Hadron Collider Physics
- Experimental Overview – Part II -

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Part II

- Electroweak Physics
- Top Physics

Electroweak Physics

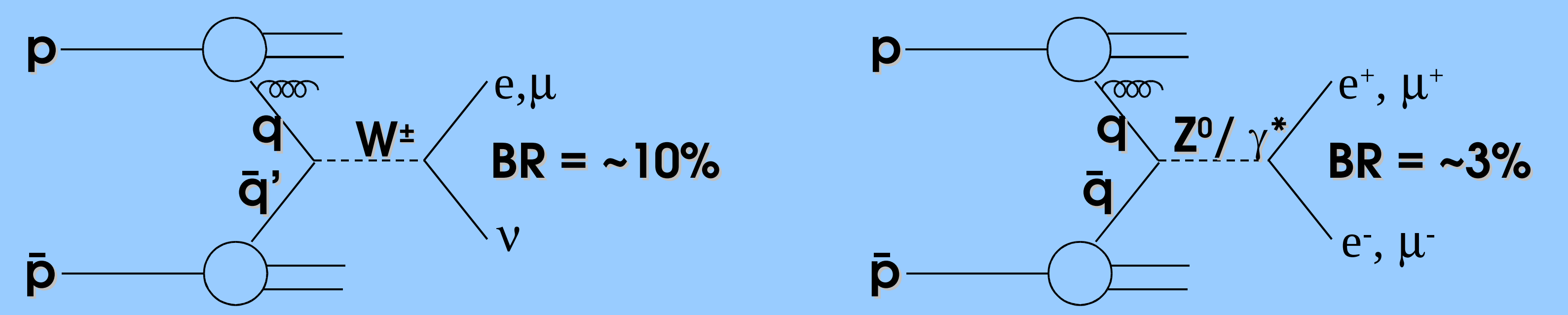
Electroweak Overview

- W/Z Production at the Tevatron
  - inclusive W/Z production cross section
- Z Production Characteristics
  - Drell-Yan, Asymmetry, ...

... here only a small selection ...

- W Production Characteristics
  - M_W, charge asymmetry, ...
- Associated Production of Vector Bosons
  - WW, WZ, Wγ, Zγ, ...

W and Z Production

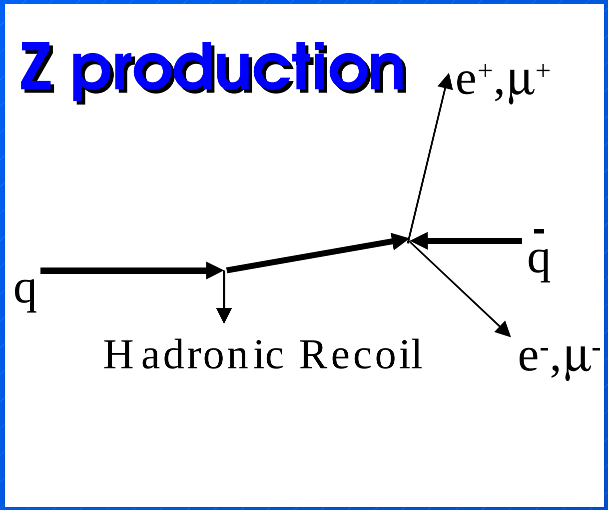


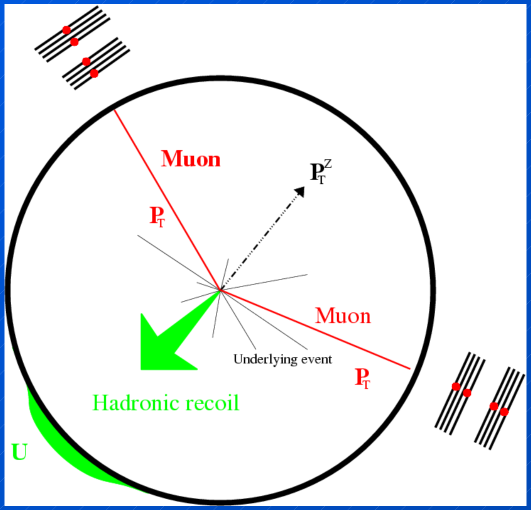
well understood event signatures

- leptonic decay modes avoid high jets background
- increase understanding of detector by studying W/Z production
- cross section relatively well known and high

σ_W *Br(W → lν) ~ 2.7 nb $\sigma_{Z/\gamma}$ * Br(Z/γ → ll) ~ 0.25 nb

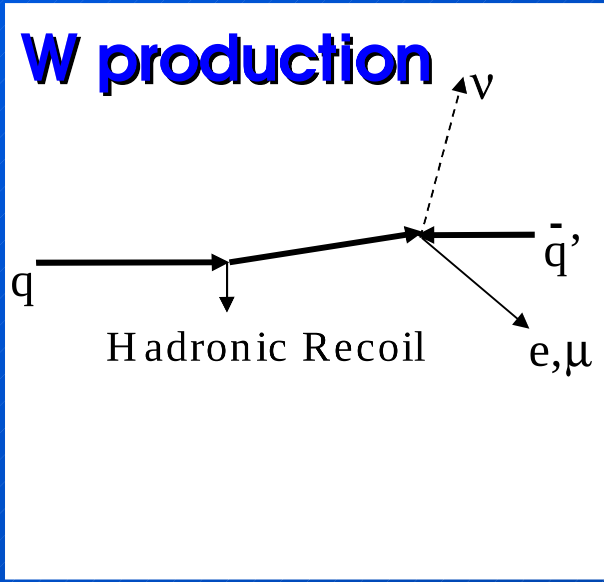
W/Z Event Signatures

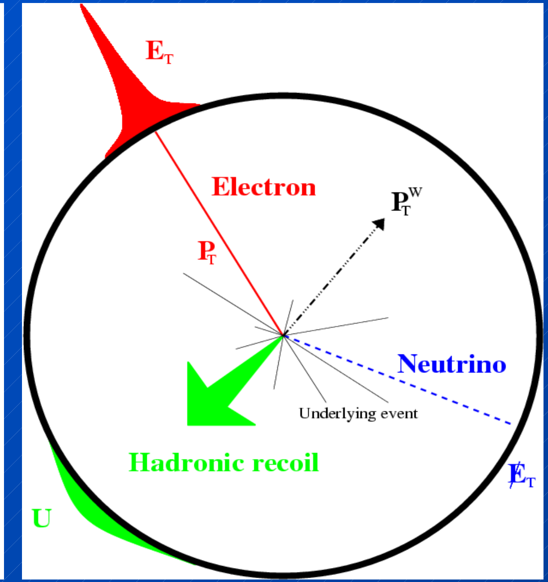




$$M_{l^+l^-}=\sqrt{(p_{l^+}+p_{l^-})^2}=\sqrt{2(E_{l^+}E_{l^-}-\vec{p}_{l^+}\vec{p}_{l^-})}$$

M_Z = 91.1876 ± 0.0021 (LEP/PDG)





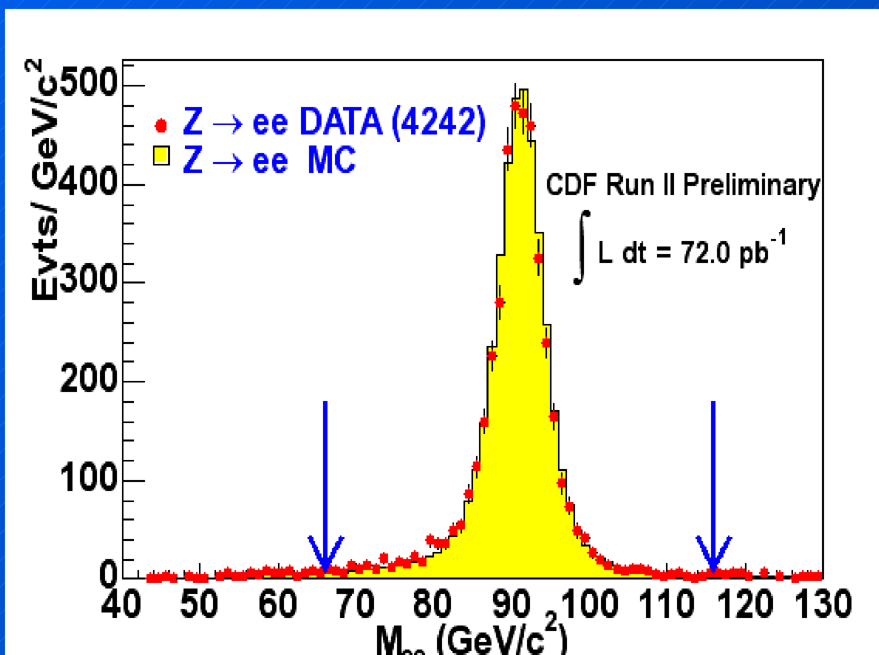
$M_{l\nu}=?$ cannot measure p_z of ν

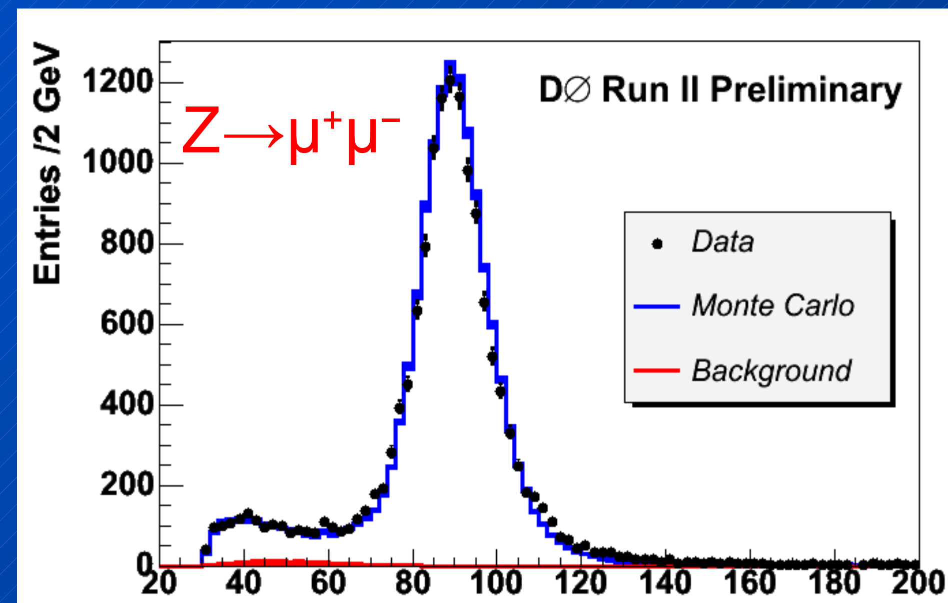
$$M_T=\sqrt{2(E_T^l E_T^{miss}(1-\cos\Delta\phi^{l,miss}))}$$

M_W = 80.425 ± 0.038 (LEP/TeV/PDG)

Z Production

- select 2 opposite charged high-p_T leptons
- backgrounds: $Z \to \tau\tau$ and qq/bb production for ee/$\mu\mu$
- systematics: lepton-ID, PDF, acceptance, background
- correct from Z^*/γ^* to Z using MC





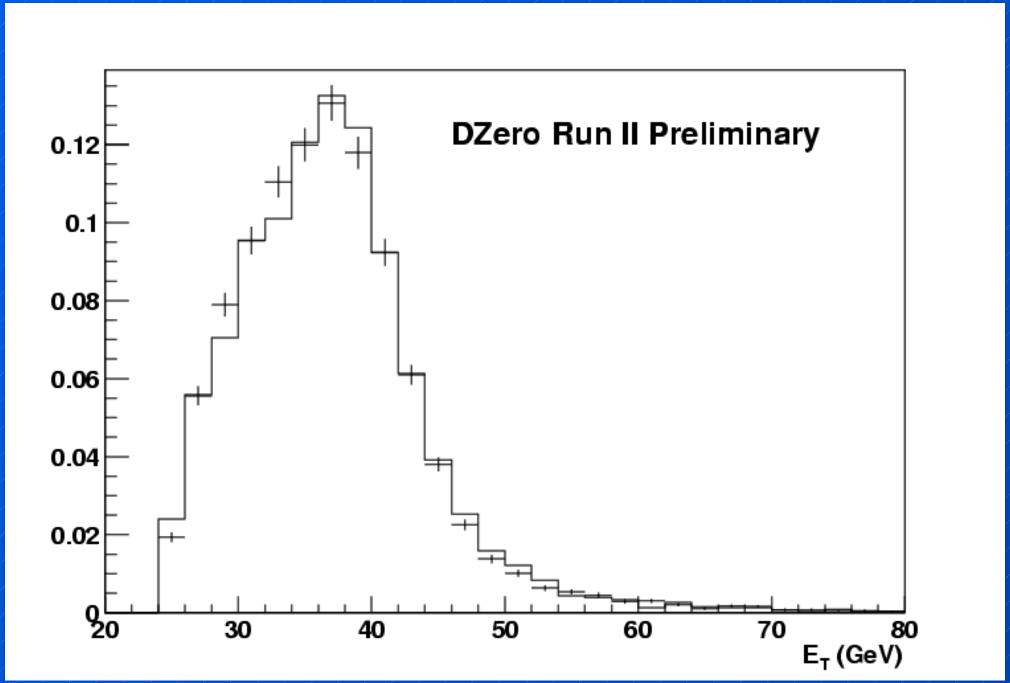
14790 Z/γ^* events in 147 pb-1

eff*acc ~ 16 – 29% !!!

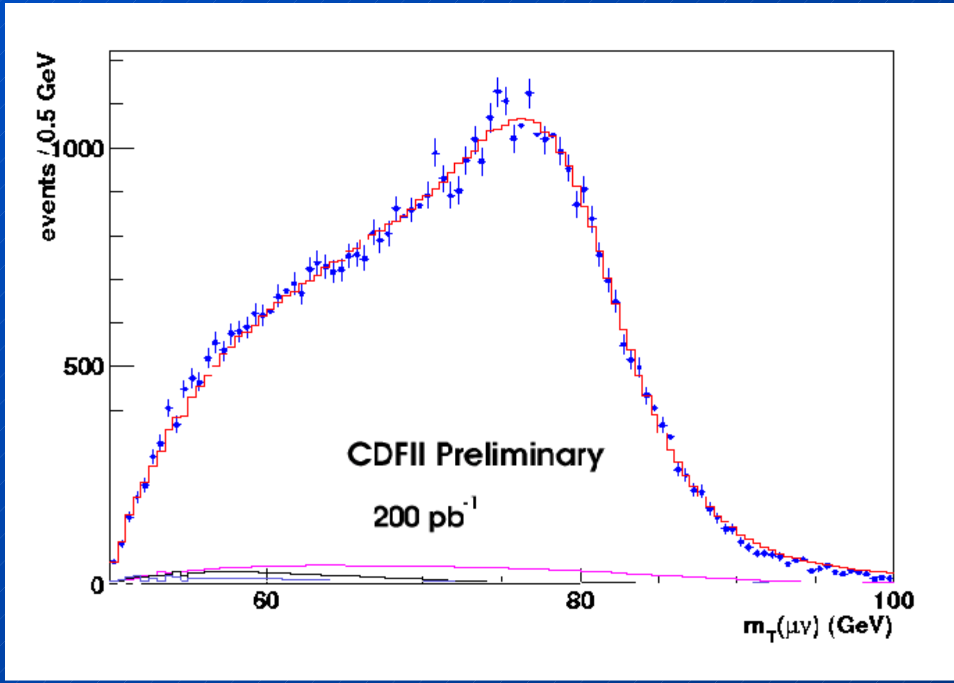
W Production

- select 1 high-p_T charged lepton and large missing E_T

$W \rightarrow e\nu$



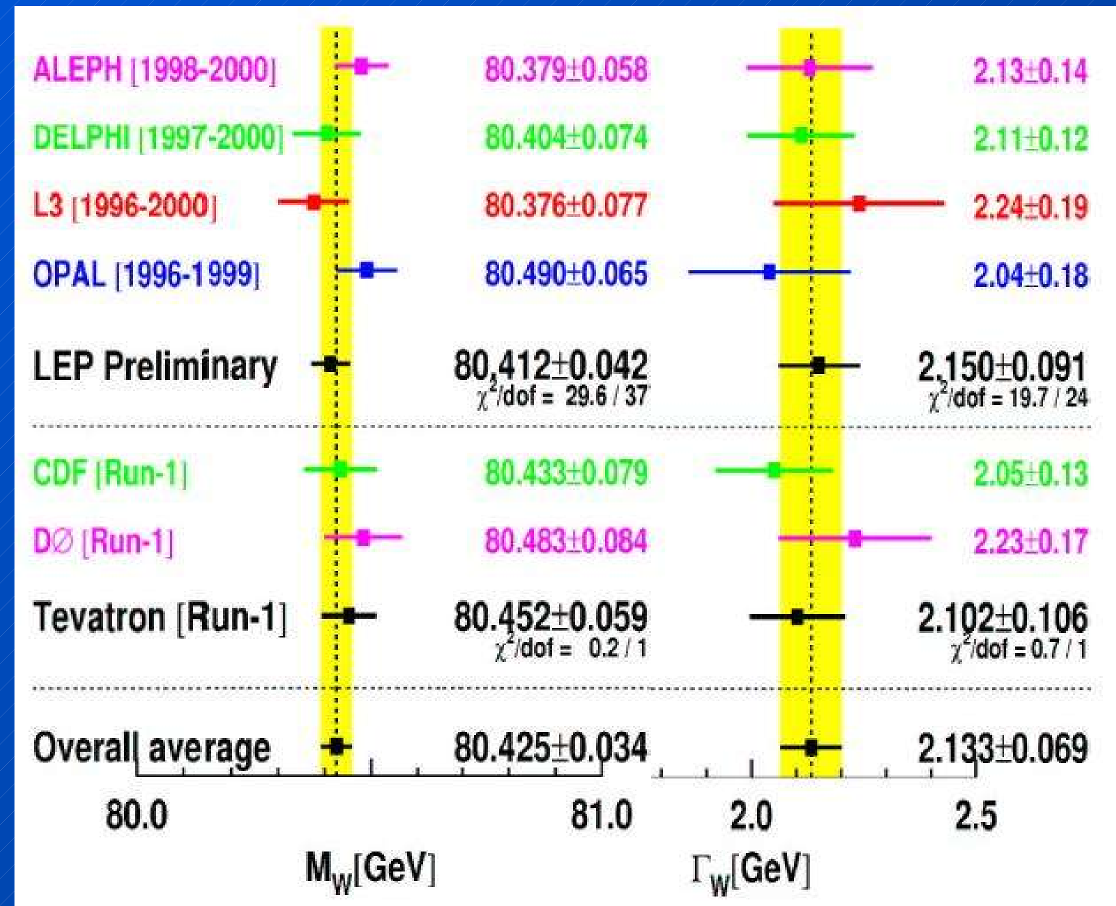
$W \rightarrow \mu\nu$



... can use this analysis as luminosity measurement; goal $\Delta\sigma = \pm 1\%$ ...

... with 2 fb^{-1} expectation: δm_W 40 MeV

W Mass



Tevatron W mass and width

- from fits to M_T spectrum

  expect Δm_W = 40 MeV

  per experiment, 25 MeV combined

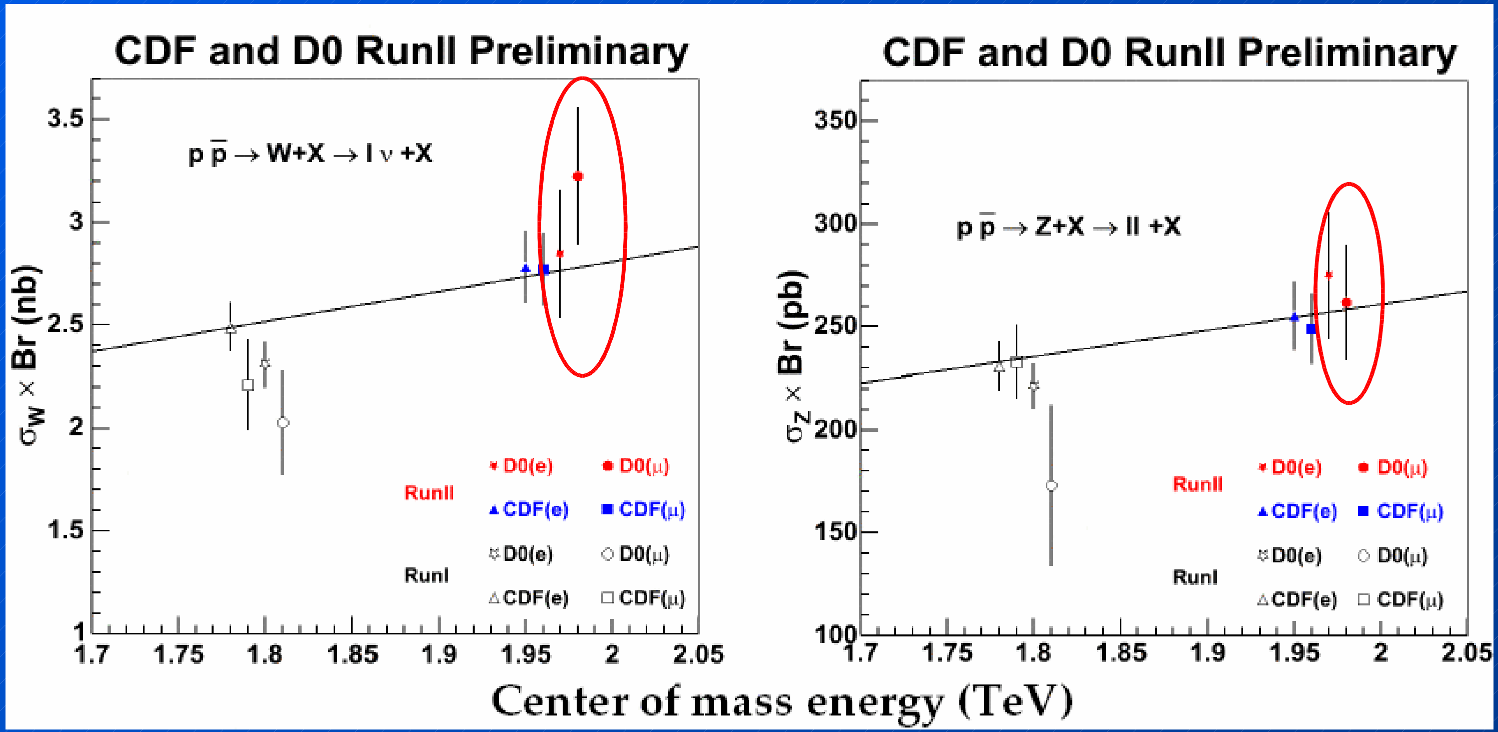
LEP-2 W mass and width

- from reconstructing W's

  ee → WW → qqqq or qqlv

  difference between two final states: Δm_W = 22 +- 43 MeV

Summary of W/Z Cross Section



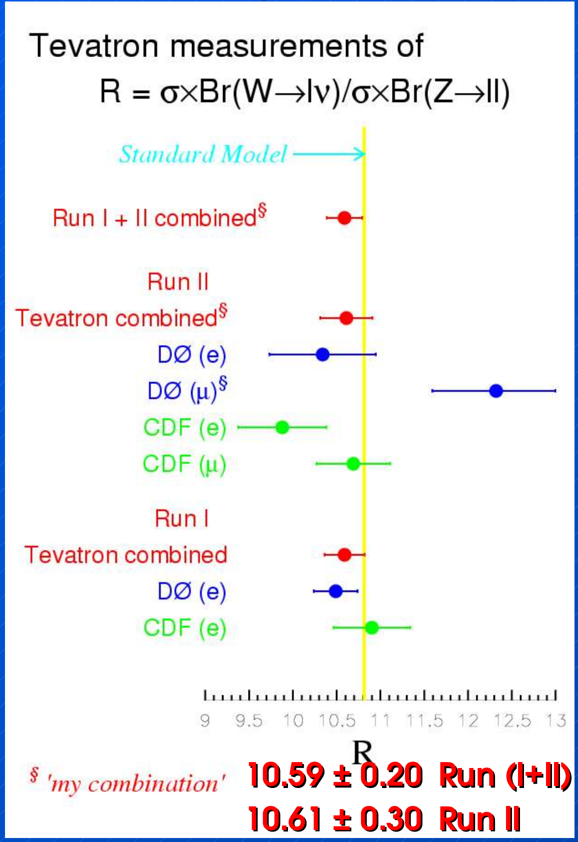
here CDF and DØ use different normalization
common normalization agreed recently for Run-II
... combination of results easier ...

Indirect Measurement of Γ_W

measurement :

$$R = \frac{\sigma_W \cdot Br(W \to l\,\nu)}{\sigma_Z \cdot Br(Z \to l^+ l^-)}$$

- luminosity error cancels
- other systematics partially cancel:
  - PDFs
  - experi.: high pT, isolated leptons



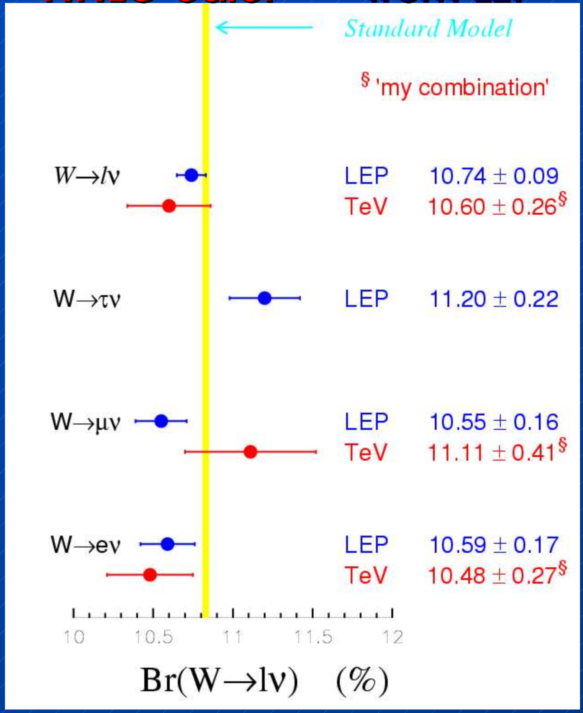
summer'03

interpretation :

measurement

$$R = \frac{\sigma_W}{\sigma_Z} \cdot \frac{Br(W \to l\,\nu)}{Br(Z \to l^+ l^-)}$$

NNLO calc. from LEP



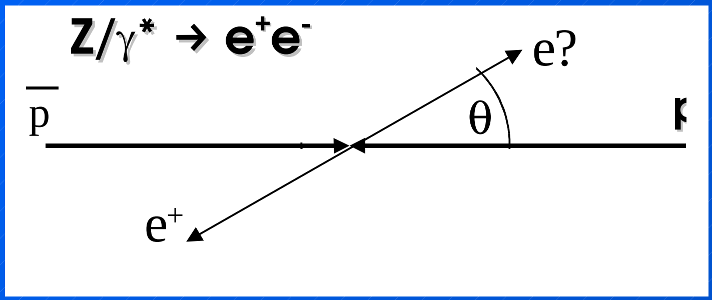
$$Br(W \to l\nu) = \Gamma(W \to l\nu)\,/\,\Gamma_W$$

Tevatron combined :	$\Gamma(W \to l\nu)$ = 2.135 ± 0.053 GeV
LEP & Tevatron direct:	$\Gamma(W \to l\nu)$ = 2.139 ± 0.069 GeV

direct measurement of Γ_W from lineshape of M_T distribution

... consistency test of direct and indirect Γ_W ...

