Top Physics Studies at ATLAS/LHC

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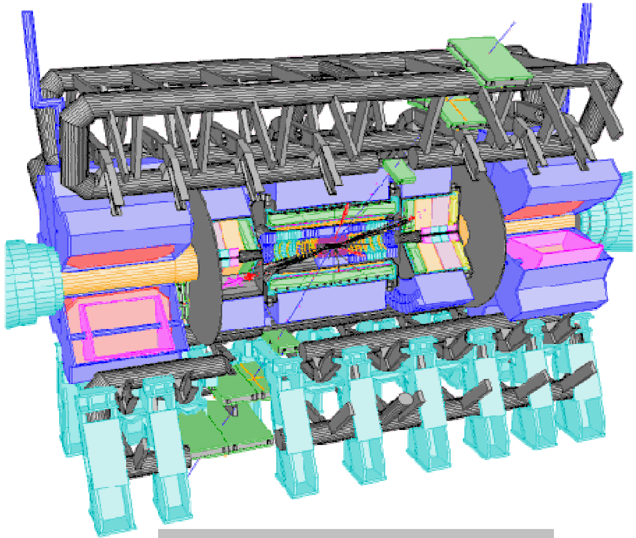
Topics in This Talk

- Top production cross section
  precisious QCD tests
- Top quark mass
  constraint on Higgs mass via EW physics
- Single top production
  top partial width, V_{tb}, spin effects…
- Top spin effects
  - Top-antitop spin correlations
- Anomalous couplings
  - FCNC in top physics
- Rare decays of top and exotics
  - Search for charged Higgs, superpartners



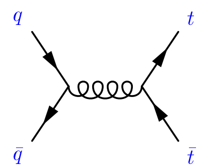
ATLAS detector

LHC: pp 14 TeV
ATLAS per year
pp @ L=10 fb^{-1} $\Rightarrow$
10^7 $t\bar{t}$ pairs
Start: 2007

Top Quark Production at LHC

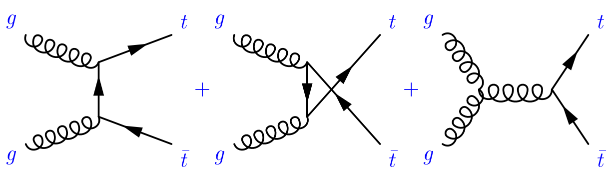
Strong t $\overline{t}$ pair production

EW single top quark production



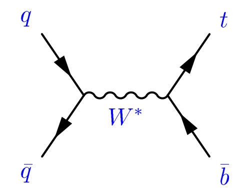
$q\overline{q} \to t\overline{t}$

(13%)



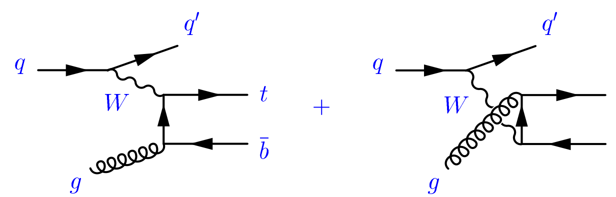
$gg \to t\overline{t}$

(87%)



$q\overline{q} \to t\overline{b}$

(Drell-Yan)



$qg \to q' t\overline{b}$

(W-g fusion)

X-section (NLO+NLL) ≈ 830 pb

X-section (NLO) ≈ 300 pb

at CDF X-section ≈ 6 pb

Bonciani et al, NuclPhysB529(1998)424

CERN 2000-004 (eds. Altarelli, Mangano)

at LHC $\sqrt{s}$ = 14 TeV

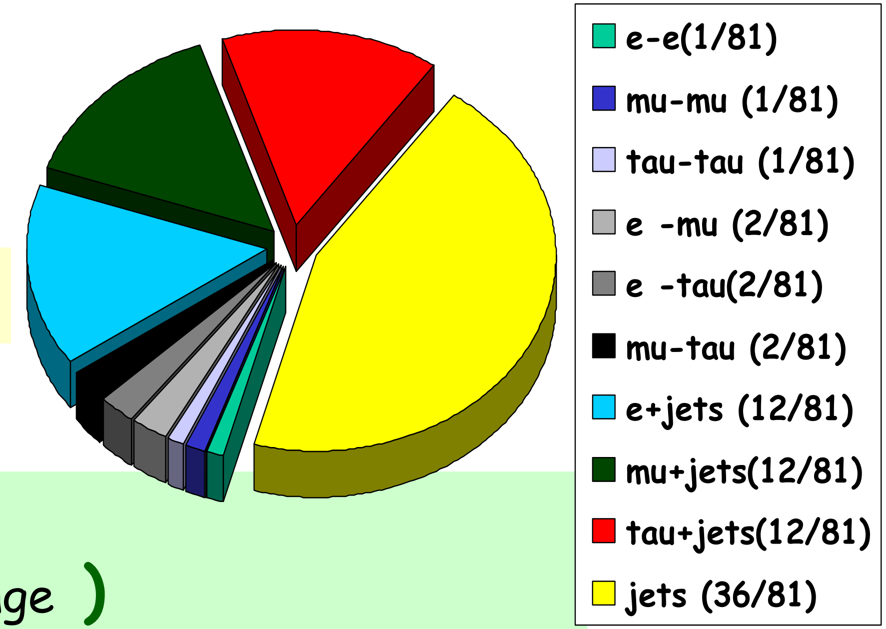
Top Quark Decay

SM: by far dominant $t \to bW$

$$\frac{\Gamma(t \to bW)}{|V_{tb}|^2} \approx 0.807 \times \frac{G_F m_t^3}{8\pi\sqrt{2}} = 1.42\,GeV$$

$\tau_{top} \approx 5\times10^{-25}$sec $<< \tau_{hadr}$ (10^{-23}sec)

(m_t=175 GeV, M_W=80.4 GeV, α_S=0.03475)



Top decays before hadronization !!!

