Top Quark Physics

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University of California, Davis

Hadron Collider Physics Summer School
Fermilab - August 2016

Lecture Outline

- A little bit of history of discoveries
- About the top quark
- Top quark pair production
- Single top quark - electroweak production?
- ~~Top quark mass~~
- ~~Top quark properties~~
- ~~Boosted top quarks~~
- ~~Searches for new physics in top~~

These are summer school lectures, not the latest plots, but useful for teaching!

Ancient Greeks: What is the world made of?

"By Convention there is color,

by convention sweetness,

by convention bitterness,

but in reality there are atoms and space."

-Democritus (c. 585 BC)

Atom = Mushy Ball (c. 1900)

1894-1897: JJ Thomson discovers the electron

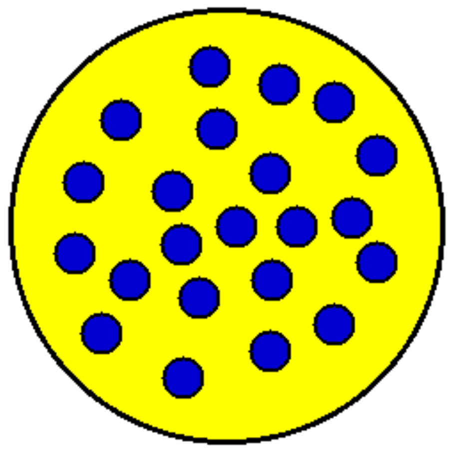
Study of "cathode rays": electric current in tubes at very low gas pressure ("glow discharge")

Measurement of the electron mass: $m_e \approx M_H/1836$

> **"Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?" (J.J. Thomson)**

ATOMS ARE NOT ELEMENTARY!

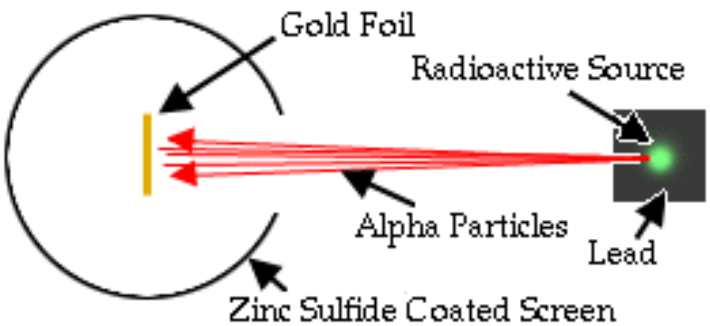
- Electrically charged sphere
- Radius ~ 10^{-8} cm
- Positive electric charge
- Electrons with negative electric charge embedded in the sphere



Thomson's atomic model

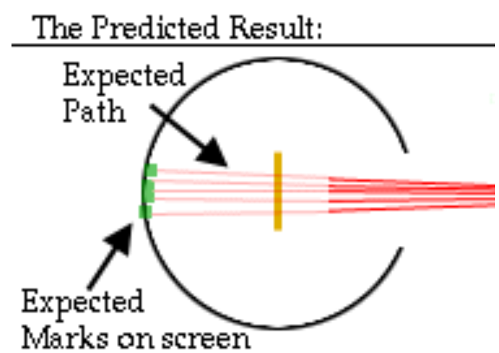
1906: "..*in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity by gases.*"

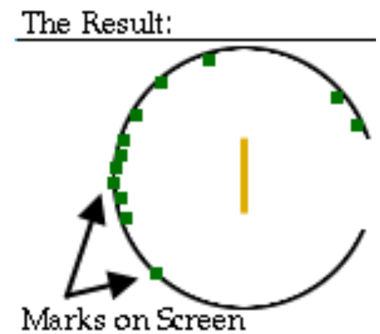
Rutherford's scattering experiment



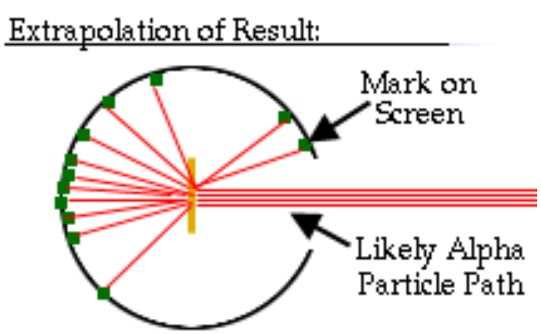
Apparatus

Hypothesis

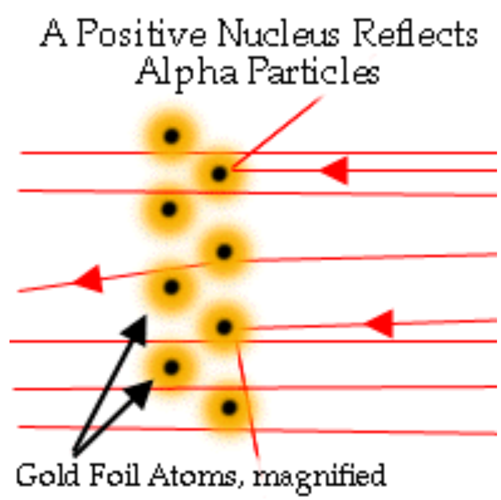




Results (data)



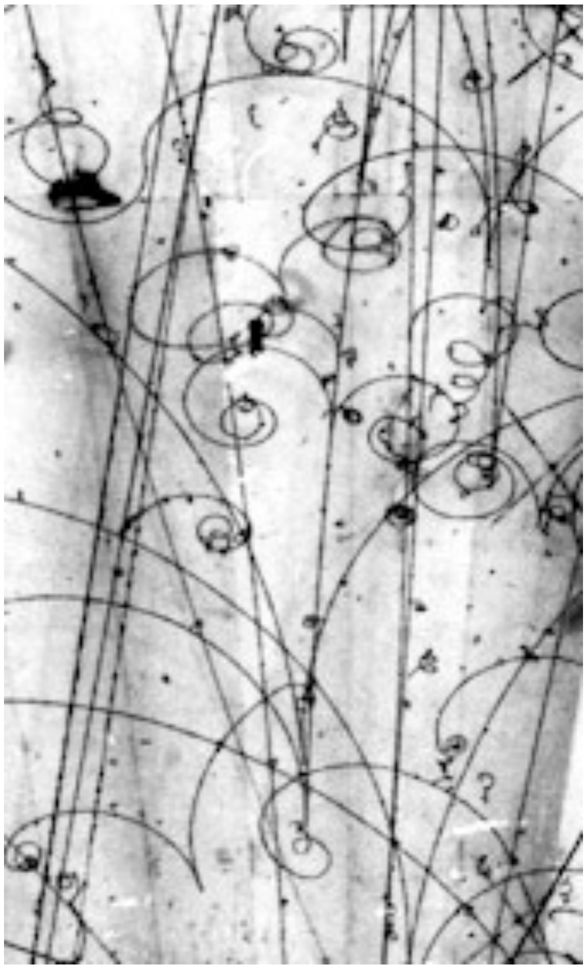
Analysis



Conclusion: A Nucleus!

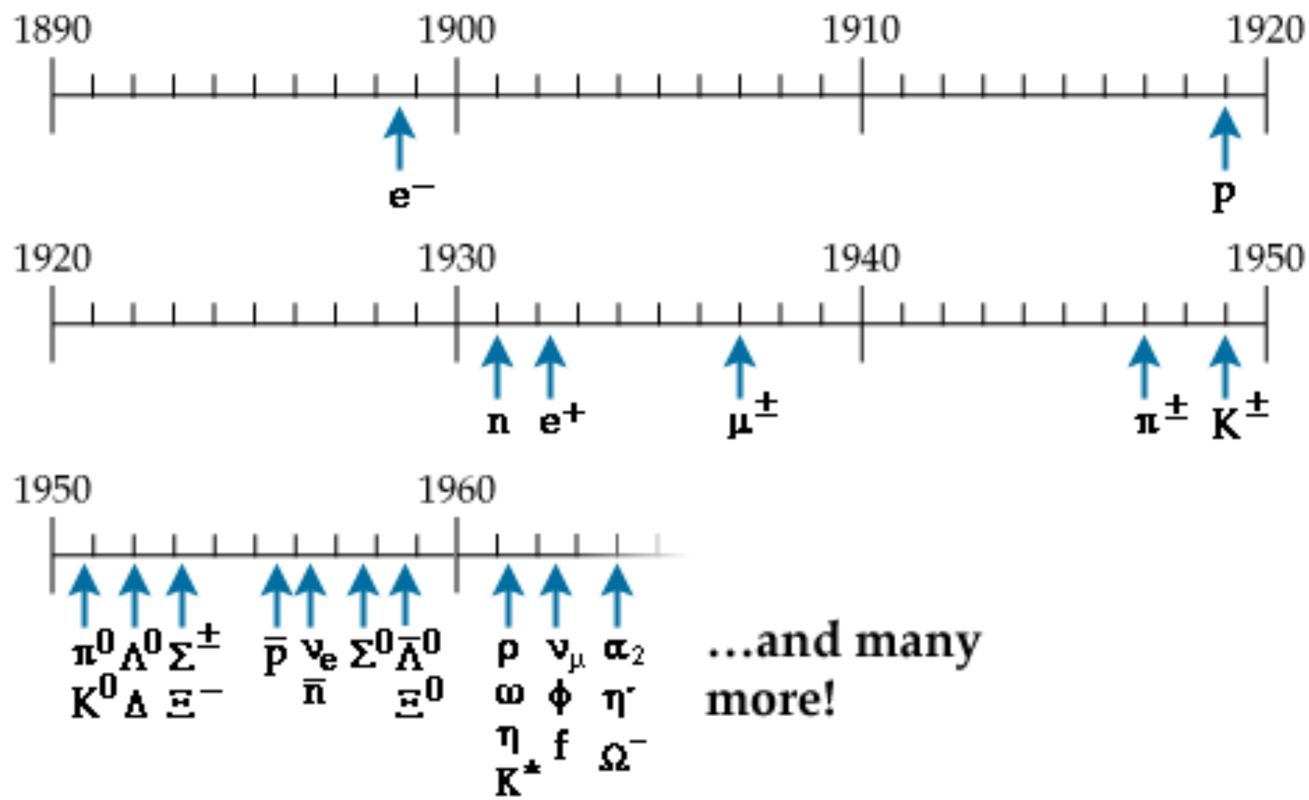
students: Geiger and Marsden

Experiments progressed: new types of matter!



Fermilab: Bubble Chamber Photo

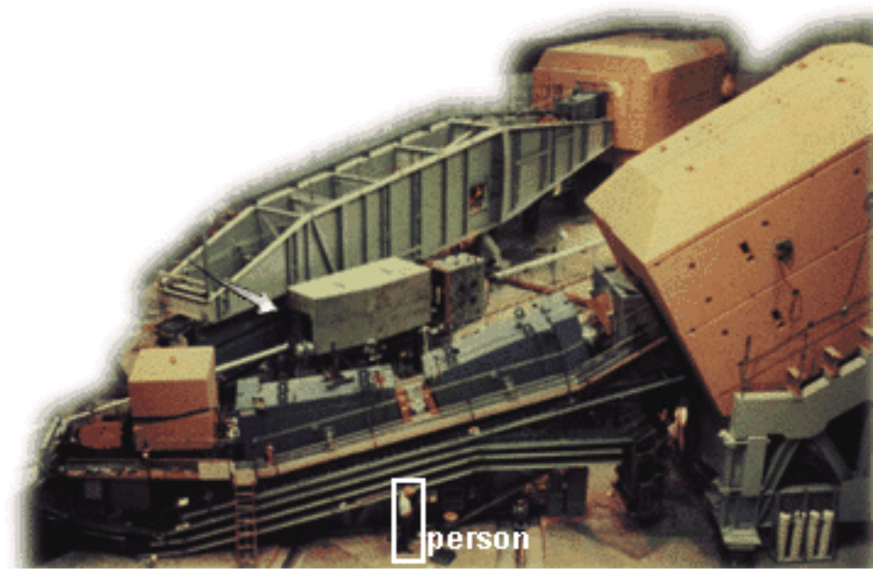
more and more mystery particles...



Electron-Proton Scattering

Test of the Quark Idea

The Stanford
Linear Accelerator
Center



EndStation A:
Beam of Electrons onto Target

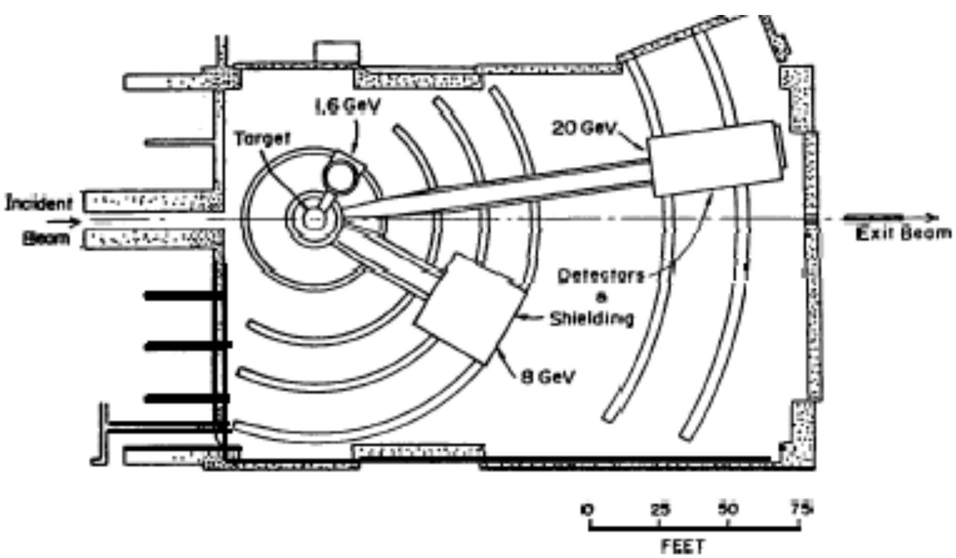
The Stanford two-mile electron linear accelerator (SLAC)

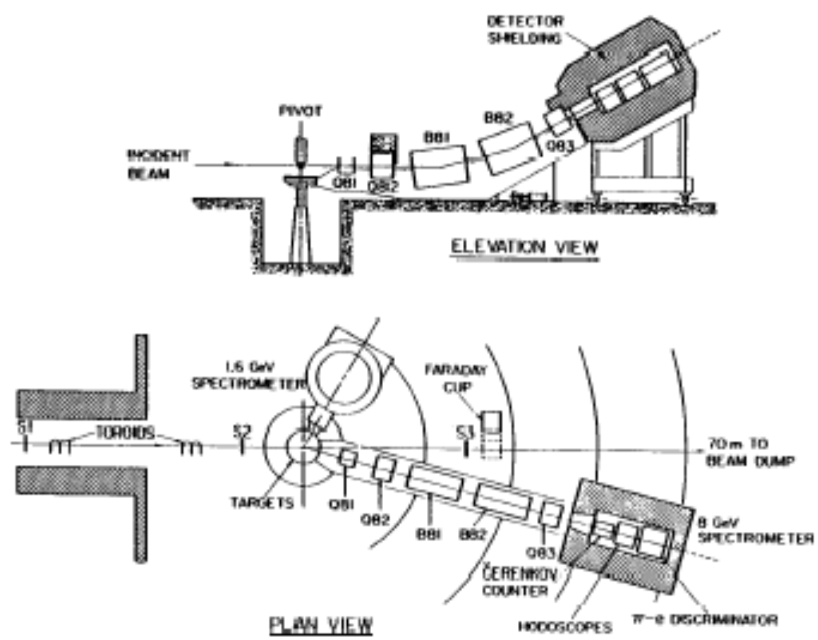
The modern version of Rutherford's original experiment: resolving power ≈ wavelength associated with 20 GeV electron ≈10-15 cm

Electron – proton scattering using a 20 GeV electron beam from the Stanford two – mile Linear Accelerator (1968 – 69).

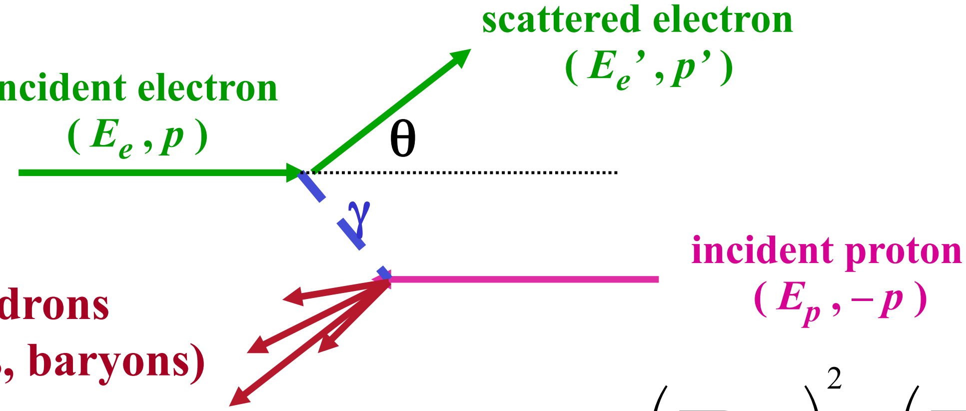
Three magnetic spectrometers to detect the scattered electron:

- **20 GeV spectrometer (to study elastic scattering $e^- + p \rightarrow e^- + p$)**
- **8 GeV spectrometer (to study inelastic scattering $e^- + p \rightarrow e^- +$ hadrons)**
- **1.6 GeV spectrometer (to study extremely inelastic collisions)**

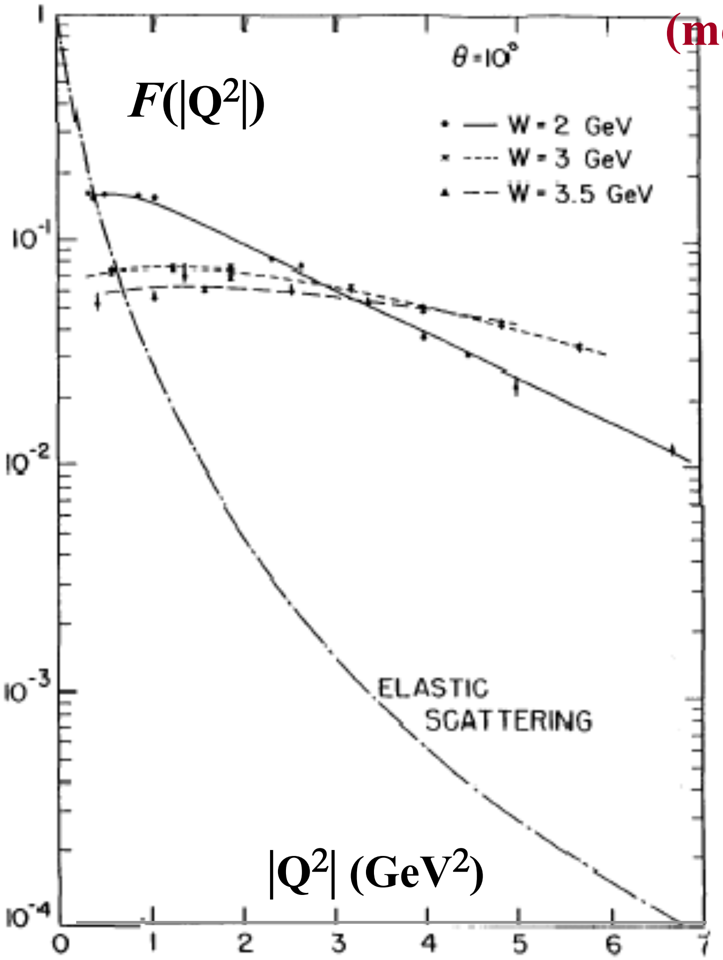




Inelastic electron – proton collisions



Total hadronic energy : $W^2 = \left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right)^2 c^2$



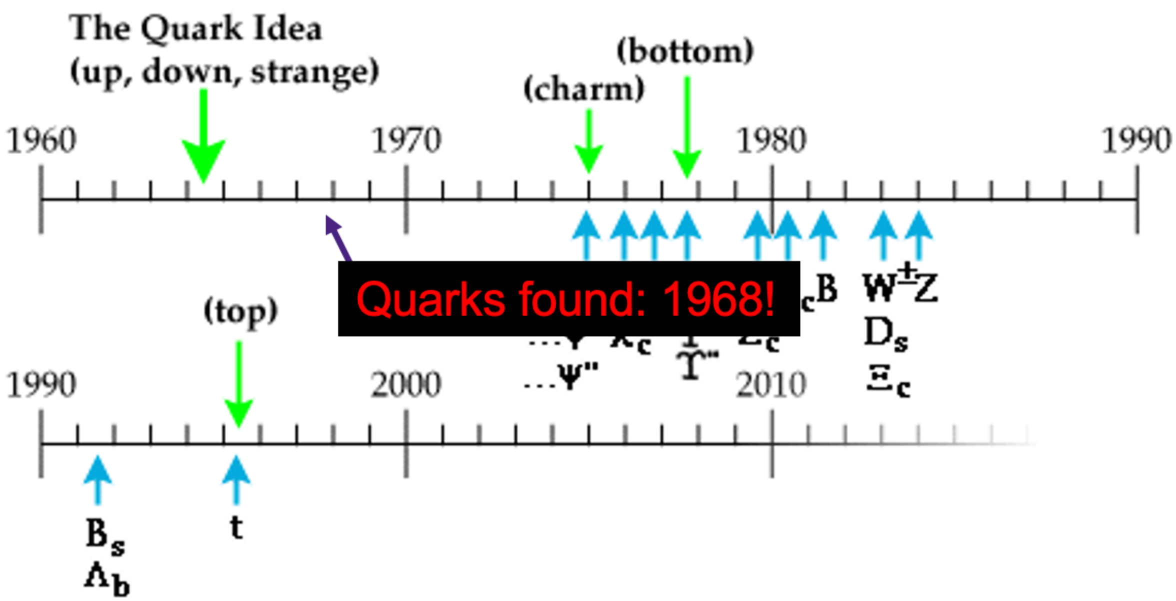
For deeply inelastic collisions, the cross-section depends only weakly on $|Q^2|$, suggesting a collision with a POINT-LIKE object

$F(|Q^2|) = 1$ for a point-like particle

⇒ the proton is not a point-like particle

Quarks are found!

‘Three Quarks for Muster Mark!’



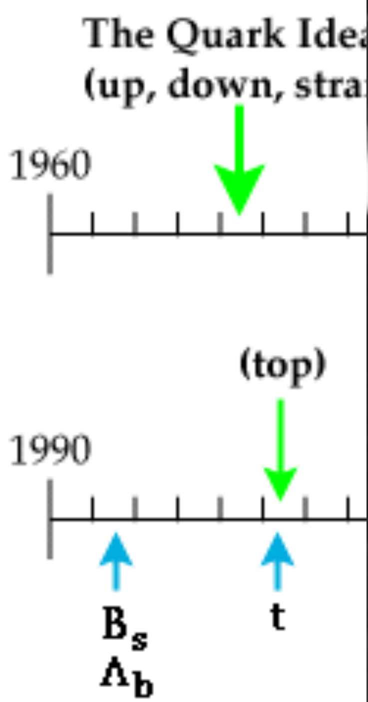
NOBEL

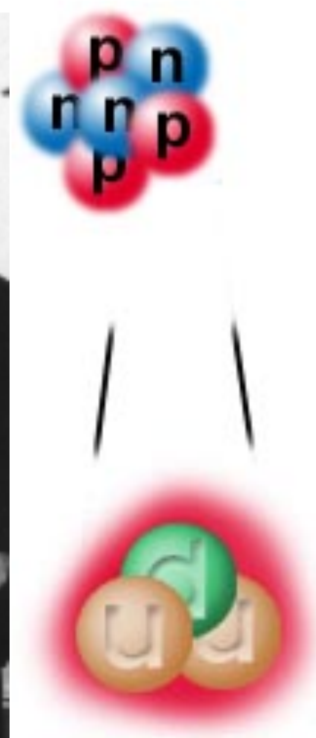
1990 Nobel Prize in Physics: Quarks Revealed!

- **Structure Inside Protons and Neutrons**

Quarks are found!

‘Three Quarks for Muster Mark!’



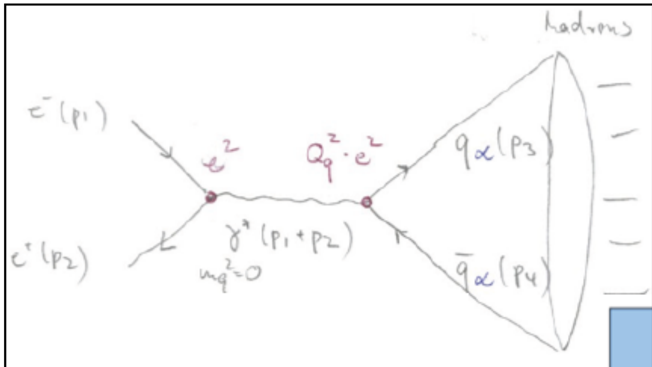


NOBEL

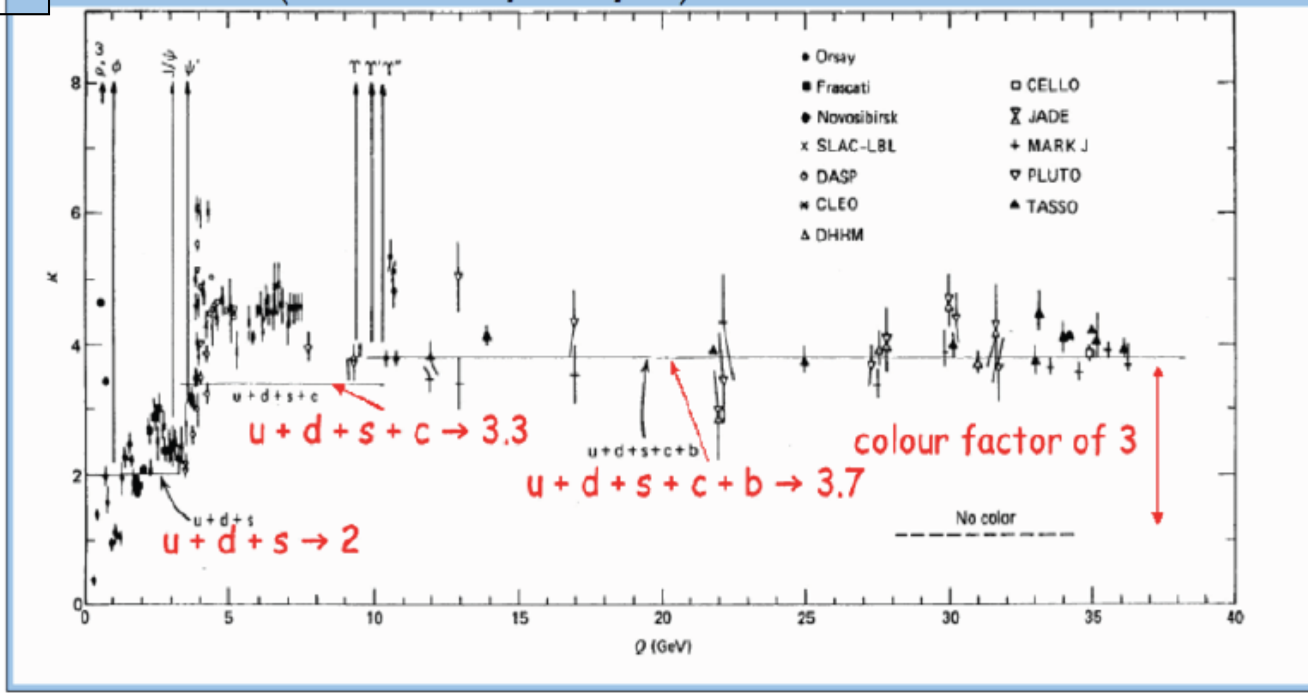
1990 Nobel Prize in Physics: Quarks Revealed!

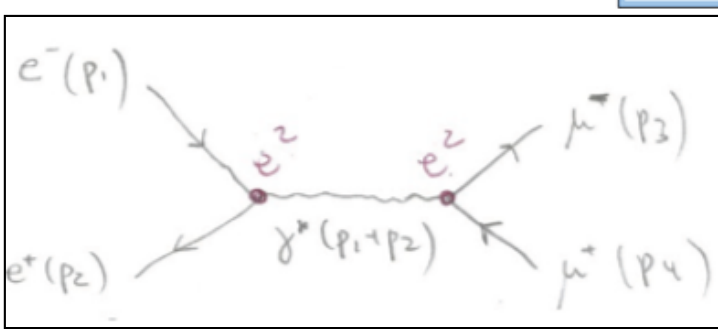
Structure Inside Protons and Neutrons

R scattering ratio…

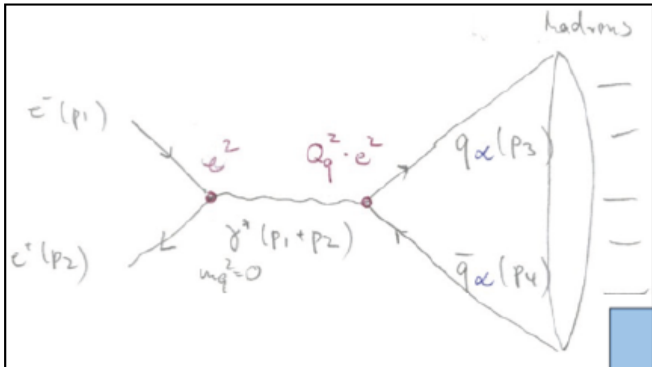


$$R = \frac{\sigma(e^+ + e^- \rightarrow hadrons)}{\sigma(e^+ + e^- \rightarrow \mu^+ + \mu^-)} = \frac{3\sum(quark\ charge)^2}{1^2}$$

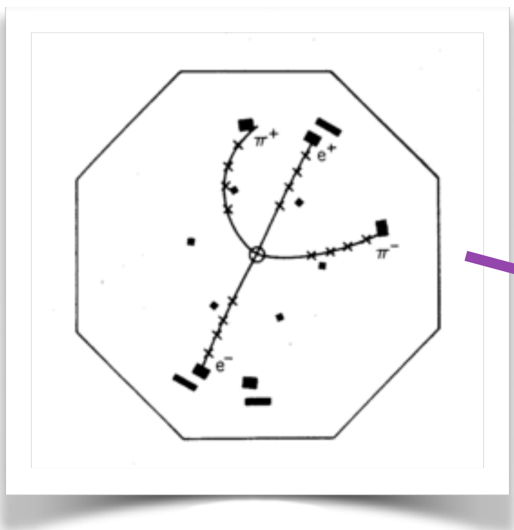


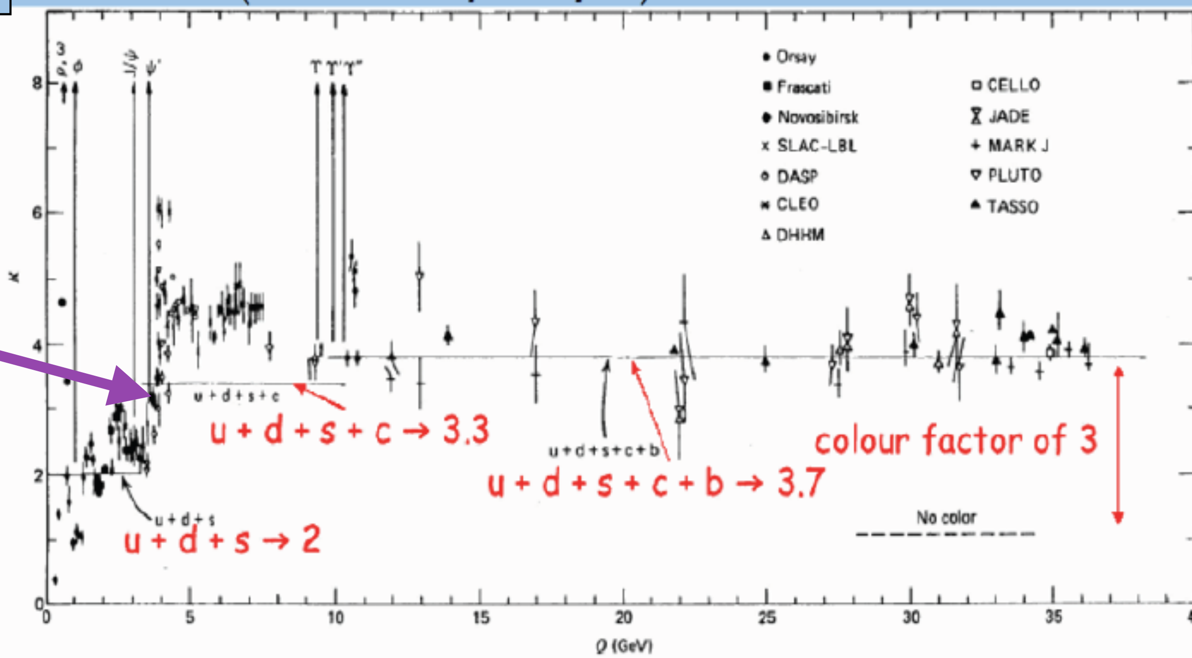


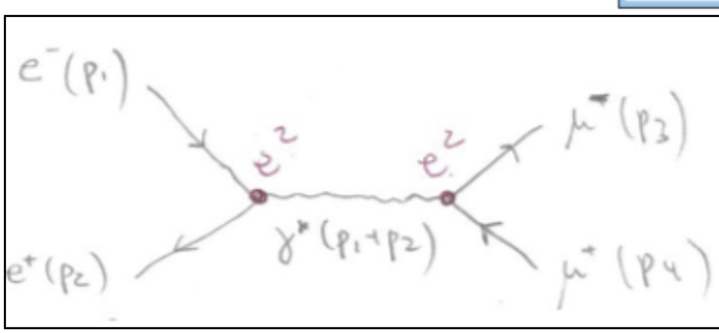
more quarks predicted…



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







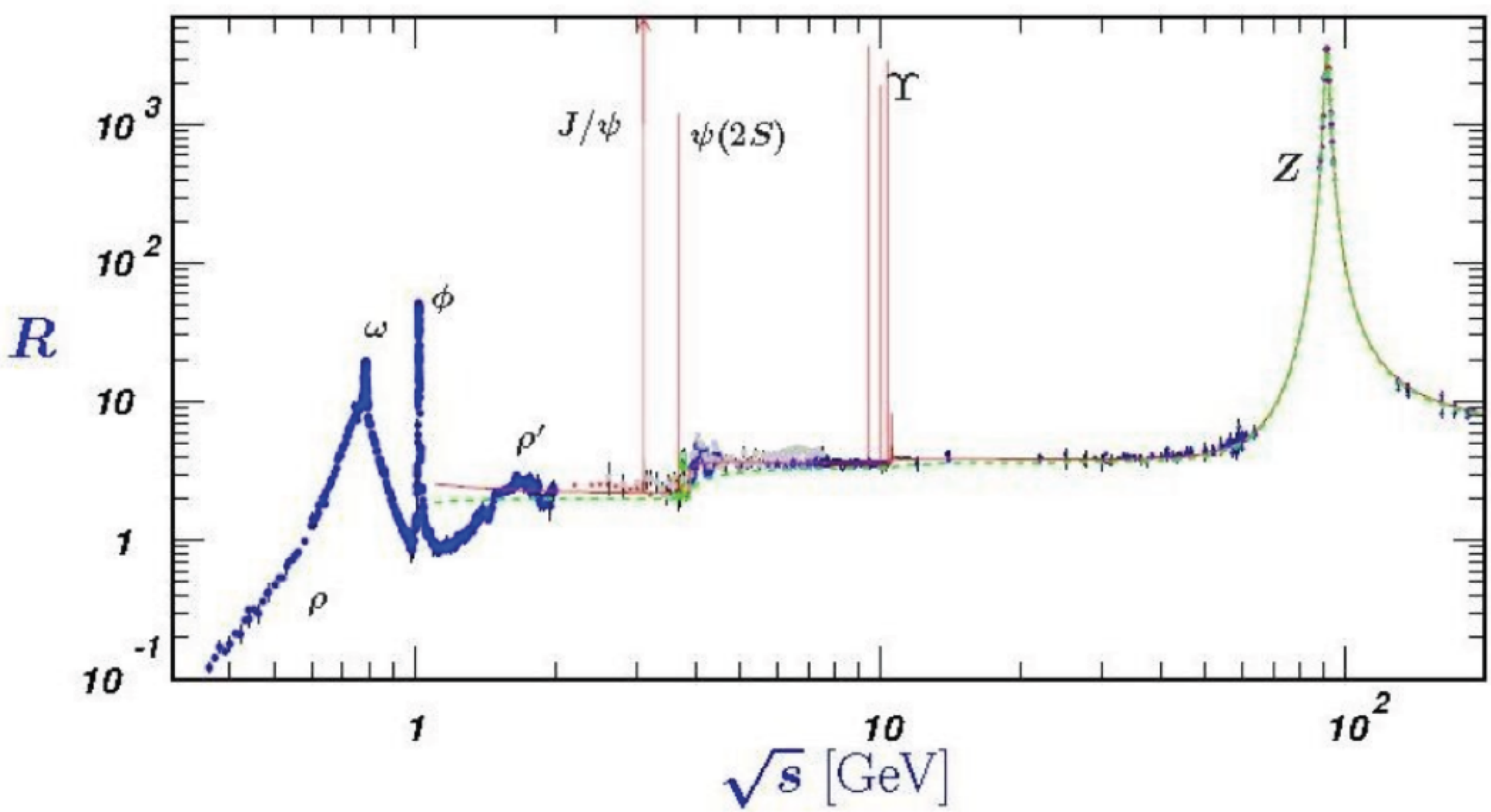
charm quark
discovery: J/Ψ particle

b quark discovery…

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

Contains a 5th quark: the b-quark

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



Quark discoveries

$\begin{pmatrix} u \\ d \end{pmatrix}$

- Quarks (u,d,s) were postulated in 1964 by Gell-Mann and Zweig, discovered in 1968

- The charm quark c was discovered in 1974 by Brookhaven and SLAC

$\begin{pmatrix} c \\ s \end{pmatrix}$

$\begin{pmatrix} \ldots \\ b \end{pmatrix}$

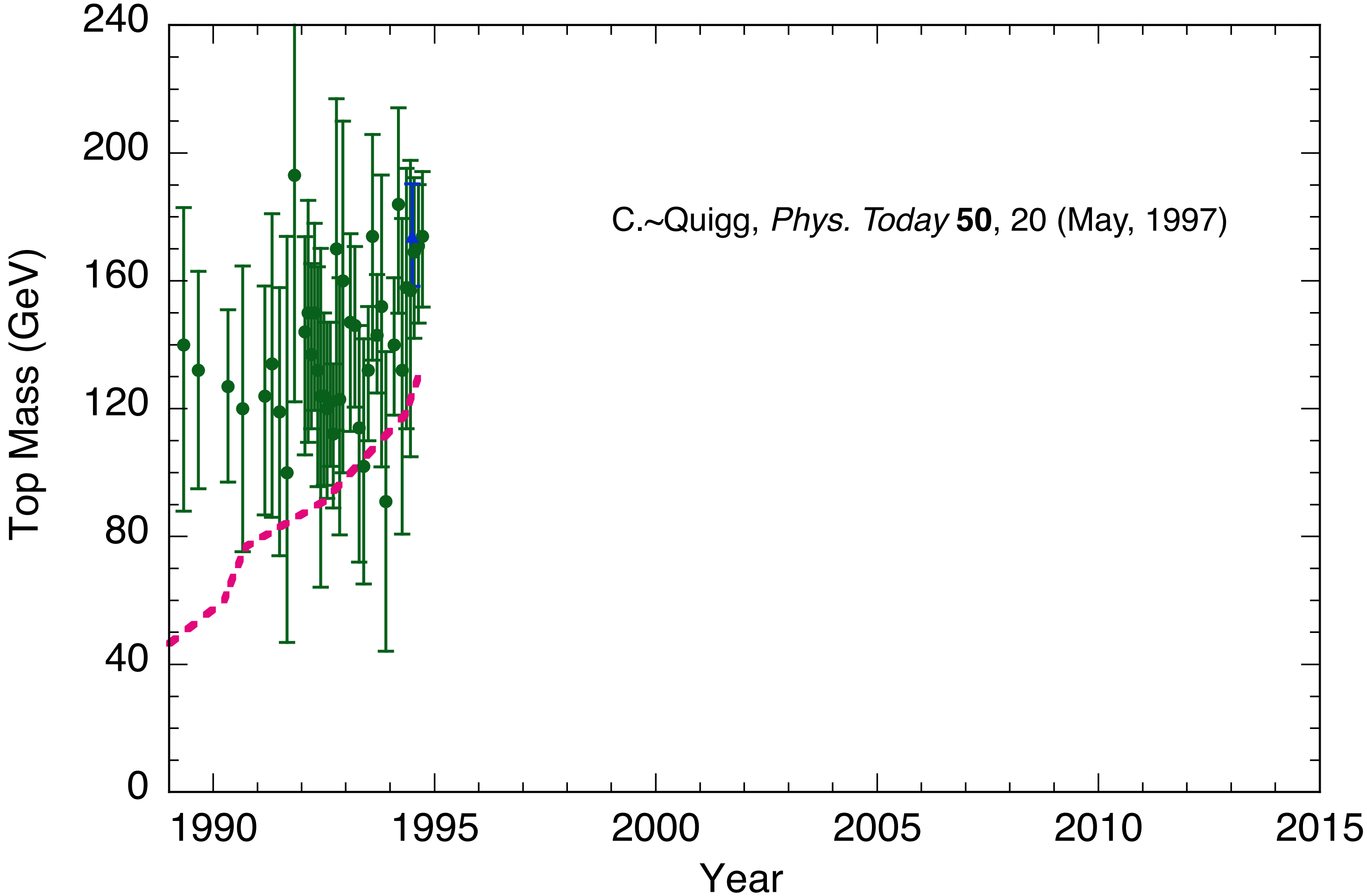
- The bottom b quark was discovered In 1977 at Fermilab

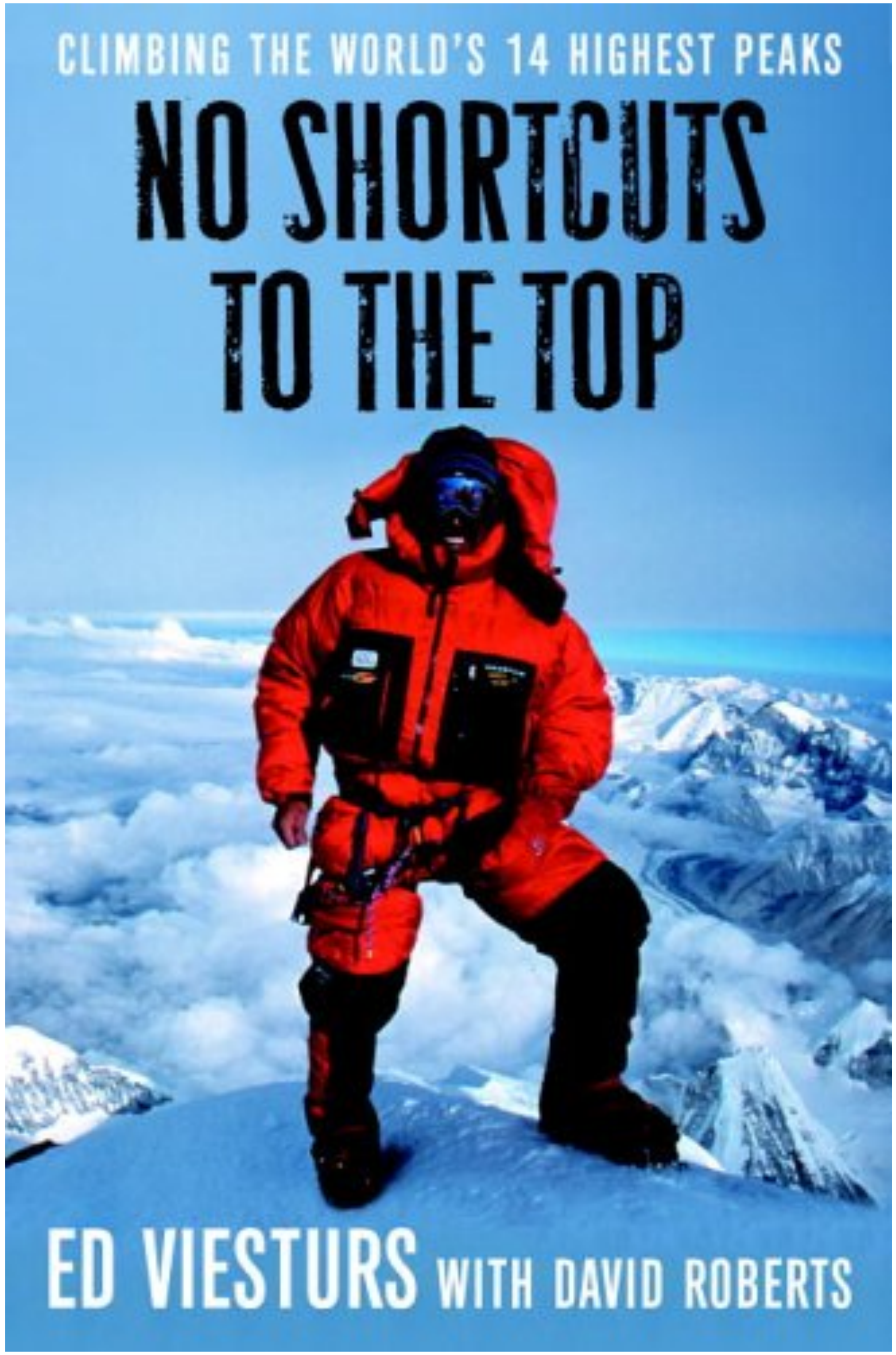
The bottom quark needed a partner… => top!

search for the top was on!

- 1976: Discovery of Upsilon (Fermilab)
  - Contains a 5th quark - the b-quark
  - From family structure of SM
    - Expect a 6th quark - race to find it
- Petra (e+e-) at DESY, Hamburg, $m_t > 23.3$ GeV (1984)
- Tristan (e+e-) in Japan: $m_t > 30.2$ GeV (late 1980s)
- UA1@SPS at CERN: $m_t > 44$ GeV (1988)
- LEP (e+e-) at CERN: $m_t > 45.8$ GeV (1990)
- UA2@SPS: $m_t > 69$ GeV

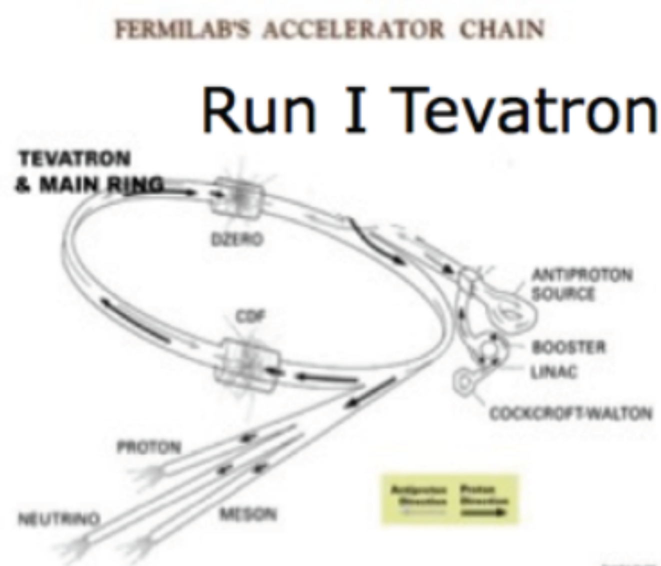
Indirect constraints on top quark



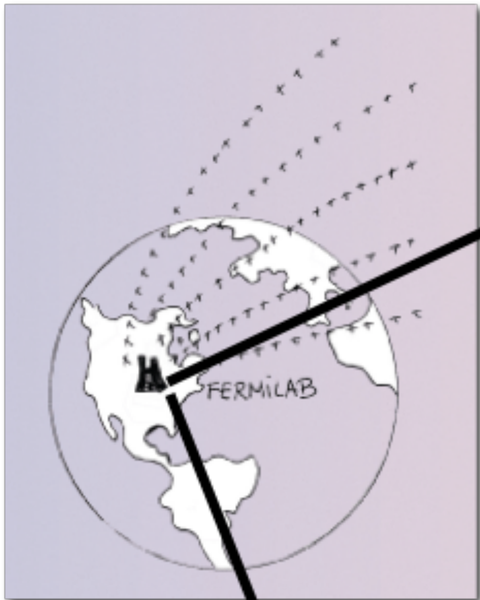

CLIMBING THE WORLD'S 14 HIGHEST PEAKS
NO SHORTCUTS
TO THE TOP
ED VIESTURS WITH DAVID ROBERTS

search for the top was on!

- 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 $\sim 120 pb^{-1}$ per experiment
  - DØ: more focused on calorimetry
  - CDF: more focused on tracking



Fermilab's Tevatron



5

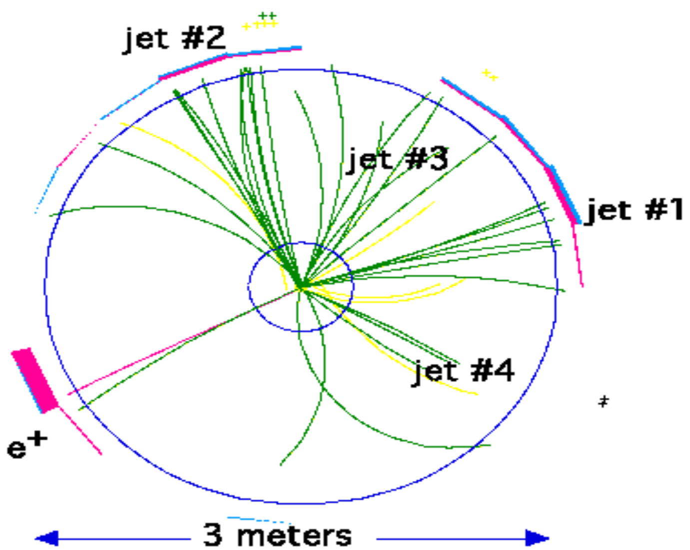
Eureka!

Physicists Discover Top Quark

News Release - March 2, 1995

PHYSICISTS DISCOVER TOP QUARK

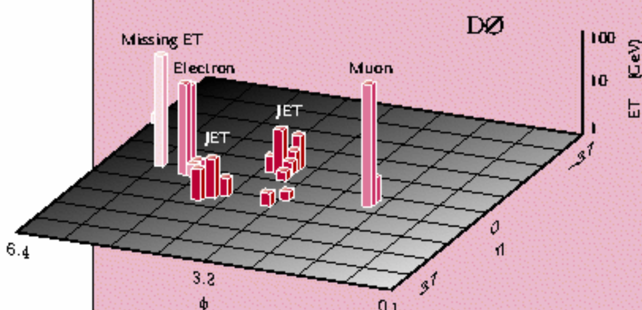
Batavia, IL--Physicists at the Department of Energy's Fermi Natic
subatomic particle called the top quark, the last undiscovered quai
sought the top quark since the discovery of the bottom quark at Fe
of the structure of matter.



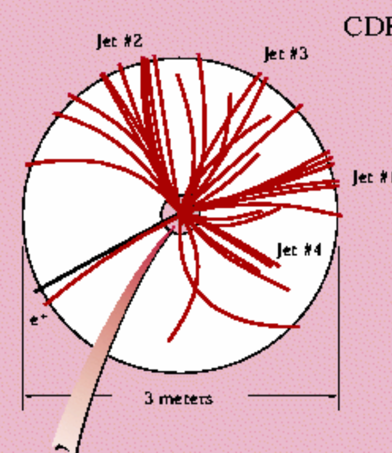
Tracking View

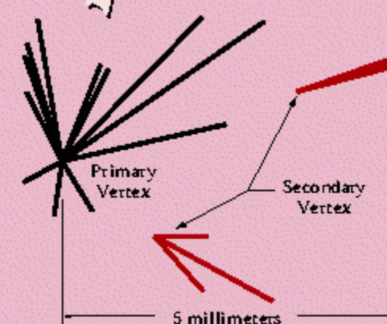
CDF AND DØ RESULTS

THE RESULTS FROM THE TWO COLLABORATIONS were remarkably similar. CDF found 6 dilepton events with a background of 1.3; 21 single-lepton events in which 27 cases of a *b* quark tag by the vertex detector (with 6.7 background tags expected); and 22 single-lepton events with 23 cases of a *b* tag through leptonic decay (with 15.4 background tags expected). DØ found 3 dilepton events (0.65 background events); 8 single-lepton events with topological tagging (1.9 background events); and 6 single-lepton events with *b*-to-lepton tags (1.2 background events). A particularly striking example of a dilepton event with very energetic electron, muon, and missing E_T (due to the neutrinos), plus two jets, is shown below from the DØ data. The plot shows the detector unfolded on to a plane, with the energy of the various objects indicated by the height of the bars. This event has a very low probability to be explained by any known background. The probability that background fluctuations could explain the observed signal was one-in-a-million for CDF and two-in-a-million for DØ—sufficiently solid that each experiment was able to claim the observation of the top independently.



Additional studies helped to establish that the new signal

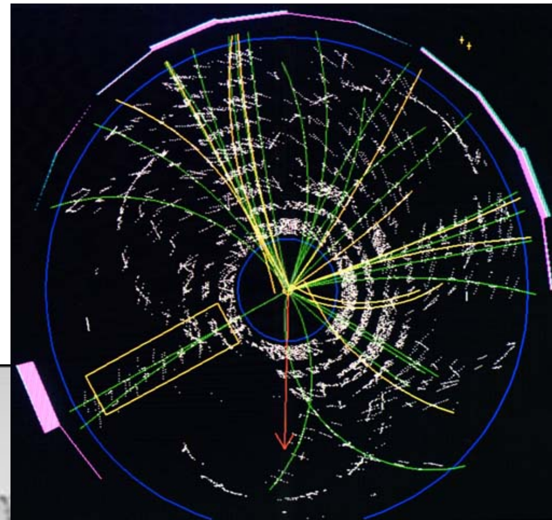




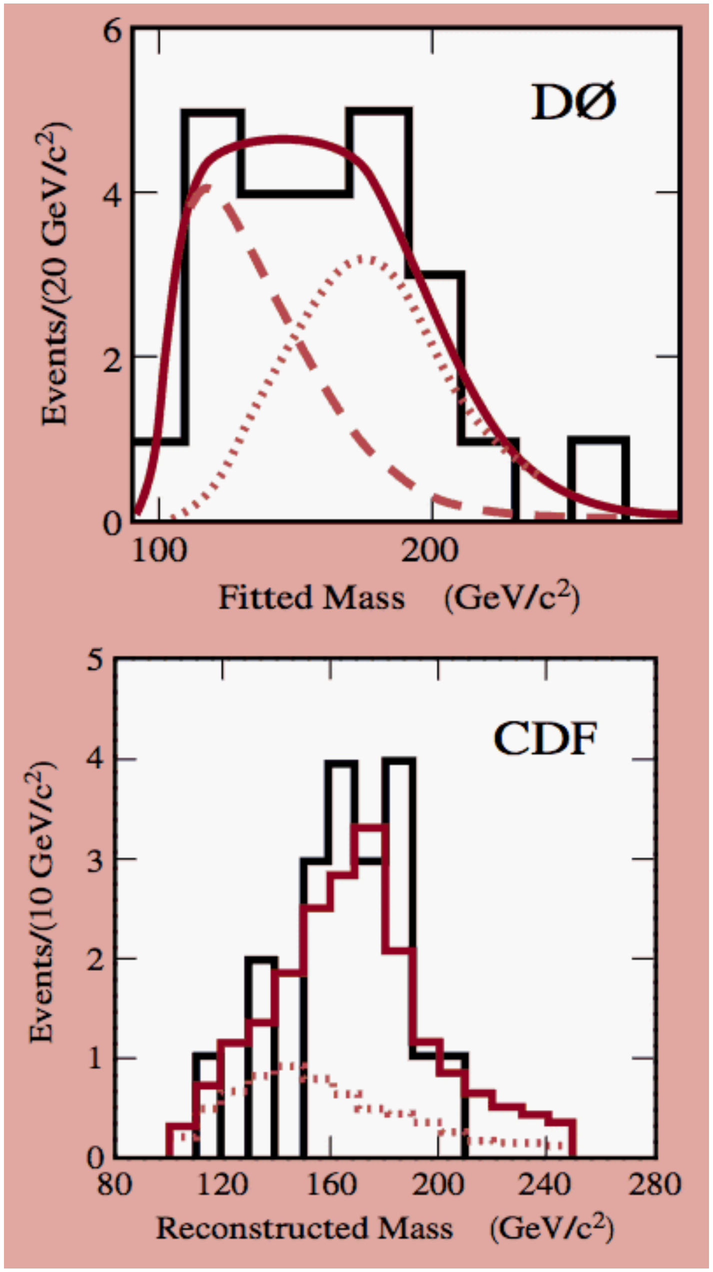
by the need to identify the correct combination of jets with parent quarks in the decay and to accommodate the tendency of the strong interaction to generate additional jets. The two experiments obtained consistent results for this

March 2nd, 1995

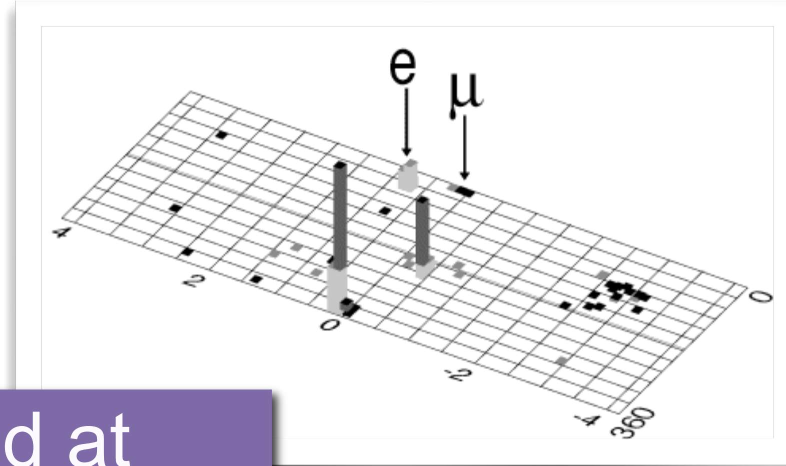
Discovery is Exciting!

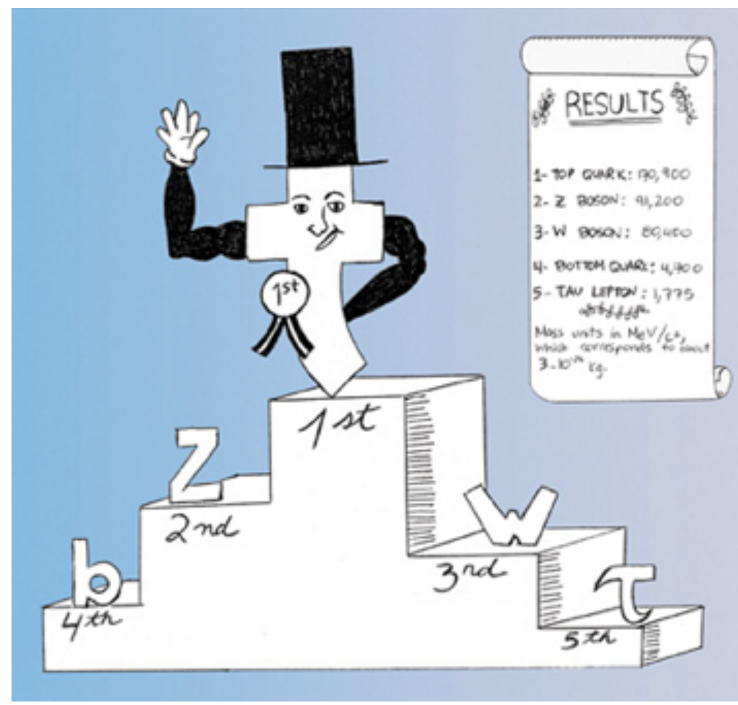


Adding something to the core of human knowledge is profoundly satisfying.

