Top-Quark Physics at the Tevatron

Wolfgang Wagner

Karlsruhe Institute of Technology
Center for Elementary Particle and Astroparticle Physics

Loops and Legs in Quantum Field Theory

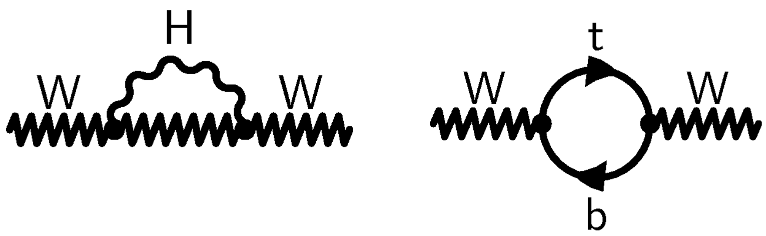
Sondershausen, April 22, 2008

Contents:

Why Do Top-Quark Physics?

- $M_t >> M_b > M_c >> M_s$

  $\Rightarrow$ large contribution of top loop-diagrams



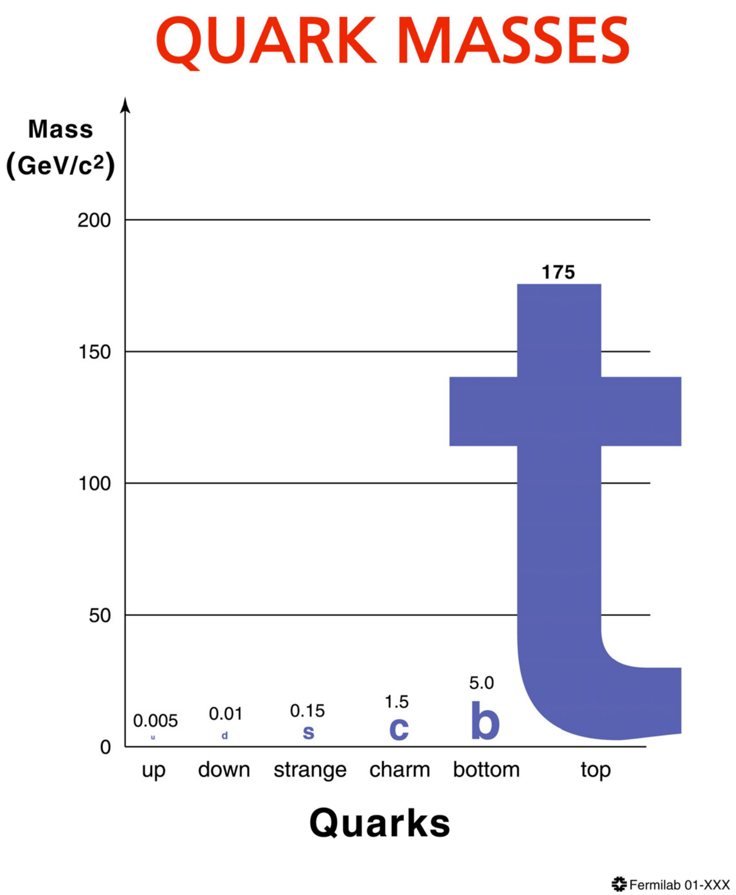
- $\tau_{top} << \tau_{QCD}$: decays as „naked“ quark

- M_t ~ scale of electroweak symmetry breaking → special top dynamics?

- Is the observed particle the SM top quark?

  charge, branching ratios, spin, polarisation, …

  top quark samples are still small
  $\Rightarrow$ plenty of room for new phenomena



5 orders of magnitude between quark masses!

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The Tevatron at Fermilab

Run 1 (1992 – 1995): $\sqrt{s}$ = 1.8 TeV

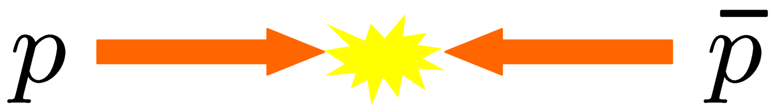
L_{int} = 100 pb^{-1}

Run 2 (since 2002): **$\sqrt{s}$ = 1.96 TeV**

L_{int} = 3.8 fb^{-1}

Most energetic collider until the turn on of the LHC!

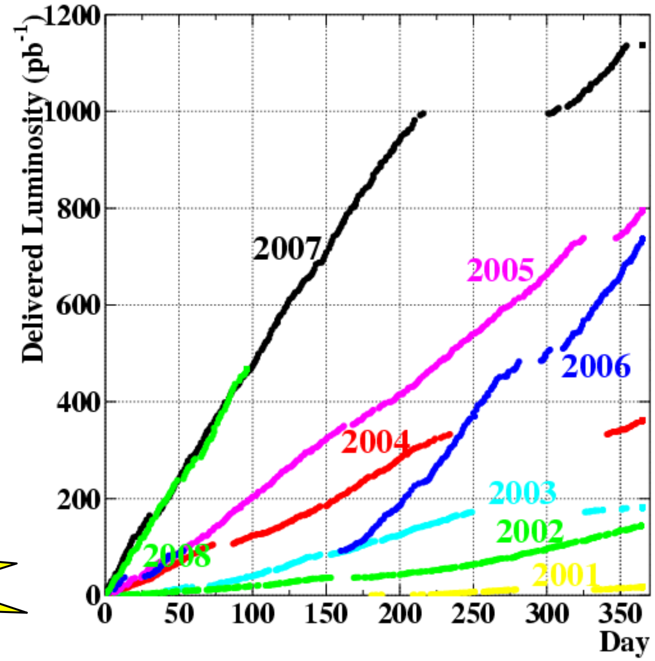
Accumulating > 1 fb^{-1} / year



record luminosity: $\mathscr{L} = 3.1 \cdot 10^{32}\ cm^{-2}\ s^{-1}$

(goal: $1.6 - 2.7 \cdot 10^{32}$)

new on 17.03.08



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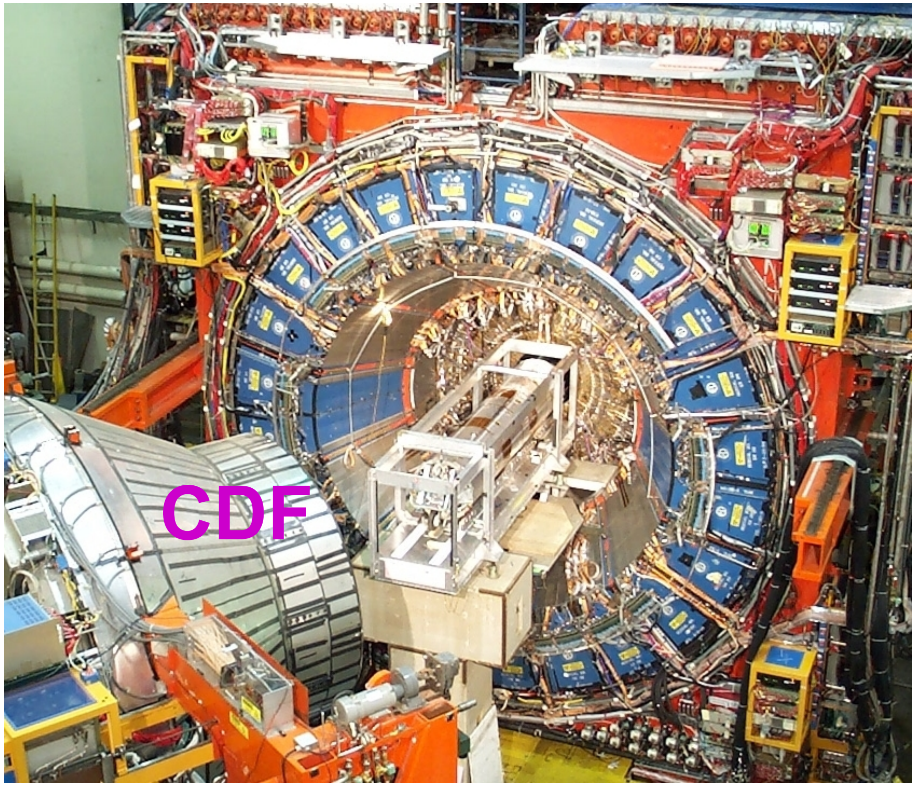
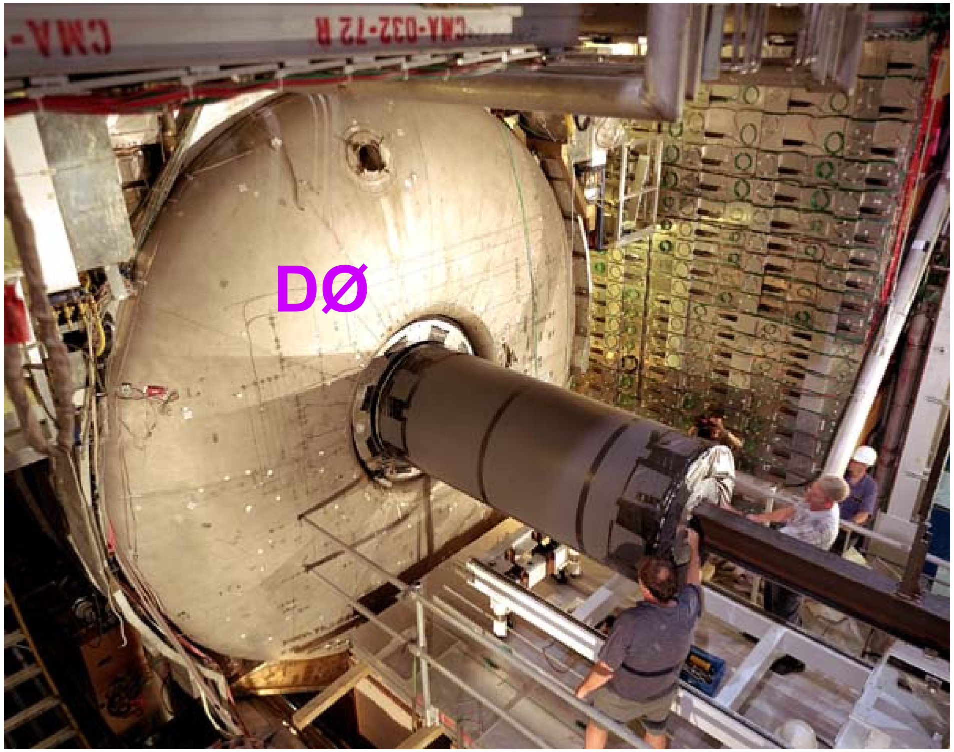
Detectors at the Tevatron

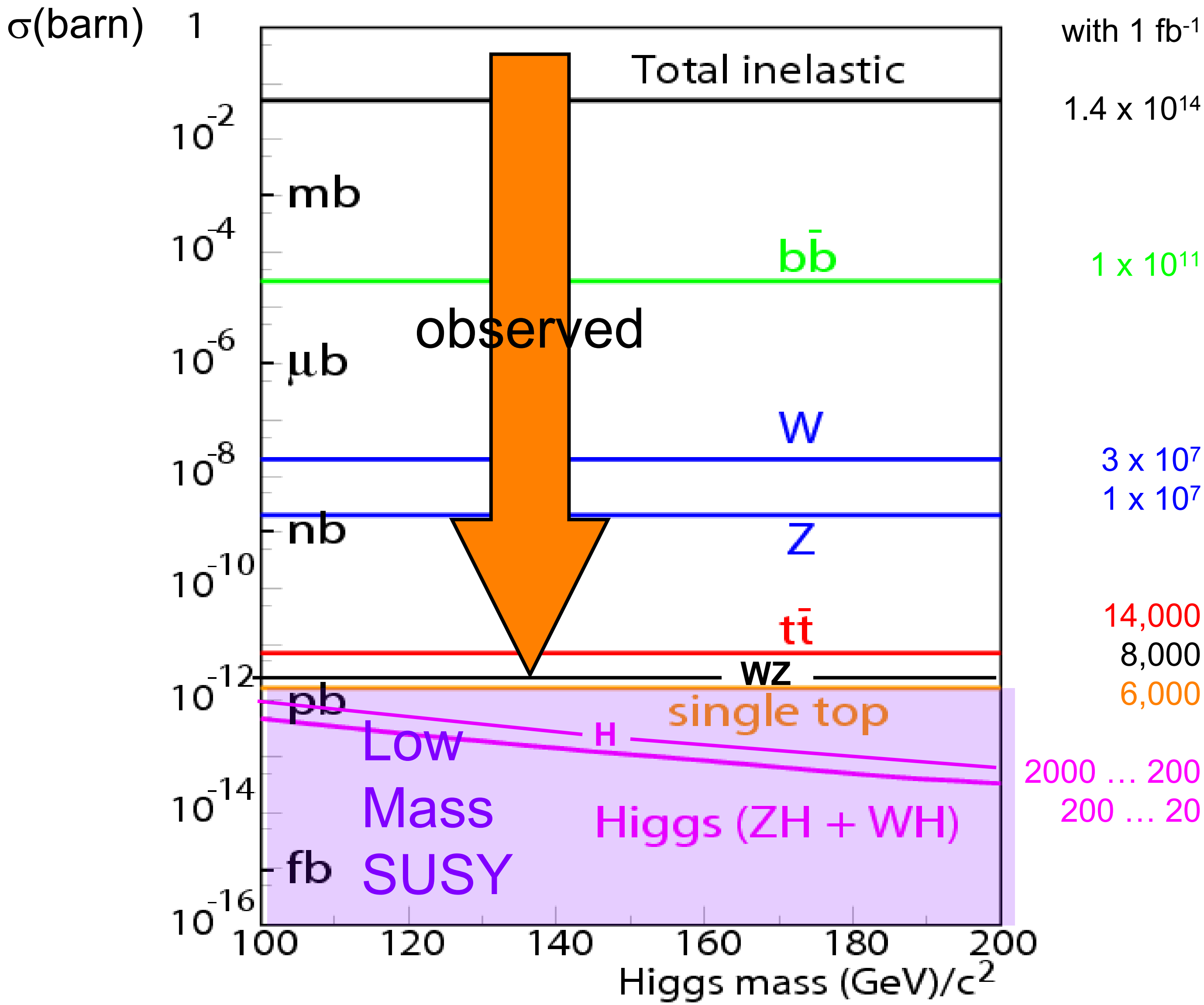




multi-purpose detectors: tracking, b-tagging, calorimeter, muon system, …

strength of CDF: momentum resolution and particle ID (K,π)
strength of DØ: muon coverage and jet energy resolution

Physics at the Tevatron



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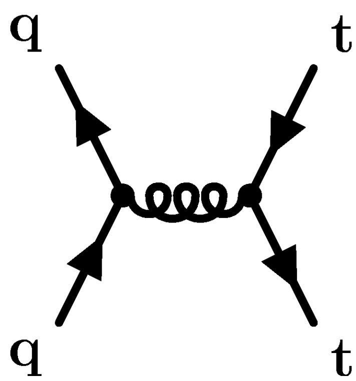
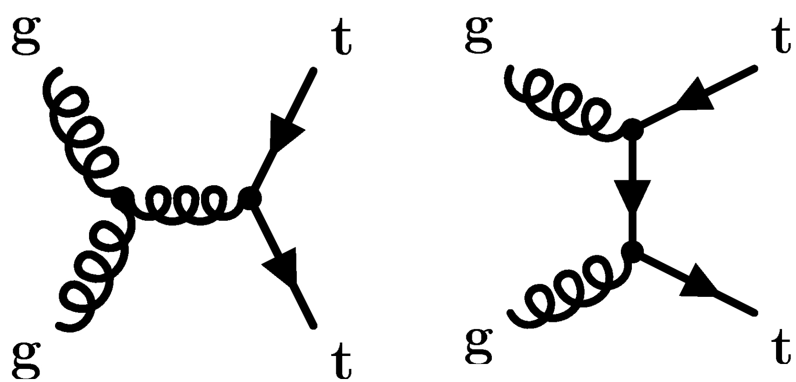
Top-Antitop-Quark Production

	quark-antiquark annihilation	gluon-gluon fusion
		
Tevatron	~85%	~15%
LHC	~15%	~85%

	predicted total cross-section
Tevatron	6.7 ± 0.8 pb
LHC	830 ± 50 pb

↓ top quark factory

NLO calculation + resummation of leading and subleading logarithms due to soft gluon radiation near threshold

Cacciari et al. JHEP 0404,068 (2004); Kidonakis et al. Phys. Rev. D 68, 114014 (2003).

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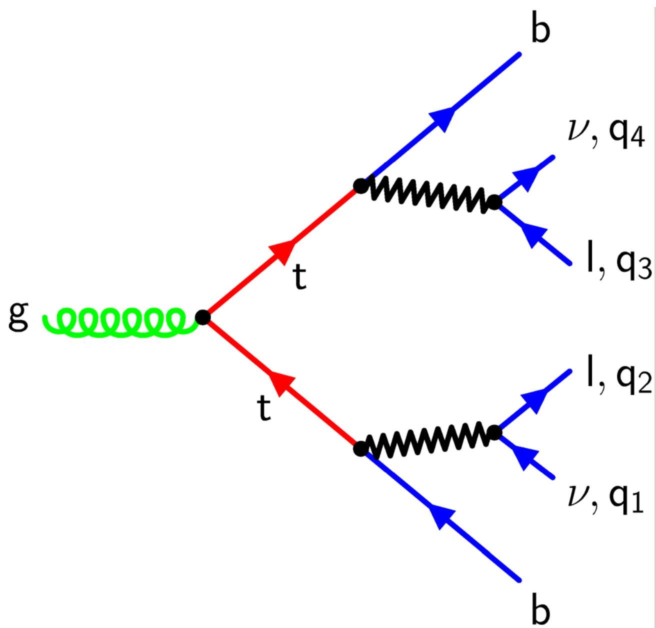
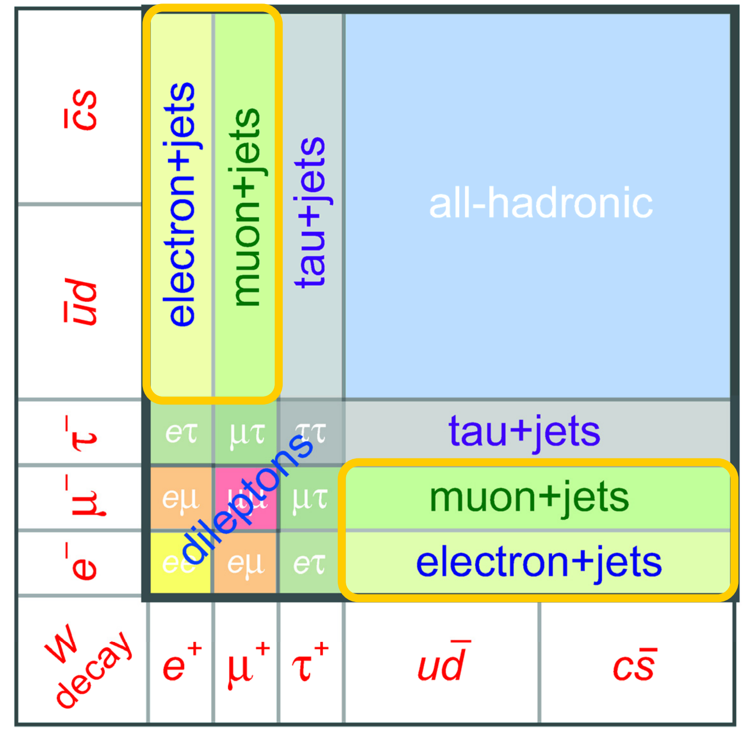
Classification of Top-Antitop Events

classification according to the decay modes of the W bosons



Top Pair Decay Channels



lepton (e, μ) + jets channel = "golden channel"

+ large branching fraction (30%)

