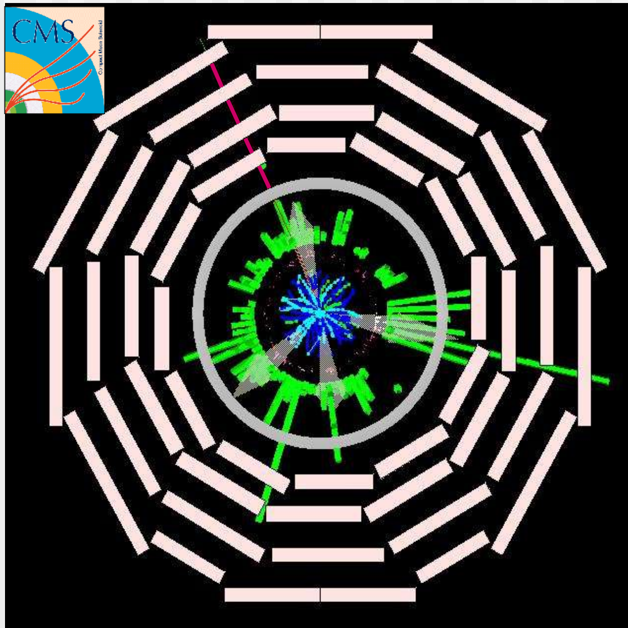
Top quark studies at CMS

Andrea Giammanco – SNS & INFN Pisa

- Advantages of LHC
- QCD production (ttbar pairs)
- EW production (single top)
- What can Tevatron do for LHC?

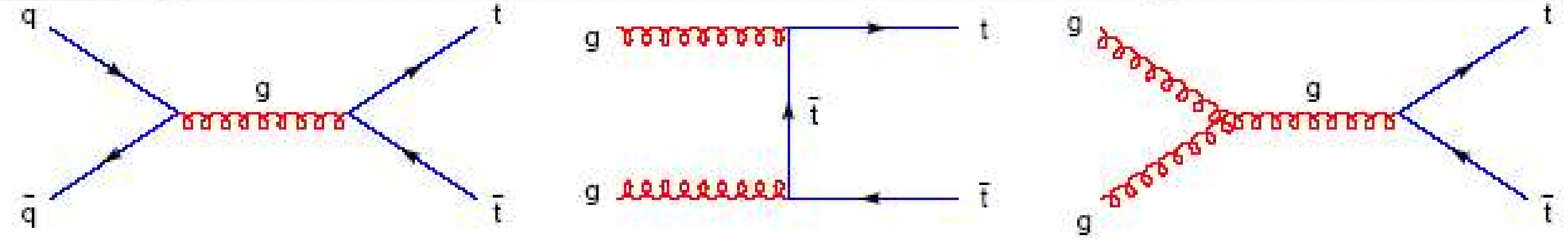


LHC is a top factory

σ_{tt}(th)=825±150 pb

NNLO-NNNLL: Kidonakis, Vogt, PRD 68 (03) 114014

This means 8 millions tt pairs/year (1 pair/second) at low luminosity!



qq->tt: 13%

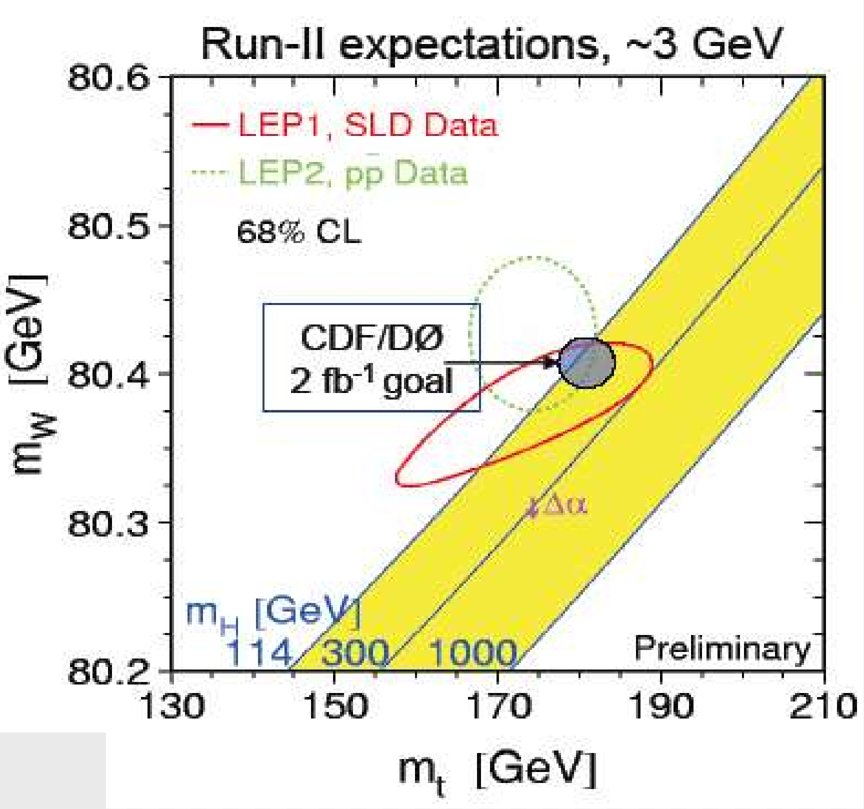
gg->tt: 87%

Advantage of LHC: S/B

	1.96 TeV	14 TeV	
ttbar pairs	$6.70^{+0.71}_{-0.88}$ pb	825±150 pb	(x120)
Single top (s-channel)	0.75±0.12 pb	10±1 pb	(x10)
Single top (t-channel)	1.47±0.22 pb	245±17 pb	(x170)
Single top (Wt channel)	0.15±0.04 pb	60±10 pb	(x400)
Wjj (*)	~1200 pb	~7500 pb	(x6)
bb+other jets (*)	~2.4x10^5 pb	~5x10^5 pb	(x2)

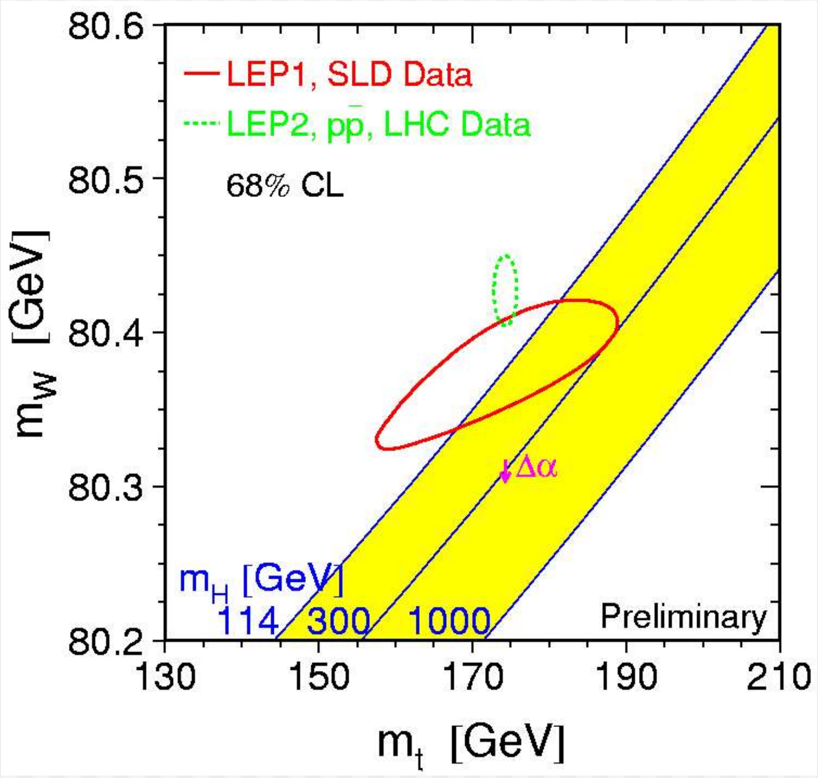
(*) Belyaev, Boos, and Dudko [hep-ph/9806332]

Top mass



Tevatron expectations

($\Delta m_t \approx \pm$ 3 GeV)



LHC expectations

($\Delta m_t \approx \pm$ 1 GeV)

(Note: mostly based on fast simulation studies)

