Top Quark at Hadron Colliders

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Hadron Collider Physics Summer School
Fermilab

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MANCHESTER 1824

THE ROYAL SOCIETY
CELEBRATING 350 YEARS

New Results for Summer 2012

ICHEP2012 Melbourne

36th International Conference on High Energy Physics

4 – 11 July 2012

Melbourne Convention and Exhibition Centre

Outline

Introduction
History of the Top Quark
Top Quark Production
Top Quark Properties
Searches in Top Sector
Conclusions

Outline 1st Lecture

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Introduction

History of the Top Quark

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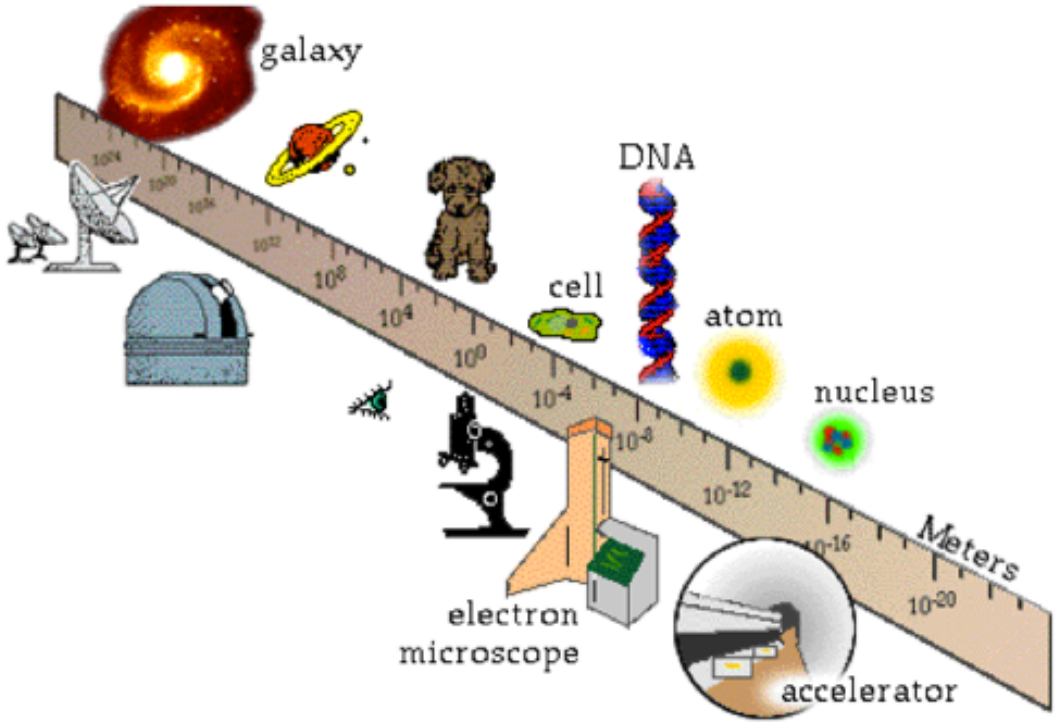
Objective of Elementary Particle Physics

"So that I may perceive whatever holds the world together in its inmost folds."

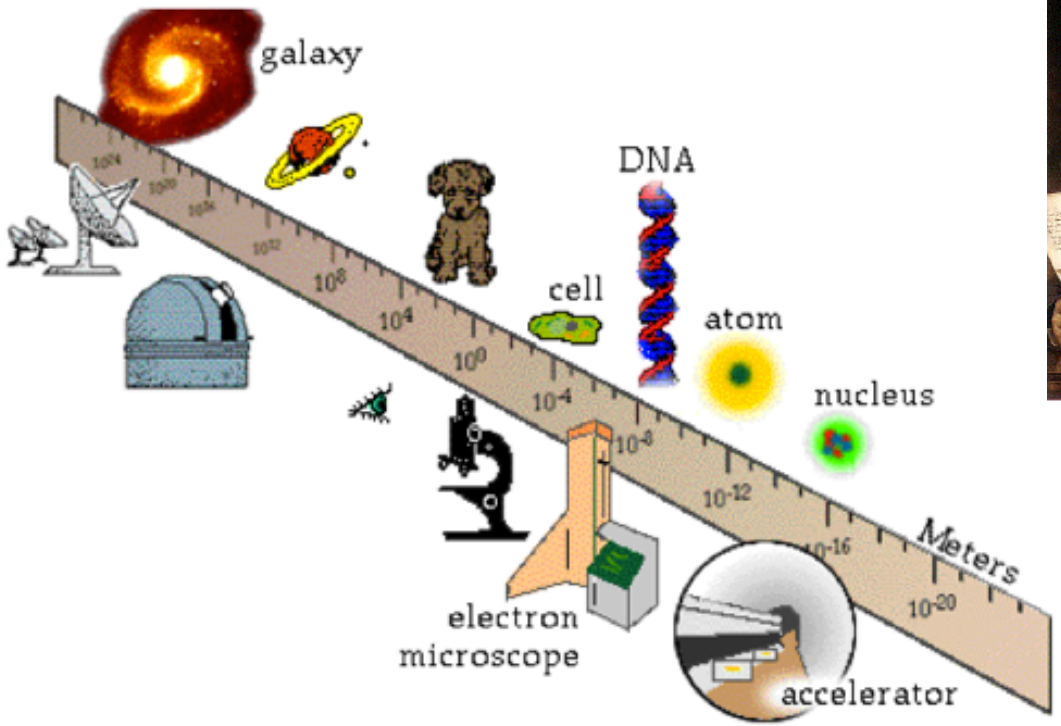


➔ **from the smallest dimensions in microcosm to the largest dimensions in the Universe**

Objective of Elementary Particle Physics

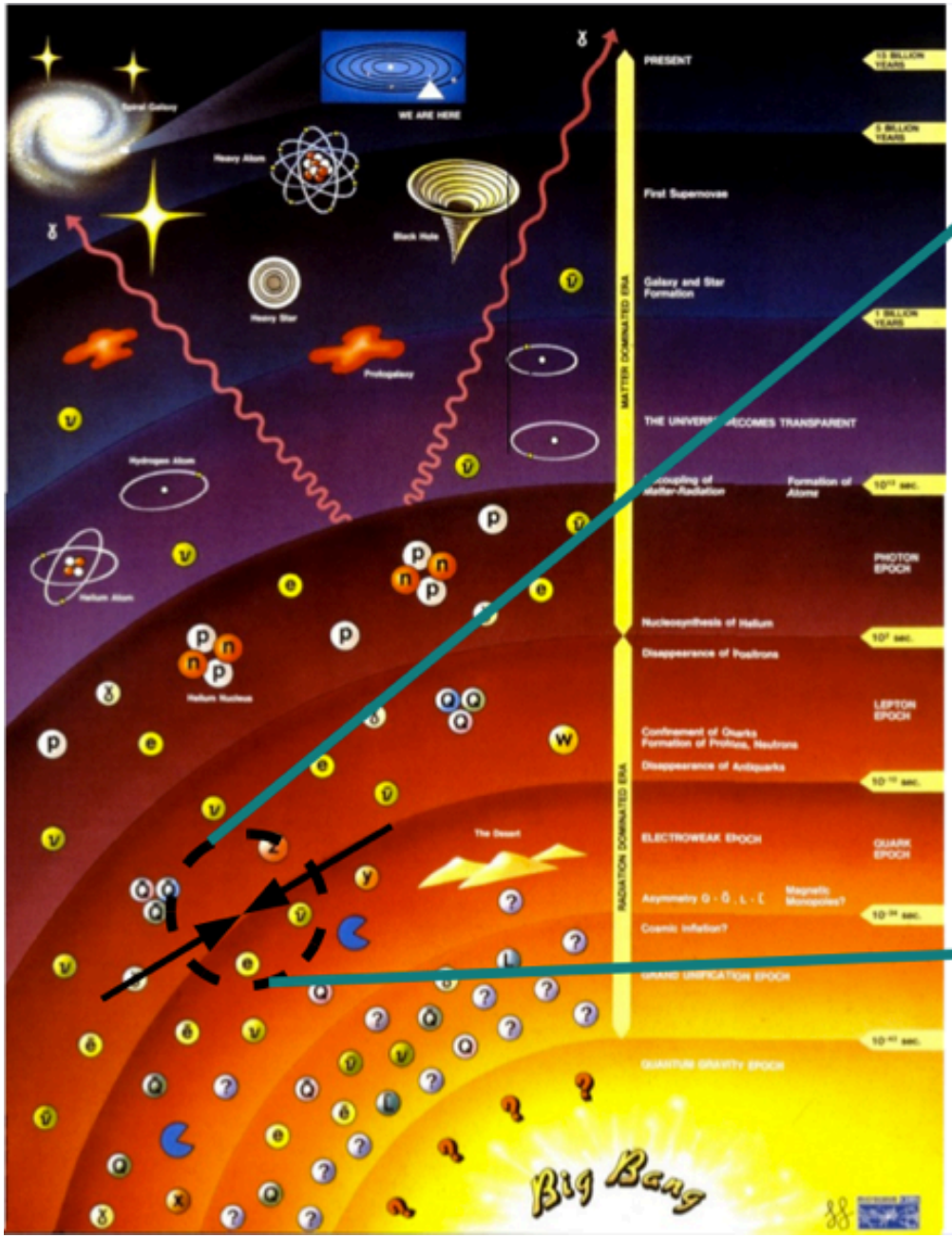
"Dass ich erkenne, was die Welt im Innersten zusammenhält."

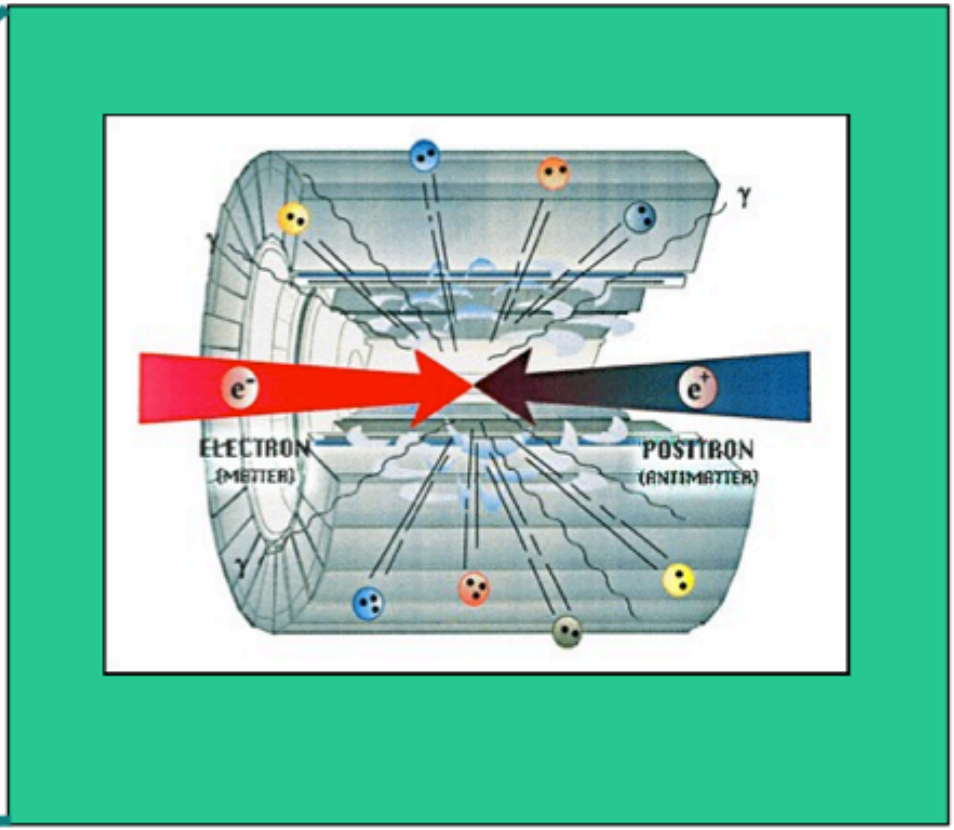
Goethe, Faust



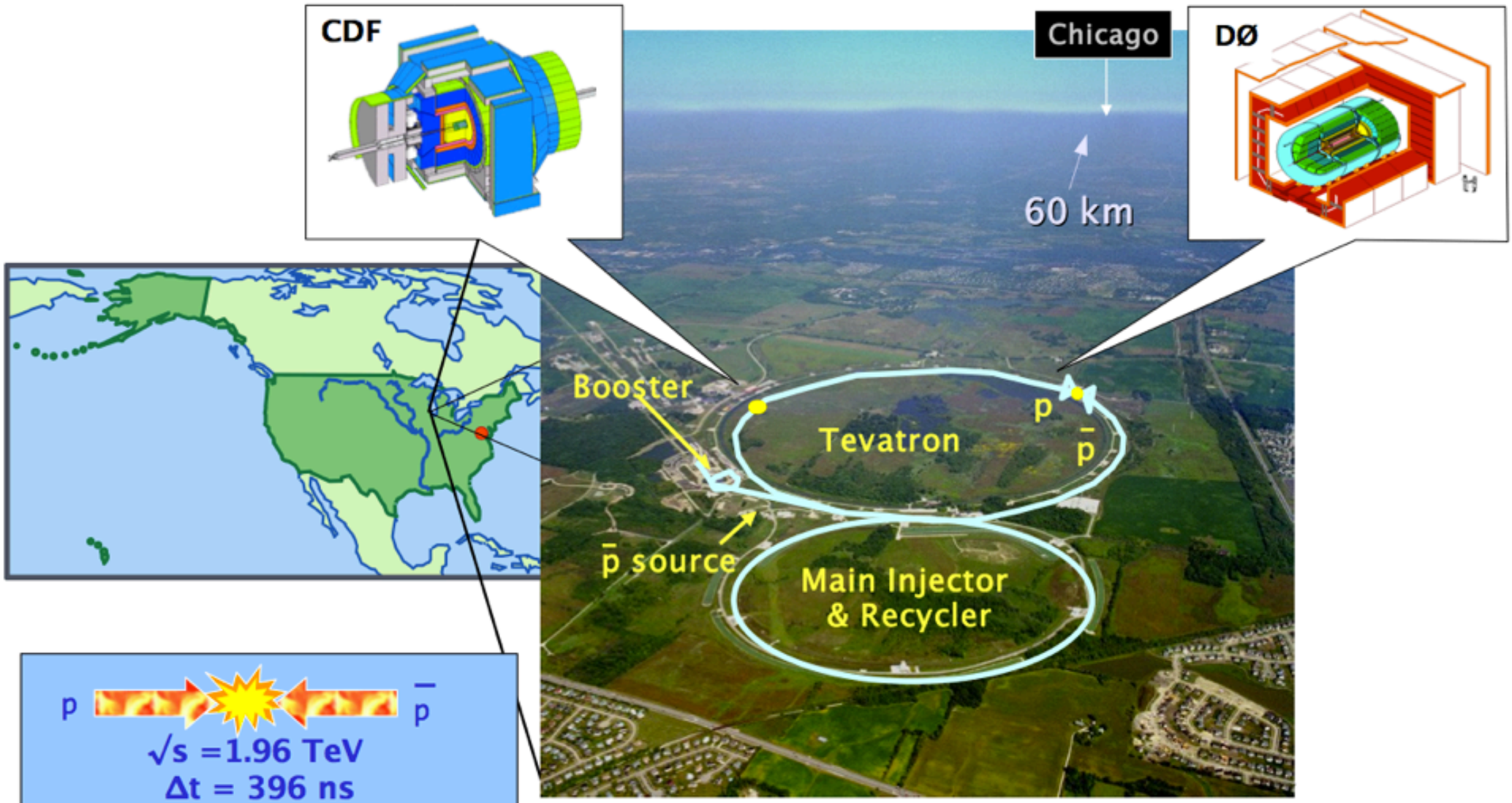
➔ **from the smallest dimensions in microcosm to the largest dimensions in the Universe**

Big Bang in the Lab?





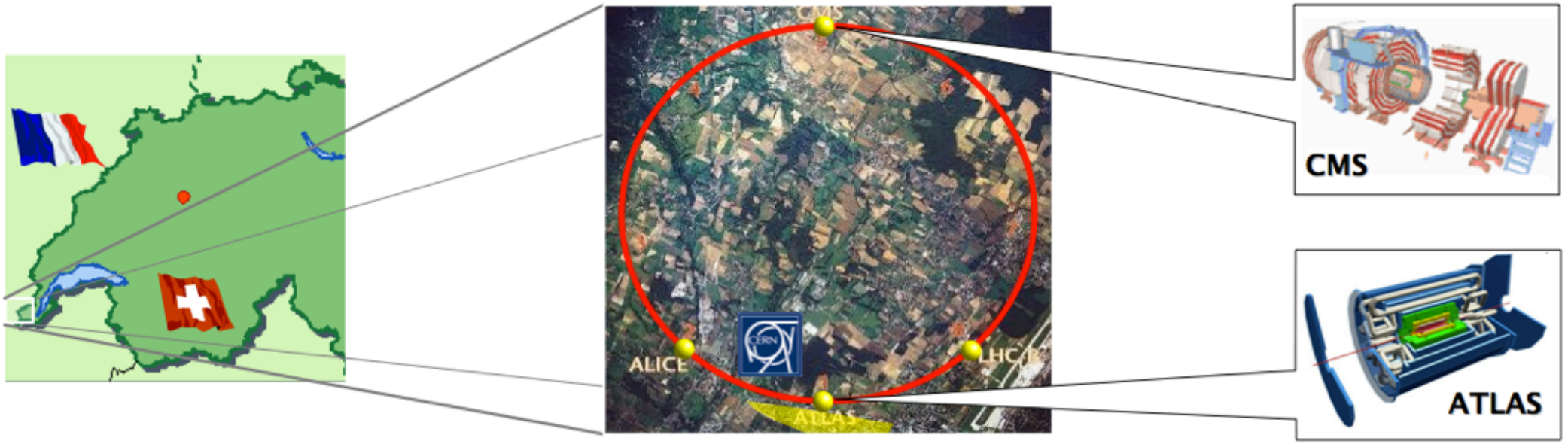
The Tevatron $p\bar{p}$ Collider at Fermilab



30 September 2011

Tevatron complex shut down after 26 years of successful operation.

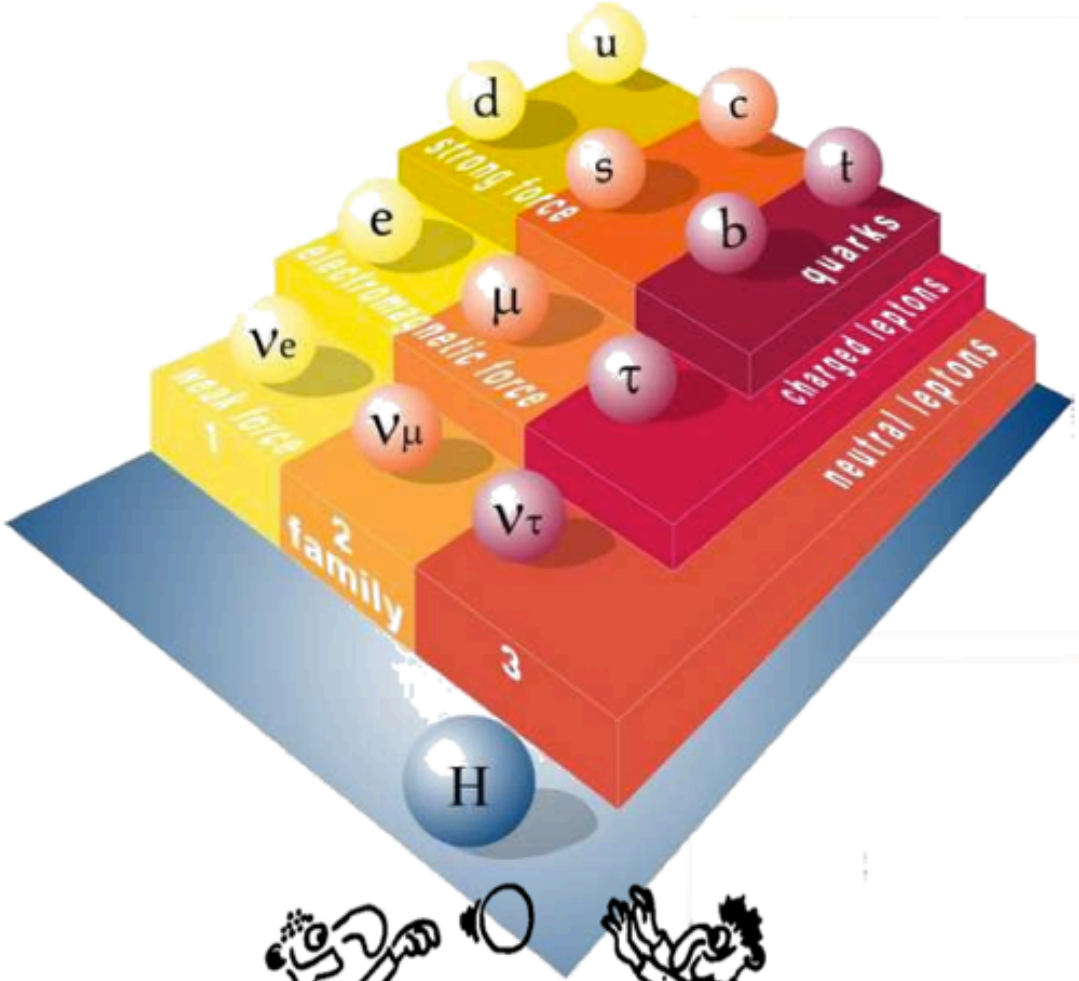
The LHC pp Collider at CERN

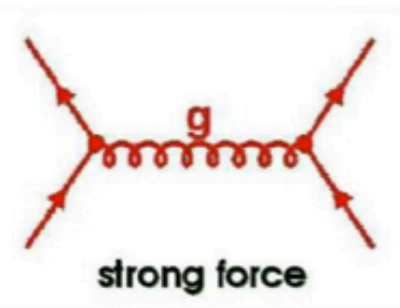


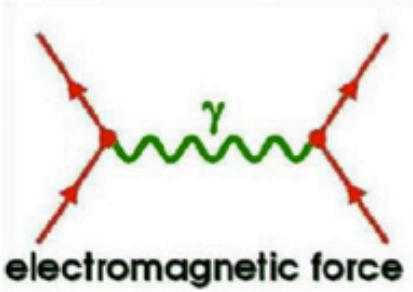
The Large Hadron Collider:

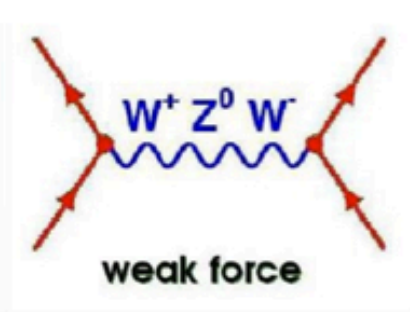
- proton–proton collider
- high energy: $\sqrt{s}$ = 7 TeV
- since 2012: $\sqrt{s}$ = 8 TeV
- 2014–2030??: $\sqrt{s}$ = 13 TeV

