Searches for b' and W' at the Tevatron

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Overview of Latest Searches

- **Heavy quarks decaying to tW**
  - ∆ Pair production of b'
  - ∆ Single production of heavy vector-like quarks

- **Heavy charged bosons W' decaying to tb**
  - ∆ Look in the single top sample

- **Searches for resonances W'→WZ**
 - ∆ See Adam Lyon's talk

Fourth Generation Quarks b'

- Fourth generation suggested by several BSM models
  - Δ Baryon asymmetry, heavier Higgs boson

- Previous limits on fourth generation at LEP:
  - Δ $m_{V4} > M_z/2$ from Z width
  - Δ $m_{b'} > 100$ GeV/c^2

- From CKM matrix constraint, expected low mixing with light quarks:
  - Δ Pair production favorite
  - Δ Decays likely into third generation quarks: b'→tW

- Look for b' pair production

- Same-charge dilepton channel:
  - Δ Two same-charge leptons p_T>20 GeV/c, one isolated
  - Δ Two jets E_T>15 GeV, at least one tagged as b-jet
  - Δ Missing transverse energy $\not{E}_T$>20 GeV

- Lepton+jets channel:
  - Δ One isolated lepton, p_T>20 GeV/c
  - Δ Five jets E_T>20 GeV, at least one tagged as b-jet
  - Δ Missing transverse energy $\not{E}_T$>20 GeV

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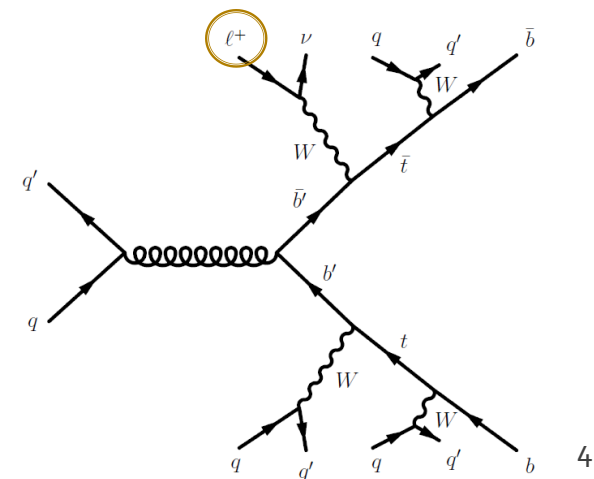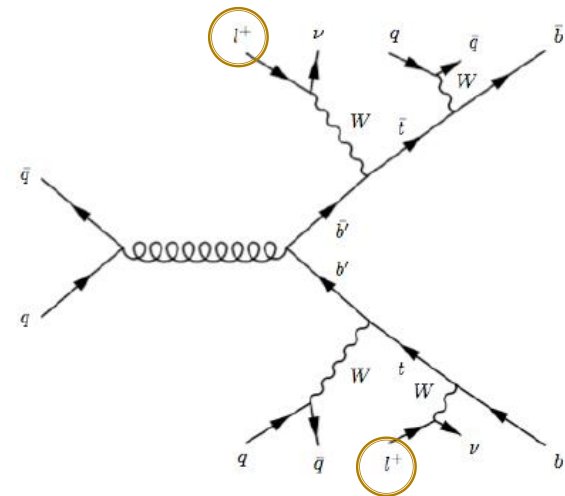
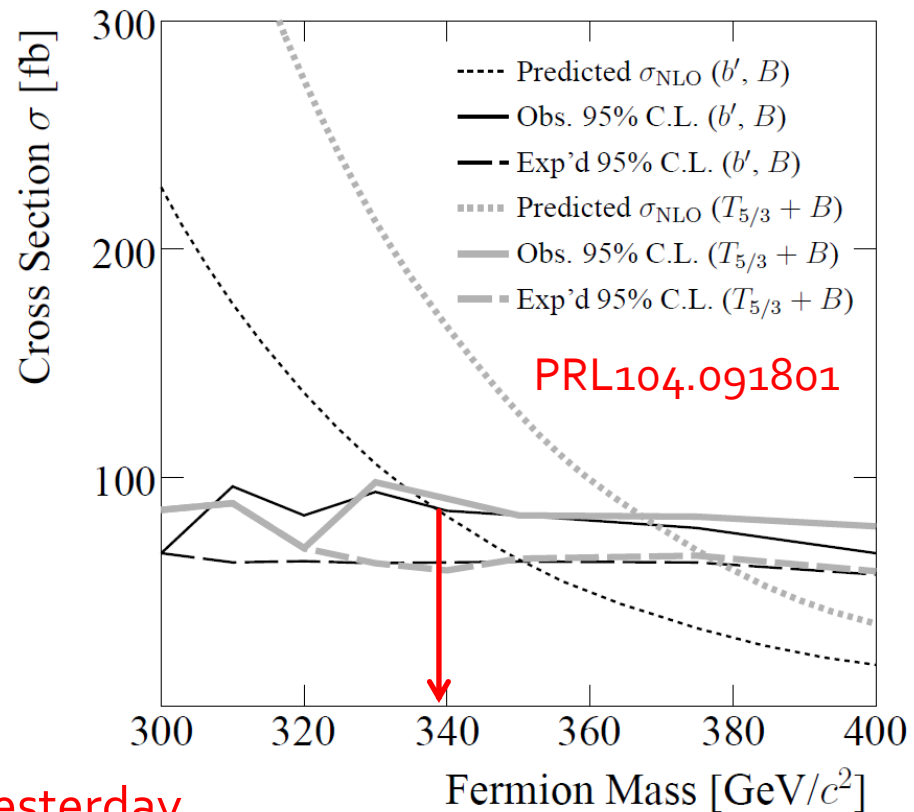# b'→Wt: Dilepton Channel

- No signal observed in 2.7 fb⁻¹ of data

$m_{b'}$ > 338 GeV/c²

PRL104.091801

Analysis details in Adam's talk yesterday

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b'→Wt: Lepton+Jets Channel

- ## Same analysis technique as for top searches
  - △ Improved modeling of top events with high jet multiplicity

- ## Good agreement data-simulation in 4.8 fb^{-1} of data

Process	Electron	Muon
Top pair production	137±17	166±14
Single top	0.8±0.1	1.1±0.2
Z+jets	0.9±0.1	1.3±0.2
W+heavy flavor	14±5	15±3
W+light flavor	5±3	5.1±1.5
QCD multijets	15±12	1.4±0.9
Dibosons	1.3±0.1	1.9±0.2
Total	174±21	192±14
Data	157	200

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b′→Wt: Lepton+Jets Channel

- Discriminant variable: Jet-HT

    Δ Njets = 5: Jet-HT = H_T ($H_T = \sum_{jet} E_T + p_T^{lept.} + E\!\!\!/_T$)
    Δ Njets = 6: Jet-HT = H_T + 1000
    Δ Njets $\geq$ 7: Jet-HT = H_T + 2000
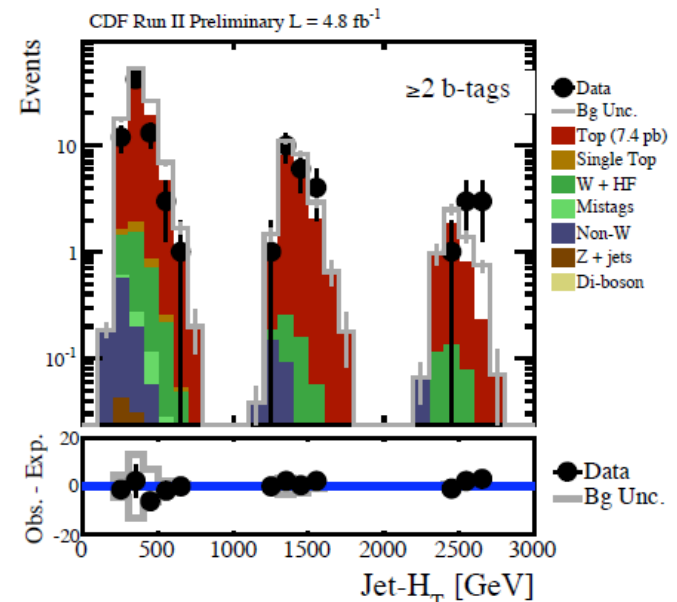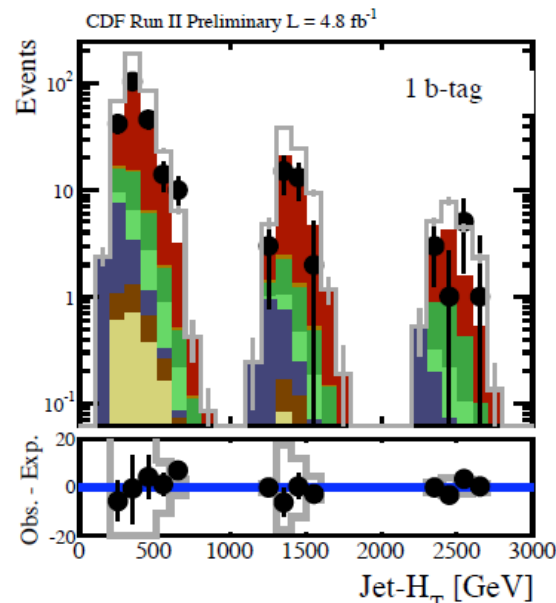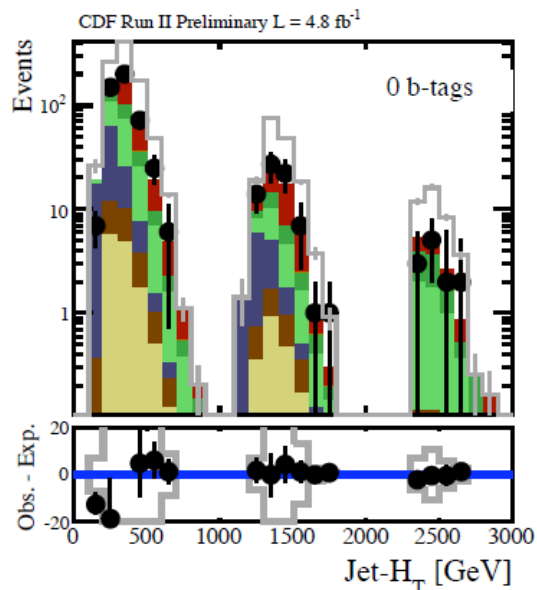
b'→Wt: Lepton+Jets Channel

