# SM+Higgs at Hadron Colliders

Christian Schwanenberger

University of Manchester

Hadron Collider Physics Summer School
CERN
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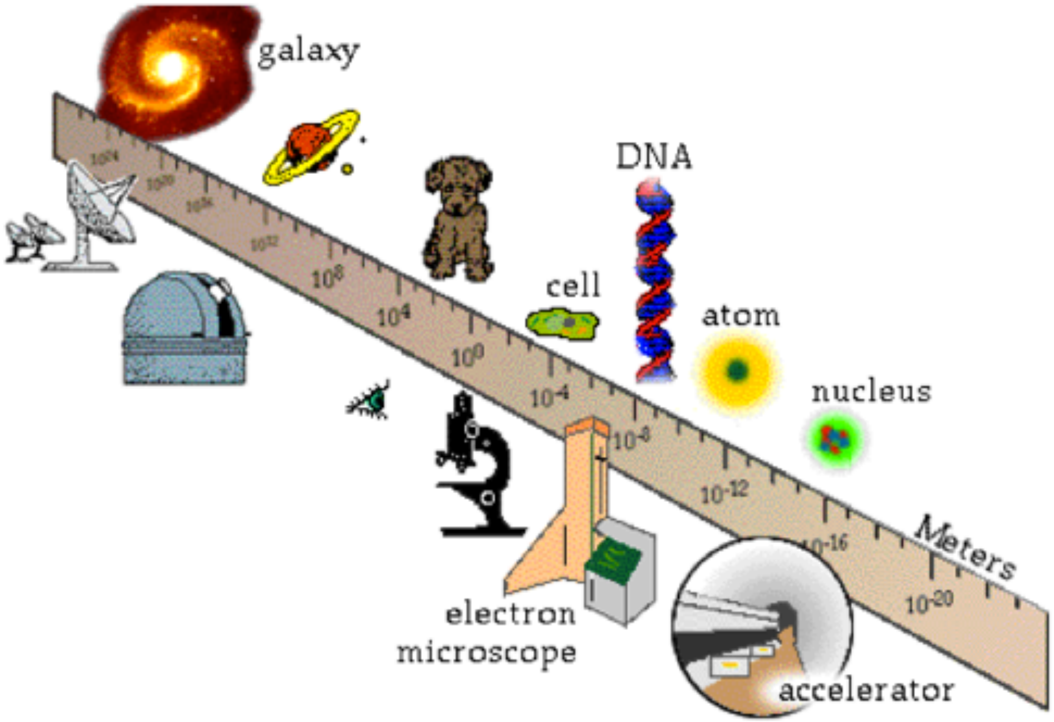
# Objective of Elementary Particle Physics

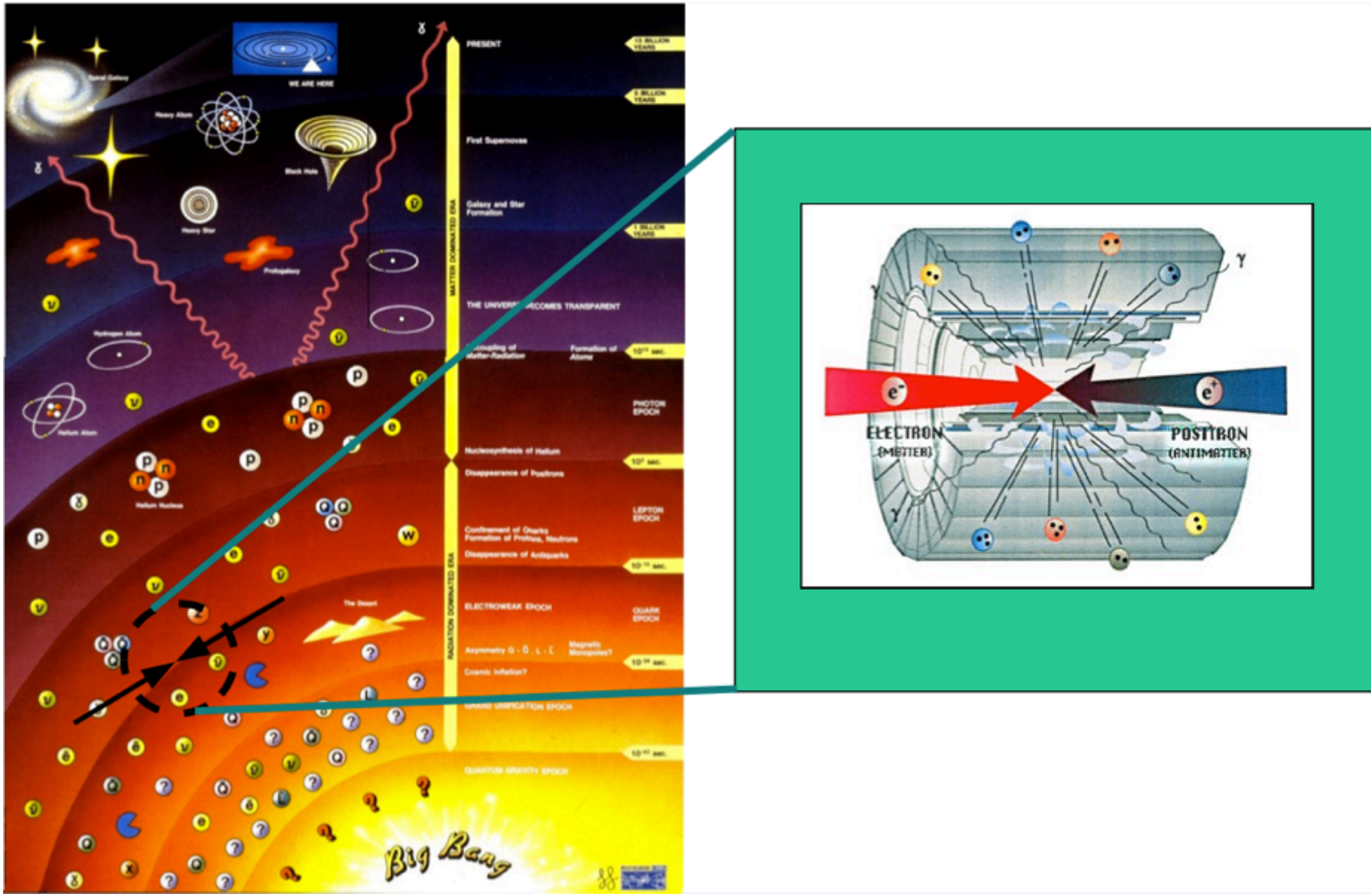
**"So that I may perceive whatever holds the world together in its inmost folds."**

**Goethe, Faust**

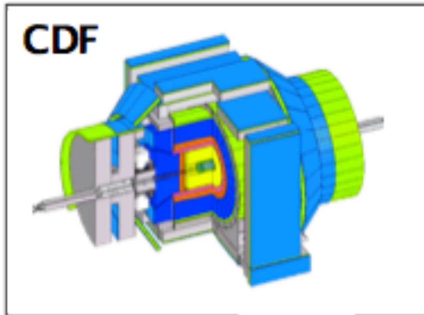


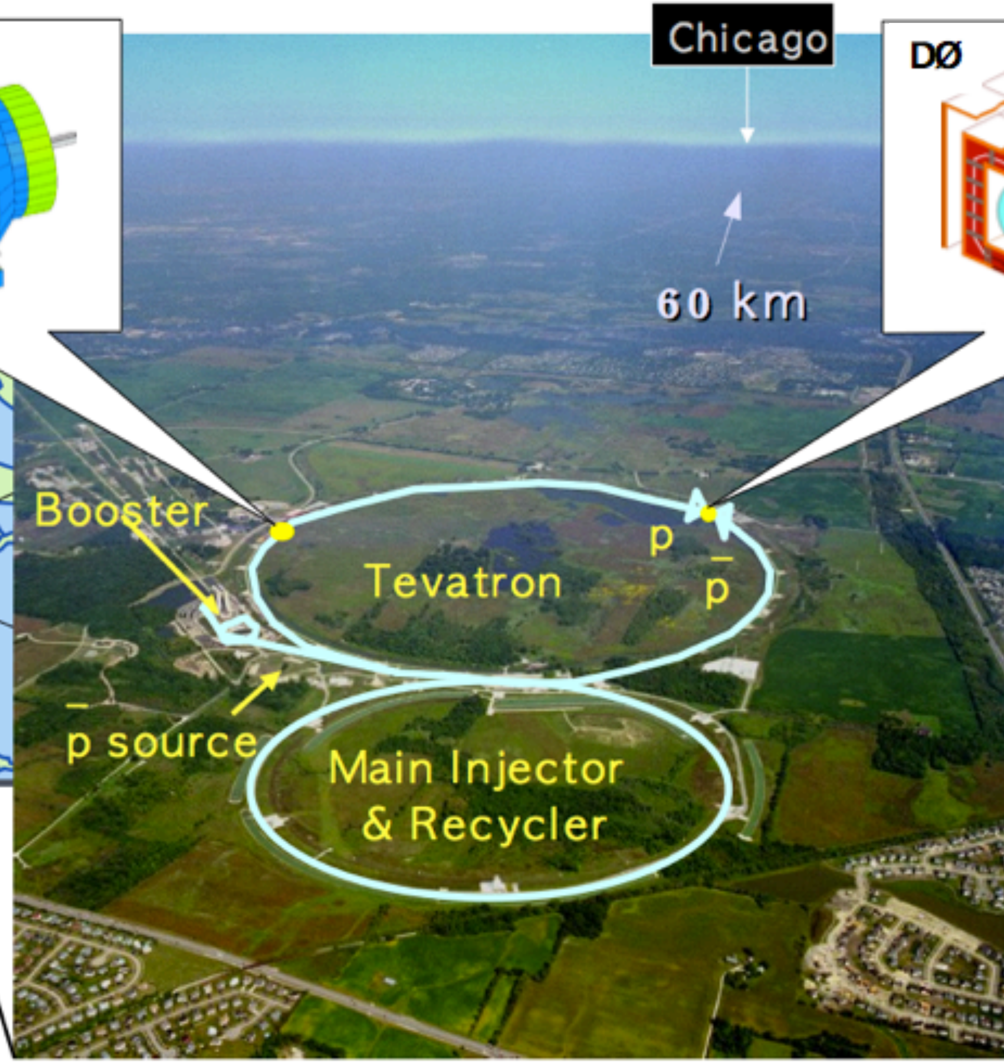

➔ **from the smallest dimensions in microcosm to the largest dimensions in the universe**

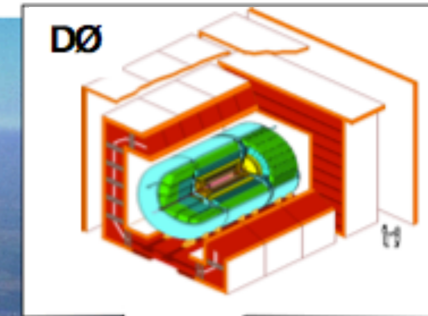
# Big Bang in the Lab?



# The Tevatron Collider at Fermilab



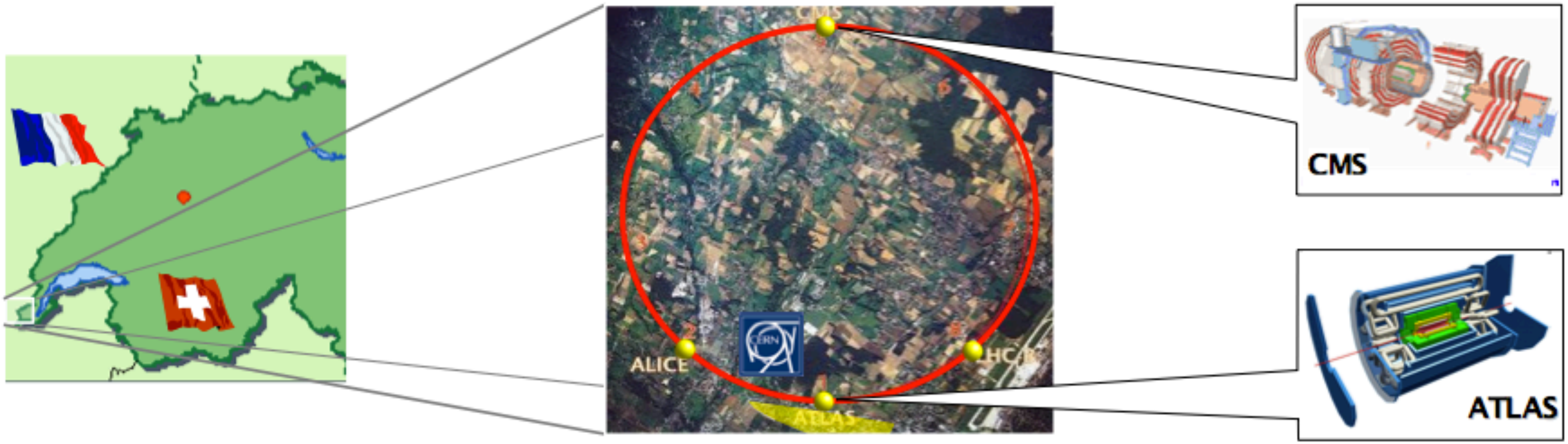





$\sqrt{s}$ = 1.96 TeV
$\Delta t$ = 396 ns

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

# The Large Hadron Collider (LHC) at CERN




**The Large Hadron Collider:**
- proton-proton collider
- high energy: $\sqrt{s}$ = 14 TeV

currently: $\sqrt{s}$ = 7 TeV

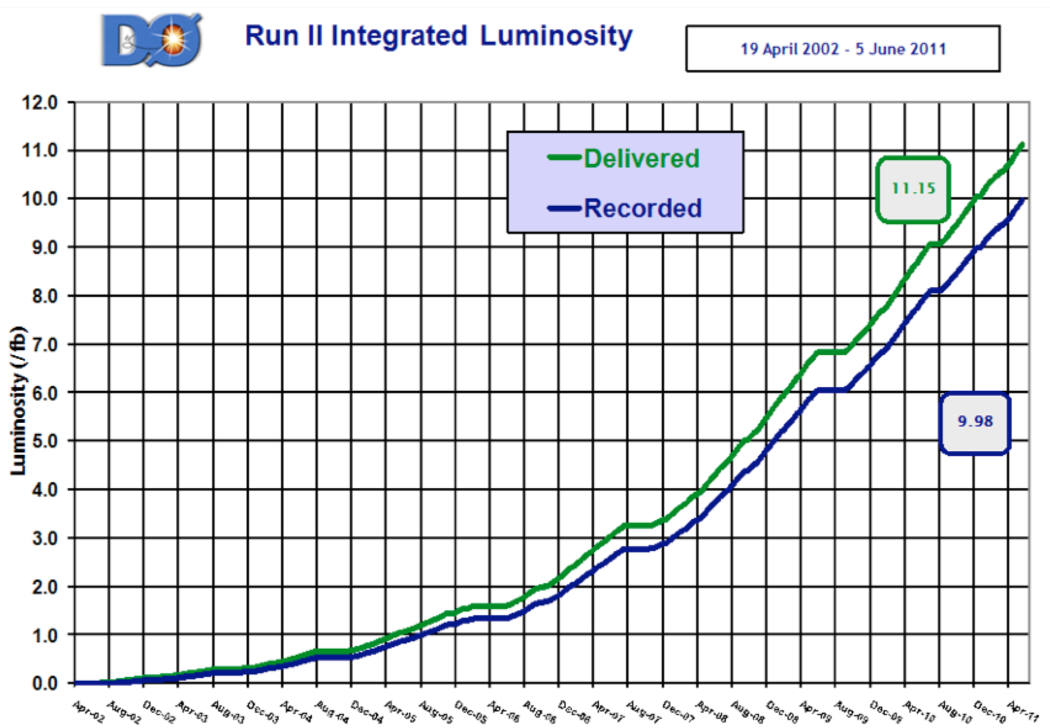
# Number of Events for Data Analysis

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

- cross section: Given by Nature (calculated by theorists)
- $\int L dt$: accelerator
- Efficiency: Detector (Experimentalist)

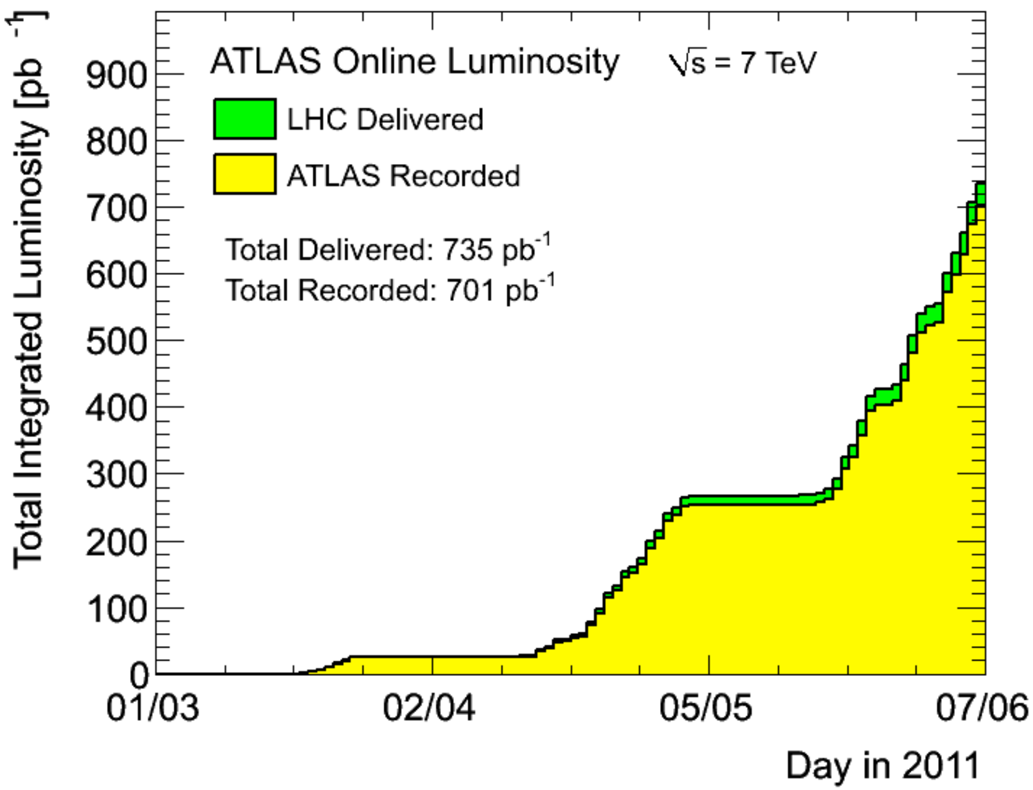
# Integrated Luminosity

## Tevatron




**11 fb$^{-1}$ delivered**

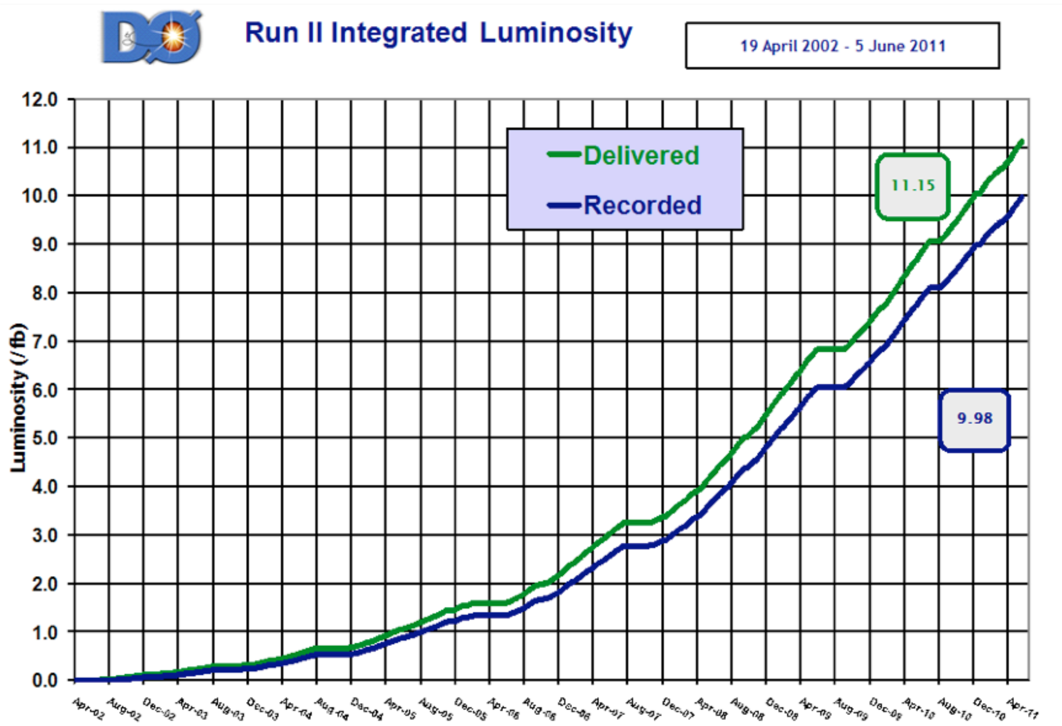
## LHC

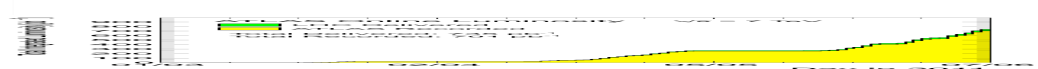



**0.74 fb$^{-1}$ delivered**

# Integrated Luminosity

**Tevatron** | **LHC**



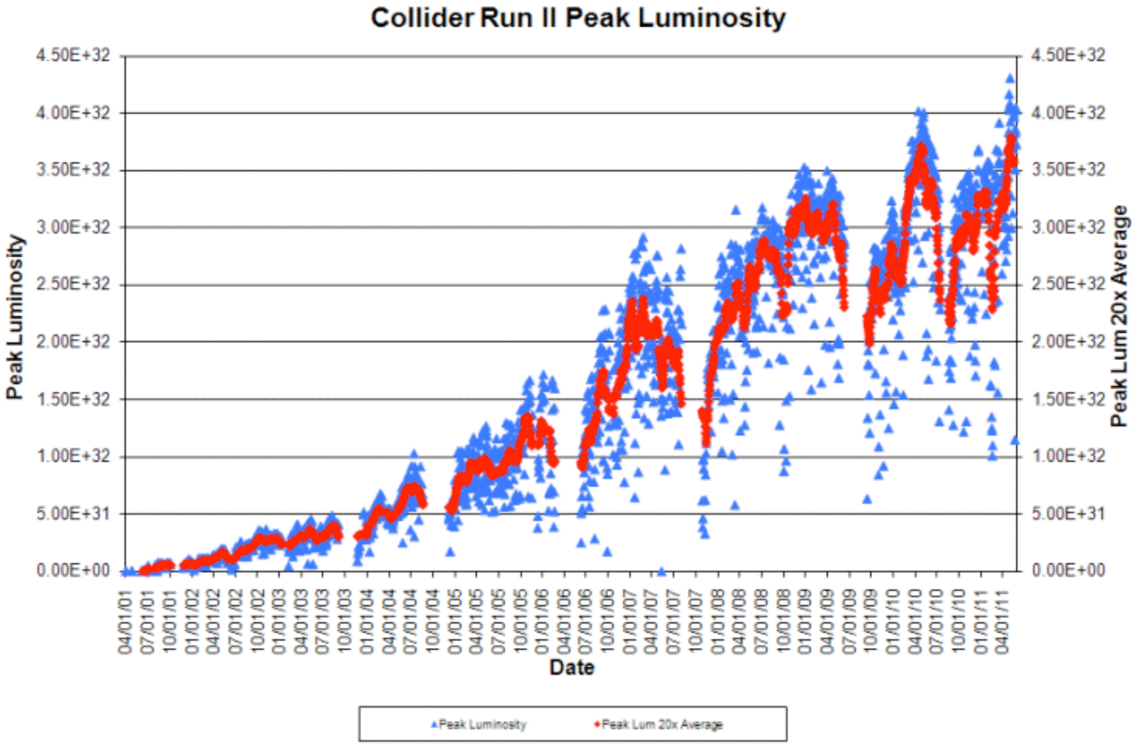



**11 $fb^{-1}$ delivered**

**0.74 $fb^{-1}$ delivered**

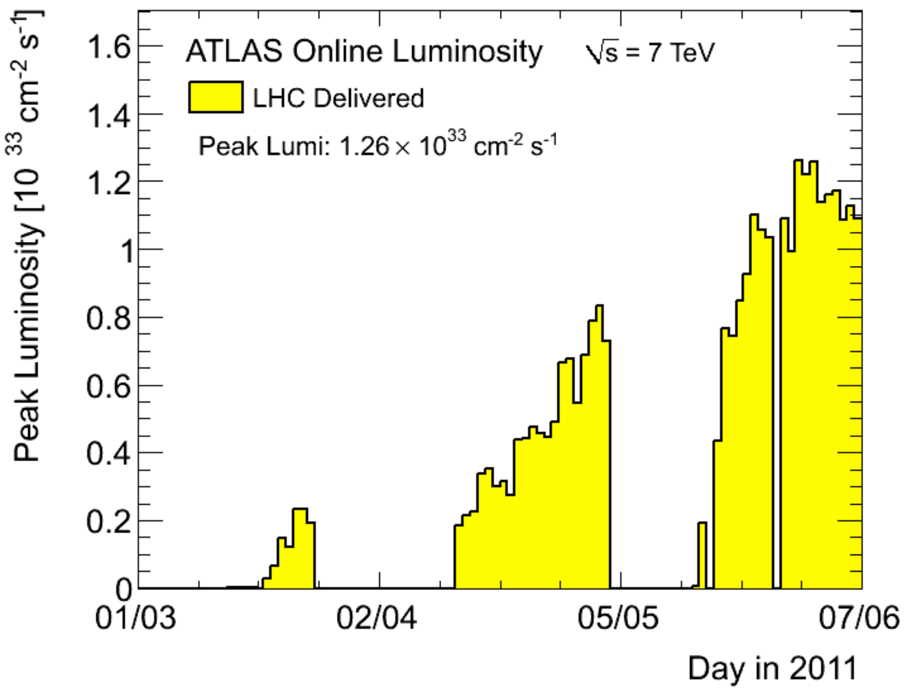
# Peak Luminosity

## Tevatron




$4.3 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

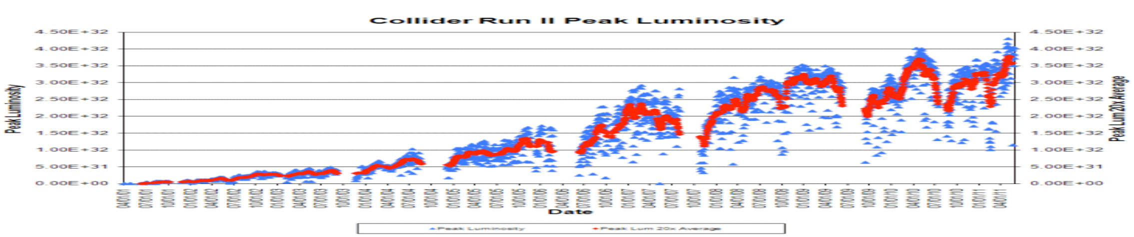
## LHC




$13 \times 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

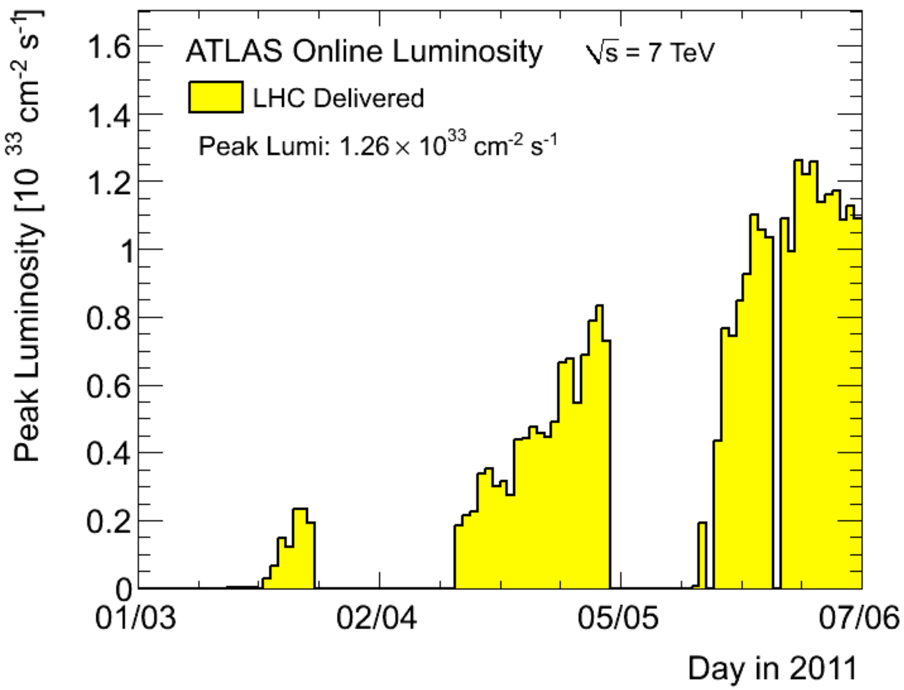
# Peak Luminosity

## Tevatron




$4.3\text{x}10^{32}$ cm$^{-2}$ s$^{-1}$

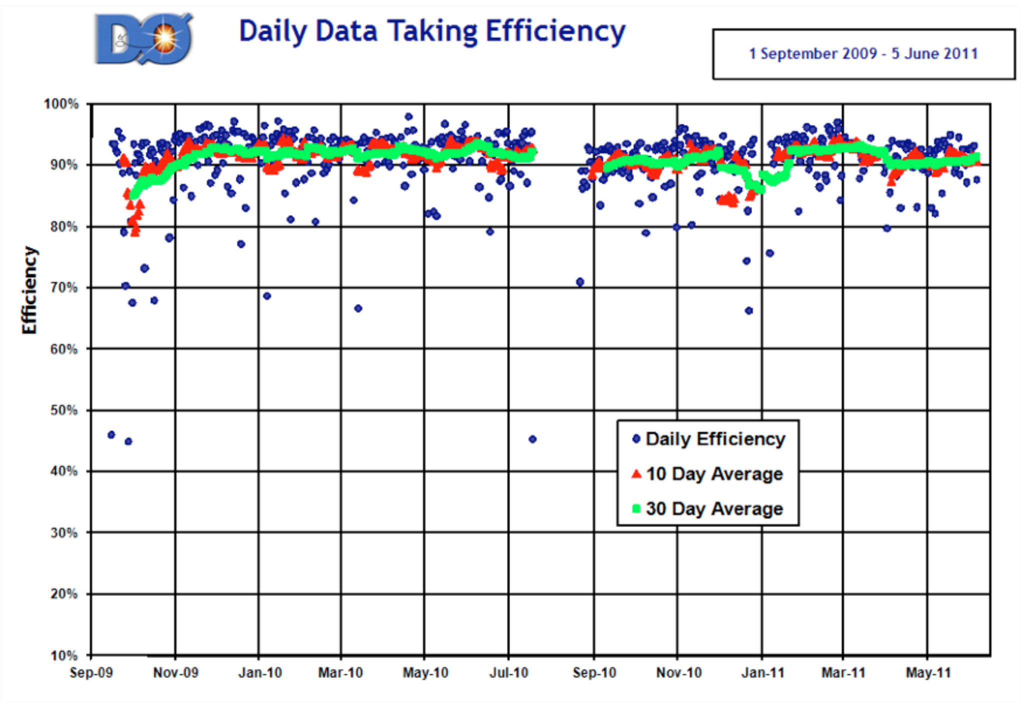
## LHC



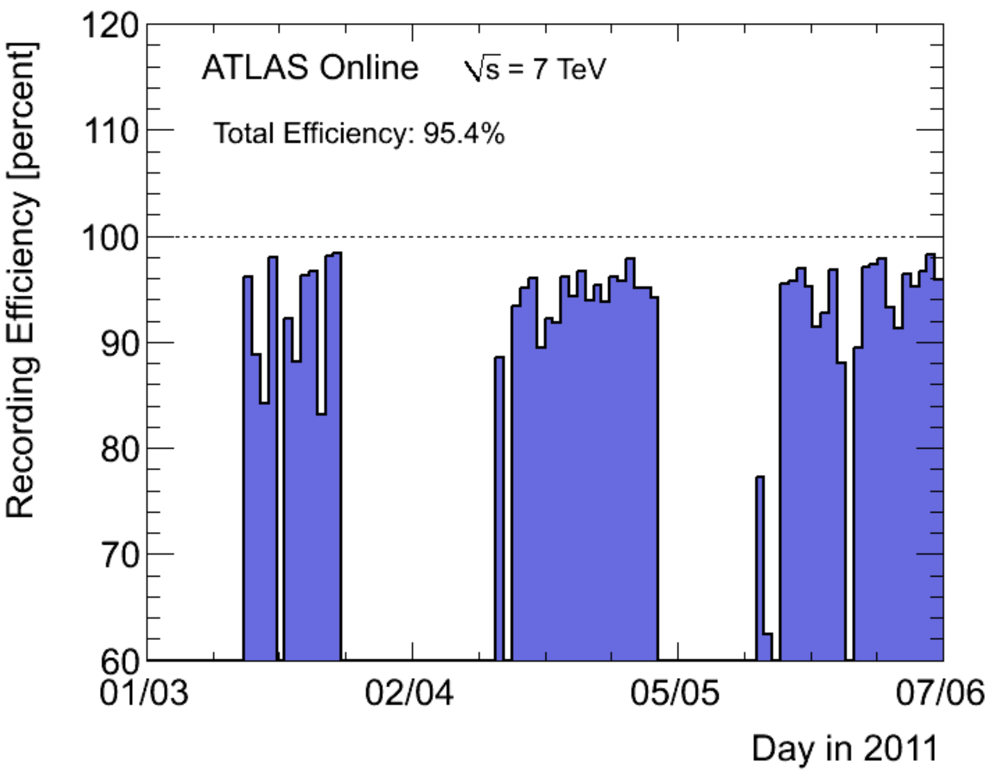

$13\text{x}10^{32}$ cm$^{-2}$ s$^{-1}$

# Data Taking Efficiency

## Tevatron

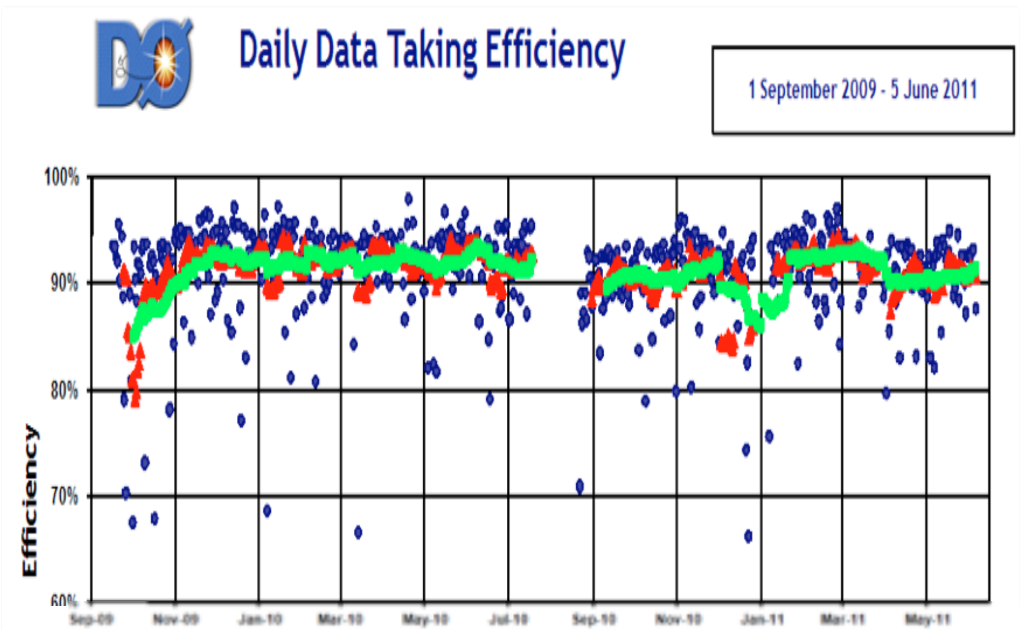



## LHC

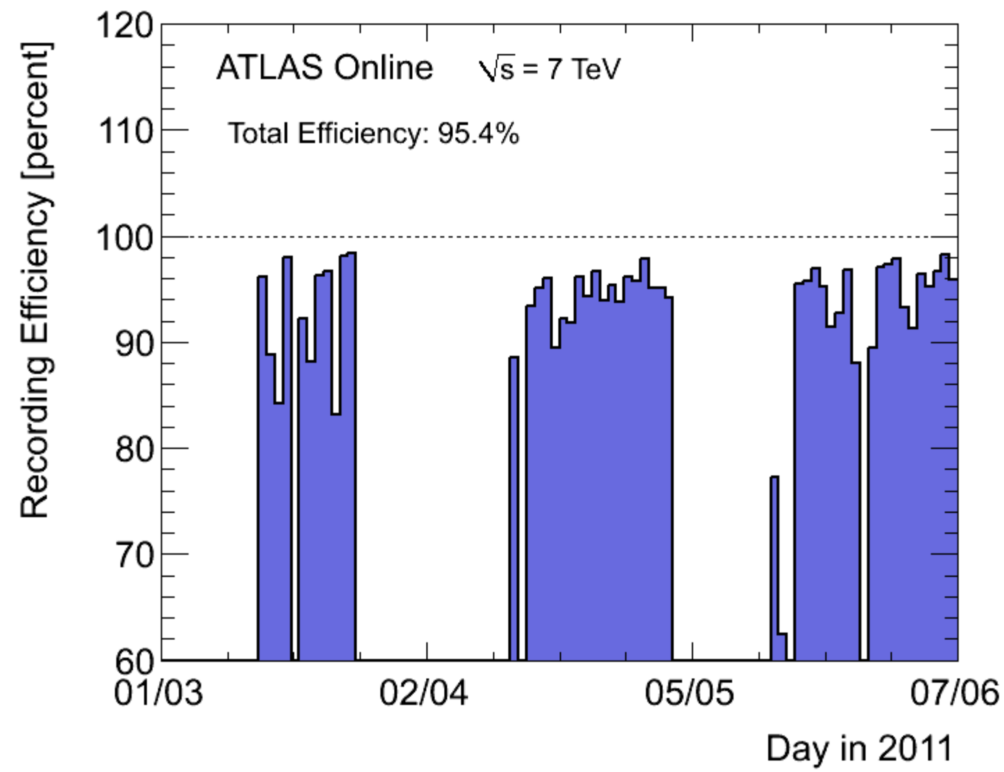


# Data Taking Efficiency

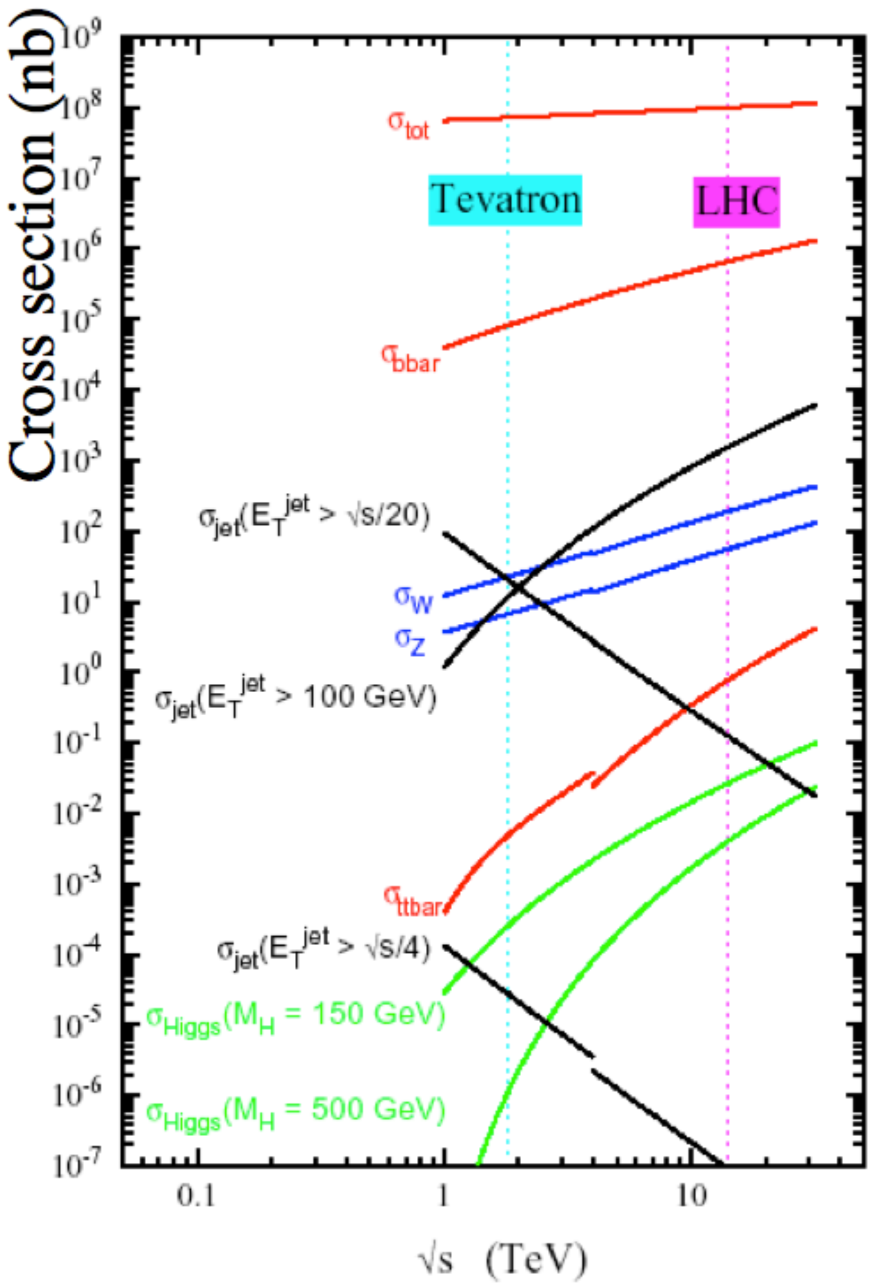
## Tevatron




## LHC



# Cross Sections



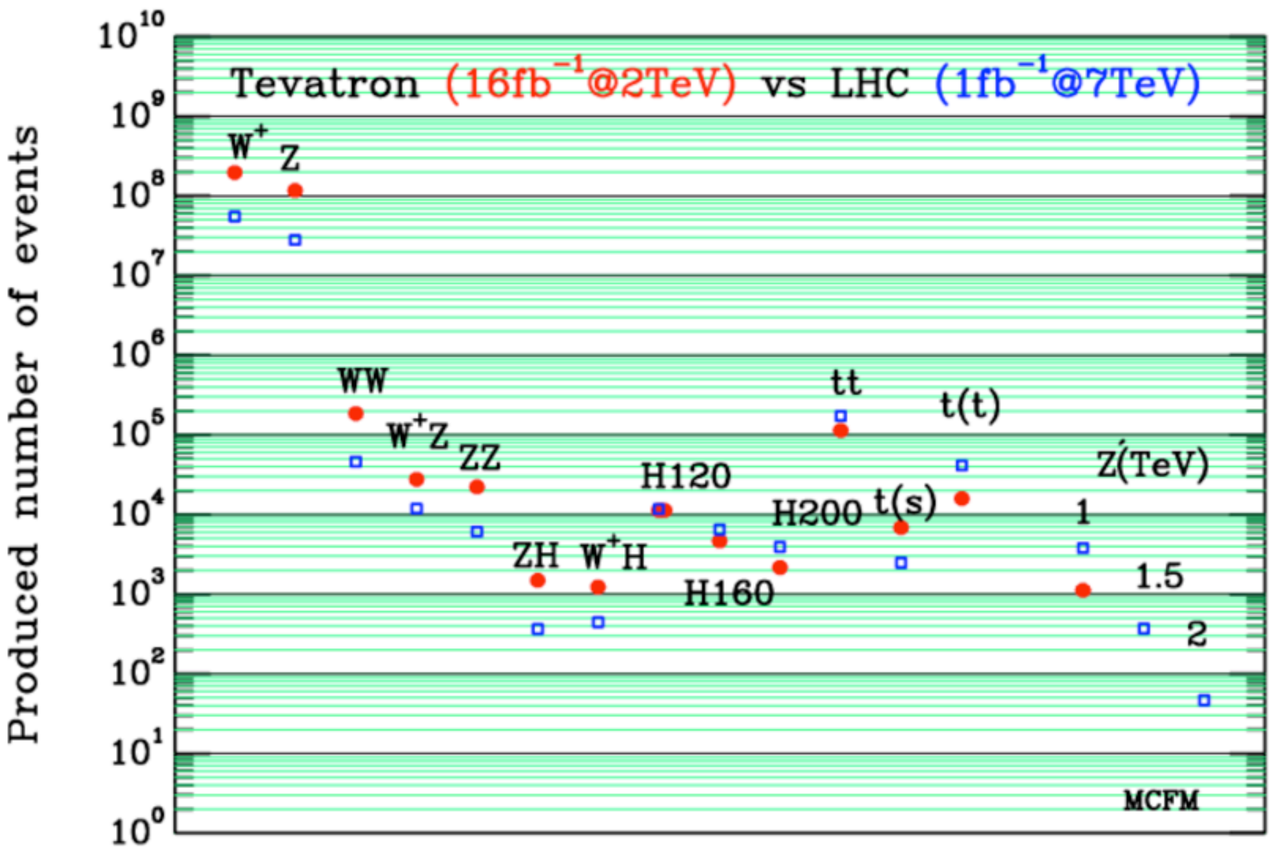

- a lot more "uninteresting" than "interesting" processes, at design luminosity ($L=10^{34}\ cm^{-2}s^{-1}$):

| | |
|---|---|
| – any event: | $10^9$ / second |
| – W boson: | 150 / second |
| – top quark: | 8 / second |
| – Higgs (150 GeV): | 0.2 / second |

- "interesting" events get selected by

– trigger: online selection to find events with hard jets, leptons etc.
– physics analysis: offline selection to enhance signal over background ratio

# Number of Events




- similar size of electroweak samples: top, W, Z
- LHC is superior for
  - production of heavy particles (e.g. squark&gluons, Z' and W' bosons, ...)
  - high $p_T$ physics (e.g. quark substructure)
  - many B physics analyses (e.g. rare decays in $B_s \to \mu^+\mu^-$, CP violation in $B_s \to J/\Psi\ \phi$

# Outline

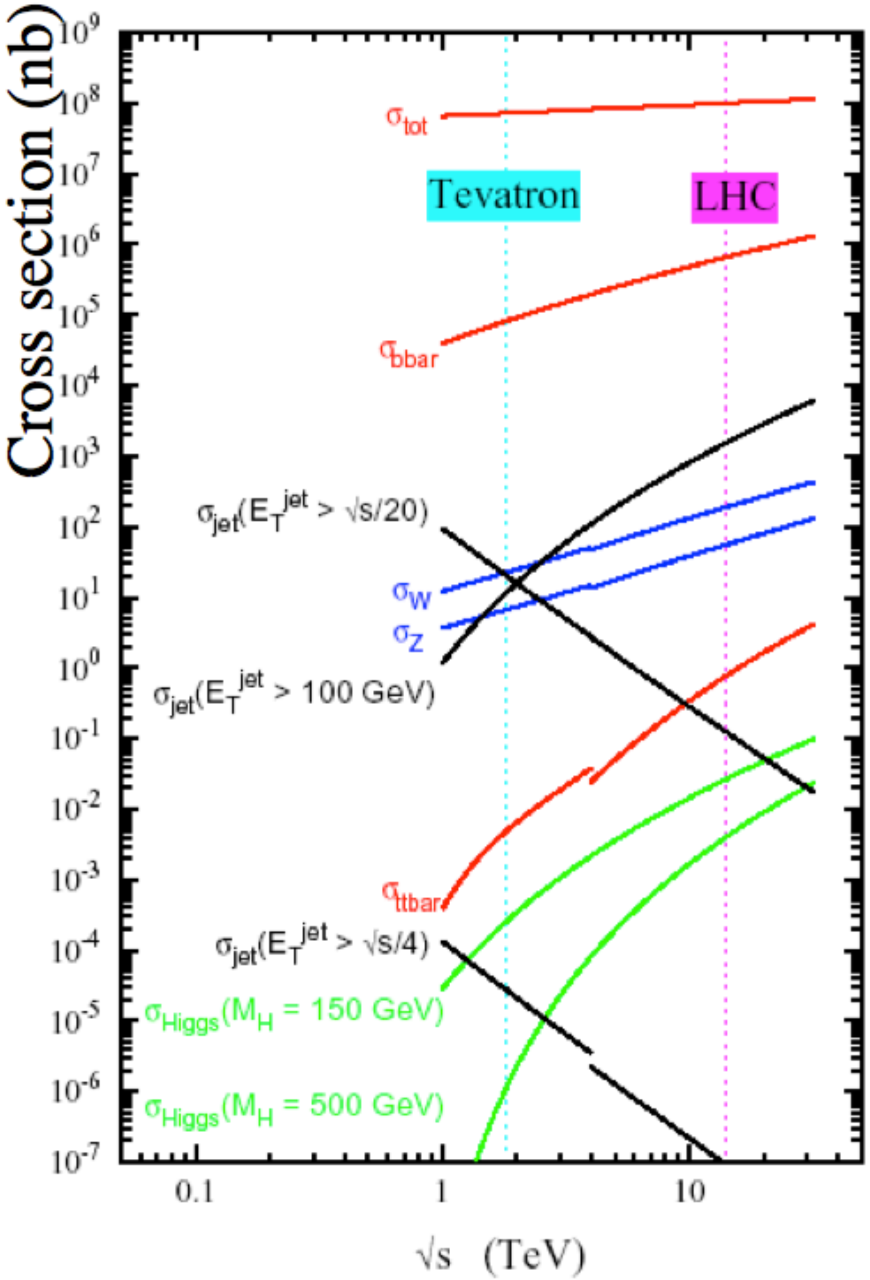
## Part I:

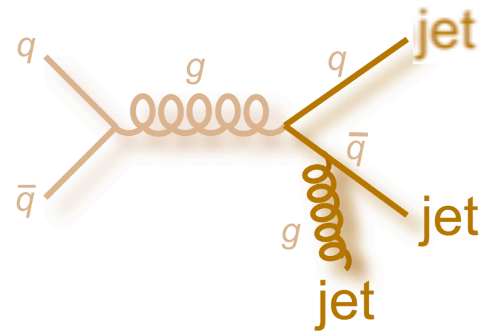
QDC
Electroweak Physics
Top Quark Physics
Search for the SM Higgs

## Part II:

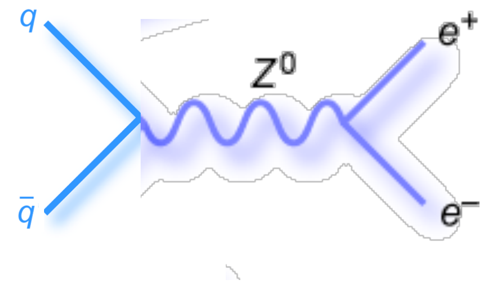
Searches for Physics Beyond the SM

# Outline

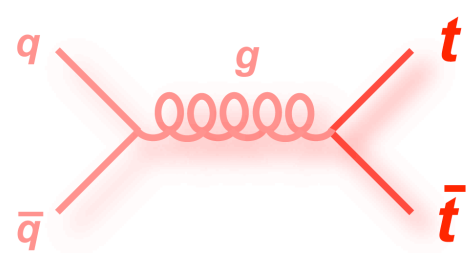


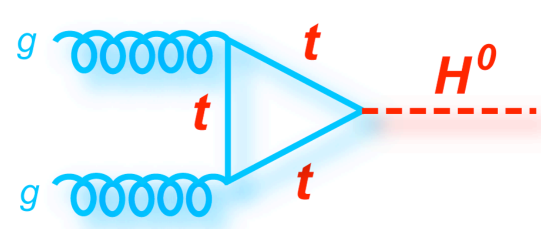

**jets**




**W, Z bosons**

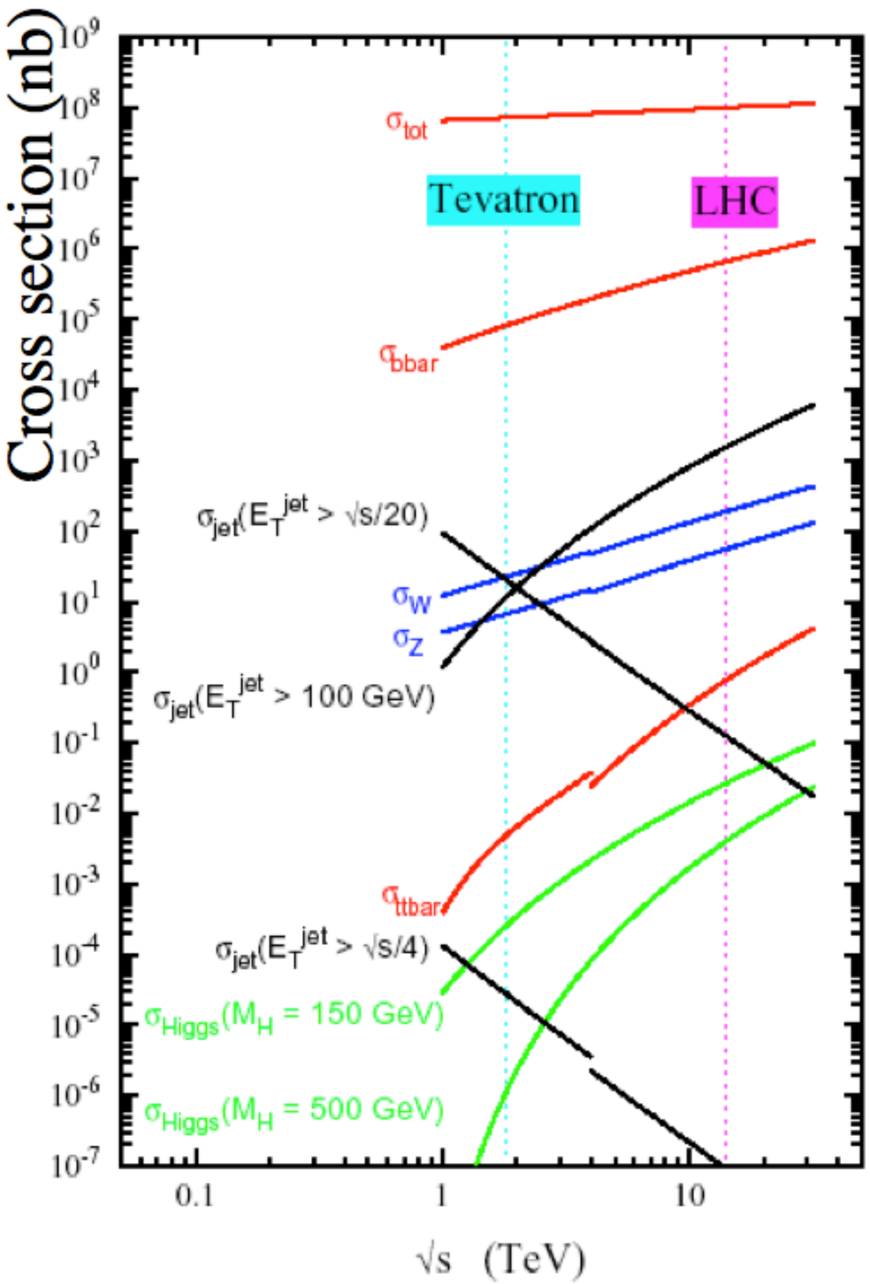


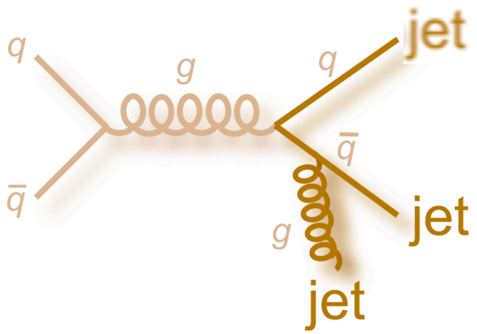

**top quark**




**Higgs boson**

# Outline




**jets**

# 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: $d\sigma/dE_T(\text{jet})$
  - 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

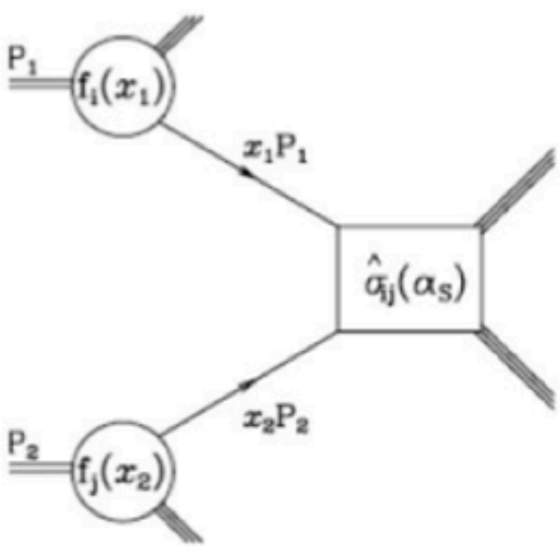
Parton distribution function

Renormalization scale $\mu_R$

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

Factorization scale $\mu_F$

Short distance cross section, calculated as a perturbation series in $\alpha_S$

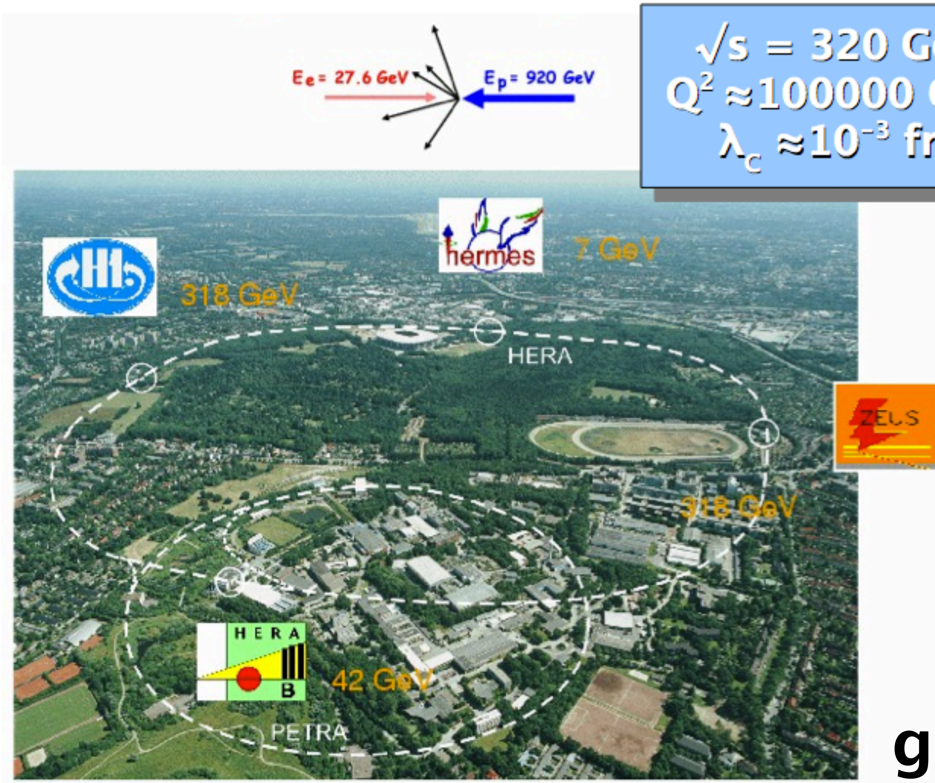


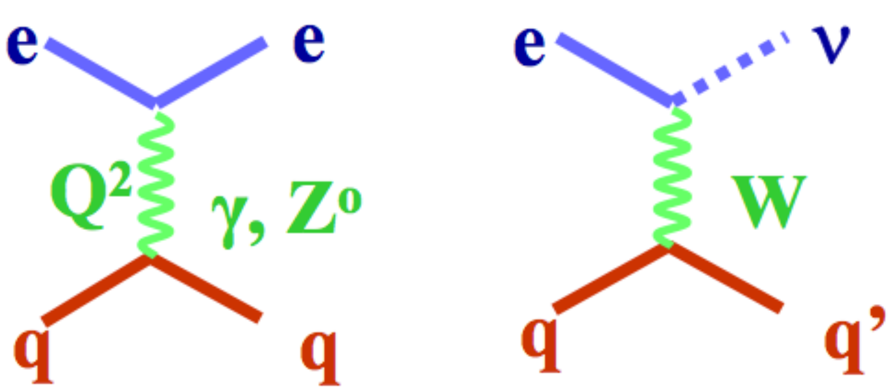

- **calculations are done in perturbative QCD:**
  - possible due to factorization of hard ME and pdf (can be treated independently)
  - strong coupling $\alpha_s$ is relatively large higher orders needed, complicated calculations

