Top Quark Physics I

Christian Schwanenberger

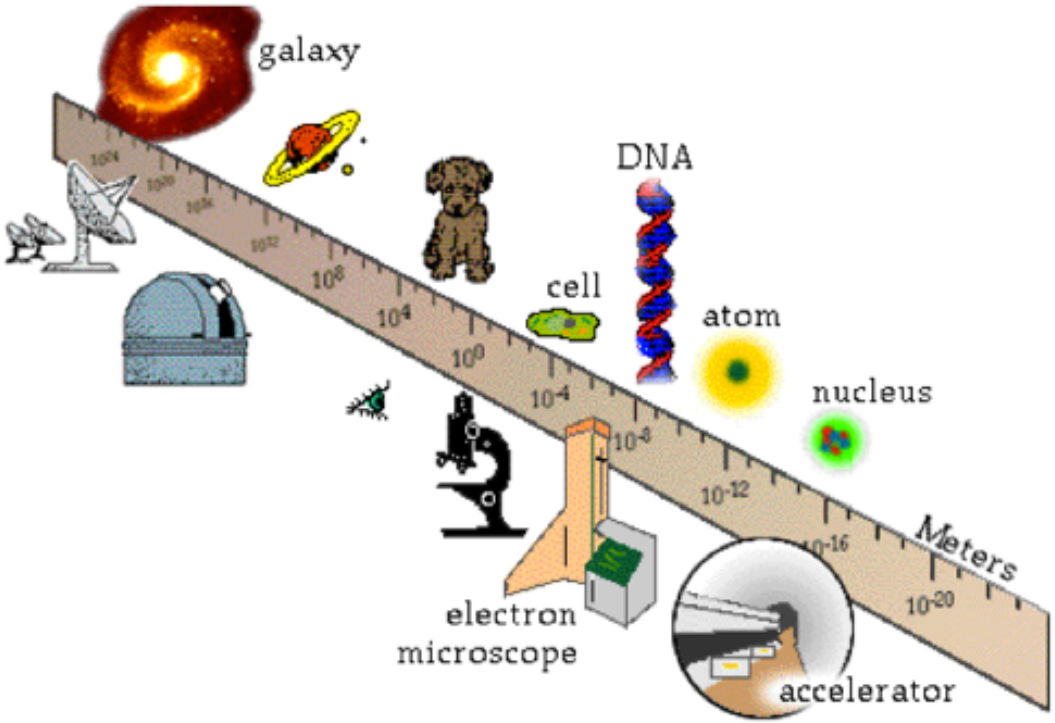
Deutsches Elektronensynchrotron (DESY)
Hamburg

DESY Summer Student Programme 2016

http://www-d0.fnal.gov/~schwanen/top_desy_summer16/Top_lecture1.pdf

Objective of Elementary Particle Physics

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

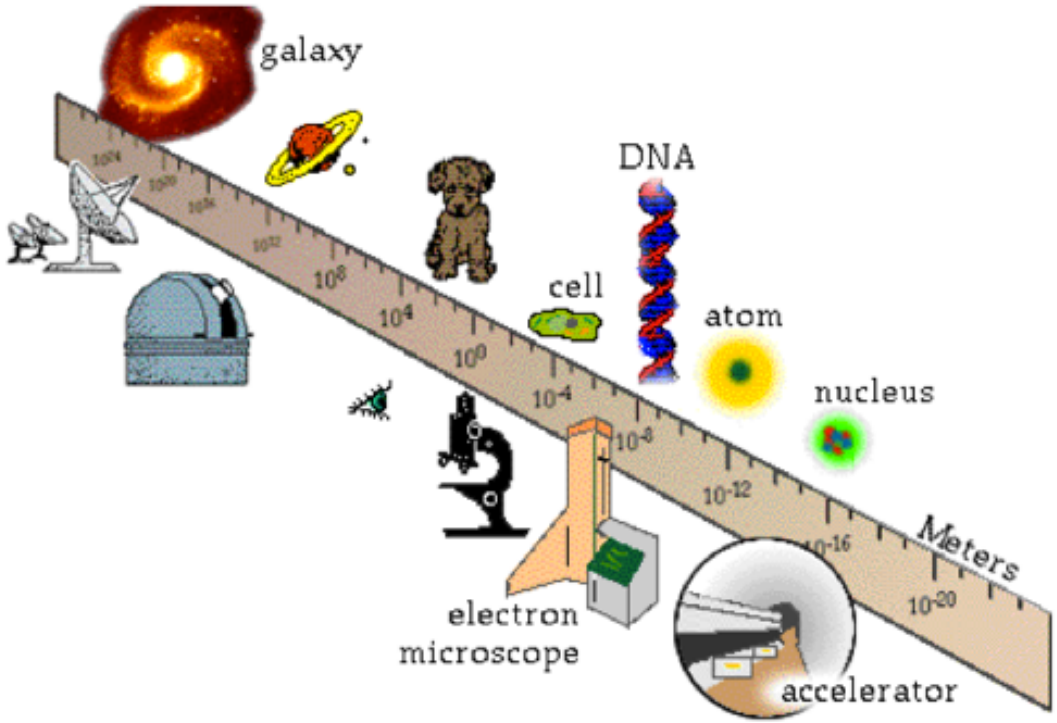


➔ **from the smallest dimensions in microcosm to the largest dimensions in the Universe**

Objective of Elementary Particle Physics

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

Goethe, Faust

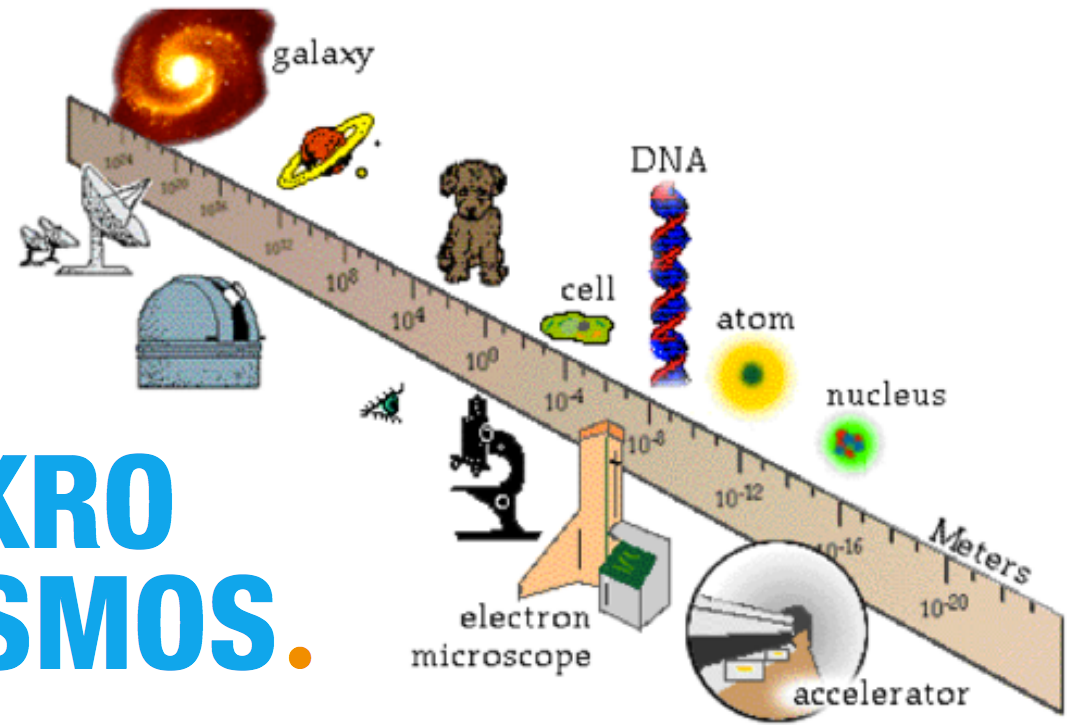


➔ **from the smallest dimensions in microcosm to the largest dimensions in the Universe**

Objective of Elementary Particle Physics

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

Goethe, Faust

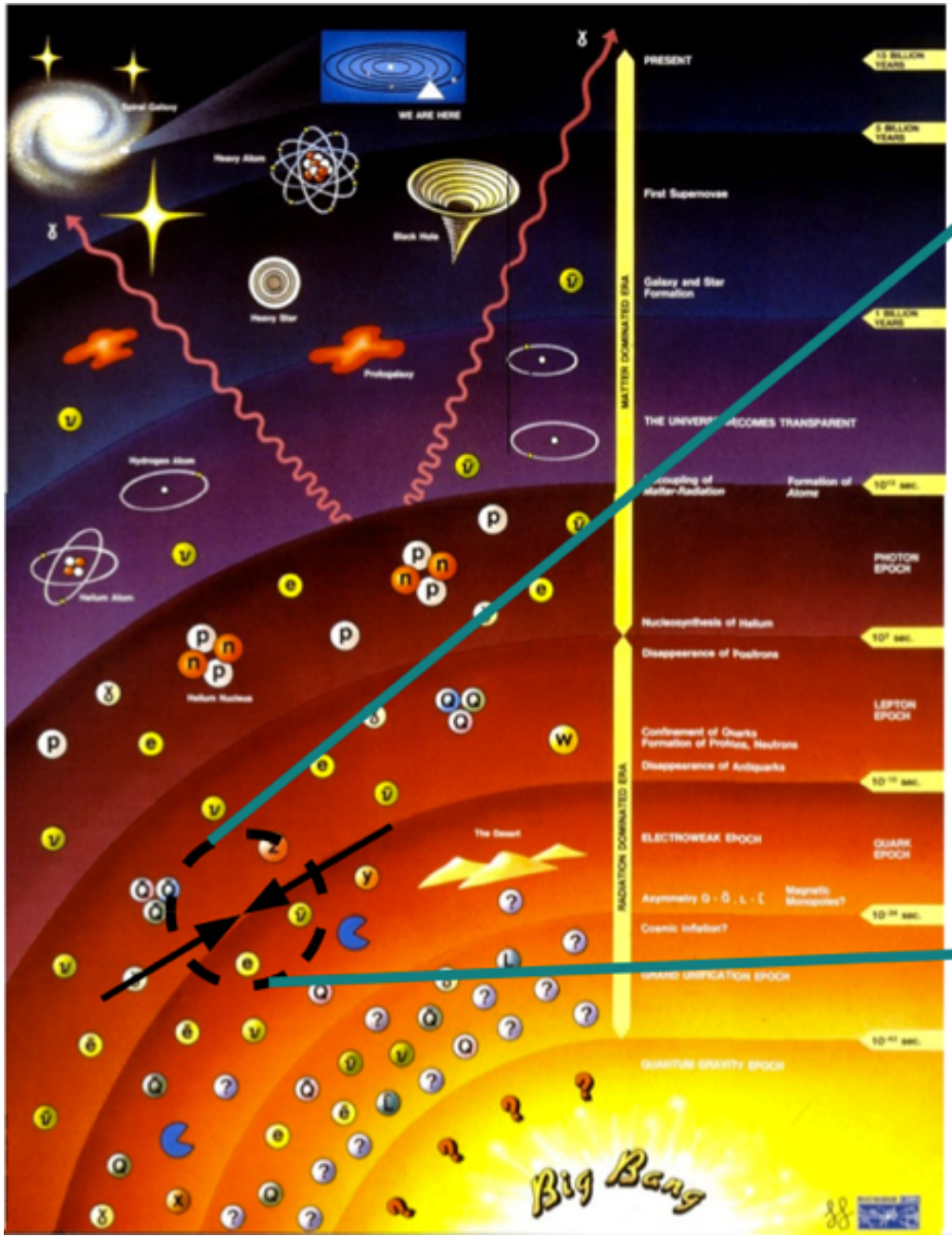


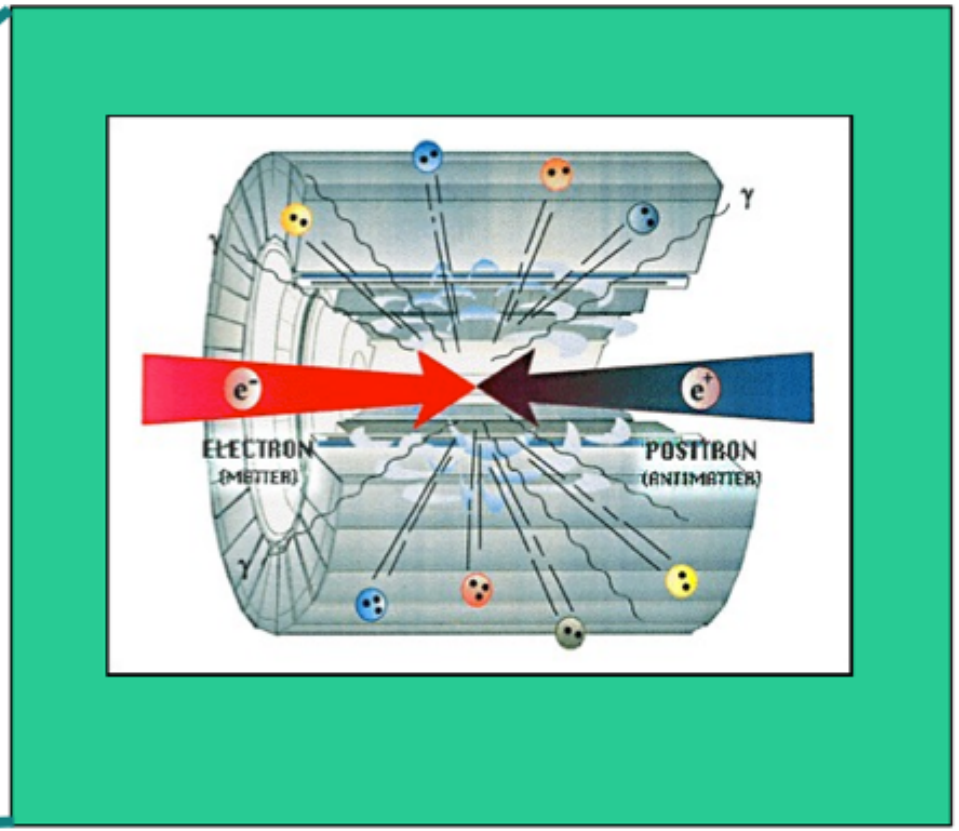
MIKRO KOSMOS.

DESY erforscht, was die Welt im Innersten zusammenhält

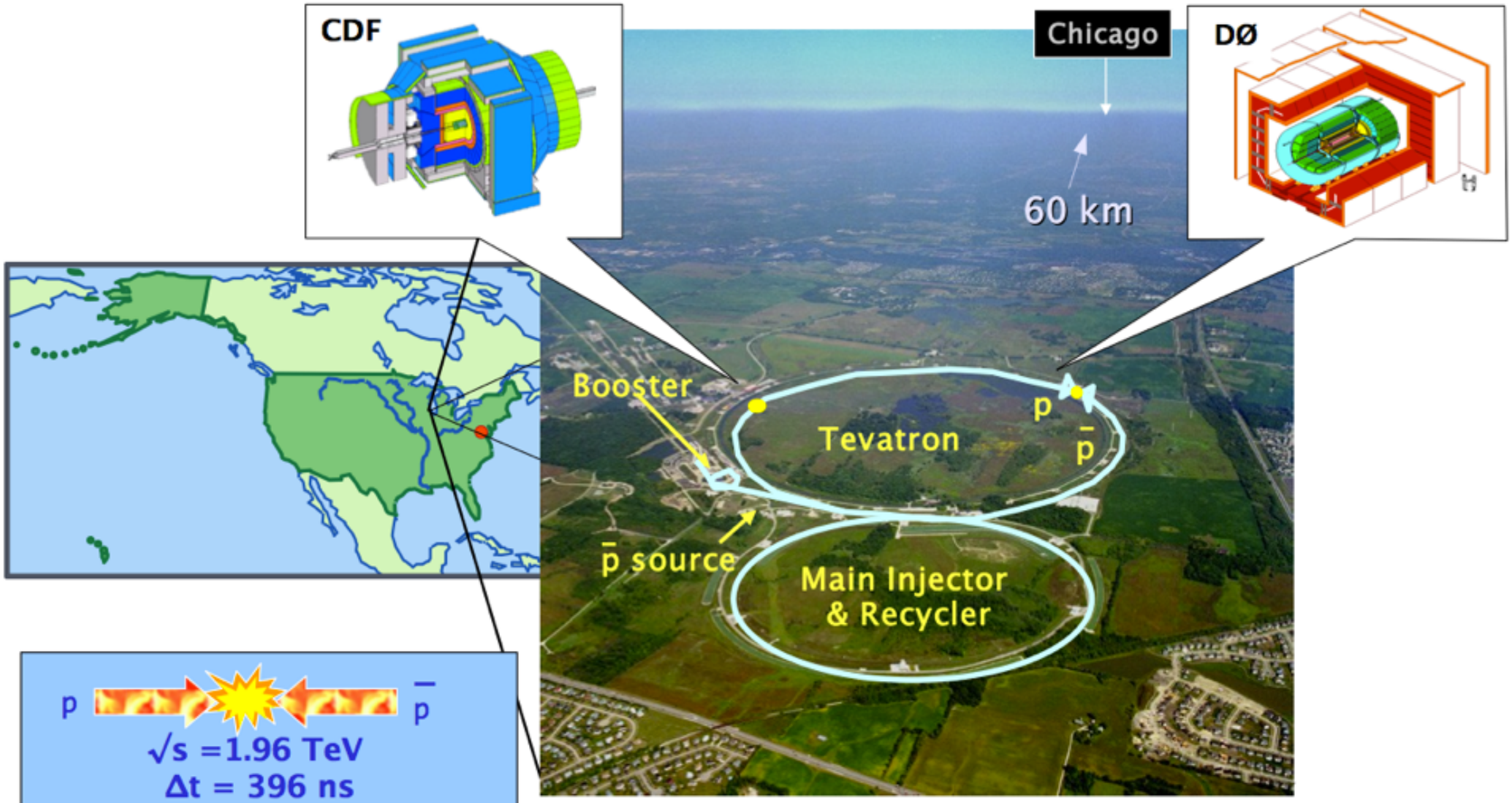
➔ **from the smallest dimensions in microcosm to the largest dimensions in the Universe**

Big Bang in the Lab?





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



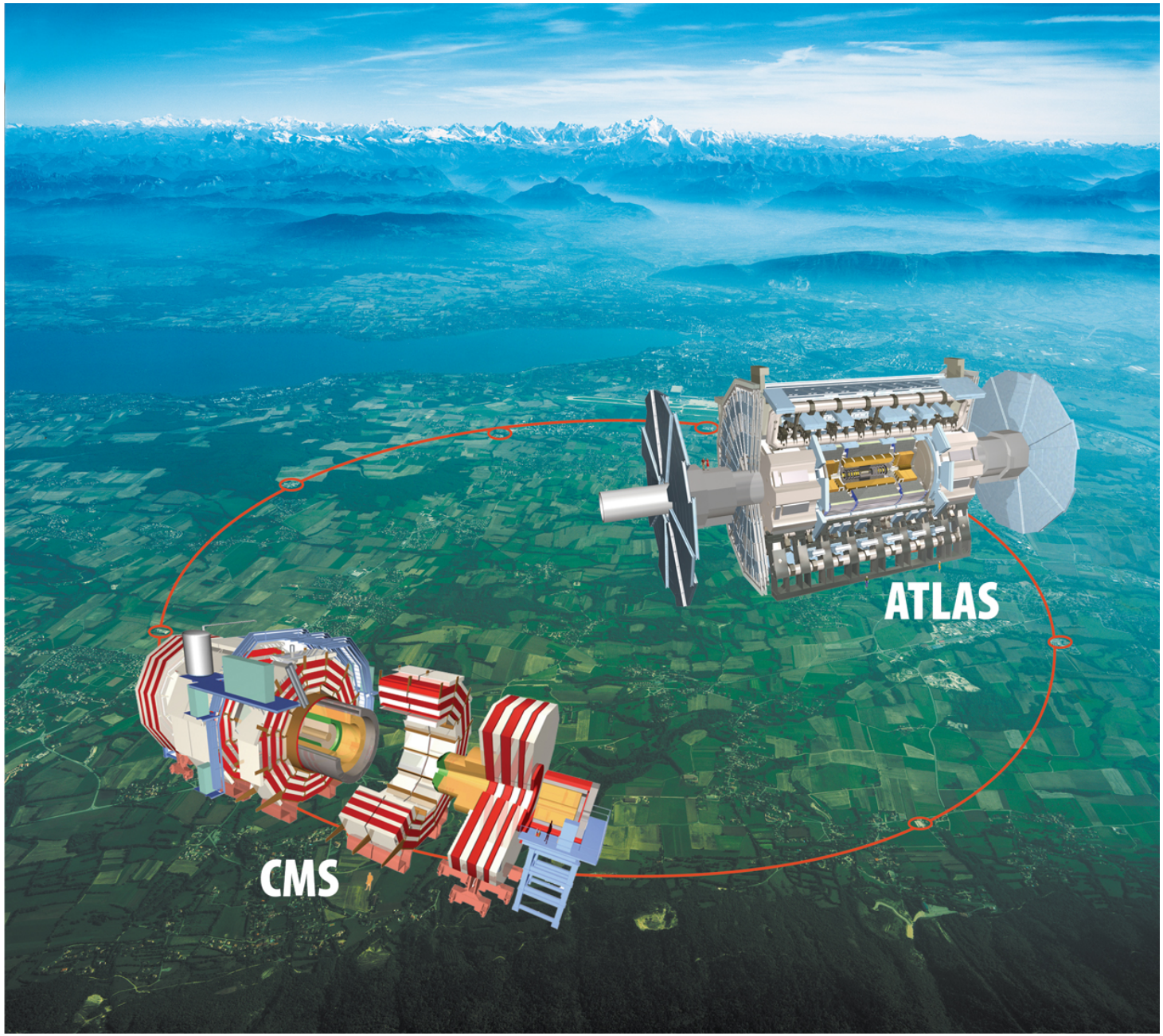
$\sqrt{s}$ =1.96 TeV
Δt = 396 ns

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

30 September 2011

Tevatron complex shut down after 26 years of successful operation.

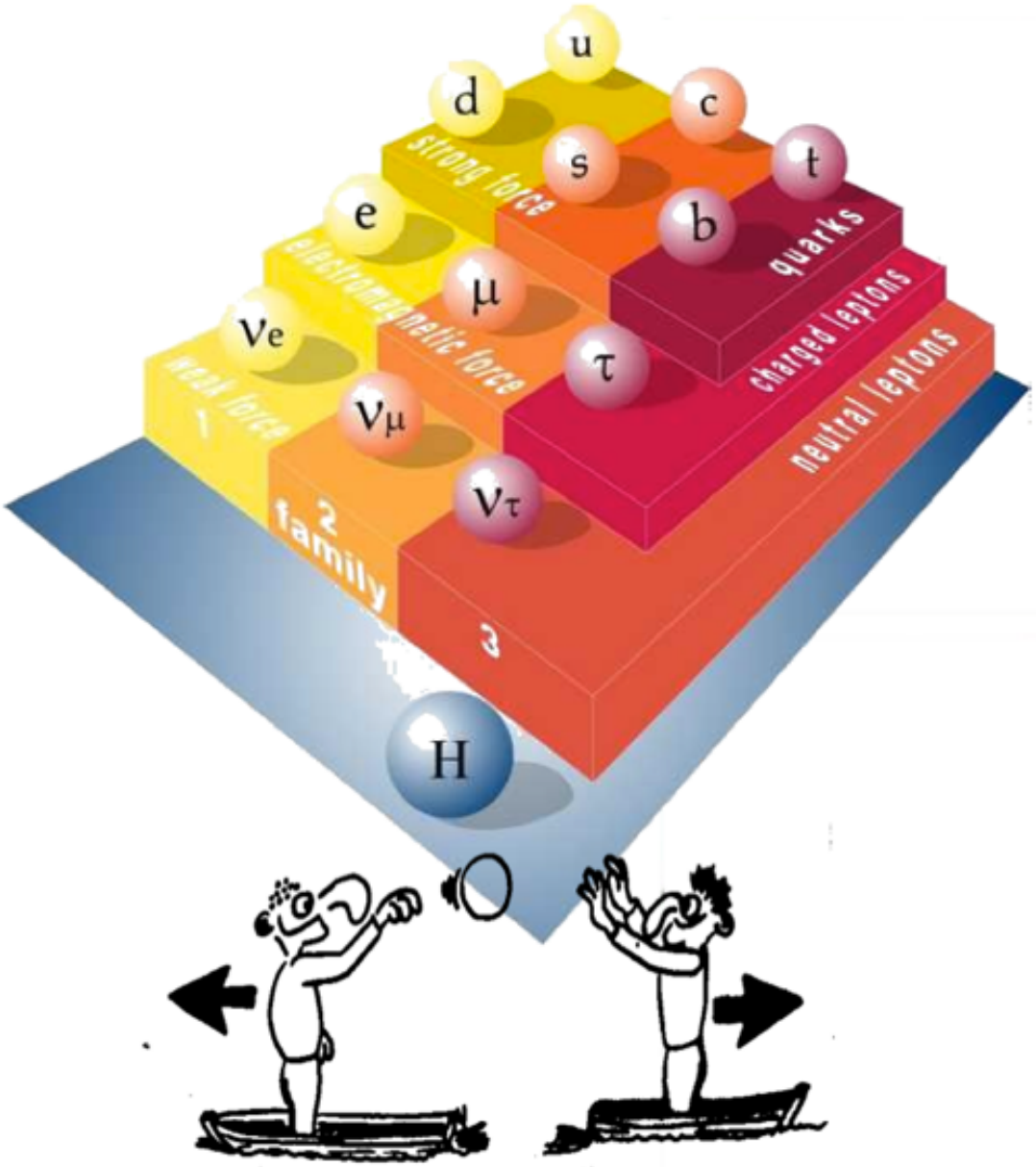
The LHC pp Collider at CERN

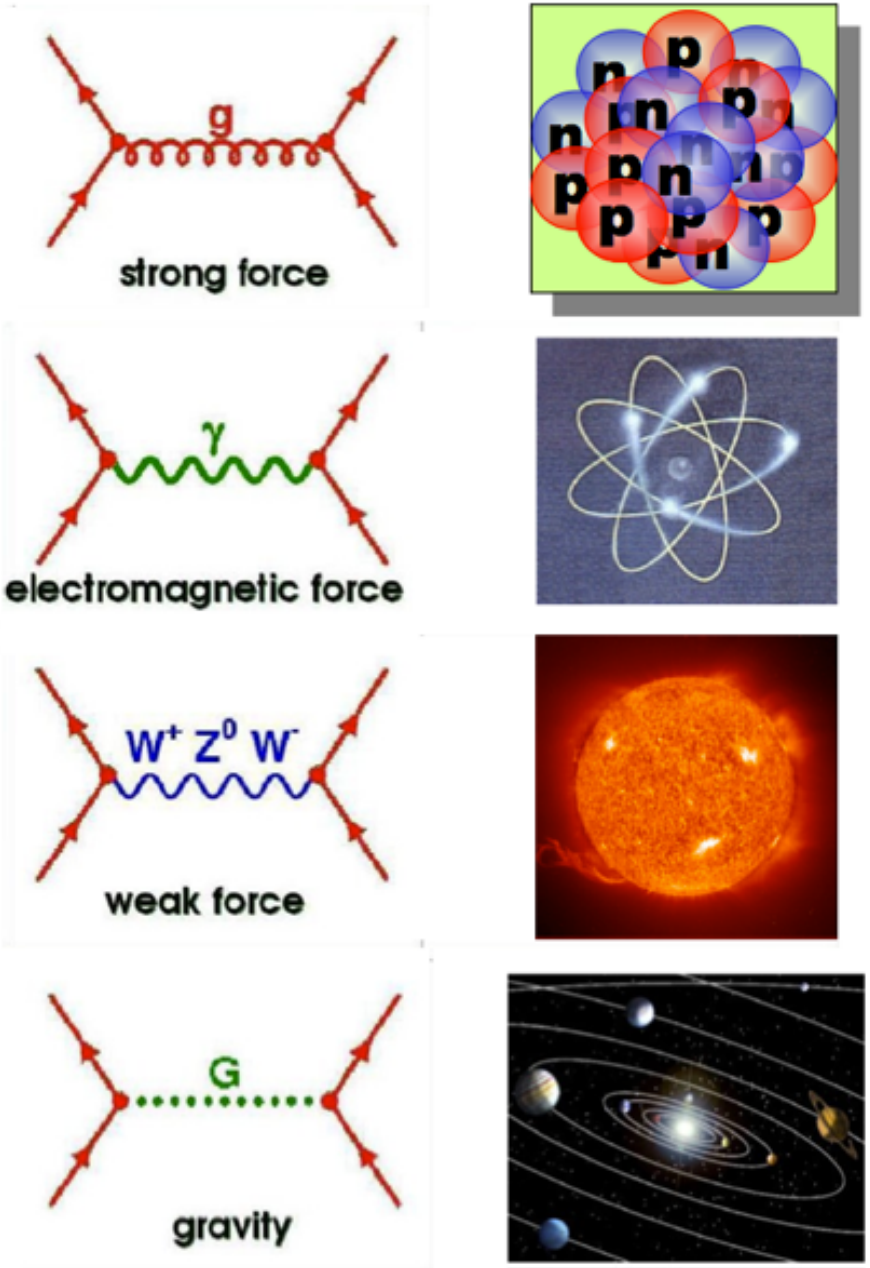


	Vs [TeV]	years	Ldt (rec.)
pp	7	2010-11	5.1 fb-1
pp	8	2012	21.3 fb-1
Pb+Pb	2.76	2010-11	160 µb-1
Pb+p	5	2013	30 nb-1

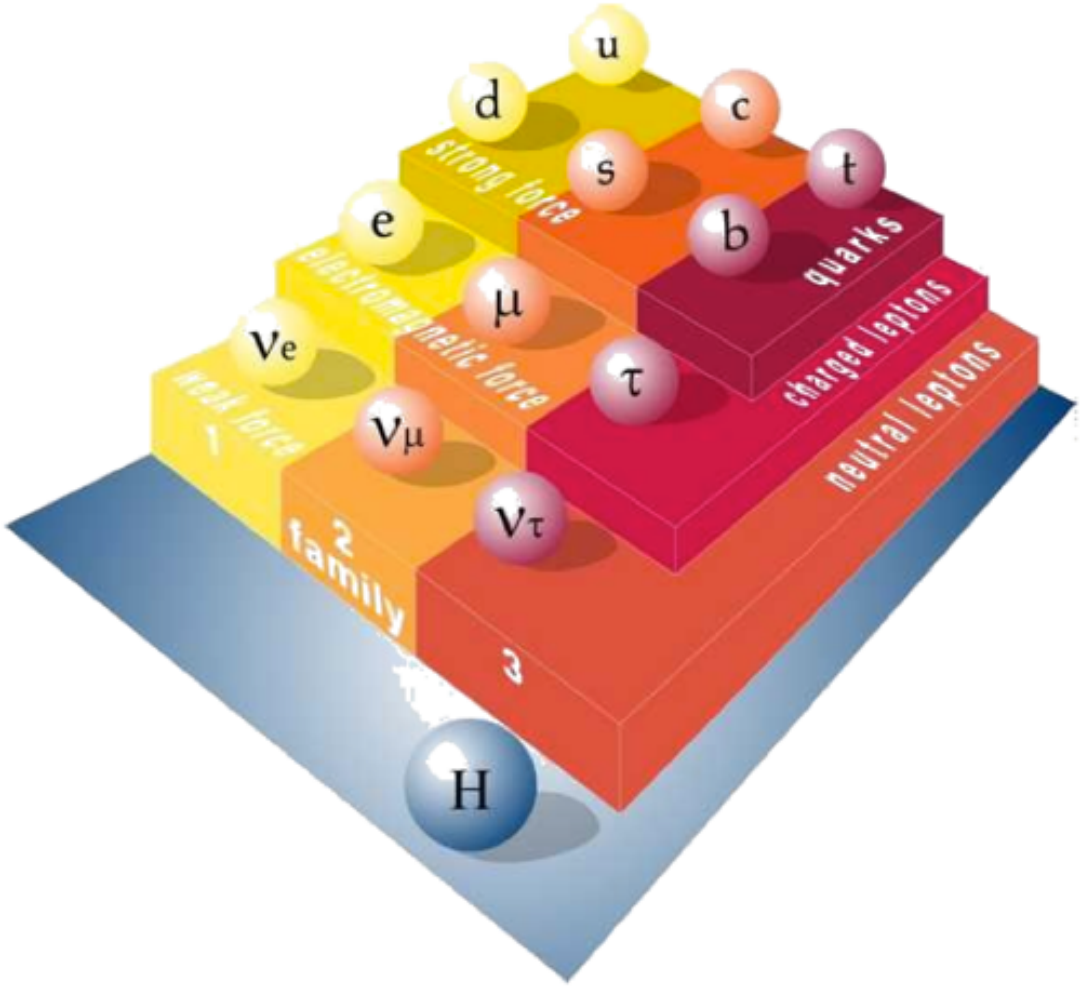
June 3rd, 2015: First Collisions @ 13 TeV