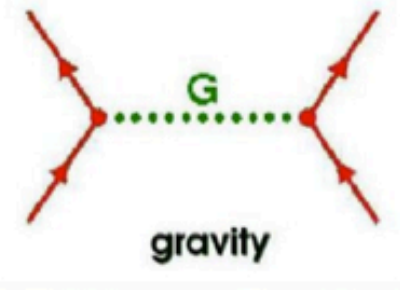
The Standard Model of Particle Physics

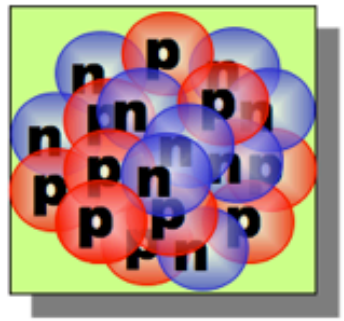


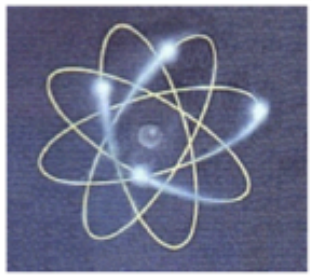


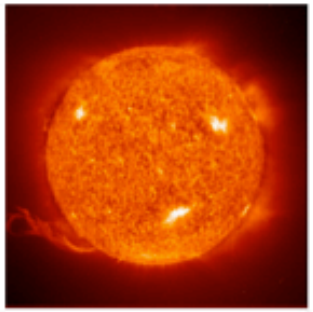


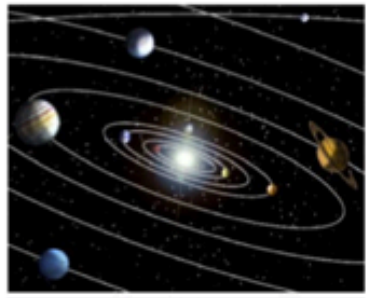




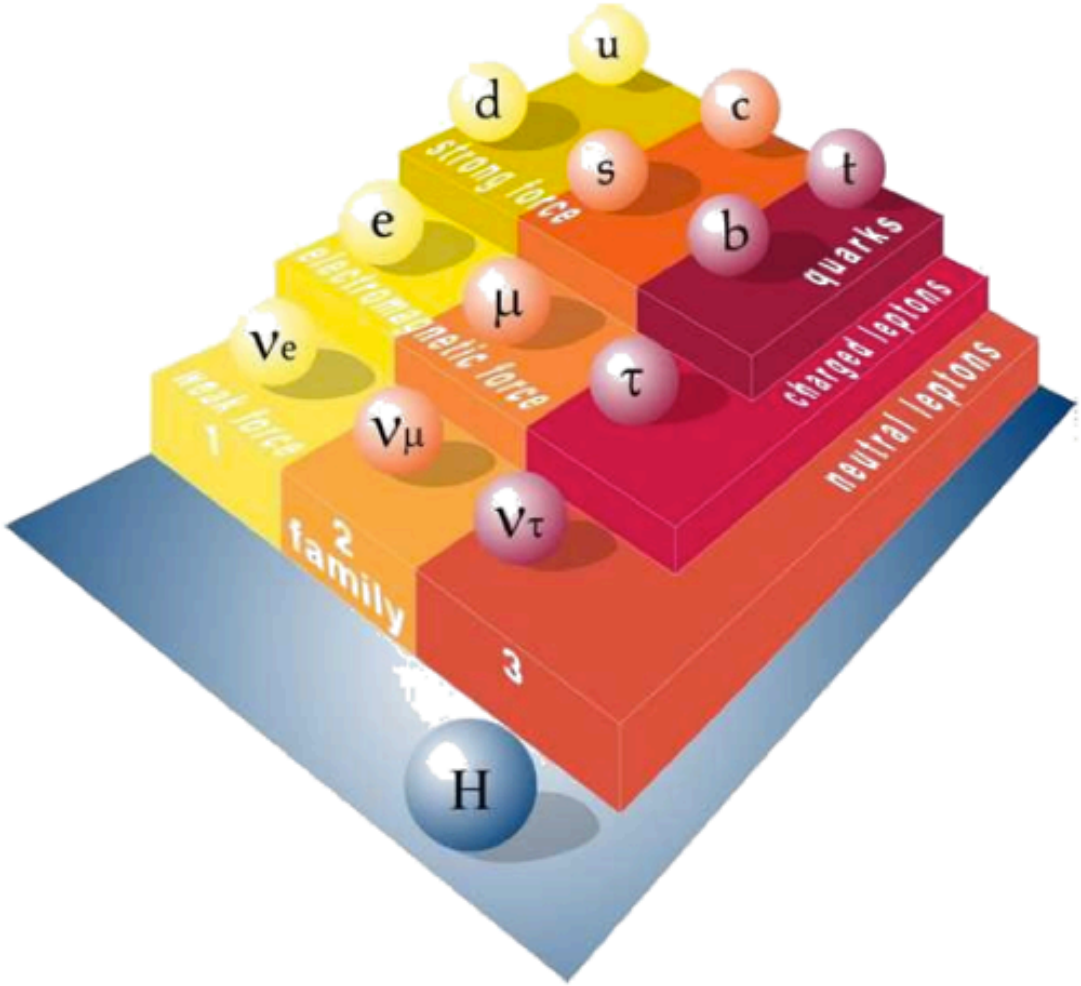


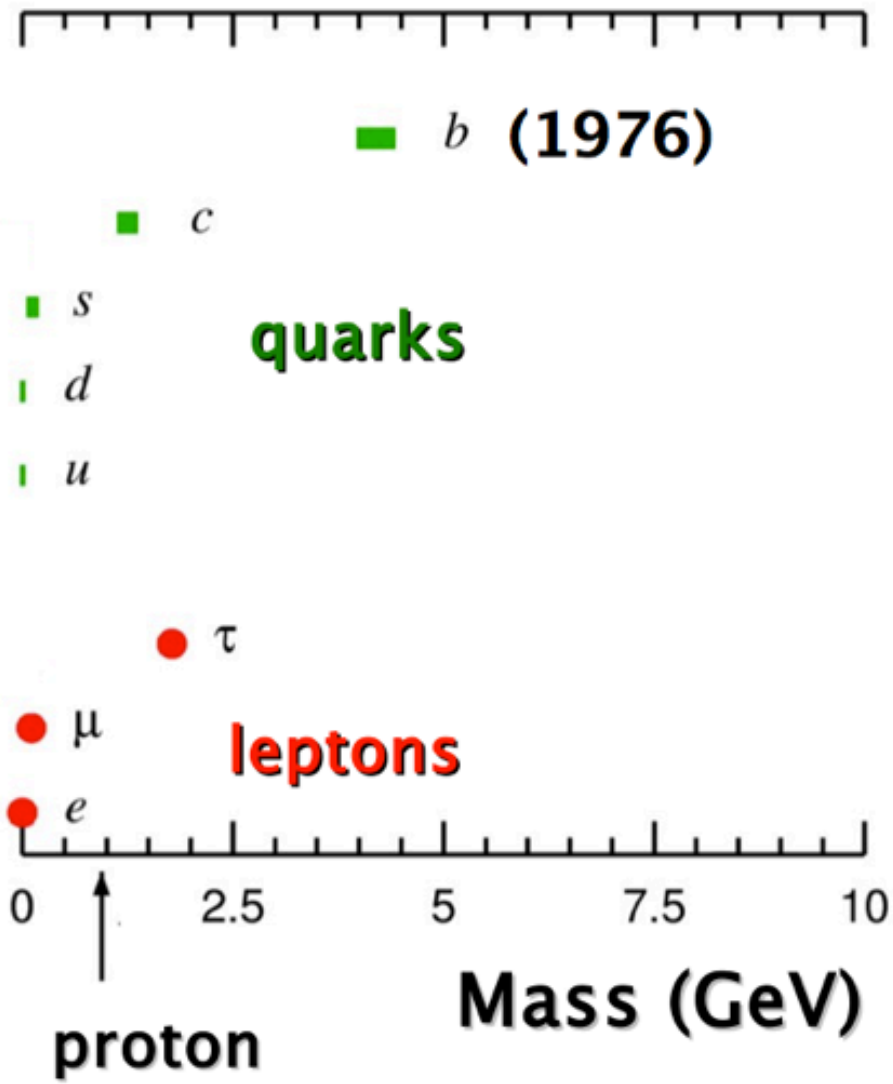






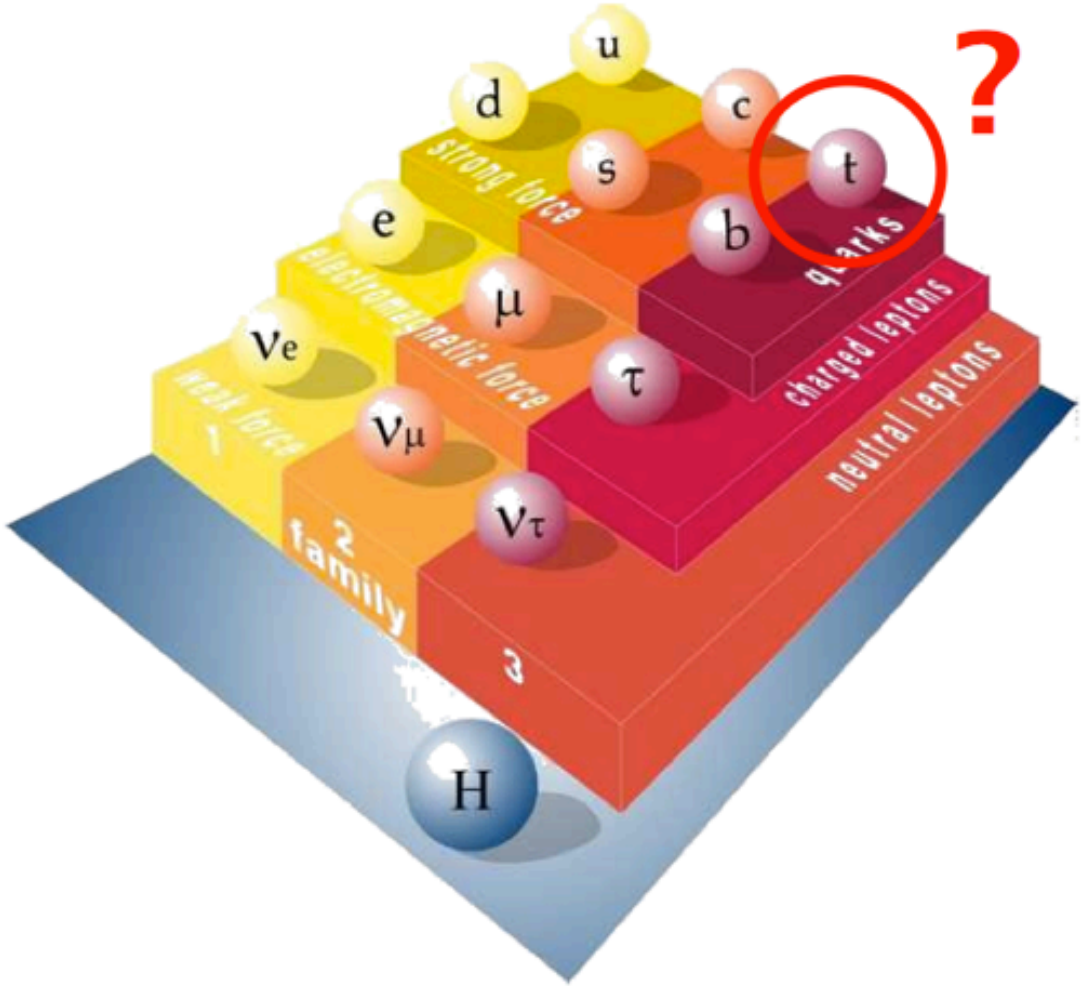
Particle Masses

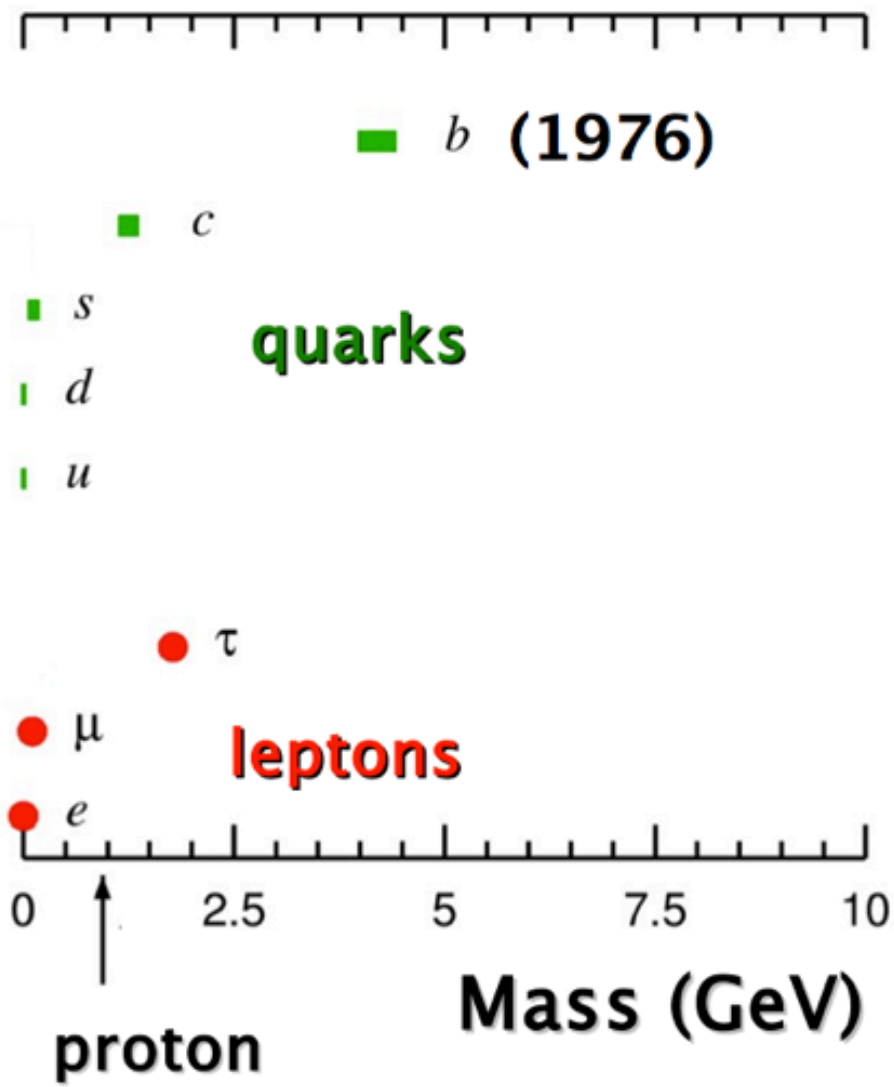




neutrino masses ≪ 1 eV

The Top Quark





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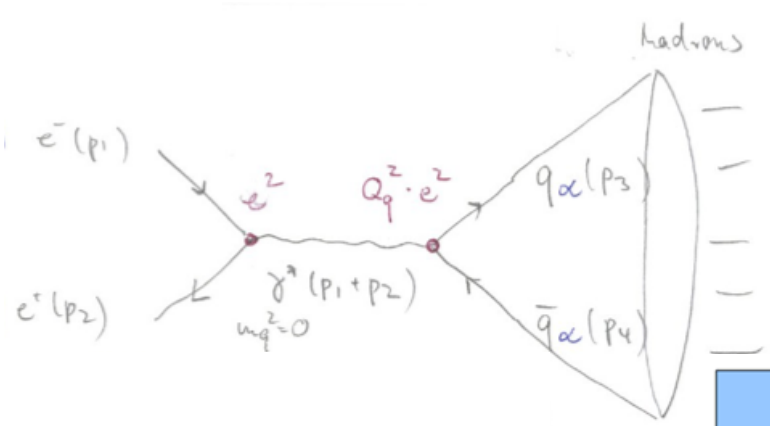
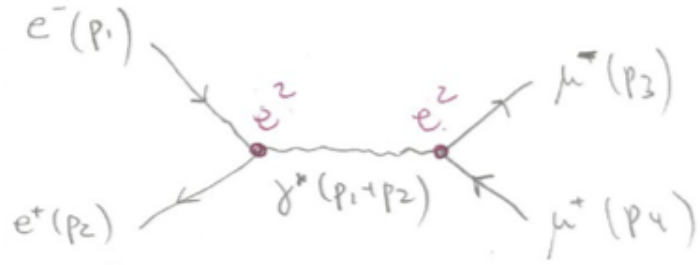
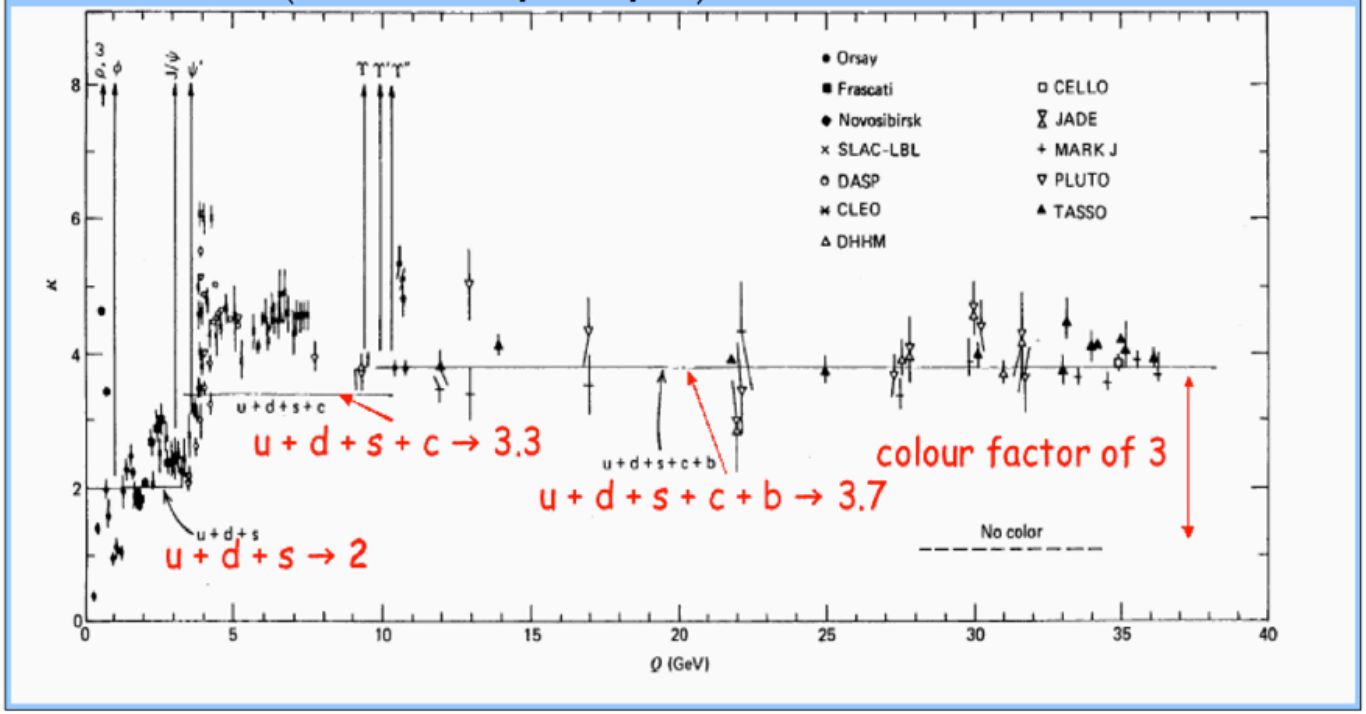
History of the Top Quark Search





$$R = \frac{\sigma(e^+ + e^- \to hadrons)}{\sigma(e^+ + e^- \to \mu^+ + \mu^-)} = \frac{3\sum(quark\ charge)^2}{1^2}$$

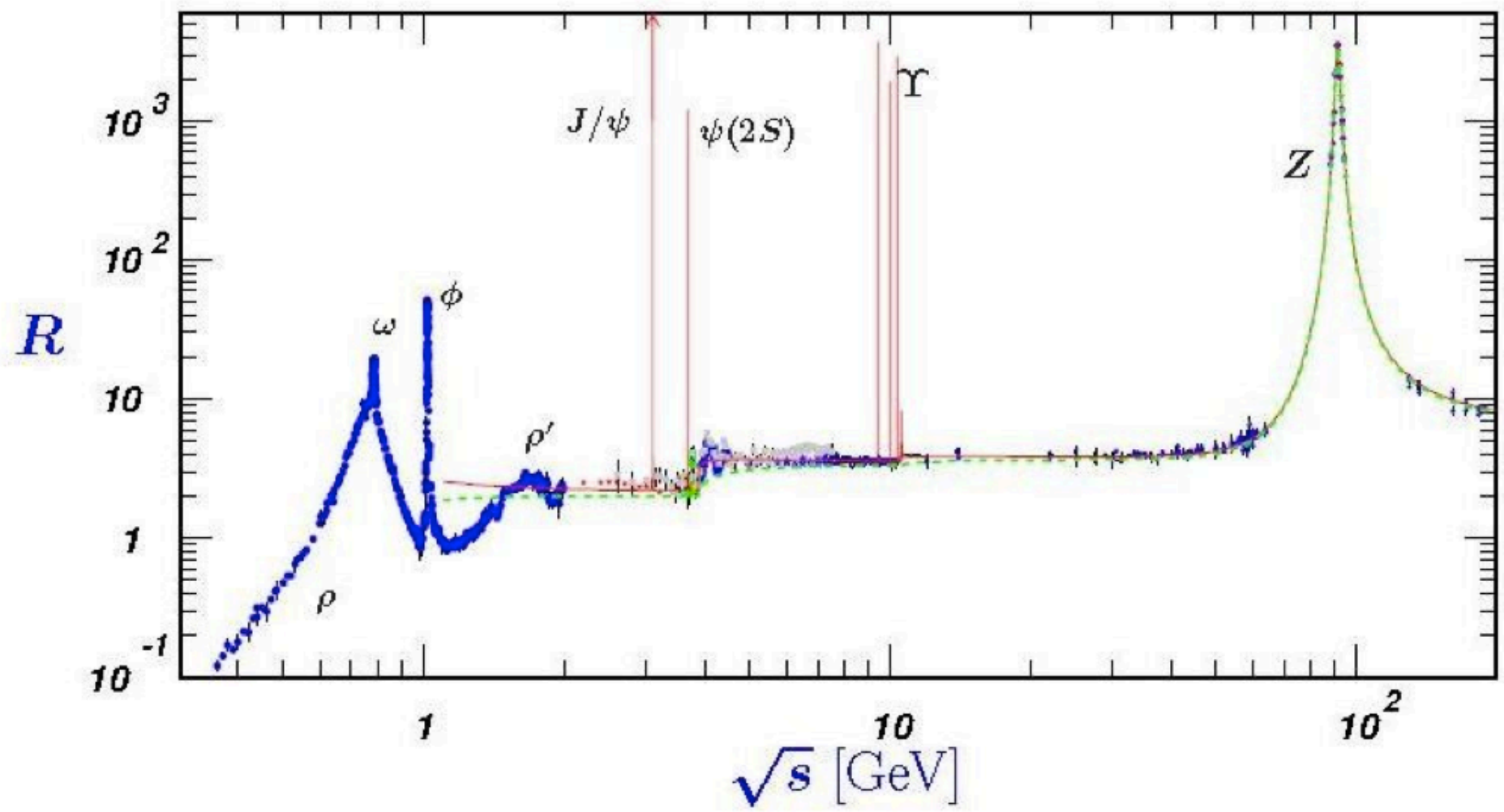


History of the Top Quark Search

- **1976: Discovery of Upsilon at Fermilab**

Contains a 5th quark: the b-quark

→ Structure of quark families suggested existence of a 6th quark: the top

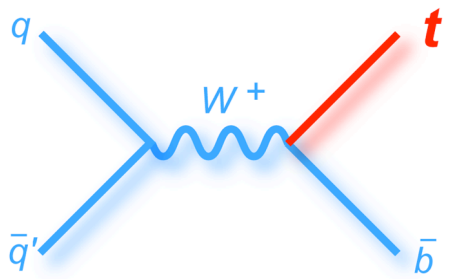


History of the Top Quark Search

- From here on the race to find the top began
  - Petra (e^+e^-) at DESY, Hamburg: m_t>23.3 GeV in 1984
  - Tristan (e^+e^-) in Japan: m_t>30.2 GeV in late 80s
  - UA1&UA2@SPS ($p\bar{p}$) at CERN: discovery of W and Z in 1983
  - UA1: m_t>44 GeV in 1988

    (after having an excess in 1984 which they thought was evidence for top)
  - LEP (e^+e^-) at CERN : m_t>45.8 GeV in 1990
  - UA2: m_t>69 GeV

    ⇒ W → tb search channel closed down



$M_W > m_t + m_b$

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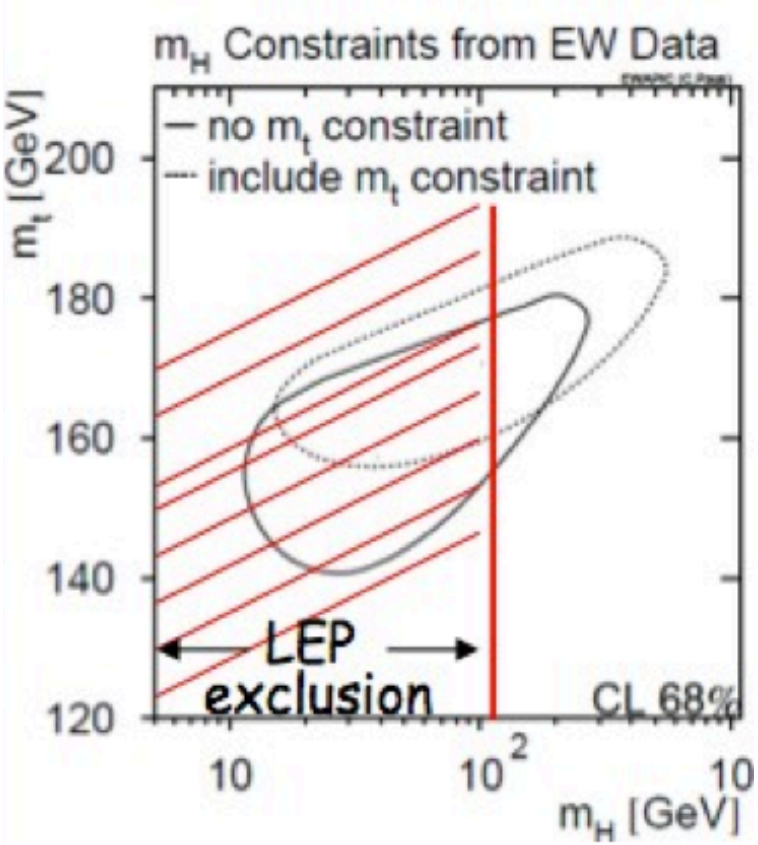
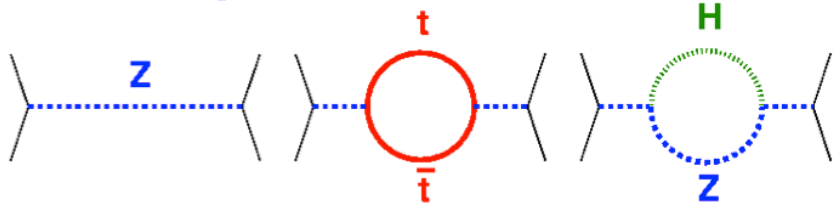


Electroweak precision data

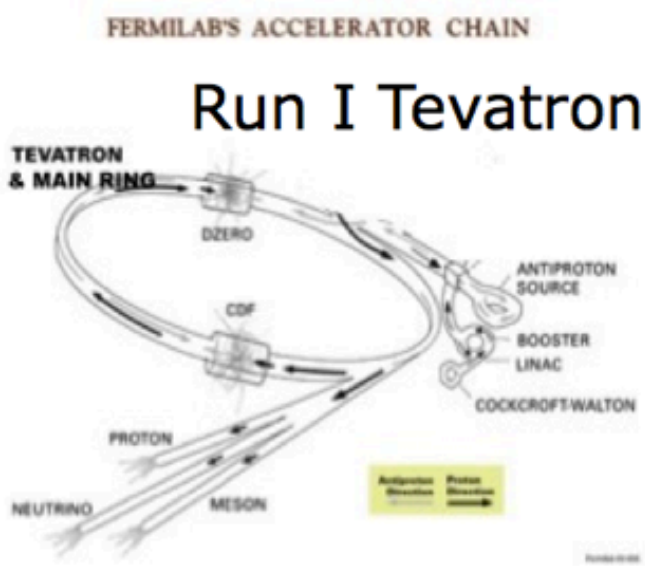


$$M_Z^2 = M_Z^{2\ 0.order} / (1 - \Delta)$$

$$\Delta \approx \ldots m_t^2 \ldots + \ldots \ln m_h \ldots$$

History of the Top Quark Search

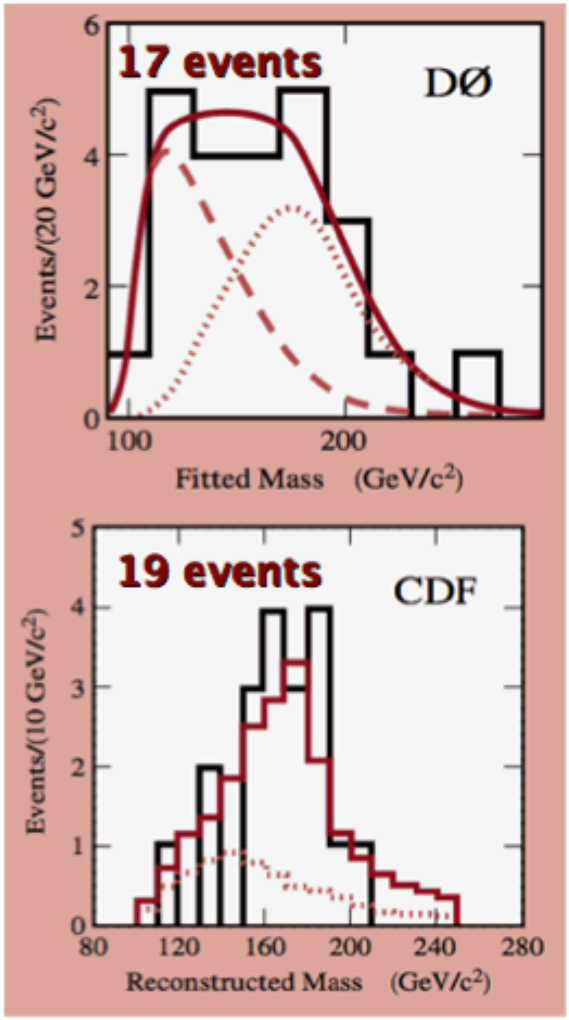
- 1984/85: Tevatron collider commissioned and dedicated
- October 1985:
  First collisions recorded by CDF
  - DØ: still in construction
- 1987: CDF Run-0
- 1992: First collisions by DØ
- Run I (1.8 TeV): 1992-1996
  - 1995: Discovery of the top quark!
  - In total ~120pb^{-1} per experiment
  - DØ: more focused on calorimetry
  - CDF: more focused on tracking



The Top Quark

discovery

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



1995, CDF and DØ experiments, Fermilab

The Top Quark

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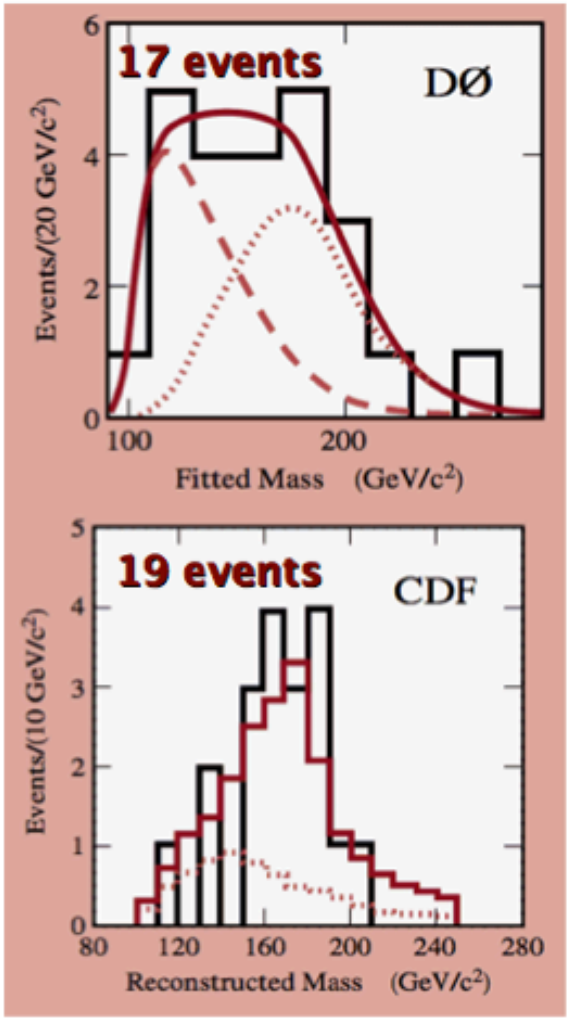

1995, CDF and DØ experiments, Fermilab

March 2nd, 1995:
First announcement of Top Discovery
in public seminar at Fermilab

The Top Quark

discovery

PRL 74, 2632 (1995)
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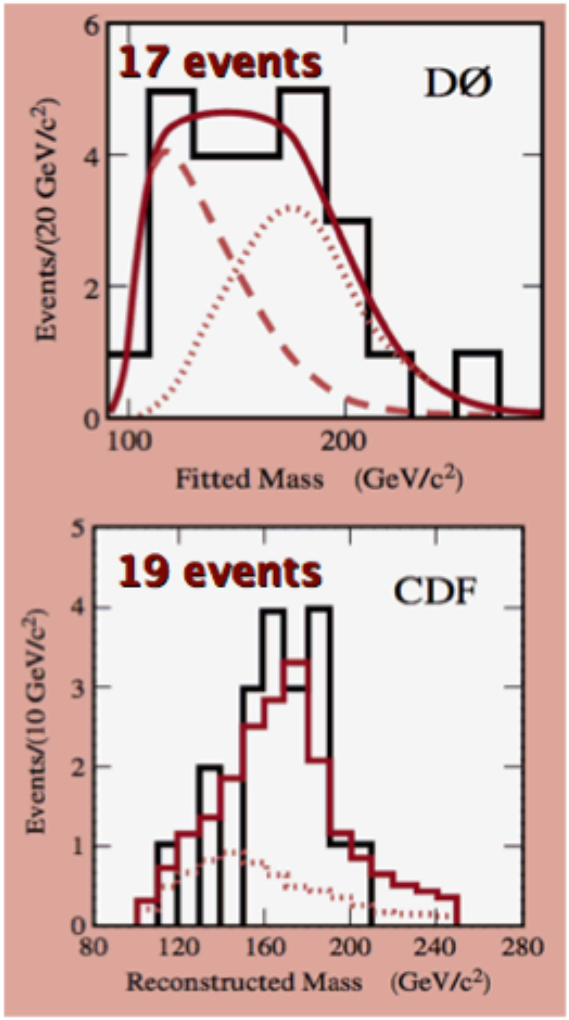
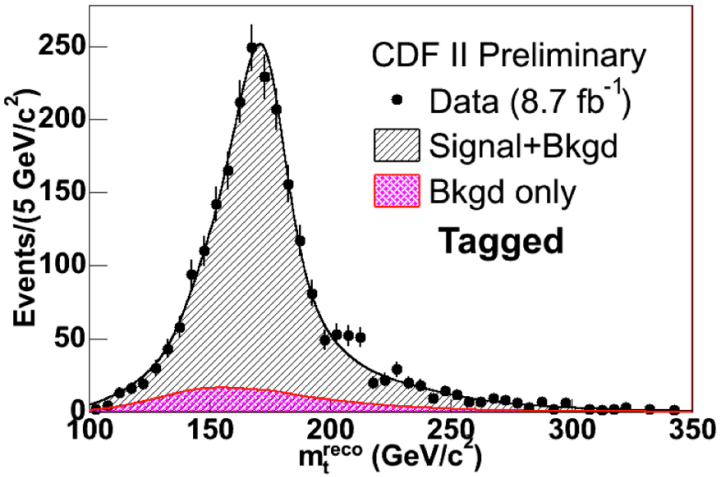


1995, CDF and DØ experiments, Fermilab

today

1000s of events



The Top Quark

discovery

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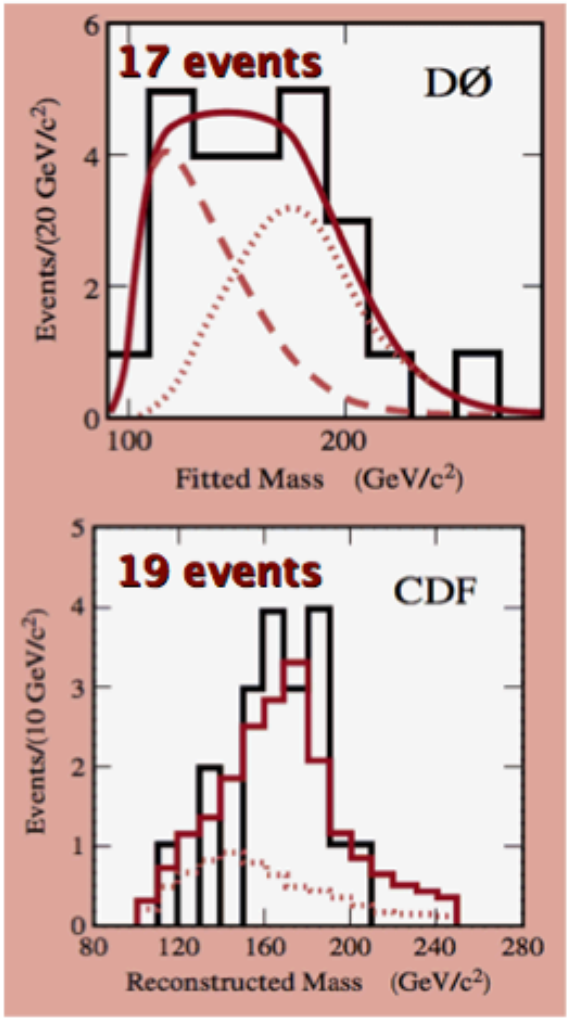

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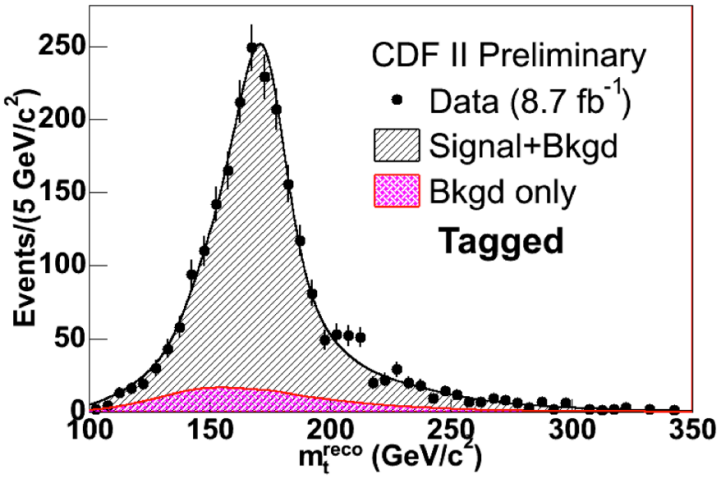
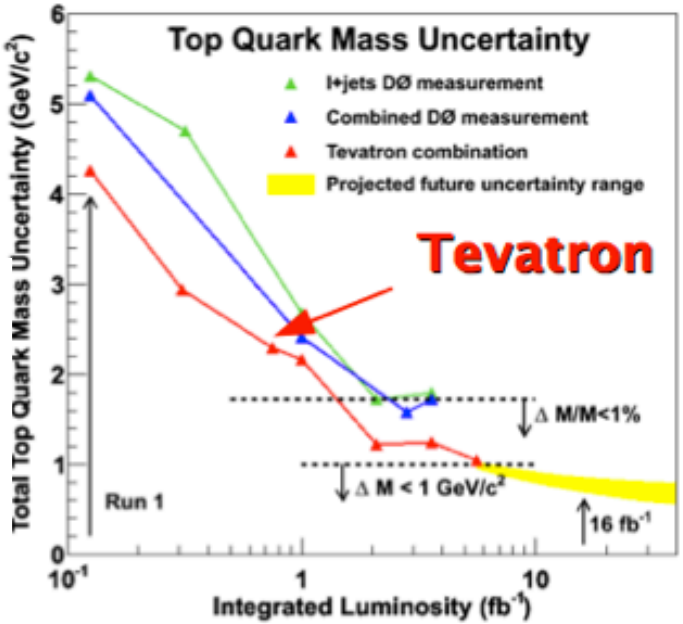


precision



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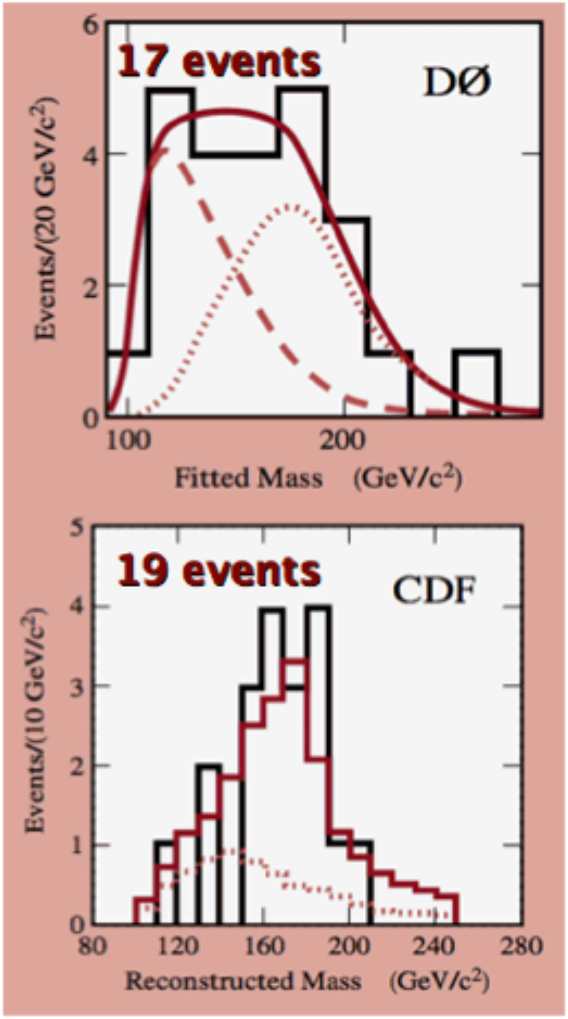

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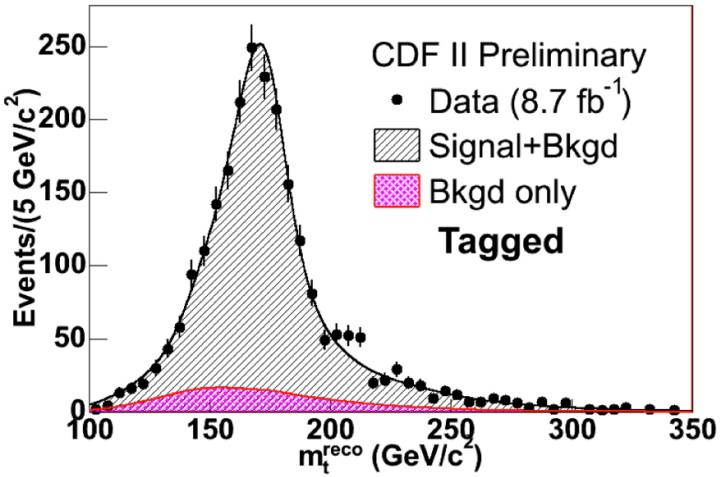

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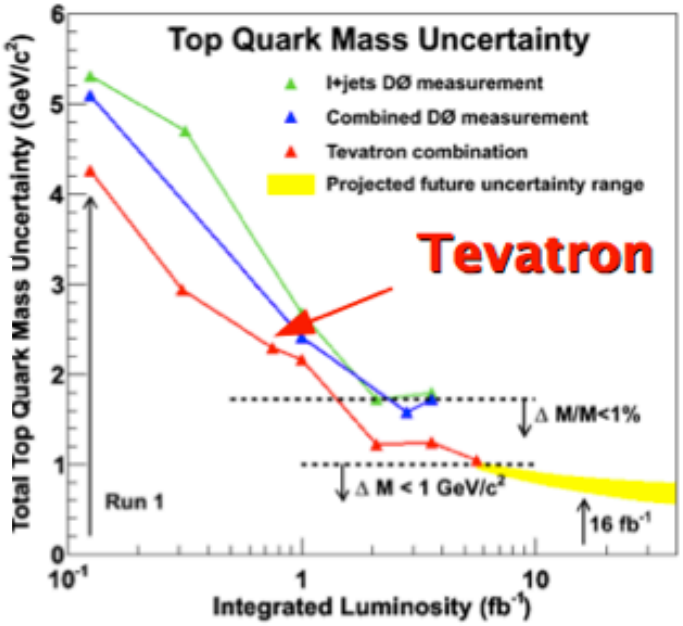

searches

The Top Quark

discovery

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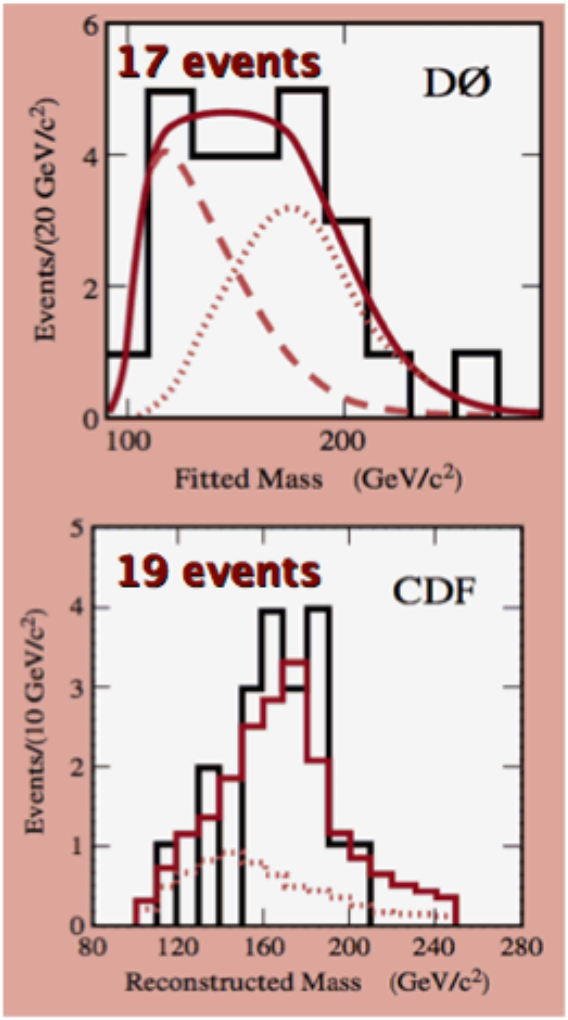

1995, CDF and DØ experiments, Fermilab

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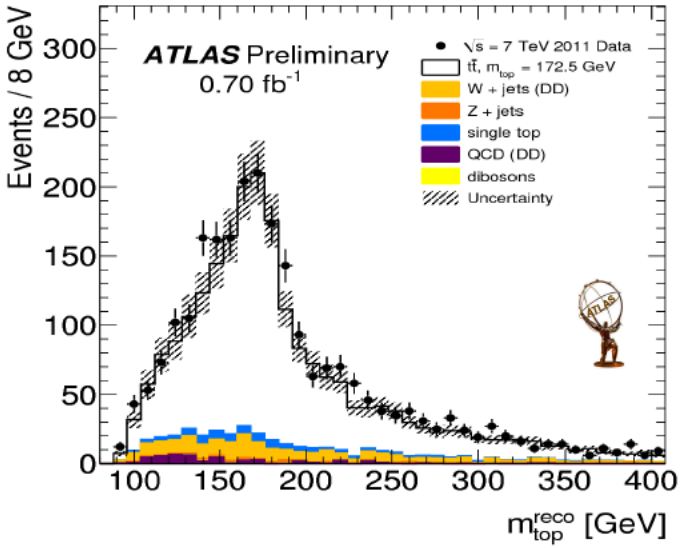
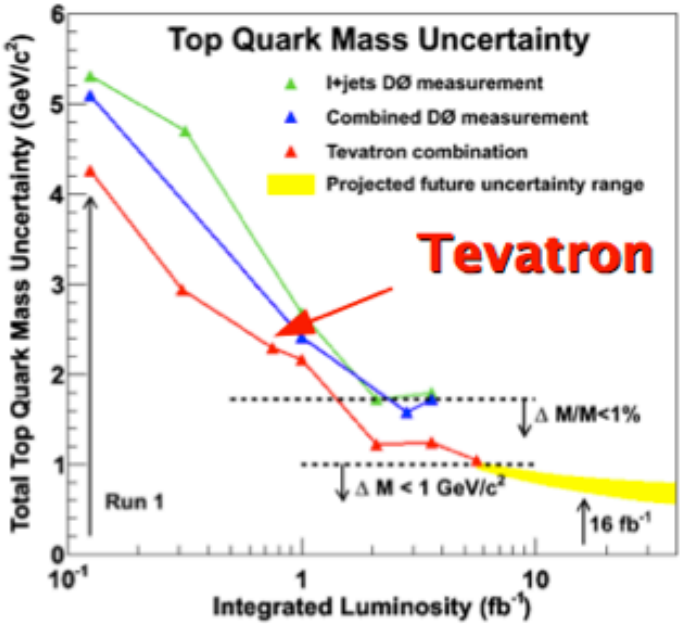


