Physics at hadron collider with Atlas

2nd lecture

Simonetta Gentile

Università di Roma La Sapienza, INFN

on behalf of Atlas Collaboration

Outline

- Introduction to Hadron Collider Physics
- LHC and ATLAS detector
- Test of Standard Model at LHC
- Parton distribution function
- QCD + jet physics
- **Electroweak physics (Z/W –bosons)**
- **Top physics**
- Search for Higgs boson
- Supersymmetry
- Conclusions

1st **2nd** **3rd** **4th**

Cross Section of Various SM Processes

The LHC uniquely combines the two most important virtues of HEP experiments:

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

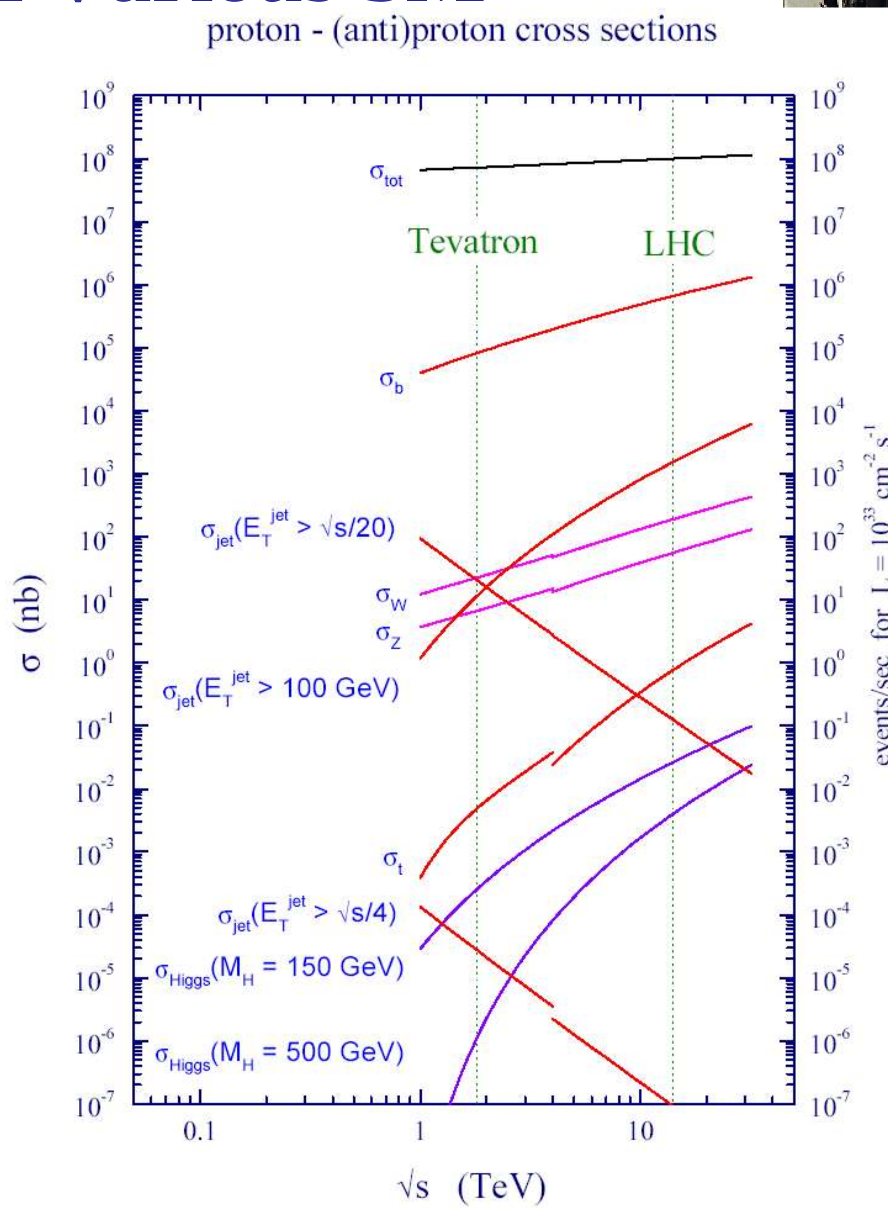
$\Rightarrow$ Low luminosity phase

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

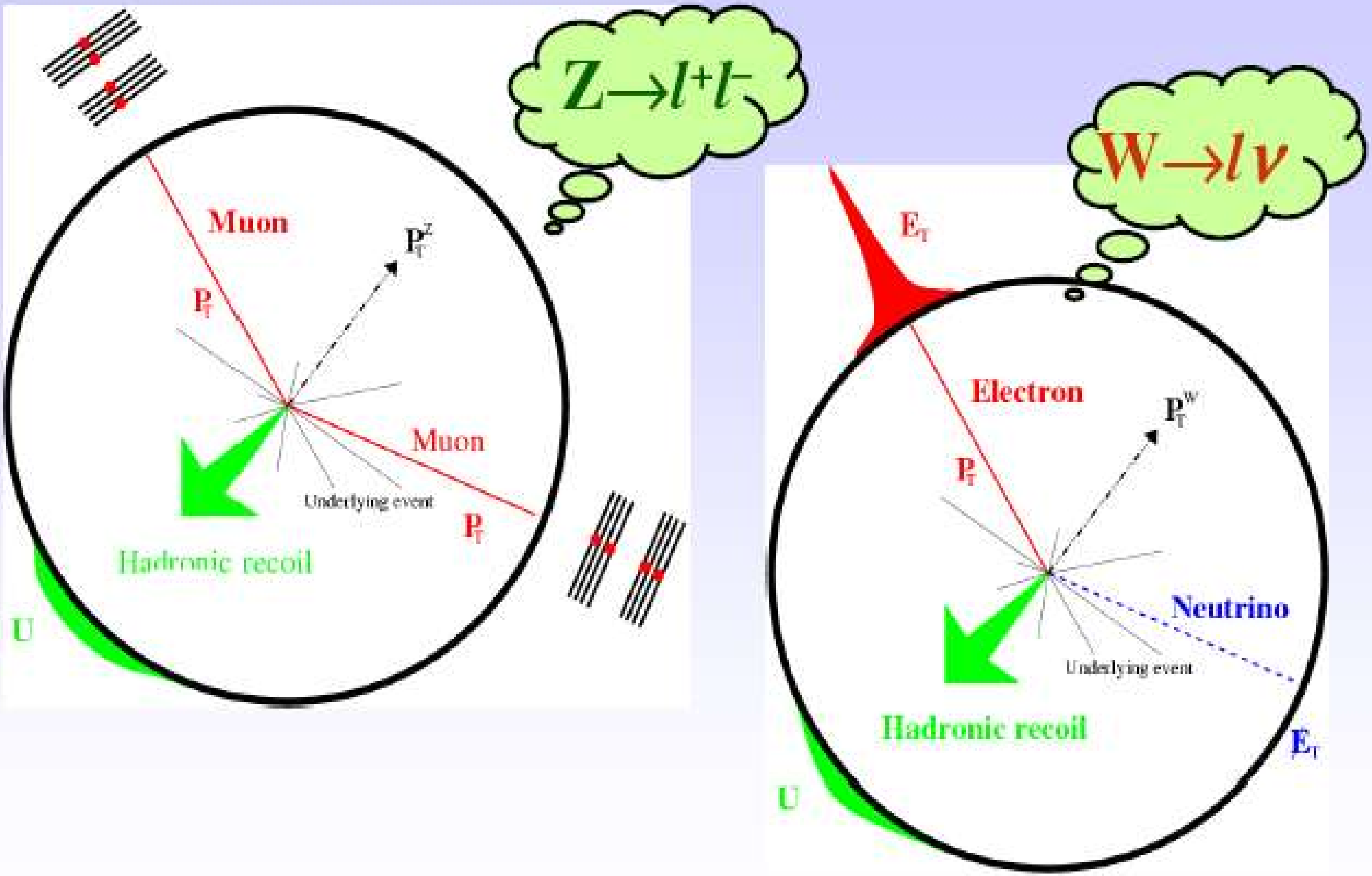
approximately

- 200 W-bosons
- 50 Z-bosons
- 1 tt-pair

will be produced per second!