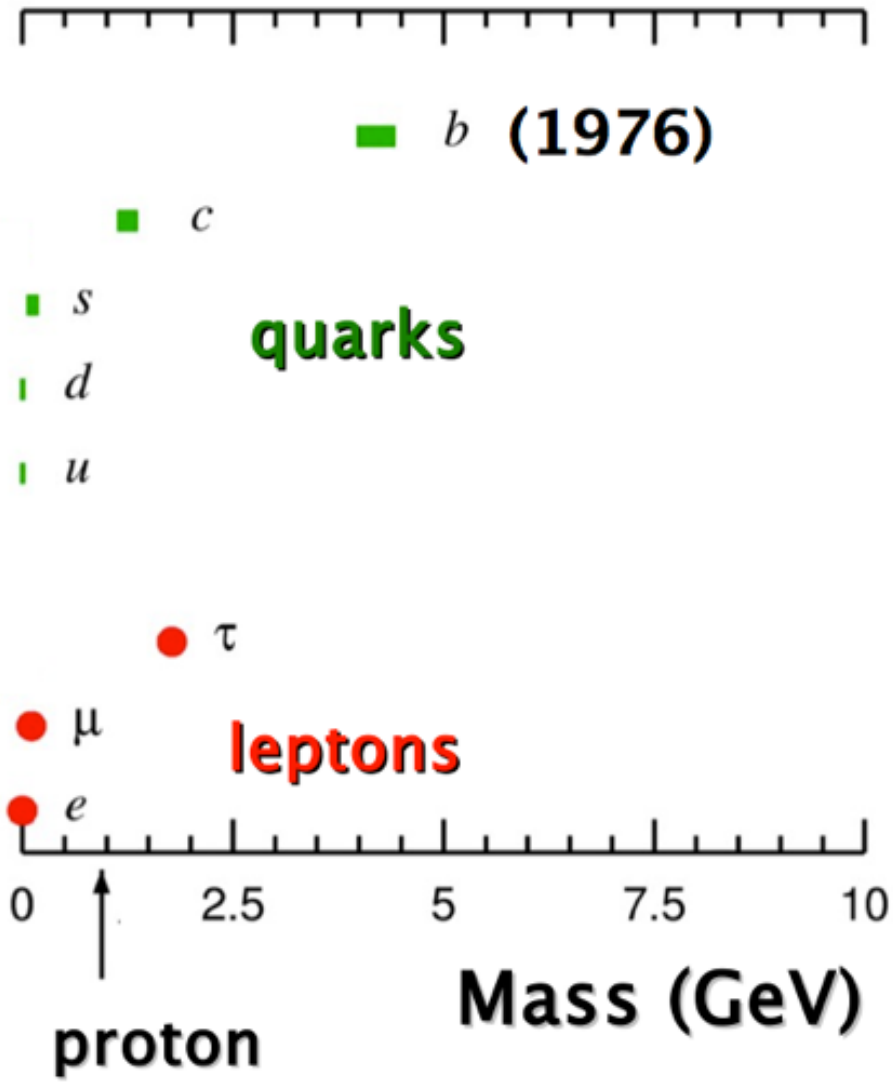
The Standard Model of Particle Physics





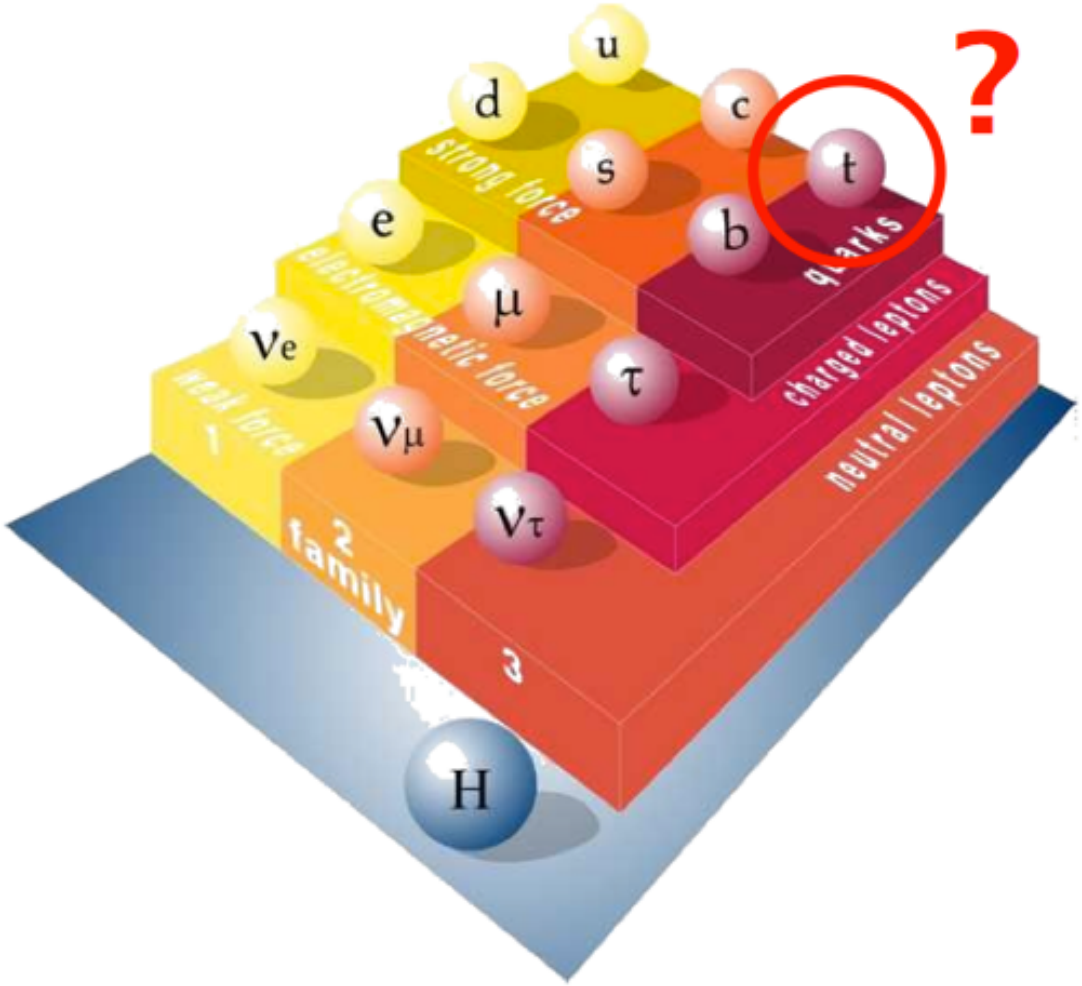
Particle Masses

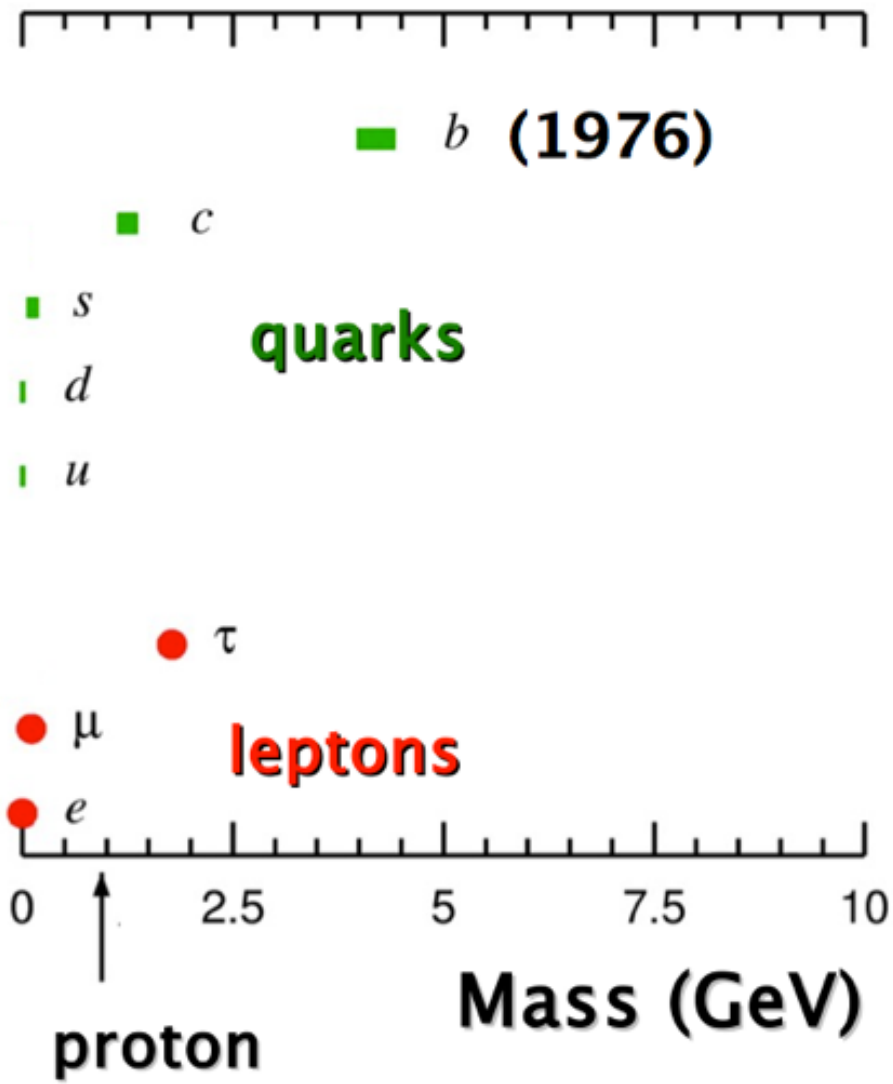




neutrino masses ≪ 1 eV

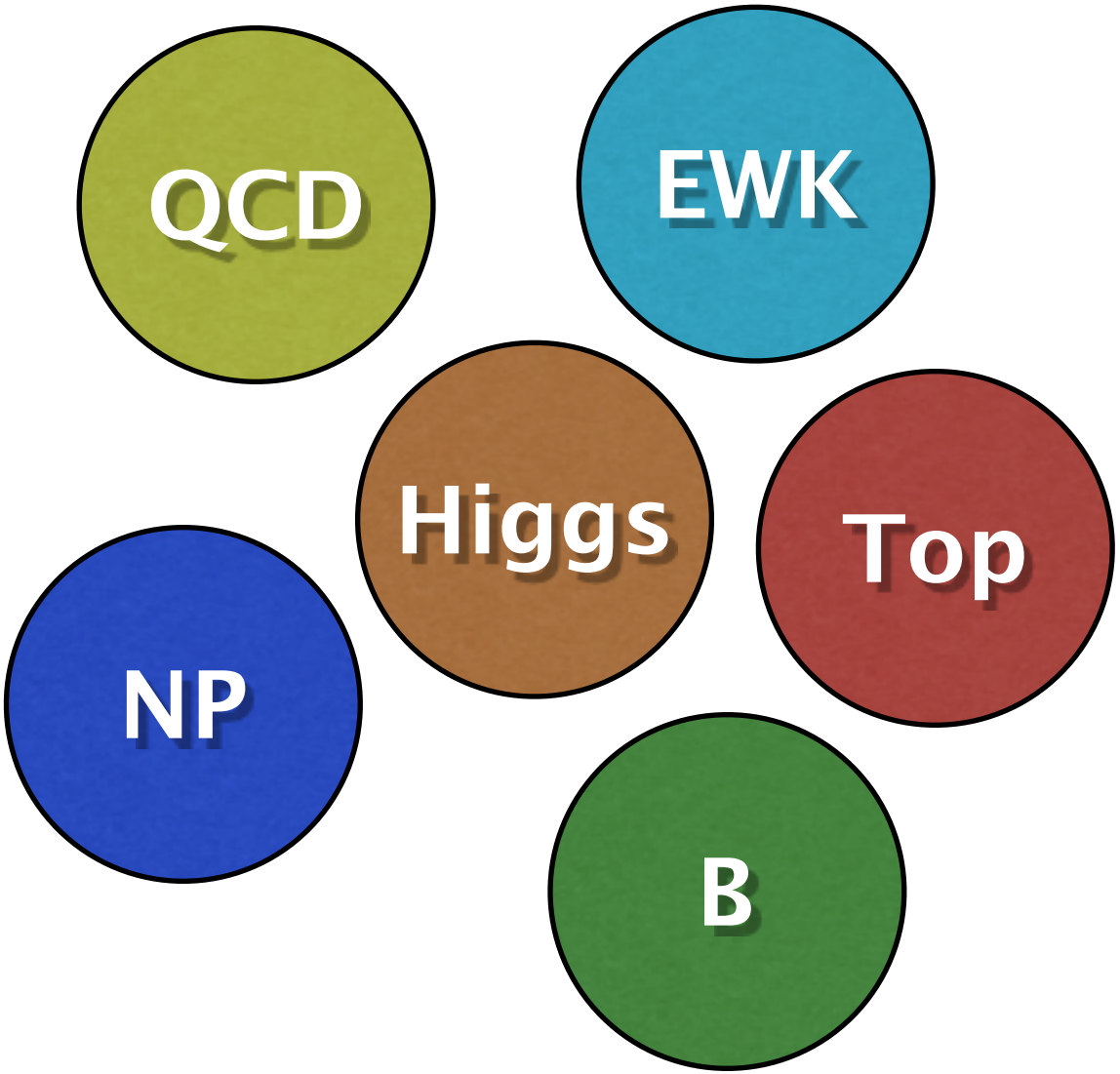
The Top Quark



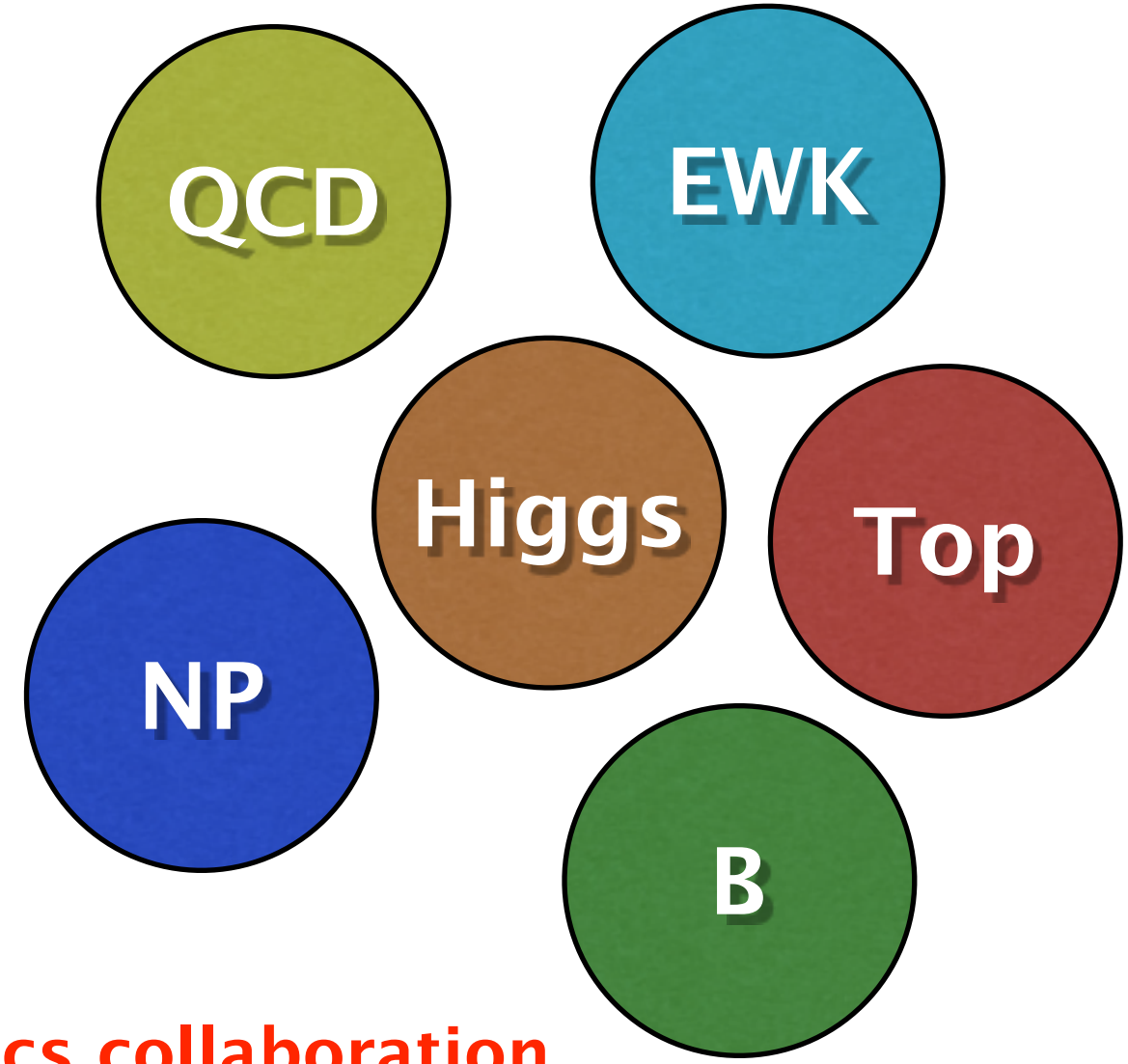


neutrino masses ≪ 1 eV

Physics Groups: DØ Collaboration

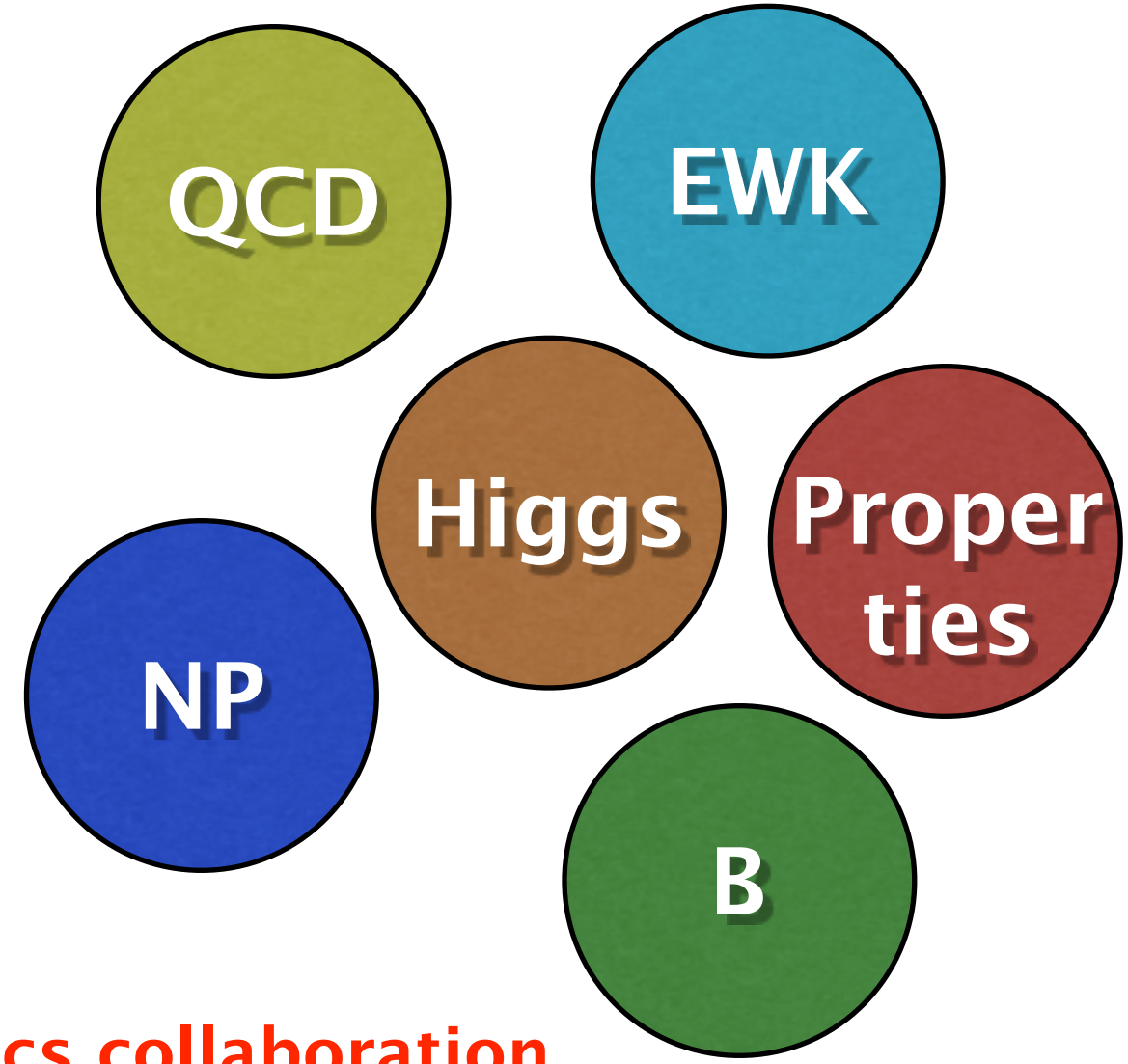


Top Quark Physics Topics



→ top physics collaboration

Top Quark Physics Topics

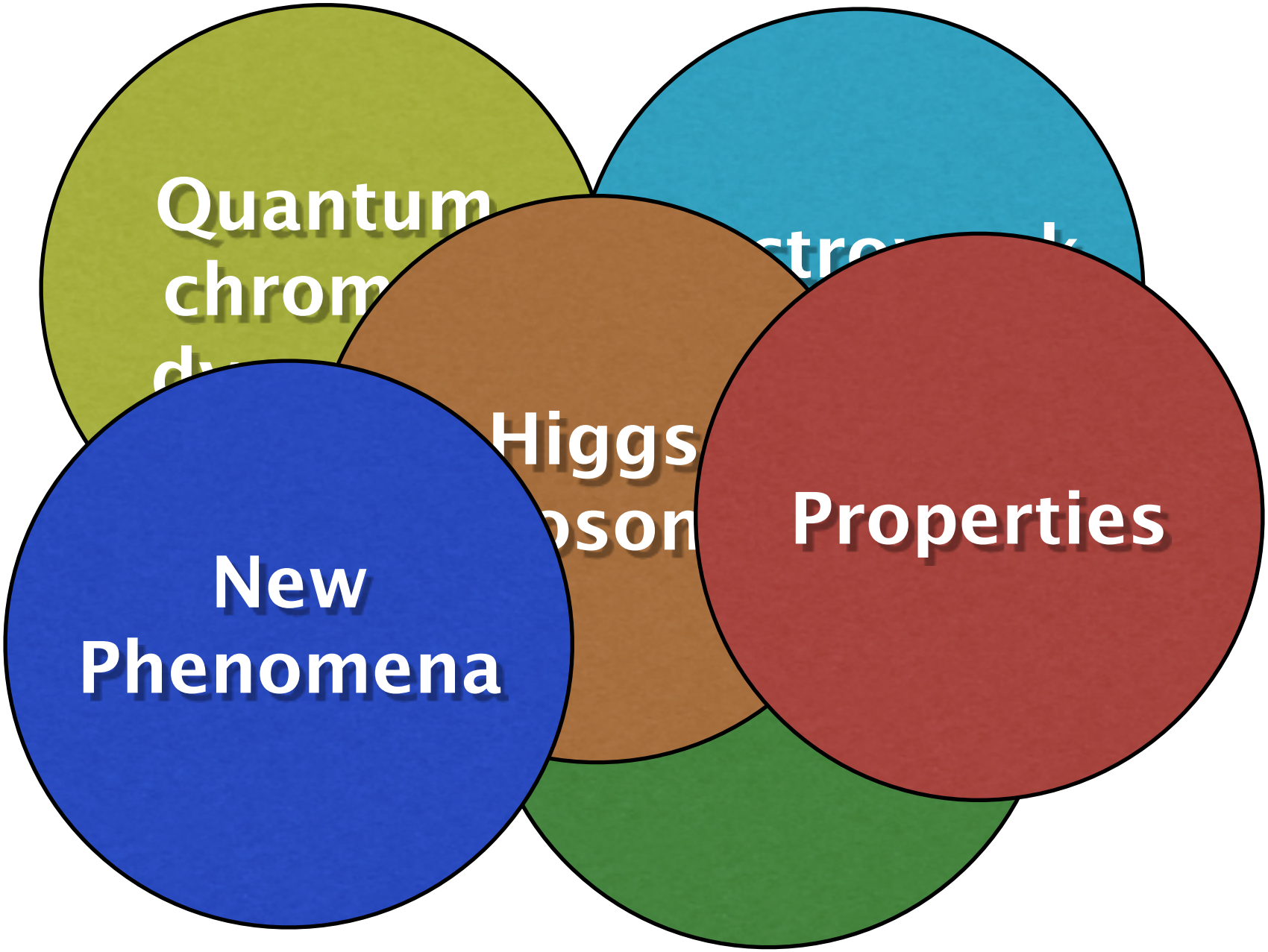


→ top physics collaboration

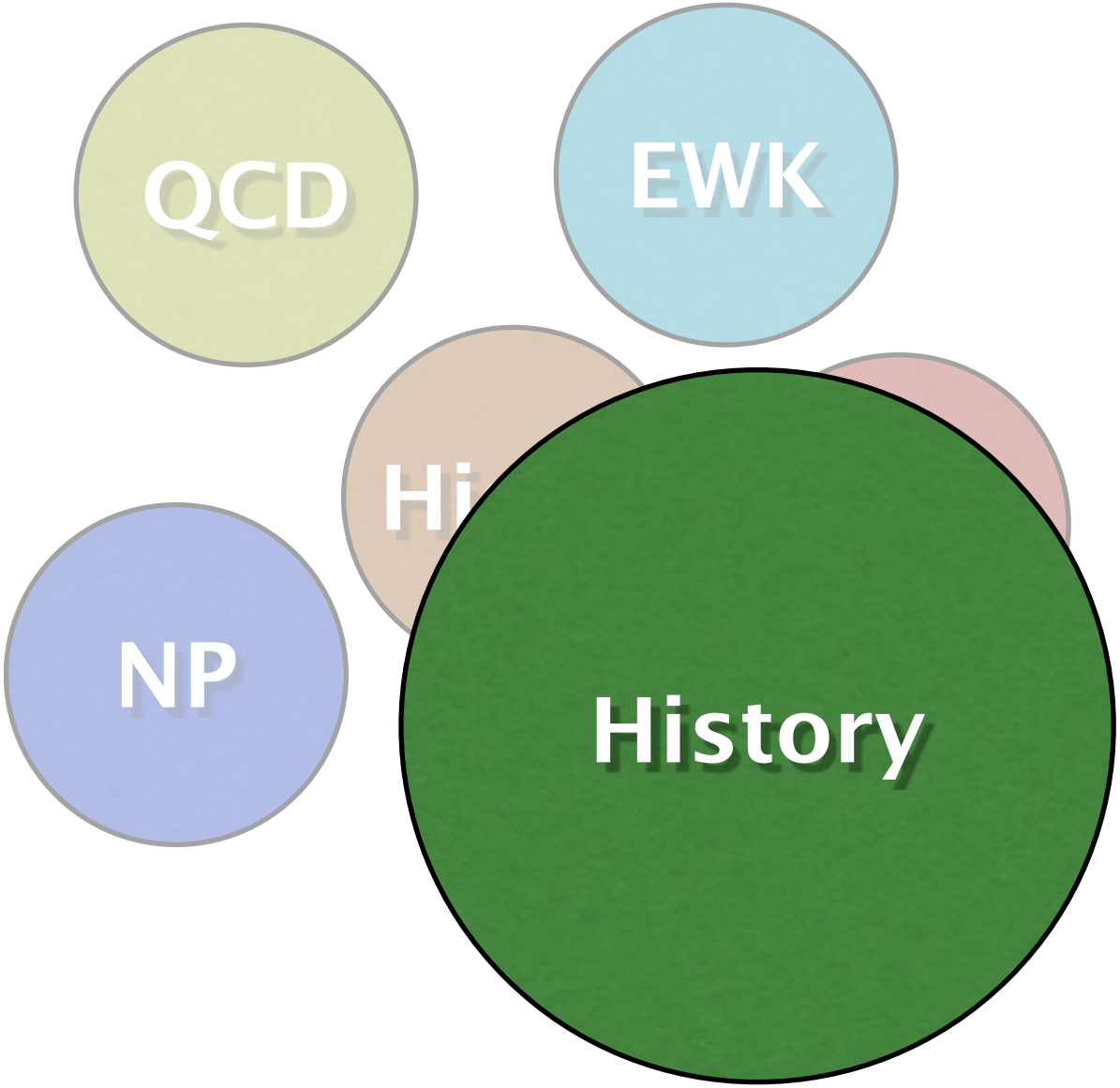
Top Quark Physics Topics

→ top physics collaboration

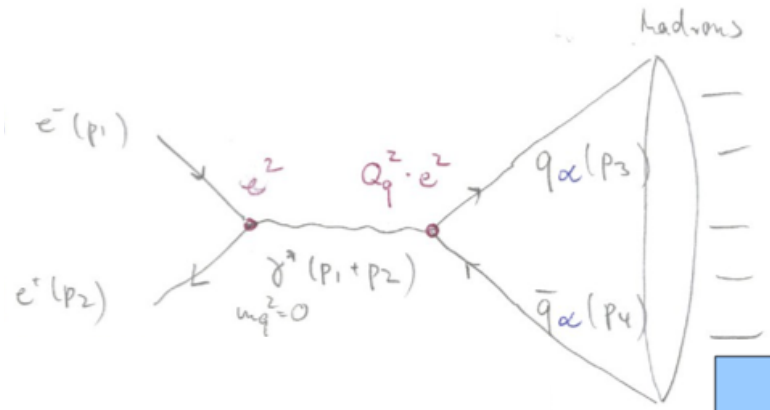
Top Quark Physics Topics

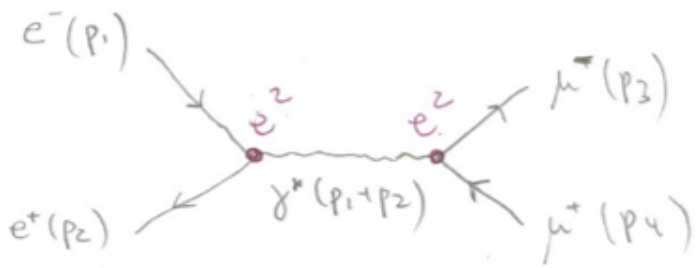


Top Quark Physics Topics

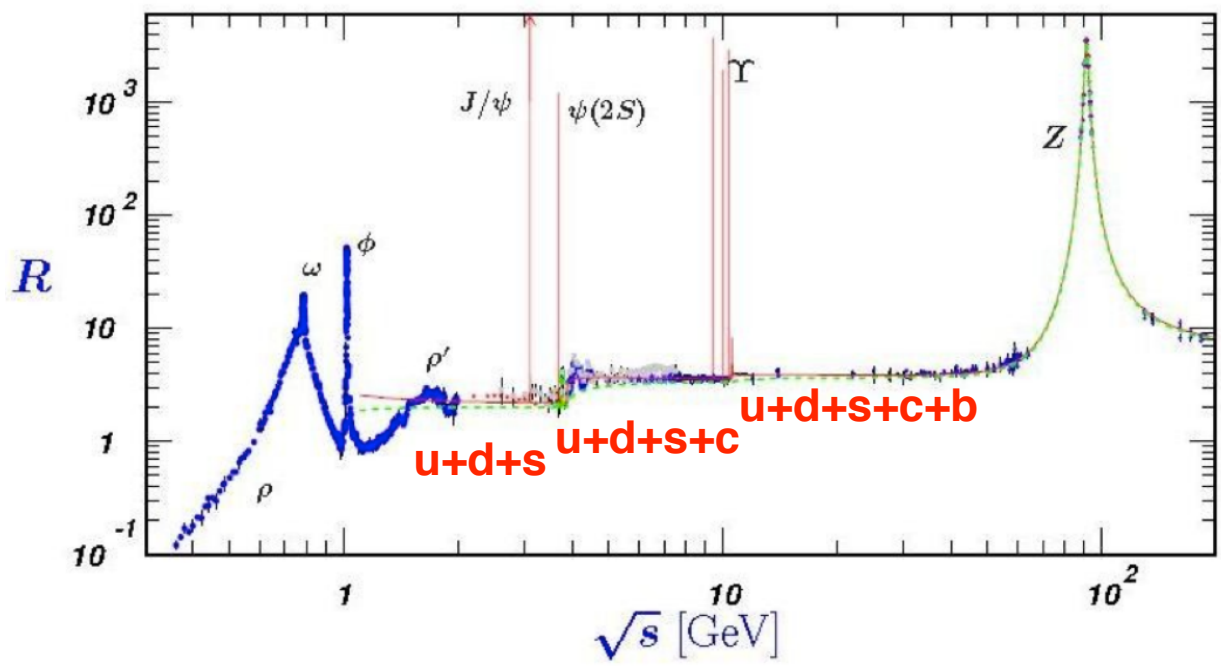


History of the Top Quark Search





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

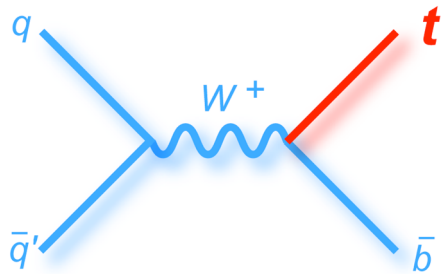


→ structure of quark families suggested existence of a 6th quark:

where is the top?

History of the Top Quark Search

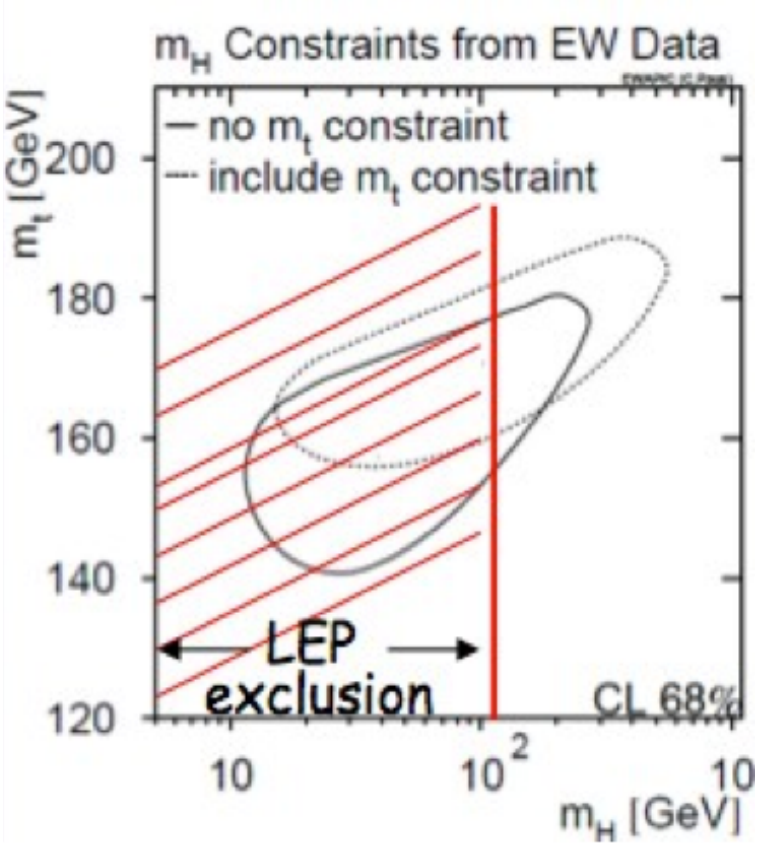
- From here on the race to find the top began
  - Petra (e^+e^-) at DESY, Hamburg: m_t>23.3 GeV in 1984
  - Tristan (e^+e^-) in Japan: m_t>30.2 GeV in late 80s
  - UA1&UA2@SPS ($p\bar{p}$) at CERN: discovery of W and Z in 1983
  - UA1: m_t>44 GeV in 1988
    (after having an excess in 1984 which they thought was evidence for top)
  - LEP (e^+e^-) at CERN : m_t>45.8 GeV in 1990
  - UA2: m_t>69 GeV
    ⇒ W → tb search channel closed down



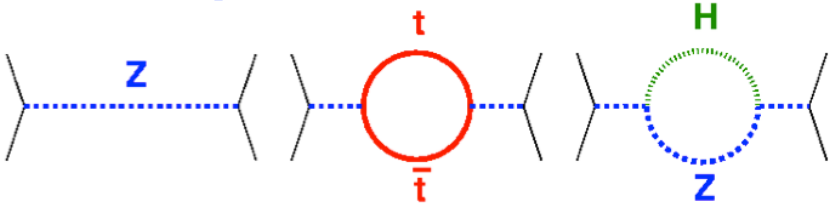
$M_W > m_t + m_b$

History of the Top Quark Search

- From here on the race to find the top began
  - Petra (e^+e^-) at DESY, Hamburg: m_t>23.3 GeV in 1984
  - Tristan (e^+e^-) in Japan: m_t>30.2 GeV in late 80s
  - UA1&UA2@SPS ($p\bar{p}$) at CERN: discovery of W and Z in 1983
  - UA1: m_t>44 GeV in 1988
    (after having an excess in 1984 which they thought was evidence for top)
  - LEP (e^+e^-) at CERN : m_t>45.8 GeV in 1990
  - UA2: m_t>69 GeV



Electroweak precision data

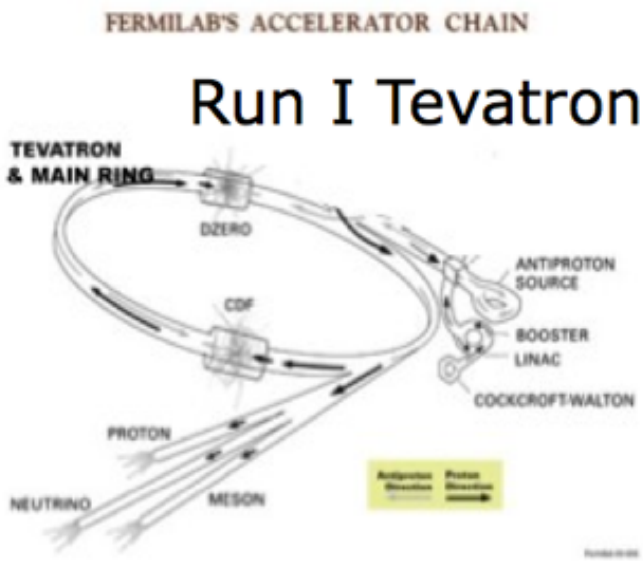


$$M_Z^2 = M_Z^{2\,0.order} / (1 - \Delta)$$

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

History of the Top Quark Search

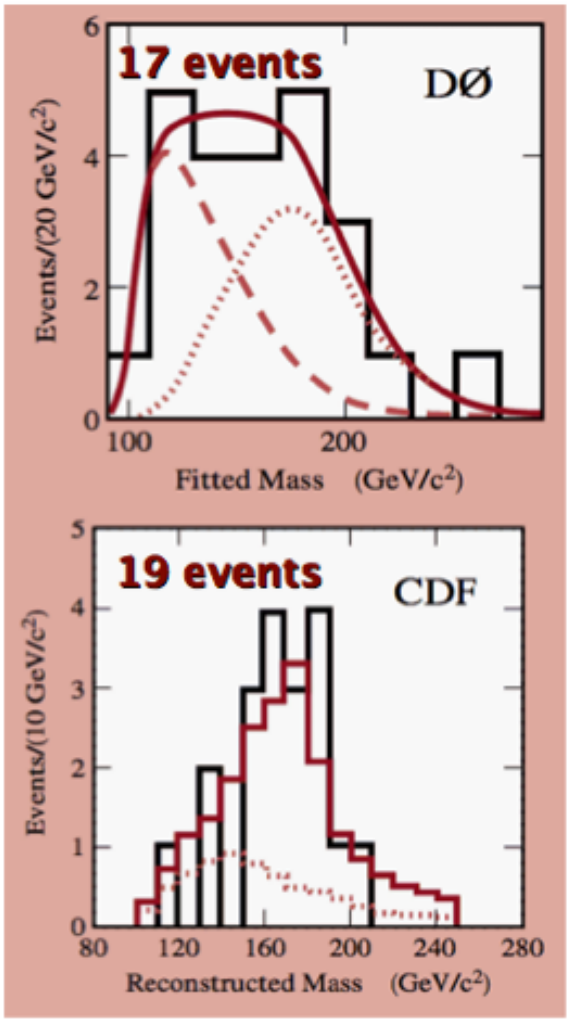
- 1984/85: Tevatron collider commissioned and dedicated
- October 1985: First collisions recorded by CDF
  - DØ: still in construction
- 1987: CDF Run-0
- 1992: First collisions by DØ
- Run I (1.8 TeV): 1992-1996
  - 1995: Discovery of the top quark!
  - In total ~120pb^{-1} per experiment
  - DØ: more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



