Tevatron Results
QCD, Top Quark, Exotic Physics

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on behalf of
the CDF and DØ Collaborations

Hadron Collider Physics Summer School
Fermilab
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Tevatron Results – Outline

Part I:

QCD

Top quark physics

Searches for new physics

Part II:

Higgs

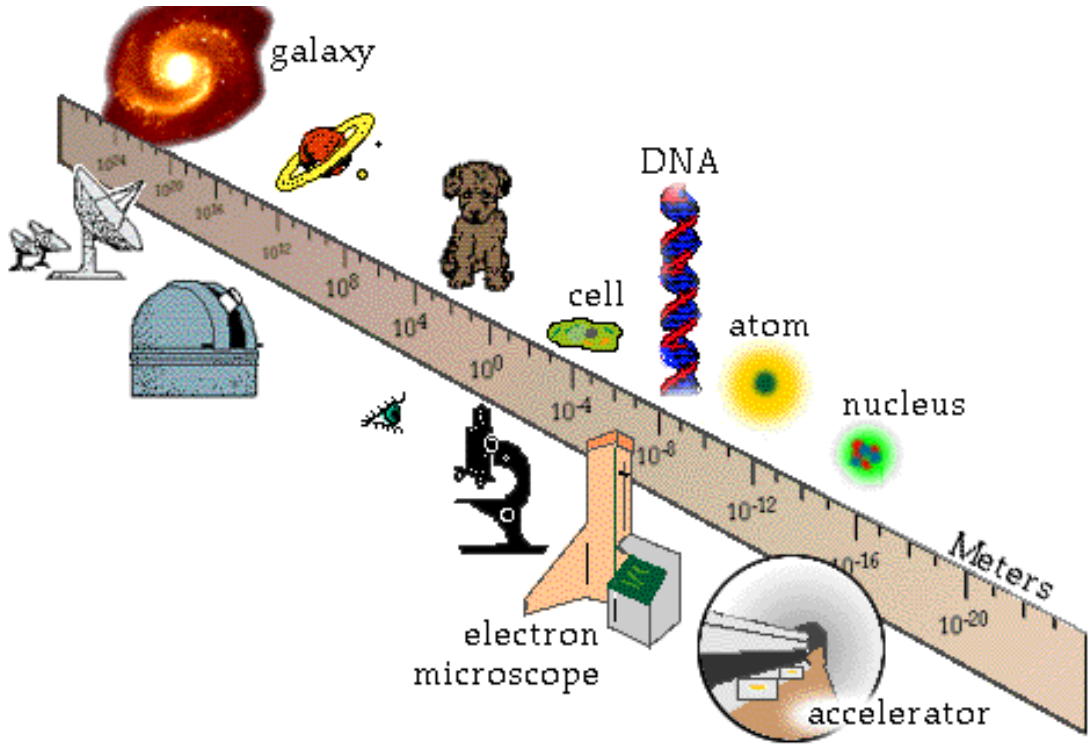
Electroweak physics

B physics

Objective of Elementary Particle Physics

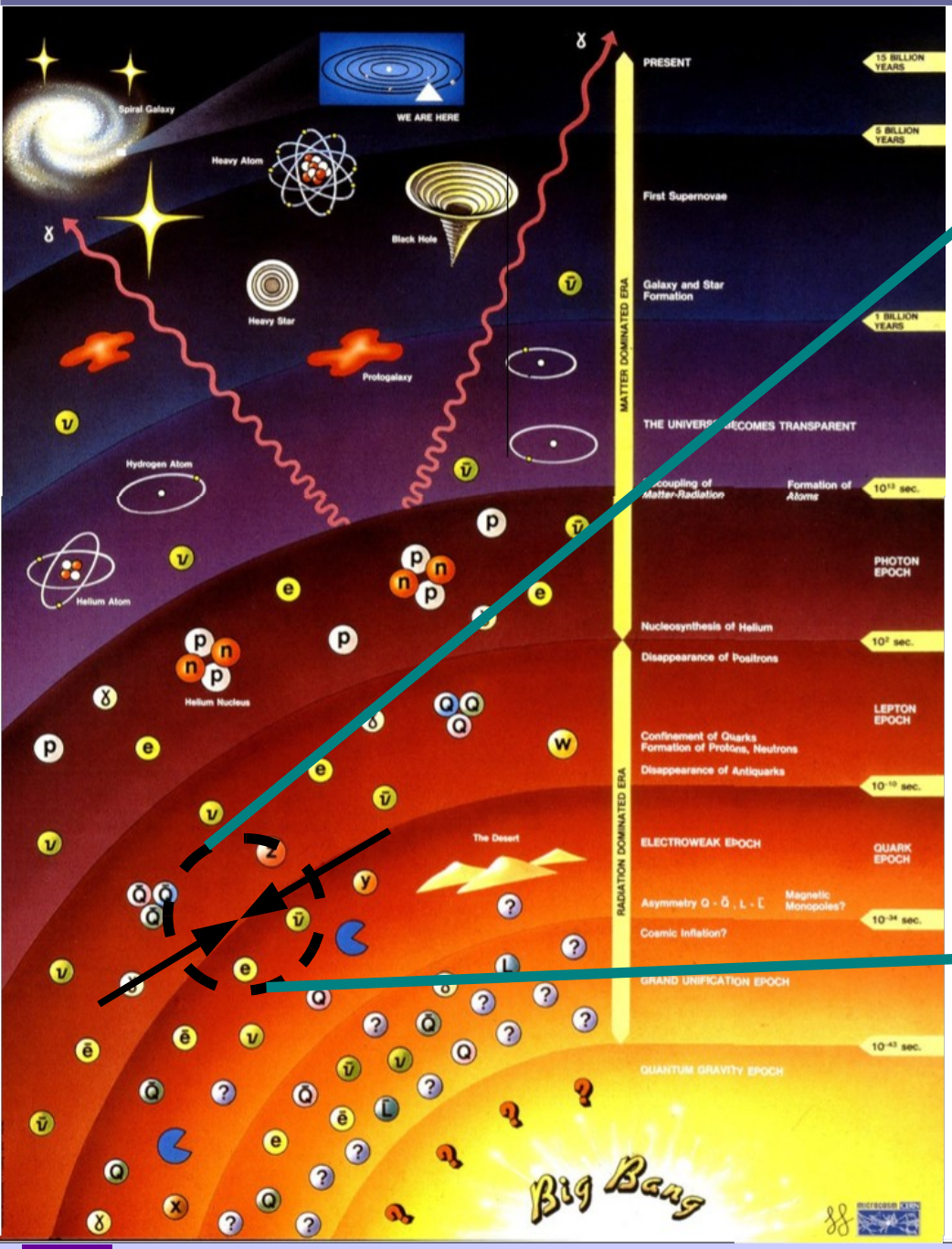
"So that I may perceive whatever holds the world together in its inmost folds."

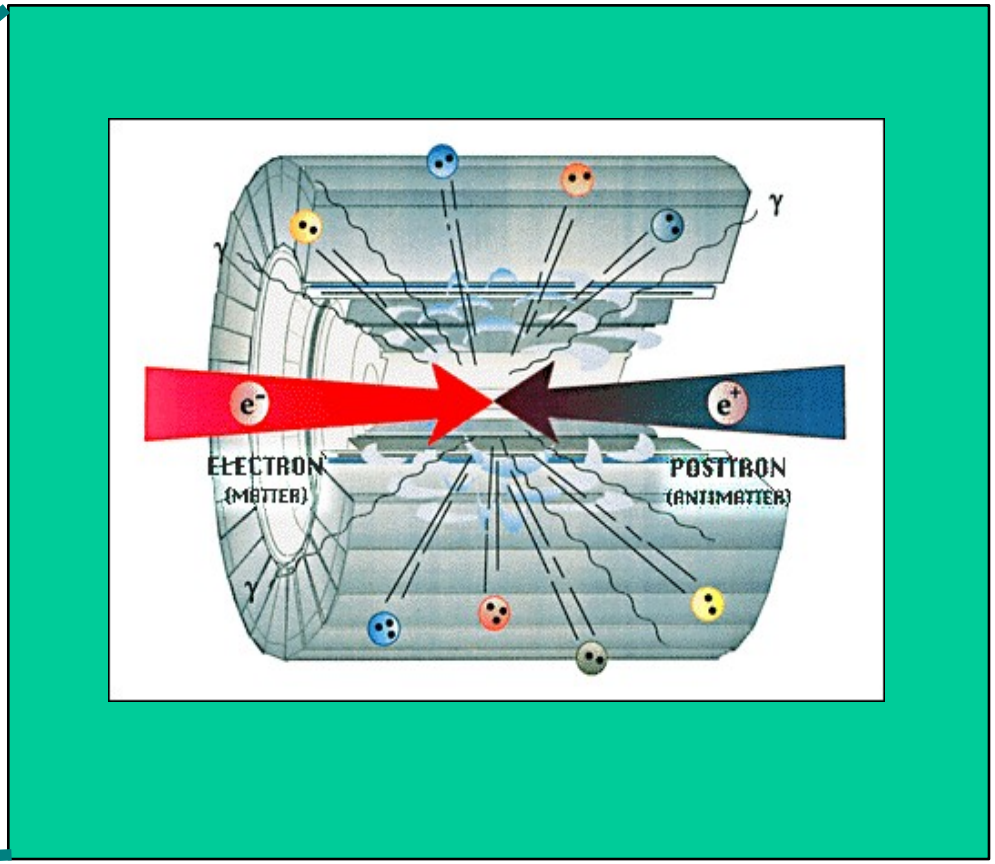
Goethe, Faust



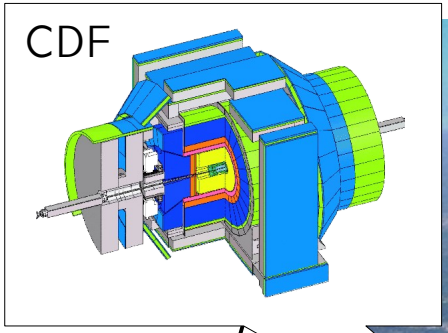
➔ **from the smallest dimensions in microcosm to the largest dimensions in the universe**

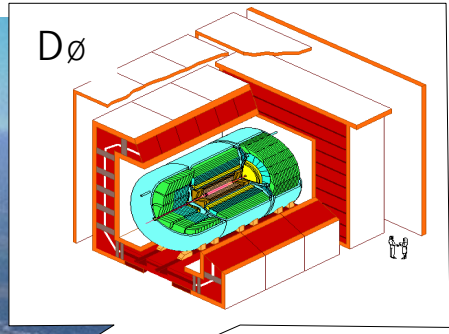
Big Bang in the Lab?

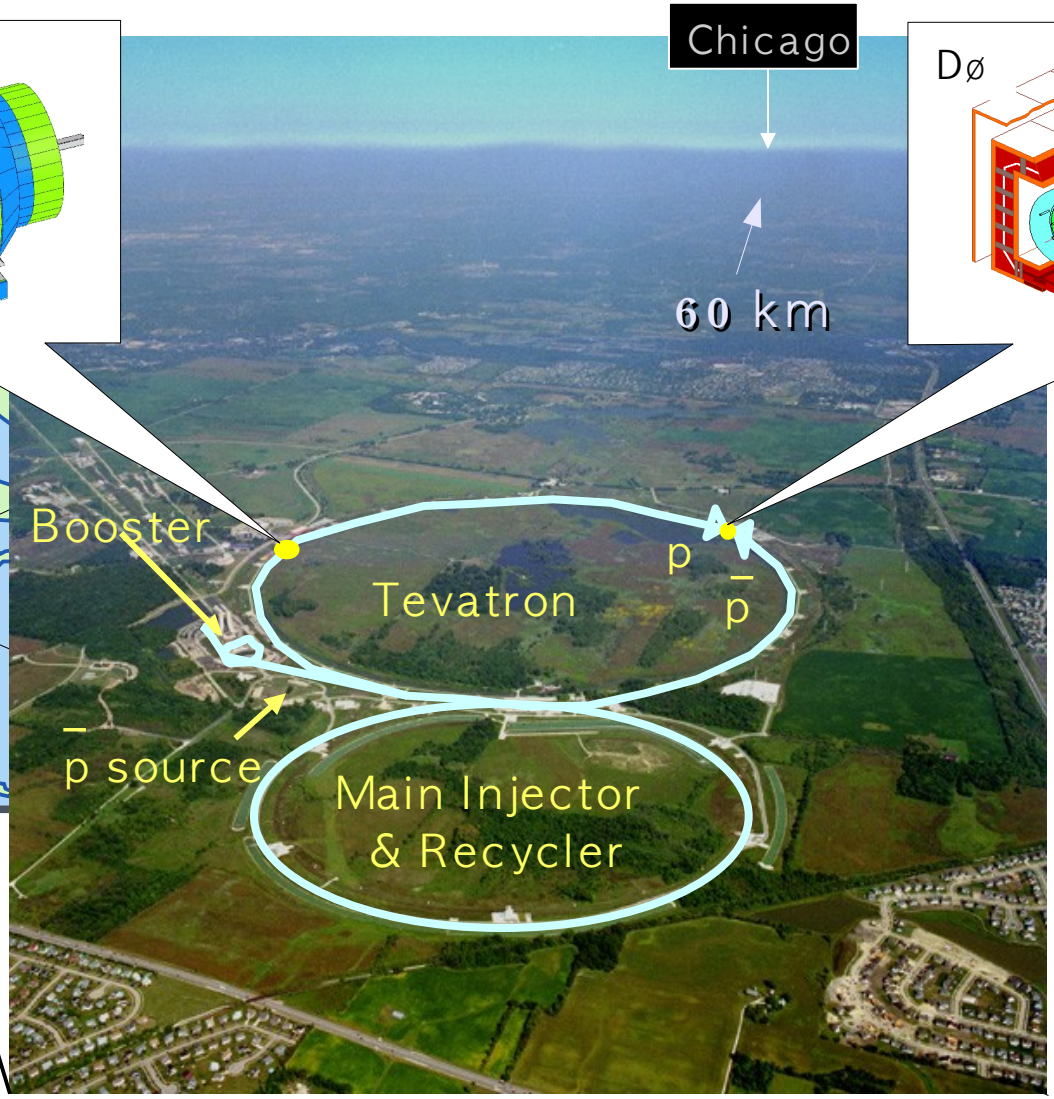


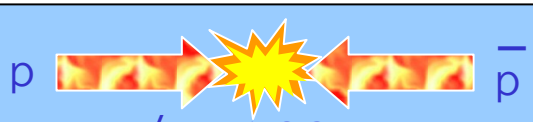


The Tevatron at FERMILAB: $p\bar{p}$ Collisions









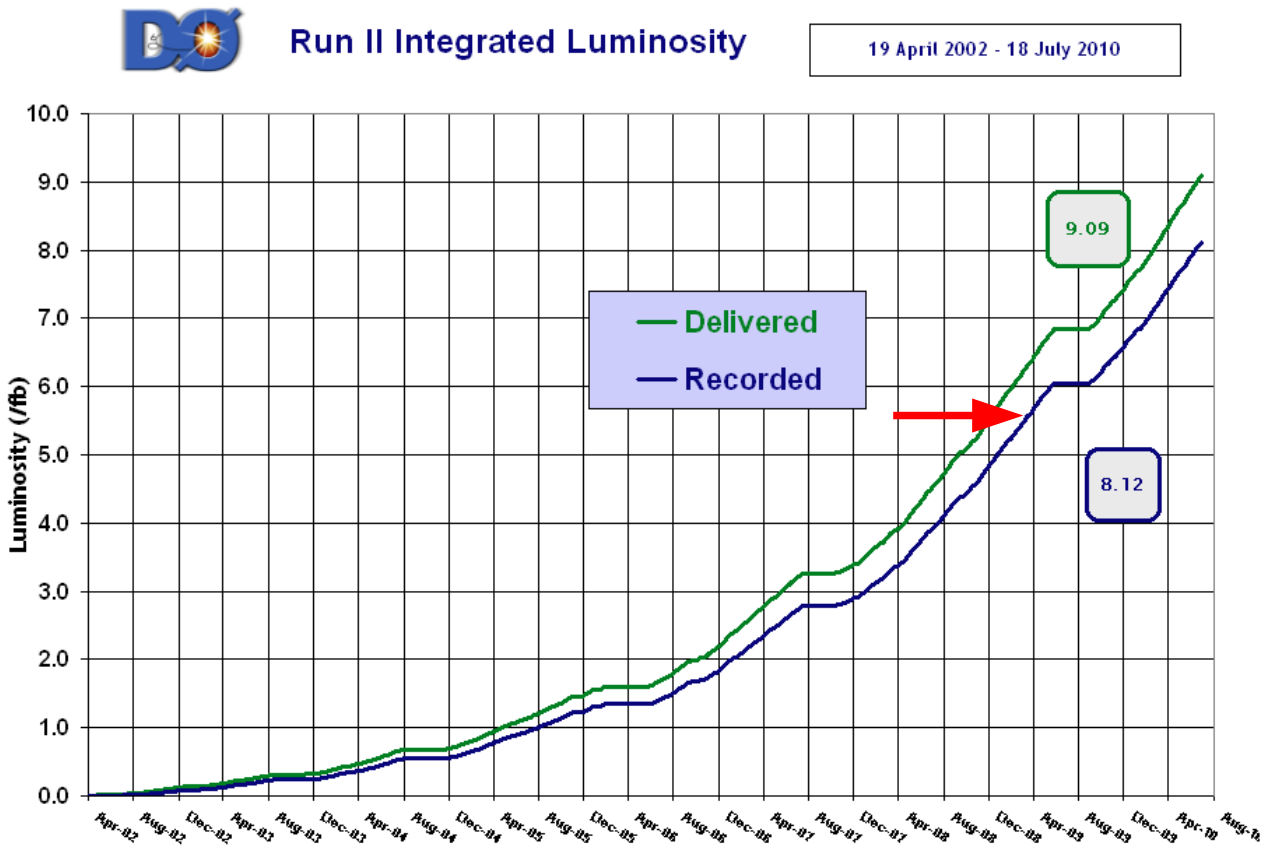
$\sqrt{s}$ =1.96 TeV

Δt = 396 ns

Run I 1987 (92)-95
Run II 2001-11: 100x larger dataset at increased energy

10^{-12}s after big bang!

Tevatron Integrated Luminosity



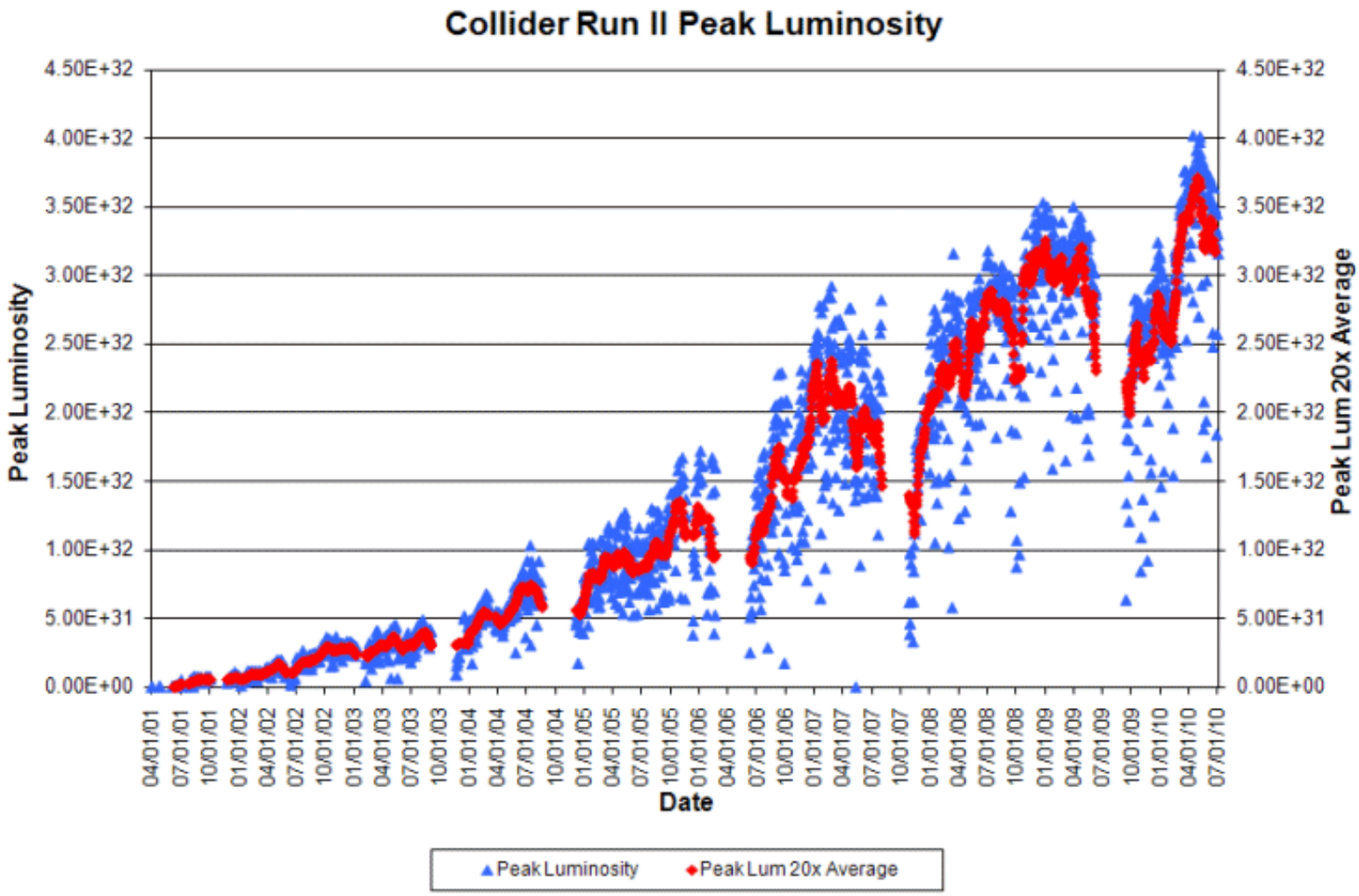
$$N_{event} = \text{cross section} \times \int L dt \times \text{Efficiency}$$

Given by Nature (calculated by theorists)

accelerator

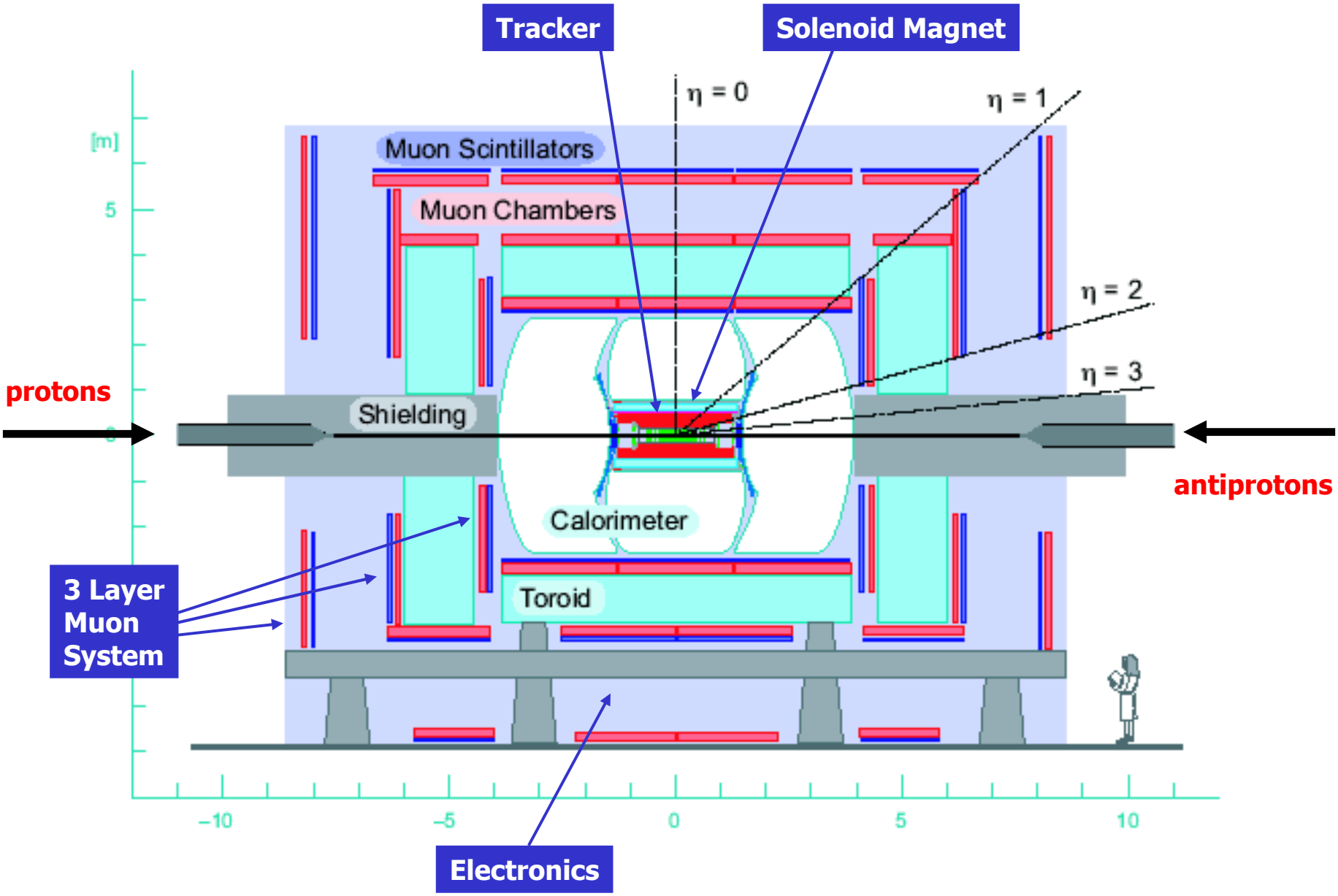
Detector (Experimentalist)

Tevatron Instantaneous Luminosity



- peak luminosity of $4.0 \cdot 10^{32}$ cm^{-2} s^{-1}
- took many years to achieve this!

The DØ Experiment



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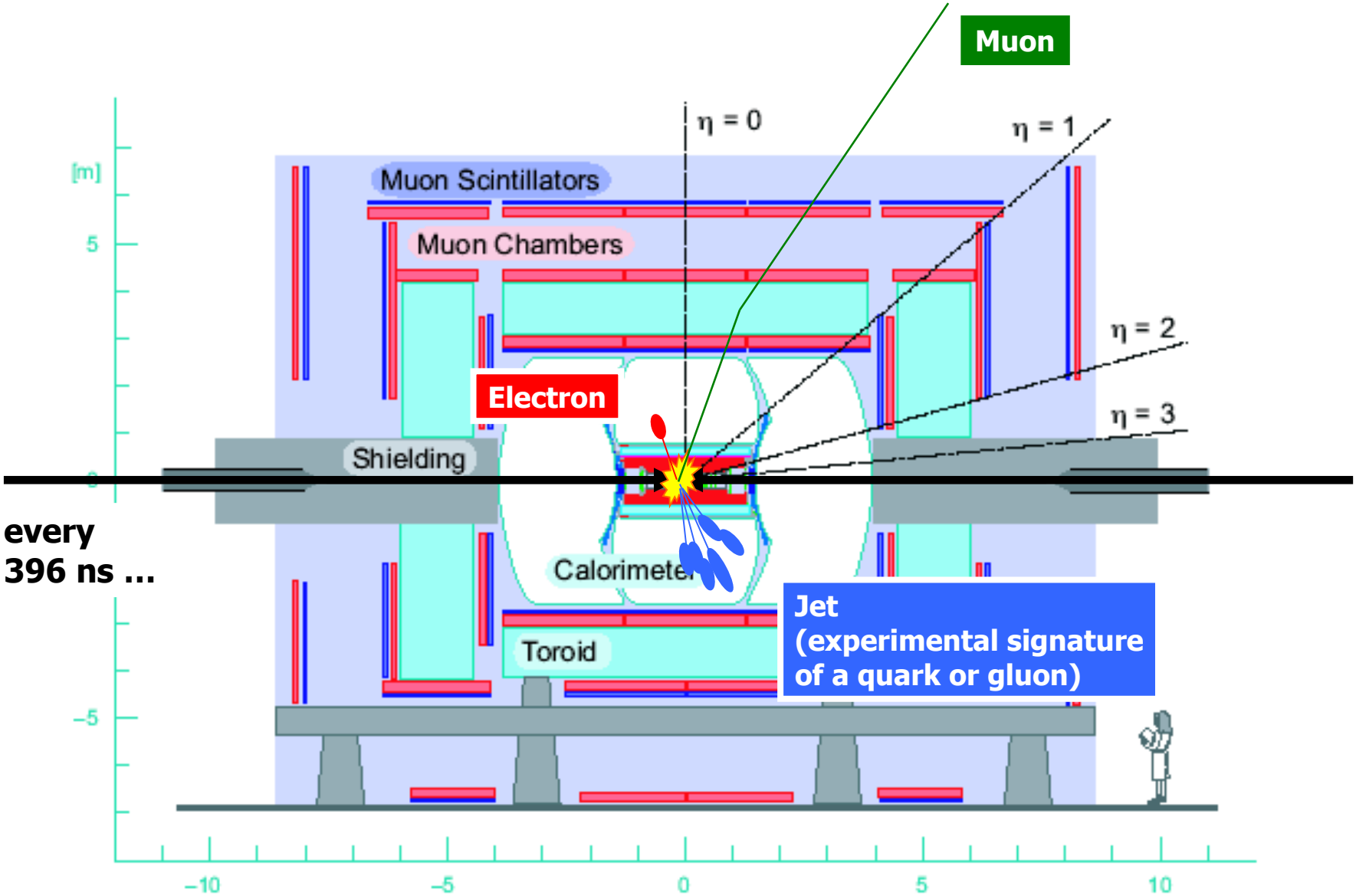
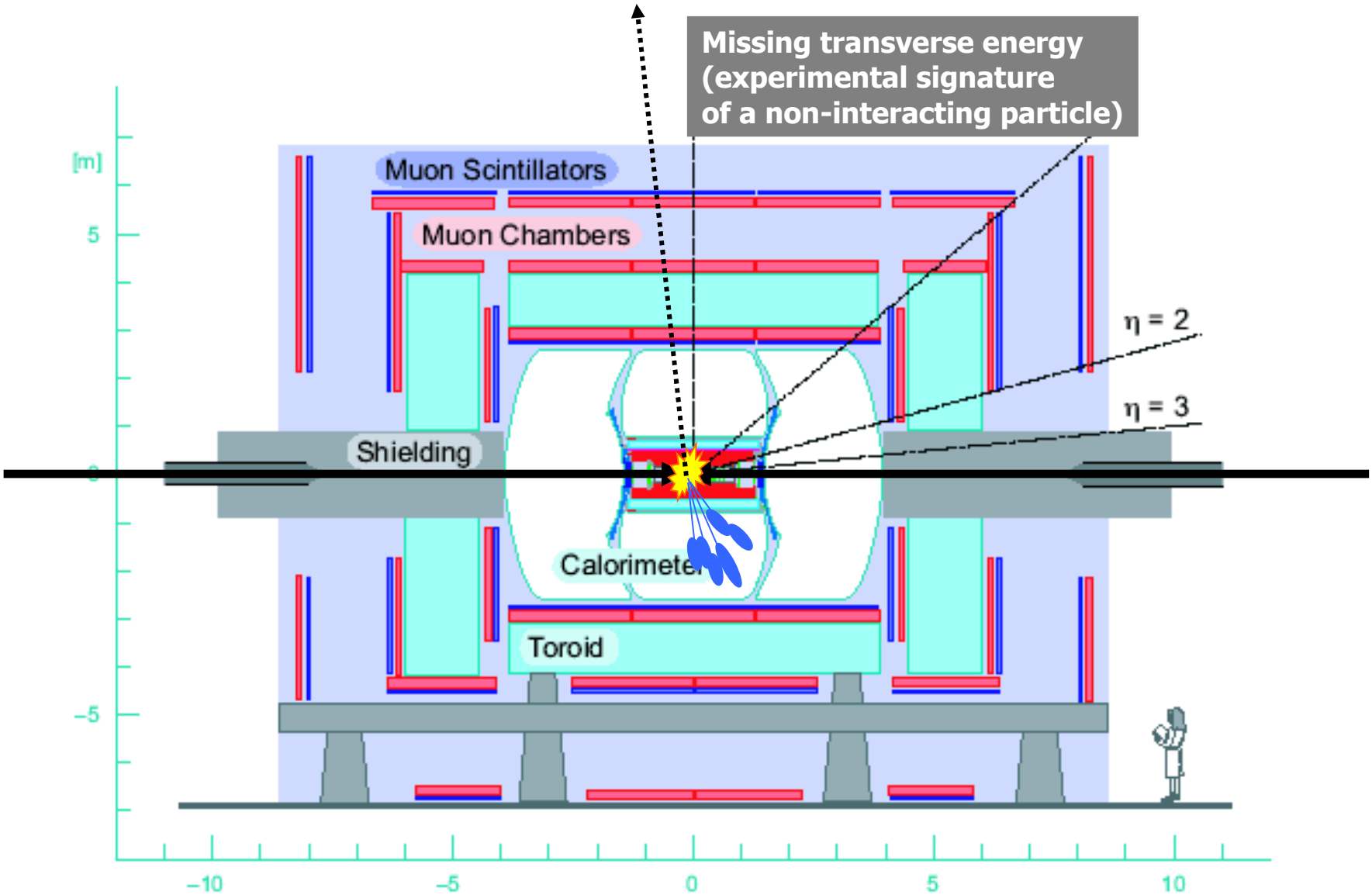
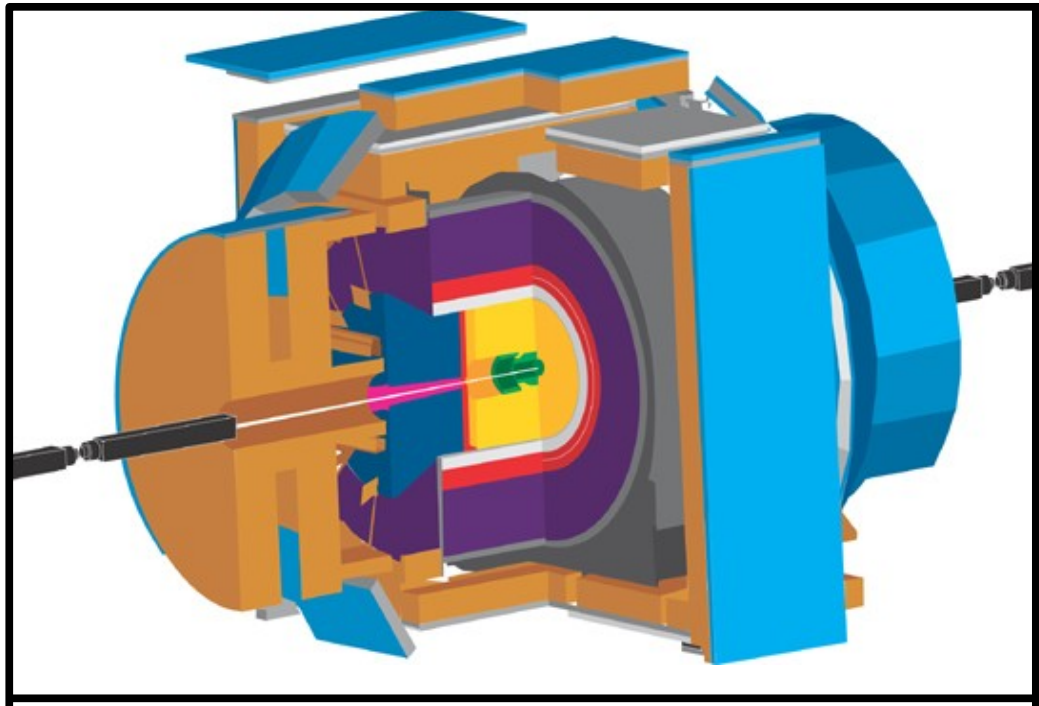


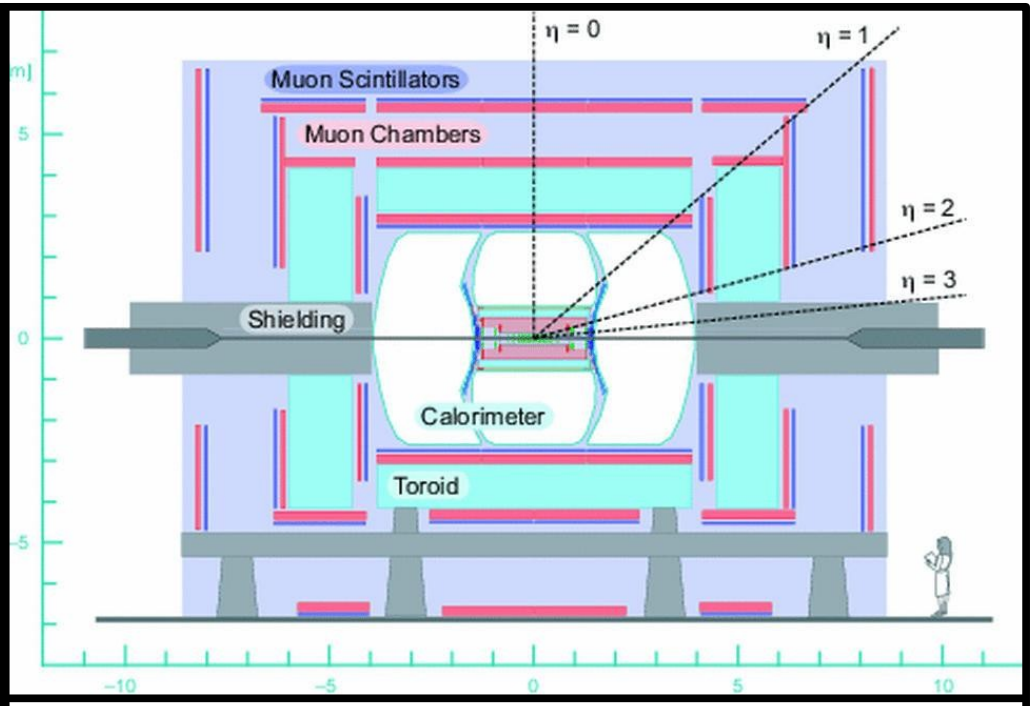
every
396 ns …

The DØ Experiment



The CDF and DØ Experiment





- **basic detector operates since 1985:**
  - central calorimeter
  - central muon chambers
- **major upgrades for Run II:**
  - new bigger silicon,
  - new drift chamber, TOF
  - upgraded calorimeter (forward) and muon system
  - upgraded DAQ/trigger
  - displaced track trigger

- **retained from Run I:**
  - excellent muon coverage
  - compact high granularity Lar calorimeter
- **new for Run II:**
  - new silicon and fibre tracker
  - new ~2 T solenoid
  - upgraded muon system
  - upgraded (track) trigger/DAQ

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
- **other differential cross sections: $d\sigma/dE_T(jet)$**
  - probability of a jet with given E_T
- **integrated cross section: $\sigma = \int d\sigma/d\Omega \, d\Omega$**

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

Luminosity

Cross Section in Hadron Hadron Scattering

- **cross section is convolution of pdf's and matrix element**

Physical cross section

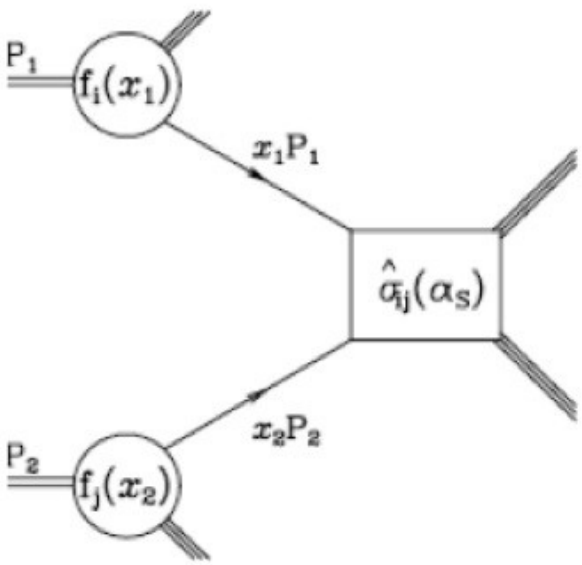
Parton distribution function

Renormalization scale μ_R

$$\sigma(P_1, P_2) = \sum_{i,j} \int dx_1 dx_2 \, f_i(x_1, \mu_F) f_j(x_2, \mu_F) \, \hat{\sigma}_{ij}(p_1, p_2, \alpha_S(\mu_R), Q^2, \mu_R, \mu_F).$$

