Studies of Single Top Quark Production at the Tevatron

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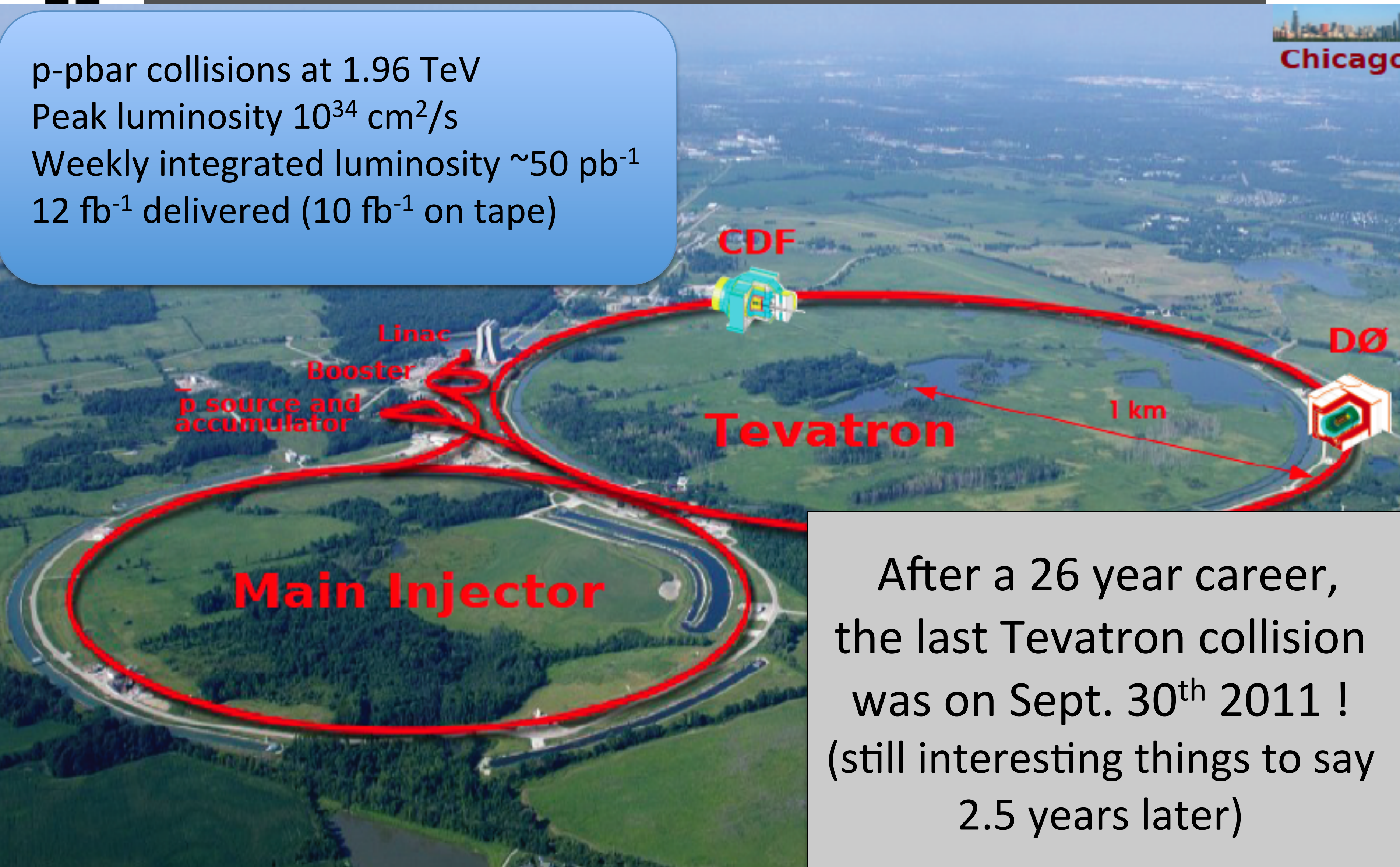
on behalf of the CDF and D0 Collaborations

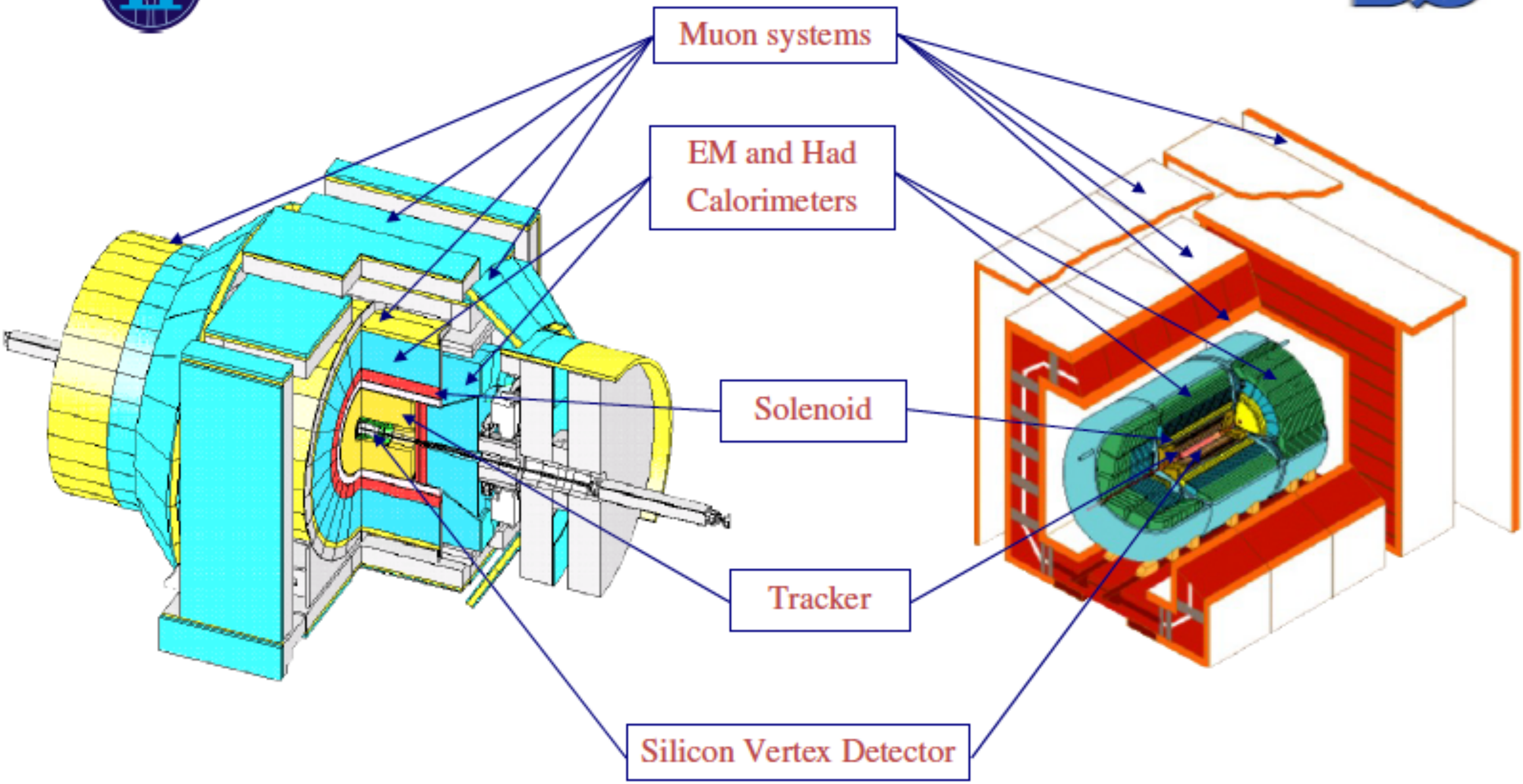
The Tevatron

p-pbar collisions at 1.96 TeV
Peak luminosity 10^{34} cm^2/s
Weekly integrated luminosity ~50 pb^{-1}
12 fb^{-1} delivered (10 fb^{-1} on tape)



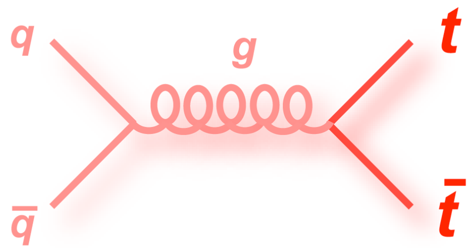
After a 26 year career, the last Tevatron collision was on Sept. 30th 2011 ! (still interesting things to say 2.5 years later)

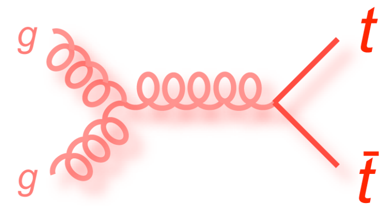
The CDF and D0 detectors

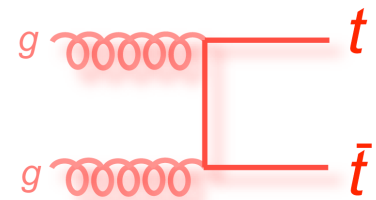


Top Quarks at the Tevatron

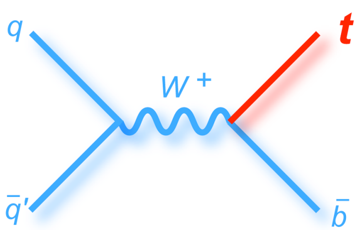
Top quark pair production, through strong interaction, was first observed at Tevatron in 1995.



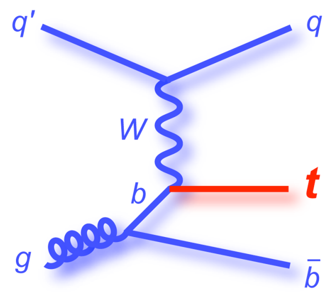




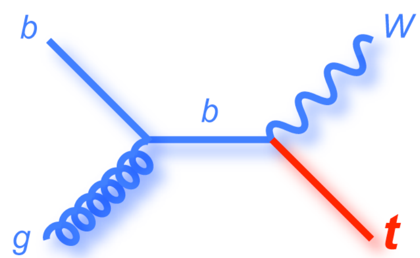
Dominant modes at Tevatron



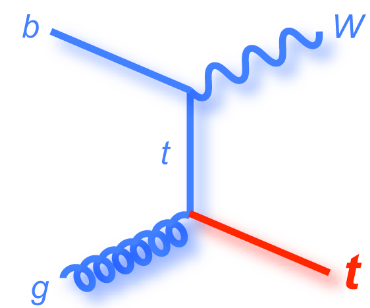
s-channel



t-channel



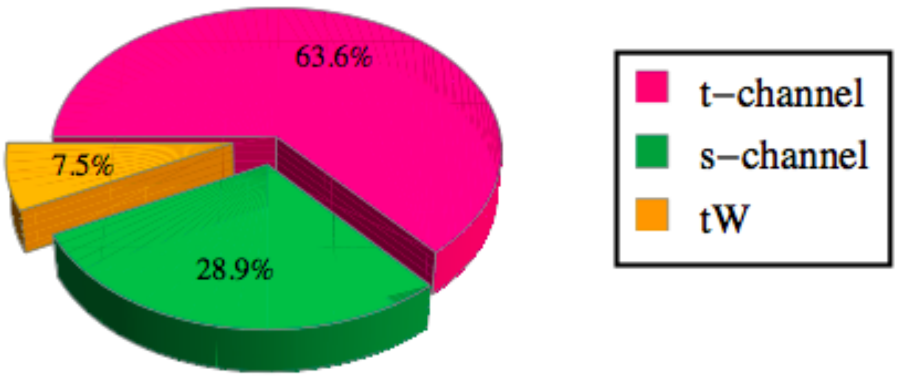
tW-channel



Single top quark production, through electroweak interactions, was first observed at Tevatron in 2009.

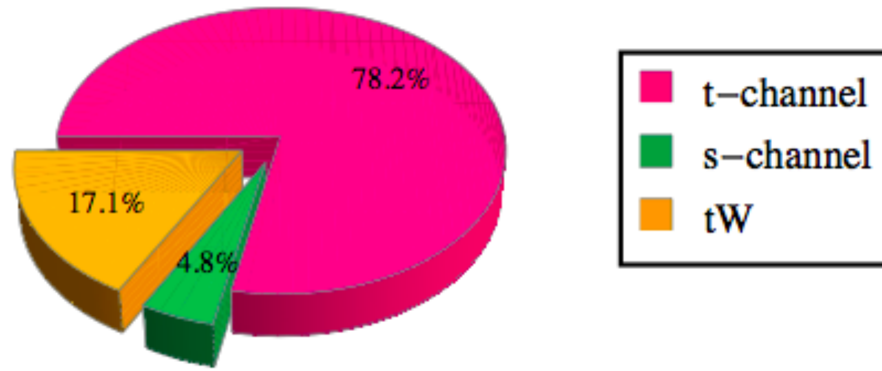
Tevatron v/s LHC

Tevatron σ_{ST} ~ 3.4 pb



proton-antiproton

LHC (7 TeV) σ_{ST} ~ 114 pb (@ 8 TeV)



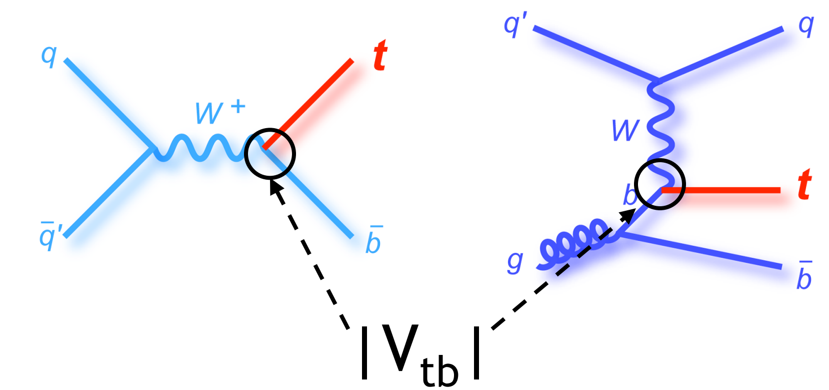
proton-proton

Both the Tevatron and LHC are sensitive to t-channel.

