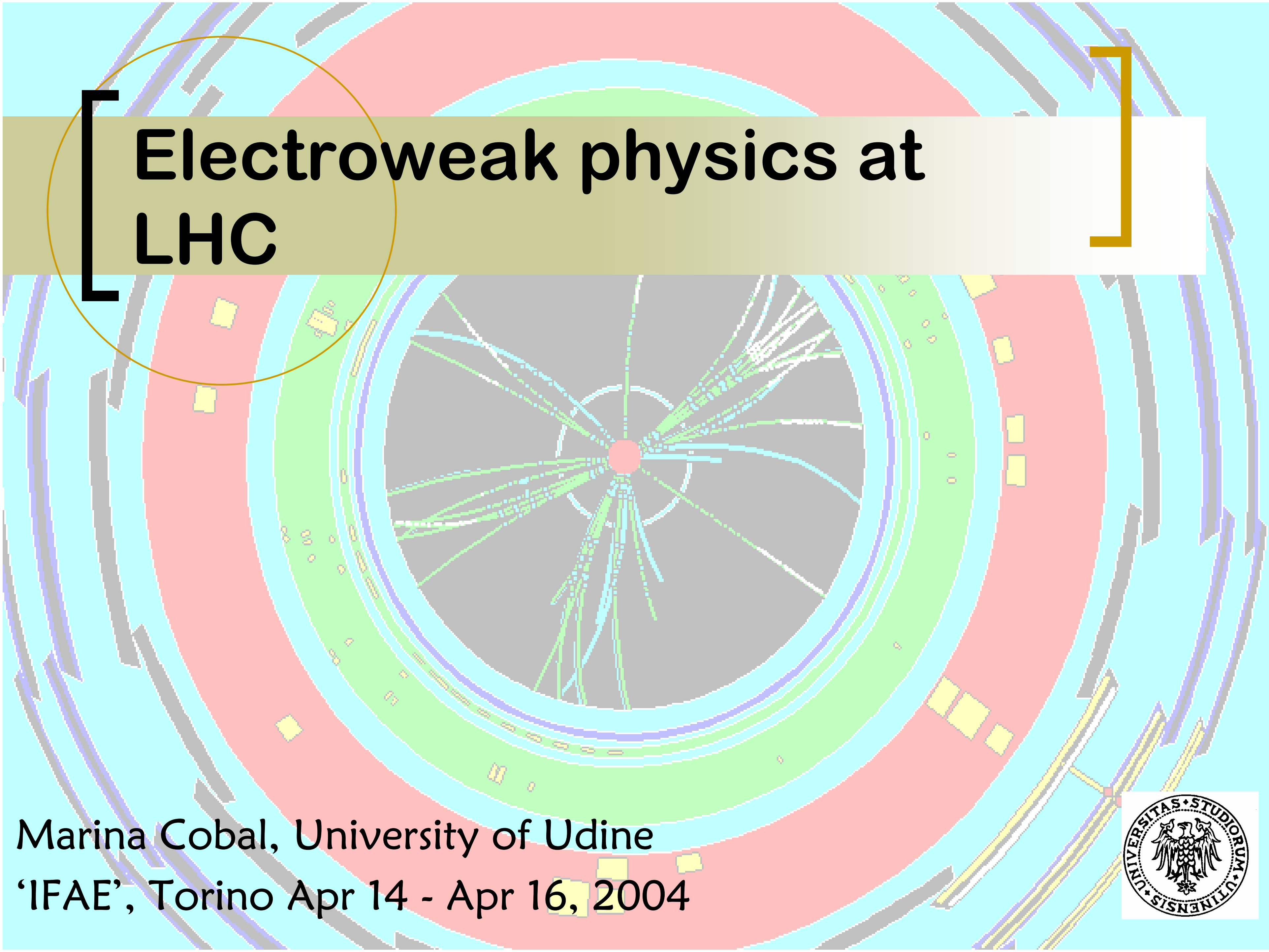
Electroweak physics at LHC



Marina Cobal, University of Udine

'IFAE', Torino Apr 14 - Apr 16, 2004

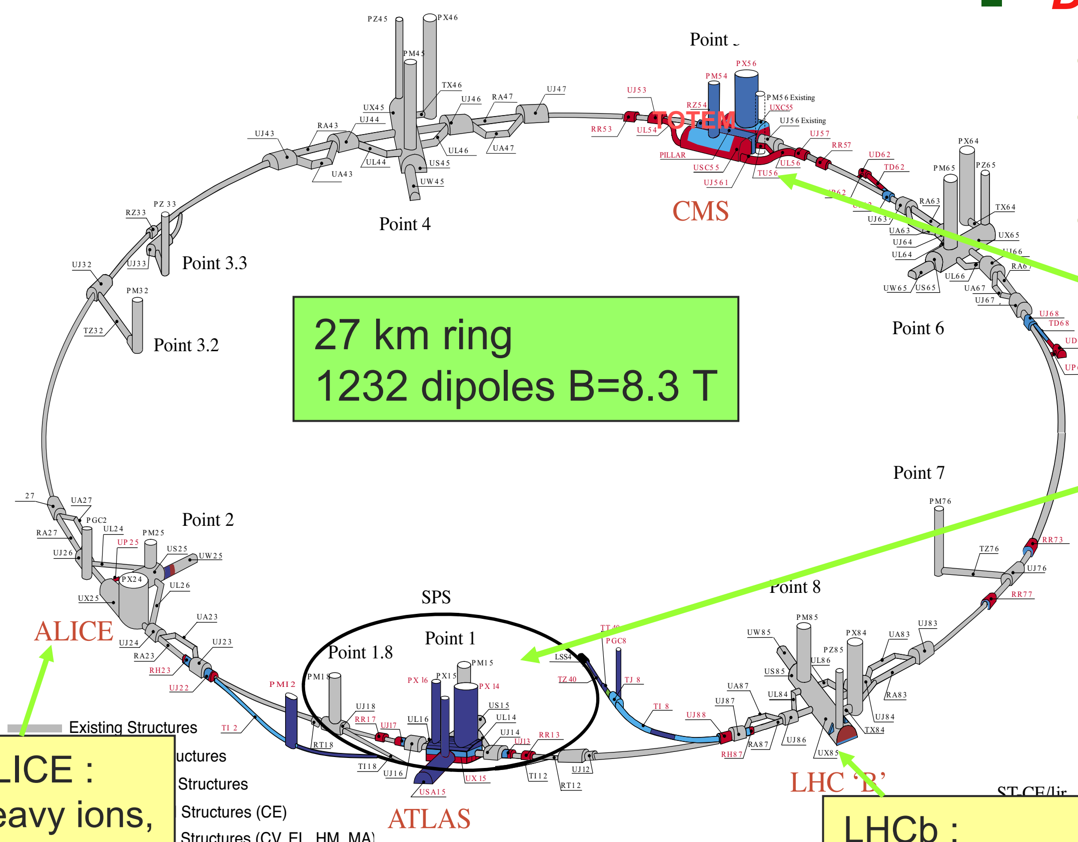
Outline

- Introduction
- W mass measurement
- Top mass measurement
- EW single top quark production: measurement of V_{tb}.
- A_{FB} asymmetry in dilepton production: $\sin^2\theta_{eff}^{lept}(M_Z^2)$.
- Conclusion.