Factorization scale μ_F

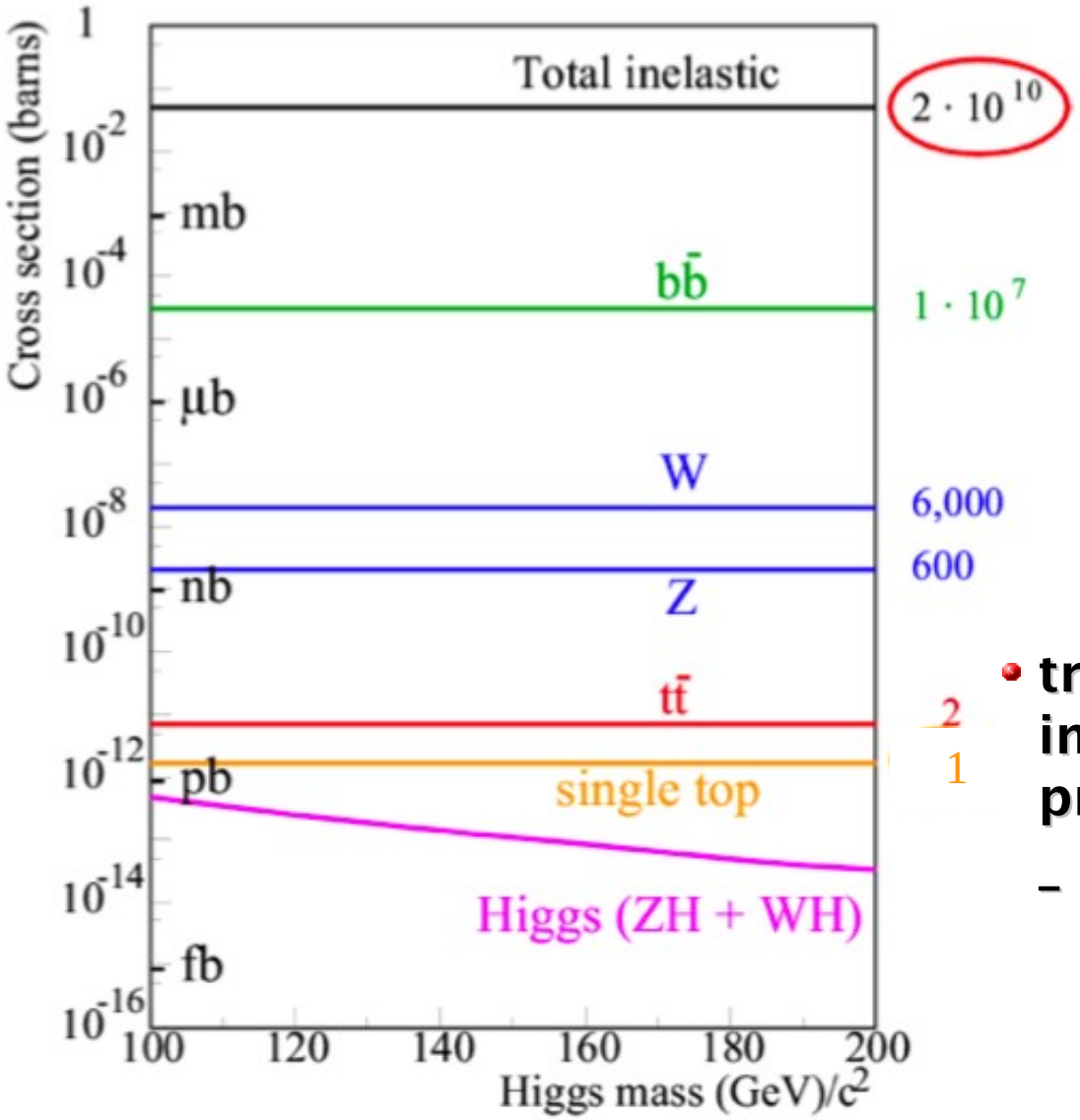
Short distance cross section, calculated as a perturbation series in α_S



- **calculations are done in perturbative QCD:**
  - **possible due to factorization of hard ME and pdf (can be treated independently)**
  - **strong coupling α_S is relatively large higher orders needed, complicated calculations**

→ **measure to test underlying theory**

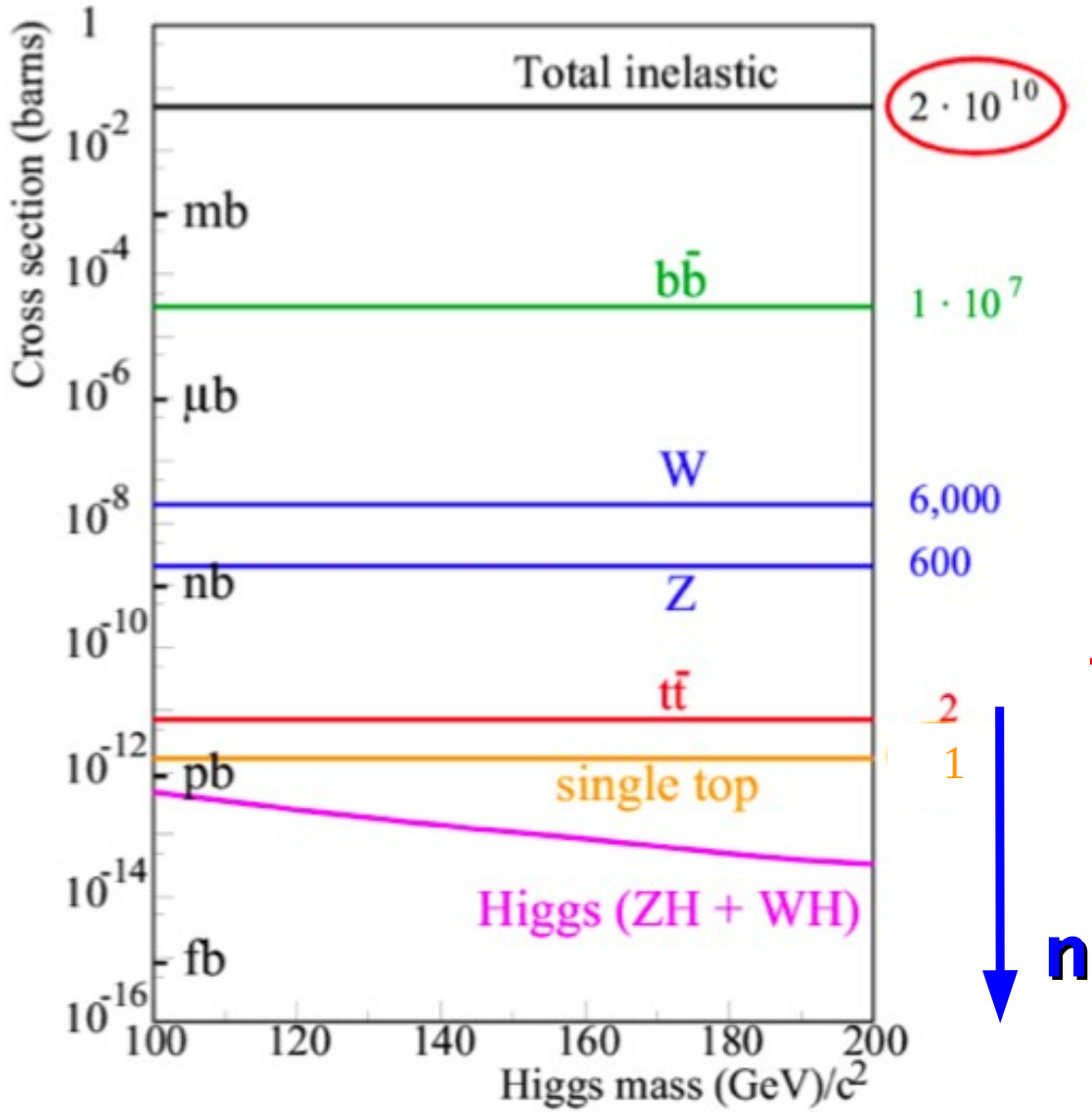
Cross Sections at the Tevatron



- trigger filters out interesting processes
  - makes a fast decision of wether to keep an event at all for analysis
  - crucial at hadron colliders

Cross Sections at the Tevatron

jets
tests of
QCD

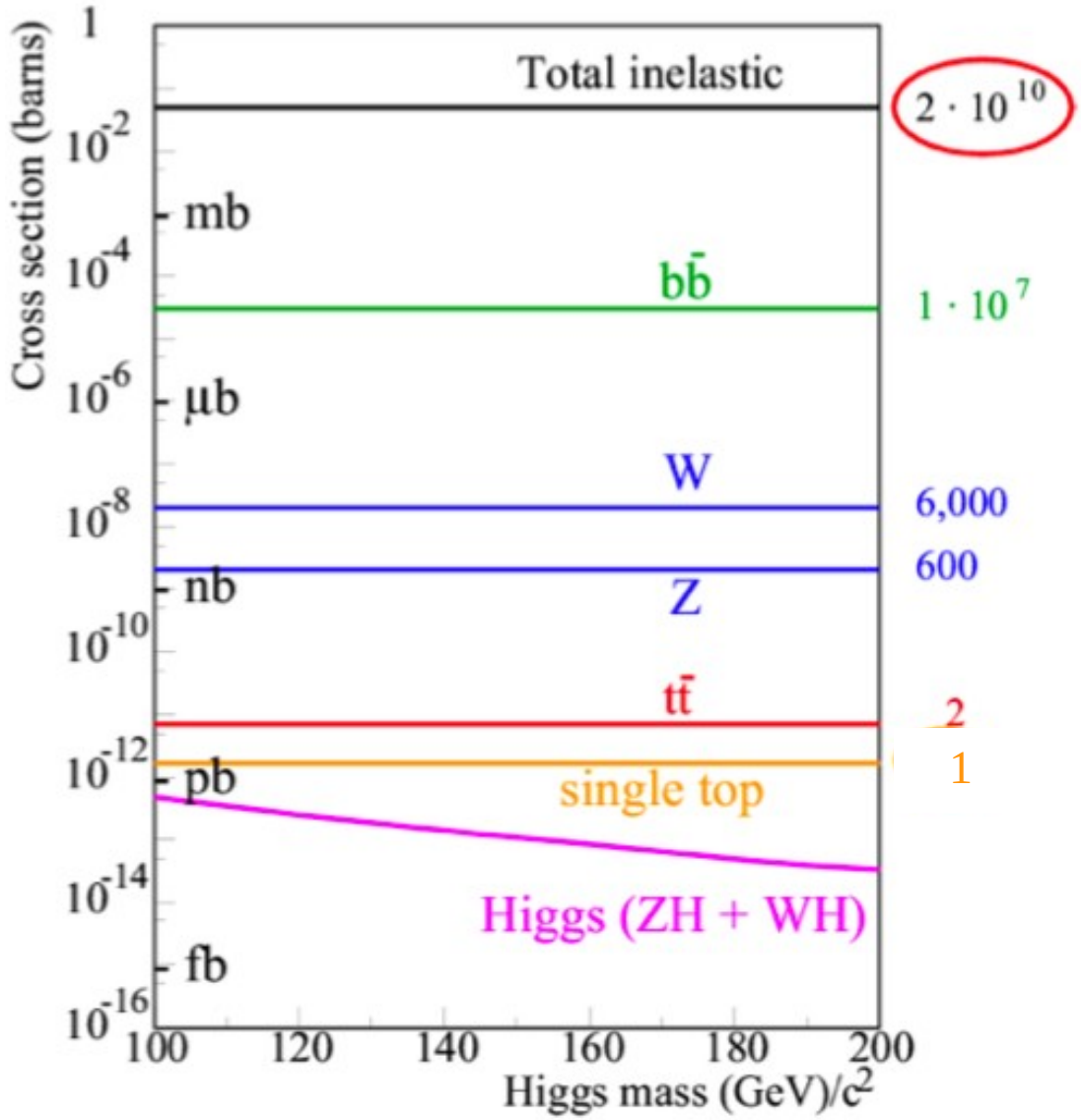


top quark
physics

new physics?

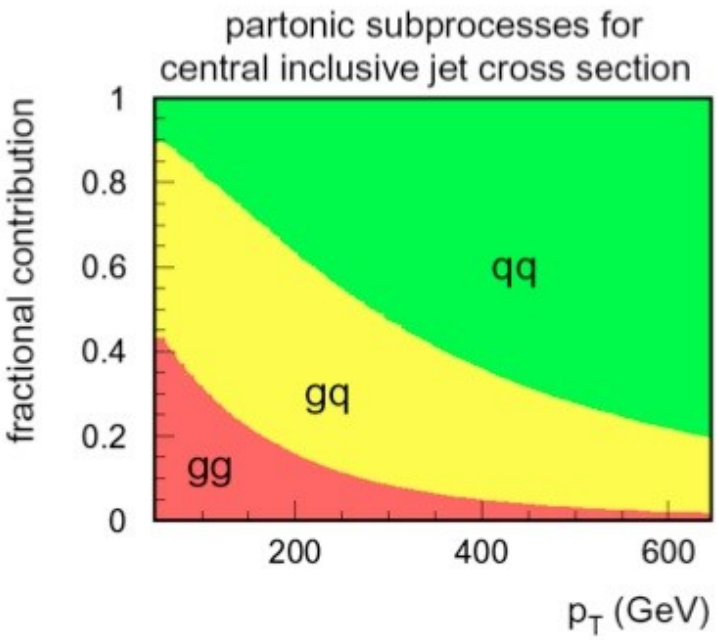
Cross Sections at the Tevatron

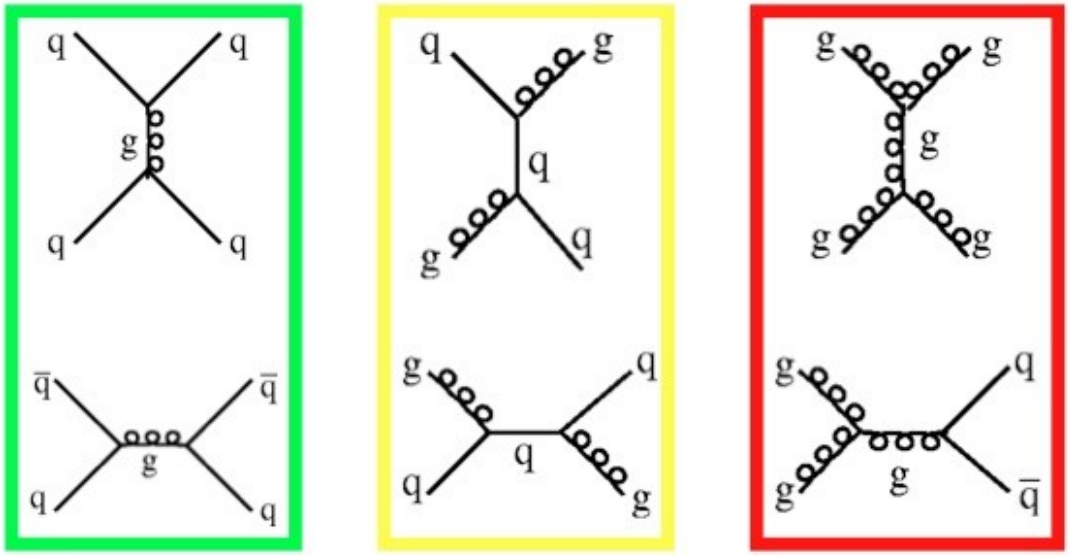
jets tests of QCD



Jet Cross Sections

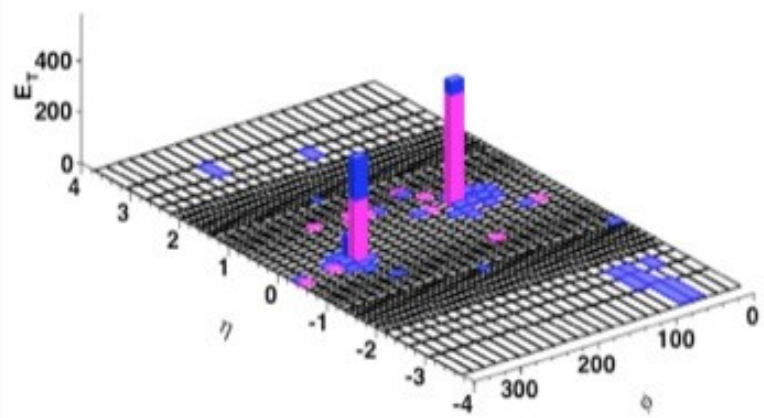
- **inclusive jet processes: qq, qg, gg**





- **tests perturbative QCD at highest energies**
- **highest E_T probes shortest distances**
  - **Tevatron: $r_q < 10^{-18}$ m**
  - **could e.g. reveal substructure of quarks**

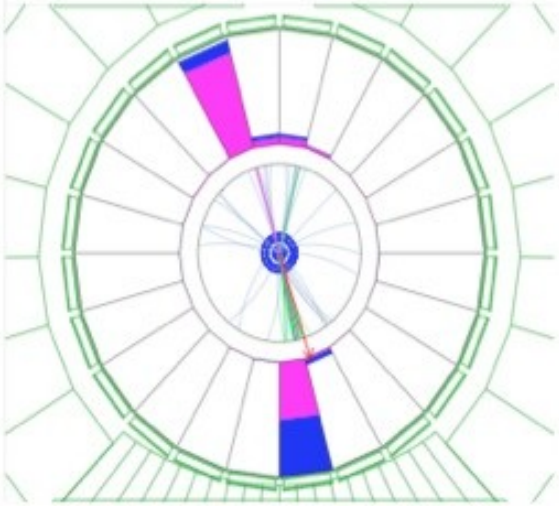
High Mass Dijet Event: M=1.4 TeV



CDF Run II Preliminary

Jet Et1 = 666 GeV (corr)
583 GeV (raw)
eta1 = 0.31 (detector)
0.43 (corr z)

Jet Et2 = 633 GeV (corr)
546 GeV (raw)
eta2 = -0.30 (detector)
-0.19 (corr z)

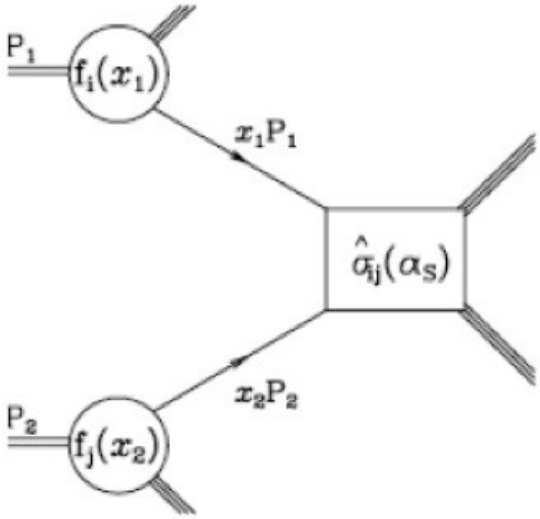


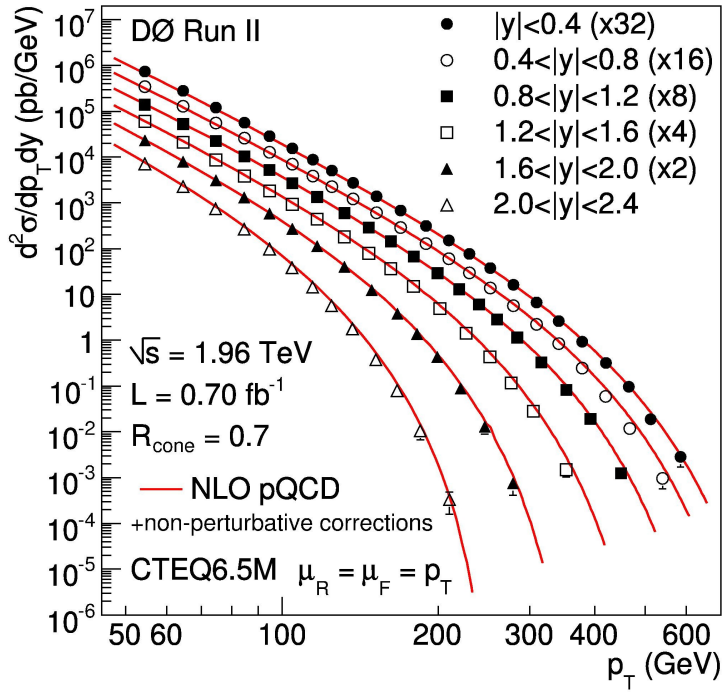
Run 152507
Event 1222318

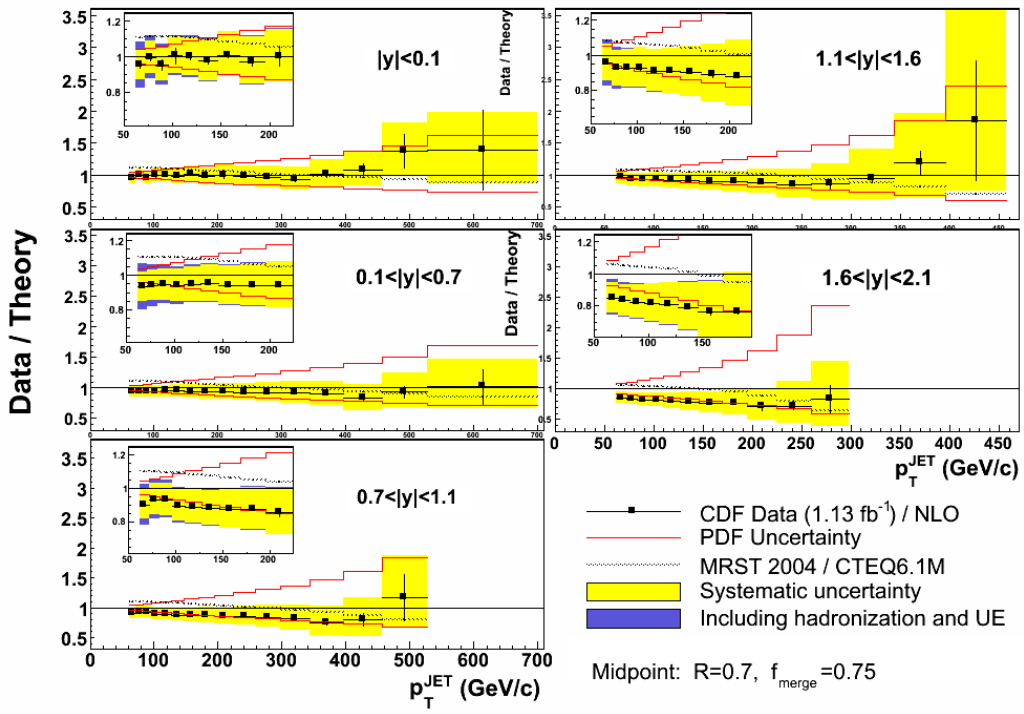
DiJet Mass = 1364 GeV (corr)

z vertex = -25 cm

Jet Cross Sections

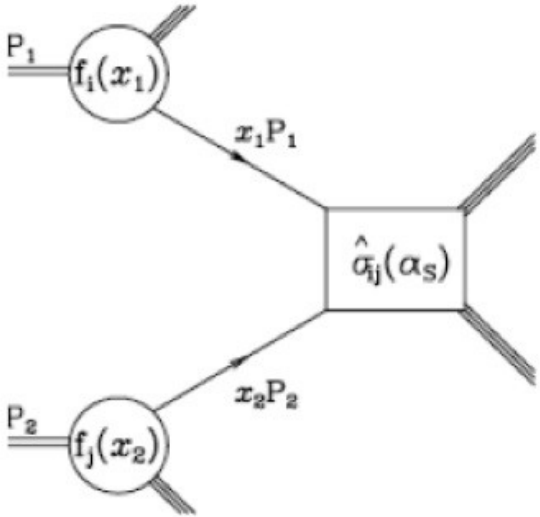


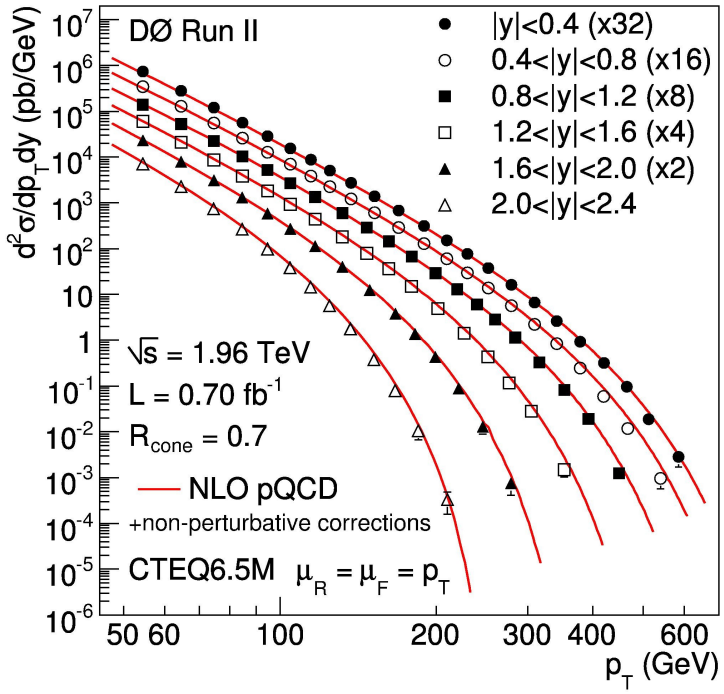


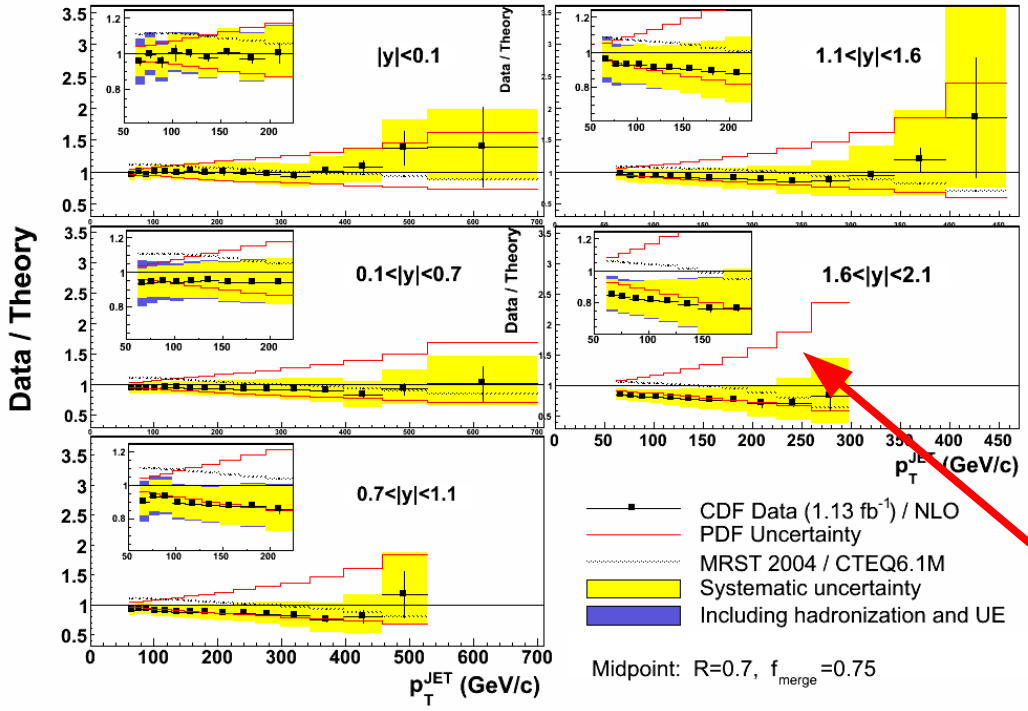


- **excellent agreement with QCD calculation over 9 orders of magnitude!**
- **no excess at high E_T**
  - **no hint for quark substructure**

Jet Cross Sections

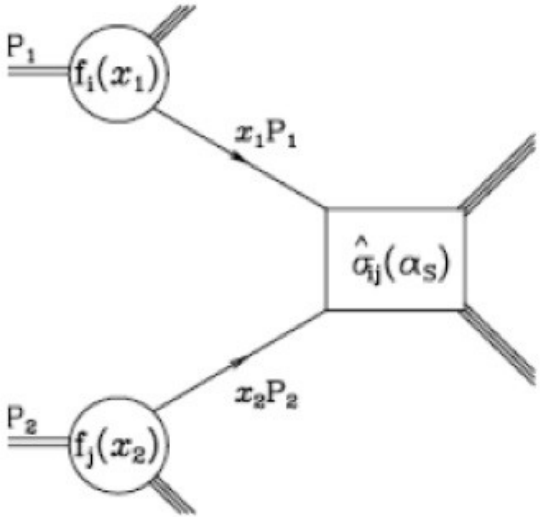


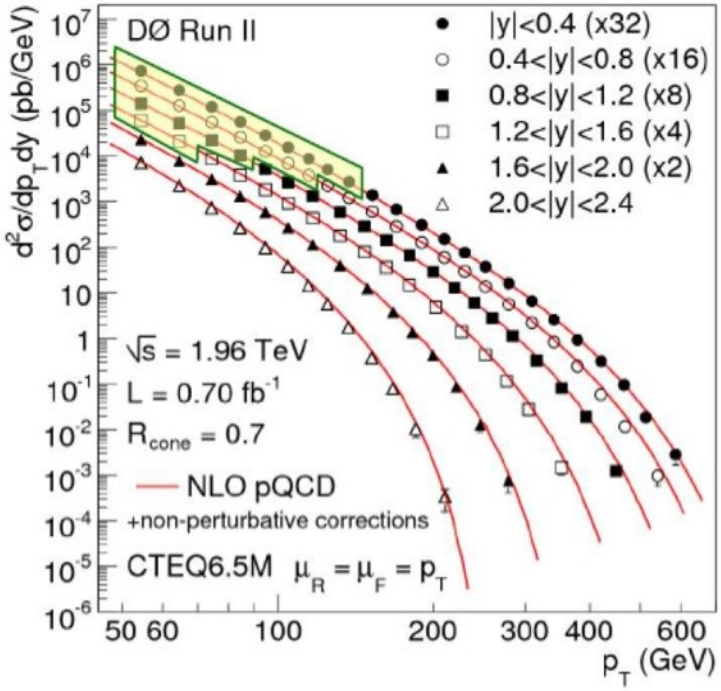


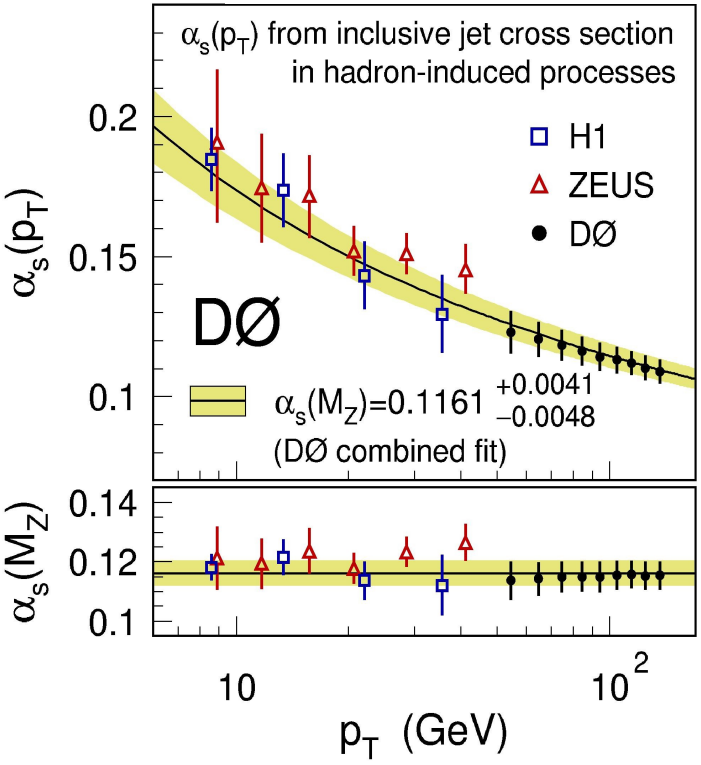


- **excellent agreement with QCD calculation over 9 orders of magnitude!**
- **no excess at high E_T**
  - **no hint for quark substructure**
  - **large pdf uncertainties can be constrained by this data**

Strong Coupling Constant





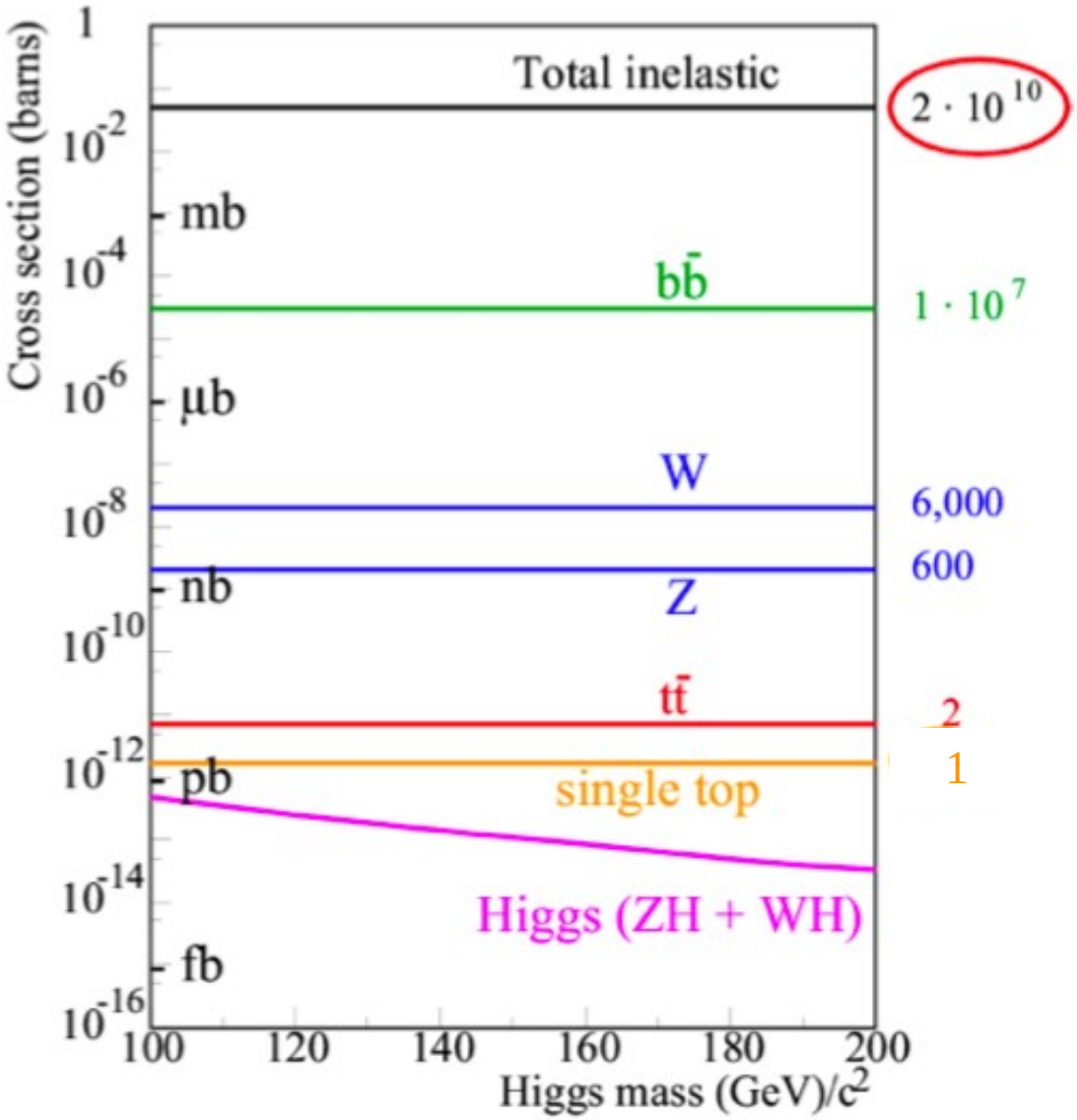


- **minimize correlations between data and pdf's by restricting analysis to kinematic regions where Tevatron data do not dominate the pdf determination**
  - **keep 21 data points**

$$\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$$

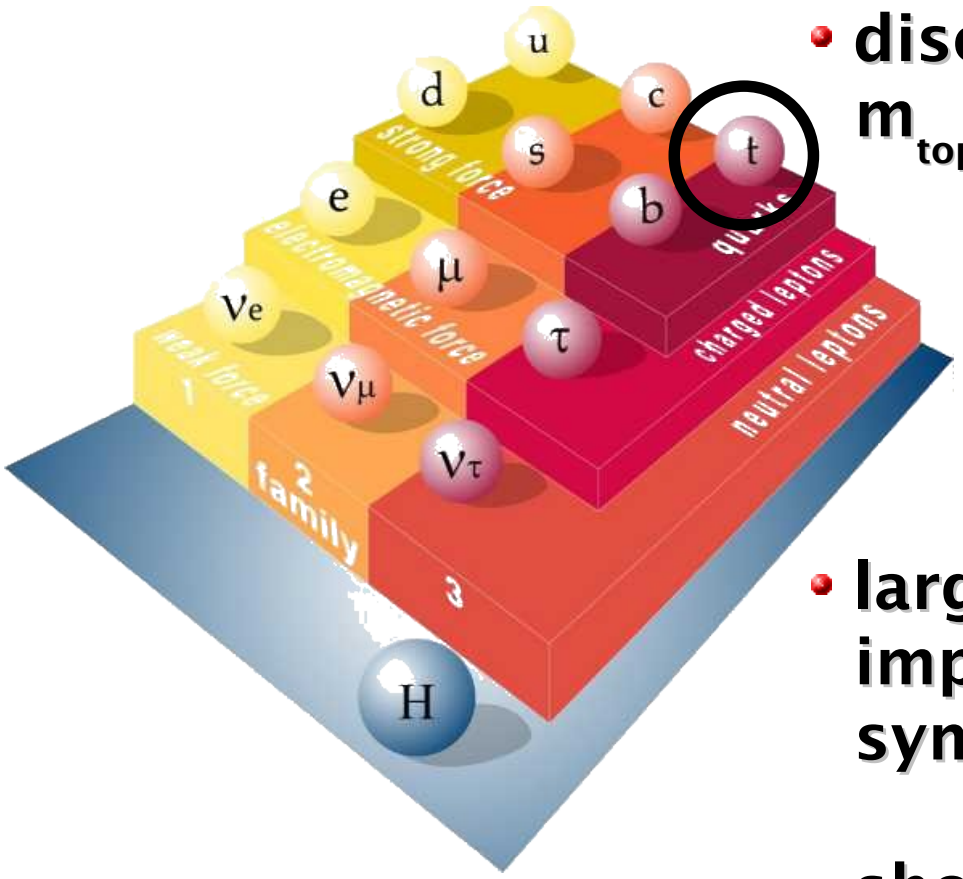
±4%

Cross Sections at the Tevatron



top quark physics

The Top Quark

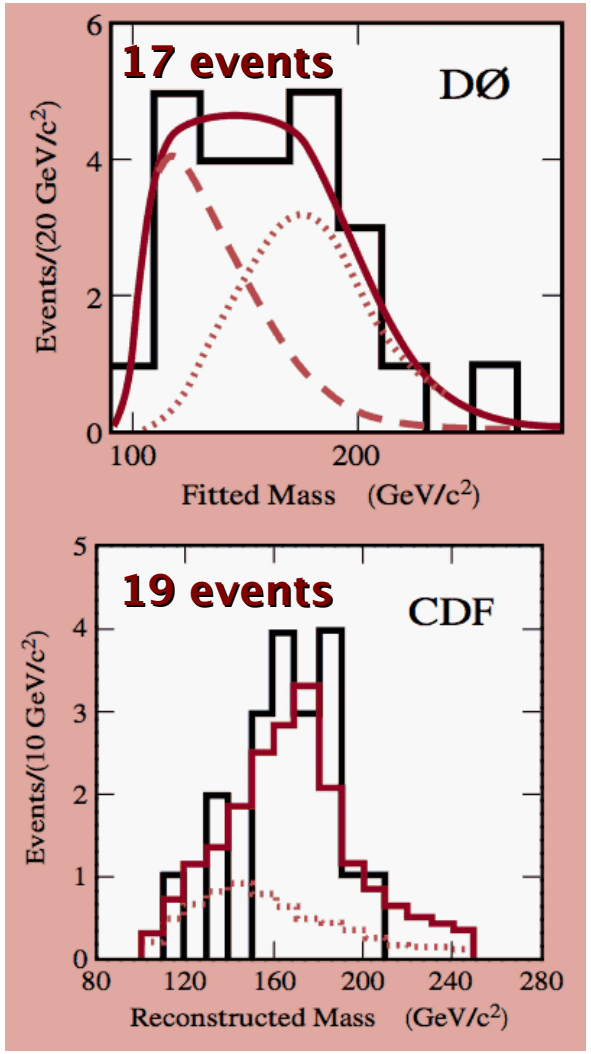


- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe "naked"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

