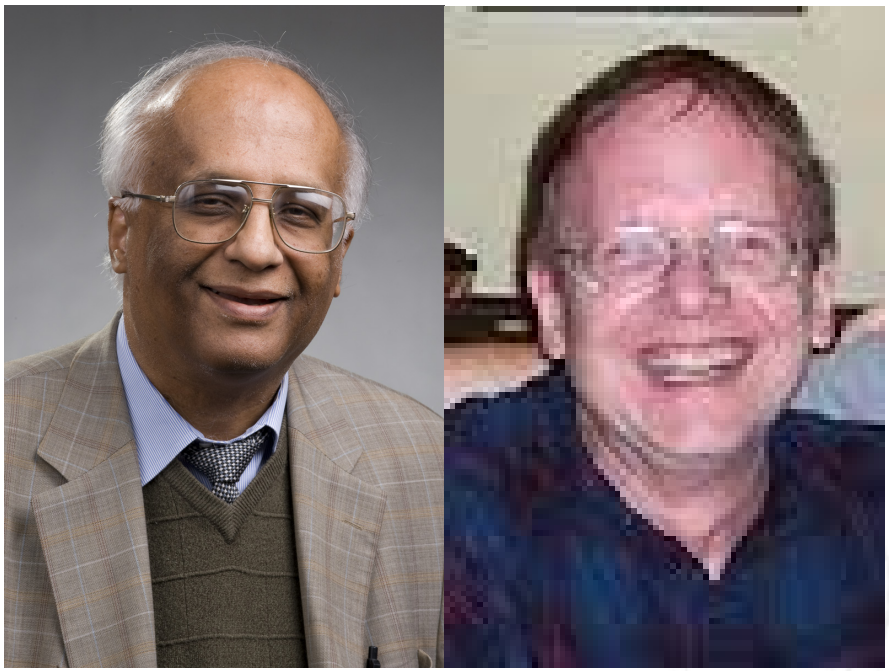
Observation of *s*-channel Single Top Quark Production at the Tevatron

Matteo Cremonesi & **Reinhard Schwienhorst**
on behalf of the **CDF** & **D0** Collaborations

To Raja and Rick



The Top Quark

Heaviest known elementary particle:

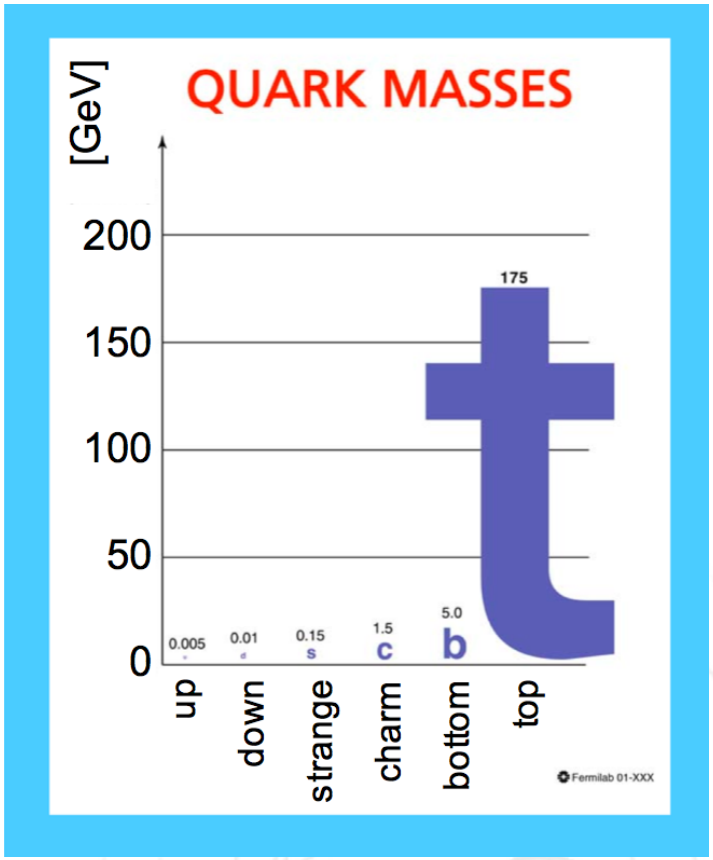
- Like a **gold atom**!

Short lifetime:

- No hadronization, opportunity to study a *bare quark*
- It decays, nearly 100% of the times in a W boson and in a b quark

The top quark can be produced:

- in $t\bar{t}$ pairs through strong interaction
- as **single top** via EW interaction

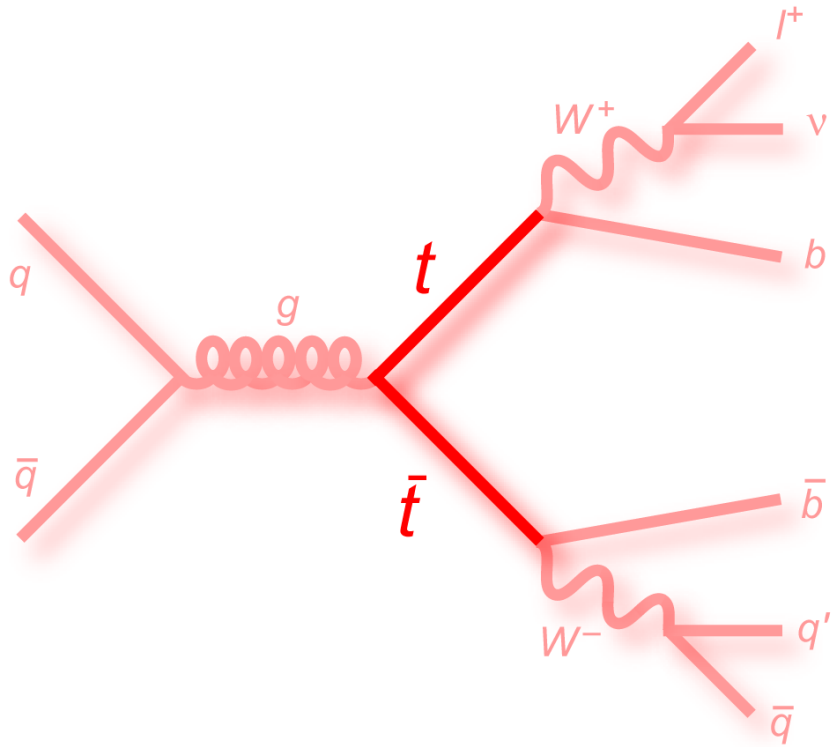


$t\bar{t}$ Pair Production

Top quark was discovered by CDF and D0 in 1995, in $t\bar{t}$ events

$\sigma_{t\bar{t}} \cong$ 7 pb; $S/B \cong 1$

- The distinctive kinematic properties
- **Quite pure sample**
- Strong production easier to observe

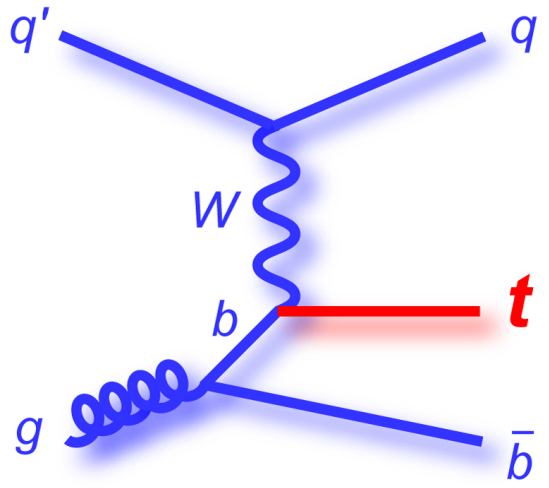


Single Top Quark Production

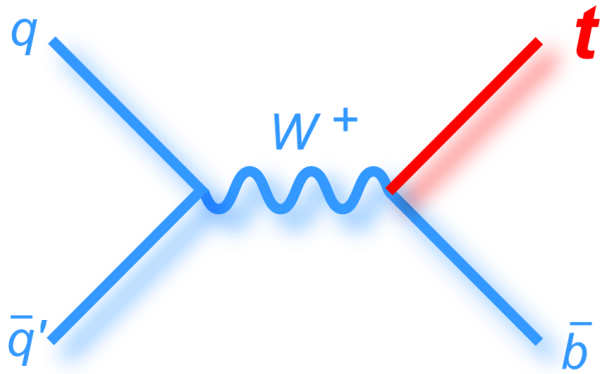
Observed by CDF and D0 in 2009

$\sigma_{s+t} \cong$ 3 pb; $S/B \cong 0.1$

- Compared to the $t\bar{t}$:
  - Smaller cross section
  - Less distinctive signature
    $\Rightarrow$ higher background
- It took 14 years, 50 times the data, and sophisticated analysis techniques in order to observe it

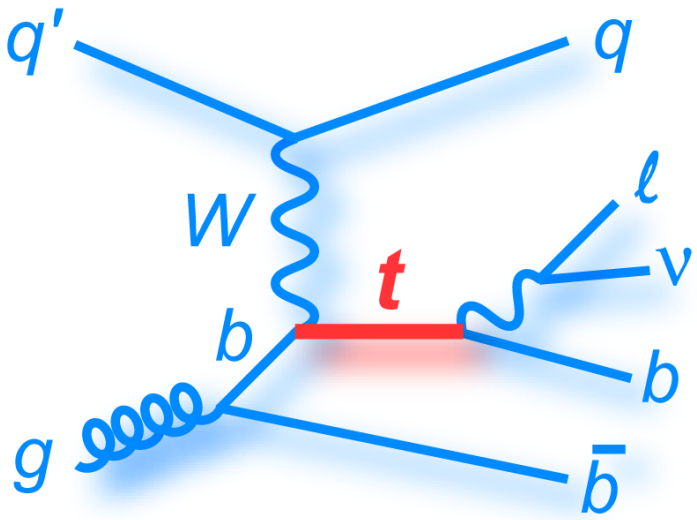


t-channel



s-channel

t-channel Single Top Quark Production



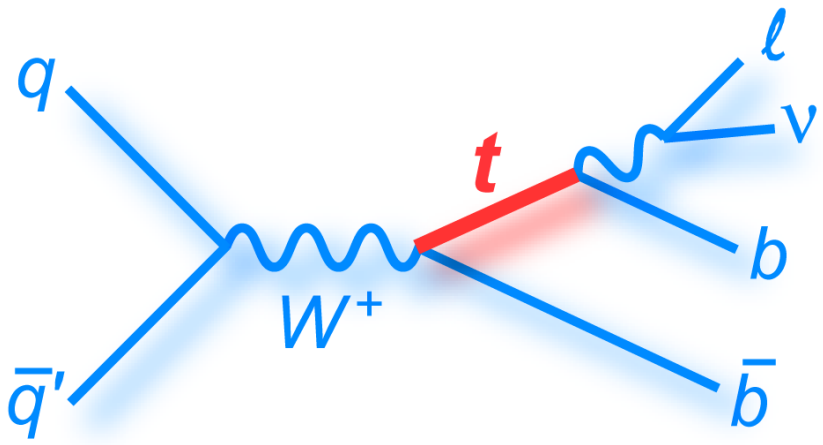
First observed by D0 and confirmed by the LHC experiments

$\sigma_t \cong$ 2 pb; **$S/B \cong$ 0.05**

Powerful discriminating features:

- Light-flavor jet is more forward
- Second b-jet really soft; does not satisfy the minumum jet energy requirements

s-channel Production



It has not been observed yet:

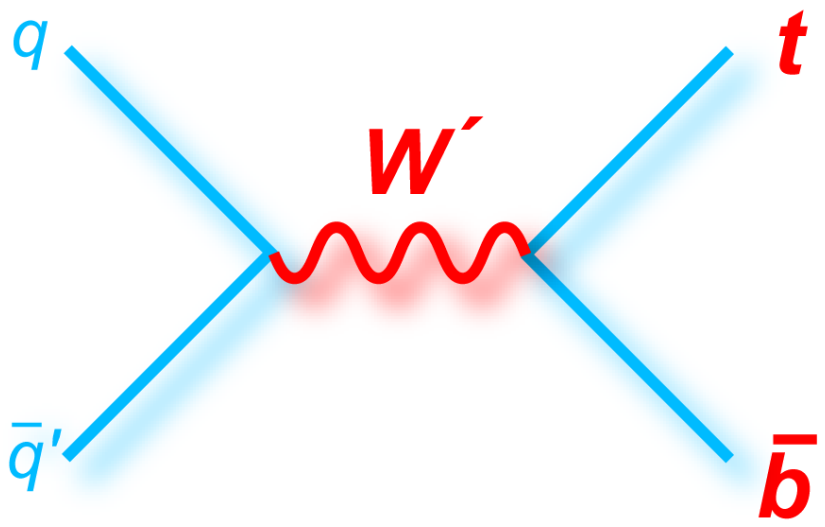
- D0 claimed the **first evidence** in a W&C talk last summer

$\sigma_s \cong$ 1 pb; ***S/B*** $\cong$ **0.03**

More difficult at LHC, S/B lower than the Tevatron;

- 5 times more signal, 15 times more background

New Physics in $t\bar{b}$ Final State

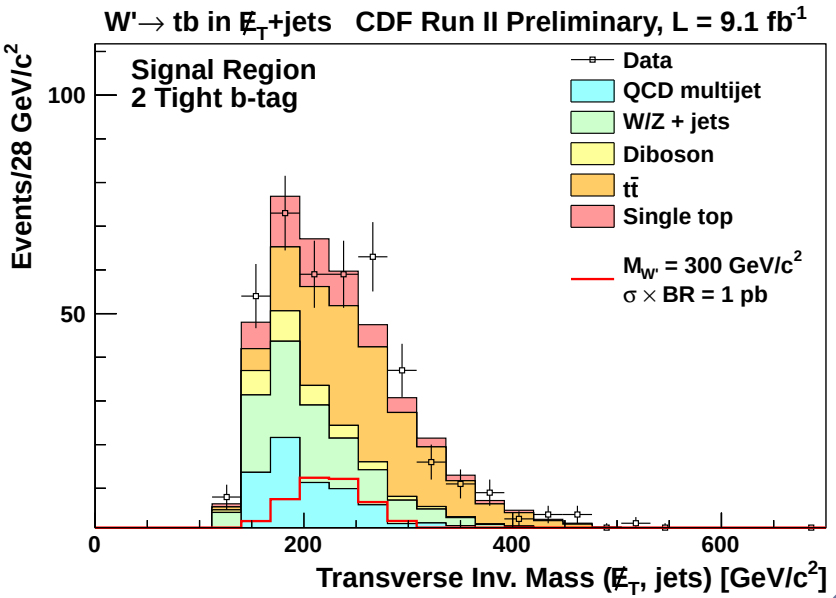


A deviation from SM prediction may indicate new physics

- W', charged Higgs bosons, etc.