The Tevatron has an advantage in s-channel studies but is not sensitive to Wt production.

Motivation

- New physics may affect the rate of *s*- and *t*-channel differently:
  - *s*-channel: new bosons
  - t-channel: FCNC



- Access to the W-t-b vertex
- Allows measurement of CKM matrix element $|V_{tb}|$:
  - Is this Matrix 3x3 ?
    Is there a 4th generation ?
  - Does unitarity hold ?
  - "simple" 4th generation ruled out by EW fits but see e.g.

Direct measurements

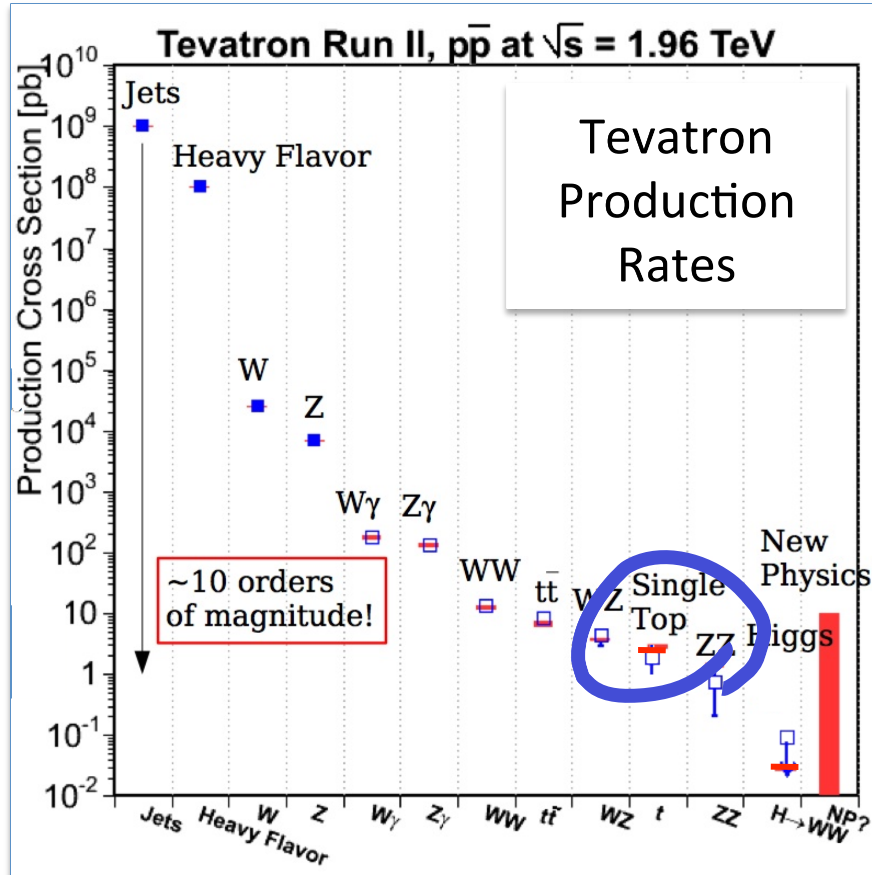
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Ratio from Bs oscillations

Not precisely measured
Inferred using unitarity

Production Rates

- Single Top production is a rare process at the Tevatron
  - Signal:Background (S:B) ~ **1:10^9**
    (before any selection)
- First step:
  - Trigger on leptons/MET
  - S:B to **~ 1:1000**
  - High p_T lepton triggers (e,μ)
  - MET + jets triggers
- Second step:
  - Topological event selection
  - *b*-jet selection
  - S:B **~ 1:20**
- Third step:
  - Advanced analysis techniques to separate signal from background using discriminants
  - S:B **> 1:1** in most significant bins



Event Selection

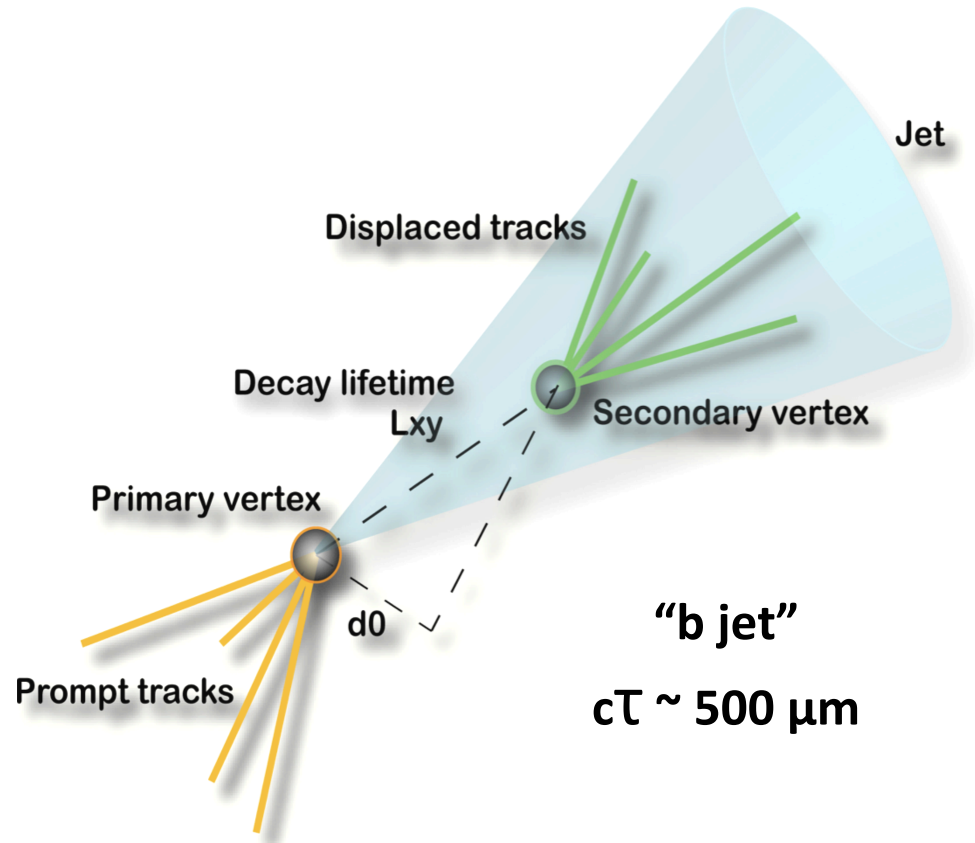
(1) Lepton + MET + jets Selection:

- 1 Lepton
- Missing E_T (MET)
- 2 or more jets
- Veto "non-W", Z, dileptons, Conversions, Cosmics
- At least one *b*-tagged jet
  (displaced secondary vertex)

(2) MET + jets Selection:

- Large MET
- Veto leptons
- 2 or more jets
- At least one *b*-tagged jet
- Neural Network to suppress QCD background

Only!



"b jet"

$c\tau \sim 500\ \mu m$

=> Orthogonal Event Selections:
(2) adds 33% acceptance to (1)

Single Top Background Estimate

Top/EWK (WW/WZ/Z→ττ, ttbar)

- MC normalized to theoretical cross-section
- Modeled by Pythia Monte Carlo

MC driven

W+HF jets (Wbb/Wcc/Wc)

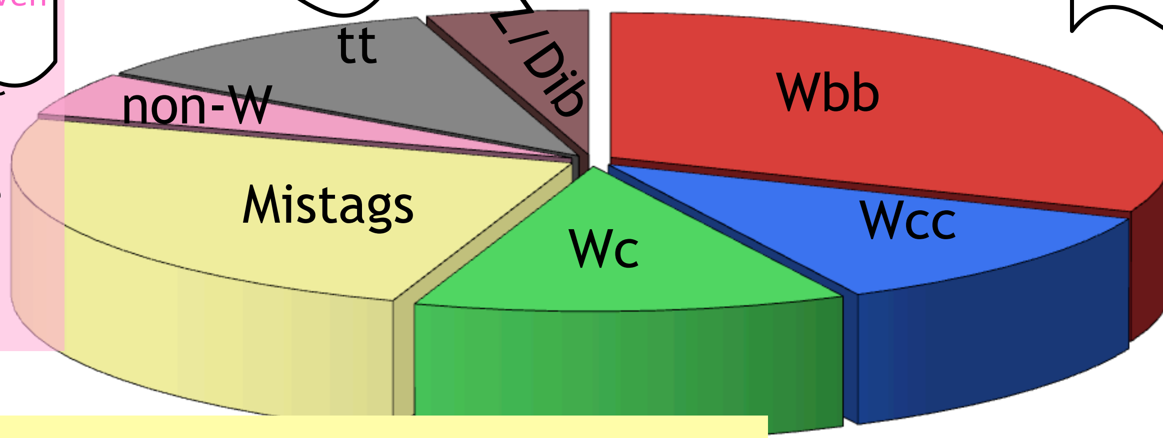
- W+jets normalization from data and heavy flavor (HF) fractions from ALPGEN Monte Carlo
- Modeled by Alpgen W+HF MC

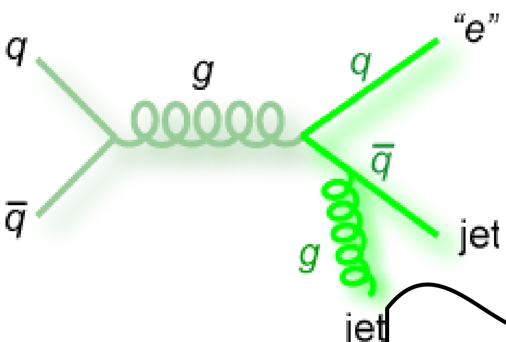
MC+ data driven

Non-*W* (QCD)

Data driven

- Multijet events with semileptonic *b*-decays or mismeasured jets
- Fit low MET data and extrapolate into signal region
- Modeled by 'Anti/Jet-electons'