LHC: top quark factory

precision



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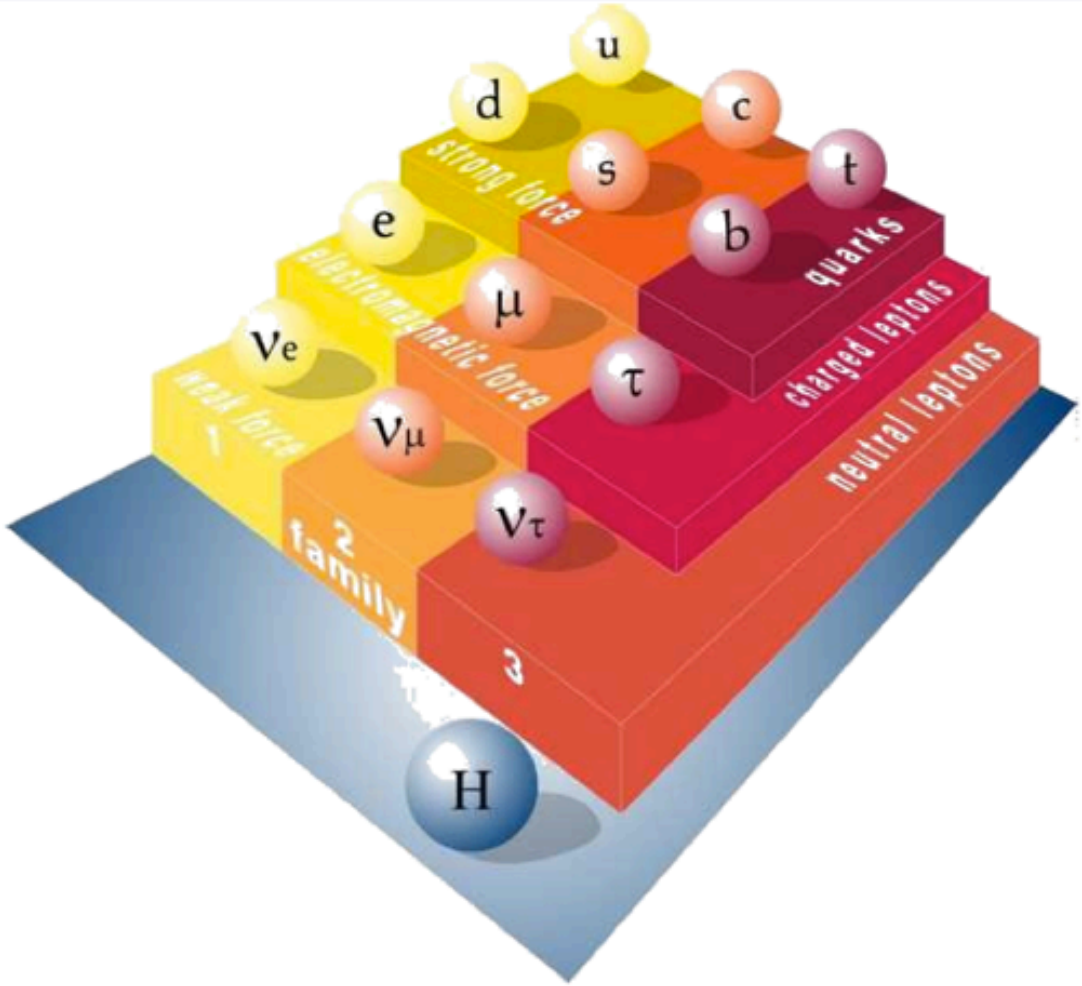
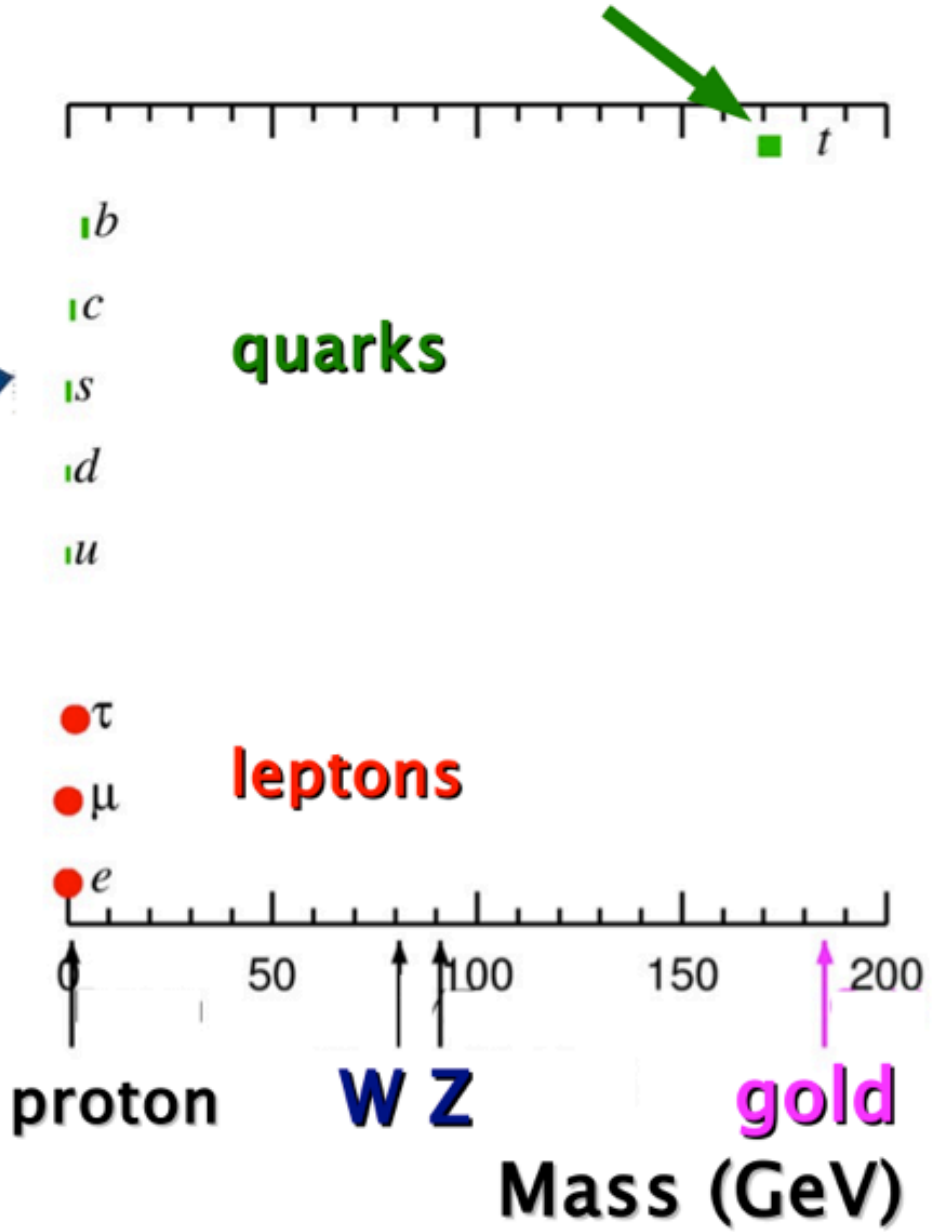
The Top Quark





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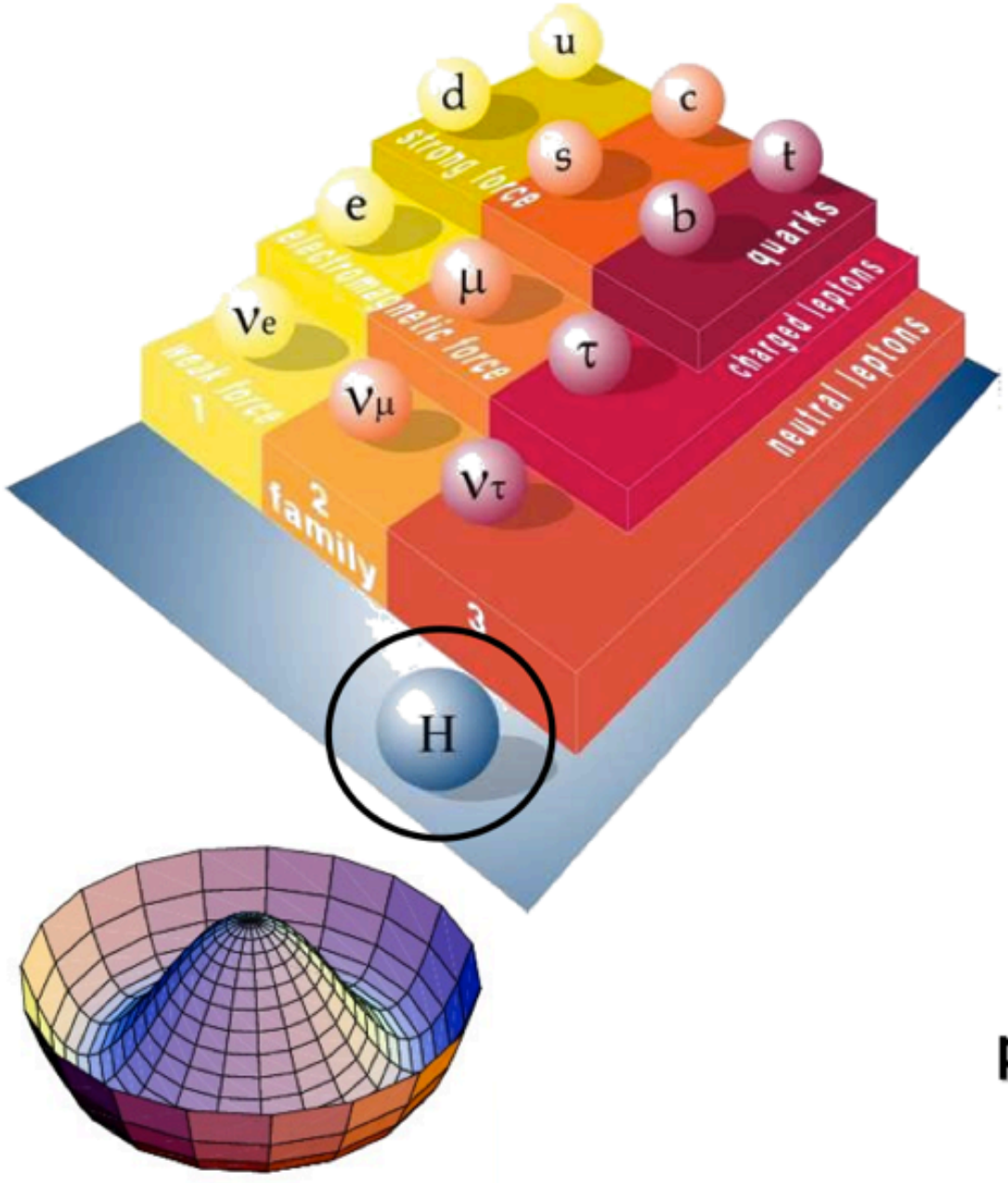

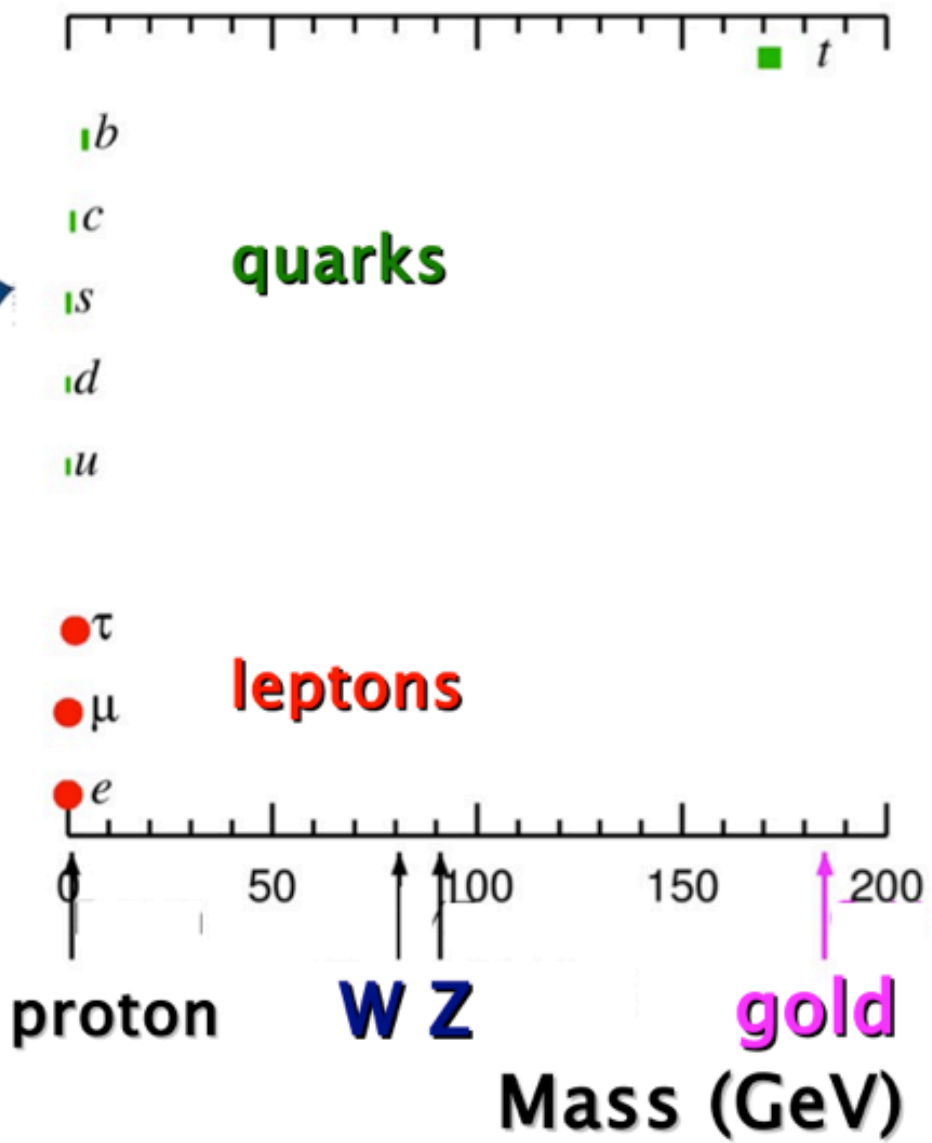

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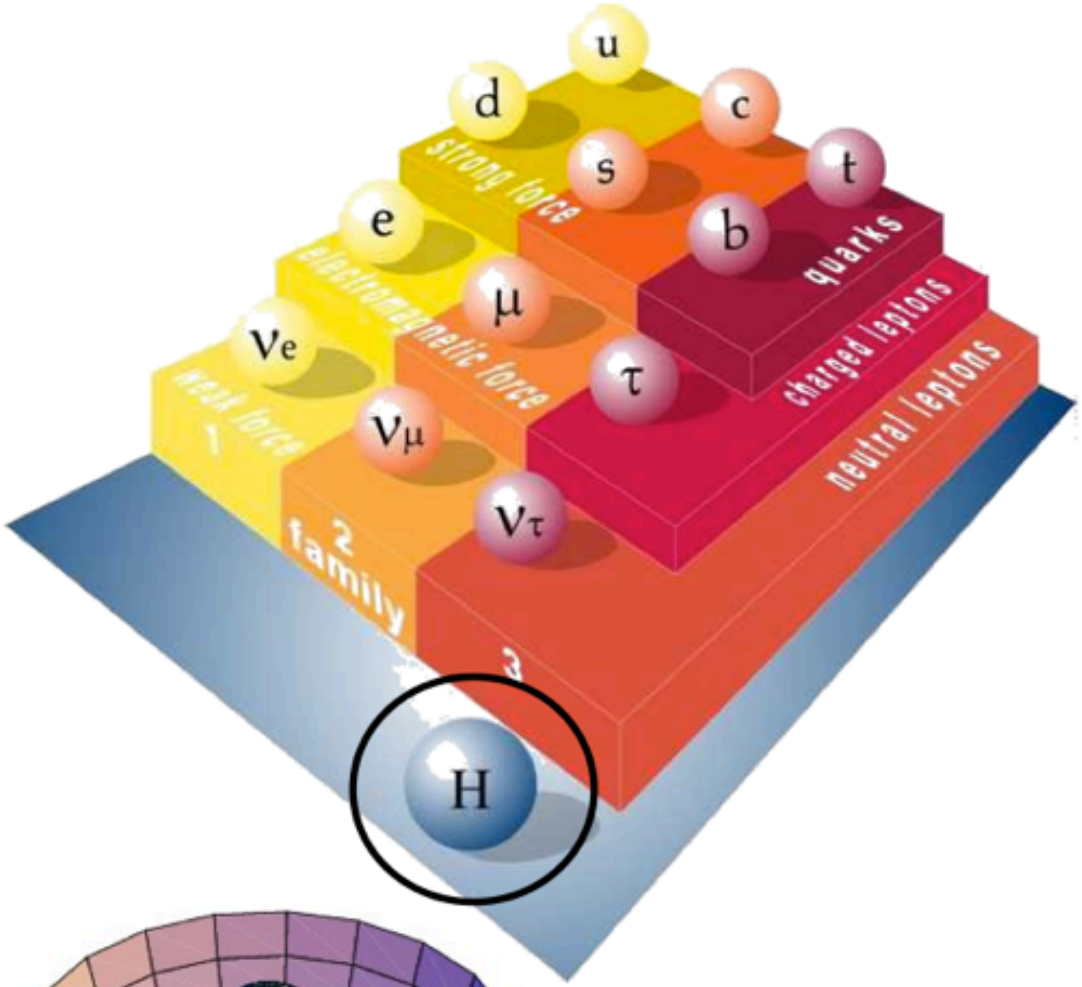
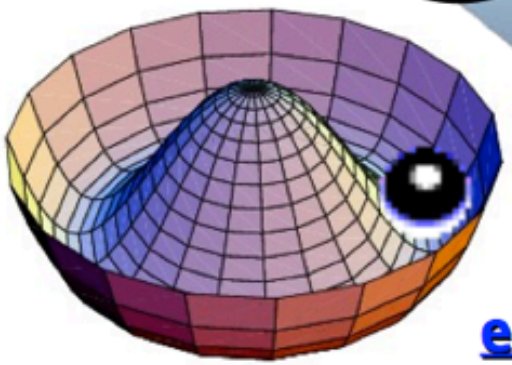
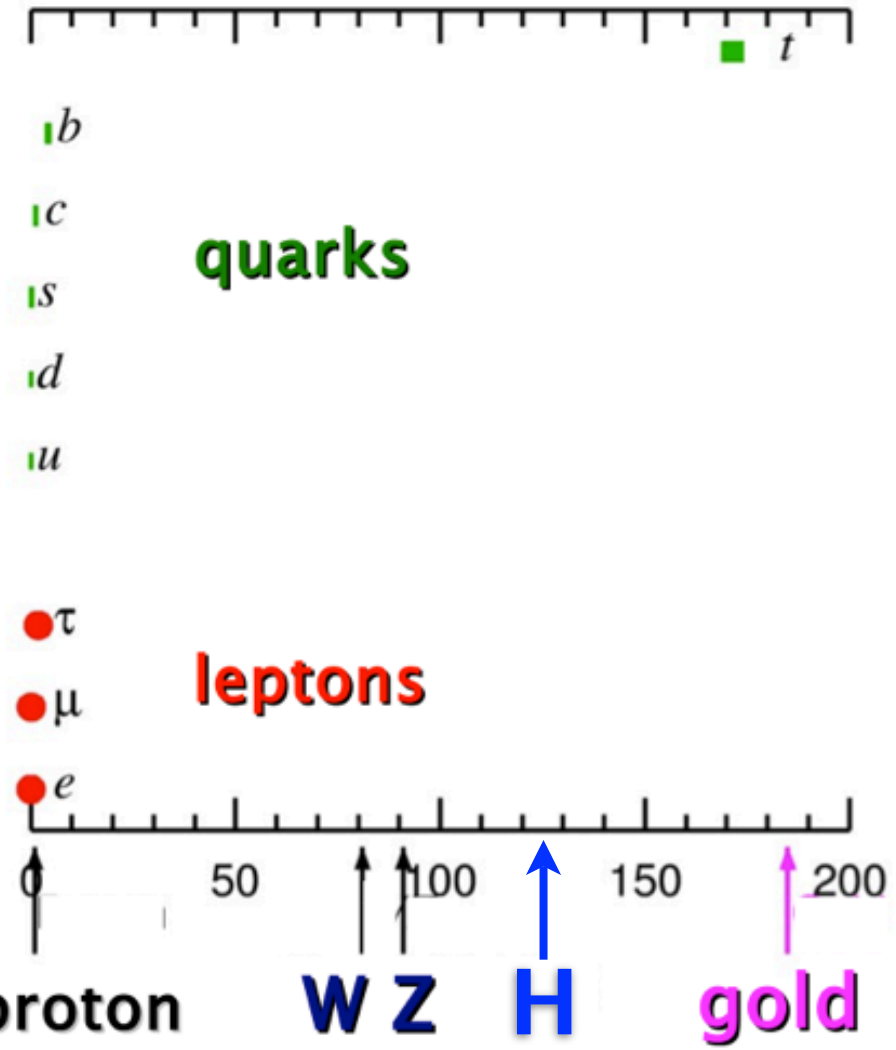
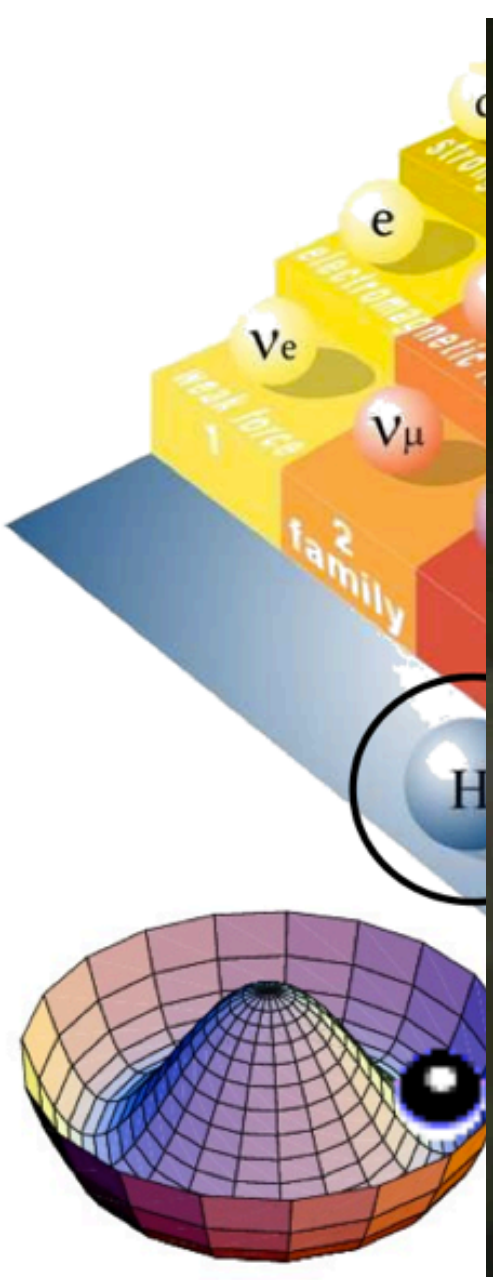






electroweak symmetry breaking

The Top Quark



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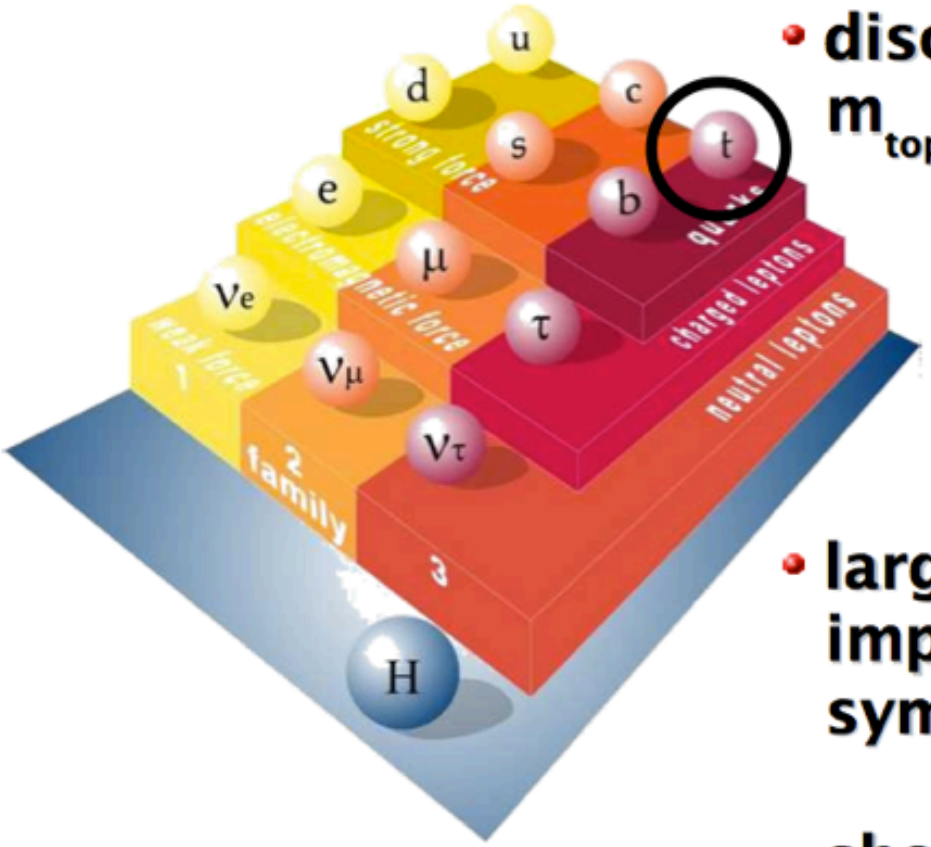
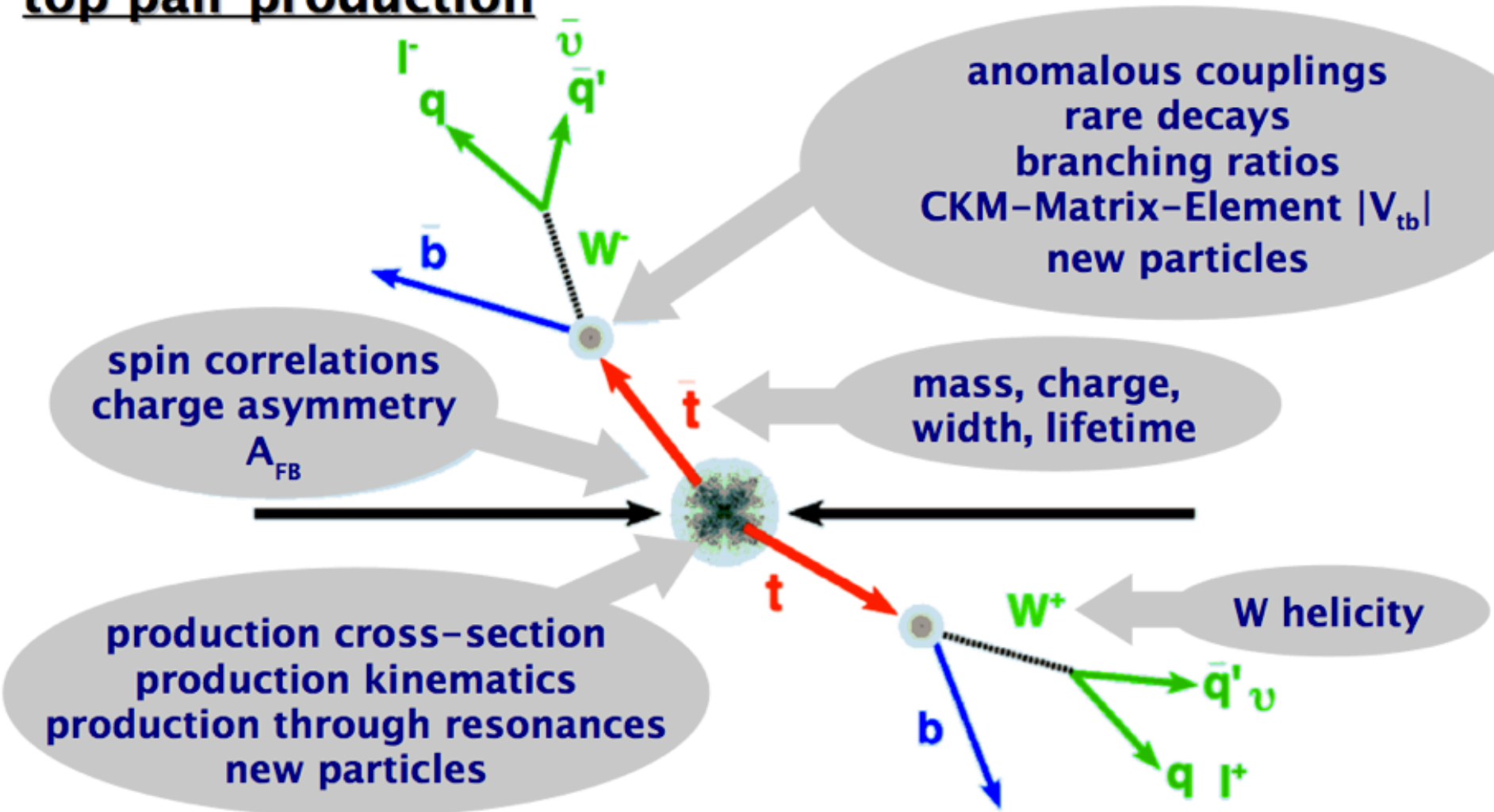


- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}\text{s} \ll \Lambda^{-1}_{QCD}$: decays before fragmenting
  → observe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

Top Quark Analyses

top pair production



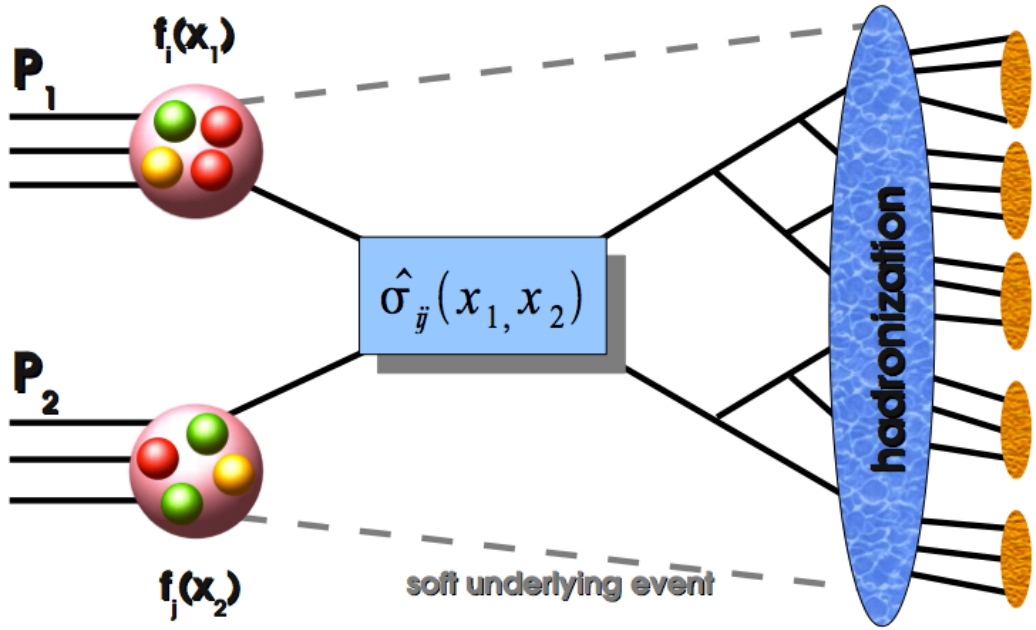
single top production

production cross section, CKM-Matrix-Element $|V_{tb}|$, anomalous couplings, searches for new particles

Outline

Introduction
History of the Top Quark
Top Quark Production
Top Quark Properties
Searches in Top Sector
Conclusions

Cross Section in Hadron Hadron Scattering



$$\sigma = \sum_{i,j=q,\bar{q},g} \int dx_1\, dx_2\, f_i(x_1, Q^2) \cdot \bar{f}_j(x_2, Q^2) \cdot \hat{\sigma}(Q^2)$$

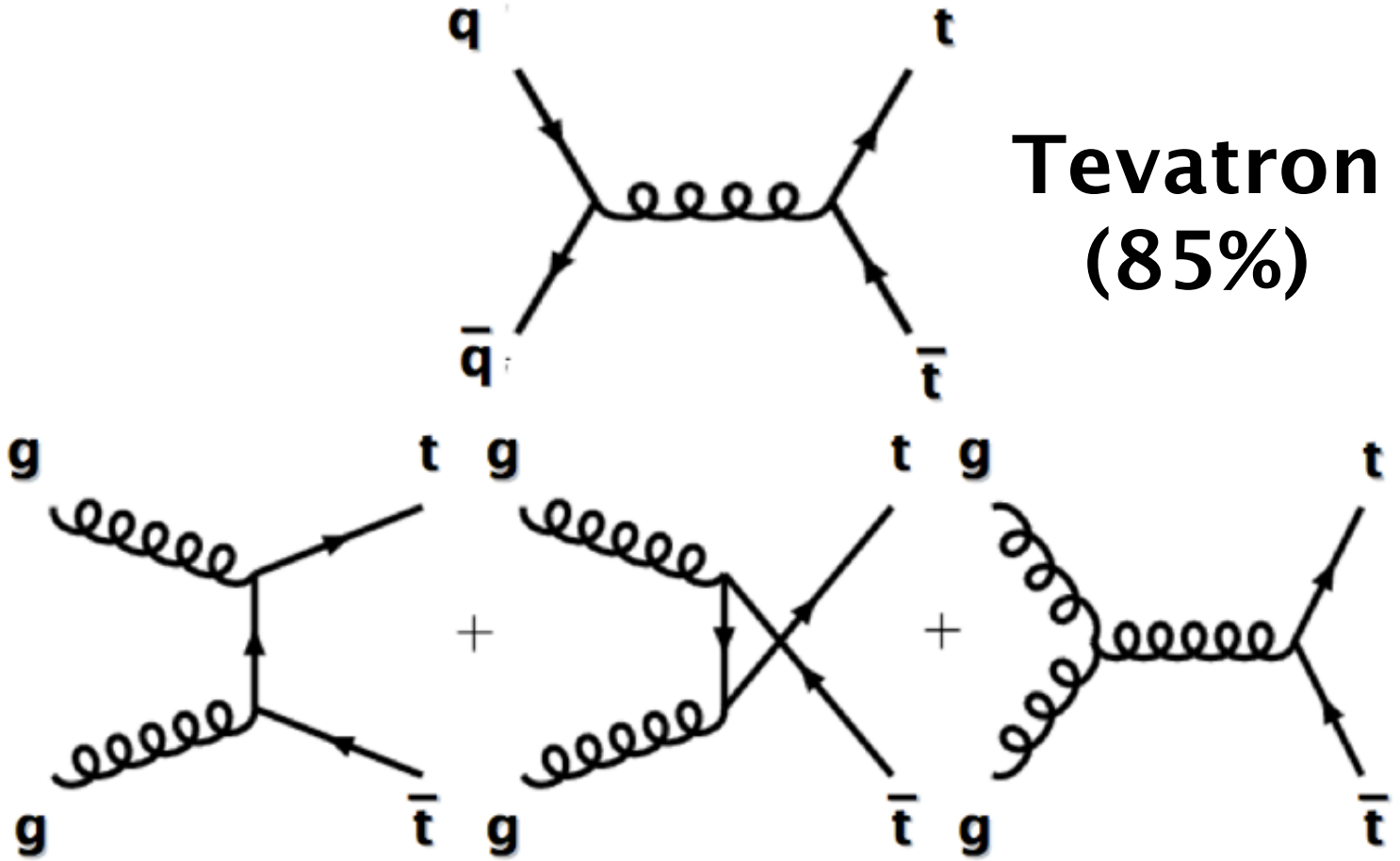
Sum over incoming partons i, j

Momentum fraction for incoming parton

PDF for incoming parton i

"partonic" cross section

Top Quark Pair Production

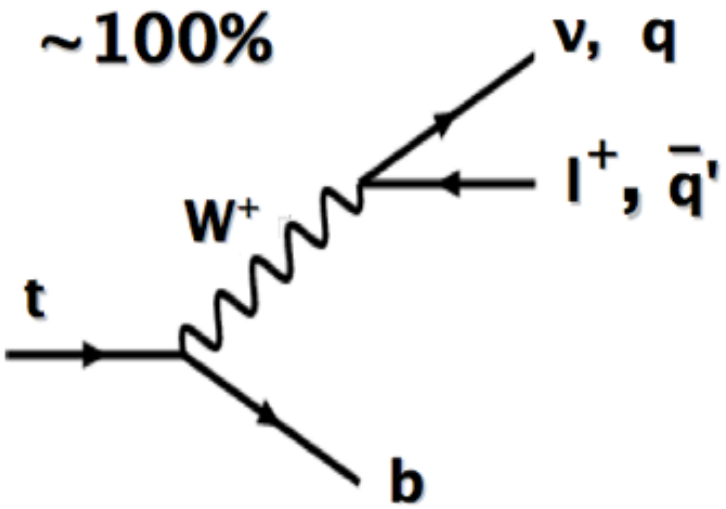


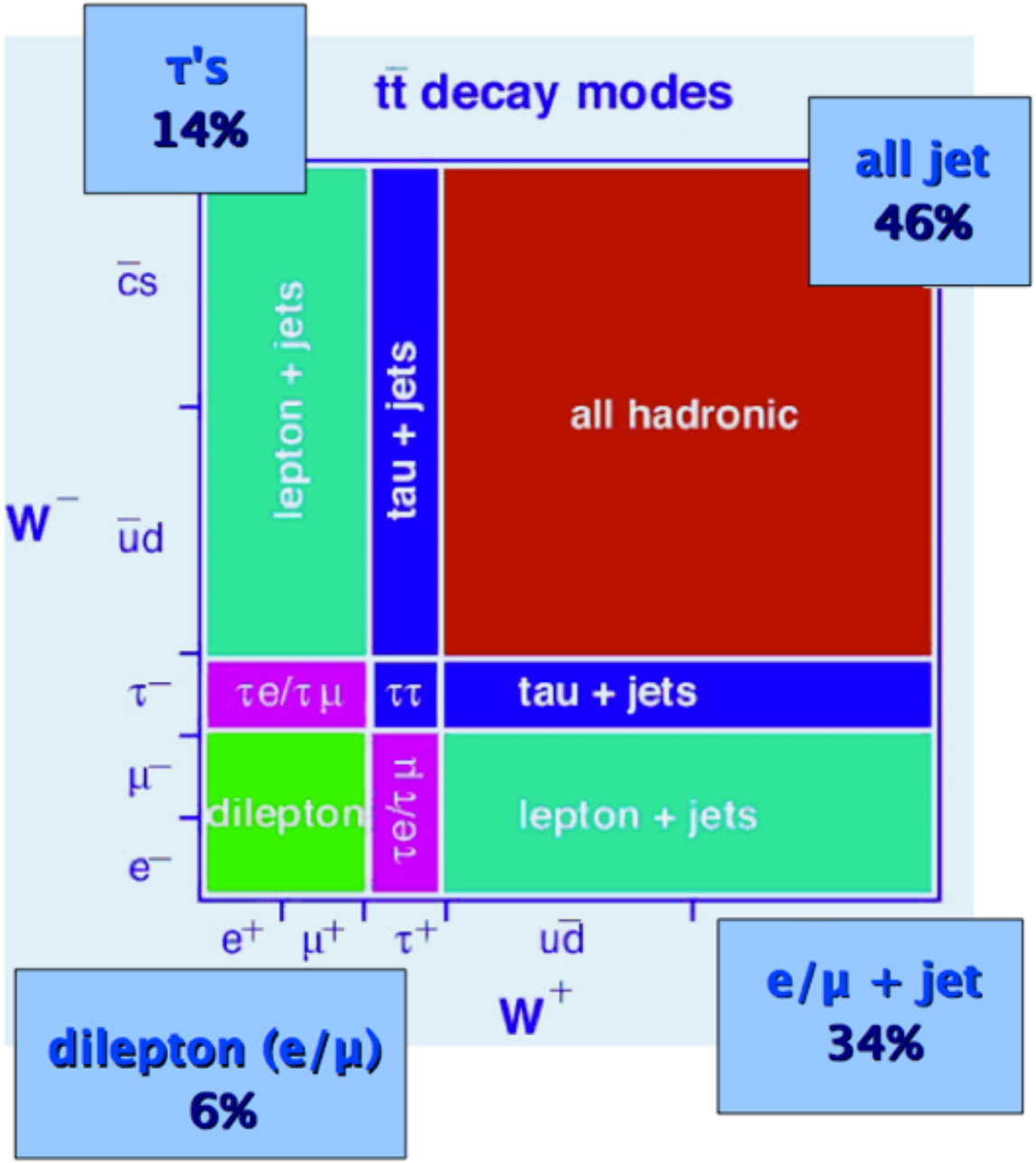
Tevatron (85%)