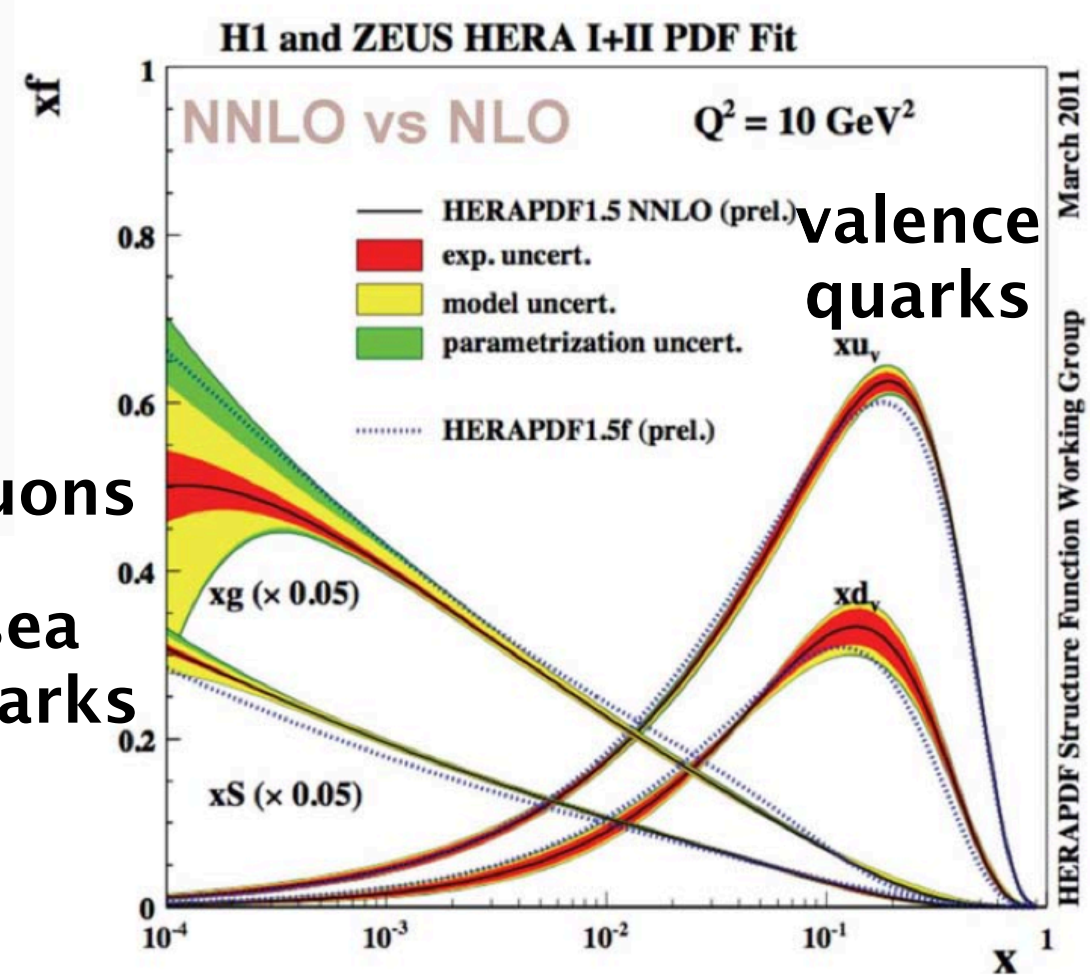
→ **measure to test underlying theory**

# Parton Density Functions: HERA

$\sqrt{s} = 320$ GeV
$Q^2 \approx 100000$ GeV$^2$
$\lambda_c \approx 10^{-3}$ fm

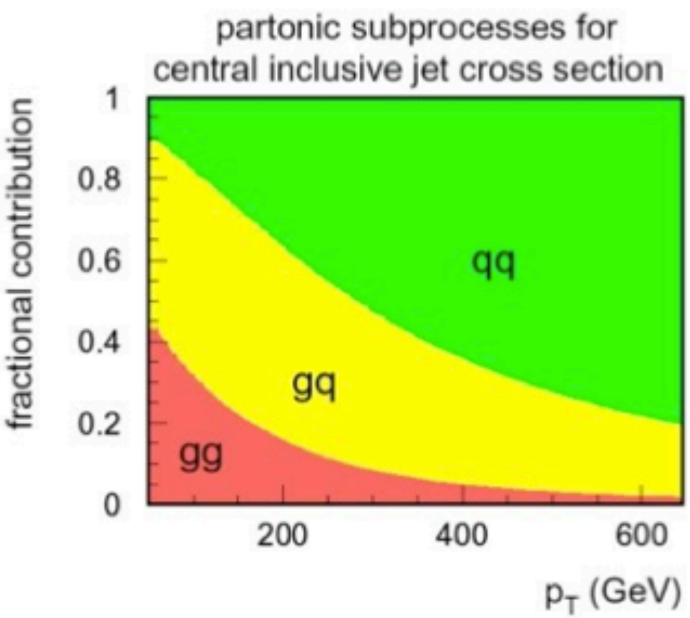


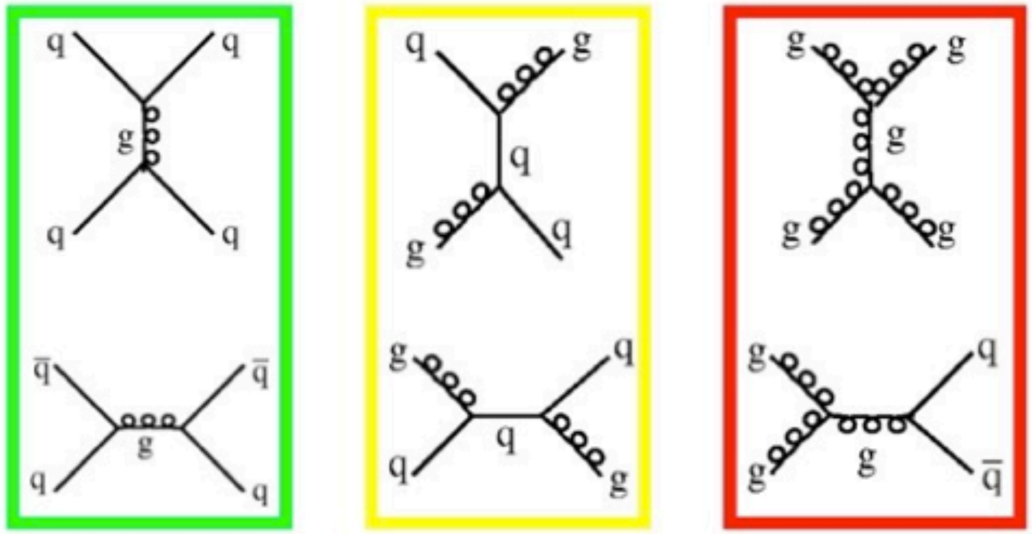



# Jet Cross Sections

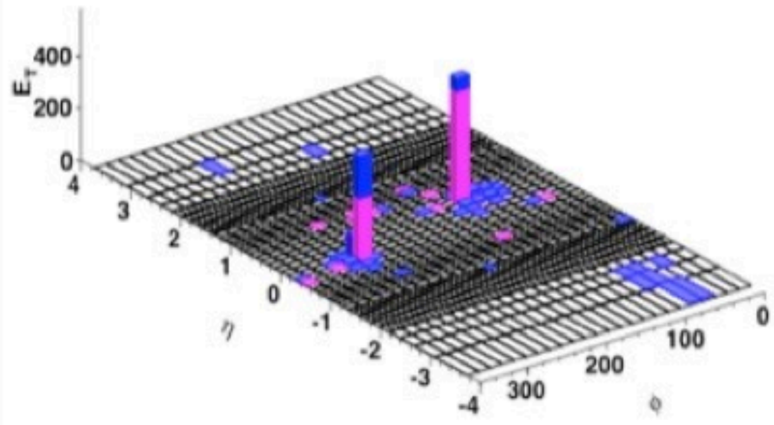
- inclusive jet processes: qq, qg, gg



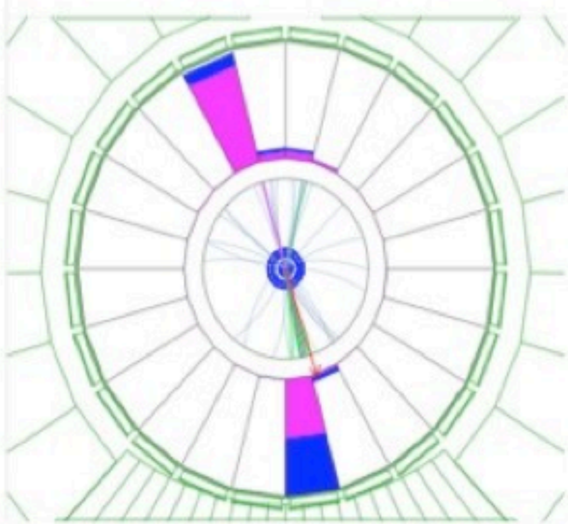
- tests perturbative QCD at highest energies
- highest $E_T$ probes shortest distances
  - Tevatron: $r_q < 10^{-18}$ m, LHC: $r_q < 10^{-19}$ m
  - could e.g. reveal substructure of quarks

# High Mass Dijet event, M=1.4 TeV




*CDF Run II Preliminary*

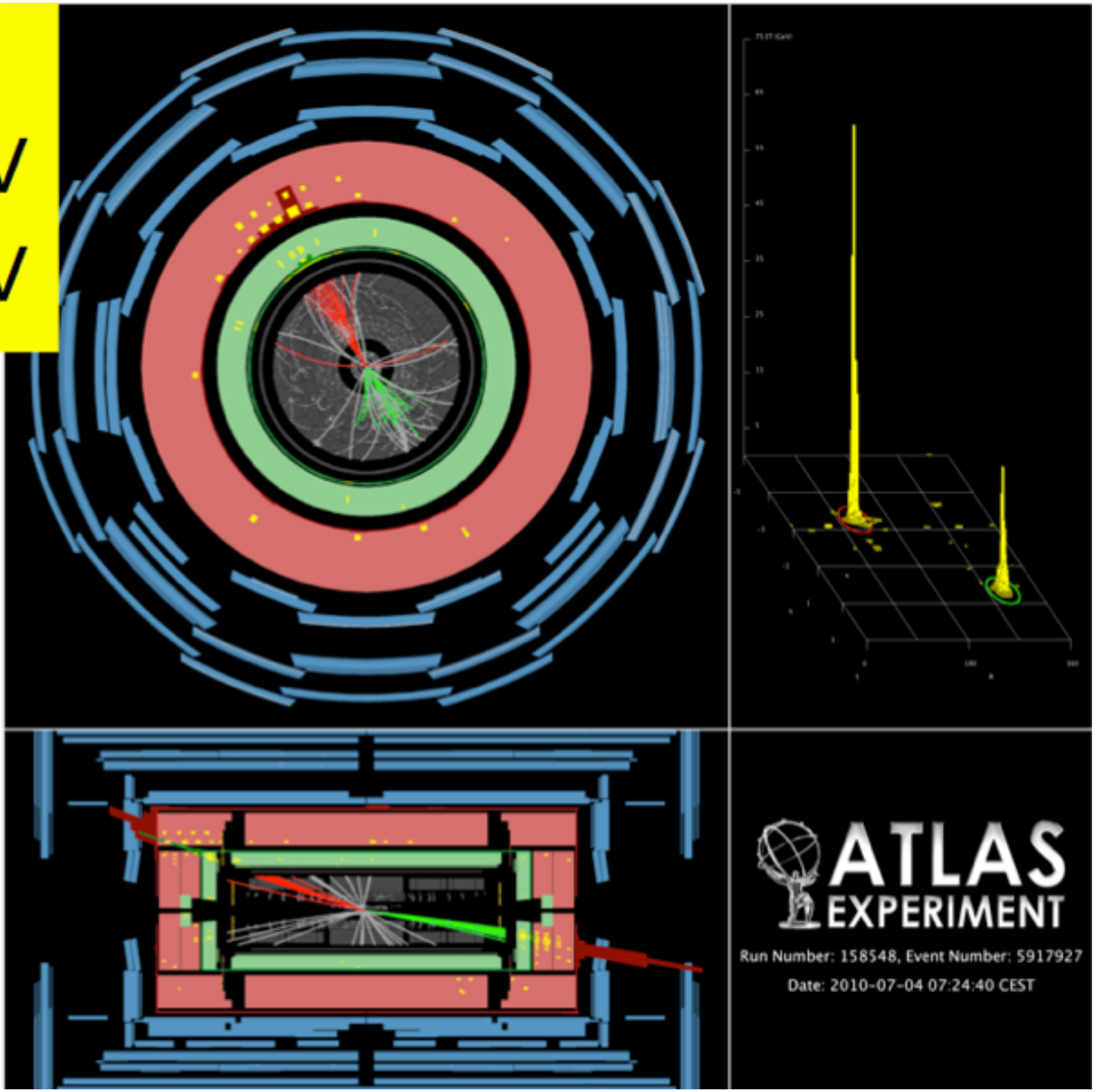
```
Jet Et1 = 666 GeV (corr)
          583 GeV (raw)
eta1    = 0.31 (detector)
          0.43 (corr z)

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



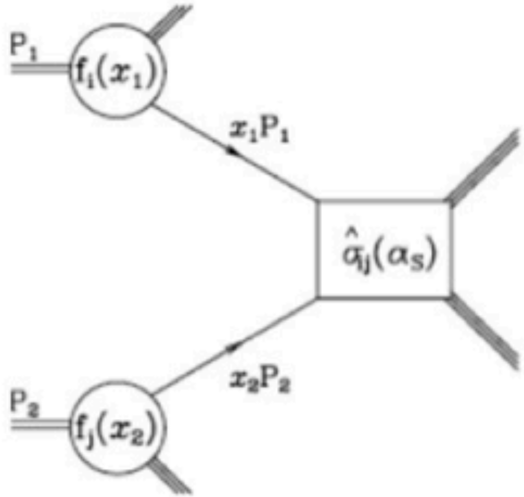
```
Run    152507
Event  1222318

DiJet Mass = 1364 GeV (corr)