The Top Quark

discovery

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

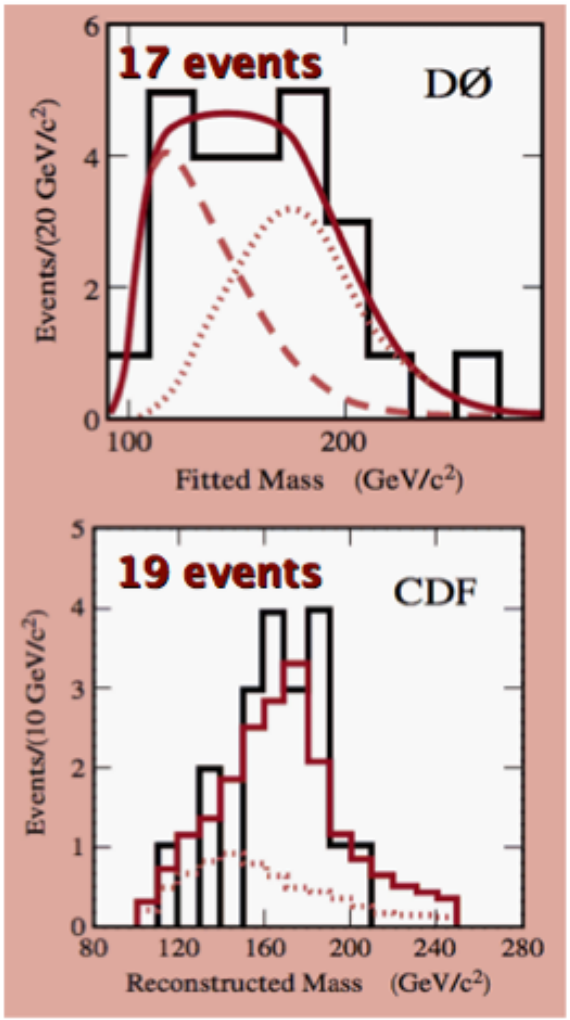


1995, CDF and DØ experiments, Fermilab

The Top Quark

discovery

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



1995, CDF and DØ experiments, Fermilab

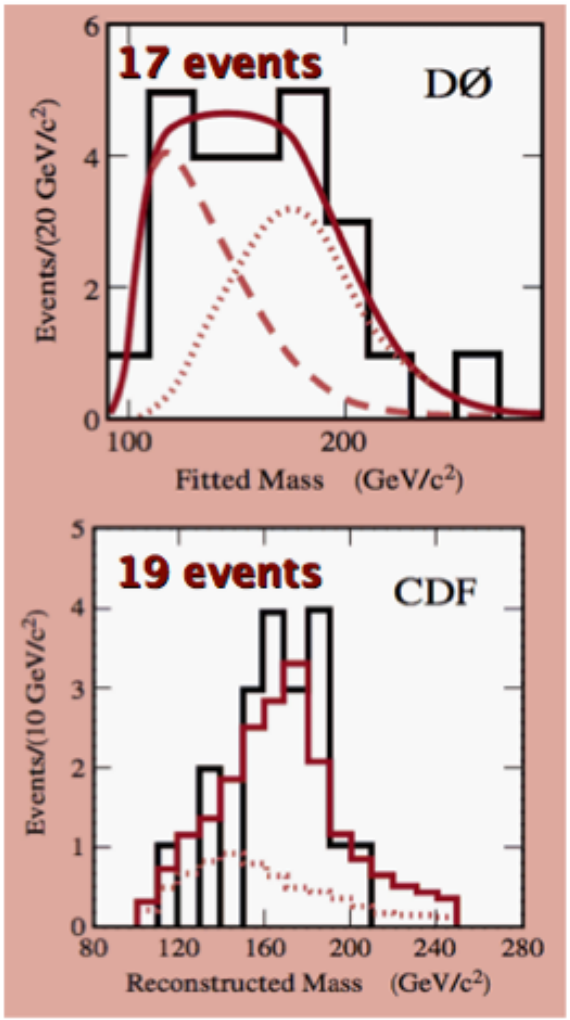
March 2nd, 1995:

First announcement of Top Discovery in public seminar at Fermilab

The Top Quark

discovery

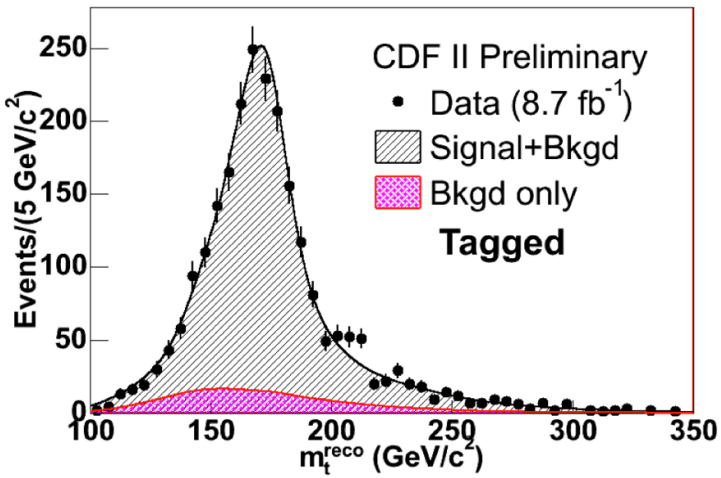
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

today

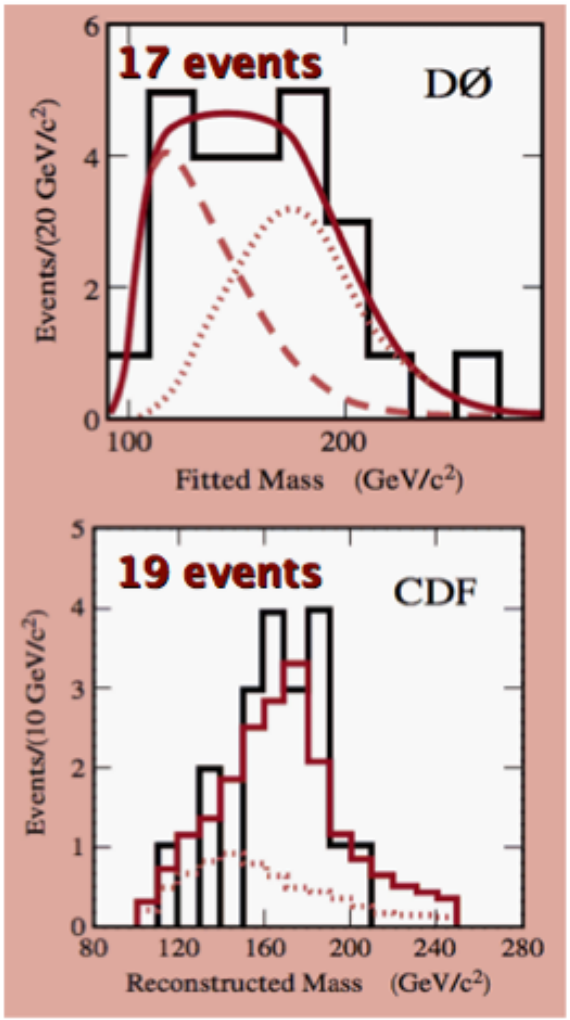
1000s of events



The Top Quark

discovery

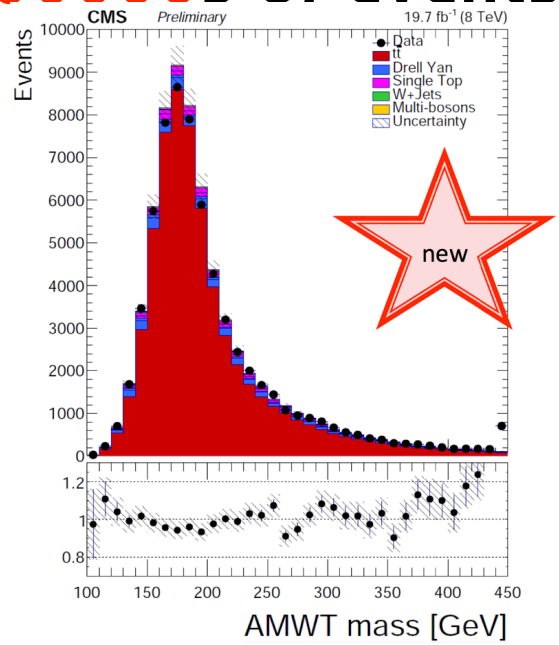
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

today

100000s of events

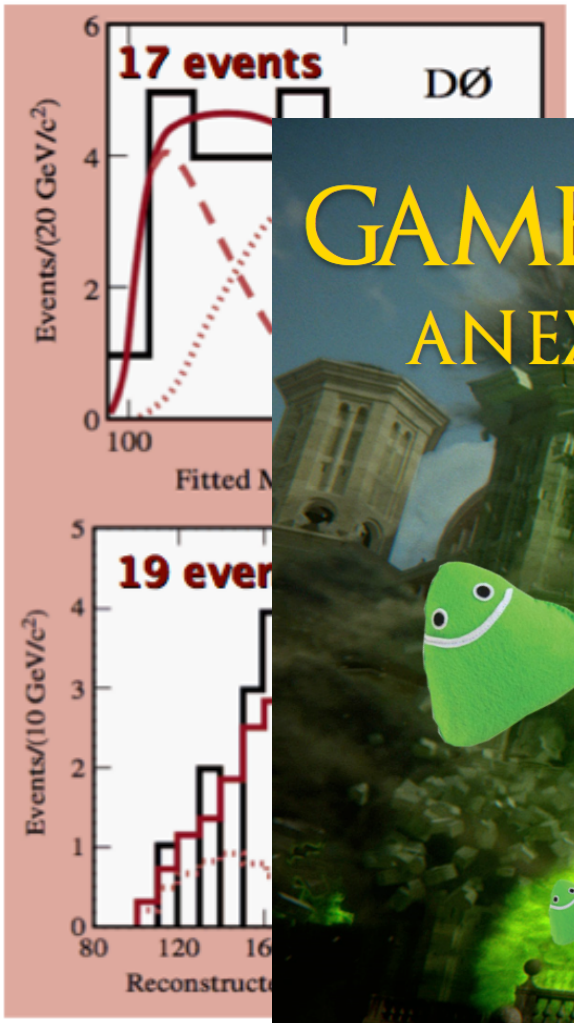


LHC: top quark factory

The Top Quark

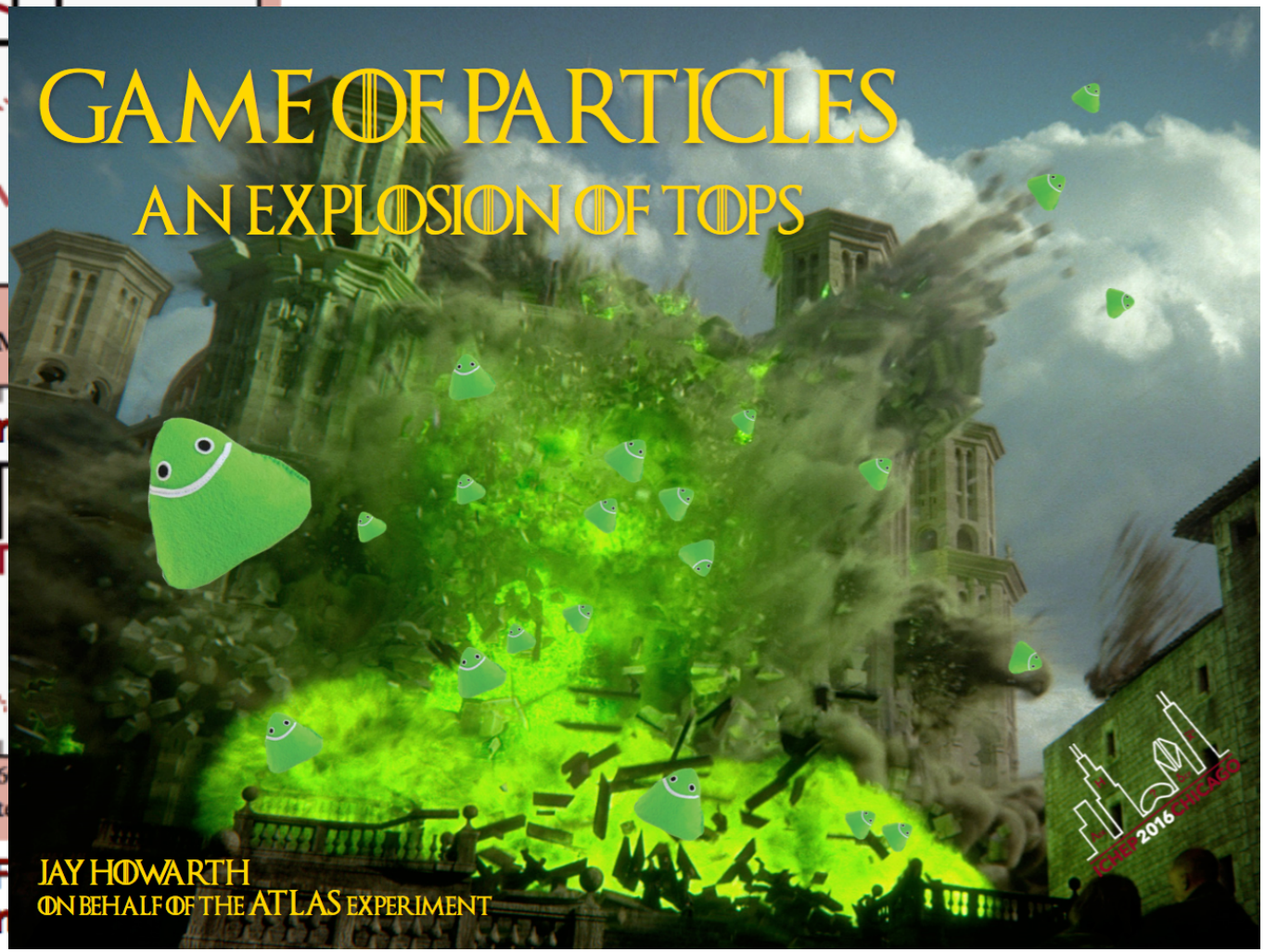
discovery

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



1995, CDF experimen

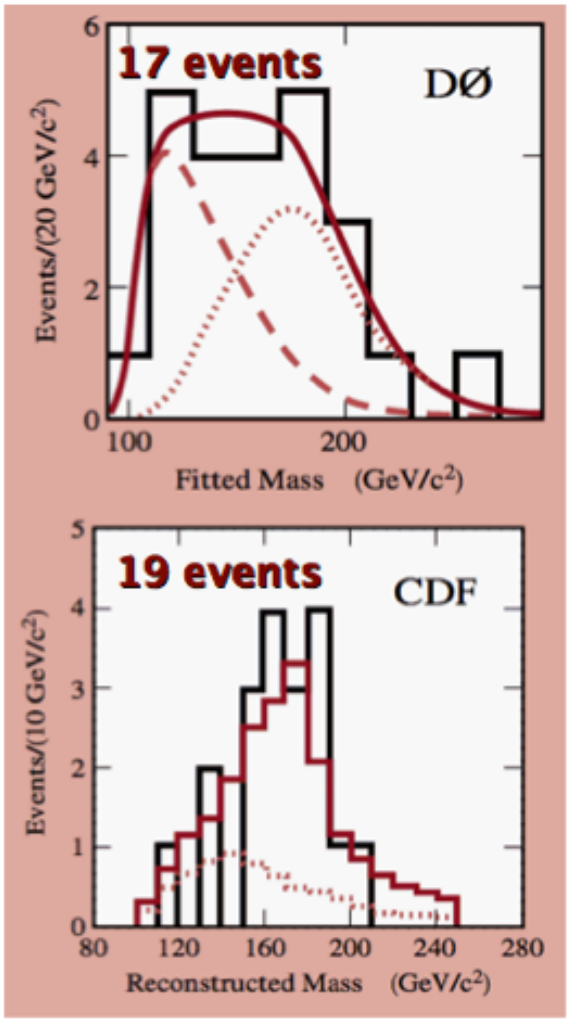
today



The Top Quark

discovery

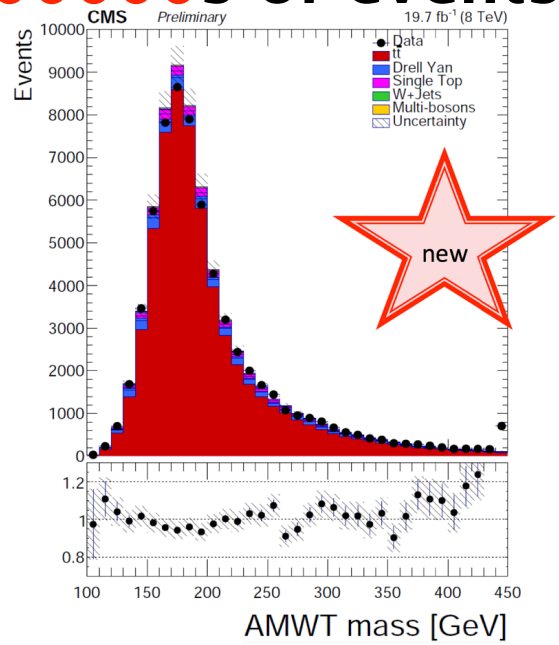
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

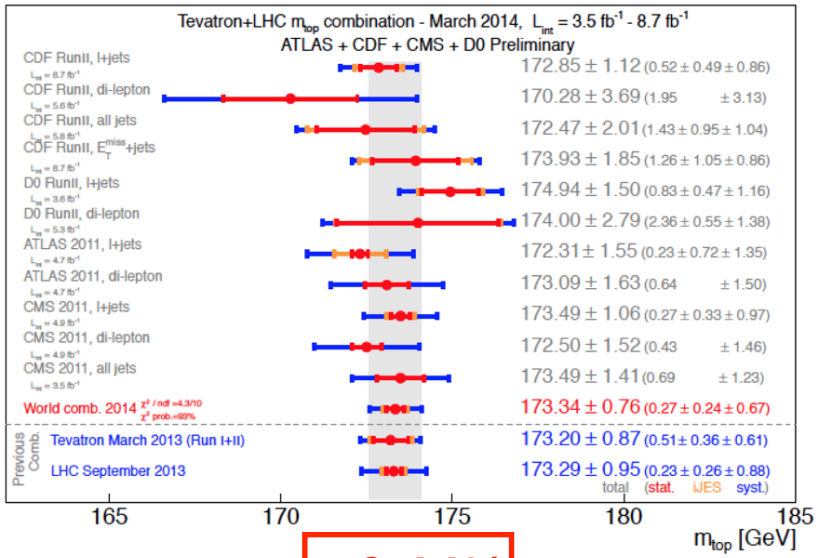
today

100000s of events



LHC: top quark factory

precision

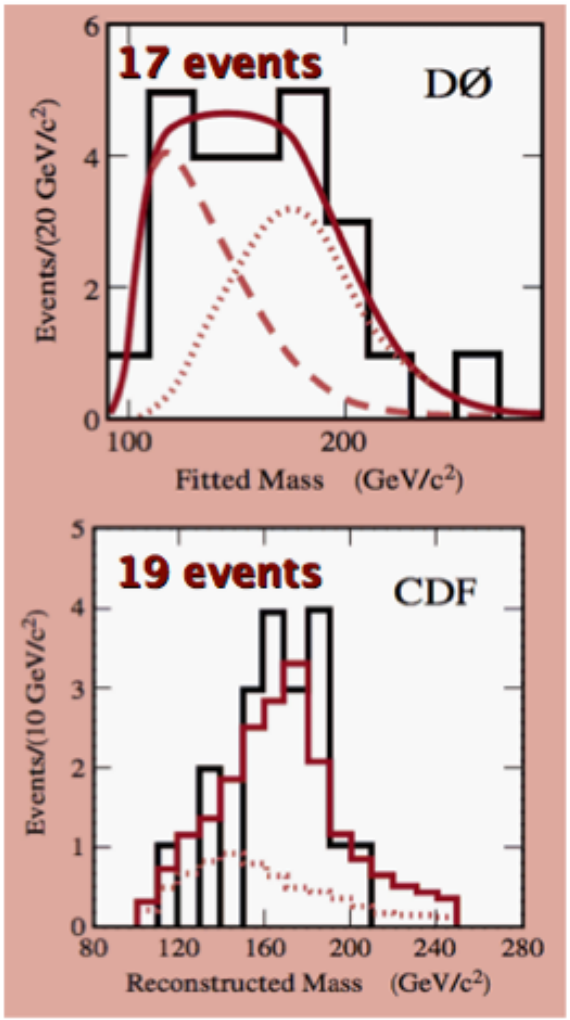


±0.44%

The Top Quark

discovery

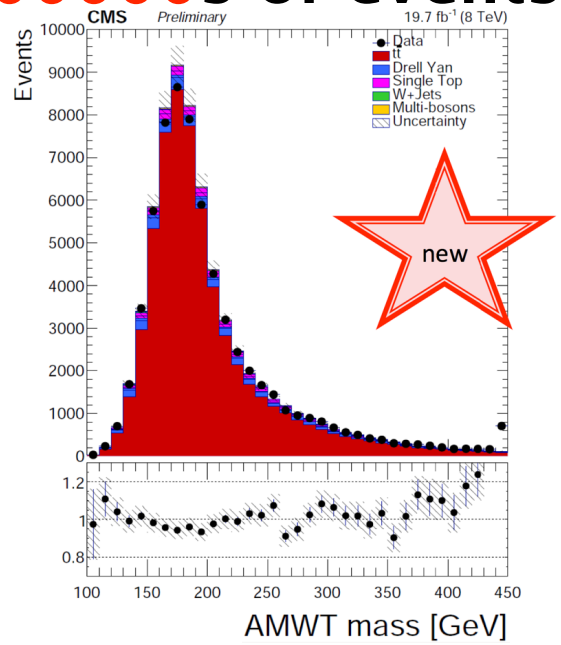
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