Signature of Z and W decays



K.Jacobs

Detector performance requirements

- **Lepton measurement**: $p_T \approx$ GeV $\rightarrow$ 5 TeV
  ($b \rightarrow \ell X$, W'/Z')
- **Mass resolution** (m ~ 100 GeV) :
  $\approx$ 1 % (H $\rightarrow \gamma\gamma$, 4ℓ)
  $\approx$ 10 % (W $\rightarrow$ jj, H $\rightarrow$ bb)
- **Calorimeter coverage** : $|\eta| < 5$
  (E_T^{miss}, forward jet tag)
- **Particle identification** : e, γ, τ, b

Three crucial parameters for precise measurements

- **Absolute luminosity** : **goal < 5%**

  Main tools: machine, optical theorem, rate of known processes (W, Z, QED pp → pp ℓℓ)

- **ℓ energy scale** : goal **1‰** most cases

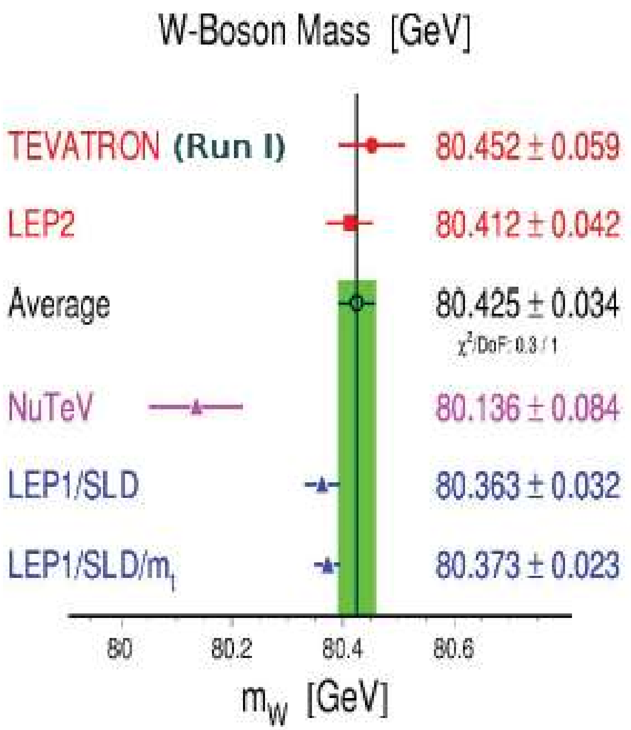
  0.2‰ W mass

  Main tool: large statistics of **Z → ℓℓ** (close to m_W , m_H)

- **jet energy scale**: goal **1%** (m_{top}, SUSY)

  Main tools: Z+1jet (Z → ℓℓ) , **W → jj** from top decay

LEP



New published OPAL: M_W=80.415±0.052 (preliminary error was 67 MeV)

Analysis in progress at Tevatron Run II: $M_{W,}$ Br(W→τ)

M_w is an important parameter in precison test of SM

- **M_W=80.425 ± 0.034 GeV**.
- 2007 M_w 80…± 20 MeV (Tevatron Run II)

2.9σ

Improvement at LHC requires Control systematic better 10^{-4} level

W mass measurements motivation

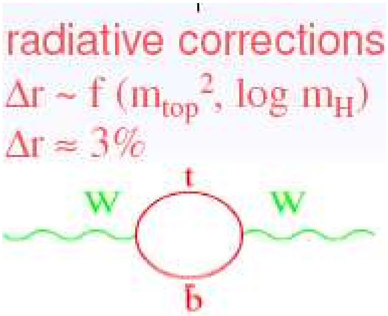
- m_w m_t are fundamental parameters of Standard Model; there are well defined relations between m_w,m_t,m_H.

Dependance on top and Higgs mass via loop corrections

$$M_W^2 = \frac{\pi\cdot\alpha}{\sqrt{2}\cdot G_F}\cdot\frac{1}{\sin^2\theta_W\cdot(1-r)}$$

$$r \approx m_t^2$$

$$r \approx \log M_H$$

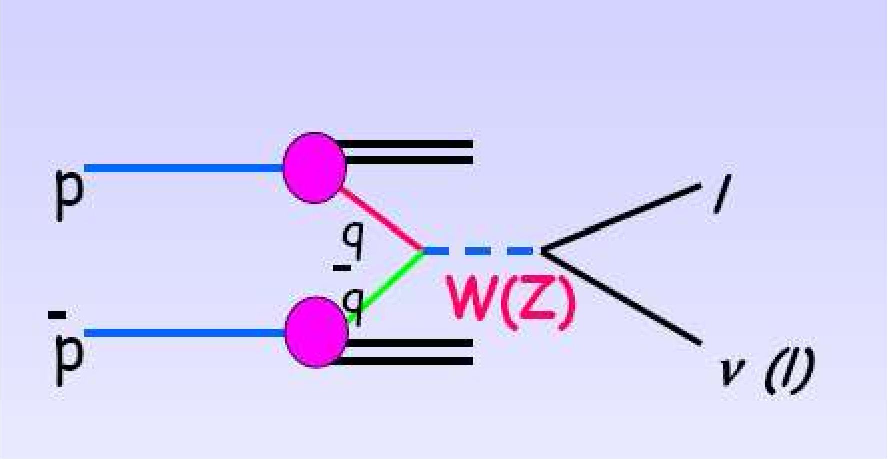


- α electromagnetic constant Measured in atomic transitions, e+e- machines
- G_F Fermi constant measured in muon decay
- S in θ w measured at LEP/SLC
- **Δ r radiative corrections**

- G_F, α, sin θ_w are known with high precision precise measurements of W mass an top-quark mass constrains Higgs boson mass

- To match precision of top mass measurement of 2 GeV: M_W=15 MeV
  $\Delta m_W \sim 0.7 \times 10^{-2}\, \Delta m_t$

W production process



~ 50 times larger statistics than at Tevatron

~ 6000 times larger statistics than at LEP

$$\sigma\,(pp \to W + X) \approx 30\ \text{nb}$$

$W \to e\nu,\ \mu\nu$

~ 300×10^6 events produced	}	one year at low $\mathcal{L}$, per experiment
~ 60×10^6 events selected after analysis cuts		

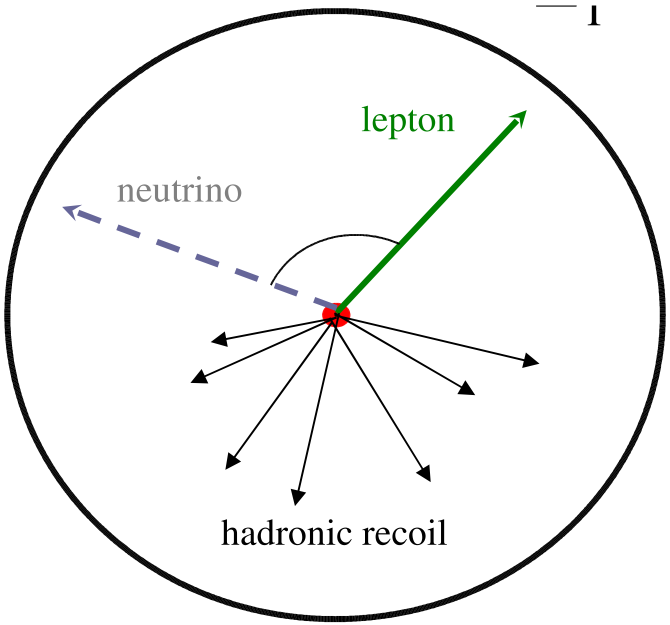
Method of mass measurements

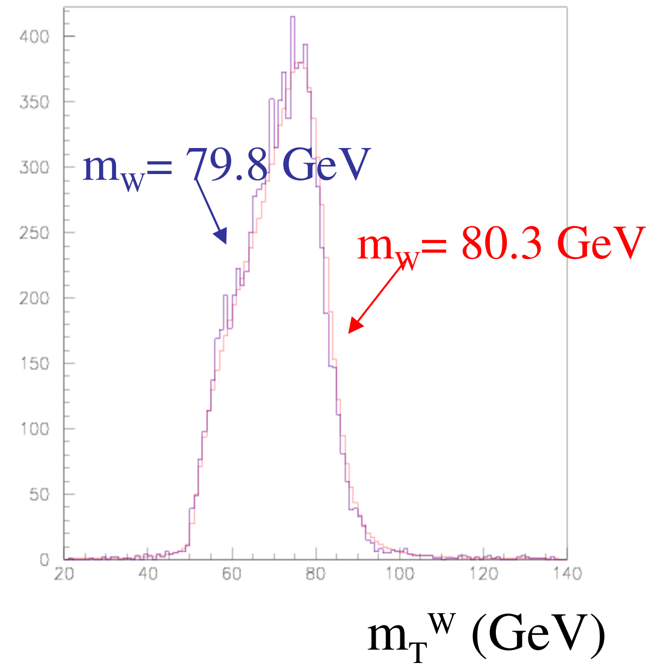
Since p_L^ν not known (only p_T^ν can be measured through E_T^{miss}), measure **transverse mass**, i.e. invariant of $\ell\nu$ perpendicular to the beam :

$$m_T^W = \sqrt{p_T p_T (1-\cos)}$$

m_T^W distribution is sensitive to m_W

$$P_T( ) = -(P_T(e) + P_T(had))$$





⇒ fit experimental distributions with SM prediction (Monte Carlo simulation) for different values of m_W → find m_W which best fits data

