Top Quark: experimental results from Tevatron and prospects at LHC and ILC

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Top quark in the SM

- 1995 Top quark discovery at Tevatron
- Complete the 3rd quark family
  - $SU2_L$ weak isospin Partnair of bottom quark
  - Spin=1/2
- electricCharge=2/3
- Color Triplet
- RQ: NO direct measurement of quantum numbers of theTOP quark, only indirect informations
- The free parameters in the Top sector are
  - The Top Mass (free fondamental parameter of the SM)
  - CKM matrix elements

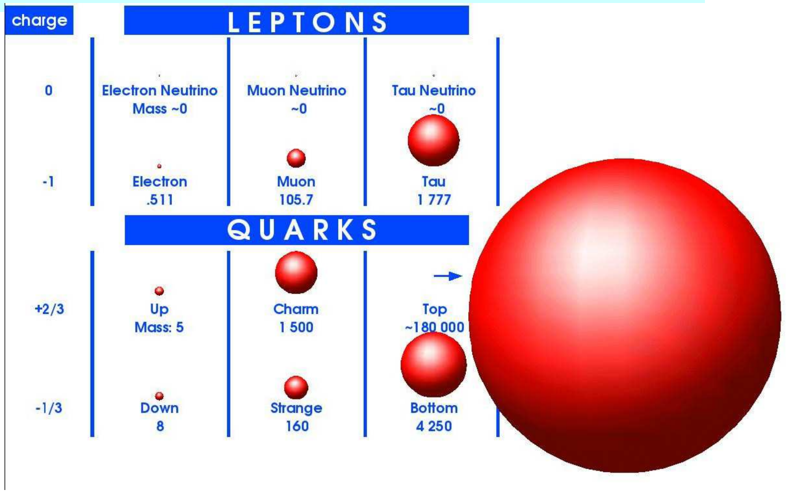
    unitarity => V_{tb} =0.9990 -0.9992 => $t \to Wb$

  Coupling fixed by the gauge structure
- Width computable from the SM

$$
\begin{aligned}
\Gamma_t &= \frac{G_F m_t^3}{8\pi\sqrt{2}}\left(1-\frac{m_W^2}{m_t^2}\right)^2\left(1+\frac{2m_W^2}{m_t^2}\right)\left(1-\frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3}-\frac{5}{2}\right)\right) \\
&\approx 1.48 \quad GeV
\end{aligned}
$$

Why the Top quark is so interesting ?

- Large mass
  - The only fermion heavier than the W
  - $M_t = 35 M_b$
  - Top-Higgs Yukawa coupling :
    $\lambda_t = \sqrt{2}\, M_T / v \sim 1$
  - Interact heavily with the higgs sector



=> Suggest that the Top quark play a specific role in the electro weak symmetry breaking (EWSB).

=> All New Physics in connection with EWSB should couple preferentially to the Top quark : Top sector is an ideal laboratory to search for 'New Physics'

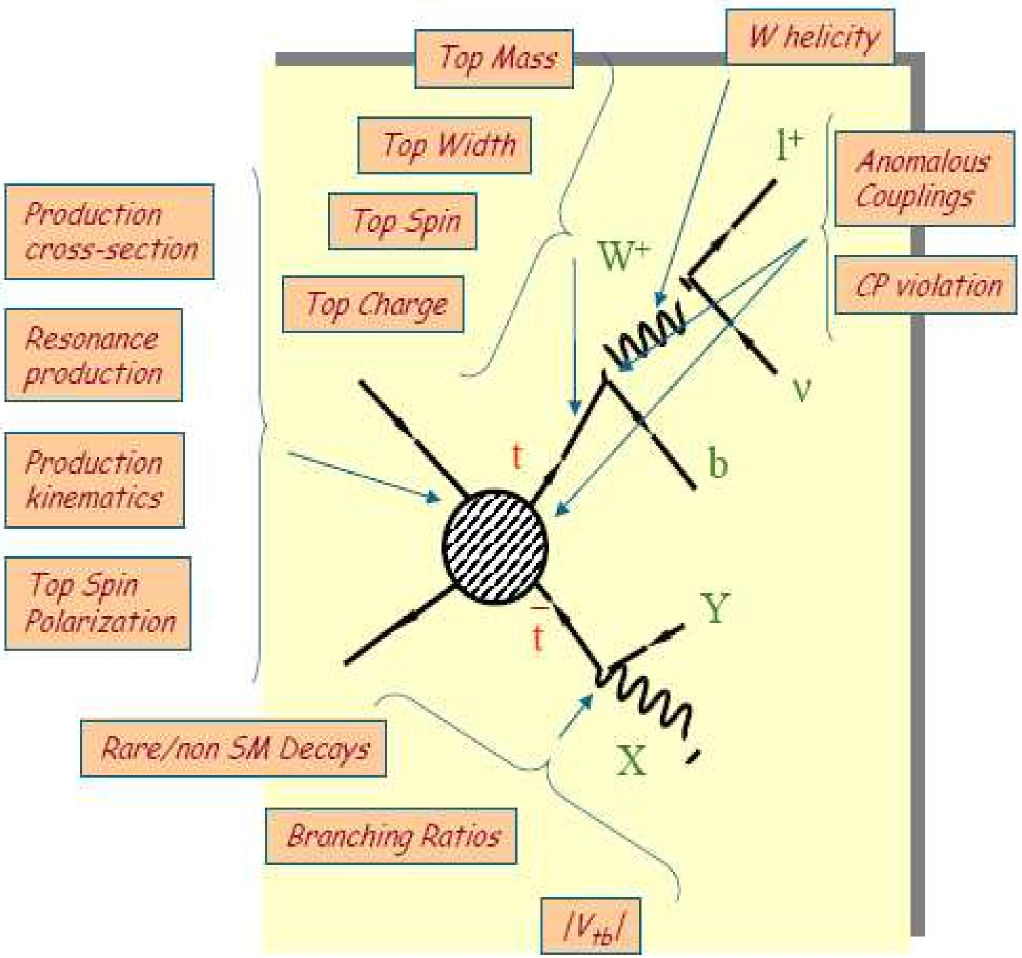
- Short lifetime

$$\Gamma_t = 1.48 GeV \rightarrow \tau_t = 0.44 \times 10^{-24} s < \tau_{QCD} \approx 3 \times 10^{-24} s$$

  - The Top Quark decays before hadronisation
  - => We can study the properties of a « nude » quark (Top Mass)

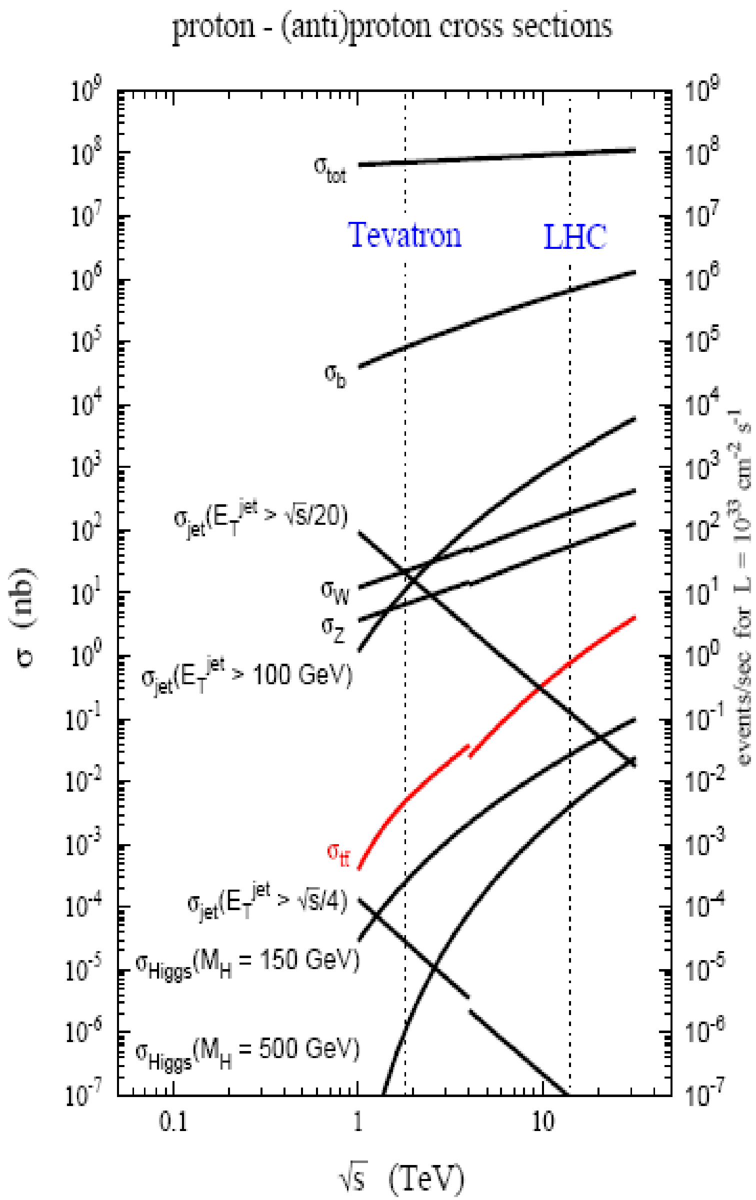
Top physics: which measurements ?

- Productions mechanisms
  - Production X-sections
  - Vtb
  - Spin correlations
  - Ttbar production by new resonances
- Properties
  - Top mass
  - Charge
  - Decay properties
    - Electroweak (V-A) vertex W helicity
    - Rare Top decays
- Search for New physics using heavy flavour



$t\bar{t}$ production at hadron colliders: total cross section

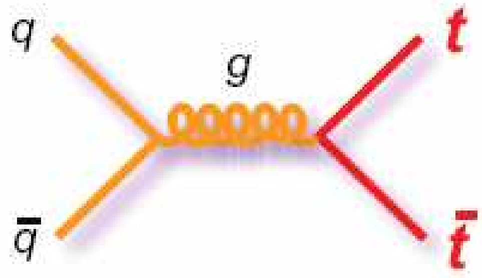
- The top quark has been observed only at Tevatron:
  - $p\bar{p}$: $\sqrt{s}$ = 1.8 TeV $_{\text{RunI}}$ and 1.96 TeV$_{\text{RunII}}$
- LHC will be a top factory
- Total cross section for tt-production ia about a factor of 100 larger at LHC than at Tevatron
  - $\sigma_{t\bar{t}}(1.80\,\text{TeV}) = 5\,\text{pb}$
  - $\sigma_{t\bar{t}}(1.96\,\text{TeV}) = 7\,\text{pb}$
  - $\sigma_{t\bar{t}}(14.0\,\text{TeV}) = 800\,\text{pb}$



$t\bar{t}$ production at Tevatron and LHC

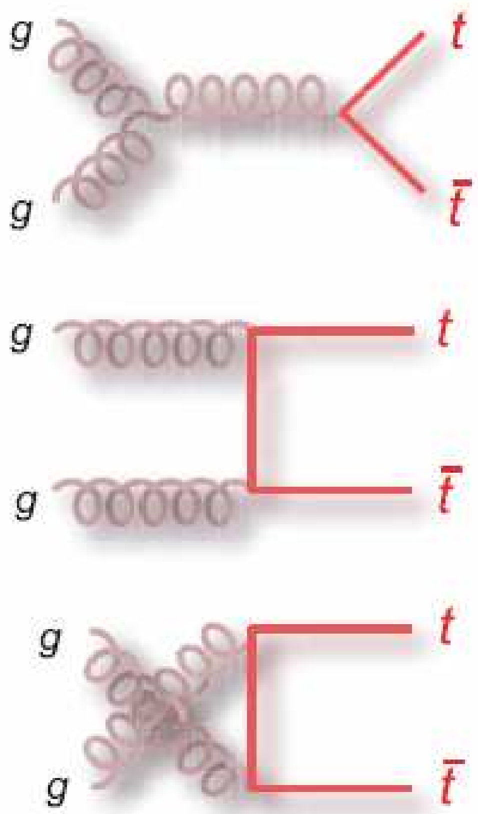
► $q\bar{q}$ annihilation

$\sqrt{s}$	$\sigma_{q\bar{q}\to t\bar{t}}/\sigma_{t\bar{t}}$
1.8TeV	90%
1.96TeV	85%
14TeV	5%