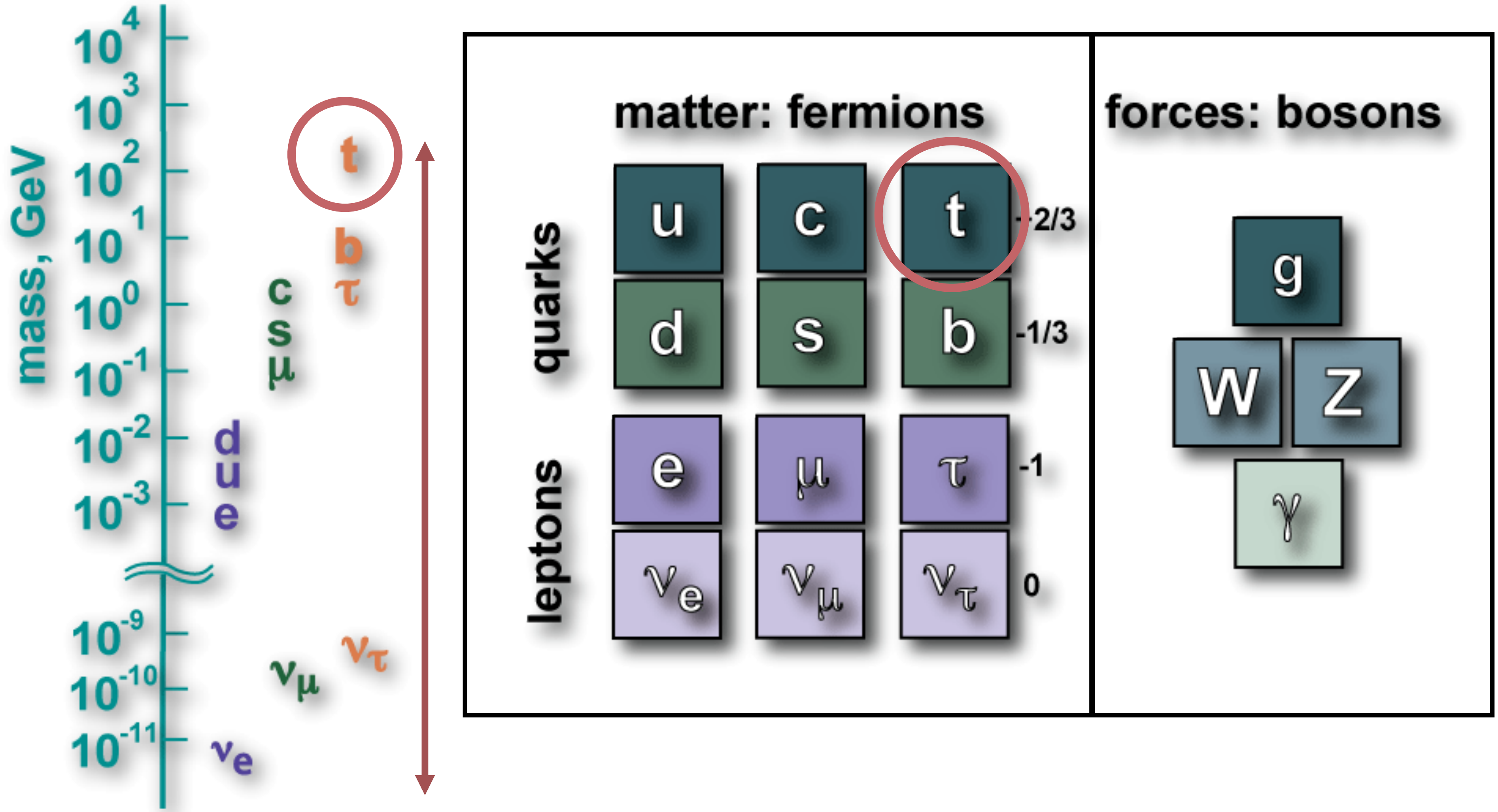


Top found at a peculiarly high mass





Periodic Table of the Particles



5 orders of magnitude!

- needed as isospin partner of bottom quark

- discovered in 1995 by CDF and DØ: m_{top} ~ gold atom

Top Quark is now standard!

- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?

- short lifetime: $\tau \sim 5 \cdot 10^{-25}\text{s} \ll \Lambda^{-1}_{QCD}$: decays before fragmenting
  → observe "naked" quark

Tevatron became the only place to study top through Run 1 and most of Run 2…

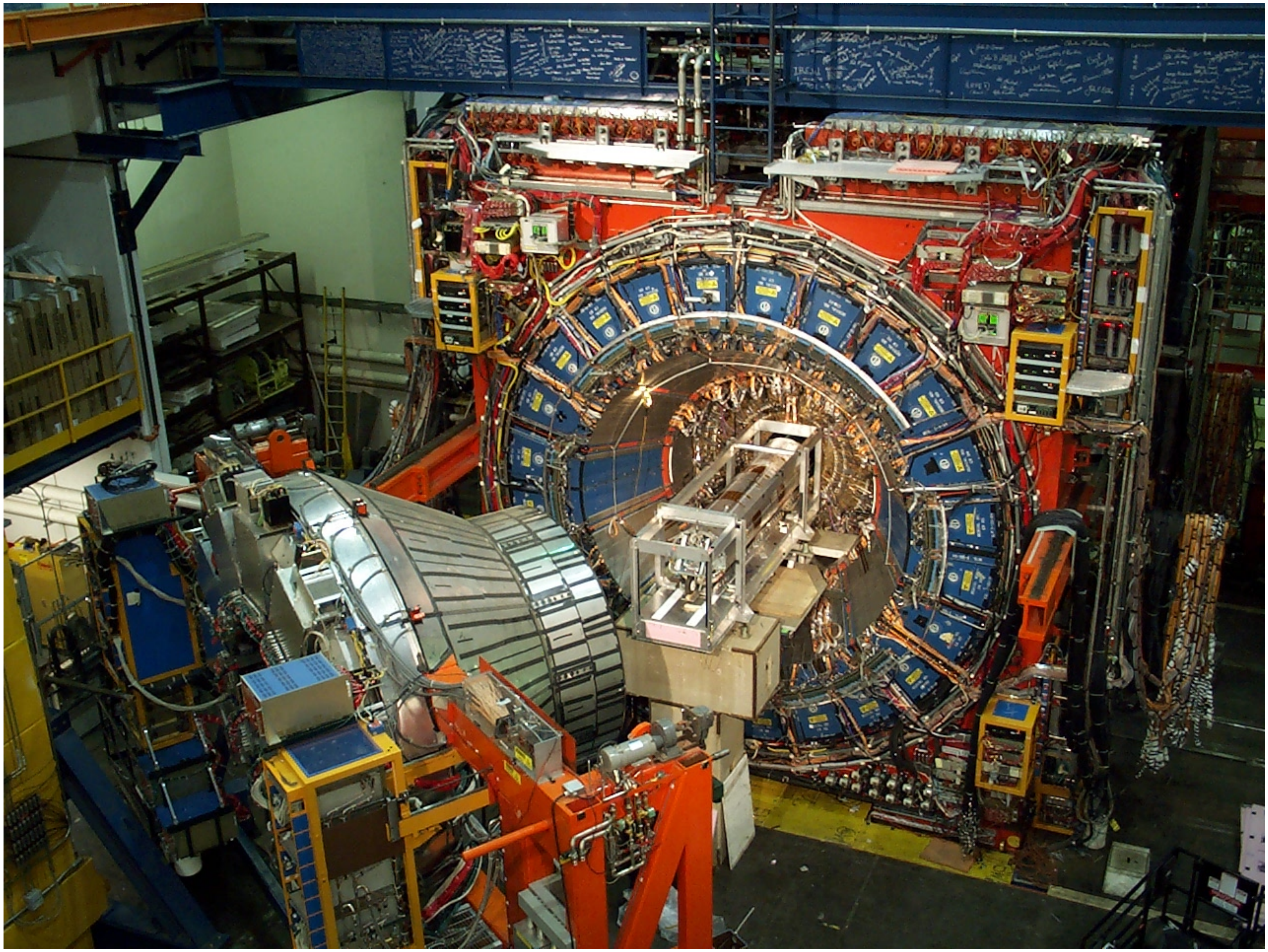
Flagship program

Top Quarks are one of the most sexy things to study…

When Trish discovers Ned works exclusively with top quarks, she will be putty in his hands.

CDF Detector

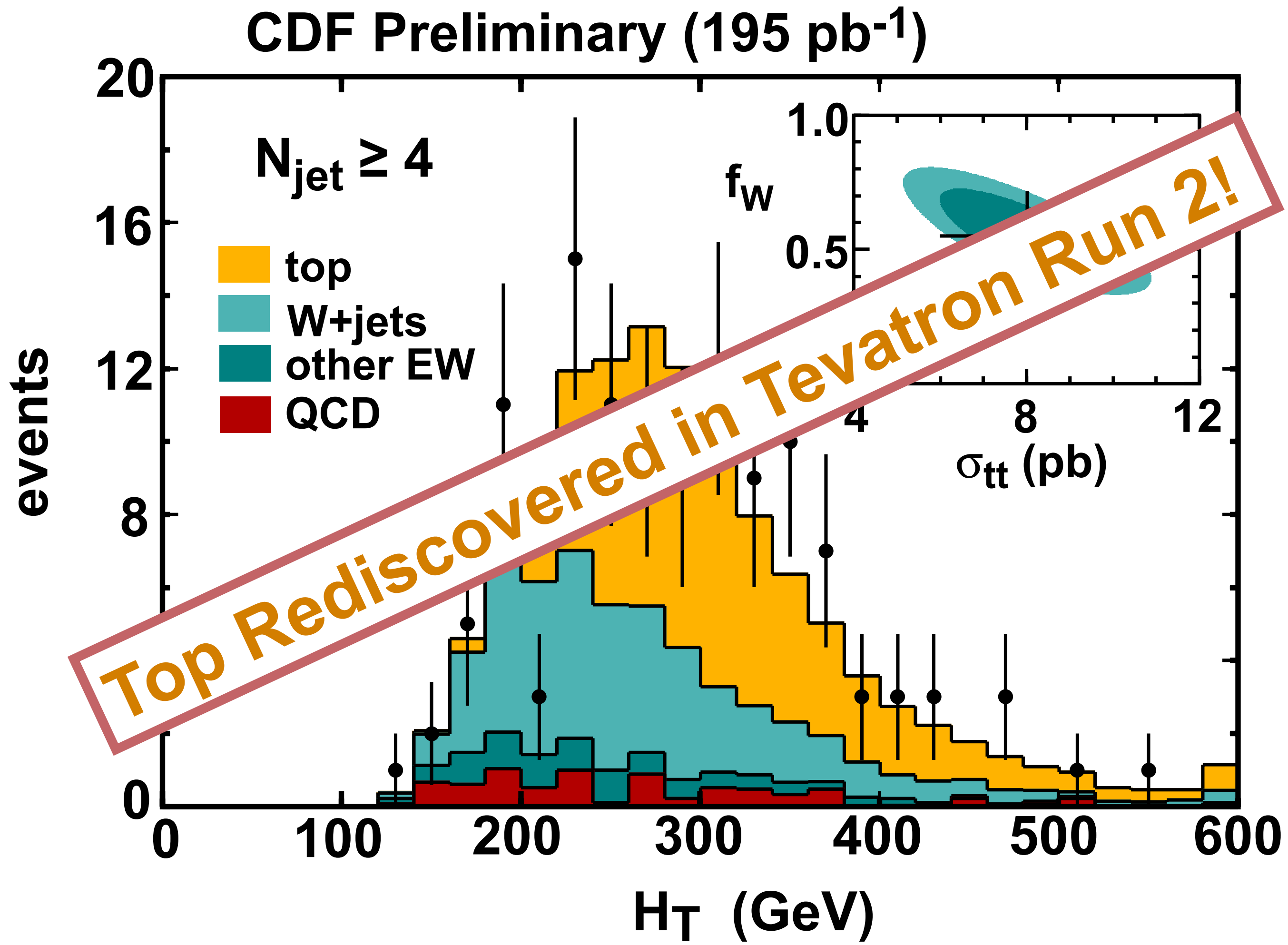
CDF



X

D0 Detector

X

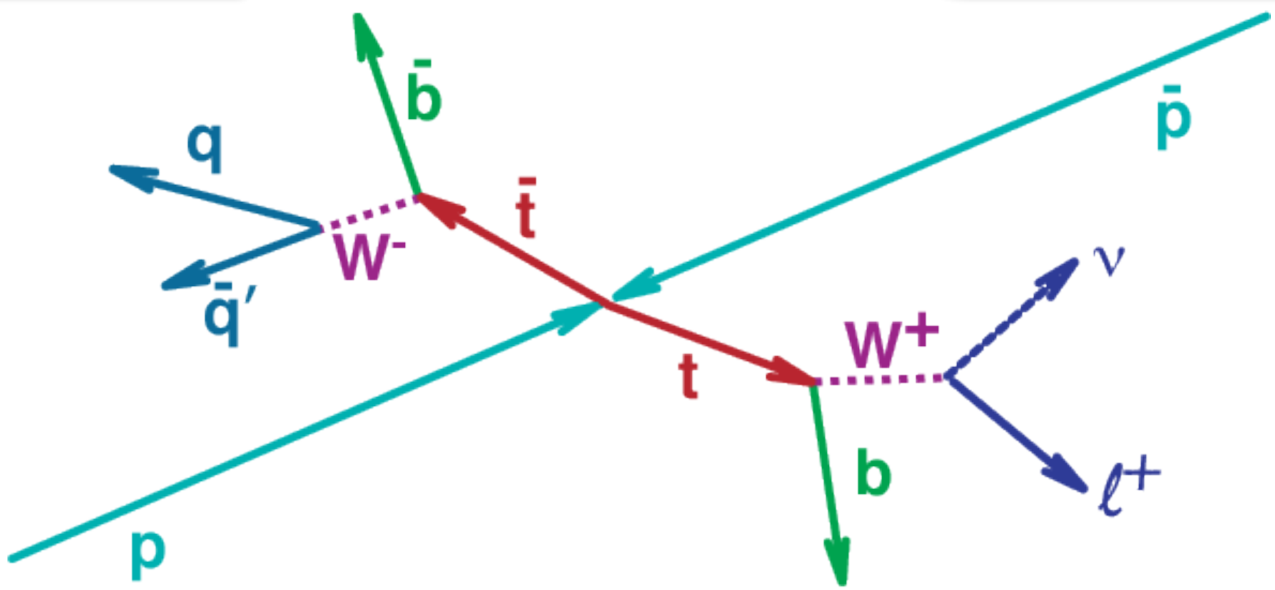

CDF Preliminary (195 pb-1)
Njet ≥ 4
top
W+jets
other EW
QCD
events
HT (GeV)
fW
σtt (pb)
Top Rediscovered in Tevatron Run 2!

Top Event Decays

- W helicity (V-A)
- Branching ratios
- Top to charged higgs
- Top sample (W+HF)
- FCNC

Top Quark Production

- Mechanism
- Top Pair Cross Section
- Ewk Production (single top)
- Forward-backward asymmetry
- Resonances decaying to top
- stop or t' production



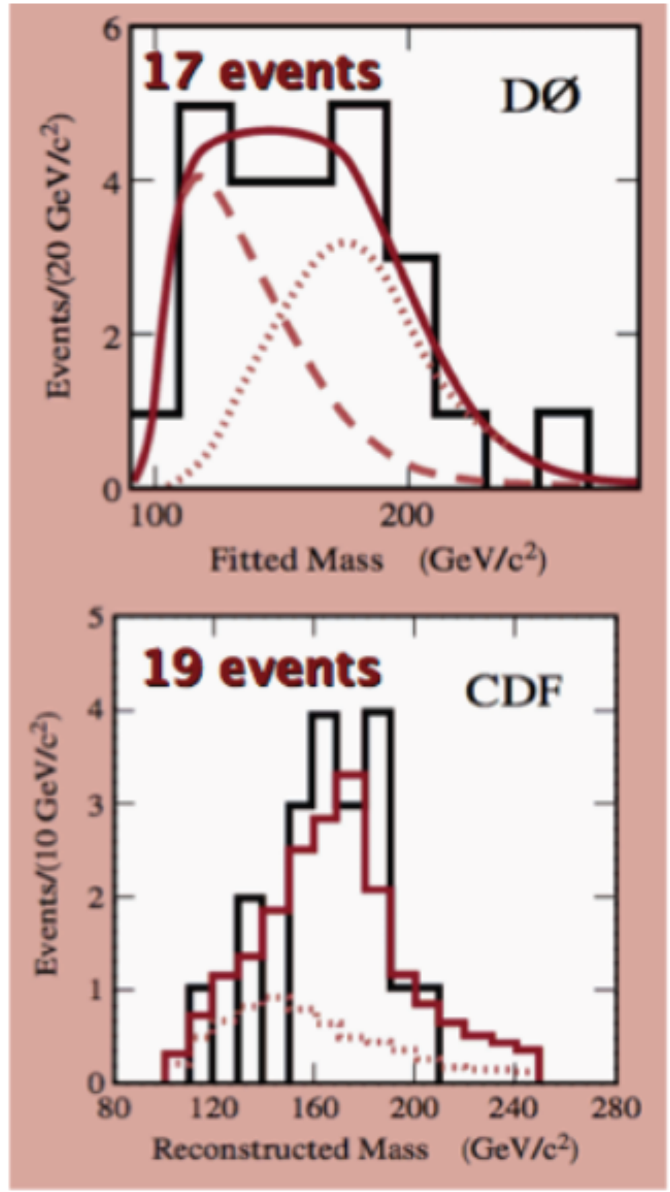
Top Properties

- Top Mass
- Top Quark Width
- Charge of Top Quark
- Mt – Mtbar & CPT

sample of many things to study!

Discovery

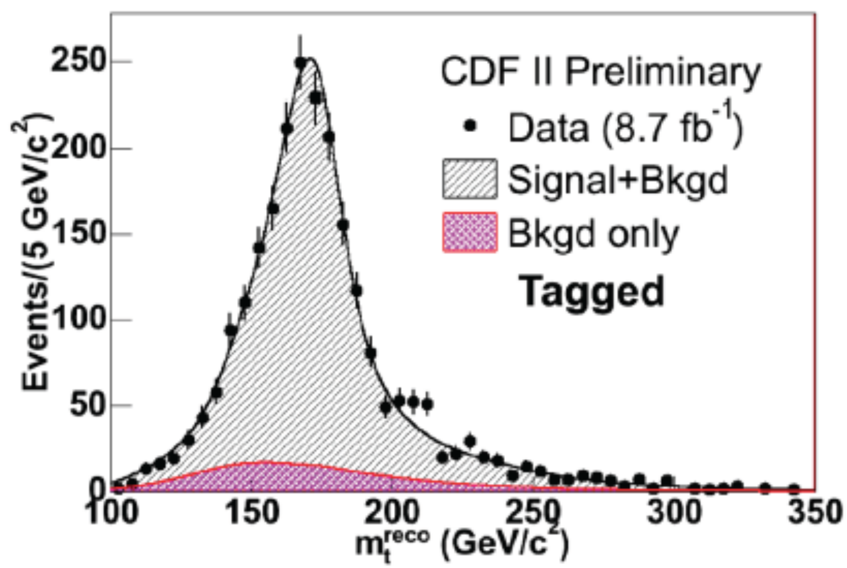
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



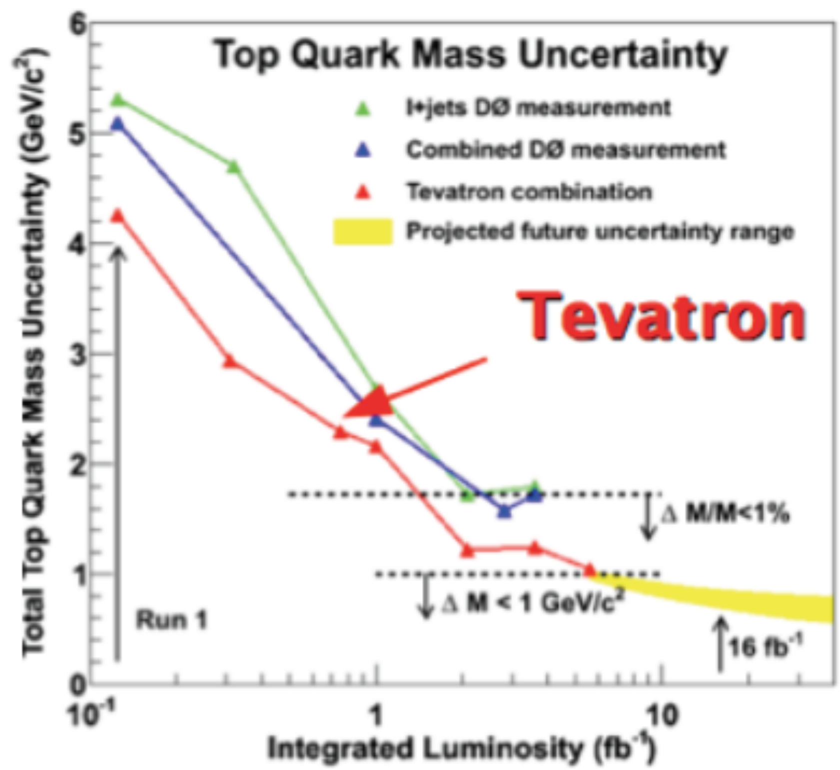
1995, CDF and DØ experiments, Fermilab

handful of events

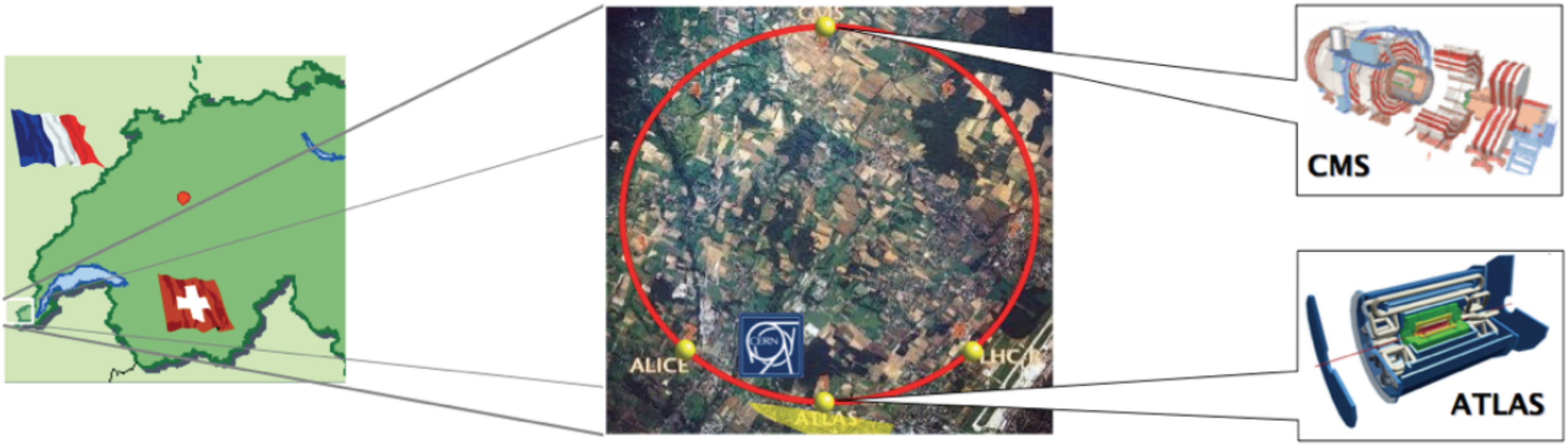
Tevatron Run 2

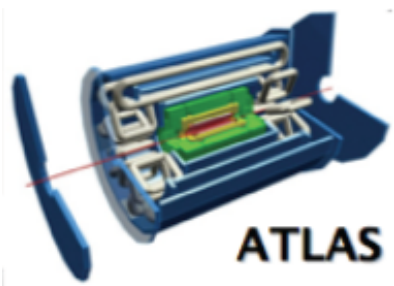


1000s of events



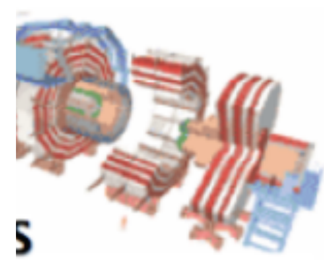
Then in 2010... enter the LHC!



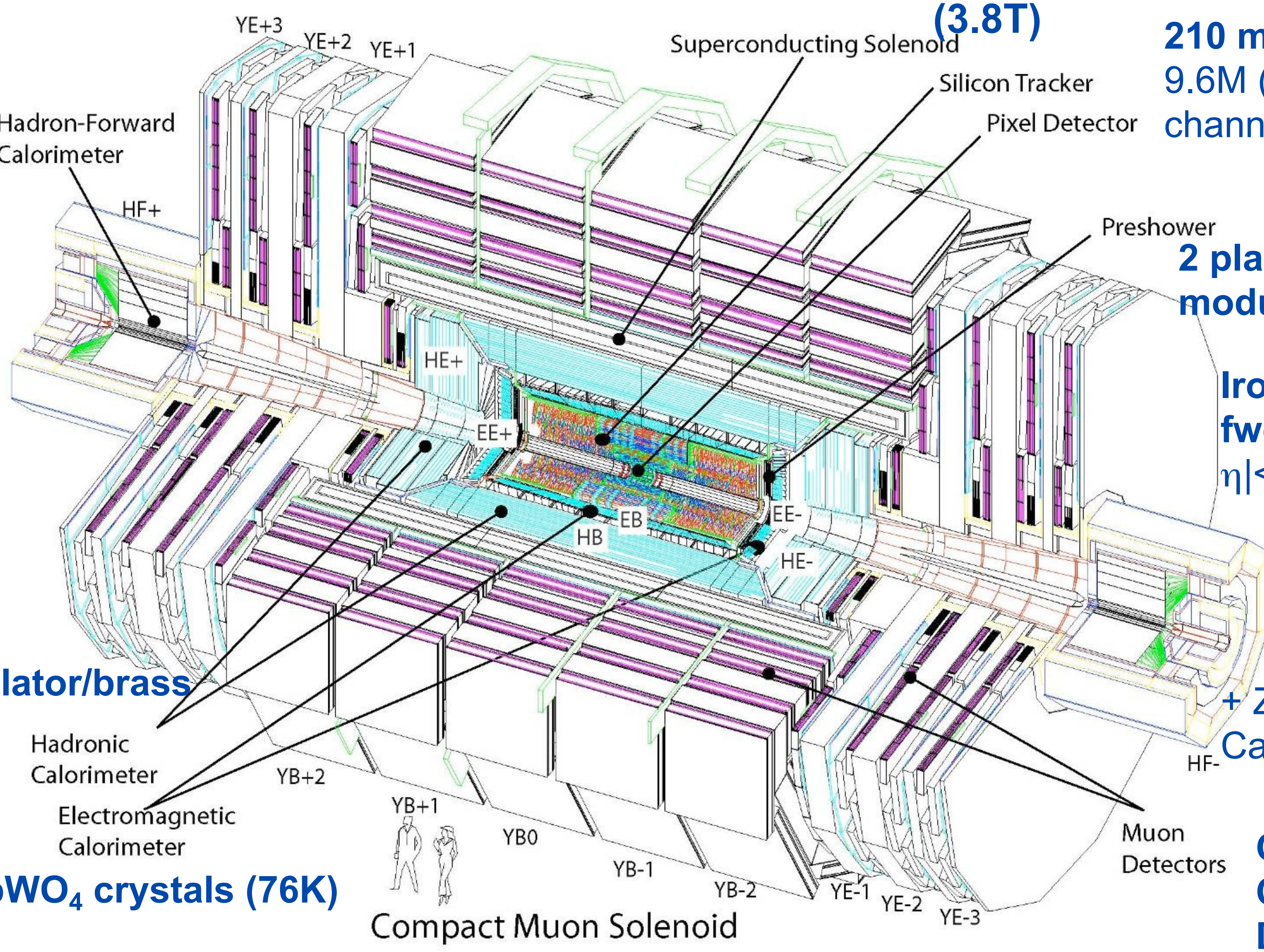


The Large Hadron Collider:

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



The Compact Muon Solenoid



(3.8T)

210 m² of silicon sensors:
9.6M (Str) & 66M (Pix) channels

2 planes of silicon modules for ECAL

Iron / Quartz fiber fwd calorimeter, $3<|\eta|<5$;

+ Castor, $5<|\eta|<6.55$

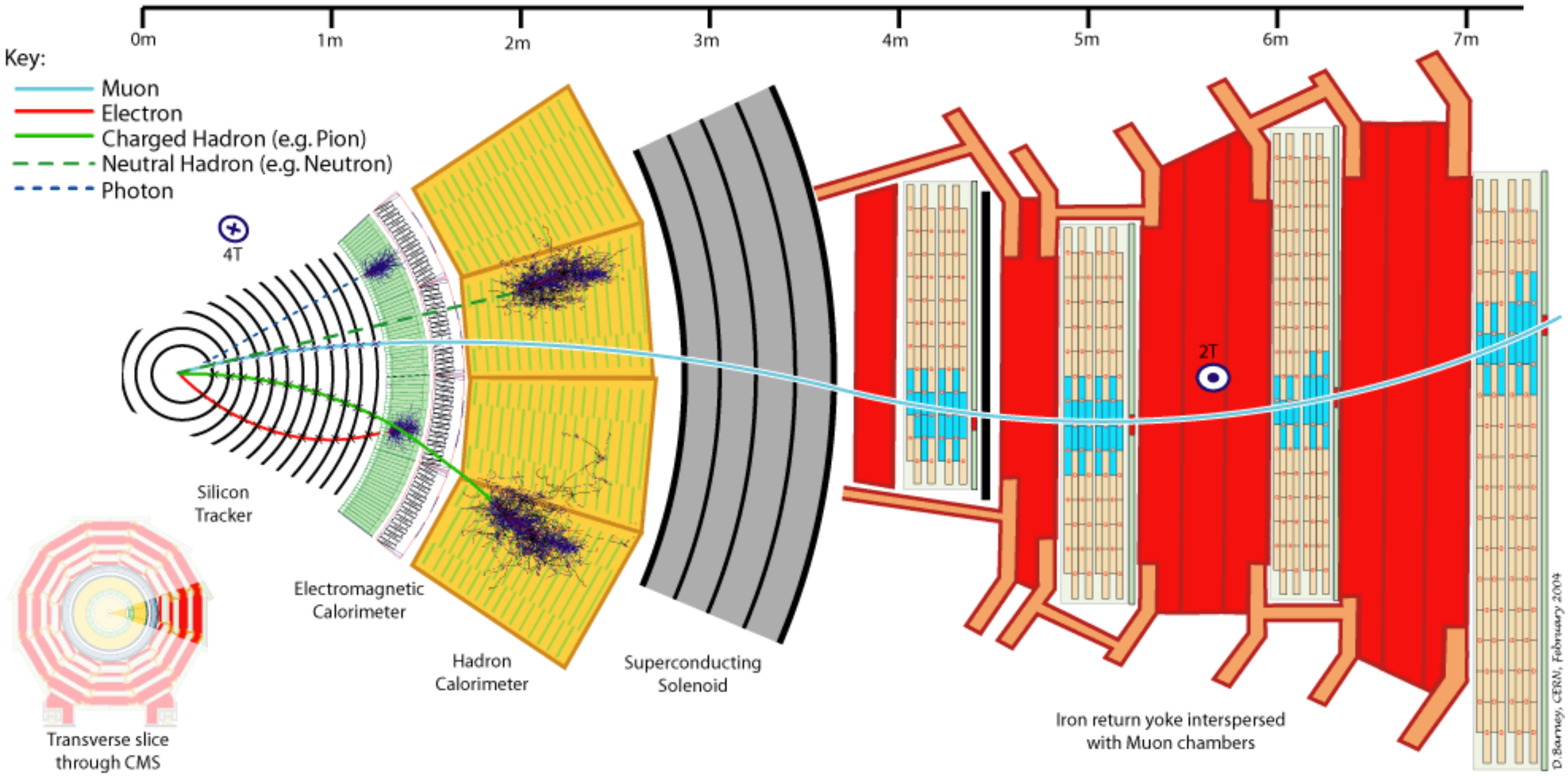
+ Zero Degree Calorimeter

Scintillator/brass

$PbWO_4$ crystals (76K)

Cathode Strip Chambers, Drift Tubes, Resistive Plates

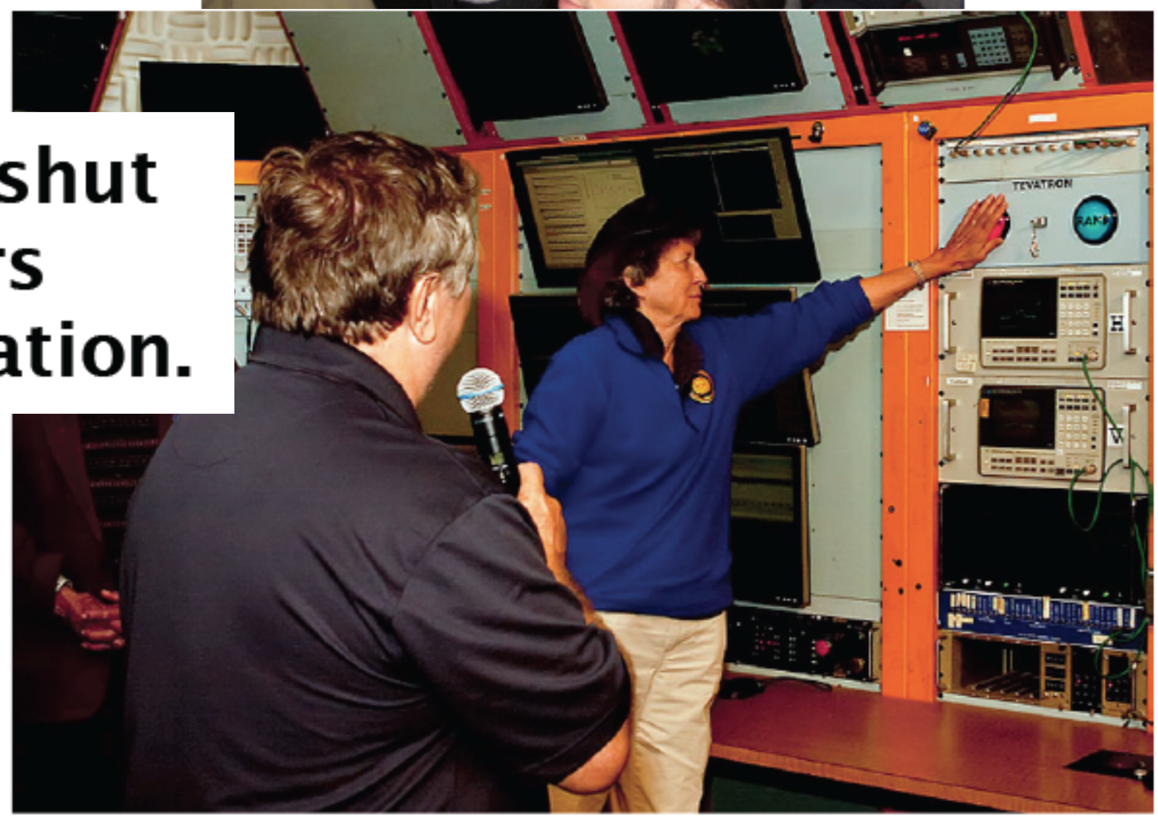
Physics Object Reconstruction



Individual objects are followed through subdetectors:

CMS Particle flow!

https://cds.cern.ch/record/1194487/files/PFT-09-001-pas.pdf

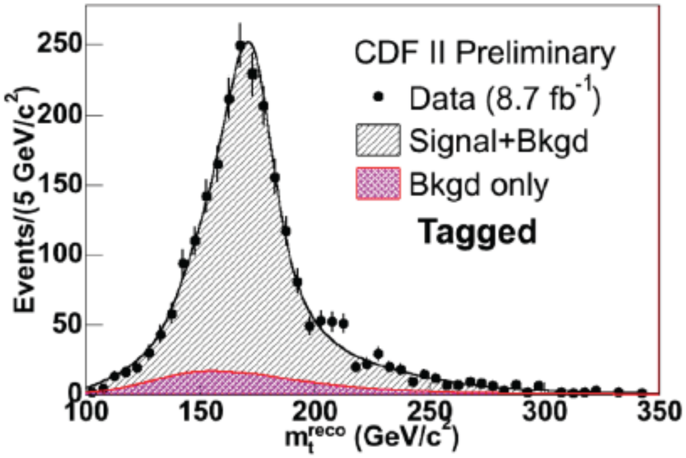


Tevatron complex shut down after 26 years of successful operation.

b. 10-13-85
d. 09-30-11

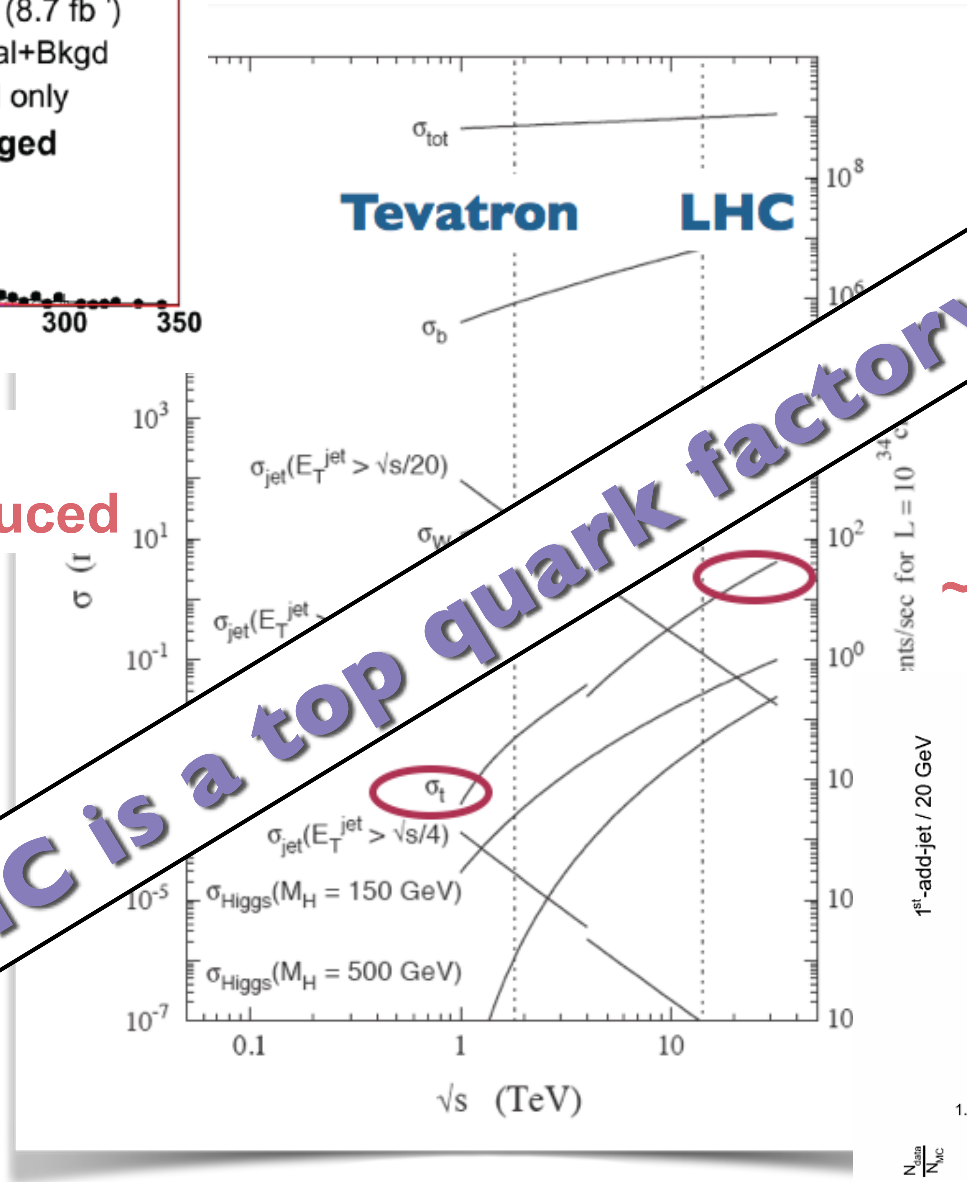
First 13 TeV Collisions!

June 3, 2015



Tevatron Run 2 :

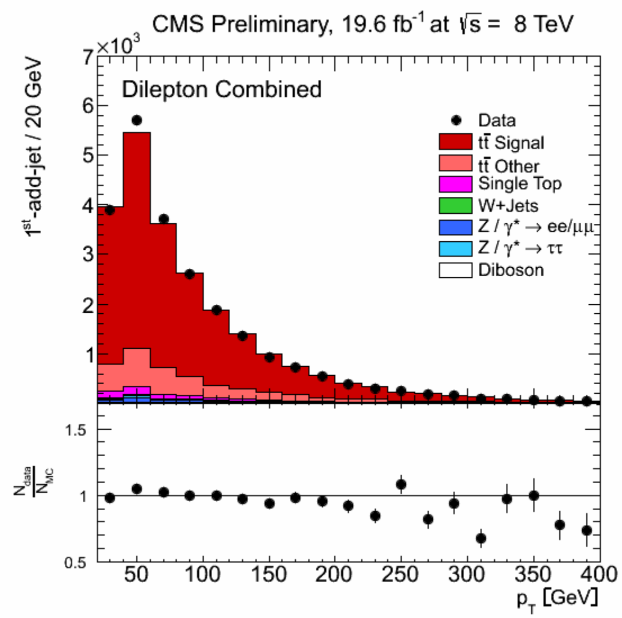
~100k tops produced



LHC is a top quark factory!

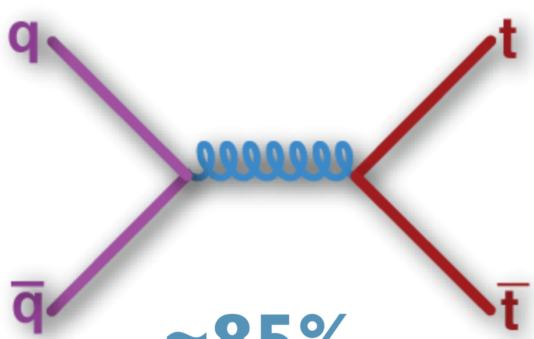
LHC Run 1:

~5.8M tops produced



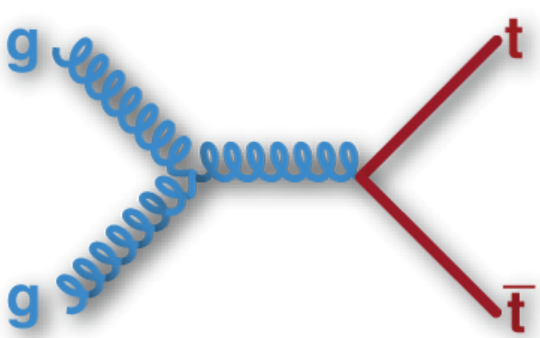
Tevatron:
Top Pair Production

How is Top Produced?

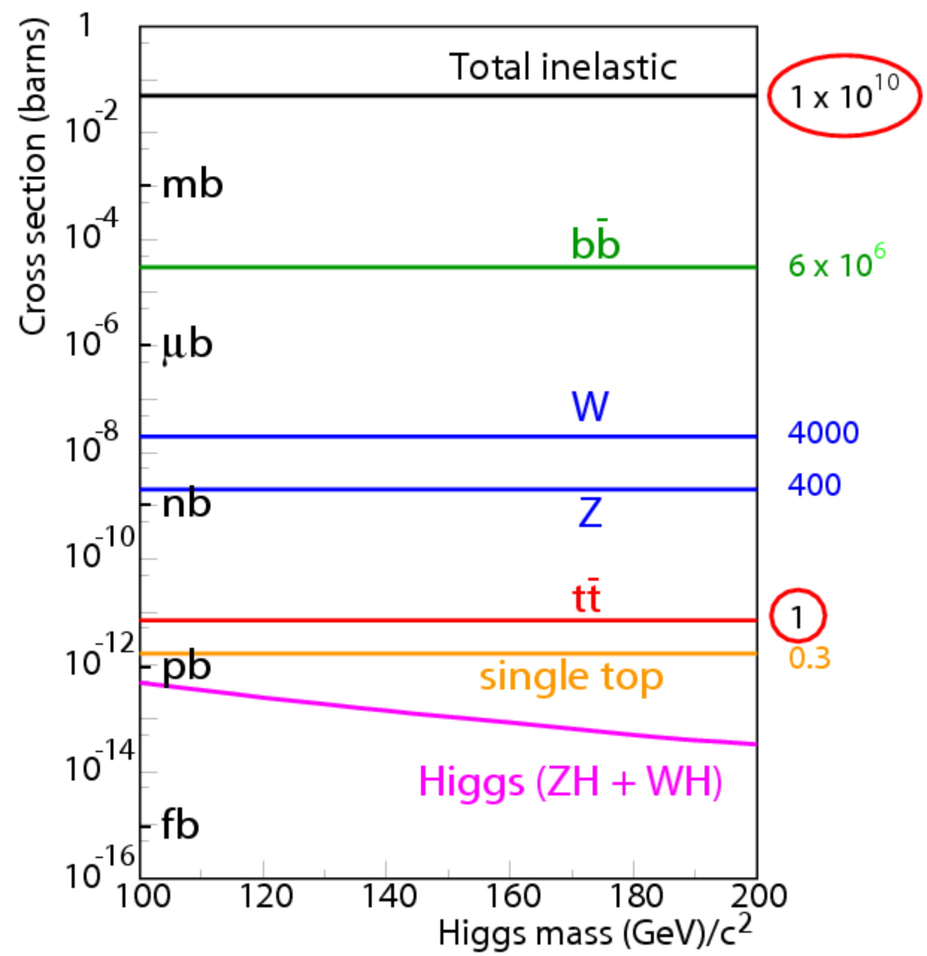


~85%

strong pair production



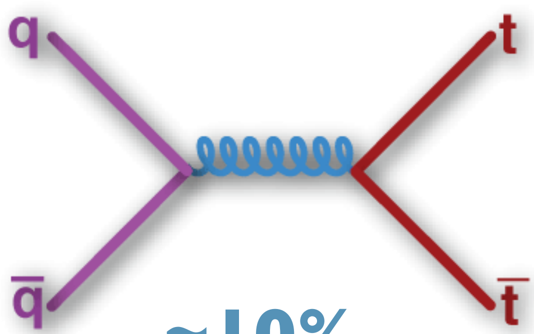
~15%



One top pair each 10^{10} inelastic collisions at $\sqrt{s}$ = 1.96 TeV

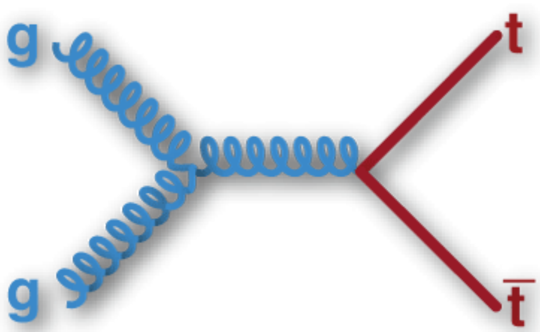
LHC (13 TeV): Top Pair Production

How is Top Produced?

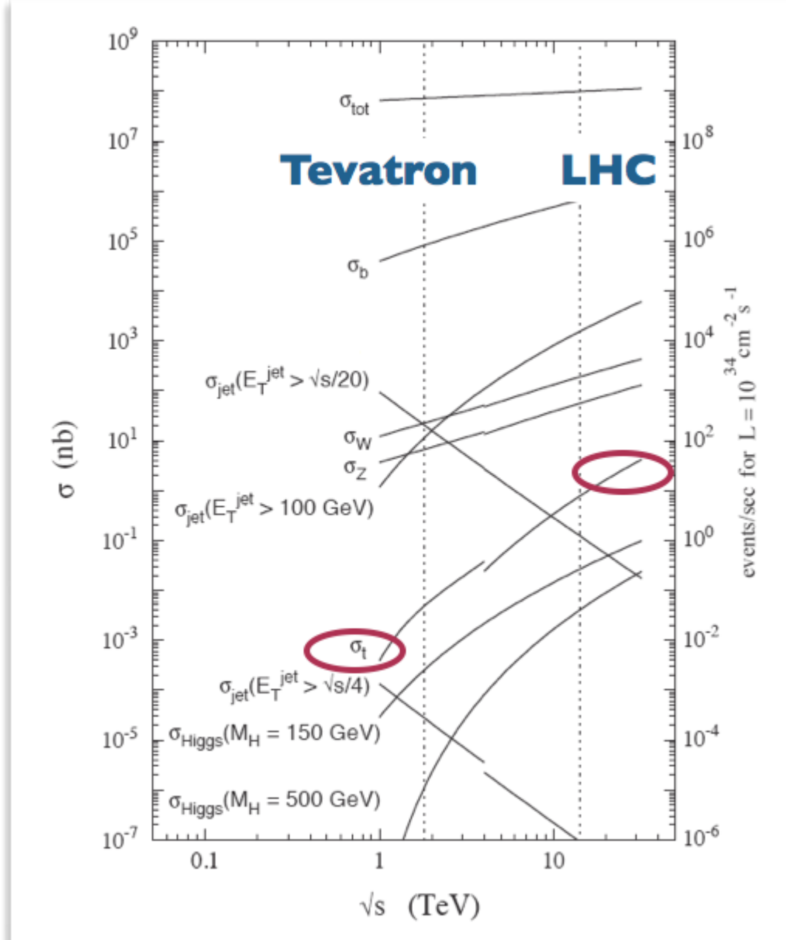


~10%

strong pair production



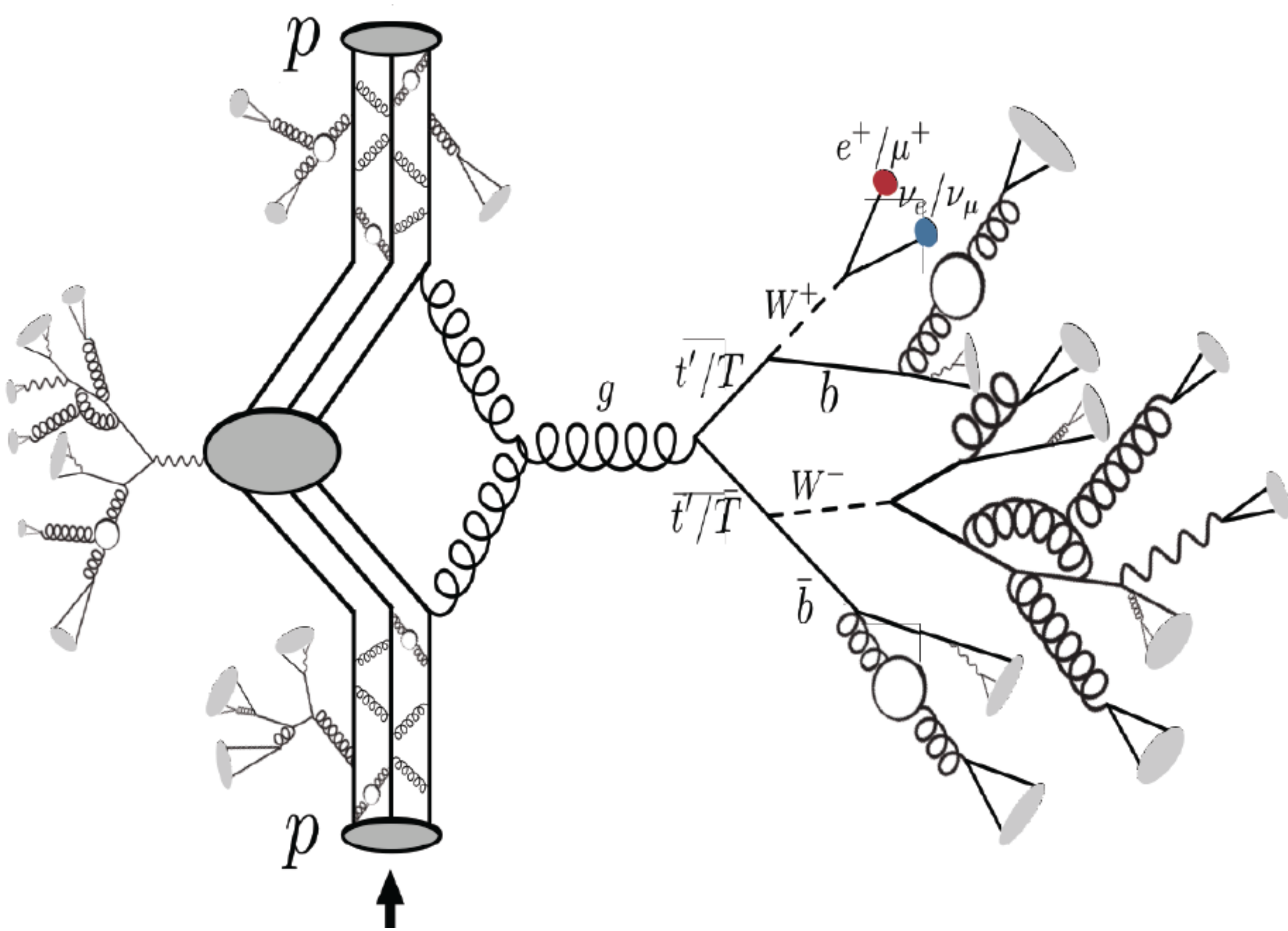
~90%



One top pair each 10^8 inelastic collisions at $\sqrt{s}$ =13 TeV

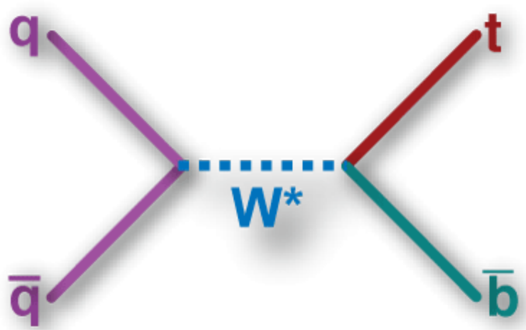
How is Top Produced?

Actually things can get more complicated…

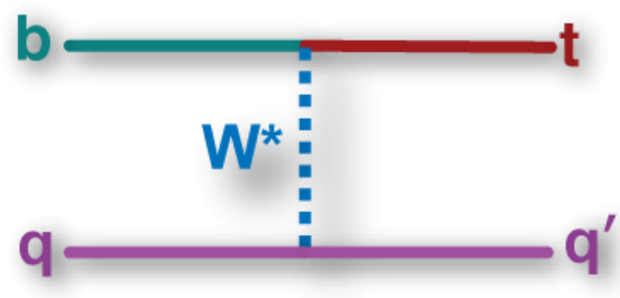


Electroweak
Single Top Production

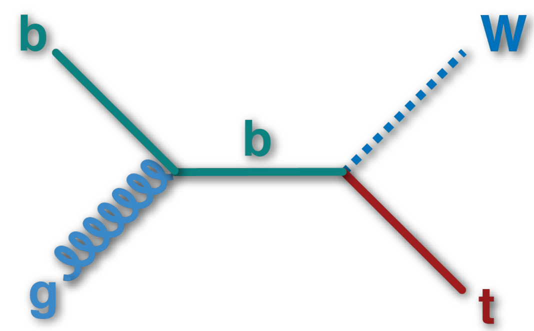
How else is top produced?



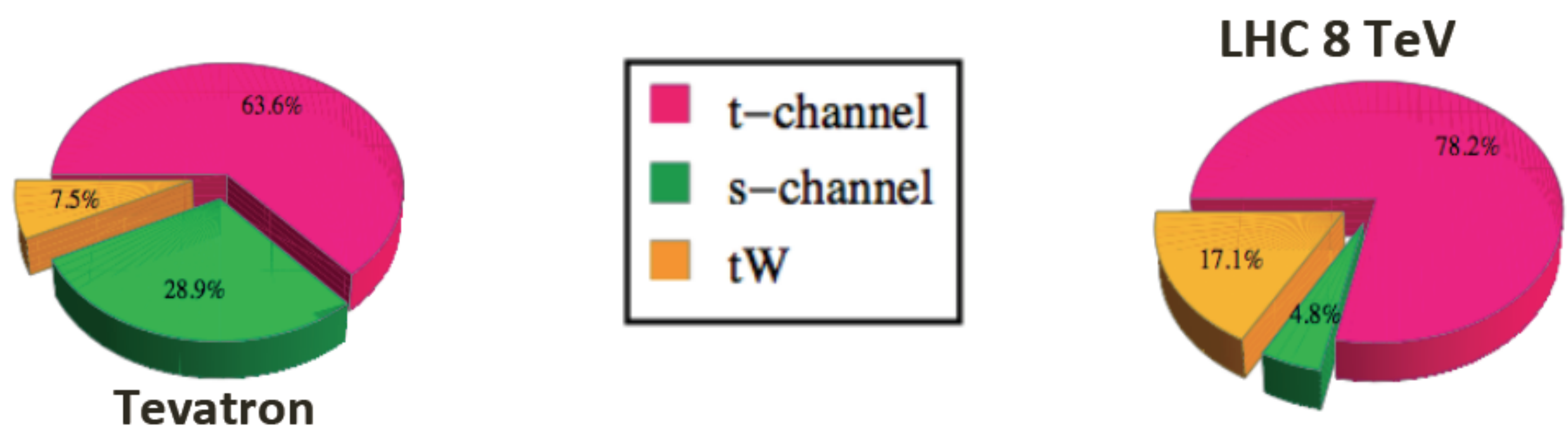
s-channel



t-channel

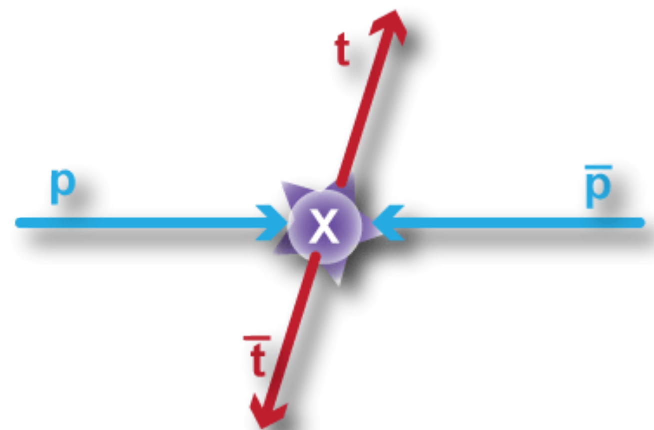


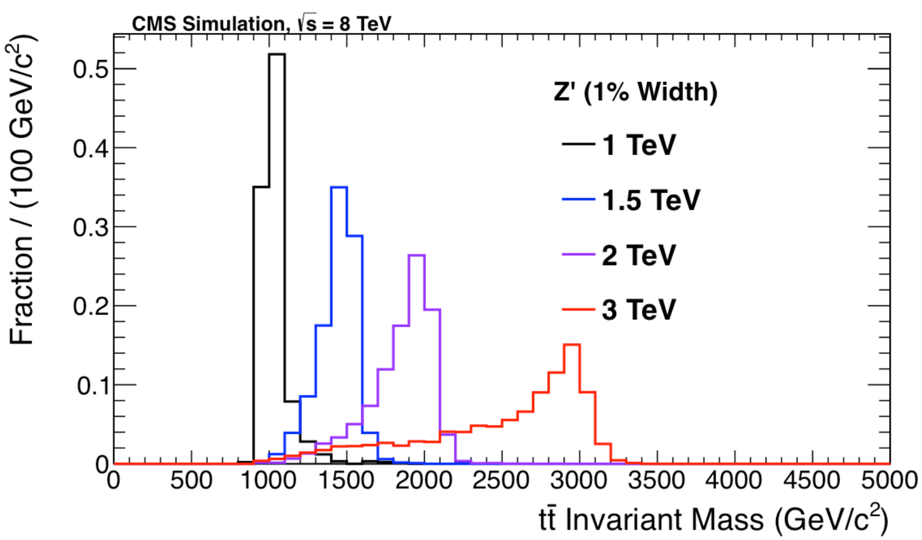
Wt-production



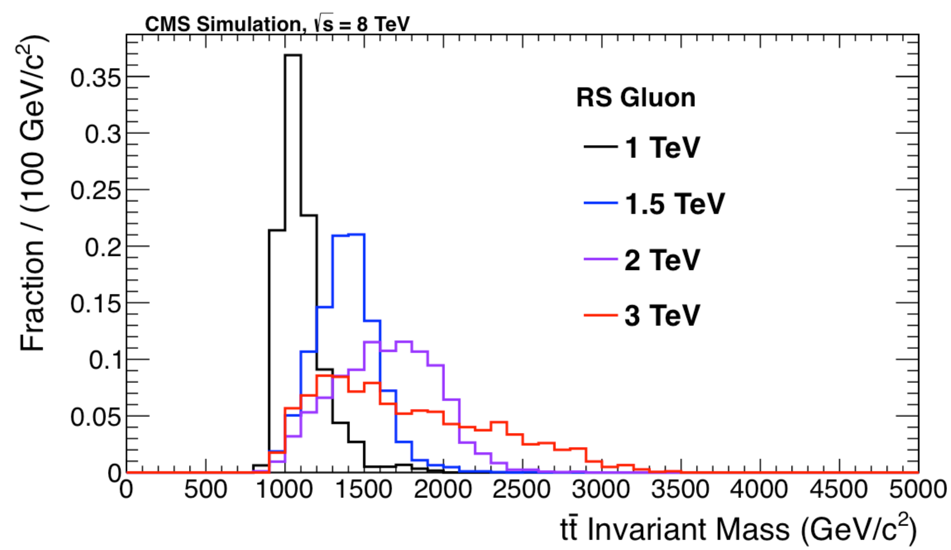
New Resonance Production?

