Top Quark Cross Section and Spin Correlations

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- $t\bar{t}$ Production Cross-section measurements at Tevatron
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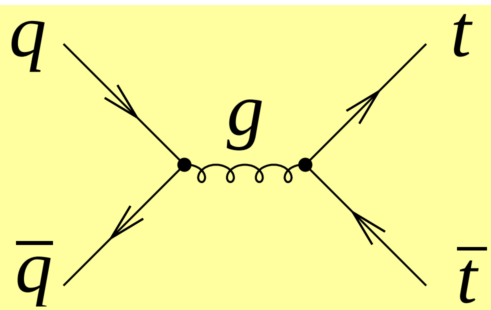
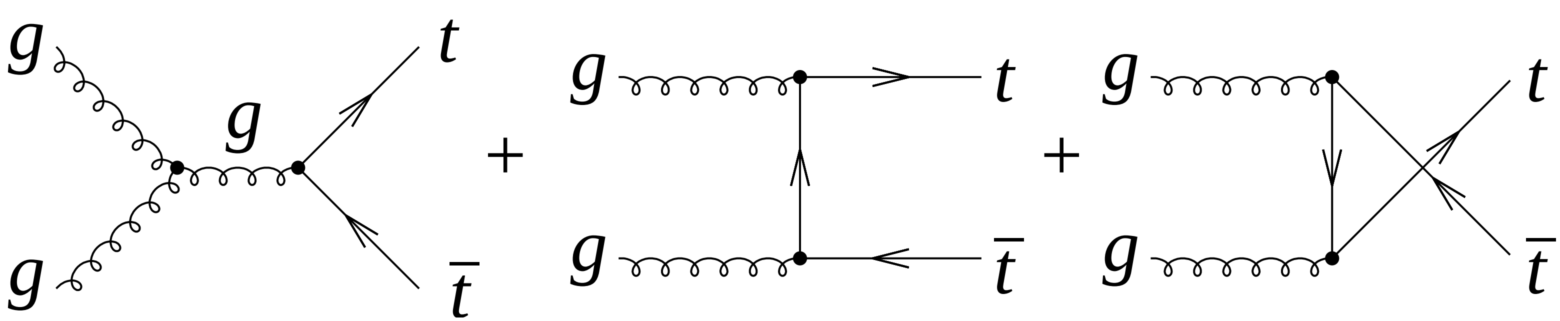
$t\bar{t}$ Pair Production at the Tevatron

- Tevatron ($p\bar{p}$ collisions, $\sqrt{s} = 1.96\,\mathrm{TeV}$)
  - Pair production through strong interaction.
    ⇔ Single top production through electro-weak interaction.
  - $q\bar{q}$ annihilation is dominant process.
    ⇔ Gluon fusion is dominant for LHC.



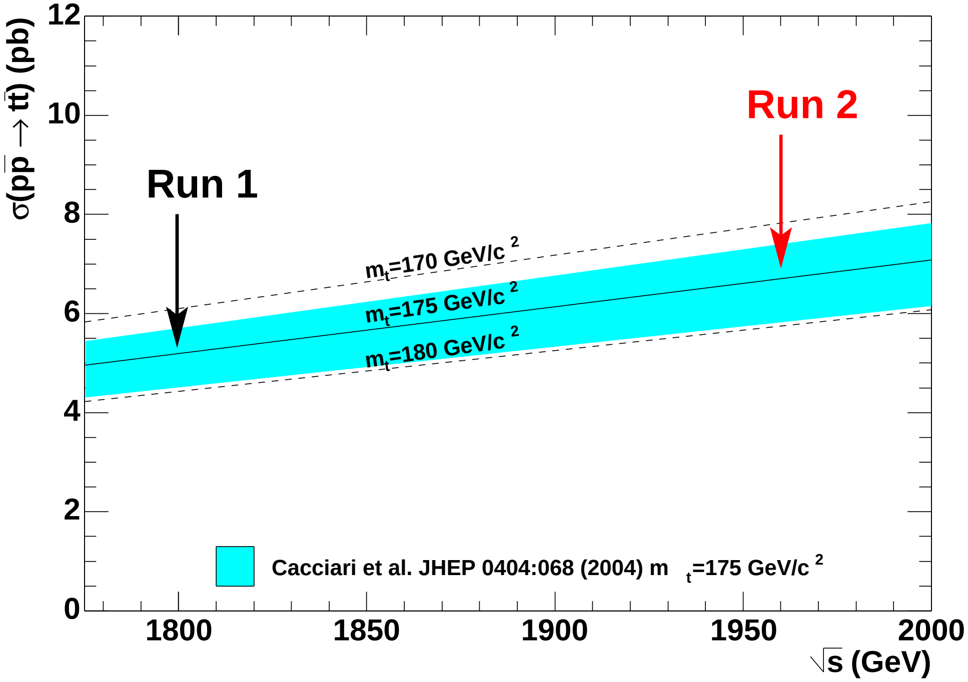
$q\bar{q}$ annihilation($\sim 85\%$)

$$\sigma(\mathrm{gg} \to t\bar{t}) : \sigma(\mathrm{qq} \to t\bar{t}) = 15\% : 85\% \,(\mathrm{NLO})$$



gluon fusion ($\sim 15\%$)

Theoretical prediction for $t\bar{t}$ production cross-section at NLL



$\Rightarrow \ \sigma(t\bar{t}) \sim 6.7\,\mathrm{pb}\ (M_t = 175\,\mathrm{GeV}/c^2)$

uncertainty(PDF, α_s, μ_R, μ_F) $\sim 15\%$

M. Cacciari, et al., JHEP 404,68 (2004)

$t\bar{t}$ cross-section measurement is

$\rightarrow$ Important test of perturbative QCD.

$\rightarrow$ Sensitive to new physics (e.g. resonance production of $t\bar{t}$).

and

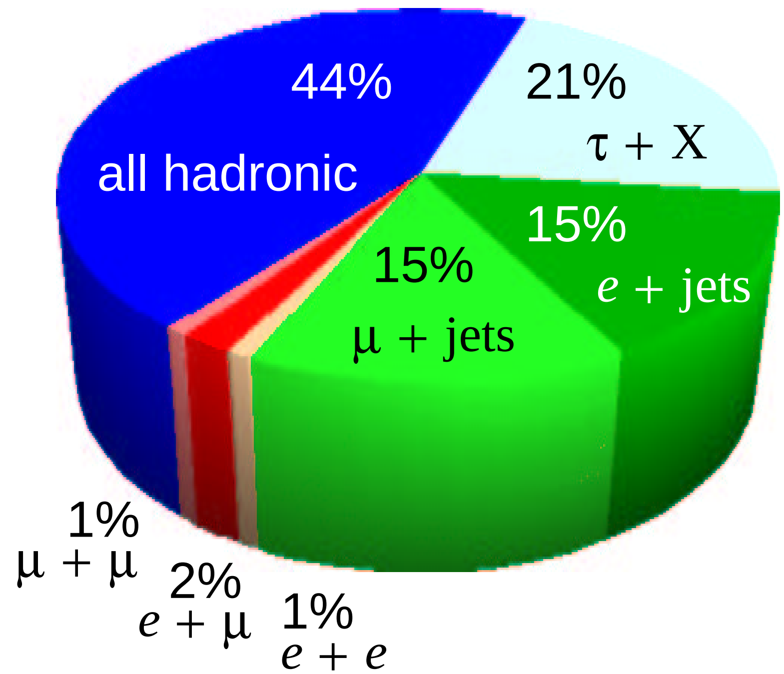
$\rightarrow$ To identify $t\bar{t}$ signal is a fundamental step to any top property analysis.

3 Categories of Event Signature in $t\bar{t}$ Production

Top quark decays to W and b at a rate of $\sim$100% $\mathrm{Br}(t \to W^+ b) \simeq 1$

Decay channels of $t\bar{t}$

$t \to W^+ b$	b	b	b	b
$\hookrightarrow$	$\ell^+\nu$	$q\bar{q}'$	$\ell^+\nu$	$q\bar{q}'$
$\bar{t} \to W^- \bar{b}$	$\bar{b}$	$\bar{b}$	$\bar{b}$	$\bar{b}$
$\hookrightarrow$	$\ell^-\bar{\nu}$	$\ell^-\bar{\nu}$	$q\bar{q}'$	$q\bar{q}'$



dilepton channel

$\Rightarrow$ 2 leptons, $\not\!\!E_T$, 2 b-jets

lepton+jets channel

$\Rightarrow$ 1 lepton, $\not\!\!E_T$, 4 jets (including 2 b-jets)

all hadronic channel

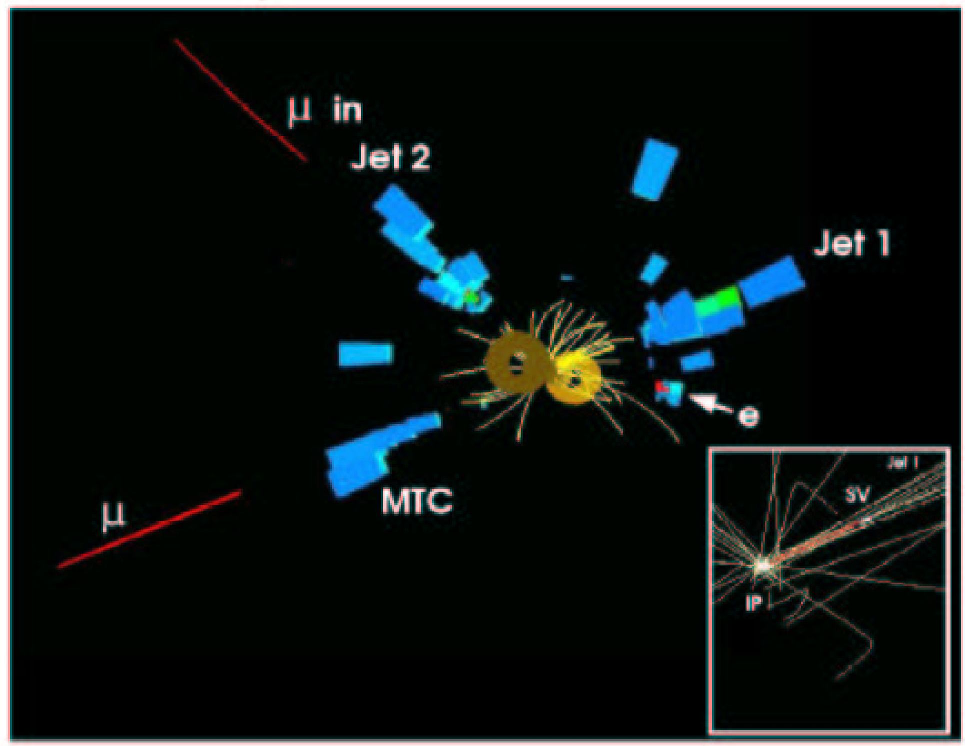
$\Rightarrow$ 6 jets (including 2 b-jets)