- Fitting Jet-HT distribution on 4.8 fb^{-1} of data

$m_{b'} > 385$ GeV/c^2

CDF Run II Preliminary L=4.8 fb^{-1}

Legend:
— Median Bg
■ 68% Bg
■ 95% Bg
--- Theory
— Observed
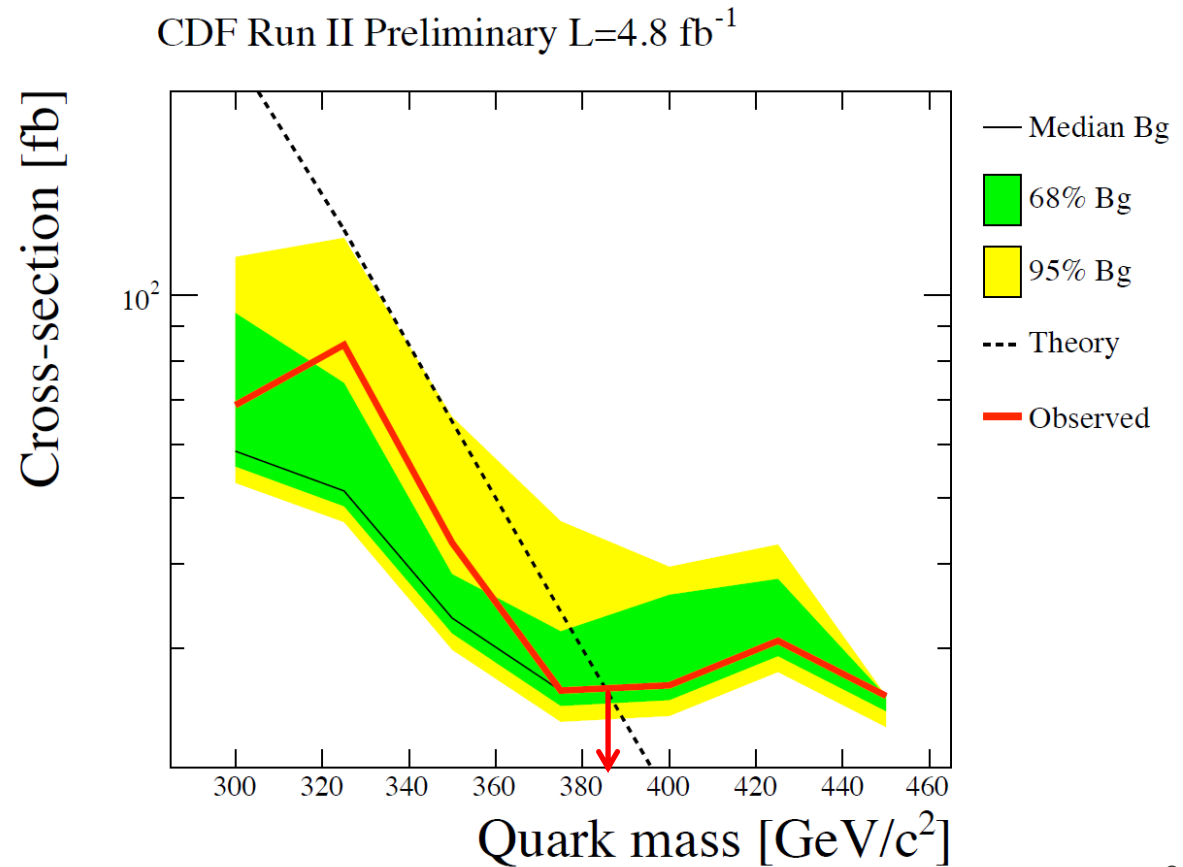
Heavy Vector-Like Quarks

- Heavy quarks with vector-like couplings to W boson
  - △ Avoid mass limit from perturbativity in Yukawa couplings

- Recent models with warped extra dimension allows sizable mixing with light SM quarks (PRD79.054018)

- Focus on two new heavy quarks, U and D:
  - △ Assume dominant decay to W: $U \to Wd$, $D \to Wu$
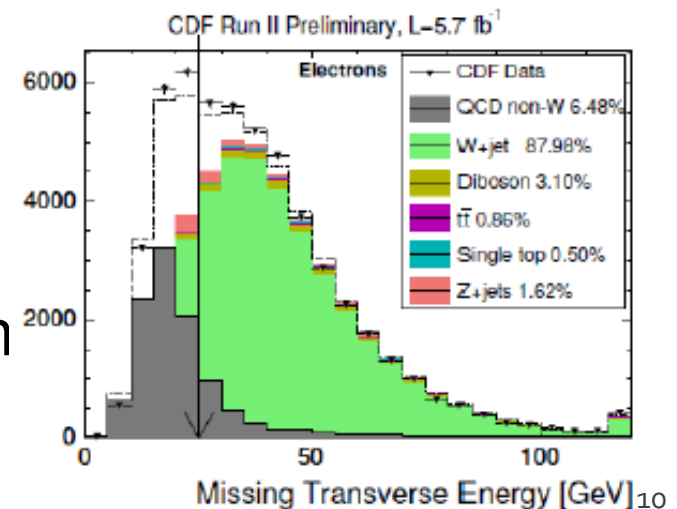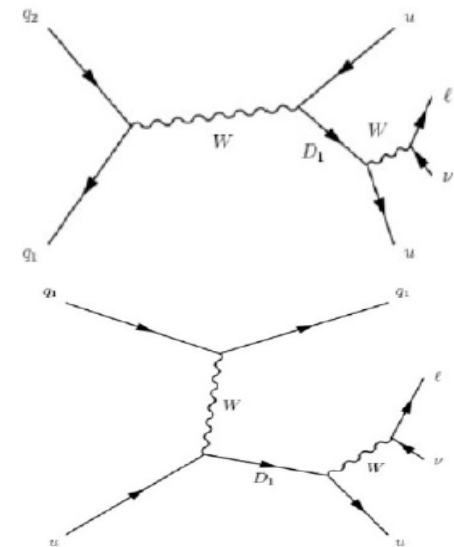 - △ $\sigma(q\bar{q}' \to qQ) = \tilde{K}^2_{qQ} \sigma_{th.}(q\bar{q}' \to qQ)$

Coupling between heavy quark Q and light SM quark q

Computation of cross section within SM: depends only on Q mass

Heavy Quarks: Sample Selection and Composition

- Sample selection (5.7 fb^{-1}):
  △ One isolated lepton p_T>20 GeV/c
  △ Two jets: E_T^{jet1}>25 GeV, E_T^{jet2}>20 GeV
  △ Missing transverse energy $\not{E}_T$>20 GeV