Top mass at CMS

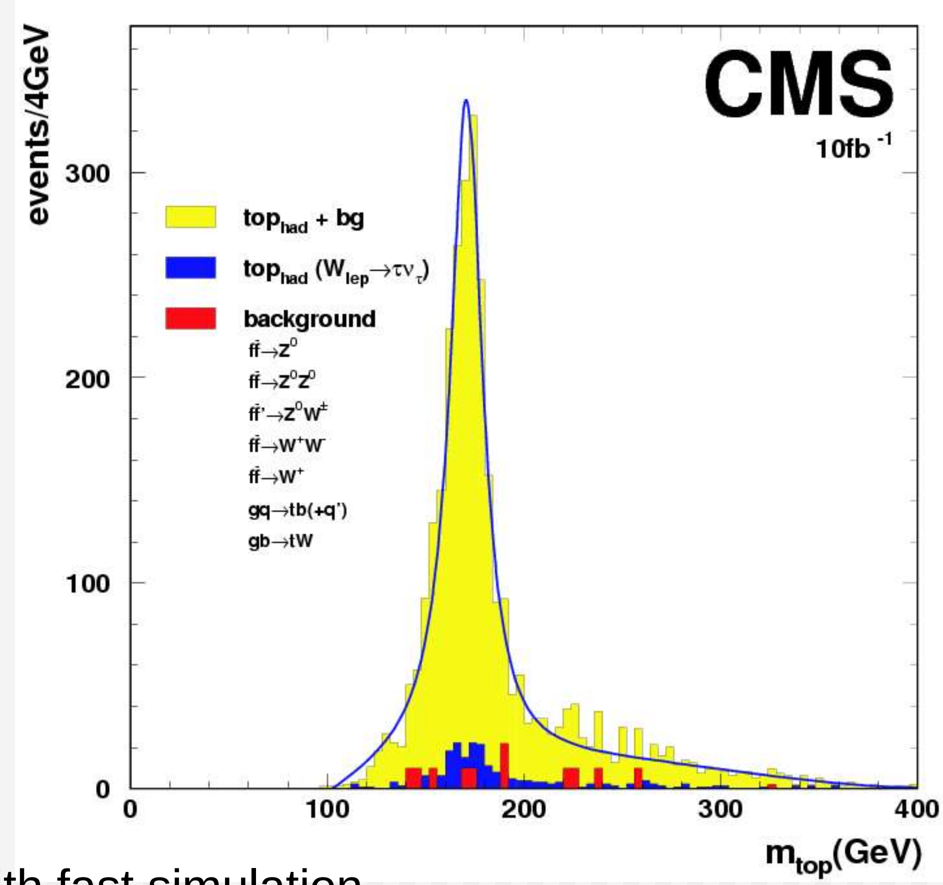
Semileptonic channel:

CMS note 2001/001

- 0.2% efficiency
- Total background 5%
- **Mass extracted from jjb system**

(-> large error from jet scale uncertainty)

- Stat. error: ±0.25 GeV
- Error from $P_t(t)$ spectrum: ±0.4 GeV
- Jet scale: $\Delta E_j/E_j$~1% -> ΔM~±0.3 GeV



$\Delta m_t \approx \pm$ 1-2 GeV

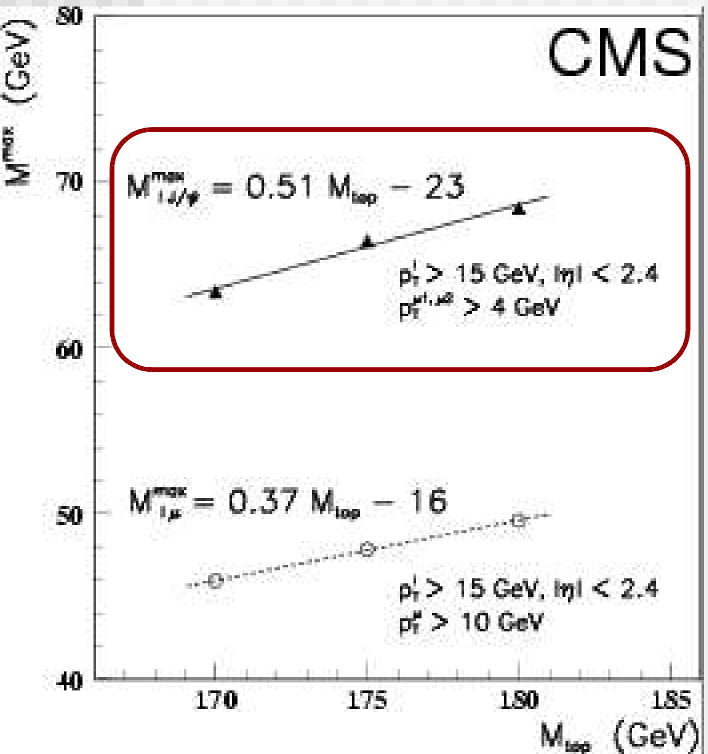
Caveat: this result has been obtained with fast simulation.
Full simulation analyses (also with higher degree of sofistication) are under way, also for fully leptonic & fully hadronic channels.

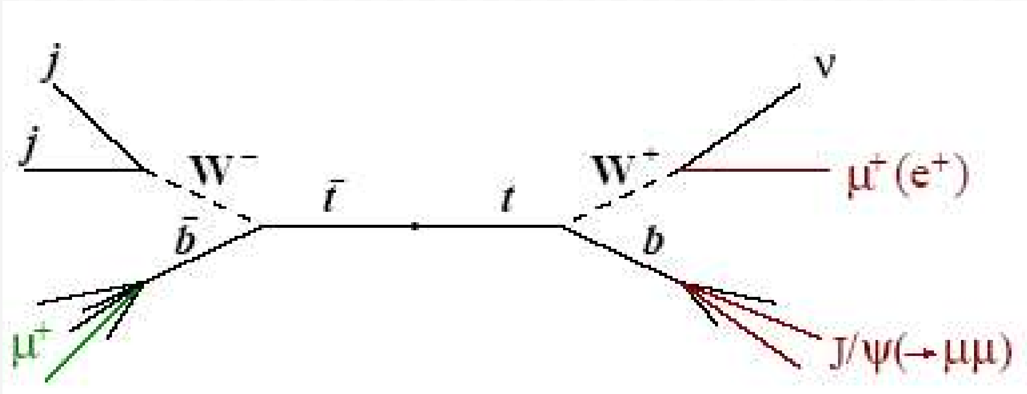
Top mass at CMS: t->J/ψ

CMS note 1999/065

Hard lepton + J/ψ:

1000 events/year @ L=10[34]





J/ψ->μμ easy to identify.
$M_{lJ/\psi}$ has a dependence on M_t.

- **Independent from jet scale**
- **Unfeasible at low luminosity**
- **Promising at high luminosity**
- **Among main systematics: b fragmentation**

$\Delta m_t \approx \pm 1$ GeV

Currently being reproduced with full simulation and J/ψ->μμ + J/ψ->ee

Spin correlations

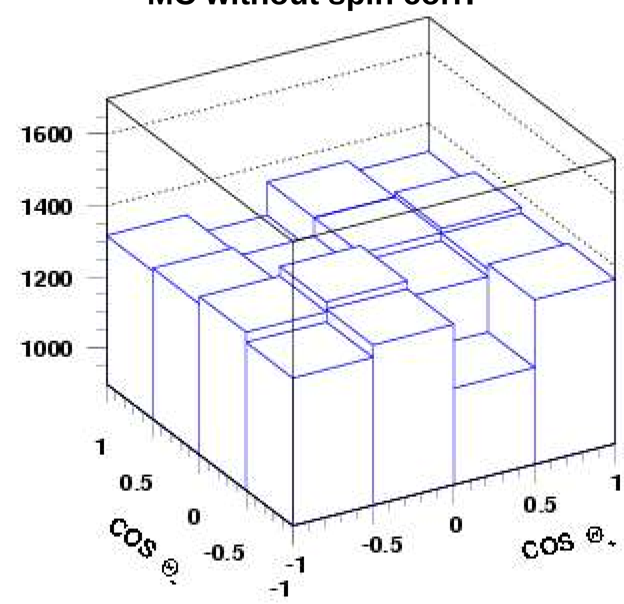
Since $\tau_{decay} < \tau_{hadr}$, decay products retain "memory" of the top spin
(not washed out by hadronization)

$$\mathcal{A} = \frac{N(t_L\bar{t}_L + t_R\bar{t}_R) - N(t_L\bar{t}_R + t_R\bar{t}_L)}{N(t_L\bar{t}_L + t_R\bar{t}_R) + N(t_L\bar{t}_R + t_R\bar{t}_L)}$$

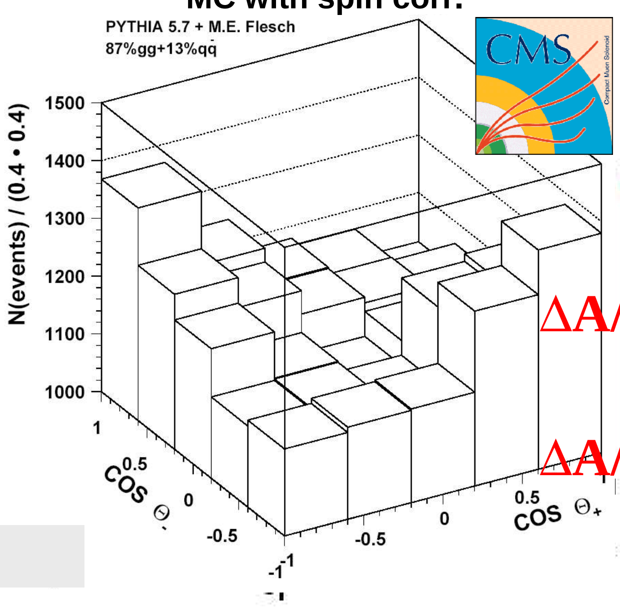
$$\frac{1}{N}\frac{d^2N}{d\cos\theta^*_{\ell+}\, d\cos\theta^*_{\ell-}} = \frac{1}{4}(1 - \mathcal{A}\cos\theta^*_{\ell+}\cos\theta^*_{\ell-})$$

Discriminates between qq->tt (A = -0.469) and gg->tt (A = +0.431)

MC without spin corr.