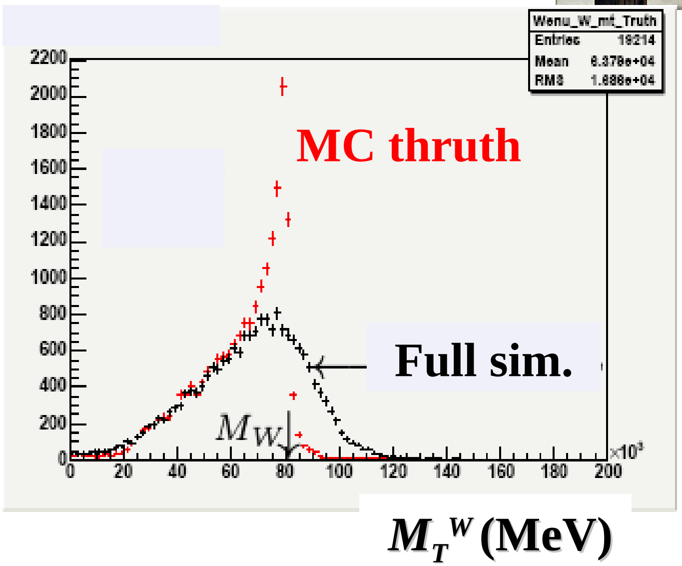
W mass

$$M_T^W = \sqrt{2\, p_T^l\, p_T \qquad (1-\cos \qquad\qquad _{l\nu})}$$

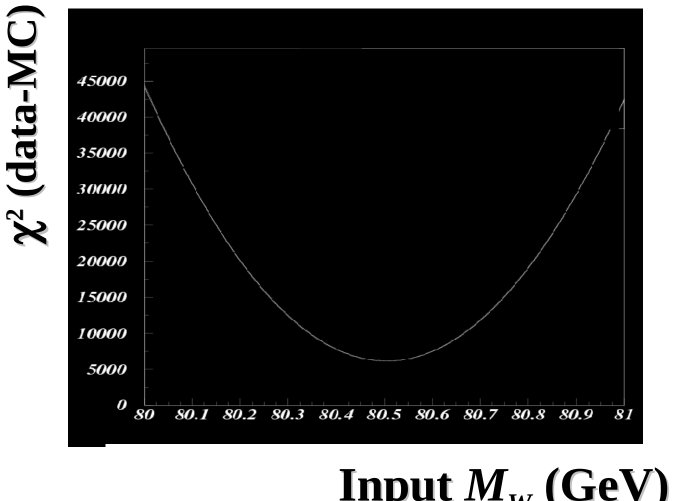
Estimated with W recoil

- Isolated lepton P_T>25 GeV
- E_T^{miss}>25 GeV
- No high pt jet E_T<20 GeV
- W recoil < 20 GeV

➔ Sensitivity to M_W through falling edge



➔ Compare data with Z⁰ tuned MC samples where input M_W varies in [80-81] GeV by 1 MeV steps



➔ Minimize χ^2(data-MC): 2 MeV statistical precision

W mass

➢Uncertainties

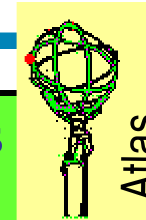
Come mainly from capability of Monte Carlo prediction to reproduce real life:

- detector performance: energy resolution, energy scale, etc.
- physics: p_T^W, θ_W,, backgrounds, etc.

Dominant error (today at Tevatron, most likely also at LHC): knowledge of lepton energy scale of the detector: if measurement of lepton energy wrong by 1%, then measured m_W wrong by 1%

➢Trailing edge of distribution is sensitive to *W*-mass
Detector resolution smears the trailing edge of m_T distribution

M_W



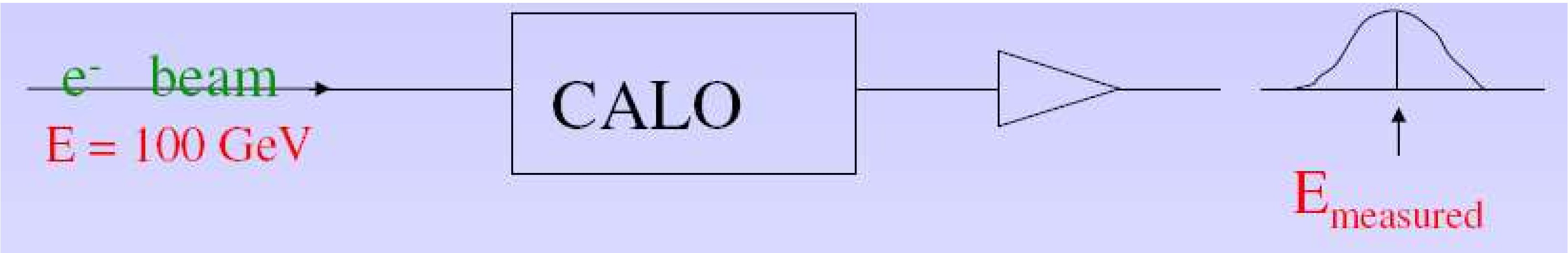
Source	CDF,runI b PRD64,052001	ATLAS 10 fb^{-1}	Comments
Lepton $E,_p$ scale	75	15*	B at 0.1%, align. 1μm, tracker material to 1%
PDF	15	10*	
Rad. decays	11	<10	Improved theory calc.
W width	10	7	$\Delta\Gamma_W$=30 MeV (Run II)
Recoil model	37	5*	Scales with Z stat
p_T^W	15	5*	Use p_T^Z as reference
Background	5	5	
E resolution	25	5*	
Pile-up, UE	-	??*	Measured in Z events
Stat⊕syst	113	< 25	W→e ν
TOTAL	89	< 20	W→e ν + W→μ ν

Most serious challenge

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

$\Rightarrow \Delta m_W \leq 15$ MeV

Calibration of the detector energy scale



•$E_{measured}$ = 100.000 GeV for all calorimeter cells → perfect calibration

•To mesaure M_w to ~ 20 MeV need a enegy scale to 0.2 ‰, (E_{electr} = 100 GeV then 99.98 GeV < $E_{measured}$ < 100.02 GeV)

Calibrations strategy.

- Calorimeter modules are calibrated with test beam of known energy
- In Atlas calorimeter sits behind Inner Detector:
  - electrons lose energy in material in front of calorimeter (inner detector)

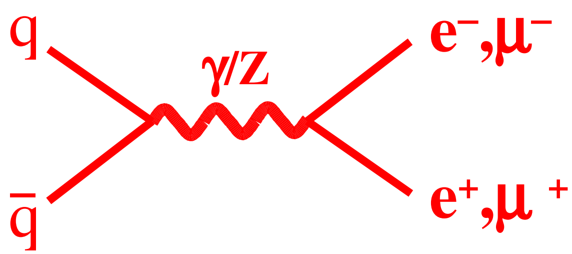
→ calibration "in situ" using physics sample

$Z \rightarrow e^+e^-$ with the constrain $m_{ee} = m_Z$

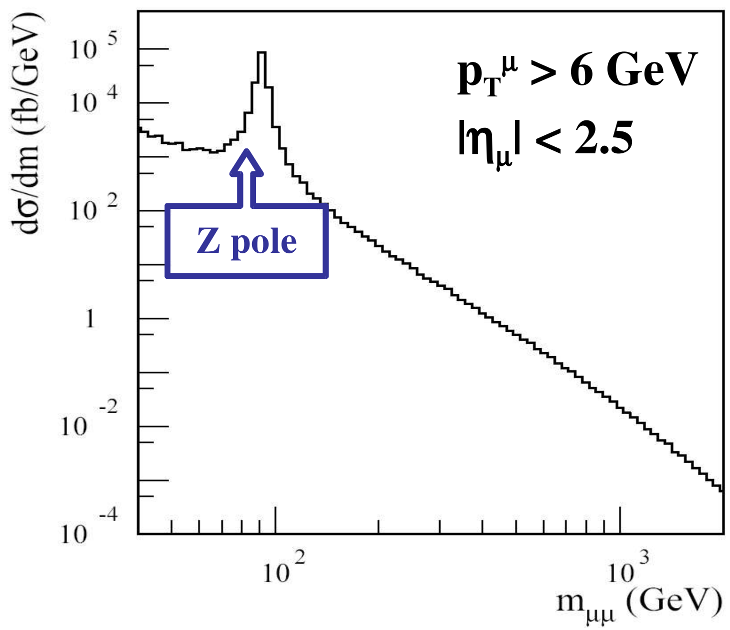
known to ≈ 10^{-5}

- same strategy for muon spectrometer, using $Z \rightarrow \mu^+\mu^-$

Drell-Yan Lepton-Pair Production



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



- **Total cross section**

  pdf

  search for Z′, extra dim. , ...

Much higher mass reach as compared to Tevatron

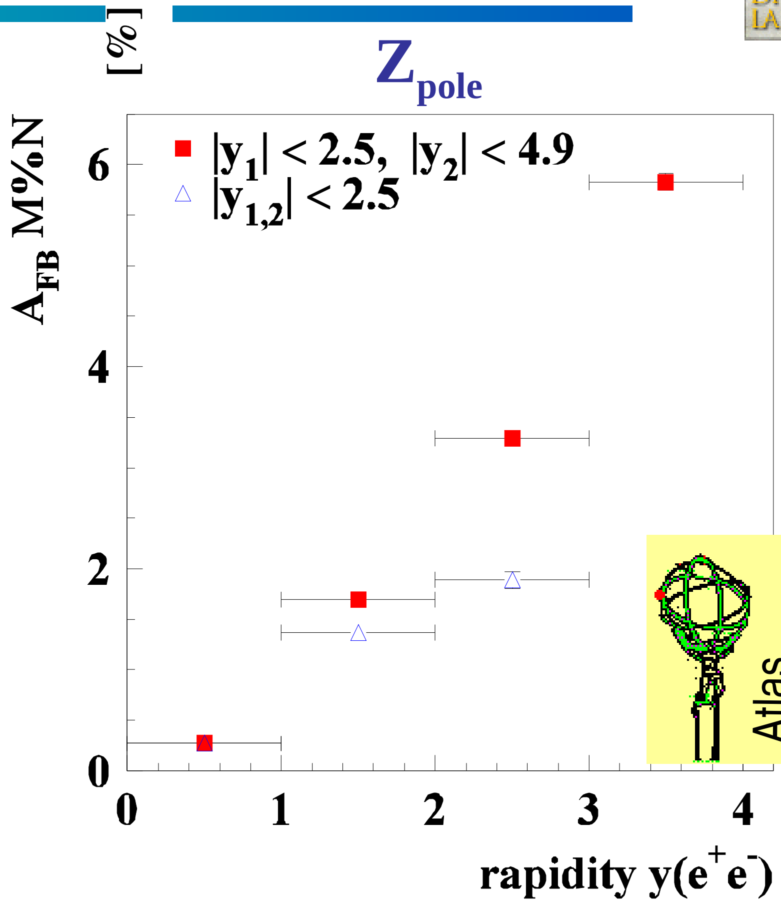
Drell-Yan Lepton-Pair Production

- Forward-backward asymmetry
  estimate quark direction
  assuming $x_q > x_{\bar{q}}$
- Measurement of $\sin^2\vartheta_W$ effective
  - 2005: LEP & SLD

