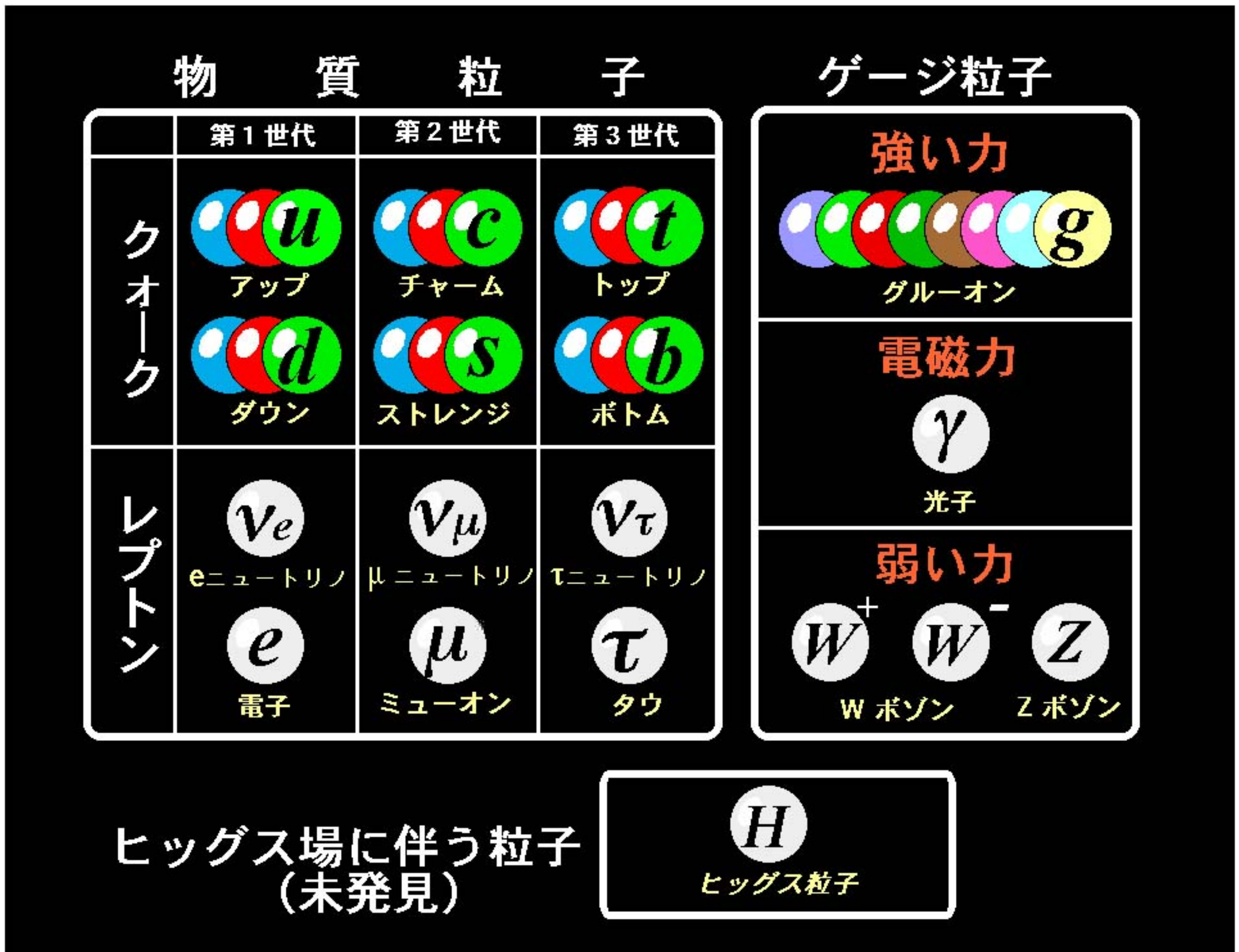
# University of Rochester — Physics Colloquium

## November 30, 2011

# The life of top quarks



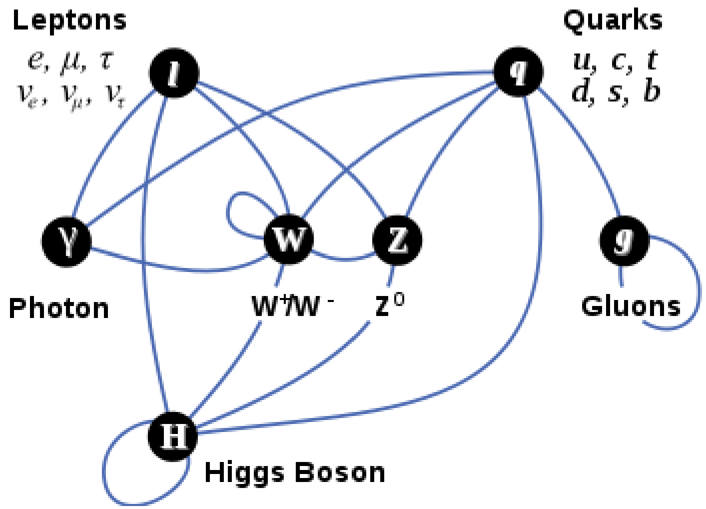


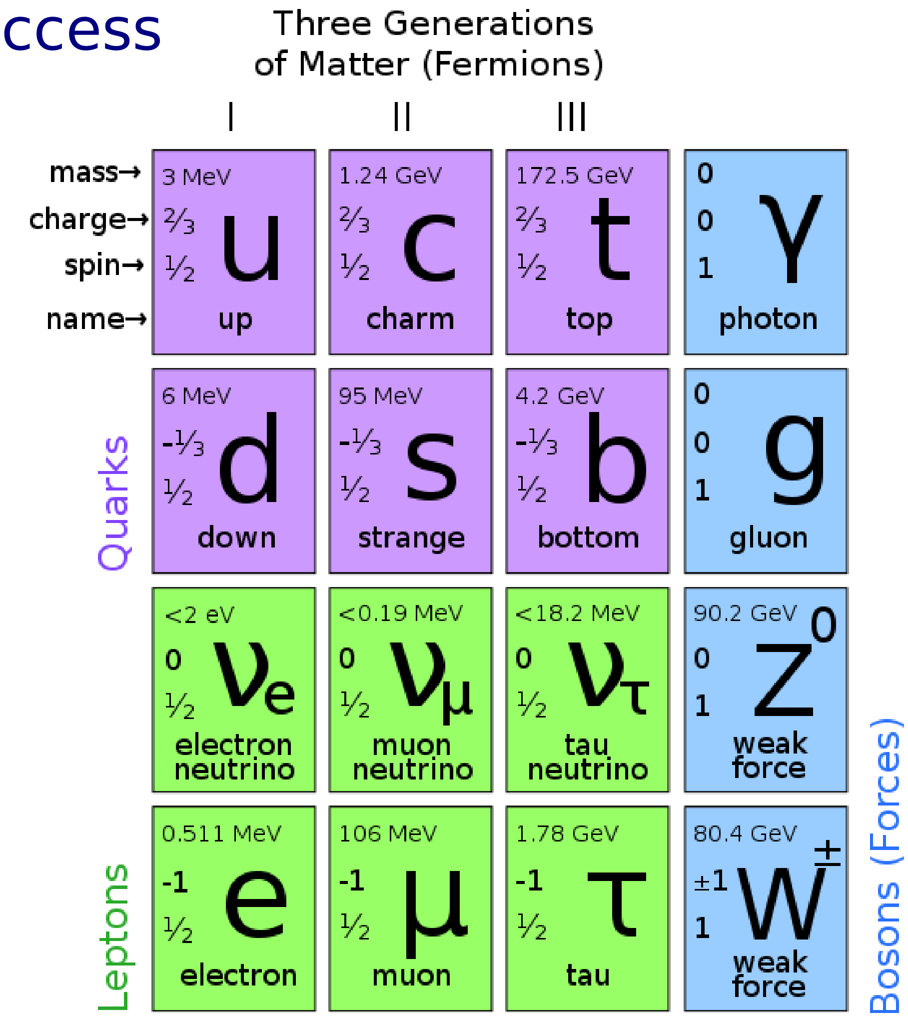
UNIVERSITY of ROCHESTER

Arán García-Bellido

# The SM under attack

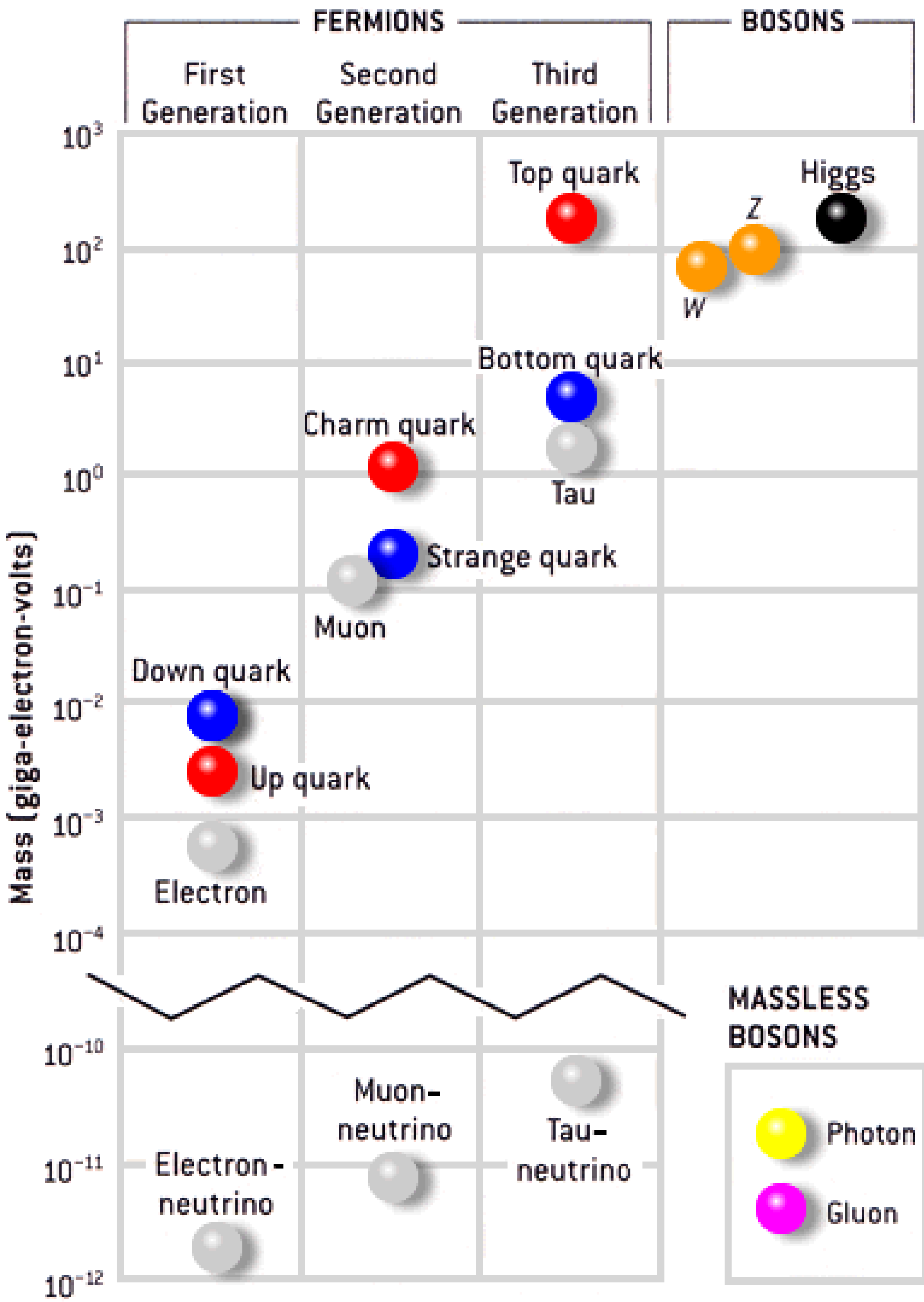
- The Standard Model is a fantastic success




- But recently: Neutrino masses, dark matter
- So we know it is not a complete description of Nature
- Many unanswered questions:
  - Why three generations?
  - What is the mechanism responsible for particles' masses?
  - Why that hierarchy of masses?
  - What's with so many free parameters?
  - Gravity is not in the picture
  - Unification of three couplings is not possible

# Top quark: not just the sixth quark

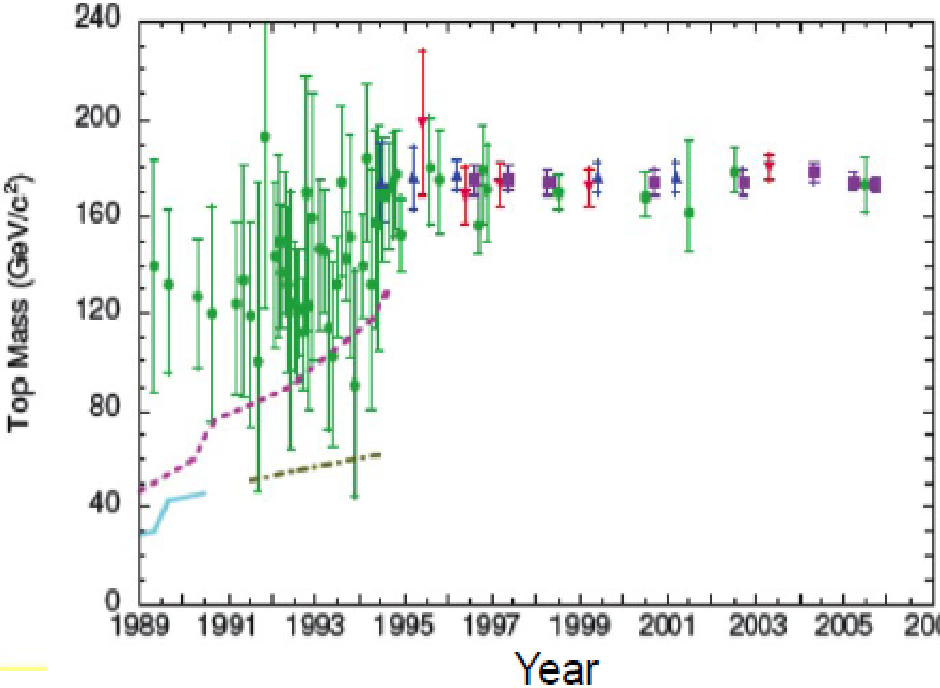


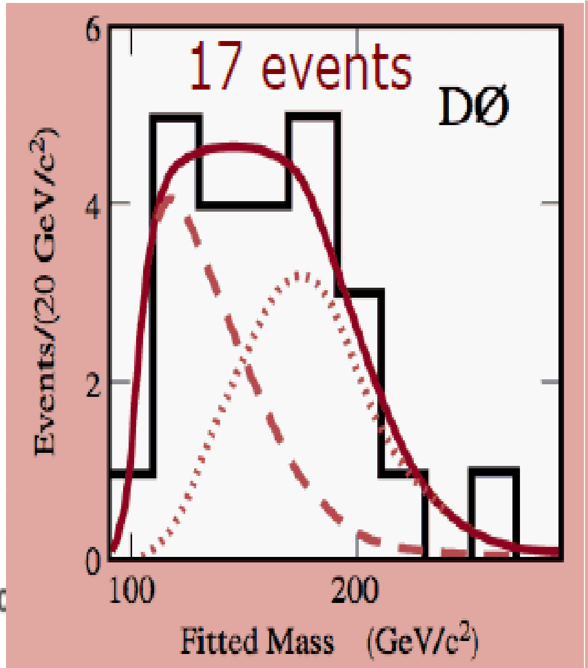

- Heaviest known particle
  - 40 times heavier than b
  - As heavy as one Tungsten atom
- Only quark that decays before hadronization
  - lifetime ~$10^{-25}$s
- Couples strongly to EWSB boson
  - Related to the origin of mass?
- Unique laboratory to study the SM and beyond

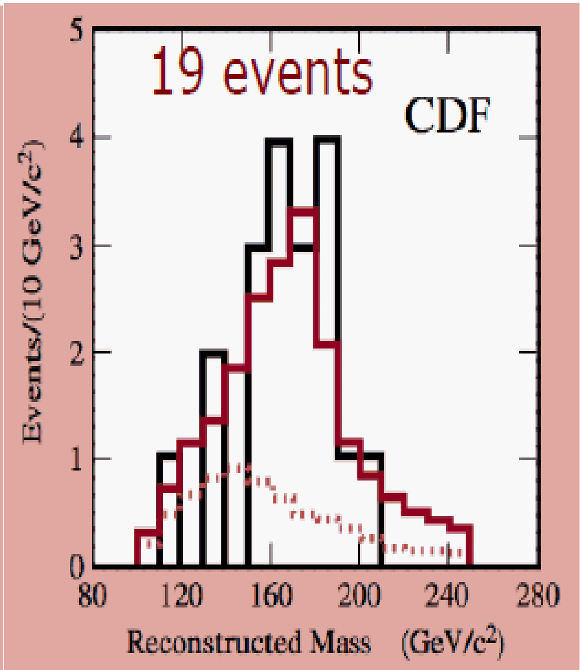
# A brief history of top

- 1976: Discovery of Upsilon ($b\bar{b}$ meson): a 5th quark means there is a 6th

  A race to find the 6th quark begins:
- 1984: Petra $e^+e^-$ (Germany) $m_t > 23$ GeV
- 1988: UA1 (CERN) $m_t > 44$ GeV
- 1992: CDF (Fermilab) $m_t > 91$ GeV, DØ (1994) $m_t > 131$ GeV
- 1994: Electroweak fits (LEP/SLC/TeV): 155 GeV $< m_t <$ 185 GeV
- 1995: DØ and CDF announce joint discovery
  - DØ: 50 $pb^{-1}$, 17 events, $\sigma=6.4\pm2.2$ pb, $m_t=199\pm30$ GeV
  - CDF: 67 $pb^{-1}$, 19 events, $\sigma=6.8^{+3.6}_{-2.4}$ pb, $m_t=176\pm13$ GeV
- 2009: DØ and CDF announce joint discovery of single top production

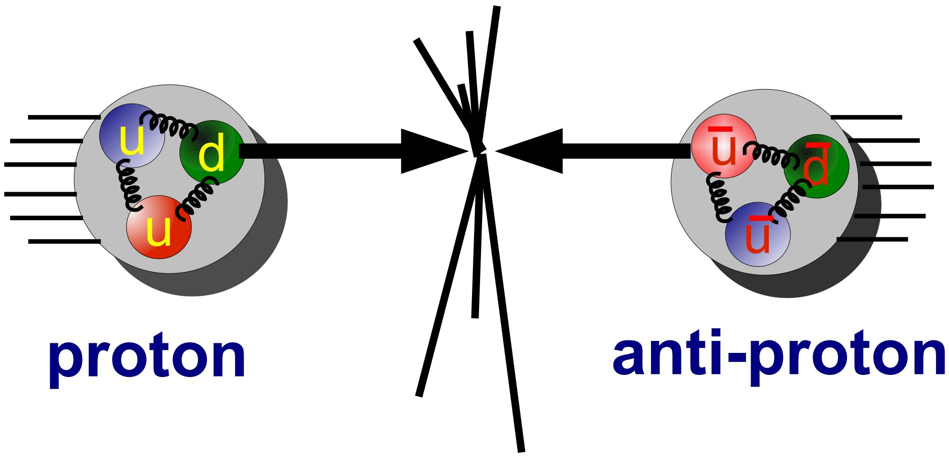


# Tools of the trade

- Particle physicists use high energy colliders to probe physics at small distances




Note on units: N[collisions] = $\sigma$[pb] L[$pb^{-1}$]

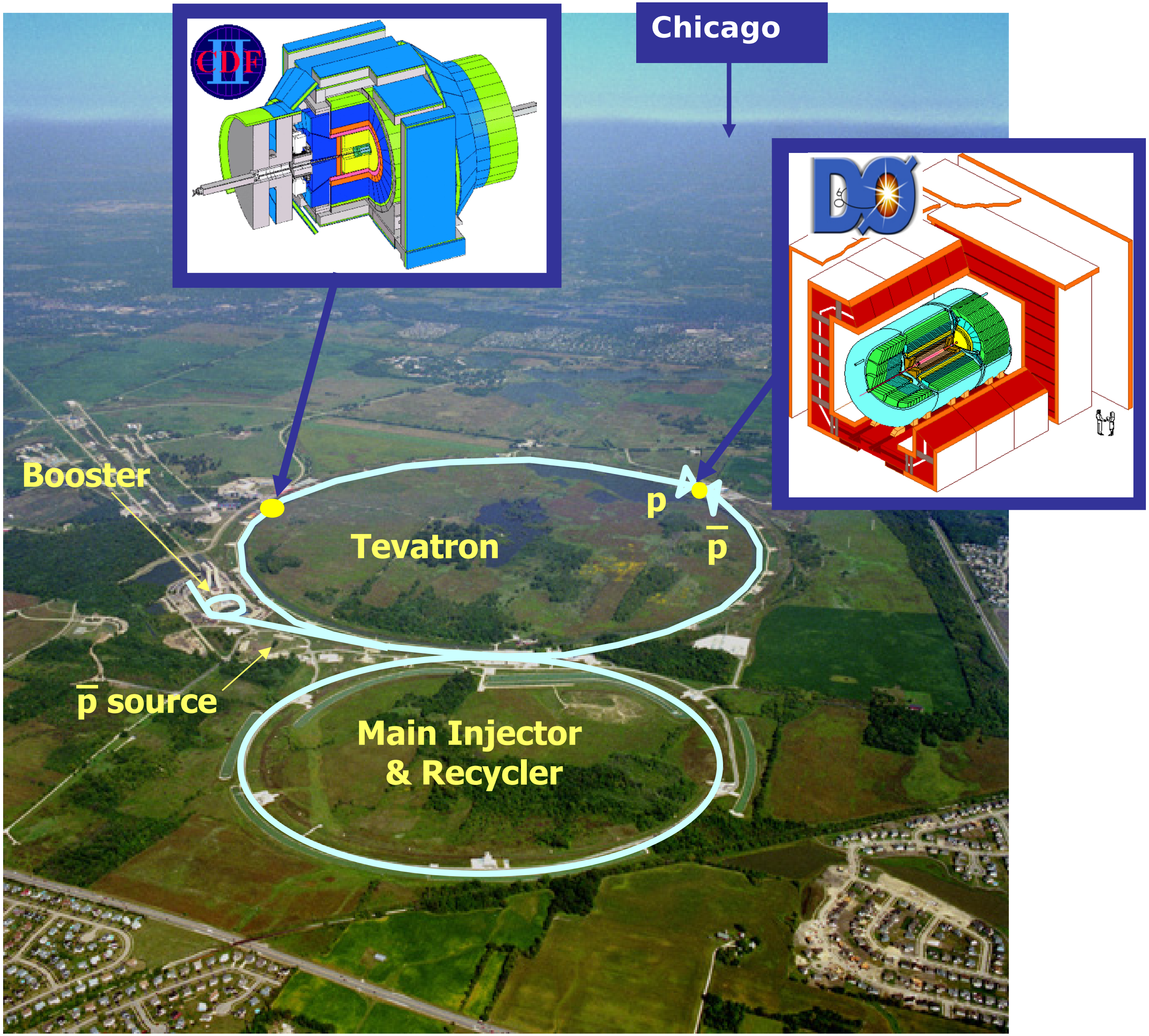
- **Picobarns** (pb) is a measure of “cross section” ($\sigma$=interaction probability). 1 barn = $10^{-24}$ $cm^2$.
- **Inverse picobarns** ($pb^{-1}$) is a measure of the “integrated luminosity” (L=collected data)