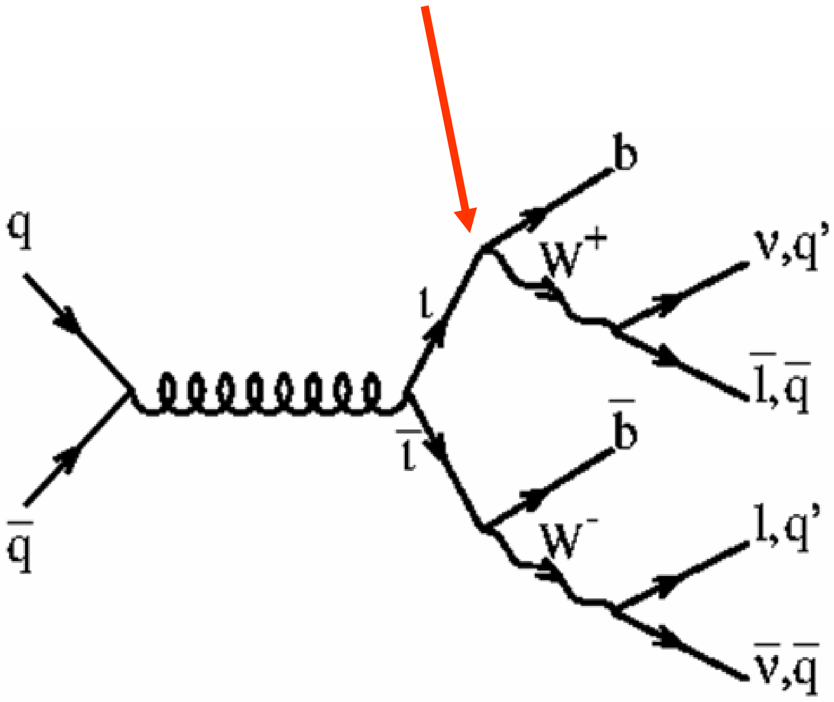
► Gluon fusion

$\sqrt{s}$	$\sigma_{gg\to t\bar{t}}/\sigma_{t\bar{t}}$
1.8TeV	10%
1.96TeV	15%
14TeV	95%

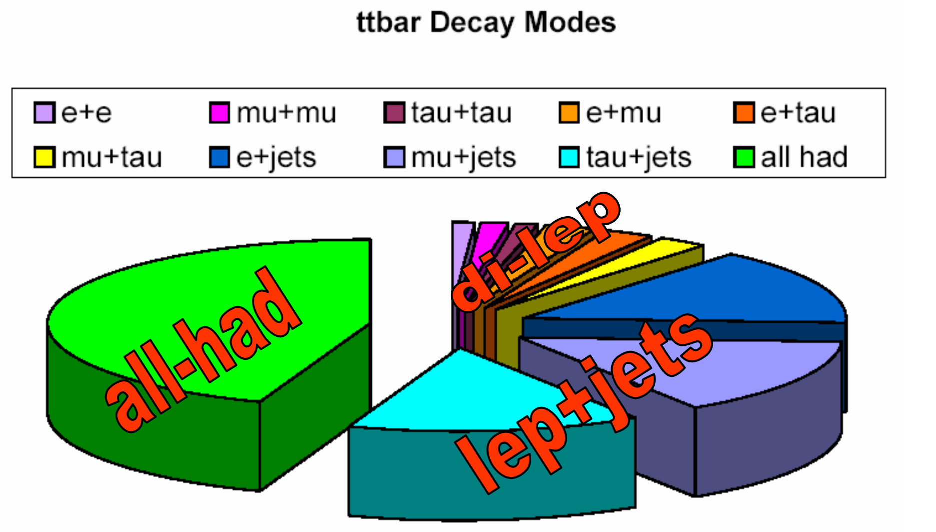


Top Decays

• Decay: BR(t → W b) ~ 100%



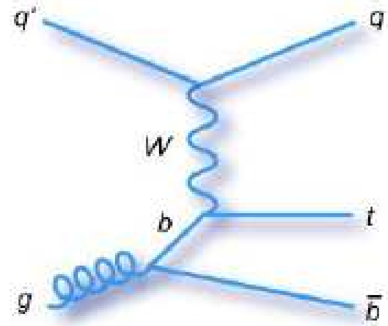
• All-hadronic: 44%
• Lepton + jets: 30%
• Dilepton: 5%



Single Top production at Tevatron and LHC

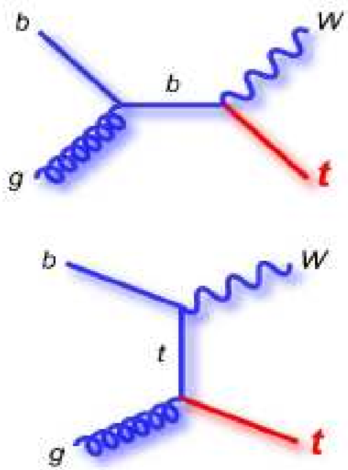
- W-boson and gluon fusion. It includes the t-channel contribution or Wg

$\sqrt{s}$	$\sigma_{EWt}/\sigma_{\text{single t}}$
1.8TeV	60%
1.96TeV	65%
14TeV	77%



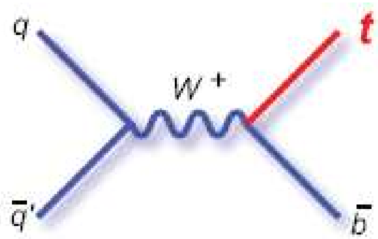
- Associated production of top quark and W-boson, Wt

$\sqrt{s}$	$\sigma_{EWt}/\sigma_{\text{single t}}$
1.8TeV	5%
1.96TeV	5%
14TeV	20%



- s-channel production

$\sqrt{s}$	$\sigma_{EWs}/\sigma_{\text{single t}}$
1.8TeV	35%
1.96TeV	30%
14TeV	3%

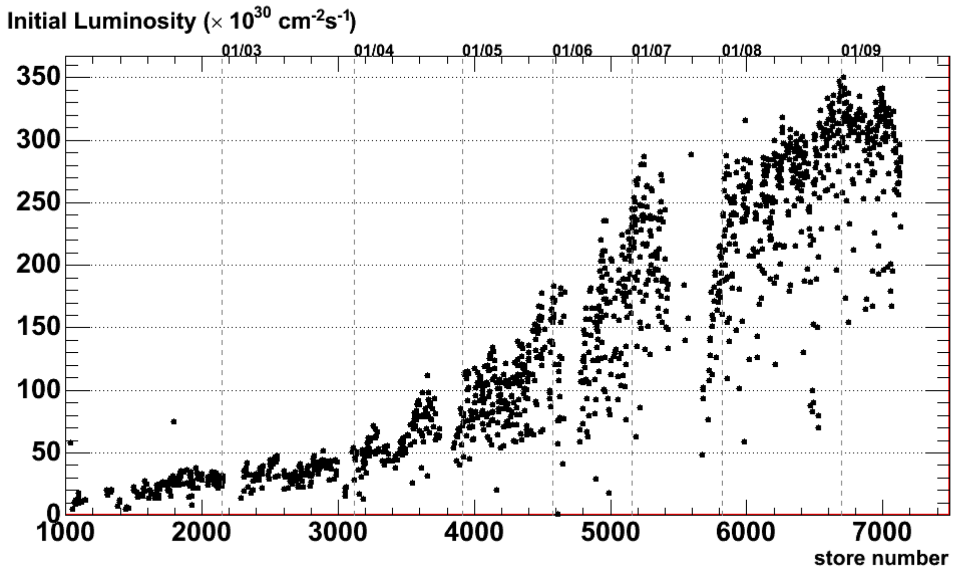


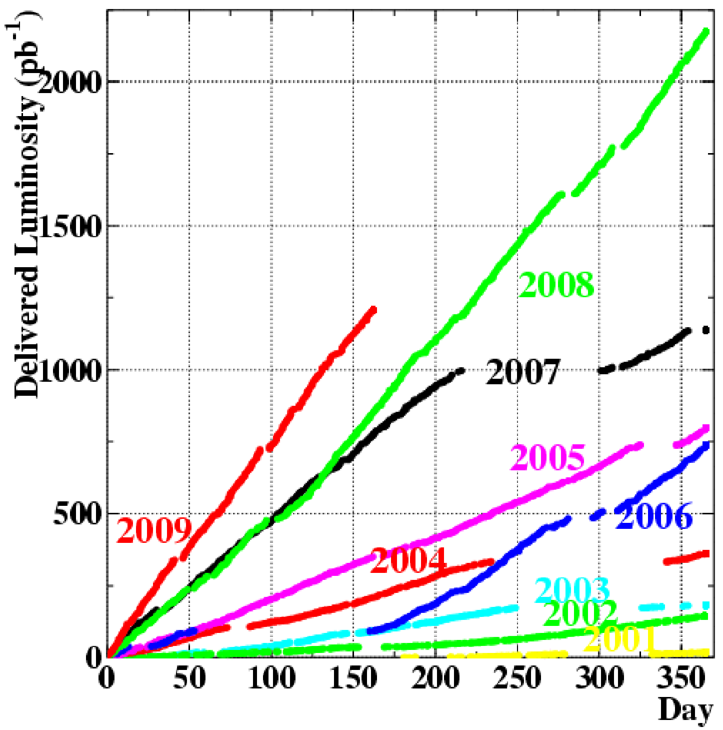
Top Physics results from Tevatron

- **Tevatron CDF & D0 at the moment are the unique source of Top**

Tevatron Performance in Run 2

record luminosity: $\mathcal{L} = 3.7 \cdot 10^{32}\ cm^{-2}\ s^{-1}$ (goal: $1.6 – 2.7 \cdot 10^{32}$)



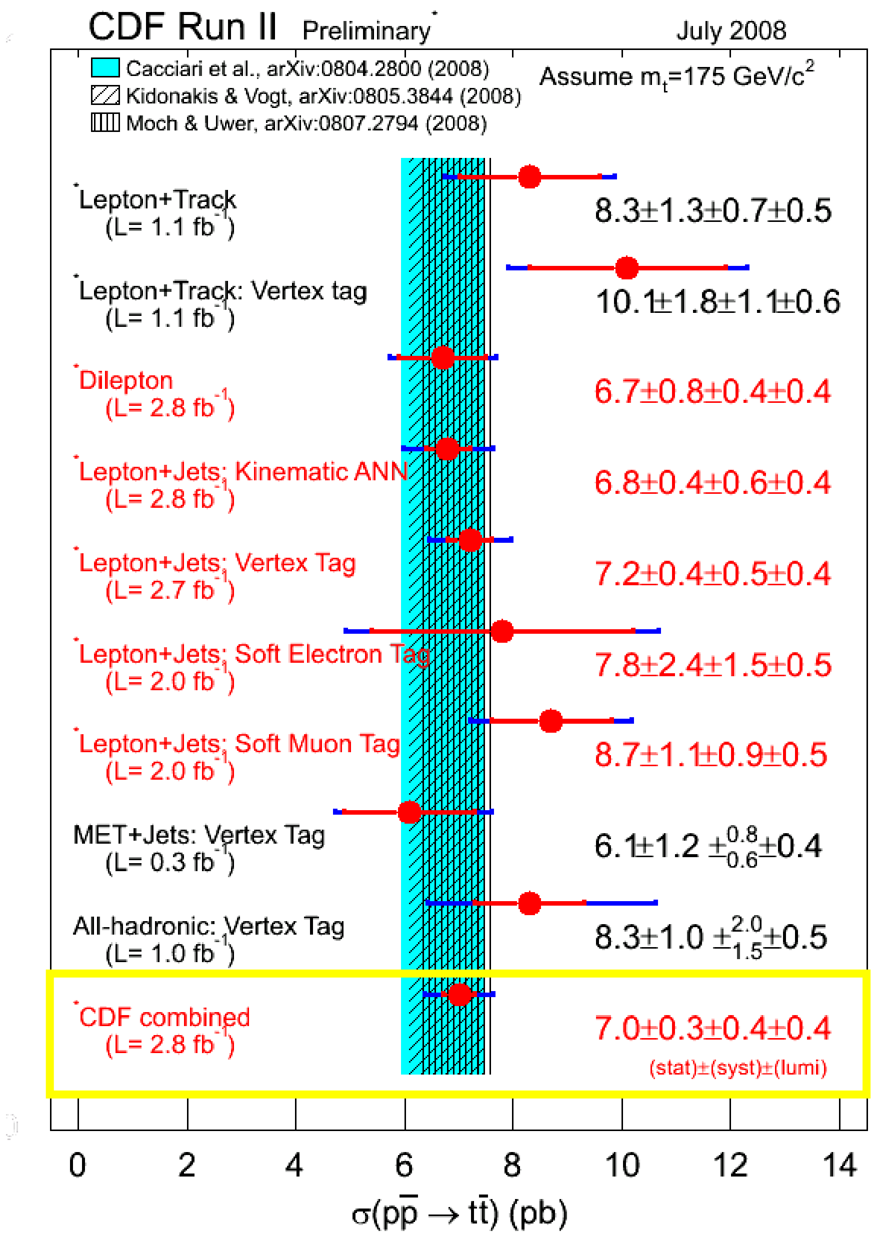


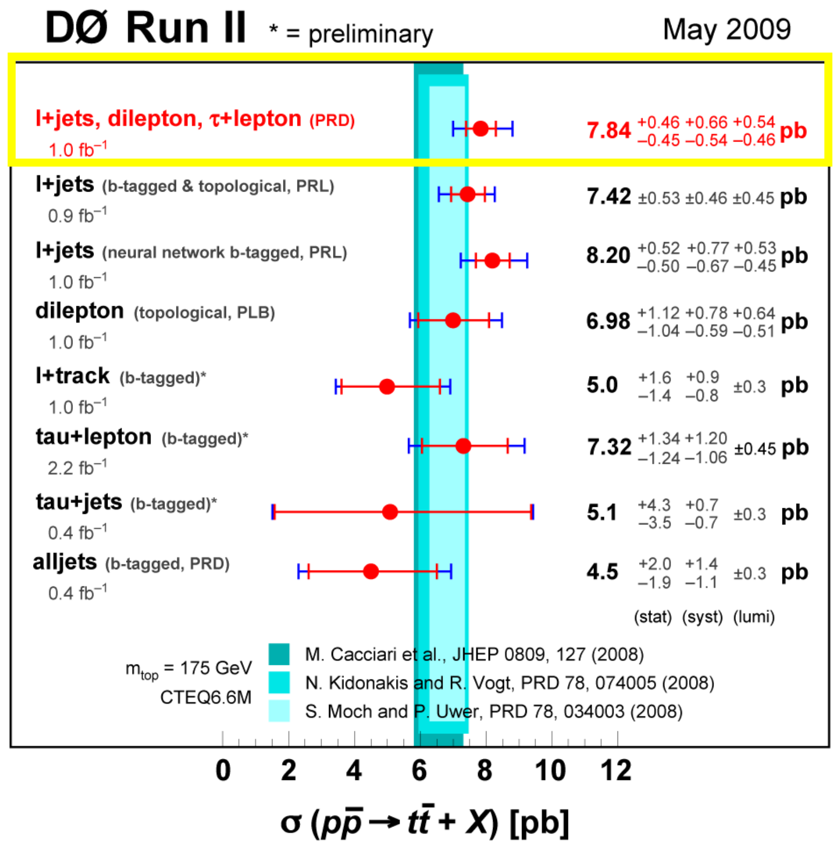
Since April 2002 7.0 fb^{-1} were delivered by the accelerator

Why Cross-section measurement?