LHC and experiments

- pp (mainly) at $\sqrt{s}$ = 14 TeV
  - Startup in April 2007

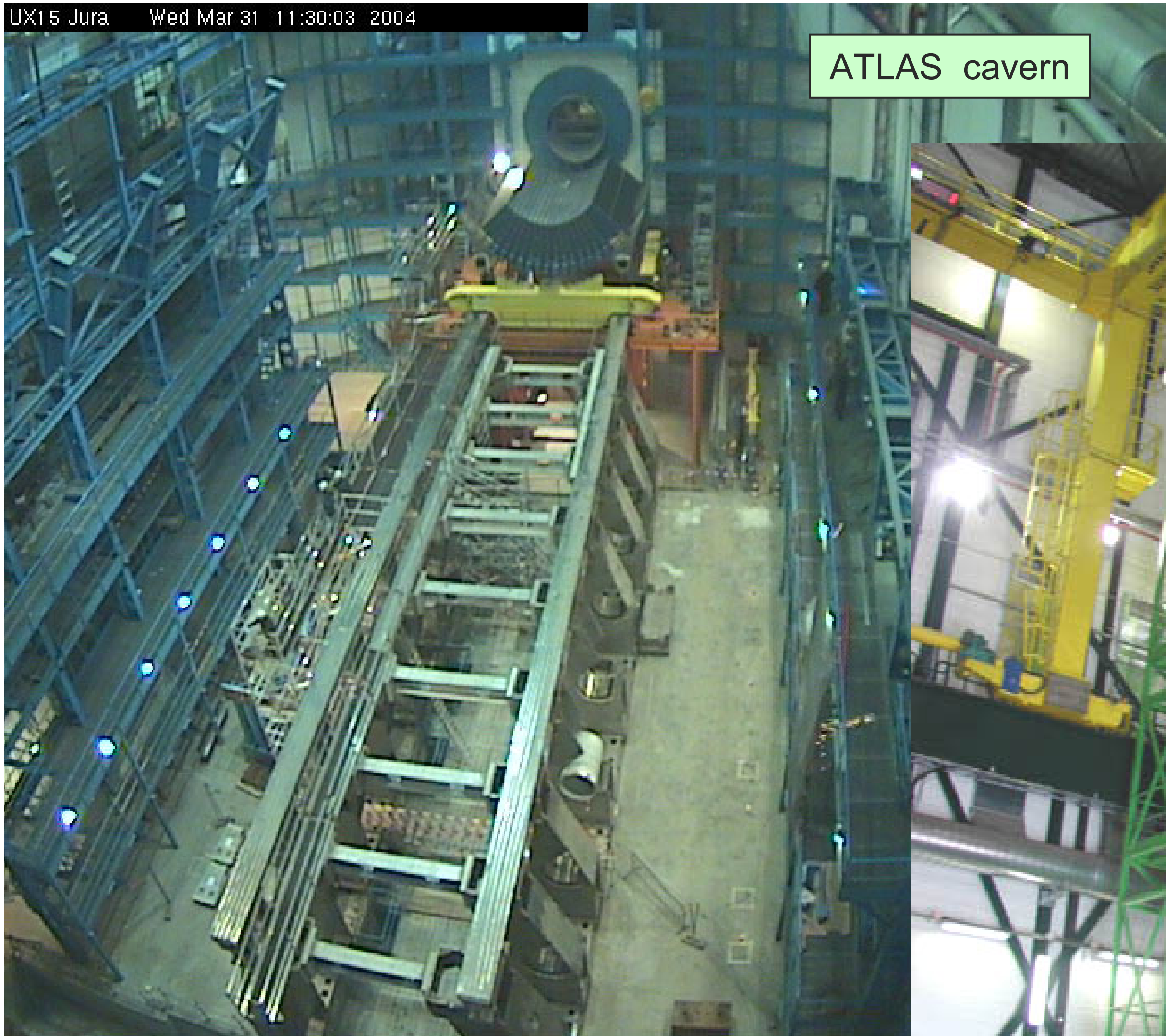
- ***Initial/low lumi*** $\mathcal{L}\sim10^{33}$ cm^{-2} s^{-1}
  - $\leq$ 2 minimum bias/x-ing
    → "Tevatron-like" environment
  - **10 fb^{-1} /year**
- ***Design/high lumi*** $\mathcal{L}=10^{34}$ cm^{-2} s^{-1}
  - after ~ 3 years
  - ~ 20 minimum bias/x-ing
    → fast ($\leq$ 50 ns) radhard detect
  - **100 fb^{-1} /year**



ATLAS and CMS :
pp, general purpose

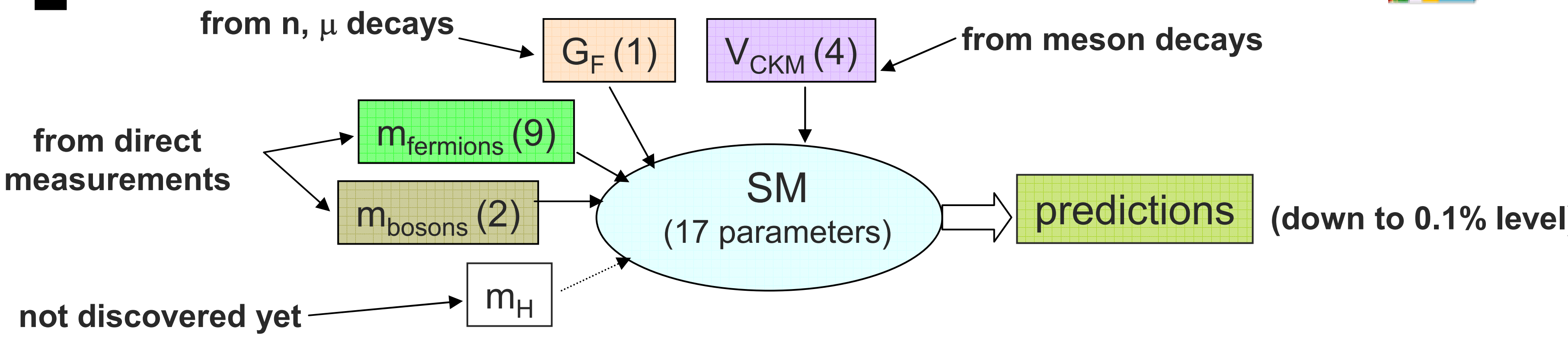
ALICE :
heavy ions,
p-ions

LHCb :
pp, B-physics



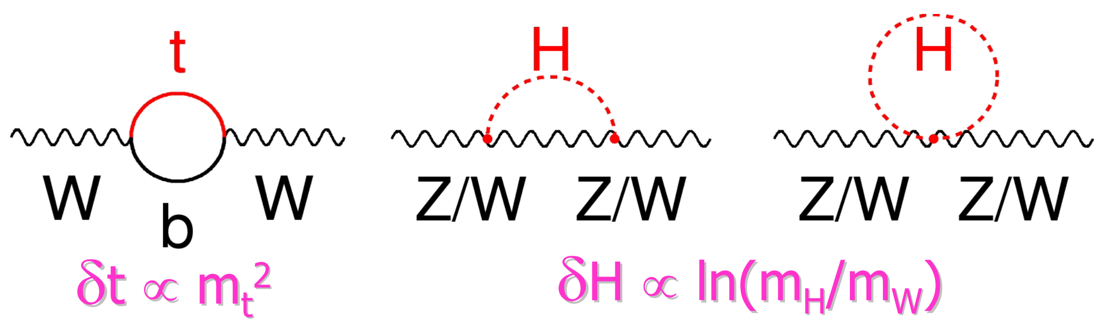
Huge activities in construction of both CMS and ATLAS

What we know



No observable directly related to m_H. Dependence through radiative corrections.

Example: $m_W = m_W(m_t^2, \log(m_H))$



By making precision measurements (already interesting per se):

- one can get information on the missing parameter m_H
- one can test the validity of the Standard Model

Where we are

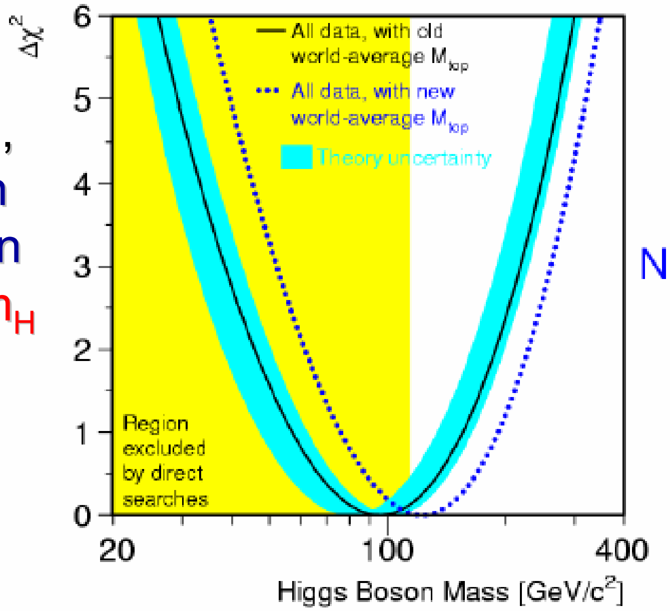
Uncertainties on m_t, m_W are the dominating ones in the ew fit

Each "observable" (A_q, A_l, R_q, R_l, Γ, m, $\sin\theta_W$,…) can be calculated as a function of: $\Delta\alpha_{had}$, $\alpha_s(m_Z)$, m_Z, m_t, m_H

Consequences for Standard-Model Higgs

Precision electroweak data:

Constrain M_H in the MSM



Old:

$$M_{top} = 174.3 \pm 5.1 \text{ GeV}$$
$$\log M_H = 1.98^{+0.21}_{-0.22}$$
$$M_H = 96^{+60}_{-38} \text{ GeV}$$
$$\text{or} < 219 \text{ GeV (95\% CL)}$$

New:

$$M_{top} = 178.0 \pm 4.3 \text{ GeV}$$
$$\log M_H = 2.07^{+0.20}_{-0.21}$$
$$M_H = 117^{+67}_{-45} \text{ GeV}$$
$$\text{or} < 251 \text{ GeV (95\% CL)}$$

(Procedure as in hep-ex/0312023!)

