Top Quark Highlights

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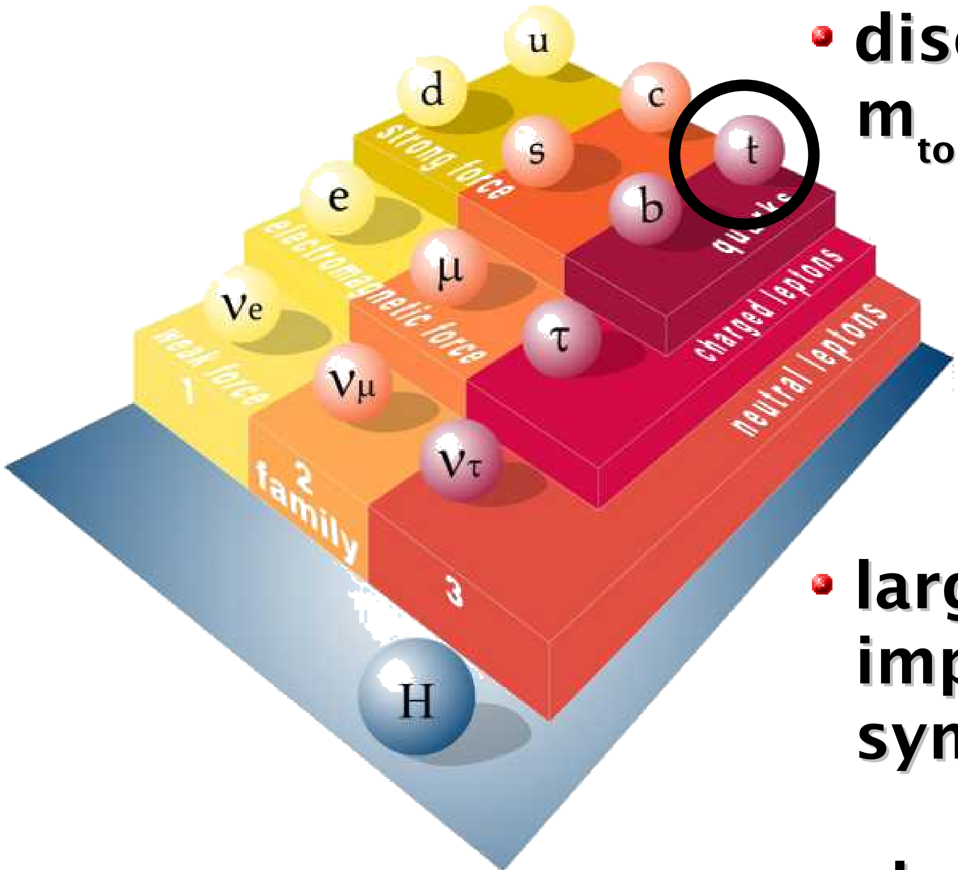
Thanks to Florencia Canelli, Yvonne Peters, Verónica Sorin, Frédéric Déliot, Stefan Söldner-Rembold, George Velet for helping in preparing this talk!

The Top Quark

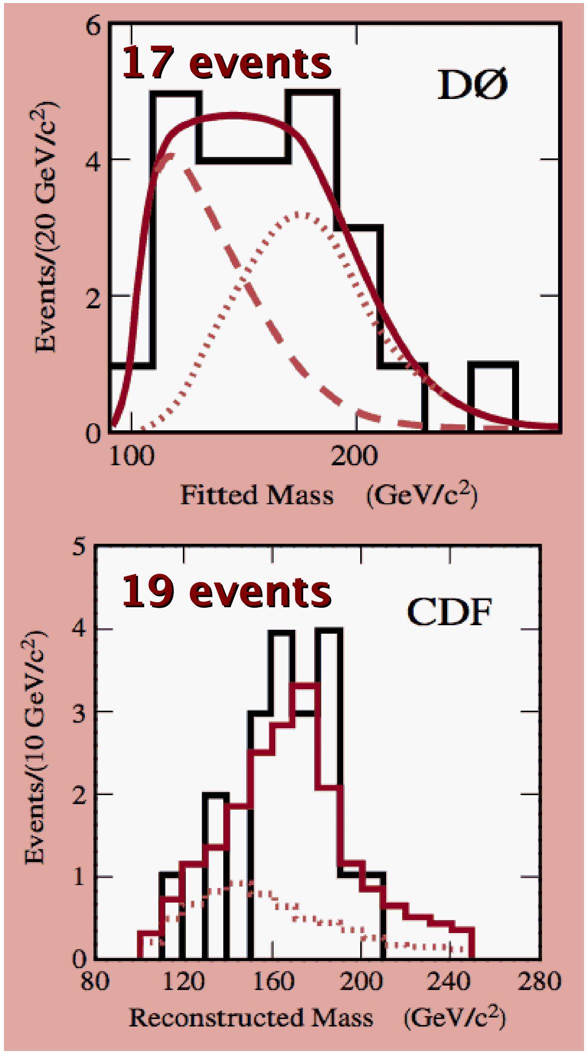


- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe "naked" quark

Top History

discovery

PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

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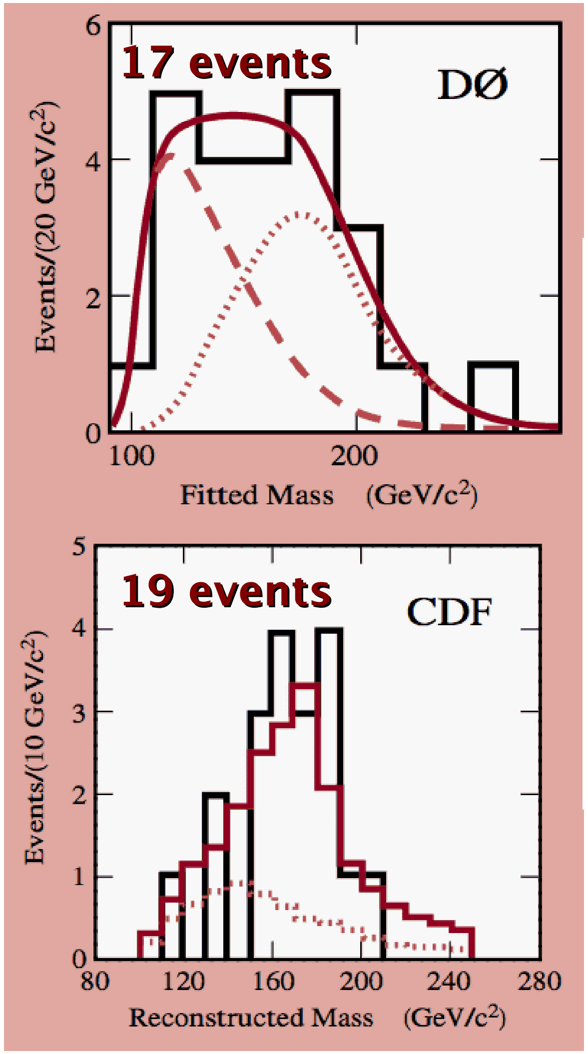
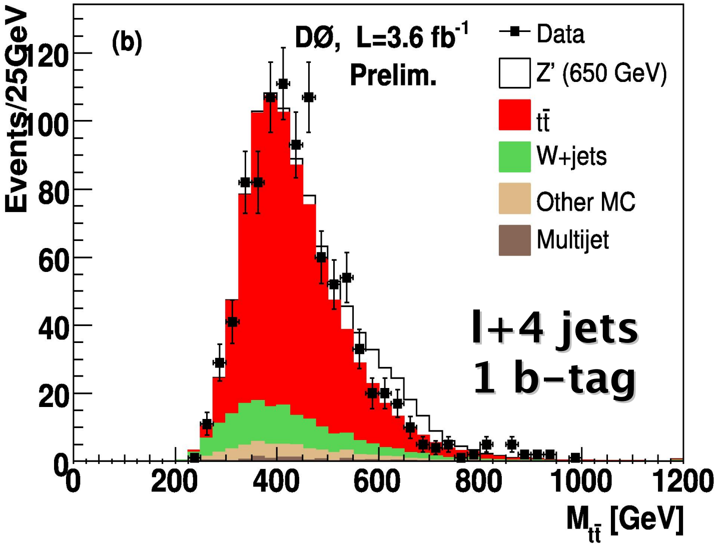


1995, CDF and DØ experiments, Fermilab

today

~1000 events



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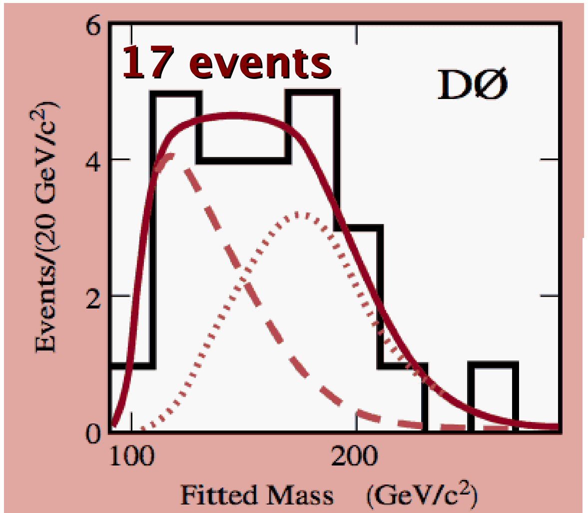

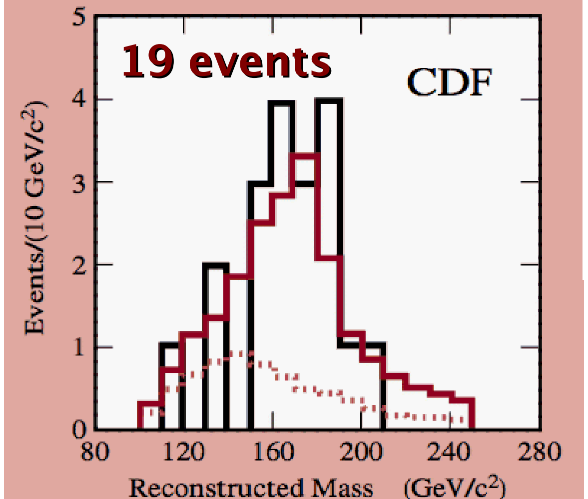

1995, CDF and DØ experiments, Fermilab

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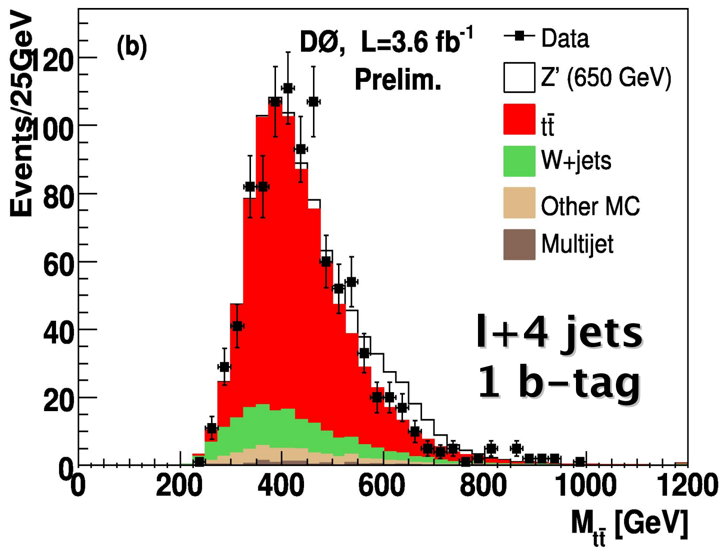
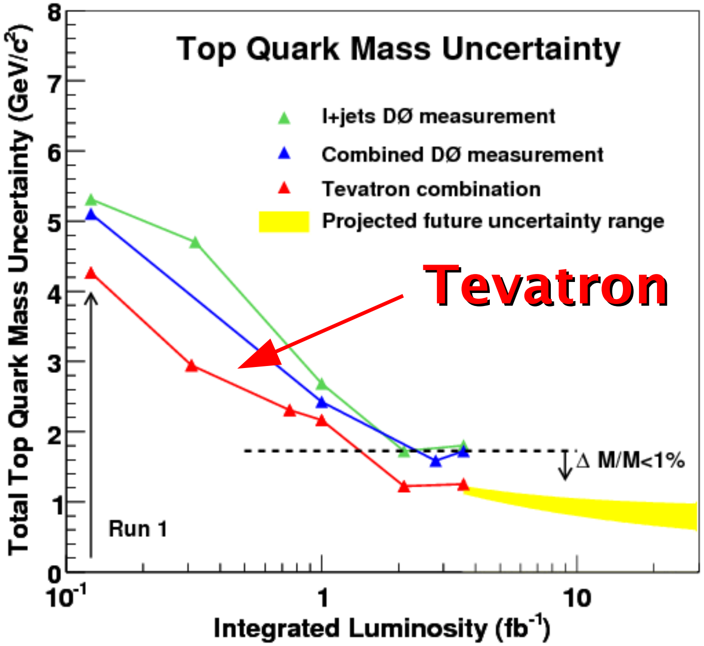


precision



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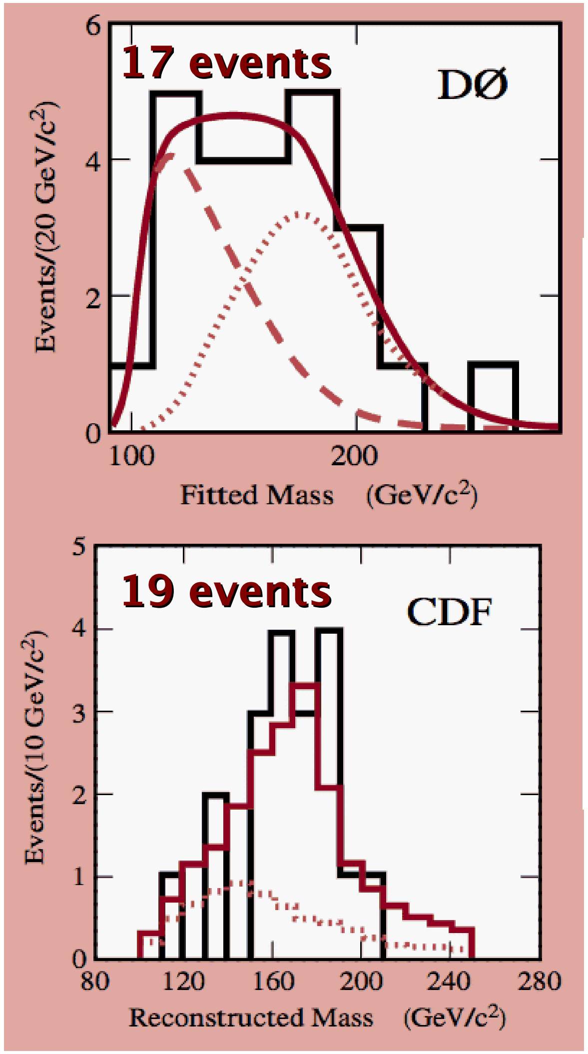

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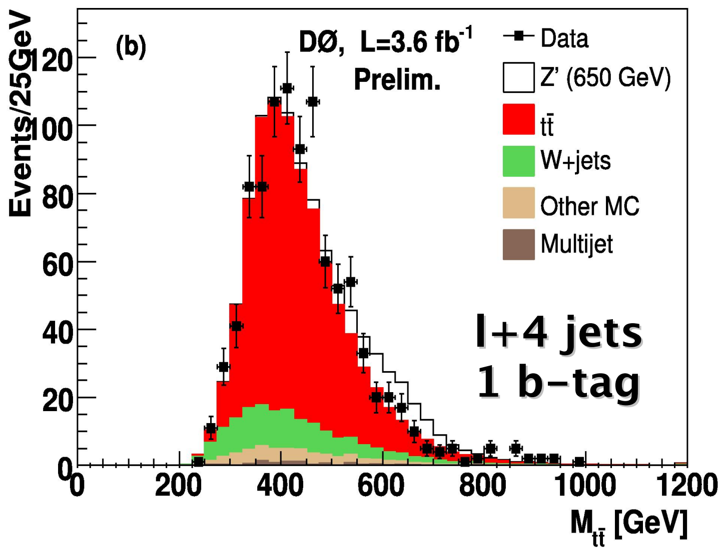
today

~1000 events



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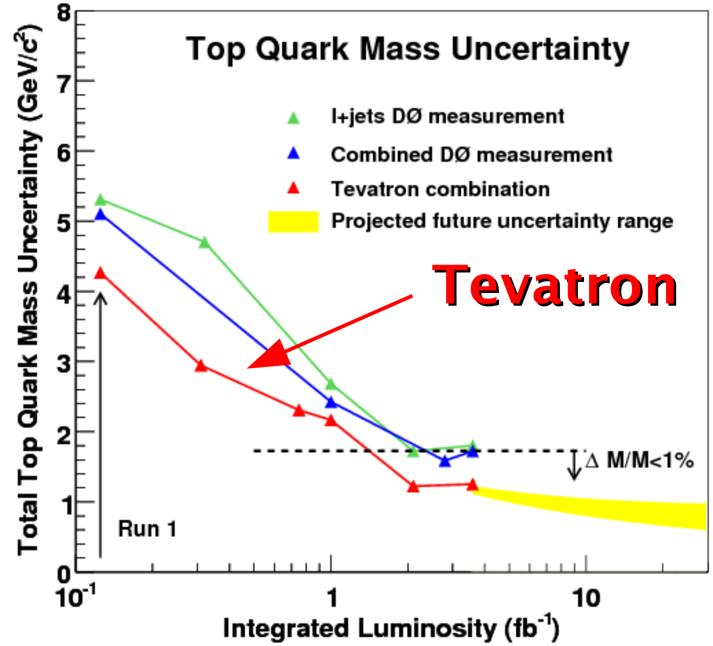
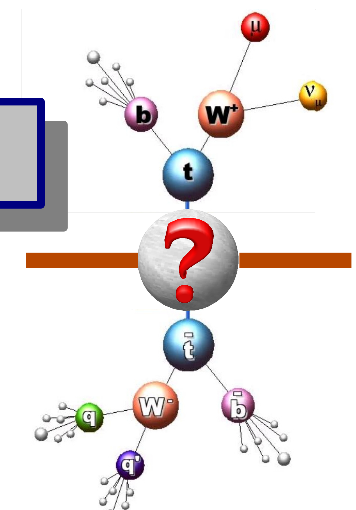


searches



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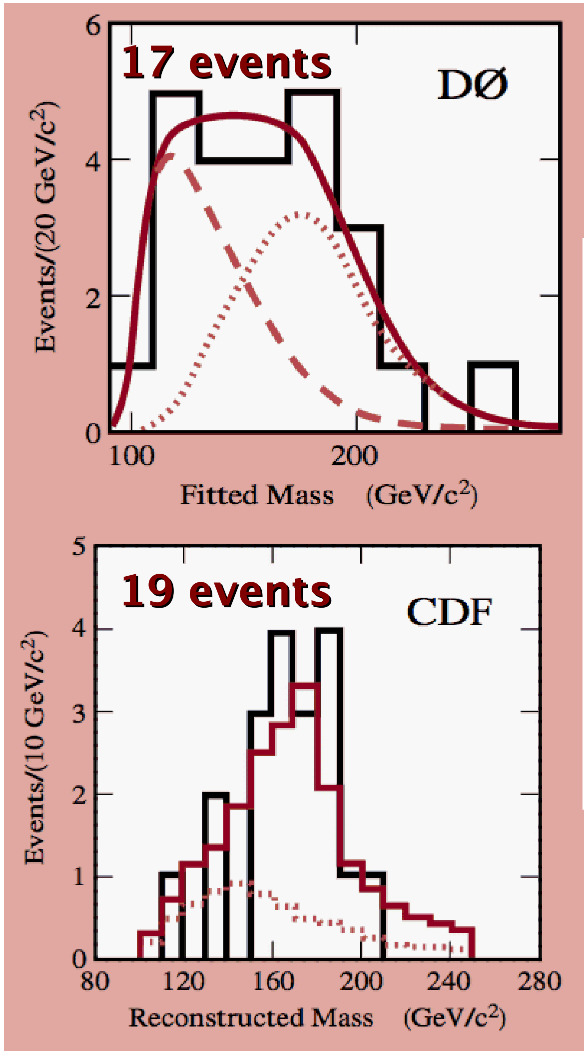

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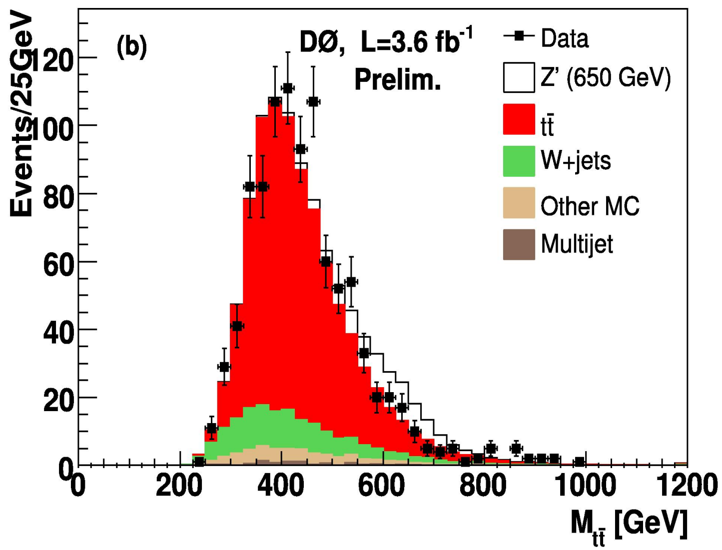
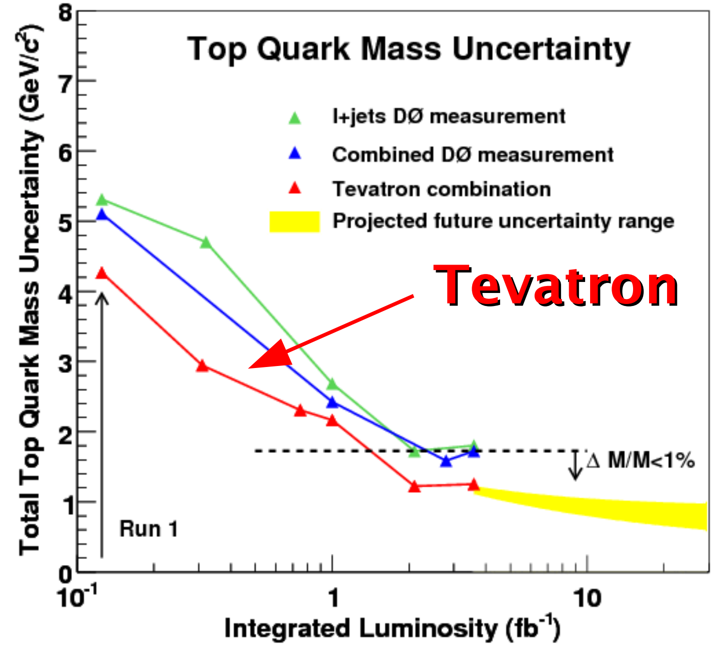
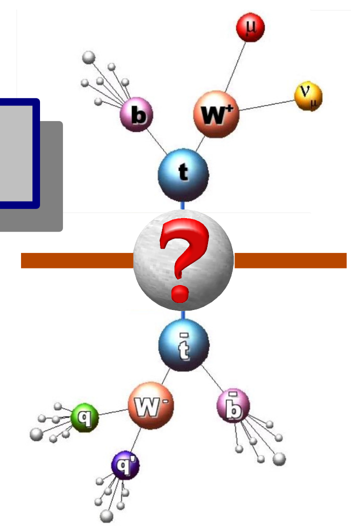


LHC: top factory

precision



searches



Outline

top physics at the Tevatron

top production cross sections

top properties

searches in production and decay

prospects at the LHC

conclusions

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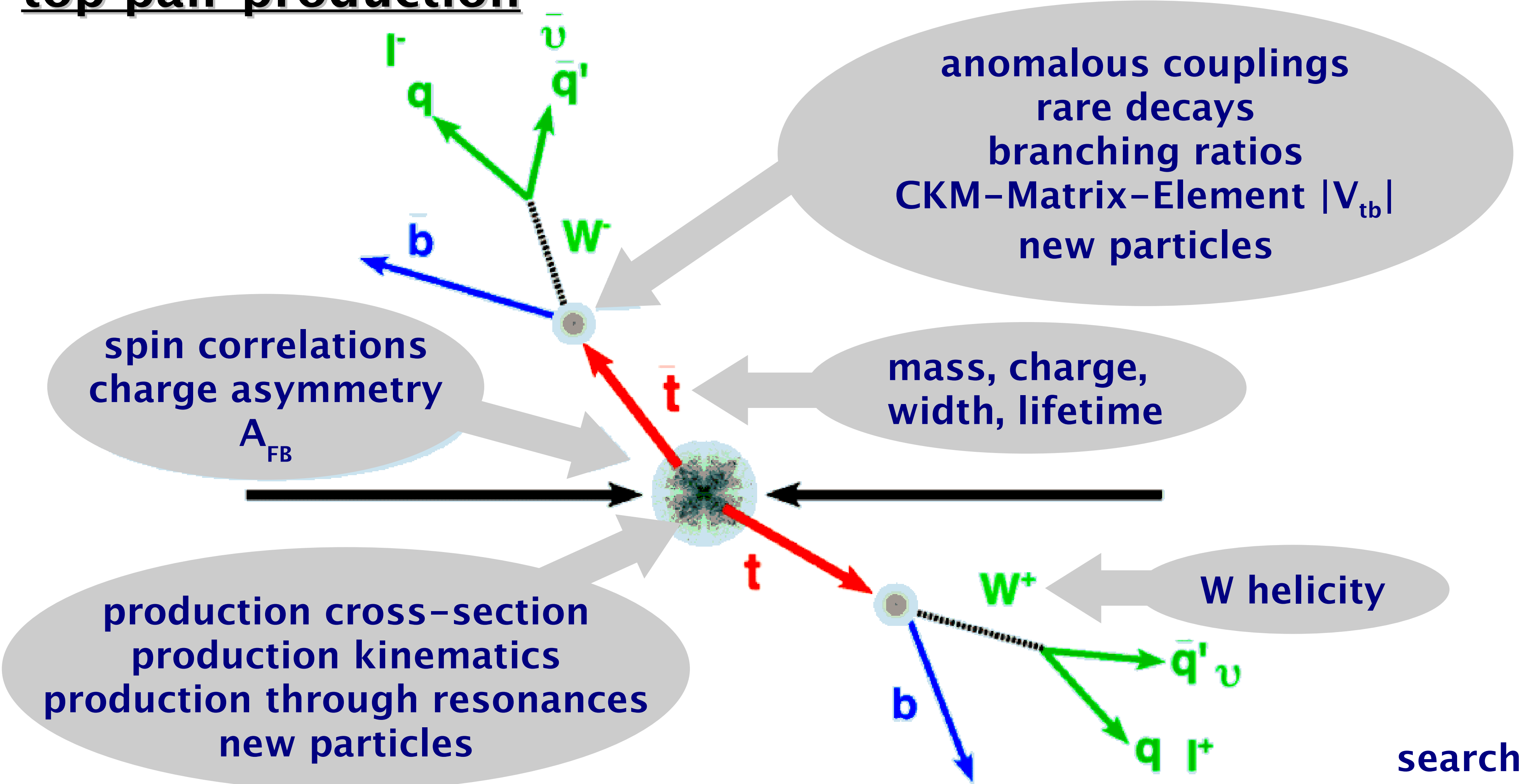
Top Quark Analyses at the Tevatron

analyses with up to 4 fb^{-1} of data:
several thousand top candidate events per experiment

top pair production



single top production

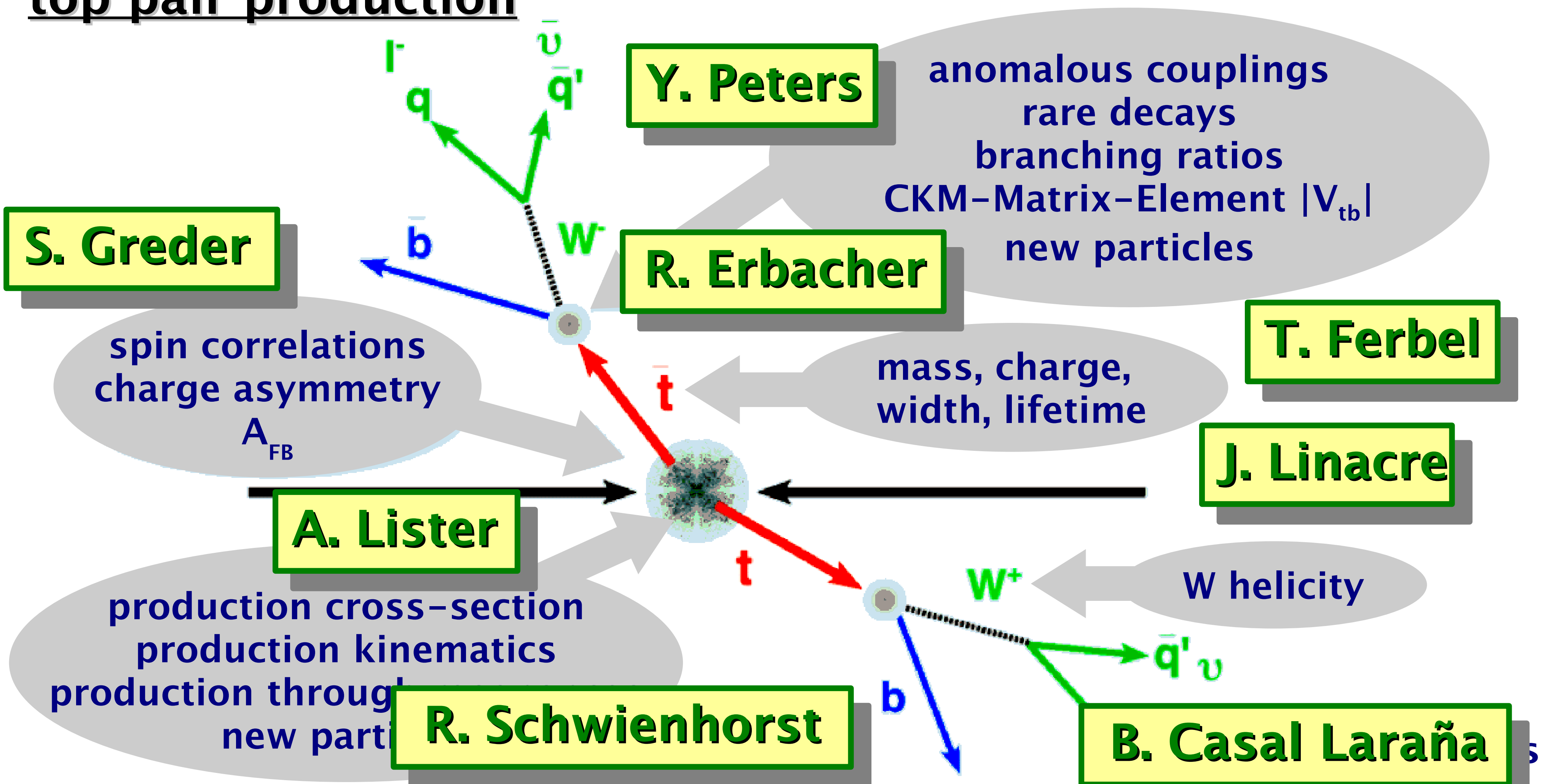
observation by CDF and DØ!