Cross Section Measurements in Dilepton Channels

- $t\bar{t} \to W^+ b W^- \bar{b} \to \ell^+ \nu b \ell^- \bar{\nu} \bar{b}$
- Signiture: 2 high P_T leptons, $\not{E}_T$, 2 b-jets
- Good signal to background ratio without b-tagging.
- Dominant backgrounds
  - Drell-Yan: $Z/\gamma^* \to ee$, $\mu\mu$, $\tau\tau$
  - Diboson: WW, WZ, ZZ
  - Fake: W+QCD jets
- Smallest braching fraction $\sim 5\%$

$t\bar{t}$ dilepton($e\mu$ channel) candidate at DØ $\Rightarrow$

$e\mu$ candidate event



Counting Method with Standard(Traditional) Selection

- Cross-section based on counting number of candidates and bkg.

$$\sigma(t\bar{t}) = \frac{N_{\rm obs} - N_{\rm bkg}}{\epsilon_{\rm tot} \int \mathcal{L} {\rm d}t}$$

$N_{\rm obs}$: Number of observed candidates

$\epsilon_{\rm tot}$: Acceptance $\times$ efficiency

- Signal selection
  - 2 high P_T lepton (e or μ)
  - Missing transverse energy($\not\!\!E_T$)
  - 2 (or more) jets
  - Veto Z inclusive events

- Result at DØ

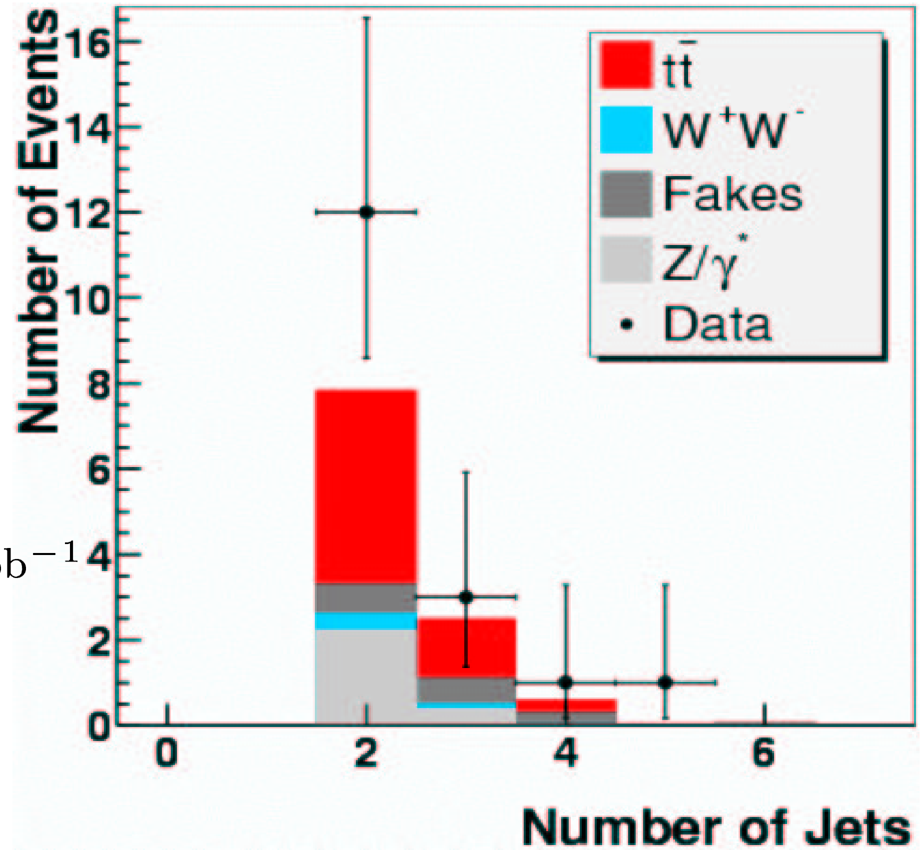
  ee: $156\,{\rm pb}^{-1}$, $\mu\mu$: $139.6\,{\rm pb}^{-1}$, $e\mu$: $142.7\,{\rm pb}^{-1}$

  - Observed candidates

    $N_{\rm obs} = 17$

  - Expected backgrounds

    $N_{\rm bkg} = 4.76 \pm 0.65$

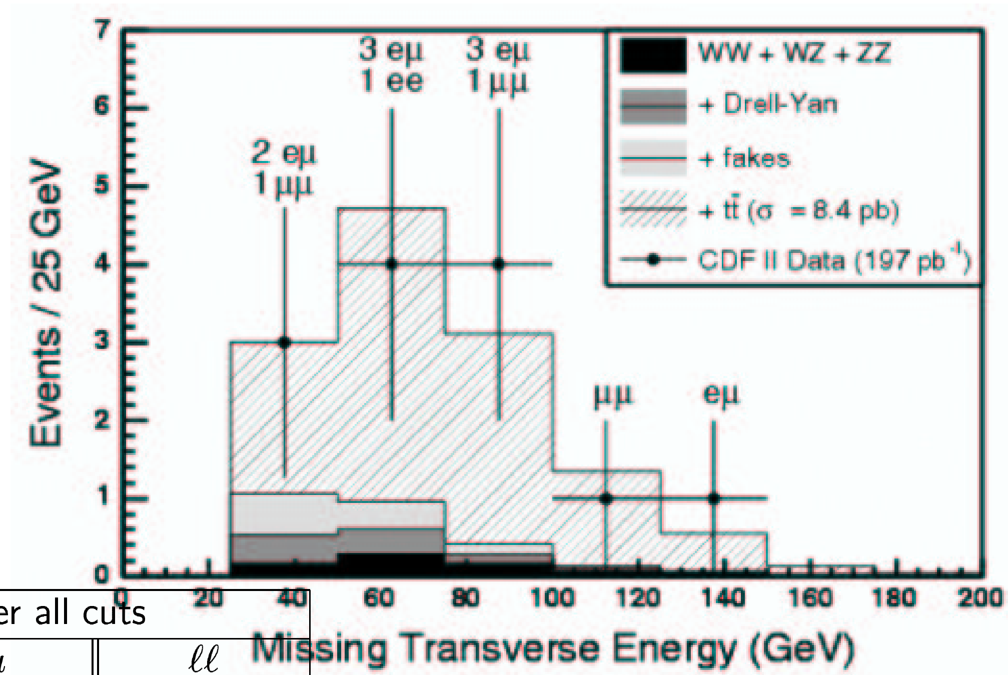


S/B~3

$\Rightarrow$ $\sigma = 14.3^{+5.1}_{-4.3}({\rm stat})\,^{+2.6}_{-1.9}({\rm syst}) \pm 0.9({\rm lum})\,{\rm pb}$ (DØ $\sim 150{\rm pb}^{-1}$)

Ready for kinematic distributions in the $t\bar{t}$ candidates with good S:B ratio

- Result at CDF $(197\mathrm{pb}^{-1})$
  - Observed candidates
    $$N_{\mathrm{obs}} = 13$$
  - Expected backgrounds
    $$N_{\mathrm{bkg}} = 2.7 \pm 0.7$$



Source	Events per 193 pb^{-1} after all cuts			
	ee	$\mu\mu$	eμ	$\ell\ell$
WW/WZ	0.21 ± 0.06	0.18 ± 0.05	0.35 ± 0.10	0.74 ± 0.21
Drell-Yan	0.36 ± 0.28	0.07 ± 0.34	-	0.43 ± 0.44
Z $\rightarrow \tau\tau$	0.09 ± 0.03	0.11 ± 0.03	0.22 ± 0.07	0.42 ± 0.13
Fakes	0.26 ± 0.11	0.16 ± 0.07	0.69 ± 0.28	1.1 ± 0.45
Total Background	0.9 ± 0.3	0.5 ± 0.4	1.3 ± 0.3	2.7 ± 0.7
t$\bar{\mathrm{t}}$ (σ = 6.7 pb)	1.9 ± 0.3	1.8 ± 0.3	4.5 ± 0.6	8.2 ± 1.1
Total SM expectation	2.8 ± 0.4	2.4 ± 0.5	5.7 ± 0.7	10.9 ± 1.4
Run II data	1	3	9	13

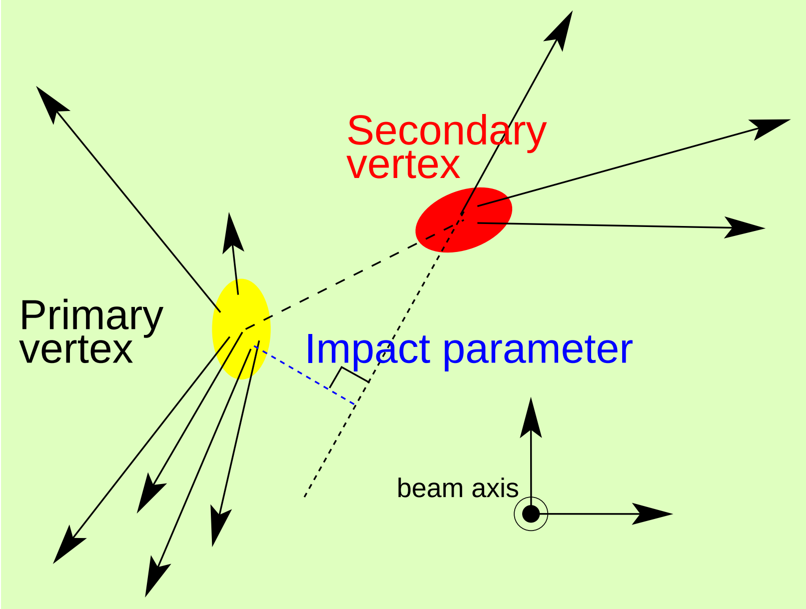
S/B~4

$\rightarrow$ $\sigma = 8.4^{+3.2}_{-2.7}(\mathrm{stat})^{+1.5}_{-1.1}(\mathrm{syst}) \pm 0.5\,(\mathrm{lum})\,\mathrm{pb}$ (CDF $197\mathrm{pb}^{-1}$)