z vertex   = -25 cm
```

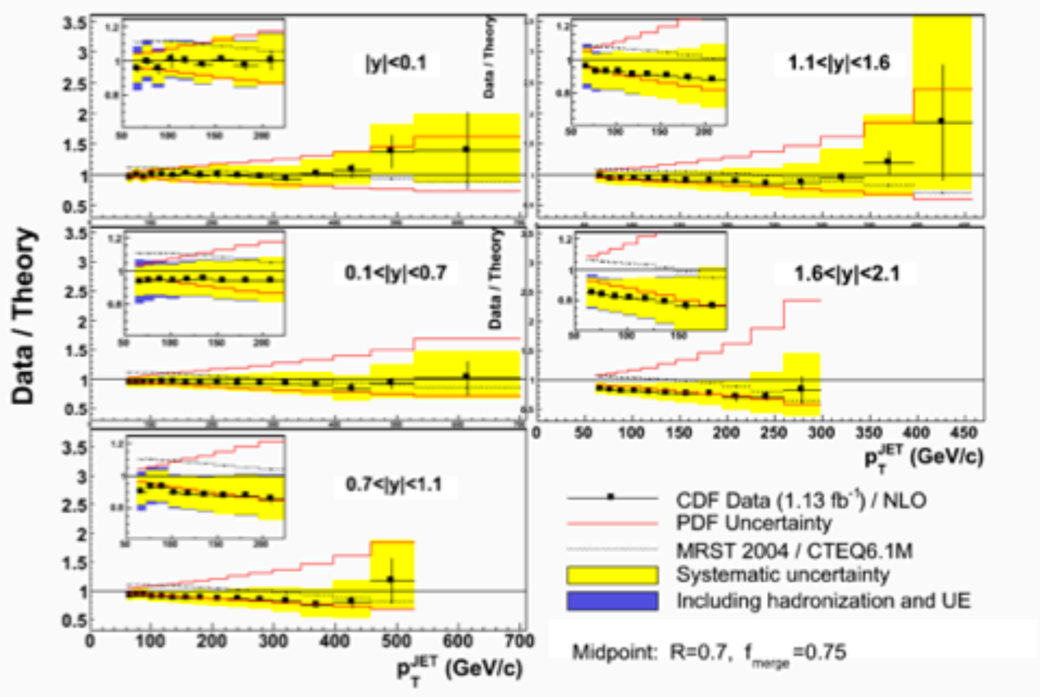
# Dijet Event at the LHC

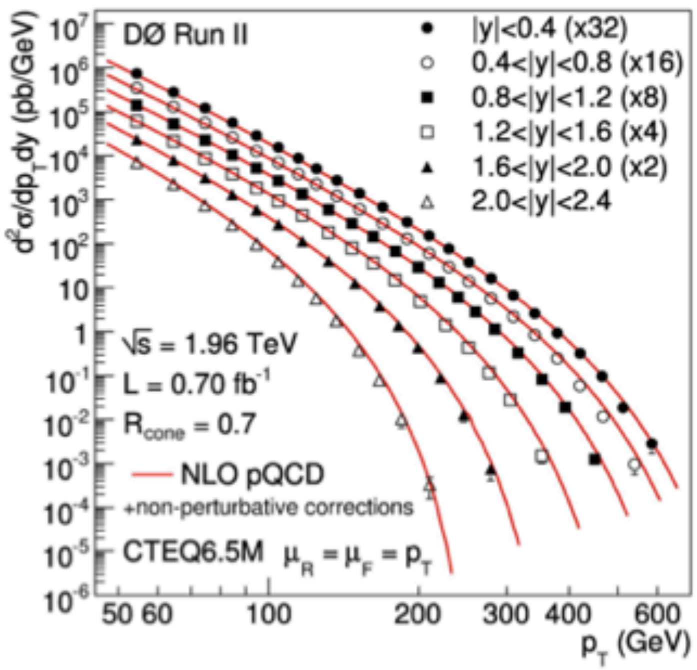
- M(jj)=2.55 GeV
- pT(j1)=420 GeV
- pT(j2)=320 GeV



# Jet Cross Sections, Tevatron

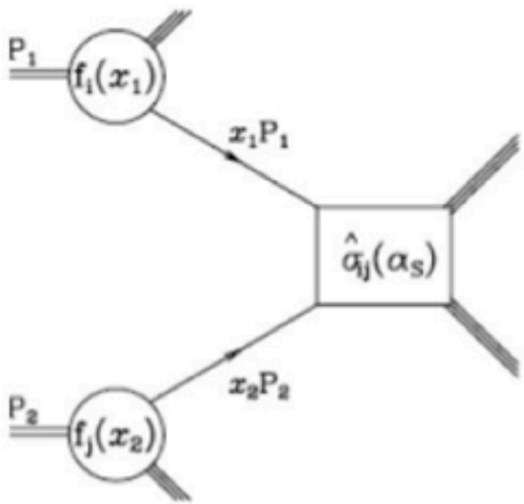


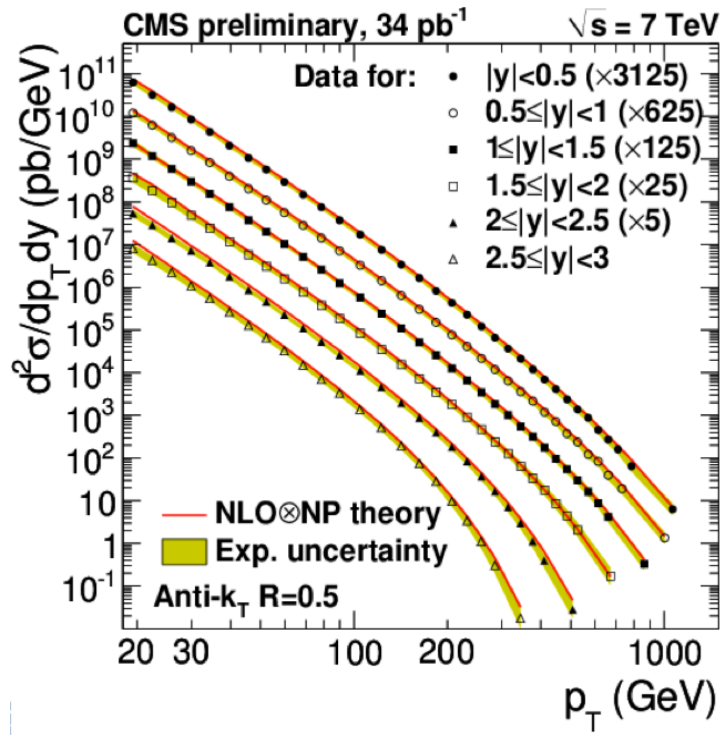



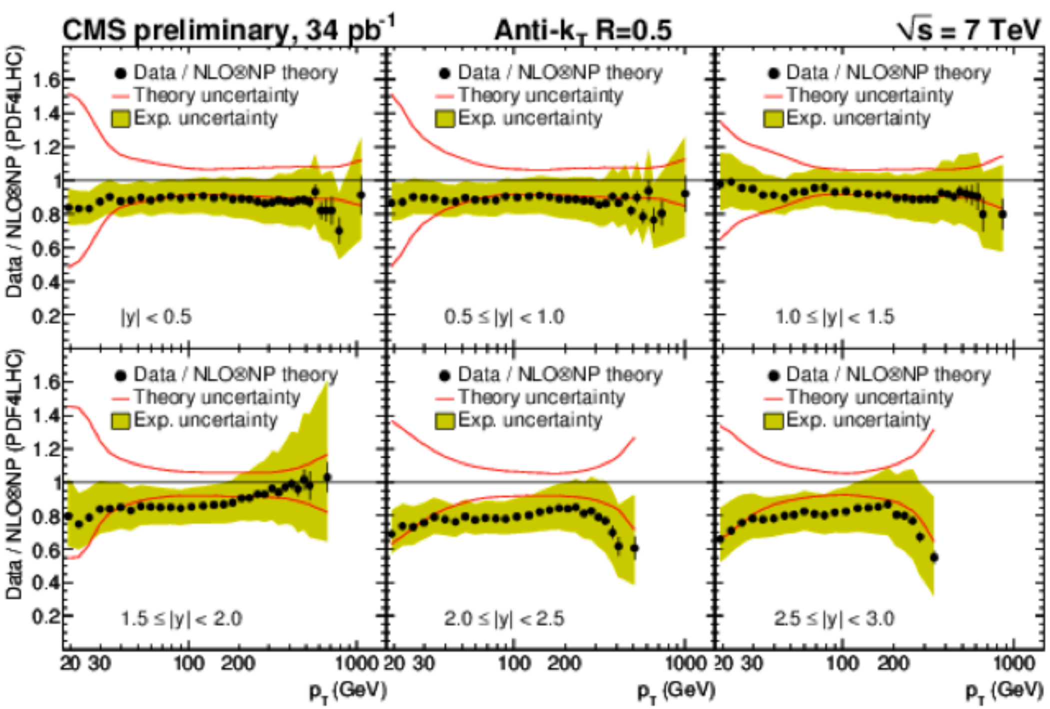




- **excellent agreement with QCD calculation over 9 orders of magnitude!**
- **no excess at high $E_T$**
  - **no hint for quark substructure**

# Jet Cross Sections, LHC

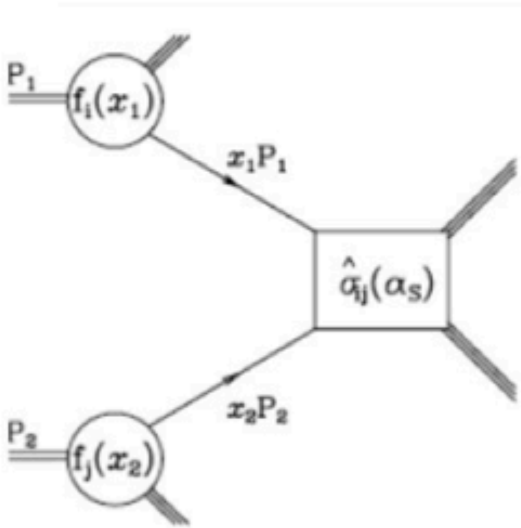


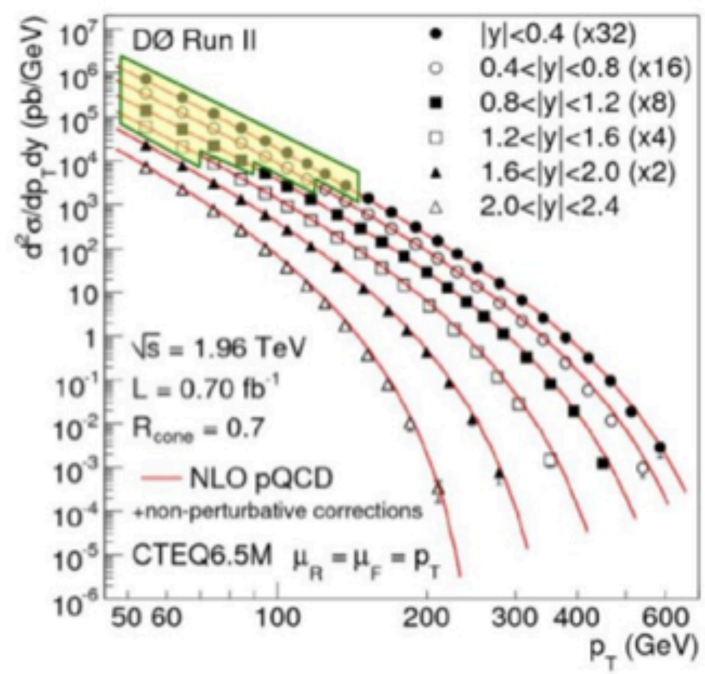



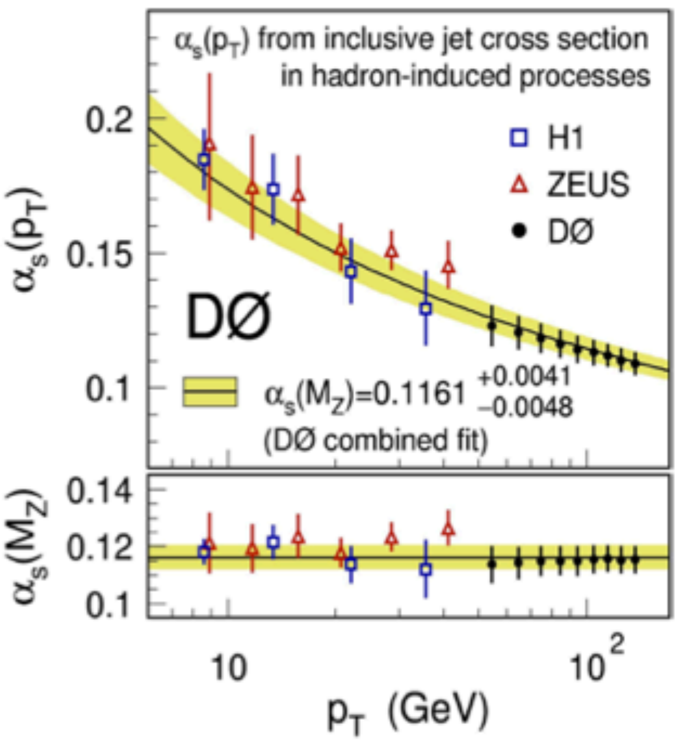




- **excellent agreement with QCD calculation over 10 orders of magnitude!**
- **no excess at high $E_T$**
  - **no hint for quark substructure**

# Strong Coupling Constant



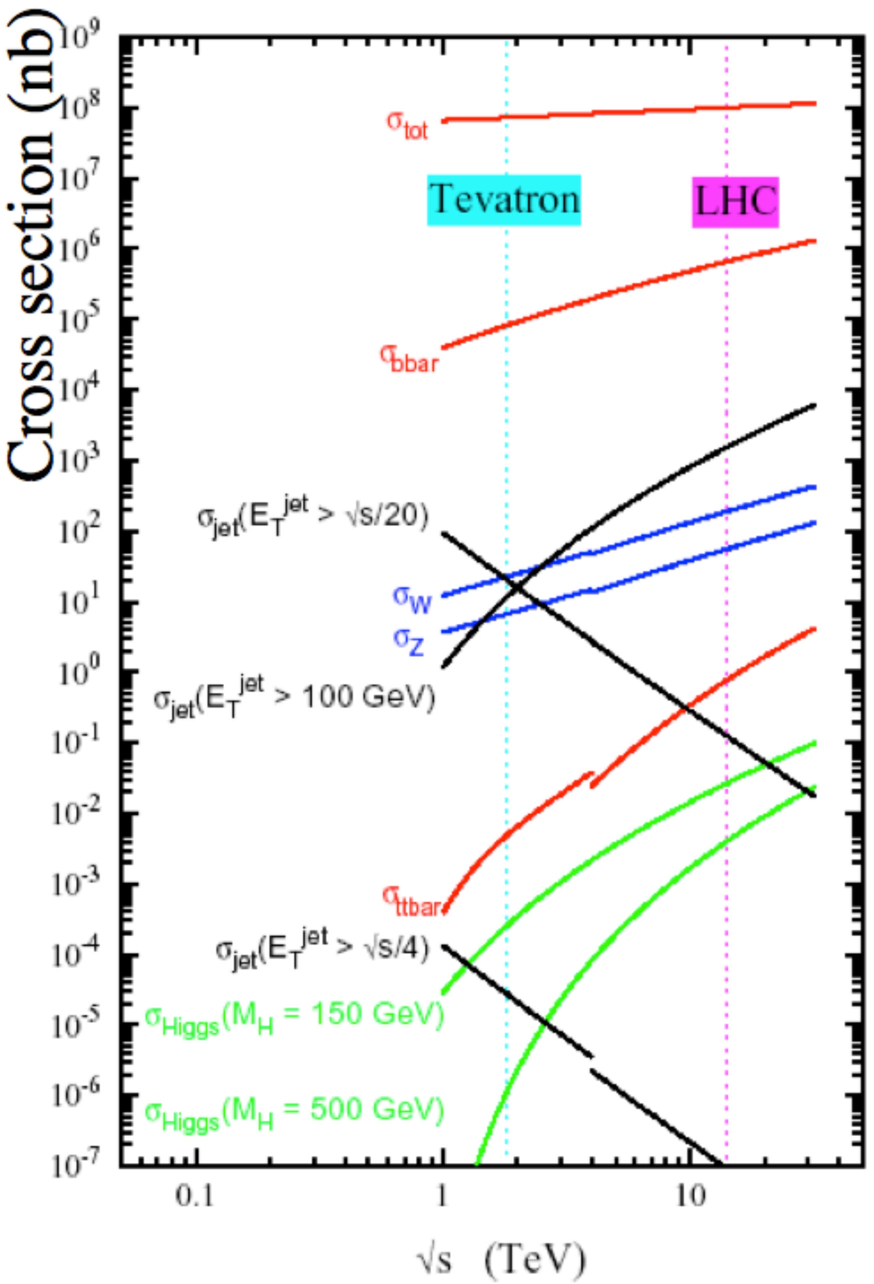



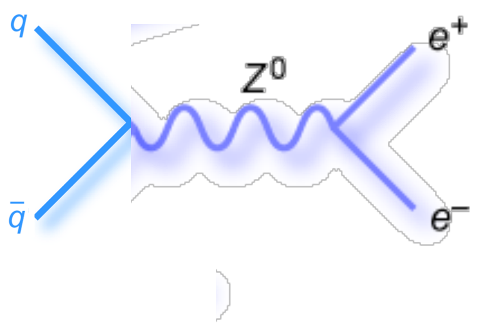

- **minimize correlations between data and pdf's by restricting analysis to kinematic regions where Tevatron data do not dominate the pdf determination**
  - **keep 21 data points**

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

**±4%**

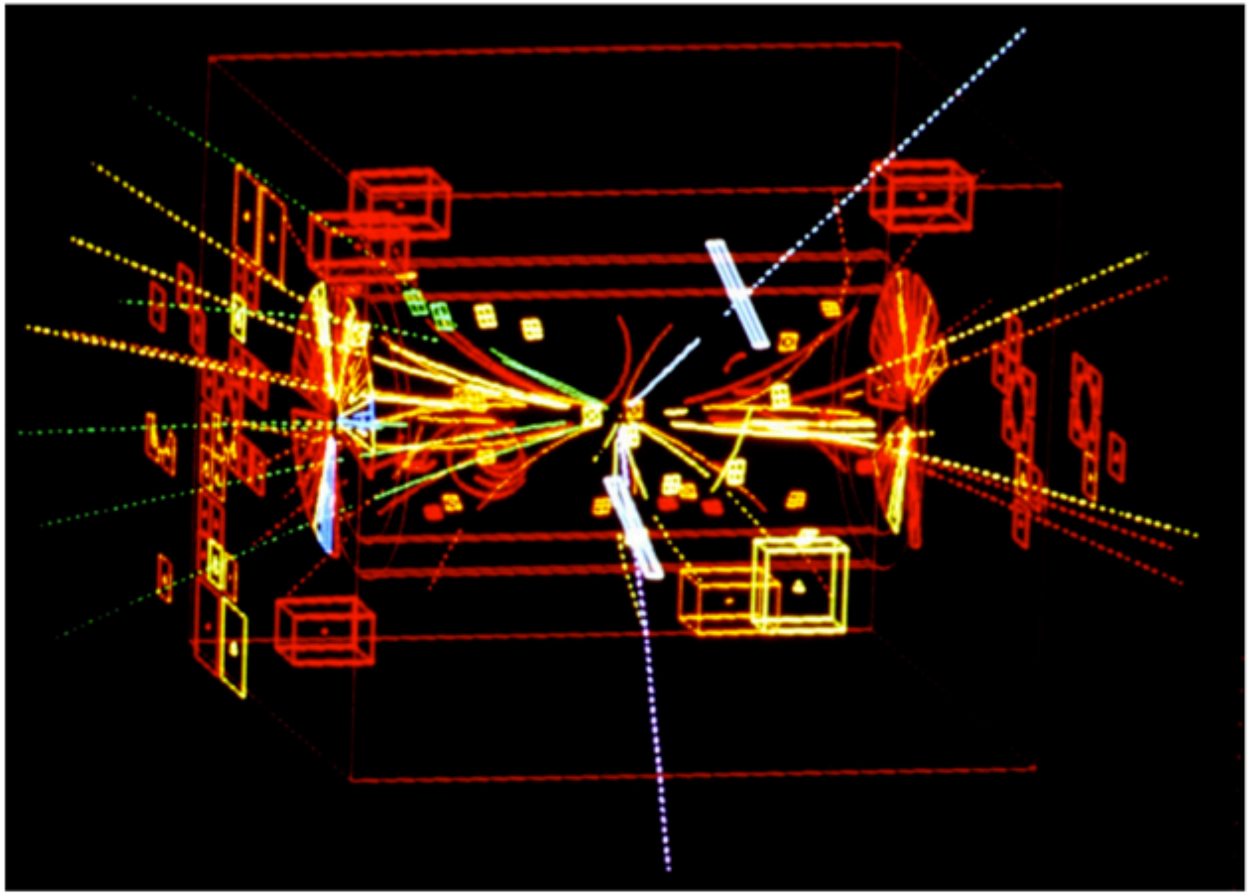
# Outline




**W, Z bosons**

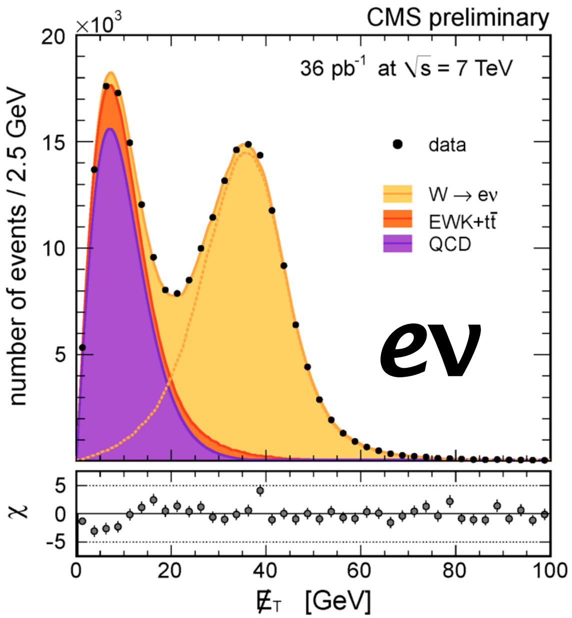
# Electroweak Interaction

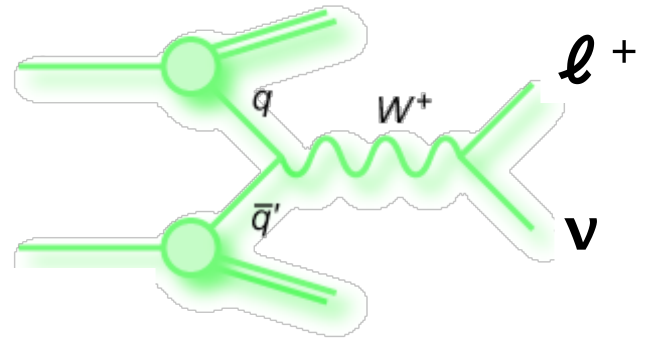


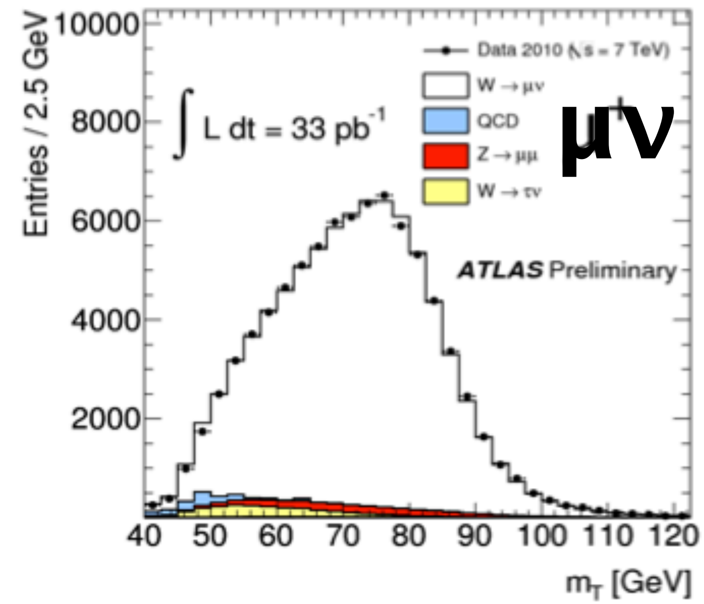
1983, UA1 experiment, $\sqrt{s}$=540 GeV

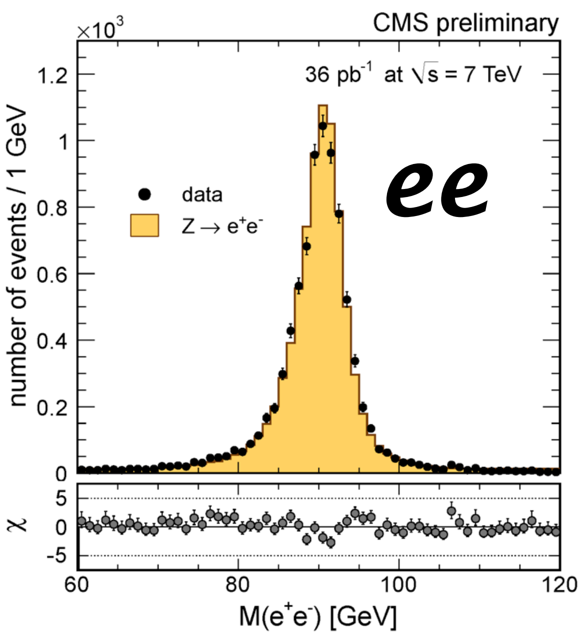
**discovery of Z boson at $\bar{p}p$ accelerator SPS (CERN, Geneva)**

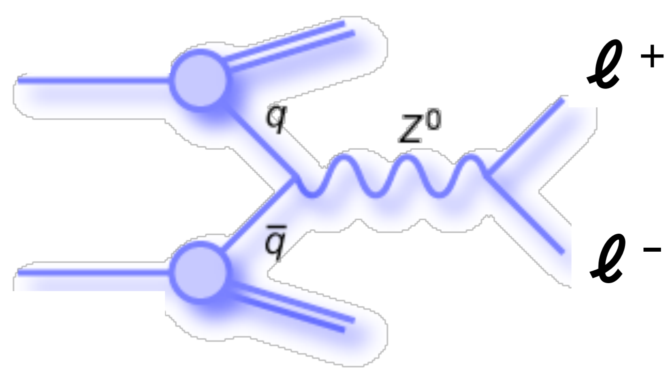
# W and Z Production at the LHC



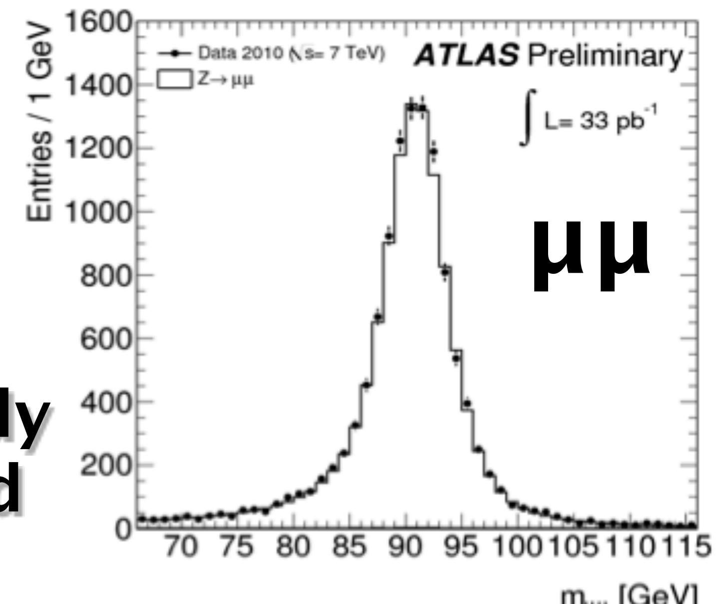



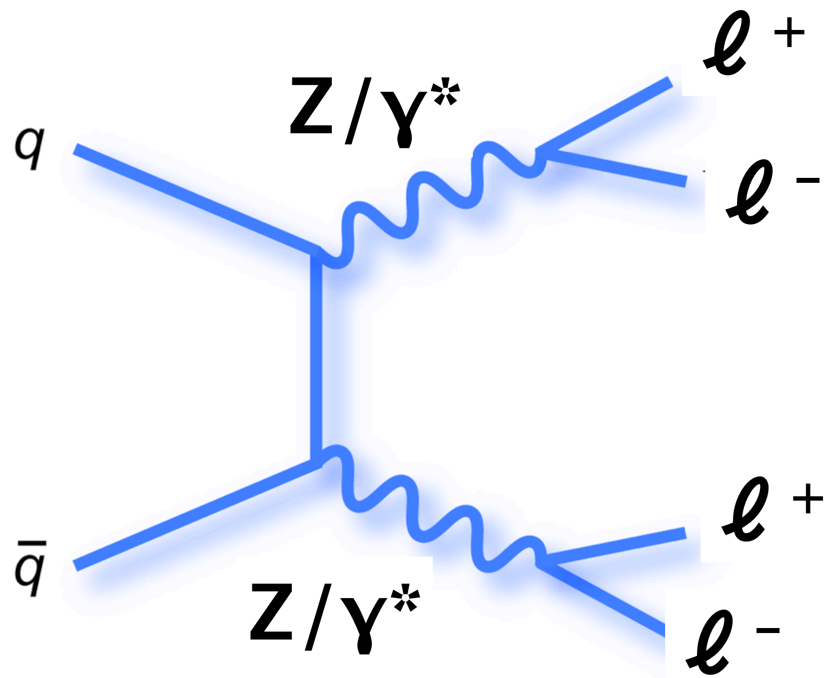




**measurements already systematically limited (luminosity)**



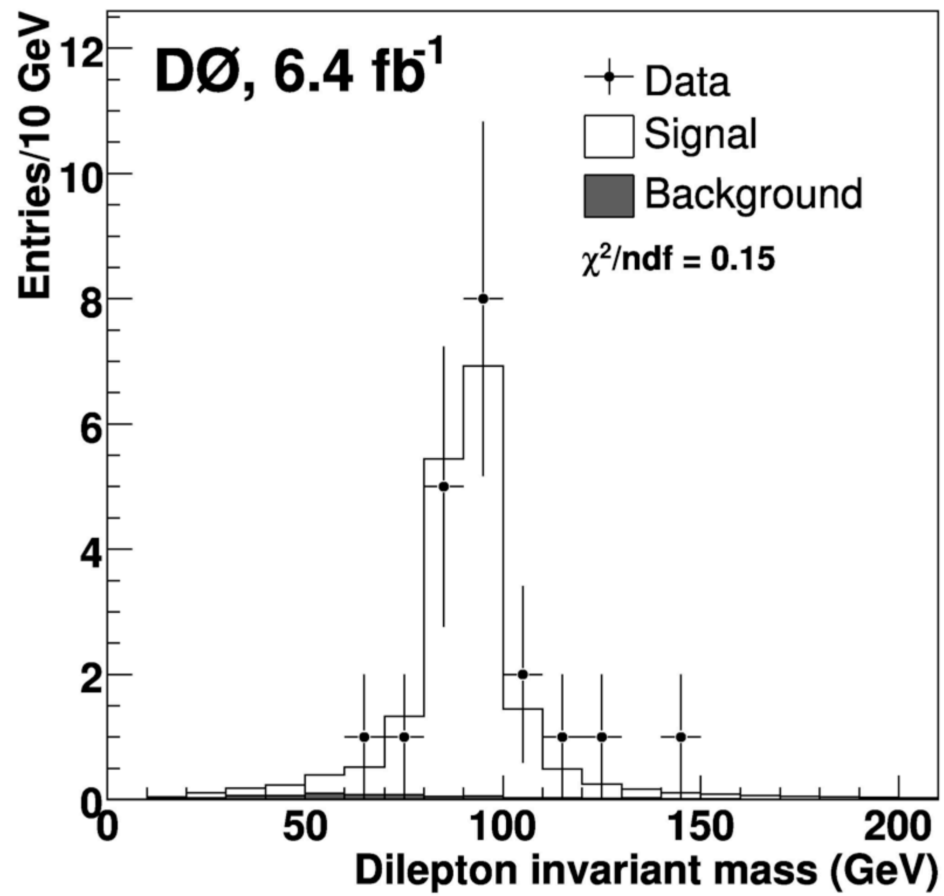
# ZZ→ℓ ℓ ℓ ℓ Production



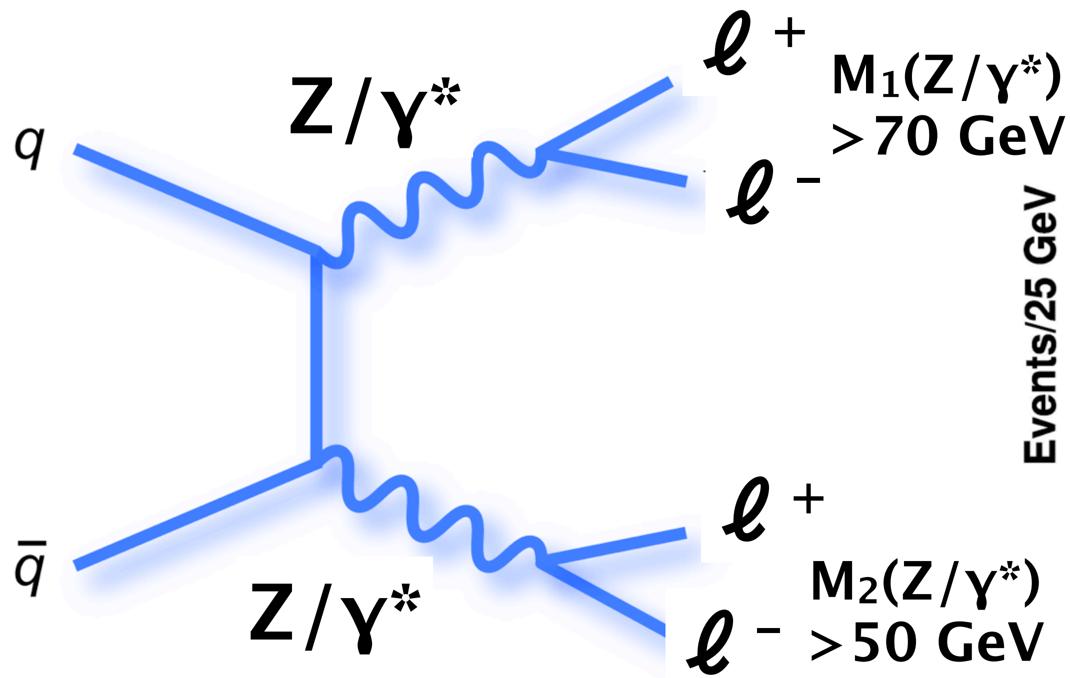

**important background to H→ZZ searches...**

- data: 10 events
- signal: 8.73±0.45
- background: 0.35±0.04 (jets faking electrons, muons in jets, top pair production)

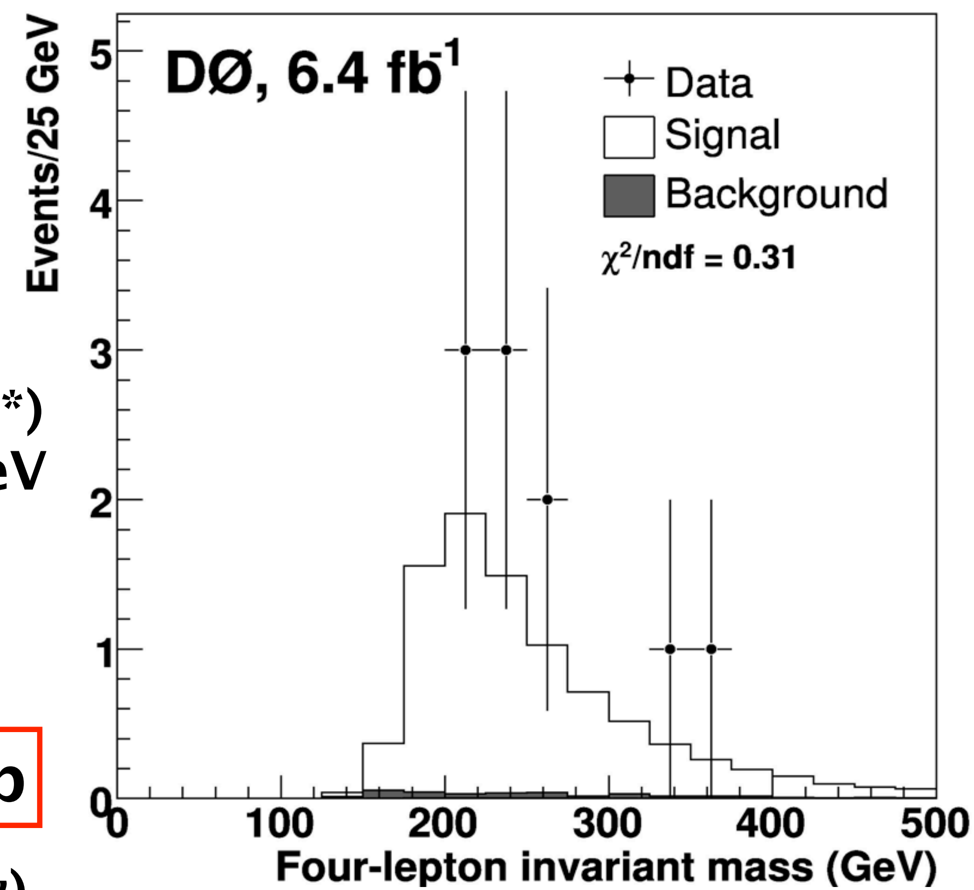
***eeee, eeμμ, μμμμ***



# $ZZ \to \ell\ell\ell\ell$ Production




***eeee, eeμμ, μμμμ***



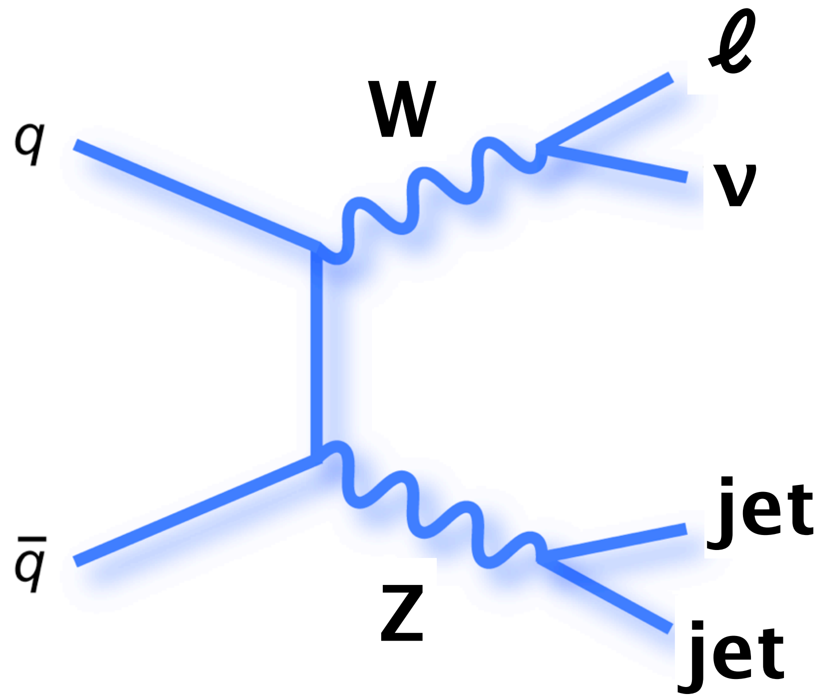

**SM: $\sigma(Z/\gamma^* Z/\gamma^*) = 1.4 \pm 0.1$ pb**

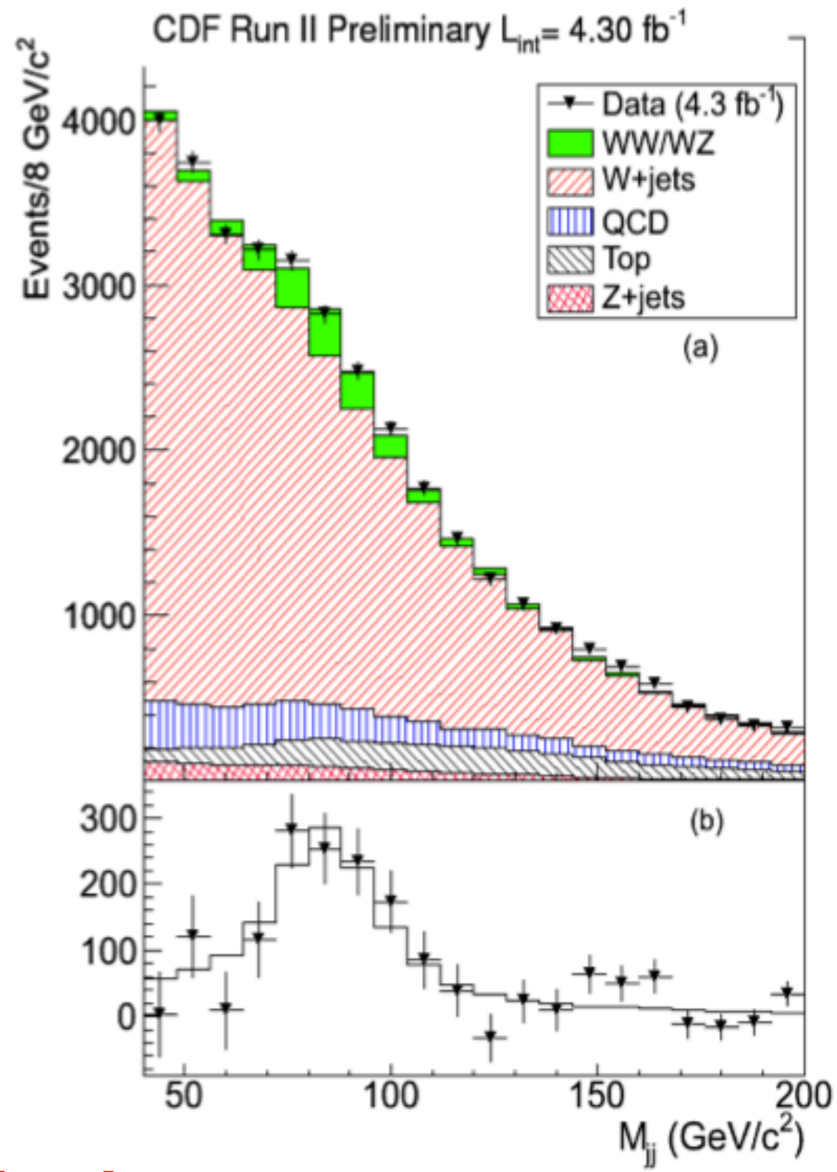
**$\sigma(p\bar{p} \to Z/\gamma^* Z/\gamma^*) = 1.40 \pm 0.42$pb**

(combined with $\ell\ell\nu\nu$)

**smallest cross section measured at hadron collider**

# WW/WZ Production



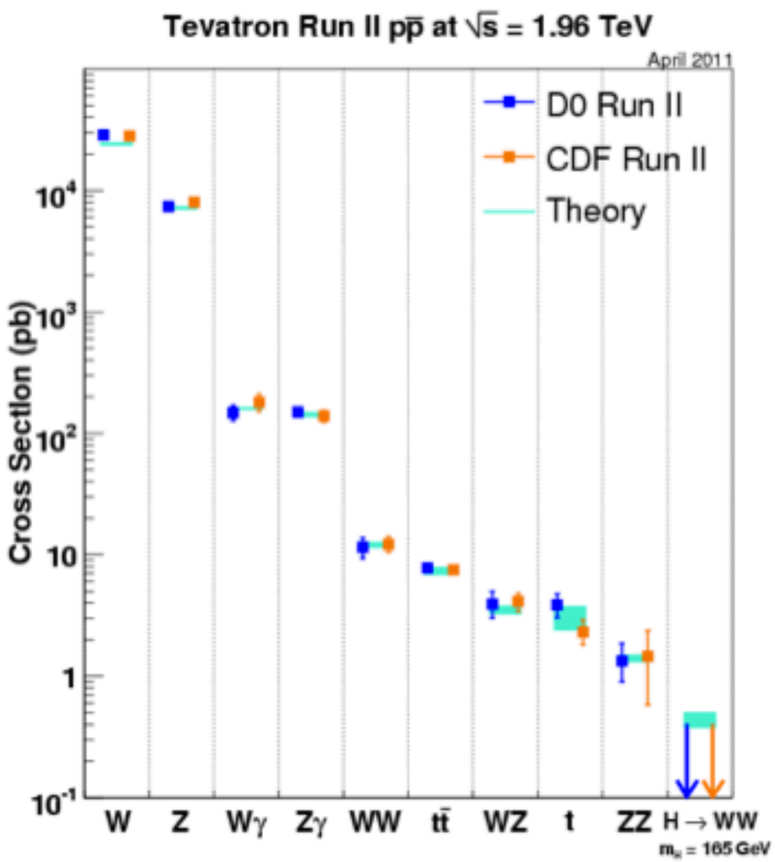

fit to dijet mass:

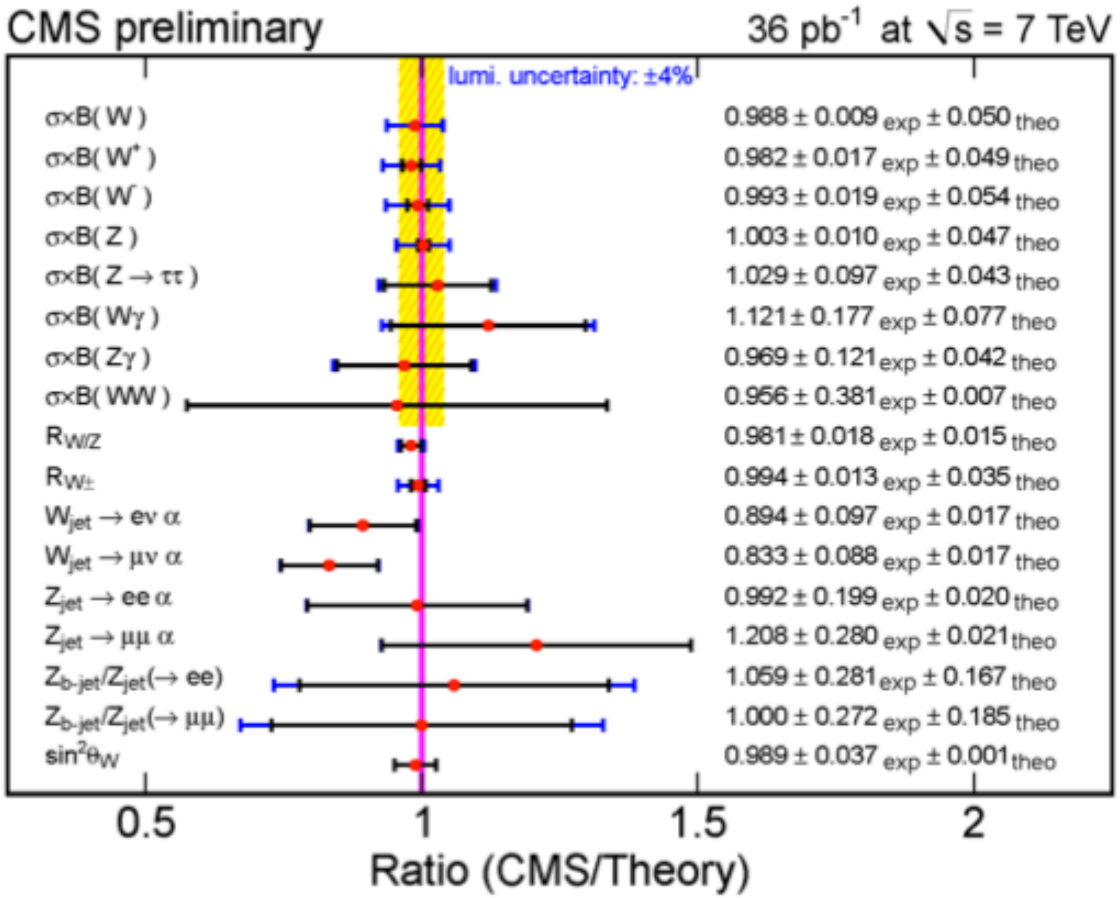
$\sigma(\bar{p}p \rightarrow WW/WZ) = 18.1 \pm 4.1 pb$

SM: $\sigma(WW/WZ) = 15.9 \pm 0.9$ pb

**Albert will discuss the bump...**

# Electroweak Cross Sections: Summary

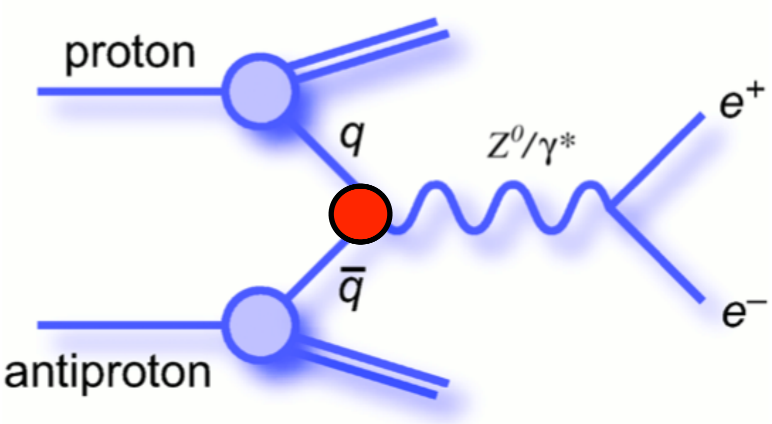


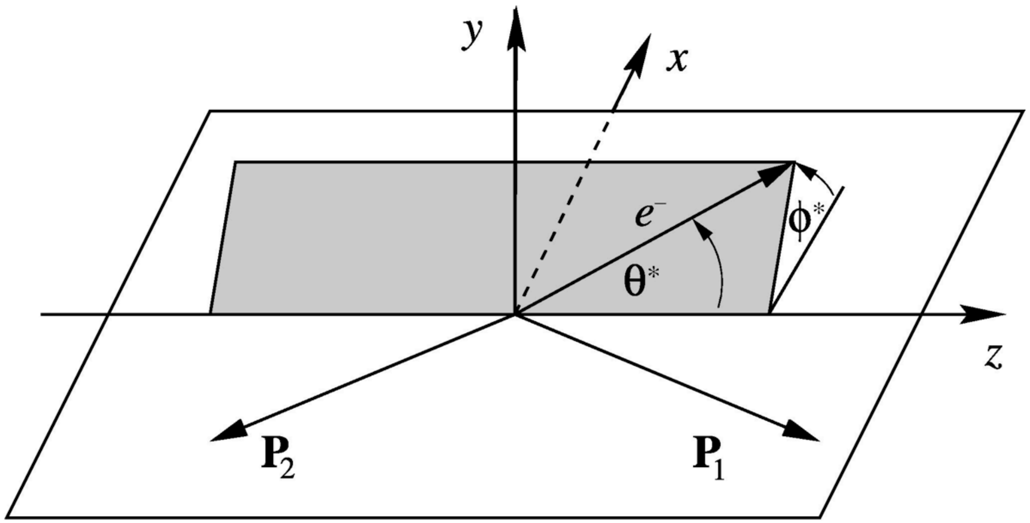

**LHC: impressive progress (including τs, diboson)**

**Tevatron: measured cross sections O(1 pb)**

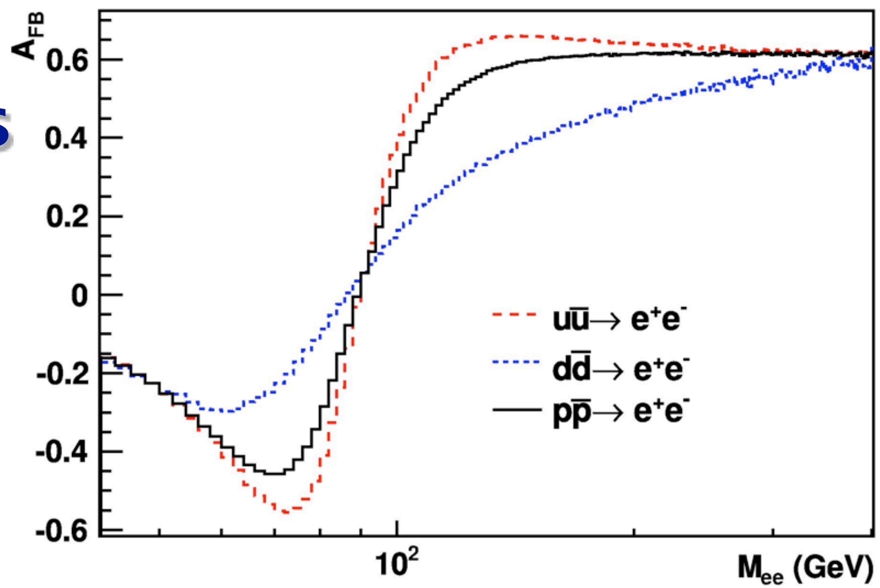
# Z Boson-Quark Couplings



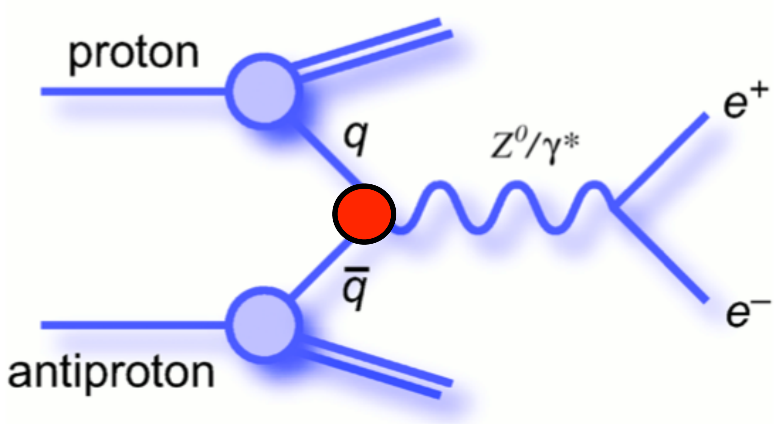

$$g_V^f = I_3^f - 2Q_f \cdot \sin^2\theta_W$$
$$g_A^f = I_3^f$$

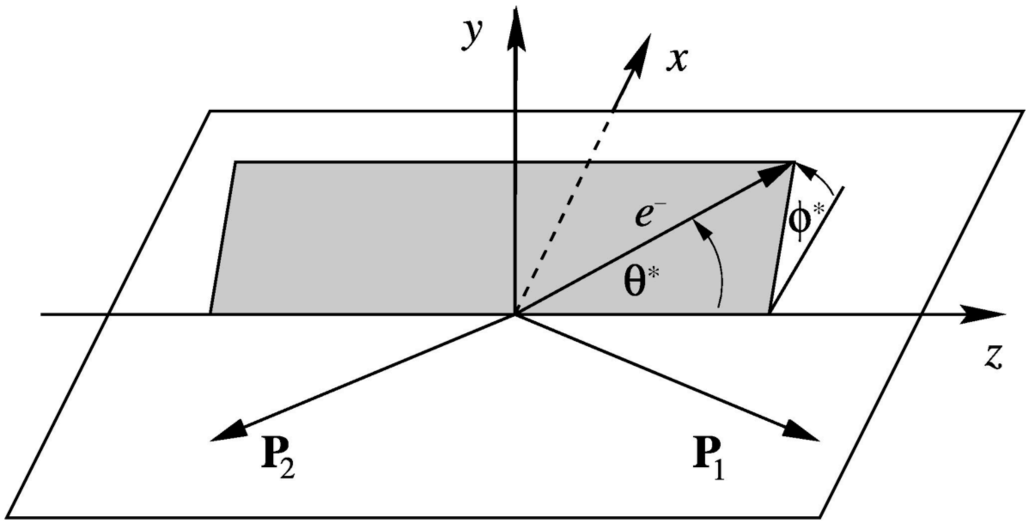



**T reversed process compared to LEP**



# Z Boson-Quark Couplings

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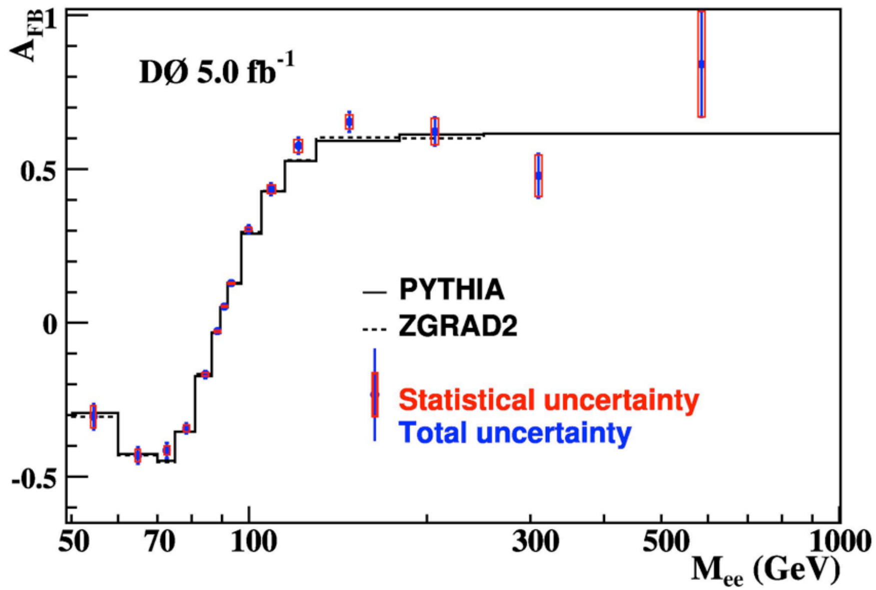
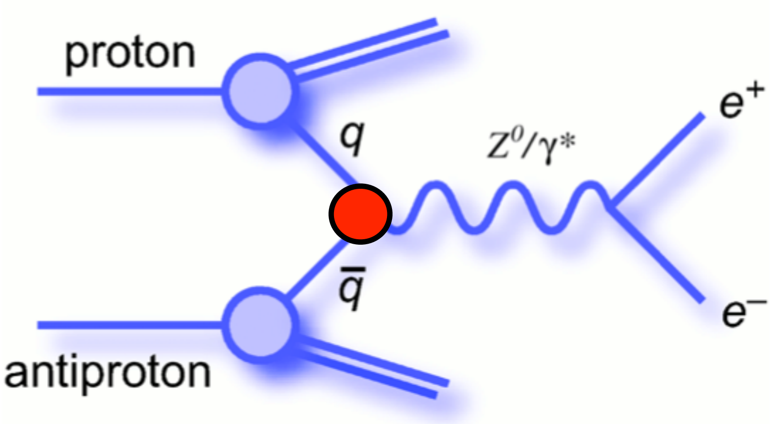


# Z Boson-Quark Couplings

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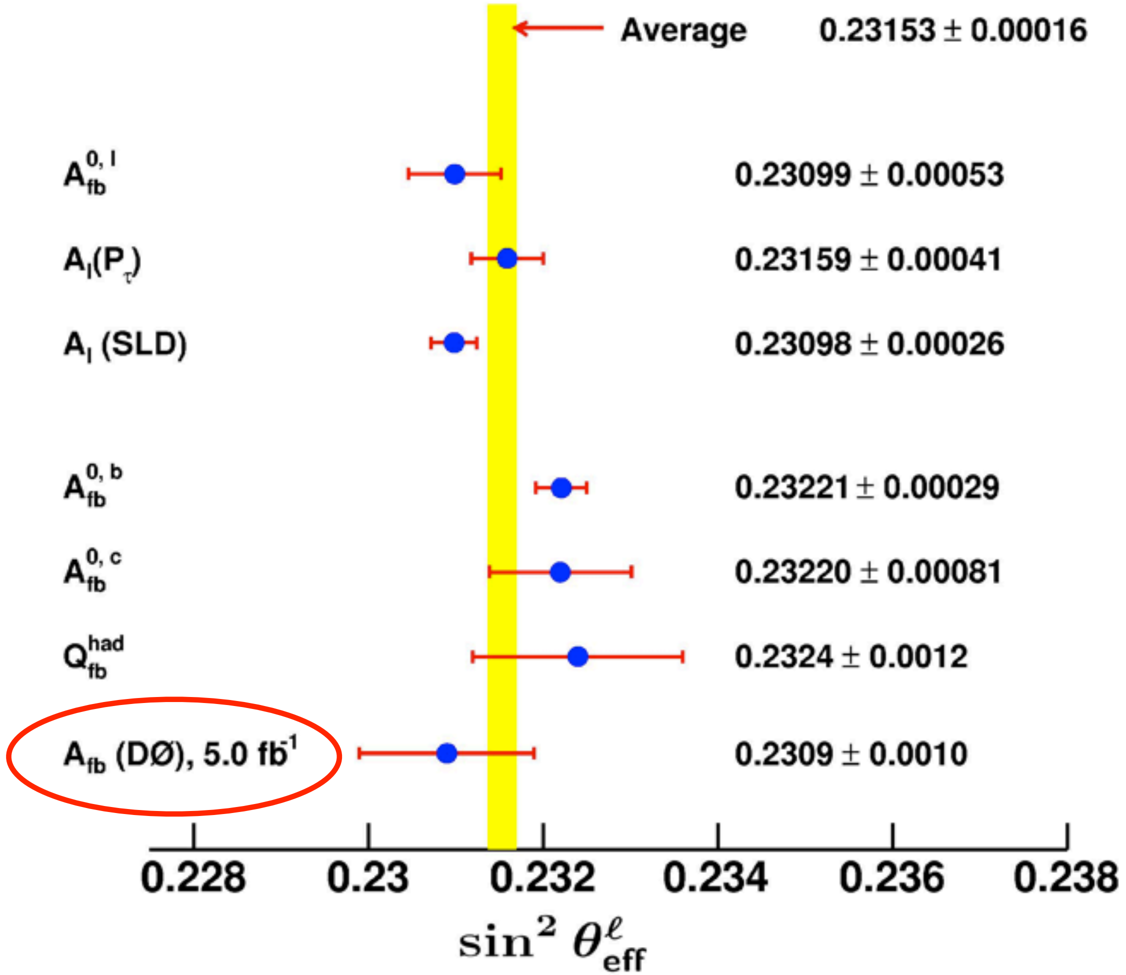
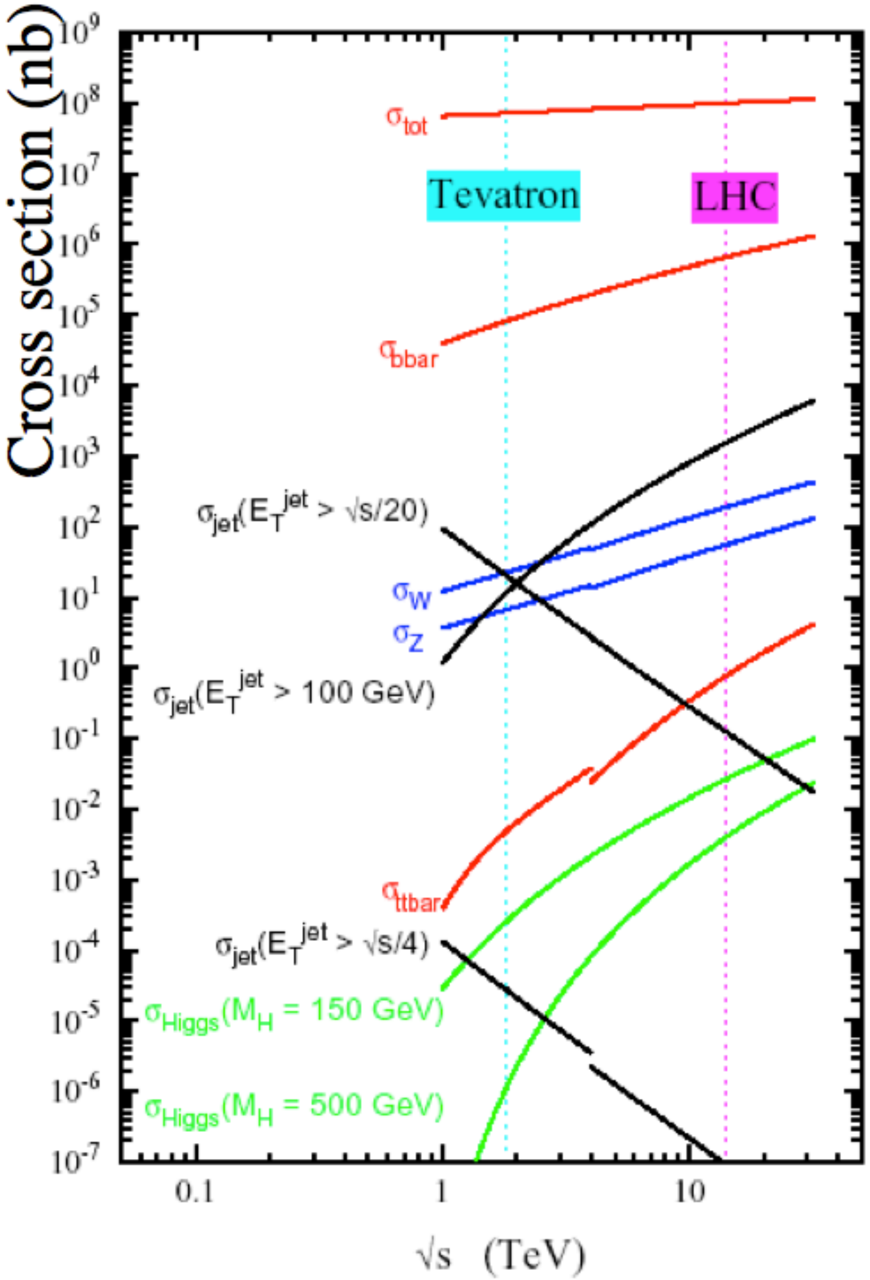
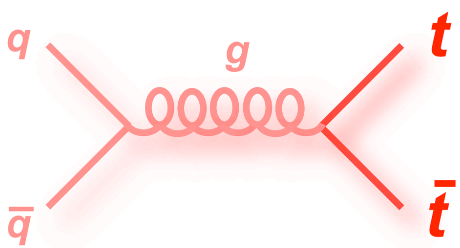



**surpassed LEP precision using inclusive jets**

# Outline



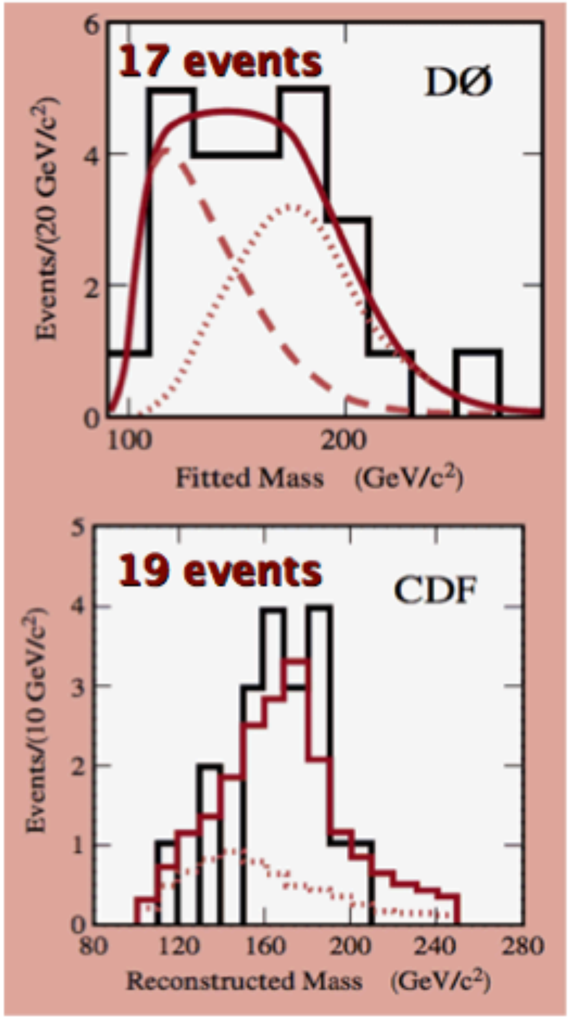




**top quark**

# Top Quark

**discovery**

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

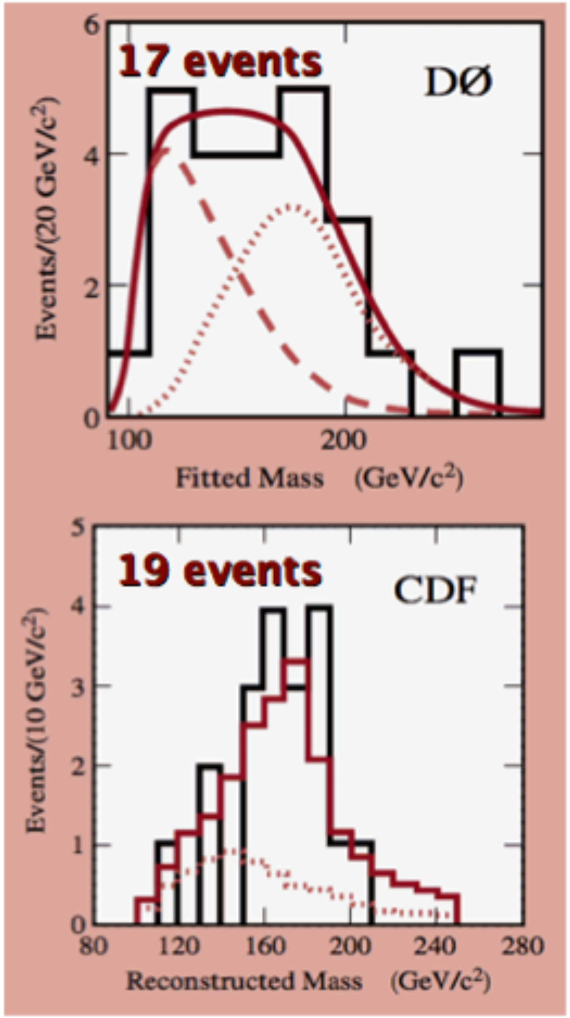



**1995, CDF and DØ experiments, Fermilab**

# Top Quark

**discovery**

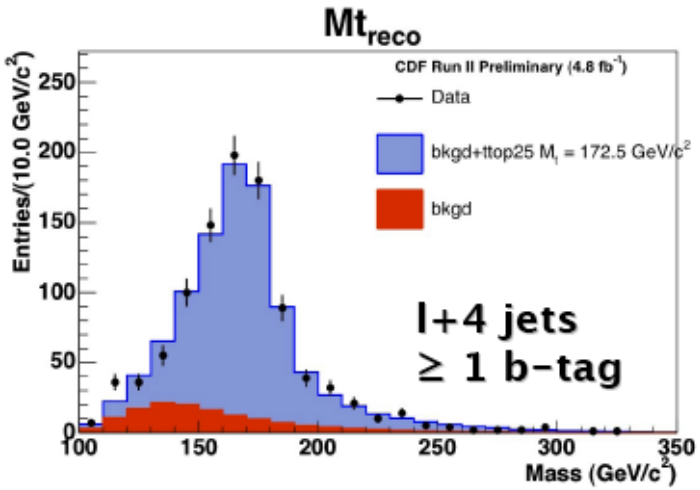
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)




**1995, CDF and DØ experiments, Fermilab**

**today**

**~1000 events**

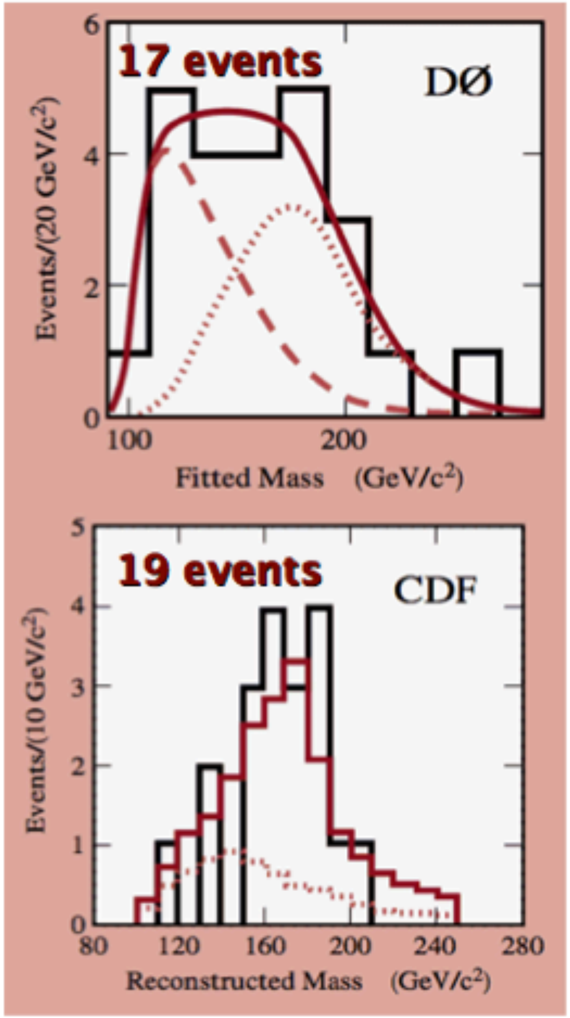


# Top Quark

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

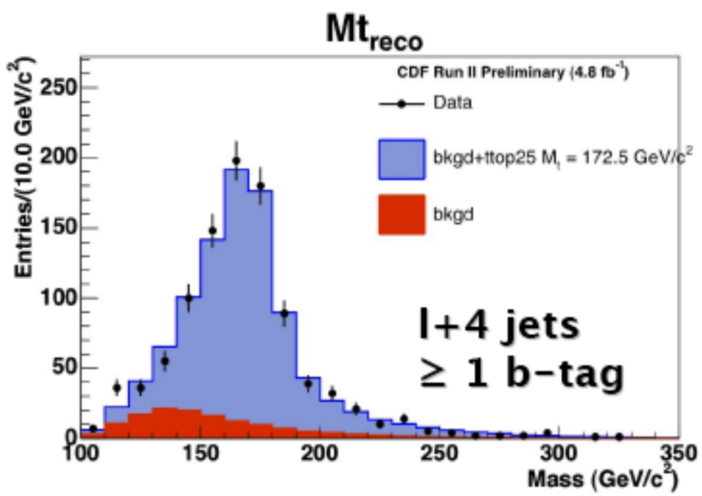
**today**

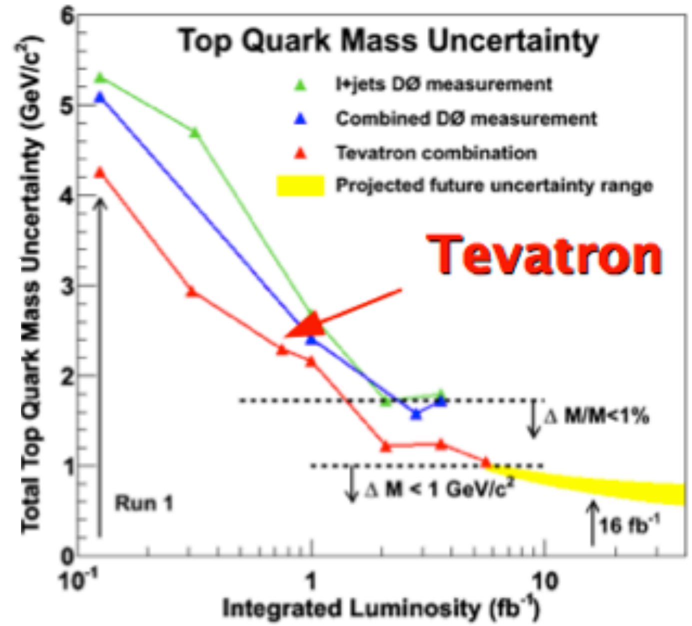