Top History

discovery

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



1995, CDF and DØ experiments, Fermilab

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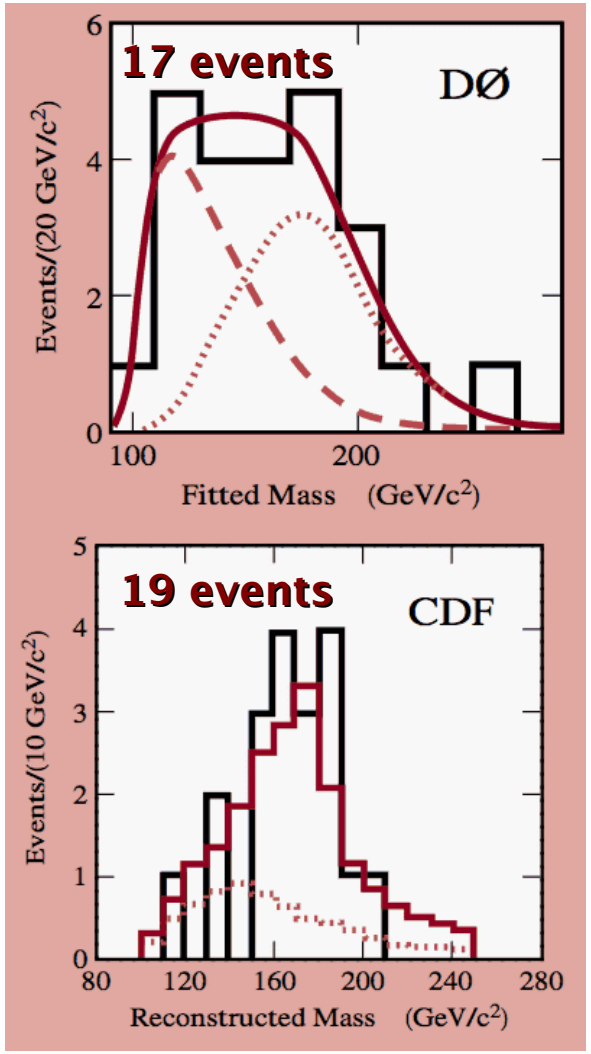
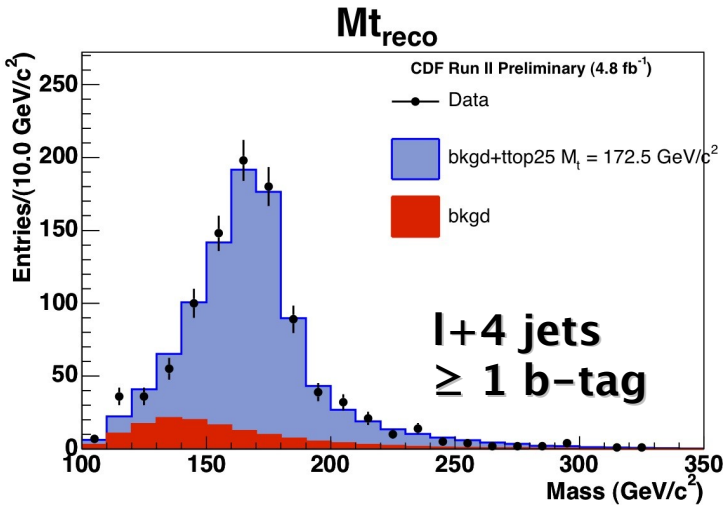


1995, CDF and DØ experiments, Fermilab

today

~1000 events



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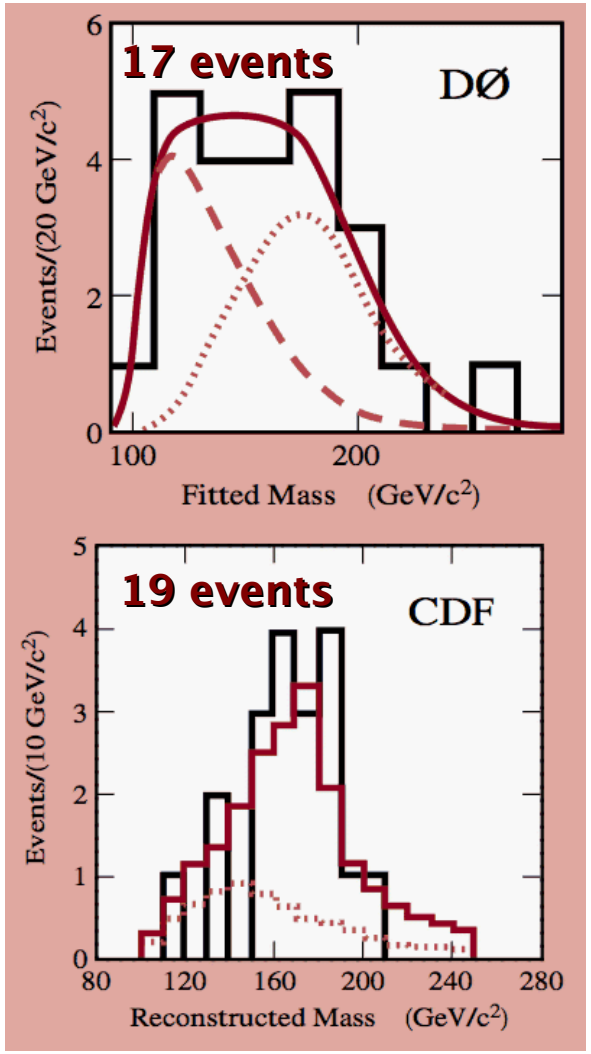

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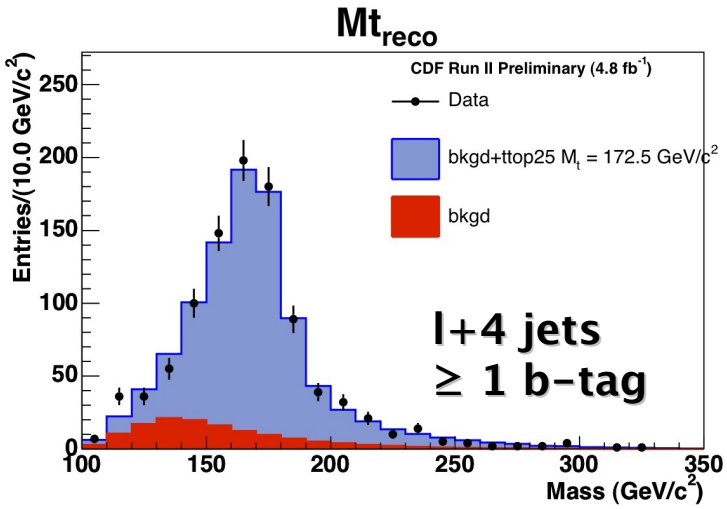
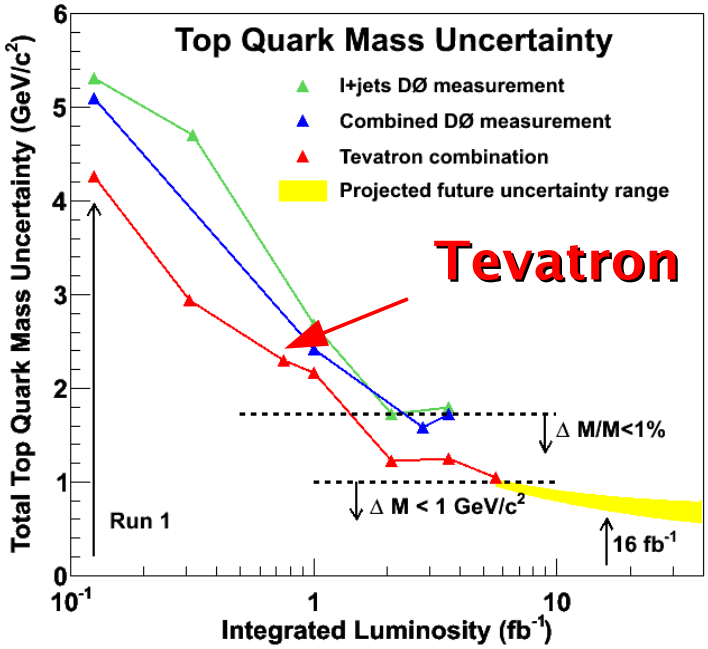


precision



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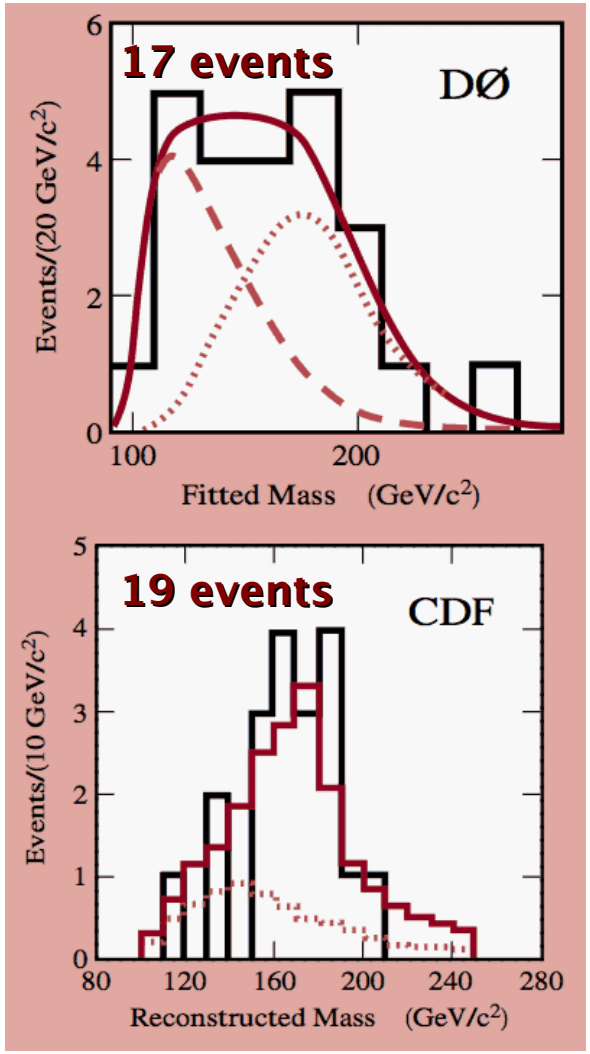

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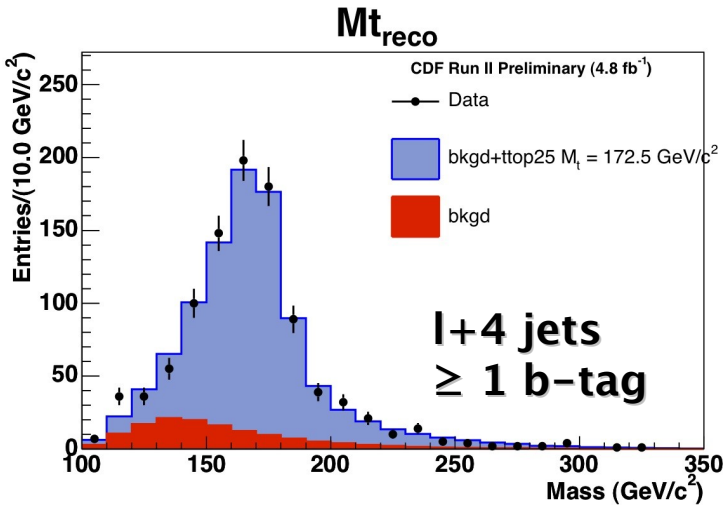

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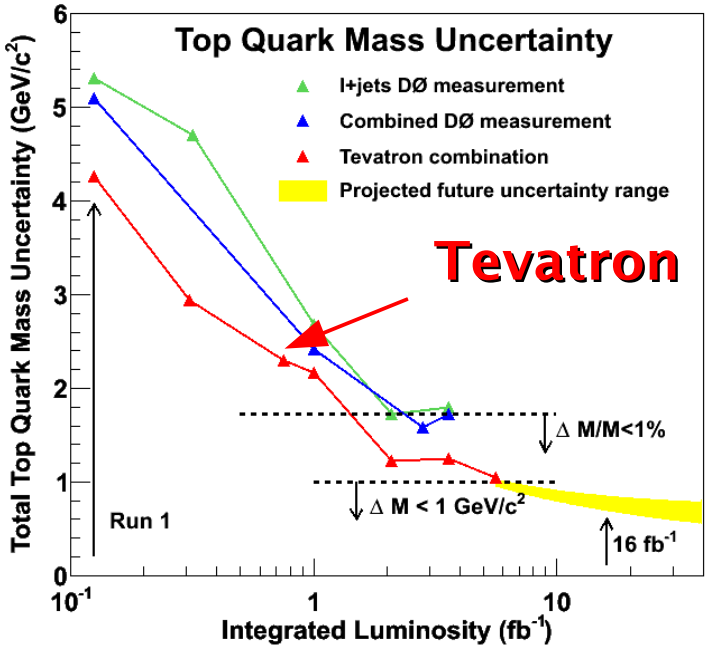
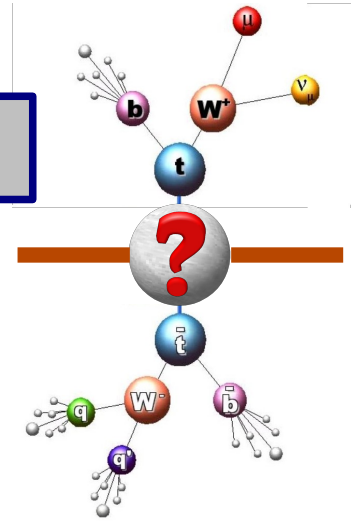


searches



Top History

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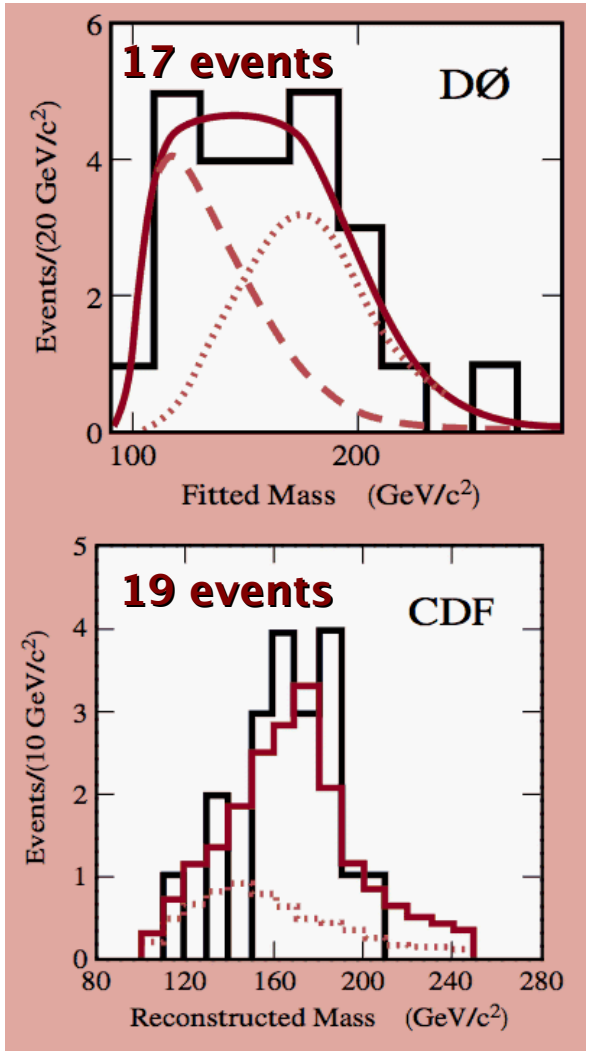
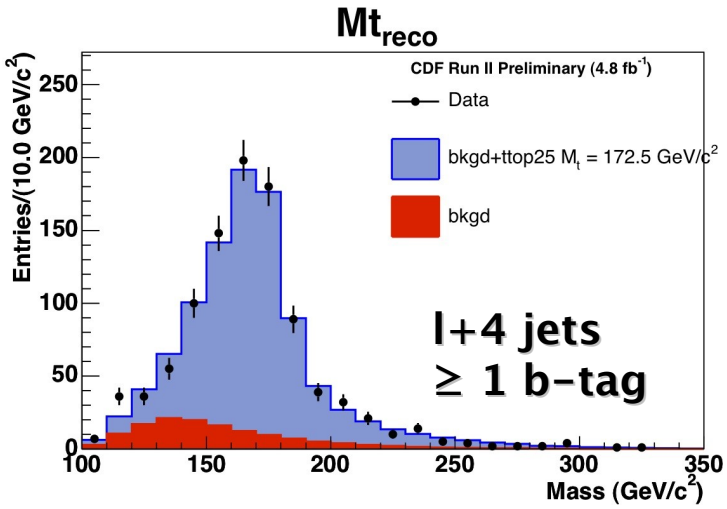


1995, CDF and DØ experiments, Fermilab

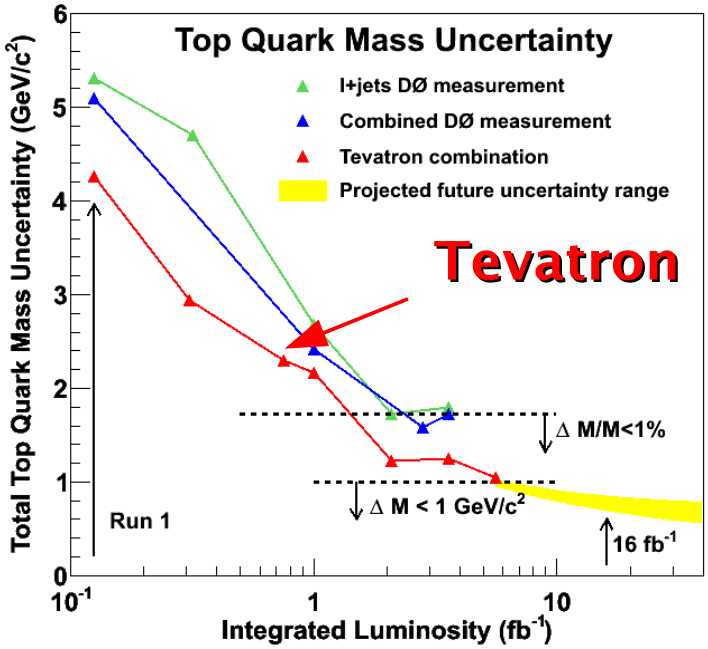
today

~1000 events

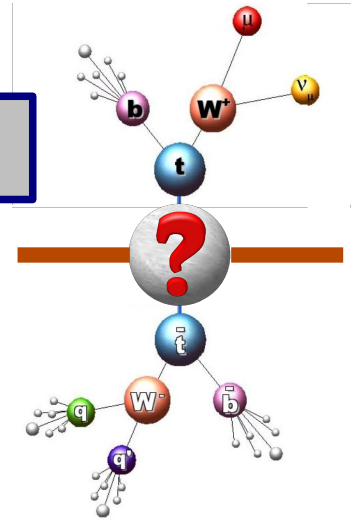


LHC: top factory

precision



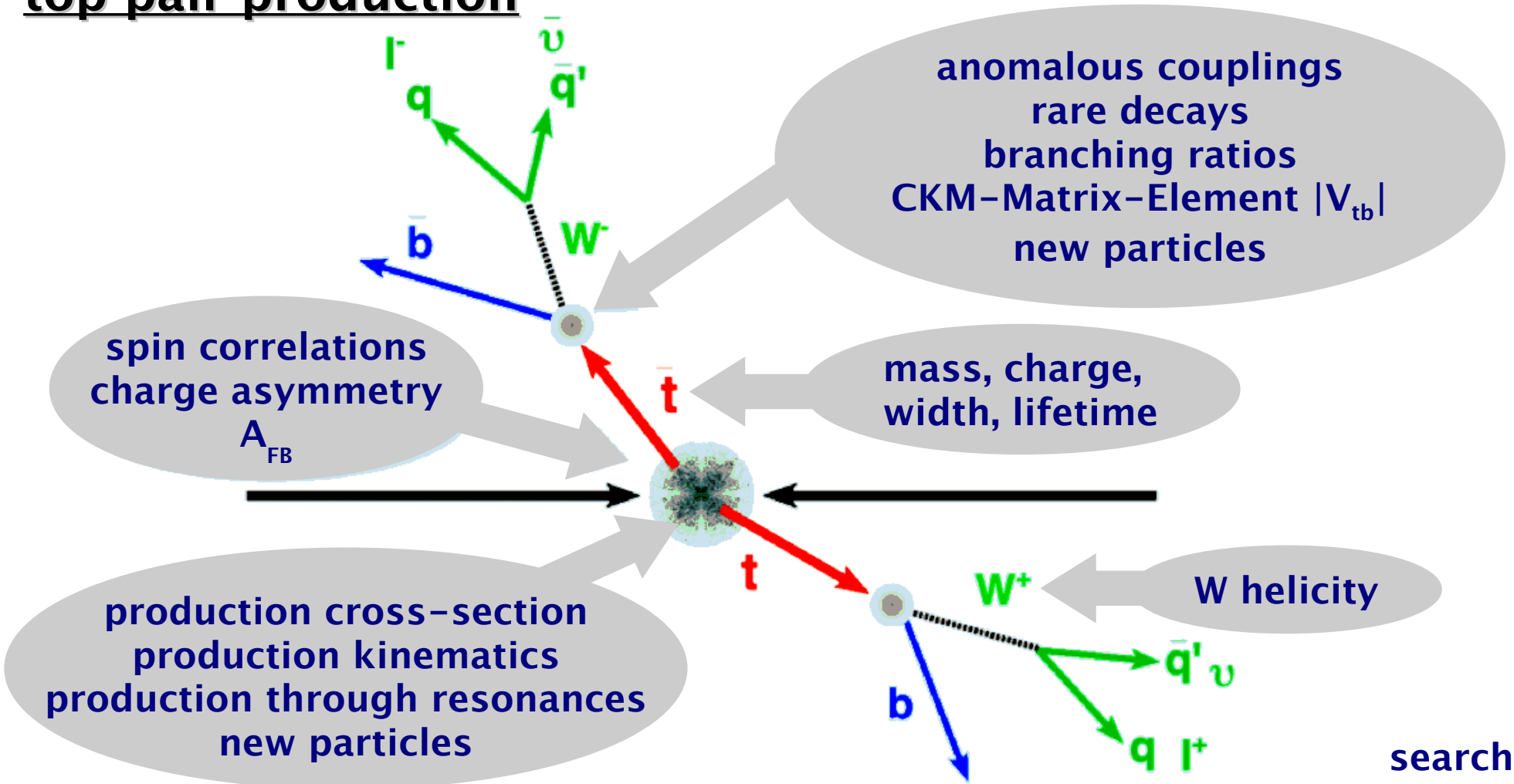
searches



Top Quark Analyses at the Tevatron

analyses with up to 5.6 fb^{-1} of data:
several thousands top candidate events per experiment

top pair production



single top production

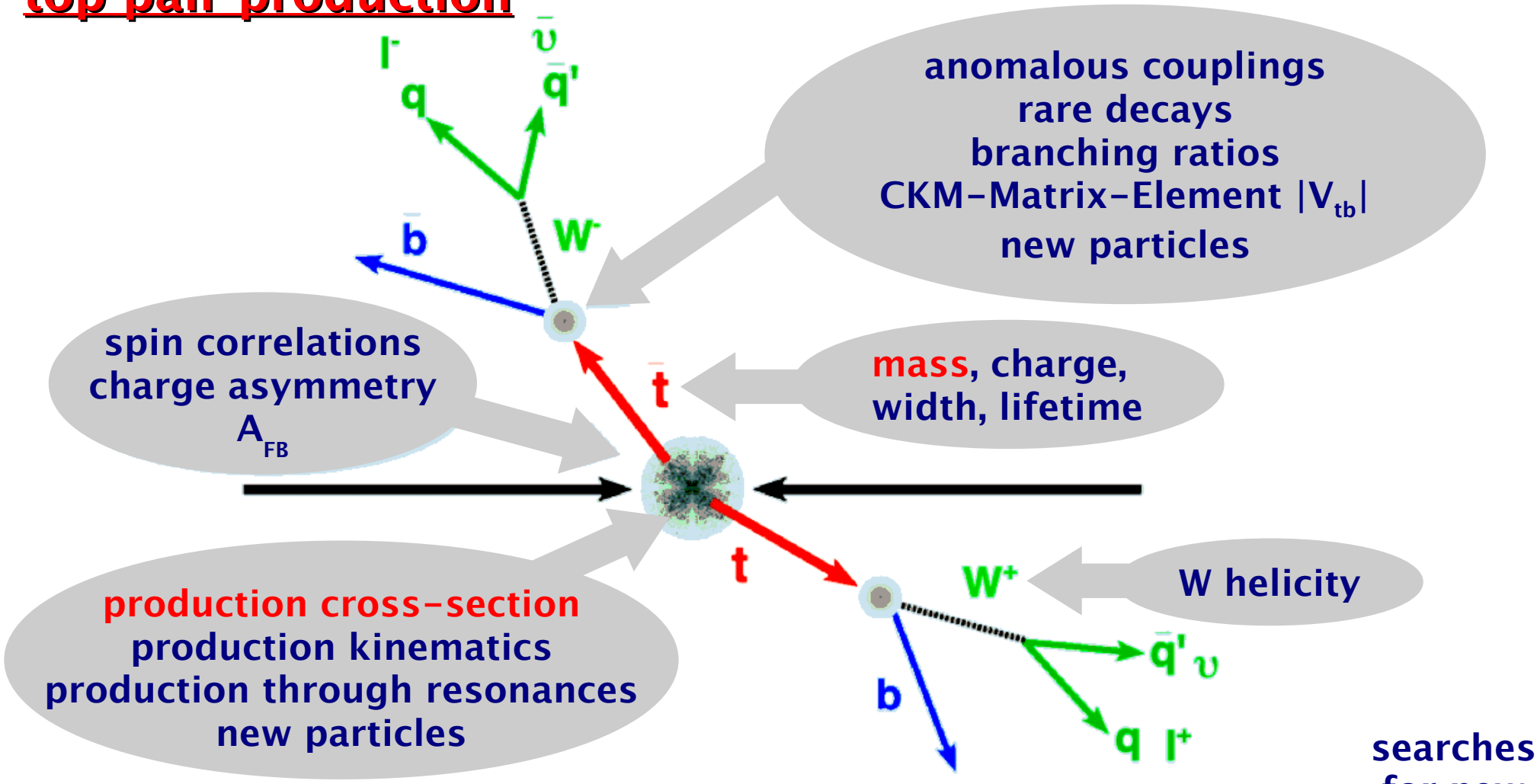
observation by CDF and DØ!

searches
for new
particles

Top Quark Analyses at the Tevatron

analyses with up to 5 fb^{-1} of data:
several thousand top candidate events per experiment

top pair production

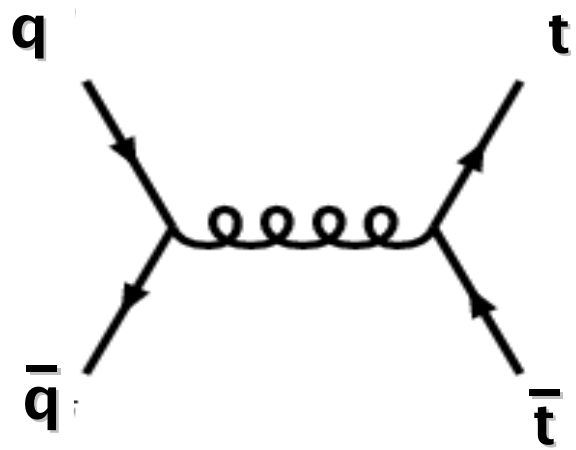


single top production

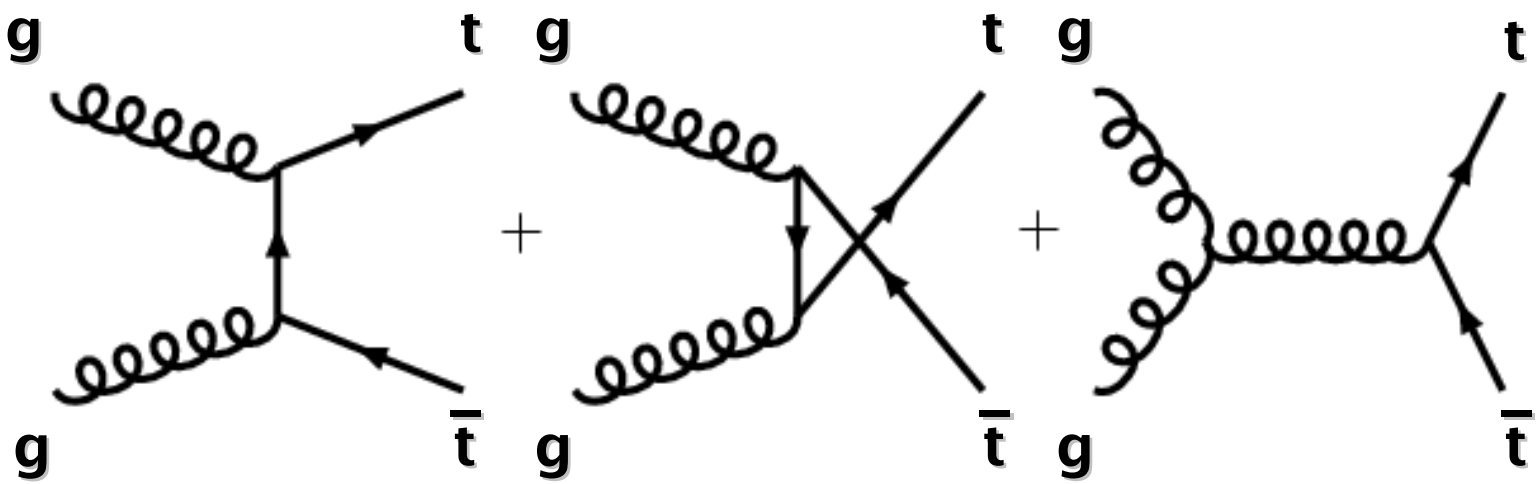
observation by CDF and DØ!

searches for new particles

Top Quark Pair Production



85%



15%

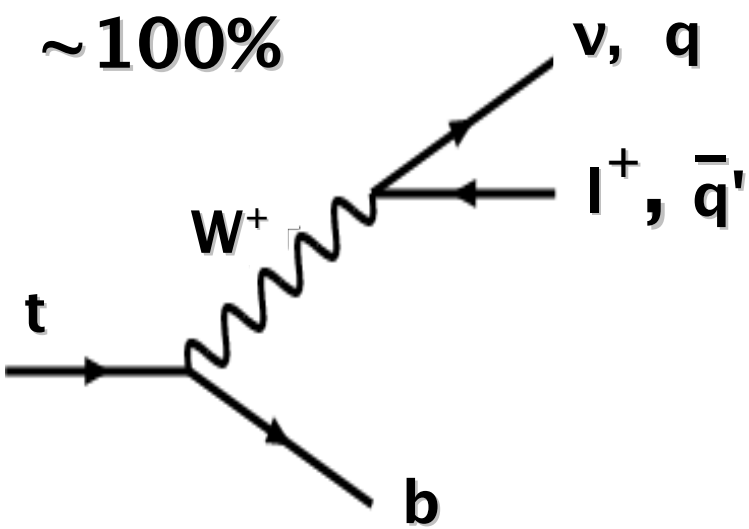
PRD 78, 034003 (2008)

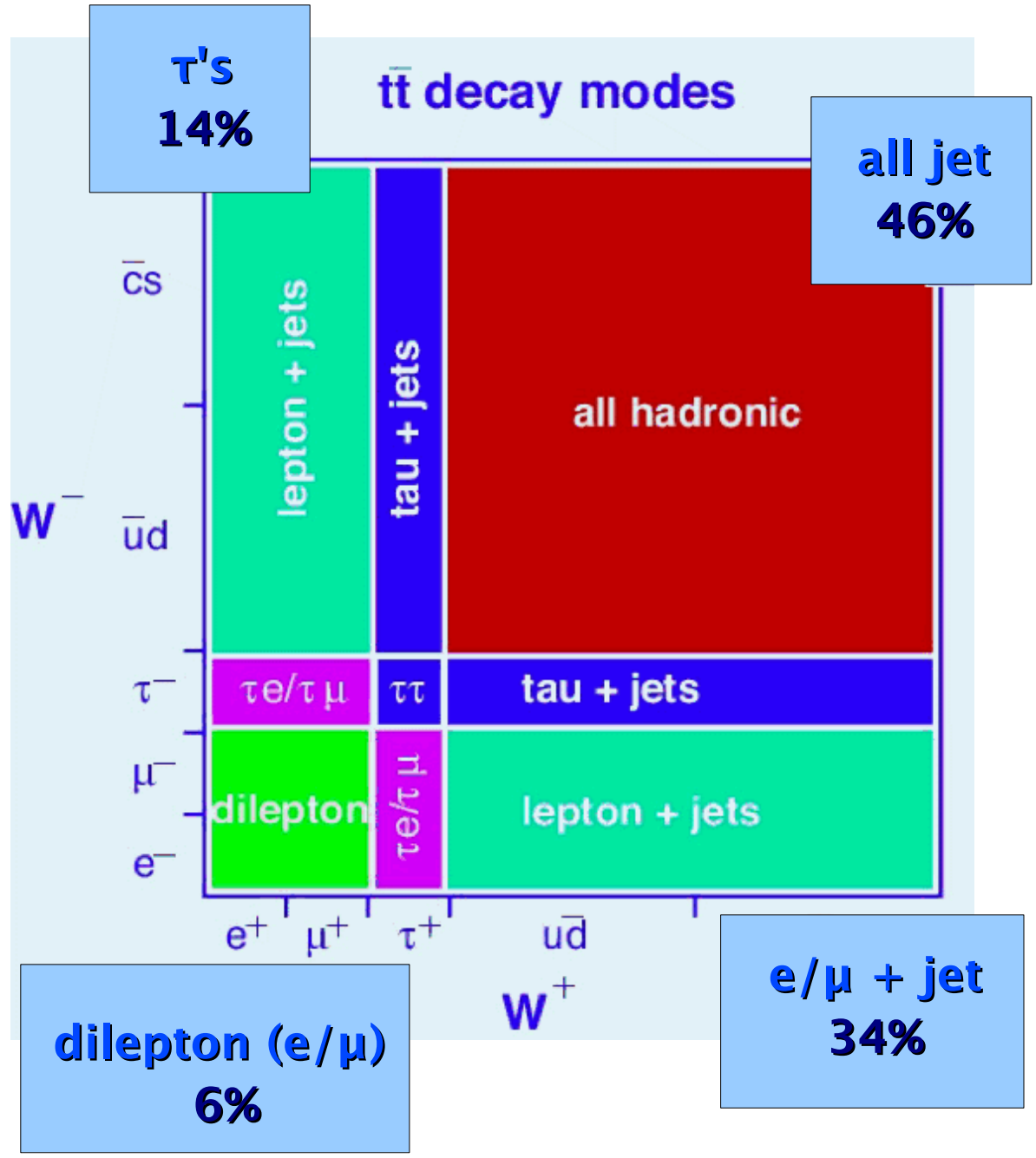
$\sigma_{t\bar{t}} = 7.46^{+0.48}_{-0.67}$ pb in NNLO$_{approx}$
(m_{top} = 172.5 GeV)

Top Pair Signatures

top decay:

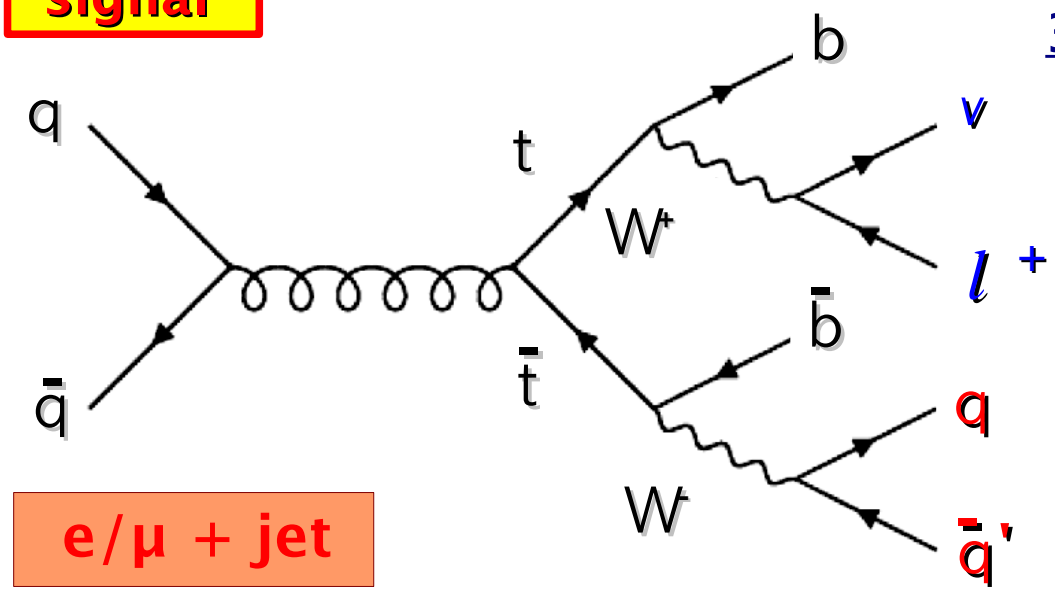
~100%



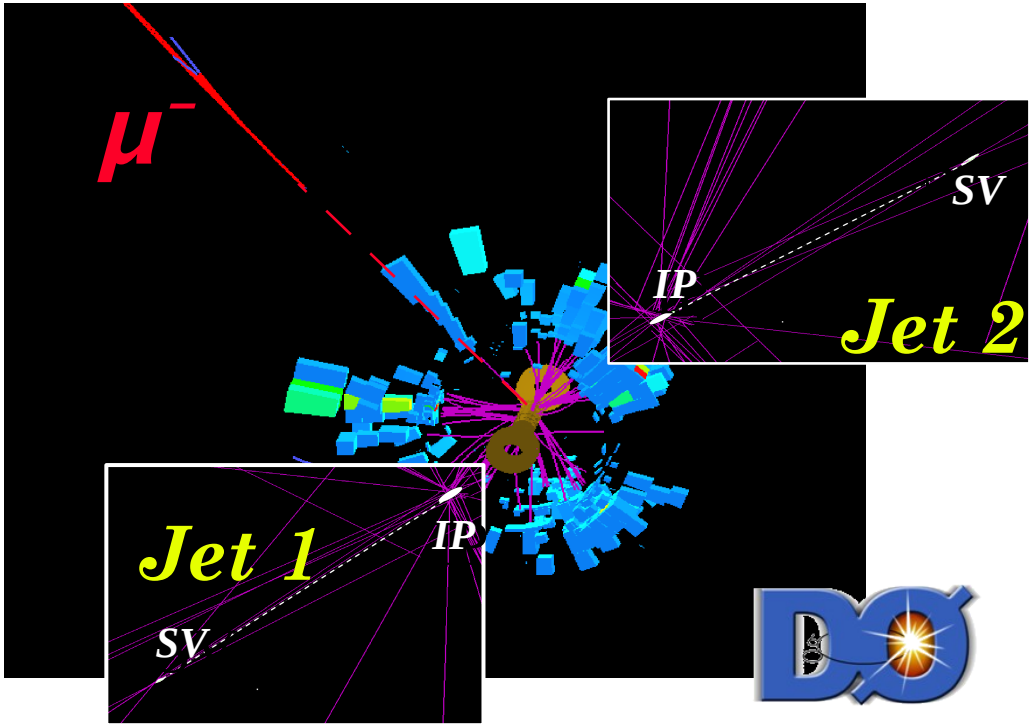


Lepton+jets Signatures

signal

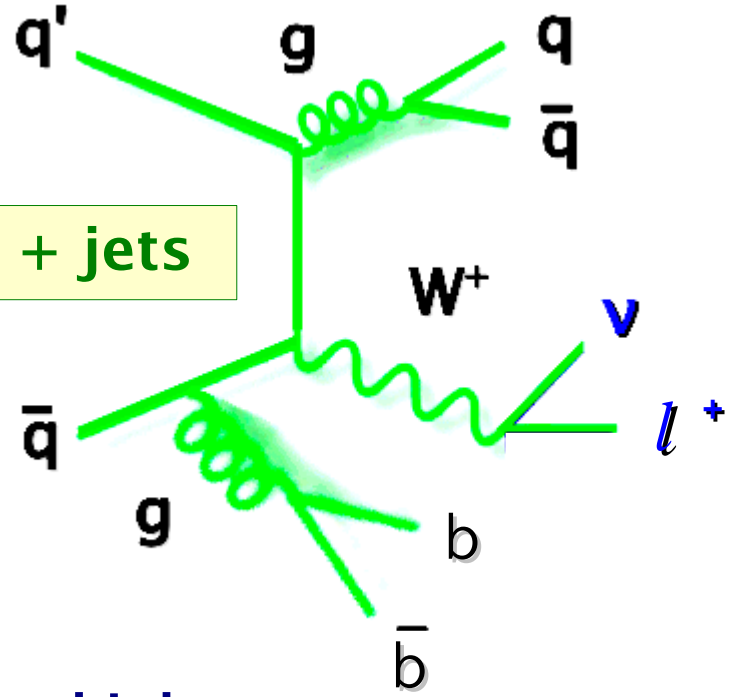


e/μ + jet



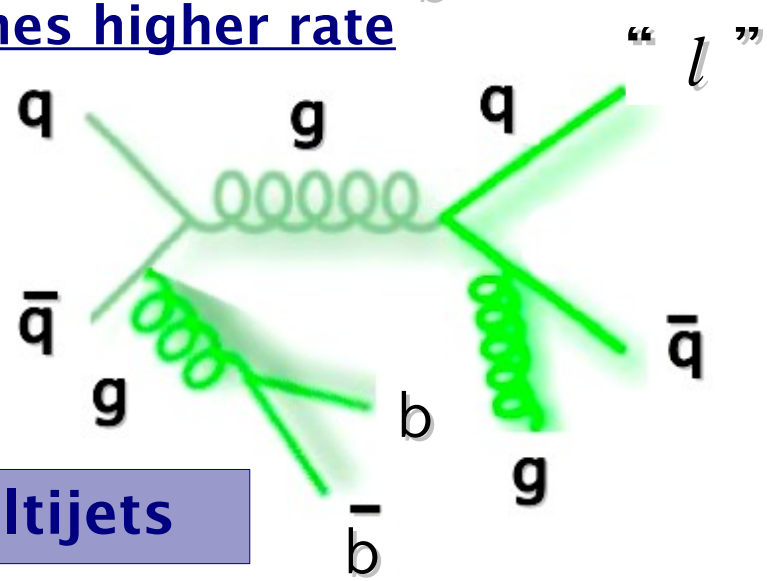
background

3000 times higher rate



W + jets

10^{10} times higher rate



multijets

Lepton+Jets Topological Cross Section

measure if production rate is as predicted by NLO QCD

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

use variables such as:

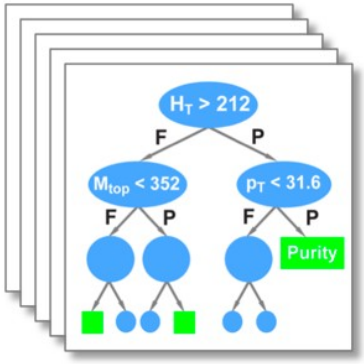
energy-dependent quantities:

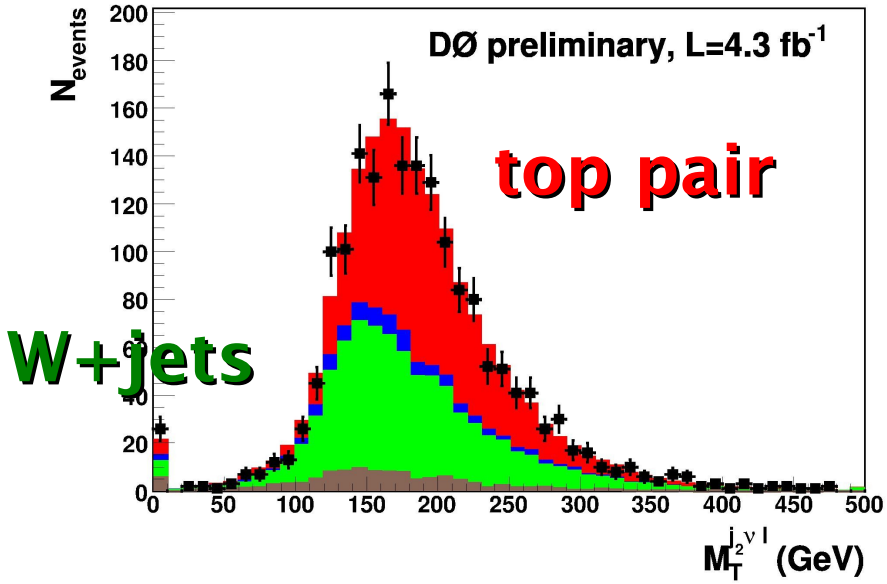
- **e.g. Transverse mass of leptonic top**

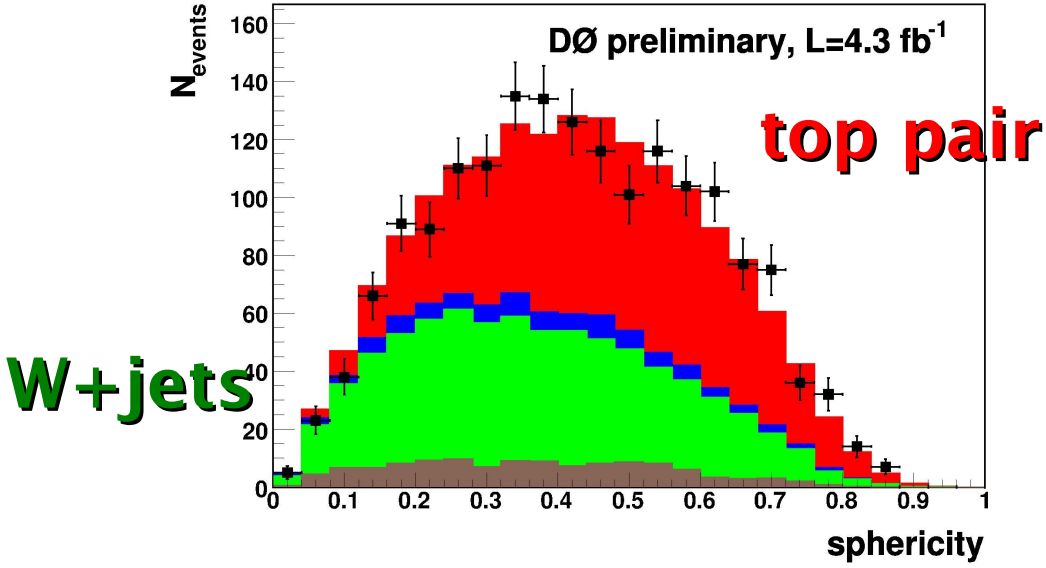
angular dependent:

- **e.g. sphericity**

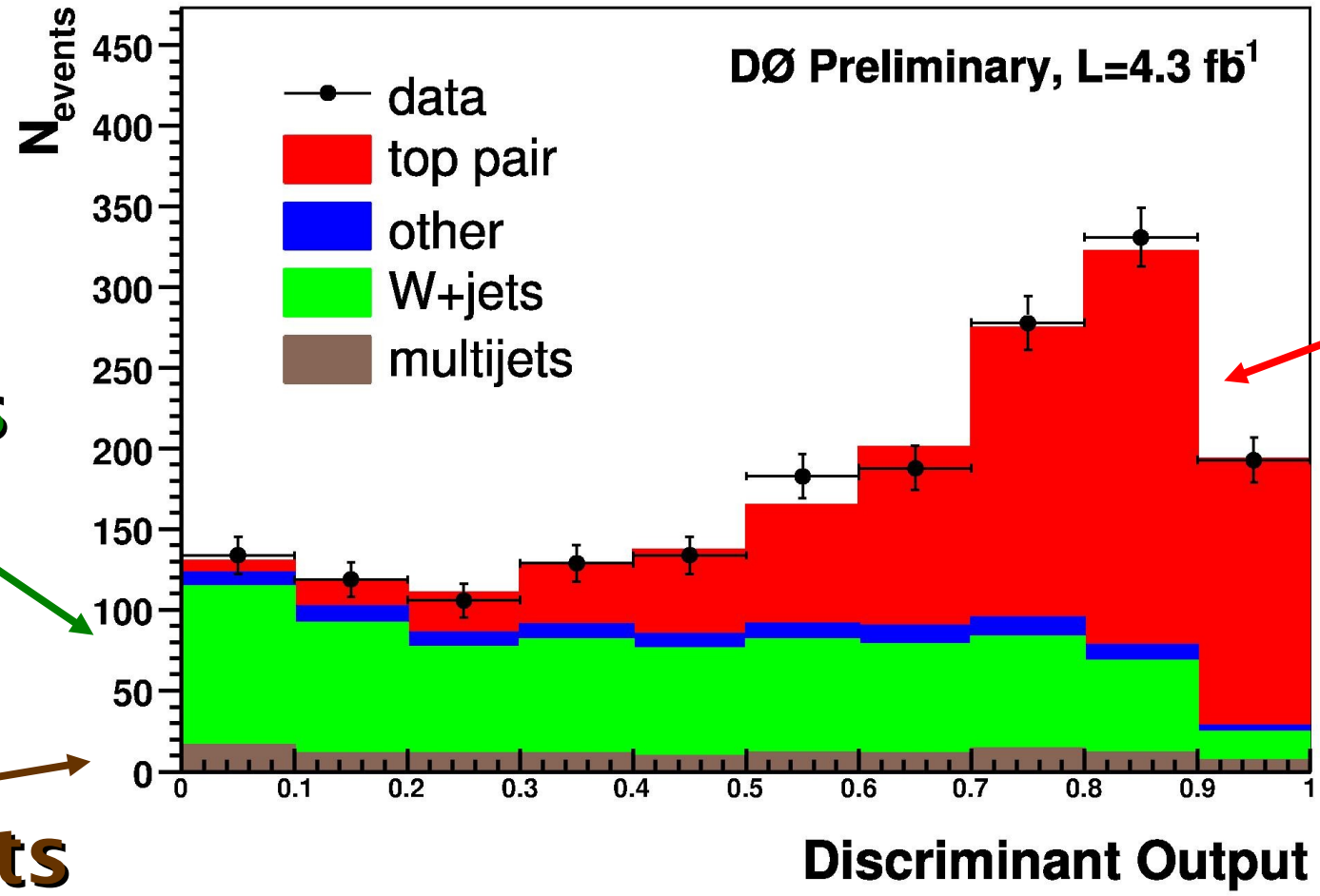
Boosted Decision Trees







Lepton+Jets Topological Cross Section



top pair

W+jets

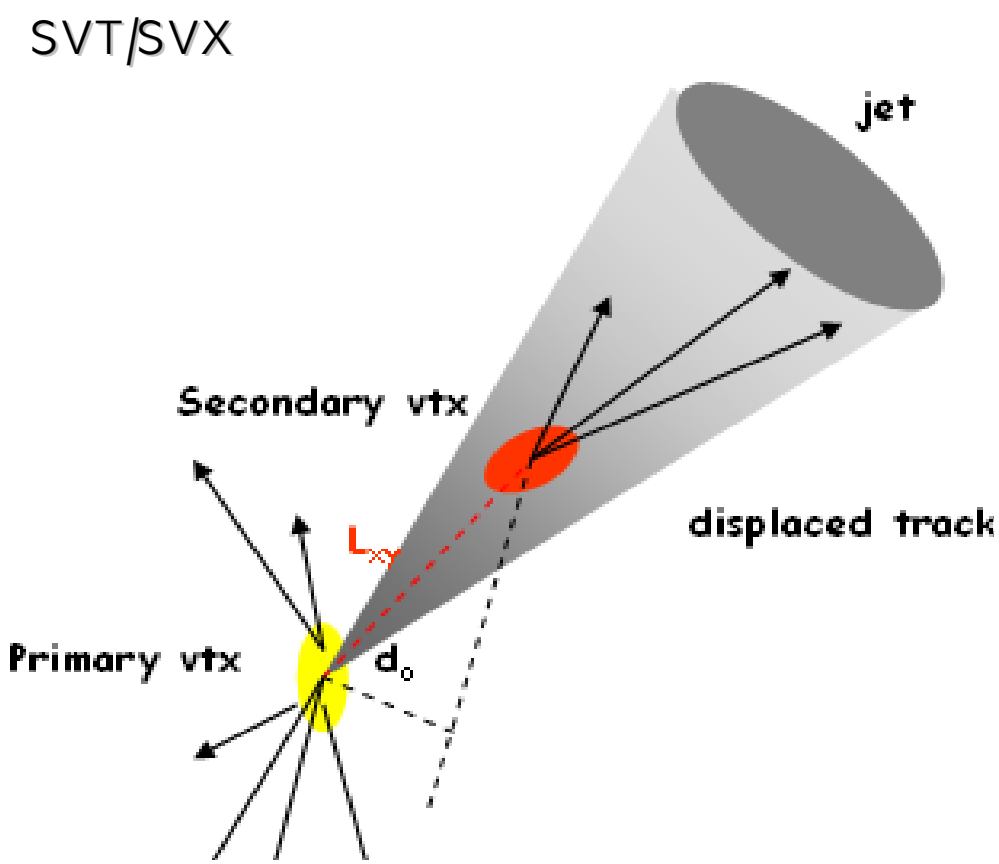
multijets

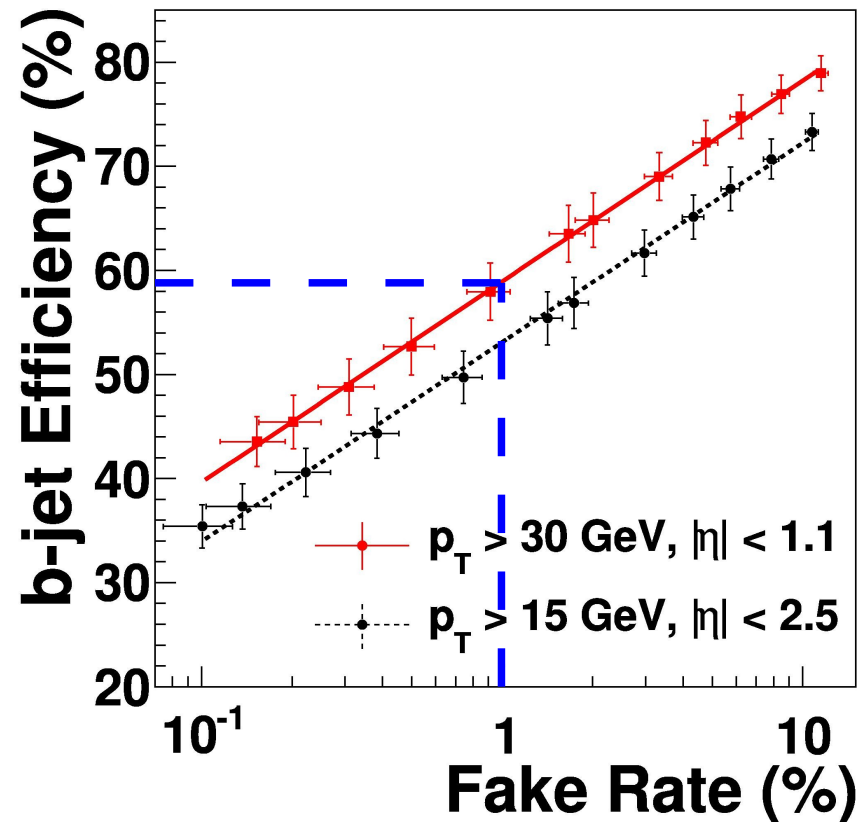
m_{top} = 172.5 GeV

$$\sigma_{t\bar{t}} = 7.70^{+0.70}_{-0.79} \text{ (stat+syst+lumi) pb}$$

b-tagging

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

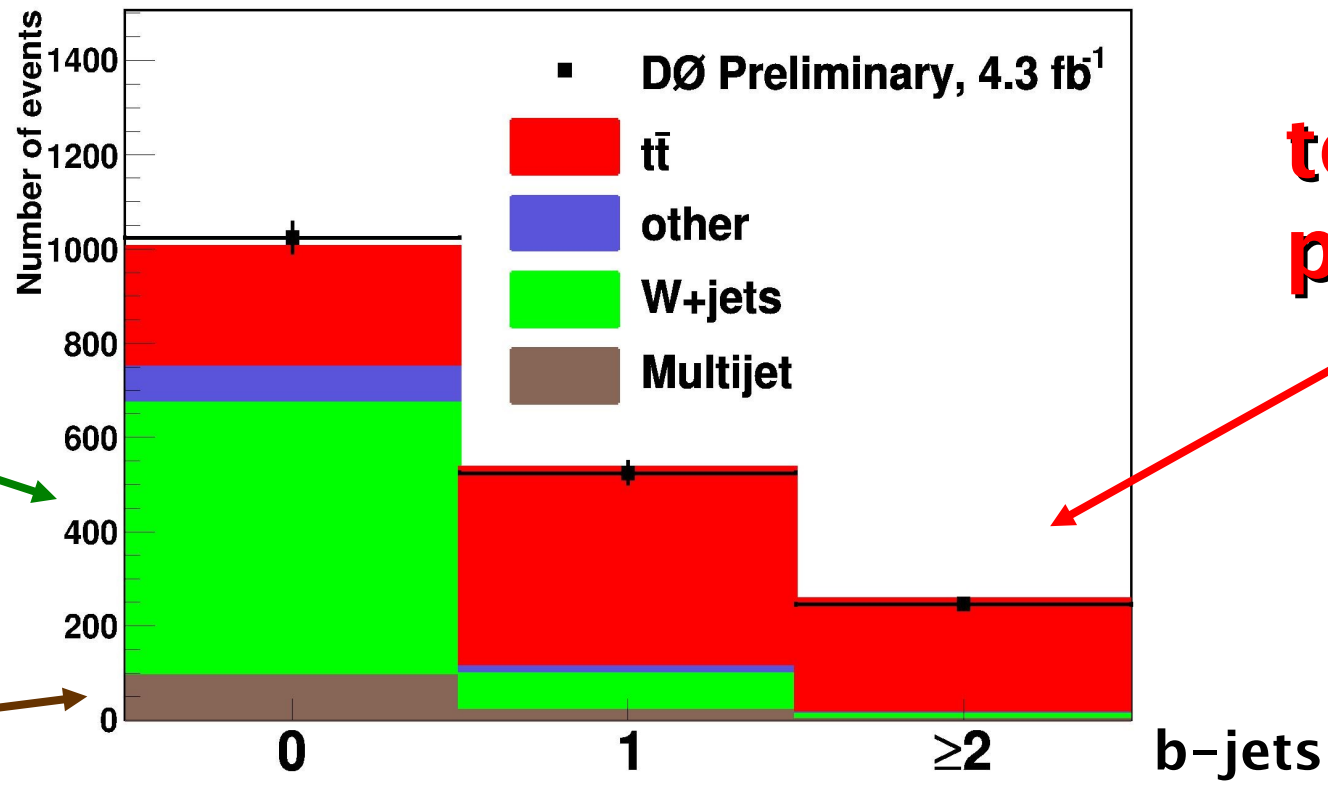




- form a 7-variable neural network
- event tagging efficiency 59% (with fake rate of 1%)

Lepton+Jets Cross Section with b-tagging

very powerful tool to reduce the background



W+jets

top pair

multijets

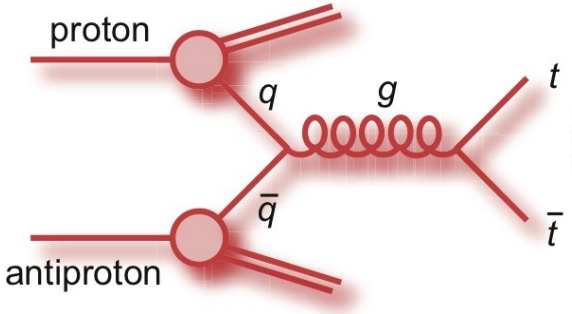
m_{top} = 172.5 GeV

$$\sigma_{t\bar{t}} = 7.93^{+1.04}_{-0.91} \text{ (stat+syst+lumi) pb}$$

- **limited by systematics**
- **luminosity dominates at ~6%**
- **b-tagging second largest**

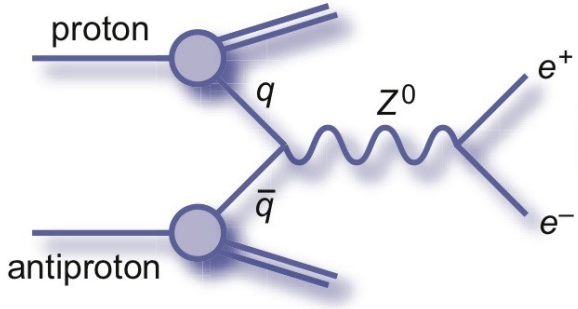
Top Pair Production Cross Section

- measure $t\bar{t}$/Z+jets cross section and trade luminosity uncertainty for theory uncertainty for Z+jets production



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

Luminosity

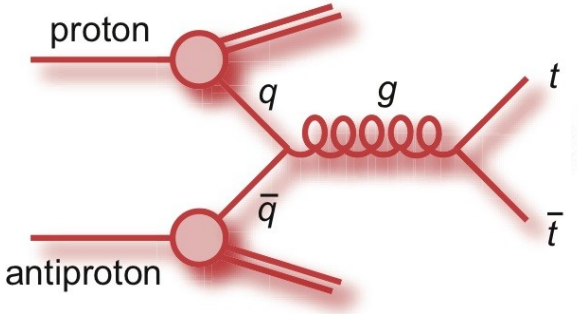


$$\sigma=(N_{obs}-N_{bg})/(\varepsilon L)$$

Luminosity

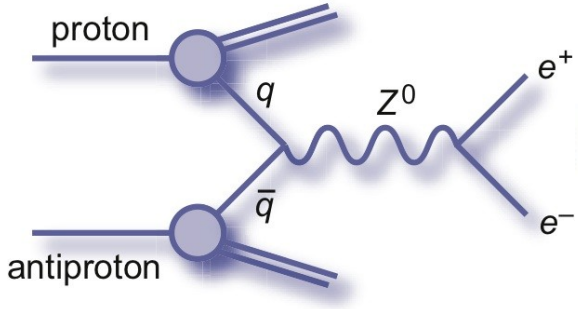
Cross Section Ratios

- measure $t\bar{t}$/Z+jets cross section and trade luminosity uncertainty for theory uncertainty for Z+jets production



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

~~Luminosity~~



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

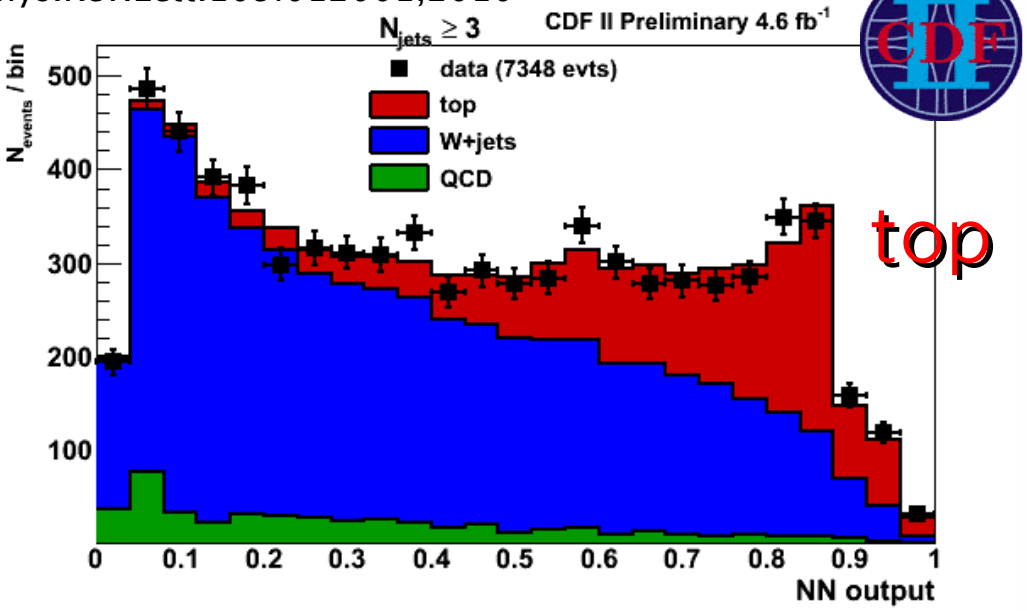
~~Luminosity~~

Top Pair Production Cross Section

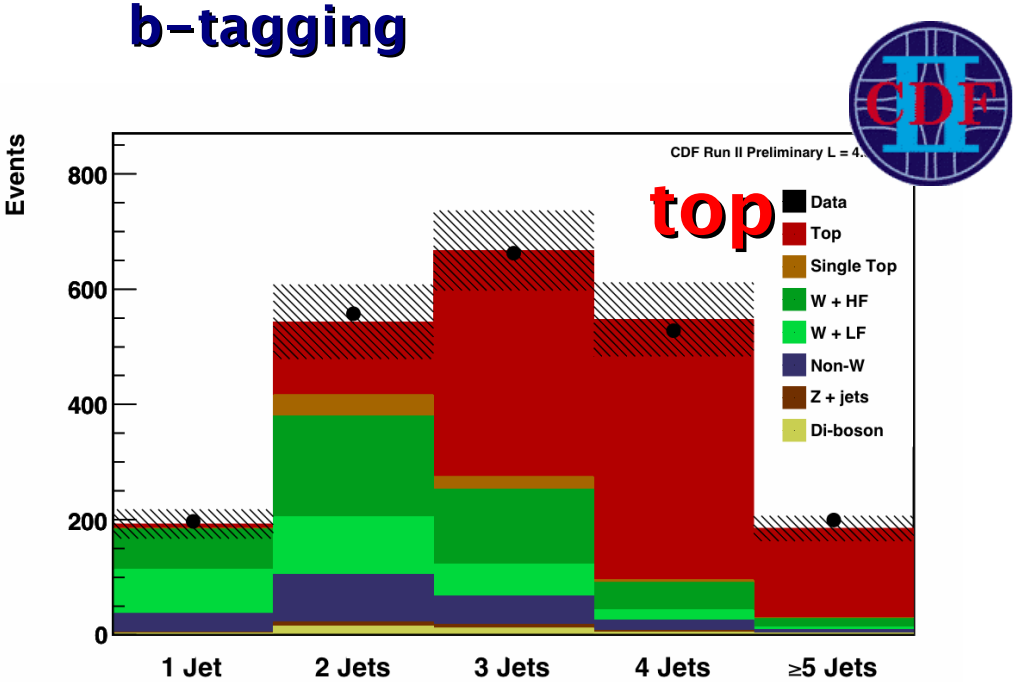
$t\bar{t}$/Z+jets cross section ratio

topological information (NN)

Phys.Rev.Lett.105:012001,2010



b-tagging



$\sigma_{t\bar{t}} = 7.82 \pm 0.38$ (stat) ± 0.37 (syst) ± 0.15 (Z theory) pb

$m_{top} = 172.5$ GeV

±7%

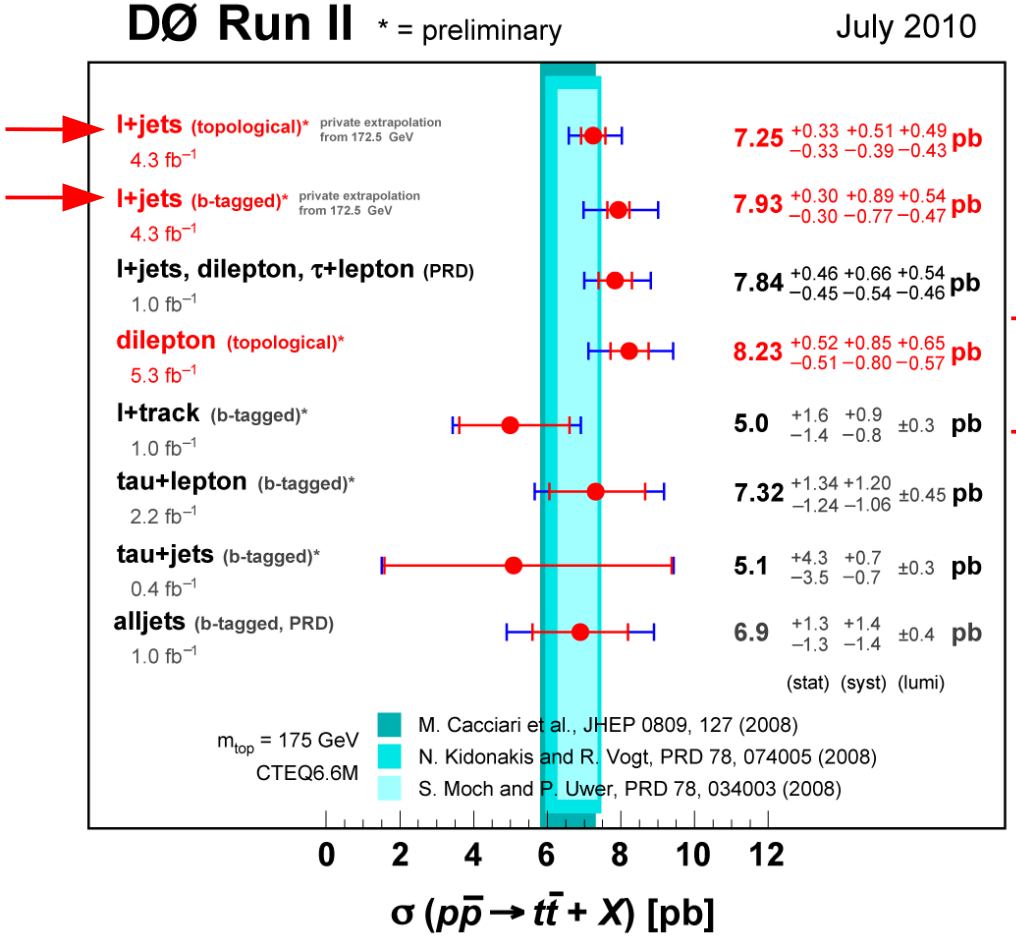
$\sigma_{t\bar{t}} = 7.32 \pm 0.36$ (stat) ± 0.59 (syst) ± 0.14 (Z theory) pb

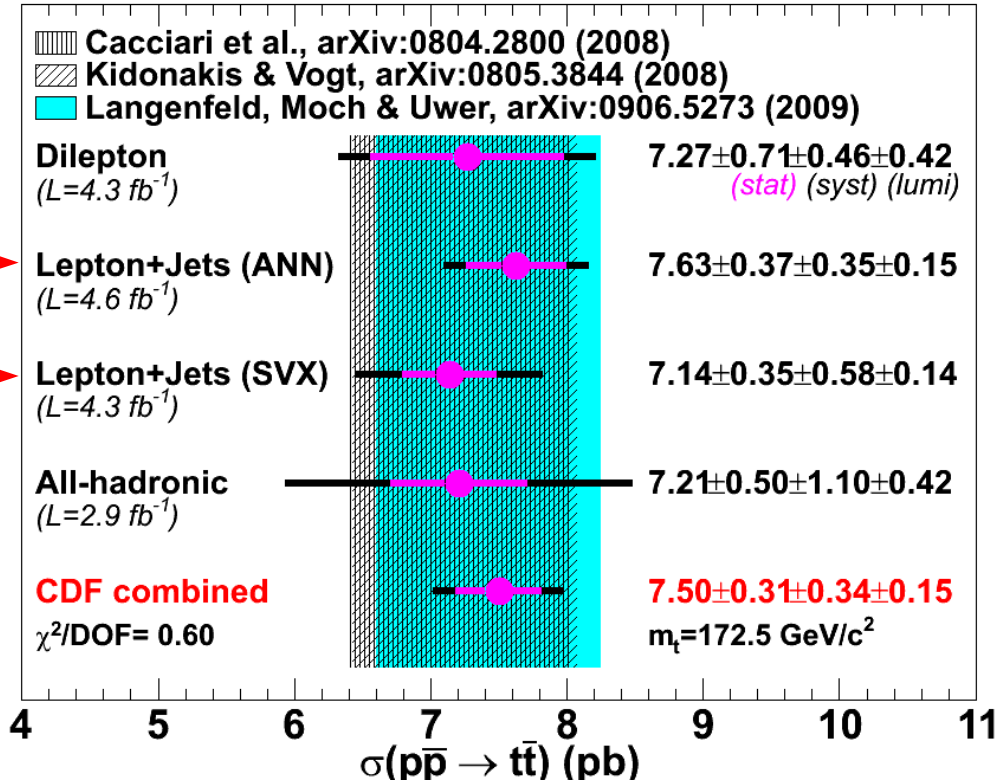
$m_{top} = 172.5$ GeV

±10%

to be compared to Tevatron goal of ±10%...

Top Pair Production Cross Sections





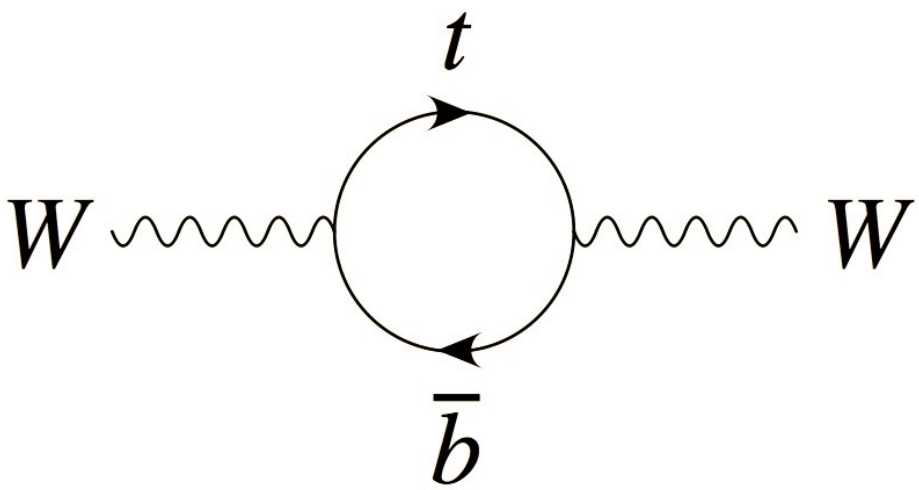
combination: ±6% !

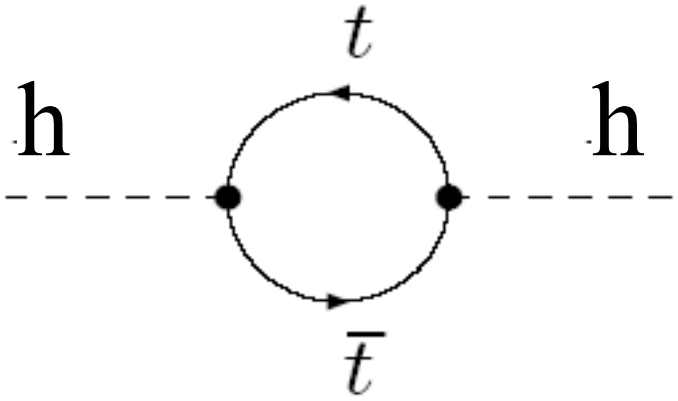
all channels measured except for τ_{had} τ_{had}

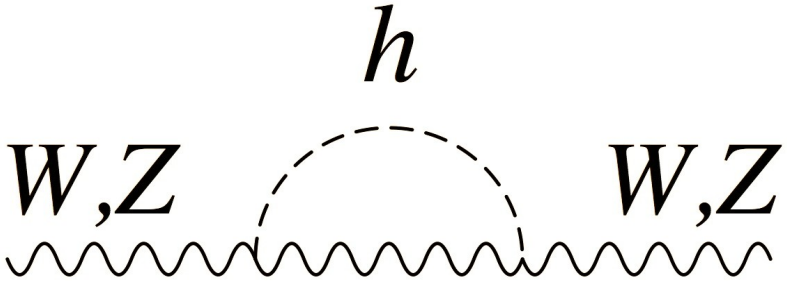
⇒ **good agreement with SM in all channels**

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**



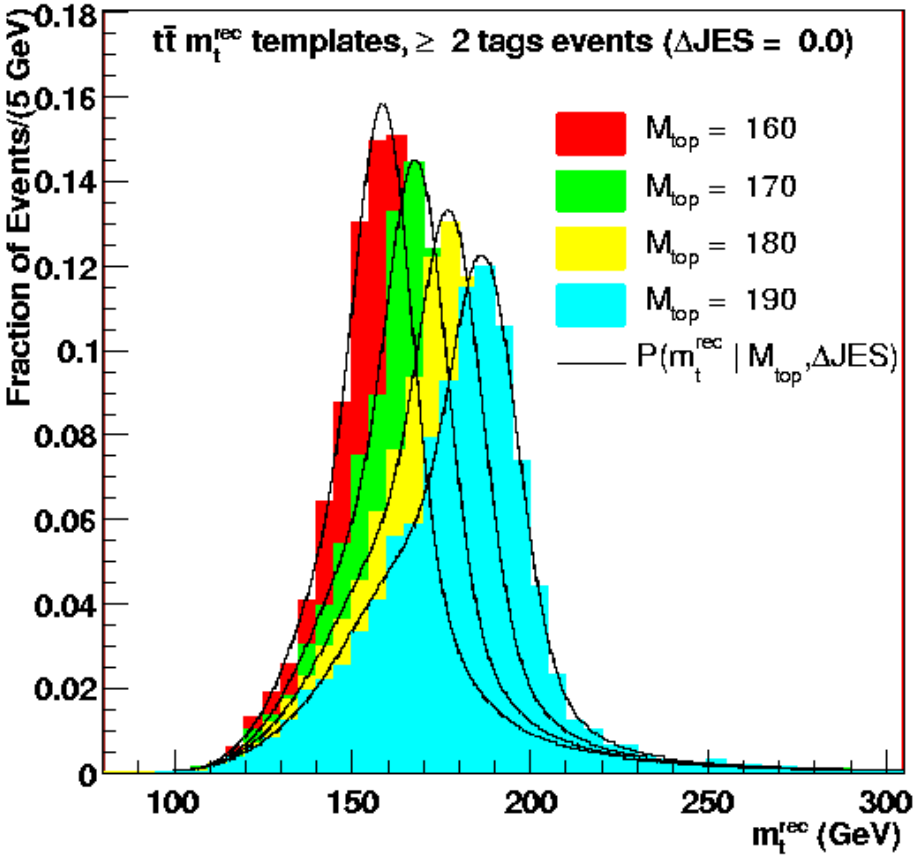




Extraction Techniques: template

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

all hadronic



Extraction Techniques: template

- use variables strongly correlated with m_{top}
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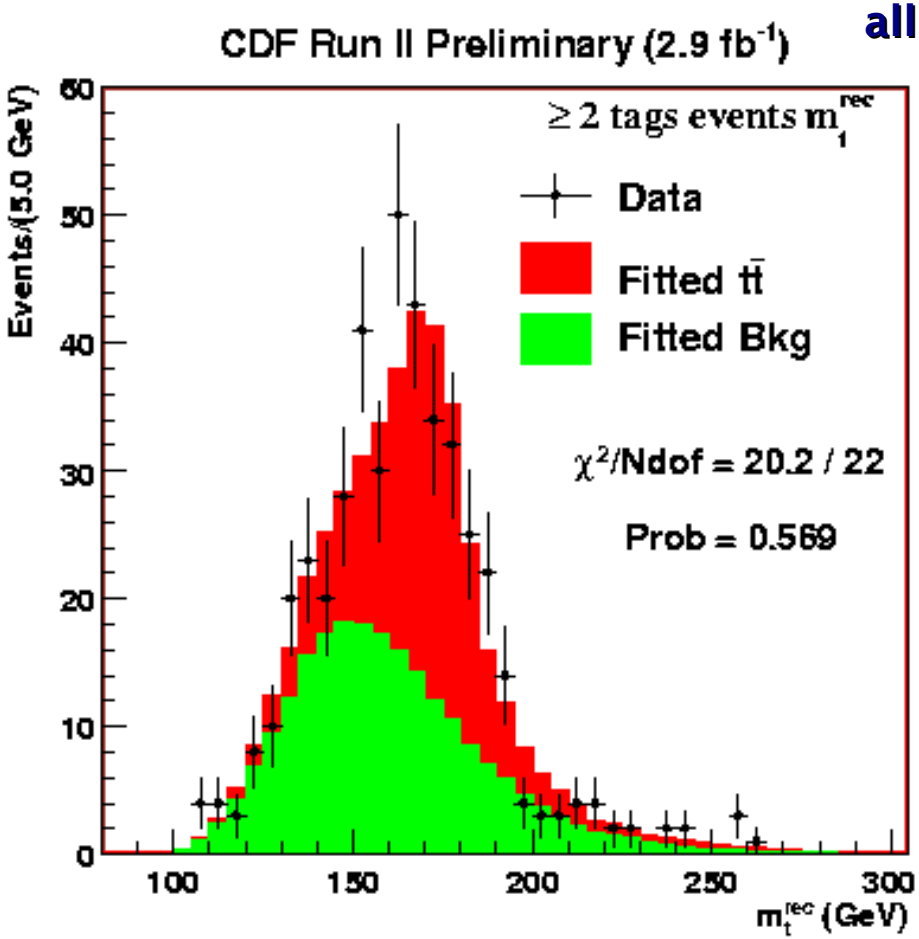
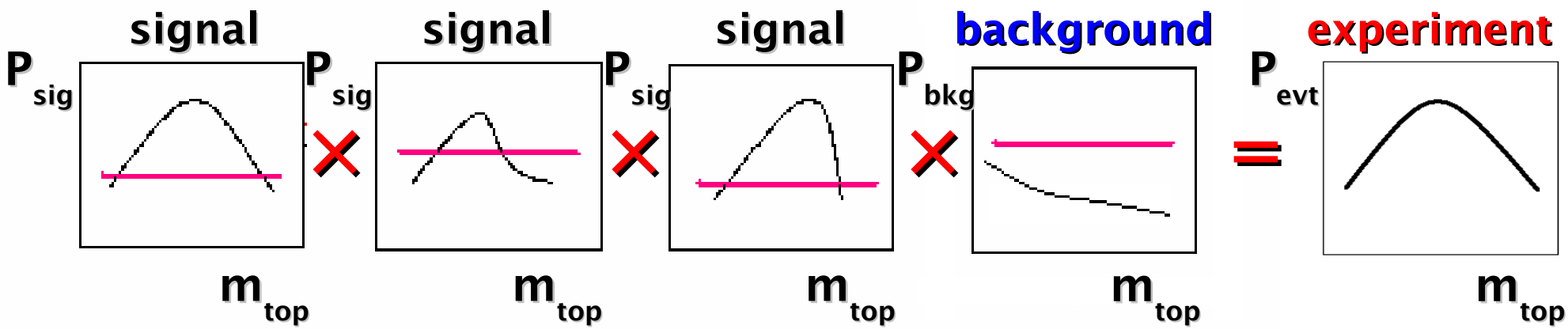
all hadronic