MC with spin corr.



CMS:

ΔA/A=±11%(st)±9%(sys) (30 fb^{-1})

ATLAS:

ΔA/A=±7%(st)±19%(sys) (30 fb^{-1})

>5 σ from 0 @ 30 fb^{-1}

W polarization in top decay

M predicts the fraction of W from t->W with longitudinal polarization

$$\frac{\Gamma(h_W=-1)}{\Gamma_{tot}}=0.297 \qquad \frac{\Gamma(h_W=0)}{\Gamma(h_W=-1)}=\frac{1}{2}\left(\frac{m_t}{m_W}\right)^2=2.37$$

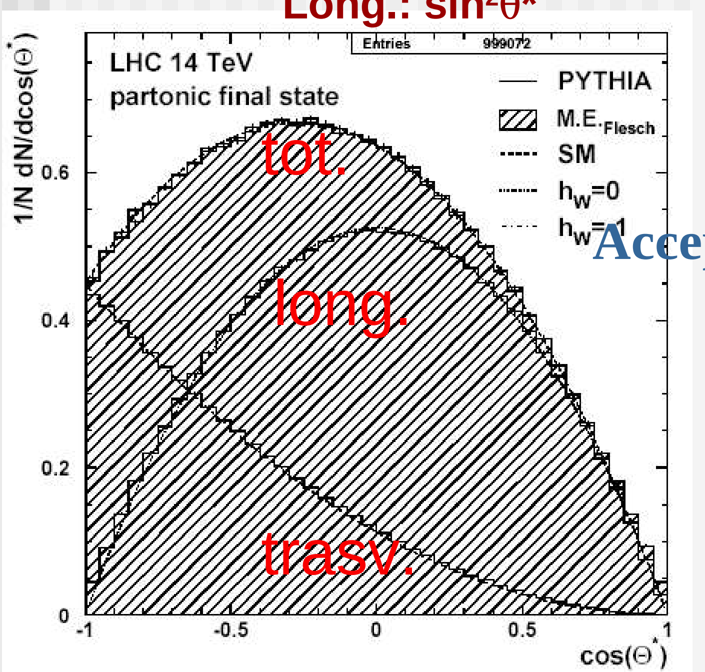
$$\frac{\Gamma(h_W=0)}{\Gamma_{tot}}=0.703$$

$$\frac{\Gamma(h_W=+1)}{\Gamma_{tot}}=0$$

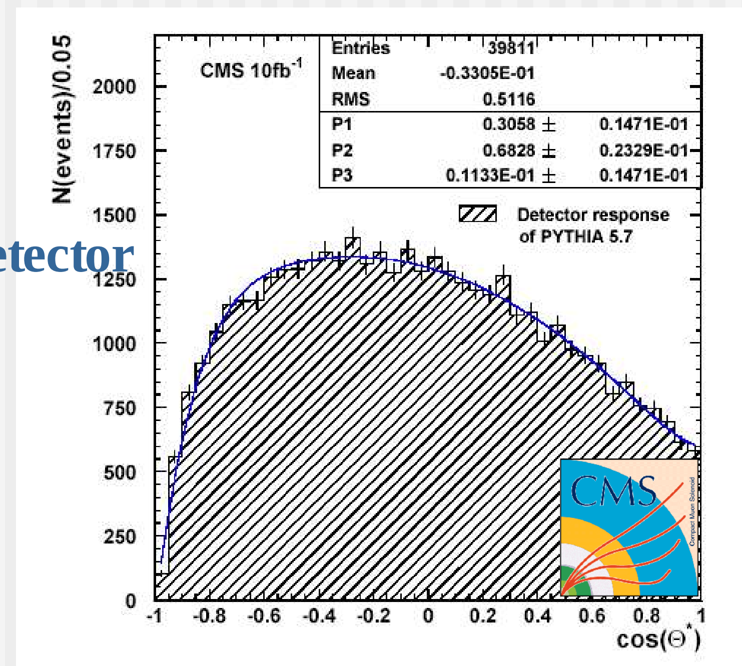
θ*:angle between lepton (in W r.f.) and W (in top r.f.)

Trasv.: $(1\pm\cos\theta^*)^2$

Long.: $\sin^2\theta^*$



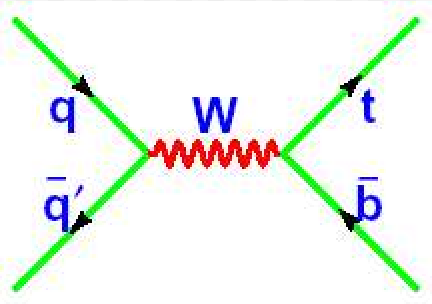
Acceptance and detector smearing →



⇒ uncertainty on the fraction of long.pol. W's: ± 0.023 (stat) ± 0.022 (sys)

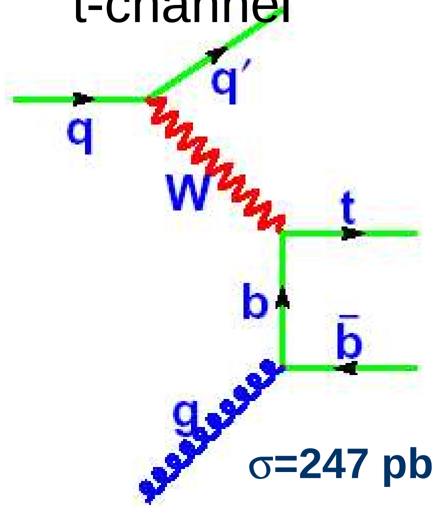
Single top

s-channel



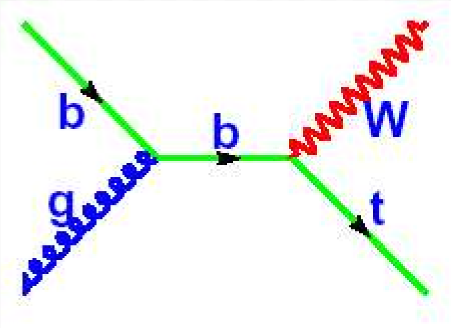
σ=10 pb

t-channel



σ=247 pb

Wt-channel



σ=56 pb

- Never observed so far
- Directly related to $|V_{tb}|$

(not a $V_{tb}/\Sigma V_{ti}$ ratio -> no assumption on the number of quark generations)

- Sensitivity to new physics: FCNC (t-ch.), new gauge bosons (s-ch.), $H^{\pm}$->tb …
- Background to tt and several searches (ttH, WH->lνbb, …)
- Possibility to study top properties (mass, polarization, charge) with very little reconstruction ambiguities

Single top: "how to"

General strategy (both s/t-ch.):

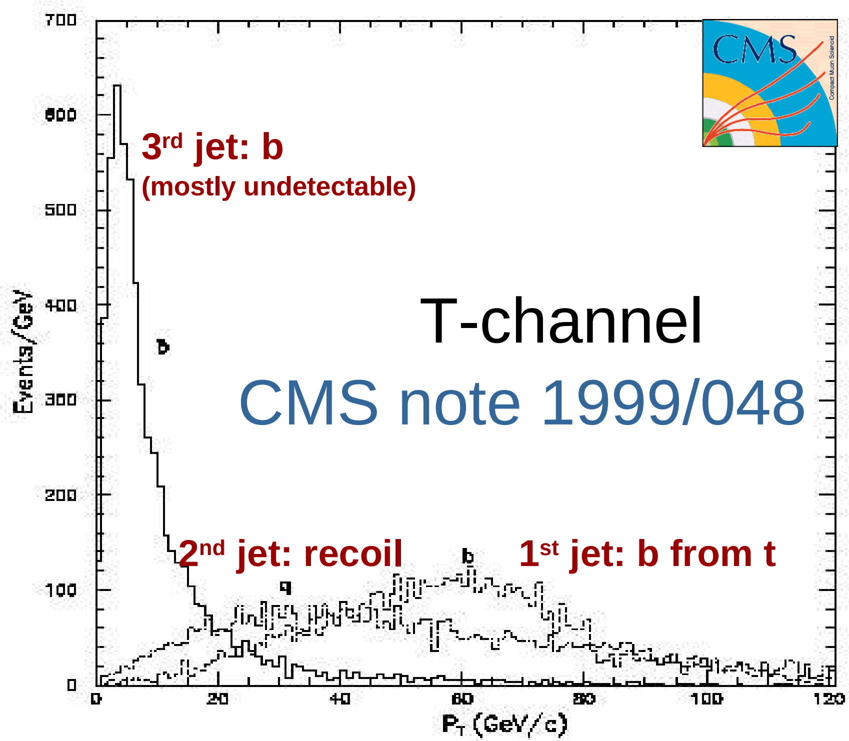
- 1 isolated lepton
- 2 high E_t jets
- at least 1 tagged b-jet
- missing E_t
- l+MET: M_T compatible with W
- H_t (scalar sum of all E_t's)
- M(lνb) in a window around M_t

s/t-channel separation:

- 2(b-t-b)/1 tagged b-jets
- 0/1 jets in the forward calo
- 2/1 central jets
- angular distance between the reco top and the remaining jet

For MET and H_t, single top lies in the middle between non-top and ttbar bkgs. S-channel: S/B<0.2, main bkgs: ttbar->2l (1 lost), Wbb, t-channel.