LHC (87%)
(14 TeV)

Top Quark Pair Signatures

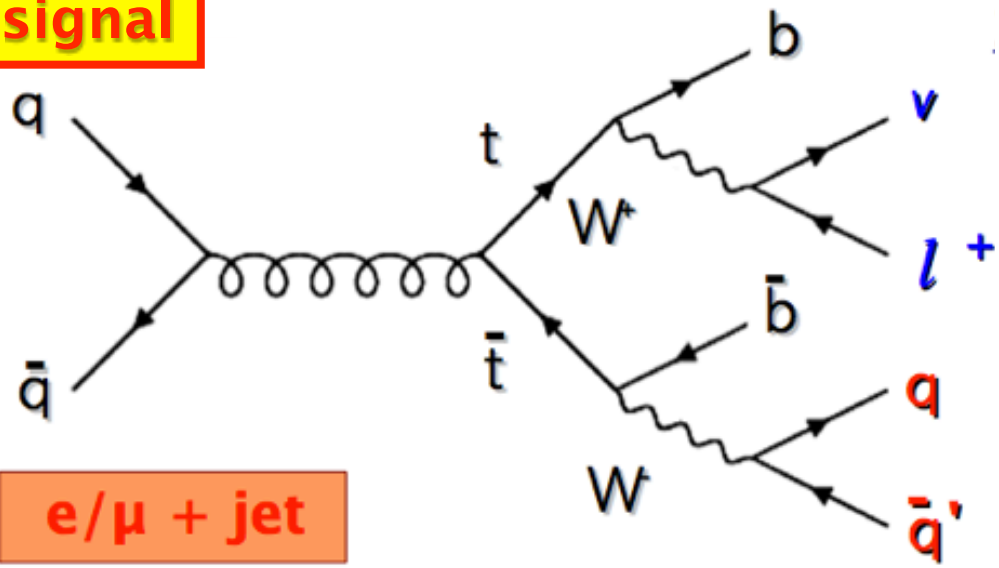
top decay:



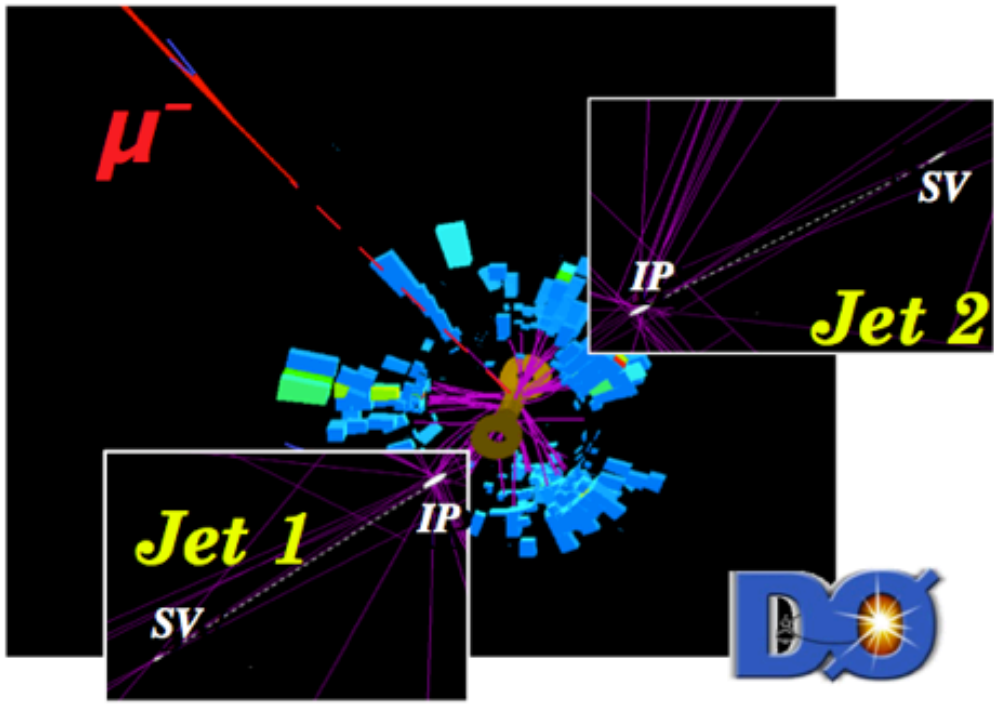


Lepton+jets Signatures

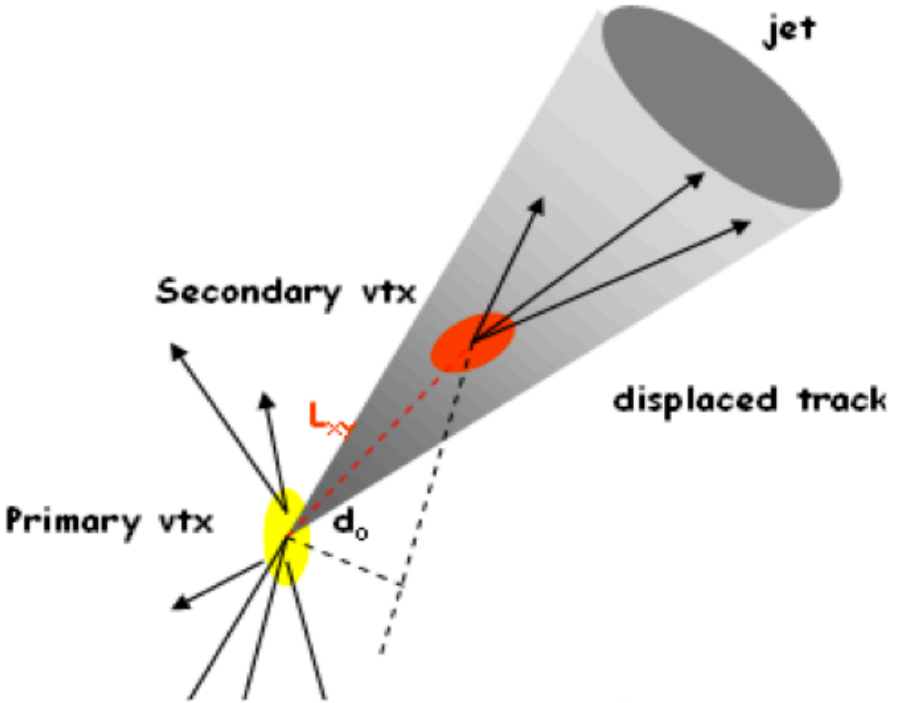
signal



e/μ + jet

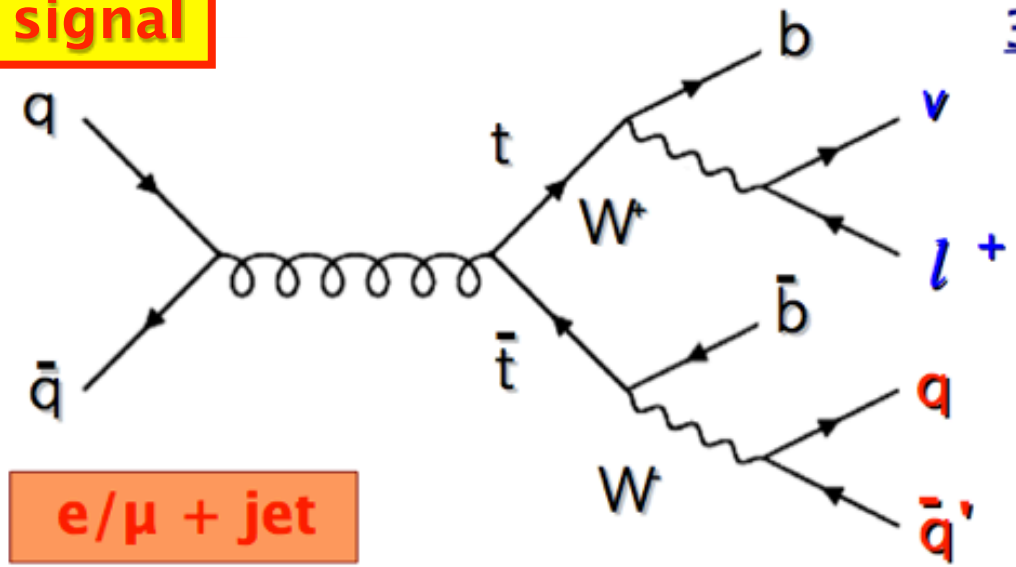


- **B hadron lifetime τ ~ 1 ps**
- **B hadron travel L_{xy} ~ 3 mm before decay**

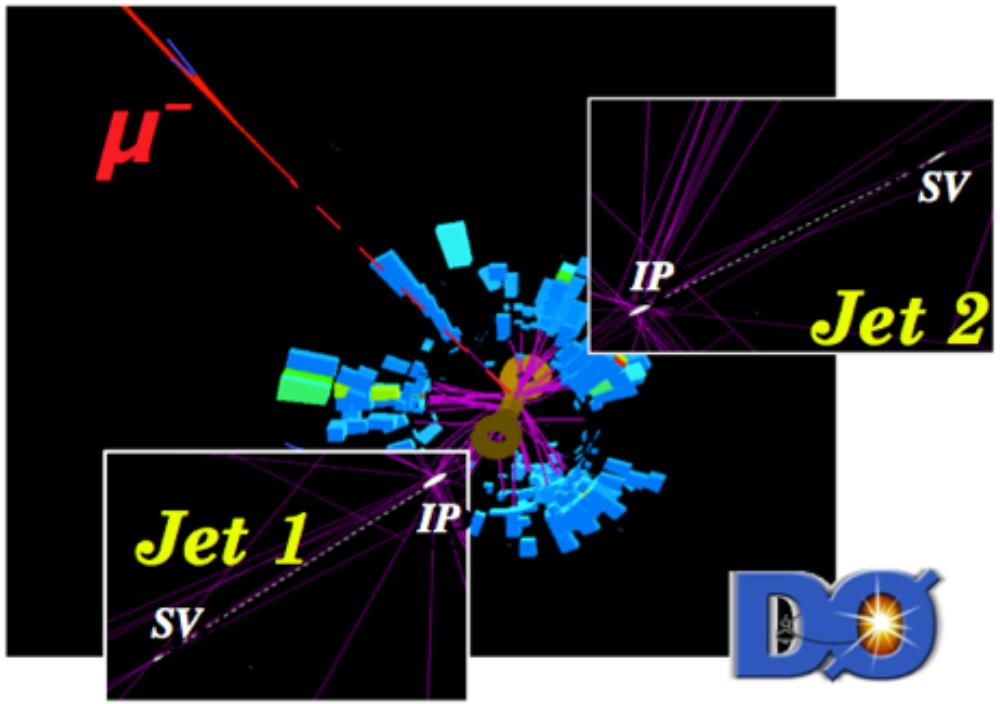


Lepton+jets Signatures

signal

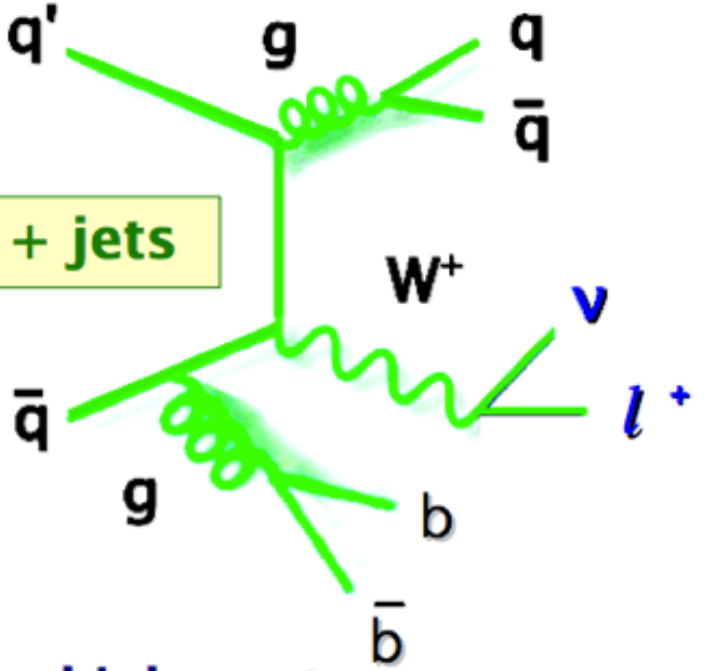


e/μ + jet



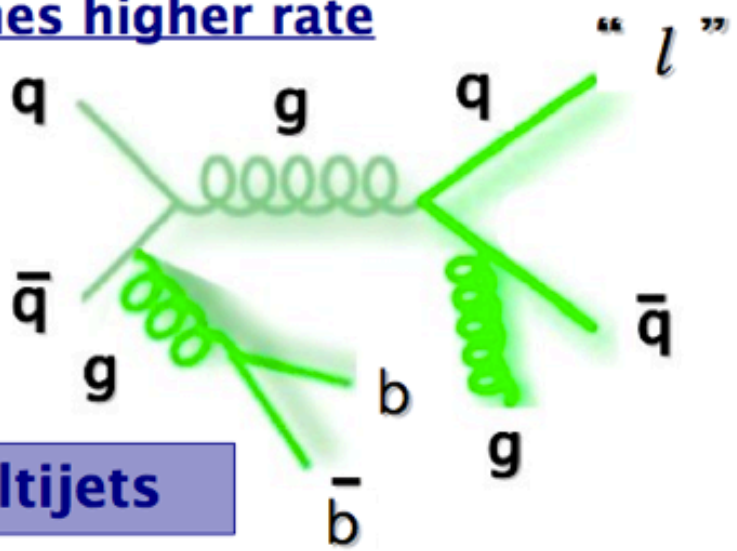
background

3000 times higher rate



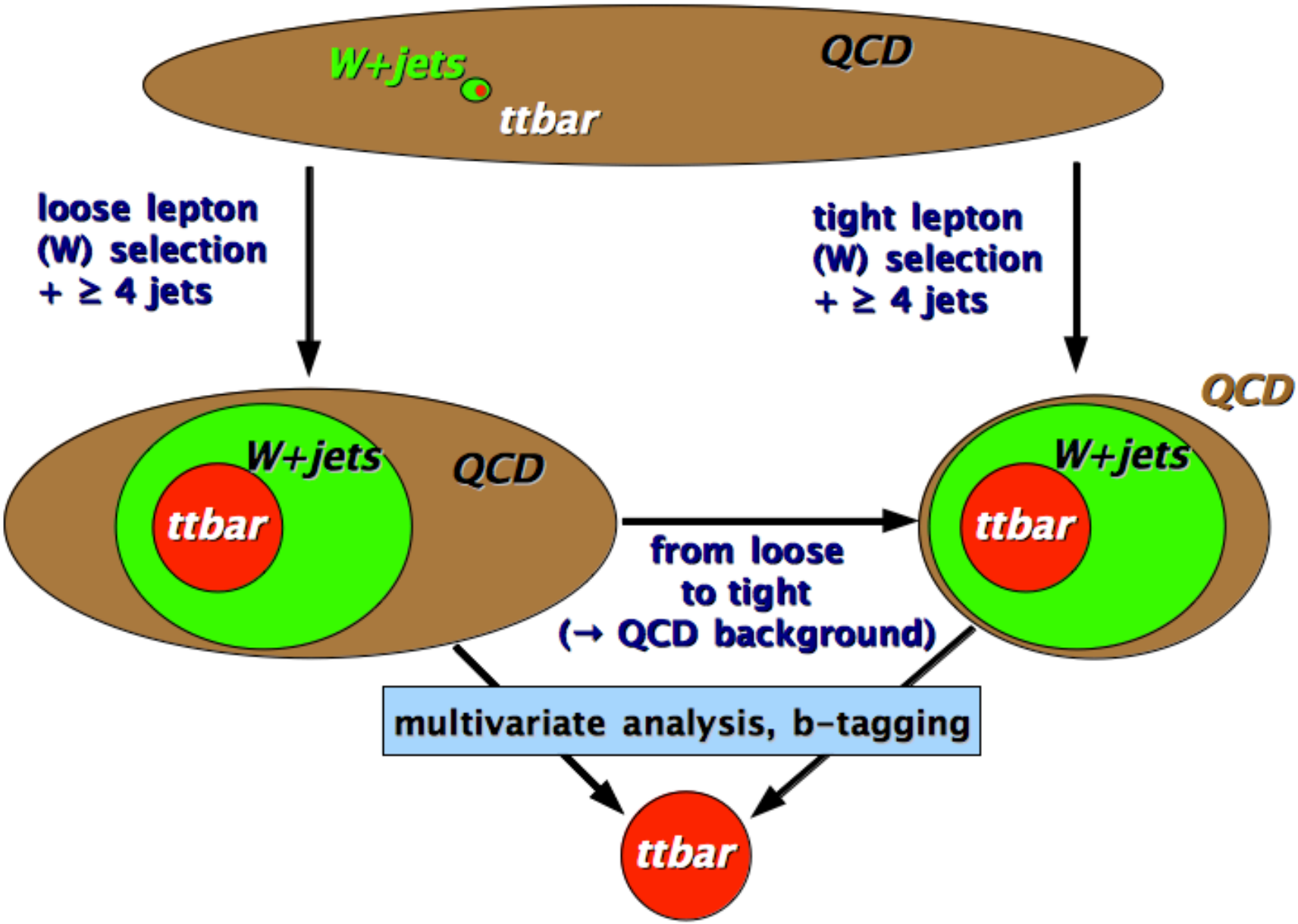
W + jets

10^{10} times higher rate



multijets

Overview Lepton+jets Selection



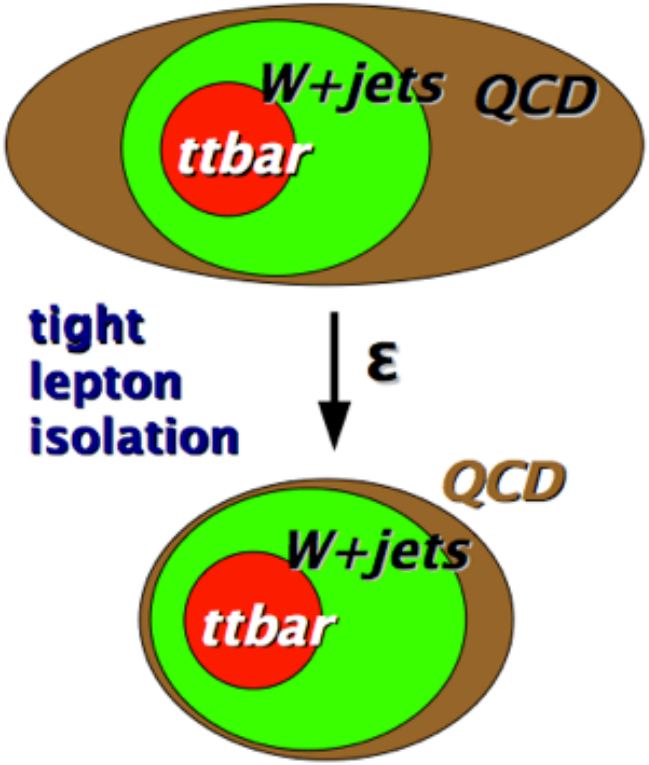
Determination of Multijets Background

lepton+jets

$$N_{loose} = N_{QCD} + N_{W+ttbar}$$

$$\downarrow \varepsilon \qquad \varepsilon_{QCD} \downarrow \qquad \varepsilon_{W+ttbar} \downarrow$$

$$N_{tight} = \varepsilon_{QCD} * N_{QCD} + \varepsilon_{W+ttbar} * N_{W+ttbar}$$



- N_{loose} und N_{tight}: signal dataset
- ε_{QCD} : independent multijet (QCD) data set (e.g. small $\not{E}_T$)
- $\varepsilon_{W+ttbar}$: W+jets Monte Carlo simulation (normalization to data)

→ solve equations for N_{QCD} and $N_{W+ttbar}$

→ determine multijet (QCD) background <u>entirely from data</u>

What is a Cross Section?

- **differential cross section: $d\sigma/d\Omega$:**
  - probability of a scattered particle in a given quantum state per solid angle $d\Omega$
  - e.g. Rutherford scattering experiment

Geiger and Rutherford in Manchester

- **integrated cross section: $\sigma = \int d\sigma/d\Omega \, d\Omega$**

Measurement: $\sigma=(N_{obs}-N_{bg})/(\varepsilon L)$

Luminosity

Lepton+Jets Topological Cross Section

powerful test of QCD and search for new physics

- **kinematic properties allow separation between signal and background**

use variables such as:

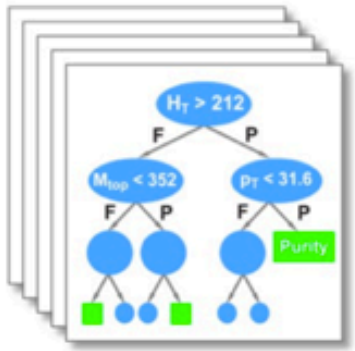
energy-dependent quantities:

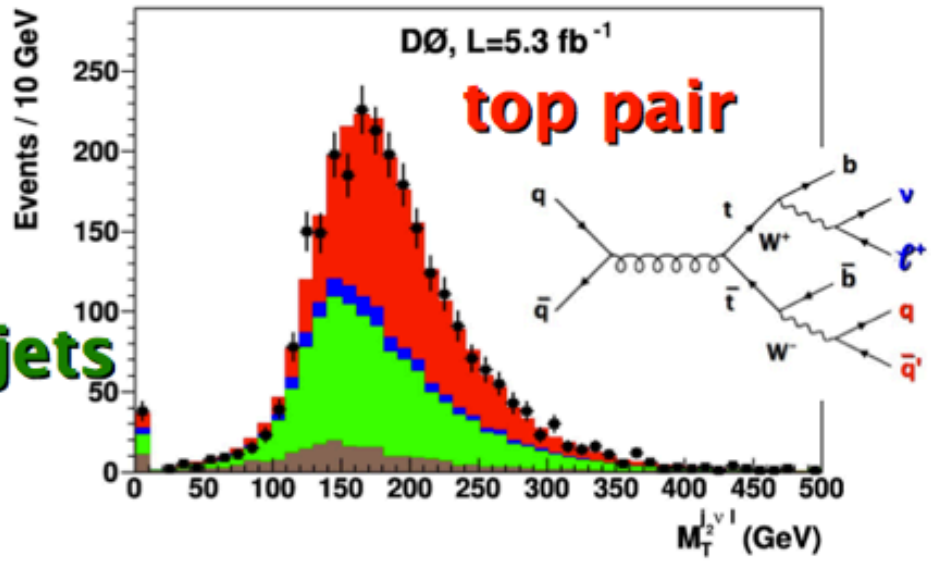
- **e.g. transverse mass of leptonic top**

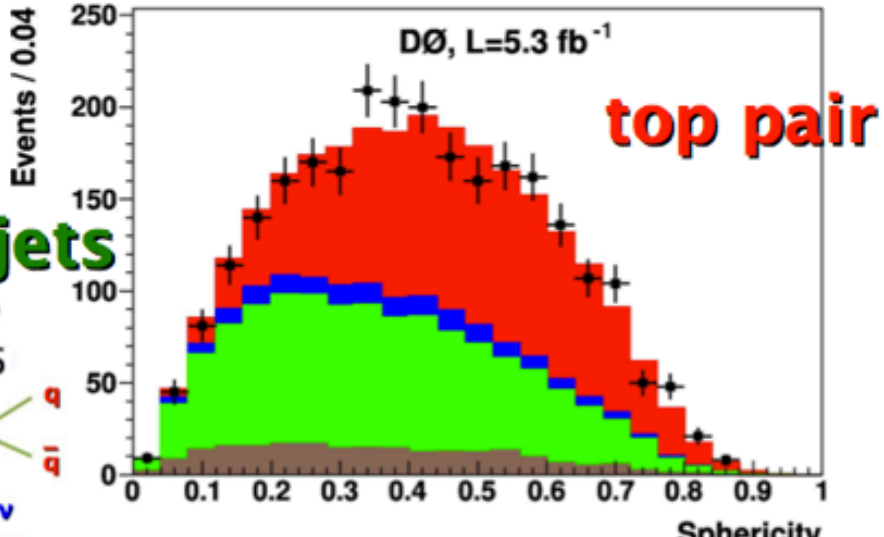
angular dependent:

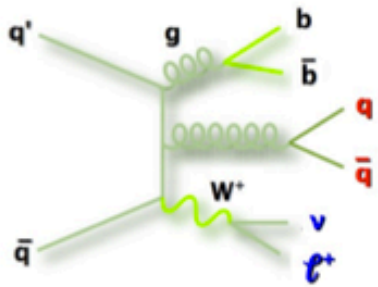
- **e.g. sphericity**

Random Forests of Boosted Decision Trees









Lepton+Jets Topological Cross Section

powerful test of QCD and search for new physics

- **kinematic properties allow separation between signal and background**

use variables such as:

energy-dependent quantities:

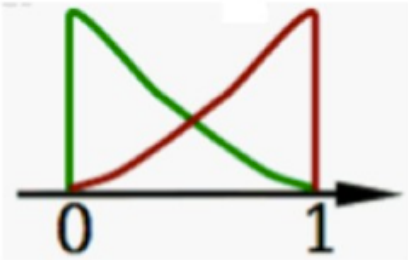
- **e.g. transverse mass of leptonic top**

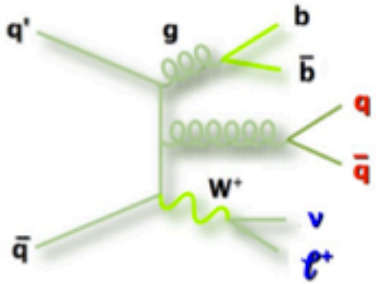
angular dependent:

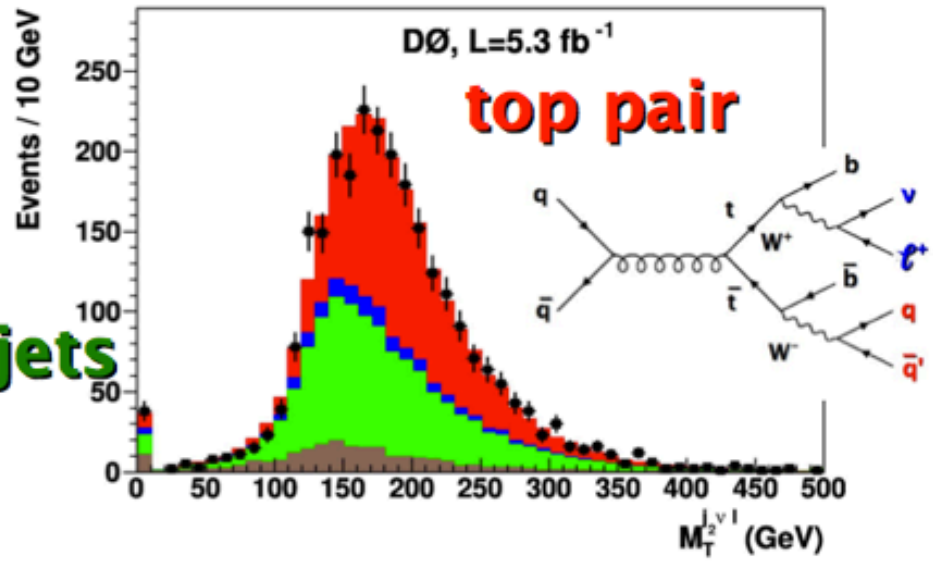
- **e.g. sphericity**

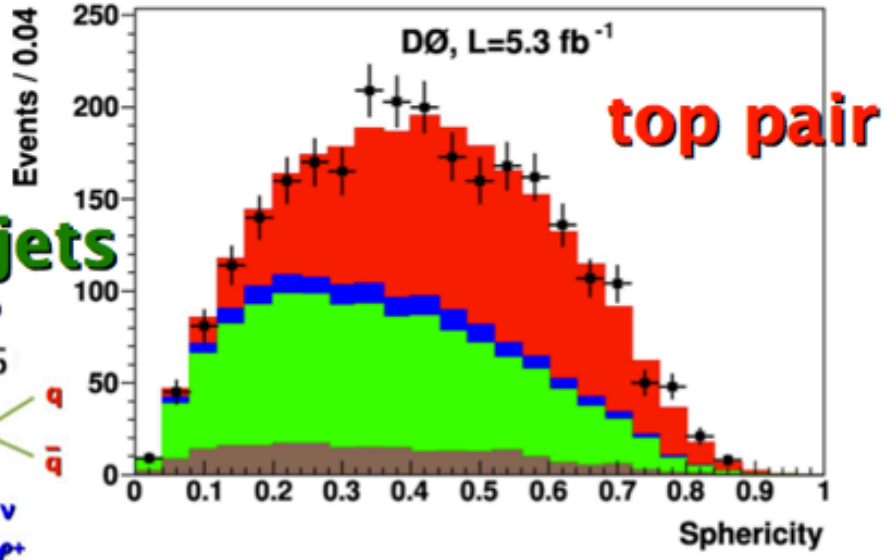
Random Forests of Boosted Decision Trees