How else is top produced?



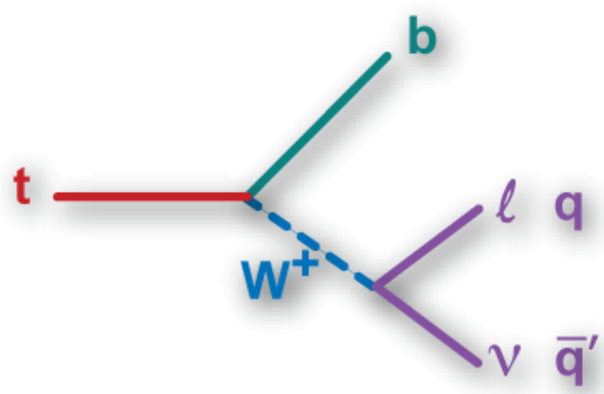


$Z' \rightarrow tt$, $\Gamma/m_{Z'} = 1\%, 10\%$, xs∝width but SM couplings

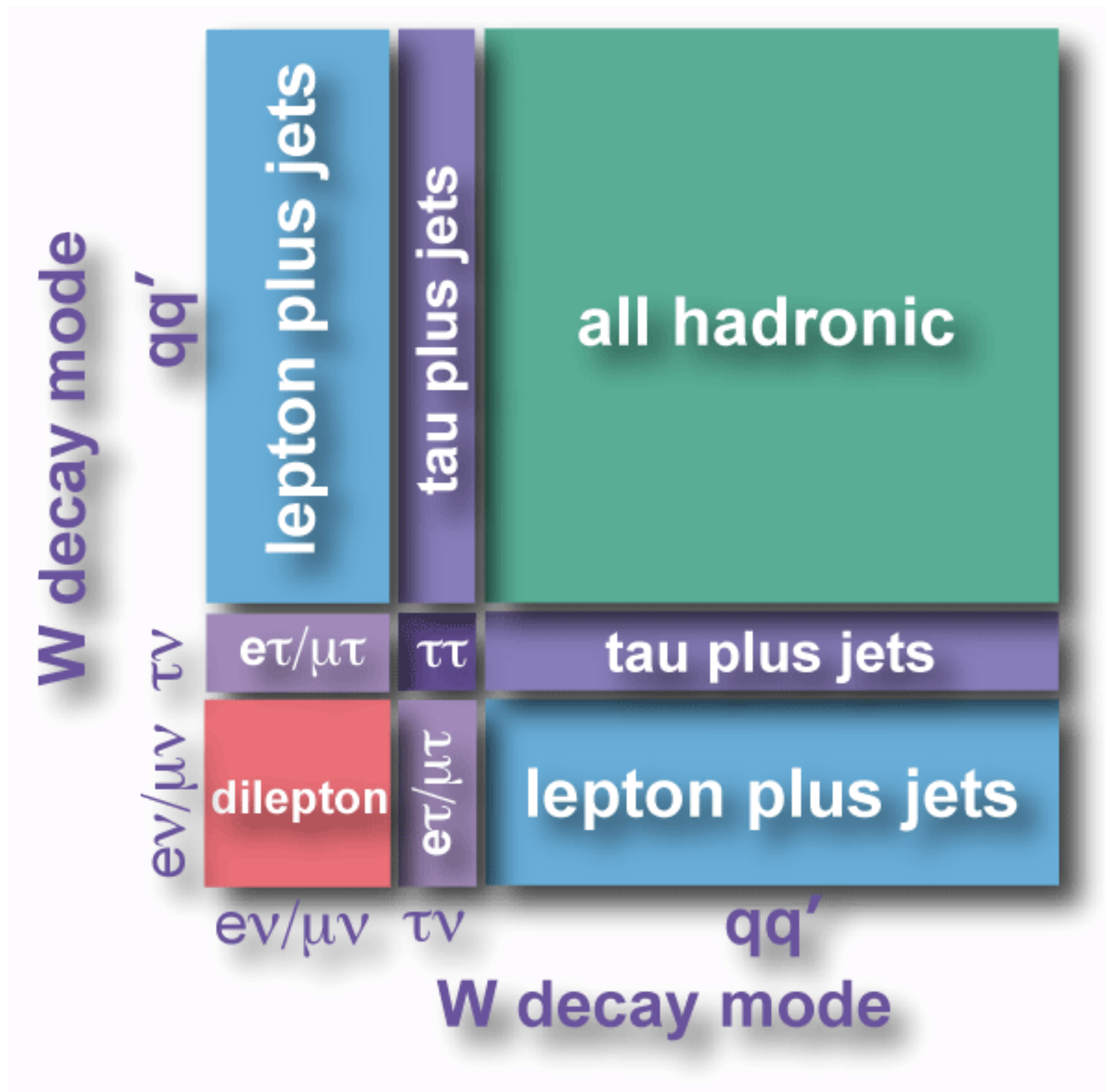


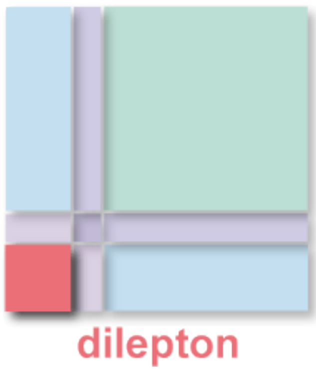
RS KK gluon→tt

How does Top decay?

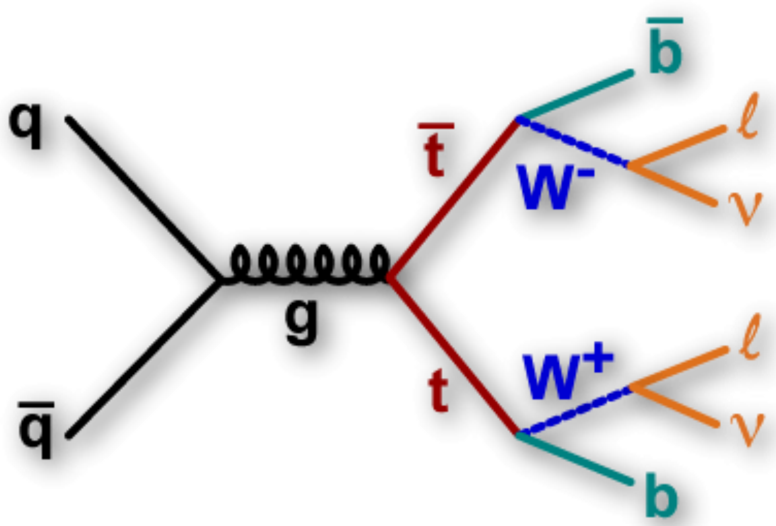


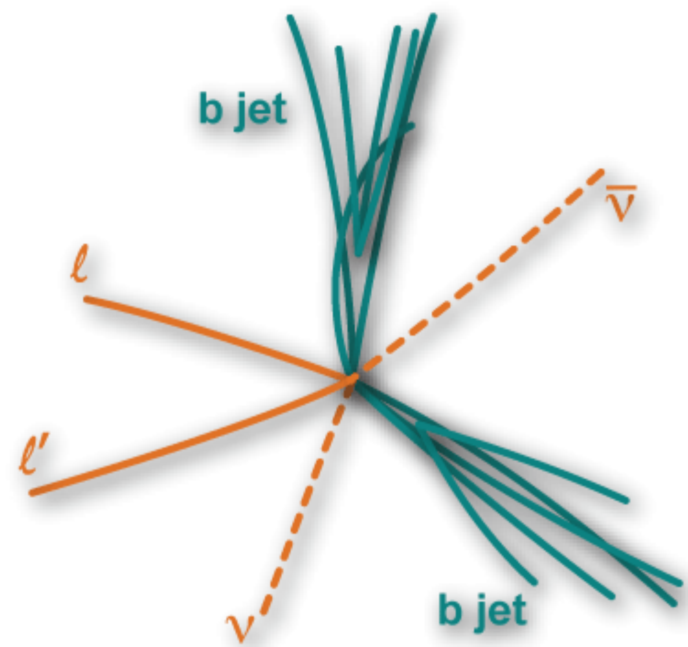
t→Wb ~ 100%





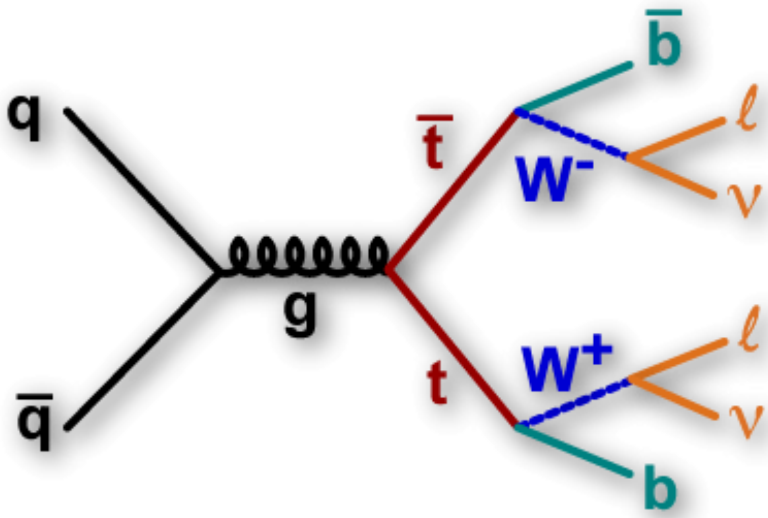
Dilepton Decay Mode

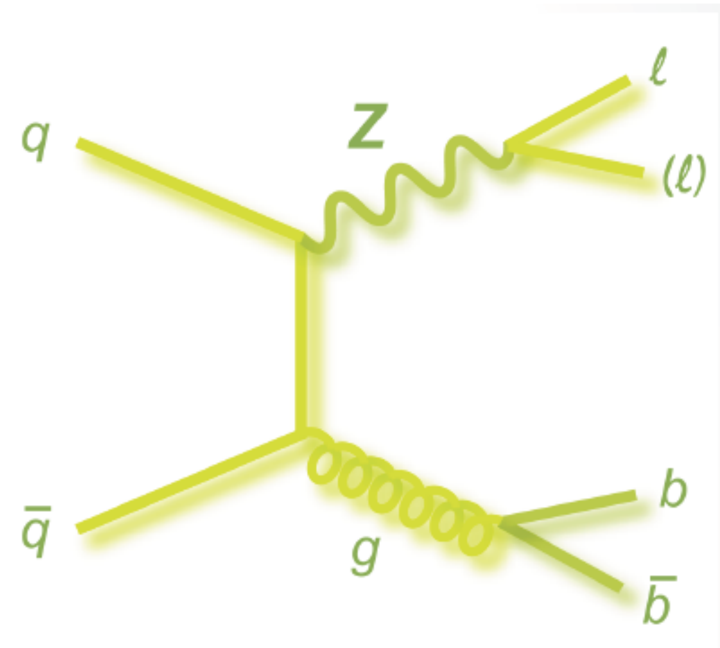




e/μ *BR* 6%

Dilepton Decay Mode





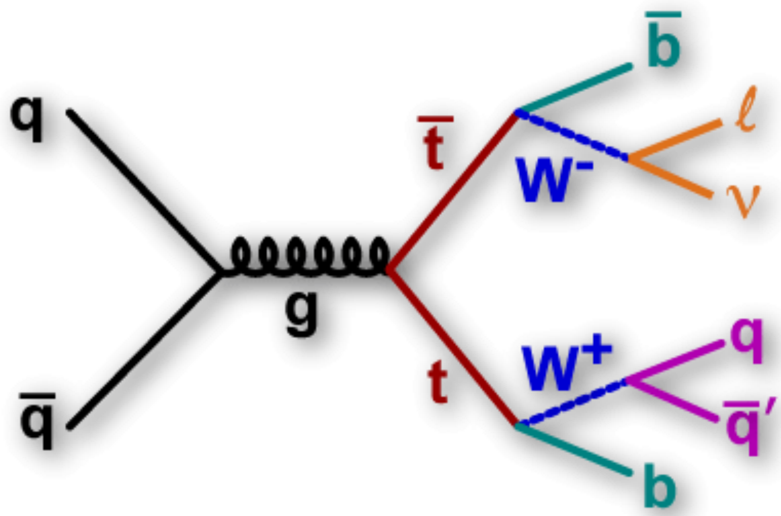
Event selection:

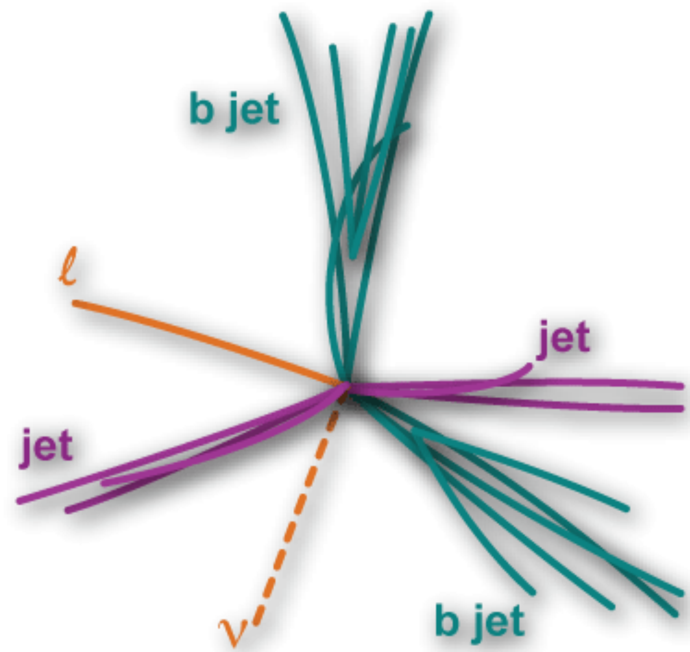
- 2 leptons (e,μ)
- MET (2ν)
- b-jets

Main Backgrounds

- Z + jets
- single top
- dibosons
- QCD "fakes"

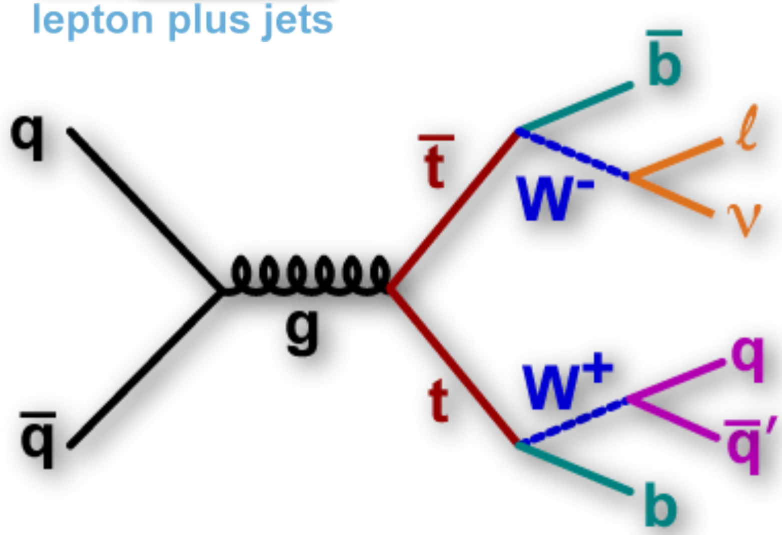
Lepton+Jets Decays

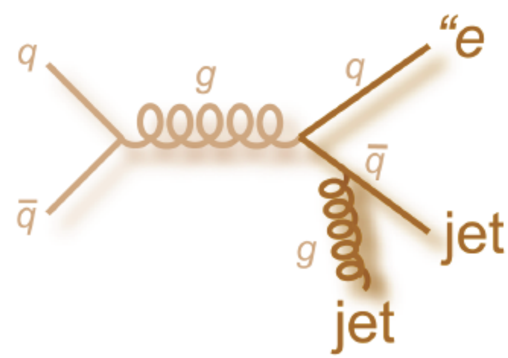


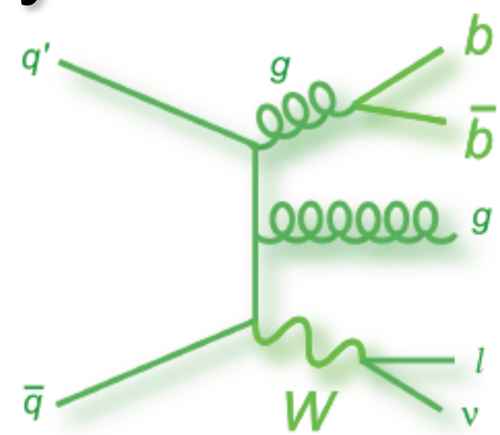


e/μ+jet *BR* 34%

Lepton+Jets Decays







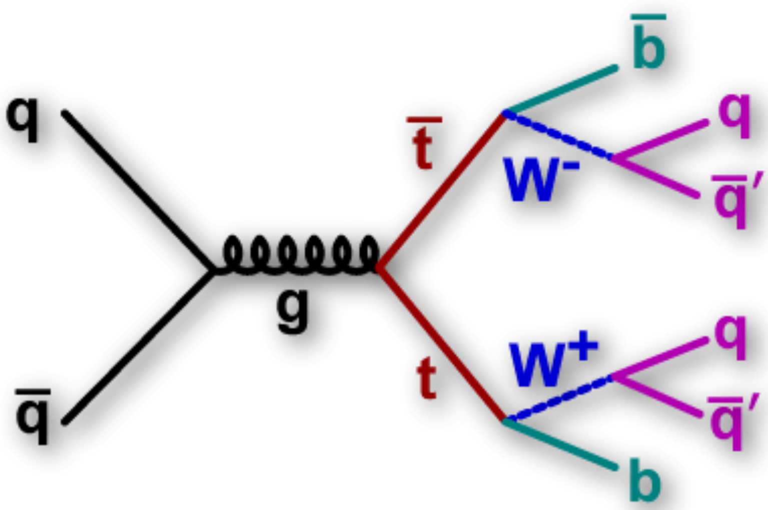
Event selection:

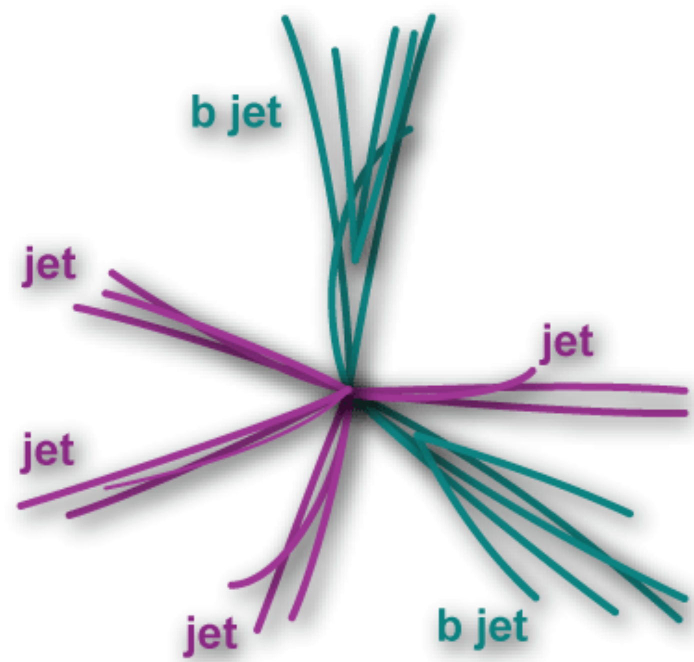
- 1 lepton (e or μ)
- MET (1ν)
- b-jets
- 2 jets

Main Backgrounds

- W + jets
- single top
- dibosons
- Z + jets
- QCD “fakes”

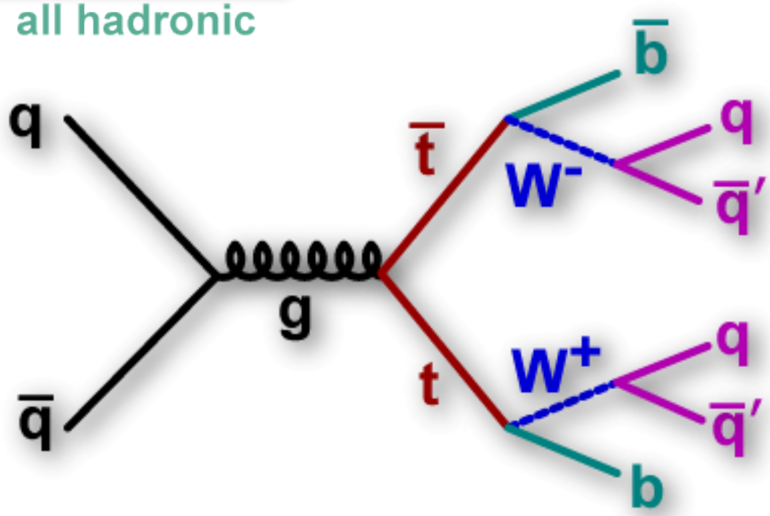
All-Hadronic Decays

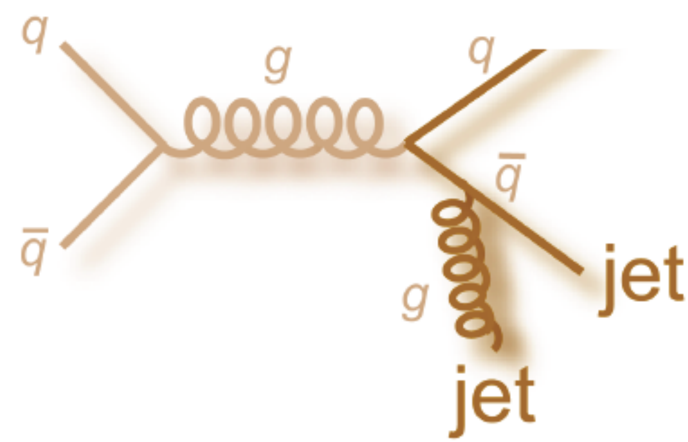




all jets *BR* 46%

All-Hadronic Decays





Event selection:

- 0 leptons (veto)
- no MET
- >4 jets
- b jets

Main Backgrounds

- QCD: light quark jets

Pros and cons by final state channel:

lepton plus jets

- fairly good branching ratio
- decent S/B ratio
- one ν so can fully reconstruct t-tbar system

dilepton

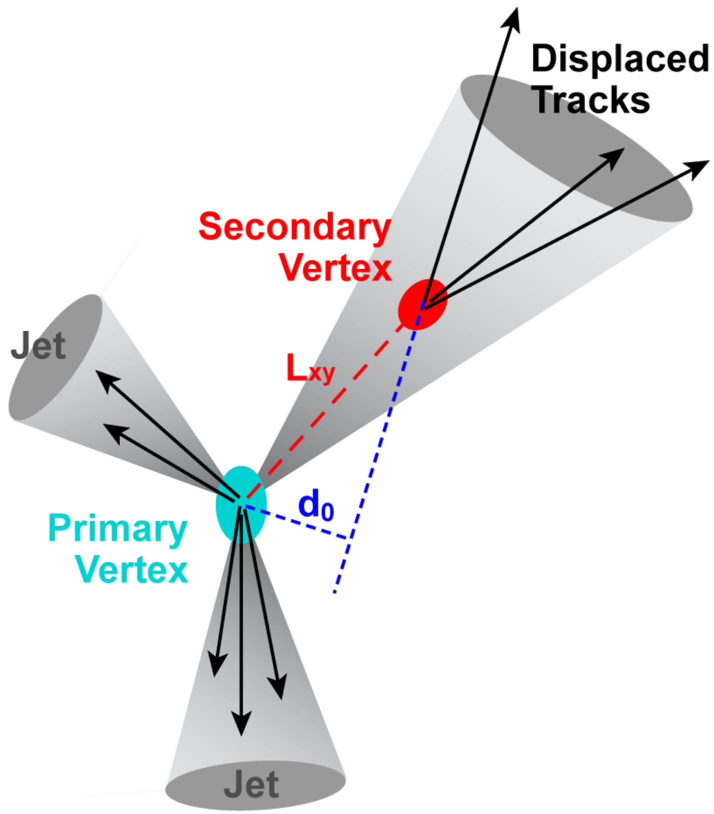
- smallest branching ratio, but…
- highest S/B ratio
- $2\nu \rightarrow$ reconstruction of t-tbar system ambiguous

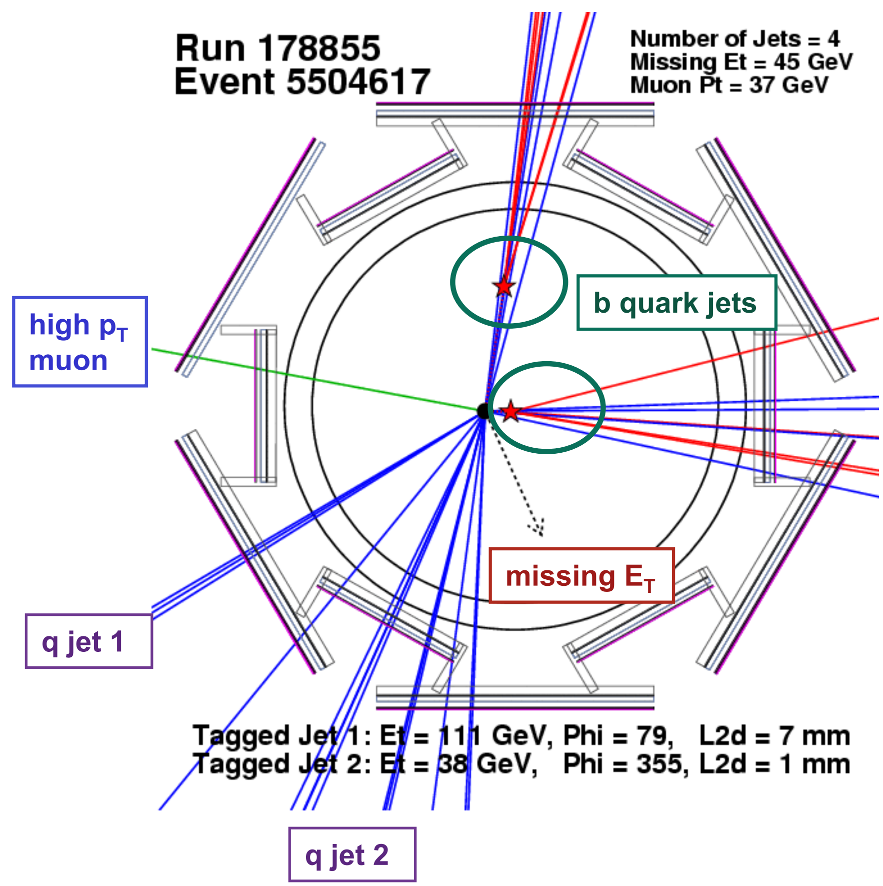
all hadronic

- highest branching ratio, but…
- lowest S/B ratio
- QCD backgrounds difficult but dominant
- combinatorics of t-tbar reconstruction complex

b-quark lifetime: cτ~450 μm
can travel ~3 mm before decaying

“Tagging”
b-quark jets



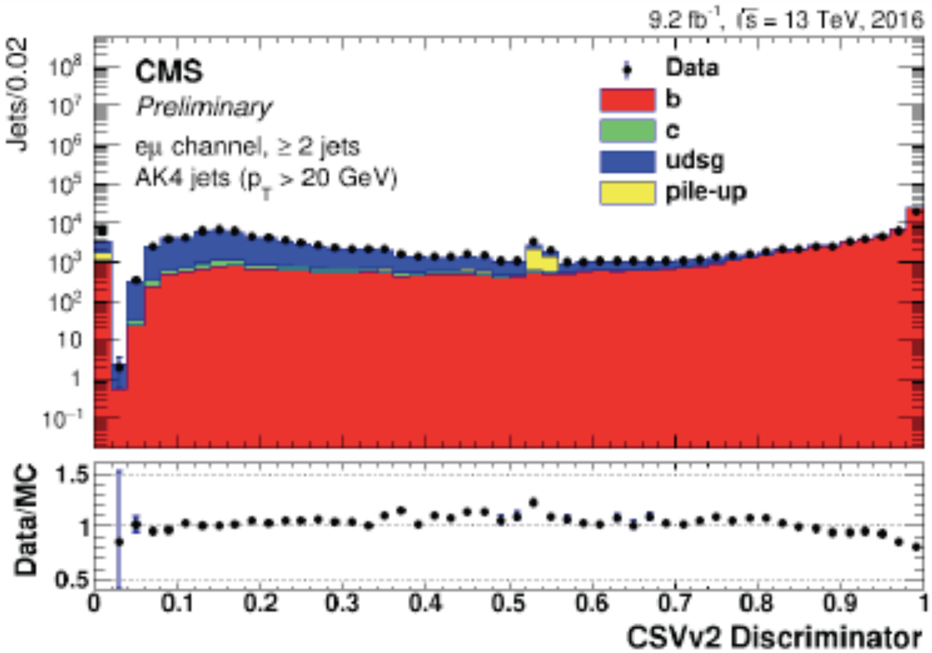


- secondary vertex tagging
  - use silicon tracking
- soft lepton tagging
  - low p_T lepton inside jet from b,c $\rightarrow l\nu X$ decay

lepton plus jets

multi-variate b-tagging at LHC

"Tagging"
b-quark jets

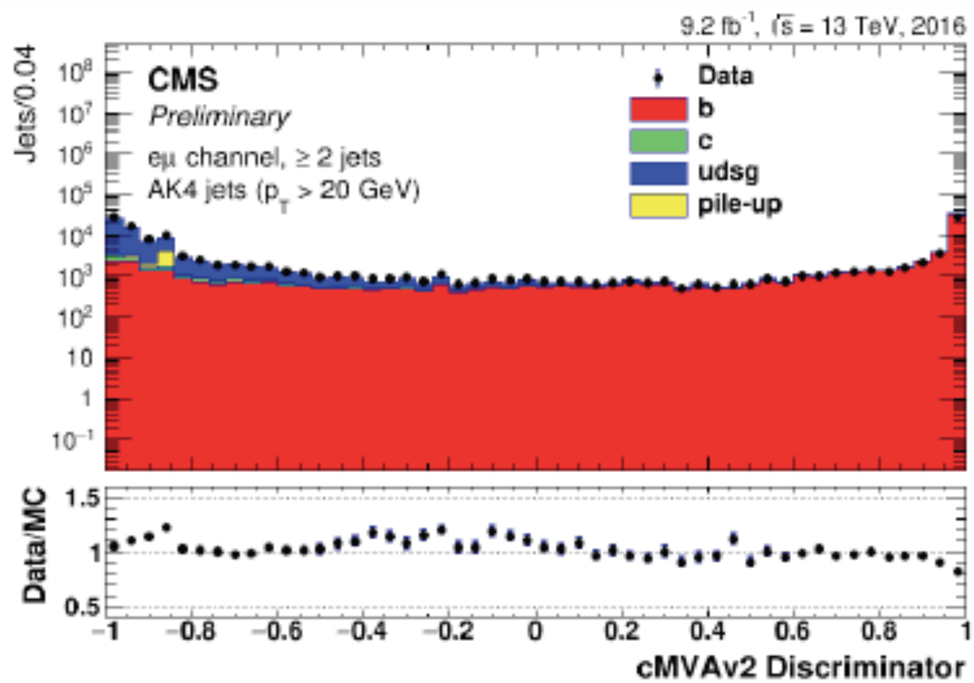


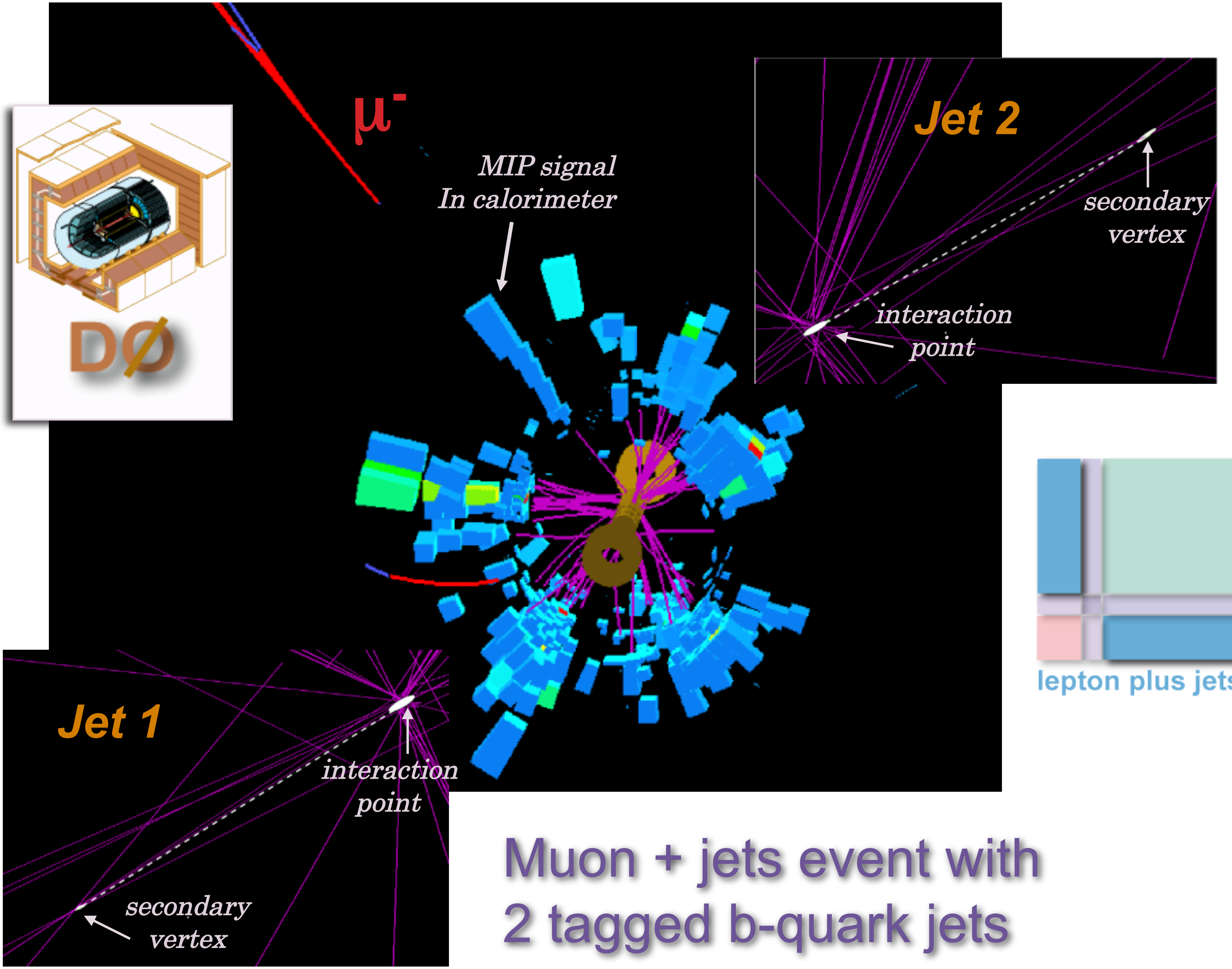
CSVv2 (top pair selection):

- neural network with inputs from "inclusive vertex finder"
- tight, med, loose working pts

cMVAv2 (top pair selection):

- boosted decision tree (BDT)
- jet probability and soft lep tags





Muon + jets event with 2 tagged b-quark jets

Top Production Cross Section

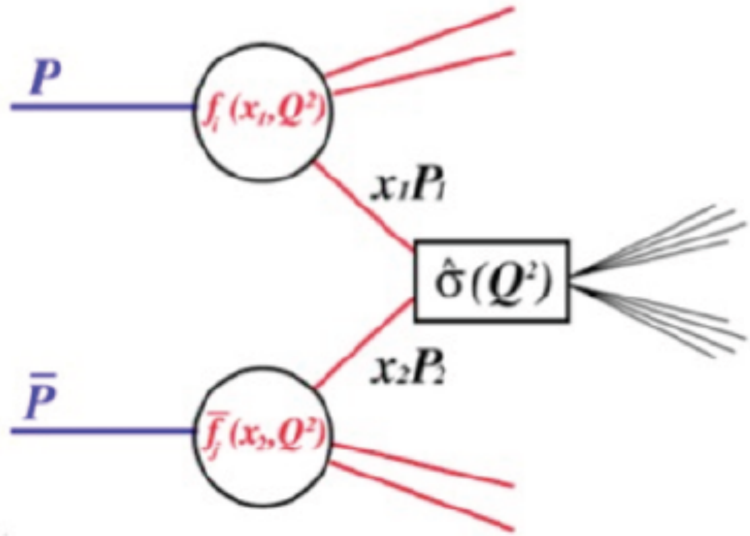
What is a cross section?

Geiger and Rutherford

differential cross section $d\sigma/d\Omega$: Probability of a scattered particle in a given quantum state per unit solid angle $d\Omega$

integrated cross section: $\sigma = \int [d\sigma/d\Omega]\, d\Omega$

Cross section calculation



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

Sum over incoming partons i, j

Momentum fraction for incoming parton

PDF for incoming parton i

"partonic" cross section

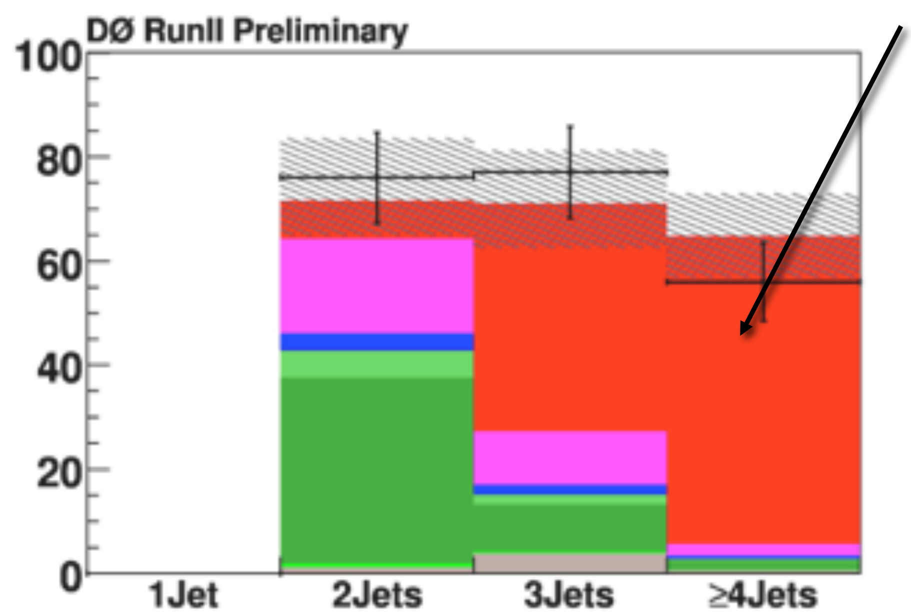
How do we measure the cross section?

$$\sigma(tt) = \frac{N_{events} - N_{background}}{\mathcal{L}uminosity * \varepsilon}$$

t-tbar!

Why measure the Top Pair Production Cross Section:

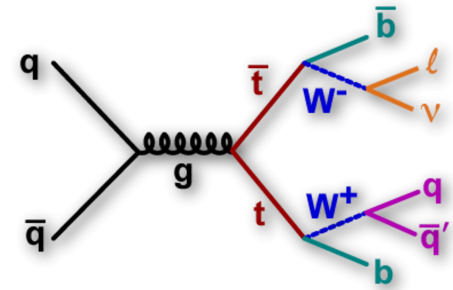
- As QCD predicts?
- Only SM top?
- By heavy particles?



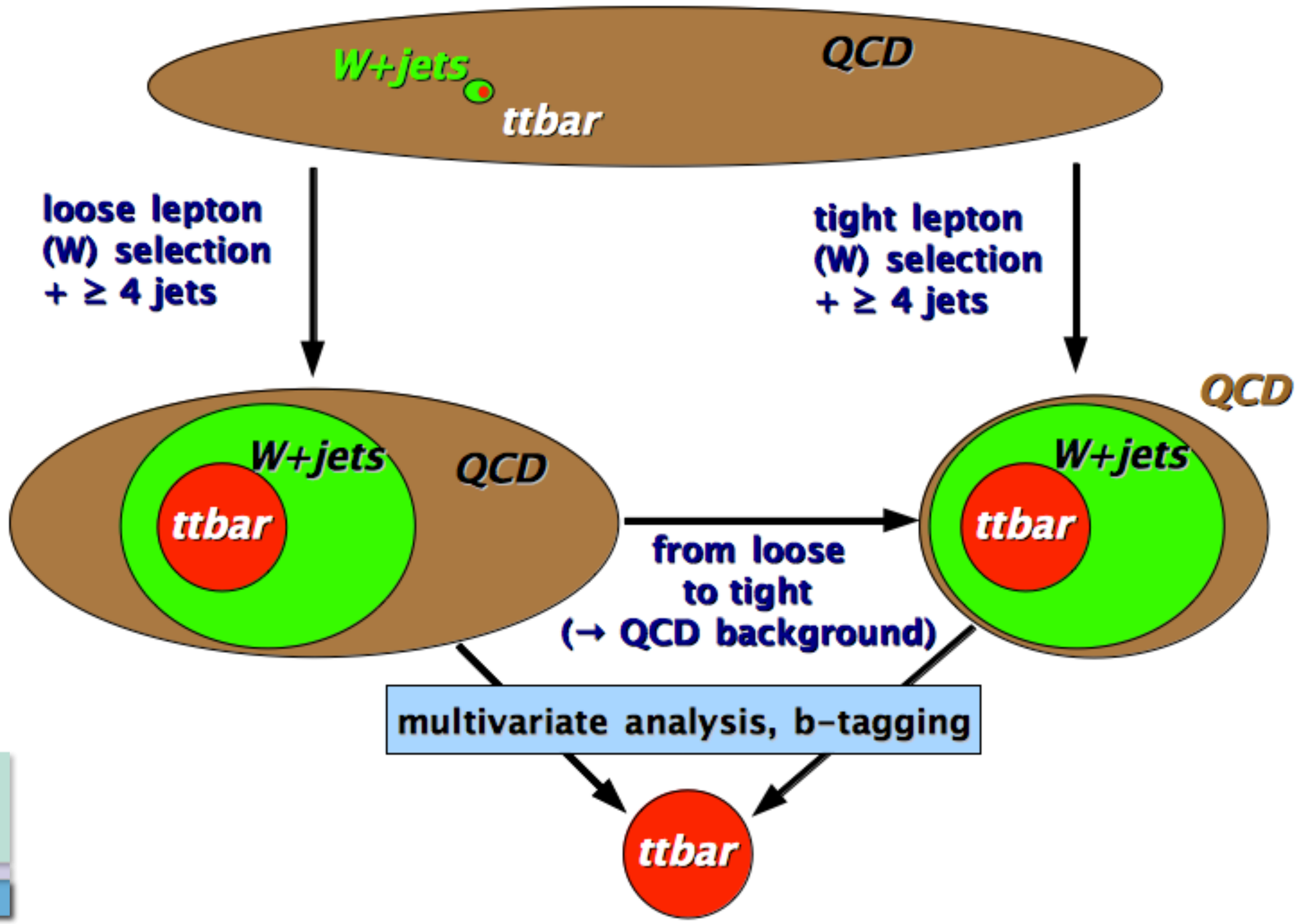
counting experiment

lepton plus jets

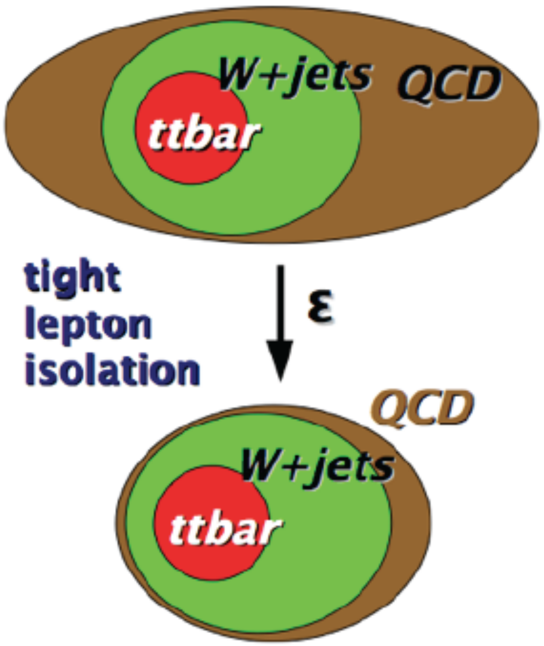
How do we measure the cross section?



triggered sample: isolated e/μ



How do we measure the cross section?



determining QCD from data:

matrix method

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

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

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

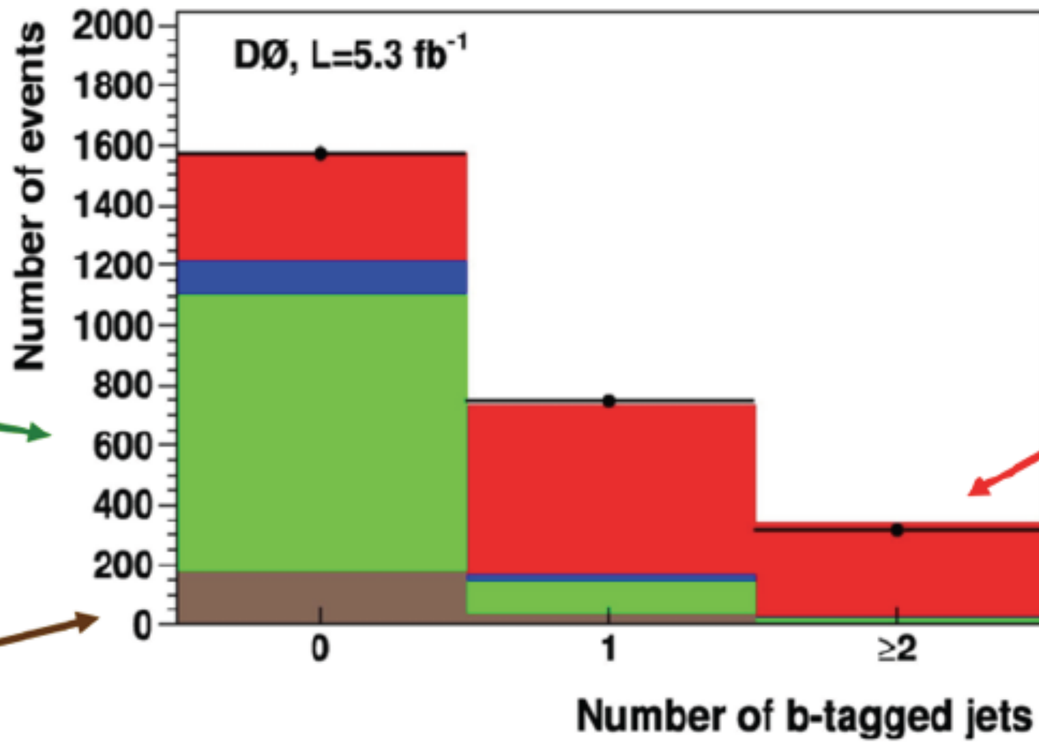
- N_{loose} and N_{tight}: signal datasets
- ε_{QCD} from independent QCD multi-jet dataset *(e.g. low MET sideband)*
- $\varepsilon_{W+ttbar}$ from W+jets MC simulation, normalized to data
- Solve for N_{QCD} and $N_{W+ttbar}$
- Determine multi-jet QCD entirely from data!

Counting Experiment

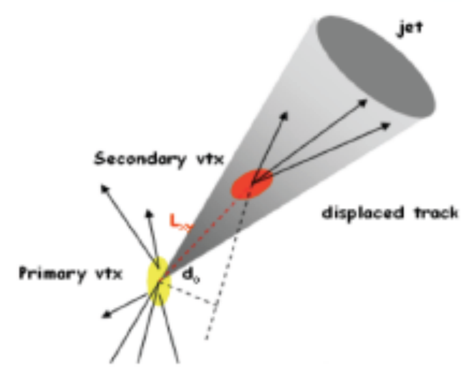
b-tagging: powerful tool to reduce background

W+jets

multijets



top pair

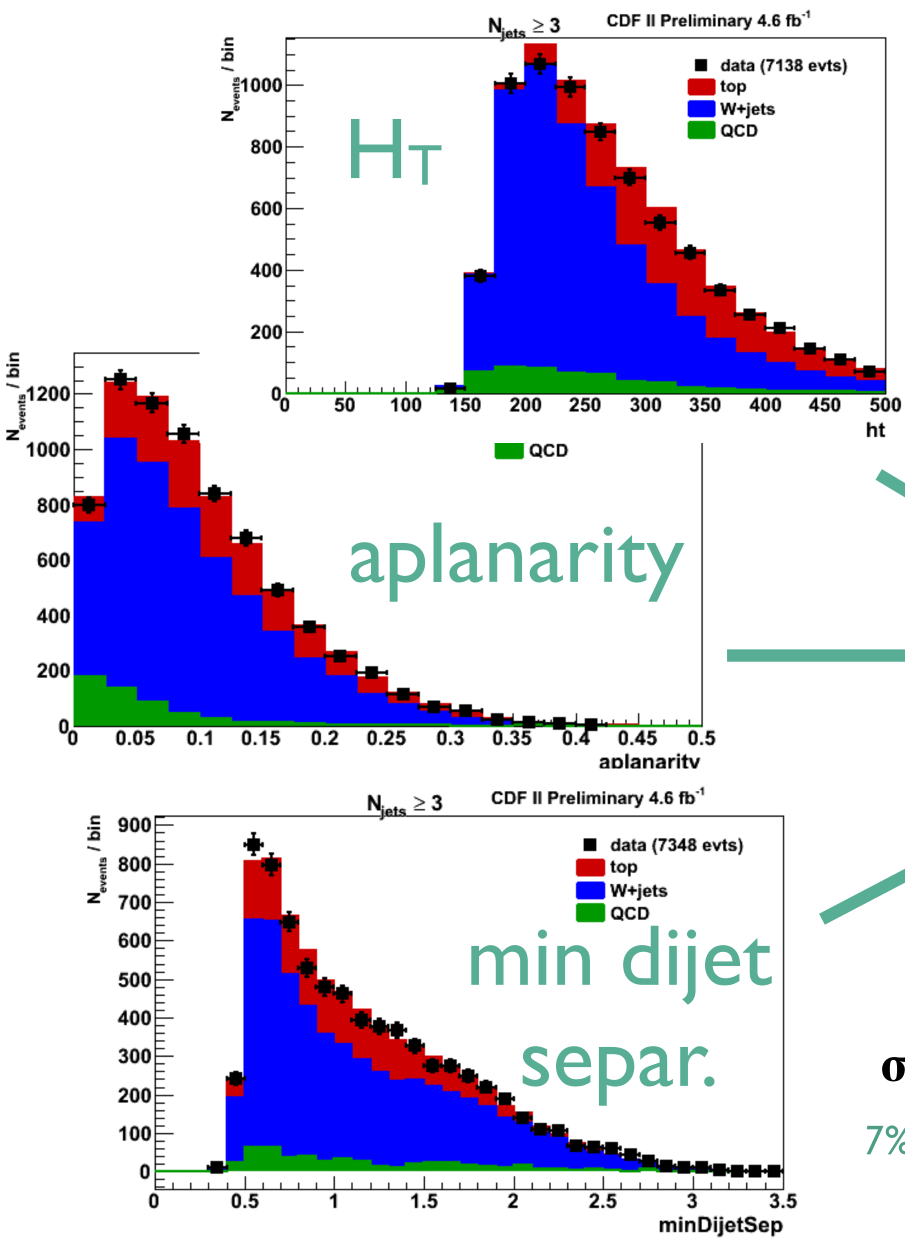


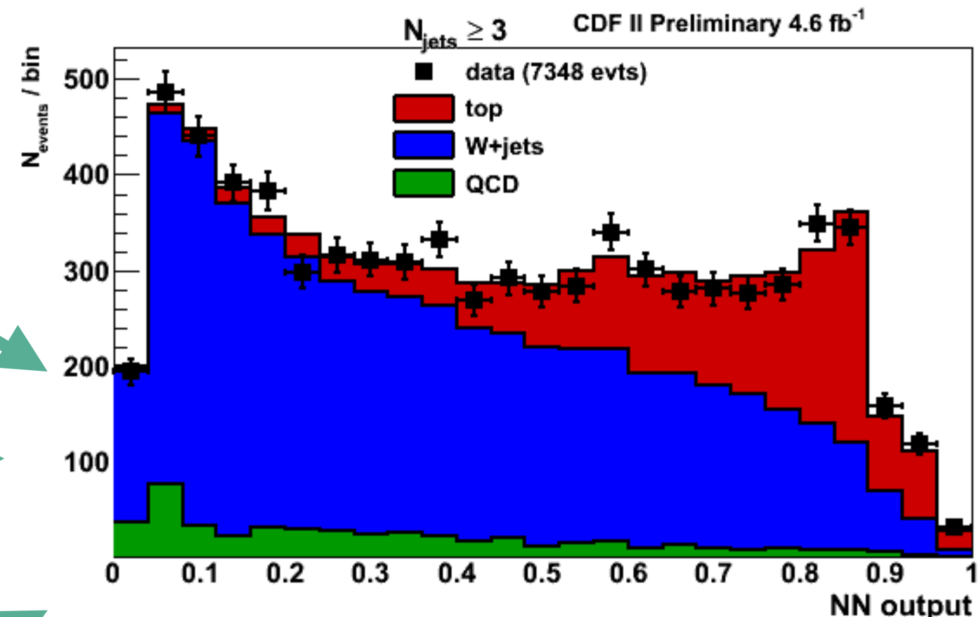
$$\sigma_{t\bar{t}} = 8.13^{+1.02}_{-0.90} \text{ (stat+syst+lumi) pb}$$

m_{top} = 172.5 GeV

How do we measure the cross section?