Forward-Backward Asymm. in Z Production



coupling ~ $(g_V + g_A\gamma^5)$

$g_V = I_3 - 2Q_f \sin^2\theta_W$

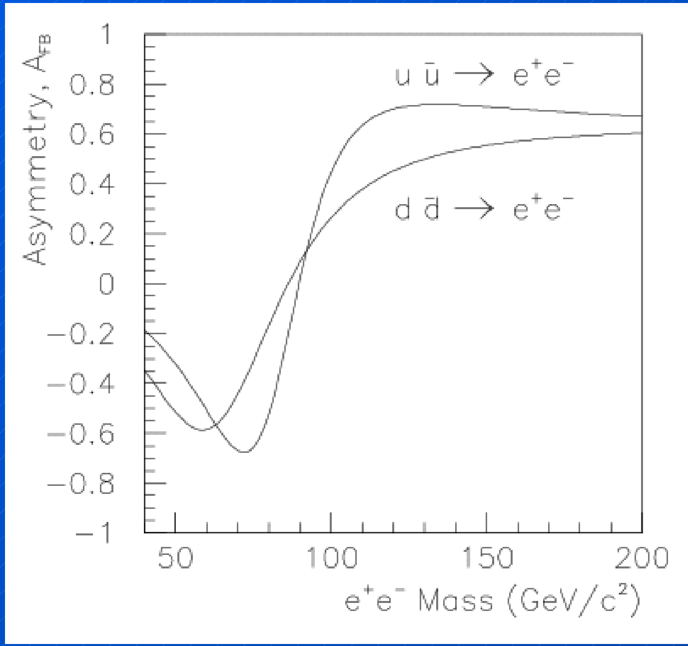
$g_A = I_3$

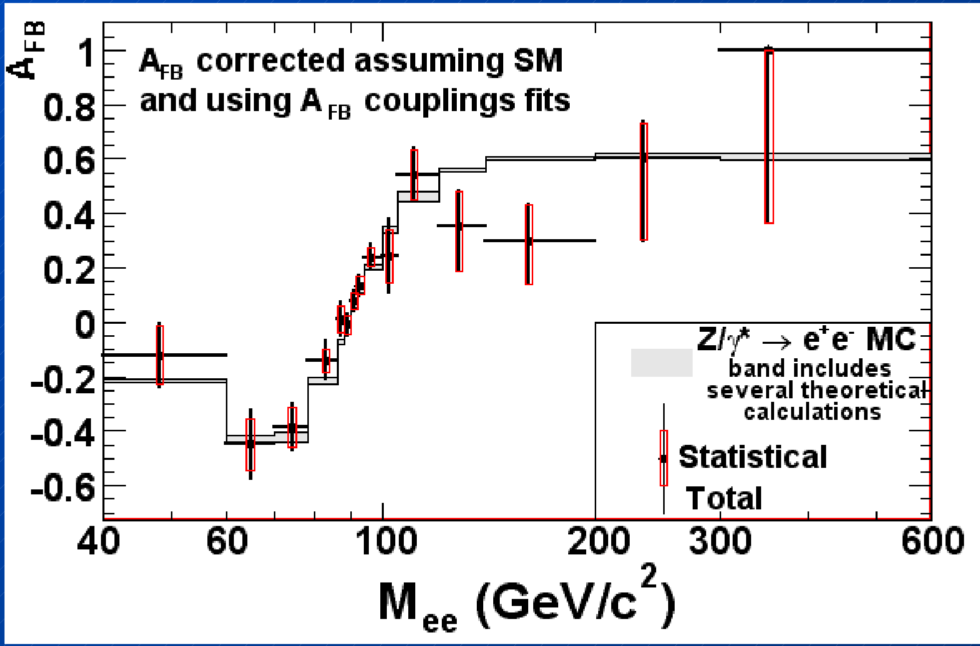
$$\frac{1}{\sigma}\frac{d\sigma(s)}{d\cos\theta^*} = \frac{3}{8}(1+\cos^2\theta^*) + A_{FB}(s)\cos\theta^*$$

$$\Rightarrow \quad A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- at Tevatron can measure at Z pole, and above and below
- directly probes V-A, extract $\sin^2\theta_W$ and u/d couplings to Z

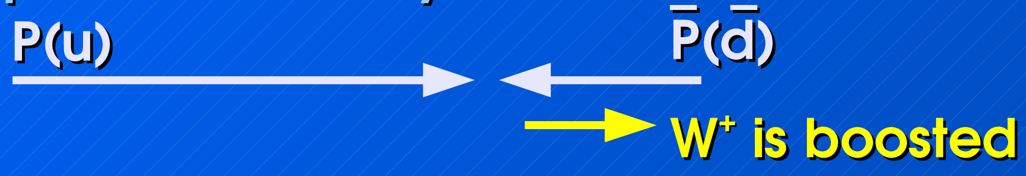
$\sin^2\theta_W = 0.2238 \pm 0.0046(\text{stat.}) \pm 0.0020(\text{syst.})$





W Charge Asymmetry (1)

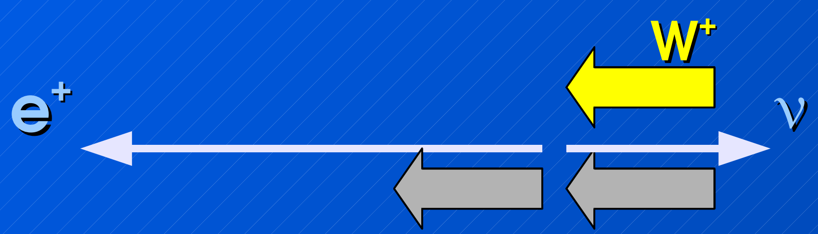
W production is asymmetric



u-quark in proton carries more momentum then d-quark (dbar-quark in antiproton)

- ⇨ more W^+ in direction of P
- ⇨ more W^- in direction of Pbar

V-A decay: opposite asymmetry

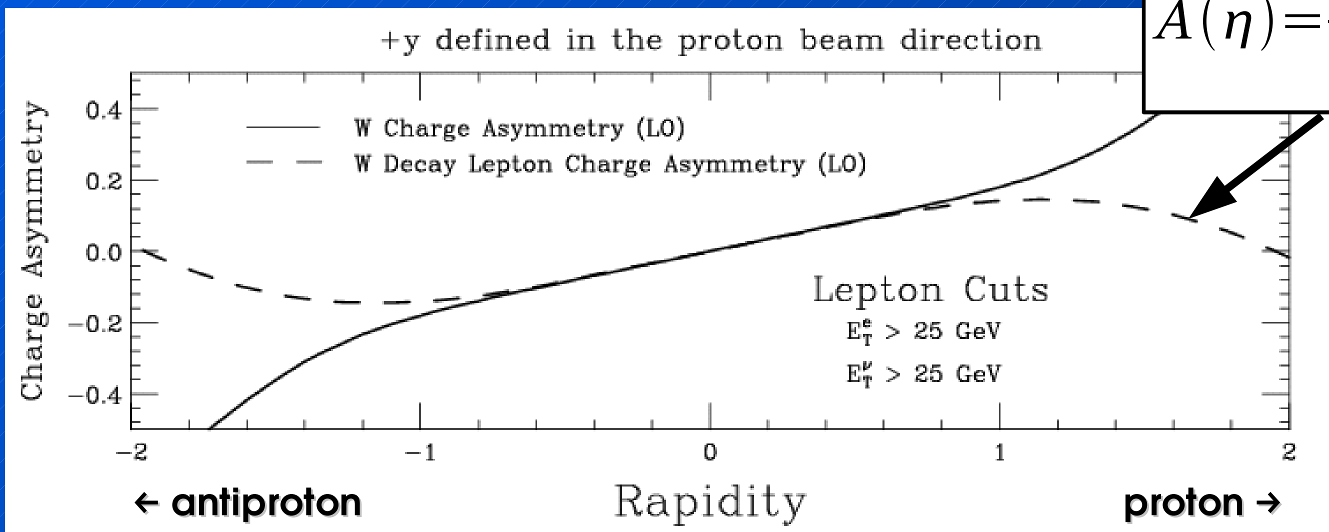


W almost fully polarized

lepton decay angular distribution $\propto (1 - \cos\theta^*)^2$

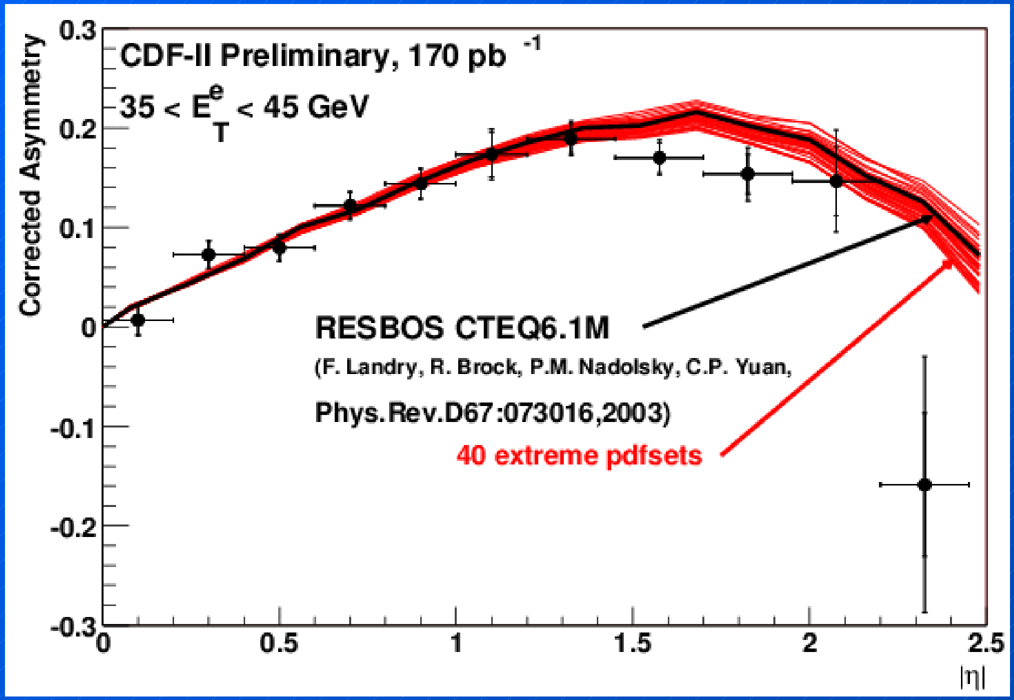
- ⇨ more e^+ in direction of Pbar
- ⇨ more e^- in direction of P

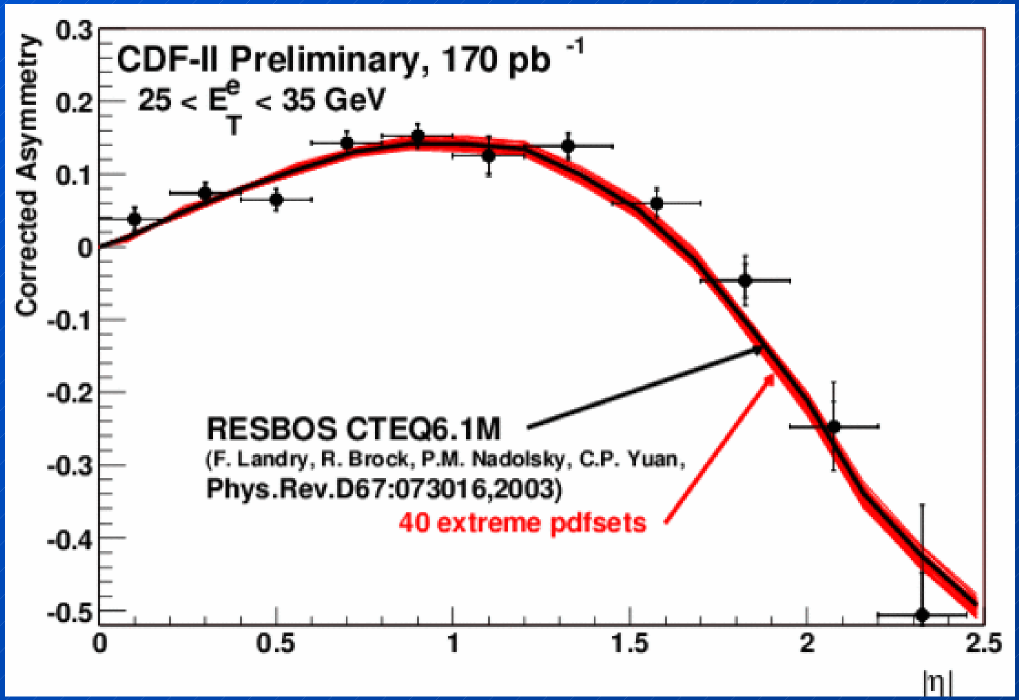
$$A(\eta) = \frac{d\sigma/d\eta(e^+) - d\sigma/d\eta(e^-)}{d\sigma/d\eta(e^+) + d\sigma/d\eta(e^-)}$$



... probes u(x)/d(x) ratio ...

W Charge Asymmetry (2)

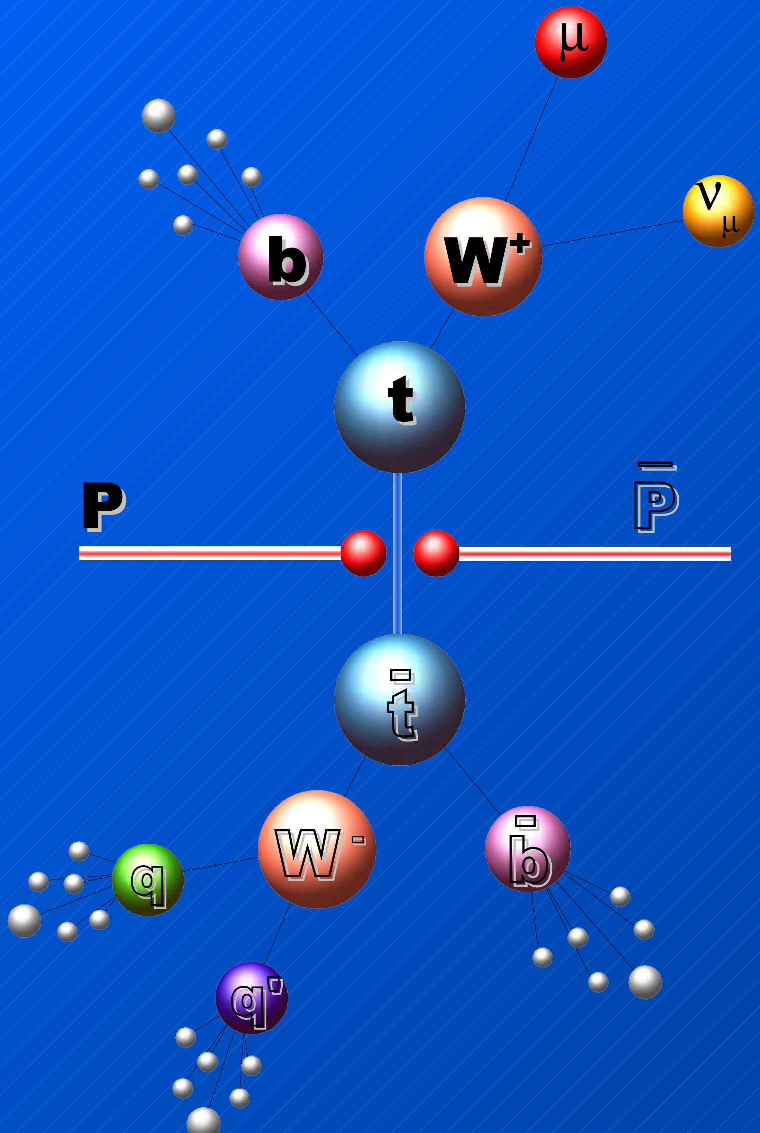




... Tevatron measurement provides
main constraint of high-x PDF's at large scales ...

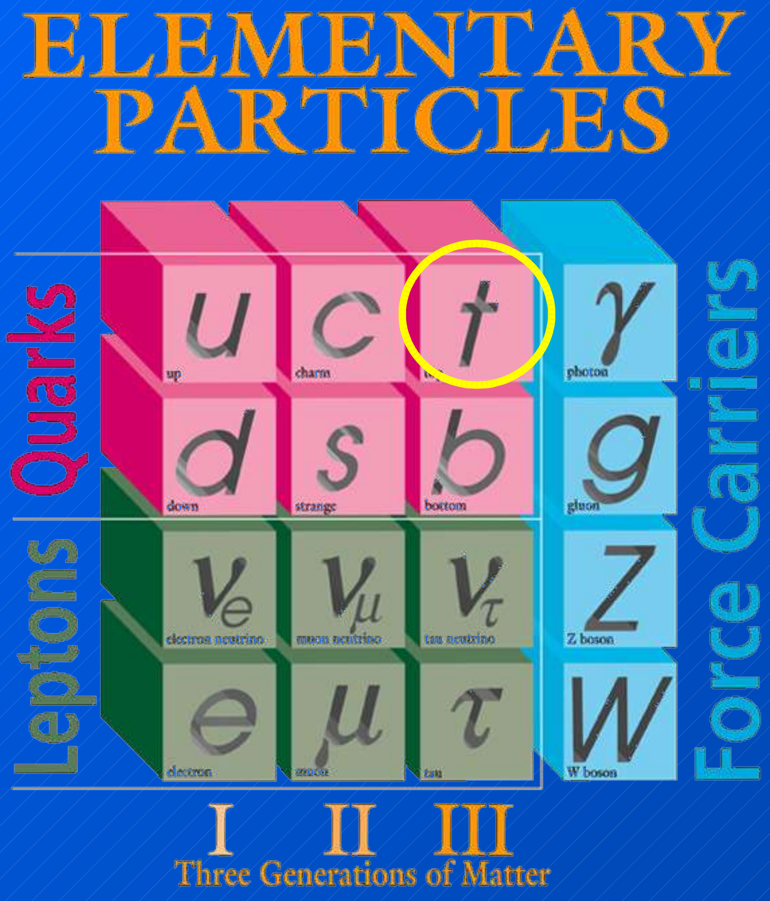
Top Quark Physics

Top Quark Physics



- Introduction: The Top Quark in the Standard Model
- Top-Antitop Production Cross Section
- Top Mass Measurement
- W-Helicity in Top Quark Decays

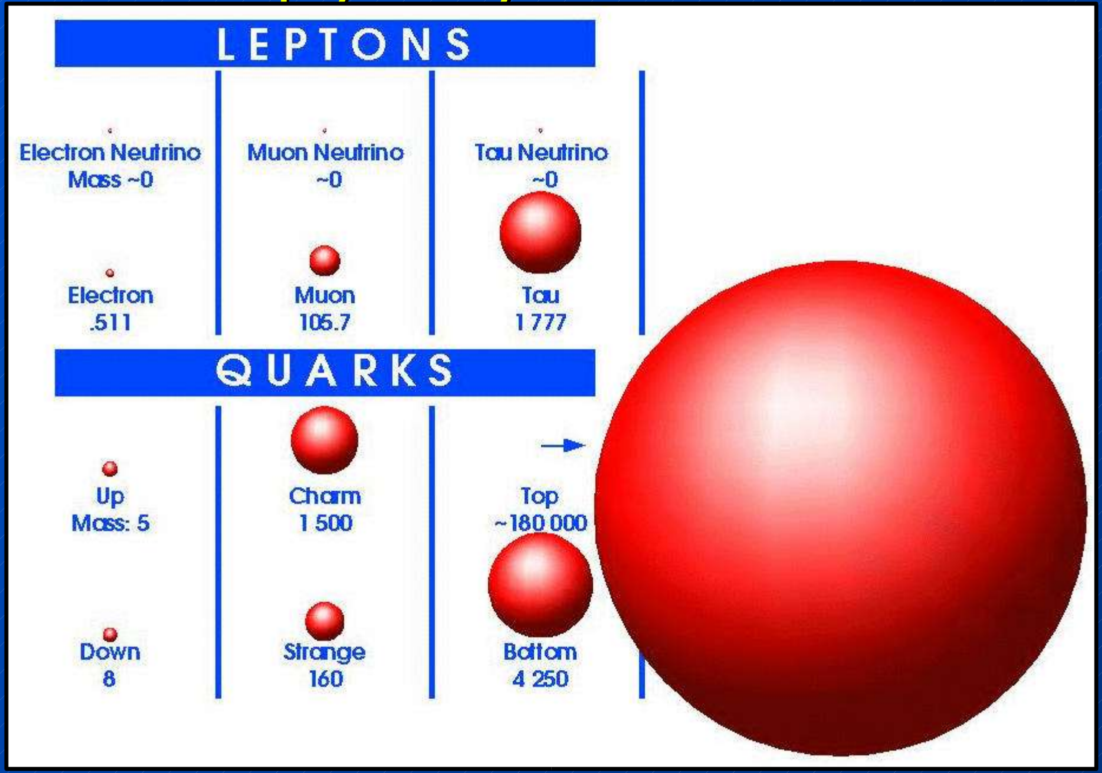
Top Quark in the Standardmodel



Discovery of the Top Quark in 1995 by the CDF and DØ Collaborations.

Why is the Top Quark so interesting ?

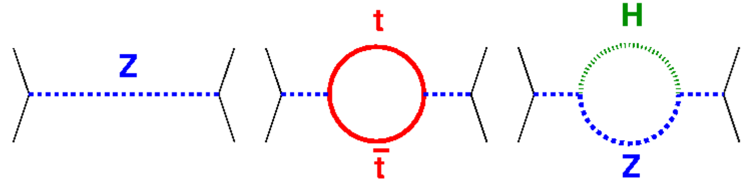
- completes the quark sector
- large mass $m_{top} \sim 180\ GeV / c^2$
- short lifetime $\tau \sim 5 \cdot 10^{-25} s \ll \Lambda^{-1}_{QCD}$
- sensitive to physics beyond the Standard Model



Higgs-Boson coupling to fermions : $g \sim m_f$

$m_t \sim v/\sqrt{2}$, Yukawa coupling $\lambda_t \sim 1$

Top Quark in the Standardmodel



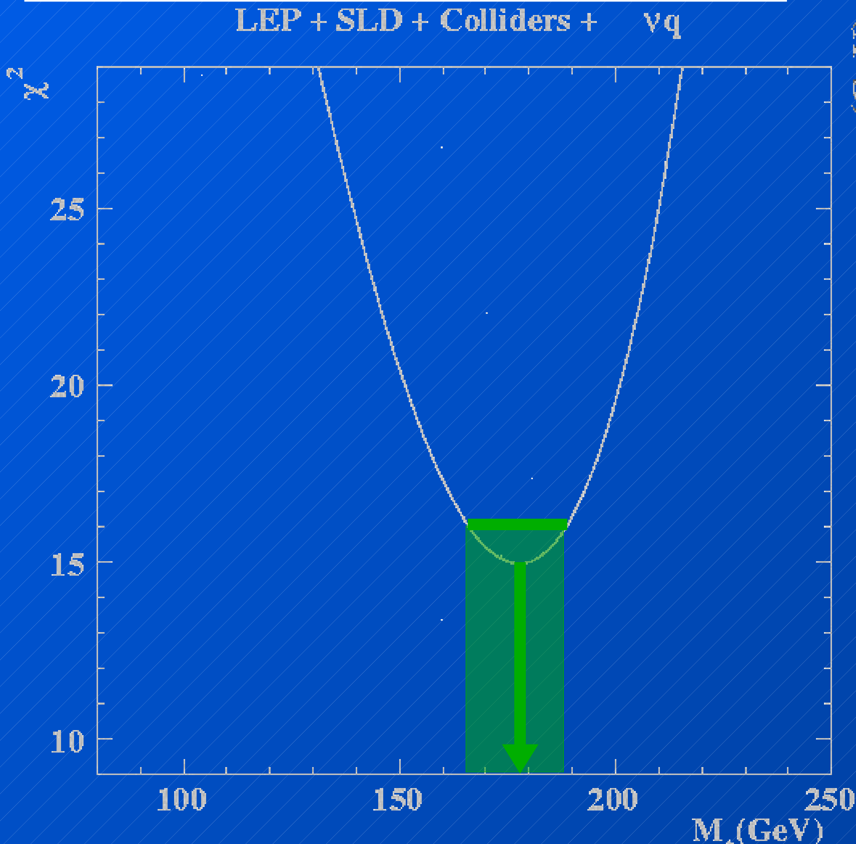
$$M_Z^2 = M_Z^{2\;0.Ordnung} \cdot (1 + \Delta)$$

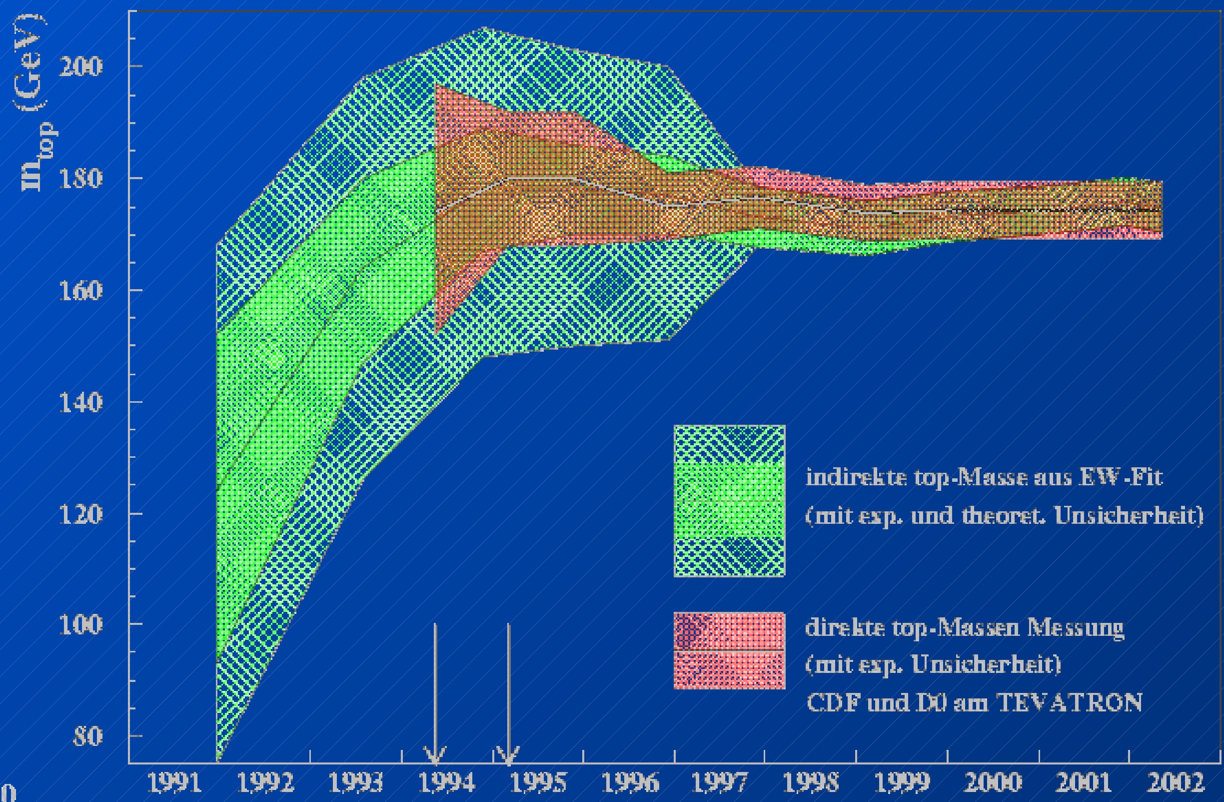
$$\Delta^{-1} = \dots M_t^2 \dots + \dots \ln M_H \dots$$

corrections to W and Z boson mass from top quark and Higgs boson loops allow prediction of the top quark and the Higgs boson mass

comparison of precision EW measurement ↔ corrections

⇒ prediction of top quark mass





Top Quark in the Standardmodel

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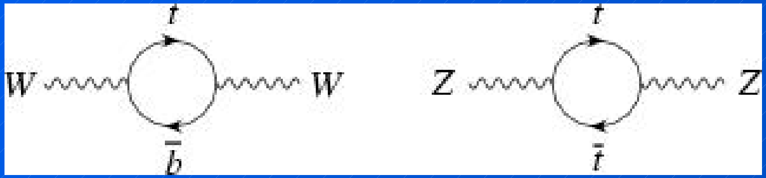
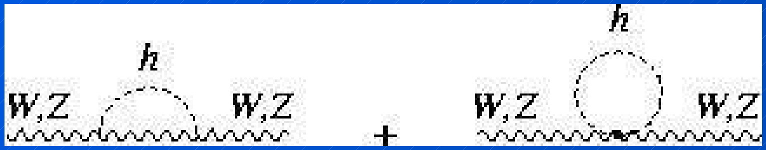
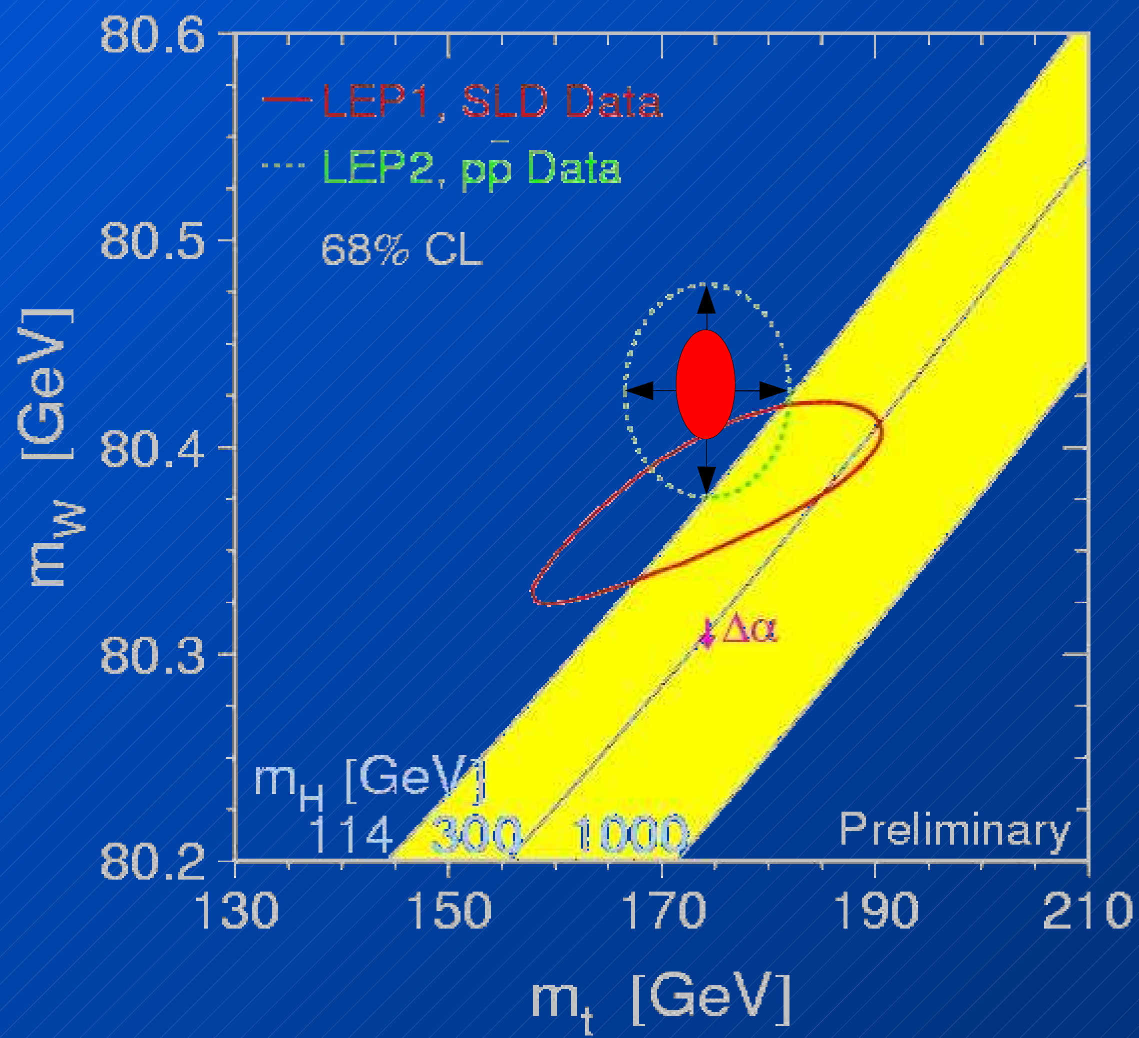


corrections: ~ m_{top}^2



corrections: ~ ln (m_{higgs})

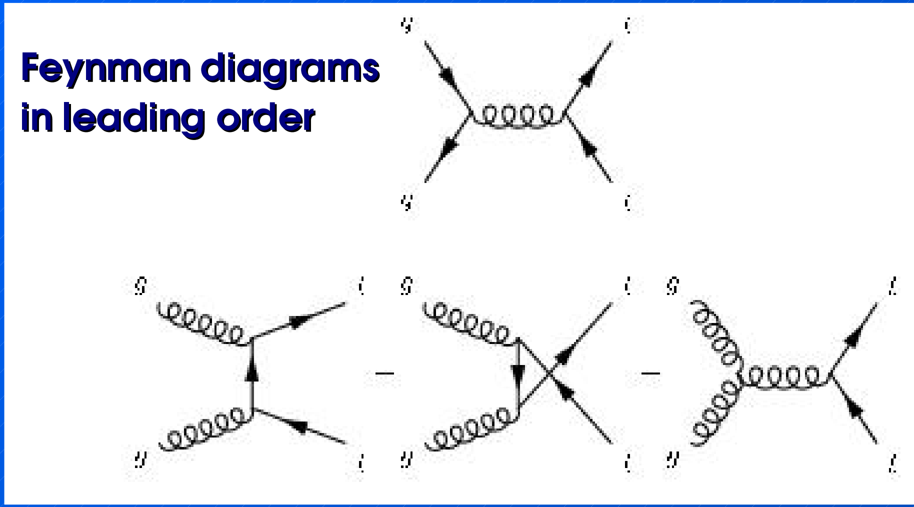


goal for Tevatron in Run II:

Δm_{top} = 3 GeV

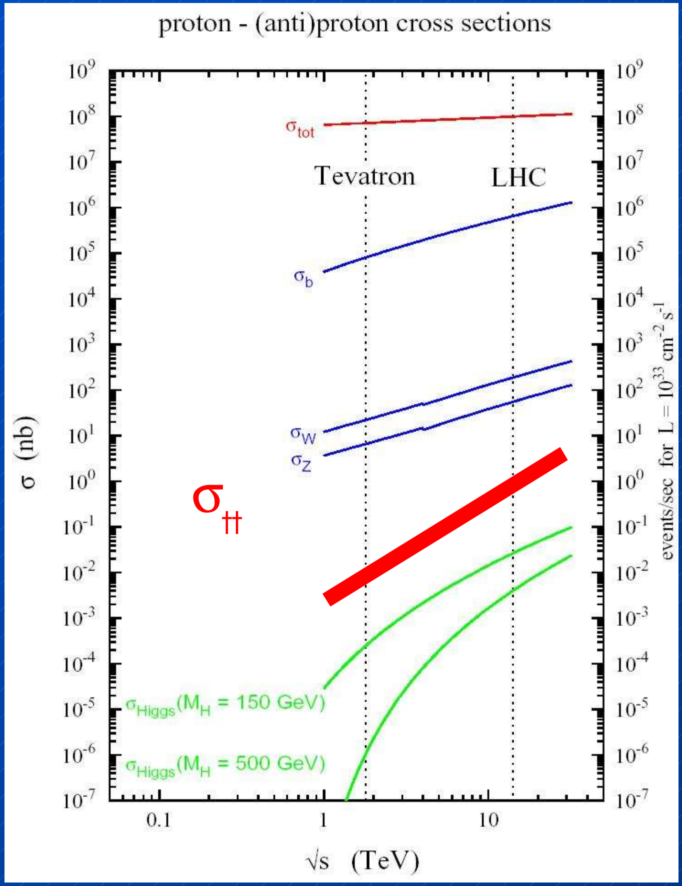
Δm_W = 20 MeV

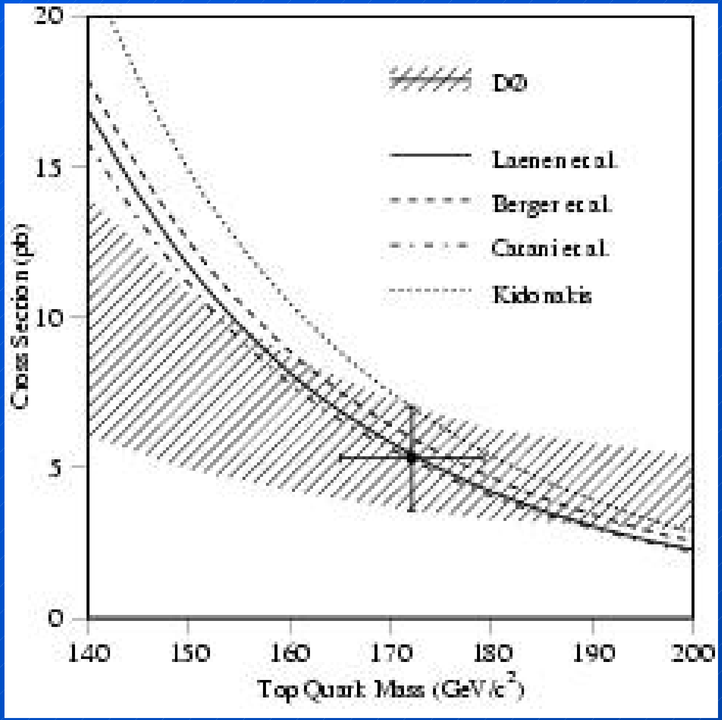
Top Quark in the Standardmodel



qq ~ 85 %

gg ~ 15 %



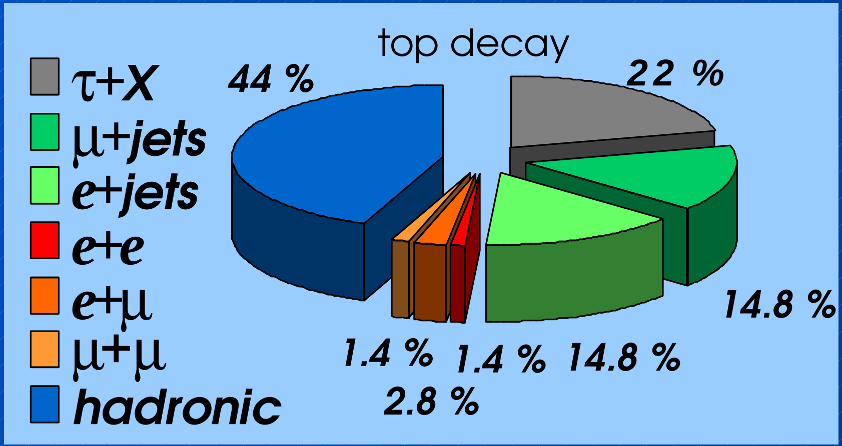


	Run I	Run II (2 fb^{-1})	LHC (10 fb^{-1})
ttbar (m_t sample 1 b-tag)	20	800	8 * 10^6
single top	4	100	...