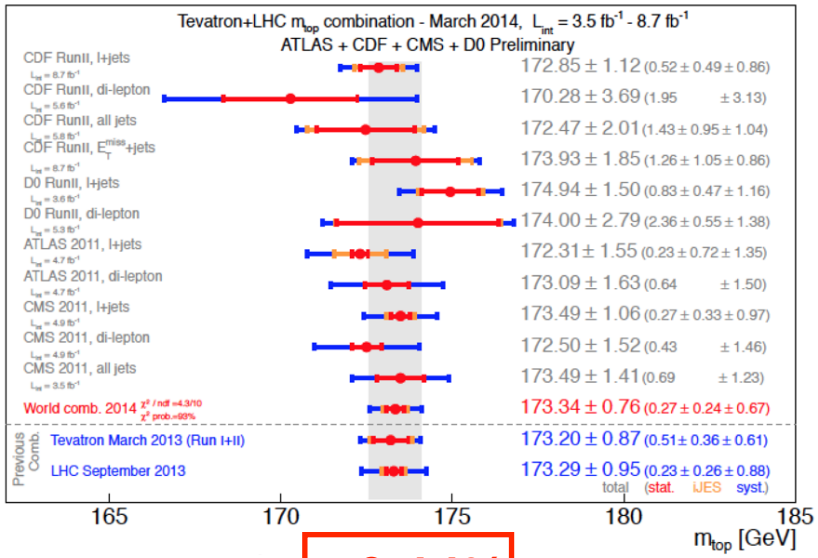
today

100000s of events



LHC: top quark factory

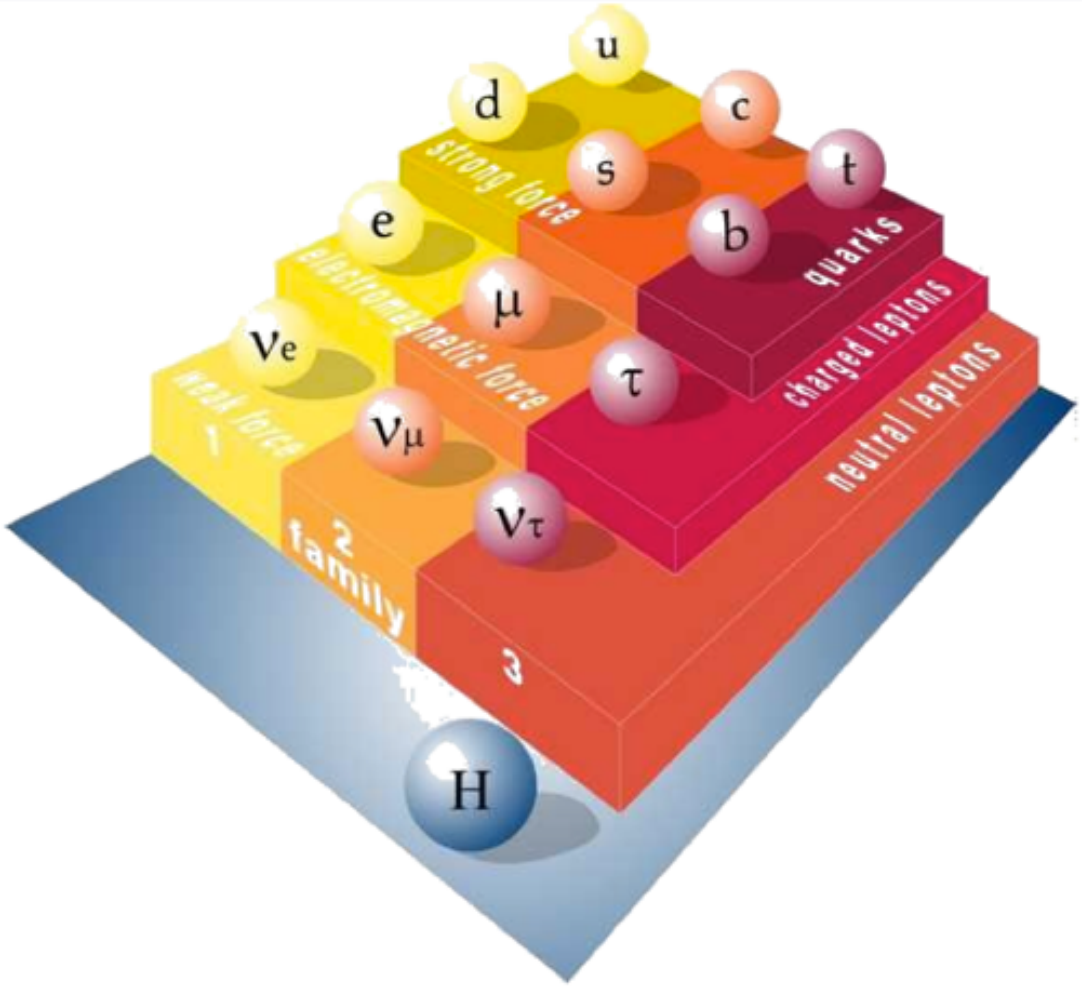
precision

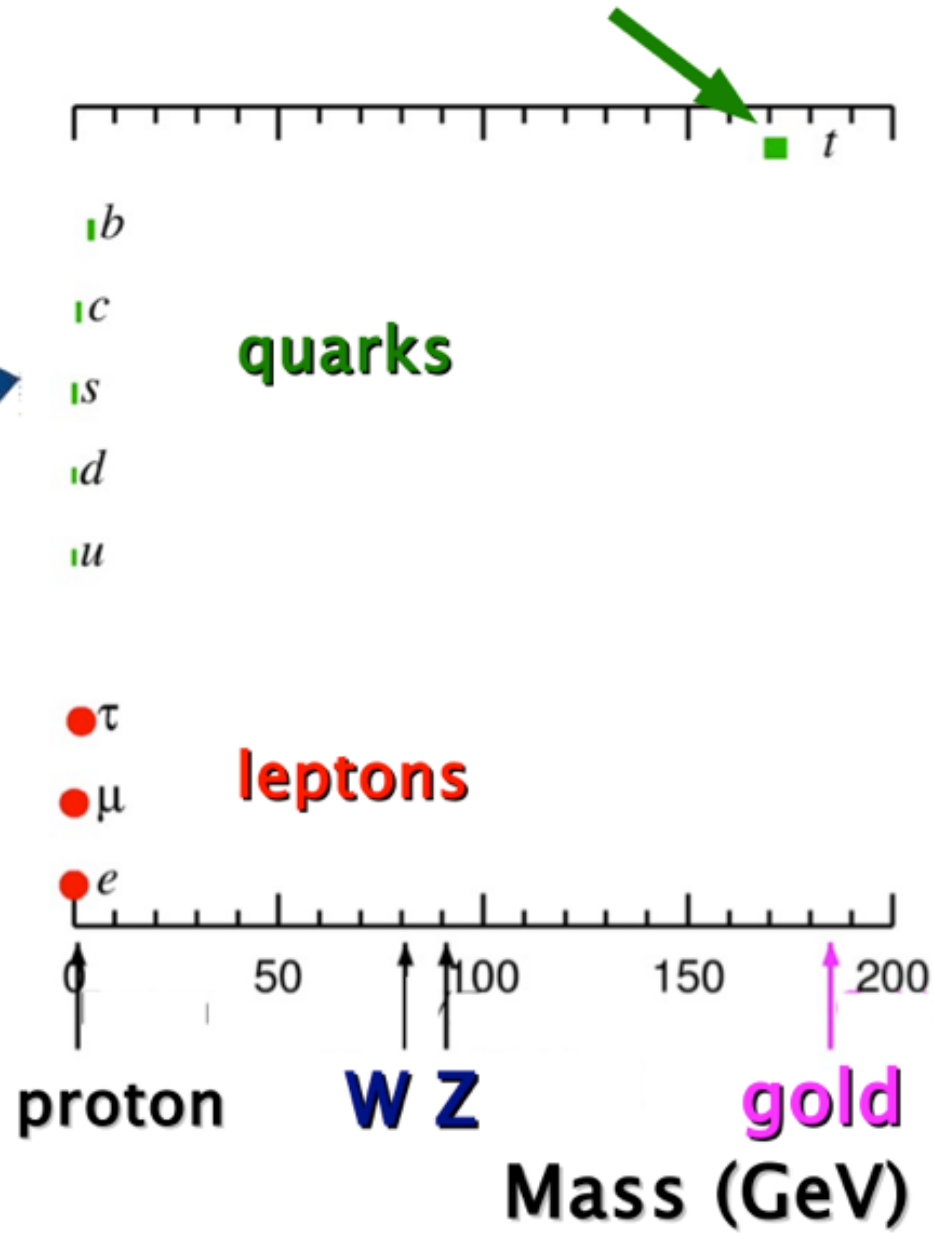


±0.44%

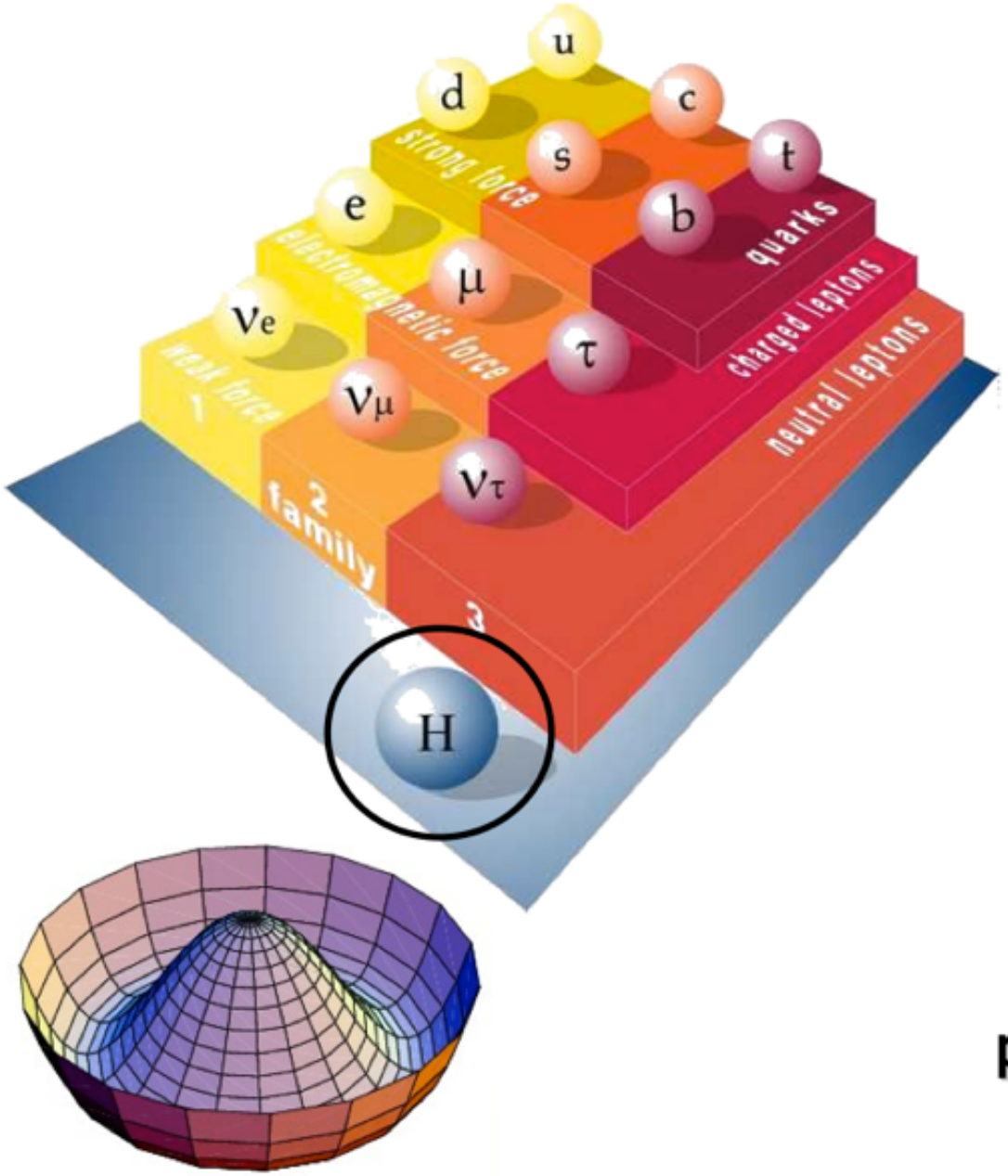
searches

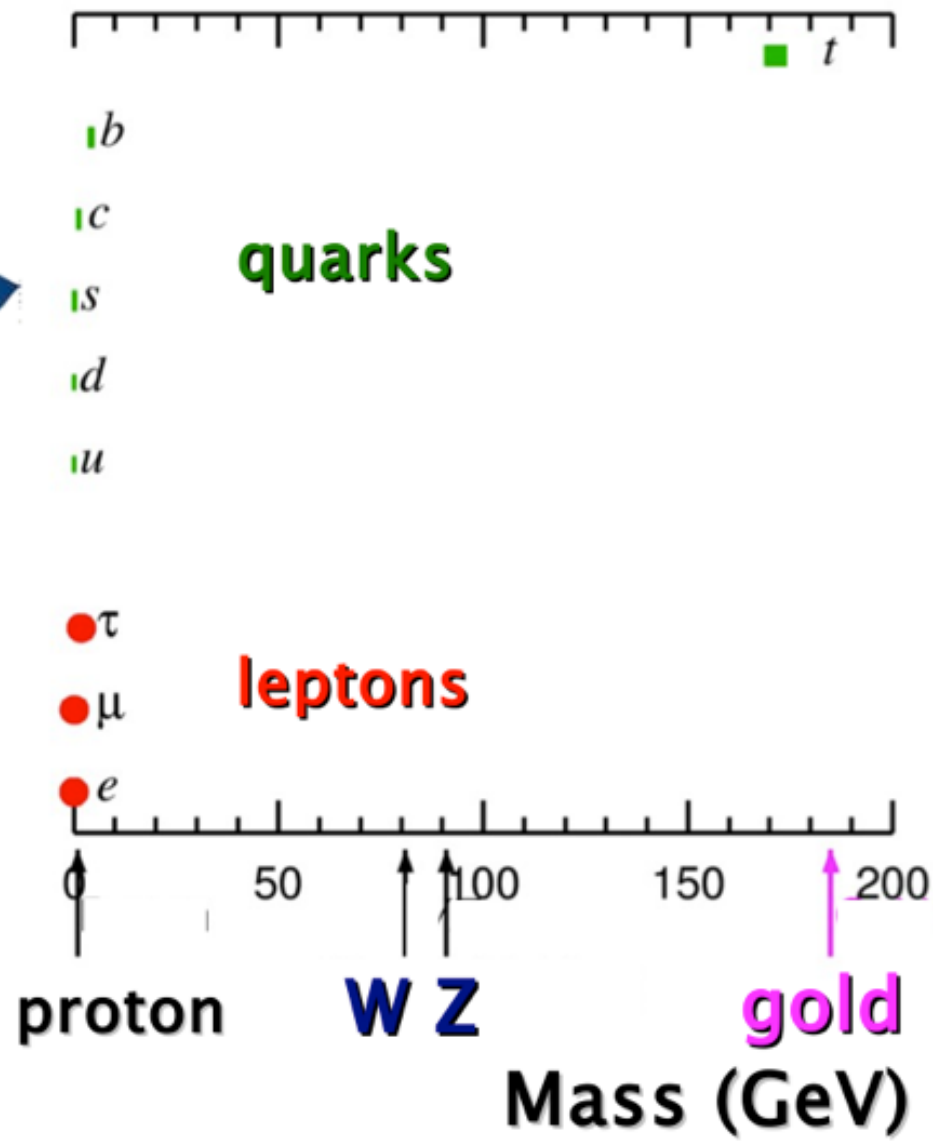
The Top Quark



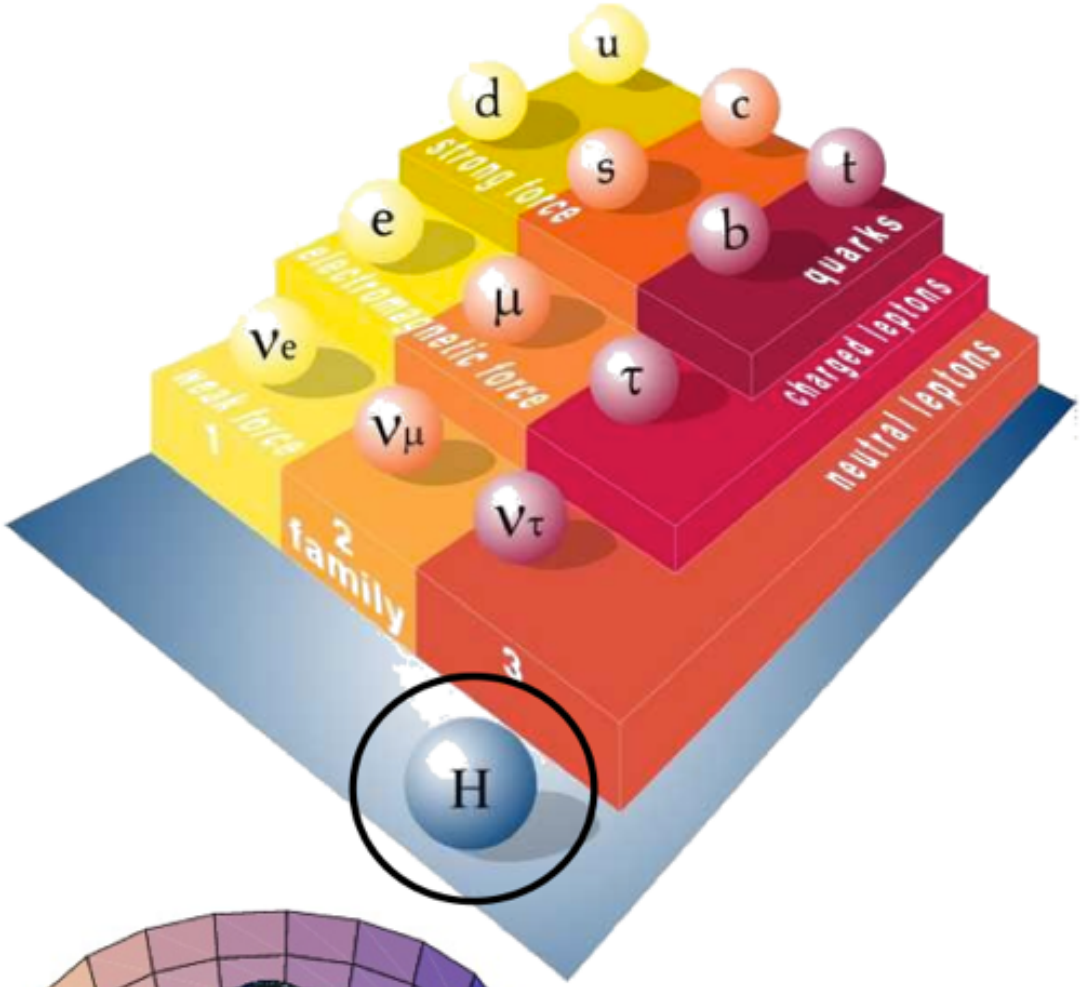


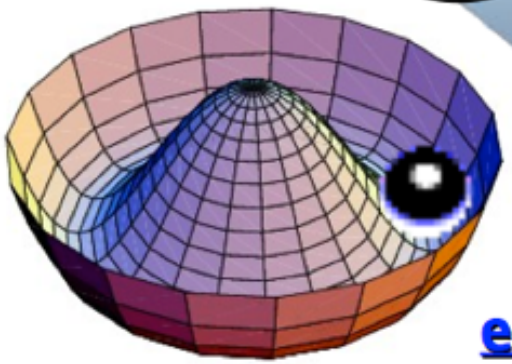
The Top Quark

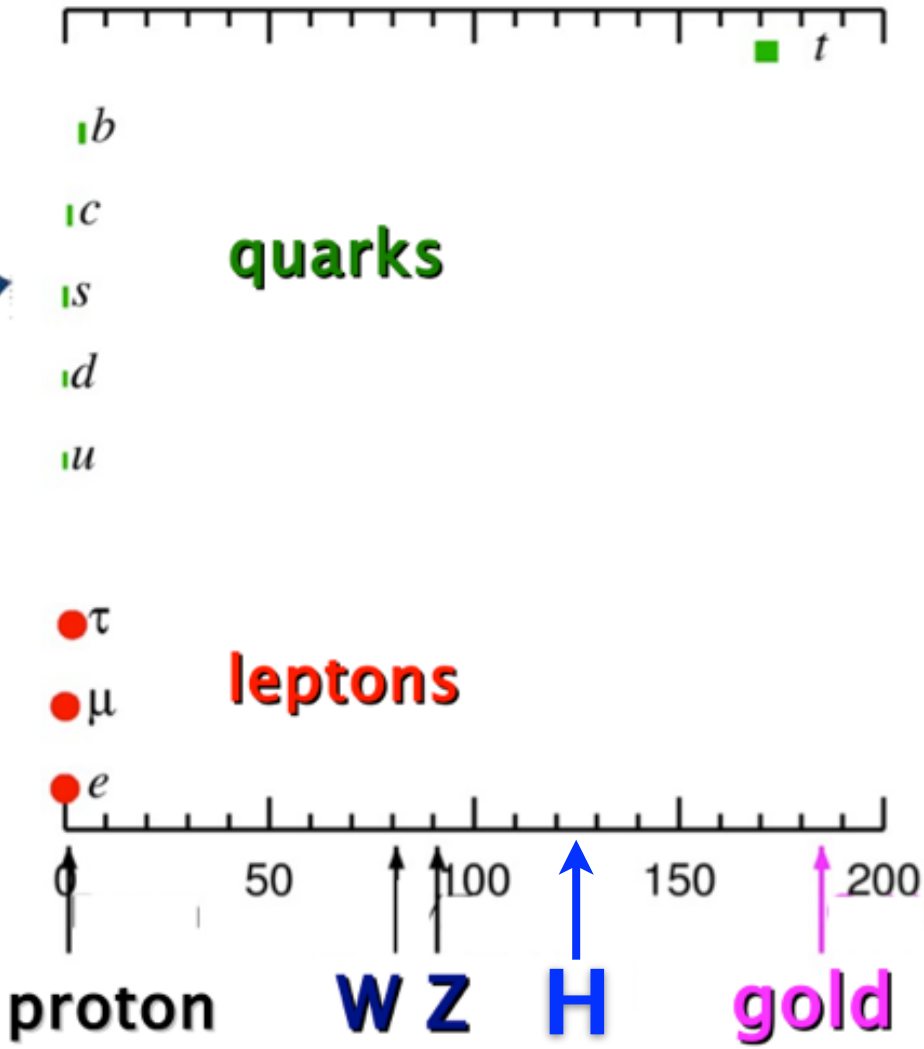




The Top Quark

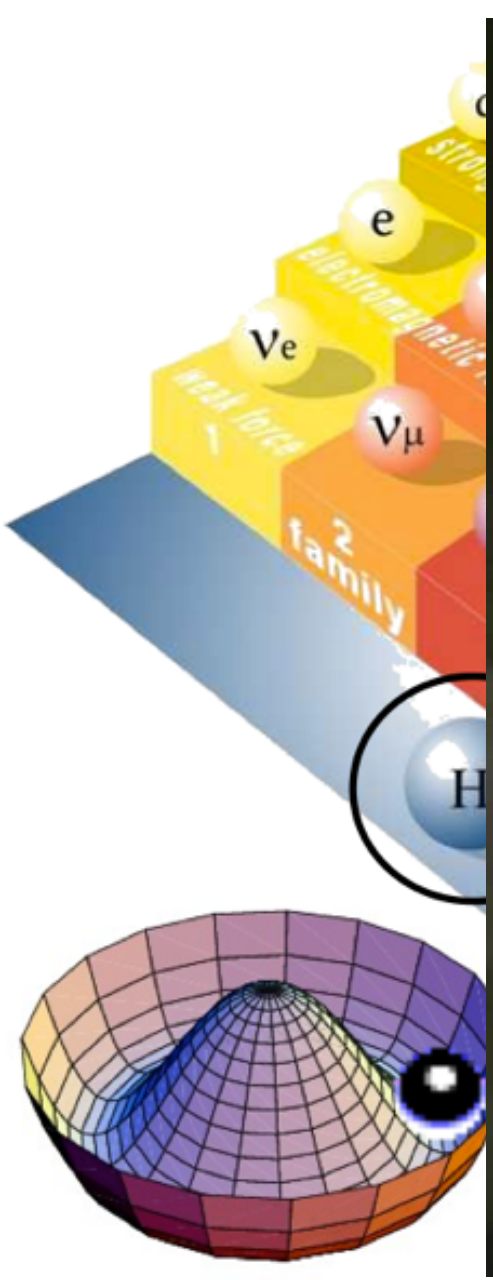




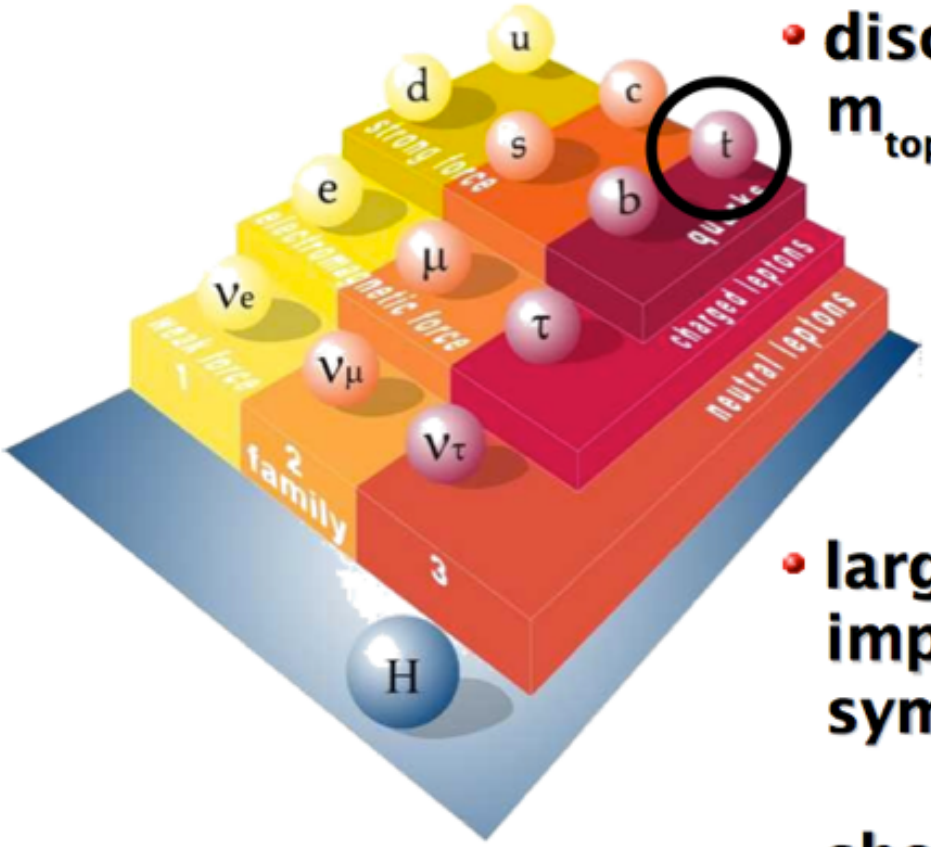


electroweak symmetry breaking

The Top Quark

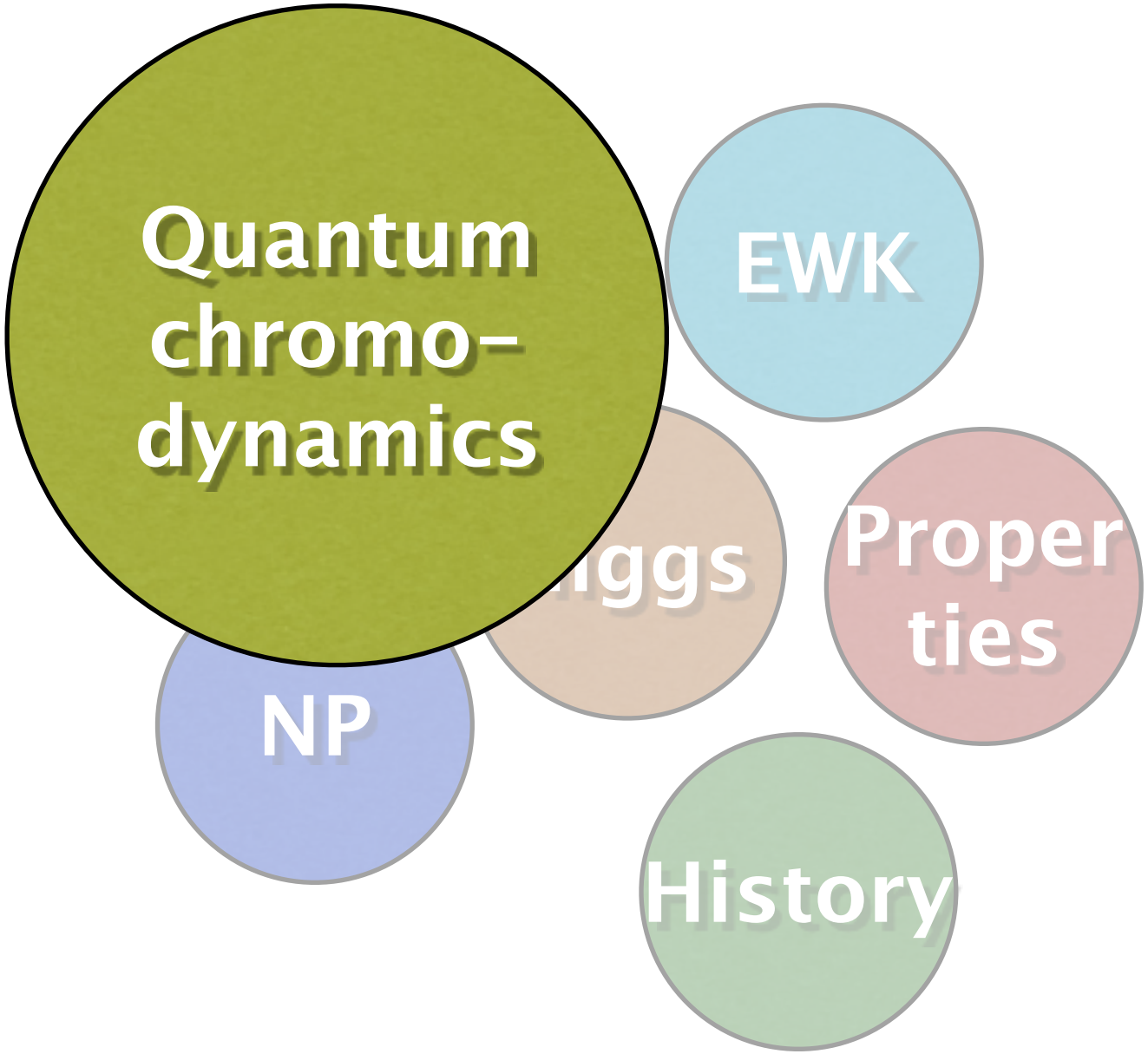


The Top Quark

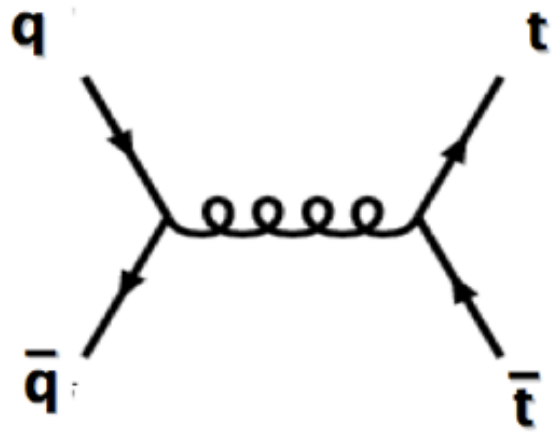


- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$: decays before fragmenting
  → observe "naked"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

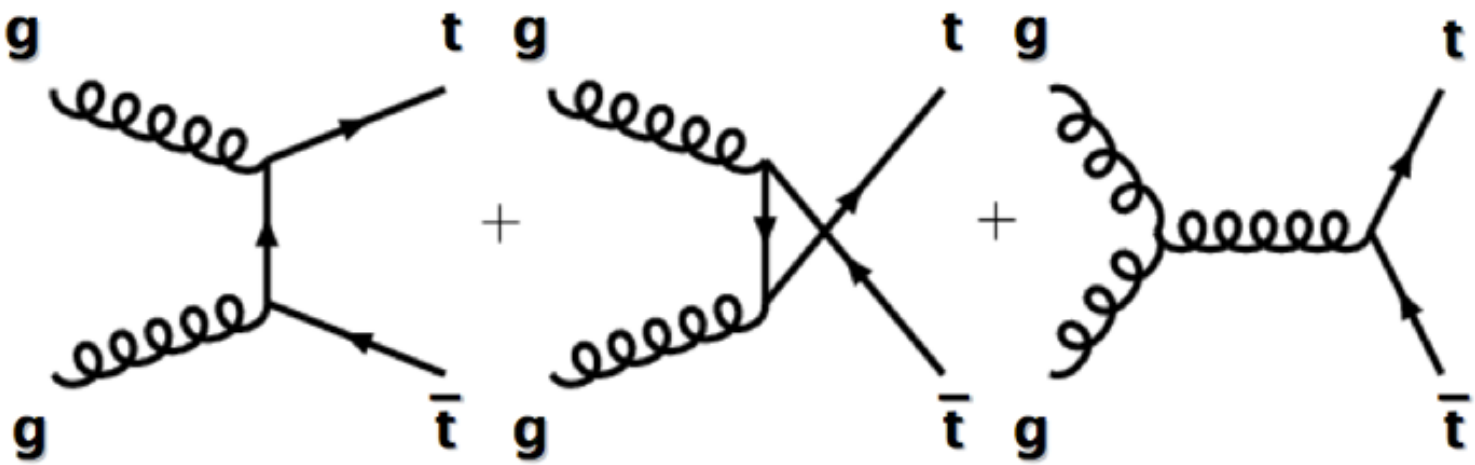
Top Quark Physics Topics



Top Quark Pair Production



Tevatron (85%)



LHC (87%)
(14 TeV)

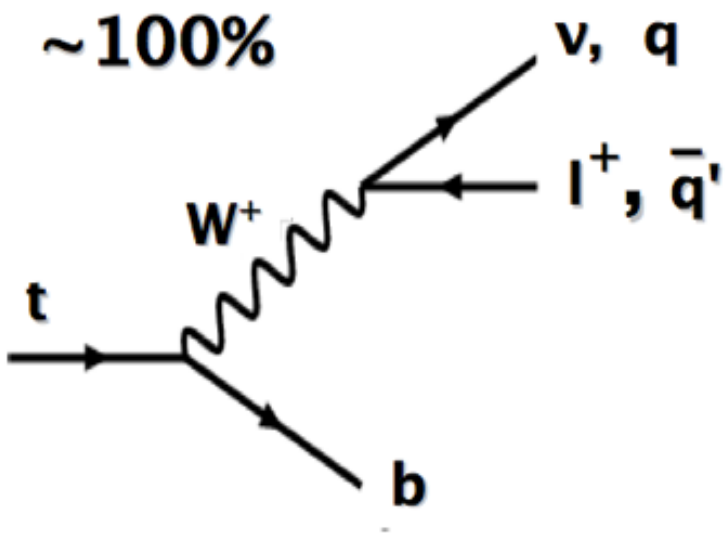
Top Quark Pair Signatures

τ's
14%

alljets
46%

top decay:

~100%



- high p_T leptons, missing E_T
- jets
- b-jets

Top Pair Decay Channels

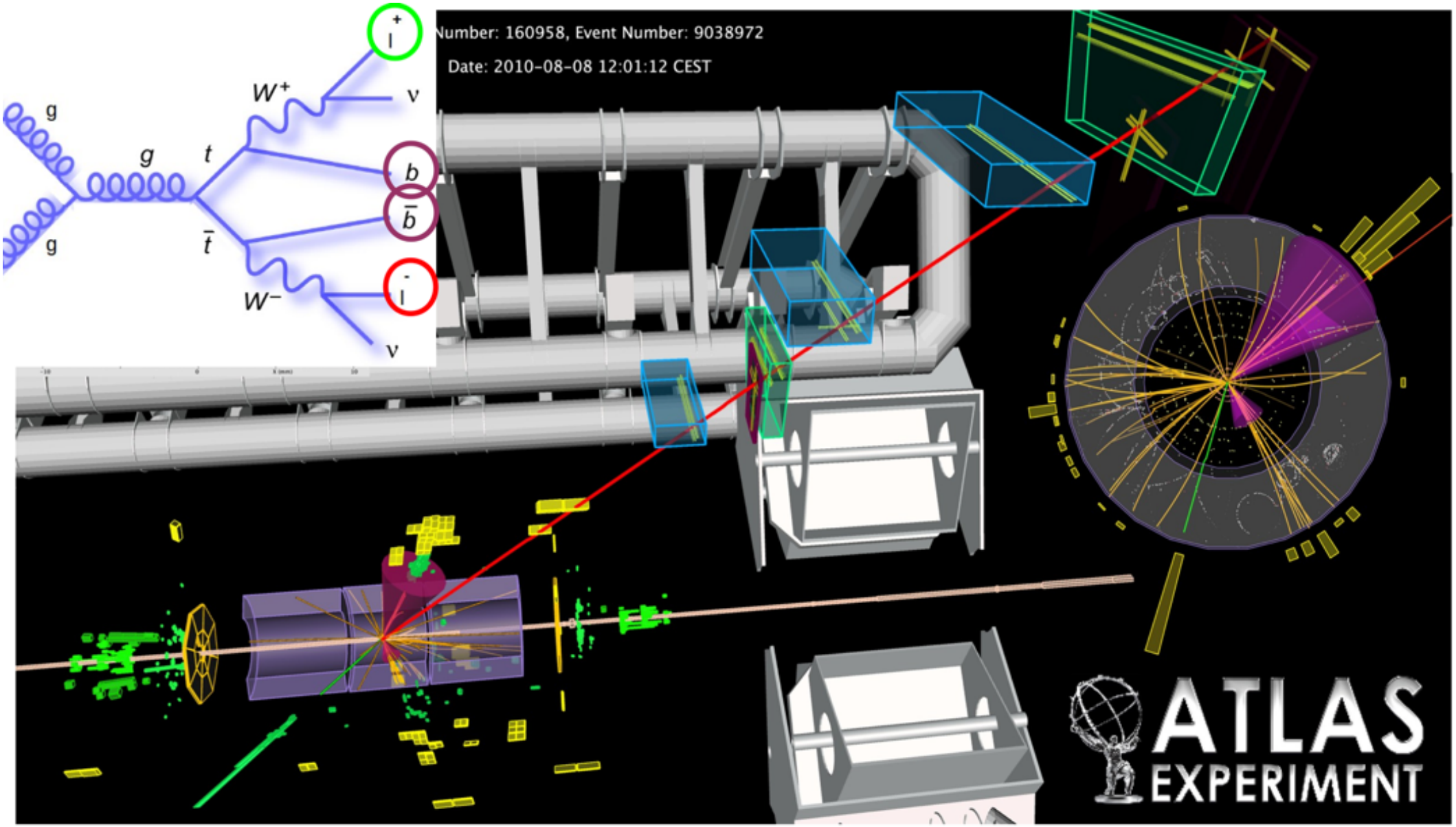
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
$\bar{c}s$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{u}d$					
τ^-	eτ	μτ	ττ	tau+jets	
μ^-	eμ	μμ	μτ	muon+jets	
e^-	ee	eμ	eτ	electron+jets	

dileptons

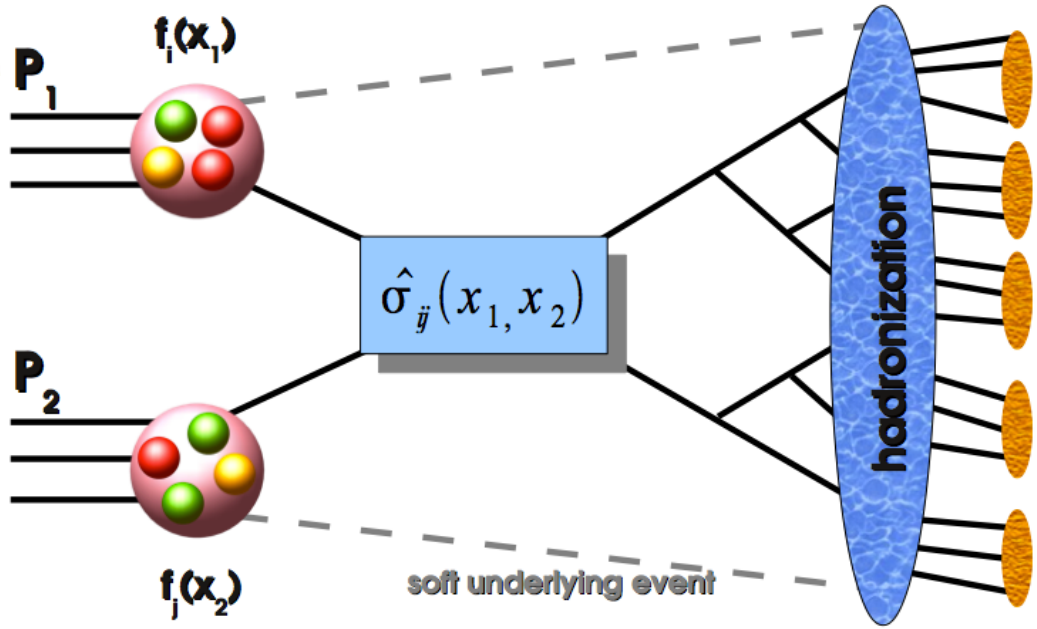
dilepton (e/μ)
6%

e/μ+jets
34%

Dilepton Event



Cross Section in Hadron Hadron Scattering



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

Sum over incoming partons i, j

Momentum fraction for incoming parton

PDF for incoming parton i

"partonic" cross section

What is a Cross Section?

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

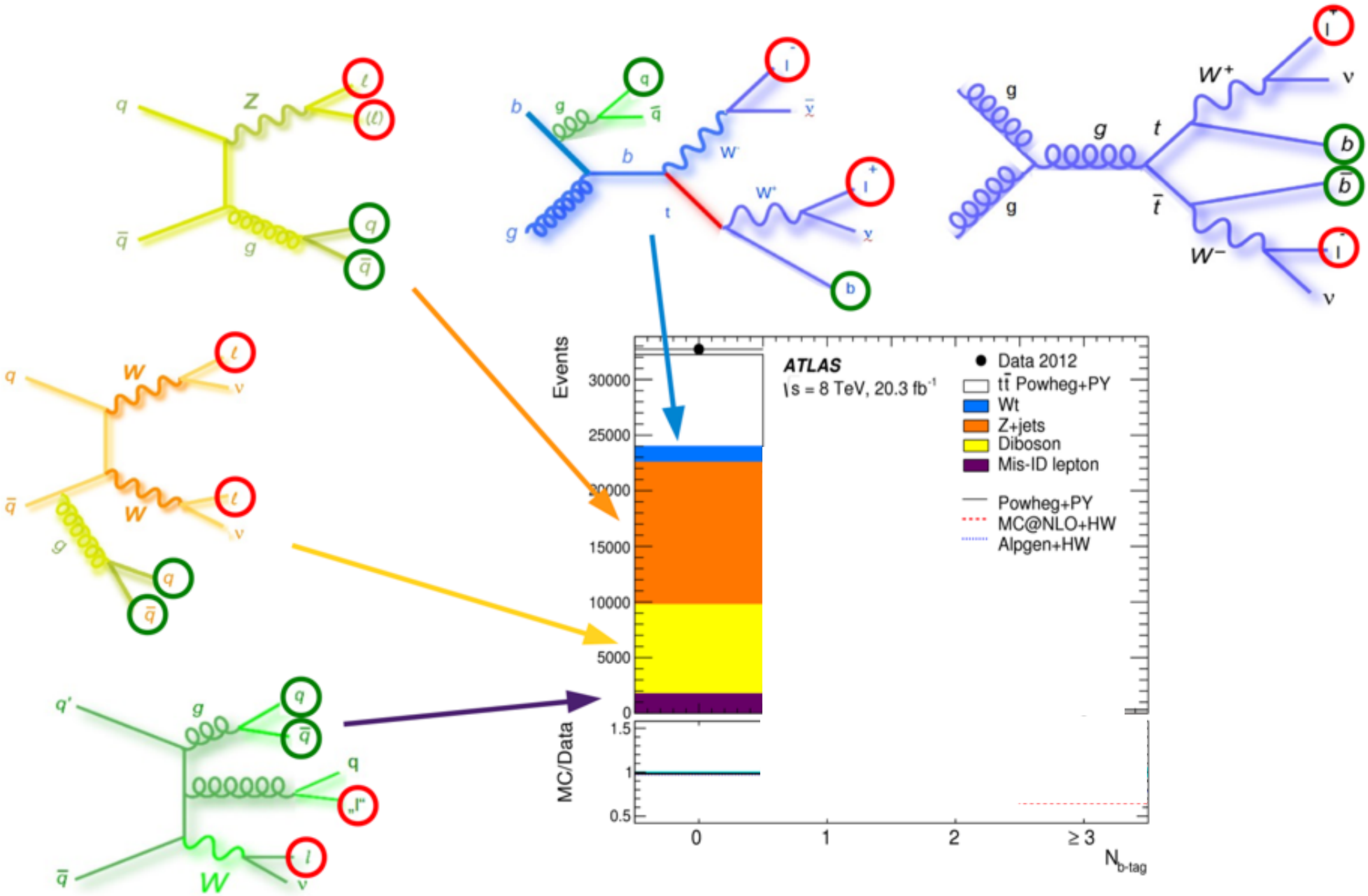
Geiger and Rutherford in Manchester

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

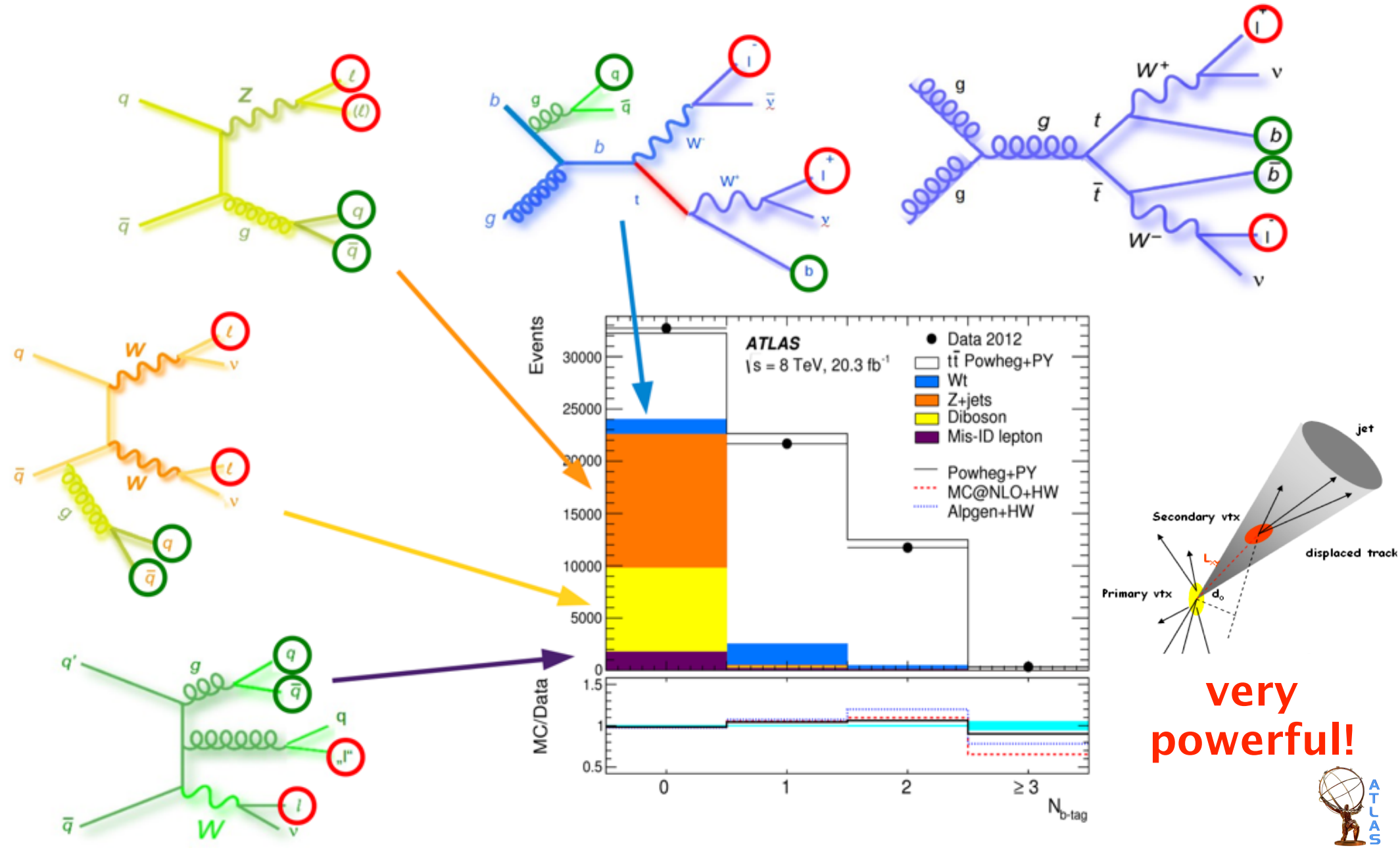
Measurement: $\sigma=(N_{obs}-N_{bg})/(\varepsilon L)$

Luminosity

Dilepton Signatures

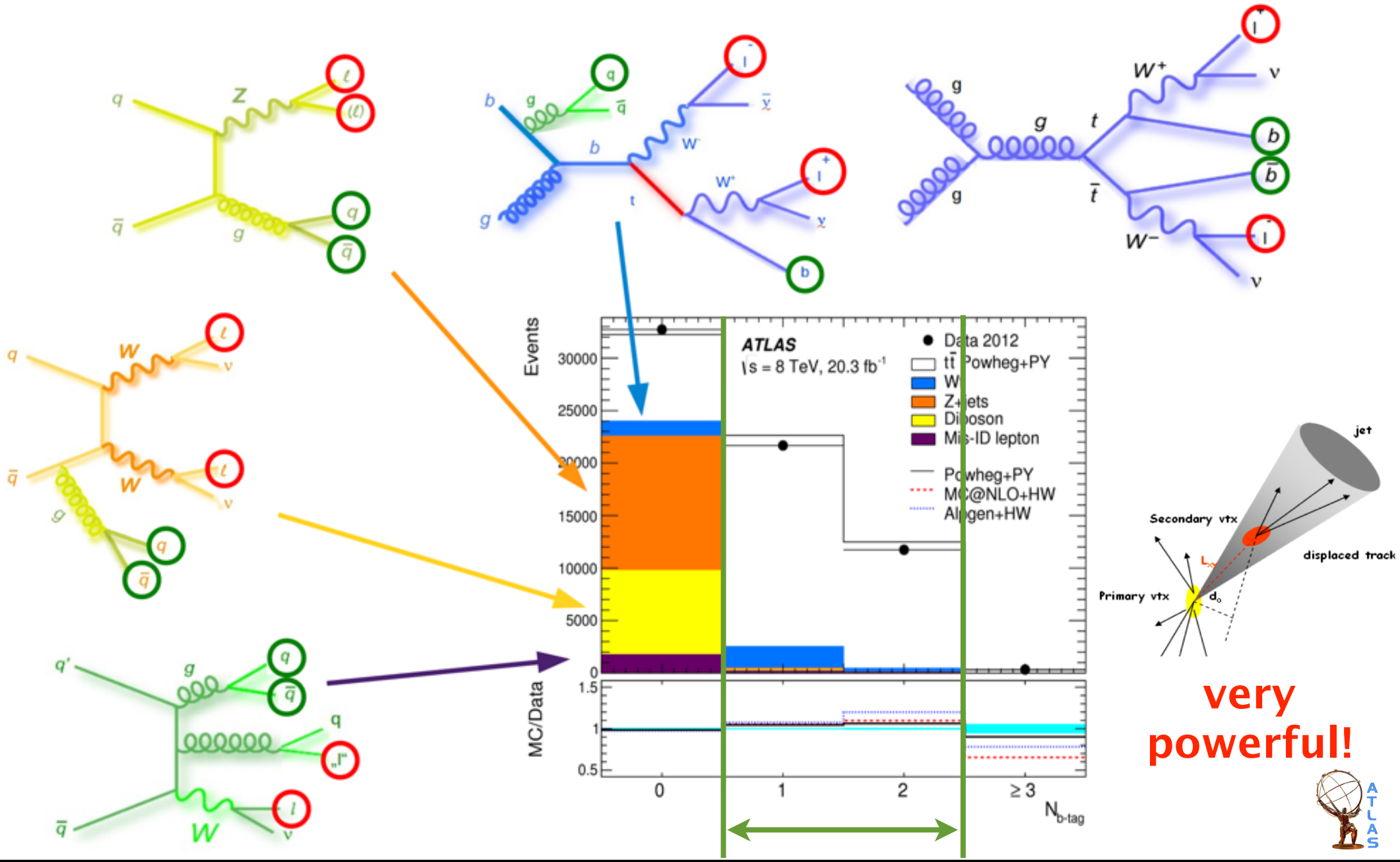


Dilepton Signatures



very powerful!