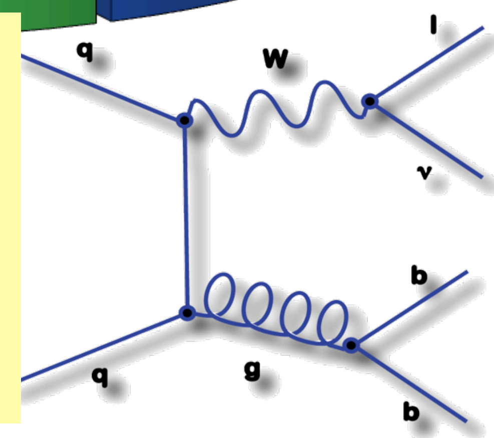




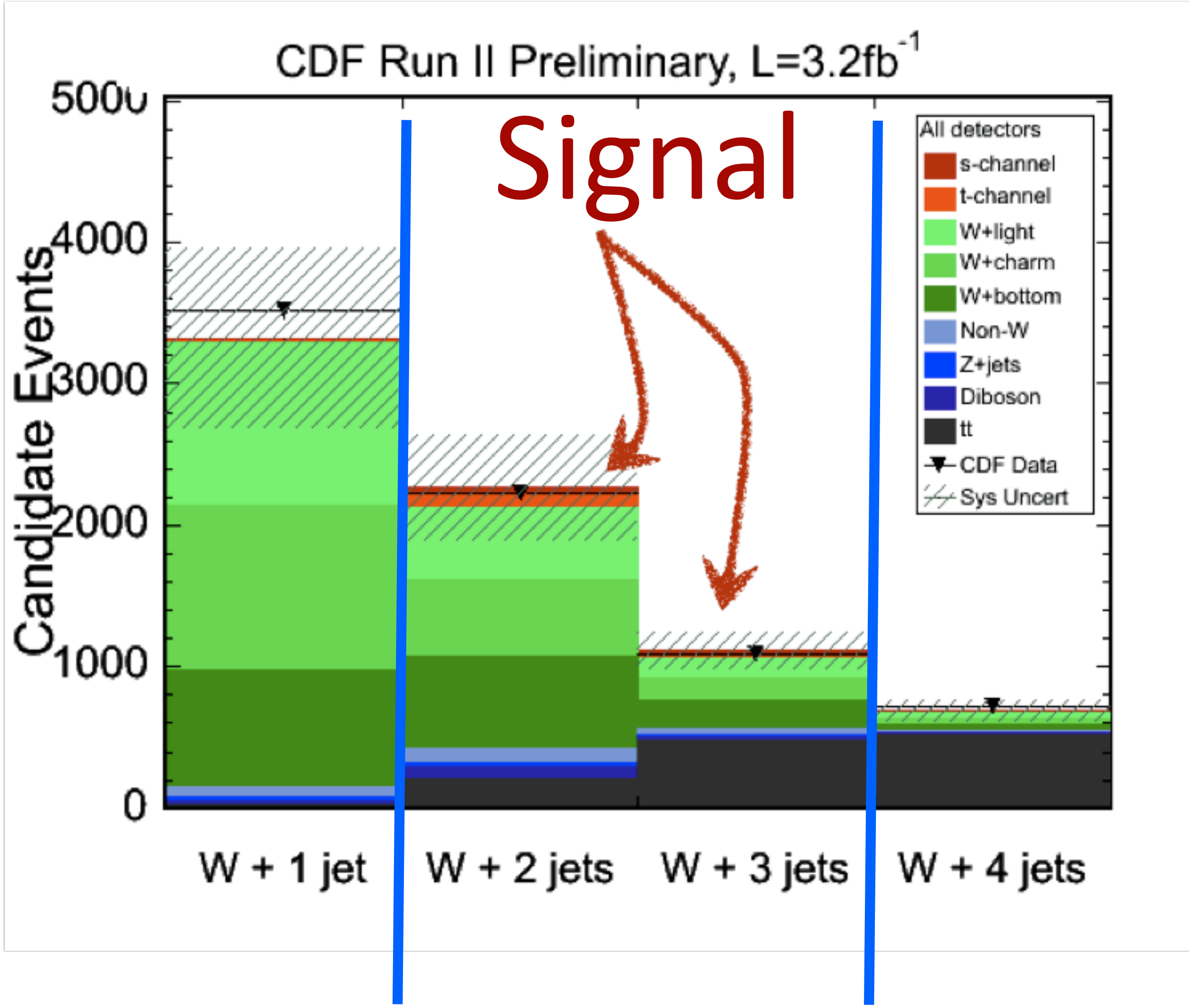
data driven

Mistags (W+2jets)

- Falsely tagged light quark or gluon jets
- Mistag probability parameterization obtained from inclusive jet data
- Apply mistag probability to generic W +jets sample

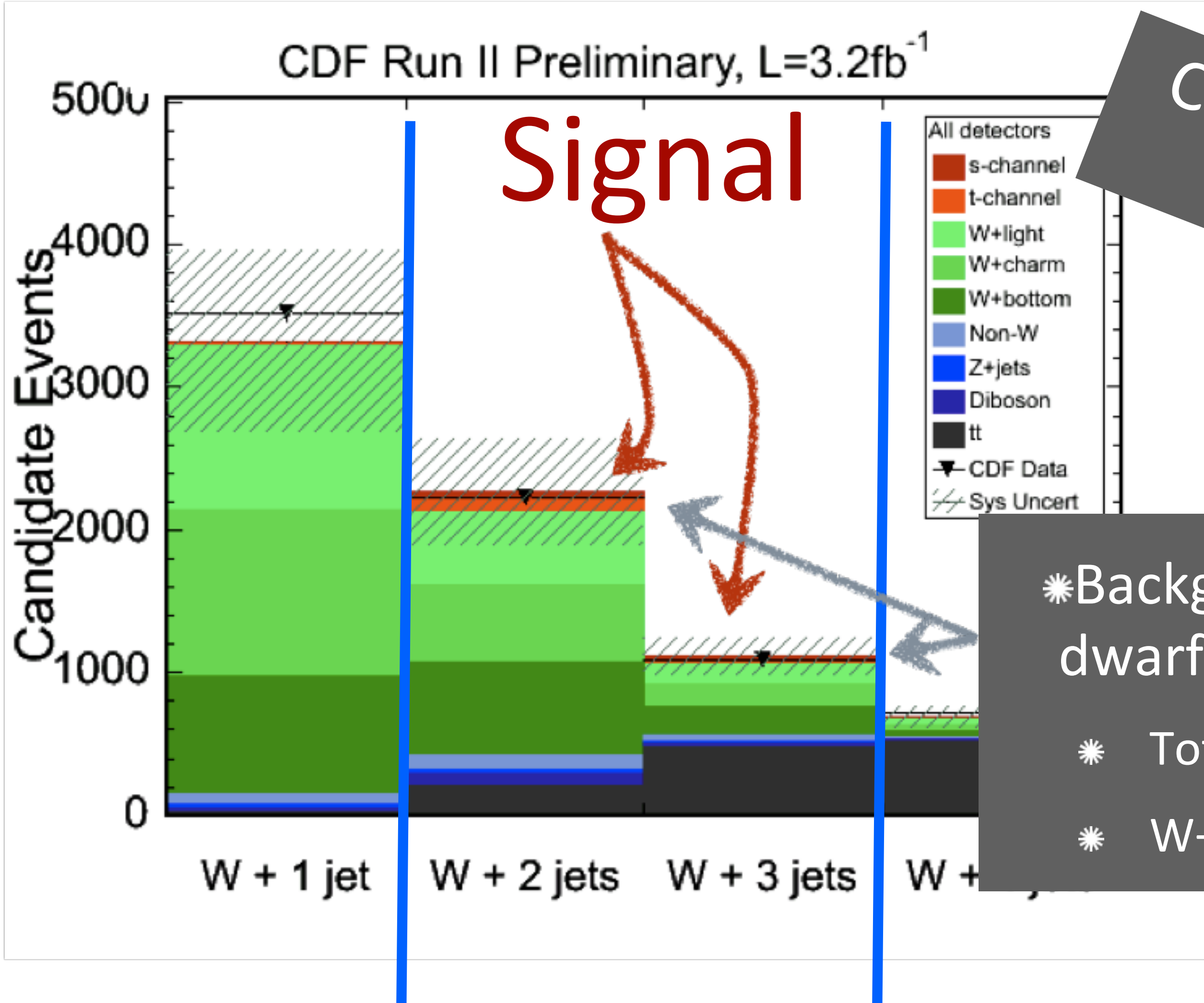


The Challenge



Note: DØ also includes events with 4-jets in the signal region

The Challenge



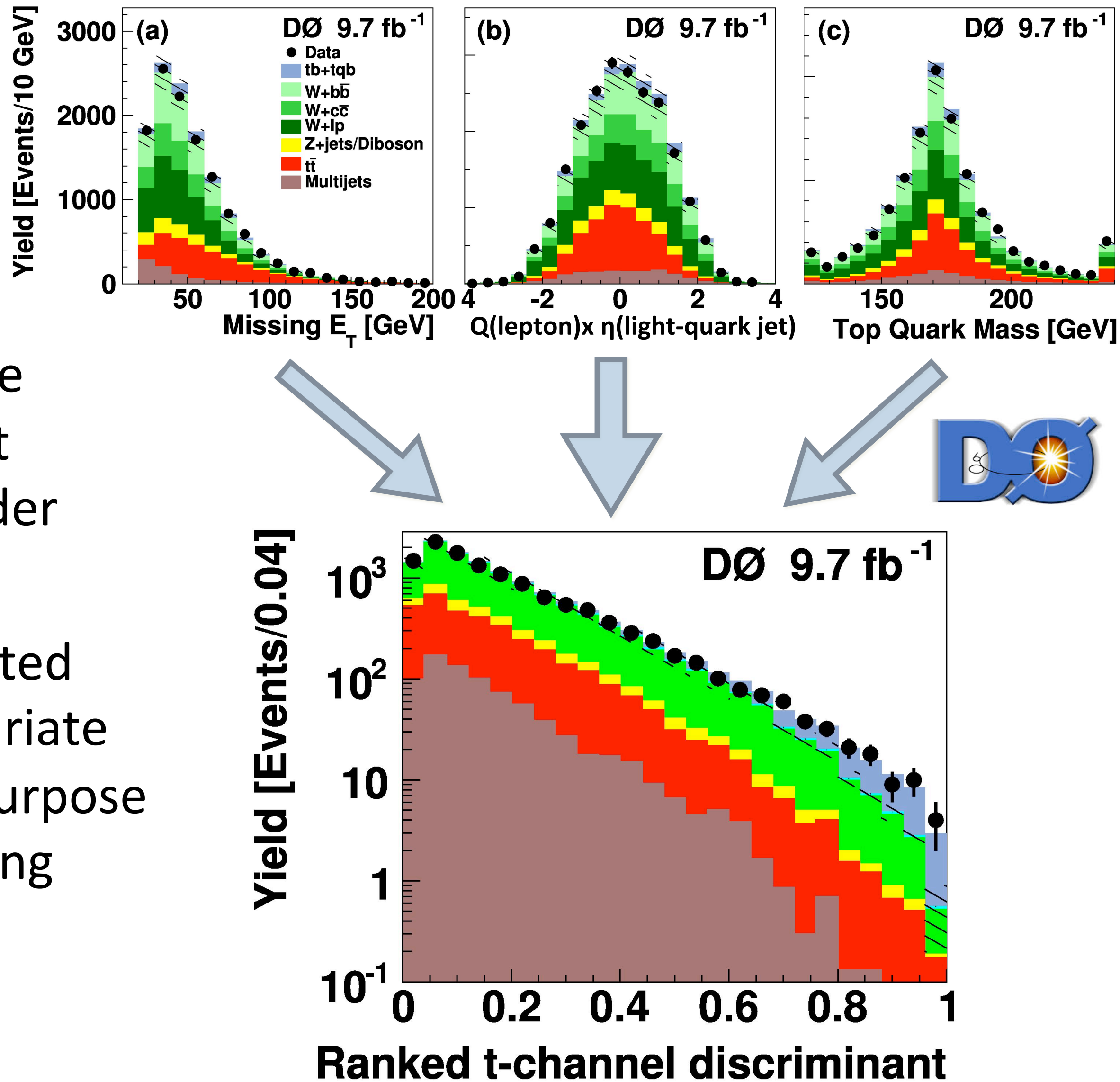
Can't do counting experiment!

- Background uncertainties dwarf signal
  - Total uncertainty ~17%
  - W+HF uncertainty ~30%

Note: DØ also includes events with 4-jets in the signal region

Multivariate Techniques

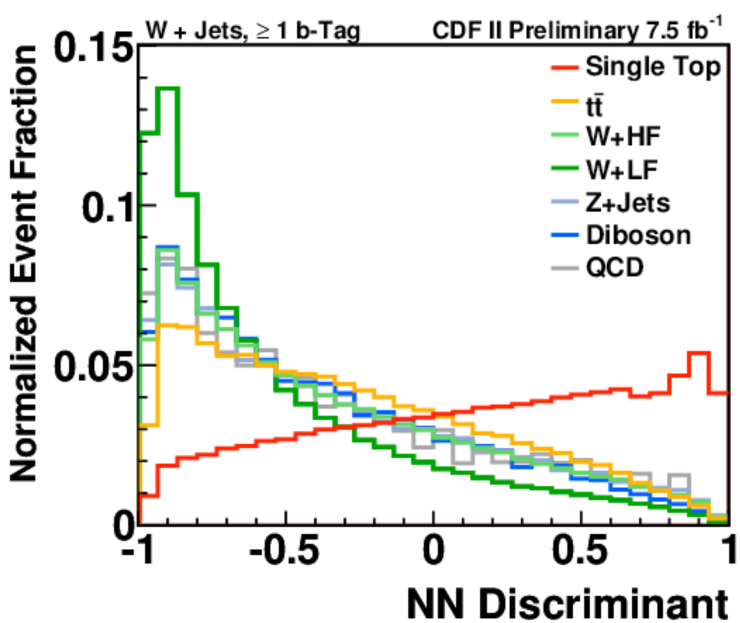
- Goal: Combine multiple variables into single, more powerful discriminant
- Techniques range from
  - Matrix Elements: Derive discriminant from "first principals" (leading-order amplitudes)
  - Neural Networks, Boosted Decision Trees, Multivariate Likelihoods: General purpose techniques for combining multiple variables

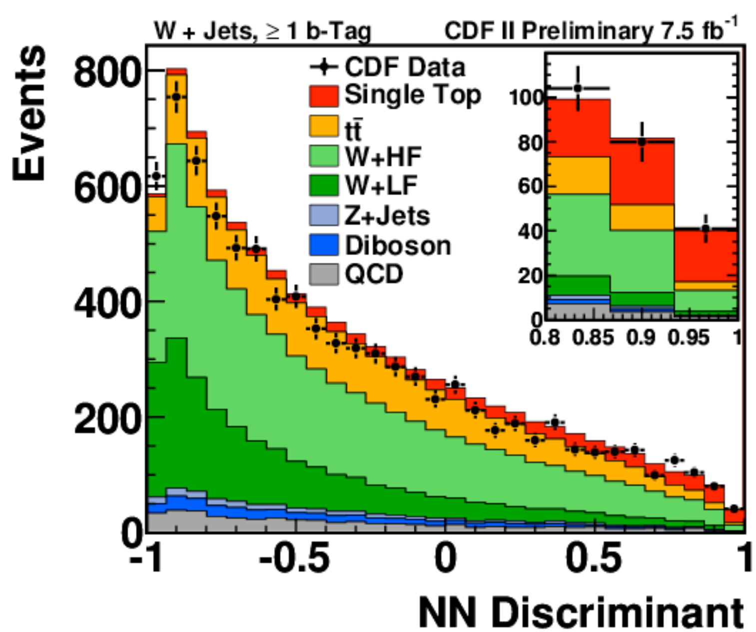


- Train NN with 11-14 variables
- Use s-channel as signal in only 2 jet 2 tag channel, t-channel for the rest
- Validate data-background agreement in 0-tag sample
- CDF Note 10739