- establish top signal
- measure cross section as QCD test
- cross section and topology close to Higgs physics

W-Decay Determines Topology

Top quarks decay predominantly (~100%) to a W-Boson and a b-quark



Top-Antitop Signatures:

`dilepton channel'

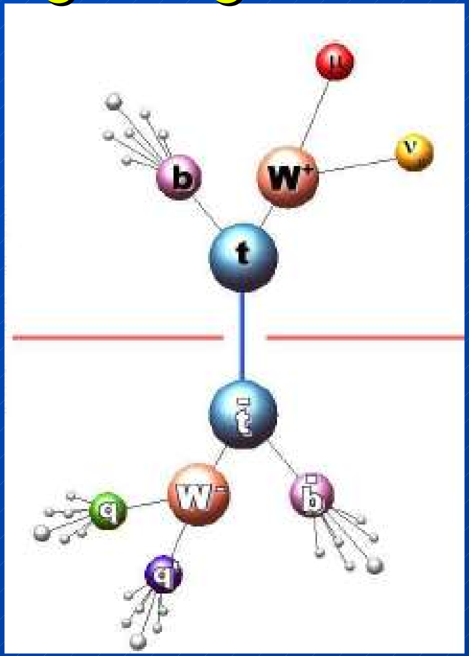
5% : 2 jets, 2 charged leptons, 2 ν

... measure top production cross section (strong and weak) and properties ...

'lepton+jets channel'

30%: 4 jets, 1 charged lepton, 1 ν

signal signature



'all-jets channel'

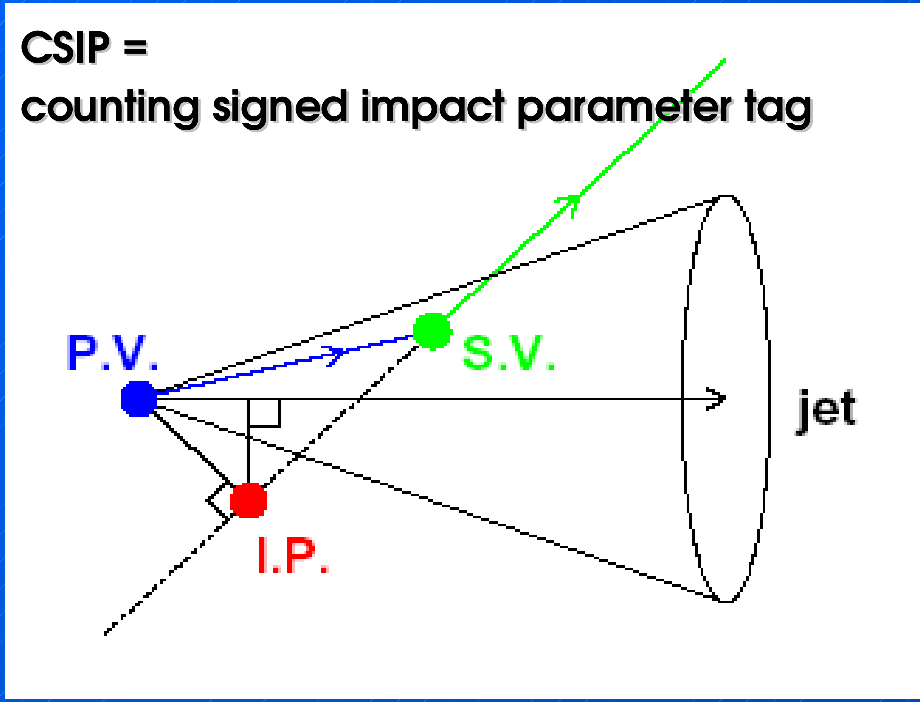
40%: 6 jets

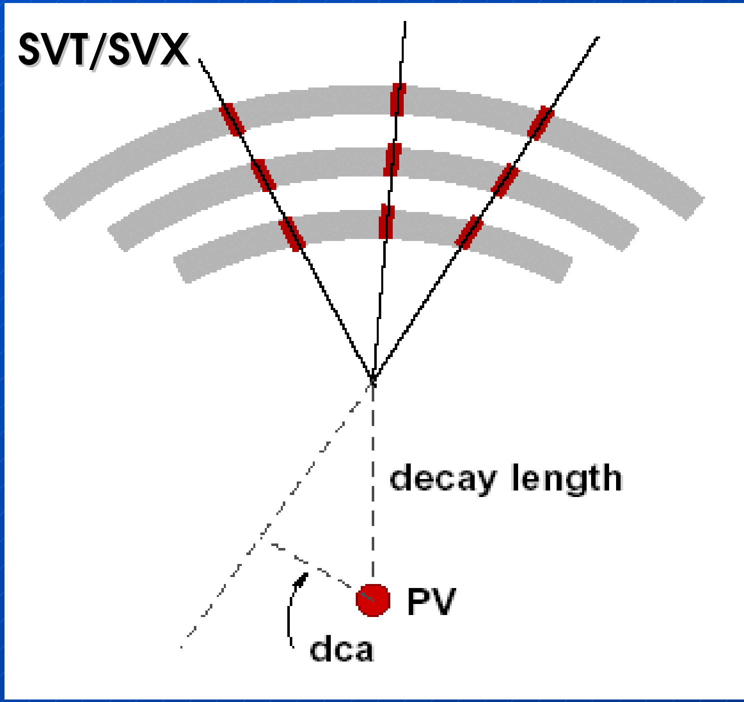
let' s look at the various topologies ...

always 2 jets are b-jets

also look for lifetime- or μ-tag

b-tagging in CDF and DØ



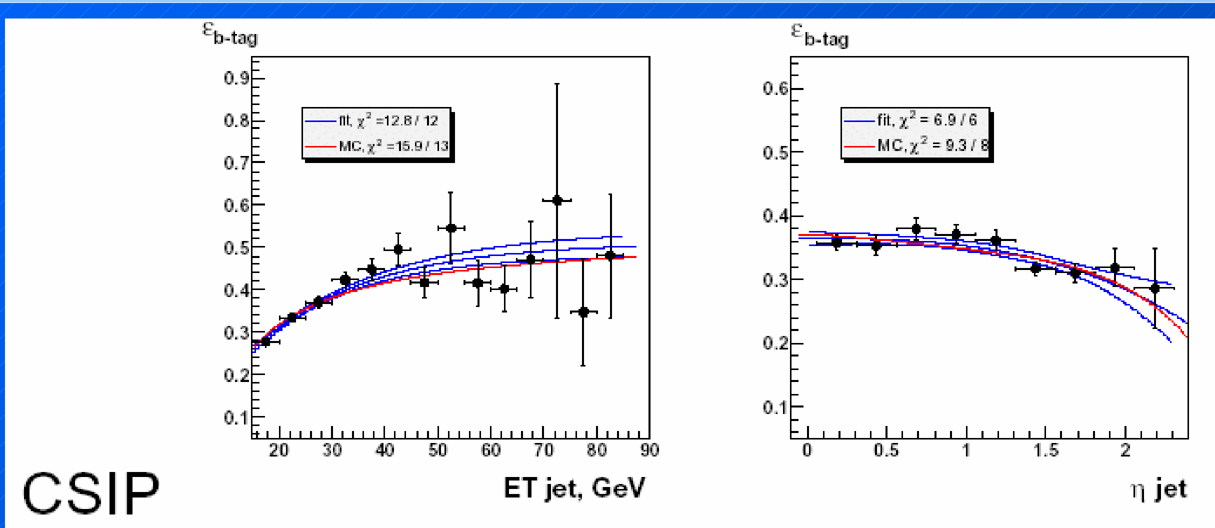


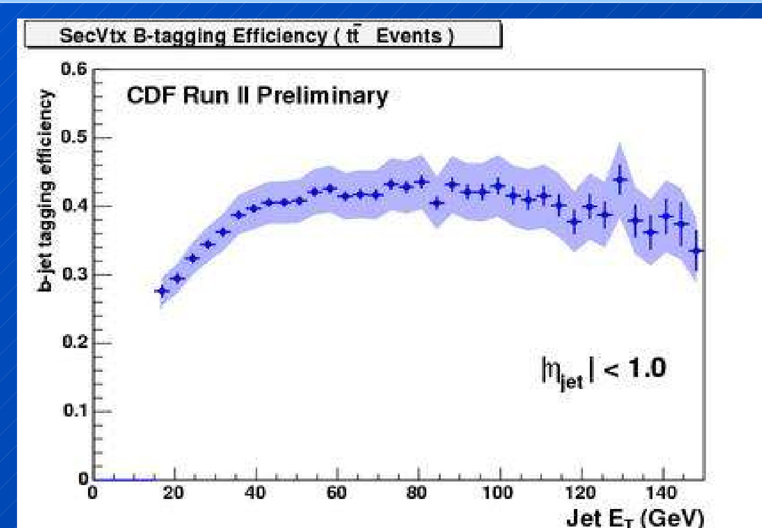
- count the number of track with large positive DCA significance σ
- jet is tagged if
  $N_{tr}(\sigma>2)>3$ or
  $N_{tr}(\sigma>3)>2$

- explicitely reconstruct 3d vertices out of track jets
- cut on decay length significance

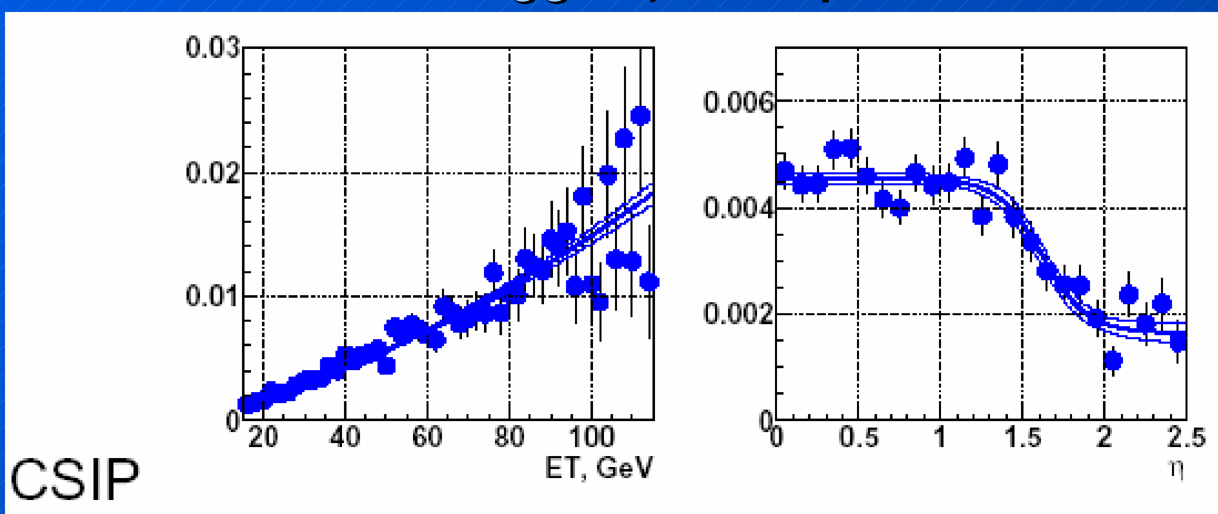
⇨ can also tag muon in jet from soft-lepton decay

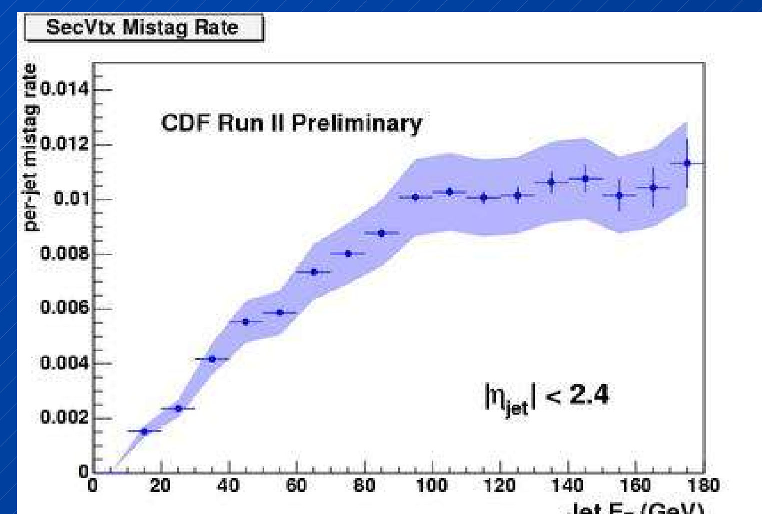
b-tagging Efficiency and Fakre Rate





measured in muon-tagged jet sample

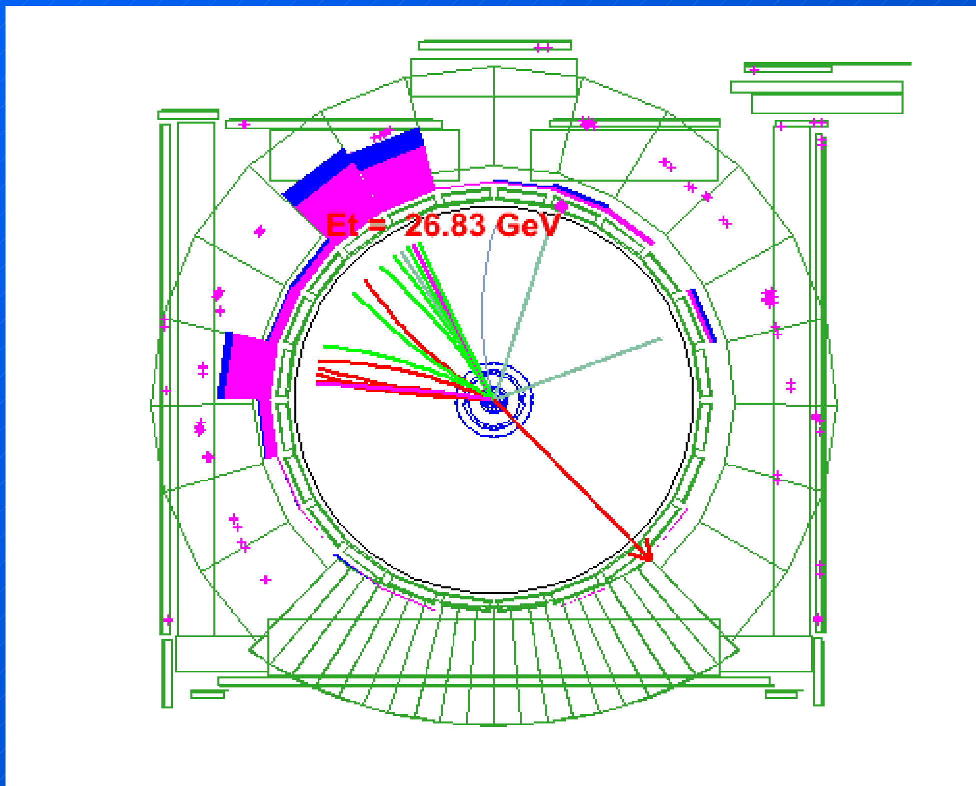


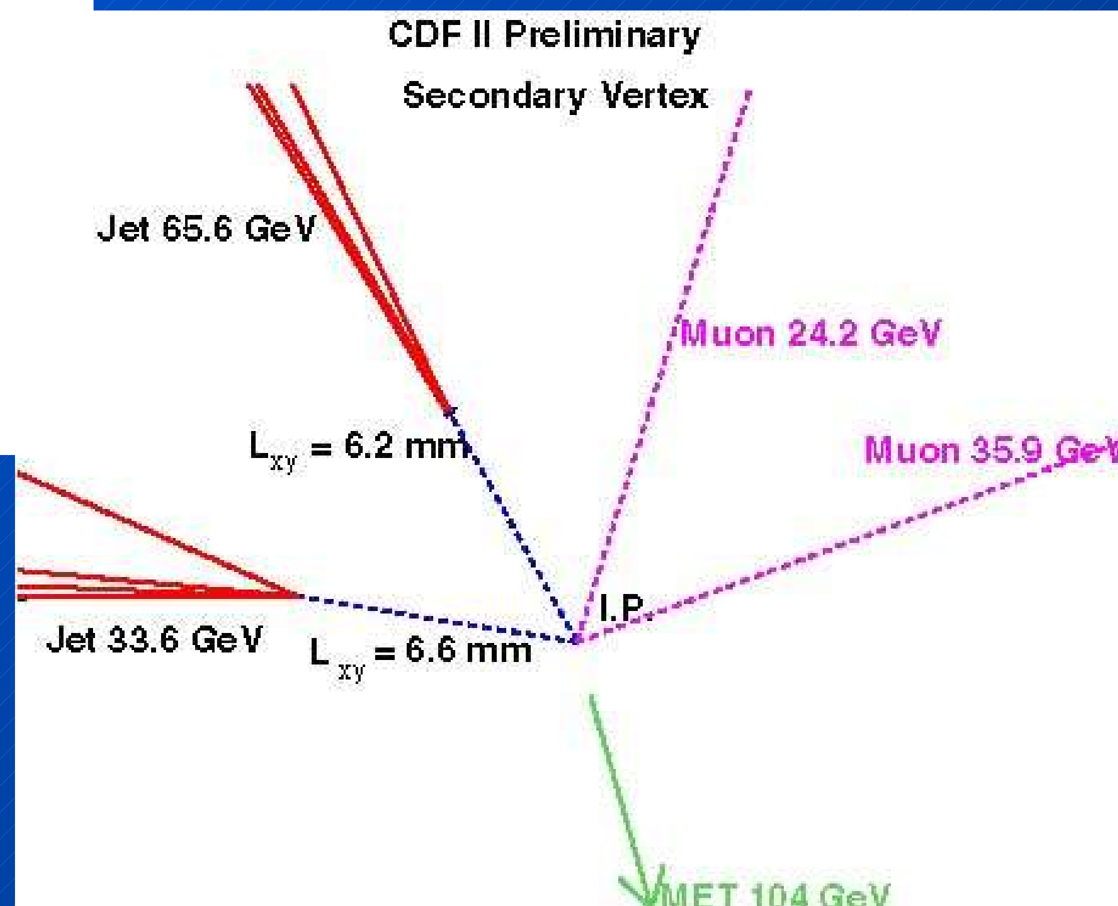


measured in inclusive sample, converted to light-tag rate using MC

DØ CSIP/SVT slightly higher/lower fake rate ⇒ CDF/DØ similar performance

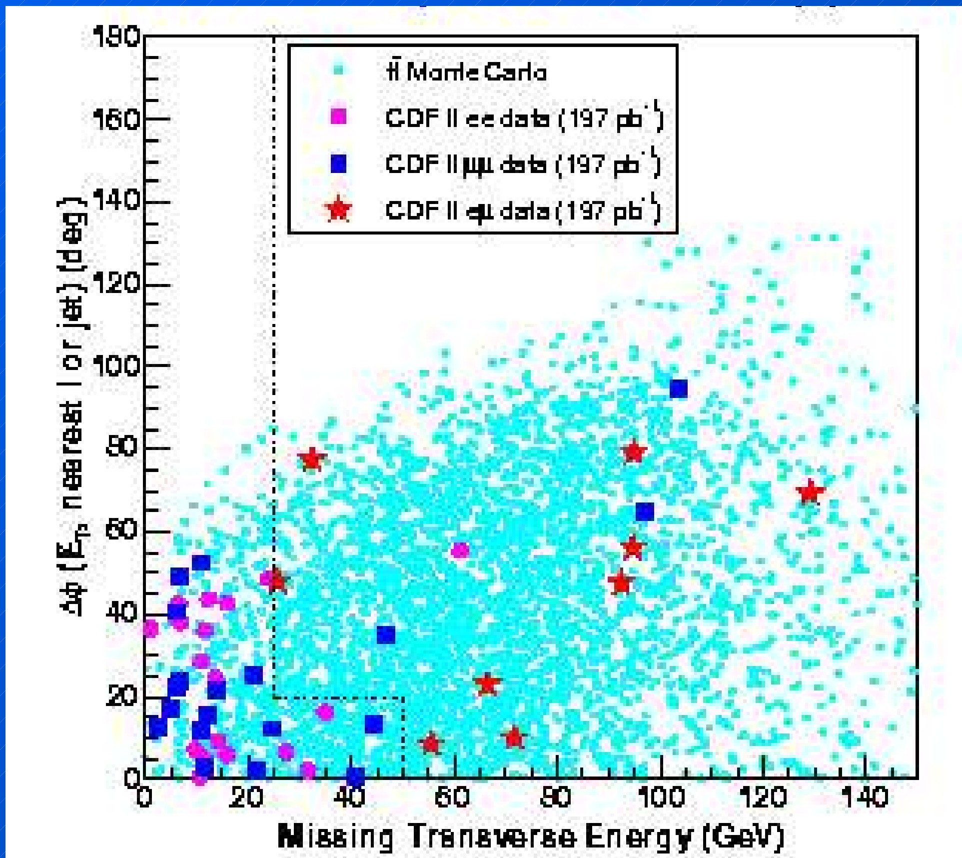
An Example μμ-Event



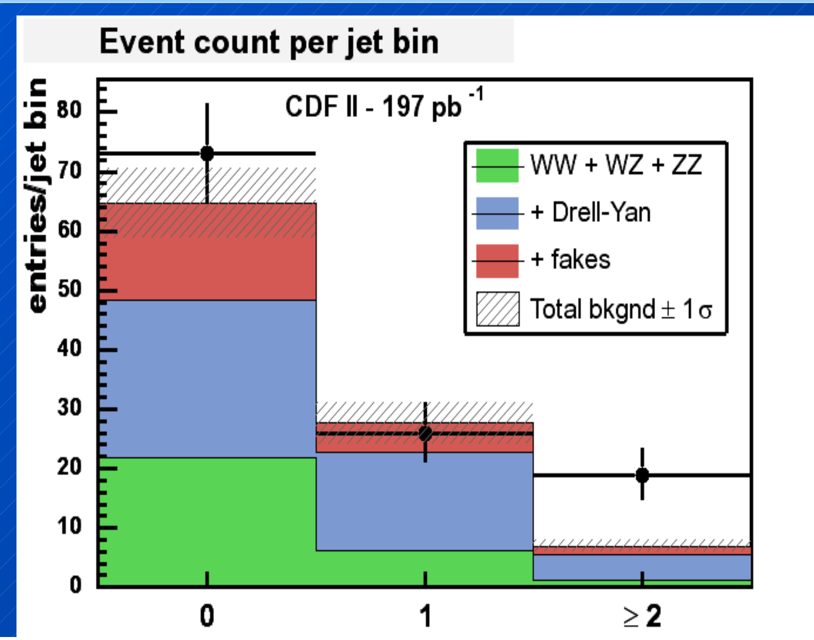


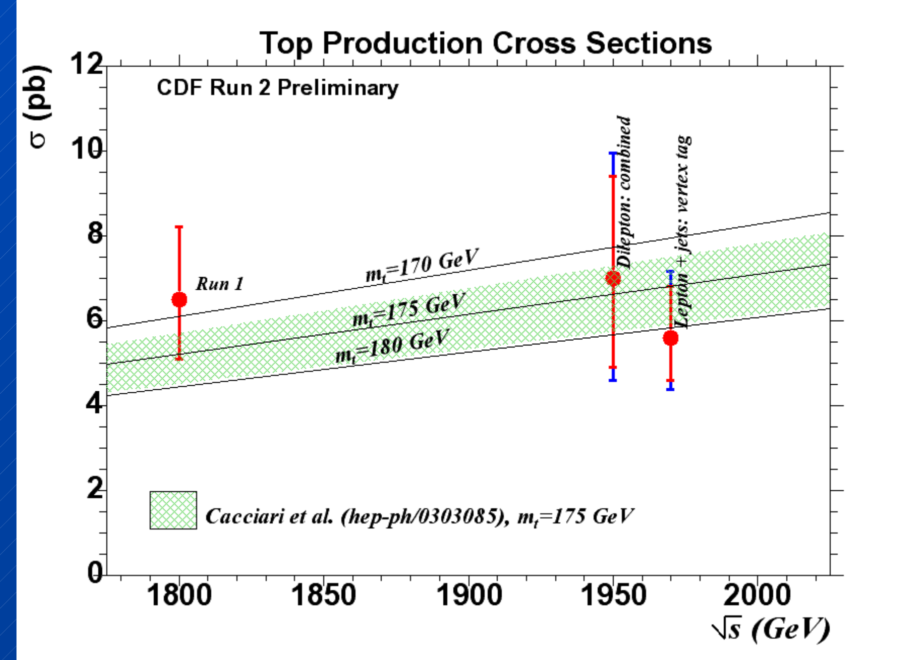
CDF Top Cross Sections in Di-Leptons

- 197 pb^{-1} data sample for all channels
- combine ee, $\mu\mu$ and eμ channels for best precision



$$\sigma_{t\bar{t}} = 7.0^{+2.4}_{-2.1}(\text{stat.})^{+1.6}_{-1.1}(\text{syst.}) \pm 0.4(\text{lum.})$$