Dilepton Signatures with b-tagging



very powerful!

Dilepton cross section

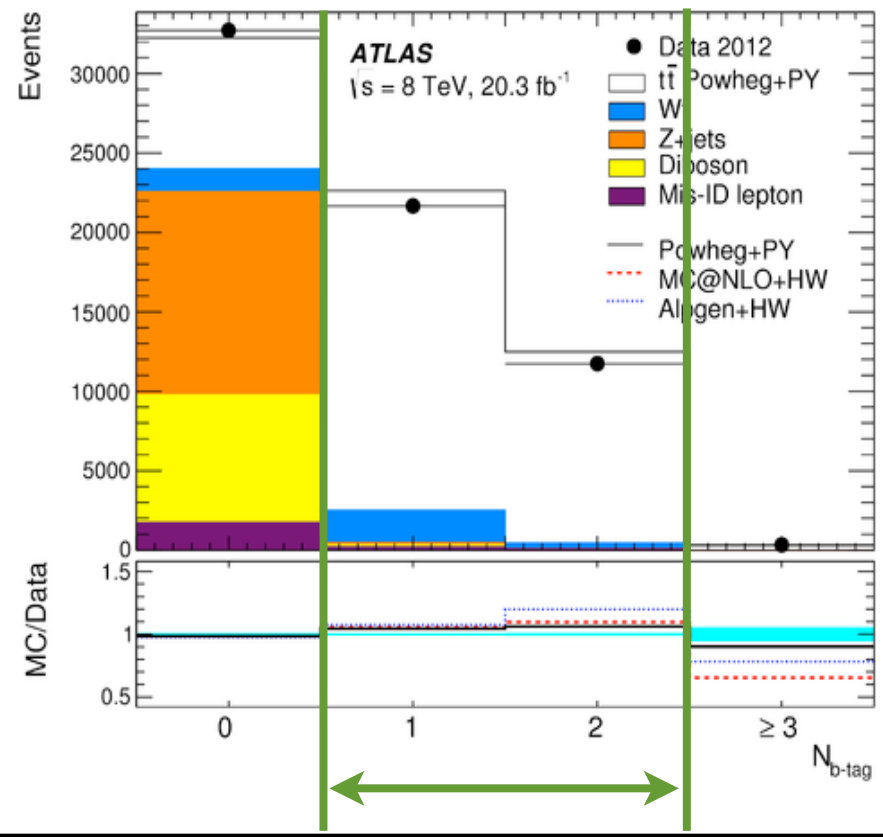
$$\sigma_{t\bar{t}} = 182.9 \pm 3.1 \pm 4.2 \pm 3.6 \pm 3.3\,\text{pb}\ (\sqrt{s} = 7\,\text{TeV})$$ ±3.9%

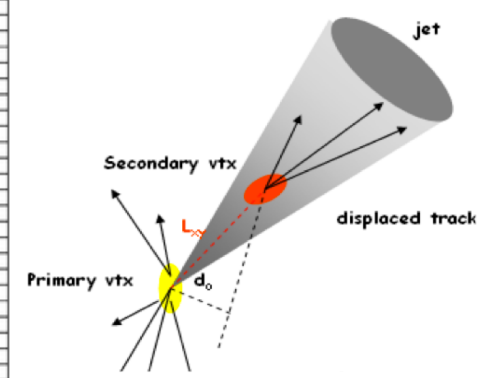
$$\sigma_{t\bar{t}} = 242.4 \pm 1.7 \pm 5.5 \pm 7.5 \pm 4.2\,\text{pb}\ (\sqrt{s} = 8\,\text{TeV})$$ ±4.3%

(stat) (syst) (lumi) (beam)

Eur. Phys. J. C74 3109 (2014)

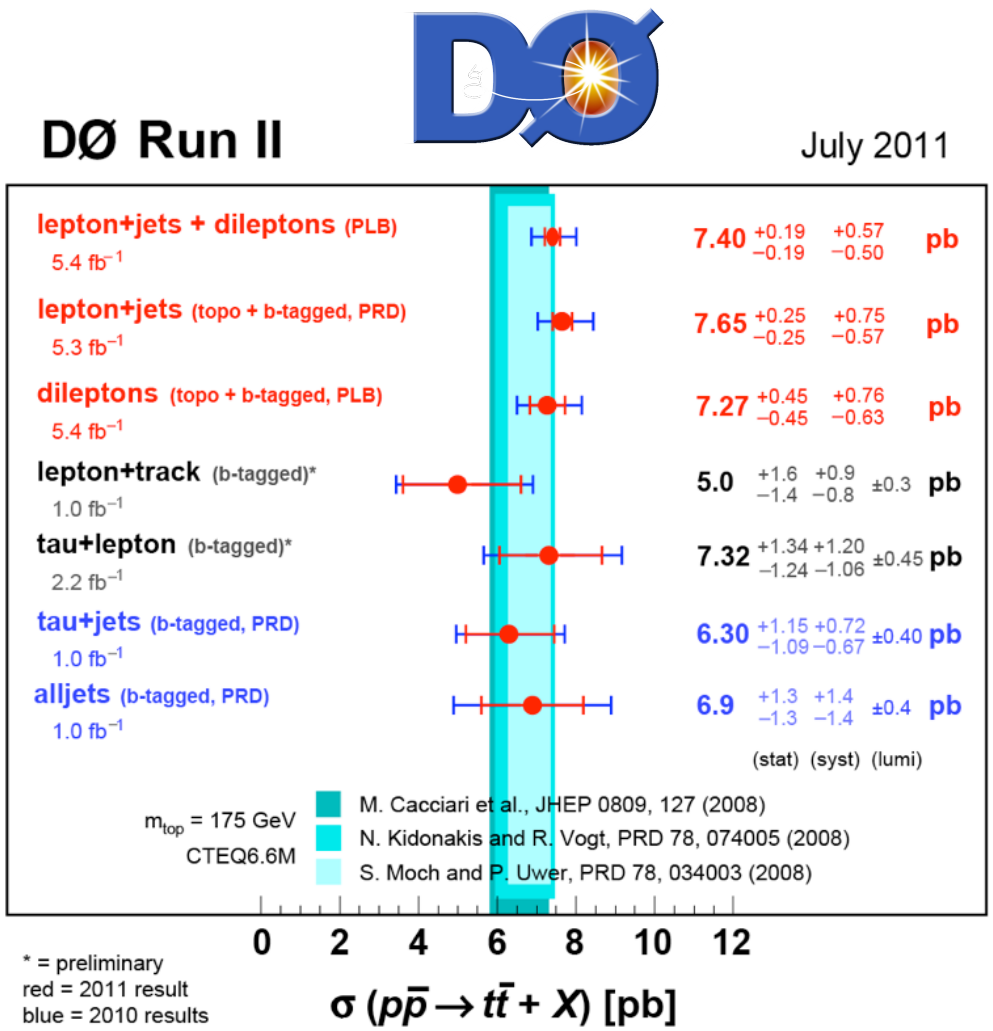
basically background free: just counting…

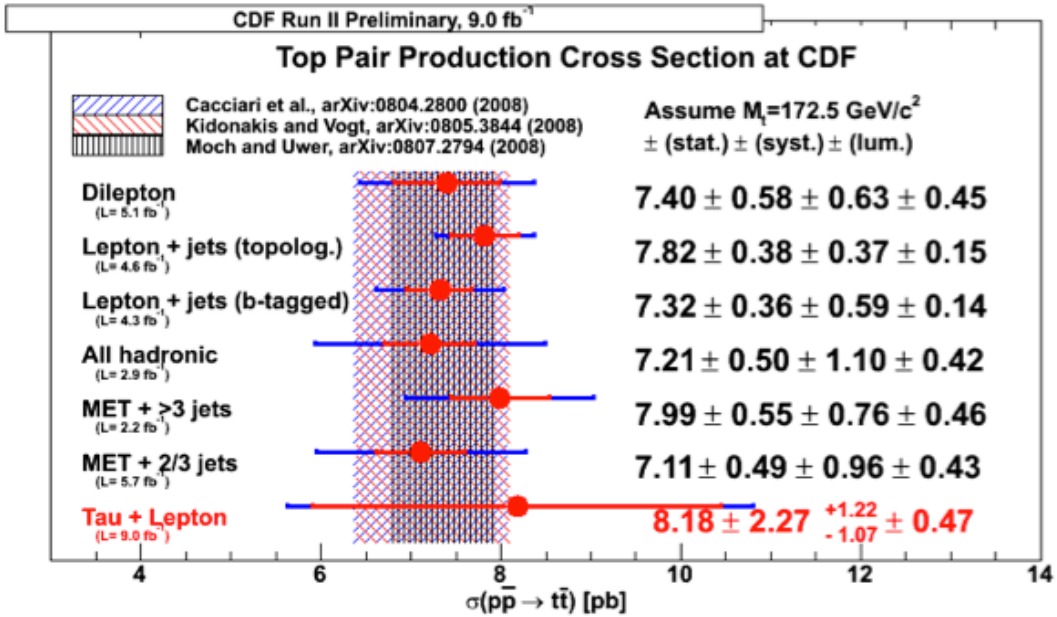




very powerful!

Top Pair Production Cross Section

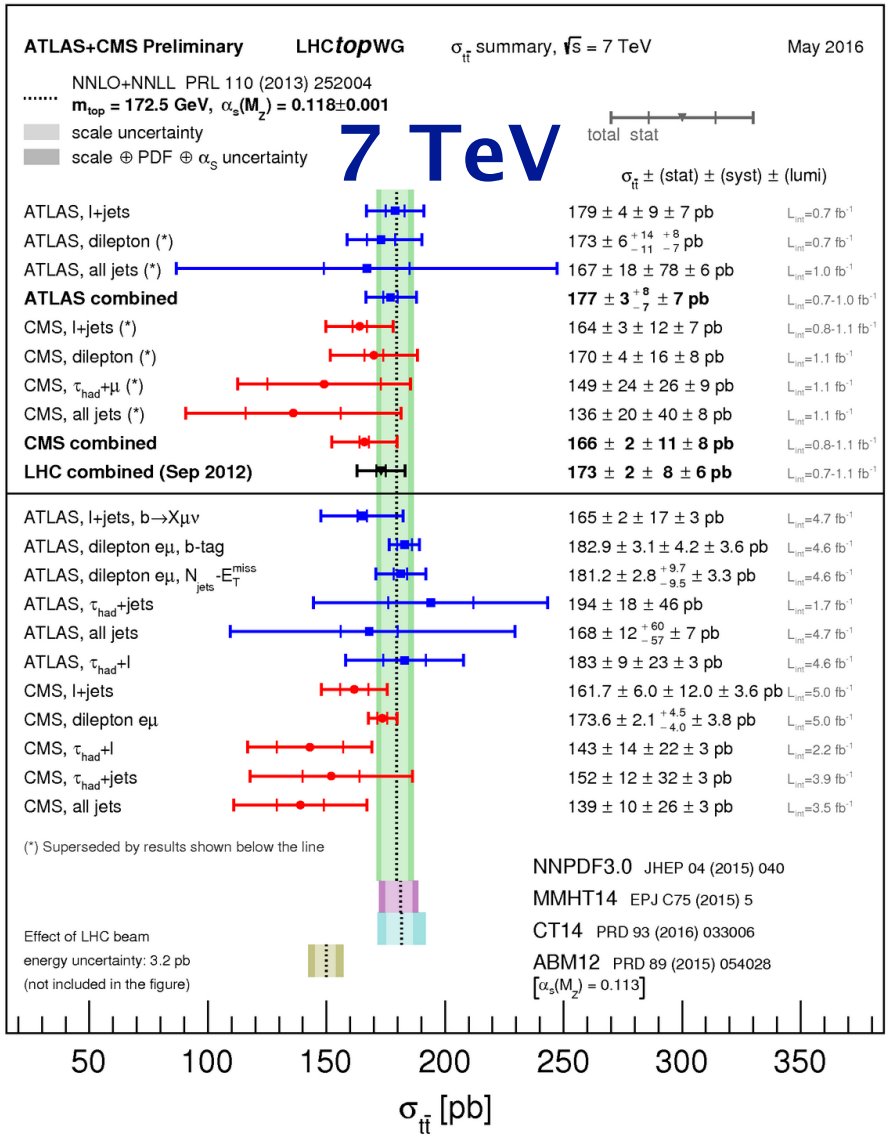


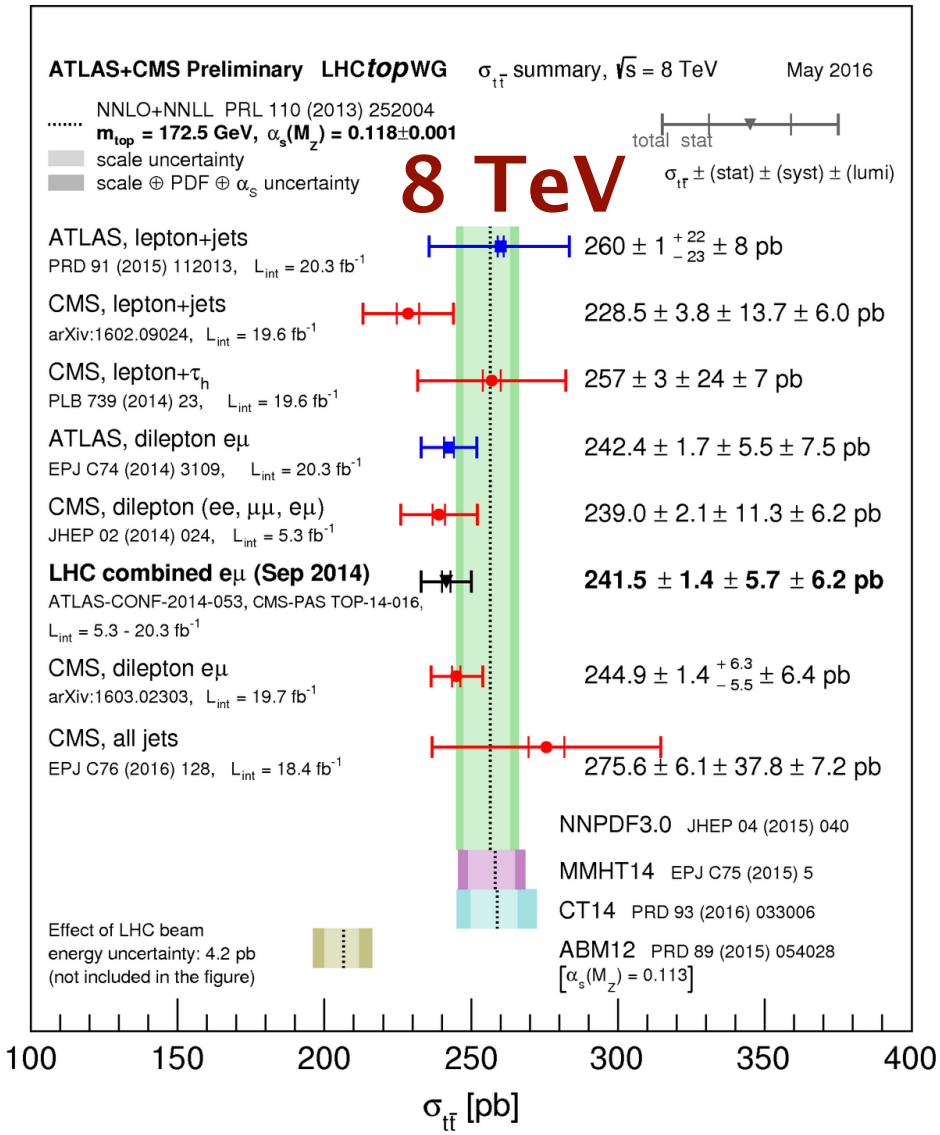


all channels measured except for $\tau_{had}\,\tau_{had}$

→ good agreement with each other

Top pair production cross section

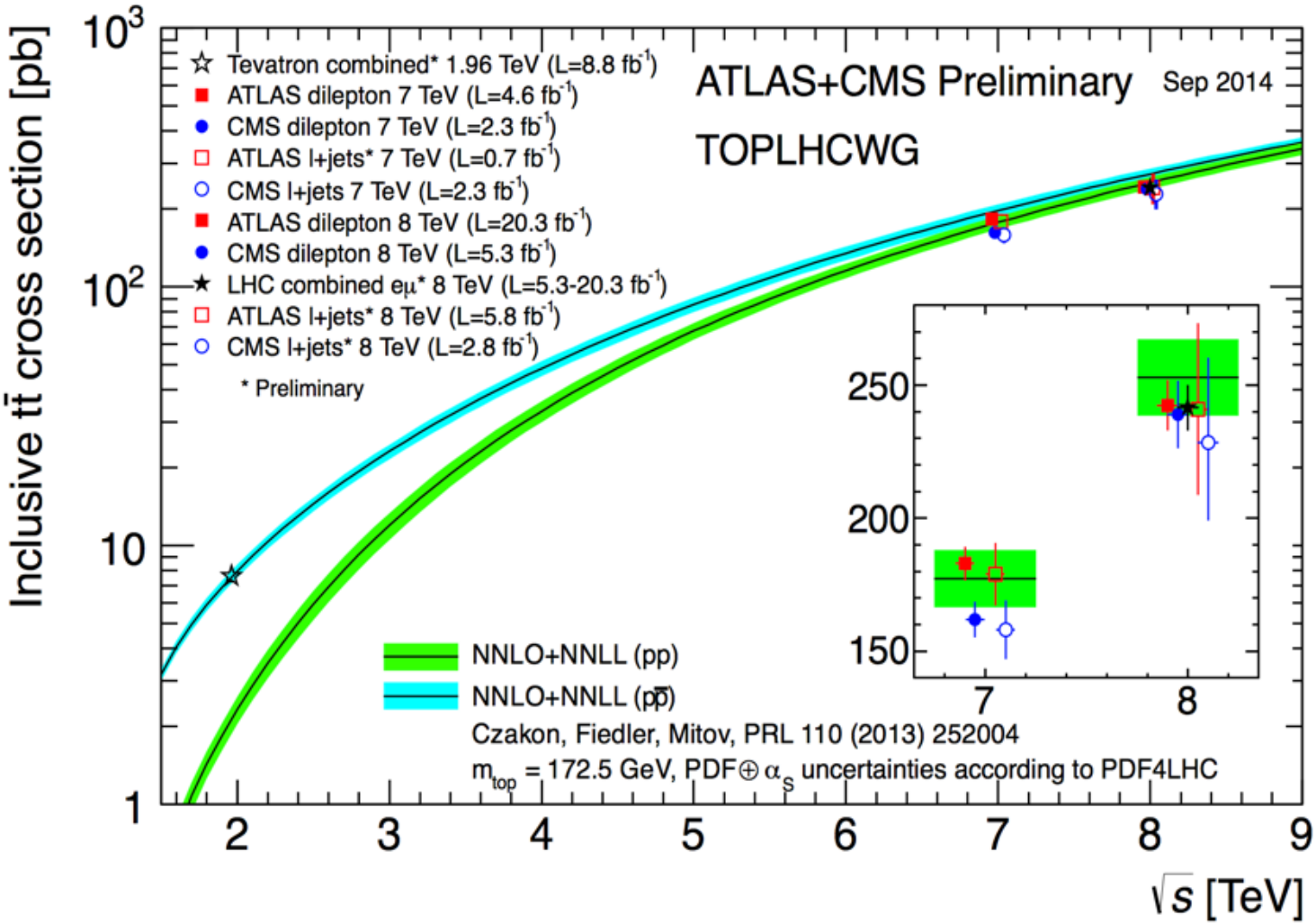




→ (all) channels measured to look for the unexpected

→ no new physics

Top pair production at hadron colliders



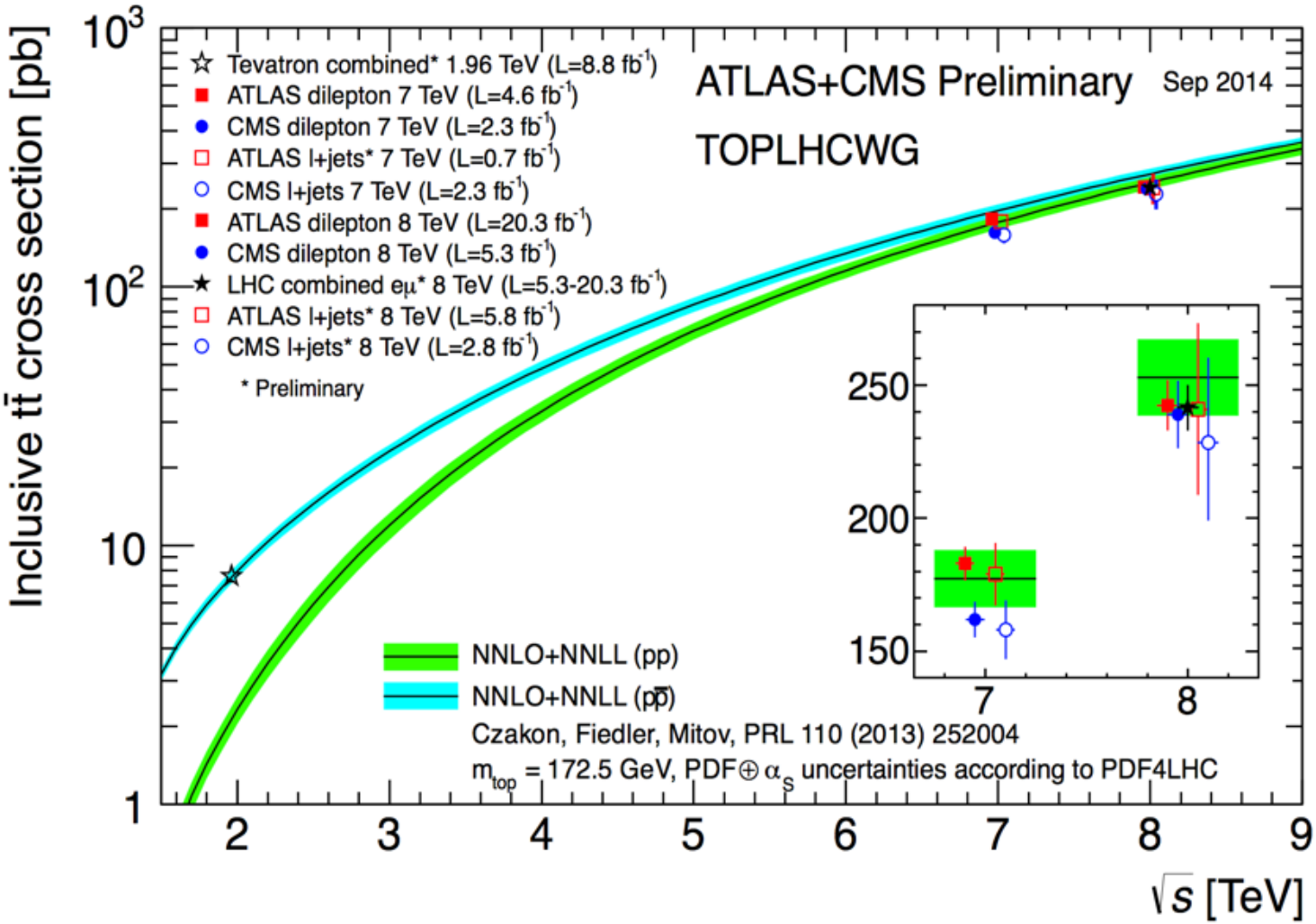
±5.7% (theo)

±3.9% (eμ)

→ experiments challenge theory again

Top pair production at hadron colliders

eager to put a point here

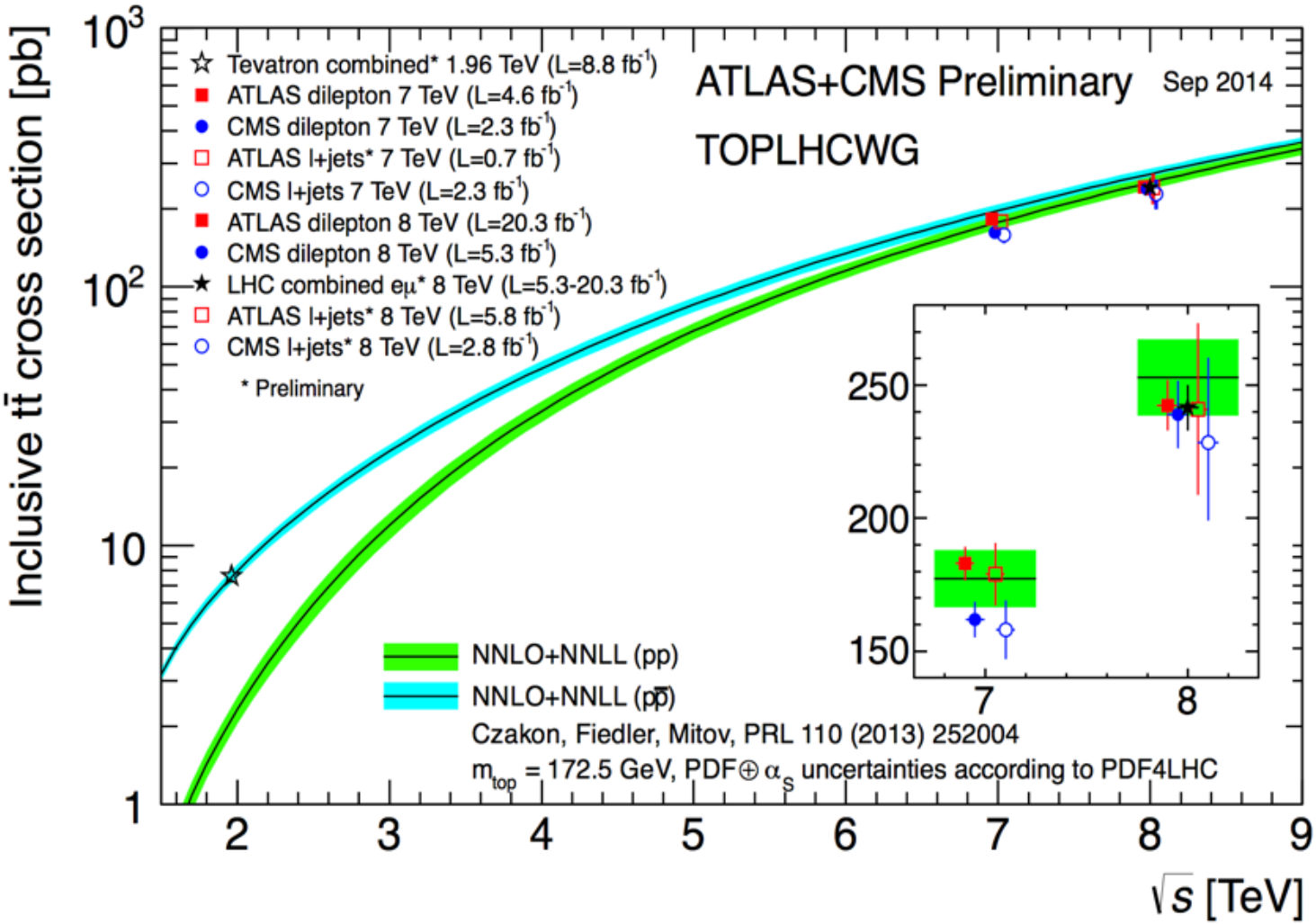


±5.7% (theo)

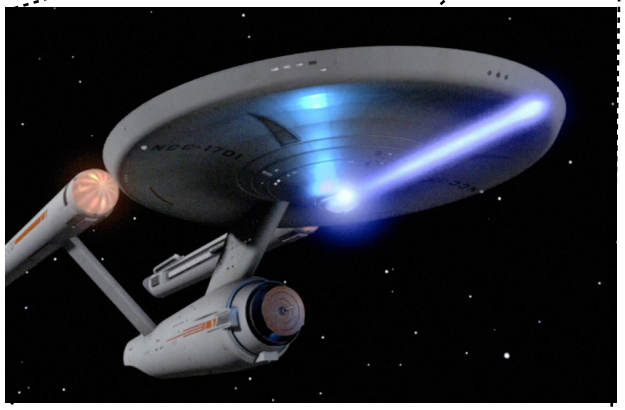
±3.9% (eμ)

→ experiments challenge theory again

Top pair production at hadron colliders



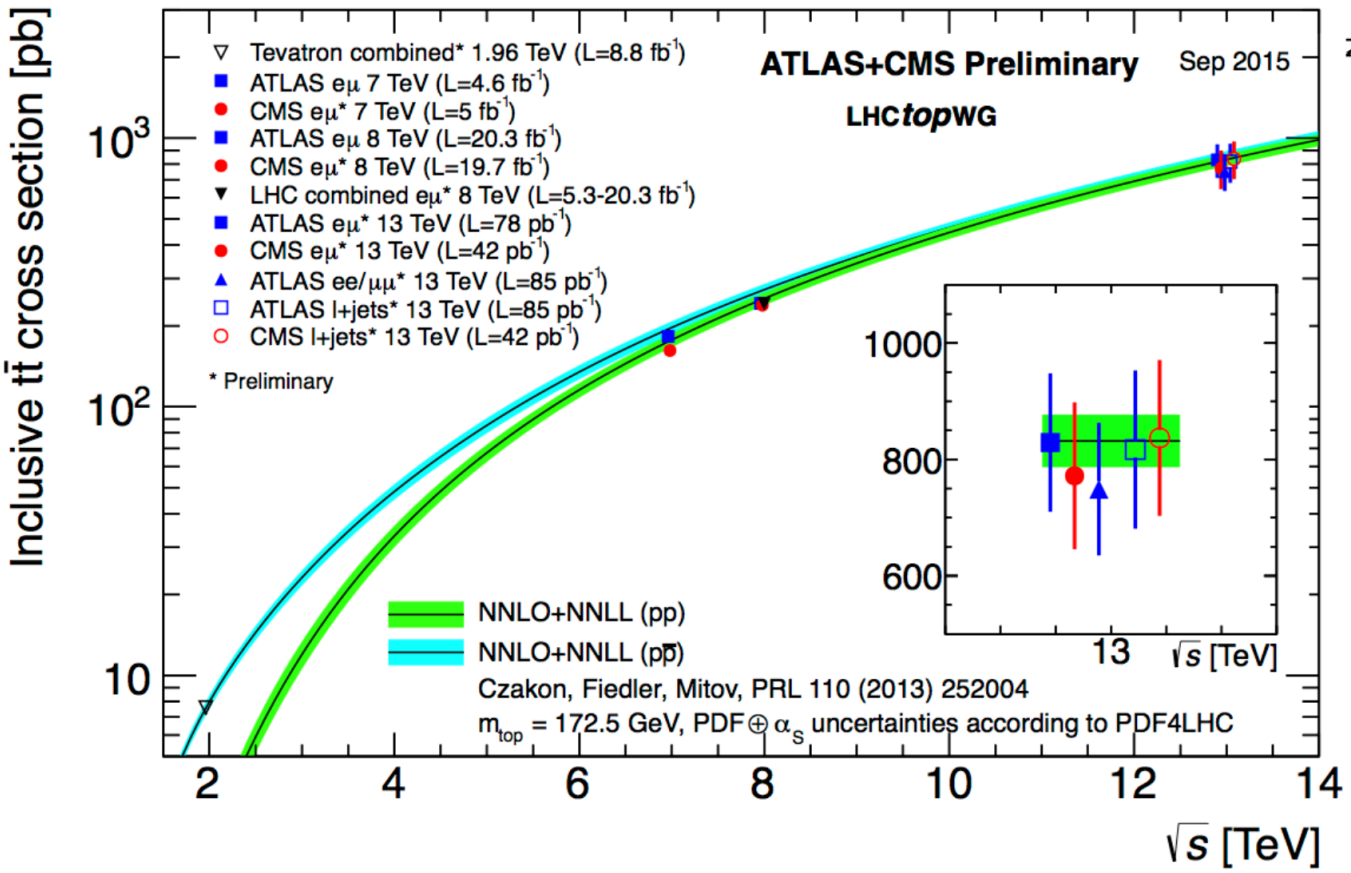
boldly go where no man has gone before



→ **experiments challenge theory again**

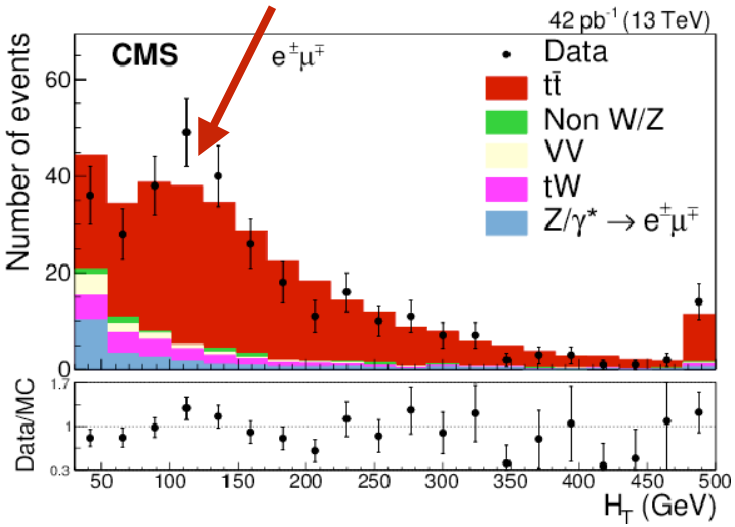
Top pair production at 13 TeV

first look at the new world energy frontier



"top quark peak"