T-channel is much easier to select, due to higher cross section and unique topology.



Direct $|V_{tb}|$ extraction

$\sigma \sim |V_{tb}|^2$ ➡ $\Delta V_{tb}/V_{tb} = ½\Delta\sigma/\sigma = ½[(S+B)^{½}/S$ + *th. err.*]

	s-channel:	t-channel:
PDF	4%	10%
renorm. scale	4%	5%
ΔM_t (±2GeV)	5%	2%

We need to know better the gluon and b PDFs

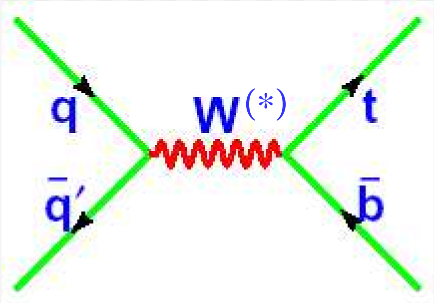
Wt-channel: 50% th. error (range of values in literature)

(ATLAS stat. err.: s-ch. 5.4%, t-ch. 0.7%, Wt 2.8%)

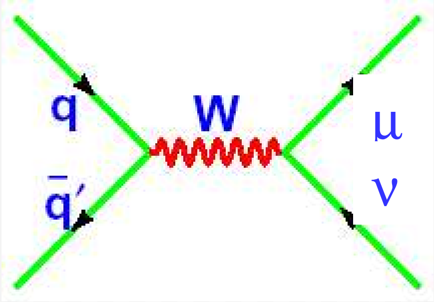
➡ This makes s-channel preferred

Direct $|V_{tb}|$ extraction: single top / single W

Moreover, in principle, many theoretical errors would disappear by normalising s-channel events over single W events:



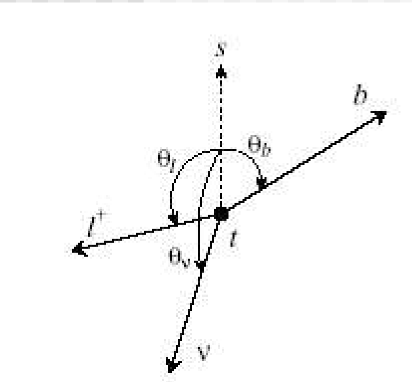
$R(|V_{tb}|)=$ ———

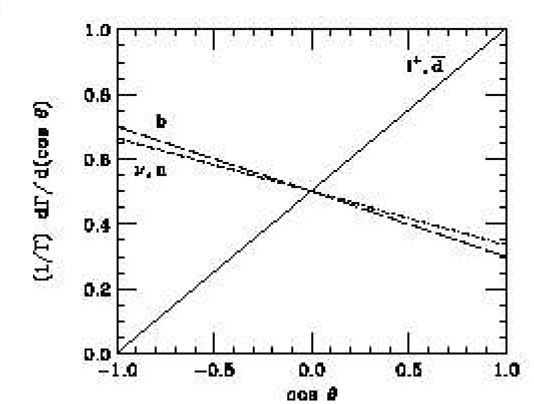


(with care in choosing coherent cuts for the two processes, to avoid the reintroduction of the same errors in a subtler way)

Polarization in t-channel

- Standard Model consistency check: single tops <u>have</u> to be polarized
- Many new physics scenarios give $|g_R|>0$





$(d\Gamma/\Gamma)/d(\cos\theta)=\frac{1}{2}(1+A\cos\theta)$

$A(l)=+1$, $A(b)=-0.40$, $A(\nu)=-0.33$

θ: lepton/chirality axis angle

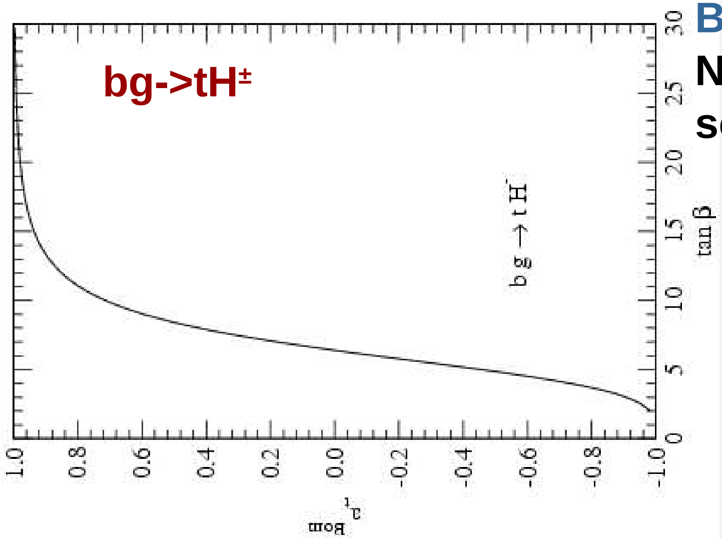
In the ultrarelativistic limit, chirality~elicity. Not the top case!

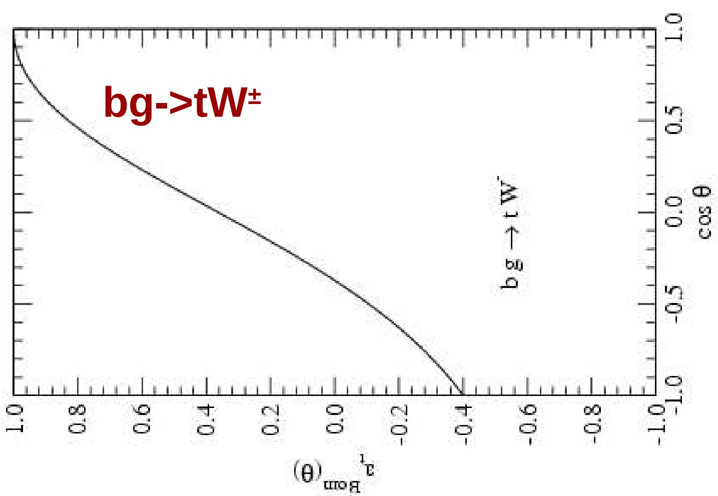
Mahlon (hep-ph/9811219): in the top r.f., spin axis is always parallel to the "down" quark direction.

In t-channel its better approximation is the recoil jet axis.

ATLAS: ±1.6% precision on top polarization @10 fb^{-1}

Single top and SUSY





Beccaria, Renard, Verzegnassi (hep-ph/0410089)

NLL computation of single top production in a "light" SUSY scenario (350-400 GeV).

Main consideration: the only relevant SUSY parameter is *tan*β

Effects: >10% in any channel, in particular in <u>associated production</u> (bg->tY, Y=W,H).
Strong dependence on *tan*β.

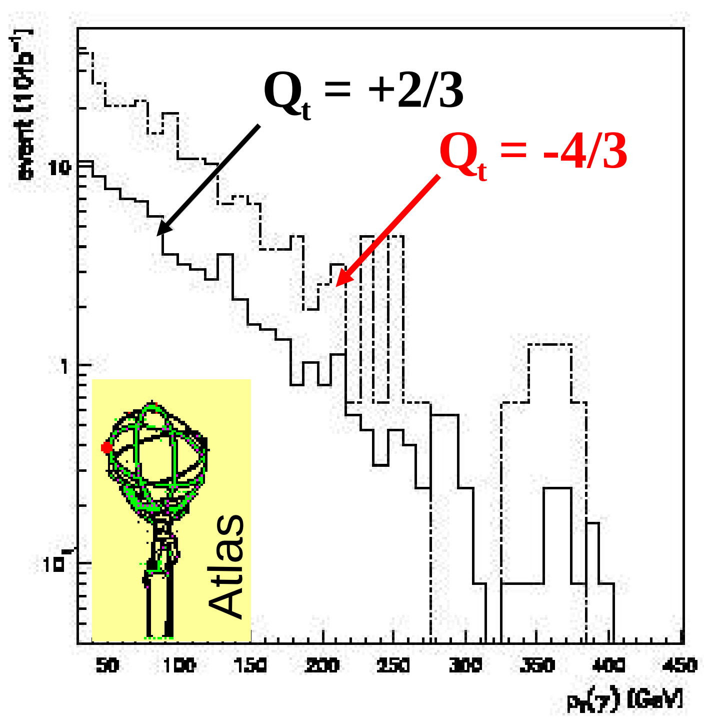
bg->tW±:

- *cos*θ asimmetry
- no *tan*β dependence

bg->tH±:

- no *cos*θ asimmetry
- *tan*β dependence

Top charge



- Is the discovered "top quark" **a charge 4/3 pseudo-quark?**

D. Chang, W.F. Chang, E. Ma, Physical Review D 59 091503

- Global EW fit is consistent with this hypothesis, given a "true top" mass ~230 GeV
- In Run I, CDF and D0 were not able to distinguish among $(W^+b)(W^-\bar{b})$ and $(W^-b)(W^+\bar{b})$: angular correlations + jet charge determination is a very difficult task.