- Z+jets, diboson, tt, single top
  △ From simulations

- W+jets, QCD multijet production
  △ From fit to $\not{E}_T$ distribution

CDF Run II Preliminary, L-5.7 fb^{-1}

Electrons
- CDF Data
- QCD non-W 6.48%
- W+jet 87.98%
- Diboson 3.10%
- t$\bar{t}$ 0.86%
- Single top 0.50%
- Z+jets 1.62%

Missing Transverse Energy [GeV]

- Signal region:

  $\Delta E_T^{jet1} > 60$ GeV, $\Delta \phi(\not{E}_T, \text{lepton}) < 2.2$, $\not{E}_T > 30$ GeV

- Yields:

Process	Events
W+jets	10648 ± 319
Dibosons	599 ± 60
QCD multijets	581 ± 232
Z+jets	497 ± 75
tt	355 ± 43
Single top	149 ± 18
Total	12829 ± 409
Data	13243

- Invariant mass of lνj system:

CDF Run II Preliminary, L = 5.7 fb^{-1} — Signal region — $M_{l\nu j}$ [GeV/c^2]
Legend: W+jets, Non-W, Diboson, Z+jets, t$\bar{t}$, Single_top, Data
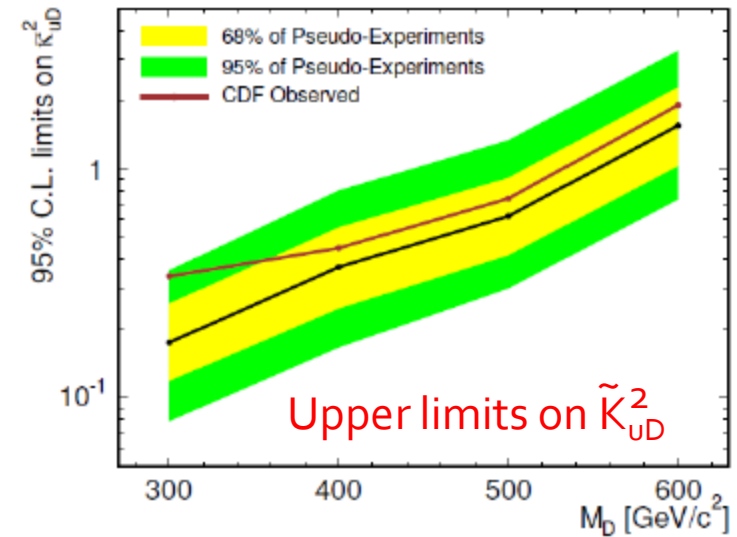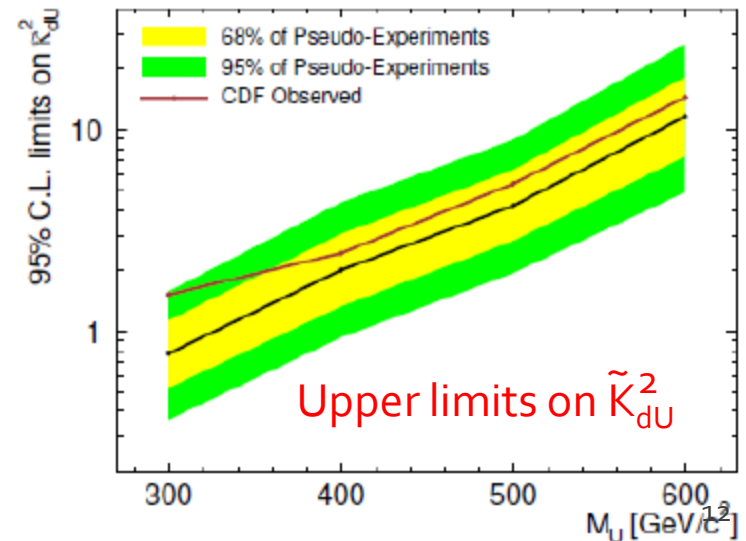
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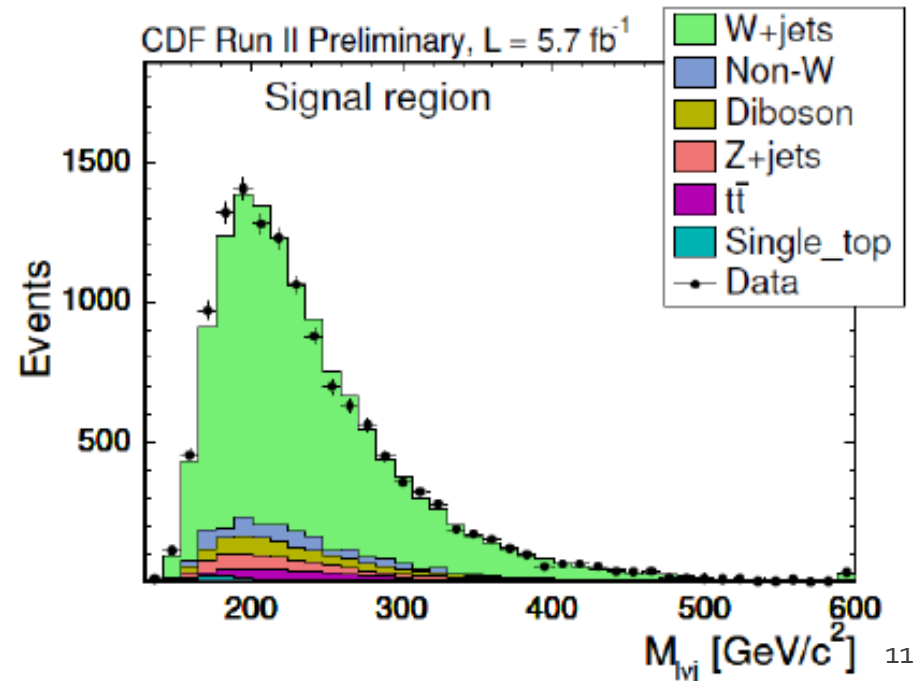
- Upper limits on $\sigma(q\bar{q}' \rightarrow qQ)$
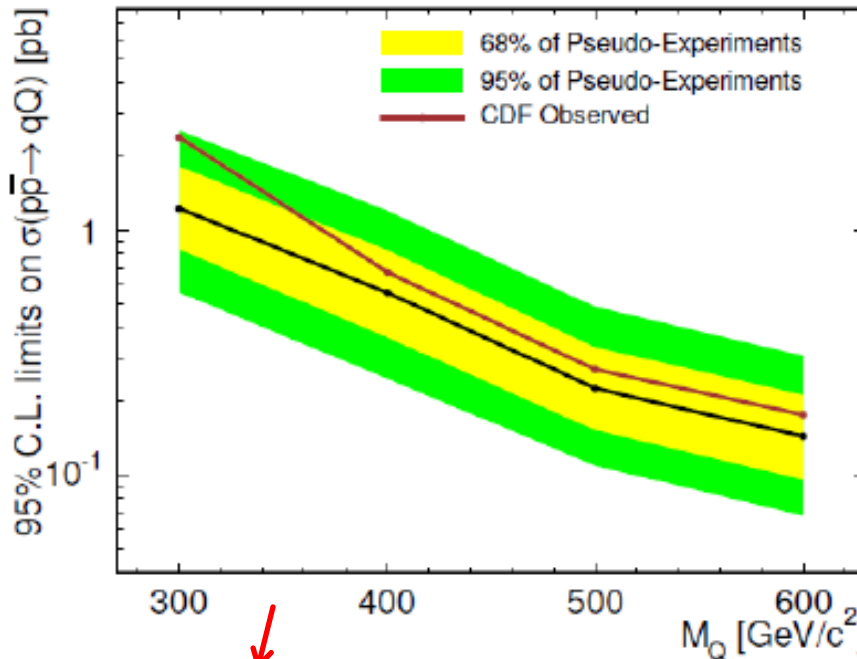
- $\sigma(q\bar{q}' \rightarrow qQ) = \tilde{K}^2_{qQ}\sigma_{th.}(q\bar{q}' \rightarrow qQ)$

From SM computation
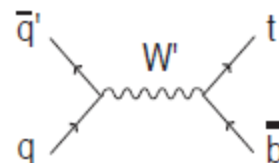
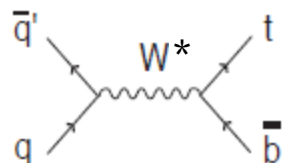Upper limits on $\tilde{K}^2_{uD}$

Upper limits on $\tilde{K}^2_{dU}$

Heavy Charged Bosons W'

- Predicted by several BSM theories
- General lagrangian depends on left and right-handed couplings to fermions:

$$\mathcal{L} \sim g_W f_i \gamma_\mu (a^R_{ij}(1+\gamma^5) + a^L_{ij}(1-\gamma^5))W'^\mu f_j + h.c.$$