CDF and D0 looked for new bosons decaying to $t\bar{b}$

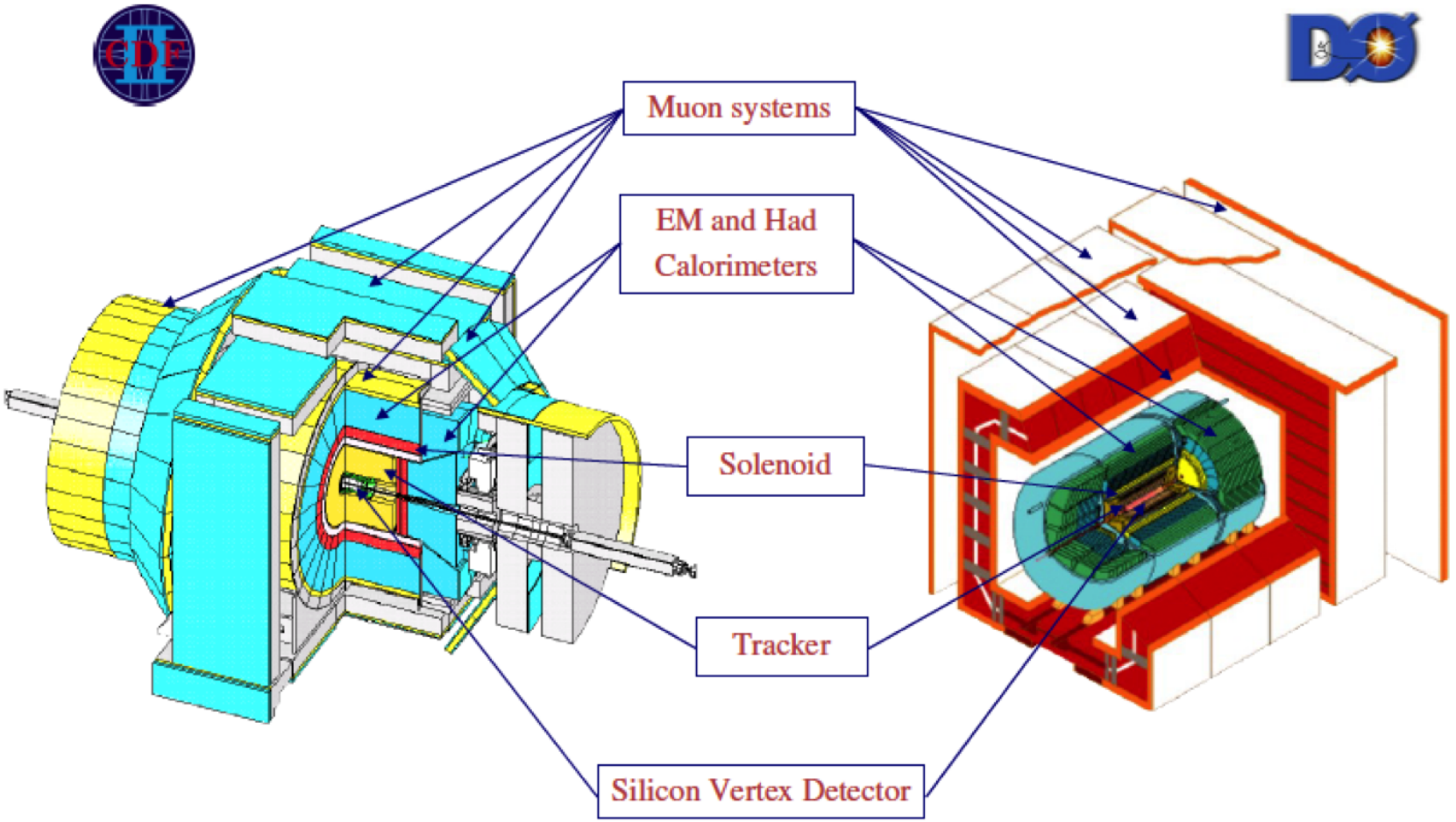
More sensitive than LHC for relatively low mass resonances



The Tevatron

- Collider $p\bar{p}$ $\sqrt{s} = 1.96$ TeV
- Radius $R = 1$ km
- Two experiments: CDF and D0
- Run II (2001–2011):
  ~ 12 fb^{-1} of $p\bar{p}$ collisions,
  ~ 10 fb^{-1} recorded per experiment

The CDF and D0 Detectors



Overview

***s*-channel signal is really difficult to extract**:

- exploiting both CDF and D0 data is necessary to try to observe it

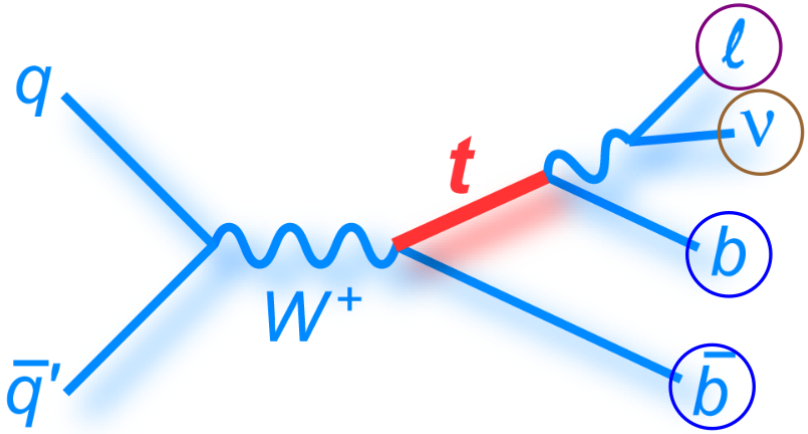
In this talk:

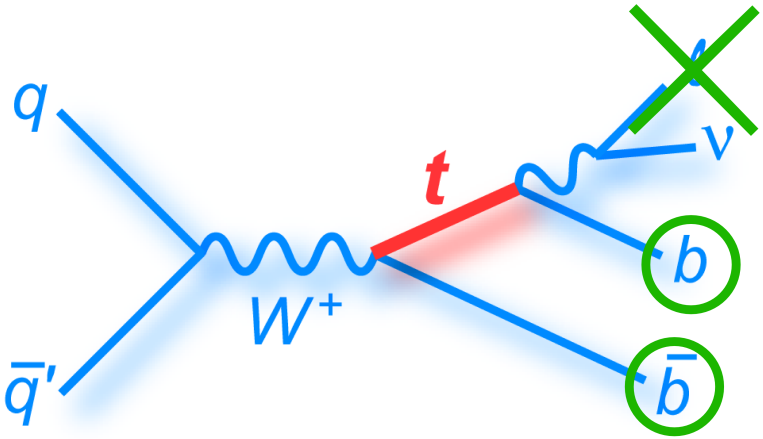
- New result from **CDF** on *s*-channel single top quark production
- Reminder of the **D0** result
- **Tevatron** combined measurement

s-channel Searches at CDF

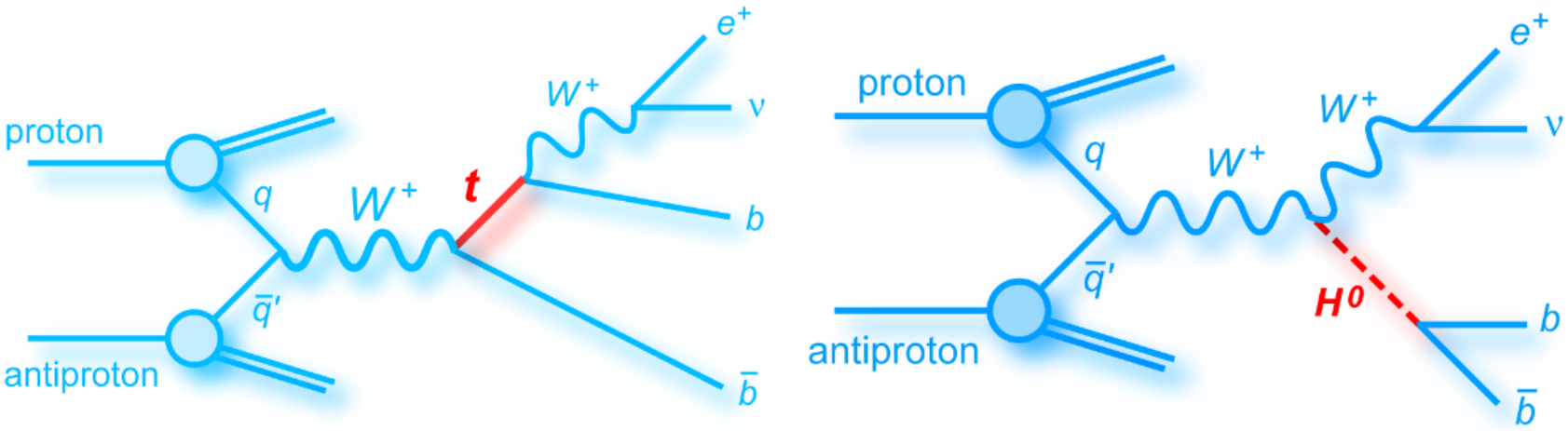
At **CDF**, two statistically independent samples are analyzed, looking for single top *s*-channel production:

- the $\ell\nu b\bar{b}$ sample: events with one lepton, missing transverse energy and jets
- the $\not\!\!E_T b\bar{b}$ sample: events with no leptons, missing transverse energy and jets





Higgs search at CDF



- Sophisticated tools developed at CDF in the search for the **Higgs** boson
- Most sensitive channels: WH/ZH production with $H \to b\bar{b}$
  $\Rightarrow$ s-channel has the **same event topology**

We are going to take advantage of the improvements introduced in the Higgs search

Analysis Challenges

Small signal, large background

$\Rightarrow$ Use a loose set of selection cuts, to preserve signal

$\Rightarrow$ Require b-tagged jets, to reduce background

Large background uncertainties:

- The main backgrounds are also the ones with the largest uncertainties

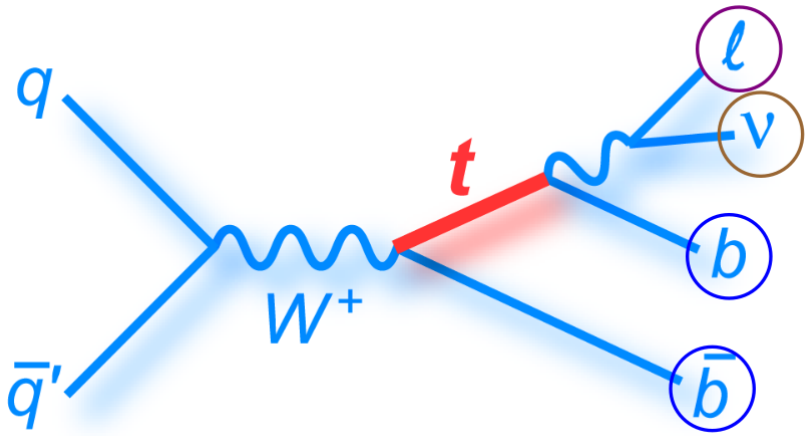
$\Rightarrow$ Carefully model signal and backgrounds

Poor separation:

- Compared to the t-channel: no specific kinematic features
- Compared to the Higgs: no resonance

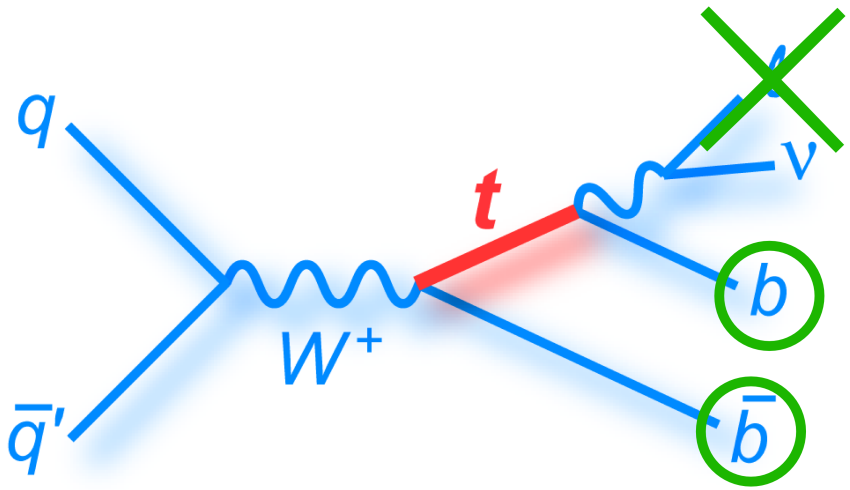
$\Rightarrow$ Use multivariate techniques

$\ell\nu b\bar{b}$ Event Selection



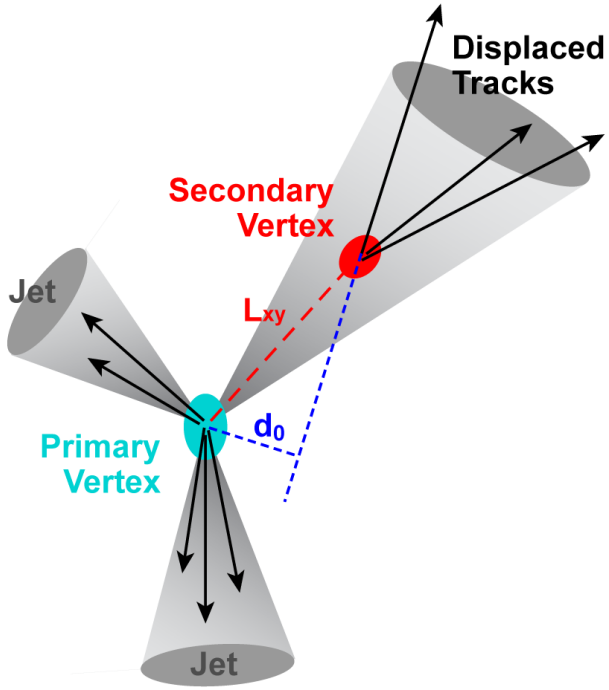
- **One high p_T isolated lepton** (e,μ)
  - $p_T > 20$ GeV
- $\not{E}_T$:
  - > 10 GeV (for central muons)
  - > 20 GeV (other leptons)
- **Two jets**:
  - transverse energy $(E_T) > 20$ GeV; $|\eta| < 2$
  - leading jet E_T $(E_T^{j_1}) > 30$ GeV
- Additional cuts:
  - $H_T > 125$ GeV
    - $H_T = E_T^{j_1} + E_T^{j_2} + p_T^{e,\mu} + \not{E}_T$
  - dijet invariant mass > 30 GeV

$\not\!\!E_T b\bar{b}$ Event Selection



- **No isolated leptons** (e,μ)
  - We use loose identification cuts to reject events with isolated leptons
- **Large** $\not\!\!E_T$:
  - > 35 GeV
- **Two or three jets**:
  - $E_T^{j_1} > 25$ GeV; $E_T^{j_1} > 20$ GeV
  - $|\eta| < 2$, at least one with $|\eta| < 0.9$
- Additional cuts:
  - $\Delta\phi(\not\!\!E_T, j_2) > 0.4$

b-jets Identification



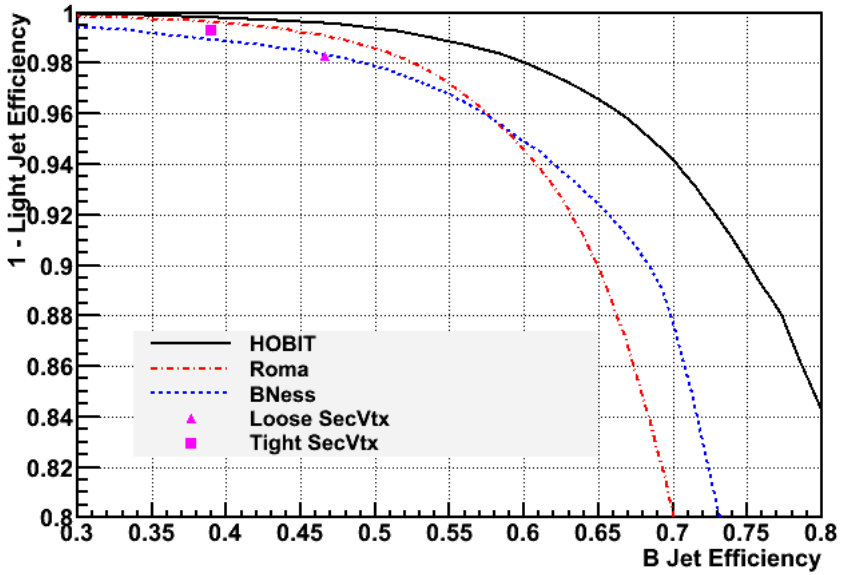
***b*-jets can be identified**:

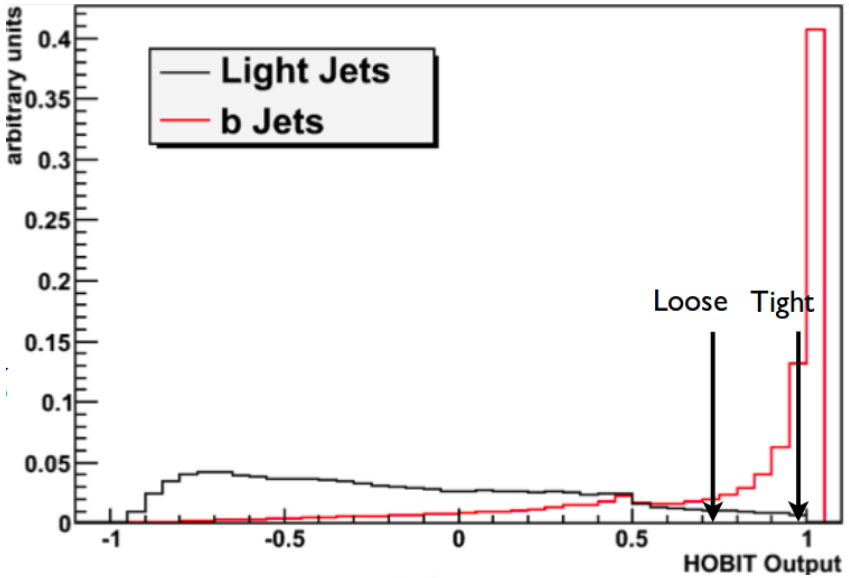
- B hadrons with long lifetime $\cong$ 1.6 ps $\Rightarrow \beta\gamma c\tau \cong$ 4 mm
  $\Rightarrow$ jets with displaced secondary vertex