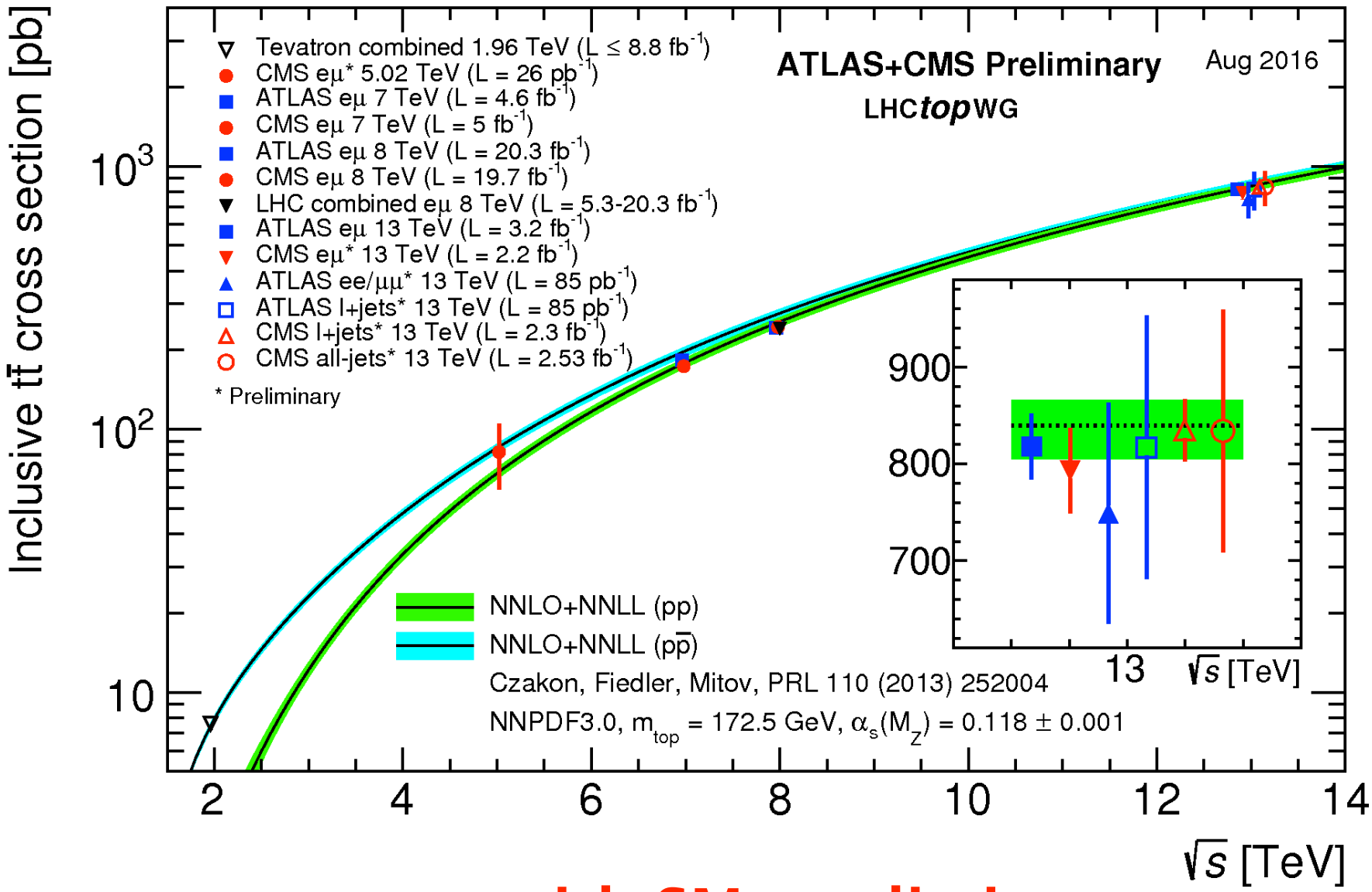
July 2015



sum of scalar p_T of all jets

→ agreement with SM prediction

Top pair production at 13 TeV



→ agreement with SM prediction

“Revolution” in Phenomenology

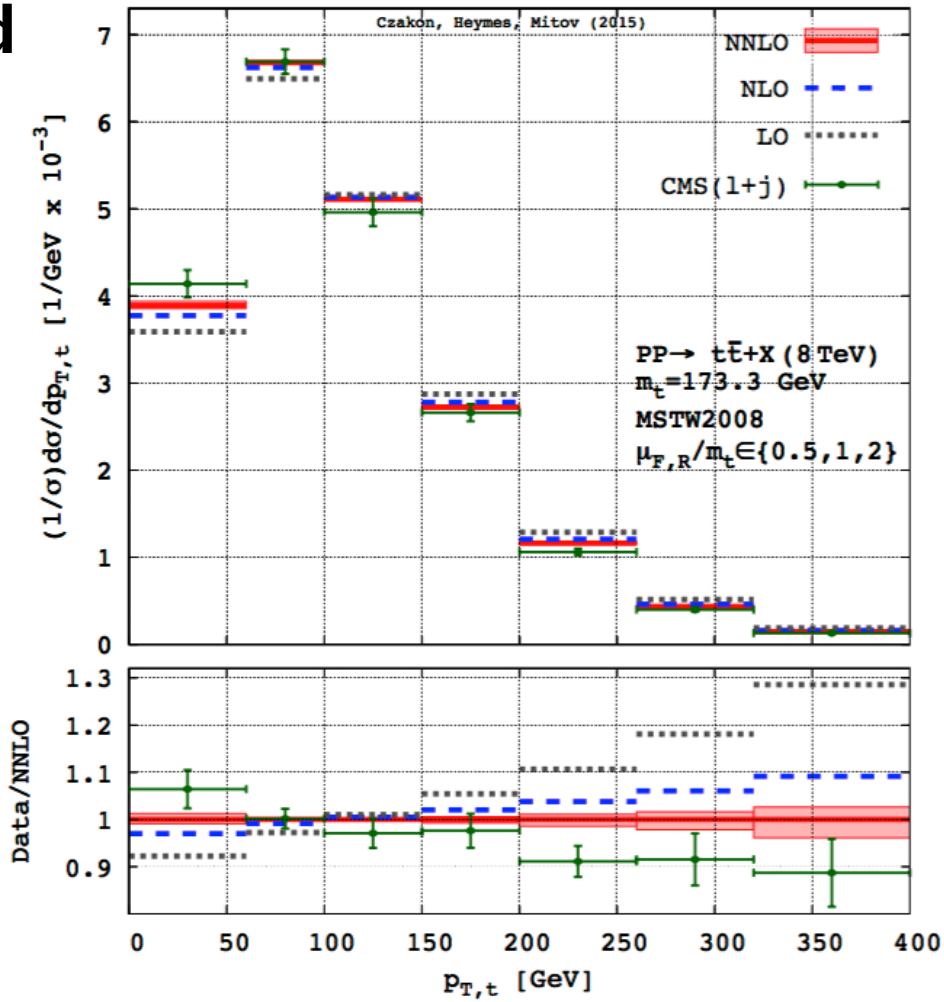
- **LO QCD+parton shower generators**
  Pythia, Herwig, ...

- **LO multileg generators matched with parton shower**
  Alpgen+Pythia, Alpgen+Herwig, ...

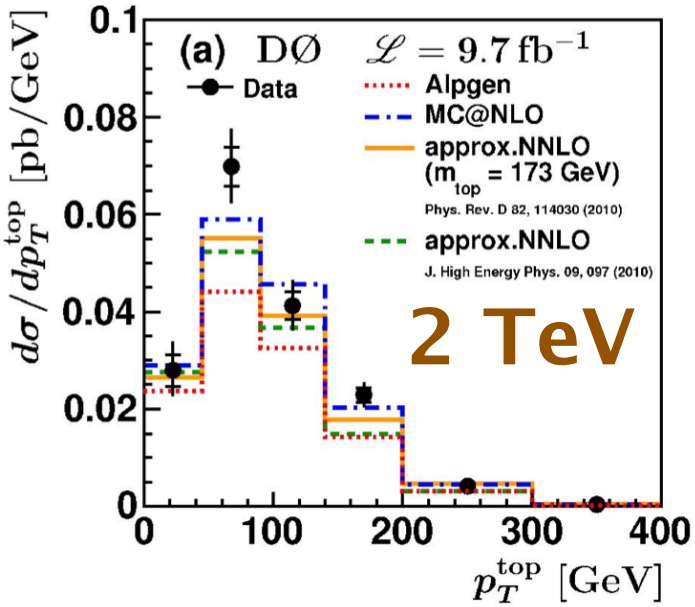
- **NLO+parton shower generators**
  Powheg+Pythia, MC@NLO+Herwig, ...

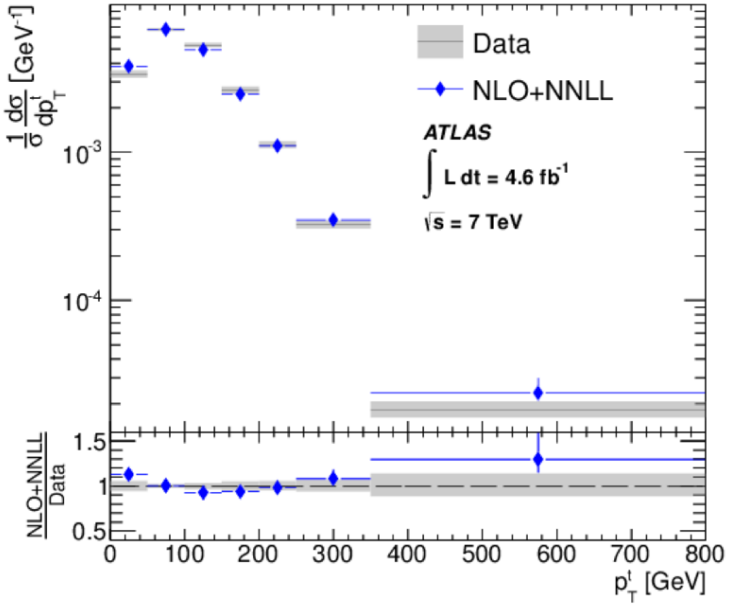
- **NLO+LO multileg generators matched with parton showers**

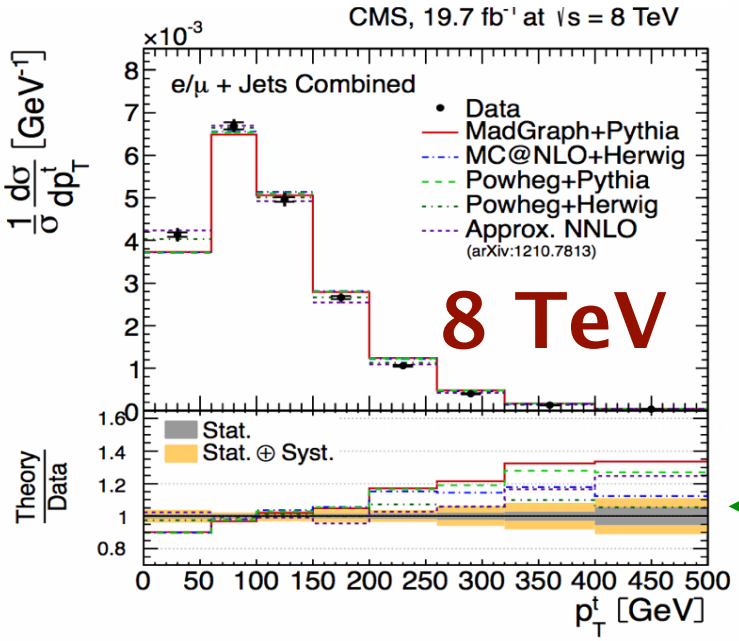
- **NNLO QCD calculations**



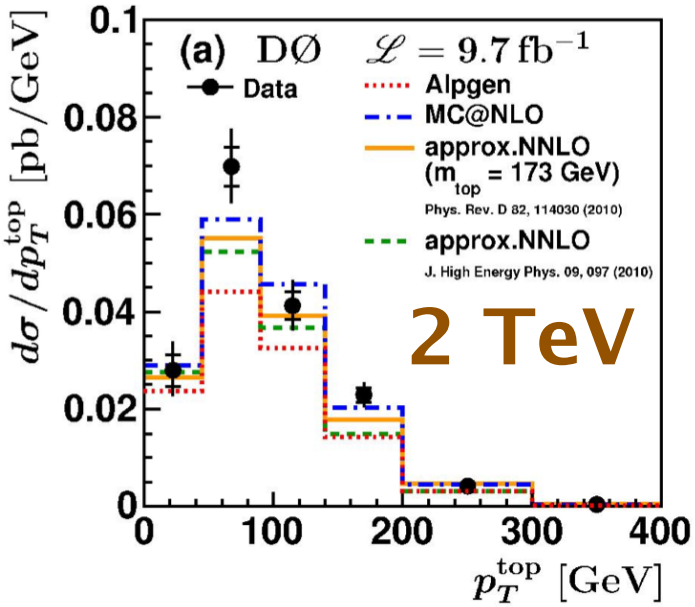
Differential, unfolded: top p_T

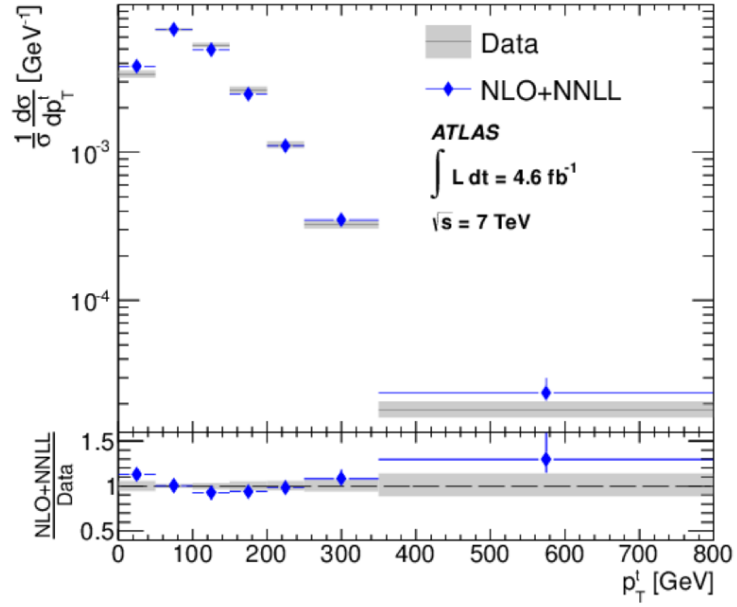




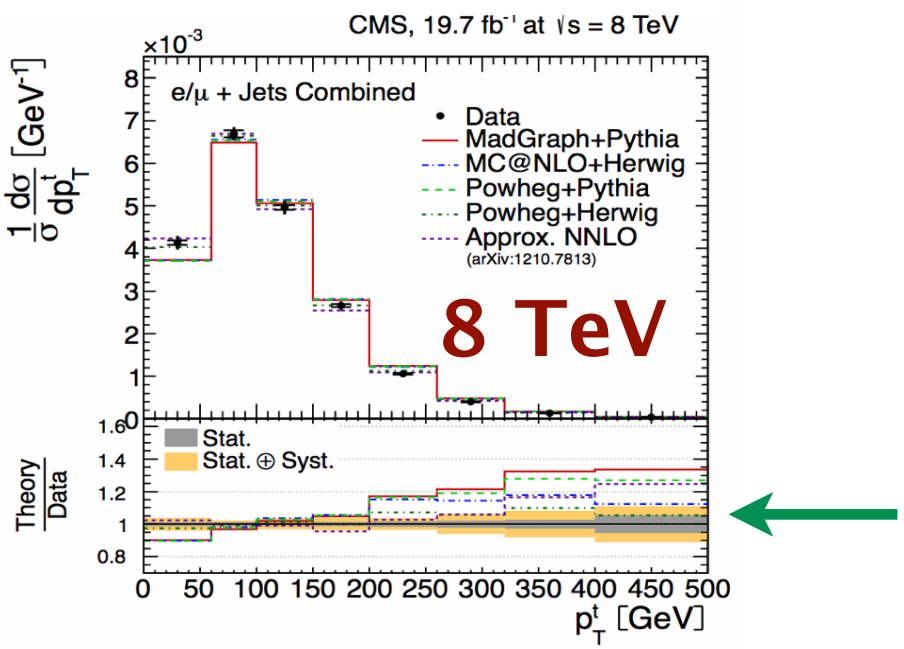


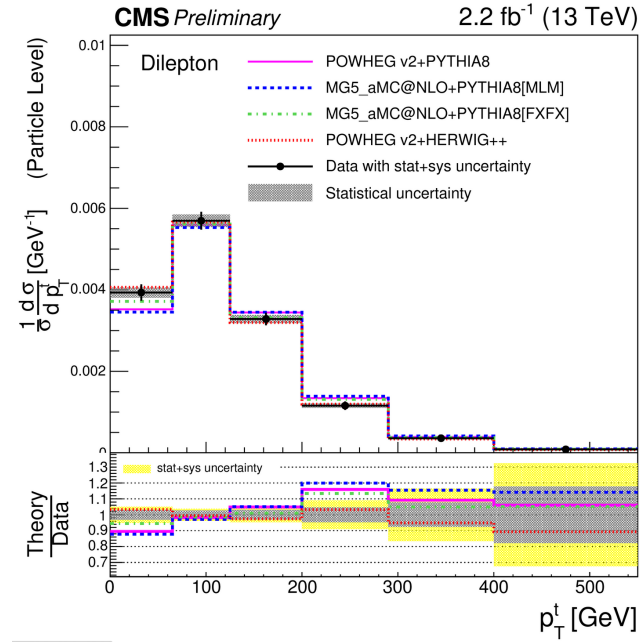
Differential, unfolded: top p_T





7 TeV

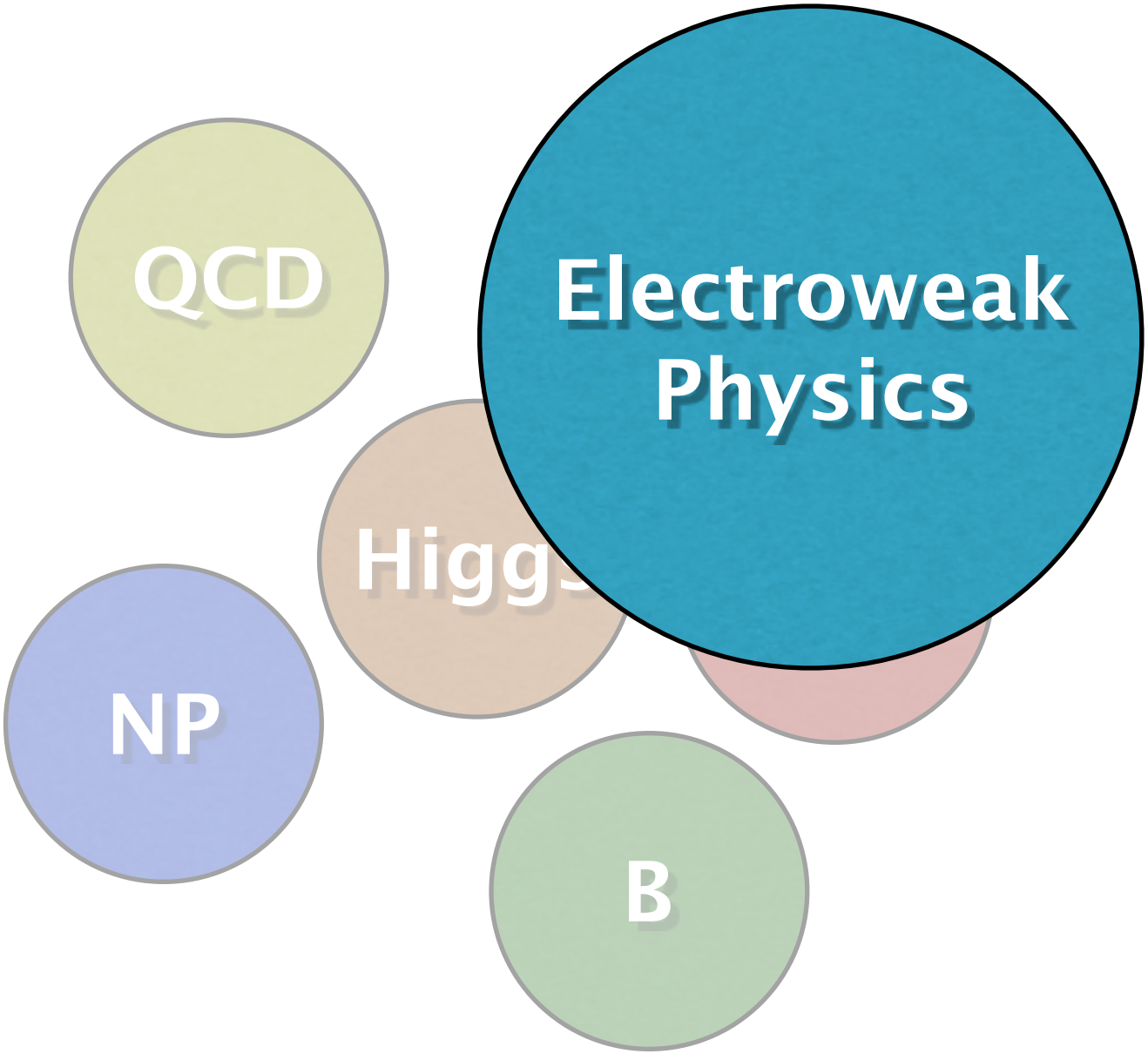




13 TeV

looks better

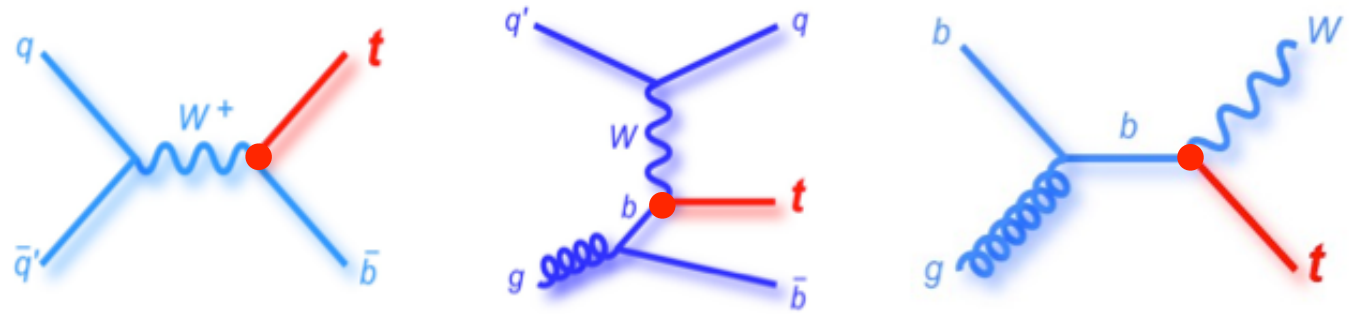
Top Quark Physics Topics

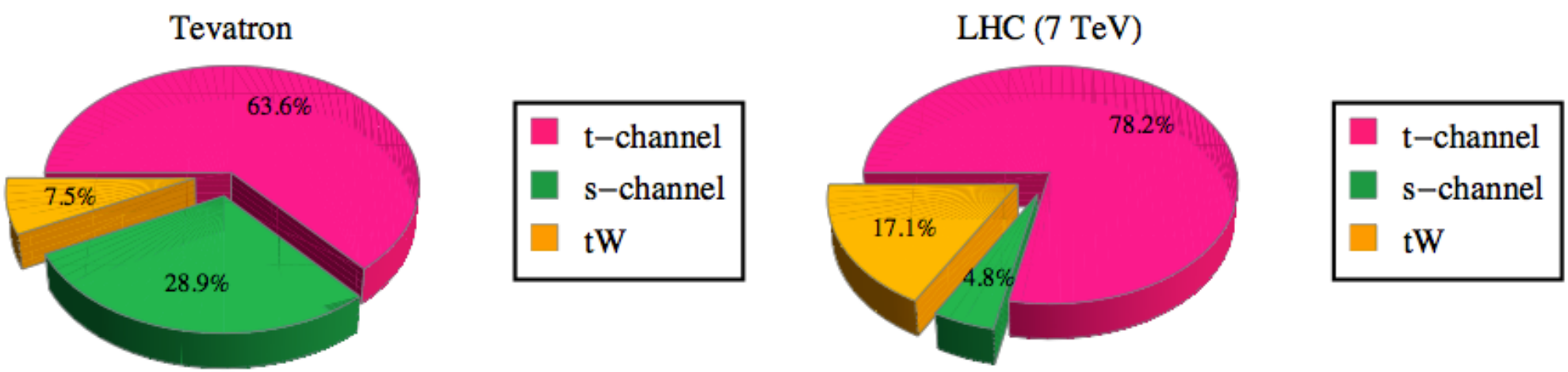


Single Top Quark Production

direct measurement of $|V_{tb}|$

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





⇒ important to measure all channels separately to search for new physics

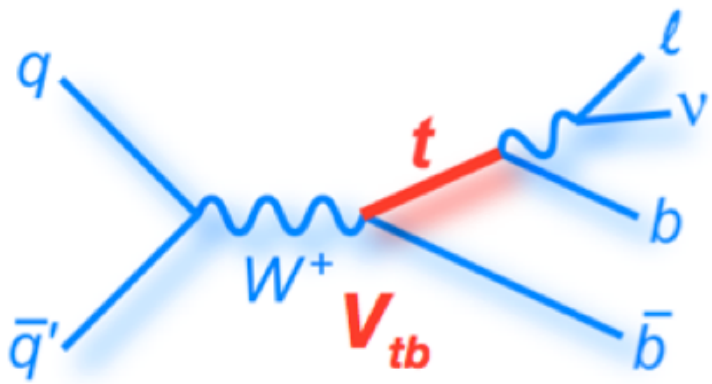
BUT: do not separate Wt in higher orders –an unphysical question!

Single Top Quark Selection

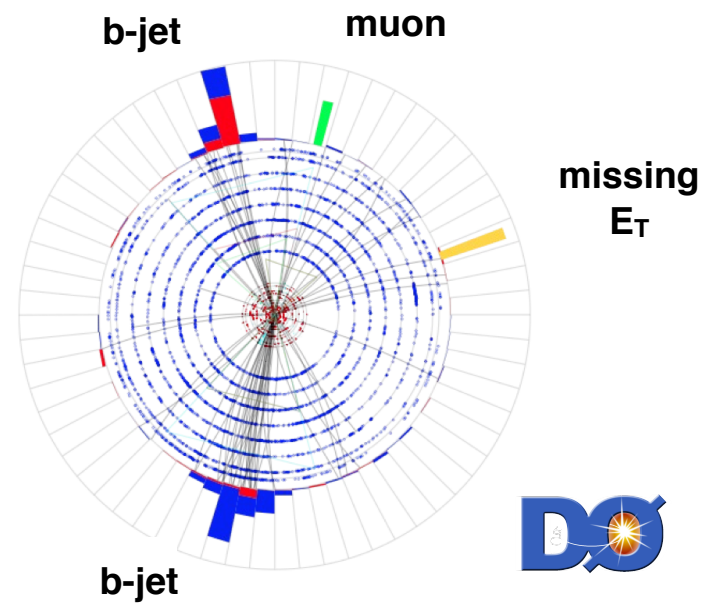
s-channel: $\sigma_s = 1.05 \pm 0.06$ pb

NLO+NNLL, $m_t = 172.5$ GeV

Kidonakis, PRD 81, 054028 (2010)



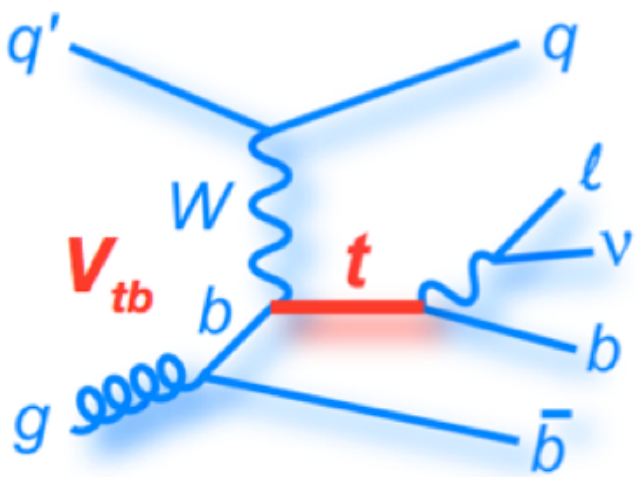
- lepton
- missing E_T
- b-jets



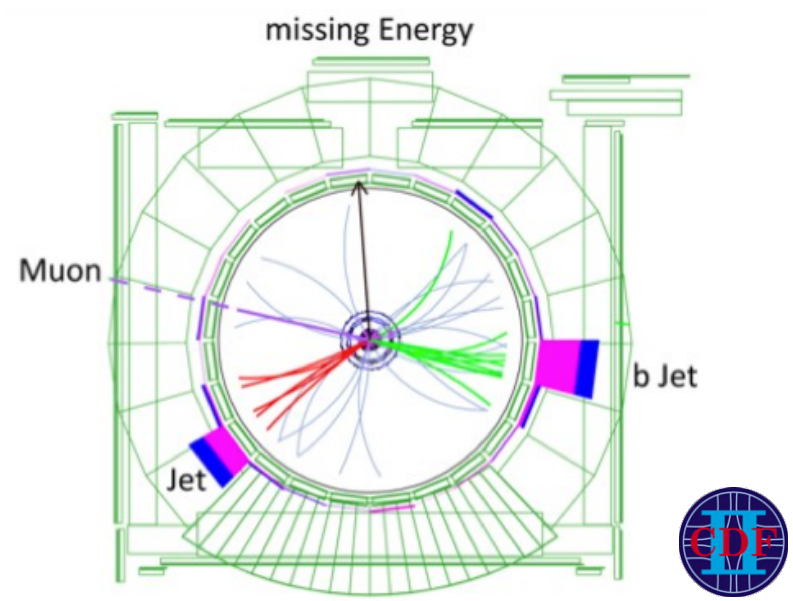
t-channel: $\sigma_t = 2.12 \pm 0.16$ pb

NLO+NNLL, $m_t = 172.5$ GeV

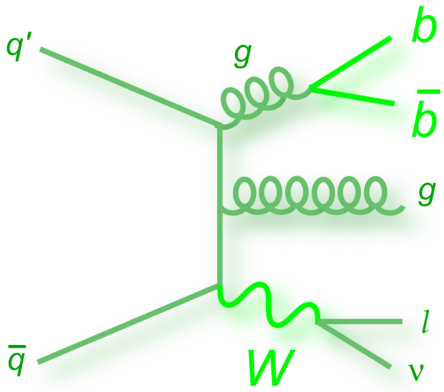
Kidonakis, PRD 83, 091503 (2011)

