# Standard Model Physics at ATLAS/LHC

S. Tokár
Comenius Univ., Bratislava
On behalf of the ATLAS collaboration

# Outline

- LHC and ATLAS performances

  (Parameters of LHC, ATLAS structure and performances)

- Higgs boson physics

  (very briefly)

- Prospects of QCD at 14 TeV

  Multijets, top production, p.d.f. sensitive processes

- Measurements for precision SM physics

  W and Top mass, constraints on Higgs mass via EW physics

- Some top physics topics

  Single top production, spin effects, anomalous top couplings

# LHC (Large Hadron Collider)

- pp collisions at $\sqrt{s}$ = 14 TeV
- Bunch crossing: 25 ns
- Low luminosity L= 20 $fb^{-1}$
- High luminosity L= 100 $fb^{-1}$ ($\approx 10^{34} cm^{-2}s^{-1}$)


LHC is top,W,Z, … factory ↓

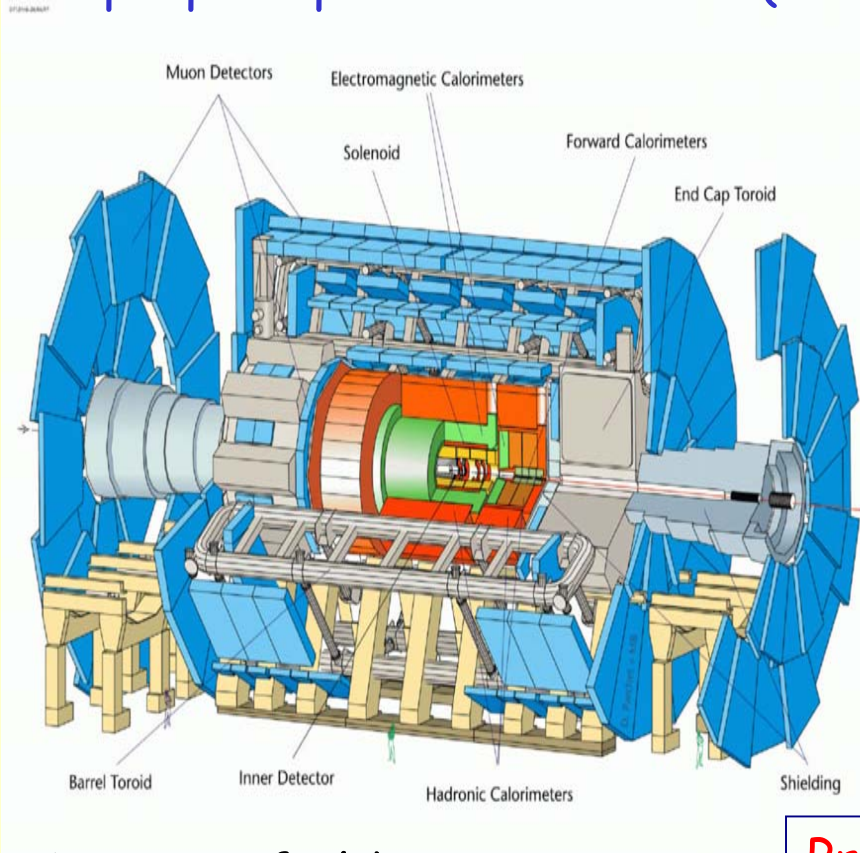
| Process | $\sigma$(mb) | Ev./10$fb^{-1}$ |
|---|---|---|
| $W \to e\,\nu$ | 15 | $\sim 10^8$ |
| $Z \to e^+ e^-$ | 1.5 | $\sim 10^7$ |
| $t\bar{t}$ | 0.8 | $\sim 10^7$ |
| jets ($p_T$>200 GeV) | 100 | $\sim 10^9$ |

Large statistics for SM processes ⇒

- SM precision physics (EW, top-,b-physics, multijets…)
- Big potential for new physics (Higgs,SuSy…)

# ATLAS performance

Multi purpose particle detector (coverage up to $|\eta|=5$, $L=10^{34}\ cm^{-2}s^{-1}$)




- **Inner Detector**

$$\sigma/p_T \approx 0.05\% \cdot p_T(GeV) \oplus 0.1\%$$

Tracking range $|\eta|< 2.5$

- **EM Calorimetry**

$$\sigma/E \approx 10\%/\sqrt{E(GeV)} \oplus 1\%$$

**Fine granularity up to $|\eta| < 2.5$**

- **Hadronic Calorimetry**

$$\sigma/E \approx 50\%/\sqrt{E(GeV)} \oplus 3\%$$

**Range: $|\eta| < 4.9$**

- **Muon System**

$$\sigma/p_T \sim 2-7\%, \quad \text{range: } |\eta| < 2.7$$

Magnetic field :
2T Solenoid + 3 air core toroids
Luminosity precision ≤ 5%

Precision physics in $|\eta|<2.5$
Lepton energy scale: 0.02% ($Z \rightarrow ll$)
Jet energy scale: 1.0 % ($W \rightarrow jj$)

# Higgs boson Production

Production of SM Higgs:

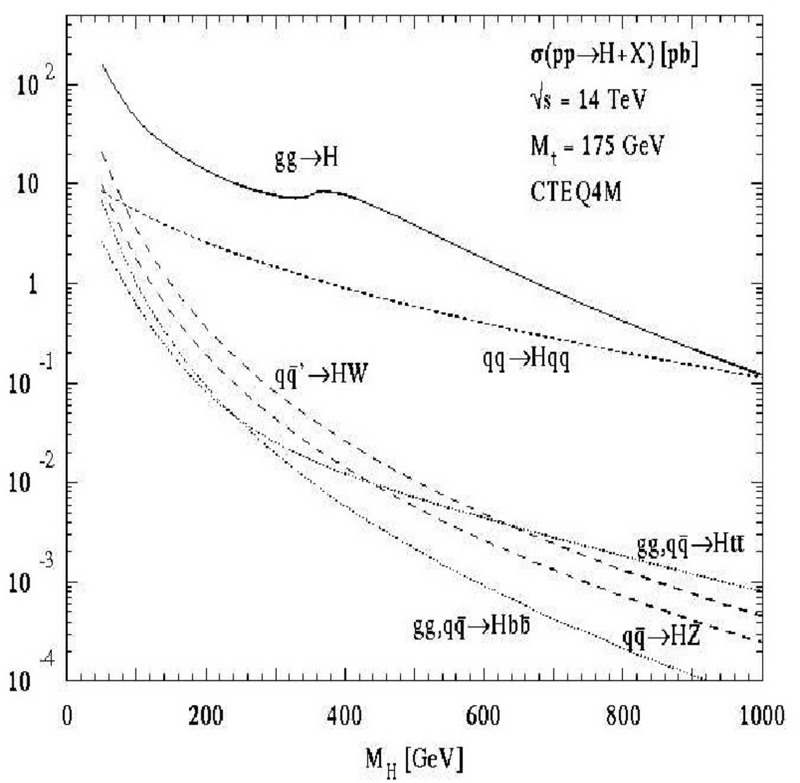
- Gluon fusion $gg \to H$
- Weak boson (W,Z) fusion
  WBF: $q\bar{q} \to q'\bar{q}'H$
- Top-quark associated production $gg,\ q\bar{q} \to t\bar{t}H$
- Weak boson associated production $q\bar{q} \to q'\bar{q}'H$