For *s*-channel production, ***b*-tagging is crucial**:

- Two *b*-jets in the final state, one of the most separating features
- Reduce the background coming from light-flavor contributions

HOBIT

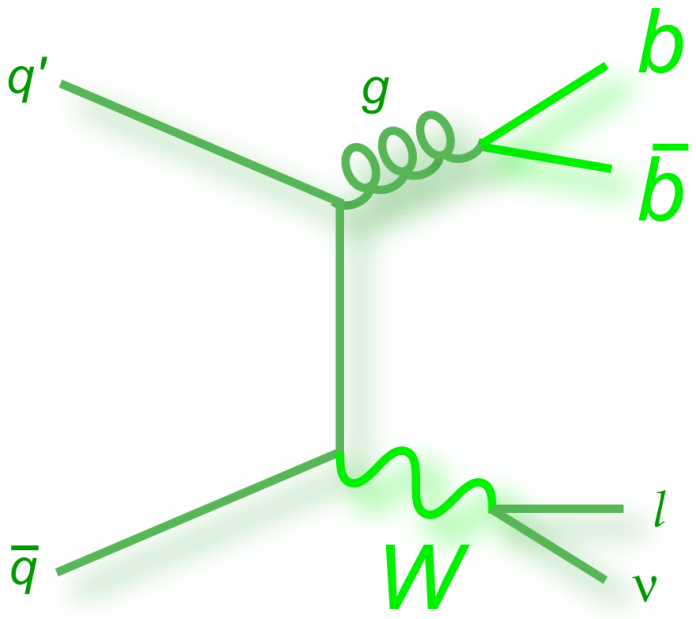


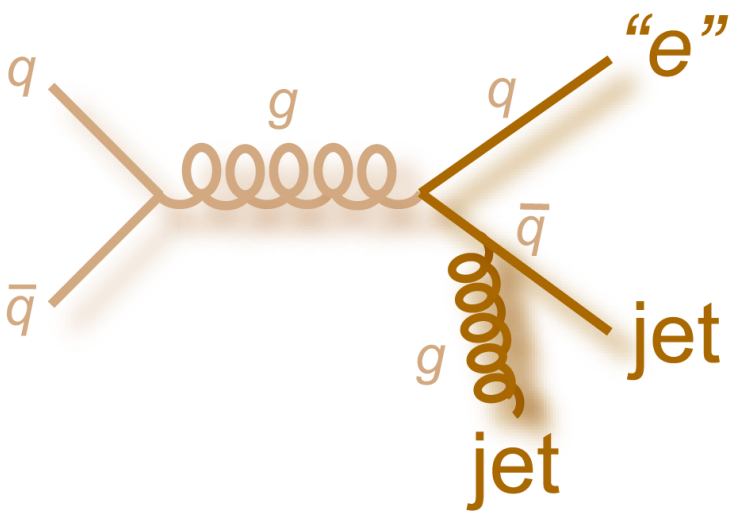


A new b-jet identification algorithm optimized for $H \to b\bar{b}$ searches is employed: **HOBIT**

- Incorporates all the features of the previous CDF b-taggers
- Two different HOBIT cuts are used: tight b-tag (T), loose b-tag (L)

Signal and Background Model





Electroweak/Top: single top, diboson, and $t\bar{t}$:

- modeled by Monte Carlo
- MC normalized to theoretical cross-section

***W*+Heavy Flavor**:

- modeled by MC
- normalization from data

Mistags: falsely tagged light quark or gluon jets

- mistag probability parameterization obtained from data
- applied to electroweak light flavor production

QCD multijet: Data-derived model

$\ell\nu b\bar{b}$ Event Yield

Category	TT+TL	1T+LL
$t\bar{t}$	357 ± 40	560 ± 57
Diboson	58.7 ± 7.8	279 ± 34
Higgs	12.5 ± 1.0	12.0 ± 0.9
Z+jets	31.6 ± 3.5	190 ± 21
QCD	76 ± 31	326 ± 130
W+HF	712 ± 286	2597 ± 1046
W+LF	66 ± 14	1220 ± 175
t-channel	53.4 ± 6.7	265 ± 30
s-channel	116 ± 12	127 ± 12
Total	1484 ± 403	5574 ± 1501
Data	1231	5338

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$\ell\nu b\bar{b}$ Event Yield

Even in the most sensitive channel, the background uncertainty is larger than the predicted signal
$\Rightarrow$ **cannot do a simple counting experiment**

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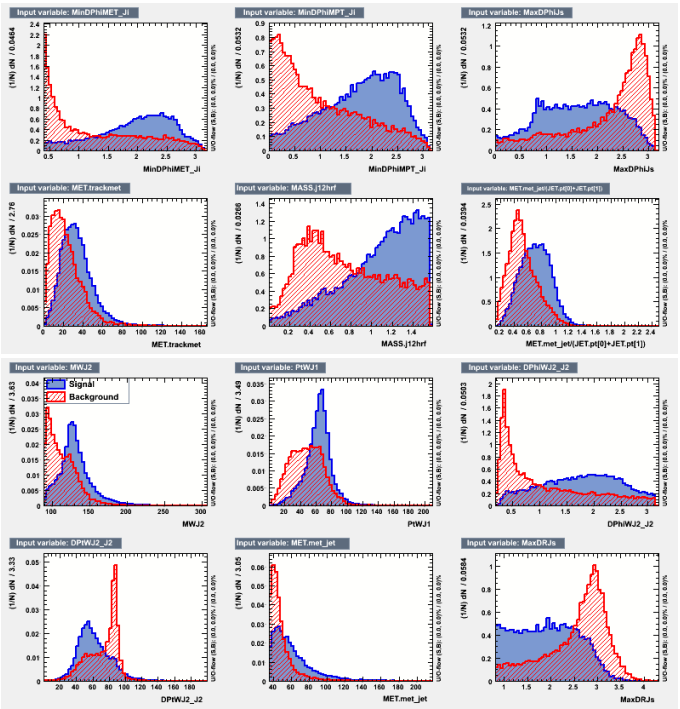
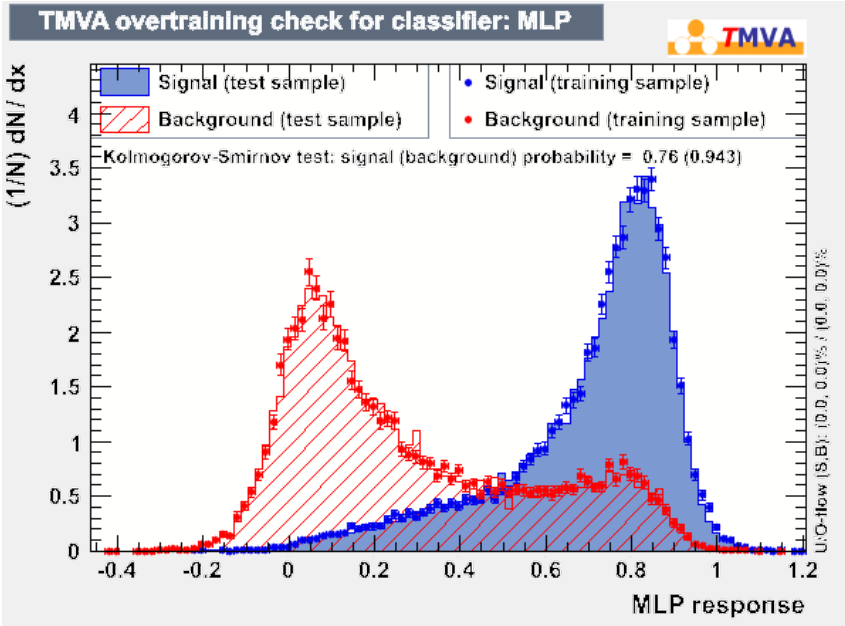
Multivariate Techniques

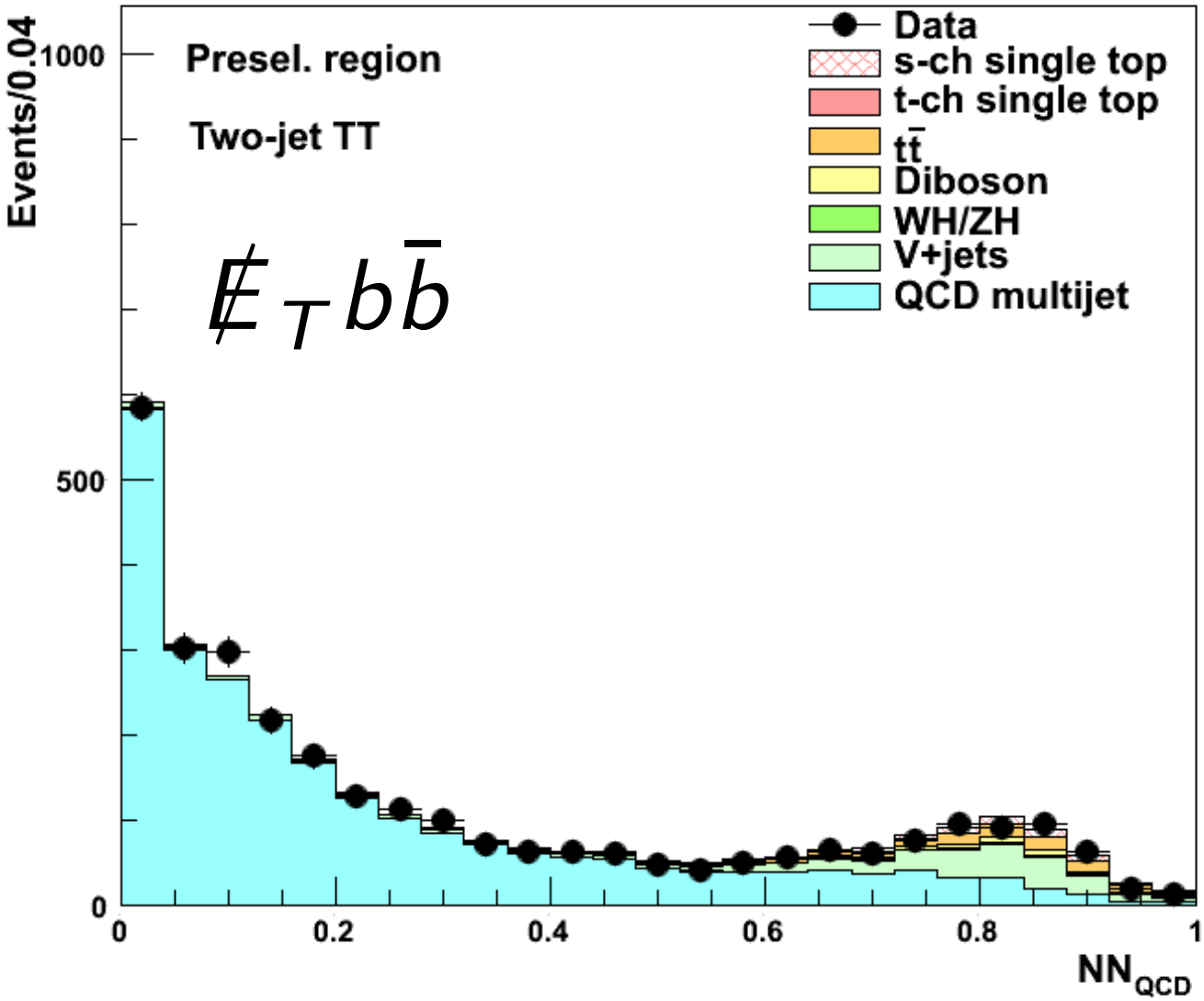




- Combine multiple variables into single, more powerful discriminant. Fully exploit the kinematic information
- Different purposes: *b*-tagging (e.g.: HOBIT), background rejection, top reconstruction, final discrimination

Background Rejection

In the $\not\!\!E_T b\bar{b}$ analysis, QCD multijet production is by far the largest background with largest uncertainties



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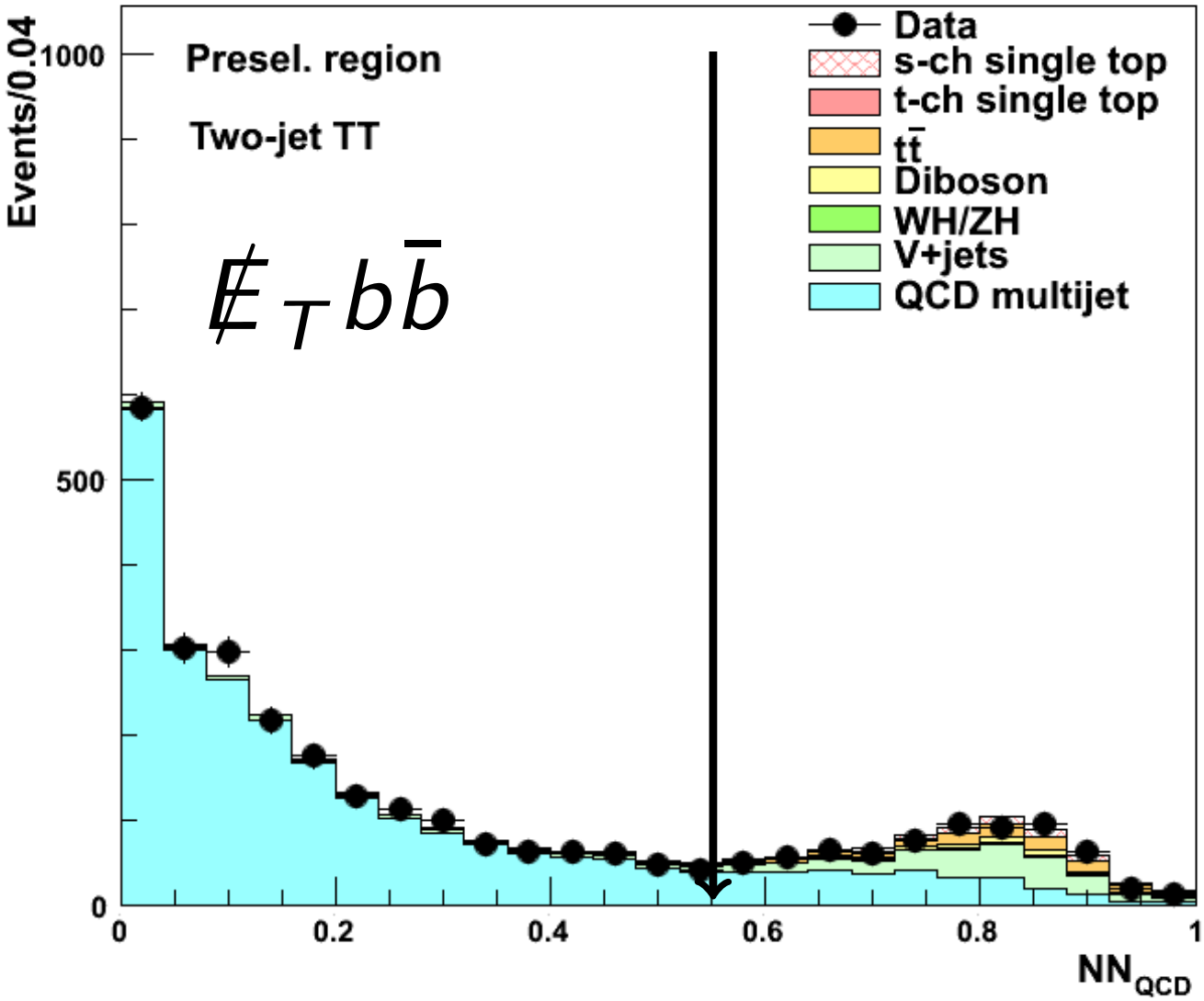