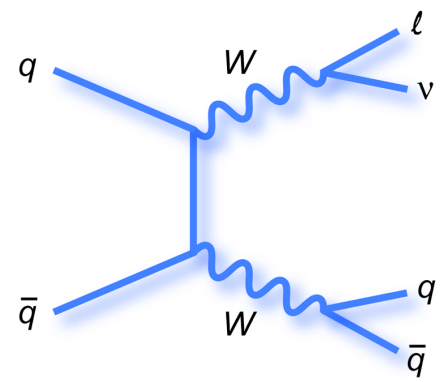


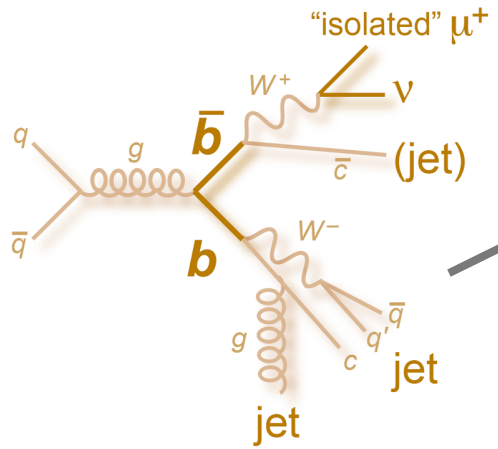
- jets
- lepton
- missing E_T
- b-jets

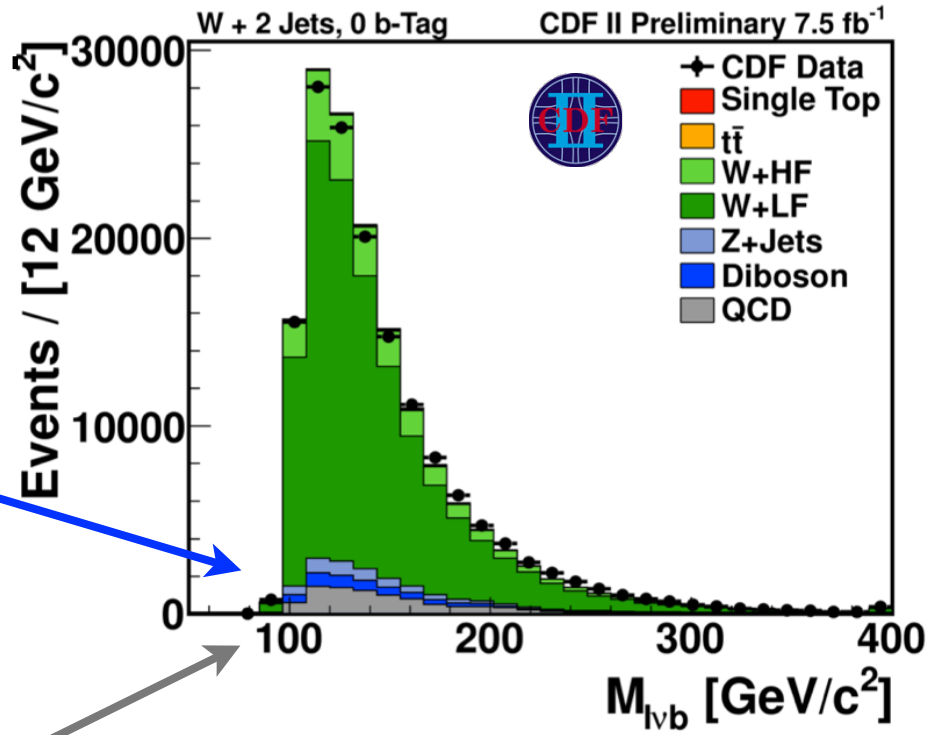


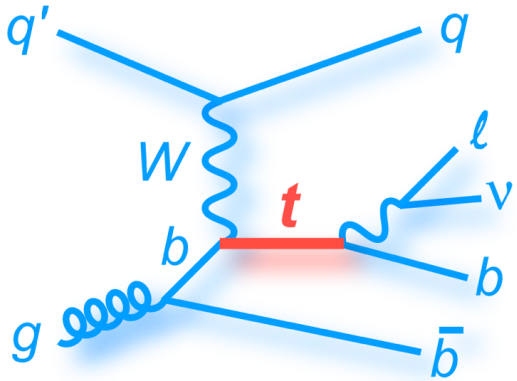
Single Top Quark Yields: pretag

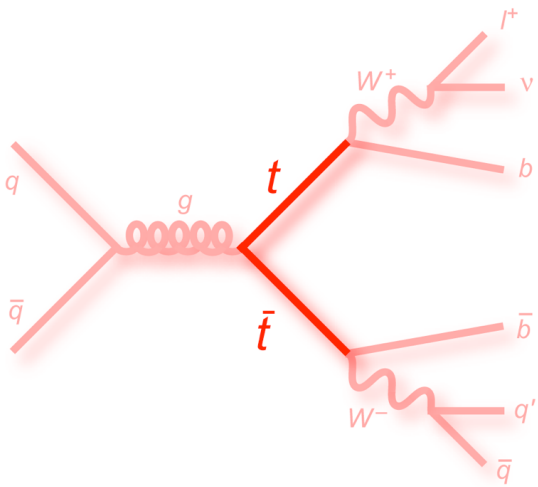






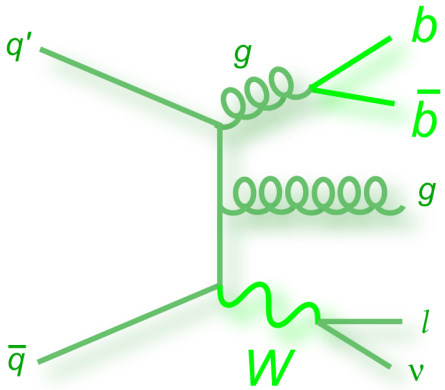


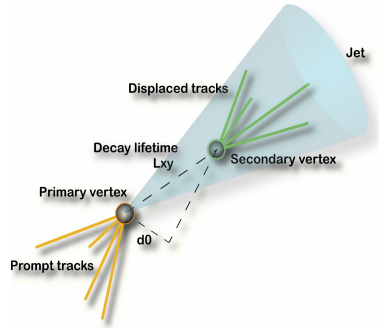


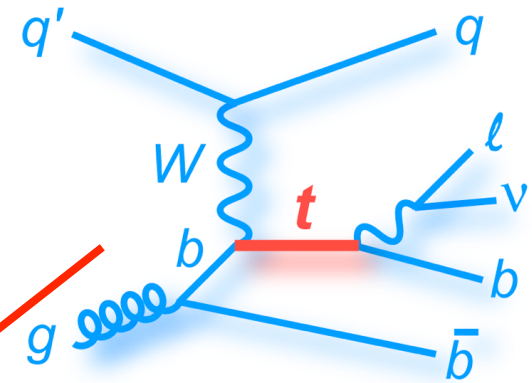


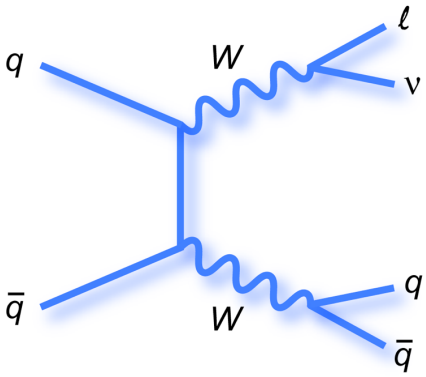
- **best s/b: ~1/200 before b-tagging**

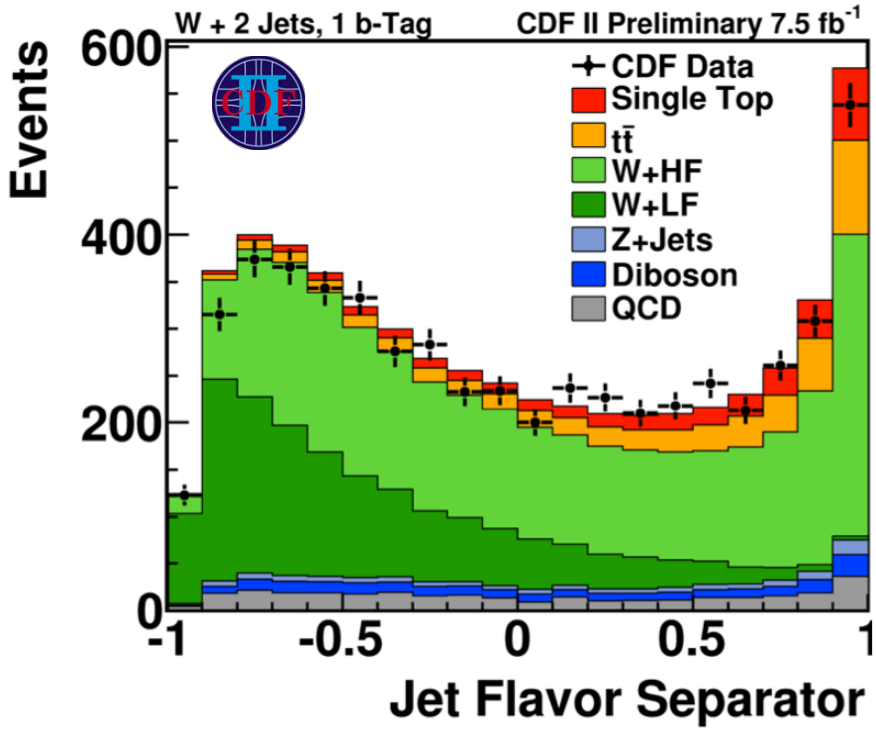
Single Top Quark Yields: b-tagged

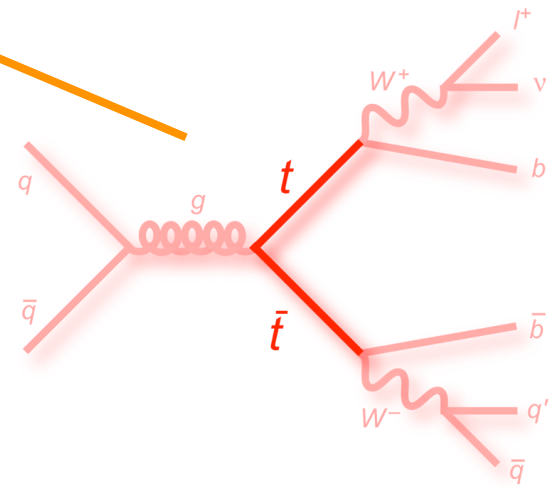


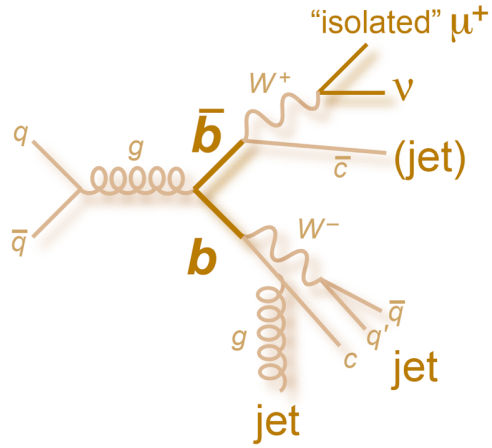






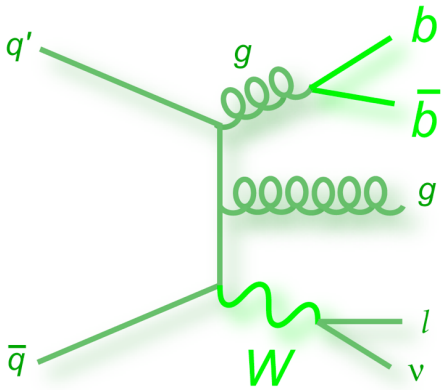


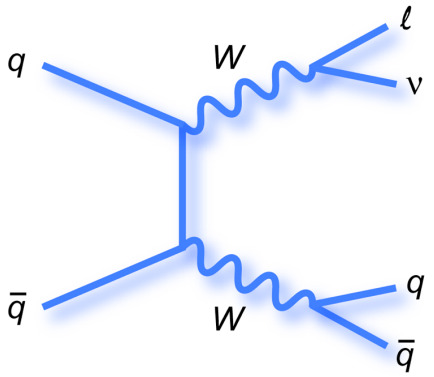


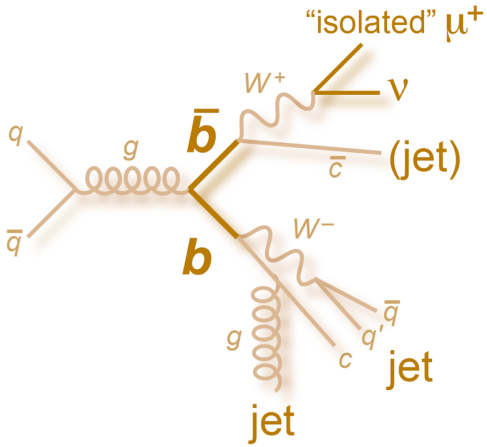


- best s/b: ~1/200 before b-tagging
- best s/b: ~1/10 after b-tagging

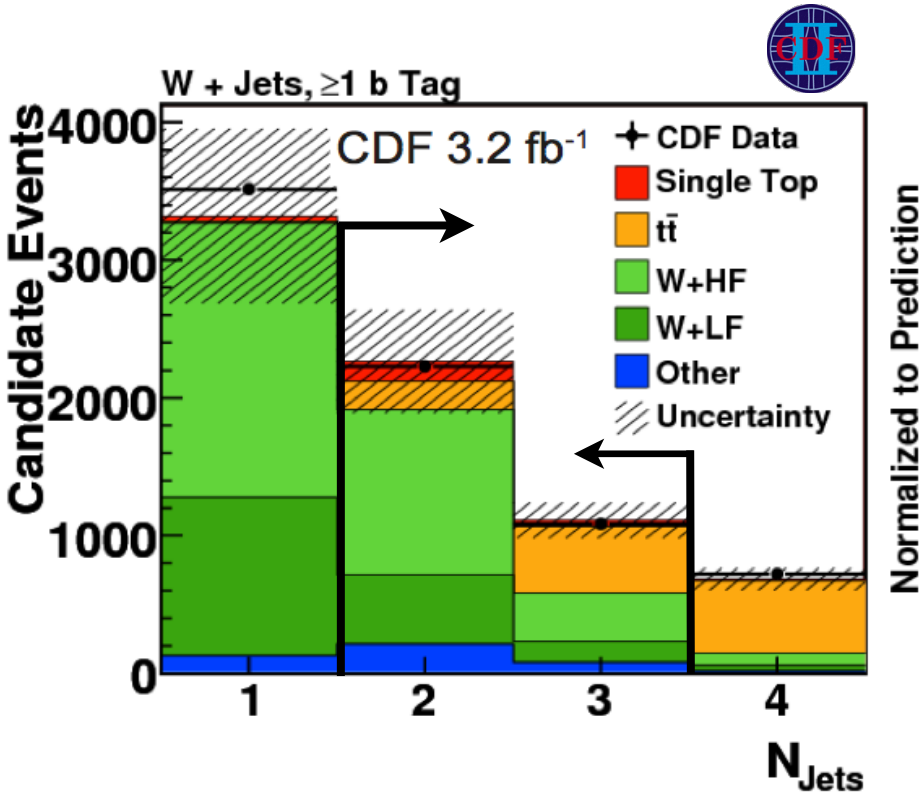
Single Top Quark Yields: b-tagged

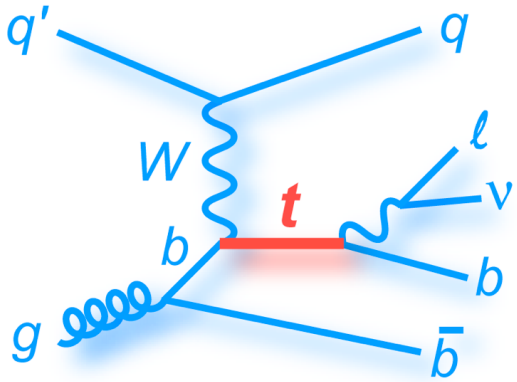


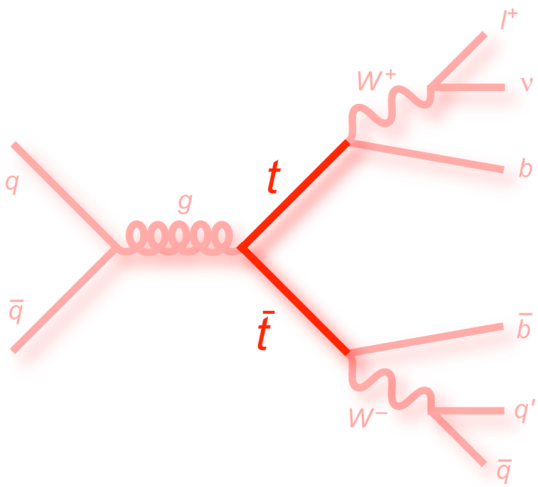




- number of jets and number of b tags to define samples



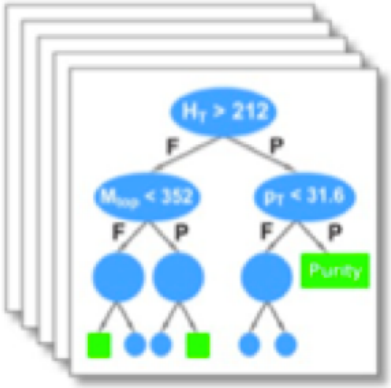




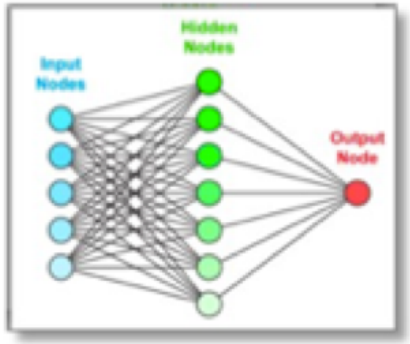
- best s/b: ~1/200 before b-tagging
- best s/b: ~1/10 after b-tagging

Multivariate Analyses

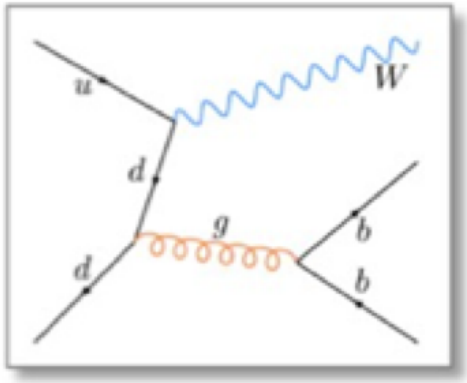
Boosted Decision Trees



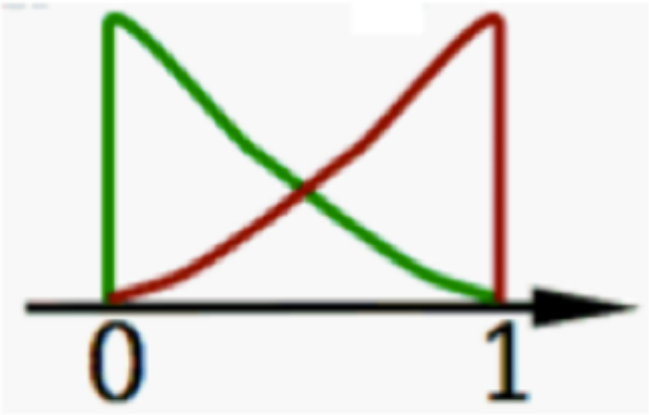
Neural Networks



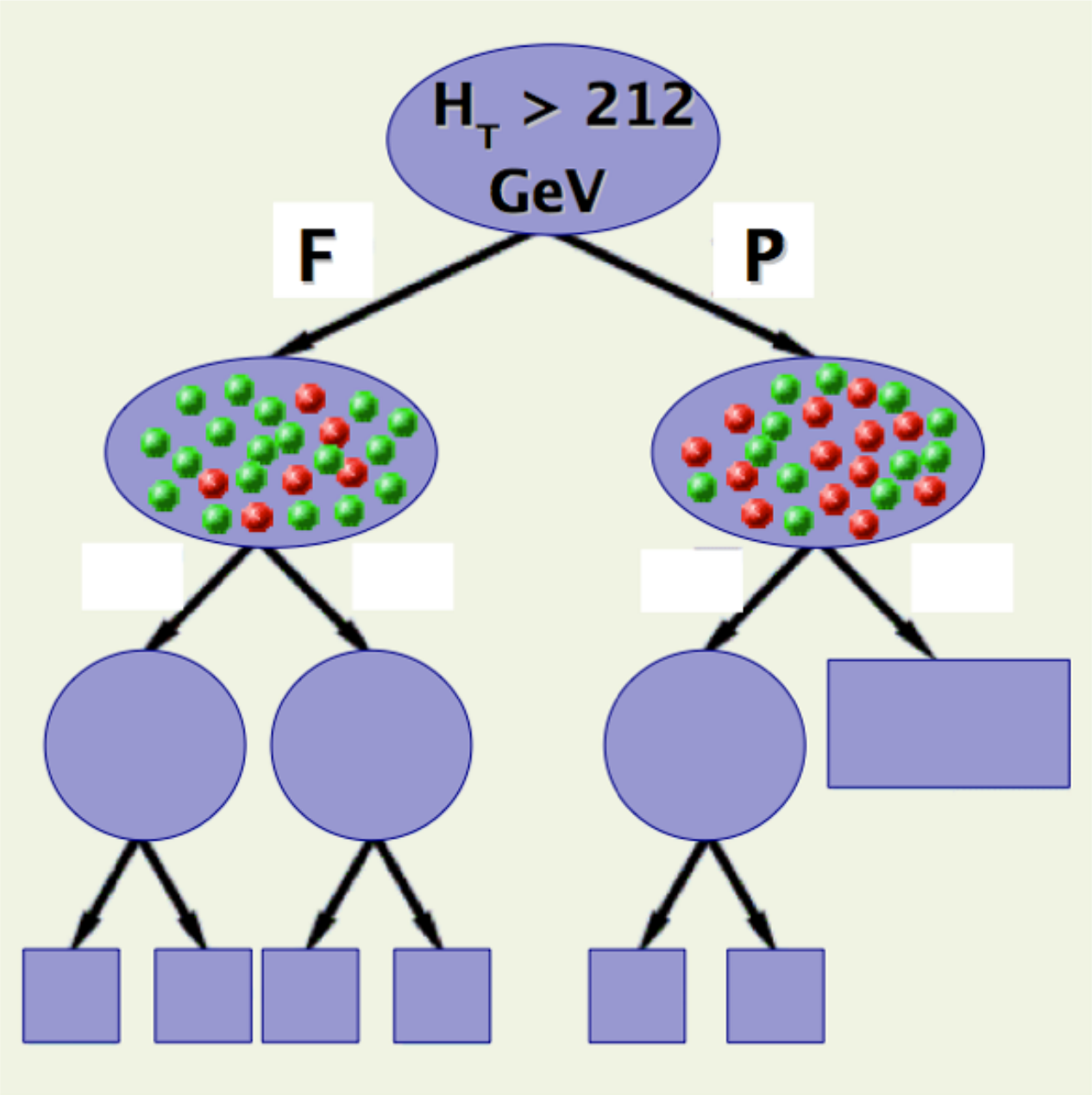
Matrix Elements



background **signal**

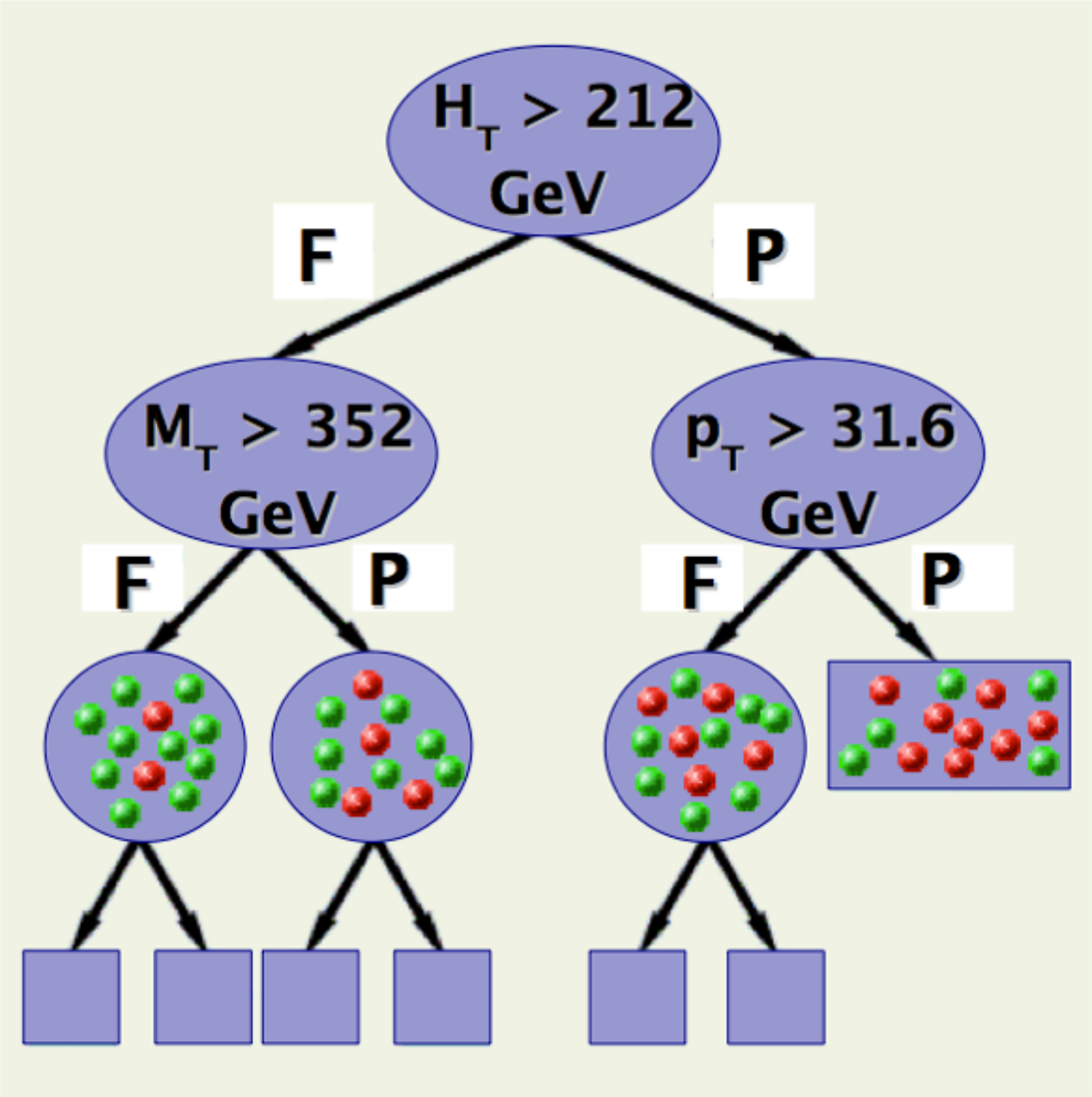


Boosted Decision Trees



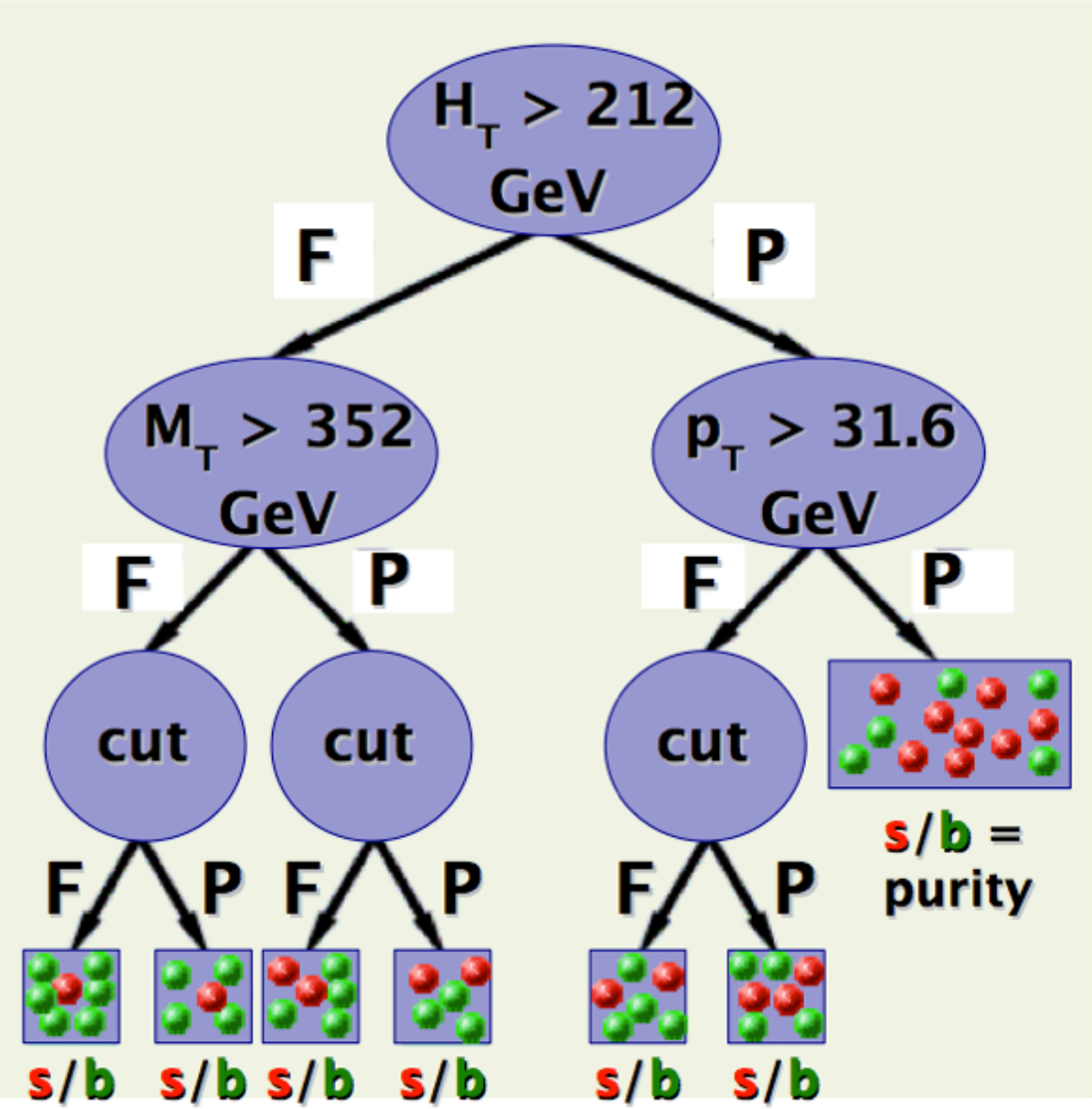
- **IDEA: recover events that fail criteria in cut-based analyses**

Boosted Decision Trees



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

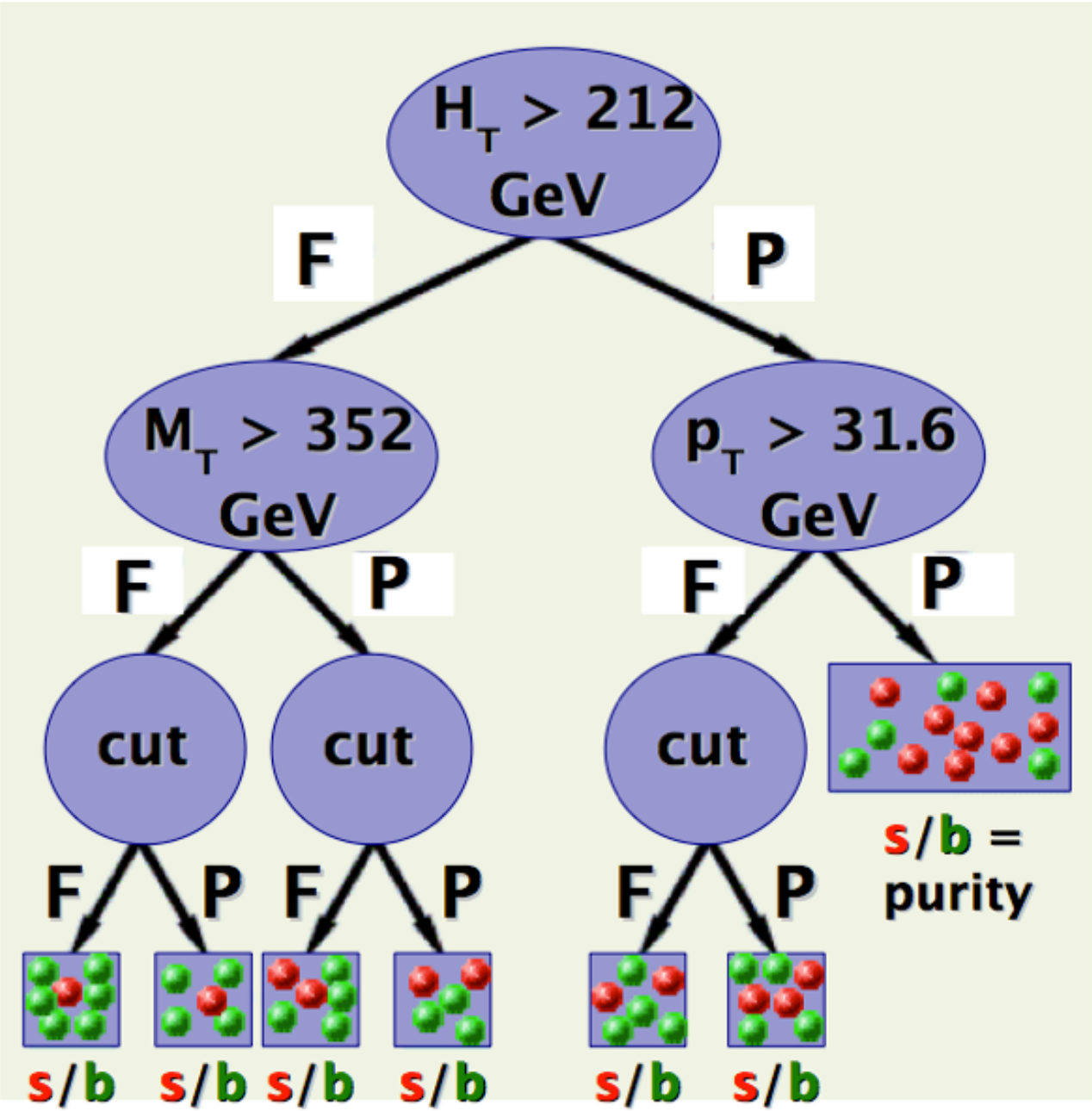
Boosted Decision Trees



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

- **result: weight for every event**

Boosted Decision Trees

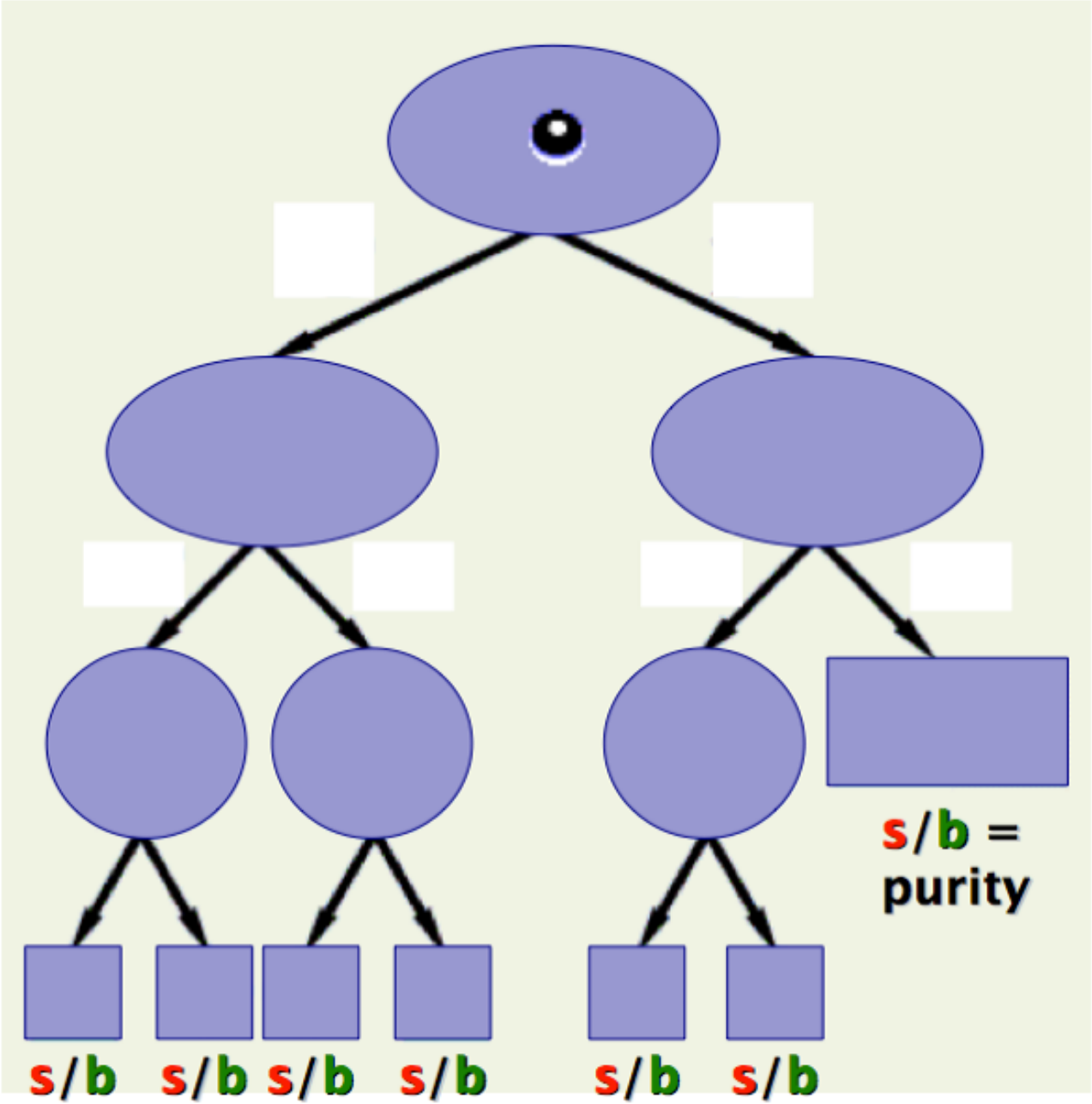


- **IDEA: recover events that fail criteria in cut-based analyses**

boosting:

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

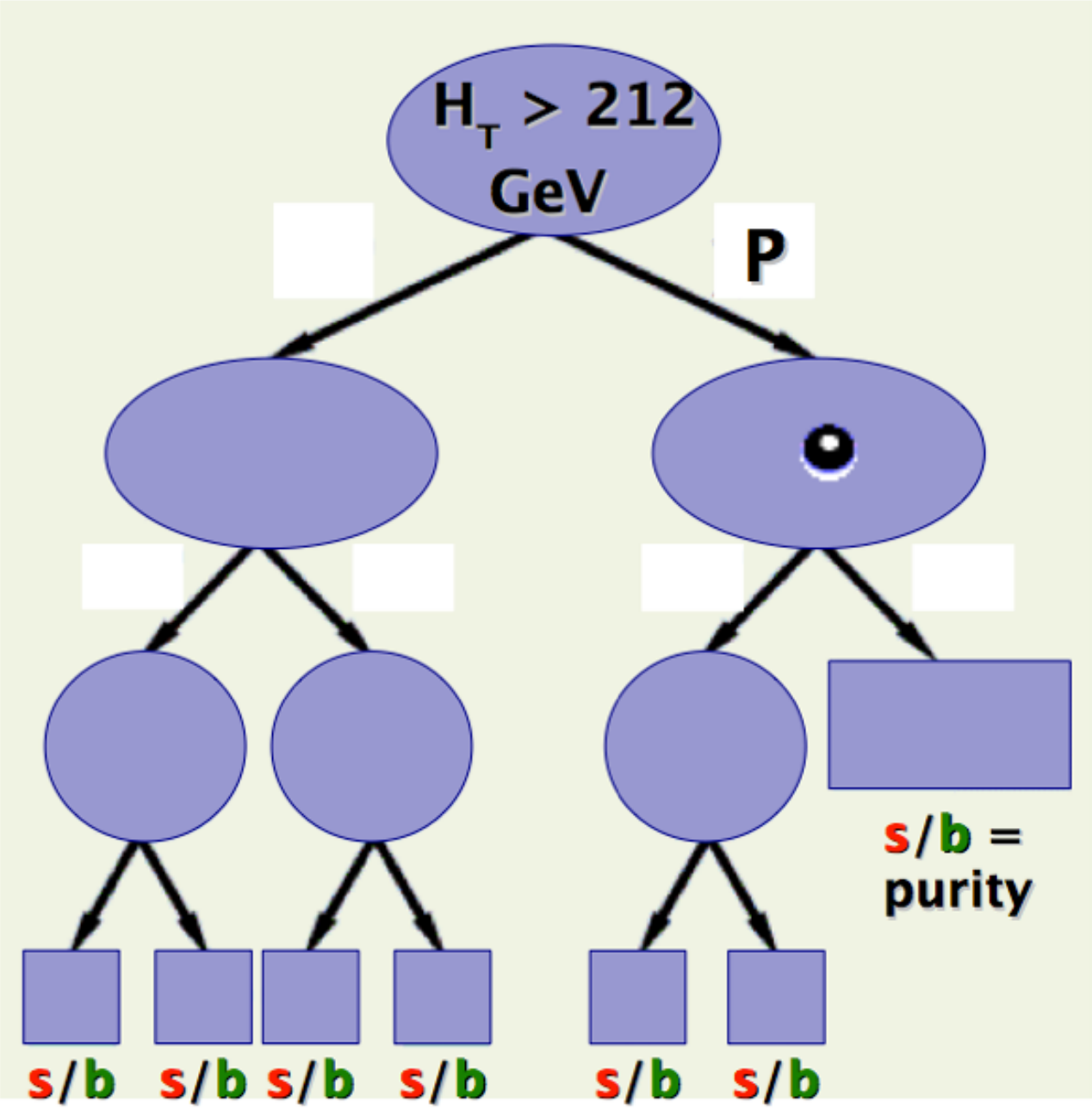
Boosted Decision Trees



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

- **result: weight for every event**

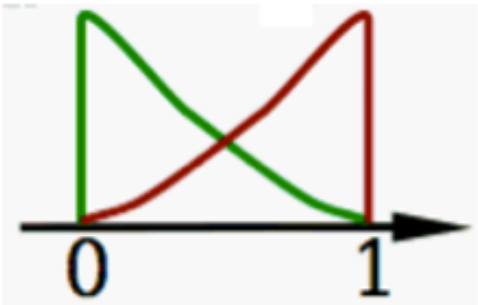
Boosted Decision Trees



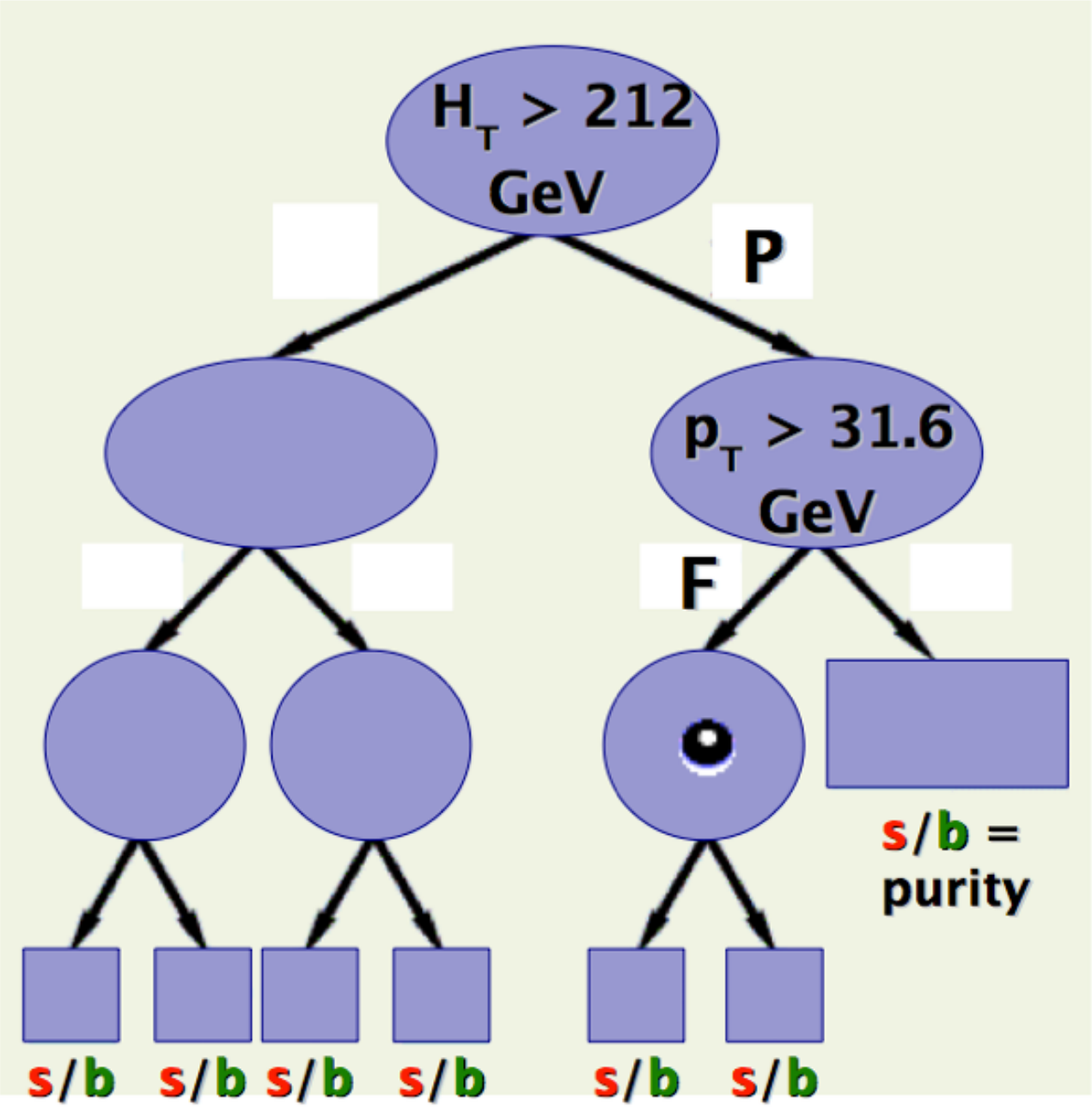
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background **signal**