σ_{s+t} = 3.04 $^{+0.57}_{-0.53}$ pb (17%)

(SM prediction 3.34 pb)

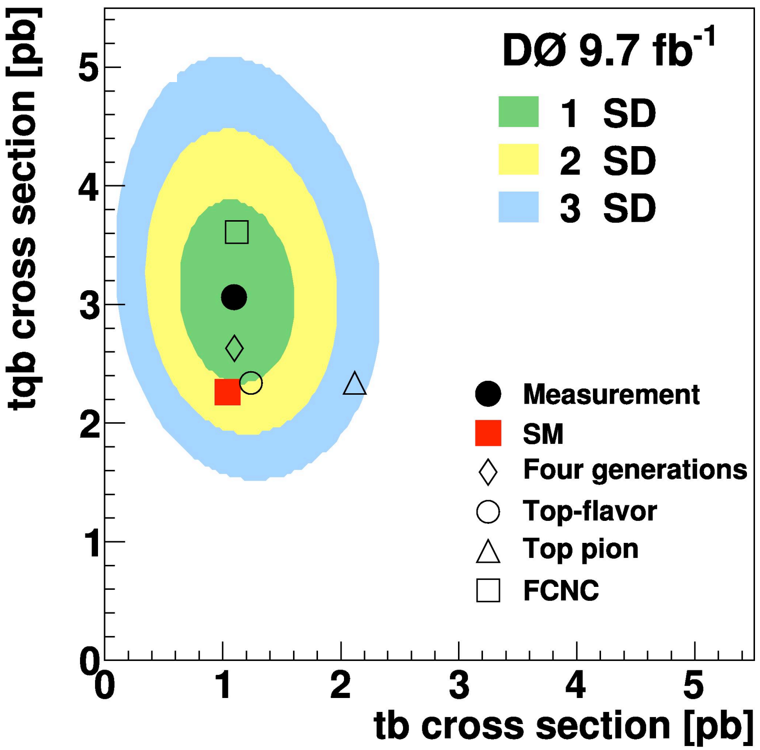




D0 9.7 fb^{-1}

Phys.Lett. B726 (2013) 656-664

- Multipurpose analysis for s+t, s-only, and t-only
- Optimized selection for s-channel production
- D0 has used three different techniques: BDT, BNN, ME
  - BDT uses 30 well-modeled variables, BNN uses 4-vectors
  - Improved ME, better tt model, and b-tag weights for discriminants
- Simultaneous s- and t- channel cross section measurements on same data



New!

$$\sigma_{s+t} = 4.11\,^{+0.60}_{-0.55}\ \text{pb}\ (14\%)$$

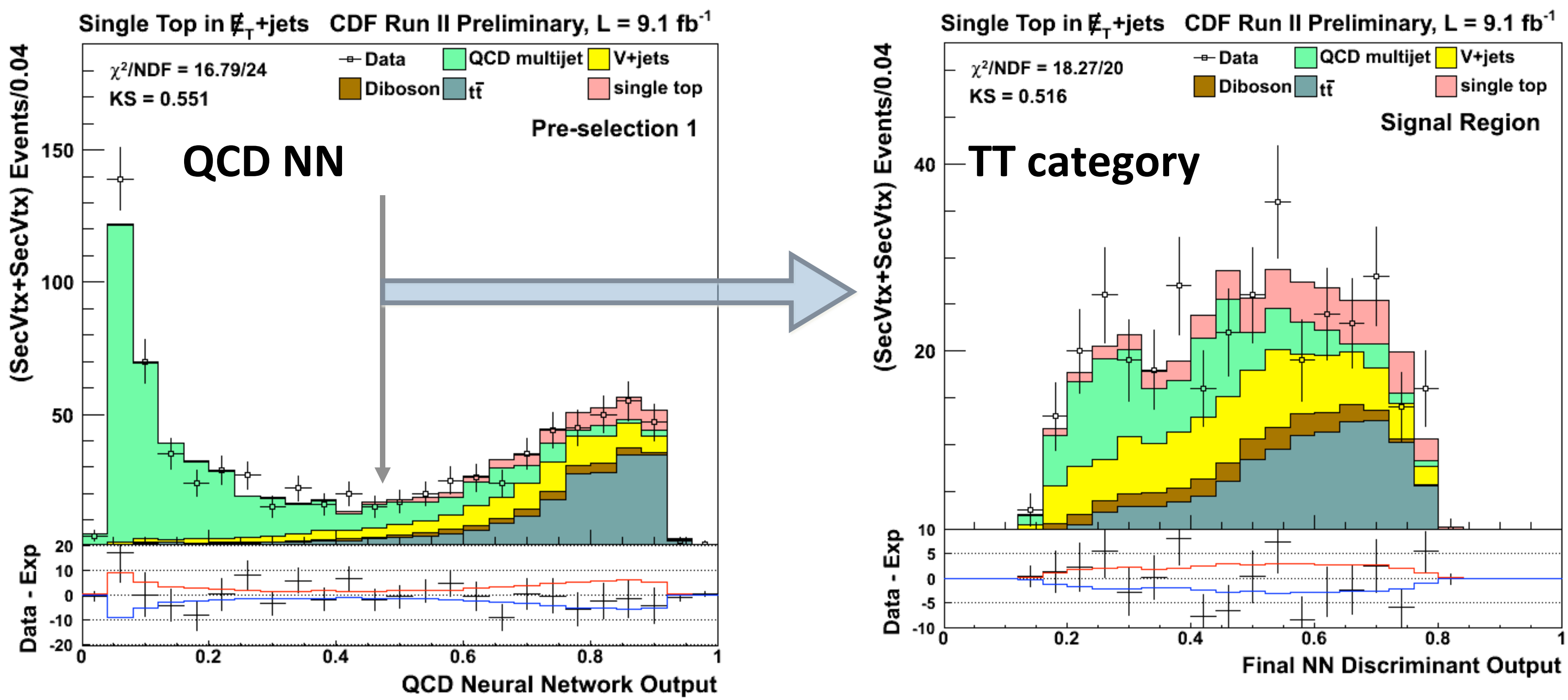
(SM prediction 3.34 pb)

CDF MET+jets 9.1 fb^{-1}

CDF Note 10979

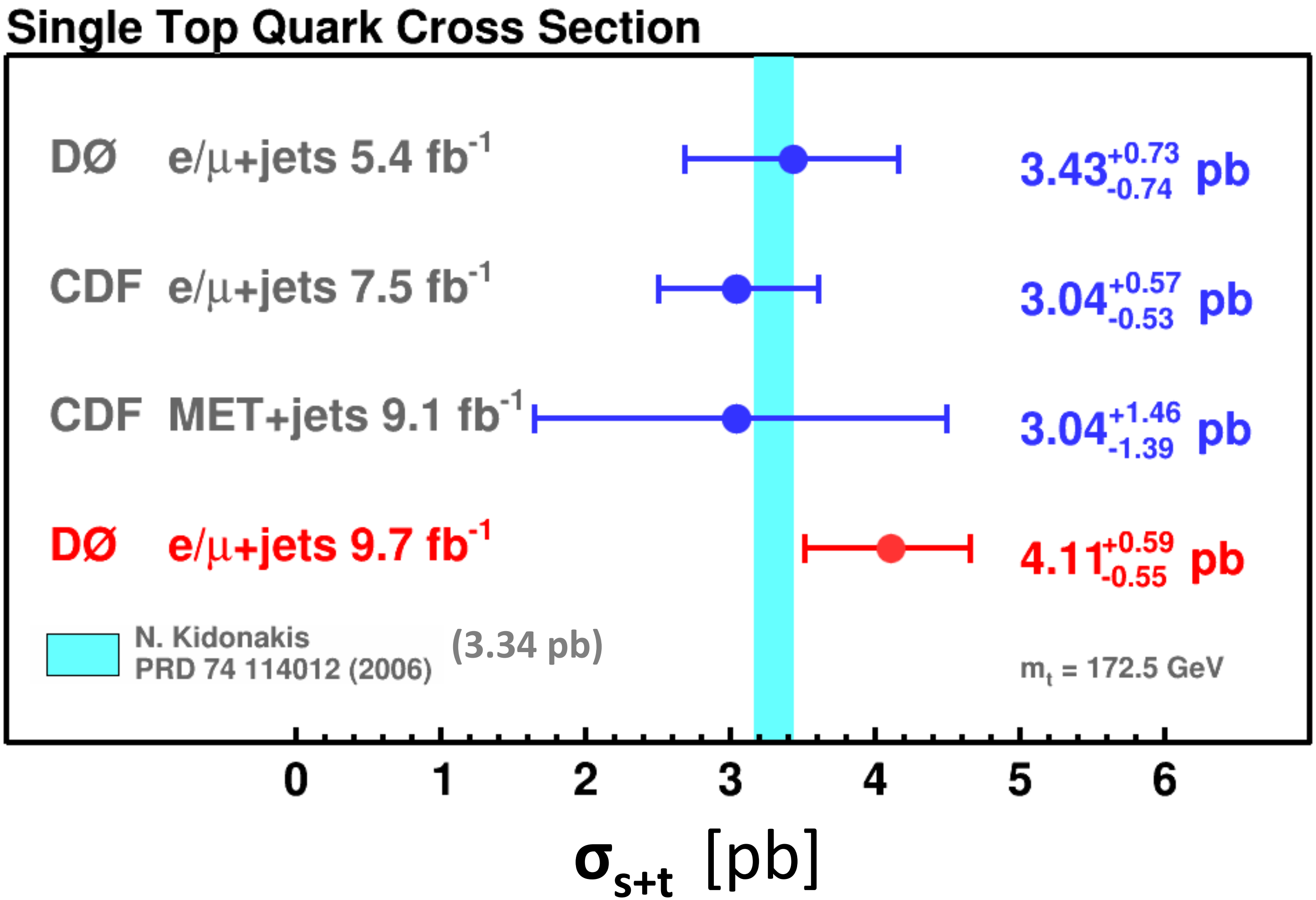
- MET+jets selection only – lepton veto
- Recover non-reconstructed electrons and muons and $W \rightarrow \tau\nu$ (hadronic decay)
- Completely orthogonal dataset to ℓ+jets selection
- Train several MVA against QCD and $t\bar{t}$, then combine with NN

New!



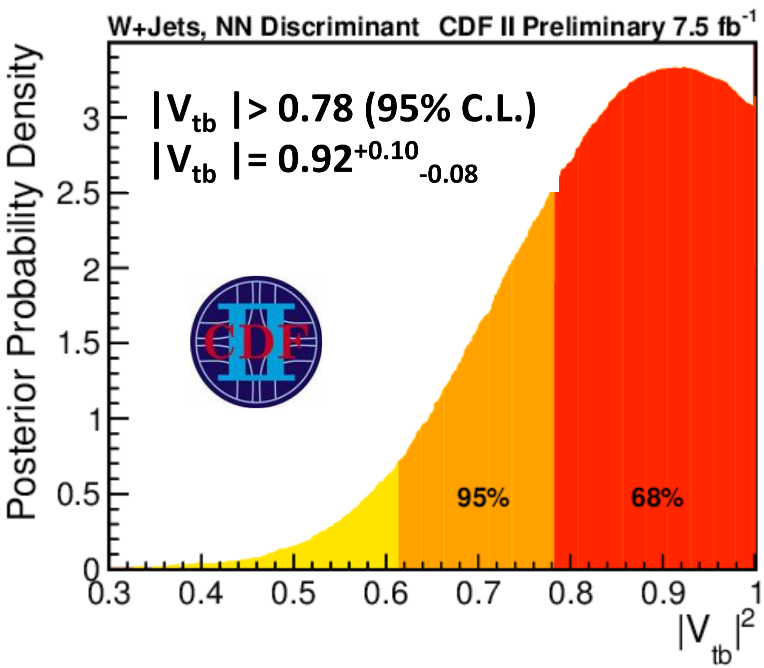
$$\sigma_{s+t} = 3.2^{\,+1.39}_{\,-1.43}\ \text{pb}\ (45\%)$$