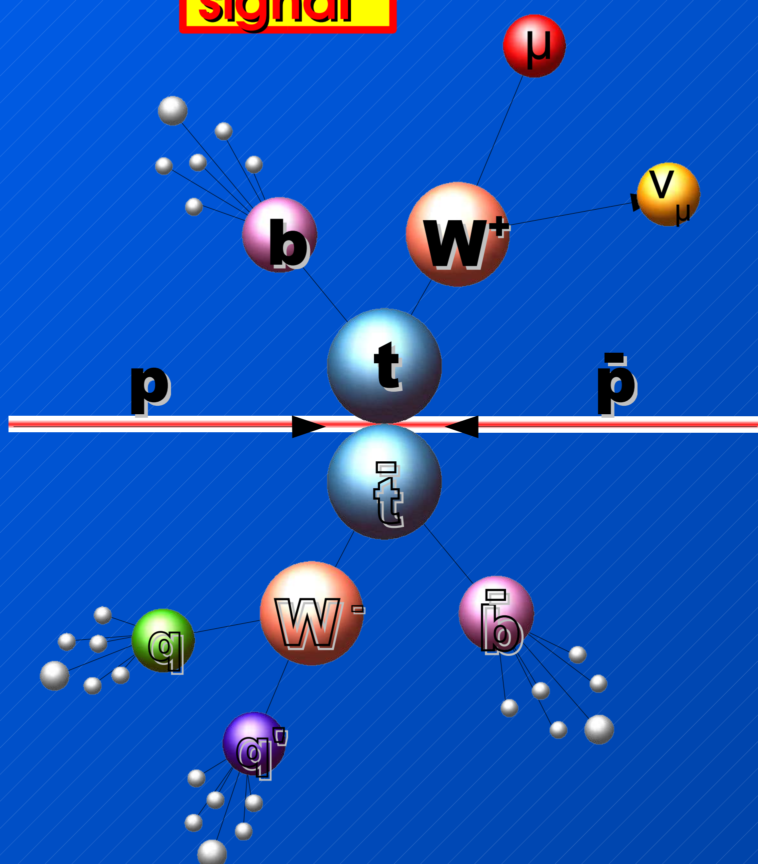




Event Topology in Lepton+Jets

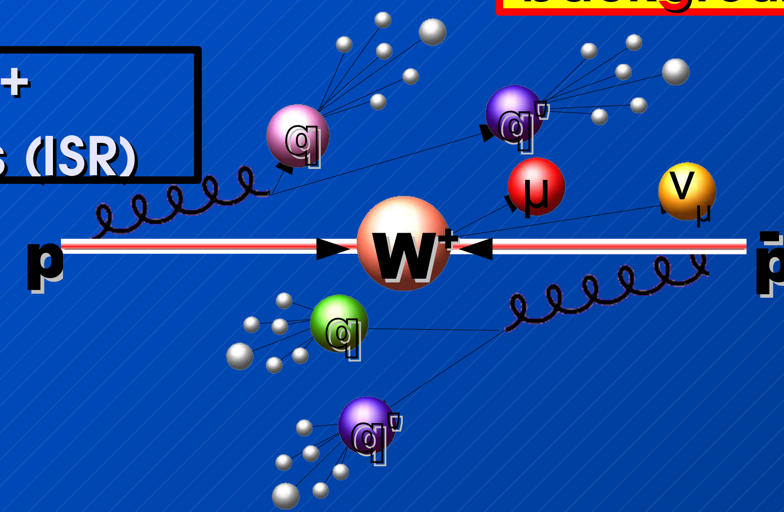
- 1 lepton with high p_T
- 1 ν (reconstructed as transverse energy (met))
- $\geq$ 4 jets

signal

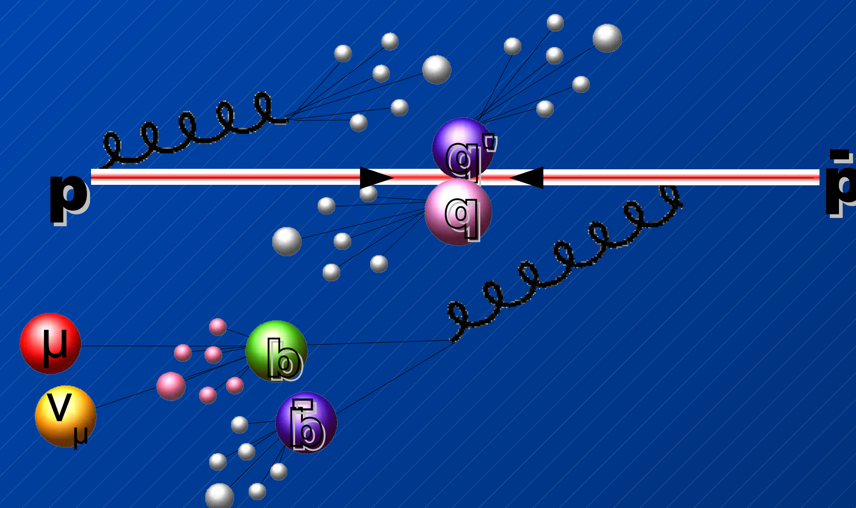


background

W → l ν +
≥ 4 jets (ISR)

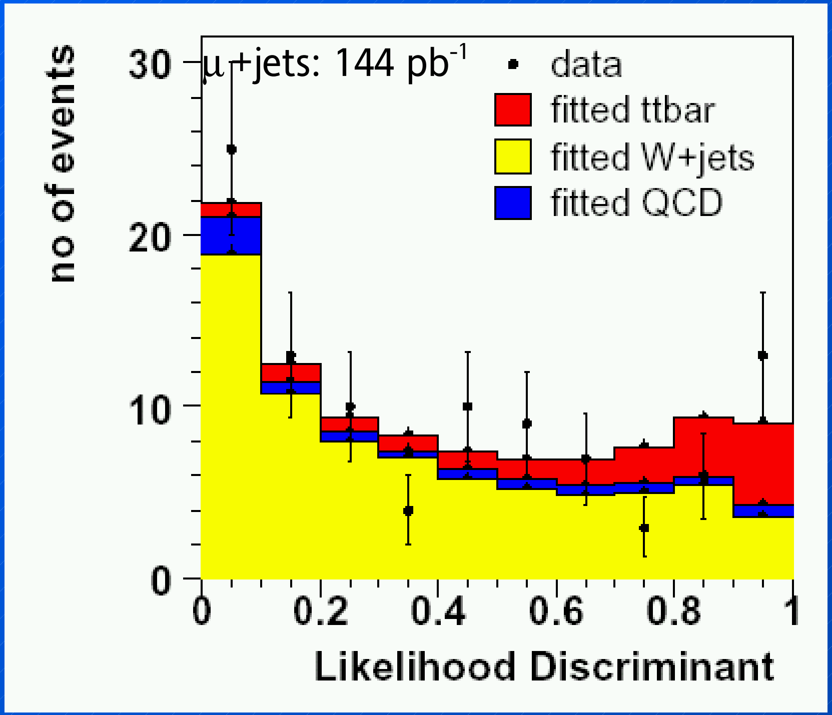


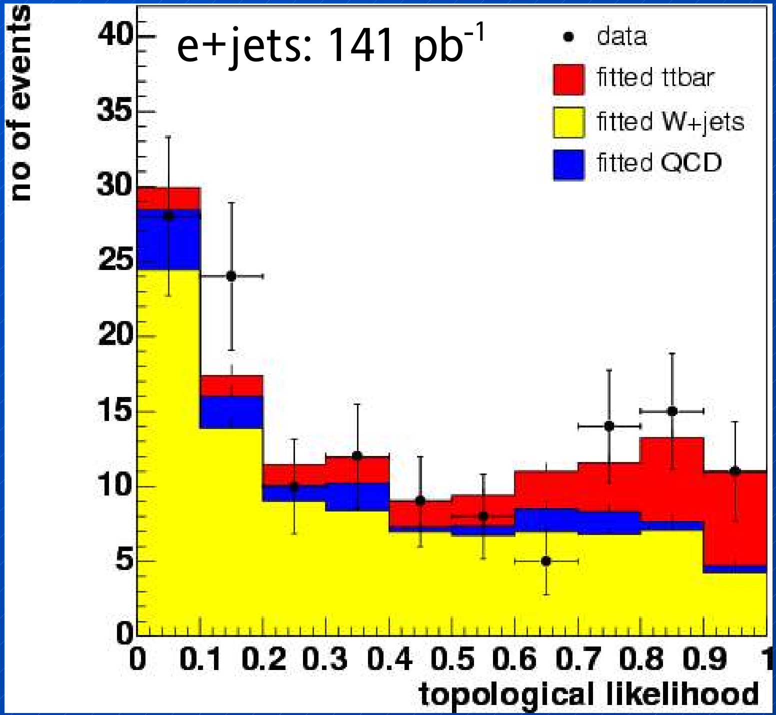
multijet background (QCD)
+ misreconstructed met
+ fake isolated μ or e



Likelihood Fits in l+jets Channel

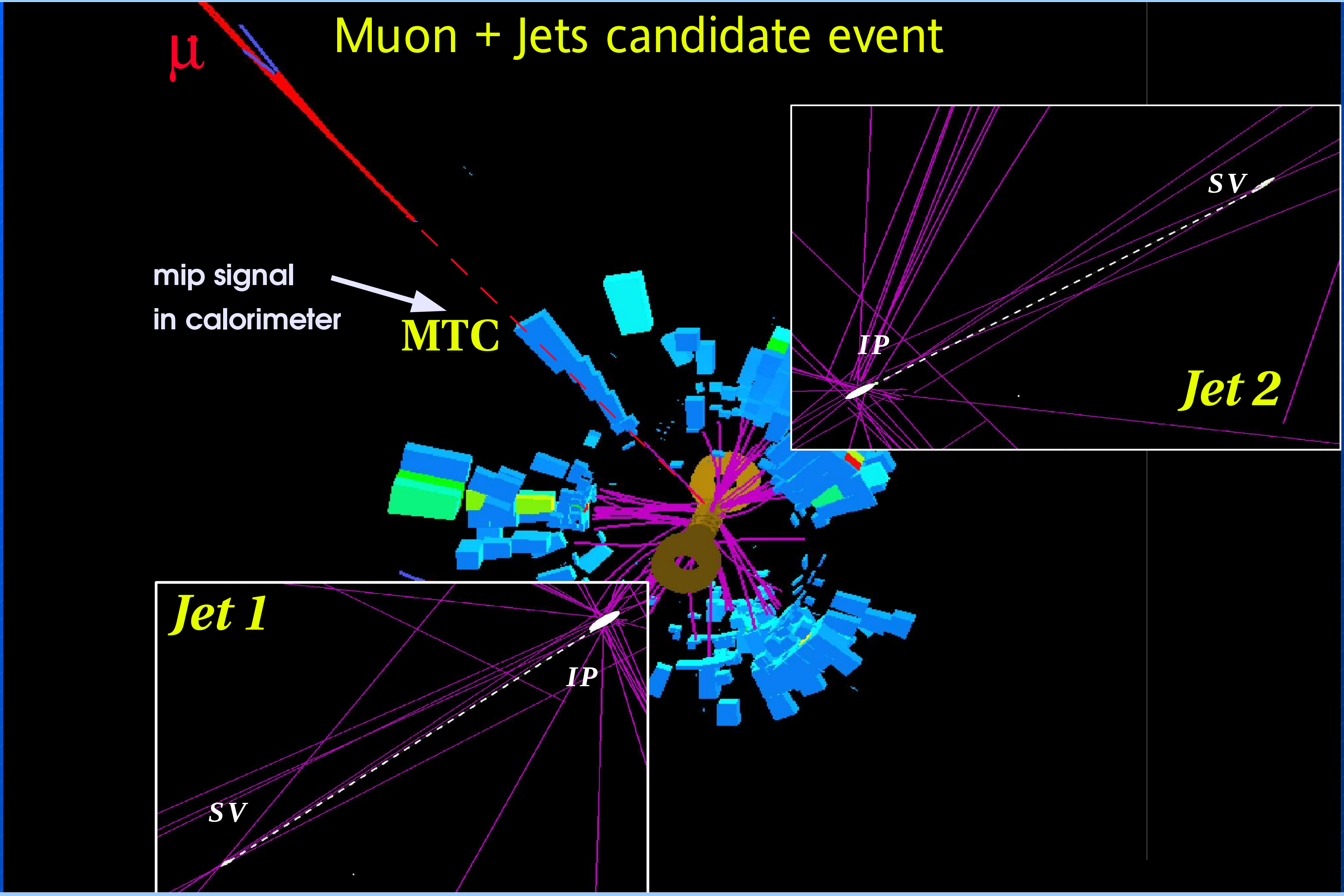
fit linear combination of QCD (inverted tight selection in data), W+4jet and ttbar to data





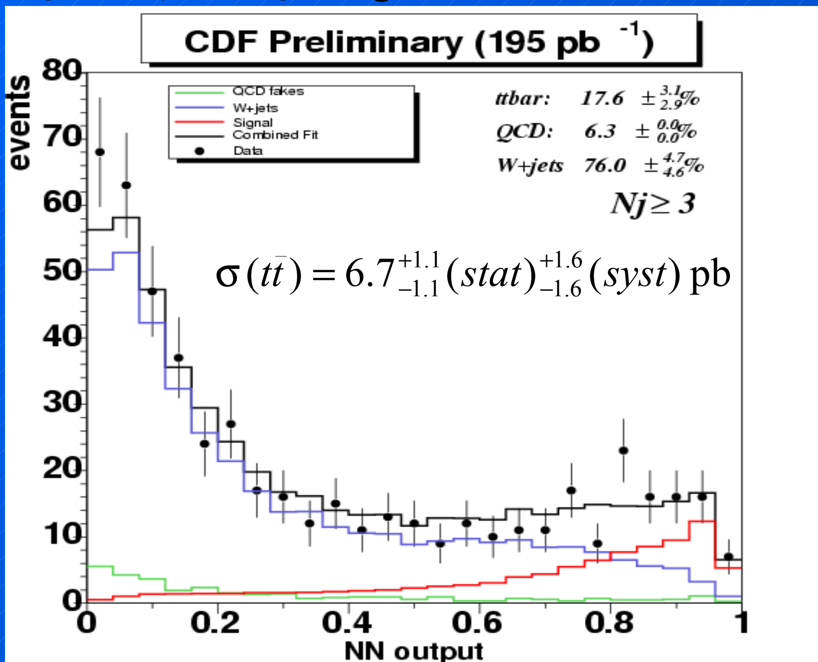
	muons	electrons
Nev	100	136
fitted N^W	74.7 + 12.7 – 12.0	94.6 + 15.8 - 15.0
fitted N^{QCD}	7.1 + 0.9 – 0.9	14.1 + 1.2 - 1.2
fitted N^{tt}	17.8 + 9.9 – 8.7	27.5 + 12.7 - 11.7

A Typical μ+Jets Candidate Event

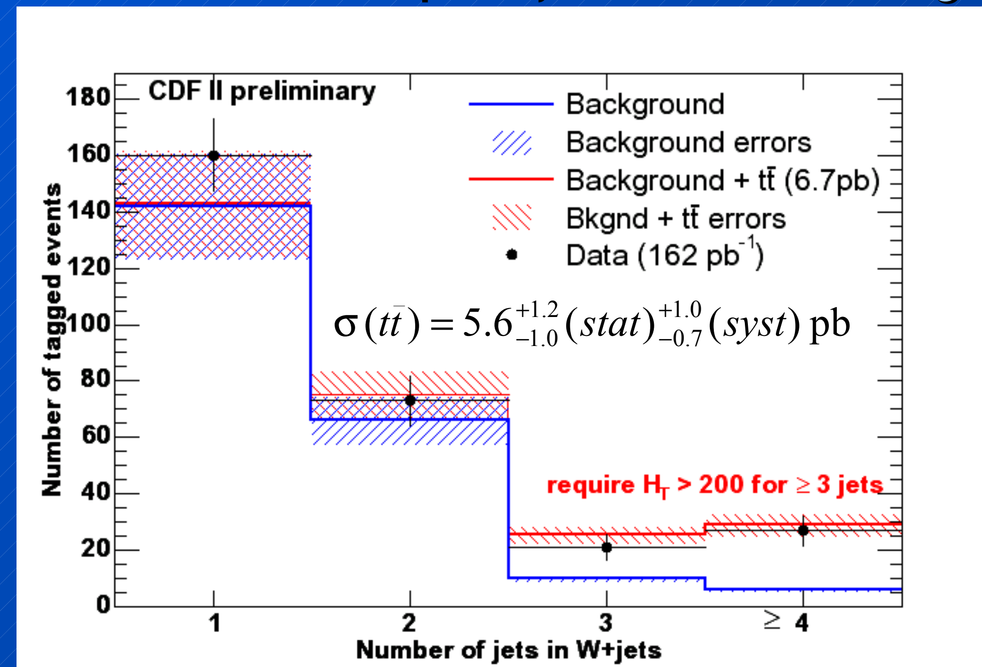


Lepton+Jets Analysis in CDF

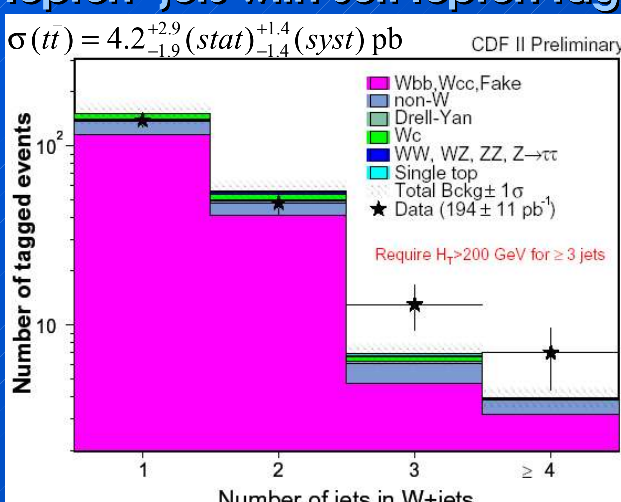
lepton+jets topological



lepton+jets with vertex b-tag



lepton+jets with soft lepton tagging



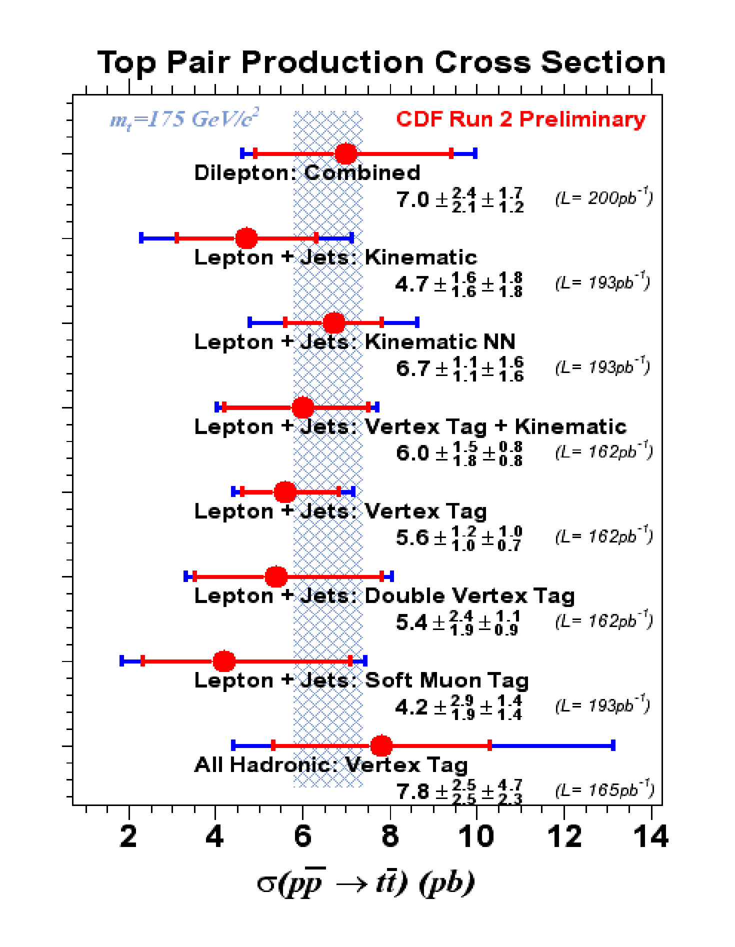
exploit different strategies :

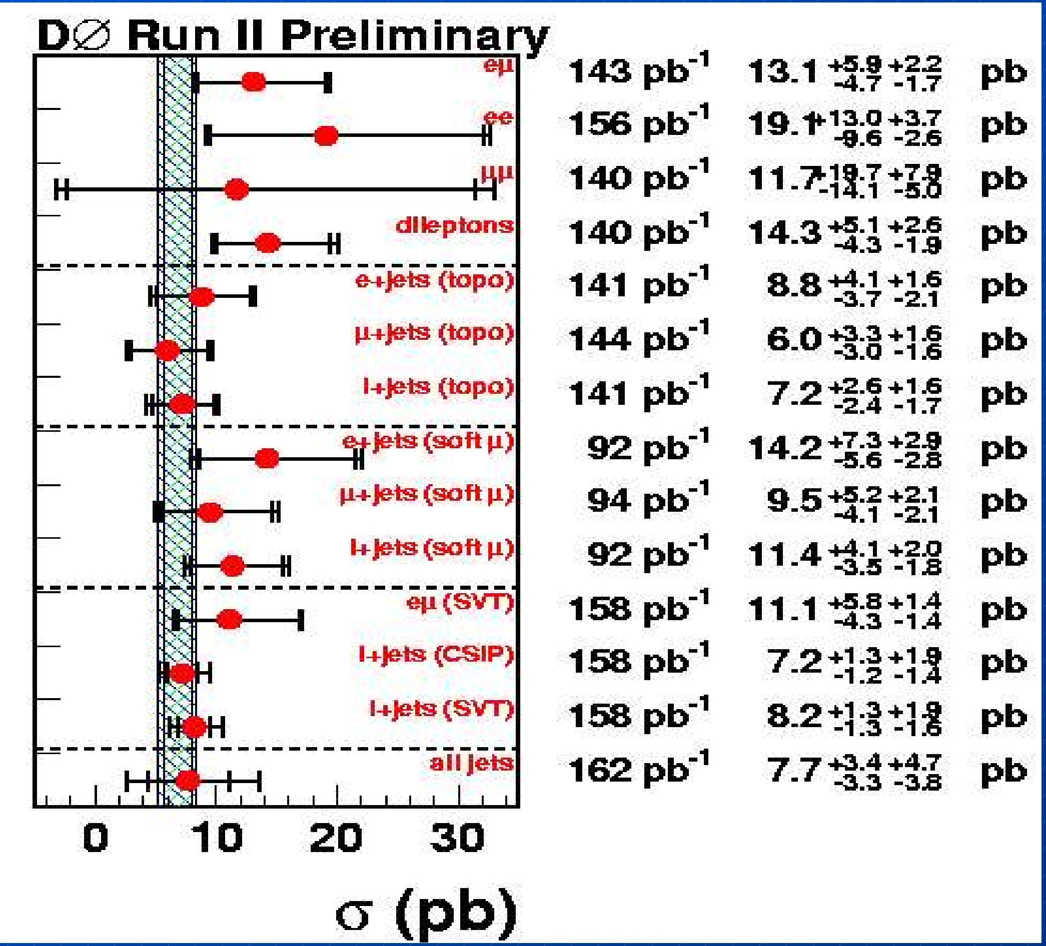
- **high statistics – topological**
- **b-jets tagging**
  - **displaced vertex**
  - **soft lepton (μ)**

obtain consistent results

Run II Top Cross Section - Summary

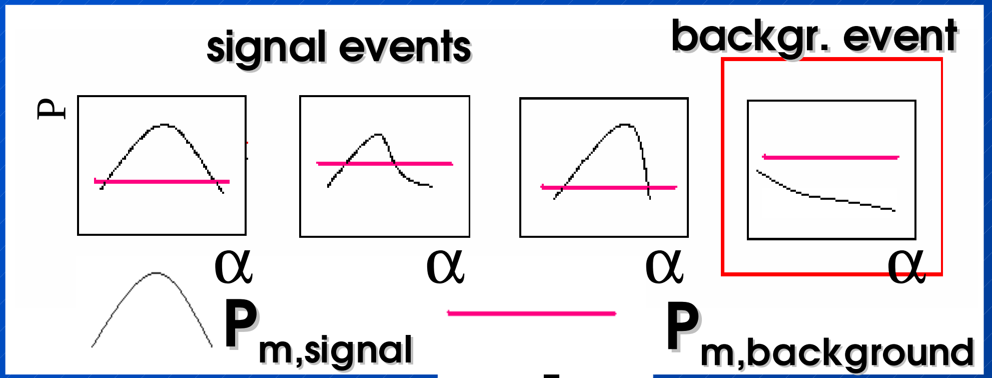
errors between different channels are correlated





Measurements demonstrate success of various top detection techniques results within errors consistent with NNLO SM prediction for 1.96 TeV of ~7 pb^{-1}

Measurement of the Top Mass in L+jets

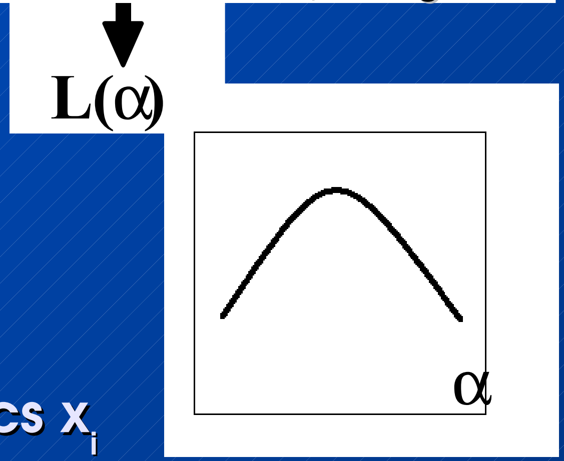


- quantity α

- N events with reconstructed objects (leptons, jets, ...) and kinematics x_i

- best estimate by maximizing the **Likelihood function**:

$$L(\alpha;x_1\ldots x_N)=e^{-N\int P_m(\alpha,x)dx}\prod_{i=1}^{N}P_m(\alpha,x_i)$$



- $P_m(\alpha,x_i)$: probability to measure an event with kinematics x_i

$$P_m(\alpha;x_i)=c_1P_{m,t\bar{t}}(\alpha,x_i)+c_2P_{m,bkg}(x_i)$$

- include **background**:

- minimize -log-Likelihood to measured a and fix the signal/bkg.-fractions !

- the challenge: **obtain the P(α,x)** !

Measurement of the Top Mass in L+jets

- Obtain probabilities by folding differential X-section with object resolutions:

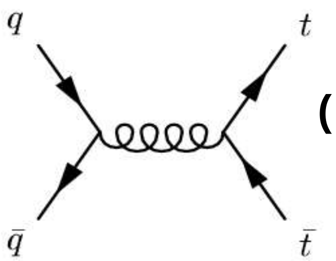
$$P_m(\alpha, x) = Acc(x) \times \frac{1}{\sigma} \int d^n\sigma(y;\alpha)\, dq_1\, dq_2\, f(q_1)\, f(q_2)\, W(x,y)$$

Acceptance (selection, trigger,...)

LO-Matrix element x phase space

PDF's

Transfer Functions (Probability to measure x when y was produced)



Signal (No ISR or FSR)

Background (VECBOS-ME)
W+ 4 Jets
(also found adequate for QCD bkg.)

→ need to constrain to exactly 4 Jets

- take permutations (jet-parton-assignment) and reconstruction ambiguities into account by summing over different possibilities
- Transfer functions are set to δ-functions for well-measured quantities (jet-angles, electron momentum)
- for jet-energies: $W_{jets}(E_{part}, E_{jet})$ relating parton- and jet-energies, obtained as parametrization for b- and non-b-Jets from MC

Application to Run-I Data

Signature : 1 charged lepton, 4 jets, Missing energy

DØ Statistics Run I : 125 pb^{-1}

Standard Selections:

- Lepton: E_T>20 GeV, $|\eta^e|<2$, $|\eta^\mu|<1.7$
- Jets: 4, E_T>15 GeV, $|\eta^\mu|<2$
- Missing E_T > 20 GeV
- "E_T^W"> 60 GeV ; $|\eta^W|<2$

91 events

Ref. PRD 58 (1998), 052001:

After kinematic cut (77 events): **~29 signal + ~48 backg.**

(80% *W+jets* and 20% QCD)

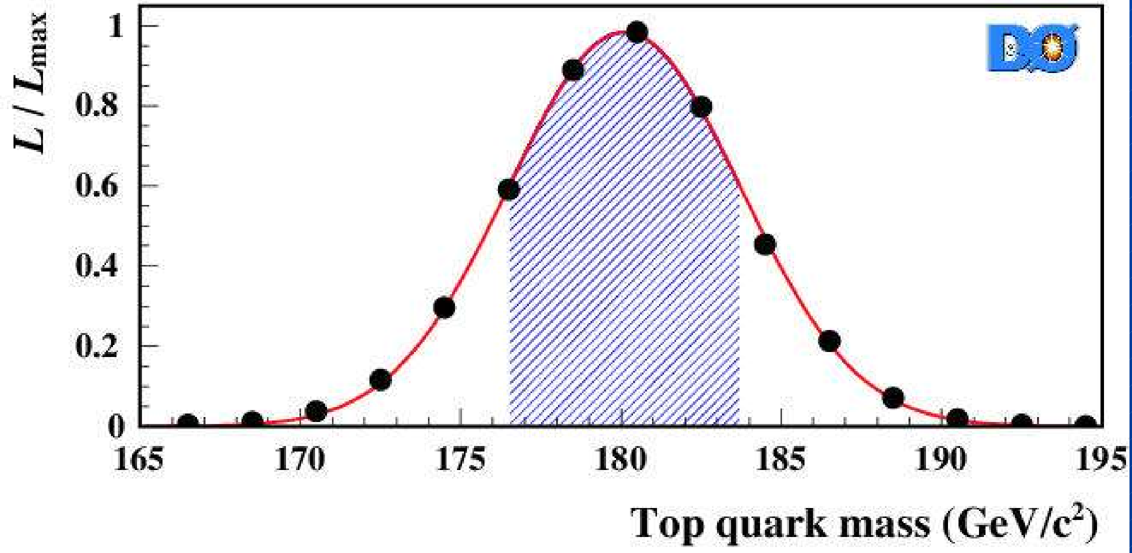
Specific cuts for this analysis:

- **4 Jets only :** **71 events**
- **Background Prob. :** **22 events**

Application to Run-I Data

$M_t = 180.1 \pm 3.6_{stat} \pm 4.0_{sys}$ GeV

Nature 429, 638-642 (10 June 2004)



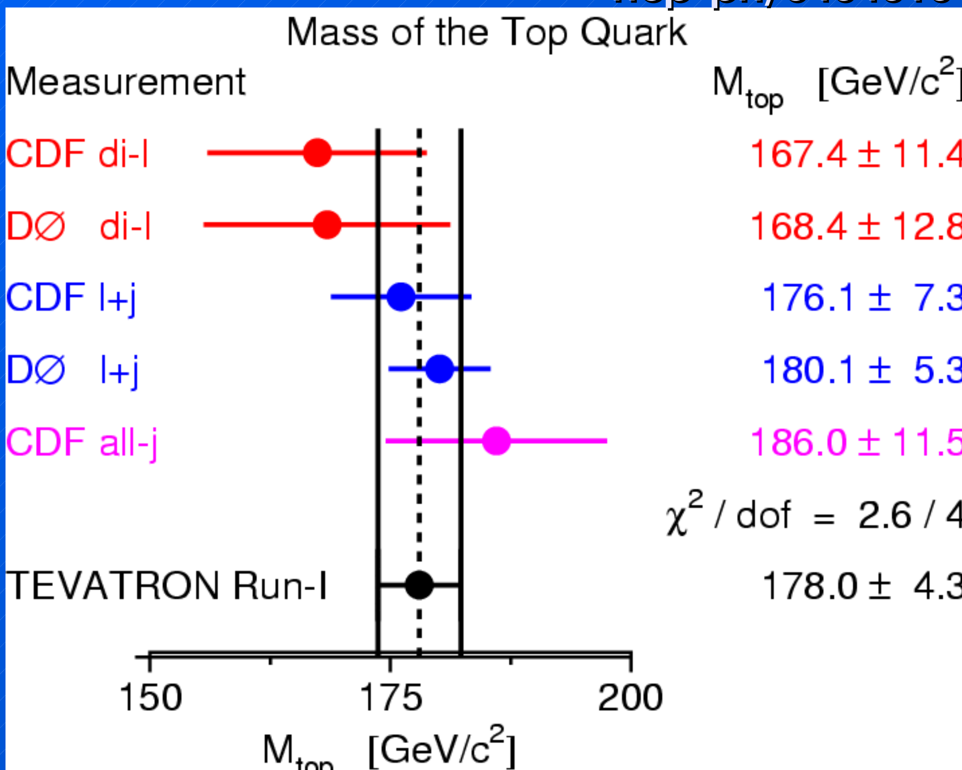
- improvement corresponds to 2.4-times statistics !
- result compatible with previous measurement in the lepton+jets channel at about the 1.7 sigma level !

ttbar model	1.5 GeV
W+jets model	1.0 GeV
Noise and multiple i.a.	1.3 GeV
Jet energy scale (JES)	3.3 GeV
PDF's	0.2 GeV
Acceptance correction	0.5 GeV

Error estimated by rescaling jet energies by the JES uncertainty and taking the maximum difference.

