II workshop sulla fisica di ATLAS e CMS

Napoli 12-15 Ottobre 2004

W and Z physics at the LHC

P.Ferrari (CERN)

The LHC hadron collider
Gauge-bosons precision measurements
- -W mass
- -Drell Yan asymmetries

Triple Gauge-boson Couplings
The first years of LHC data taking:
- -detector calibration
- -PDF determination

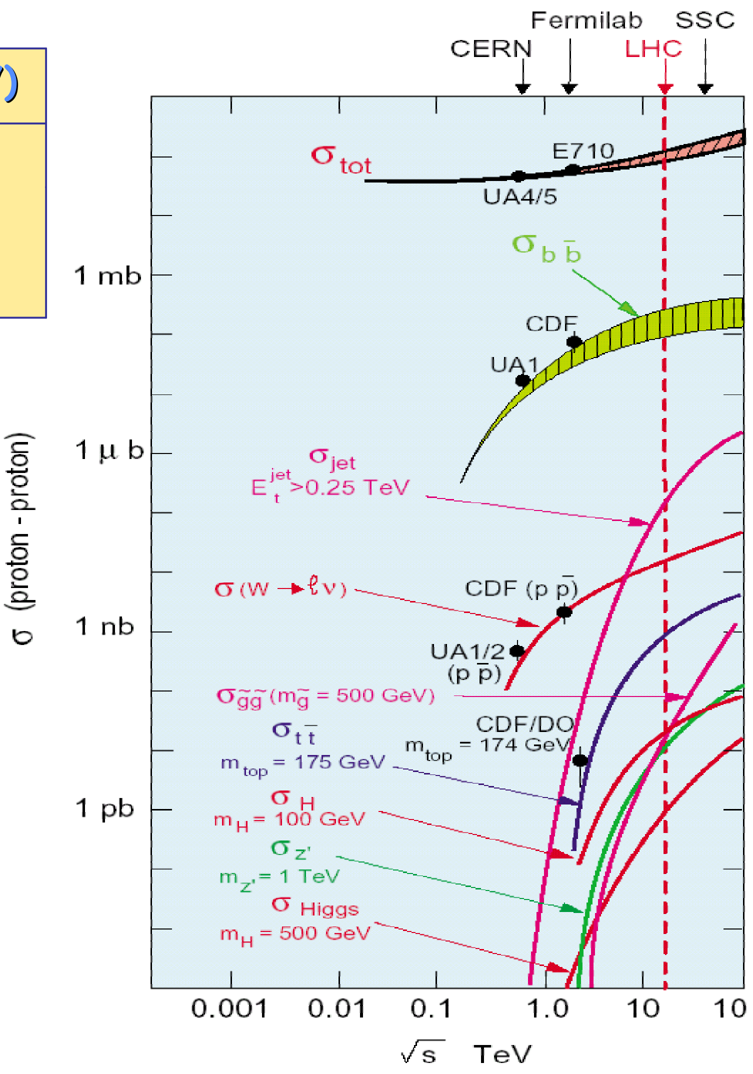
Large Hadron Collider

proton-proton collisions

	□$_{int}$/y (fb^{-1})	□ (cm^2/s)	√s (TeV)
LHC (low □)	10	2x10^{33}	14
LHC (high □)	100	10^{34}	14
Tevatron	0.3	< 10^{32}	2

Precision physics in low □ phase

process	Tevatron Events 2fb^{-1}	LHC Events 10 fb^{-1}
W→eν	10^6	10^8
Z→ee	10^5	10^7
bb	10^{11}	10^{12}
tt	5x10^3	10^7
QCD jets E$_T$>100 GeV	10^6	10^{10}



Present status of EW fit

M_{top} , M_W and EW precision measurements = cross check of SM and constrain M_H

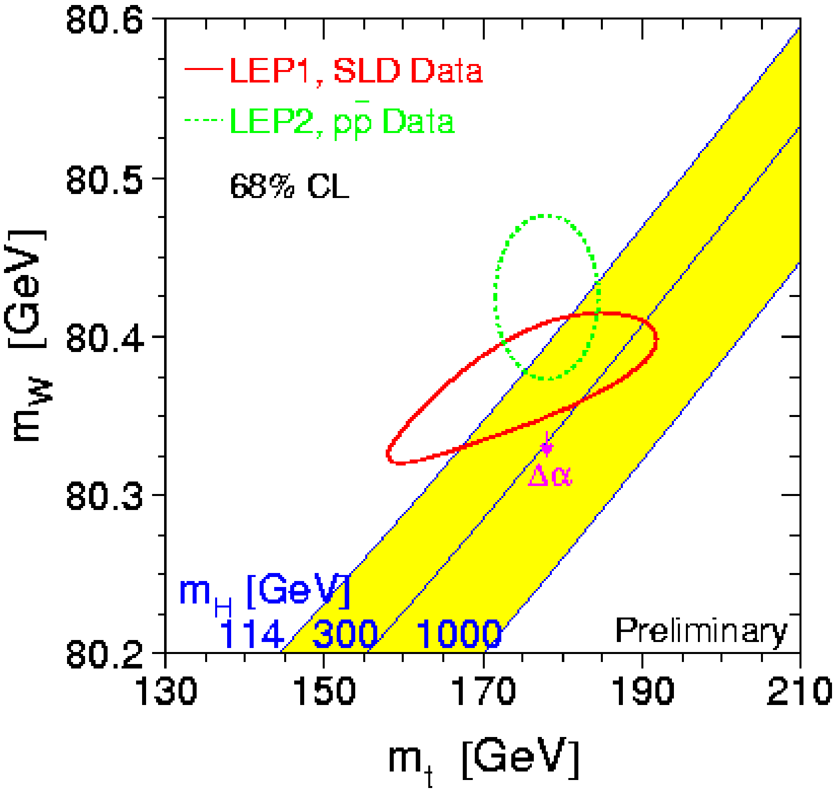
EW fit dominating uncertainties:

ΔM_{top} and ΔM_W

$$M_W = \sqrt{\frac{\pi \alpha_{EM}}{\sqrt{2} G_F}} \frac{1}{\sin\theta_W \sqrt{(1-\underbrace{\Delta r}_{M^2_{top},\ \ln M_H})}}$$

For ΔM_W not to be the dominant error in the EW fit:

$$\Delta M_W \sim 0.007 \Delta M_{top}$$



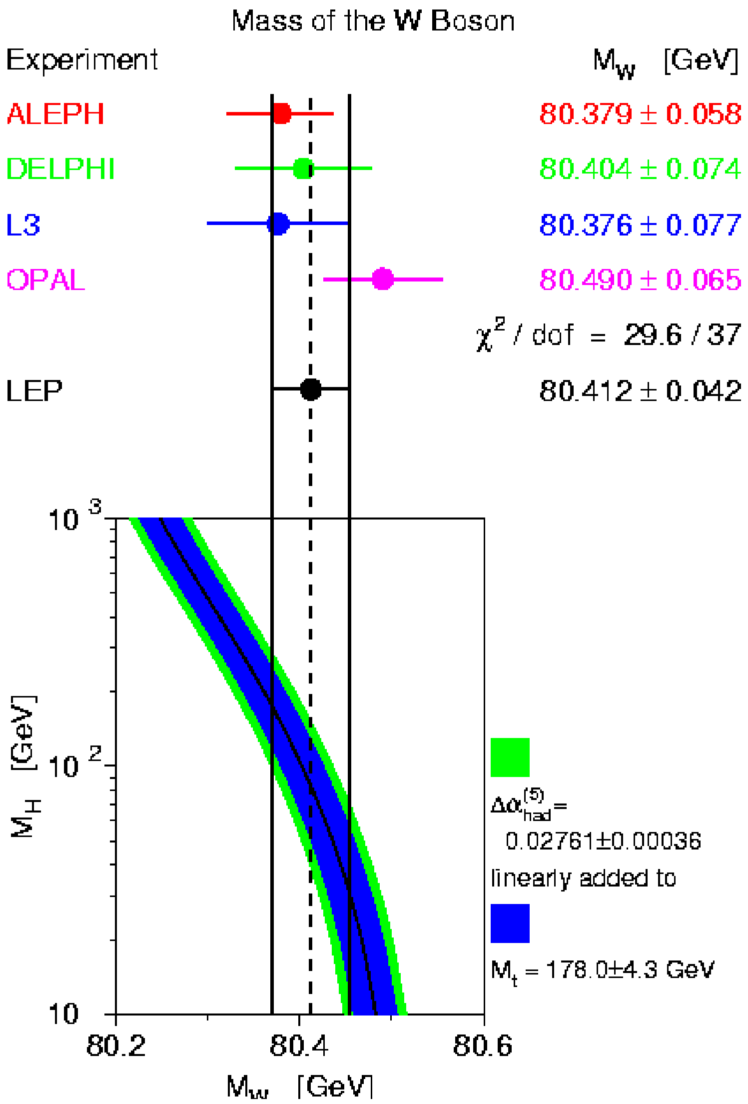
Constraints on M_H

From present EW fit:

$$M_H = 114^{+69}_{-45}\ \text{GeV}$$

$$M_H < 260\ \text{GeV}\quad @95\%CL$$

ΔM_W	ΔM_{top}	experiment
42 MeV	-	LEP2
59 MeV	4.3 GeV	Tevatron runI
25 MeV	2.5 GeV	Tevatron runII