Example: 1000 $pb^{-1}$ = 1 $fb^{-1}$ = enough data to observe 1000 events of a process having 1 pb cross section

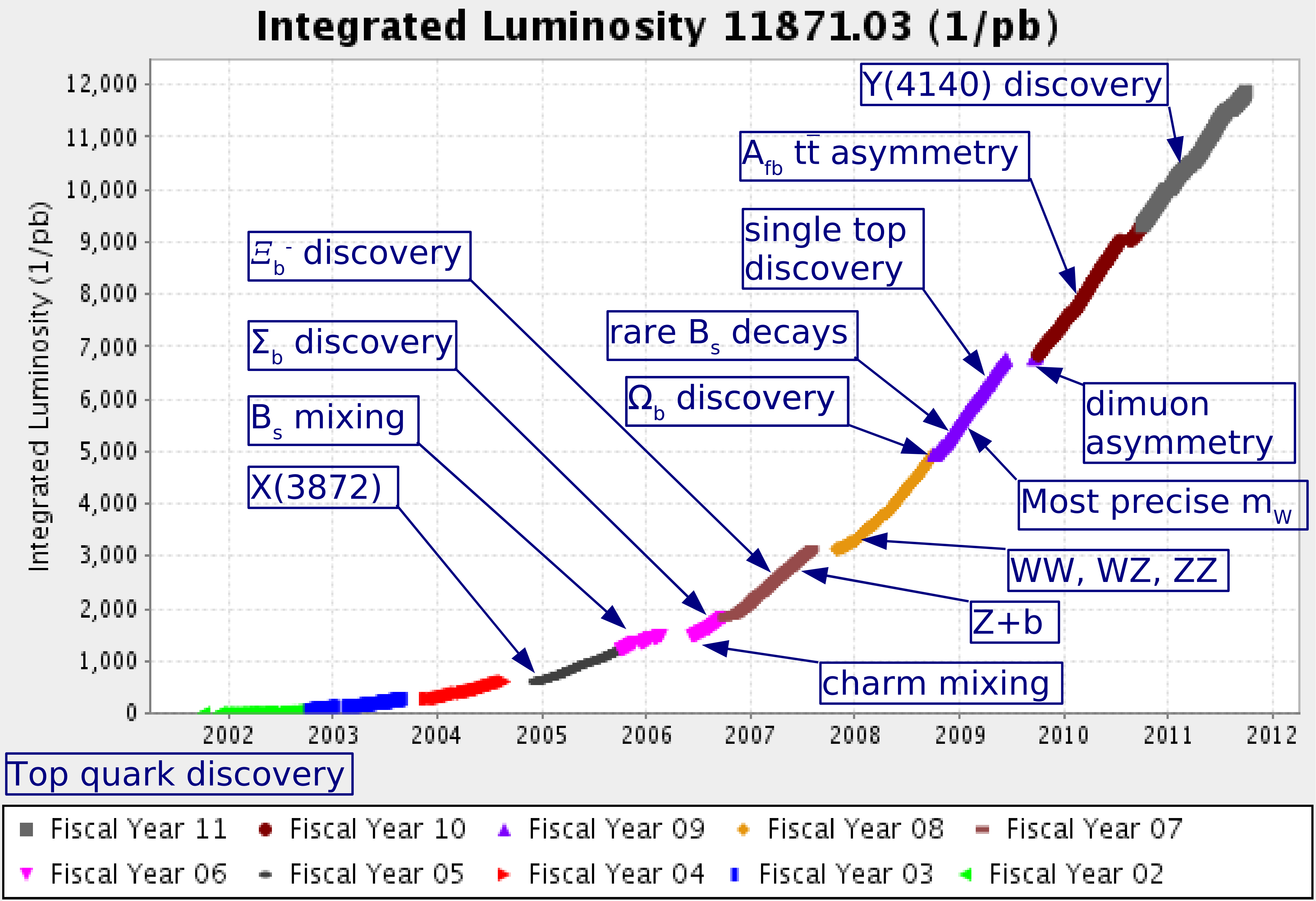
- **GeV** are used interchangeably for mass, energy, and momentum

# The Tevatron

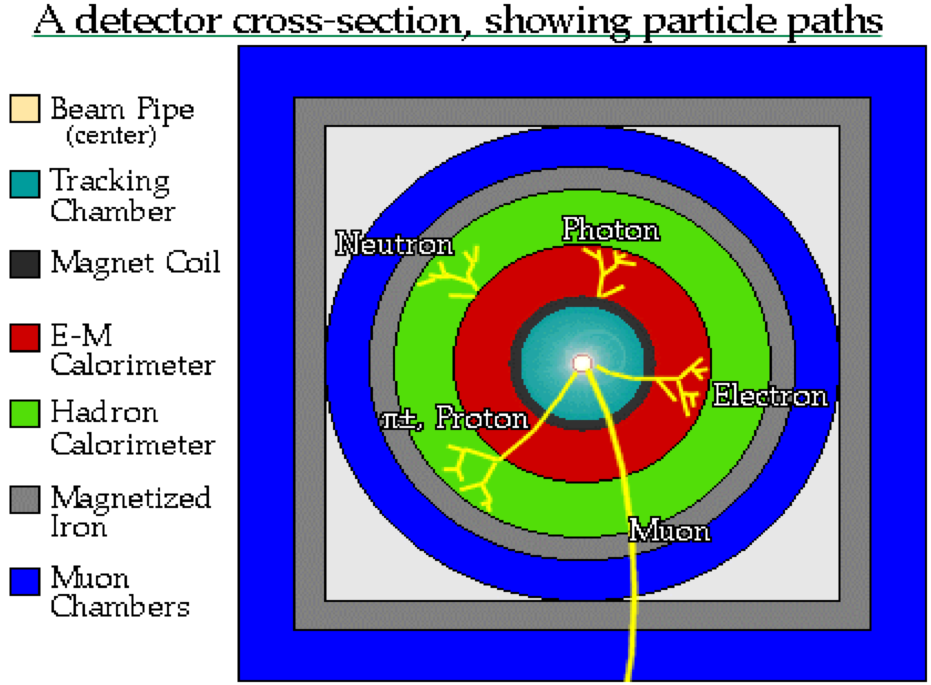
- 6.3 km $p\bar{p}$ collider
- $\sqrt{s}$ = 1.96 TeV
- Run I: 1987-1996
- Run II: 2002-2011
  - 36x36 bunches
  - $10^{11}$ $\bar{p}$ per bunch
  - 396 ns bunch spacing
  - 1.8 M crossings/s
  - $4.3 \cdot 10^{32}$ $cm^2 s^{-1}$ peak lumi
  - 12 $fb^{-1}$ delivered luminosity
- Detectors recorded data with 90% efficiency



# Tevatron milestones

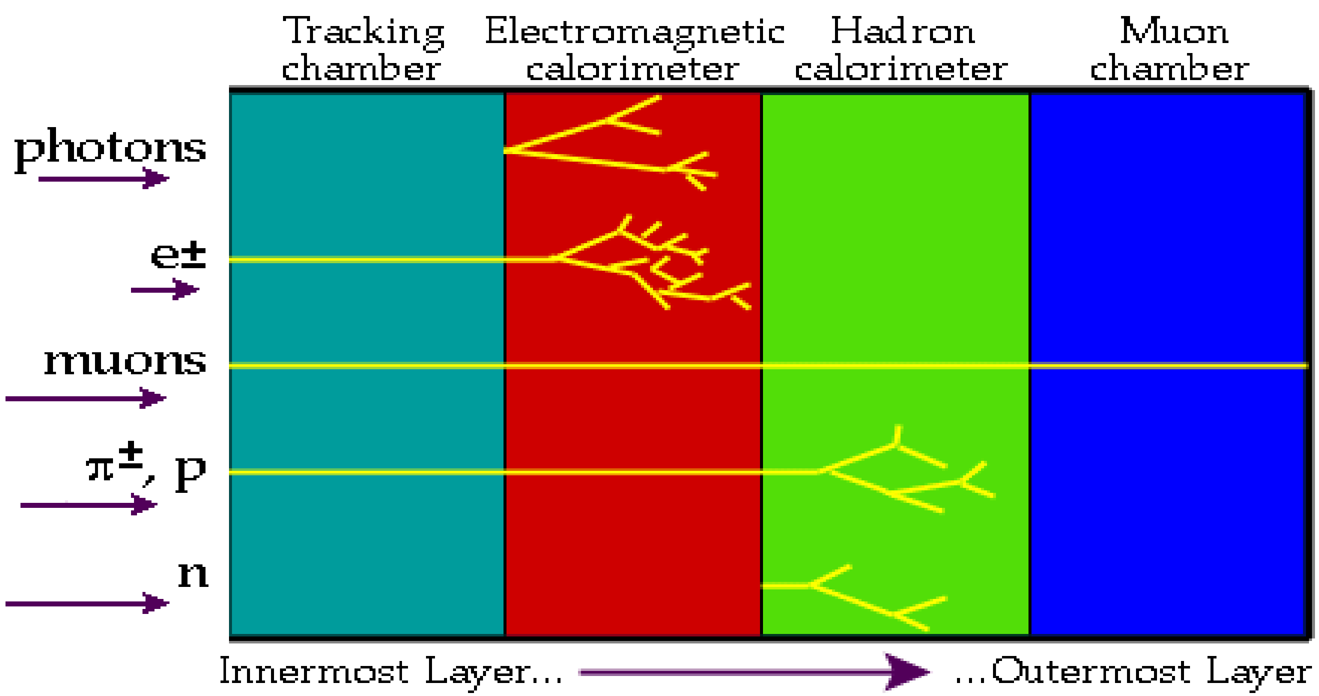


# General detector and particle ID

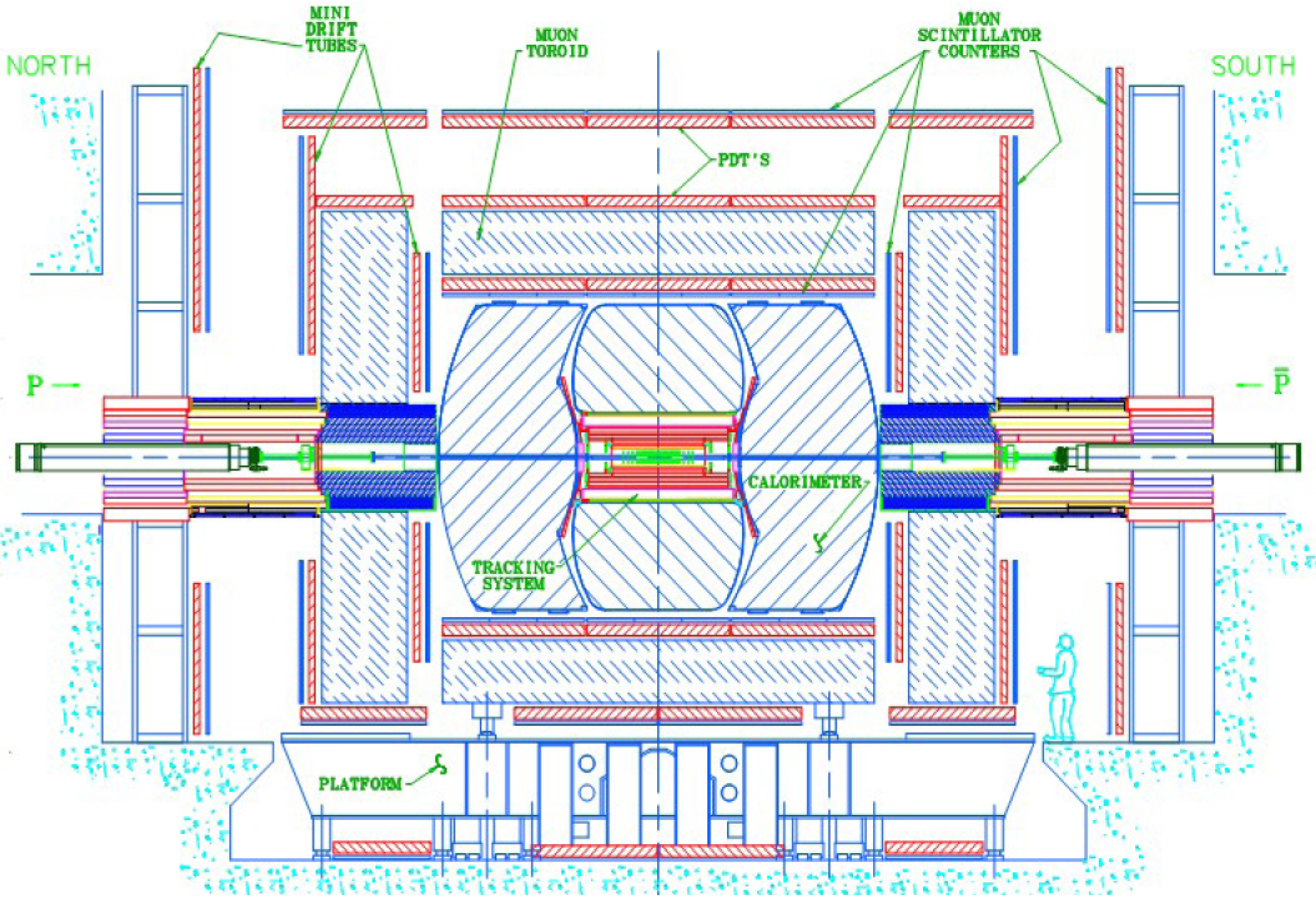



We detect particles by the EM and strong interaction fingerprints they leave behind

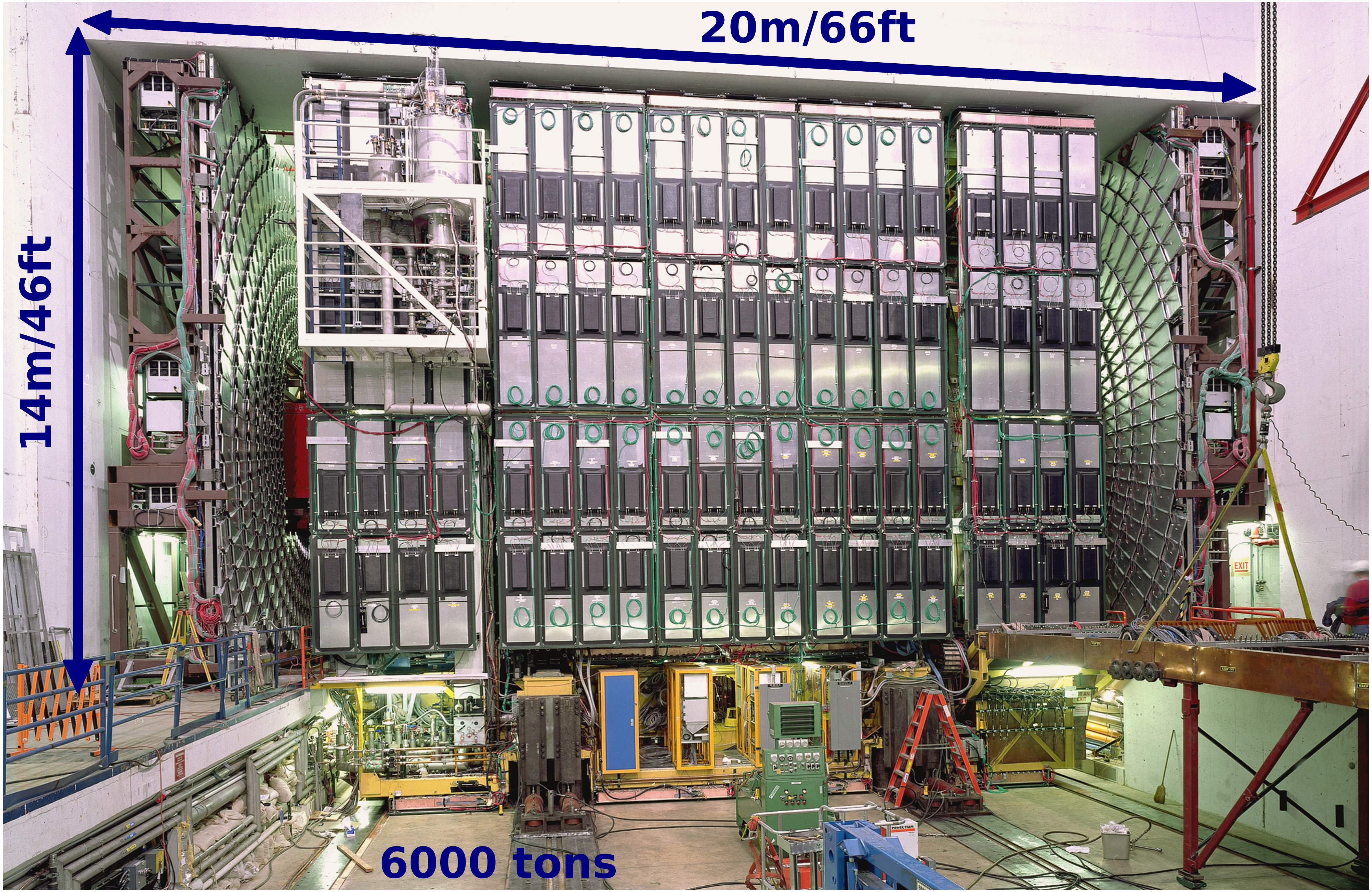
- Tracking is first (measure $p_T$)
- Calorimetry (EM and hadronic)
- Muons
- All the rest is neutrinos