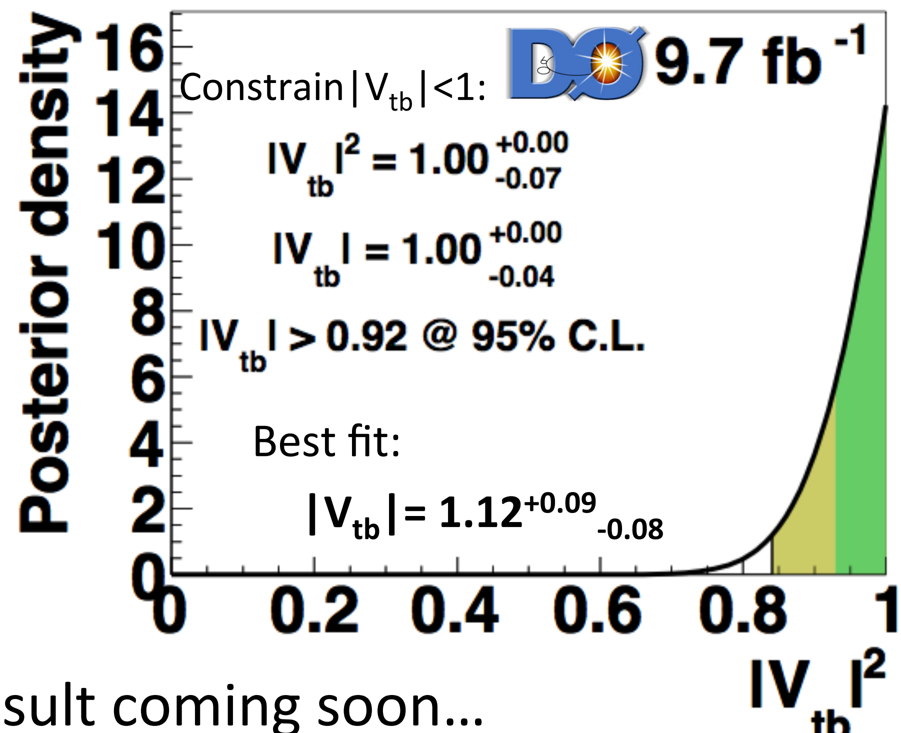
Summary of s+t measurements



Constraints on V_{tb}

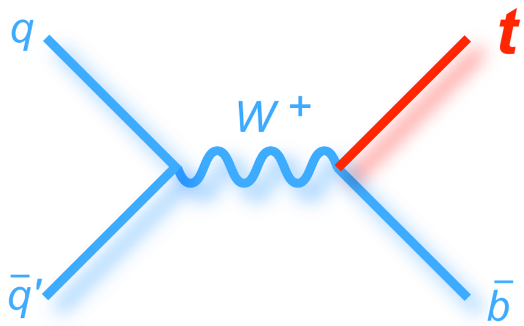
- $\sigma(s,t) \propto |V_{tb}|^2 \rightarrow$ calculate posterior pdf in terms of $|V_{tb}|^2$
- To transform σ(s+t) measurement into Vtb, assume:
  - SM top quark decay: $|V_{td}|^2+|V_{ts}|^2 \ll |V_{tb}|^2$
  - Pure V-A and CP conserving Wtb vertex
  - No assumption on number of families or CKM unitarity
    (D0 doesn't assume SM σ_s/σ_t ratio either)
- Complementary with tt decay measurements of R



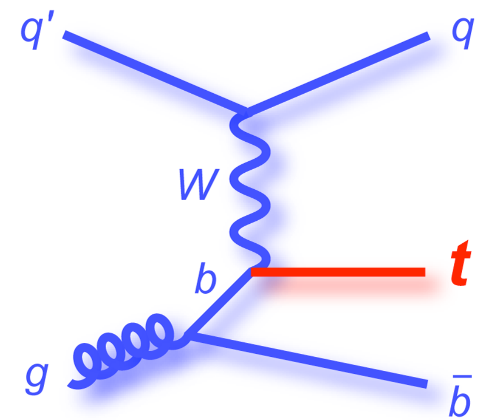


Look for a combined Tevatron V_{tb} result coming soon…

s-channel v/s t-channel



s-channel



t-channel

Can we measure s-channel and t-channel independently?

- t-channel events tend to have a distinctive forward jet whose direction is correlated with the lepton charge.
- s-channel is more likely to have central jets and to two identifiable b jets while t-channel tends to only have one
- Other subtle differences in event kinematic properties

s-channel v/s t-channel

Relax SM ratio in posterior

D0 9.7 fb-1:

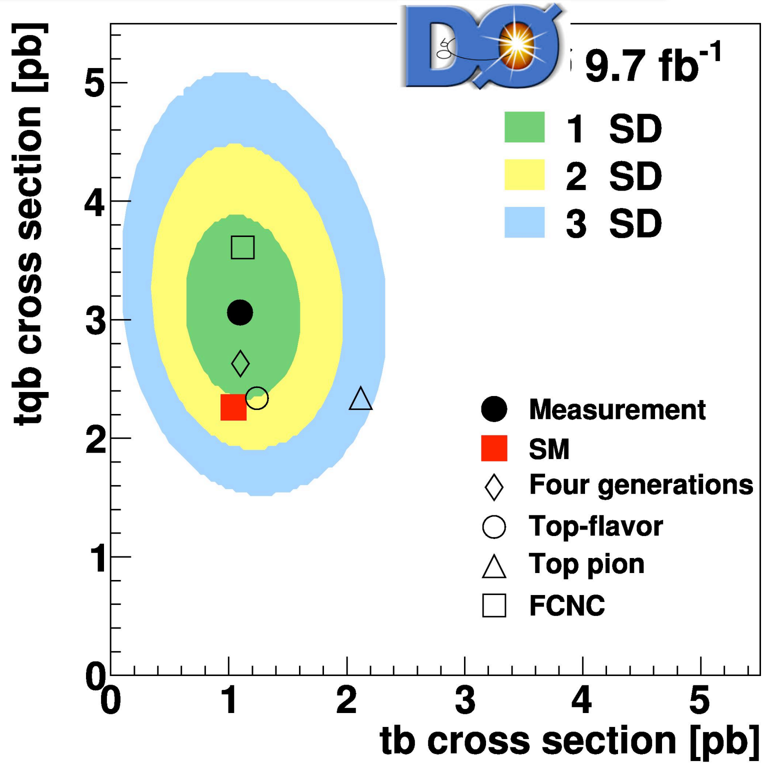
$\boldsymbol{\sigma_s = 1.10 \pm 0.33}$ **pb** (29%)

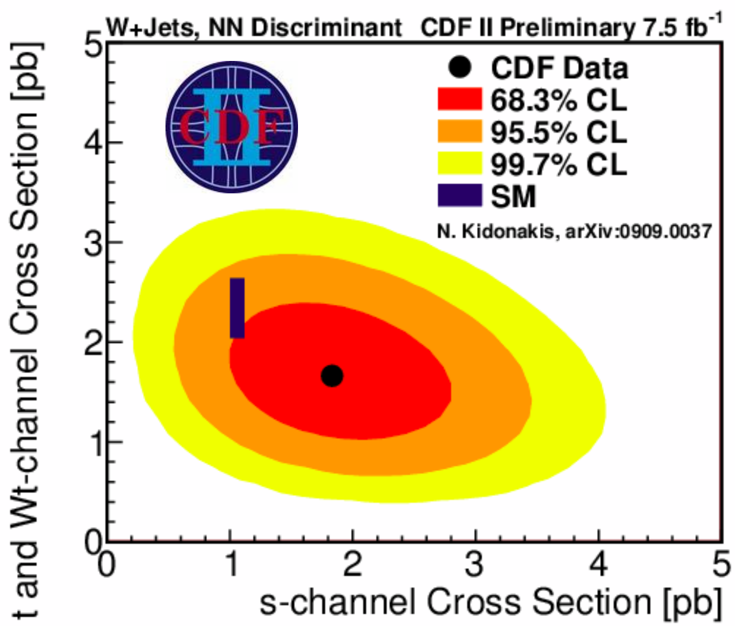
$\boldsymbol{\sigma_t = 3.07 \pm 0.53}$ **pb** (17%)

CDF 7.5 fb-1:

$\boldsymbol{\sigma_s = 1.81 \pm 0.63}$ **pb** (33%)

$\boldsymbol{\sigma_t = 1.49 \pm 0.47}$ **pb** (30%)



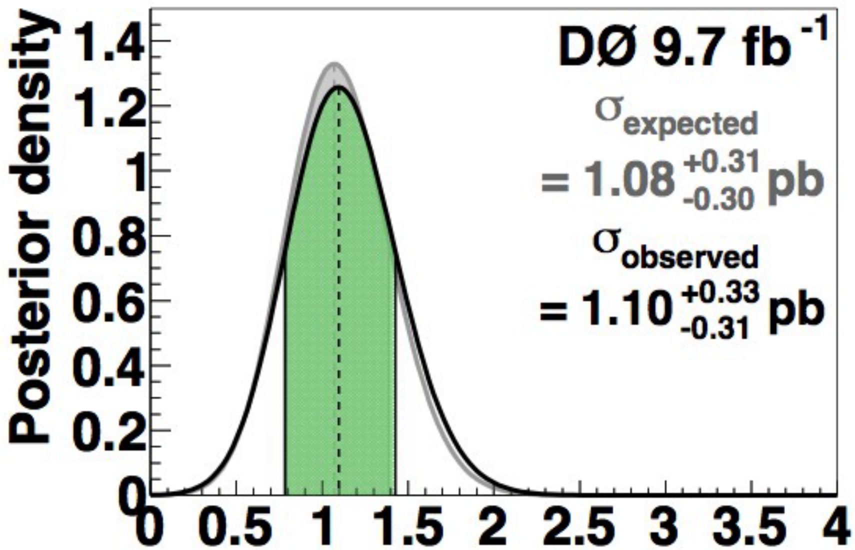


	σ(pb)
s-ch	1.05 ± 0.05^a
t-ch	2.10 ± 0.06^b

[a] N. Kidonakis, arXiv:1001.5034

[b] N. Kidonakis, arXiv:1103.2792

First Evidence for s-channel!



s-channel cross section [pb]

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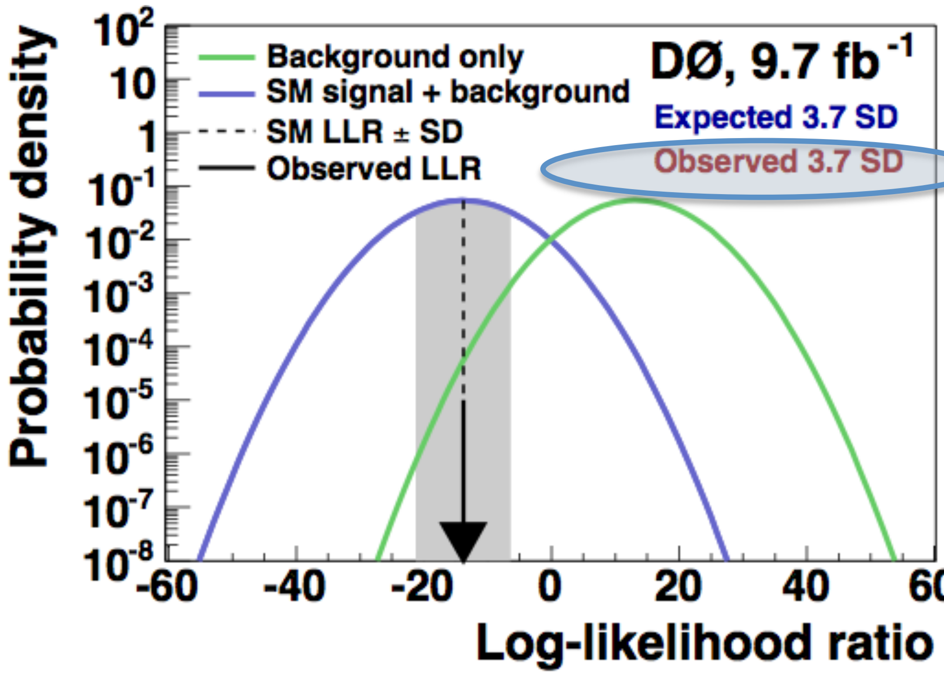


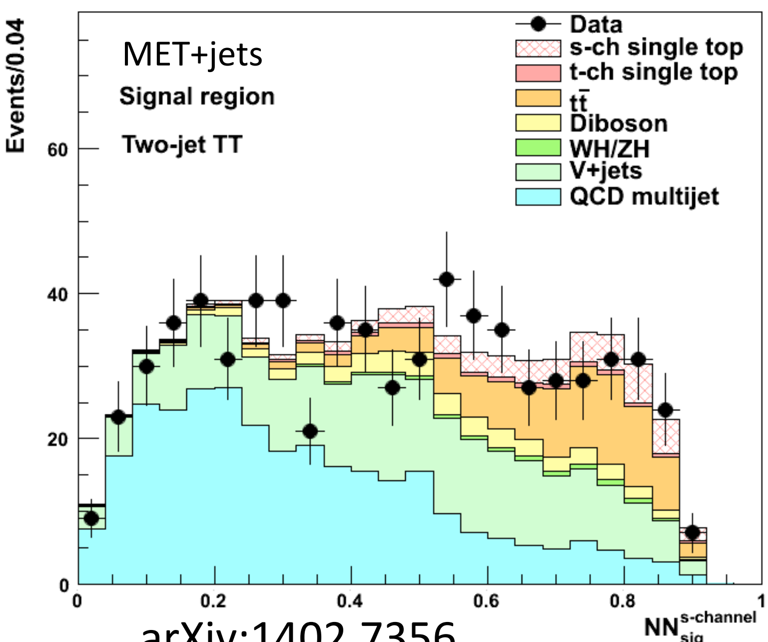
Excess of 3.7 standard deviations!