Multivariate techniques using event topologies





Neural Net

$$\sigma_{ttbar} = 7.82 \pm 0.38(\text{stat}) \pm 0.37(\text{syst}) \pm 0.15\ (\text{theory})\ \text{pb}$$

7% relative uncertainty better than 10% Run 2 goal and theory at the time

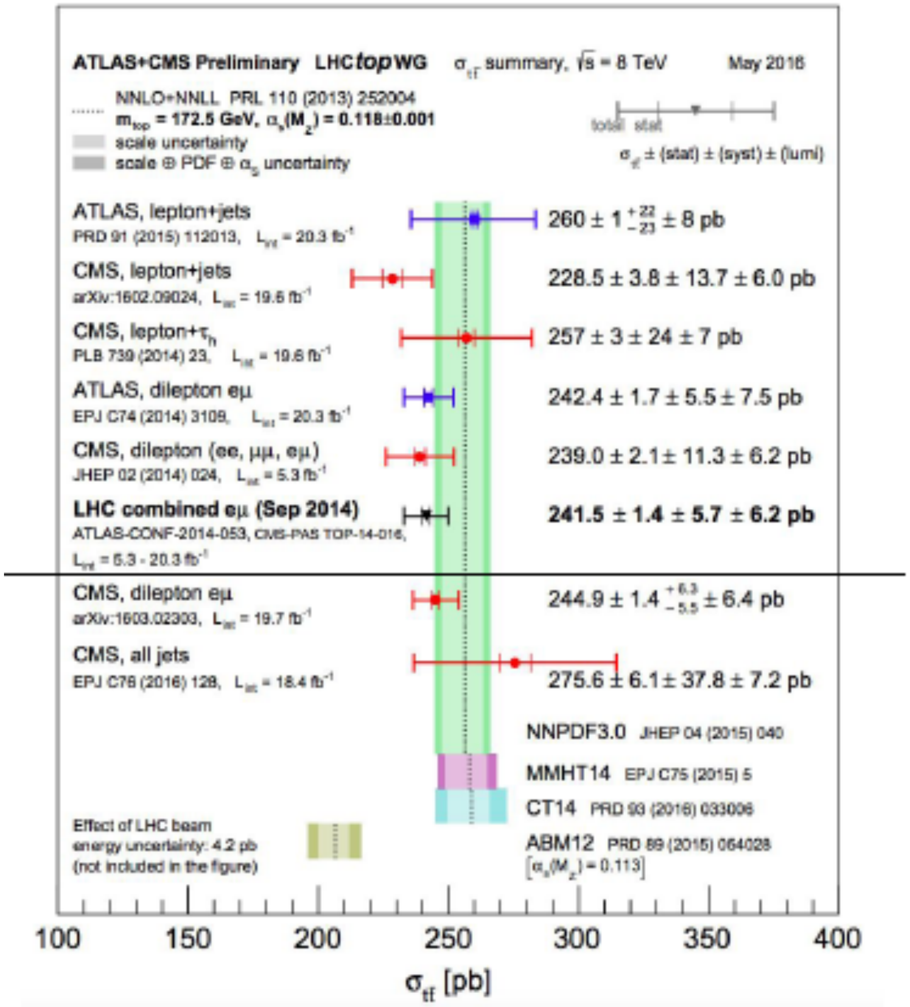
How do we measure the cross section?

menu of uncertainties at the LHC

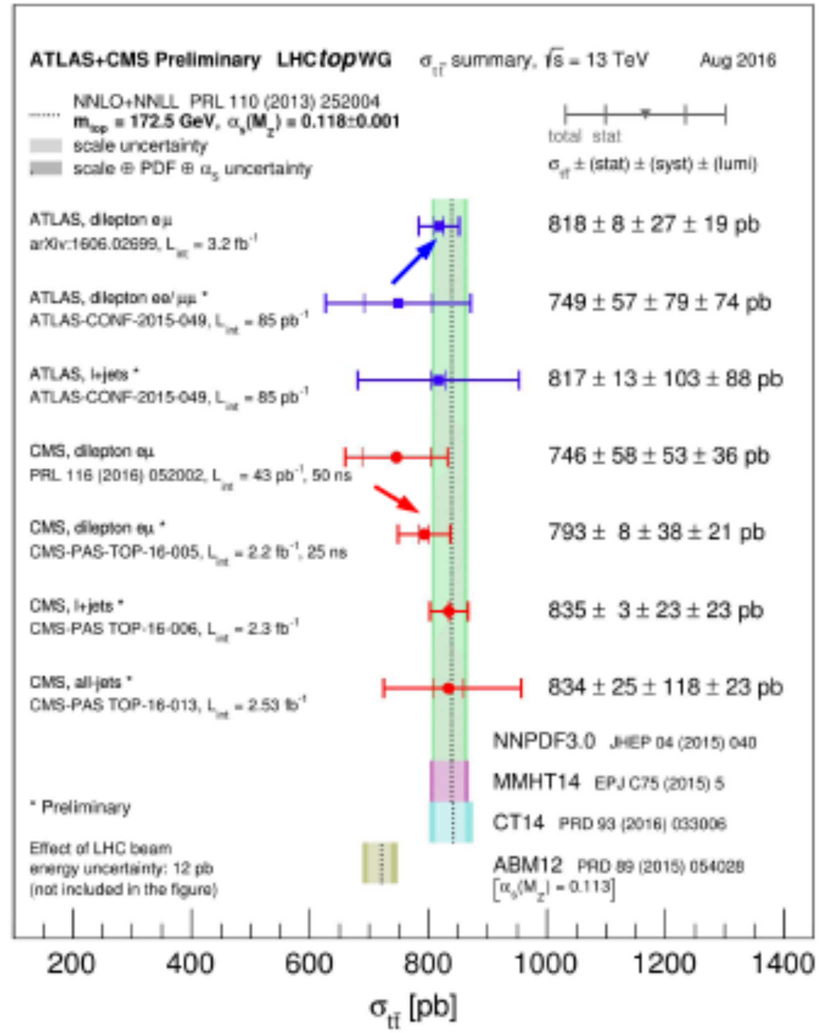
$\sqrt{s}$ Uncertainty (inclusive $\sigma_{t\bar{t}}$)	7 TeV $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	7 TeV $\Delta C_b/C_b$ (%)	7 TeV $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	8 TeV $\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	8 TeV $\Delta C_b/C_b$ (%)	8 TeV $\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)
Data statistics			1.69			0.71
$t\bar{t}$ modelling	0.71	−0.72	1.43	0.65	−0.57	1.22
Parton distribution functions	1.03	-	1.04	1.12	-	1.13
QCD scale choice	0.30	-	0.30	0.30	-	0.30
Single-top modelling	-	-	0.34	-	-	0.42
Single-top/$t\bar{t}$ interference	-	-	0.22	-	-	0.15
Single-top Wt cross-section	-	-	0.72	-	-	0.69
Diboson modelling	-	-	0.12	-	-	0.13
Diboson cross-sections	-	-	0.03	-	-	0.03
Z+jets extrapolation	-	-	0.05	-	-	0.02
Electron energy scale/resolution	0.19	−0.00	0.22	0.46	0.02	0.51
Electron identification	0.12	0.00	0.13	0.36	0.00	0.41
Muon momentum scale/resolution	0.12	0.00	0.14	0.01	0.01	0.02
Muon identification	0.27	0.00	0.30	0.38	0.00	0.42
Lepton isolation	0.74	-	0.74	0.37	-	0.37
Lepton trigger	0.15	−0.02	0.19	0.15	0.00	0.16
Jet energy scale	0.22	0.06	0.27	0.47	0.07	0.52
Jet energy resolution	−0.16	0.08	0.30	−0.36	0.05	0.51
Jet reconstruction/vertex fraction	0.00	0.00	0.06	0.01	0.01	0.03
b-tagging	-	0.18	0.41	-	0.14	0.40
Misidentified leptons	-	-	0.41	-	-	0.34
Analysis systematics ($\sigma_{t\bar{t}}$)	1.56	0.75	2.27	1.66	0.59	2.26
Integrated luminosity	-	-	1.98	-	-	3.10
LHC beam energy	-	-	1.79	-	-	1.72
Total uncertainty ($\sigma_{t\bar{t}}$)	1.56	0.75	3.89	1.66	0.59	4.27

All channels measured: look for the unexpected!

ATLAS & CMS 8TeV

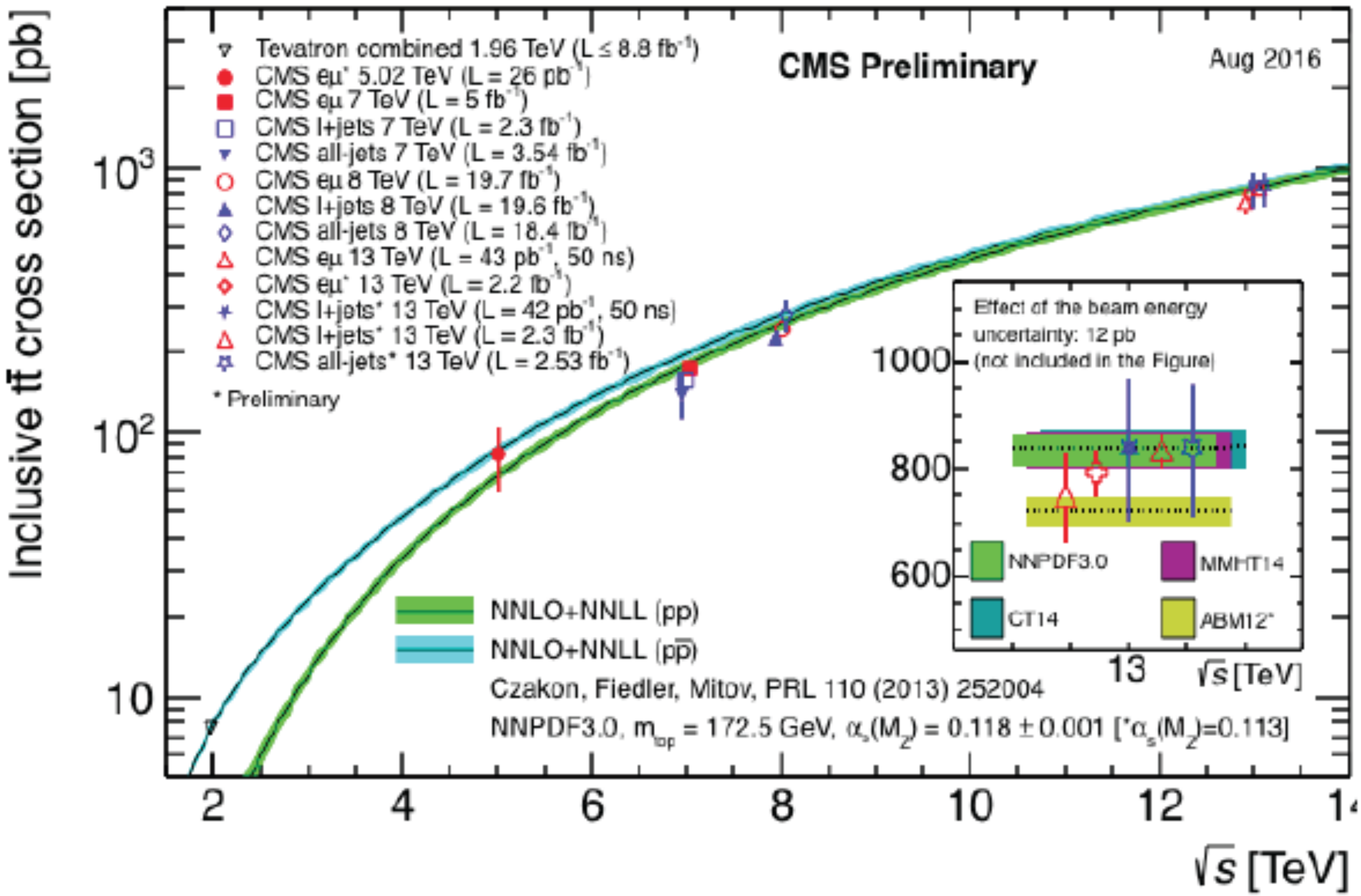


ATLAS & CMS 13TeV

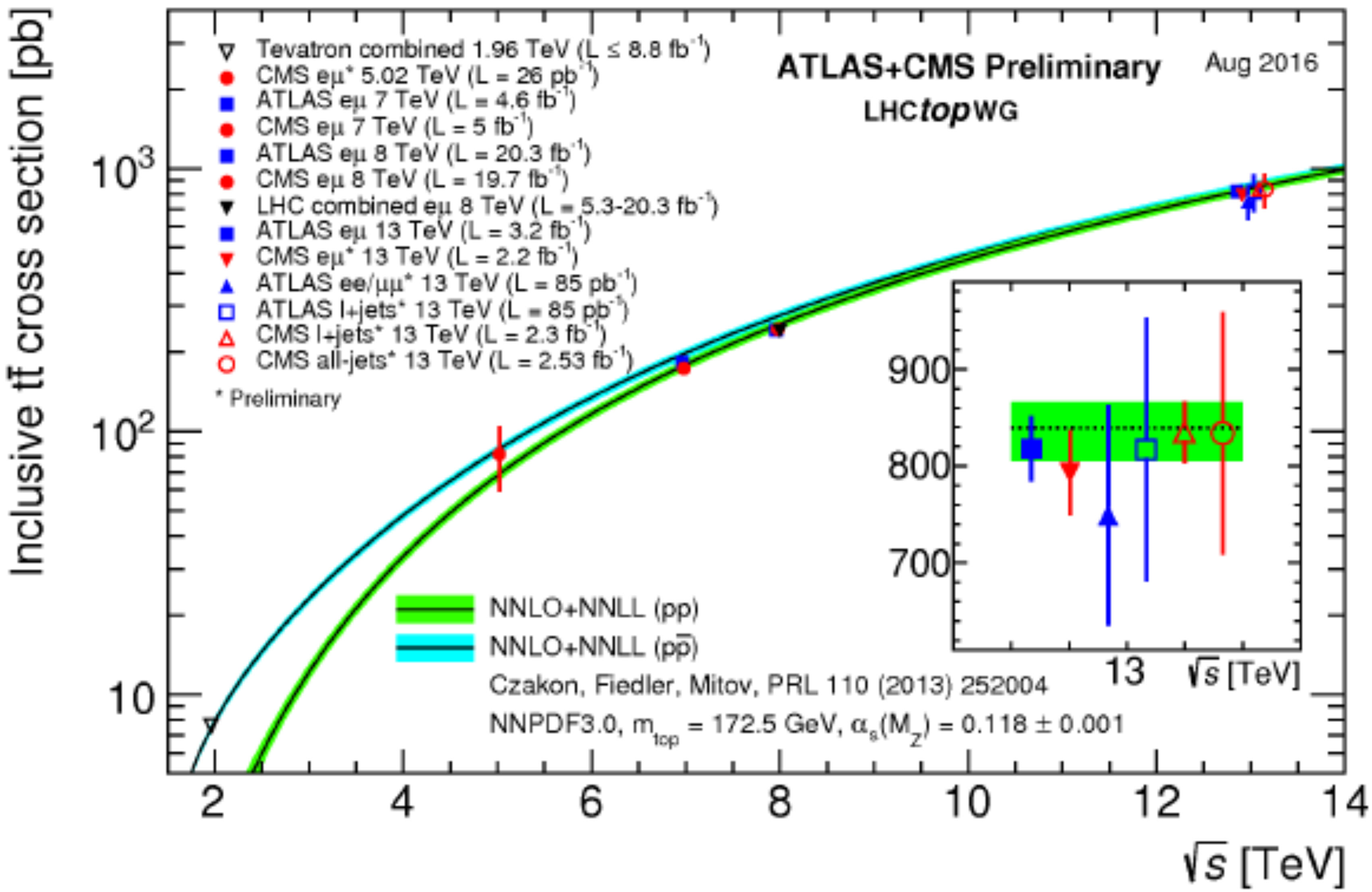


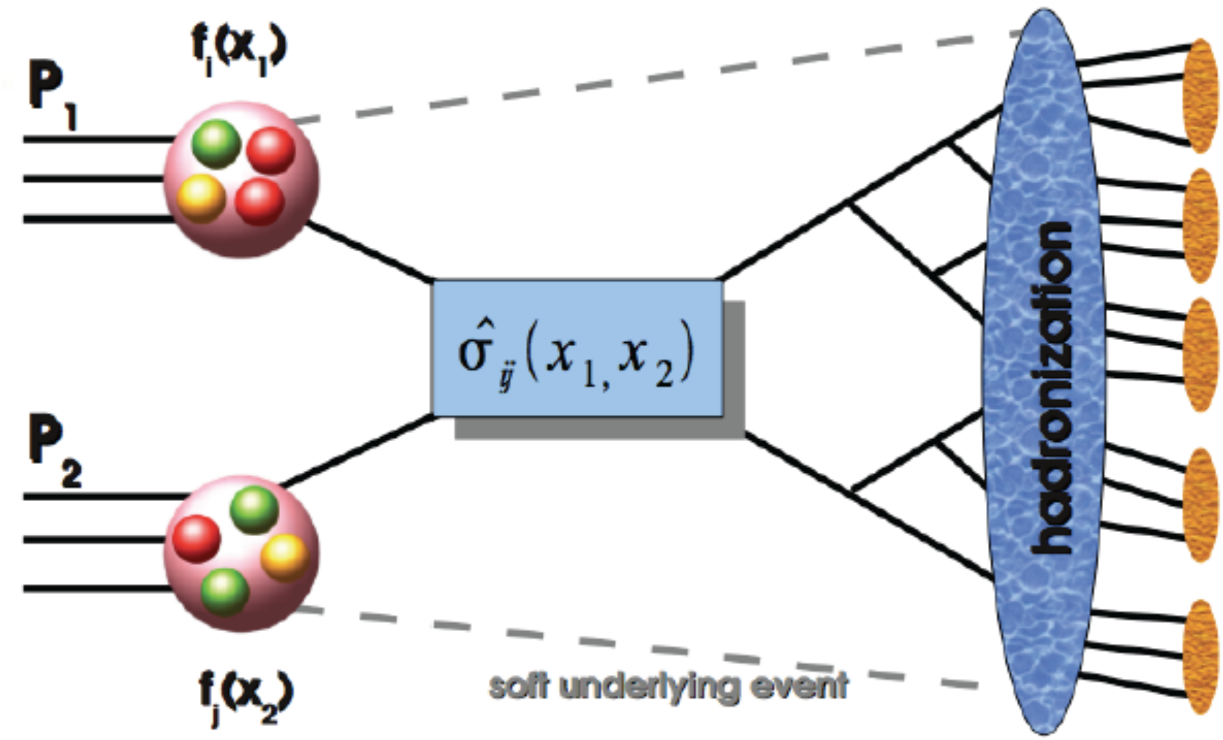
Measurement precision now comparable to theory

Four different energies (CMS)



Tevatron and LHC results consistent with NNLO+NNLL over a large range of CM energies

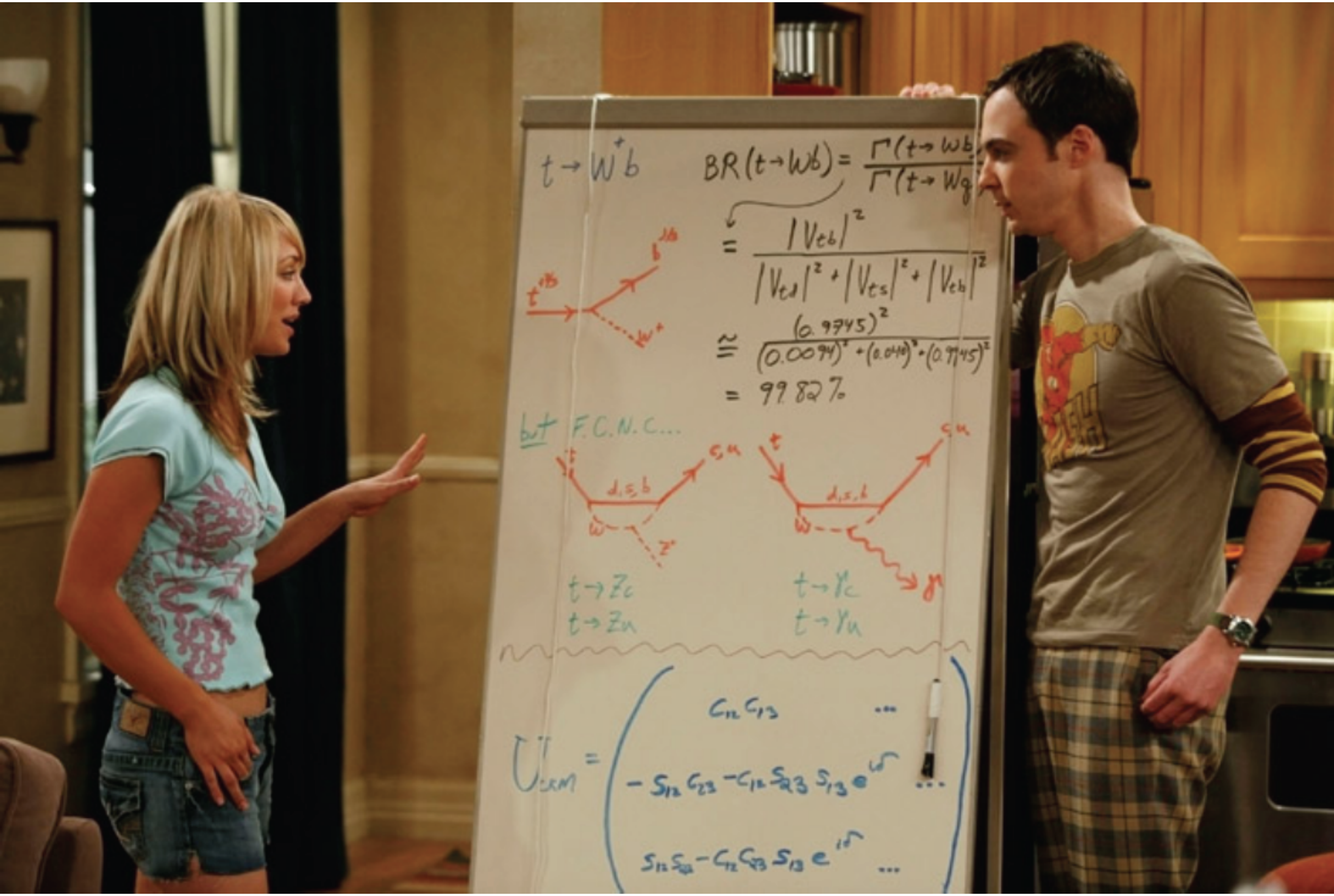




Differential Top Cross Sections:
sensitive to new physics on the tails…

Another time…

Electroweak Single Top Production

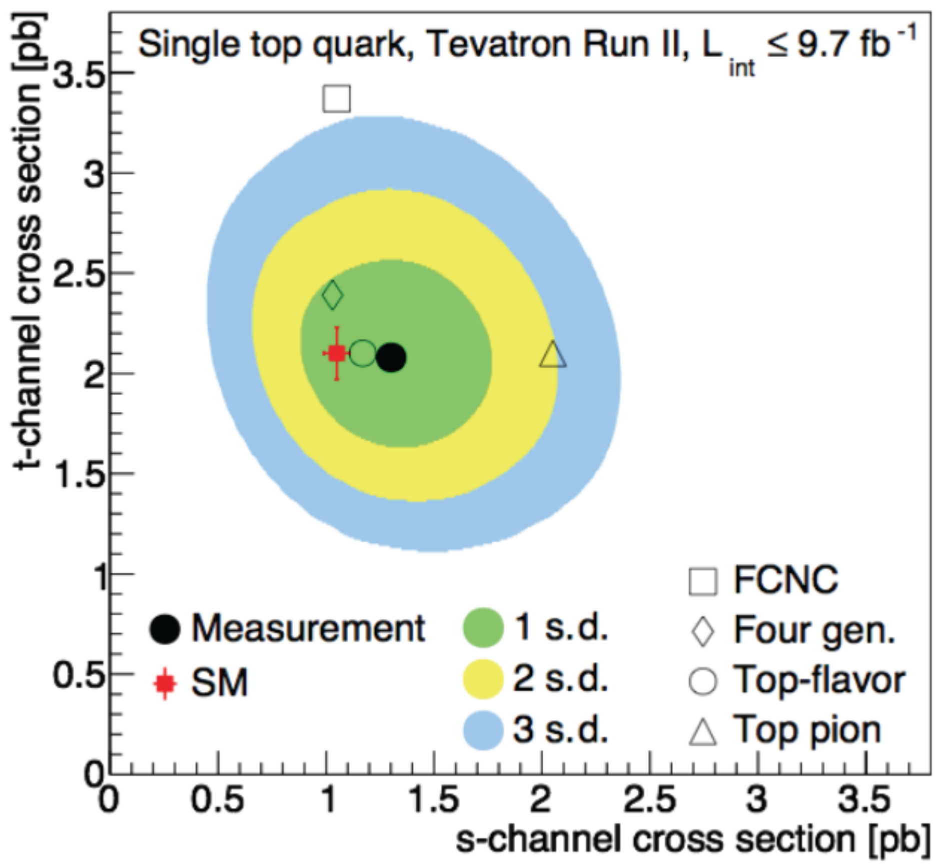

t → W+b
BR(t→Wb) =
= |Vtb|^2 / (|Vtd|^2 + |Vts|^2 + |Vtb|^2)
= 99.82%
but F.C.N.C...
d,s,b
t → Zc
t → Zu
t → γc
t → γu
U_CKM =

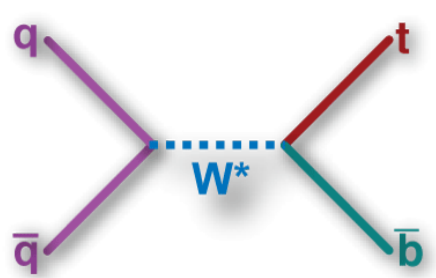
Searches for Single top at the Tevatron

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

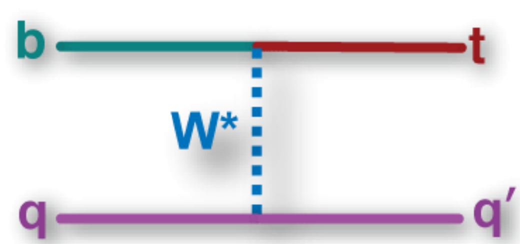
- direct measurement of $|V_{tb}|$
- sensitive to new physics models

Single top quark production as a window to physics beyond the standard model
Timothy M.P. Tait, C.-P. Yuan
Published in **Phys.Rev. D63** (2000) 014018
e-Print: hep-ph/0007298

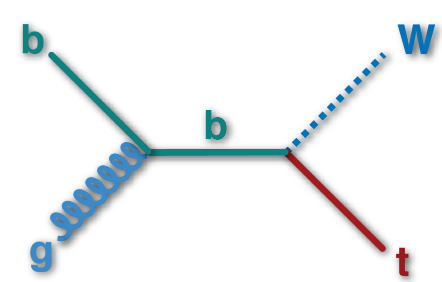




s-channel



t-channel

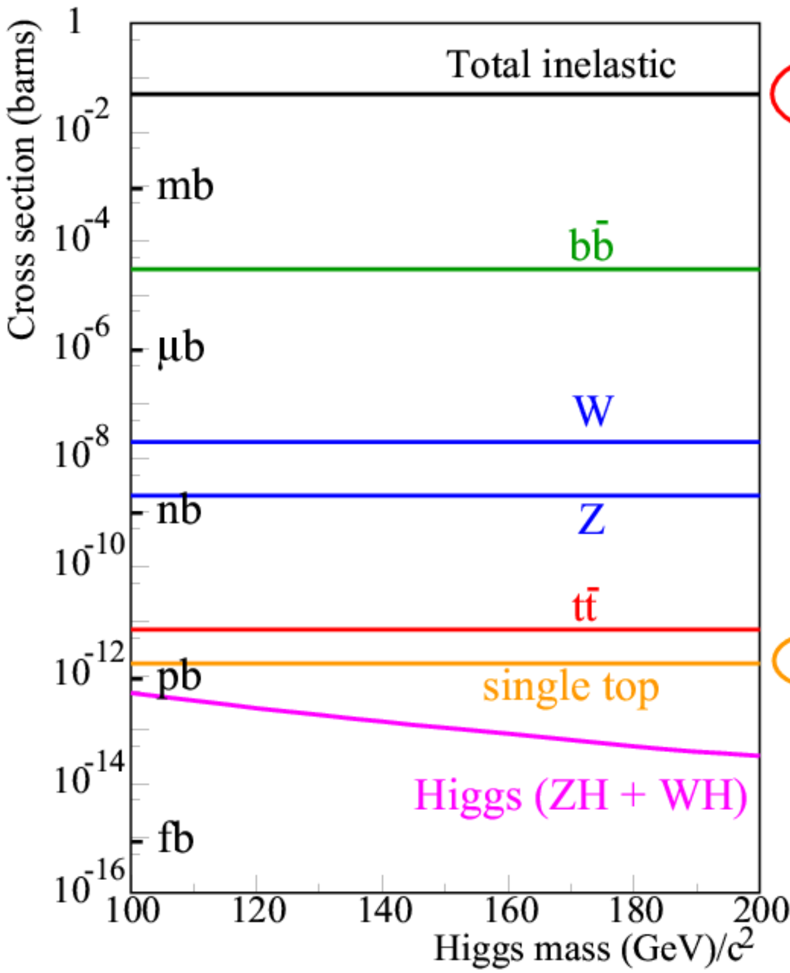


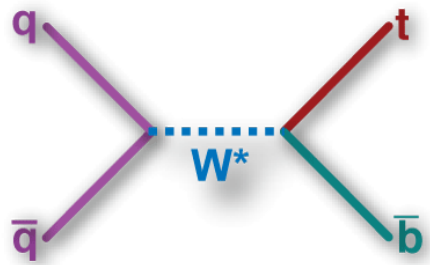
Wt-production

Searches for Single top at the Tevatron

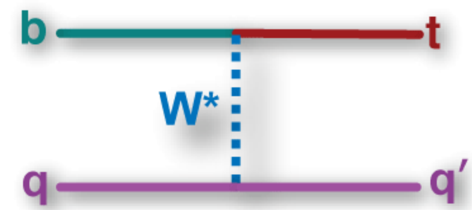
Single top backgrounds much larger than signal: Only ~2 jets! (QCD dijet events)

=>Statistically & systematically challenging



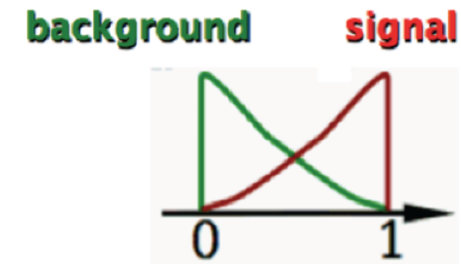


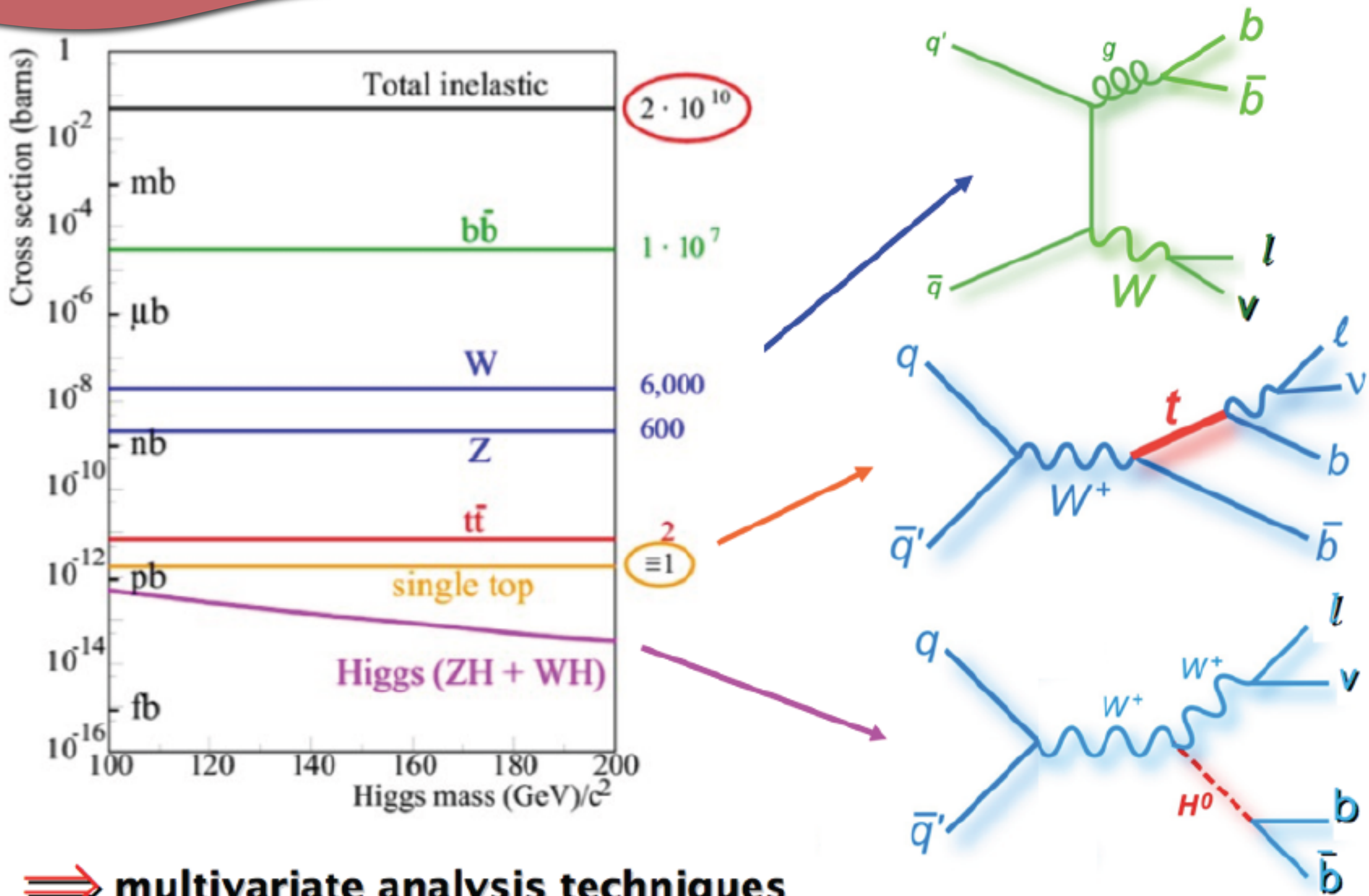
s-channel
1.05 ± 0.06 pb



t-channel
2.12 ± 0.16 pb

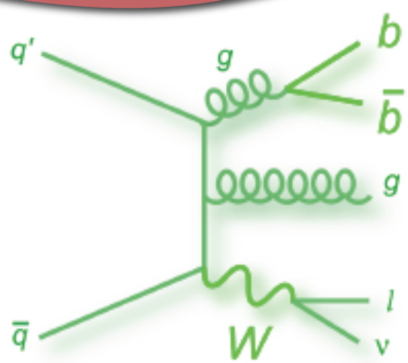
Searches for Single top at the Tevatron

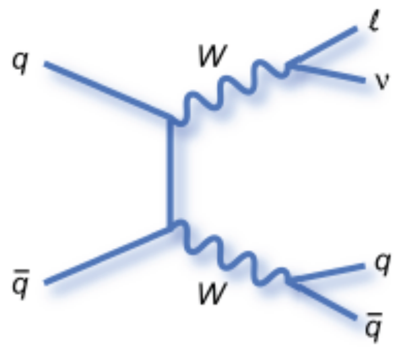


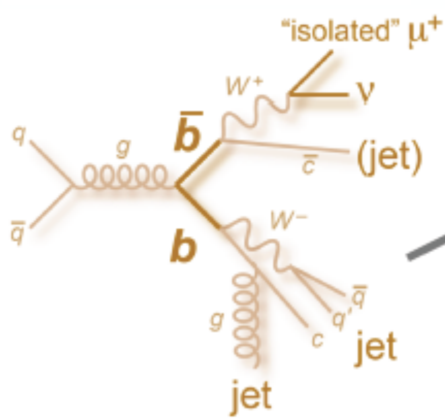


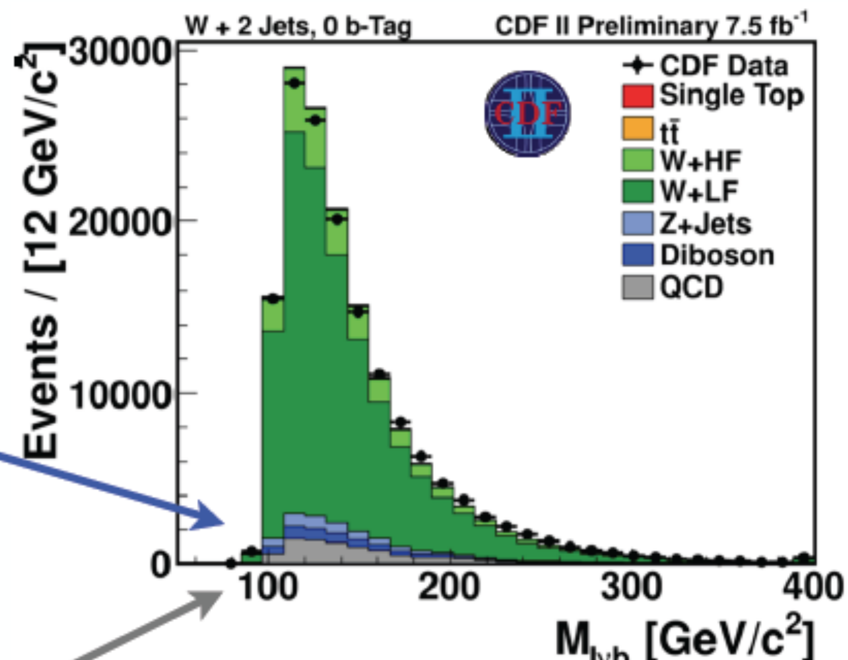
⟹ **multivariate analysis techniques**

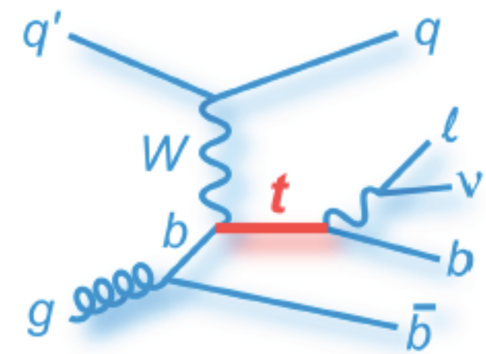
Searches for Single top at the Tevatron

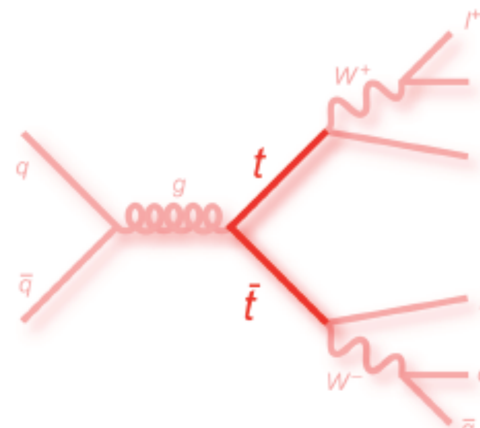






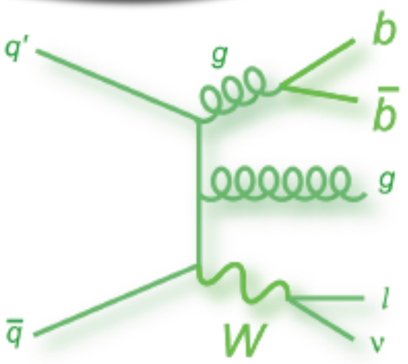


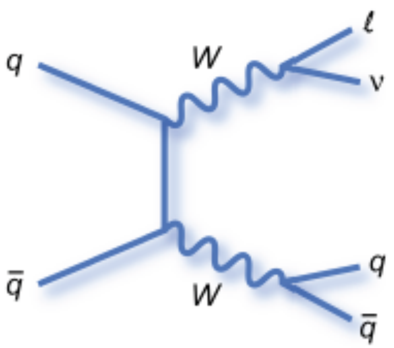


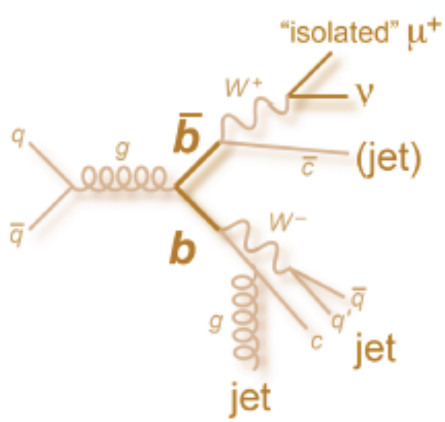


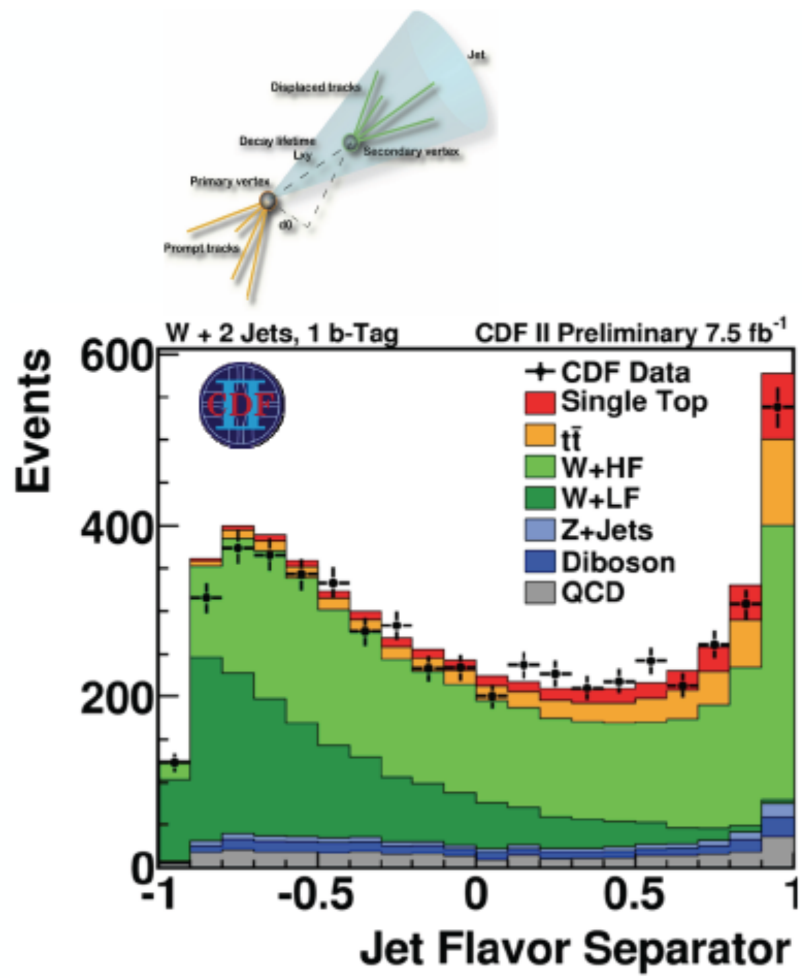
- best s/b: ~1/200 before b-tagging

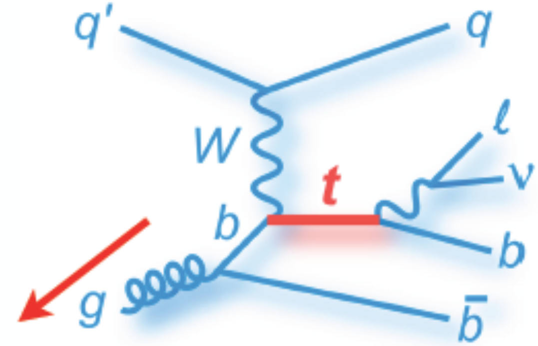
Searches for Single top at the Tevatron

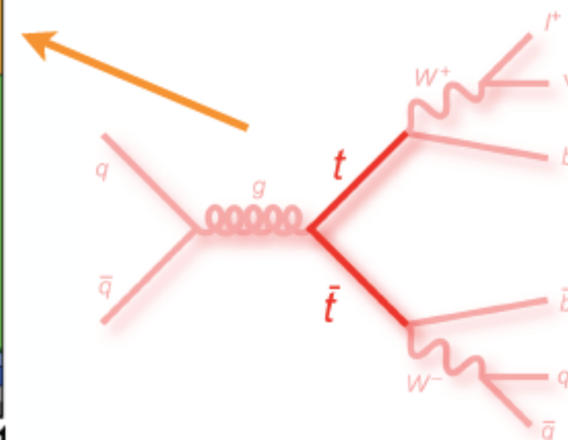






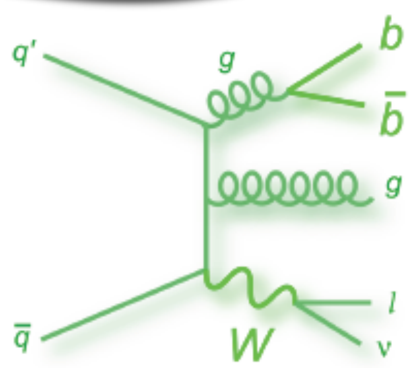




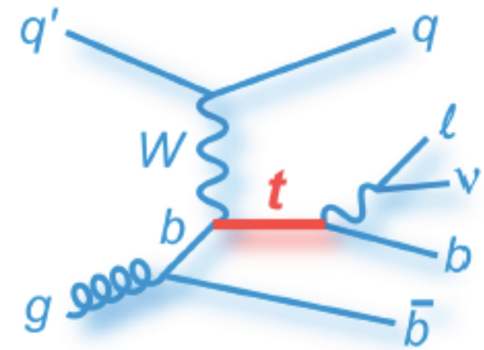


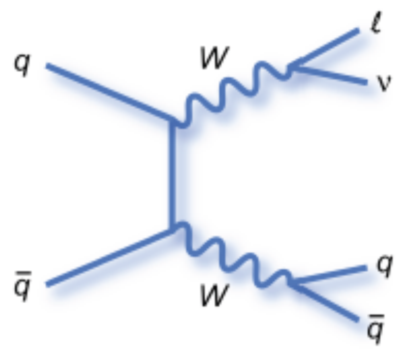
- best s/b: ~1/200 before b-tagging
- best s/b: ~1/10 after b-tagging

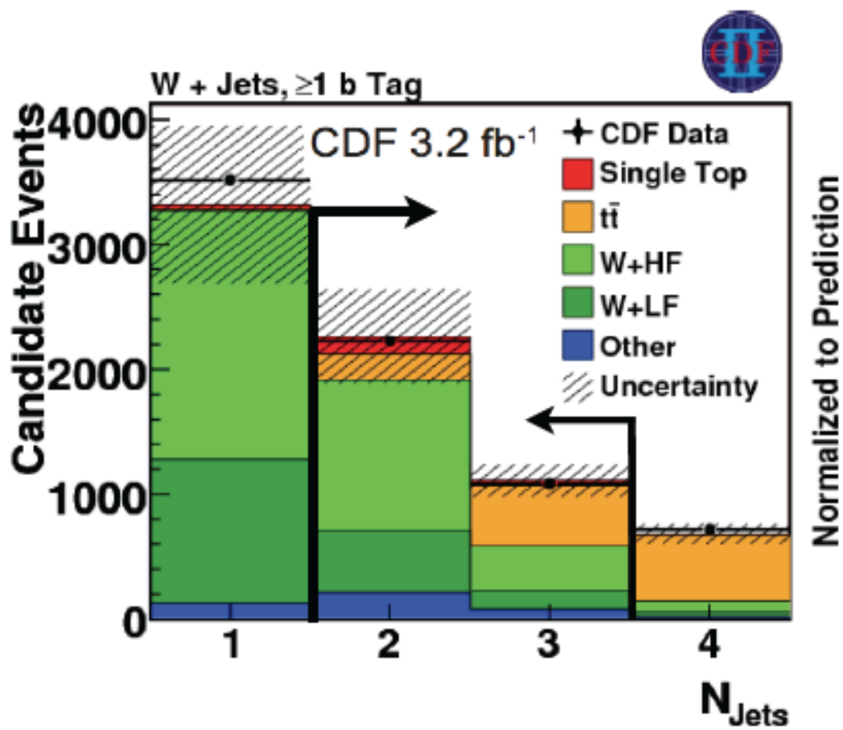
Searches for Single top at the Tevatron

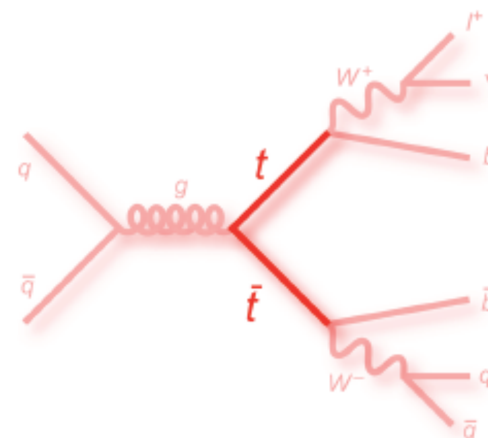


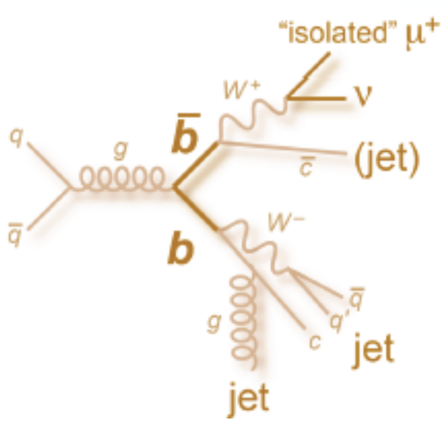
- number of jets and number of b tags to define samples





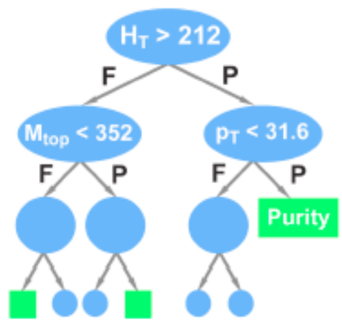




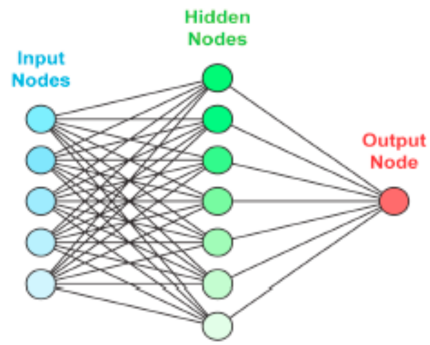


- best s/b: ~1/200 before b-tagging
- best s/b: ~1/10 after b-tagging

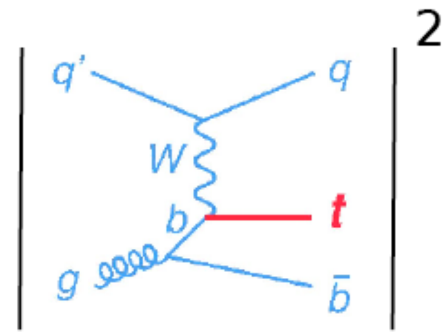
Decision Trees



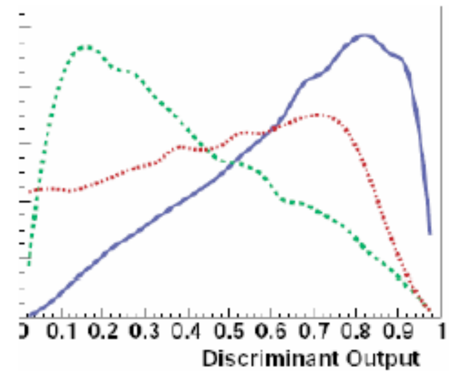
Neural Networks



Matrix Elements



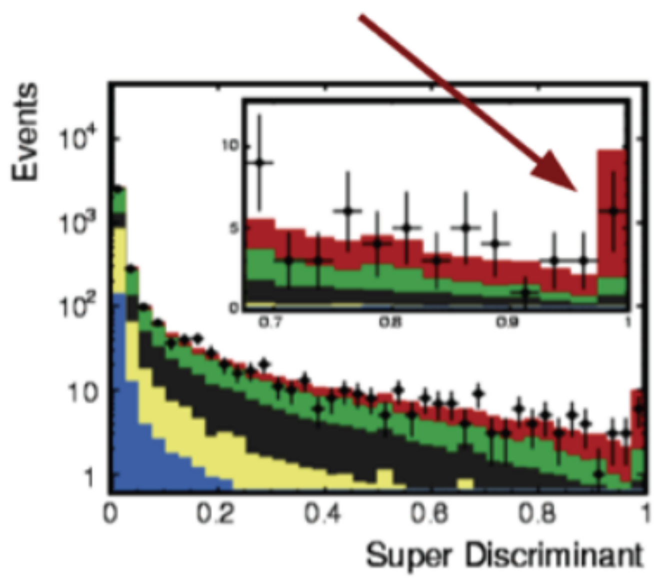
Likelihoods

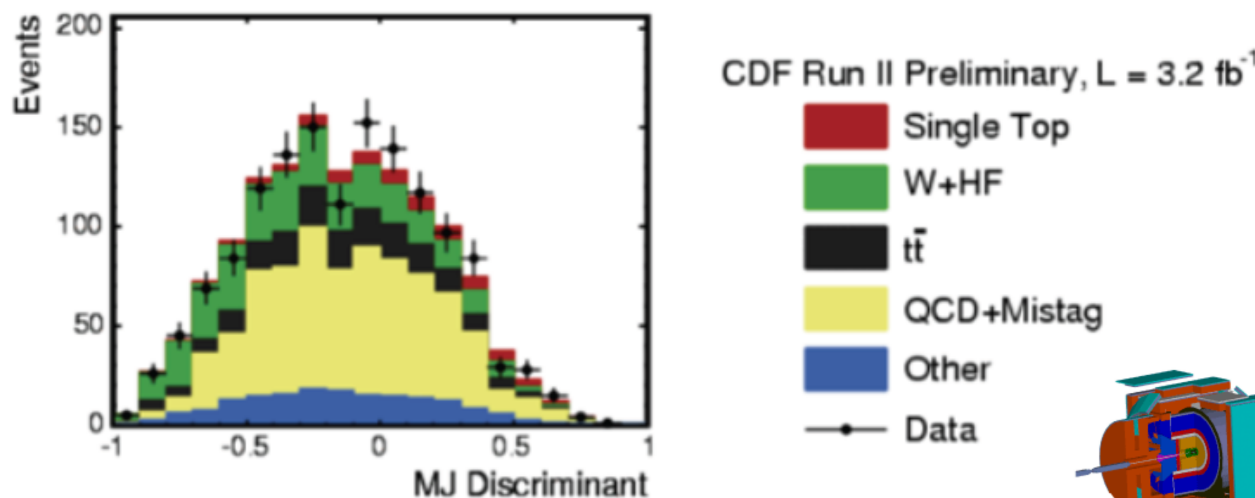


Combined up to 8 different analysis channels

single top

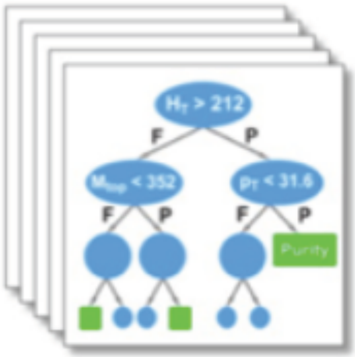
- **$\not\!\!E_T$+jets selection :**
  recover badly reconstructed e, μ; include τ



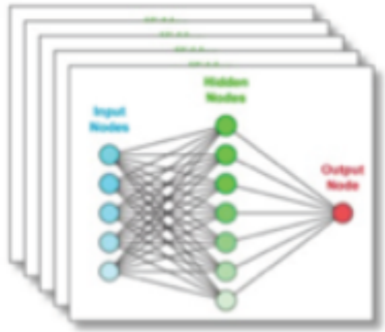


CDF

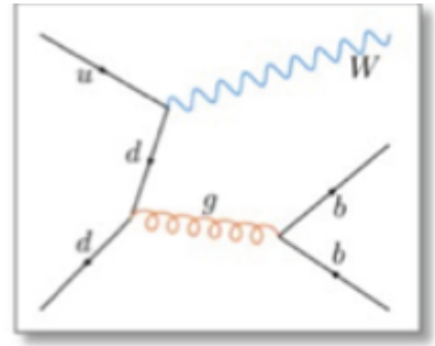
boosted decision trees



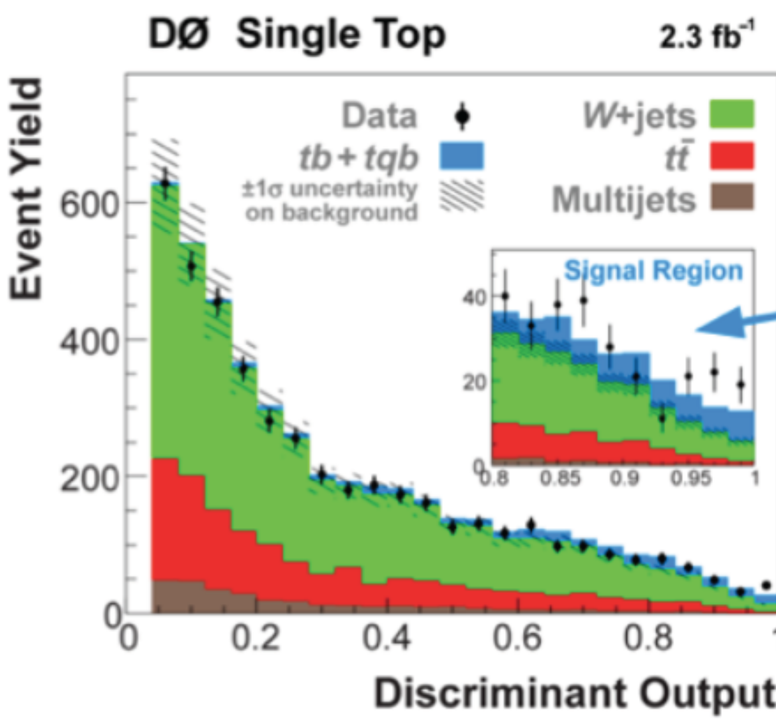
neural nets



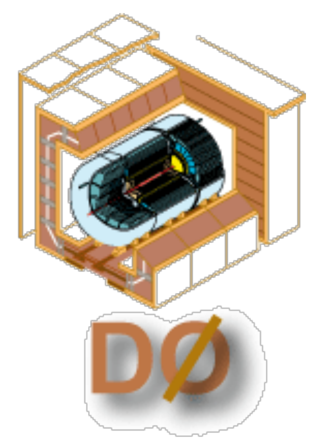
matrix elements



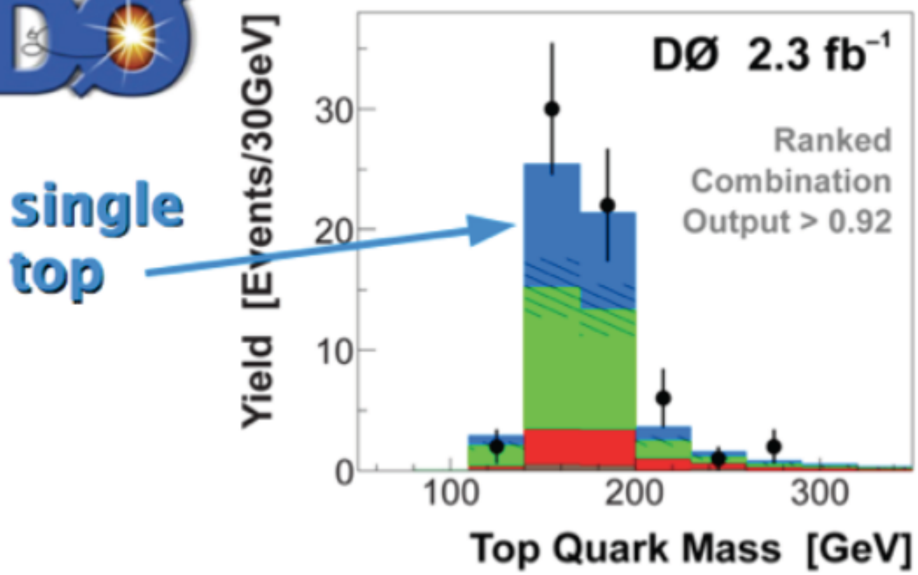
Combined up to 12 different analysis channels

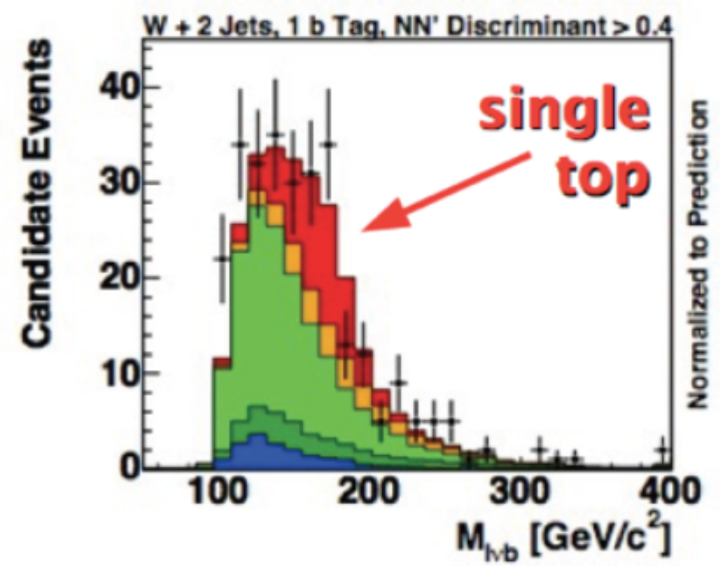


single top



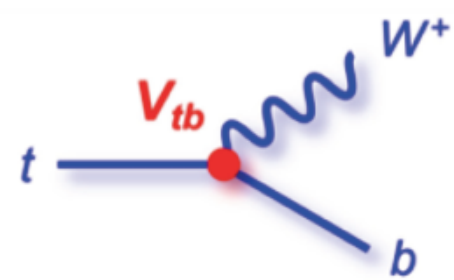
Single Top Discovered!