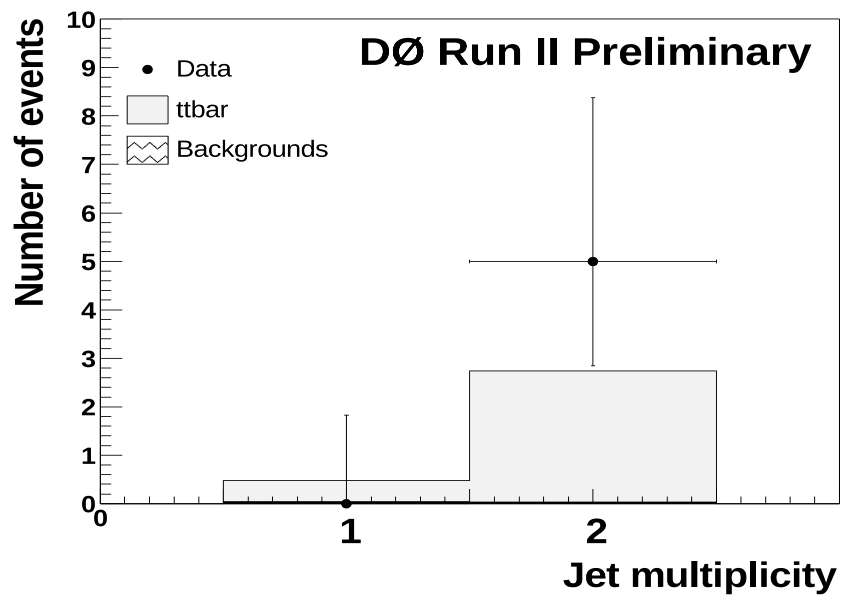
Tighten selection $\Rightarrow$ Trade off signal efficiency for S:B

- Signal selection
  - Use only e-μ channel candidate $\rightarrow$ Suppress Z bkg
    - Branching fraction $\sim 50\%$ eff.
  - At least 1 b-tagged jet $\rightarrow$ Suppress light flavor or gluon QCD jets
    - $\geqslant 1$ b-tagging $\sim 60\%$ eff. ($\Leftrightarrow$ mistag rate for W+4jets $\sim 2.4\%$)
  - $\not{E}_T$

b-tagging (Secondary vertex base)



$N_{\rm obs} = 5$ with expected $N_{\rm bkg} = 0.04$



$\Rightarrow$ $\sigma = 11.1^{+5.8}_{-4.3}({\rm stat}) \pm 1.4({\rm syst}) \pm 0.7({\rm lum})\,{\rm pb}$ (DØ $158\,{\rm pb}^{-1}$)

Almost background free $t\bar{t}$ sample!

Loosen selection $\Rightarrow$ Trade off S/B for signal efficiency

- ℓ+isolated track selection
  - 1 tight lepton(e,μ)+1 isolated track
  - $\not\!\!E_T$, 2 or more jets

$\rightarrow$ Worse S:B ratio, but better signal efficiency.

$\rightarrow$ $t\bar{t}$ Cross-section with less uncertainty.

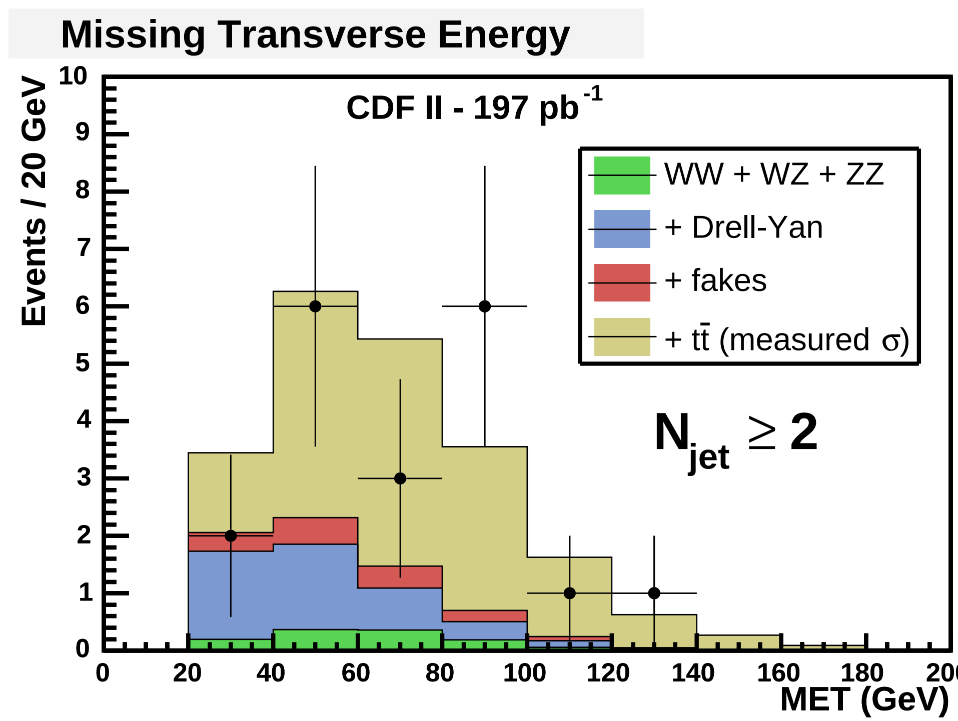
- CDF result $(197\,\mathrm{pb}^{-1})$
  - Observed candidates

$$N_{\mathrm{obs}} = 19$$

  - Expected backgrounds

$$N_{\mathrm{bkg}} = 6.9 \pm 1.7$$

S/B~2



$\Rightarrow$ $\sigma = 7.0^{+2.7}_{-2.3}(\mathrm{stat})^{+1.5}_{-1.3}(\mathrm{syst}) \pm 0.4\,(\mathrm{lum})\,\mathrm{pb}$ (CDF $197\,\mathrm{pb}^{-1}$)

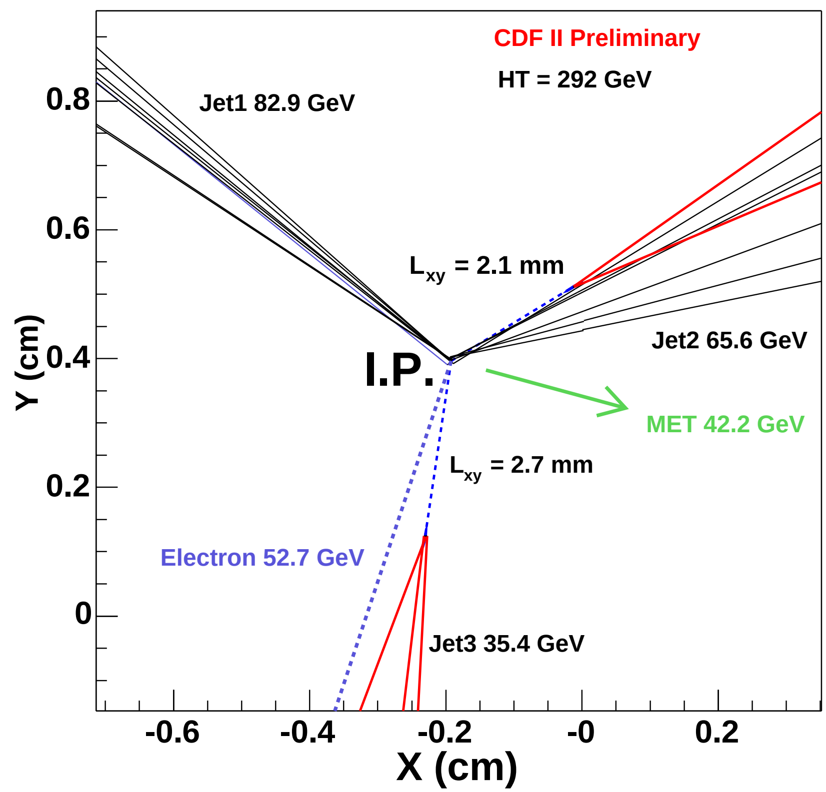
Cross Section Measurements in ℓ+Jets Channels

- $t\bar{t} \to W^+ b W^- \bar{b} \to \ell^+ \nu b j j' \bar{b}$ or $j j' b \ell^- \bar{\nu} \bar{b}$
- Signiture: 1 high P_T leptons, $\not{E}_T$, 4 jets (including 2 b-jets)
- Dominant backgrounds: W+jets.
- Good signal to background ratio after b-tagging.
- Large braching fraction $\sim 30\%$

  $\to$ Large sample suitable for top mass analysis. ($N_{\rm jet} \geqslant 4$)