+ manageable backgrounds

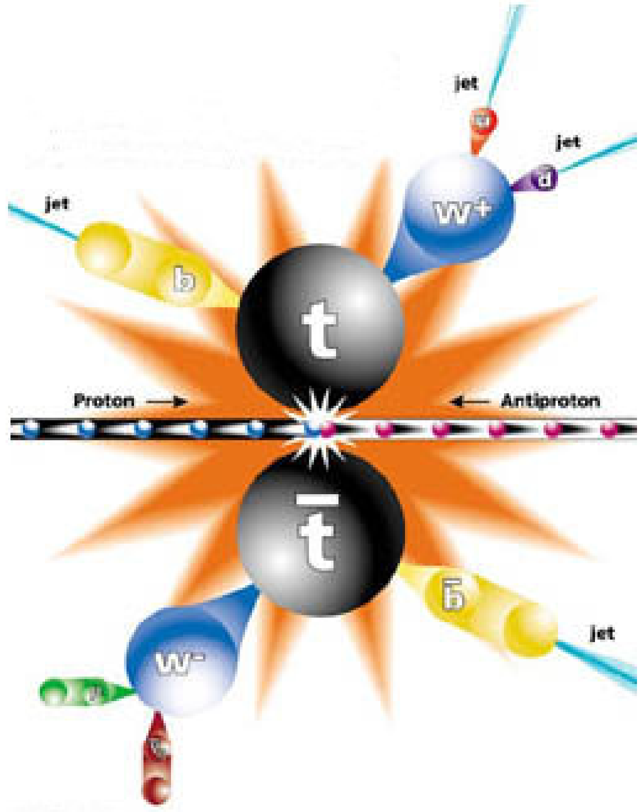
+ allows full event reconstruction

2. Topics in Top-Quark Physics

tt production (1)
- cross section
- production mechanism
- charge asymmetry
- $X \rightarrow$ ttbar
- spin correlations

top quark decay (2)
- W helicity
- branching ratio
- FCNC decays
- $t \rightarrow H^{+} + b$

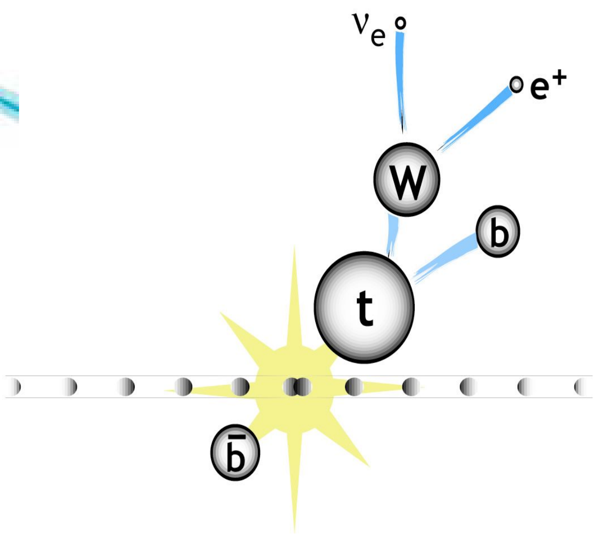
intrinsic properties (3)
- mass
- width
- charge



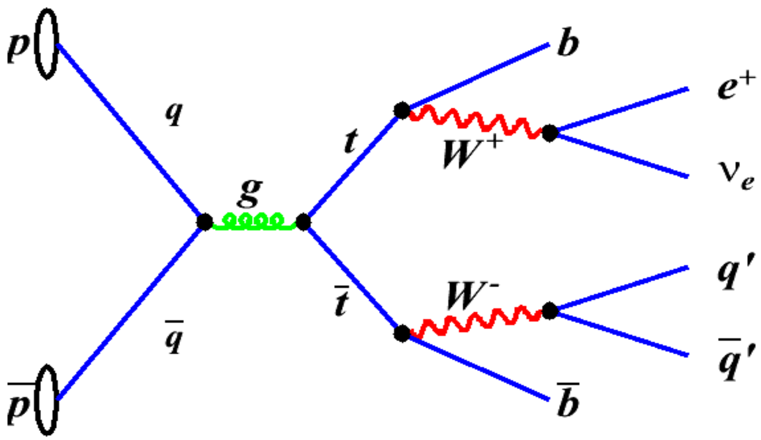
single-top quarks (4)

$\sigma \approx |V_{tb}|^2$

single-top production via FCNC

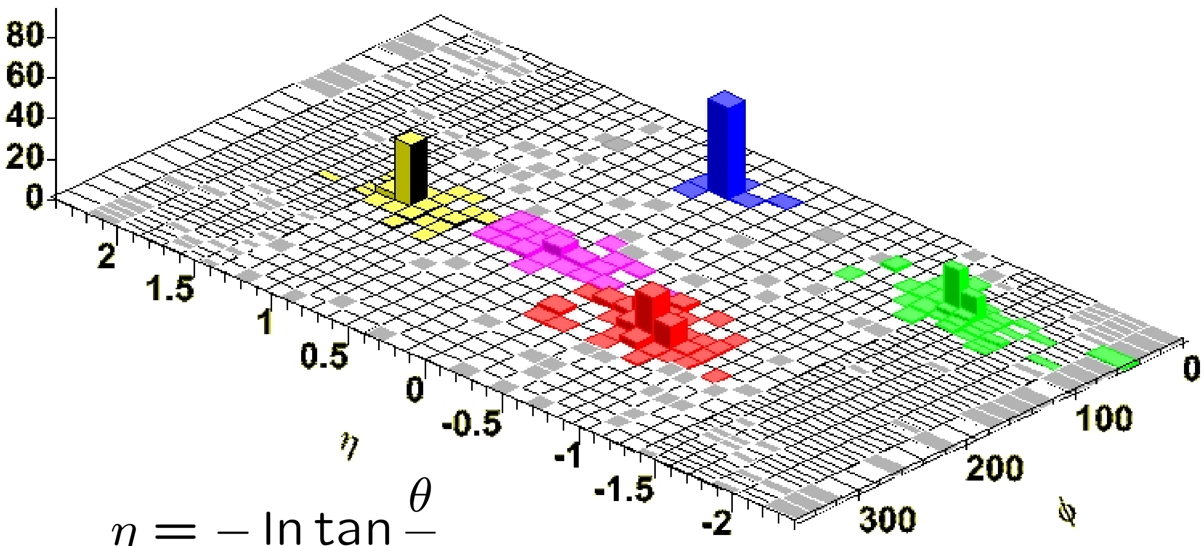


2.1 Selection of Top-Antitop Candidates



event signature:

- one isolated lepton
- missing transverse energy
- at least 4 Jets,
  2 of them b jets



$$\eta = -\ln\tan\frac{\theta}{2}$$

selection cuts:

- $\geq$ 4 jets mit
  E_T > 20 GeV
  $|\eta|$ < 2.0
- lepton: E_T > 20 GeV
- MET > 20 GeV
- $\geq$ 1 b tag

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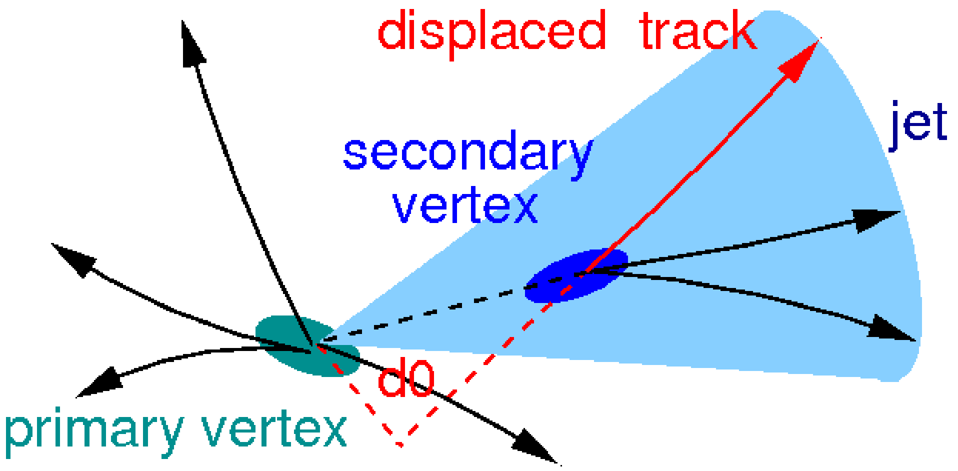
Background Reduction

gold-plated method: secondary vertex reconstruction in *b* Jets

b hadron lifetime: $\tau \approx 1.5$ ps $\rightarrow c\tau \approx 450\ \mu$m

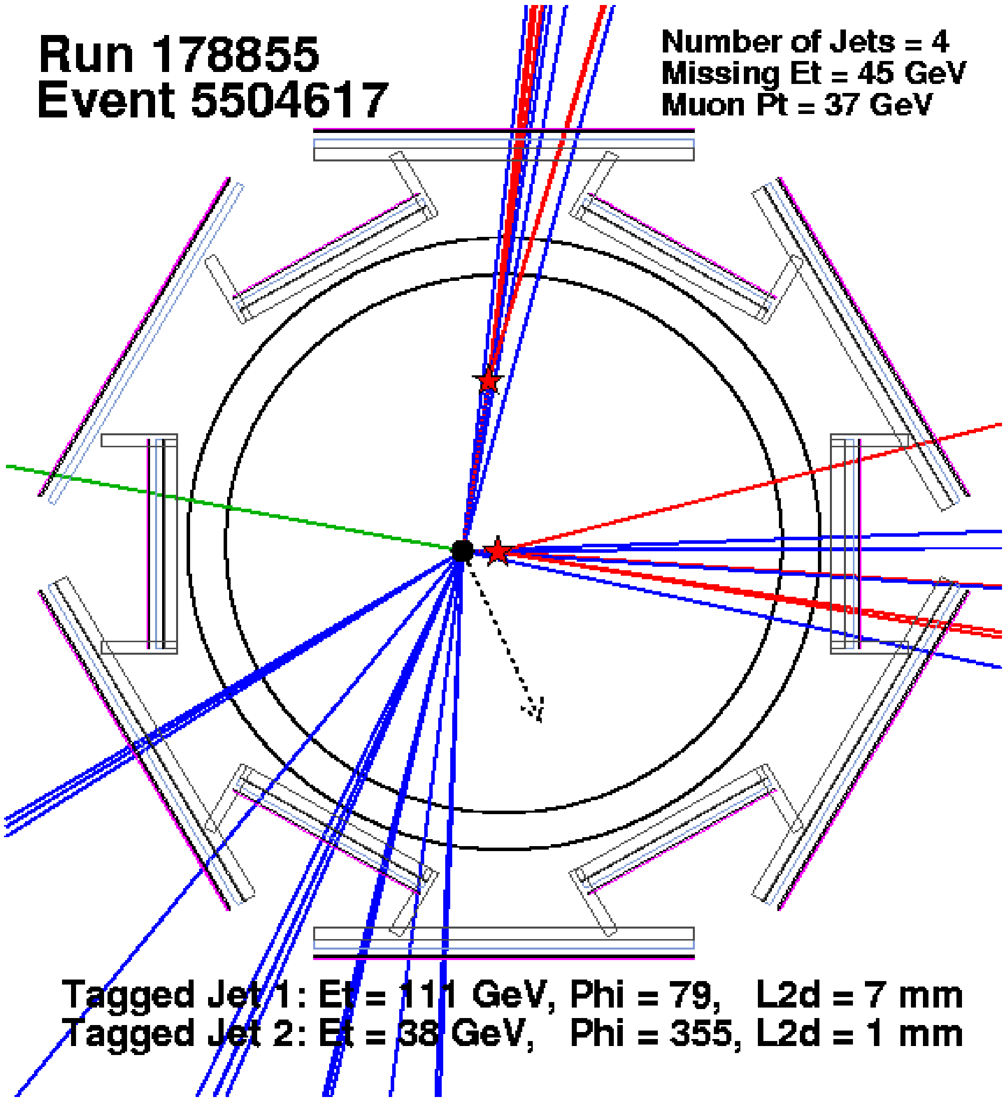
typical decay length in CDF: *O*(mm)



requirement of a secondary vertex:
$\rightarrow$ large reduction of generic W + jets events

jargon: reconstruction of a secondary vertex = *b* tag

Event with Two Secondary Vertices



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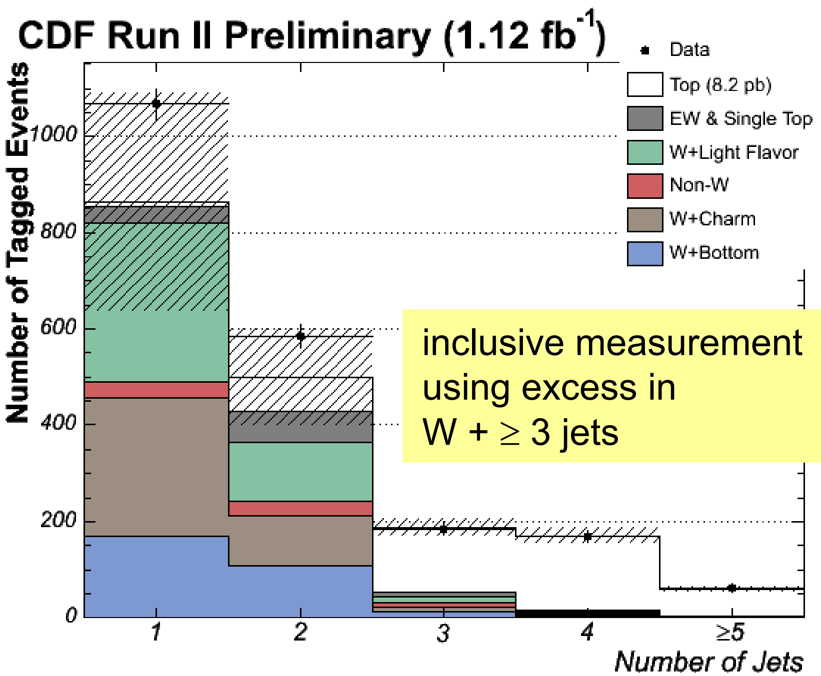
Top-Antitop Cross Section

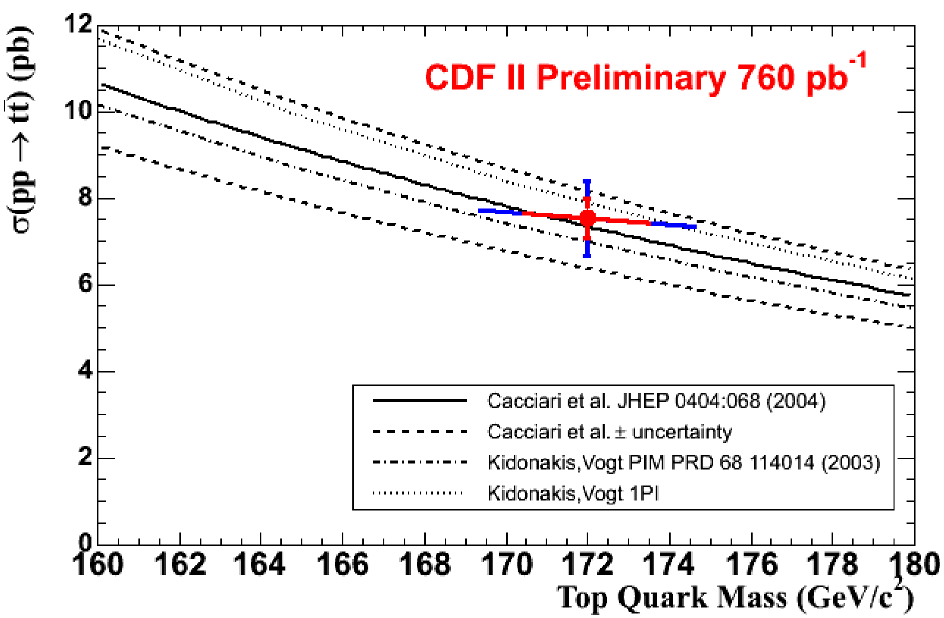
e.g. counting experiment with secondary vertex reconstruction

combination of different measurements:



inclusive measurement using excess in W + ≥ 3 jets

$$\sigma(t\bar{t}) = 7.3 \pm 0.5\,(\text{stat}) \pm 0.7\,(\text{syst})\ \text{pb}$$



$$\sigma(t\bar{t}) = 8.2 \pm 0.5\,(\text{stat}) \pm 0.9\,(\text{syst})\ \text{pb}$$

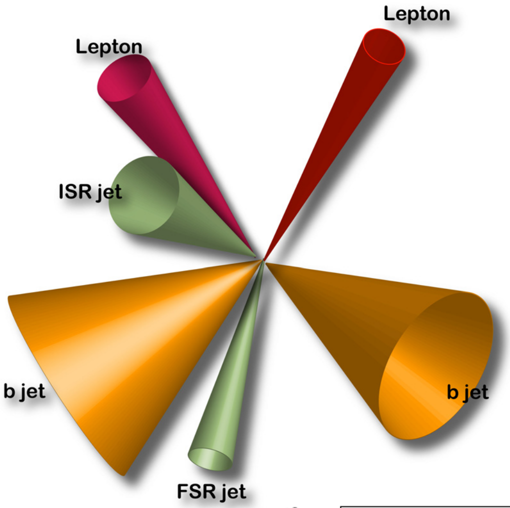
includes luminosity uncertainty

good agreement with theory curve (NLO + NLL resummation)

LHC will allow to investigate $t\bar{t} + N$ jets spectrum

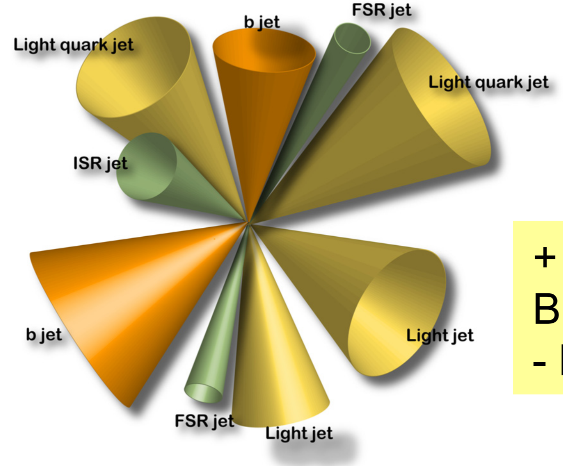
compare: Dittmaier, Uwer, Weinzierl: **Phys. Rev. Lett. 98:262002, 2007**

Dilepton and Hadronic Channel

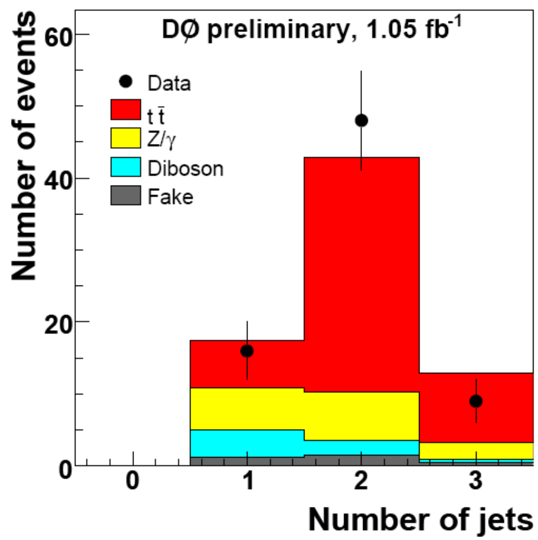


+ very clean
- lower statistics

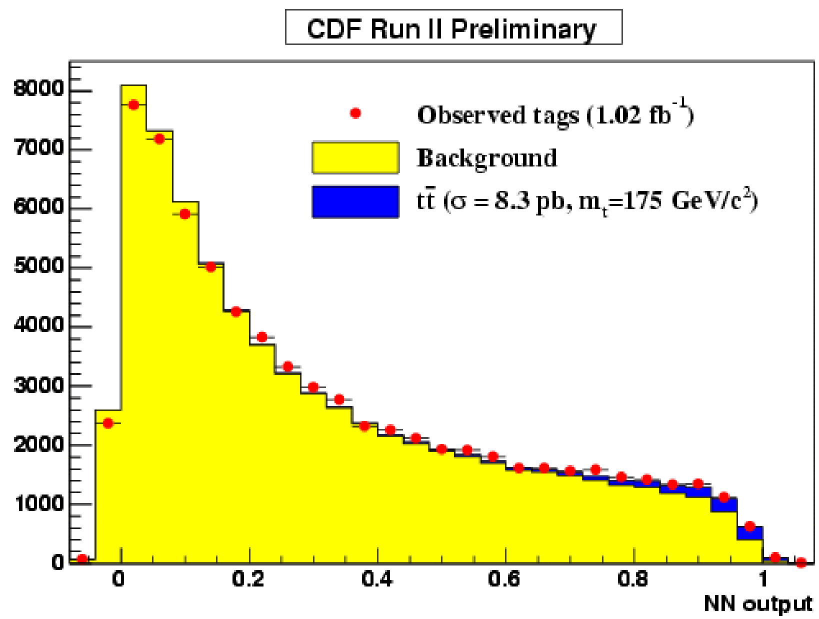
challenge: fake rate of leptons



+ large statistics: BR = 44%
- huge backgrounds



$$\sigma(t\bar{t}) = 6.8 \pm 1.2\,(\text{stat}) \pm 1.0\,(\text{syst})\text{ pb}$$



$$\sigma(t\bar{t}) = 8.3 \pm 1.0\,(\text{stat}) \pm 1.9\,(\text{syst})\text{ pb}$$

