e}{M_Z^2}[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta].$$

- **Unitarity :** $f_i^V \to \dfrac{f_i^V(\hat{s})}{(1+\hat{s}/\Lambda^2)^3}$ $i=4,5$

ZZ : $\sigma^{NLO}(SM) \sim 20$ pb [t-channel, s-channel suppressed $O(10^{-4})$]
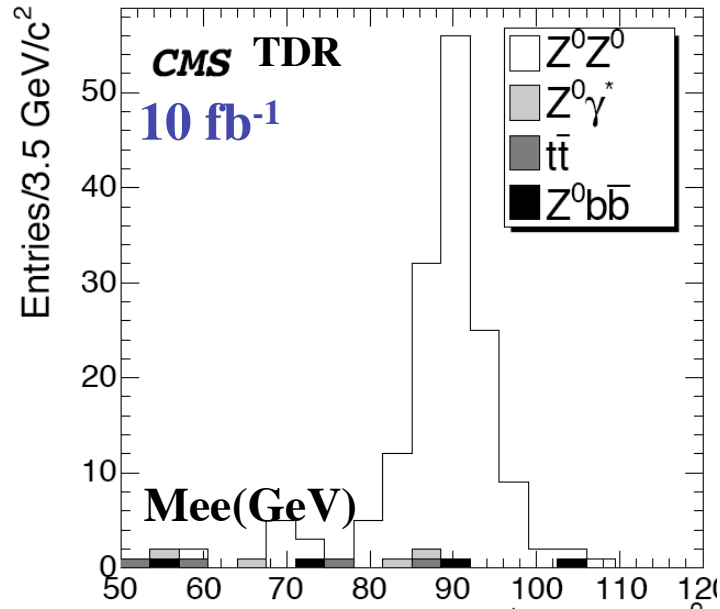
ZZ : clean signal: 4 isolated leptons

ATLAS (1 fb^{-1})

$N_{sig} = 17\pm0.5$
$N_{bkg} = 2\pm0.2$
$\varepsilon = 7.7\%$
$S = 6.8$

⚠ **'irreducible' bkg for H->4l**

- **@LHC with 0.1 fb⁻¹ and 20% systematic uncertainties, SM signal of WW, WZ, Wγ, Zγ established with significance S (=N/√B) better than 5σ (1 fb⁻¹ for ZZ)**

- **Systematics (lumi, ε_{lept}, PDF, factorization scale) will start to dominate the cross-sections uncertainties from 5-30 fb⁻¹**

- **95% CL limit on AC (Λ=2 TeV) 10 fb⁻¹ (~ 10 x better than present CDF 2 fb⁻¹)**

Diboson,	λ_Z	$\Delta\kappa_Z$	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ
WZ, (M_T)	[−0.015, 0.013]		[−0.011, 0.034]		
Wγ, (p_T^γ)					[−0.05, 0.02]
WW, (M_T)		[−0.035, 0.073]		[−0.088, 0.089]	
WW, (LEP)			[−0.051,0.034]	[−0.105,0.069]	[−0.059,0.026]

- **95% CL limit on AC (Λ=2 TeV) 10 fb⁻¹**

	f_4^Z	f_5^Z	f_4^γ	f_5^γ
$ZZ \to \ell\ell\ell\ell$ + $ZZ \to \ell\ell\nu\nu$	[−0.009, 0.009]	[−0.009, 0.009]	[−0.010, 0.010]	[−0.011, 0.010]
LEP Limit	[−0.30, 0.30]	[−0.34, 0.38]	[−0.17, 0.19]	[−0.32, 0.36]

LHC improves wrt TeVatron and LEP

Conclusions

- **LHC will be a W, Z, top factory. LHC goals:**
  - $\Delta M_W < 10$ MeV ⎫
  - $\Delta M_{top} < 1$ GeV ⎬ **SM M_H constraint to < 15%**
  - $\Delta \sin^2\vartheta_{eff}^{lept} \approx 10^{-4}$

- **EW dibosons signals are expected to be established @ ATLAS & CMS with ~ 100 pb^{-1} to 1 fb^{-1}**

- **Anomalous Gauge boson Couplings improved with $\approx$ 10 fb^{-1} data**

  ┌───┐
  │ **Main issues: understand detector response, measure soft QCD** │
  └───┘

❖ **Even after finding a Higgs signal, (precision)EW measurements important:**
  * A Higgs is not necessarily a SM Higgs --> indirect constraints will help interpretation

❖ **Ultimately understanding systematics will be our main concern. This will come from data driven method and especially from the use of independent analysis methods**

      --> LHC will play a major role in establishing a coherent picture of the (EW) theory

Altarelli '2008

Fit results Here only m_W and not m_t is used: shows m_t from rad. corr.s March '08

	only m_W	only m_t	m_W, m_t
m_t(GeV)	178.7+12-9	172.6±1.4	172.8±1.4
m_H(GeV)	143+236-80	111+56-39	87+36-27
$\log[m_H$(GeV)]	2.16±0.39	2.05 ± 0.18	1.94± 0.16
$\alpha_s(m_Z)$	0.1190(28)	0.1190 (27)	0.1185 (26)
χ^2/dof	16.8/12	16.0/11	17.2/13
m_W(MeV)	80385(19)	80363(20)	80377(15)

WA: m_W=80398(25)