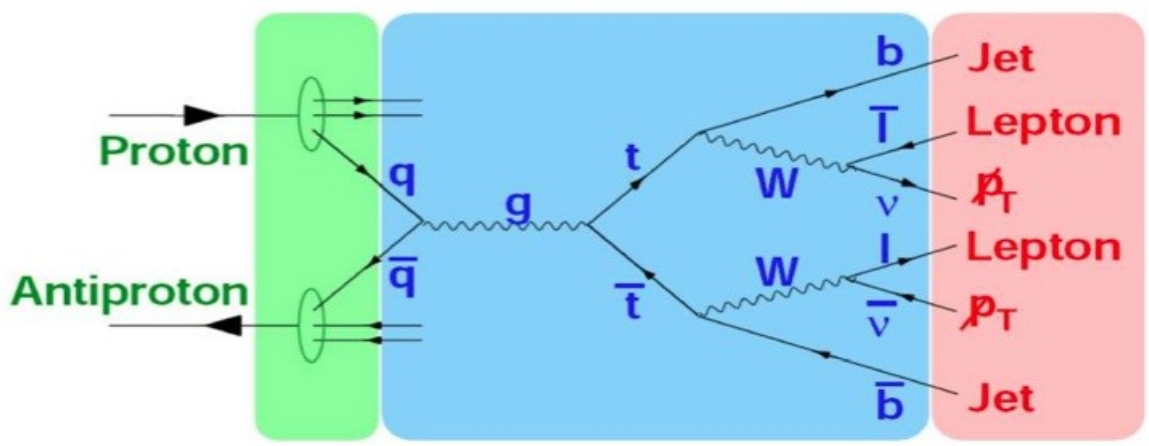


Extraction techniques: matrix element

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



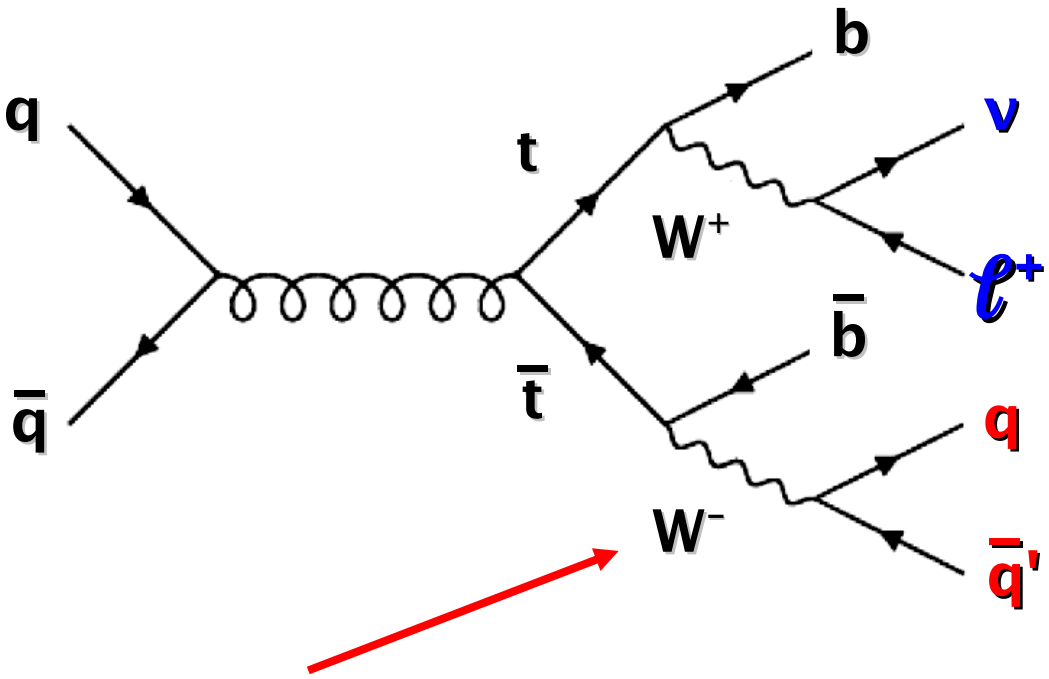
$$P_{sig}(x;m_{top},JES)=Acc(x)\times\frac{1}{\sigma}\int d^n\sigma(y;m_{top})\,dq_1\,dq_2\,f(q_1)\,f(q_2)\,W(x,y;JES)$$



PDF's LO-Matrix element

transfer functions
(probability to measure x
when y was produced)

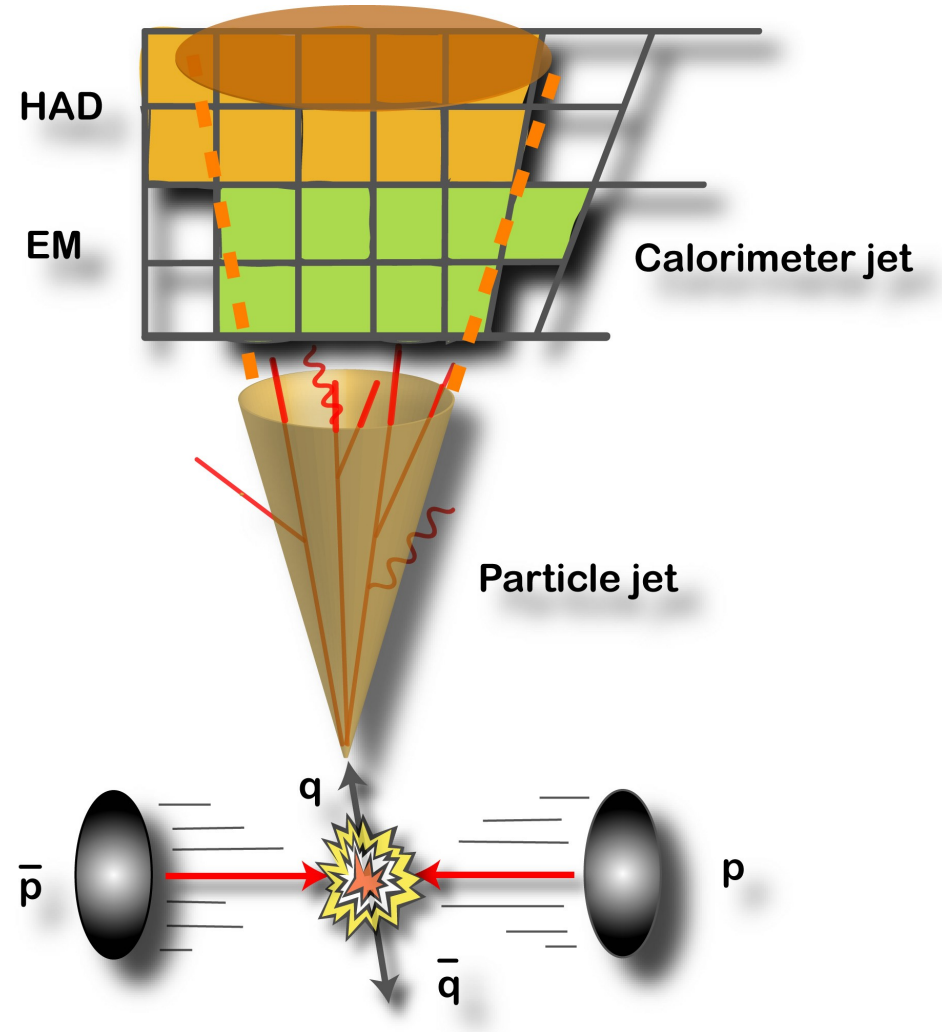
Lepton+Jets Channel



W mass constrains jet energy scale

jet energy scale:

translate jet into parton energy

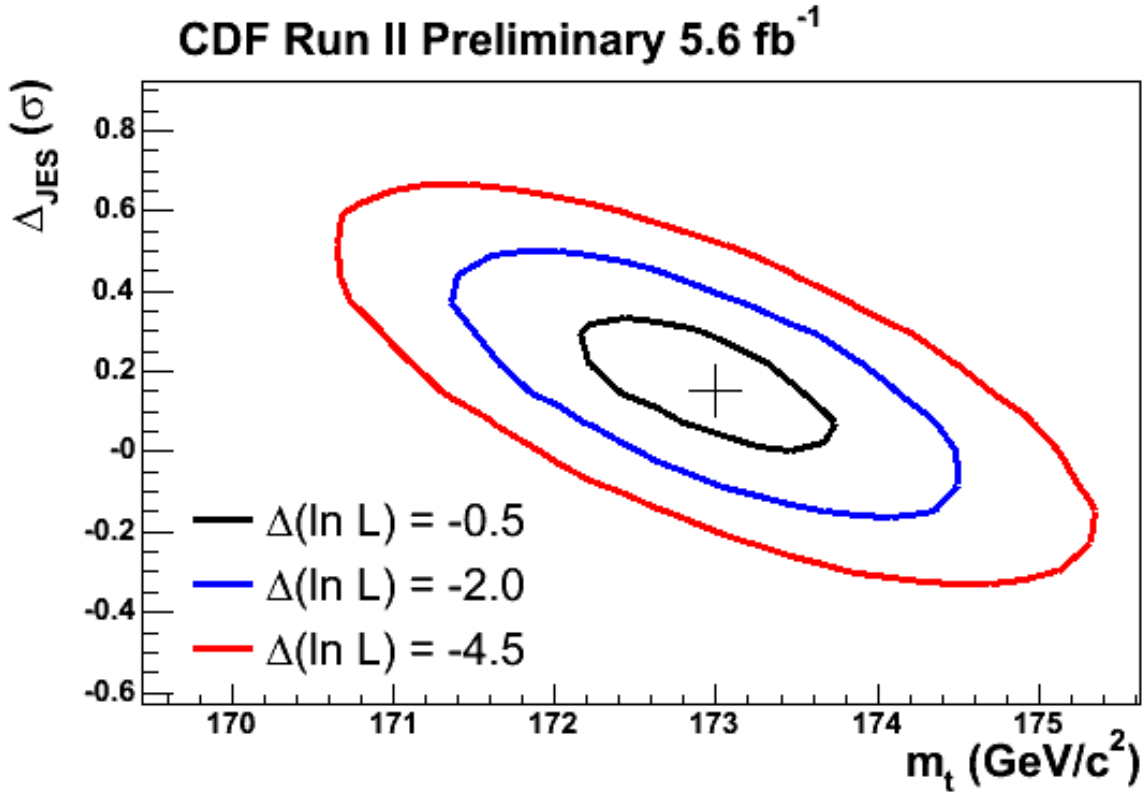


Results in l+jets Channel

maximum Likelihood fit to data:

jet energy scale:

translate jet into parton energy



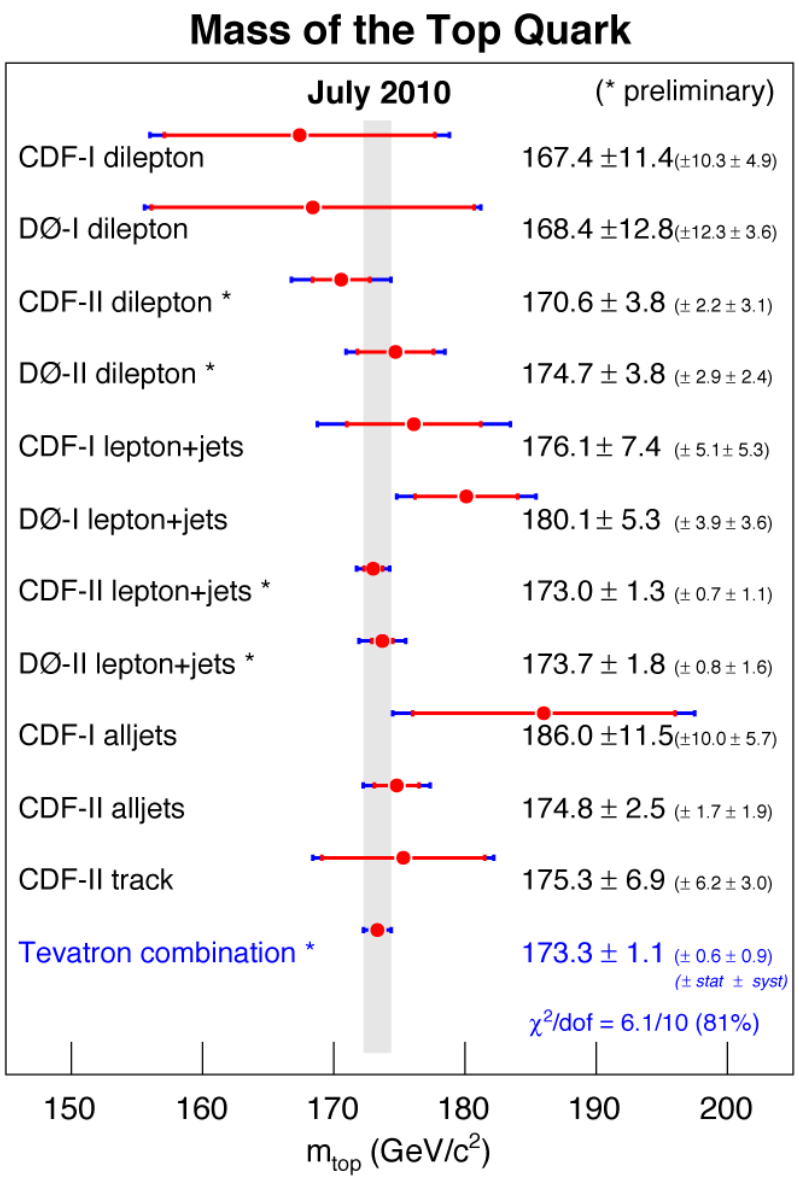
5.6 fb^{-1}

$$m_{top} = 173.0 \pm 0.7\ (stat) \pm 0.6\ (JES) \pm 0.9\ (syst)\ \ GeV$$
$$= 173.0 \pm 1.2\ GeV$$

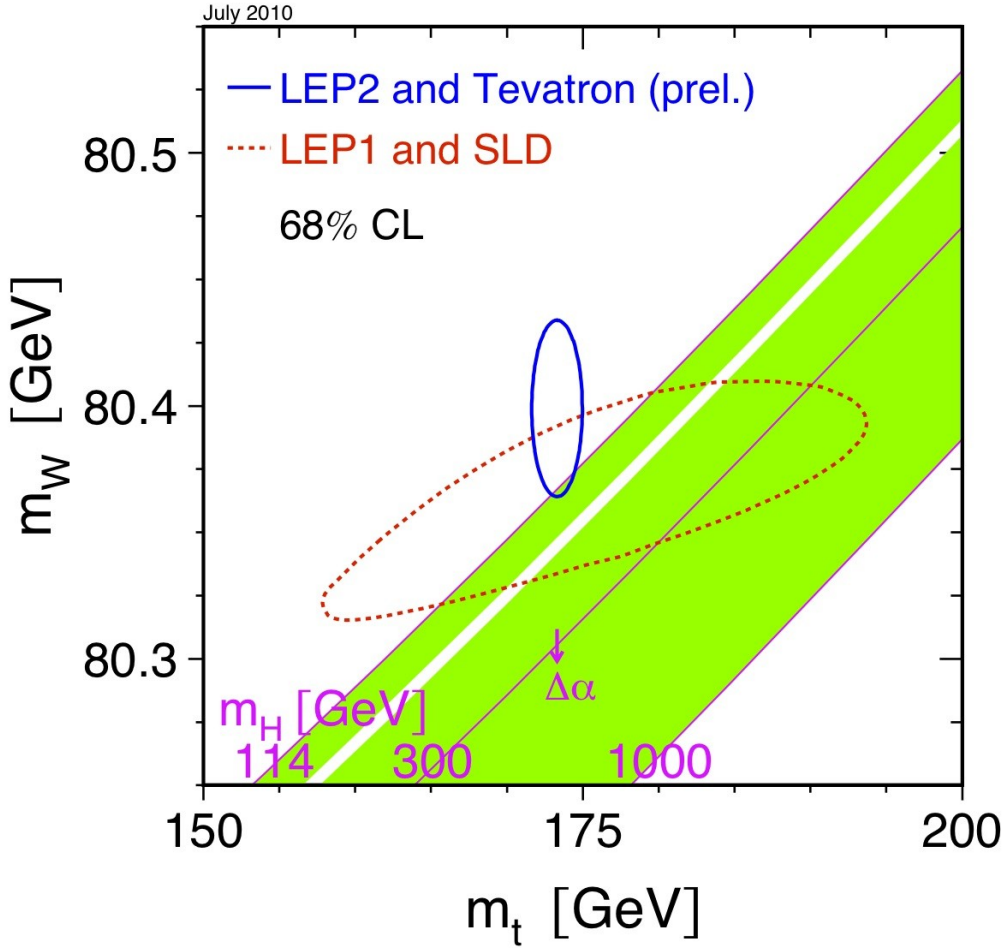
±0.7%

Tevatron Combination: July 2010

arXiv:1007.3178



$$m_{top} = 173.3 \pm 1.1 \text{ GeV}$$ **±0.6%**



theory & experiment: uniform treatment of systematics

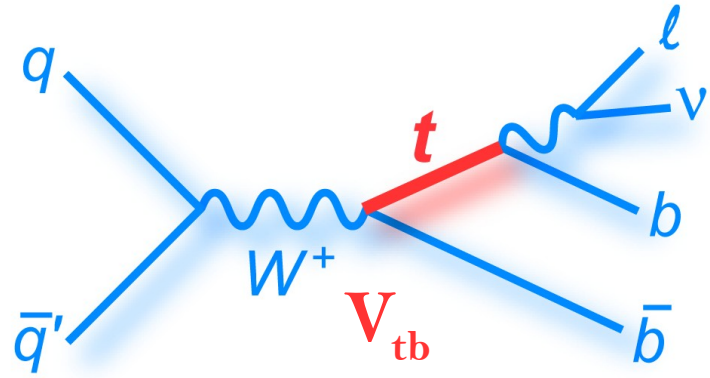
Single Top Quark Production

direct measurement of $|V_{tb}|$

PRD 74, 114012 (2006)

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

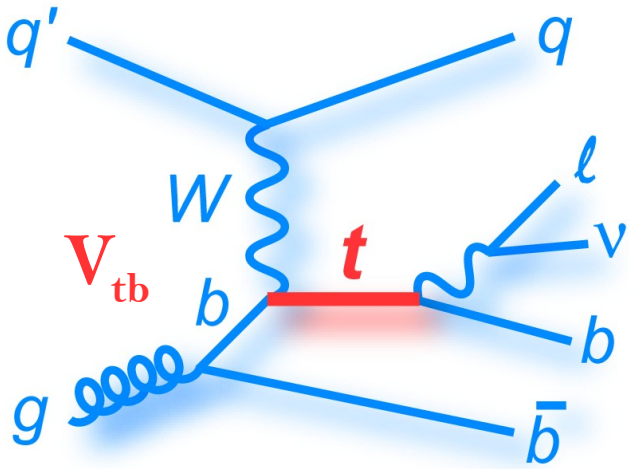
$NNNLO_{approx}$, $m_{top} = 172.5$ GeV



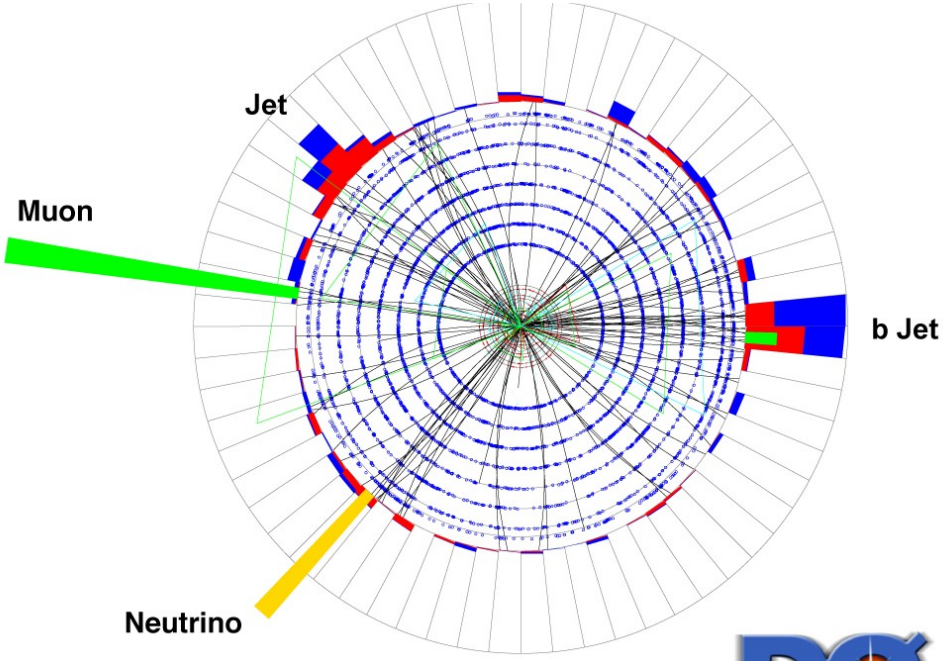
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

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

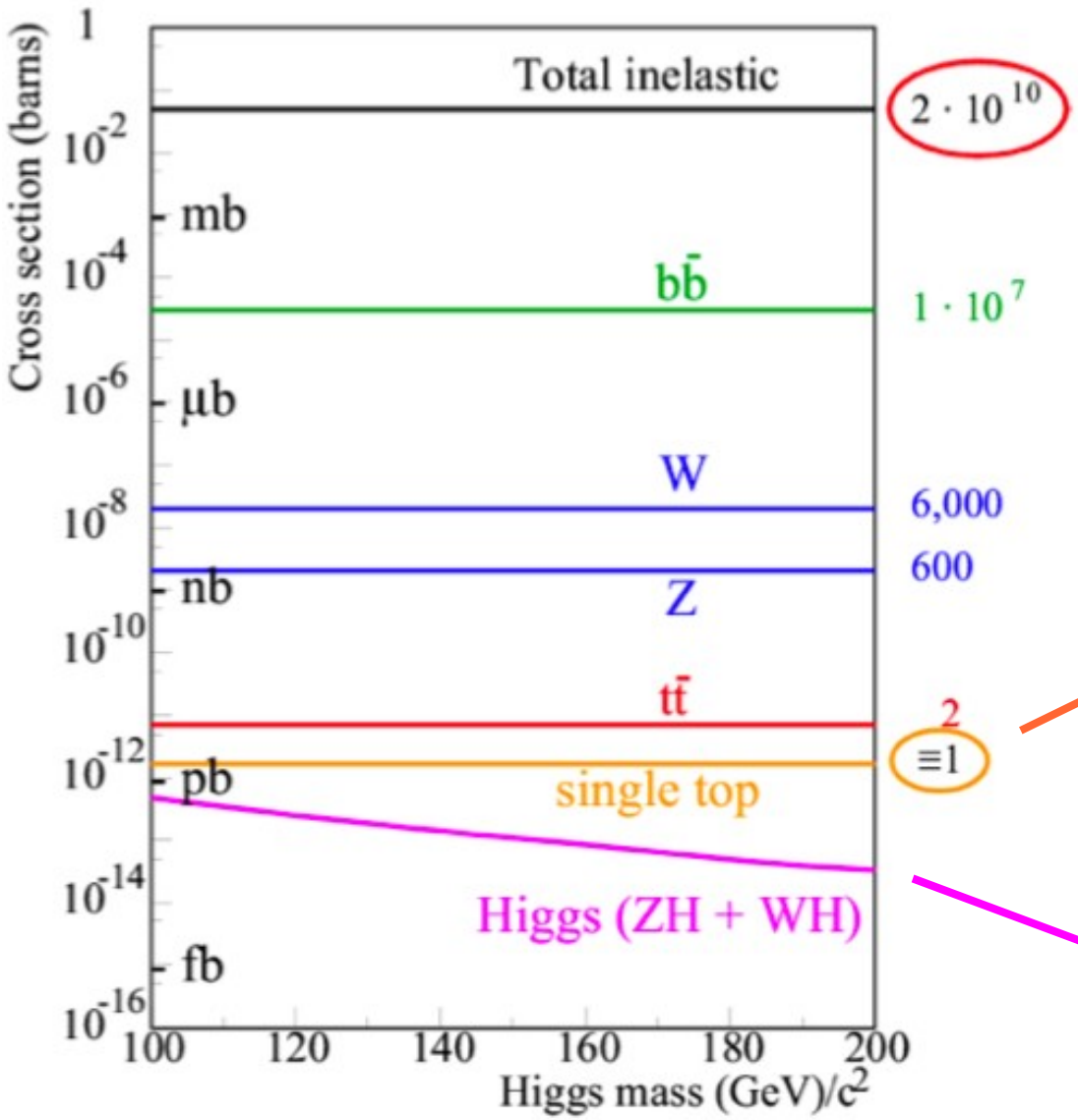
$NNNLO_{approx}$, $m_{top} = 172.5$ GeV

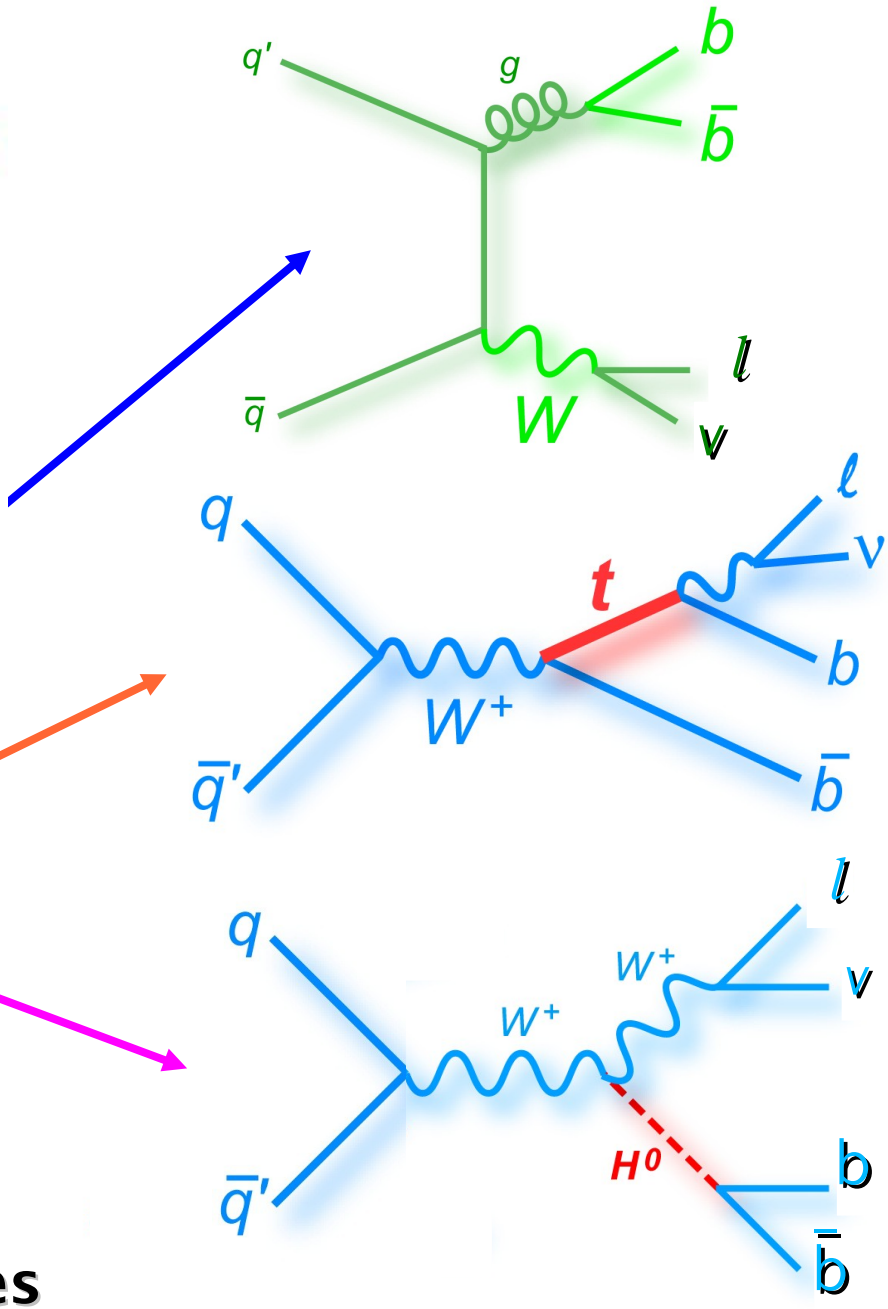


- jets
- lepton
- missing E_T
- b-jets



It has been challenging for years...

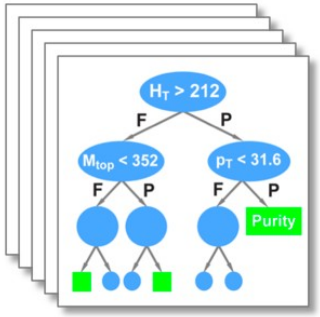




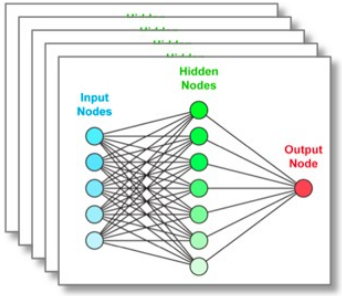
⟹ **multivariate analysis techniques**

Multivariate Analyses

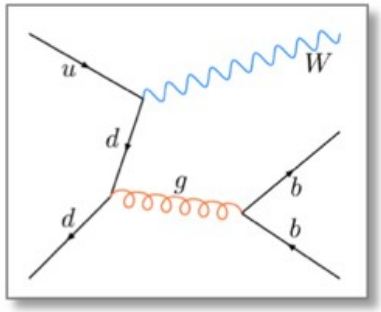
Boosted Decision Trees



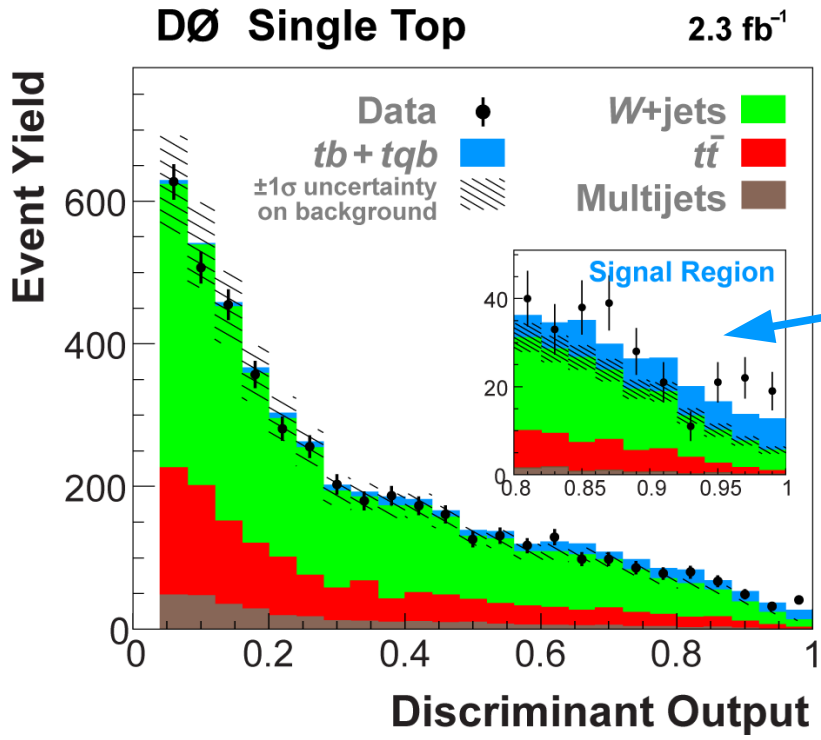
Boosted Neural Networks



Matrix Elements



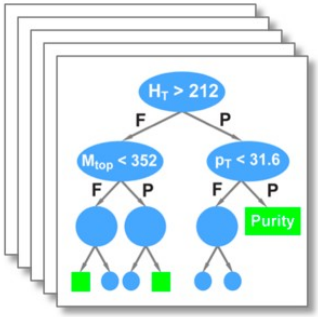
combine up to 12 different analysis channels:



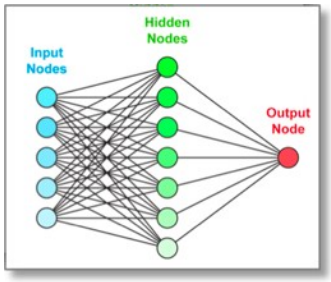
single top

Multivariate Analyses

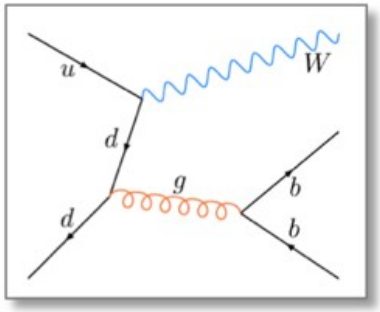
Boosted Decision Trees



Neural Networks



Matrix Elements



Likelihood

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

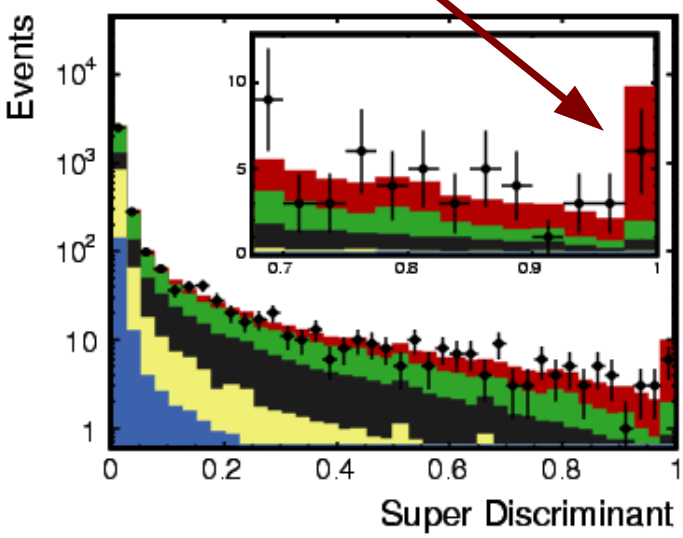
$$\mathcal{L}_k(\{x_i\}) = \frac{\prod_{i=1}^{n_{var}} p_{ik}}{\sum_{m=1}^{5} \prod_{i=1}^{n_{var}} p_{ik}}.$$

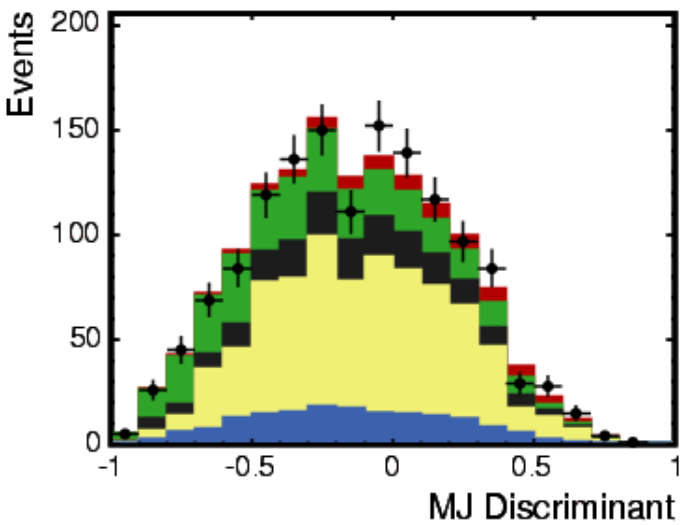
combine up to 8 different analysis channels:

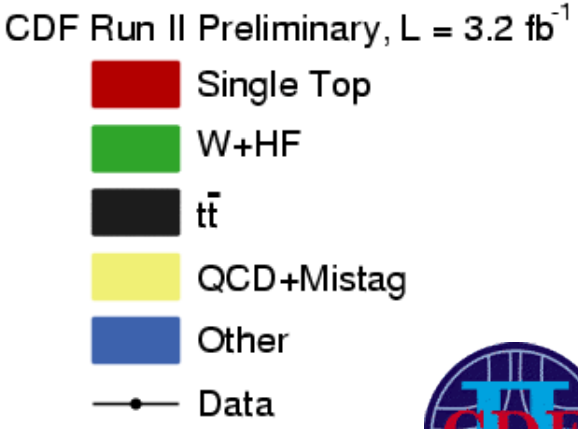
single top

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

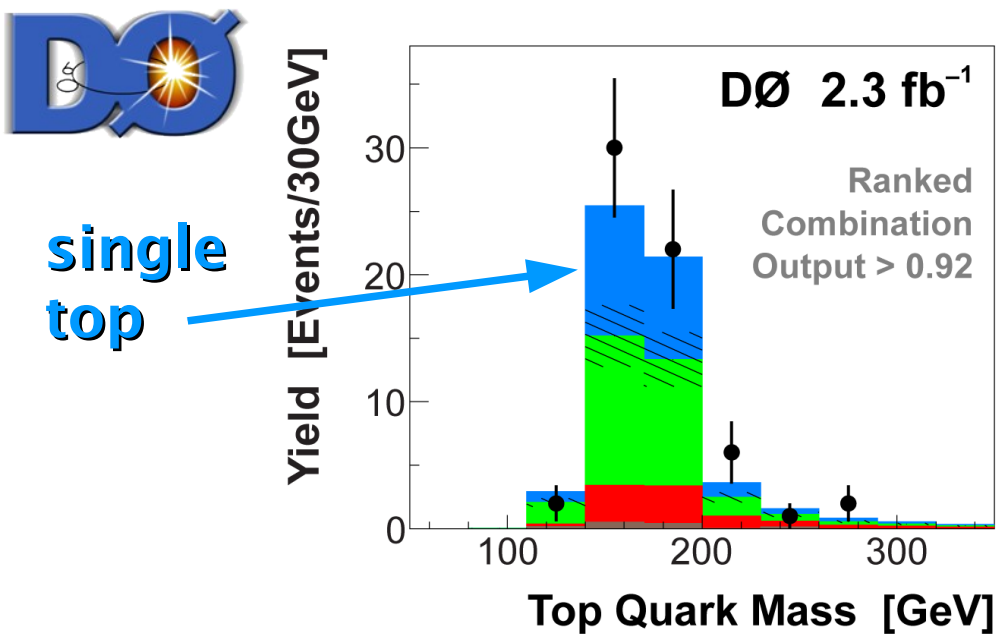
  recover badly reconstructed e, μ; include τ