# The DØ detector

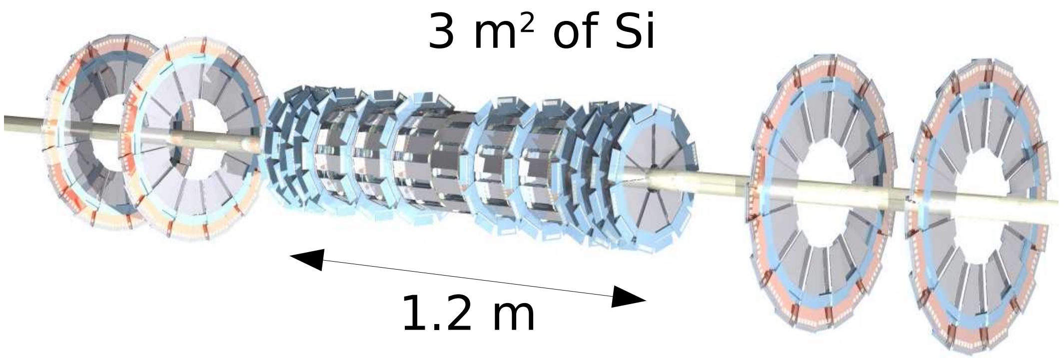


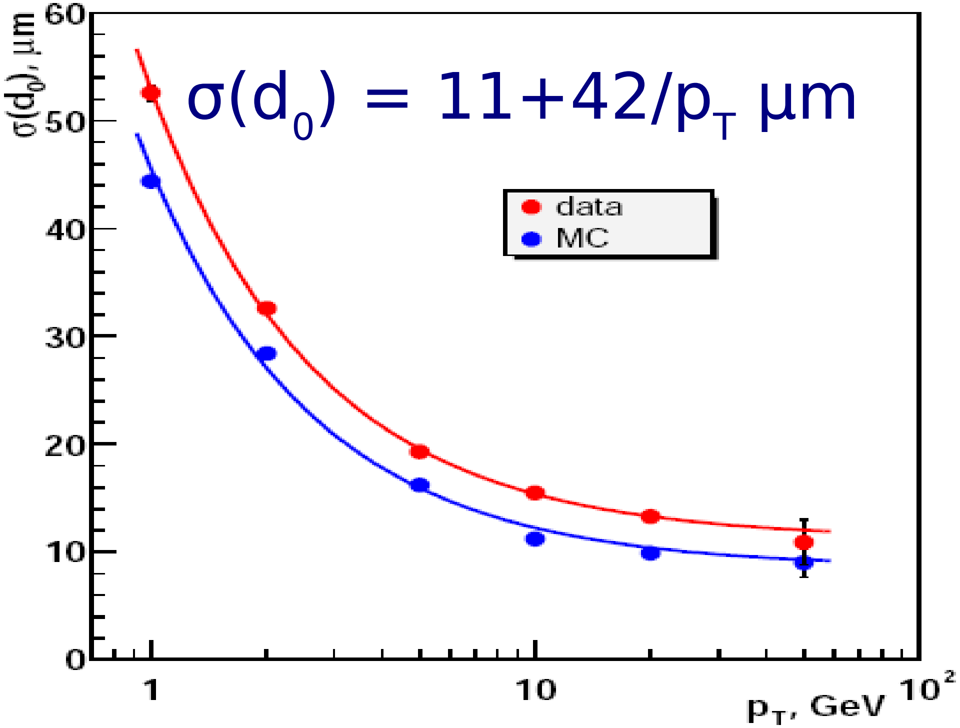
# The real thing: the DØ detector

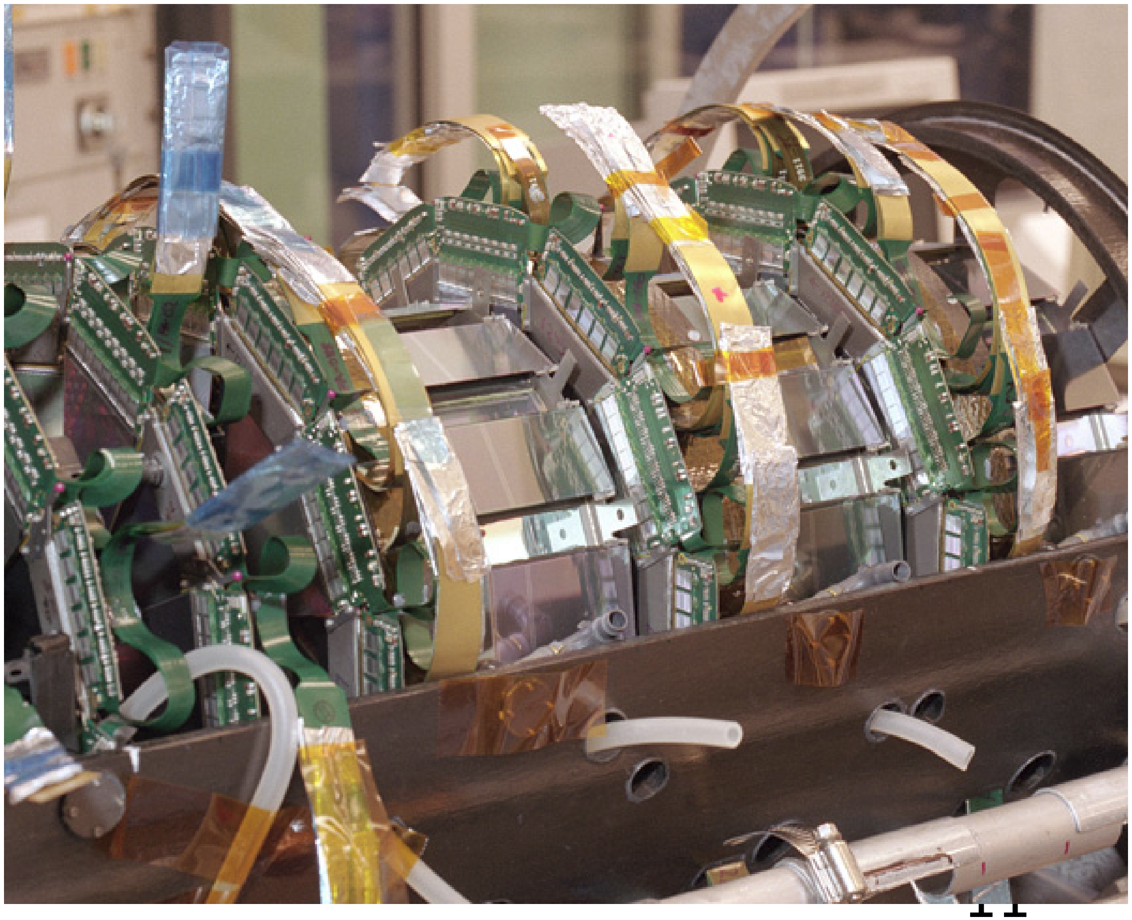


# You better have good tracking

- The Silicon Microstrip Tracker allows resolutions of ~10 $\mu$m
- Inner radius: 1.7cm away from the interaction point



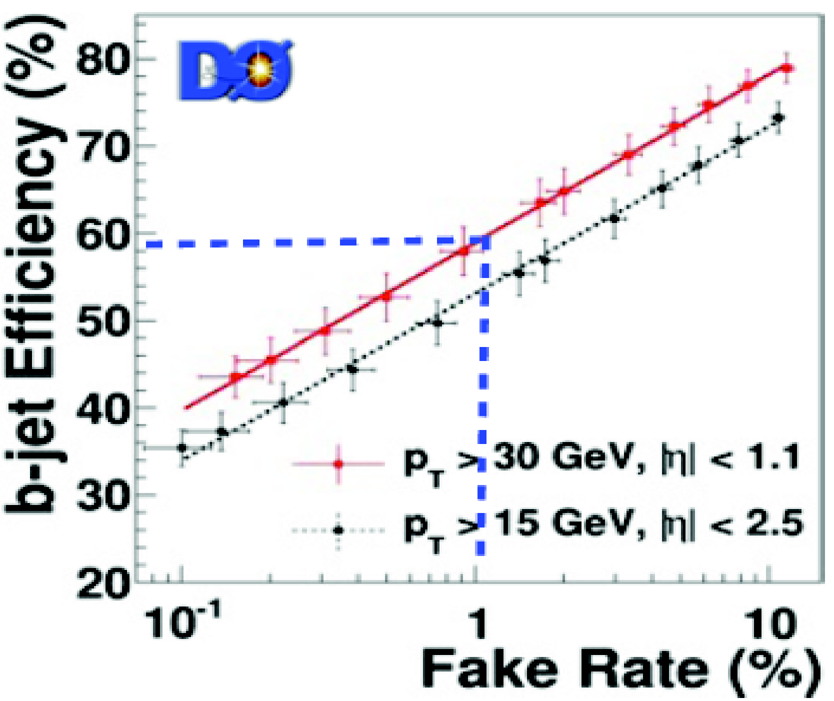
# Bottom quark decays can be tagged

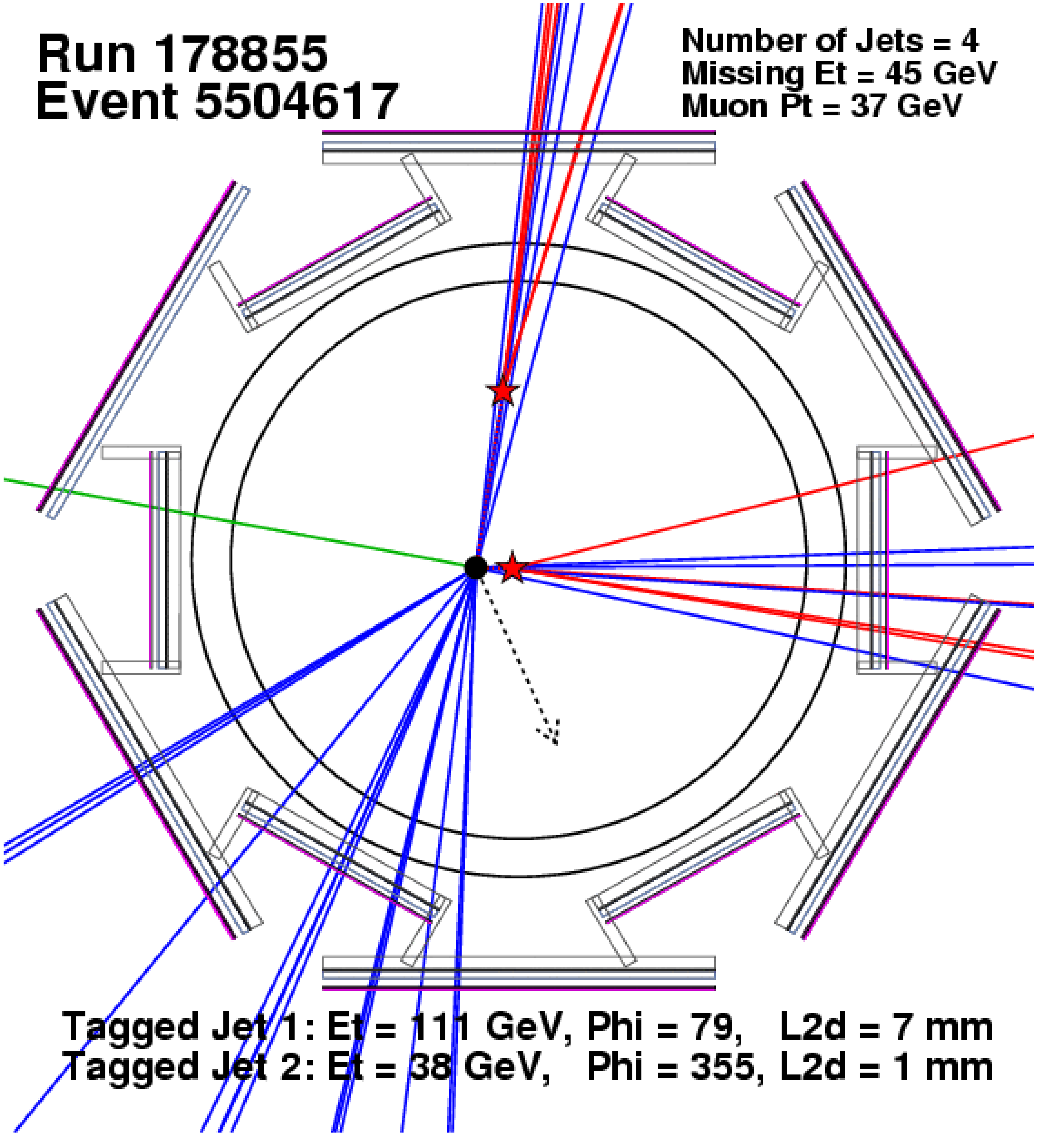
B hadrons have a lifetime: ~$10^{-12}$ s

They can travel a few mm in the detector before decaying

Signature: displaced tracks and secondary vertices

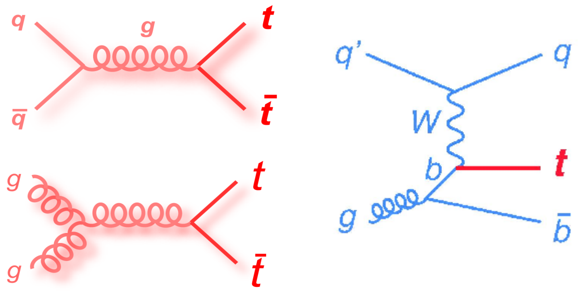
NIM, A620, 400 (2010)



# Top quark Tevatron program

## How is it produced



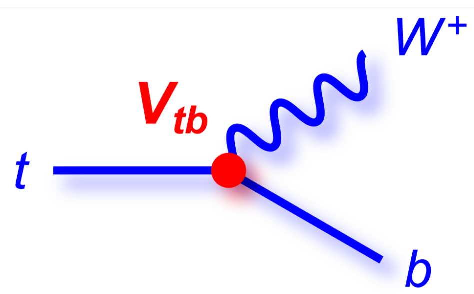

**Strong force:**

**$\sigma_{tt}$ ~ 7 pb**

**Electroweak force:**

**$\sigma_{tb+tbq}$ ~ 3 pb**

## How does it decay




**$V_{tb}$ ~ 1**

**V-A coupling:**

**$F_0$~0.7**

**$F_+$~0**

## What are its intrinsic properties

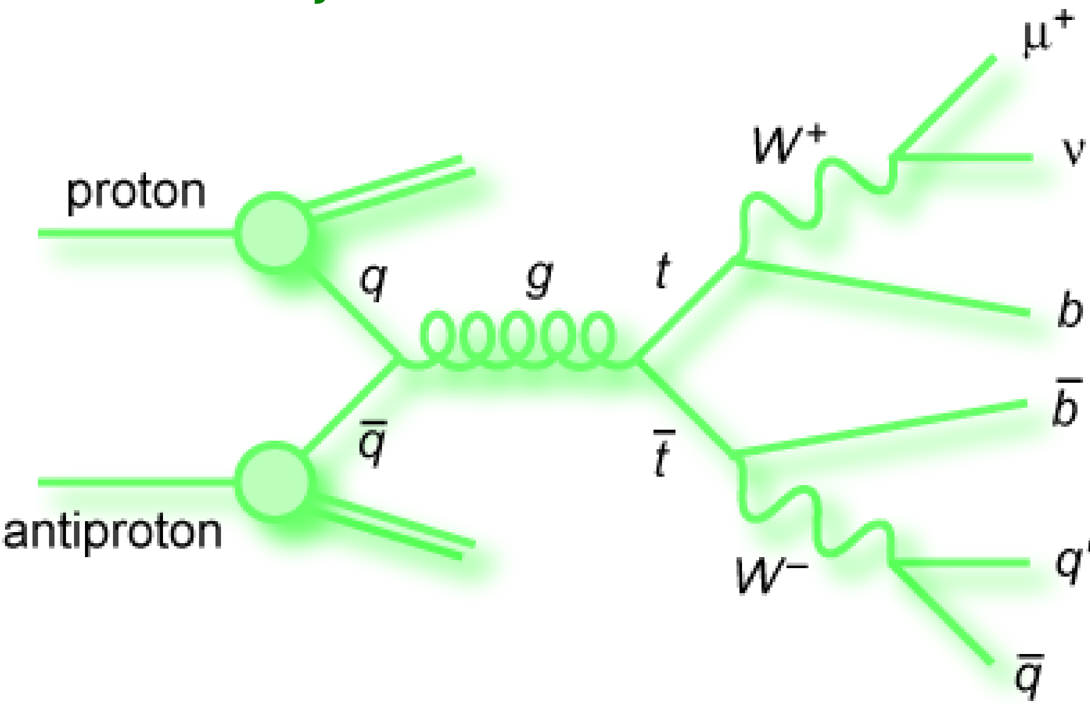

| | |
|---|---|
| **Mass:** | **173 GeV** |
| **Width:** | **1.3 GeV** |
| **Charge:** | **+2/3** |
| **Spin:** | **1/2** |

## Are there signs of new physics anywhere

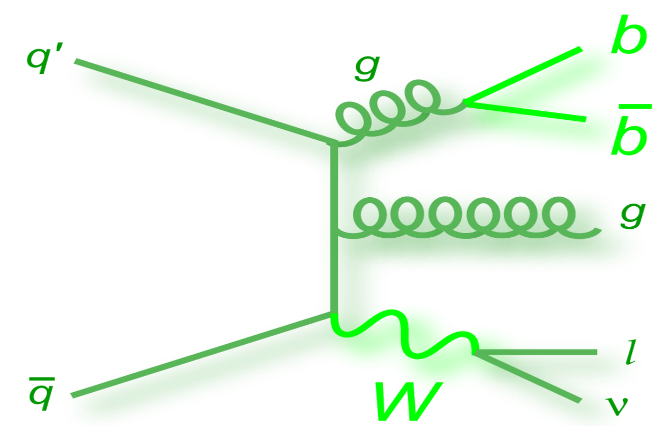
**t', W', Z', $H^+$, resonances, FCNC, anomalous charge...**

# Pair-production in ℓ+jets

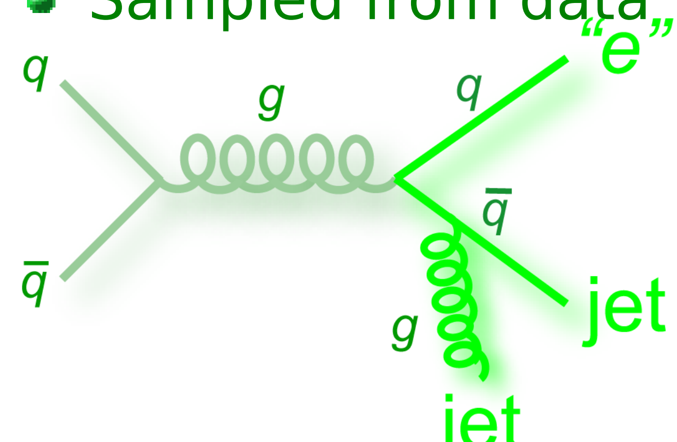
- **Signal**: $t\bar{t} \to Wb\,Wb \to \ell\nu b\,qqb$
  - $\sigma(t\bar{t}) = 7$ pb
  - One high energy e or μ
  - Missing energy
  - ≥4 jets
  - 2 b-jets



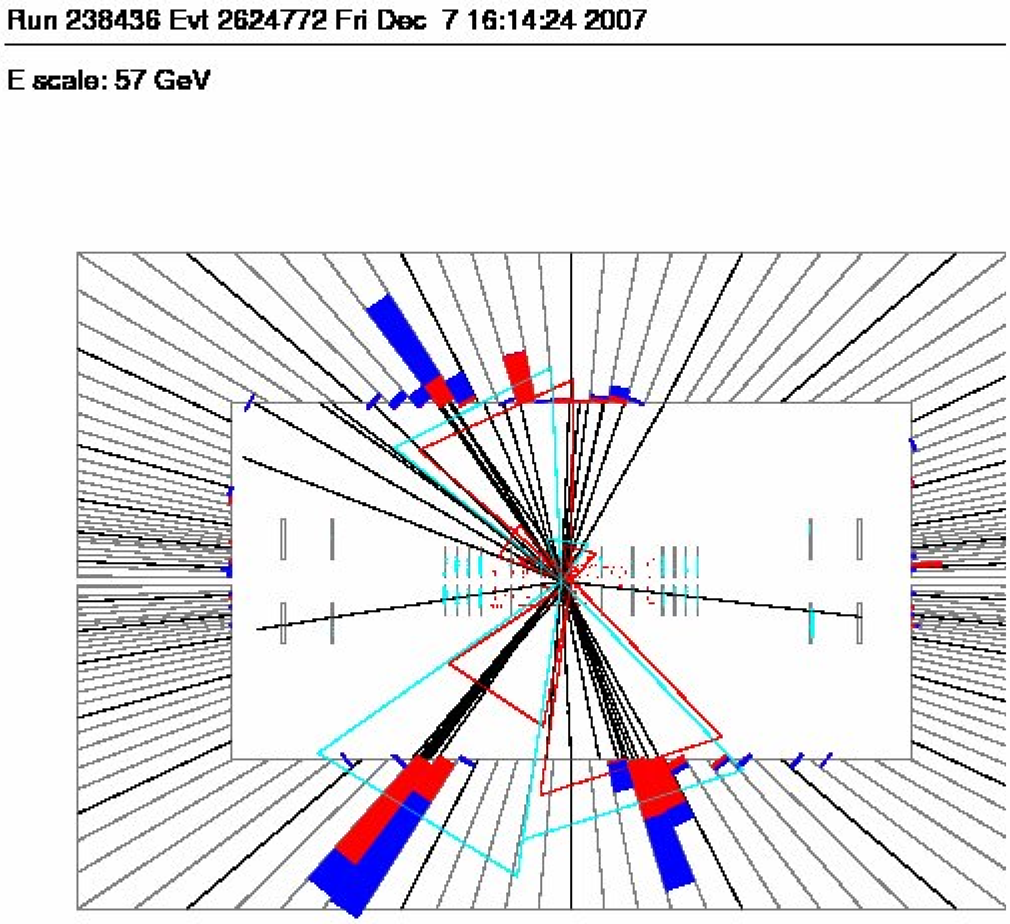

- **Backgrounds**:
- W+jets: σ ~ o(1000) pb
  - From simulation
  - Rate normalized to data