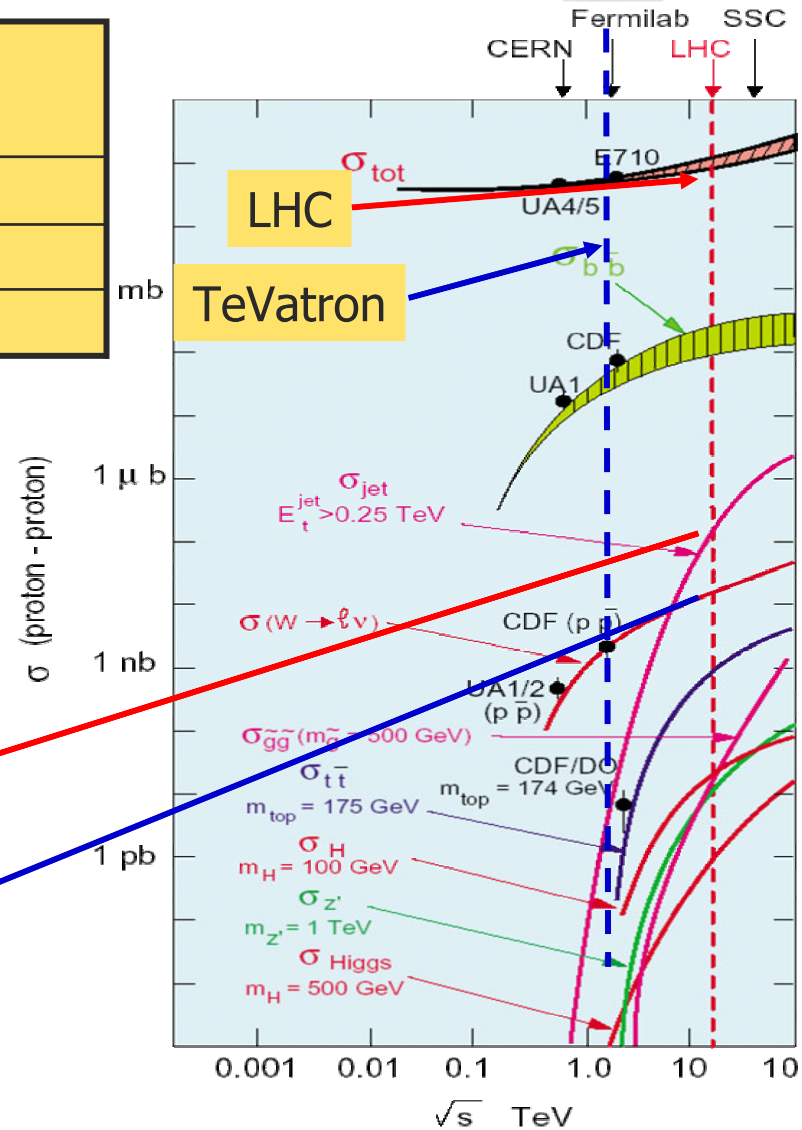
At the Tevatron run II: $\delta m_t \leq 2.5$ GeV ; $\delta m_W \leq 30$ MeV $\Rightarrow \delta m_H/m_H \leq 35\%$

What can we expect/should be our goal at LHC?

Predictions

	√s [TeV]	Luminosity [cm^{-2}s^{-1}]	∫L [fb^{-1}/y]
TeVatron	2	<10^{32}	0.3
LHC (low lum)	14	10^{33}	10
LHC (high lum)	14	10^{34}	100

process	σ(pb)	Events/s	Events/y
$b\bar{b}$	5×10^8	10^6	10^{13}
Z→ee	1.5×10^3	~3	10^7
W→ℓν (ℓ=e,μ)	3×10^4	~60	10^8
WW→eνX	6	10^{-2}	10^5
$t\bar{t}$	830	~1.7	10^7
H(700 GeV/c^2)	1	2×10^{-3}	10^4



M_W measurement at the LHC

year 2004: $\Delta M_W \approx 30$ MeV , year 2007: $\Delta M_W < 30$ MeV (Lep2+Tevatron)

- m_{top} and M_W: equal weight in the EW fit if $\Delta M_W \approx 0.007\ \Delta m_{top}$

  at LHC: $\Delta m_{top} \leq 2$ GeV gives the precision **$\Delta M_W : \leq 15$ MeV**

- Methods: same as at the Tevatron, with $W \to l\nu$ decays

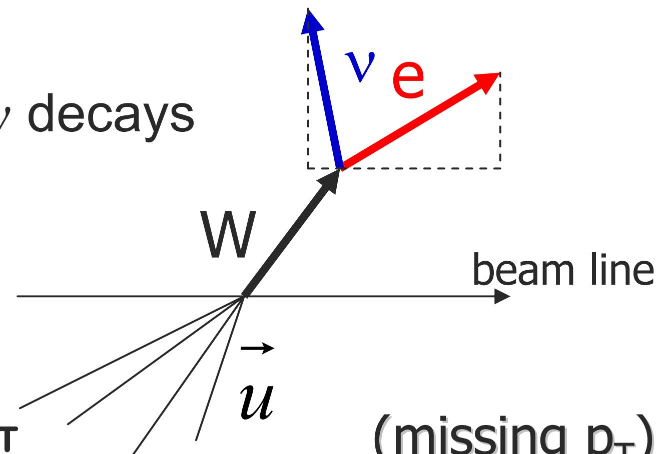
  but LHC statistics is higher

  $W \to l\nu$ 60 M reconstructed @ low $\mathcal{L}$ (x10 RunII)

  ✓ P^T_l spectrum **Pile-up , theo. know. of P^T_W**

  ✓ $R = M^T_W / M^T_Z$ spectrum **Small syst, sample /10**

  ✓ M^T_W **Best choice for low lum phase**



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

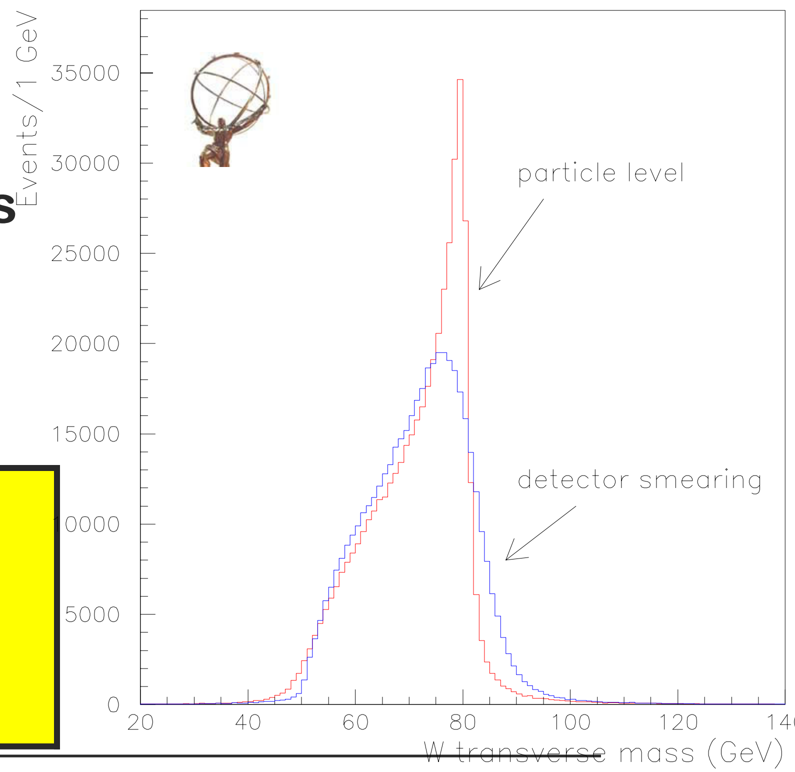
M_W measurement: Transverse Mass

- ✓ Use Transverse mass to cope with unmeasured P^L_ν

$$M_W^T = \sqrt{2 p_T^l \underbrace{p_T^\nu}_{P_T^{miss}} (1-\cos\Delta\phi^{l,\nu})} \qquad l=e,\mu$$