- No tt-bar bound states (gluon exchange)
- t,W helicity from SM V-A(no depolarization via hadronization)

tt-bar samples
defined via W decays

- Dilepton channels (ee, eμ, $\mu\mu$)
  topological variables and b-tagging
- Lepton + jets ch. (e+jets, μ+jets)
  topological analysis and b-tagging
- All hadronic channel

$t\bar{t}$ Production Cross Section

Big $m_t \Rightarrow \alpha_s(m_t) \sim 0.1 \Rightarrow$ pExpansion coverges rapidly :

- $t\bar{t}$ cross section is a test of QCD predictions
  (Inclusive and differential cross sections)
- Acurate Xsection $\Rightarrow$ indirect determination of m_t
  (in SM is expected: $\Delta m/m \approx \Delta\, \sigma(tt)/\sigma(tt)$)
- Rapidity distr. asymmetries of t and $\bar{t}$ are sensitive to light-quark PDF

- A discrepancy may indicate a new physics
  - Production via a high mass intermediate state
  - Non Wb decay model

ATLAS: Statistical uncertainties < 1%

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

$t\bar{t}$ Production Cross Section

Theory for top X-section (Inclusive and differential):
NNLO-NNNLL (Kidonakis et al., PRD68,114014 (2003))

- Factorization

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

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

- Total Partonic Xsection:

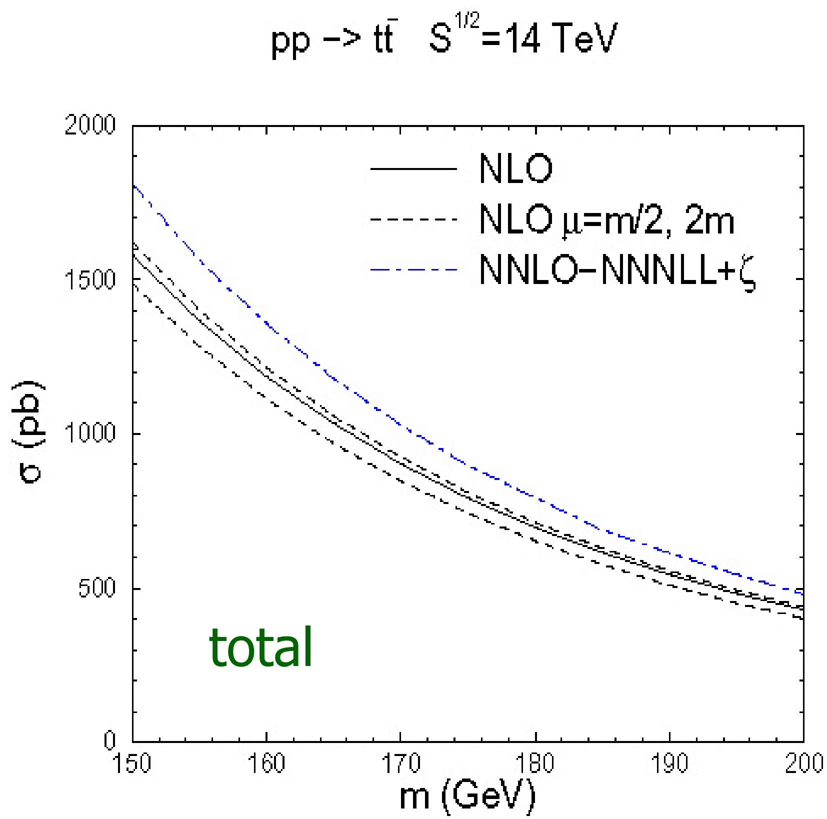
$$\hat{\sigma}_{ij} = \frac{\alpha_S^2(\mu)}{m^2} \sum_{n=0}^{\infty} \left(4\pi\alpha_S(\mu)\right)^n \sum_{k=0}^{n} f_{ij}^{(n,k)}(\eta) \ln^k\left(\frac{\mu^2}{m^2}\right)$$

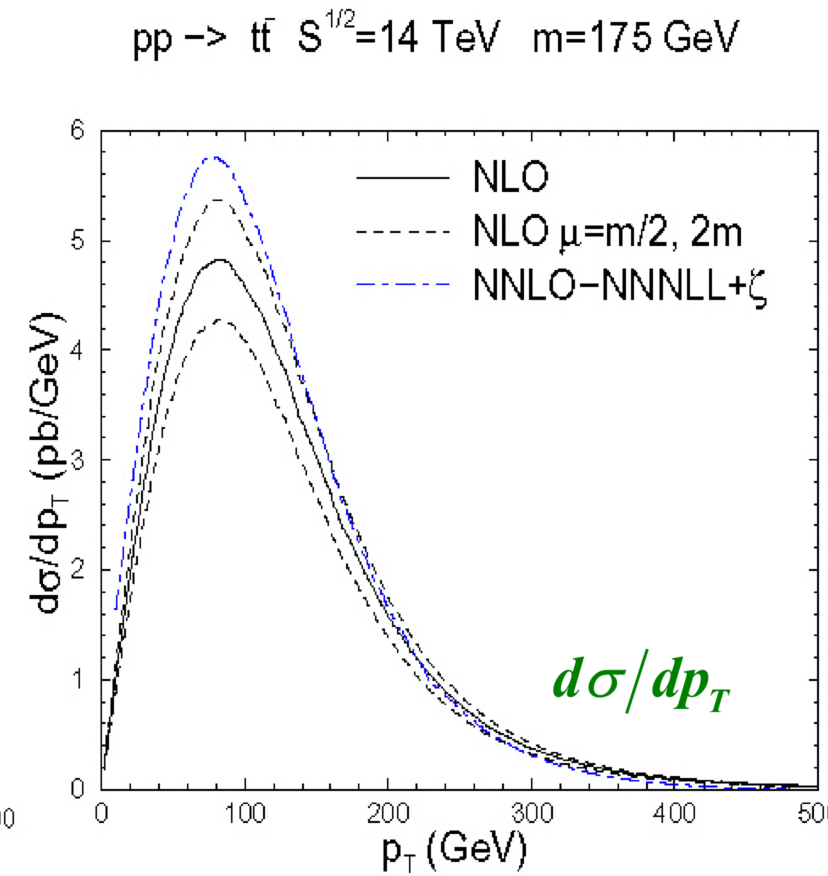
$$\eta = \frac{s}{4m^2} - 1$$

$$s = (p_i + p_j)^2$$

Progress at MC: radiative gluon corrections included: MCatNLO (Frixione et al, hep-ph/0311223)

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



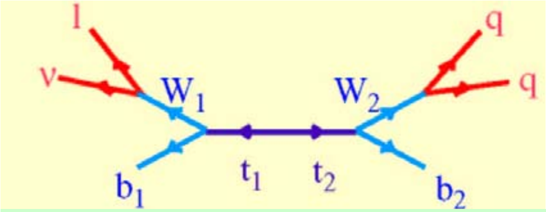


NNLO: uncertainty from scale ($m_t/2$, $2m_t$) < 3% !!!