- W'→tb decay sensitive to both left and right-handed couplings
- Interference with SM single top production:

W'→tb: Sample Selection

- Same analysis setup as in single top searches

- CDF selection:
  - One isolated lepton $p_T > 20$ GeV/c
  - Two or three jets $E_T > 15$ GeV, at least one tagged as b-jet
  - Large missing transverse energy $\not{E}_T > 25$ GeV

- DØ selection:
  - One isolated lepton $p_T > 15$ (20) GeV/c
  - Two (three or four) jets $p_T > 15$ GeV/c $p_T^{jet1} > 25$ GeV/c, at least one b-tagged jet
  - Missing transverse momentum $\not{p}_T > 20(25)$ GeV/c

W'→tb: Yields

- ## CDF: 1.9 fb^{-1}

Process	2 jets	3 jets
Wbb	409 ± 123	126 ± 38
Wcc+Wcj	412 ± 127	10 ± 34
Wjj (mistags)	277 ± 35	83 ± 11
QCD multijets	52 ± 21	17 ± 7
Top pair production	127 ± 13	292 ± 37
Single top (t-channel)	53 ± 8	16 ± 2
Single top (s-channel)	35 ± 5	12 ± 2
Dibosons	54 ± 4	18 ± 2
Z+jets	23 ± 3	9 ± 2
Total	1444±255	682±83
Data	1362	617

- ## DØ: 2.3 fb^{-1}

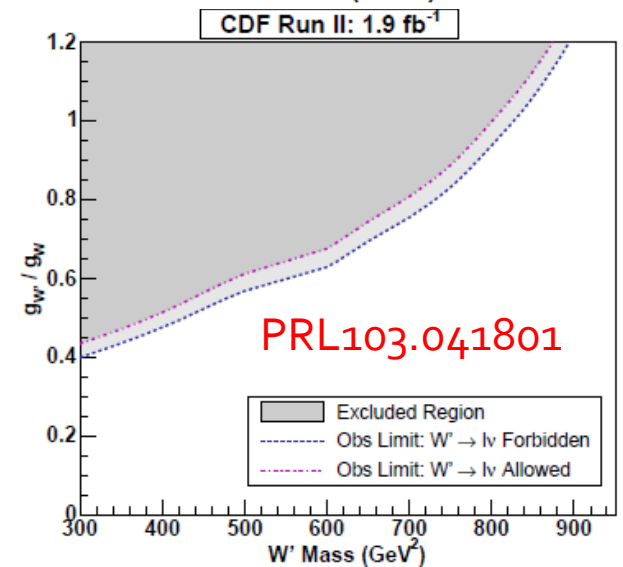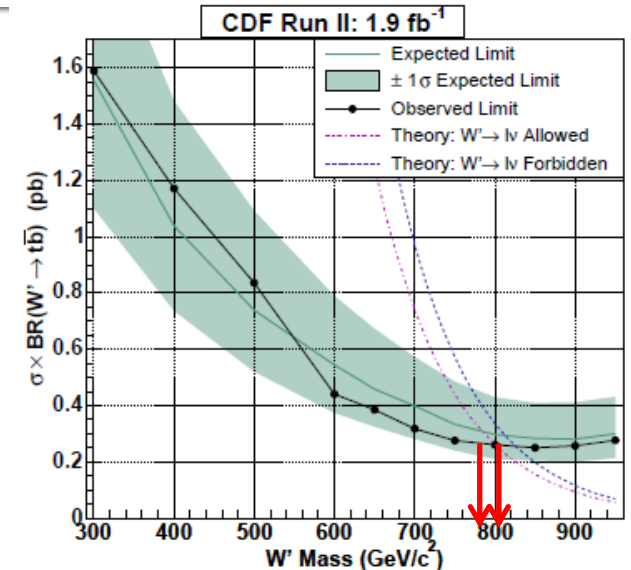| Process	2, 3 and 4 jets
W+jets	280 ± 18
QCD multijets	61 ± 11
Top pair production	425 ± 59
Single top (t-channel)	26 ± 3
Dibosons	13 ± 2
Z+jets	26± 3
Total	831 ± 62
Data	831

W'→tb: Signal Extraction

- CDF: fit to the invariant mass of the tb system

- DØ: enhance sensitivity through multivariate discriminant based on boosted decision trees
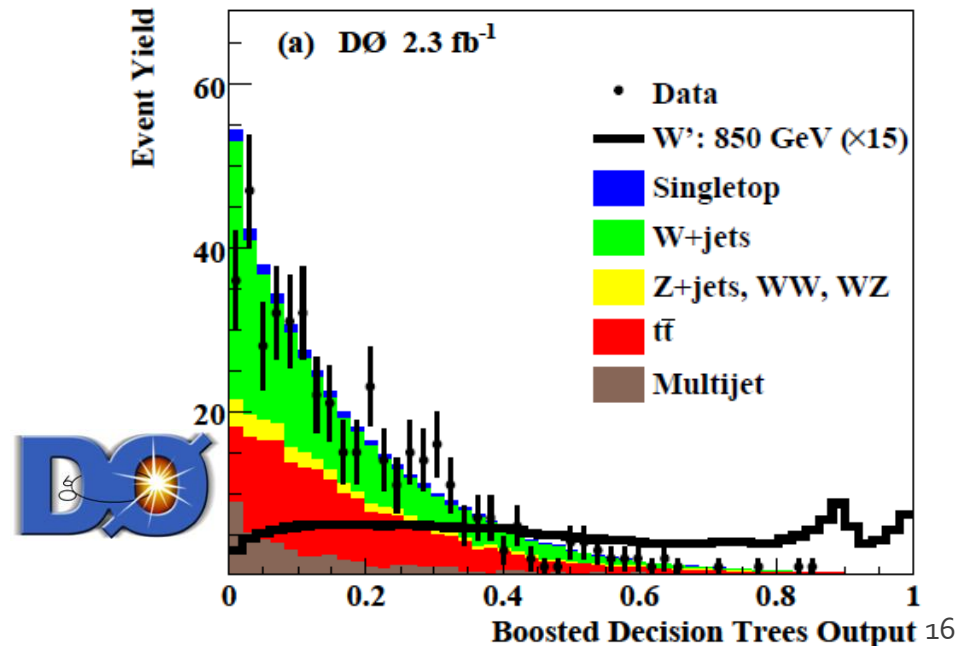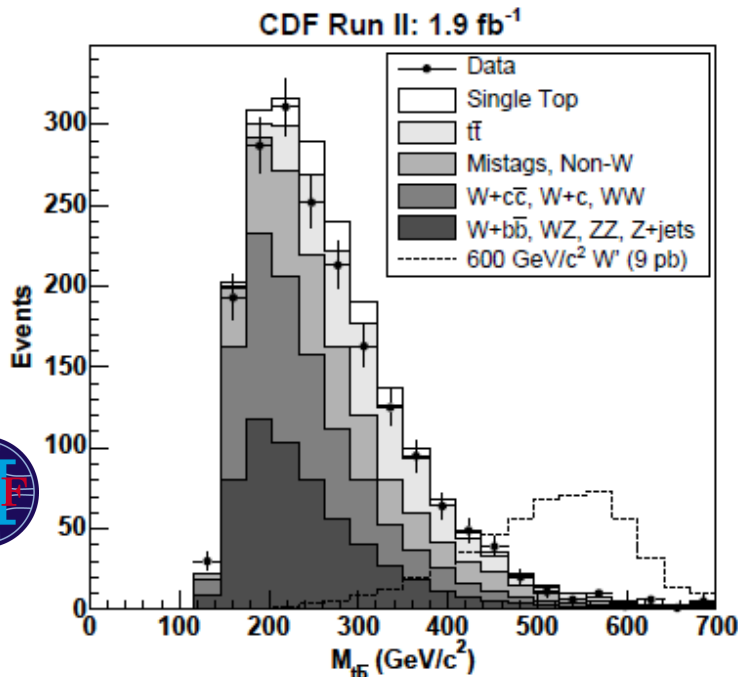
W'→tb: Limits

- Signal model: right-handed W'
  - △ No W-W' interference

- Assuming SM couplings ($g_{W'} = g_w$):
  - △ $M_{W'} > m_{\nu_R}$: $M_{W'} > 800$ GeV/c²
  - △ $M_{W'} < m_{\nu_R}$: $M_{W'} > 825$ GeV/c²

- Relaxing assumptions on W' couplings ($g_{W'}/g_W = a^R$):
  - △ Exclusion region in the $g_{W'}/g_w$-$M_{W'}$ plane