Single Top Cross Section	Signal Significance	
	Expected	Observed
DØ 2.3 fb^{-1} arXiv:0903.0850 m_{top} = 170 GeV		
3.94 ± 0.88 pb	4.5 σ	5.0 σ
CDF 3.2 fb^{-1} arXiv:0903.0885 m_{top} = 175 GeV		
2.3 $^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ

⇒ **observation with 5.0σ!**



DØ: $|V_{tb}| = 1.07 \pm 0.12$

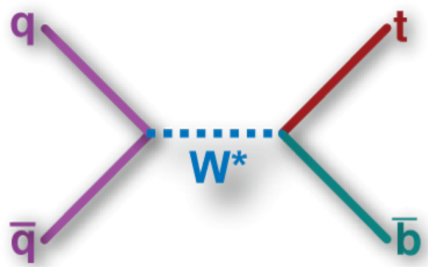
CDF: $|V_{tb}| = 0.91 \pm 0.13$

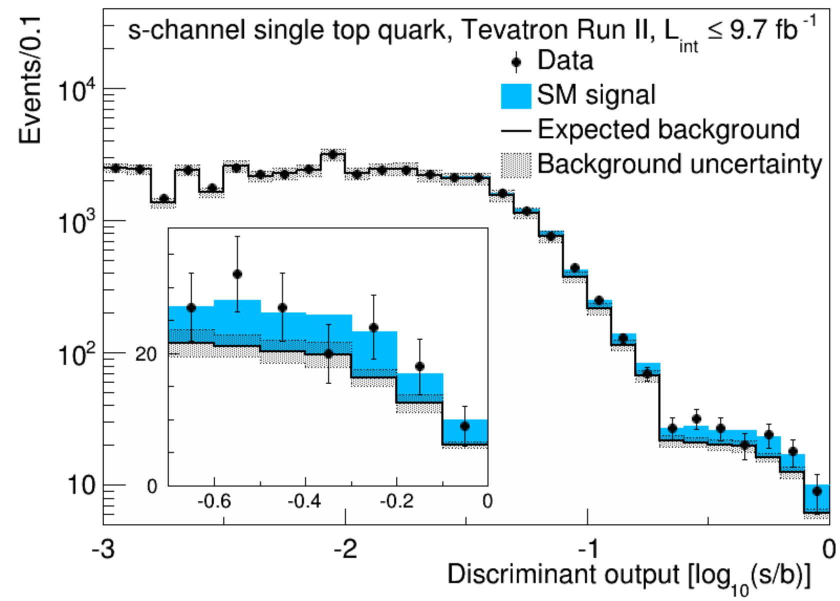
Single Top Discovered!

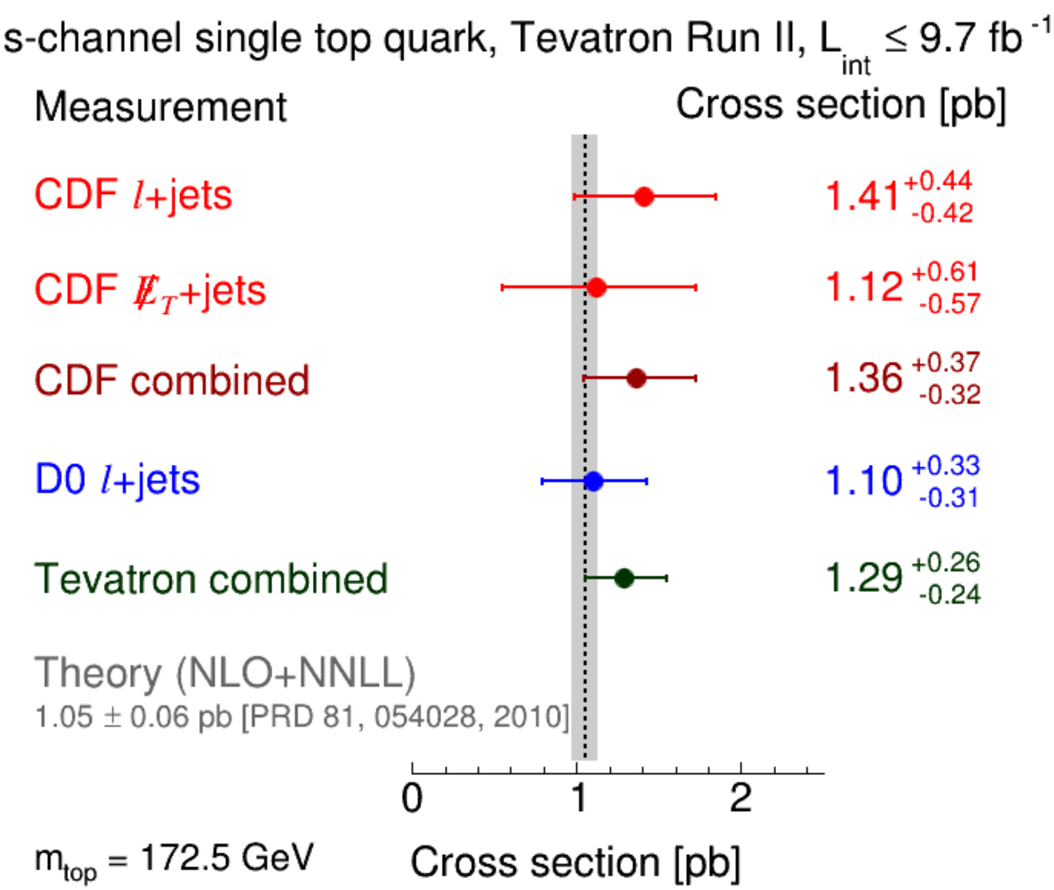
2009

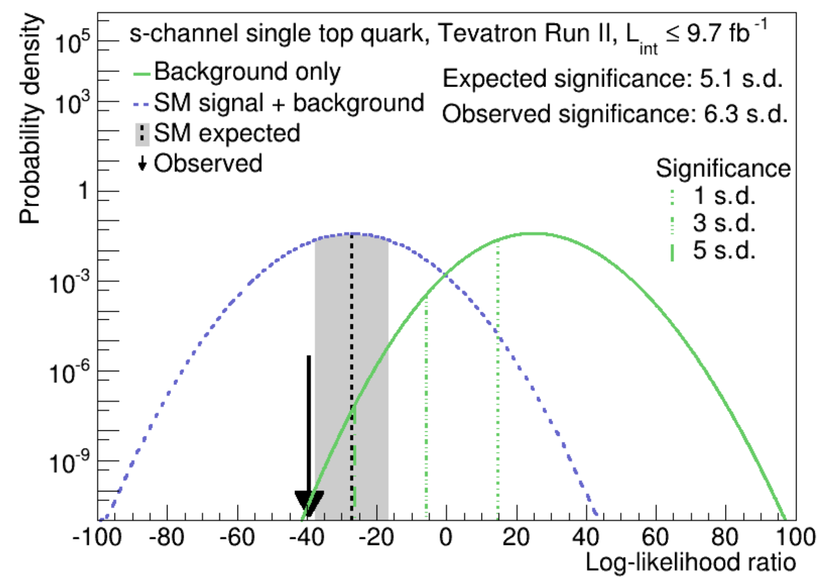
Single top at the Tevatron

Observation of the s-channel in 2014

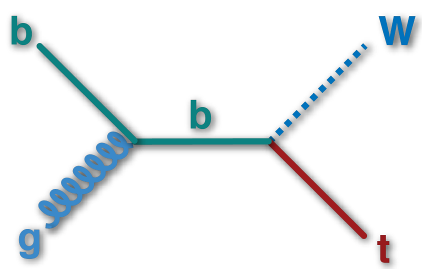




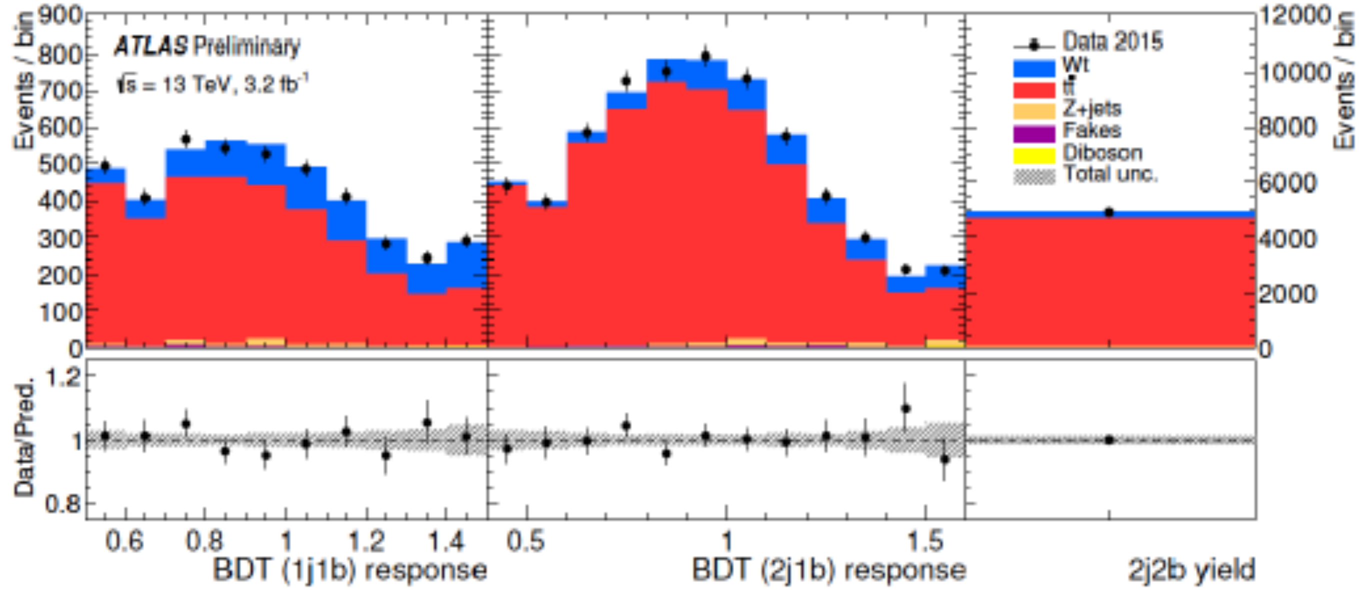




Recent results: Single top at the LHC

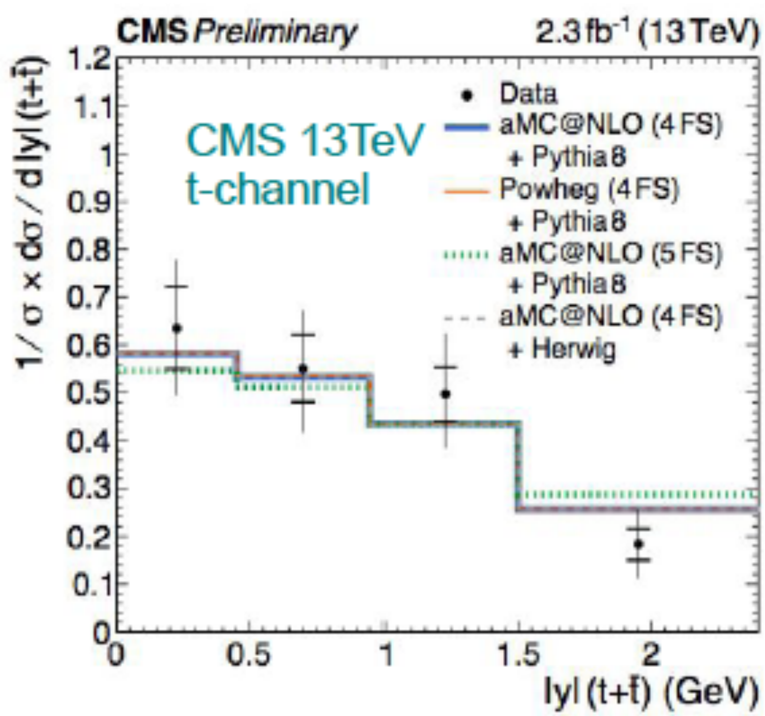


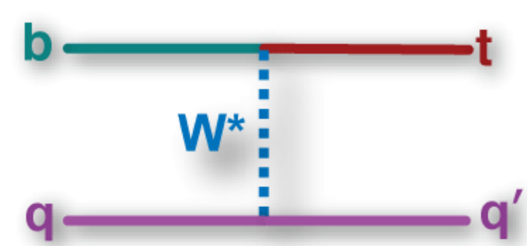
Binned profile LLH, on BDT, σ(Wt) = 94 ±10+28-23 pb



ATLAS 13 TeV - Wt channel

Full program of single top studies

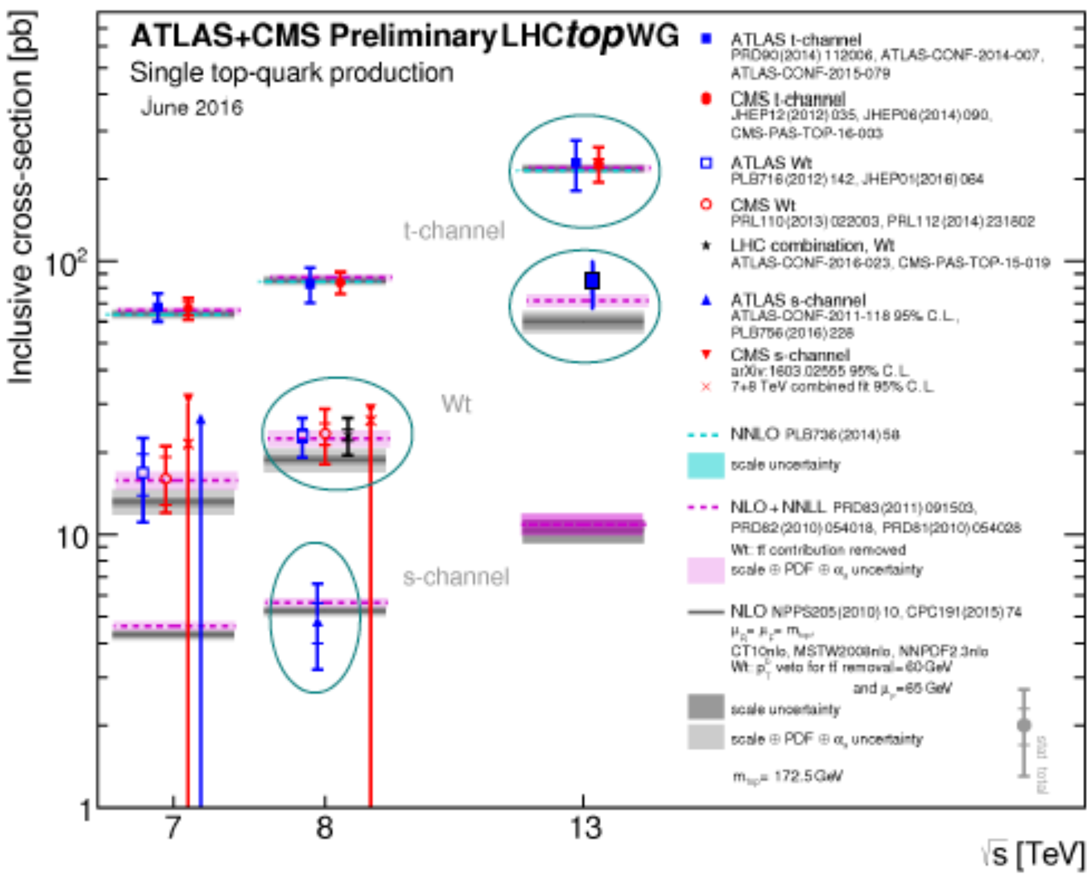




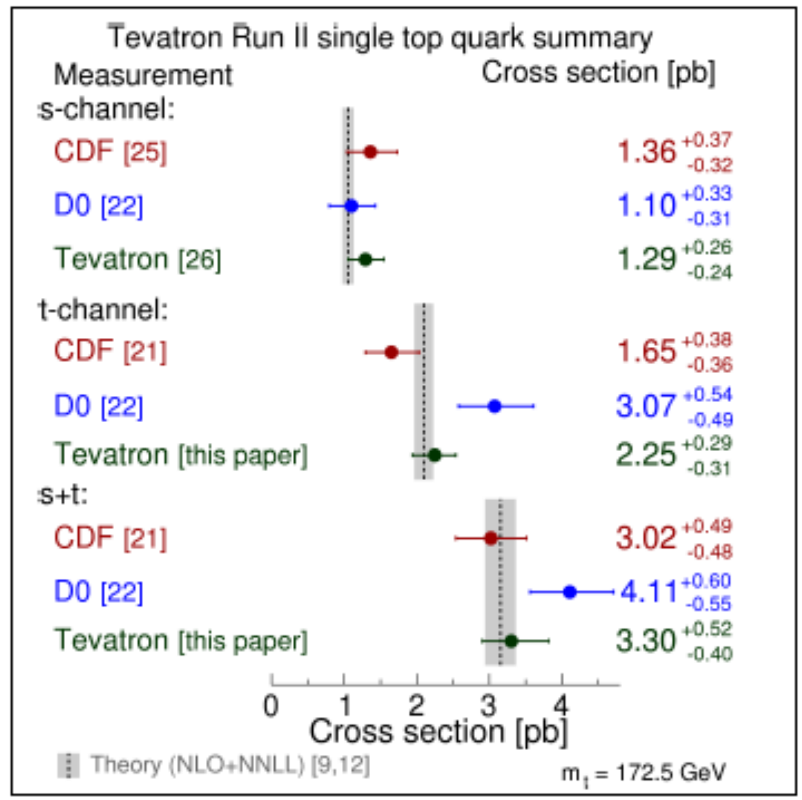
CMS 13 TeV t-channel

Latest on single top results

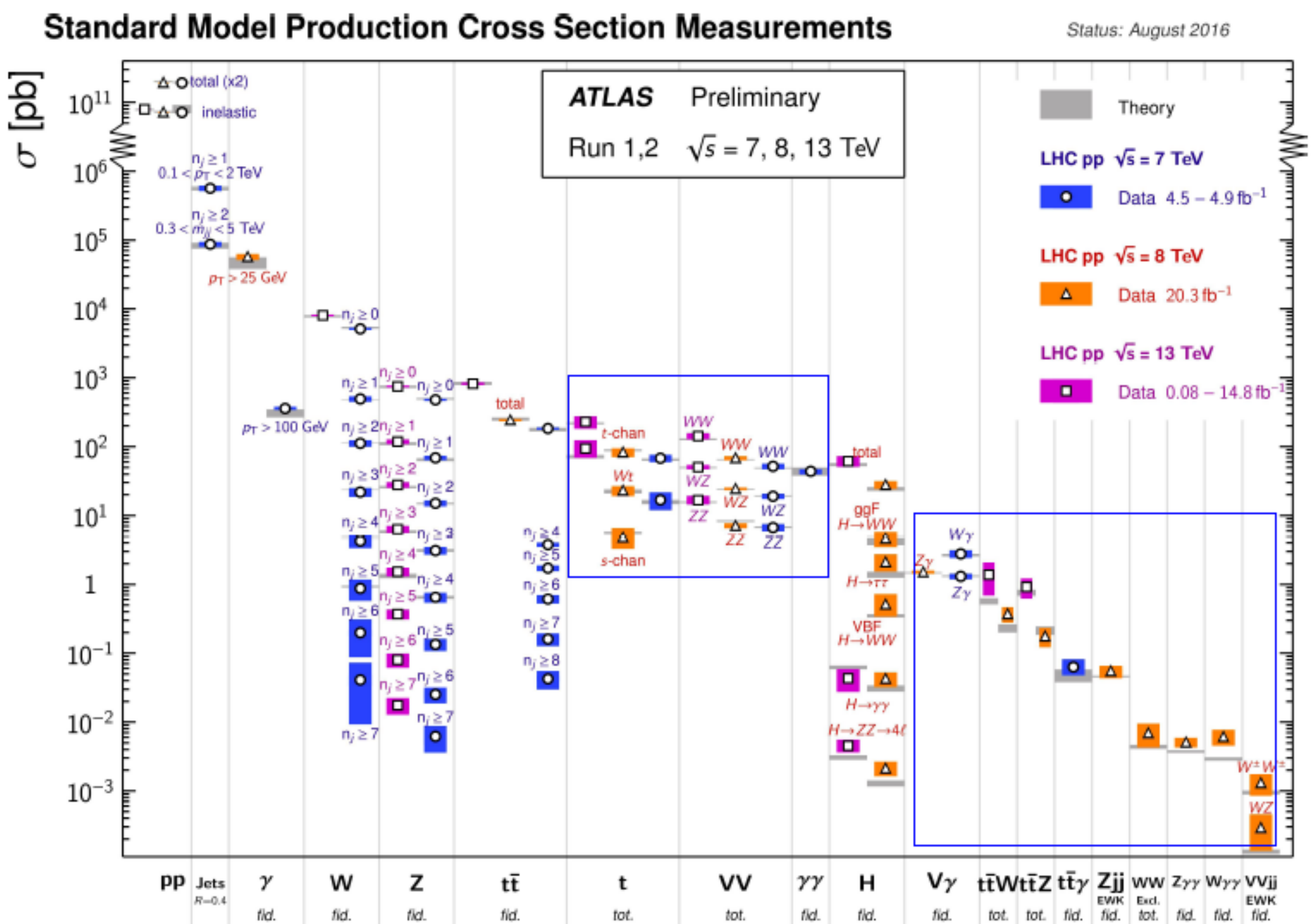
- 2015: s-channel “observed” at the Tevatron 5σ (t-channel a while ago)
- LHC: recently observed t-channel and t-W, getting closer to s-channel!



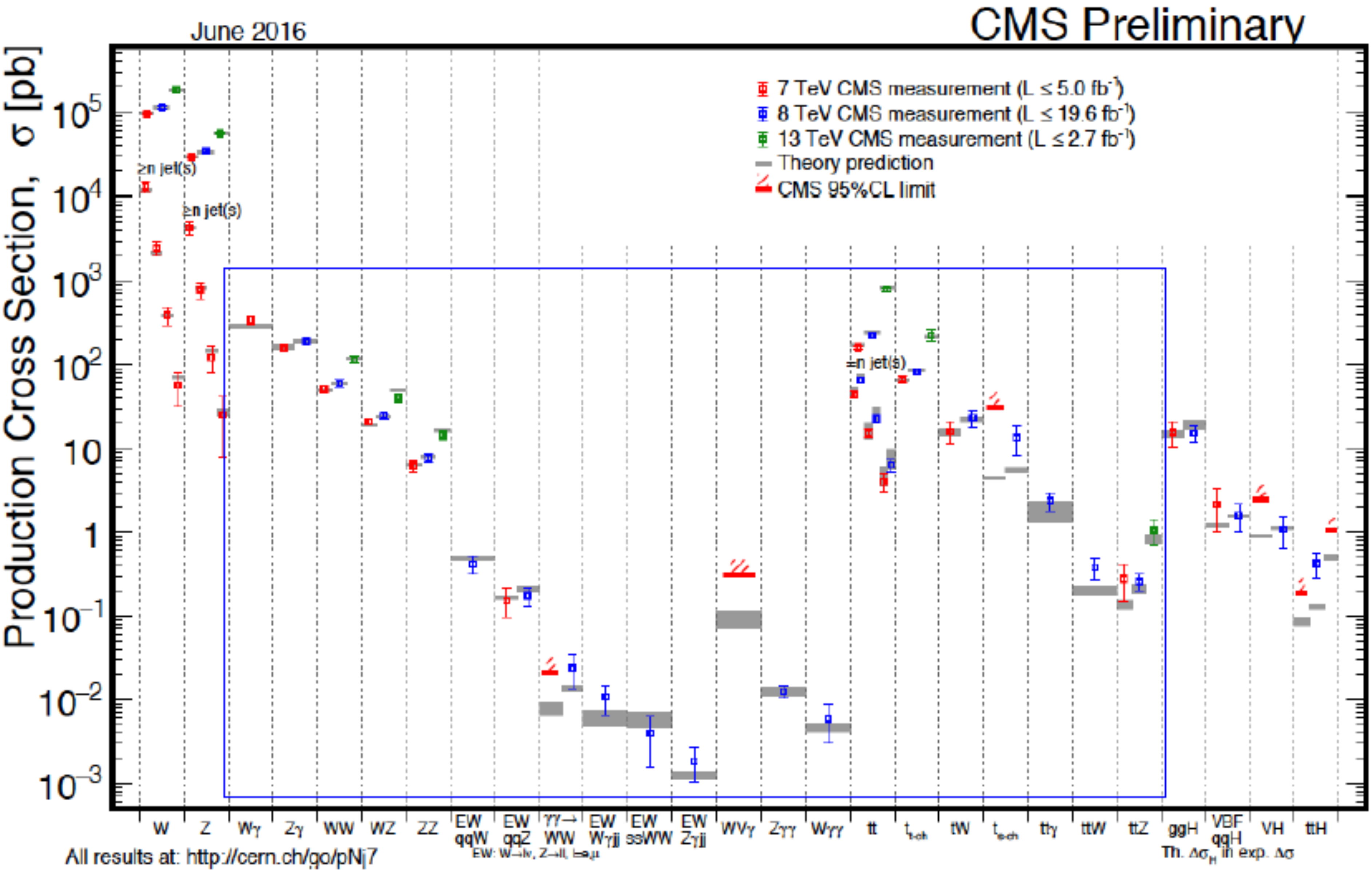
Phys. Rev. Lett. 115, 152003 (2015)



Down to smaller cross sections: tt+V

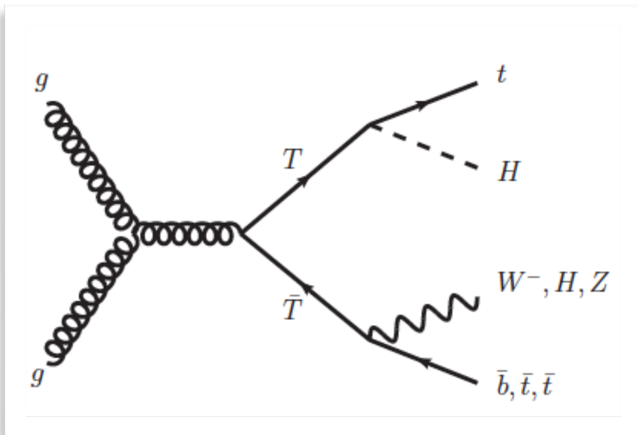


Down to smaller cross sections: tt+V



TT→tH+X and 4-top production

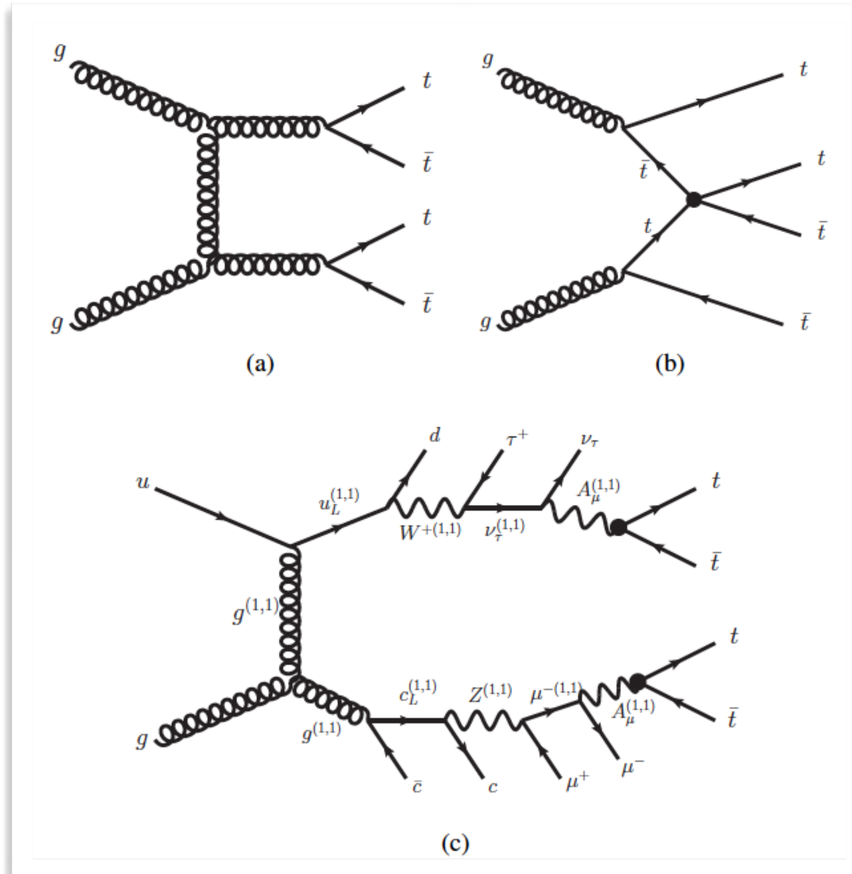
leading TT production diagram



ATLAS-CONF-2016-013

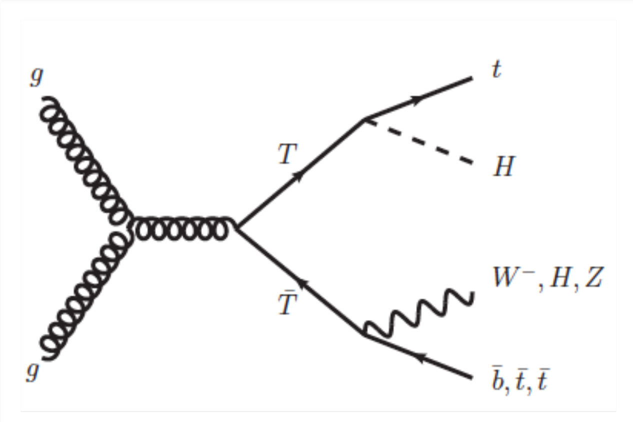
- Many final states: 11 search channels!

4 tops (SM and BSM)



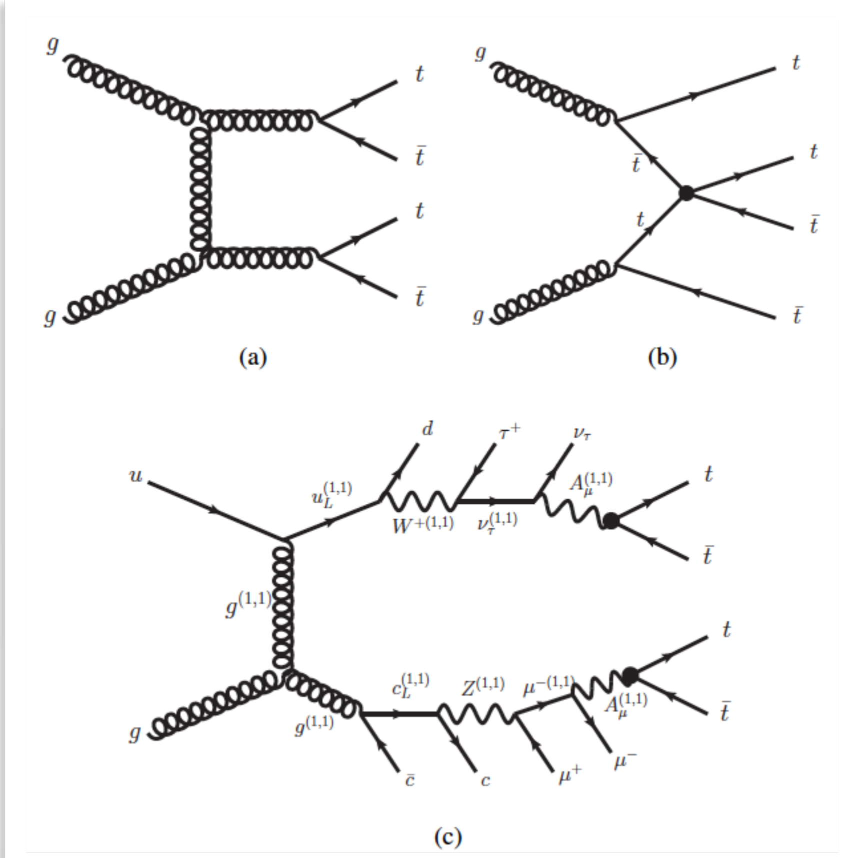
TT→tH+X and 4-top production

leading TT production diagram



ATLAS-CONF-2016-013

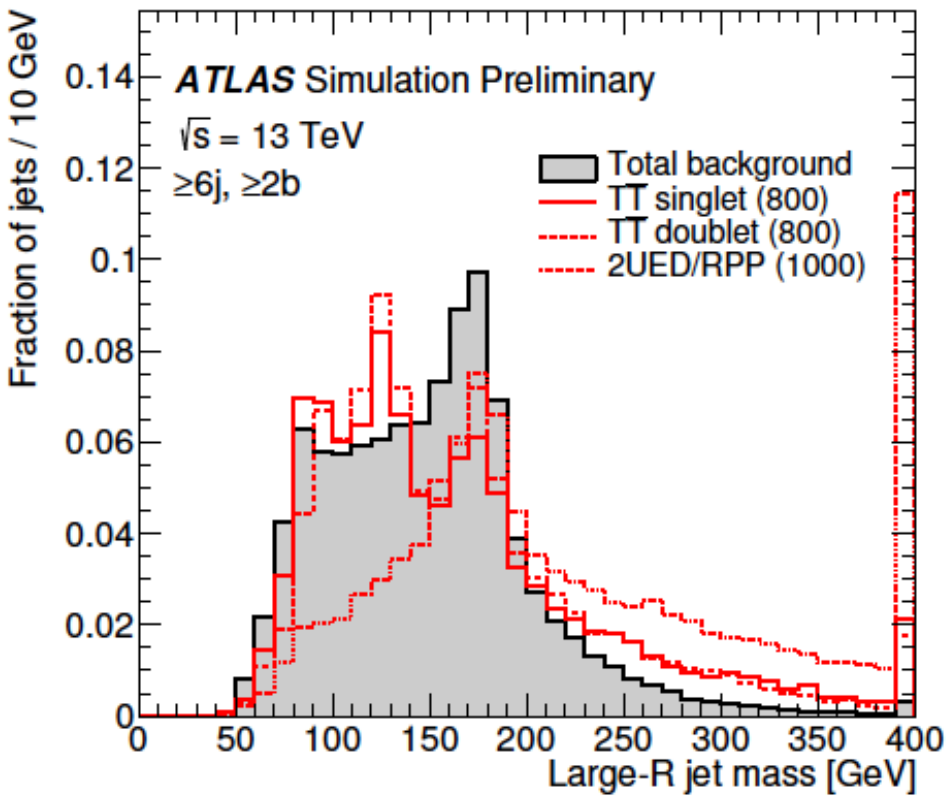
4 tops (SM and BSM)

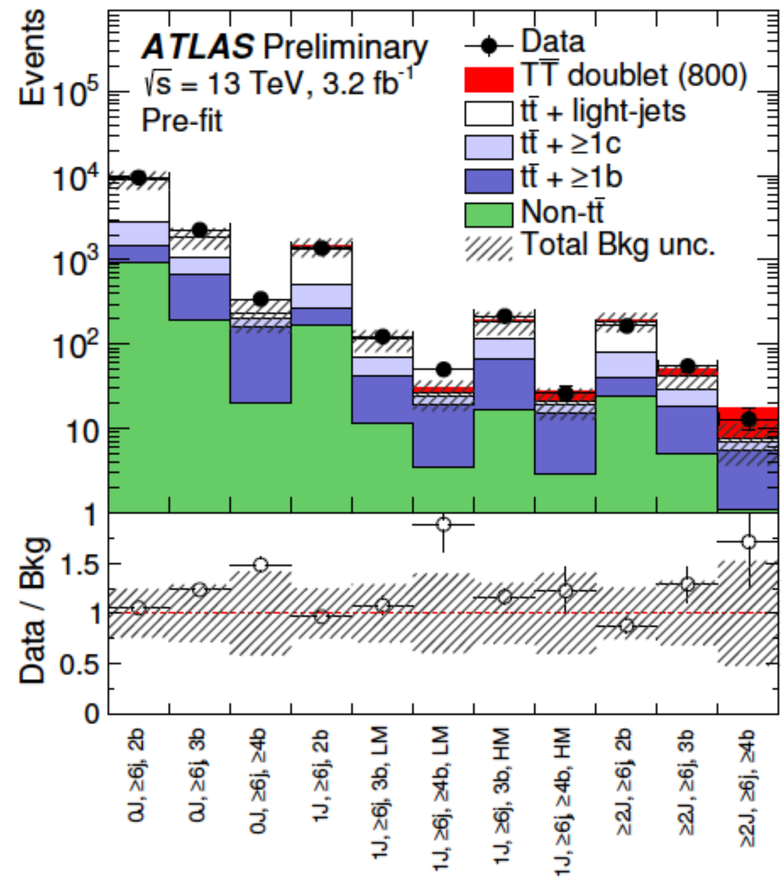


- Many final states: 11 search channels!
- Search for VLQ pair production TT decays to tH and bW, tH, tZ
- Final state also sensitive to 4-top production in the SM and BSM models
- Compositeness, RS extra dimensions, colored scalars, UED.

TT→tH+X and 4-top production

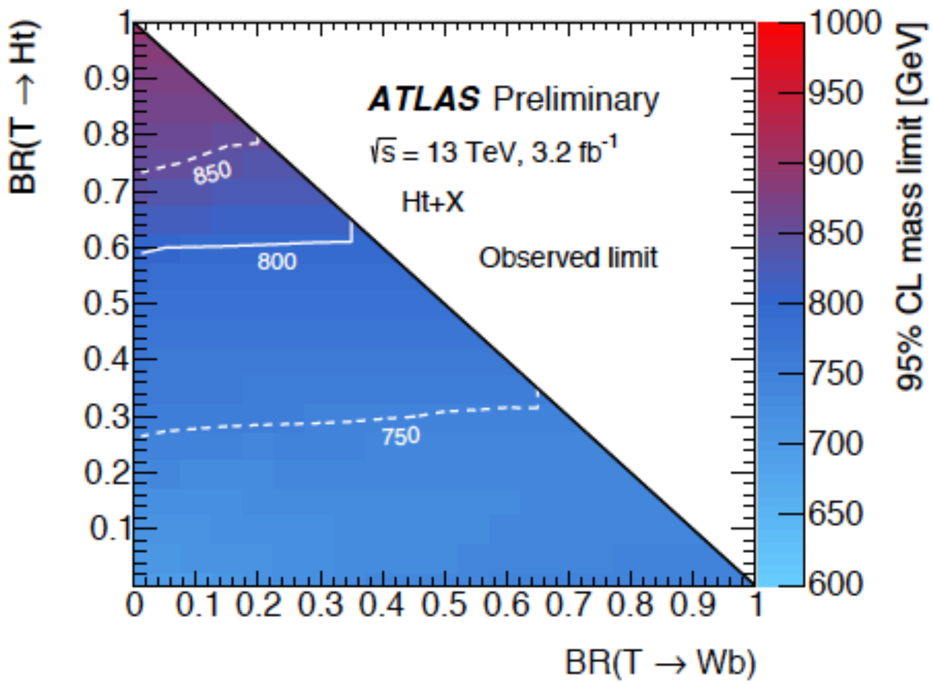
ATLAS-CONF-2016-013

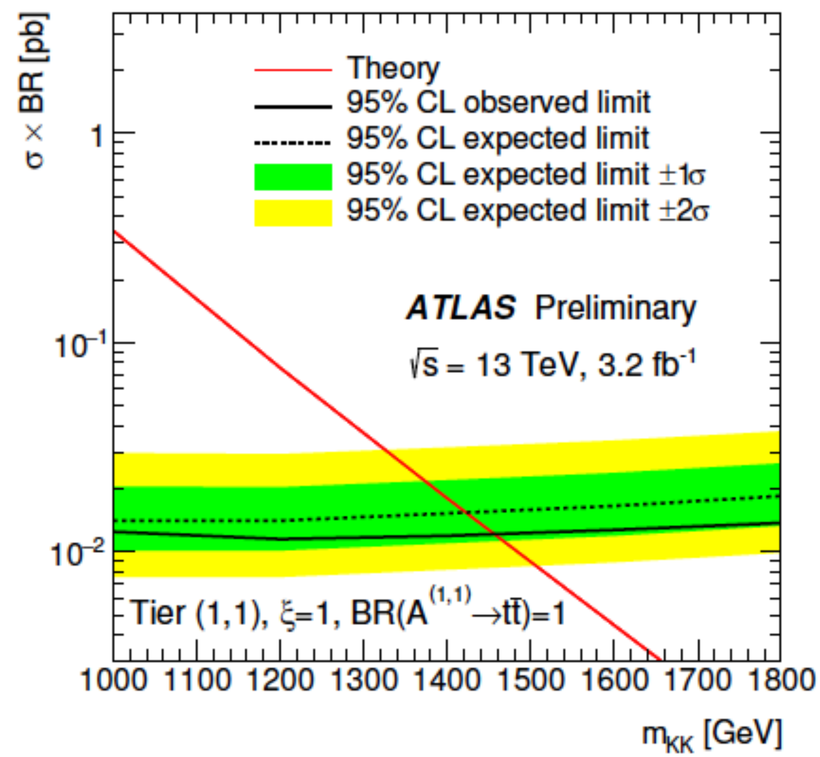




- Uses jet re-clustering for the first time in ATLAS exotics searches!
- Small-R (anti-kT 0.4) jets surviving overlap removal are input to large-R (anti-kT 1.0) jet re-clustering, which is then trimmed
- Large-R jets used for hadronic top and H→bb candidates: p_T>300 GeV, $|\eta|$<2.0, and reclustered jet mass >100 GeV.

TT→tH+X and 4-top production

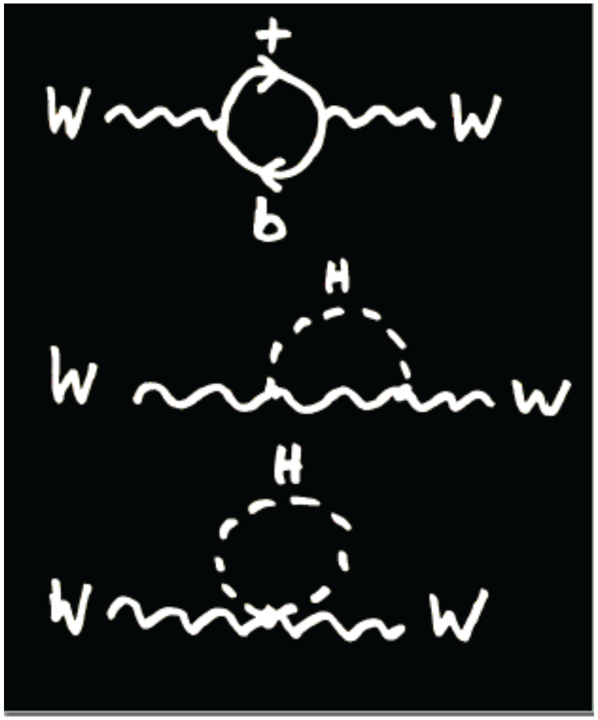


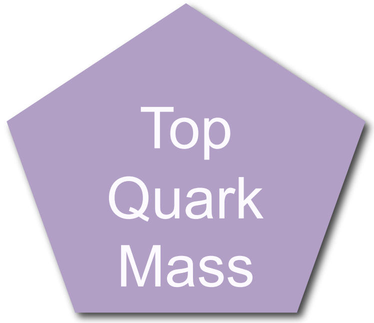


more results: ATLAS-CONF-2016-013

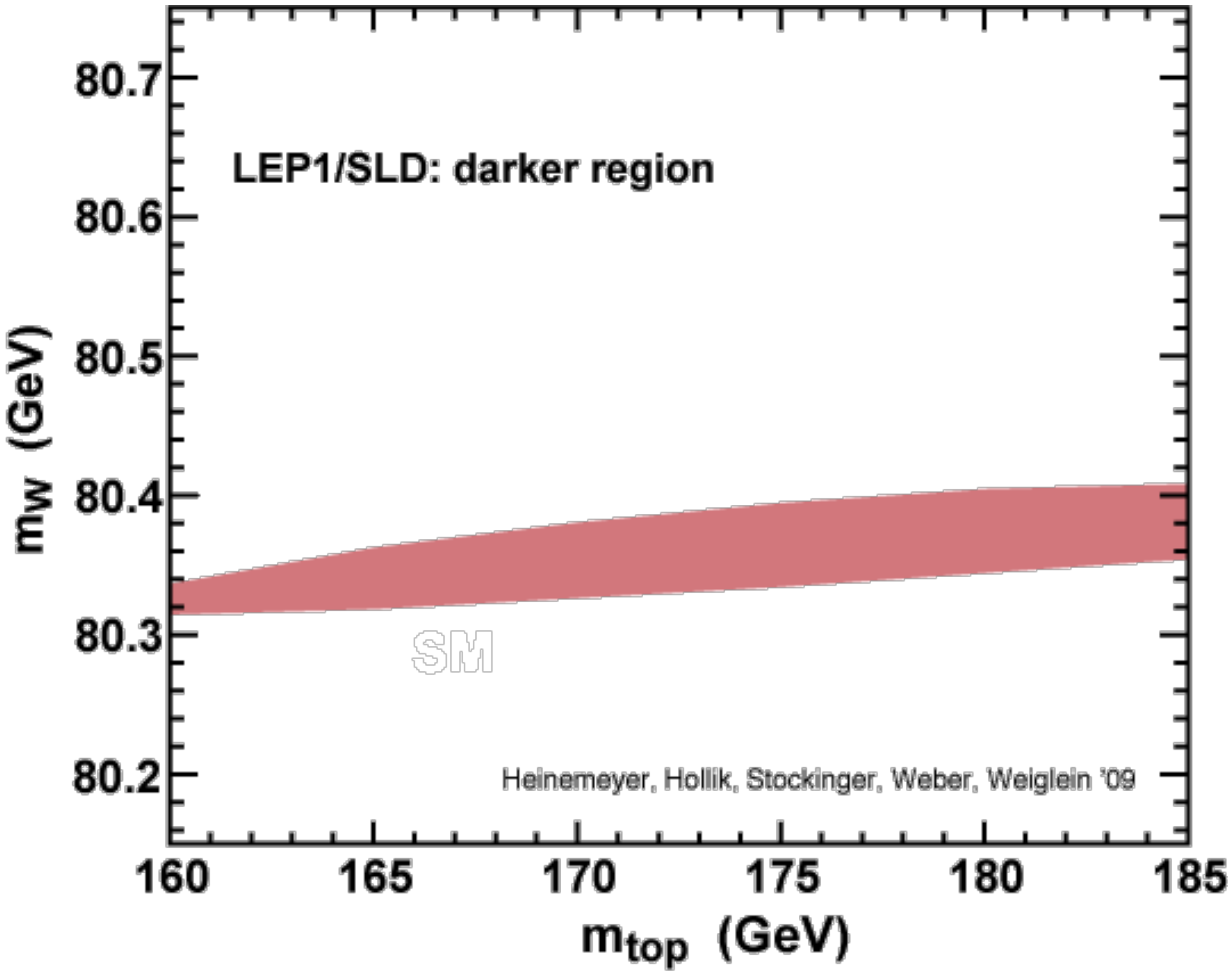
- No significant excesses compared to background found in any channel
- Left: observed limit on T quark mass in BR plane of tH, bW.
- Right: UED/RPP model - cross section limits shown as a function of m_{KK} for the symmetric case (ξ=1) assuming Tier (1,1) production alone.

Top Mass Measurements



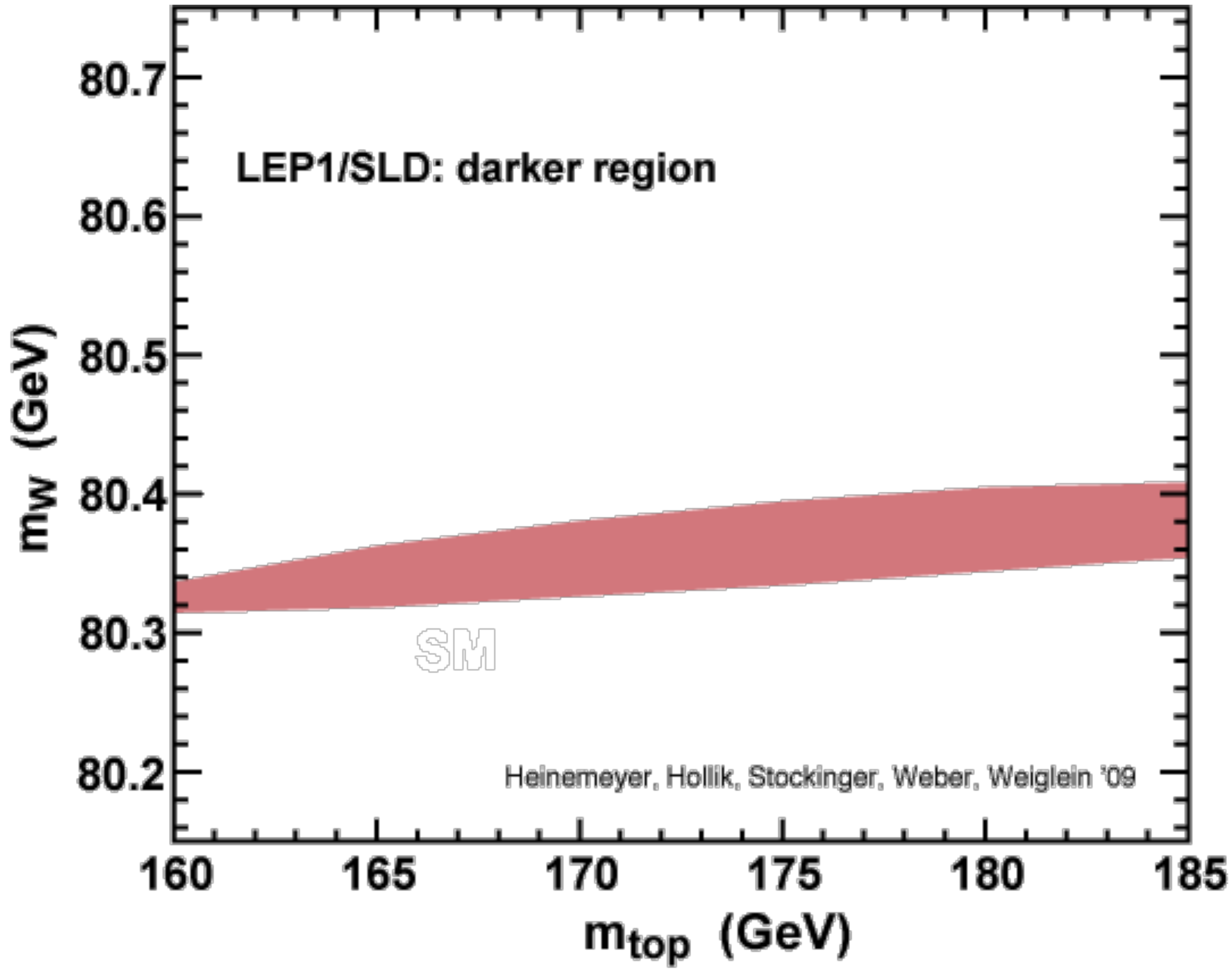


Important EWK parameter



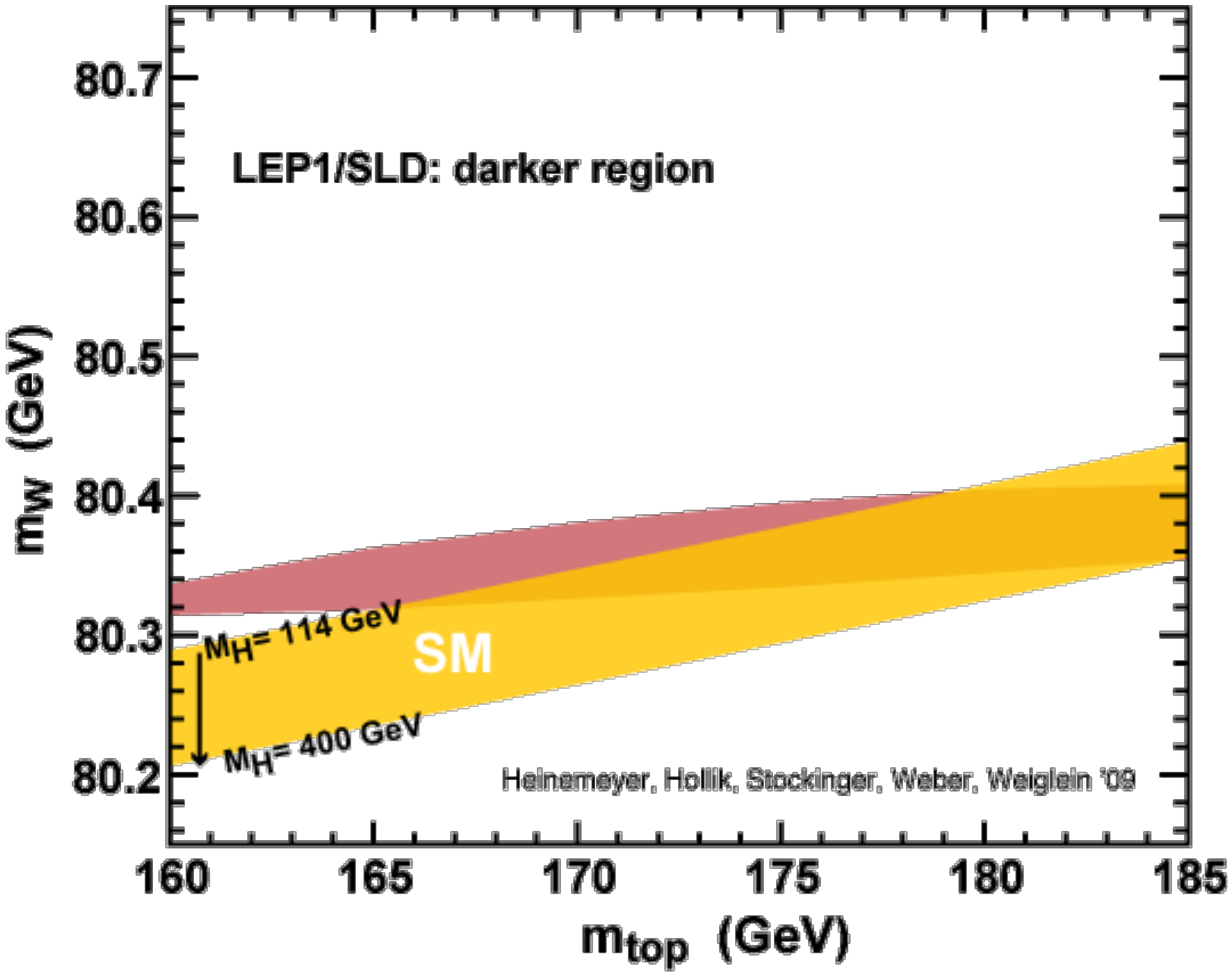
Top Quark Mass

Important EWK parameter



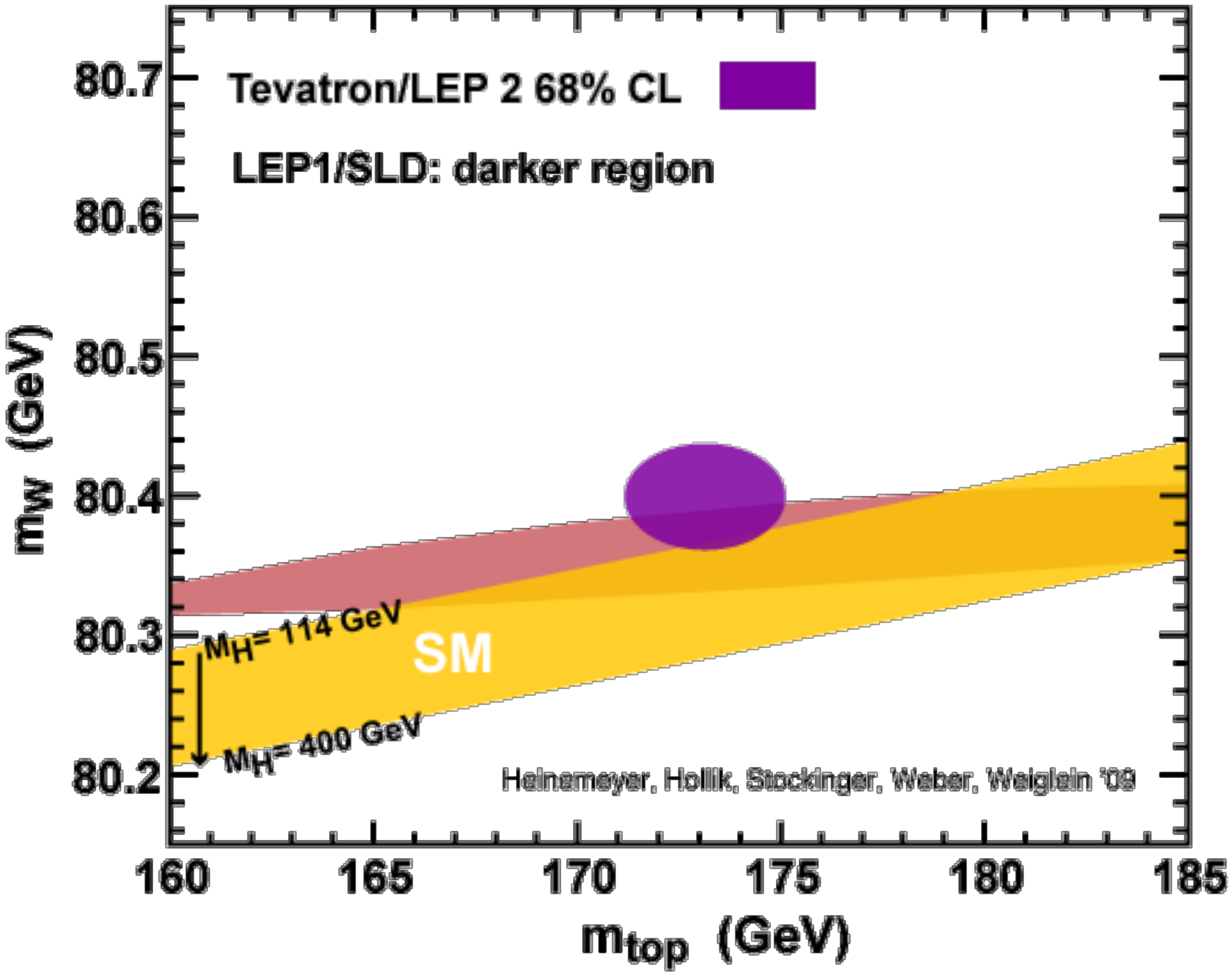
Top Quark Mass

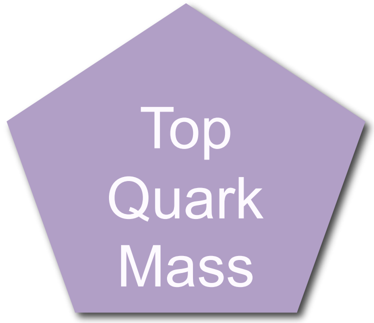
Important EWK parameter



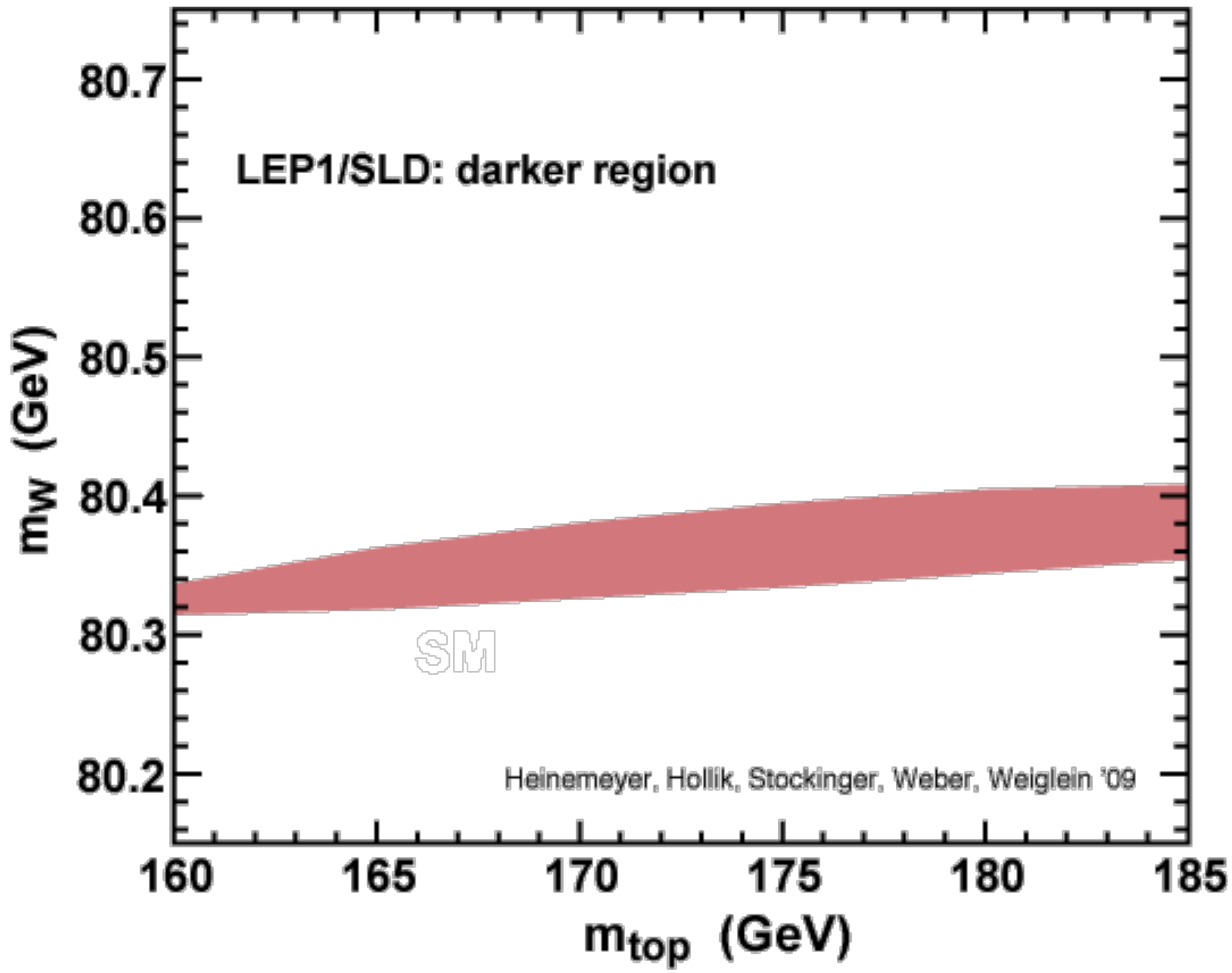
Top Quark Mass

Important EWK parameter





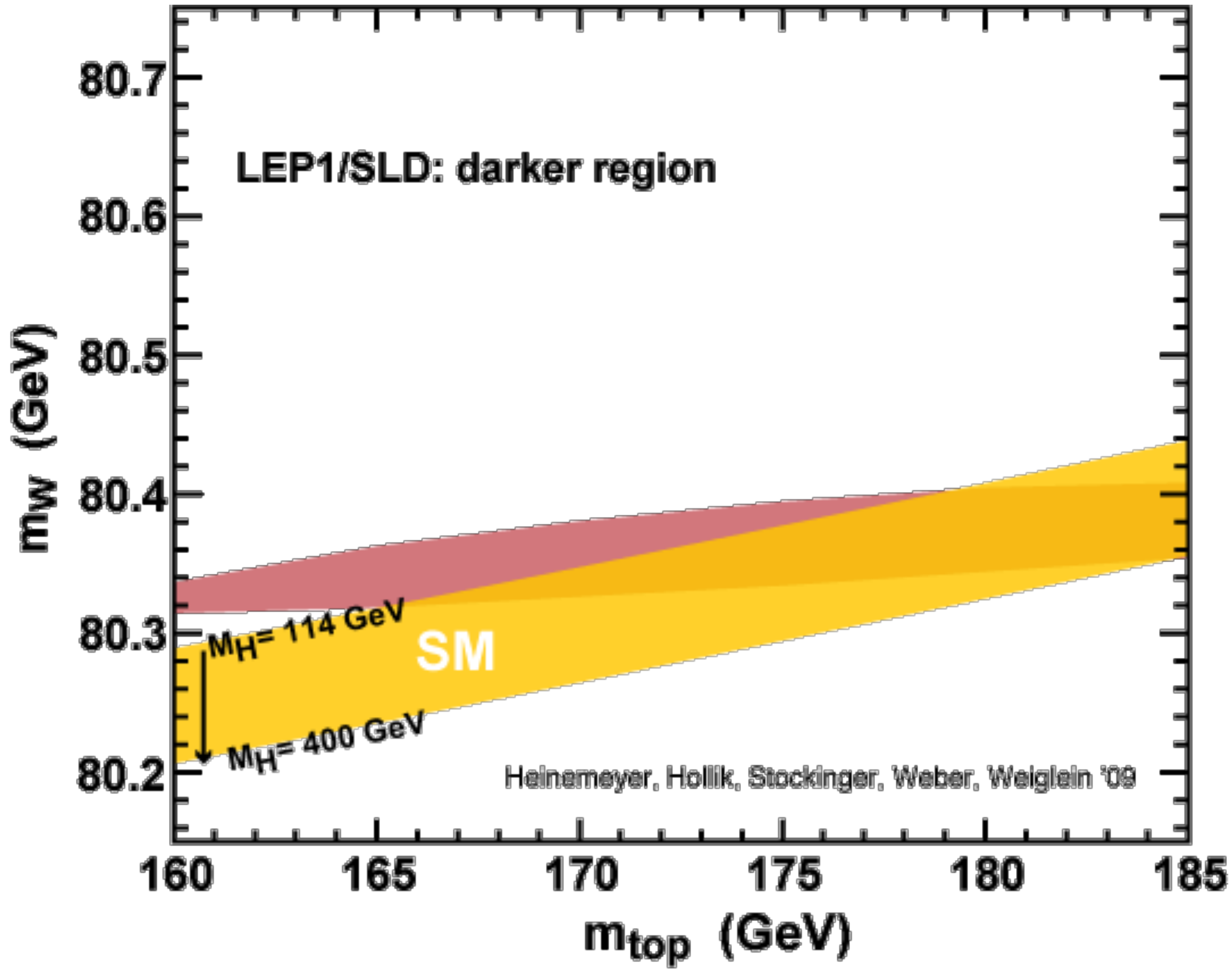
Where is the Higgs?