(N.Kidonakis, hep-ph/0401147)

Top Mass measurement at ATLAS/LHC

Lepton +jets channel



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

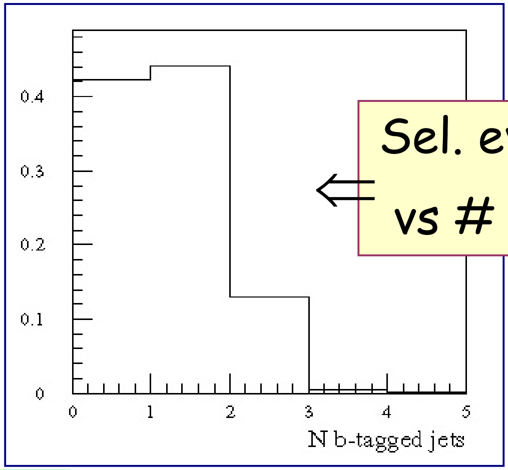
At prod. level: S/B=10^{-5}
⇒ cuts applied:

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

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

Process	Cross section (pb)	Efficiency (%)
tt signal	250	3.5
bb→ $l\nu + jets$	2.2×10^6	3×10^{-8}
W+jets→ $l\nu + jets$	7.8×10^3	2×10^{-4}
Z+jets→ $l^- l^+ + jets$	1.2×10^3	6×10^{-5}
WW→ $l\nu + jets$	17.1	7×10^{-3}
WZ→ $l\nu + jets$	3.4	1×10^{-3}
ZZ→ $l^- l^+ + jets$	9.2	3×10^{-3}

Signal vs Bkgd: x-section and sel. efficiency



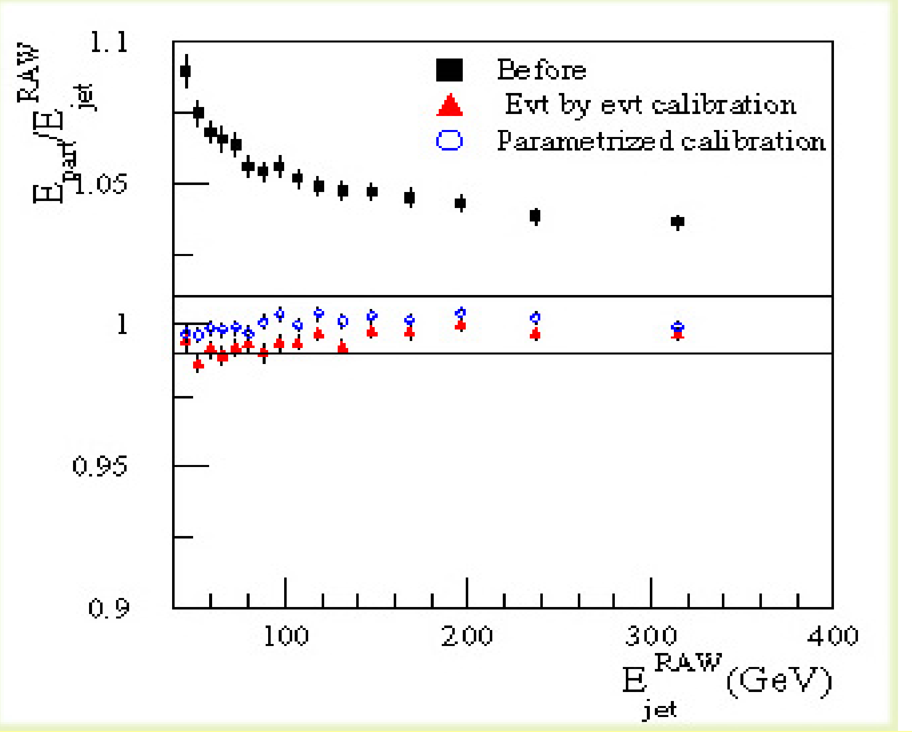
⇐ Sel. events vs # b-tags

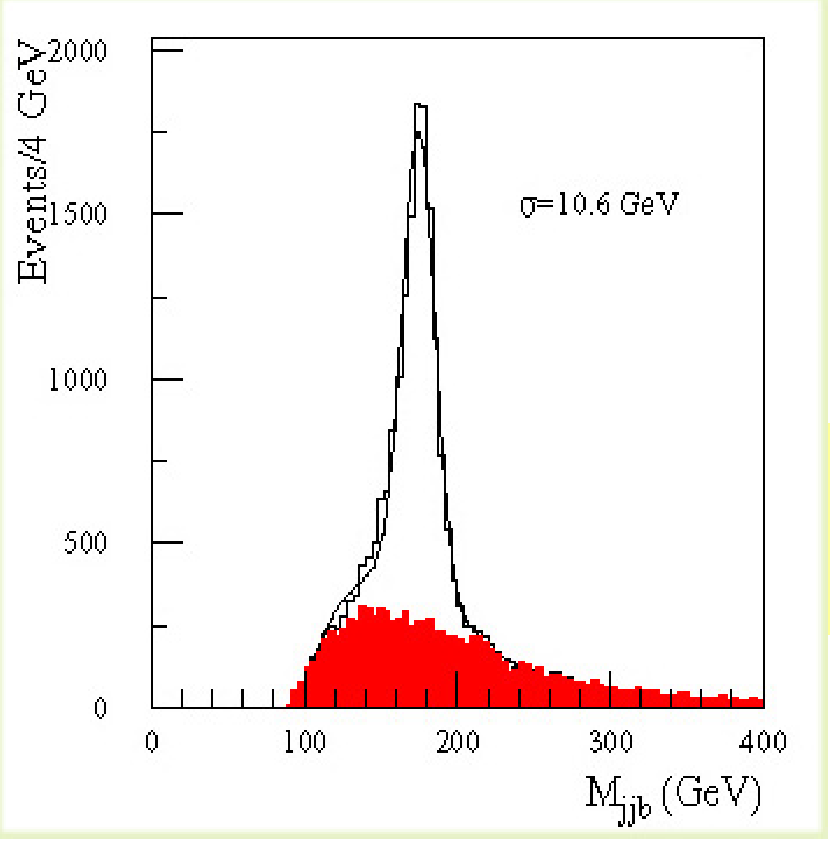
Purity 55% for 1 b-tagged, eff=2.5 %
66% for 2 b-tagged, eff=1.2 %
Top mass window : ±35 GeV

Jet energy correction

$K=1.029+3.20/E_{raw}$

Needed to minimize Δm_t





⇐ **Invariant mass of jjb**

(b-jets calibtrated using Z+b events, M_W window: ±20 GeV)