Rad. corr.'s predict m_t and m_W very well. May be also m_H!
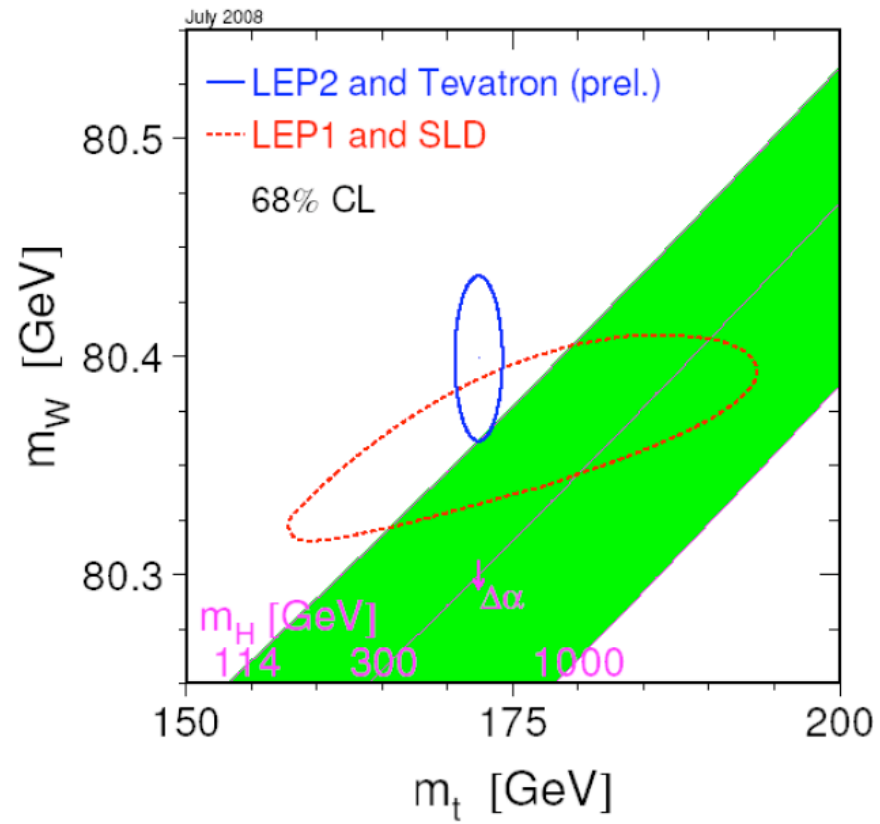
Mass of W boson : longer term perspectives

**10 fb⁻¹ :** Systematics on the result of the method based on p_T^{lep} (1 experiment)

Source	effect	δm_W (MeV)
Theoretical model	Γ_W	0.5
	y_W	1
	p_{tW}	3
	QED radiation	<1
Lepton measurement	linearity and scale	4
	resolution	1
	efficiency	4.5 (e); <1 (μ)
Backgrounds	$W \to \tau\nu$	2.0
	$Z \to I (I)$	0.3
	$Z \to \tau\tau$	0.1
	jet events	0.5
Pile-up and UE		<1 (e); ~0 (μ)
Beam crossing angle		<0.1
total		**~7(e); 6(μ)**

N.Besson et al. : SN-ATLAS-2008-70

- For equal contribution to M_H (indirect) uncertainty :

if ΔM_W < 10 MeV --> ΔM_{top} < 1.5 GeV

Anomalous Quartic Couplings

- **Signature : three bosons in the final state**
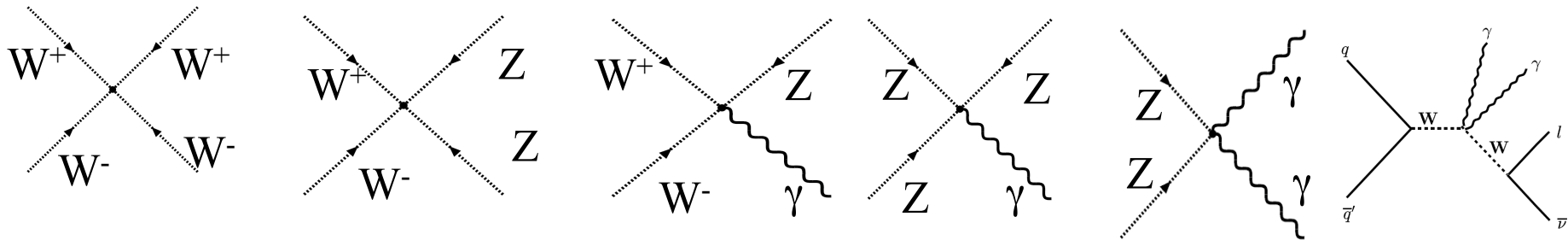
- **Small yields, not an early measurement :**

  SM: 100 fb^{-1} in leptonic channels
  (p_T> 20 GeV, |η|< 3) hep-ph/0003275

M_{Higgs} (GeV)	200	400	600	800
$W^+W^-W^-$	68	28	25	25
$W^+W^+W^-$	112	49	44	44
W^+W^-Z	32	17	15	15
W^-ZZ	1.0	0.51	0.46	0.45
W^+ZZ	1.7	0.88	0.79	0.79
ZZZ	0.62	0.18	0.13	0.12

--> limits on AQC probably difficult

- **Useful cross-check:**
  if something new seen in the trilinears, one might need the quartics to sort things out.