- ✓ W mass : fit exp. shape to MC sample with different Values of M_W
- ✓ stat. error negligible
- ✓ syst. error: MC modelling of the physics and the detector responses

physics		detector	
P^T_W spectrum PDF W width W rad. decays Background	Z→ll LHC data Z→ll,R,CDF/D0 Theory, MC	Lep. E/p Lep. res. Recoil	Z→ll, E/p for e± Z→ll, E/p for e± Z→ll



Advantages of LHC

Profit from Tevatron experience:

Many potential hidden sources of systematics from the detector description in the simulations (+pile-up, + radiation)

⇒ use data samples for in-situ calibrations !

Advantages of the LHC:

Huge statistics of signal & control samples like Z leptonic decays:

⇒ Larger production cross-section for the control process $Z \to (e/\mu)(e/\mu)$ (6 millions/y/exp)
⇒ granularity + acceptance + resolution are better

Error from control samples at the LHC < than at the Tevatron

Detector systematics

0.02% on lepton E/p scale precision needed

$\Rightarrow$ $Z \to ee$, $Z \to \mu\mu$ mass reconstruction
$\Rightarrow$ leptonic decays of Υ, J/ψ

~15 MeV/y-e-l can be reached

… and ~1-2% uncertainty in E+p resolution

$\Rightarrow$ Z width reconstruction
$\Rightarrow$ beam tests data

low extrapolation error $Z \to W$

~5 MeV/y-e-l can be reached

Recoil modelling (UE + detector)

$\Rightarrow$ determine response/resolution of the recoil (+UE) from $Z \to \ell\ell$ data

~5 MeV/y-e-l can be reached

Physics systematics

$p_T(W)$

$\Rightarrow$ use $p_T(Z)$ from $Z\rightarrow\ell\ell$, use $p_T(W)/p_T(Z)$ to model MC.

~5 MeV/y-e-l can be reached

Uncertainties on the parton density functions

$\Rightarrow$ Compare different models, constrain pdfs through Z+W data

~10 MeV/y-e-l can be reached

W width

$\Rightarrow$ use measurement of

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

$BR(W \rightarrow \ell\nu)$: Implicit SM assumption to determine Γ_W

$BR(Z \rightarrow \ell\ell)$: From LEP

σ_Z: From theory

<10 MeV/y-e-l can be reached

Radiative decays

$\Rightarrow$ constrained through $W\rightarrow\ell\nu\gamma$?

<10 MeV/y-e-l, theory work needed

Background

$\Rightarrow$ checks on Z and $W\rightarrow\tau\nu$
(composition similar to Tevatron)

<5 MeV/y-e-l should be reached

M_W measurement: errors

- M_W , $W \to l\nu$ one lepton species low lum , per exp., per year

source	CDF RunIb	LHC
	30K evts,84pb⁻¹	*60M evts,10fb⁻¹*
Statistics	65 MeV	<2 MeV
Lepton scale	75 MeV	15 MeV
Energy resolution	25 MeV	5 MeV
Recoil model	37 MeV	5 MeV
Lepton id.	----------	5 MeV
P^T_W	15 MeV	5 MeV
PDF	15 MeV	10 MeV
W width	----------	7 MeV
Radiative decays	20 MeV	<10 MeV
Background	5 MeV	5 MeV
TOTAL	92 MeV	< 25 MeV

Much better!

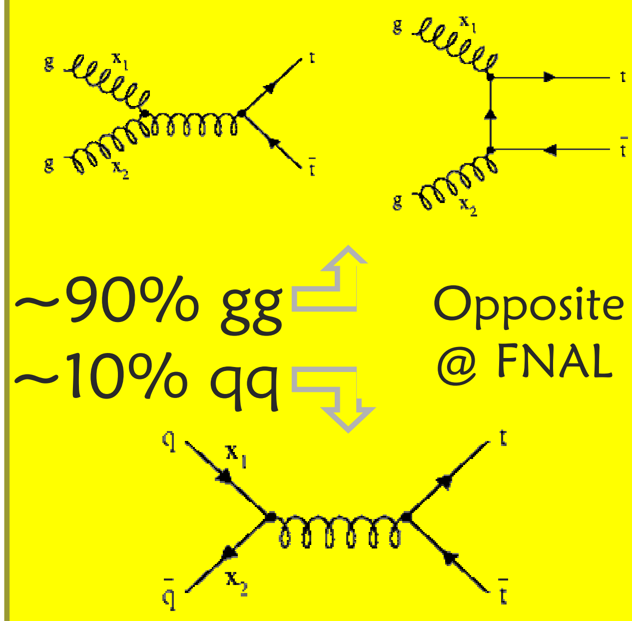
Internal calibration from Z data mainly.
Need excellent control of energy flow+ p scale

- Combining channels and exp., should reach $\Delta M_W \approx 15$ MeV

M_{top} measurement: production

- Cross section determined to NLO precision
  - Total $\sigma_{NLO}(tt)$ = 834 ± 100 pb
  - Largest uncertainty from scale variation
- Compare to other production processes:

$$\hat{s} = s x_1 x_2 \quad ; \quad x_1 x_2 \sim 10^{-3}$$



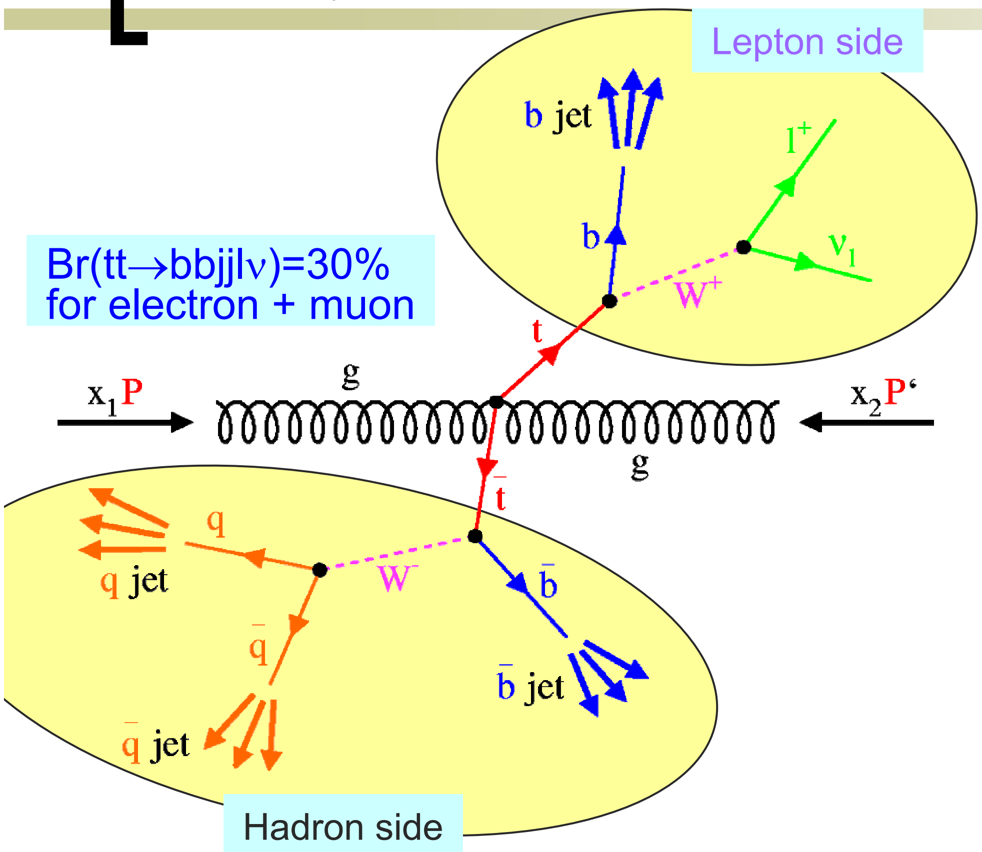
Low lumi

Process	N/s	N/year	Total collected before start LHC
W→ eν	15	10^8	10^4 LEP / 10^7 FNAL
Z→ ee	1.5	10^7	10^7 LEP
tt	1	10^7	10^4 Tevatron
bb	10^6	10^{12-13}	10^9 Belle/BaBar ?
H (130)	0.02	10^5	?