For **10 fb^{-1}** sample: Δm_t

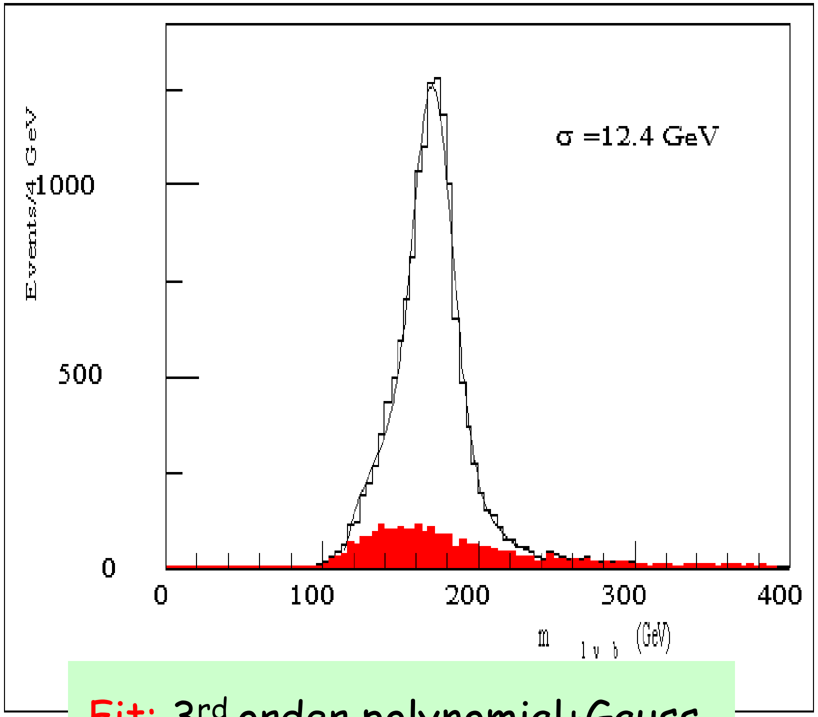
- statistical error 100 MeV
- systematics ~ 1.3 GeV (FSR,..)

Top mass in lepton + jets channel

Leptonic part - mass reconstructed via :

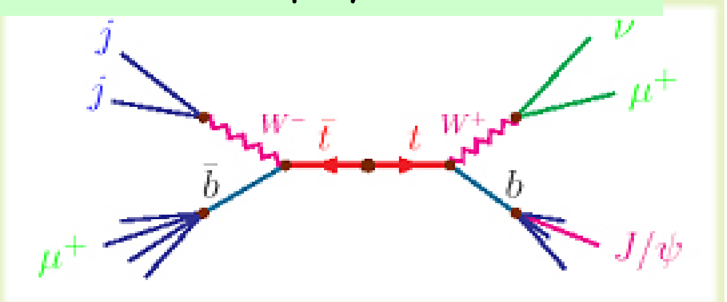
- missing transverse energy ($E_T^{\nu} = E_T^{miss}$)
- constraint m(lν)=M_W for neutrino p_z

Result: two leptonic top masses due to twofold ambiguity in neutrino p_z



Kinematic fit (event by event):
Lepton and jets energy, jets direction (φ,η), neutrino p_x,p_y,p_z vary freely (in errors inter.)
χ^2 uses constraints $M_{jjb}=m_t$, $M_{l\nu b}=m_t$, $M_{jj}=M_W$
$\Rightarrow$ m_t find by fit , χ^2 < 4 $\rightarrow$ purity > 80%

Fit: 3[rd] order polynomial+Gauss



Promising: ***l +J/ψ channel***

- Strong correlation between m_t & m(l,J/ψ)
- BR=3.2×10^{-5} (2700 ev/100fb^{-1}, sel. $\varepsilon\approx$16%)
- non-sensitive to jet energy, S/B$\approx$55

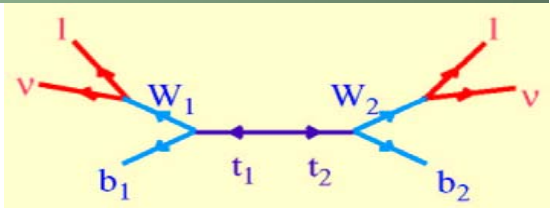
$t\rightarrow W^+b$, $W^+\rightarrow l\nu$, $b\rightarrow J/\psi X$

Top mass in di-lepton 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 found from:

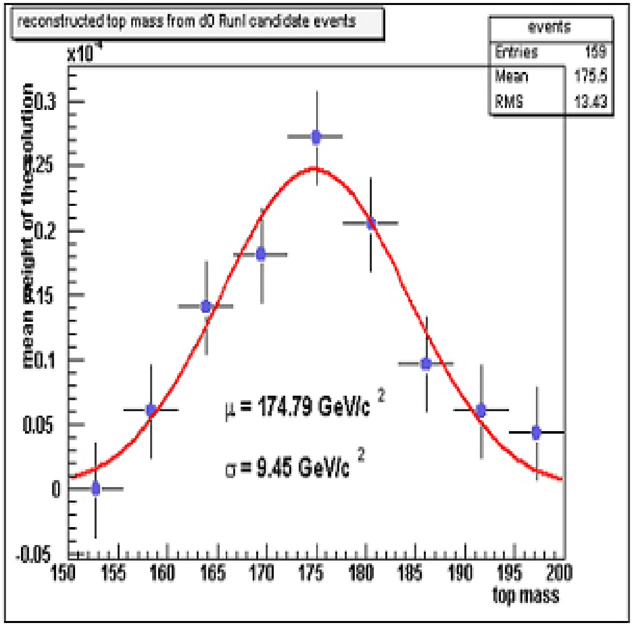
$$\sum p_x = \sum p_y = 0,\ m_{l^+\nu} = M_W,\ m_{l^-\tilde{\nu}} = M_W,$$

$$m(l^+\nu b) = m_t,\quad m(l^-\tilde{\nu} b) = m_t \qquad m_t \text{ is known}$$

For weight $\Rightarrow m_t^2 = M_W^2 + 2\langle m_{lb}^2\rangle / \left(1 - \langle \cos\theta_{lb}\rangle\right)$

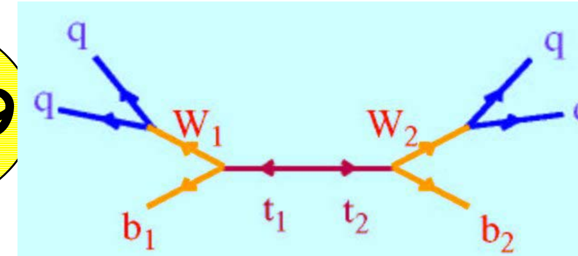
For each event: full reconstruction is done for different input top masses and mean weight is calculated for each input m_t