- Comparison with a theoretical calculations: SM test, probe of the new production mechanism
  - N.Kidonakis and R. Vogt, arXiv:hep-ph/0805.3844, PRD 78, 074005(2008): NLO+NNLO soft gluon correction,
    $\sigma = 7.27^{+0.76}_{-0.85}$ pb, $m_t = 172.5$ GeV
  - S.Moch and P.Uwer, arXive:hep-ph/0804.1476, PRD 78, 034003(2008): NNLO(approx), $\sigma = 7.45^{+0.50}_{-0.70}$ pb, $m_t = 172.5$ GeV
  - M. Cacciare, S. Froxione, M.M. Mangano, P. Nason and G. Ridolfi, arXiv:hep-ph/0804.2800, JHEP 09, 127(2008): NLO + next-to-leading threshold logarithm correction, $\sigma = 7.14^{+0.76}_{-0.86}$ pb,
    $m_t = 172.5$ GeV
  - Errors ~ 7-10 %, depends how the scale uncertainty is defined
  - RunI, 2E = 1.80 TeV, L ~ 100 pb-1: $\delta\sigma/\sigma \sim 25\%$
- Important background for the new phenomena and Higgs search
- Allow to extract the top mass from the cross-section dependence with a “clean” definition of a top mass from the theoretical point of view

Top-Antitop Cross Section





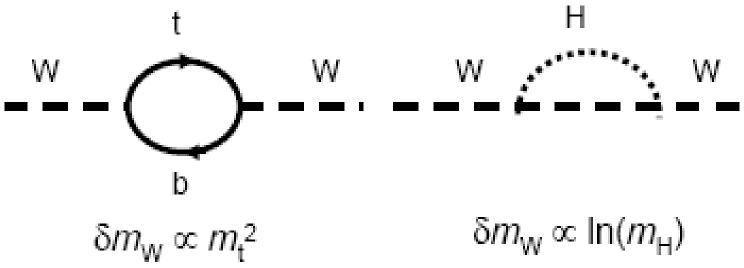
Most measurements are counting experiments:

$$\sigma(t\bar{t}) = \frac{N_{\rm obs} - N_{\rm b}}{\epsilon_{t\bar{t}} \cdot \int \mathcal{L} dt}$$

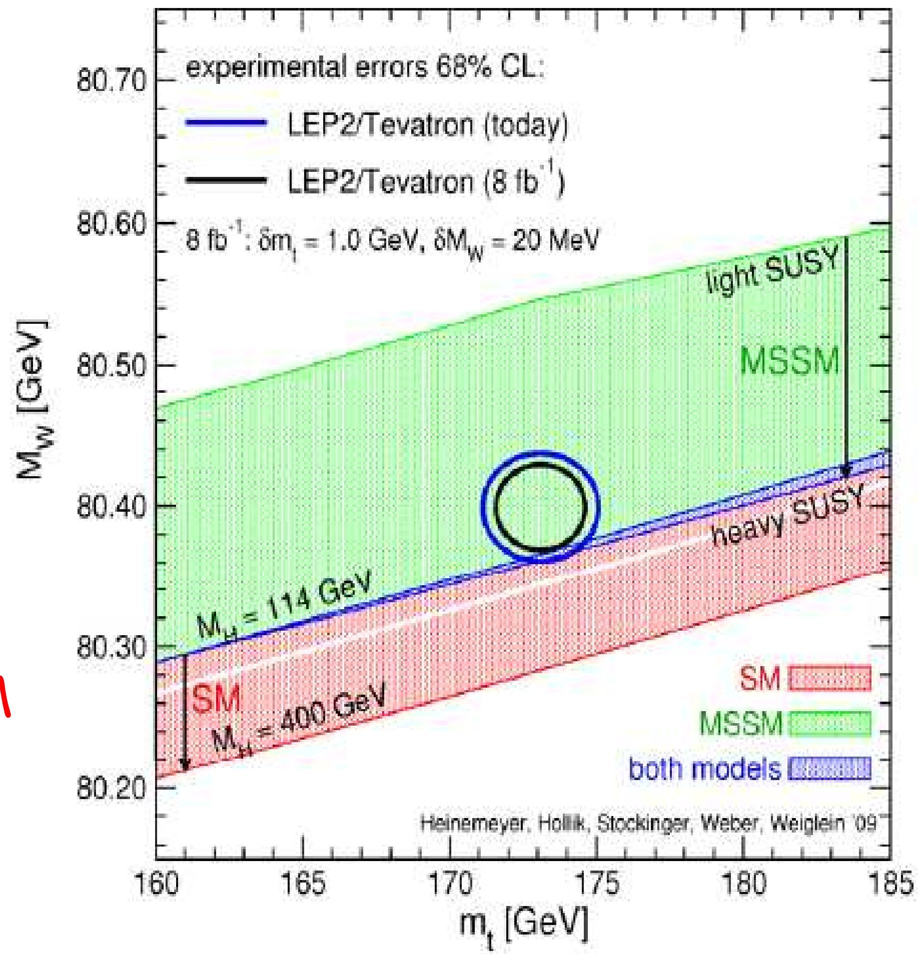
Main job: background estimate

Why Top quark mass measurement?

- Top mass m_t is fundamental parameter of Standard Model
- Electroweak mass corrections $\propto m_t^2$ and $\ln(m_H)$

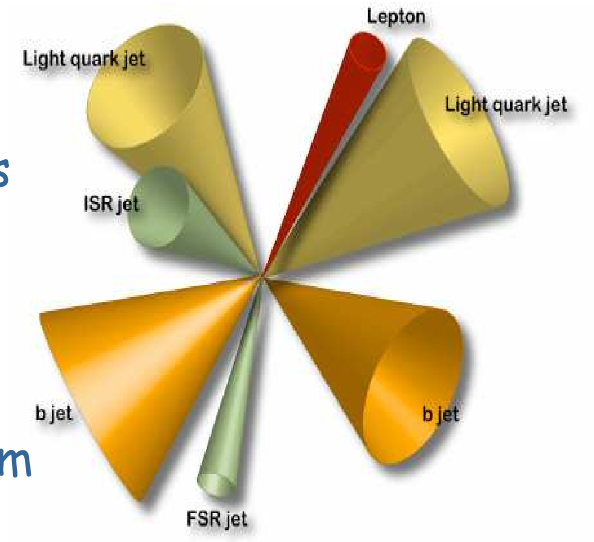


- Precision measurement of m_W and m_t give a constraints on SM m_H
  - Consistency test of SM
  - New physics?

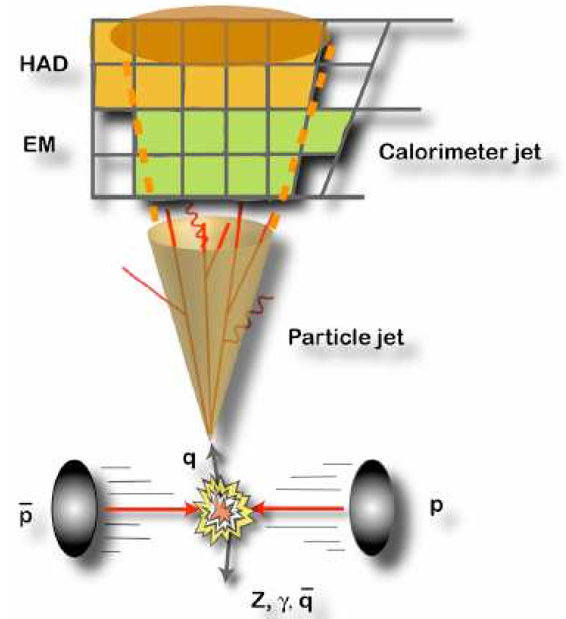


Top Mass measurement

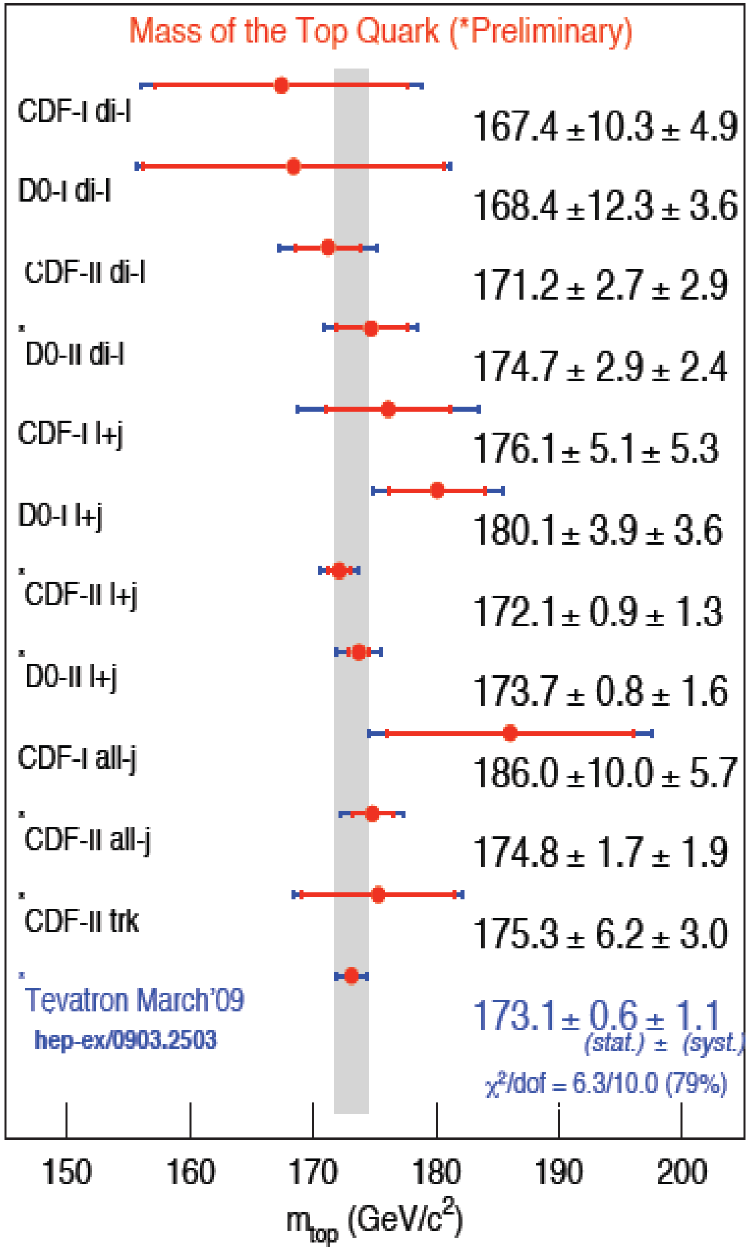
- Difficult measurement
  - Most information carried in quarks
    - Can only measure jets resulting from quarks
    - Jet-parton assignment
    - QCD radiation
  - Jet energy scale (JES) uncertaintly dominated (~3%)
    - Can be reduced via in situ measurement from hadronic W



- Mass measurement techniques
  - Matrix element: from probabilities as function of m_t and JES from SM MEs, convolute with detector resolution functions and integrate
  - Template: from templates as function of m_t and JES from fully simulated events