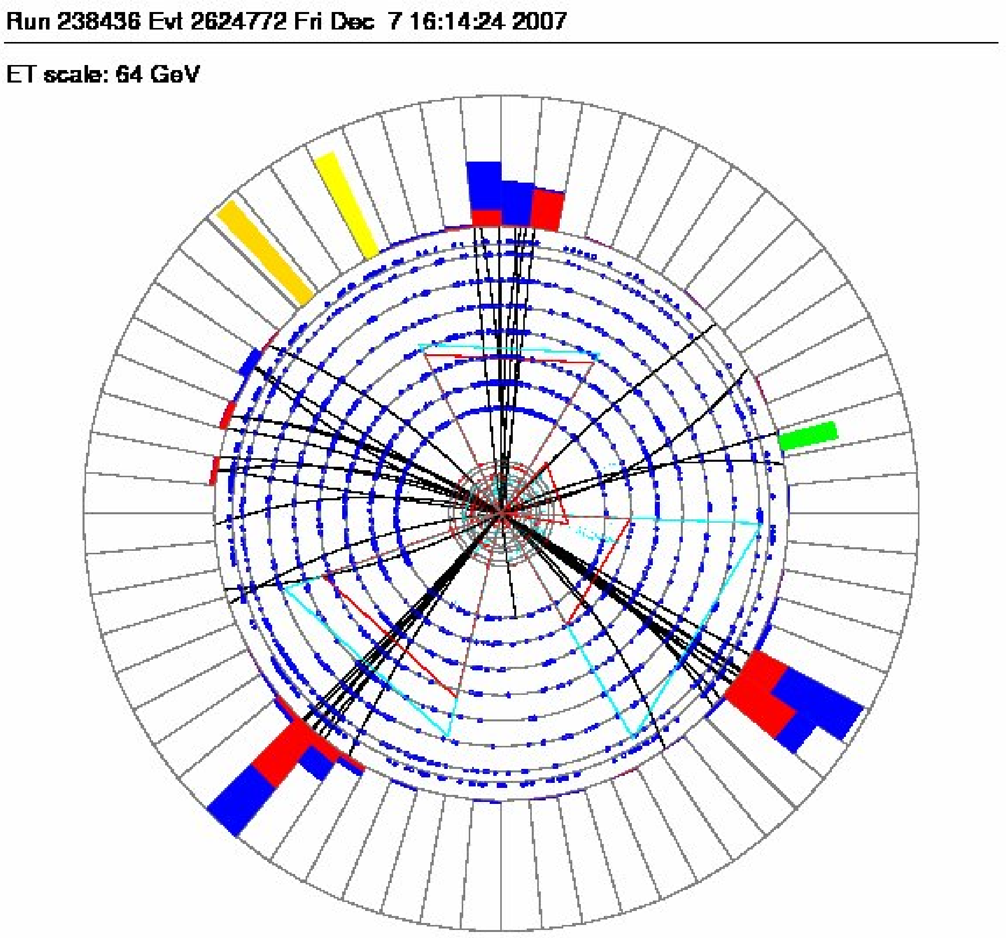



- Multijets (σ ~ $10^9$ pb)
  - Sampled from data



# A $t\bar{t}$ candidate event in the data

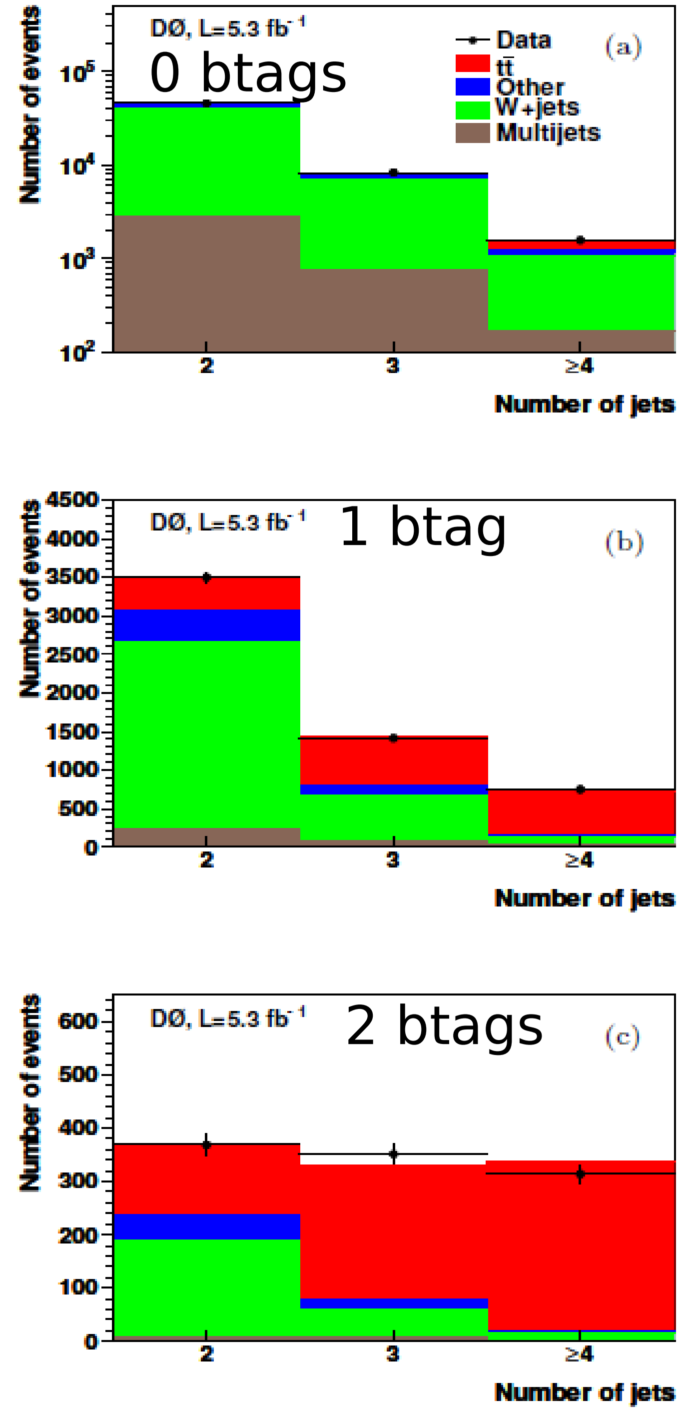


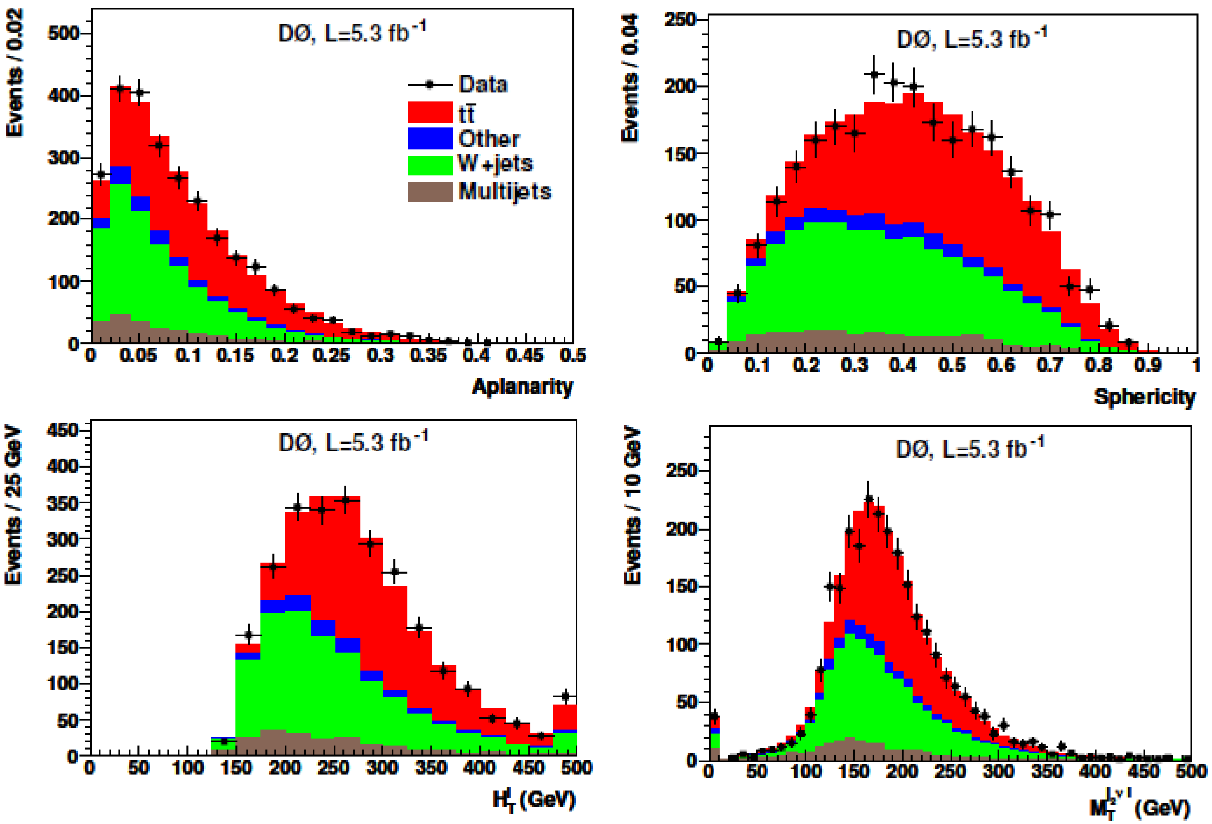
# Measuring the $t\bar{t}$ cross section

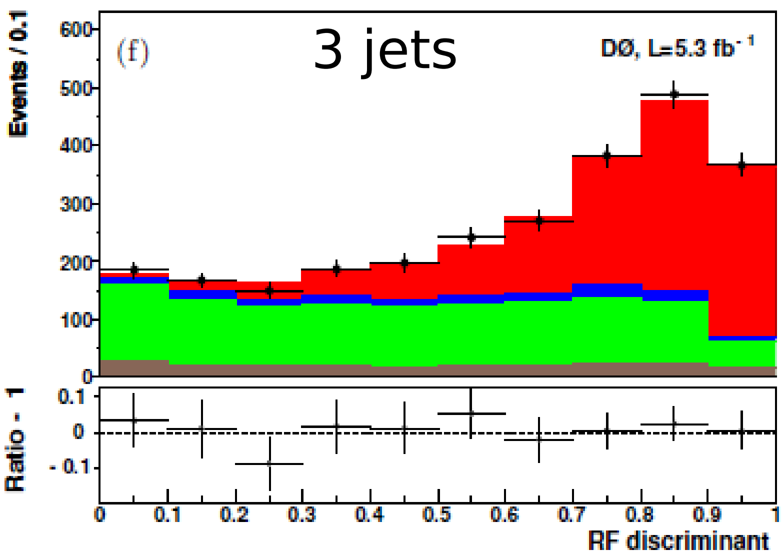
- Select events with:
  - Isolated e or μ with $p_T$>20 GeV
  - Missing energy > 20 GeV
  - 2 or more jets with $p_T$>20 GeV
  - Leading jet $p_T$>40 GeV
  - Other clean-up cuts
  - 0, 1, or 2 b-tagged jets

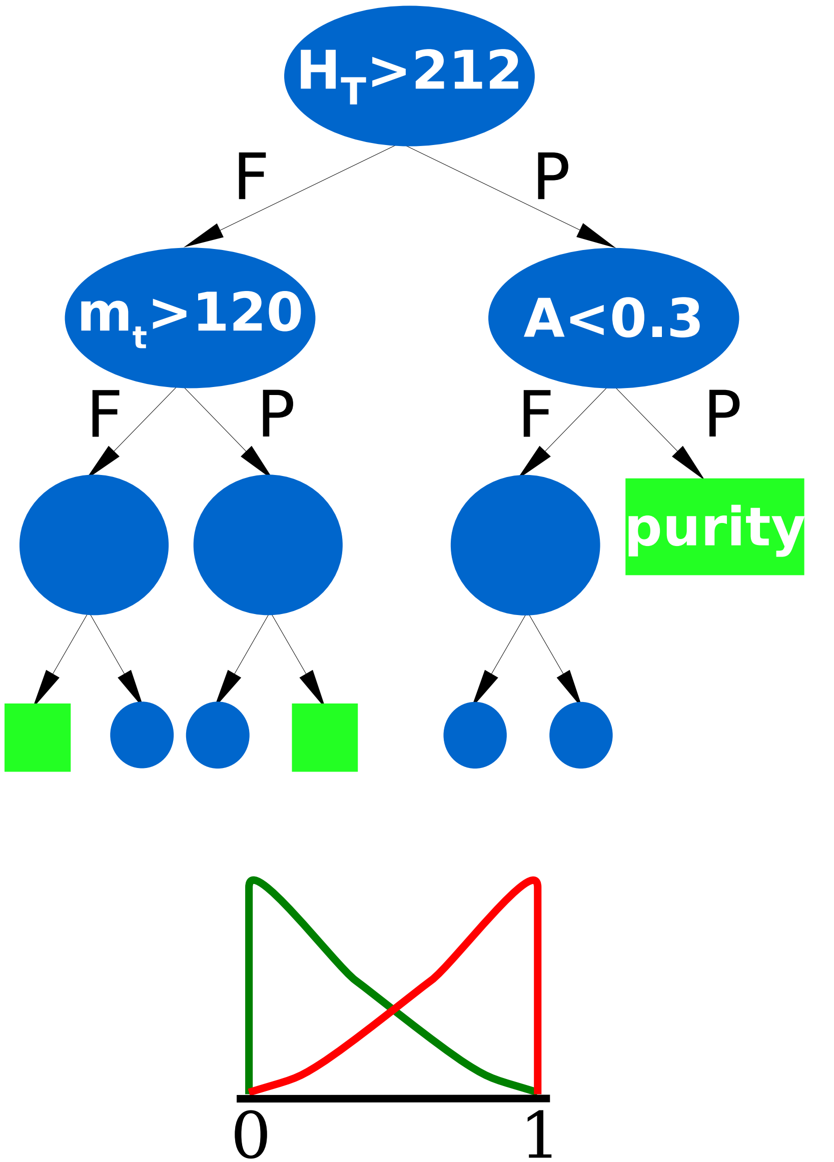
| e+mu, ≥4 jets, ≥1 b-tag | |
|---|---|
| W+jets | 131 ± 13 |
| Multijet | 31 ± 4 |
| Z+jets | 12 ± 2 |
| Other | 19 ± 1 |
| $t\bar{t}$ | 877 ± 45 |
| Total | 1066 ± 38 |
| Observed | 1060 |



# 0 b-tags: kinematic variables discriminant



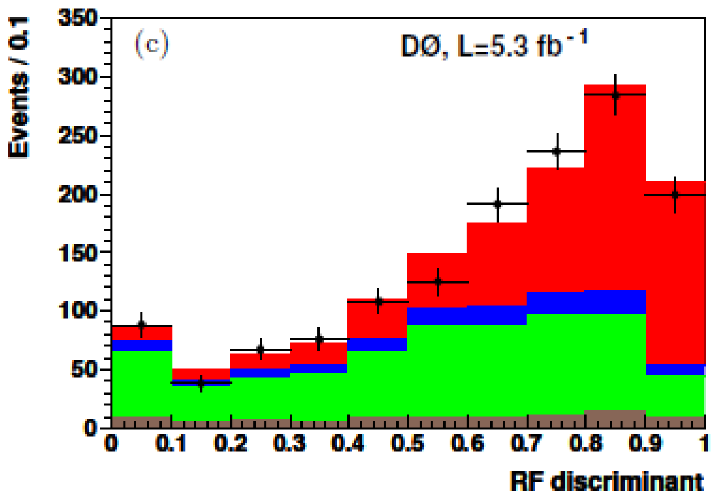



# Combined method (0,1,2 b-tags)

- Combine non tagged and b-tagged data for 3 and 4 jets
- Where S:B is large, just count the signal events
- Production cross section ($\sigma_{t\bar{t}}$) is proportional to the number of data-background events

| | 0 b-tag | 1 b-tag | 2 b-tags |
|---|---|---|---|
| 3 jets | discr. | discr. | count |
| 4 jets | | count | count |

$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bkg}}{\varepsilon \cdot L}$$



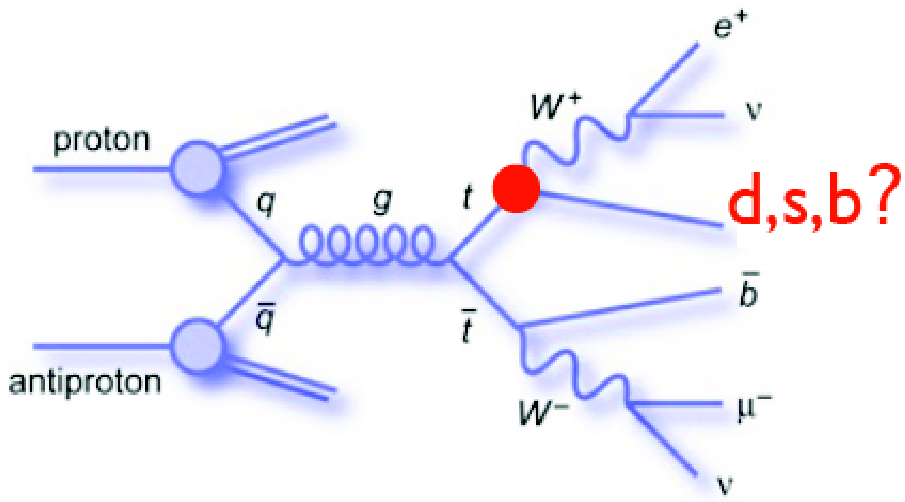

**$\sigma_{t\bar{t}} = 7.8^{+0.8}_{-0.6}$(stat+sys) pb**

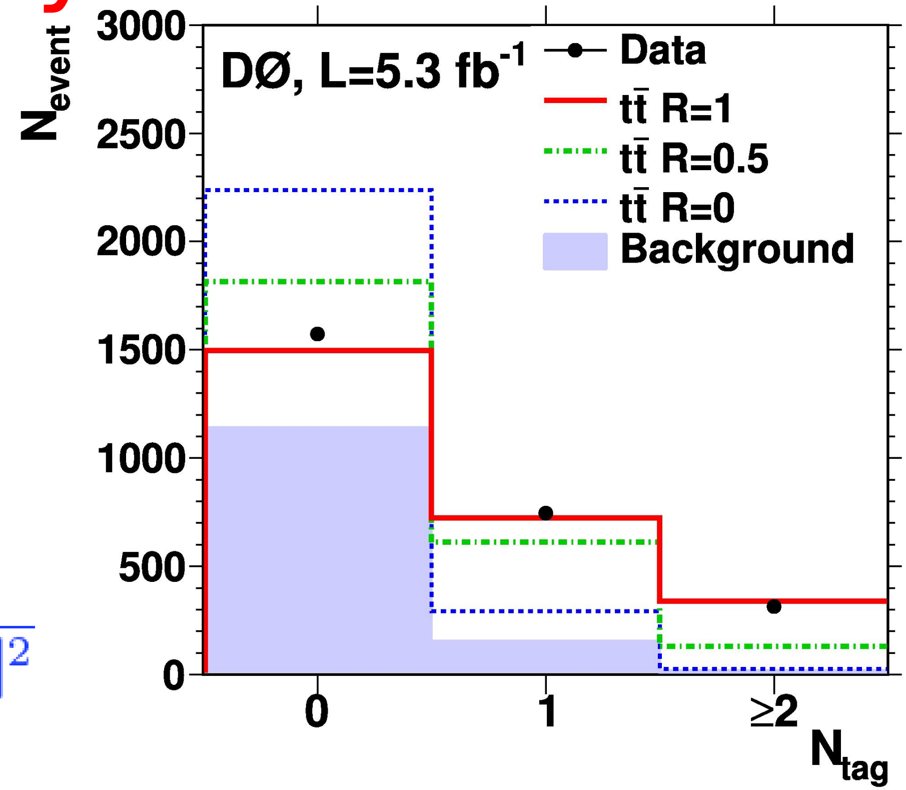
8-10% relative uncertainty

Expected in SM: $7.5^{+0.5}_{-0.7}$ pb at $m_t$ = 172.5 GeV

- Result is systematics limited
- Main systematic uncertainties: luminosity determination and b-tagging efficiency

# Top quark decay: $t \to Wb$




$$R = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

- In the SM, R=1. R<1 could indicate new physics (additional quarks)
- Drop assumption of R=1 in σ(ℓ+jets) analysis
  - Changes the predicted fraction of events with 0, 1 and 2 b-tags

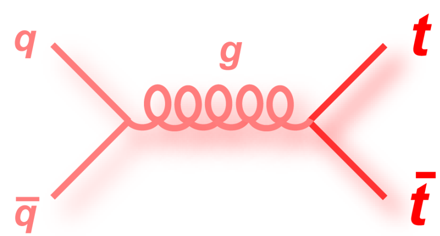
$$N_{0,1,2}(R,\sigma_{tt}) = \left[R^2 \varepsilon^{bb}_{0,1,2} + 2R(1-R)\varepsilon^{bl}_{0,1,2} + (1-R)^2 \varepsilon^{ll}_{0,1,2}\right] \sigma_{tt} \; B^2(t \to Wq) \; L$$

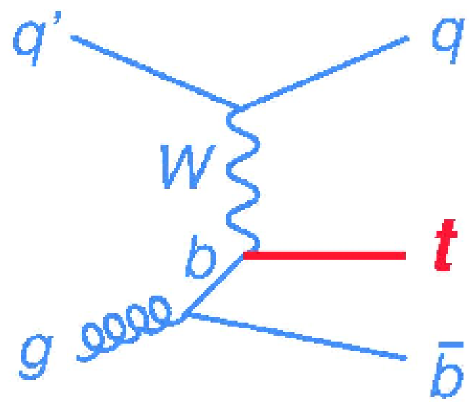
- Measure simultaneously with the ℓ+jets cross section