Source of uncertainty	*δM_{Top} (GeV)*	*Comments*
Statistic & reconstruction method	0.3	
b-jet energy scale	0.6	1% error
b-quark frag.	0.7	(ε_b=-0.006)-(ε_b=-0.035)
ISR	0.1	20%(ON-OFF)
FSR	0.6	20%(ON-OFF)
Parton distribution function	1.2	Mass shift from 2 different sets
Total	1.7	



Top mass in all jet channel

Selection:
≥6jets with p_T>40 GeV , ≥2 b-jets ⇒ **S/B =1/19**
Small missing E_T



Kinematic fit (two steps)

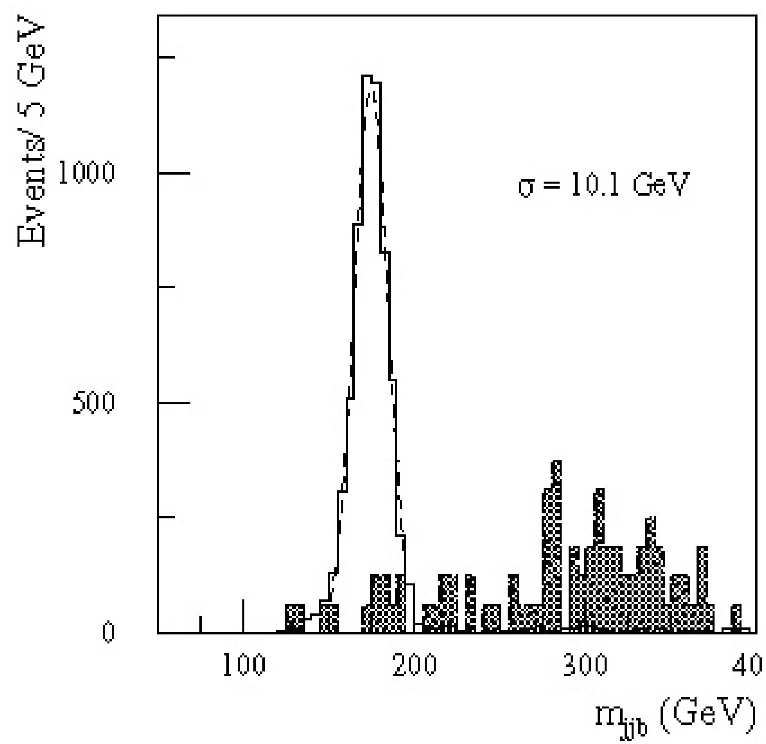
- **W's selection and reconstruction with W mass constraints**
- **Both W candidates are combined with the b-jets.**

Combination chosen using top mass constraint: m(t1) = m(t2)

Top mass window (130-200 GeV) ⇒ S/B = 6/1

High PT subsample ⇒ Selection

- **pT (t) > 200 GeV**
- **3300 evts/10 fb^{-1} ⇒S/B = 18/1**
- **$\Delta m^{stat}(t)$ = 0.2 GeV/c^2**
- **$\Delta m^{sys}(t)$ = 3 GeV/c^2**

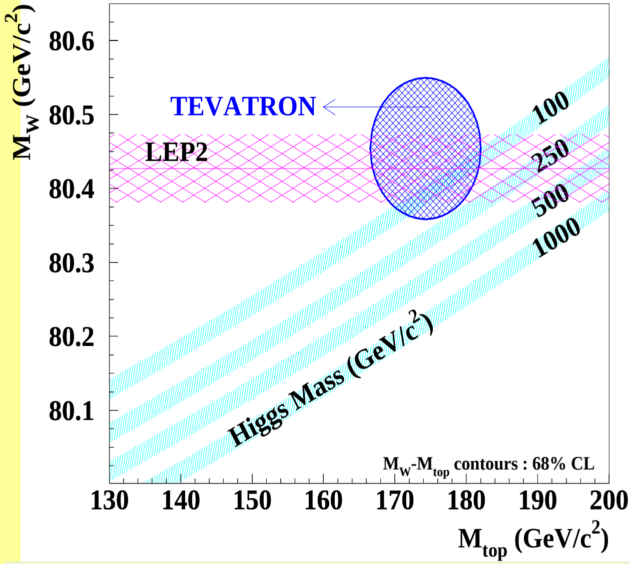


Top mass and EW precision physics

Atlas top mass systematics ($L=10fb^{-1}$) : jet energy scale, b-jet frag., ISR, FSR, comb. Bckgd.
All mass method combined ⇒

$$\Delta m_t(stat) = \pm 0.1\,GeV \qquad \Delta m_t(syst) = \begin{cases} +0.6 \\ -0.8 \end{cases} GeV$$

ISR, FSR via Pythia ⇒ Realistic: $\Delta m_t \approx$ **1 GeV**



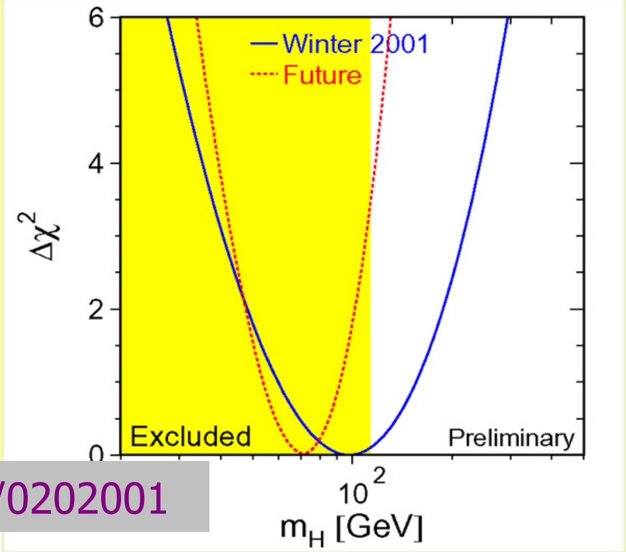
Masses of top, W and Higgs are bounded by

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

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

Precise M_W and m_t ⇒ constraint on M_H !