    $\sin^2\vartheta_W = 0.2324 \pm 0.00012$
- A_{FB} around Z-pole
  - large cross section at the LHC

    $\sigma(Z \rightarrow e^+e^-) \approx 1.5$ 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



Asymmetry → $\sin^2\vartheta_W$

Controlled at required level
For the significance of measurement

Di - Boson production

Measuring Triple Gauge Couplings (TGC) & Testing gauge boson self couplings to SM

- **WWγ WWZ vertices exist**

→ 5 parameters:

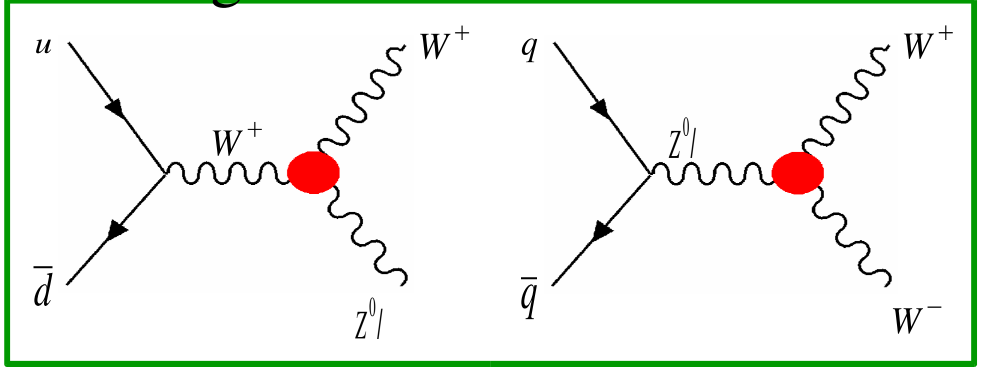
in SM $g^1_Z, k_\gamma, k_Z = 1; \lambda_\gamma, \lambda_Z = 0$

- **ZZγ , ZZZ do NOT exist in SM:**

12 couplings parameters

h_i^V, f_i^V (V=γ,Z)

Charged & Neutral TGS's



- Some anomalous contributions (λ-type) increase with s → high sensitivity at LHC
- Sensitivity from :

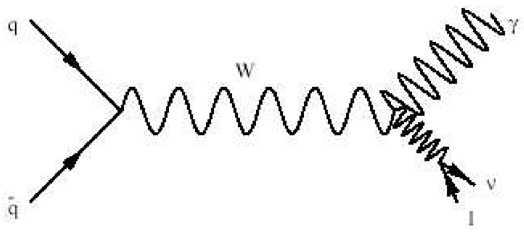
  -- cross-section (mainly λ-type) and p_T measurements

  -- angular distributions (mainly k-type)

WWγ Couplings

Charged TGS's

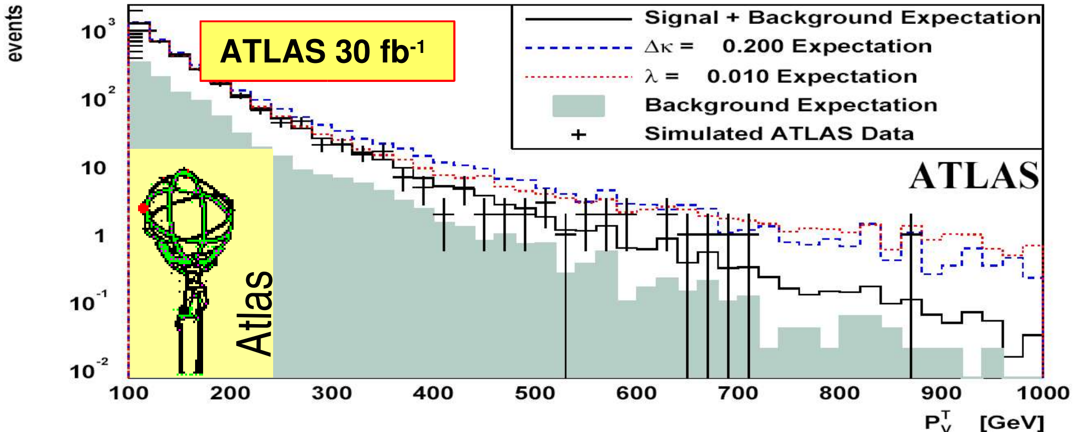
Test CP conserving anomalous couplings at the WWγ vertex Δκ and λ



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

Wγ

Sensitivity to anomalous couplings from high end of the p_T spectrum

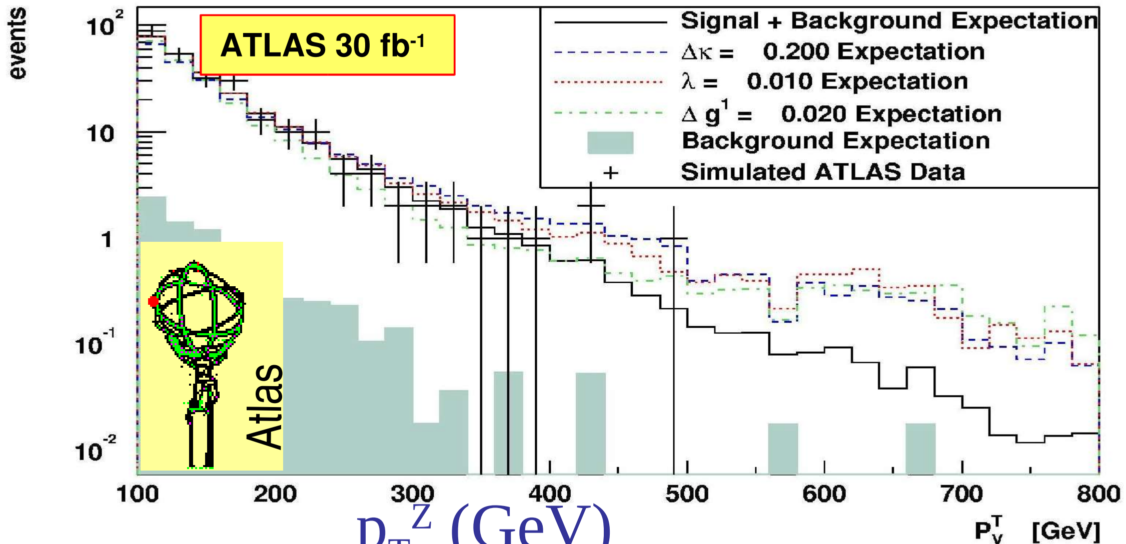


p_T^γ (GeV)

Simonetta Gentile
Gomel School of Physics 2005

ZZγ Couplings

- P_T^Z distribution



p_T^Z (GeV)

WZ

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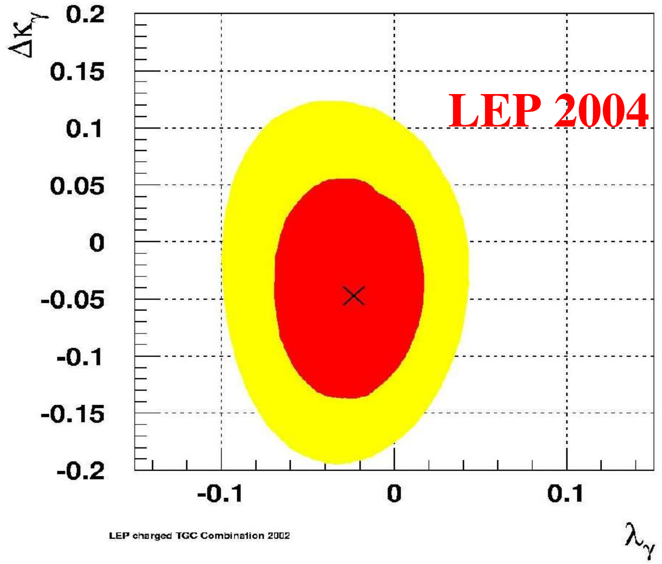
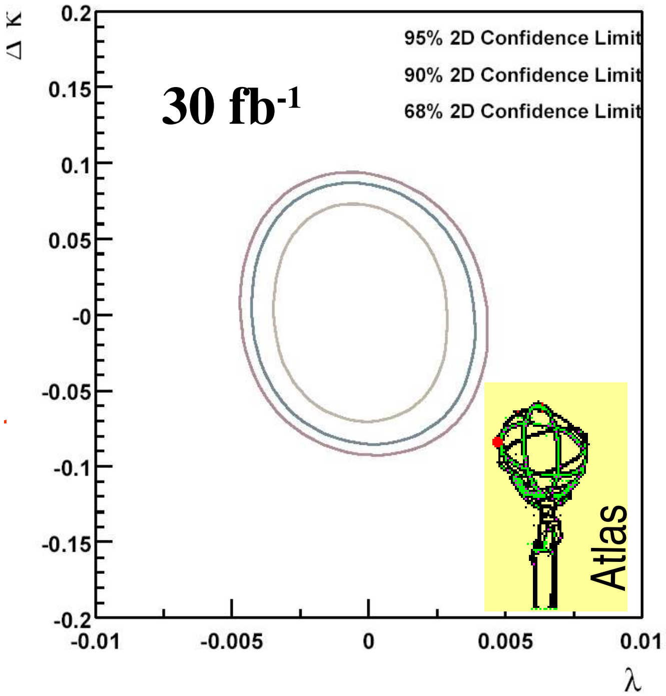
Sensitivity to WWγ Couplings