**precision**




**1995, CDF and DØ experiments, Fermilab**

~1000 events



# Top Quark

**discovery**

PRL 74, 2632 (1995)
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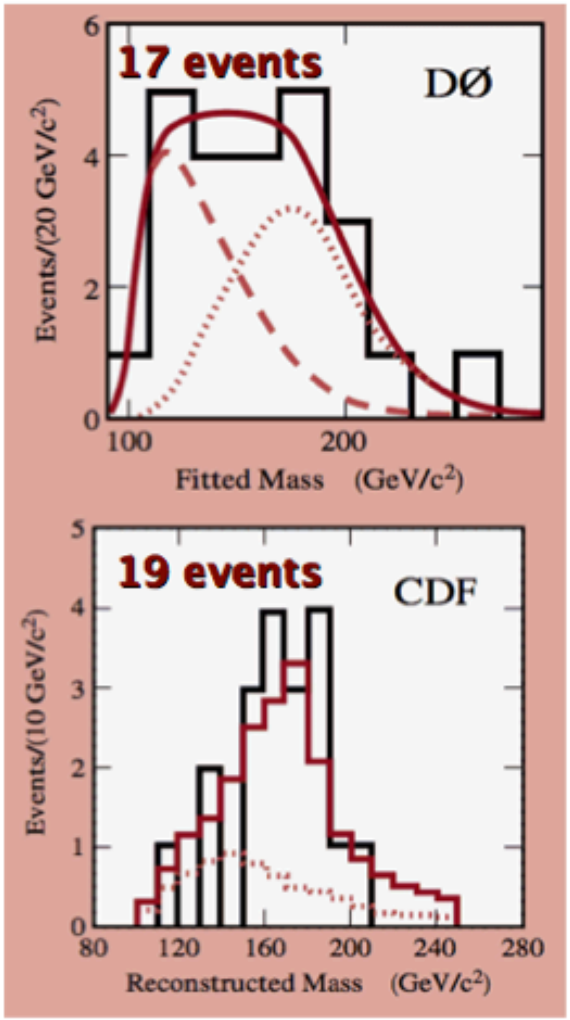
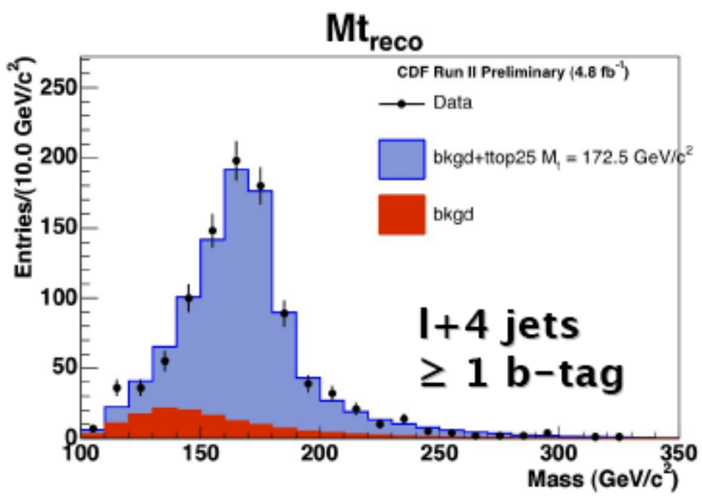


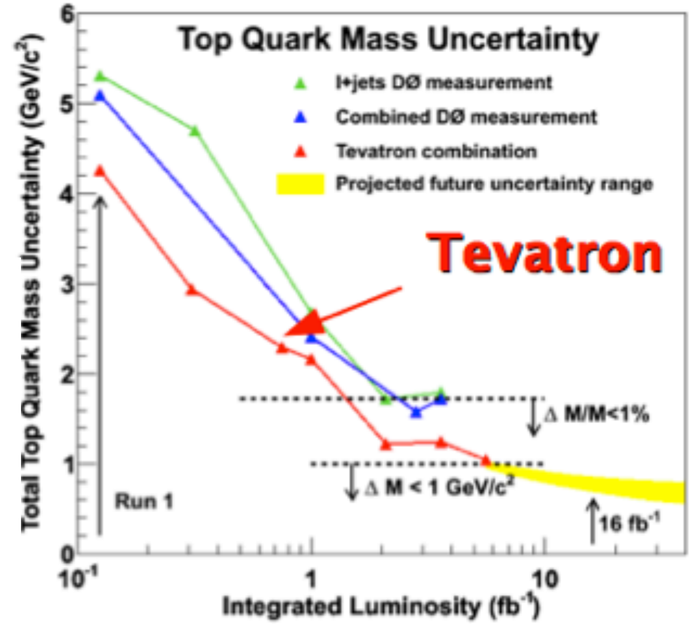

**1995, CDF and DØ experiments, Fermilab**

**today**

**~1000 events**



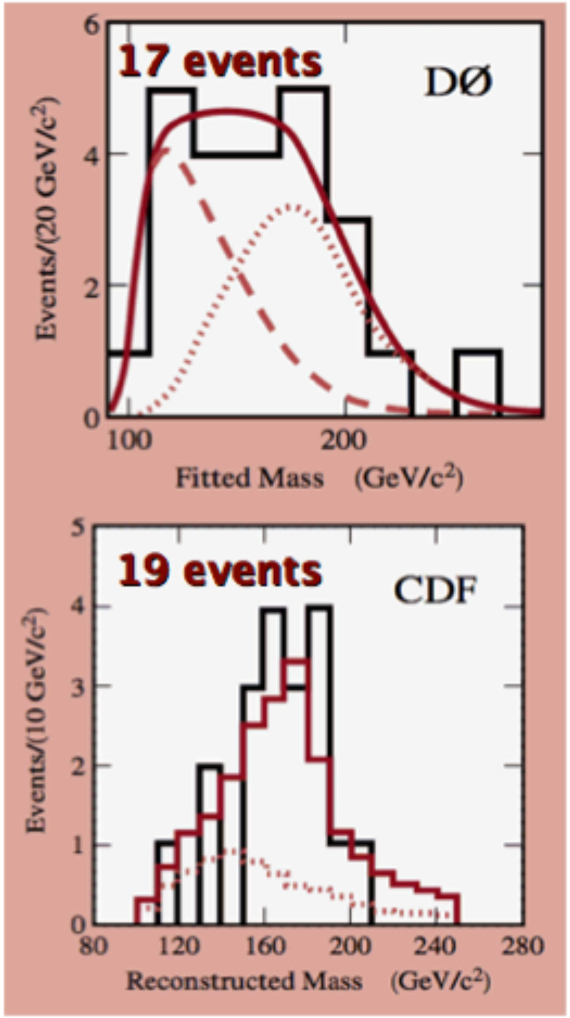

**precision**




**searches**

# Top Quark

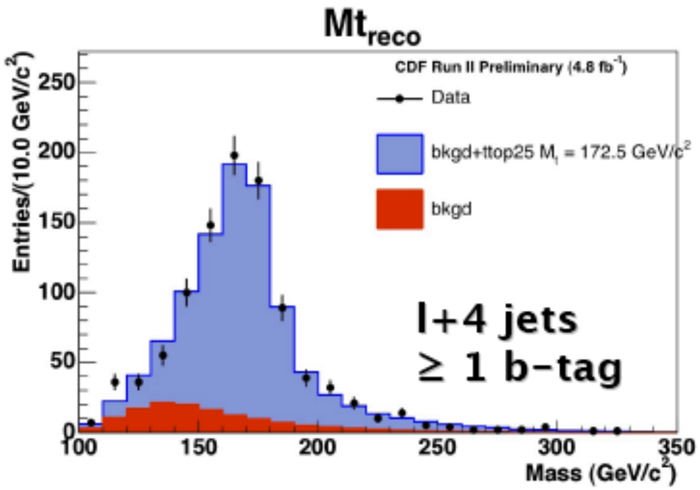
**discovery** PRL 74, 2632 (1995)
PRL 74, 2626 (1995)




1995, CDF and DØ experiments, Fermilab

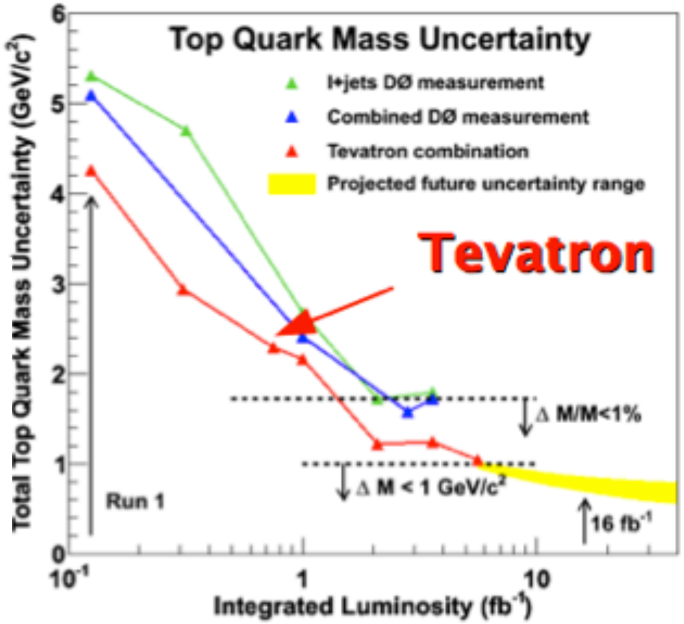
**today**

~1000 events



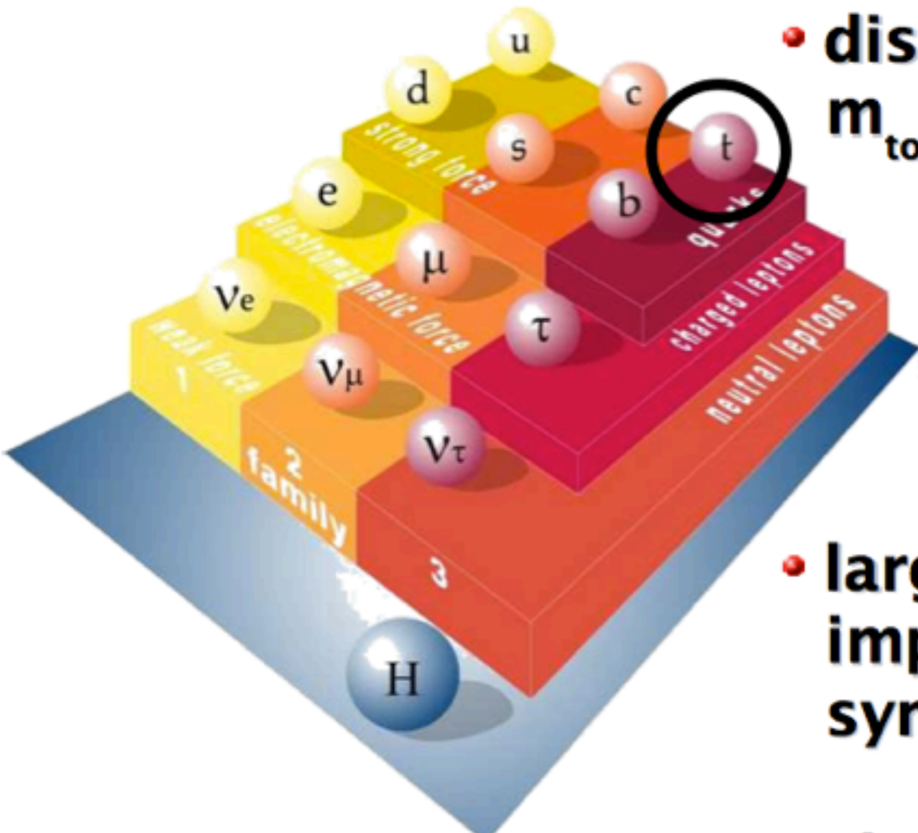

**LHC: top quark factory**

**precision**



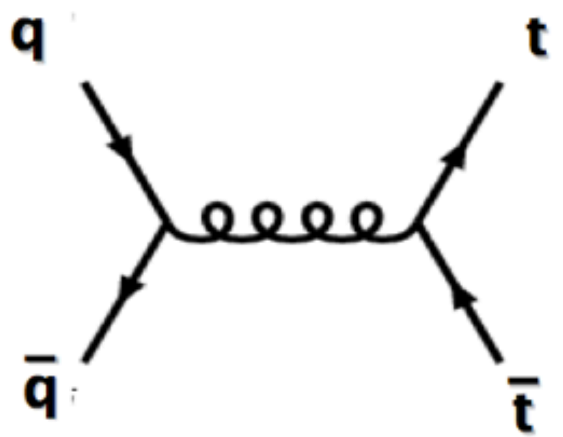

**searches**

# The Top Quark

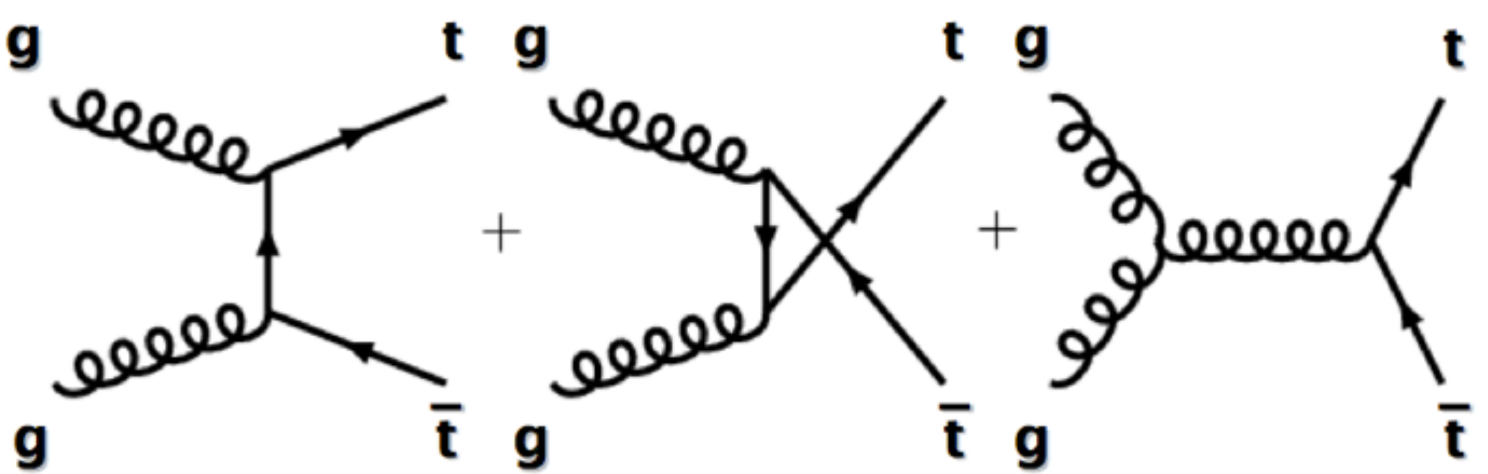



- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: $m_{top}$ ~ gold atom
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$: decays before fragmenting
  → observe “naked”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

# Top Quark Pair Production




**Tevatron (85%)**

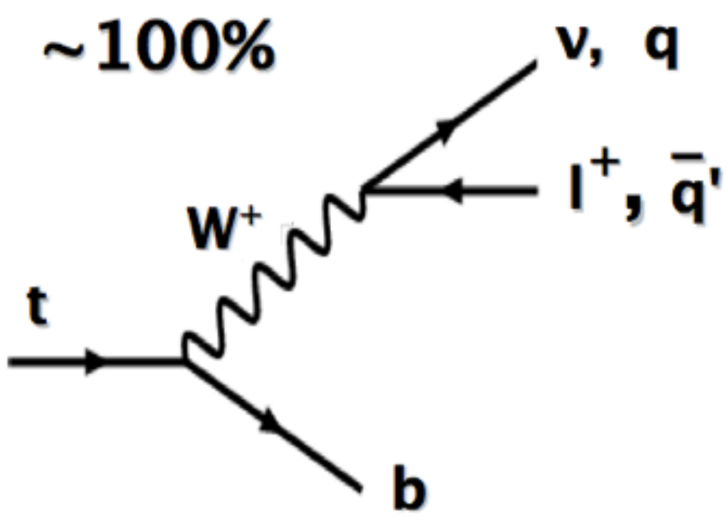


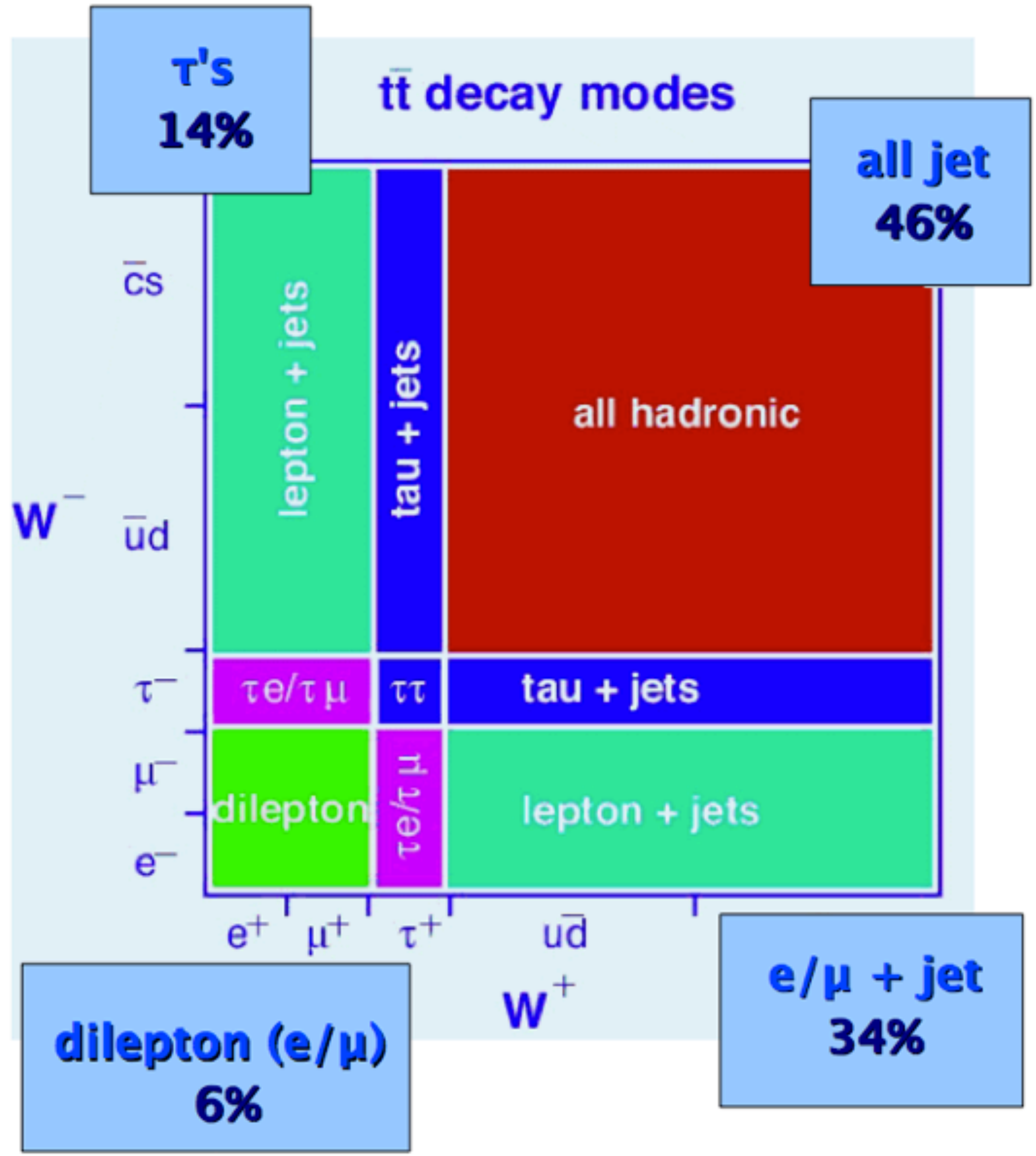

**LHC (87%)**

# Top Quark Pair Signatures

**top decay:**

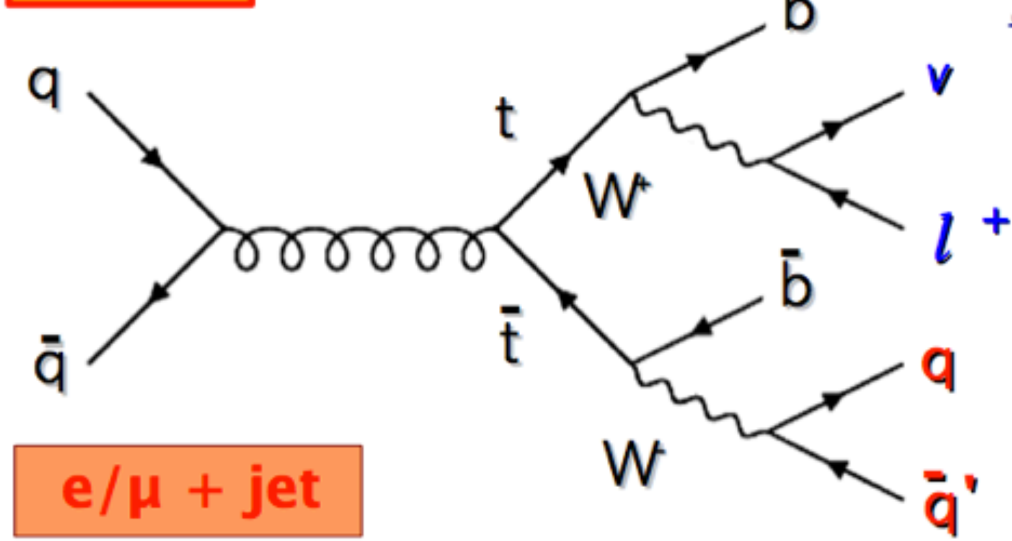
~100%



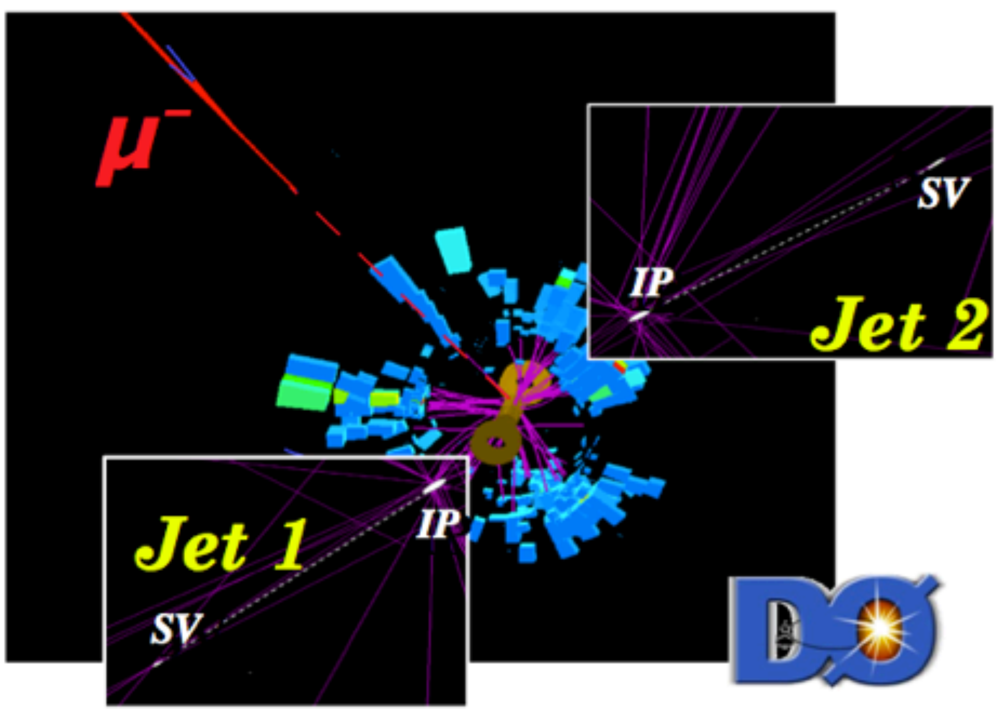



# Lepton+jets Signatures

**Signal**

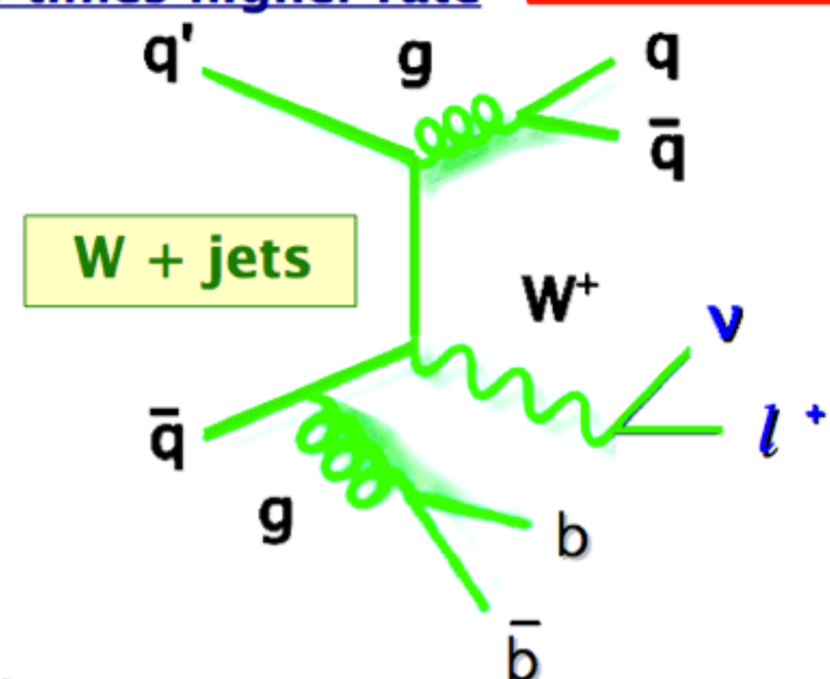



**e/μ + jet**

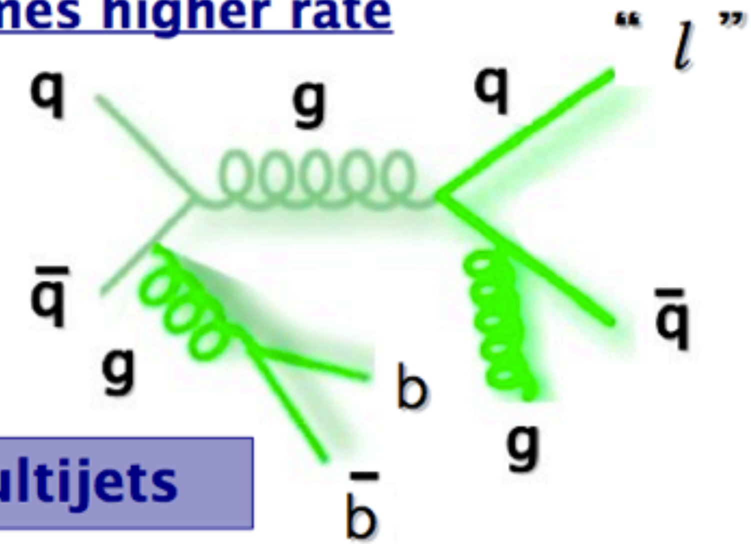



3000 times higher rate

**background**




$10^{10}$ times higher rate



# 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:**

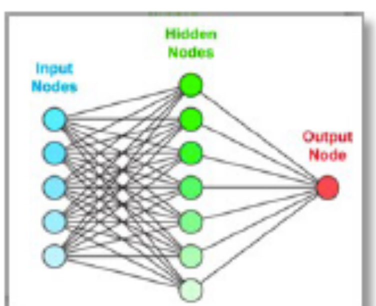
**energy-dependent quantities:**

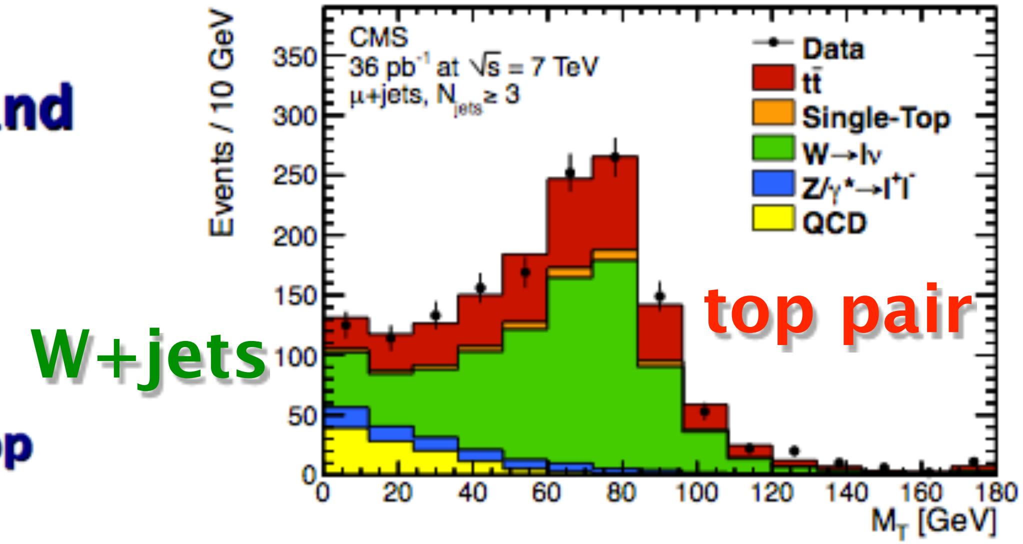
- **e.g. Transverse mass of leptonic top**

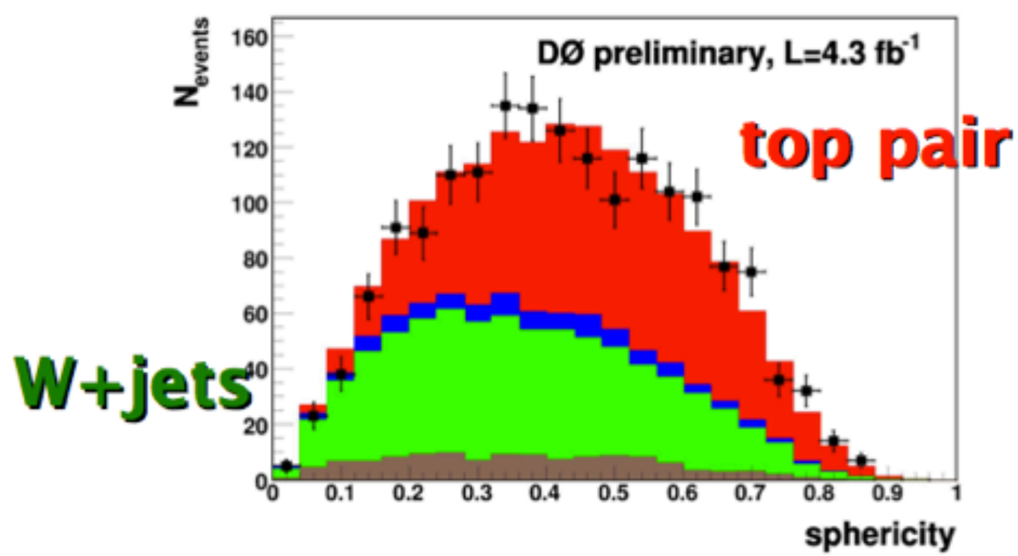
**angular dependent:**

- **e.g. sphericity**

→ Neural Networks



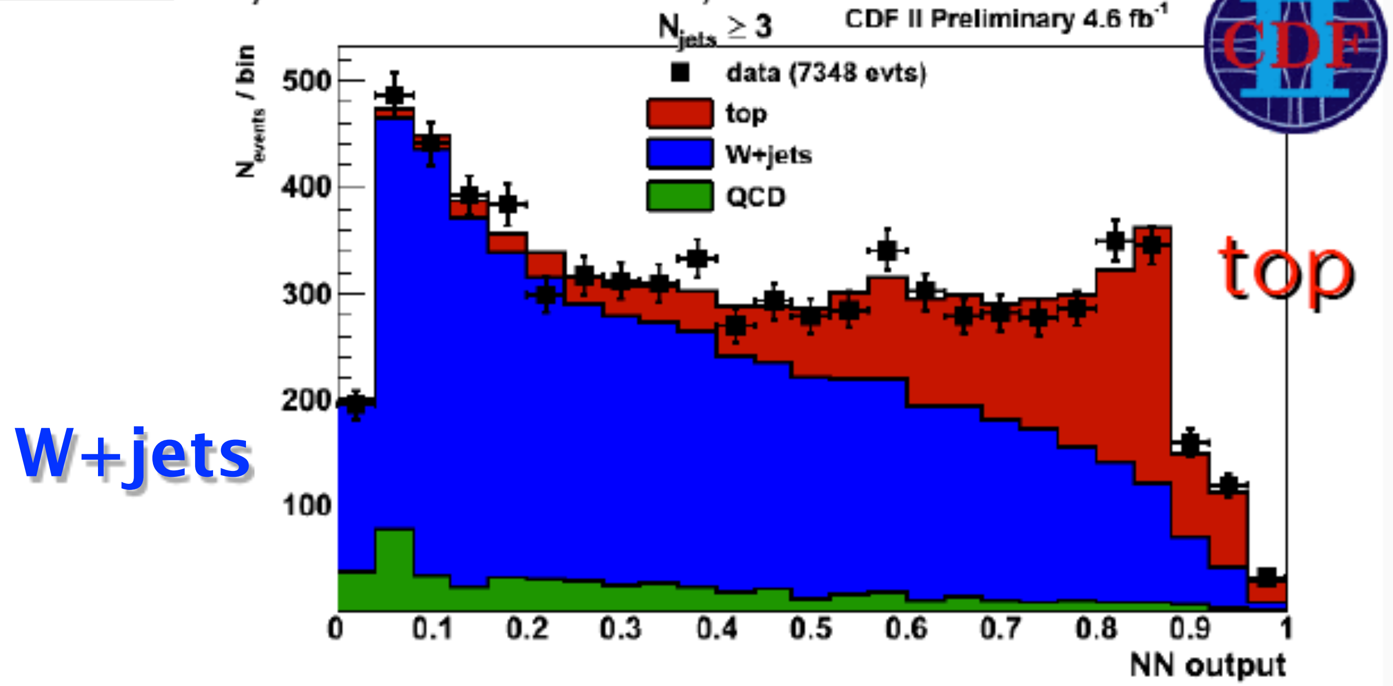



# Lepton+Jets Topological Cross Section

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

**topological information (NN)**

Phys.Rev.Lett.105:012001,2010

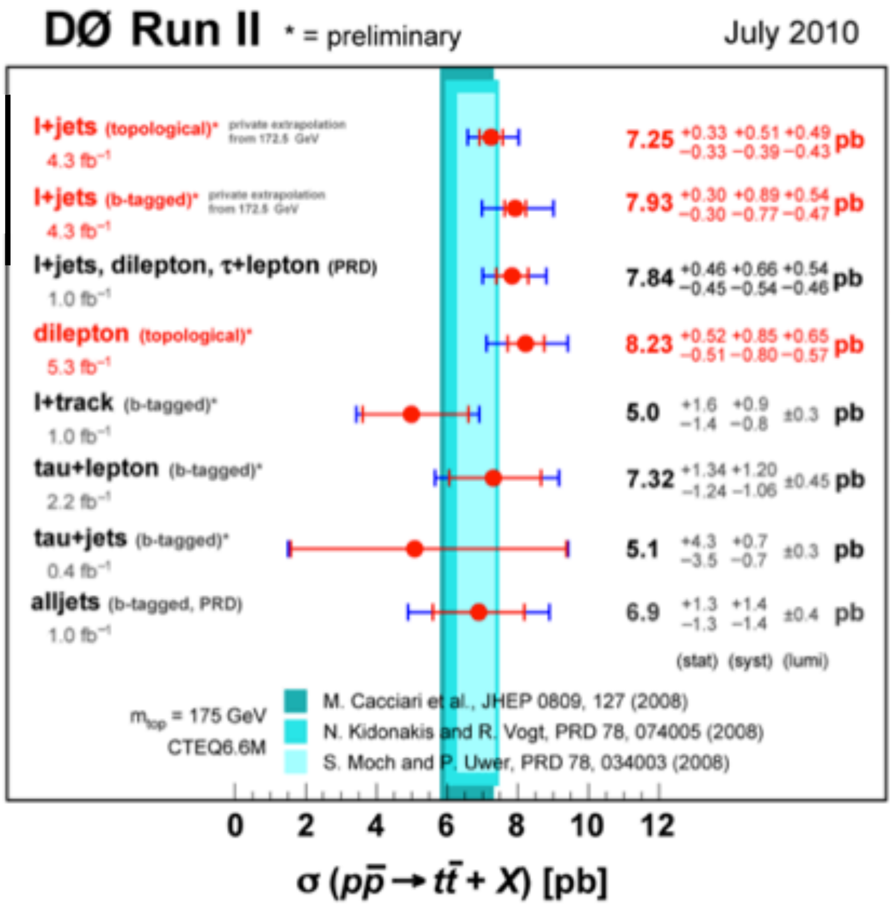


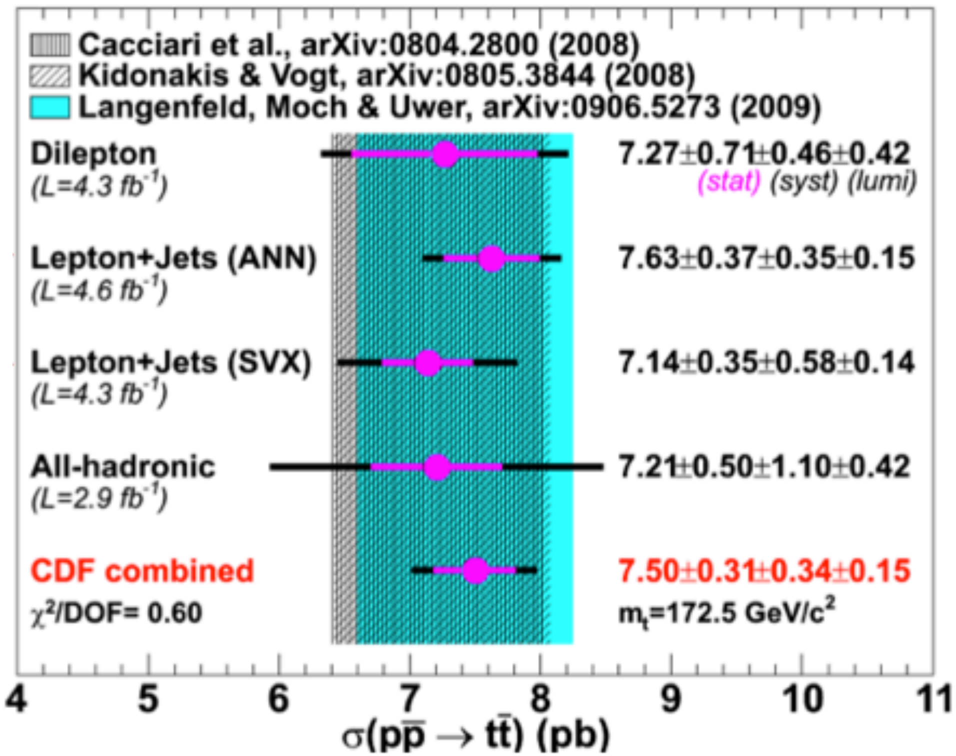

$\sigma_{t\bar{t}}$ = 7.82 ± 0.38 (stat) ± 0.37 (syst) ± 0.15 (Z theory) pb

$m_{top}$ = 172.5 GeV

**±7%**

# Top Pair Production Cross Section



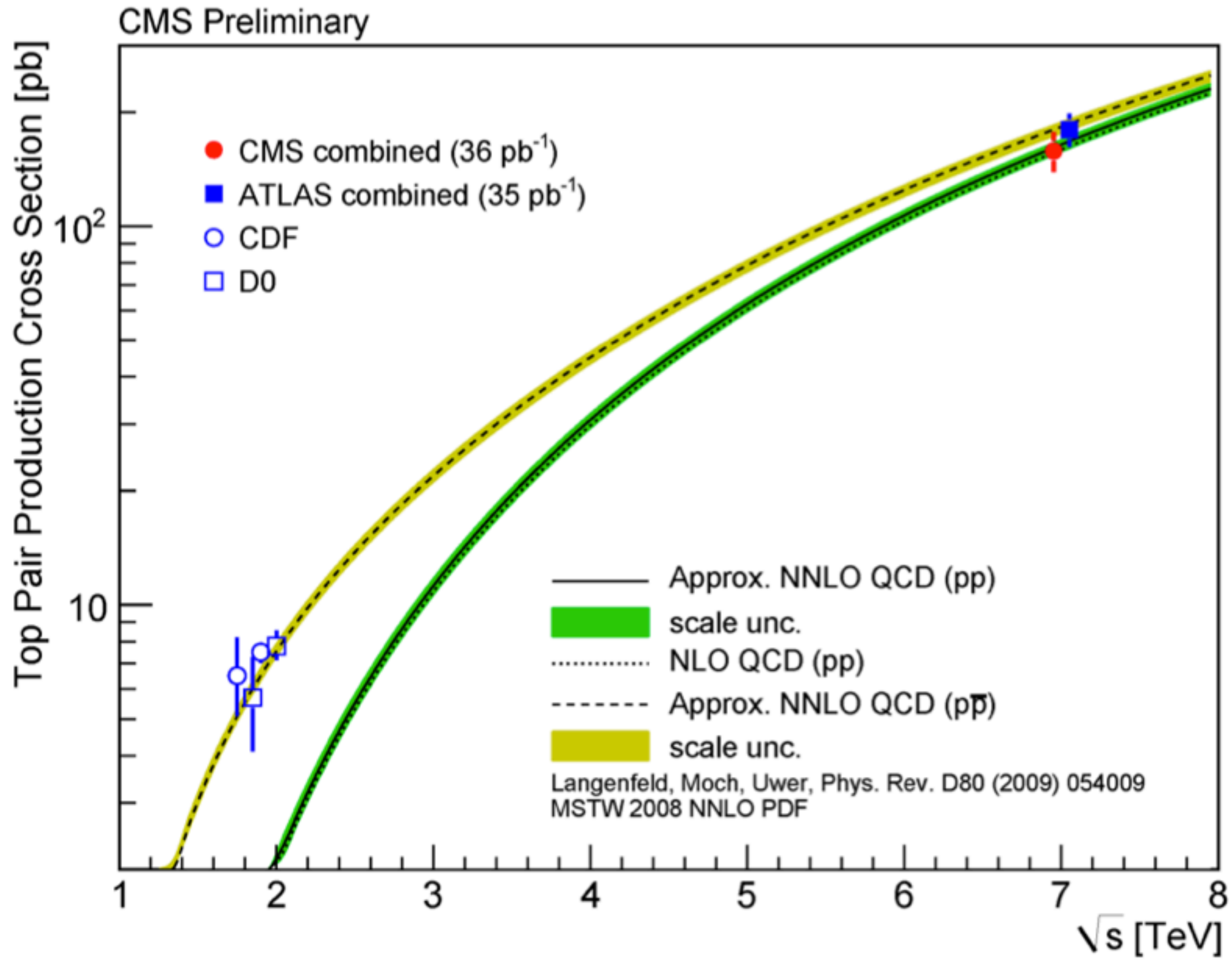




**all channels measured except for $\tau_{had}\ \tau_{had}$**

**combination: ±6% !**

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

# Top Pair Production Cross Section

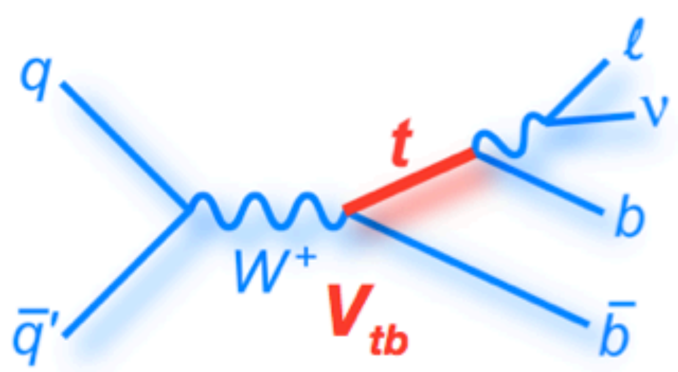



⟹ **good agreement with SM**

# Single Top Quark Production

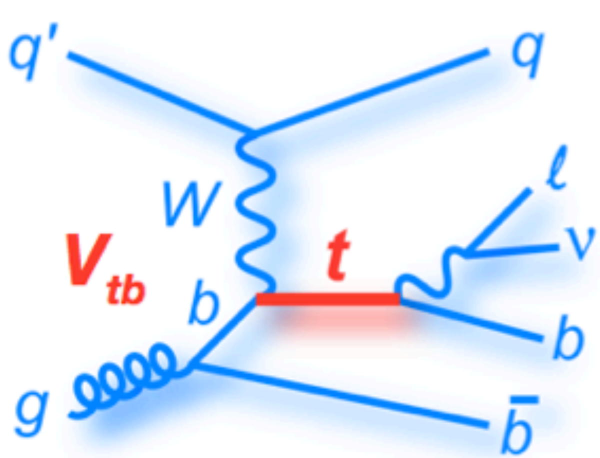
**direct measurement of $|V_{tb}|$**

**s-channel:**

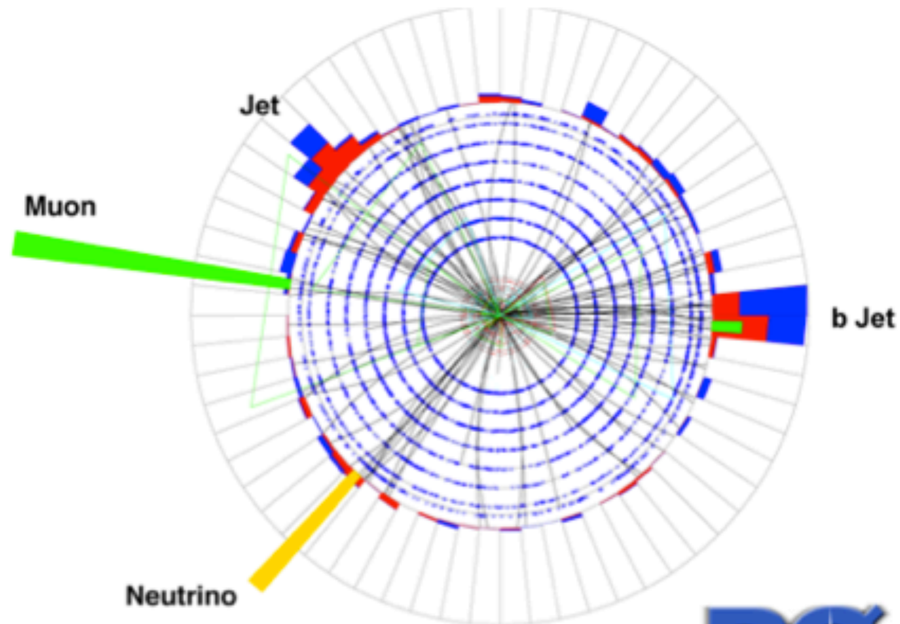



$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

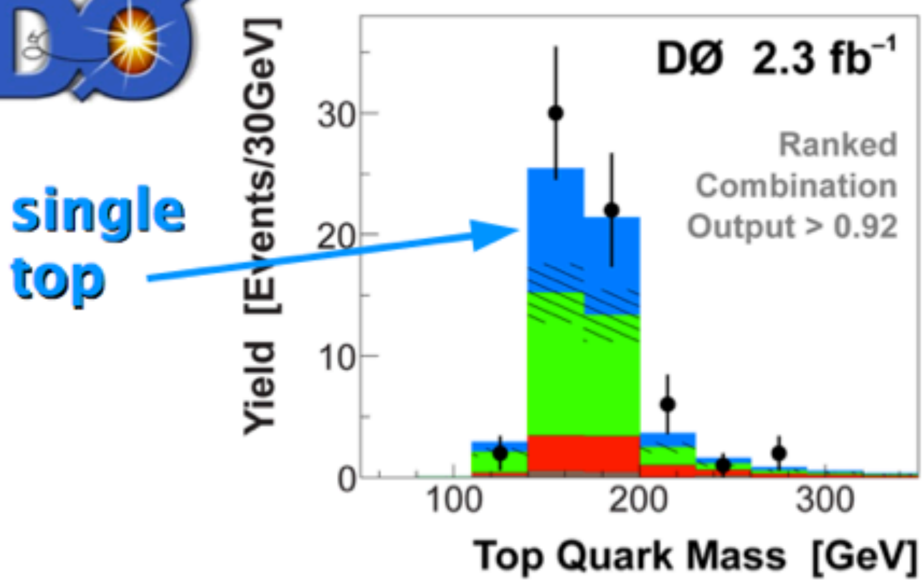
**t-channel:**

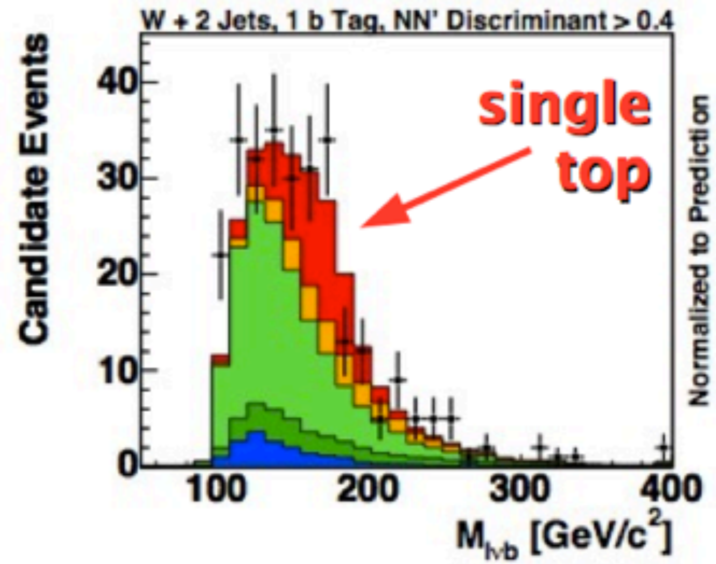


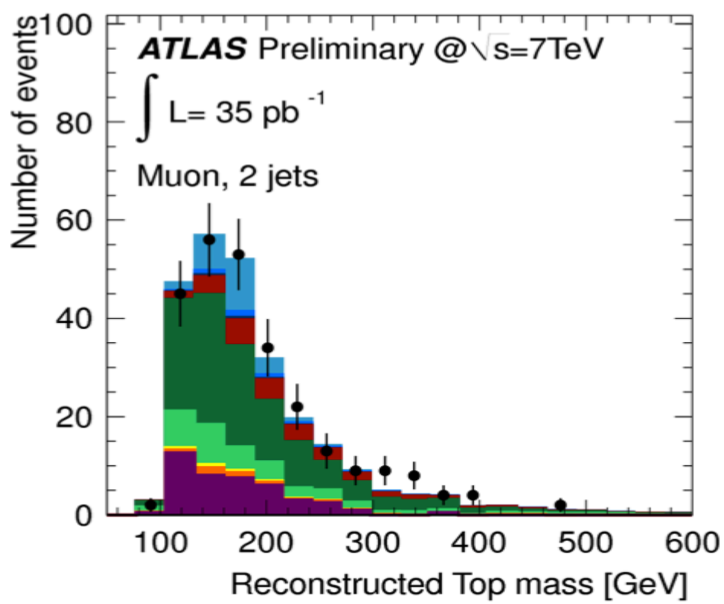

- **jets**
- **lepton**
- **missing $E_T$**
- **b-jets**

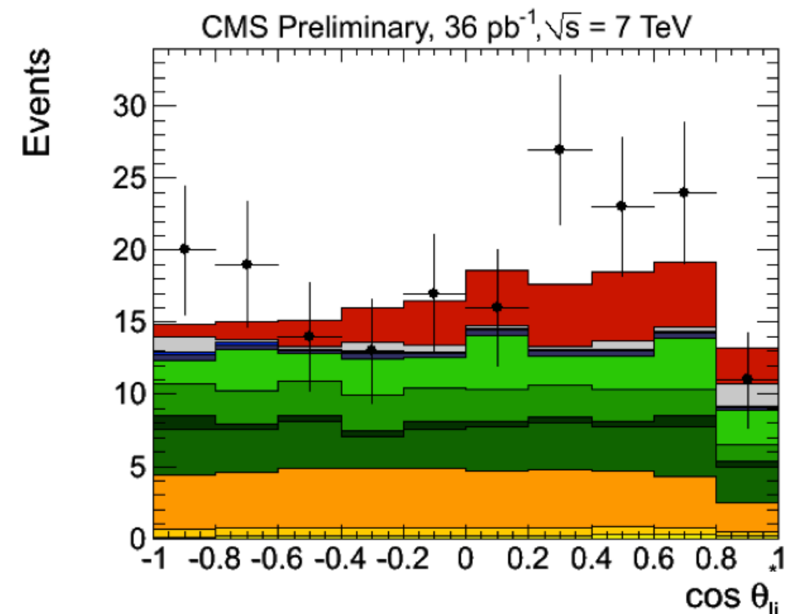


# Single Top Production



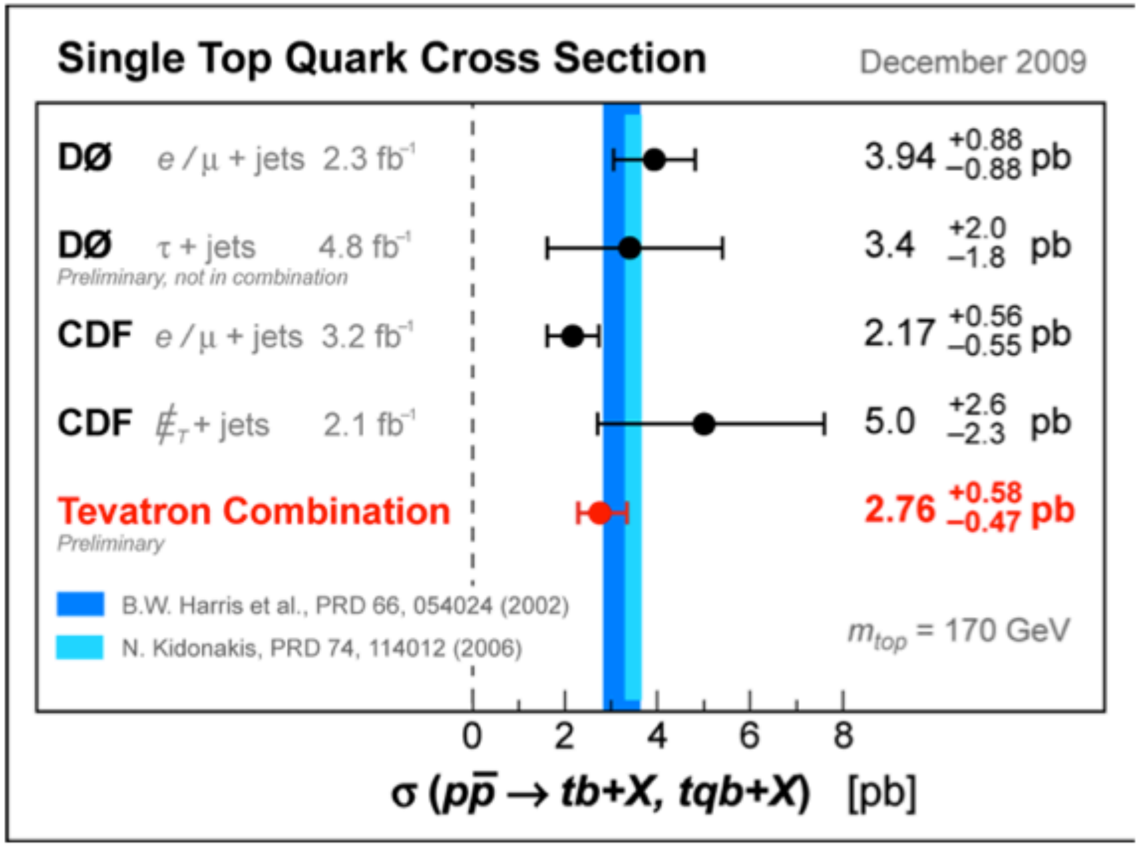



# Tevatron Single Top Cross Section

**use multivariate analysis techniques**




**5σ observation**

**5σ observation**

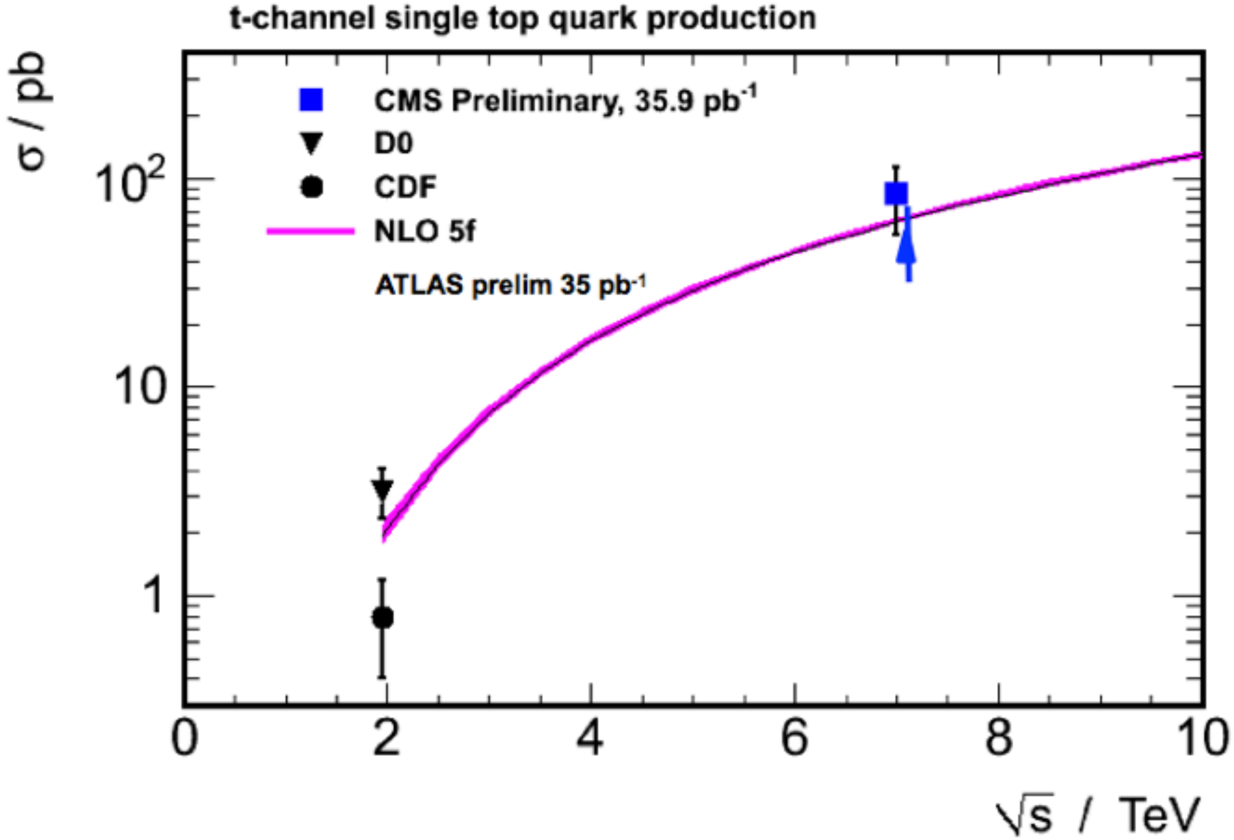
$$|V_{tb}| = 0.88 \pm 0.07$$

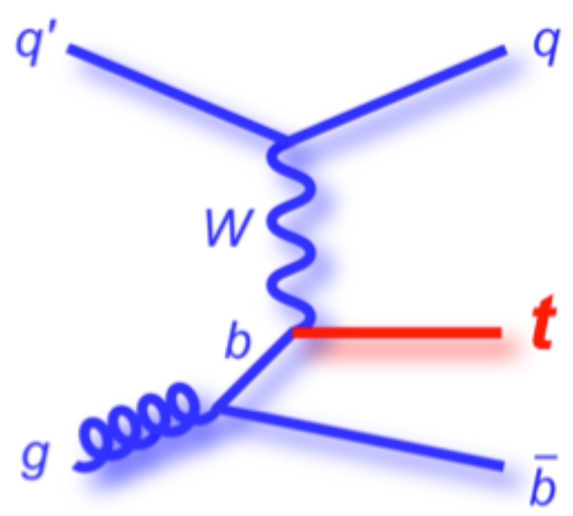
⟹ **good agreement with SM in all channels**

# t-channel Single Top Quark Production

ATLAS: $\sigma_t = 53^{+27}_{-24}\,(stat)\,^{+38}_{-27}\,(syst)$ pb

CMS: $\sigma_s = 83.6 \pm 29.8\,(stat+sys) \pm 3.3(lumi)$ pb

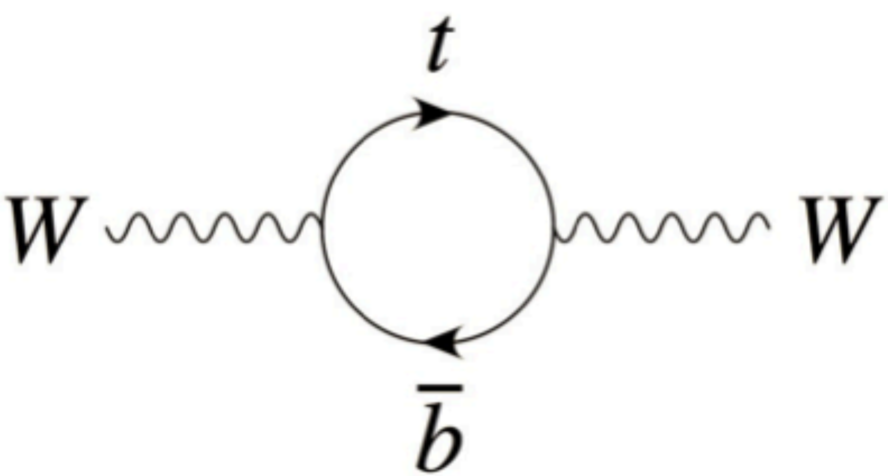


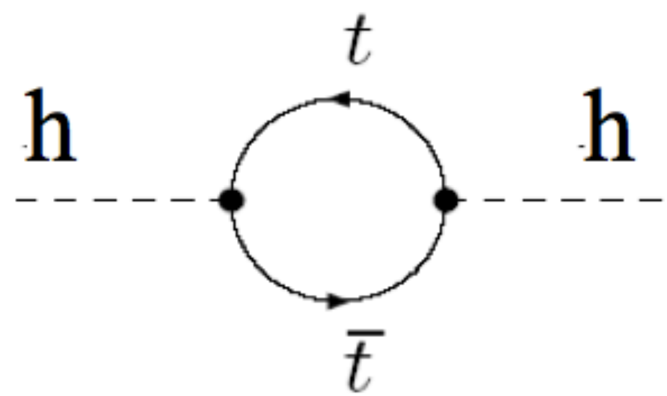



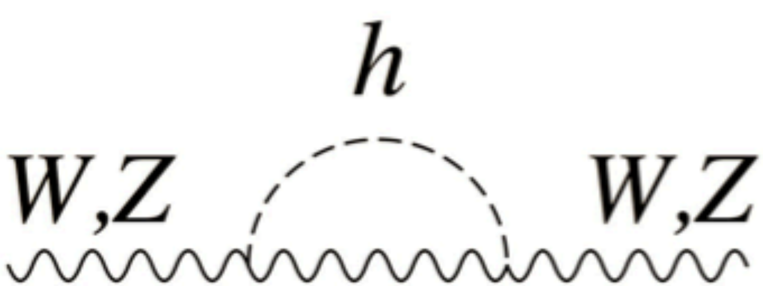

Na

# Future Legacy: Top 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



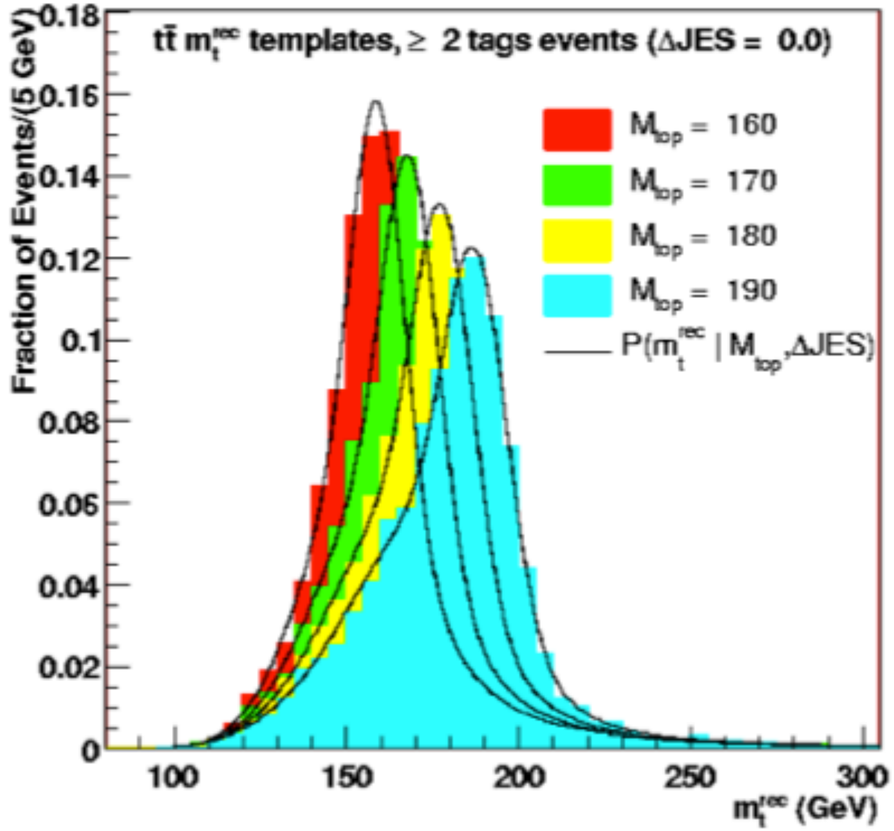



# Extraction Techniques: Templates

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

all hadronic



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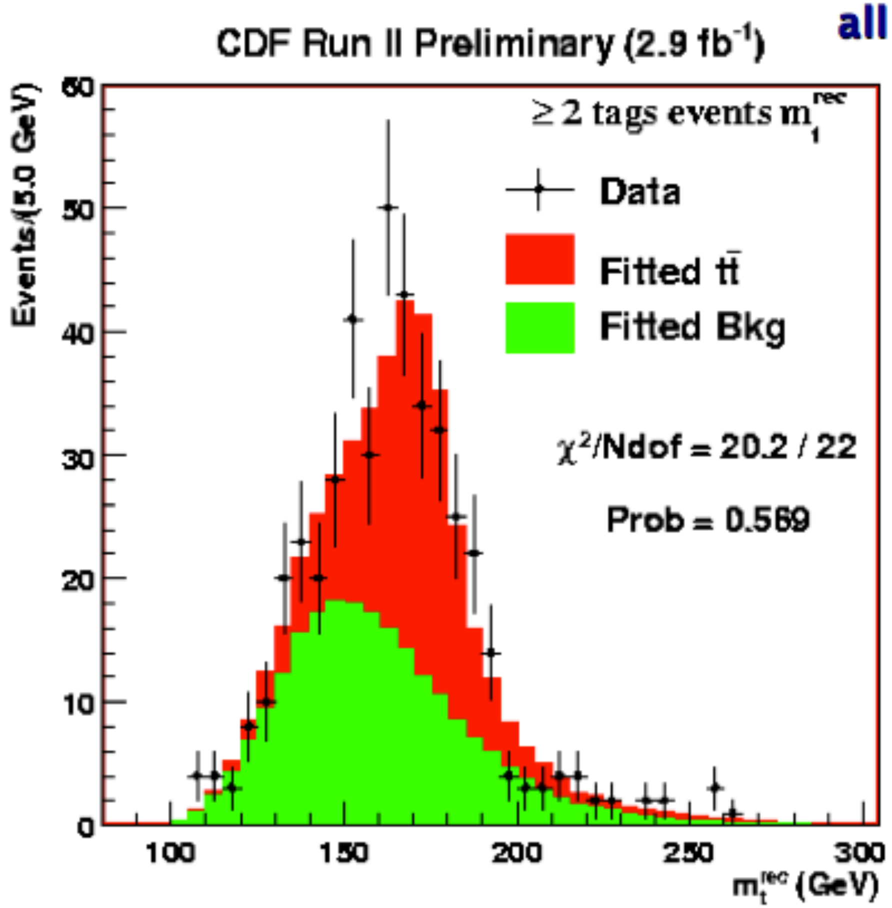
**all hadronic**



# Extraction Techniques: Templates

- use variables strongly correlated with $m_{top}$
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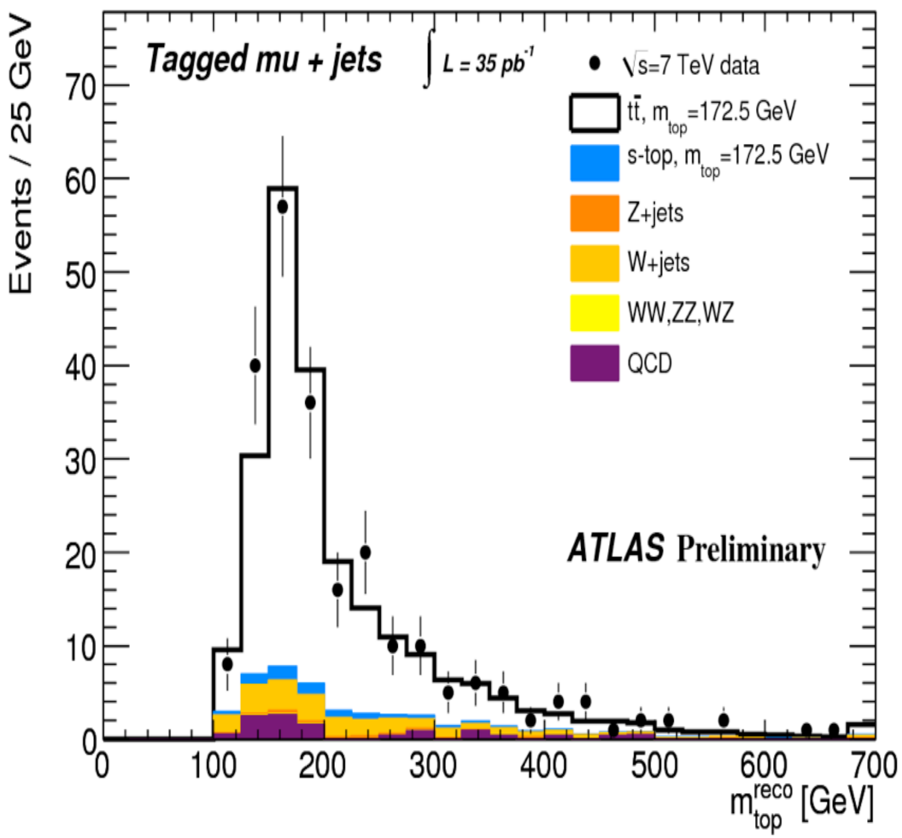