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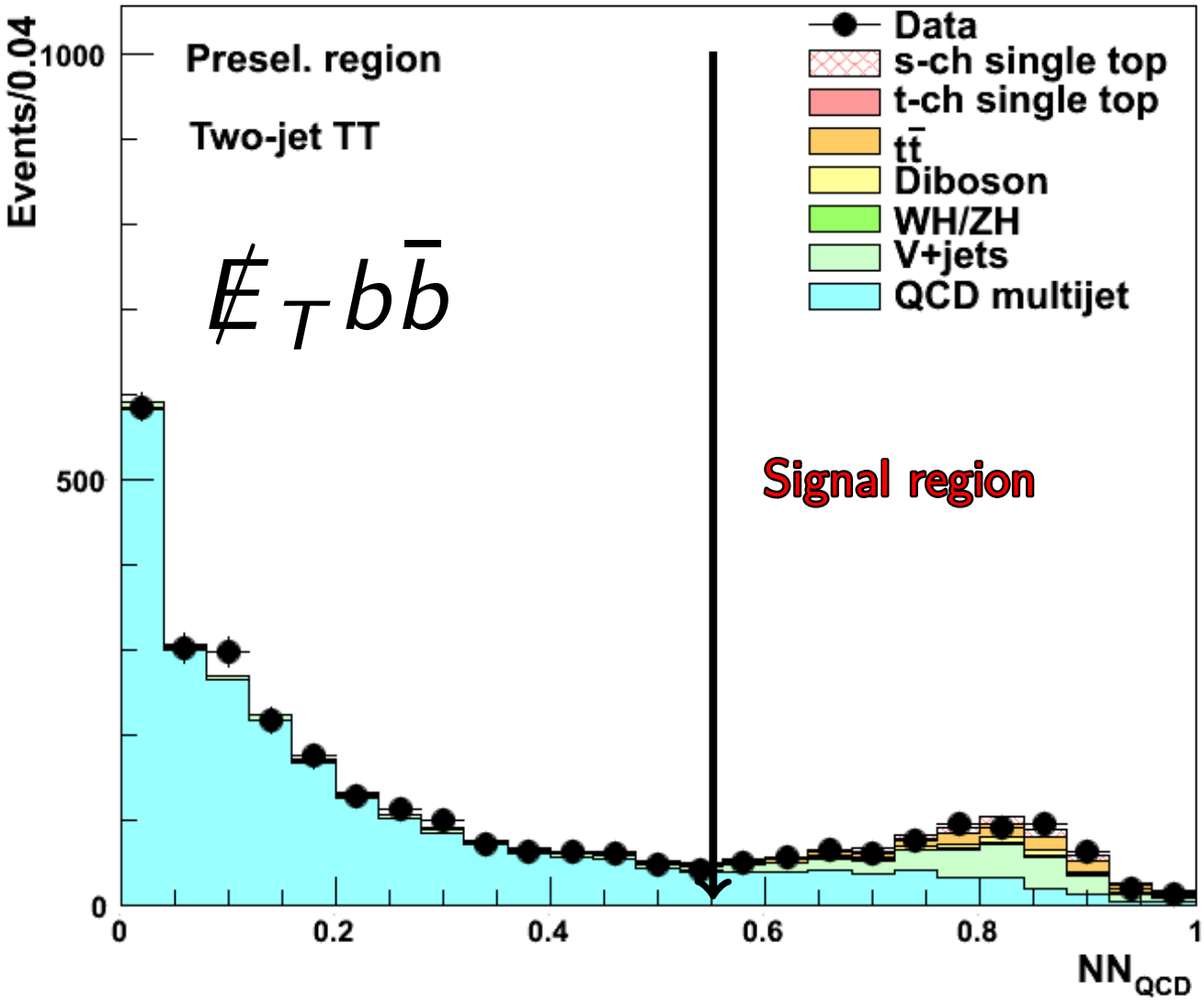

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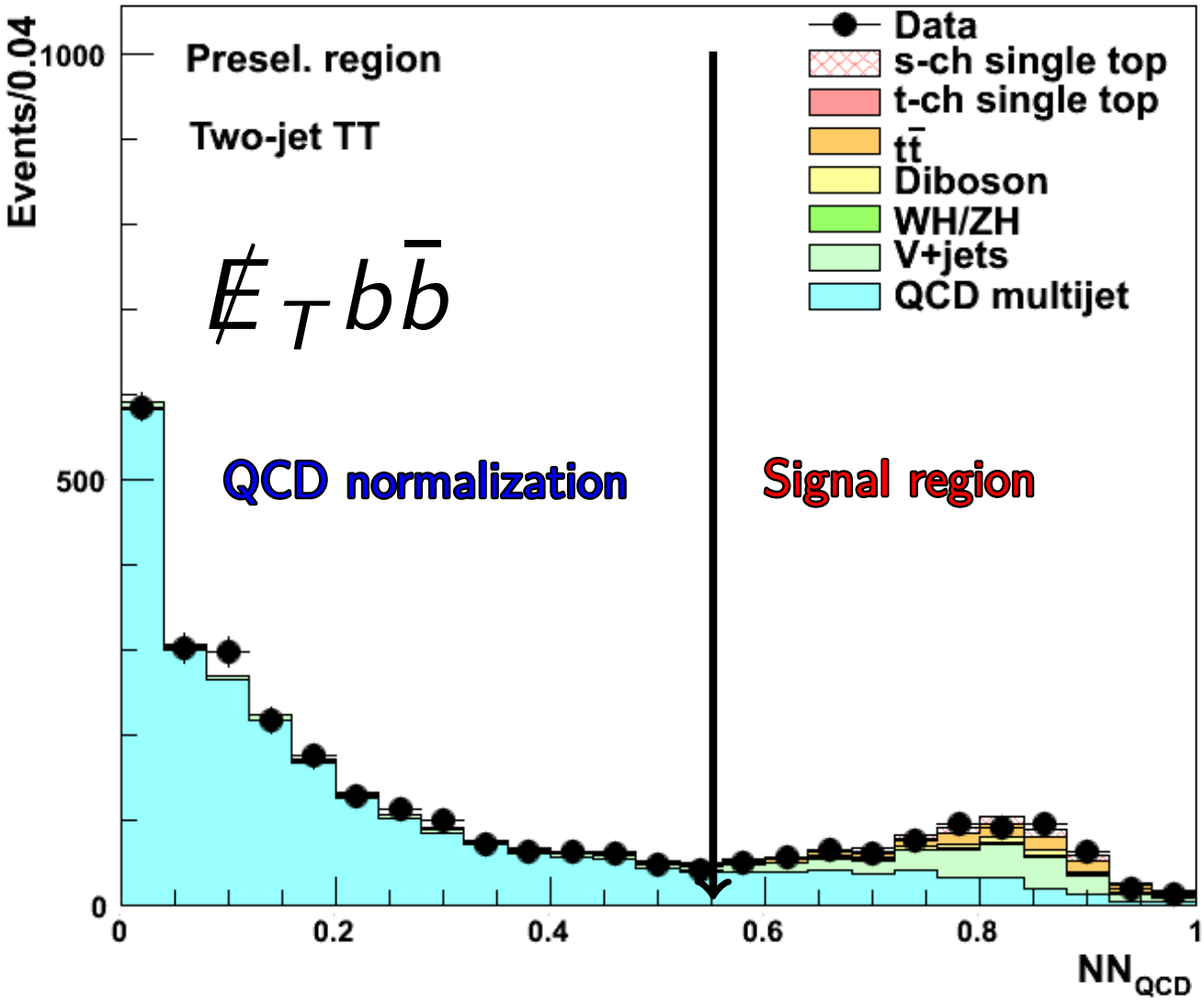

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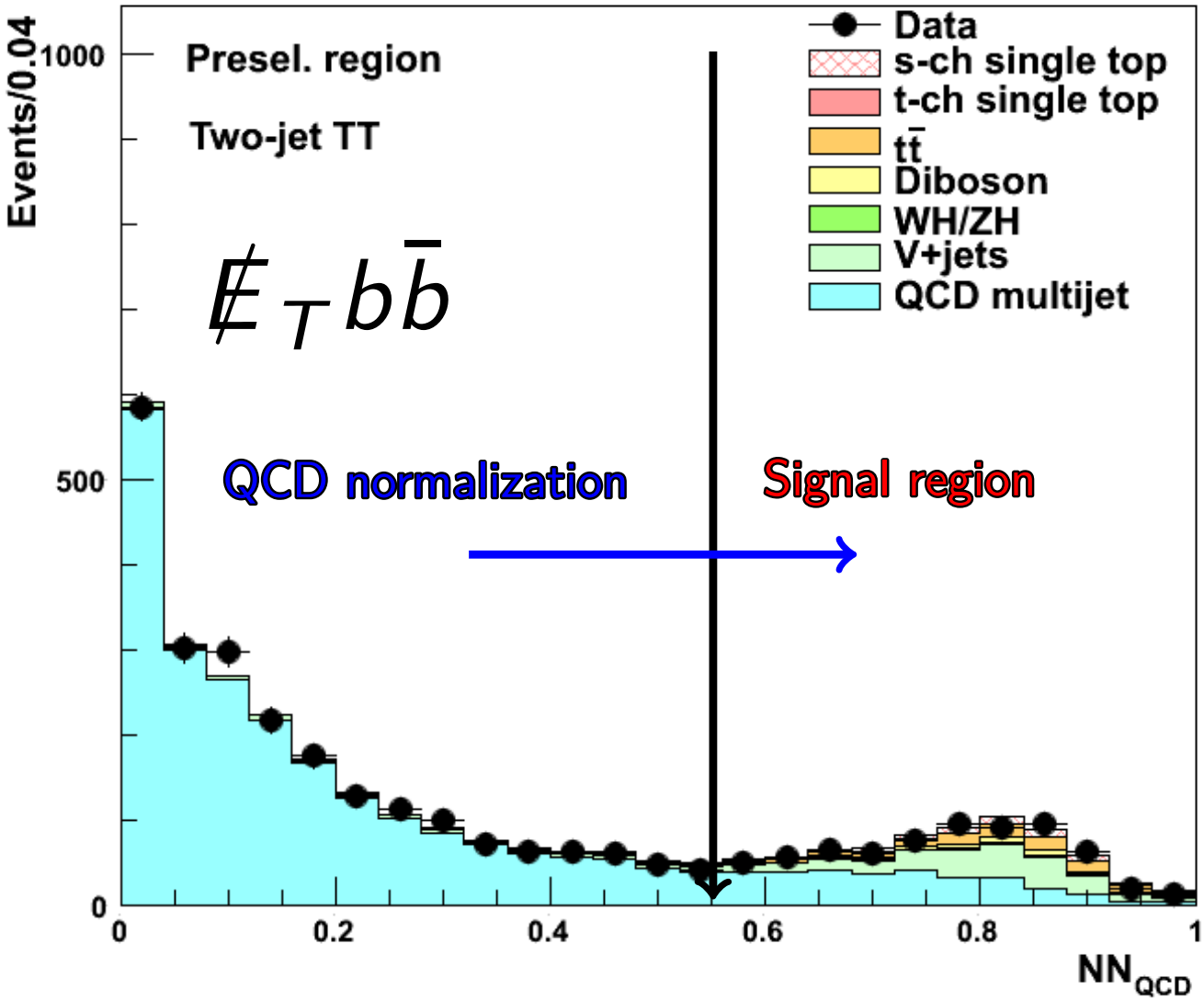
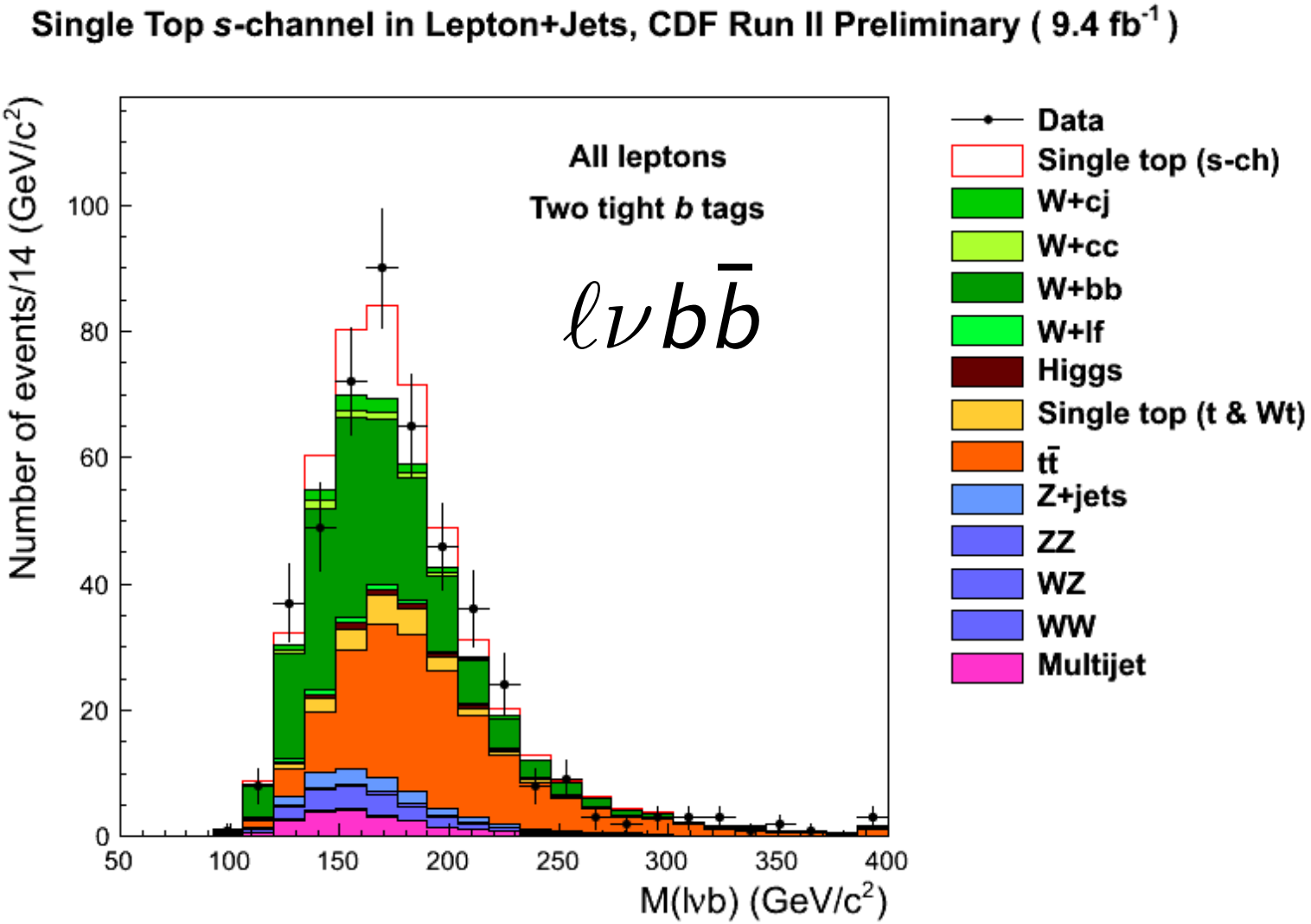


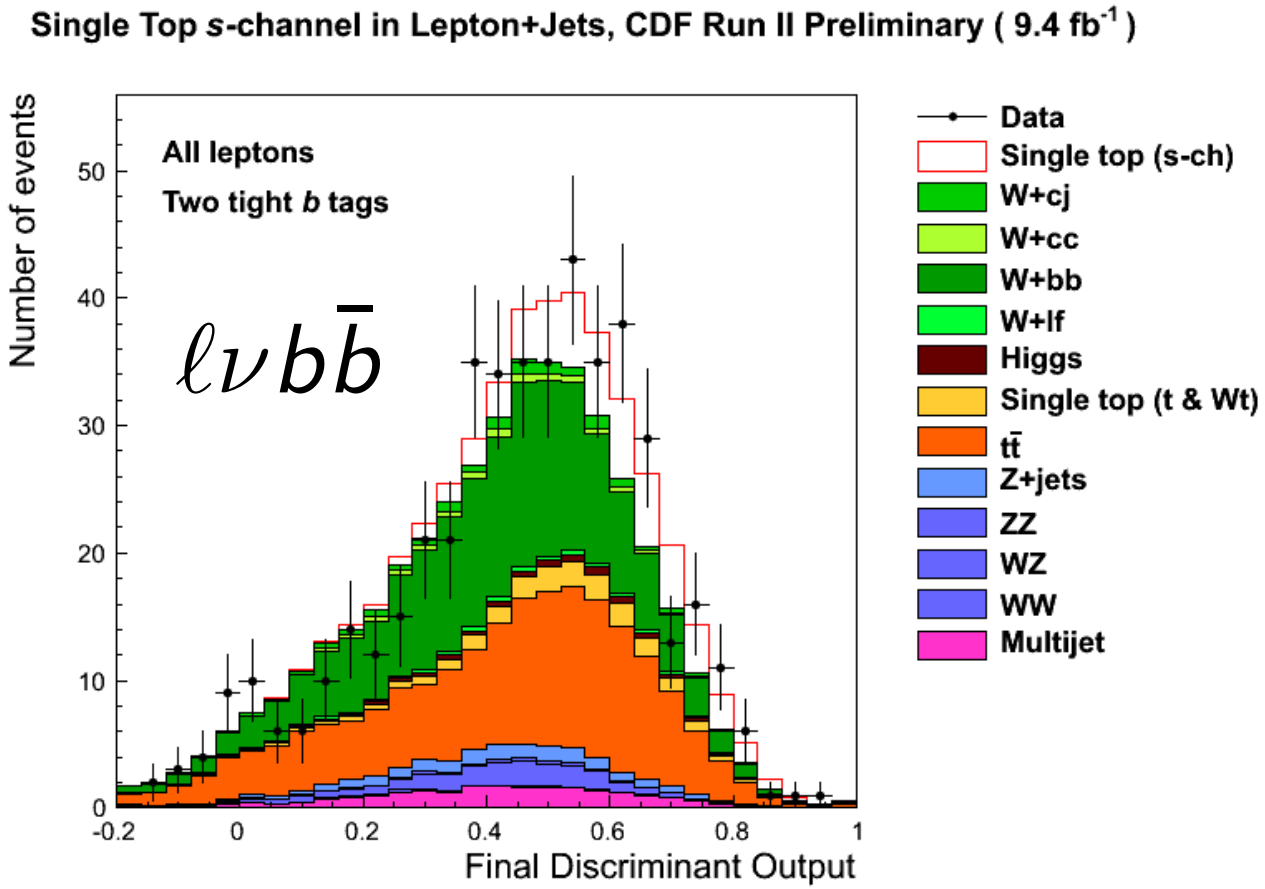
Top Quark Reconstruction

In both the CDF analyses, a neural network algorithm is employed to select the b jet which is originated from top quark.