present→LHC: Δm_t: **5→1 GeV**, ΔM_W: **33→15 MeV**

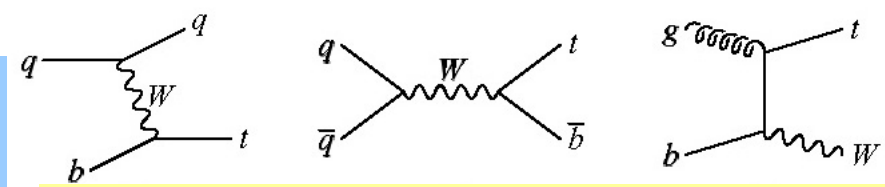


Grunwald et al, hep-ph/0202001

Single top production

Production via weak forces

- Xsection~$|V_{tb}|^2$
  (direct measurement of V_{tb})
- Significant bckgd to Higgs signal
- Single top –100% polarization
  (test of V-A structure of EW)
- Possible new physics

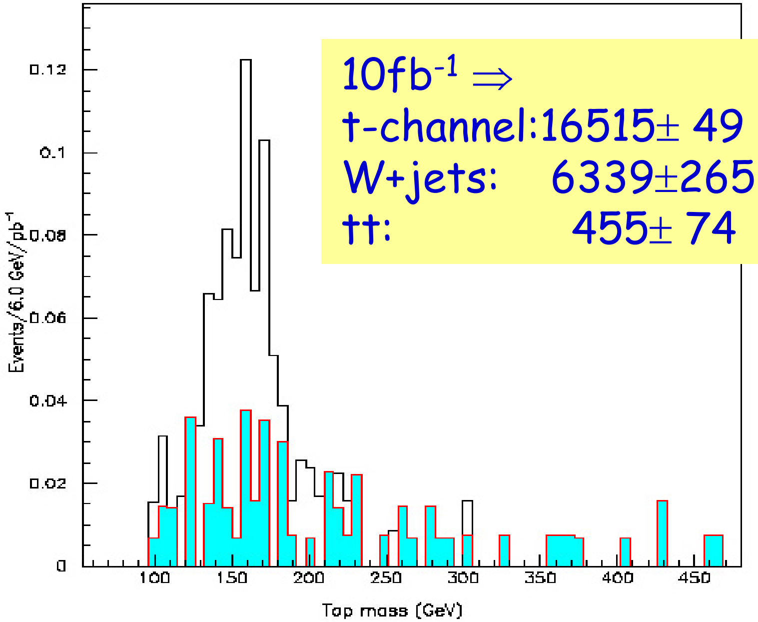


t-channel	s-channel	association production
245±27 pb	10.7±0.7 pb	51±9 pb

(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 ∈(80,100) GeV
  (rejects WZ events)

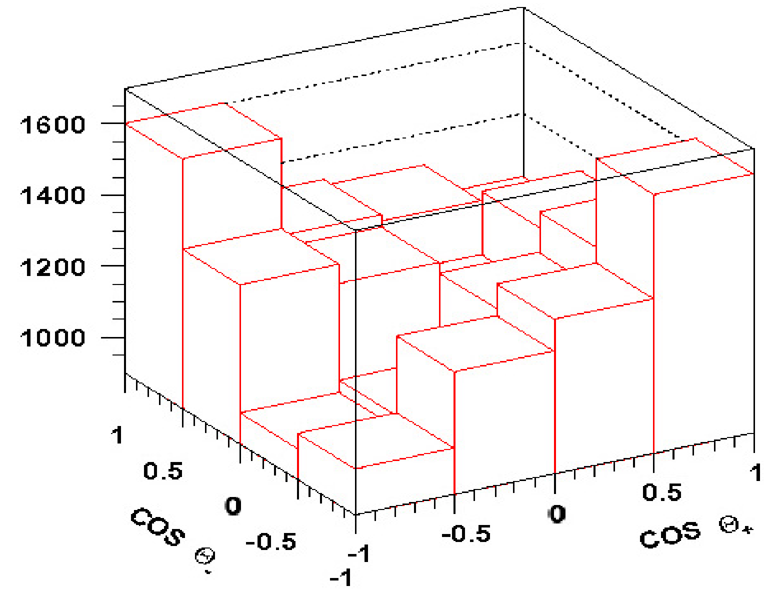


$10fb^{-1} \Rightarrow$
t-channel:16515± 49
W+jets: 6339±265
tt: 455± 74

$t\bar{t}$ spin correlations

Top decays before hadronization ⇒
- Spin of top is not diluted
- Gluon emission unlike to do $\Delta S \neq 0$

Imprint of $t\bar{t}$ production spin:
Angular distrib. of top decay prod's



Considered parton reactions:

$$gg, q\bar{q} \rightarrow t\bar{t} + X \rightarrow b\bar{b} + 4f + X \quad f \equiv q, l, \nu$$

$$\left|M^{(\lambda)}\right|^2 \propto Tr\left[\rho R^{(\lambda)} \bar{\rho}\right], \quad \lambda = gg, q\bar{q} \quad \text{(narrow w.)}$$

Decay of polarized t quark

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta_f} = \frac{1}{2}\left(1 + \kappa_f \xi_t \cdot \hat{q}_f\right)$$

$\theta_f \equiv$ angle (direction $\hat{q}_f$ of f, polarisat. ξ_t)

$\kappa_f \equiv$ Correlat. coef.for V-A current

for anti-t decay: $\kappa_f \rightarrow -\kappa_f$

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

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1 + C\kappa_{l^+}\kappa_{l^-} \cos\theta_+ \cos\theta_-}{4}$$

$\theta_+(\theta_-) \equiv$ angle $\left(n_t(n_{\bar{t}}),\ l^+(l^-)\text{direction}\right)$

$t\bar{t}$ CMS $\quad t(\bar{t})$ LS

$\kappa_{l^+}\kappa_{l^-} = -1, \quad C = 0.332$ (SM)

Top and CP violation

- CKM phase → only tiny effect on t-pair production and decay
- Non SM CP-violating interactions → in prod. density matrix (R) 2 types CP-odd spin-momentum correlations:

$$\hat{k}_t \cdot (s_t - s_{\bar{t}}), \quad \hat{k}_t \cdot (s_t \times s_{\bar{t}}), \quad \hat{k}_t \to \hat{p}$$

$\hat{k}_t \equiv$ top direction, $\hat{p} \equiv$ init. quark direction

Examples:

- In MSSM fermion-sfermion-neutralino interactions → CP violating phases from SUSY breaking terms
- Extended scalar sector → via non-degenerate neutral Higgs bosons with undefined CP parity.