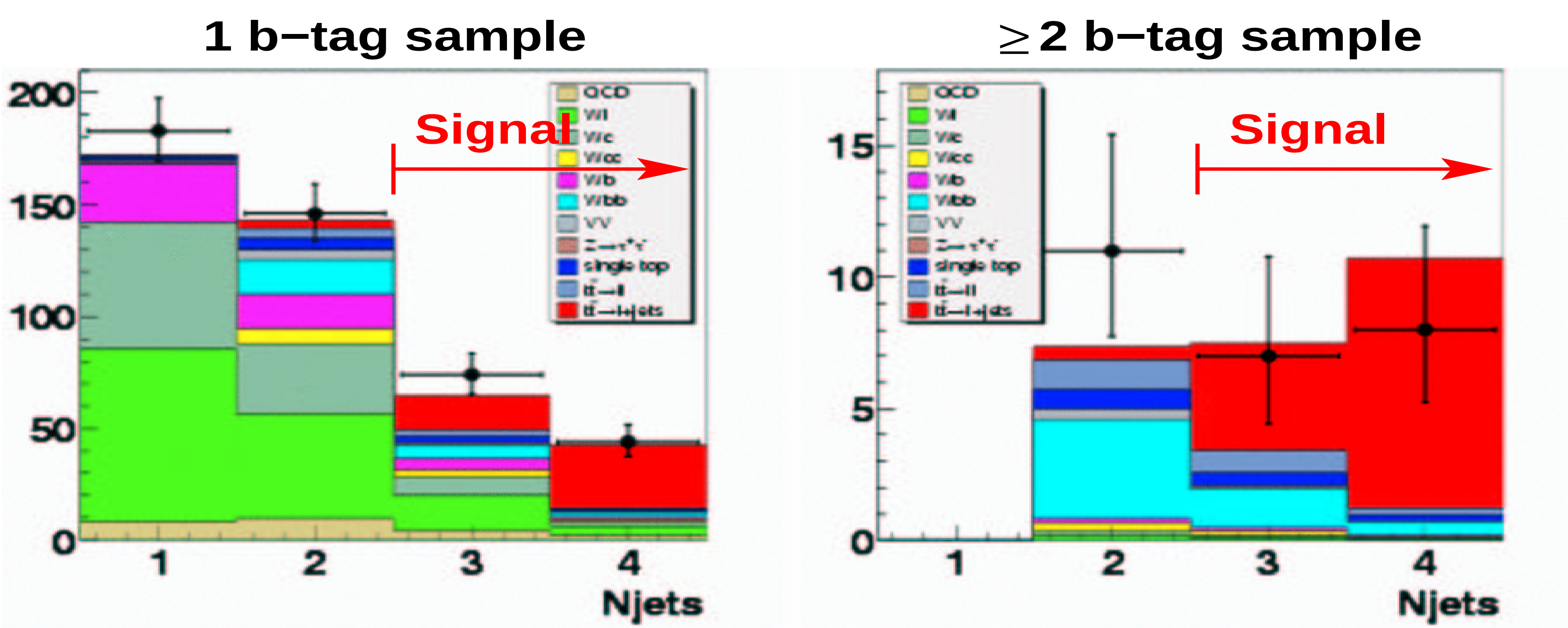
- Signal eff. and S/B depend on b-tagging eff. and mistag ratio.

$t\bar{t} \to e$+jets channel candidate at CDF $\Rightarrow$



Based on Counting Method with Standard Selection

- Event selection
  - high P_T lepton (e or μ), $\not{E}_T$, and $N_{\text{jet}} \geqslant 3$
  - At least 1 b-tagged jet
- DØ result (e +jets: $169\,\text{pb}^{-1}$, μ+jets: $158\,\text{pb}^{-1}$)
  - b-tagging eff.: ~60% (Impact parameter based tag)
  - S/B for $N_{\text{jet}} = 4$ bin: ~2(single tagged), ~5(double tagged)

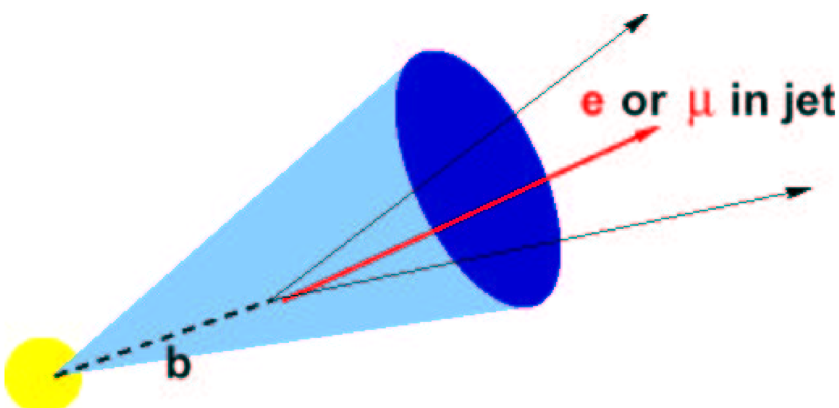


$$\Rightarrow \sigma = 7.2^{+1.3}_{-1.2}(\text{stat})^{+1.9}_{-1.4}(\text{syst}) \pm 0.5(\text{lum})\,\text{pb}$$ (DØ)

Result on another b-tagging tool

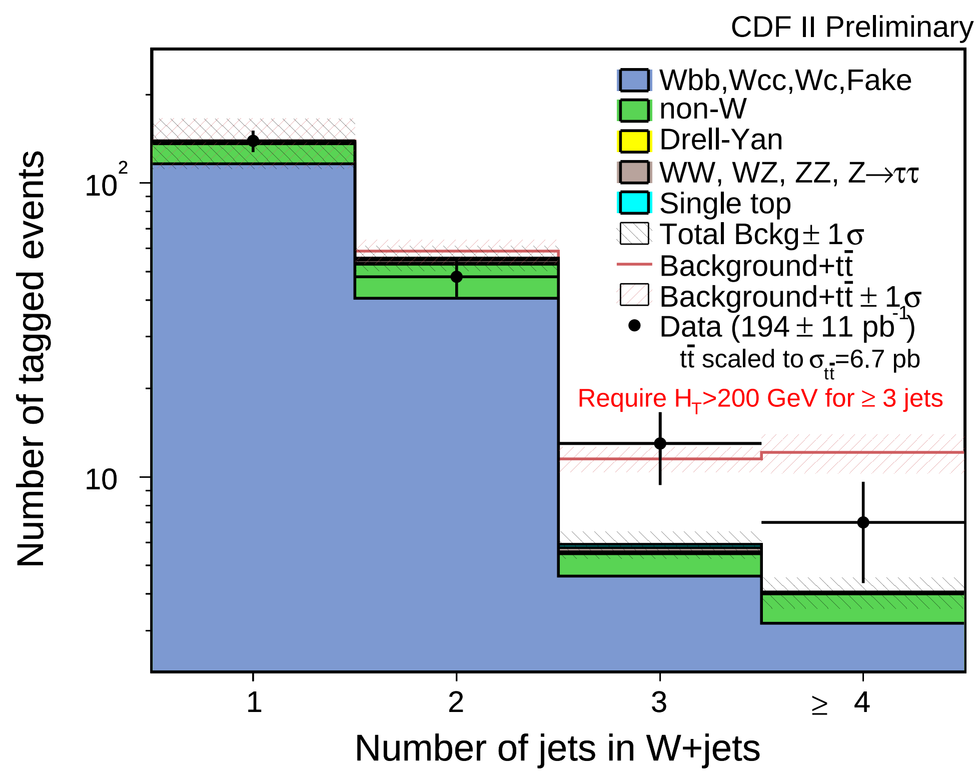
- Soft muon tag (identify semileptonic decay of B hadrons)
  - Tagging eff. : ~15%   Mistag rate: ~3.6%
  - Independent tagging information of secondary vertex tag

Based on semileptonic decay of B hadron



$\mathrm{Br}(b \to \ell\nu c) \sim 20\%$
$\mathrm{Br}(b \to c \to \ell\nu s) \sim 20\%$

Soft muon tag(CDF $193\,\mathrm{pb}^{-1}$)



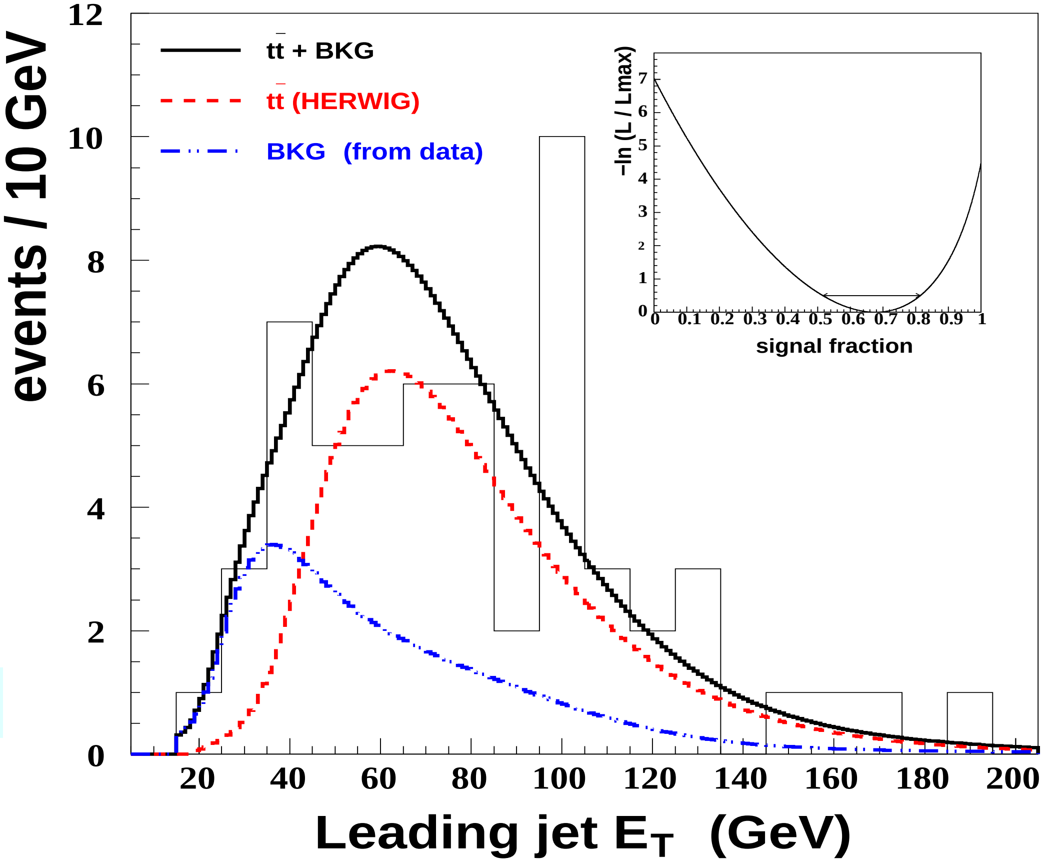
$\Rightarrow$ $\sigma = 5.2\,^{+2.9}_{-1.9}(\mathrm{stat})\,^{+1.3}_{-1.0}(\mathrm{syst})\,\mathrm{pb}$ (CDF $193\,\mathrm{pb}^{-1}$)

Kinematical Fitting Technique $\Leftrightarrow$ counting experiment

- Use $\ell + \geqslant 3$ jets sample with at least one b-tag (CDF $162\,\mathrm{pb}^{-1}$)
- Fit to leading jet E_T distribution to extract signal fraction.