Final Discriminant

- 10-20 kinematic variables are used in the training
- The training is optimized in each analysis subsample



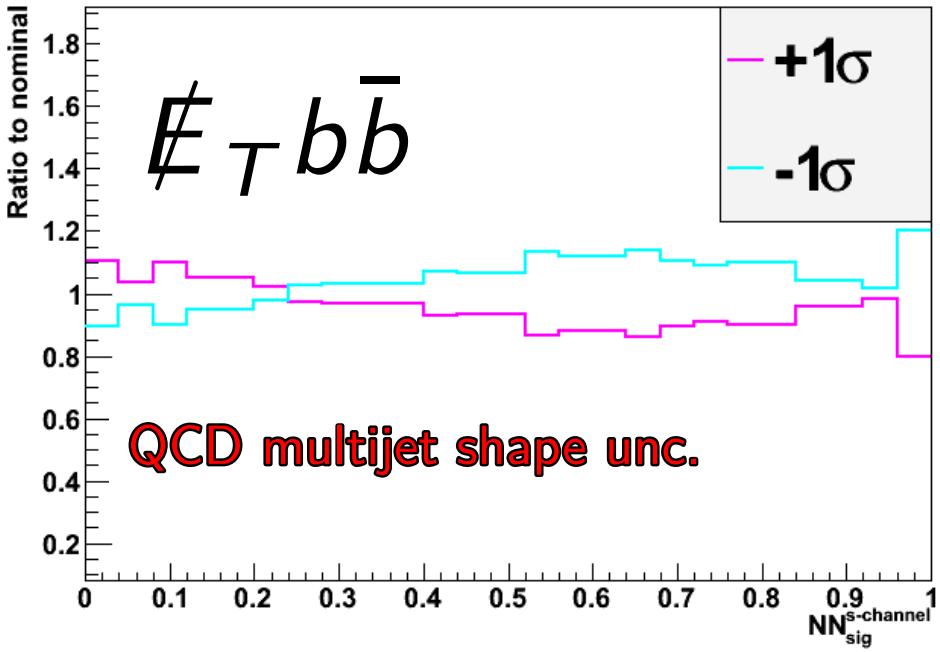
- Double-tag two-jet sample is the most sensitive
- Data clearly prefer the signal+background hypothesis

Cross Section Extraction

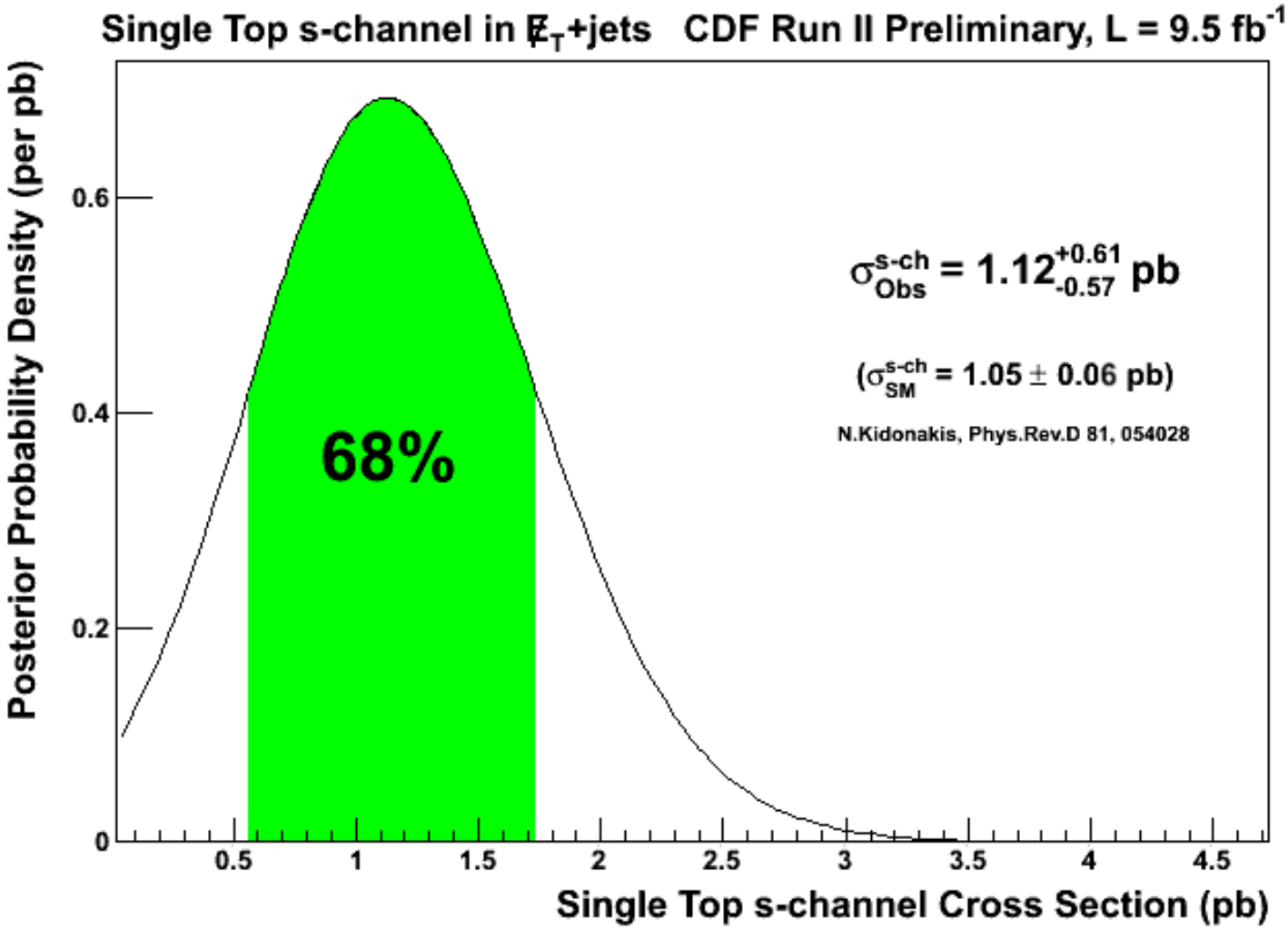
- ***t*-channel single top** and ***WH*/*ZH*** production included as backgrounds, constrained to the theoretical prediction
- Bayesian approach: likelihood fit to the binned final discriminant distribution
- Uniform, non-negative prior for signal cross section
- All the uncertainties on signal and background normalization and shape included

Systematic Uncertainties

- W+jets normalization uncertainty is the dominating one
- The **jet energy** is corrected separately for **quark** and **gluon** jets
  $\Rightarrow$ two different uncertainties
- A **shape uncertainty** on the **QCD multijet data-driven model** is included

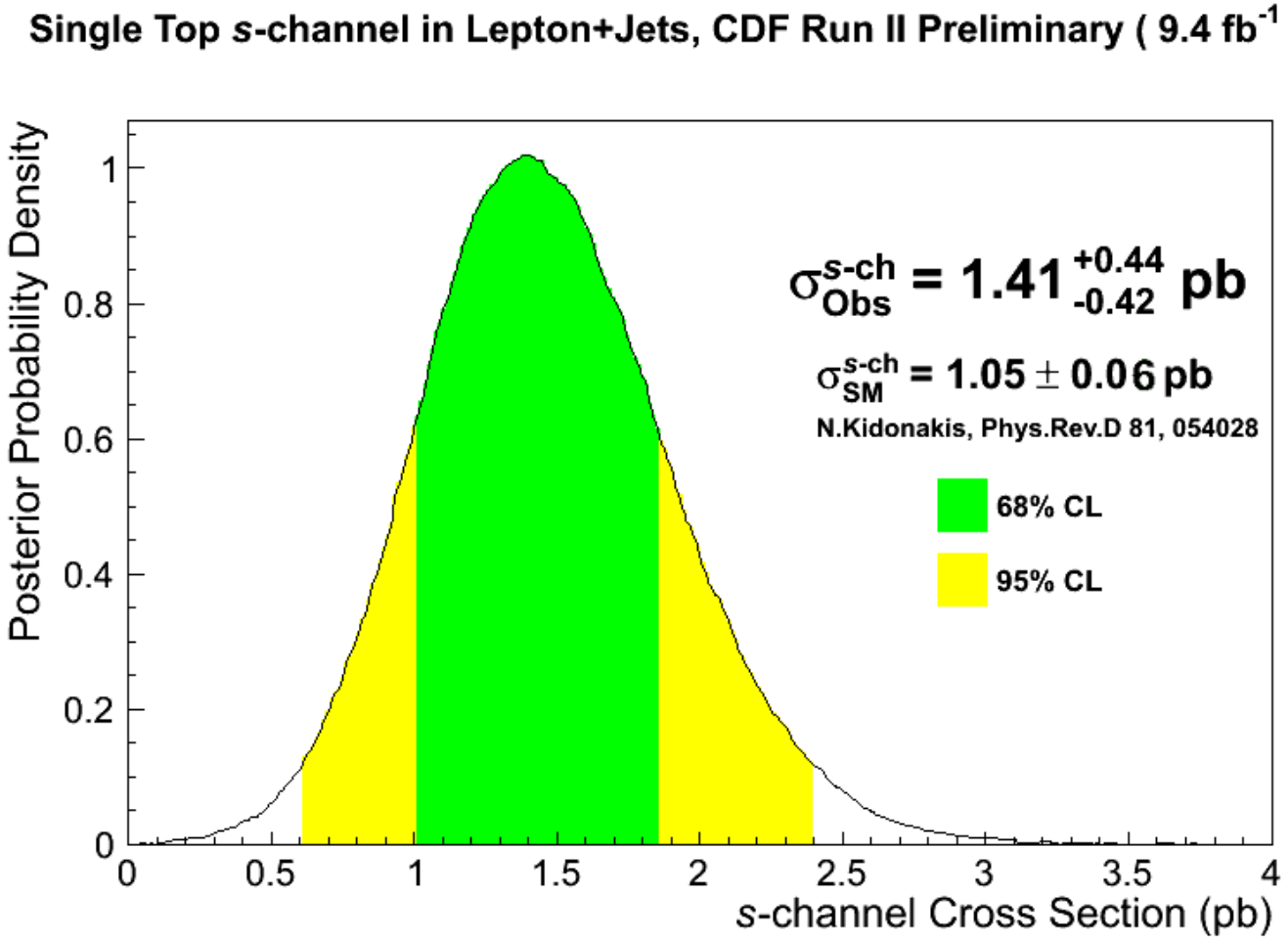


$\not\!\!E_T b\bar{b}$ Cross Section Extraction



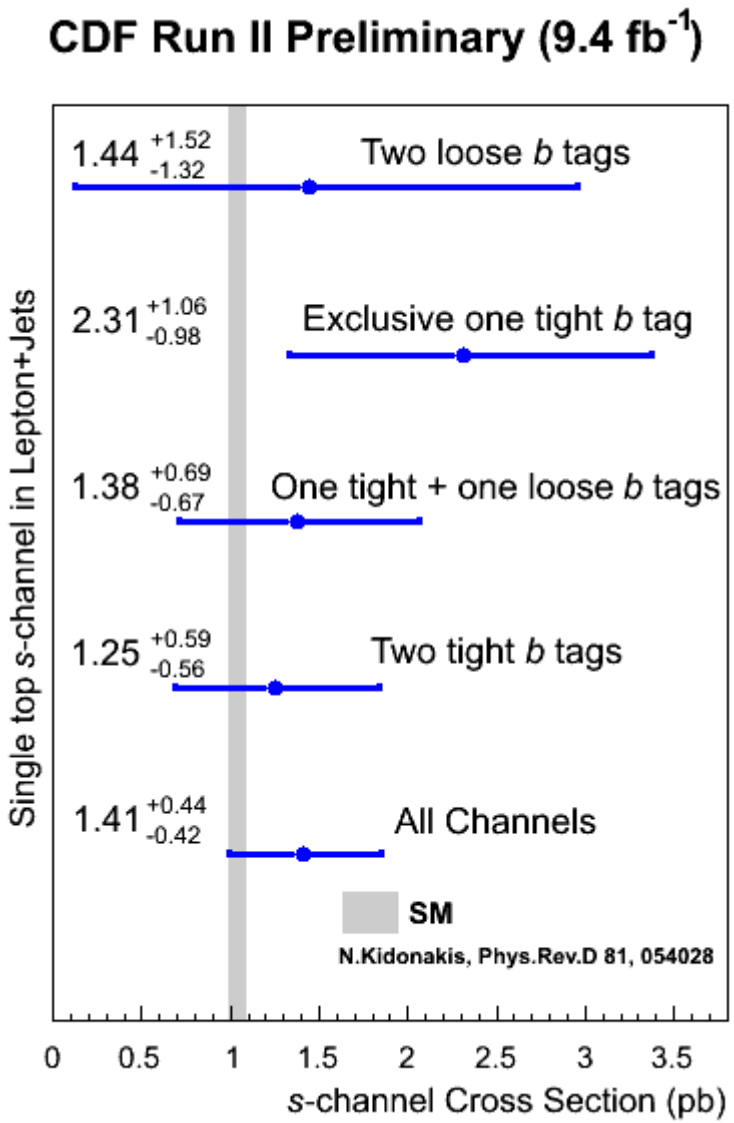
- Expected uncertainty: 57%
- Observed uncertainty: 53%