Coupling of Higgs (φ) with top: $\sim m_t \left(a_t \bar{t} t + i\tilde{a}_t \bar{t} \gamma_5 t \right) \varphi$

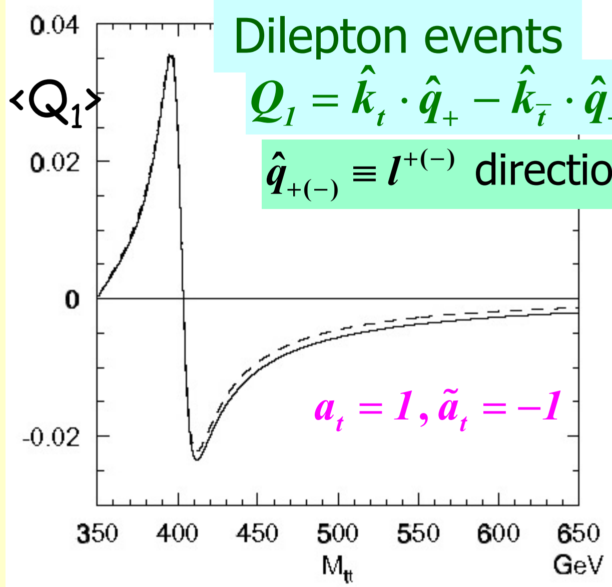
(in SM $a_t = 1, \tilde{a}_t = 0$)

$gg \to \varphi \to t\bar{t}$ becomes resonant at m_φ ~2 m_t or above

Dilepton events

$Q_1 = \hat{k}_t \cdot \hat{q}_+ - \hat{k}_{\bar{t}} \cdot \hat{q}_-$

$\hat{q}_{+(-)} \equiv l^{+(-)}$ direction



Bernreuther et al, hep-ph/9812387

Can be also employed:
Asymmetry:

$$A(Q_1) = \frac{N_{ll}(Q_1 > 0) - N_{ll}(Q_1 < 0)}{N_{ll}}$$

Top quark anomalous interactions

- Top Xsection known with ~10% accuracy
- No top hadrons
- Top decay via pure V-A weak interaction
- Only one significant decay channel: $t \to Wb$

$\Rightarrow$ Top quark a unique place for a new physics behind SM

New physics from symmetry breaking at scale Λ (~1TeV)?

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

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

Choi et al, PhysLettB415(1997)67 $\Rightarrow$

$$T_{33} = 2(p_{\bar{l}} - p_l)_3 (p_{\bar{l}} \times p_l)_3, \quad A_E = E_{\bar{l}} - E_l$$

$$Q^l_{33} = 2(p_{\bar{l}} + p_l)_3 (p_{\bar{l}} - p_l)_3 - \tfrac{2}{3}\left(p_{\bar{l}}^2 - p_l^2\right)$$

Anomalous Wtb couplings

- Can be probed in top pair and single top production.
- 4 form factors describe Wtb – two are ½ (from SM) and 2 to be analyzed:

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

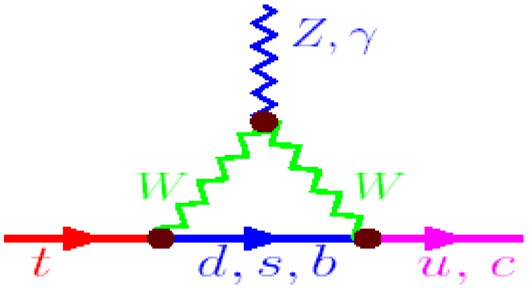
$\Rightarrow$Boos et al,EFJC11(1999)473

FCNC in Top Quark Physics

FCNC couplings tVc and tVu; V = g, γ, Z

- Absent at tree-level and highly suppressed in SM
- Present through loop contributions
- Observation of top quark FCNC processes

  ➔ New Physics!



$t \rightarrow$	SM	two-Higgs	SUSY
$g\,q$	5×10^{-11}	10^{-6}	10^{-3}
$\gamma\,q$	5×10^{-13}	10^{-6}	10^{-5}
$Z\,q$	$\sim 10^{-13}$	10^{-9}	10^{-4}

CDF & LEP2 Present Limits
BR < 17%
BR < 3.2%
BR < 18%

FCNC in top quark physics

- Top decay widths and BR for anomalous couplings(=1) and for SM
  (v=250 GeV, m_t=175 GeV, Λ=1 TeV, Han et al, NuclPhysB454(1995)527)

	Top decay mode				
	W^+b	$(c+u)g$	$(c+u)\gamma$	$(c+u)Z_\gamma$	$(c+u)Z_\sigma$
FCNC coupling		1	1	1	1
Γ(GeV)	1.56	2.86	0.17	2.91	0.14
B	0.20	0.37	0.022	0.38	0.018
FCNC coupling		8×10^{-6}	3×10^{-6}	4×10^{-7}	
Γ_{SM}(GeV)	1.56	8×10^{-11}	8×10^{-12}	2.2×10^{-13}	
B_{SM}	1	5×10^{-11}	5×10^{-13}	1.5×10^{-13}	

Limits on anomalous couplings $\Rightarrow$

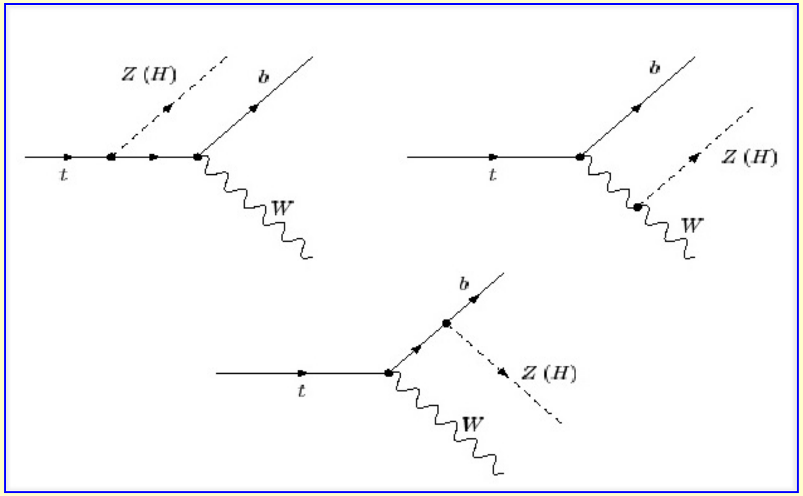
	Tevatron	LHC
$\sqrt{s}$ (TeV)	2.0	14.0
$L(fb^{-1})$	2	10
$\kappa^g_{tu}(2\to1)$	0.019	0.0033
$\kappa^g_{tu}(2\to2)$	0.026	0.0061
$\kappa^g_{tu}(2\to1)$	0.062	0.0084
$\kappa^g_{tu}(2\to2)$	0.092	0.013