s-channel optimized analyses

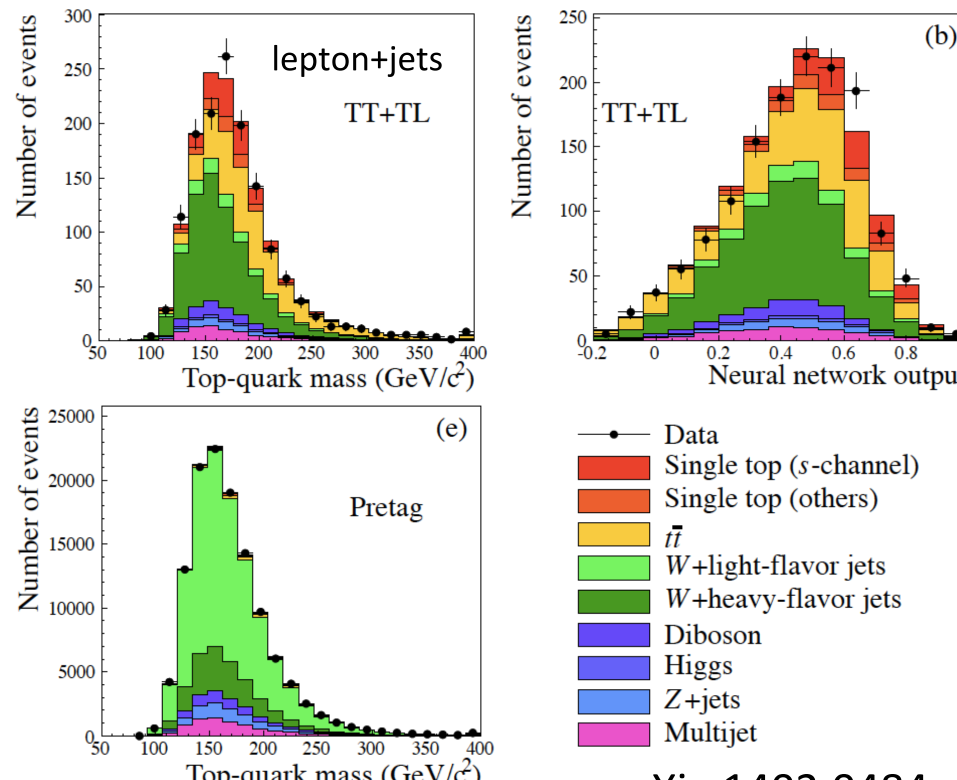
New lepton+jets and MET+jets s-channel optimized analyses inherit tools from SM Higgs search

- Extra lepton trigger > 10% more leptons
- Multivariate tagger
- Improved background modeling
- Both use NN trained for s-channel in all categories
- CDF confirms evidence for s-channel!
- Both submitted to PRL

New!

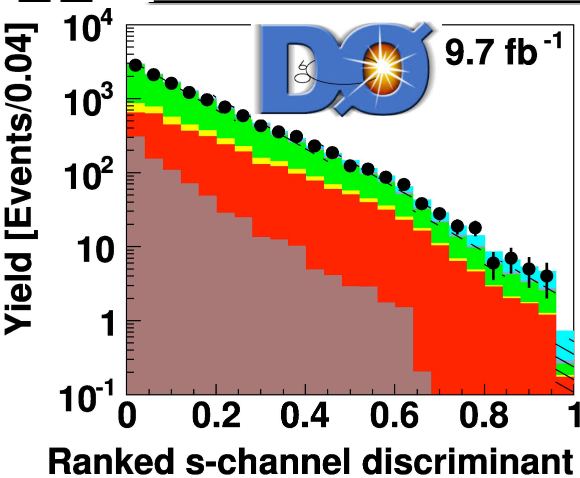


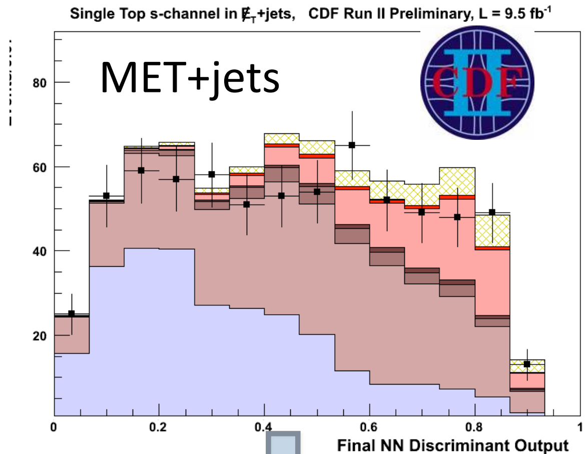
arXiv:1402.7356

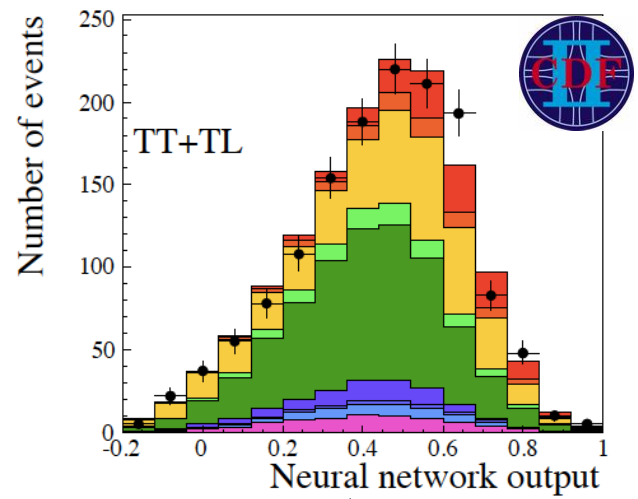


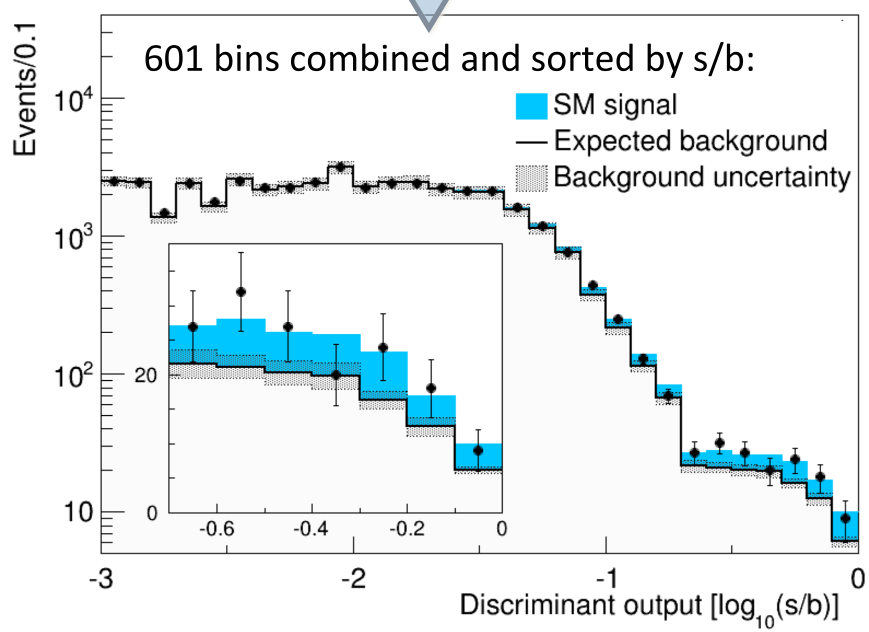
arXiv:1402.0484

New Tevatron s-channel combination



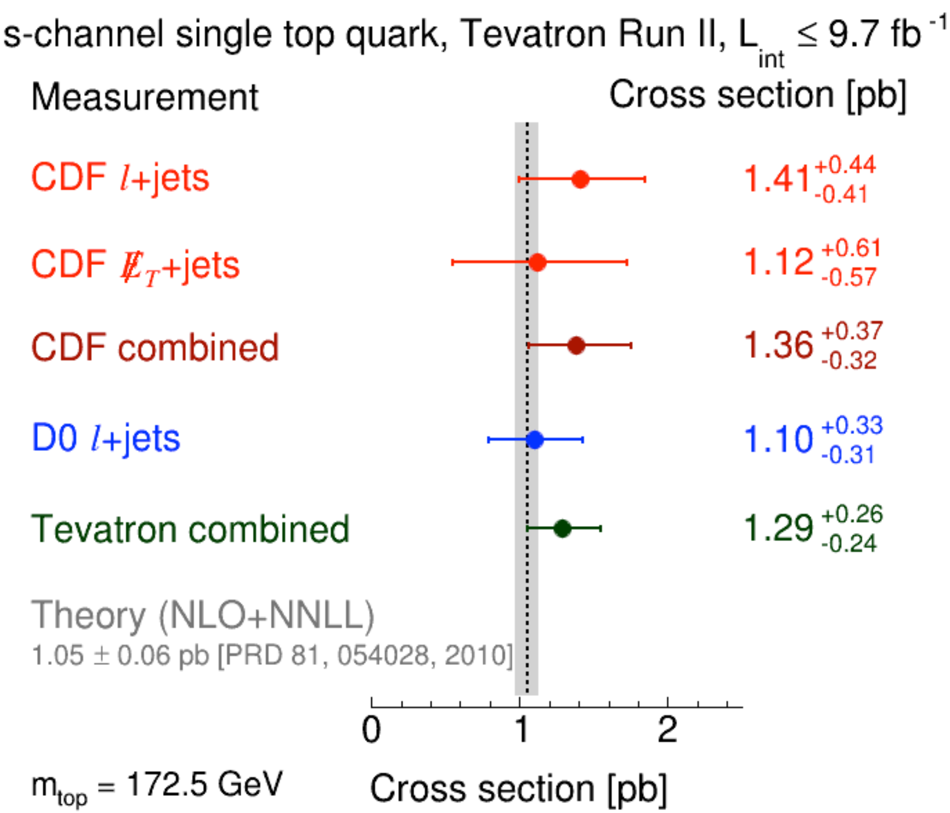


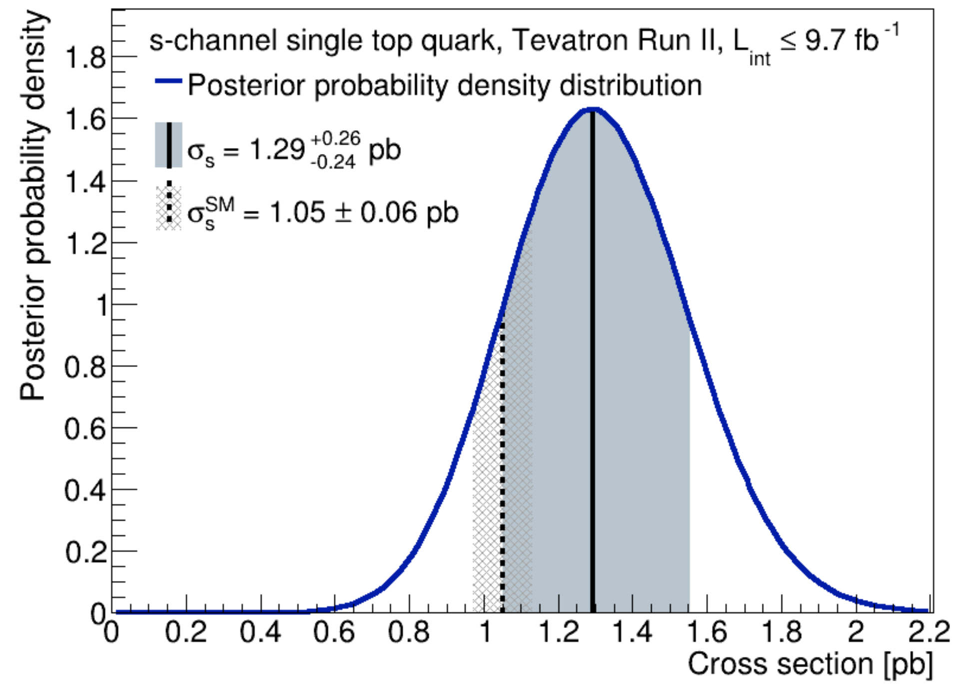




New Tevatron s-channel combination

Equal contributions from CDF and D0!