The two competing hypotheses on $|Q_t|$ may be tested from:

- QED coupling: rate of $tt\gamma$ and $t \to bW\gamma$ evts
- estimation of b-jet charge

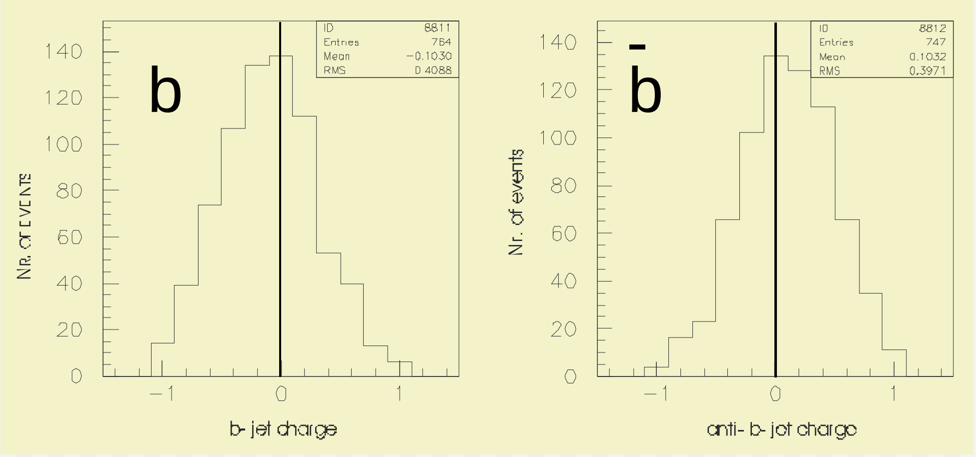
Feasible with 10 fb^{-1}

Q_t from single top, t-channel

- Cross section at LHC is not that small
  (250 pb, against 825 pb for ttbar)
- Very characteristic topology allows selection of high purity samples
- Top may be reconstructed with very little ambiguity (usually only 1 b in acceptance)
- Determination of b flavour ($b/\bar{b}$) is a determination of |Q(t)| (assuming |Q(b)|=1/3)

$$q_{bjet} = \frac{\sum_i q_i \left| \vec{j} \cdot \vec{p}_i \right|^K}{\sum_i \left| \vec{j} \cdot \vec{p}_i \right|^K}$$

ATLAS result: $b/\bar{b}$ separation already possible after 1 year at LHC



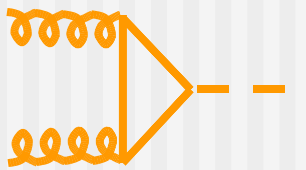
What can Tevatron do for LHC?

- Very similar environment: ideal to test analysis strategies and understand similar systematics (e.g. Underlying Event)
- W+jets, in particular Wbb(X), Wcc(X), Wc(X), are significant backgrounds for Top analyses at both accelerators; different MC models give different kinematics => sizeable differences in efficiency estimates. Improvement by tuning generators to Tevatron data?
- PDFs for LHC are currently extrapolated from a global fit heavily relying on HERA ep data.
- But Tevatron $p\bar{p}$ data contribute with a richer menu (e.g. constraints to gluon PDF), see next slides.
- Impression from the outside(*): Currently relatively few studies at CDF+D0 to constrain PDFs. Is it true?

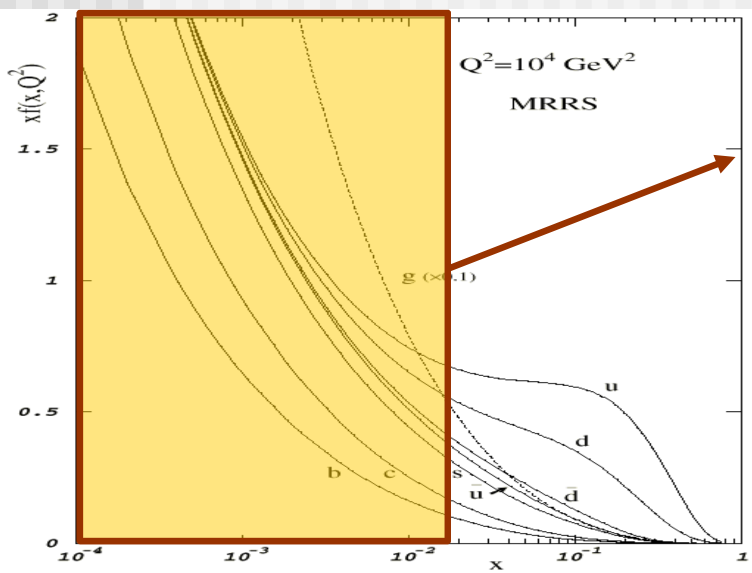
(*) I.e. by watching public results:
http://www-cdf.fnal.gov/physics/physics.html
http://www-d0.fnal.gov/Run2Physics/WWW/

Parton Distribution Functions

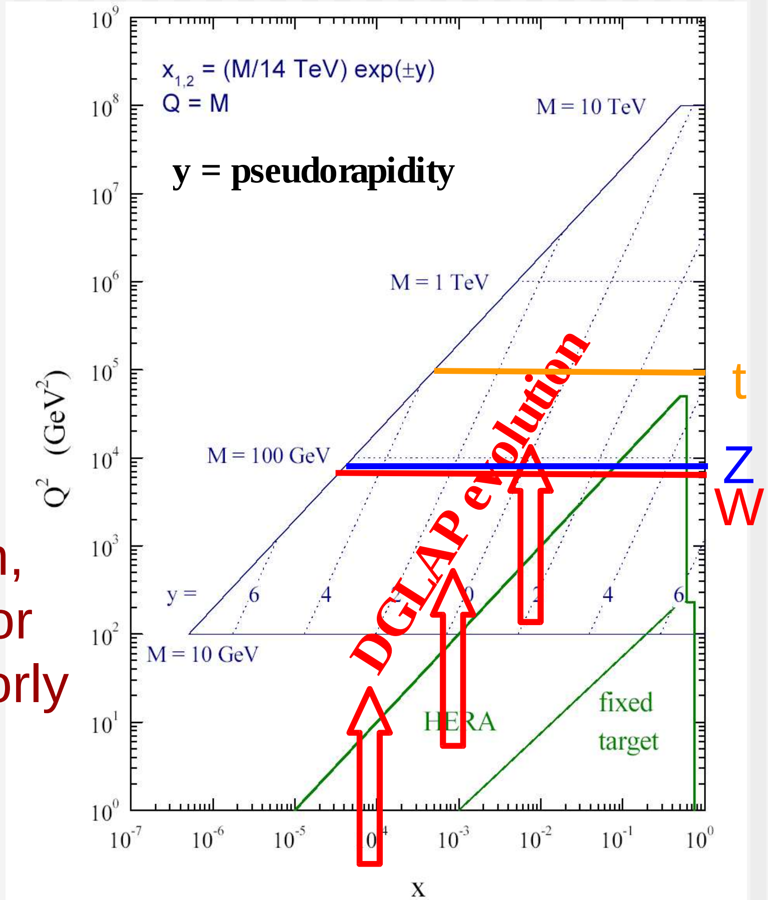
At high energy, a pp scattering is a parton scattering:



$\Rightarrow$ we need pdf(x,Q^2) to know the c.m. energy of the elementary interaction



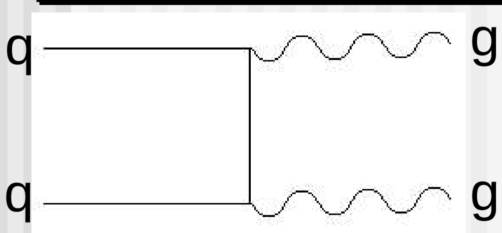
The low x region, very important for LHC, is very poorly known

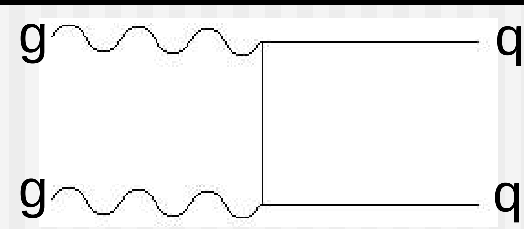


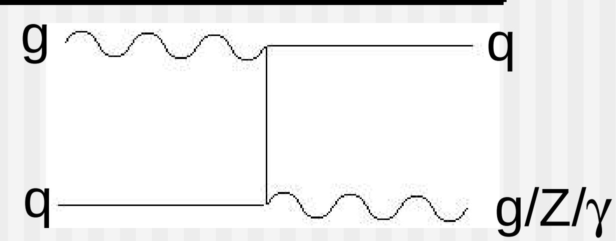
Extrapolation from HERA data

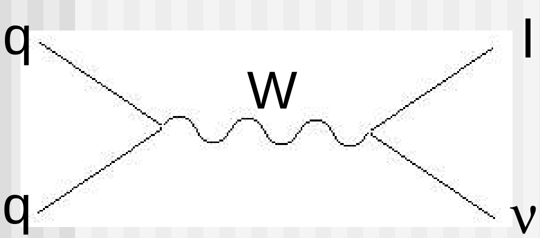
How to probe PDFs at hadron colliders

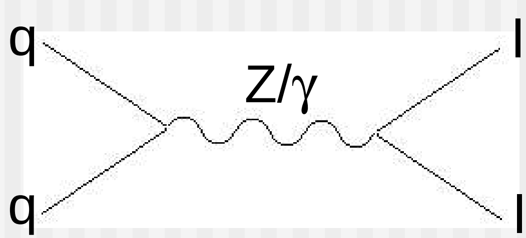
Process:	**Partons involved:**
Di-jets	Quarks and gluons
(b/c/light-)jet + γ/Z	(b/c/light) quarks and gluons
(b/c/light-)jet + W	(c/s/light) quarks and gluons
Single W's and Z's	Quarks
Drell-Yan	Quarks