$\Delta M_{top} \leq 1.5$ GeV @ LHC

⇓

$\Delta M_W \sim 15$ MeV @ LHC

$\Delta M_H \sim 30\%$

M_W measurement

pp-> WX

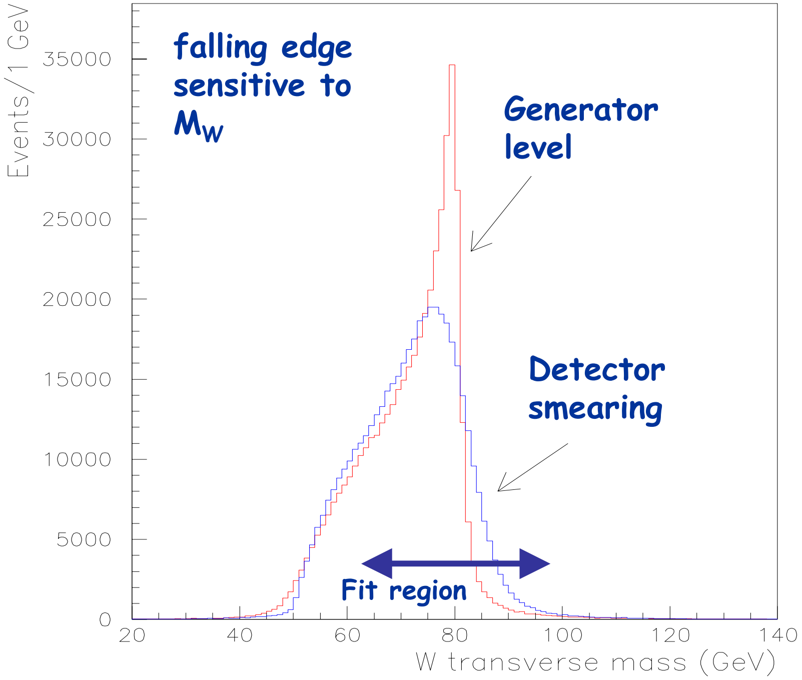
↳ $\ell\nu$ ($\ell=e,\mu$)

longitudinal components unknown

$$m_T^W = \sqrt{2p_T^l p_T^\nu (1-\cos\Delta\phi)}$$

missing $\vec{p}_T^{\,\nu}$ from W recoil system

$$\vec{p}_T^{\,\nu} = -\left(\vec{p}_T^{\,l} + \vec{u}\right)$$



falling edge sensitive to M_W

Generator level

Detector smearing

Fit region

selection:

$p_T^l > 25$ GeV $|\eta| < 2.4$

$E_T^{miss} > 30$ GeV

No jets with $p_T > 30$ GeV

Recoil <20 GeV

Huge statistics: with ε=25% 60 millions W/y per experiment

	LHC	Tevatron runIb
statististical error	<2 MeV	~ 65 MeV

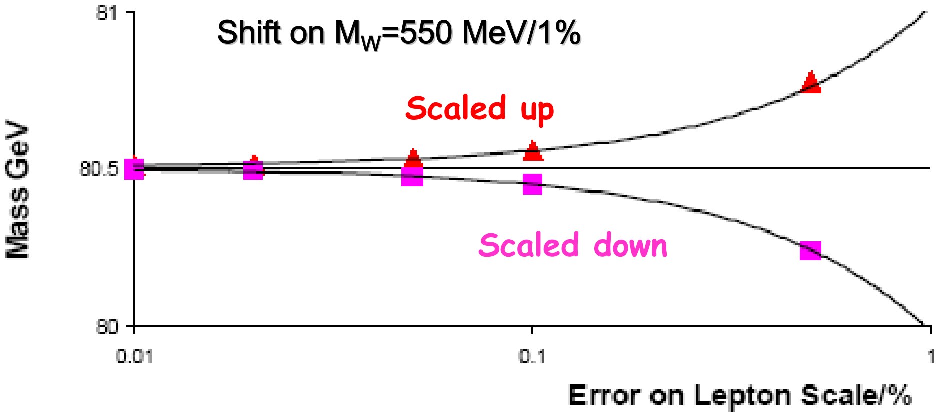
Detector systematics: what do we aim to?

Systematics is the dominant error

	LHC/y/e	Tevatron runIb 84pb^{-1}	Comments
Recoil model	5 MeV	33 MeV	detector response to soft hadrons of UE recoil in $Z \to \ell\ell$ to reconstruct M^T_Z (err÷√N)
E/p resolution	5 MeV	25 MeV	known to 1.5%: testbeam data + Z width measurements from $Z \to \ell\ell$
lepton E scale	15 MeV	75 MeV	Most challenging

Dominant error at LHC and Tevatron lepton E scale: known at 0.02% if

- alignment known to 1μm
- tracker material to 1% (e)
- B field to 0.1%,
- μ Energy loss to 0.25% in calorimeters (μ)



Tevatron reached 1% precision despite small Z samples

W-mass: detector systematics

The tracker momentum calibration:

- Alignment:
  - Constraints from metrology / laser alignment / X-ray survey / magnetic field measurements.
  - Get final precision between layers and in overlaps from tracks: $b \rightarrow \mu$, $W \rightarrow \mu$, hadrons with p_T>2 GeV
  - Cosmic runs and one beam running can help

  Statistics is not the issue, systematics need to be controlled, rough guess ATLAS: 100 μm – 2 months; 20 μm – 4 months; 5 μm – 1 year. Reach of 1 μm will be long.
- Material distribution from conversions

B-field:

  - Mapping field with Hall probe array, NMR probes during running
  - Final check using particles of known masses (J/ψ, Υ, Z)

EM calorimeter calibration:

  - Subset of detector elements calibrated in beam tests

Finally, calibrate μ/EM scale using:

  - $Z \rightarrow \mu\mu/ee$
  - E(calo)/P(tracker) of isolated electrons provides an additional constraint

Physics systematics (I)

	LHC/y/e	Tevatron runIb 84pb^{-1}
W width	7 MeV	10 MeV
p_T(W)	5 MeV	45 MeV

1) Uncertainty from W width

- Γ_W from R_{data}

$$R = \frac{\sigma_W}{\sigma_Z} \times \frac{BR(W \to \ell\nu)}{BR(Z \to \ell\ell)}$$

Theory

LEP

Limiting factor: knowledge of σ_W/σ_Z.

-Fitting high p_T tail of transverse mass distribution

2) p_T(W) model: theoretical uncertainties in predicting gluon emission (QCD recoil modeling)

- use $p^T(W)_{approx} = p^T(Z)_{data} \times \left(\frac{p^T(W)}{p^T(Z)}\right)_{theory}$ as input to MC

$p_T(Z)_{data}$ from $Z \to \ell\ell$ data

high statistics ⇨ improvement wrt Tevatron

Physics systematics (II)

Backgrounds: Use Z and W→ τν samples
Z → ℓ ℓ ,Multijet, W → τν → ℓ ν ν ,
Z → τ τ→ ℓ ℓ νν

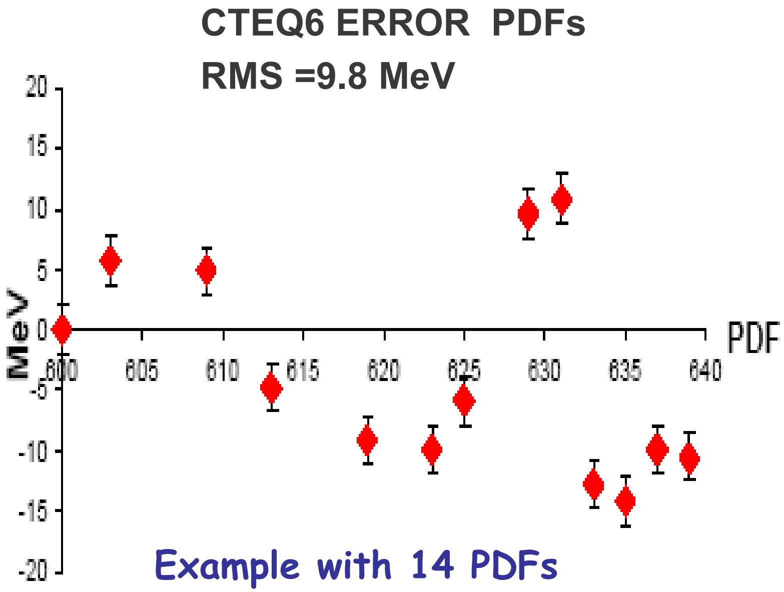
	LHC/y/e	Tevatron runIb 84pb^{-1}
Backg	5 MeV	5 MeV
Radiative decays	<10 MeV	20 MeV
PDF	10 MeV	15 MeV

Radiative decays: shifts in M^T_W

-Will improve wrt to Tevatron due to improved theoretical calculations: EW effect involved in resummation of final state observables

- Constrain using W → ℓνγ?

constrained PDF's: one of the most challenging systematics on M_W
CTEQ5 → CTEQ6 ΔM_W~74 MeV
-Use LHC data to improve PDF's
-Reduce theoretical error


CTEQ6 ERROR PDFs
RMS =9.8 MeV

Example with 14 PDFs

Once we understand all..1 year of data will provide

	LHC/y/e	Tevatron runIb $84 pb^{-1}$
statistical	2 MeV	65 MeV
lepton scale	15 MeV	75 MeV
E/p resolution	5 MeV	25 MeV
Recoil model	5 MeV	33 MeV
W width	7 MeV	10 MeV
$p_T(W)$	5 MeV	45 MeV
Backg	5 MeV	5 MeV
Radiative decays	<10 MeV	20 MeV
PDF	10 MeV	15 MeV
Total	25 MeV	113 MeV