CDF Run II: 1.9 fb⁻¹

- Expected Limit
- ± 1σ Expected Limit
- Observed Limit
- Theory: W'→ lν Allowed
- Theory: W'→ lν Forbidden

$\sigma \times BR(W' \to t\bar{b})$ (pb)

W' Mass (GeV/c²)

CDF Run II: 1.9 fb⁻¹

$g_{W'}/g_W$

PRL103.041801

- Excluded Region
- Obs Limit: W' → lν Forbidden
- Obs Limit: W' → lν Allowed

W' Mass (GeV²)

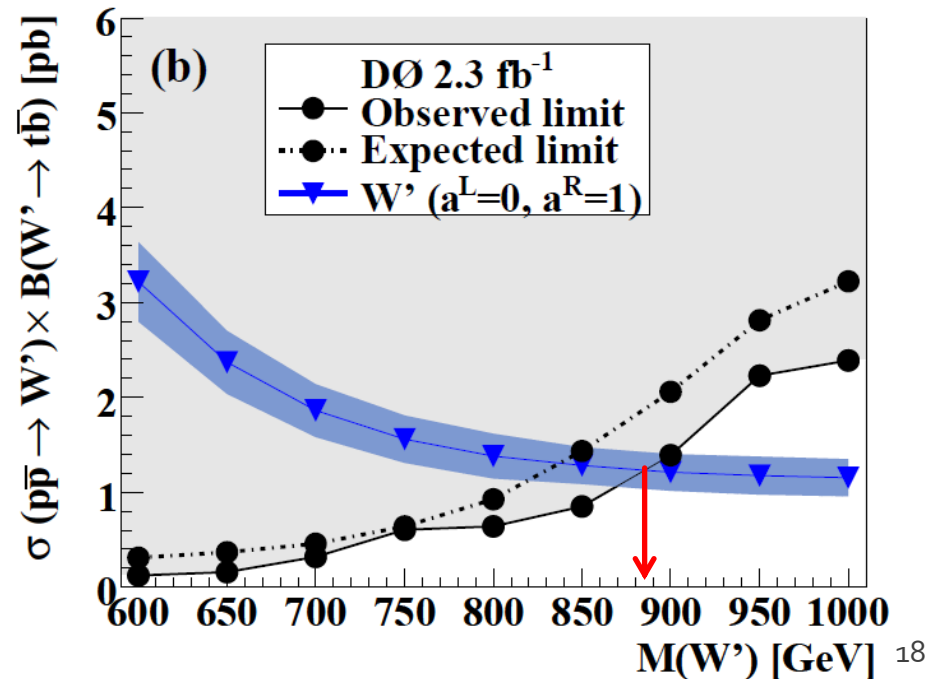# W'→tb: Limits

- Construct signal templates varying left/right-handed couplings $a^{L/R}$ between 0 and 1 in steps of 0.1
  - △ Couplings to first and third generation quarks taken as equal
  - △ W-W' interference accounted for

- Pure right-handed W': $a^L = 0$, $a^R = 1$
  - △ $M_{W'} > m_{\nu R}$: $M_{W'} > 885$ GeV/c^2
  - △ $M_{W'} < m_{\nu R}$: $M_{W'} > 890$ GeV/c^2

(b) DØ 2.3 fb^{-1}
- Observed limit
- Expected limit
- W' ($a^L=0$, $a^R=1$)

$\sigma(p\bar{p} \to W') \times B(W' \to t\bar{b})$ [pb] vs M(W') [GeV]

W'→tb: Limits

- Pure left-handed W':
  $a^L = 1$, $a^R = 0$
  Δ $M_{W'} > 863$ GeV/c²

- Mixed couplings W':
  $a^L = 1$, $a^R = 1$
  Δ $M_{W'} > 916$ GeV/c²
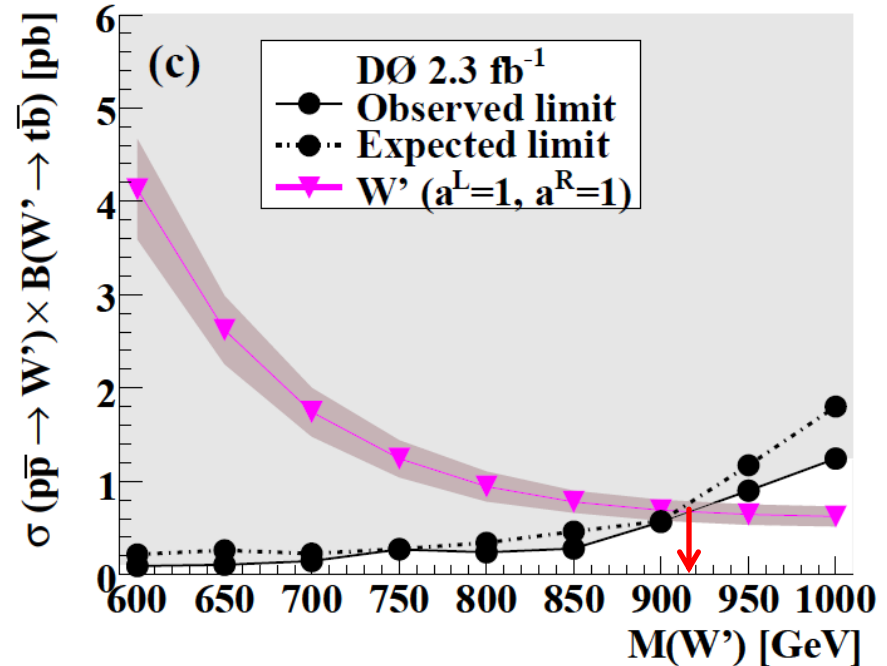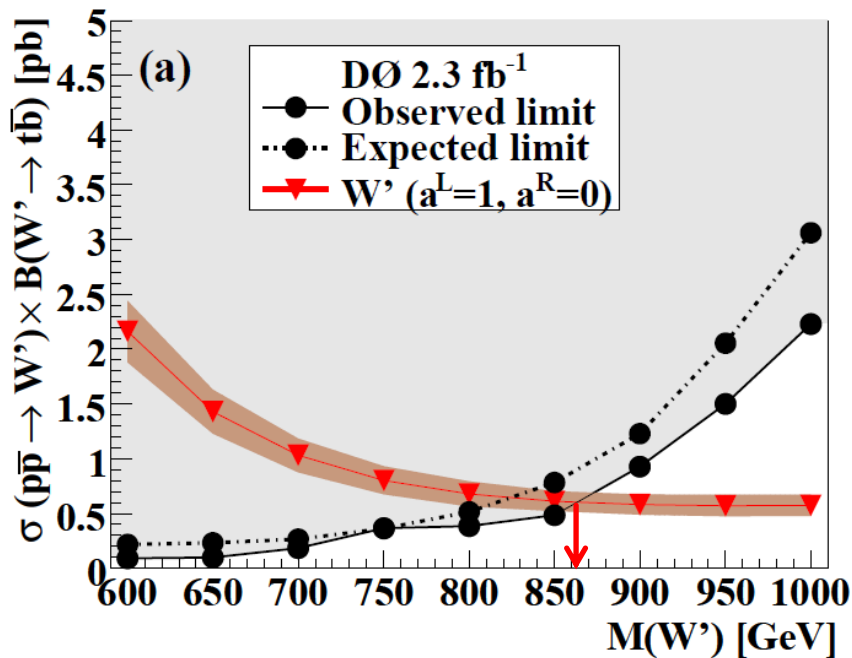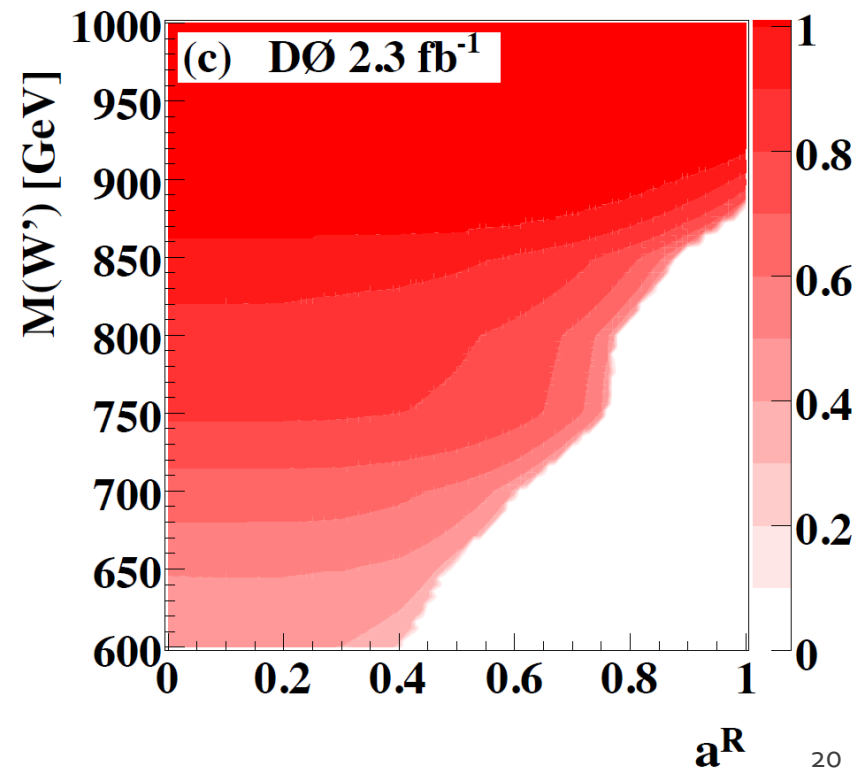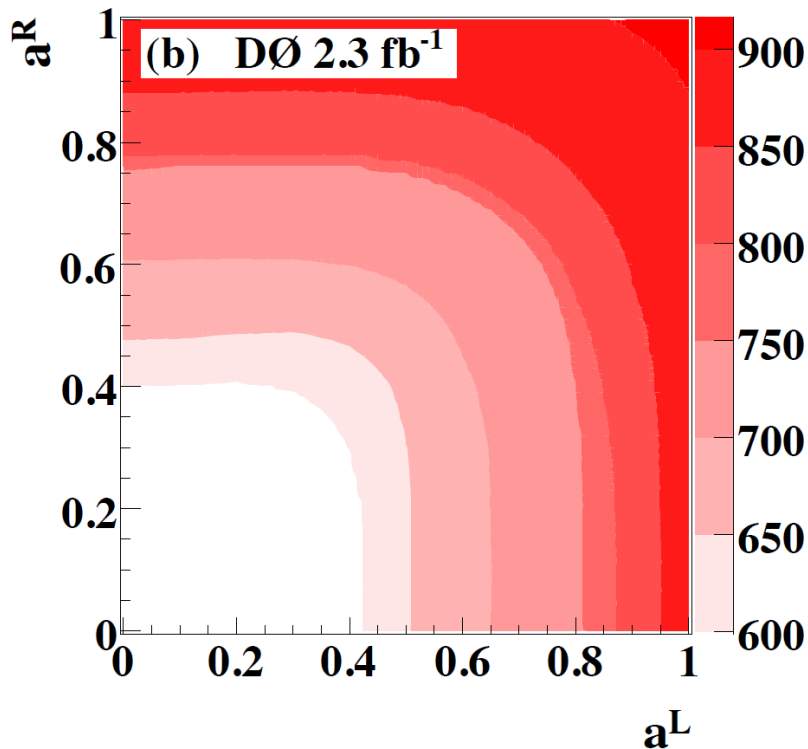
- Summary plots for DØ limits on W' mass and couplings