Channels for detection:

$$H \to Z^{(*)}Z^{(*)} \to 4l, \qquad H \to \gamma\gamma$$

$$H \to W^{+(*)}W^{-(*)} \to l^+l^- + p_T^{miss}$$

$$H \to \tau^+\tau^- \qquad t\bar{t}H, H \to b\bar{b}$$




The cross sections for different H boson production processes vs $M_H$

# Higgs couplings

To verify Higgs mechanism experimentally:

- Higgs mass(es), spin, CP
- Higgs widths and couplings to different particles:

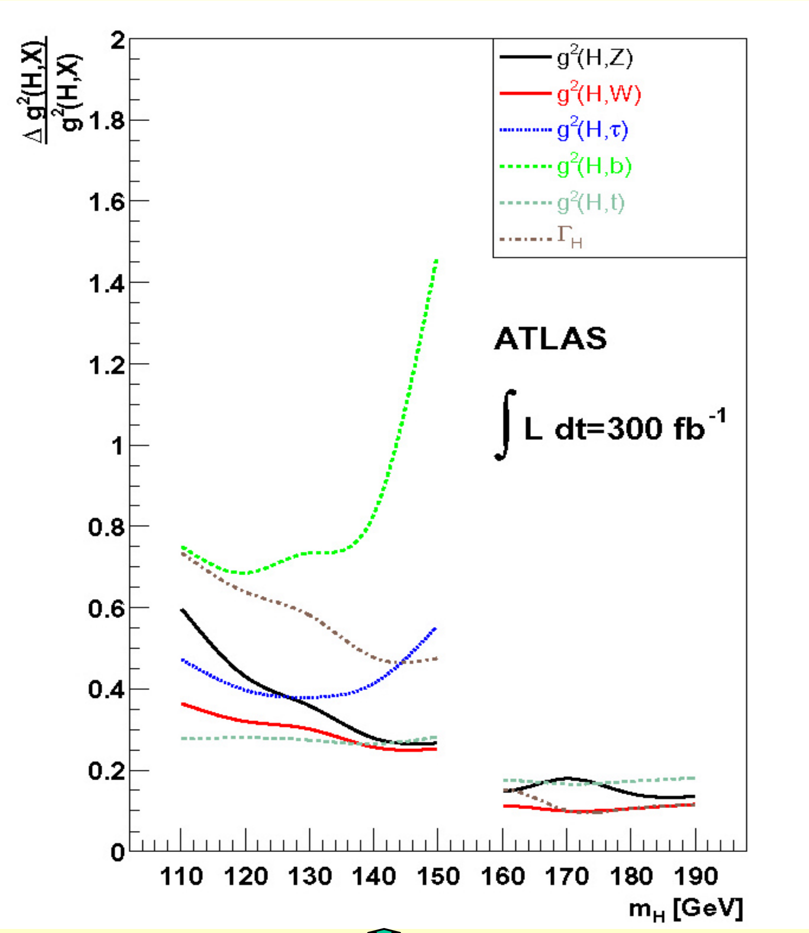
$Hb\bar{b}$, $Ht\bar{t}$, $H\tau^+\tau^-$, $HW^+W^-$,
HZZ, Hgg, $H\gamma\gamma$, HHH,...

Typical accuracies for couplings and widths : 20-30%

10% accuracy for HZZ, HWW couplings over W threshold

Systematic errors contribute up to half the total error

$5\sigma$ discrepancy from SM up to $m_A \approx 300$ GeV (MSSM)




Precision of Higgs boson couplings determination vs Higgs mass

# QCD measurements

- The LHC physics is based on the interactions of quarks and gluons
- Factorization : a convolution of partonic x-section and PDF's:

$$\sigma = \sum_f \int dx_1 dx_2\, F_i^{(1)}(x_1, \mu_F) F_j^{(2)}(x_2, \mu_F) \hat{\sigma}_{ij}(s; \mu_F, \mu_R)$$

- PDF's are obtained from a global fit of DIS and DY data + DGLAP evolution to higher scales $Q^2$ $\rightarrow$ DGLAP splitting functions: theory is at NNLO.
- Partonic x-section: perturbative expansion in $\alpha_S$ (LO, NLO, NNLO, …)
- Scale choice: $\mu_F = \mu_R = Q \Leftarrow$ typical process scale (usually set by invariant mass or $p_T$ of hard probe)

➢ Problems: if two (or more) scales present in the hard scattering process $\rightarrow$ $\hat{\sigma}$ -expansion contains: $(\alpha_S L^2)^n$ and $(\alpha_S L)^n$ ($L=\ln(Q/Q_1)$)