searches for new particles

Top Quark Analyses at the Tevatron

analyses with up to 4 fb^{-1} of data:
several thousand top candidate events per experiment

top pair production



single top production

observation by CDF and DØ!

particles

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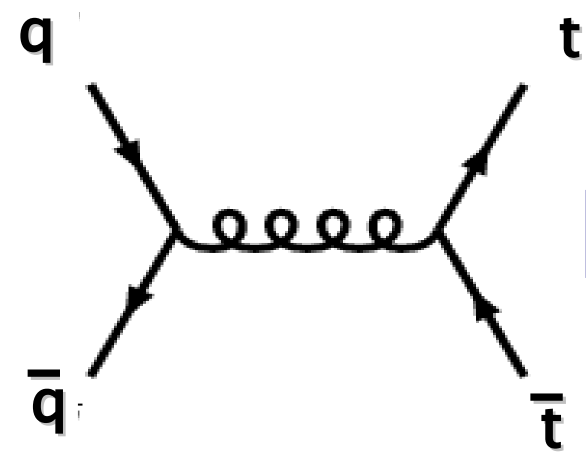
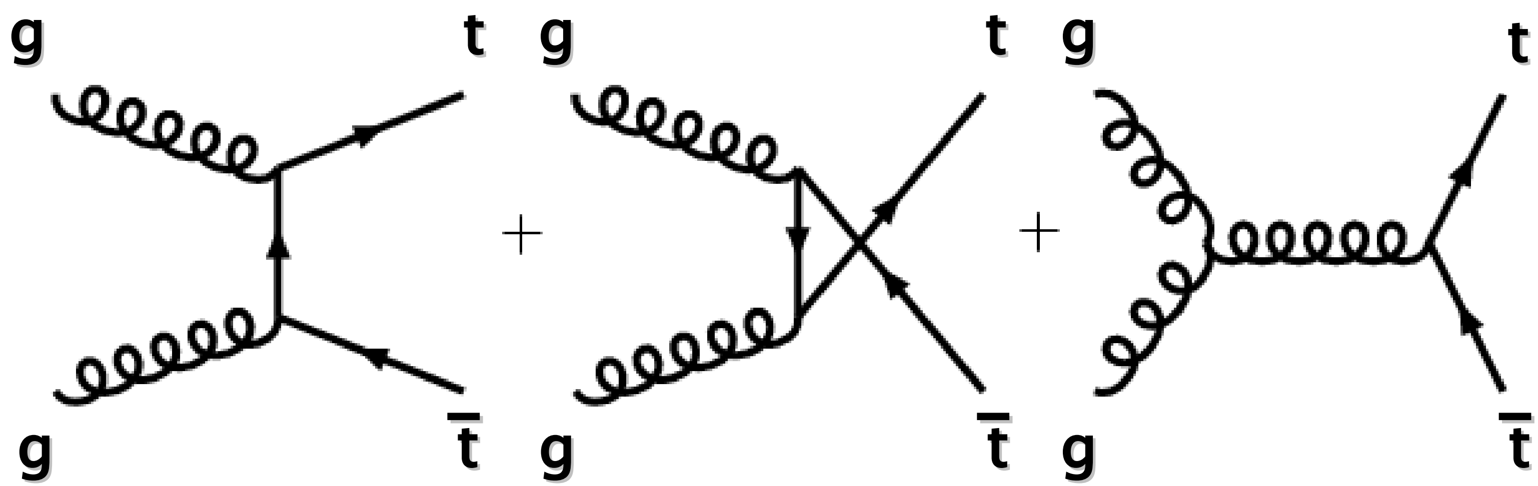
Top Quark Pair Production



85%



15%

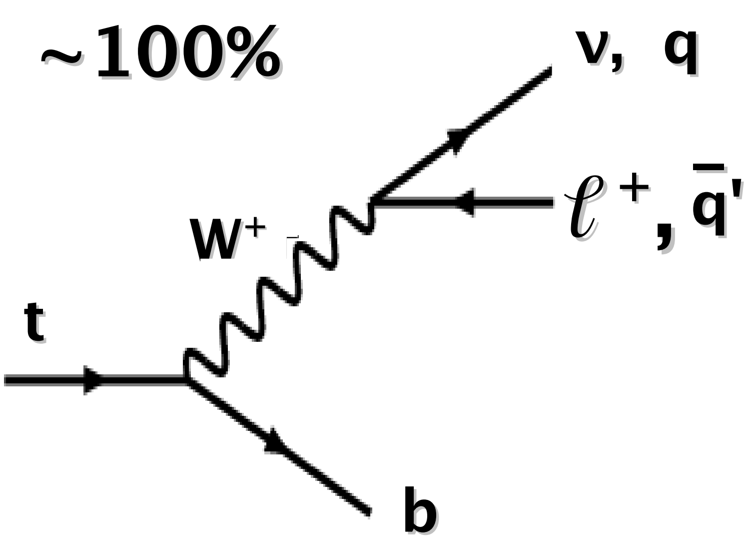
PRD 78, 034003 (2008)

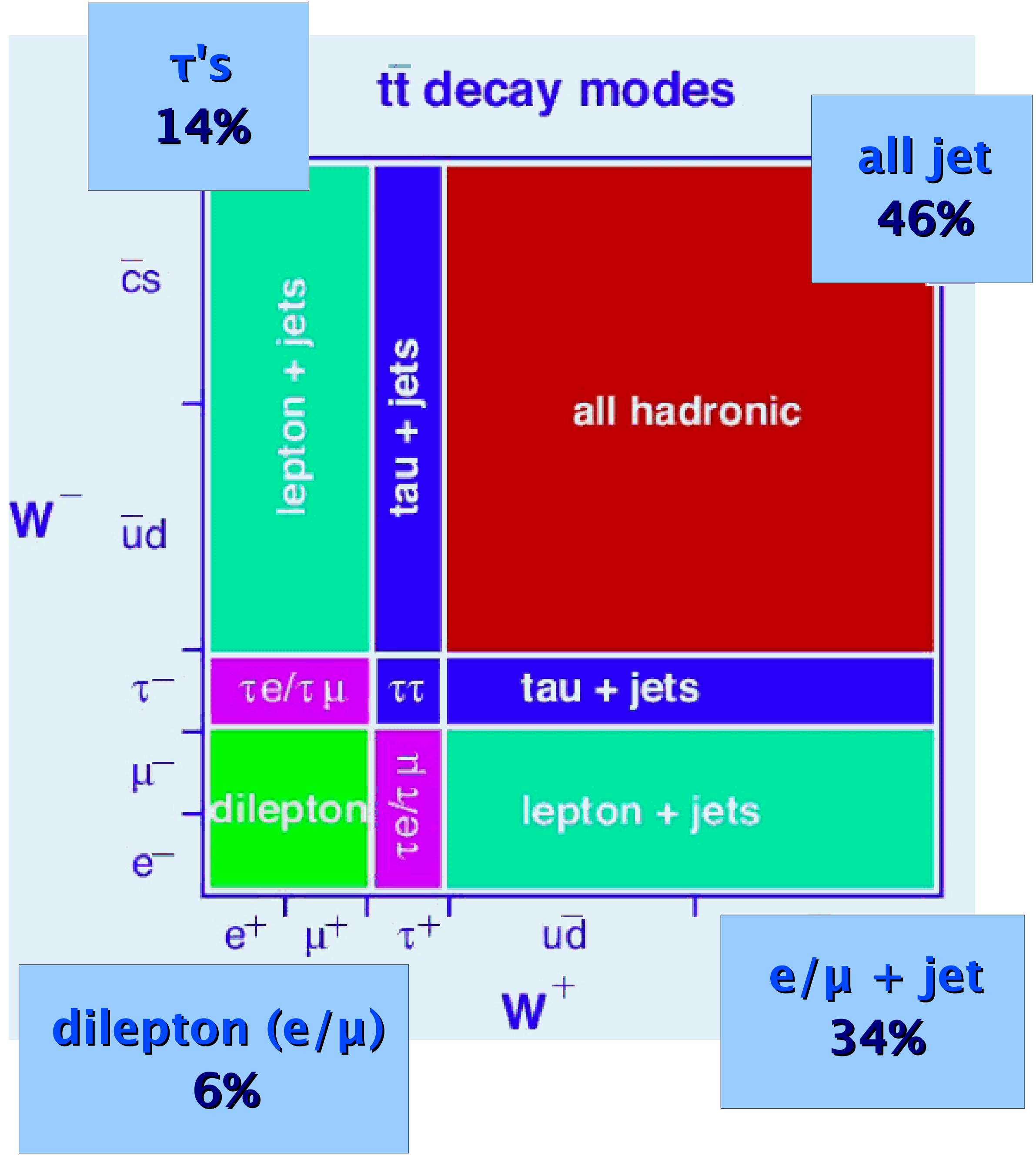
$\sigma_{t\bar{t}} = 7.46\,^{+0.48}_{-0.67}$ pb in $\text{NNLO}_{\text{approx}}$

(m_{top} = 172.5 GeV)

Top Pair Signatures

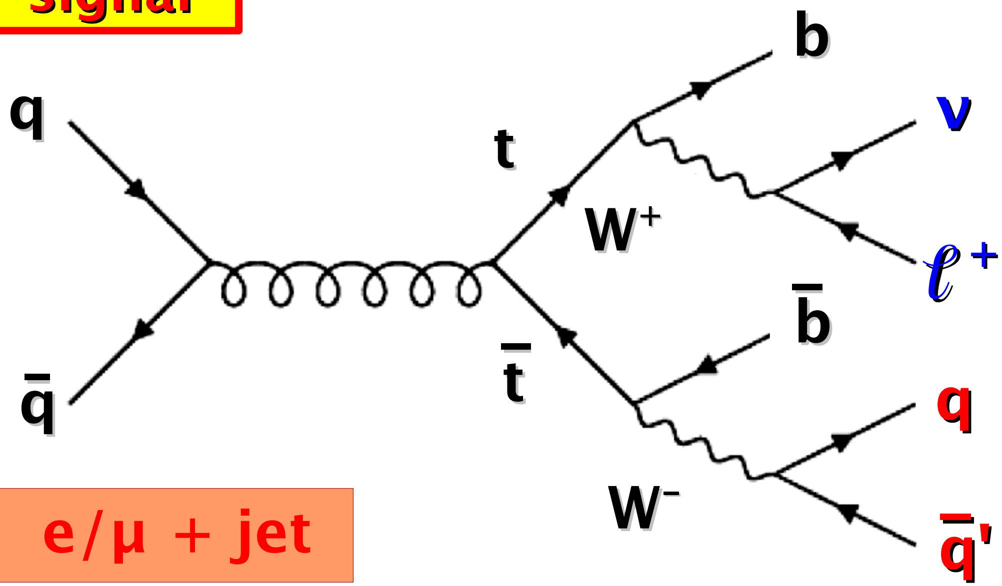
top decay:



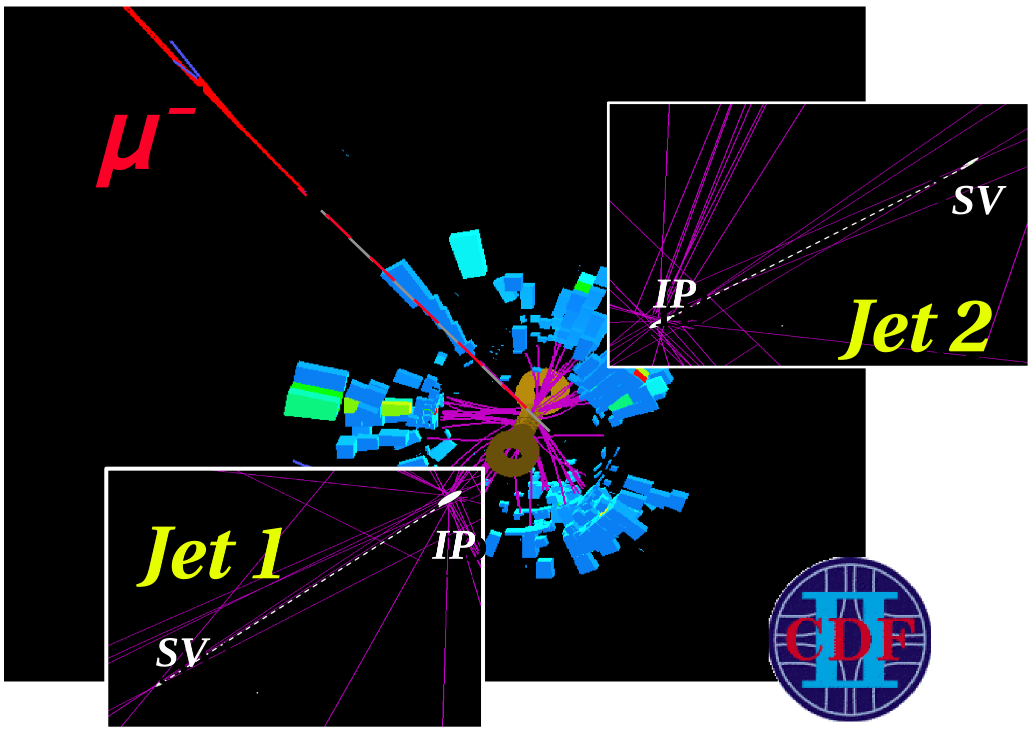


Lepton+jets Signatures

signal



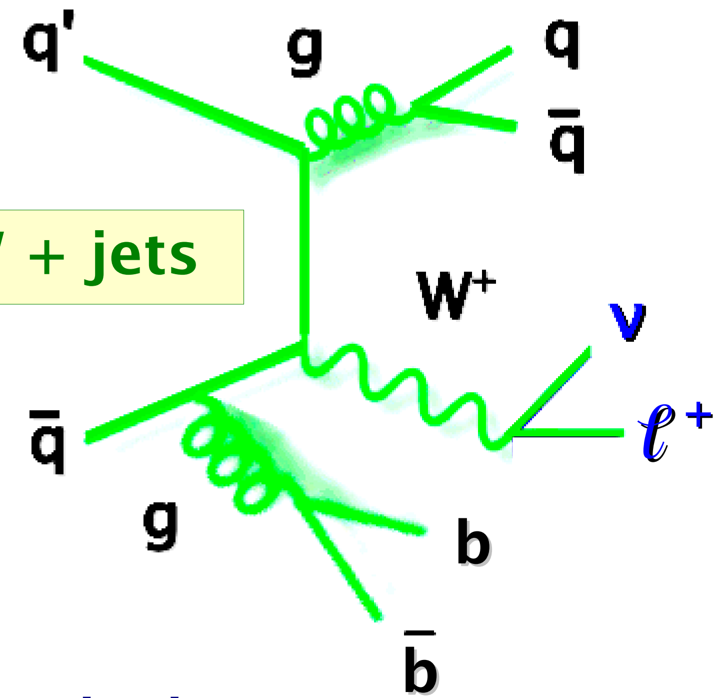
e/μ + jet



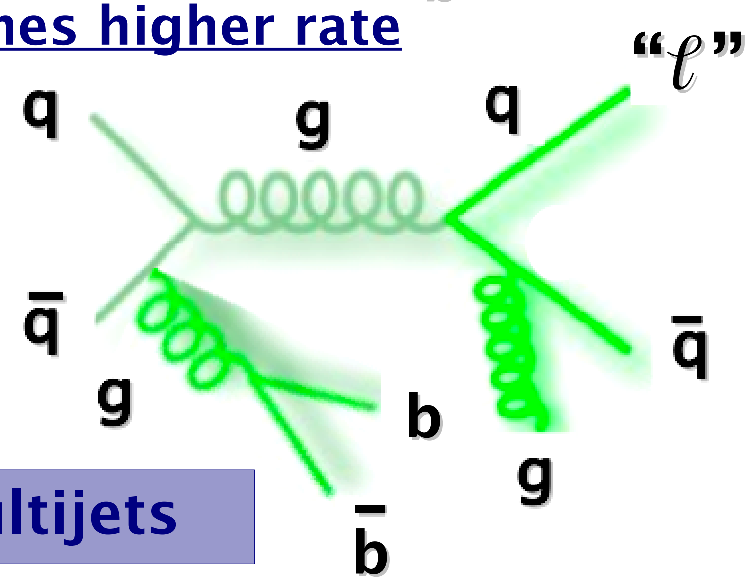
background

3000 times higher rate

W + jets



10^{10} times higher rate



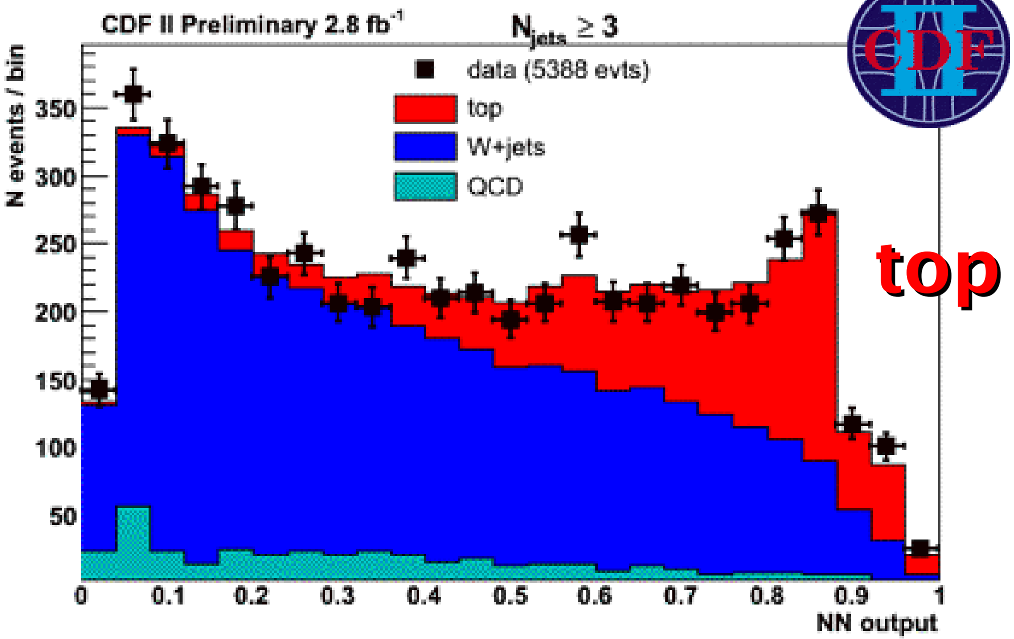
multijets

Top Pair Production Cross Section

measure if production rate is as predicted by NLO QCD

lepton+jets channel:

topological information (NN)



$t\bar{t}$/Z+jets cross section ratio

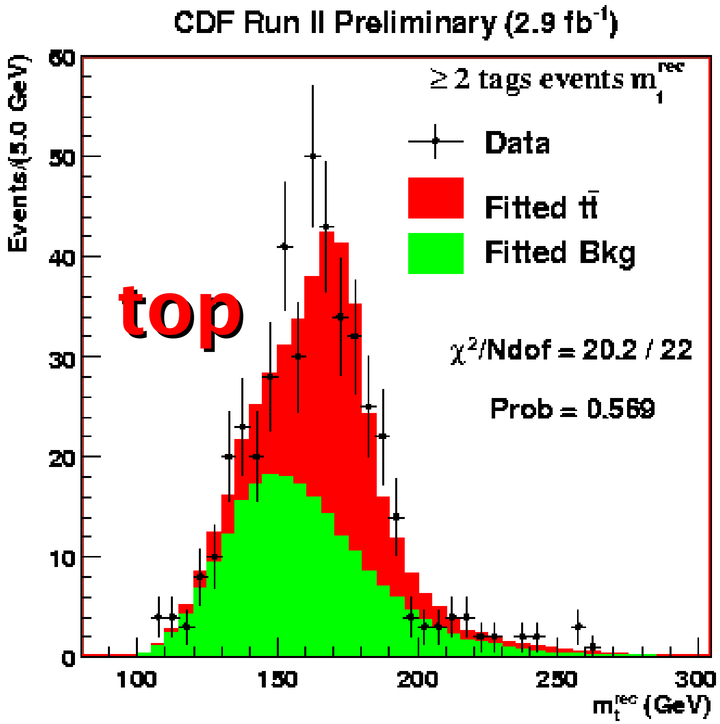
$\sigma_{t\bar{t}}$ =
6.9 ± 0.4 (stat) ± 0.4 (syst) ± 0.1 (Z theo) pb

m_{top} = 175 GeV

±8%

all hadronic channel:

b-tagging

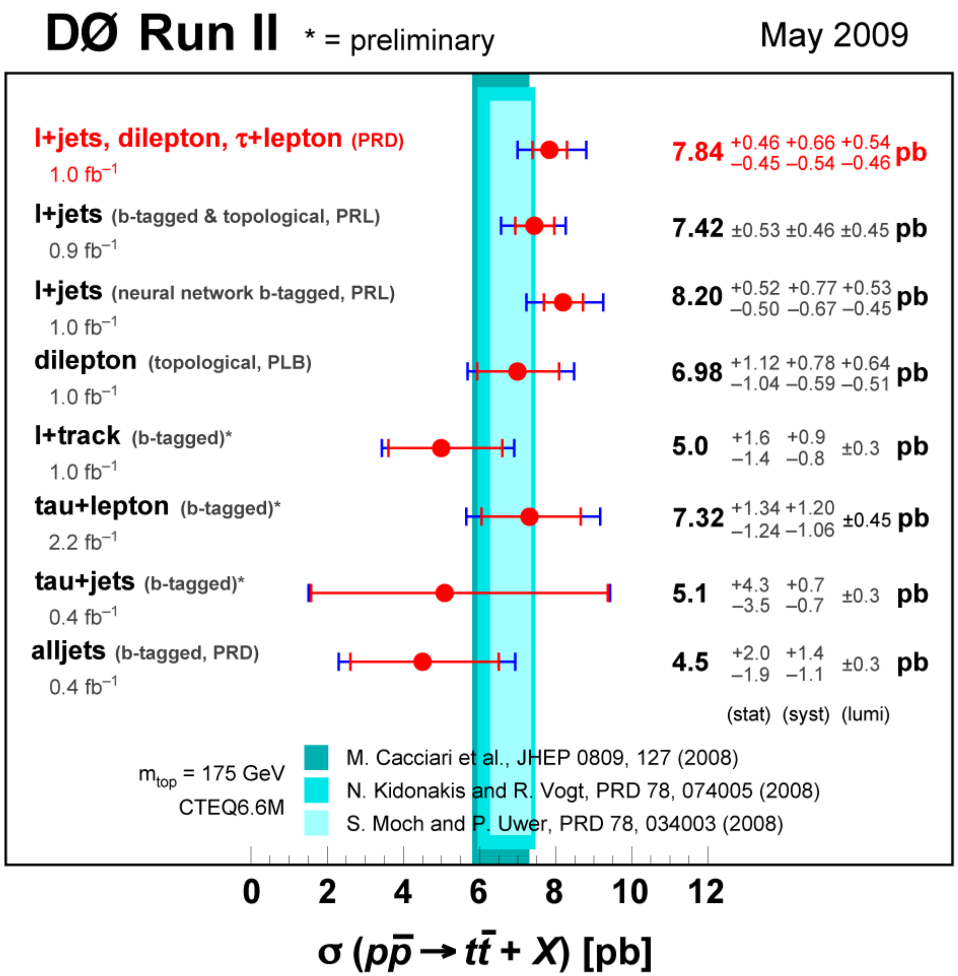


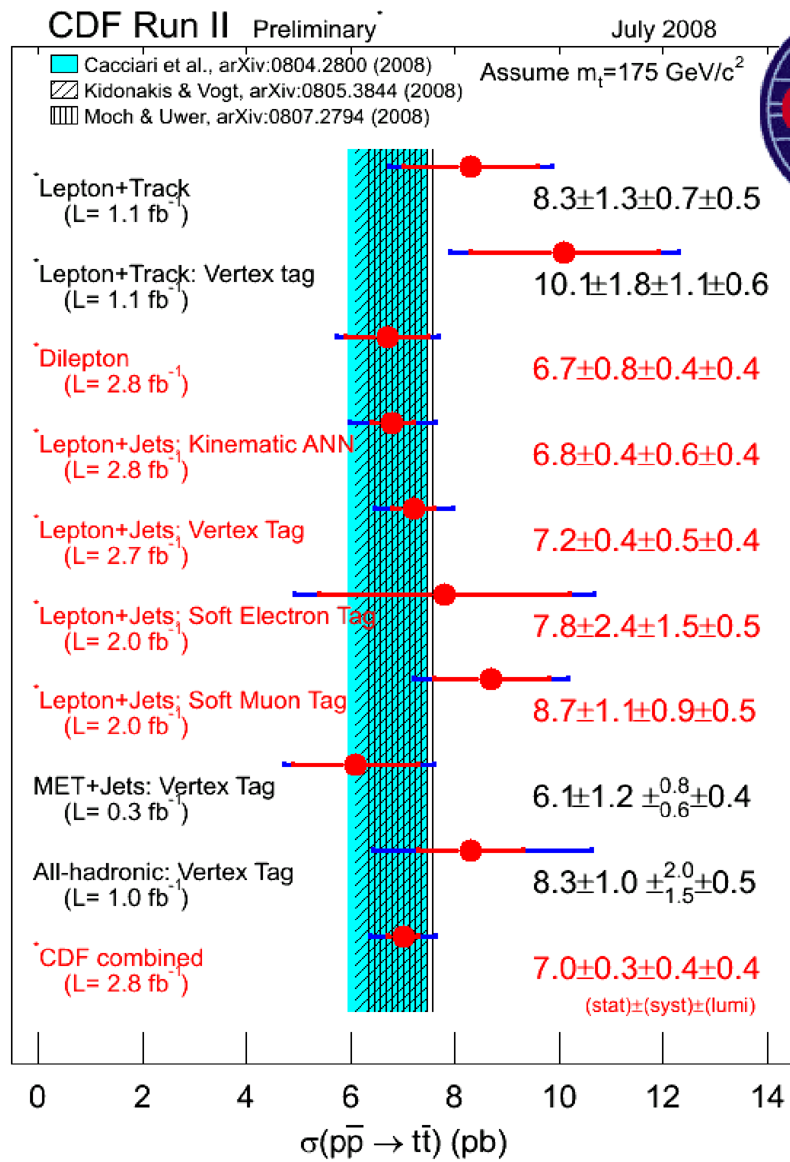
$\sigma_{t\bar{t}}$ =
7.2 ± 0.5 (stat) ± 1.4 (syst) ± 0.4 (lumi) pb