World Average m_{top} and Higgs Mass

hep-ph/0404010



new world average

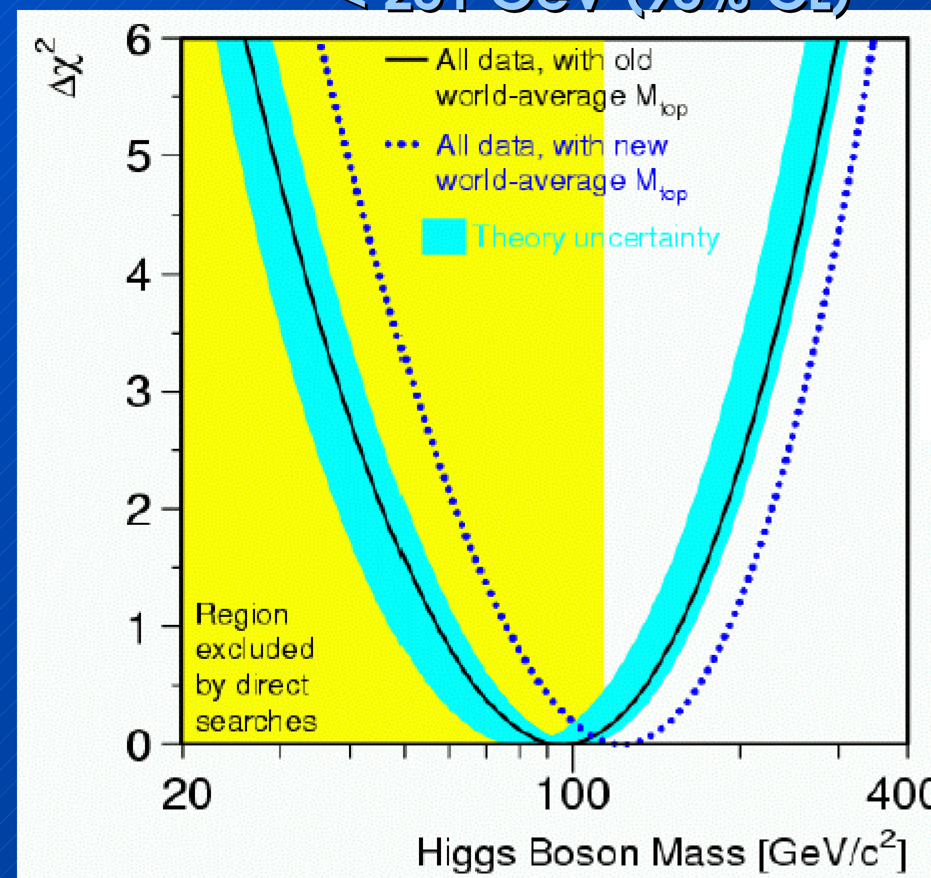
(TeV EW/TOP working group, 1.April'04):

178.0 ± 4.3 GeV/c²

$\log M_H = 2.07^{+0.20}_{-0.21}$

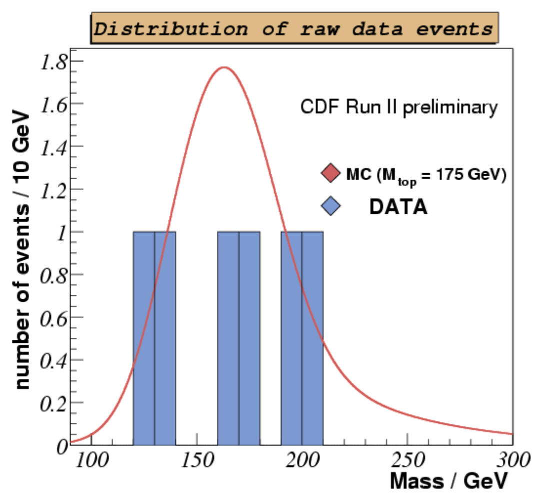
$M_H = 117^{+67}_{-45}$ GeV

< 251 GeV (95% CL)

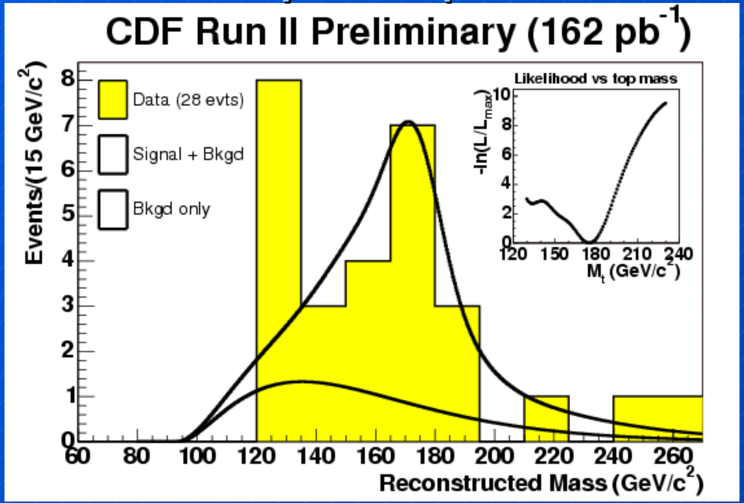


Run II Top Mass Measurement in CDF

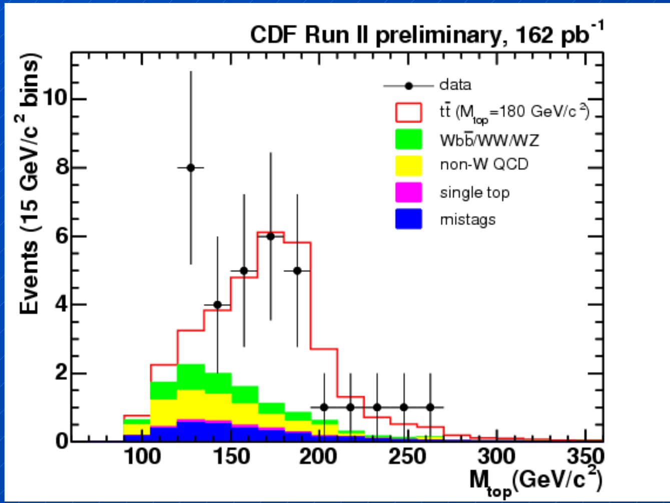
Run I style `template' method



Di-leptons

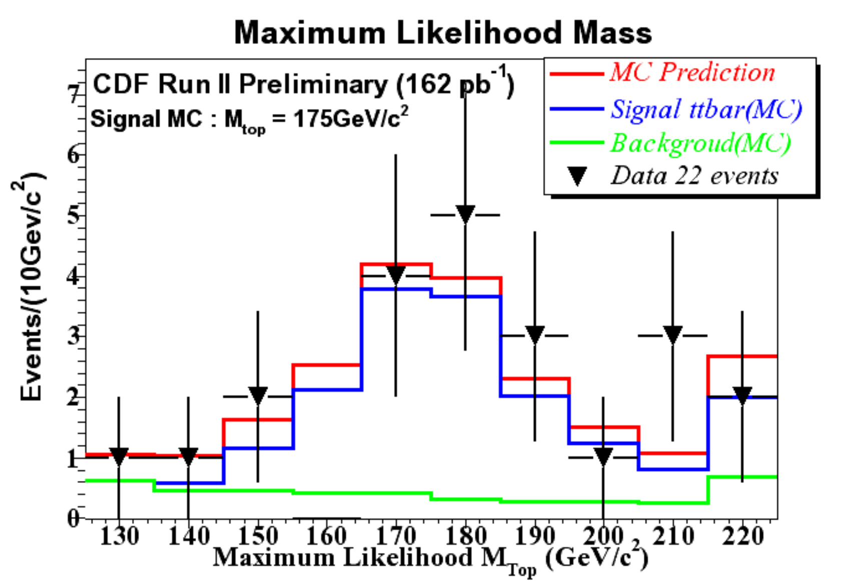


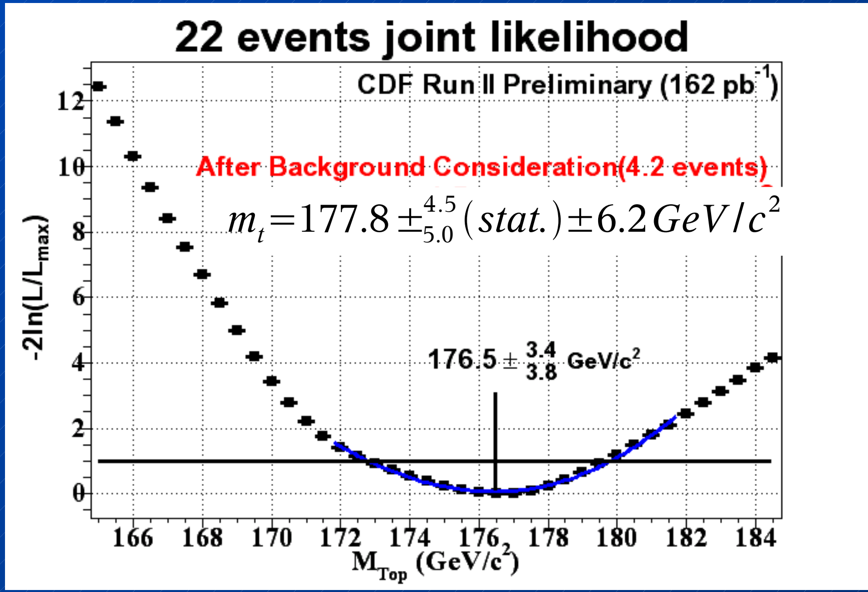
l+jets, b-tagged



l+jets, b-tag+jet E_T

Dynamical Likelihood Method is similar to DØ `matrix element method'

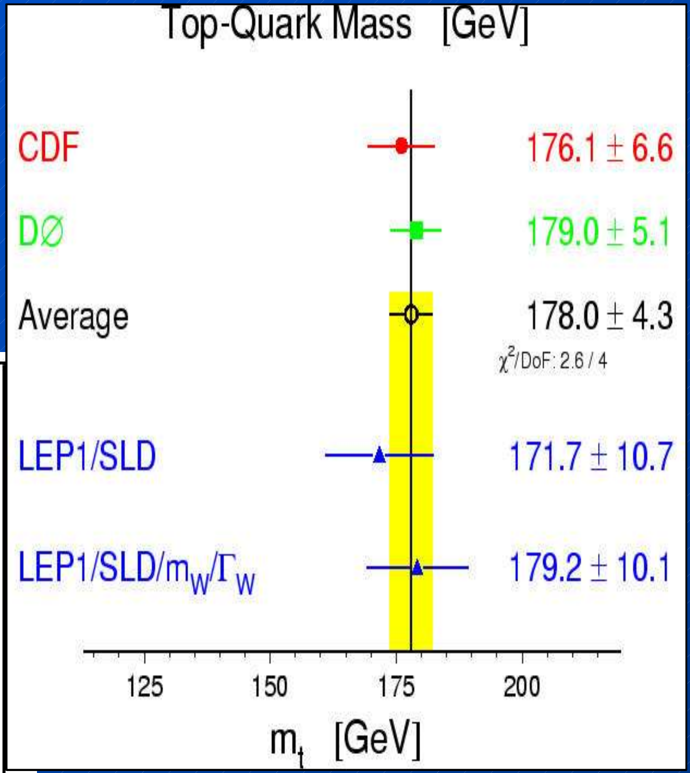


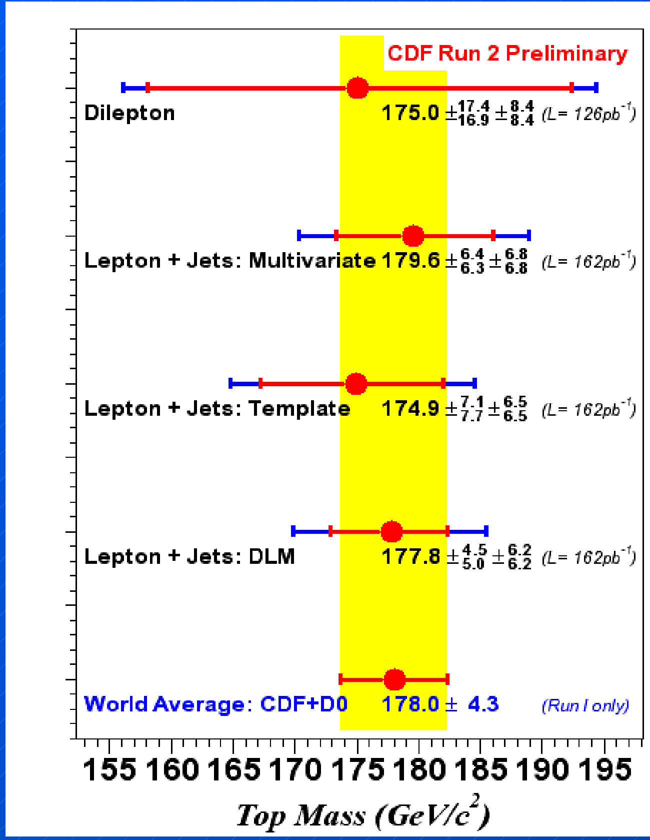


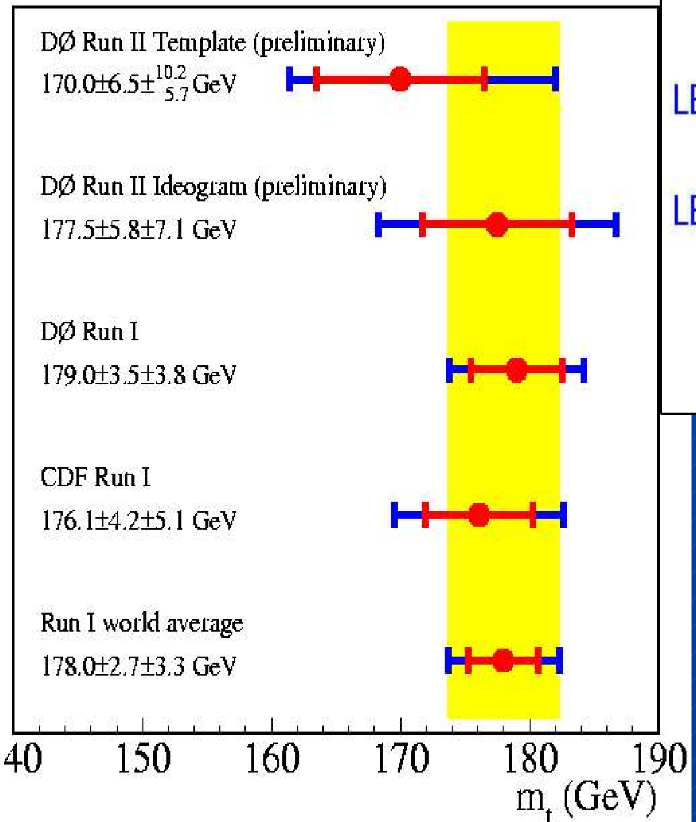
Top Mass Summary

new combined Run I result → m_t = 178.0 ± 4.3 GeV

(was m_t = 174.3 ± 5.1 GeV)







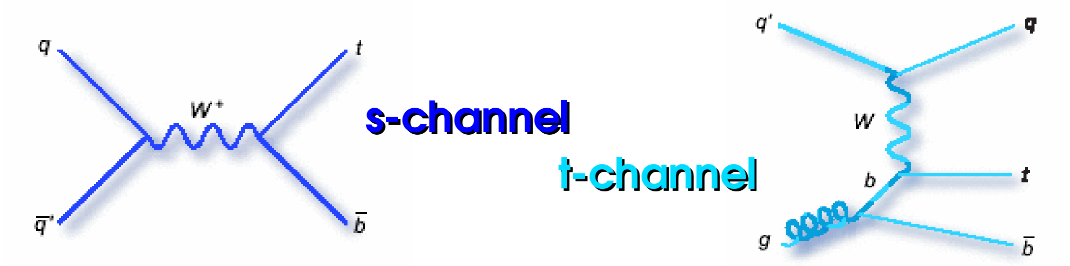
systematics limited:

- jet energy scale
- ttbar modeling
- W+jets modeling
- ...

TeV EWWG is working on combination of Run II m_t measurement from CDF and DØ

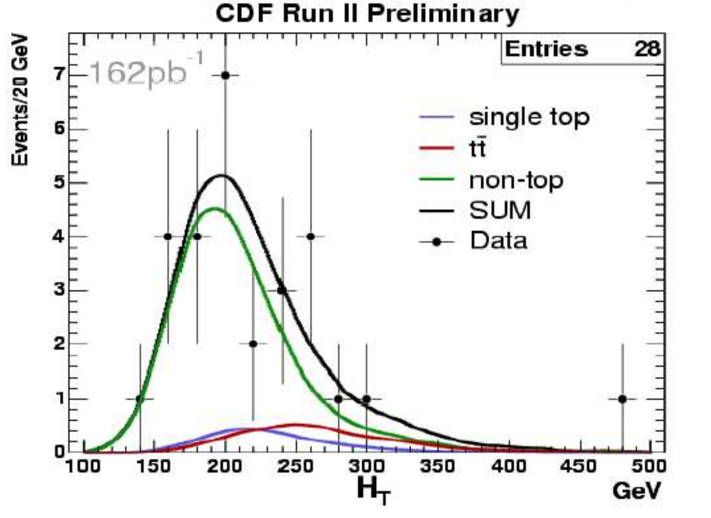
Search for Single Top Production

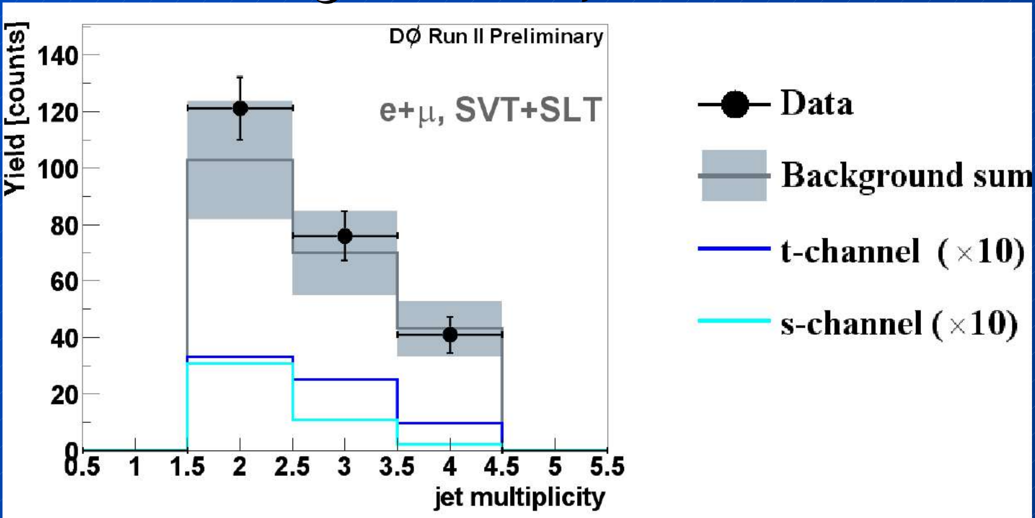
EW production of top quark
similar strength as strong production !!!
- direct probe of $|V_{tb}|$
- search for new physics
- topology similar to ttbar in l+jets,
  but lower jet multiplicity and more forward more background (W+jets, tt, dibosons, ...)



σ_s = 0.88 ± 0.07 pb

σ_t = 1.98 ± 0.21 pb





need ~ 1 fb^{-1}
for observation

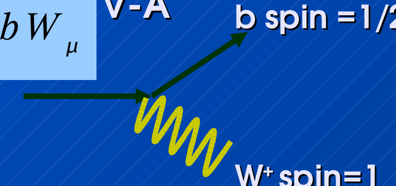
95% CL limits	CDF	DØ
σ(s-channel)	< 13.6 pb	< 19 pb
σ(t-channel)	< 10.1 pb	< 25 pb
σ(s+t channels)	< 17.8 pb	< 23 pb

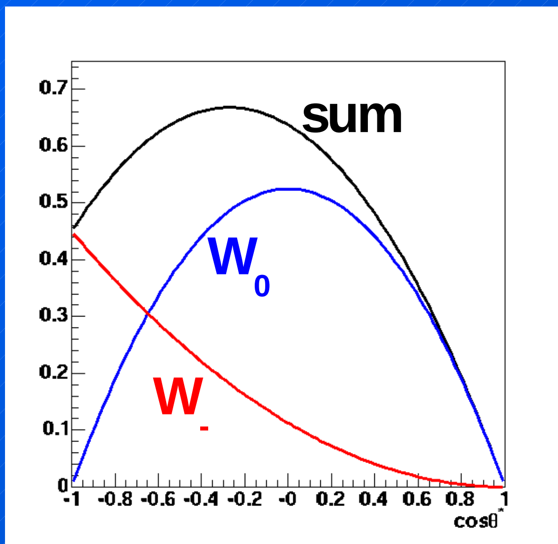
Helicity of the W in ttbar Events

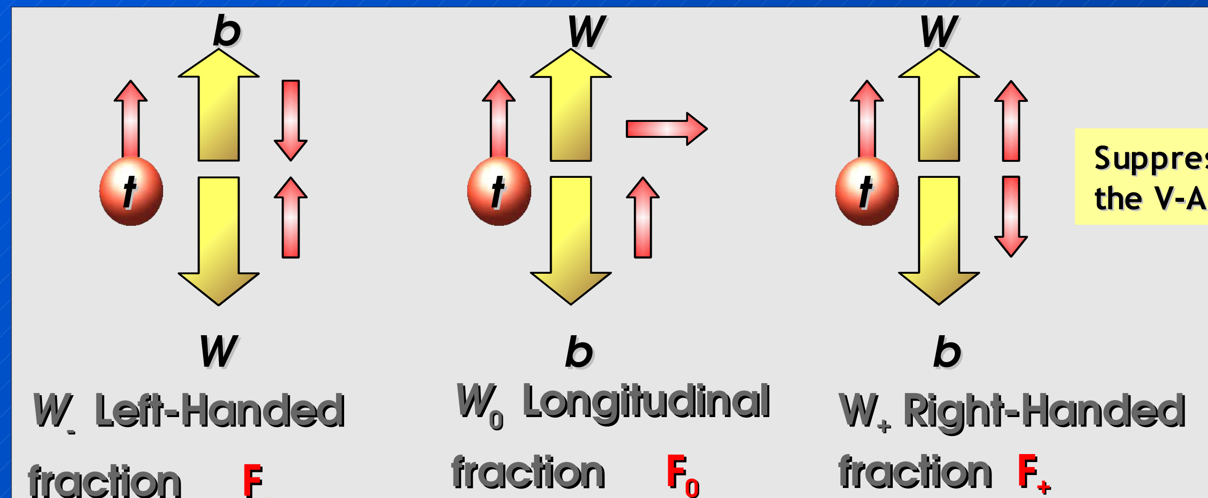
Top Standard Model weak decay →

V-A coupling as it is for all the other fermions

$$\frac{-ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}\left(1-\gamma^{5}\right)V_{tb}\,b\,W_{\mu}$$ V-A







$$w(\cos\phi_{l\bar{b}})=F_{-}\cdot\frac{3}{8}(1-\cos\phi_{l\bar{b}})^{2}+F_{0}\cdot\frac{3}{8}(1-\cos^{2}\phi_{l\bar{b}})+F_{+}\cdot\frac{3}{8}(1+\cos\phi_{l\bar{b}})^{2}$$

In SM (with m_b=0, M_{top} = 175 GeV and m_W = 80.4 GeV),

$$F_{-}=\frac{2\frac{m_W^2}{M_{top}^2}}{1+2\frac{m_W^2}{M_{top}^2}}\approx 0.30$$

$$F_{0}=\frac{1}{1+2\frac{m_W^2}{M_{top}^2}}\approx 0.70$$

$$F_{+}=0$$

Helicity of W manifests itself in decay product kinematics

Helicity of the W in ttbar Events (Run I)

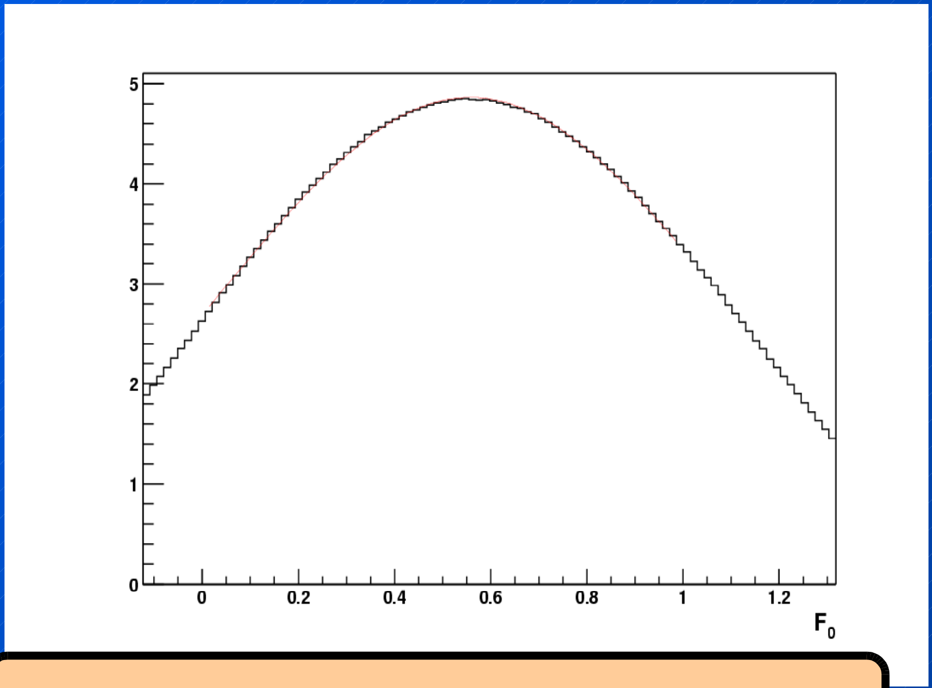
- Uncertainty on the top mass translates into a systematic error on the measurement of F_0

DØ Run I analysis using `Matrix Element' technique

$$L(F_0) = \int L(M_{top}, F_0)\, dM_t$$

- Integrate over M_{top} from 165 to 190 GeV
- Most probable value and 68.27% interval using M_{top}=175 GeV

- 22 events pass our cuts => from fit, 12 signal + 10 background events



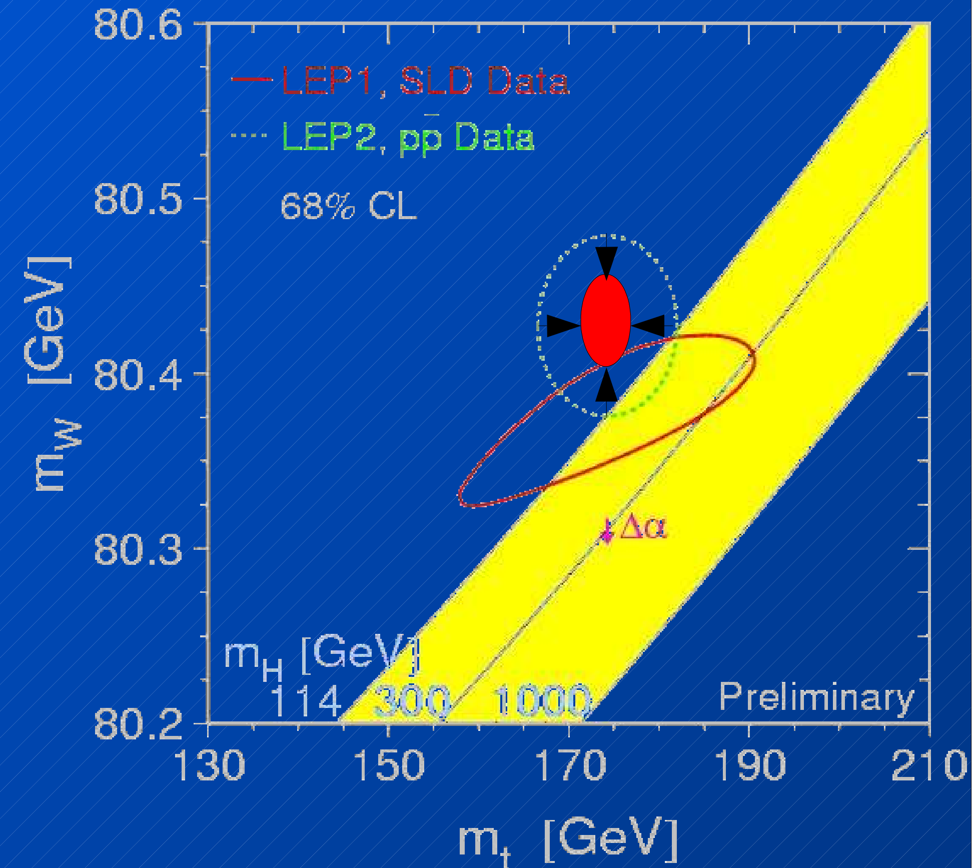
$F_0 \pm \delta F_0$(Stat+ M_{top}) = 0.558 ± 0.306

From data	Statistics + M_{top} uncertainty	0.306
From data	Jet Energy Scale	0.014
From data	Parton Distribution Function	0.007
From data	Acceptance-Linearity Corr.	0.021
From Monte Carlo	Background	0.010
From Monte Carlo	Signal Model	0.020
From Monte Carlo	Multiple Interactions	0.009
From Monte Carlo	ttbar Spin Correlations	0.008

Top Quark Outlook

further top properties measurements in preparation:

- top coupling
- anomalous kinematics
- rate of top decays to $\tau\nu b$ (charged Higgs)
- branching ratios
- top charge
- ...