Charged TGS's





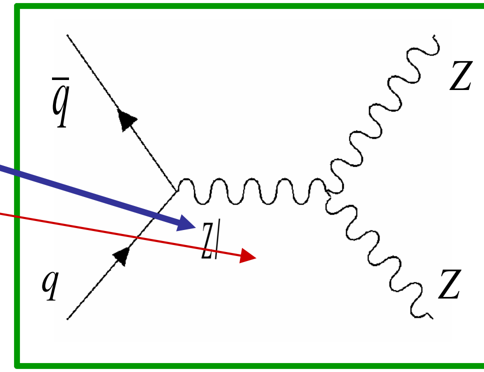
- At LHC limits depend on energy scale .
- Large improvement wrt LEP

  in particular on λ due to higher energy

Triple Gauge Couplings

Neutral TGS's

- **ZZZ vertex doesn't exist in SM**
- **γZZ vertex does exist in SM**



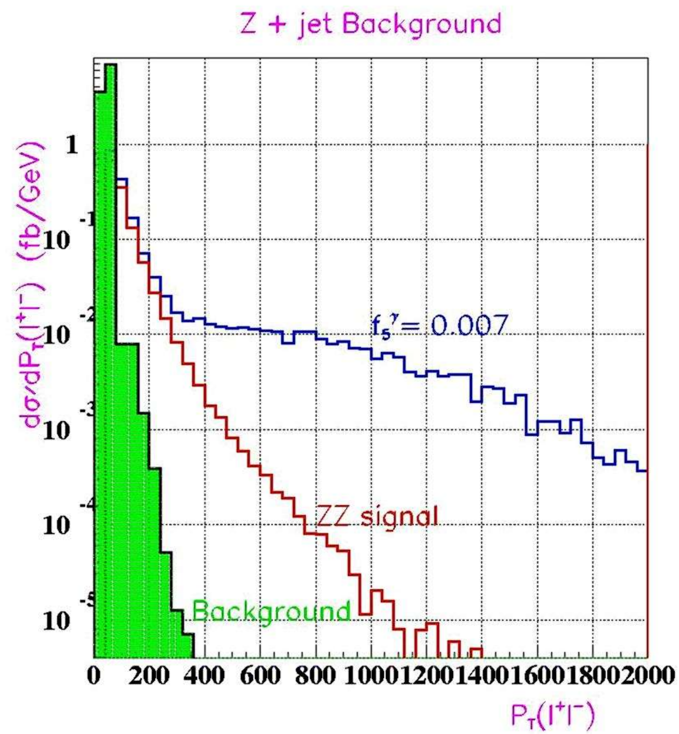
Analysis: search for ZZ → 4 leptons ($e^{\pm}$, $\mu^{\pm}$)

Main background

- real ZZ events (=12pb)
- Z+jet

Sensitivity: ~7·10^{-4}

(100fb^{-1} and $_{FF}$=6 TeV)

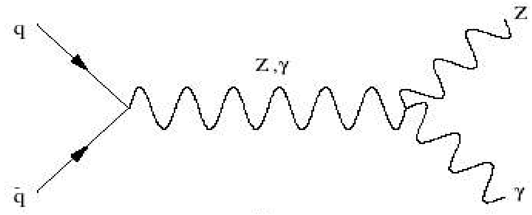


ZZγ Couplings

Neutral TGS's

Example: Couplings at the ZZγ vertex h_i^{γ}

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

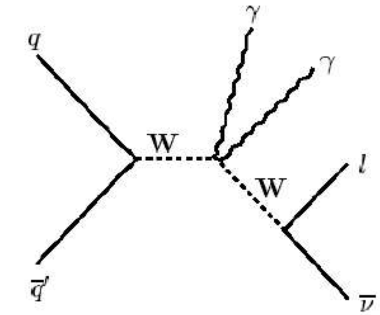


Zγ

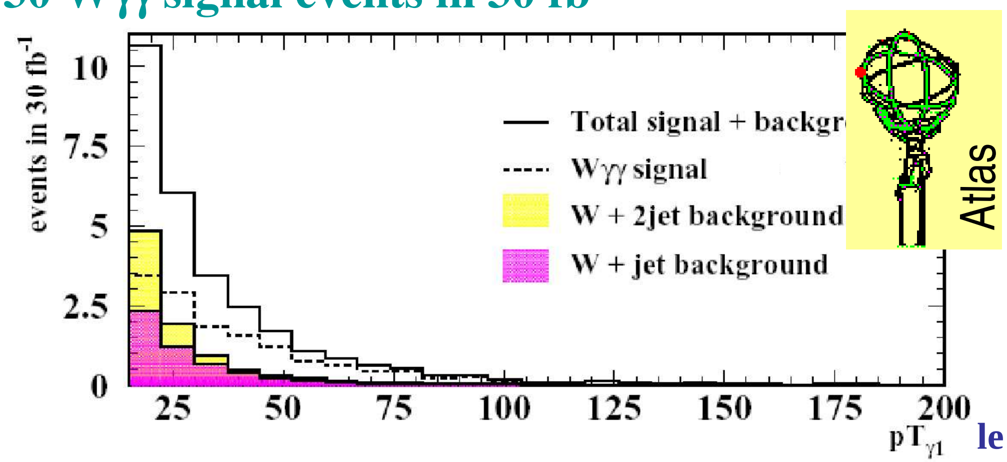
Triple-Boson Production

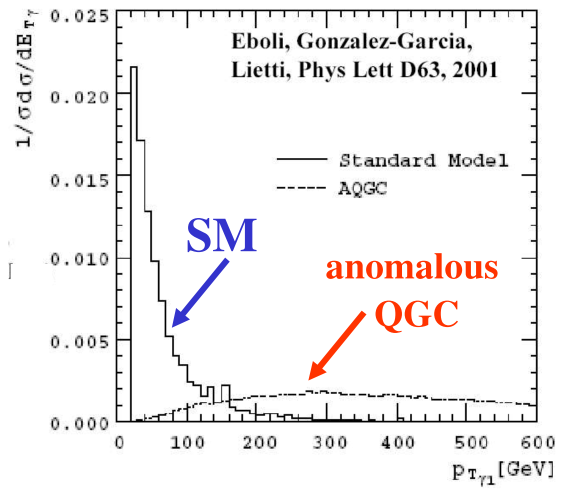
Events for 100 fb^{-1} (m_H = 200 GeV)	Produced (no cuts,no BR)	Selected (leptons, p_T>20 GeV, $\|\eta\|$ < 3)
$pp \to WWW$ (3 ν´s)	31925	180
$pp \to WWZ$ (2 ν´s)	20915	32
$pp \to ZZW$	6378	2.7
$pp \to ZZZ$	4883	0.6
$pp \to W\gamma\gamma$	best channel for analysis	

Sensitive to quartic gauge boson couplings (QGC)



30 Wγγ signal events in 30 fb^{-1}





Triple gauge couplings

- **SM allowed charged TGC in WZ, Wγ with 30 fb^{-1}**
  - ≥1000 WZ (Wγ) selected with S/B = 17 (2)
  - 5 parameters for anomalous contributions

  scale with $\sqrt{\hat{s}}$ for g_1^Z,**k**s and $\hat{s}$ for **λ**s
  - Measurements still dominated by statistics, but improve LEP/Tevatron results by ~2-10

- **in SM $g_1^Z, k_\gamma, k_Z = 1; \lambda_\gamma, \lambda_Z = 0$**

	ATLAS 95% CL (±stat ±syst)
Δg_1^Z	± 0.010 ± 0.006
$\Delta\kappa_Z$	± 0.12 ± 0.02
λ_Z	± 0.007 ± 0.003
$\Delta\kappa_\gamma$	± 0.07 ± 0.01
λ_γ	± 0.003 ± 0.001

- **SM forbidden neutral TGC in ZZ, Zγ with 100 fb^{-1}**
  - **12** parameters, scales with $\hat{s}^{3/2}$ or $\hat{s}^{5/2}$
  - Measurements completely dominated by statistics, but improve LEP/Tevatron limits by ~10^3-10^5