$$\sigma_{t\bar{t}} = 7.9^{+0.8}_{-0.7} \text{ (stat+sys) pb}$$

$$R = 0.95 \pm 0.07$$

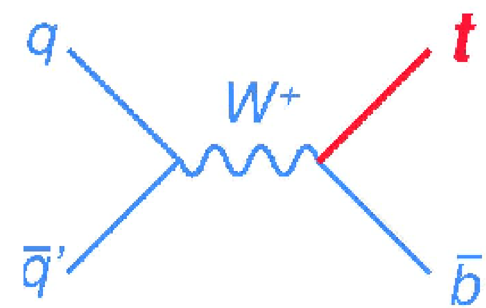
# Another way of producing t quarks




**t-channel**

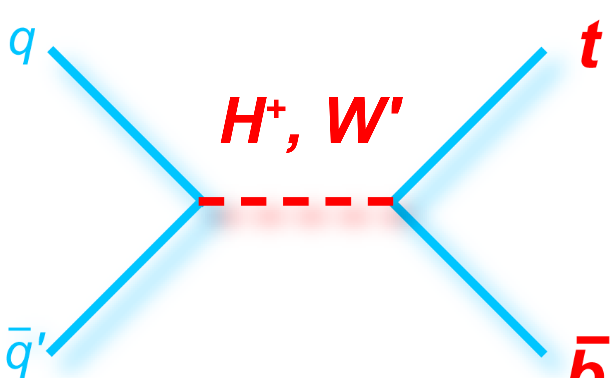
**σ=2.1±0.1 pb**

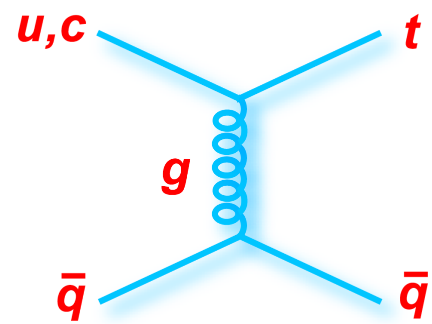



**s-channel**

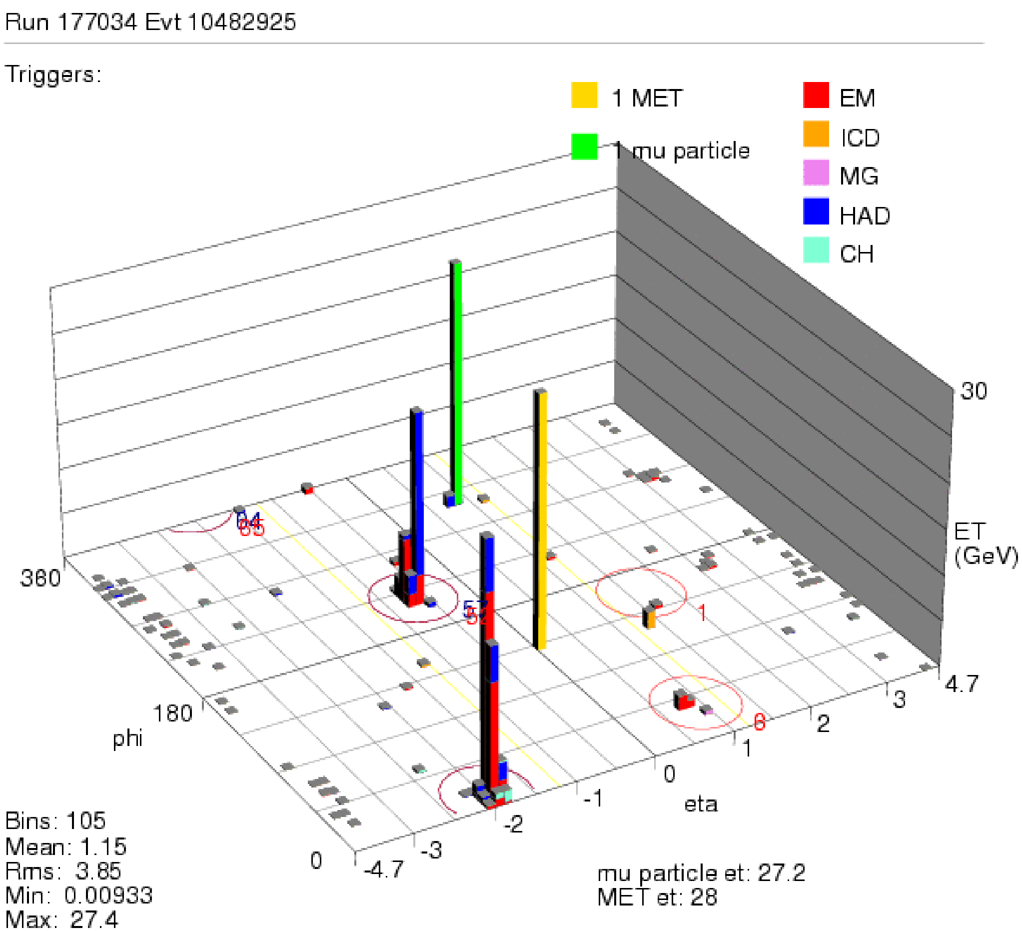
**σ=1.1±0.1 pb**

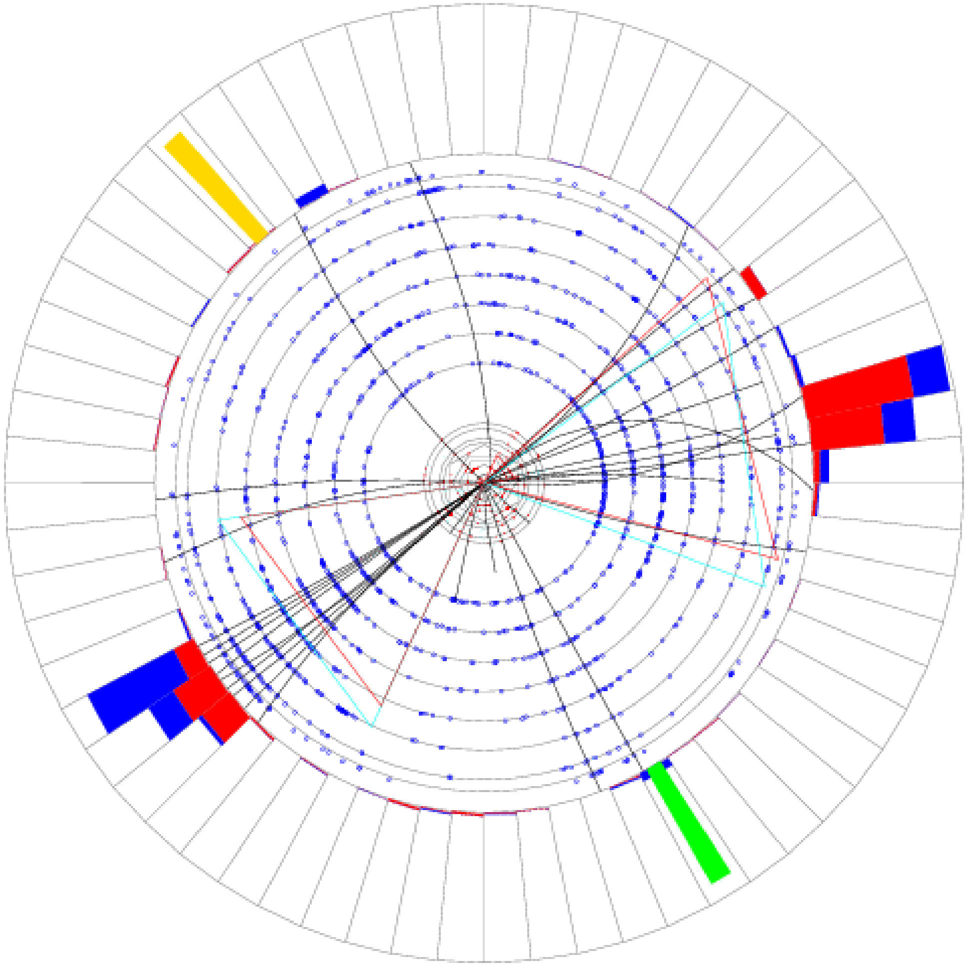
- Electroweak production of single top quarks
- This mode was only discovered in 2009!
- Can measure W-t-b coupling directly at production
- Sensitive to new physics:



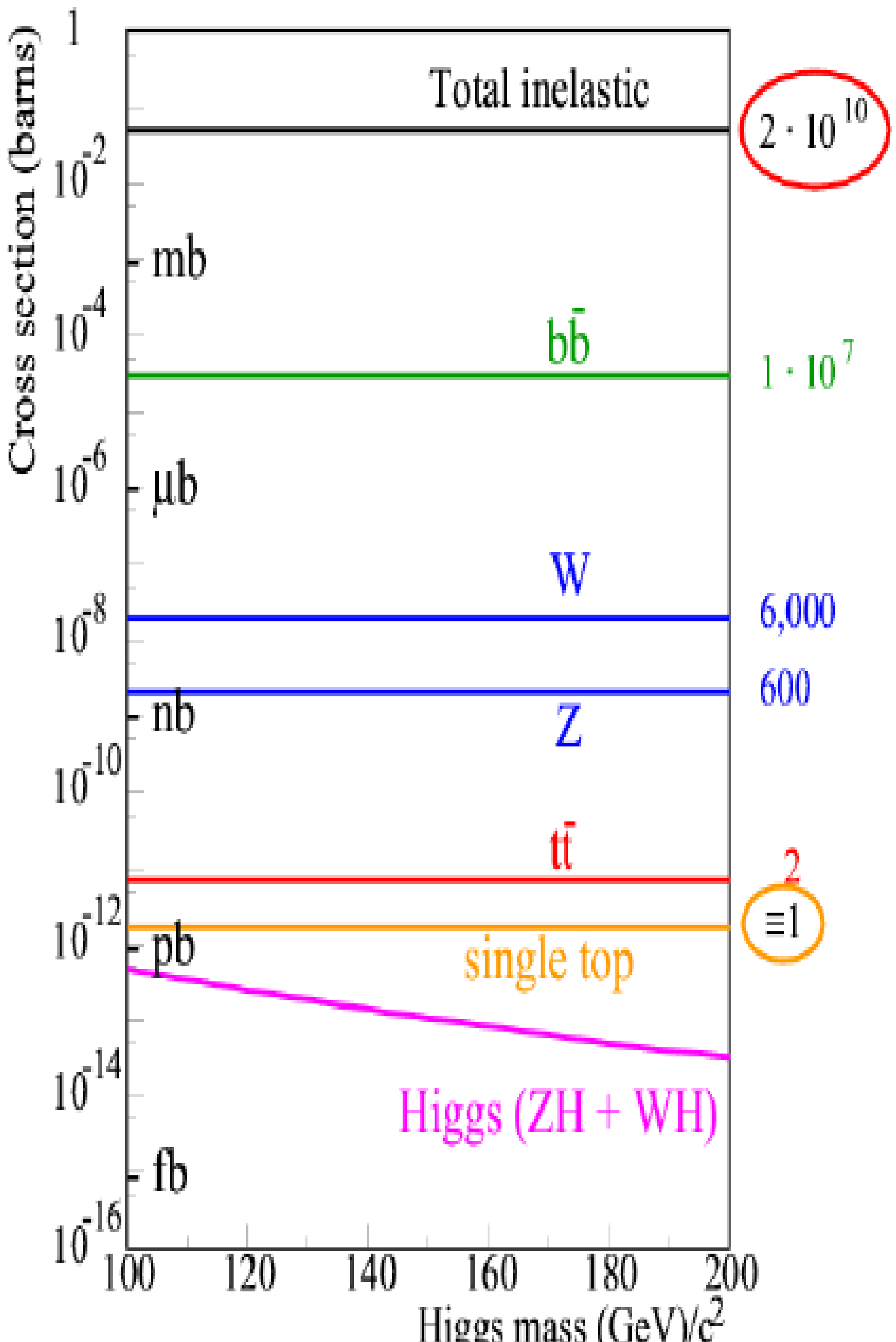
# A candidate event

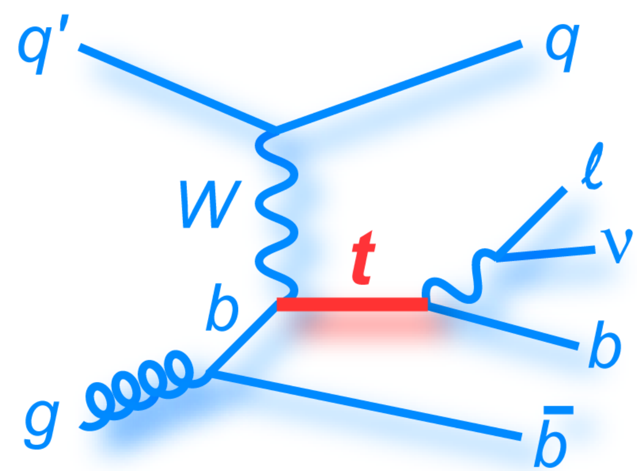


- $M_T(\ell,\nu)$ = 82 GeV
- $M(\ell,\nu,b)$ = 177 GeV
- $Q \times \eta$ = 1.88

# A challenging measurement




e or μ

missing energy

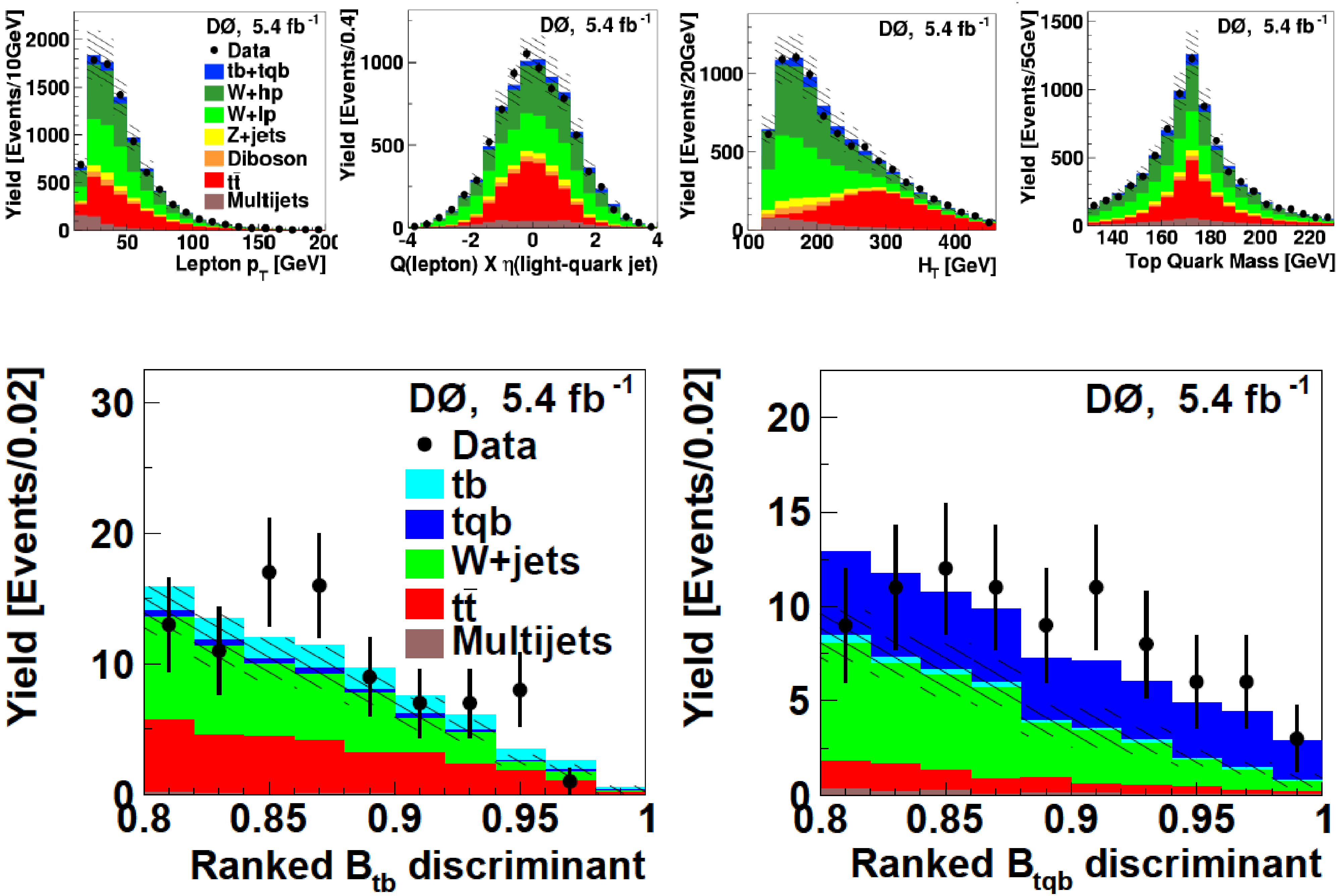
2 or 3 jets

(1 or 2 b-jets)

| e or μ, 2,3,4 jets, ≥1 b-tags | |
|---|---|
| t-channel | 239 ± 28 |
| s-channel | 160 ± 27 |
| W+jets | 4943 ± 598 |
| $t\bar{t}$ | 2124 ± 383 |
| Z+jets, diboson | 576 ± 113 |
| Multijets | 451 ± 56 |
| Total | 8492 ± 987 |
| Observed | 8471 |

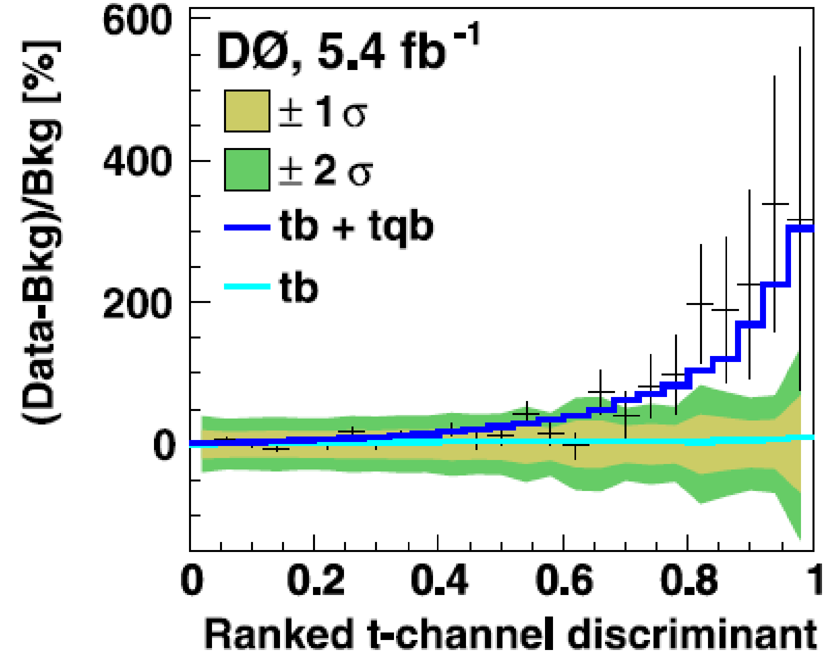
- Simple counting experiment cannot extract signal from huge background

# Combine several machine learning methods



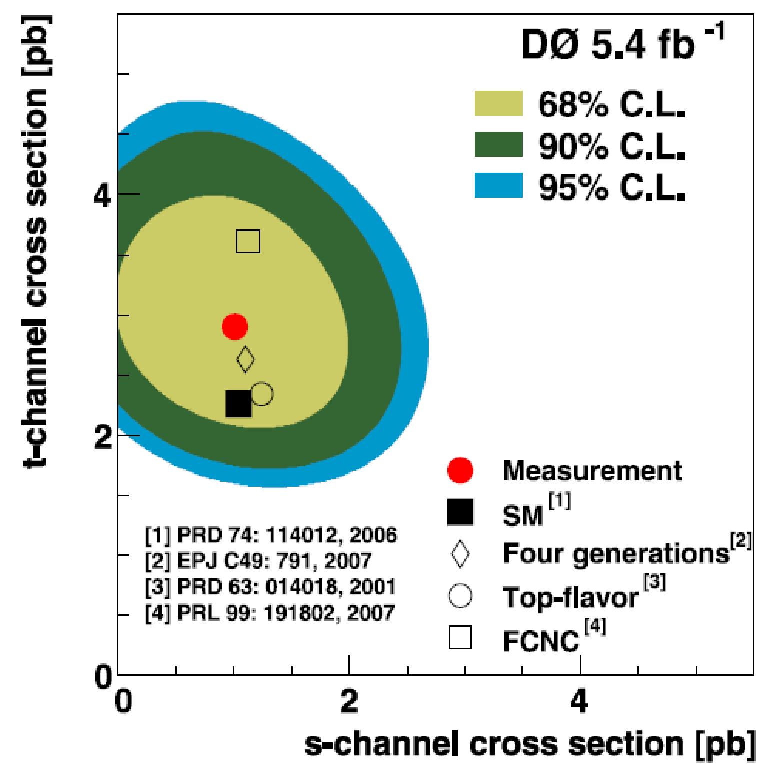
# Single top measurement results

| | t-channel | s-channel |
|---|---|---|
| **Measured σ** | **2.9 ± 0.6 pb** | **1.0 ± 0.6 pb** |
| SM expected σ | 2.3 ± 0.1 pb | 1.04 ± 0.04 pb |
| p-value | 5.5 std. dev. | - |



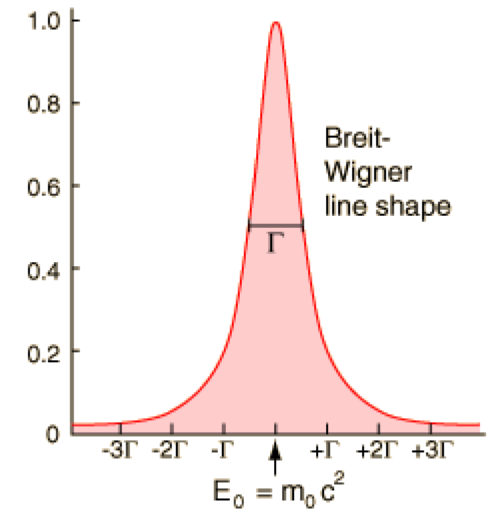

- t-channel can now be measured on its own, independently of s-channel
- Does not assume SM for s-channel
- Obtain 20% precision on t-channel measurement
- Translate tb+tqb measurement in constrain on $|V_{tb}|$ without assuming 3 families:

$$|V_{tb}\ f_L| = 1.02 \pm 0.11$$



# Top decay lifetime

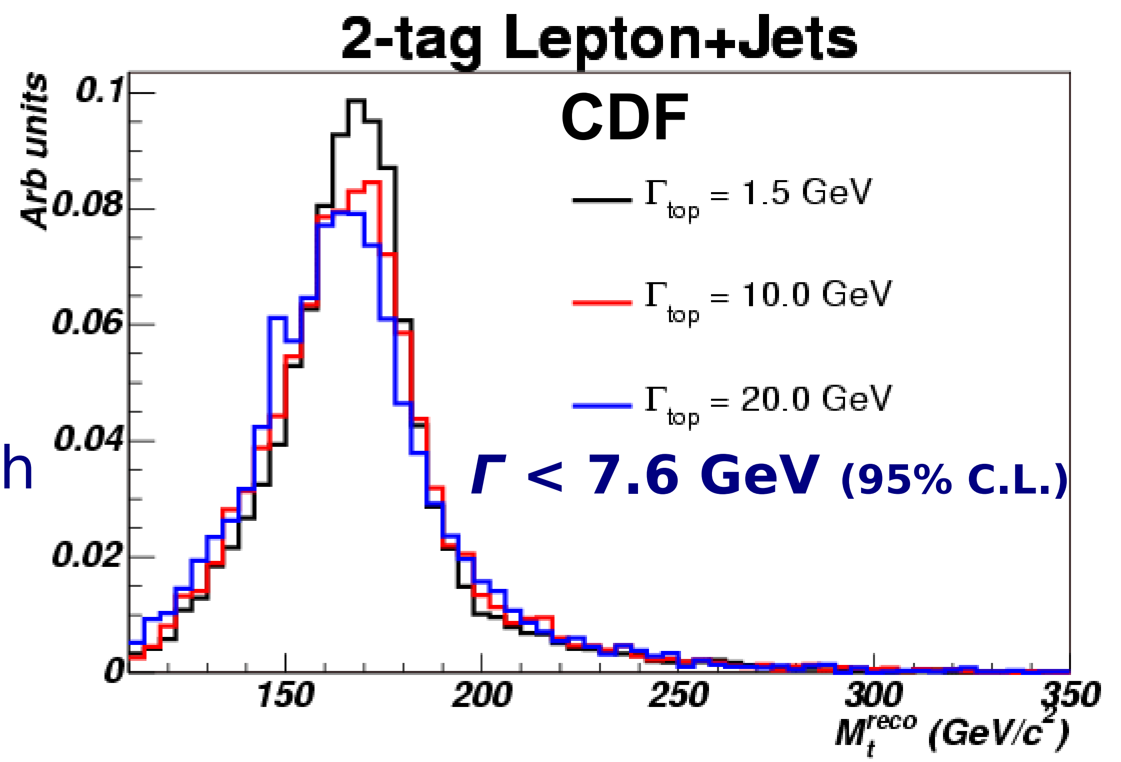
- The decay lifetime (half-life) tends to decrease with larger mass
  - $\tau(\mu \rightarrow e^{-} \bar{\nu}_e \nu_\mu) = 2 \cdot 10^{-6}$ s ($m_\mu$ = 0.1 GeV)
  - $\tau(\bar{u}b \rightarrow c+X) = 1 \cdot 10^{-12}$ s ($m_B$ = 5 GeV)
  - SM expected $\tau(t \rightarrow Wb) \sim 10^{-25}$ s ($m_t$=173 GeV)
- The decay width is easier to measure: $\Gamma = \hbar/\tau$
- $\Gamma$ is the spread in measured energy due to Heisenberg's unc. principle