Combining e,μ channels ΔM_W=20 MeV

Combining ATLAS & CMS ΔM_W=15 MeV

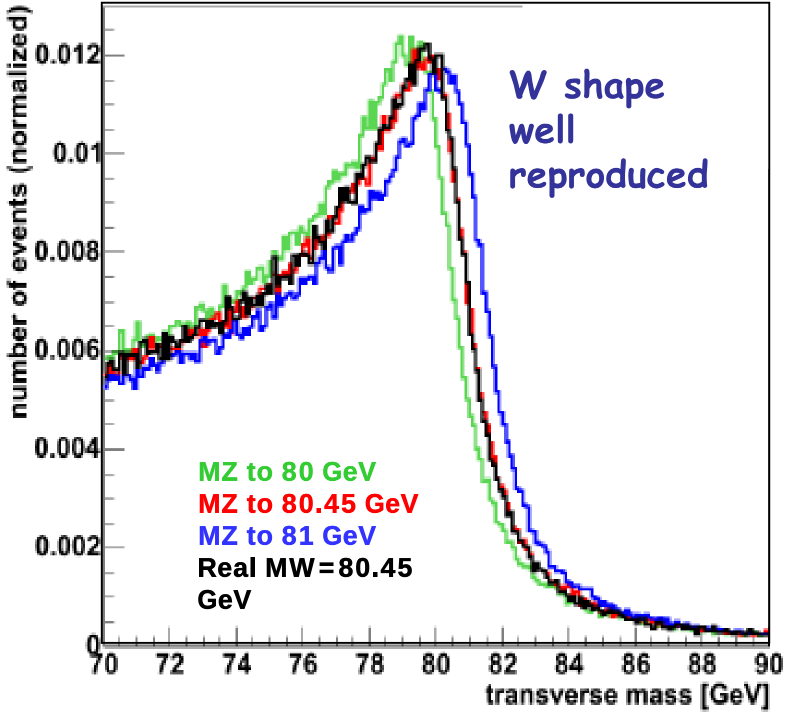
Alternative method to measure M_T^W

In first year of LHC the M_W determination will be hard due to systematics

Use data from Z → μμ to reconstruct Z

- Substitute μ to neutrino (M_T^Z from other μ and recoil)
- Transform $M_T^Z{}_{data}$ distribution in $M_T^W{}_{data}$
- find best M^W comparing M^W / M^Z histograms

A.Schmidt and G. Quast (Karlsruhe) in CMS



W shape well reproduced

Advantages:

-NO errors from theory of QCD recoil

-common systematics cancel in ratio: detector response for μ and recoil.

Disadvantages:

-factor 10 less statistics

-Z and W production mechanisms differ: affect p_T & η distributions

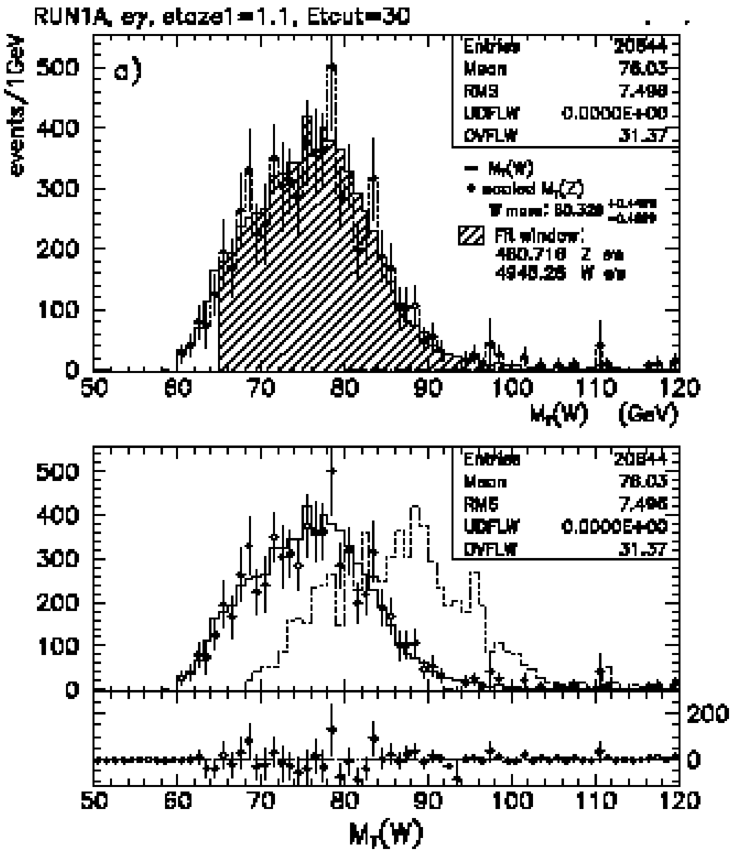
-differences in FSR (ν doesn't radiate)

Alternative method to measure M_T^W

Possible improvement of the systematic error in the 1st year of LHC

$\Delta M_W \sim 10$ MeV with 10 fb^{-1}

Proof-of-principle study by D0 on run I
FERMILAB-CONF-96-236-EF



Ratio method:

M_W= 80.155±0.211(stat) ±0.050(syst) GeV

To be compared to:

M_W= 80.440±0.070(stat) ±0.096(syst) GeV

- The systematics are much reduced.
- In D0 the cost (in Z statistics) is larger than the gain.

Weinberg angle $\sin^2\vartheta_W^{lep}$

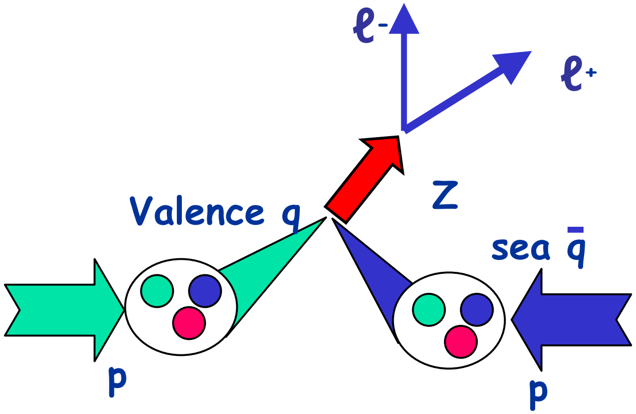
Increasing the precision on $\sin^2\vartheta_W^{lep}$ will constrain m_H

Measurement of Drell Yan forward backward asymmetry A_{FB} provides $\sin^2\vartheta_W^{lep}$

$$A_{FB}=b(a-\sin^2\vartheta_W^{lep})$$ a,b @NLO QCD and EW

<u>Asymmetry measurement at LHC</u> :

$$A_{FB}=\frac{(\sigma_F-\sigma_B)}{(\sigma_F+\sigma_B)}$$



measure the ℓ asymmetry wrt the boost direction of centre-of-mass system

$y(\ell^+\ell^-)$ gives info on direction of incoming q

<u>systematic uncertainties:</u>

1) Higher order QCD and EW corrections
2) pdf's determination
   NEED a factor 5-10 reduction of error
   - use W leptonic decays at LHC
   - multidimensional fits of A_{FB} and PDF's
3) lepton acceptance and reconstruction eff.
   should be known to 0.1%

Weinberg angle $\sin^2\vartheta_W^{lep}$

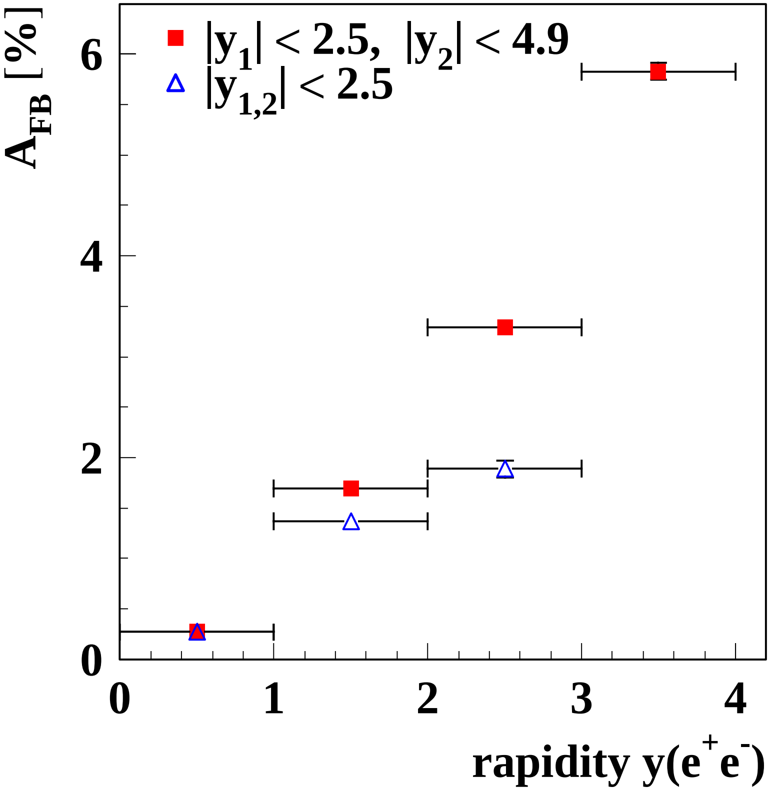
Asymmetry increases at high y(ℓℓ)
Increasing the forward acceptance?