➢ Tools: DGLAP + BFKL evolution equations $\rightarrow$ resummations

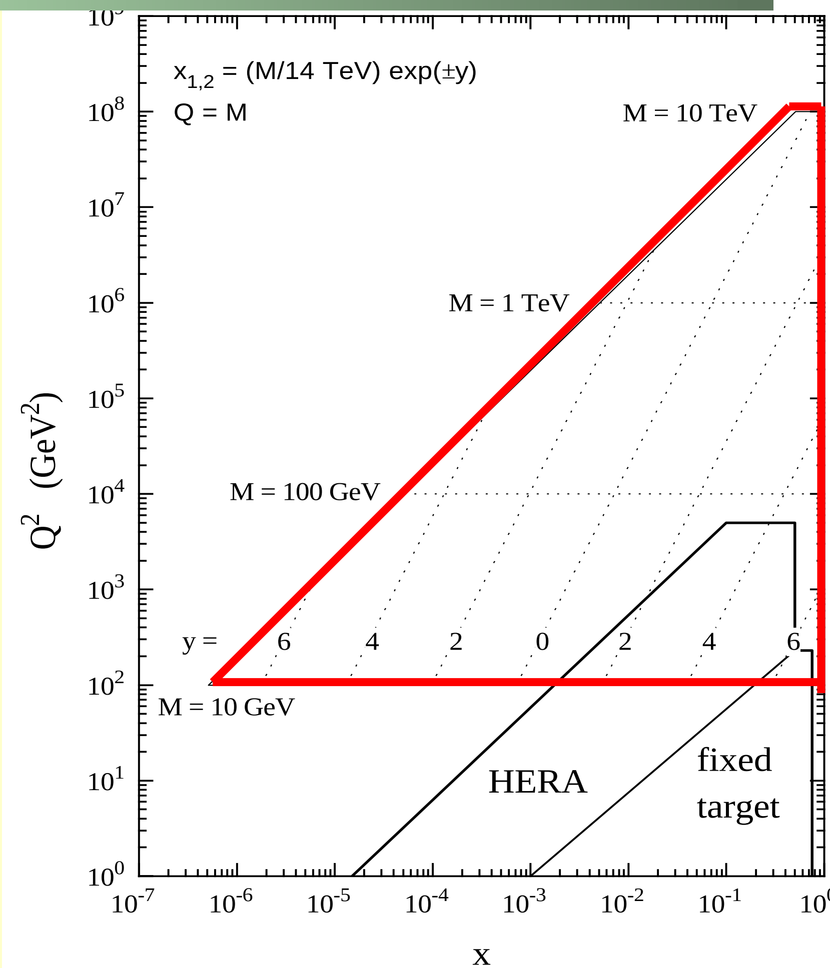
# LHC Parton Kinematics

- Accurate measurements of QCD related processes at LHC will constrain the PDF's.

- The kinematic acceptance of the LHC detectors allows a large range of x and $Q^2$ to be probed

Processes to be studied:

- Multijet physics – test of pQCD, dijet physics: constraints on PDF's
- Drel-Yan processes , $pp \xrightarrow{Z,\gamma} l^+ l^-$
  (q and $\bar{q}$ densities)
- Direct photon production $q\bar{q} \rightarrow \gamma g$
  $qg \rightarrow \gamma q$ (sensitive to gluon density)
- Top and heavy quark (c,b) production




Values of x and $Q^2$ probed in the production of an object (mass M, rapidity y) at $\sqrt{s}$=14 GeV

# $t\bar{t}$ Production Cross Section

Test of QCD predictions: top pair production (inclusive and differential x-sections) is an effective tool:

- big $m_t \Rightarrow \alpha_S(m_t)\sim 0.1 \Rightarrow$ pExpansion converges rapidly
- top decays before hadronization $\Rightarrow$ spin of top is not diluted

Theory for top X-section: NNLO-NNNLL

(Kidonakis et al., PRD68,114014 (2003) )

- Partonic Xsection:

$$\hat{\sigma}_{ij} = \frac{\alpha_S^2(\mu)}{m^2} \sum_{n=0}^{\infty} \left(4\pi\alpha_S(\mu)\right)^n \sum_{k=0}^{n} f_{ij}^{(n,k)}(\eta) \ln^k\left(\frac{\mu^2}{m^2}\right) \qquad \eta = \frac{s}{4m^2} - 1$$

Usual scale choice: $\mu_F = \mu_R = \mu \in (m_t/2,\ 2m_t)$ or top $p_T$

A discrepancy may indicate a new physics!

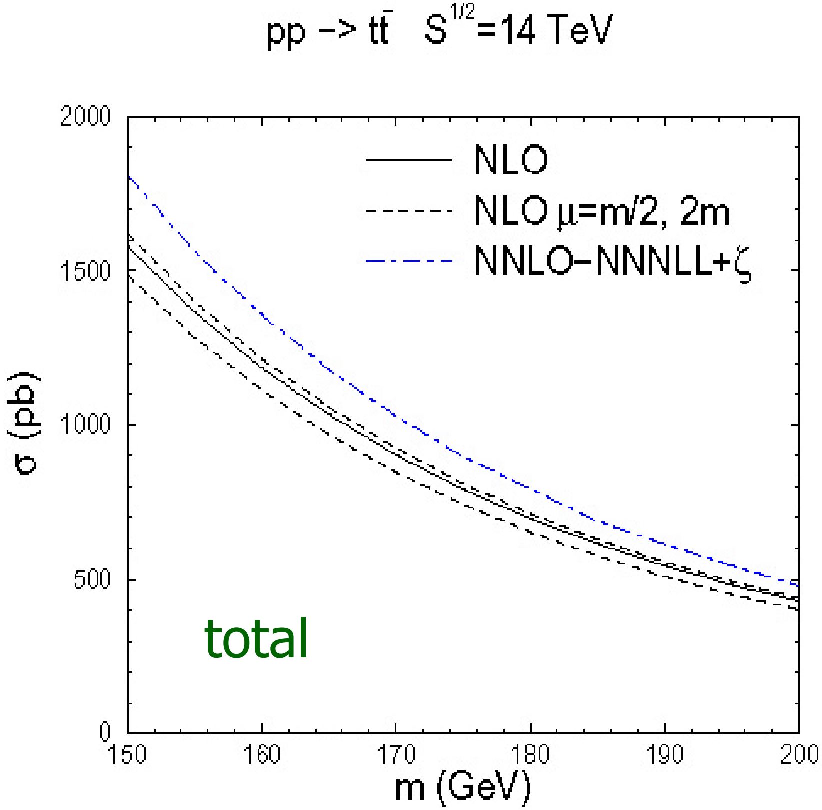
Progress at MC: radiative gluon corrections included: MCatNLO