Indirect constraint (from $K_L\to\mu\mu$, $\Delta m(K_L-K_S$, …): $\sqrt{|v^Z_{tu}|^2+|a^Z_{tu}|^2} < 0.15$

CDF results (decays $t\to\gamma c(u)$ and $t\to Zc(u)$): $\sqrt{|v^Z_{tq}|^2+|a^Z_{tq}|^2} < 0.73, \quad \kappa^\gamma_{tq} < 0.78$

Rare SM top decays

- Direct measurement of V_{ts}, V_{td} via decays $t \to sW$, $t \to dW$



- Decay $t \to bWZ$ is near threshold
  $(m_t \sim M_W + M_Z + m_b) \Rightarrow$
  $BR_{cut}(t \to bWZ) \approx 6\times10^{-7}$
  (cut on m(ee) is 0.8 M_W)
- Decay $t \to cWW$ suppressed by GIM
  factor m_b^2 / M_W^2 $BR(t \to cWW) \sim 1\times10^{-13}$

- If Higgs boson is light: $t \to bWH$
- FCNC decays: $t \to cg$, $t \to c\gamma$, $t \to cZ$ (BR: 5×10^{-11} , 5×10^{-13} , 1.3×10^{-13})
- Semi-exclusive t-decays $t \to bM$
  (final state 1 hadron recoiling against a jet:
  $BR(t \to b\pi) \approx 4\times10^{-8}$, $BR(t \to bD_s) \approx 2\times10^{-7}$)

Non-SM Decays of Top

- 4^{th} fermion family

  Constraints on $|V_{tq}|$ relaxed: $BR(t \to W^+ b'(\to W^- c)) \sim 10^{-3}$ at $m_{b'} = 100\,GeV$

- Supersymmetry (MSSM)
  - Observed bosons and fermions would have superpartners $\Rightarrow$

    2-body decays into squarks and gauginos ($t \to H^+ b$)

    $$\left(t \to \tilde{t}_1 \tilde{g},\ t \to \tilde{b}_1 \tilde{\chi}_1^+, t \to \tilde{t}_1 \tilde{\chi}_1^{+0}\right)$$
  - Big impact on 1 loop FCNC
- two Higgs doublets
  - $H^\pm$ LEP limit 77.4 GeV (LEP WG 2000)
  - Decay $t \to H^+ b$ can compete with $t \to W^+ b$
  - 5 states (h^0, H^0, A^0, H^+, H^-) survive after giving W & Z masses
  - $H^\pm$ couples to heaviest fermions $\Rightarrow$ detection through breakdown of e / μ / τ universality in $t\ \bar{t}$ production

Top quark charge

CDF, D0+precission EW data do not exclude :"top" quark is an exotic quark with charge –4/3 (Chang et al. PRD59, 091503)

Exotics: $t \to W^- b$ (in SM: $t \to W^+ b$)

Top charge determination:

- by measuring charges of top decay products
  $t \to W^+ b$ (W charge: $W^+ \to l^+ \nu$, $Q_{bjet} = \sum_i Q_i \left|\vec{j} \cdot \vec{p}_i\right| / \sum_i \left|\vec{j} \cdot \vec{p}_i\right|$)
- Via radiative $t\bar{t}$ events (sensitive to Q_t)

Analysis for ATLAS (10fb^{-1}) (Ciljak et al, Atl-Phys-2003-35):

- $l^+(l^-)$-bjet association criteria can be found to distinguish between mean $Q(b_{jet}l+)$) and Q(b-jet(l-)).

- Radiative top production ($pp \to tt\gamma$) can be used to measure foton-top coupling $\left(\sigma \sim Q_t^2\right)$ $\Rightarrow$

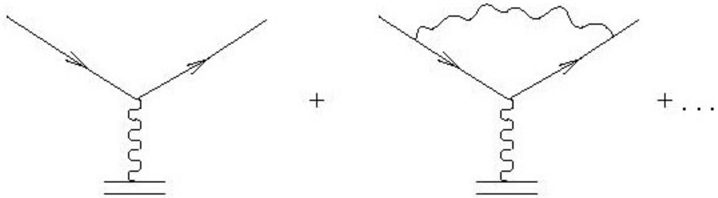
Integrated Xsection: $\sigma^{seen}(Q=2/3)$ =7.8fb^{-1}, $\sigma^{seen}(Q=2/3)$ =24.8fb^{-1}
Background: σ^{seen}=6.5fb^{-1}

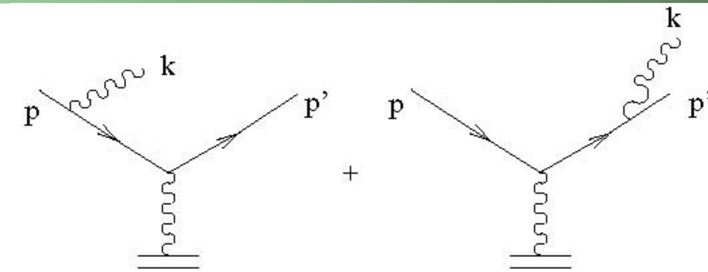
Conclusions

- Top quark physics is rich even at low luminosity LHC ($10fb^{-1}$/year)
  - SM: EW and QCD tests
  - Behind SM: probe SUSY
  - Determination of top characteristics (X-section, mass, width,charge..)
- Important background
  - Top quark production (pair and single) is main background to processes with multi lepton + jets in final state e.g. Higgs physics, SuSy
- High statistics studies at LHC ($100fb^{-1}$/year)
  - $\Delta m_t \leq 1$ GeV
  - BR for FCNC tVq $\approx 10^{-3} - 10^{-6}$
  - Measurenent of CKM V_{tq}

❖ We are looking forward to 2007…(LHC starts)

NLO,NNLO+LL,NLL,...





Jet not seen if $m_{qg}^2 < M^2 = ys$

$$\sigma_{2j} = \sigma_0 \left[1 - \frac{\alpha_s C_F}{\pi} \ln^2 y + \frac{1}{2!} \left(\frac{\alpha_s C_F}{\pi} \ln^2 y \right)^2 + \dots \right] = \sigma_0 \exp\left(- \frac{\alpha_s C_F}{\pi} \ln^2 y \right)$$

$$\sigma_{3j} = \sigma_0 \frac{\alpha_s C_F}{\pi} \ln^2 y \times \exp\left(- \frac{\alpha_s C_F}{\pi} \ln^2 y \right)$$