- LEP+SLD result:
  0.23150 ± 0.00016

ATL-PHYS-2000-018 CMS IN 2000/035

	$A_{FB} \pm \Delta A_{FB}$(%)	$\Delta \sin^2\vartheta_W(M_Z)$
Both e $\lvert\eta\rvert<2.5$	0.77 ± 0.02	0.00066
1st e $\lvert\eta\rvert<2.5$ 2nd e $\lvert\eta\rvert<4.9$	1.98 ± 0.018	0.00014

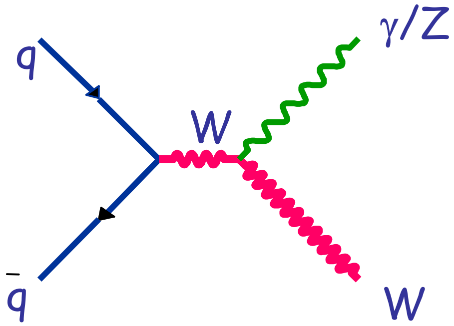
☐=100 fb^{-1} only statistical sources



Triple Gauge-boson Couplings

- Self couplings of EW Gauge-bosons are predicted by the non abelian $SU(II)_L \times U(1)_Y$ Gauge group.
- In SM assuming EW gauge invariance and C & P conservation WWZ and WWγ vertices are parametrized by:

  $\lambda_Z, \lambda_\gamma = 0 \qquad \Delta g^1{}_Z, \Delta k_\gamma, \Delta k_Z = 0$



- Sensitive to new physics
- $\lambda_Z, \lambda_\gamma \div \hat{s} \quad \Delta g^1{}_Z, \Delta k_\gamma, \Delta k_Z \div \sqrt{\hat{s}}$ ⇨ high E_{CM} advantages LHC
- Limits on ATGC :
  1) Compare expected and observed event rates: large systematics
  2) Binned likelihood fit of specific variables distribution to MC prediction

WWγ coupling

- pp $\rightarrow$Wγ
  - $\hookrightarrow$ $\ell\nu$ (ℓ=e,μ)
- **Sensitive to Δk_γ, λ_γ**
- Larger sensitivity in high p_T tail

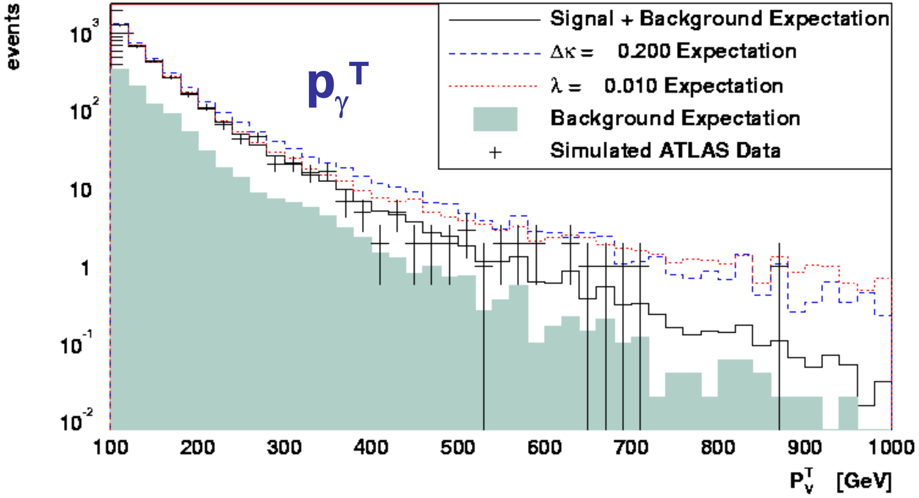
Example Selection:

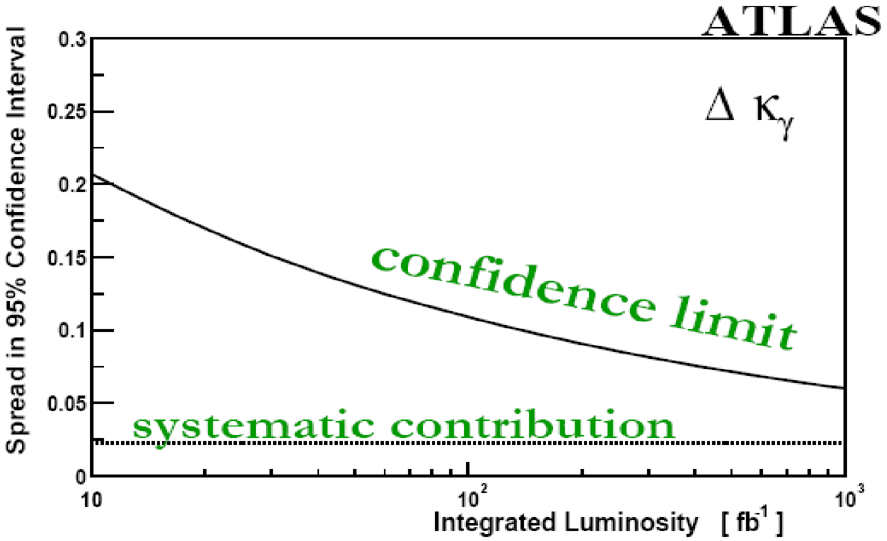
- Photon isolation
- p^γ_T >100 GeV
- p^l_T>25 GeV in $|\eta|$<2.5
- p_T miss > 25 GeV

Statistical error dominates LHC measurements

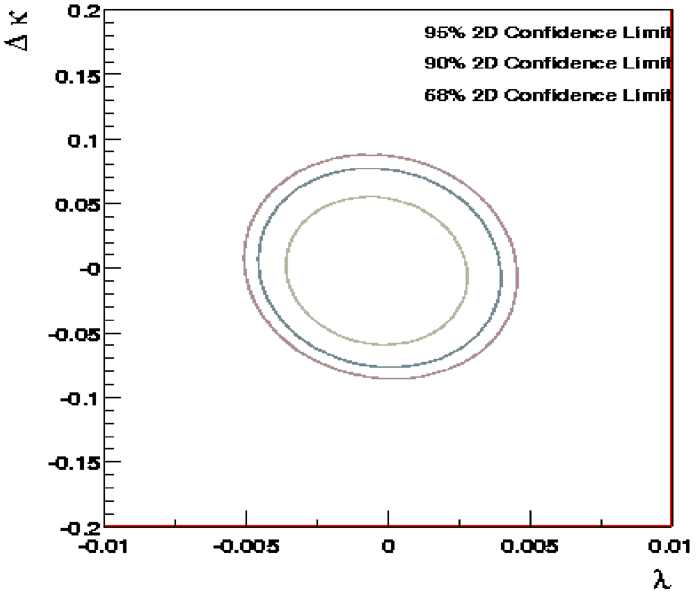
Dominant systematic error: pdf's and higher order QCD

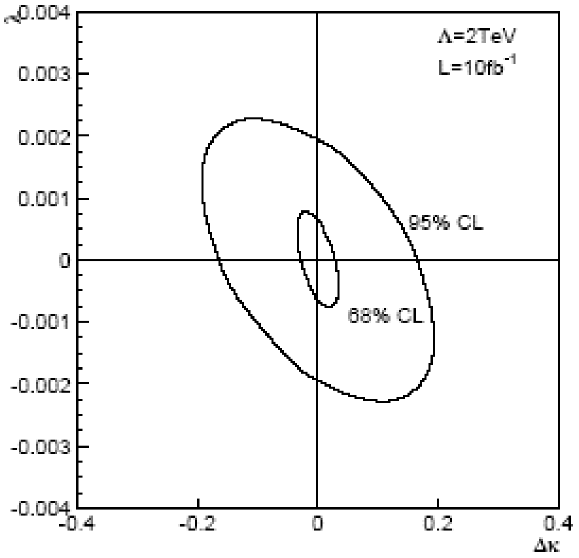
□ =30 fb^{-1}





WWγ coupling





Order of magnitude improvement wrt LEP2

ATLAS: ATL-COM-PHYS-2002-019

□=30 fb^{-1} Λ_{FF} =∞ const. form factor

$-0.0035 < \lambda_\gamma < 0.0035$ stat&syst

$-0.075 < \Delta k_\gamma < 0.076$ stat&syst

CMS: CMS-NOTE-2001-056

□=10 fb^{-1} Λ_{FF} =2 TeV

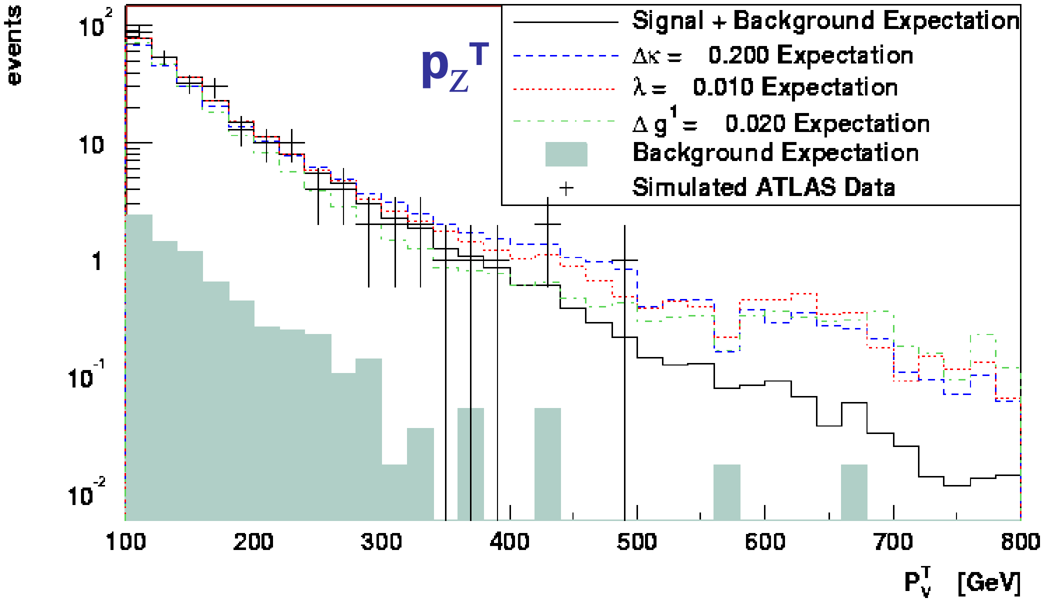
$-0.0019 < \lambda_\gamma < 0.0019$ stat

$-0.17 < \Delta k_\gamma < 0.17$ stat

WWZ coupling

$pp \rightarrow WZ \rightarrow \ell^+\ell^-$

$\hookrightarrow \ell\nu \ (\ell = e, \mu)$



Sensitive to:

Δg^1_Z , Δk_Z , λ_Z

Most sensitive observables:

- p^T_Z for λ_Z
- p^T_Z vs p^T_W for Δg^1_Z , Δk_Z

Selection:

- 3 leptons with p_T>25 GeV in $|\eta|$<2.5
- p_T miss> 25 GeV

Dominant systematic:

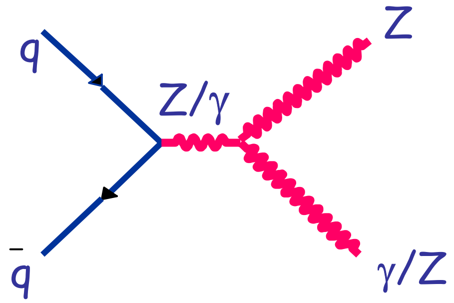
PDF's

ATL-COM-PHYS-2002-020 $\Lambda_{FF} = \infty$

limits ($\mathscr{L}$=30 fb^{-1})	error
$-0.0086 < \Delta g^1_Z < 0.011$	stat & syst
$-0.11 < \Delta k_Z < 0.12$	stat & syst
$-0.0072 < \lambda_Z < 0.0072$	stat & syst

Order of magnitude improvement wrt LEP2

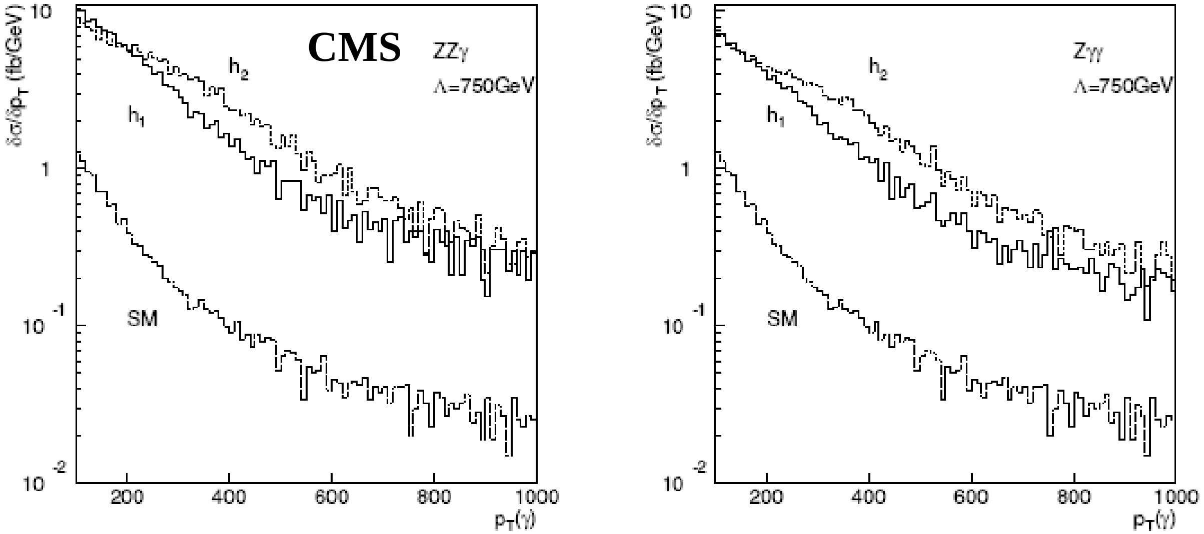
Neutral TGC's



Not present in the SM:

$pp \to Z\gamma \to \ell\ell\gamma$, $\ell=e,\mu$ constrains $h^V_{1,3} \div \sqrt{\hat{s}}^3$ $h^V_{2,4} \div \sqrt{\hat{s}}^5$ $V=Z/\gamma$

$pp \to ZZ \to \ell\ell\nu\nu$ $(\ell\ell\ell'\ell')$ $\ell/\ell'=e/\mu$ constrains $f^V_{4,5} \div \sqrt{\hat{s}}^3$



3-5 orders of magnitude better than LEP2

sensitive variables:

p^T_Z , p^T_γ

coupling	Limit	$\mathcal{L}$ (fb^{-1})	Λ_{FF} (TeV)
$f^V_{4,5}$	$O(7 \cdot 10^{-4})$	100	6
$h^V_{1,3}$	$O(3 \cdot 10^{-4})$	100	8
$h^V_{2,4}$	$O(7 \cdot 10^{-7})$	100	8

CMS-NOTE-2000-017
CMS-NOTE-2002-028
ATL-PHYS-2003-023
ATL-PHYS-2003-023

First years of LHC running

- In the initial phase of LHC before being to able to perform physics analyses, and especially EW precision measurements large effort will be needed to complete detector calibrations and alignment:
    - $Z \rightarrow \mu\mu/ee$: muon system calibration/alignment, EM inter-calibration , cross-calibration ee vs. $\mu\mu$
    - $Z \rightarrow ll\gamma$: Photon energy scale and linearity from $< M_{ll\gamma} > = M_Z$
    - Z +1jet : Jet energy scale (light jets, b-jets) from $<p^T_{jet}> = <p^T_Z>$
    - $tt \rightarrow bl\nu bjj$: Jet energy scale using $W \rightarrow jj$ and M_W constraint, b-tag performance
    - Tracking alignment: Generic tracks, isolated μ, $Z \rightarrow \mu\mu$
    - HCAL uniformity: QCD jets
- Understand basic events properties
    - Properties of minimum bias events/underlying event
    - MC tuning
    - PDFs knowledge is the dominant syst. error for many measurements
    - Measure cross-sections: W,Z,tt,QCD jets (with 10-20% precision)

Constraining PDF's at LHC

1. First step use PDF's from global fits (dominated by DIS Hera data)
2. Measure PDF's at LHC

$N = \mathcal{L}_{pp} \times \mathrm{PDF}(q,g) \times \sigma_{q,g \to X}$ $M^2 = s x_1 x_2$ and $Y = 1/2 \ln(x_1/x_2)$

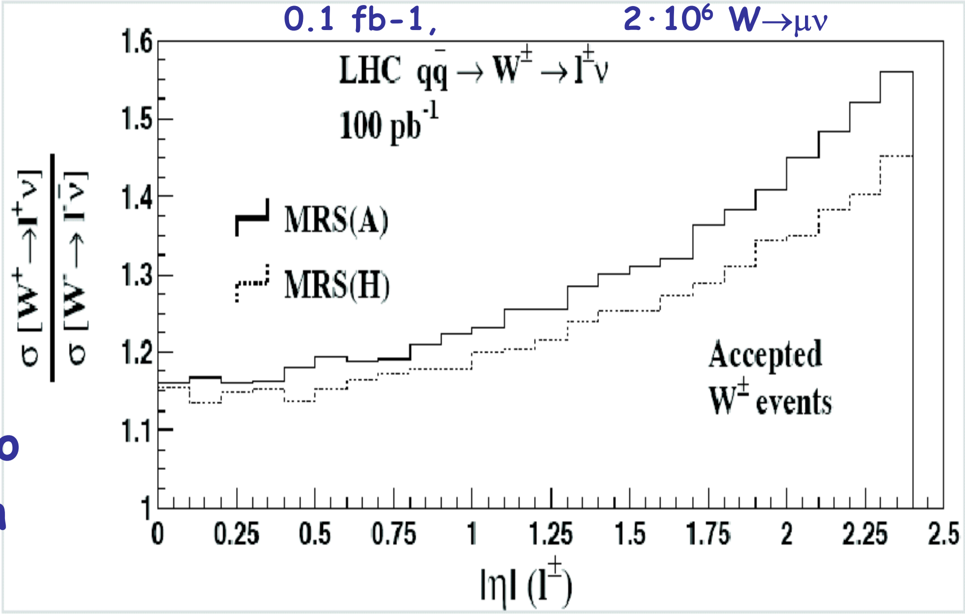
syst: ~ 5% $\mathcal{L}_{pp}$ (1% TOTEM) + theoretical errors on x-sections

Alternatively @LHC measure parton luminosites: uncertainties reduced to 1%.

Use W/Z as $q,\bar{q}$ Luminosity Monitor.

$u\bar{d}$ ($d\bar{u}$) → W^+(W^-) → $\ell^+\nu$ ($\ell^-\bar{\nu}$) ,
$d\bar{d}$ ($\bar{u}u$) → Z → $\ell\ell$

η distribution is very sensitive even to small differences in sea q distribution
$|\eta| < 2.5$ implies $0.0003 < x < 0.1$


0.1 fb-1, $2 \cdot 10^6$ $W \to \mu\nu$

Constraining PDF's at LHC

Process:	PDF of:	Comments
b/c Jet + γ	b/c	$0.0005<x_{b,c}<0.1$ err=5-10% c/b tag eff.
c Jet + W	s	$0.0005<x_s<0.1$ err=5-10% c tag eff.
Jet + γ	gluons	Large π^0 backg , theory? err=few %?
Jet + Z	q & gluons	lower statistics but cleaner than Jet + γ err=1% $0.0005<x_g<0.2$
Leptonic W/Z	q	$0.0003<x_s<0.1$ err=1%
σ_{W+}/σ_{W-}	u(x)/d(x)	at large y

- Careful: at present photons are not used in PDFs determinations
- Negligible statistical errors
- Δ(eff,bkg)~1% difficult but possible
- Mandatory to include higher order QCD corrections,
- Gluon measurements always correlated to α_s determination

Conclusions

- At LHC large statistics and large centre of mass energy are favoring Gauge-boson physics:
  - Important tests of the electroweak sector of the SM can be provided.
  - Competitive EW precision measurement can also be performed.