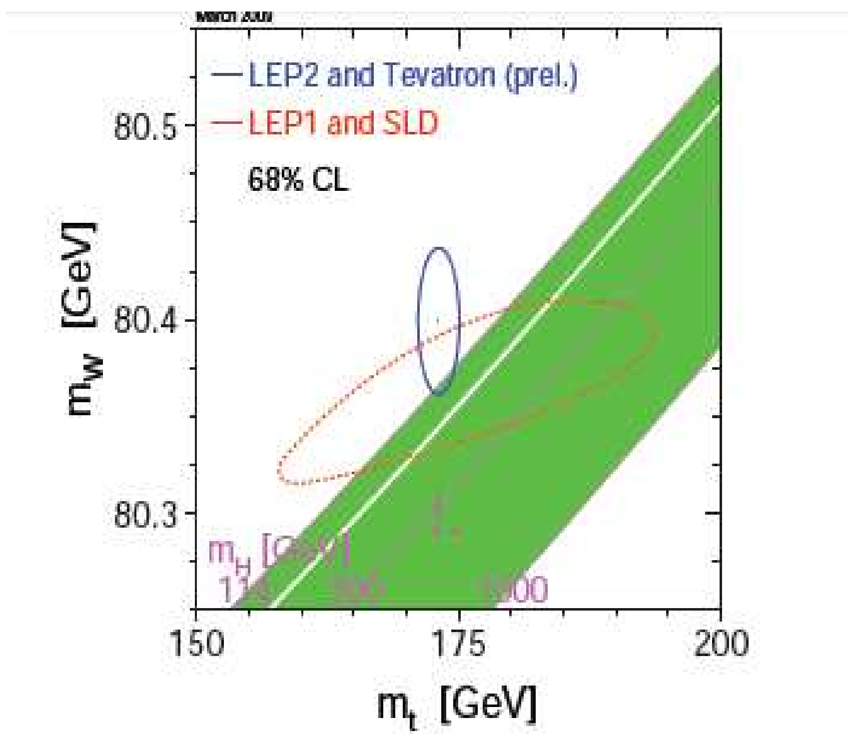


Tevatron Top Mass combination



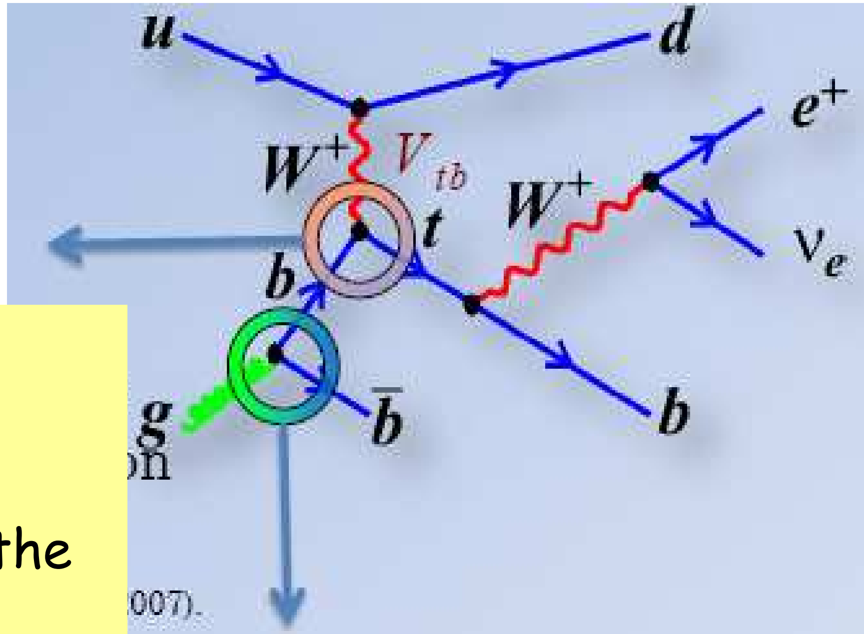
$M_t = 173.1 \pm 0.6(stat) \pm 1.1(syst) GeV/c^2$

- Combine using best measurement per channel, per experiment: 0.75% uncertainty
- New electroweak fit incorporating new top mass combination and W mass measurement: $m_H < 163 GeV/c^2$ @95%CL
- Both experiments working to better understand systematics



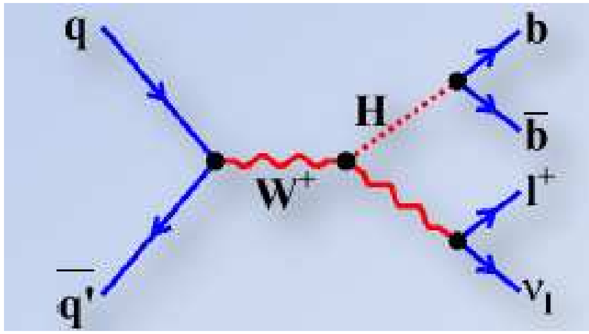
Why measure Single Top?

- Test of Standard Model predictions:



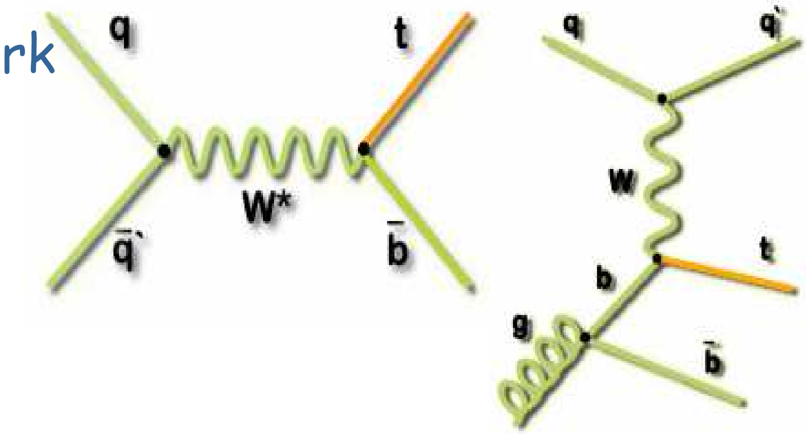
  - Does this process exist?
  - Cross section $\propto |V_{tb}|^2$
  - Test of the unitarity of the CKM Matrix

- Preparation of Higgs searches

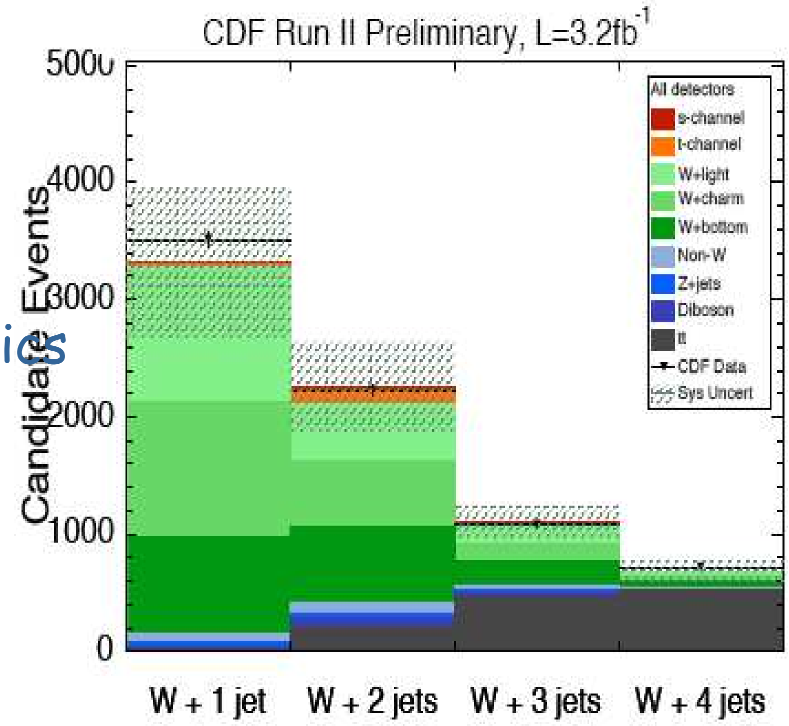


Single Top at Tevatron

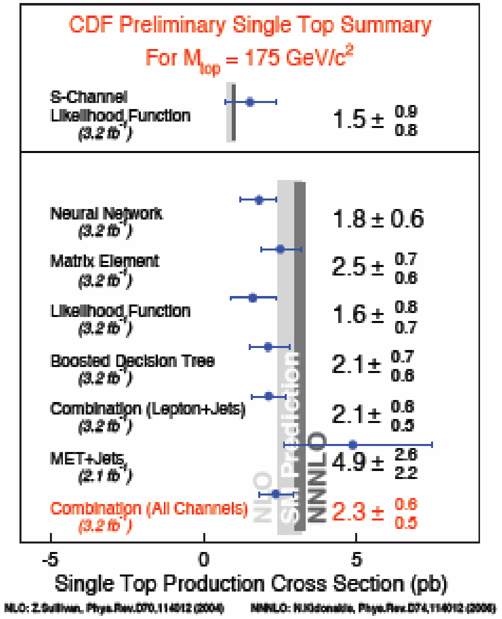
- Electroweak production of single top quark
  - S-channel: σ_{NLO} = 1.98 ± 0.21 pb
  - T-channel: σ_{NLO} = 0.88 ± 0.07 pb

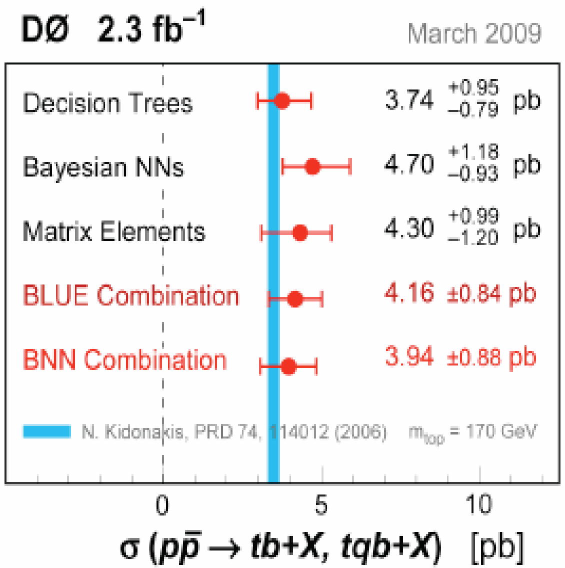


- Allows for
  - Direct probe of t-b vertex
  - Several BSM phenomena (W′, charged Higgs, etc)
  - Similar final state as WH→lνbb
- Not as easy as top pair measurement
  - Large background with large systematics
    - Makes counting experiment difficult
  - Rely on multivariate techniques



Tevatron Single Top result





Single Top Cross Section	Signal Significance Expected	Observed	CKM Matrix Element V_{tb}
CDF (3.2 fb^{-1}) *March 2009* [m_t=175 GeV/c^2] *arXiv:0903.0885*			
$2.3^{+0.6}_{+0.5}$ pb	>5.9σ	5.0σ	$\lvert V_{tb}\rvert$>0.71 @95%CL $\lvert V_{tb}\rvert$=0.91±0.13
DØ (2.3 fb^{-1}) *March 2009* [m_t=170 GeV/c^2] *arXiv:0903.0850*			
3.94±0.88 pb	4.5σ	5.0σ	$\lvert V_{tb}\rvert$>0.78 @95%CL $\lvert V_{tb}\rvert$=1.07±0.12

5σ Observation from both CDF and DØ!

The next step at the Energy Frontier

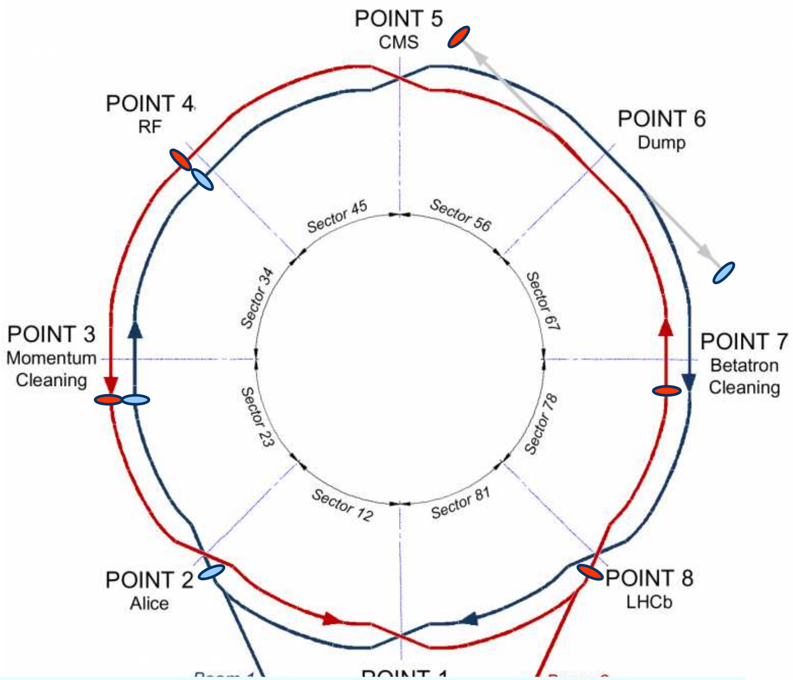
- Key question of particle physics:
  - Origin of mass/matter or origin of EWSB
  - Unification of forces
  - Fundamental symmetry of forces and matter
  - Unification of quantum physics and general reletivity
  - Dark matter/dark energy

- How to get the experimental answers? There are two distinct and complementary strategies for gaining new understanding of matter, space and time at future particle accelerators
  - HIGH ENERGY

    direct discovery of new phenomena i.e. accelerators operating at the energy scale of the new particles
  - HIGH PRECISION

    access to new physics at high energies through the precision measurement of phenomena at lower scales