	ATLAS 95% CL stat
$f_{4,5}^{Z,\gamma}$	$7\ 10^{-4}$
$h_{1,3}^{Z,\gamma}$	$3\ 10^{-4}$
$h_{2,4}^{Z,\gamma}$	$7\ 10^{-7}$

- **Quartic Gauge boson Coupling in Wγγ can be probed with 100 fb^{-1}**

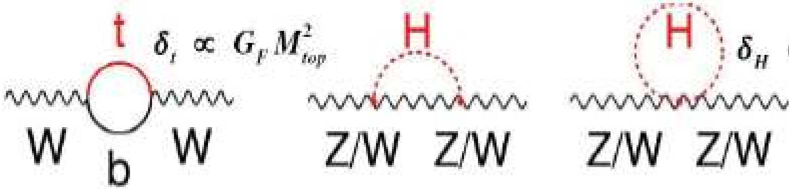
Status of SM model

- **High precision measurements→ Test of Standard Model**
- **1000 data points combined in 17 observables calculated in SM**

TOP MASS

- M_z(precision 2 10^{-5})from line-shape
- $\alpha_s(M_z)$ precision 2 10^{-2} hadronic observable

M_{top} and M_{Higgs}



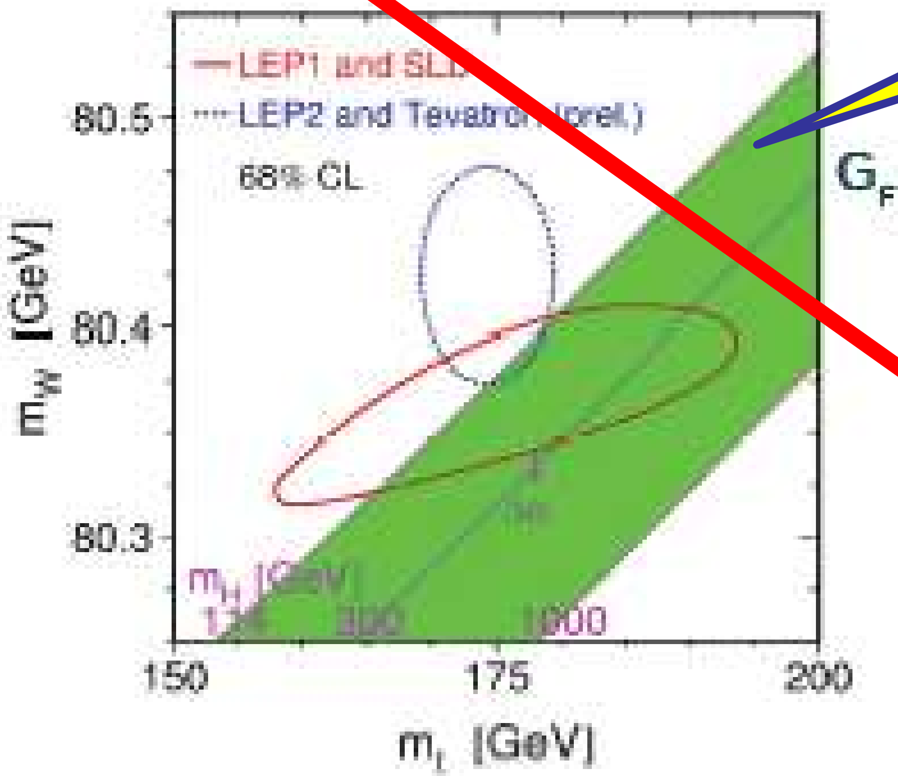
$\delta_t \propto G_F M_{top}^2$ $\delta_H \propto \ln \frac{M_{Higgs}}{M_W}$

Istituto Nazionale di Fisica Nucleare

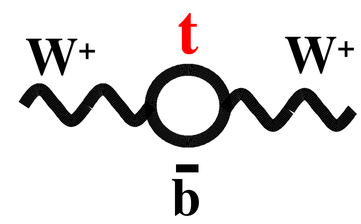
UNIVERSITÀ DEGLI STUDI DI ROMA LA SAPIENZA

Measurement of the Top Mass: Motivation

$$\frac{G_F}{\sqrt{2}} = \frac{\quad}{2}\,\frac{1}{m_W^2 \sin^2 {}_W}\,\frac{1}{1-r}$$

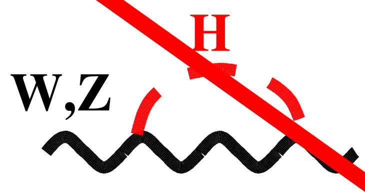


$1-\Delta r \approx (1-\Delta\alpha)(1-\Delta r_W)$



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

$\oplus$



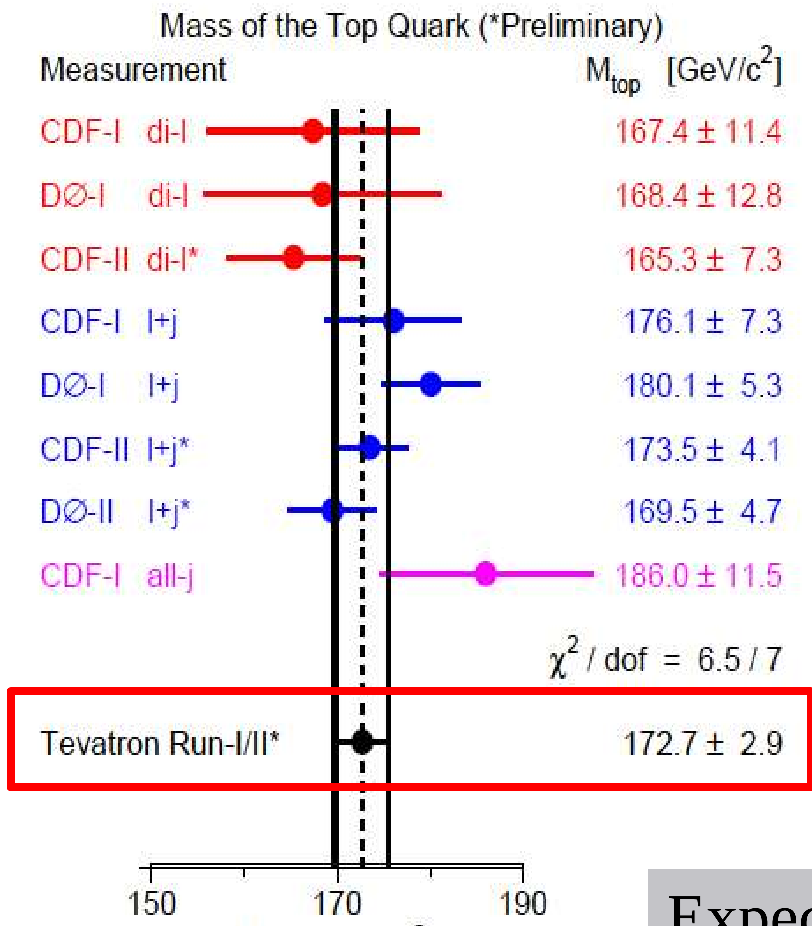
$\Delta r_W \propto \log m_H$

Top mass from Tevatron (2005) :

$$m_t = 174.3 \pm 3.4\ GeV$$

Combination of Measurements

Only best analysis from each decay mode, each experiment.

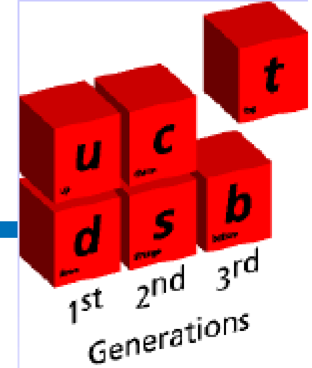


Year	M_{top} [GEV]	M_{Higgs} [GEV]
2003	174.3±5.1	< 219
2004	178.0±4.3	< 251
2005 (june)	174.3±3.4	< 208
2005 (july)	172.7±2.9	?

Expected precision in 2007 at Tevatron: ± ~1GeV

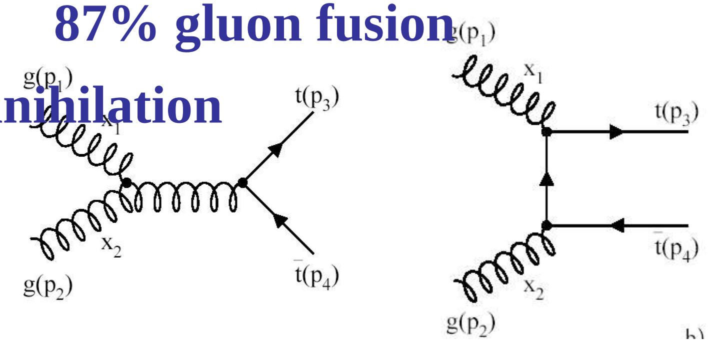
EPS95 KojiSato

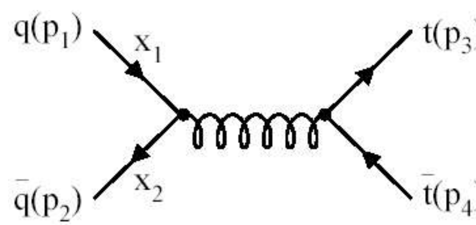
Top Physics



- $t\bar{t}$ production

  87% gluon fusion 13% quark annihilation

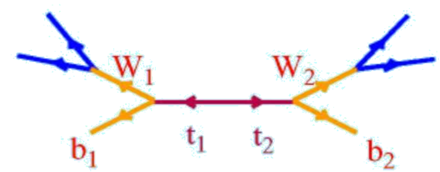




Inverse ratio of production mechanism as compared to Tevatron

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

  LHC is a top factory!