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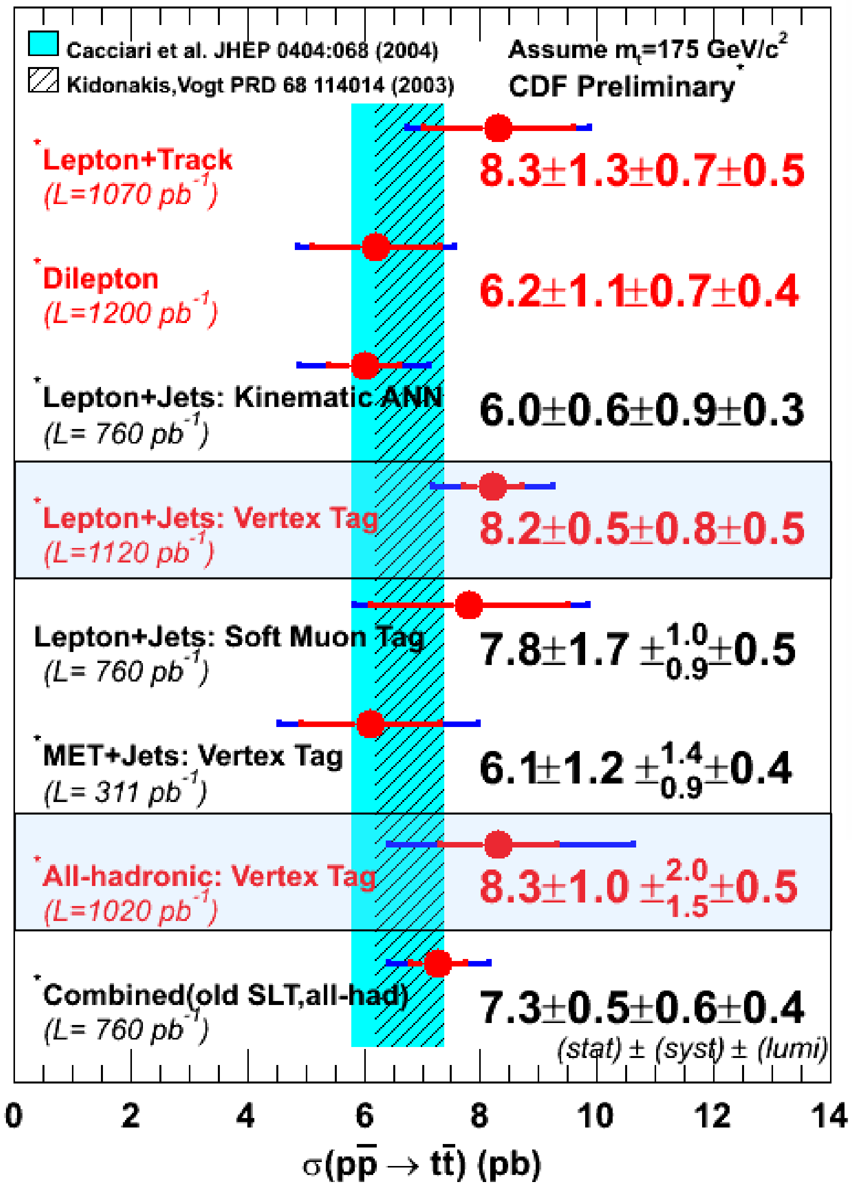
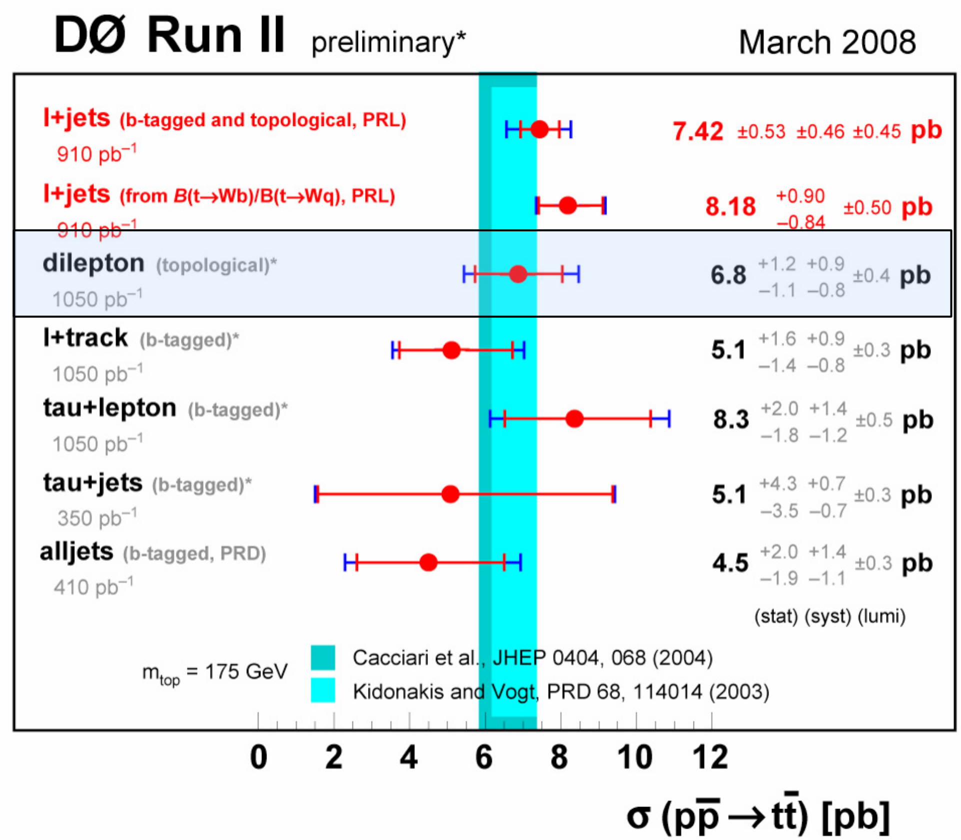
Overview: Top-Antitop Cross Sections





Essentially all measurements are counting experiments:

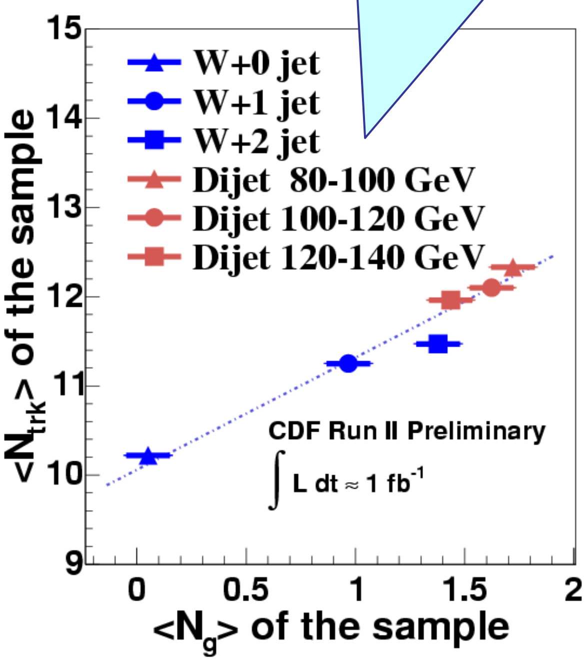
$$\sigma(t\bar{t}) = \frac{N_{\rm obs} - N_{\rm b}}{\epsilon_{t\bar{t}} \cdot \int \mathcal{L} dt}$$

Main job: background estimate

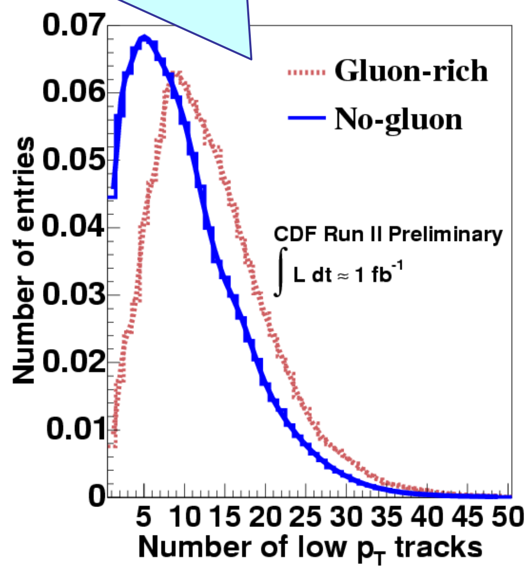
Production Mechanism: qq vs. gg

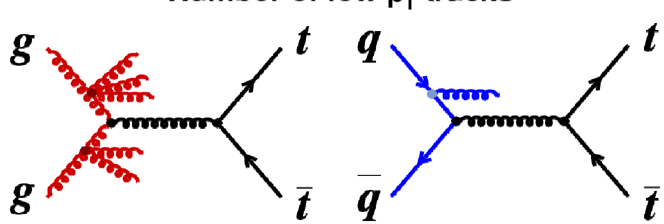
Analysis idea: number of low p_T tracks $\propto$ gluon content

calibration with W + jets and dijet samples

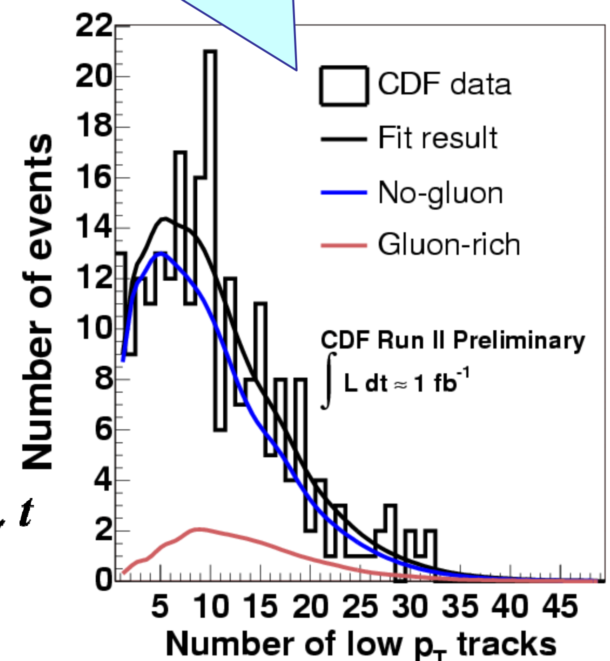


templates for ttbar sample: gluon rich vs. quark initiated





fit to data (1 fb^{-1})

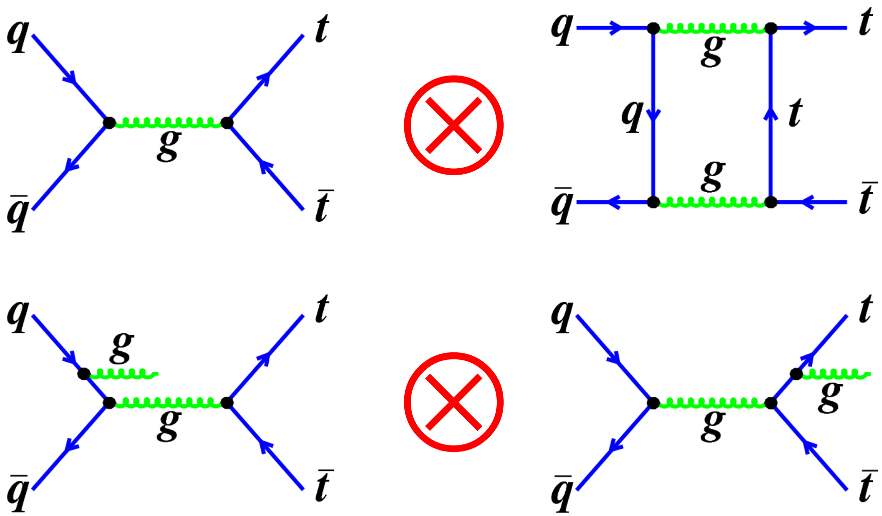


Result: $\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t}) = 0.07 \pm 0.14(\text{stat.}) \pm 0.07(\text{syst.})$

SM prediction: 0.15

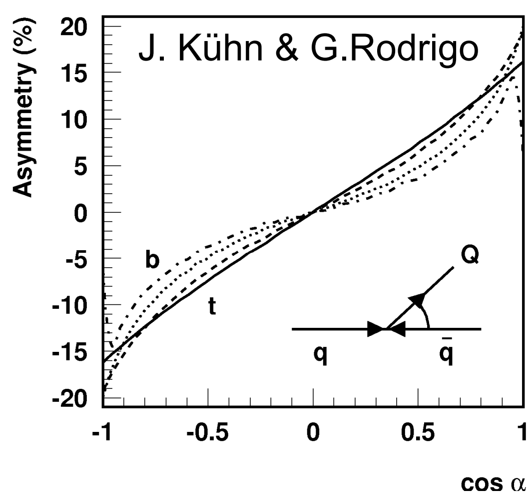
Charge Asymmetry in Top-Antitop Events

Interference effect at NLO

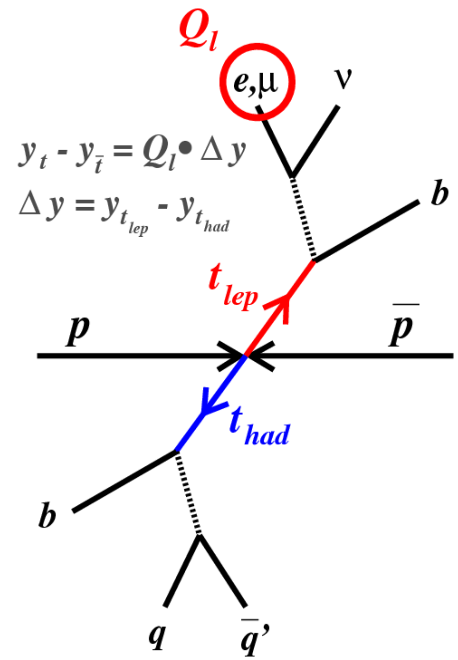


$\Rightarrow$ quasi forward-backward asymmetry

Top quarks more likely to be produced in proton direction, antitop quarks more likely produced in antiproton direction.



measured observable:
rapidity difference of top quarks (Lorentz-invariant !) × Q_{lepton}

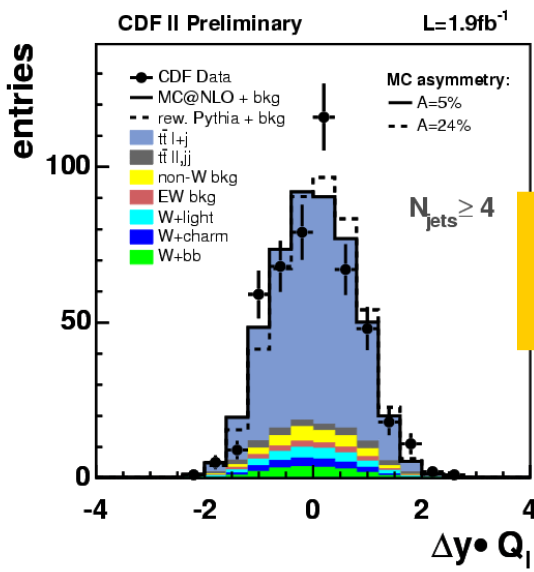


Asymmetry:

$$A = \frac{N(Q_l \Delta y > 0) - N(Q_l \Delta y < 0)}{N(Q_l \Delta y < 0) + N(Q_l \Delta y < 0)}$$

Charge Asymmetry Results

measured „raw“ distribution



background subtraction

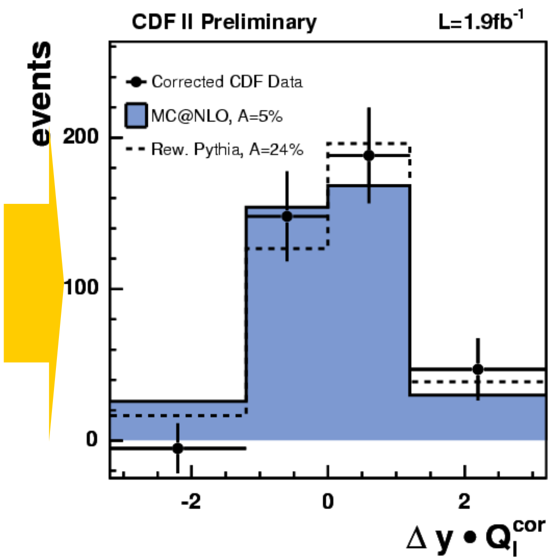
⊕

efficiency correction

⊕

migration unfolding

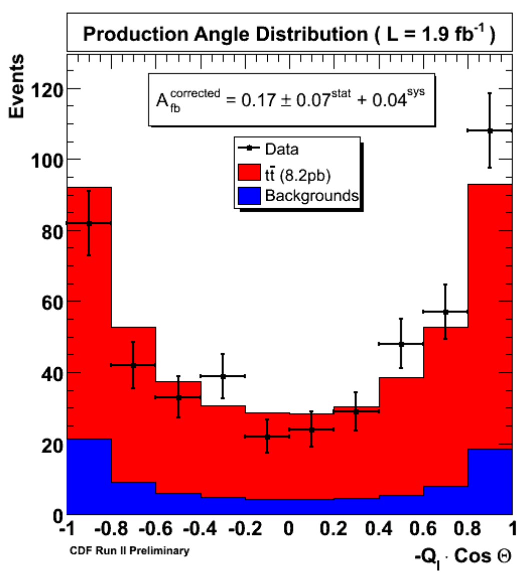
unfolded distribution



observed total asymmetry:
24 ± 13 ± 4 %

QCD expectation:
6 – 8 %

2nd CDF analysis using cos θ* in lab frame:



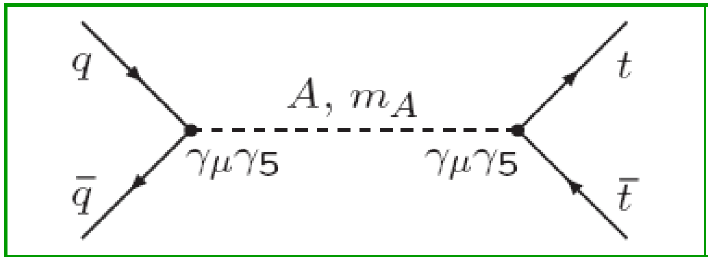
DØ:

no unfolding and acceptance correction:

A_{FB} = 12 ± 8 ± 1 %

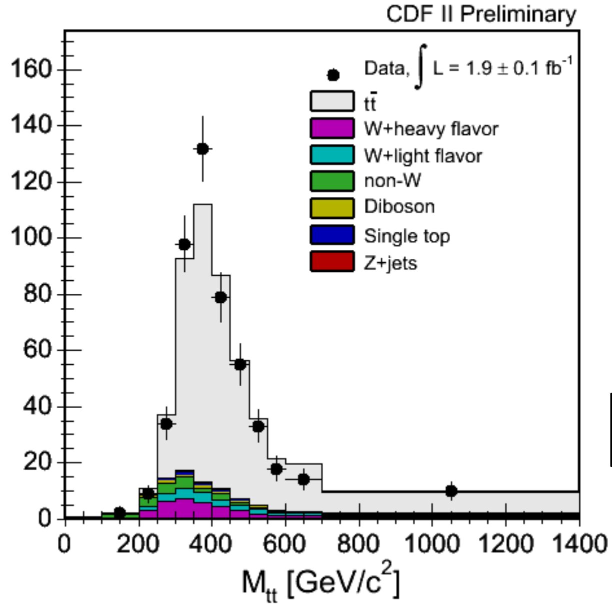
PRL 100, 142002 (2008)

limit on axigluon mass: > 1.2 TeV



Kühn / Rodrigo: arXiv:0709.1652 [hep-ph]

Differential Cross Section

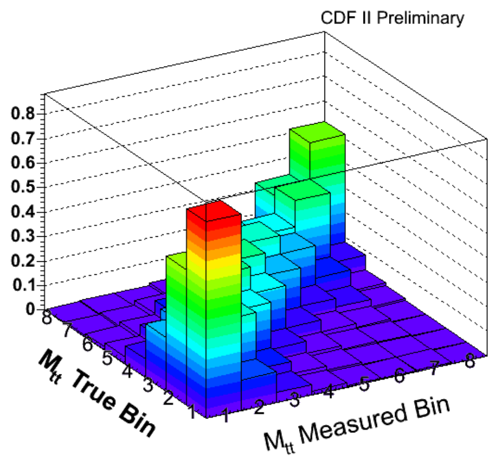


… as a function of top-antitop pair mass

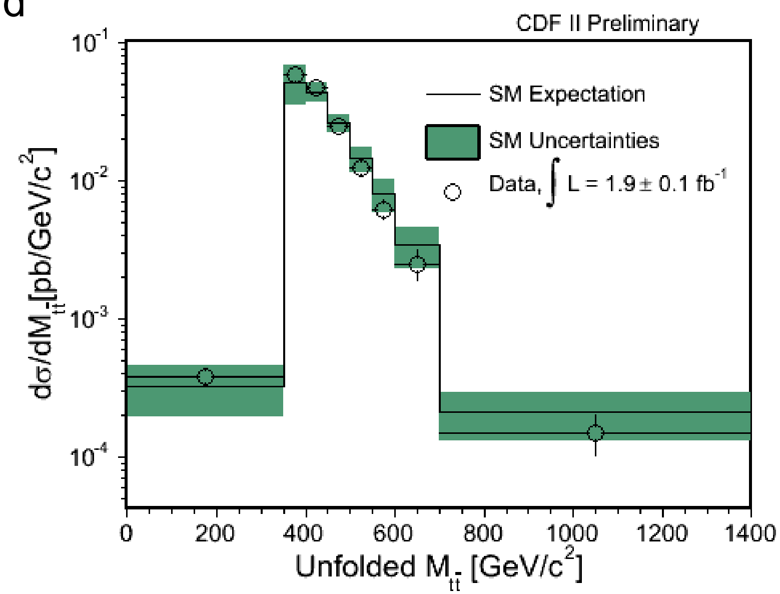
$$\frac{d\sigma^i_{t\bar{t}}}{dM_{t\bar{t}}} = \frac{N^i_{\text{obs}} - N^i_{\text{bkg}}}{\epsilon_{t\bar{t}} \cdot \Delta^i_{M_{t\bar{t}}} \cdot \int \mathcal{L}dt}$$

subtract background

good agreement with SM prediction



regularised unfolding of event migration



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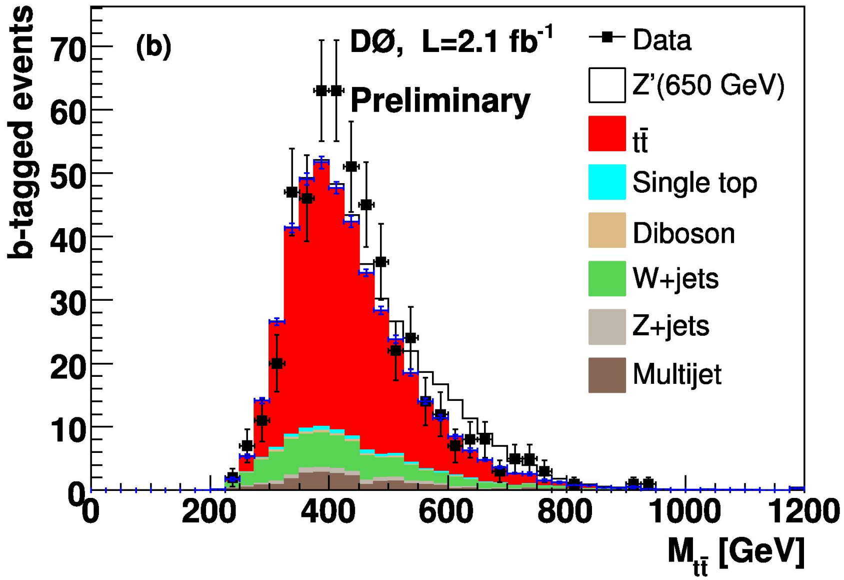
Top-Antitop Resonances



Search for a narrow width resonance:

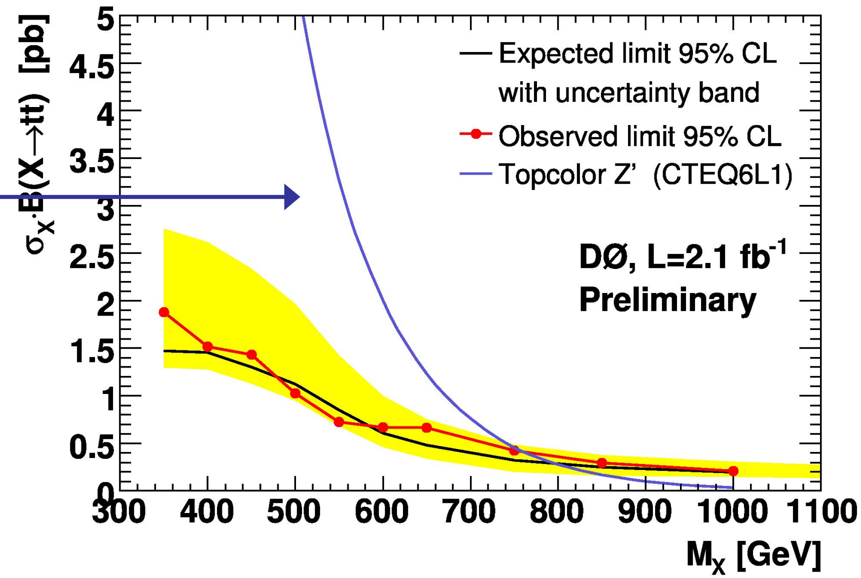
$$X^0 \to t\bar{t}$$

- Analyze lepton+jets events
- b jet ID: NN b tagger

Interpretation in frame of topcolor-assisted technicolor model

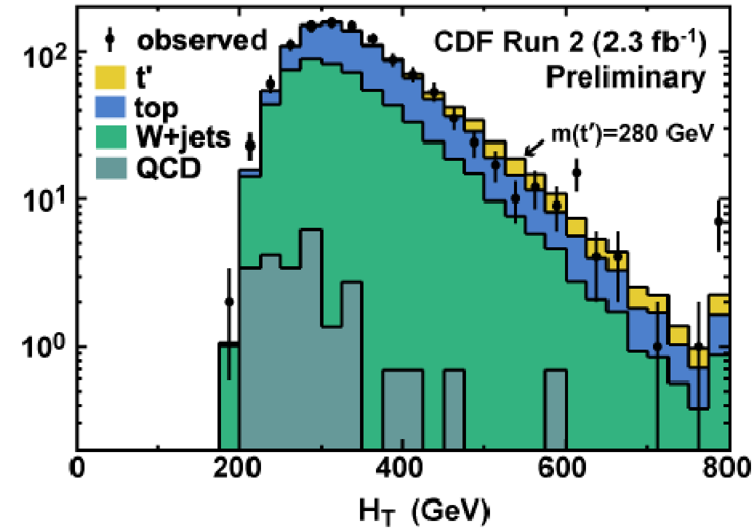
narrow lepto-phobic Z´ excluded

with M(Z´) < 760 GeV/c² and
Γ (Z´) = 0.012 M(Z´) at the 95% CL

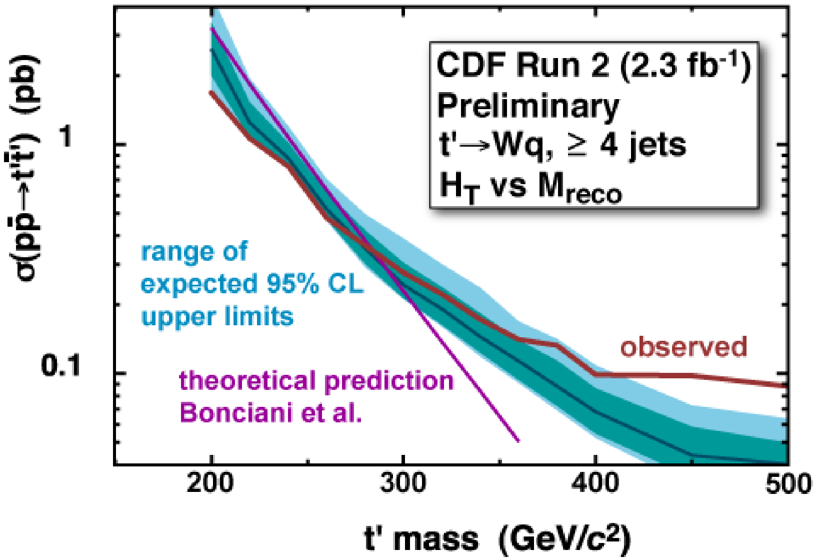


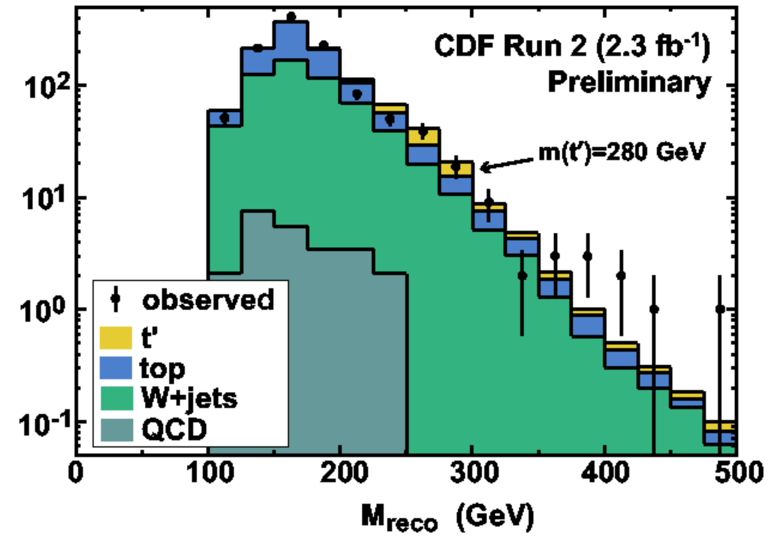
Search for t´

- Search for a 4th generation t´ suggested in flavor democracy, some GUT, little Higgs, or 2HD models
- leptonic W + 4 jets data set (no b-tagging required)
- fit to H_T and M_{reco} (kinemativ fit)



include t´ scaled to 95% CL limit





M(t´) > 284 GeV/c² at 95% CL

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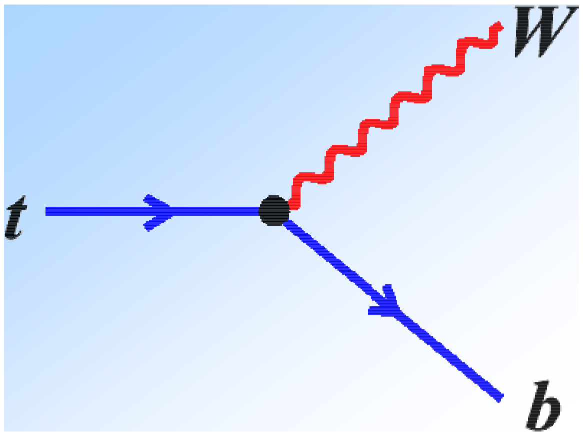
2.2 Top Decay



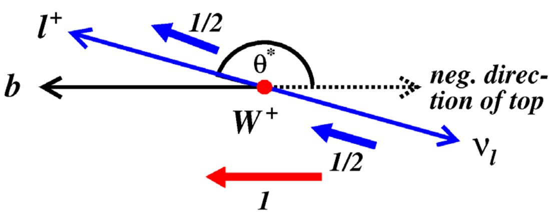
1. W helicity
2. Branching Ratio
3. FCNC decay

SM:

≈ 100% decay into W + b

W Helicity in Top Decay and cos θ*

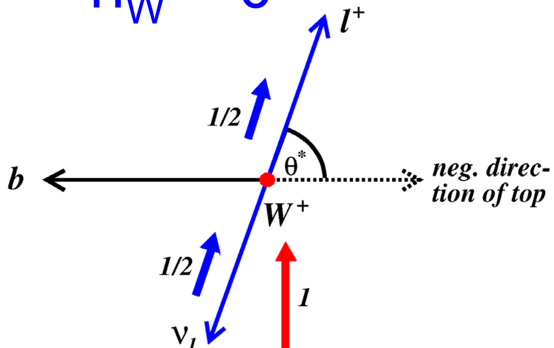
$h_W = -1$



$$\frac{dN}{d\cos\theta^*} \propto \frac{3}{8}(1-\cos\theta^*)^2$$

$f_- = 0.3$

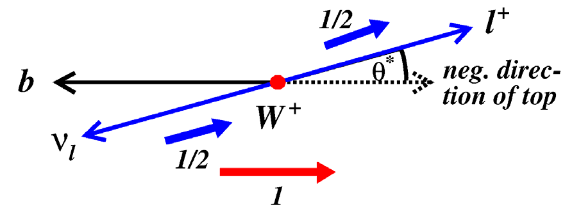
$h_W = 0$



$$\frac{dN}{d\cos\theta^*} \propto \frac{3}{4}(1-\cos^2\theta^*)$$

$f_0 = 0.7$

$h_W = +1$

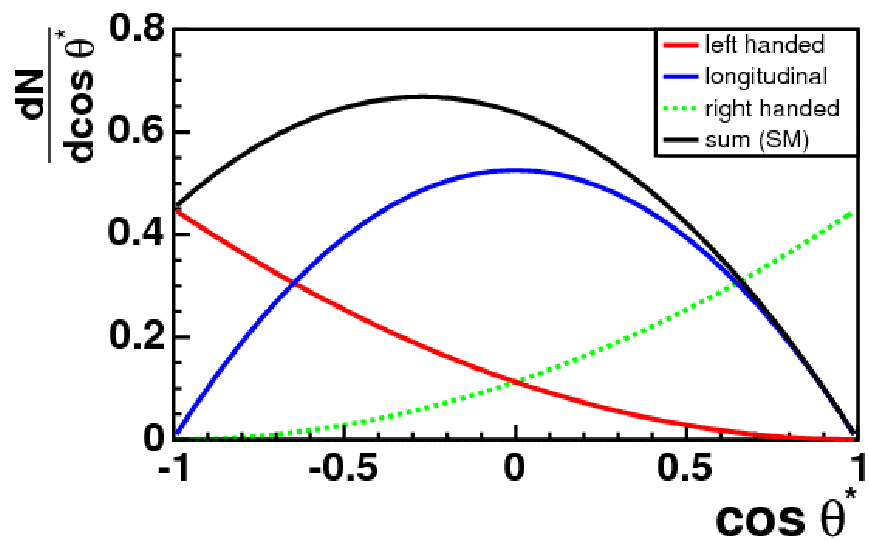


$$\frac{dN}{d\cos\theta^*} \propto \frac{3}{8}(1+\cos\theta^*)^2$$

$f_+ = 0.0$

cos θ* :
angle between charged lepton and negative direction of the top quark in the W rest frame.

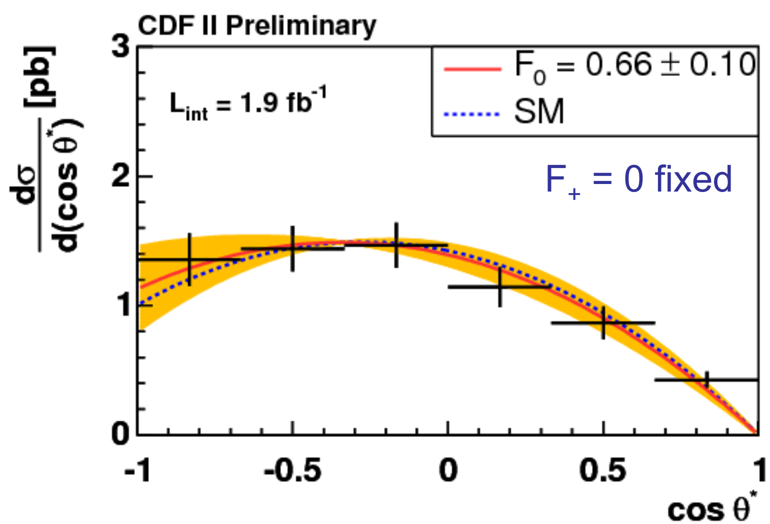
Highly sensitive to W helicity!



W Helicity: Measurement Results

1D maximum likelihood fits to reconstructed cos θ* distribution

⊕ unfolding

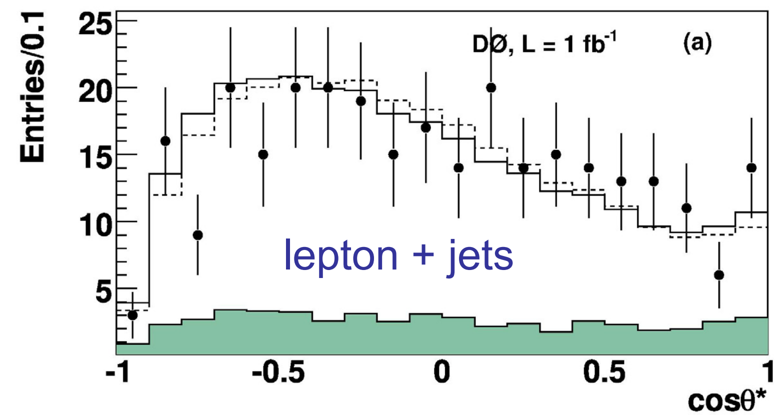


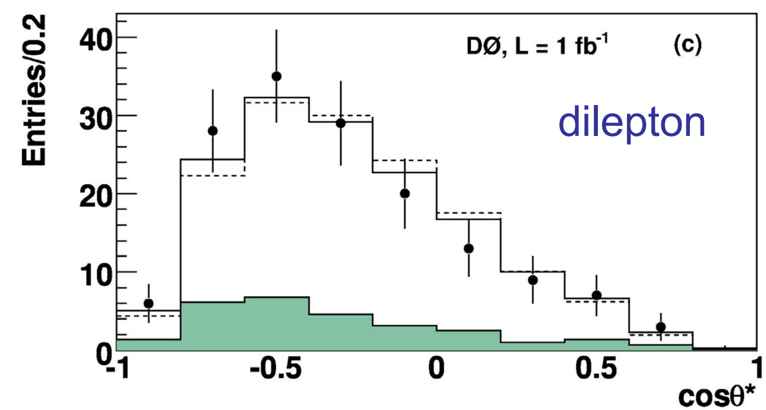
F_0 = 0.66 ± 0.10 (stat) ± 0.06 (syst)

F_+ = 0.01 ± 0.05 (stat) ± 0.03 (syst)

$F_+ <$ 0.12 @ 95% C.L.