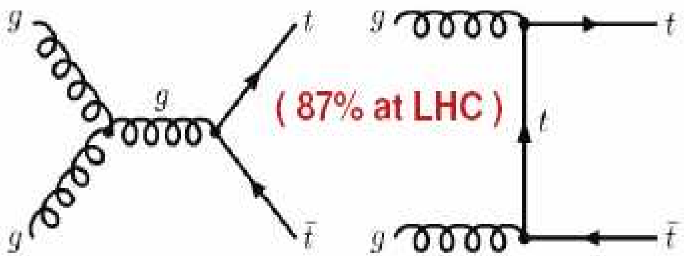
The Large Hadron Collider



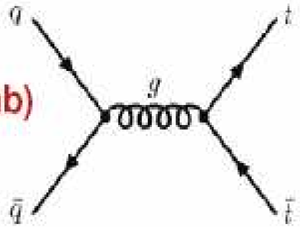
- 1st beam in LHC September 10, 2008
- 1st collision at 450+450 GeV expected end september
- Incident (dipole connection) on Sept 19.
  - No collisions in 2008
  - Remember everyone that LHC machine represents a challenge
- O(100 pb-1) expected in 2009-2010 @ 10 TeV

Top quark production measurement

LHC: Gluonic production dominates



(90% at FermiLab)



Ref: hep-ex 0804.1476

$\sigma(tt\ 1.96\ TeV)^{approx\ NNLO} = 7.5 \pm 0.5$ pb Tevatron

$\sigma(tt\ 14TeV)^{approx\ NNLO} = 883 \pm 45$ pb

$\sigma(tt\ 10TeV)^{approx\ NNLO} = 401 \pm 25$ pb

$\Rightarrow$ ***1 tt/sec @ L=10^{33}***

Cross section LHC = 100 x Tevatron

Background LHC = 10 x Tevatron

Use of b-tagging not essential to establish ttbar signal at LHC

LHC Single top production

$\sigma(t, 14\ TeV) \cong 320$ pb

dominated by t-channel

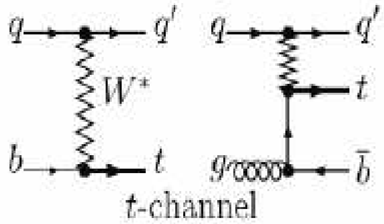
Tevatron: 5σ discovery this year:

D0 (arXiv:0903.0850)

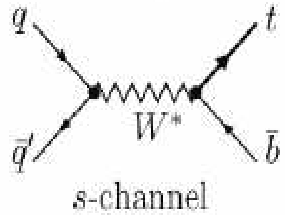
CDF (arXiv:0903.0885)

$\sigma(t, 1.96\ TeV) = 3.9 \pm 0.9$ pb

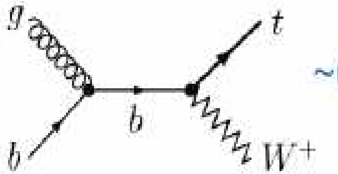
~250 pb



~10 pb



tW-channel



~60 pb

Top Rediscovery

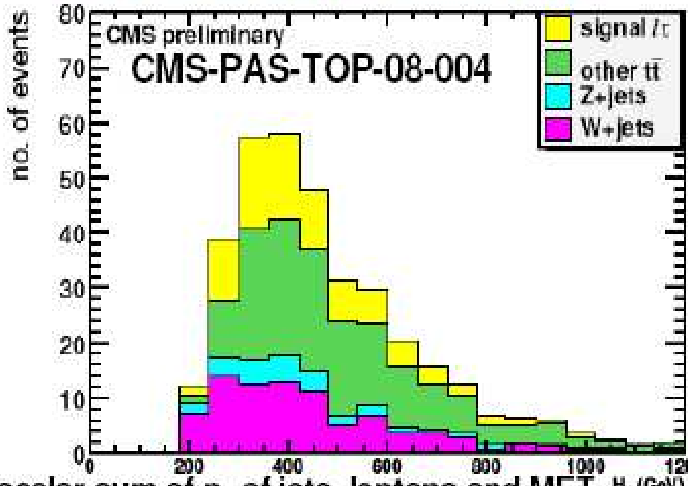
- ttbar production measurement at 10 and 14 TeV

- 10 TeV, 20pb^{-1} muon+jets: S: 390 events.
  S/B = 2.0 BDT analysis, data driven estimation of the QCD.
  $\Delta\sigma/\sigma = 9\%_{(stat)} \pm 22\%_{(syst)} \pm 10\%_{(lumi)}$

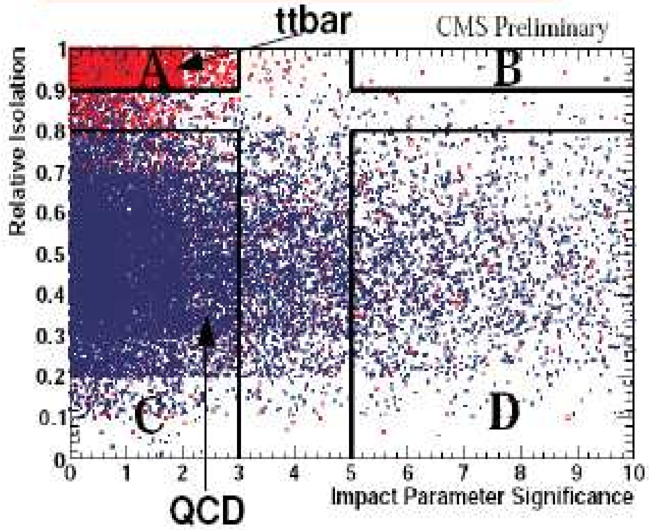
μ+jets:
TMVA BDT analysis
1 isolated muon from the IP, 4 jets.

14 TeV, 100 pb^{-1} $e,\mu+\tau$: S/B= 0.4

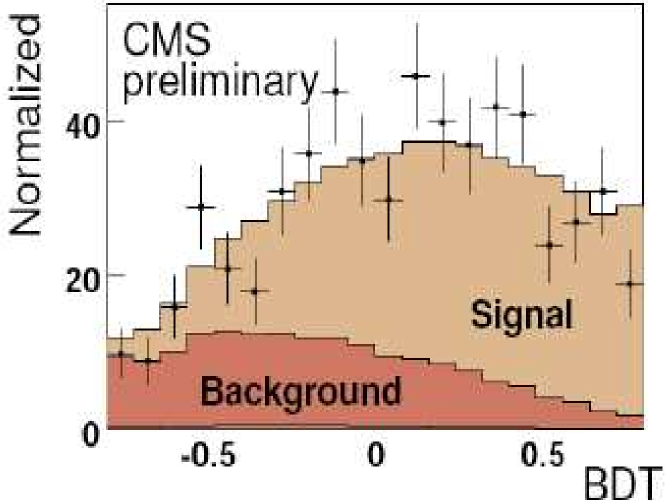
- Stat Uncertainty on xsec: 11%



scalar sum of p_T of jets, leptons and MET



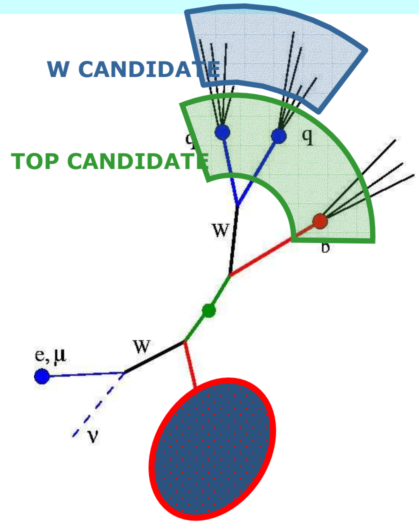
CMS-PAS-TOP-09-010



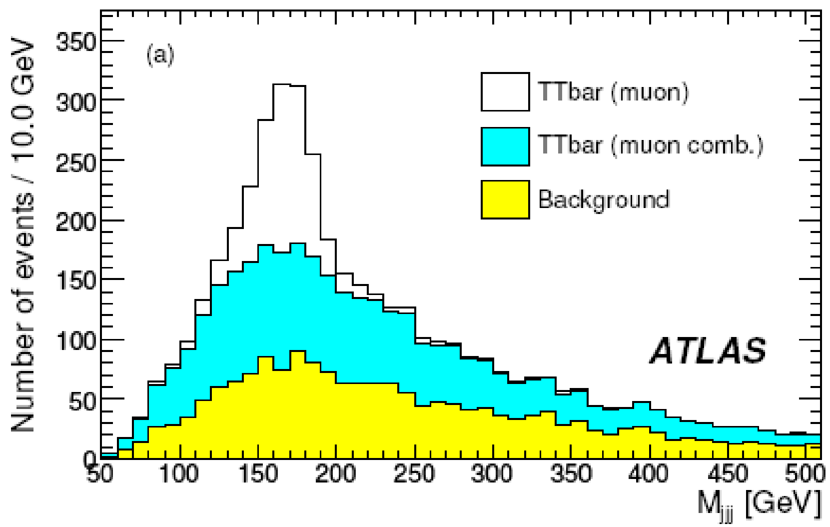
Top pair cross section measurement

Lepton+jets events:

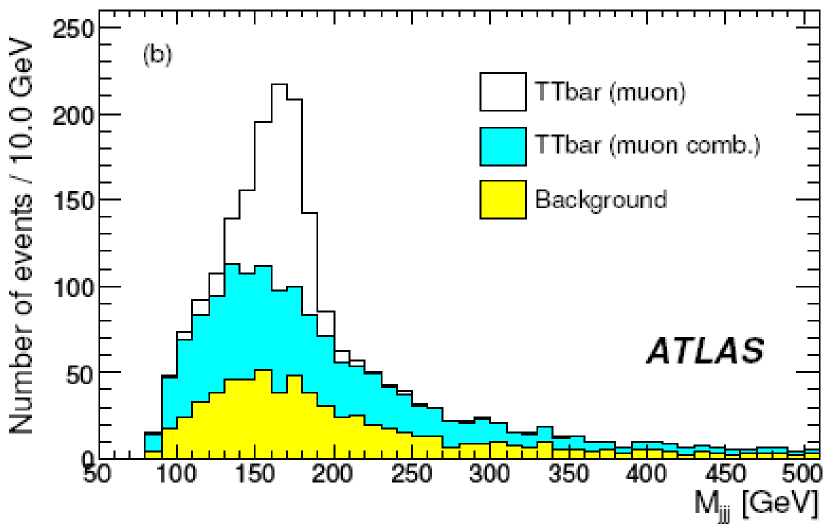
- Lepton trigger p_T > 20 GeV
- 4 jets p_T>20GeV, 3 jets p_T>40GeV
- MET > 20 GeV
- Top = 3 jets giving Highest Pt sum
- No btag



Default selection S/B~2.3, eff~24%

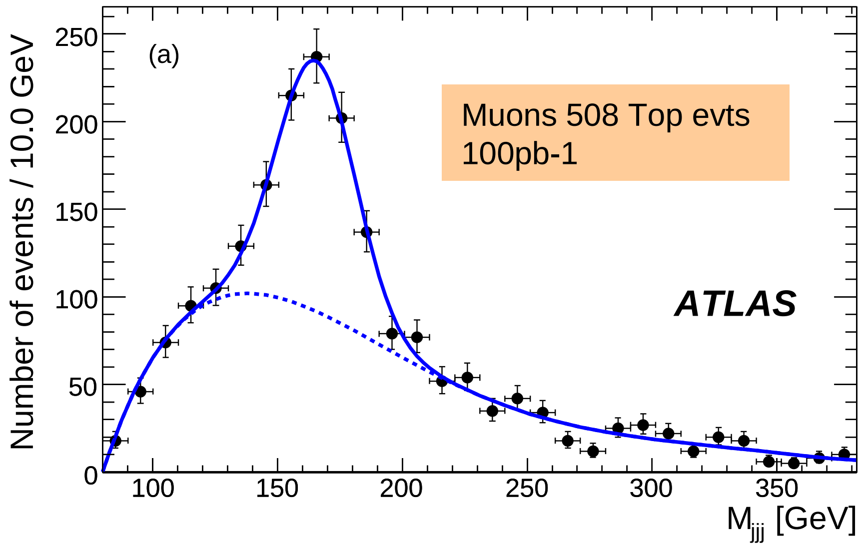


With W constraint S/B~3.5



Top contribution visible even with 10 pb-1

- Likelihood fit
  - Gaussian+chebychev bkg
  - Extract X-sec by scaling with eff

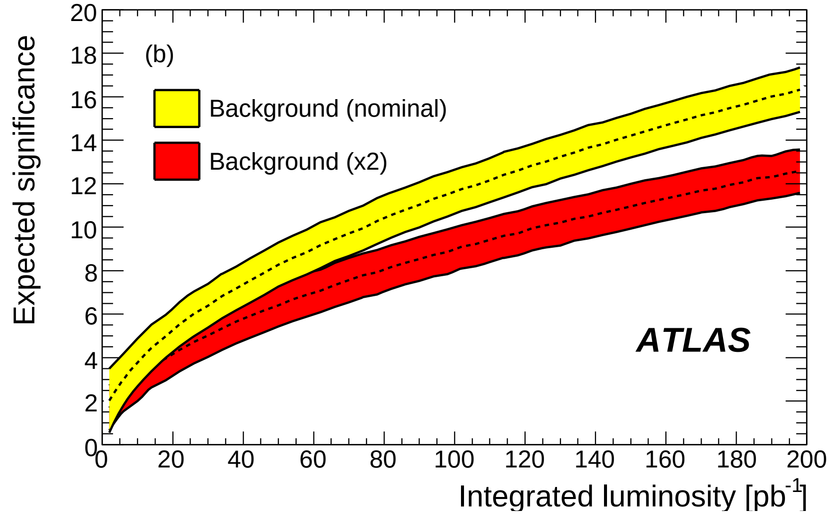


- Counting Method

$$\sigma = \frac{N_{\text{sig}}}{\mathscr{L} \times \varepsilon} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathscr{L} \times \varepsilon}$$