- Top production cross section approximately 100x Tevatron

LHC is a top factory!

M_{Top} from lepton+jet



Br(tt→bbjjlν)=30%
for electron + muon

Typical selection efficiency: ~5-10%:

- Isolated lepton P_T>20 GeV
- E_T^{miss}>20 GeV
- 4 jets with E_T>40 GeV
- >1 b-jet ($\varepsilon_b \approx 40\%$, $\varepsilon_{uds} \approx 10^{-3}$, $\varepsilon_c \approx 10^{-2}$)

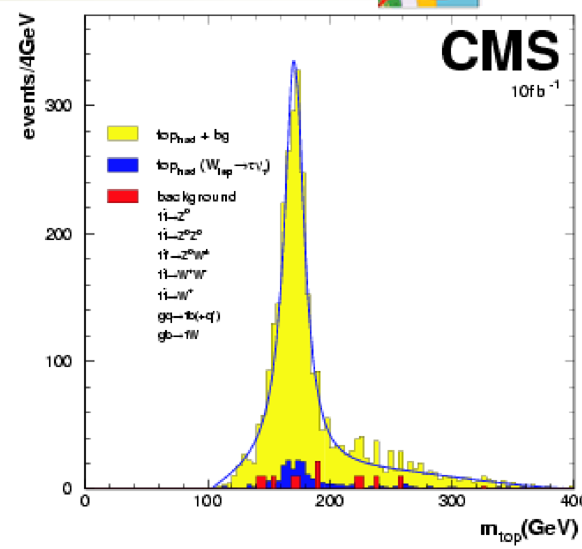
Background: <2%

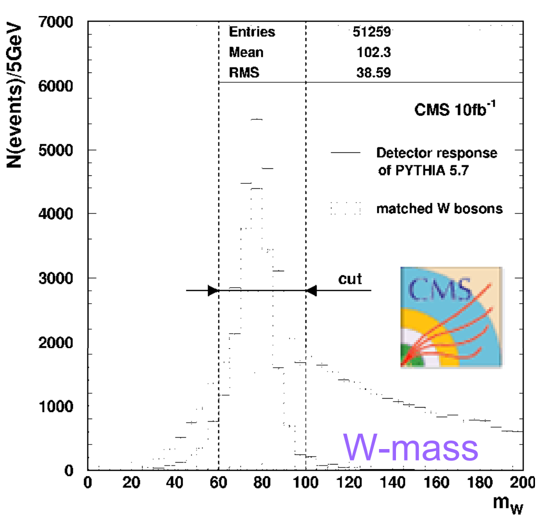
W/Z+jets, WW/ZZ/WZ

- Golden channel
  - Clean trigger from isolated lepton
- The reconstruction starts with the W mass:
  - different ways to pair the right jets to form the W
  - jet energies calibrated using m_W
- Important to tag the b-jets:
  - enormously reduces background (physics and combinatorial)
  - clean up the reconstruction

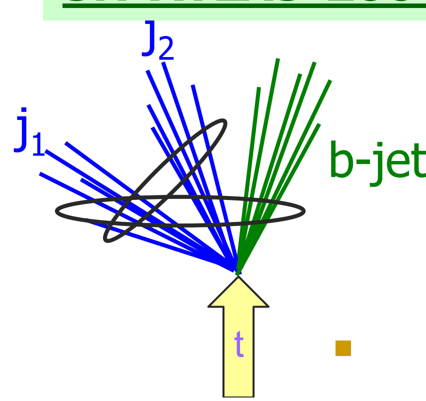
Lepton + jet: reconstruct top

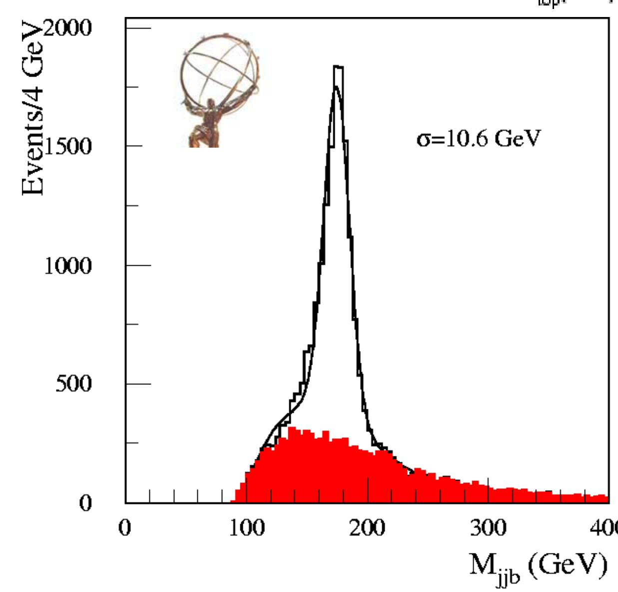
- Hadronic side
  - W from jet pair with closest invariant mass to M_W
    - Require $|M_W - M_{jj}| < 20$ GeV
  - Assign a b-jet to the W to reconstruct M_{top}
- Kinematic fit
  - Using remaining l+b-jet, the leptonic part is reconstructed
    - $|m_{l\nu b} - \langle m_{jjb} \rangle| < 35$ GeV
    - Kinematic fit to the tt hypothesis, using M_W constraints





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

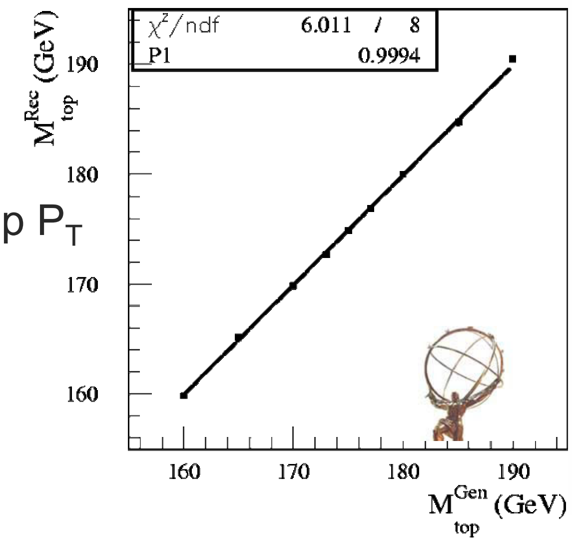


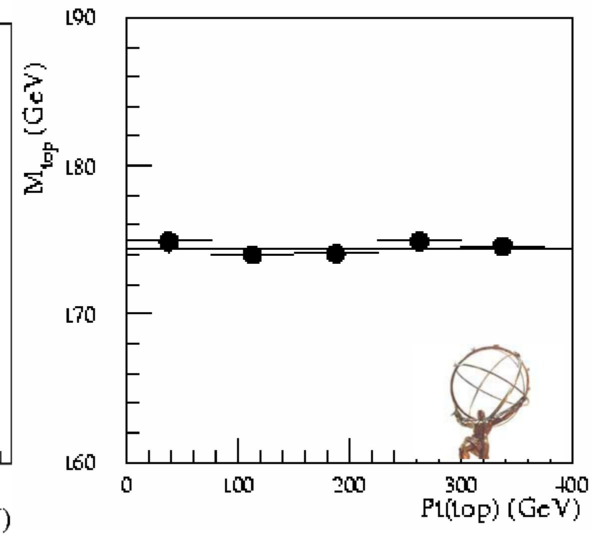


- Selection efficiency 5-10%

M_{top} systematics

- Method works:
  - Linear with input M_{top}
  - Largely independent on Top P_T





- Biggest uncertainties:
  - Jet energy calibration
  - FSR: 'out of cone' give large variations in mass
  - B-fragmentation