m_{top} = 172.5 GeV

±21%

Top Pair Production Cross Sections





⇒ **good agreement with SM in all channels**

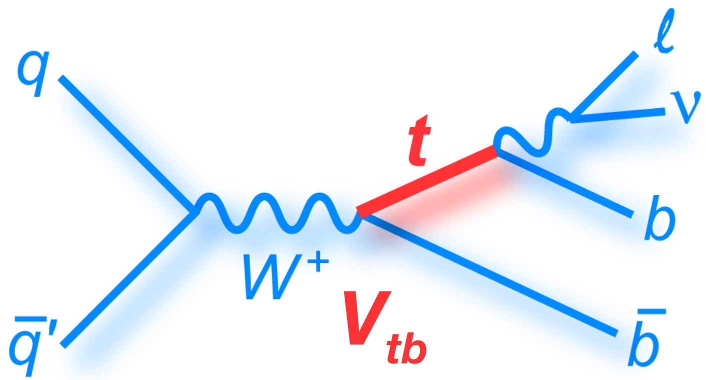
Single Top Quark Production

direct measurement of $|V_{tb}|$

PRD 74, 114012 (2006)

s-channel: $\sigma_{tb} = 1.04 \pm 0.04$ pb

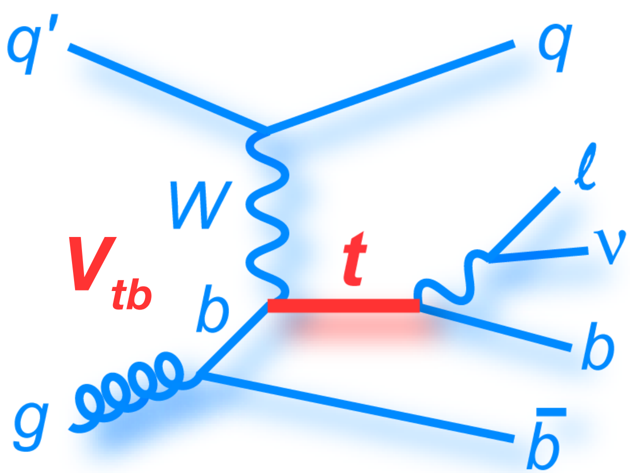
NNNLO$_{approx}$, m_{top} = 172.5 GeV



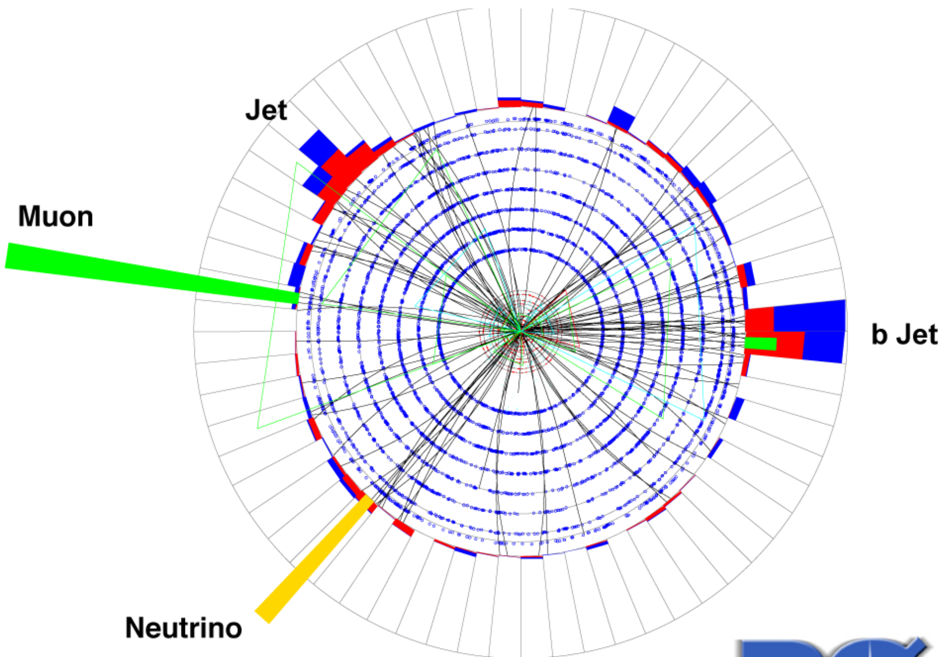
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

t-channel: $\sigma_{tb} = 2.26 \pm 0.12$ pb

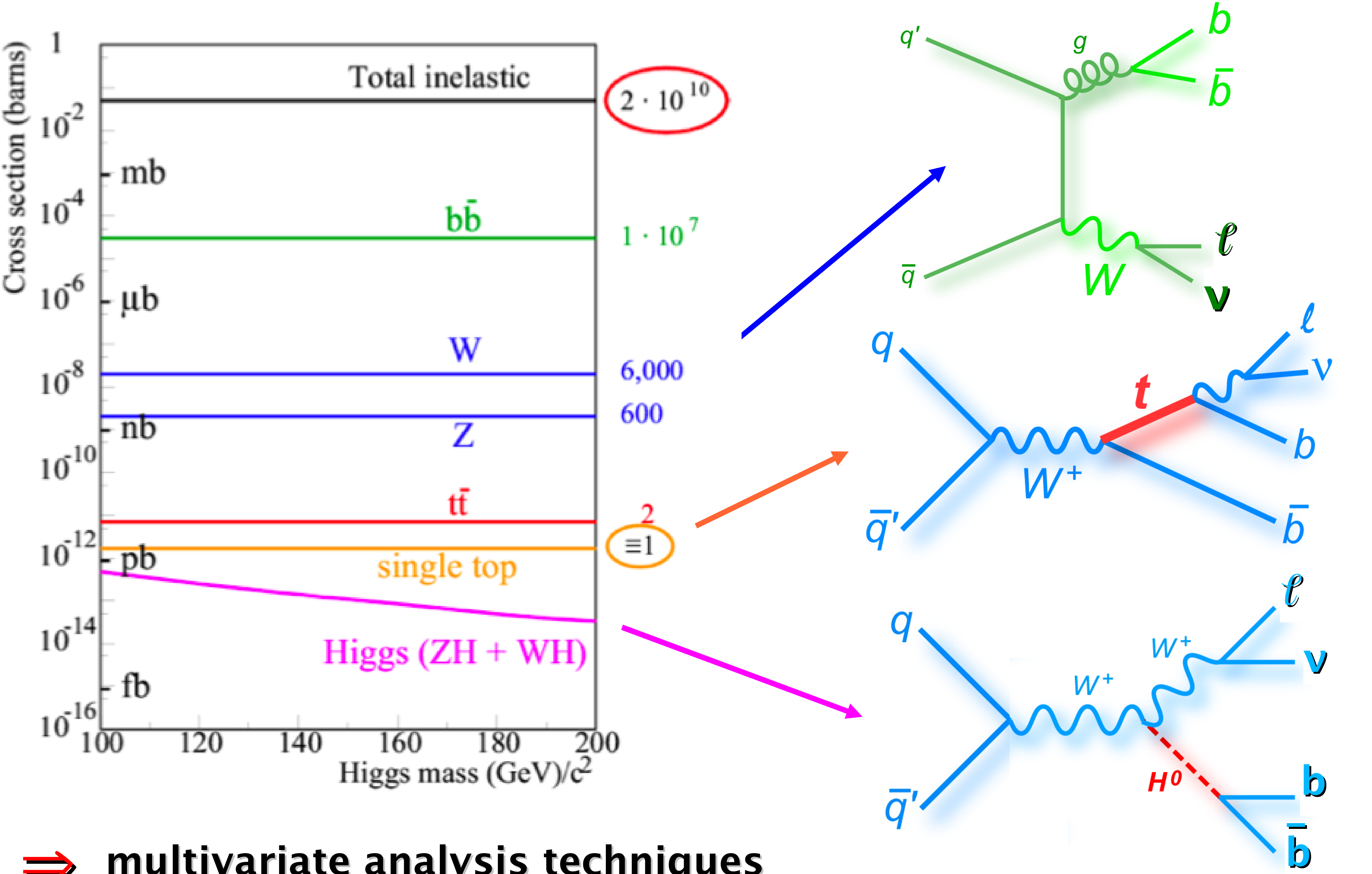
NNNLO$_{approx}$, m_{top} = 172.5 GeV



- jets
- lepton
- missing E_T
- b-jets



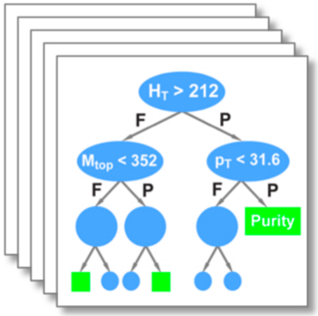
It has been challenging for years...

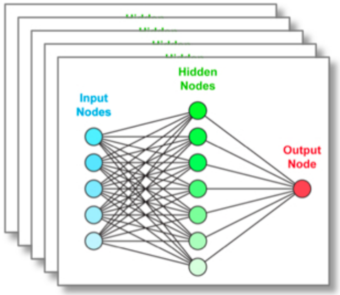


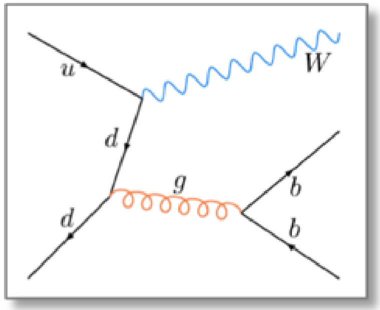
⇒ **multivariate analysis techniques**

Multivariate Analyses

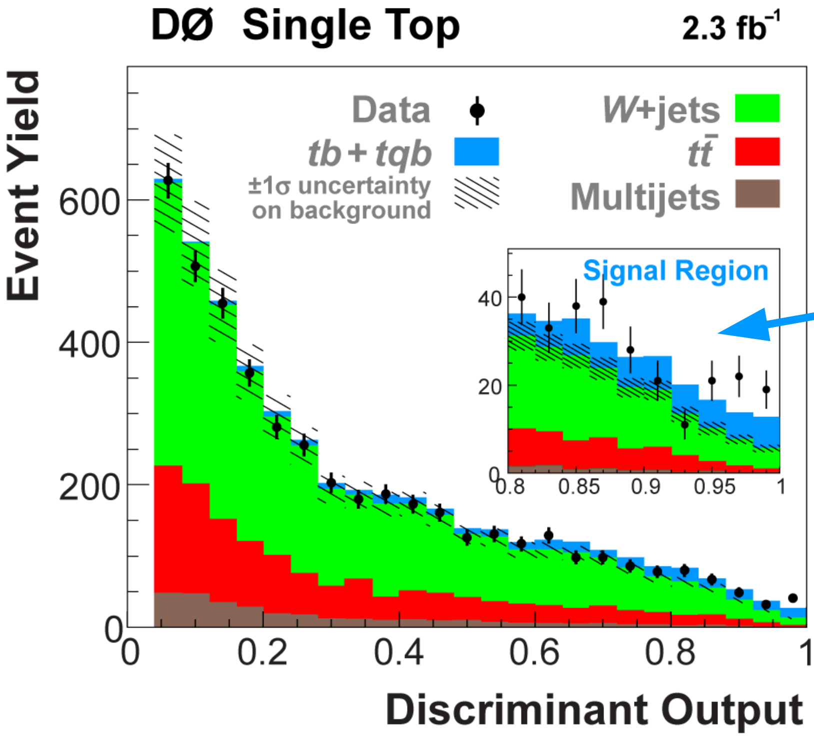
Boosted Decision Trees	Boosted Neural Networks	Matrix Elements







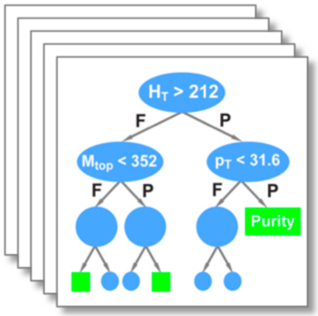
combine up to 12 different analysis channels:

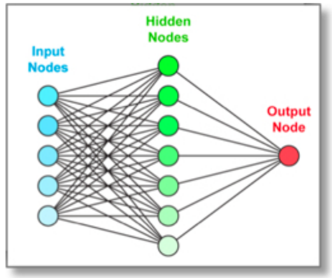


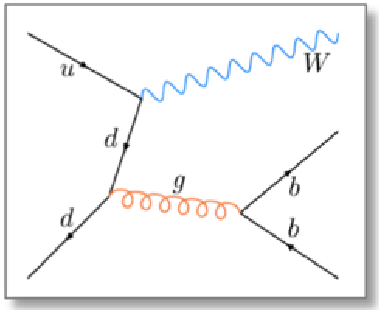
single top

Multivariate Analyses

Boosted Decision Trees	Neural Networks	Matrix Elements	Likelihood







$$p_{ik} = \frac{f_{ijk}}{\sum_{m=1}^{5} f_{ijm}},$$

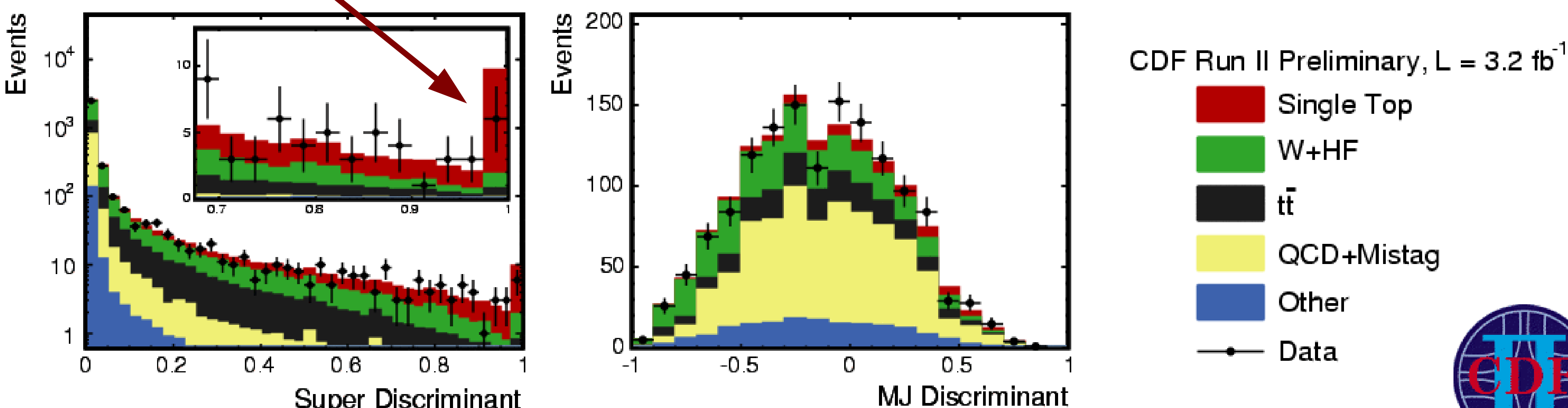
$$\mathcal{L}_k(\{x_i\}) = \frac{\prod_{i=1}^{n_{var}} p_{ik}}{\sum_{m=1}^{5} \prod_{i=1}^{n_{var}} p_{ik}}.$$

combine up to 8 different analysis channels:

single top

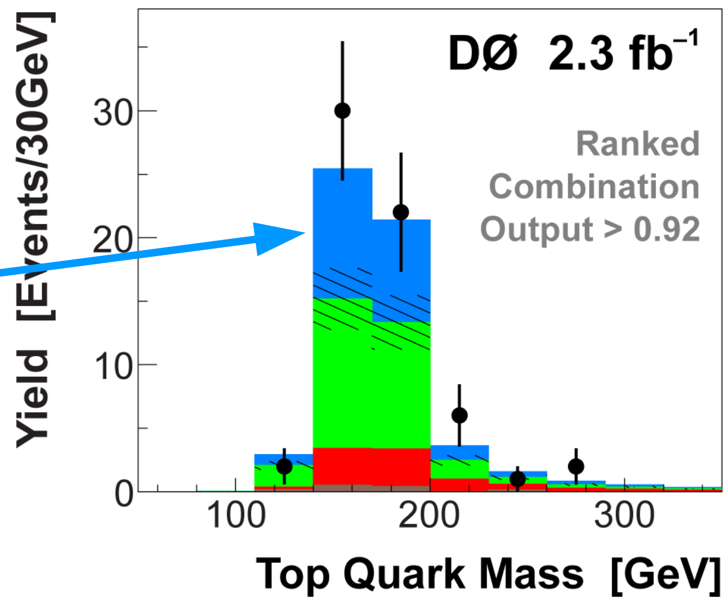
- $\not{E}_T$+jets selection :

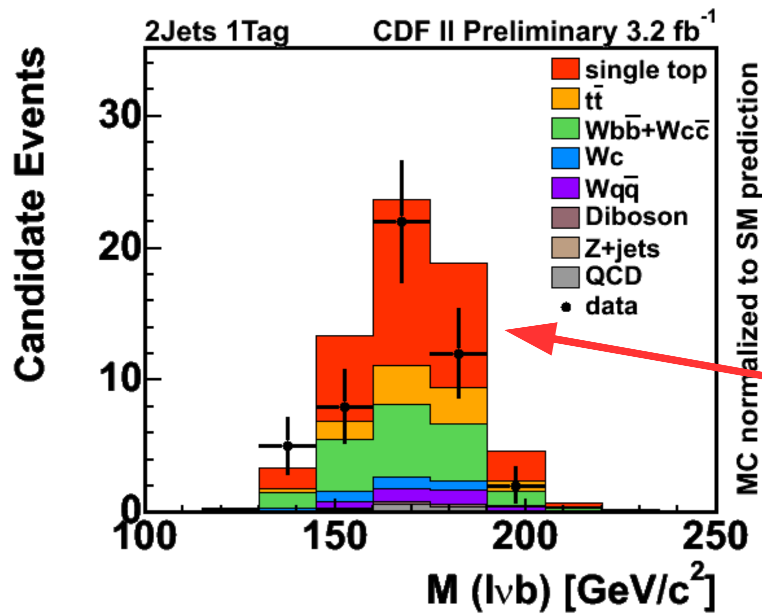
  recover badly reconstructed e, μ; include τ



Single Top Observation

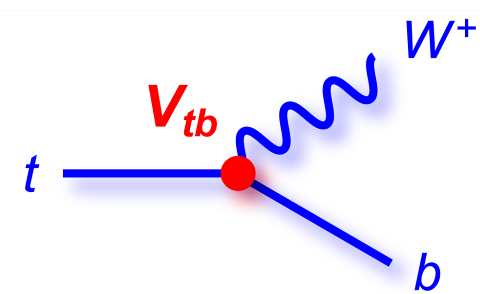
single top





single top

Single Top Cross Section	Signal Significance	
	Expected	Observed
DØ 2.3 fb^{-1} arXiv:0903.0850 m_{top} = 170 GeV		
3.94 ± 0.88 pb	4.5 σ	5.0 σ
CDF 3.2 fb^{-1} arXiv:0903.0885 m_{top} = 175 GeV		
2.3 $^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ



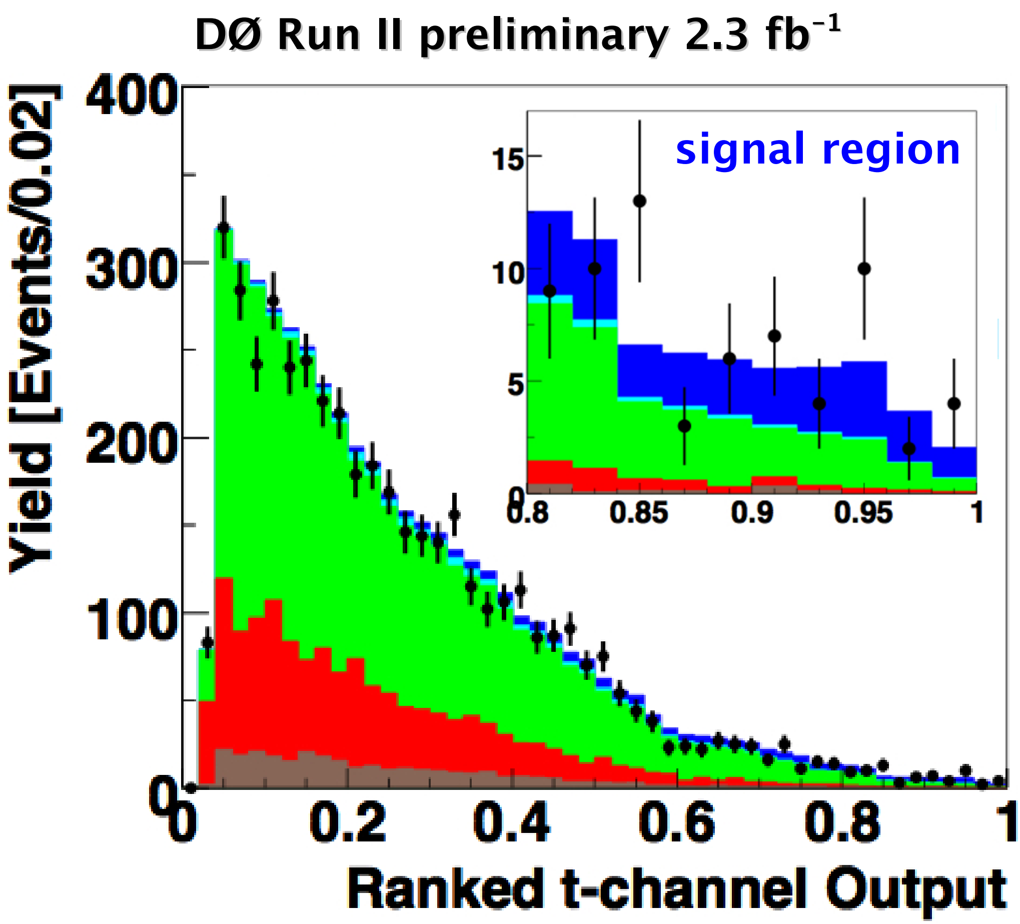
$|V_{tb}| = 1.07 \pm 0.12$

$|V_{tb}| = 0.91 \pm 0.13$

⇒ observation with 5.0σ!

First Evidence for t-Channel Production

- **remove s/t channel constraint which could be changed by**
  - additional quark generation
  - new heavy bosons
  - FCNC
  - anomalous top quark couplings



- **train multivariate analysis for t-channel**
- **measure t-channel and s-channel simultaneously**

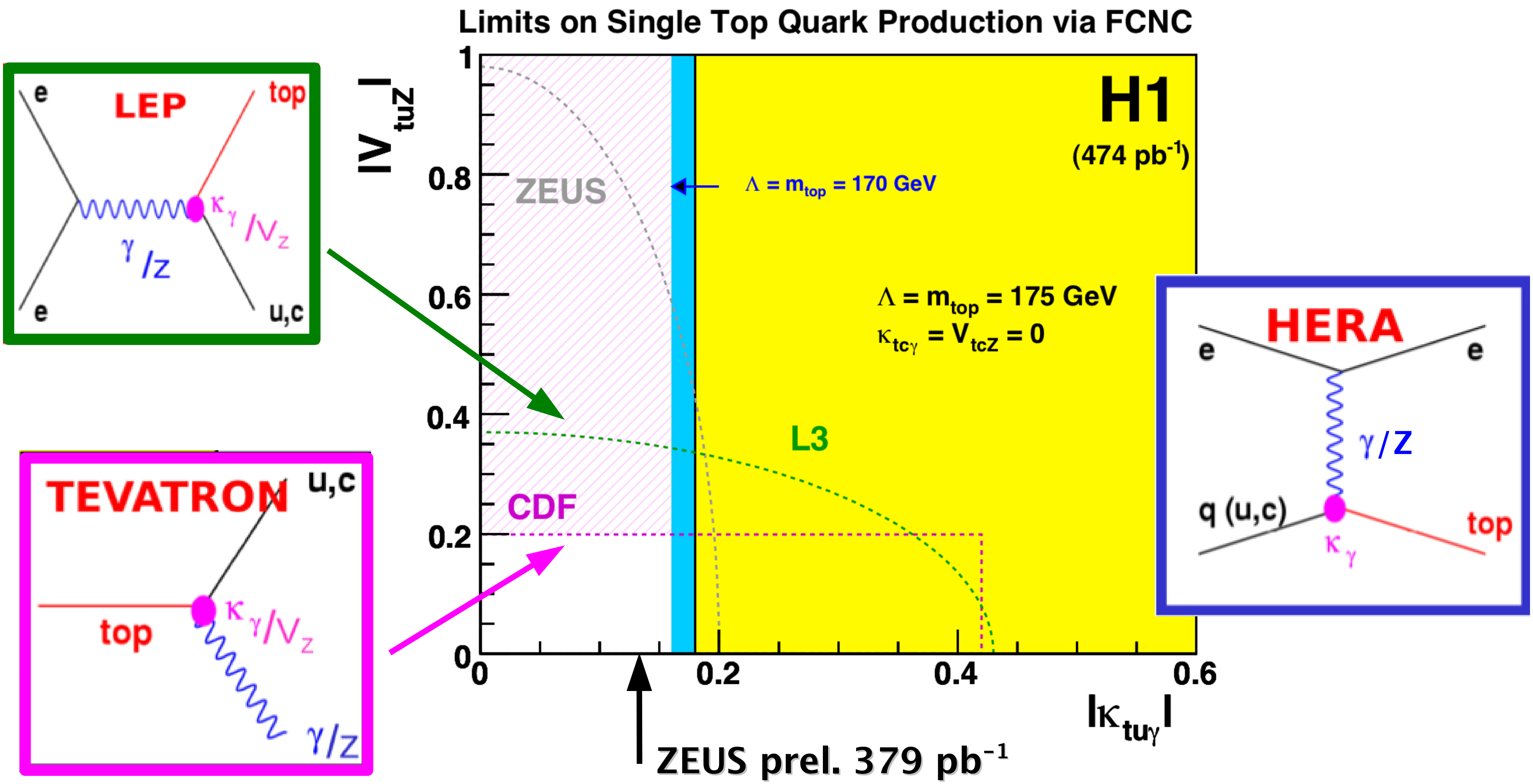
$$\sigma(\text{t-channel}) = 3.14^{+0.94}_{-0.81}\ \text{pb}$$

evidence with 4.8σ

Single Top Production at HERA

- not possible in SM, but via flavour changing neutral currents
- results complementary to LEP and Tevatron
- full data set analysed

L. Bellagamba



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top physics at the Tevatron

top production cross sections

top properties

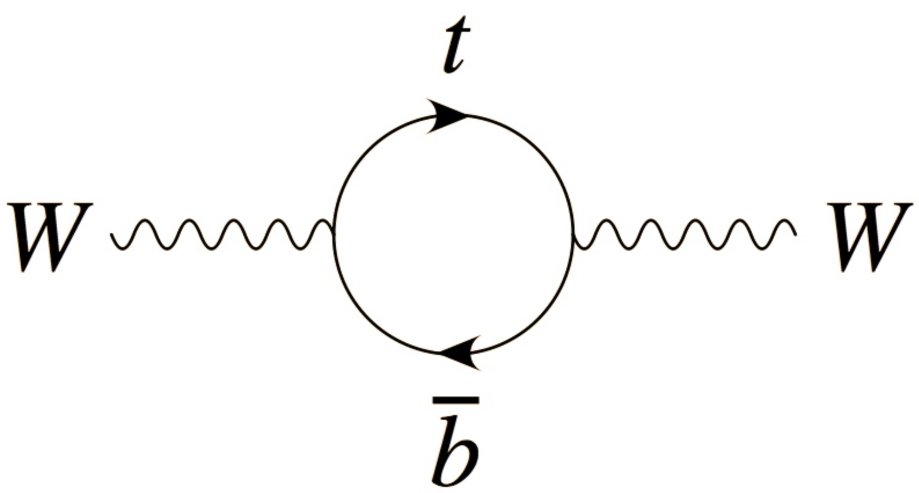
searches in production and decay

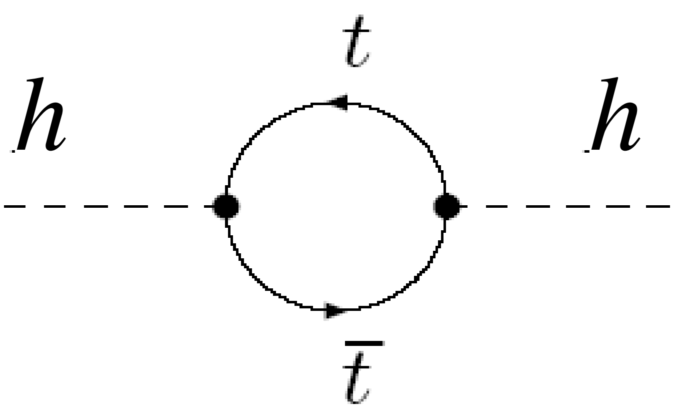
prospects at the LHC

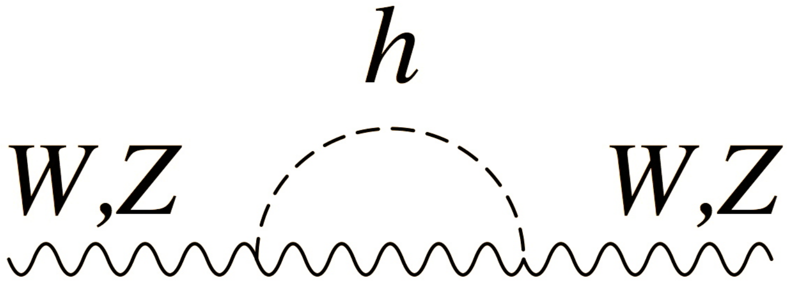
conclusions

The Top Quark Mass

- free parameter in the Standard Model
- check the **self-consistency of the Standard Model** in combination with W mass measurement
- prediction on **Higgs mass**