Posterior probability density for the combined result

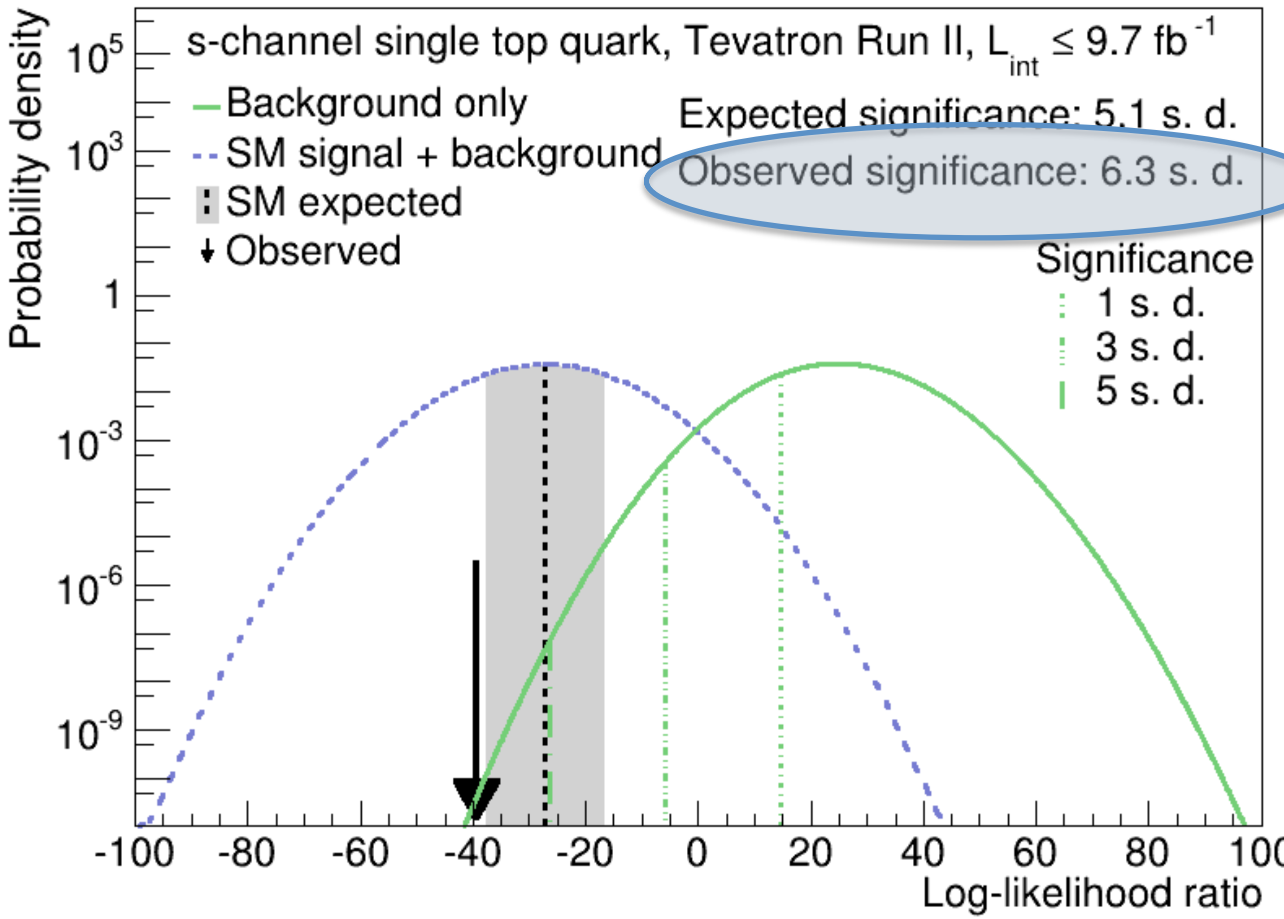
$$\sigma_s = 1.29^{+0.26}_{-0.24}\ \textbf{pb}\ (19\%)$$

Submitted to PRL

arXiv:1402.5126

New Tevatron s-channel combination

CDF + DØ = 1st observation of a new process!



Asymptotic approximation, log-likelihood ratio → Observed p-value: 2 **x** 10^{-10}

Conclusions

- The Tevatron single top program is almost complete:
    - Single top first observation in 2009
    - t-channel observation 2011
    - s-channel observation 2014

- $\boldsymbol{\sigma}_{s+t}$: 14% precision
- $\boldsymbol{\sigma}_{t}$:   17% precision
- $\boldsymbol{\sigma}_{s}$:   19% precision
- Vtb: 8% precision

- First observation of s-channel single top production!

- Final Tevatron combination coming soon…
    → Expect updates on V_{tb}, $\boldsymbol{\sigma}_{s+t}$, and 2-D s v/s t

Bibliography: Single Top at the Tevatron

SM Measurements:

- D0 Search: Phys. Lett. B **622**, 265 (2005)
- D0 PRD: Phys. Rev. D **75**, 092007 (2007)
- D0 Evidence: Phys. Rev. Lett. **98**, 181802 (2007), Phys. Rev. D **78**, 012005 (2008)
- CDF Evidence: Phys. Rev. Lett. 101, 252001 (2008)
- D0 Observation: Phys. Rev. Lett. **103**, 092001 (2009)
- CDF Observation:Phys. Rev. Lett. 103, 092002 (2009)
- Tevatron Combination: arXiv:0908.2171
- CDF PRD: Phys. Rev. D82, 112005 (2010)
- CDF MET+jets PRD: Phys. Rev. D81, 072003 (2010)
- D0 t-channel: Phys. Lett. B **682**, 363 (2010), Phys. Lett. B **705**, 313 (2011)
- D0 PRD: Phys. Rev. D **84**, 112001 (2011)
- D0 s-channel evidence: Phys. Lett B 726, 656 (2013)
- CDF s-channel evidence: arXiv:1402.0484 (submitted to PRL)
- CDF s-channel MET+jets: (submitted to PRL)
- Tevatron s-channel observation: arXiv:**arXiv:1402.5126** (submitted to PRL)

Exotics and properties:

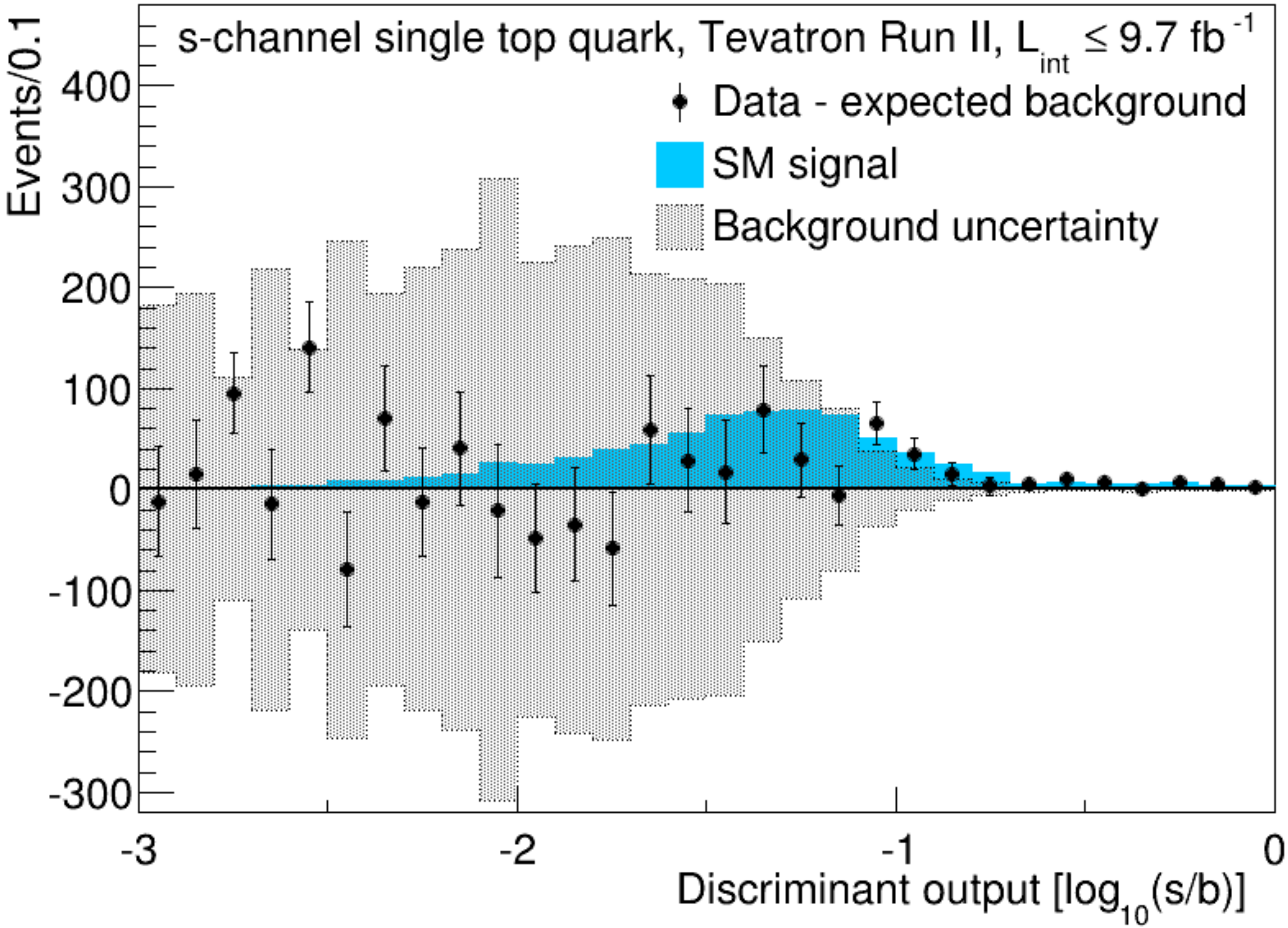
- D0 Anomalous couplings: Phys. Rev. Lett. **101**, 221801 (2008), Phys. Lett. B **708**, 21 (2012)
- D0 FCNC: Phys. Rev. Lett. **99**, 191802 (2007),Phys. Lett. B **693**, 81 (2010)
- CDF Dark Matter + single top: Phys. Rev. Lett. 108, 201802 (2012)
- CDF FCNC: Phys. Rev. Lett. 102, 151801 (2009)

S-channel (TeV → LHC)

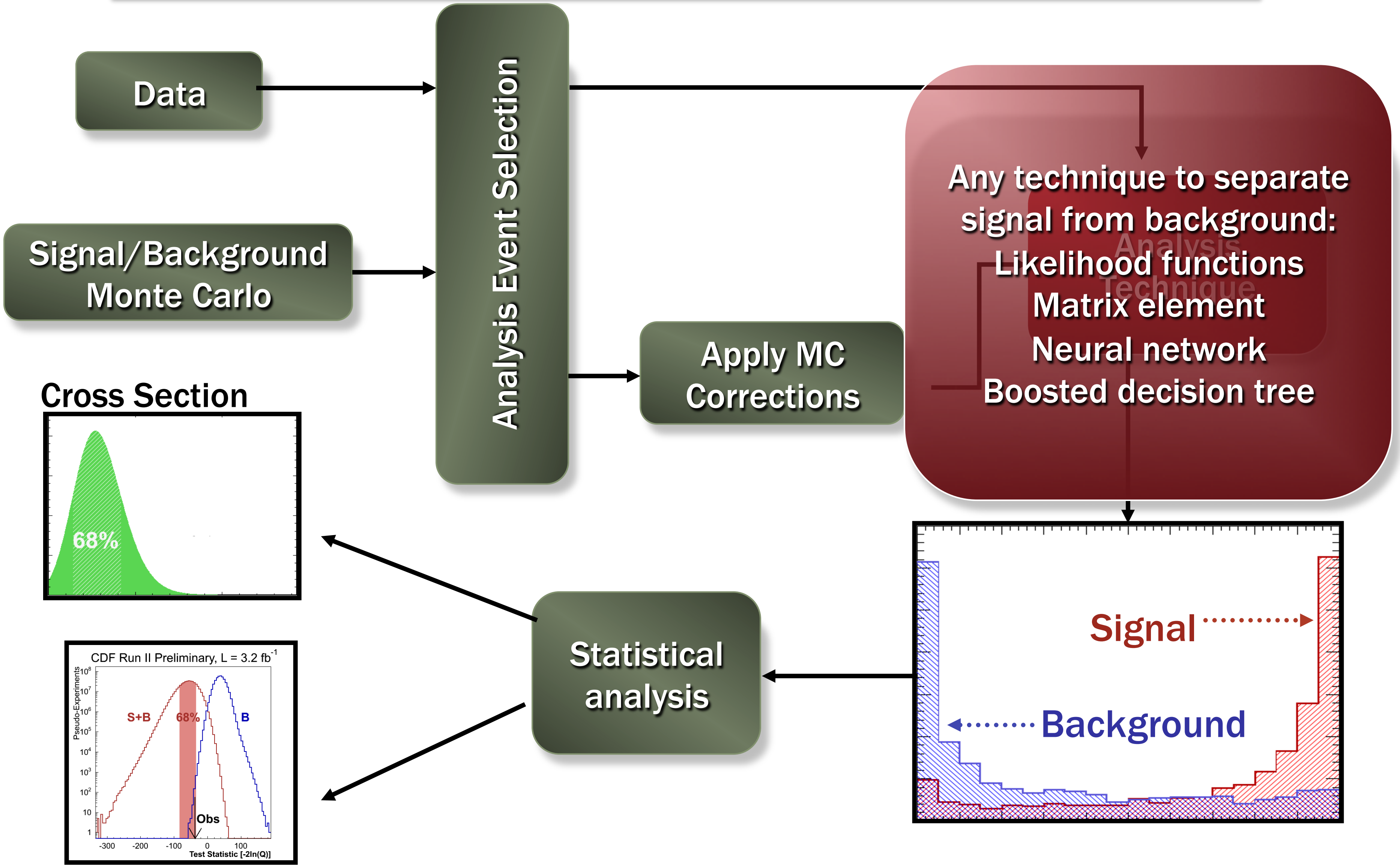
Cross section(pb)	$t\bar{t}$	s-channel	t-channel
Tevatron(1.96 TeV)	7.08	1.05	2.08
	x33	x5.3	x42
LHC(8 TeV)	234	5.55	87.2