- Verified with detailed detector simulation and realistic calibration

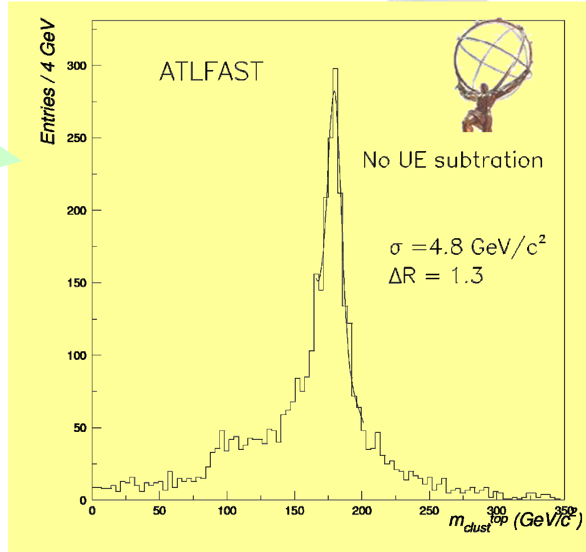
Source of uncertainty	Hadronic δM_{top} (GeV)	Fitted δM_{top} (GeV)
Light jet scale	0.9	0.2
b-jet scale	0.7	0.7
b-quark fragm	0.1	0.1
ISR	0.1	0.1
FSR	1.9	0.5
Comb bkg	0.4	0.1
Total	2.3	0.9

Challenge:

determine the mass of the top around 1 GeV accuracy in one year of LHC

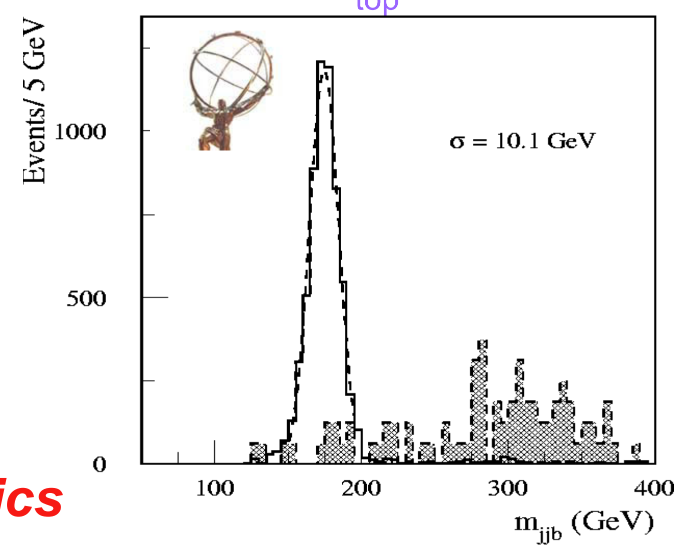
Alternative mass determination

- Select high P_T back-to-back top events:
  - Hemisphere separation (bckgnd reduction, much less combinatorial)
  - Higher probability for jet overlapping



M_{top}

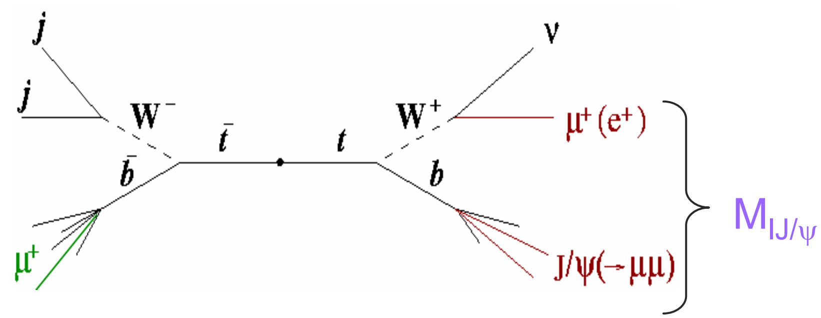
- Use the events where both W's decay leptonically (Br~5%)
  - Much cleaner environment
  - Less information available from two ν's
- Use events where both W's decay hadronically (Br~45%)
  - Difficult 'jet' environment
  - Select P_T>200 GeV

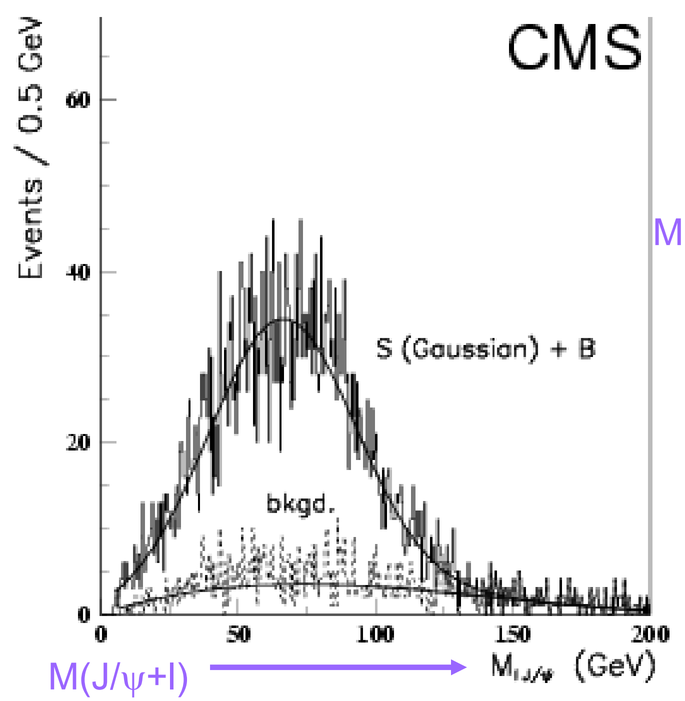


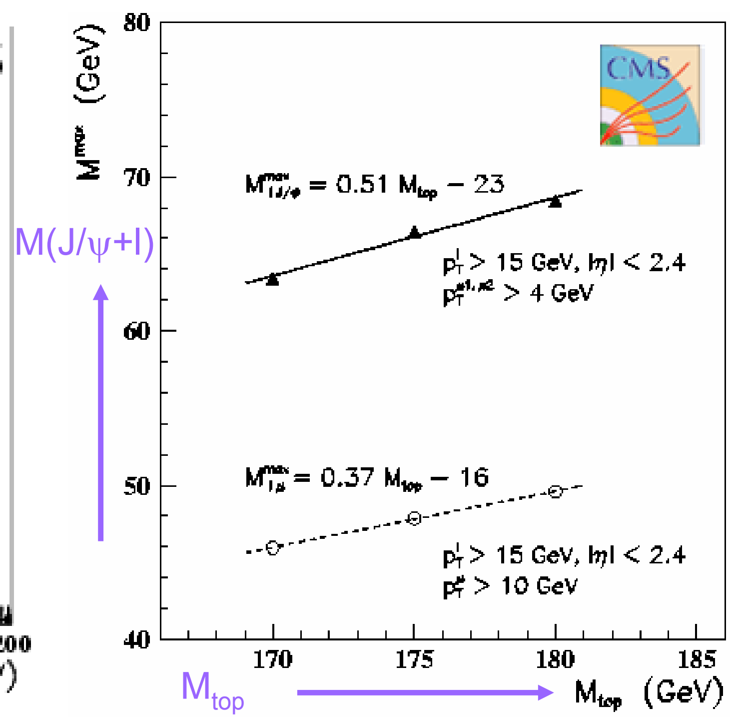
Various methods all have different systematics

M_{top} from J/ψ

- Use exclusive b-decays with high mass products (J/ψ)
  - Higher correlation with M_{top}
  - Clean reconstruction (background free)
  - $BR(t\bar{t} \to qqb\ell\nu + J/\psi \to \ell\ell) \approx 5\ 10^{-5}$
  - $\varepsilon \sim 30\% \Rightarrow 10^3$ ev./100 fb-1 (need high lumi)







Different systematics (almost no sensitivity to FSR)

Uncertainty on the b-quark fragmentation function becomes the dominant error

Commissioning the detectors

- Determination M_{Top} in initial phase
  - Use 'Golden plated' lepton+jet

Period	Stat δM_{top} (GeV)	Stat $\delta\sigma/\sigma$
1 year	0.1	0.2%
1 month	0.2	0.4%
1 week	0.4	2.5%