$\rightarrow \quad R = S/(S+B) = 0.68^{+0.14}_{-0.16}$

$$\sigma(t\bar{t}) = \frac{R \cdot N_{\mathrm{obs}}}{\epsilon_{\mathrm{tot}} \int \mathcal{L}\mathrm{dt}}$$



- No assumption of absolute value of N_{bkg}.
- Bkg shape extracted from data

$\rightarrow$ Reliable prediction

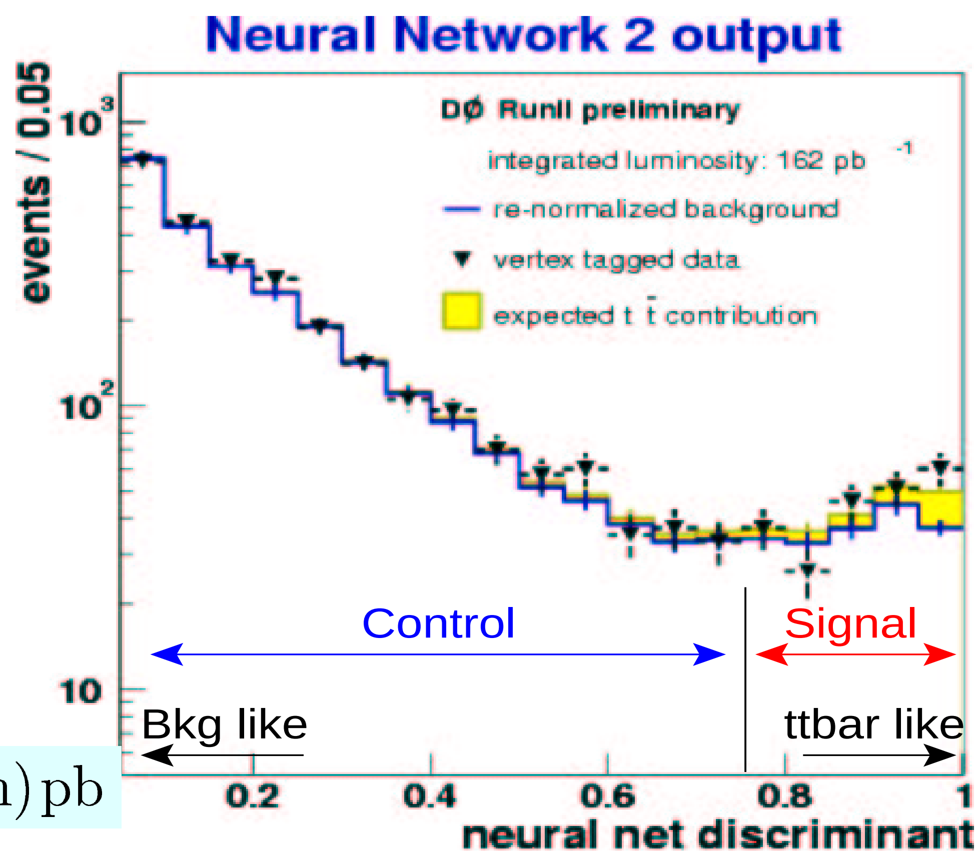
$\Rightarrow \sigma = 6.0 \pm 1.6(\mathrm{stat}) \pm 1.2(\mathrm{syst})\,\mathrm{pb}$

Cross Section Measurements in All-Hadronic Channels

- Final state: 6 jets including 2 b-jets
- Overwhelming QCD multijet background even after b-tagging.
- Data sample: $\geqslant 6$ jets (1 b-tag) with no lepton
- Neural network technique (use H_T, Centrality, Aplanarity, ...)

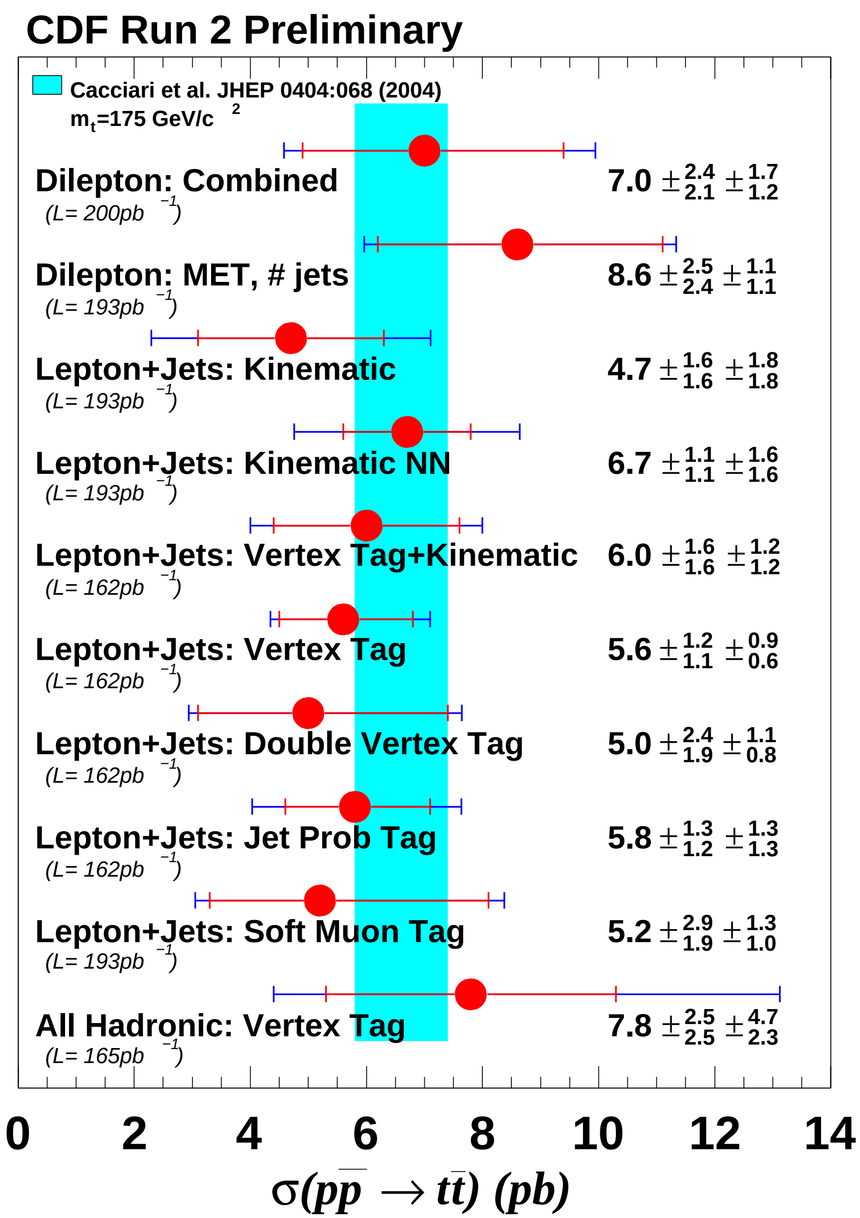
DØ Run2 preliminary($162\,\mathrm{pb}^{-1}$)

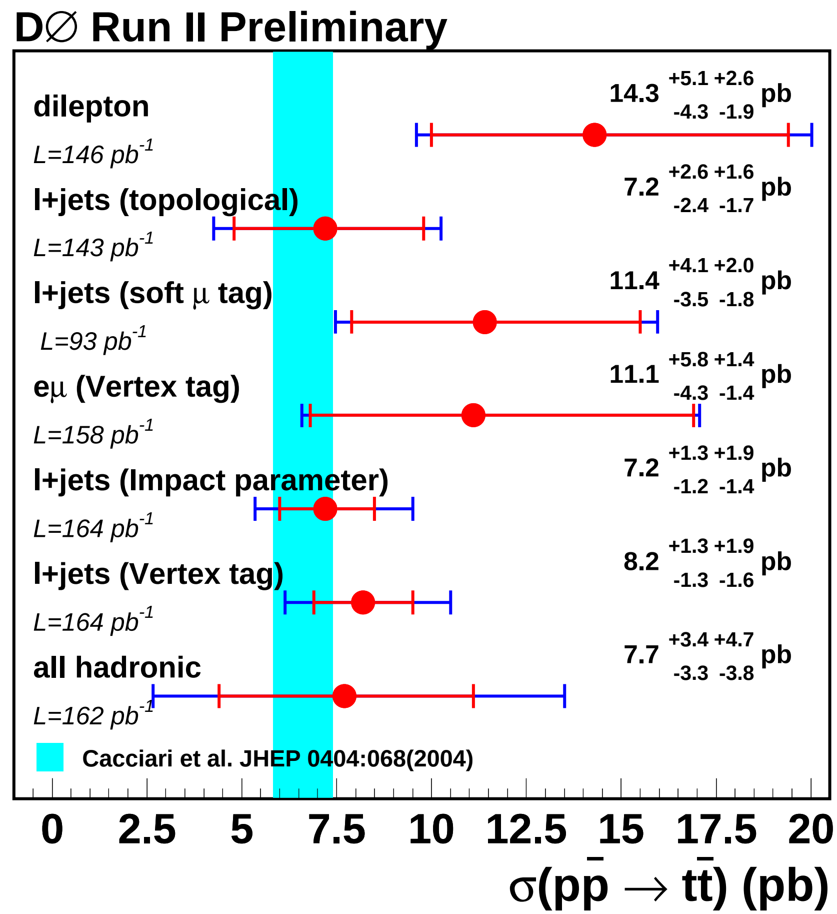
- $N_{\mathrm{obs}} = 220$ in signal region
- expected $N_{\mathrm{bkg}} = 186 \pm 5$