(N. Kidonakis, arXiv:1210.7813)

Background subtracted

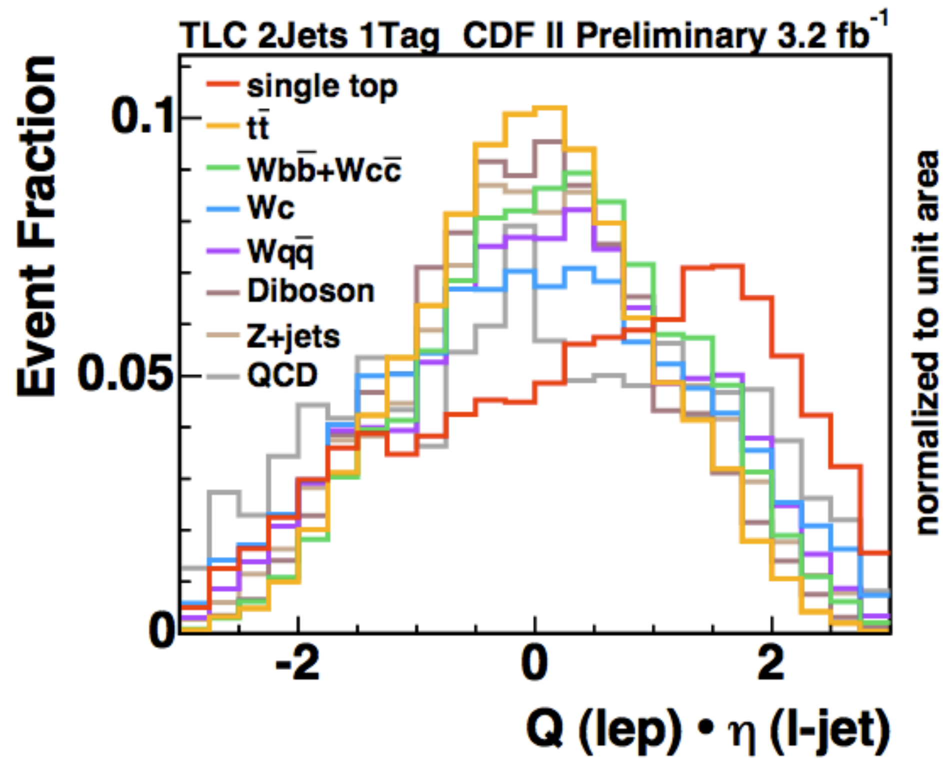


General analysis method



Shape Fit

- To go beyond counting experiment, use shape fit
  - Provides in-situ constraint on background
  - Parts of the distribution have much better purity
- Which variable is best?



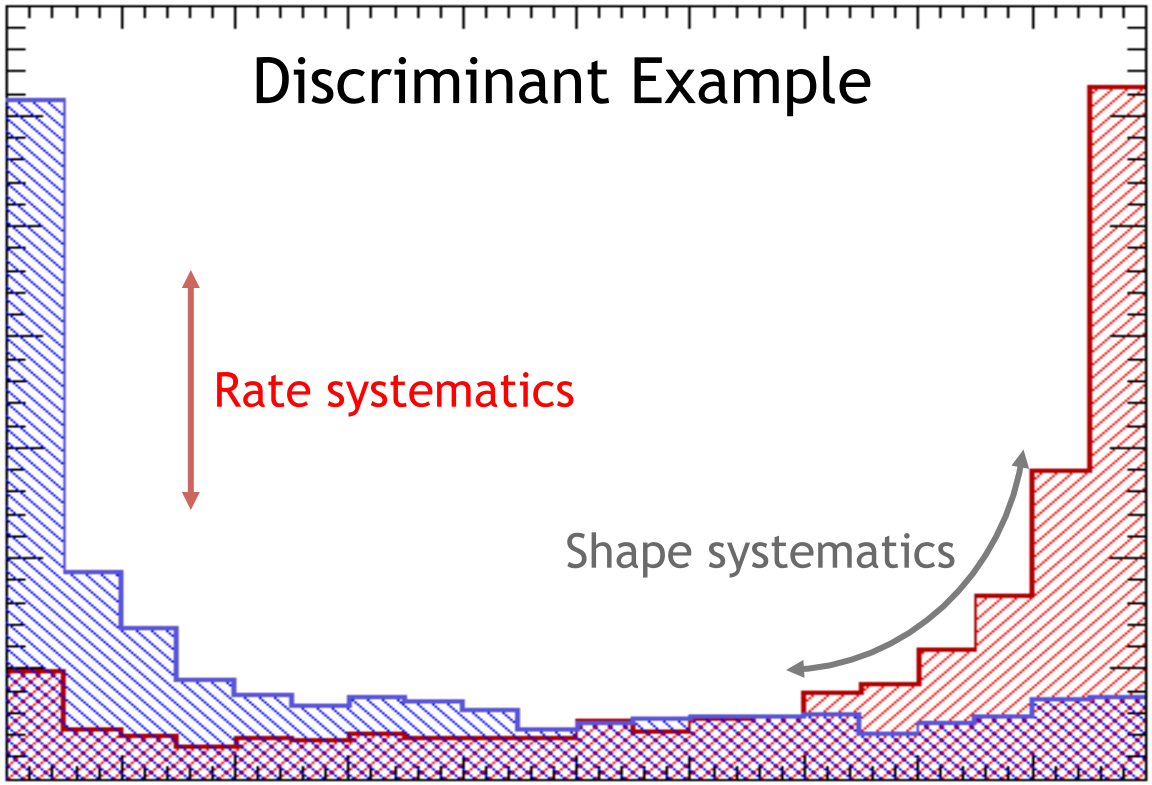
- Perform binned likelihood fit :

$$L(sig, bkg_1 \ldots bkg_N) = \prod_{k=1}^{B} \frac{e^{-\mu_k} \mu_k^{n_k}}{n_k!} \prod_{j=1}^{4} G(bkg_j \mid 1, \Delta_j)$$

Background Constraints

Binned Maximum Likelihood Fit

We perform a binned maximum likelihood fit to the data using templates for signal and background:



Systematic uncertainties can affect rate and template shape and are taken into account:

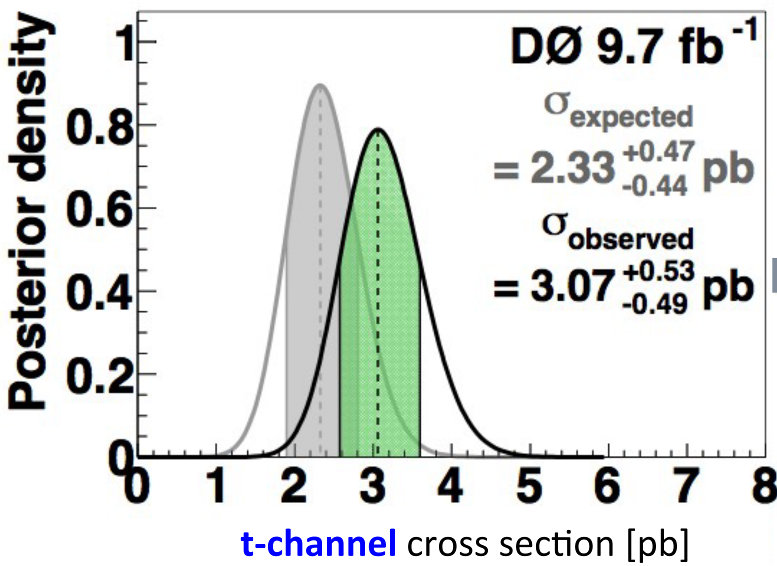
- Rate systematics give fit templates freedom to move vertically only
- Shape systematics allow templates to 'slide horizontally' (bin by bin)

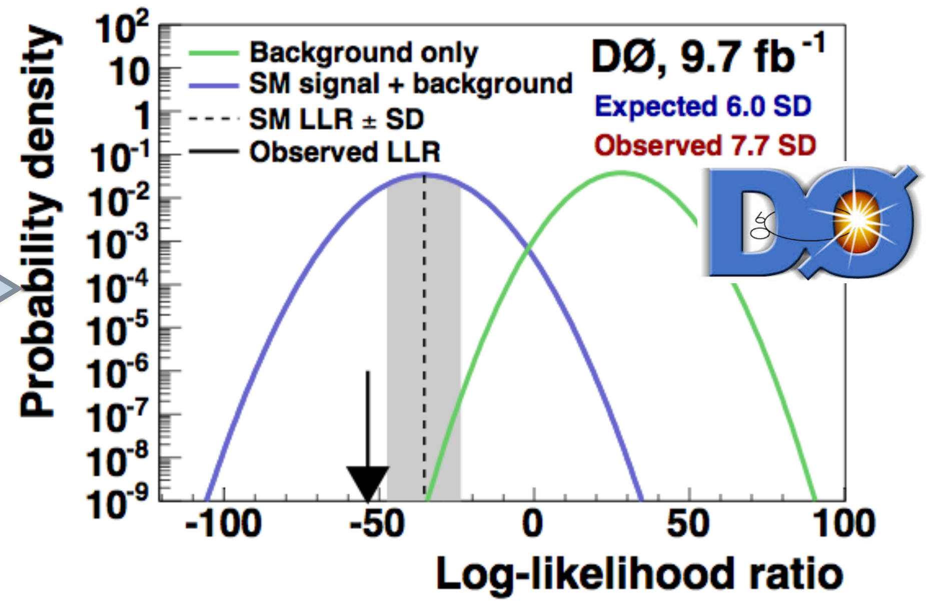
Systematics

s-channel combination

Systematic uncertainty	CDF Norm	CDF Dist	D0 Norm	D0 Dist	Correlated
Lumi from detector	4.5%		4.5%		No
Lumi from cross section	4.0%		4.0%		Yes
Signal modeling	2–10%	•	3–8%		Yes
Background (simulation)	2–12%	•	2–11%	•	Yes
Background (data)	15–40%	•	19–50%	•	No
Detector modeling	2–10%	•	1–5%	•	No
b-jet-tagging	10–30%		15–40%	•	No
JES	0–20%	•	9–40%	•	No

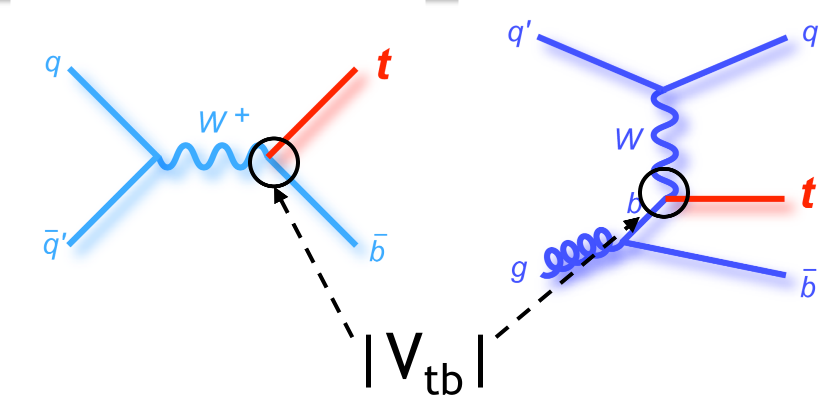
Total uncertainty on background 15-20%


DØ 9.7 fb^{-1}
$\sigma_{expected} = 2.33^{+0.47}_{-0.44}$ pb
$\sigma_{observed} = 3.07^{+0.53}_{-0.49}$ pb
Posterior density
0 0.2 0.4 0.6 0.8 1
0 1 2 3 4 5 6 7 8
t-channel cross section [pb]


Background only
SM signal + background
SM LLR ± SD
Observed LLR
DØ, 9.7 fb^{-1}
Expected 6.0 SD
Observed 7.7 SD
Probability density
10^{2} 10 1 10^{-1} 10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9}
-100 -50 0 50 100
Log-likelihood ratio

Motivation

- New physics may affect the rate of *s*- and *t*-channel differently:
  - *s*-channel: new bosons
  - t-channel: FCNC



- Access to the W-t-b vertex
- Allows measurement of CKM matrix element $|V_{tb}|$:
  - Is this Matrix 3x3 ? Is there a 4th generation ?
  - Does unitarity hold ?
  - "simple" 4th generation ruled out by EW fits but see e.g.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{uX}? \\ V_{cd} & V_{cs} & V_{cb} & V_{cX}? \\ V_{td} & V_{ts} & V_{tb} & V_{tX}? \\ V_{Yd}? & V_{Ys}? & V_{Yt}? & V_{YX}? \end{pmatrix}$$

J. Alwall et. al., "Is $|V_{tb}|$~1?" Eur. Phys. J. C49 791-801 (2007).