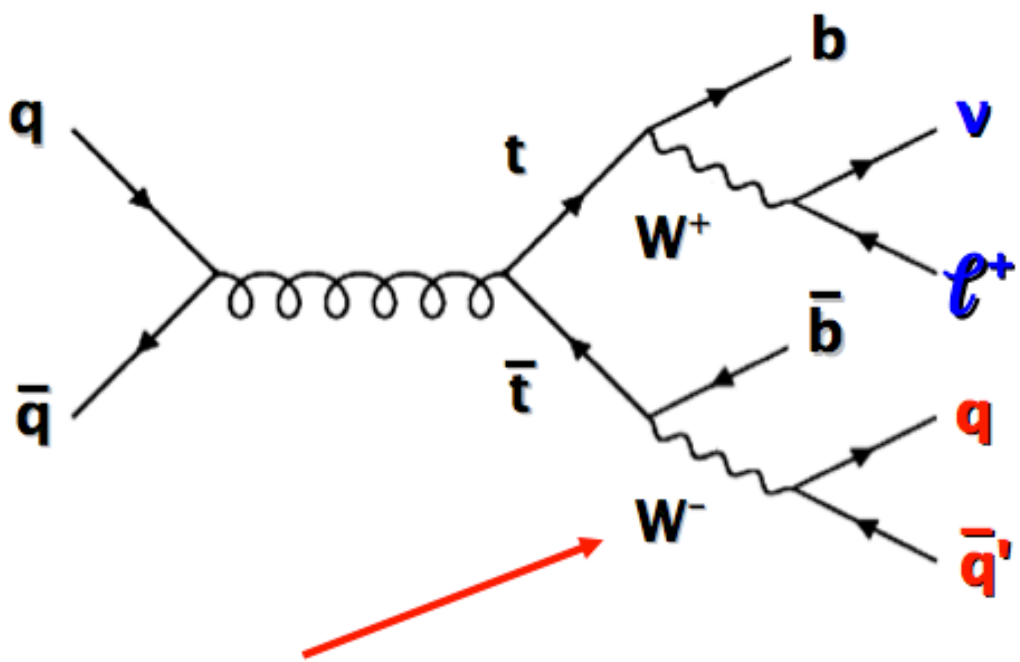


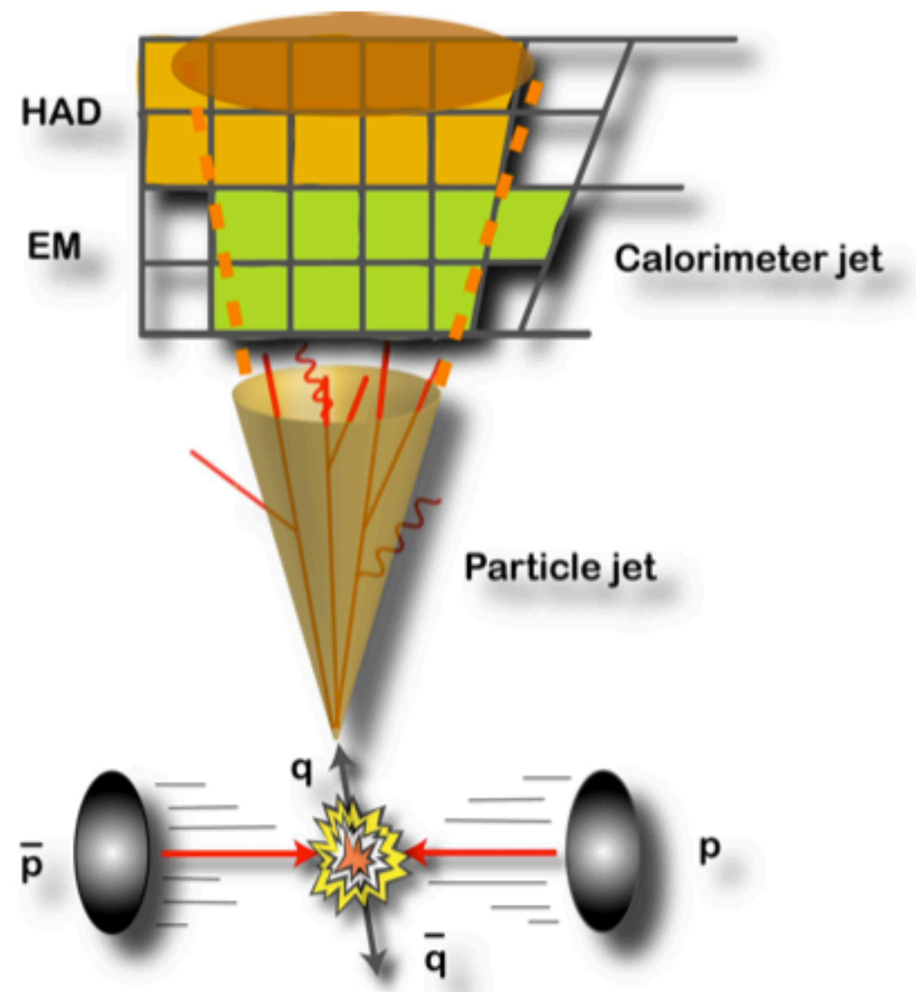
# JES calibration




**W mass constrains jet energy scale**

**jet energy scale:**

**translate jet into parton energy**



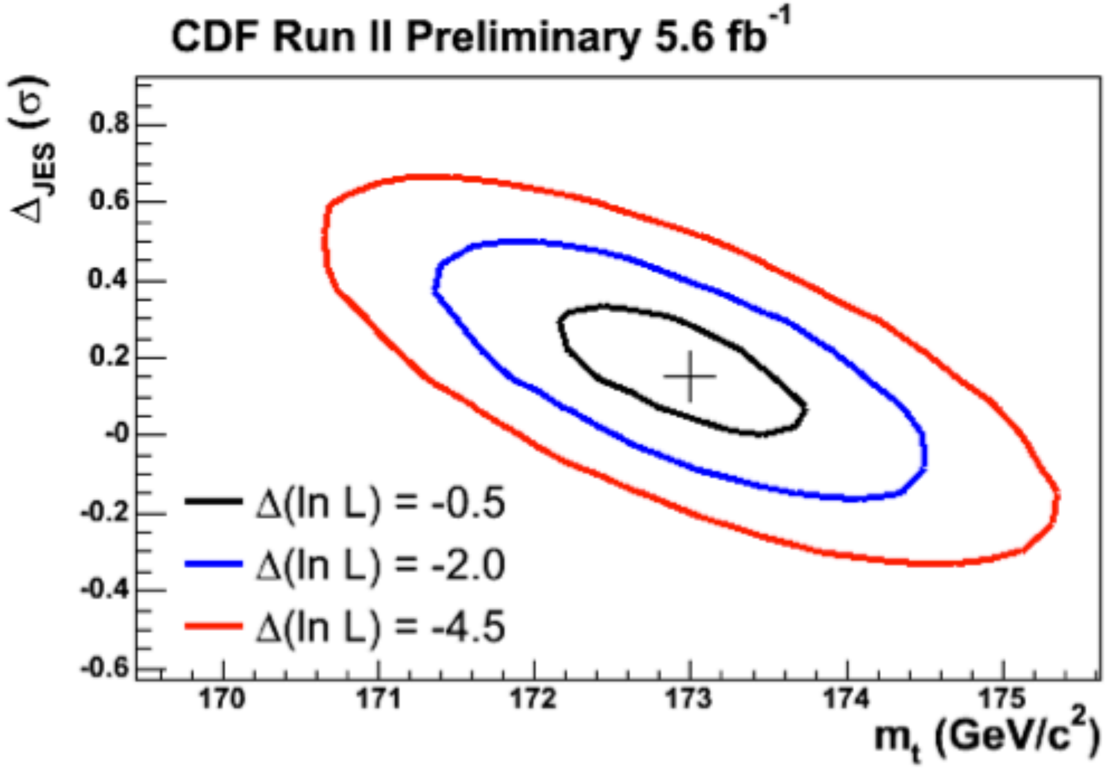
# Result in l+jets Channel

**maximum Likelihood fit to data:**

**matrix element method**

**jet energy scale:**

**translate jet into parton energy**




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

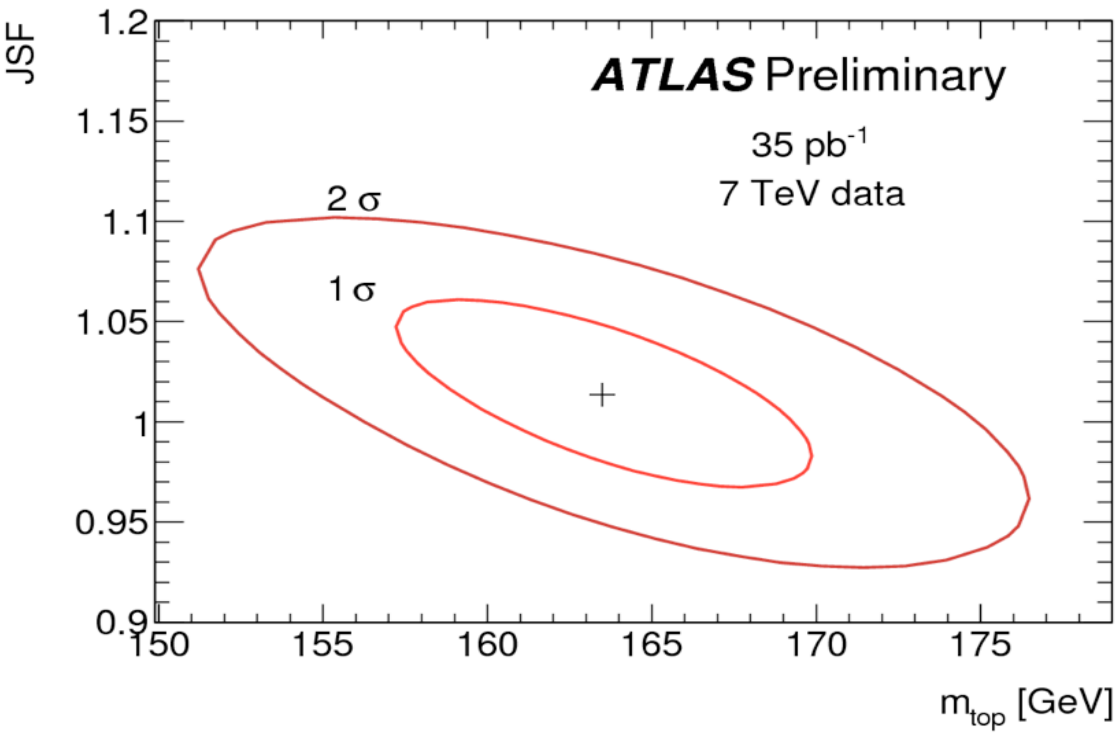
**±0.7%**

# Result in l+jets Channel

**template method**

jet energy scale

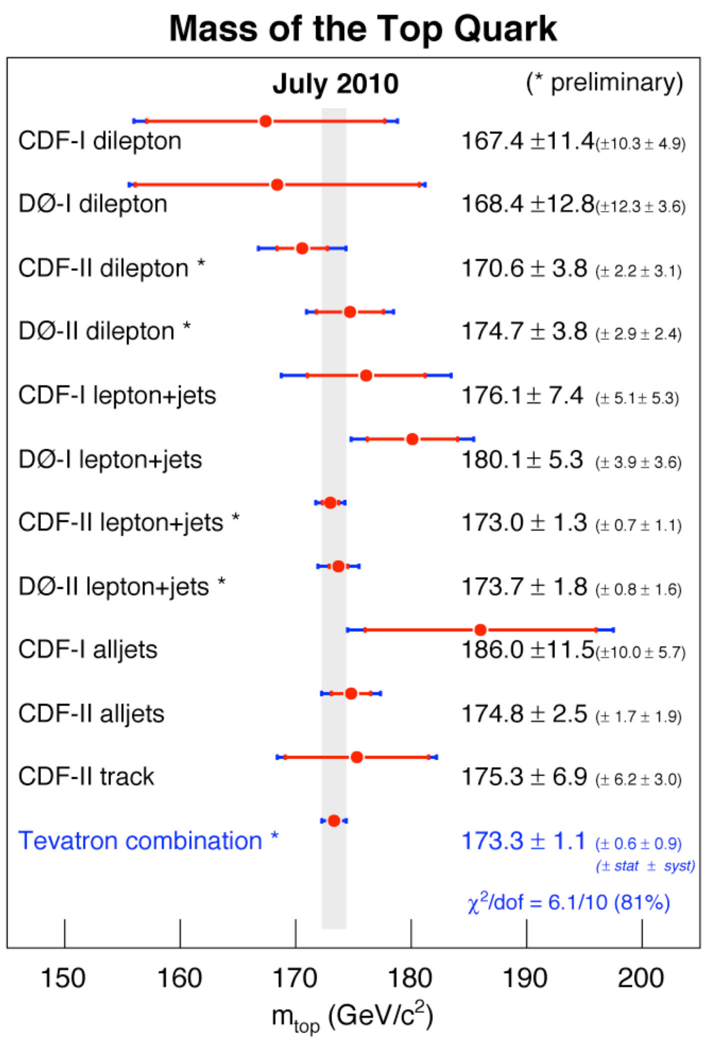
translate jet into parton energy

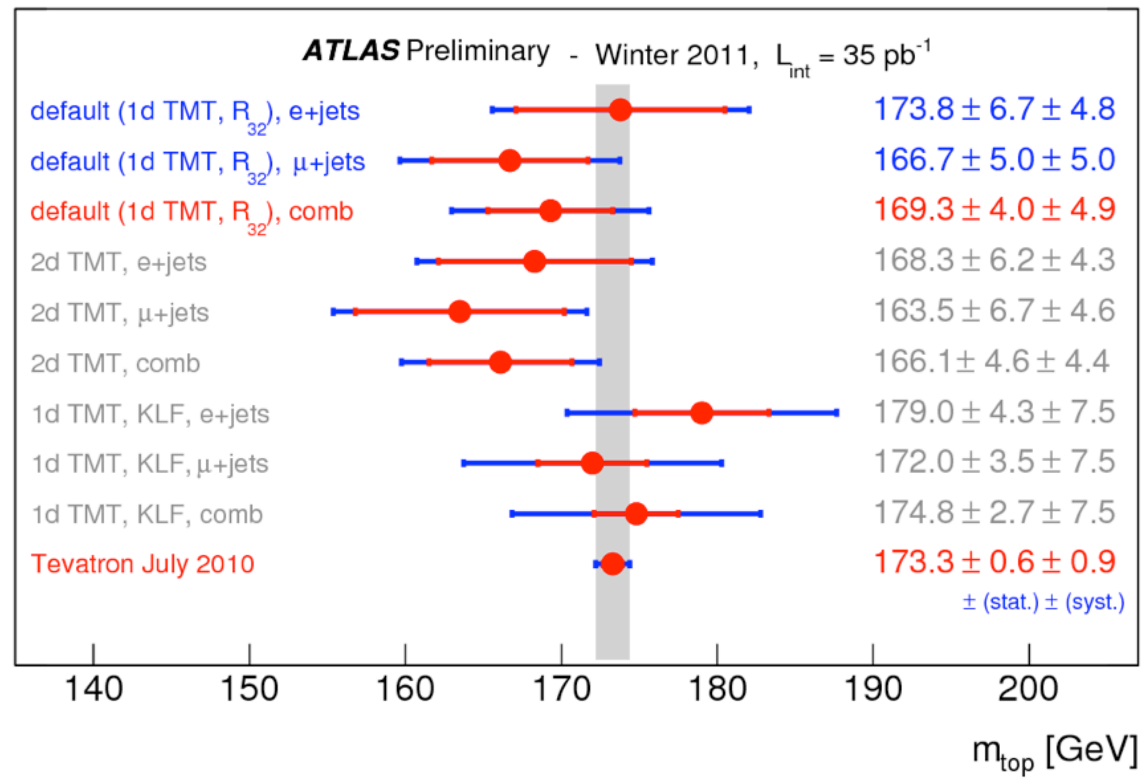



$$m_{top} = 169.3 \pm 4.0 \pm 4.9 \text{ GeV}$$

±3.7%

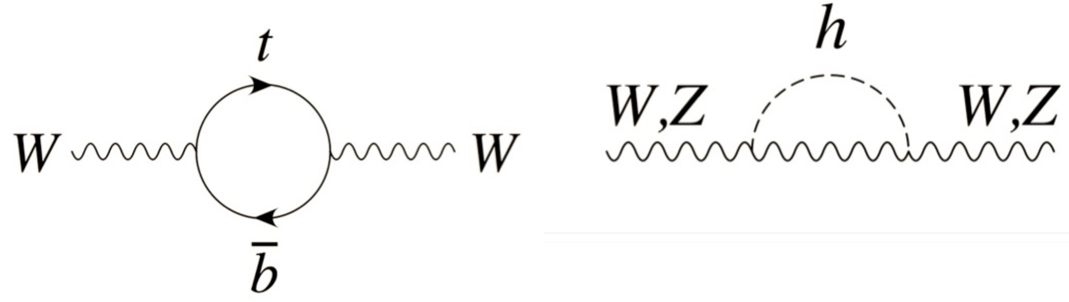
# Top Mass Summary

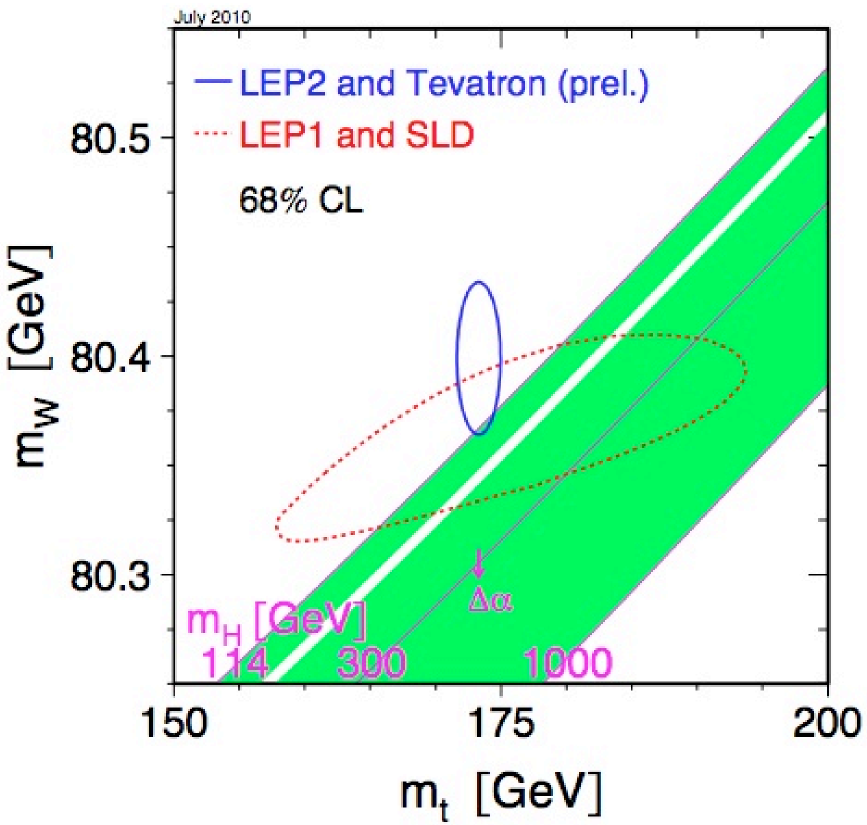


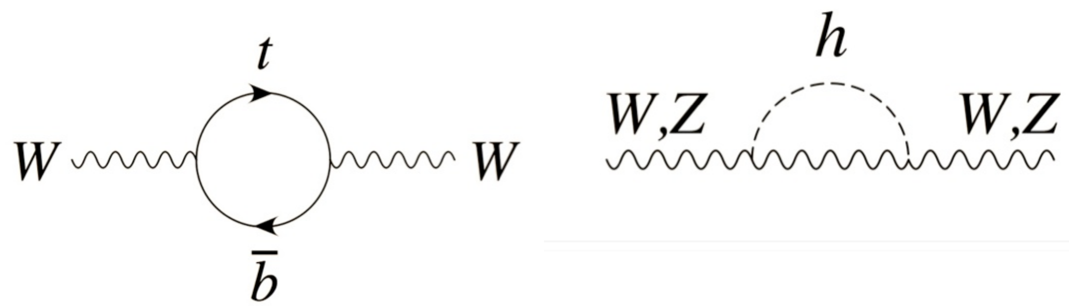

**$m_{top}$ = 173.3 ± 1.1 GeV** **±0.6%**

# Self-consistency of the SM

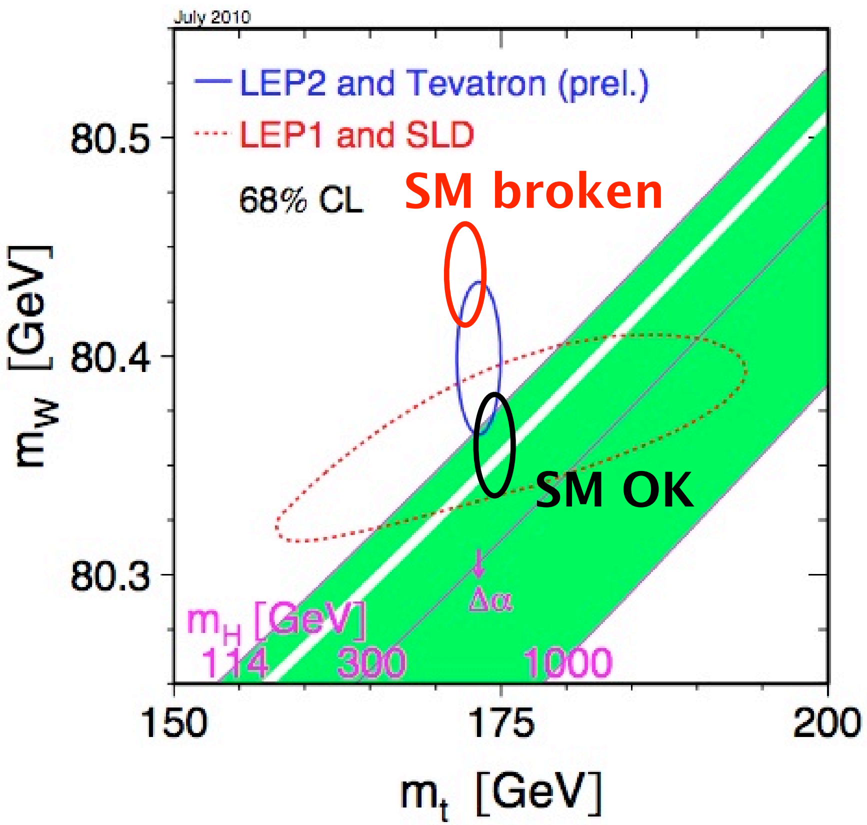


# Self-consistency of the SM

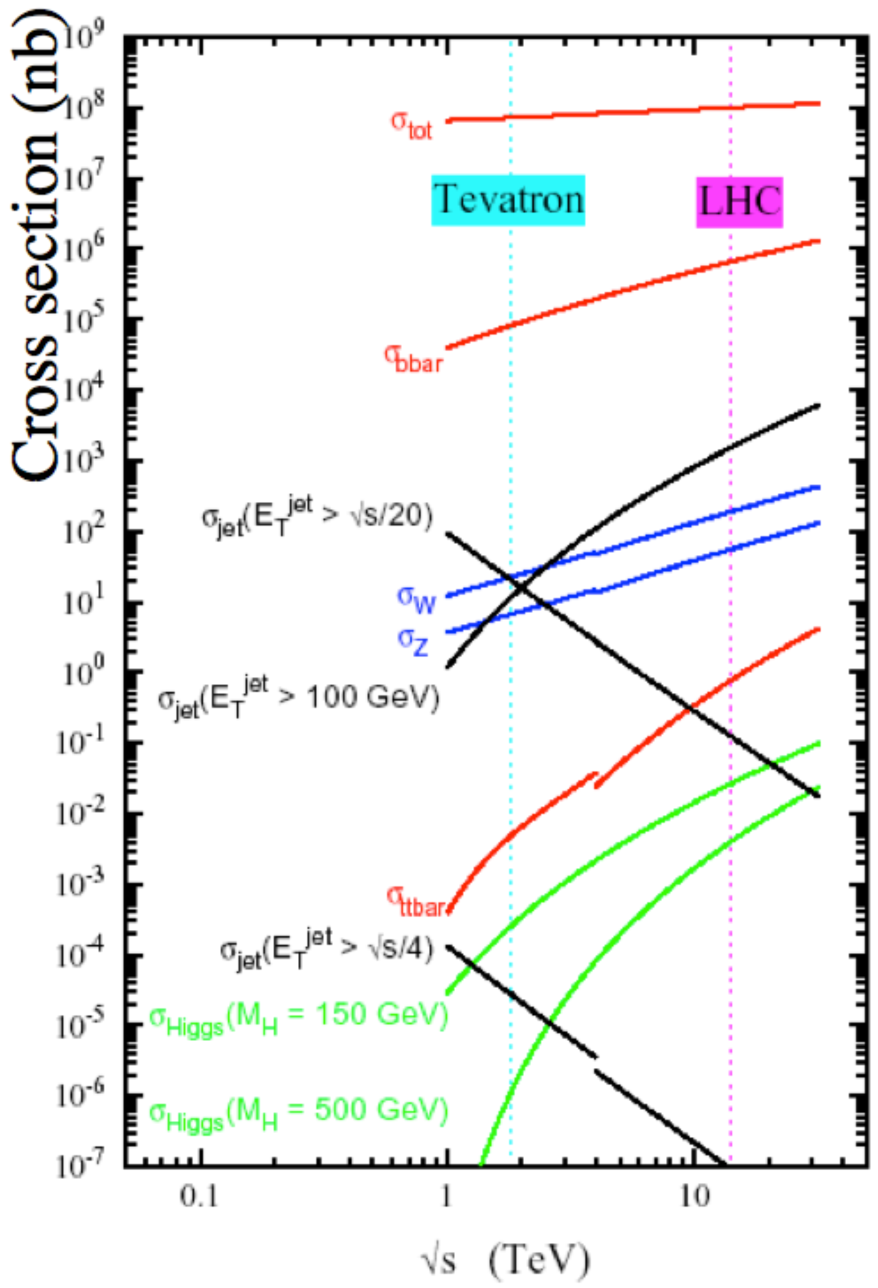


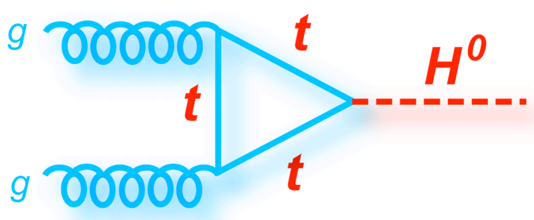

**future:**
**15 MeV, 1 GeV**




**improved W mass measurement is critical**

# Outline



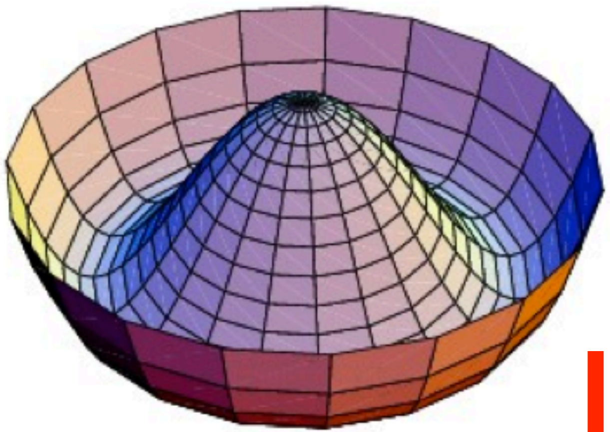




**Higgs boson**

# The Higgs Boson and the SM Lagrangian

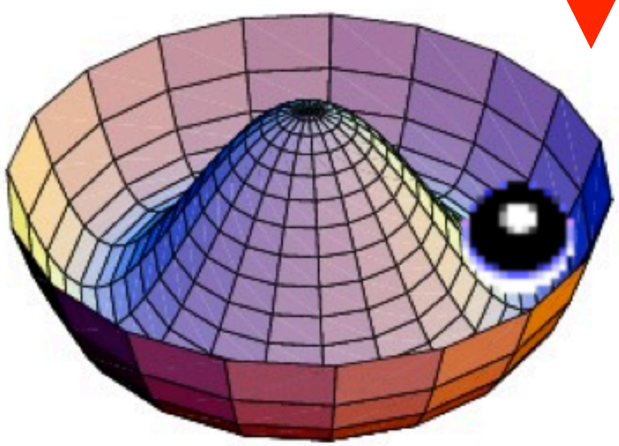
$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{2}\,\mathrm{Tr}\left(W_{\lambda\rho} W^{\lambda\rho}\right) \\
& -\frac{1}{4} B_{\lambda\rho} B^{\lambda\rho} \\
& + W^+_\lambda W^{-\lambda} m_W^2 \left(1 + \frac{H}{v}\right)^2 \\
& + \frac{1}{2} Z_\lambda Z^\lambda m_Z^2 \left(1 + \frac{H}{v}\right)^2 \\
& + \left\{ \bar{\psi} \frac{i}{2} \gamma^\lambda D_\lambda \psi + h.c. \right\} \\
& - \bar{\psi} M \psi \left(1 + \frac{H}{v}\right) \\
& + \frac{1}{2} \partial_\lambda H \partial^\lambda H - \frac{1}{2} m_H^2 H^2 \Big[1 \\
& \qquad + \frac{H}{v} + \frac{1}{4}\left(\frac{H}{v}\right)^2\Big]
\end{aligned}
$$

**Higgs potential:**



spontaneous symmetry breaking

**Higgs ground state:**



# The Higgs Boson and the SM Lagrangian

$$\mathcal{L} = -\frac{1}{2}\,\mathrm{Tr}\left(W_{\lambda\rho} W^{\lambda\rho}\right)$$

$$-\frac{1}{4} B_{\lambda\rho} B^{\lambda\rho}$$

$$+ W^{+}_{\lambda} W^{-\lambda} m_W^2 \left(1 + \frac{H}{v}\right)^2$$

$$+ \frac{1}{2} Z_\lambda Z^\lambda m_Z^2 \left(1 + \frac{H}{v}\right)^2$$

W, Z mass term and coupling to Higgs

$$+ \left\{ \bar{\psi} \frac{i}{2} \gamma^\lambda D_\lambda \psi + h.c. \right\}$$

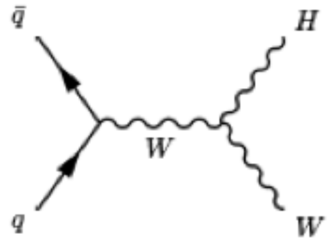
$$- \bar{\psi} M \psi \left(1 + \frac{H}{v}\right)$$

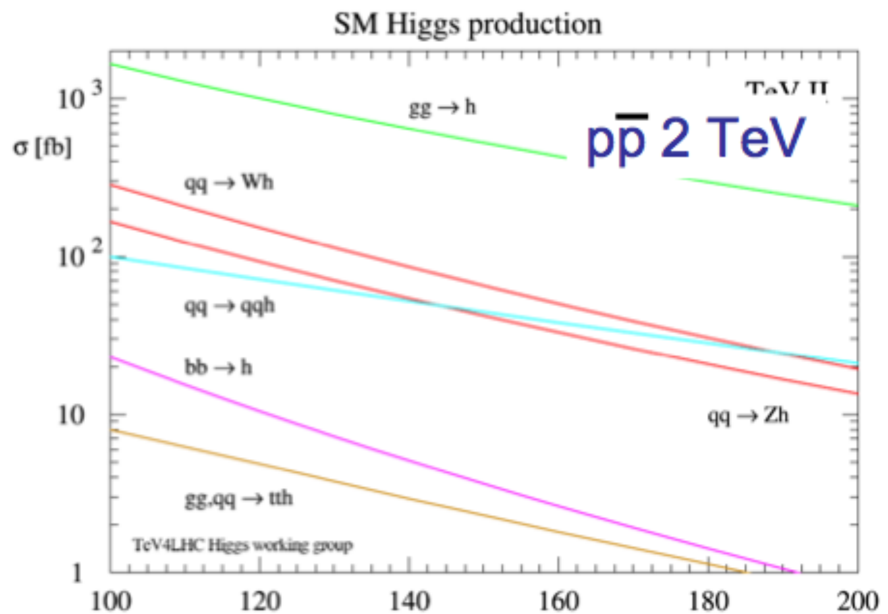
fermion mass term and coupling to Higgs

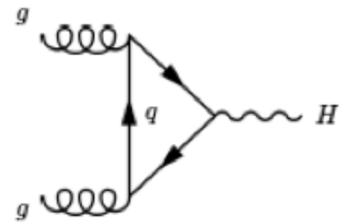
$$+ \frac{1}{2} \partial_\lambda H \partial^\lambda H - \frac{1}{2} m_H^2 H^2 \left[1 + \frac{H}{v} + \frac{1}{4}\left(\frac{H}{v}\right)^2\right]$$

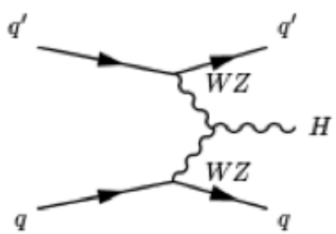
dynamic term and Higgs self-couplings

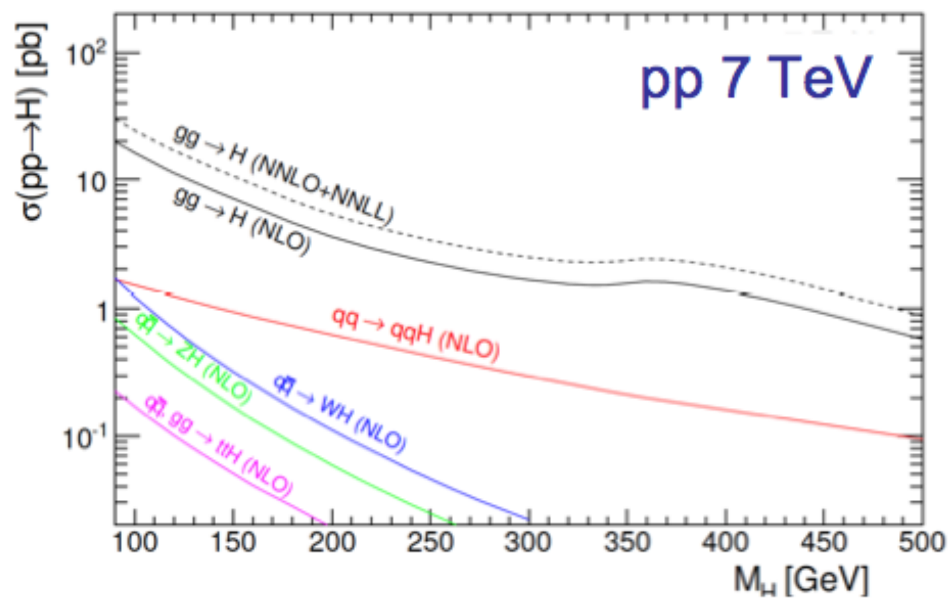
# SM Higgs Production

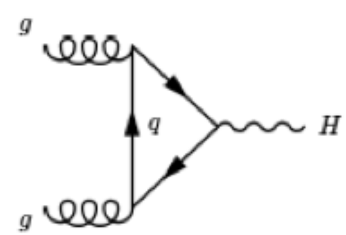


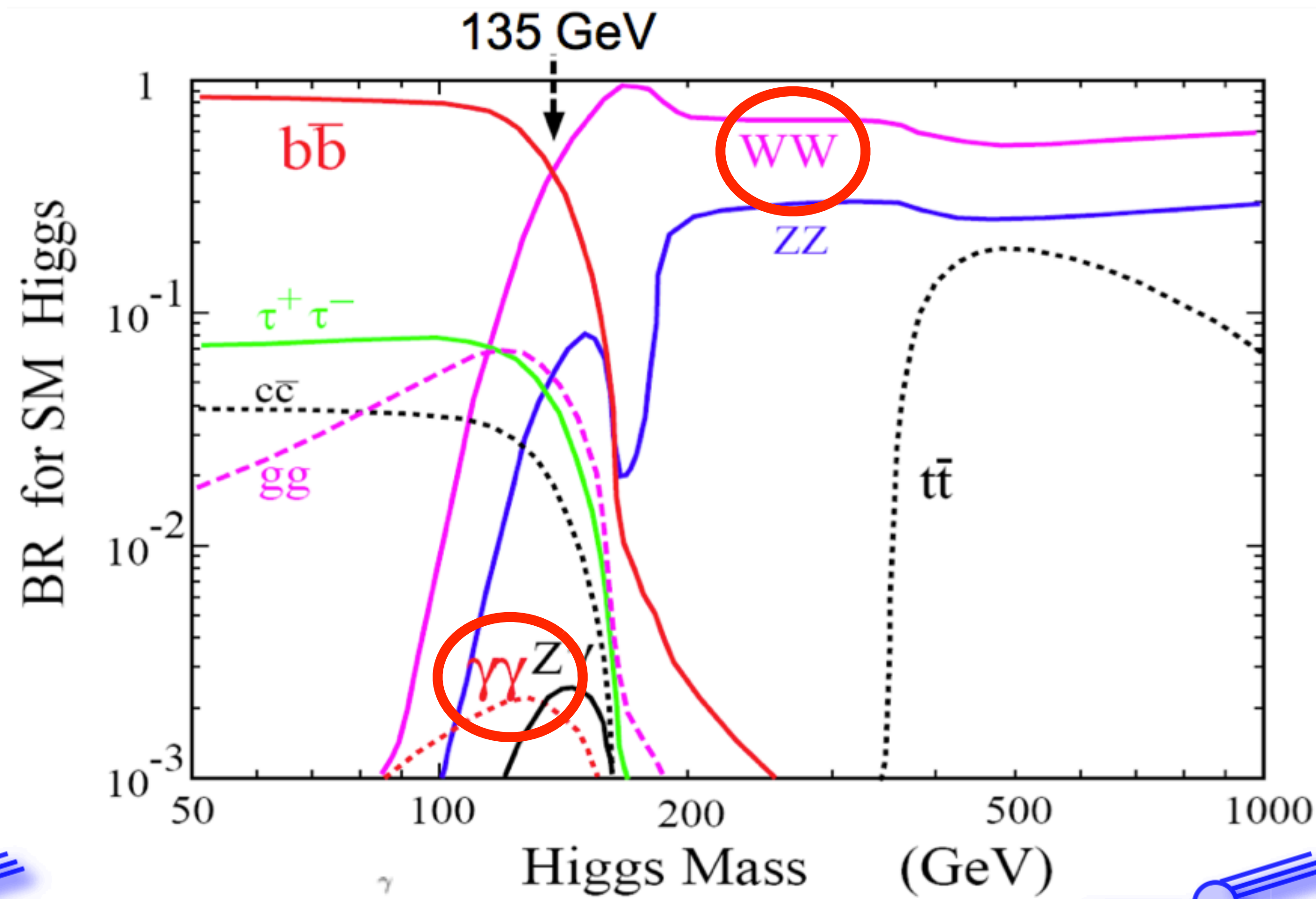



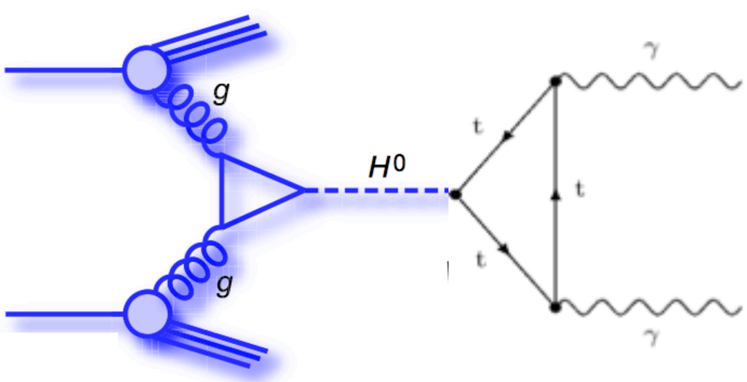



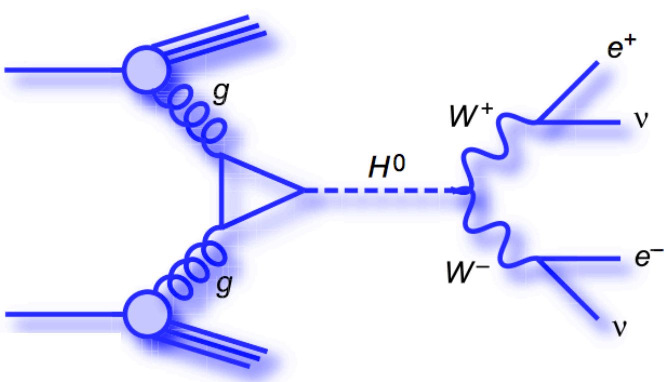



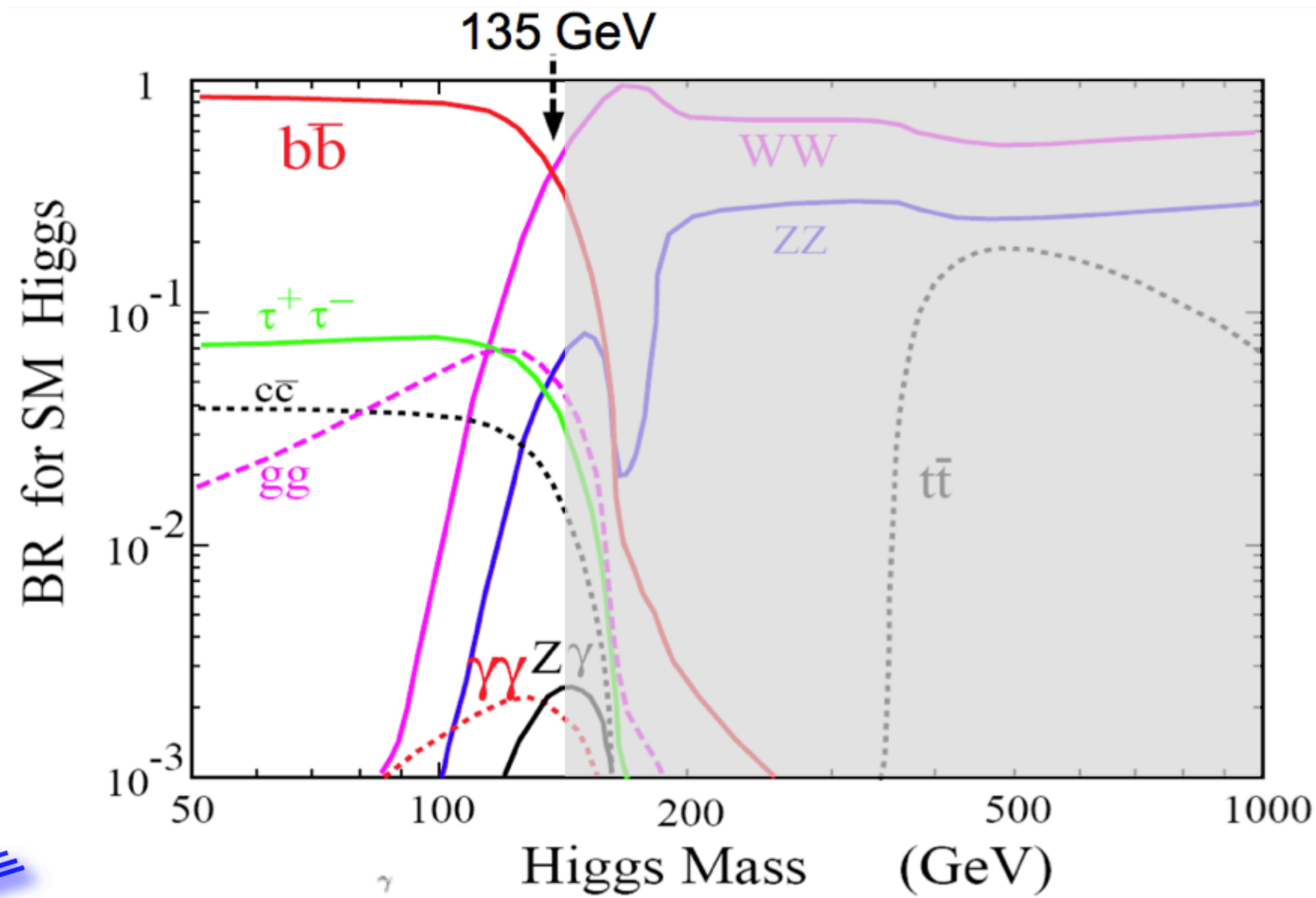
# SM Higgs Decays

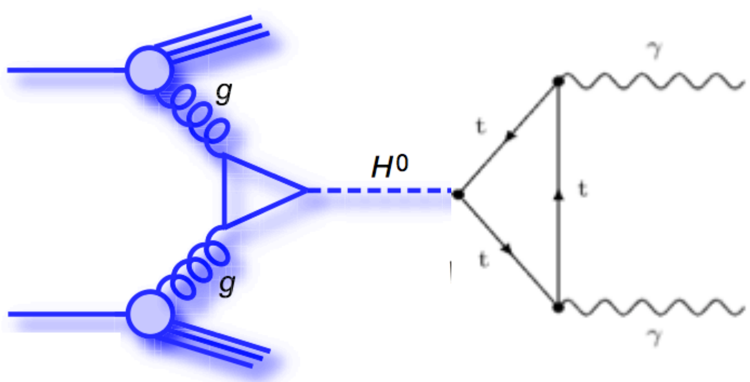


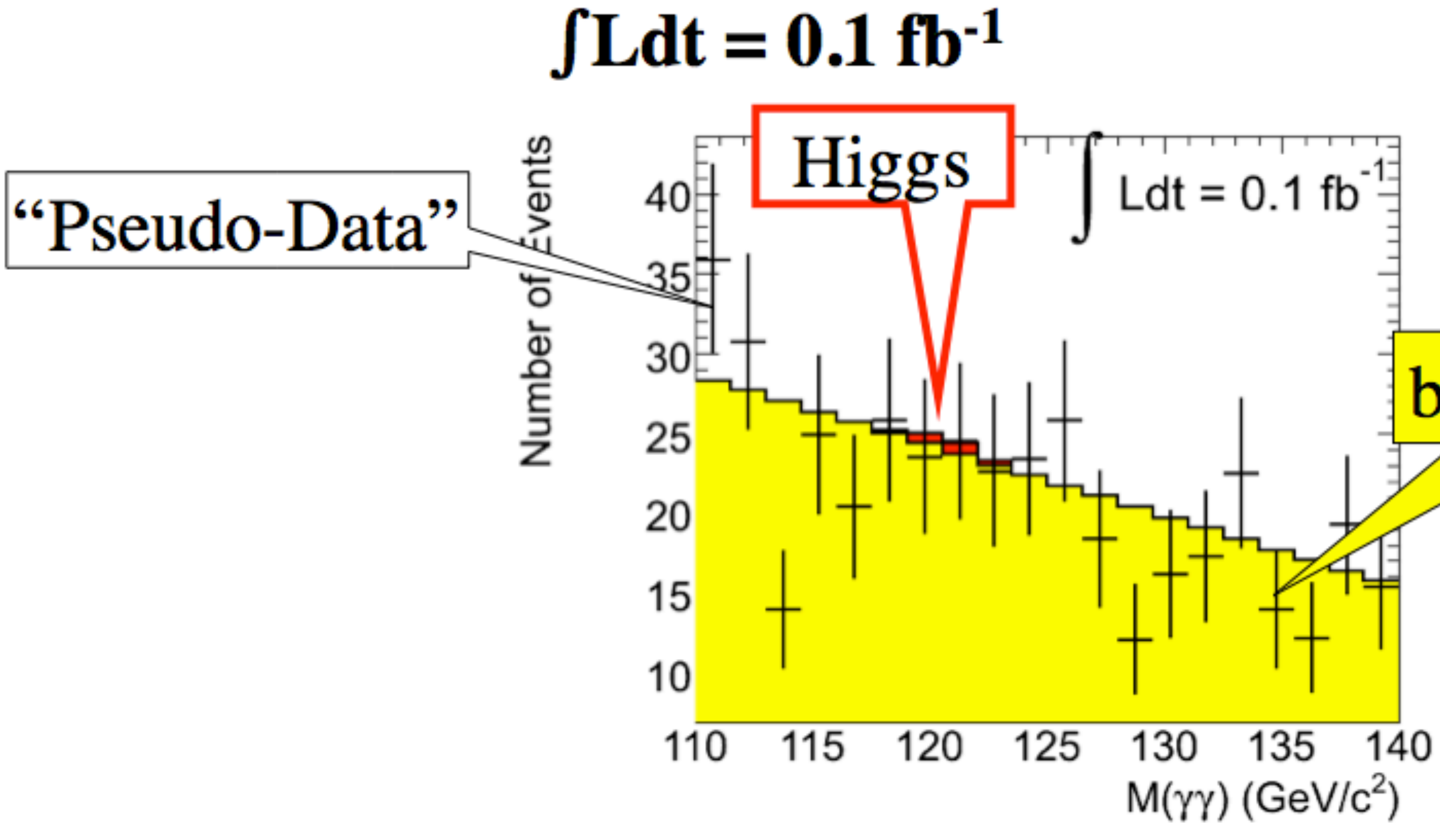
# Low Mass Higgs Searches




- rare in SM, but good mass resolution
- can be enhanced in BSM models (e.g. fermiophobic Higgs)

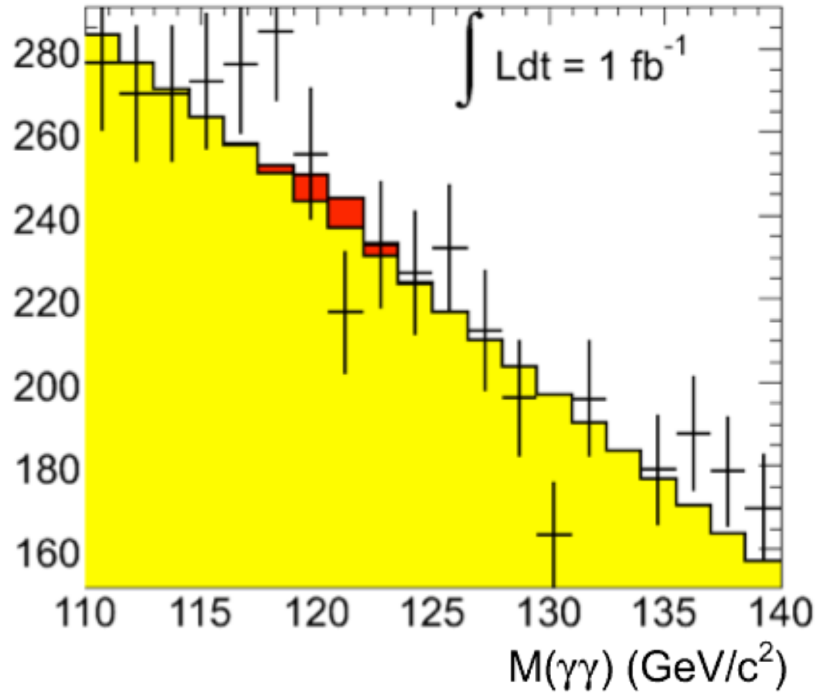
# A signal emerging with time




- **expected events:**
  - $N_{higgs}$~2, $N_{bg}$=96±9.8
  - $S/\sqrt{B}$=0.2
- **no sensitivity to signal**

# A signal emerging with time

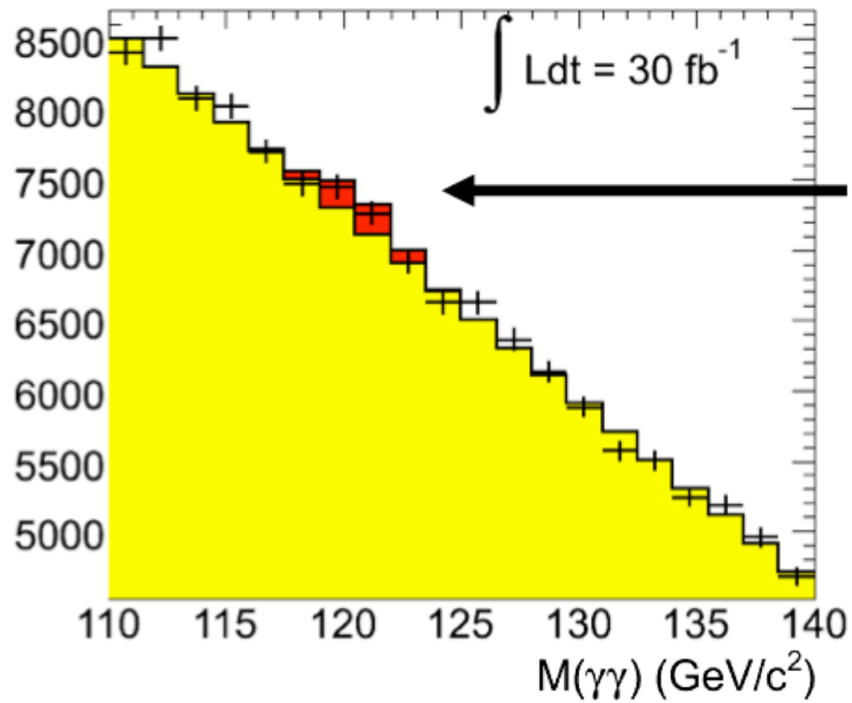
$\int Ldt = 1\ fb^{-1}$




- expected events:
  - $N_{higgs}$~25, $N_{bg}$=960±30
  - $S/\sqrt{B}$=0.8
- still no sensitivity to signal

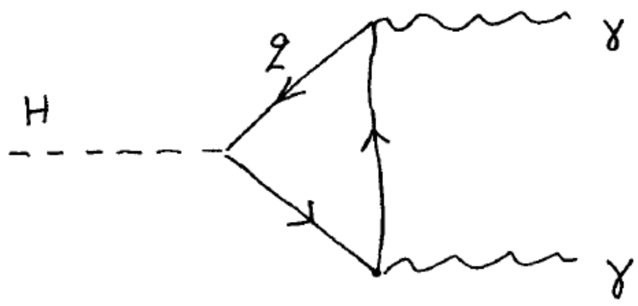
# There it is!

$\int L dt = 30\ fb^{-1}$

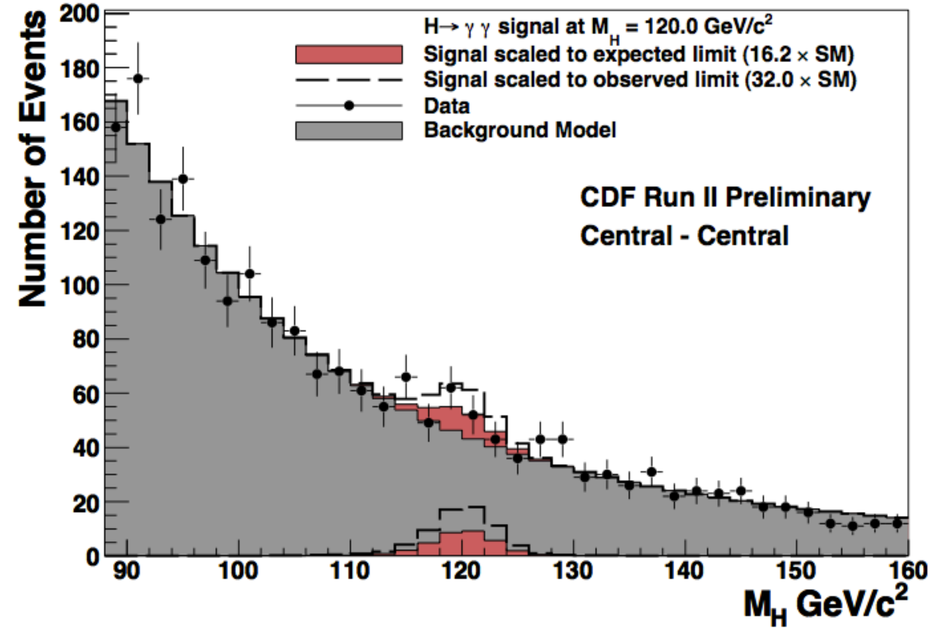


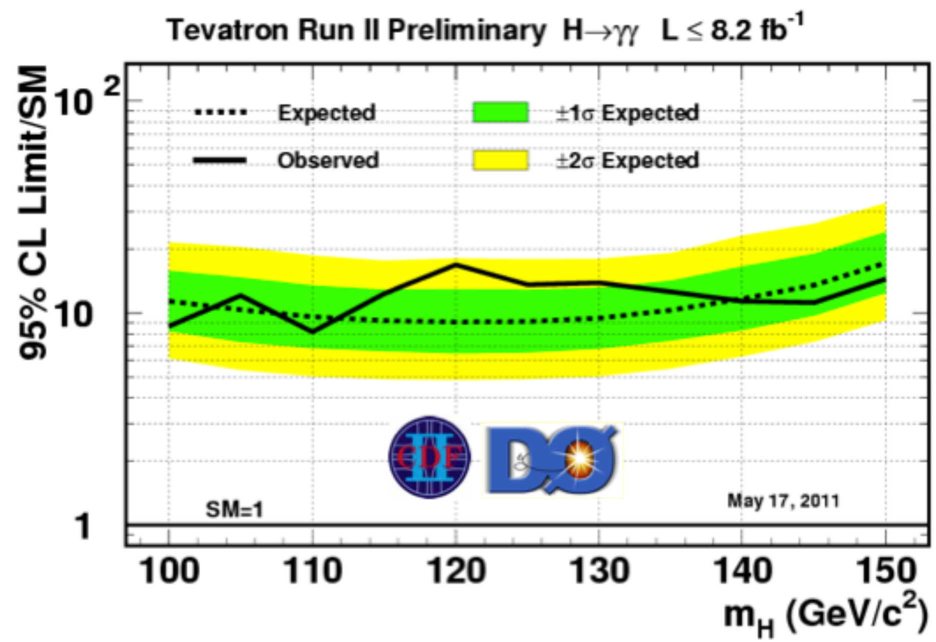

- expected events:
  - $N_{higgs} \sim 700$, $N_{bg} = 28700 \pm 170$
  - $S/\sqrt{B} = 4.1$
- got it!!!

# Search for H→γγ Production, Tevatron







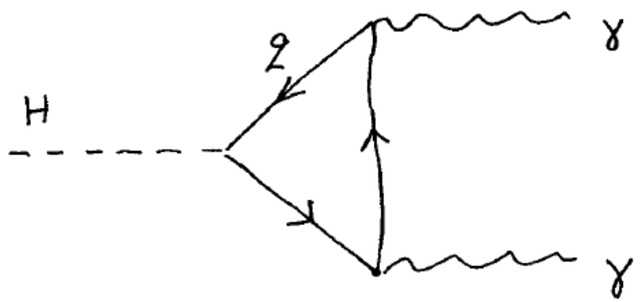




**$m_H$=115 GeV, 95% CL**

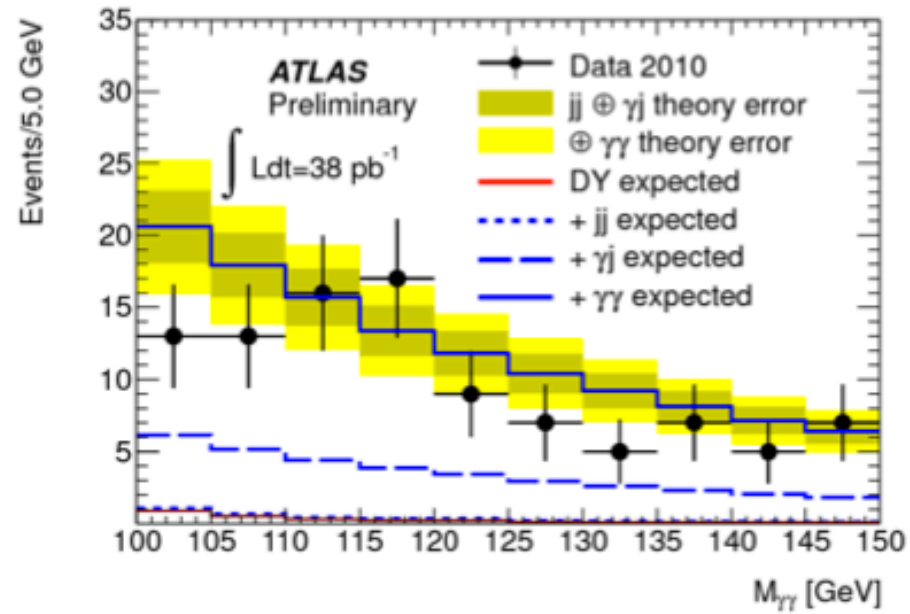