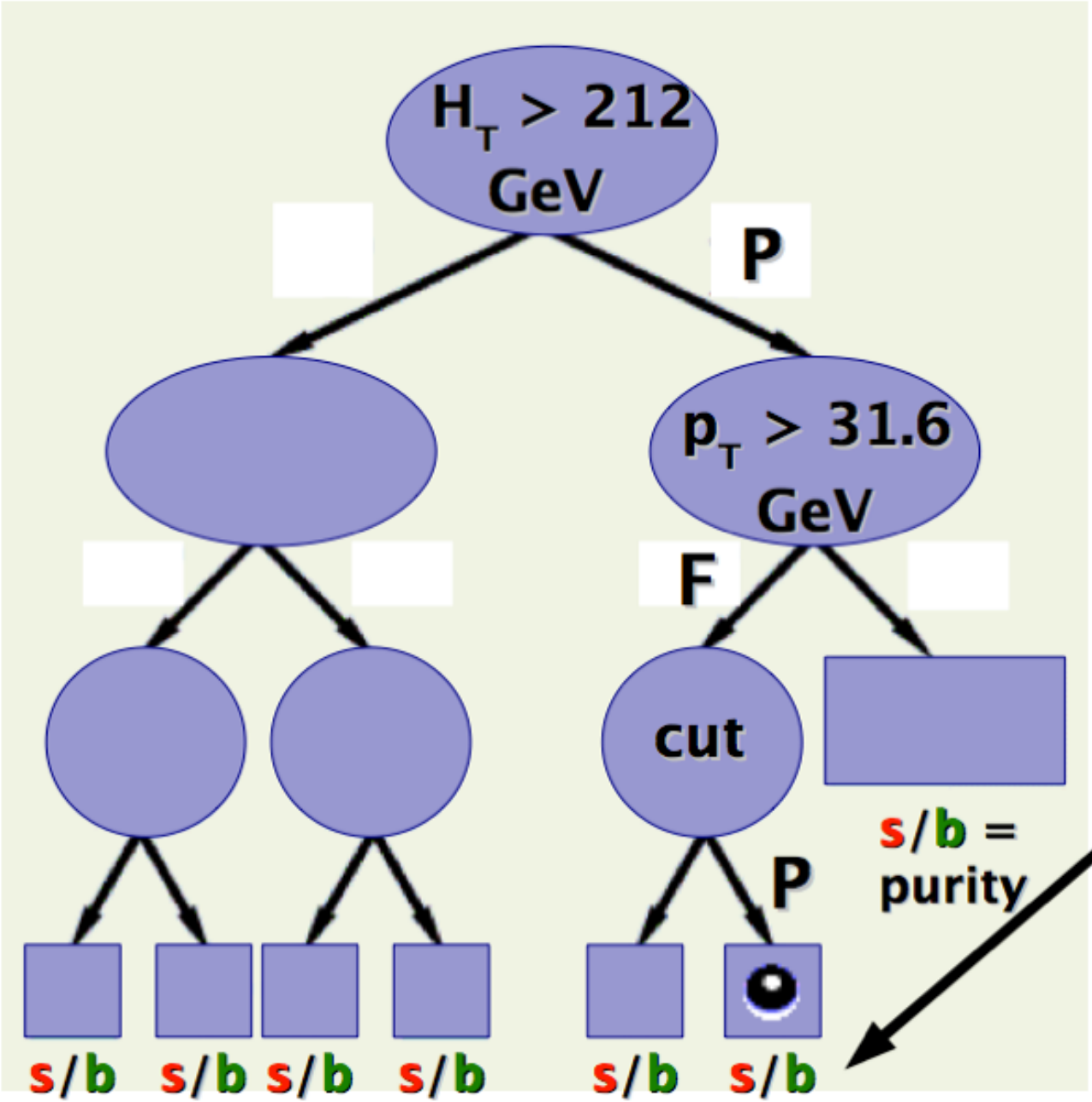
Boosted Decision Trees



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

- **result: weight for every event**

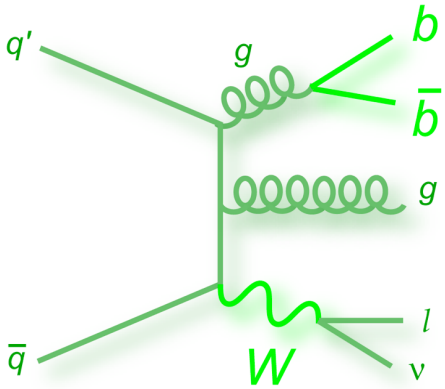
Boosted Decision Trees

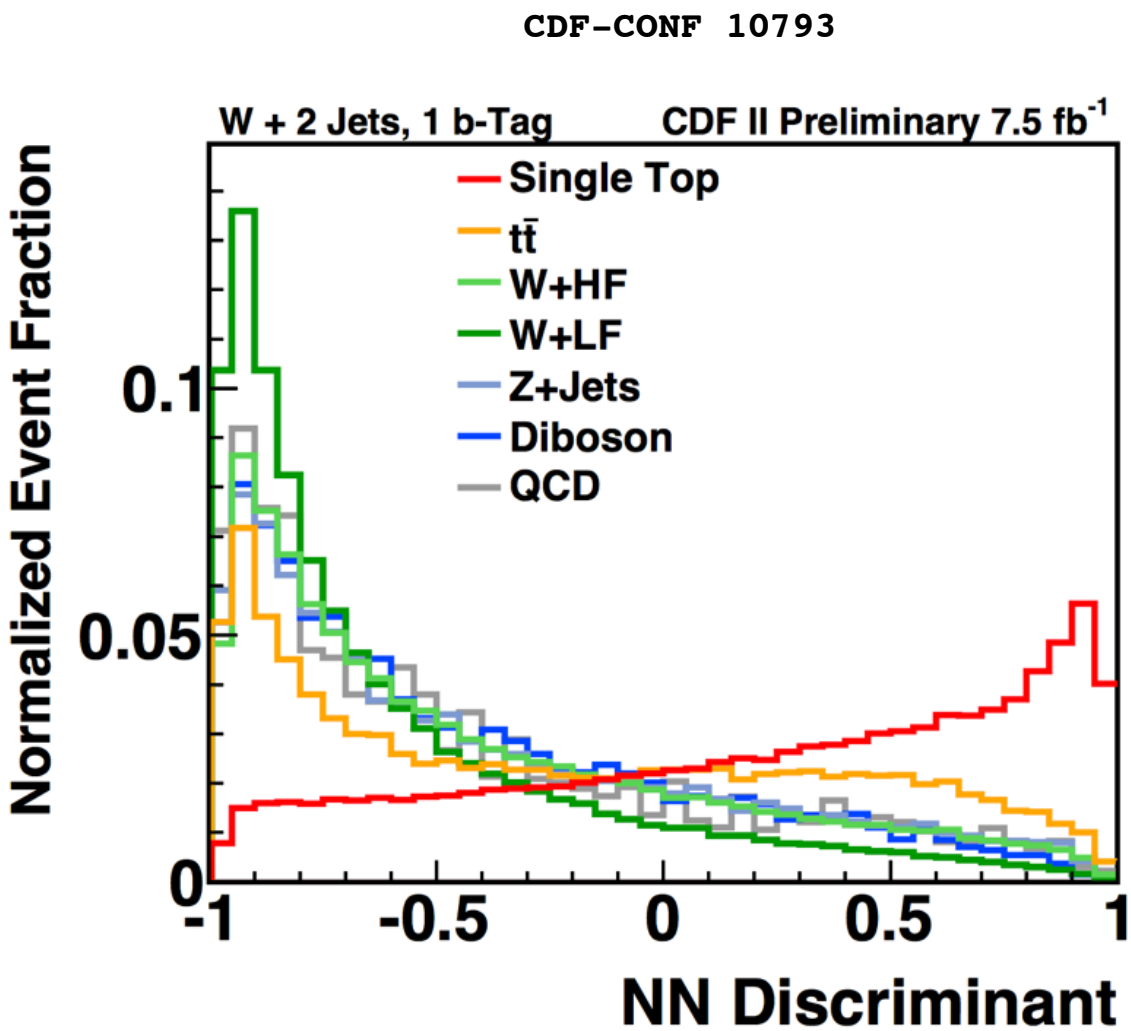


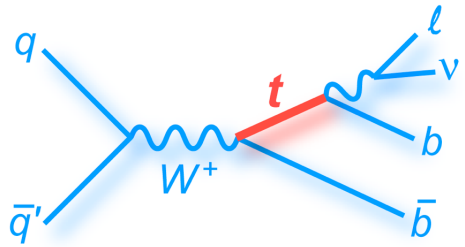
- **IDEA: recover events that fail criteria in cut-based analyses**

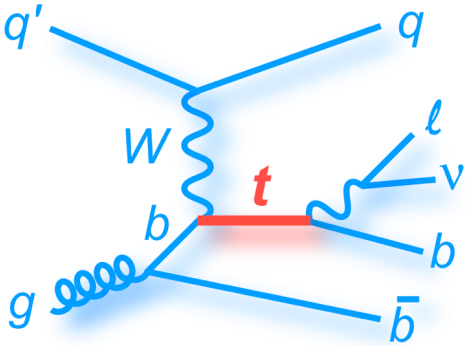
- **result: weight for every event**

Output Discriminant for s+t channel

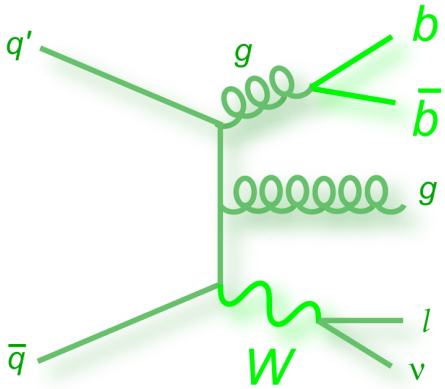




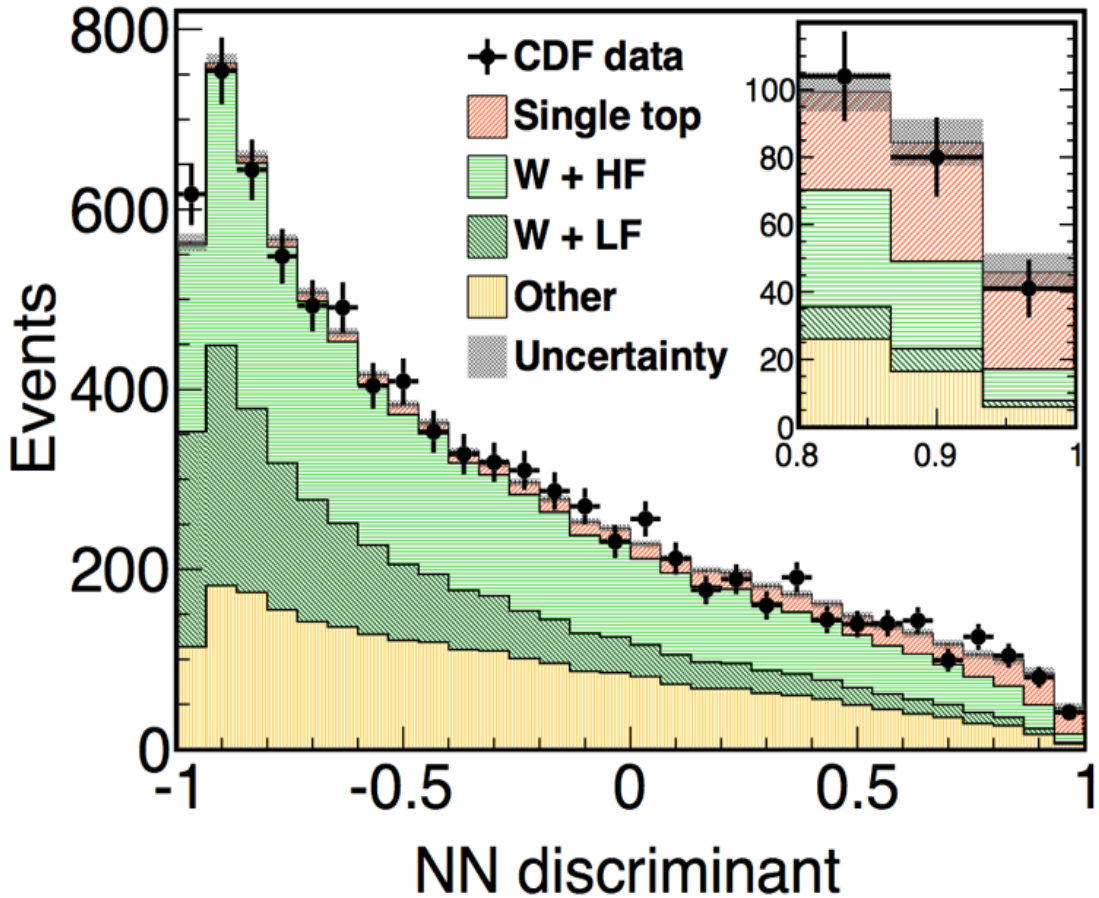


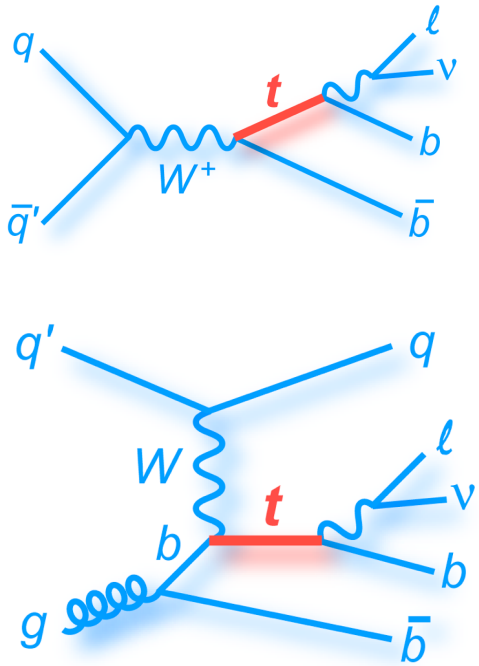


Output Discriminant for s+t channel



Phys. Rev. Lett. 113, 261804 (2014)

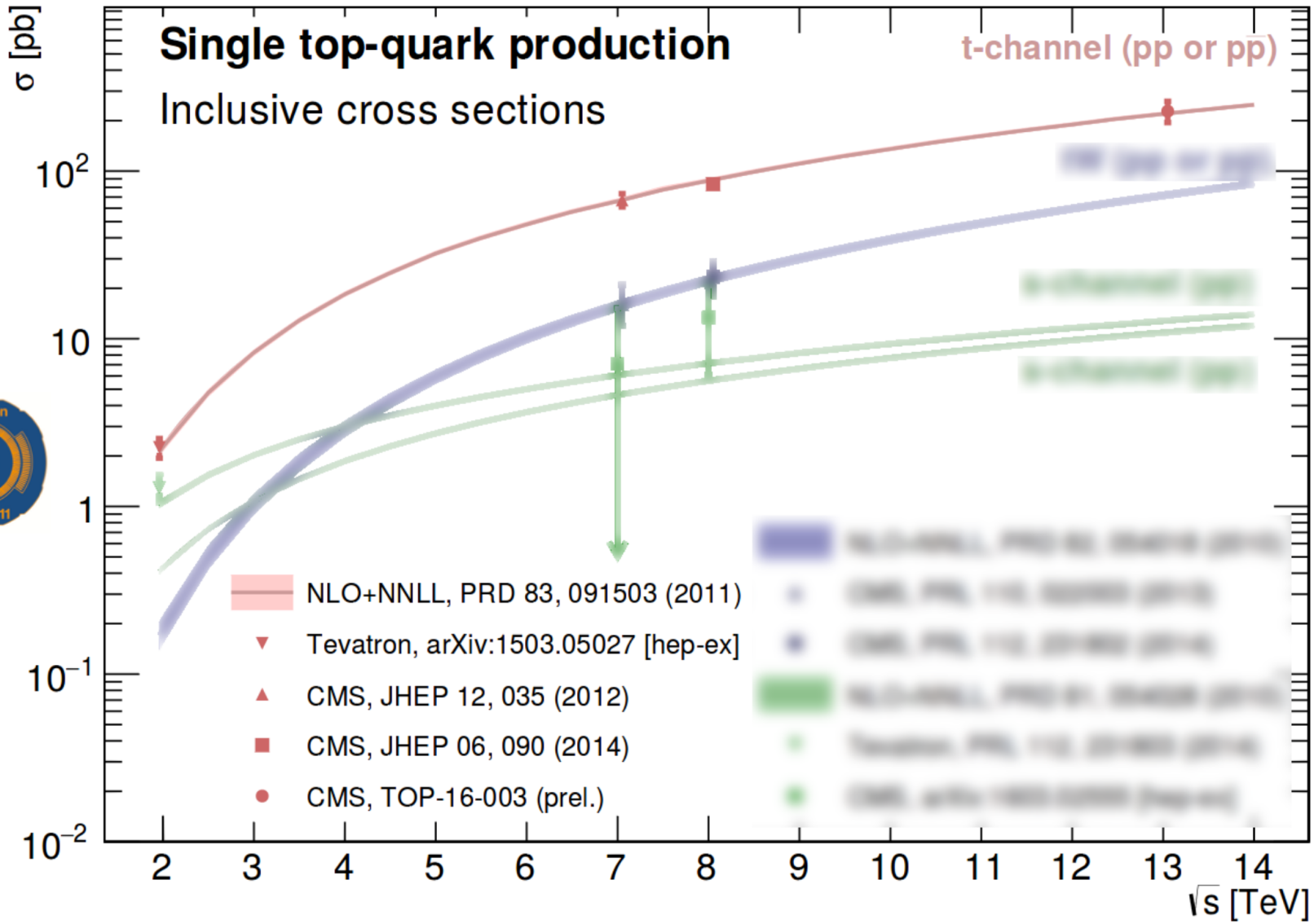


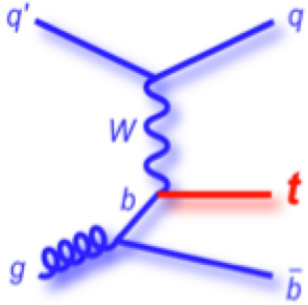


→ s+t channel observed by CDF and D0 in 2009

Single Top Quark Observation

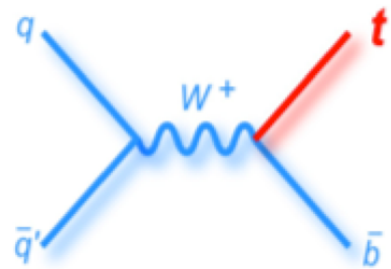
Single top t-channel cross section

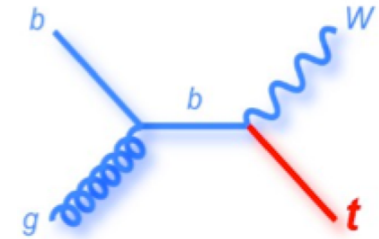


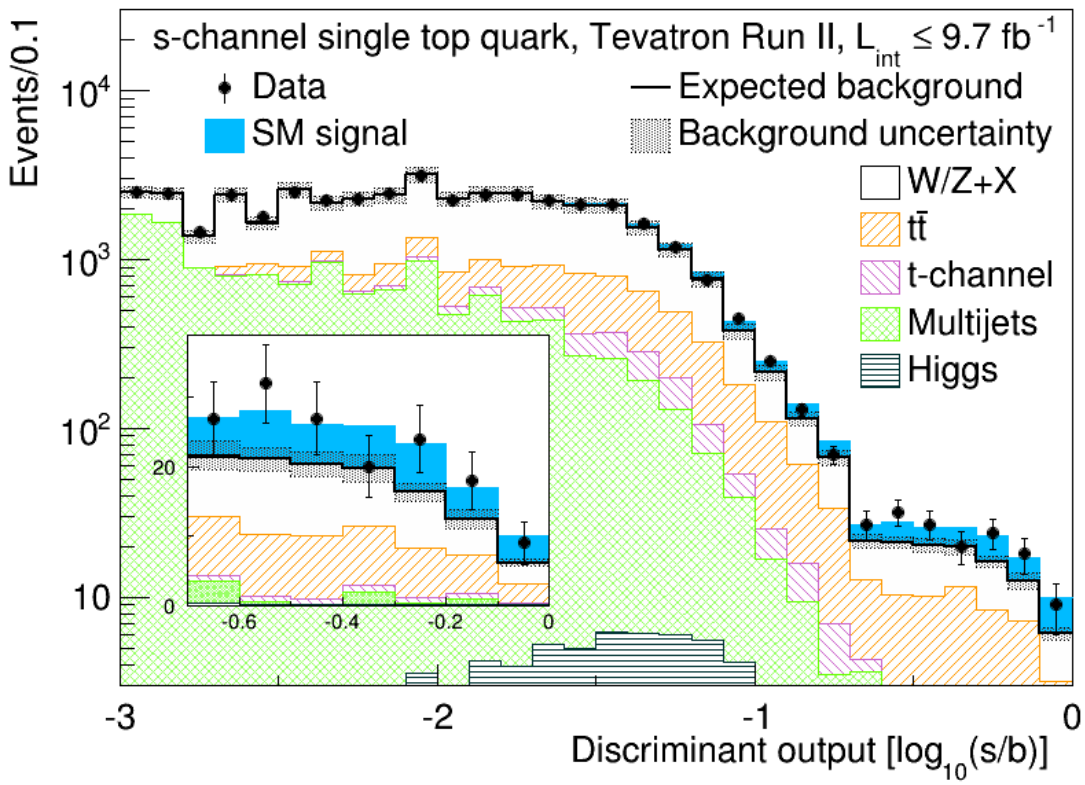


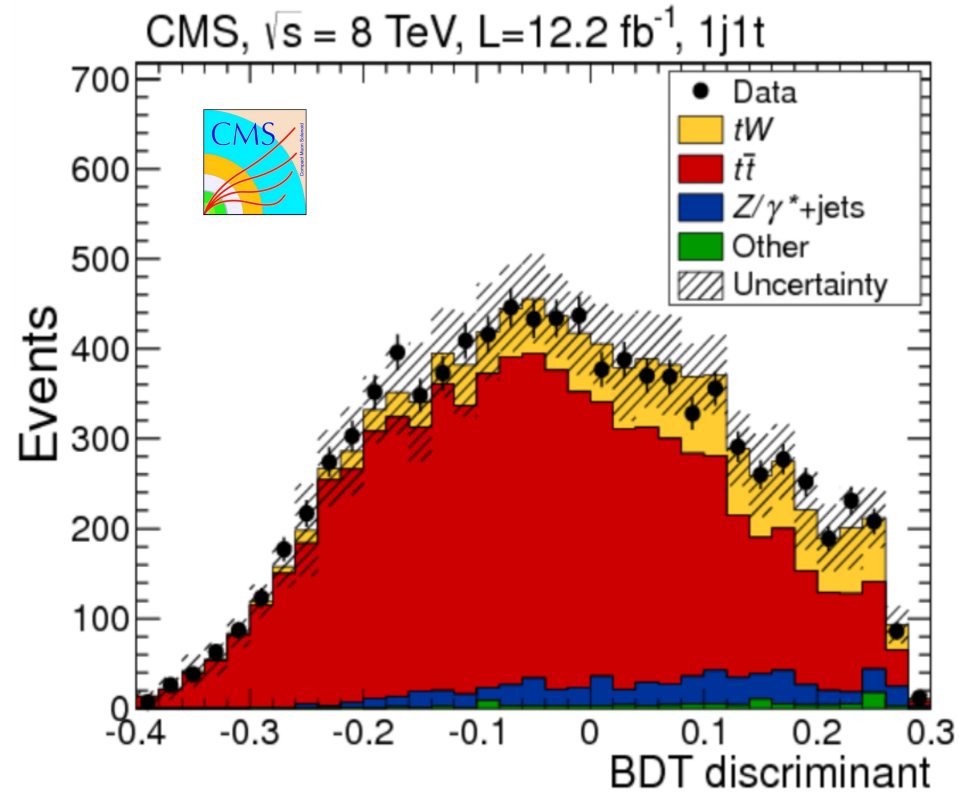
→ agreement with SM predictions!

s- and Wt-channel Production





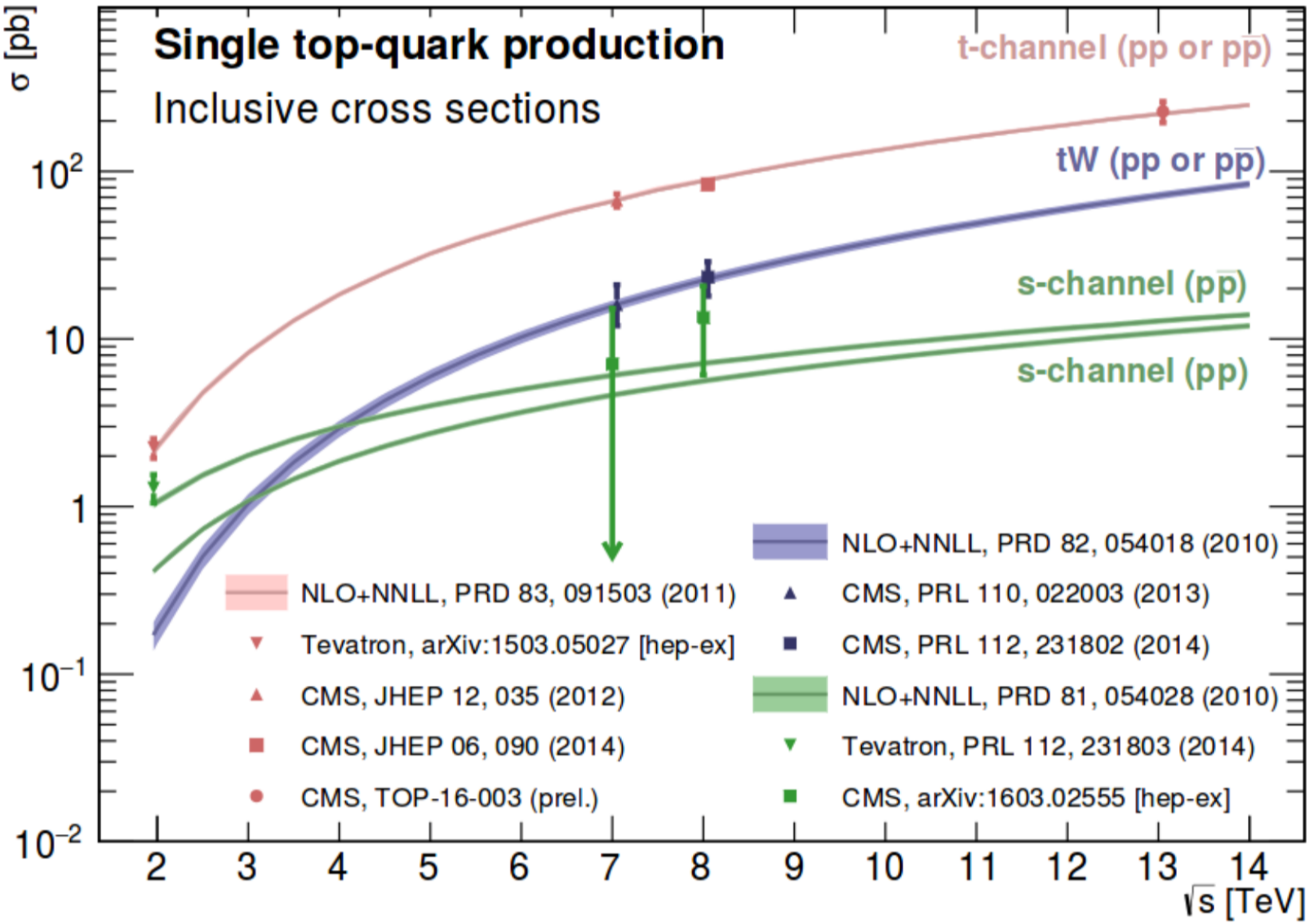


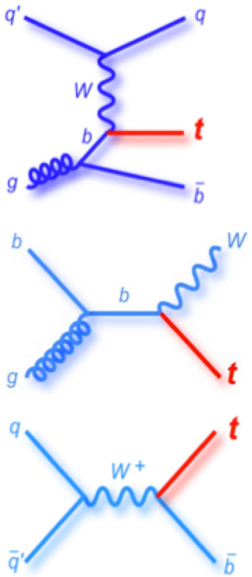


→ observation: 6.3 s.d.

→ observation: 6.1 s.d.

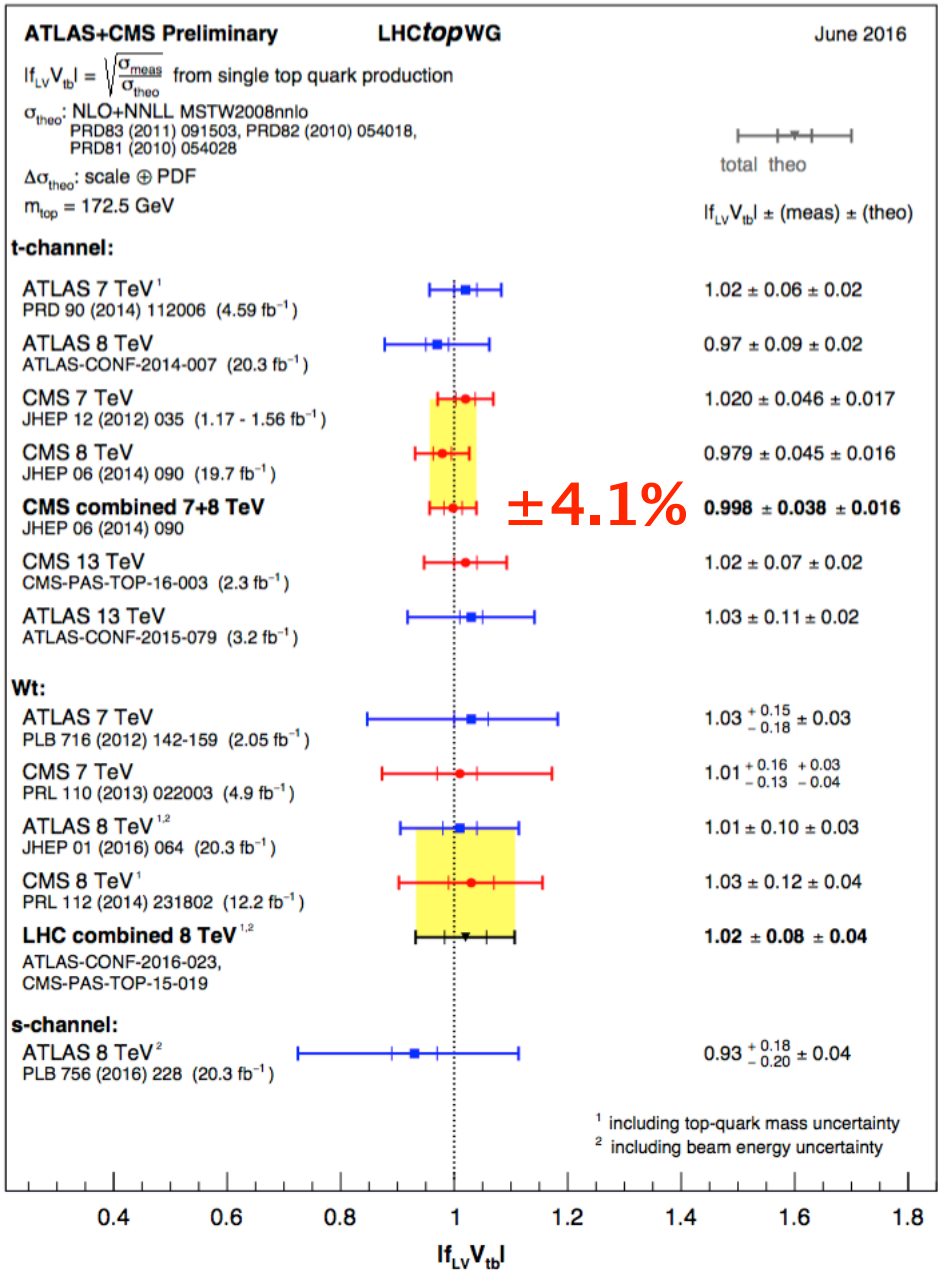
Single channel cross sections



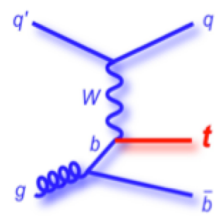


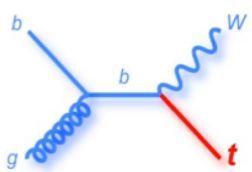
→ all production modes observed!

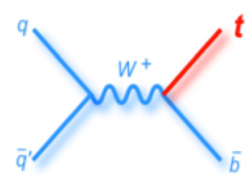
Direct measurement of $|V_{tb}|$



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







→ agrees with SM