  - Sensitive to bkg normalisation, number of jets, JES, shape

Source	Likelihood fit Electron (%)	Likelihood fit Muon (%)	Counting method (elec) Default (%)	Counting method (elec) W const. (%)
Statistical	10.5	8.0	2.7	3.5
Lepton ID efficiency	1.0	1.0	1.0	1.0
Lepton trigger efficiency	1.0	1.0	1.0	1.0
50% more W+jets	1.0	0.6	14.7	9.5
20% more W+jets	0.3	0.3	5.9	3.8
Jet Energy Scale (5%)	2.3	0.9	13.3	9.7
PDFs	2.5	2.2	2.3	2.5
ISR/FSR	8.9	8.9	10.6	8.9
Shape of fit function	14.0	10.4	-	-

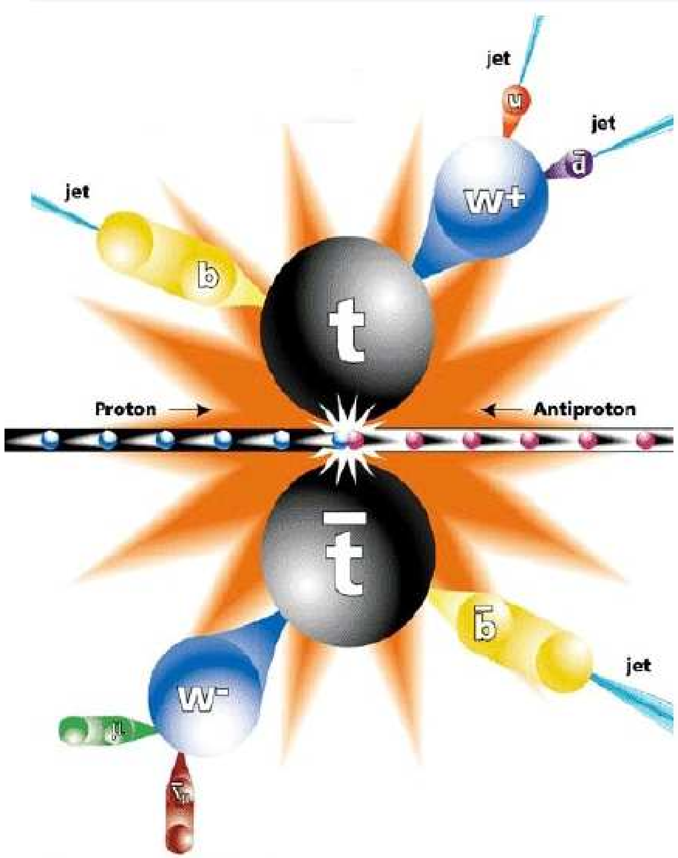


$$\text{Likelihood method:} \quad \Delta\sigma/\sigma = \quad (7(\text{stat}) \pm 15(\text{syst}) \pm 3(\text{pdf}) \pm 5(\text{lumi}))\%$$

$$\text{Counting method:} \quad \Delta\sigma/\sigma = \quad (3(\text{stat}) \pm 16(\text{syst}) \pm 3(\text{pdf}) \pm 5(\text{lumi}))\%$$

Top mass measurement with 1 fb^{-1}

- The lepton+jets is the golden channel: one W decays leptonically (e,μ) and the other W decays hadronically
  - Clean trigger from the isolated lepton
- The reconstruction starts with the W mass:
  - JES using the W
- Important to tag the b-jets:
  - Reduces the background
  - Clean top quark samples
- Main background comes from W + Jets events
- $S/B \approx 10$

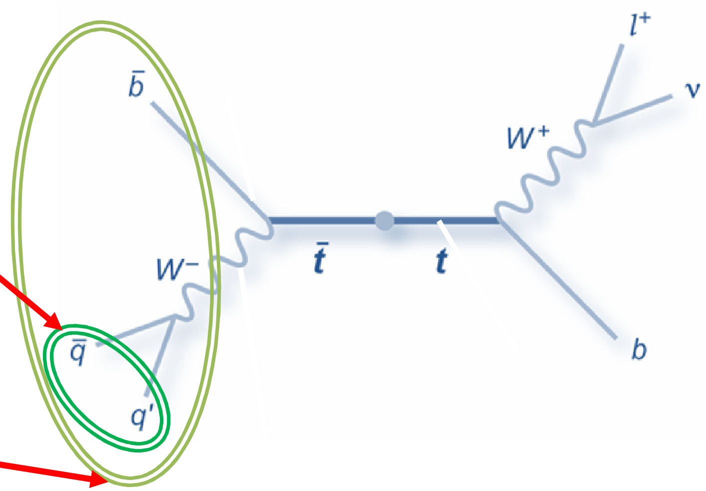


Hadronic Top reconstruction

- Find first the W jets
  - Closest jets
  - Min(M_{jj}-$M_W$peak)

50% of the events have more than 2 light jets

- Then the b jet in $t \rightarrow Wb$
  - Closest b jet from W

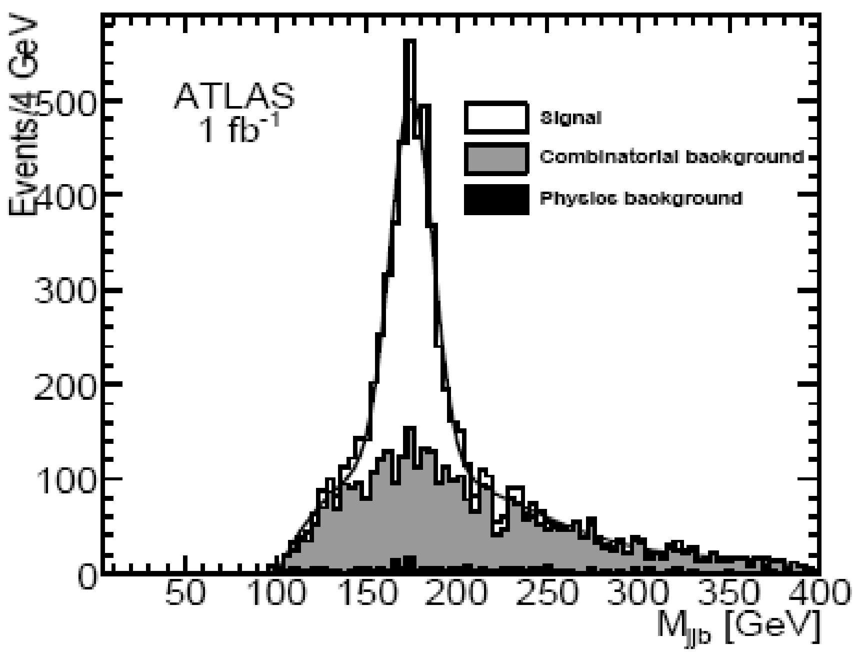


The final efficiency of reconstruction with respect to l(e,μ)+jets events is 2.22±0.03% with a top purity of 40.2±0.8%

For a generated mass of 175 GeV we reconstruct:

M_{top}= 175.0 ±0.2 GeV

Γ=11.6±0.2 GeV



Uncertainties on Top mass measurement

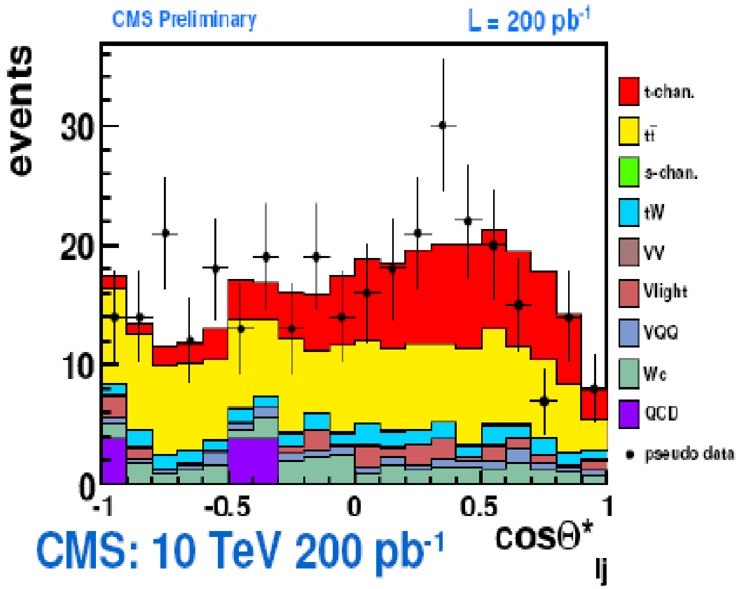
- Statistical uncertainty
  - Estimated for $1fb^{-1}$ using a bootstrap resampling technique
  - $\delta(Mtop)_{stat} < 0.4$ GeV
- Systematics uncertainties
  - Dominant uncertainty after a few fb^{-1} of data
  - Main contribution to syst are JES & JES_b
  - $\delta(Mtop)_{syst} \sim 1$ (3.5) GeV if JES accuracy is 1 (5)%

Source of systematics	Top mass shift (GeV/c^2)
Light JES	**0.2 /%**
b jet scale (1%)	**0.7 /%**
ISR/FSR	**≤ 0.3**
b quark fragmentation	**≤ 0.1**
background	**negligible**
method	**0;1-0.2**
TOTAL	0.8

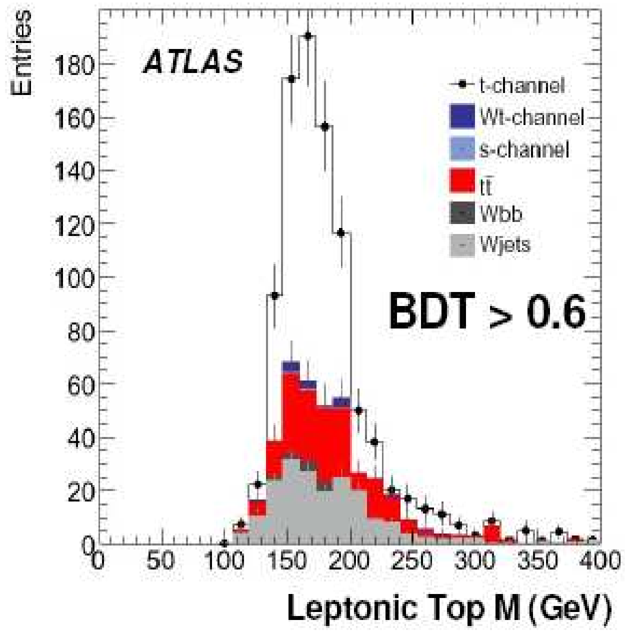
$1fb^{-1}$

Single Top at LHC: t-channel

CMS-PAS-TOP-09-005



CMS: 10 TeV 200 pb^{-1}



- **CMS**: 10 TeV 200 pb^{-1}
  likelihood fit of the cosθ^*_{lj} distribution in the top rest frame

$\Delta\sigma/\sigma$=35%(stat)±14%(syst)±10%(lumi)

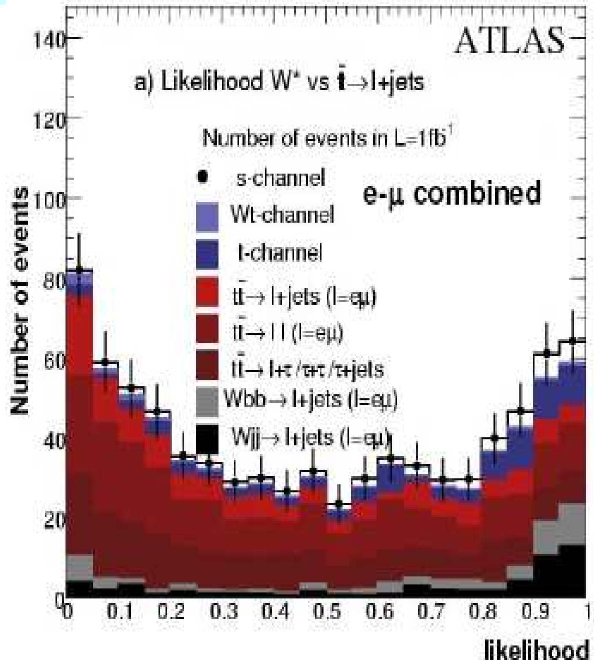
- **ATLAS**: cut-based analysis (baseline), and multivariate (BDT) 1 fb^{-1}:

$\Delta\sigma/\sigma$ = 5.7% (stat)±22%(syst)