 △ Lower limits on W' mass   △ Upper limits on a^L

Conclusions

- Tevatron has strong effort in searches for heavy BSM particles

- World's strongest limits on searches for heavy quarks b' and heavy charged bosons W'
    - $m_{b'} > 385$ GeV/c^2
    - Right-handed W': $M_{W'} > 885$ GeV/c^2
    - Left-handed W': $M_{W'} > 863$ GeV/c^2

- Still great potential to exploit in next years
    - More statistics to analyze and channels to investigate

Backup Material

The Tevatron Collider
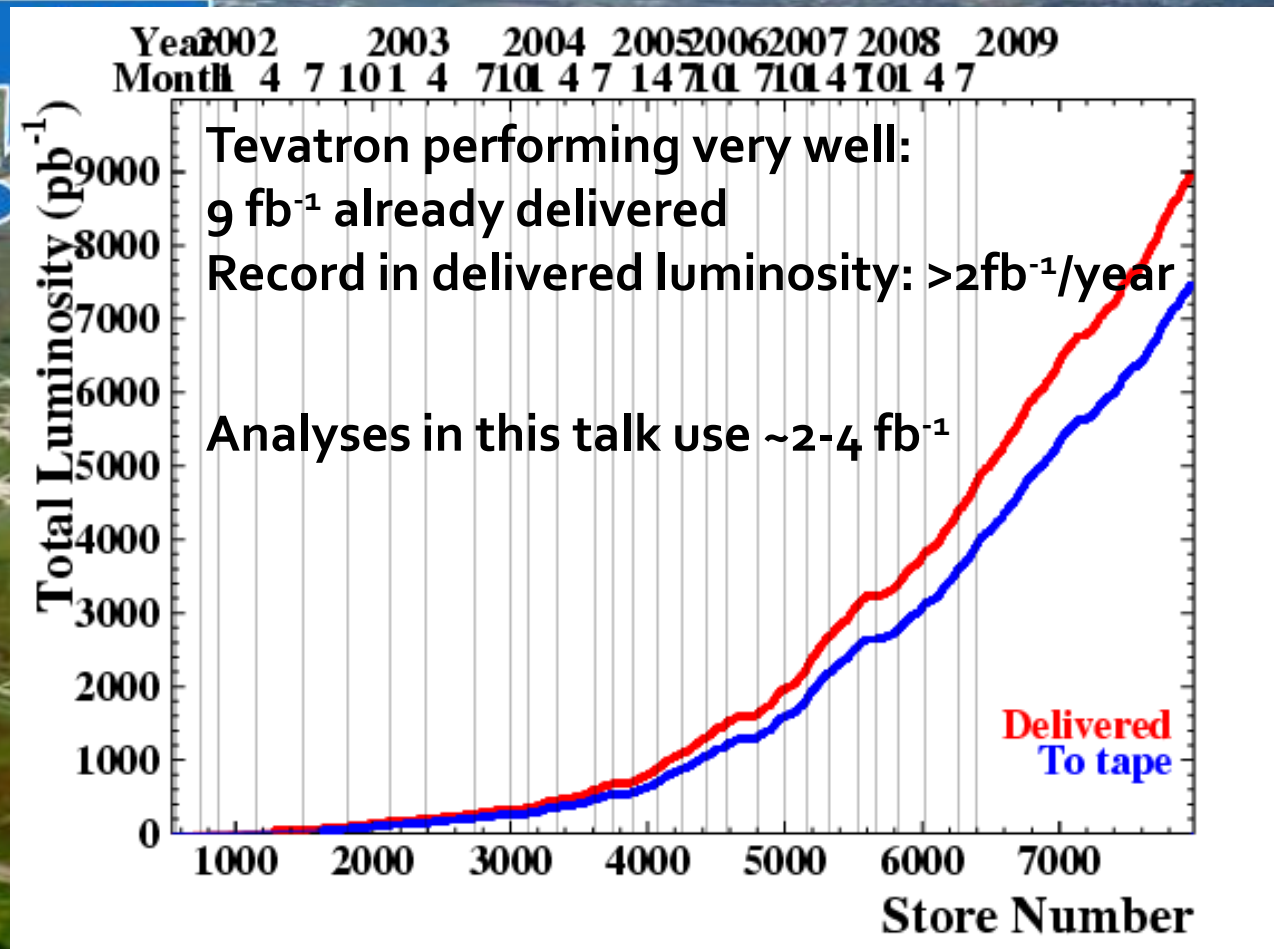