CDF + DØ combined expected precision with 2 fb^{-1}
ATLAS/CMS separate with 10-30 fb^{-1}
(mass precision from total lumi)

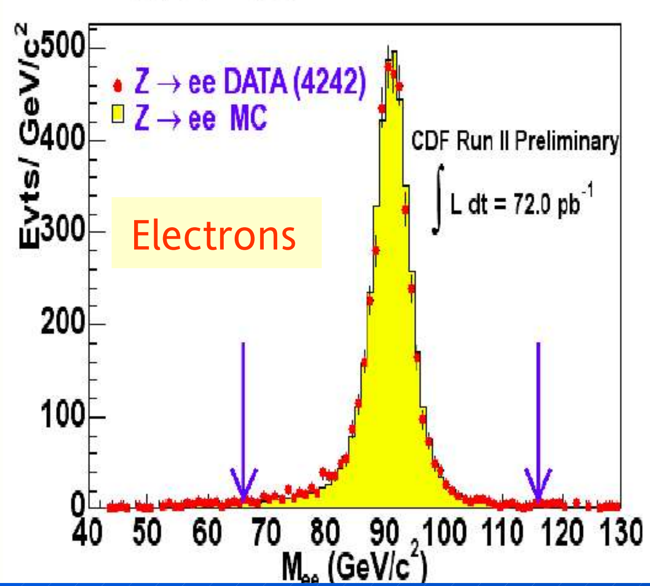
	CDF+DØ	ATLAS/CMS		CDF+DØ	ATLAS/CMS
W helicity F_0, F_+	0.09, 0.03	...	single top	20.00%	0.71%
$R_{2b/1b}$	4.50%	~0.2%	Γ_t from single top	25.00%	...
$\vert V_{tb}\vert$	from R	...	$\vert V_{tb}\vert$ from single top	12.00%	0.36%
$B(t \to \gamma q)$	$2 * 10^{-3}$	$1.0*10^{-4}$	$B(t \to Zq)$	0.02	$1.1*10^{-4}$
Δm_{top}	2 GeV	1-2 GeV	Higgs	discovery ?	discovery !
Δm_W	20 MeV	20 MeV	Yukawa Coupl. y_t	---	12-16%

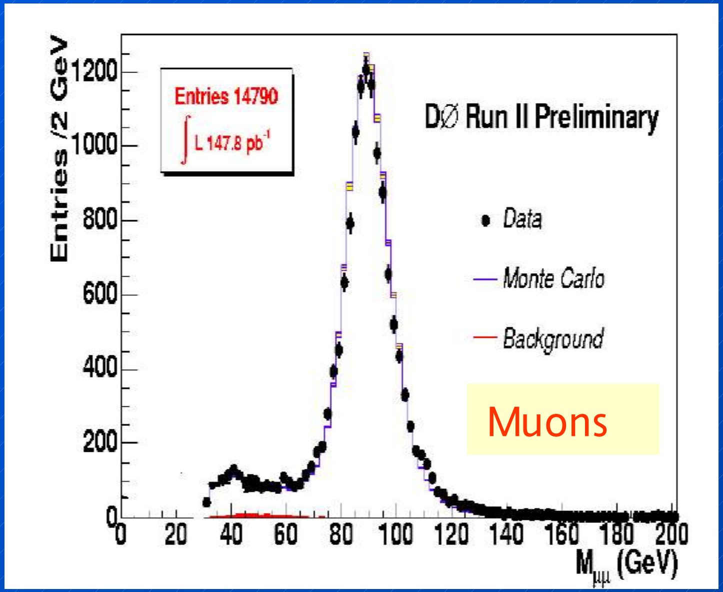
Summary - Part II

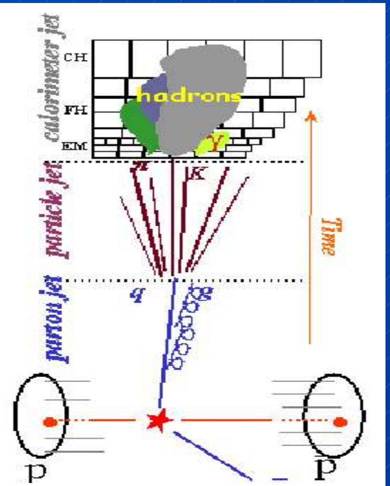
- Electroweak Physics
- Top Physics

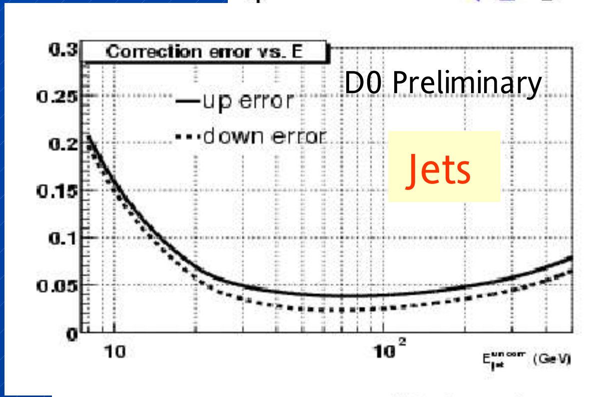
Backup Slides

Detection of High p_T Objects





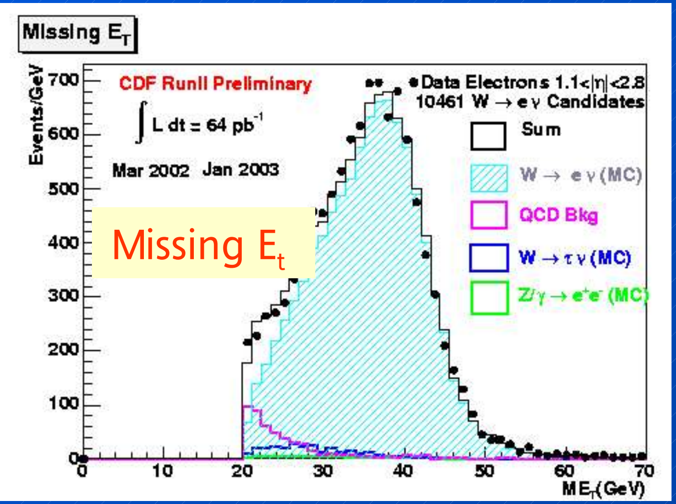


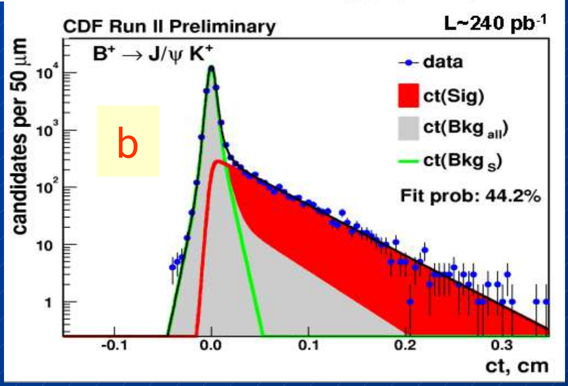


W, Z, Top and Higgs
final decay products

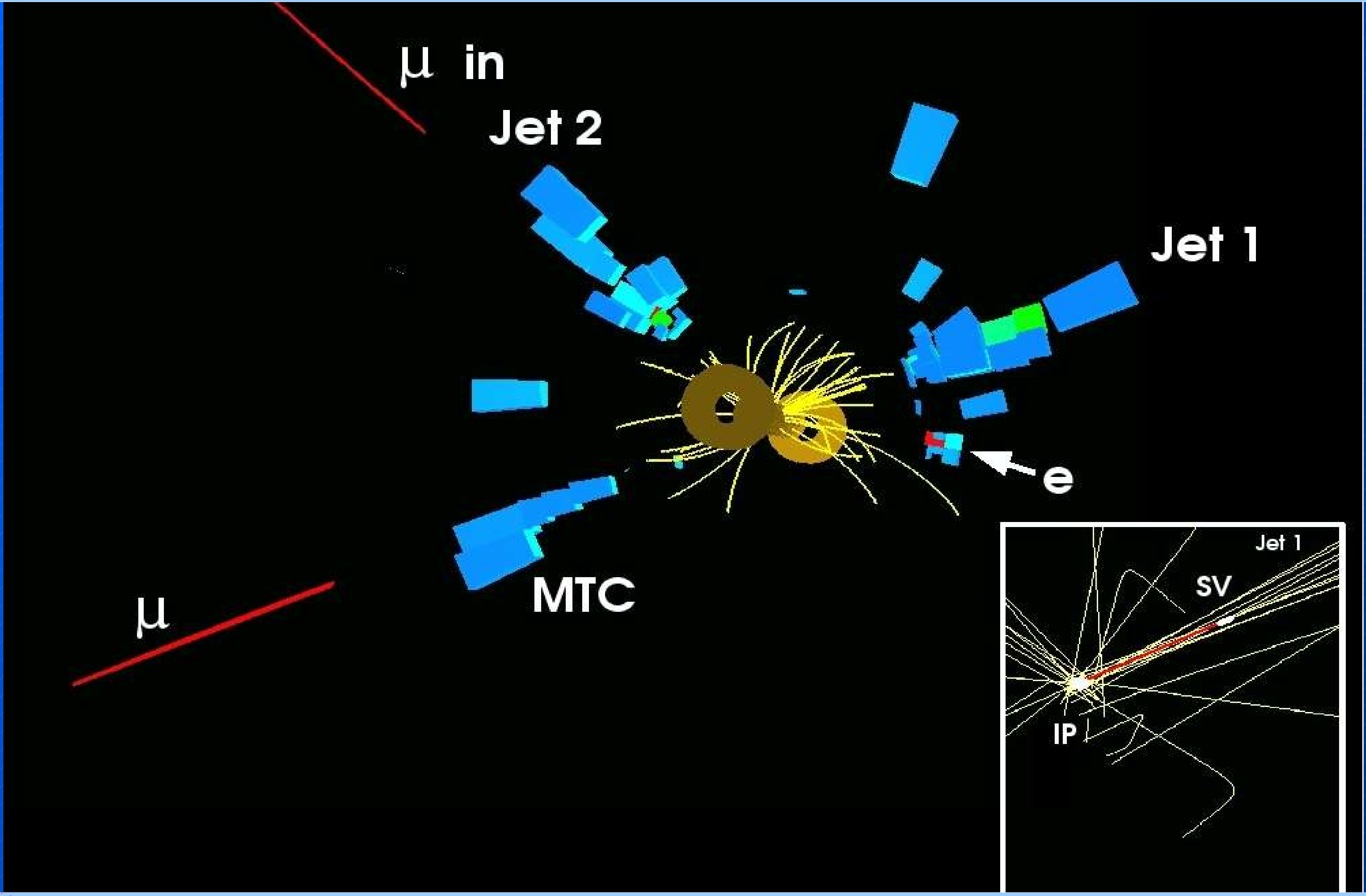
electrons
muons
jets (b)
Missing E_t (ν)

Detection and MC
optimization using well
known objects



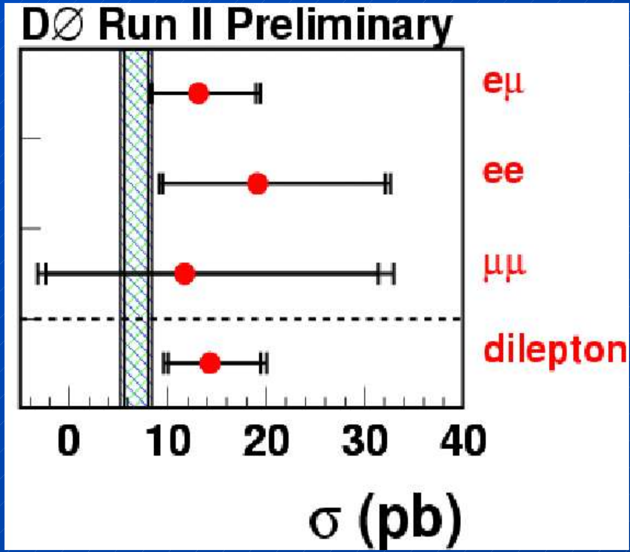


An Example eμ-Event



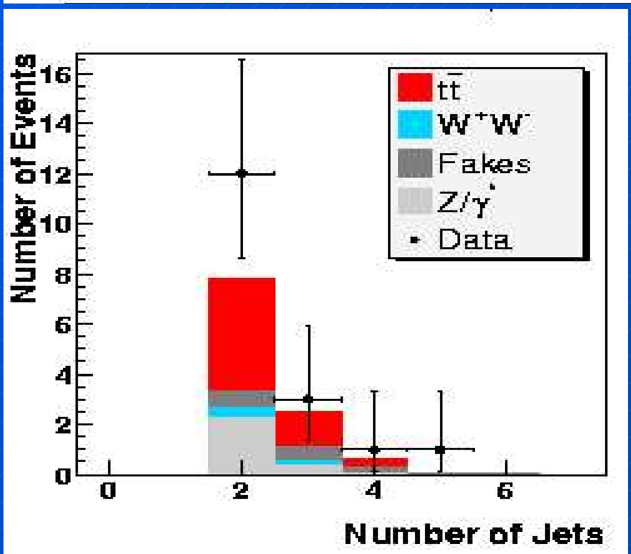
DØ Top Cross Sections in Di-Leptons

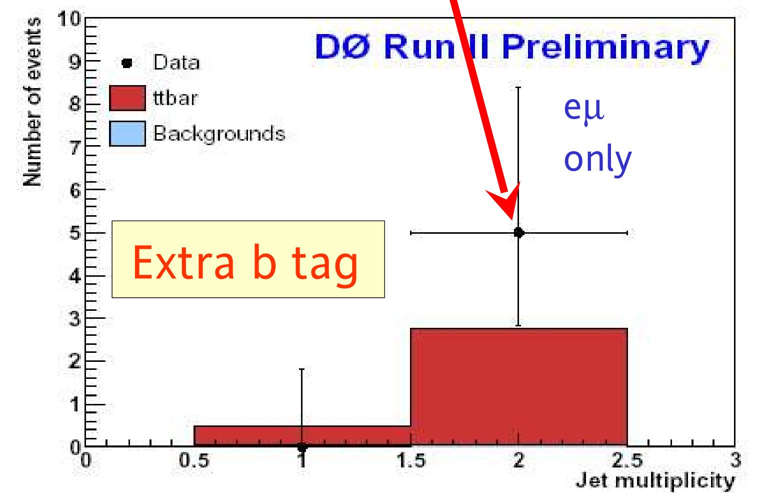
Golden mode signature (topological selection)
-> isolated (not in jet) high P_t ee(156 pb^{-1}),
$\mu\mu$(140 pb^{-1}), eμ (143 pb^{-1}) pair
-> 2 or more jets
-> Missing E_t
Backgrounds: WW, Z+jets, W+jets, QCD jets, fakes



Category	ee	$\mu\mu$	$e\mu$	$\ell\ell$
Z/γ^*	0.15 ± 0.10	2.04 ± 0.49	0.47 ± 0.17	2.66 ± 0.53
WW	0.14 ± 0.08	0.10 ± 0.04	0.29 ± 0.06	0.53 ± 0.11
Fakes	0.91 ± 0.30	0.46 ± 0.20	0.19 ± 0.06	1.56 ± 0.36
Total background	1.20 ± 0.33	2.61 ± 0.53	0.95 ± 0.19	4.76 ± 0.65
Expected signal	1.39 ± 0.19	0.83 ± 0.15	3.77 ± 0.44	5.99 ± 0.50
SM expectation	2.59 ± 0.38	3.44 ± 0.55	4.73 ± 0.49	10.76 ± 0.83
Selected events	5	4	8	17

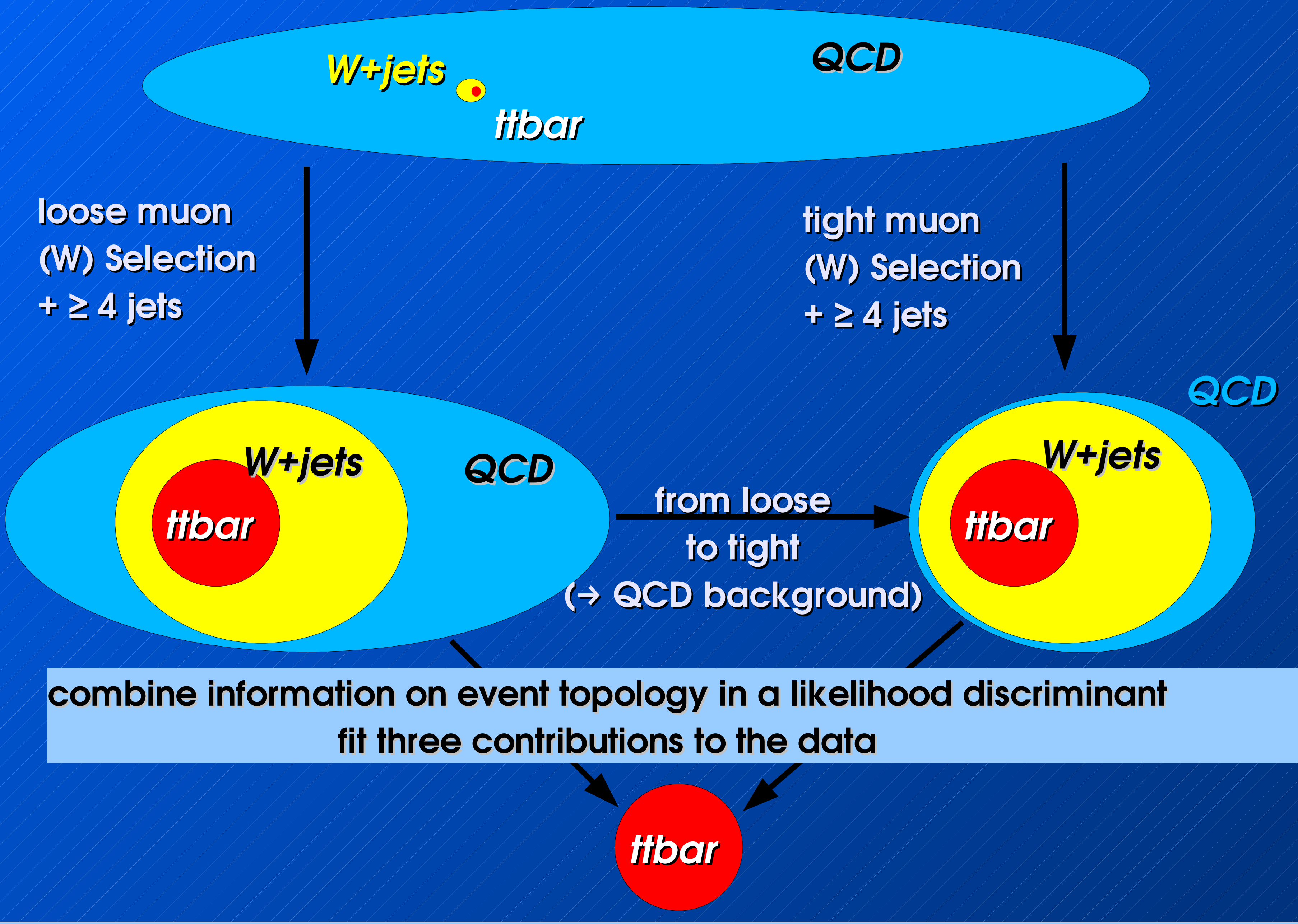
Ultra-pure sample of top events





$$\sigma_{t\bar{t}} = 11.1^{+5.8}_{-4.3}\ (\mathrm{stat}) \pm 1.4\ (\mathrm{syst}) \pm 0.7\ (\mathrm{lumi})\ \mathrm{pb}.$$

Overview over µ+Jets Analysis



Determination of Multijet Background

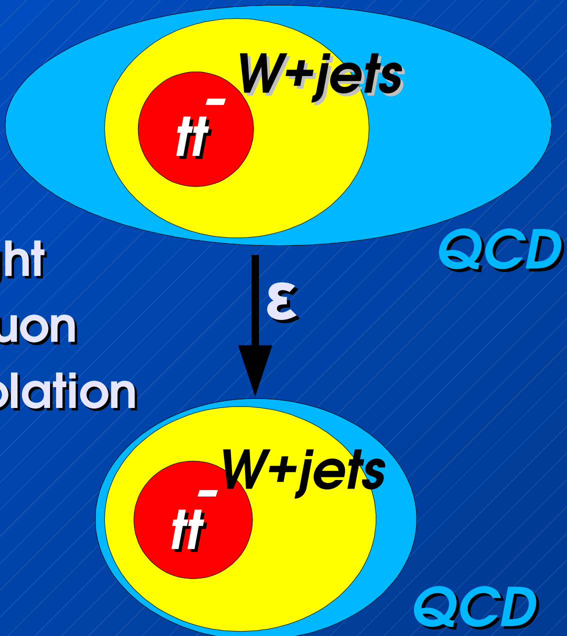
μ+jets

$$N_{loose} = N_{QCD} + N_{W+ttbar}$$

↓ ε ${}_{QCD} = 8\%$ ↓ ${}_{W+ttbar} = 82\%$ ↓

$$N_{tight} = {}_{QCD} * N_{QCD} + {}_{W+ttbar} * N_{W+ttbar}$$

tight muon isolation



- N_{loose} und N_{tight}: Signal-Datensatz
- ${}_{QCD}$: independent multijet (QCD) data set (met < 10 GeV)
- ${}_{W+ttbar}$: W+Jets Monte Carlo simulation (Monte Carlo to Data calibration from Z+Jets events)

→ solve equations for N_{QCD} and $N_{W+ttbar}$

→ determine multijet (QCD) background entirely from data

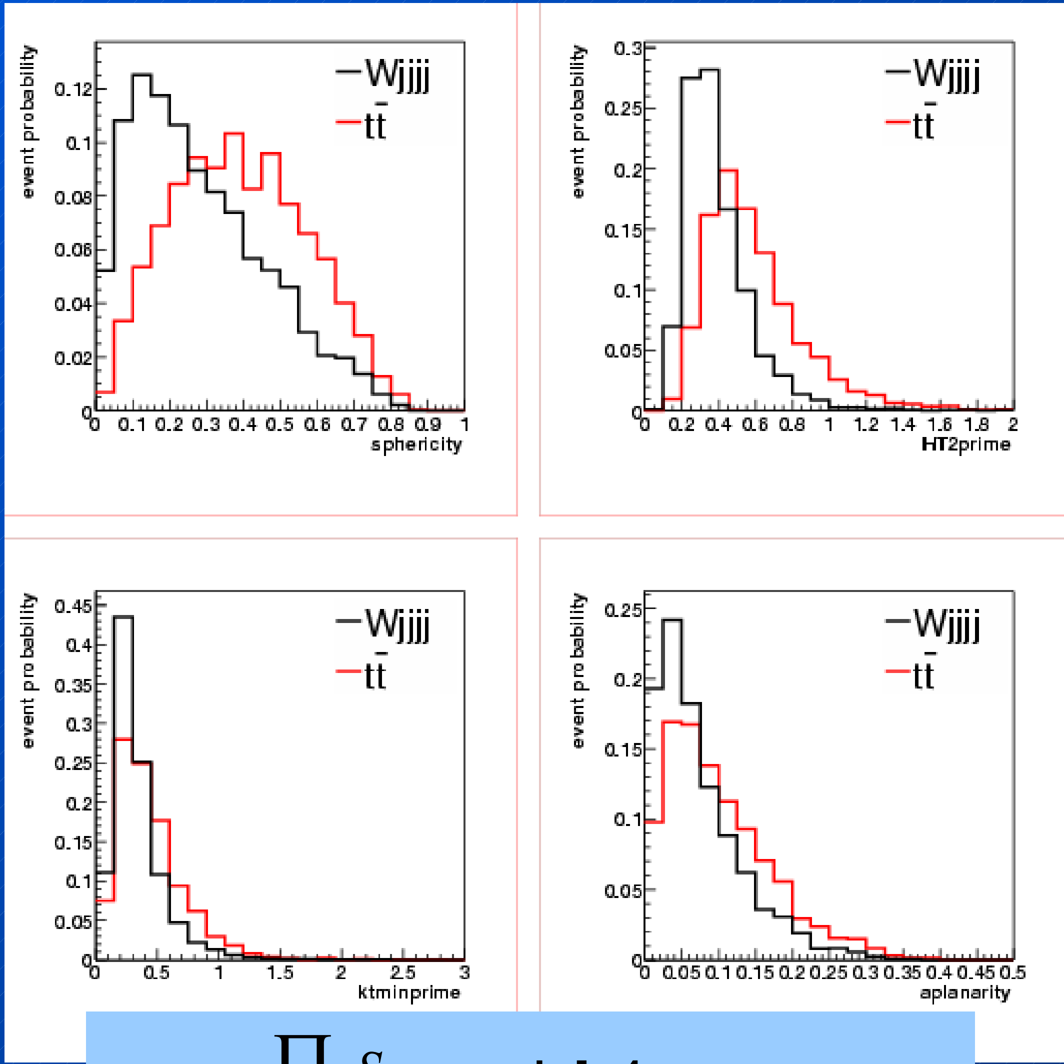
Topological Event Likelihood

choose topological variables:
- with **strong separation** potential
- with **small sensitivity to jet energy scale**

use the following variables:

angular dependent:
- sphericity
- aplanarity

ratio of energy-dependent quantities:
- HT2prime
- ktminprime



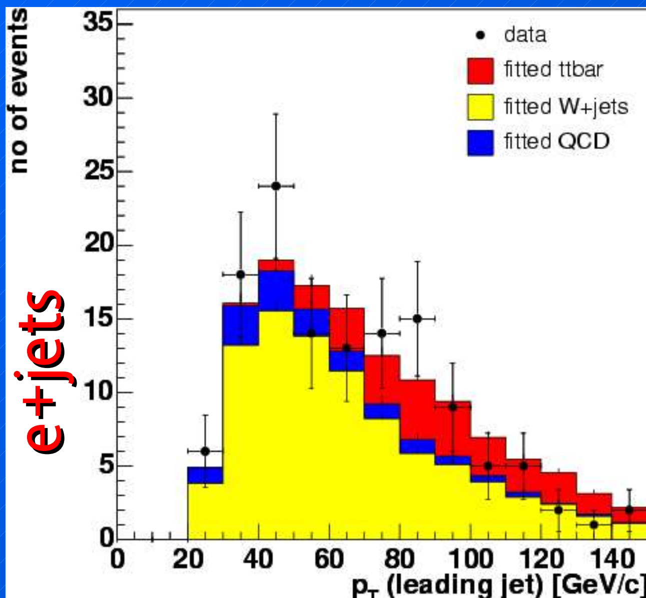
topological likelihood:

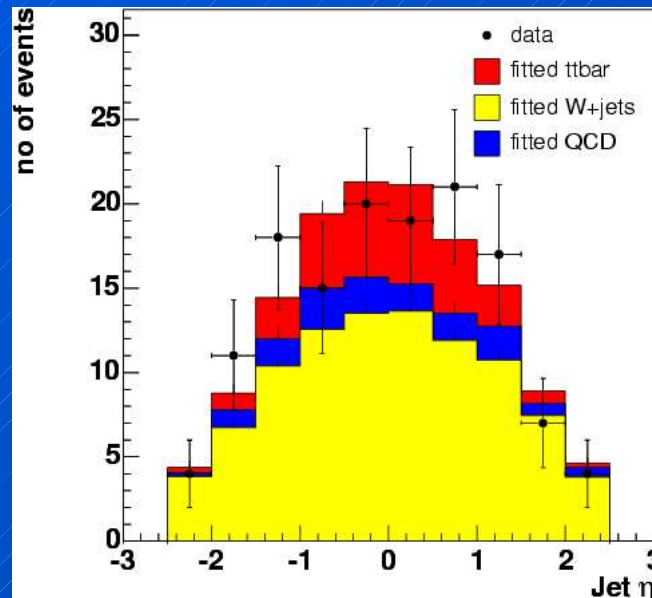
$$P = \frac{\prod_i S_i}{\prod_i S_i + \prod_i B_i}$$

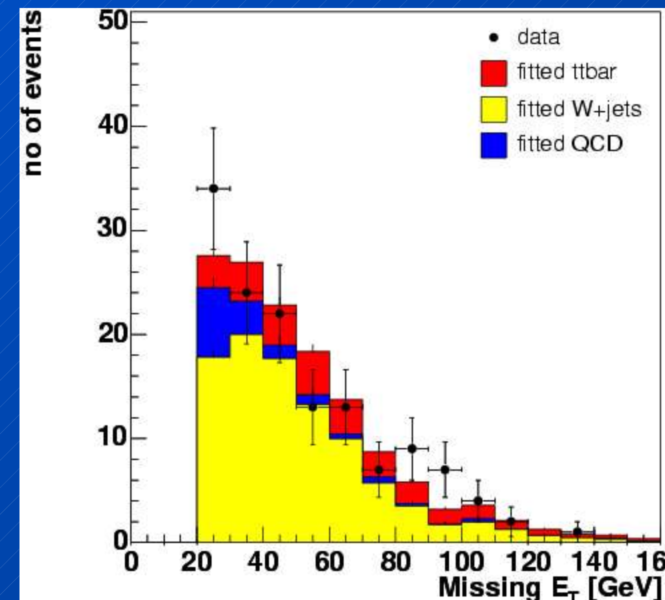
i=1..4,
S = tt̄-distribution,
B = Wjjjj-distribution