W and top quark mass tells us Higgs mass

Top Quark Mass

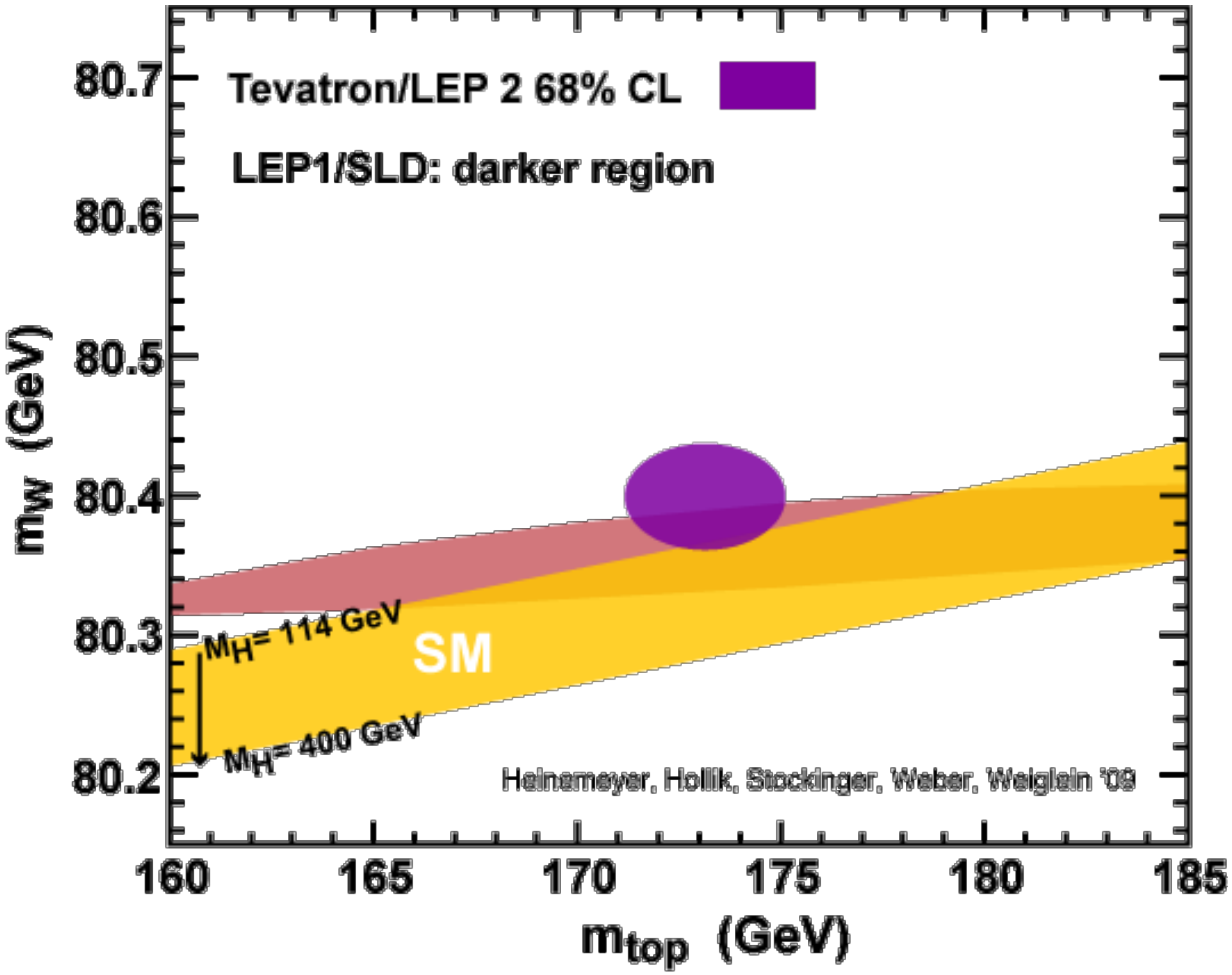
Where is the Higgs?



W and top quark mass tells us Higgs mass

Top Quark Mass

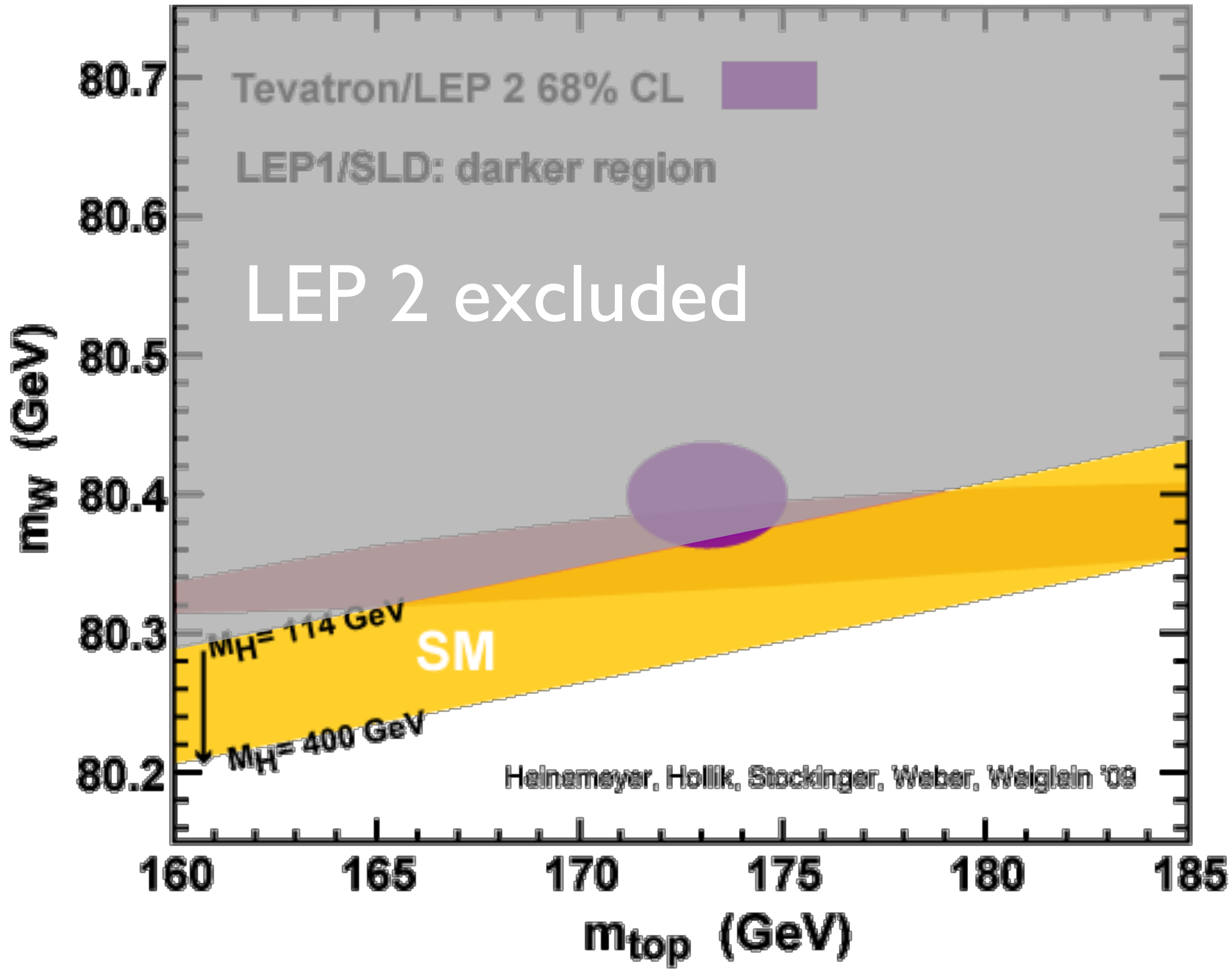
Where is the Higgs?



W and top quark mass tells us Higgs mass

Top Quark Mass

Where is the Higgs?

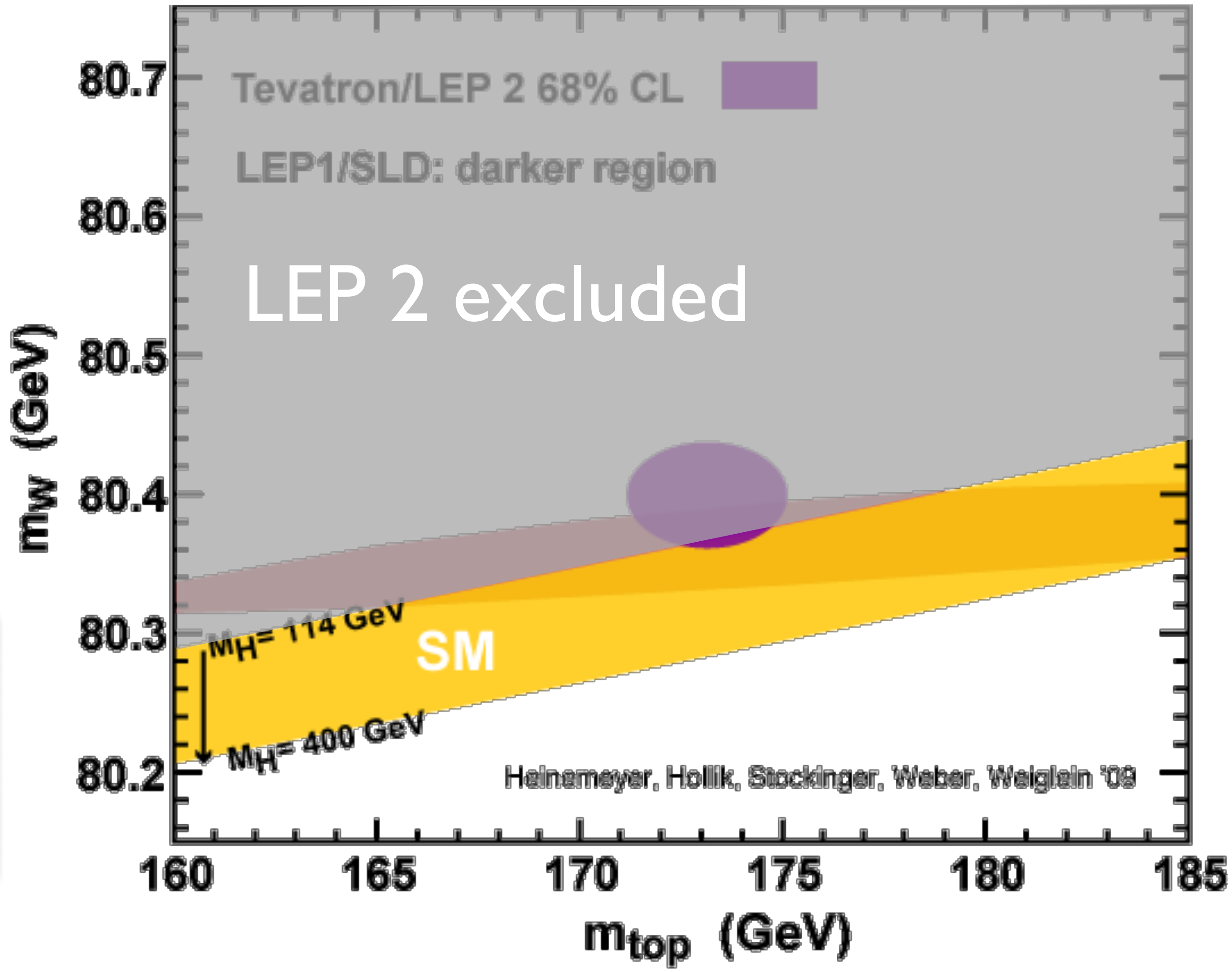


W and top quark mass tells us Higgs mass

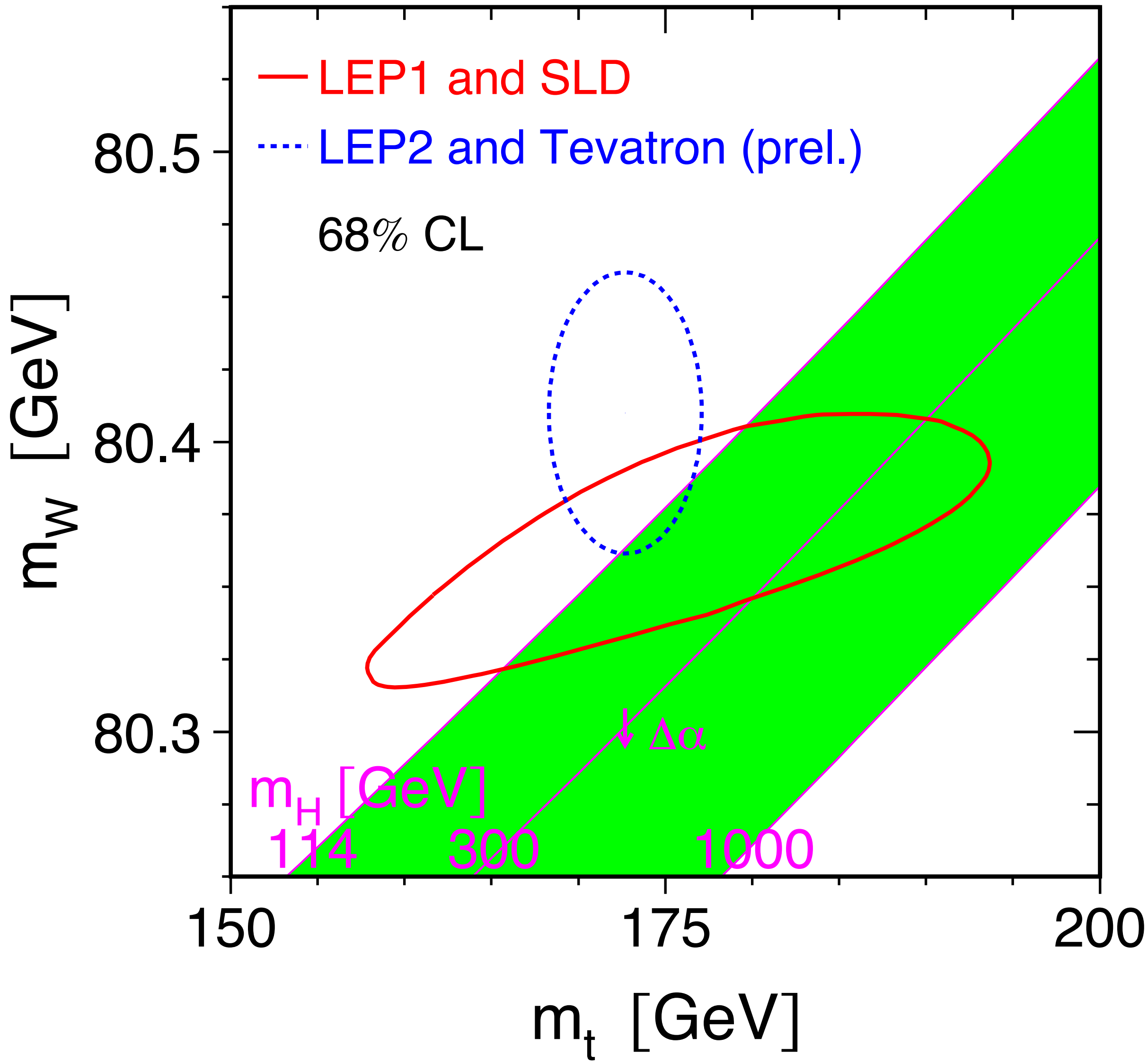
Where is the Higgs?

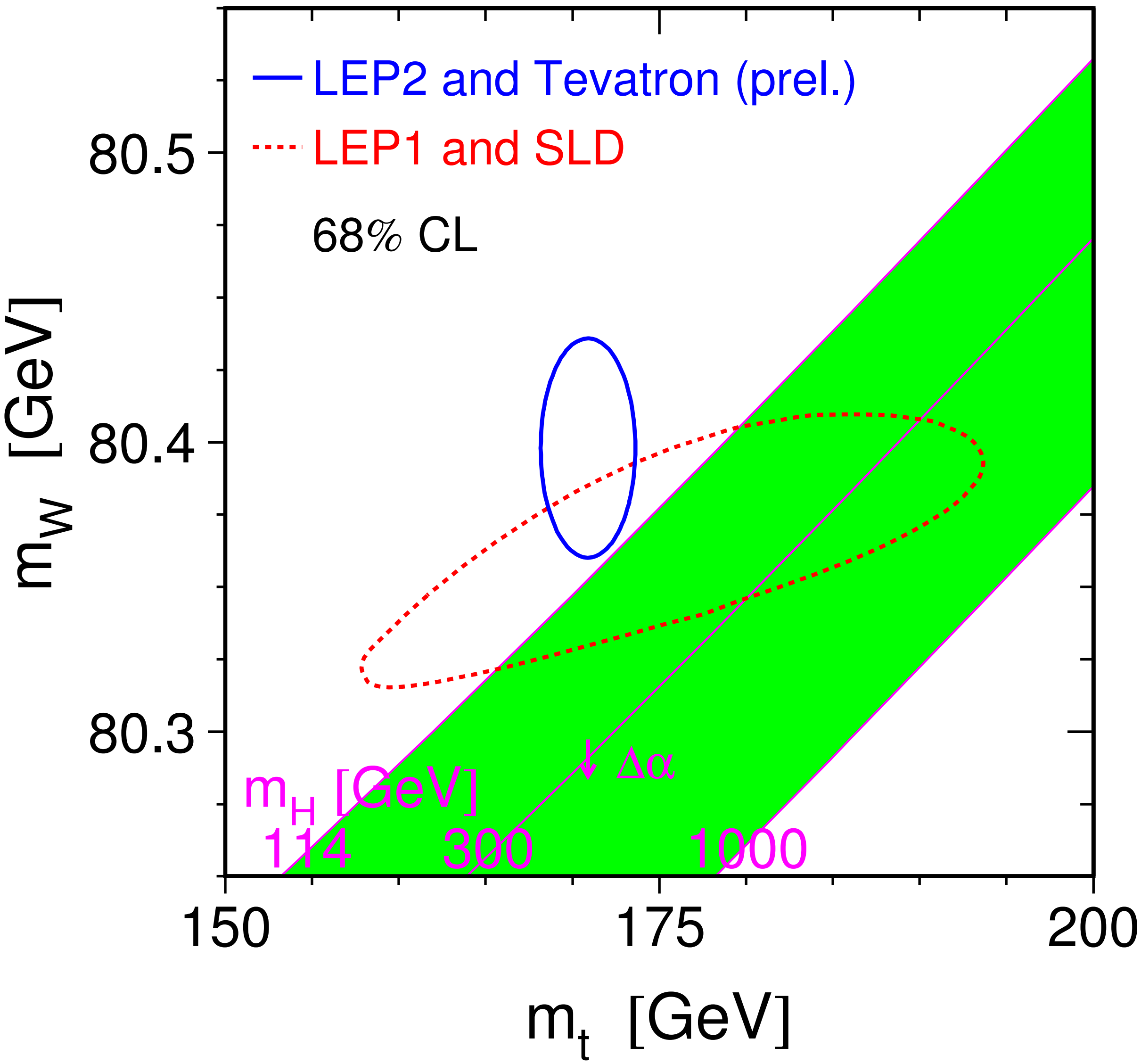
Top Quark Mass

$$m_H = 87 \pm^{35}_{26} \text{ GeV}$$
$$m_H < 157 \text{ GeV} @ 95\% \text{C.L.}$$
$$m_H > 114 \text{ GeV(direct)}$$

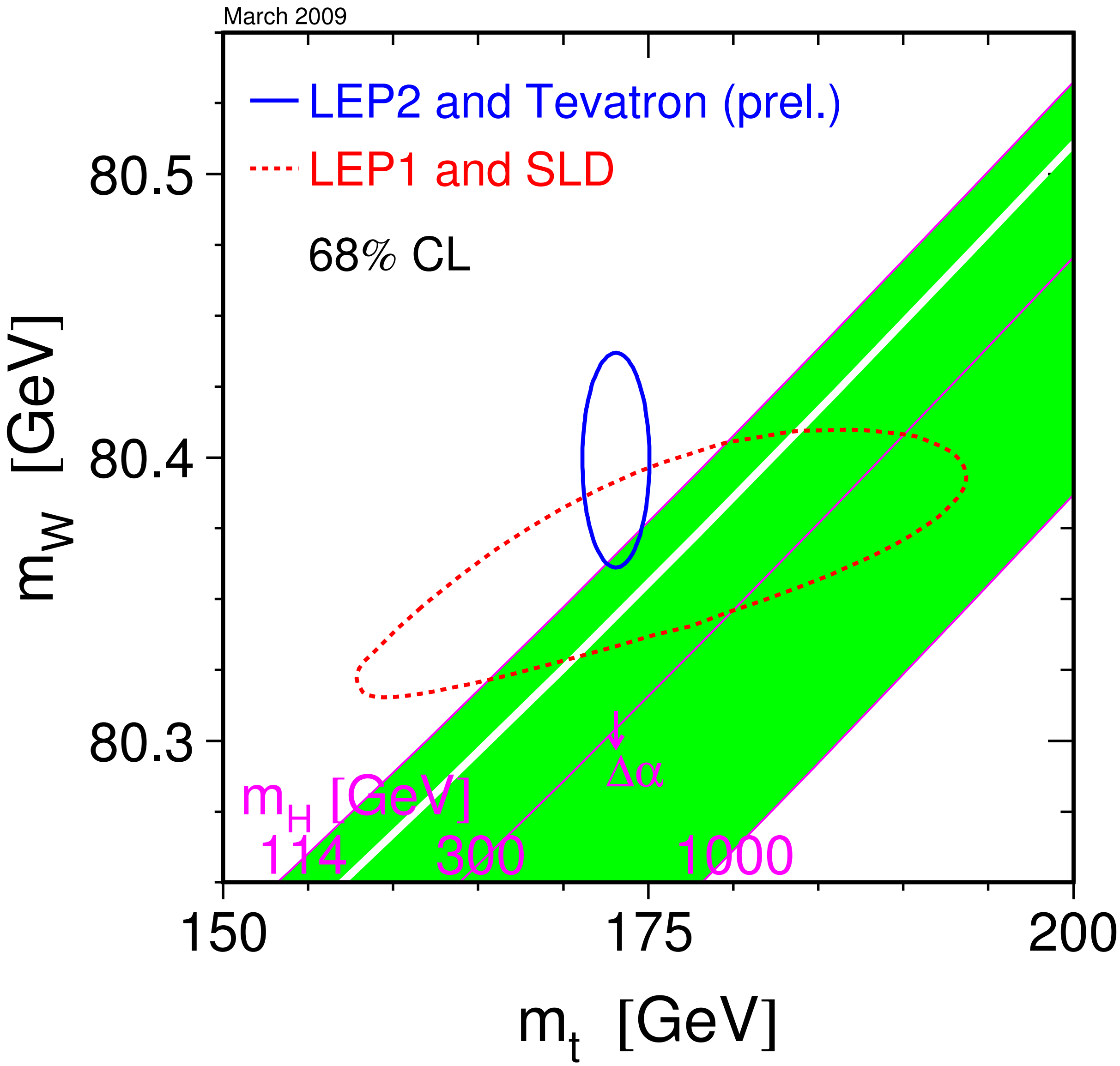


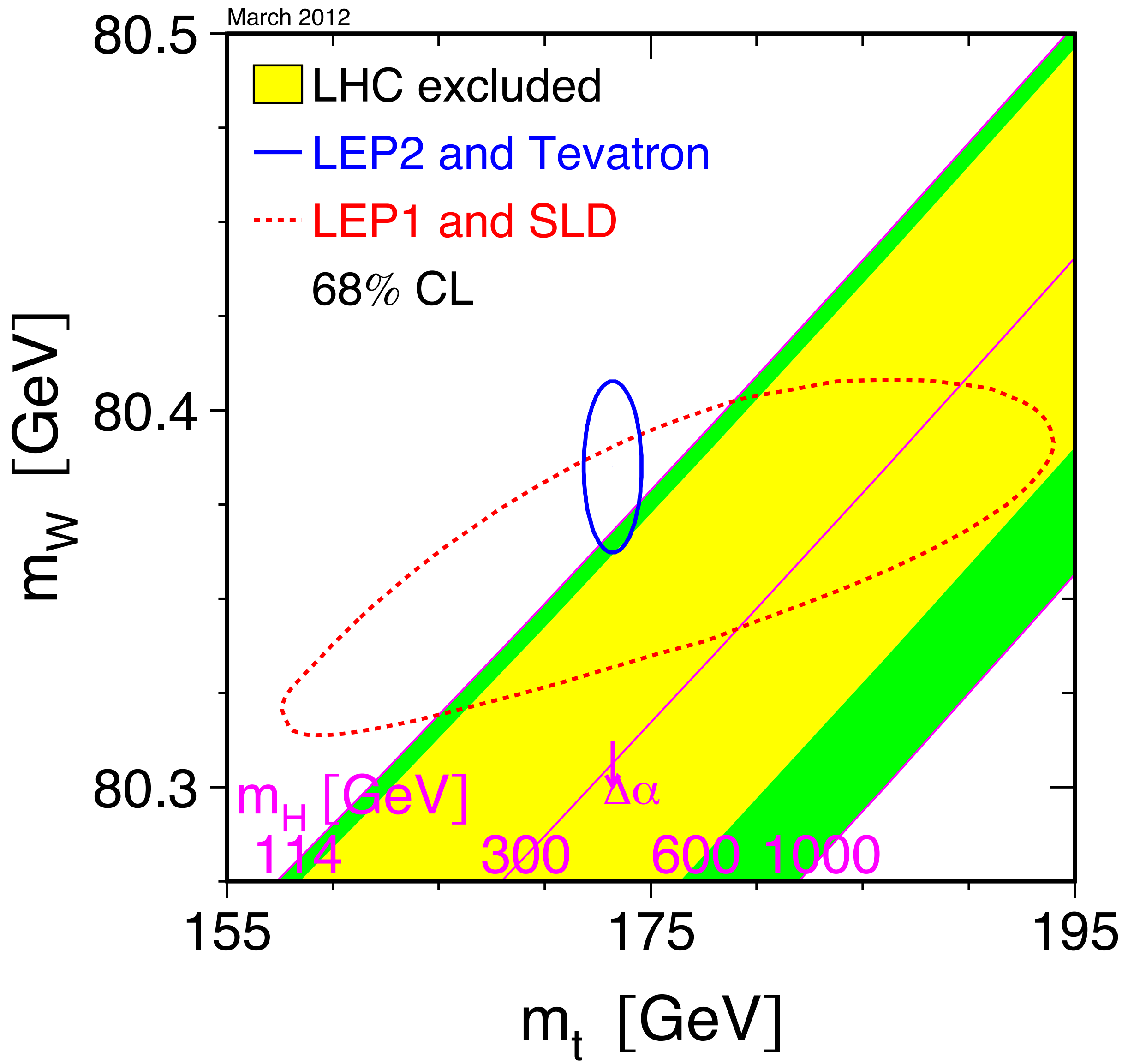
W and top quark mass tells us Higgs mass

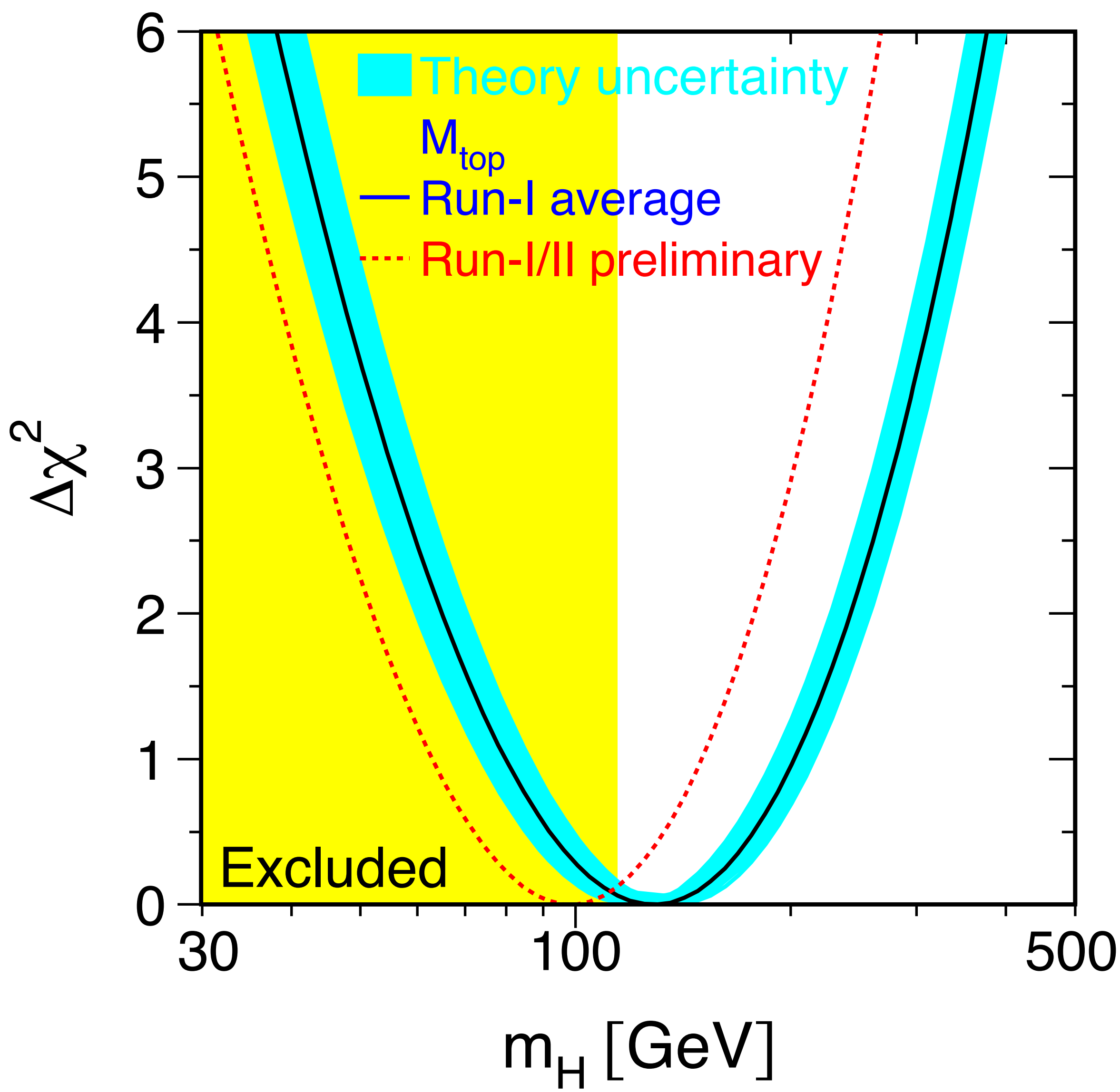

LEP1 and SLD
LEP2 and Tevatron (prel.)
68% CL
80.5
80.4
80.3
m_W [GeV]
Δα
m_H [GeV]
114
300
1000
150
175
200
m_t [GeV]



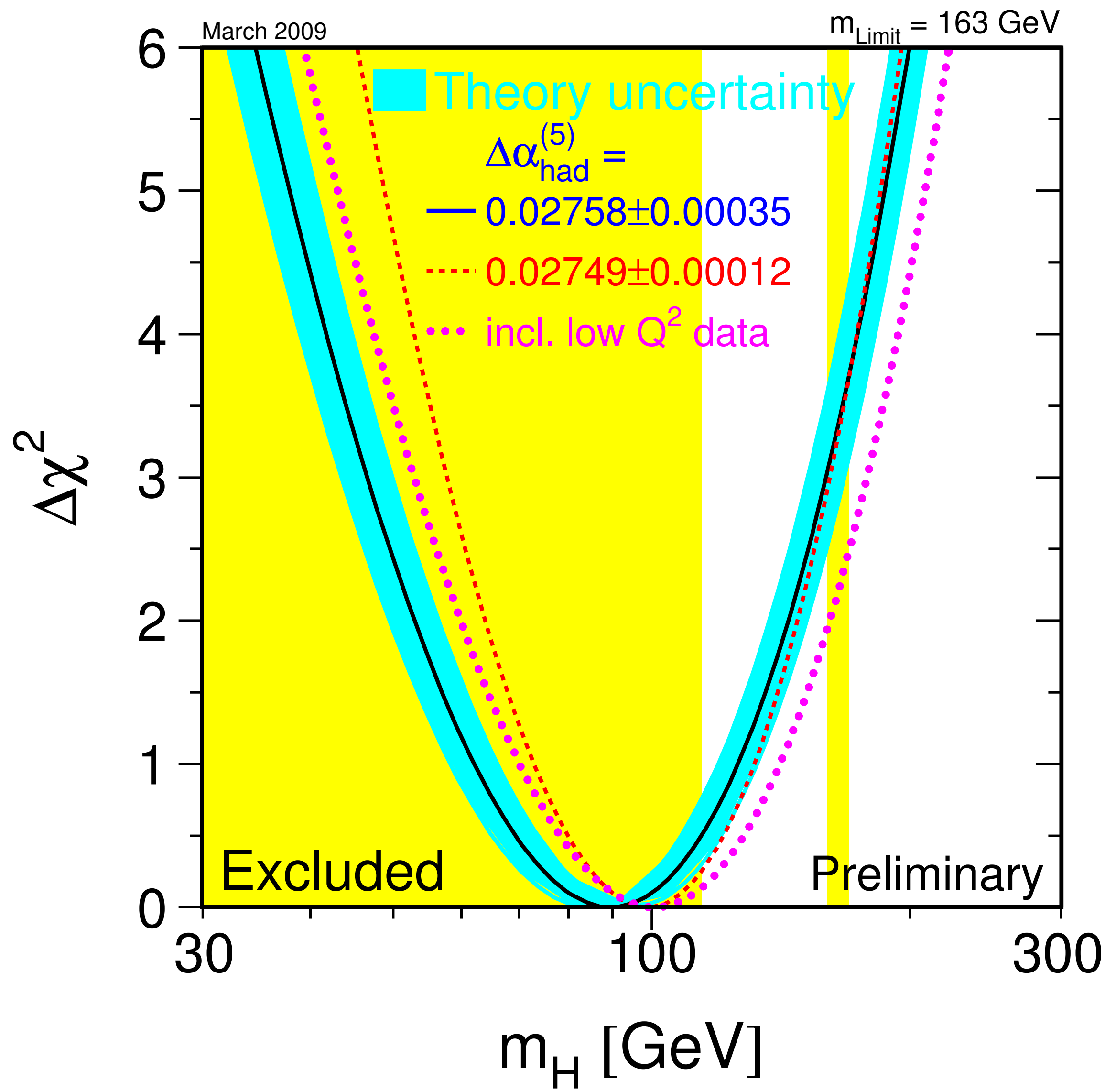
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
1000
$\Delta\alpha$
150
175
200
m_t [GeV]

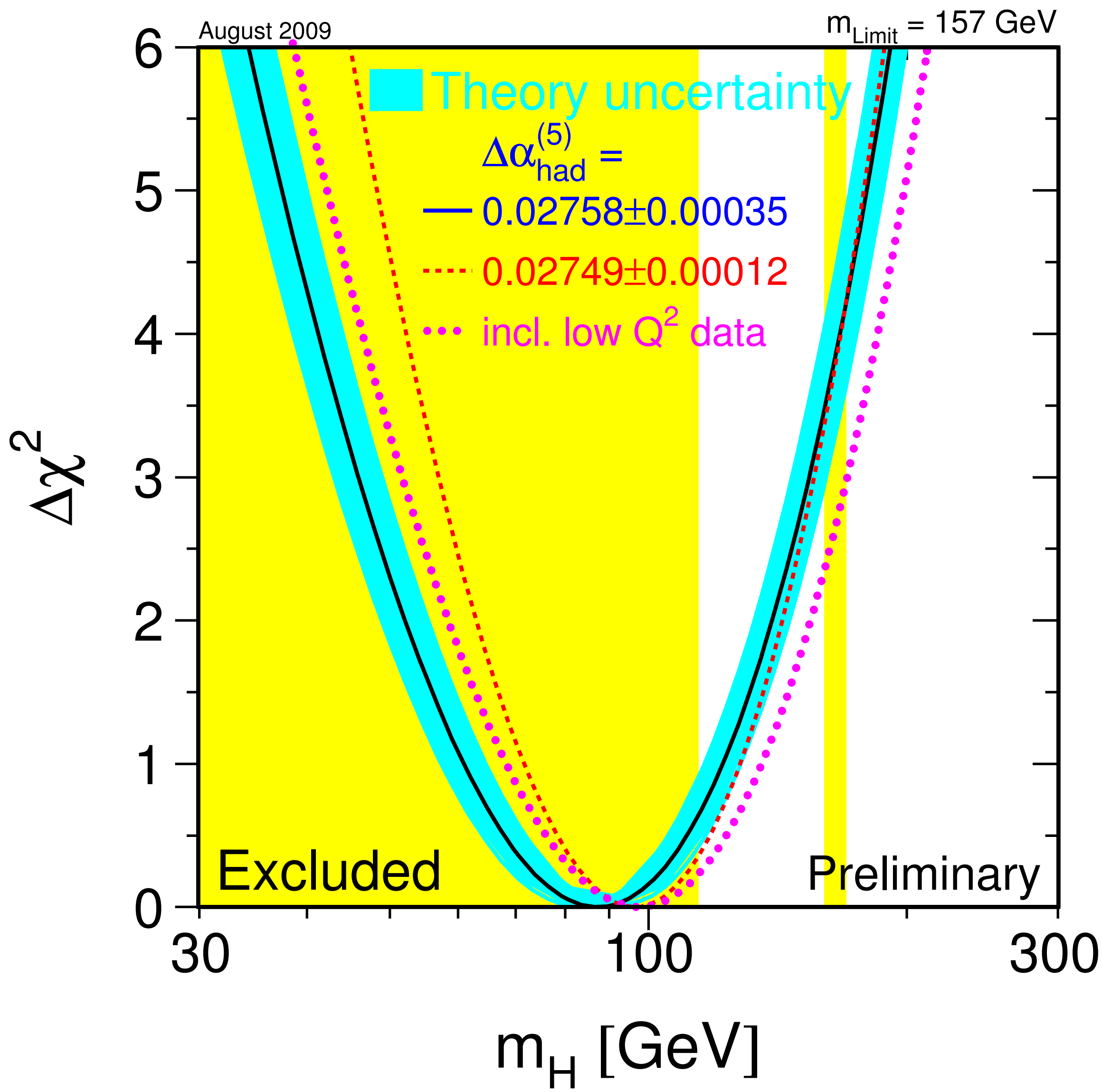

March 2009
LEP2 and Tevatron (prel.)
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
1000
Δα
150
175
200
m_t [GeV]

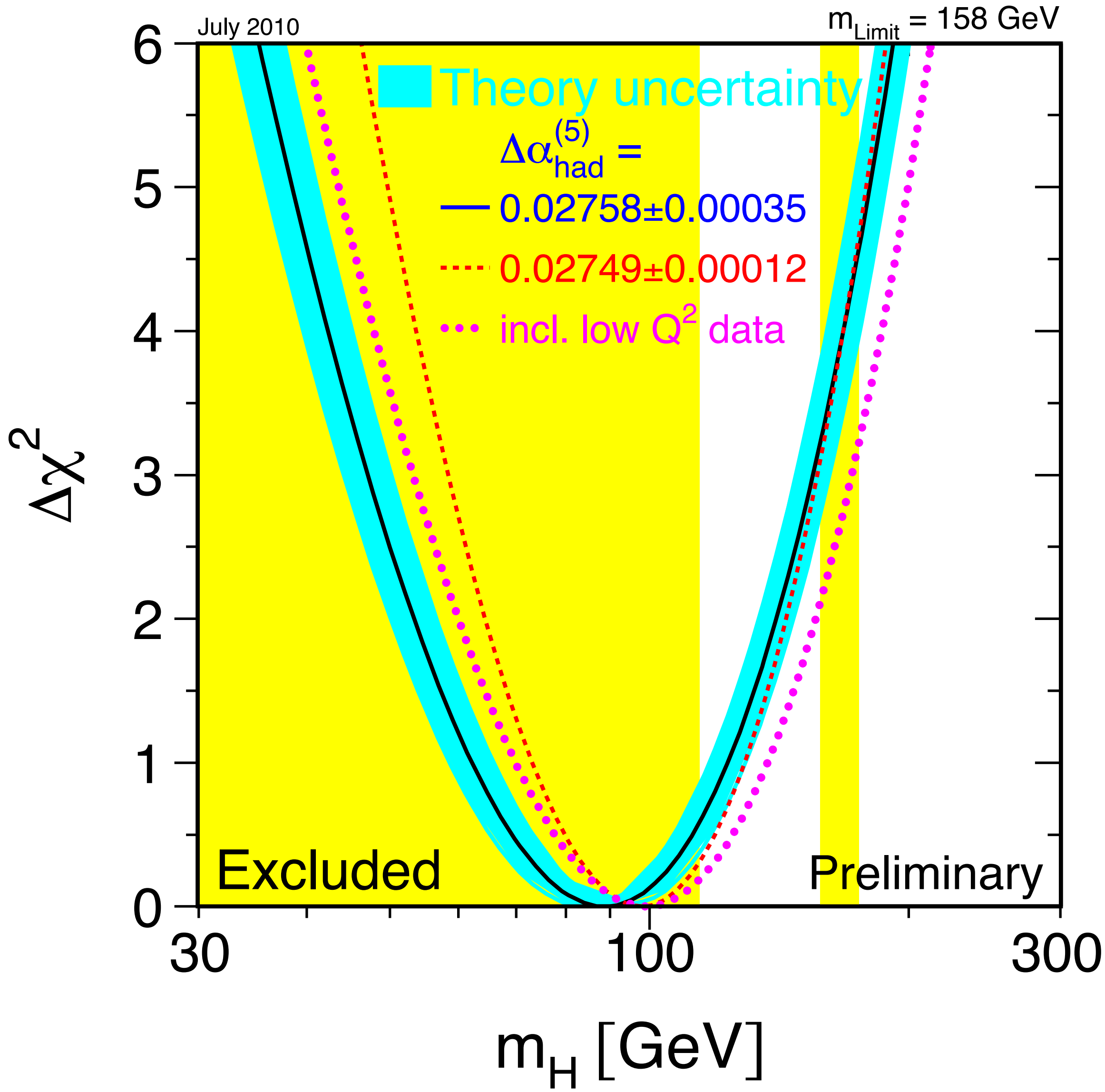

March 2012
LHC excluded
LEP2 and Tevatron
LEP1 and SLD
68% CL
80.5
80.4
80.3
m_W [GeV]
m_H [GeV]
114
300
600
1000
Δα
155
175
195
m_t [GeV]

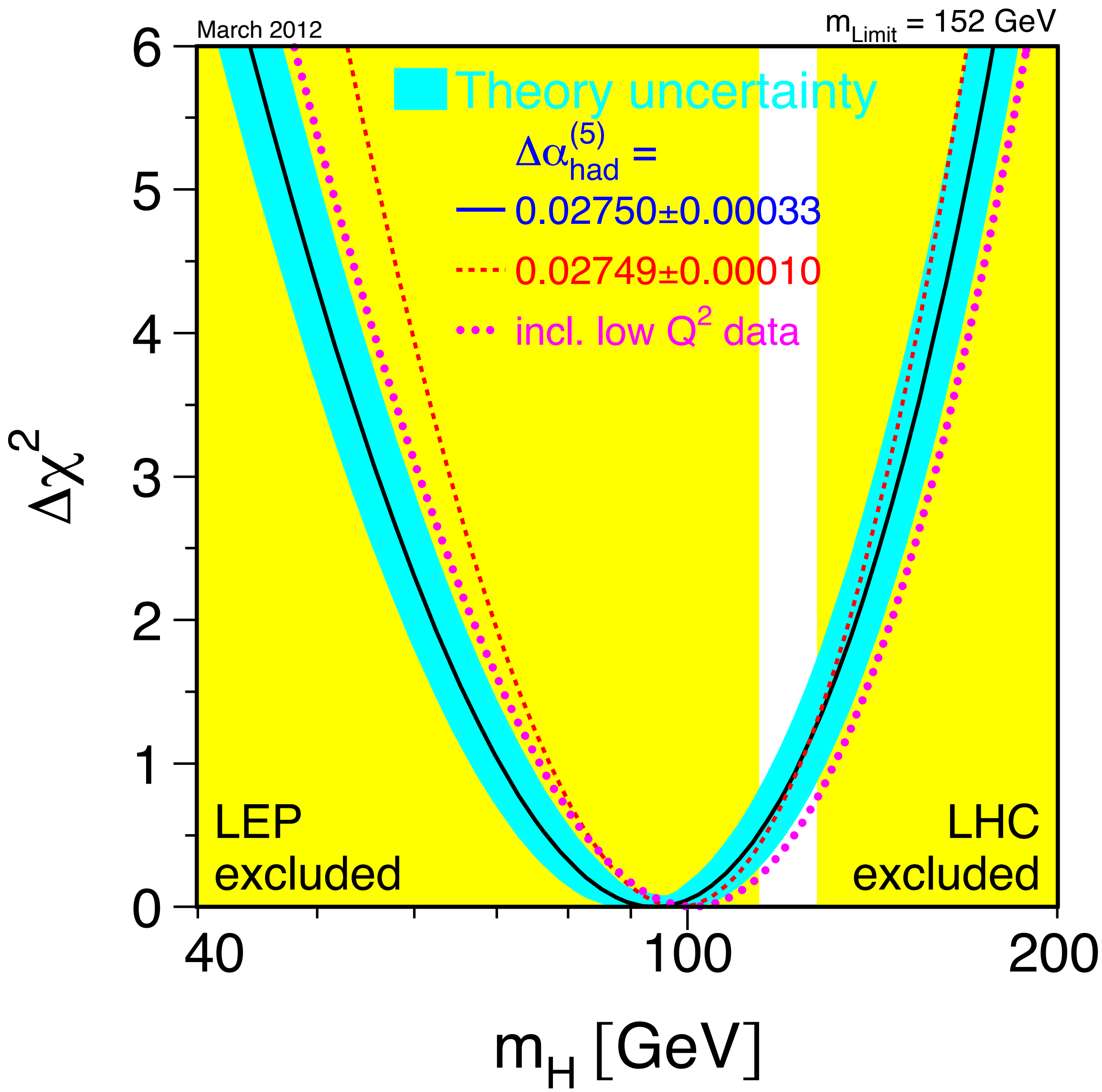


Theory uncertainty
M top
Run-I average
Run-I/II preliminary
Excluded
Δχ 2
6
5
4
3
2
1
0
30
100
500
m H [GeV]

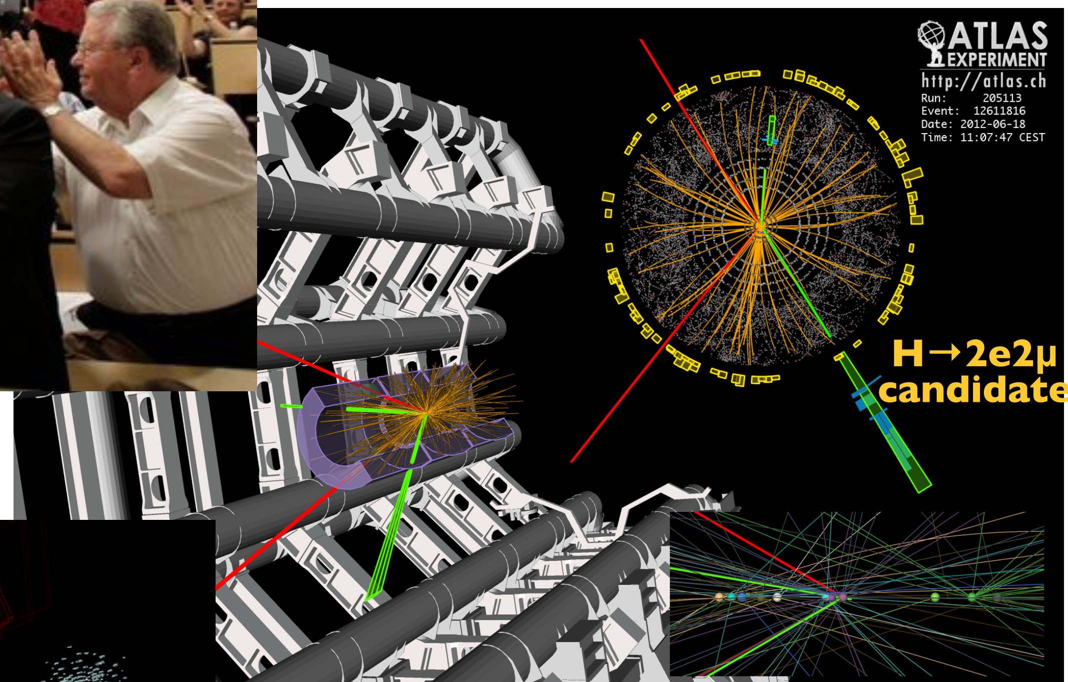

March 2009
m_{Limit} = 163 GeV
Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
Preliminary
$\Delta\chi^2$
m_H [GeV]
0
1
2
3
4
5
6
30
100
300

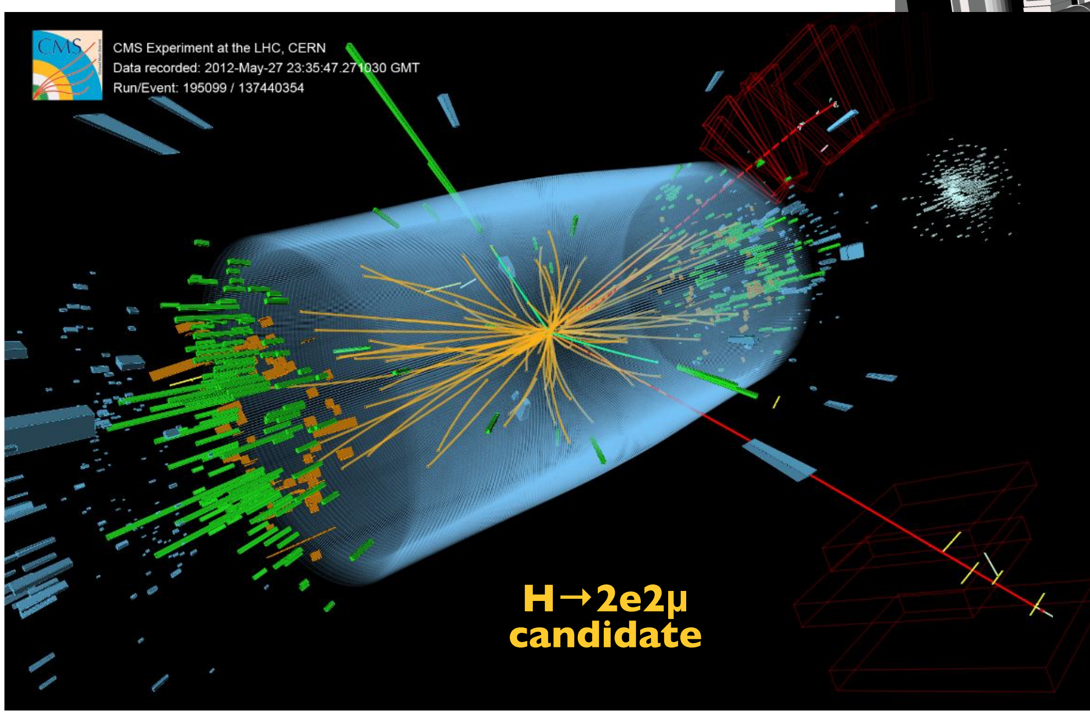

August 2009
m_Limit = 157 GeV
Theory uncertainty
Δα_had^(5) =
0.02758±0.00035
0.02749±0.00012
incl. low Q^2 data
Excluded
Preliminary
Δχ^2
m_H [GeV]
0
1
2
3
4
5
6
30
100
300


July 2010
m_Limit = 158 GeV
Theory uncertainty
Δα(5)had =
0.02758±0.00035
0.02749±0.00012
incl. low Q2 data
Excluded
Preliminary
Δχ2
6
5
4
3
2
1
0
30
100
300
mH [GeV]


March 2012
m_{Limit} = 152 GeV
Theory uncertainty
$\Delta\alpha_{had}^{(5)}$ =
0.02750±0.00033
0.02749±0.00010
incl. low Q^2 data
LEP excluded
LHC excluded
$\Delta\chi^2$
m_H [GeV]
0
1
2
3
4
5
6
40
100
200