- Systematic effects are the dominating errors at LHC

- It is mandatory in the initial phase to:
  - understand the detector: most challenging is the knowledge to 0.02% of the lepton energy scale needed for a precise M_W measurement
  - determine PDF's

- Last but not least: we need improvement on the generator side:
  - QCD and QED higher order corrections

Thank Marcel Vos and Craig Buttar for the very useful discussions

BACK-UP TRANSPARENCIES

WWγ coupling

New strategy: limits given in terms of diboson invariant mass cutoff assuming constant form factor ($\Lambda_{FF} = \infty$)

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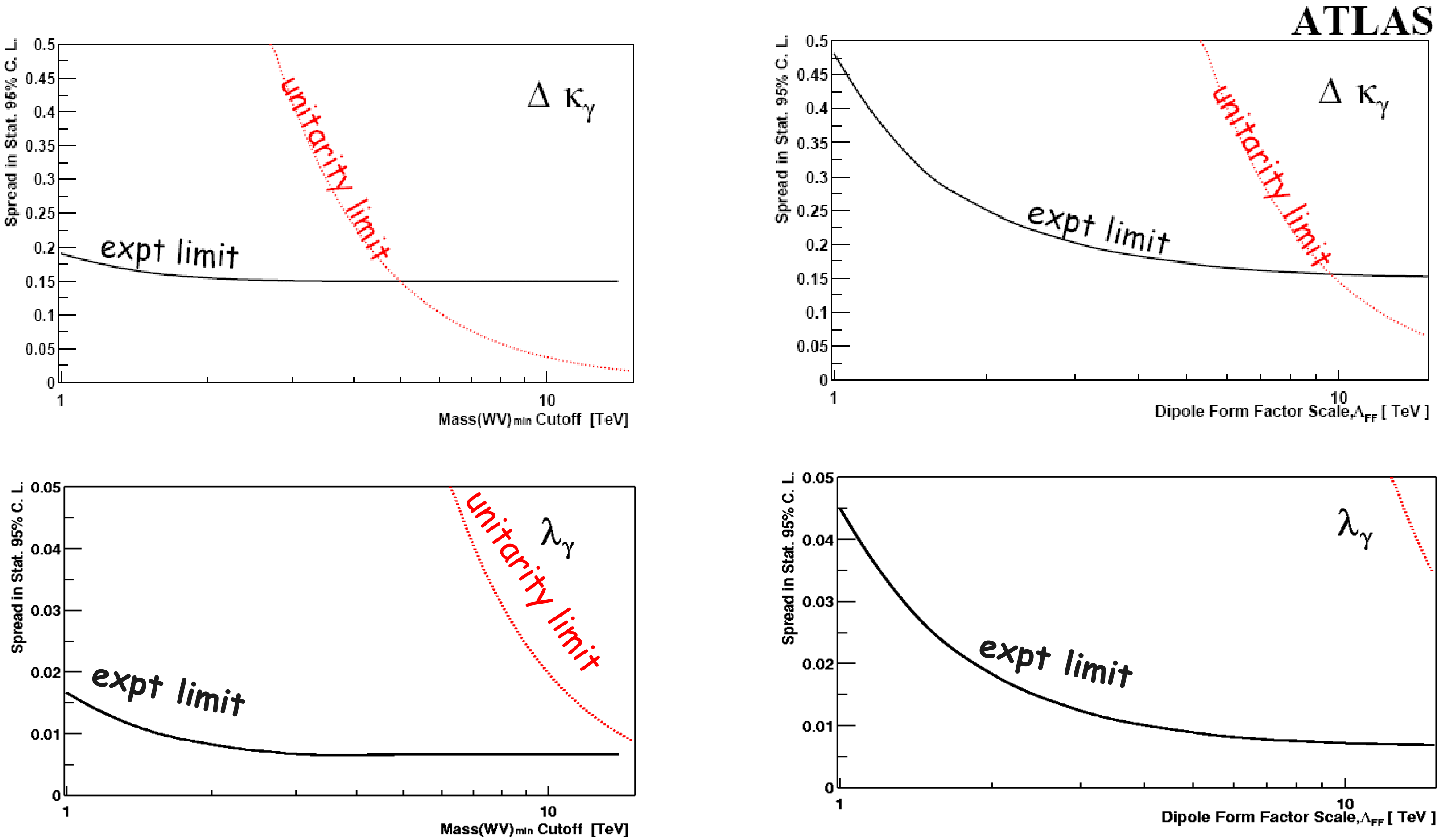
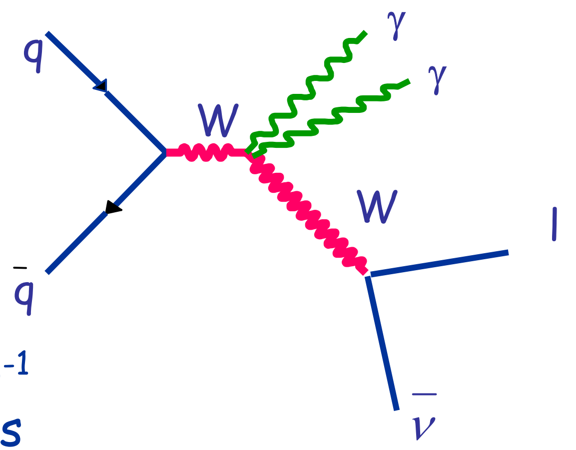


Tri-boson production

pp→WWW	difficult 3 neutrinos
pp→WWZ	difficult 2 neutrinos
pp →WZZ	few events~ 2.7 on 100fb^{-1}
pp →ZZZ	few events~ 0.6 on 100fb^{-1}
pp →W$\gamma\gamma$	preferred channel 30 events on 30fb^{-1} after efficiency and detector effects



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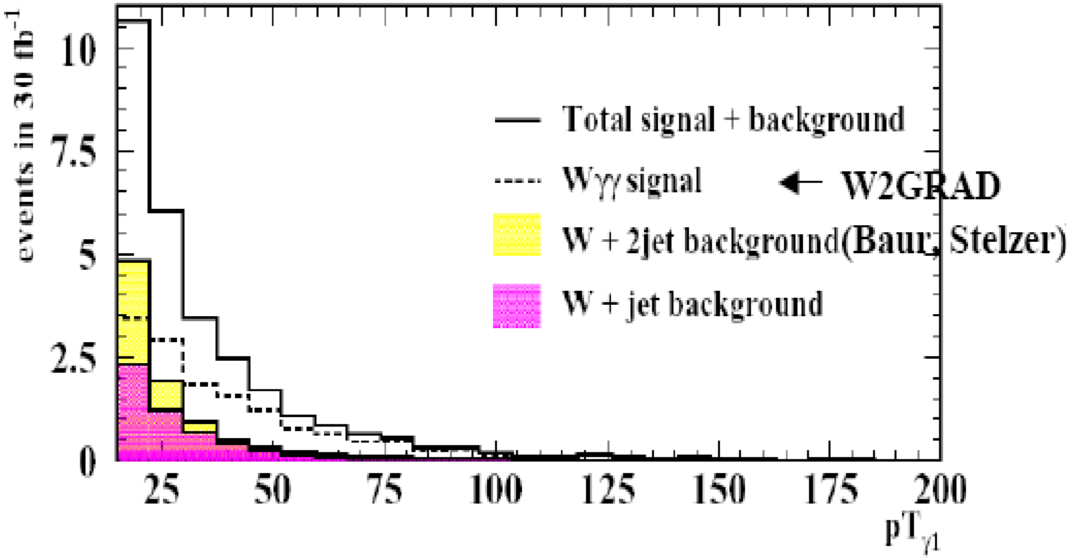
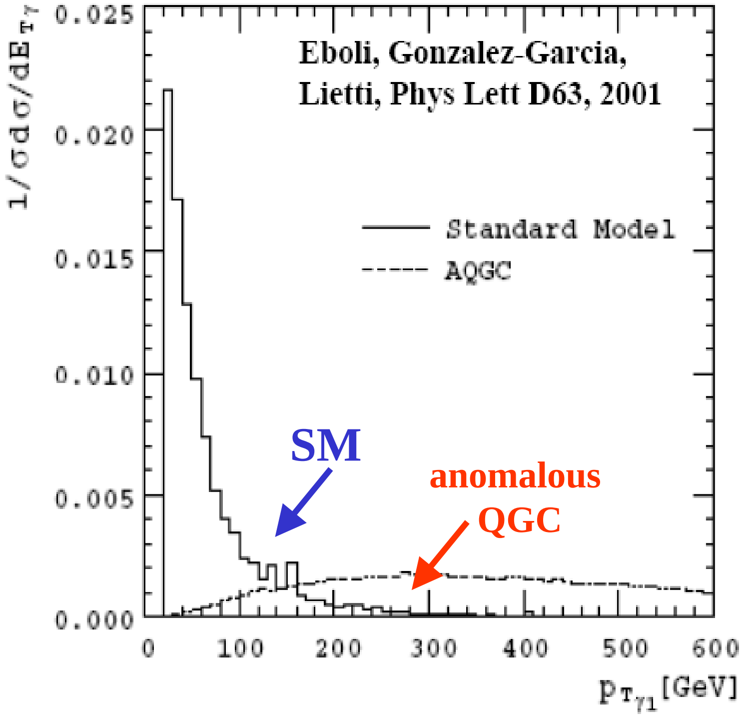


Eboli, Gonzalez-Garcia, Lietti, Phys Lett D63, 2001



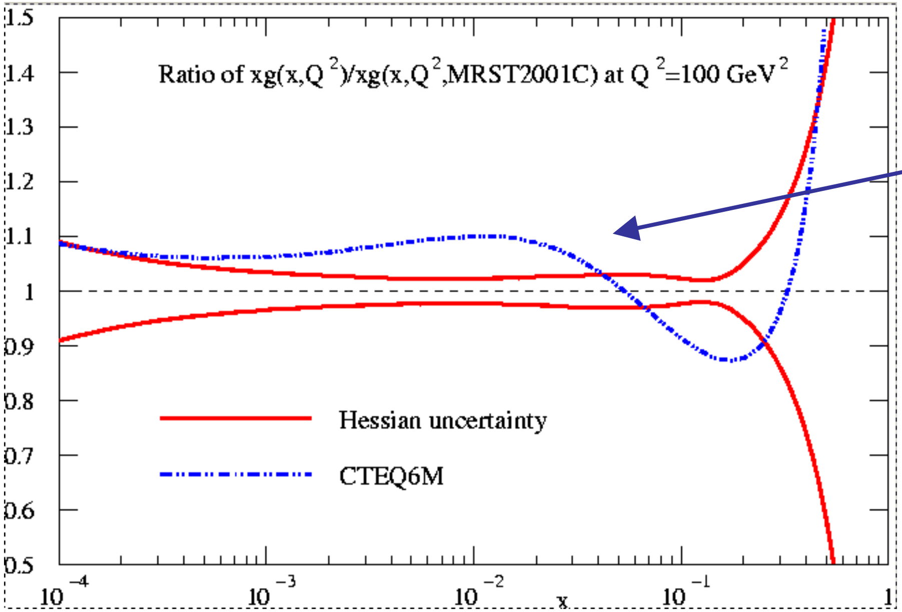
First years of running

- Calibration and alignment: day one performance

	Performance day 1	Physics sample
ECAL uniformity e/γ scale	~1% (ATLAS),4% CMS 1-2%	Minimum bias, Z→ee Z→ee
HCAL uniformity Jet scale	2-3% <10%	Single pions, QCD jets Z→ll+1j, W→jj (tt events)
Tracking alingment	~500μm	Generic tracks, isolated μ Z→μμ