**expected: 9.2×SM**

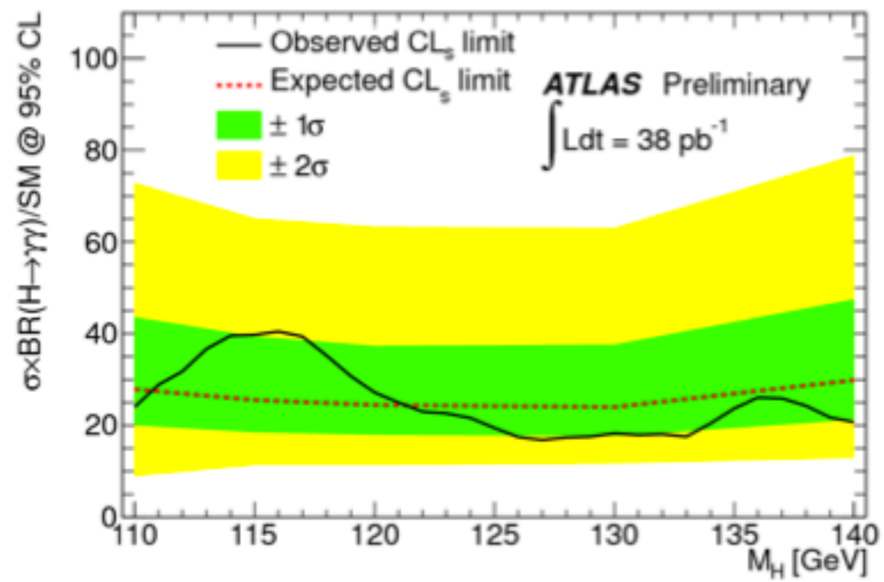
**observed: 12×SM**

# Search for H→γγ Production, LHC







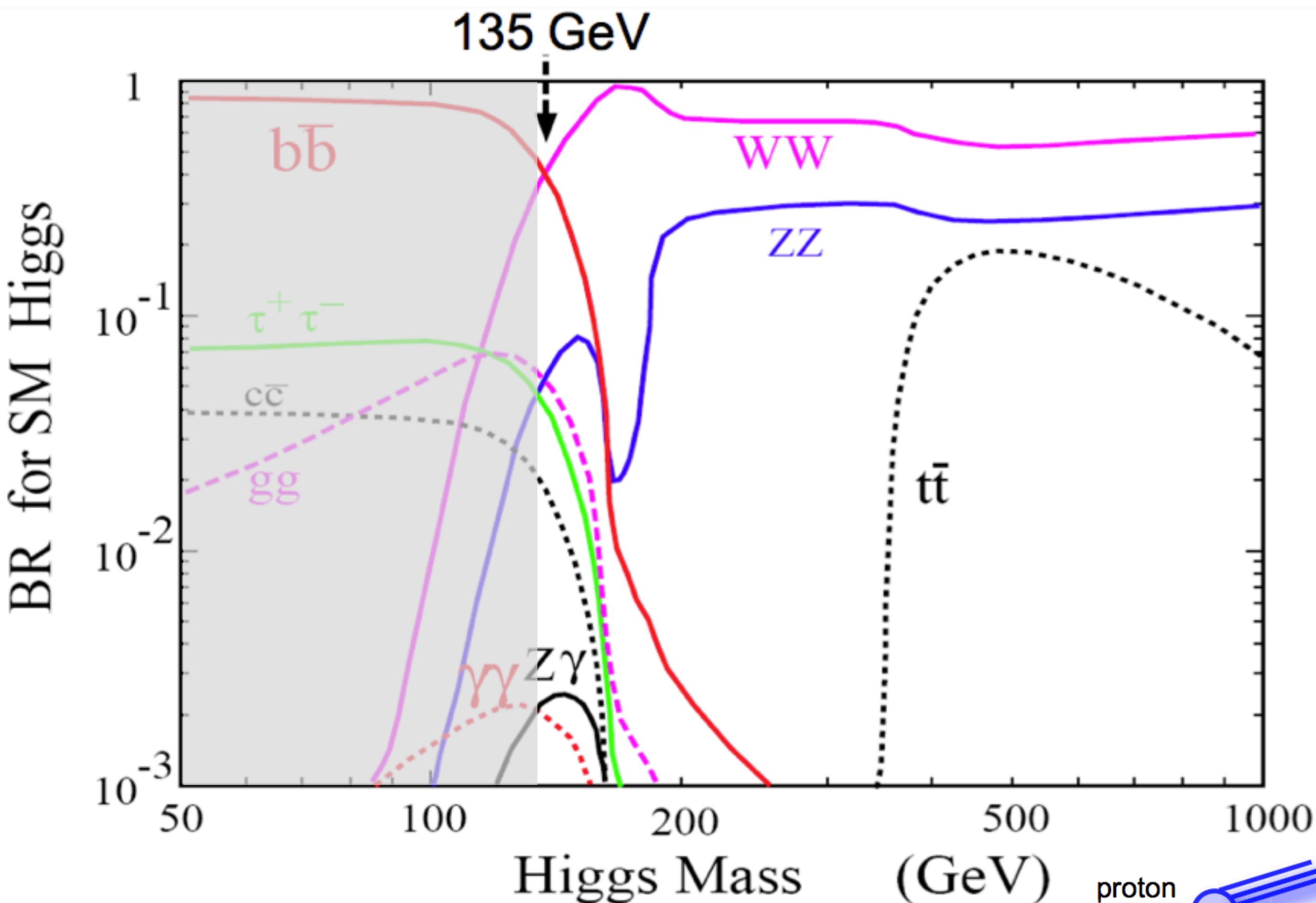



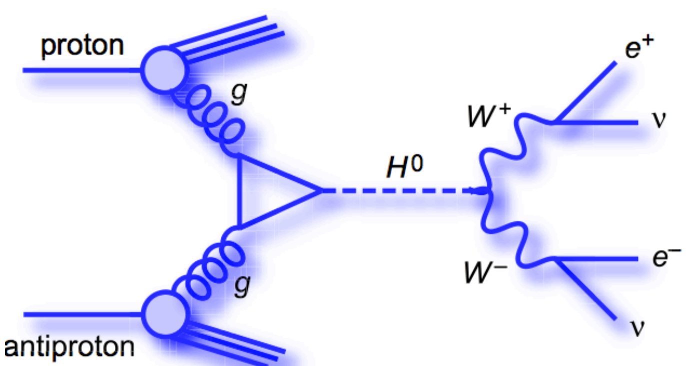

**$m_H$=115 GeV, 95% CL**

**expected: ~25×SM**

**observed: ~40×SM**

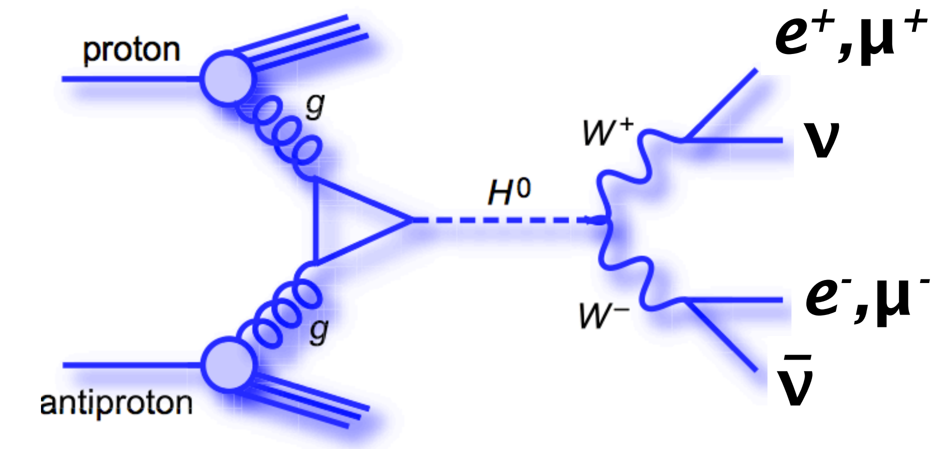
# High Mass Higgs Searches

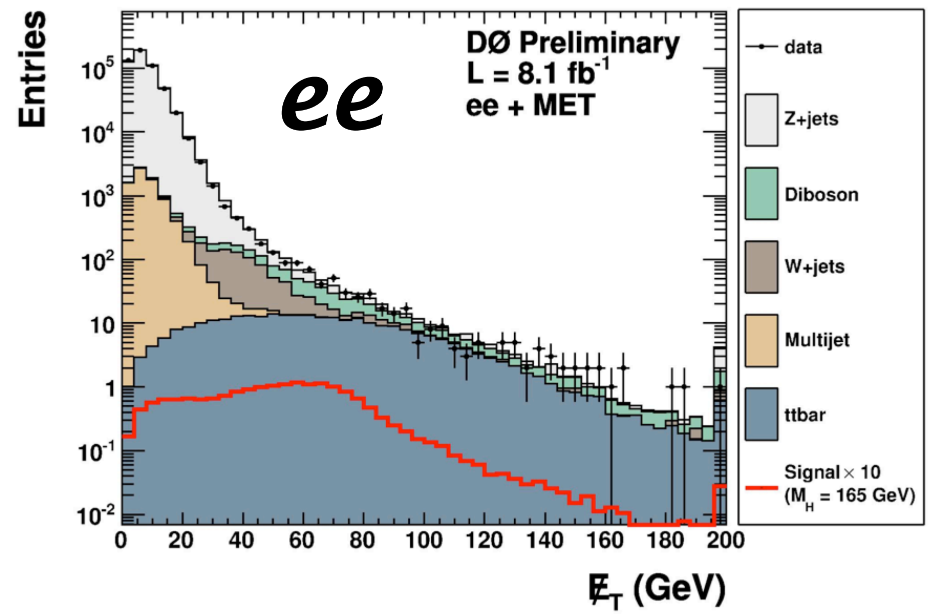


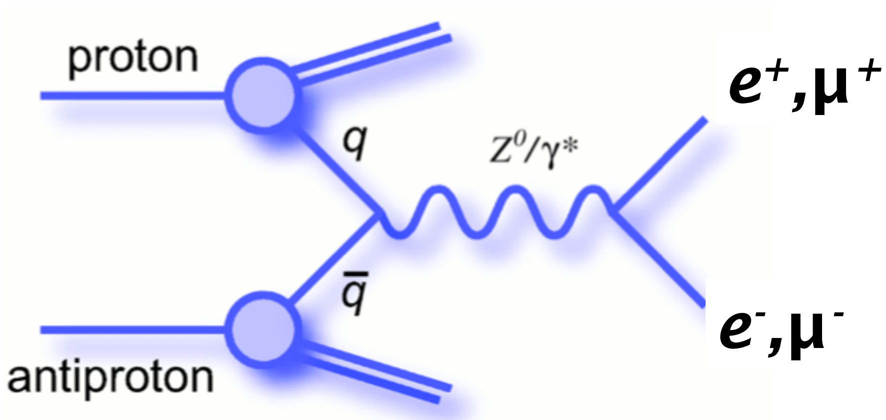
# Search for H→WW→ee, eμ, μμ

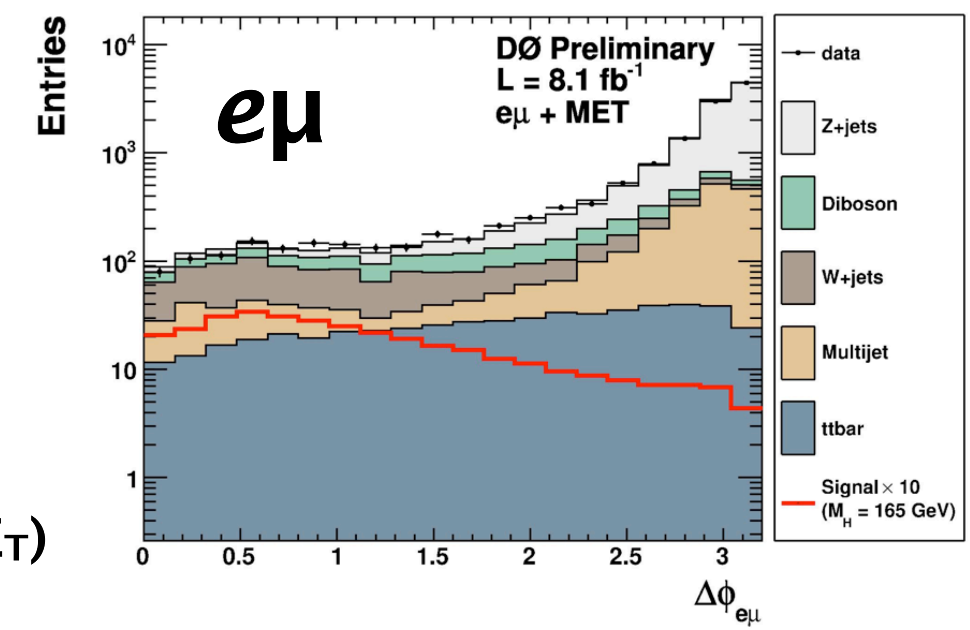
signal




background



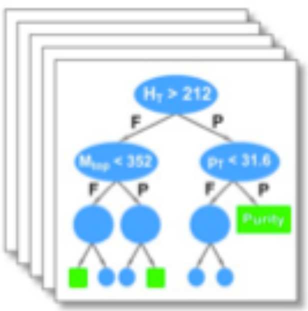

**background rejection**

- eμ: minimal transverse mass $M_T(e/\mu,\not{E}_T)$
- ee, μμ: BDT discriminant

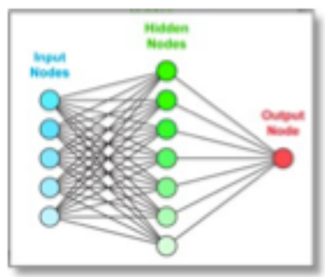
# Multivariate Analysis Techniques

- increase sensitivity by combining many variables to one discriminant for each channel

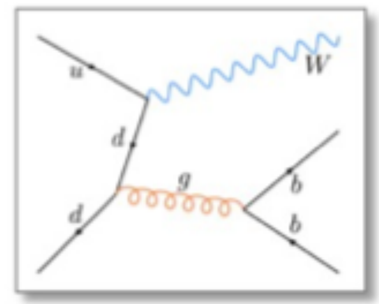
**Boosted Decision Trees**




**Neural Networks**




**Matrix Elements**

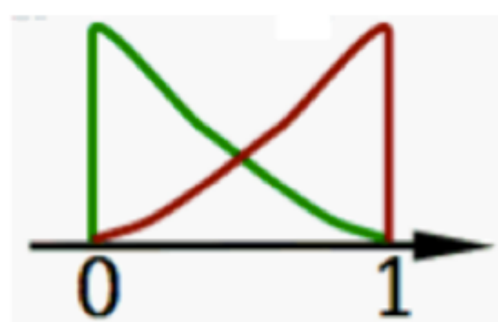



**Likelihood**

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

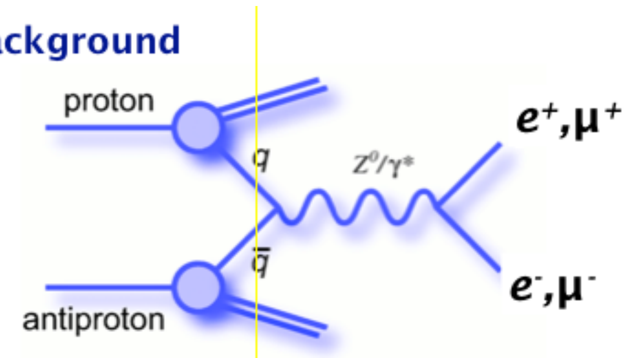
$$\mathcal{L}_k(\{x_i\}) = \frac{\prod_{i=1}^{n_{var}} p_{ik}}{\sum_{m=1}^{5} \prod_{i=1}^{n_{var}} p_{ik}}.$$

background signal



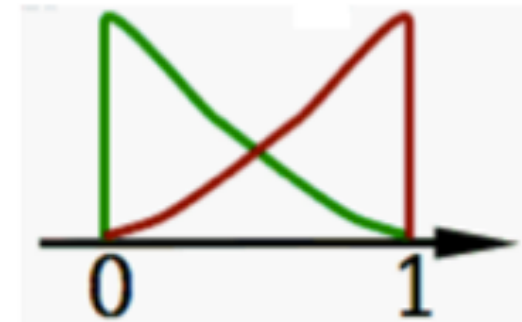
# Search for H→WW→ee, eμ, μμ

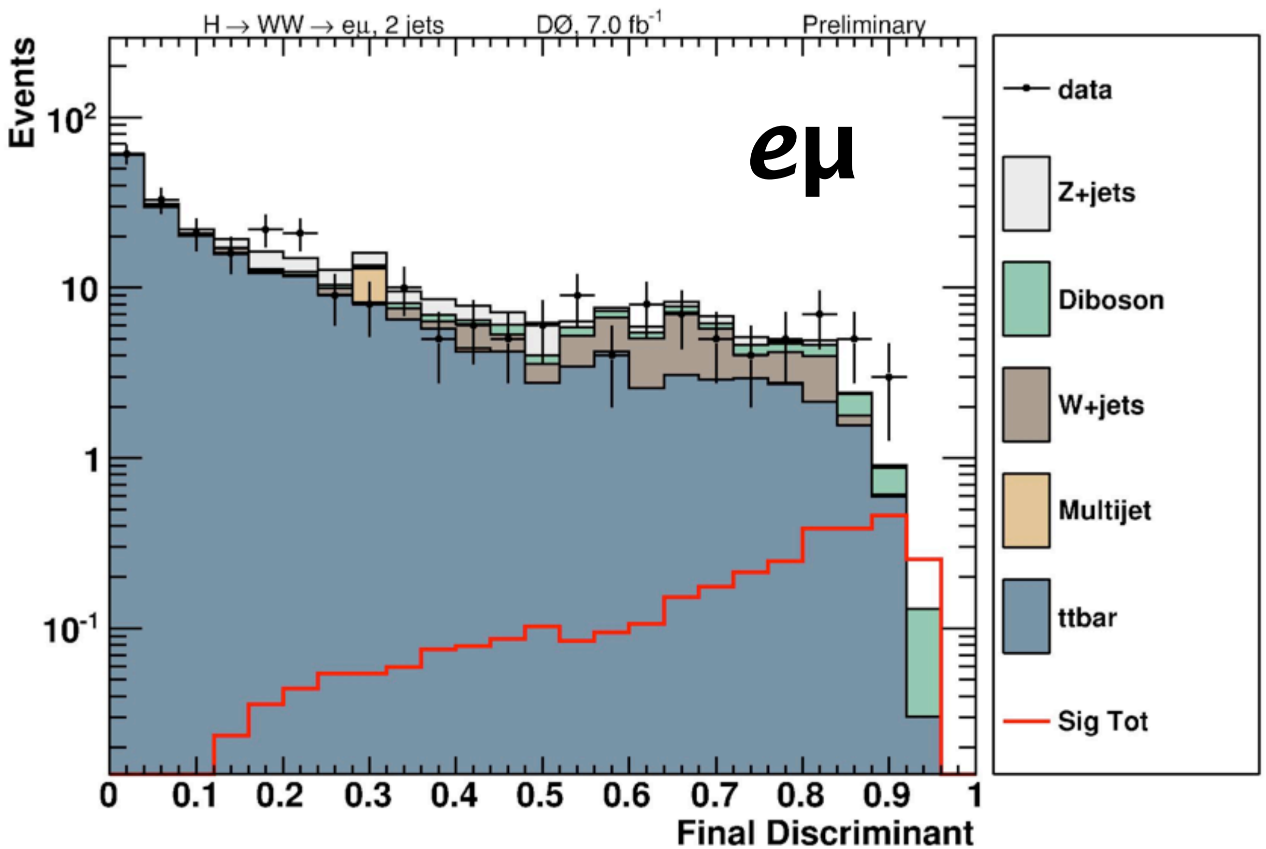
background



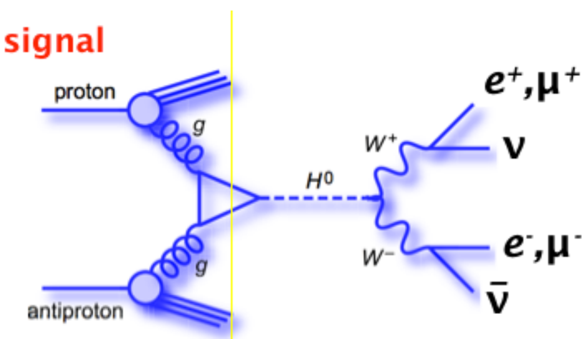

- analyse 0, 1, and ≥ 2 jets
- final BDT discriminant

background signal



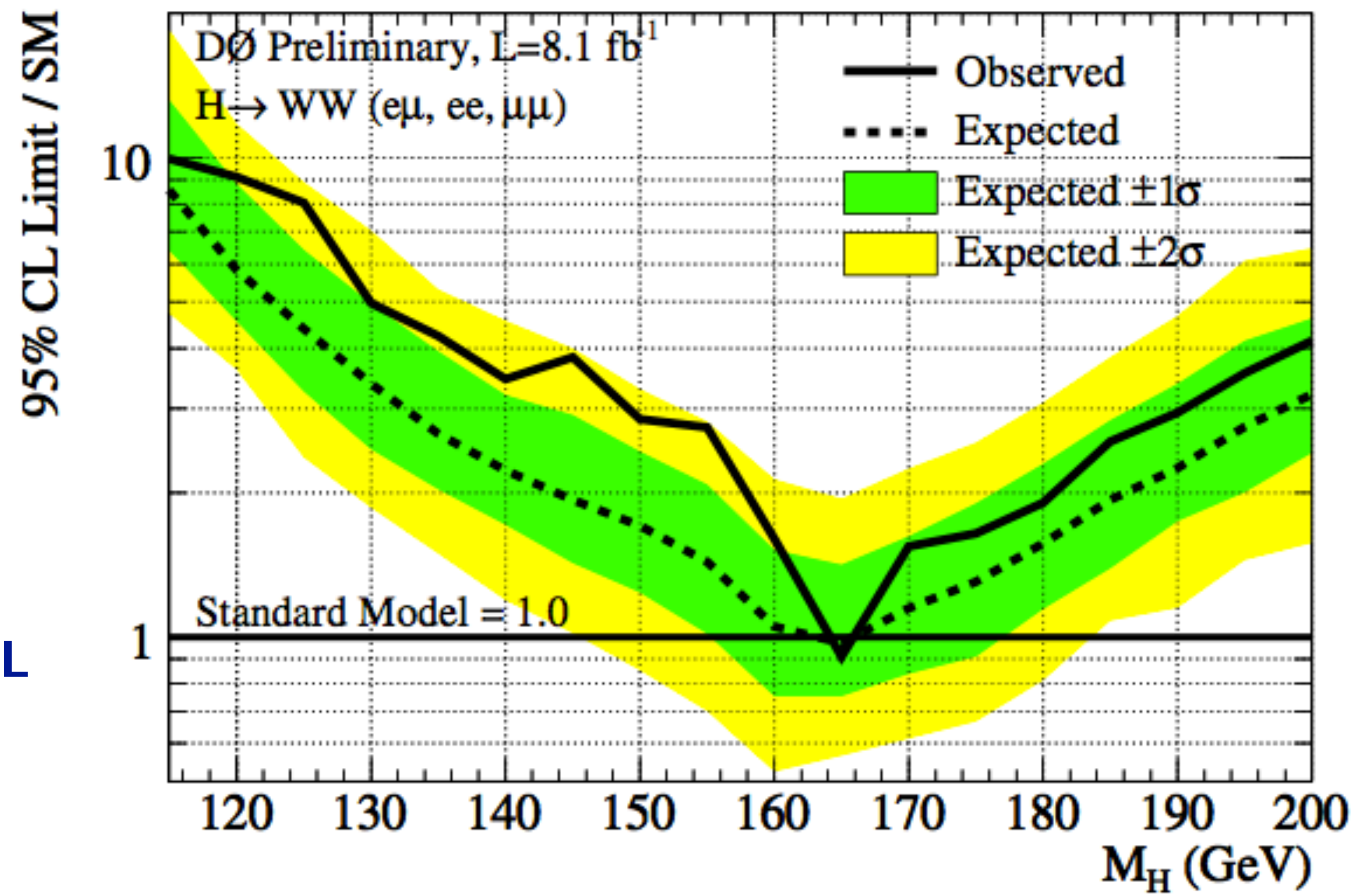




signal



# Search for H→WW→ee, eμ, μμ

***ee+eμ+μμ***




**$m_H$=165 GeV, 95% CL**

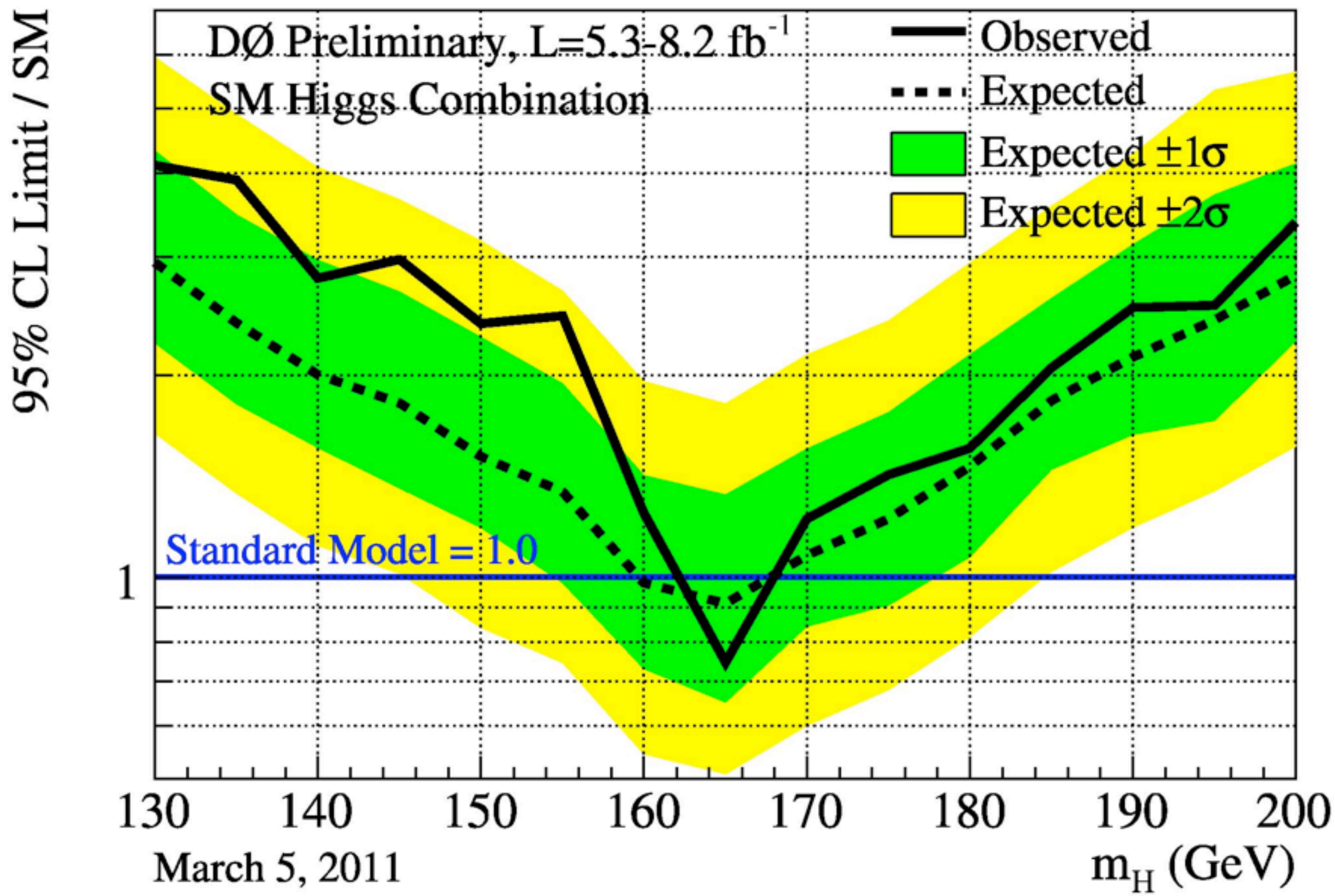
**expected: 0.97×SM**
**observed: 0.91×SM**

**exclusion at 95% CL for $M_H$=165 GeV**

**exclusion in one channel for the first time!**

# SM Higgs Combination

$H \to W^+W^- \to \ell^\pm \nu \ell^\mp \nu$
0/1/2+ jet
$H \to W^+W^- \to \ell \nu q\bar{q}$
$H+X \to \mu^\pm \tau^\mp_{had} + \leq 1j$
$H+X \to \mu^\pm \tau^\mp_{had} jj$
$H+X \to e^\pm \tau^\mp_{had} jj$
$VH \to \ell^\pm \ell^\mp + X$
$H \to \gamma\gamma$




$m_H$=165 GeV, 95% CL

**expected: 0.91×SM**
**observed: 0.75×SM**

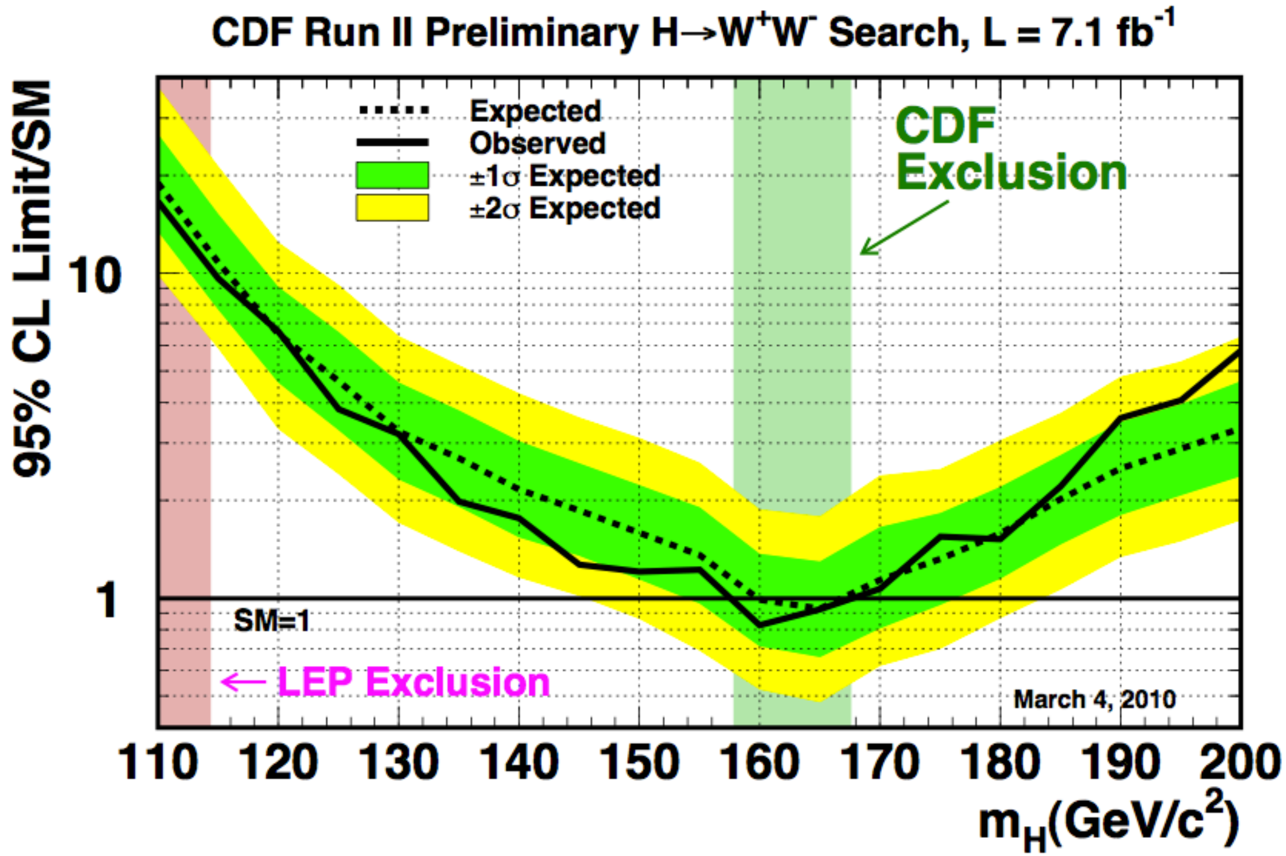
**exclusion at 95% CL for 163 < $M_H$ < 168 GeV**
**exclusion by a single experiment for the first time!**

# SM Higgs Combination

$H \to W^+W^-$ $2\times$(0,1 jets)+(2+ jets)+(low-$m_{\ell\ell}$)+($e$-$\tau_{had}$)+($\mu$-$\tau_{had}$)

$WH \to WW^+W^-$ (same-sign leptons 1+ jets)+(tri-leptons)

$ZH \to ZW^+W^-$ (tri-leptons 1 jet)+(tri-leptons 2+ jets)




**$m_H$=165 GeV, 95% CL**

**expected: 0.93×SM**

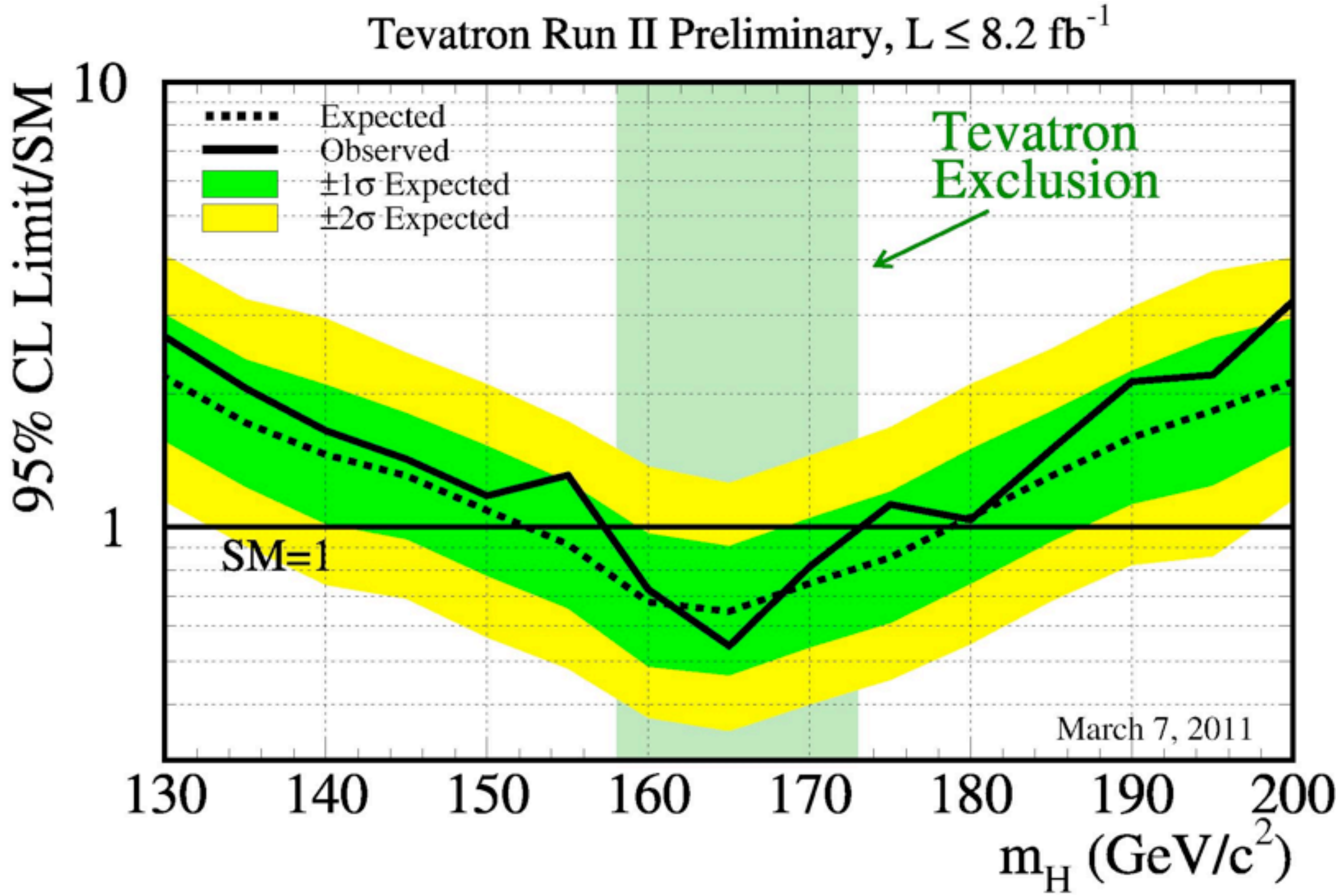
**observed: 0.92×SM**

**exclusion at 95% CL for 158 < $M_H$ < 168 GeV**

**exclusion by a single experiment for the first time!**

# Tevatron Combination

5.3–8.2 $fb^{-1}$

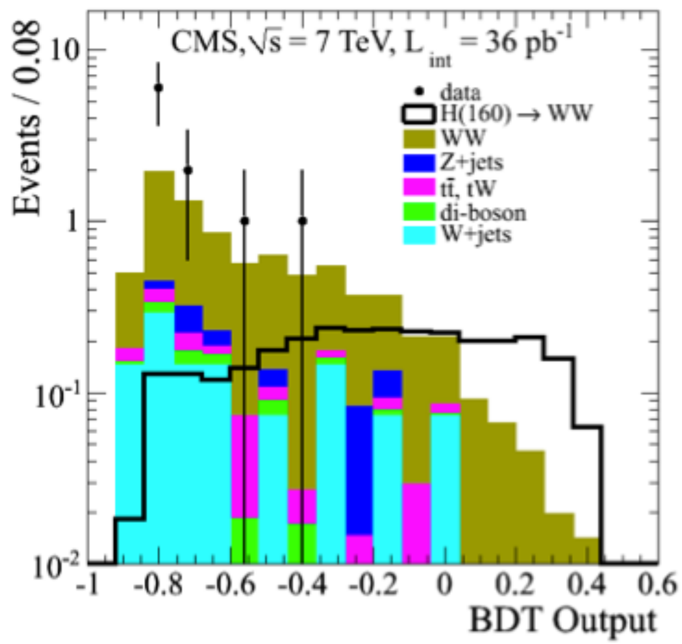


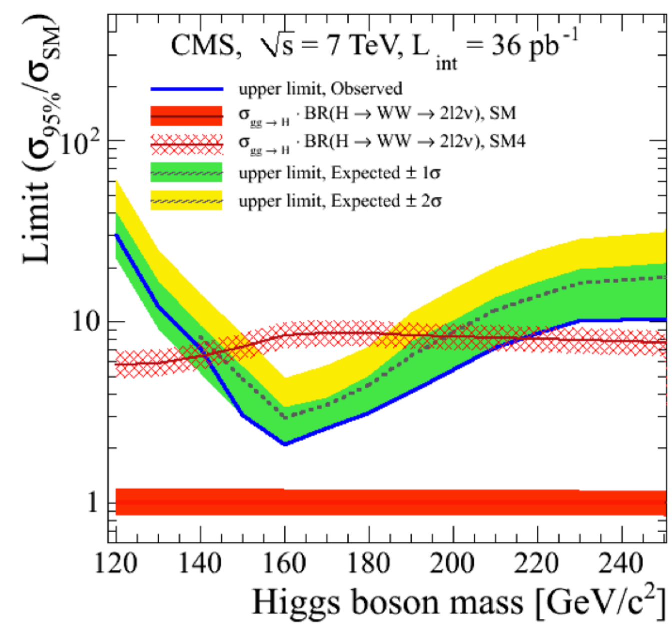

$m_H$=165 GeV, 95% CL

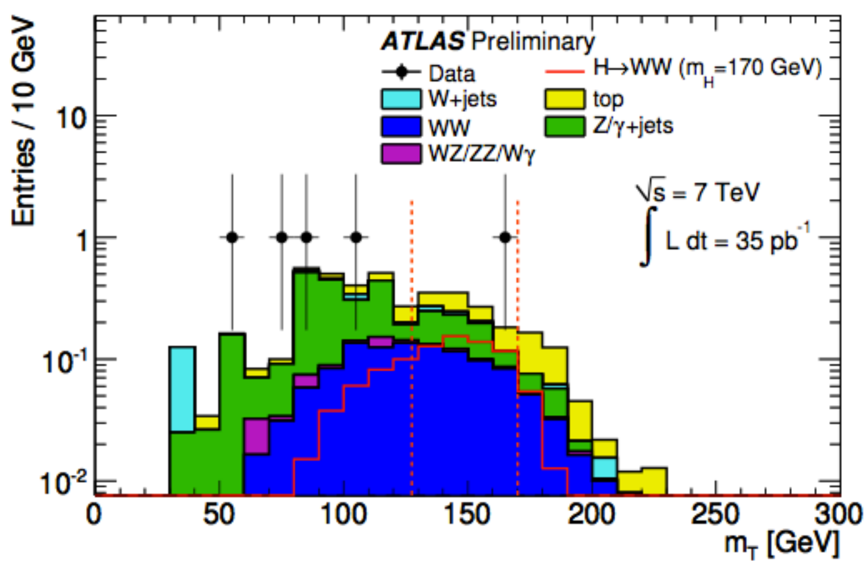
**expected: 0.64×SM**
**observed: 0.52×SM**

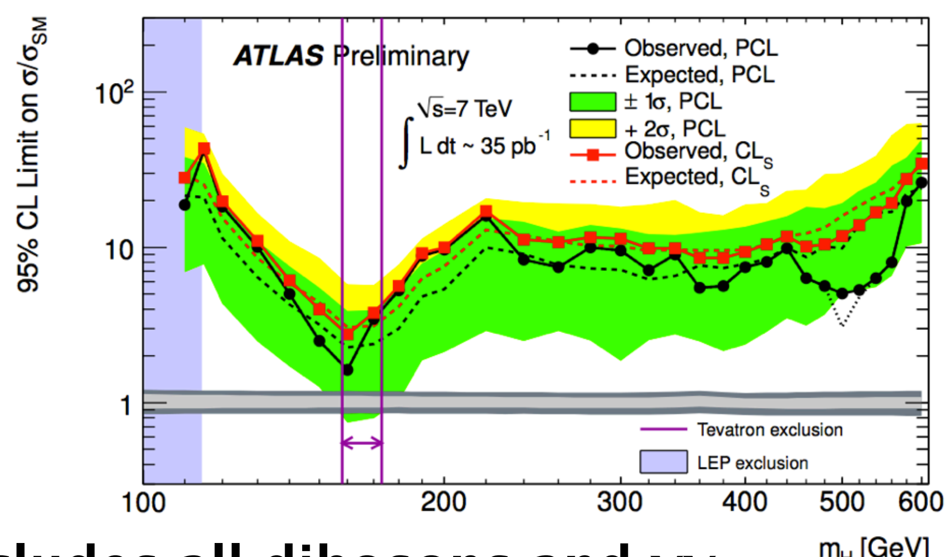
**exclusion at 95% CL for 158 < $M_H$ < 173 GeV**

# Search for H→WW→ee, eμ, μμ



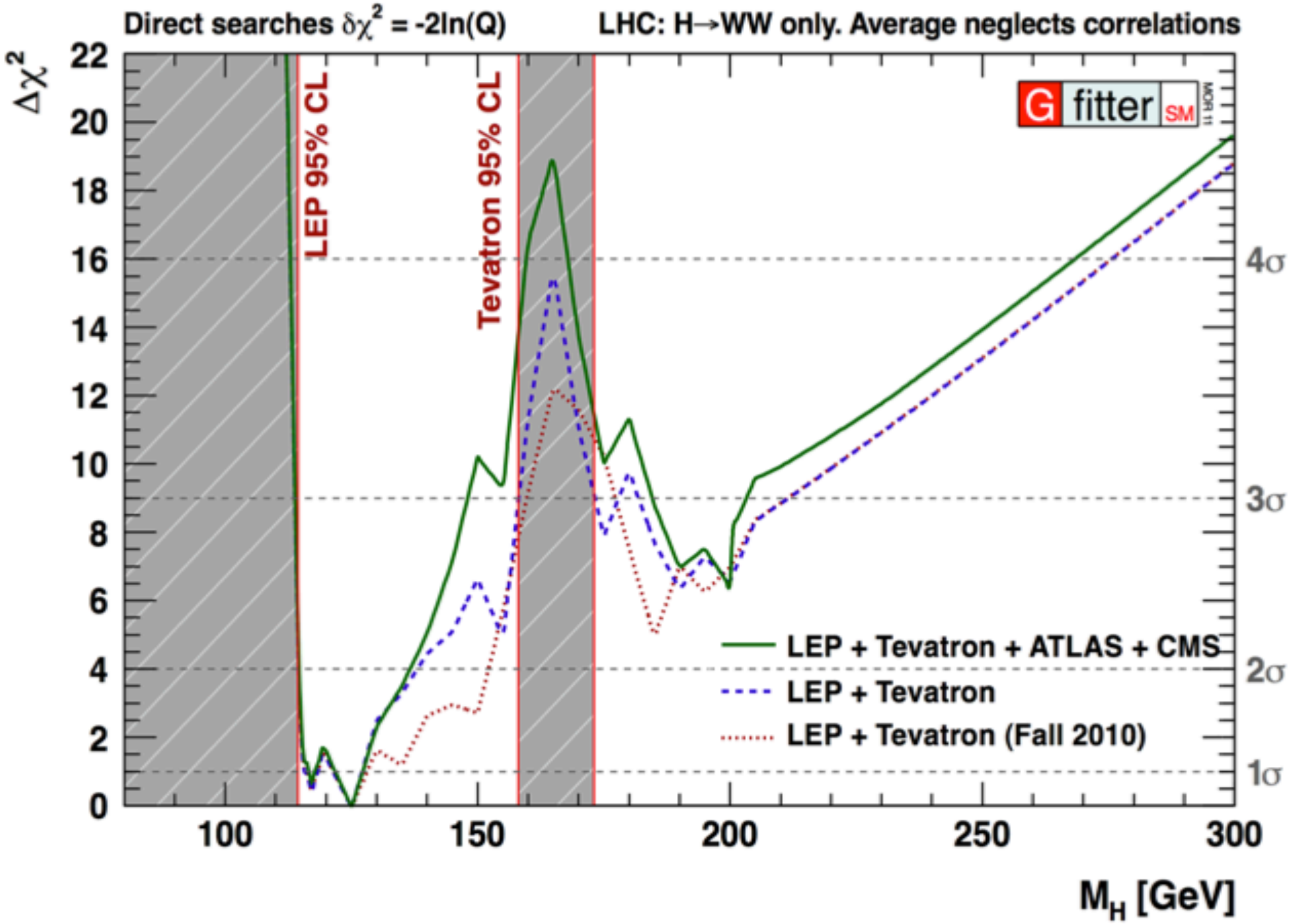




**includes all dibosons and γγ**

# Global SM Electroweak Fit

## Fit: LEP + Tevatron + LHC (H→WW)




$$m_H = 120.2^{+12.3}_{-4.7}\ \text{GeV}$$

≤ 10% if SM is correct

# Conclusions

- we live in a golden era of particle physics
  two running colliders: Tevatron & LHC

- high precision measurements in QCD, Electroweak and top quark physics

→ much more to come!

- We know quite a lot already about the Higgs, e.g. the SM Higgs mass is very constrained

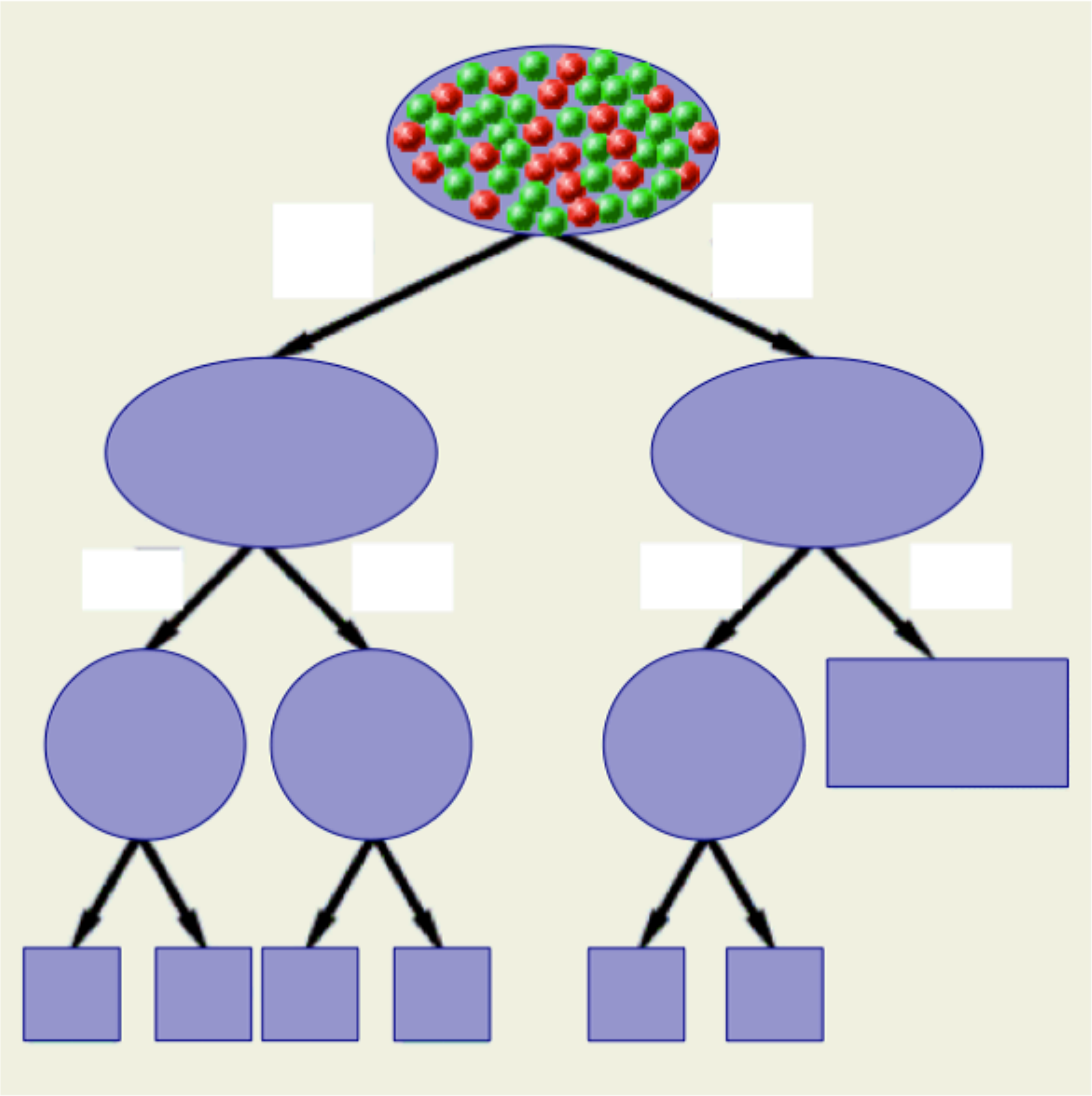
→ we still have to find it...

- the next step is to find out if SM is right or wrong

→ many more exciting results are ahead of us!

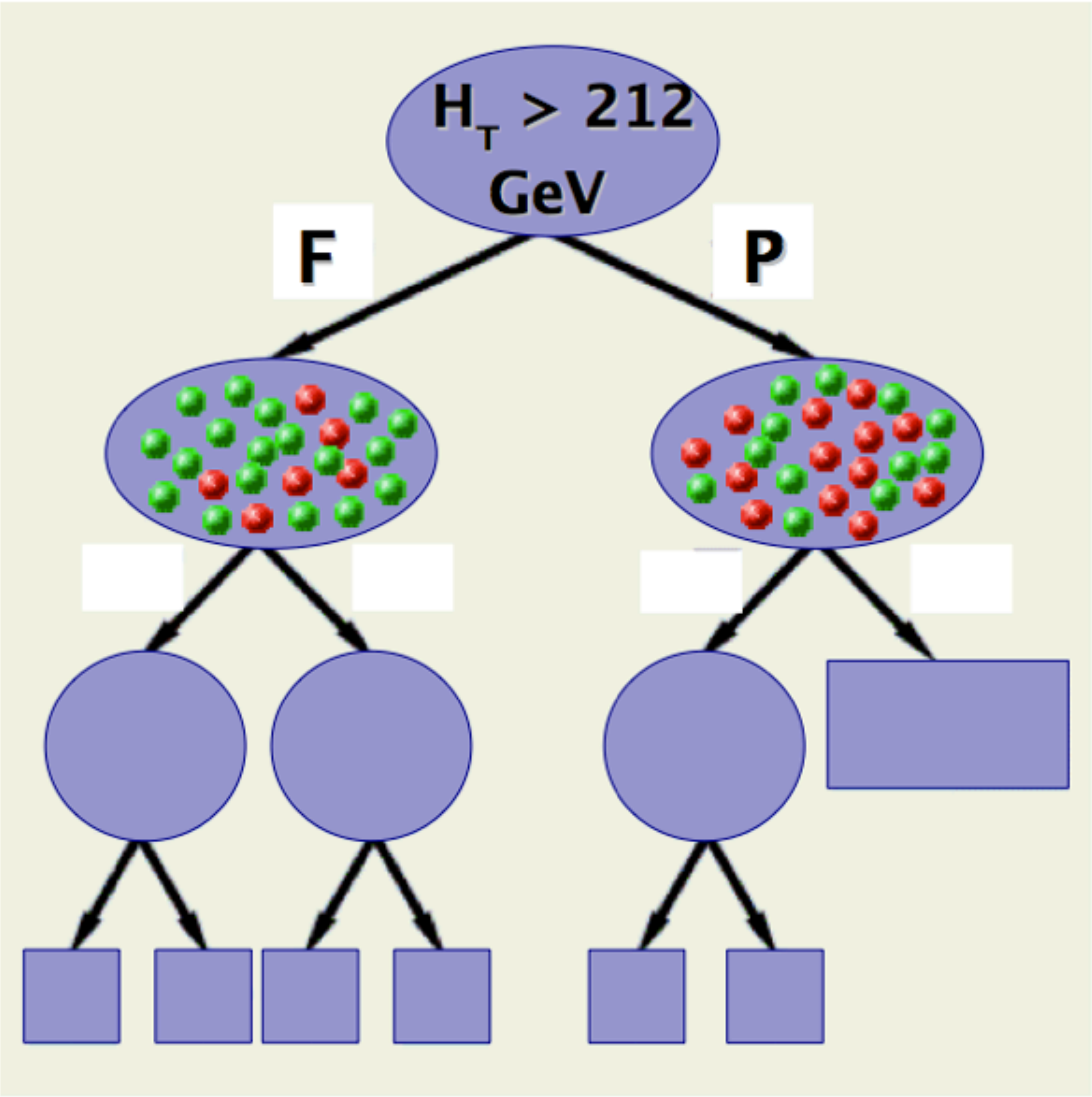
# Backup

# Boosted Decision Trees



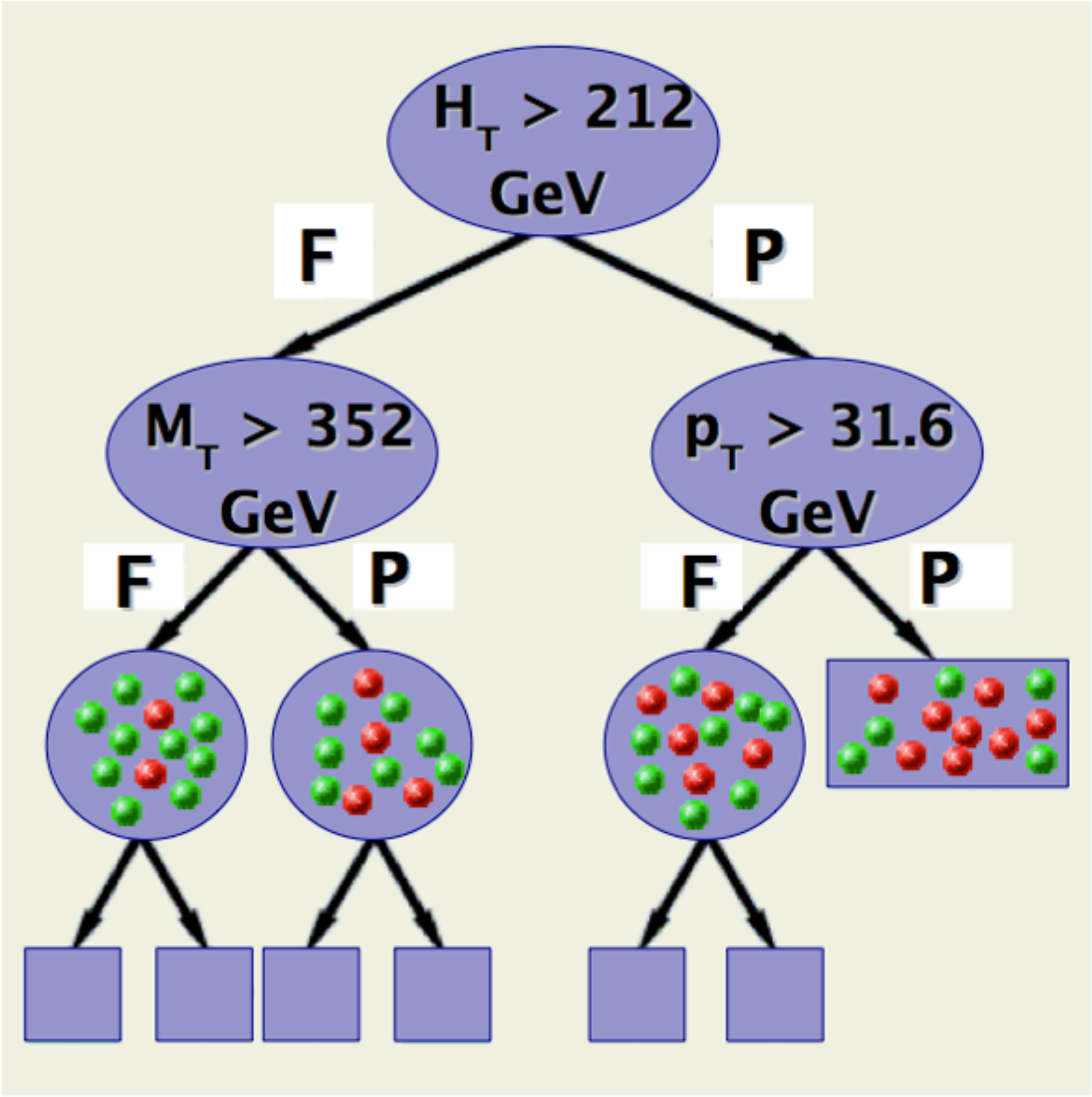
- **IDEA: recover events that fail criteria in cut-based analyses**

# Boosted Decision Trees



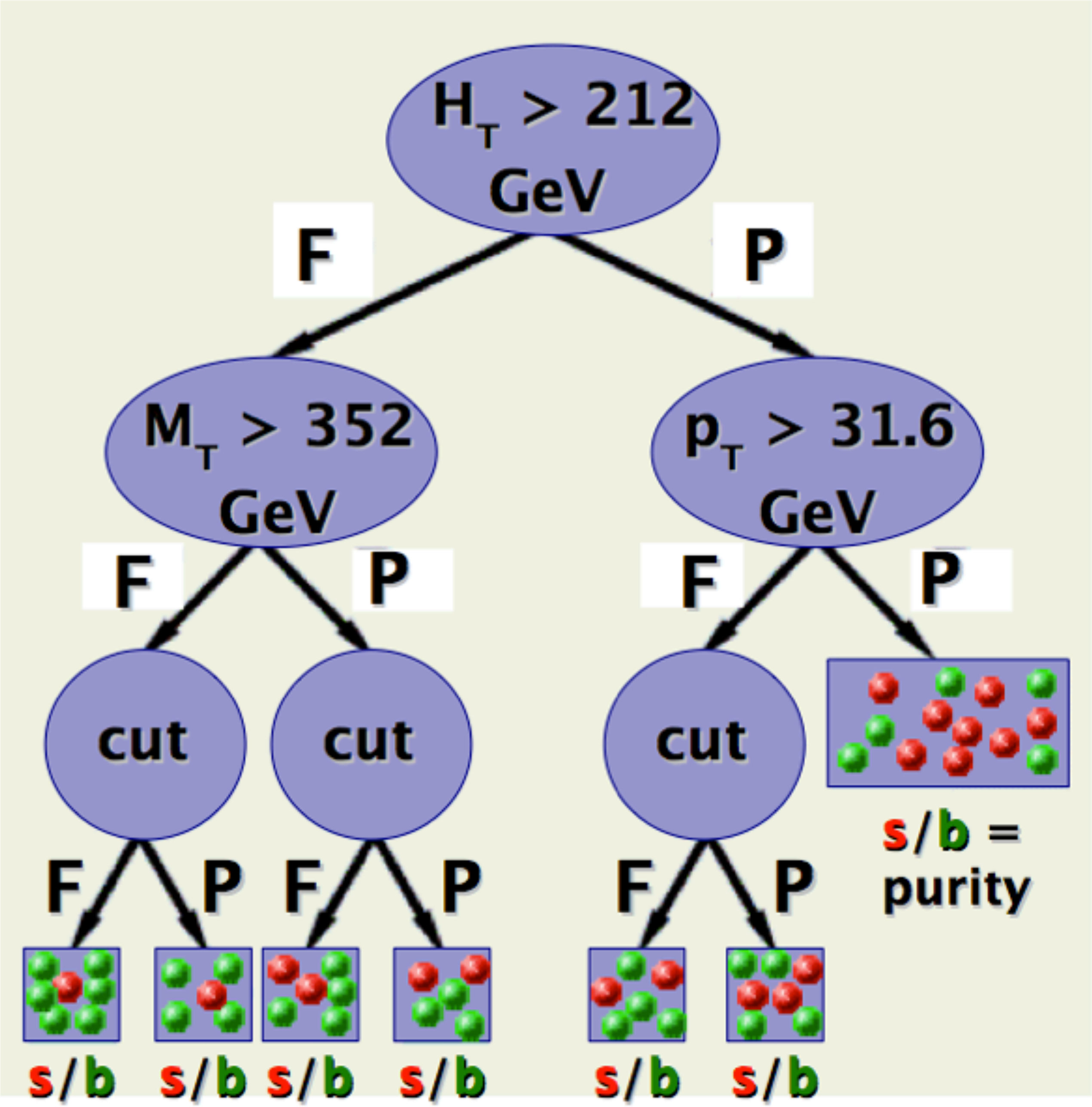

- **IDEA: recover events that fail criteria in cut-based analyses**

# Boosted Decision Trees




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

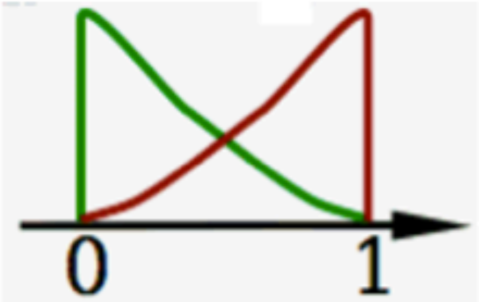
# Boosted Decision Trees



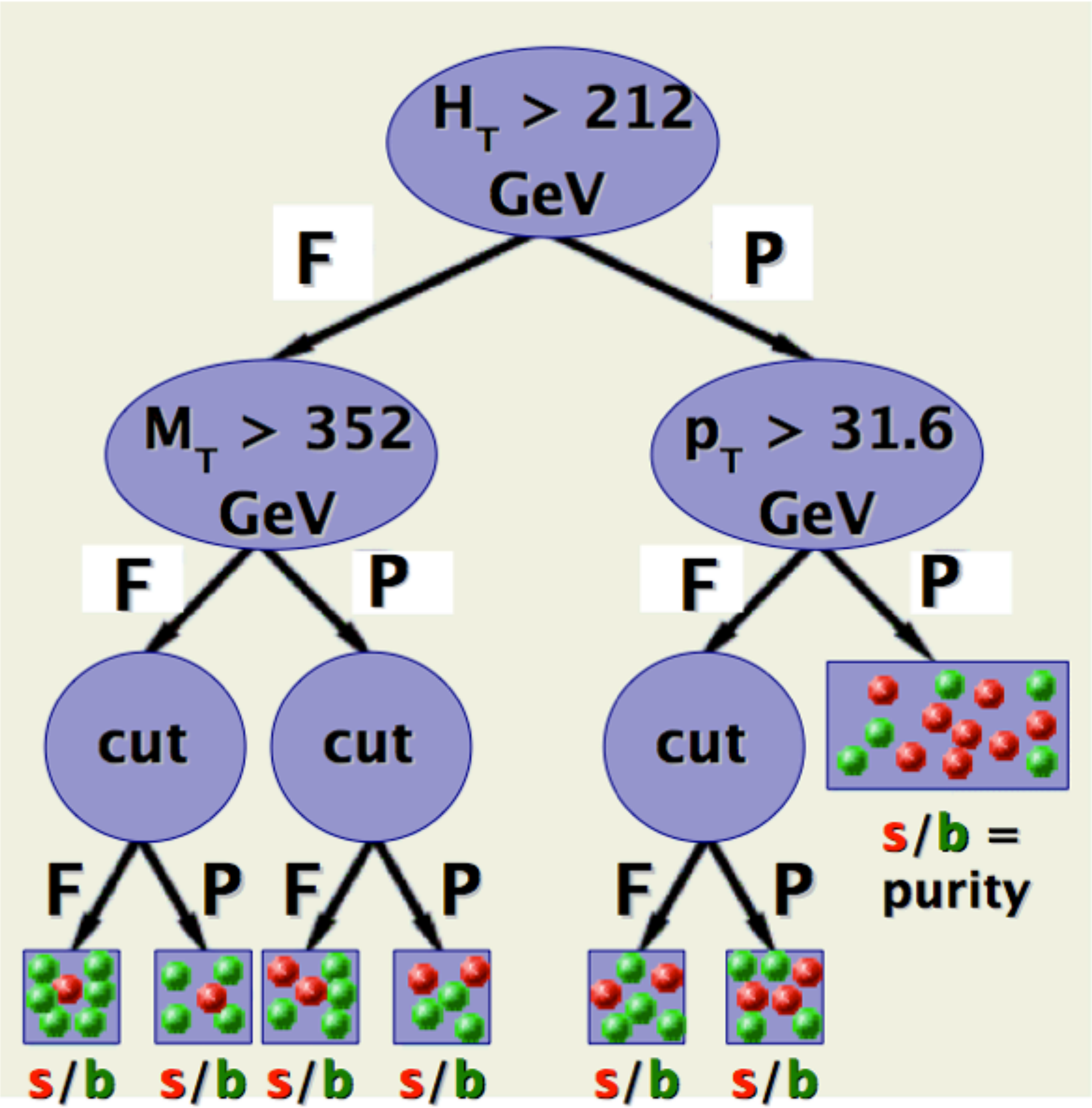

- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

**background** **signal**



# Boosted Decision Trees

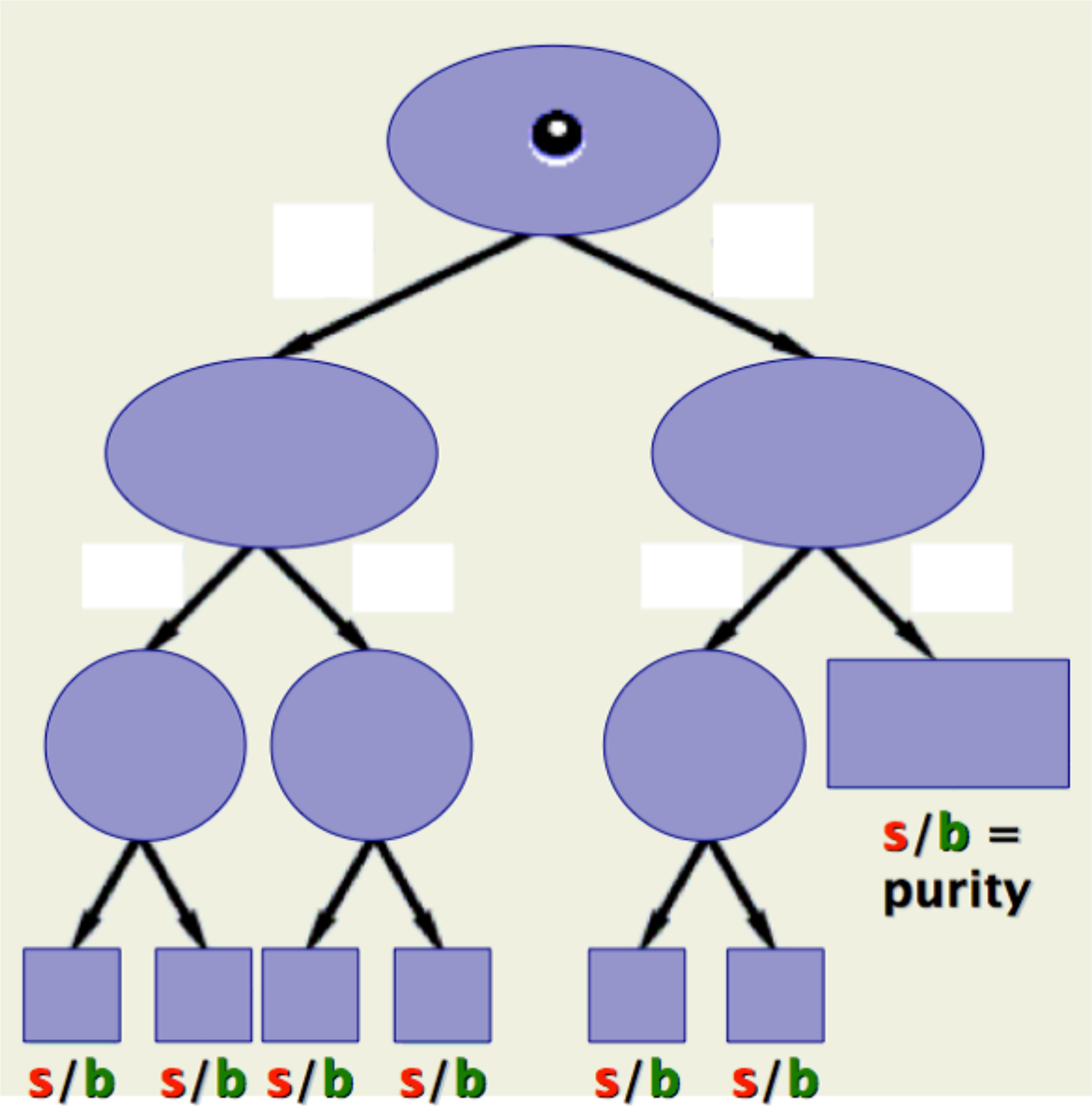



- **IDEA: recover events that fail criteria in cut-based analyses**

**boosting:**

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

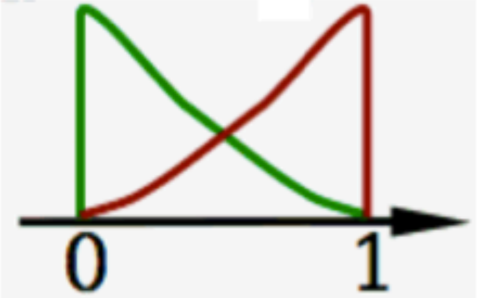
# Boosted Decision Trees



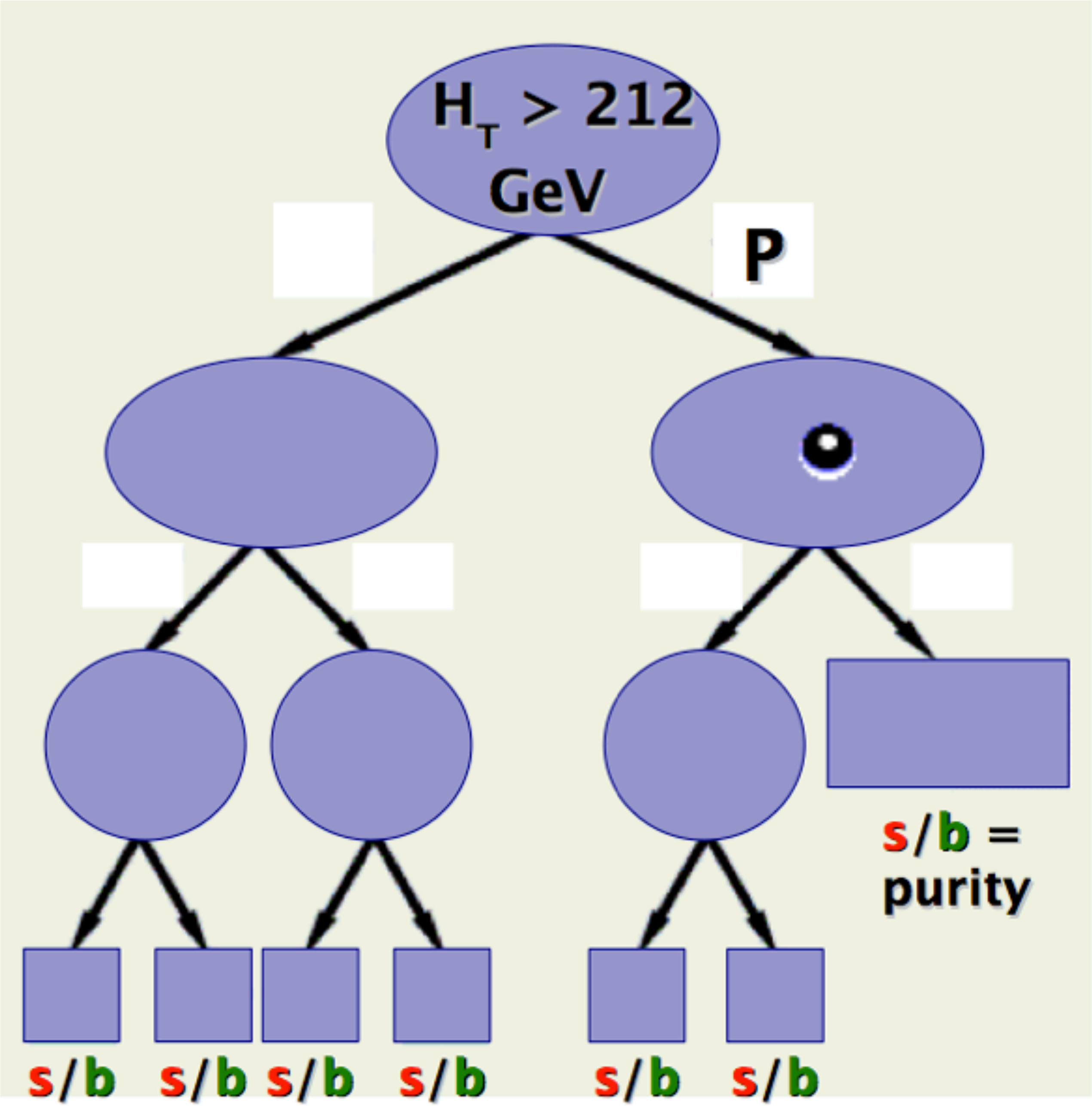

- **IDEA: recover events that fail criteria in cut-based analyses**

- **result:**
  **weight for every event**

**background** **signal**

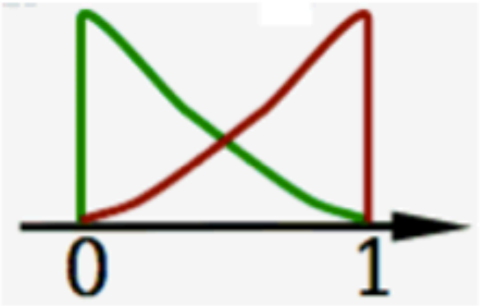


# Boosted Decision Trees

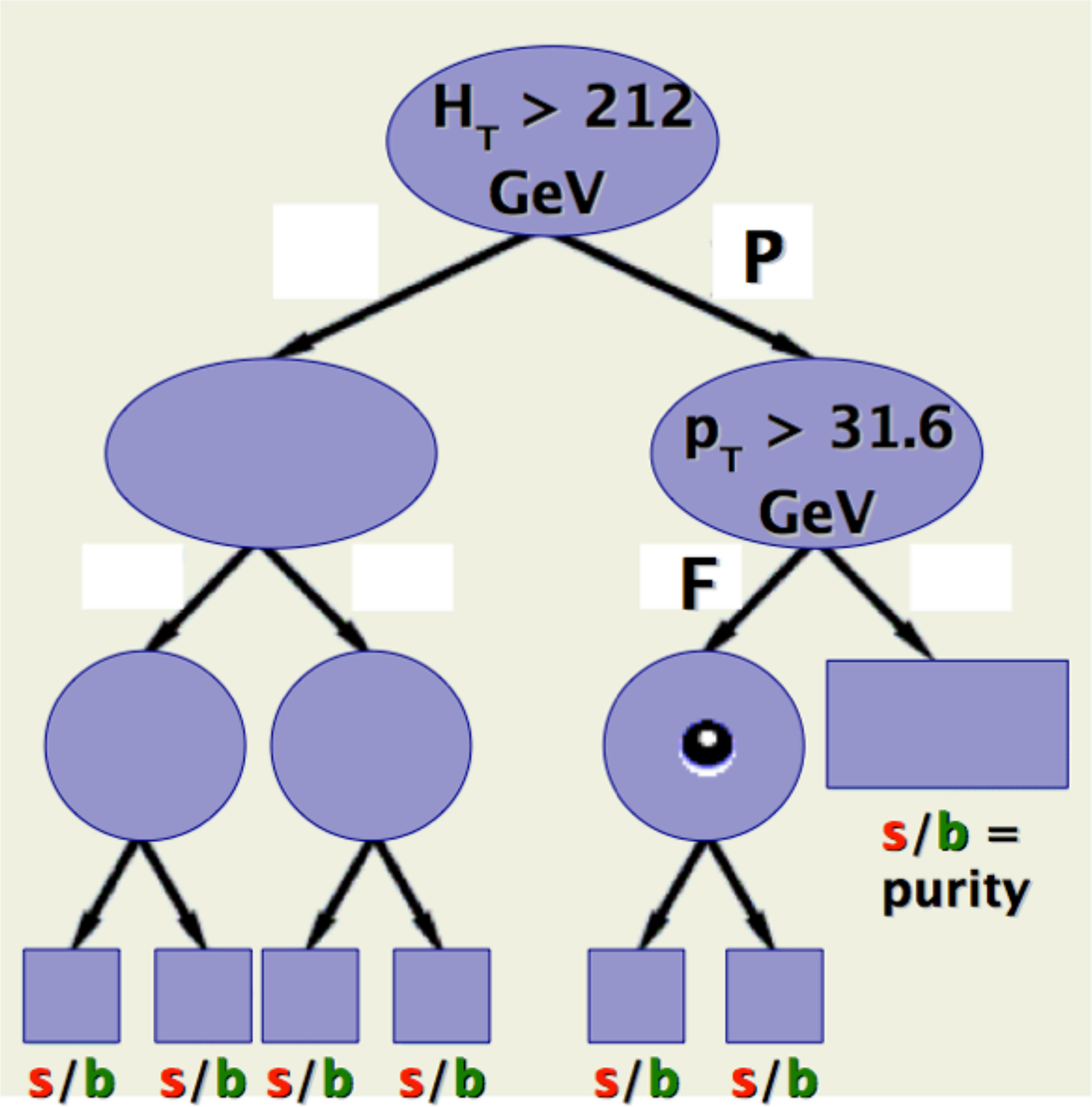



- **IDEA: recover events that fail criteria in cut-based analyses**

- **result:**
  **weight for every event**

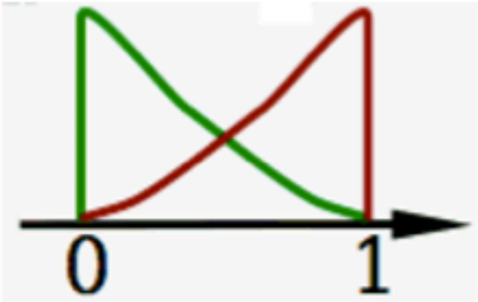


# Boosted Decision Trees

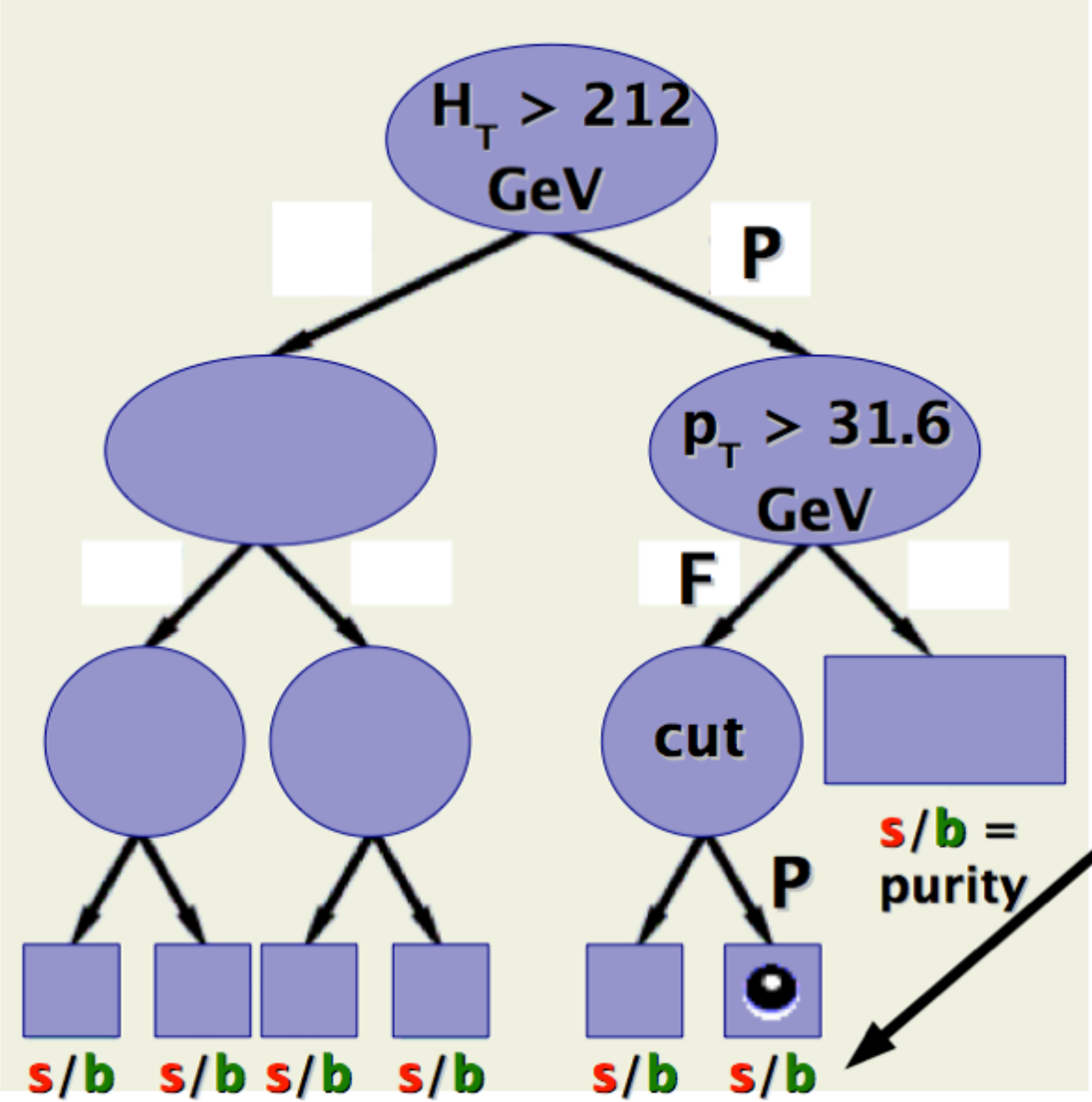



- **IDEA: recover events that fail criteria in cut-based analyses**
- **result: weight for every event**

**background** **signal**

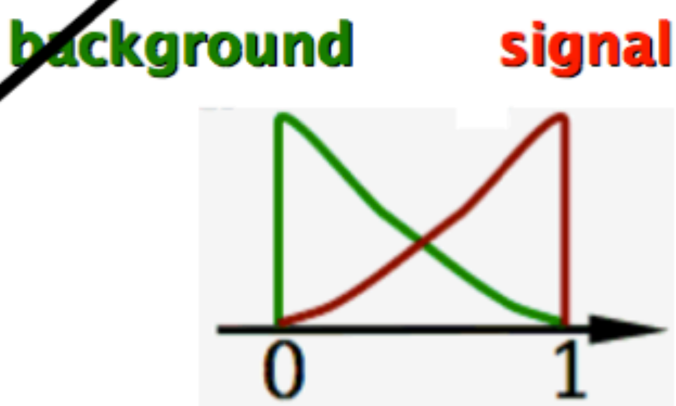


# Boosted Decision Trees

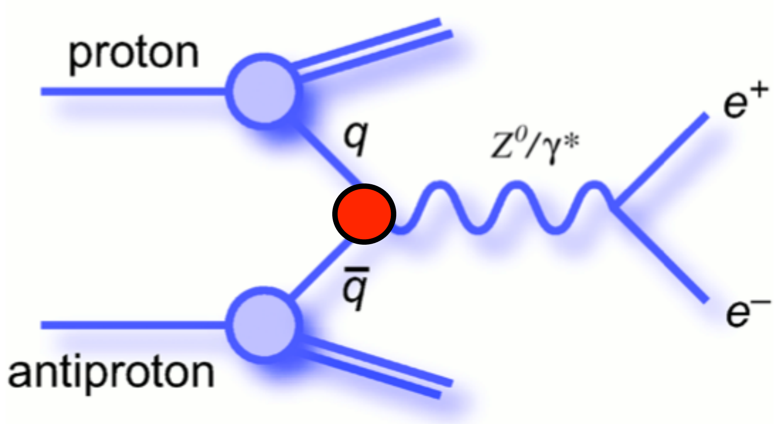



- **IDEA: recover events that fail criteria in cut-based analyses**

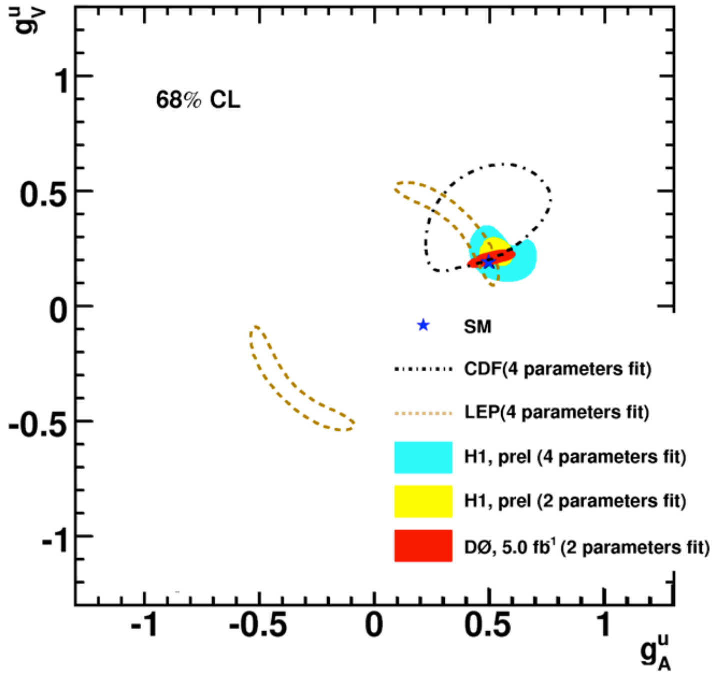
- **result: weight for every event**

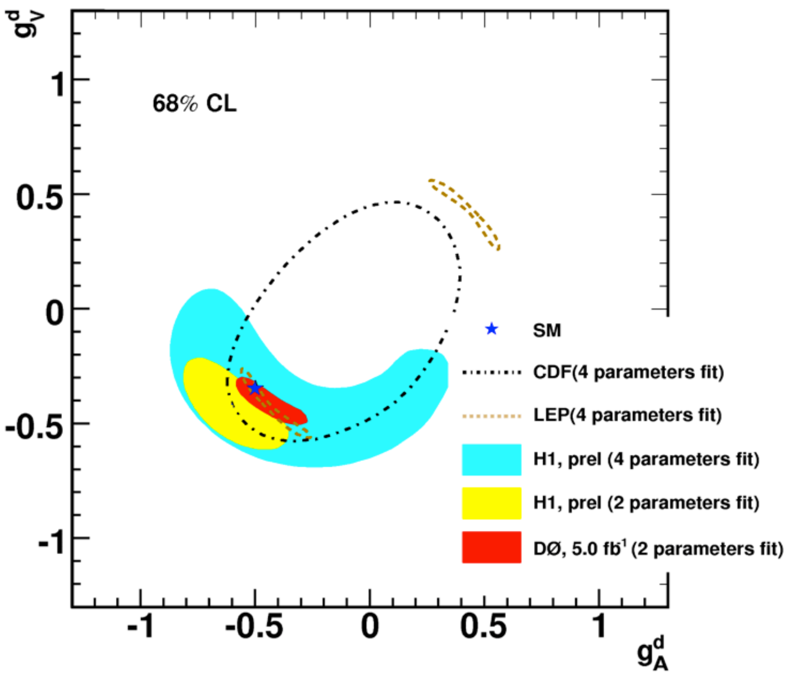


# Z Boson-Quark Couplings

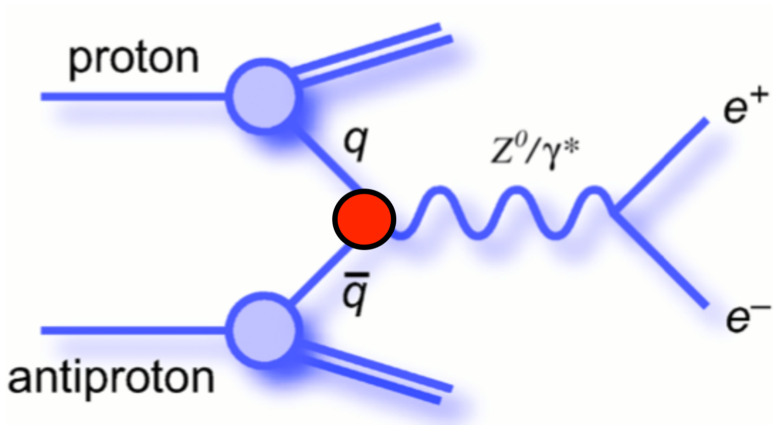



$$g_V^f = I_3^f - 2Q_f \cdot \sin^2\theta_W$$
$$g_A^f = I_3^f$$

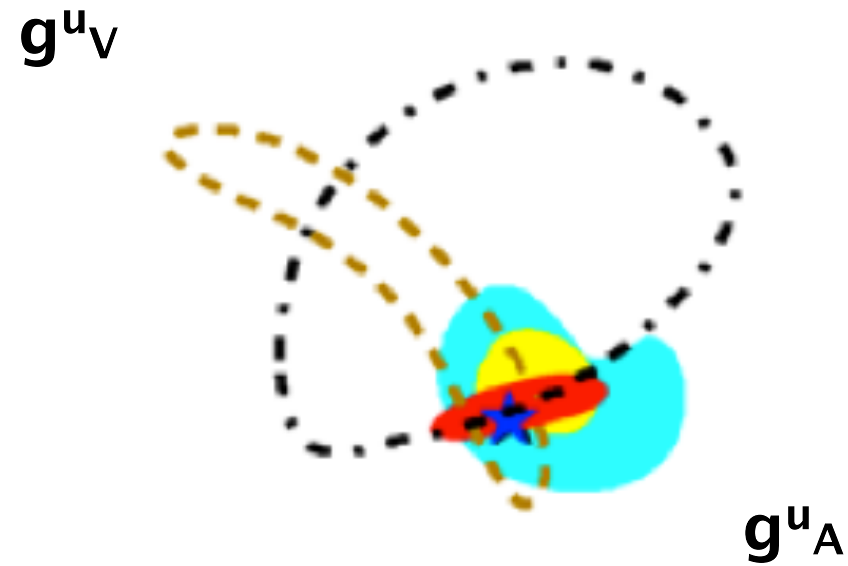


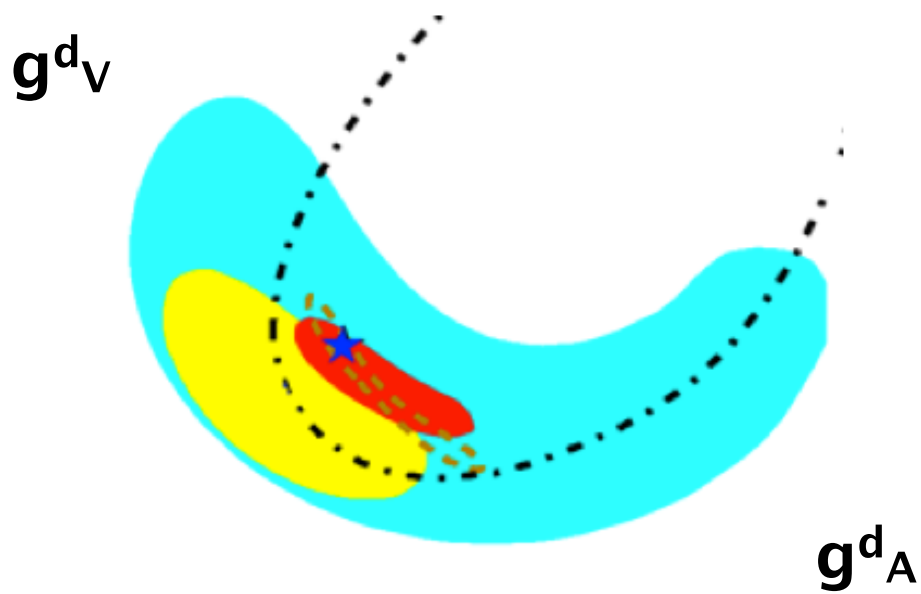



# Z Boson-Quark Couplings



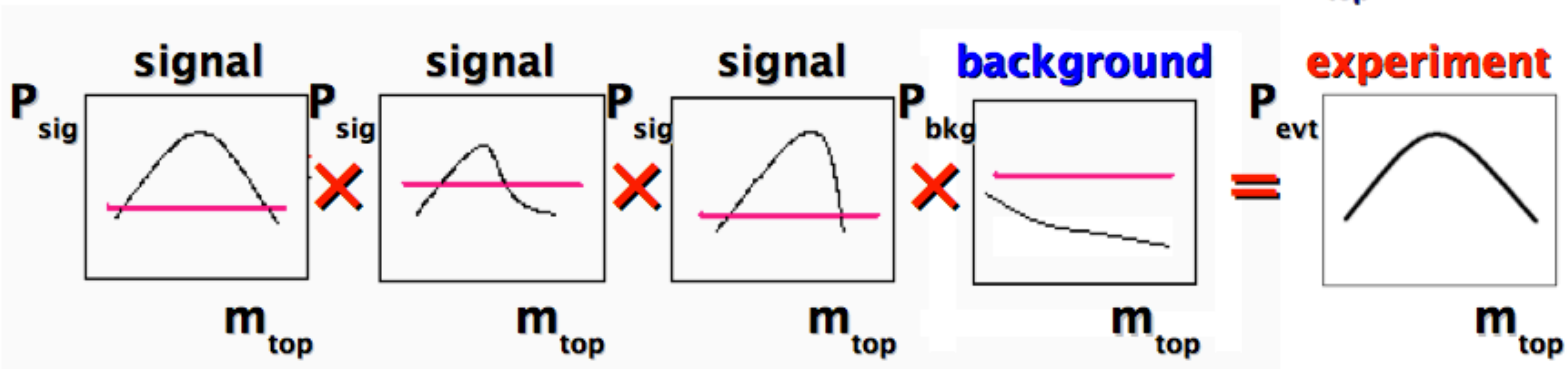

$$g_V^f = I_3^f - 2Q_f \cdot \sin^2\theta_W$$
$$g_A^f = I_3^f$$



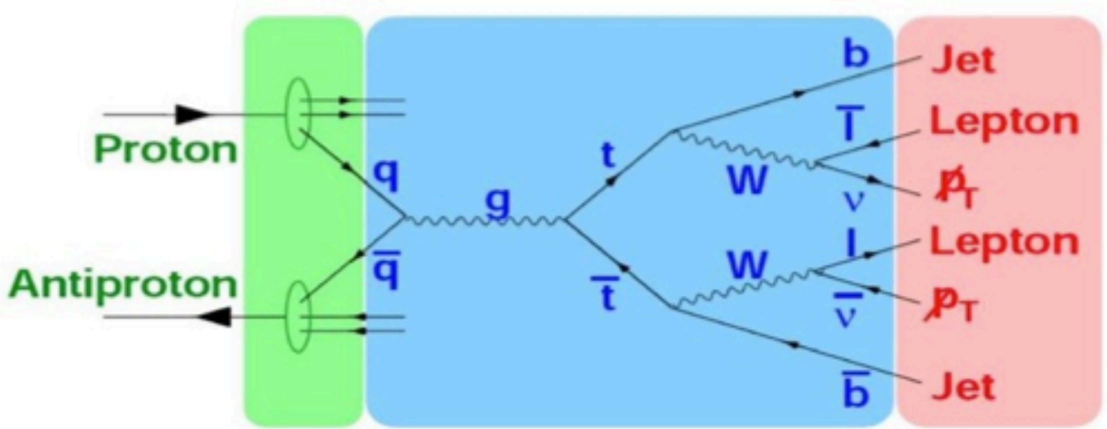



# Extraction Techniques: Matrix Element

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

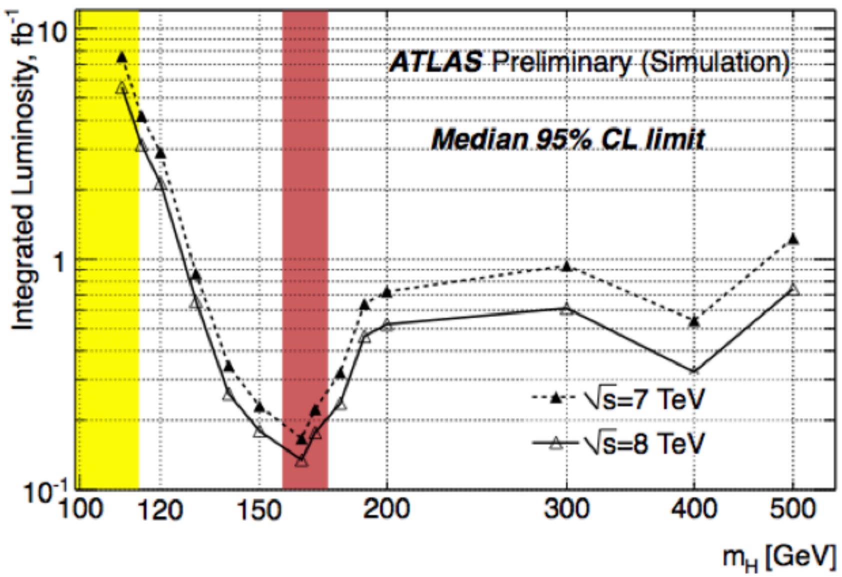


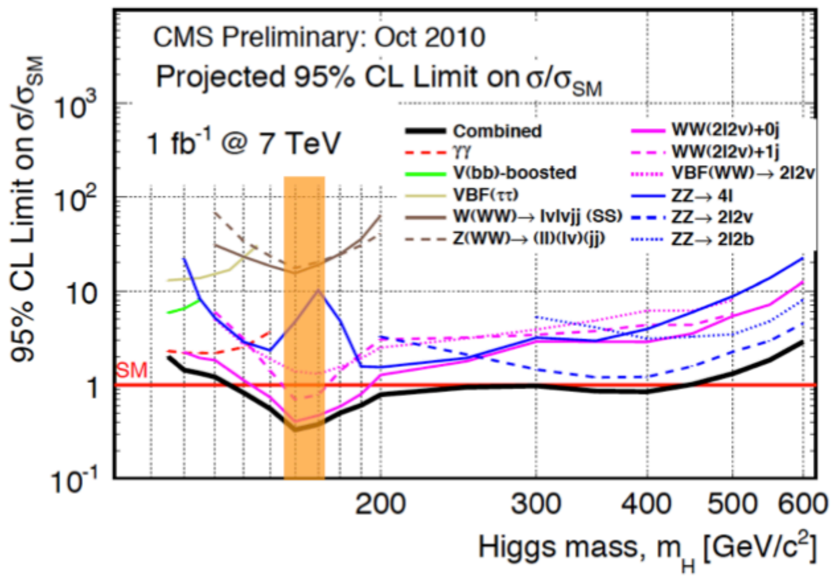

$$P_{sig}(x;m_{top},JES)=Acc(x)\times\frac{1}{\sigma}\int d^n\sigma(y;m_{top})\,dq_1\,dq_2\,f(q_1)\,f(q_2)\,W(x,y;JES)$$



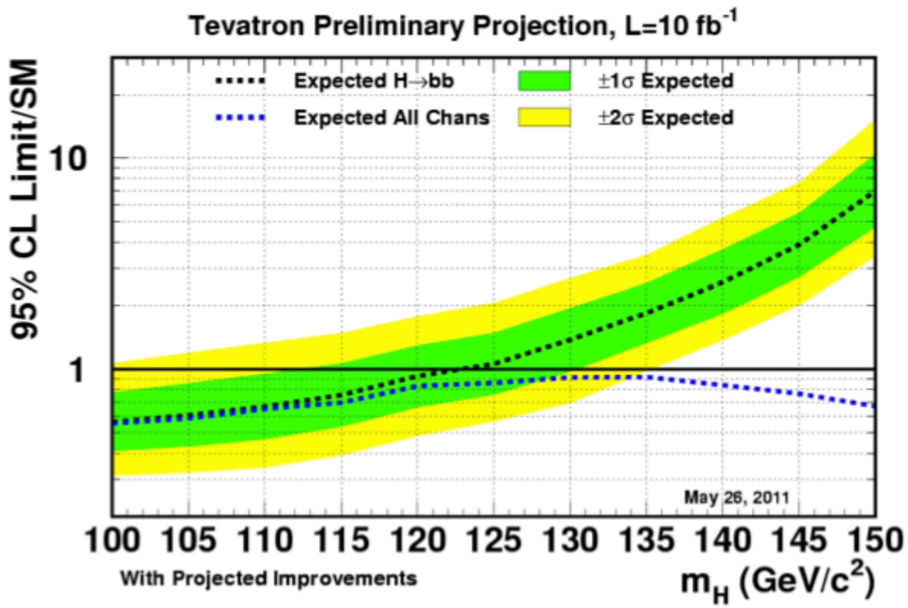

PDF's LO-Matrix element transfer functions (probability to measure x when y was produced)

# Future Higgs Projections

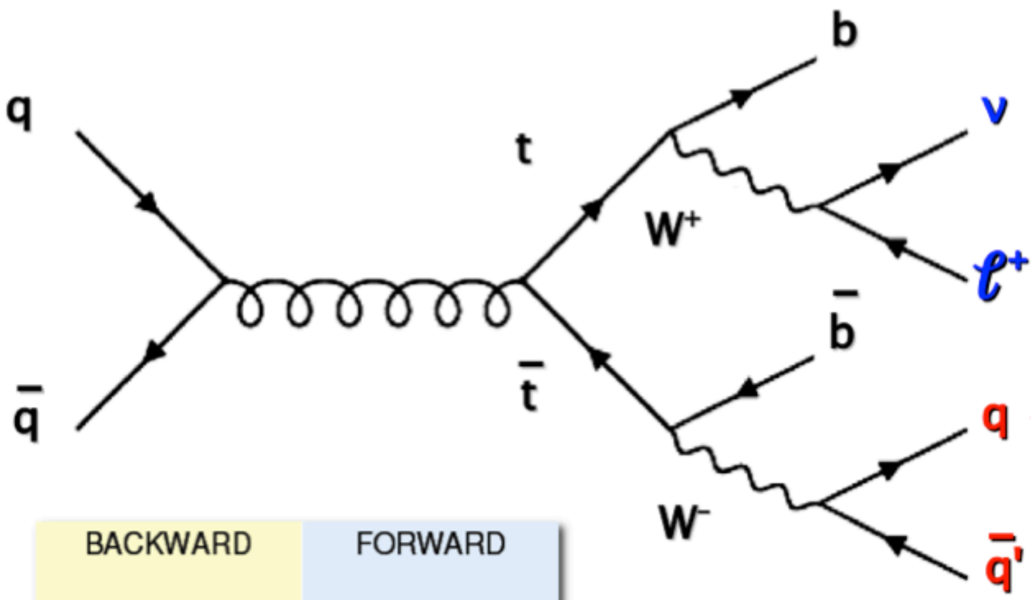


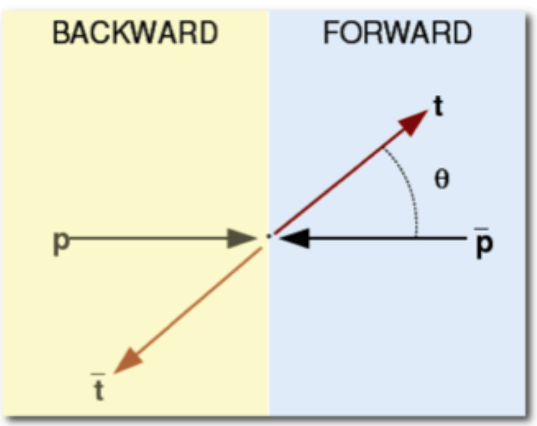




- 1fb-1 cover the full range above ~130, driven by VV modes
- 1fb-1 cover the full range above ~130, driven by VV modes

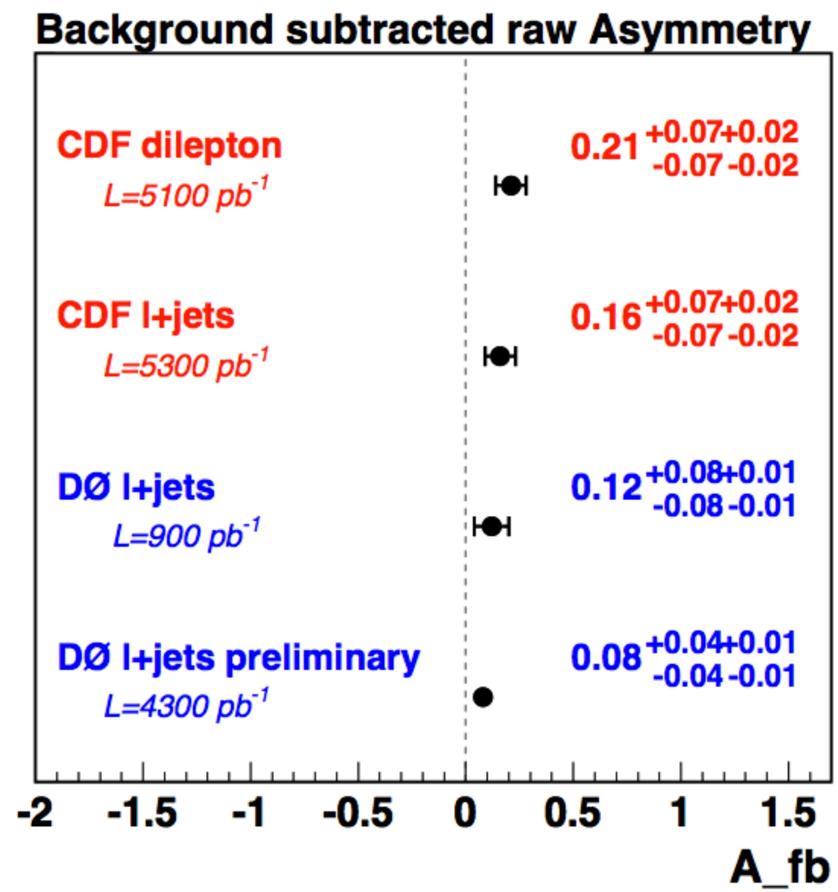


# Forward Backward Asymmetry



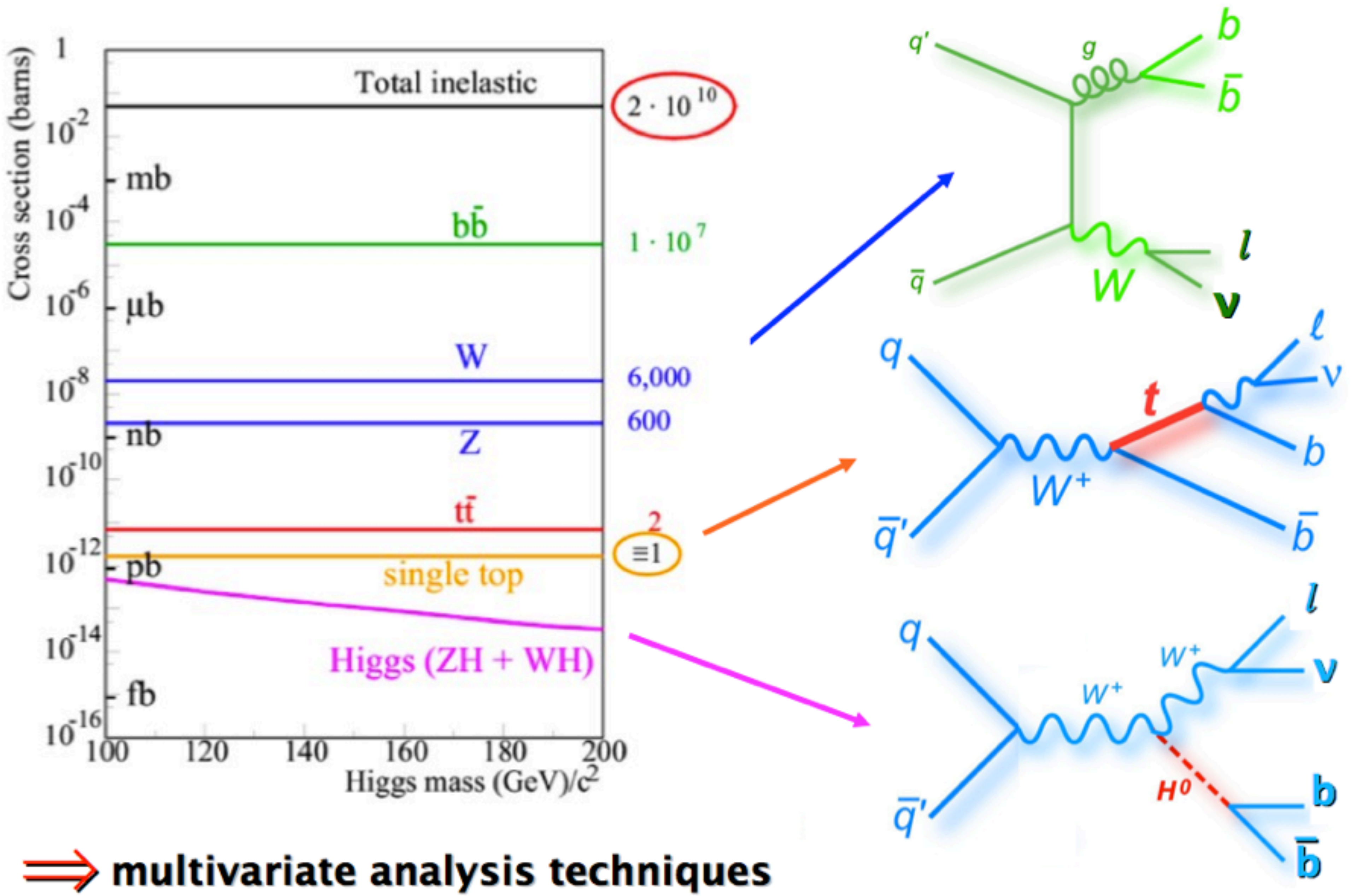




$$A_{fb} = \frac{F - B}{F + B}$$




**new DØ measurement is on its way!**

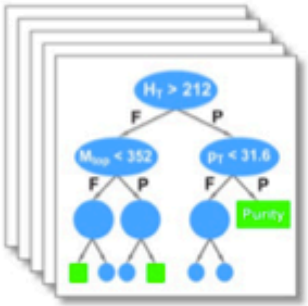
# Single Top Quark Production



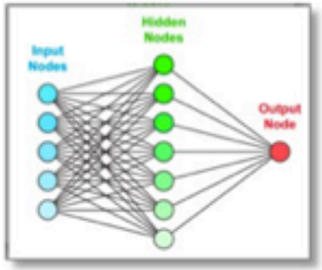

⟹ **multivariate analysis techniques**

# Multivariate Analyses

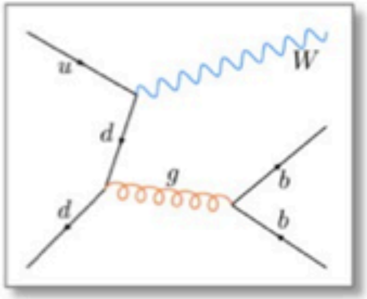
**Boosted Decision Trees**




**Neural Networks**




**Matrix Elements**




**Likelihood**

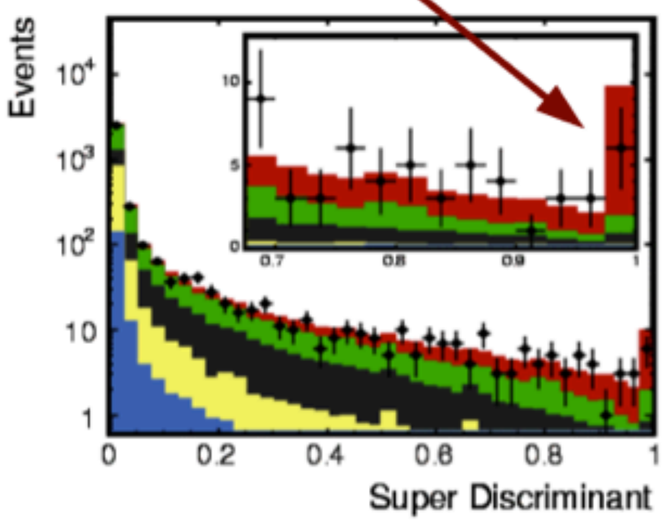
$$p_{ik} = \frac{f_{ij_ik}}{\sum_{m=1}^{5} f_{ij_im}},$$

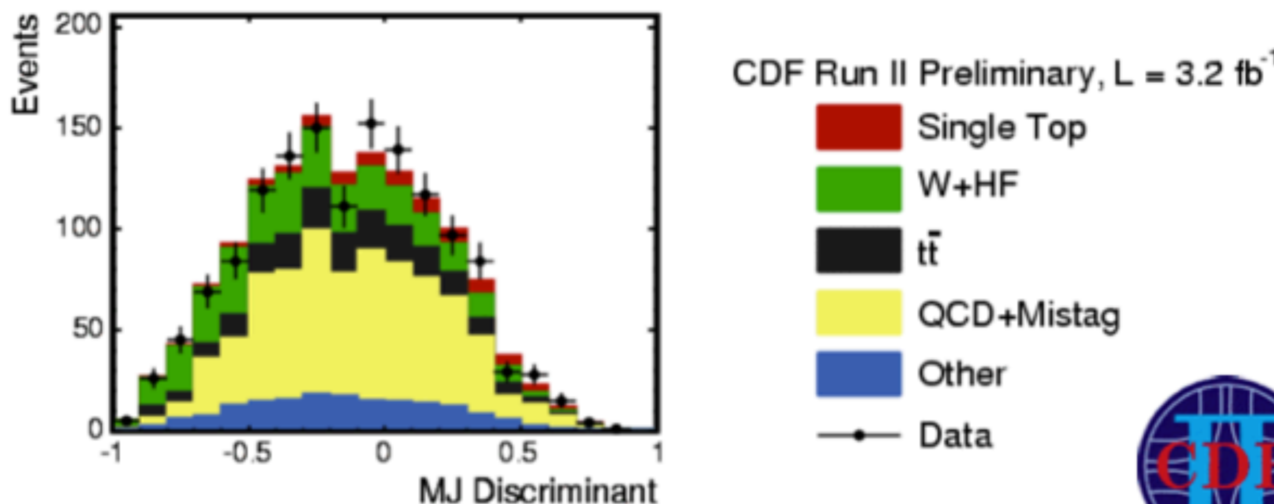
$$\mathcal{L}_k(\{x_i\}) = \frac{\prod_{i=1}^{n_{var}} p_{ik}}{\sum_{m=1}^{5} \prod_{i=1}^{n_{var}} p_{im}}.$$

**combine up to 8 different analysis channels:**

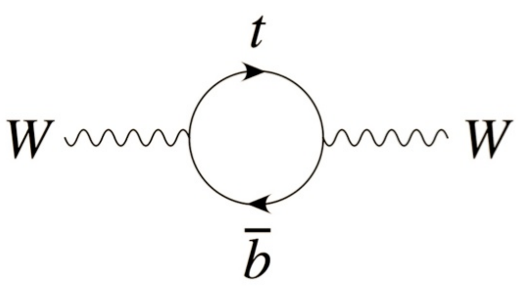
**single top**

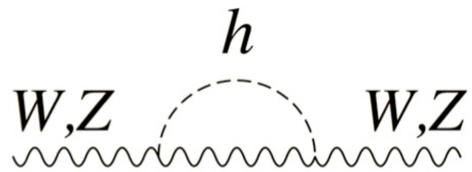
- $\not{E}_T$+jets selection :
  recover badly reconstructed e, μ; include τ



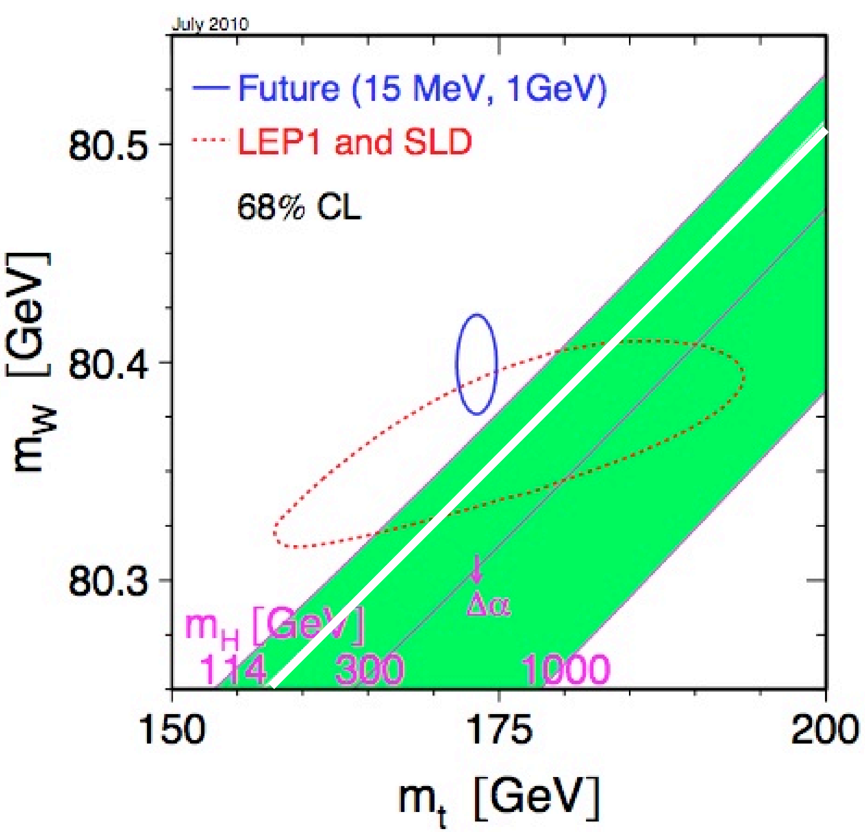



# Self-consistency of the SM

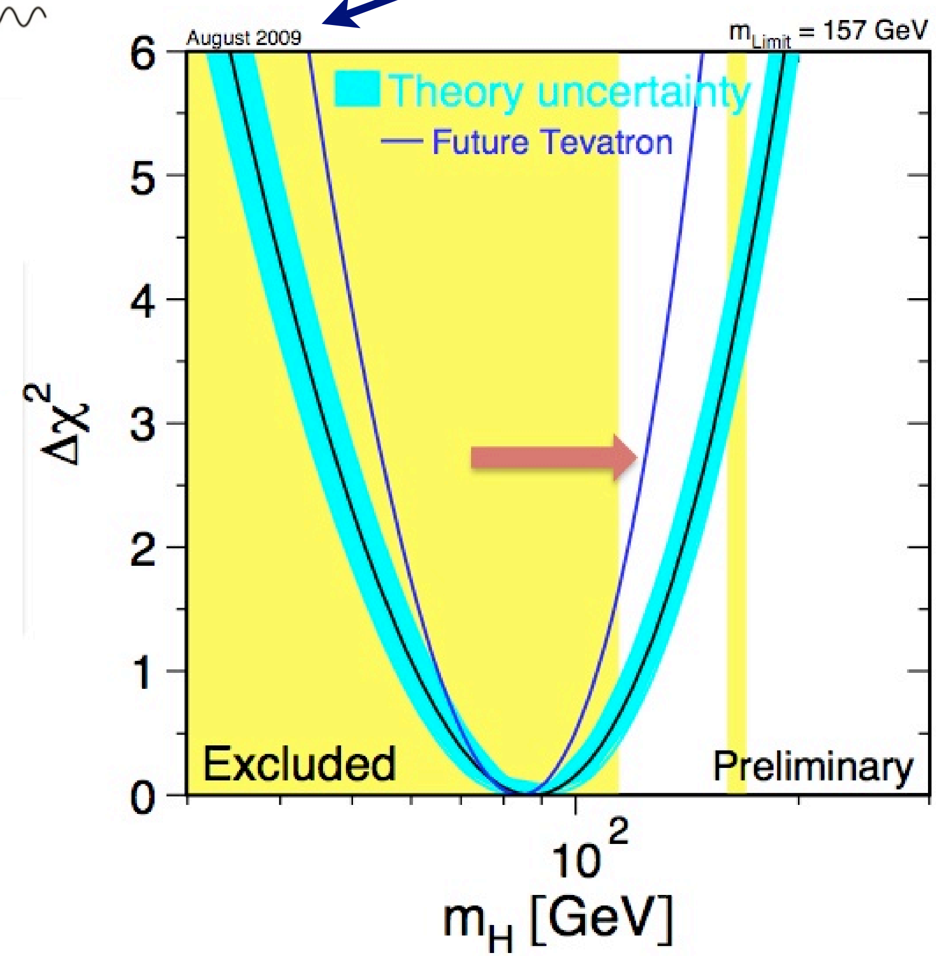



assume precision of top mass: 1 GeV
assume precision of W mass: 15 MeV

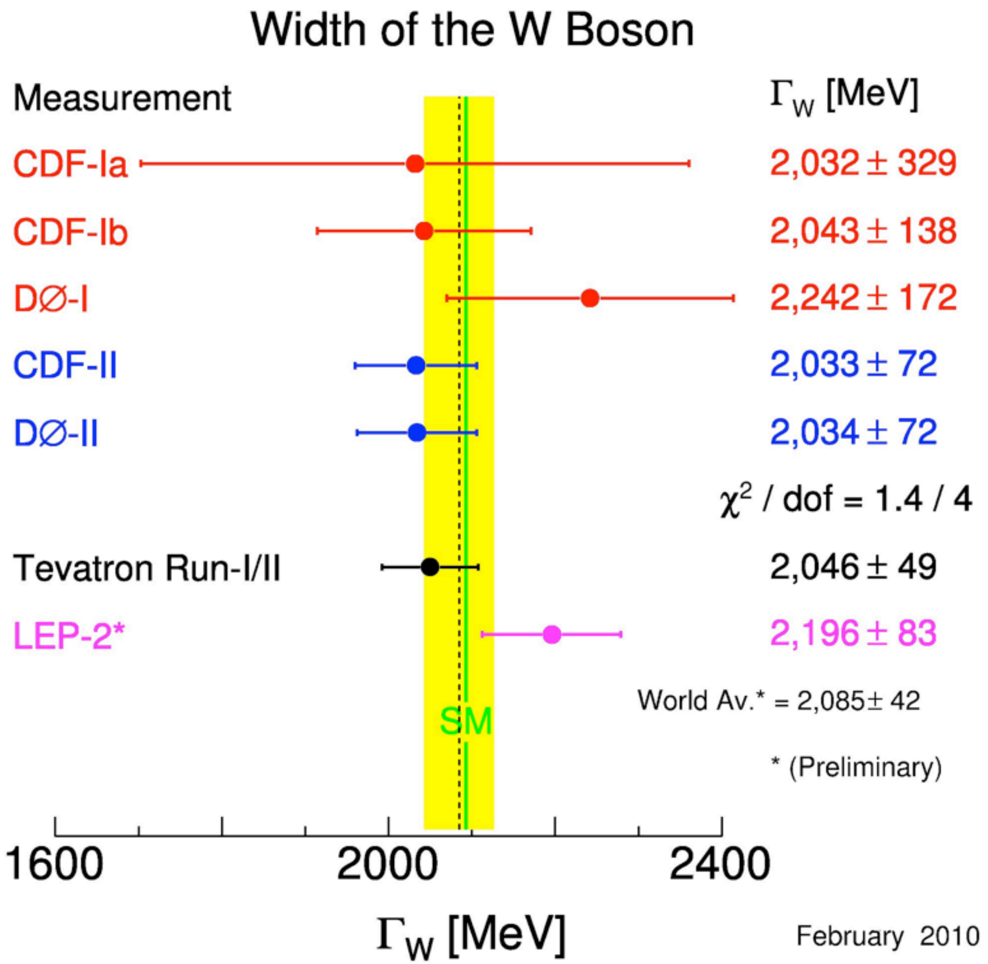



Improved W mass measurement is critical




$m_H$ < 117 GeV at 95% CL
at current minimum

# W Boson Properties




**more W properties:**

- charge asymmetry
- $g_2$ measurement
- asymmetry in Z→ee
- ...

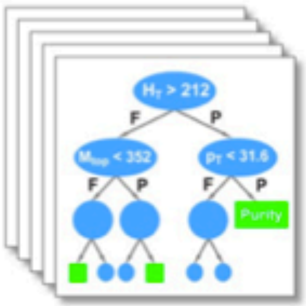
- all very important measurements
- some will help constraining the W mass
- some will help constraining the PDFs and therefore improving the theory error of the W mass

**current Tevatron precision: 2.3%**

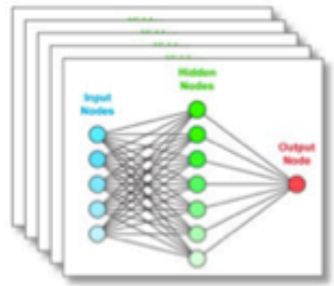
**→ expect improvements (statistics +systematics) with larger data sets**

# Multivariate Analyses

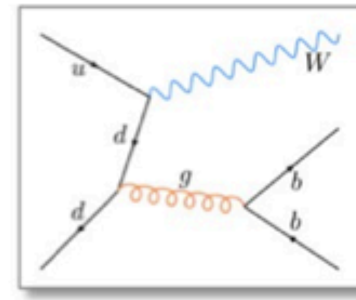