Higgs is Discovered! 2012

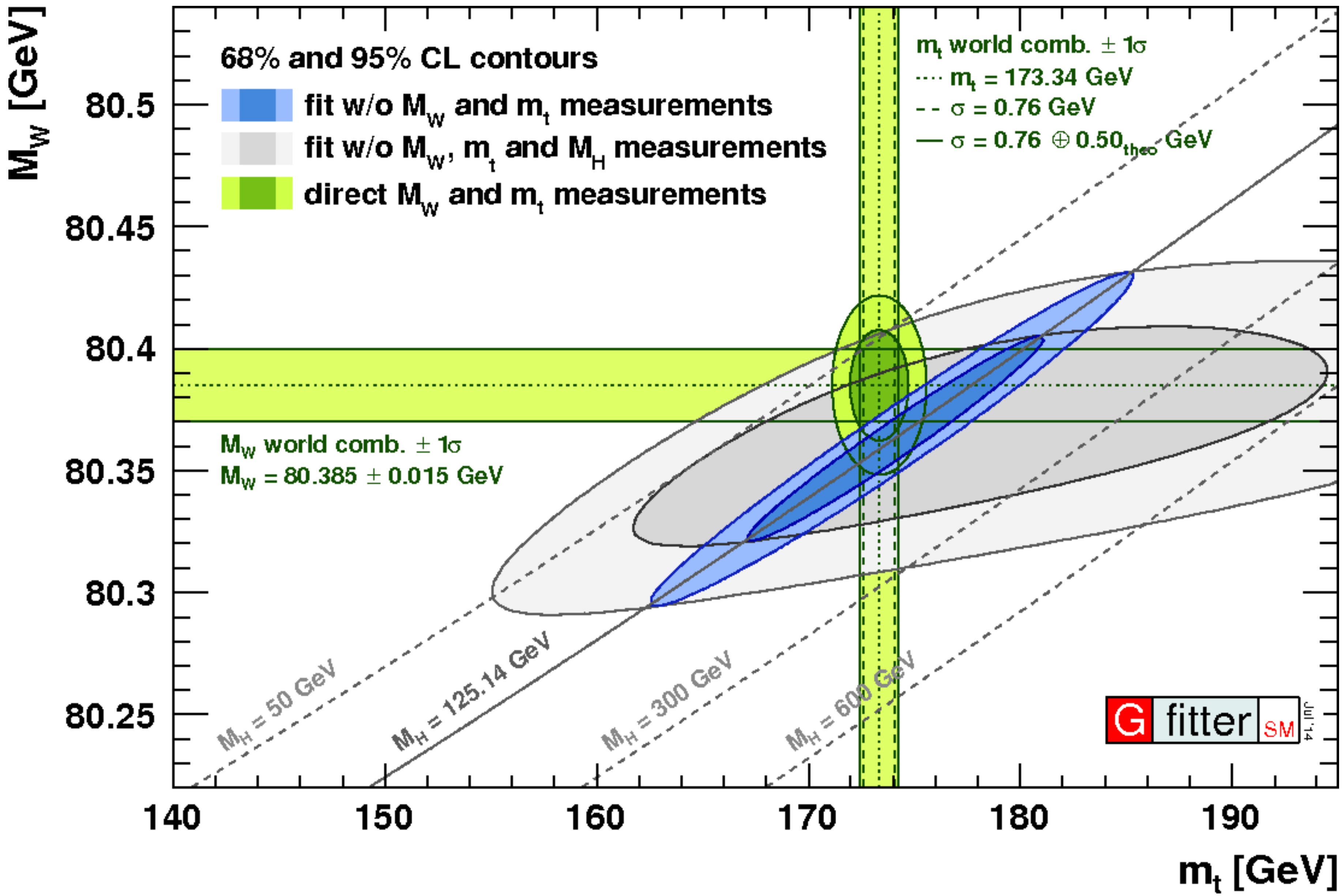




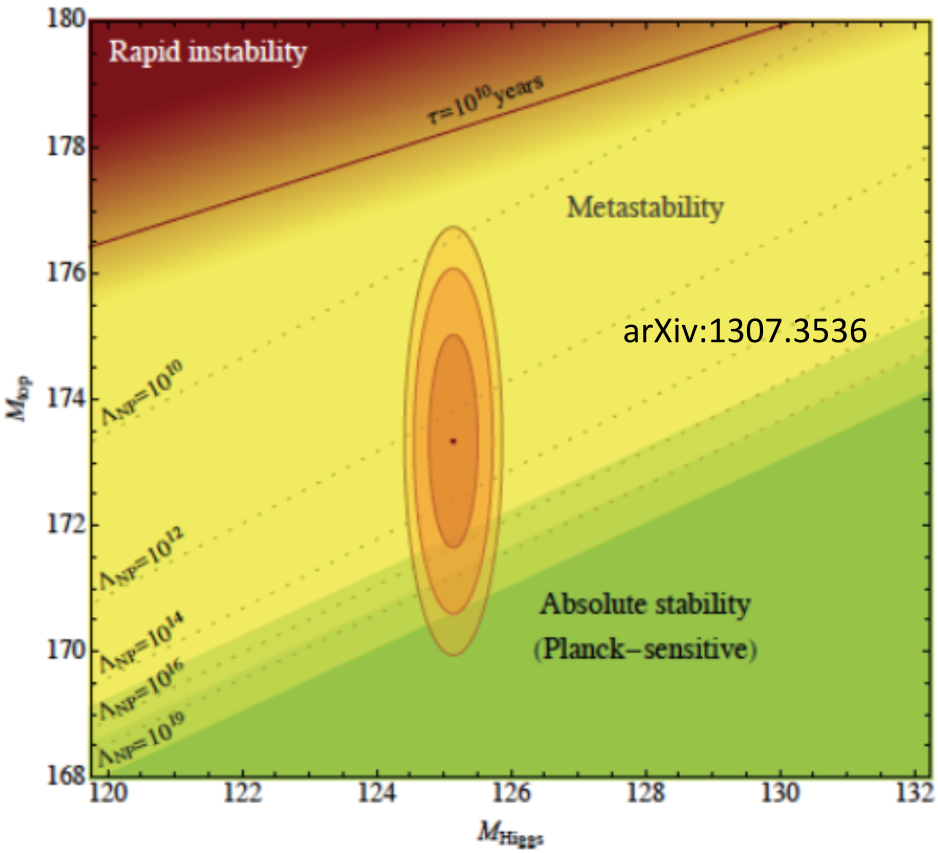
theory: 1964
design: 1984
construction: 1998
collisions: 2010


Science
21 December 2012 | $10
BREAKTHROUGH
of the YEAR
The HIGGS
BOSON
AAAS

Consistency of the Standard Model



Top Quark Mass



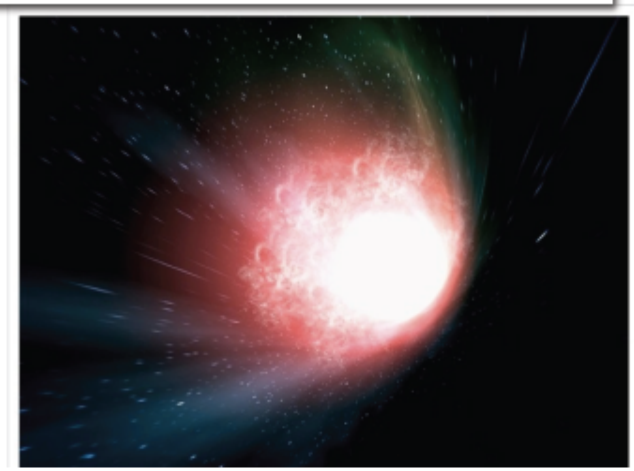
- Stability of the EW vacuum is an important property of the SM
- Measurements of the top mass and Higgs mass for the first time allow us to infer properties of the vacuum we live in!

$$M_h > 129.6\,\mathrm{GeV} + 2.0(M_t - 173.34\,\mathrm{GeV}) - 0.5\,\mathrm{GeV}\,\frac{\alpha_3(M_Z) - 0.1184}{0.0007} \pm 0.3\,\mathrm{GeV}$$

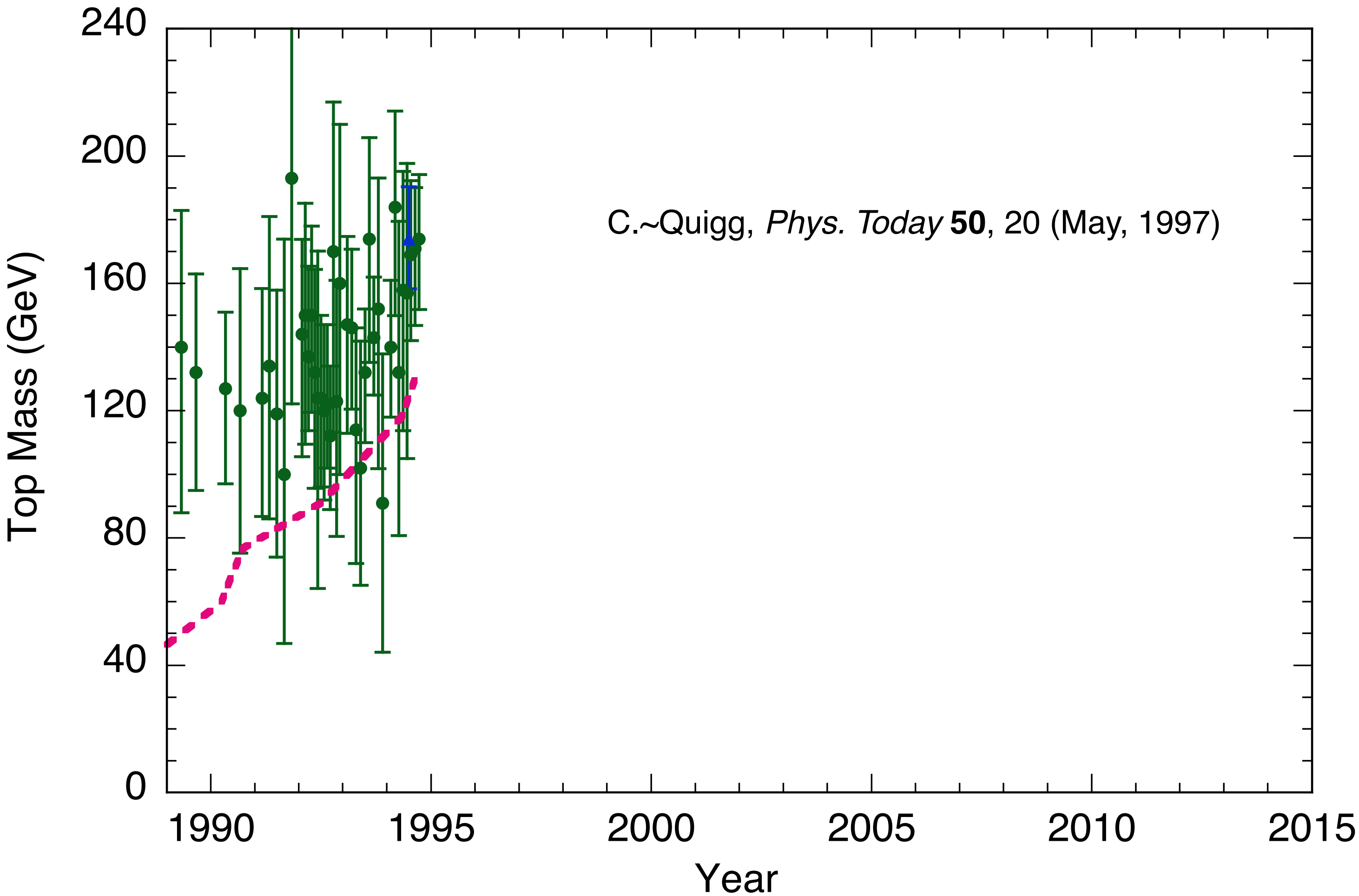
- A fine-tuned situation: vacuum on the verge of being either stable or unstable. ~1-2 GeV in either mass could tip the scales. (But new physics could possibly change this scenario.)
- What mass are we measuring?? Pole mass or MC mass?

Will our universe end in a 'big slurp'?

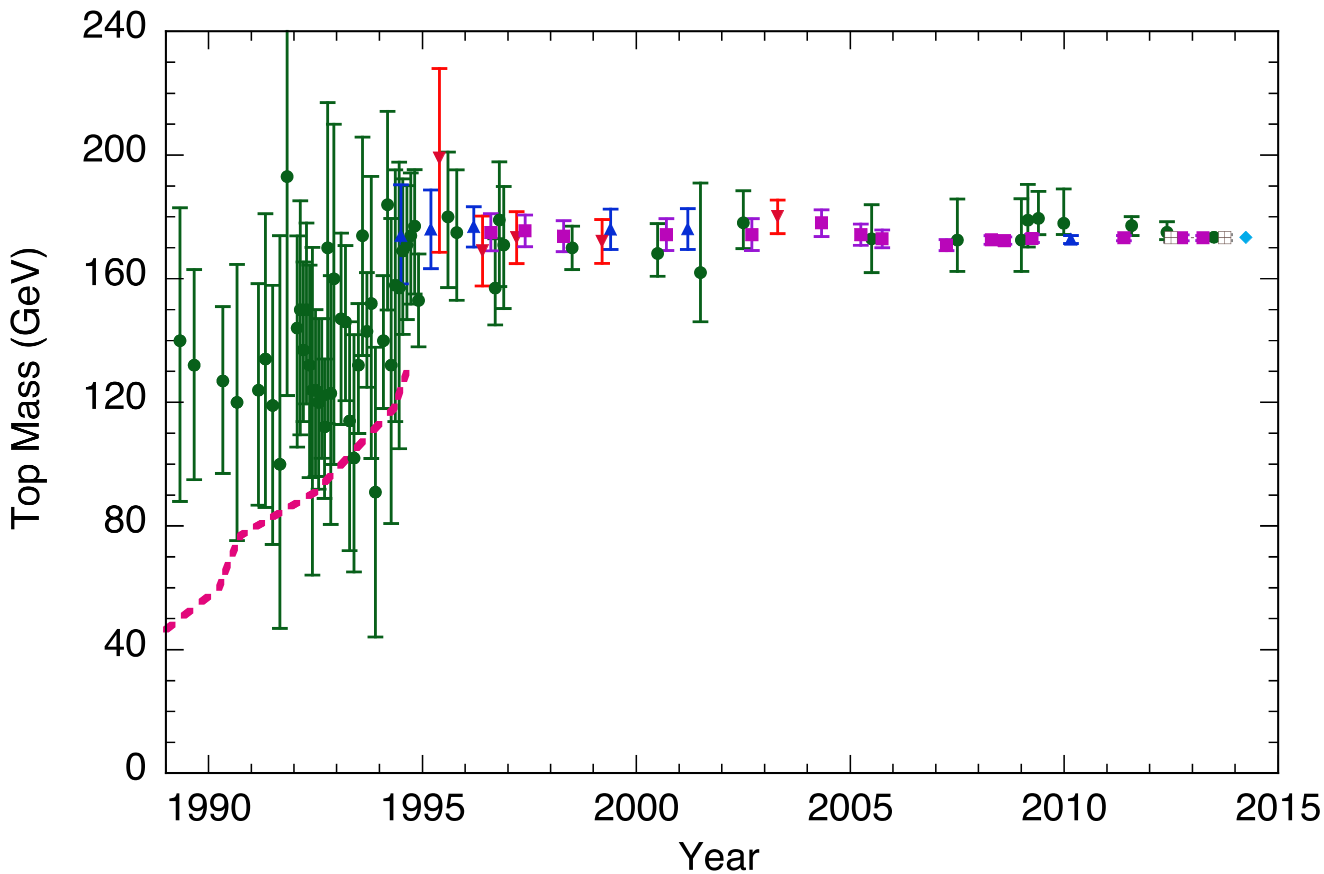
nbcnews.com



Indirect constraints on top quark



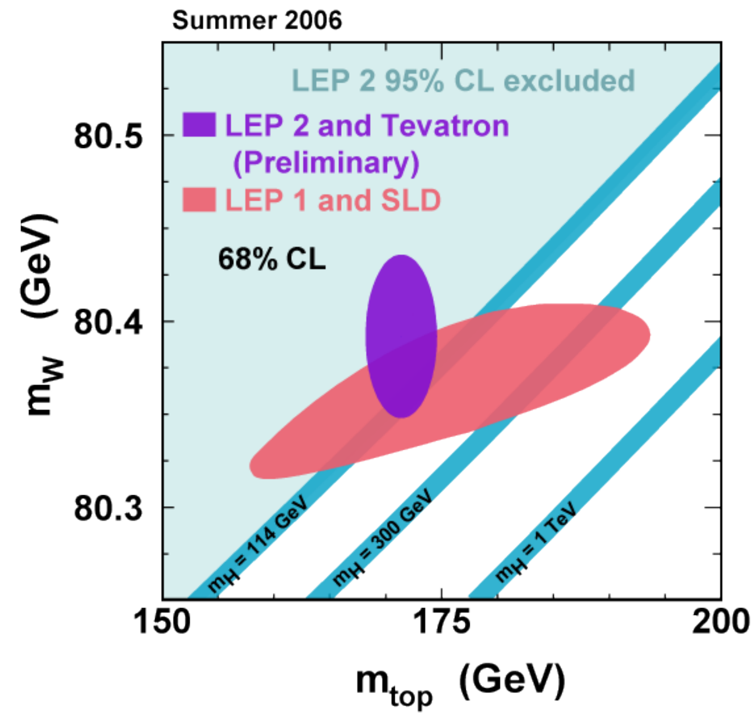
Evolution of Top Mass Measurements



C.~Quigg, *Phys. Today* **50**, 20 (May, 1997); extended version circulated as arXiv:hep-ph/9704332, and private communication.

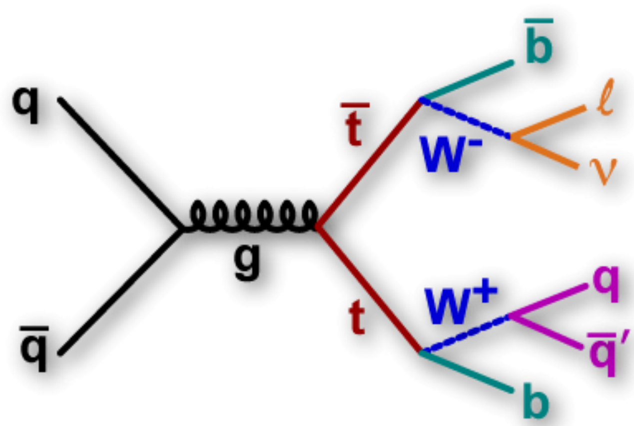
Top Quark Mass

- Important EWK parameter
- Key role in BSM physics models
- Constrains the Higgs mass
- Heavy: Unexpected role in EWSB?

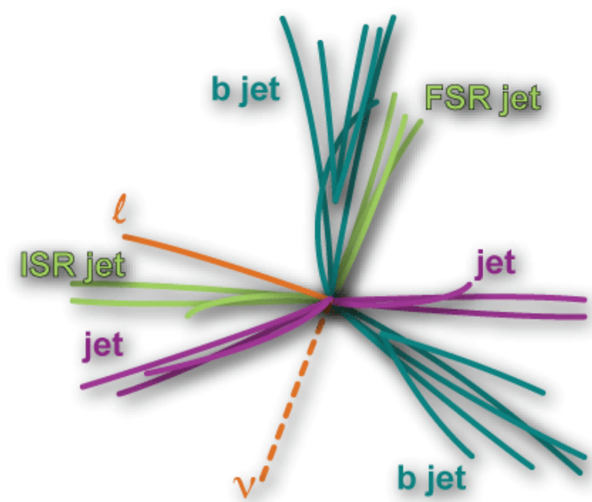


Challenges: combinatorics, b-tagging efficiencies, jet energy scale.

Solutions: sophisticated analyses, in-situ W→jj calibration



What a theorist sees…

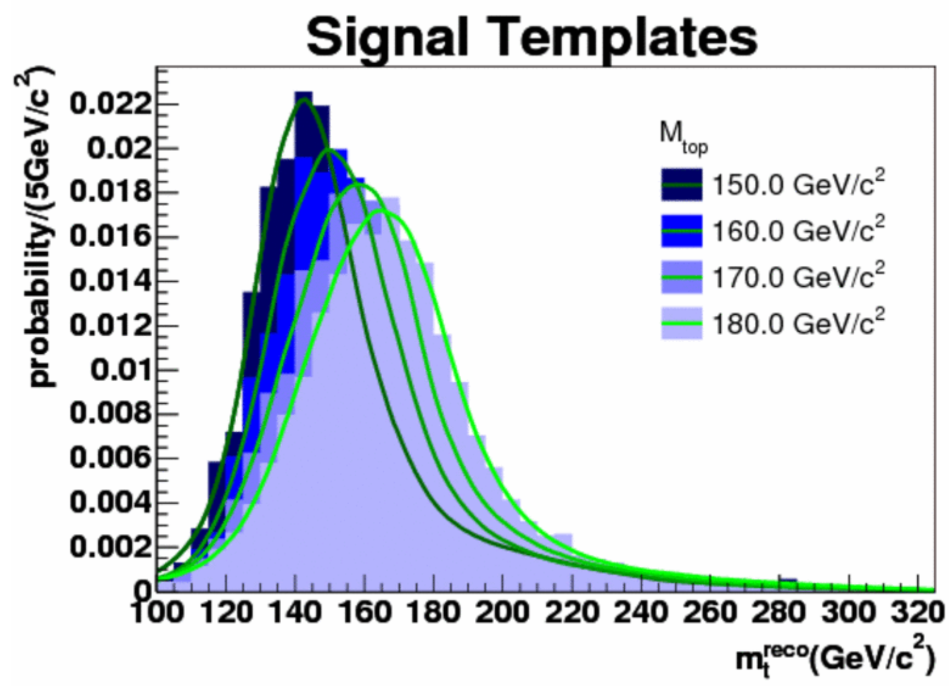


What an experimentalist sees

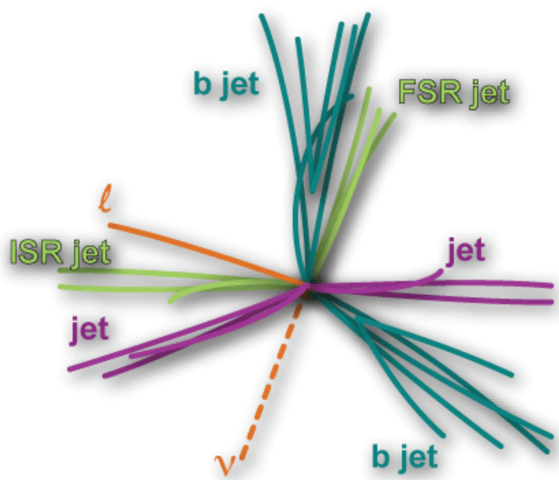
How we measure the top quark mass?

Template: measure most quantities in an event and reconstruct the mass

- p_T leptons
- E_T jets
- missing E_T
- b-tags



difficult combinatorics:



minimize the chi-square:

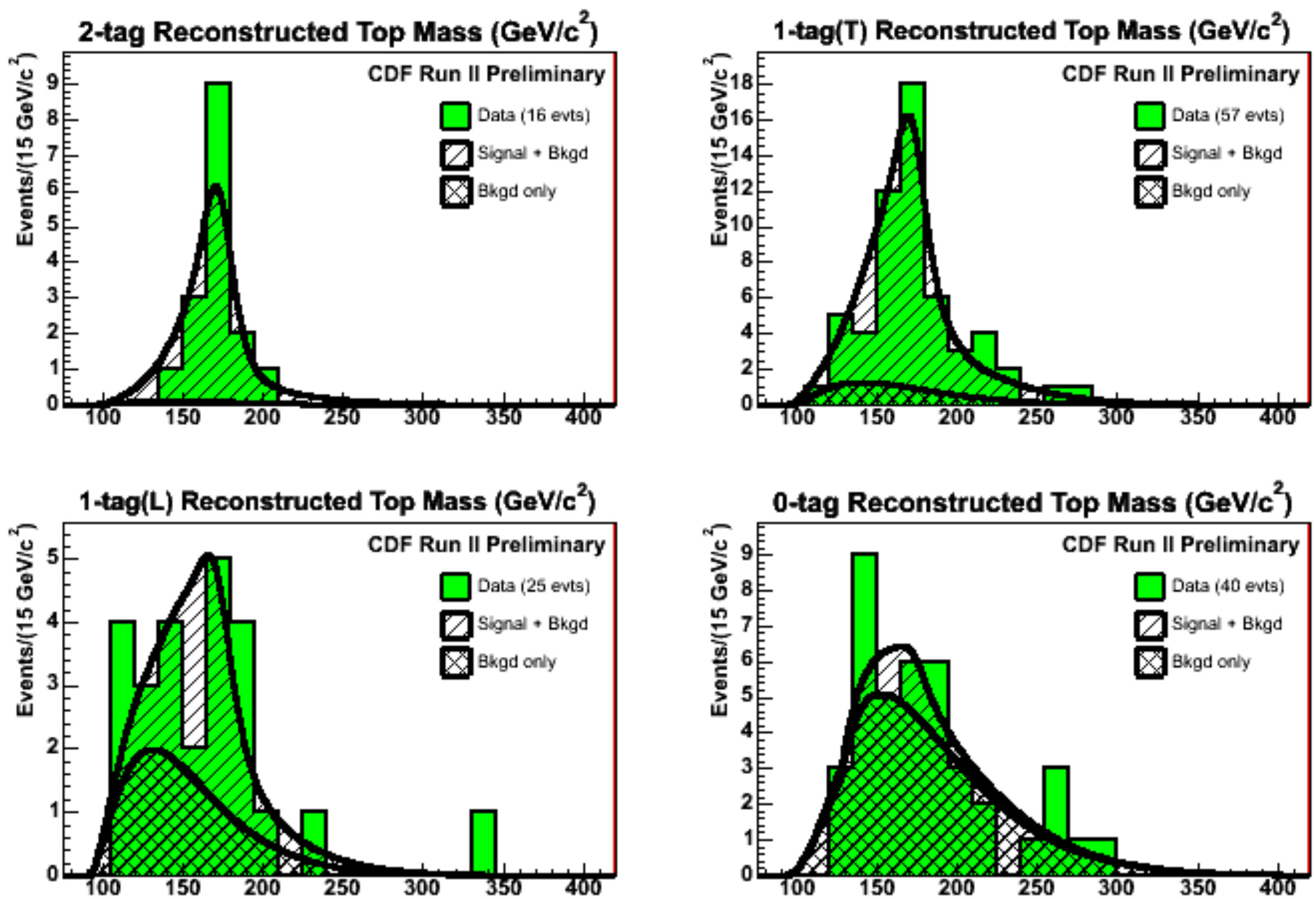
$$\chi^2 = \Sigma_{i=\ell,4jets}\frac{(p_T^{i,fit}-p_T^{i,meas})^2}{\sigma_i^2} + \Sigma_{j=x,y}\frac{(U_j^{fit}-U_j^{meas})^2}{\sigma_j^2} + \frac{(M_{jj}-M_W)^2}{\Gamma_W^2} + \frac{(M_{\ell\nu}-M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj}-m_t^{reco})^2}{\Gamma_t^2} + \frac{(M_{b\ell\nu}-m_t^{reco})^2}{\Gamma_t^2}$$

How we measure the top quark mass?

Template: measure most quantities in an event and reconstruct the mass

early Tevatron Run 2 example:

spring 2005



Better sensitivity by splitting in S/B bins, in this case, number of b-tags

How we measure the top quark mass?

Template: one of the largest systematic uncertainties: Jet energy scale (JES)

JES calibrations are complicated!

Quark/gluon produced from p-p (p-pbar) interaction.

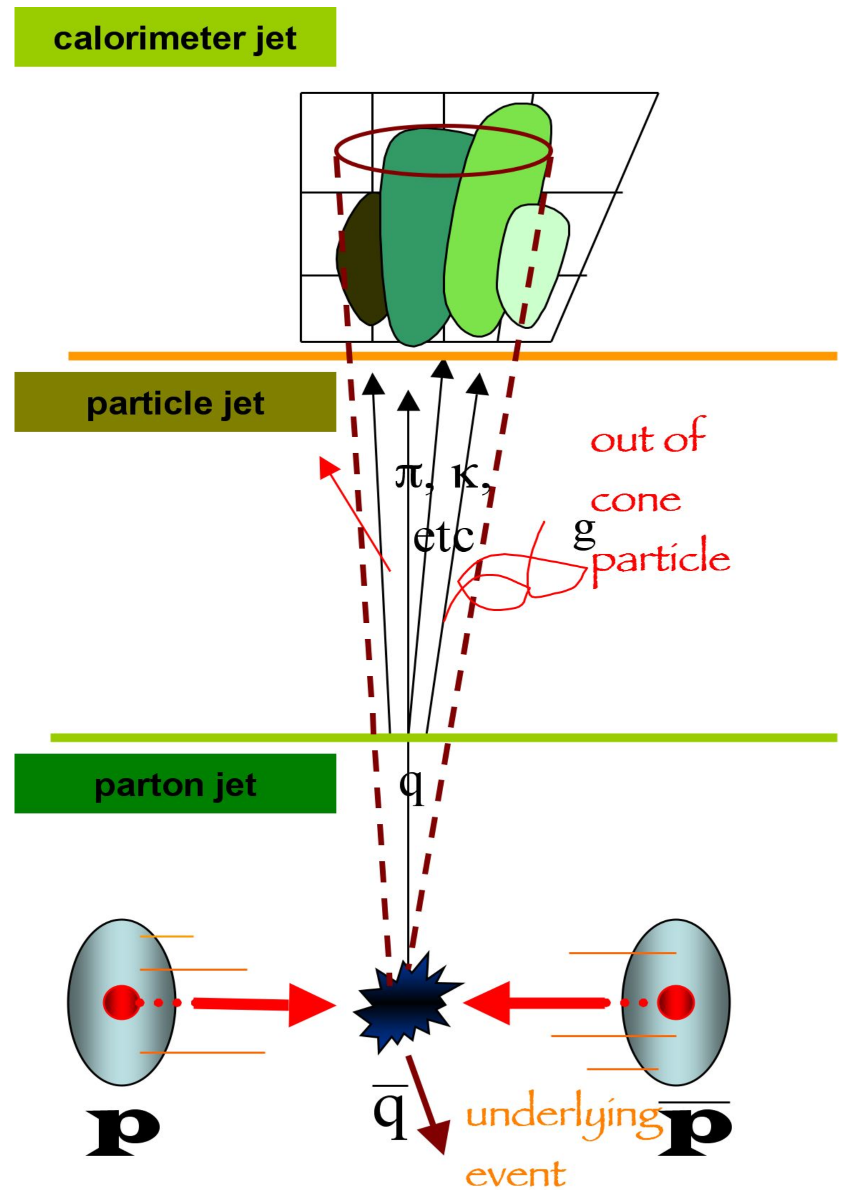
Fragmentation into hadrons.

Jet clustering algorithm (adds towers inside cone).

Fraction of energy is outside of cone.

Underlying event contributes to energy inside of cone.

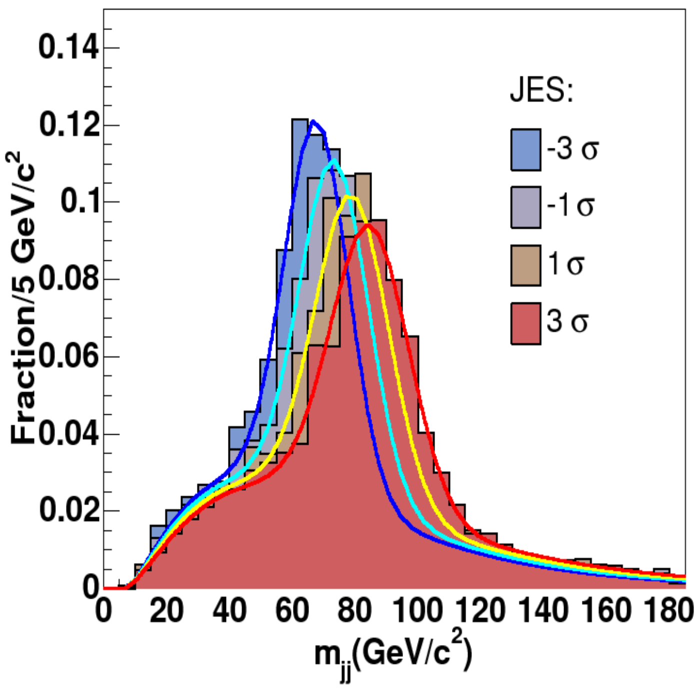
⇒Need to get original parton energy!



How we measure the top quark mass?

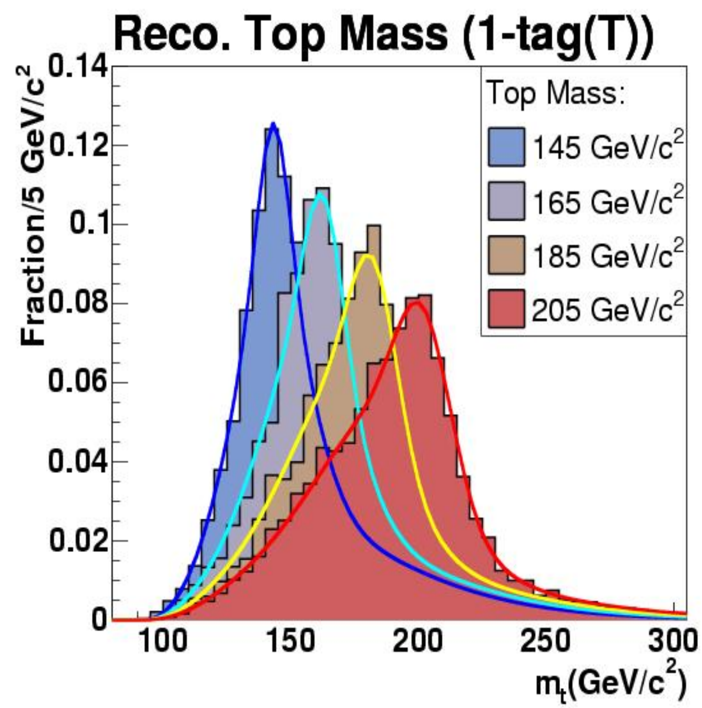
Template: one of the largest systematic uncertainties: Jet energy scale (JES)

Creative solution: fit for the JES using known W mass peak

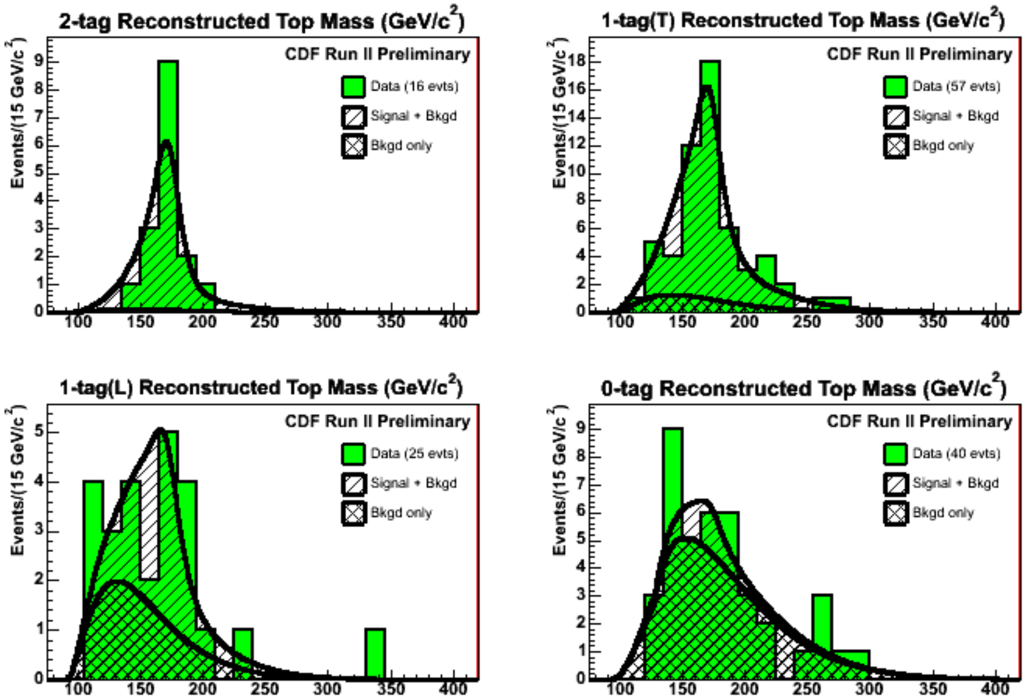


in-situ JES calibration with W→jj

↔



same data: same JES, reduced systematics



With 138 candidate ttbar events:

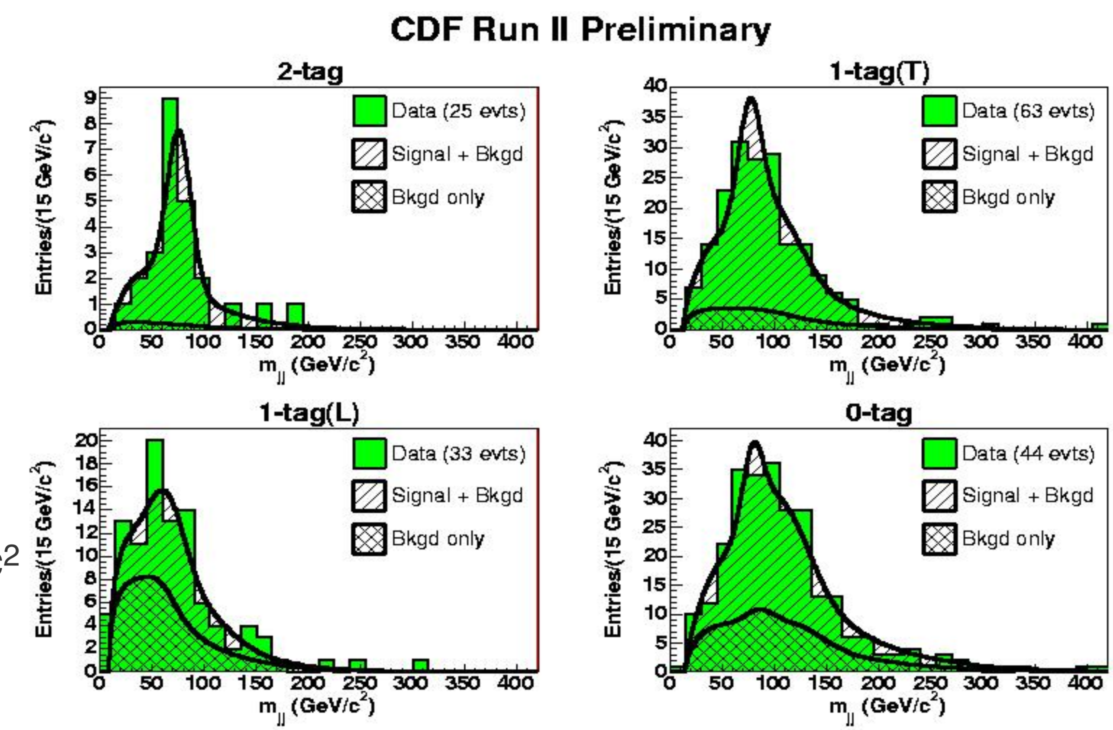
M_{top}= 173.2 +/- 2.8 (stat.) +/- 3.4 (syst.) GeV/c

before in-situ Wjj calibration

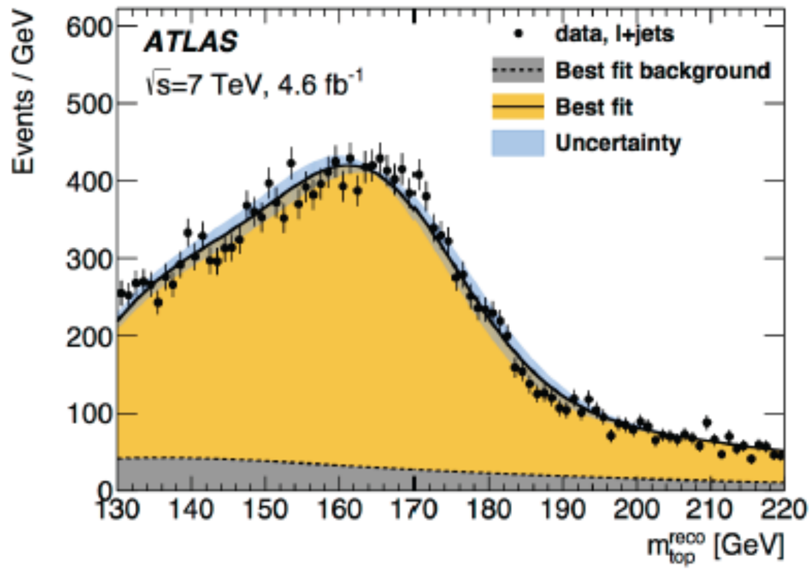
after in-situ Wjj calibration

With the same data as previously:

M_{top}= 173.5 +/- 2.7 (stat.) +/- 2.8 (syst.) GeV/c^2

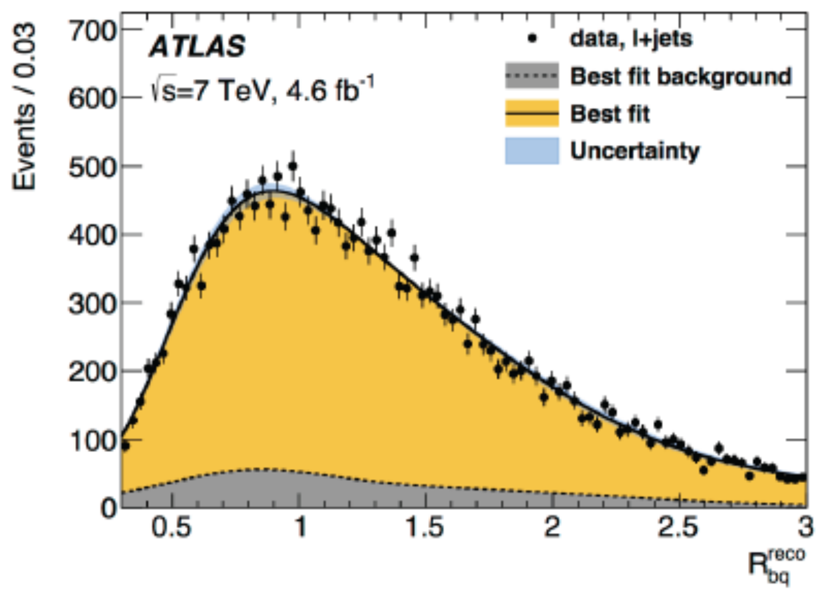


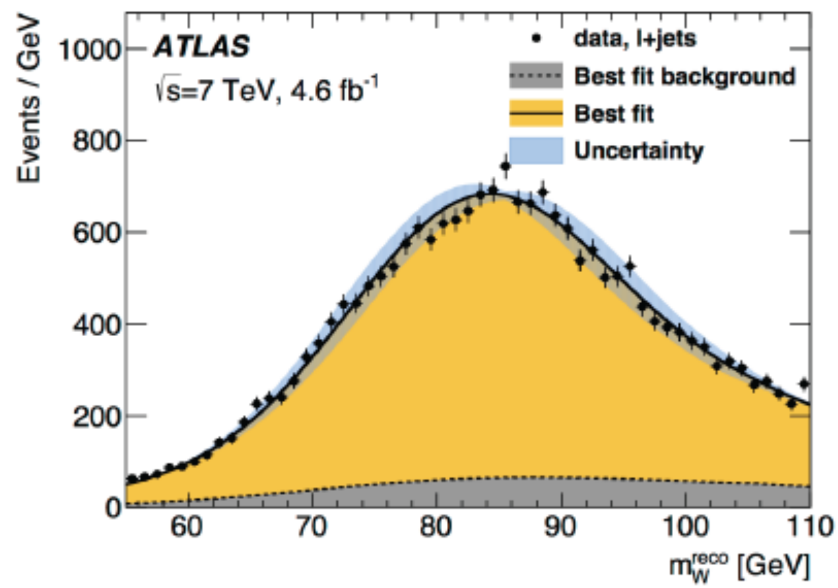
ATLAS 3D in-situ calibration:



- 3D template fit in l+jets
- Reconstruct the top pairs using kinematic likelihood fit to select combination of assignments that best fits ttbar hypothesis

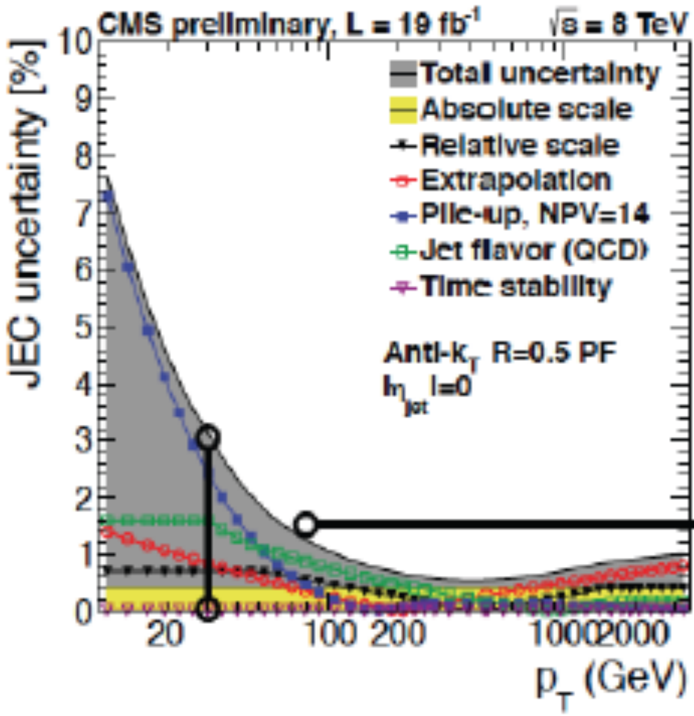
fit W→jj JES and ratio b/q JES

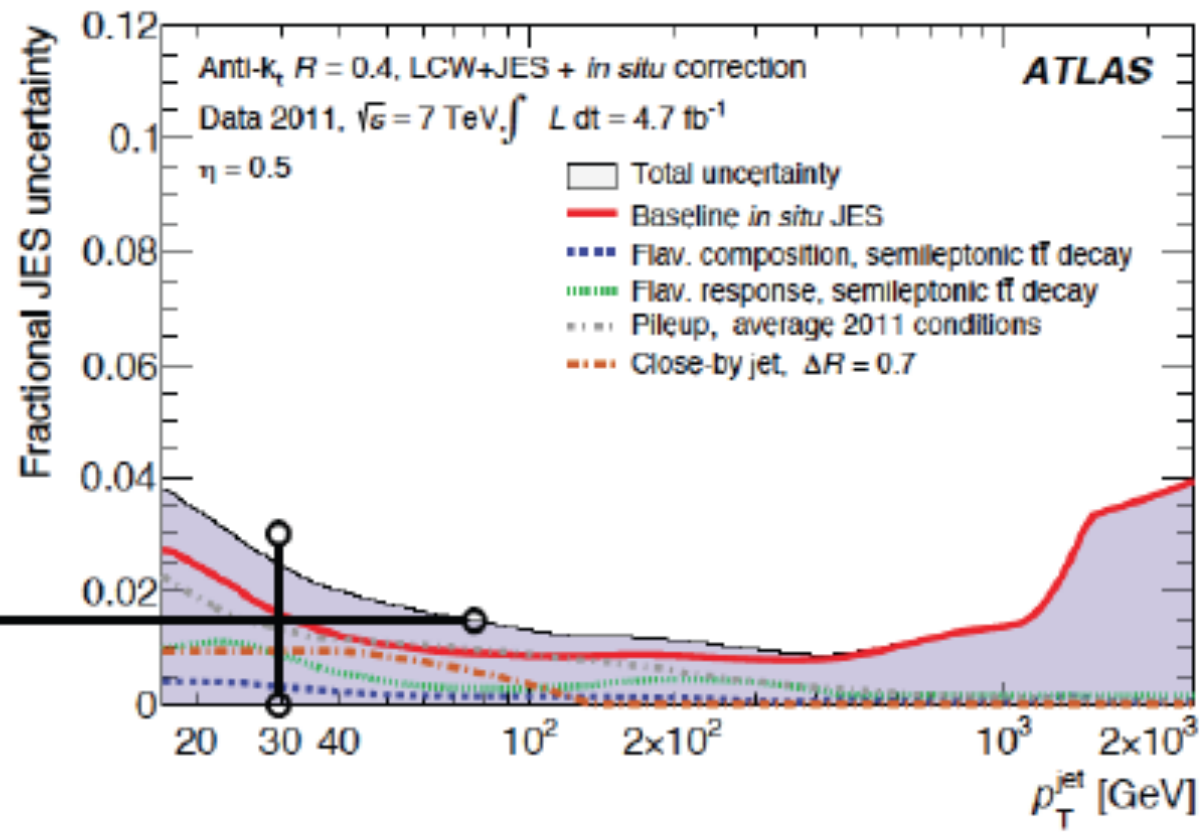




How we measure the top quark mass?

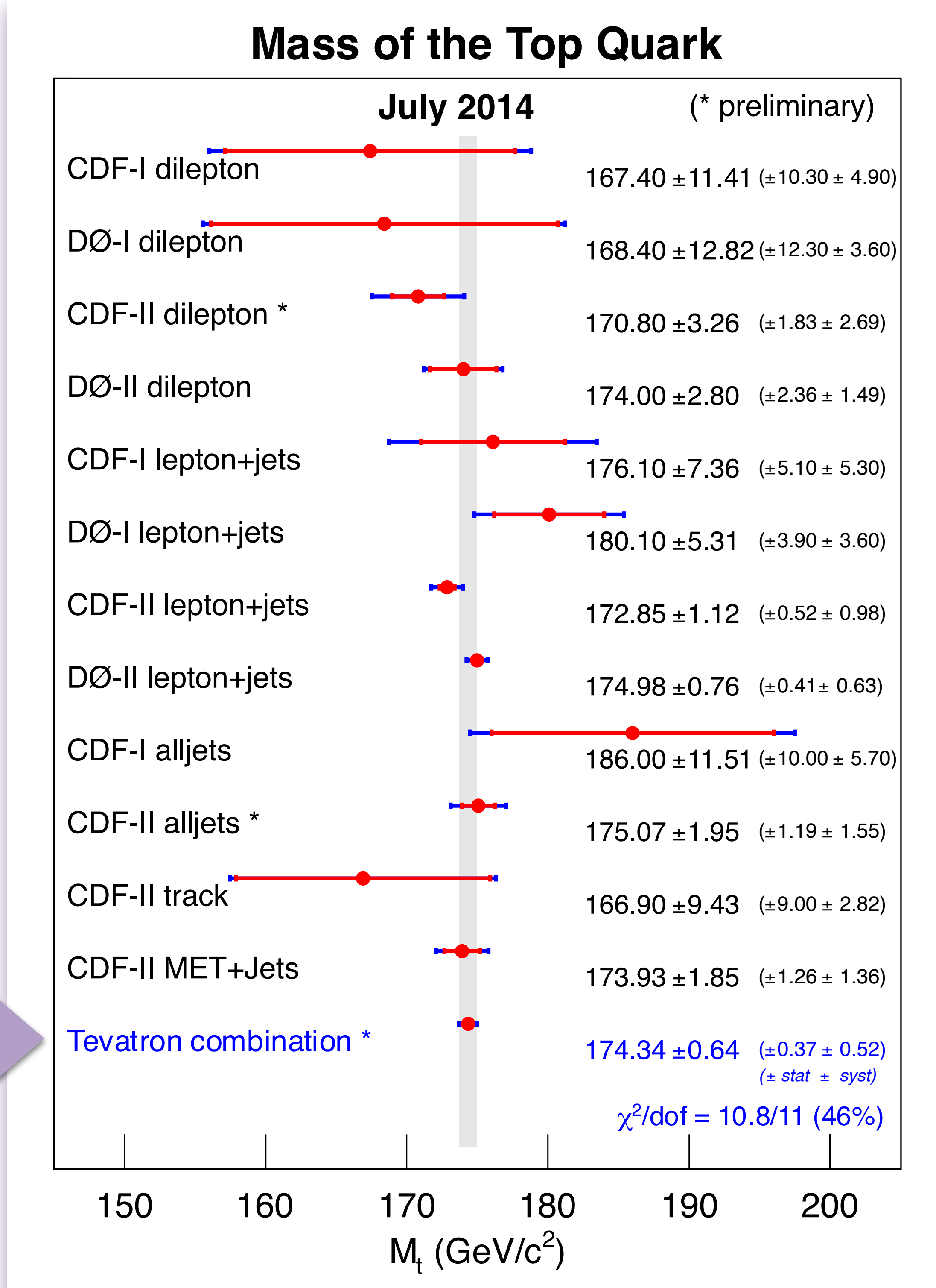
LHC JEC/JES Uncertainties





Top Quark Mass

Tevatron combination

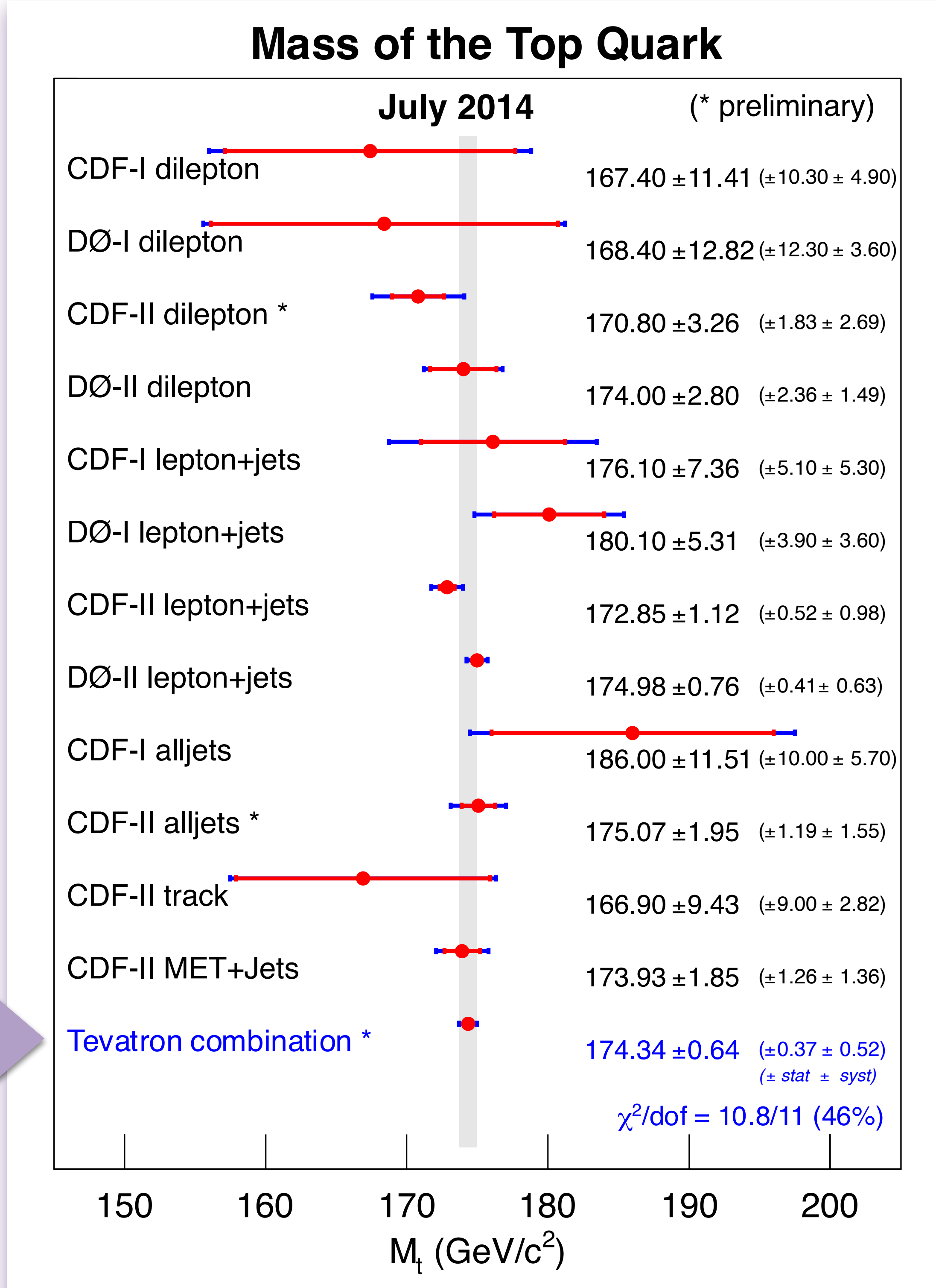


<4% relative uncertainty

arXiv: 1608.01881

Top Quark Mass

Tevatron combination

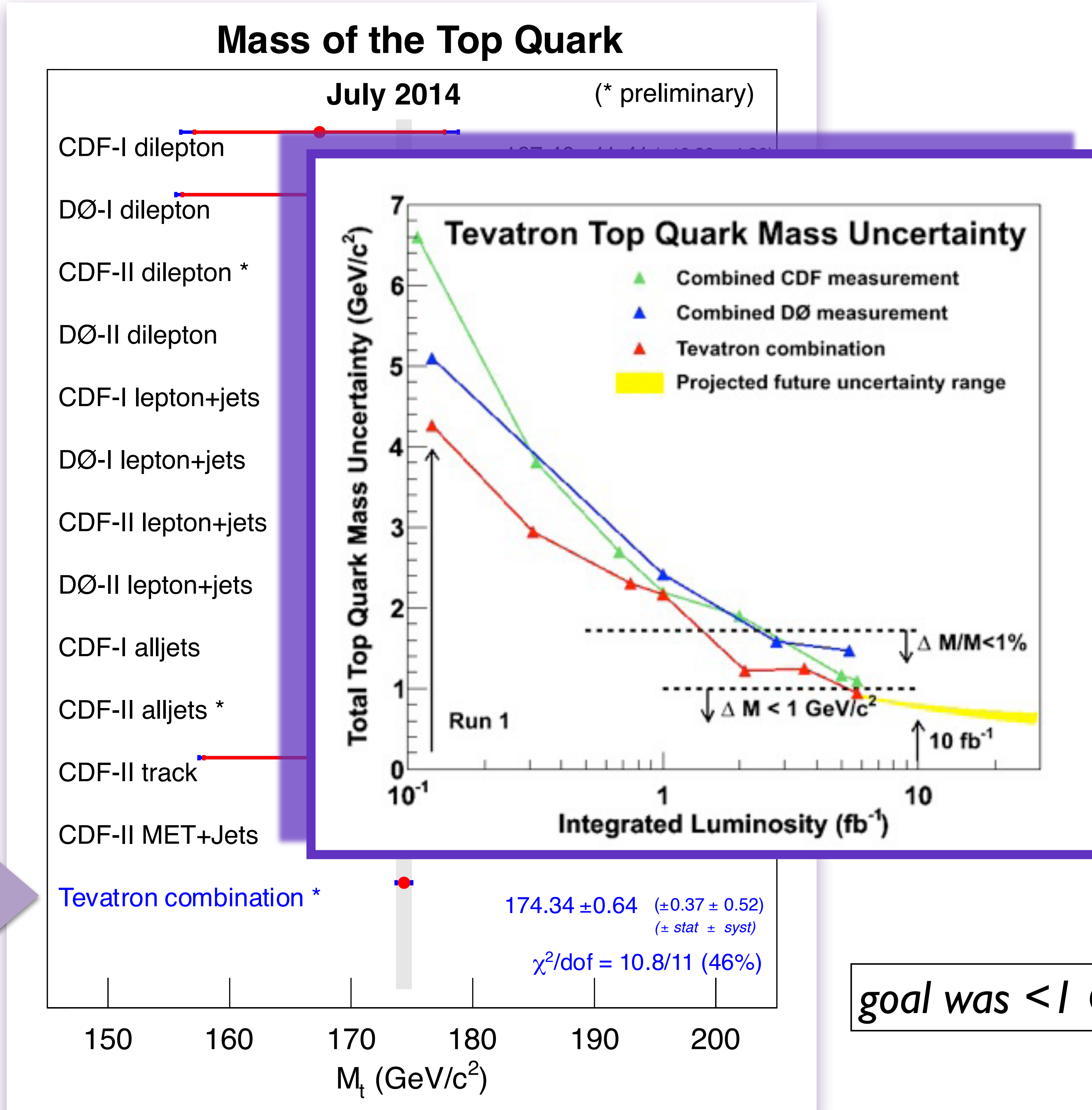


<4% relative uncertainty

goal was <1 GeV

Top Quark Mass

Tevatron combination



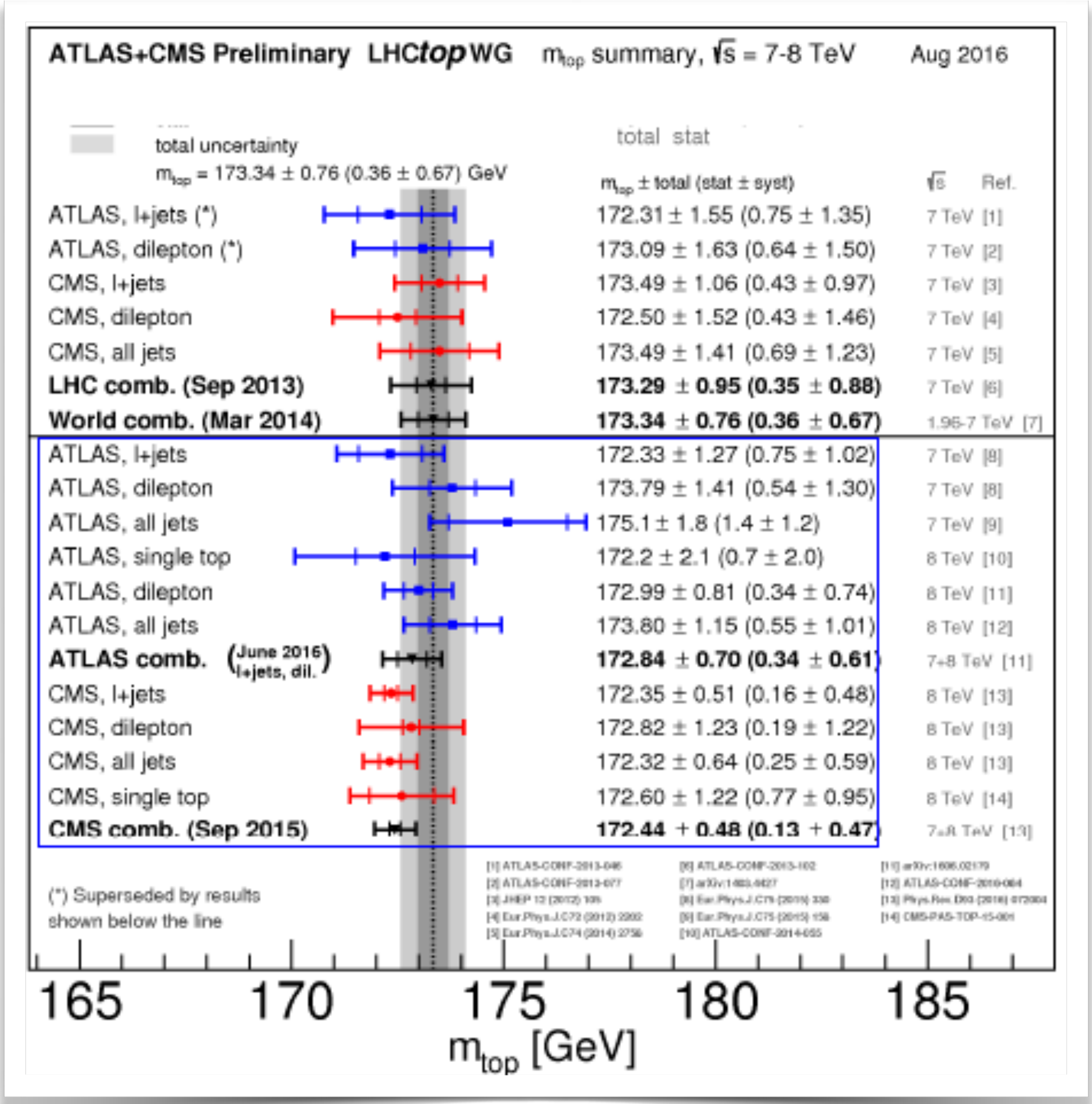
<4% relative uncertainty

goal was <1 GeV

Top Quark Mass

ATLAS and CMS combined: direct measurements

<3% relative uncertainty

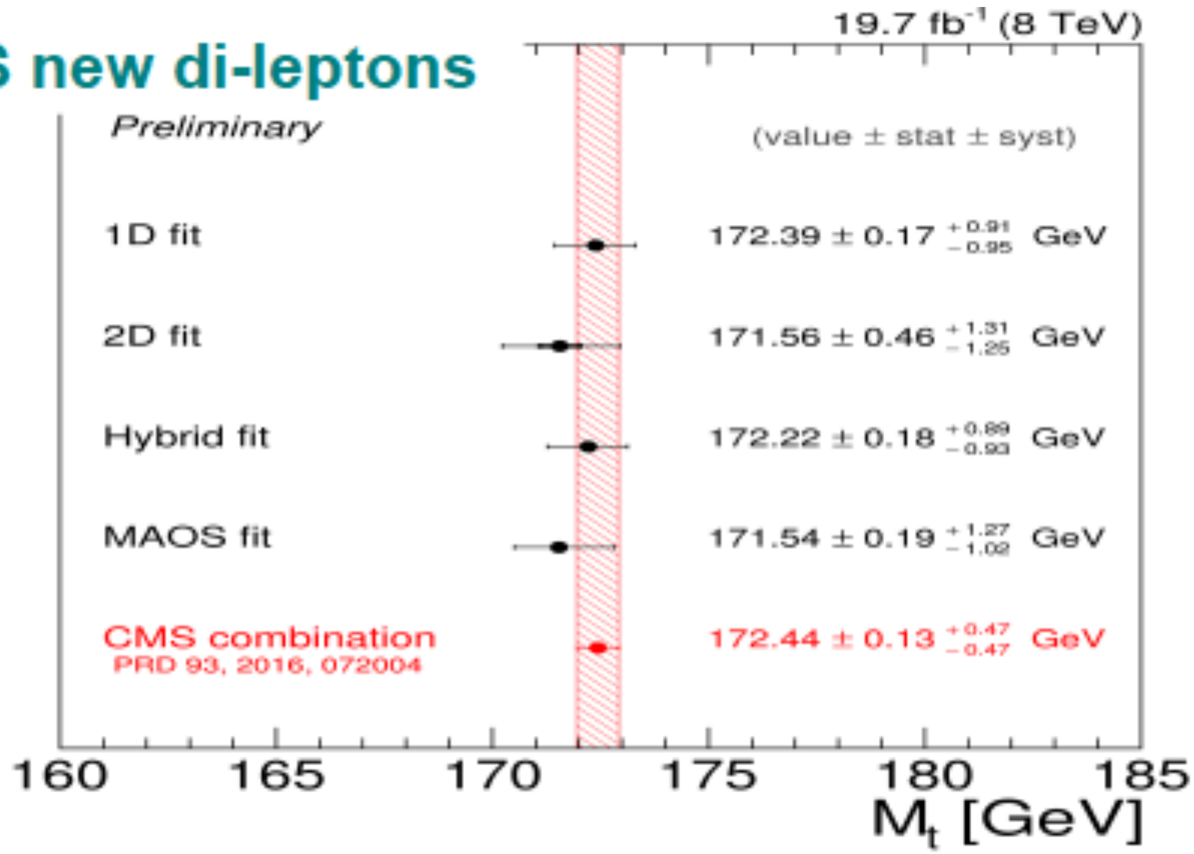


LHC and Tevatron results with nearly comparable precision of 3-4 permille (0.5 GeV)
LHC top mass systematically limited: MC modelling, (b)JES
Template/Matrix element methods → Monte Carlo top mass parameter