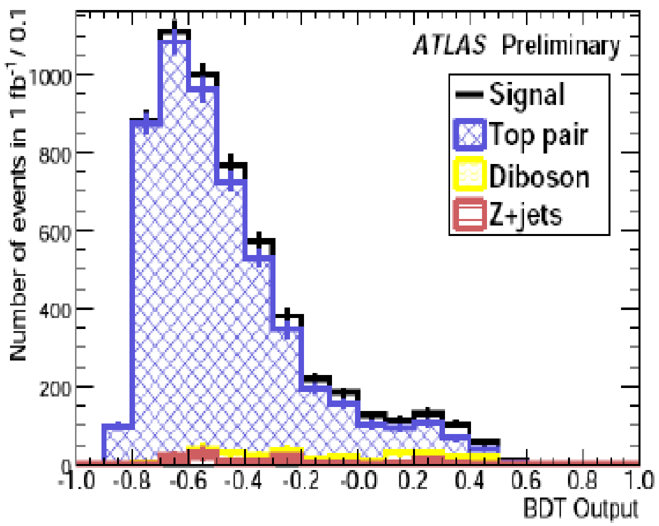
$\Delta V_{tb}/V_{tb}$ =±11%(stat+syst)±4%(theory)

Single Top at LHC: s-channel and tW channel

- **s-channel**: very low cross section. Could be mediated by new physiscs (H±)
  ATLAS: likelihood analysis
  50% uncert at 10 fb^{-1}
  3σ evidence at 30 fb^{-1}



ATL-PHYS-PUB-2009-001



tt discriminant e-μ channel

- **tW channel (associated W prod)**: signature similar to tt but with one less b-jet
  ATLAS: cut based analysis and boosted decision tree
  Expected results for 1fb-1
  - lepton+jets channel: 48% uncert. (BDT analysis)
  - di-leptons channel: 34% uncert. (BDT analysis)

Lepton Colliders ‘versus’ Hadron Colliders

Electron-positron collisions and proton-proton collisions at high energy provide powerful and complementary tools to explore TeV-scale physics (“Terascale”-Physics)

- collisions of point-like particles
- Initial states: electroweak interaction
- Moderate background
- $\sqrt{s}$ = tunable but restricted

PRECISION

- collisions of composite particles
- Initial states: strong interaction
- Underline events
- $\sqrt{s}$ = higher reach

DISCOVERY

Baseline Machine

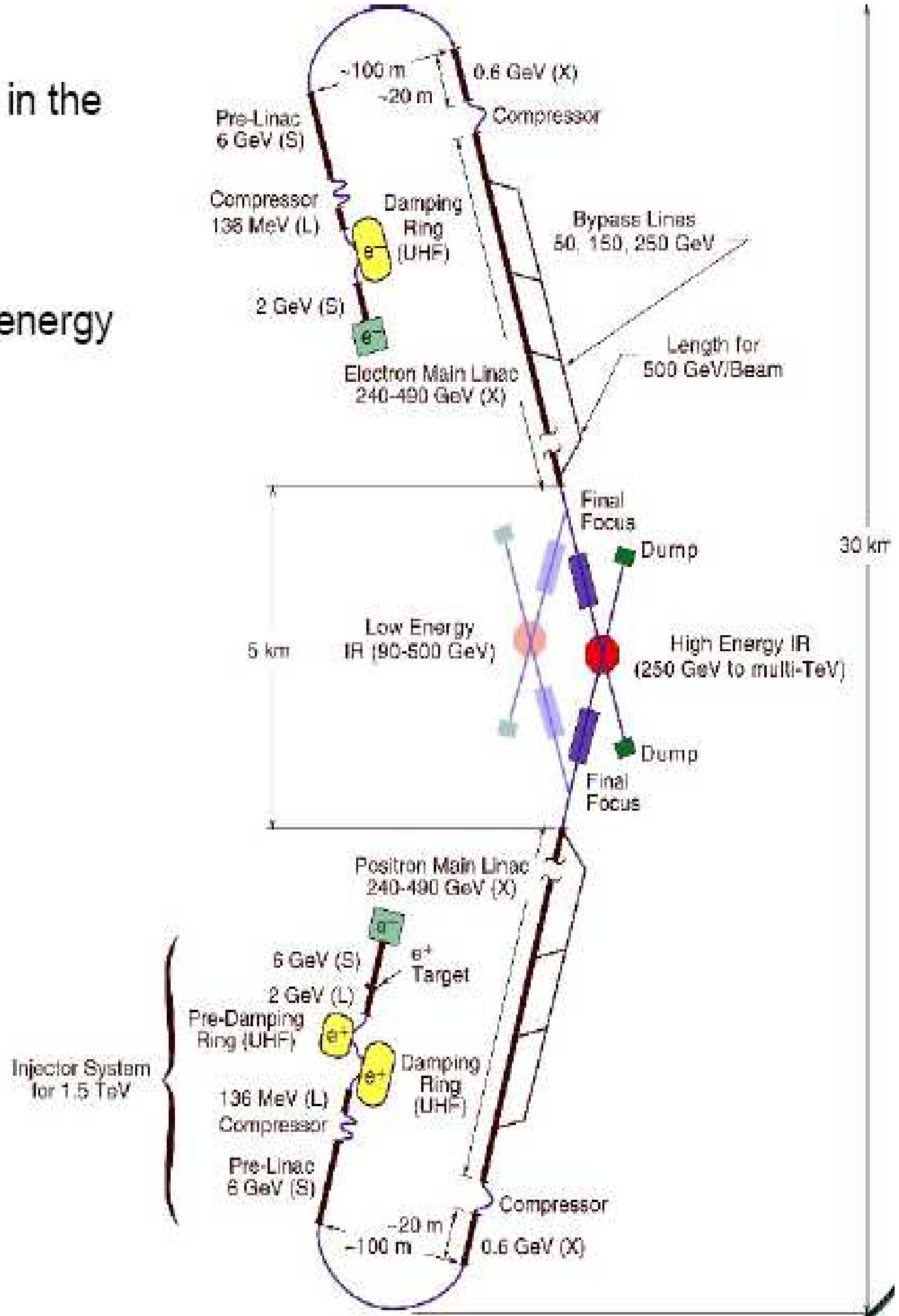
- $(\sqrt{s})_{max}$= 500 GeV but can operate at at any $\sqrt{s}$ in the range 200-500 GeV
- 500 fb^{-1} in first 4 years of running
- Possibility of energy scans at any $\sqrt{s}$ in whole energy range
- Possibility to go down to Z peak for calibration
- Beam energy precision < 0.1%
- $P(e^-) \geq 80\%$ in whole energy range
- 2 interaction regions

Upgrade

- $(\sqrt{s})_{max} \sim$ 1 TeV
- 1000 fb^{-1} in ~3-4 years

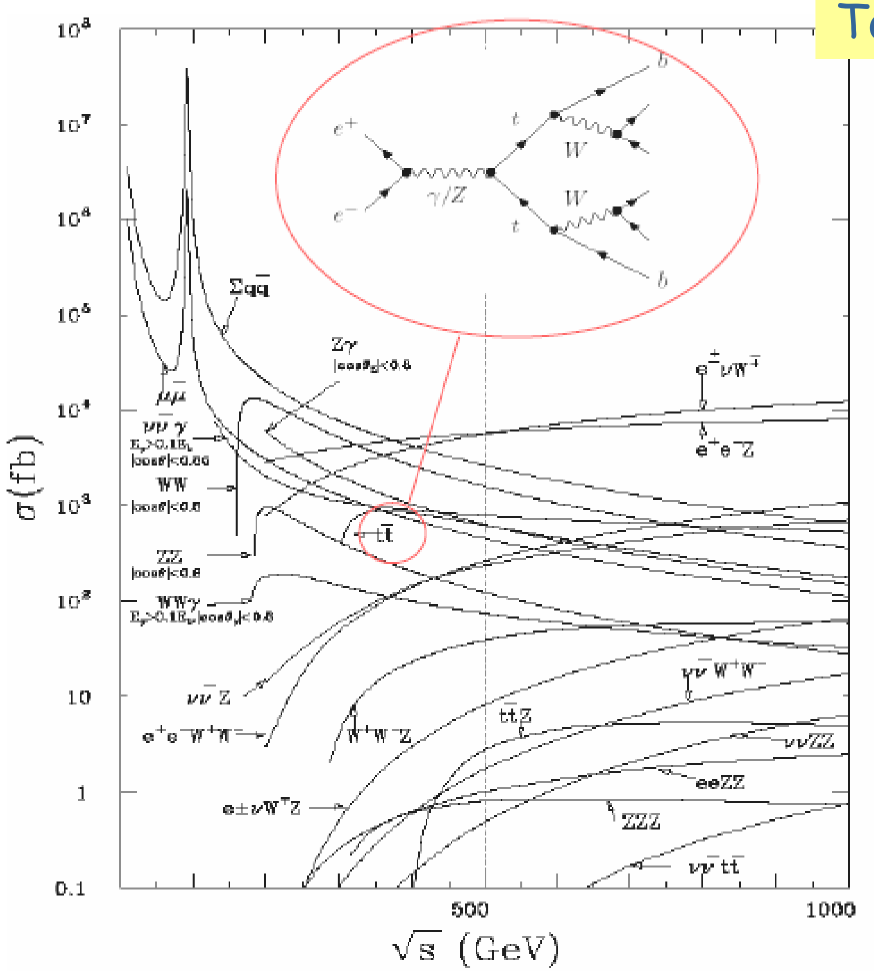
Options

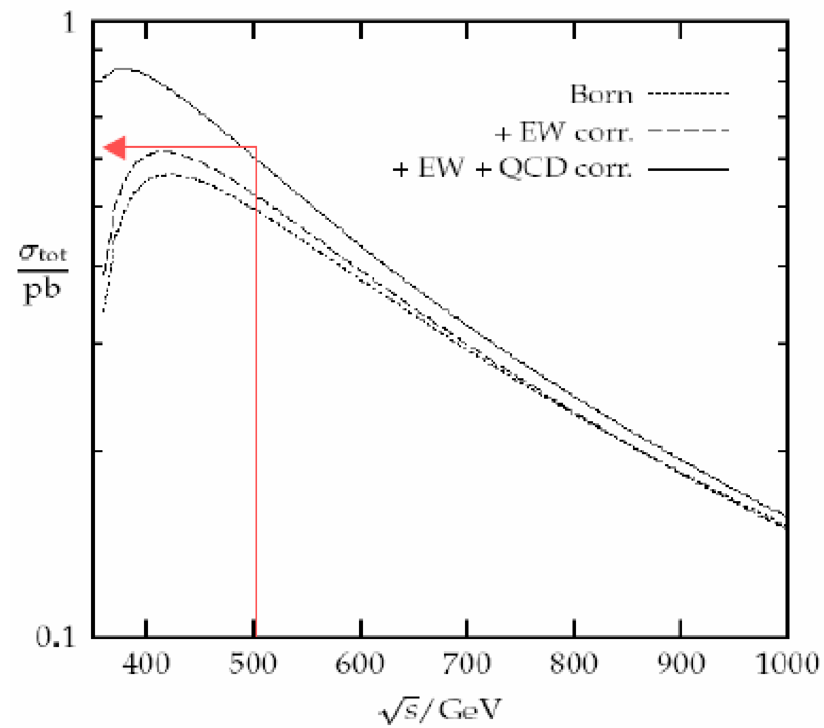
- Additional 500 fb^{-1} at $\sqrt{s}$ = 500 GeV in 2 years
- $P(e^+) \geq 50\%$ in whole energy range
- Low energy running ($\sqrt{s} = m_Z$ and $2m_W$) with $L \sim 10^{33}\ cm^{-2}s^{-1}$
- e^-e^- collisions
- $e^-\gamma$ and $\gamma\gamma$ collisions



Top production in e^+e^- Collisions

Top pair production via γ/Z exchange dominates





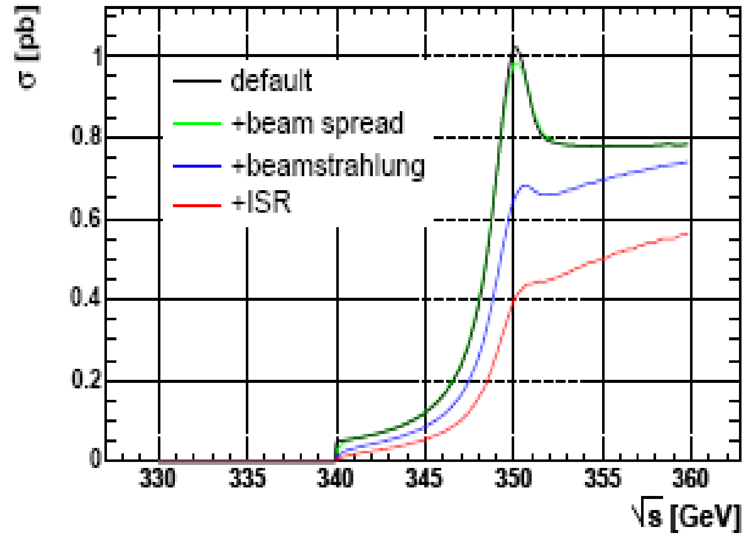
$\sigma_{tt} \sim 0.6\text{pb}$ at $\sqrt{s} = 500$ GeV

$\Rightarrow$ 200k events/year ($L = 2\times10^{34}\text{cm}^{-2}\text{s}^{-1}$)