$\Rightarrow \sigma = 7.7^{+3.4}_{-3.3}(\mathrm{stat})\,^{+4.7}_{-3.8}(\mathrm{syst}) \pm 0.5(\mathrm{lum})\,\mathrm{pb}$

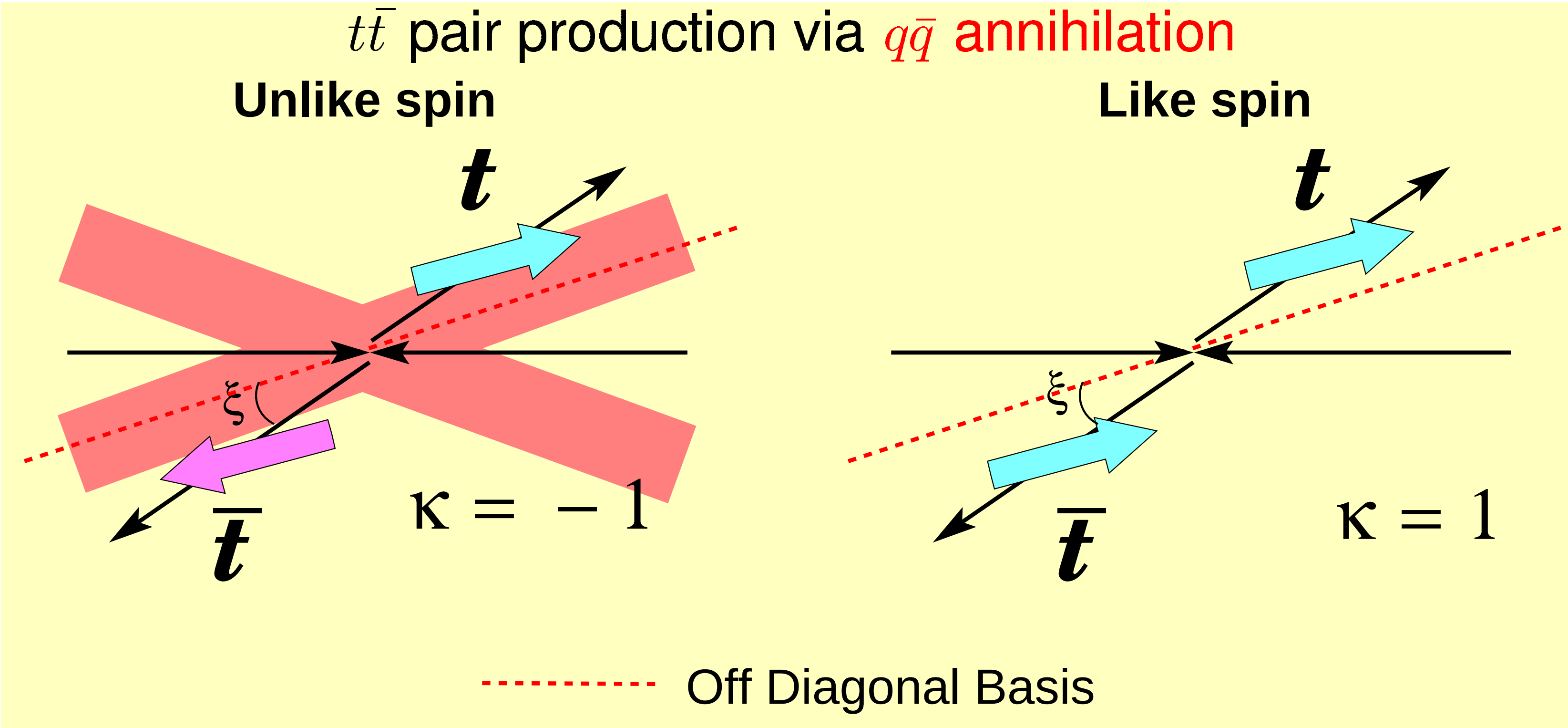
All Tevatron Run2 Results and Comparison with Prediction





All results are consistent with prediction so far.

$t\bar{t}$ Spin Correlations



- At tree-level $q\bar{q}$ annihilation, only like-spin combinations are allowed, if take a proper basis so-called "off-diagonal".
- Correlation parameter κ is defined as the correlation coefficient between top and anti-top spin polarizations.

Top Quark Decay

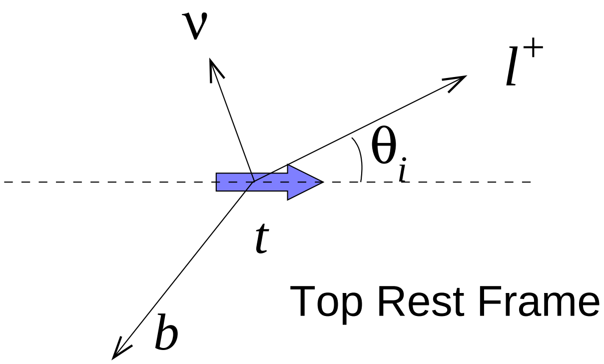
- Spin-flip time after hadronization: $O(m_t/\Lambda^2_{\rm QCD}) \simeq (1.3\,{\rm MeV})^{-1}$
- Top decay width: $\Gamma_t \simeq 1.42\,{\rm GeV}$

$$O(m_t/\Lambda^2_{\rm QCD}) \gg 1/\Gamma_t$$

$\Rightarrow$ Top quark decays before losing the spin information at the production.

- V-A decay

$\Rightarrow$ Flight direction of decay products has spin information of its mother.



Differential decay rate

$$\frac{1}{\Gamma}\cdot\frac{d\Gamma}{d\cos\theta_i} = \frac{1+\alpha_i\cos\theta_i}{2}$$

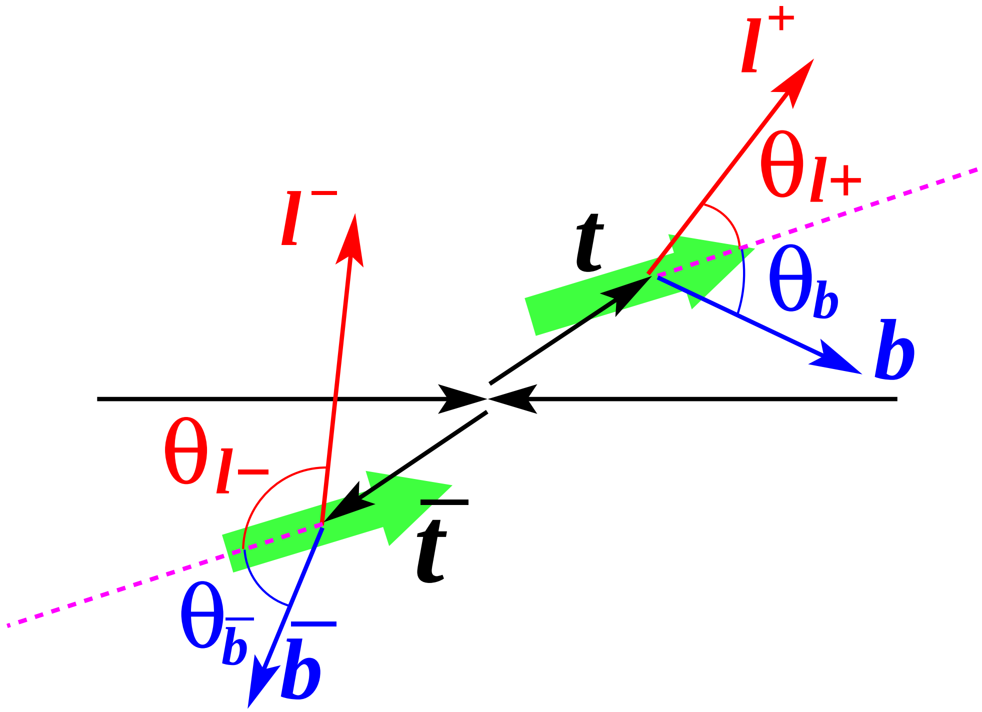
Particle	α_i
ℓ^+	1
ν	-0.32
W^+	0.40
b	-0.40

$\theta_+(\theta_-)$: Angle of $\ell^+(\ell^-)$ flight direction w.r.t. quantization basisin $t(\bar{t})$ rest frame.

Top is the only quark we can study its spin polarization at the production.

Correlations in Angular Distributions of Decay Product

$t\bar{t}$ spin correlation can be seen as angular correlation of decay products



Differential production cross-section

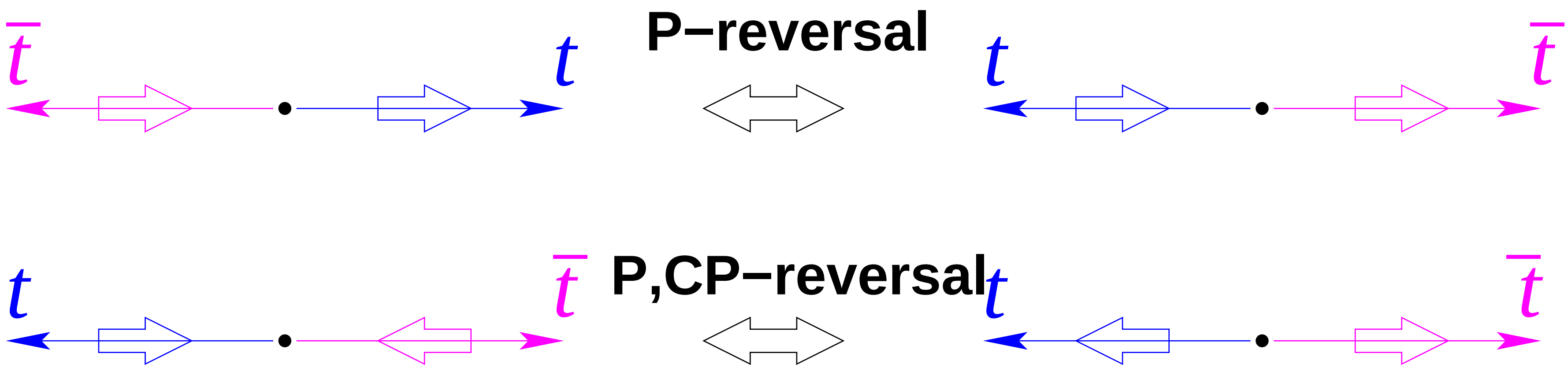
$$\frac{1}{\sigma} \cdot \frac{d^2\sigma}{d\cos\theta_+ \, d\cos\theta_-} = \frac{1 + \kappa\, \alpha_+ \alpha_- \cos\theta_+ \cos\theta_-}{4}$$

κ : correlation parameter (~ 0.8 in NLO prediction @ $\sqrt{s} = 2\,\mathrm{TeV}$)

Look at angular distribution such as $(\cos\theta_{\ell+}, \cos\theta_{\ell-})$ and $(\cos\theta_b, \cos\theta_{\bar{b}})$.