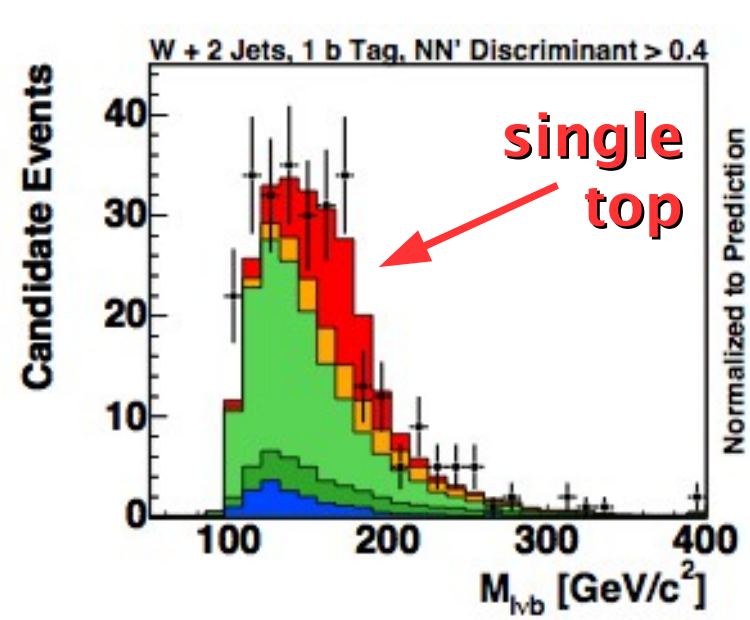




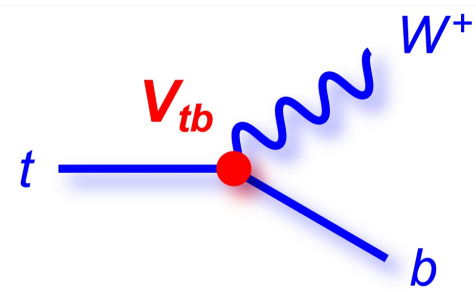


Single Top Observation





Single Top Cross Section	Signal Significance Expected	Signal Significance 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



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

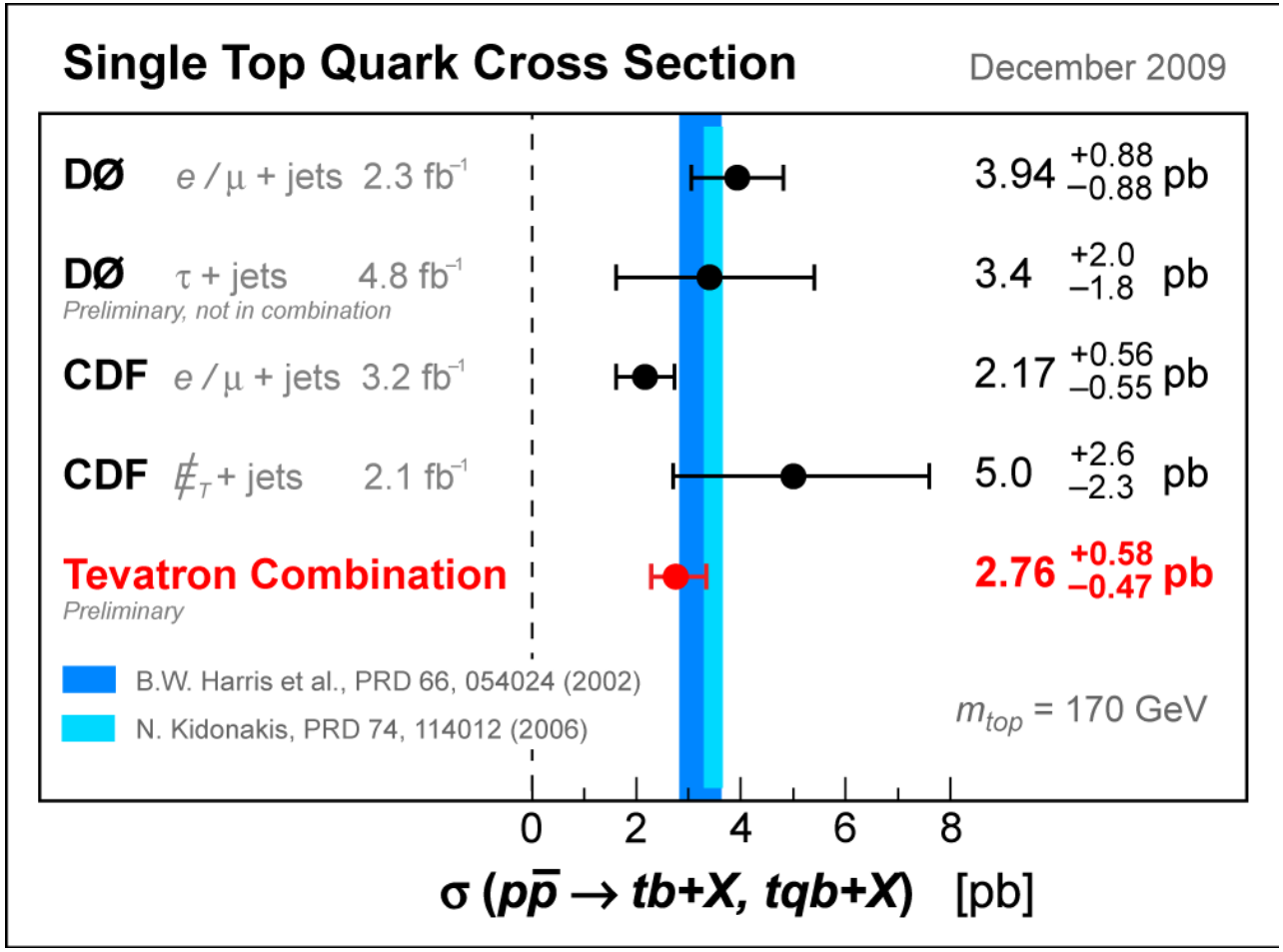
$|V_{tb}| = 0.91 \pm 0.13$

⇒ **observation with 5.0σ!**

Single Top Quark Observation

1 year ago

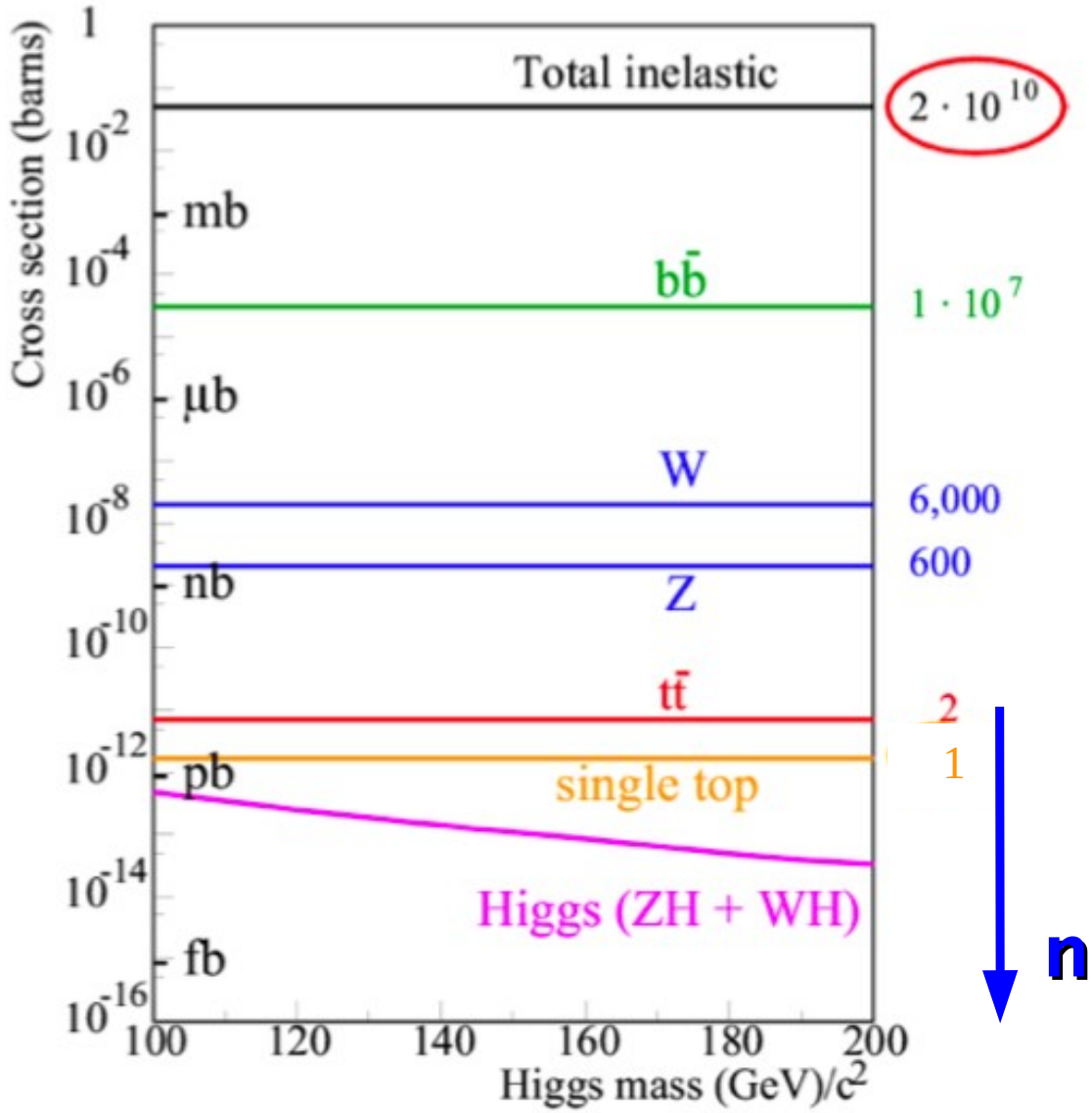
Tevatron Single Top Cross Section



$$|V_{tb}| = 0.88 \pm 0.07$$

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

Cross Sections at the Tevatron

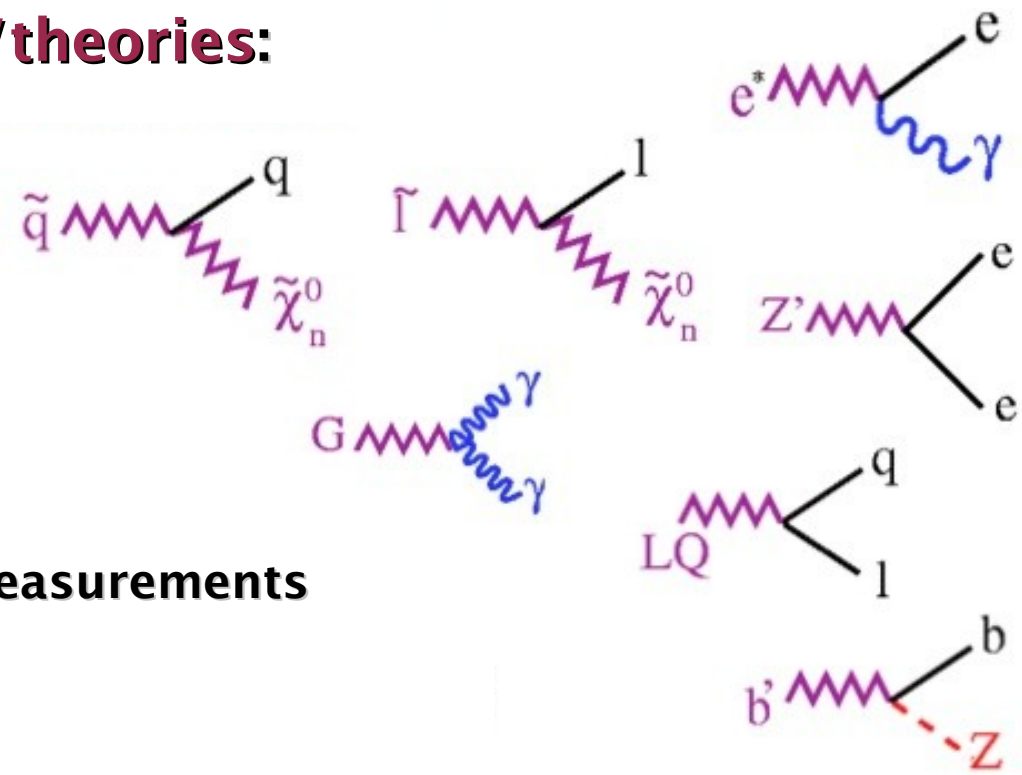


new physics?

The Unknown beyond the SM

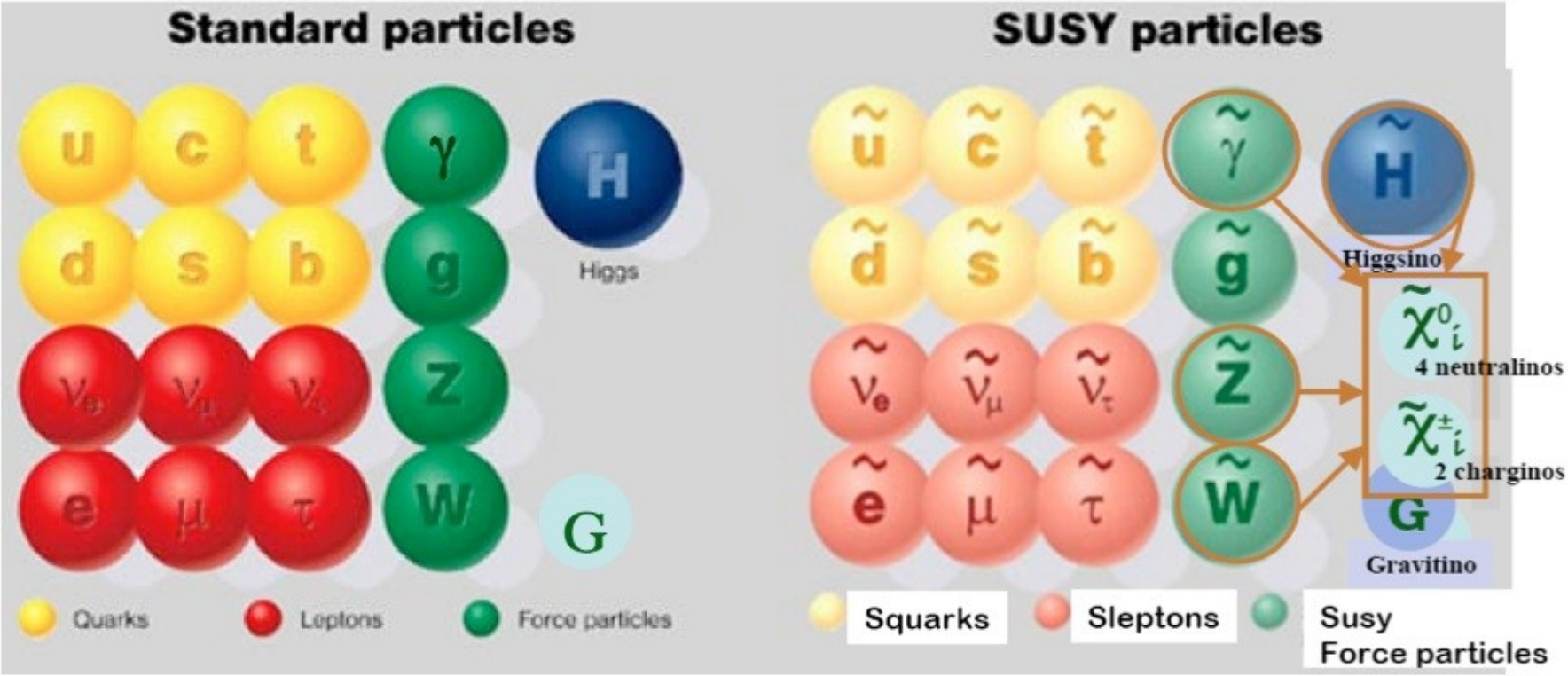
- many good reasons to believe there is as yet **unknown physics** beyond the SM
  - dark matter+energy, matter/anti-matter asymmetry, neutrino masses/mixing and many more

- many possible **new particles/theories**:
  - **supersymmetry**
  - extra dimensions (G)
  - new gauge groups (Z', W', G', …)
  - new fermions (t', b', e*, …)
  - leptoquarks



- new physics can show up…
  - as subtle deviations in precision measurements
  - in direct searches for new particles

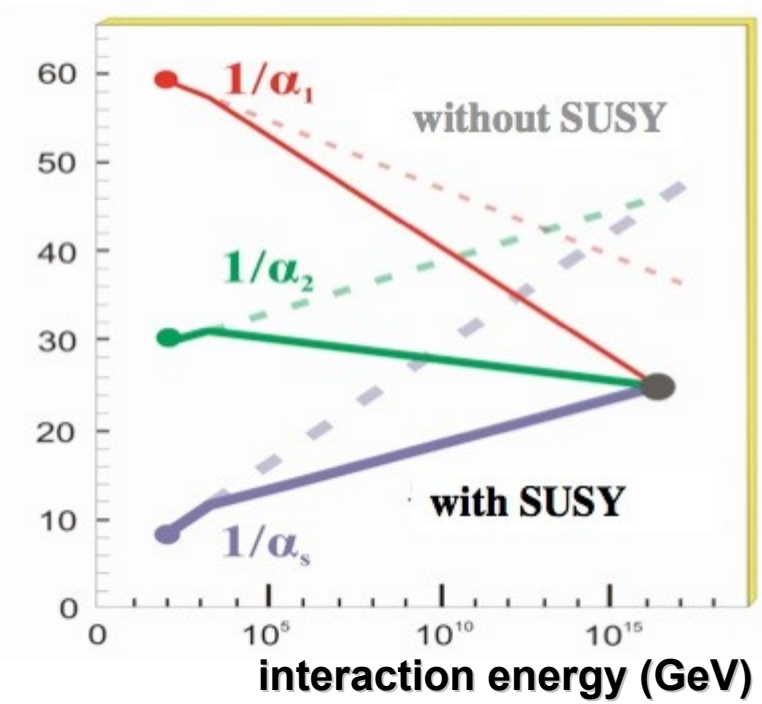
Supersymmetry (SUSY)

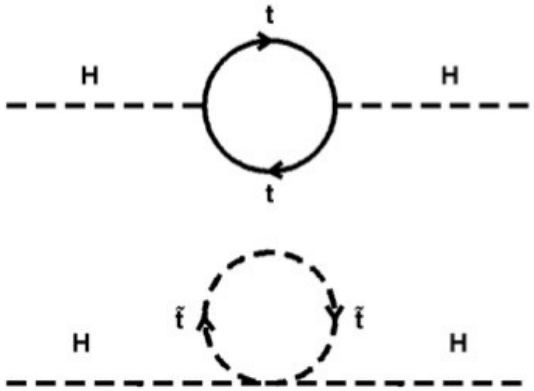


- SM particles have SUSY partners: differ by ½ unit in spin
  - sfermions (squark, selectron, smuon, ...): spin 0
  - gauginos (chargino, neutralino, gluino, ...): spin 1/2
- no SUSY particles found as yet
  - SUSY must be broken: breaking mechanism determines phenomenology (e.g. mSUGRA, where neutralino is lightest SUSY particle)
  - more than 100 parameters even in "minimal" models

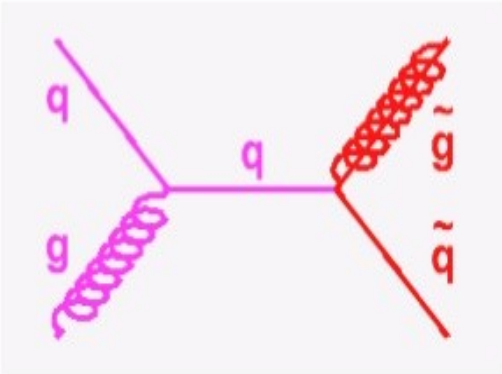
What's nice about SUSY?

- introduces a **symmetry between bosons and fermions**
- **unification of forces** possible
  - SUSY changes running of couplings
- **dark matter candidate** exists:
  - the lightest neutral gaugino
  - consistent with cosmology data
- **no fine-tuning required**
  - radiative corrections to Higgs acquire SUSY corrections
  - cancellation of fermion and sfermion loops
- also **consistent with precision measurements** of M_W and M_{top}

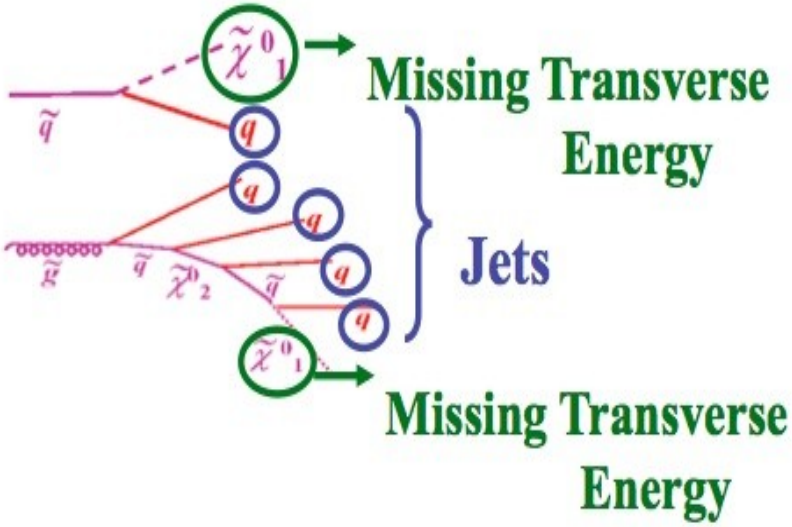




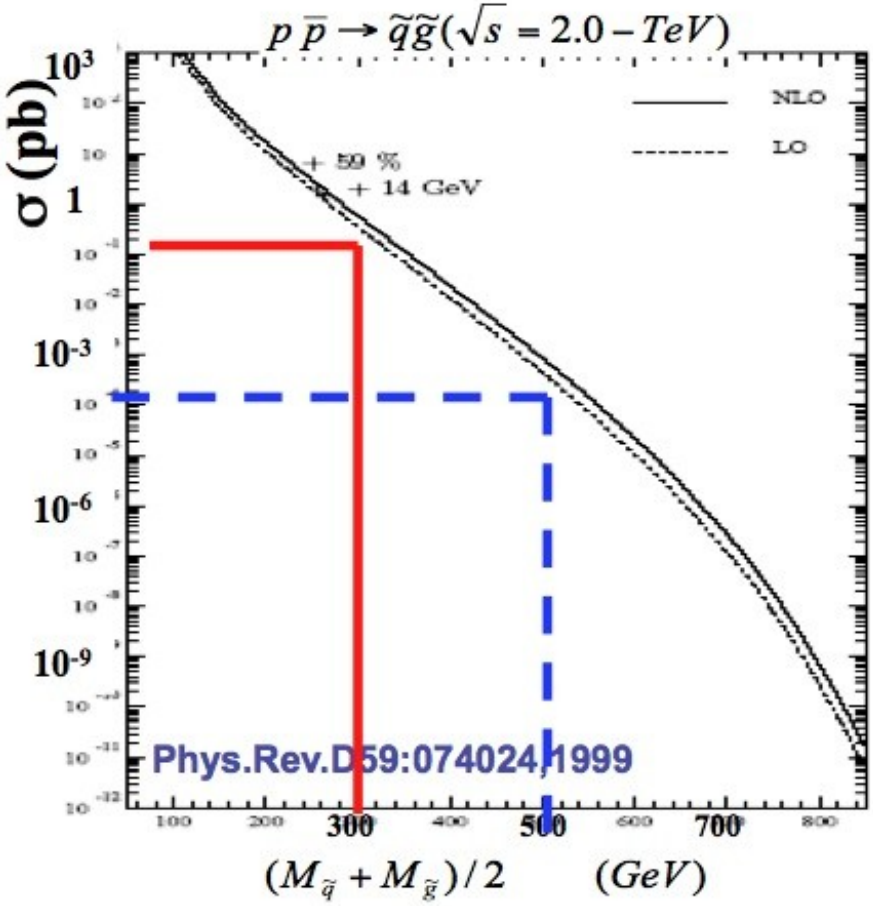
Squarks and Gluinos



- strong interaction
  → large production cross section



top pair →

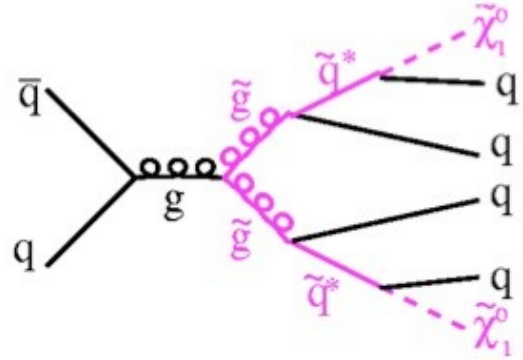


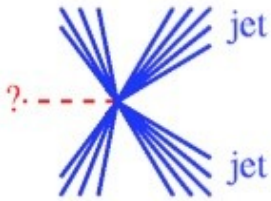
- squark and gluino production
  - signature: jets and $\not{E}_T$

Squark and Gluino Mass Scenarios

consider 3 cases:

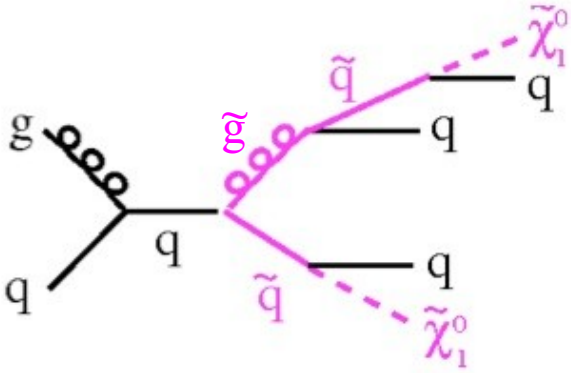
1. $m(\tilde{g})<m(\tilde{q})$

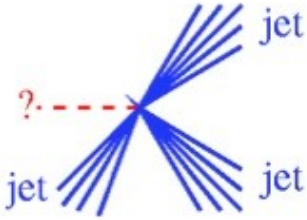




4 jets + E_T^{miss}

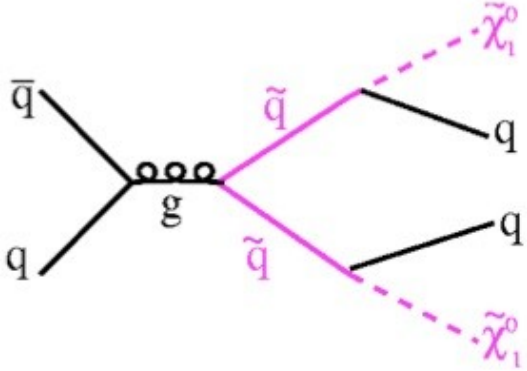
2. $m(\tilde{g})\approx m(\tilde{q})$

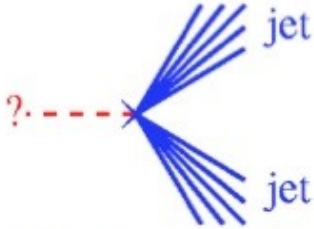




3 jets + E_T^{miss}

3. $m(\tilde{g})>m(\tilde{q})$

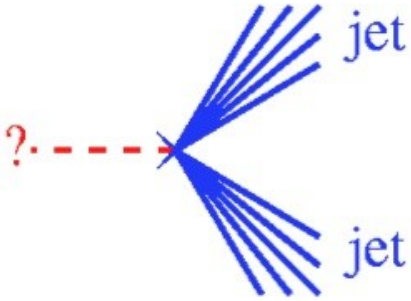




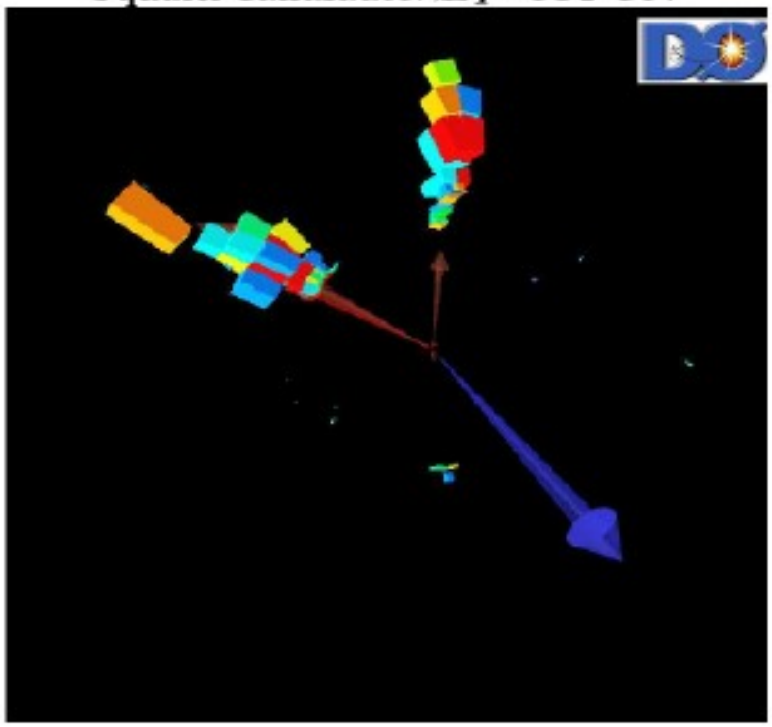
2 jets + E_T^{miss}

→ **optimize for different signatures in different scenarios**

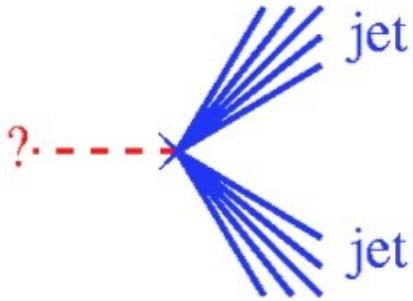
A nice Candidate Event!

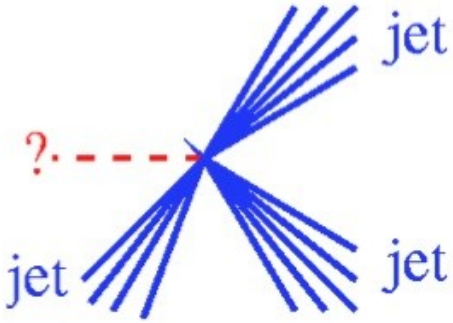


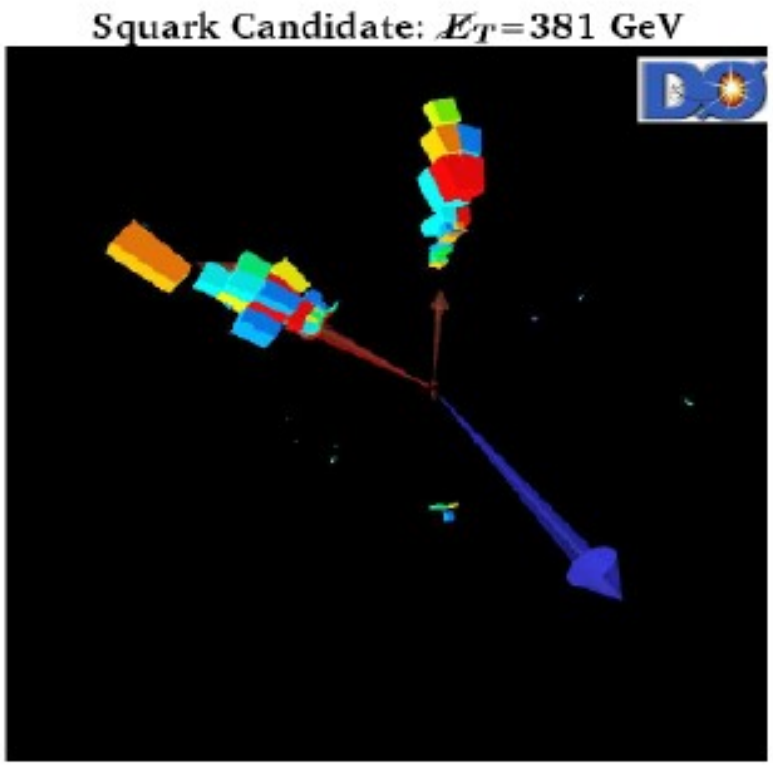
Squark Candidate: $\not{E}_T$=381 GeV

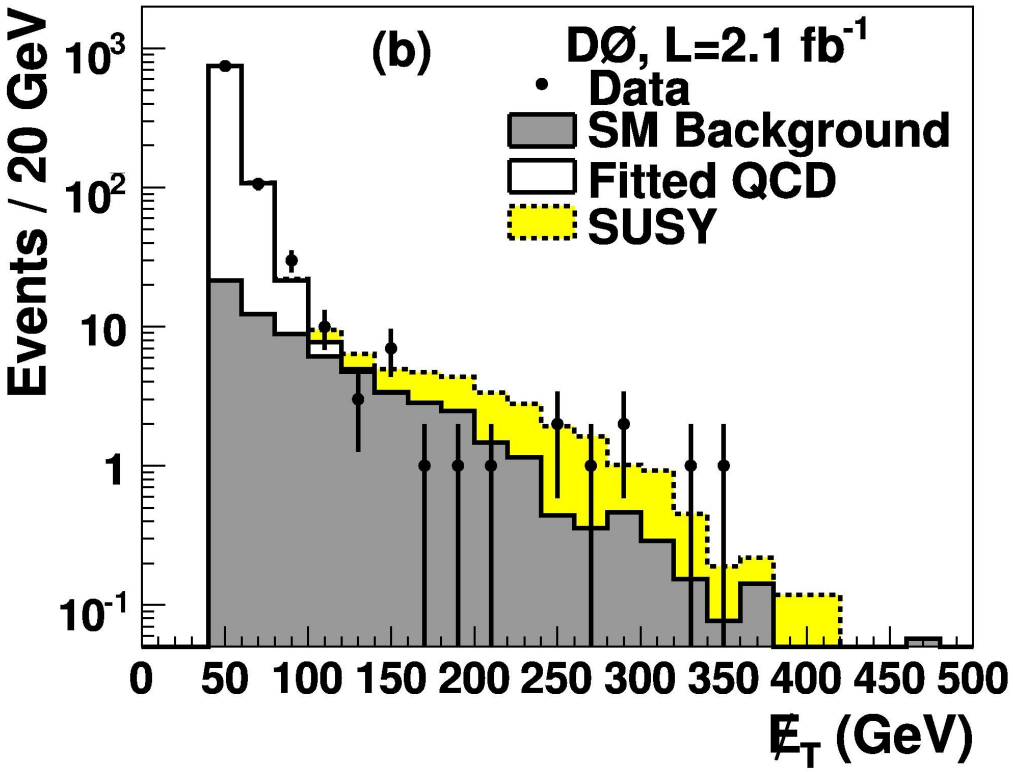


A nice Candidate Event!







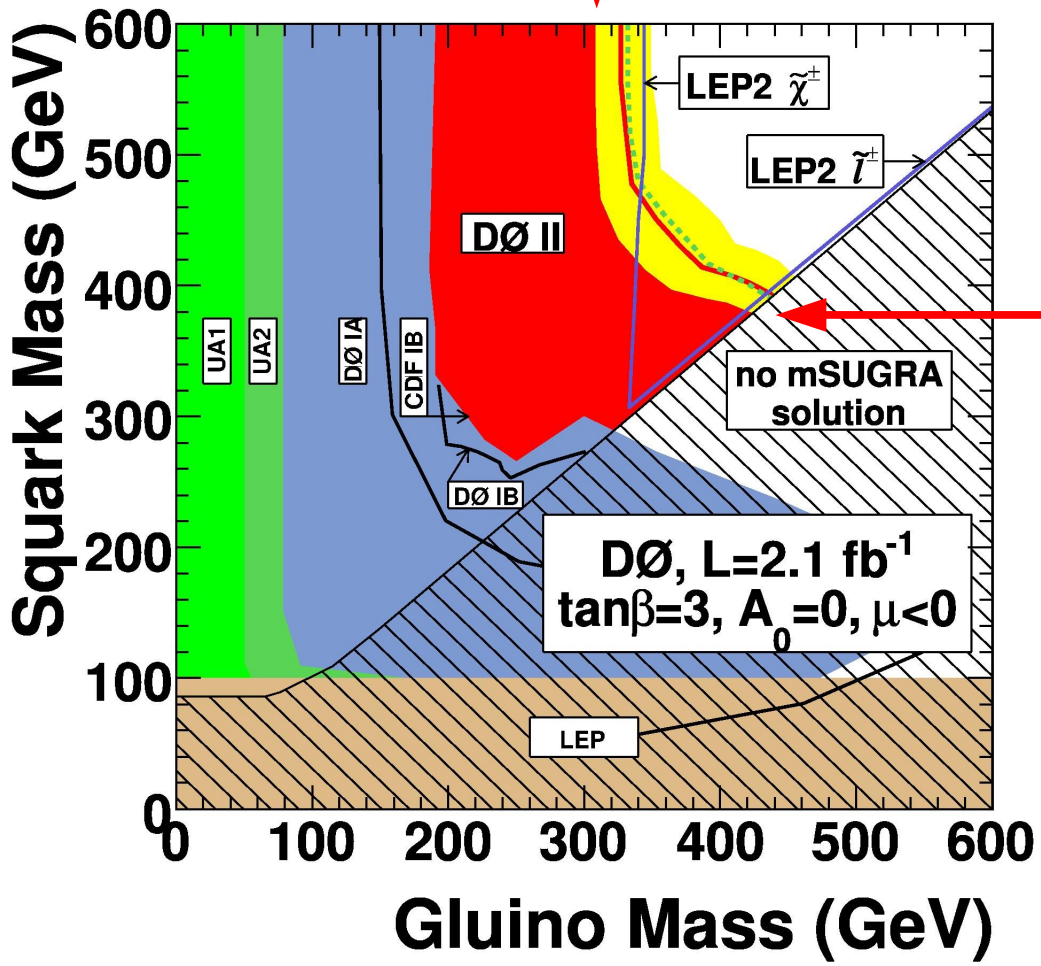


→ **but there is no clear signal...**

SUSY Breaking Mechanism: mSUGRA

$M_{\tilde{g}} > 308$ GeV

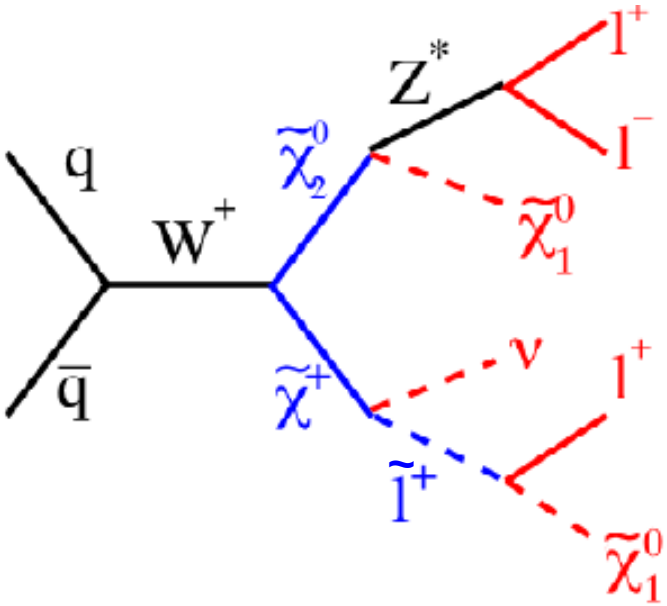
at 95% C.L.

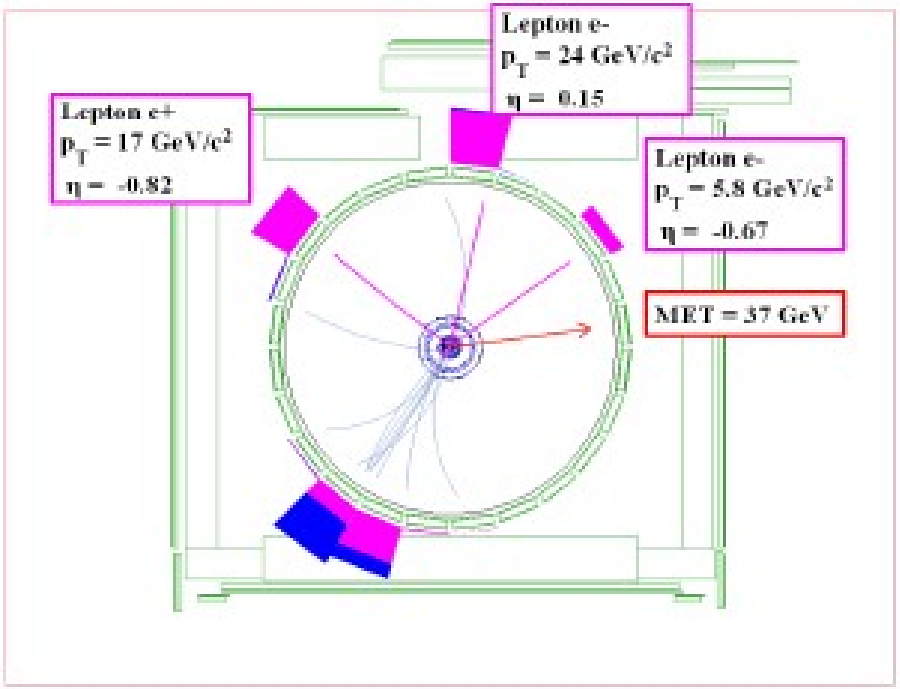


$M_{\tilde{q}} > 379$ GeV

at 95% C.L.