- Direct measurement is independent of assumptions, but is limited by experimental resolution
- For top quark:

  exp. resolution > natural width

  $\Gamma_t$ = 1.3 GeV




**$\Gamma$ < 7.6 GeV (95% C.L.)**

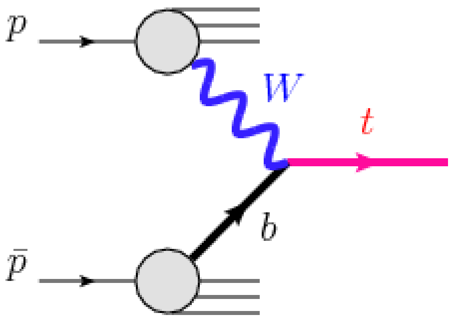
# Indirect measurement

- Idea: use the partial decay width and decay fraction

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)}$$

$$\sigma(tqb)\frac{\Gamma(t \to Wb)_{SM}}{\sigma(tqb)_{SM}}$$

single top t-channel cross section: σ(tqb) is proportional to Γ(t→Wb)




$$R = \frac{B(t \to Wb)}{B(t \to Wq)}$$

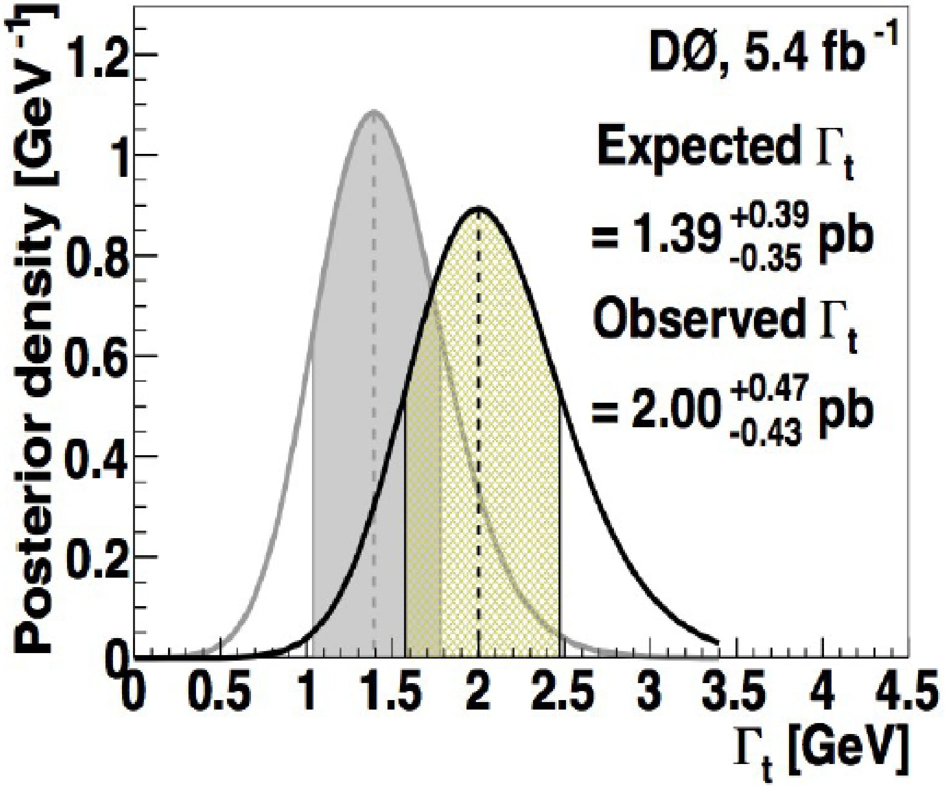
ratio of decay branching fractions assuming B(t→Wq)=1

- This result assumes that the production (in t-channel) and decay have the same properties
- New particles like b' could modify this width

**$\Gamma_t = 2.0^{+0.5}_{-0.4}$ GeV**

**$\tau_t = (3.3^{+0.9}_{-0.6})\ 10^{-25}$ s**

**$|V_{tb'}| < 0.59$**

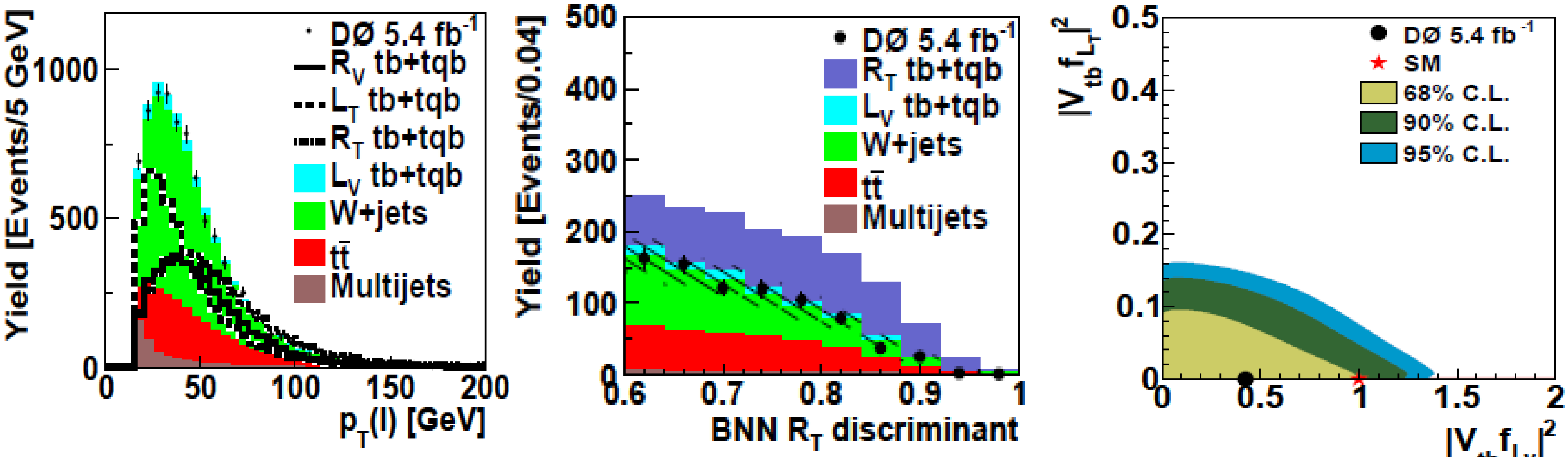


# Search for new physics

- Generic lagrangian for W-t-b interaction:

$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(L_V P_L + R_V P_R)tW_{\mu}^{-} + \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(L_T P_L + R_T P_R)tW_{\mu}^{-}$$

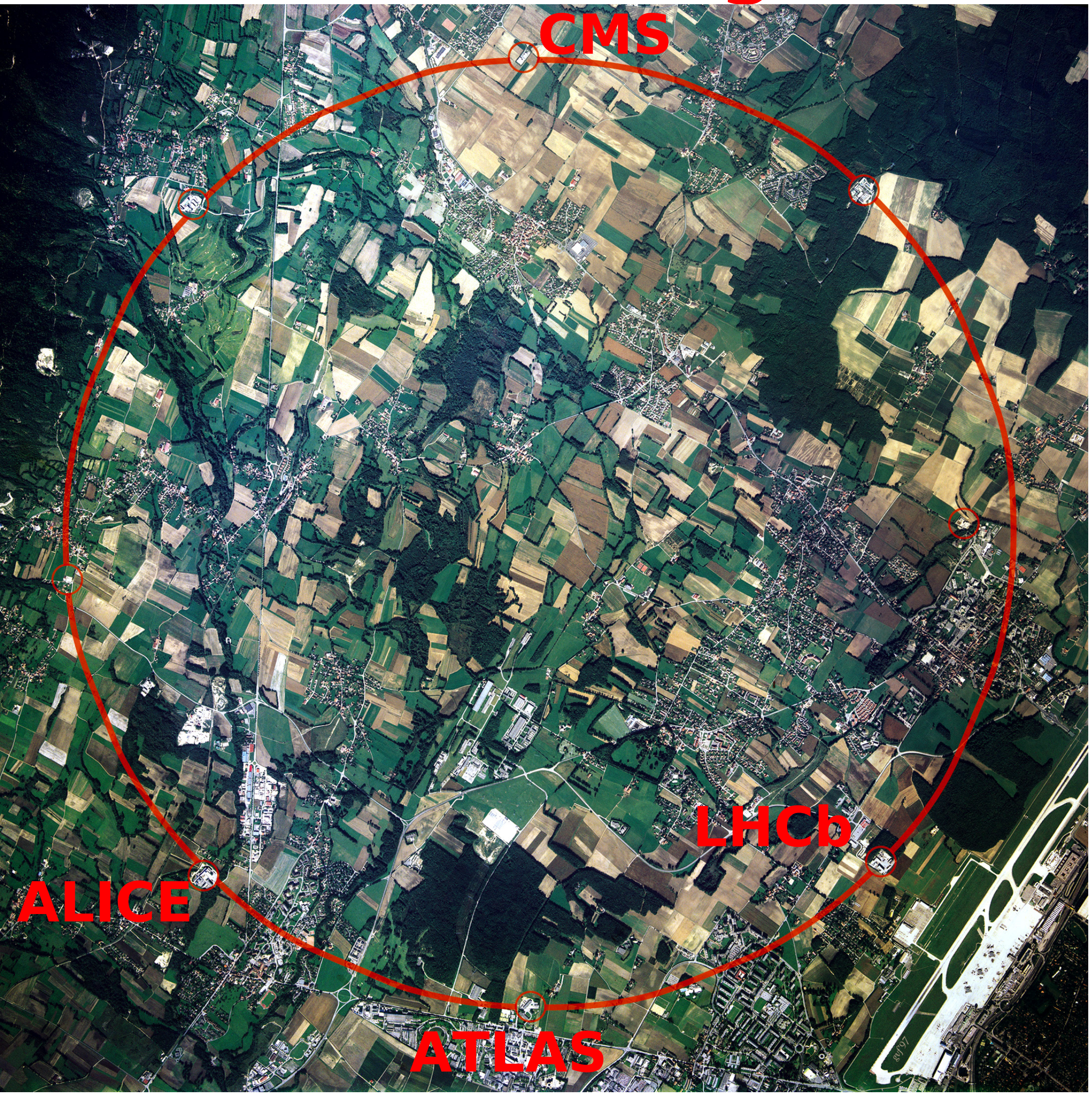
- SM: only left-handed vector couplings $L_V$ are allowed ($R_V=L_T=R_T=0$)
- Anomalous top quark couplings would change the kinematics of single top production
- No deviation is seen in the data
- We exclude one new coupling at a time, assuming the the other two are negligible: ($R_V=R_T=0$) , ($L_T=R_T=0$) , ($R_V=L_T=0$)

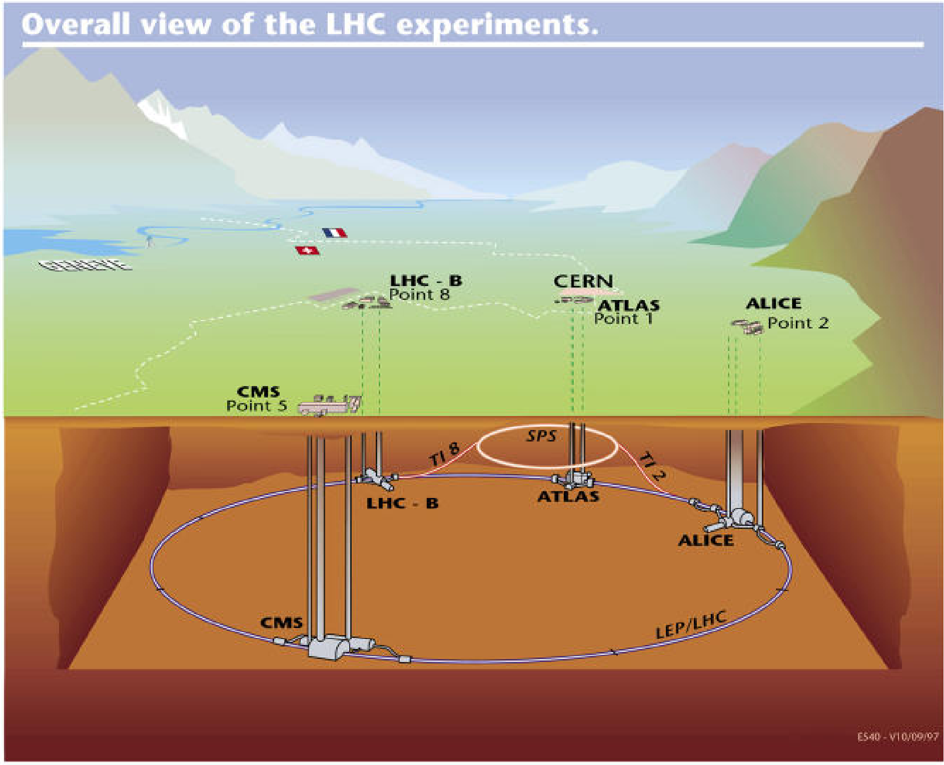


# Top quark Tevatron scorecard

| Property | Measurement | SM Prediction | Luminosity ($fb^{-1}$) |
|---|---|---|---|
| $\sigma_{t\bar{t}}$ (for $M_t = 172.5$ GeV) | CDF: $7.5 \pm 0.31(\text{stat}) \pm 0.34(\text{syst}) \pm 0.15(\text{theory})$ pb | $7.46^{+0.48}_{-0.67}$ pb | up to 4.6 |
| | D0: $7.56^{+0.63}_{-0.56}$ (stat + syst + lumi) pb | | 5.6 |
| $\sigma_{\mathbf{tbq}}$ (for $M_t = 172.5$ GeV) | CDF: $0.8 \pm 0.4$ pb ($M_t = 175$ GeV) | $2.26 \pm 0.12$ pb | 3.2 |
| | D0: $2.90 \pm 0.59$ pb | | 5.4 |
| $\sigma_{\mathbf{tb}}$ (for $M_t = 172.5$ GeV) | CDF: $1.8^{+0.7}_{-0.5}$ pb ($M_t = 175$ GeV) | $1.04 \pm 0.04$ pb | 3.2 |
| | D0: $0.68^{+0.38}_{-0.35}$ pb | | 5.4 |
| **Charge asymmetry** | CDF: $0.158 \pm 0.074$ | 0.06 | 5.3 |
| | D0: $0.196 \pm 0.065$ | | 5.4 |
| **spin correlation** | CDF: $0.72 \pm 0.64(\text{stat}) \pm 0.26(\text{syst})$ | $0.777^{+0.027}_{-0.042}$ | 5.3 |
| | D0: $0.66 \pm 0.23(\text{stat} + \text{sys})$ | | 5.4 |
| $M_t$ | Tev: $173.2 \pm 0.9$ GeV | - | up to 5.8 |
| $\sigma_{t\bar{t}\gamma}$ | CDF: $0.18 \pm 0.08$ pb | $0.17 \pm 0.03$ pb | 6.0 |
| $\lvert V_{tb} \rvert$ | CDF: $\lvert V_{tb} \rvert = 0.91 \pm 0.11(\text{stat} + \text{sys}) \pm 0.07(\text{theory})$ | 1 | 3.2 |
| | D0: $\lvert V_{tb} \rvert = 1.02^{+0.10}_{-0.11}$ | | 5.4 |
| $R = B(t \to Wb)/B(t \to Wq)$ | CDF: $> 0.61$ @ 95% CL | 1 | 0.2 |
| | D0: $0.90 \pm 0.04$ | | 5.4 |
| $\sigma(gg \to t\bar{t})/\sigma(p\bar{p} \to t\bar{t})$ | CDF: $0.07^{+0.15}_{-0.07}$ | 0.18 | 1 |
| $M_t - M_{\bar{t}}$ | CDF: $-3.3 \pm 1.4(\text{stat}) \pm 1.0(\text{syst})$ GeV | 0 | 5.6 |
| | D0: $0.8 \pm 1.8(\text{stat}) \pm 0.5(\text{syst})$ GeV | | 3.6 |
| **W helicity fraction** | Tev: $f_0 = 0.732 \pm 0.063(\text{stat}) \pm 0.052(\text{syst})$ | 0.7 | up to 5.4 |
| **Charge** | CDF: -4/3 excluded @ 95% CL | 2/3 | 5.6 |
| | D0: 4/3 excluded @ 92% CL | | 0.37 |
| $\Gamma_t$ | CDF: $< 7.6$ GeV @ 95% CL | 1.26 GeV | 4.3 |
| | D0: $1.99^{+0.69}_{-0.55}$ GeV | | up to 2.3 |

# The Large Hadron Collider

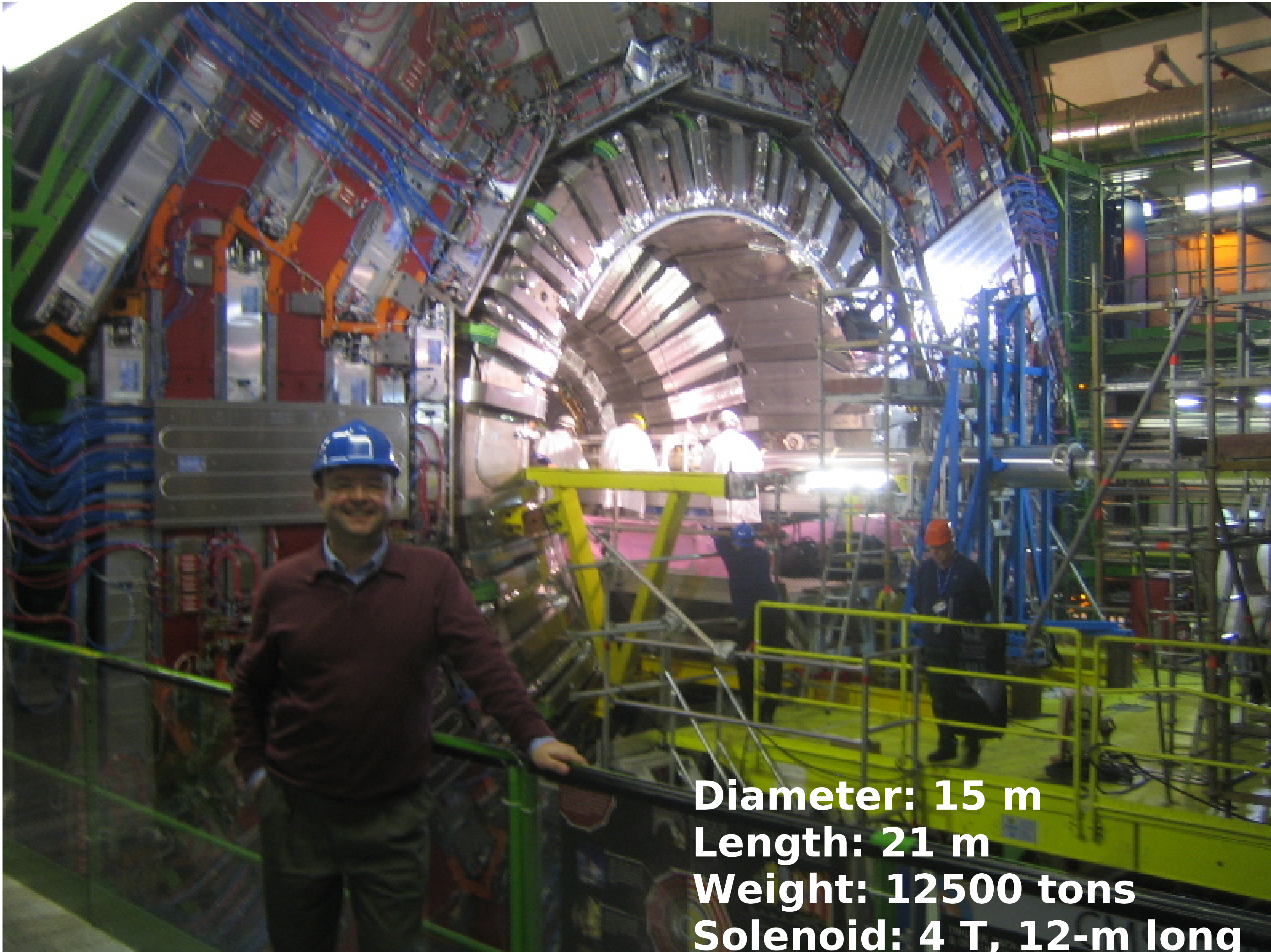



- p-p collider at $\sqrt{s}=7$ TeV
- 26 km long, 100m underground
- Delivered luminosity: 5.5 $fb^{-1}$
- Peak luminosity: $3.5 \cdot 10^{33}$ $cm^2 s^{-1}$
- Crossing rate: 40 MHz
- Rare processes: 1 in $10^{13}$