background **signal**

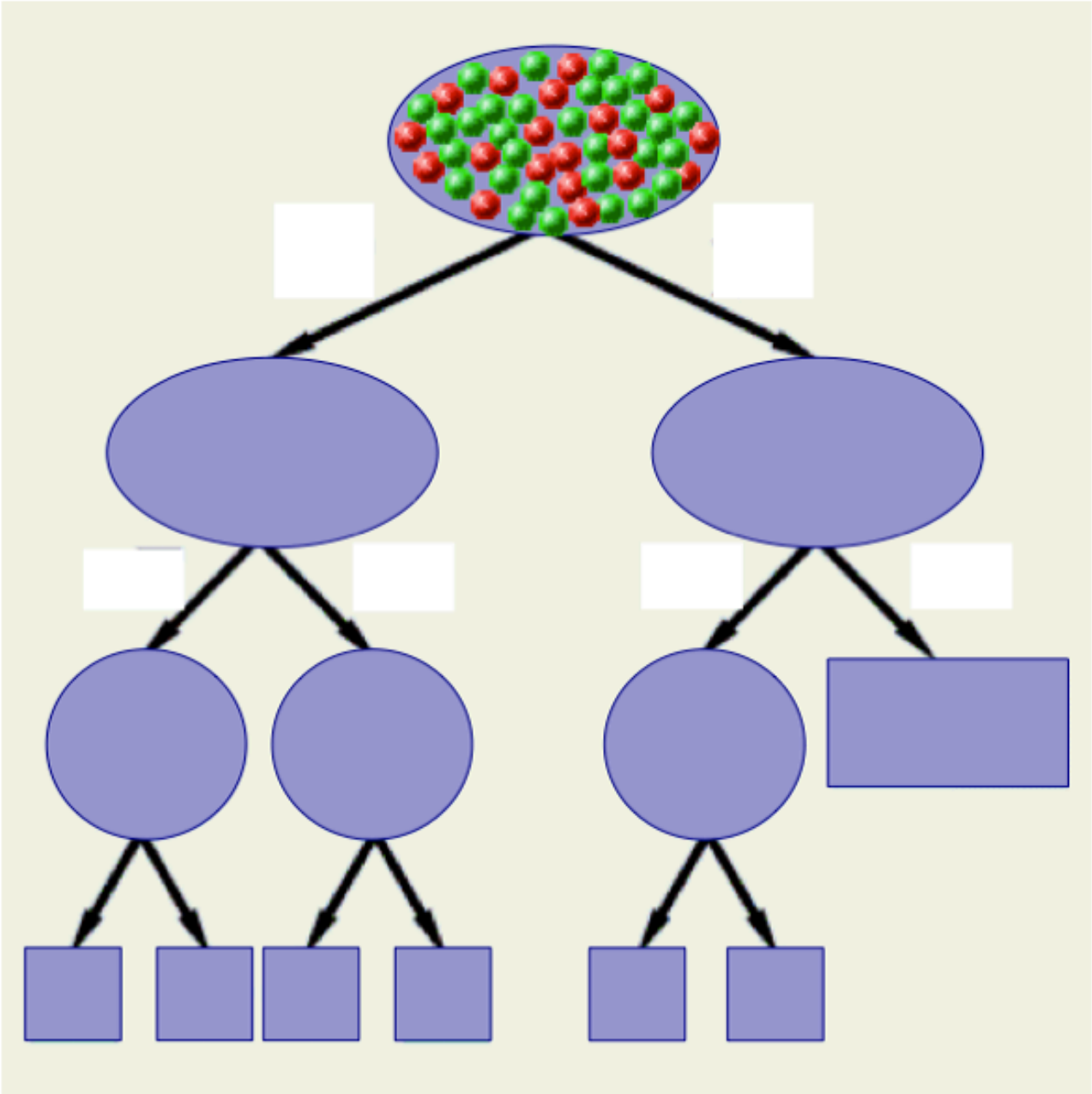






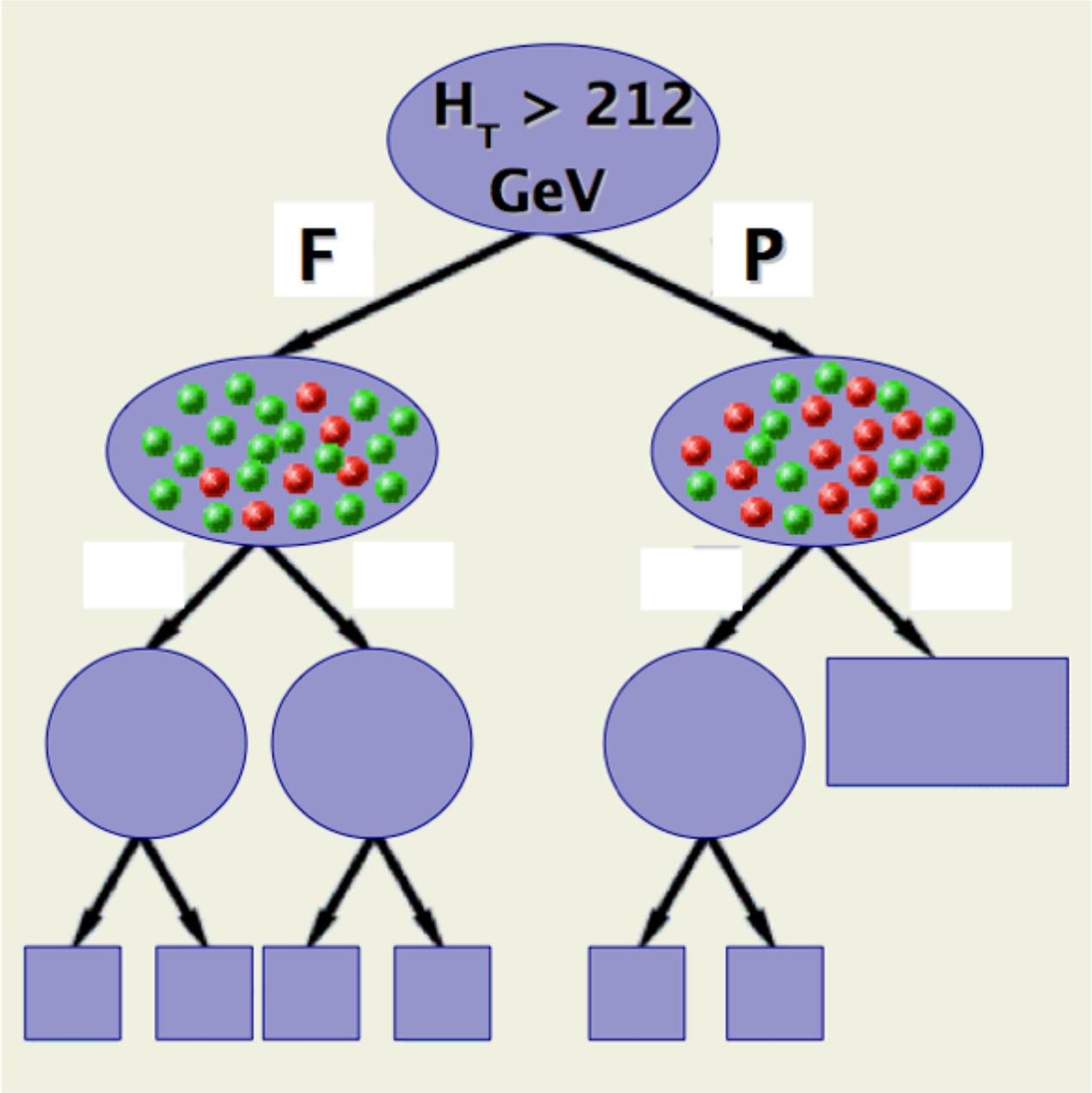


Boosted Decision Trees



- **IDEA: recover events that fail criteria in cut-based analyses**

Boosted Decision Trees



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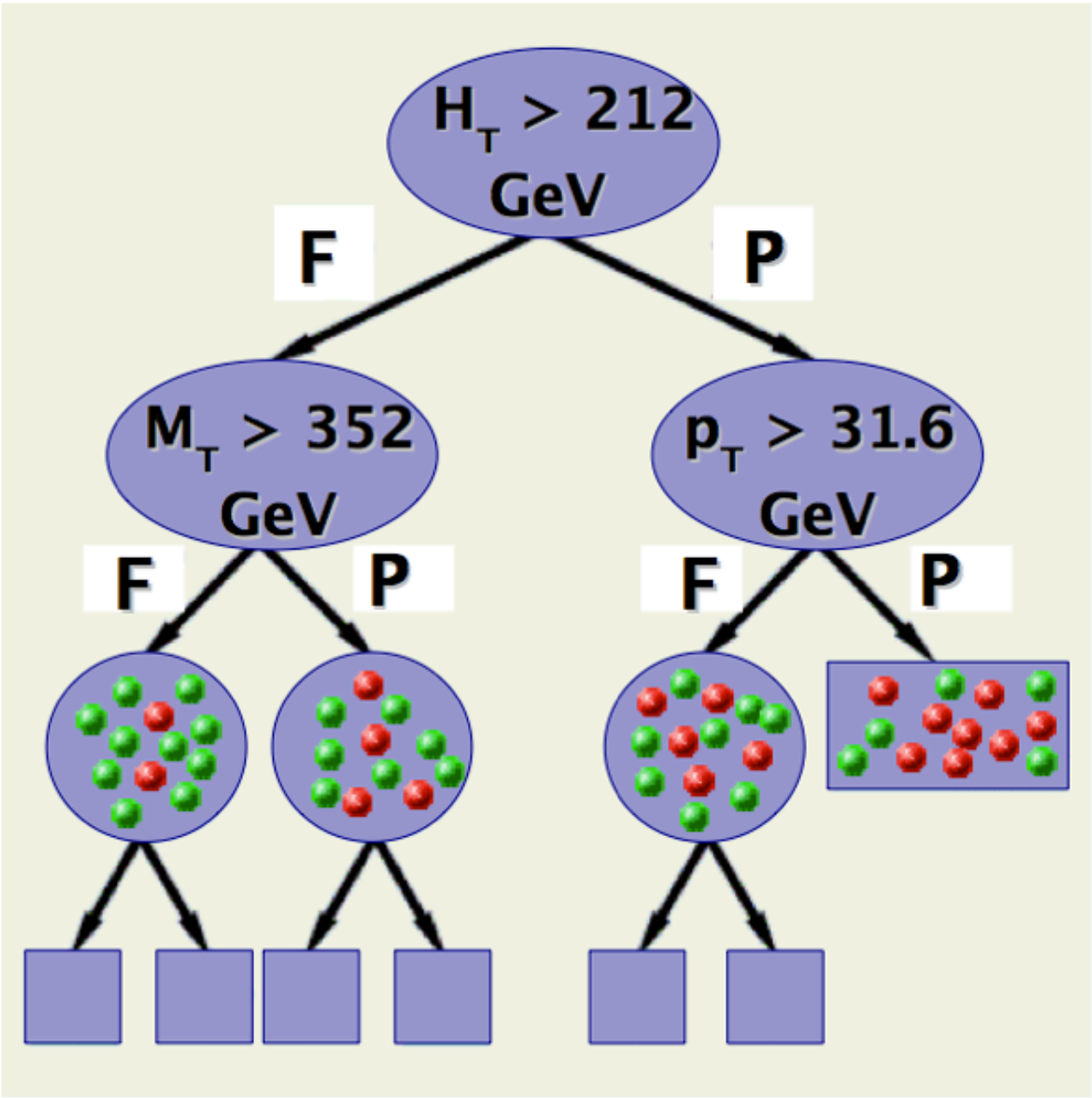
Boosted Decision Trees



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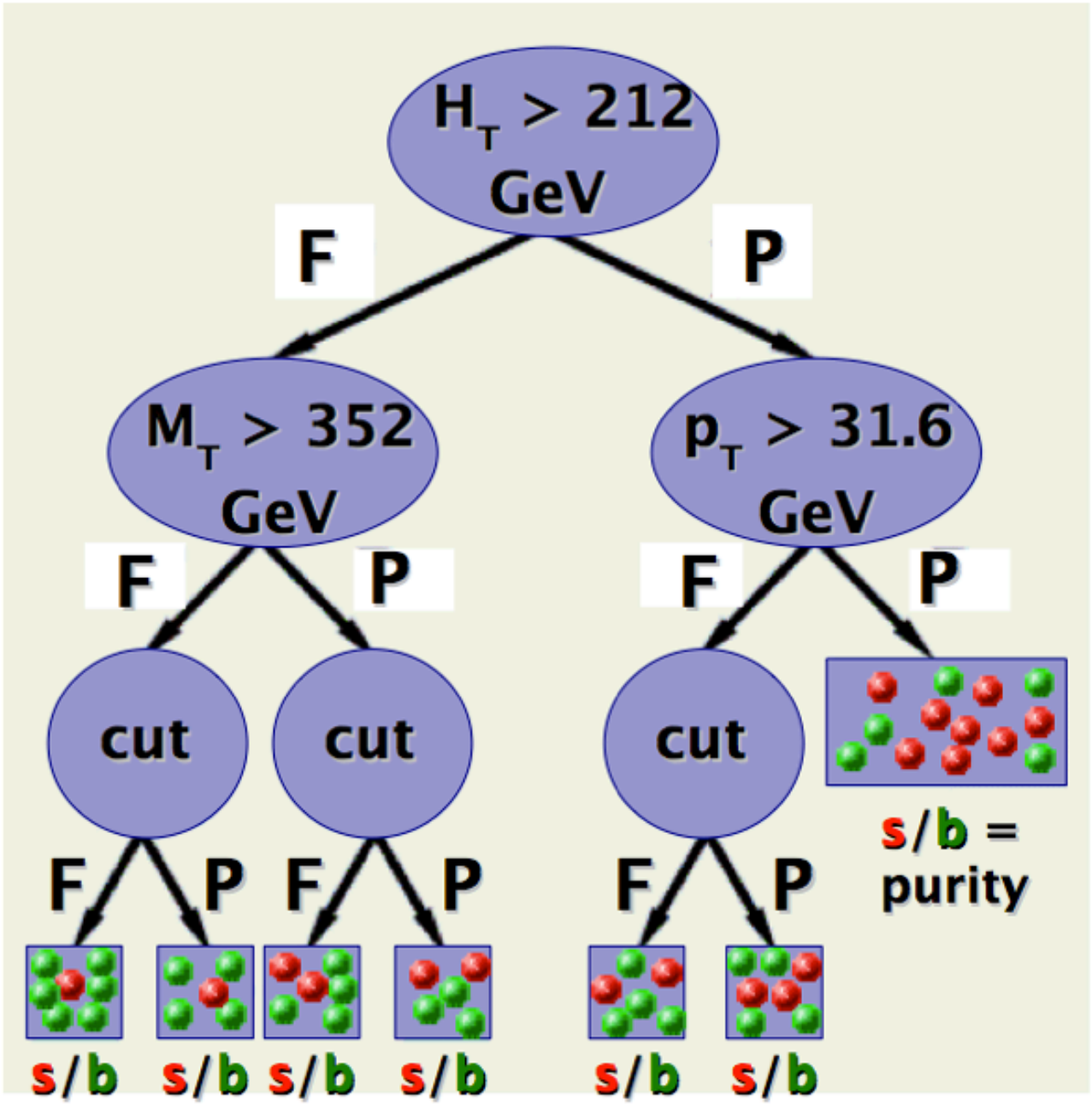
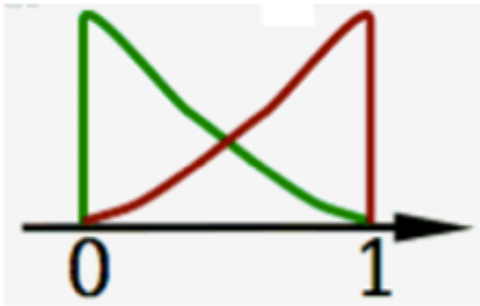
Boosted Decision Trees



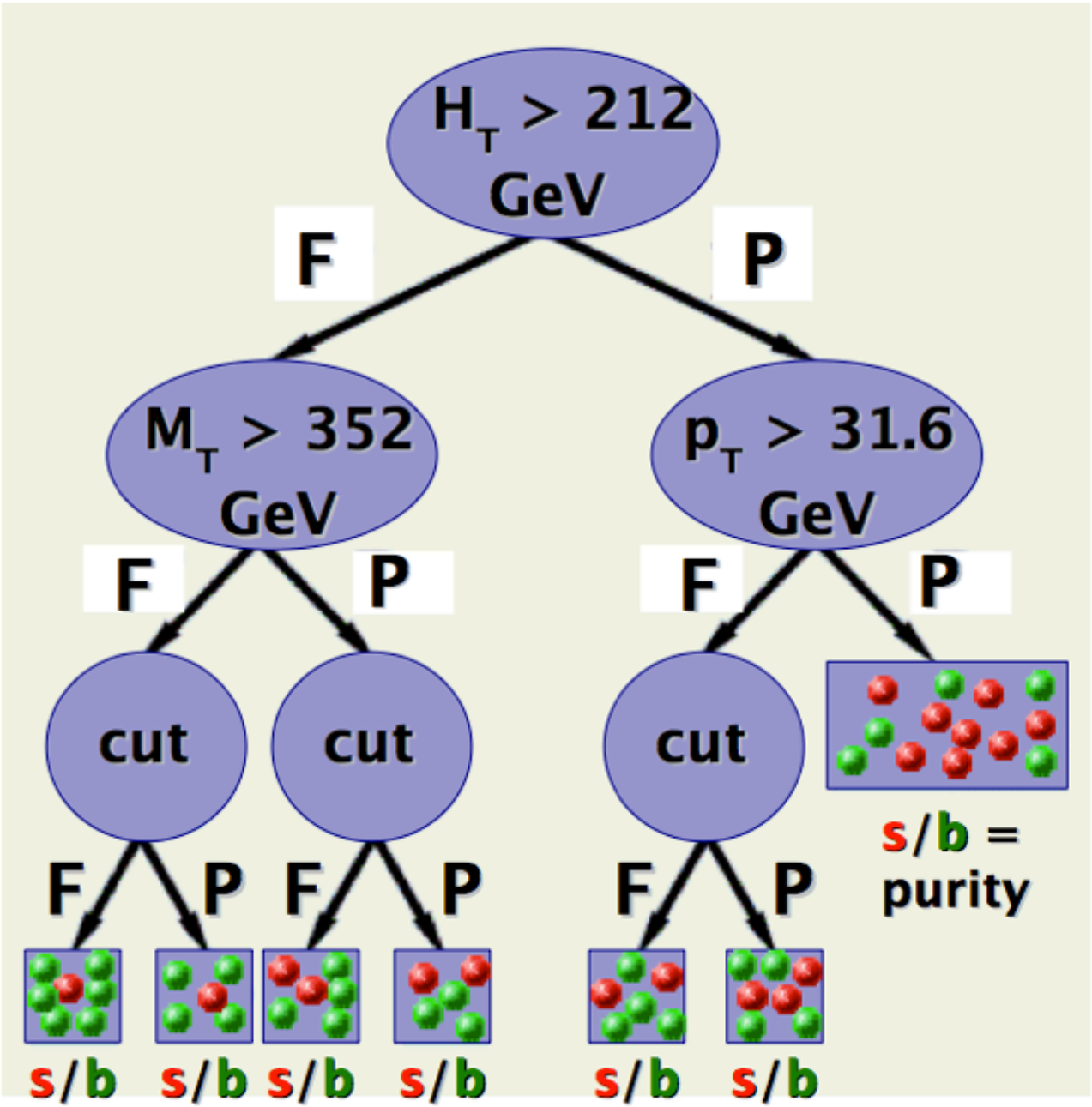
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background signal



Boosted Decision Trees

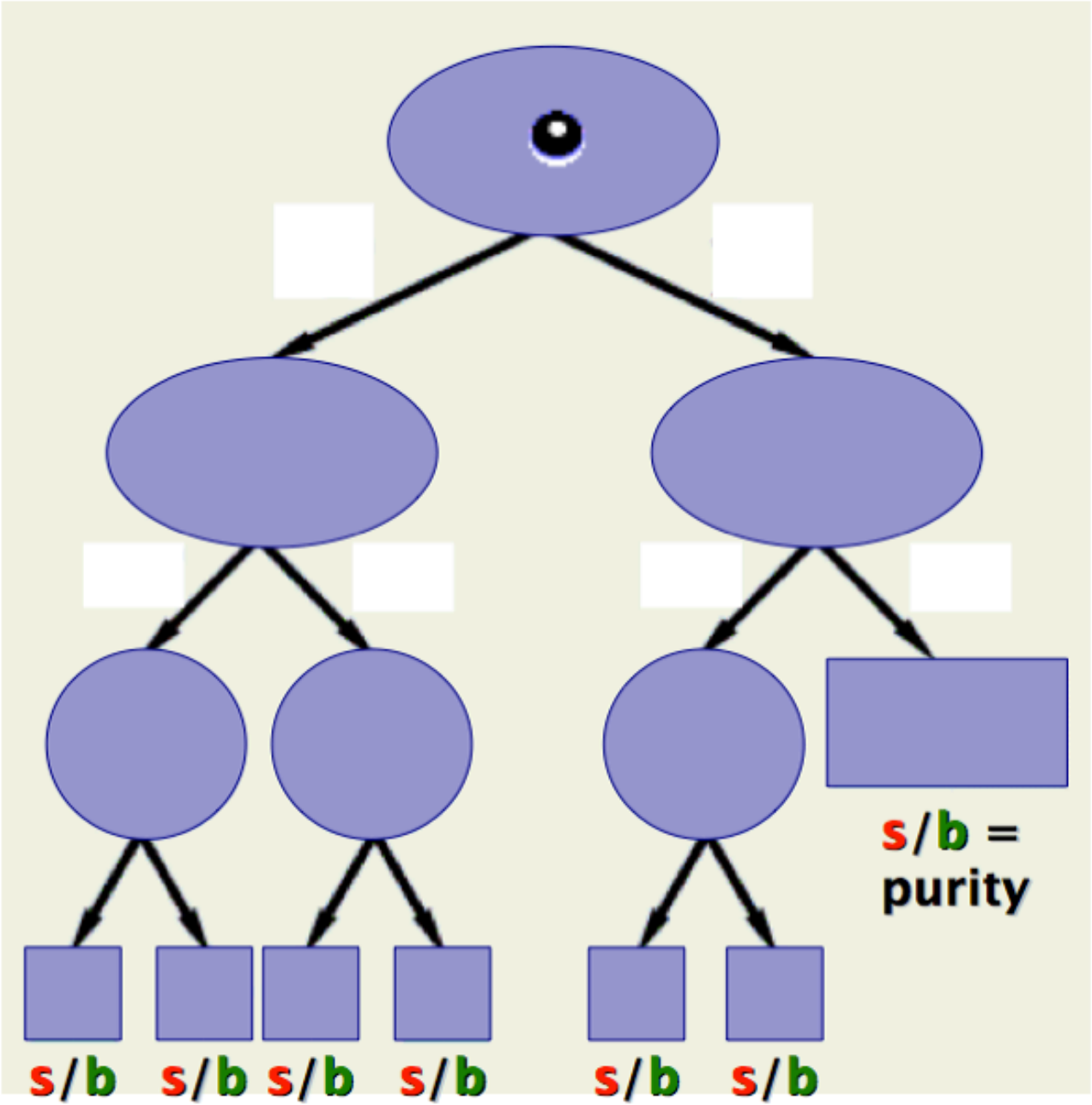


- **IDEA: recover events that fail criteria in cut-based analyses**

boosting:

- train tree: T_k
- derive weight: α_k
- retrain tree: T_{k+1} to minimize error
- average: $T = \Sigma\, \alpha_i\, T_i$

Boosted Decision Trees



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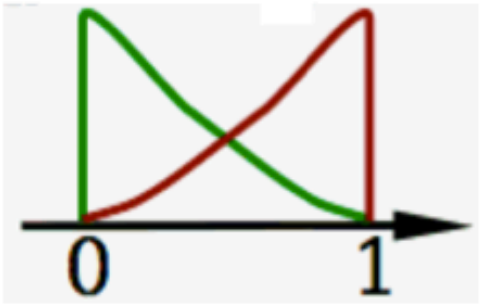
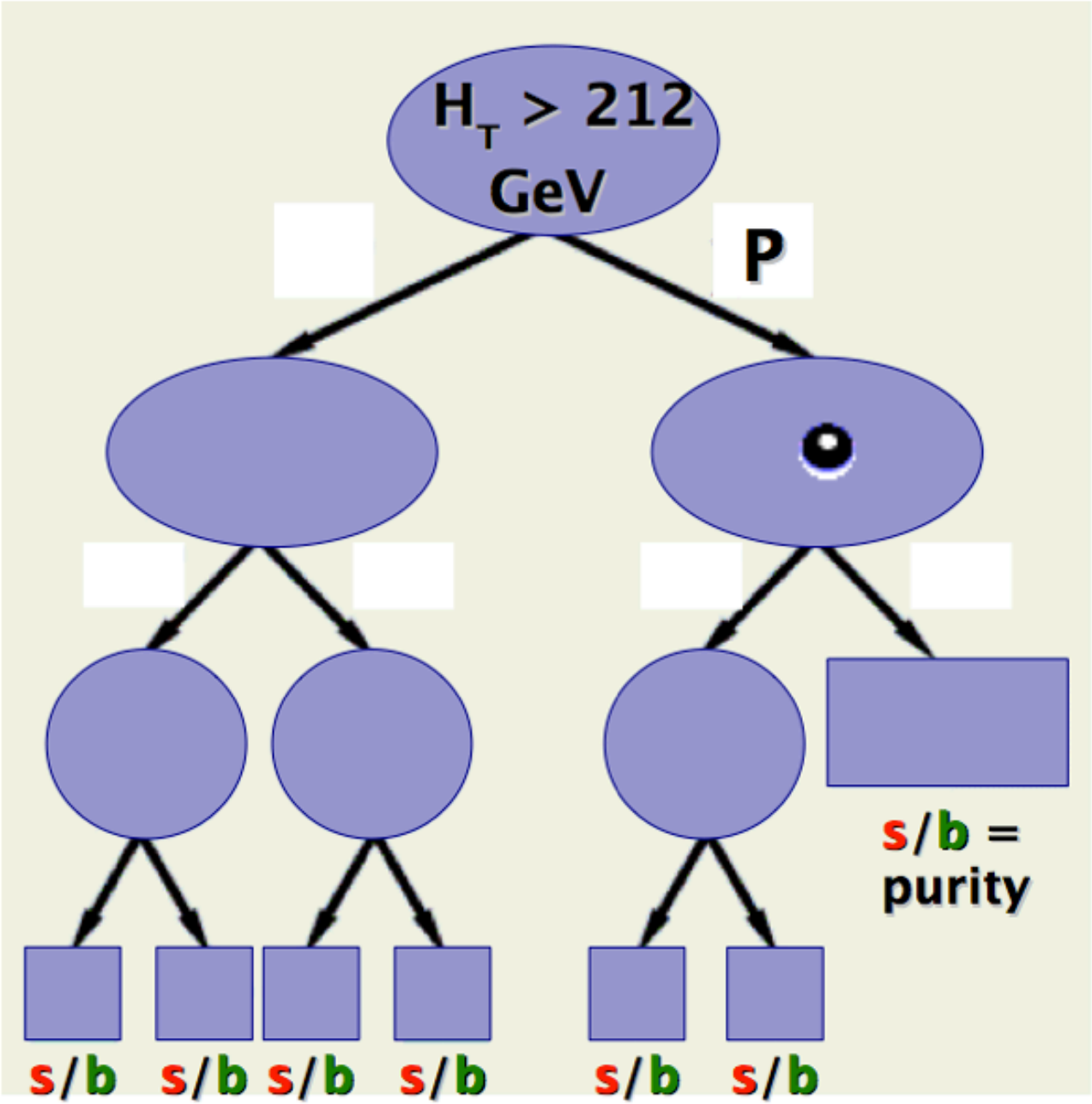


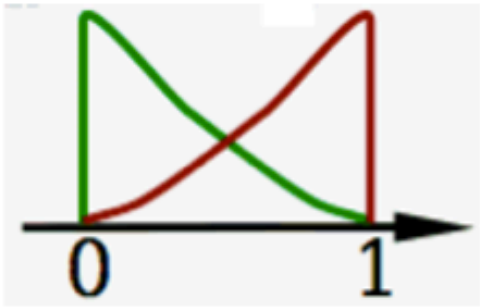
Boosted Decision Trees



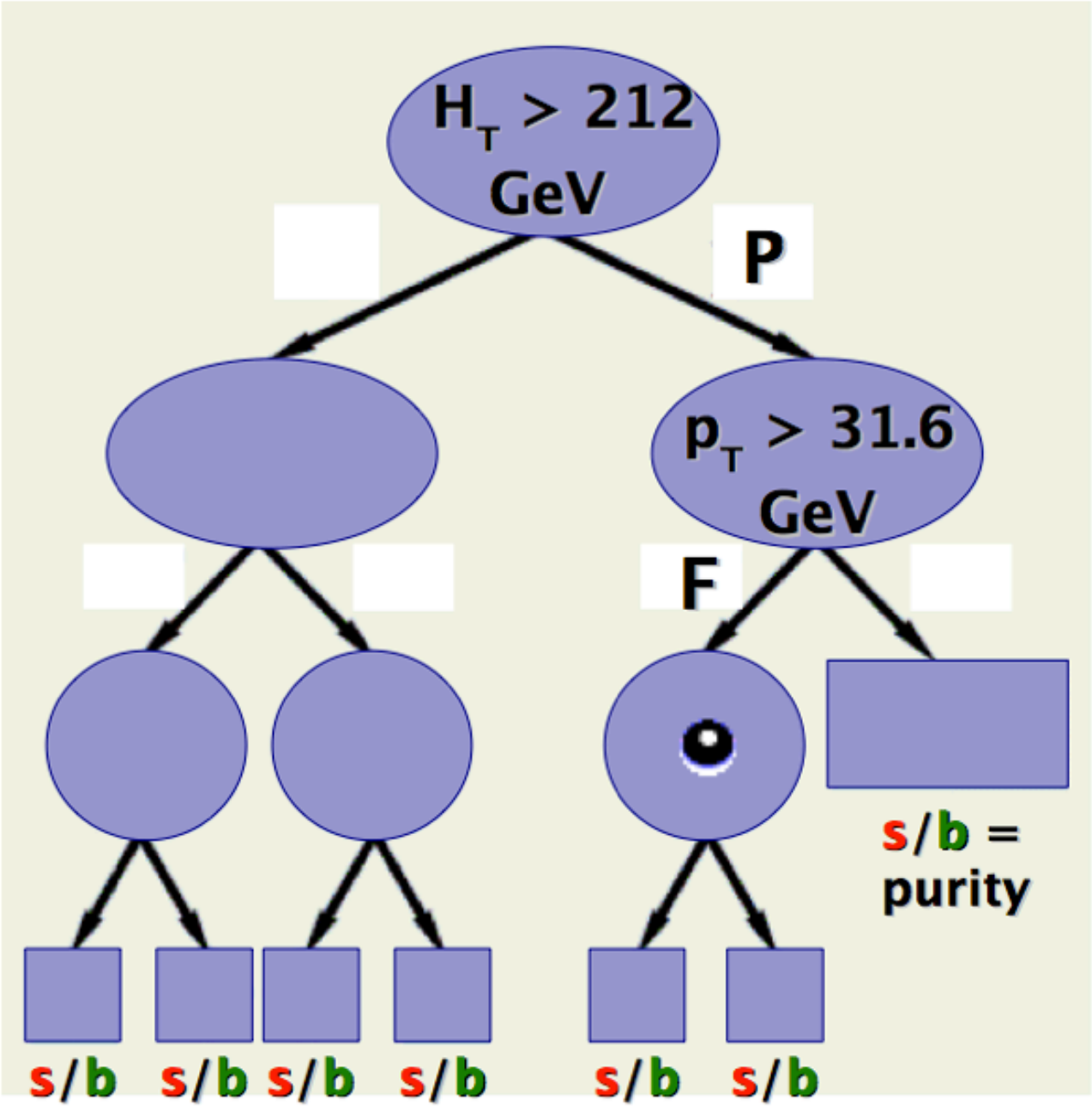
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background **signal**



Boosted Decision Trees



- **IDEA: recover events that fail criteria in cut-based analyses**

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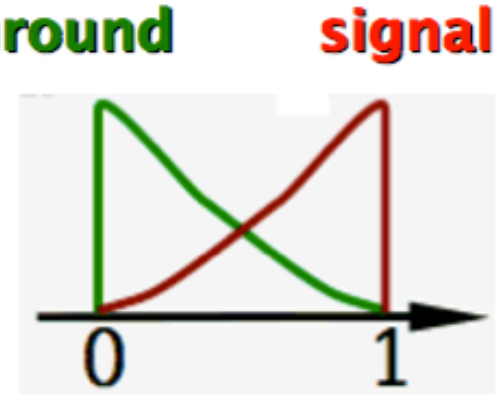
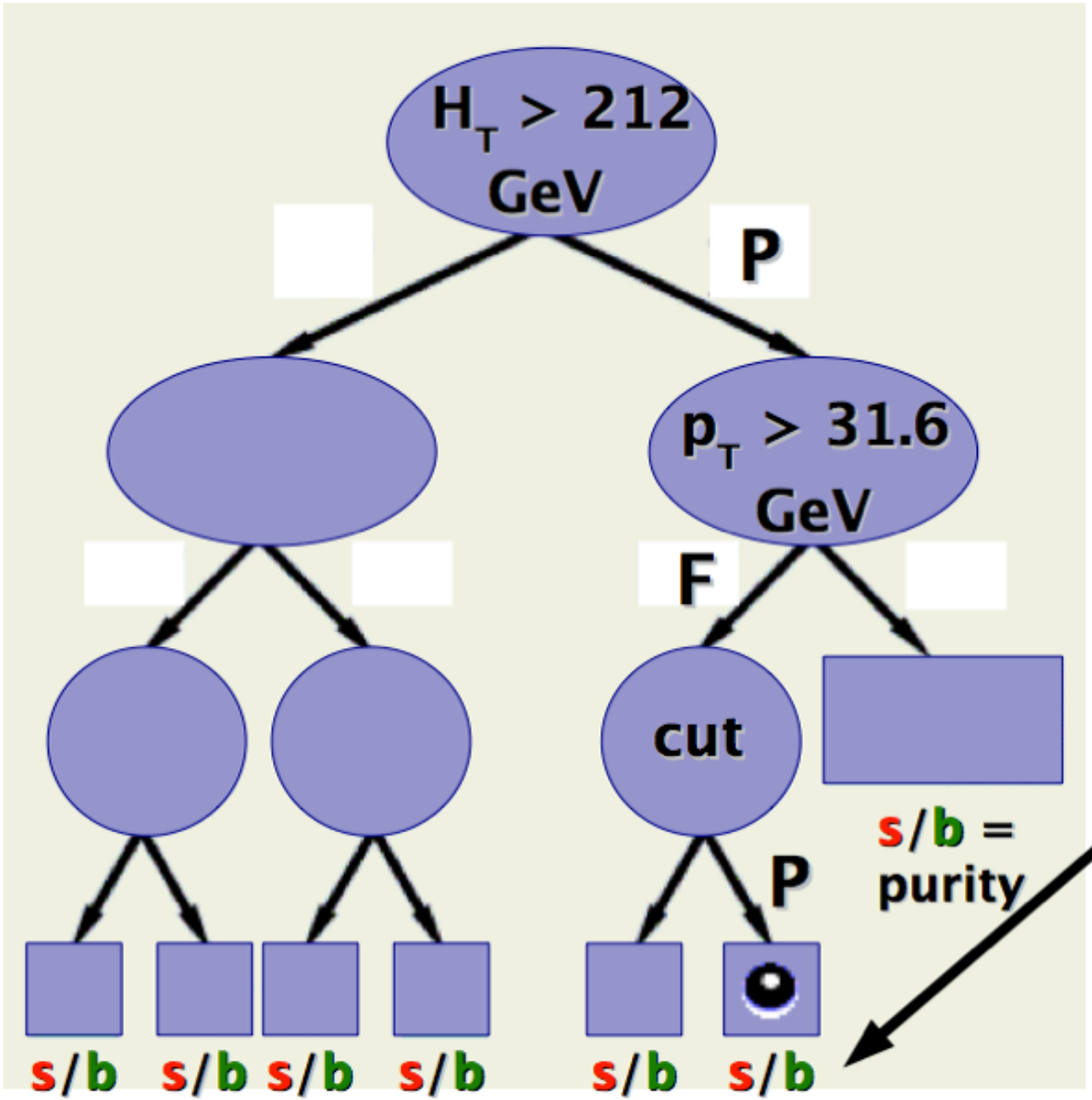


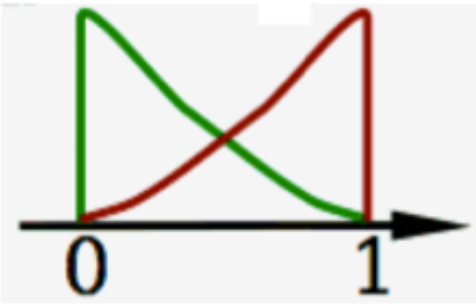
Boosted Decision Trees



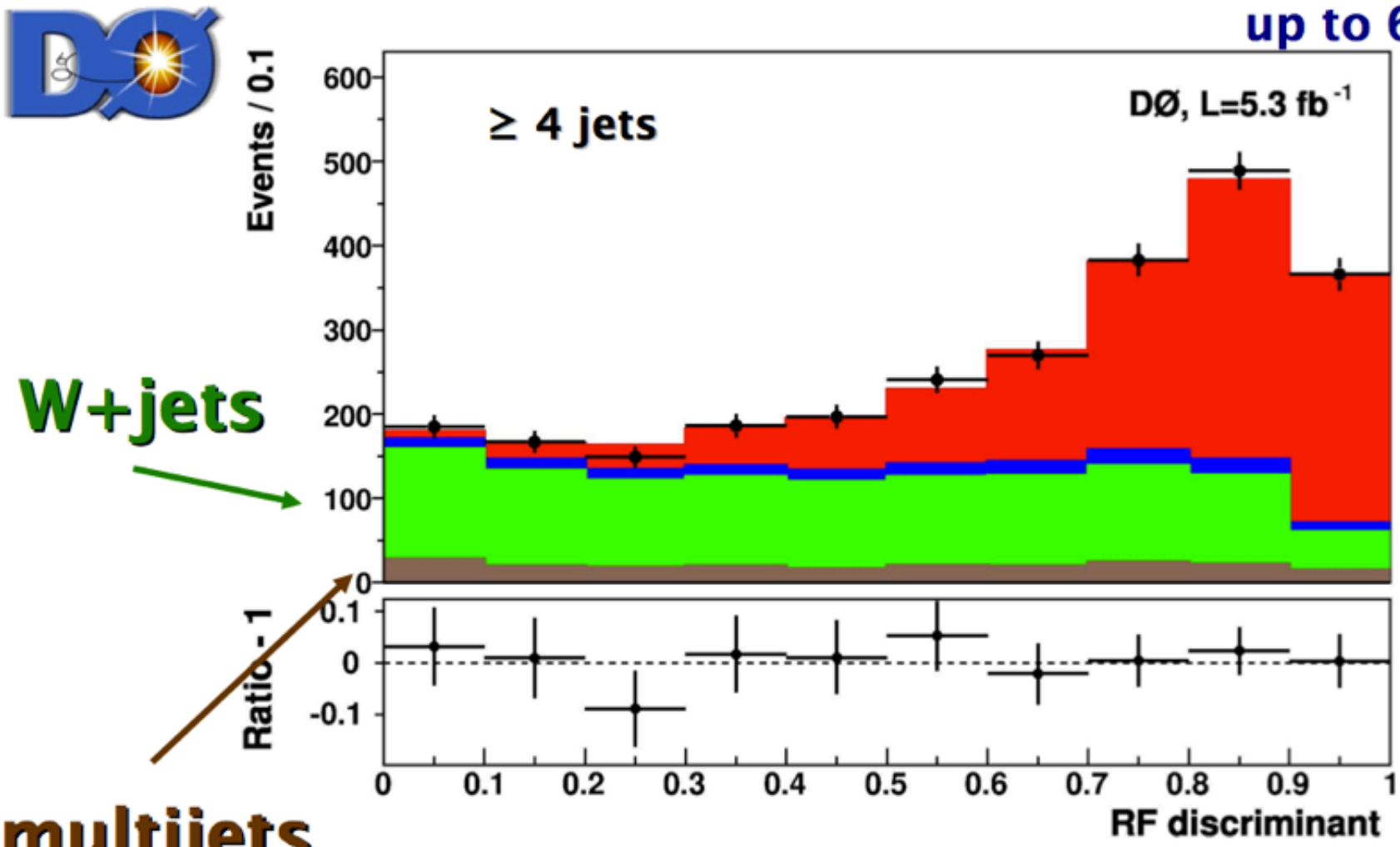
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background signal