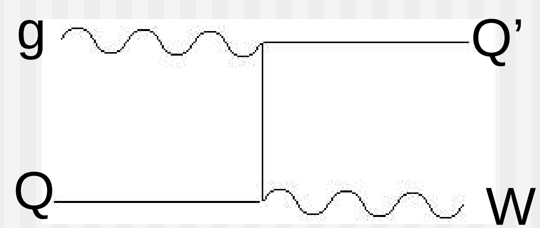






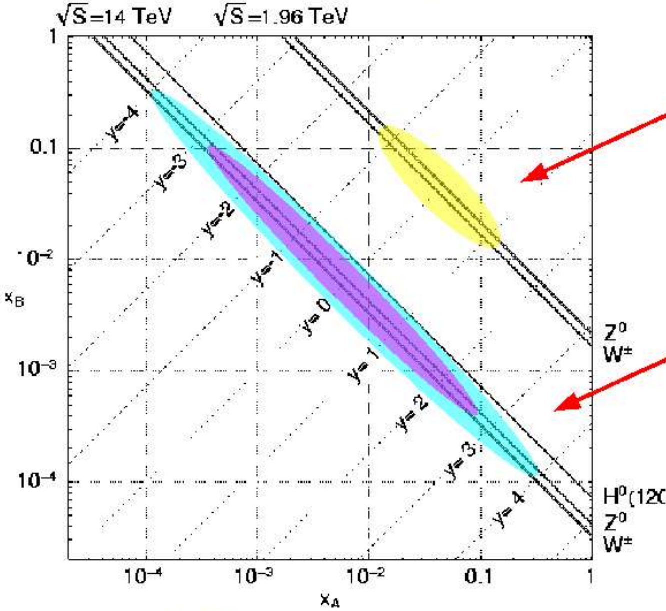






What is relative uncertainty for W / Z / Higgs Production

Kinematics of boson production $\sigma = f(x_A) f(x_B) \hat{\sigma}$



This is the region of present measurement

This is the region we need at LHC

LHC probes new {x,Q} range.

Requires extrapolation

x range for Tevatron

x range for LHC

HERA observed new effects at small-x

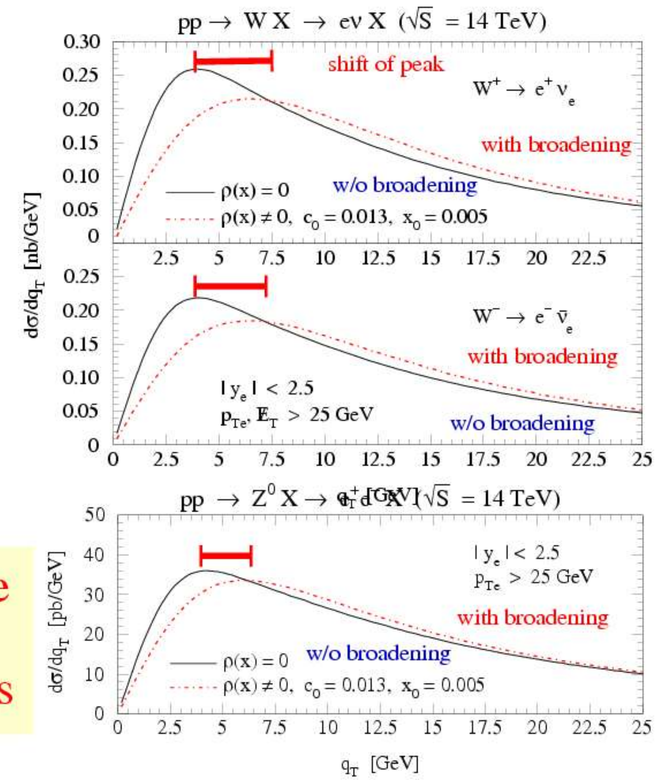
Tevatron can look for this effect by measuring forward W and Z production

These uncertainties are not acceptable for "benchmark" processes

Berge, Nadolsky, Olness, Yuan, hep-ph/0410375.

(From a talk by Fred Olness, 20 Dec.2004)

ldditional q_T broadening at LHC

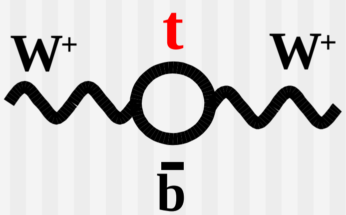


Conclusions

- LHC will be a *top factory*
- This will allow precision measurements in top physics (e.g. ΔM_t~1 GeV looks feasible)
- Measurements will be limited by systematics
- Analyses under way in CMS for ttbar and single top production (Physics-TDR completed at the end of 2005)
- Tevatron can be of big help for LHC physics by studying common sources of uncertainty, e.g. models for Underlying Event, W+jets and PDFs

Backup slides

Why do we like Top so much?

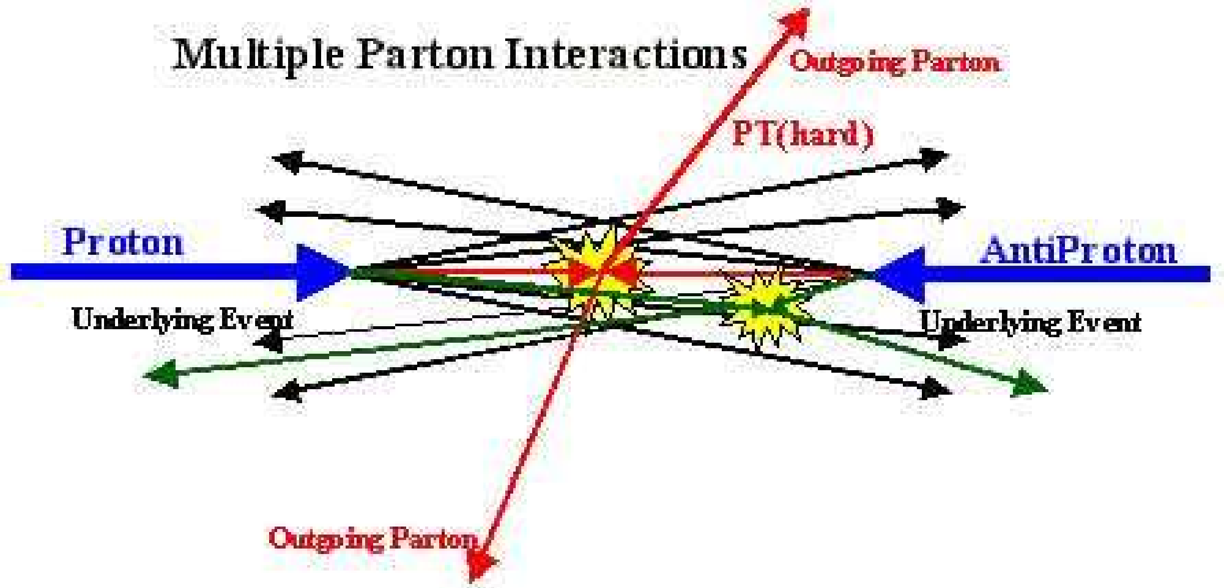


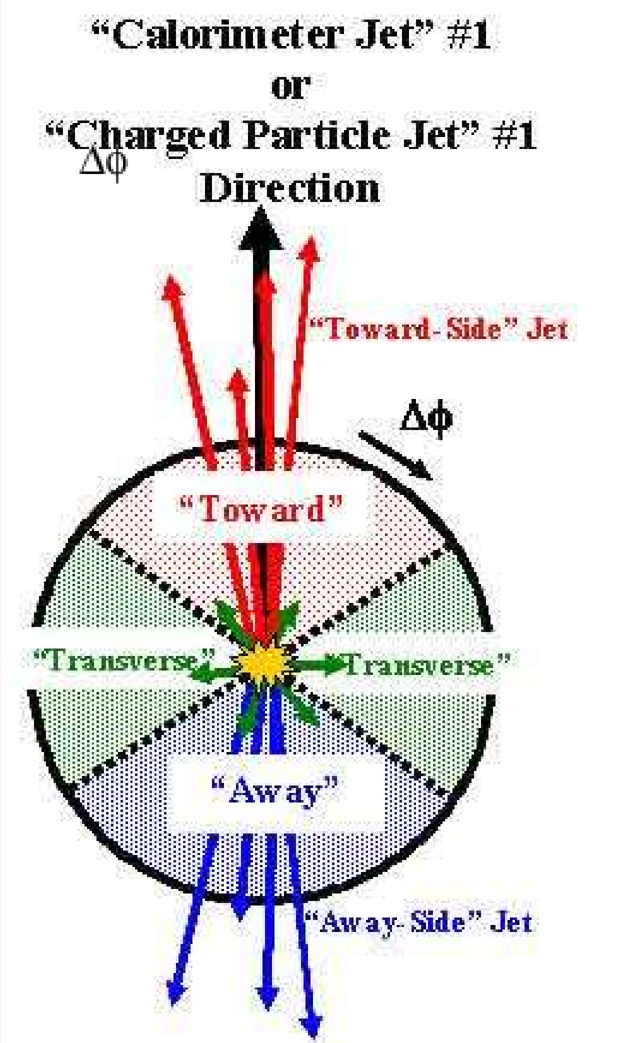
- It exists (but is the least known quark)
- Radiative corrections are proportional to M_t^2
- $M_t > M_W$: this means that the W is not virtual
- Γ proportional to G_F, not G_F^2. Result: $\tau_{decay} < \tau_{hadr}$