Proton-antiproton collisions at √s = 1.96 TeV
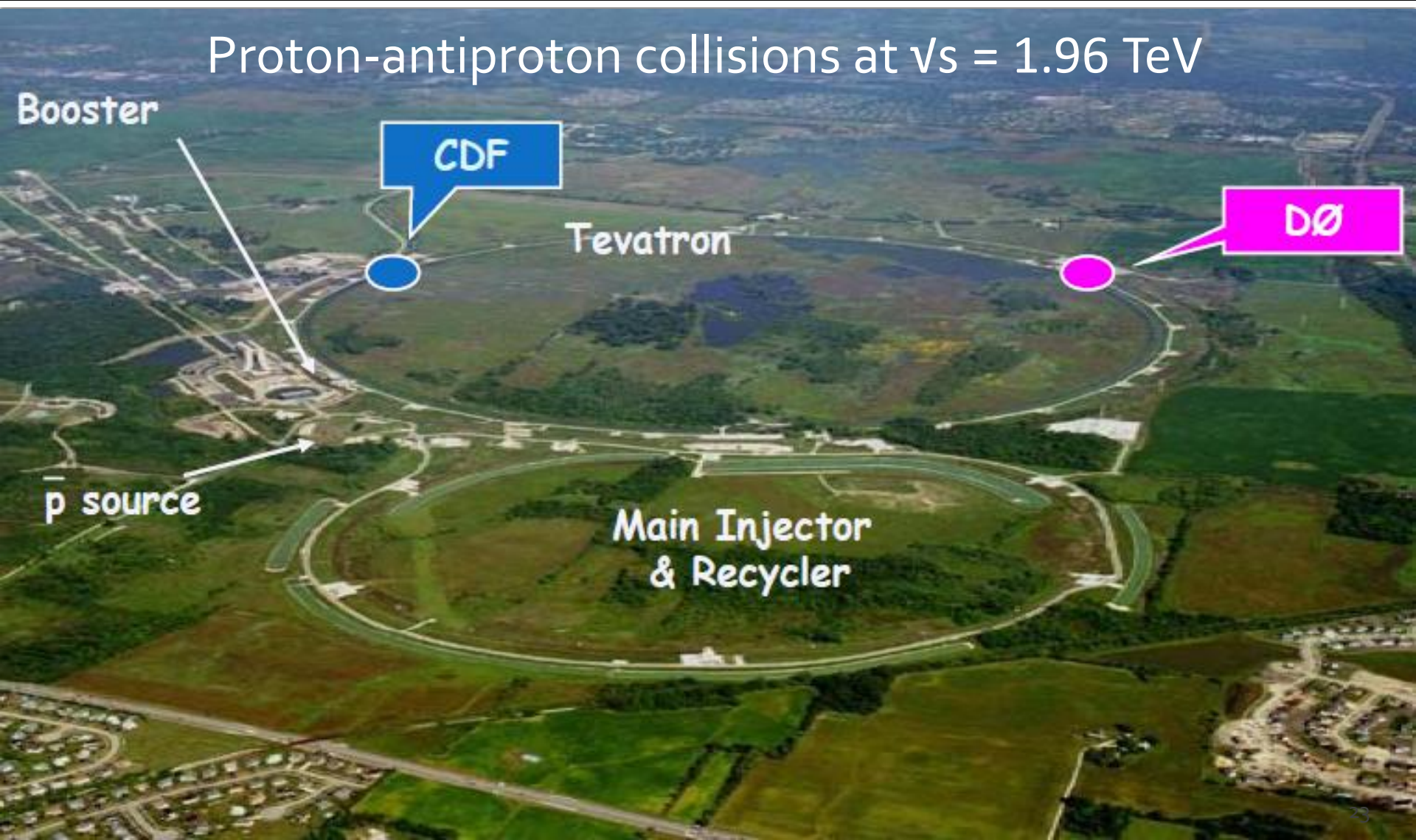
The Tevatron Collider

Record instantaneous luminosity 4×10^{32}cm^{-2}s^{-1}

Booster

$\bar{p}$ source
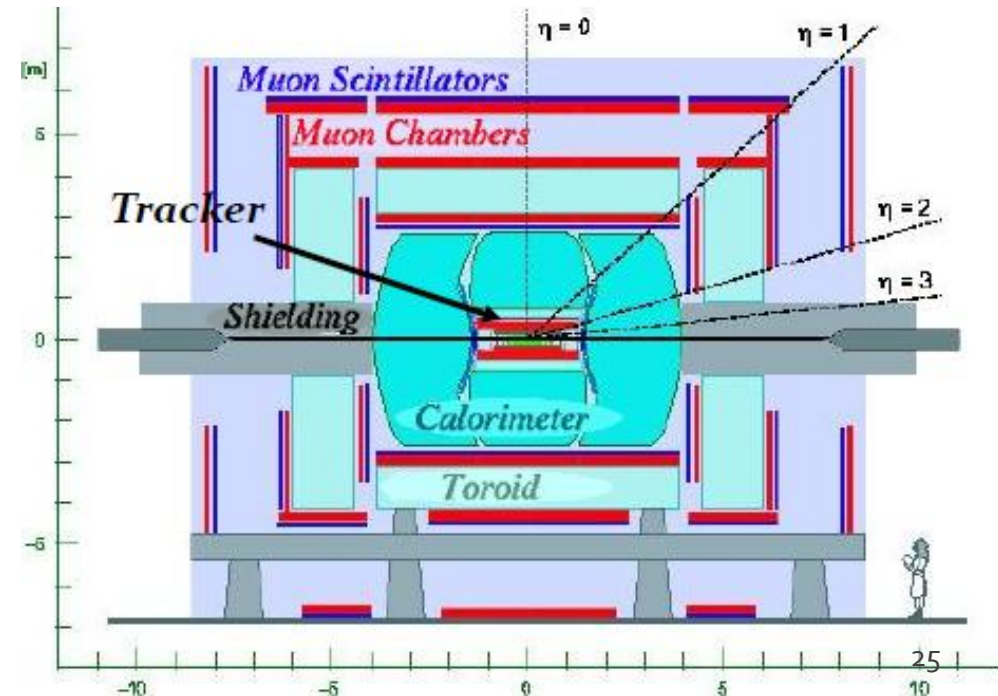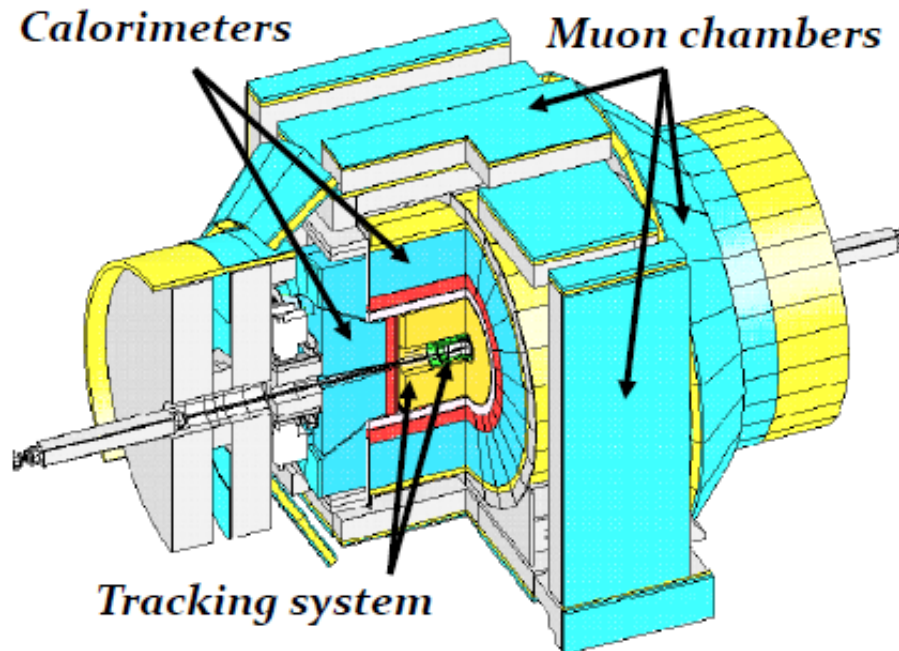
Tevatron performing very well:
9 fb^{-1} already delivered
Record in delivered luminosity: >2fb^{-1}/year
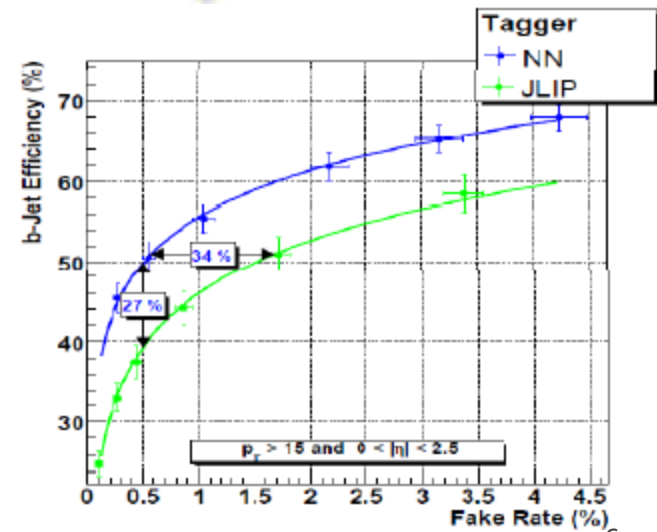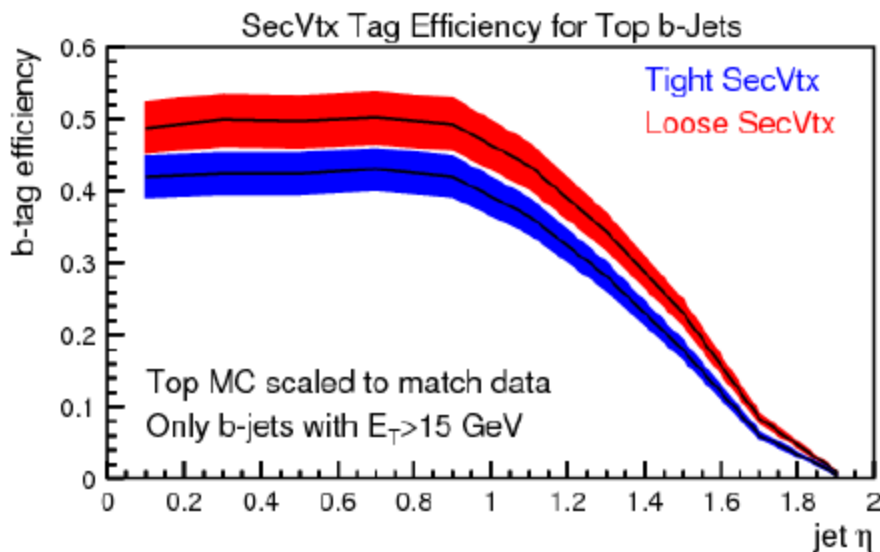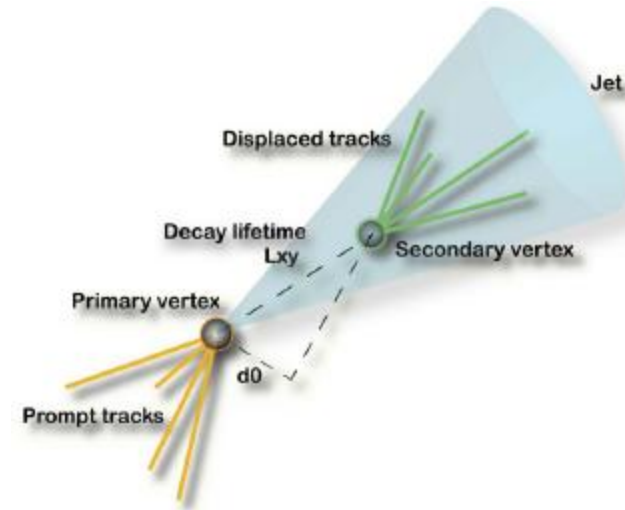
Analyses in this talk use ~2-4 fb^{-1}