Lepton+Jets Topological Cross Section



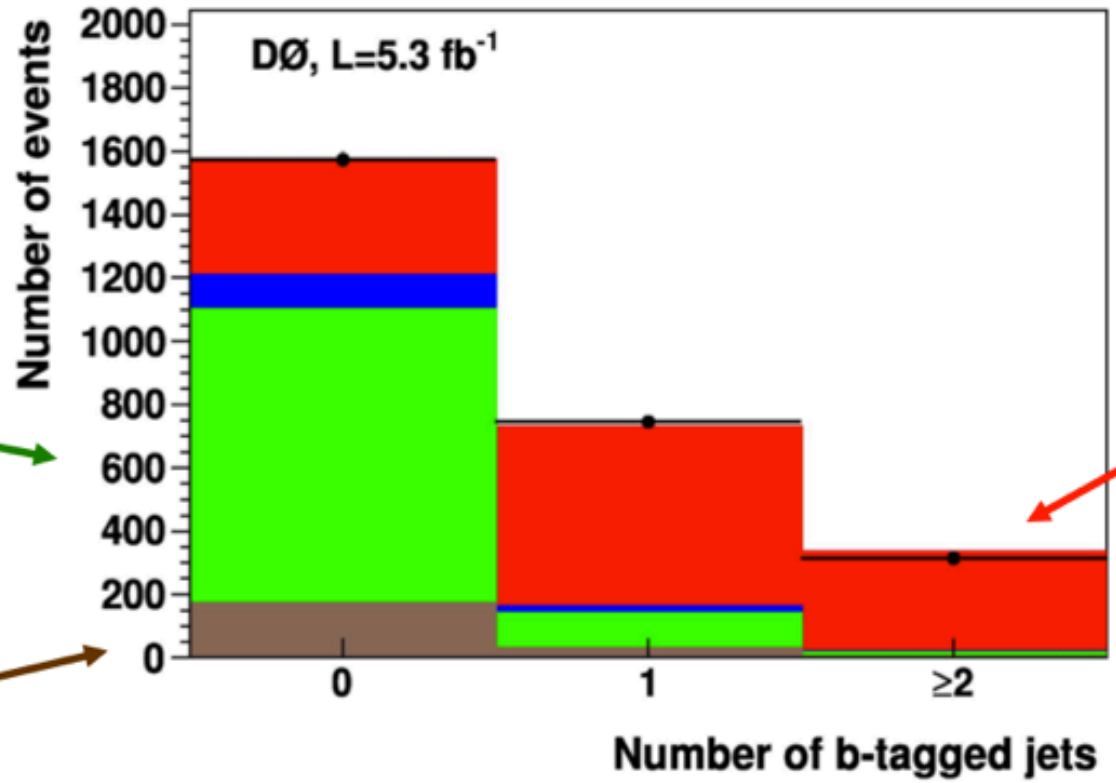
combine:
2 jets
3 jets
≥4 jets
e and μ

m_{top} = 172.5 GeV

$$\sigma_{t\bar{t}} = 7.68^{+0.71}_{-0.64}\ \text{(stat+syst+lumi) pb}$$

Lepton+Jets Cross Section with b-tagging

very powerful tool to reduce the background



W+jets

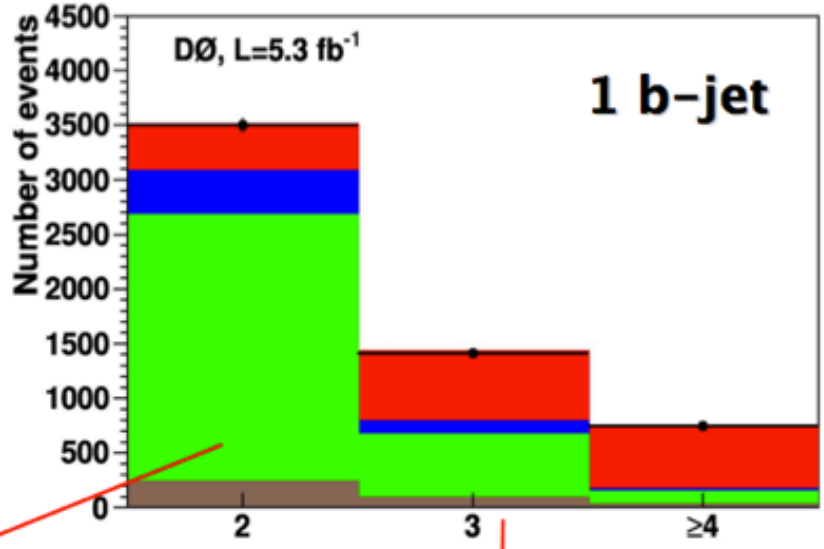
top pair

multijets

$$\sigma_{t\bar{t}} = 8.13^{+1.02}_{-0.90}\ \text{(stat+syst+lumi) pb}$$

m_{top} = 172.5 GeV

Lepton+Jets Cross Section with b-tagging



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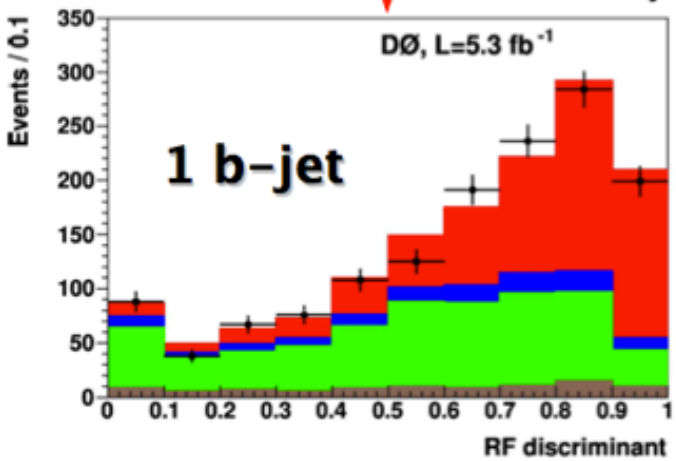
binned maximum likelihood fit (systematics included as nuisance parameters)

combine:
2, 3, ≥4 jets
0, 1, ≥2 b-jets
e and μ

W+jets & heavy flavor scale factor f_H



"counting"

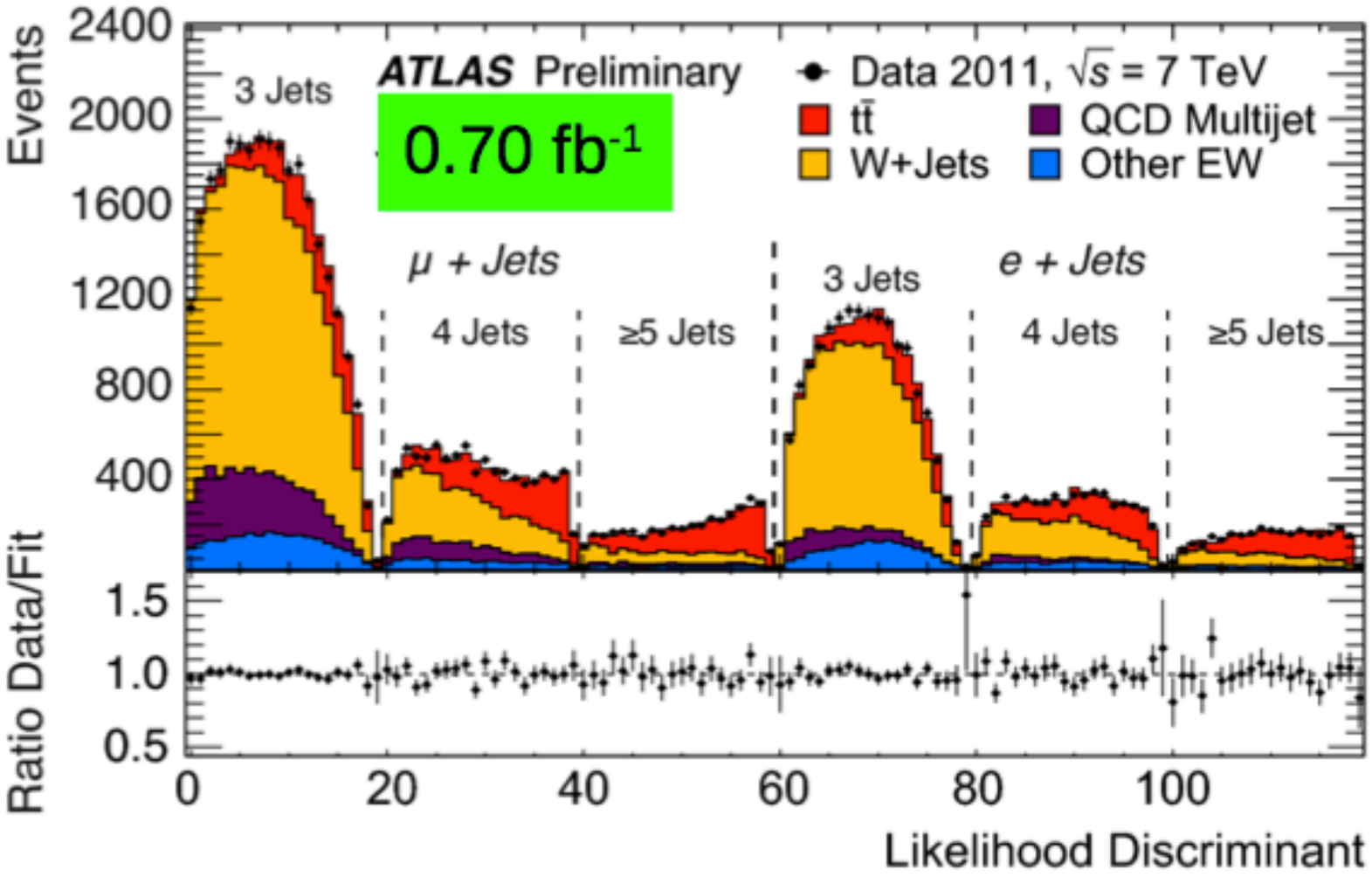
systematically limited:
- luminosity
- JES and JER
- b-tagging

$$\sigma_{t\bar{t}} = 7.78^{+0.77}_{-0.64}\ \text{(stat+syst+lumi) pb}$$

m_{top} = 172.5 GeV

±9%

Lepton+Jets Cross Section with b-tagging

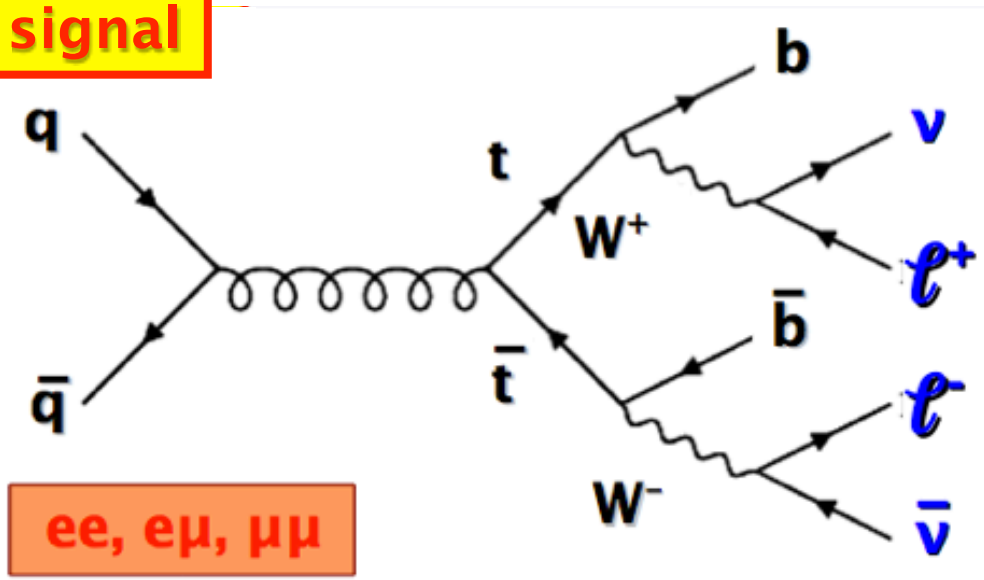


σ_{tt} = 179.0 ± 3.9 (stat) ± 9.0 (syst) ± 6.6 (lumi) pb

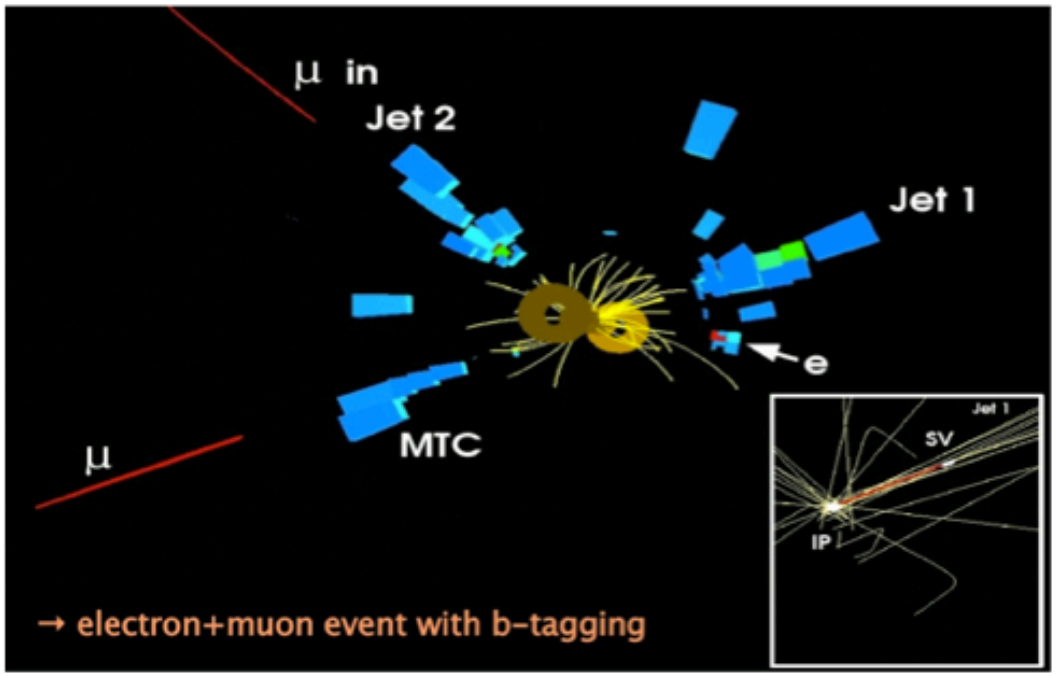
±6.5%

Dilepton Signatures

signal

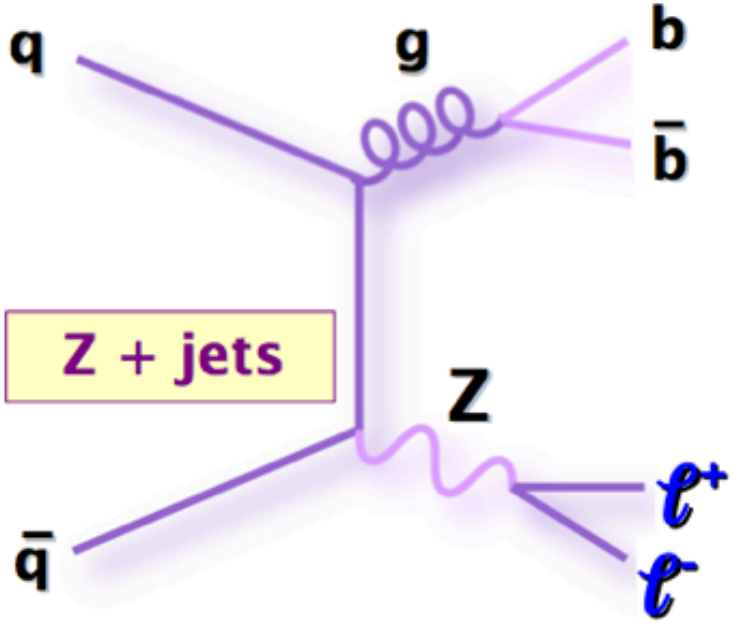


ee, eμ, μμ



background

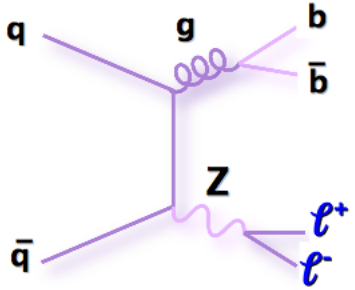
300 times higher rate

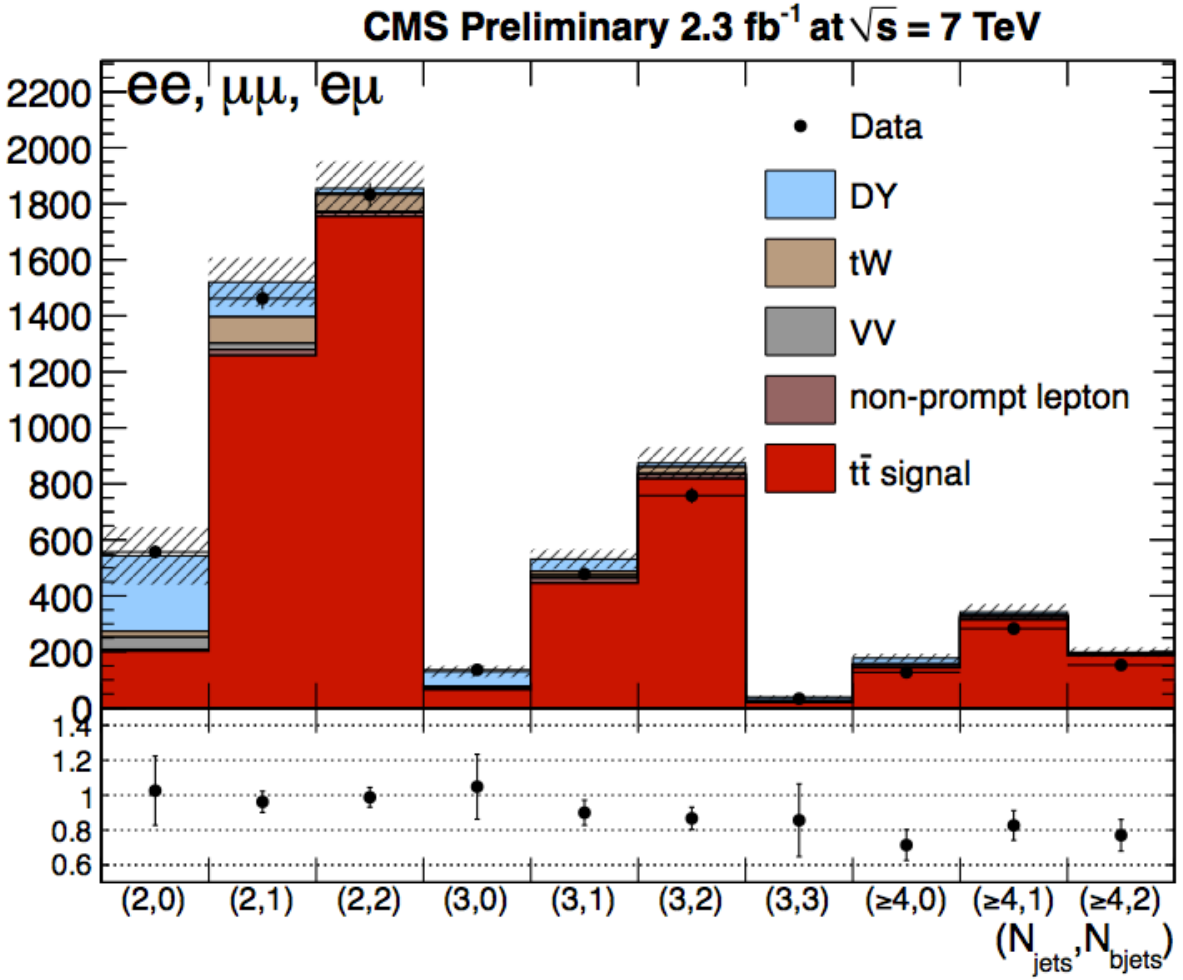


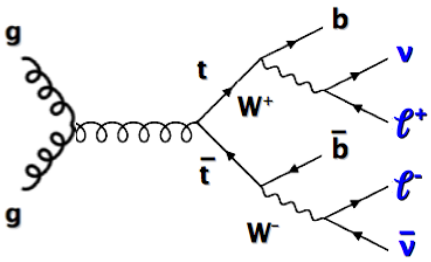
Z + jets

- less statistics
- less background

Dilepton Cross Section



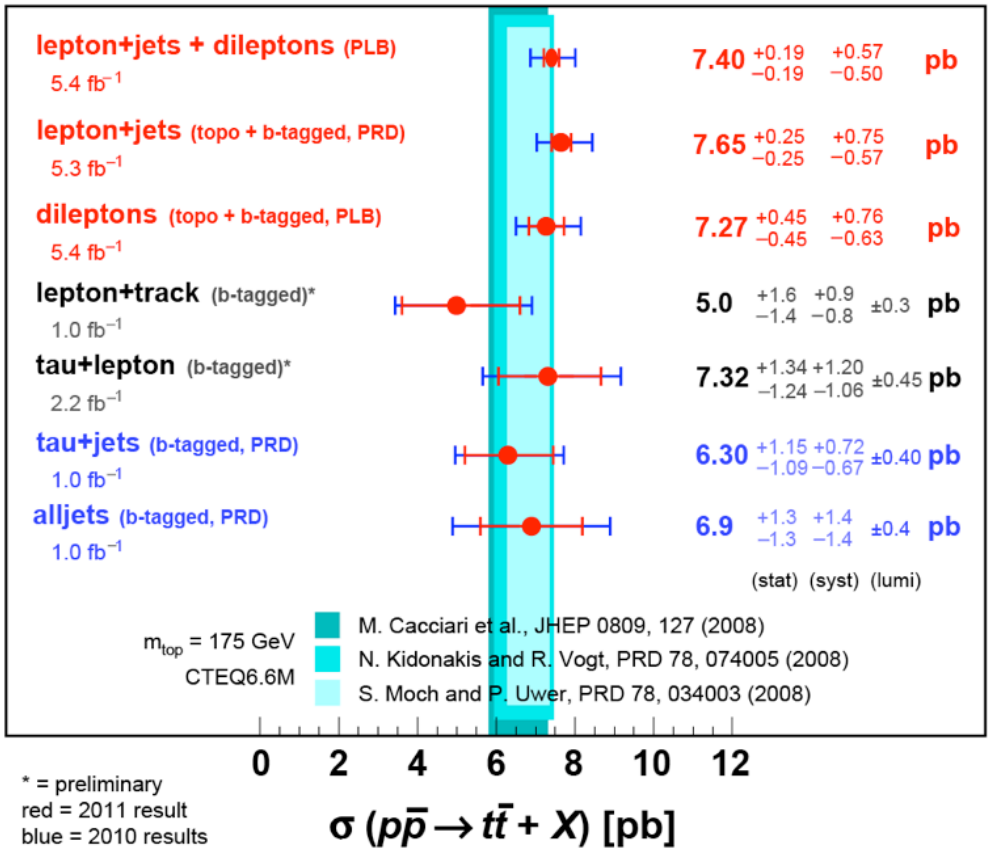


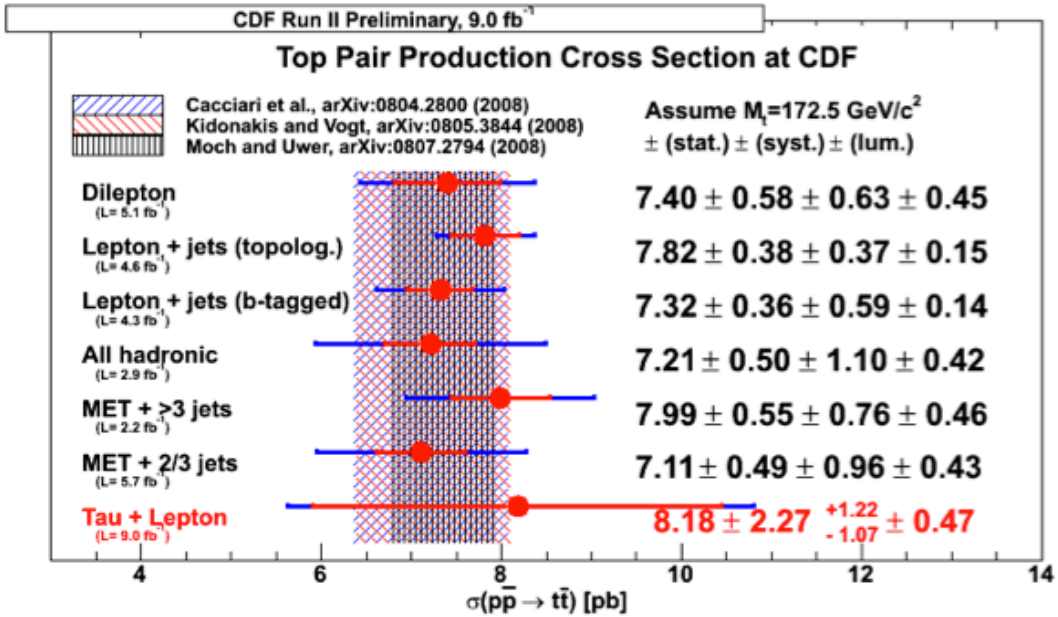


$$\sigma_{t\bar{t}} = 161.9 \pm 2.5(\text{stat.})^{+5.1}_{-5.0}(\text{syst.}) \pm 3.6(\text{lumi})\ \text{pb},\ \delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 4.2\%$$

Main systematics: lepton efficiencies $\sim$ 2%, jet energy scale $\sim$ 2%

Top Pair Production Cross Section

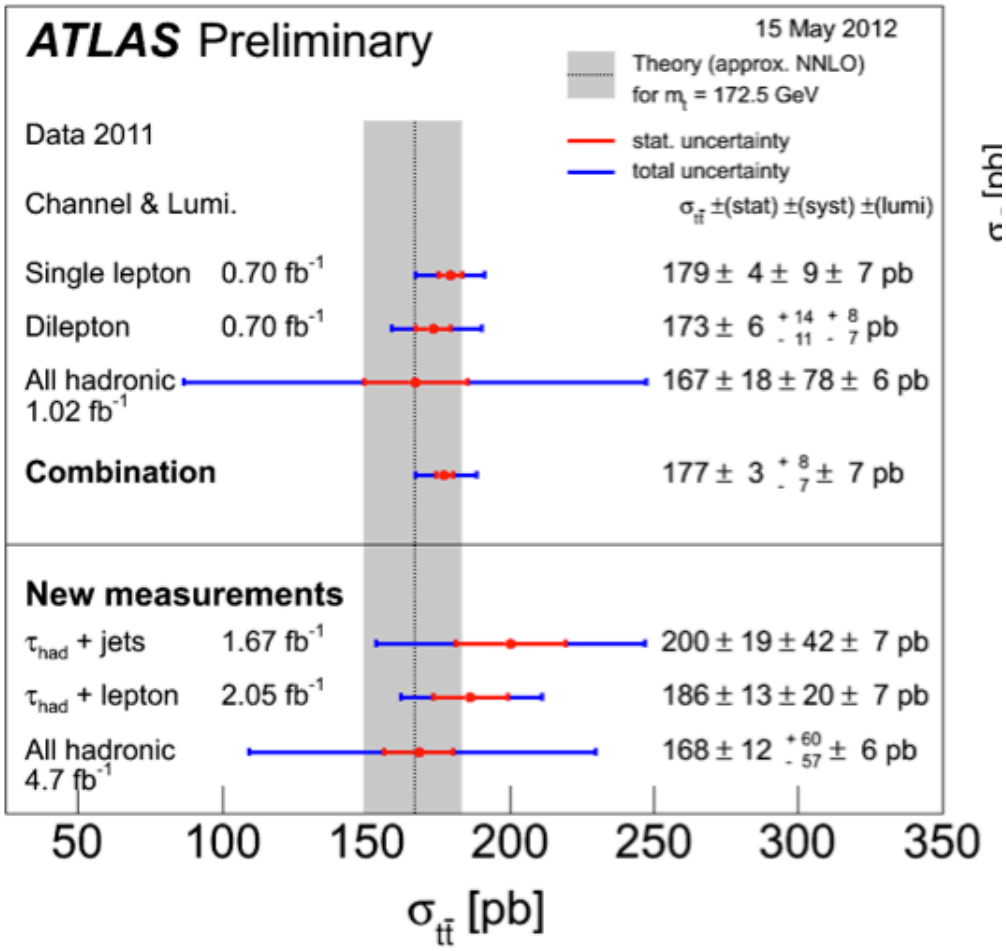


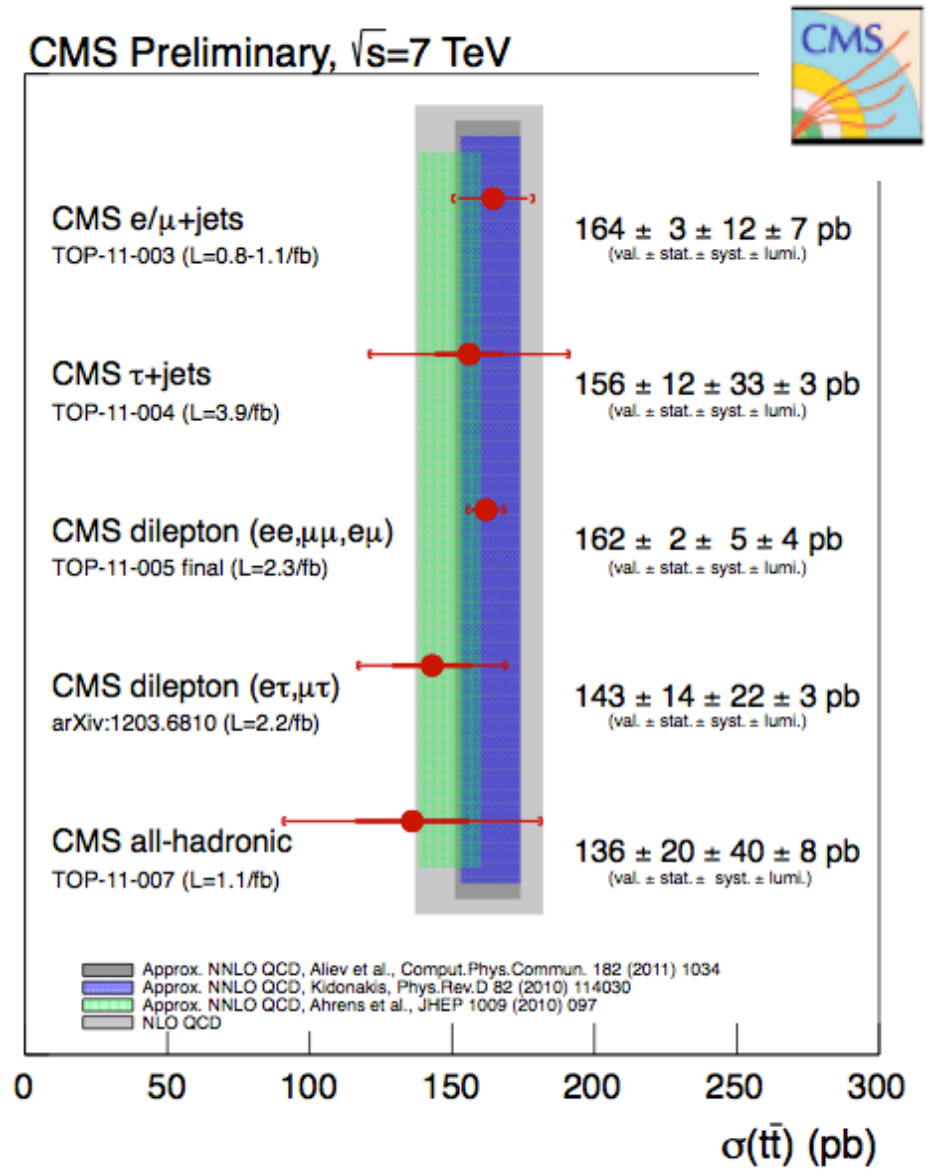


all channels measured except for $\tau_{had}\,\tau_{had}$

⇒ good agreement with SM in all channels

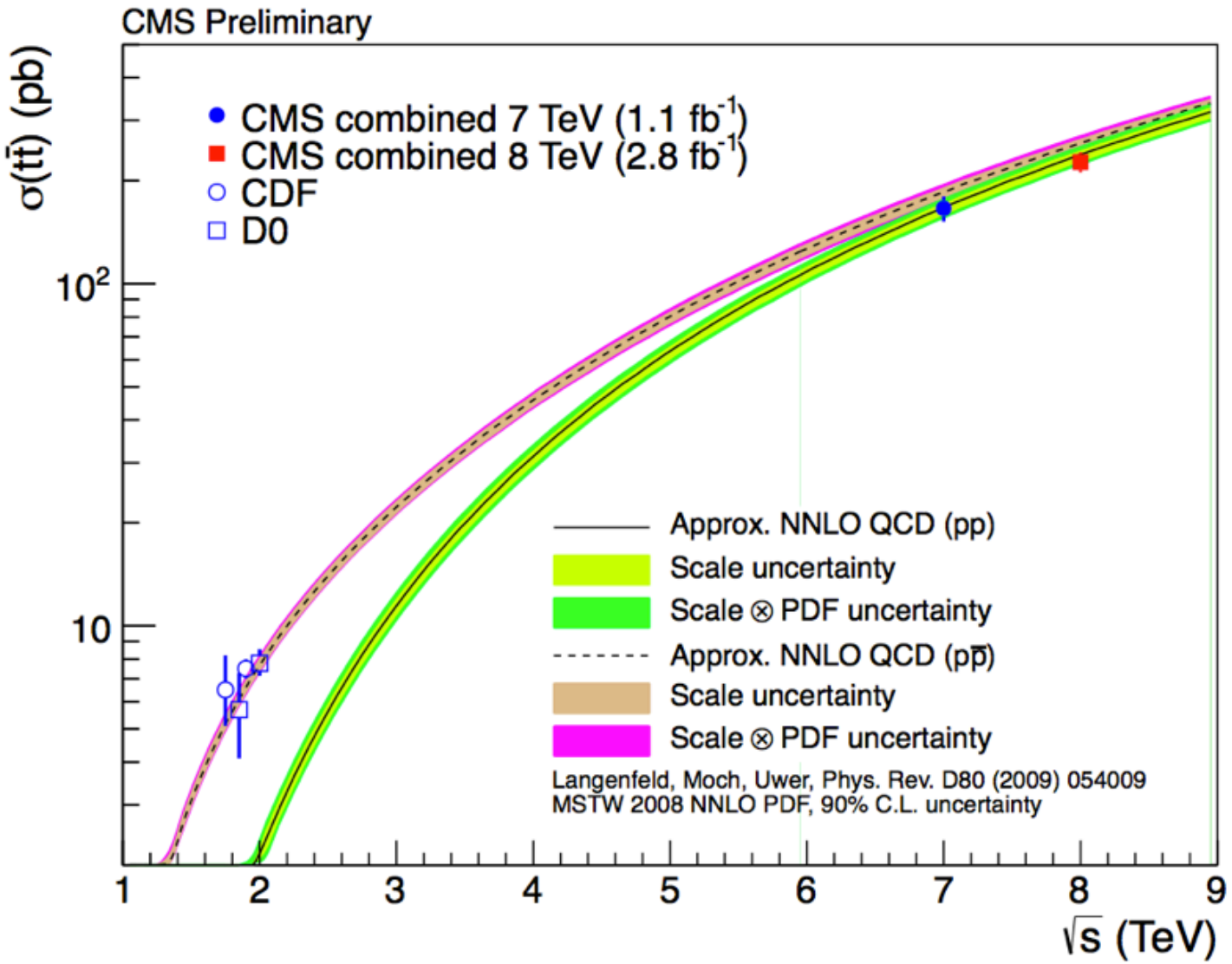
Top Pair Production Cross Section





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

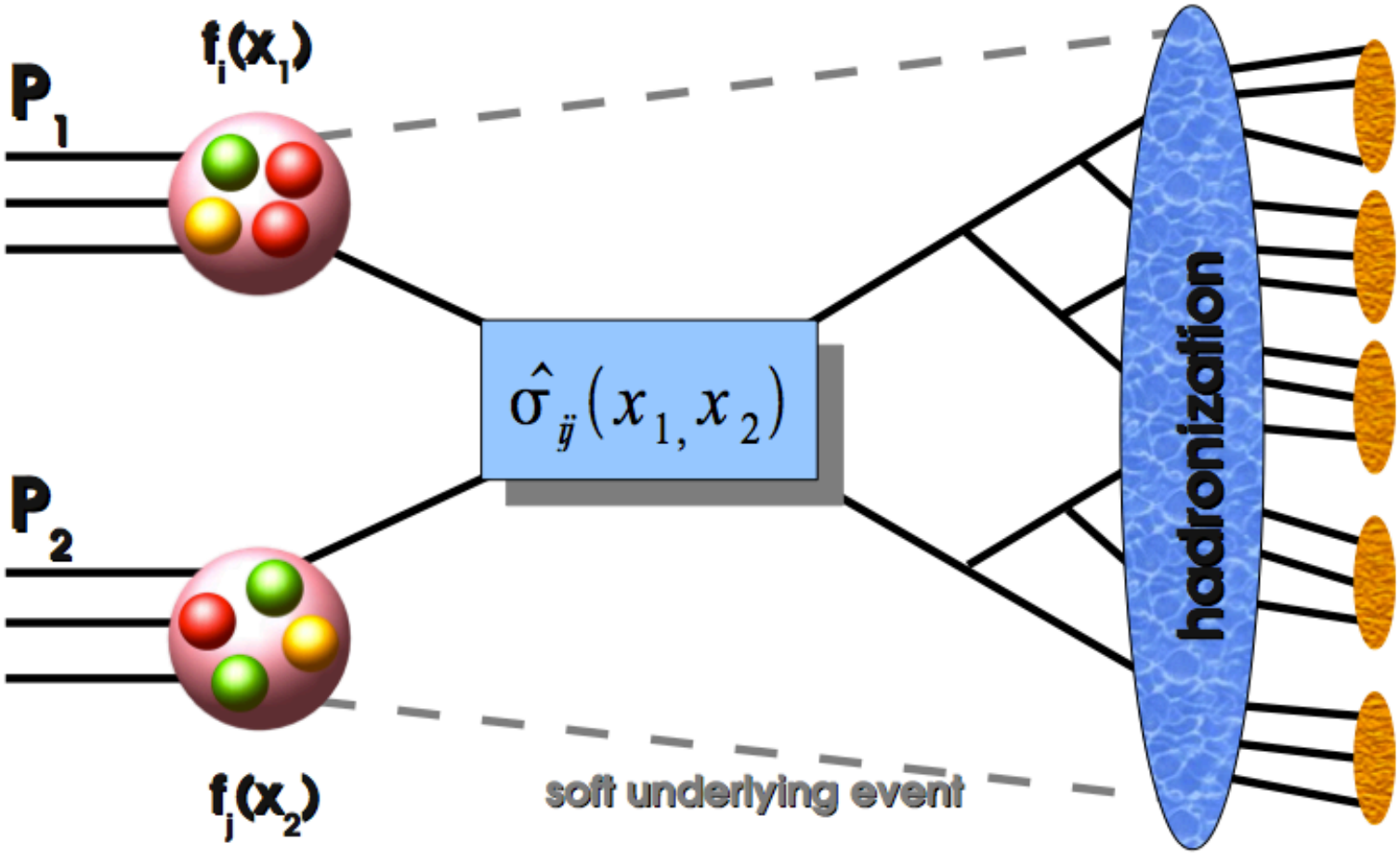
Top Pair Production Cross Section



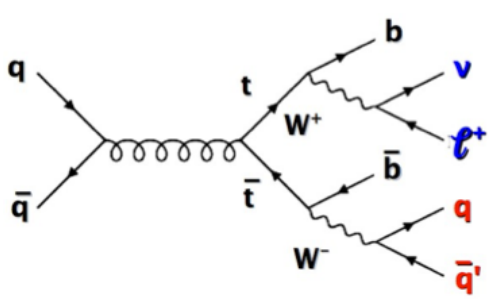
⇒ **good agreement with SM**

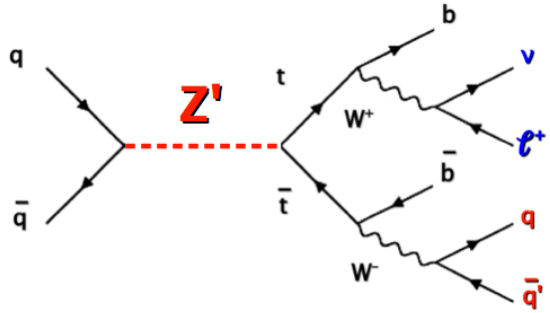
Differential Cross Sections

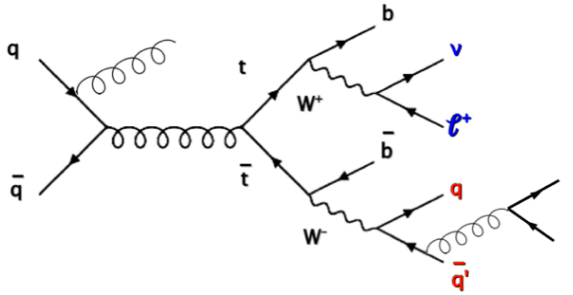
important tests of higher order QCD calculations:
requires "unfolding" to particle level