(τ_{decay}=1/Γ(~1.5 GeV), τ_{hadr}~1/Λ_{QCD}(~0.2 GeV))

- **So, even “standard” top physics is unusual!**
- For example, decay products retain information about the quark (e.g. polarization)
- New particles may decay into top
- Background for a lot of “new physics”
- Useful for detector calibration

Underlying Event

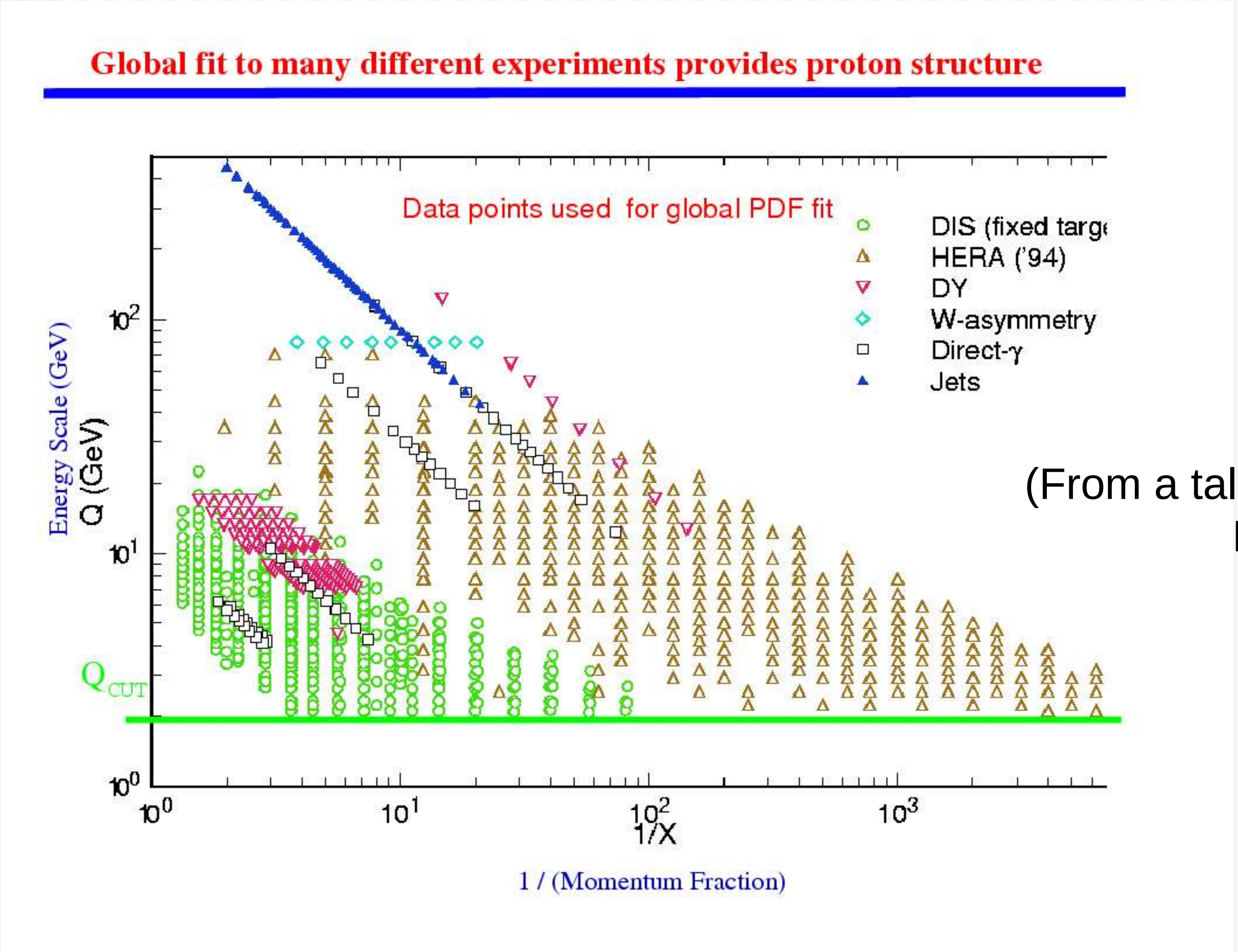




The "transverse" region is defined by $60^o<|\phi|<120^o$ and $|\eta|<1$.

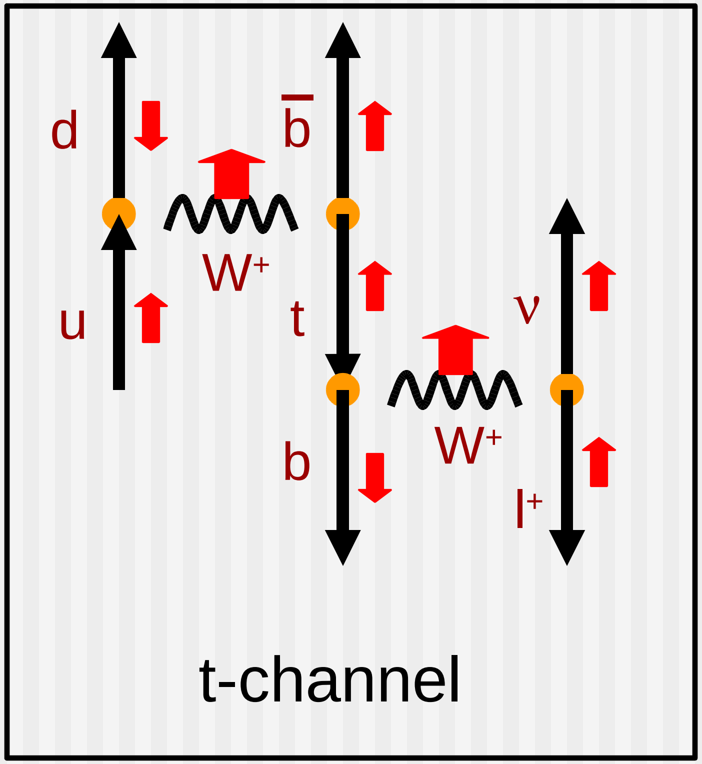
The "transverse" region is perpendicular to the plane of the hard 2-to-2 scattering and is very sensitive to the "underlying event" component of the QCD Monte-Carlo models.