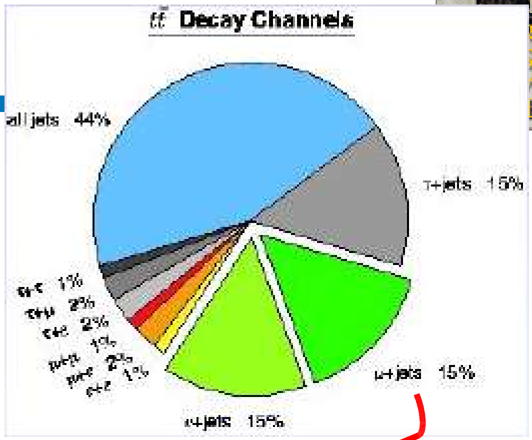


- Top decay: ≈ 100% t → bW
- Other rare SM decays:
  - CKM suppressed t → sW, dW: 10^{-3} –10^{-4} level
  - t→bWZ: O(10^{-6})

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

Top Decays

- **the tt pair cross section is ~ 600 pb**
- **Br (t→Wb) ~ 100%**
- **no top hadronization**



- Di-lepton channel

Both W's decay via W→ℓ ν (ℓ = e or μ ;5%)

- Lepton-jet channel

One W decays via W→ℓ ν (ℓ= e or μ ; 30%)

- All hadronics

Both W decay via W→ qq (44%)

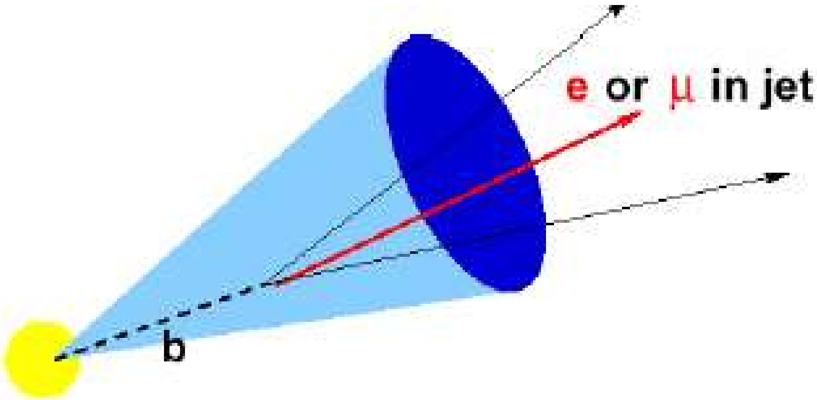
tt final states (LHC,10 fb^{-1})

- Full hadronic **(2.6M)** : 6 jets
- Semileptonic **(1.7M)** : ℓ + ν + 4jets
- Dileptonic **(0.3M)** : 2 ℓ + 2ν + 2jets

Signature: Leptons
Missing transverse energy
b-jets

Tagging b-quarks

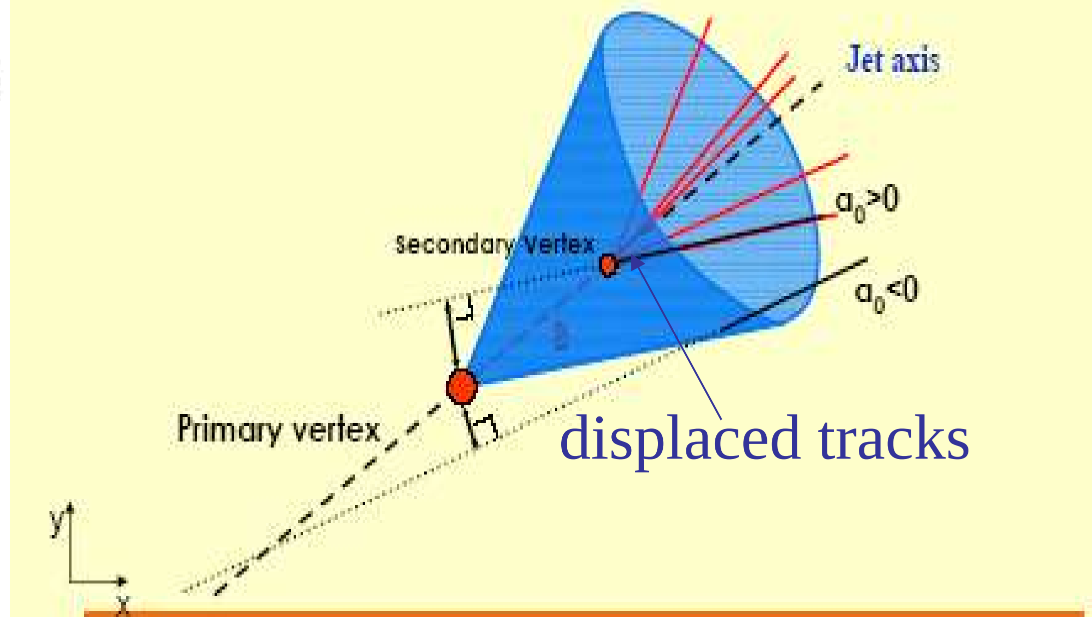
Soft lepton tag



- $b \to \ell \nu c$ (BR ~ 20%)
- $b \to c \to \ell \nu s$ (BR ~ 20%)

Search for non-isolated soft lepton in a jet

Silicon vertex tag

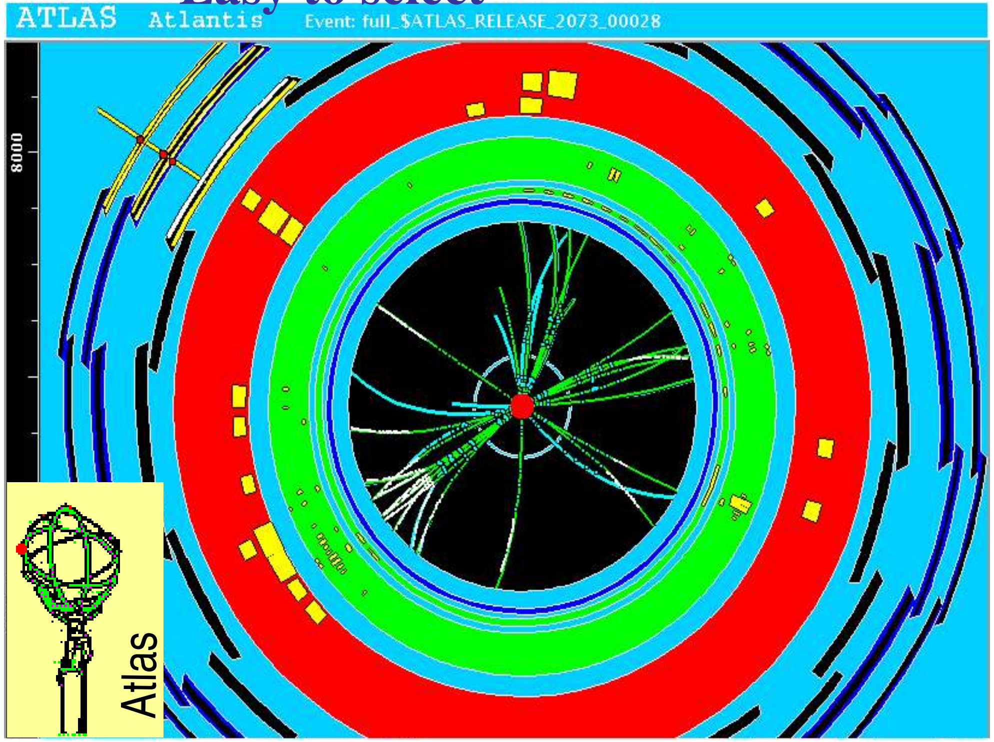


B mesons travel ~ 3mm before decaying – search for secondary vertex

Top Mass from Semi-Leptonic Events

Easiest channel tt → bb qq lν

- Large branching ratio
- Easy to select



tt → bb qq μν events from ATLAS

Measurement of m_{top}

Selection

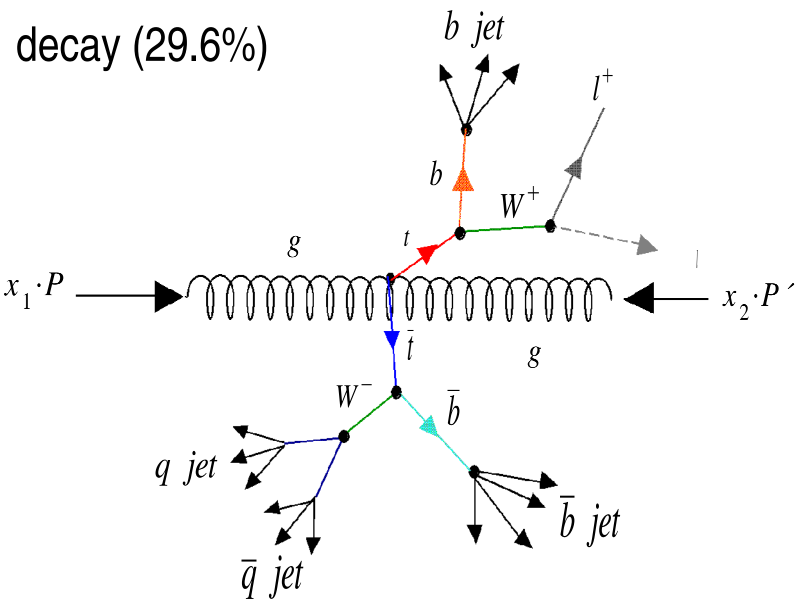
- Require at least one e or μ
  - P_T > 20 GeV/c in central detector
- 2 jets
- 2 b-jets