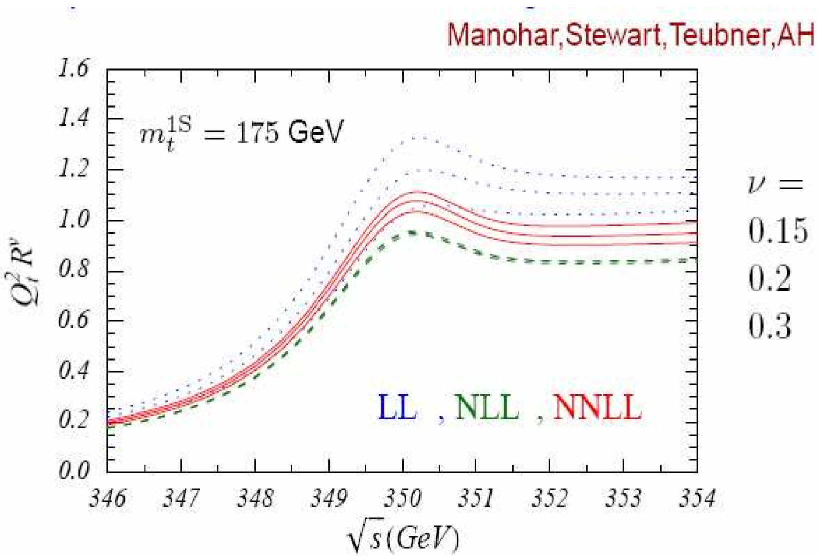
The anticipated experimental accurancy must be matched with precise theoretical predictions

Top Pair Production at Threshold

Smearing of the partonic cross section



- Lineshape significantly distorted due to:
  - Beam energy spread: ~ 0.1%
  - Breamstrahlung: coherent radiation due to beam-beam interactions. Must be measured precisely
  - Breamsstrahlung(ISR): can be calculated accurately



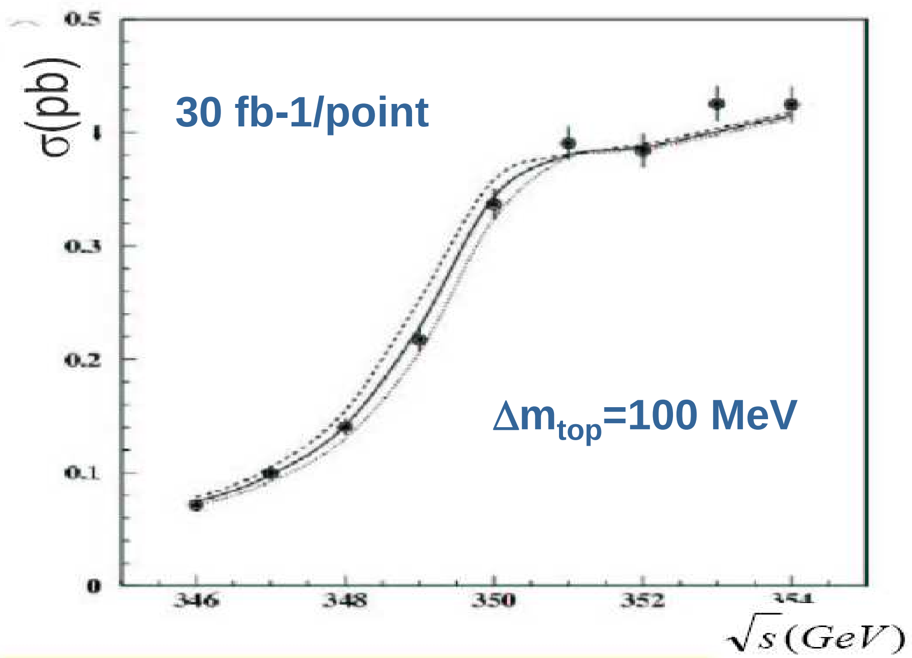
Perform scan in √s around the threshold region and compare measurement of various observables to theoretical predictions as a function of model parameters

Top quark Mass & Width

- <u>At threshold</u>
  - Simultaneous determination of m_t, α_s and Γ_t from fit to threshold observables. Assume 3% theoretical error on σ_{tt} and 9+1 point scan with 30 fb^{-1}/point:

$\Delta m_t(1S)$ = 19 MeV, $\Delta\alpha_s$=0.0012, $\Delta\Gamma_t$=32 Mev

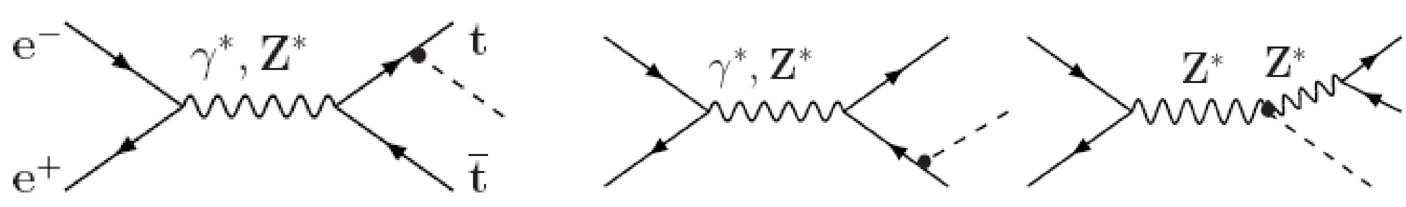
- ▷ count number of $t\bar{t}$ events
- ▷ color singlet state
- ▷ background is non-resonant
- ▷ physics well understood (renormalons, summations)



Top Yukawa coupling

- The top-Higgs Yukawa coupling is the largest coupling of the Higgs boson to fermions (g_{ttH}~0.7 vs g_{bbH}~0.02). Precise measurement important since the top quark is the only "natural" fermion from the EWSB standpoint

$\boxed{e^+e^- \rightarrow t\bar{t}H}$



ILC:

- tiny cross section for $\sqrt{s} = 500$ GeV
- measurement of Yukawa coupling diffi cult
- $\delta Y_t / Y_t \sim 30\%$ feasible at $\sqrt{s} = 500$ GeV [A. Juste, 2002]

LHC:

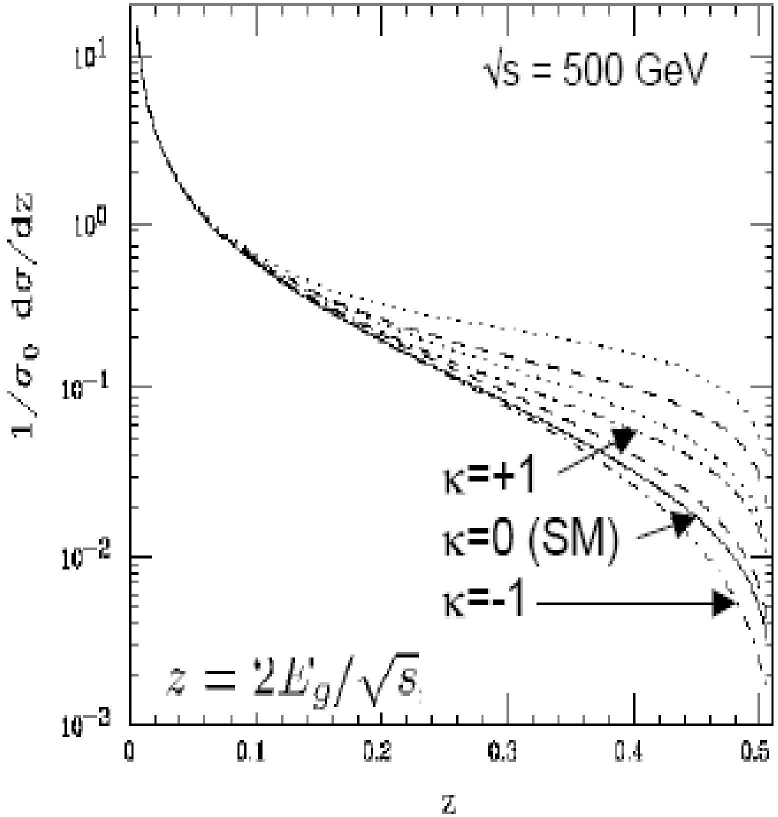
- Expected accuracy is ~12-15%, with mH=120-200 GeV and L=300fb-1

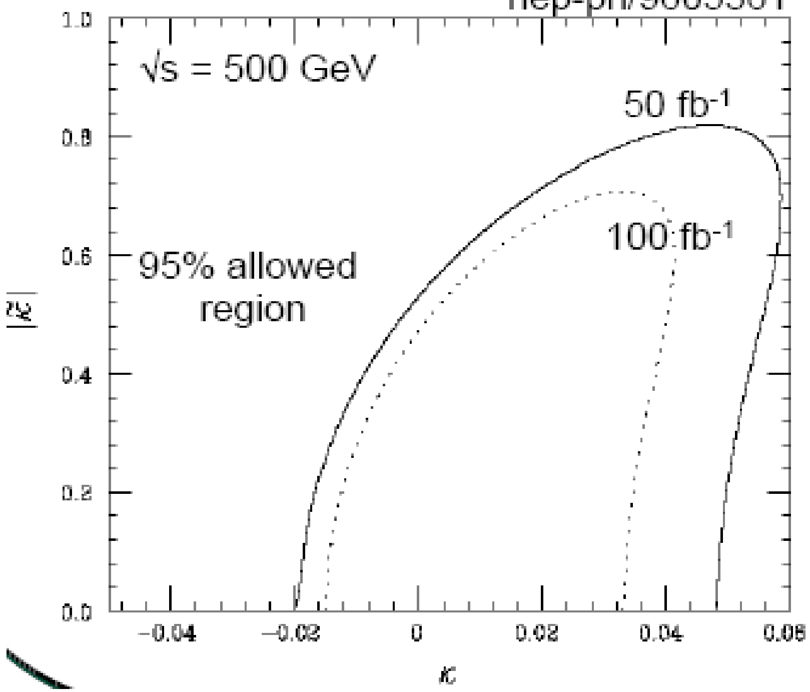
Top-Gluon coupling

- The g-t-t coupling can be affected by strong dipole moments related to New Physics:

$$\mathcal{L} = g_s \bar{t} T_a \left(\gamma_\mu + \frac{i}{2m_t} \sigma_{\mu\nu} (\kappa - i\tilde{\kappa}\gamma_5) q^\nu \right) t G_a^\mu$$

CP-conserving CP-violating





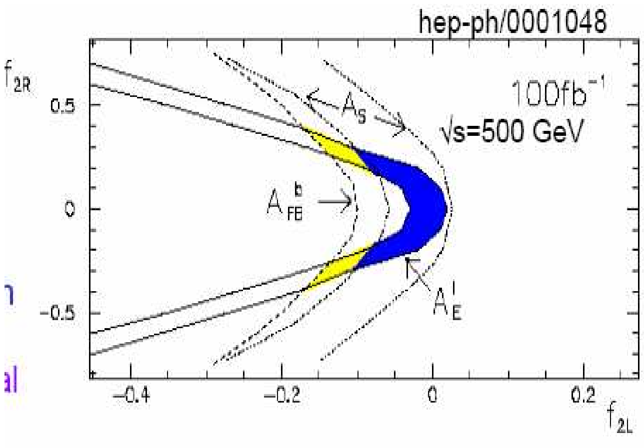
- One of the observables in e+e- collisions is the energy spectrum of extra jets radiated off the top quark

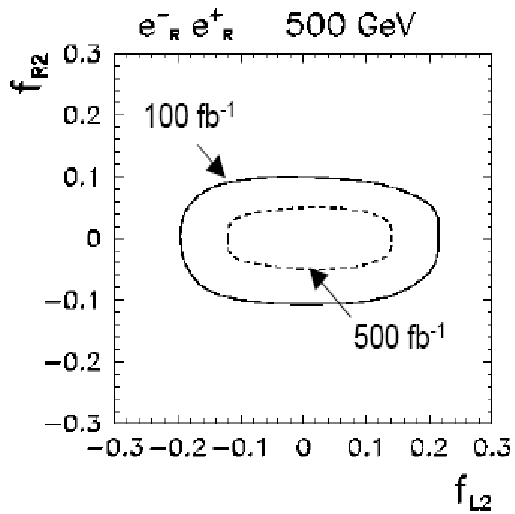
LHC will be sensitive to values ~ 0.1

Top Coupling to Weak Gauge Bosons (W,Z,γ)

Since the W and Z bosons acquire mass as a result of the EWSB mechanism, in which the top quark could possibly play a key role, the precise measurement of the top quark interactions to weak gauge bosons is extremely interesting. The use of polarized beam is an extremely powerful tool for this task.

- Within the SM, the W-t-b interaction is of the V-A type. The LHC will have probed a V+A interaction to the percent level. The ILC can in addition explore tensor-like couplings to the 5-10% level via:
  - the measurement of asymmetries in top quark pair production
  - the single top quark production rate





- The e+e-→Z/γ*->tt process is very sensitive to Z/γ-t-t couplings. In order to increase the sensitivity the use of beam polarization is crucial.

In Conclusions ...

- **From Tevatron:**
  - Single top observation+direct measurement of Vtb
  - Precion measurement: top mass with 0.75% uncertainty and general agreement with SM

...present and ...

future ...

- Elucidation of the dynamics responsible for EWSB constitues the main goal for particle physics research in the next 20 years
- The LHC will be probing the relevant energy scale and should definitelly discover signs of the EWSB dynamics.
- The ILC will complement the LHC by providing essential information to interpret and exploit these discoveries.
- In particular, the ILC shows the promise of precision measurements in top and QCD which will be crucial to point to the relevant energy scales and to possible extensions of the Standard Model