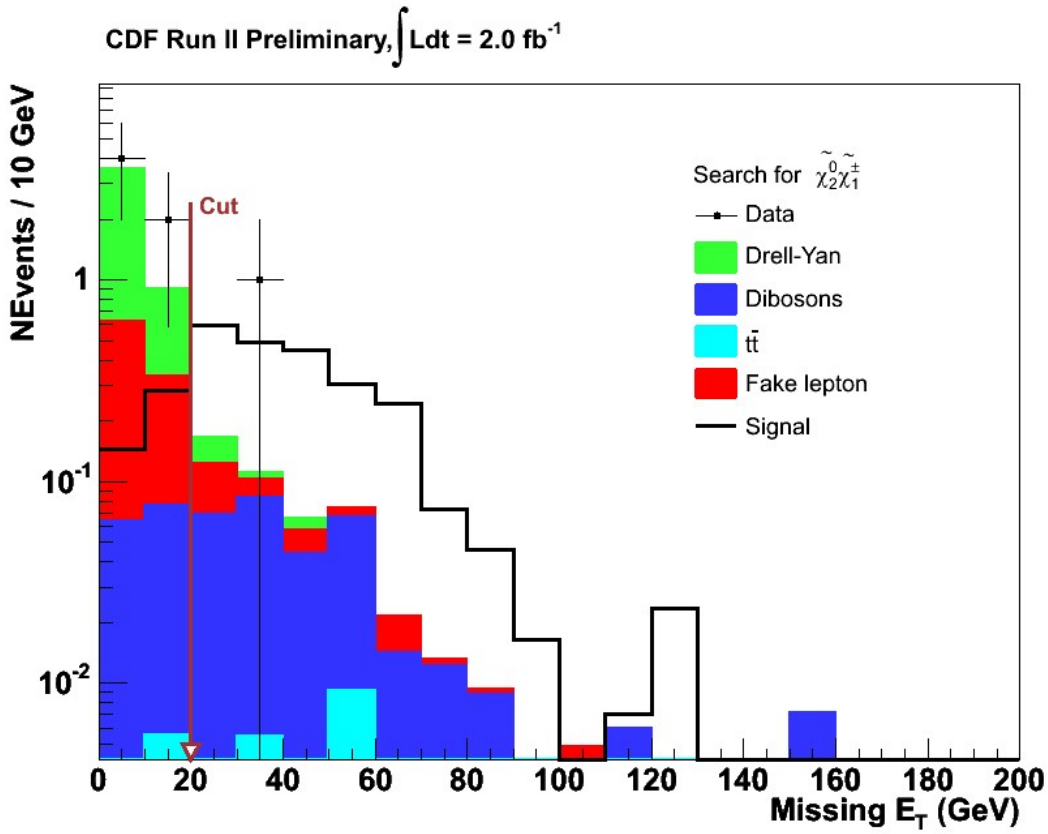
Trilepton Events: Another Look for SUSY





- **search for SUSY partners of W, Z, γ and Higgs bosons**
  - decaying via leptons
- **signal:**
  - 3 leptons and missing ET
- **very promising avenue to observe SUSY events**
  - jets are abundant at hadron colliders, leptons are rare...

Trilepton Data



- ~11 SUSY events expected for investigated mSUGRA scenario
- 7 events observed which is consistent with 6.6 expected in SM

→ exclude chargino masses up to 145 GeV at 95% C.L.

Conclusions

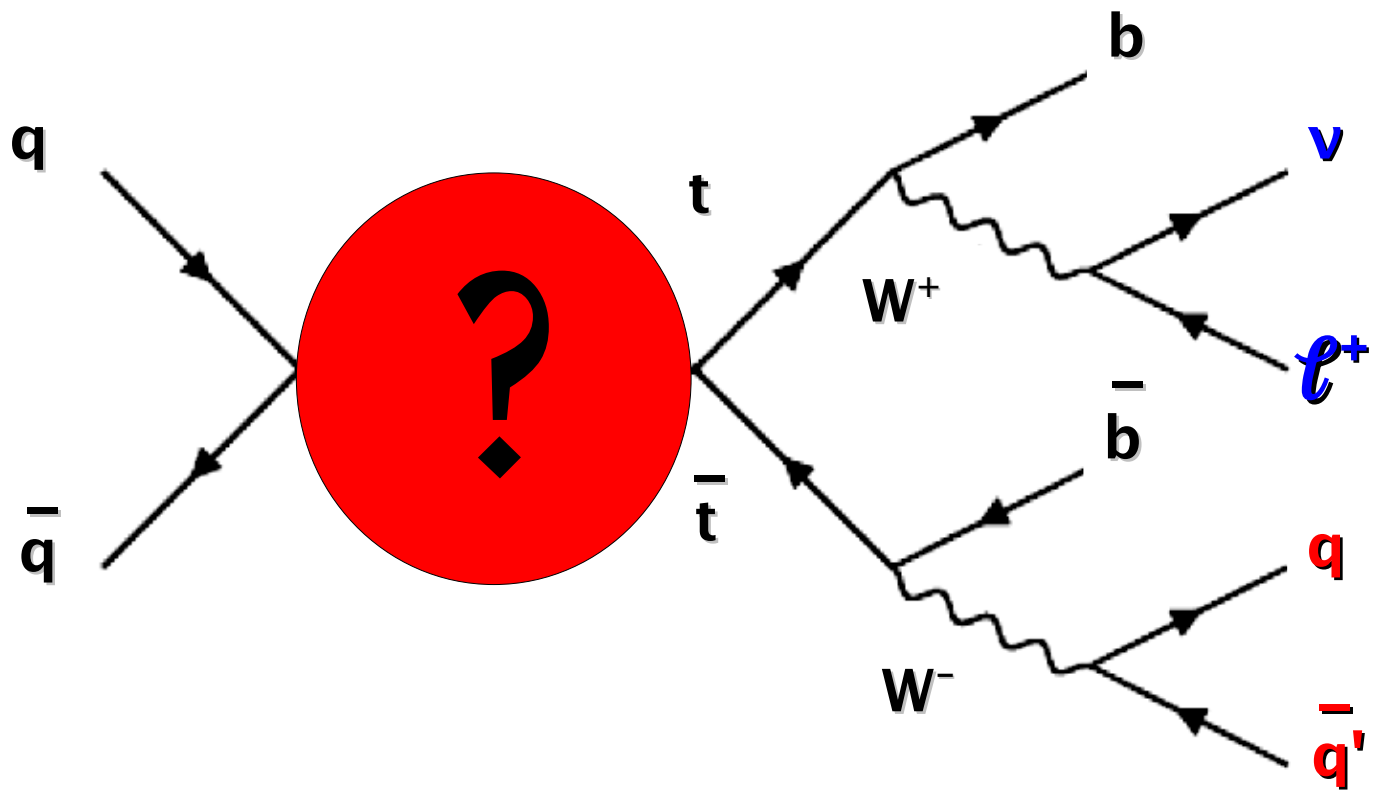
- very powerful tests of QCD
  - jet cross sections agree with NLO QCD over 9 orders of magnitude
  - strong coupling measured with 4% precision
- top quark physics
  - high precision measurements, many channels analysed
  - mass known with 0.6% uncertainties
  - other properties such as spin accessible for first time
- single top observation + direct measurement of V_{tb}
- searches for new physics: no hint yet but more data and better analysis techniques to come...
- all the results on the web:

CDF: http://www-cdf.fnal.gov/physics/preprints/index.html
and http://www-cdf.fnal.gov/physics/physics.html

D0: http://www-d0.fnal.gov/d0_publications/
and http://www-d0.fnal.gov/Run2Physics/WWW/results.htm

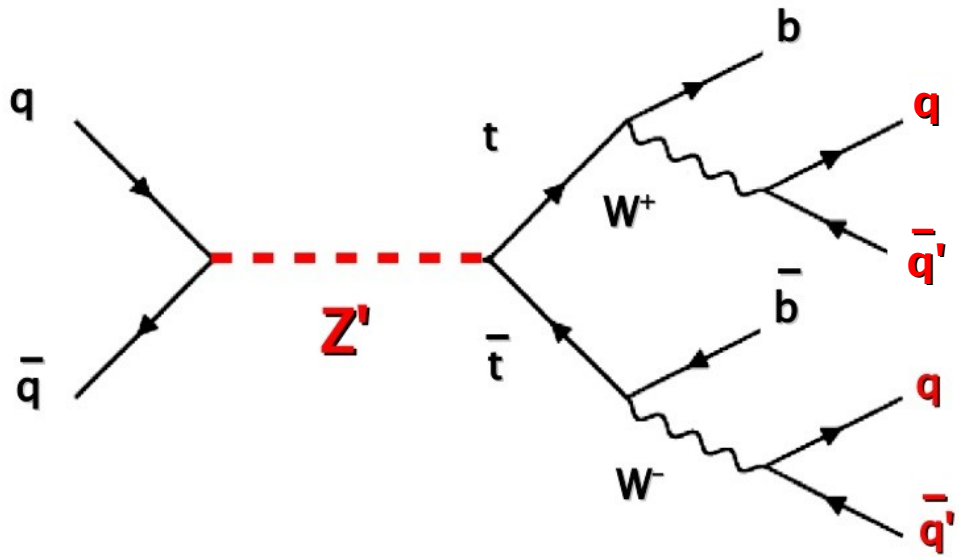
Backup

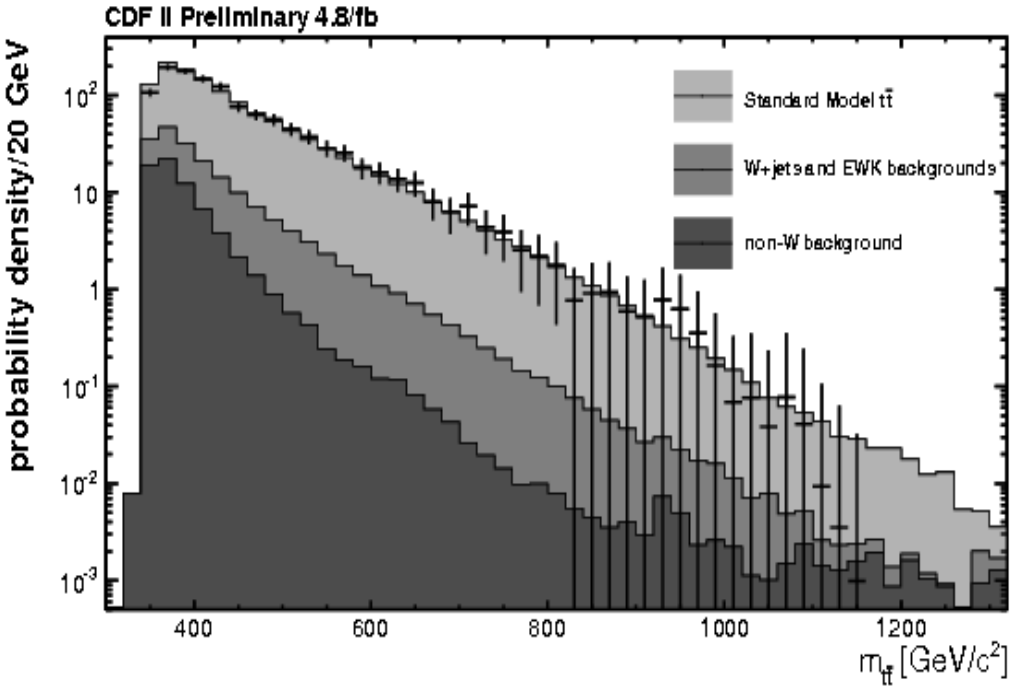
Search for New Physics in Top Production



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





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

l+jets, 3.6 fb^{-1}

$M_{Z'} > 820$ GeV

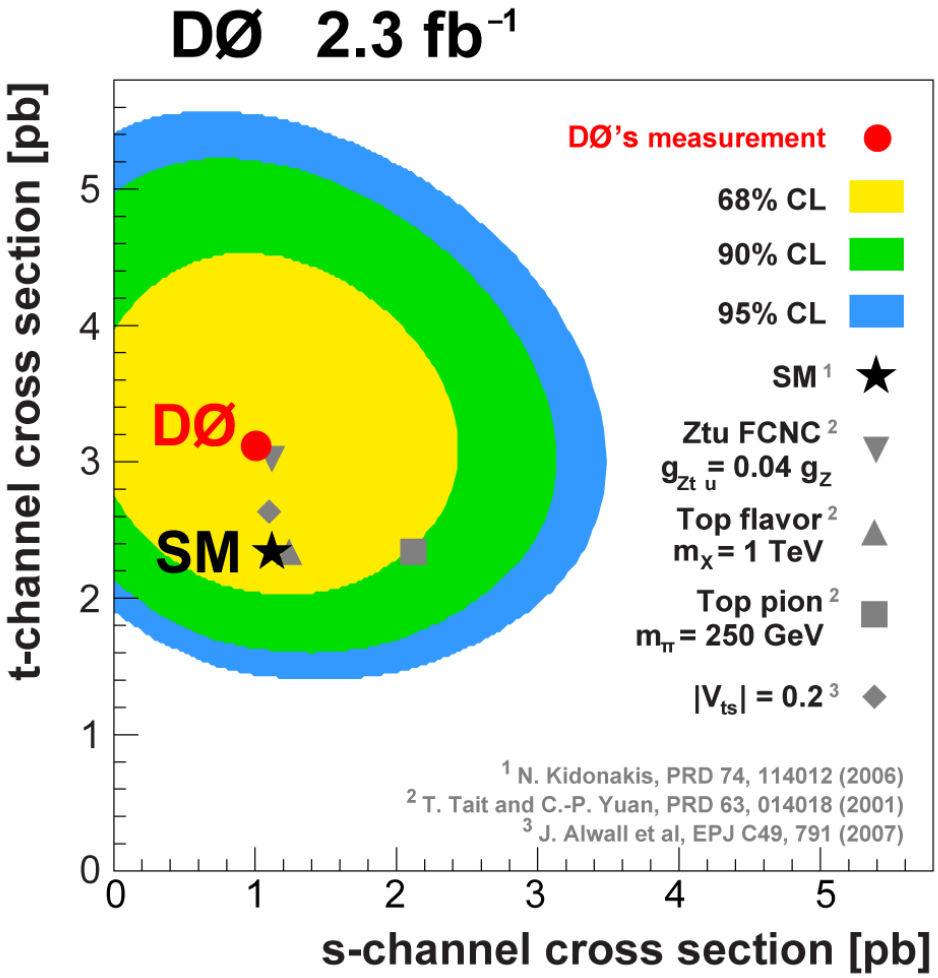
l+jets, 4.8 fb^{-1}

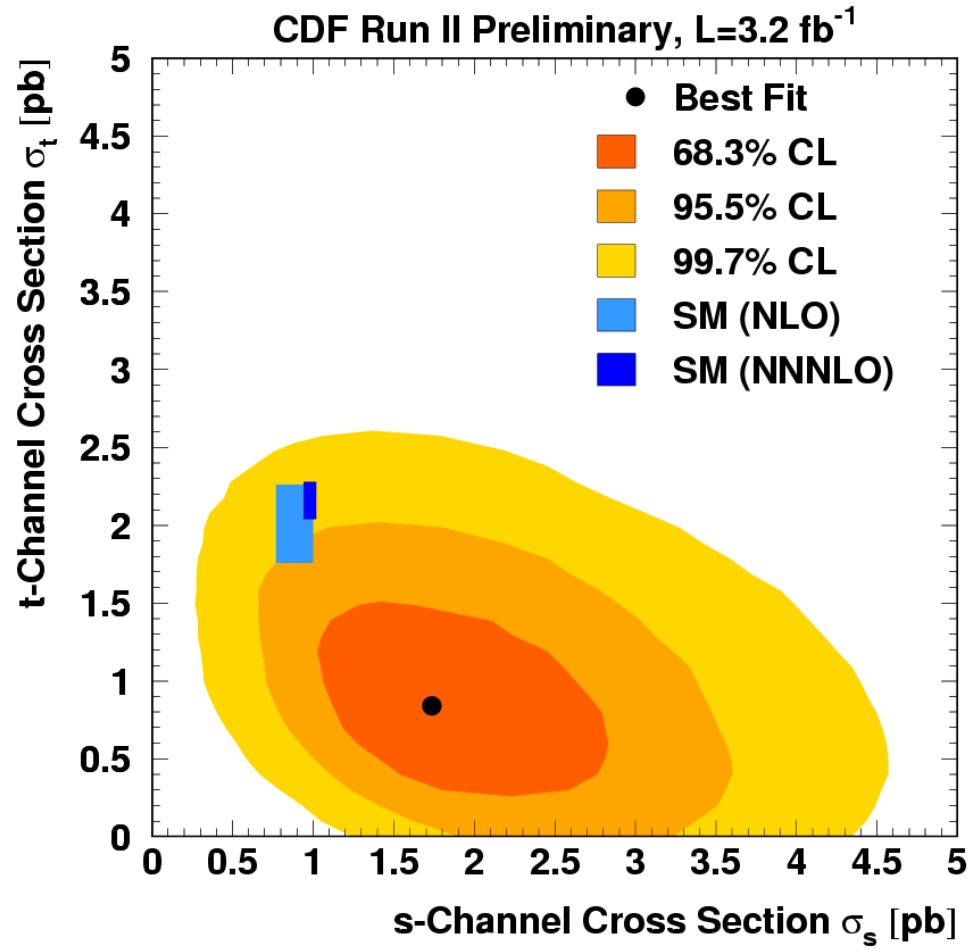
$M_{Z'} > 9??$ GeV

t-channel vs. s-channel

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

evidence with 4.8σ





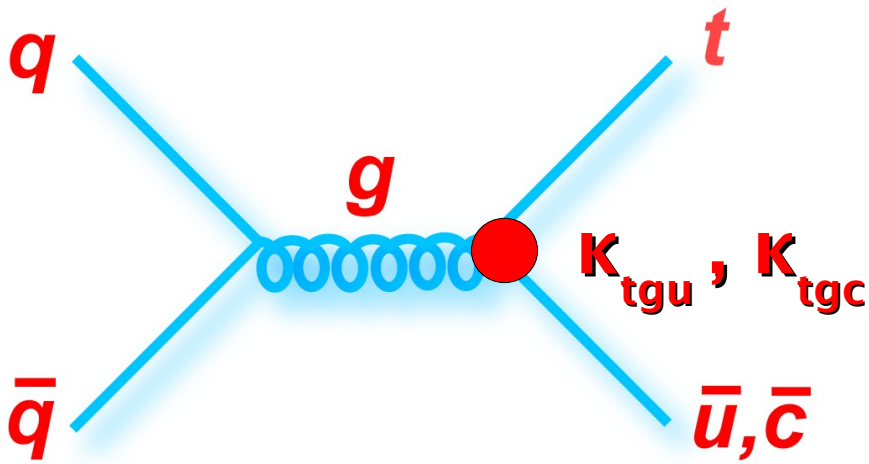
⇒ **good agreement with SM prediction**

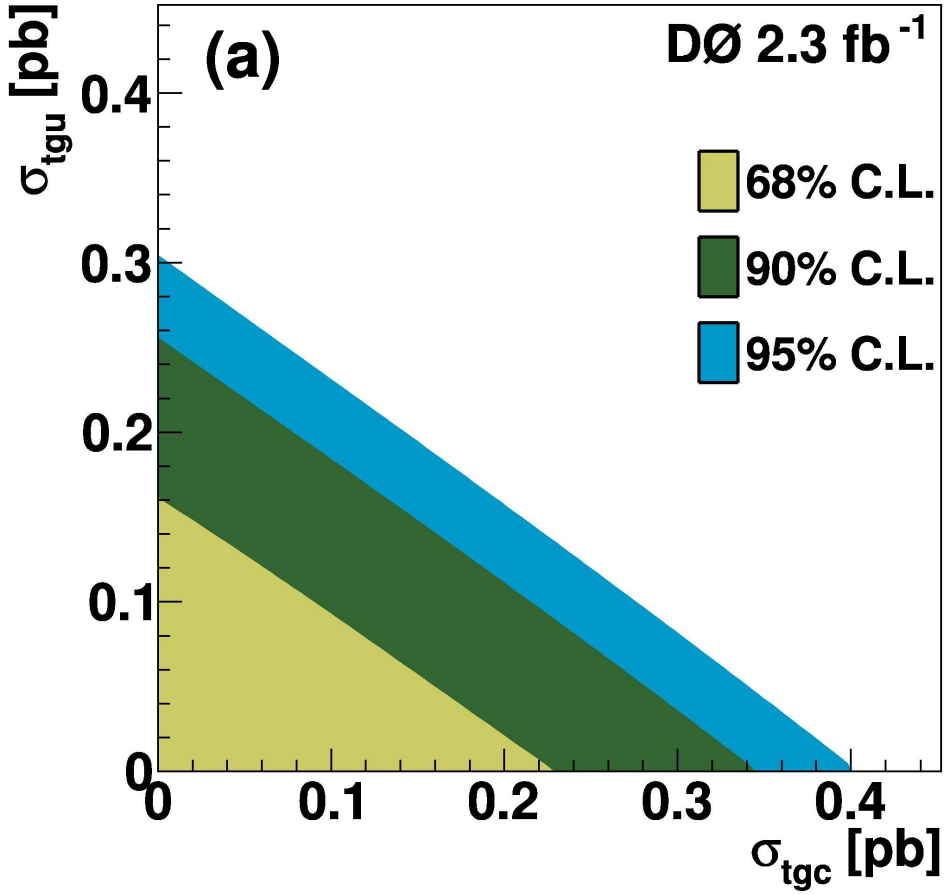
Conclusions

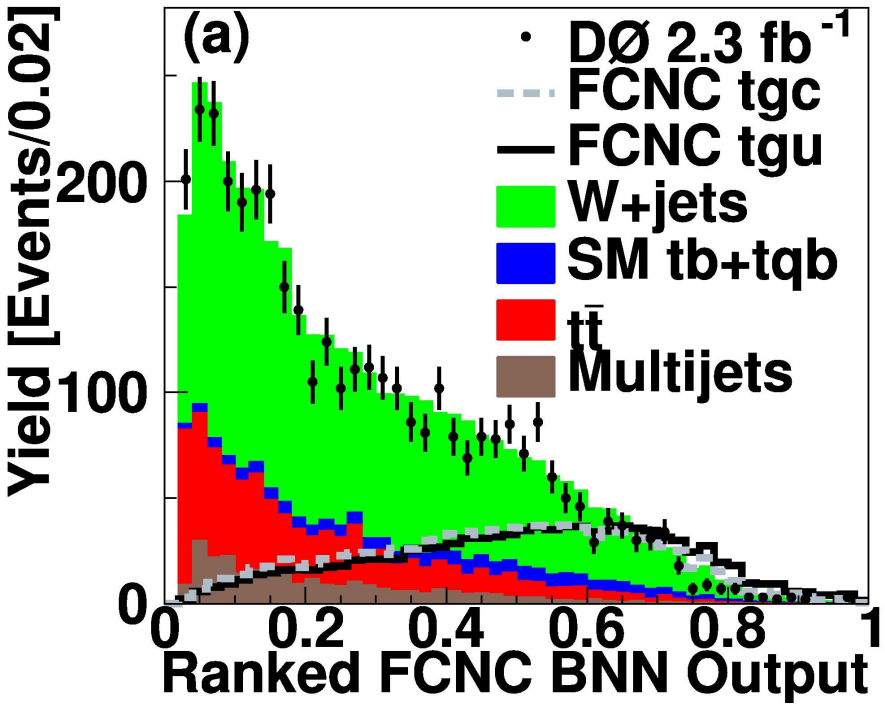
Highlights of top quark physics:

- top pair production
  6% precision, many channels analyses, differential cross section, all good agreement with NLO QCD predictions
- single top observation + direct measurement of V_{tb}
- precision measurements (see next talk)
  top mass with 0.75% uncertainty
- top properties (see next talk)
  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

Flavor Changing Neutral Currents







$\kappa_{tgu}/\Lambda < 0.013$ TeV^{-1}

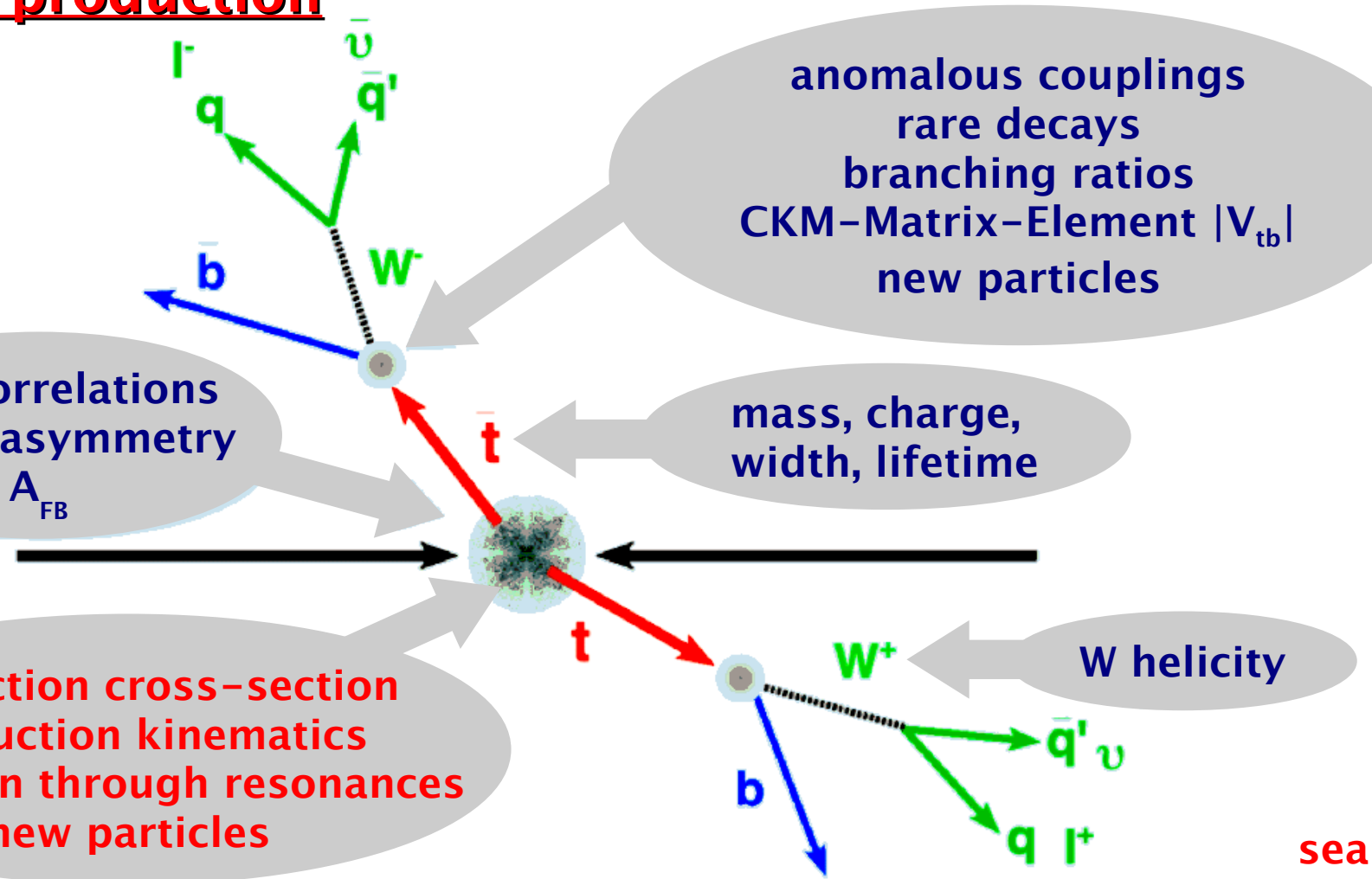
$\kappa_{tgc}/\Lambda < 0.057$ TeV^{-1}

at 95% C.L.

Top Quark Analyses at the Tevatron

analyses with up to 5 fb^{-1} of data:
several thousand top candidate events per experiment

top pair production



anomalous couplings
rare decays
branching ratios
CKM-Matrix-Element $|V_{tb}|$
new particles

spin correlations
charge asymmetry
A_{FB}

mass, charge,
width, lifetime

W helicity

production cross-section
production kinematics
production through resonances
new particles

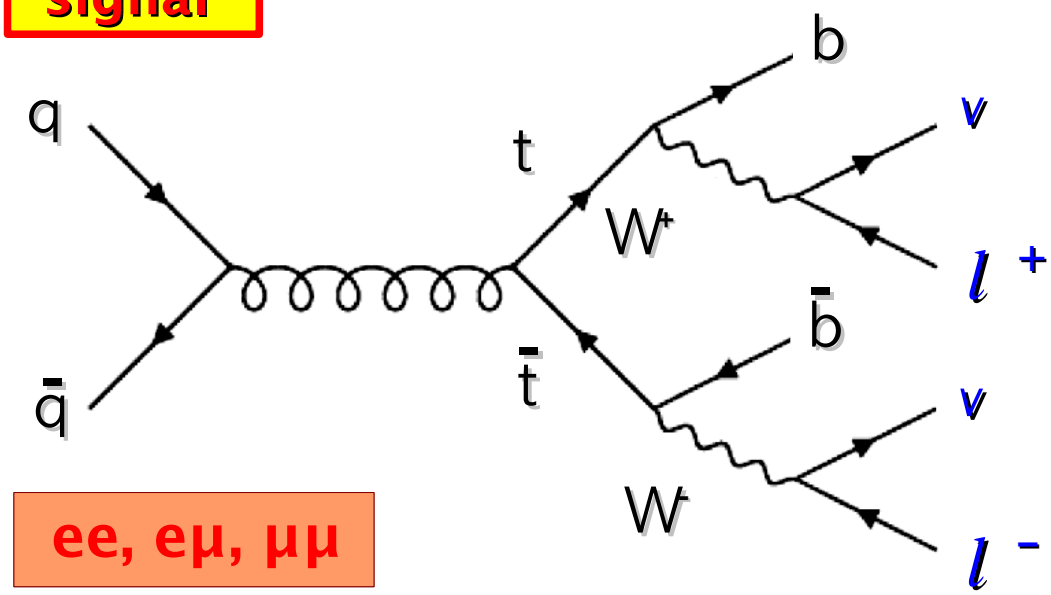
single top production

observation by CDF and DØ!

searches
for new
particles

Dilepton Signatures

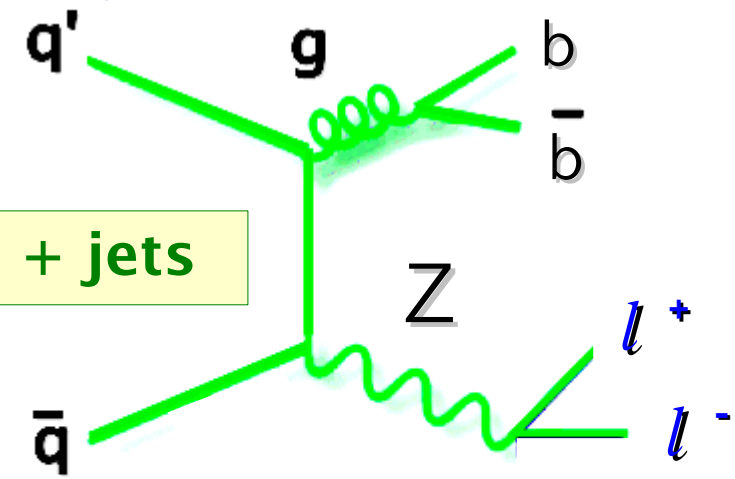
signal



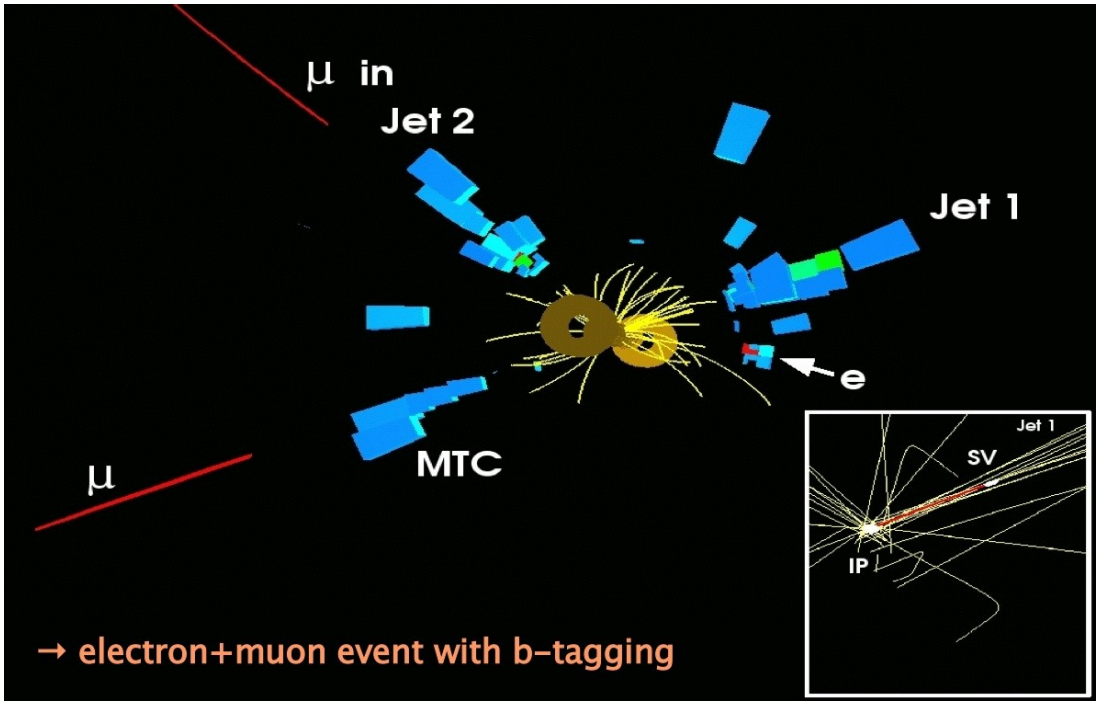
ee, eμ, μμ

background

300 times higher rate



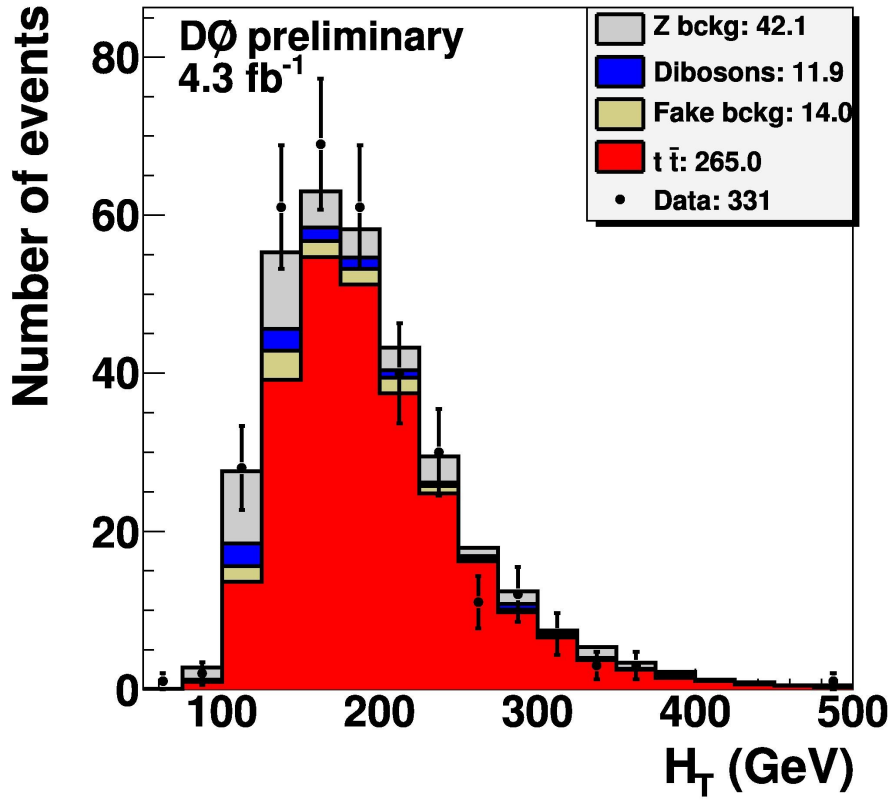
Z + jets



- less statistics
- less background

Top Pair Production Cross Section

topological information

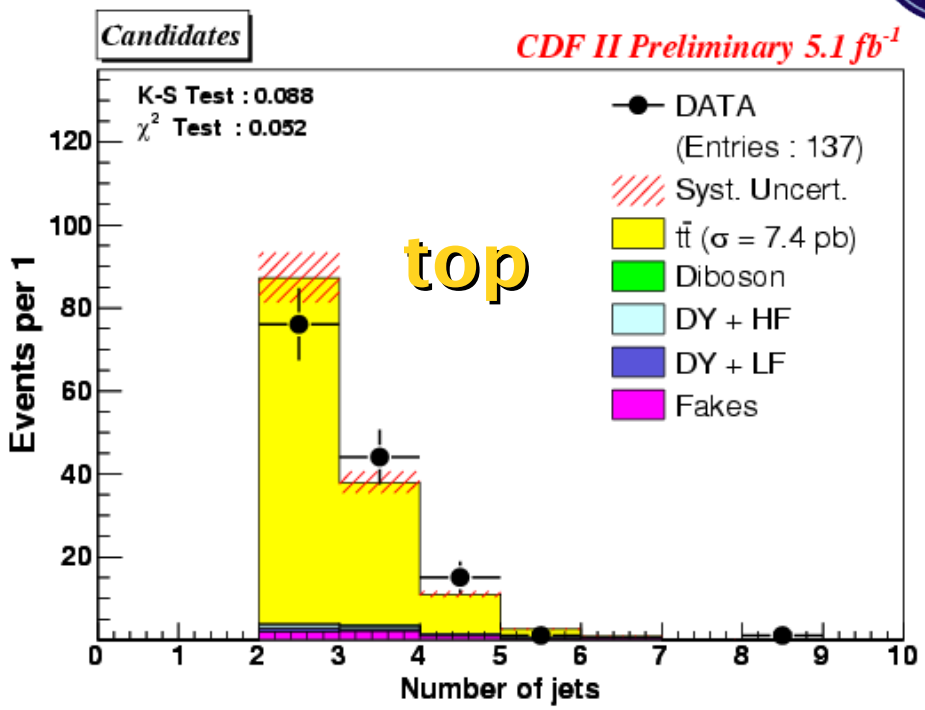


$\sigma_{t\bar{t}}$ = 8.23 ± 0.52 (stat) ± 0.83 (syst) ± 0.61 (luminosity) pb

m_{top} = 172.5 GeV

±13%

b-tagging



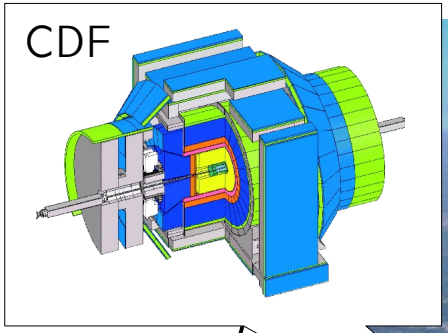
$\sigma_{t\bar{t}}$ = 7.25 ± 0.66 (stat) ± 0.47 (syst) ± 0.44 (luminosity) pb