DØ uses lepton + jets and dilepton events + 2D fit





$F_0 = 0.43 \pm 0.17$ (stat) $\pm$ 0.10 (syst)

F_+ = 0.12 ± 0.09 (stat) ± 0.05 (syst)

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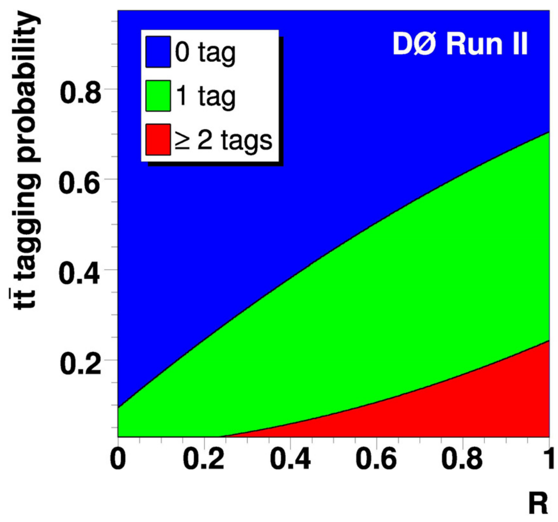
Top Branching Ratio

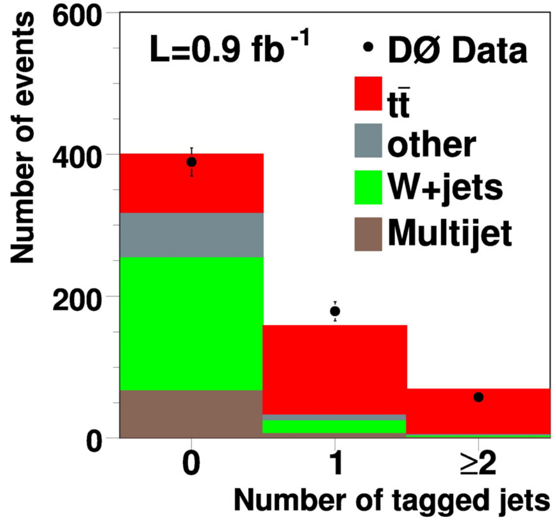
$$R = \frac{\mathcal{B}(t \to Wb)}{\mathcal{B}(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2}$$

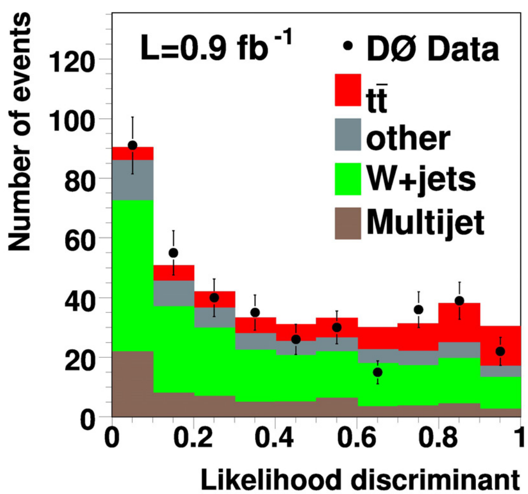
Is there room for
$t \to W + q_x$ decay ?

simultaneous measurement of R and σ (ttbar)

→ split data set in disjoint subsets: N (jets) × lepton type × N (b tags)







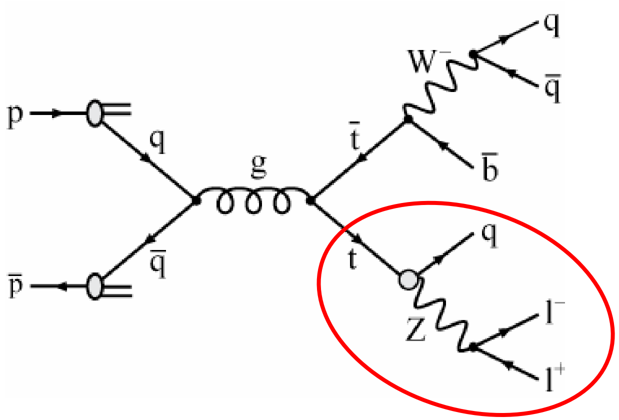
discriminant in the 0 tag sample

$$R = 0.97^{+0.09}_{-0.08} \text{ (stat+syst) and}$$
$$\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84} \text{ (stat+syst)} \pm 0.50 \text{ (lumi) pb}$$

@ M_{top} = 175 GeV

R > 0.79 @ 95% C.L.

Search for FCNC in Top-Decays

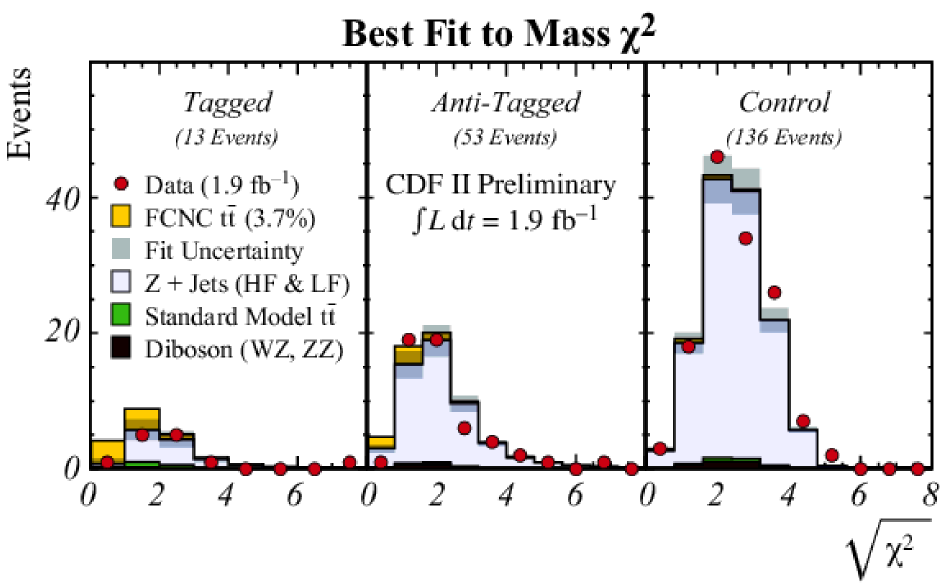


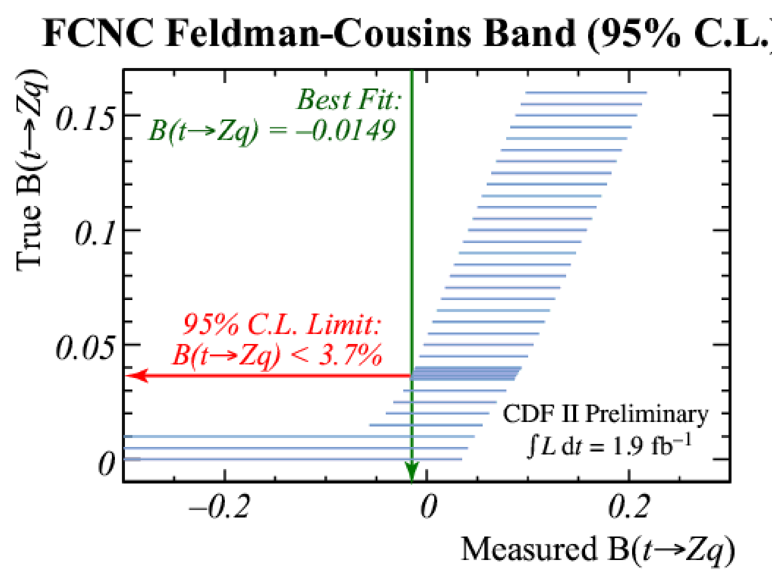
In SM FCNC strongly suppressed in the top sector: BR $\approx 10^{-14}$

Selected events: 4 jets + 2 leptons

Construct mass χ^2 to measure tt-likeness

$$\chi^2 = \left(\frac{M_{qq} - M_W}{\sigma_W}\right)^2 + \left(\frac{M_{bqq} - M_t}{\sigma_{t\to qqb}}\right)^2 + \left(\frac{M_{Zq} - M_t}{\sigma_{t\to Zq}}\right)^2$$



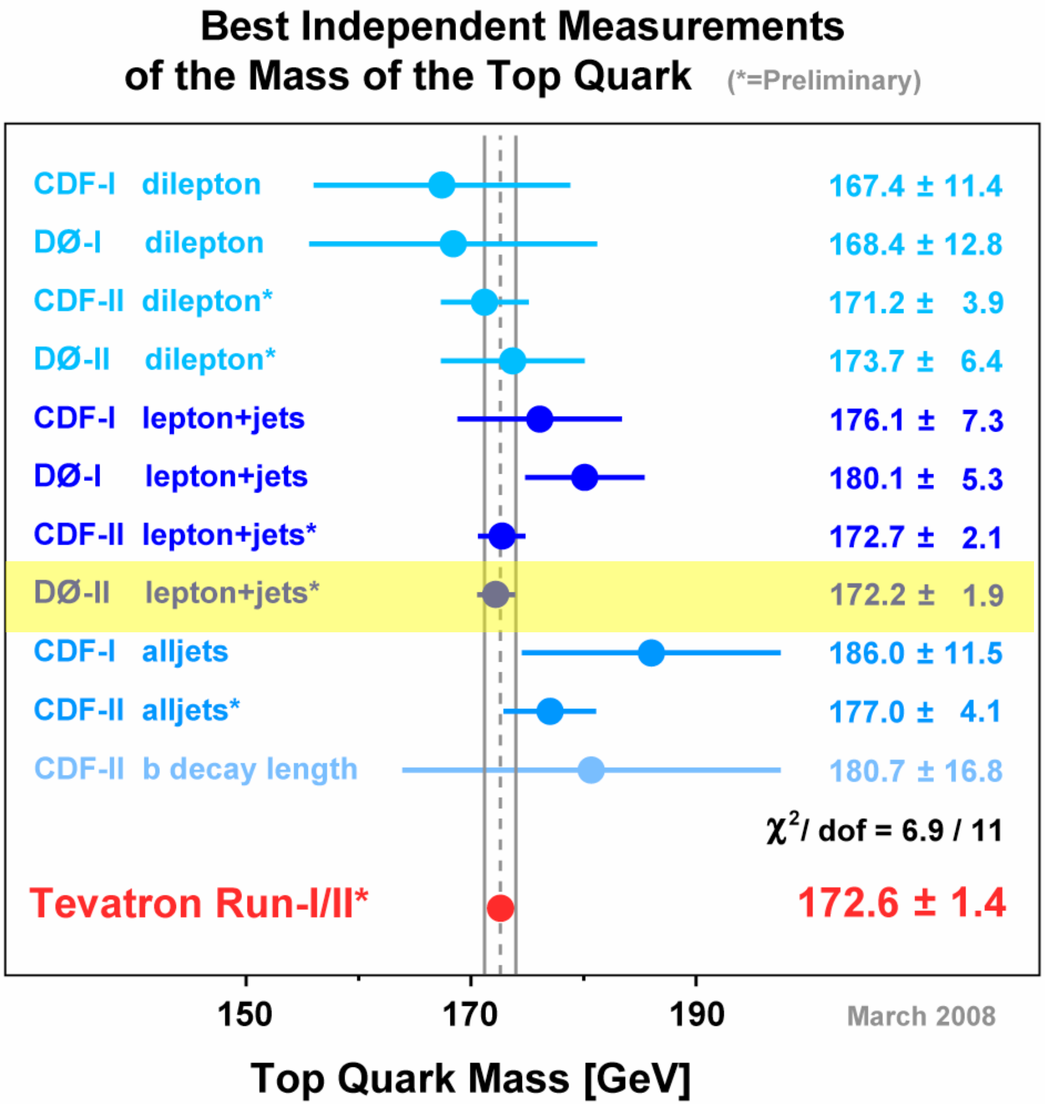


BR($t \to Zq$) < 3.7% @ 95% C.L.

2.3 Top-Quark Intrinsic Properties

1. Mass
2. Width
3. Charge

Precision on M_{top}: 0.8%



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M_t using Matix Elements

Use dependence of matrix element on M_t

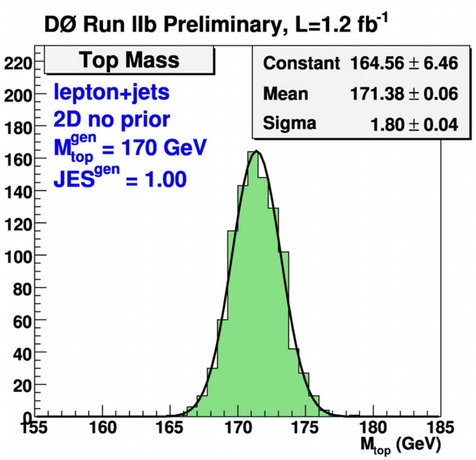
$\Rightarrow$ calculate weight $P(x \mid M_t)$ for each event as funktion of M_t

$$P(\mathbf{x}|M_t) = \frac{1}{N}\int d\Phi_8 |\mathcal{M}_{t\bar{t}}(p;M_t)|^2 \prod_{jets} W(p,j) W(p_T,U) f_{PDF}(q_1) f_{PDF}(q_2)$$

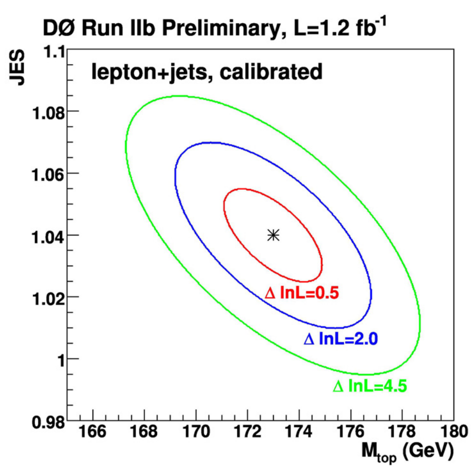
LO matrix element

transfer function for jets and „unclustered energy“

parton distribution functions



In-situ calibration of the jet energy scale with hadronic W mass!



combination of Run IIa and IIb ME results:

$M_{top} = 172.2 \pm 1.1$ (stat) ± 1.6 (syst) GeV/c^2

systematic uncertainties of Run IIb analysis (1.2 fb^{-1})

Systematic	ΔM_t (GeV/c^2)
b-jet energy scale	0.82
Signal model	0.40
Jet energy resolution	0.30
PDFs	0.24
Multijet background	0.20
b-tagging efficiency	0.16
Residual JES	0.03
W heavy flavor factor	0.07
b fragmentation	0.10
MC calibration	0.14
Background model	0.08
trigger efficiency	0.09
TOTAL	1.0

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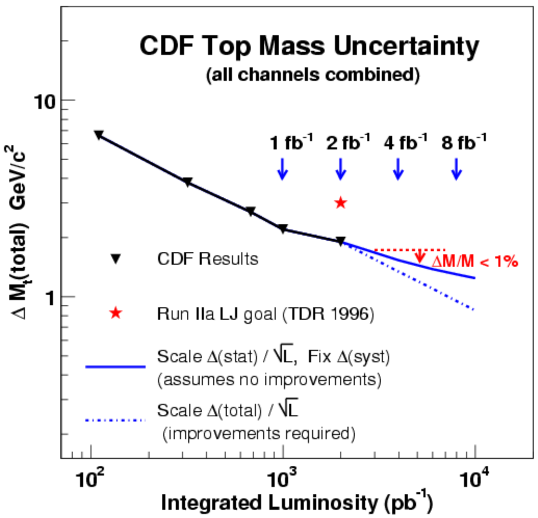
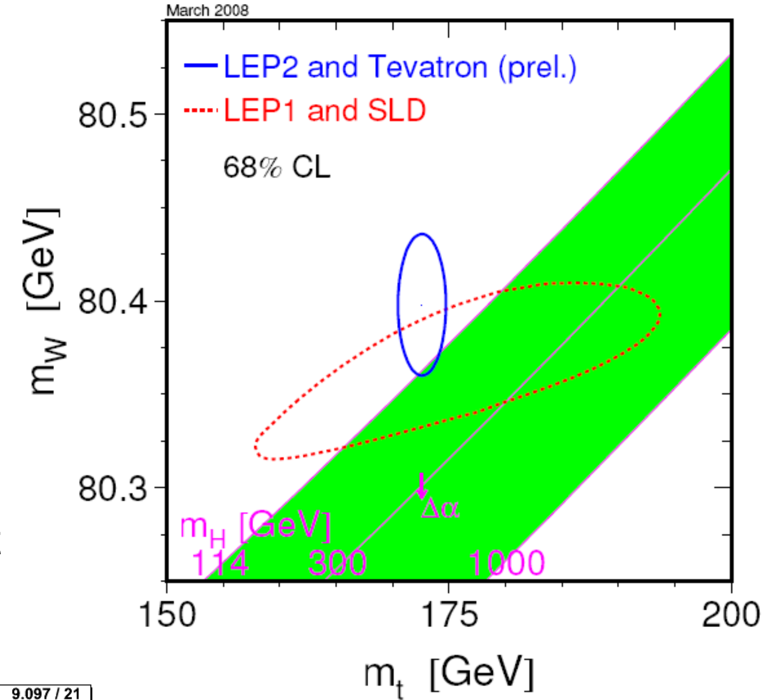
Top Mass Projections and Future

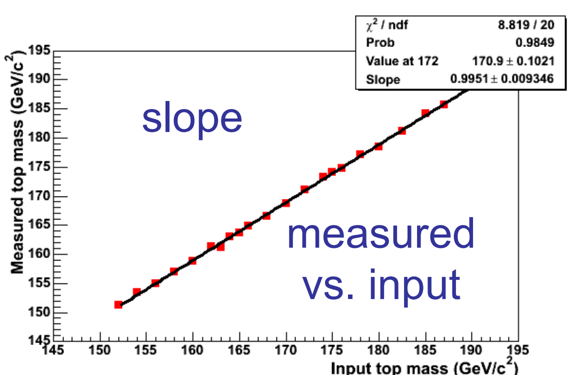


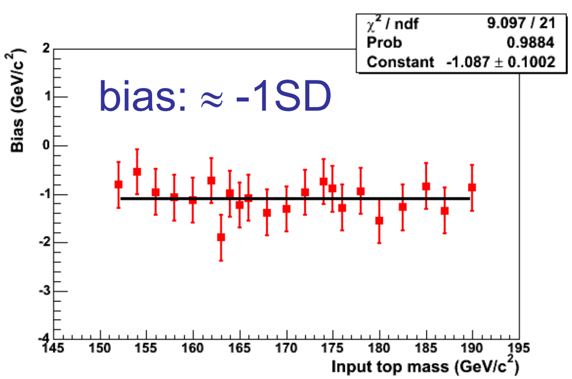
Some uncertainties scale with luminosity
→ still some room for improvements, but not much.