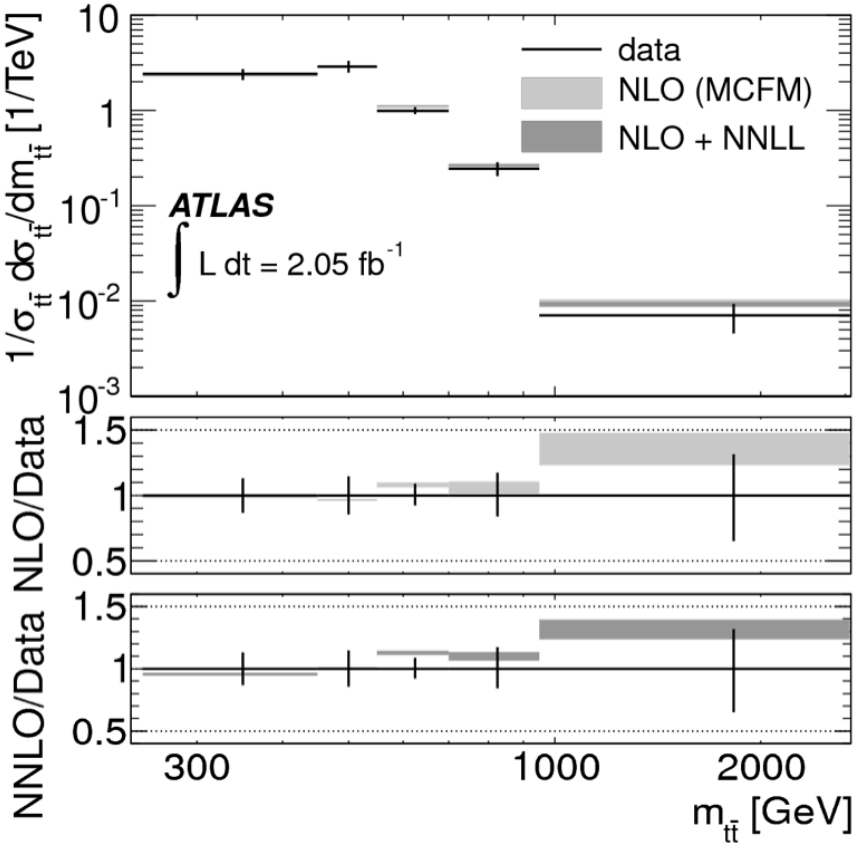


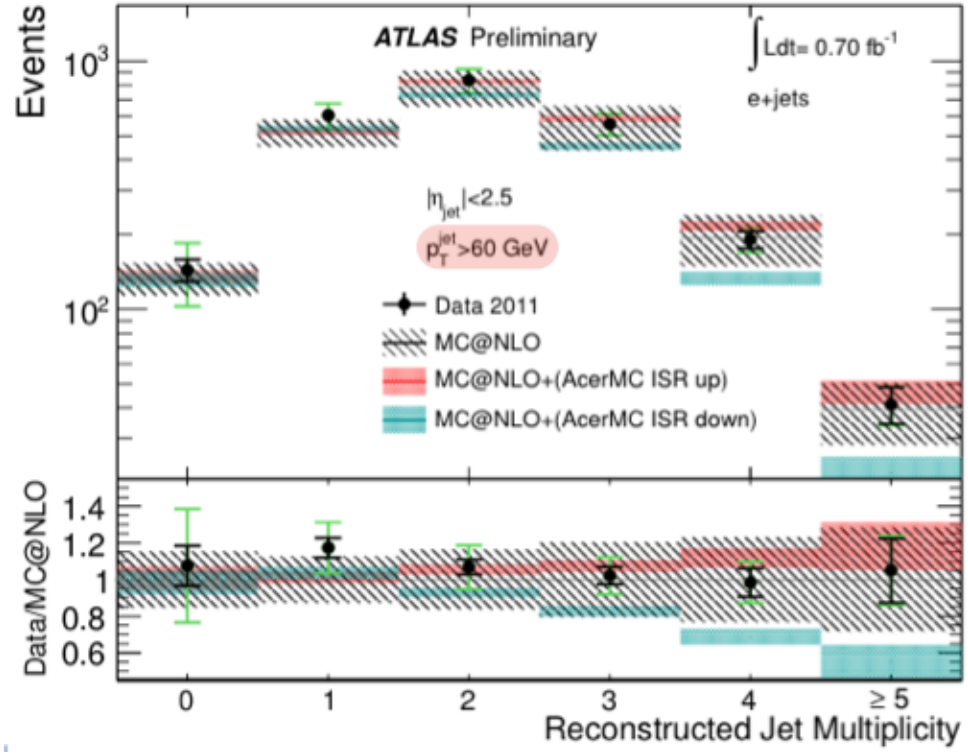
Differential Cross Sections





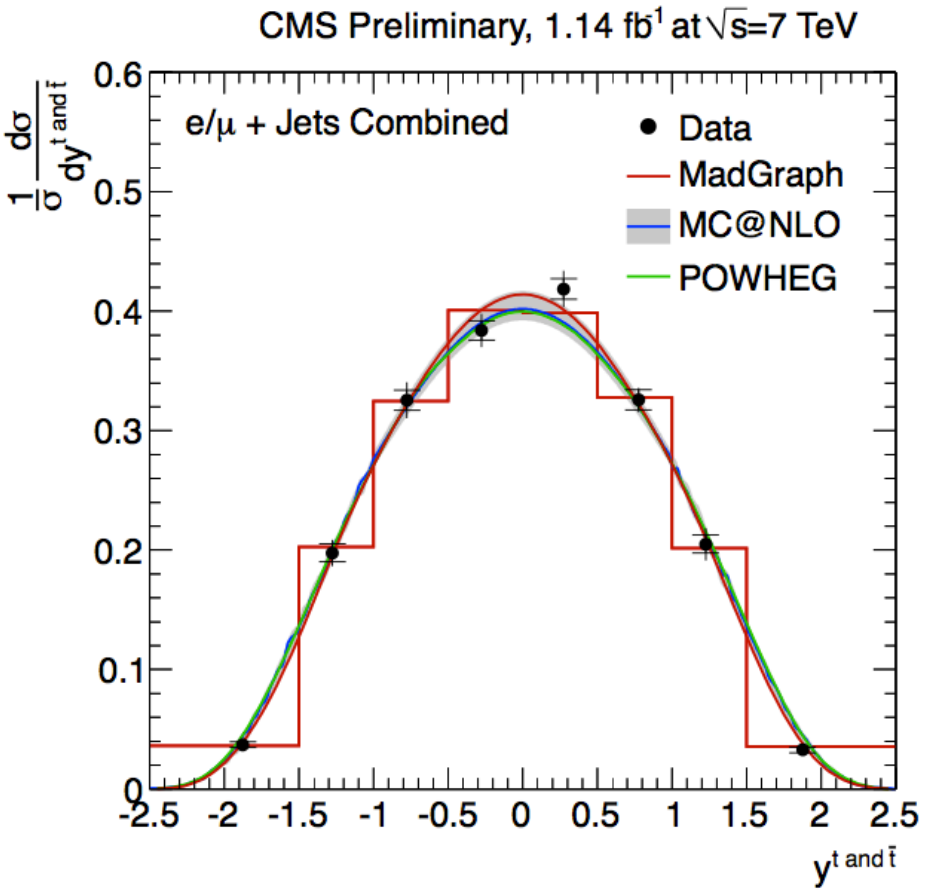


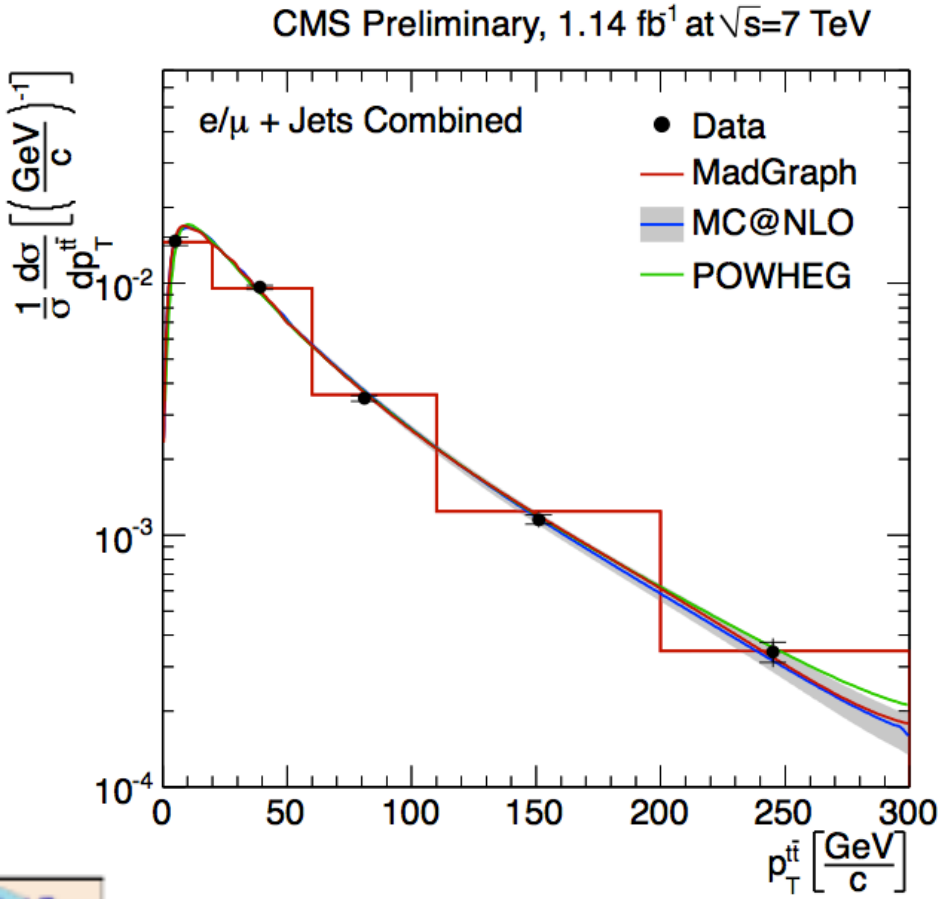




→ good agreement with higher order QCD calculations

Differential Cross Sections



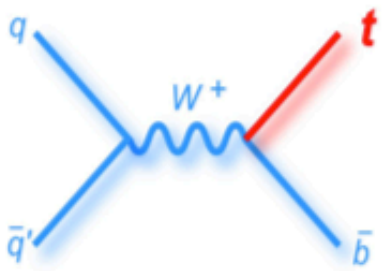


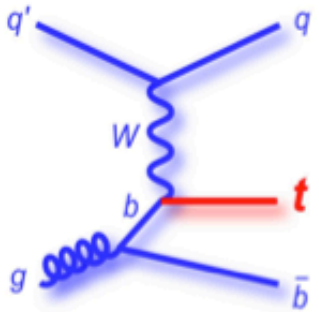
→ good agreement with higher order QCD calculations

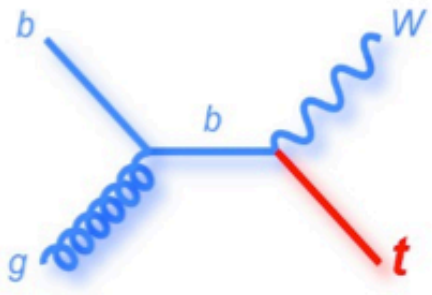
Single Top Quark Production

direct measurement of $|V_{tb}|$

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

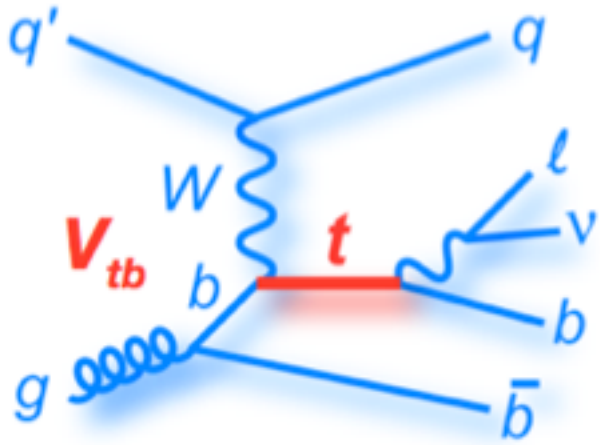




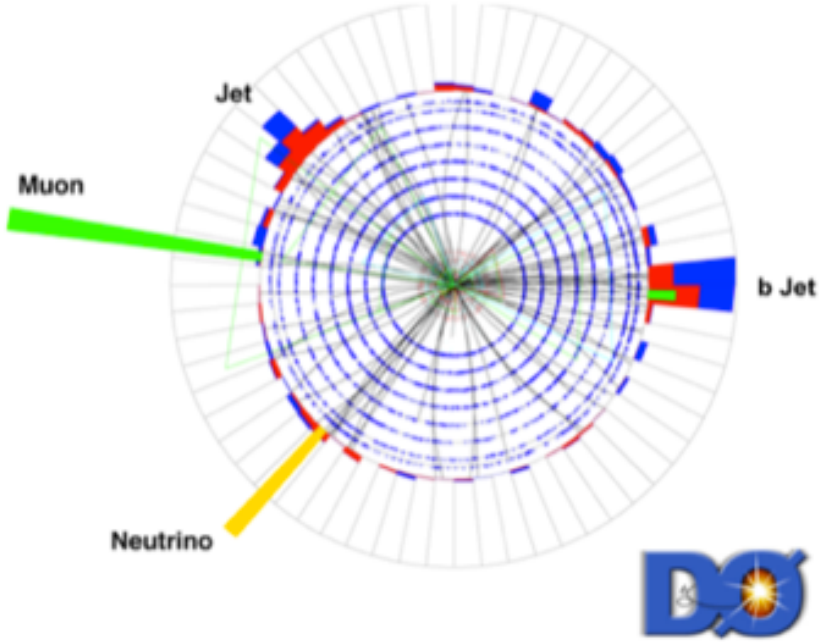


Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.04 pb	2.26 pb	0.28 pb
LHC: pp (7 TeV)	4.6 pb	64.6 pb	15.7 pb

Single Top Quark Production



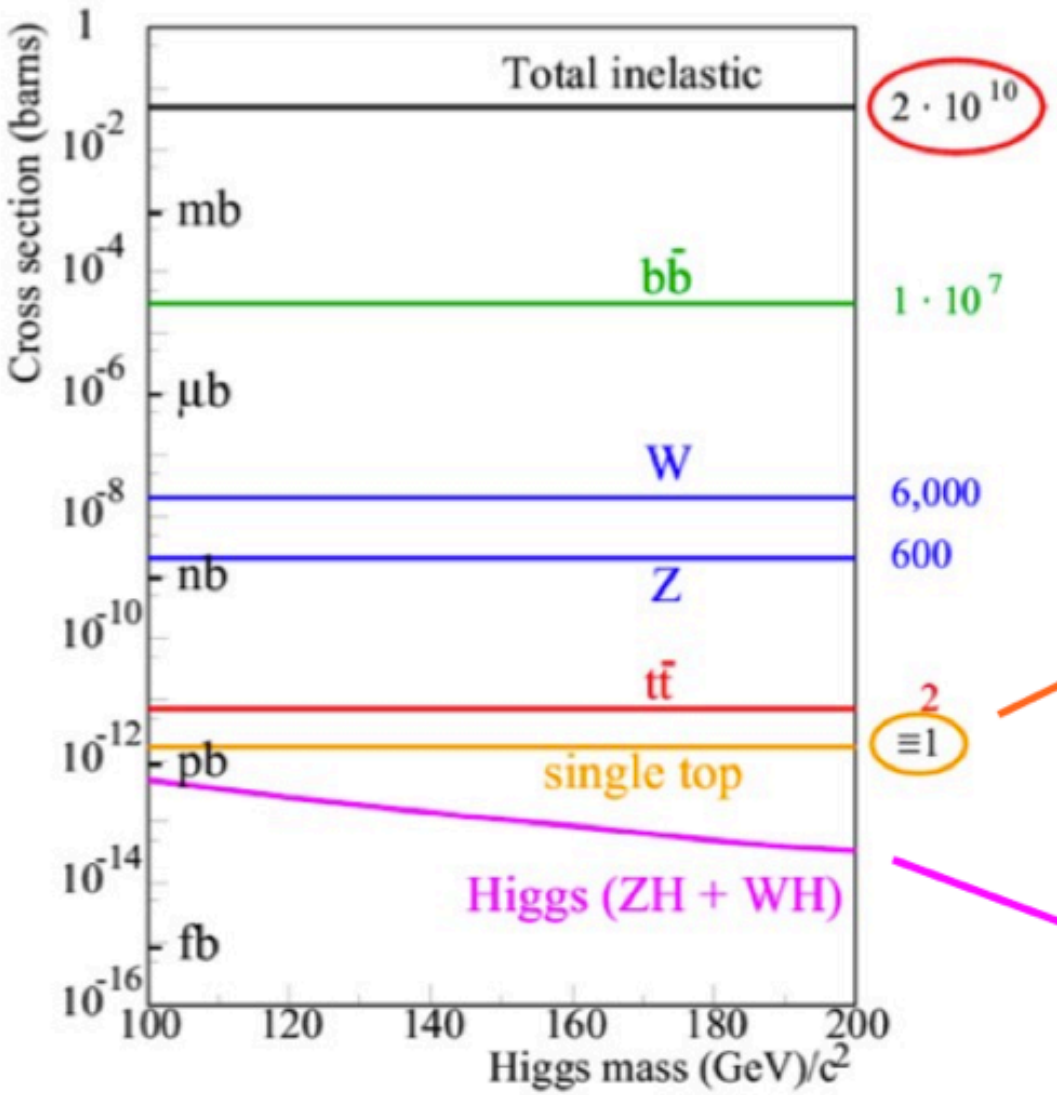
- jets
- lepton
- missing E_T
- b-jets

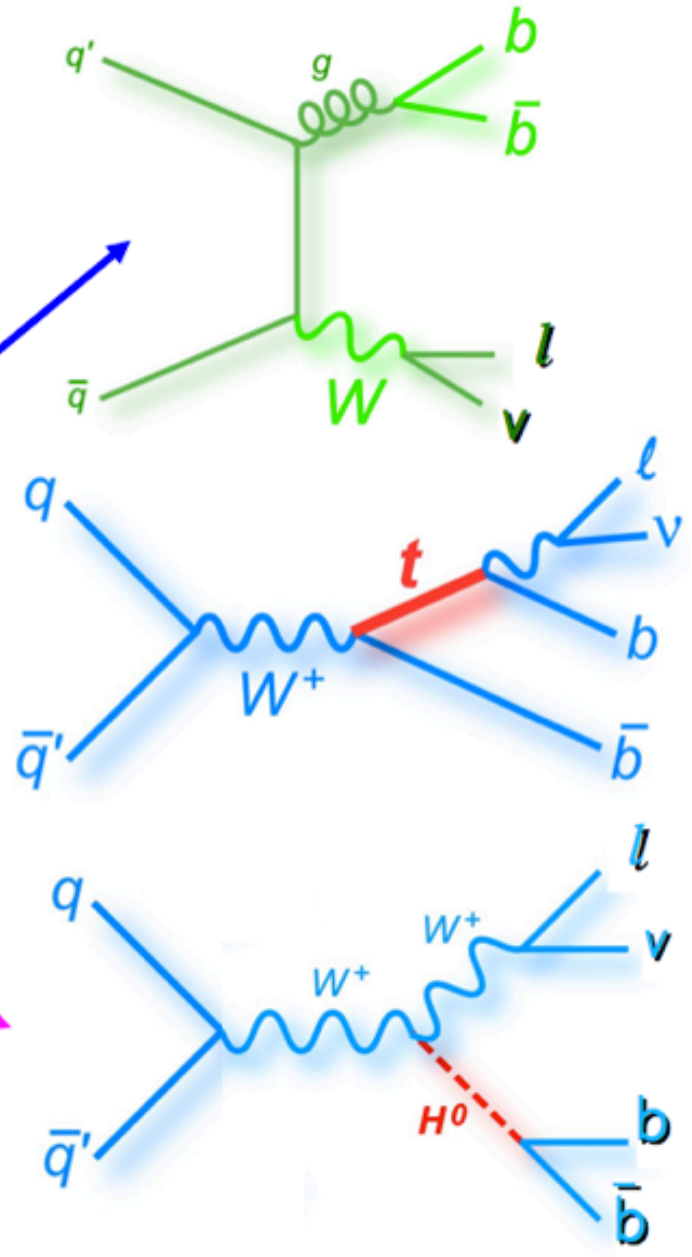


Collider
Tevatron: $p\bar{p}$ (1.96 TeV)

t-channel: σ_{tqb}
2.26 pb

It has been challenging for years...

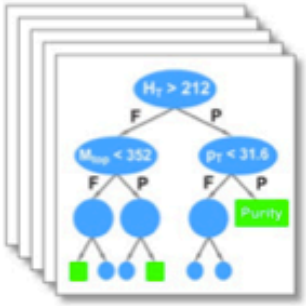




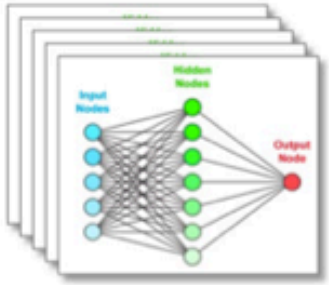
⟹ **multivariate analysis techniques**

Multivariate Analyses

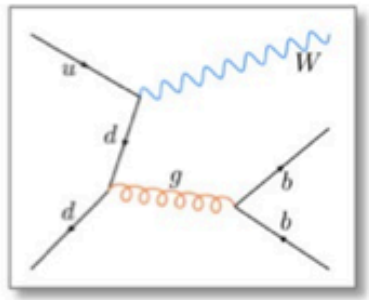
Boosted Decision Trees



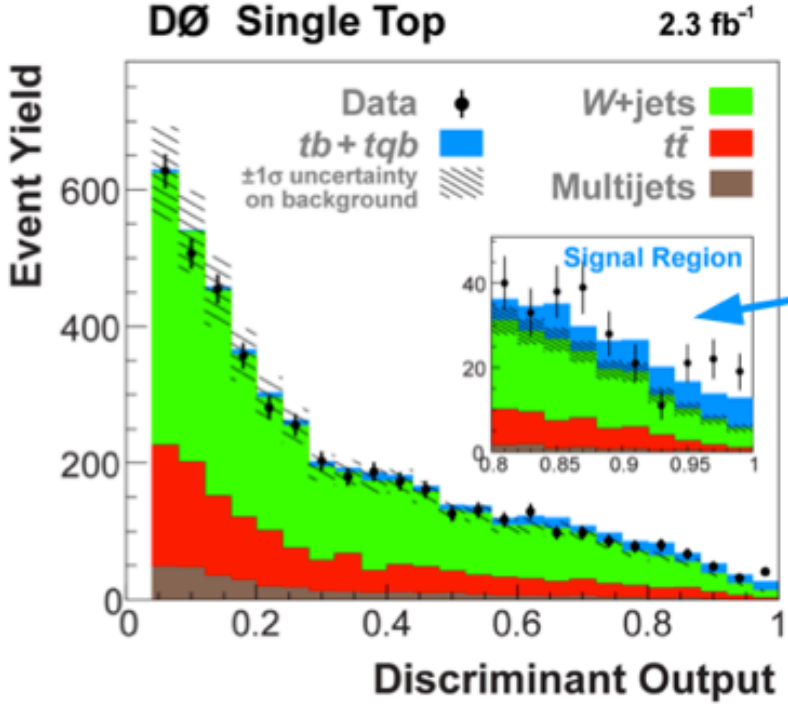
Boosted Neural Networks



Matrix Elements



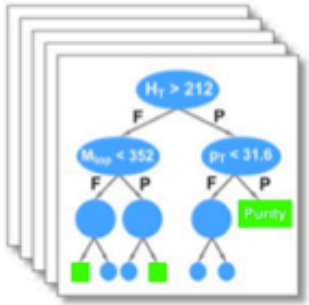
combine up to 12 different analysis channels:



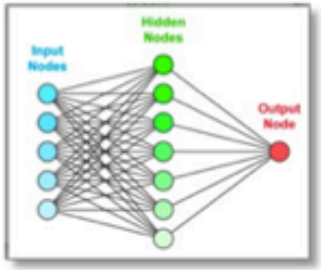
single top

Multivariate Analyses

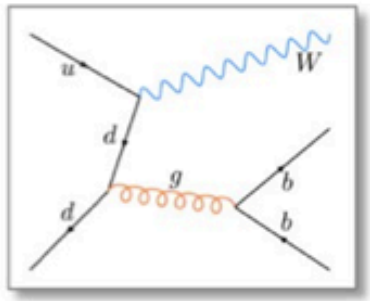
Boosted Decision Trees



Neural Networks



Matrix Elements



Likelihood

$$p_{ik} = \frac{f_{ij_ik}}{\sum_{m=1}^{5} f_{ij_im}},$$

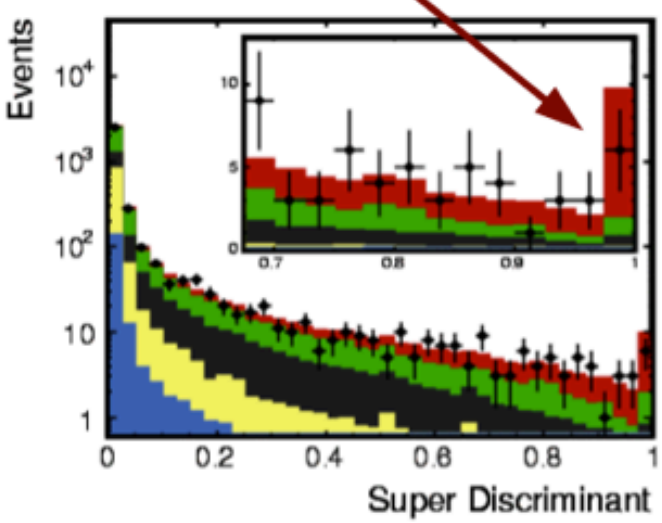
$$\mathcal{L}_k(\{x_i\}) = \frac{\prod_{i=1}^{n_{var}} p_{ik}}{\sum_{m=1}^{5} \prod_{i=1}^{n_{var}} p_{ik}}.$$

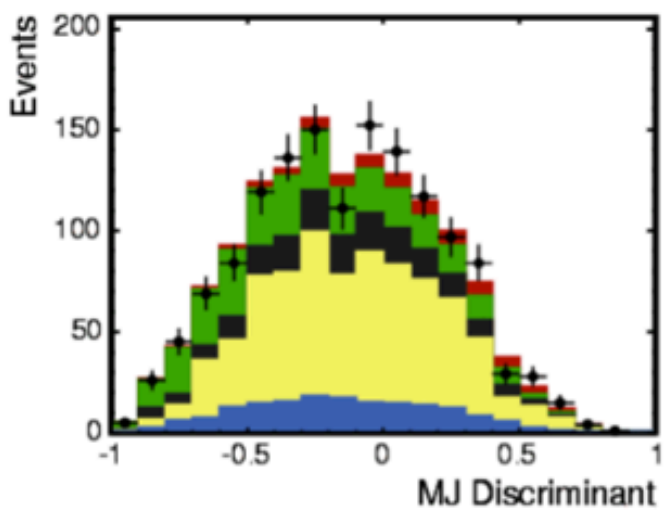
combine up to 8 different analysis channels:

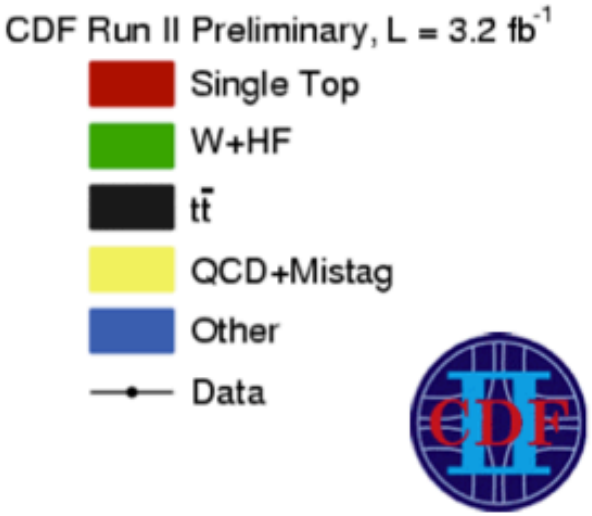
single top

- $\not\!\!E_T$+jets selection :

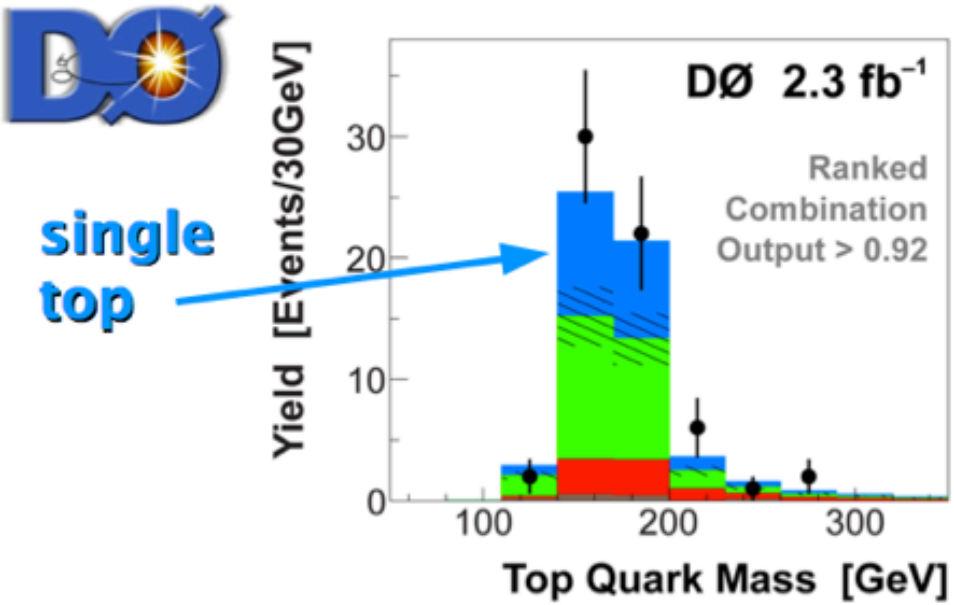
  recover badly reconstructed e, μ; include τ