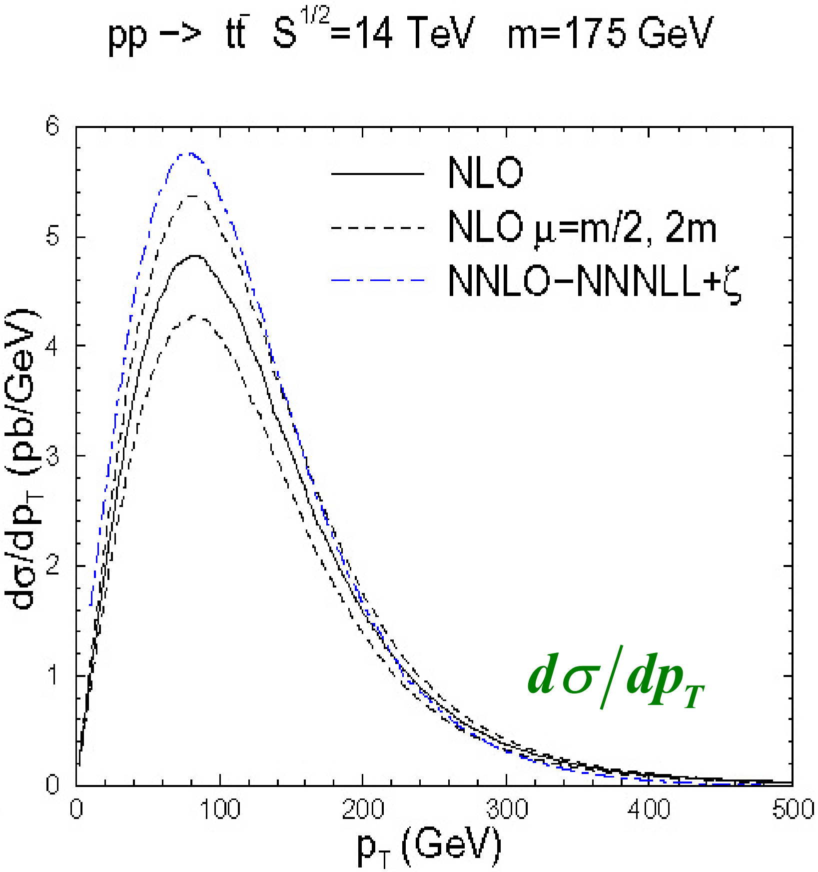
(Frixione et al, hep-ph/0311223)

**ATLAS: Statistical uncertainties < 1%**

$\rightarrow$ Systematics (Exp.& Theo.) will be dominant

# $t\,\bar{t}$ Cross Section at 14TeV




NNLO: uncertainty from scale ($m_t/2$, $2m_t$) < 3% !!!

(N.Kidonakis, hep-ph/0401147)

# Top Mass Measurement

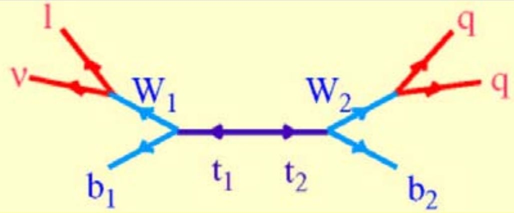
$m_{top} \equiv$ fundamental SM param. ( with $m_W$ consistency check of SM Higgs)

Top samples ($t \to Wb$):

Dileton ($W \to l\nu$ and $W \to l\nu$ ), 4.9%
Lepton+jets ($W \to l\nu$ and $W \to jj$ ), 29.6%
All jets ($W \to jj$ and $W \to jj$ ), 44.6%

## Lepton +jets channel

***Borjanovic et al., SN-ATLAS-2004-040***

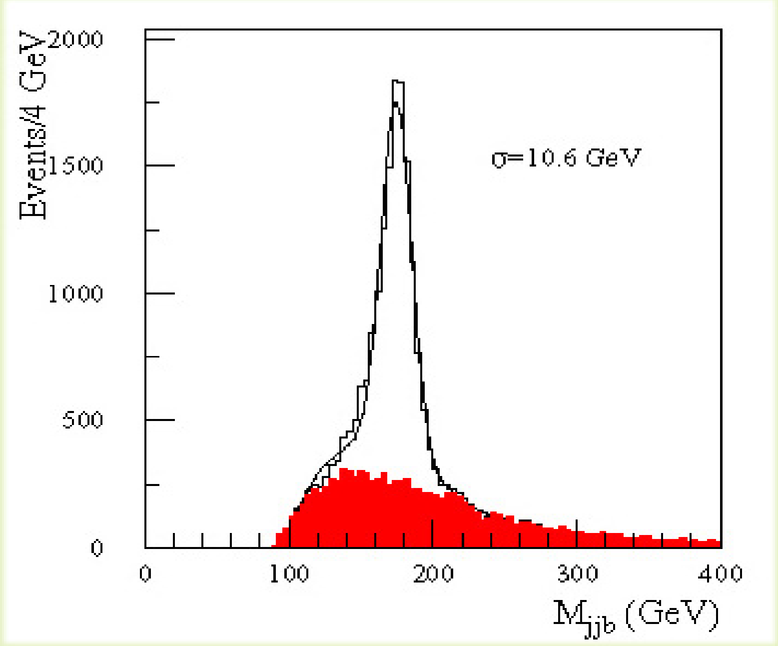



At prod. level:
$S/B=10^{-5}$

Sel. cuts : $p_T(l) \geq 20\,GeV,\ E_T^{miss} \geq 20\,GeV$
$\geq 4\ jets\ \left(p_T > 40\,GeV,\ |\eta| \leq 2.5,\ \Delta R = 0.4\right)$

$\Rightarrow$ S/B~78, 8700 tt events /$10fb^{-1}$,2b-tag

Invariant mass of jjb $\Rightarrow$
(b-jets calibtrated using Z+b events,
$M_W$ window used: ±20 GeV )



# Top mass in lepton + jets channel

Mass uncertainty

- Statistics ~ 0.1 GeV
- Systematics ~ 1.3 GeV

$\Rightarrow$

Reduction of systematics (FSR, b-jet energy scale) possible via full tt-bar reconstruction using kinematic fit $\Rightarrow$