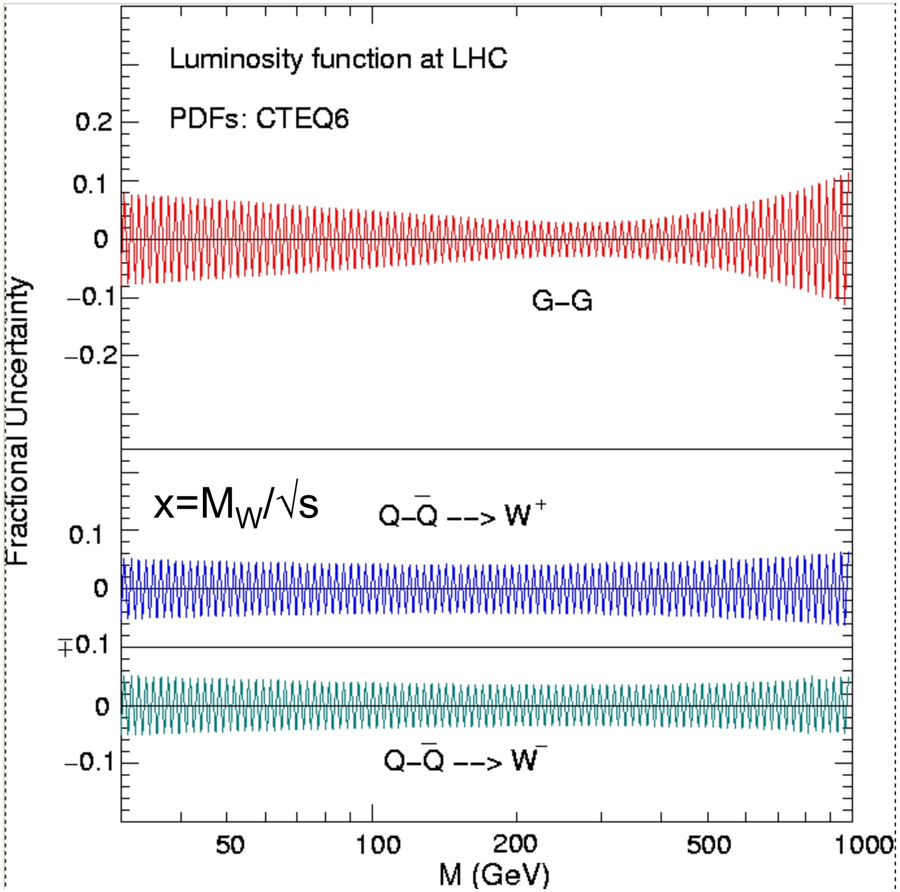
Ultimate statistical precision obtainable is reached in few days..
Then face systematics.

PDF present status



The gluon PDF central fit of CTEQ is not Contained in the error band of MRST

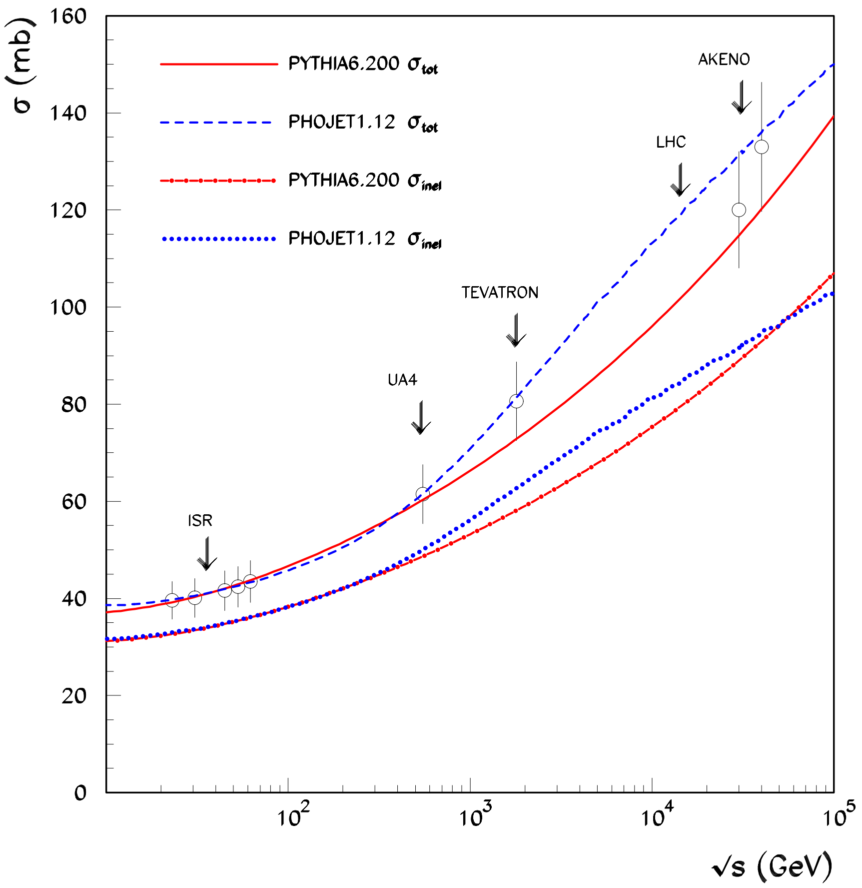
The CTEQ parton luminosity error of gg ud and d$\bar{u}$



Minimum bias events

- Minimum Bias event: no high-p_T signature
- Combination of several physical processes: mainly non-diffractive inelastic, double diffractive
- Understanding of minimum bias events: agreement at 20% level

  comparing predictions of PYTHIA and PHOJET, QCD+multi-parton vs DPM+multi-chain fragmentation



- At low lumi 1.5 MB event/crossing
- At high lumi 15 MB events/ crossing

Underlying event

- important for energy corrections, central jet veto
- Underlying event associated with 'hard'-scatters:

  Beam remnants, ISR. Related to multi-parton interactions as from CDF studies.
- Multi-parton interactions are a good model
- We can define parameters by comparing PYTHIA model to
  - min-bias data from ISR, SppS, Tevatron;
  - underlying event data from HERA and Tevatron
- Need to look at other data to try resolve ambiguities on the best way to fit the data
- Need to determine energy dependence to allow extrapolation to the LHC
- Put data into JETWEB to make quantitative comparisons

Alignment

- With cosmics and One beam running one can exceed initial survey

  Precision by 10-100μm
  - Cosmic running for 40 days equivalent to a few days of 10 Hz 6 GeV muon trigger: good statistics to start some initial alignment/calibration
  - One-beam running for 2 months: track statistics equivalent to hadrons from few days at 10^{33}, p_t spectrum softer (if we can trigger on them)
    - More realistic: track distributions similar to those from collider running (unlike cosmics)
- First collisions:
  - Statistics is not the issue
  - Systematics and understanding will be the key issue: bringing together the knowledge from survey, tracking and FSI
  - Precision rough guess:100 μm – 2 months; 20 μm – 4 months; 5 μm – 1 year
- Other things to be done with initial low luminosity running
  - Start to understand ID material distributions
    - Reconstruct photon conversions – map ID material distribution

Tevatron Run I M_W and Γ_W

- Results incorporate correlated and uncorrelated errors

hep-ex/0311039

Correlated uncertainties due to production and decay model

Mass	CDF	D0	Width	CDF	D0
PDF	15	8	PDF	15	27
Rad. Corr.	11	12	Rad corr	10	10
Γ_W	10	10	M_W	10	15

Correlated uncertainty 19 MeV 26 MeV

M_W=80.454±0.059 GeV Γ_W =2.115 ±0.105 GeV

Uncorrelated uncertainties:
Lepton E scale and resolution
$P_T(W)$, recoil model
selection bias and bkg