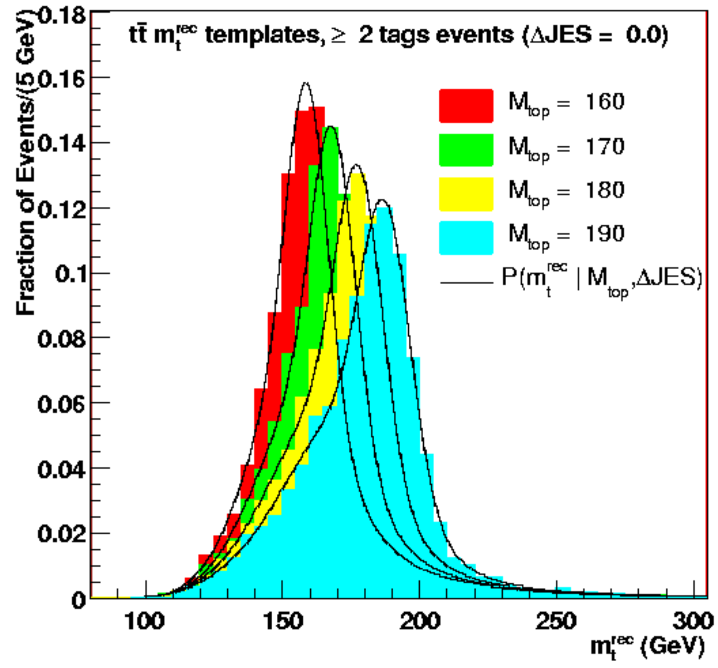


Extraction Techniques

template method:

- reconstruct m_{top}
- compare data to MC with different m_{top} hypotheses

all hadronic



matrix element method:

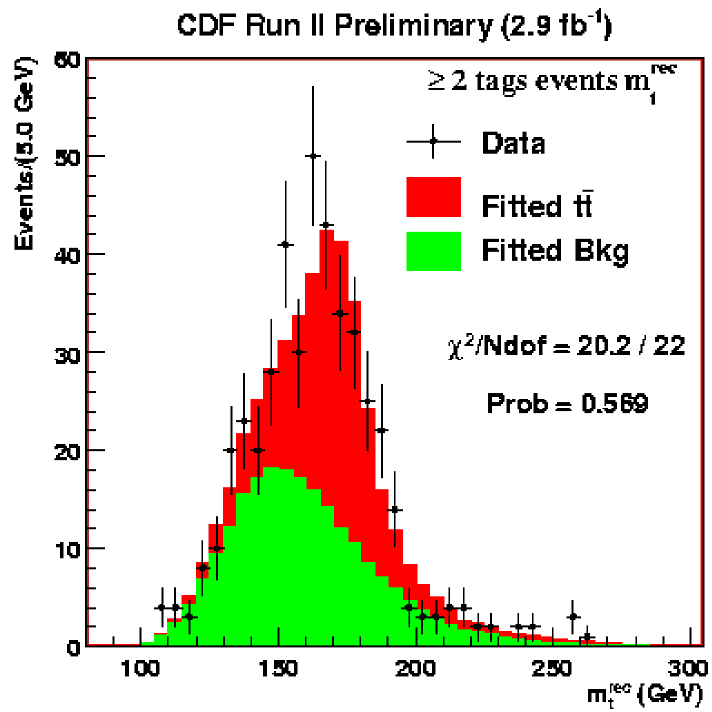
- probability densities for every event as function of m_{top}

$$P_{sig}(x;m_{top},JES)=\underbrace{Acc(x)}_{\text{Acceptance (selection, trigger,...)}}\times\frac{1}{\sigma}\int d^n\underbrace{\sigma(y;m_{top})}_{\text{LO-Matrix element x phase space}}\,\underbrace{dq_1\,dq_2\,f(q_1)\,f(q_2)}_{\text{PDF's}}\,\underbrace{W(x,y;JES)}_{\text{Transfer Functions (Probability to measure x when y was produced)}}$$

Extraction Techniques

template method:

- use variables strongly correlated with m_{top}
- compare data to MC with different m_{top} hypotheses



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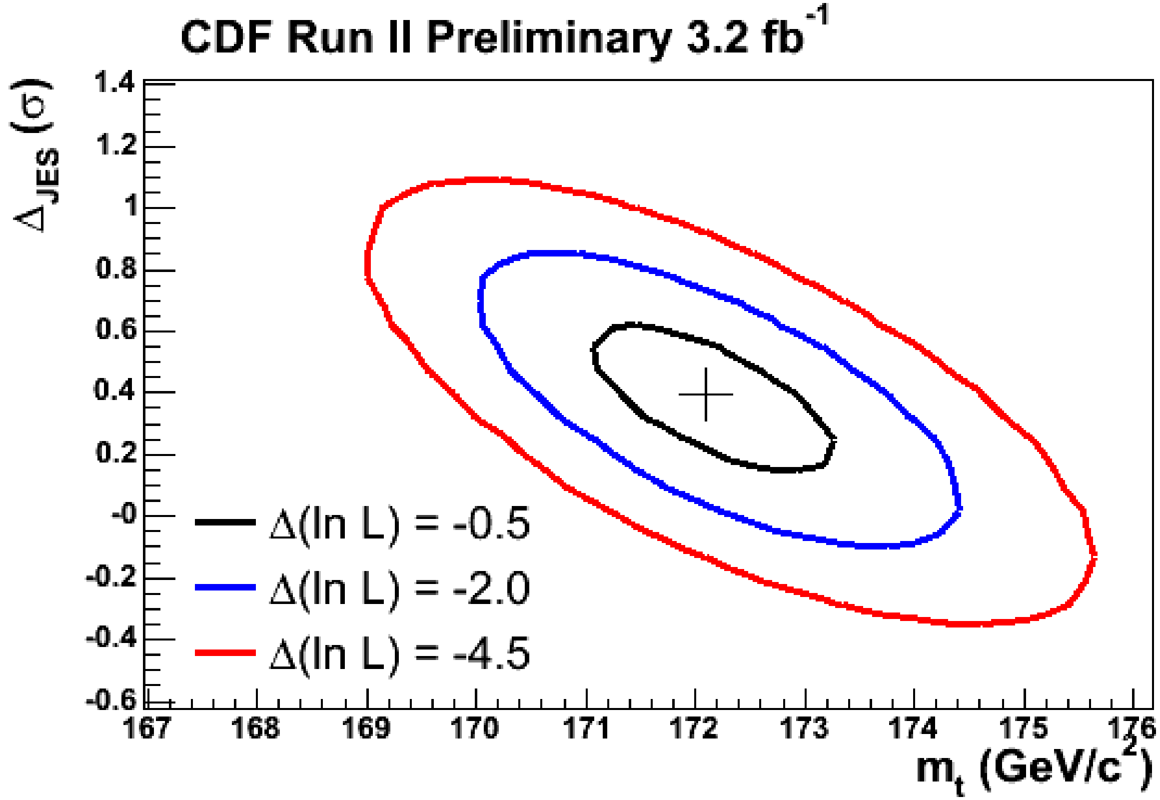
Results in l+jets Channel

maximum Likelihood fit to data:

jet energy scale:

translate jet into parton energy



m_{top} = 173.7 ± 0.8 (stat) ± 1.6 (syst) GeV

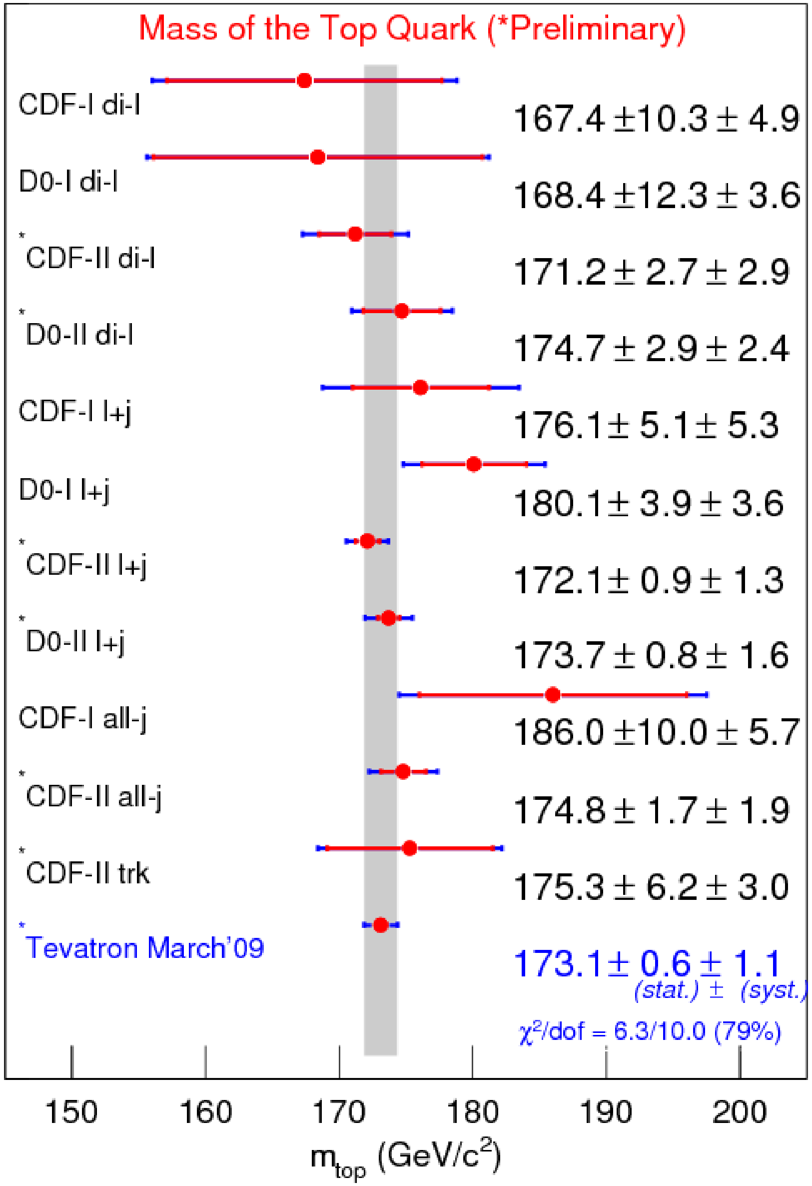
3.6 fb^{-1} **±1.0%**

m_{top} = 172.1 ± 0.9 (stat) ± 1.3 (syst) GeV

3.2 fb^{-1} **±0.9%**

Tevatron Combination: March 2009

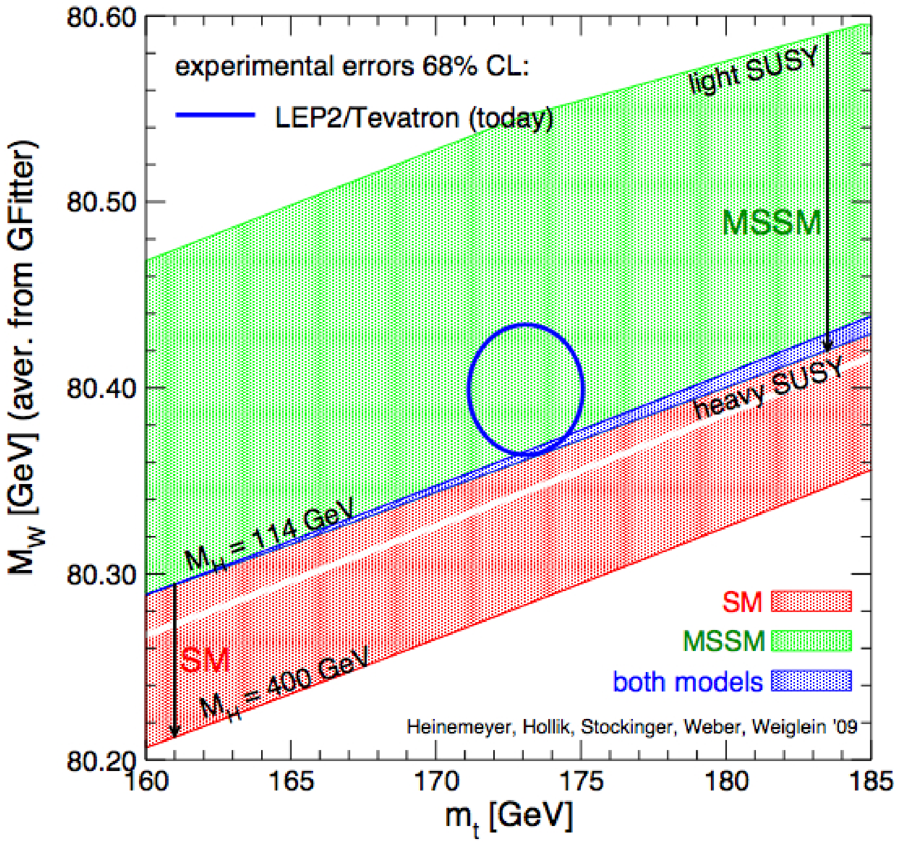
arXiv:0903.2503



$m_{top} = 173.1 \pm 1.3$ GeV

±0.75%

Heinemeyer et al.

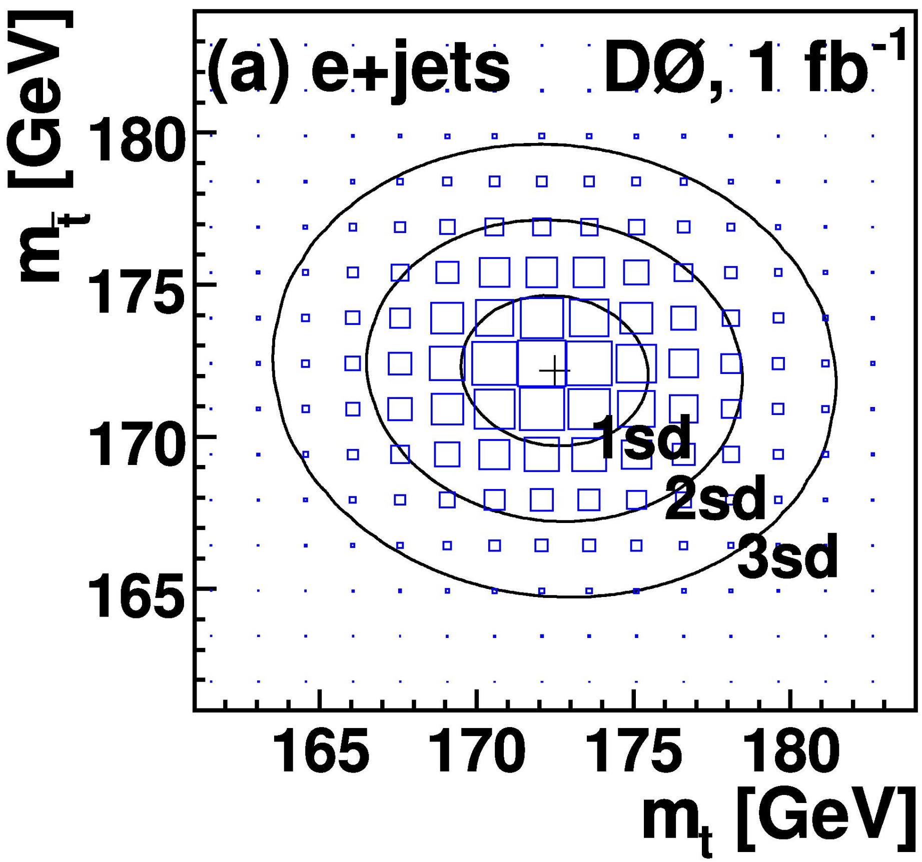


theory & experiment: uniform treatment of systematics

t–$\bar{t}$ Mass Difference

arXiv:0906.1172

mass difference would imply CPT–violation



- l+jets channel
- use matrix element method
- modified MC to allow for different top and anti–top masses

e, μ+jets

$$\boxed{m_t - m_{\bar{t}} = 3.8 \pm 3.7 \text{ GeV}}$$

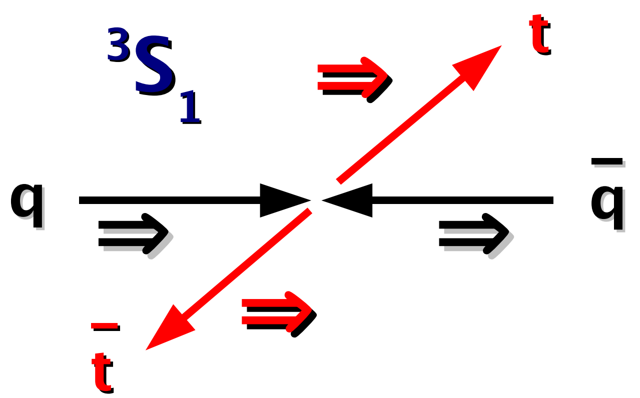
statistics dominated

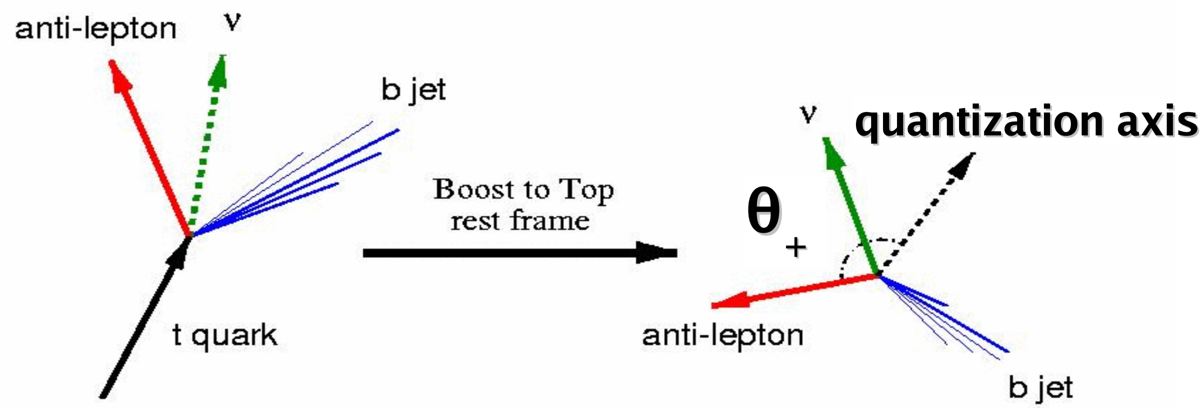
⇒ agreement with SM

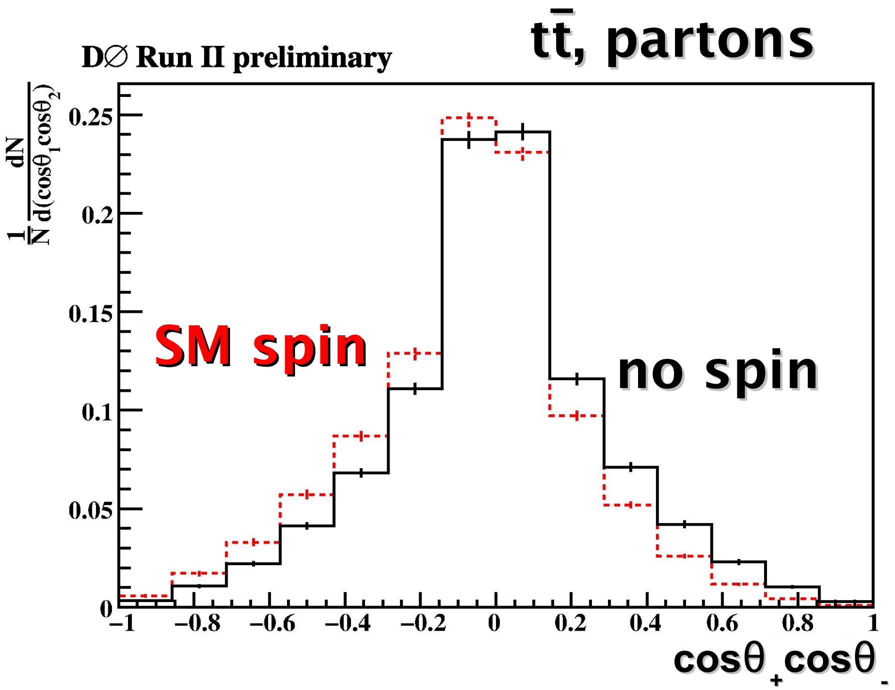
⇒ measured for the first time for 'bare' quarks

Spin Correlation in Dilepton Channel

spins correlated only if top lifetime is short enough







Spin Correlation in Dilepton Channel

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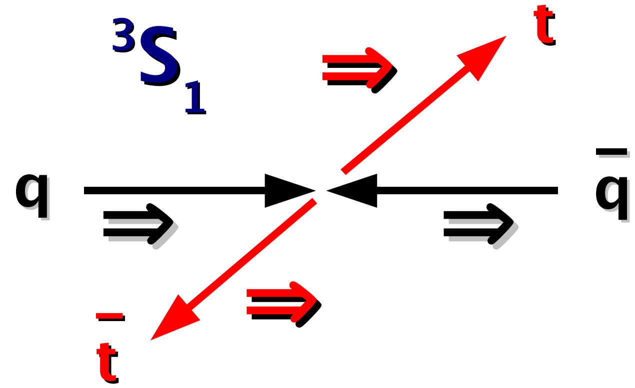
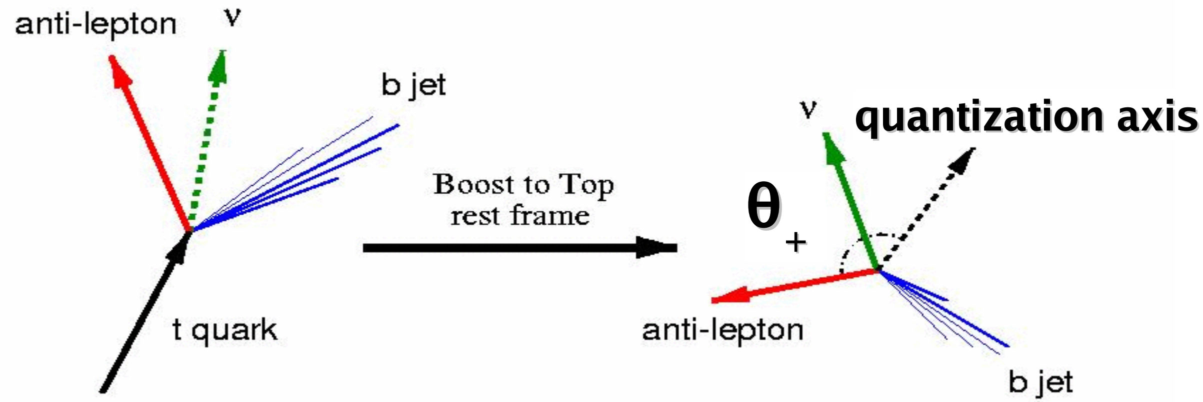
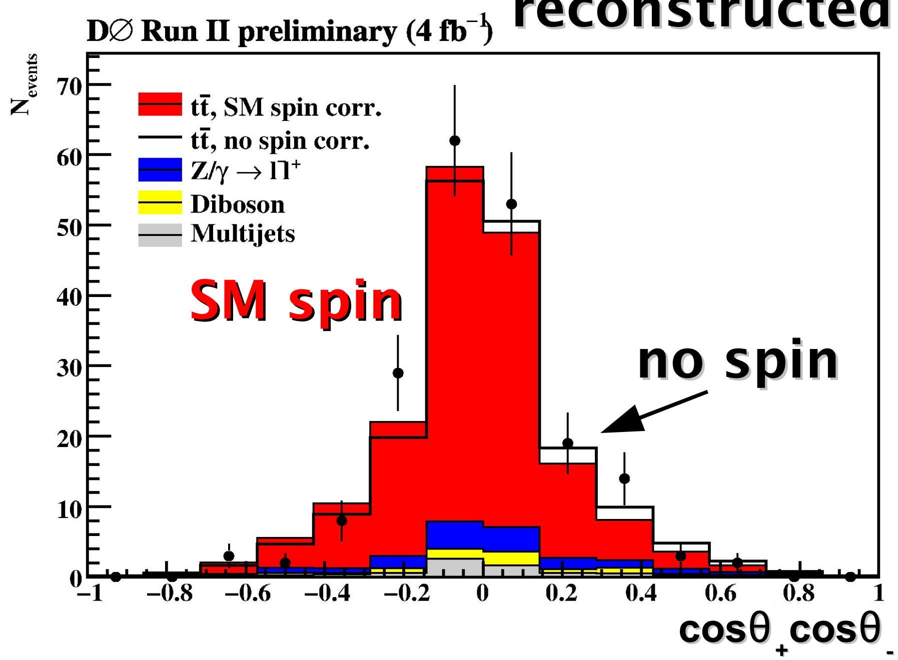




reconstructed



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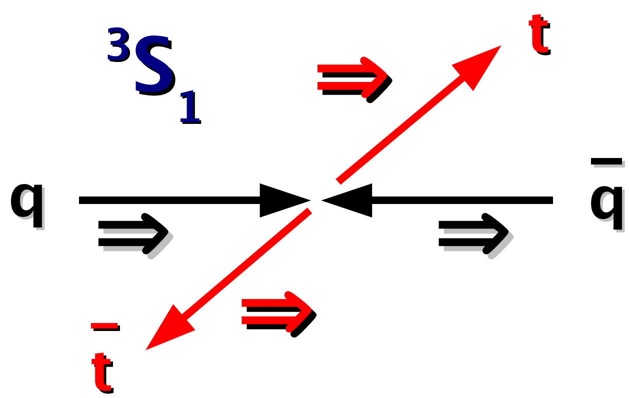
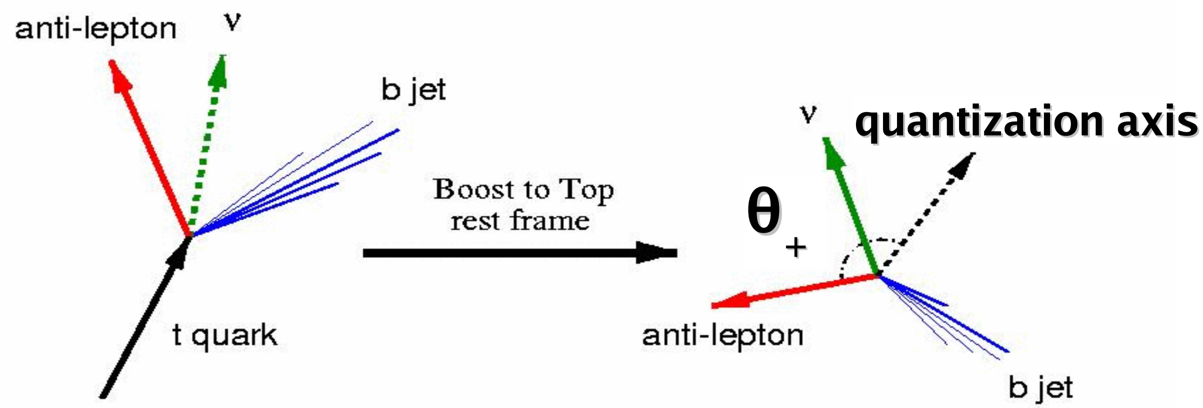
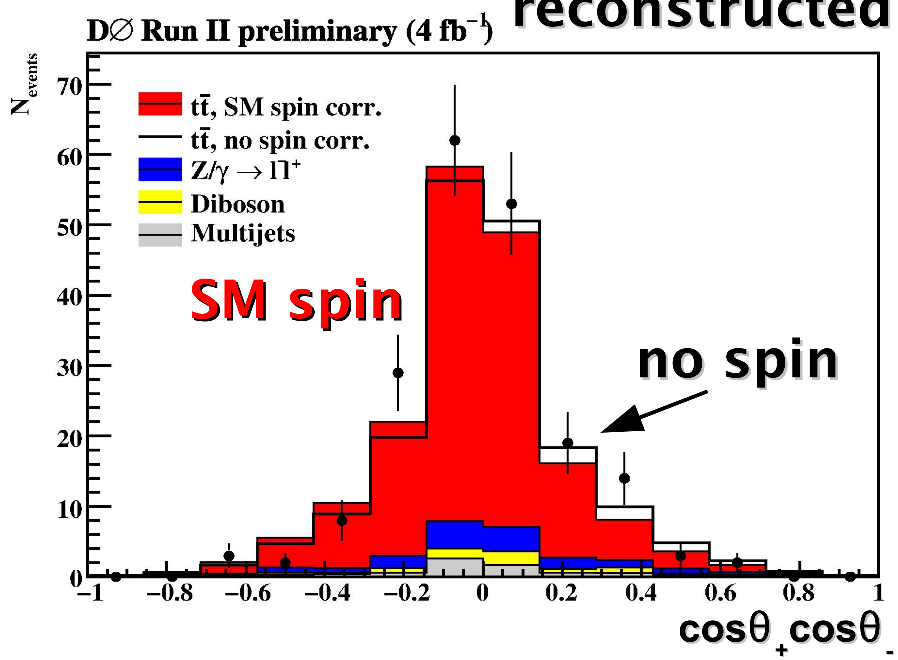




reconstructed



$$\kappa = \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}$$

NLO QCD: $\kappa \approx 0.78$

Nucl.Phys.B690, 81 (2004)