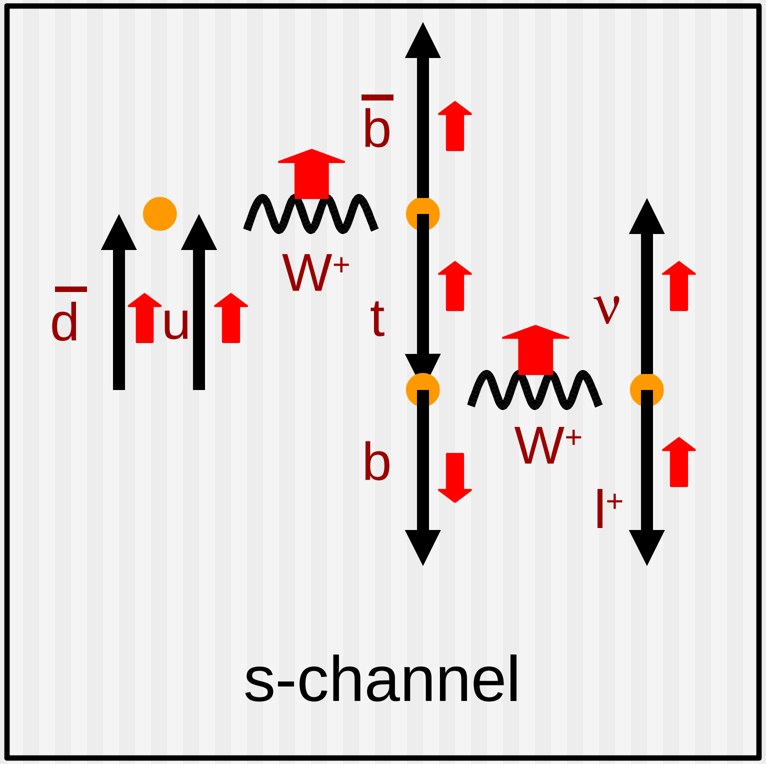
PDF global fit inputs



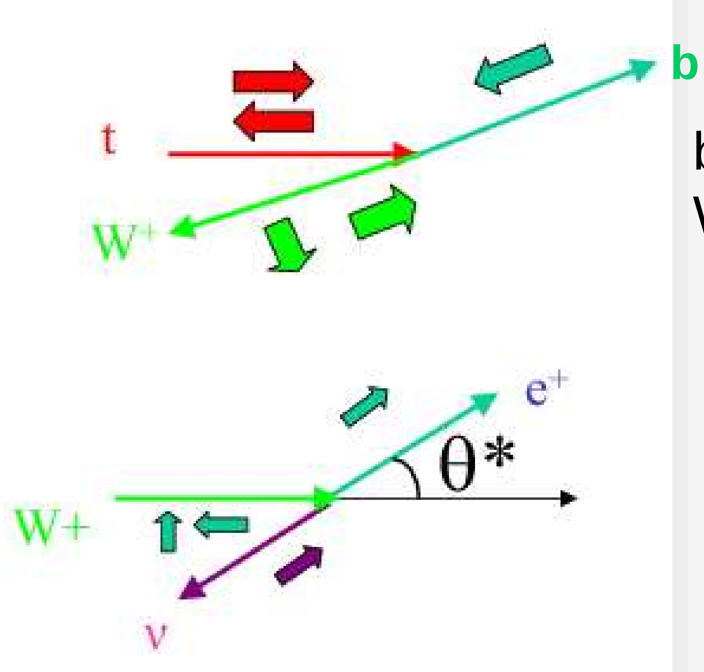
(From a talk by Fred Olness, 20 Dec.2004)

Spin flow for single top





Angular distrib. t->W->l



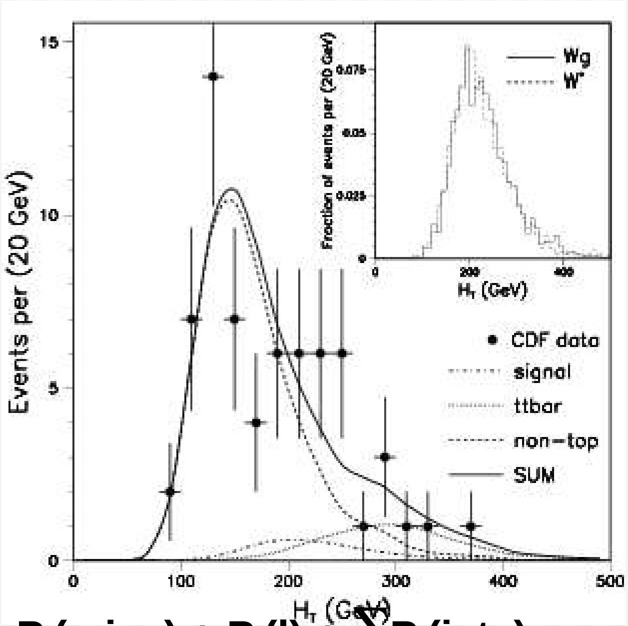
b is relativistic and left-handed.
W can be left-handed or longitudinal.

In W's r.f.: final state of +1 elicity from (1,0) or (1,-1).

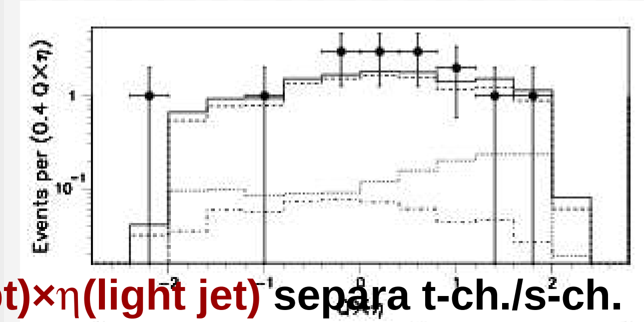
$$d^1_{1,0} = \frac{-\sin\theta^*}{\sqrt{2}}, \; d^1_{1,-1} = \frac{1.-\cos\theta^*}{2}$$

$$\frac{dN}{d\cos\theta^*} = \frac{3}{4(m_t^2 + 2M_W^2)}\left[m_t^2 \sin^2\theta^* + M_W^2(1-\cos\theta^*)^2\right]$$

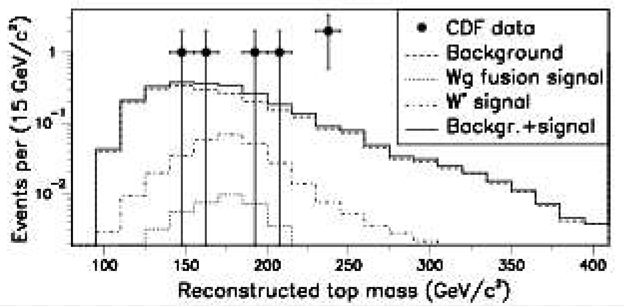
Single top at Tevatron



H_t= P_t(miss) + P_t(l) + ΣP_t(jets)



Q(lept)×η(light jet) separa t-ch./s-ch.



M(lνb) discrimina top/non top

Expected cross sections:

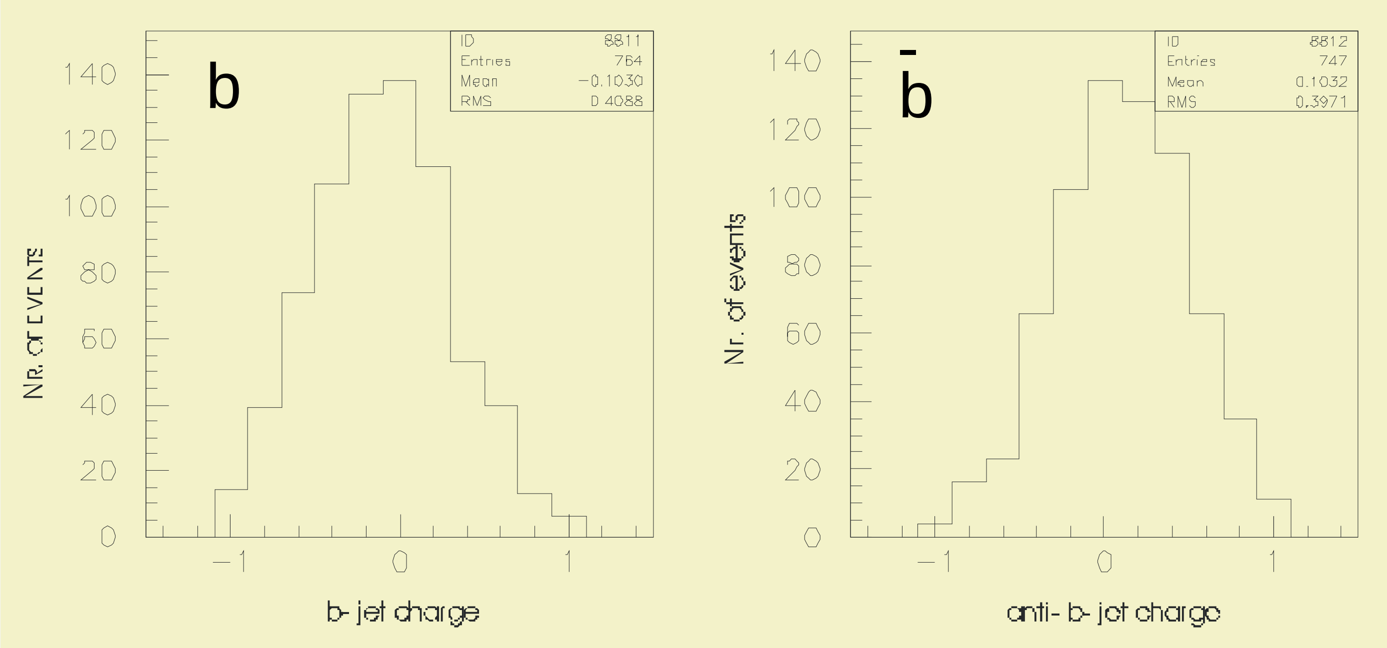
- s-channel: σ=0.88±0.11 pb
- t-channel: σ=1.98±0.24 pb

Run II (162 pb^{-1}):

- s+t channels: σ<13.7 pb @95% CL
- t-channel only: σ<8.5 pb @95% CL

Jet charge method

$$q_{bjet} = \frac{\sum_i q_i |\vec{j} \cdot \vec{p}_i|^K}{\sum_i |\vec{j} \cdot \vec{p}_i|^K}$$



b/b̄ separation feasible already after first years at LHC

Top mass at LHC

Errors per year, per channel, per experiment:

Error:	qqbblν	qqbblν (high p_T)	bblνlν	σ_{tt}	qqbblν (+J/ψ)
statistic	0.10	0.25	0.90?	<0.05	<1.0
light jet E scale	0.20	1.2?	-	-	-
b-jet E scale	0.60	0.60	0.60	-	-
ISR/FSR	1.5?	0.2?	1.0	?	0.30?
B fragm.	0.25	0.10	0.70	-	0.60
backgrounds	0.15	0.10	0.10?	negl.	0.20
PDF	negl.	negl.	negl.	4.0	0.20
Total	<2.0?	<2.0?	<2.0?	<4.0?	<1.3?

Note: systematics are correlated

Studies by ATLAS

Δm_t < 1 GeV looks realistic.