**Boosted Decision Trees**



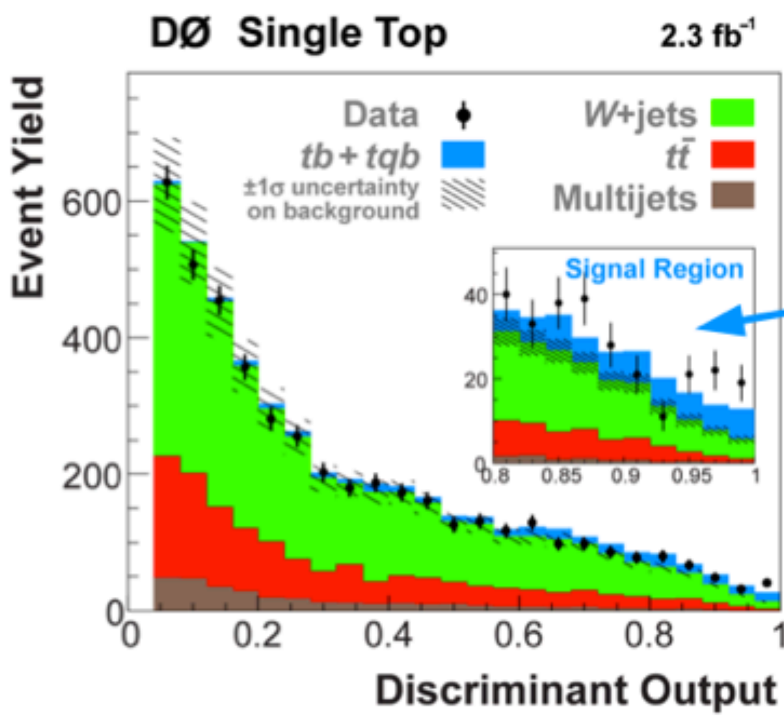

**Boosted Neural Networks**




**Matrix Elements**



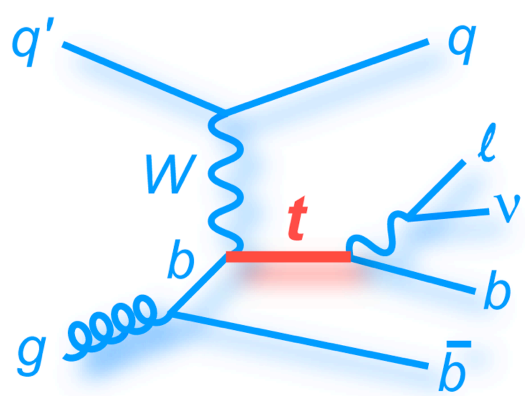

**combine up to 12 different analysis channels:**

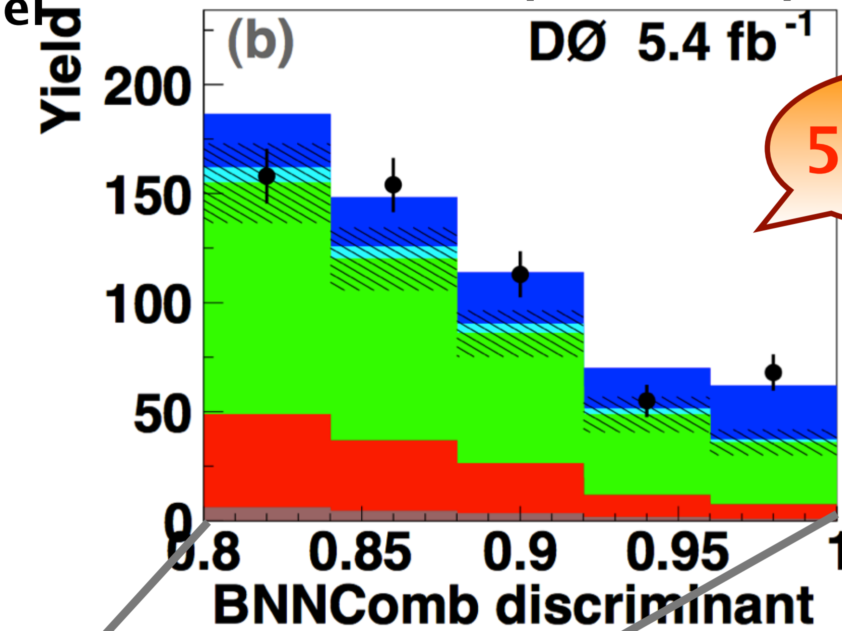



single top

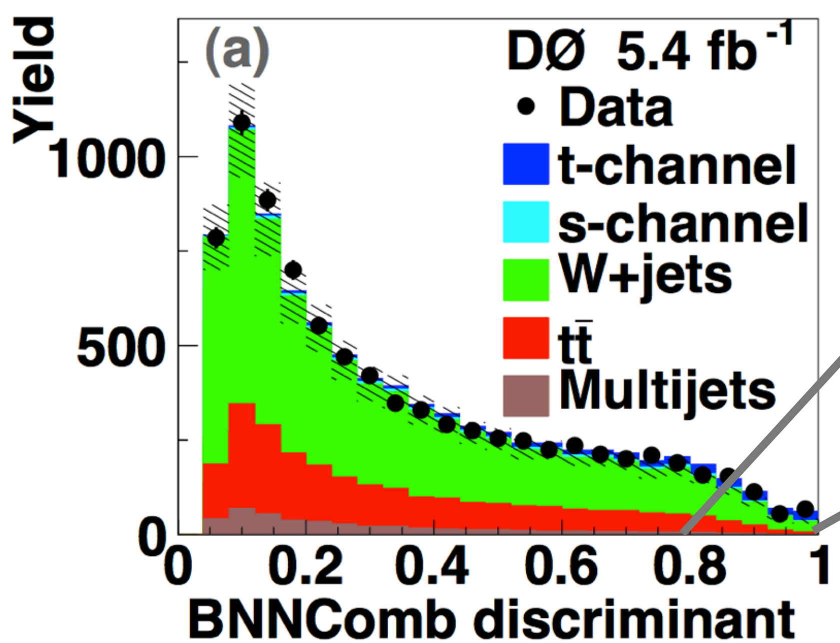
# Single Top t-channel

- 2, 3, 4 jets with 1, 2 b tags
- train multivariate analysis for t-channel
- double data set




5.4 $fb^{-1}$

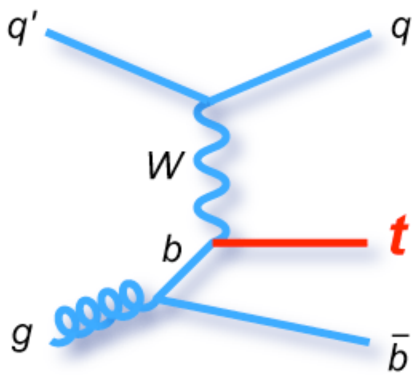


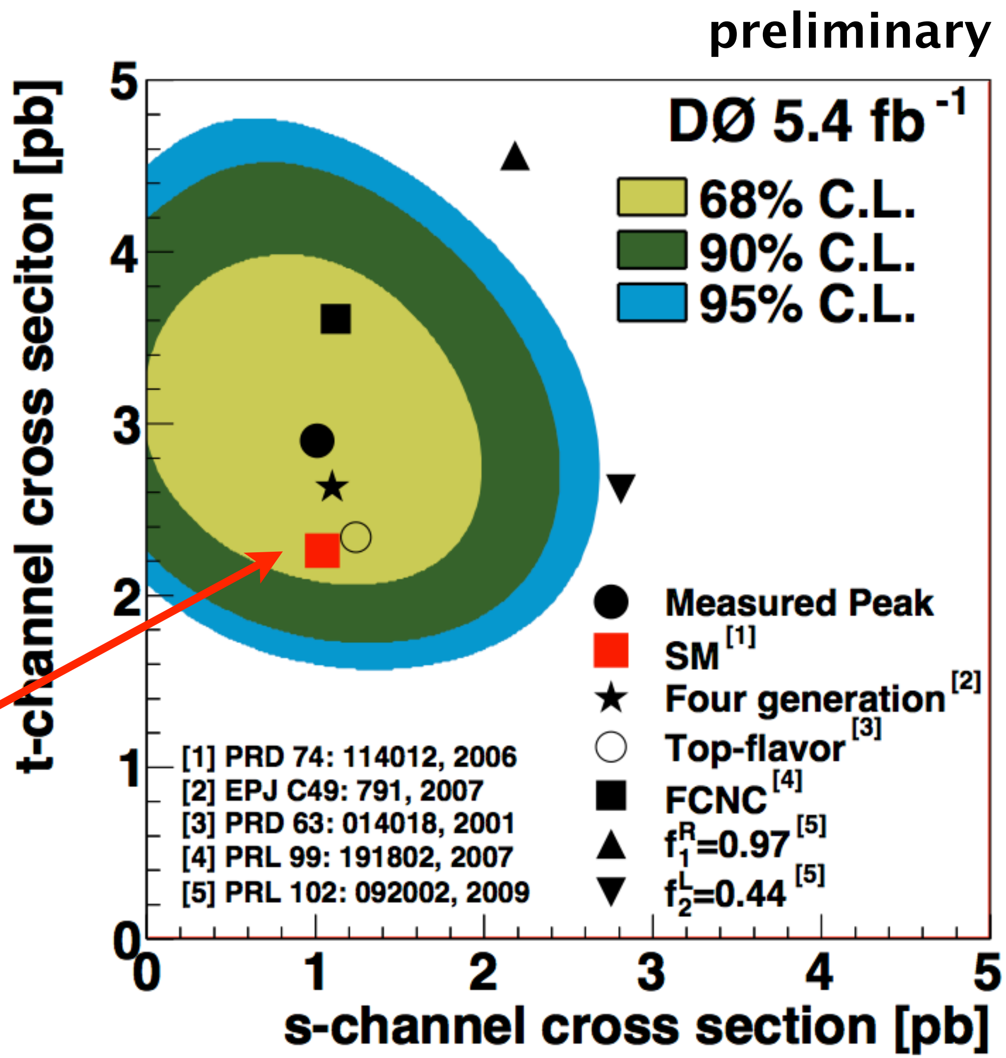

$\sigma_{tb}$ = 2.26 ± 0.12 pb

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

**σ(t-channel)=2.90±0.59 pb**

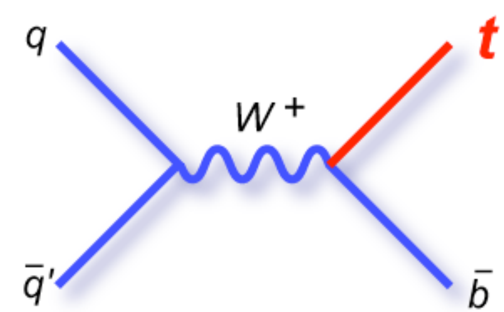
# Single Top s- vs. t-channel



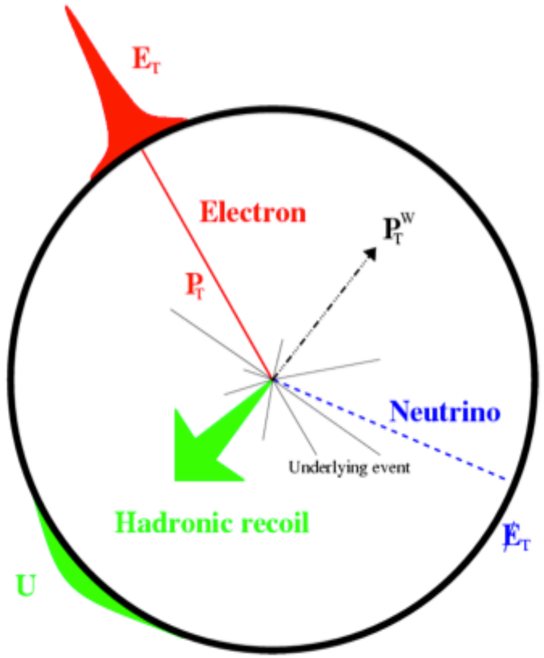

5.4 $fb^{-1}$

SM

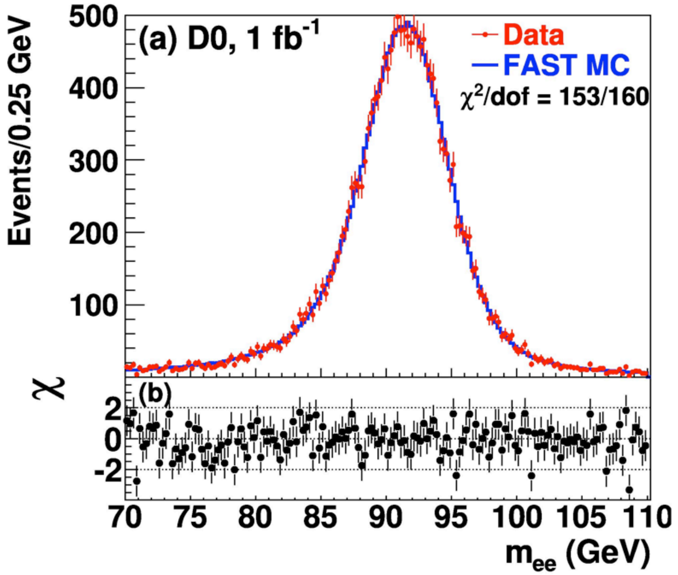



**good agreement with Standard Model**

# Future Legacy: W mass

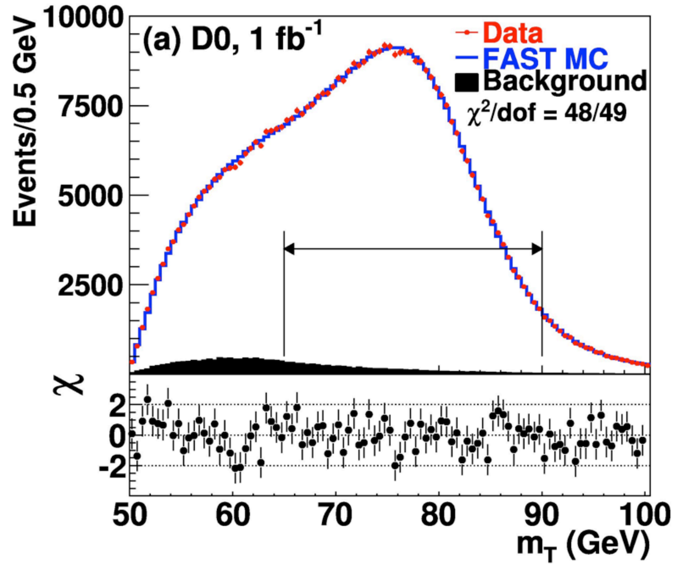



calibration




~18k events in 1 fb$^{-1}$

signal



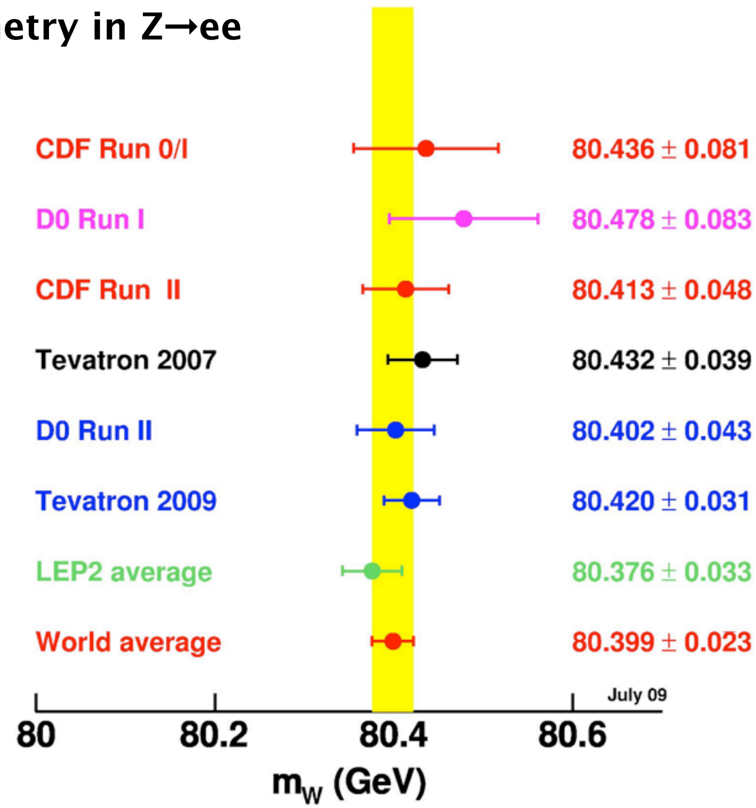

~485k events in 1 fb$^{-1}$

$$m_T = \sqrt{2 p_T^e p_T^\nu (1 - \cos\Delta\phi)}$$

# Future Legacy: W mass

**more W properties:**

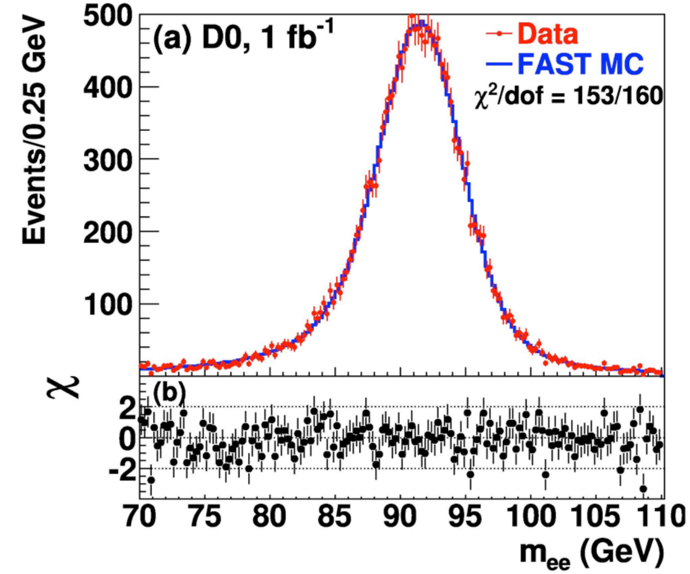
- W width
- charge asymmetry
- $g_2$ measurement
- asymmetry in $Z \to ee$




current Tevatron precision: 0.04%

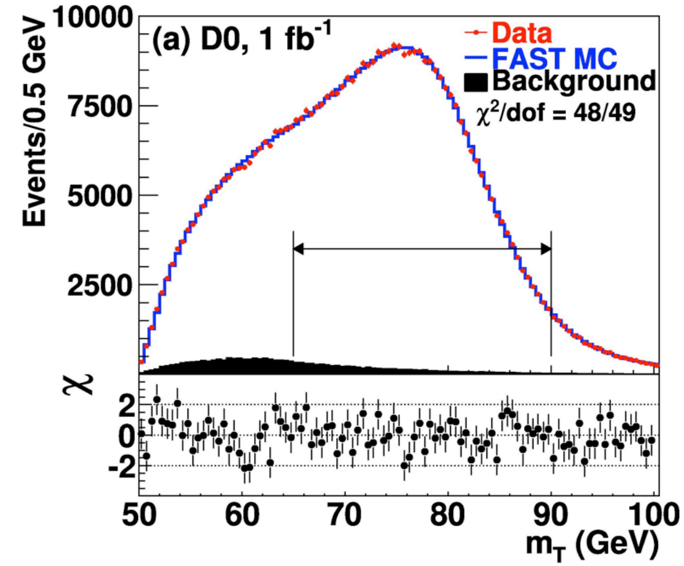
→ expect improvements (statistics +systematics) with larger data sets

calibration




~18k events in 1 $fb^{-1}$

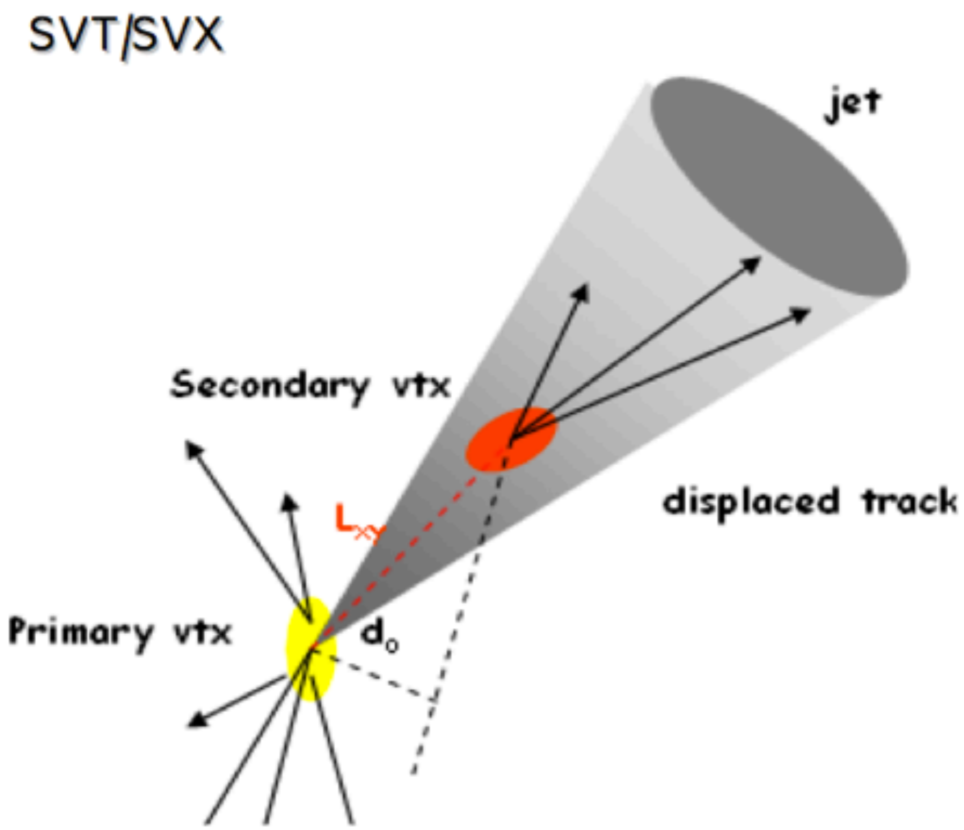
signal

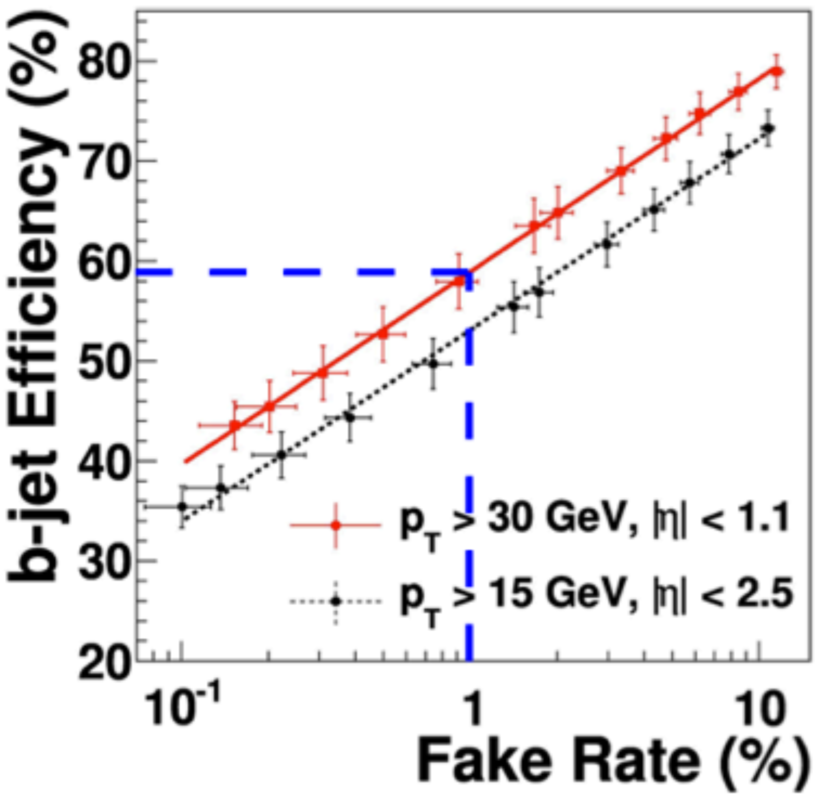



~485k events in 1 $fb^{-1}$

# b-tagging

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

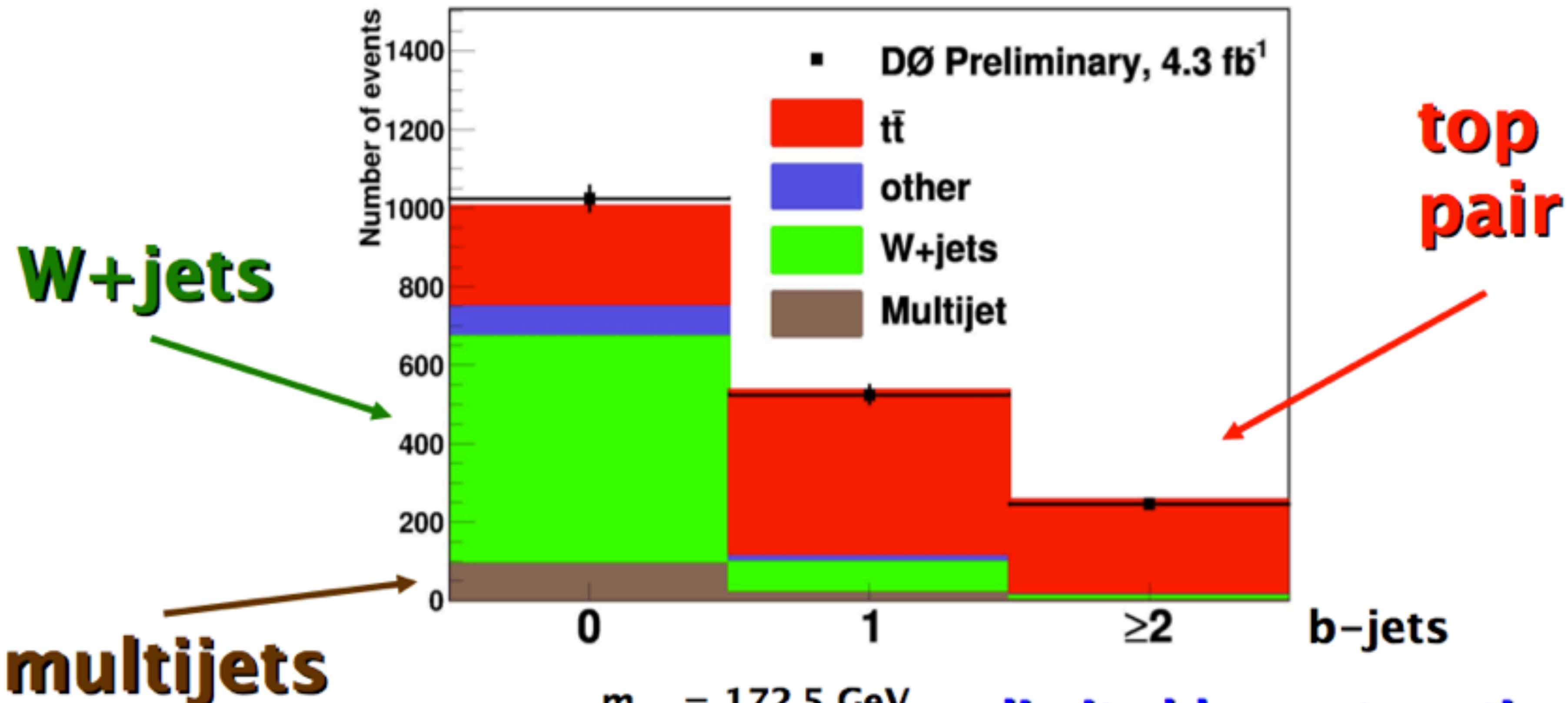



- form a 7-variable neural network
- event tagging efficiency 59% (with fake rate of 1%)

# Lepton+Jets Cross Section with b-tagging

**very powerful tool to reduce the background**




$m_{top}$ = 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

# What Mass Do We Measure?

$$\mathcal{L} = \ldots - \bar{\psi} M \psi \left(1 + \frac{H}{v}\right) \ldots$$

$m_{top}$

- LO QCD: free parameter
- NLO QCD: dependent on the renormalisation scale M

"Bare" parameters of QCD:

$g_s, m_u, m_d, m_s, m_c, m_b, m_t$

Renormalised parameters of QCD:

$g_s(M), m_u(M), m_d(M), m_s(M), m_c(M), m_b(M), m_t(M)$

**the concept of quark mass is convention-dependent!**

# Different Top Mass Definitions

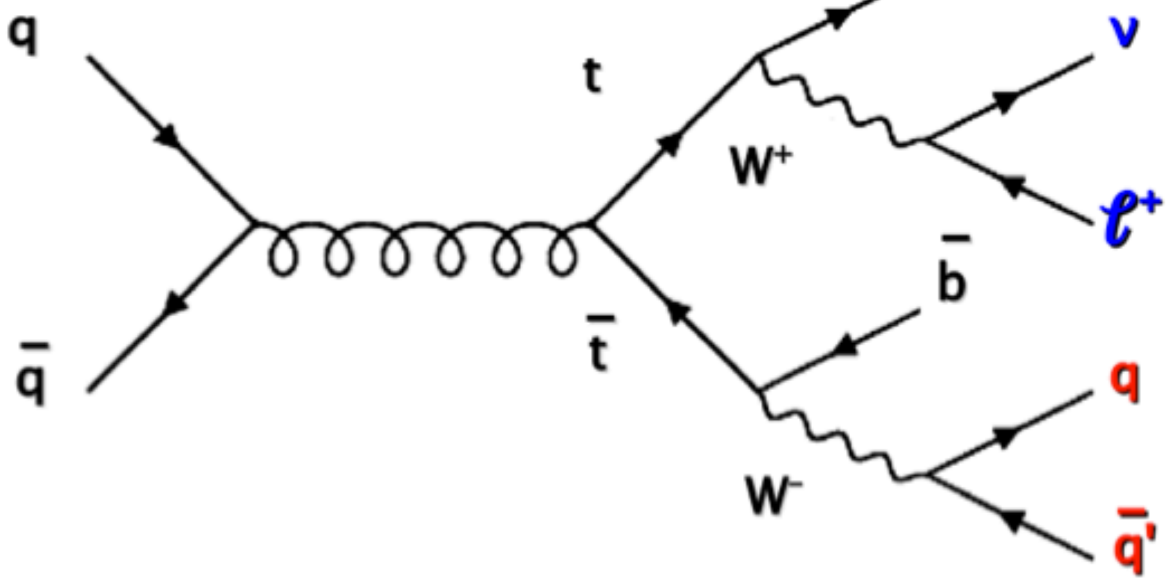
hep-ph/0001002

$$\overline{m}_t \equiv m_t^{\overline{\rm MS}}(m_t) = \frac{M_t}{1 + \frac{4}{3\pi}\alpha_s(M_t)}$$

$\overline{\rm MS}$ scheme

pole mass

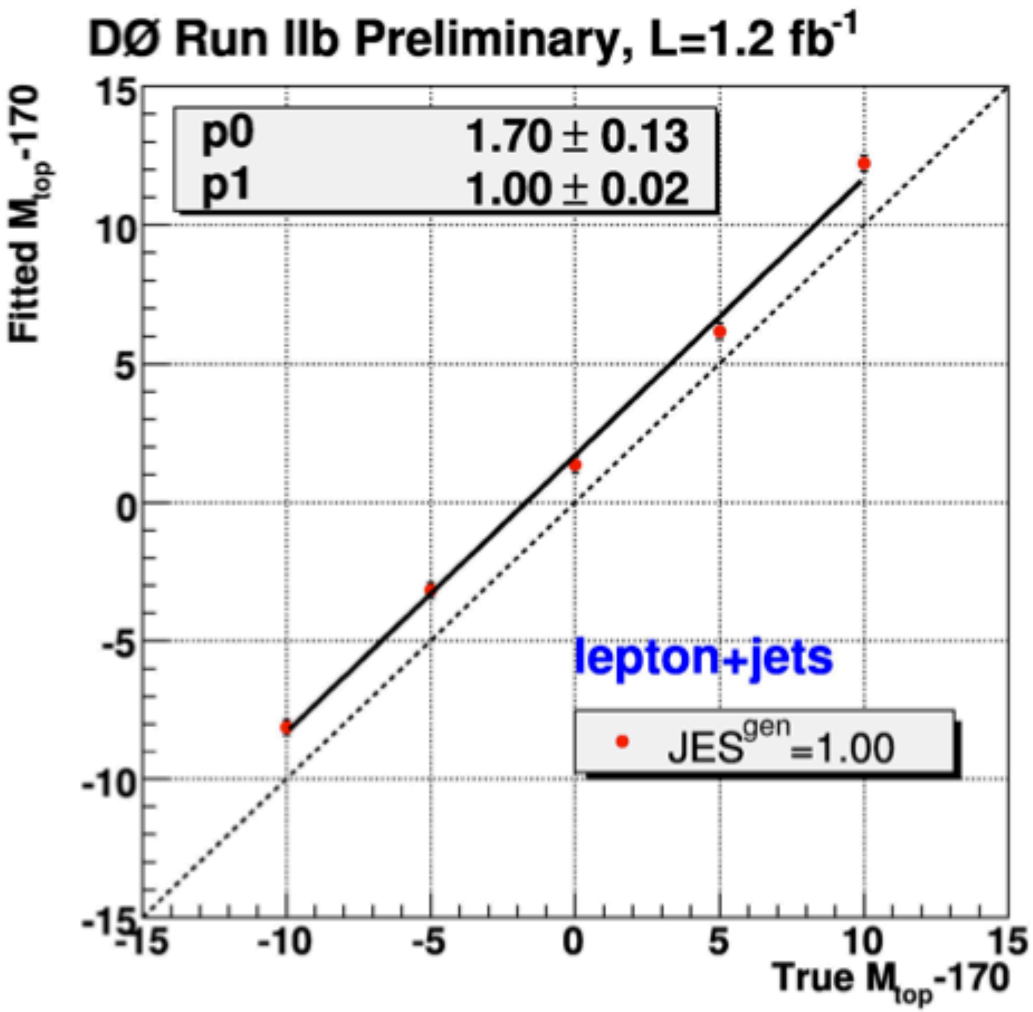
$$\frac{1}{p^2 - M_t^2 - i\,\Gamma_t M_t}$$




⇒ difference between $\overline{\rm MS}$ and pole mass is ≈7 GeV...

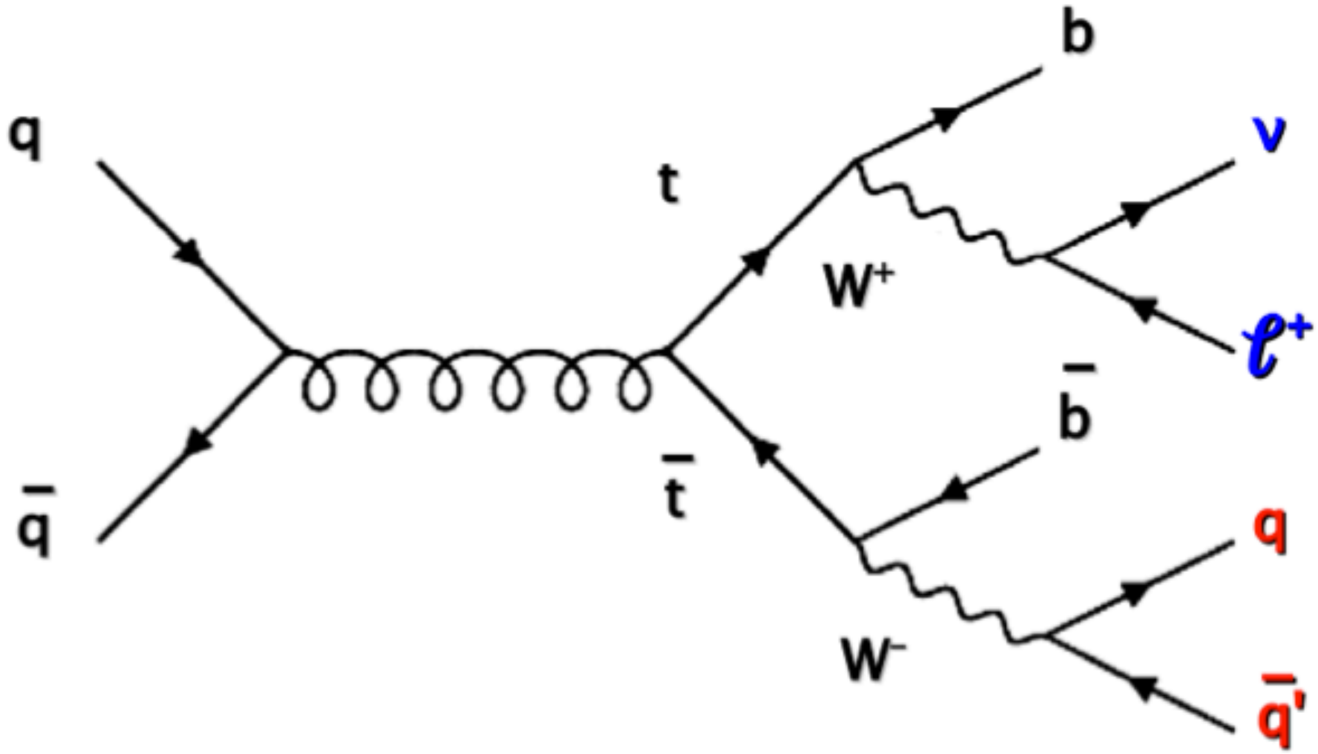
# Calibration of the Method

- pseudo experiments: compare measured mass with generated
- correct for differences: calibration curve



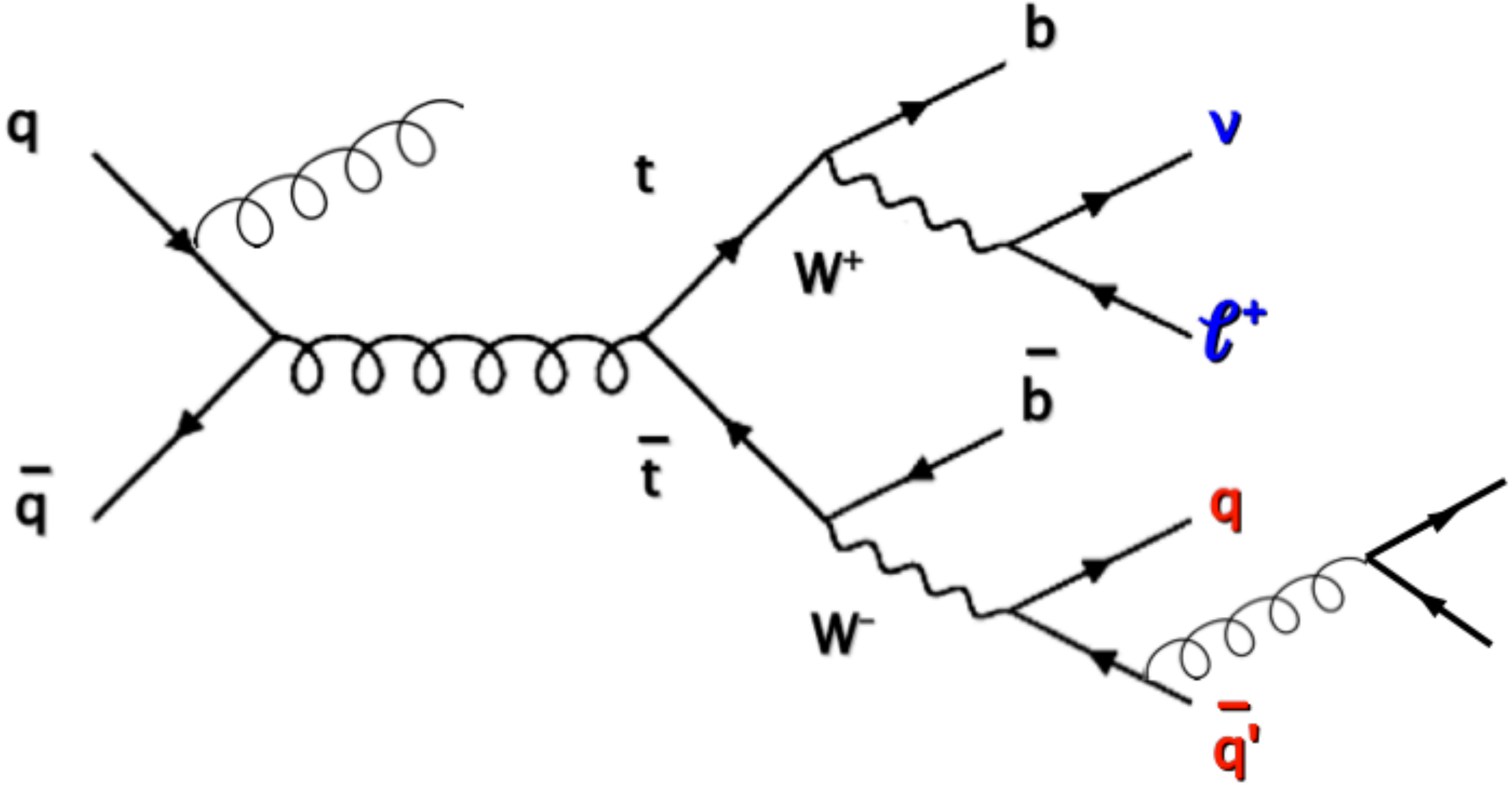
# Which Top Mass Does a LO MC Contain?

- matrix element in LO QCD



# Which Top Mass Does a LO MC Contain?

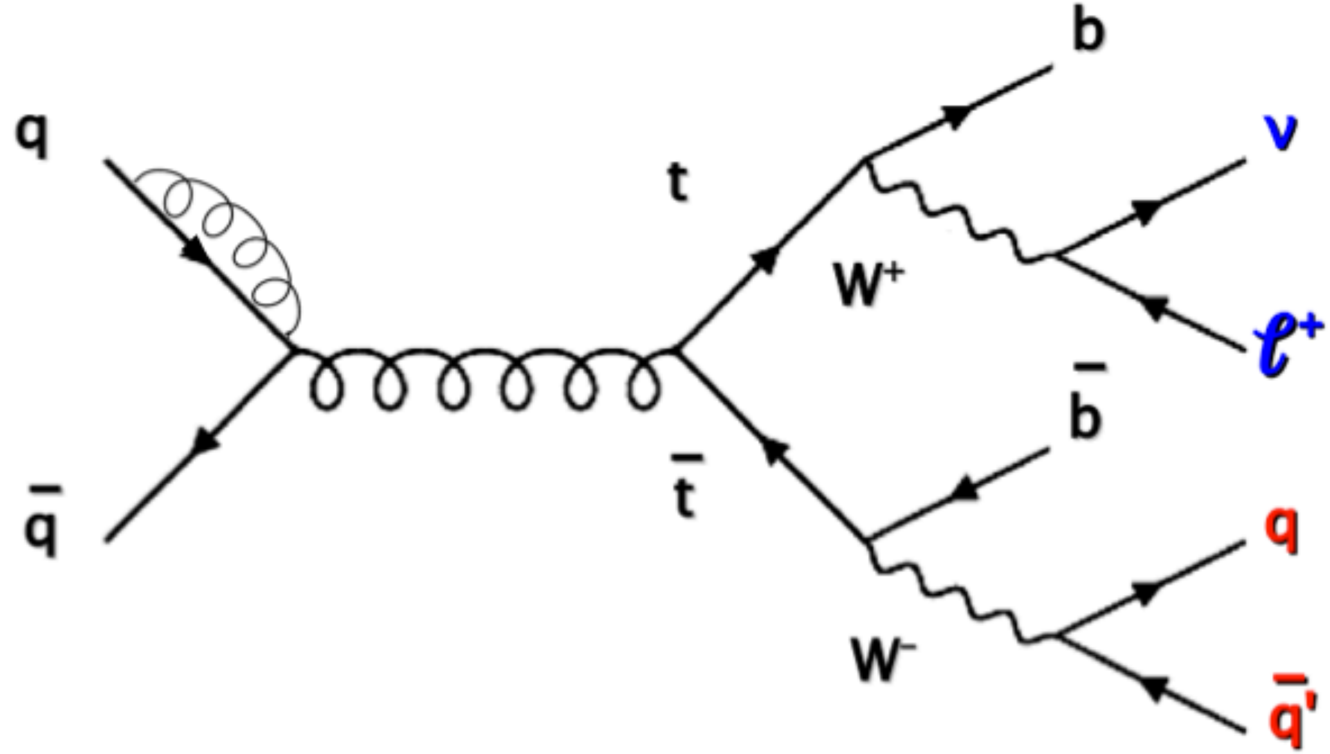
- matrix element in LO QCD




- parton showers simulate higher orders,

# Which Top Mass Does a LO MC Contain?

- matrix element in LO QCD

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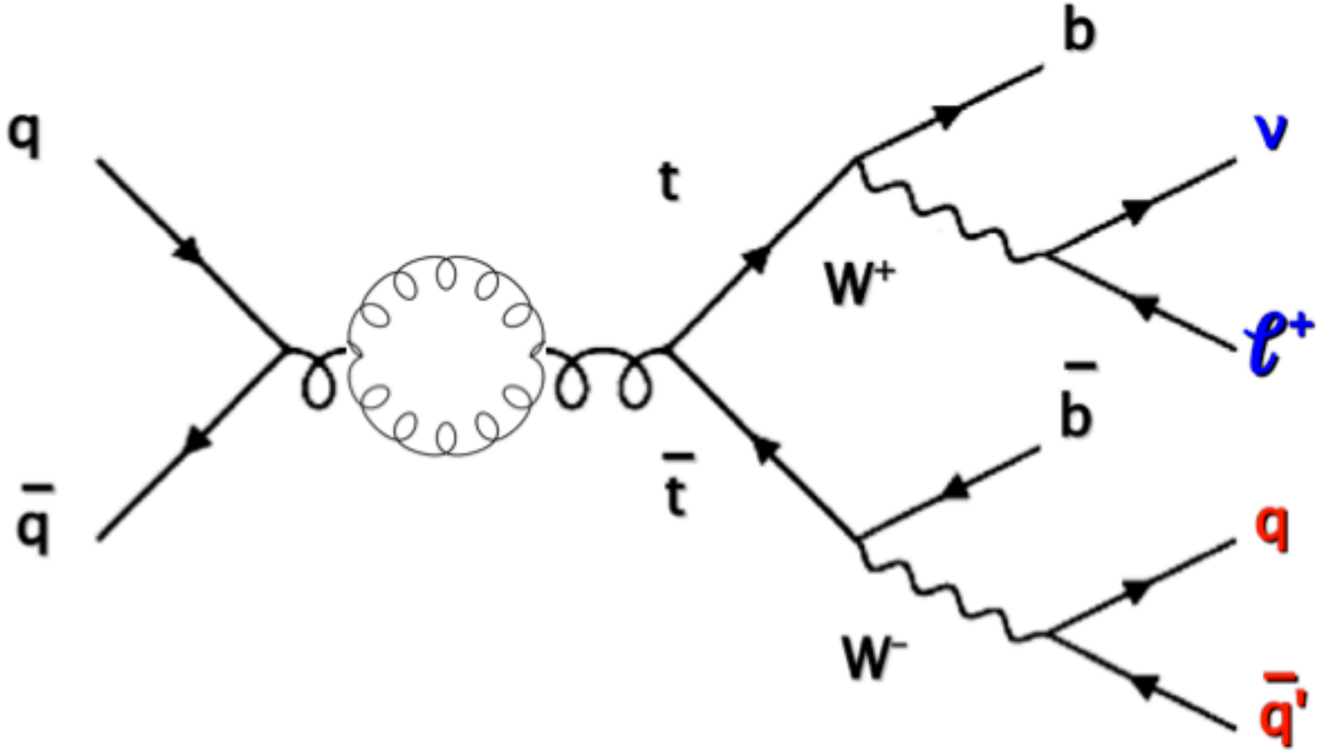


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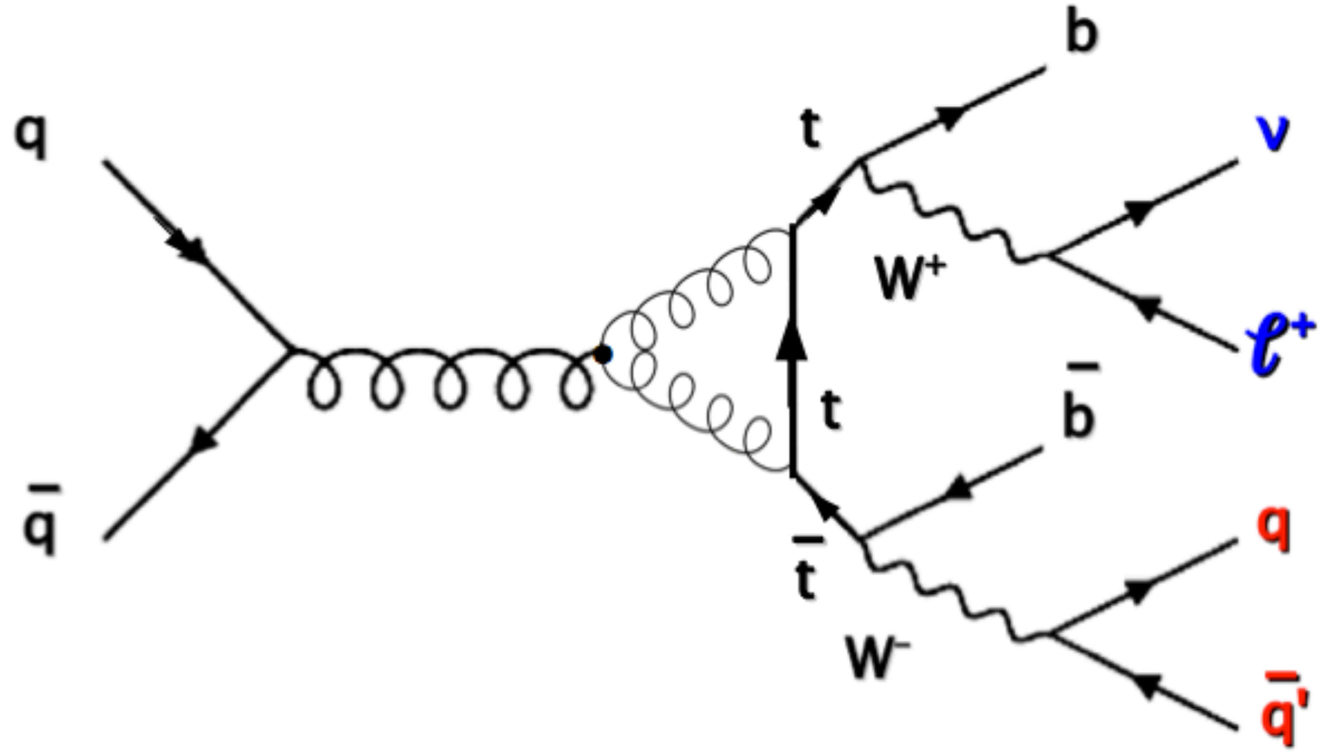


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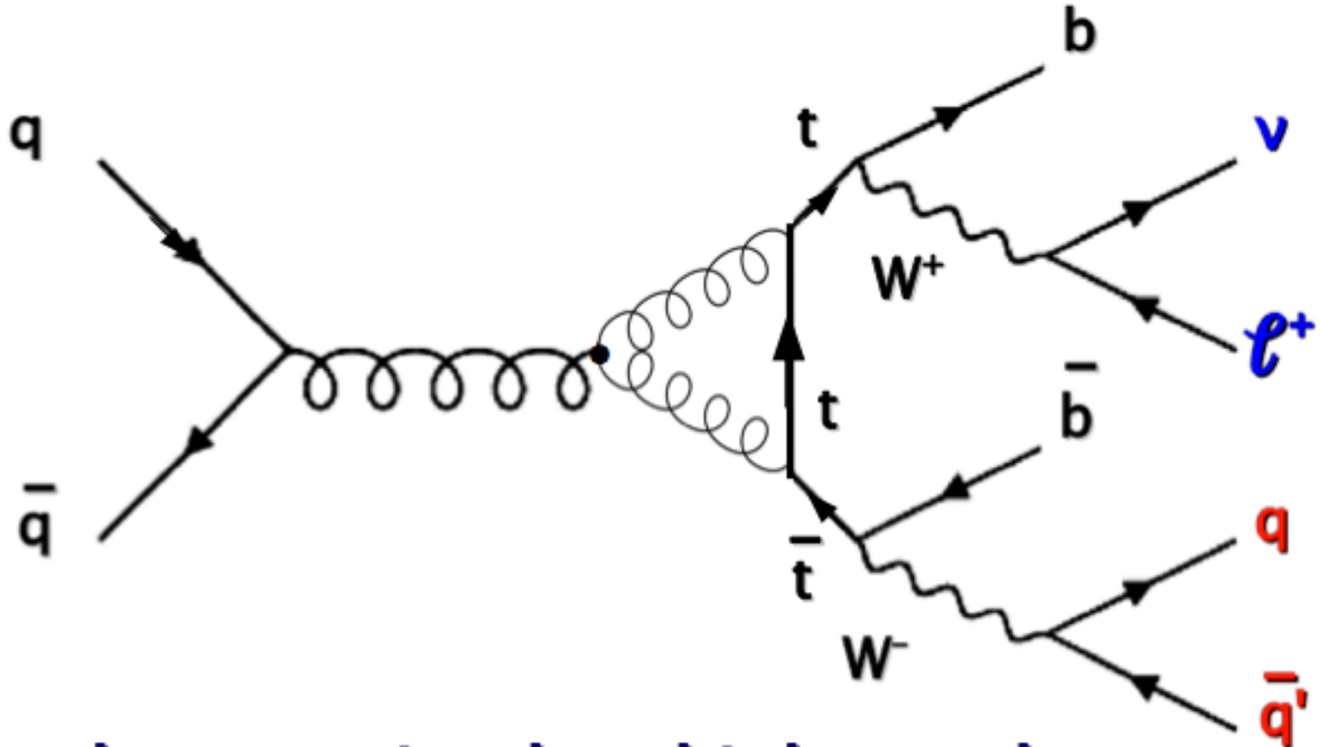
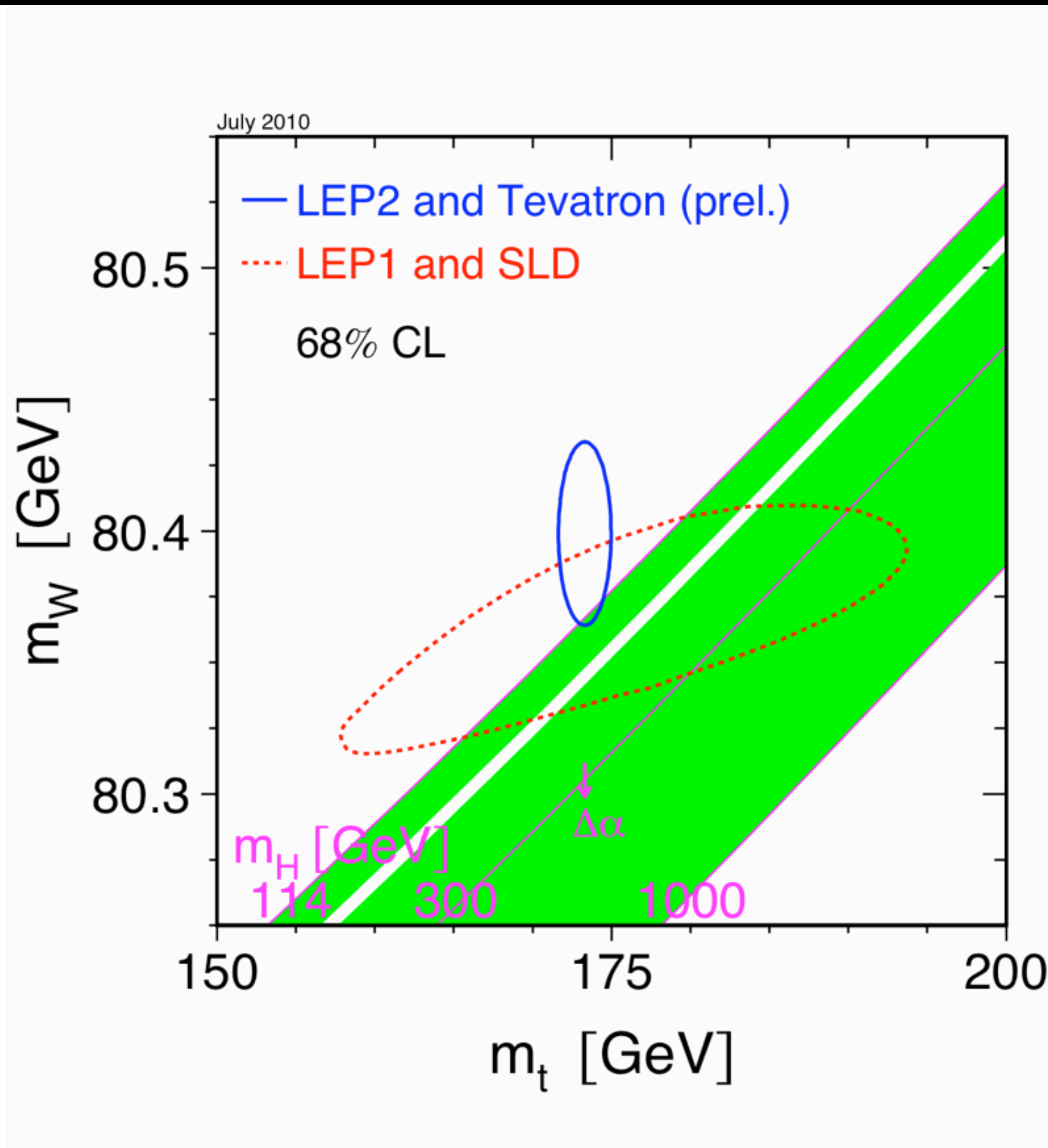



- parton showers simulate higher orders, i.e. not only radiating additional gluons!

$\Rightarrow$ NOBODY KNOWS...

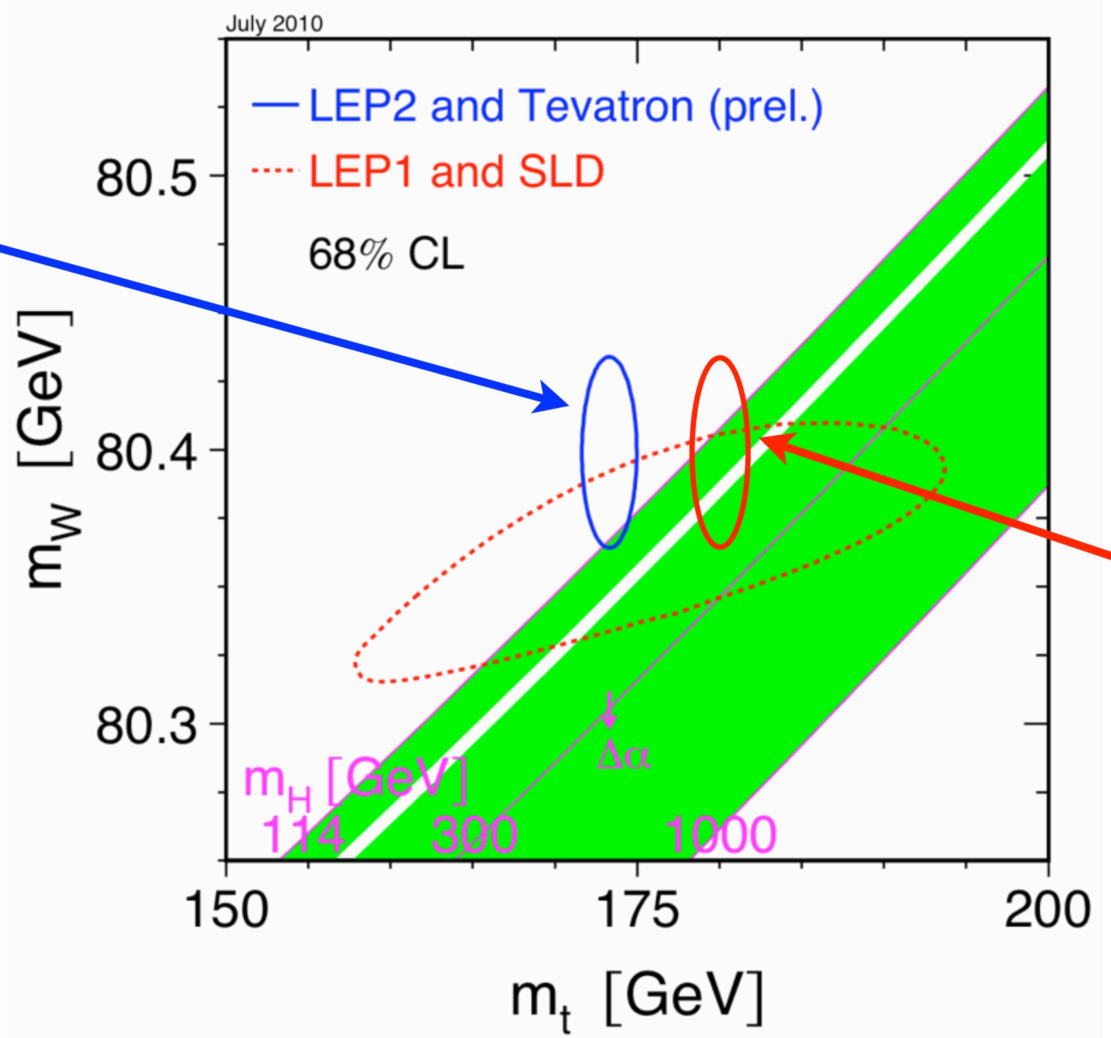
- arguments that it should be close to pole mass

# Important to Know...



# Important to Know...

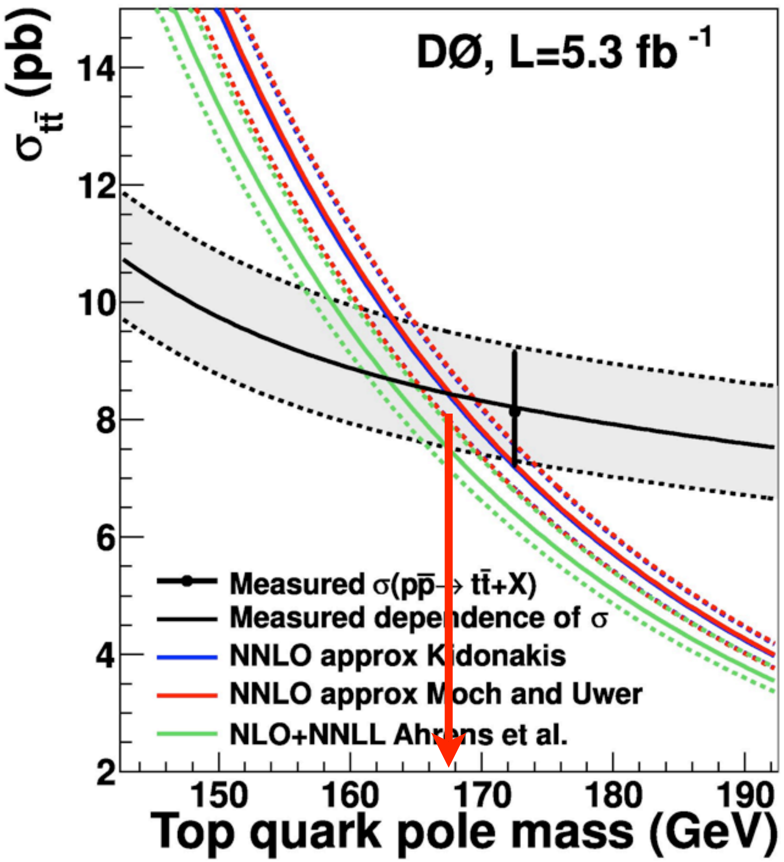
**pole mass**

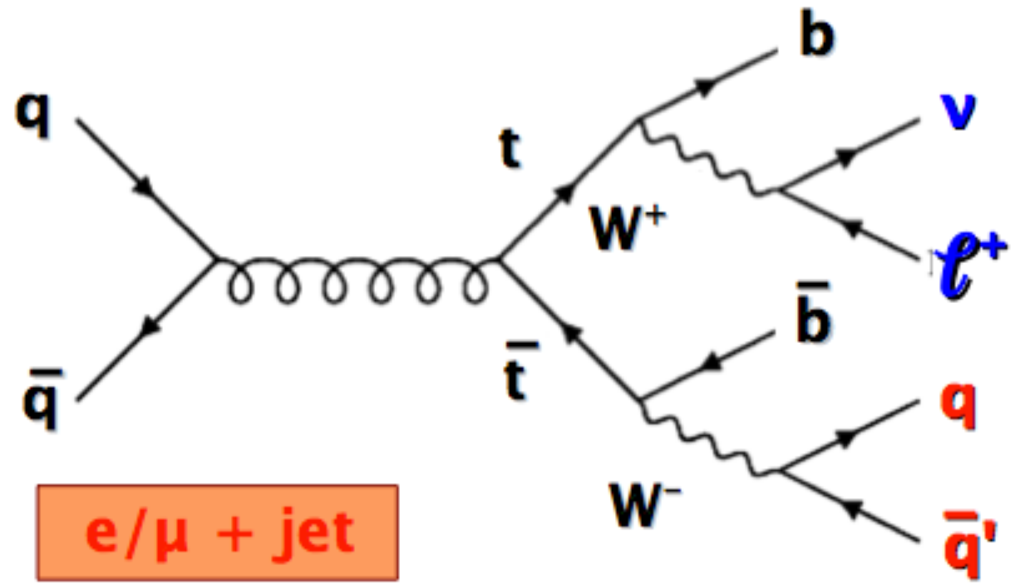



**world average interpreted as $\overline{\text{MS}}$ mass**

**together with understanding of systematics one of the most challenging questions in the future!**

# Top Cross Section and Mass




e/μ + jet

5.3 fb$^{-1}$

**NEW**

±3.1%

$\overline{\text{MS}}$ mass:

±3.0%

$$m_t^{pole} = 167.5^{+5.4}_{-4.9}\ \text{GeV}$$

$$m_t^{\overline{MS}} = 159.9^{+5.1}_{-4.4}\ \text{GeV}$$