DØ: $\kappa = -0.17^{+0.64}_{-0.53}$

- beam axis
- 4.2 fb^{-1}

CDF: $\kappa = 0.32^{+0.55}_{-0.78}$

- off diag. axis
- 2.8 fb^{-1}
- $\cos\theta_b$

⇒ first results in Run-II, agreement with SM within 1σ (CDF), 2σ (DØ)

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top physics at the Tevatron

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top properties

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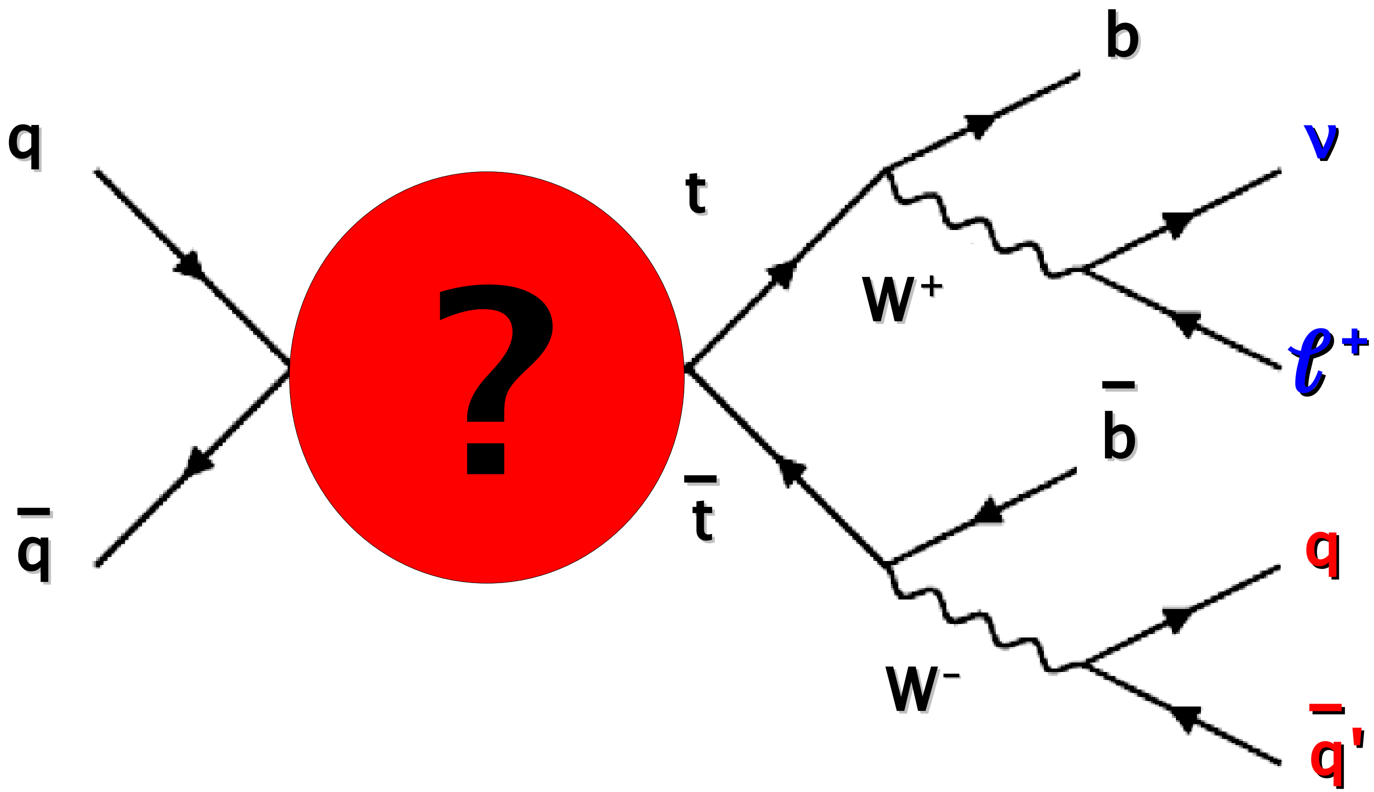
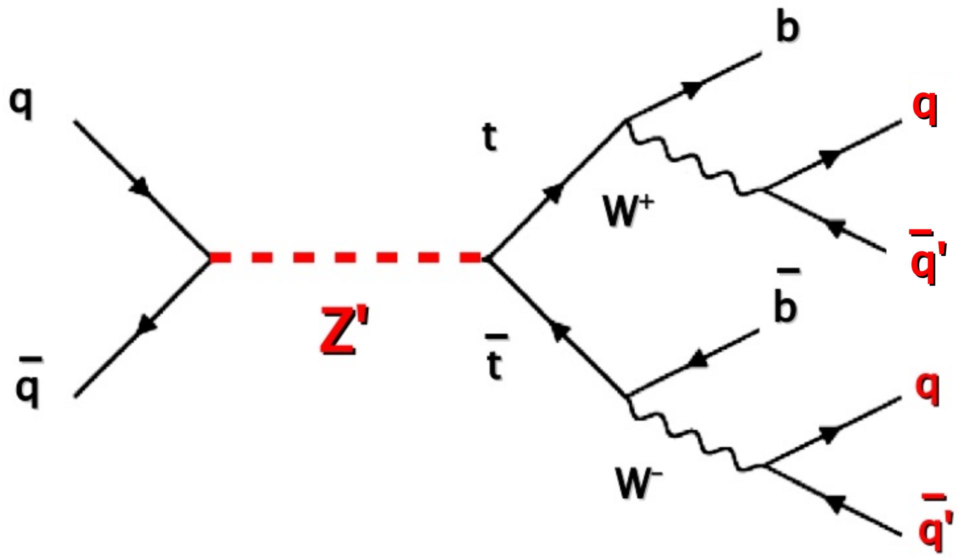
Search for New Physics in Top Production



Search for $t\bar{t}$ Resonances

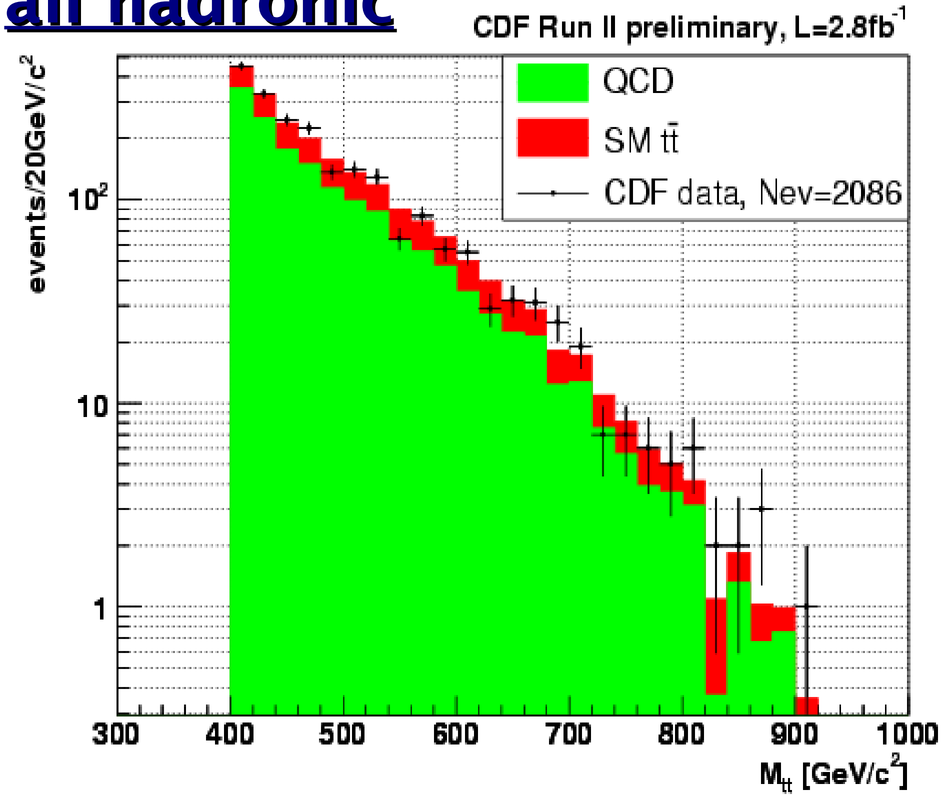
- no resonance production in $t\bar{t}$ system is expected in **SM**
- some models predict **$t\bar{t}$ bound states**: e.g. **leptophobic Z'** with strong 3rd generation coupling



l+jets, 3.6 fb^{-1}

$M_{Z'} > 820$ GeV

all hadronic

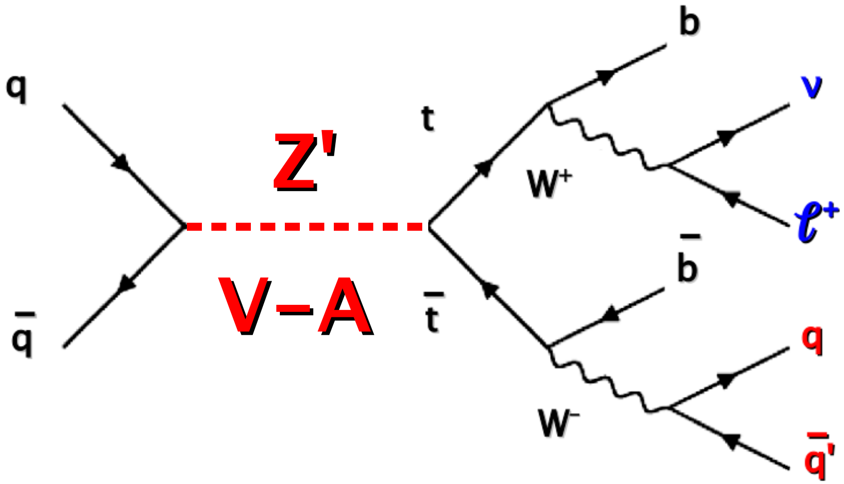


- search for bumps in $t\bar{t}$ reconstructed mass spectrum

$M_{Z'} > 805$ GeV

Forward Backward Charge Asymmetry

- **test coupling to top pairs**



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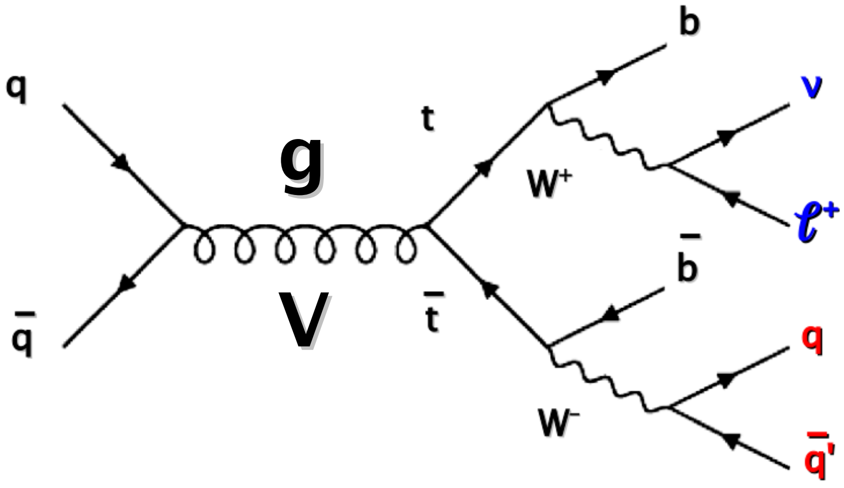

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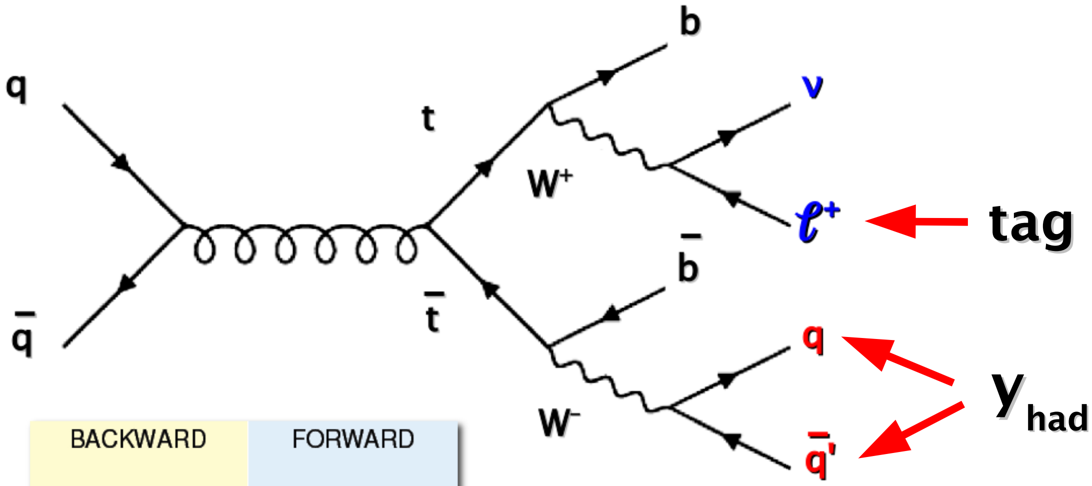
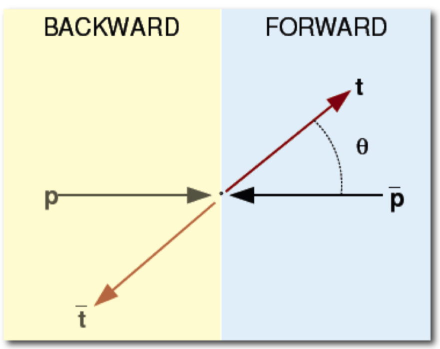
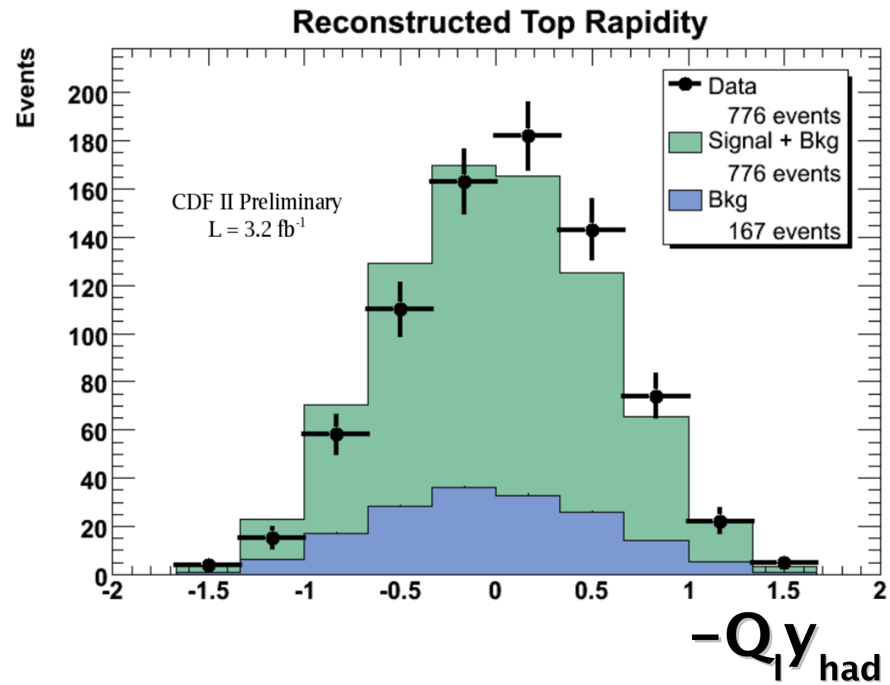




$$A_{fb} = \frac{F-B}{F+B}$$

detector level:



template fit, corrected:

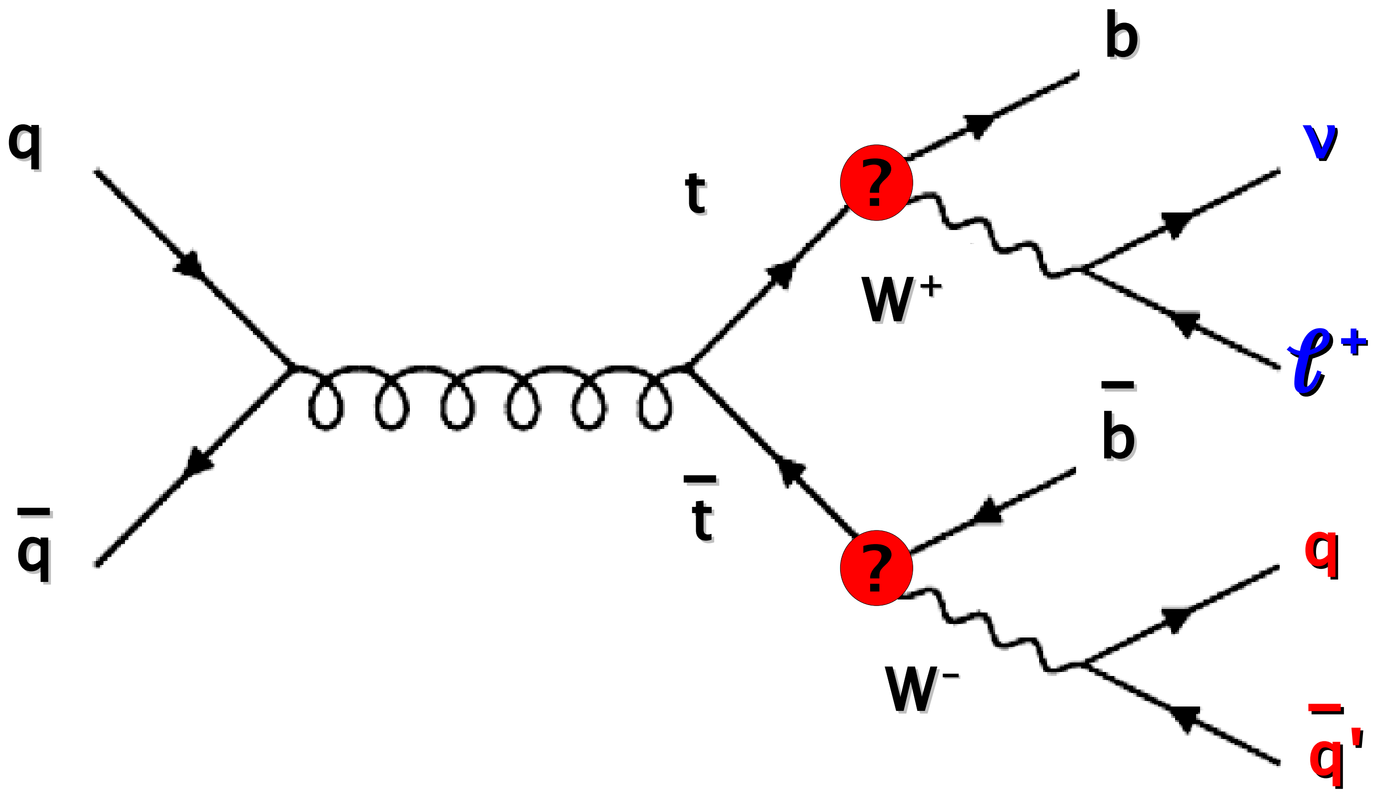
$$\boxed{A_{fb} = 0.193 \pm 0.065\ (\text{stat}) \pm 0.024\ (\text{syst})}$$

NLO QCD in $O(\alpha_s^3)$: $A_{fb} = 0.05 \pm 0.015$ ⇒ **agrees within 2σ**

$$\boxed{A_{fb}^{det} = 0.12 \pm 0.08\ (\text{stat}) \pm 0.01\ (\text{syst})}$$ with 1 fb^{-1}

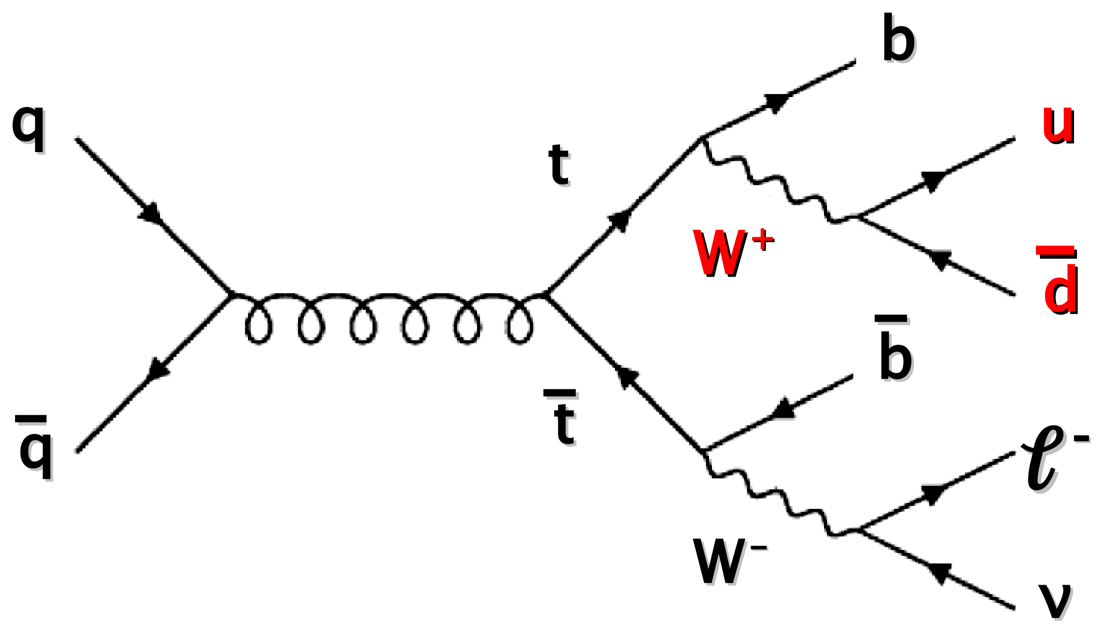
PRL 100, 062004 (2008)

Search for New Physics in Top Decays

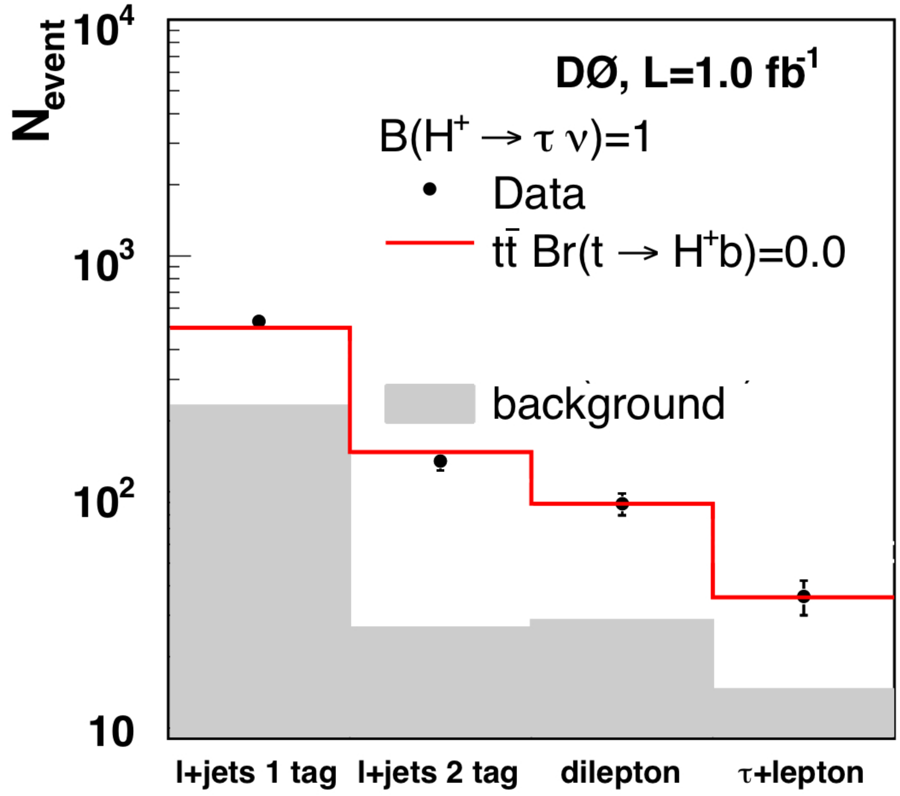


Search for Charged Higgs Bosons

- supersymmetry can remedy shortcomings of the SM



M_{H+}=80 GeV



Search for Charged Higgs Bosons

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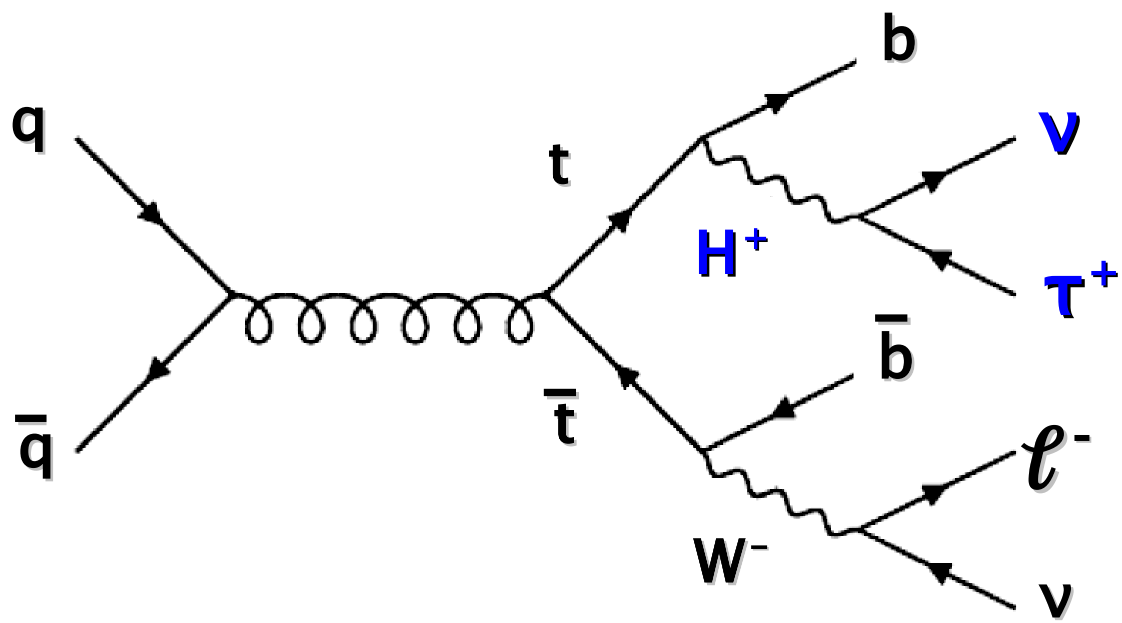