M_W, M_t and M_H



M_t measurements are calibrated to Monte Carlo input masses, e.g. CDF best measurement:





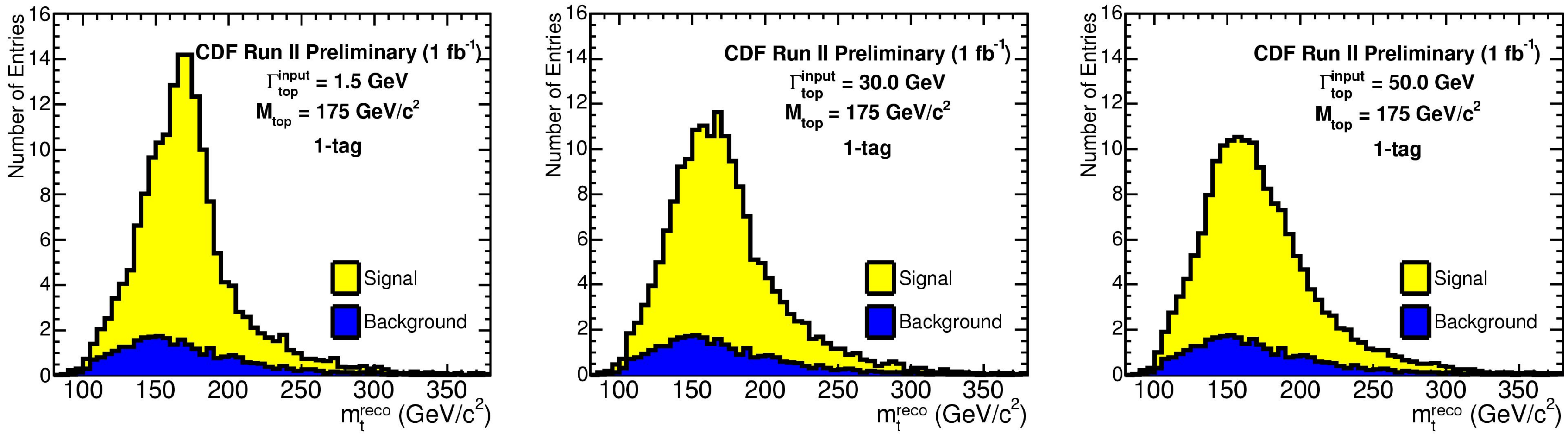
Electroweak fits interpret measured Mt as pole mass.

Is this right?

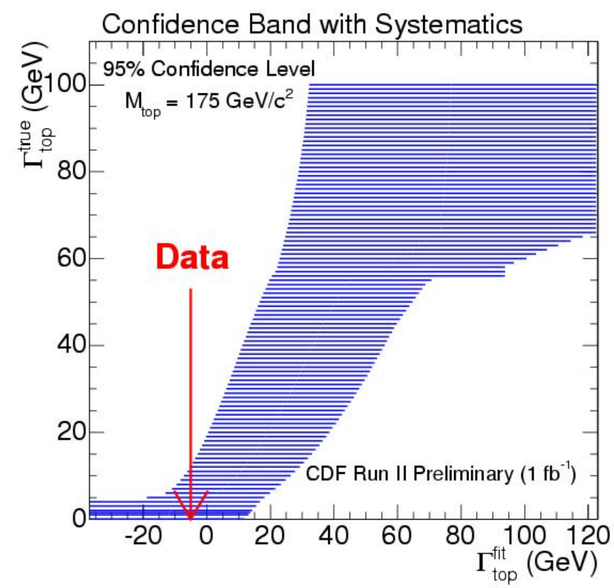
Need dialogue between experiment and theory.

Top Width

standard model prediction: $|V_{tb}| \sim 1$, $\Gamma(t \rightarrow Wb) \sim 1.5$ GeV

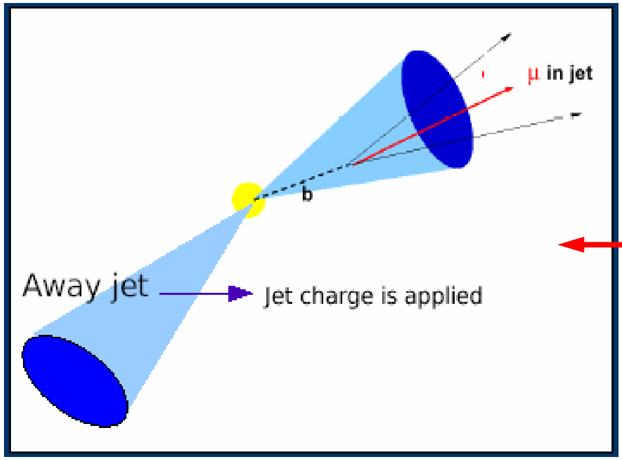


- Uses standard template technique
- Not sensitive yet to SM prediction, but shows direction (think of Γ_W)
- Feldman-Cousins technique to extract uppper limit



Result: $\Gamma_{top} < 12.7$ GeV @ 95% CL

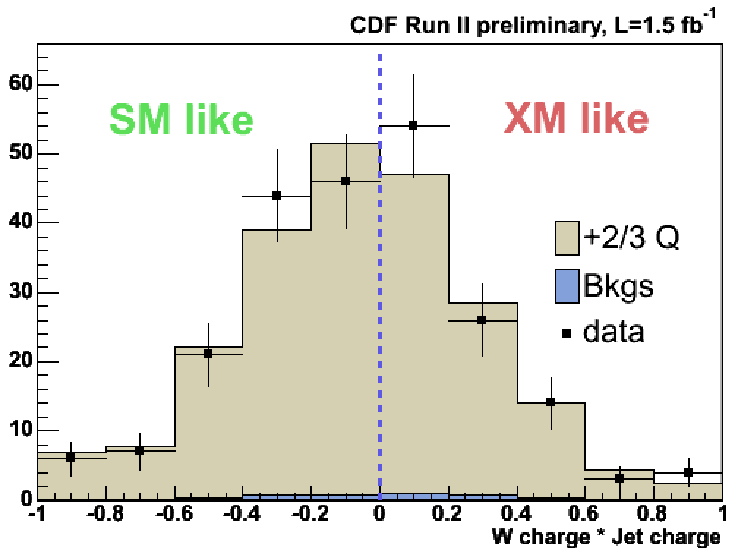
Top Charge



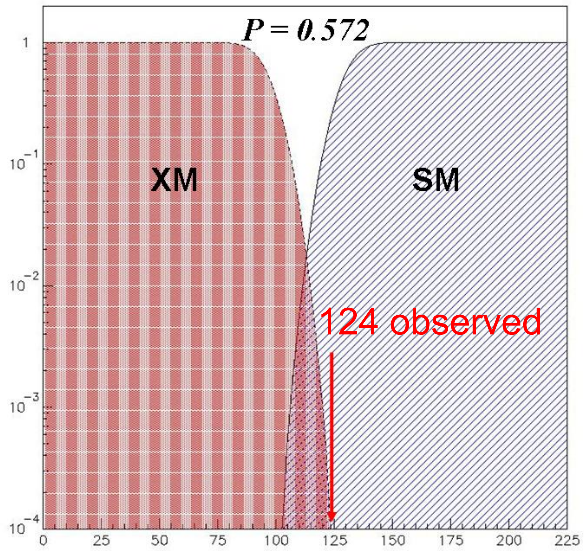
- Use dilepton and lepton + jets events
- b-jet flavor tagging (b or bbar) based on jet charge algorithm
- calibration in generic jet samples

Test standard model (Q_t = +2/3) vs. exotic model (Q_t = -4/3)

$t \rightarrow W^- + b$ or $t \rightarrow W^+ + b$?



124 SM like pairs ↔ 101 XM like pairs

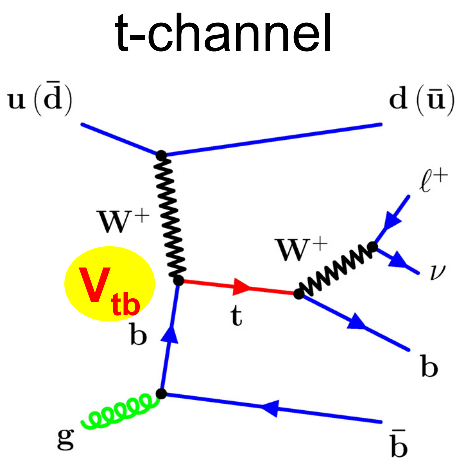


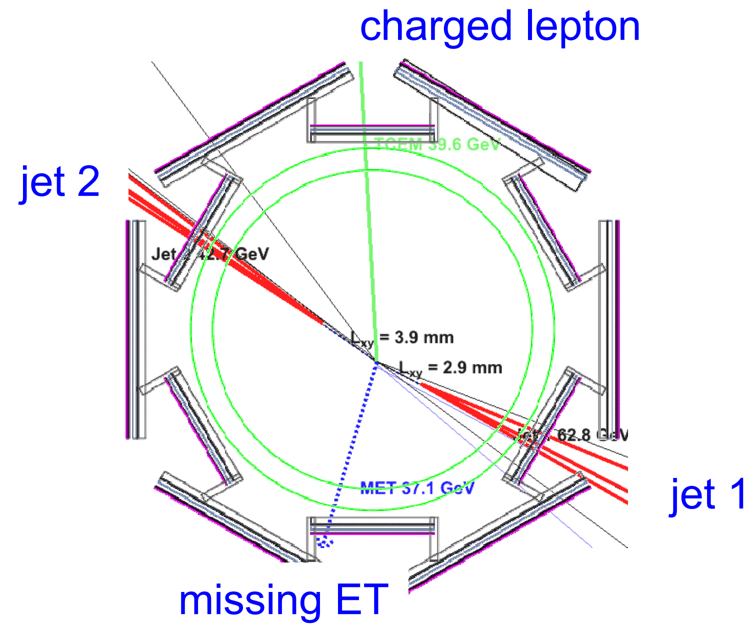
number of SM like pairs out of 225 total

SM strongly favoured over exotic model

2.4 Single Top-Quark Production

top quark production via the weak interaction





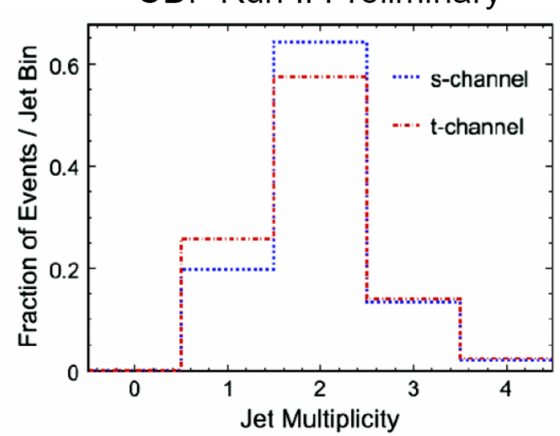
Theoretical cross section predictions at √s = 1.96 TeV

σ_t **= 1.98 ± 0.25 pb** σ_s **= 0.88 ± 0.11 pb**

B.W. Harris et al. Phys. Rev. D 66, 054024 (2002), Z. Sullivan, Phys. Rev. D 70, 114012 (2004)

compatible results: Campbell/Ellis/Tramontano, Phys. Rev. D 70, 094012 (2004), N. Kidonakis, Phys.Rev. D 74, 114012 (2006)

CDF Run II Preliminary



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The CKM Matrix

Cabbibo-Kobayashi-Maskawa (CKM) matrix rotates mass eigenstates of down type quarks into weak eigenstates.

directly measured

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

measured from B_d and B_s mixing

Only indirectly known.

Direct measurement only via single top-quark production.

Are unitarity relations valid? e.g.:

$$V_{ub}^2 + V_{cb}^2 + V_{tb}^2 \stackrel{?}{=} 1$$

Hints for the existence of a 4th generation ?

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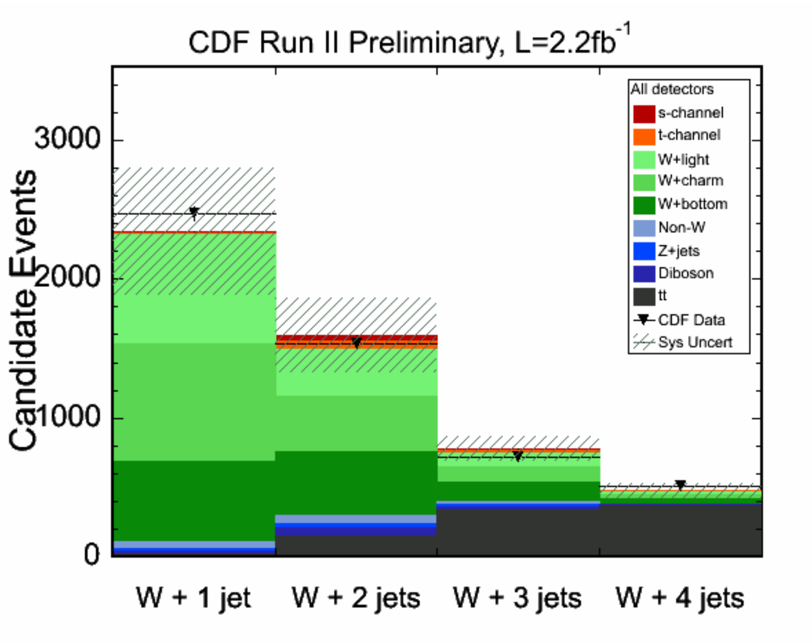
Single-Top Sample at CDF



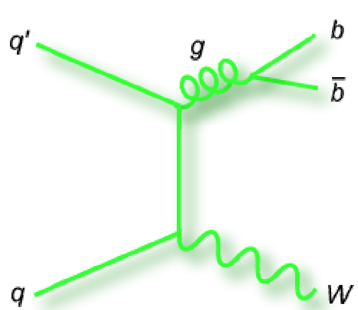
Event Selection

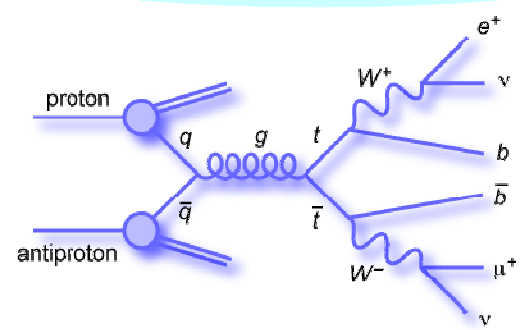
- 1 isolated high-P_T lepton (e,μ)
  p_T > 20 GeV/c, $|\eta_e|$ < 2.0 and $|\eta_\mu|$ < 1.0
- MET > 25 GeV
- Jets: N_{jets} = 2 or 3,
  E_T > 20 GeV, $|\eta|$ < 2.8
  $\geq$ 1 b tag (secondary vertex tag)

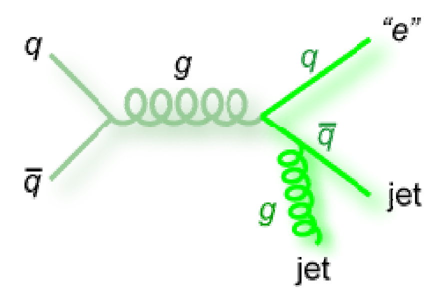
after event selection: S/B = 5.7%
$\rightarrow$ counting experiment not feasible

new analyses with 2.2 fb^{-1}

very challenging backgrounds







Single-Top Analysis Strategy

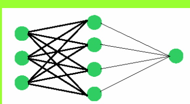
full selected data set:

split in subsets of different purity

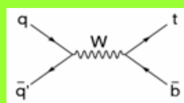
- **W + 2 jets**
  - **1 tag**
  - **≥ 2 tags**
- **W + 3 jets**
  - **1 tag**
  - **≥ 2 tags**

multivariate methods

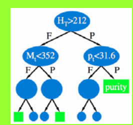
neural networks



matrix elements



decision trees



likelihood discriminants

$$L^j(\vec{x}) = \frac{\prod_{i=1}^{n_{var}} p_i^j(x_i)}{\sum_{k=1}^{5} \prod_{i=1}^{n_{var}} p_i^k(x_i)}$$

combined search

t-channel + s-channel = one single-top signal
cross section ratio is fixed to SM value.
important for „discovery“ and test $|V_{tb}| << 1$

separate search

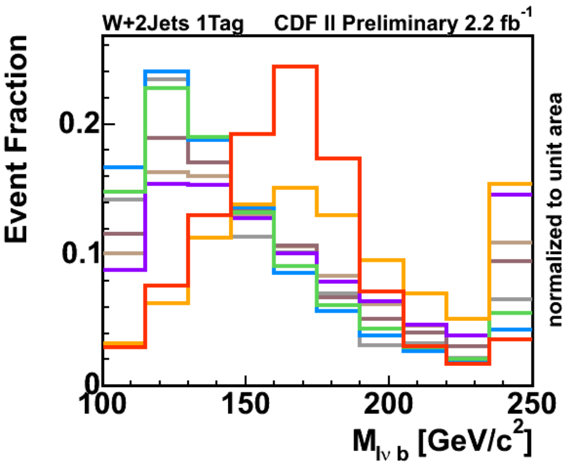
regard t-channel and s-channel as separate processes
important to be sensitive to new physics processes

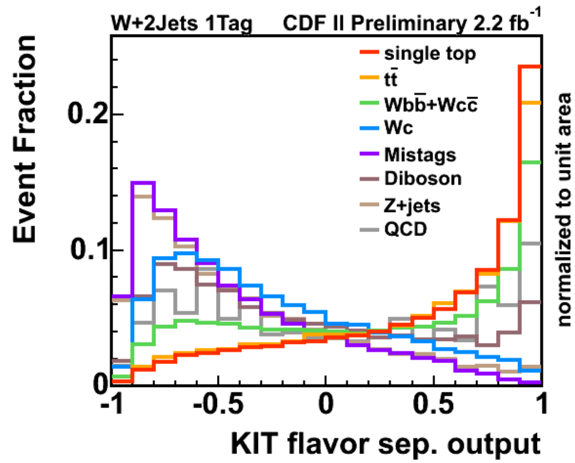
statistical analysis

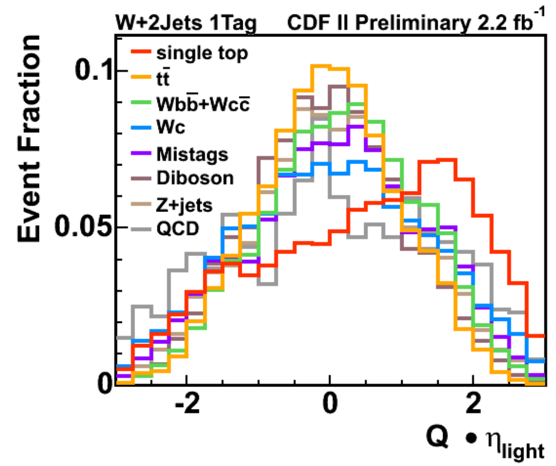
cross section measurement
Bayesian treament

hypotheses test
modified Frequentist approach

Neural Network Analysis



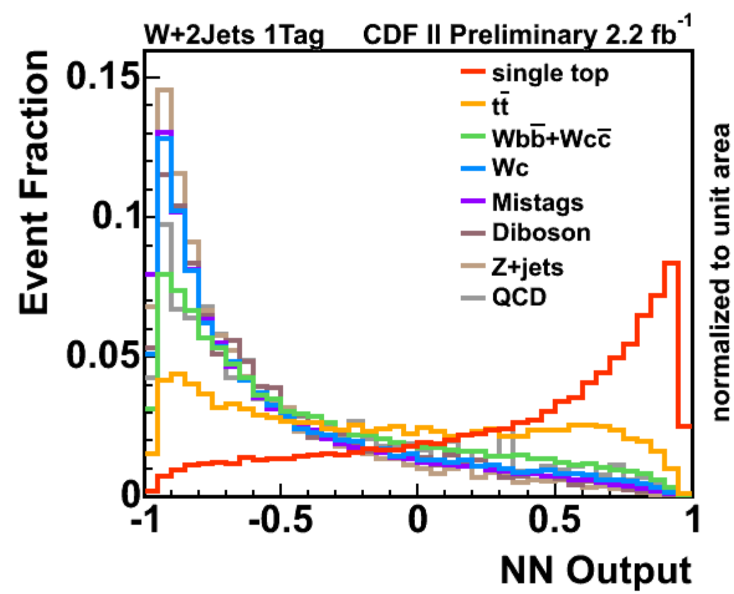




• • •

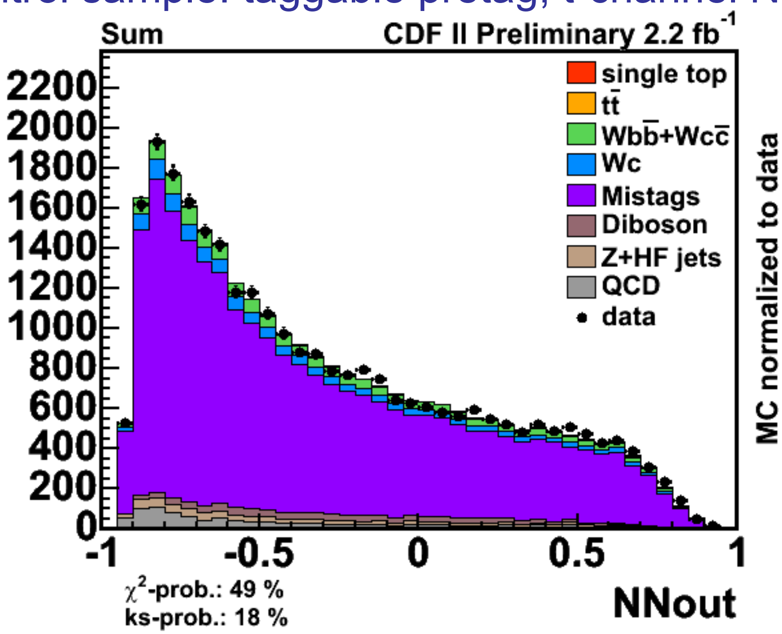
Idea:
combine many variables into one more powerful discriminant