Efficiency: ~65%

Systematics

- Dominant: Final-state radiation
- ➢jet energy calibration: 1%
  especially b-jet calibration

decay (29.6%)

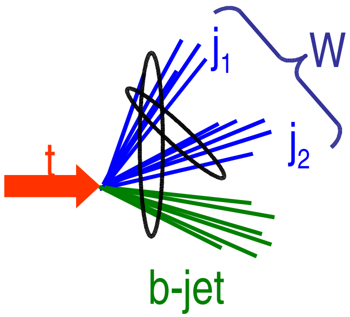


$$pp \to t\bar{t}$$
$$\to (b\,W^{+})(\bar{b}\,W^{-})$$
$$\to 2\ b-jets + 2\ quark\ \ jets + l$$

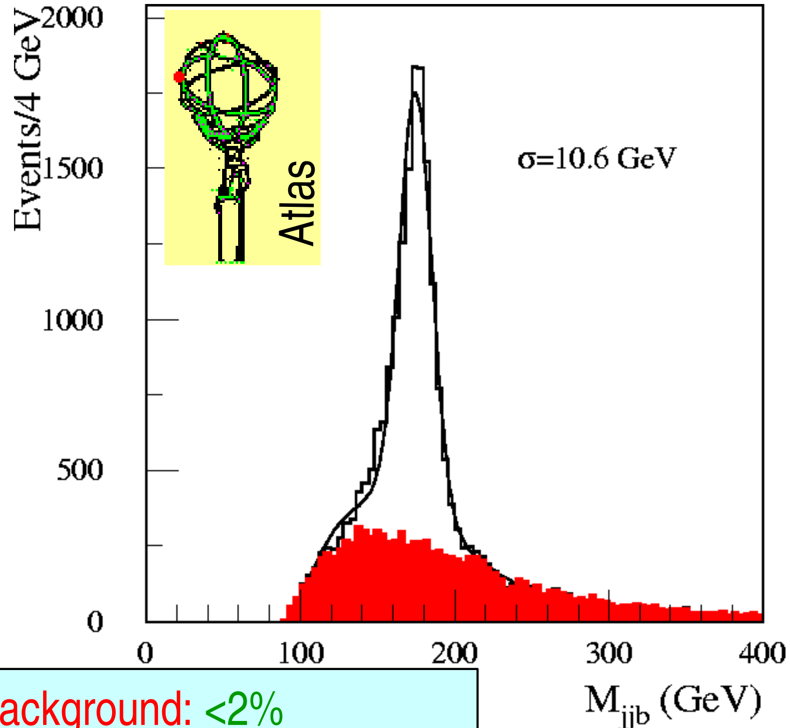
Top Mass from Semi-Leptonic Events

Reconstruct m_t from hadronic W decay

Constrain two light quark jets to m_W



70% top purity - efficiency 1.2 %



- Isolated lepton P_T>20 GeV
- E_T^{miss}>20 GeV
- 4 jets with E_T>40 GeV ΔR=0.4
- >1 b-jet ($\varepsilon_b \approx 60\%$, $r_{udc} \approx 10^2$, $r_c \approx 10^1$)

Background: <2%

W/Z+jets, WW/ZZ/WZ

M_{Top} from lepton+jet SN-ATLAS-2004-040

- Golden channel

  BR 30% and clean trigger from isolated lepton
- **Important to tag the b-jets:**

  enormously reduces background (physics and combinatorial)
- **Hadronic side**: W from jet pair with closest invariant mass to MW
  - Require $|M_W - M_{jj}| < 20$ GeV
  - Ligth jet calibrated with M_w constraint

  Assign a b-jet to the W to reconstruct M_{top}
- Leptonic side Using remaining ℓ +b-jet, the leptonic part is reconstructed
  - $|m_{\ell b} - \langle m_{jjb} \rangle| < 35$ GeV
  - Kinematic fit to the t t hypothesis, using M_W constraints

Br(tt→bbjj ℓ ν)=30%
for electron + muon

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- E_T^{miss}>20 GeV
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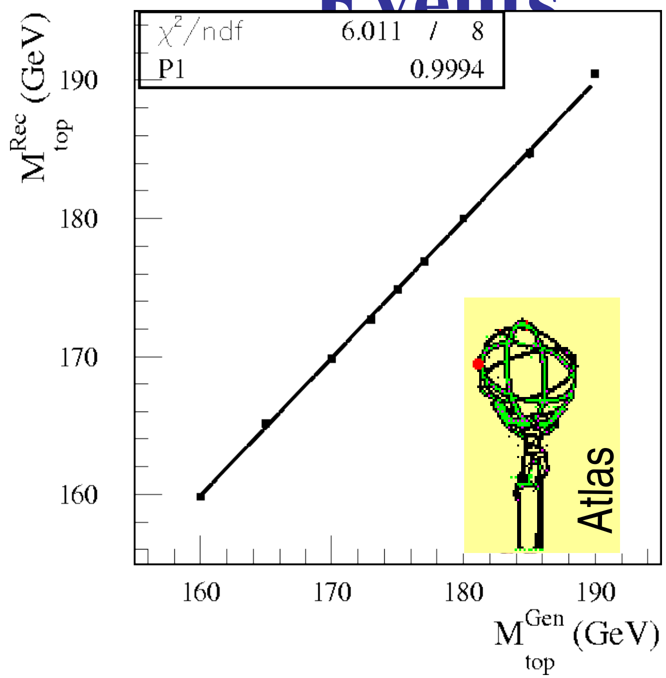
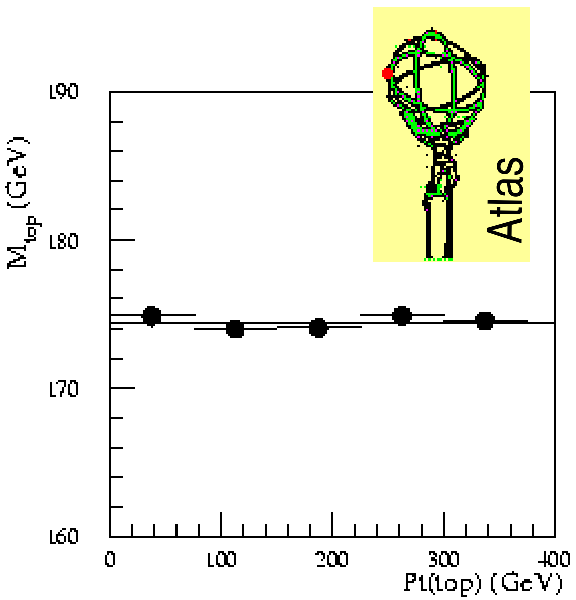
Top Mass from Semi-Leptonic Events

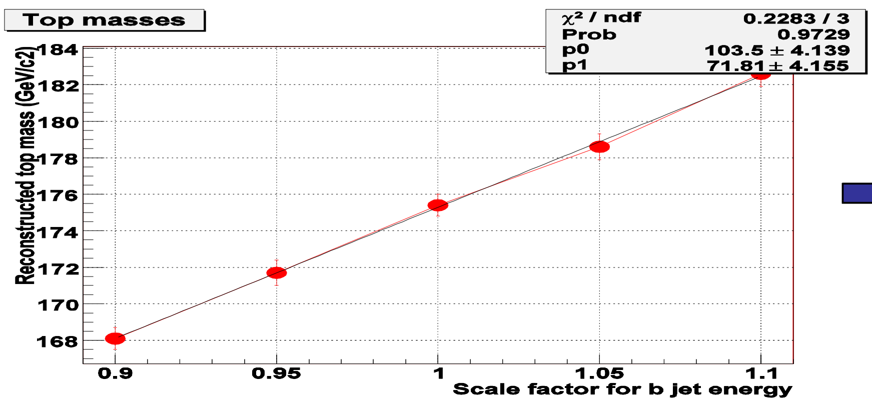




- Linear with input Mtop
  - Largely independent on Top P_T

Top mass systematics

- Systematics from b-jet scale:



Source	**ATLAS 10 fb^{-1}**
b-jet scale (±1%)	0.7
Final State Radiation	0.5
Light jet scale (±1%)	0.2
b-quark fragmentation	0.1
Initial State Radiation	0.1
Combinatorial bkg	0.1
TOTAL: Stat ⊕ Syst	0.9

- **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**