Physics Topics on $t\bar{t}$ spin correlation

- If correlation is observed,
  - $\rightarrow$ Direct proof of $1/\Gamma_t \ll O(m_t/\Lambda^2_{\rm QCD})$
  - $\rightarrow$ Lower bound on Γ_t
- Asymmetry in angular distribution will provide a probe into $\not{P}$ and $\not{C}\not{P}$ at $t\bar{t}$ production process.

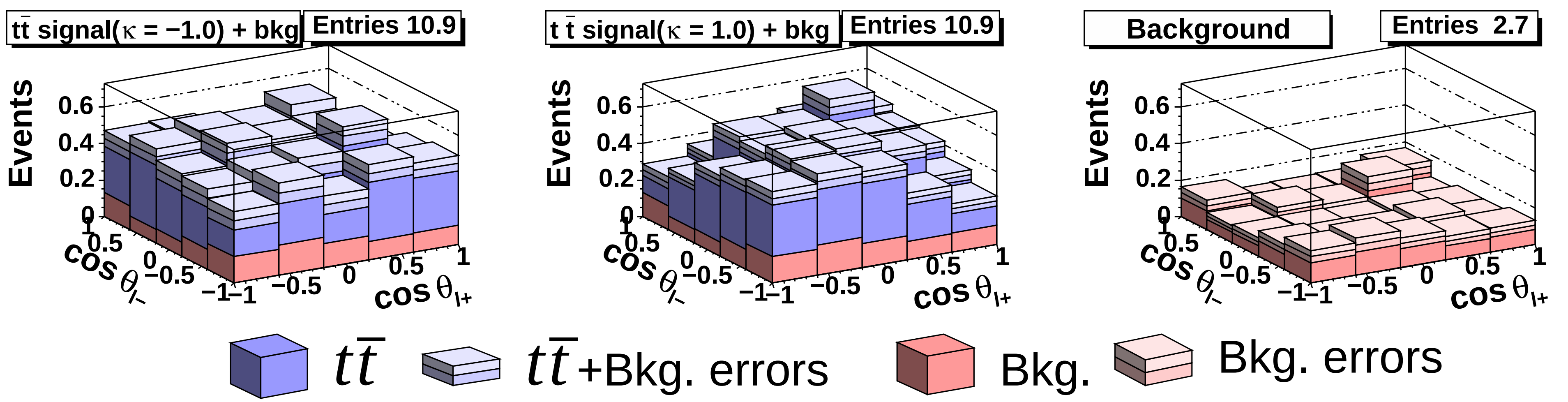


Prospects for Spin Correlation at CDF Run2

- Use dilepton channel candidates in $t\bar{t}$ MC sample + backgrounds MC with CDF Run2 detector.
  - Lepton has maximum analyzing power to top spin polarization.
- For $t\bar{t}$ MC sample, prepair the sample with $\kappa = 1$ and $\kappa = -1$.
- Assume the expected numbers of signal and backgrounds from dilepton cross-section analysis at CDF Run2.

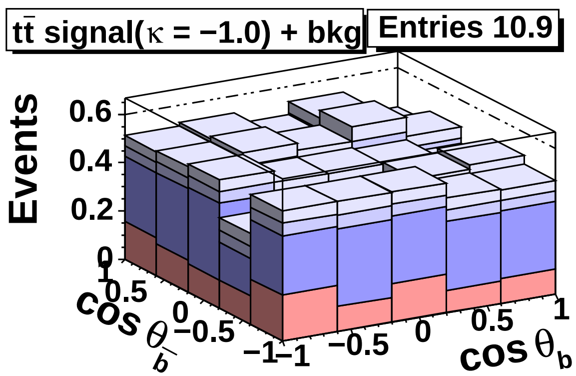
Expected distribution of $(\cos\theta_{\ell+}, \cos\theta_{\ell-})$ reconstructed with CDF detector

$t\bar{t}$ $(\kappa = -1)$ + bkg | $t\bar{t}$ $(\kappa = 1)$ + bkg | bkg$(Z/\gamma^* \to \ell\ell, WW, WZ, W$+jets$)$

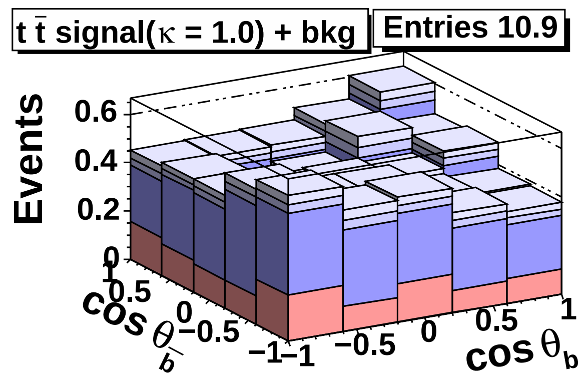


Expected $(\cos\theta_b, \cos\theta_{\bar{b}})$ distributions

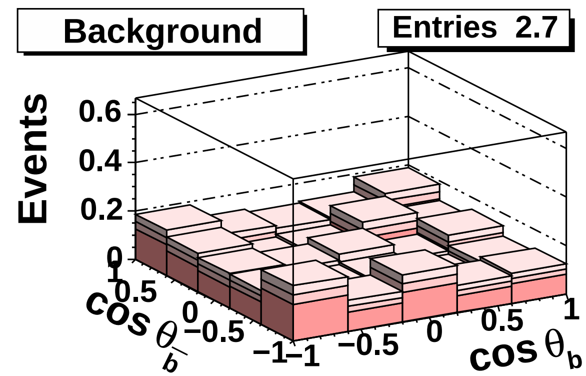
$t\bar{t}$ $(\kappa=-1)$ + bkg



$t\bar{t}$ $(\kappa=1)$ + bkg



bkg



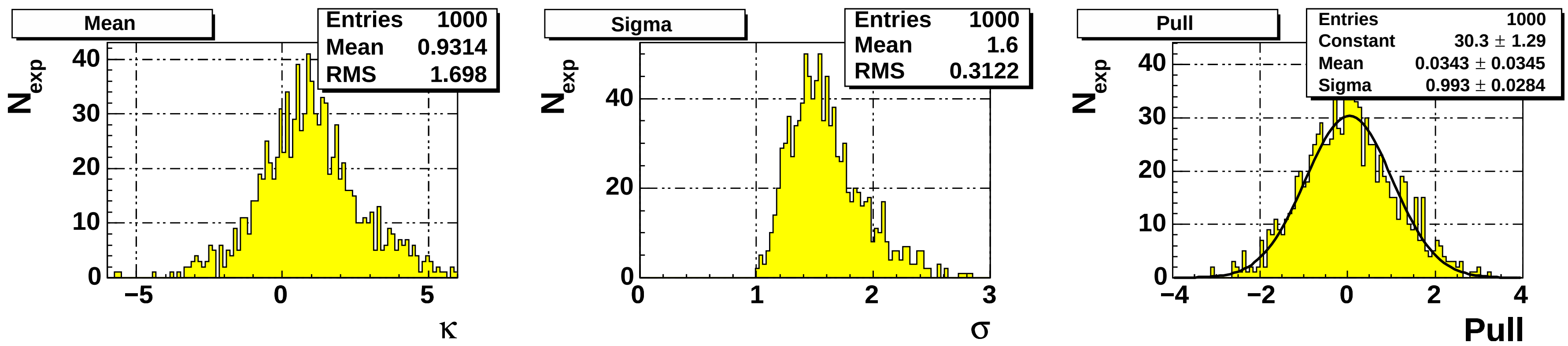
$\rightarrow$ $(\cos\theta_b, \cos\theta_{\bar{b}})$ distribution also have sensitivity to correlation parameter κ.

- To extract correlation paramter κ, adopt binned 2D likelihood fit.
- Use $(\cos\theta_{\ell+}, \cos\theta_{\ell-})$ and $(\cos\theta_b, \cos\theta_{\bar{b}})$ distributions as templates.
- Perform pseudo-experiments

  $\rightarrow$ Obtain expected distribution of κ from each pseudo-experiments.