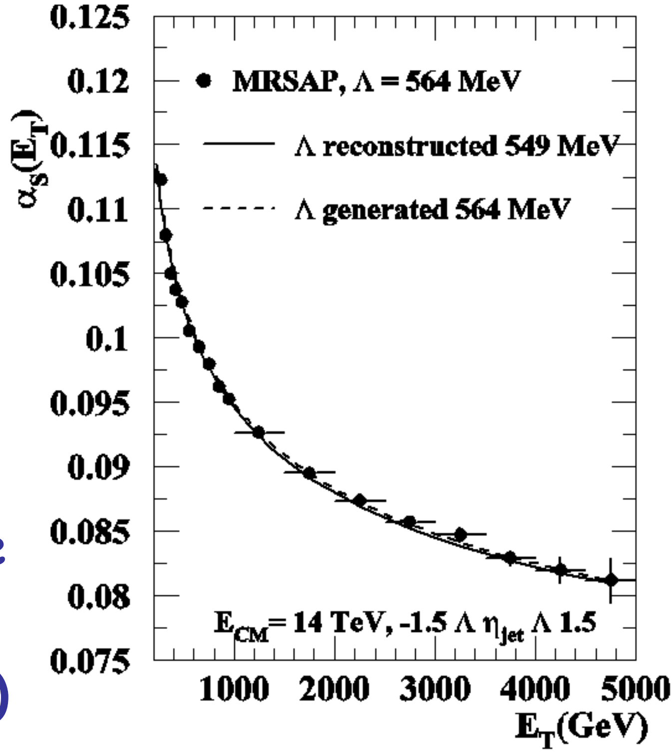
Measurement of α_s

Measurement of α_s at LHC limited by

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

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

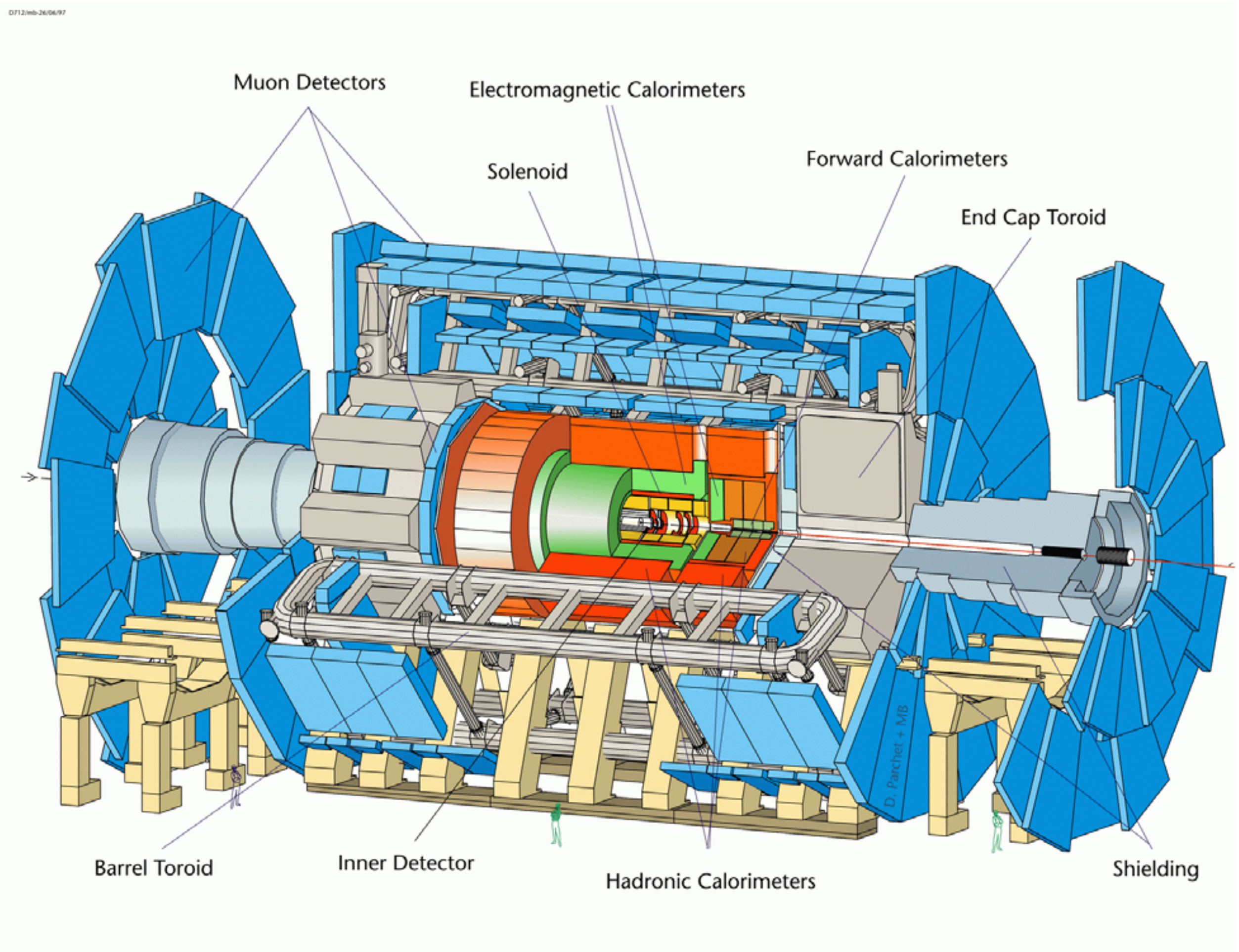
- 10% accuracy $\alpha_s(m_Z)$ from incl. jets
- Improvement from 3-jet to 2-jet rate?



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)

ATLAS: Design and Performance



Precision physics in $|\eta|<2.5$

Magnetic Field

2T solenoid plus air core toroid

Inner Detector

$$\frac{\sigma}{P_T} = 0.05\%\ P_T(GeV) \oplus 0.01$$

Tracking in range $|\eta| < 2.5$

Silicon pixels and Strips & TRT

EM Calorimetry

$$\frac{\sigma}{E} = \frac{10\%}{\sqrt{E(GeV)}} \oplus 1\%$$

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

PB/LAr Accordian

Hadronic Calorimetry

$$\frac{\sigma}{E} = \frac{50\%}{\sqrt{E(GeV)}} \oplus 3\%$$

Barrel:Fe/Scintillating tiles

Endacaps:Cu & W/LArFine

Muon Spectrometer

$\sigma/p_T \sim 2\text{-}7\ \%$

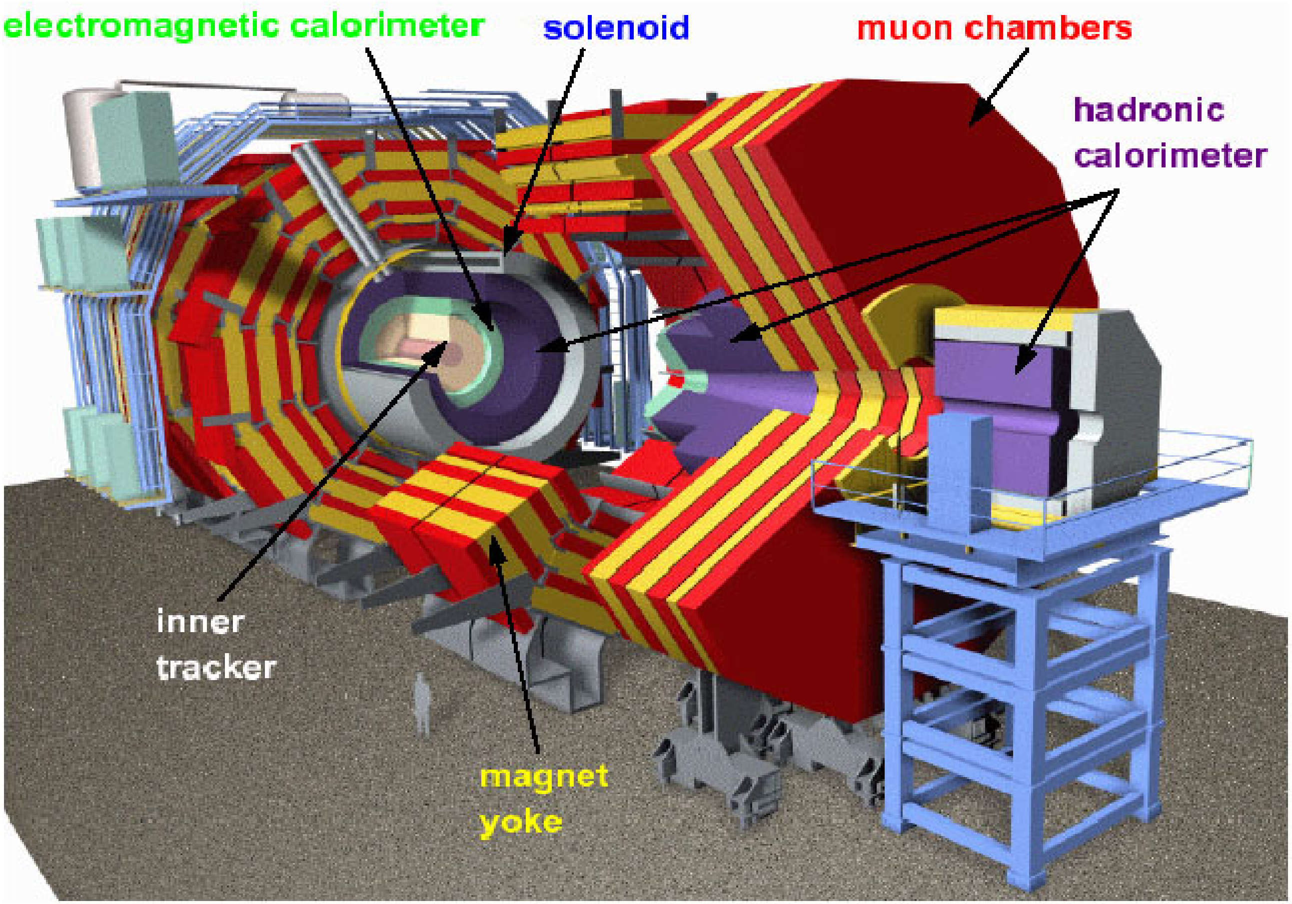
Covers $|\eta| < 2.7$

The CMS Detector

Inner Detector: Silicon pixels and strips $\frac{\sigma}{P_T} = 0.015\%\, P_T(\mathrm{GeV}) \oplus 0.005$

Preshower: Lead and silicon strips

EM Calorimeter: Lead Tungstate $\frac{\sigma}{E} = \frac{2 - 5\%}{\sqrt{E}\,(\mathrm{GeV})} \oplus 2\%$



Hadron Calorimeters:

Barrel & Endcap:

Cu/Scintillating sheets

$$\frac{\sigma}{E} = \frac{65\%}{\sqrt{E}\,(\mathrm{GeV})} \oplus 5\%$$

Forward:

Steel and Quartz fibre

Muon Spectrometer:

$$\frac{\sigma}{P_T} = 5\% \text{ @ } 1 \text{ TeV}$$

Drift tubes, cathode strip chambers and resistive plate chambers

Magnet: 4T Solenoid