$\ell\nu b\bar{b}$ Cross Section Extraction



- Expected uncertainty: 38%
- Observed uncertainty: 30%

$\ell\nu b\bar{b}$ Consistency check

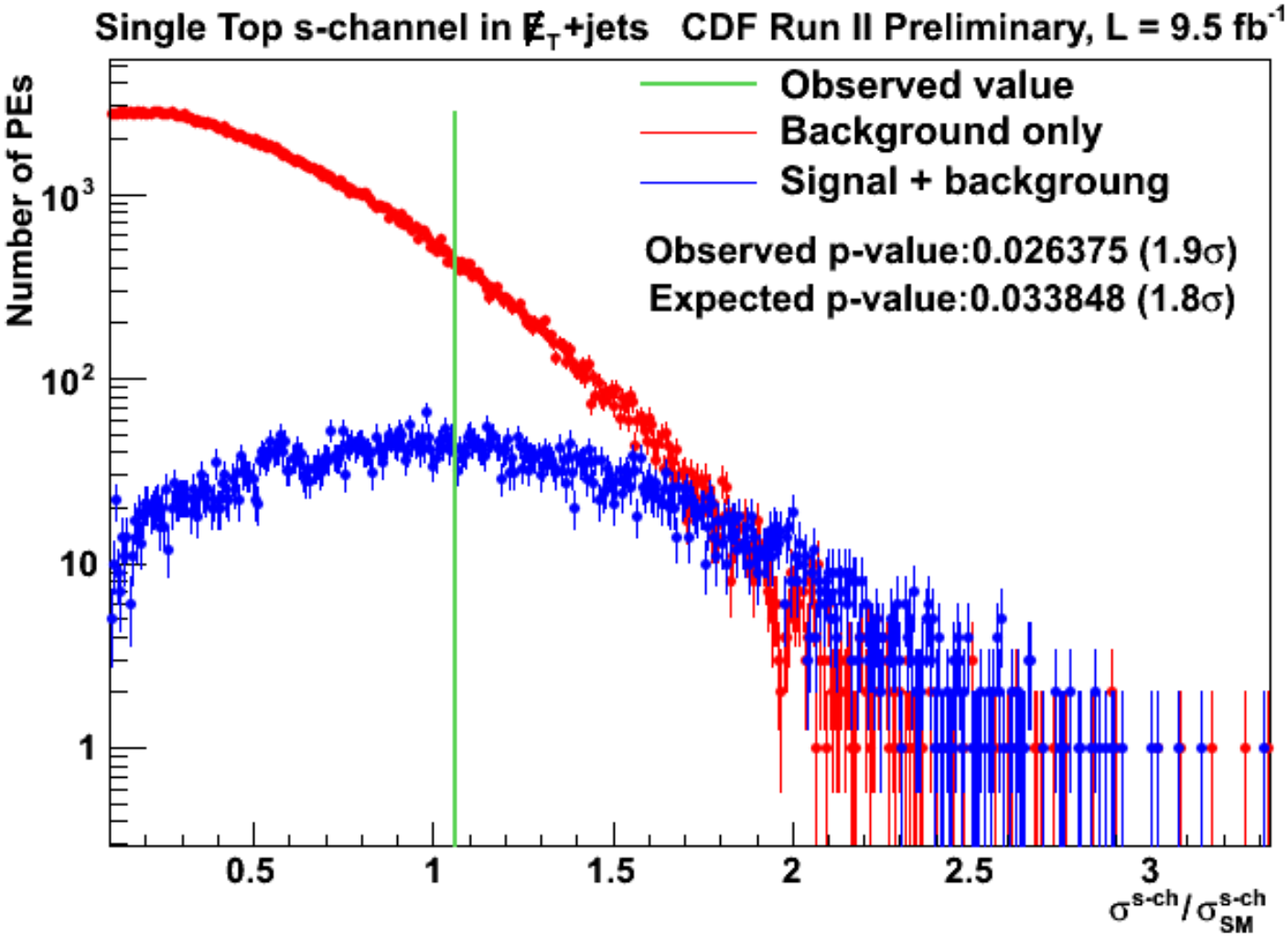


Measurements are consistent with each other in each subsample

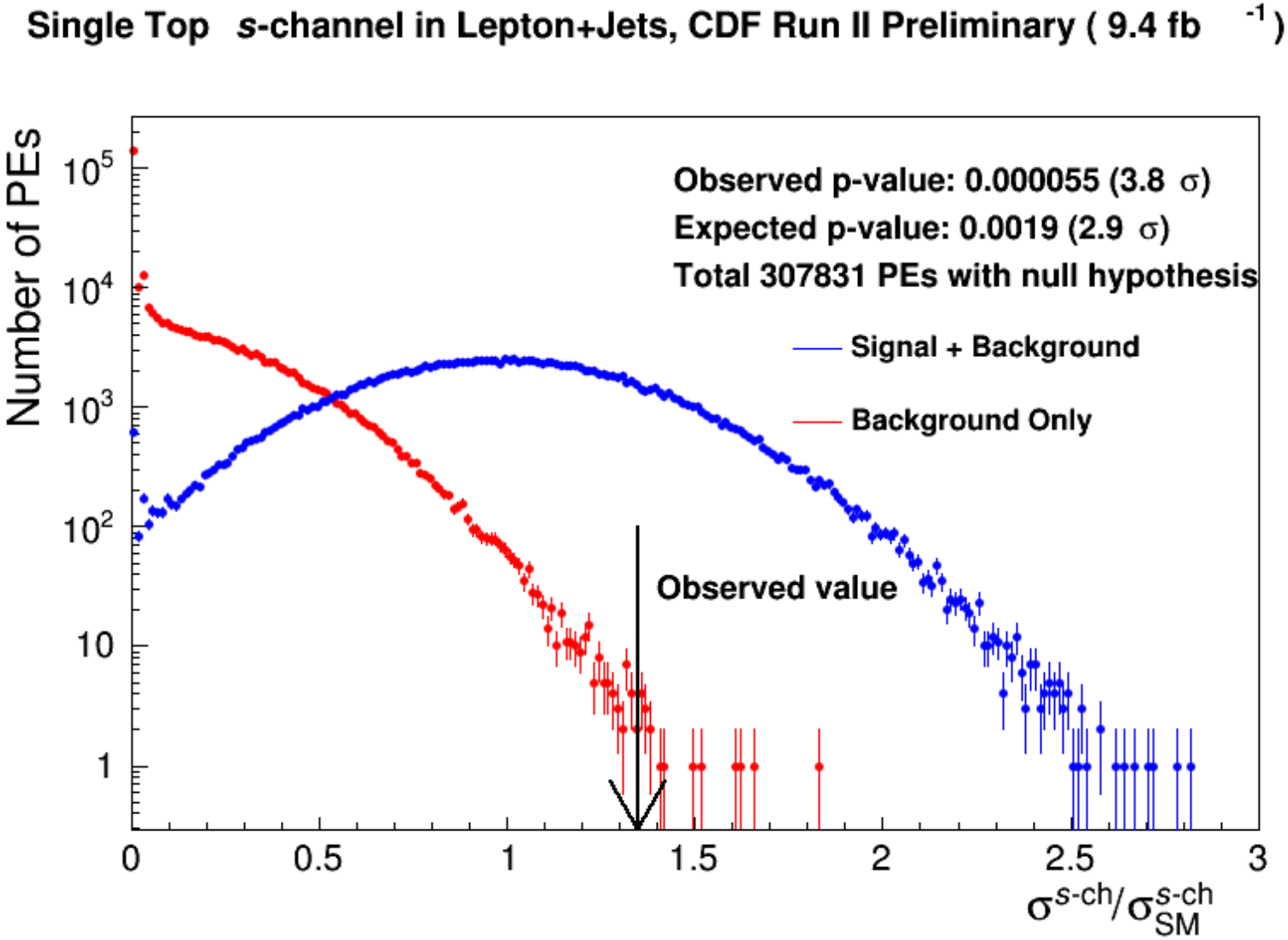
Significance

- The probability of observing a signal as large as the observed one or larger from fluctuation of the backgroud (**p-value**) is estimated
- The p-value is computed generating a large set of pseudoexperiment in signal+background and background-only hypothesis
- The expected p-value is calculated assuming a signal at the SM rate

$\not\!\!E_T b\bar{b}$ Significance



$\ell\nu b\bar{b}$ Significance

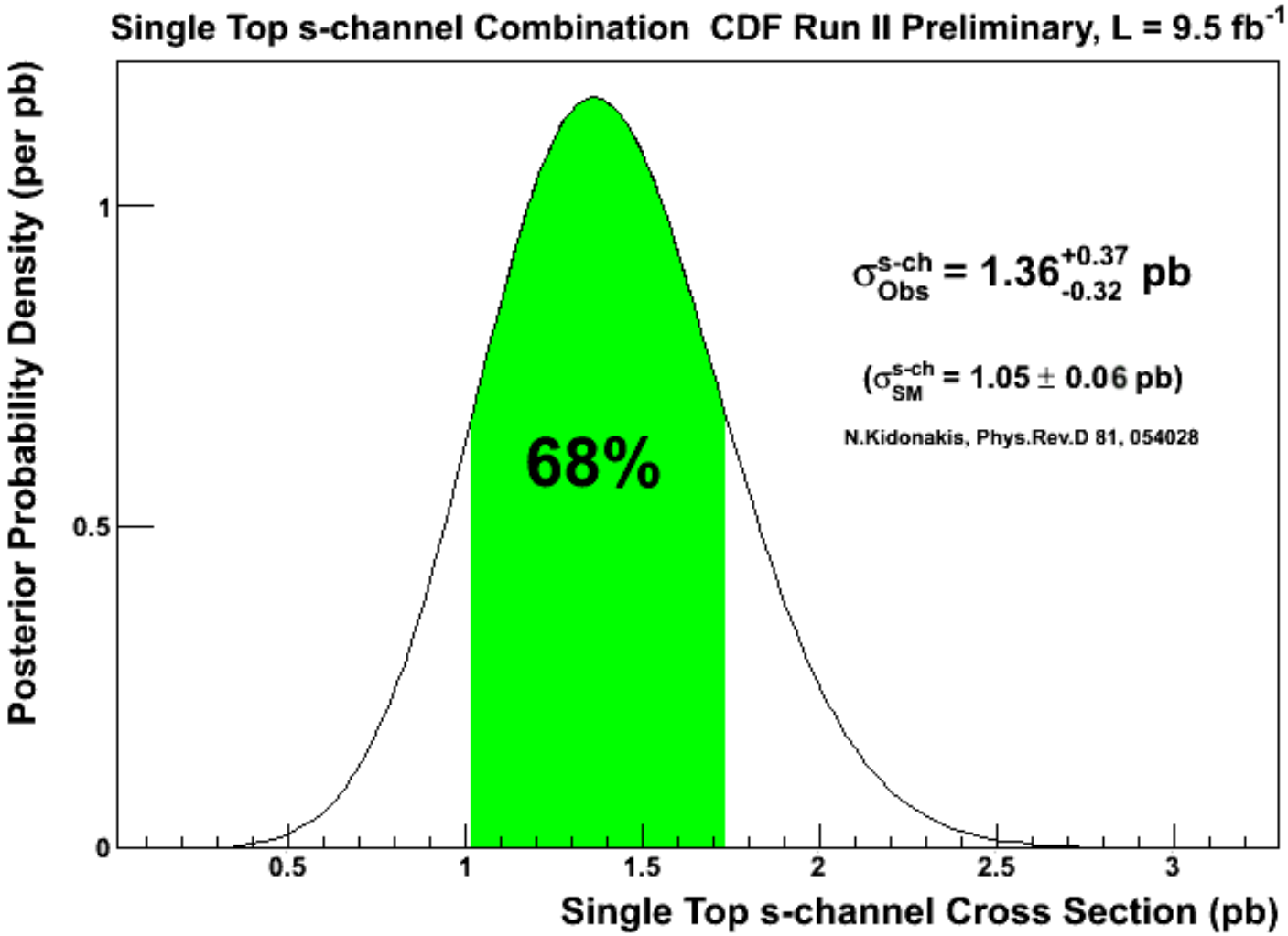


CDF Combination

CDF Combined Result

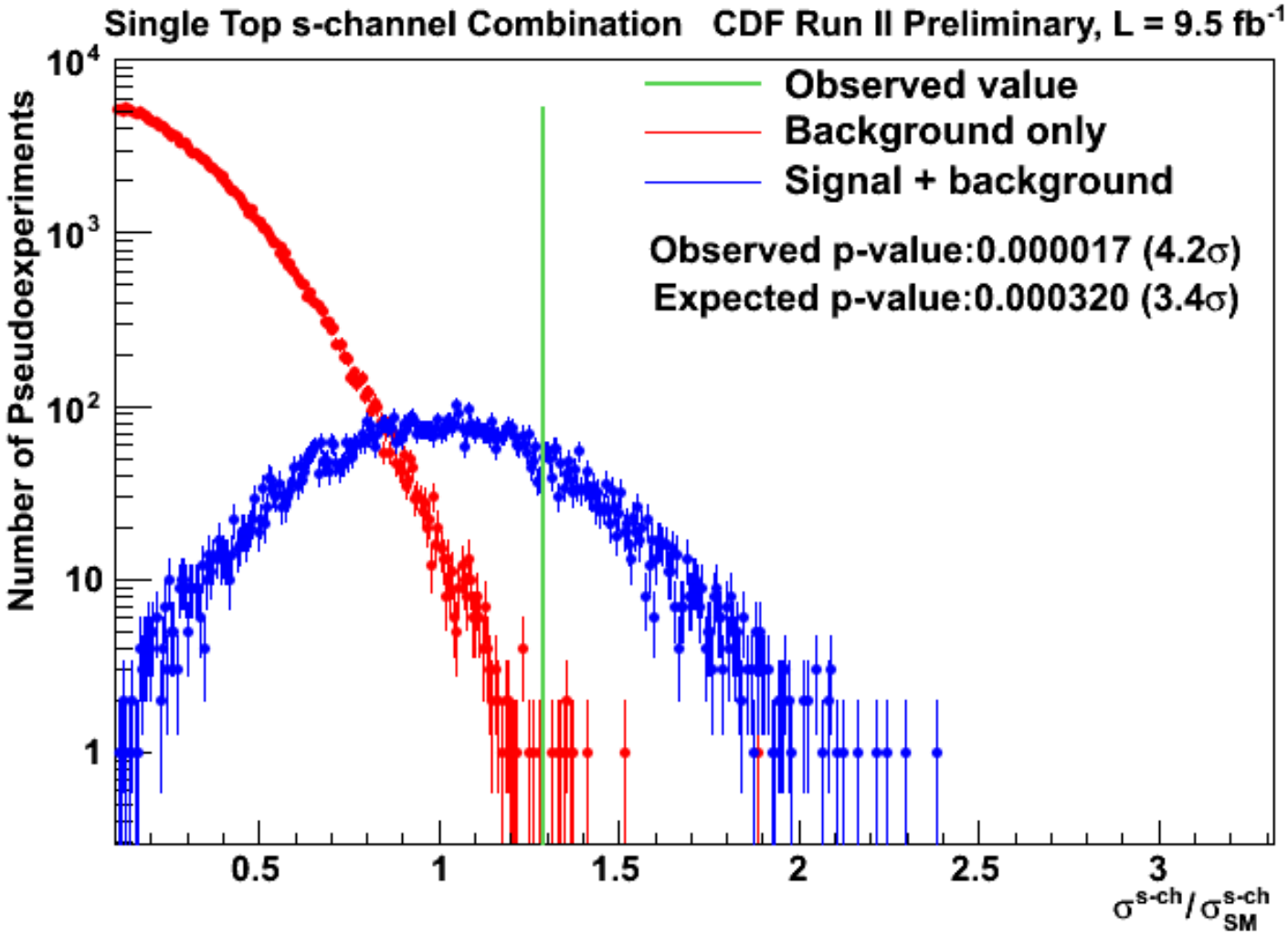
- Bayesian approach considering simultaneously all the subsamples from the $\ell\nu b\bar{b}$ and $\not\!\!E_T b\bar{b}$ analyses
- Use the same approach used in each single analysis to calculate significance
- All the uncertainties and their correlations taken into account

CDF Combined Result



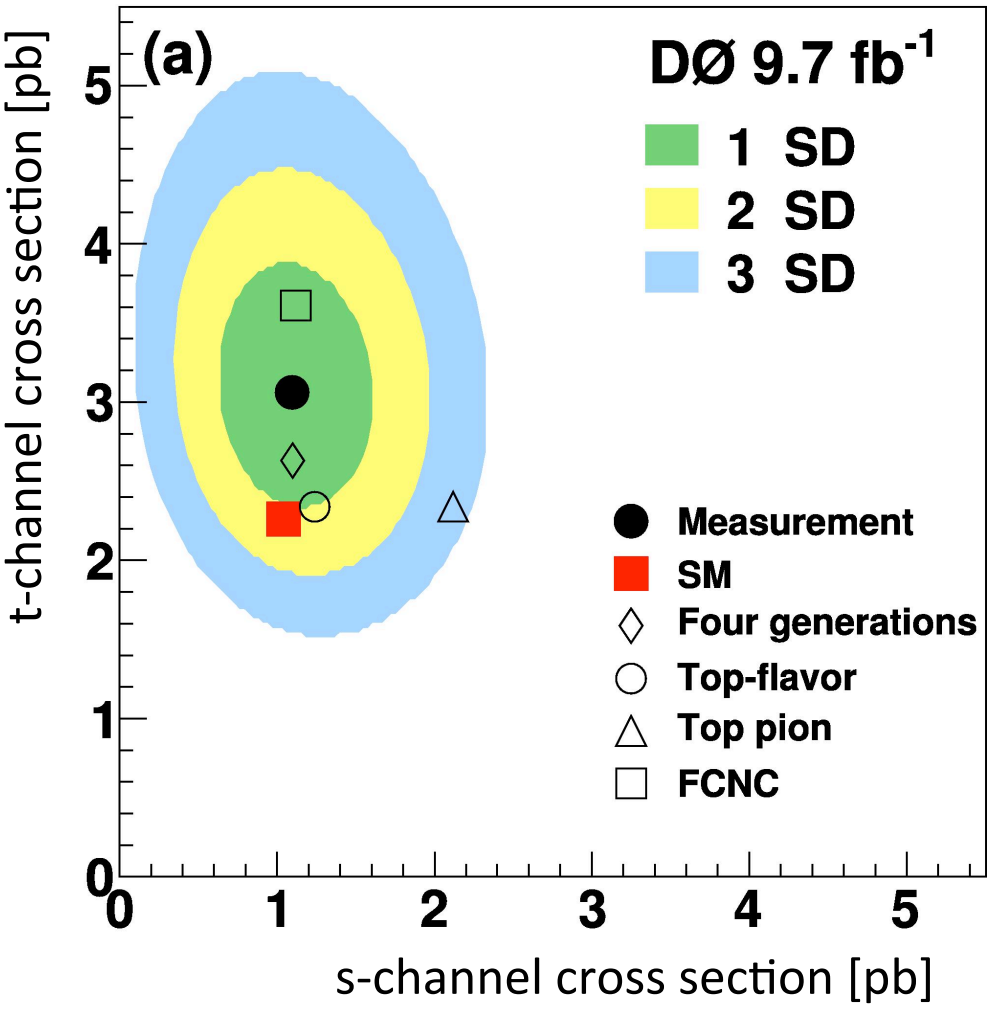
- Expected uncertainty: 33%
- Observed uncertainty: 25%