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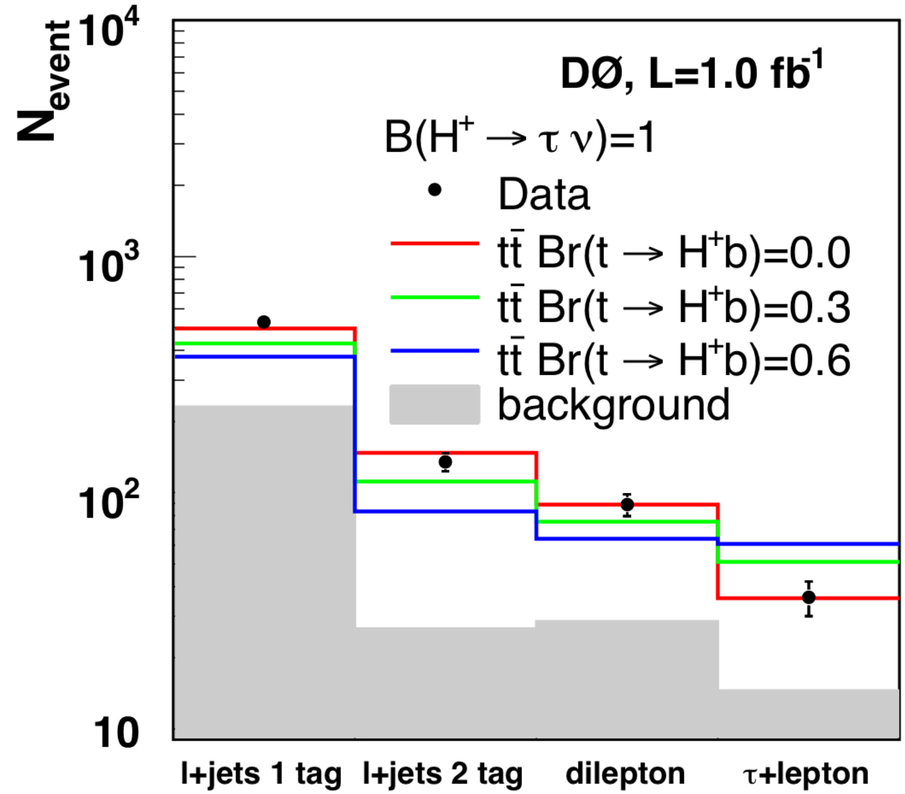
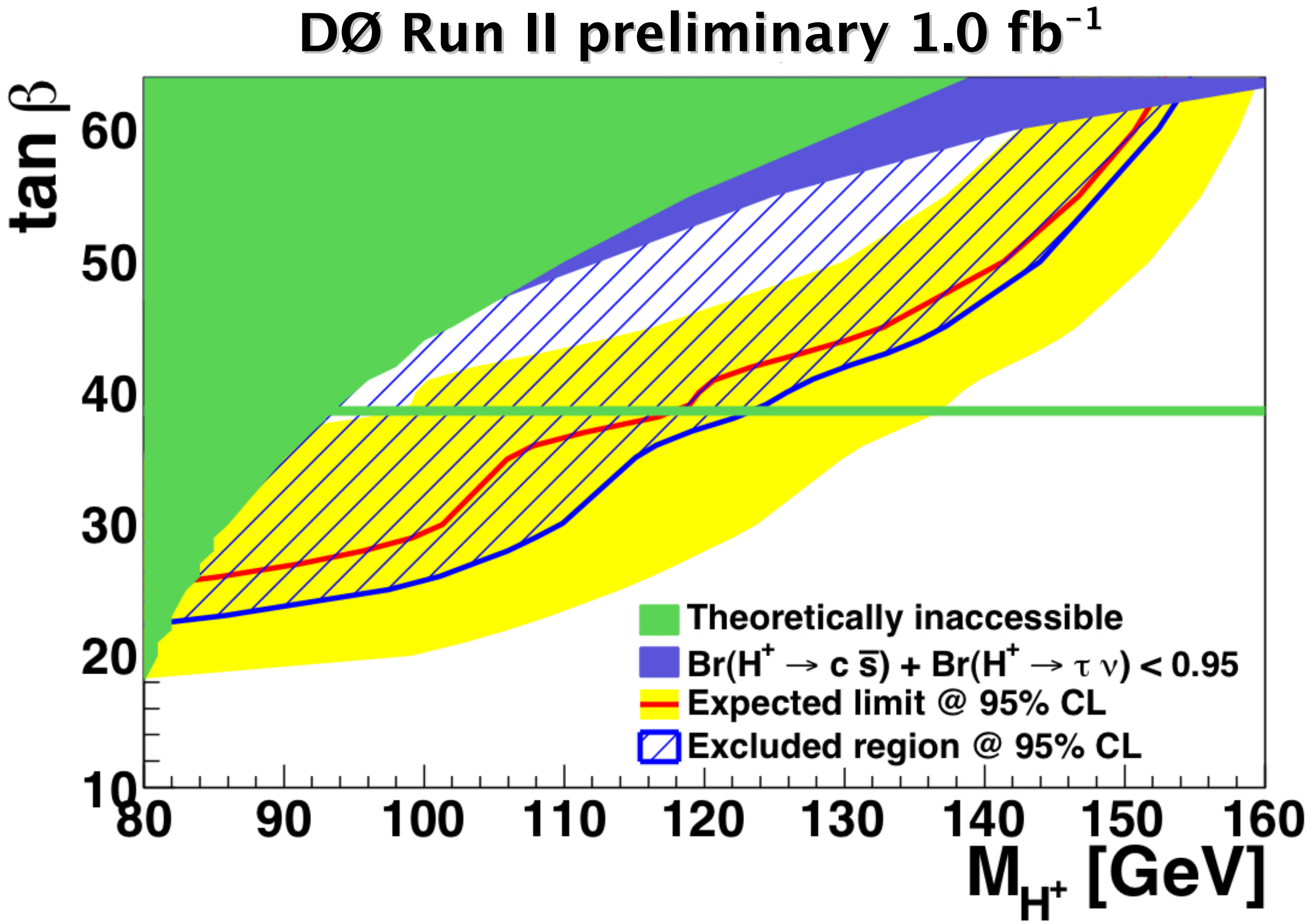


decrease decrease increase

MSSM Interpretations

CPX benchmark scenario: strangephilic Higgs

$$Br(H^+ \to \tau^+ \nu) + Br(H^+ \to c\bar{s}) = 1$$



MSSM Interpretations

<u>CPX benchmark scenario:</u> strangephilic Higgs

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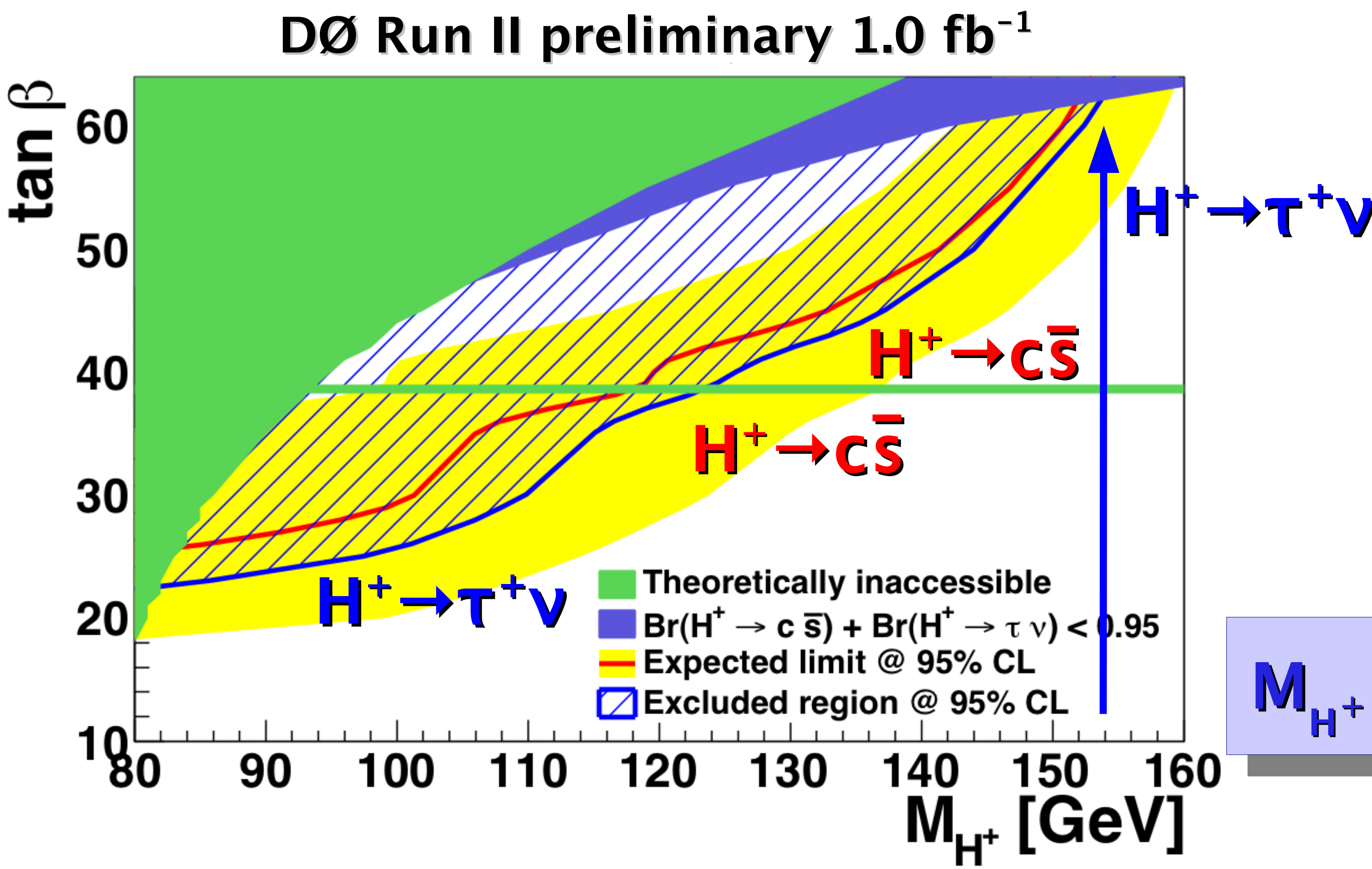

$M_{H^+} > 154$ GeV

⇒ first limit on a CP-violating MSSM scenario in H^+ searches

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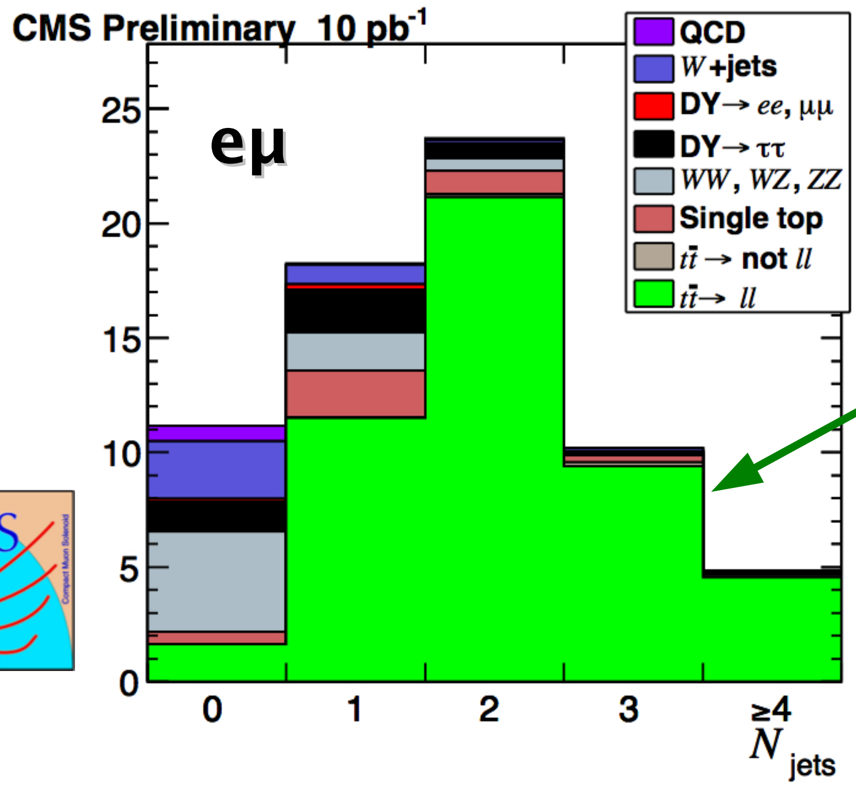
Top Pair Production at the LHC

10 top pairs per day @ Tevatron ⟷ 1 top pair per second @ LHC

- rediscovery possible already with 10 pb^{-1} at 10 TeV
  - cross section uncertainty ~20% for dilepton channels
  - test lepton identification, jet identification, b-tagging, etc.



L. Fiorini

P. Ferreira da Silva

top

$\Delta\sigma_{t\bar{t}}$ = 15% (stat) ± 10% (syst) ± 10% (lumi)

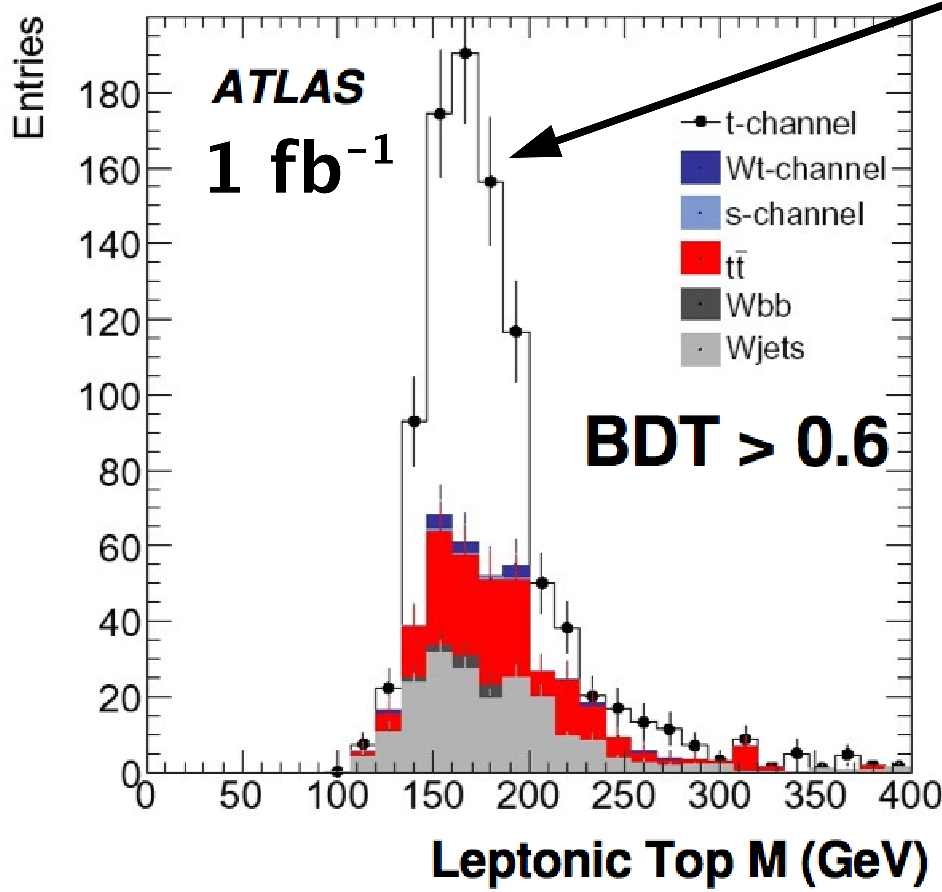
Single Top Production

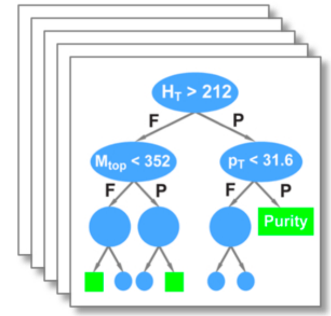
4 single tops per day @ Tevatron ⟷ 30 single tops per minute @ LHC

t-channel: most sensitive

Boosted Decision Trees

single top





$\Delta|V_{tb}|$ = 12% (stat+syst+theo)

dominated by systematic uncertainties due to b-tagging, JES, luminosity

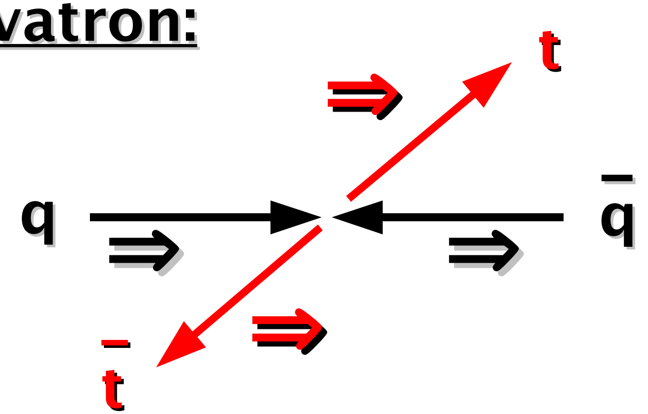
DØ $\Delta|V_{tb}|$ = 11%

CDF $\Delta|V_{tb}|$ = 14%

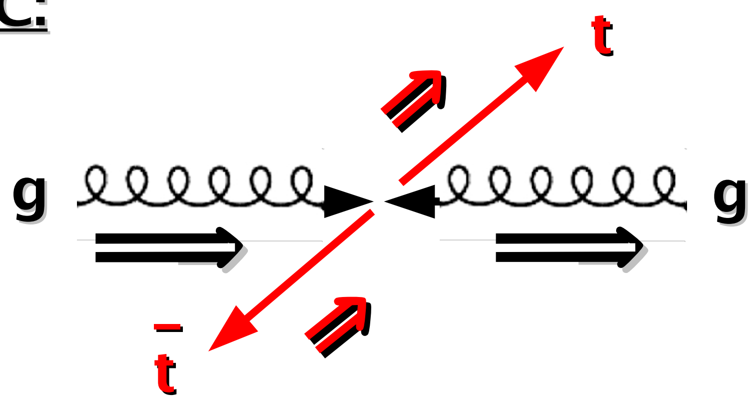
Top Properties

- systematically limited Tevatron analyses hard to beat:
  Δm_{top} ~1 GeV (instead of 1 – 1.3 GeV at the Tevatron)
- measure basic quantities as spin, charge and couplings with high precision
- measure some quantities for first time, as e.g. spin correlation

Tevatron:



LHC:



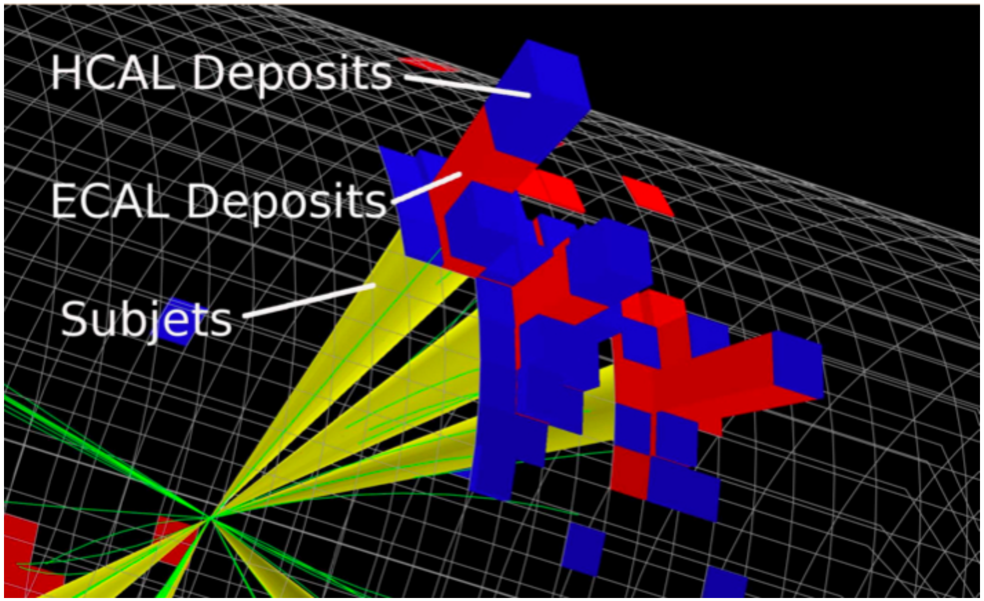
- NLO QCD: $\kappa \approx 0.78$
- measurements (dilepton) cannot separate yet between SM and 0

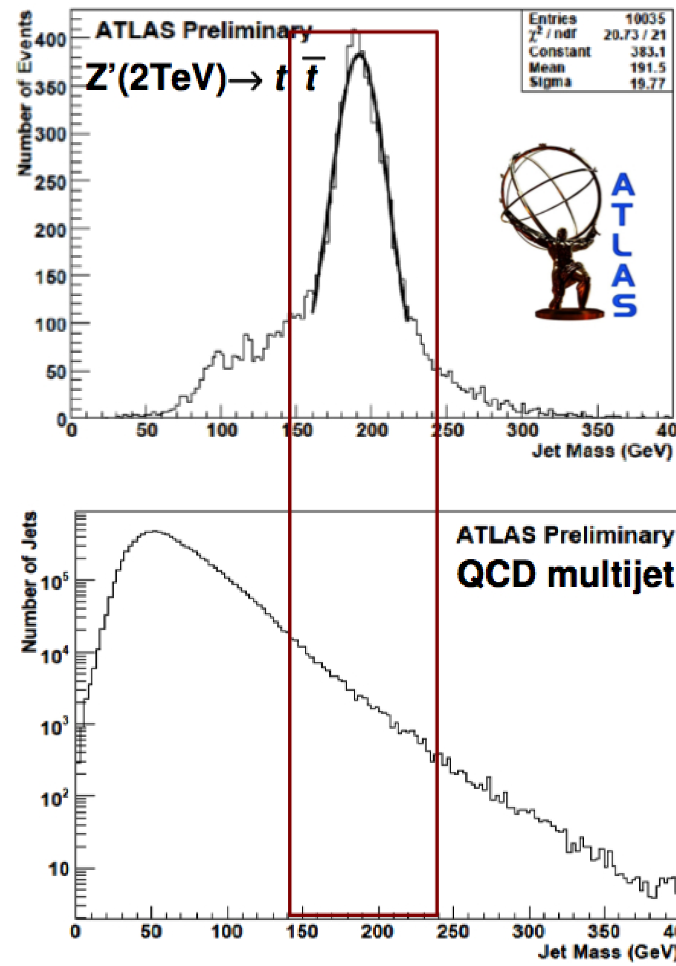
- NLO QCD: $\kappa \approx 0.33$
- l+jets with 220 pb^{-1} gives already ~50% uncertainty with ATLAS

Searches for New Physics

- in many cases LHC has a better sensitivity by orders of magnitude as e.g. flavour changing neutral currents with 10 fb^{-1}
- new development: tagging of boosted top jets

S. Rappoccio





<u>constraints:</u>
- top mass
- W mass

⇒ 46% efficiency, 2% fake rate for p_T=600 GeV top quarks

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Highlights of top quark physics:

- single top observation + direct measurement of V_{tb}
- precision measurements

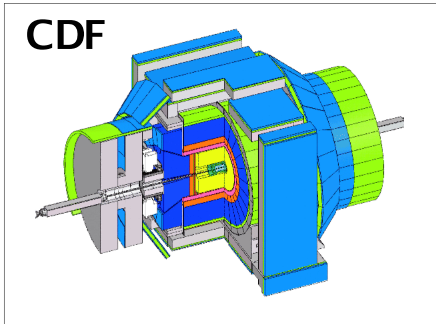
  top mass with 0.75% uncertainty
- top properties

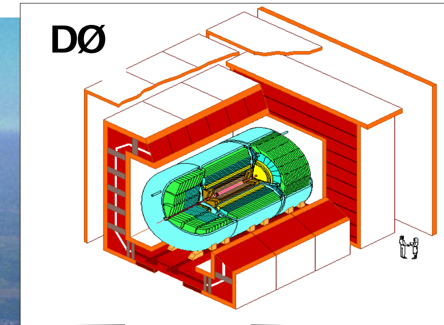
  new analyses possible such as spin correlation
- searches for new physics in top sector

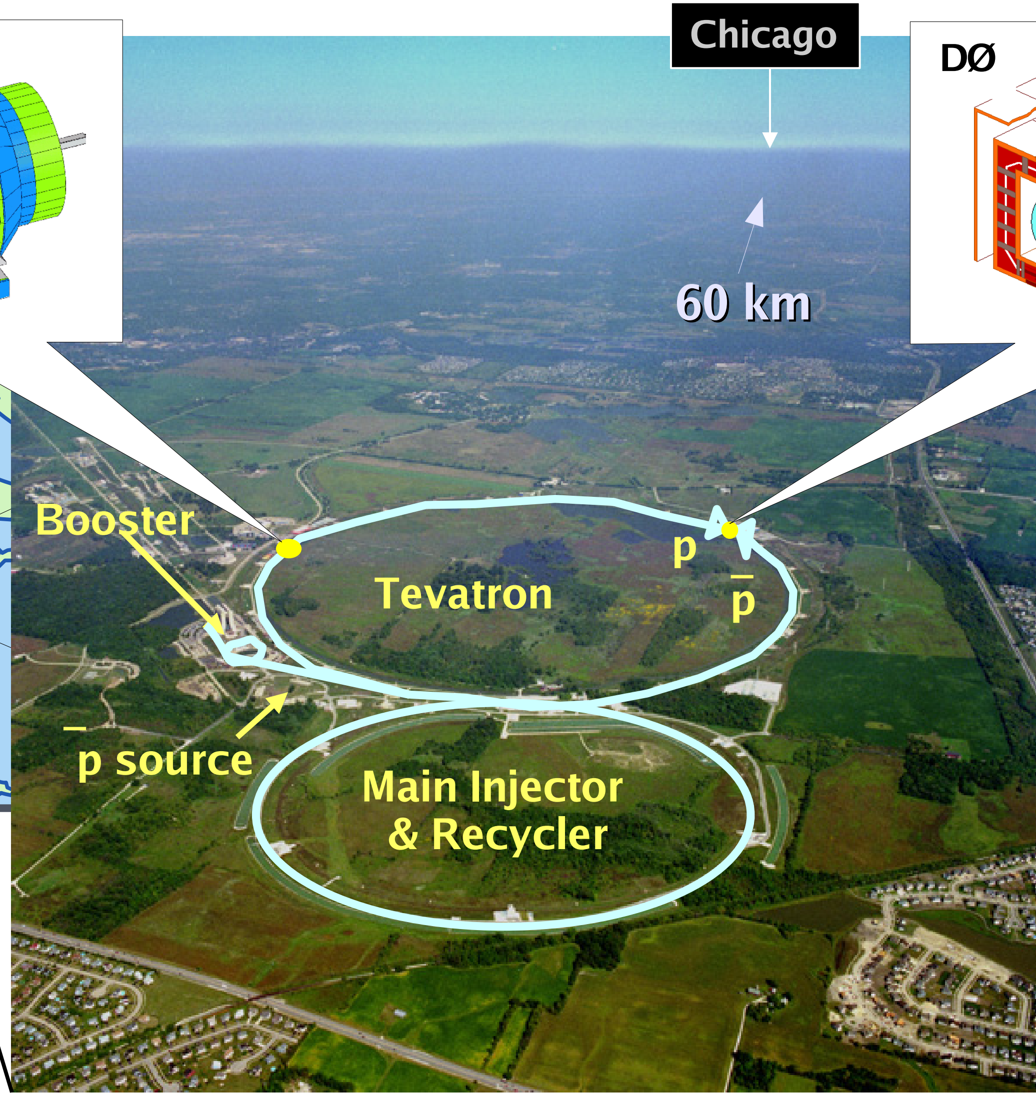
  general agreement with SM
- excellent prospects for top physics at the LHC

Backup

The Tevatron at FERMILAB: $p\bar{p}$ Collisions







$\sqrt{s}$ = 1.96 TeV
Δt = 396 ns

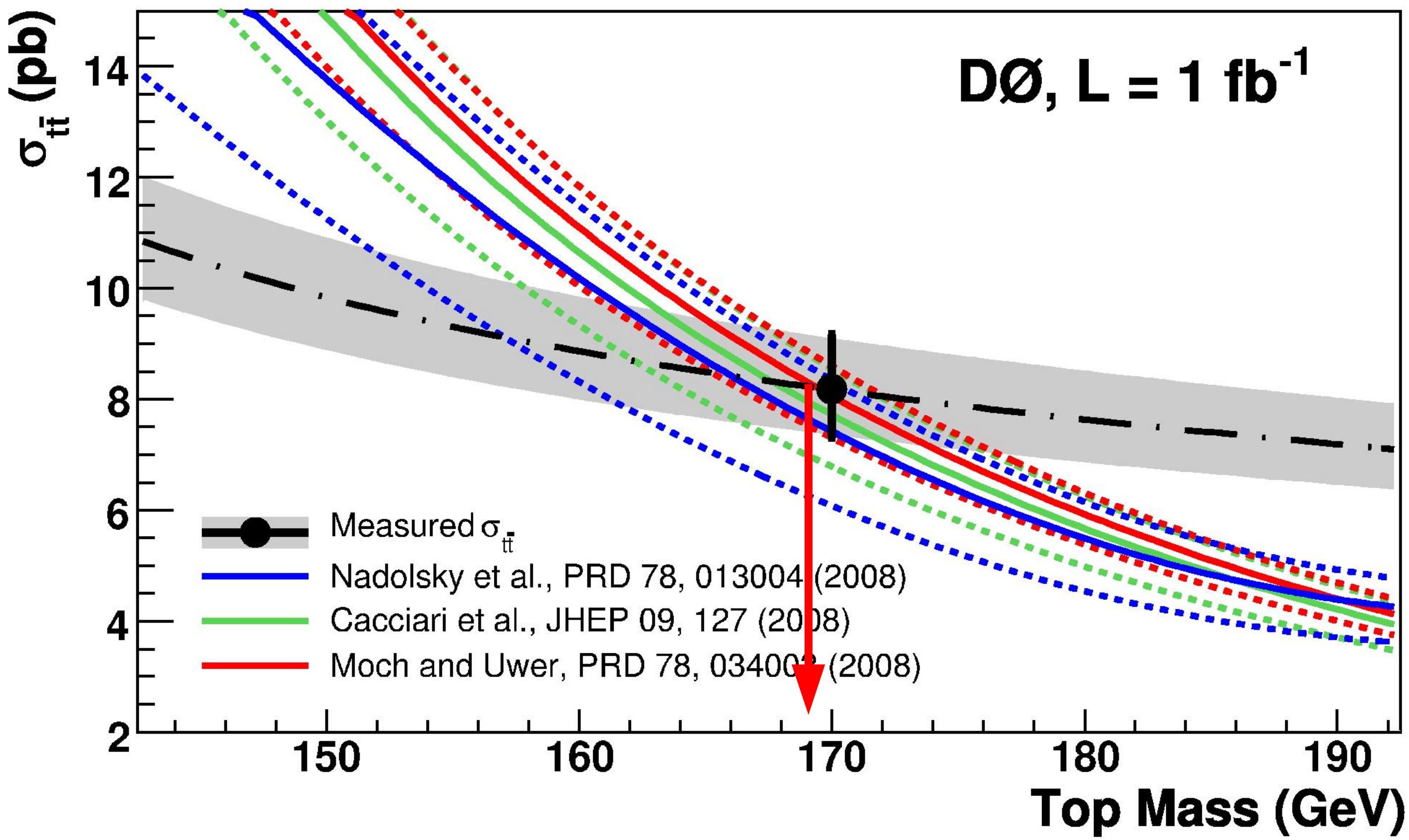
Run I 1987 (92)-95: 125 pb^{-1}
Run II 2001-11: ~100x larger dataset at increased energy

top quark discovery

measure properties with high precisions: is it really the particle expected in the SM?