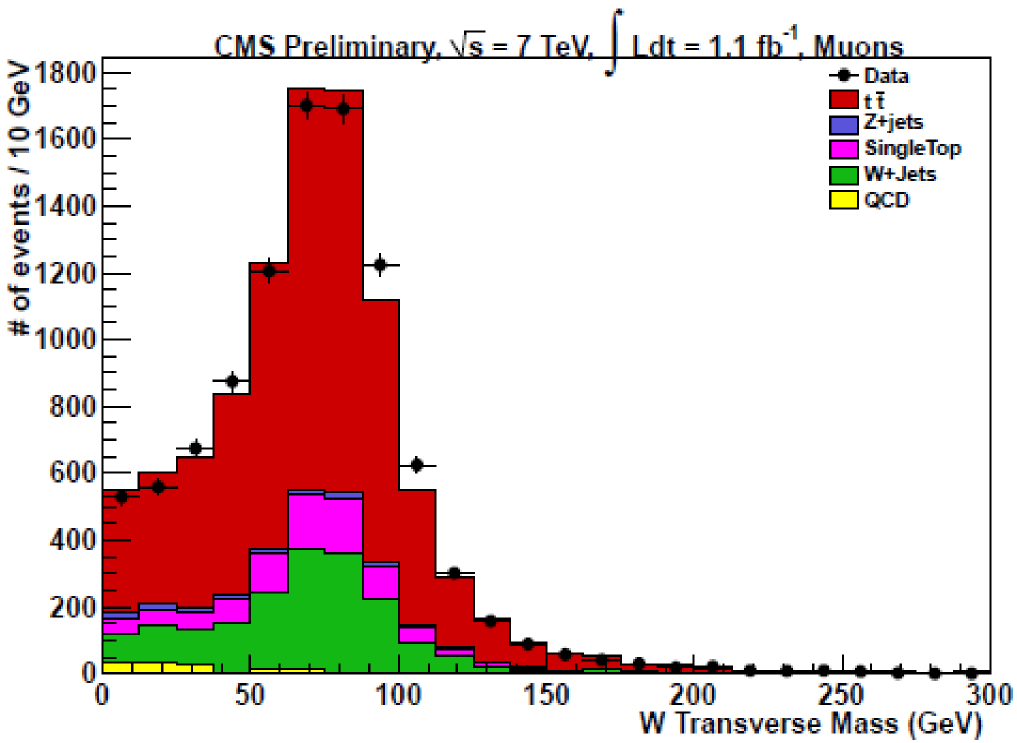
1 $fb^{-1}$ of LHC data produces 24 times more $t\bar{t}$ pairs than 1 $fb^{-1}$ of TeV data

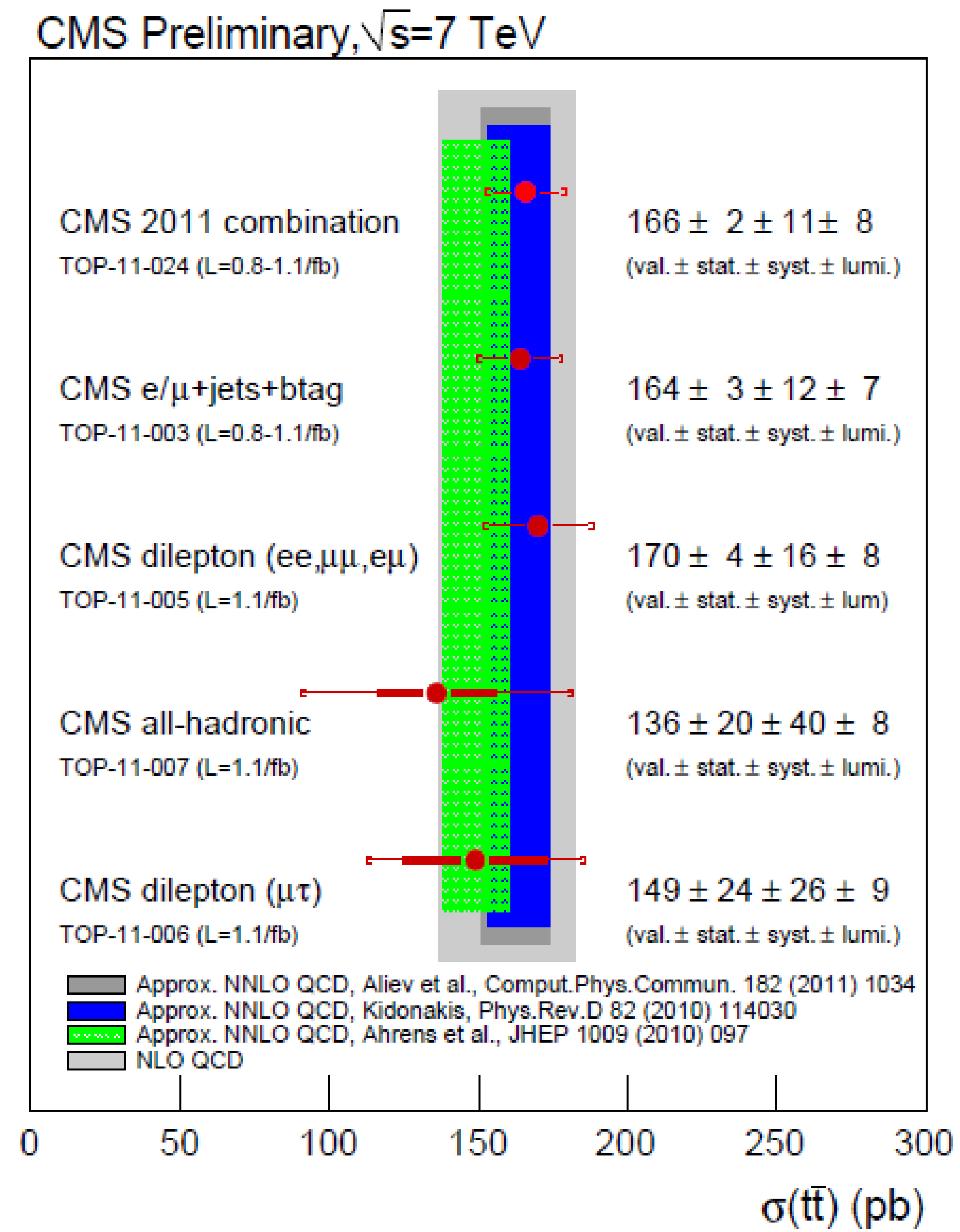
18,000 top pairs in one fill of 16 hours!


Diameter: 15 m
Length: 21 m
Weight: 12500 tons
Solenoid: 4 T, 12-m long

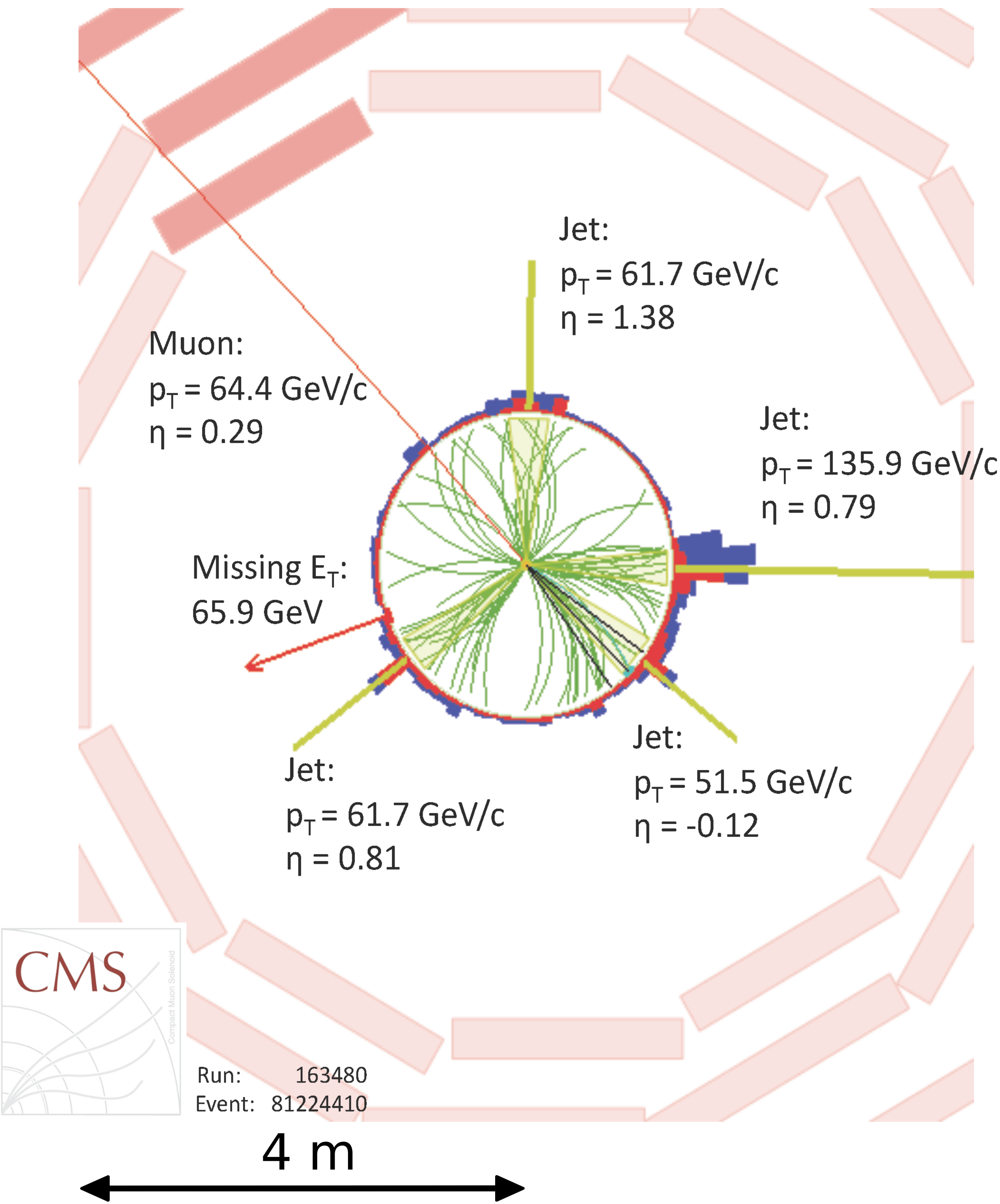
# $t\bar{t}$ pairs results from LHC

- Huge production rate: from 7 pb to 165 pb
- Latest CMS analysis has ~13,000 top pairs candidates with $1 fb^{-1}$
- Achieves 8% relative uncertainty

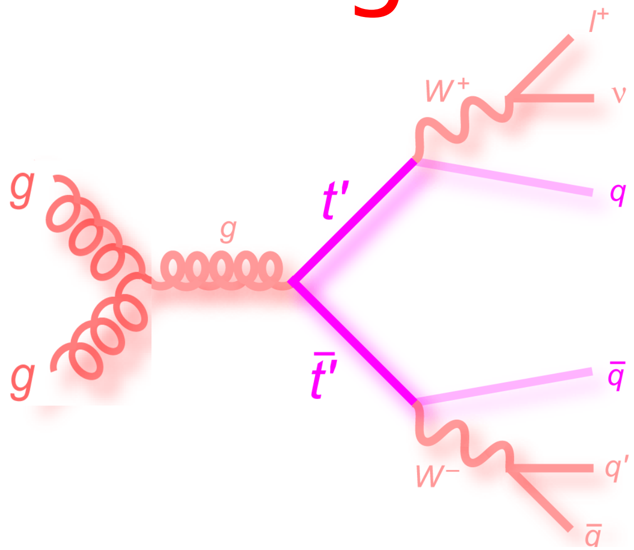


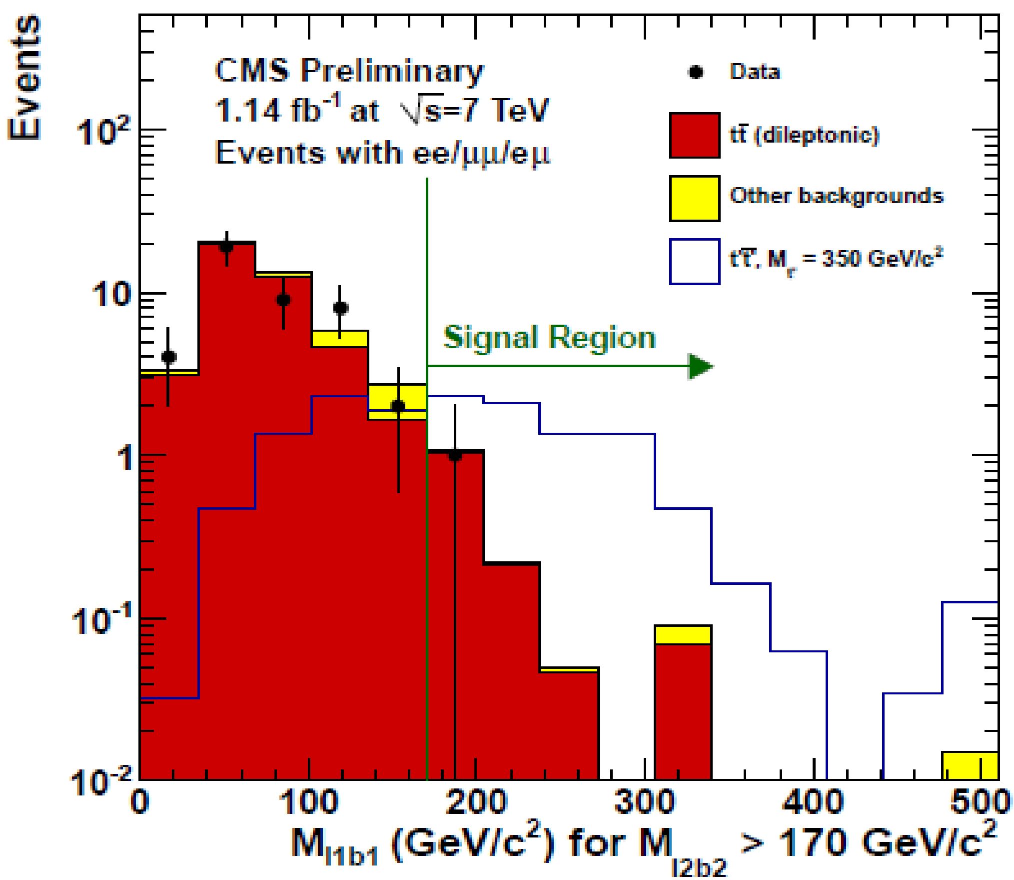



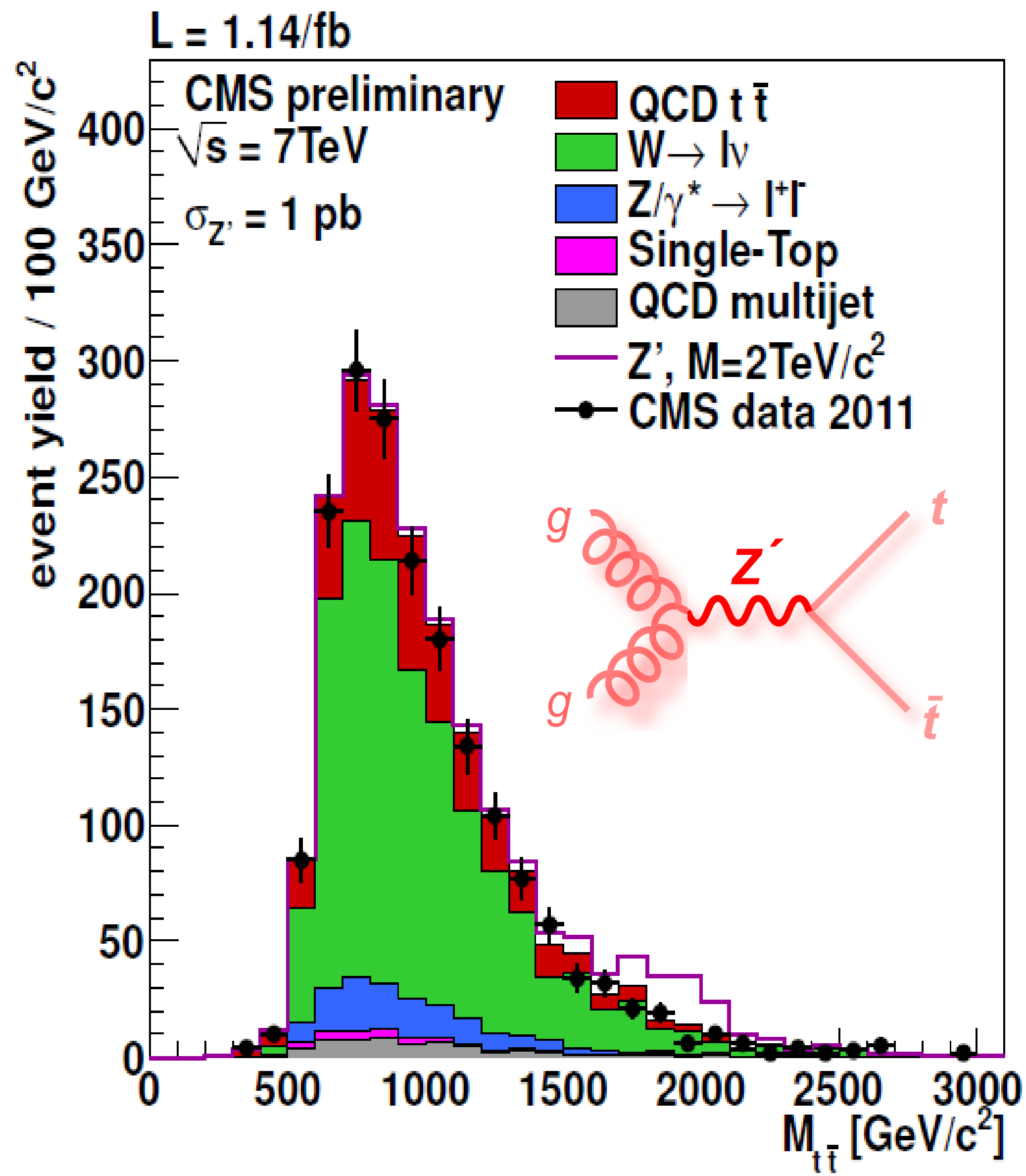

Now moving on to expand the measurements of properties and searches for new physics


Jet:
pT = 61.7 GeV/c
η = 1.38
Muon:
pT = 64.4 GeV/c
η = 0.29
Jet:
pT = 135.9 GeV/c
η = 0.79
Missing ET:
65.9 GeV
Jet:
pT = 61.7 GeV/c
η = 0.81
Jet:
pT = 51.5 GeV/c
η = -0.12
CMS
Run: 163480
Event: 81224410
4 m

# Searching for heavy new particles



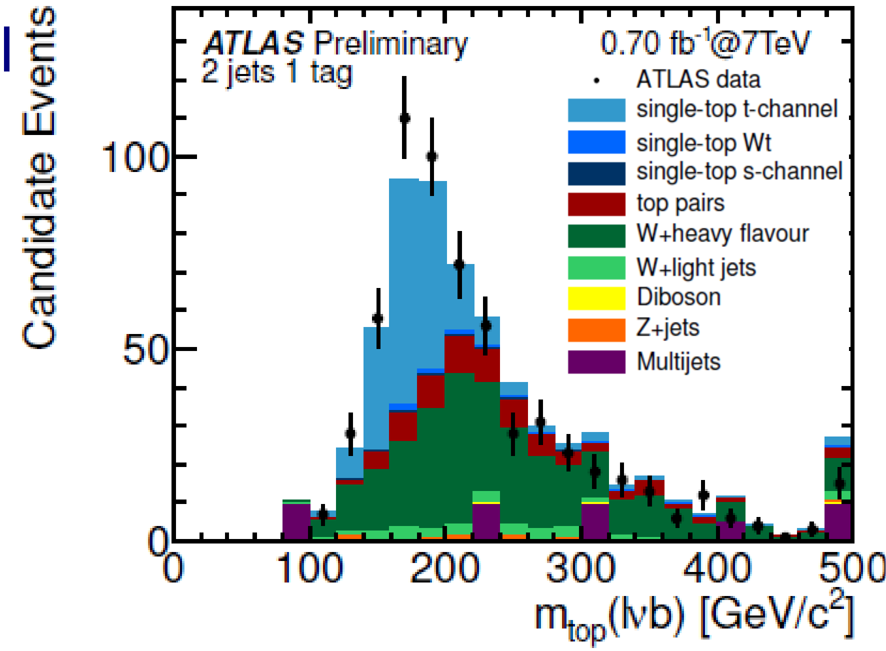

No sign of new physics yet!

# Single top results from LHC

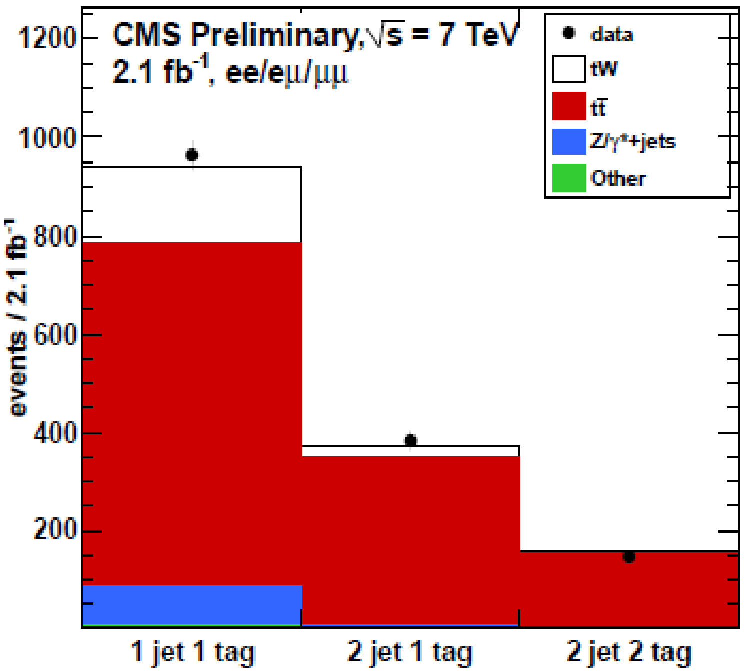
- It is possible to measure the t-channel cross section with simple cuts

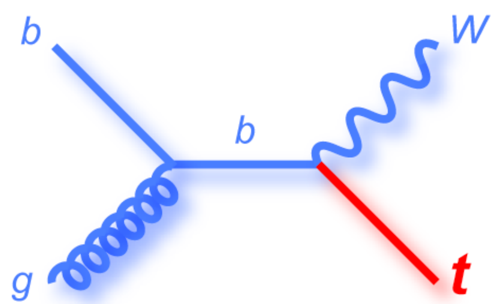
$\sigma_{tqb} = 90^{+31}_{-20}$ pb    7.6 std. dev.