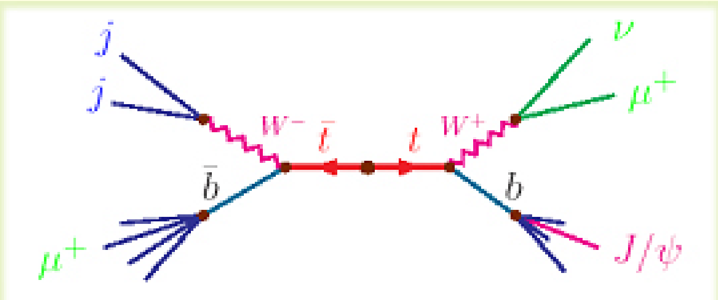
| Source | $\Delta m(t)$[GeV] |
|---|---|
| light jet energy scale | 0.2 |
| b-jet energy scale | 0.7 |
| ISR | 0.1 |
| FSR | 1.0 |
| b-fragmentation | 0.1 |
| Combinatorial bkgd | 0.1 |

Leptonic part - mass reconstructed via :

- missing transverse energy ( $E_T^{\nu} = E_T^{miss}$ )
- constraint $m(l\nu)=M_W$ for neutrino $p_z$

Promising: *l +J/ψ channel*

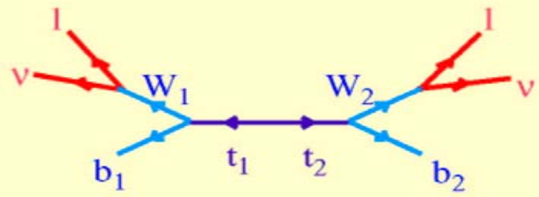
- Strong correlation between $m_t$ & $m(l,J/\psi)$
- $BR=3.2\times10^{-5}$ ($2700\ ev/100fb^{-1}$, sel. $\varepsilon\approx16\%$)
- non-sensitive to jet energy, $S/B\approx55$




$t\to W^+b,\ W^+\to l\nu,\ b\to J/\psi X$

# Top mass in other channels

## Dilepton channel




Selection: 2 isolated leptons ($p_T$>35,25 GeV)

High missing $E_T$ ( > 40 GeV)

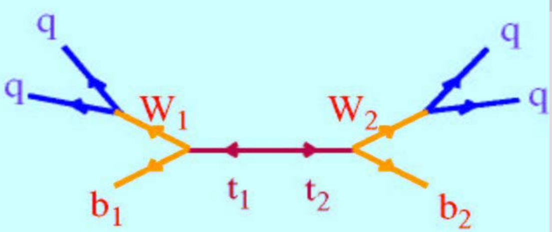
2 b-jets with $p_T$> 25 GeV

Neutrino momenta from: conservation laws, kinematic constraints

Mass uncertainty: $\Delta m^{stat+rec}(t)$ = 0.3 GeV/c$^2$, $\Delta m^{sys}(t)$ = 1.7 GeV/c$^2$

(pdf, b-fragmentation, b-jet scale, FSR)

## All jets channel




Selection: ≥6jets with $p_T$>40 GeV , ≥2 b-jets,

Small missing $E_T$ ⇒ S/B = 1/19

Kinematic fit ( W + top mass constraints used) ⇒ S/B = 6/1

High PT subsample ( $p_T$ (t) > 200 GeV) →3300 evts/10 fb$^{-1}$ ⇒ S/B = 18/1

Mass uncertainty: $\Delta m^{stat}(t)$ = 0.2 GeV/c$^2$, $\Delta m^{sys}(t)$ = 3 GeV/c$^2$

# W boson mass

Present Status: $\Delta M_W = 0.033$ GeV

Selection: $pp \rightarrow W+X$ with $W \rightarrow l\nu$, $l \equiv e,\mu$

- Isolated charge lepton: $p_T > 25$ GeV
- missing transverse Energy: $\not{E}_T > 25$ GeV
- Rejection of high $p_T$ W bosons

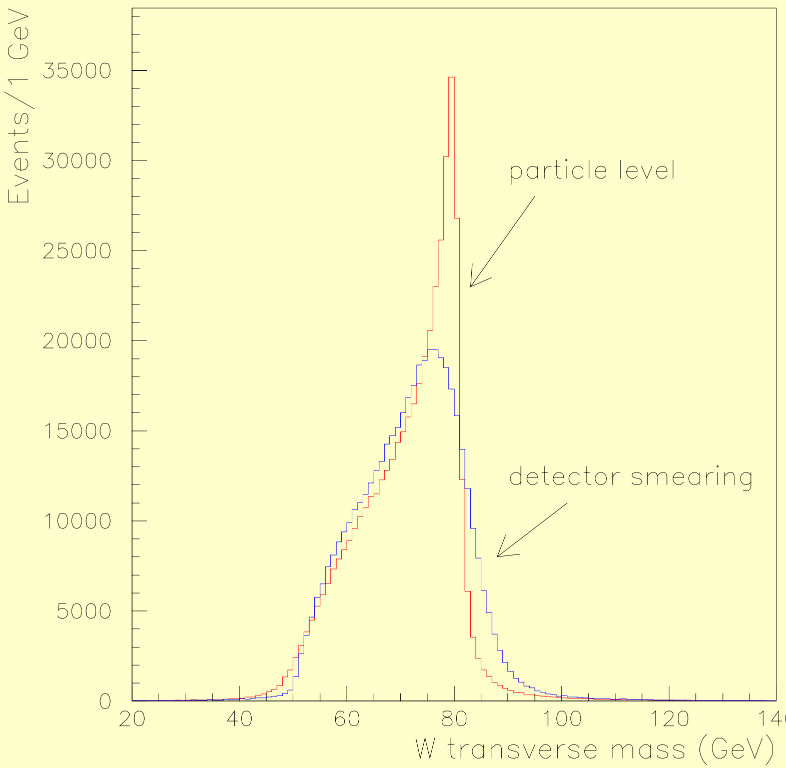
Method: transverse mass is constructed:

$$M_W^T = \sqrt{2 p_T^l p_T^\nu (1 - \cos\Delta\varphi)}$$

$\Delta\varphi \equiv$ angle $(l, \nu)$ in transverse plane

Position of Jacobian falling edge is sensitive to $M_W$

Sensitivity is reduced by detector smearing




The process x-section at LHC is 30 nb ($10^4 \times$LEP) $\rightarrow$ after selection and reconstruction 60 M W bosons are expected/ $10 fb^{-1}$.