Top mass from cross section measurement

- **lepton+jets/dilepton/lepton+tau combination**

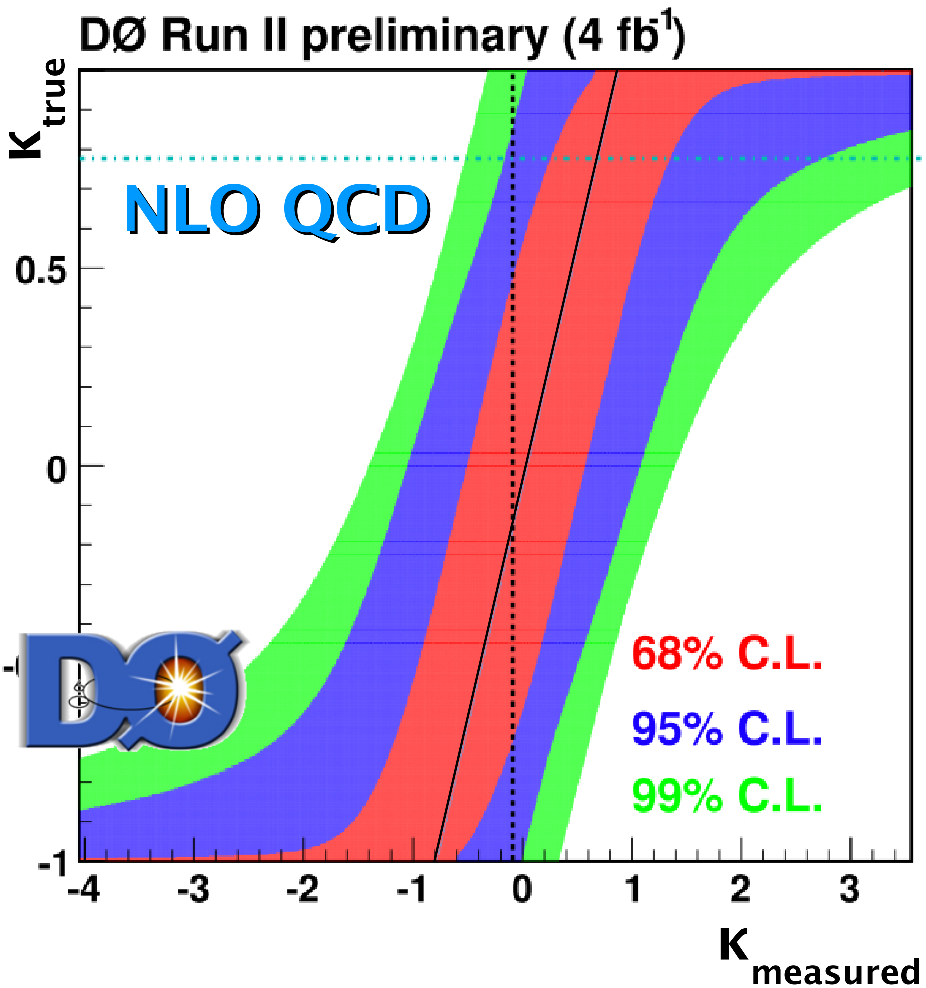


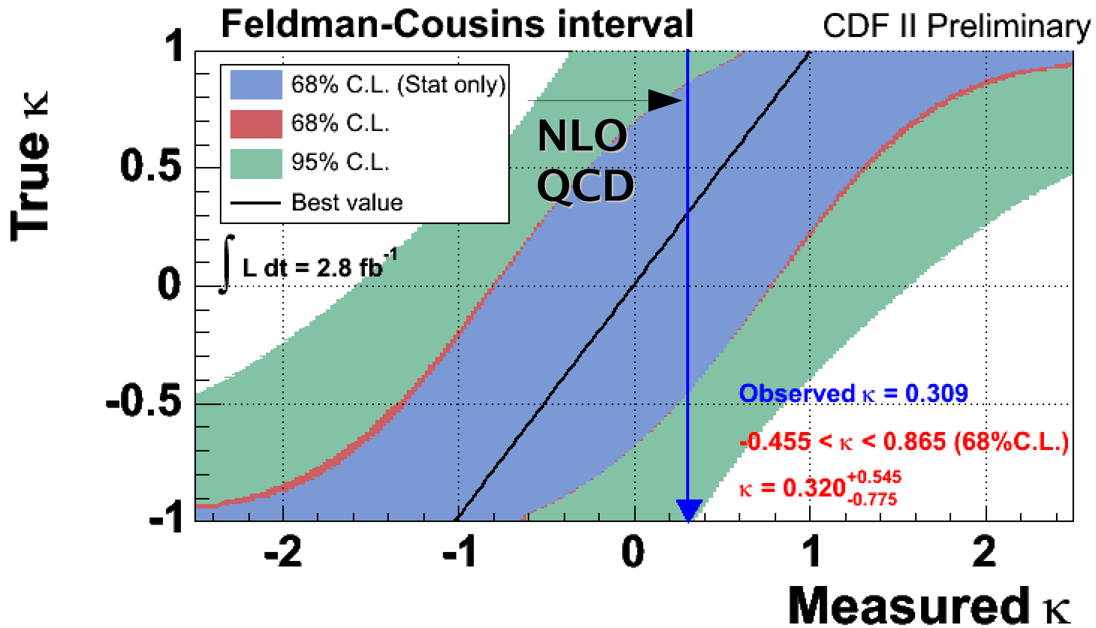
pole mass

$$M_{top} = 169.1^{+5.9}_{-5.2} \text{ GeV with NNLO}_{approx}$$

±3.3%

Spin Correlation Result



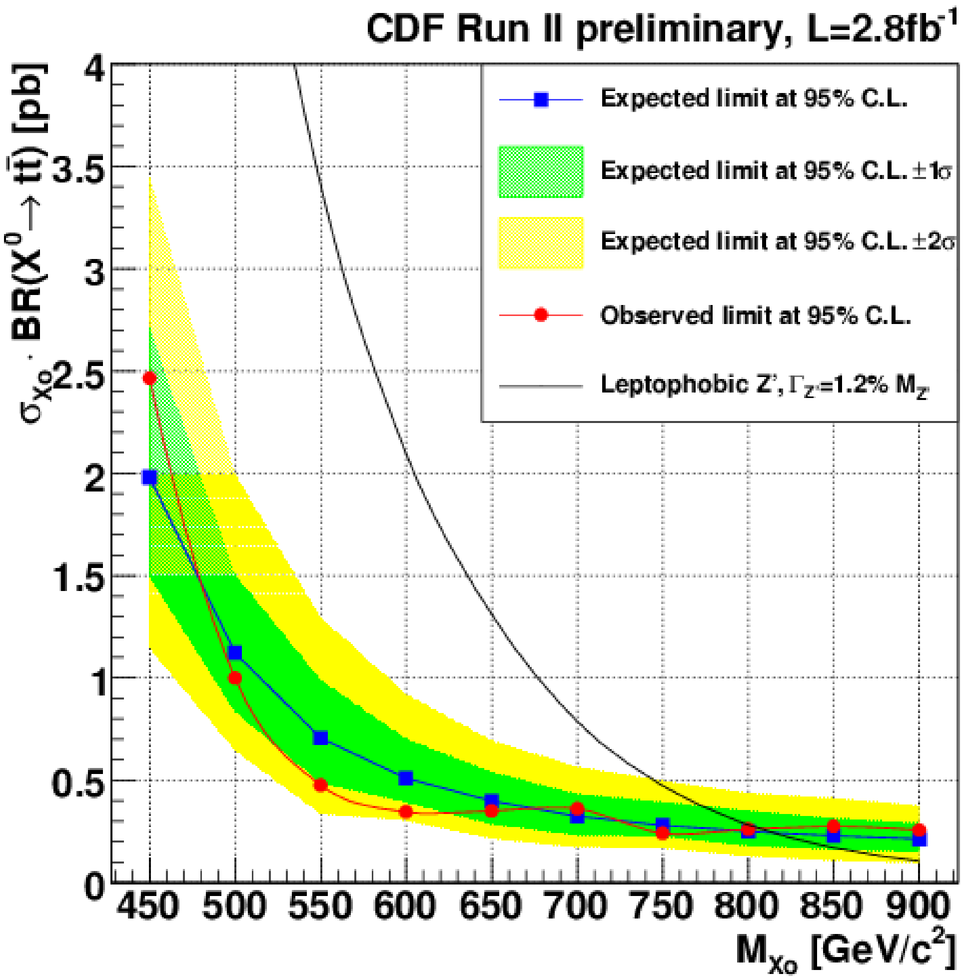


$$\kappa = -0.17\ ^{+0.64}_{-0.53}$$

$$\kappa = 0.32\ ^{+0.55}_{-0.78}$$

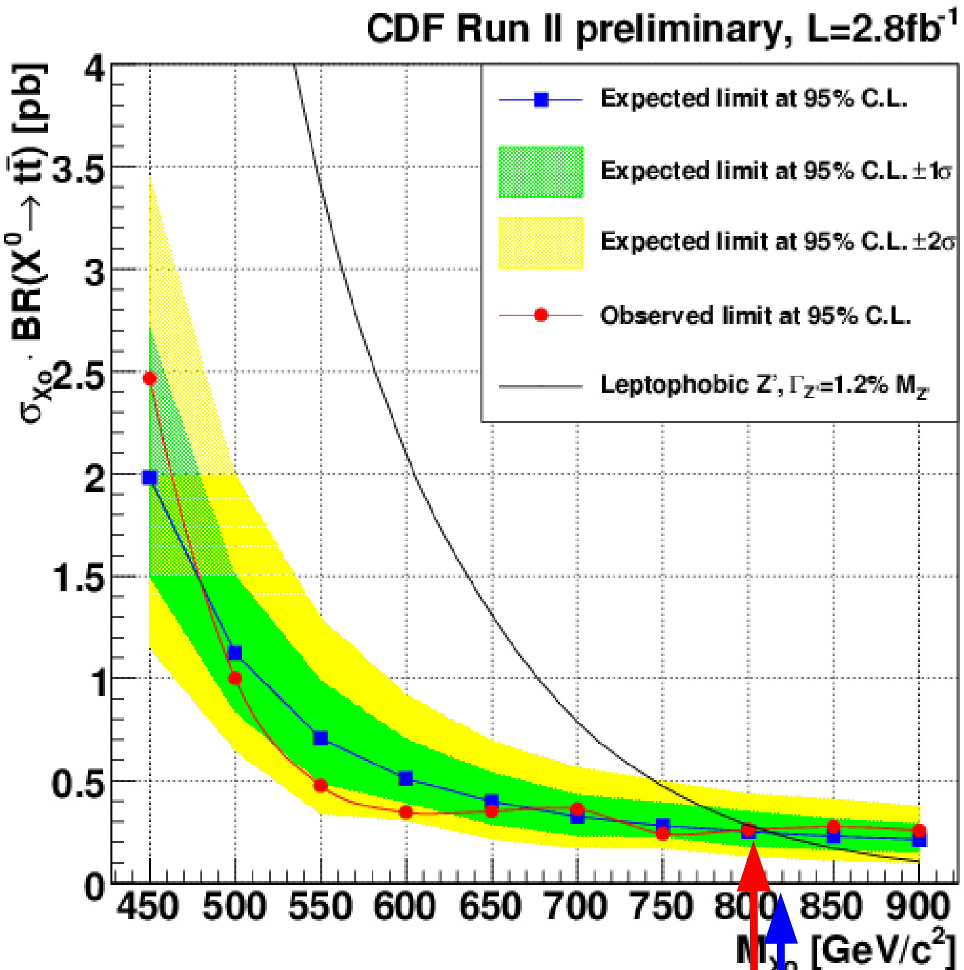
⇒ **first results in Run-II, agreement with SM**

Limits on Leptophobic Z'



all hadronic

Limits on Leptophobic Z'