14 variables are used, among them $Q \cdot \eta$, reconstructed top quark mass, top quark polarisation angle, Jet E_T and η, NN b tagger output, W boson η, …

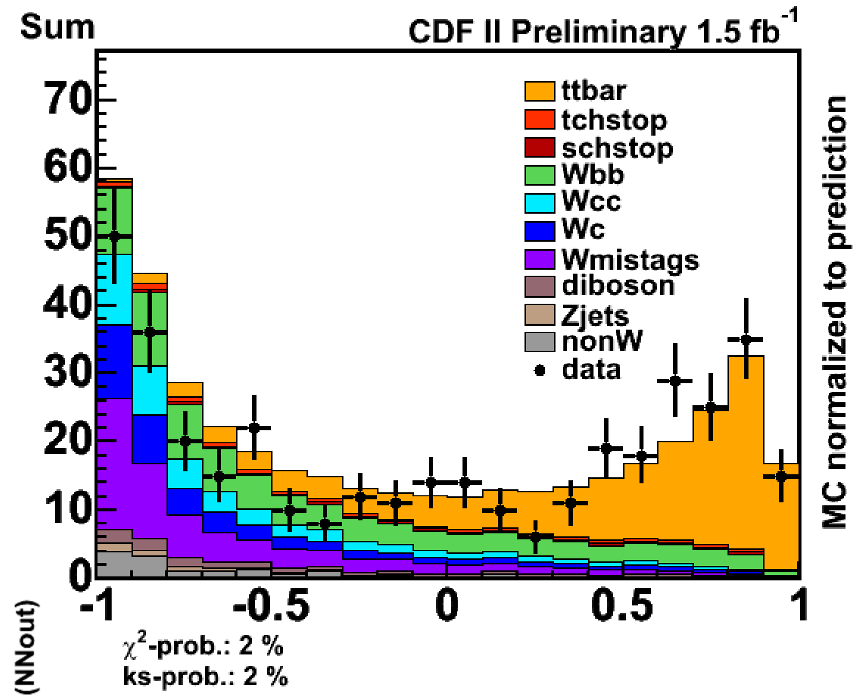


Neural Networks Validation

control sample: taggable pretag, t-channel NN



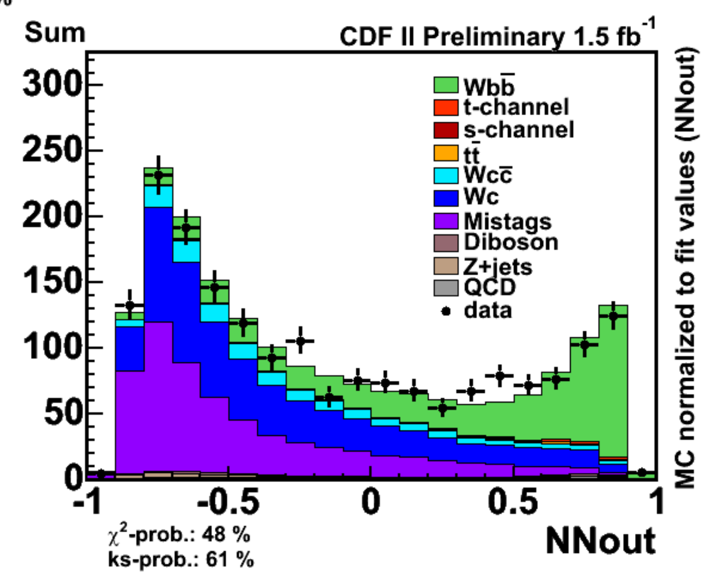
control sample: W + 3 jets, ttbar network



$\Rightarrow \quad \sigma(t\bar{t}) = 7.5 \pm 0.8$ pb

Fit value is in excellent agreement with CDF average!

control sample: W + 1 jet, Wbb network



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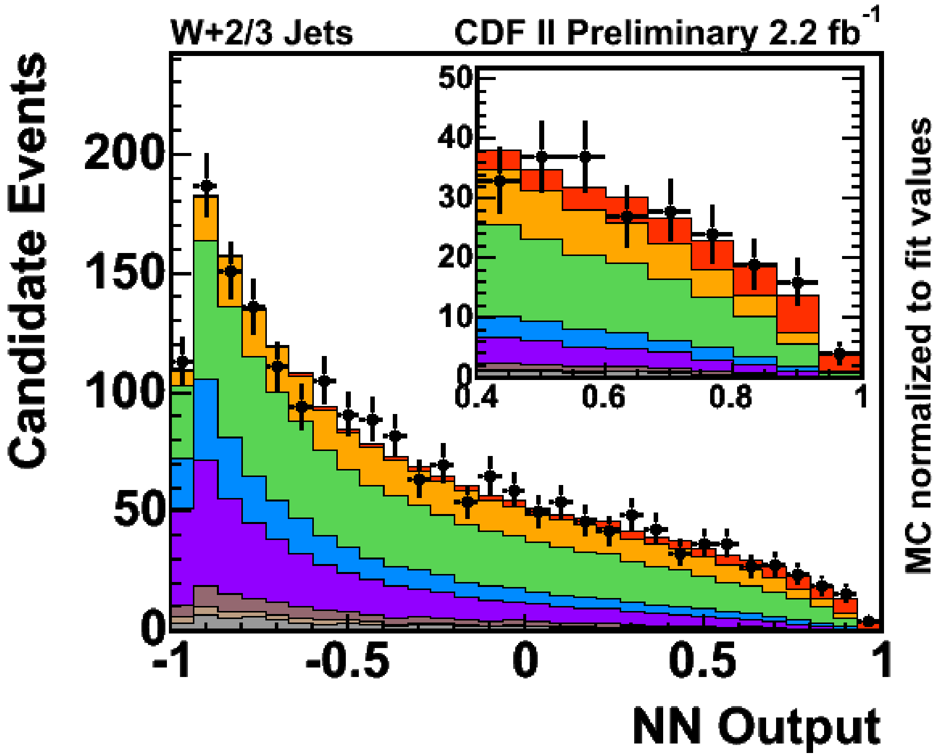
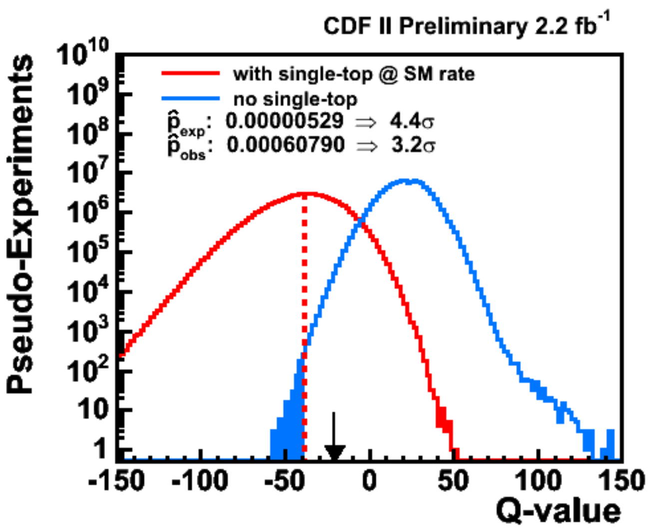
Neural Network Result

combined search



hypothesis test

Use Q-values to compute the sensitivity:
Q = 2 (ln LL(S) – ln LL(B))



$$\sigma_{\text{single-top}} = 2.0^{+0.9}_{-0.8}(\text{stat.} + \text{syst.})\ \text{pb}$$

sensitivity: 4.4 σ

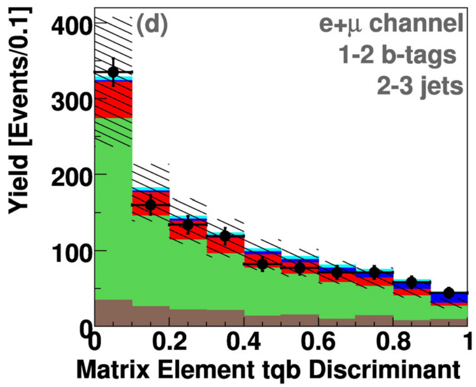
observation: 3.2 σ

prediction: $\sigma_{\text{single top}}$ **≈ 2.9 ± 0.4 pb**

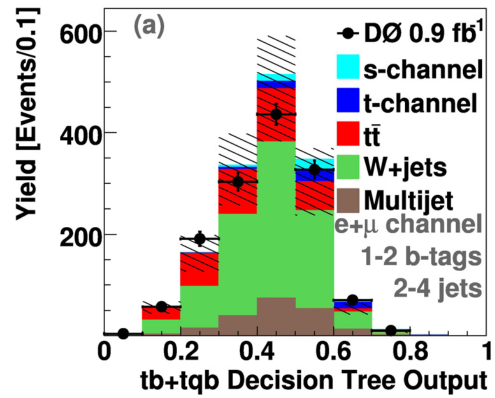
We see evidence for single-top, but less than expected!

Evidence for Single-Top at the Tevatron

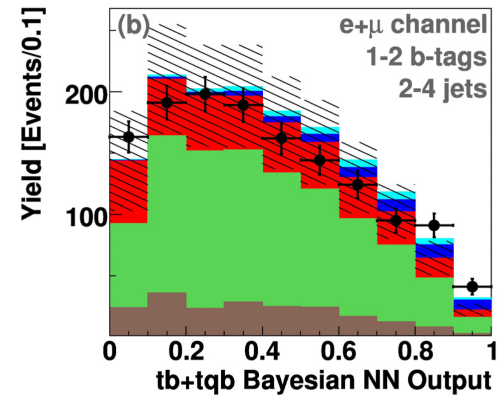
Matrix Element Method



Boosted Decision Trees

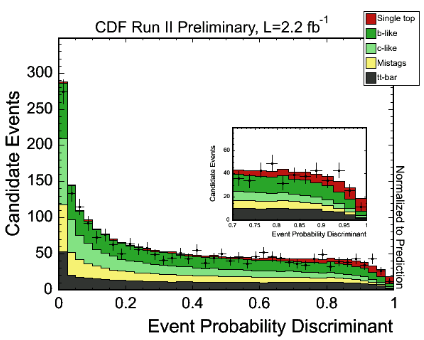


Neural Networks

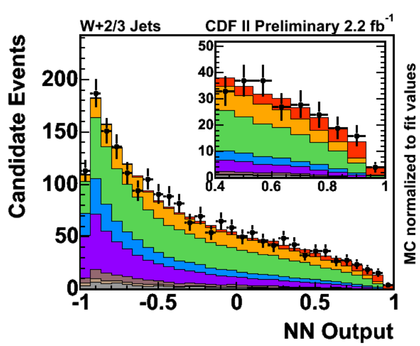


excess: 3.2 σ 3.4 σ 3.1 σ

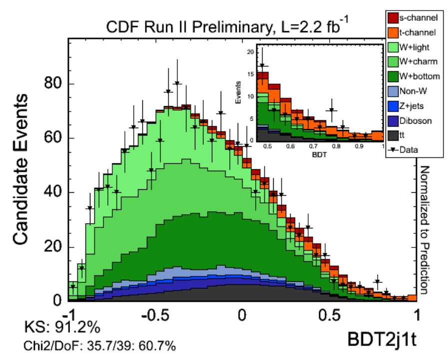
Matrix Element Method



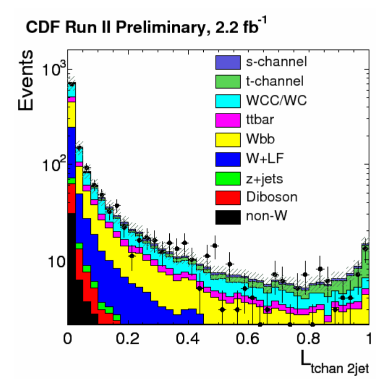
Neural Networks



Decision Trees



Likelihood Discriminants



excess: 3.4 σ 3.2 σ 2.8 σ 2.0 σ

Both experiments and most analyses see now evidence for single-top, but …

Single-Top Cross Sections

Consistent picture within the experiments:

- All CDF cross sections are low
- All DØ measurements are high

Analyses within experiment use same data set: → strong correlation

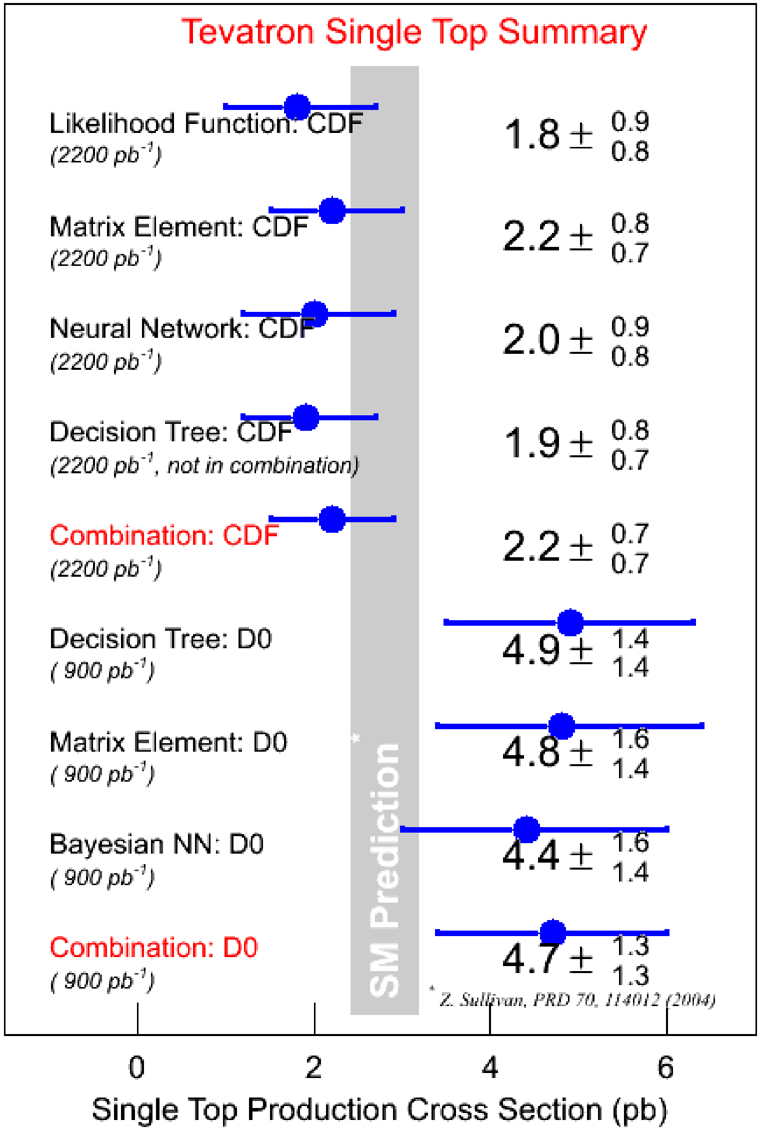
CDF: 59% - 74% DØ: 59% - 66%

Compatibility of both experiments with SM: 14%

Stay tuned! More data are being analysed.

Once experiments have settled on common value and a discrepancy with the prediction remains, single-top may become a case for „loops and legs“ again.

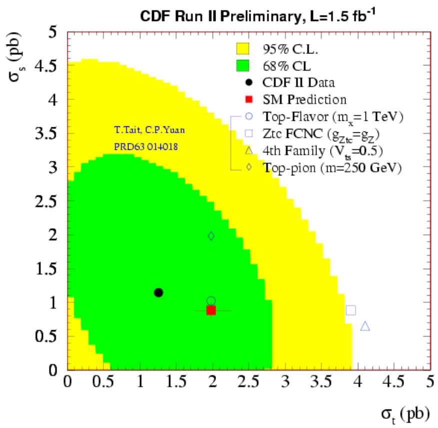
Or may be you want to get a head start on this?