Multipurpose experiments collecting data at high efficiency

> Muon chambers, EM calorimeter and tracking for lepton ID
> Calorimeters for jet reconstruction
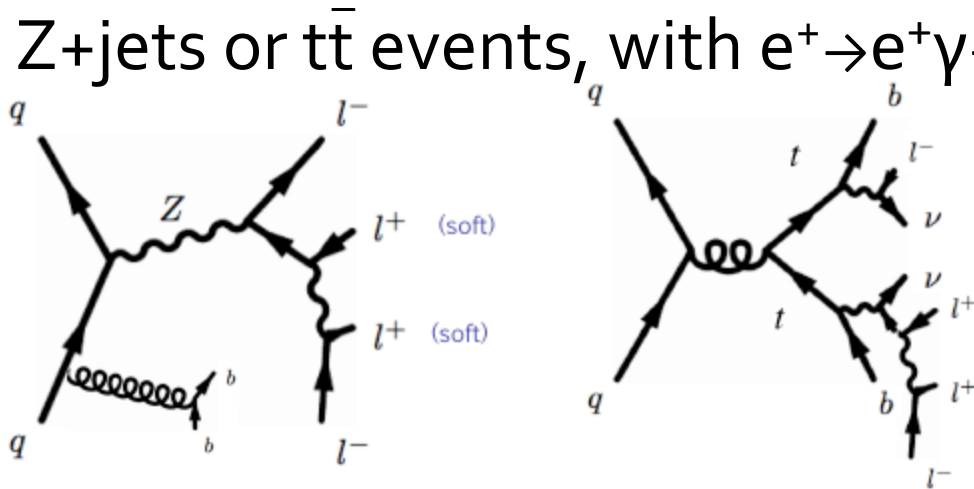> Silicon detectors for b quark tagging

B Tagging

- CDF: reconstruct displaced vertices with cut on L_{xy}/σ

  > Vertex mass separation

- DØ: use NN to combine vertex properties and displaced track info

  > Tag in $|\eta|>2$ region

Displaced tracks

Jet

Decay lifetime
L_{xy}

Secondary vertex

Primary vertex

d0

Prompt tracks

SecVtx Tag Efficiency for Top b-Jets

Tight SecVtx
Loose SecVtx

Top MC scaled to match data
Only b-jets with $E_T>15$ GeV

b-tag efficiency

jet η

Tagger
NN
JLIP

b-Jet Efficiency (%)

34 %

27 %

$p_T > 15$ and $0 < |\eta| < 2.5$

Fake Rate (%)

- Z+jets or t$\bar{\text{t}}$ events, with $e^+ \to e^+ \gamma \to e^+ e^+ e^-$

- Fakes: second lepton from jets
  > fake rate modeled in jet data

CDF Run II Preliminary (2.7 fb⁻¹)

Opposite-sign leptons

Data
Uncert.
Z,diboson
tt
Fakes

Number of Reconstructed Jets

CDF Run II Preliminary (2.7 fb⁻¹)

No b-tag

Data
Uncert.
Z,diboson
tt
Fakes

Invariant Dilepton Mass (GeV/c²)
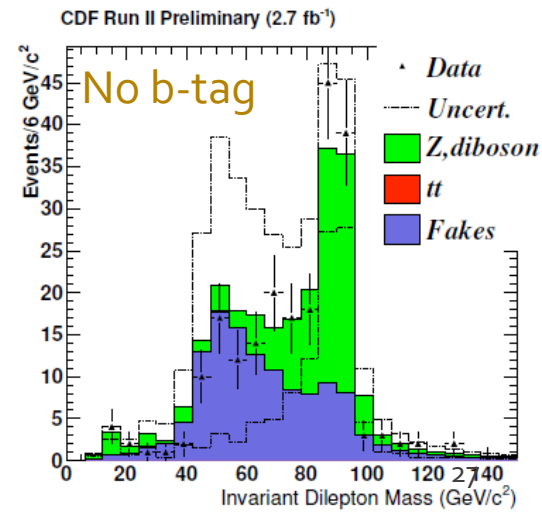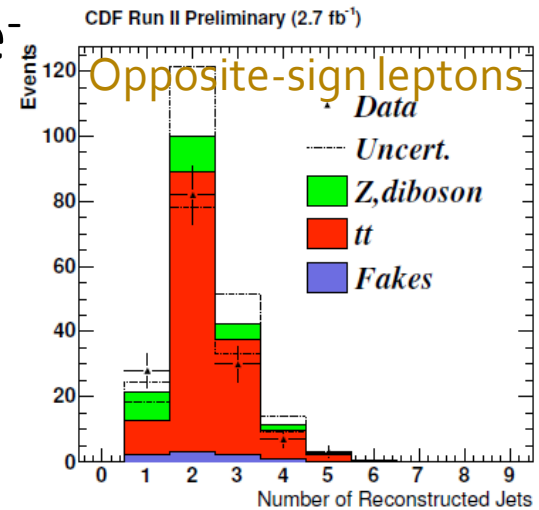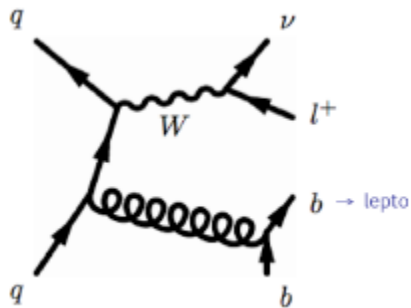
b'→Wt : Yields (2.7 fb⁻¹)

- Observed and predicted events:

Process	ee	μμ	eμ	Total
Z+jets	0.01 ± 0.01	0	0.02 ± 0.02	0.03 ± 0.03
Top dilep.	0.06 ± 0.04	0	0.02 ± 0.03	0.15 ± 0.05
Fakes	0.6 ± 0.6	0.03 ± 0.03	0.5 ± 0.5	1.4 ± 1.4
Total	0.7 ± 0.6	0.3 ± 0.3	0.6 ± 0.5	1.6 ± 1.4
Data	0	1	1	2

- Fitting the observed jet multiplicity distribution

$m_{b'} > 338$ GeV/c^2