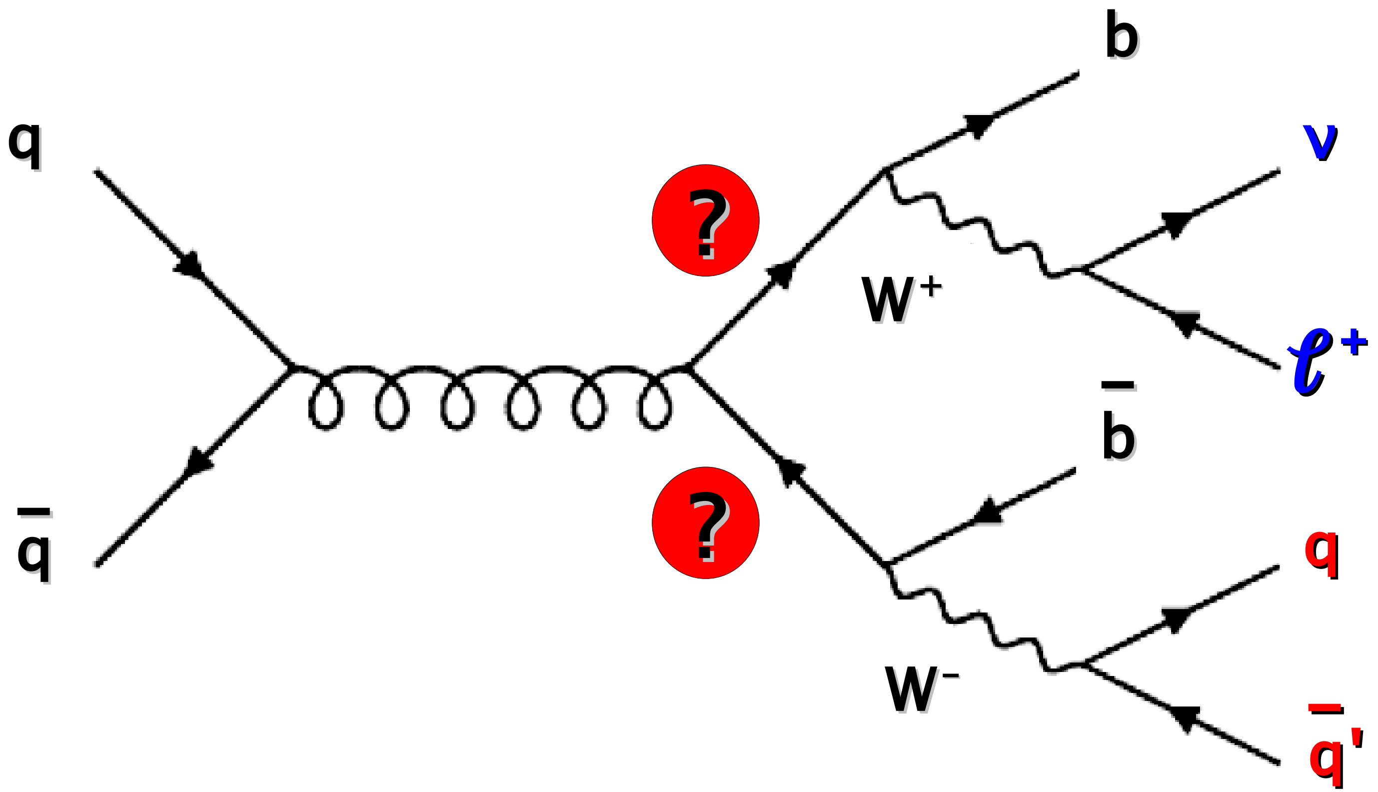
all hadronic

l+jets, 3.6 fb^{-1}

$M_{Z'}$ > 820 GeV

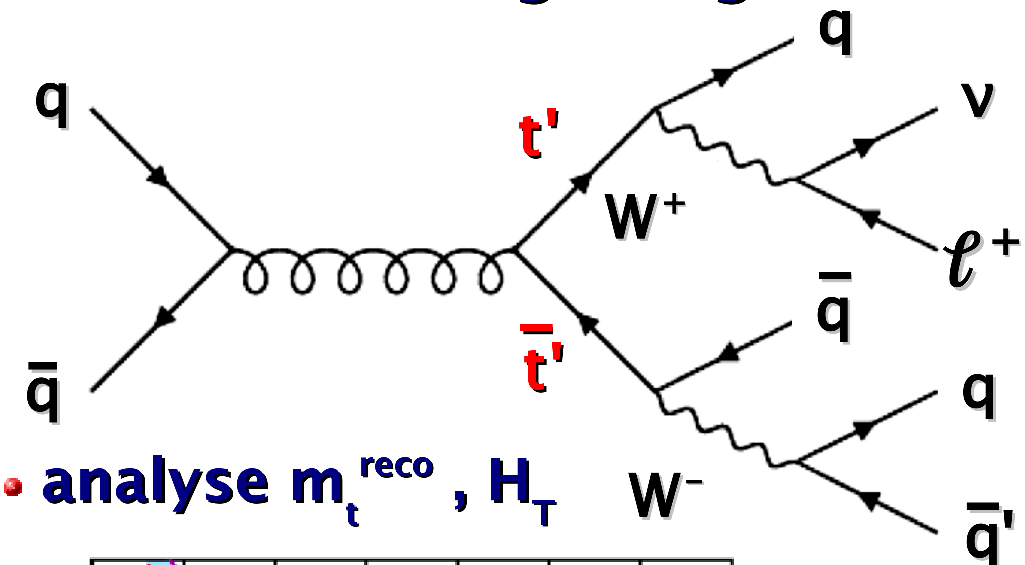
$M_{Z'}$ > 805 GeV

Search for new particles

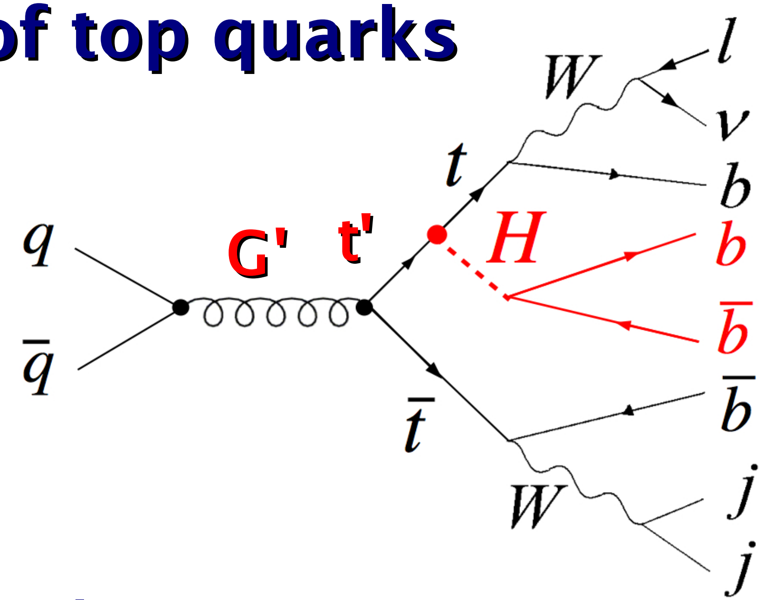


Search for t' Quarks

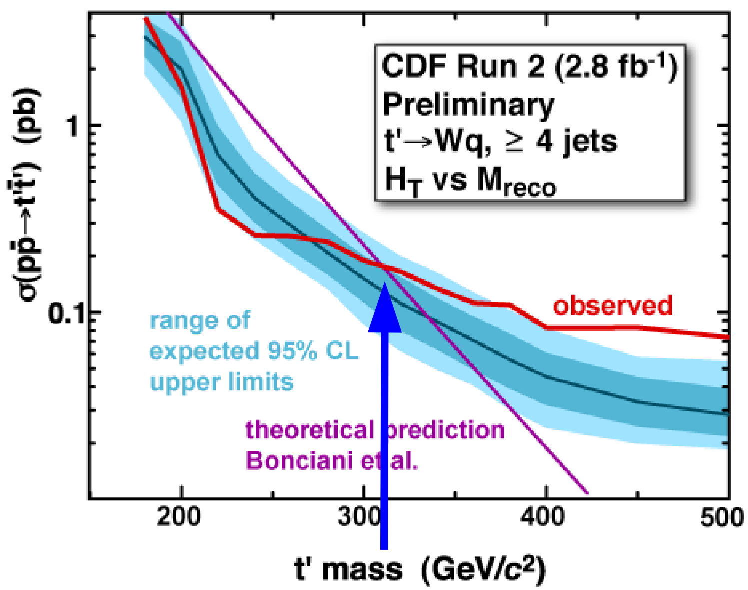
e.g. 4^{th} generation of top quarks



- analyse m_t^{reco}, H_T

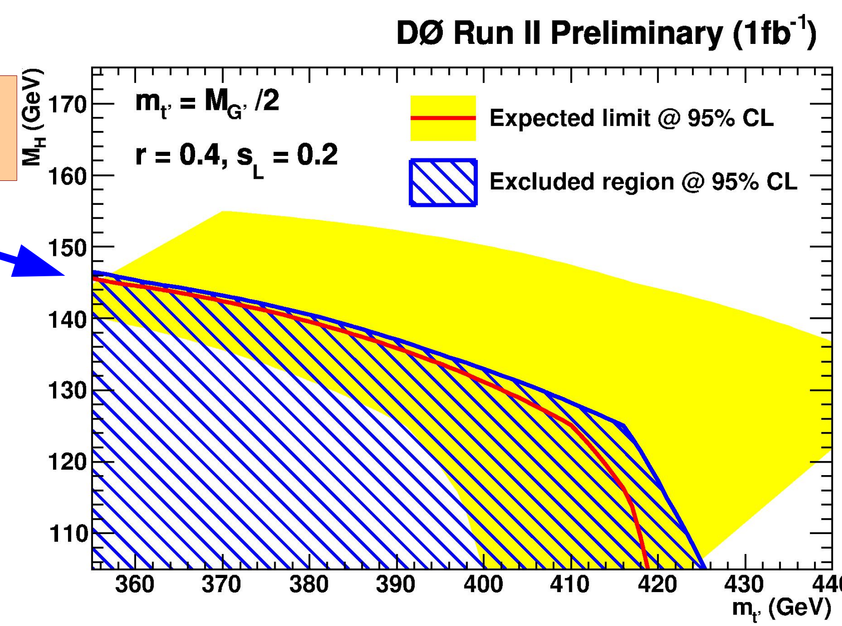


- analyse n_{jets}, $n_{b\text{-}jets}$, H_T

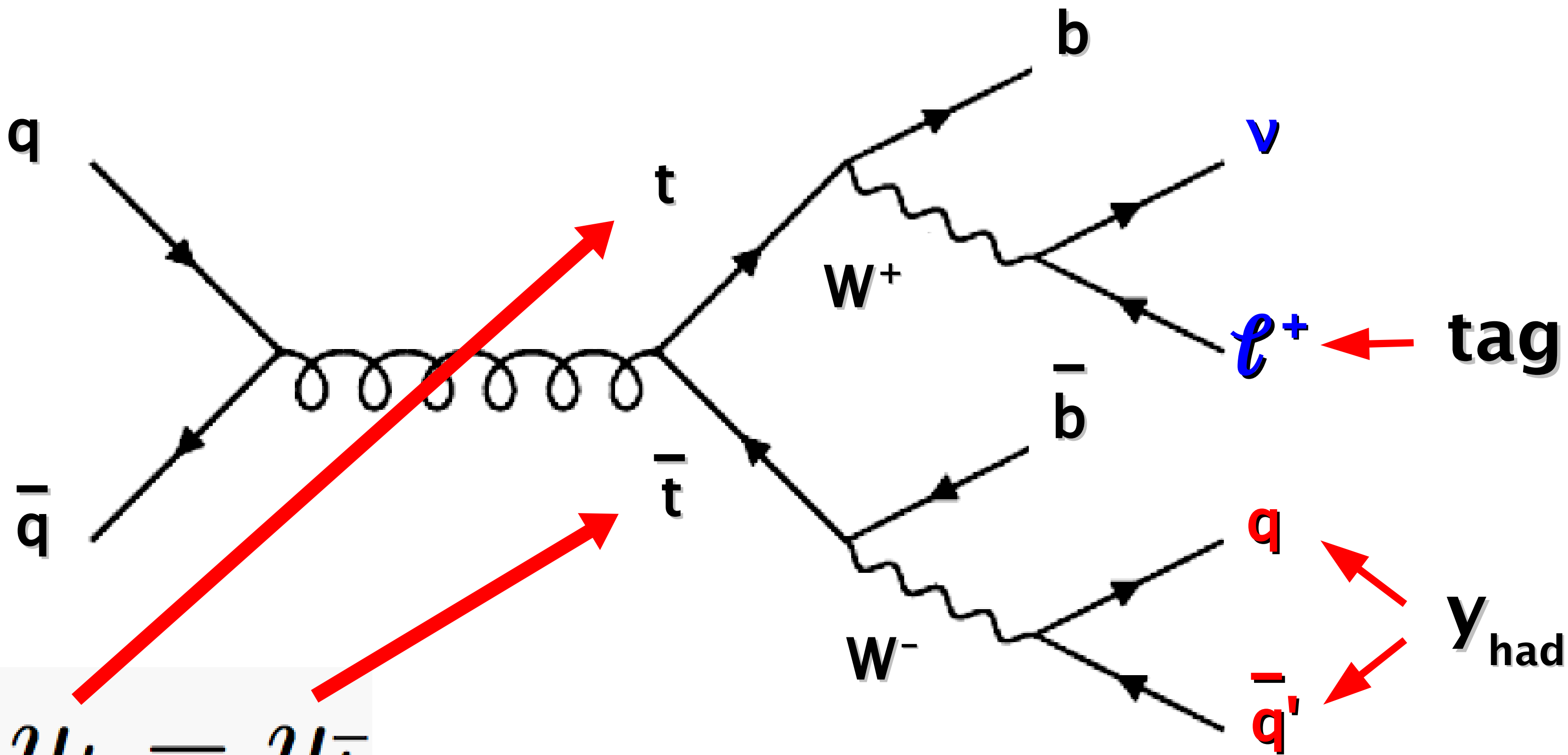


$m_{t'}$ > 311 GeV

M_H > 146 GeV



Forward backward asymmetry



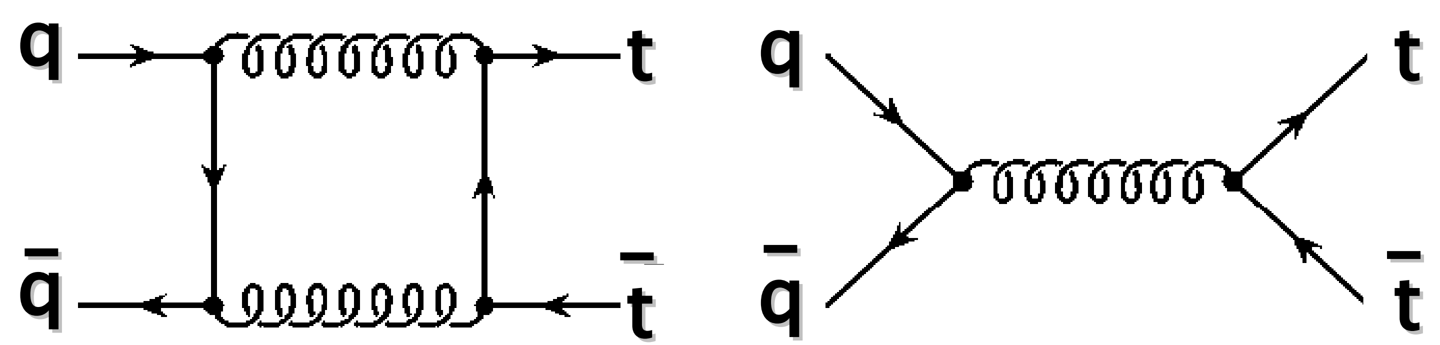
$$\Delta y \equiv y_t - y_{\bar{t}}$$

$$\boxed{A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}}$$

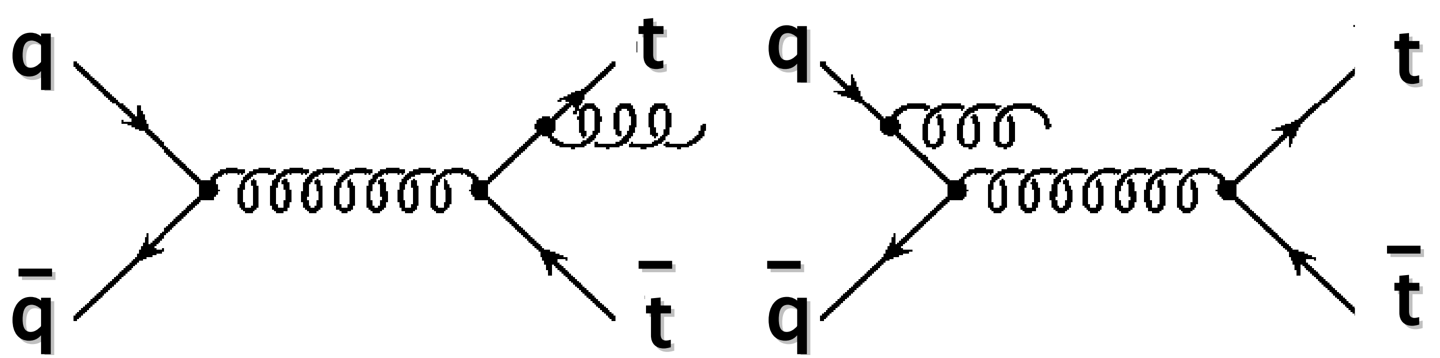
Charge asymmetry in SM

- no asymmetry in $O(\alpha_s^2)$
- asymmetry in $O(\alpha_s^3)$

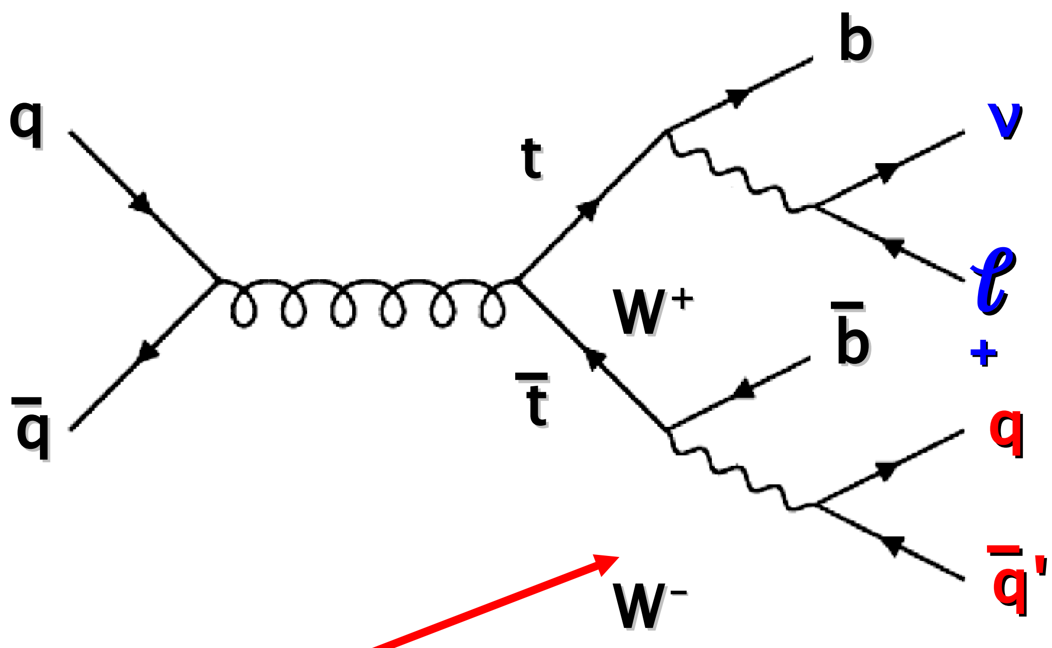
interference between:



interference between:



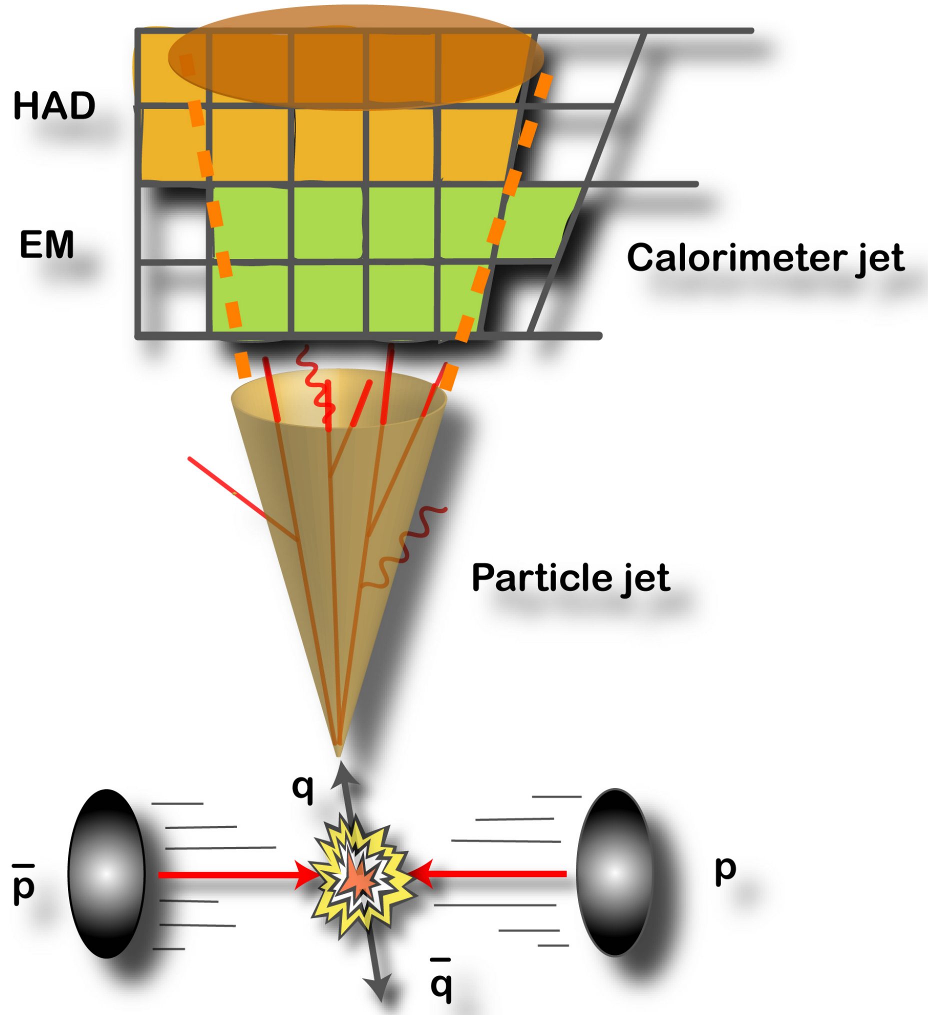
Lepton+Jets Channel



W mass constrains jet energy scale

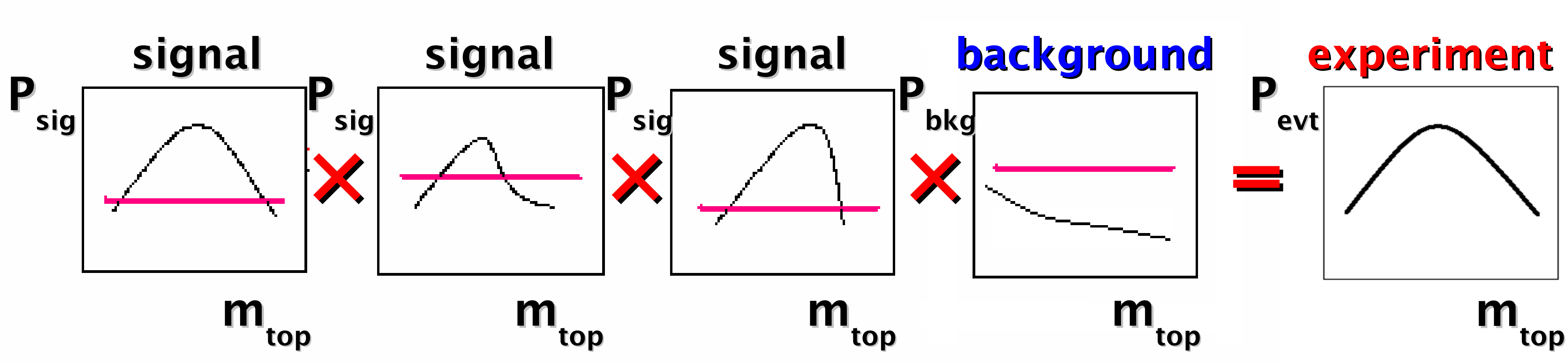
jet energy scale:

translate jet into parton energy



Extraction techniques: matrix element

- **probability densities for every event as function of m_{top}**



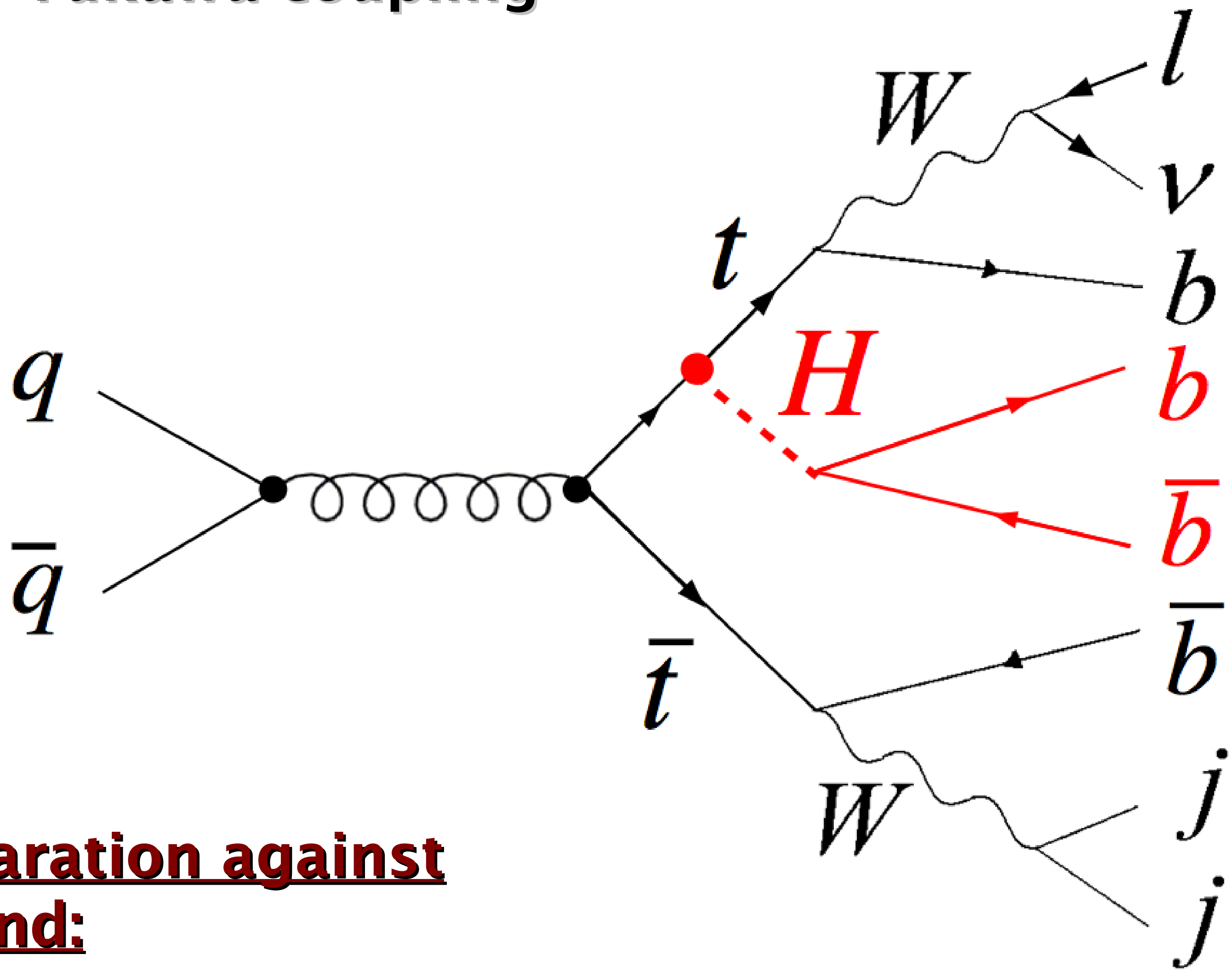
$$P_{sig}(x; m_{top}, JES) = \underbrace{Acc(x)}_{\text{Acceptance (selection, trigger,...)}} \times \frac{1}{\sigma} \int d^n \underbrace{\sigma(y; m_{top})}_{\text{LO-Matrix element x phase space}} \underbrace{dq_1\, dq_2\, f(q_1)\, f(q_2)}_{\text{PDF's}} \underbrace{W(x, y; JES)}_{\text{Transfer Functions (Probability to measure x when y was produced)}}$$

- **maximum Likelihood fit:**

$$L(x_1, .., x_n; m_{\text{top}}, JES, f_{\text{top}}) = \prod_{i=1}^{n} P_{\text{evt}}(x_i; m_{\text{top}}, JES, f_{\text{top}})$$

Search for the SM Higgs boson

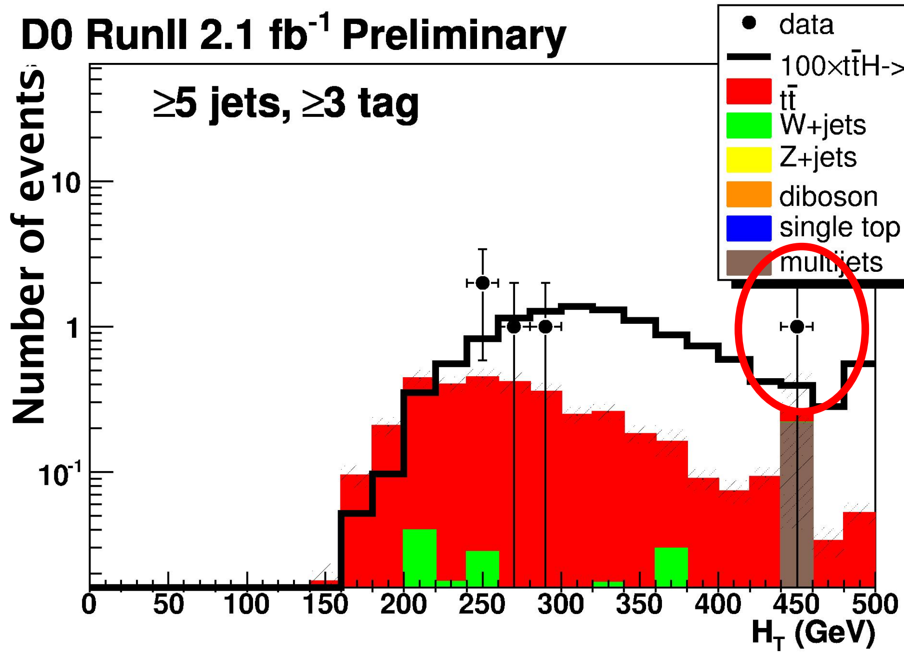
- contains Yukawa coupling

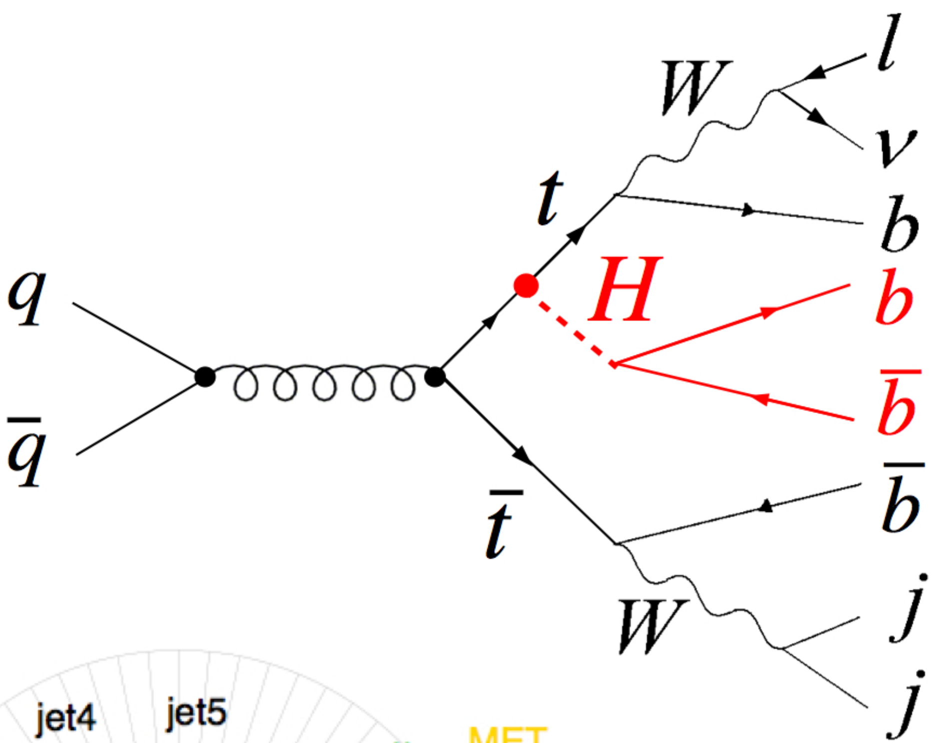


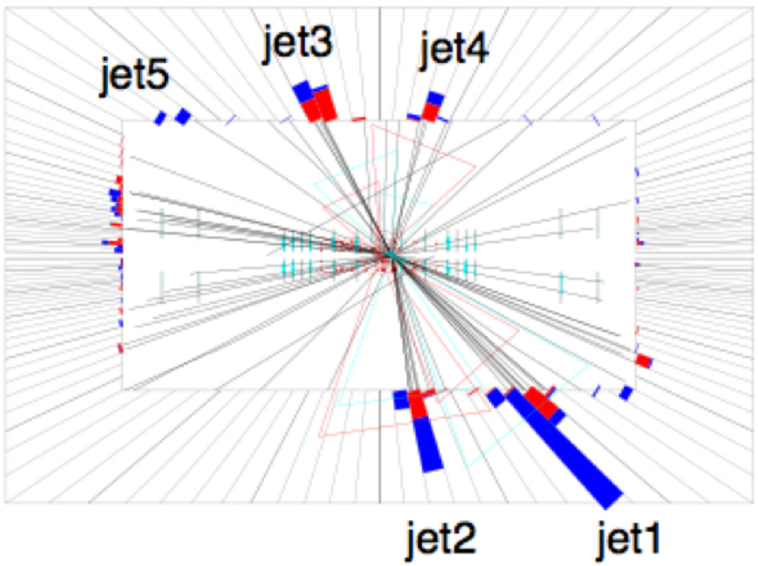
good separation against background:

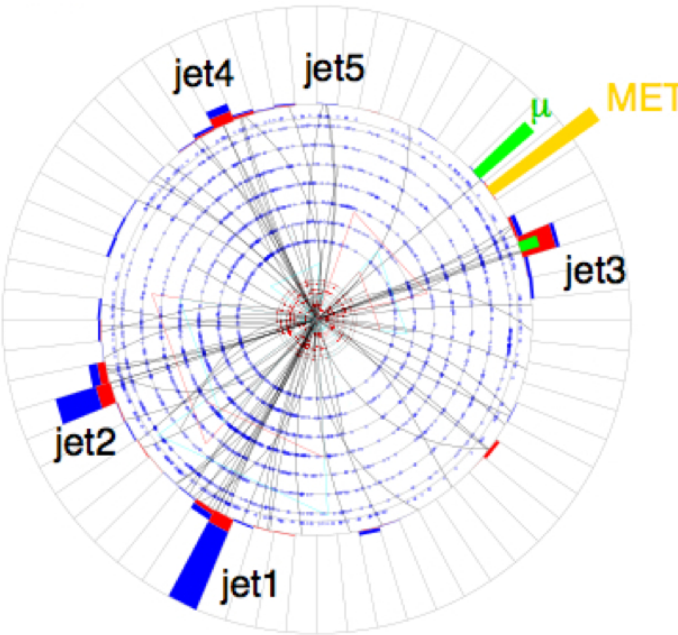
- 4, **≥5 jets** with 1, 2, **≥3 b-tags**
(lepton+jets channel)

Search for the SM Higgs boson

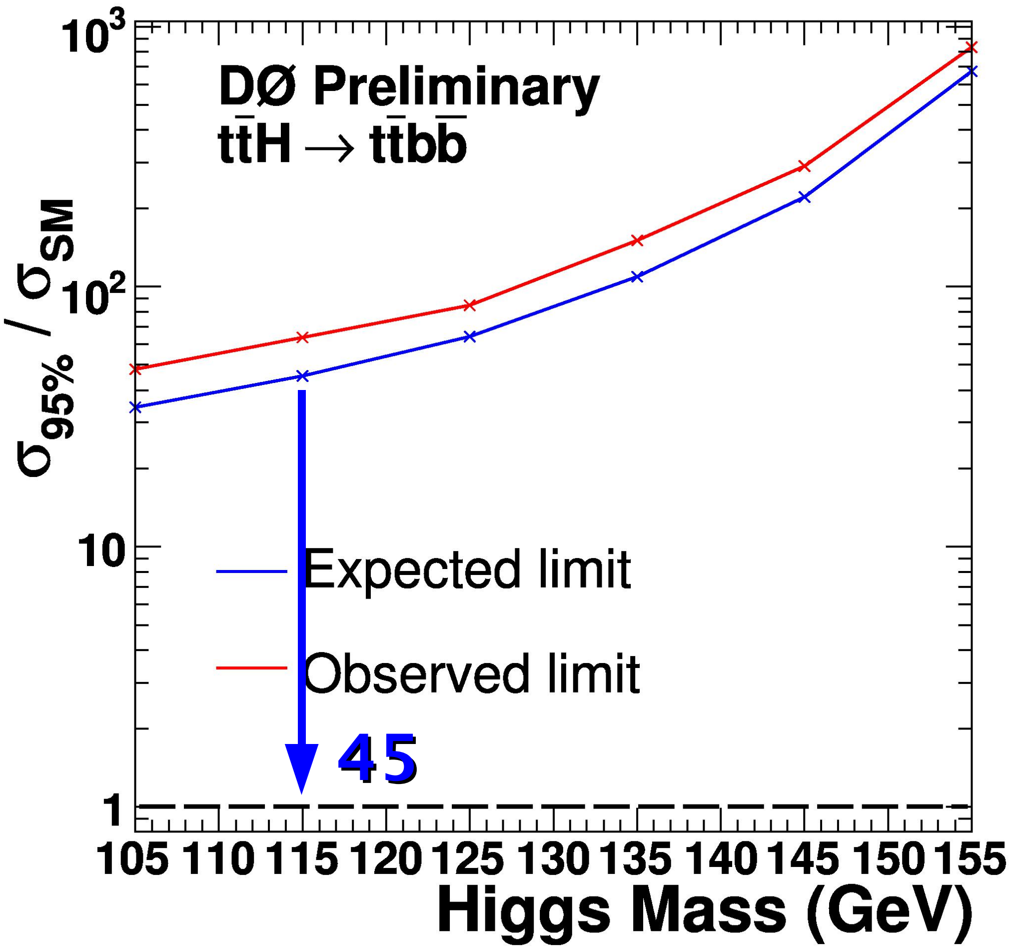








Limits for the SM Higgs boson



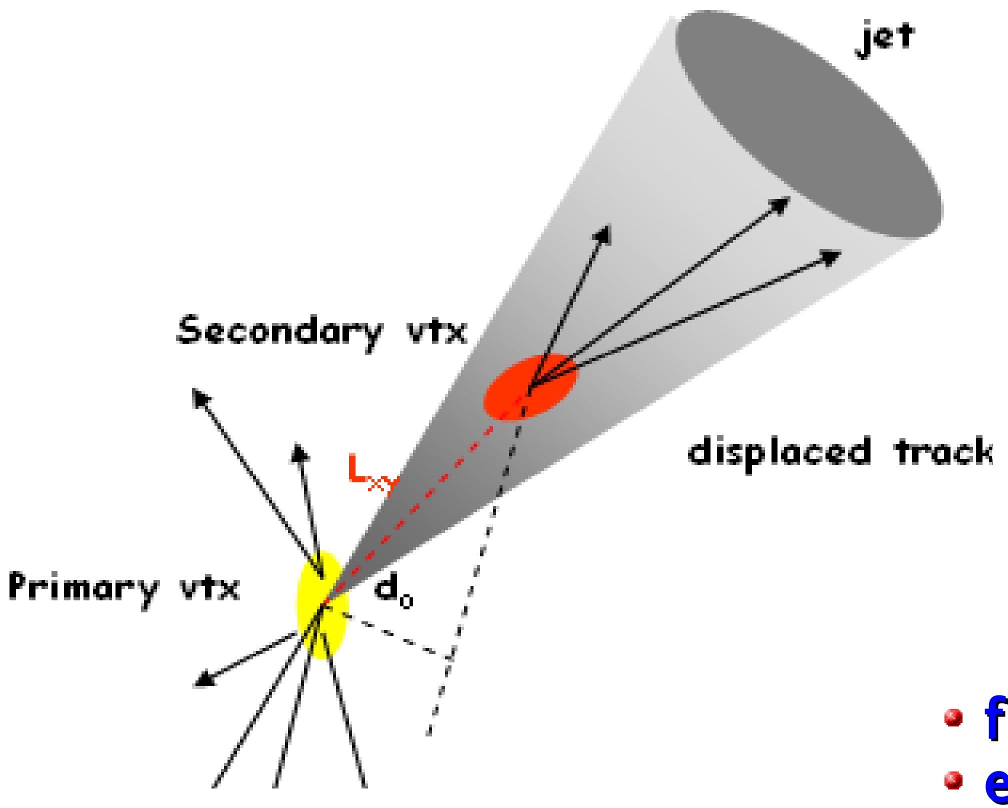
- only the beginning...
- optimize selection
- analyse more variables as e.g. invariant $b\bar{b}$ mass

→ **included in the Tevatron Higgs combination**

b-tagging at DØ

- B hadrons lifetime $\tau \sim 1$ ps
- B hadrons travel $L_{xy} \sim 3$ mm before decay

SVT/SVX



- form a 7-variable neural network
- event tagging efficiency 54% (with fake rate of 1%)

Search for Z' production

l+jets selection

ttbar resonances

Z' search

FB asymmetry

Z' search