- Selection:
  - Isolated lepton with P_T>20 GeV
  - Exactly 4 jets (ΔR=0.4) with P_T>40 GeV
- Reconstruction:
  - Select 3 jets with maximal resulting P_T

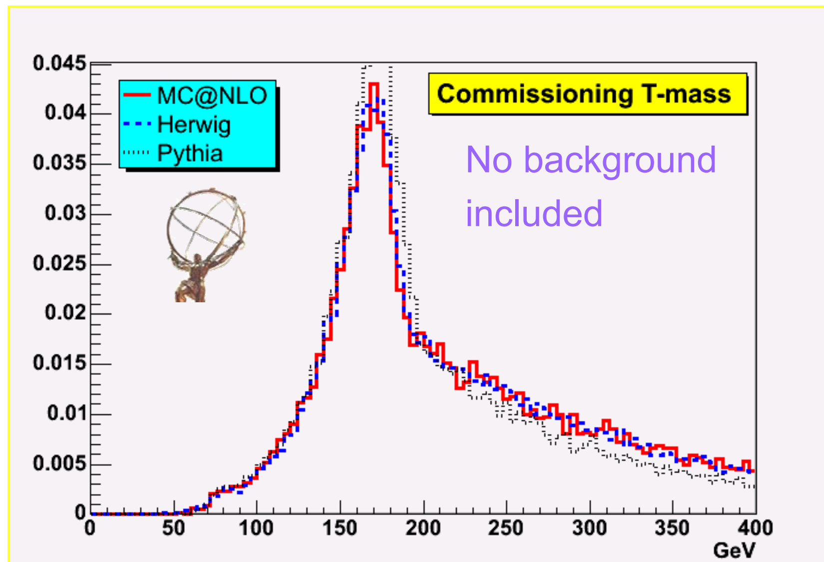
Calibrating detector in comissioning phase

Assume pessimistic scenario:

-) No b-tagging

-) No jet calibration

-) But: Good lepton identification



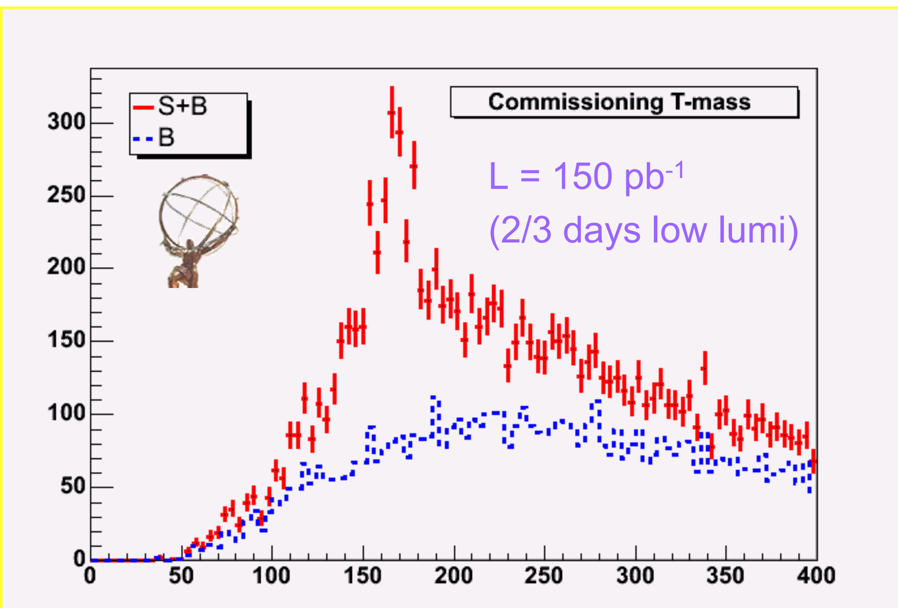
- Signal can be improved by kinematic constrained fit
  - Assuming $M_{W_1}=M_{W_2}$ and $M_{T_1}=M_{T_2}$

Commissioning the detectors

- Most important background for top: W+4 jets
  - Leptonic decay of W, with 4 extra 'light' jets
    - Alpgen, Monte Carlo has 'hard' matrix element for 4 extra jets (not available in Pythia/Herwig)

ALPGEN:
W+4 extra light jets
Jet: P_T>10, $|\eta|$<2.5, ΔR>0.4
No lepton cuts
Effective σ: ~2400 pb

- Signal plus background at initial phase of LHC



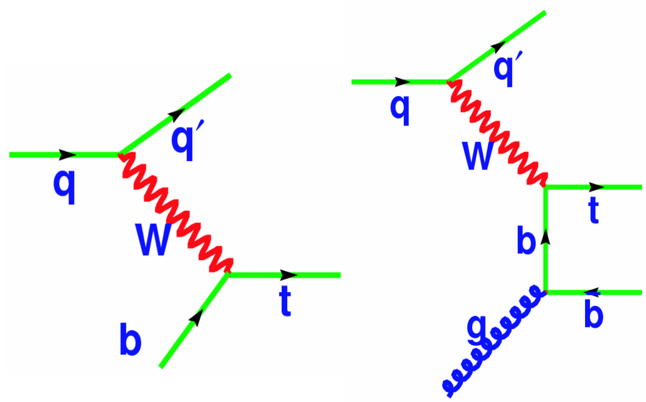
With extreme simple selection and reconstruction the top-peak should be visible at LHC

measure top mass (to 5-7 GeV)
→ give feedback on detector performance

Single top production

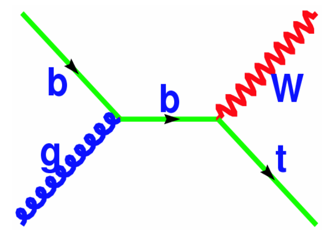
1) Determination of V_{tb}
2) Independent mass measurement

Three production mechanisms:



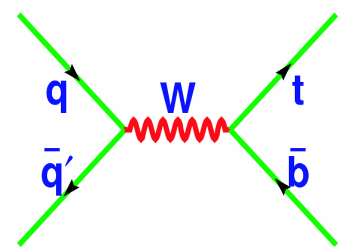
Wg fusion: 245±27 pb

S.Willenbrock *et al.*, Phys.Rev.D56, 5919



Wt: $62.2^{+16.6}_{-3.7}$ pb

A.Belyaev, E.Boos, Phys.Rev.D63, 034012



W* 10.2±0.7 pb

M.Smith *et al.*, Phys.Rev.D54, 6696

- Main Background [σxBR(W→ℓν), ℓ=e,μ]:

tt	σ=833 pb	[246 pb]	Wg	[54.2 pb]
Wbb	σ=300 pb	[66.7 pb]	Wt	[17.8 pb]
Wjj	σ=18·10³ pb	[4·10³ pb]	W*	[2.2 pb]

Single top results

- Detector performance critical to observe signal
  - Fake lepton rate
  - b and fake rate id ε
  - Reconstruction and vetoing of low energy jets
  - Identification of forward jets
- Each of the processes have different systematic errors for V_{tb} and are sensitive to different new physics
  - heavy W' ⇒ increase in the s-channel W*
  - FCNC gu → t ⇒ increase in the W-gluon fusion channel
- Signal unambiguous, after 30 fb^{-1}:

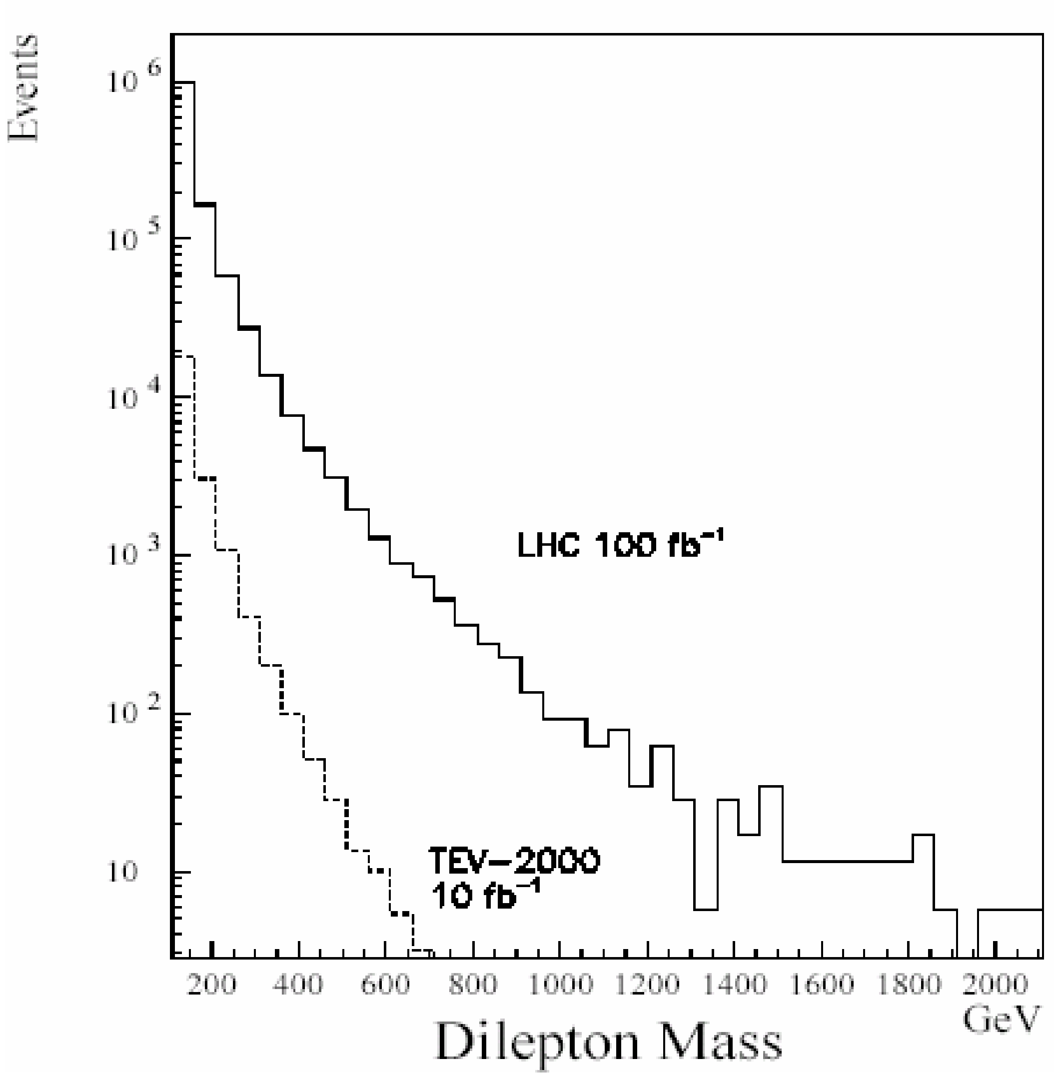
Process	Signal	Bckgnd	S/B
Wg fusion	27k	8.5k	3.1
Wt	6.8k	30k	0.22
W*	1.1k	2.4k	0.46

- Complementary methods to extract V_{tb}

Process	δV_{tb} (stat)	δV_{tb} (theory)
Wg fusion	0.4%	6%
Wt	1.4%	6%
W*	2.7%	5%

- With 30 fb^{-1} of data, V_{tb} can be determined to %-level or better (experimentally)

Drell-Yan production at the LHC



Goals:

- **Measure pdf**
- **Determine parton lumi**
- **Measure $\sin^2\theta_W$**

$\sin^2\theta^l_{eff}$ measurement

- $\sin^2\theta_{eff}^{lept}$ is one of the **fundamental parameters of the SM!**

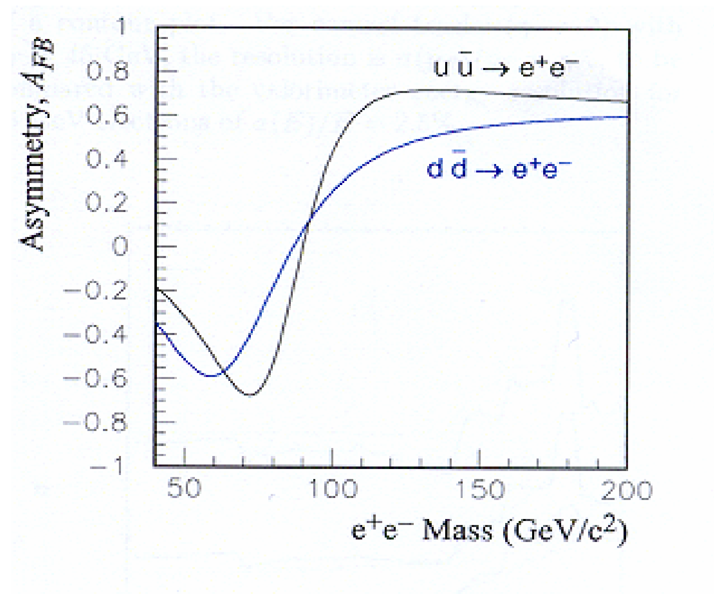
- precise determination will **constrain the Higgs mass** and check **consistency of the SM**.

➢ From A_{FB} in $p\text{-}p \rightarrow Z,\gamma^* \rightarrow l^+ l^-$

at the Z pole, A_{FB} comes from interference of the V and A components of the couplings

$A_{FB} = b \{ a - \sin^2\theta_{eff}^{lept}(M_Z^2) \}$ [hep/ph9707301]

a and b calculated to **NLO** in QED and QCD.



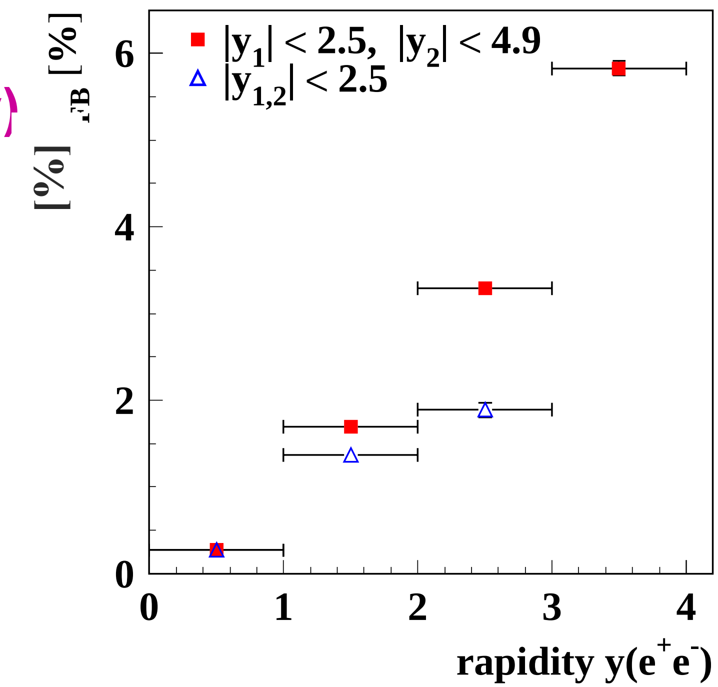
✓ At pp collider, forward direction not naturally defined BUT

- $\bar{q}$ **Always from sea → softer: direction given by the sign of y(ll)**
- **Asymmetry increase with y(ll)**

$\sin^2\theta^l_{eff}$ measurement

To reach World Average precision, need to use full calorimeter coverage (e channel only)

- $Z \rightarrow \mu^+ \mu^-$ $|\eta|<2.$
- $Z \rightarrow e^+ e^-$ $|\eta|<2.5$ jet rejection factor 1000
- $Z \rightarrow e^+ e^-$ $2.5<|\eta|<5$ jet rejection factor 10 - 100



σ ($Z \rightarrow l^+ l^-$) ~ 1.5 nb (for either e or μ)

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

$\mathcal{L} = 100\ fb^{-1}$

• Main sys. effect: **uncertainty on pdf**, lepton acceptance (~0.1%), radiative correction

Can be further improved:
combine channels/experiments.

Conclusions:

- LHC will allow precision measurements: unexplored kinematic regions, high-statistics (W, Z, b, t factory);
- **M_W** can be measured with a precision of **15 MeV** (combinig e/μ and ATLAS + CMS);
- **M_{top}: ~ 1 GeV** (combined with Δm_W~15 MeV, constrains M_H to ~ 25%);
- EW single top production: direct measurement of V_{tb}; measurement of top polarization (Wg with statistical precision of ~ 1.6%);
- $\sin^2\theta_{eff}^{lept}(M_Z^2)$ can be determined with statistical precision of 1.4×10^{-4} (competitive to lepton collider measurements!)