CDF Combined Result



D0 s-channel result

D0 single top analysis



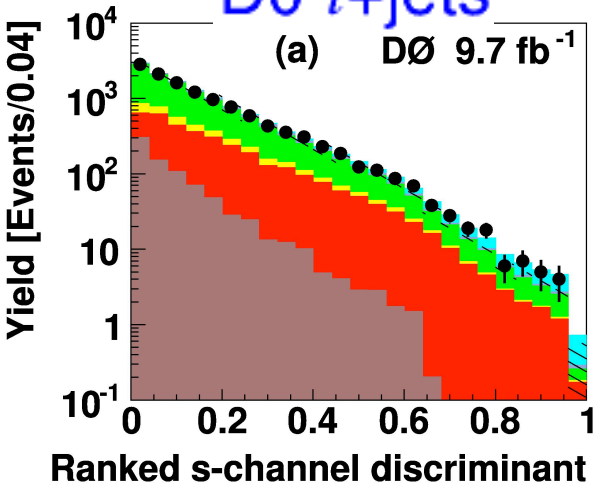
- 2d MVA discriminant sensitive to both s-channel and t-channel
- $\sigma_s^{\mathrm{D0}} = 1.10^{+0.33}_{-0.31}$ pb
- 3.7 s.d. significance

Tevatron combination

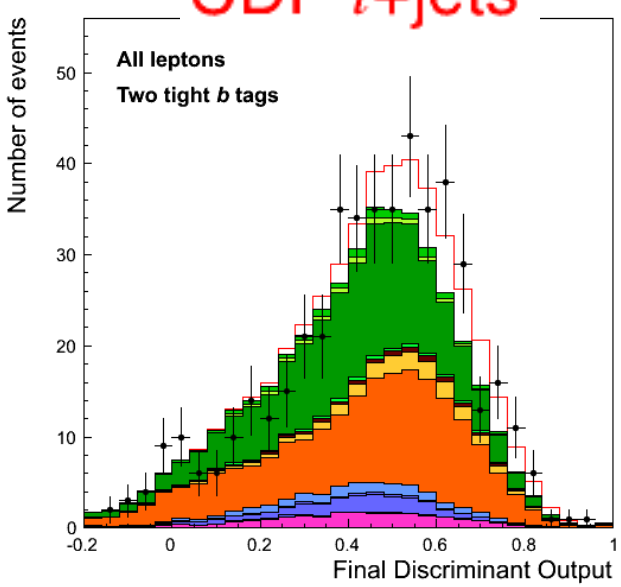
Combination inputs

- CDF l+jets analysis – arXiv:1402.0484
- CDF MET+jets analysis – arXiv:1402.3756
- D0 l+jets analysis – Phys. Lett. B 726, 656 (2013)