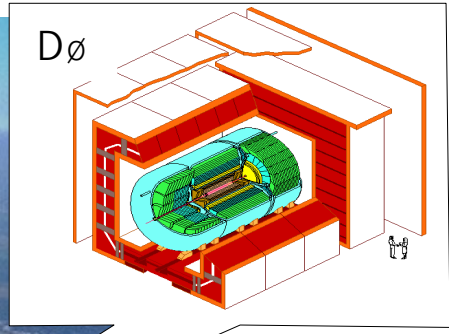
m_{top} = 172.5 GeV

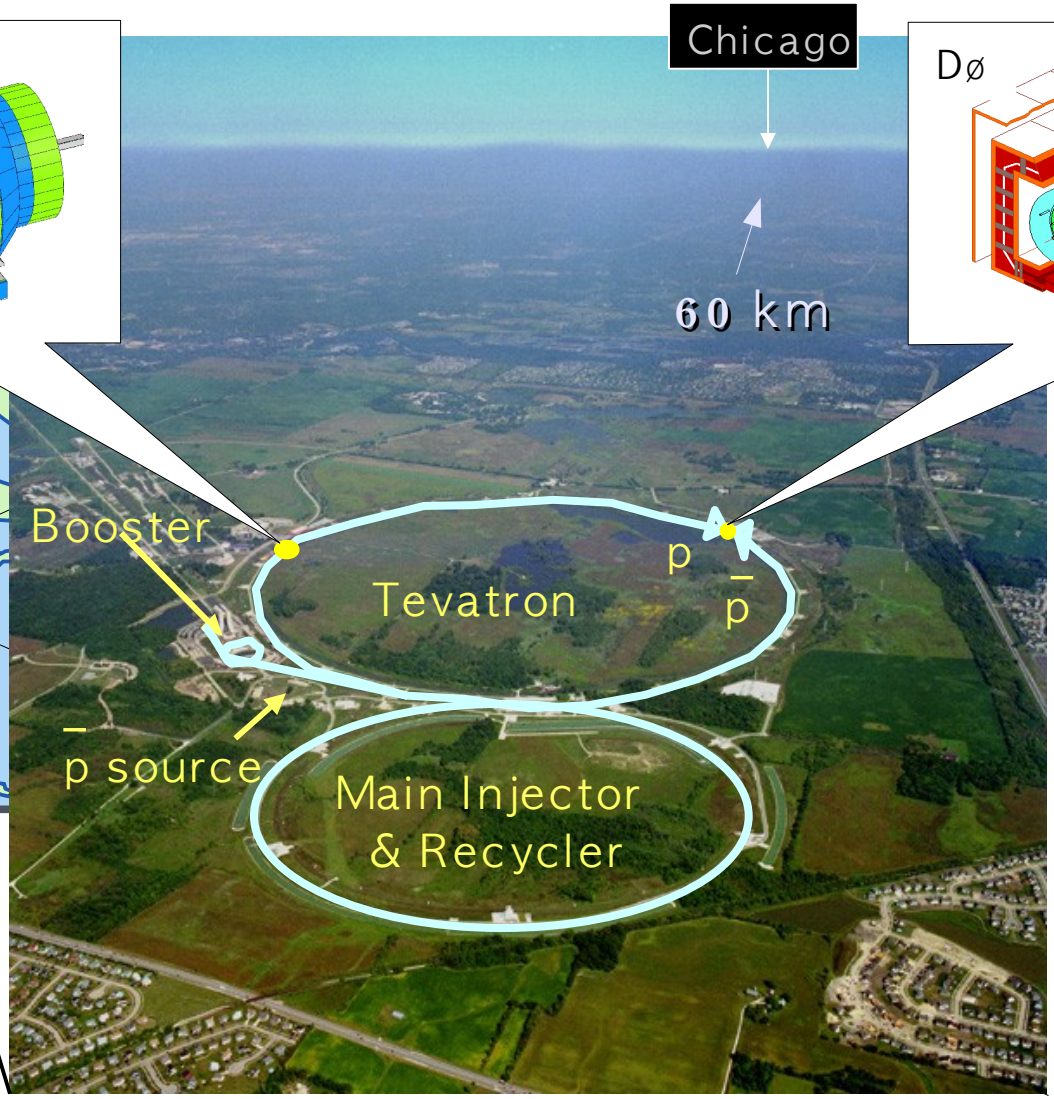
±13%

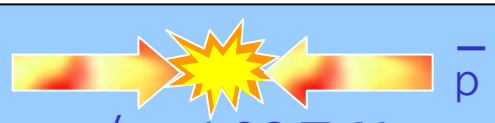
achieving good precision (~340 events)

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









$\sqrt{s}$ = 1.96 TeV

Δt = 396 ns

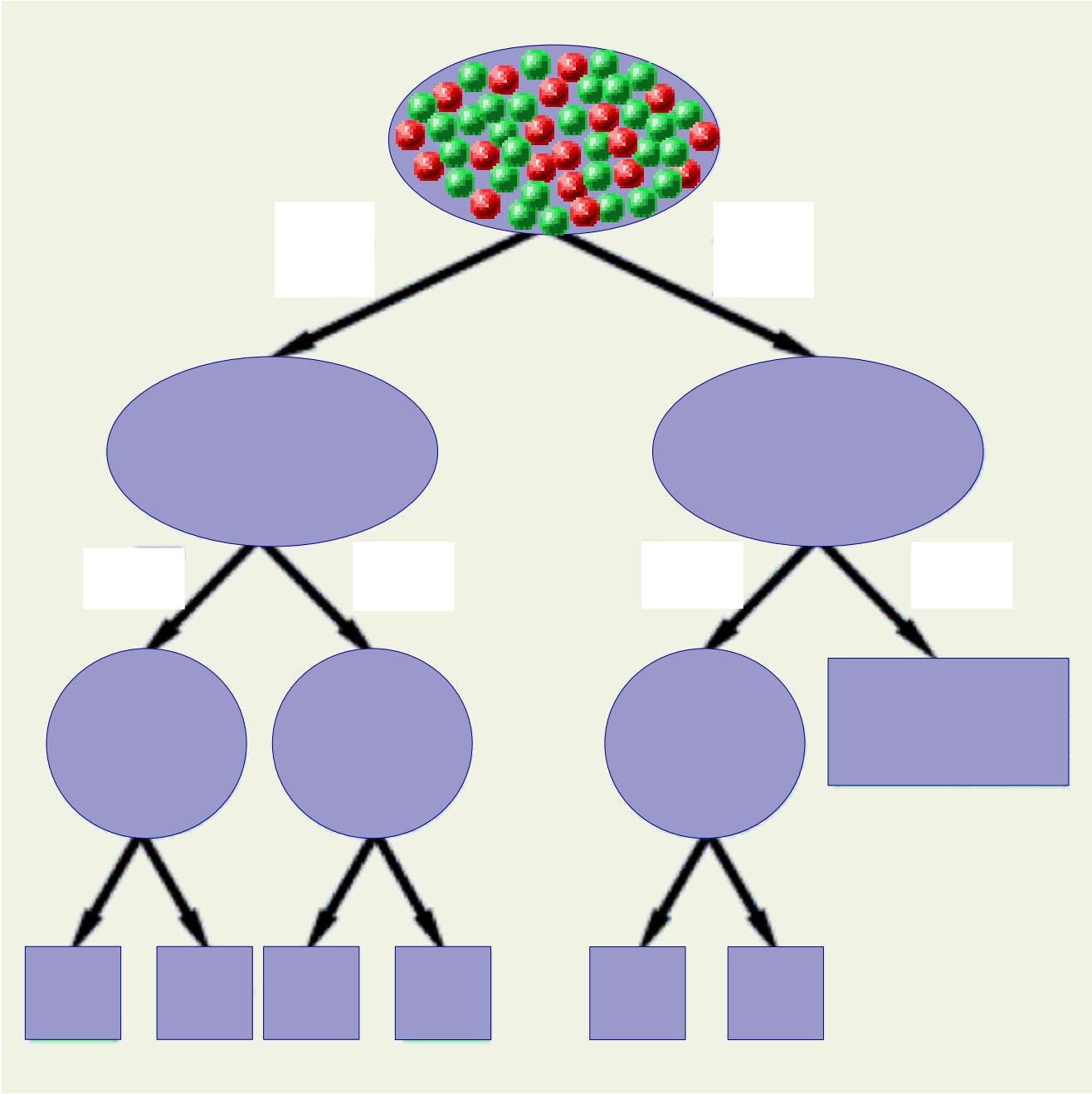
Run I 1987 (92)-95: 125 pb^{-1}

Run II 2001-11: ~100x larger dataset at increased energy

top quark discovery

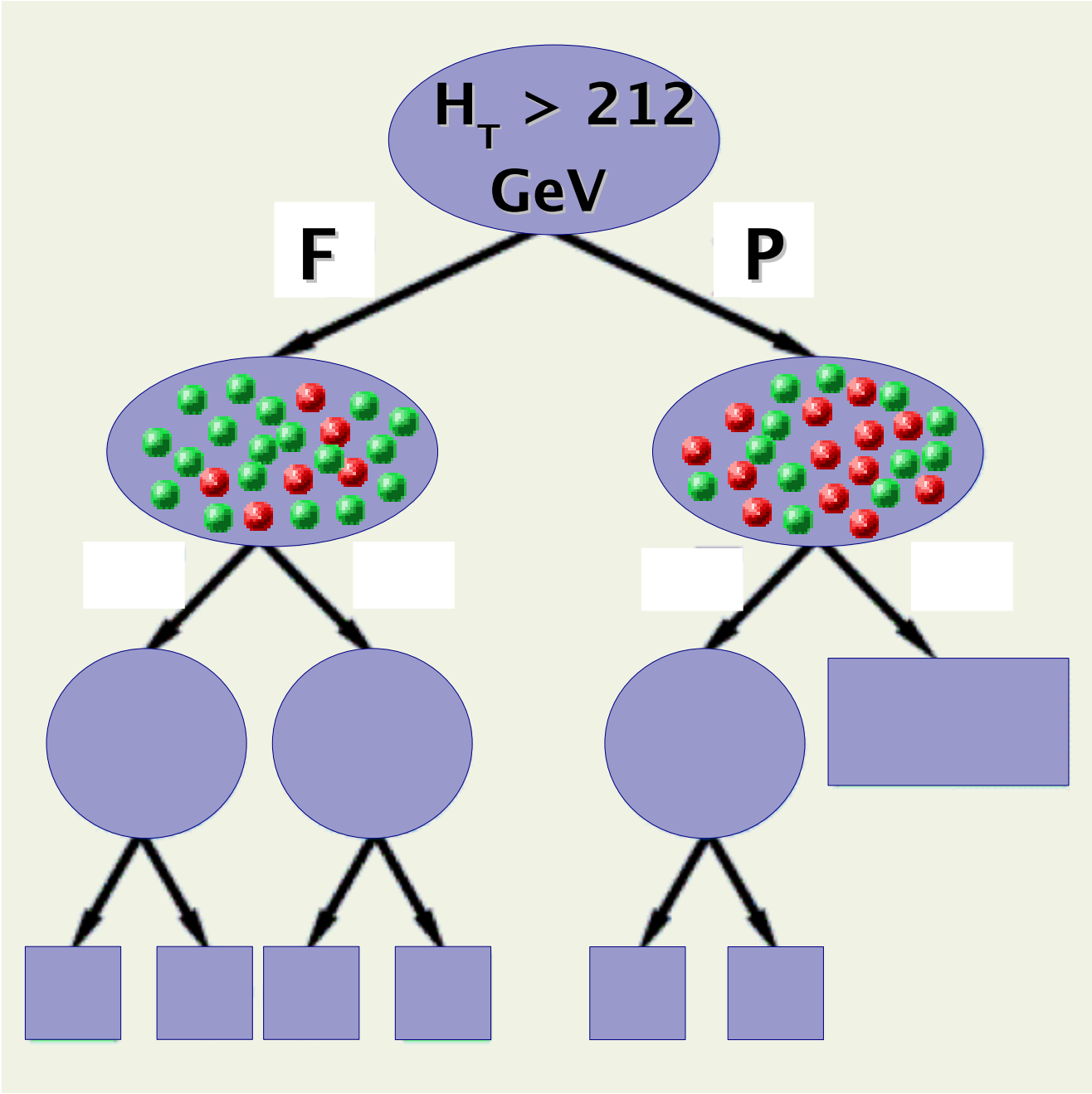
measure properties with high precisions: is it really the particle expected in the SM?

Boosted Decision Trees



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

Boosted Decision Trees



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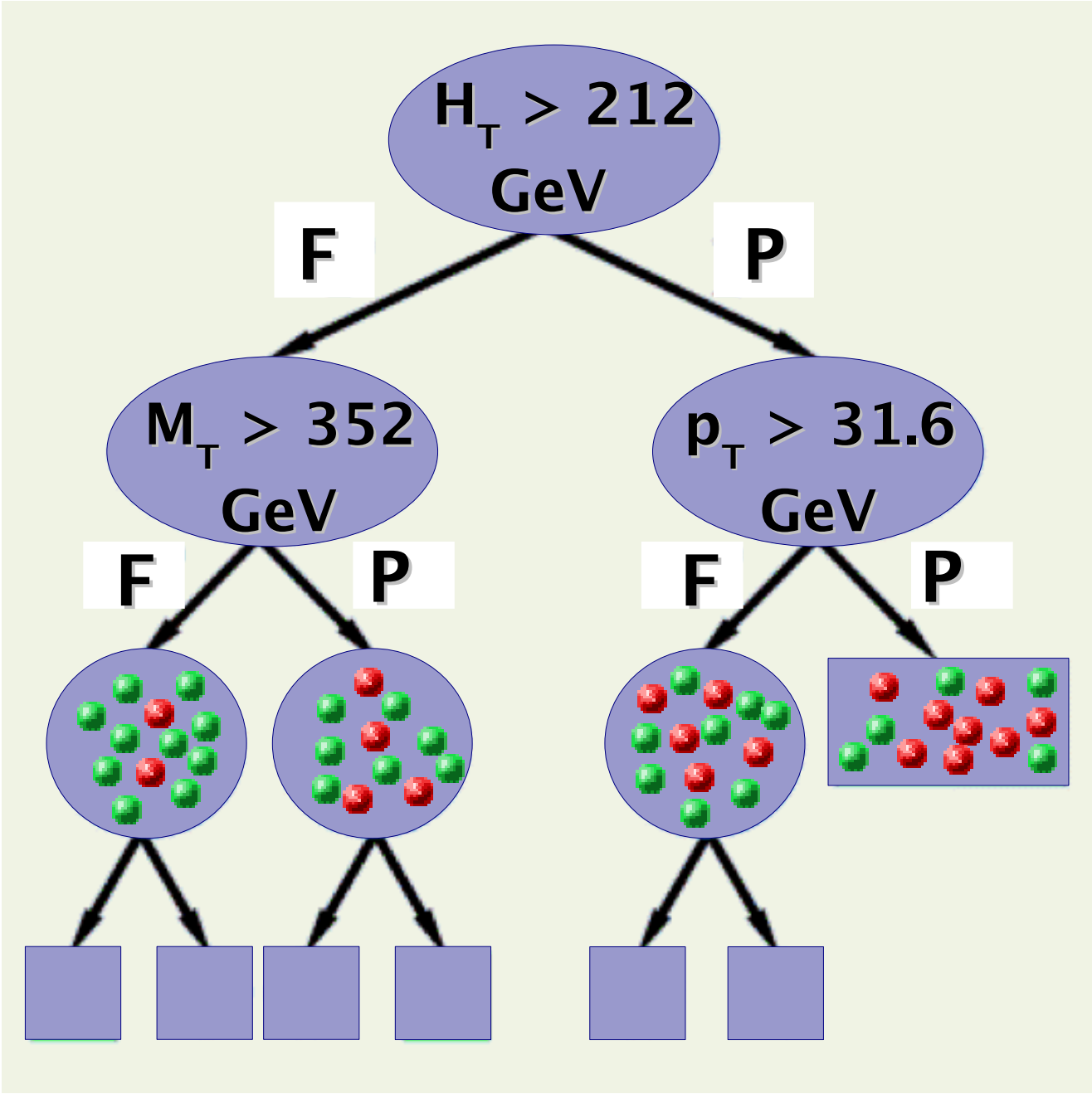

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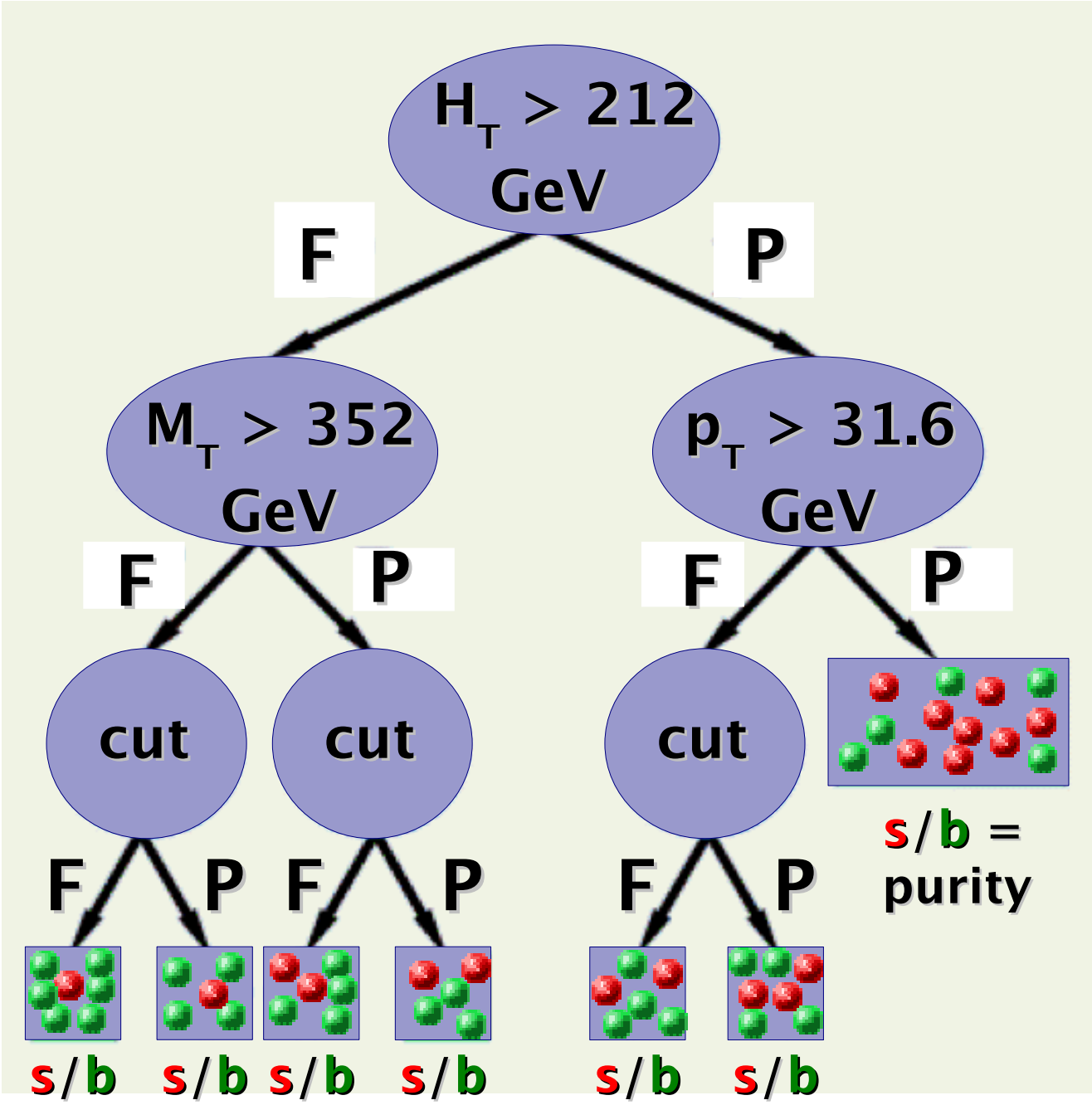
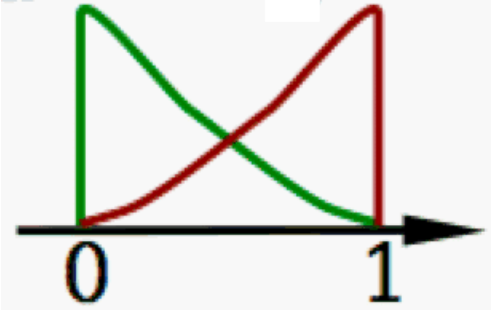


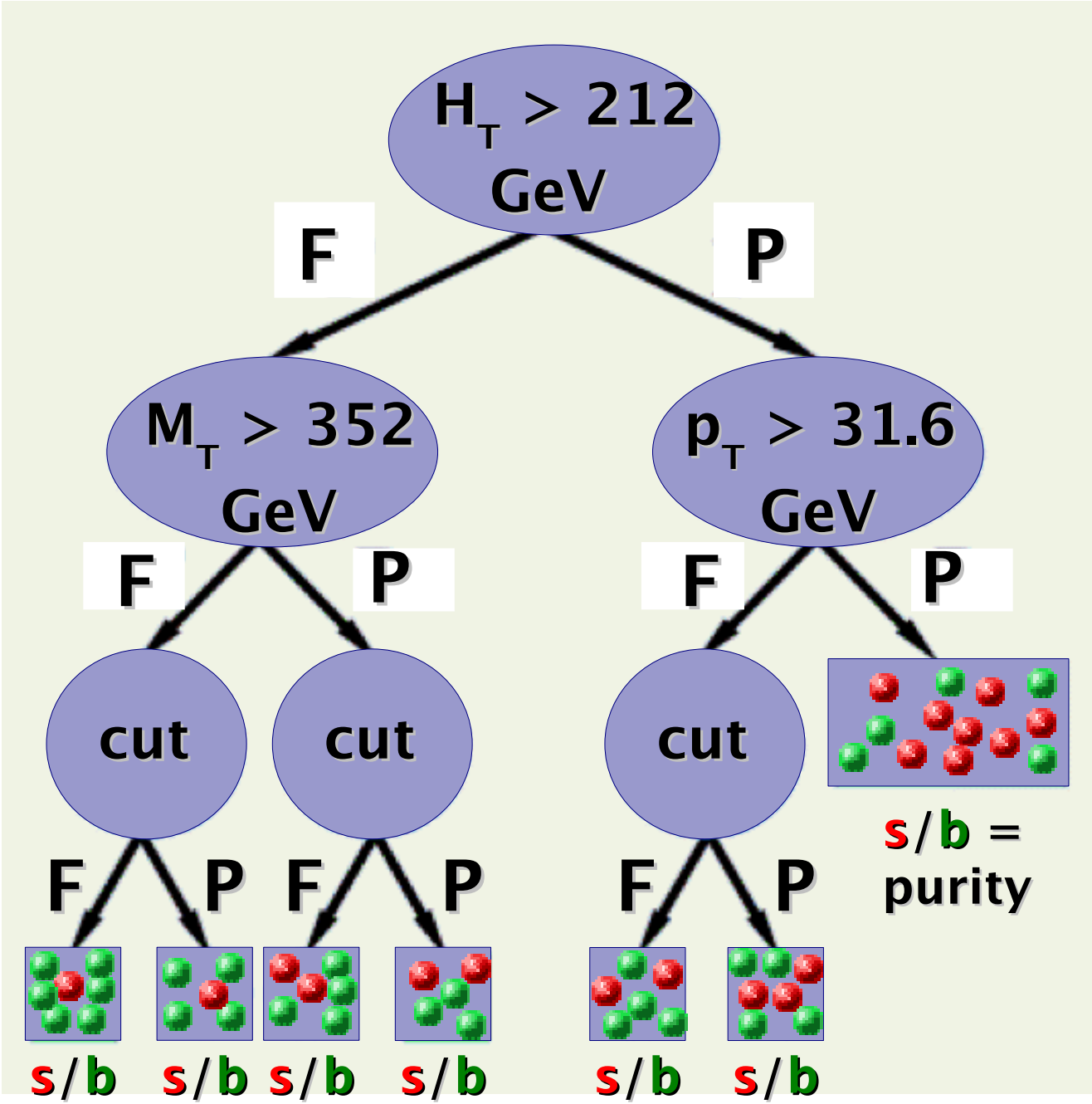
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background **signal**



Boosted Decision Trees

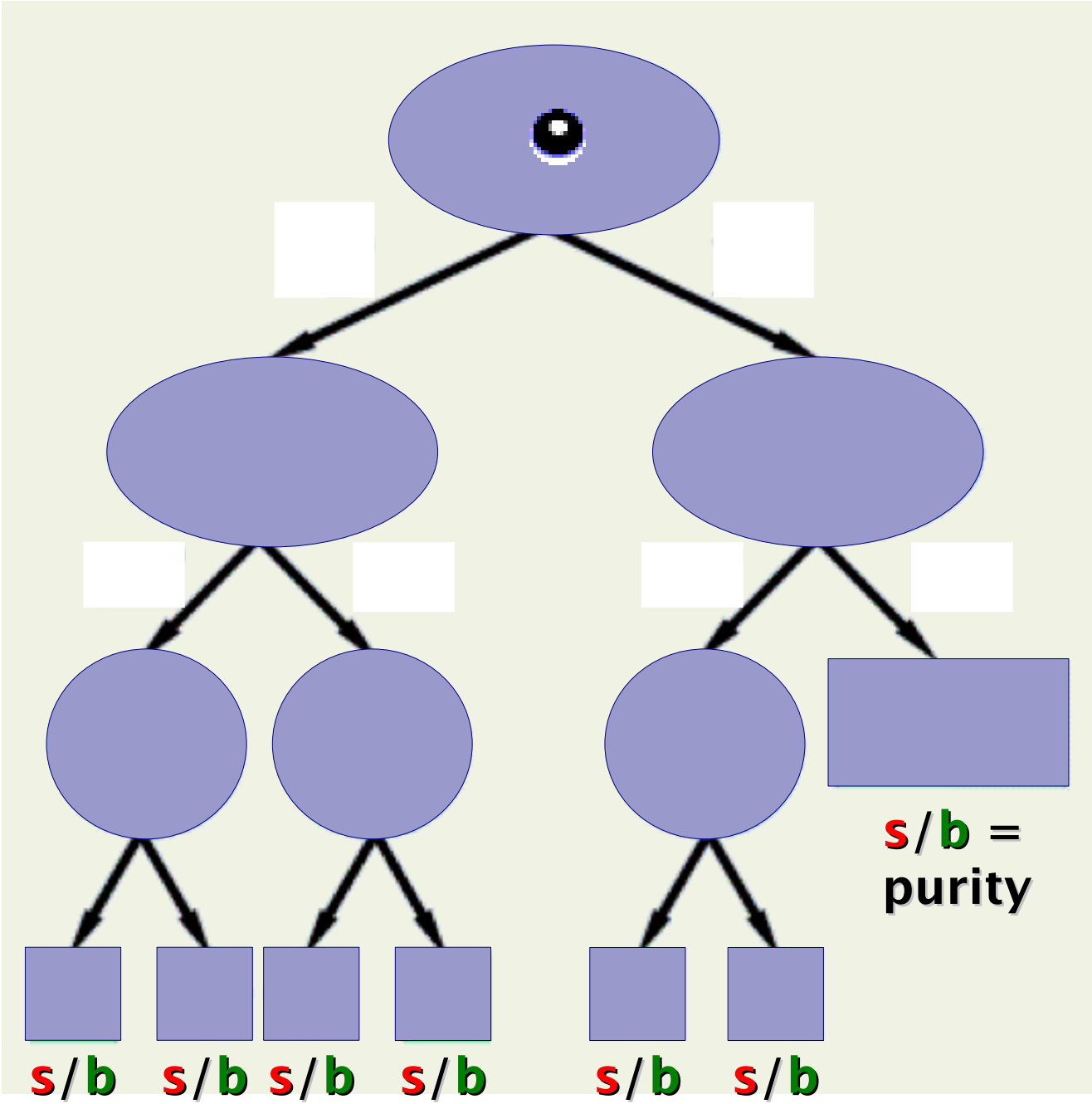


- **IDEA: recover events that fail criteria in cut-based analyses**

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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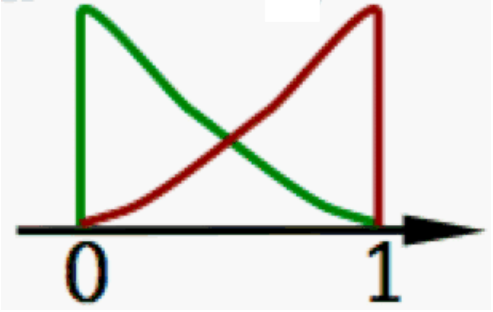
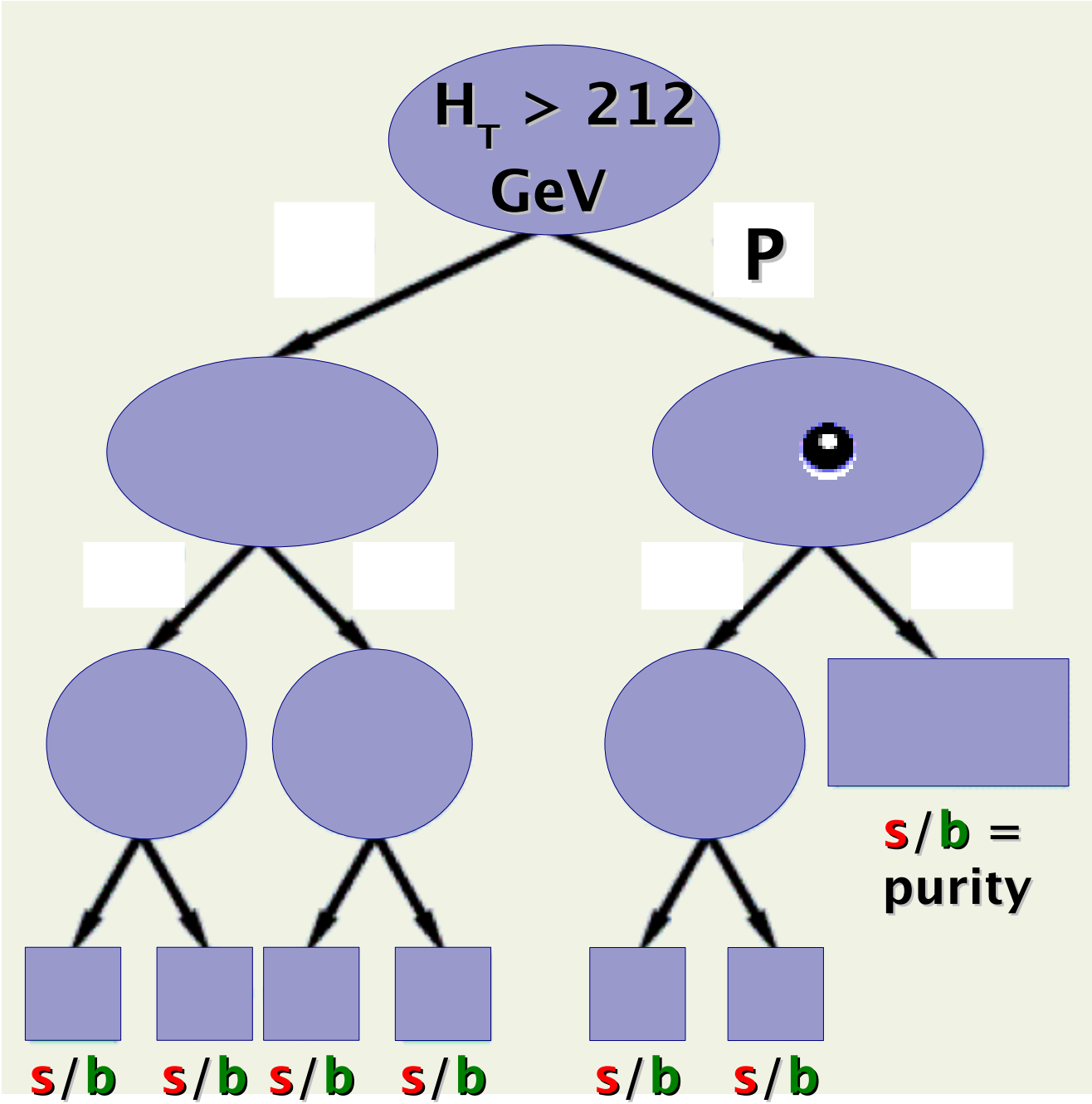


Boosted Decision Trees



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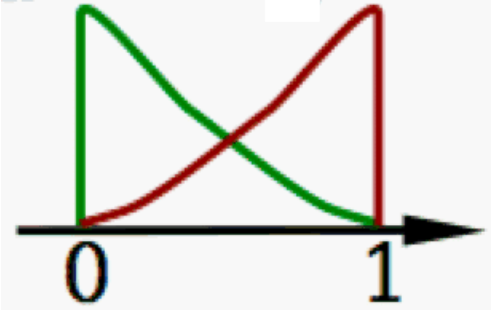
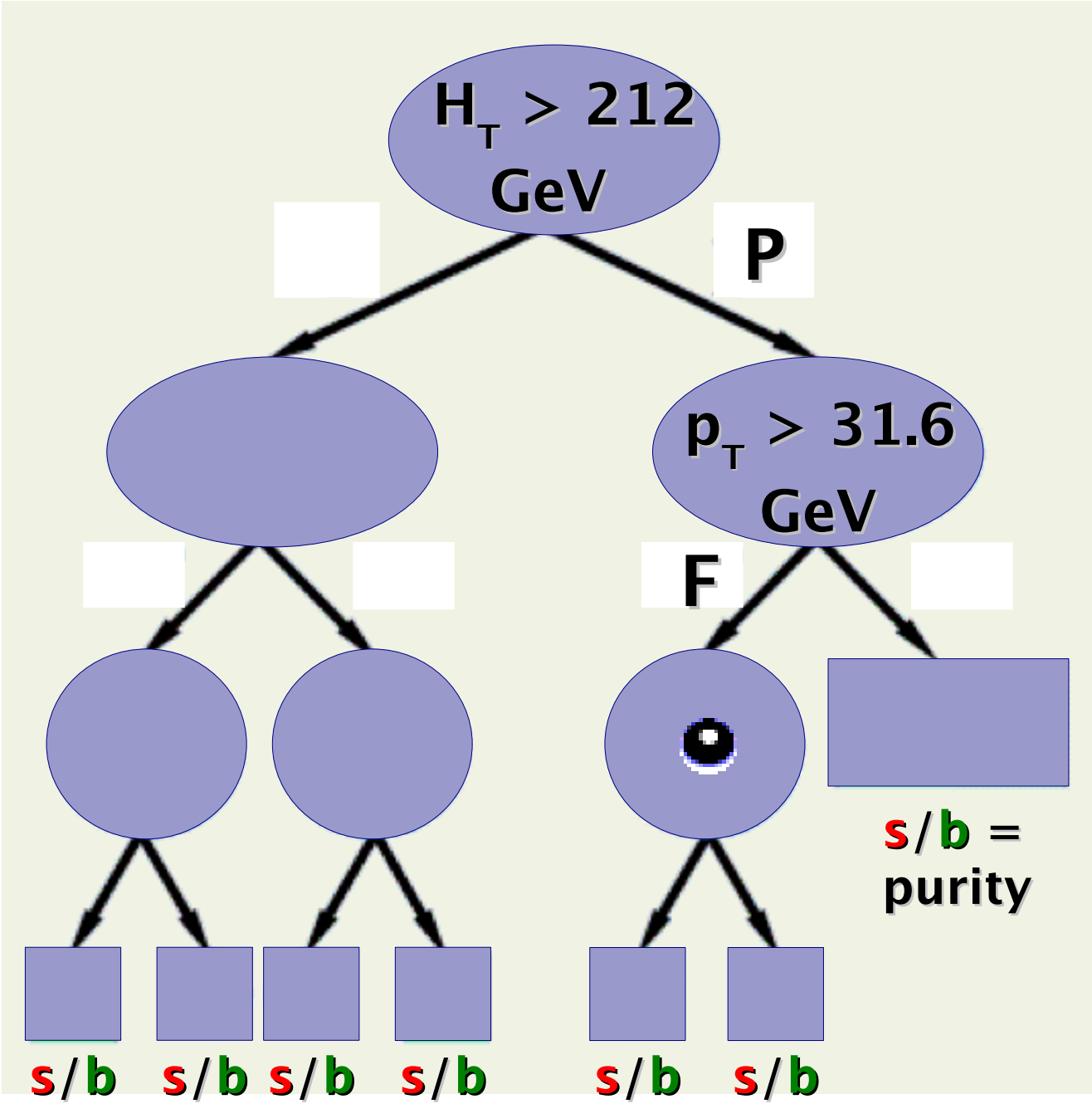


Boosted Decision Trees



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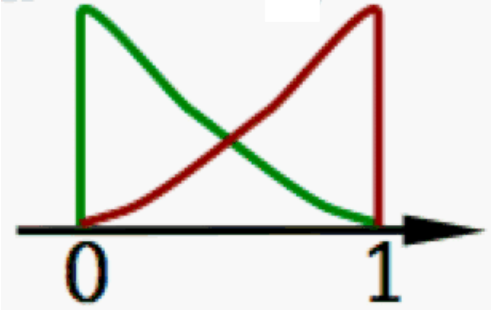
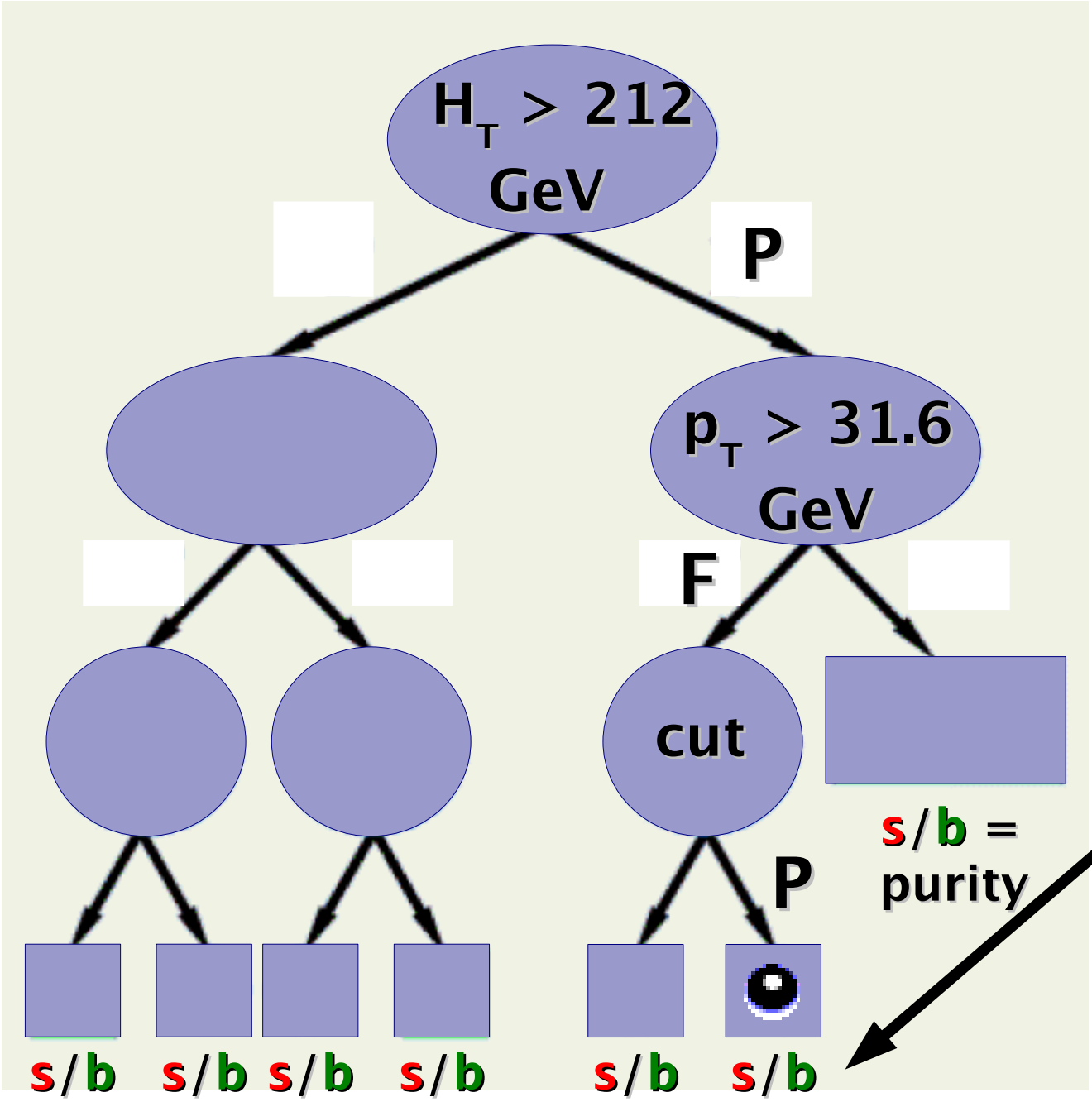
background **signal**



Boosted Decision Trees



- **IDEA: recover events that fail criteria in cut-based analyses**
- **result: weight for every event**