Kinematic Distributions in l+jets Channel

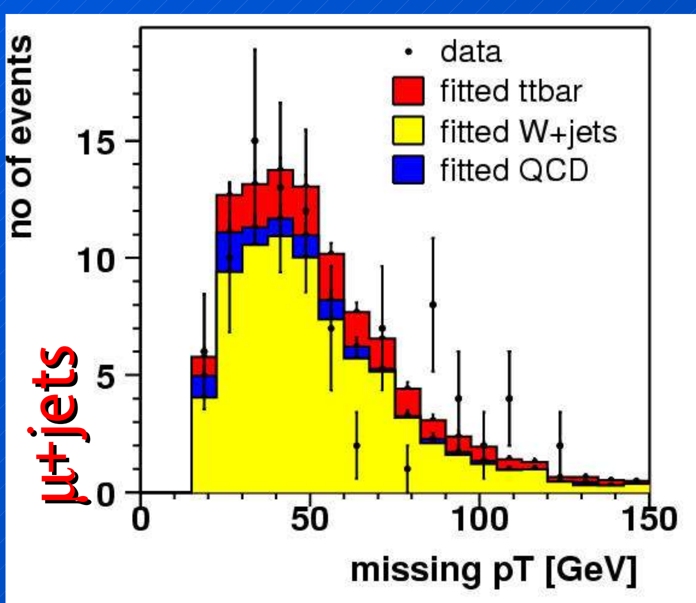
e+jets

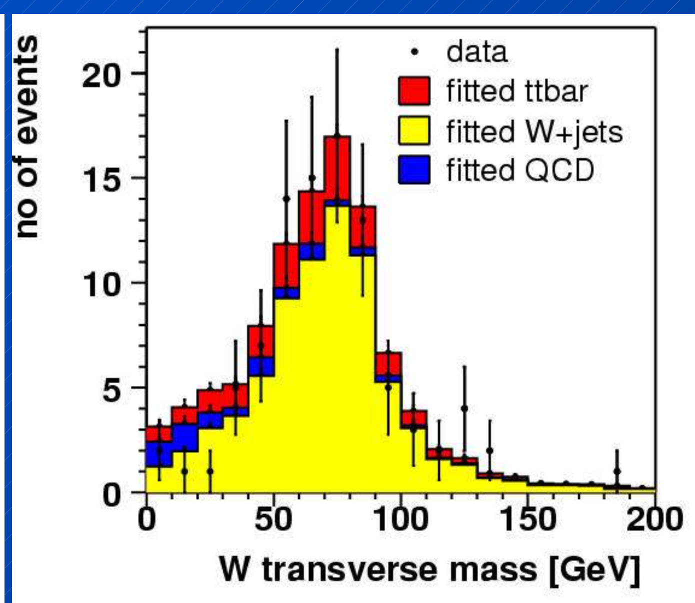


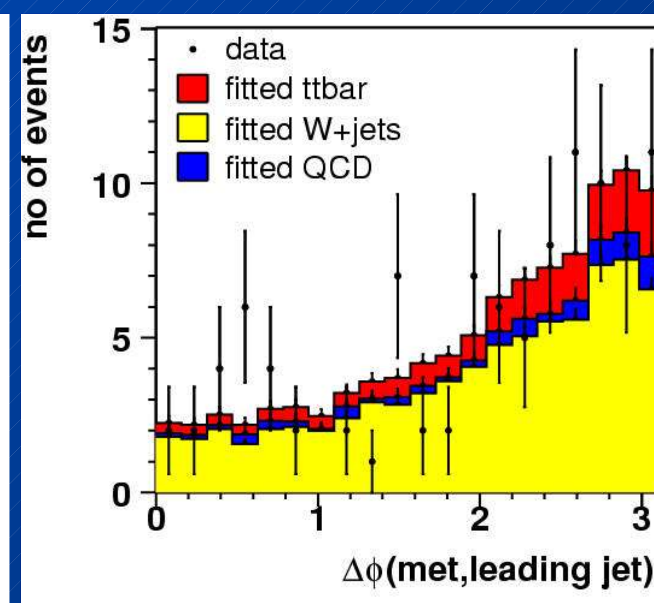




μ+jets







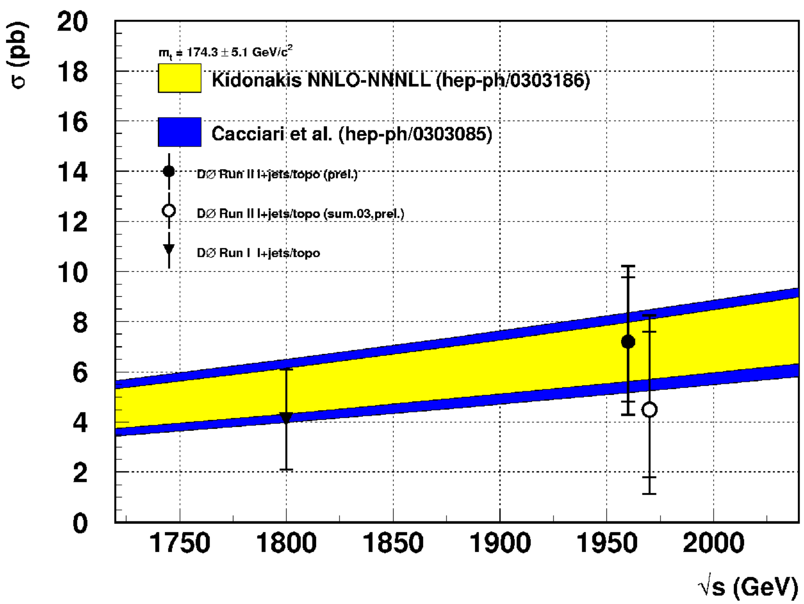
Ttbar Cross Section in l+Jets

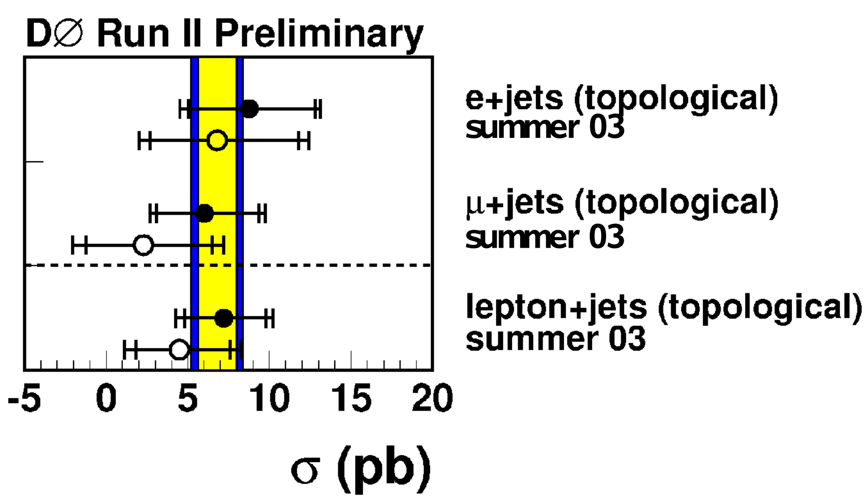
combined ttbar cross section from e+jets, μ+jets:

$$\text{e} + \text{jets (CC)} \; : \quad \sigma_{p\bar{p}\rightarrow t\bar{t}+X} = 8.8^{+4.1}_{-3.7}\,(\text{stat})\,^{+1.6}_{-2.1}\,(\text{syst}) \pm 0.6\,(\text{lumi})\,\text{pb}$$

$$\mu + \text{jets} \; : \quad \sigma_{p\bar{p}\rightarrow t\bar{t}+X} = 6.0^{+3.4}_{-3.0}\,(\text{stat})\,^{+1.6}_{-1.6}\,(\text{syst}) \pm 0.4\,(\text{lumi})\,\text{pb}$$

$$\text{l} + \text{jets} \; : \quad \sigma_{p\bar{p}\rightarrow t\bar{t}+X} = 7.2^{+2.6}_{-2.4}\,(\text{stat})\,^{+1.6}_{-1.7}\,(\text{syst}) \pm 0.5\,(\text{lumi})\,\text{pb}$$





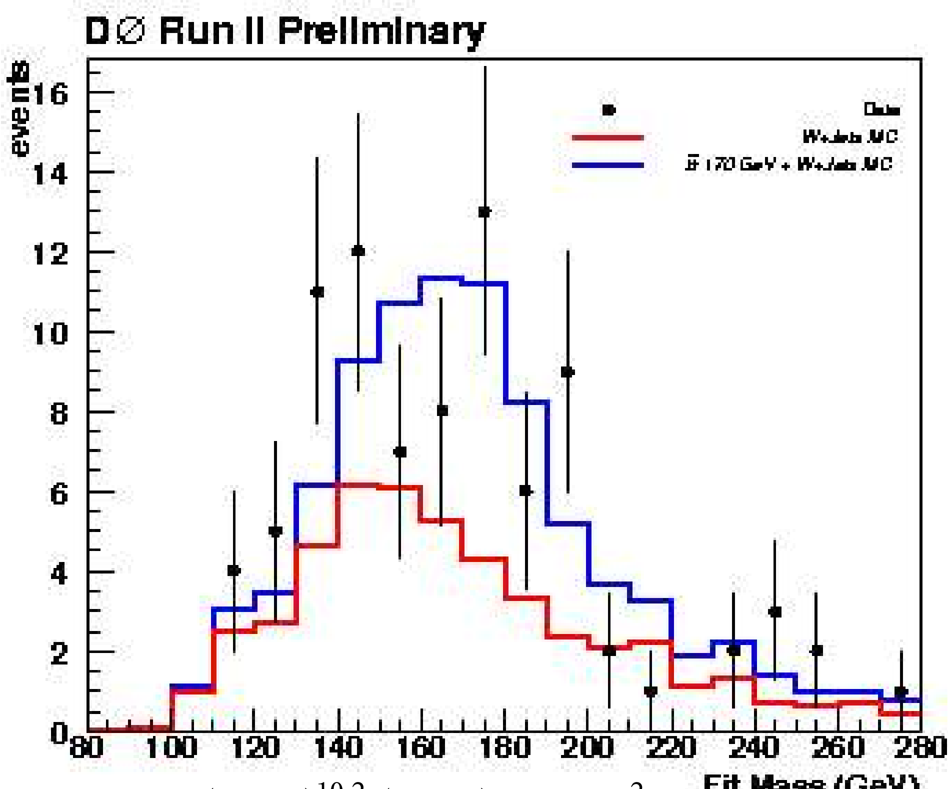
Run II Top Mass Measurement in DØ

Measurements in l+jets channel (~150 pb^{-1})

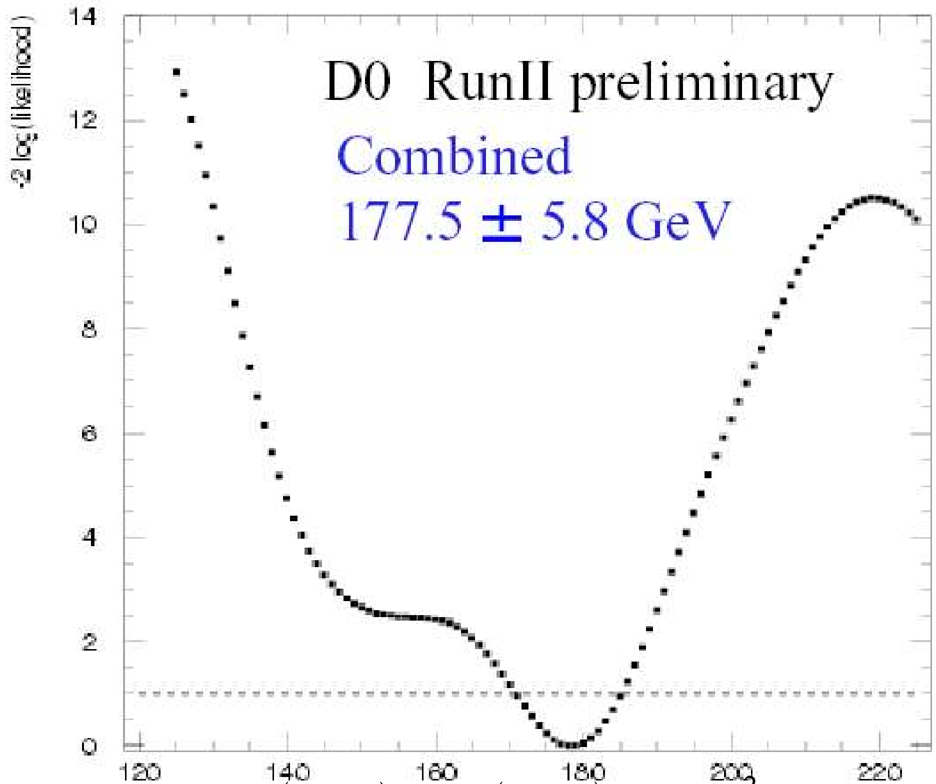
- template method uses templates for signal and background mass spectra
- ideogram method uses analytical likelihood for event to be signal or background for each event

Template

Ideogram



$m_t = 170 \pm 6.5(stat.)^{10.2}_{-5.7}(syst.)\, GeV/c^2$



$m_t = 177.5 \pm 5.8(stat.) \pm 7.1(syst.)\, GeV/c^2$

Unexpected Top Decay Modes ?

Assuming three generation CKM unitarity, $|V_{tb}|=0.999$ — $b=BR(t \to Wb)$

$\Rightarrow R = BR(t \to Wb) / BR(t \to Wq) > 0.998$

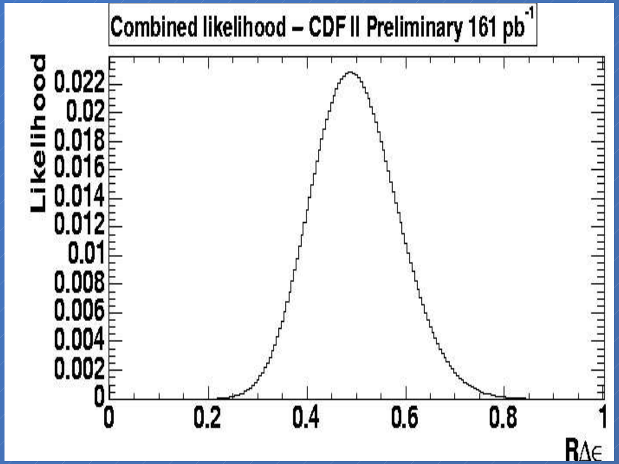
Can measure ratio by checking the b-quark content of the top sample decay if efficiency to tag a b-quark is ε_b (~0.45 at CDF), then

$\varepsilon_2=(b\,\varepsilon_b)^2$ "double tagged"

$\varepsilon_1=2b\,\varepsilon_b(1 - b\,\varepsilon_b)$ "single tagged"

$\varepsilon_0=(1 - b\,\varepsilon_b)^2$ "un-tagged"

$BR(t \to Wb) / BR(t \to Wq) > 0.62$ @ 95% CL



Does top decay into something else than Wb ?

like Xb, where $X \to qq$ (100%) or Yb, where $Y \to l\nu$ (100%) ?

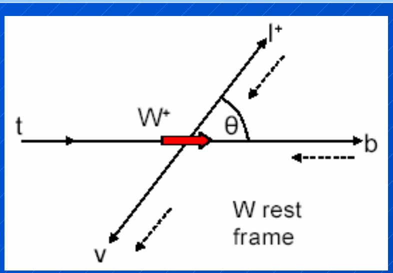
estimate using ratio of top cross section $\sigma_{ll} / \sigma_{ljets}$

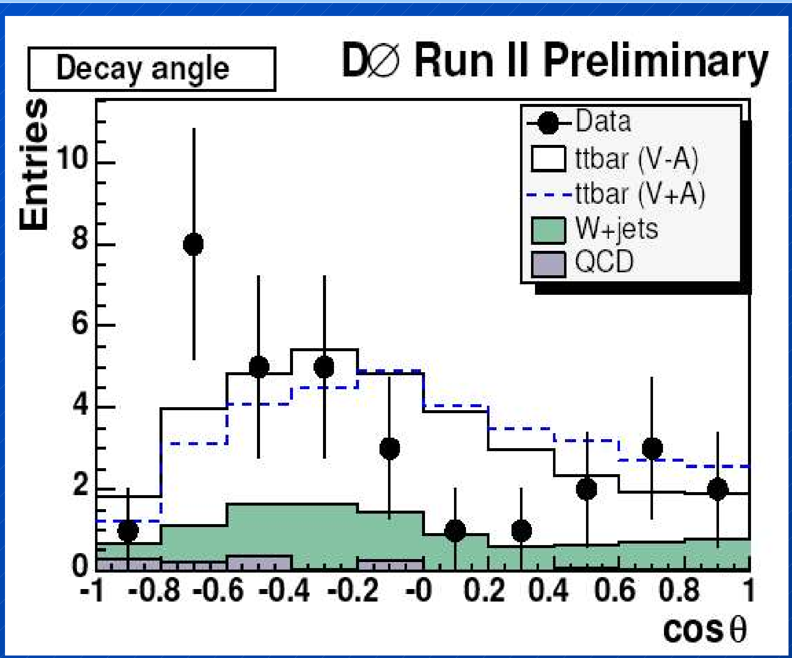
BR(t Xb) < 0.46 @ 95% CL

BR(t Yq) < 0.47 @ 95% CL

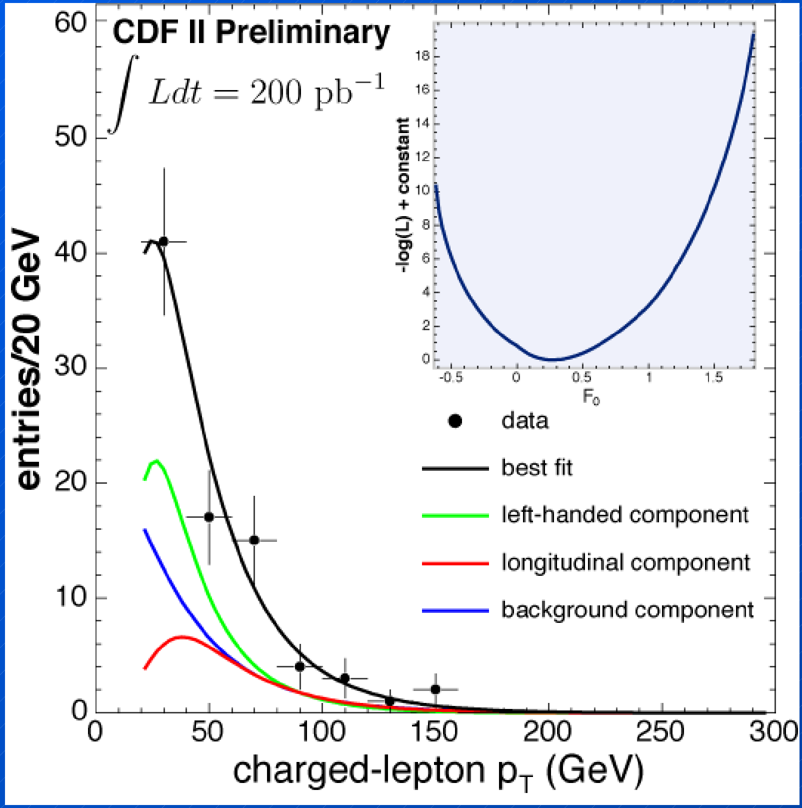
Helicity of the W in ttbar Events (Run II)

- DØ (l+jets, 160 pb-1)
- b-tag or topol. selection
- kinematic ttbar fit → boost into W rest frame
- decay angle distribution





$F_+ < 0.24$ @ 90% CL



- CDF (l+jetsand dilepton, 200 pb^{-1})
- charged lepton p_T in lab. frame

$F_0 = 0.27^{+0.35}_{-0.24}$

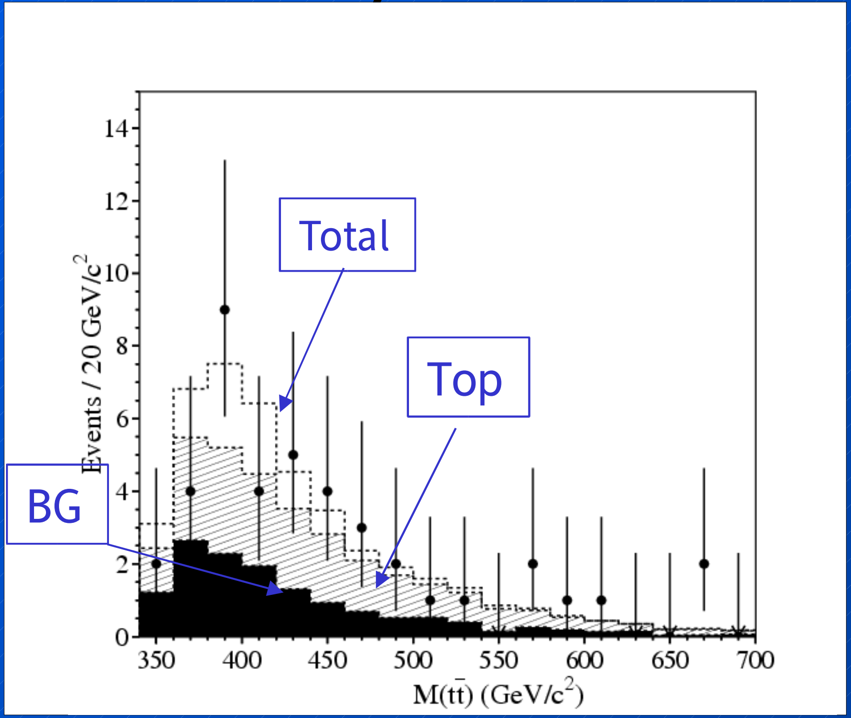
... no deviations from SM predictions
eventually simultaneous fit for F_0 and F_+ ...

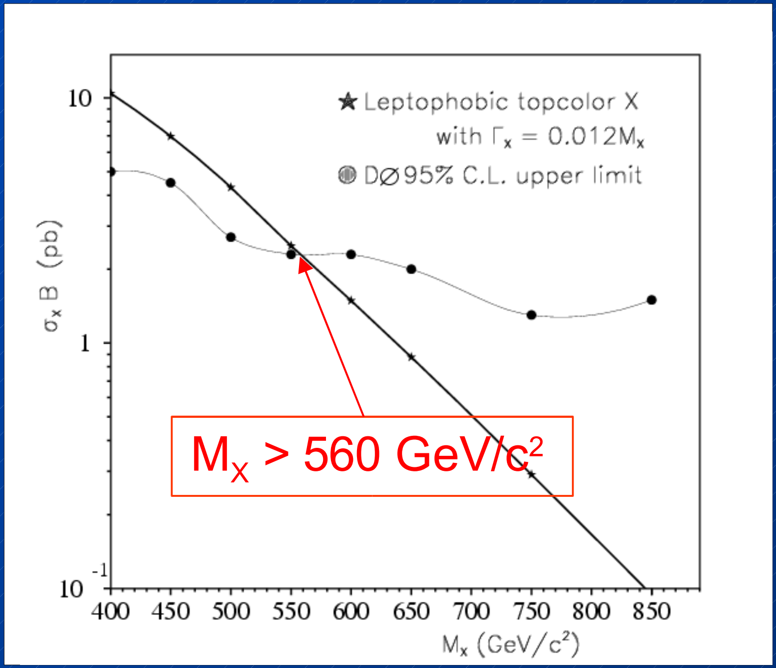
Resonances in tt System ?

No resonance production in tt system is expected in SM (cc, bb, ...)
some models predict particles which decay into ttbar
example: topcolour-assisted technicolour
⇒ predicts leptophobic Z' with strong 3rd-generation coupling

experiment: search for bumps/peaks in ttbar effective mass spectrum

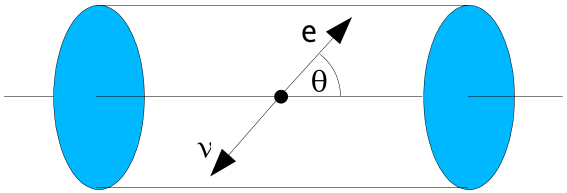
DØ Run I analysis





Transverse W-Mass

in the W rest frame:



$$p^{e,\nu}=\frac{m_W}{2} \quad \text{and} \quad p_T^{e,\nu}=\frac{m_W}{2}\cdot\sin\Theta \Rightarrow \frac{m_W}{2}\cdot\sqrt{1-\cos^2\Theta}=p_T \Rightarrow \cos\Theta=\underbrace{\sqrt{1-\frac{4p_T^2}{m_W^2}}}$$

$$\frac{\partial\cos\Theta}{\partial p_T}=\frac{1}{2\sqrt{1-\frac{4p_T^2}{m_W^2}}}\cdot\frac{8p_T}{m_w^2}$$

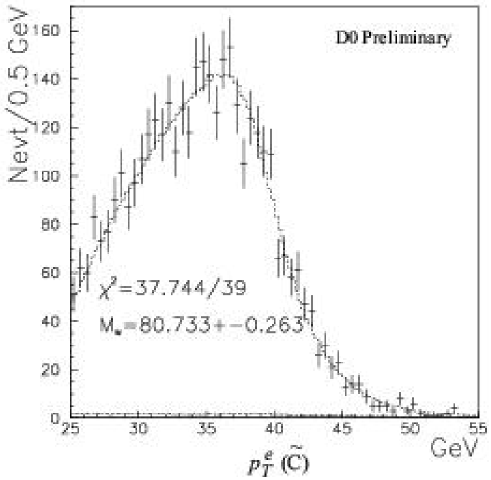
... and hence ...

"Jacobian"

$$\frac{d\sigma}{dp_T^e}=\frac{\partial\sigma}{\partial\cos\Theta}\cdot\frac{\partial\cos\Theta}{\partial p_T}$$

$$\frac{d\sigma}{dp_T^e}=\frac{\partial\sigma}{\partial\cos\Theta}\cdot\frac{2p_T}{m_w\cdot\sqrt{\left(\frac{m_w}{2}\right)^2-p_T^2}}$$

$p_T^e\le\frac{m_W}{2}$ and $\frac{d\sigma}{dp_T^e}$ **maximal for** $p_T^e=\frac{m_W}{2}$!



Transverse W-Mass

transverse mass analogous to invariant mass, except that only components transverse to the beamline are used:

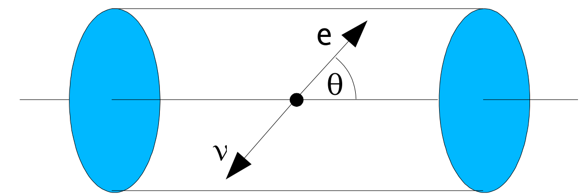
$$m_T^2 = (E_T^e + E_T^\nu)^2 - (\vec{p}_T^{\,e} + \vec{p}_T^{\,\nu})^2$$

$$= \underbrace{E_T^{e\,2} - \vec{p}_T^{\,e\,2}}_{m_e^2 \cdot \sin^2\Theta} + \underbrace{E_T^{\nu\,2} - \vec{p}_T^{\,\nu\,2}}_{m_\nu^2 \cdot \sin^2\Theta} + 2\,E_T^e E_T^\nu - 2\,\vec{p}_T^{\,e}\,\vec{p}_T^{\,\nu}$$

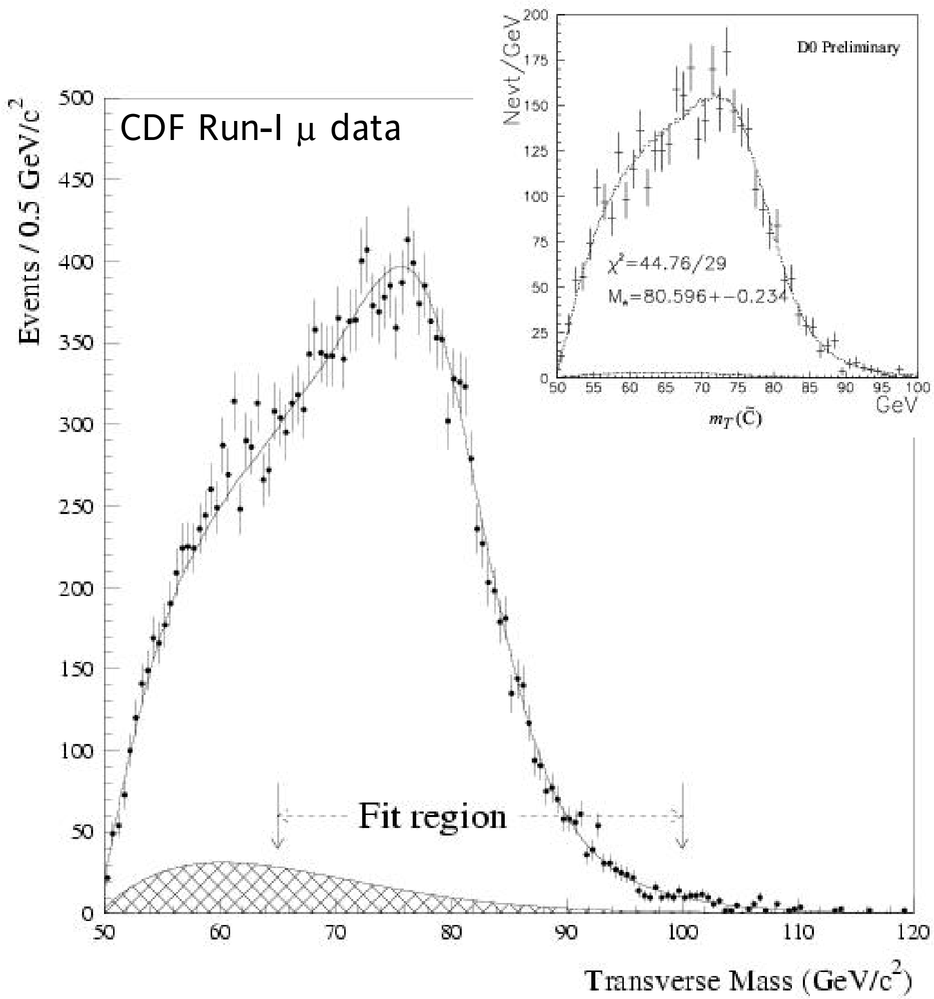
$$= 2\,E_T^e E_T^\nu \left(1 - \cos\phi^{e,\nu}\right)$$

$$m_T \le \sqrt{4\,E_T^e E_T^\nu} = 2\,E_T^e \le m_W$$

$$maximal\ for\ \phi = 180^\circ \wedge \Theta = 90^\circ$$

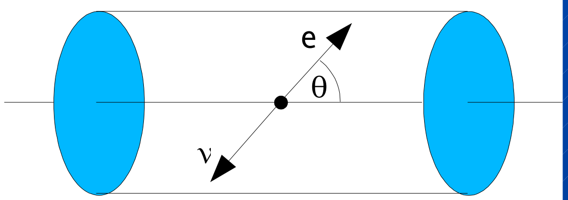


D0 Run-I electron data



Transverse W-Mass

... what if the W has got a transverse boost ?



$$\begin{pmatrix} E_T \\ p_T \end{pmatrix}_{Lab.} = \begin{pmatrix} \gamma & \beta\gamma \\ \beta\gamma & \gamma \end{pmatrix} \begin{pmatrix} E_T \\ p_T \end{pmatrix}_{rest\ frame}$$

$$\left.\begin{aligned} E_{T,L} &= \gamma E_{T,R} + \beta\gamma p_{T,R} \\ p_{T,L} &= \beta\gamma E_{T,R} + \gamma p_{T,R} \end{aligned}\right\} \Rightarrow$$

$$M^2_{T,L} = E^2_{T,L} - p^2_{T,L} = \gamma^2 E^2_{T,R} + \beta^2\gamma^2 p^2_{T,R} + 2\beta\gamma^2 E_{T,R} p_{T,R} - \beta^2\gamma^2 E^2_{T,R} - \gamma^2 p^2_{T,R} - 2\beta\gamma^2 E_{T,R} p_{T,R}$$

$$= E^2_{T,R} - p^2_{T,R} = M^2_{T,R}$$

$\gamma^2 = \frac{1}{1-\beta^2}$

1.) m_T is invariant under transverse boosts

2.) m_T=m if p_z=0, also in W rest frame

3.) m_T not invariant under longitudinal boosts, but still:

$$\frac{d\sigma}{d m_T} \text{ is maximal for } m_T = m$$

$$m_T \leq m$$

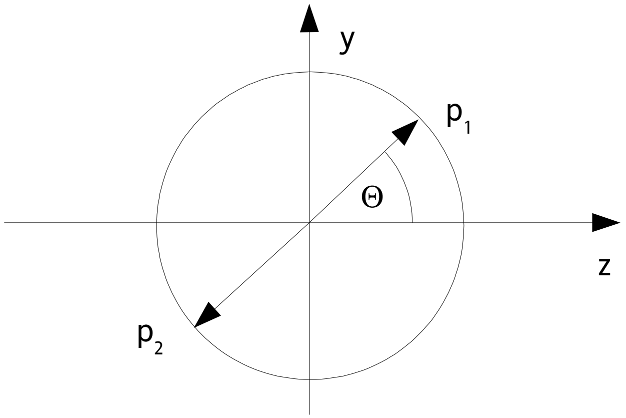
W-Decay Angular Distribution (1)

Consider a particle at rest in the state $|J; J_3>$ which decays into two particles.