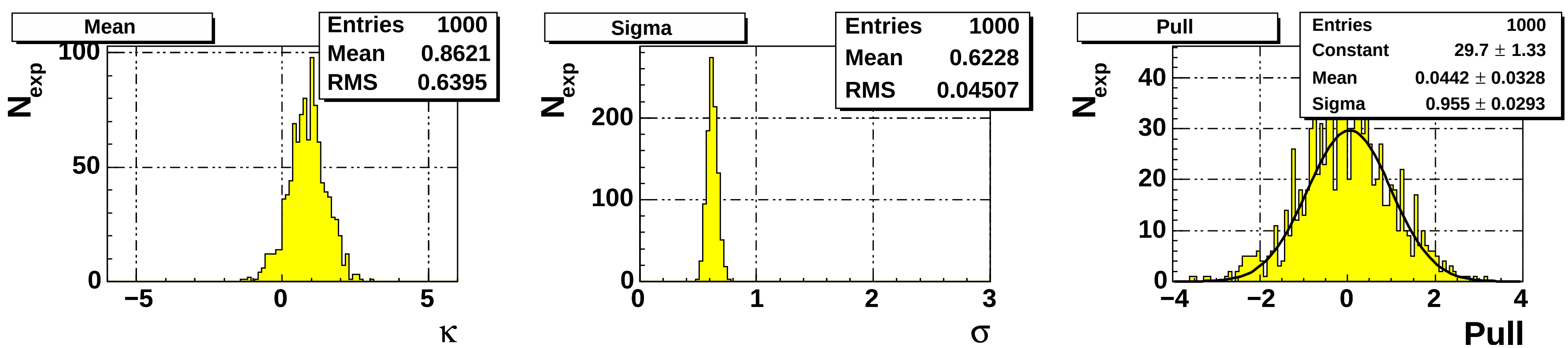
Pseudo Experiment Results

- Assume $\int \mathcal{L}\mathrm{dt} = 340\mathrm{pb}^{-1}$ $\Rightarrow$ corresponding to $\langle N_{\mathrm{obs}} \rangle = 19.2$
- input $\kappa = 0.88$



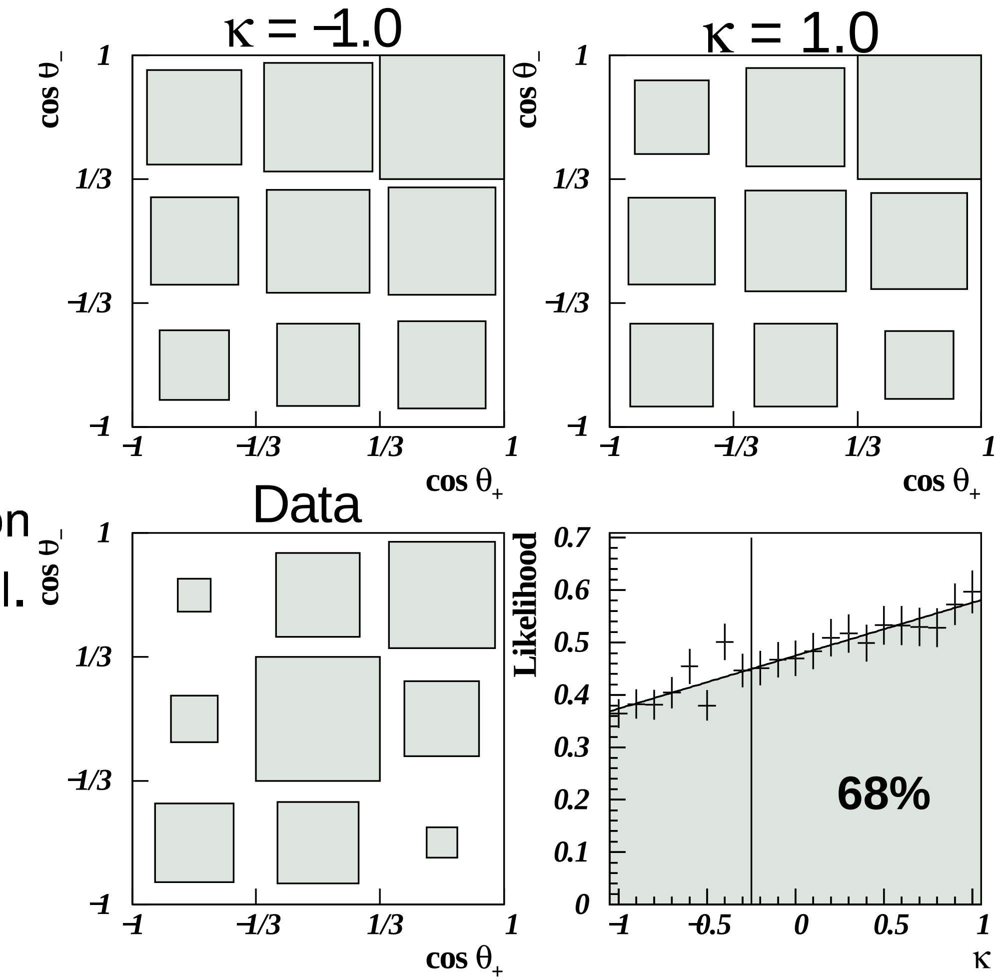
$\Rightarrow$ Expected uncertainty for κ measurement is 1.6.

- Assume $\int \mathcal{L}\mathrm{dt} = 2\mathrm{fb}^{-1}$ $\Rightarrow$ corresponding to $\langle N_{\mathrm{obs}} \rangle = 113.0$



$\Rightarrow$ Expected uncertainty for κ measurement is 0.62.

Comparing with Run1 DØ Results



Run1 DØ Results

- $\int \mathcal{L} \mathrm{dt} = 125 \mathrm{pb}^{-1}$
- Based on ($\cos\theta_{\ell+}$,$\cos\theta_{\ell-}$) distribution from 6 candiates in dilepton channel.

- Run1 DØ obtained $\kappa > -0.25$ (68%CL) corresponding to $\kappa = 2.3 \pm 2.5$
- CDF Run2 prospection for κ uncertainty (1.6 @ $340 \mathrm{pb}^{-1}$) is improved comparing with 2.5.

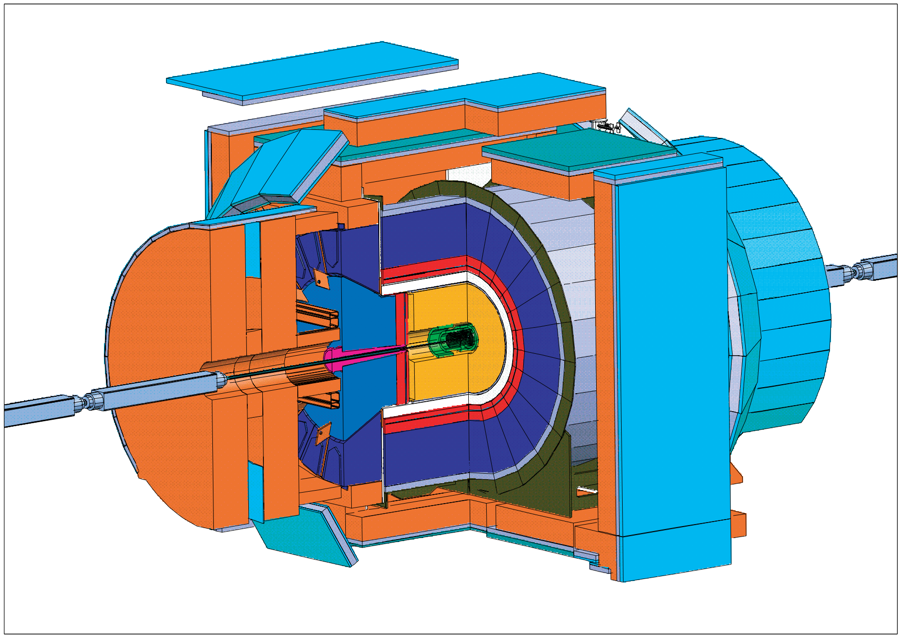
Summary

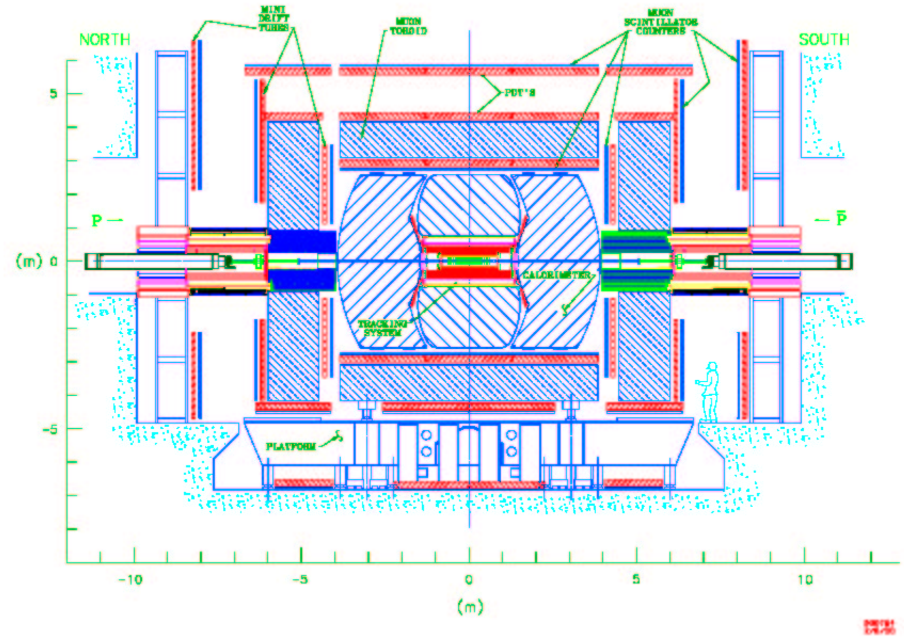
- Top pair production cross-section measurements have been performed in many experimental signatures using various techniques.
- All cross-section measurements are consistent with perturbative QCD predictions so far.
  - → Results based on $\int \mathcal{L}\mathrm{dt} = 300 \sim 350\,\mathrm{pb}^{-1}$ will coming soon.

- In the $t\bar{t}$ production at Tevatron, spin correlations can be observed.
  - → Approach to Γ_t.
  - → Sensitive to a new physics at $t\bar{t}$ production.
- Expected sensitivities (statistical only) to correlation parameter κ with CDF Run II detector by Monte Carlo simulations are:
  - → Expected uncertainty for κ is 1.6 @ $\int \mathcal{L}\mathrm{dt} = 340\,\mathrm{pb}^{-1}$
  - → 0.62 @ $\int \mathcal{L}\mathrm{dt} = 2\,\mathrm{fb}^{-1}$
- This will improve Run1 results for spin correlation.

Backups

Run 2 Detectors





CDF upgrades

New silicon vertex detector(SVX)

Faster tracking drift chamber(COT)

Scintillating tile end-pulg calorimeters

DØ upgrades

New silicon (SMT)

Fiber tracker (CFT)

2T magnetic field

Calorimeter supplemented with the preshower detectors

Improved muon system