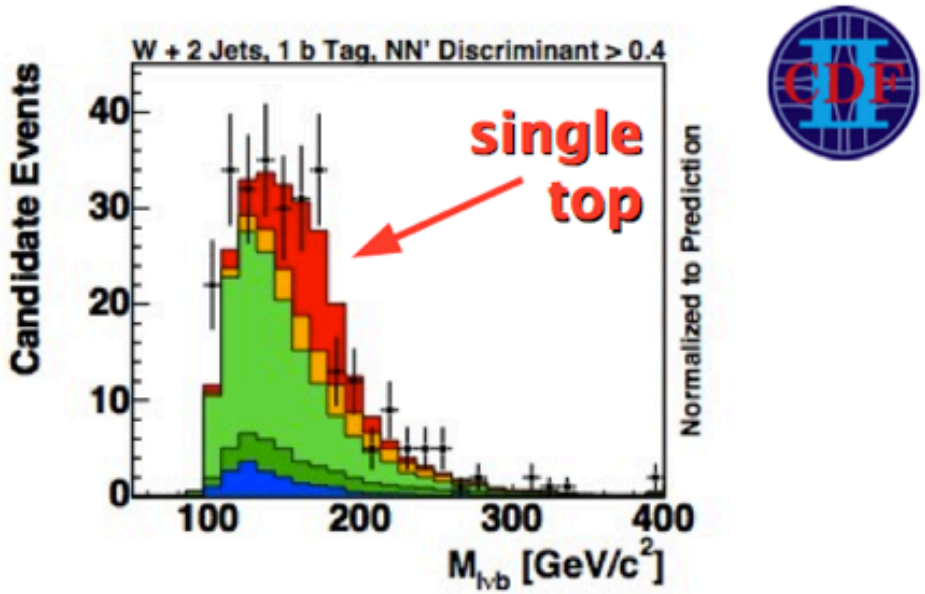






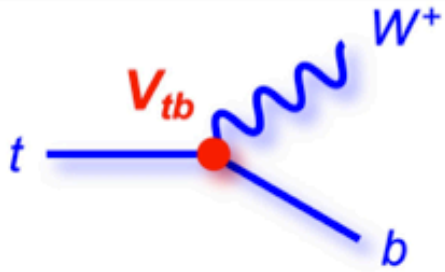
Single Top Quark Observation





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

⇒ **observation with 5.0σ!**

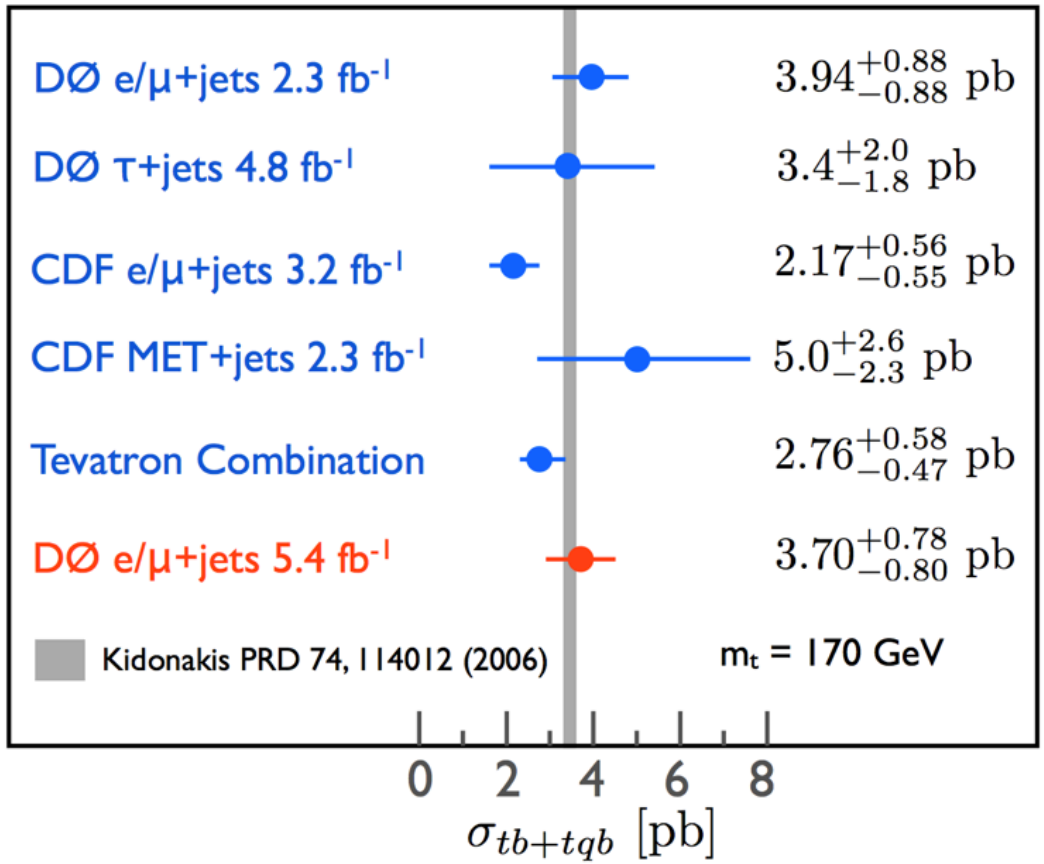


$|V_{tb}| = 1.07 \pm 0.12$

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

Single Top Quark Observation

Tevatron Single Top Cross Section

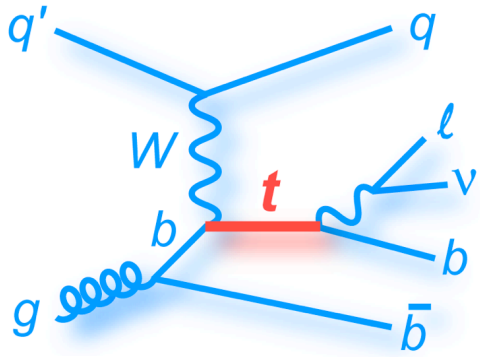


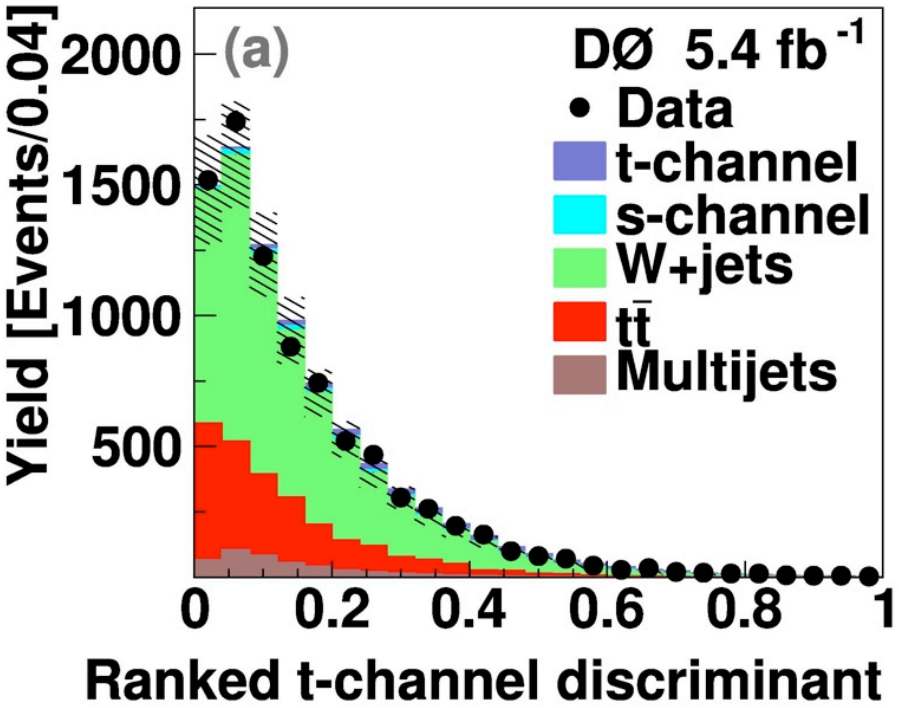
$|V_{tb}| = 0.88 \pm 0.07$ ±8%

⇒ good agreement with SM in all channels

Single Top t-channel Production

- remove s/t channel constraint which could be changed by new physics
- train multivariate analysis for t-channel
- measure s- and t-channel simultaneously





Single Top t-channel Production

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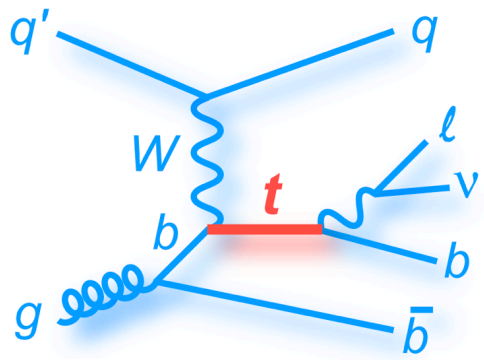
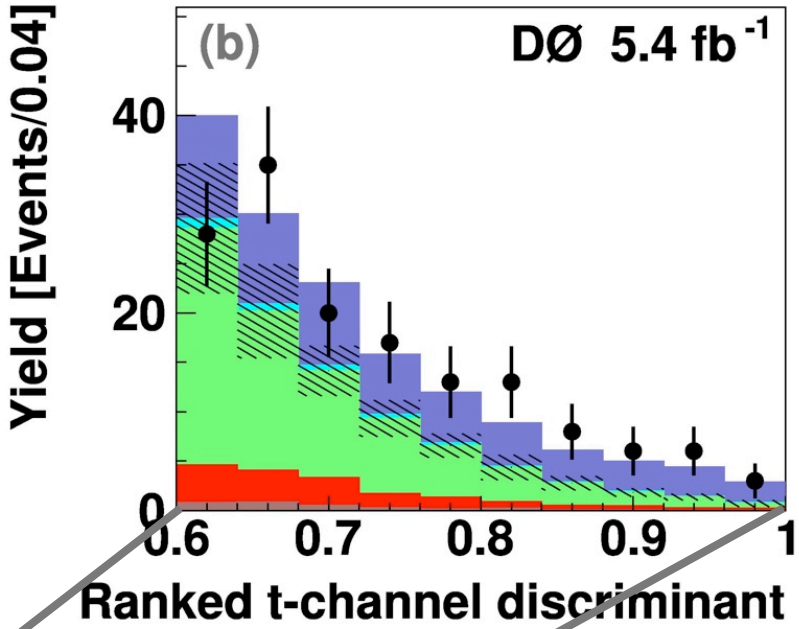
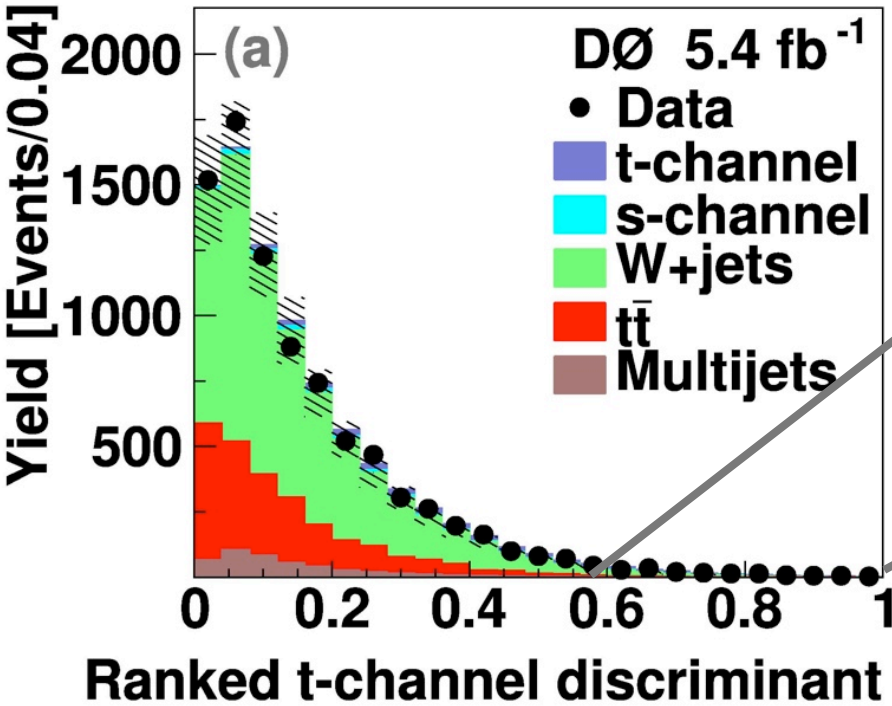






σ_{tb} = 2.26 ± 0.12 pb

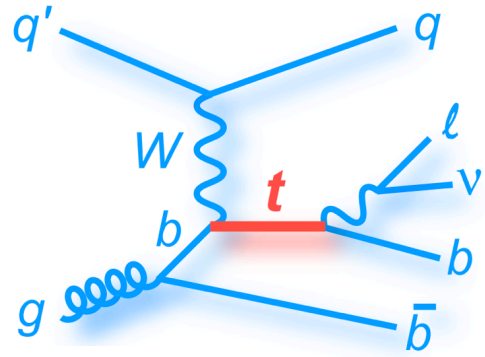
$NNLO_{approx}$, m_{top} = 172.5 GeV

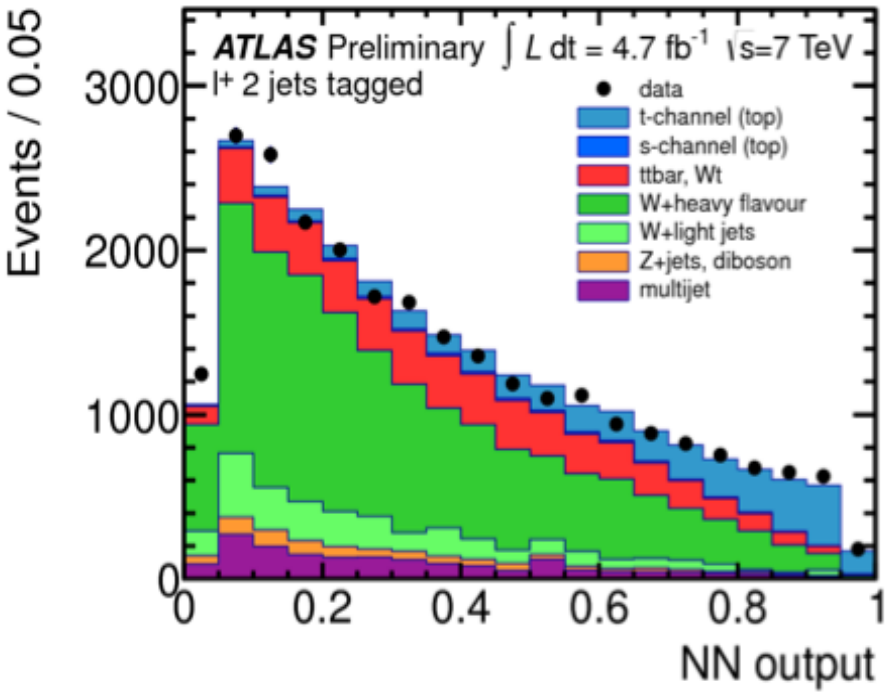
σ(t-channel)=2.90±0.59 pb

observation with 5.5σ

Single Top t-channel Production

- remove s/t channel constraint which could be changed by new physics
- train multivariate analysis for t-channel
- measure s- and t-channel simultaneously





Single Top t-channel Production

- remove s/t channel constraint which could be changed by new physics
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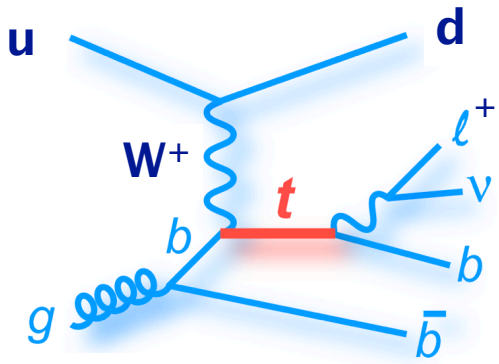
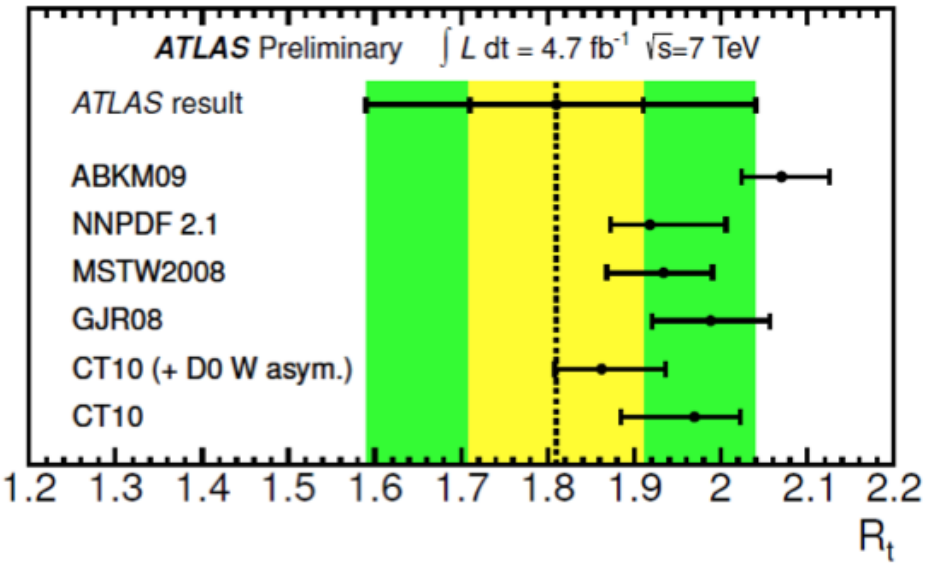
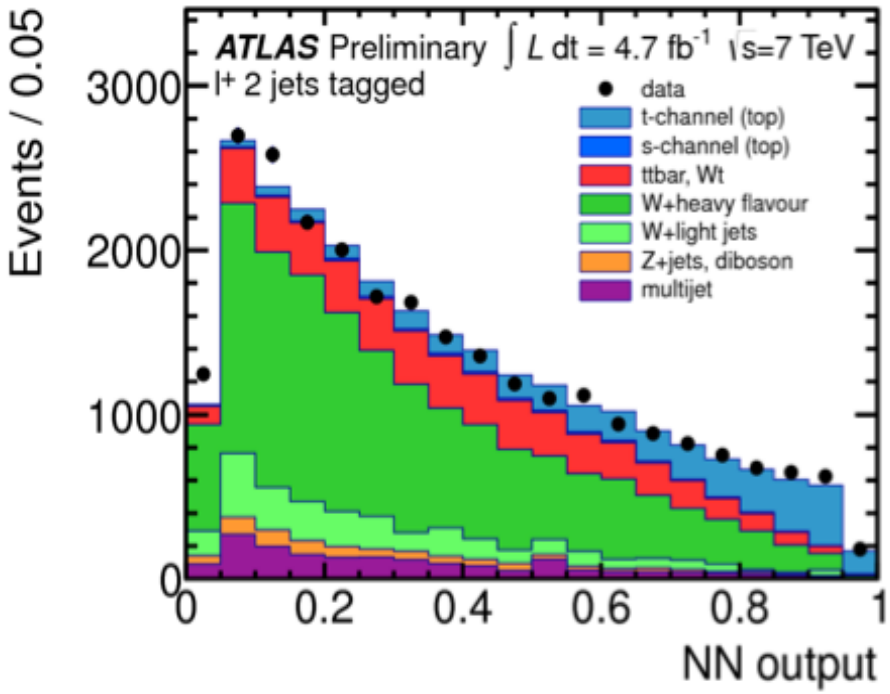


check light quark flavor content of proton:





$$\sigma_t(t) = 53.2 \pm 10.8\,\text{pb}$$

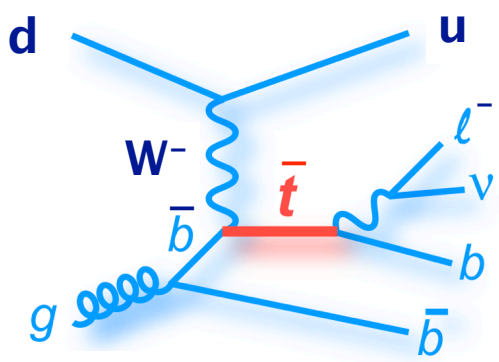
$$\sigma_t(\bar{t}) = 29.5^{+7.4}_{-7.5}\,\text{pb}$$

$$R_t = 1.81^{+0.23}_{-0.22}.$$

$$R_t \equiv \sigma_t(t)/\sigma_t(\bar{t})$$

Single Top t-channel Production

- remove s/t channel constraint which could be changed by new physics
- train multivariate analysis for t-channel
- measure s- and t-channel simultaneously



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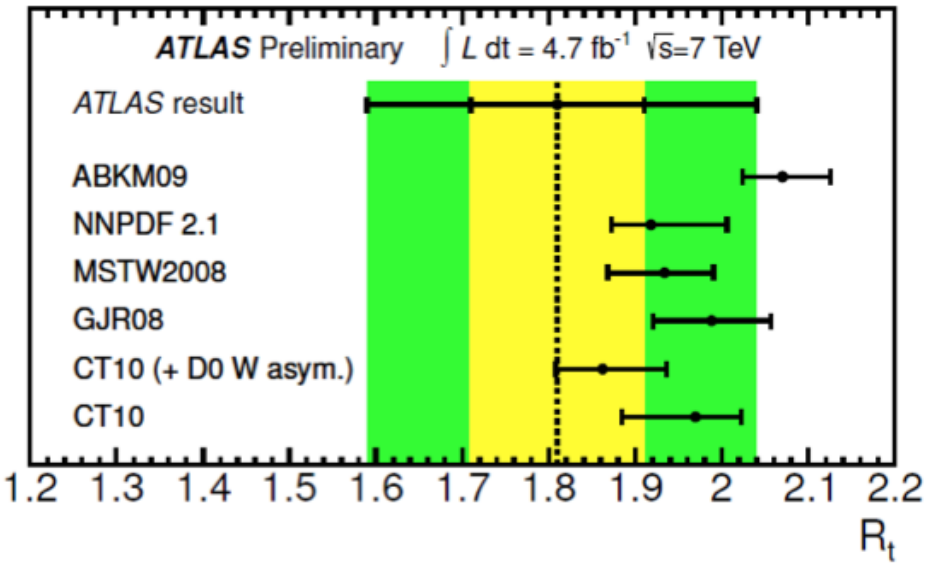

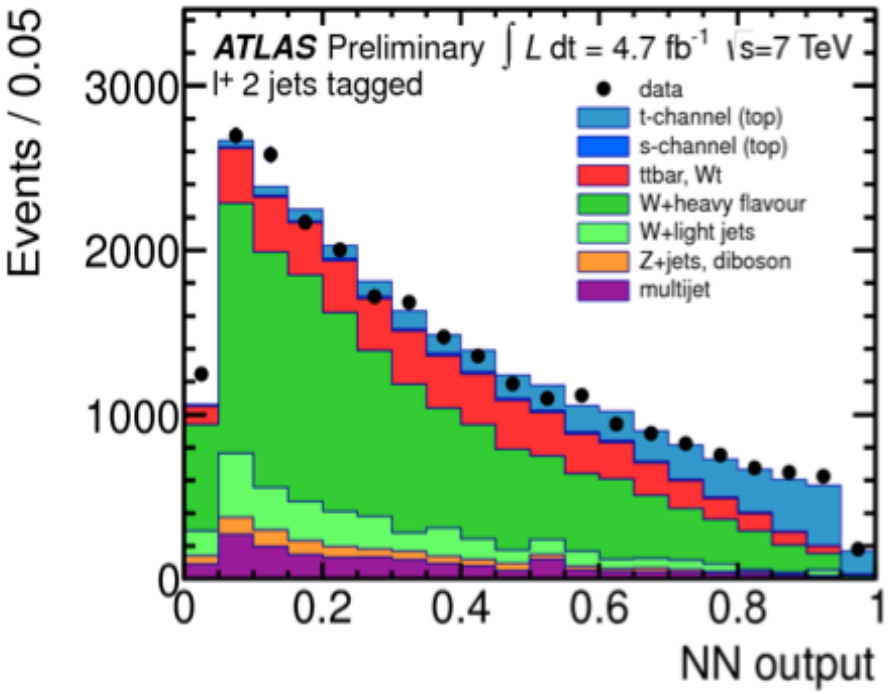

$$\sigma_t(t) = 53.2 \pm 10.8\,\text{pb}$$

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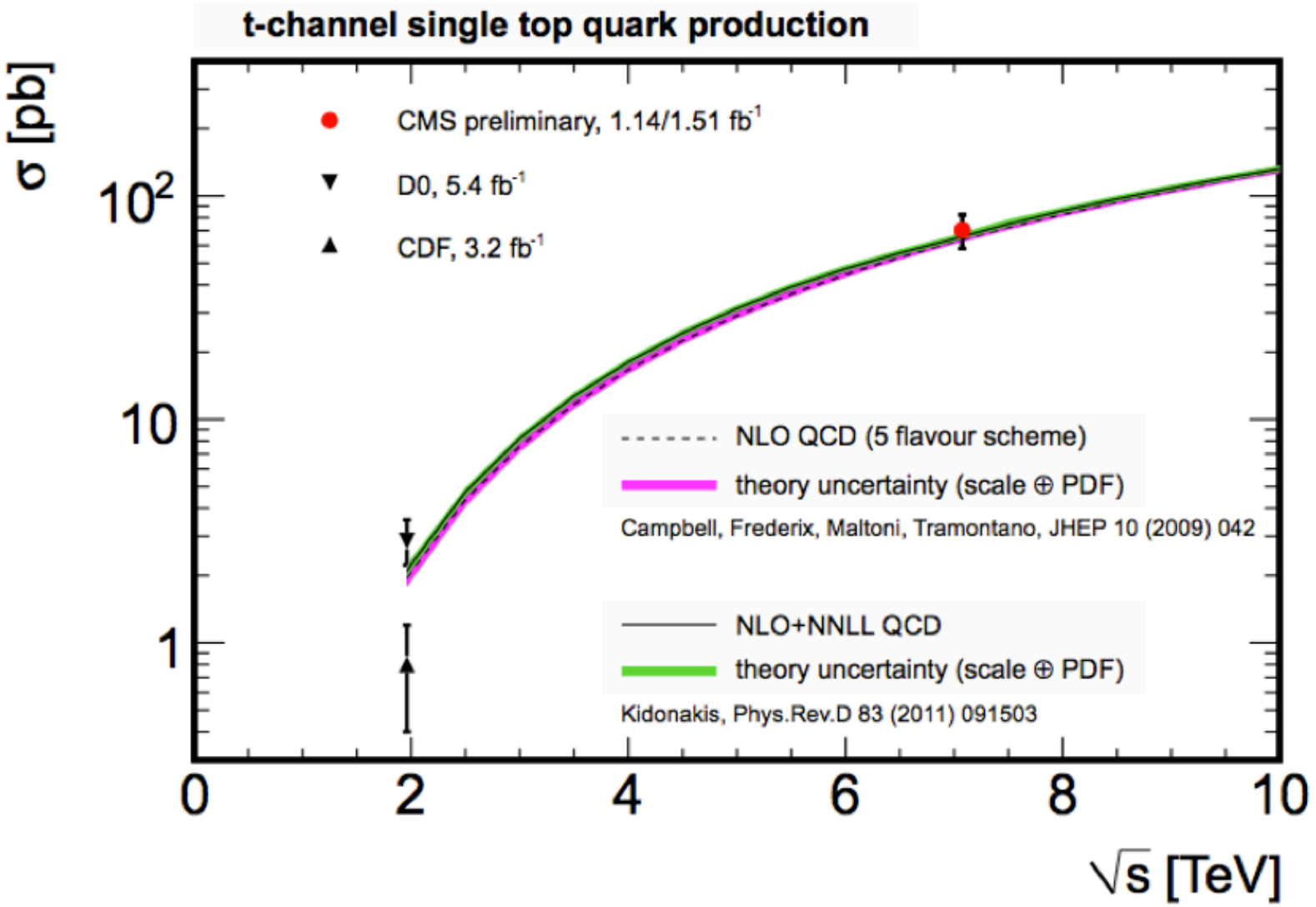
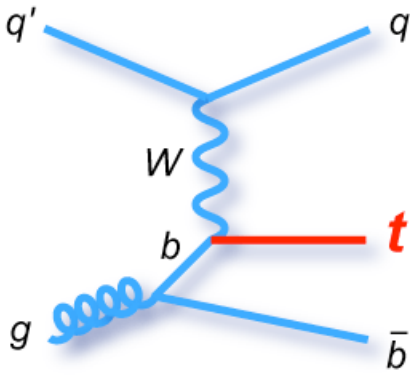
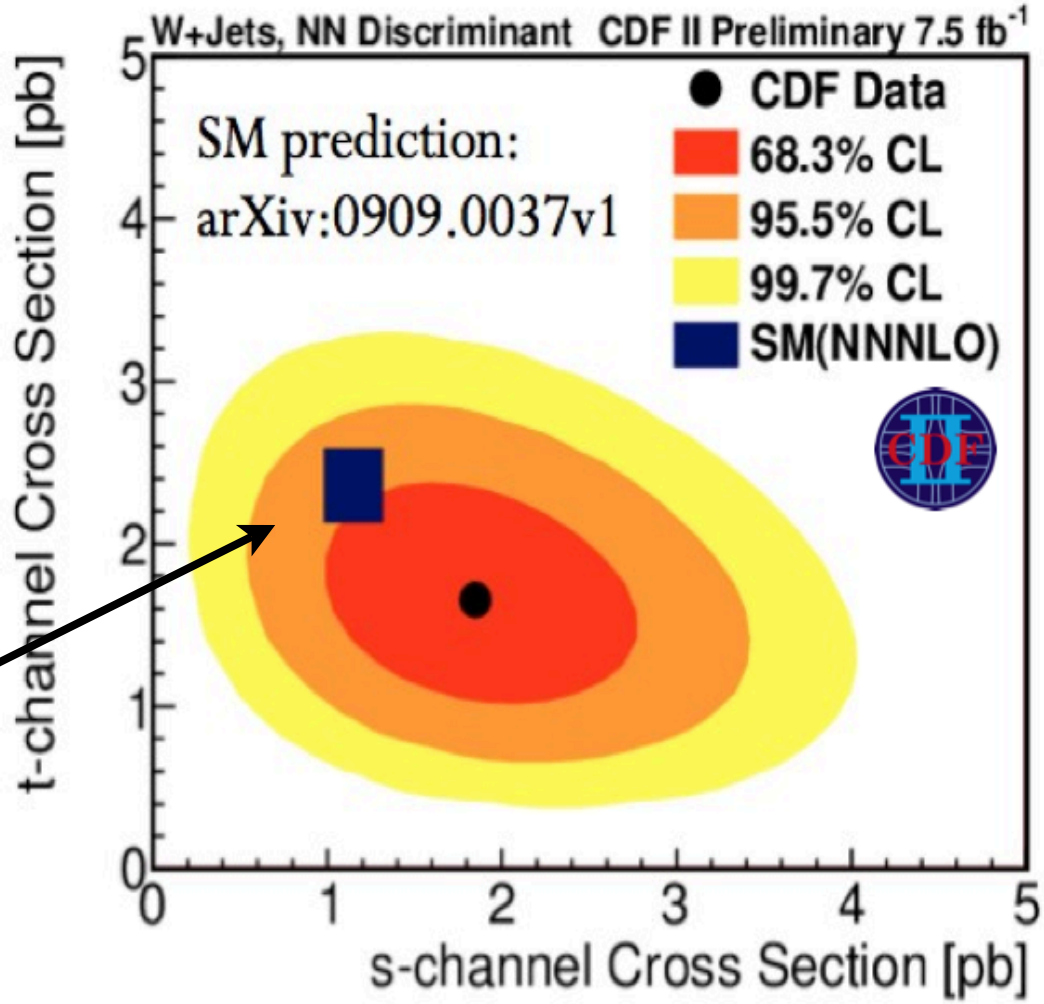
Single Top t-channel Production



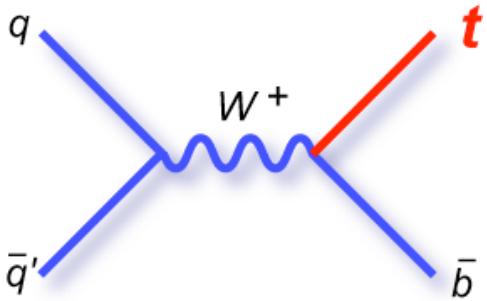
⇒ **good agreement with SM**

Single Top s- vs. t-channel



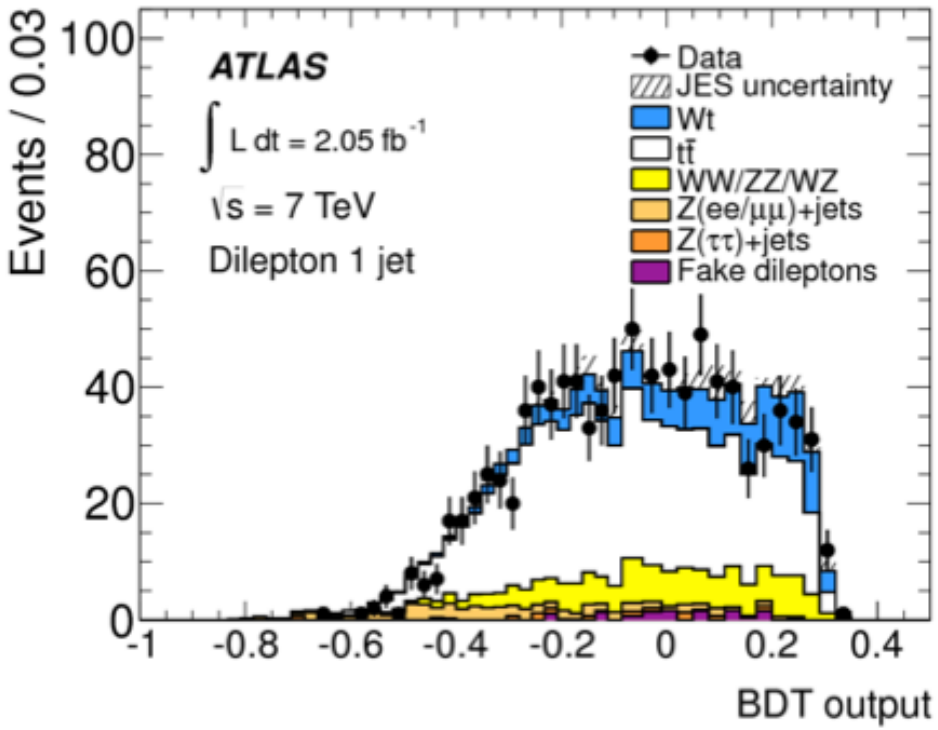


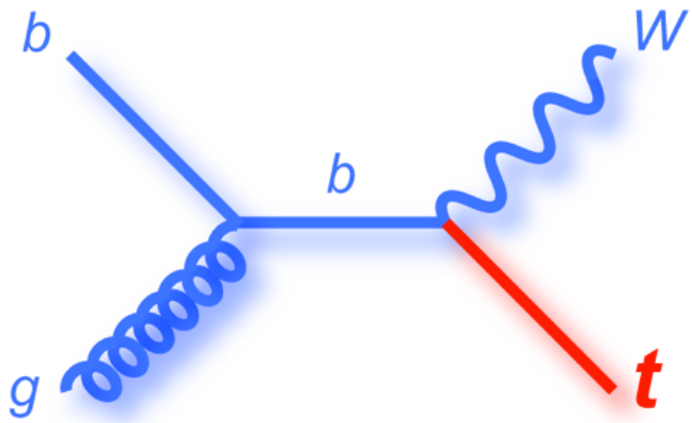
SM



good agreement with Standard Model

Single Top Wt-channel Production



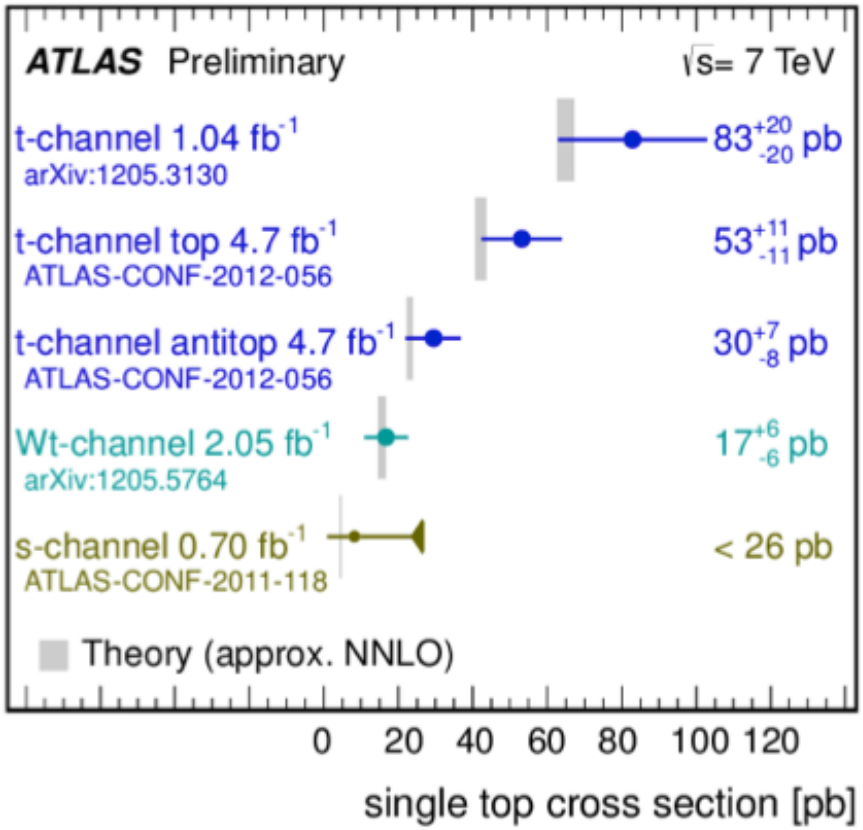


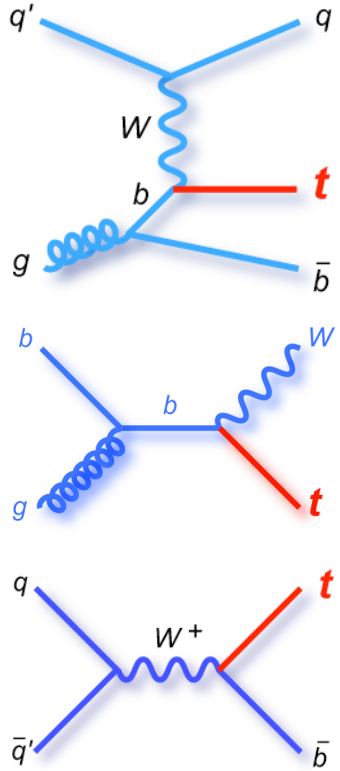
$$\sigma_{Wt} = 16.8 \pm 2.9\,(\text{stat}) \pm 4.9\,(\text{syst})\ \text{pb}$$

evidence with 3.3σ

SM: σ_{Wt}=15.7 pb

Single Top Production at the LHC





Channel	Dataset	$\|V_{tb}\|$	rel. exp. precision
t-channel	1.04 fb^{-1}	$1.13\ ^{+0.14}_{-0.13}$ (exp. + theo.)	12%
Wt	2.05 fb^{-1}	$1.03\ ^{+0.16}_{-0.19}$ (exp. + theo.)	17%

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

good agreement with Standard Model

±12%