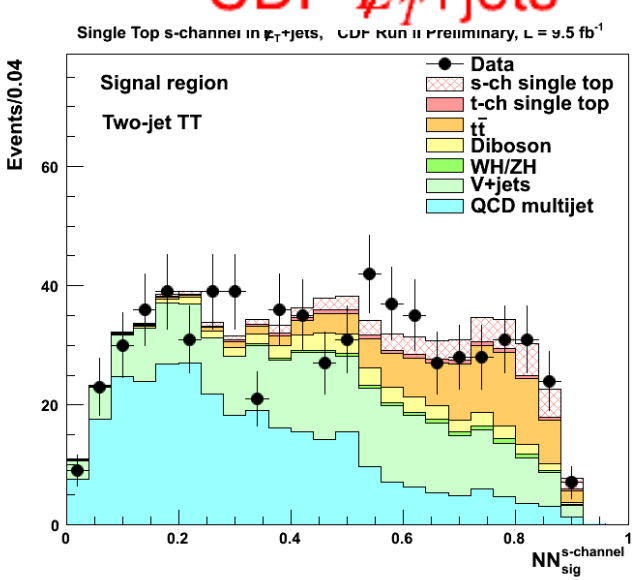
D0 *l*+jets



CDF *l*+jets



CDF $\not\!\!E_T$+jets

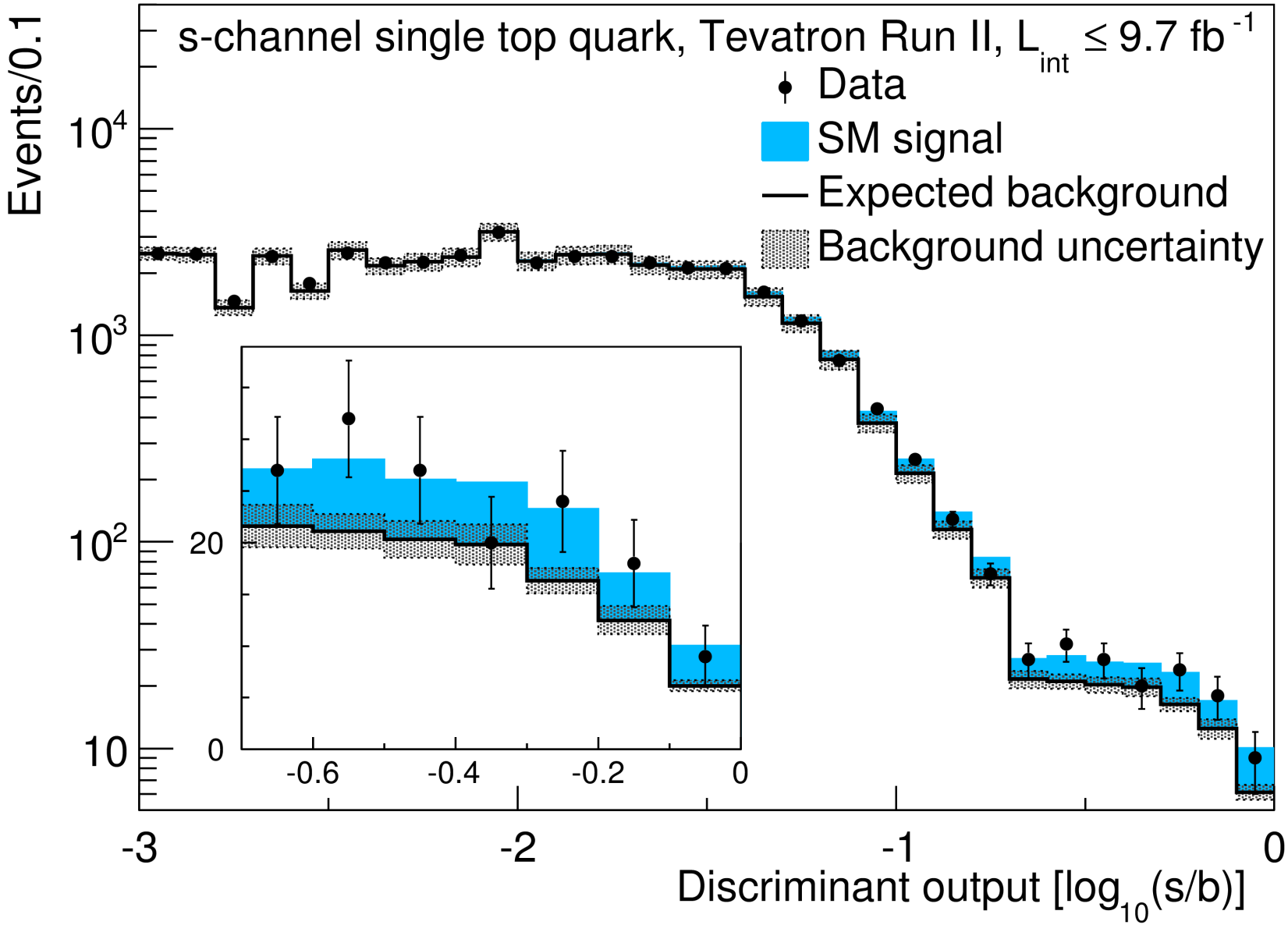


100 bins in
4 sub-samples

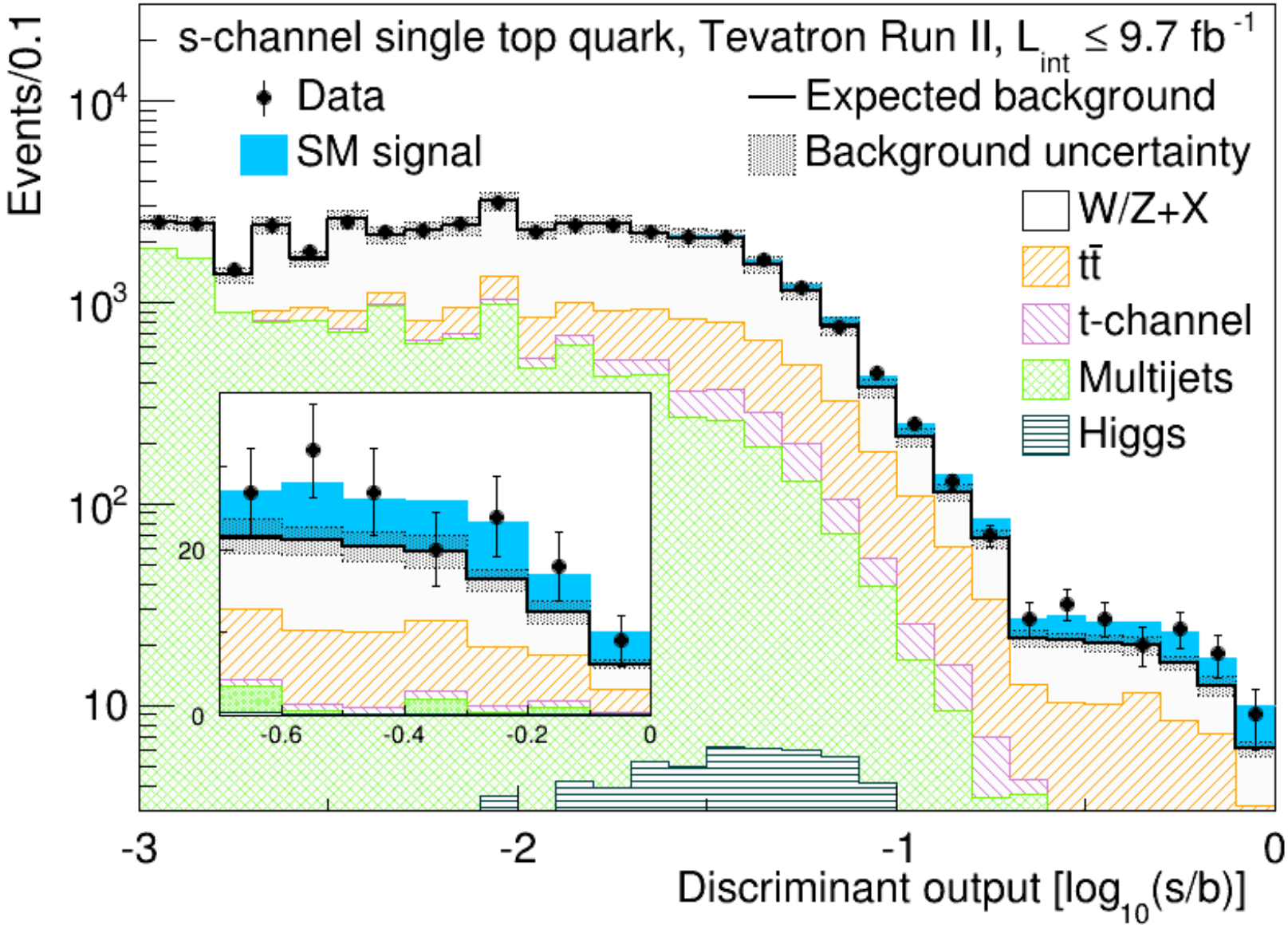
360 bins in
12 sub-samples

150 bins in
6 sub-samples

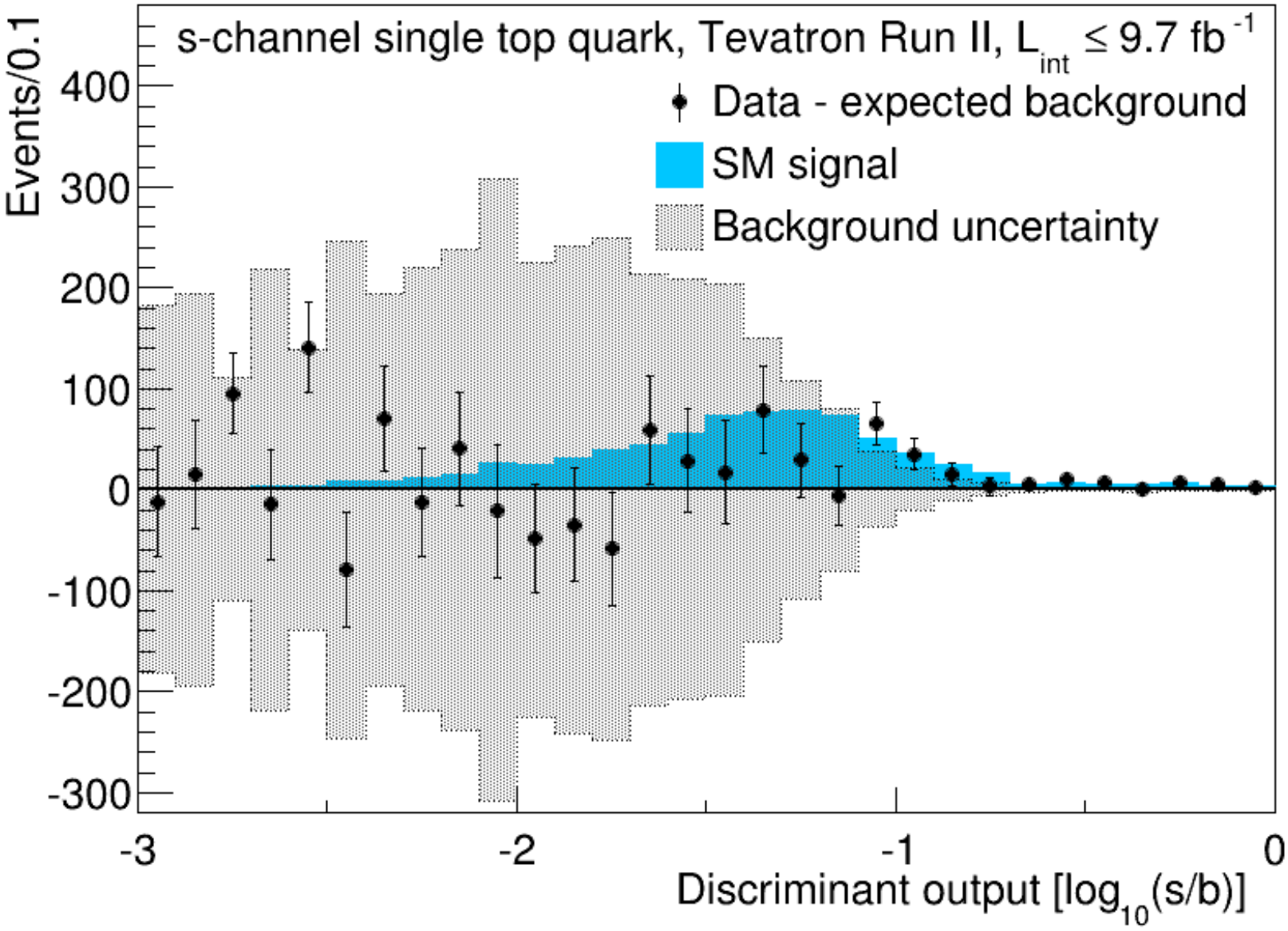
Discriminant output



Background composition



Background-subtracted discriminant



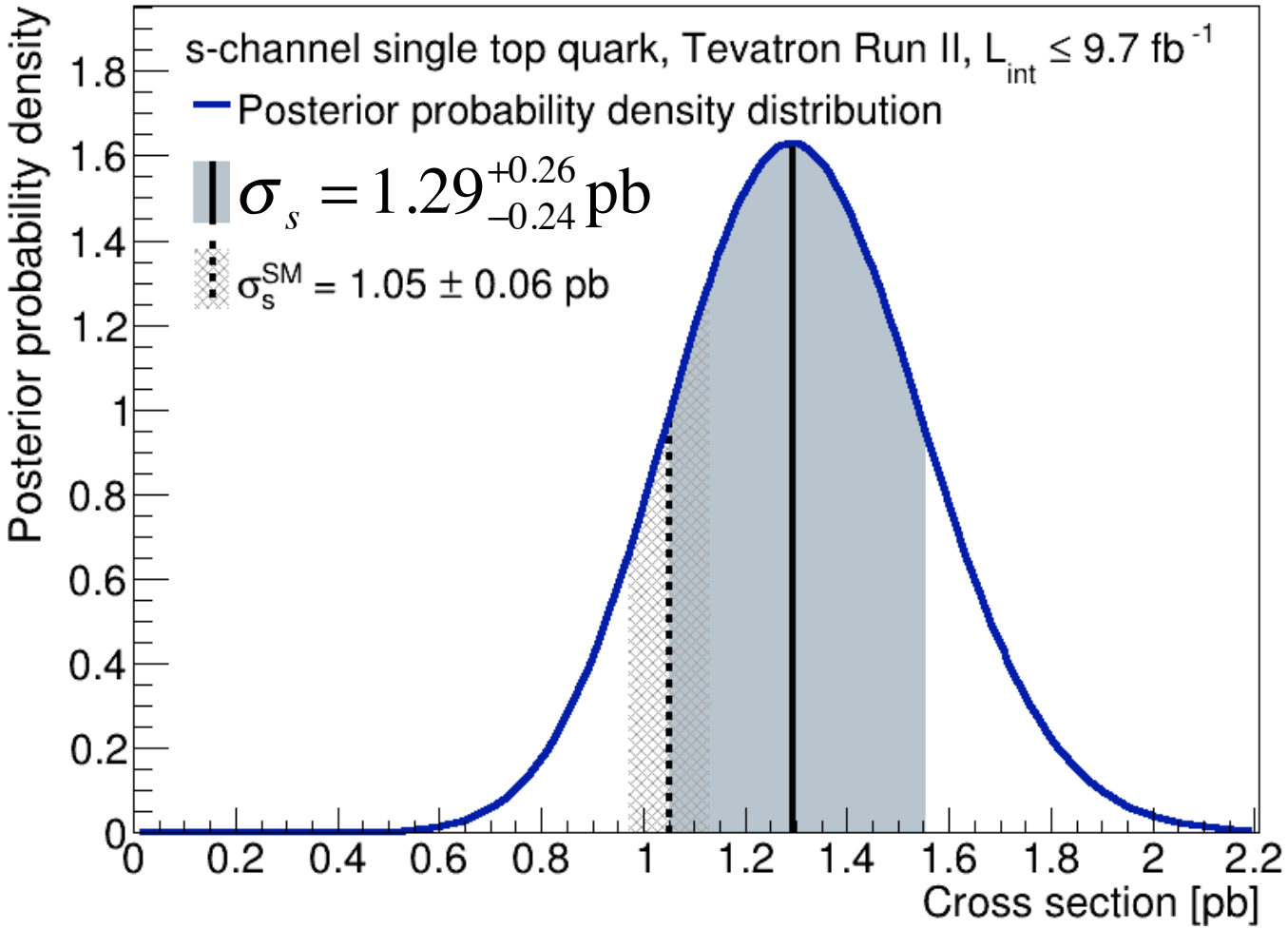
Systematic uncertainties

- Uncertainty range for individual backgrounds:

Systematic uncertainty	CDF		D0		Correlated
	Norm.	Shape	Norm.	Shape	
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%		5–40%	•	No
JES	0–20%	•	0–40%	•	No

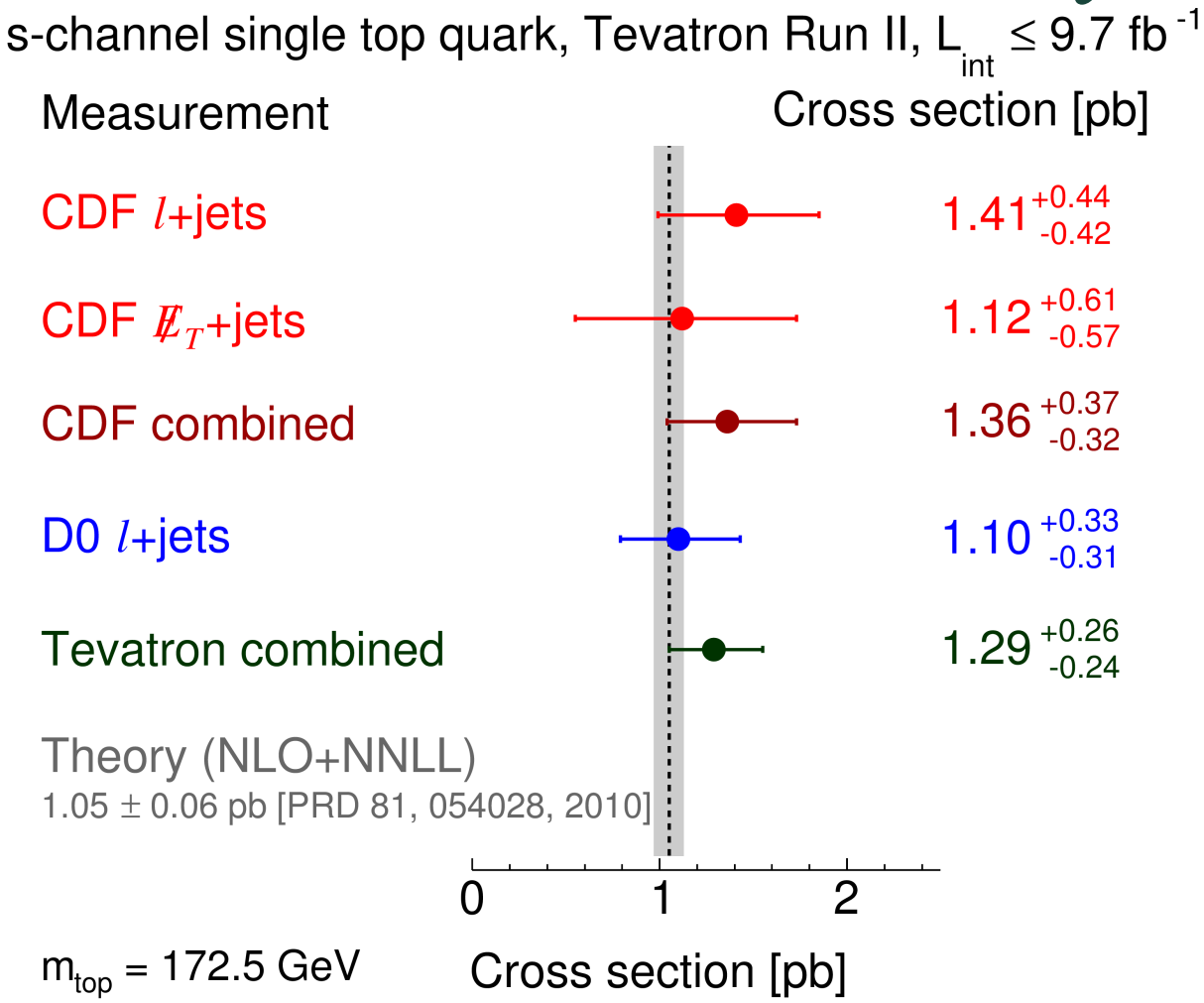
- Total uncertainty 10% to 20%

Bayesian statistical analysis



- Expected uncertainty: 20% (statistical only: 14%)
- Observed uncertainty: 19%

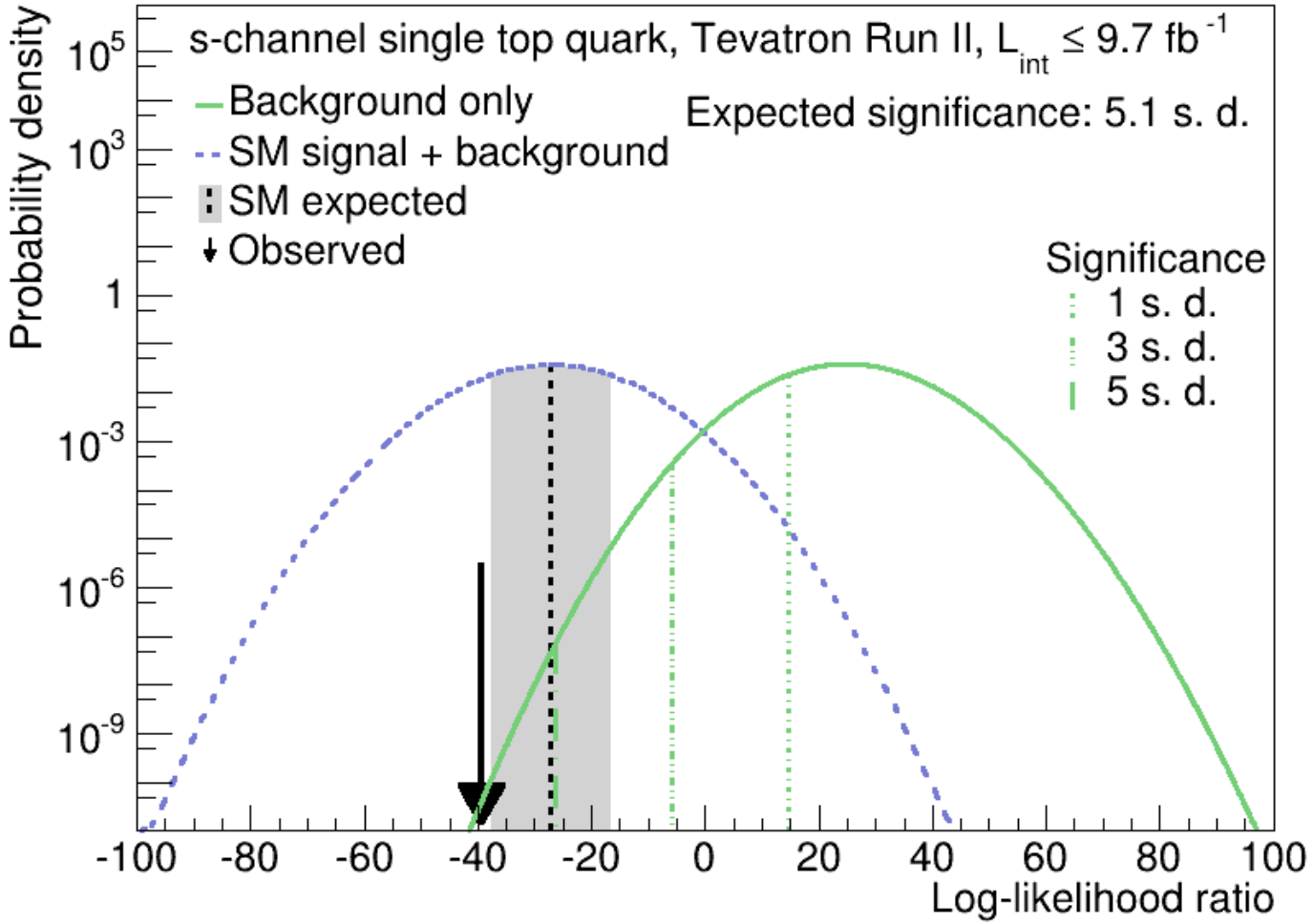
Cross section summary



- Equal contributions from CDF and D0
- Negligible top mass dependence

Significance

- LHC-style asymptotic approximation log-likelihood ratio
  - Reproduces ensemble-based significance estimate
- Observed p-value: 1.8×10^{-10}



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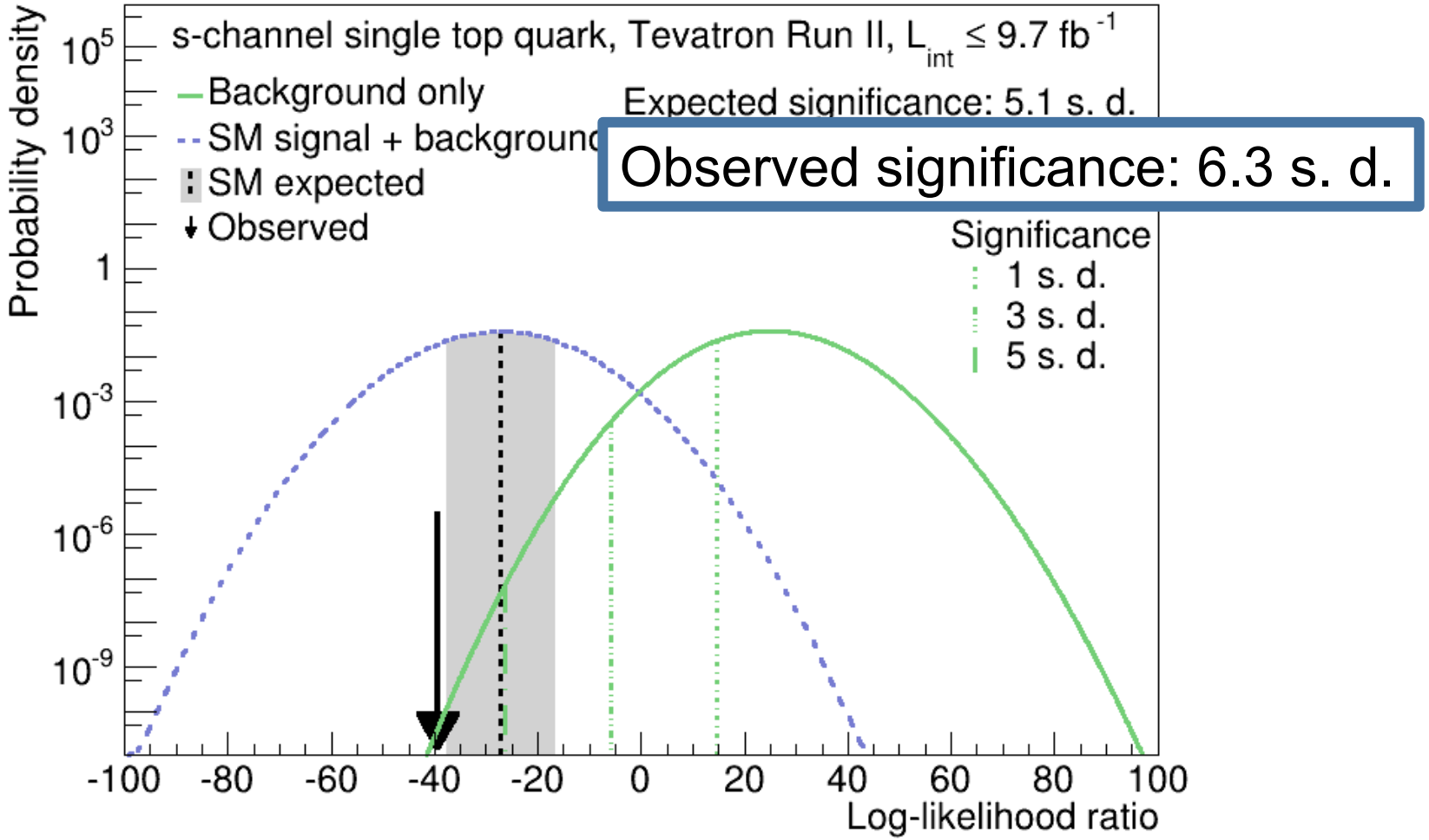

Conclusions

- CDF evidence for s-channel single top production
  - Lepton+jets and MET+jets combined
  - 4.2 s. d.
- CDF+D0 first observation of s-channel single top quark production
  - $\sigma_s = 1.29^{+0.26}_{-0.24}\,\text{pb}$ 6.3 s. d. significance
- Submitted to PRL, arXiv:1402.5126
- First observation requiring CDF + D0 combination

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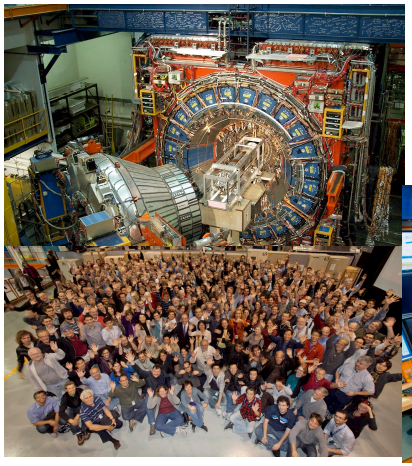

Thank You!