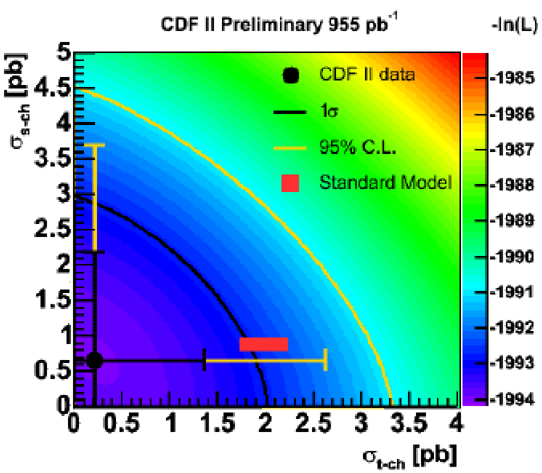
Interesting: Separate Search

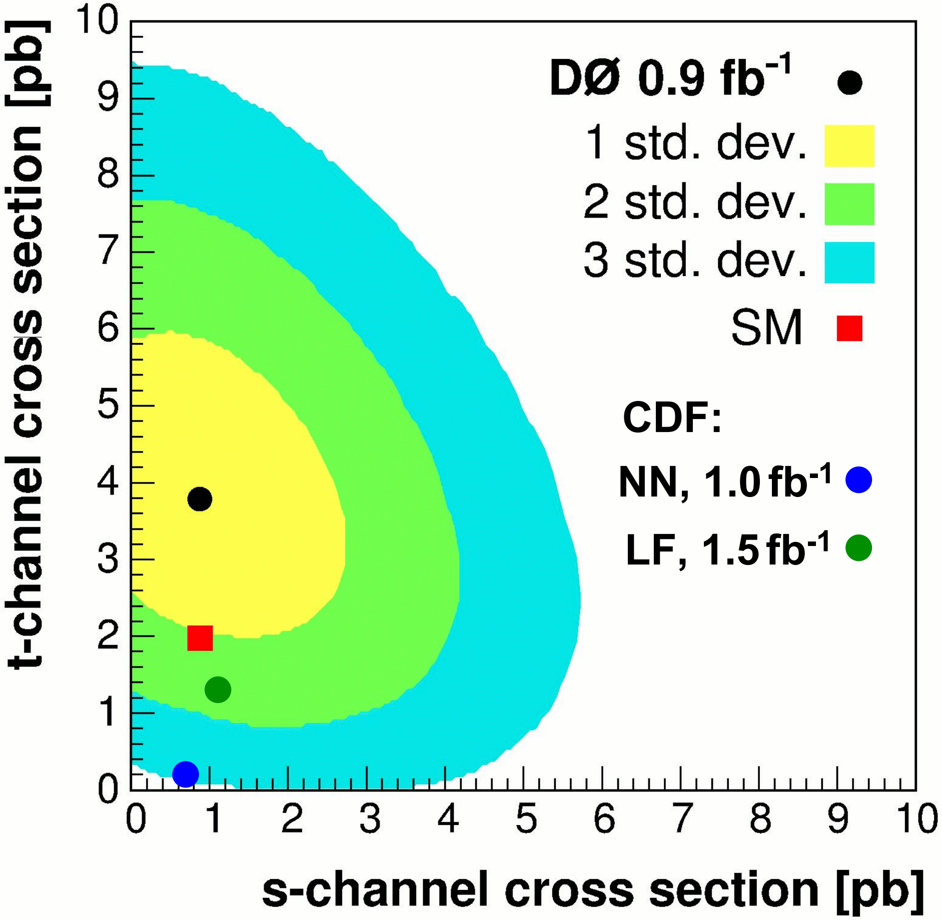
t-channel and s-channel are fitted separetely

CDF: LF



CDF: NN





- agreement on s-channel: σ ≈ SM prediction
- disagreement on t-channel:
  σ (CDF) < σ(SM) << σ(DØ)

Interpretation: V_{tb} Measurement

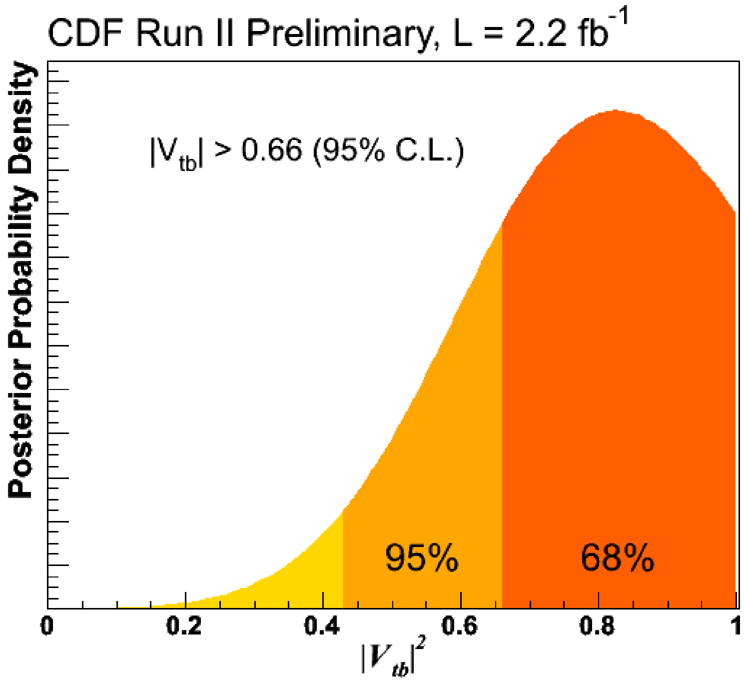
Assuming SM production:

- **Pure V-A and CP conserving interaction**
- **$|V_{tb}|^2 \gg |V_{td}|^2 + |V_{ts}|^2$ or**

B(t →Wb) ~ 100%

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$

That´s where your input from theory comes in.



Super-discriminant combination:

$|V_{tb}|$ = 0.88 ± 0.14 (exp.) ± 0.07 (theory)

$|V_{tb}|$ > 0.66 (95% C.L.)

Measurement consistent with SM prediction, $V_{tb} \approx 1$

Completing the Jig-Saw Puzzle of Top-Quark Physics

M(t′) > 284 GeV/c² @ 95% CL

large charge asymmetry

A = 24 ± 13 ± 4 %

R > 0.79 @ 95% C.L.

M_{top} = 172.6 ± 1.4 GeV

0.8% accuracy!

new Tevatron combination

3.7 σ evidence for single-top production

CDF: σ = 2.2 ± 0.7 pb

DØ: σ = 4.7 ± 1.3 pb

Γ_{top} < 12.7 GeV @ 95% CL

F_0 = 0.66 ± 0.10 ± 0.06

F_+ = 0.01 ± 0.05 ± 0.03

3 fb^{-1} results will be ready for ICHEP08

M(Z′) < 760 GeV

lepto-phobic Z′

$$\frac{\sigma(gg \to t\bar{t})}{\sigma(p\bar{p} \to t\bar{t})} = 0.07 \pm 0.14 \pm 0.07$$

σ (ttbar) = 7.3 ± 0.5 ± 0.7 pb

BR(t → Zq) < 3.7% @ 95% C.L.

Q_{top} = +2/3 strongly favoured over Q = -4/3

Backup

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Improved *b* Jet Identification

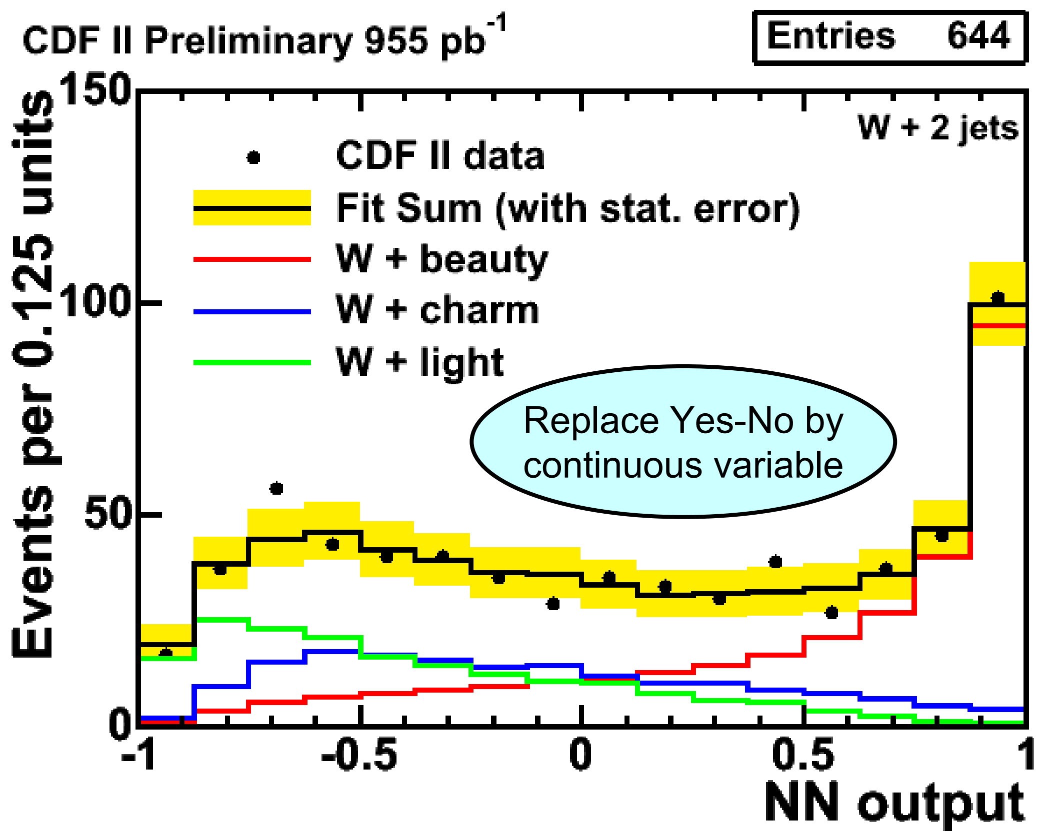
About 50% of the background in the W + 2 jets sample do **NOT** contain **b quarks** even though a secondary vertex was required!

jet and track variables, e.g. vertex mass, decay length, track multiplicity, …

⊕ neural network
⇒ powerful discriminant

New possibility:
In situ measurement of the flavor composition in the W + 2 jets sample

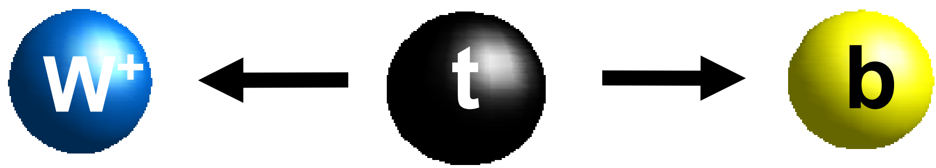
Fit to NN output for W + 2 jets events with one secondary vertex (955 pb^{-1})



mistags / charm …………………… beauty

Helicity of the W Boson in Top Decay

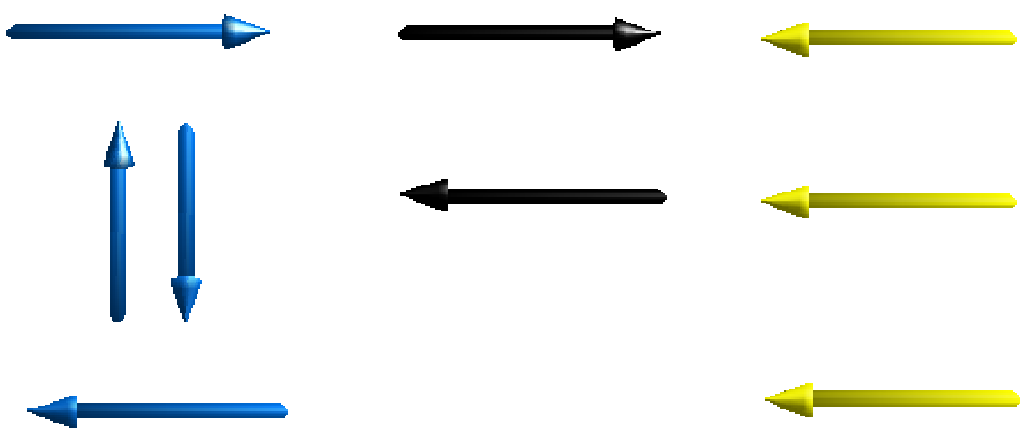
Spin : $s_W = 1$ $s_t = 1/2$ $s_b = 1/2$



assume b quark to be massless

Helicity:

standard model prediction:



$h_W = -1$

$$f_- = \frac{2m_W^2}{2m_W^2 + m_{\text{top}}^2} = 0.3$$

$h_W = 0$

$$f_0 = \frac{m_{\text{top}}^2}{2m_W^2 + m_{\text{top}}^2} = 0.7$$

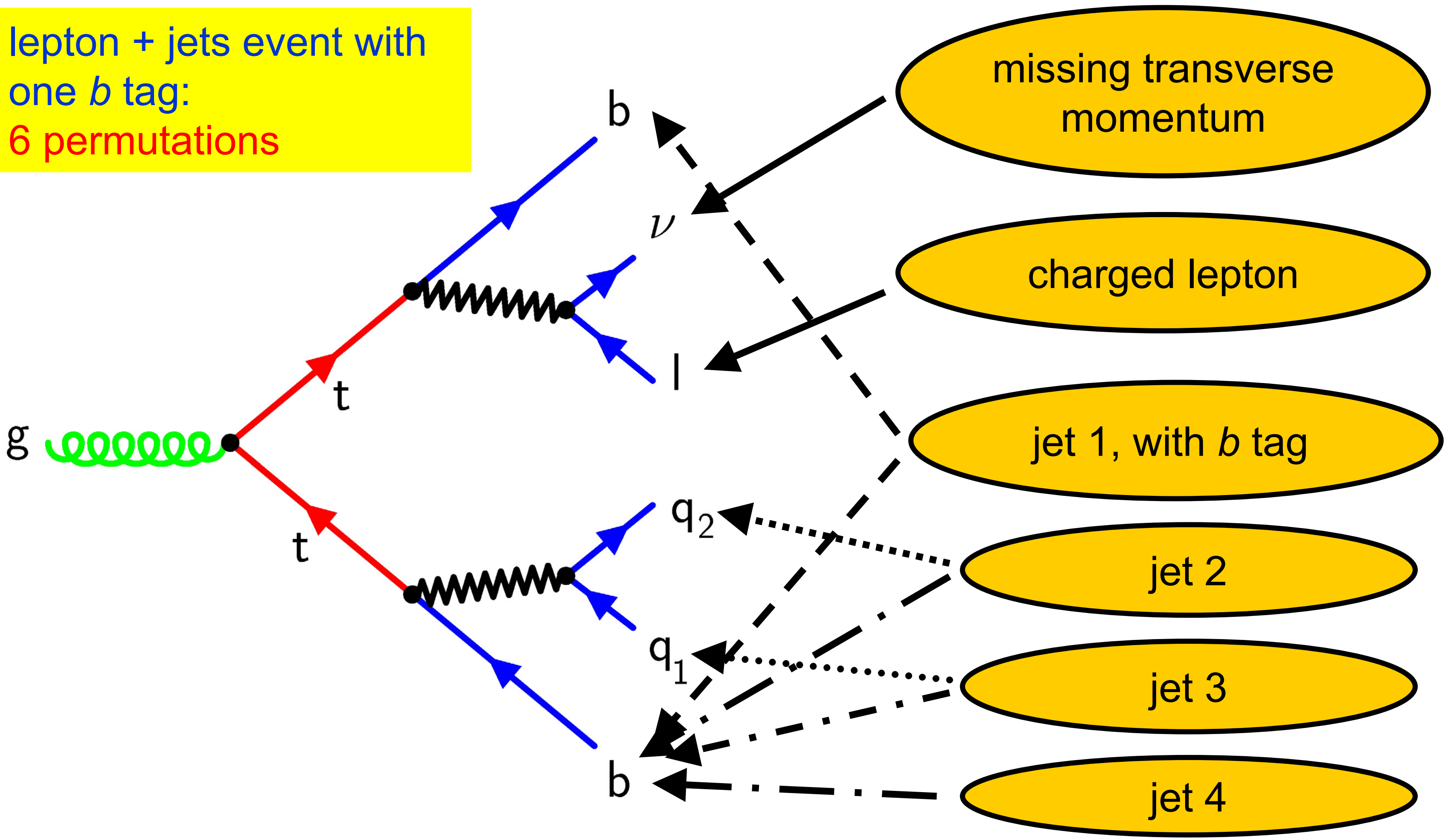
$h_W = +1$

$$f_+ = 0$$

Top-Antitop Kinematic Reconstruction

Measured objects must be matched to elementary particles.

lepton + jets event with
one *b* tag:
6 permutations



Kinematic Fit

Which one is the best assignment?

→ test all assignments
→ lepton and jet momenta are varied within their uncertainties, such that χ^2 is minimized.

$$\chi^2 = \sum_{i=\ell,4\,\text{jets}} \frac{(p_T^{i,\text{fit}} - p_T^{i,\text{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{\text{UE,fit}} - p_j^{\text{UE,meas}})^2}{\sigma_j^2}$$
$$+ \frac{(M_{\ell\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2}$$
$$+ \frac{(M_{b\ell\nu} - m_t^{\text{reco}})^2}{\Gamma_t^2} + \frac{(M_{bjj} - m_t^{\text{reco}})^2}{\Gamma_t^2}$$

Choose combination with the smallest χ^2:

⇒ estimate of m_{top} for this event

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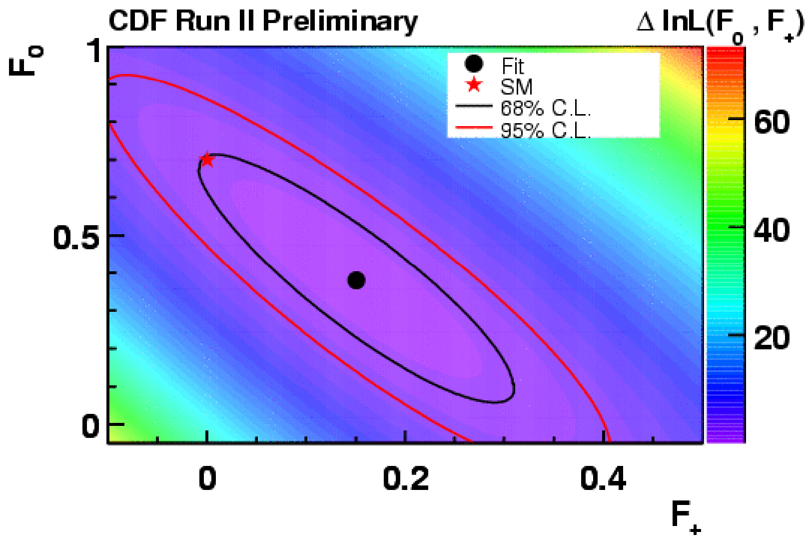
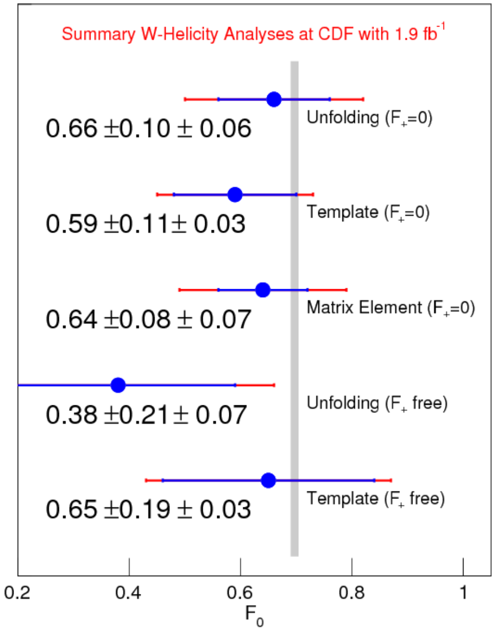
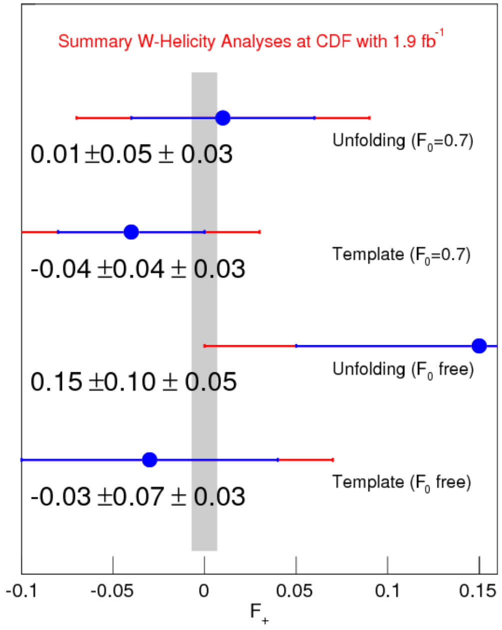
2D W helicity Result







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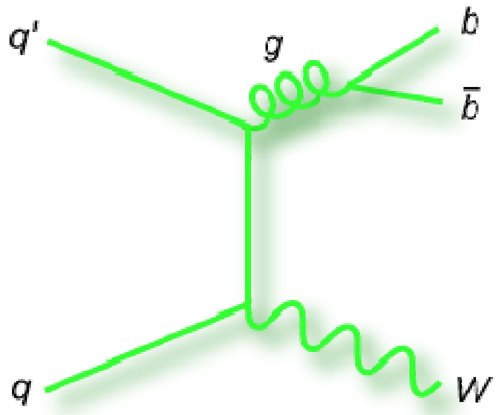
Background Processes

W + heavy flavor: Wbb, Wcc, Wc

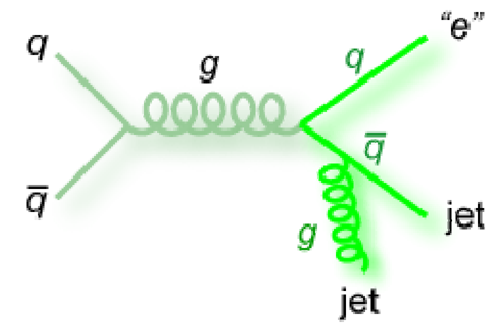


W+light jets (mistags)

diboson: WW, WZ, ZZ

Z+jets

non-W: multijet
production, bb production



top-antitop pairs