$\Rightarrow$ Precision of $M_W$ is limited by systematics !

# W mass precision

Systematics comes mainly from MC modeling (physics, detector performance)

| *Source* | *$\Delta M_W$/channel* | *comments* |
|---|---|---|
| *statistics* | $<$ 2 MeV | 60M W's/year |
| *W width* | 7 MeV | |
| *pdf* | $<$ 10 MeV | |
| *Recoil model* | 5 MeV | |
| *Radiative decays* | $<$ 10 MeV | |
| *W $p_T$ spectrum* | 5 MeV | |
| *Backgrounds* | 5 MeV | |
| *Lepton identification* | 5 MeV | |
| *Lepton E-p scale* | $<$ 15 MeV | |
| *Lepton E-p resolution* | 5 MeV | |
| *Total* | $<$ 25 MeV | Per channel |

Combining channels (e, μ) $\Rightarrow$ $\Delta M_W \approx 20$ MeV
Combining with CMS $\Rightarrow$ $\Delta M_W \approx 15$ MeV
Sample size: 10 $fb^{-1}$

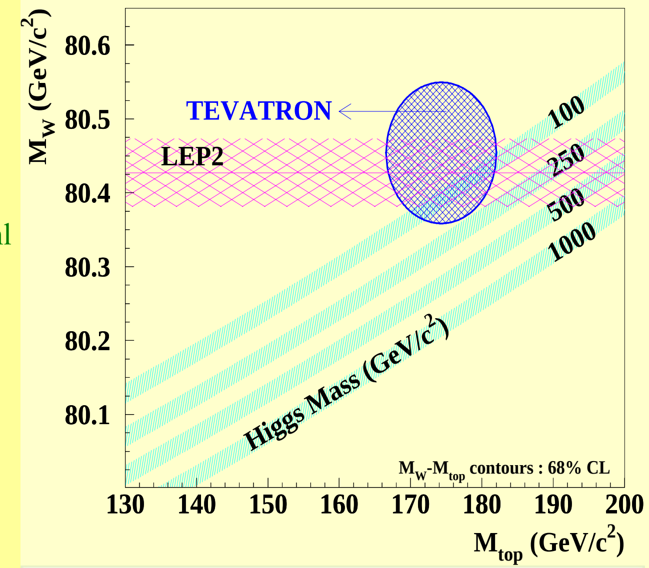
# EW precision physics vs W,top mass

Masses of top, W and Higgs are bounded by

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}\left(1+\Delta r\right),\quad \Delta r=\Delta\alpha+\frac{s_W}{c_W}\Delta\rho+(\Delta r)_{nl}$$

$\Delta r \equiv$ rad. corrections ( $\Delta\rho \sim m_t^2, \quad (\Delta r)_{nl} \propto \ln M_H$ )

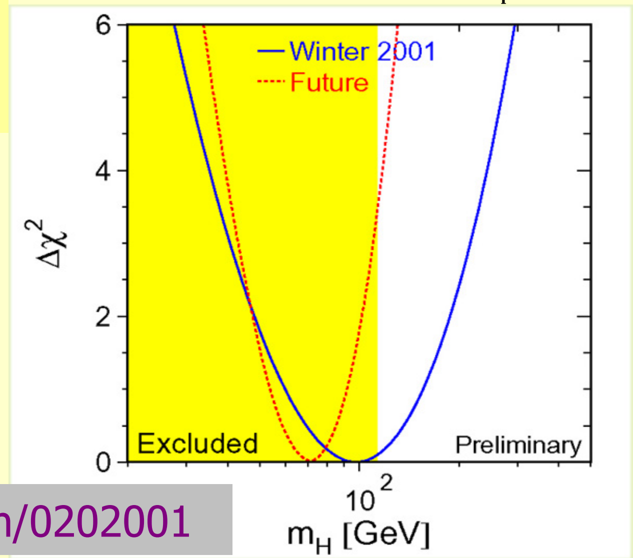
For equal weights in a $\chi^2$ test: $\Delta M_W \approx 0.7\times10^{-2}\,\Delta m_t$




Precise measurement of $M_W$ and $m_t$

$\Rightarrow$ constraint on $M_H$!

| | $\Delta m_t$ | $\Delta M_W$ |
|---|---|---|
| present | 5 GeV | 33 MeV |
| LHC | 1 GeV | 15 MeV |



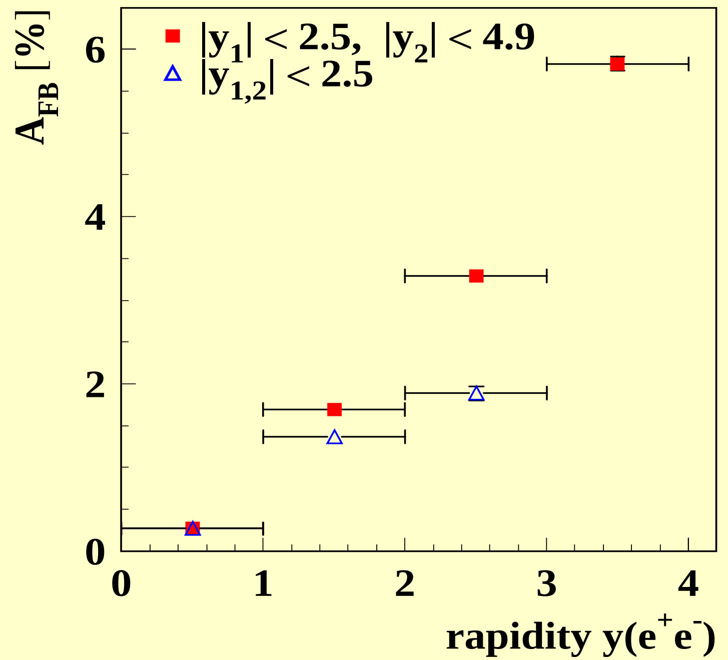

Grunwald et al, hep-ph/0202001

# Determination of $\sin^2\theta_{eff}^{lept}(M_Z)$

- $\sin^2\theta_{eff}^{lept}(M_Z)$ = 0.23126 ± 0.00017 (PDG)
  - SM fundamental parameter
- Its precise determination will constrain the Higgs mass (consistency of the SM)
- At LHC determined by measuring $A_{FB}$ in dilepton ($l^+l^-$) production near the Z pole:

$$A_{FB} = b\left\{a - \sin^2\theta_{eff}^{lept}(M_Z)\right\}$$

a,b calculated in QED and QCD to NLO




At L= 100fb$^{-1}$ per channel

| y cuts – $e^+e^-$ ( \| y(Z) \| > 1 ) | $\Delta A_{FB}$ | $\Delta\sin^2\theta_{eff}^{lept}$ |
|---|---|---|
| \| y( $l_{1,2}$ ) \| < 2.5 | 3.03 x $10^{-4}$ | 4.0 x $10^{-4}$ |
| \| y( $l_1$ ) \| < 2.5; \| y( $l_2$ ) \| < 4.9 | 2.29 x $10^{-4}$ | 1.41 x $10^{-4}$ |

Systematics:
- uncertainty on the PDF's
- lepton acceptance (~0.1%)
- radiative correction calculations

Can be improved combining channels/experiments

# Triple gauge boson couplings

- TGC of the type WWγ or WWZ provides a direct test of the non-Abelian structure of the SM
- Possible indication of new physics: new processes → anomalous contributions to the TGC.
- The sector is described by :

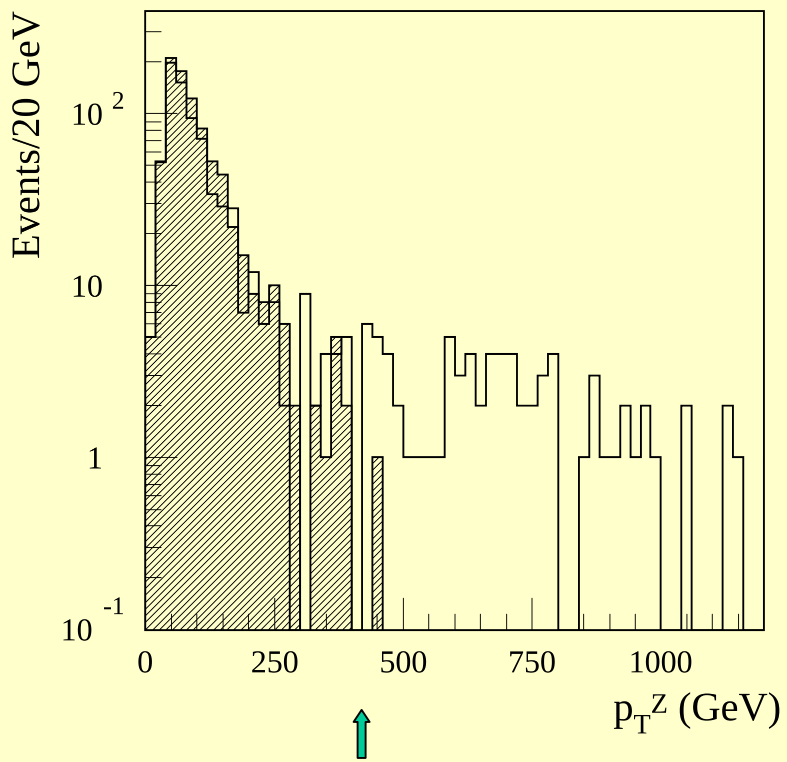
$$g_1^Z, \kappa_\gamma, \kappa_Z, \lambda_\gamma, \lambda_Z$$

SM at tree level: $g_1^Z = \kappa_\gamma = \kappa_Z = 1$ and $\lambda_\gamma = \lambda_Z = 0$

Experiment: observables sensitive to TGC are defined and their distributions are reconstructed.

Observable examples:

- Gauge boson $p_T$ (WZ,Wγ events)
- Polar decay angle of lepton in the W rest frame $\theta^*$ (WZ events)



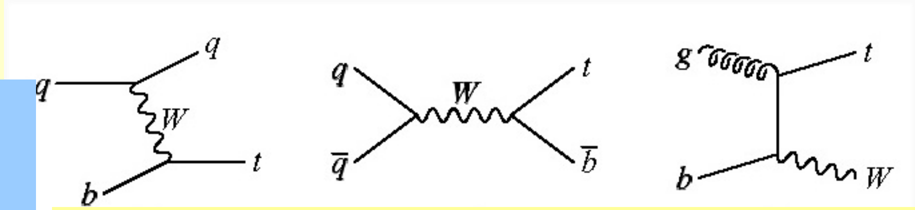

Distribution of $p_T^Z$ for WZ events, sample of 30 $fb^{-1}$,
SM - shaded histogram
non-SM : $\Delta g_1^Z = 0.05$ – white histogram

# Single top production

## Production via weak forces

- Cross section ~ $|V_{tb}|^2$
  ( direct measurement of $V_{tb}$ )
- Single top –100% polarization
  ( test of V-A structure of EW )

$\Rightarrow$ Possible new physics

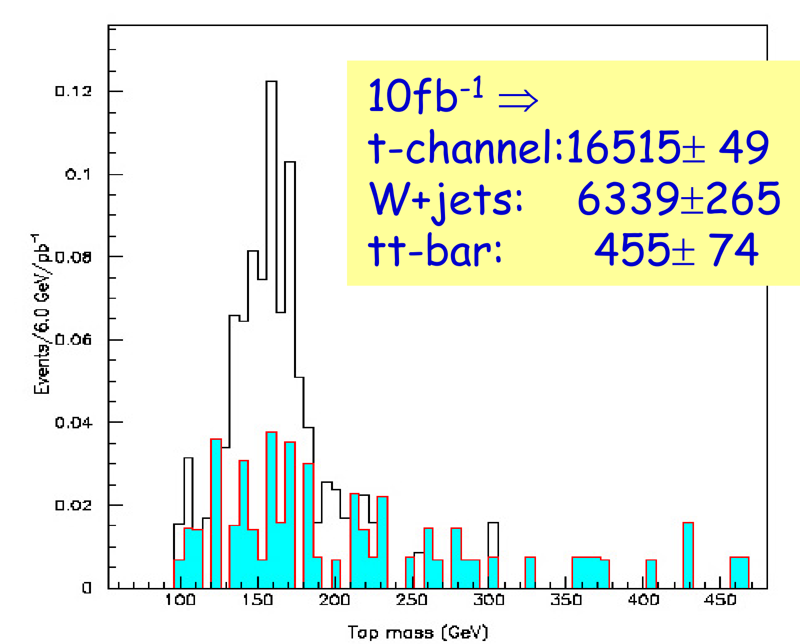



| t-channel | s-channel | association production |
|---|---|---|
| 245±27 pb | 10.7±0.7 pb | 51±9 pb |