Expected in SM: 64±3 pb at $m_t$ = 173 GeV



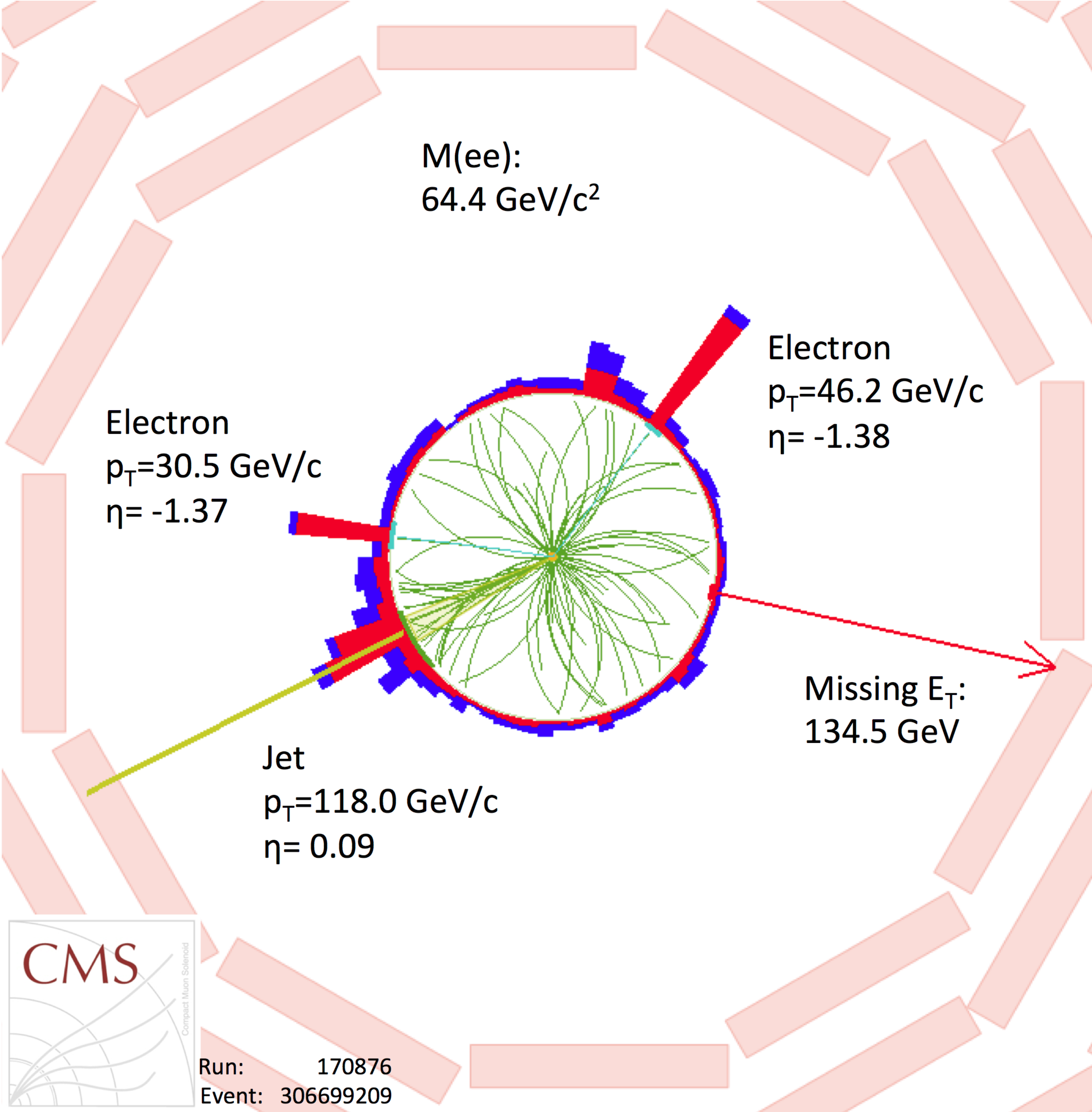

- New channel of production opens up: tW → Wb W → ℓνb ℓν




$\sigma_{tW} = 22^{+9}_{-7}$ pb    2.7 std. dev.

Expected in SM: 16±1 pb at $m_t$ = 173 GeV

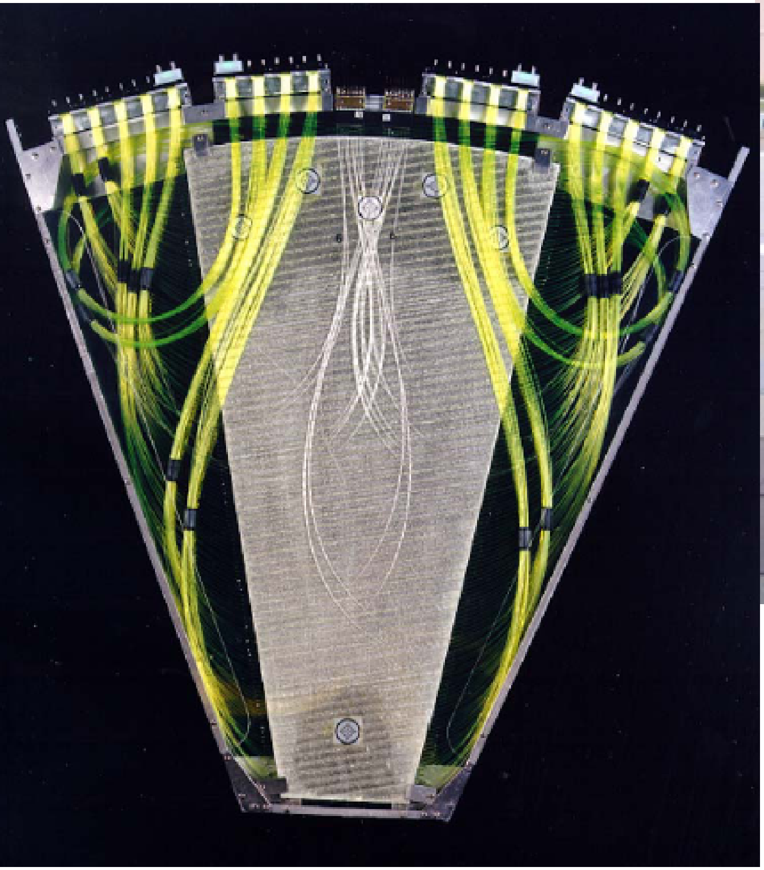

M(ee):
64.4 GeV/c²
Electron
p_T=46.2 GeV/c
η= -1.38
Electron
p_T=30.5 GeV/c
η= -1.37
Missing E_T:
134.5 GeV
Jet
p_T=118.0 GeV/c
η= 0.09
CMS
Compact Muon Solenoid
Run: 170876
Event: 306699209

# Conclusions

- After 16 years the Tevatron has studied extensively the top quark production and its properties
  - It behaves as the SM predicts
- This remains an active and exciting topic
  - Some deviations from the SM are seen
  - Will publish results with 2 times larger dataset next year
  - Pushing the precision of theoretical calculations
  - Will focus on studies that cannot be done at LHC
- The top quark discovery and its full study will remain as the main legacy from the Tevatron
- The LHC has re-established the SM at 7 TeV
  - It is a top factory: precision will be much higher soon
- No sign of new physics yet
  - Very important limits on models beyond the SM
- Will collect lots of data next year and then 14 TeV in 2014!

# Detectors as art

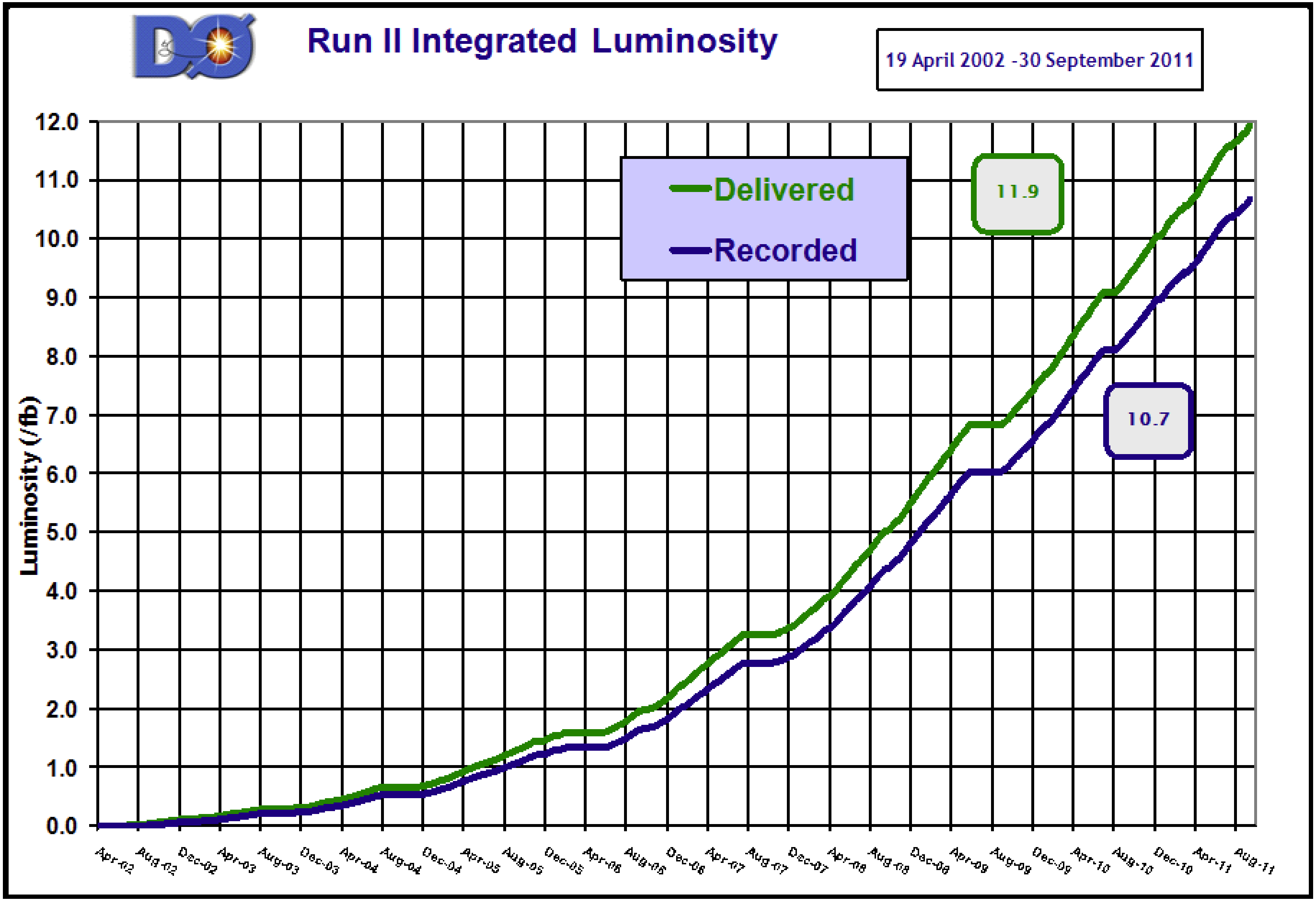

CDF Run I Silicon vertex detector at the Smithsonian museum, Washington



DØ forward preshower module at the Museum of Modern Art, New York

# Extra slides

For more information:



Run II Integrated Luminosity
19 April 2002 -30 September 2011
Delivered
Recorded
11.9
10.7
Luminosity (/fb)
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Apr-02
Aug-02
Dec-02
Apr-03
Aug-03
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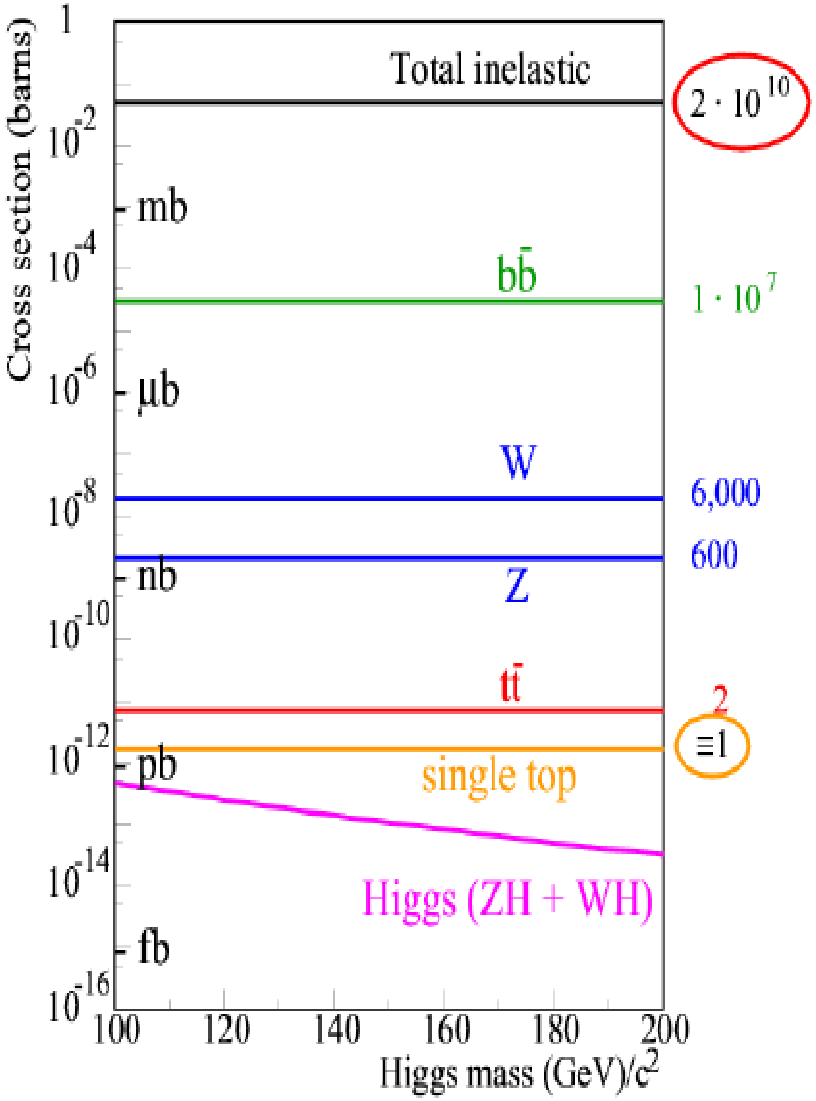
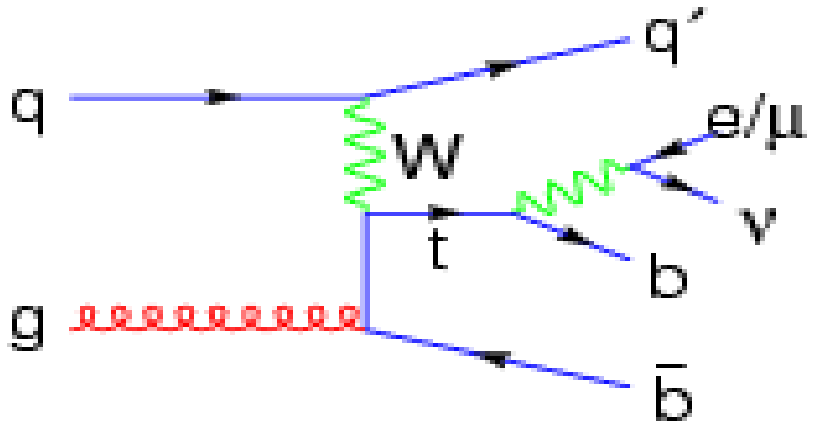
Aug-10
Dec-10
Apr-11
Aug-11

# Physics at a hadron collider is like… drinking from a fire hose

- Collision rate is huge
  - Every 396 ns → ~1.7 MHz (live crossings)
- Total cross section ~0.1b
  - 2-3 interactions per collision at L=$10^{32}$
- But W, Z, t, H are rare!
  - Around 20 single top events per day
- Need trigger system to select interesting events
  - Only store manageable size ~25MB/s

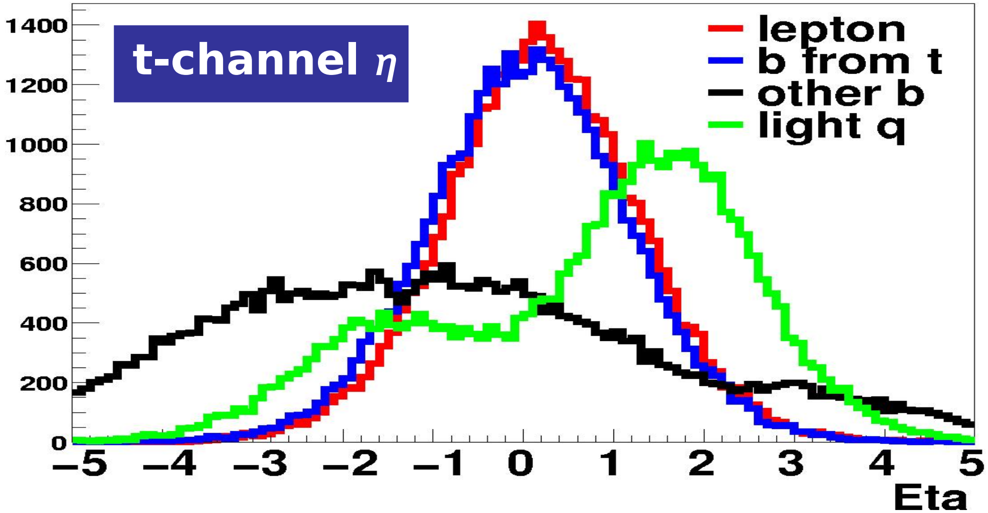


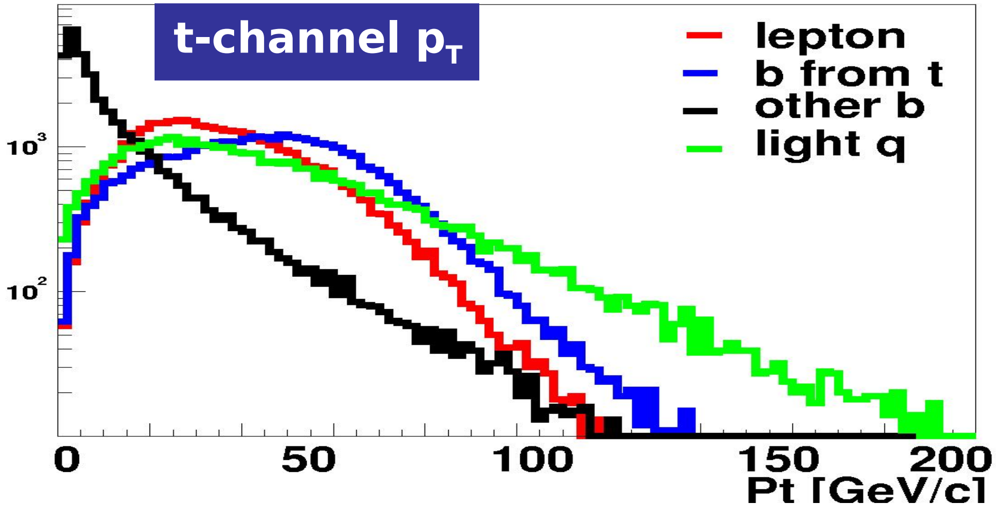
# Signal selection




Signature:

- One high $p_T$ isolated lepton (from W)
- MET ($\nu$ from W)
- One b-quark jet (from top)
- A light flavor jet and/or another b-jet




Event selection:

- Only one tight (no loose) lepton:
  - e: $p_T$ >15 GeV and $|\eta^{det}|<1.1$
  - $\mu$: $p_T$ >18 GeV and $|\eta^{det}|<2.0$
- MET > 15 GeV
- 2-4 jets: $p_T$ >15 GeV and $|\eta^{det}|<3.4$
  - Leading jet: $p_T$>25GeV ; $|\eta^{det}|<2.5$
  - Second leading jet: $p_T$ >20 GeV
- One or two b-tagged jets

# Preparing the way for the LHC

## Studies at the Tevatron will help the LHC:

- Wbb measurement (will also help WH search) (DØ: hep-ex/0410062)
  - Current limit at 4.6 pb for $p_T(b)>20$GeV
- In general, W+jets background determination techniques
  - tt will be main background, but large uncertainties come from W+jets
  - Effect of jet vetoes ($N_{jet}=2$), check other methods planned in LHC analyses
- Study charge asymmetries (Bowen, Ellis, Strassler: hep-ph/0412223)
  - Signal shows asymmetry in $(Q_\ell \times \eta_j\,,\ Q_\ell \times \eta_\ell)$ plane at TeV
- Study kinematics of forward jets in t-channel (WW→H at LHC)
- Even measure asymmetry in production rate (Yuan: hep-ph/9412214) (probe CP-violation in the top sector):

$$A_t = \frac{\sigma(p\bar{p} \to tX) - \sigma(p\bar{p} \to \bar{t}X)}{\sigma(p\bar{p} \to tX) + \sigma(p\bar{p} \to \bar{t}X)}$$

TeV4LHC workshop report: 0705.3251 [hep-ph]