The transition amplitude is given by

$$T_{fi} = \langle |\vec{p}|, \Theta, \Phi, \lambda_1, \lambda_2 | T | m, J, J_3 \rangle$$

momentum of decay products; decay angles; helicities of decay particles; decay amplitude; particle mass; total spin; 3-component of spin



In general (angular momentum in Quantum Mechanics):

$$\left| |\vec{p}|, \Theta, \Phi, \lambda_1, \lambda_2 \right\rangle = \sum_{J, J_3} \sqrt{\frac{2J+1}{4\pi}} D^J_{J_3,\lambda}(\phi, \Theta, -\phi) \underbrace{\left| \sqrt{s}, J, |\vec{p}|, J_3, \lambda_1, \lambda_2 \right\rangle}$$

basis of helicity states which are simultaneously eigenstates of angular momentum

here (neglect J, p, m since constants) (angular momentum conservation)

$$T_{fi} = \sqrt{\frac{2J+1}{4\pi}} D^J_{J_3,\lambda}(\phi, \Theta, -\phi) \underbrace{\langle J_3, \lambda_1, \lambda_2 | T | J_3 \rangle}$$

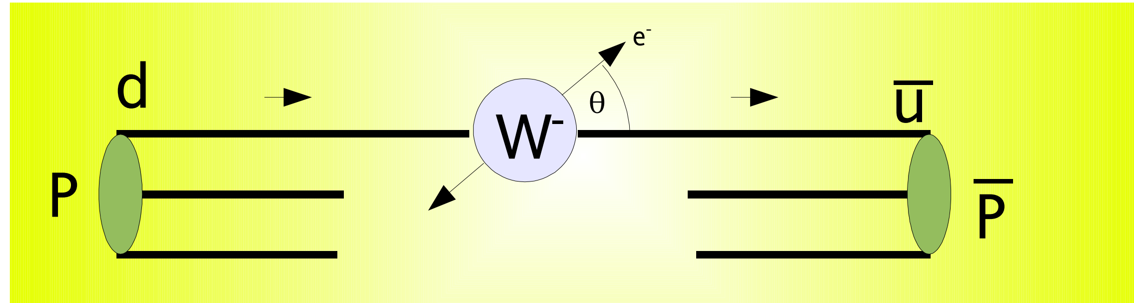
independent of J_3 due to rotational invariance → call it $t_{\lambda_1 \lambda_2}$

since polarisation of outgoing particles not observed sum over them:

$$\frac{d\Gamma}{d\Omega} \sim \sum_{\lambda_1, \lambda_2} \left[d^J_{J_3,\lambda}(\Theta) \right]^2 |t_{\lambda_1, \lambda_2}|^2$$

W-Decay Angular Distribution (2)

Special case: J=1, J_3=1



$$\frac{d\Gamma}{d\Omega} \sim (d^1_{1,1})^2 |t_{\frac{1}{2},-\frac{1}{2}}|^2 + (d^1_{1,-1})^2 |t_{-\frac{1}{2},\frac{1}{2}}|^2 + (d^1_{1,0})^2 (|t_{\frac{1}{2},\frac{1}{2}}|^2 + |t_{-\frac{1}{2},-\frac{1}{2}}|^2)^2$$

suppressed at small fermion masses

$W^- \rightarrow e^- \bar{\nu}_e$

only left-handed (-1/2)

$$d^1_{1,1} = \frac{1+\cos\Theta}{2}$$ (see PDG)

$$\frac{d\Gamma}{d\Omega} \sim (1+\cos\Theta)^2$$

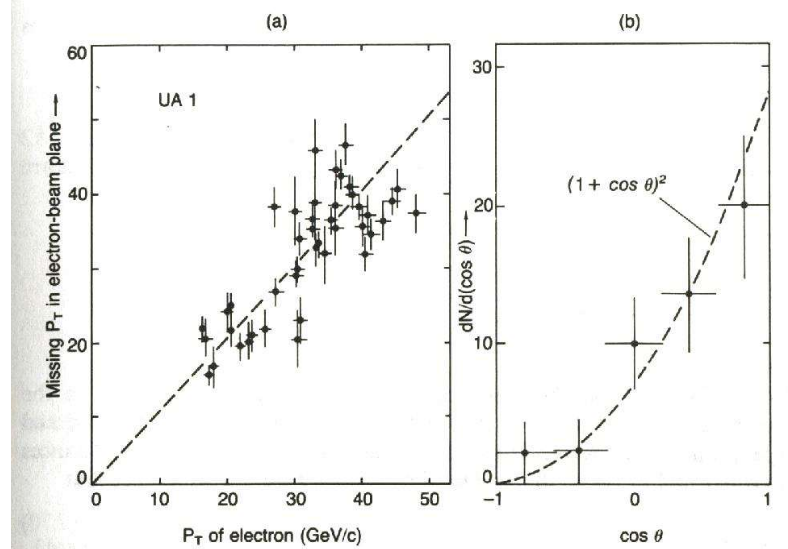
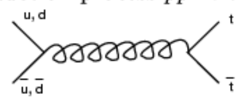


Figure 7.19 (a) Missing p_T in electron/beam plane, plotted against p_T of electron in 43 events attributed to $W \rightarrow e + \nu_e$, from the detector in Fig. 7.18. The p_T of the W-boson and the net p_T of the other particles produced in the event is small, so the missing p_T has to be ascribed to the neutrino. (b) Angular distribution of decay electrons in rest frame of W-boson. The angle θ is that between the e^- and the proton beam direction, or between the e^+ and the antiproton direction.

Top-Antitop Cross Section (1)

Question 4: Top Quark Production

Consider the top quark pair production process $p\bar{p} \to t\bar{t} + X$



In order to calculate the $t\bar{t}$ production cross-section in proton-antiproton collisions it is very helpful to recall the cross-section for the process $e^+e^- \to \mu^+\mu^-$, only mediated via photon exchange, i.e. the pure QED contribution:

$$\frac{d\sigma^{(e^+e^-\to\mu^+\mu^-)}}{d\Omega} = \frac{\alpha^2\beta_\mu}{16E^2}\left(1 + \frac{M^2}{E^2} + \beta_\mu^2 \cdot \cos^2\Theta\right) \quad (5)$$

$$\beta_\mu = \sqrt{1 - \frac{M^2}{E^2}} \text{ muon velocity} \quad (6)$$

$$M = \text{muon mass} \quad (7)$$

$$E = \text{muon energy} \quad (8)$$

$$\Theta = \text{muon scattering angle} \quad (9)$$

$$\frac{d\sigma^{(e^+e^-\to\mu^+\mu^-)}}{d\Omega} = \begin{cases} 0 \text{ for } E = M \\ \frac{\alpha^2}{16E^2}(1+\cos^2\Theta) \text{ for } E \gg M \end{cases} \quad (10)$$

The two processes differ in

- that the electromagnetic coupling α has to be replaced by the strong coupling α_s.
- we have to consider that the exchanged gluons can come in different colour states, i.e. we need to include a colour factor.
- we need to know how many quarks of which energy in the proton can participate in the t-tbar production.

Top-Antitop Cross Section (2)

- The colour factor C_F of a reaction is given by $C_F = \frac{1}{2} C_1 C_2$ where C_1 and C_2 are the Clebsch-Gordan coefficients for coupling of quarks with the gluon octett. Complete the following table for the different colour states involved in the quark-antiquark annihilation, using the table of the gluon octet colour wave functions.

gluon colour states	quark colour combination	colour factor C_F
$(\bar{R}R) \cdot (\bar{B}B)$	$q_B \bar{q}_B \to q_B \bar{q}_B$ $q_B \bar{q}_R \to q_B \bar{q}_R$ $q_B \bar{q}_R \to q_R \bar{q}_B$ $q_B \bar{q}_G \to q_B \bar{q}_G$ $q_B \bar{q}_G \to q_G \bar{q}_B$ . . . permutations	$\frac{1}{2} \cdot (\frac{1}{\sqrt{6}}) \cdot (\frac{-2}{\sqrt{6}}) = -\frac{1}{6}$

singlet	$\frac{1}{\sqrt{3}}(\vert R\bar{R}> + \vert G\bar{G}> + \vert B\bar{B}>)$
octet	$\vert G\bar{B}>$ $\vert R\bar{B}>$ $-\vert G\bar{R}>$ $\frac{1}{\sqrt{2}}(\vert G\bar{G}> - \vert R\bar{R}>)$ $\frac{1}{\sqrt{6}}(\vert R\bar{R}> + \vert G\bar{G}> - 2\vert B\bar{B}>)$ $\vert R\bar{G}>$ $-\vert B\bar{R}>$ $\vert B\bar{G}>$

Taking all the permutations into account we need to calculate $3 \times \sum_i (C_F)_i^2$. Explain why.

Equivalently to the argument of spin summation and averaging in lepton scattering we now need to average over the the colours of the incoming quarks. Show that the total colour factor is $\frac{2}{9}$.

- Let's now calculate the cross-section $\sigma(q\bar{q} \to t\bar{t})$ by integrating (5) over the solid angle. Show that this integration yields

$$\sigma(q\bar{q} \to t\bar{t}) = \frac{\pi \alpha_s^2}{27 m_t^2} \rho_t (2 + \rho_t) \sqrt{1 - \rho_t}$$

where $\rho_t = \frac{4m_t^2}{\hat{s}}$ and $\hat{s}$ is the centre-of-mass energy in the quark-antiquark system.

- Only considering valence quarks how many combinations of quark-antiquark pairs can we get in the initial state ?

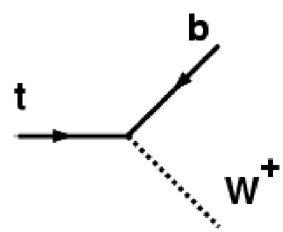
- Estimate the quark-antiquark centre-of-mass energy squared, $\hat{s}$, for the Tevatron Run-I, i.e. for proton-antiproton collisions with centre-of-mass energy $\sqrt{s} = 1.8$ TeV.

- Approximate $\alpha_s(m_t) \approx 0.1$ and plug in all numbers to calculate $\sigma_{(p\bar{p} \to t\bar{t})}^{\sqrt{s}=1.8\text{ TeV}}$.

Top-Antitop Cross Section (3)

Question 5: Top Quark Decay

Consider the decay of the top quark to a b quark and a W-boson.



- The corresponding matrix element is given by

$$T_{fi} = \underbrace{\frac{g}{\sqrt{2}}}_{\text{weak coupling}} |V_{tb}|^2 \overbrace{\bar{u}(p')}^{b} \gamma^\mu \frac{1-\gamma^5}{2} \overbrace{u(p)}^{top} \overbrace{\epsilon^*_\mu(k')}^{\text{W polarisation}} \quad (11)$$

In the top rest frame, squaring and summing over the spins, one obtains

$$\sum |T_{fi}|^2 = \frac{g^2}{2} \cdot \frac{m_t^4}{M_W^2} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \quad (12)$$

Calculating the spin average (factor 1/2) and using $\Gamma = \frac{|\vec{p}|}{8\pi M^2} \overline{\sum} |T_{fi}|^2$ where M is the mass of the decaying particle and $\vec{p}$ is the momentum of one of the decay products, calculate the decay rate Γ_t.

- Use the relation $\frac{g^2}{M_W^2} = \frac{8G_F}{\sqrt{2}}$ to calculate the numerical value of Γ_t for a top quark mass of $m_t = 175$ GeV.
- Derive the top quark lifetime τ_t from that.
  What is so special about the obtained time ?

Top-Antitop Cross Section (4)

partonic to hadronic ttbar cross section:

$$\frac{d\sigma_{p\bar{p}}}{dz} = \sigma_{q\bar{q}}(zs) \quad L_{q\bar{q}}(z)$$

$$Def.: \quad z = z_1 z_2 \quad r = z_1 / z_2$$

$$L_{q_i\bar{q}_j}(z) = \int_z^{1/z} q_i(\underbrace{\sqrt{zr}}_{z_1}) \quad q_j(\underbrace{\sqrt{z/r}}_{z_2}) \frac{1}{2r} dr$$

PDF parametrisation:

$$x u_v(x) = 1.78\, x^{0.5} (1 - x^{1.51})^{3.5}$$

$$x d_v(x) = 0.67\, x^{0.4} (1 - x^{1.51})^{4.5}$$

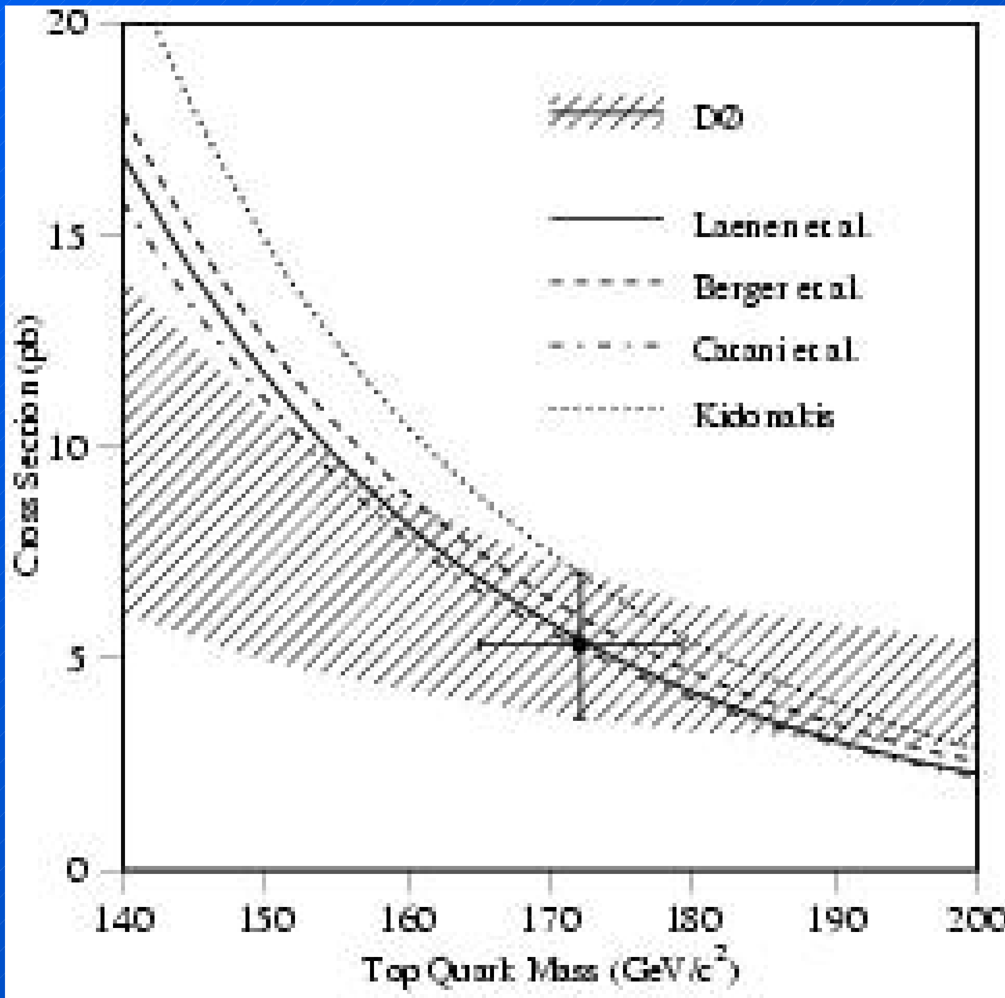
$$x u_s(x) = 0.182 (1 - x)^{8.54}$$

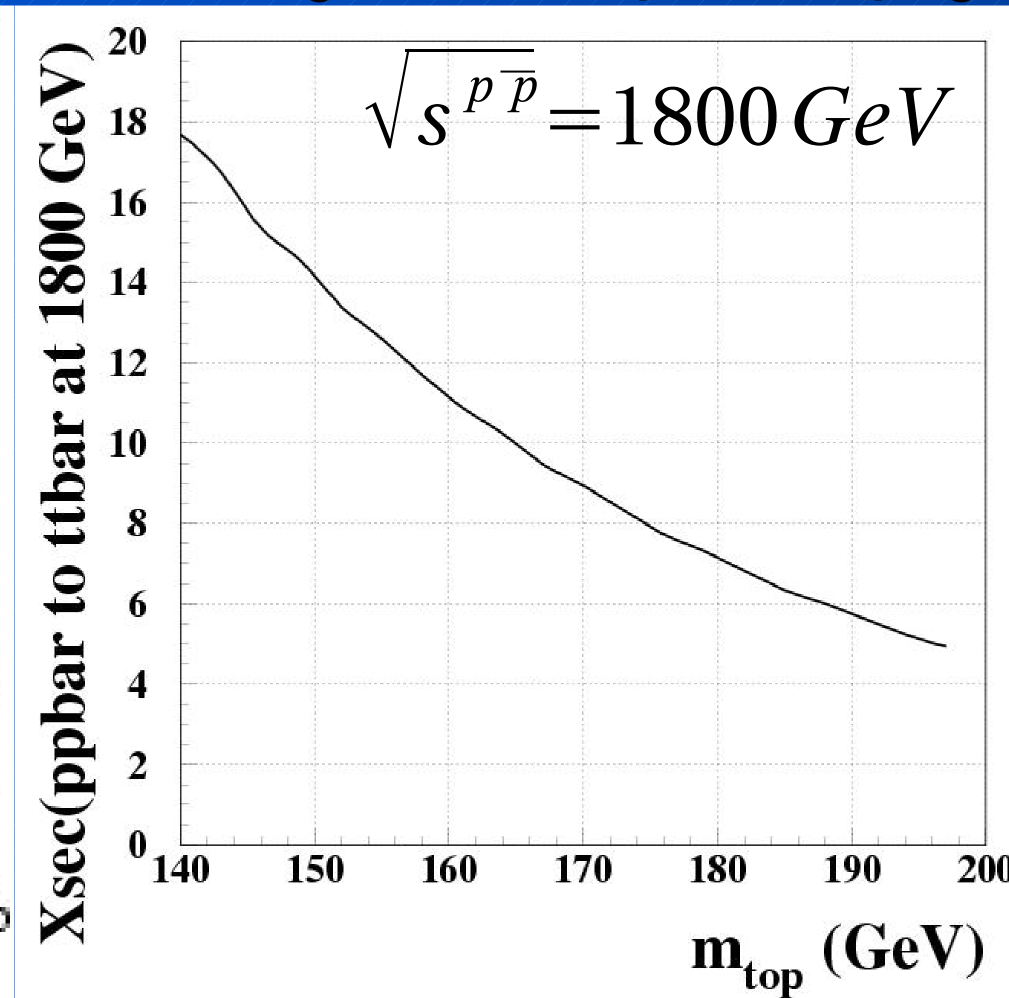
$$x d_s(x) = x u_s(x)$$

$$x s_s(x) = 0.081 (1 - x)^{8.54}$$

Top-Antitop Cross Section (5)

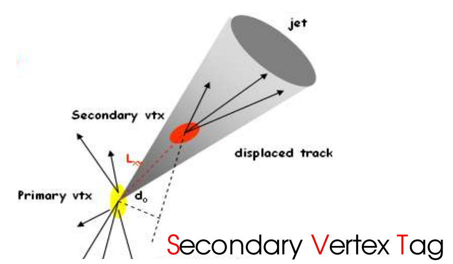
result of numerical integration from previous page:

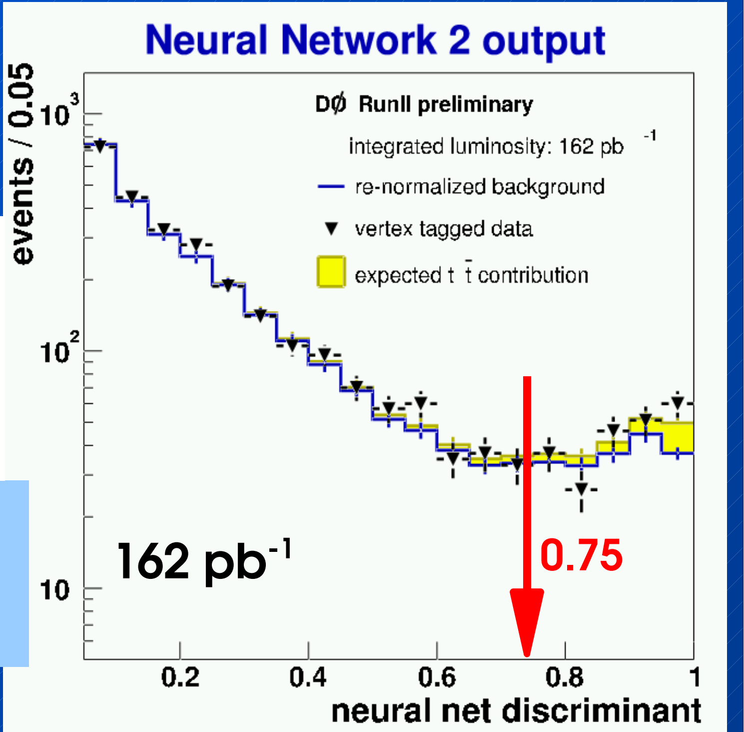




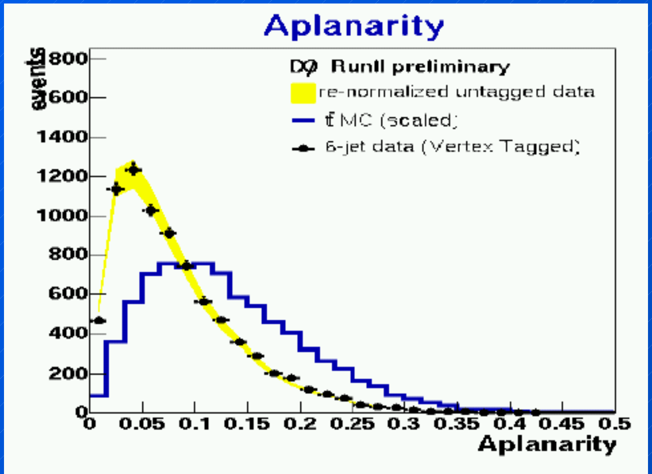
All Jets Channel

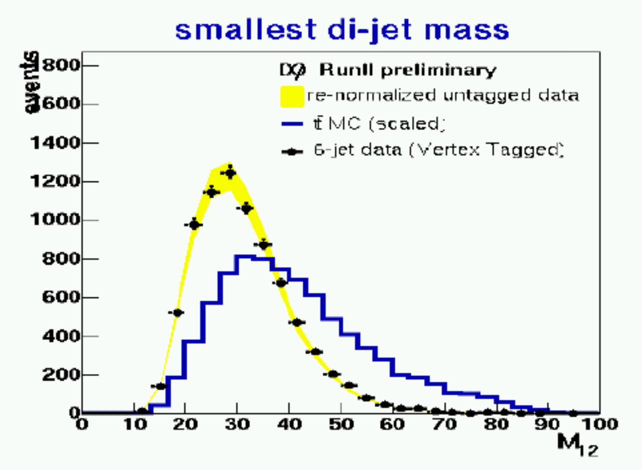
- signature: 6 jets, 2 being b-jets (46% of top production)
- background: large QCD multijet background
  ➔ need b-tagging
- use secondary vertex tagger (SVT)
- combine various kinematical variables into 3 neural networks (trained on data)

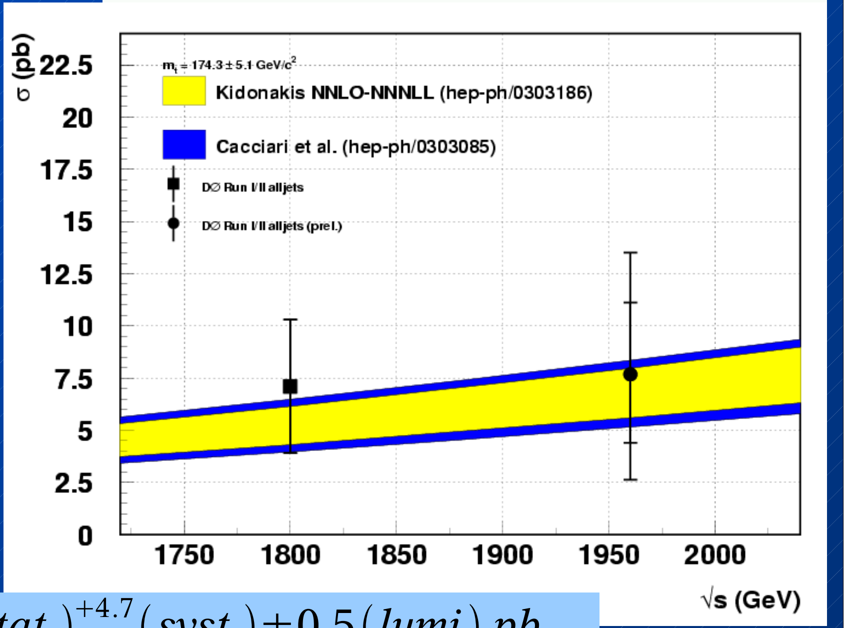




select 220 events
background expectation:
186 ± 5(stat.) ± 7.6(syst.)

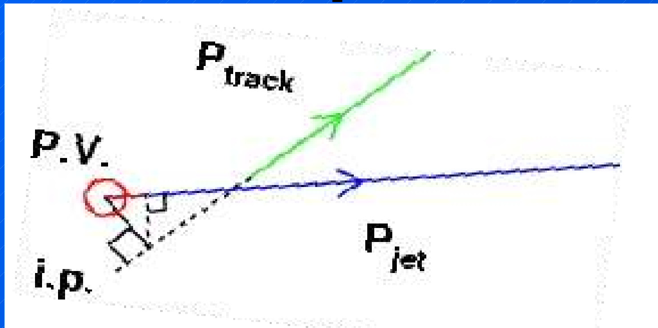




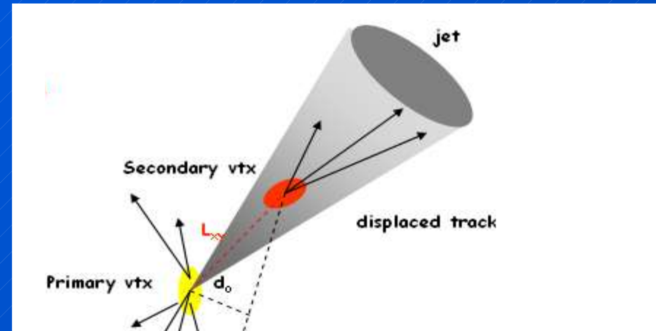


$$\sigma(t\bar{t}) = 7.7^{+3.4}_{-3.3}(stat.)^{+4.7}_{-3.8}(syst.) \pm 0.5(lumi)\ pb$$

Lepton+Jets Channels with b-tagging



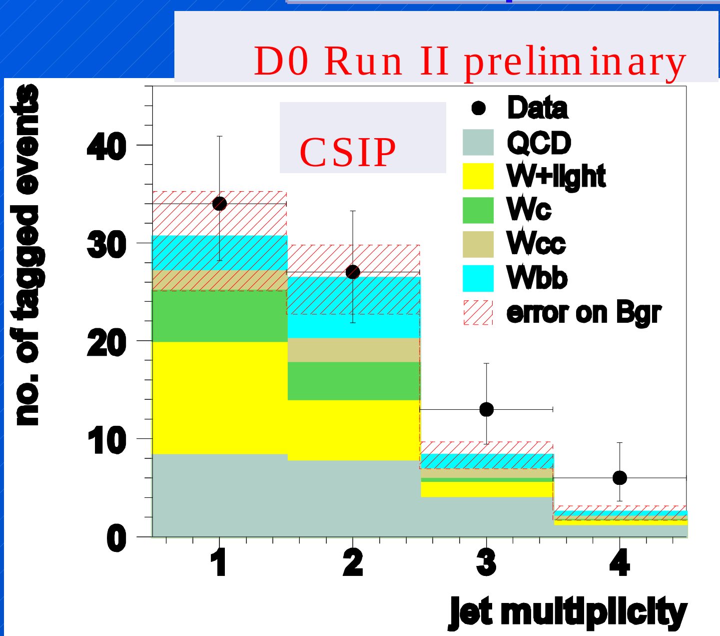
Counting Signed Impact Parameter Tag

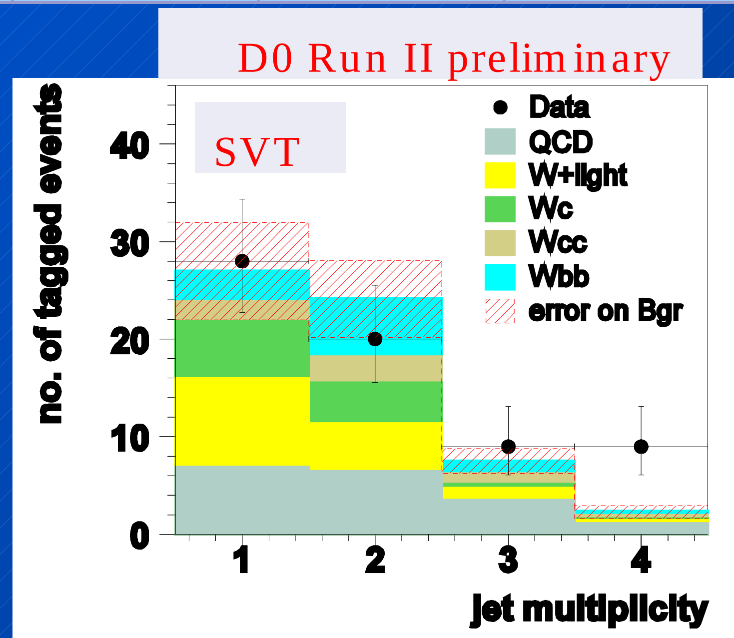


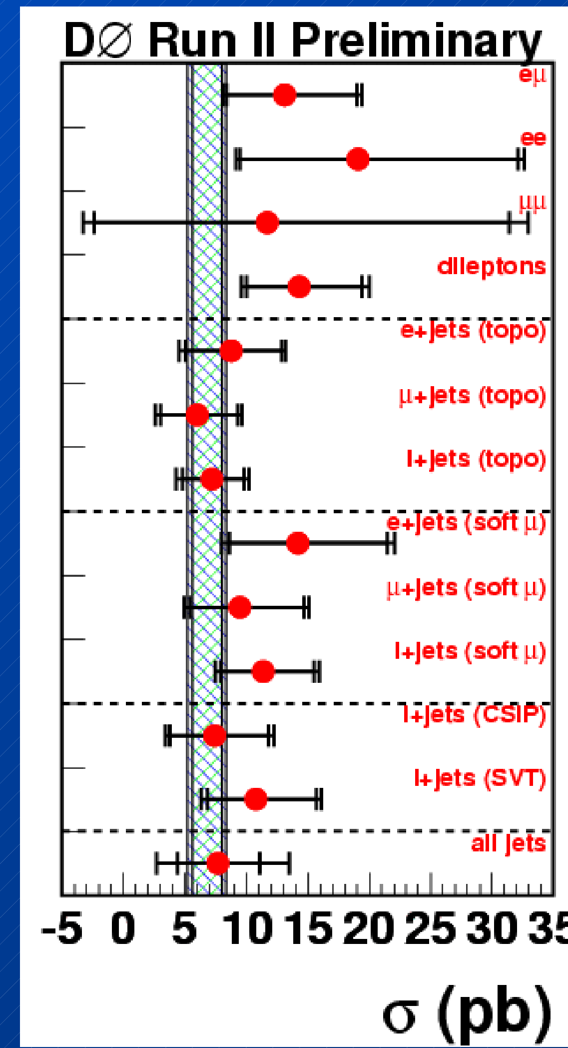
Secondary Vertex Tag

44.75 pb^{-1}

# of tags	W+1 jet	W+2 jet	W+3 jet	W+≥ 4 jet
CSIP	34	27	13	6
SVT	28	20	9	9







... update with > 4-fold data in preparation ...