( at LHC 14 TeV, NLO )

## Selection criteria

- Only 1 isolated lepton ($p_T$>20 GeV, $|\eta|$<2.5)
- miss-$p_T$ > 20 GeV, 50 < $m_T(l+\nu)$ < 100 GeV
- exactly 2 jets: ($p_T$>20 GeV, $|\eta|$< 4)
  1 jet with $p_T$>20 GeV, $|\eta|$< 2.5
  1 jet with 50<$p_T$<100 GeV, 2.5 <$|\eta|$< 4
- Exactly one b-tagged jet(reduces tt-bkgd)
- Two jet invariant mass $\in$(80,100) GeV
  (rejects WZ events)



# Other top physics issues

Top spin correlations: top decays before hadronization (spin is not diluted) $\Rightarrow$ imprint of $t\bar{t}$ production spin can be seen in angular distribution of top decay products

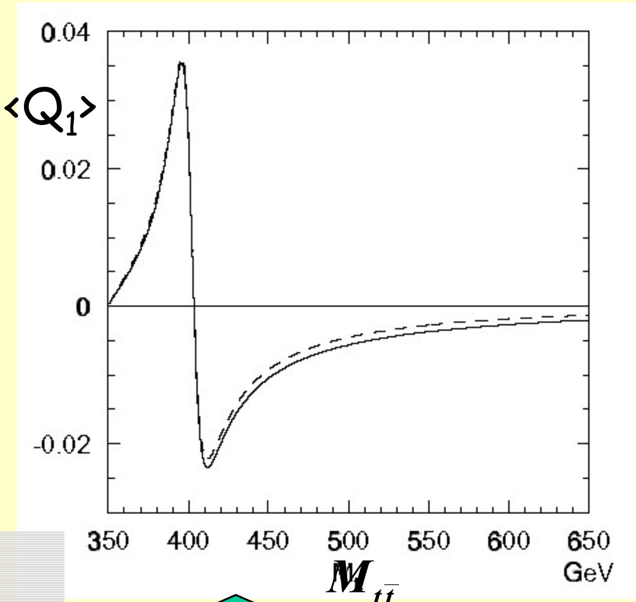
- Most promising: Dilepton $l^+l^-$ angular distribution

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1 + C\kappa_{l^+}\kappa_{l^-}\cos\theta_+\cos\theta_-}{4}, \qquad (\text{SM: } \kappa_{l^+}\kappa_{l^-} = -1, \quad C = 0.332)$$

$$\theta_+(\theta_-) \equiv \text{angle}\left(\hat{k}_t(\hat{k}_{\bar{t}}),\ l^+(l^-)\ \text{direction}\right)$$

CP-violating interactions: CKM phase only tiny effect on top production and decay

- Looking for CP violating terms in spin prod. density matrix (R)
- Di-lepton events can be used - sensitive observable: $Q_1 = \hat{k}_t \cdot \hat{q}_+ - \hat{k}_{\bar{t}} \cdot \hat{q}_-$




$Q_1$ vs tt-bar invariant mass at $\sqrt{s}$=14 TeV for the t-H Yukawa couplings $a_t = 1, \tilde{a}_t = -1$ (SM: $a_t = 1, \tilde{a}_t = 0$ )

# Top quark couplings

Study of couplings $gt\bar{t}$ , Wtb, tVc and tVu (V = g, $\gamma$, Z ) is important for New Physics

Anomalous $gt\bar{t}$ couplings: Cross section of $q\bar{q} \rightarrow t\bar{t}$ will have terms for

- anomalous chromomagnetic and chromoelectric dipole moments
- Retrieved from $l^+l^-$ (top pair decay) observables:

$$T_{33} = 2(p_{\bar{l}} - p_l)_3 (p_{\bar{l}} \times p_l)_3 , \quad A_E = E_{\bar{l}} - E_l , \quad Q^l_{33} = 2(p_{\bar{l}} + p_l)_3 (p_{\bar{l}} - p_l)_3 - \tfrac{2}{3}\left( p_{\bar{l}}^2 - p_l^2 \right)$$

Anomalous Wtb couplings: probed in top pair and single top production.

- 4 formfactors describe Wtb – two are ½ (from SM) and 2 to be analyzed:

$$F_{L(R)2} = \frac{2M_W}{\Lambda} \kappa^W_{tb} \left( -f^{W*}_{tb} - (+) i h^{W*}_{tb} \right)$$

FCNC couplings tVc, tVu: absent at tree-level and highly suppressed in SM (only through loop contributions)

Top anomalous couplings for Tevatron and LHC

| $L(fb^{-1})$ | 2 | 10 | |
|---|---|---|---|
| $\kappa^g_{tu}$ | 0.057 | 0.0097 | |
| $\kappa^g_{tc}$ | 0.18 | 0.013 | |
| $\kappa^Z_{tu}$ | 0.13 | 0.016 | |
| $\kappa^Z_{tc}$ | 0.43 | 0.040 | 0.018 |

# Summary

- The present ATLAS status:
  - • Testing and calibrating of the ATLAS sub-detector systems in test beam experiments
  - • Data Challenge 2 phase has started – the new simulated data taking into account the progress in experiment and theory are created → better understanding of the ATLAS physics potential
- LHC physics is rich even at low luminosity ($10fb^{-1}$/year)
  - o SM: EW and QCD tests (EW, jets, heavy flavor physics)
  - o Looking behind SM: probe SUSY
- High statistics studies at LHC ($100fb^{-1}$/year)
  - o Detailed study of the symmetry breaking mechanism in Higgs sector
  - o Precise top physics (Measurement of CKM $V_{tq}$ ,$\Delta m_t \leq 1$ GeV,...)
  - o New physics search

We are looking forward to 2007...(LHC starts)