Top Quark Mass

Since LHC is a top quark factory, it's all about controlling systematics

CMS new di-leptons

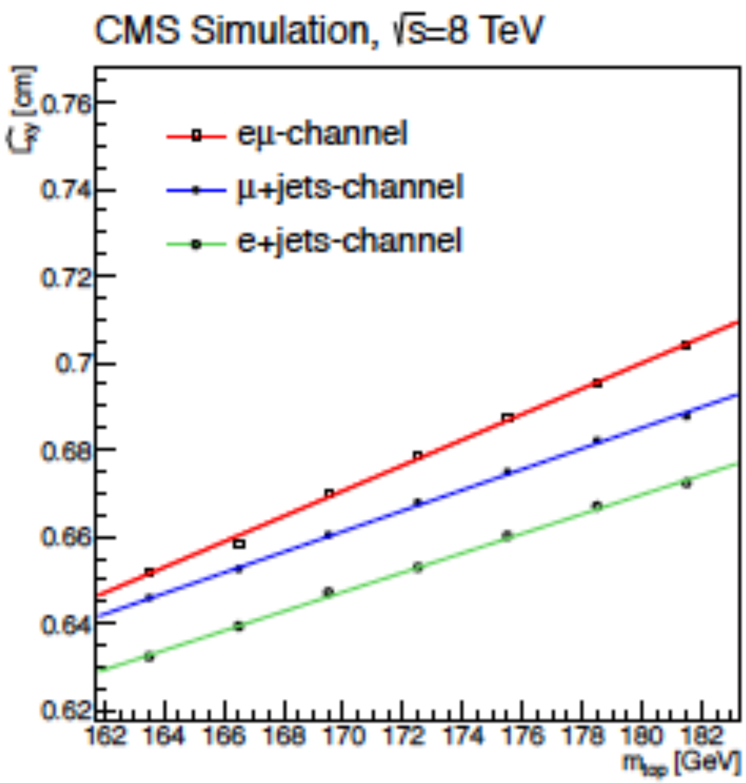


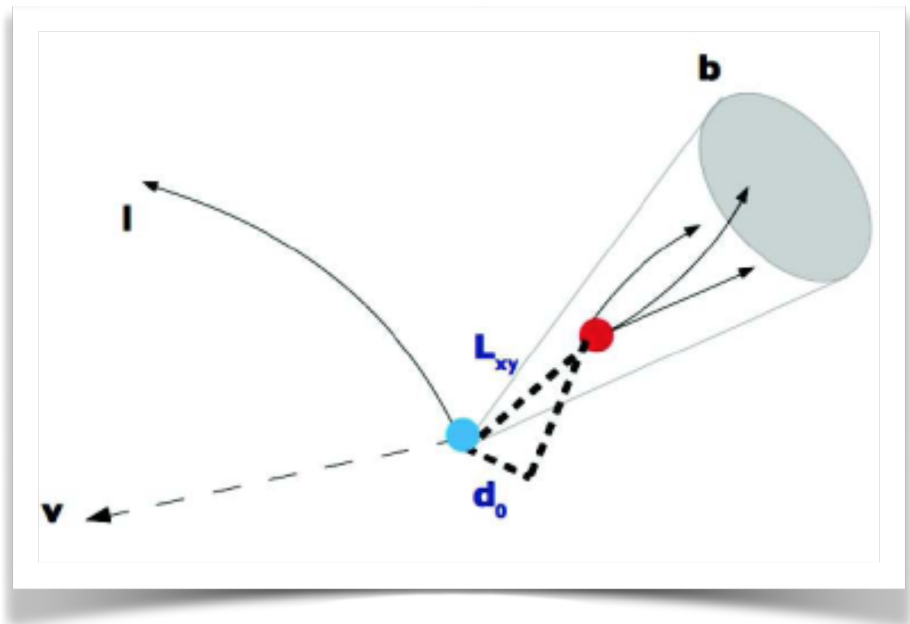
new approaches with complementary systematics can constrain combined systematics

CMS, $19.7 fb^{-1}$, dileptons, 1D, 2D, hybrid, $m_{bl}+m_{T2}$, ,MAOS $m_{bl\nu}+m_{T2}$,
M_{top} = 172.22 ± 0.18 +0.89−0.93
CMS-PAS-TOP-15-008

Top Quark Mass

New Ideas: b-lifetime

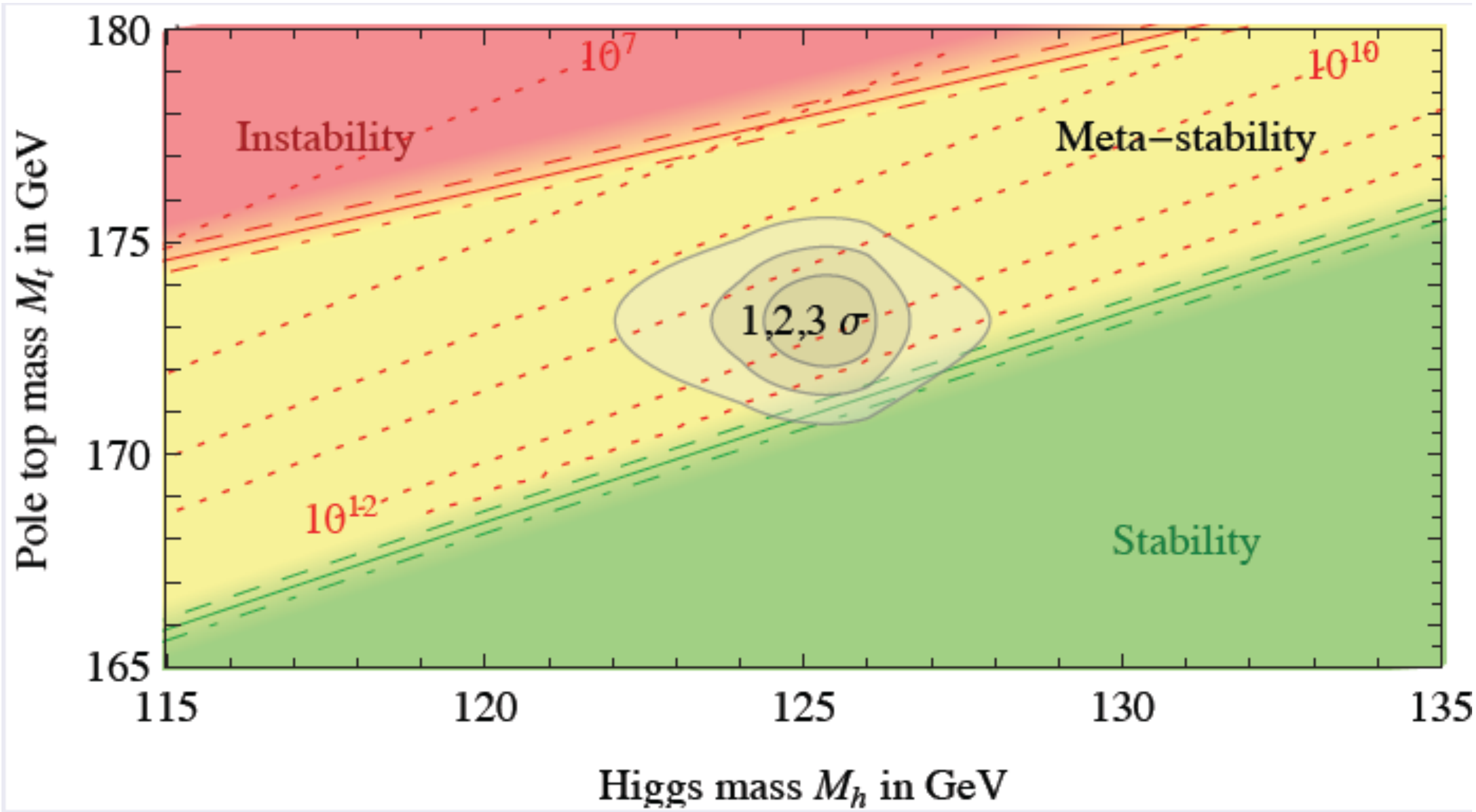




$$L_{xy} = \gamma_b \beta_B \tau_B \approx 0.4 \cdot \frac{m_t}{m_B} \beta_B \tau_B$$

First used in CDF, systematics complementary (no jets).
L_{xy} distribution gives M_{top}.

Vacuum Stability



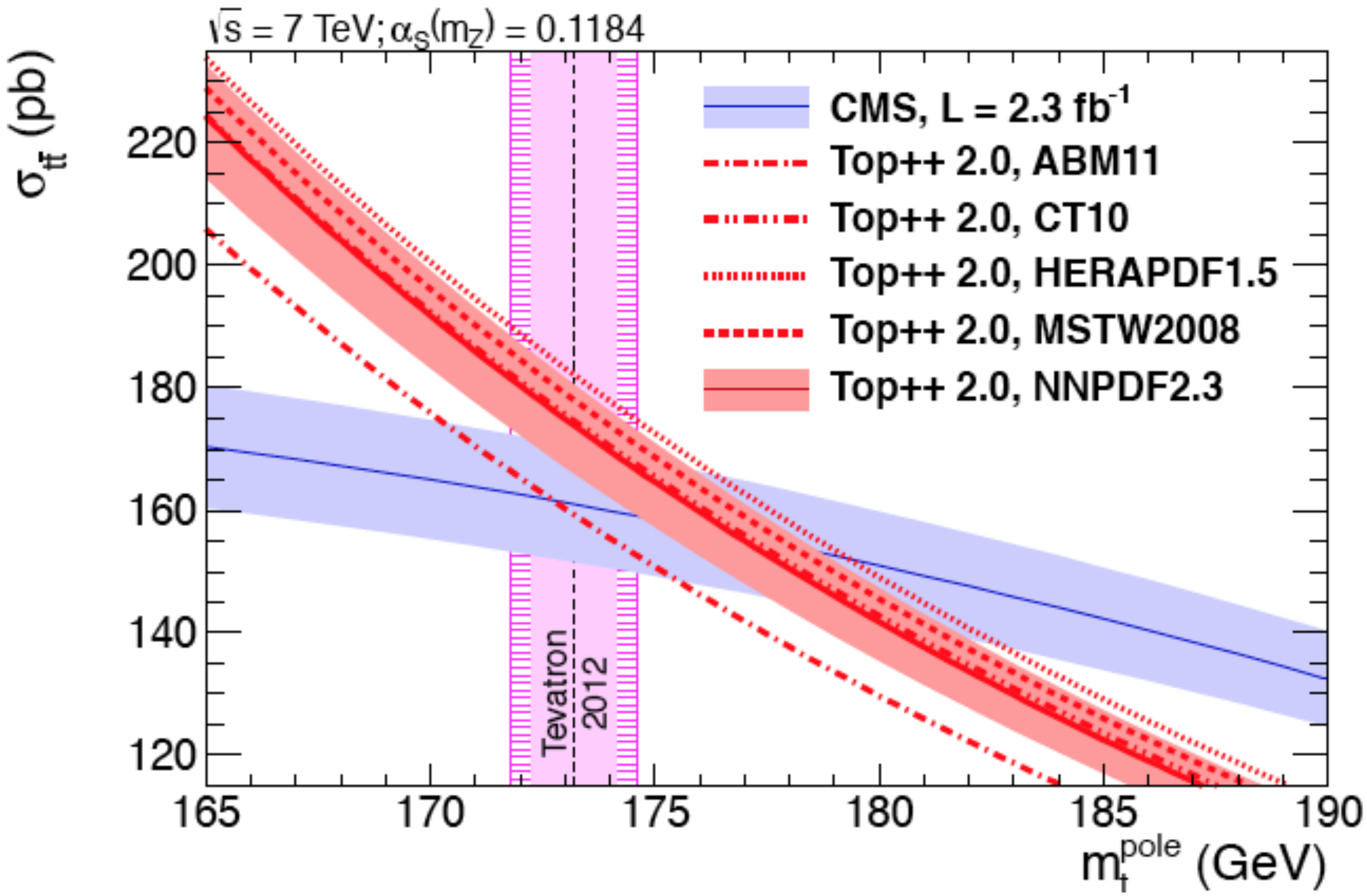
arXiv:1307.3536

150 MeV $\delta(M_H)$ ~ 100 MeV $\delta(M_t)$

Are we measuring the pole mass?

Top Quark Mass

Top mass from σ_{tt}



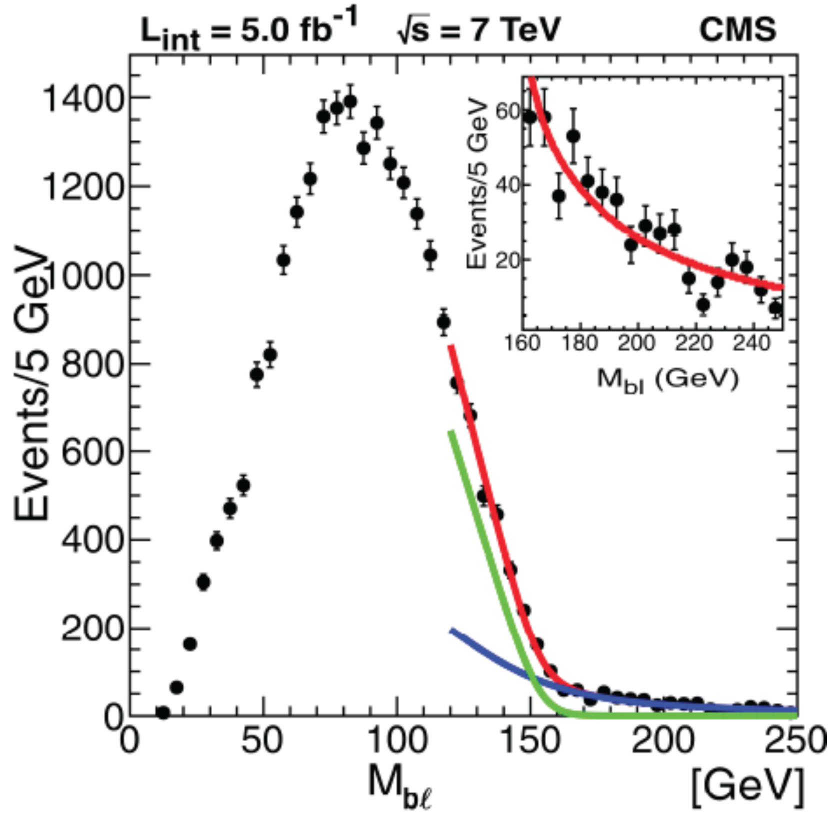
Compare precise σ_{tt} for different m_t to NNLO prediction ($\alpha_{s(PDG)}$).

Top Quark Mass

What M_t do we measure?

Normally, "MC" mass

(uncertain hadronic activity)

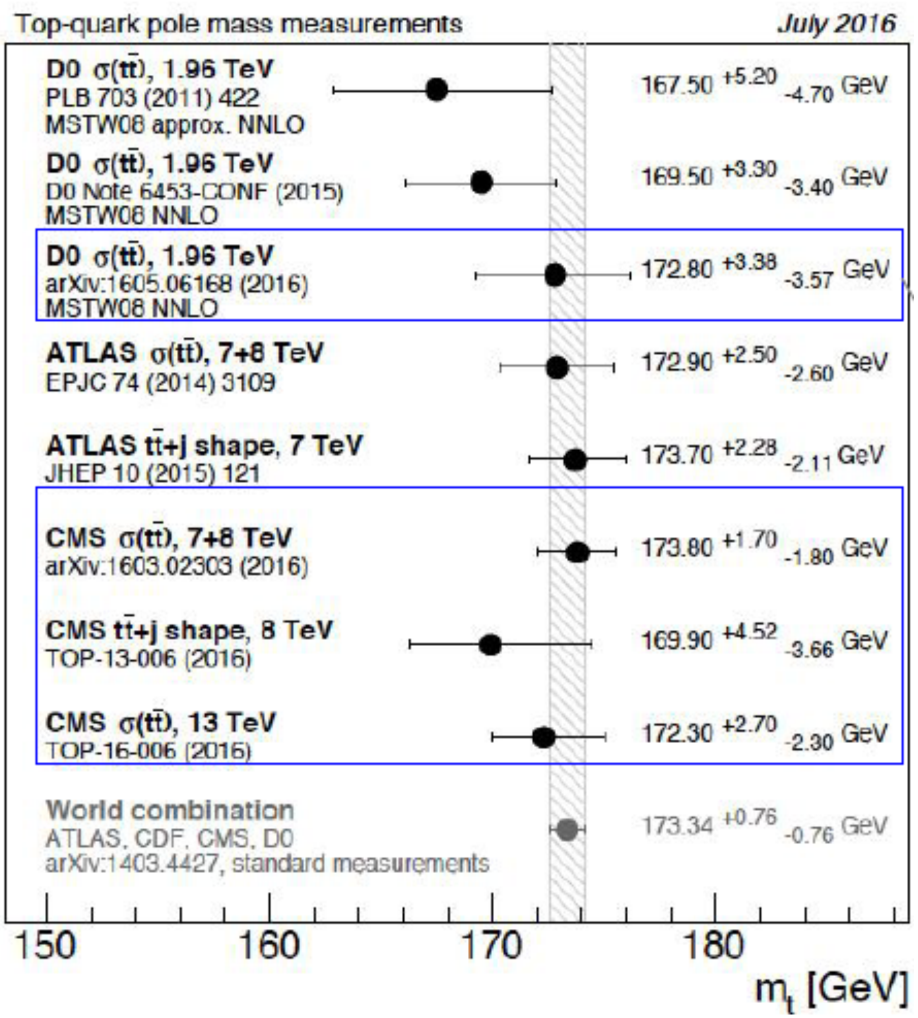


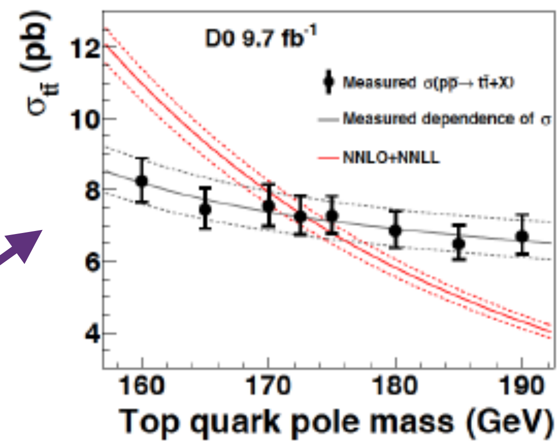
Idea: "Endpoints" of transverse distributions:

- Can fit to shapes independent of MC/theory
- Very sensitive to M_{top}
- CMS: fit to M_{T2}, M_{WT}, $M_{b\ell}$

Top Quark Mass

Pole mass vs Monte-Carlo mass measurements





Direct top mass measurements:

- Monte-Carlo mass m_t^{MC}
- precision 0.5 GeV

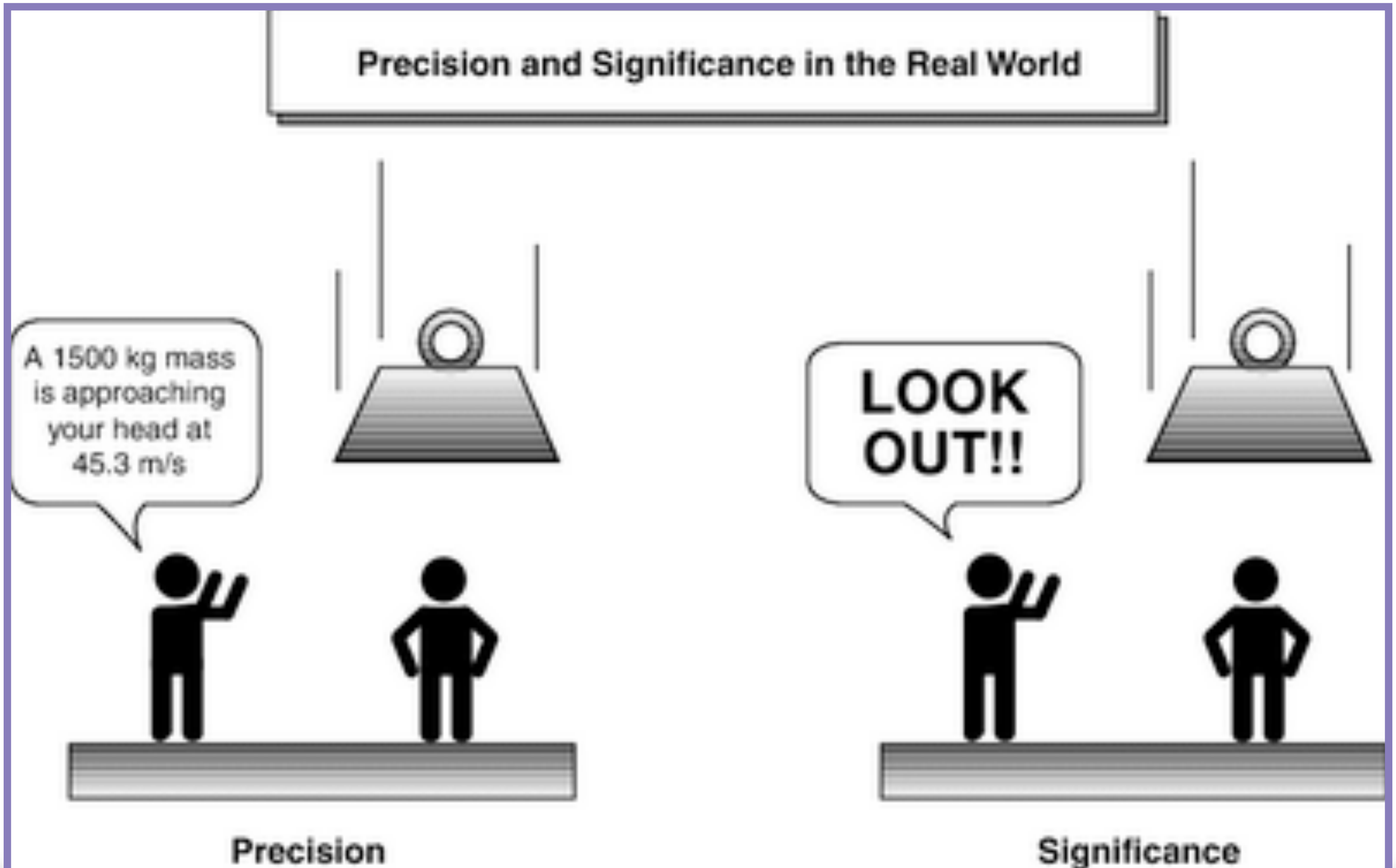
Expect m_t^{MC} - m_t^{pole} ~ 1 GeV

→ Calibrate m_t^{MC}

→ Indirect measurements of m_t^{pole}: compatible with measured m_t^{MC} within precision of ±2 GeV

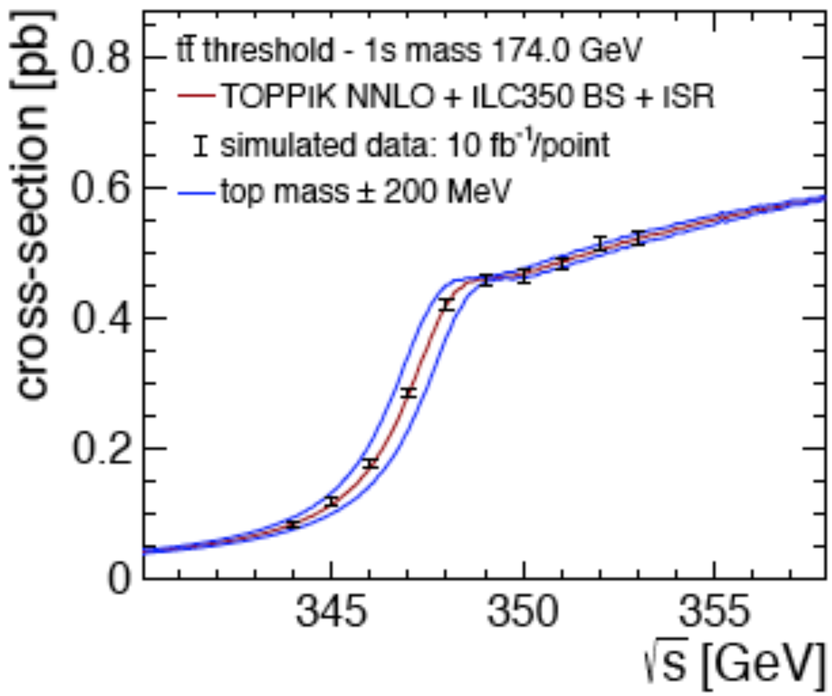
Top Quark Mass

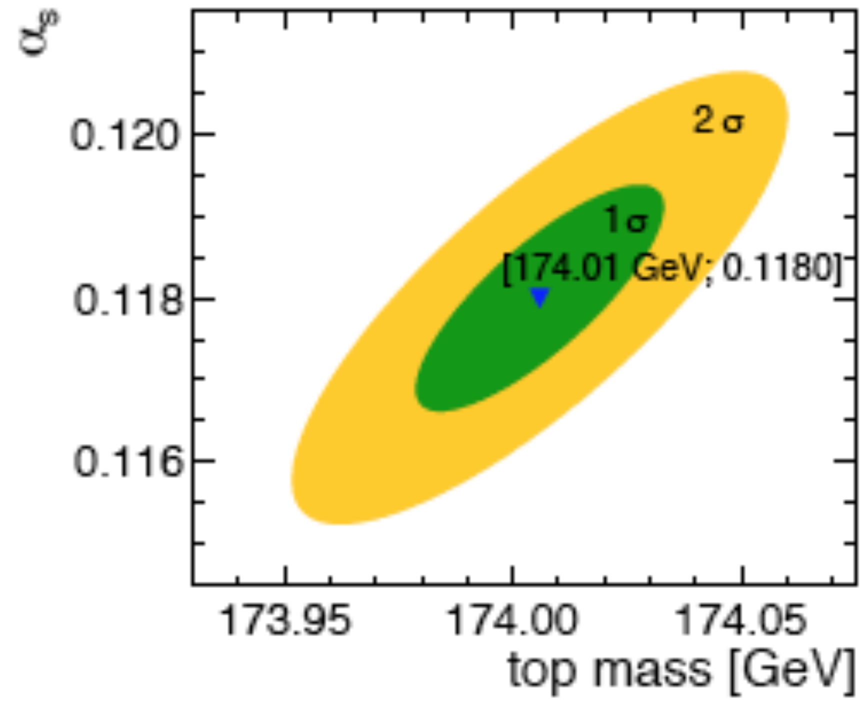
What's next? Precision! (HL-LHC, ILC)



Top Quark Mass

Linear collider threshold scans





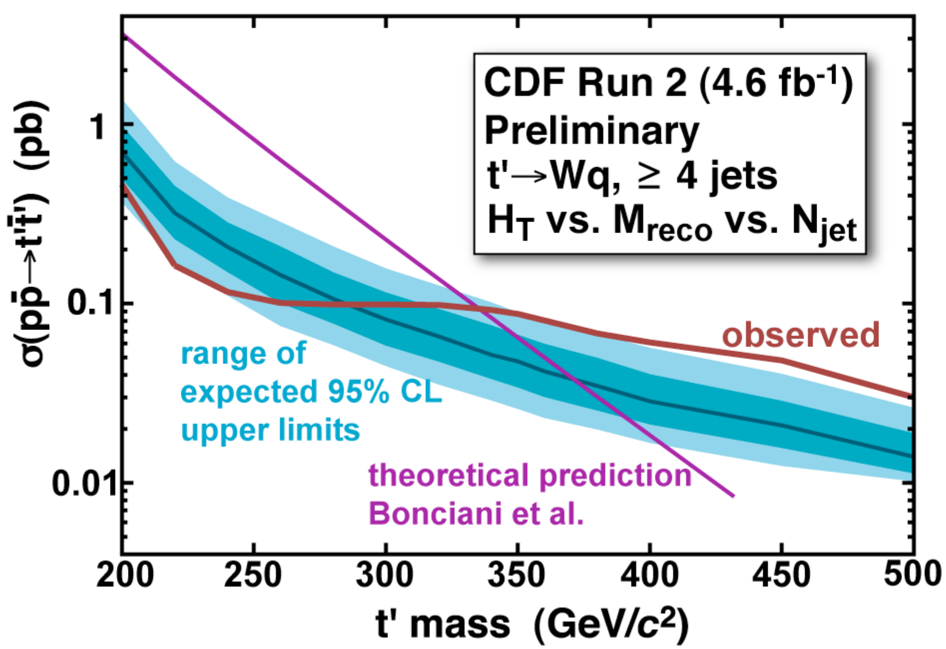
Analytical theory predictions.
Expected precision < 100 MeV.

Snowmass top ILC white paper

New or Anomalous Top Production

- Looking for anomalies in top properties or signs of new physics in the sample:
  - Top production asymmetry A_{fb}
  - $X \rightarrow tt$, most recently in all-hadronic!
  - Search for massive top
  - Charged Higgs, stop
  - ...

Another time…



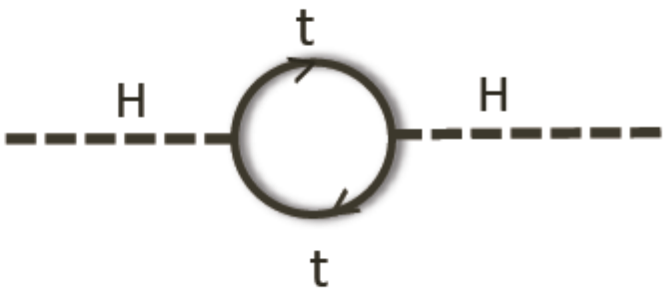
BOOSTED TOP QUARKS

and searches for new physics
at 13 TeV

The Problem:

$$m_H^2 = m_{bare}^2 + \Delta m_H^2$$

$$\Delta m_H^2 \sim 3/(8\pi^2)\, y_t^2\, \Lambda^2$$



If $\Lambda \sim$ Plank scale:

$$m_H^2 \sim \Delta m_H^2 \times 10^{-32}$$

Λ: scale of new physics

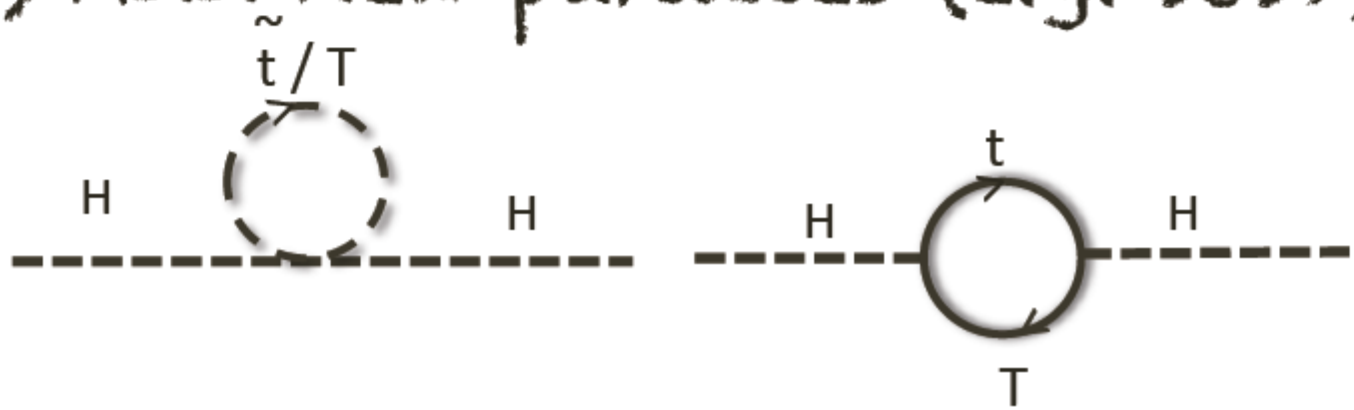
Possible Solutions:

A) SM only low energy effective theory

i.e. $\Lambda \ll$ Plank

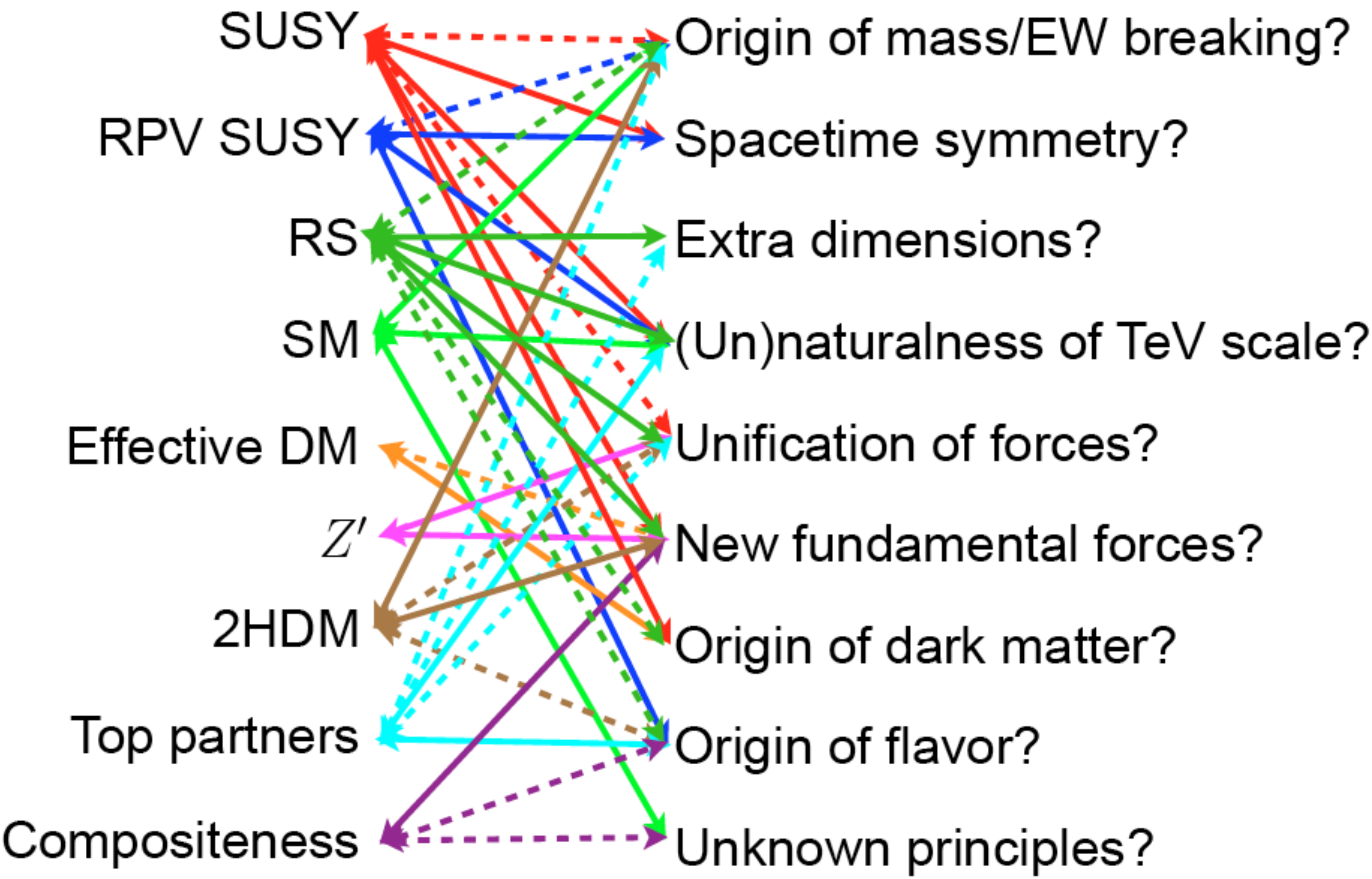
If $\Lambda \sim$ TeV: $\Delta m_H^2 \sim O(m_H^2)$

B) Add new particles (e.g. SUSY, top partners)

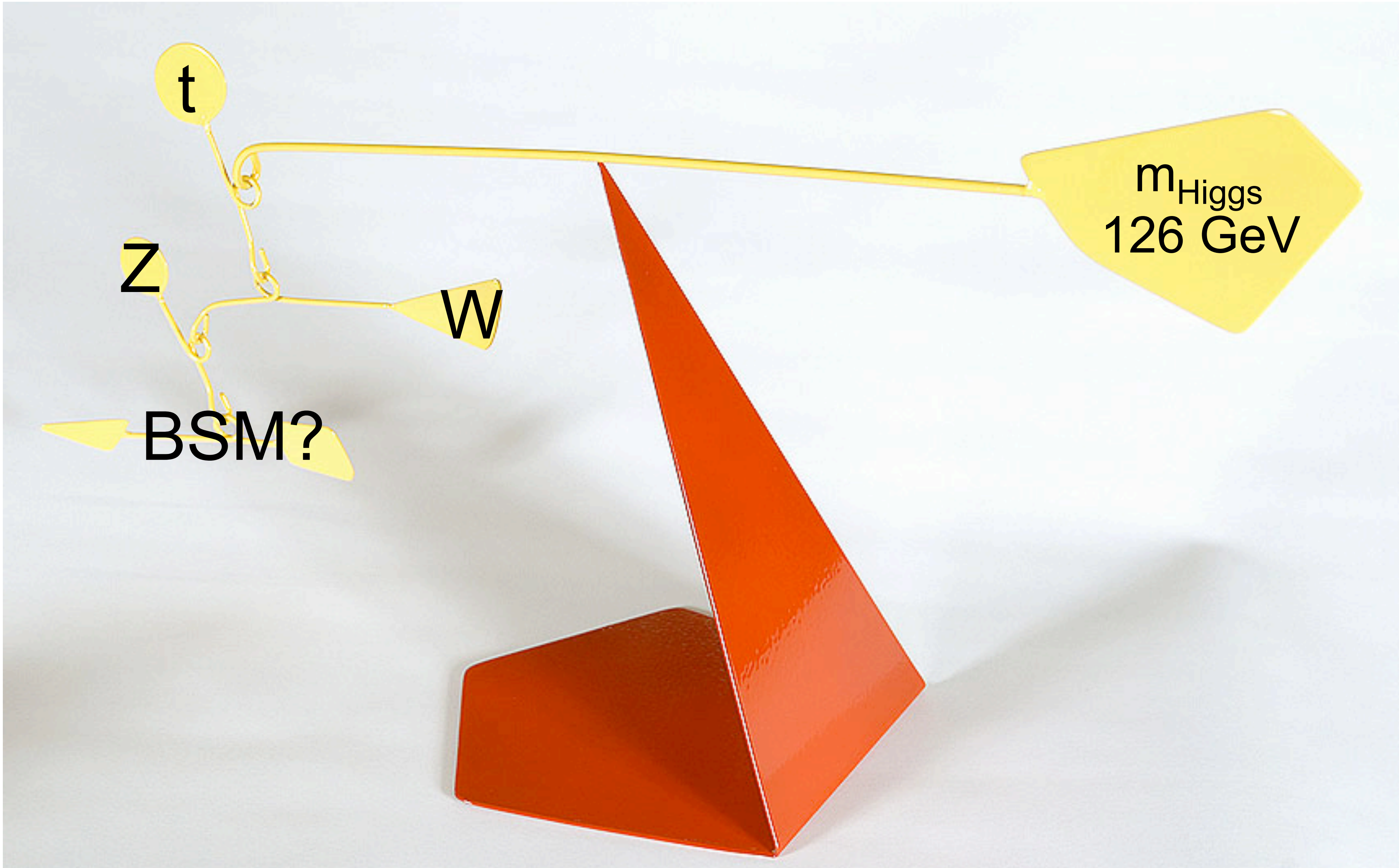


loops cancel

17 SM parameters, still many questions...



Little Hierarchy Problem: Naturalness



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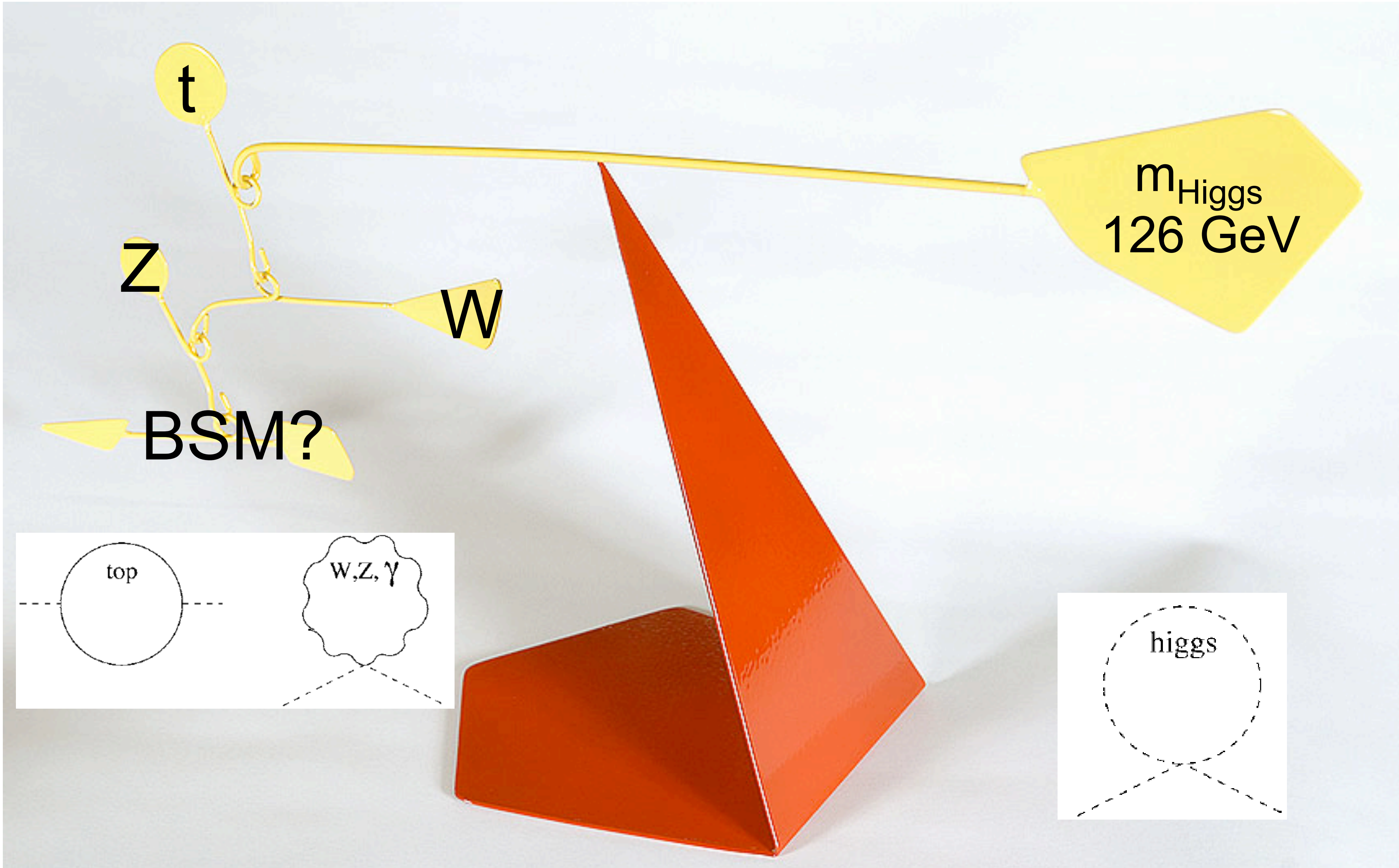

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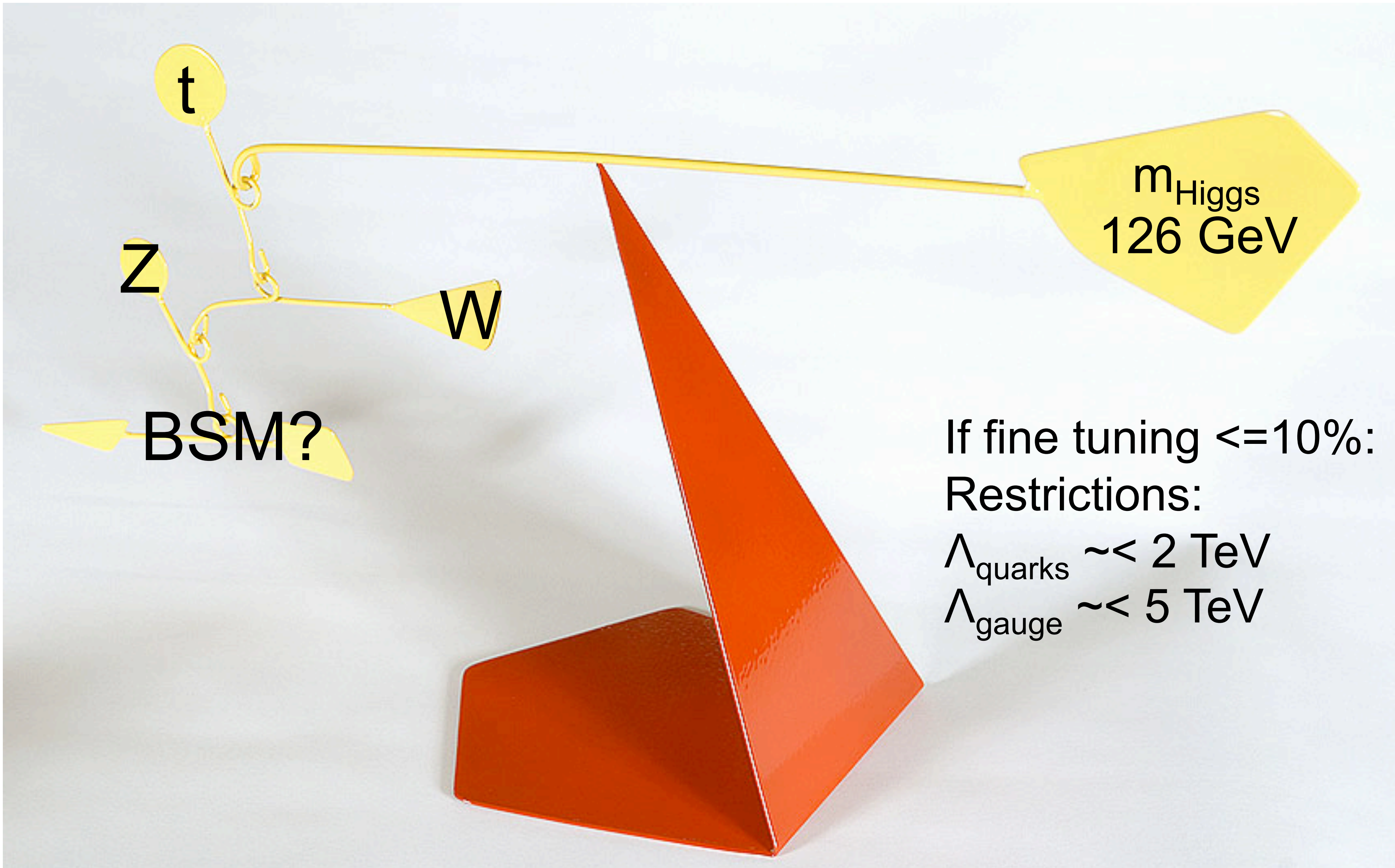

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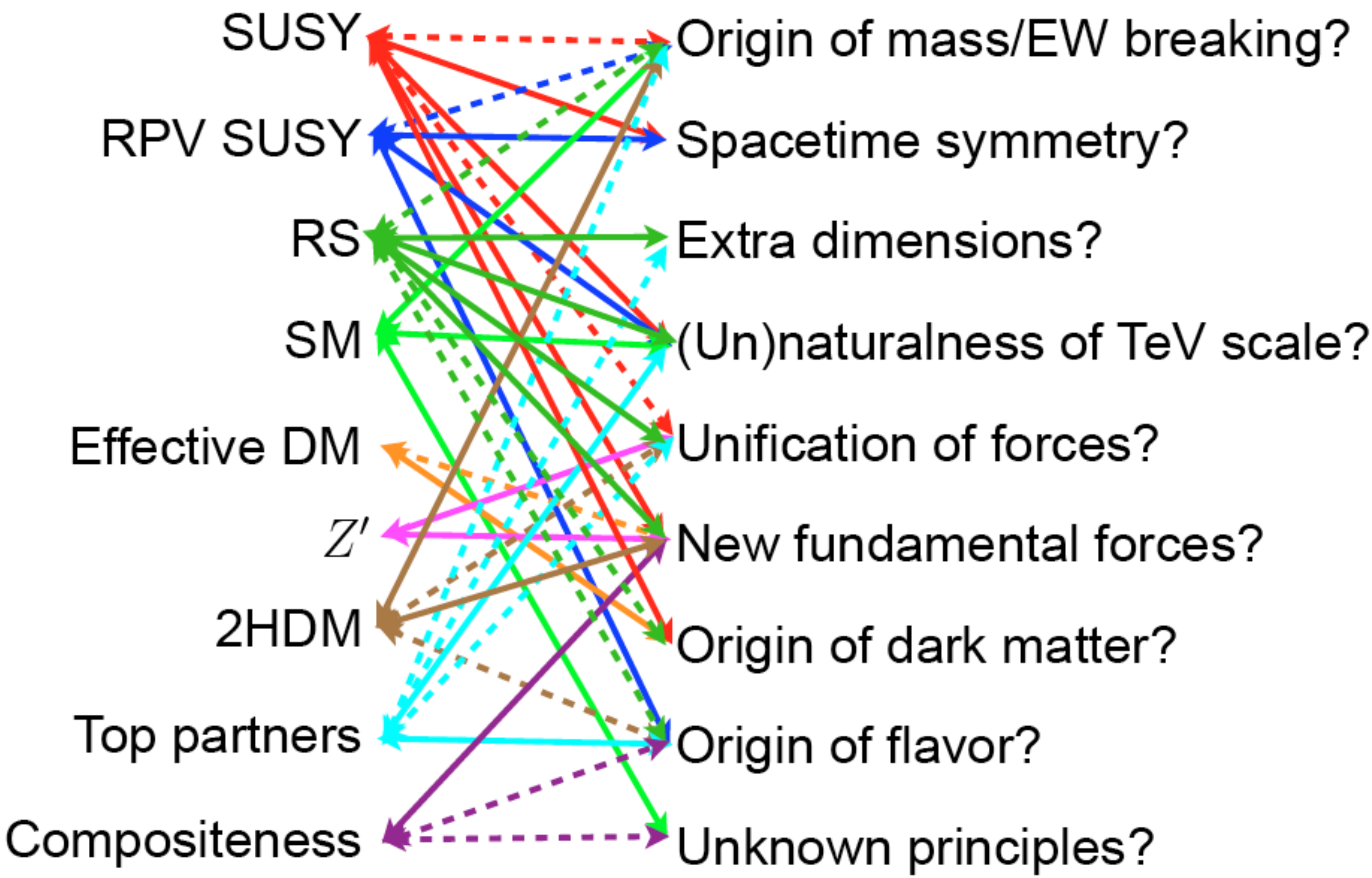

M. Luty, Snowmass BNL energy frontier workshop 2013

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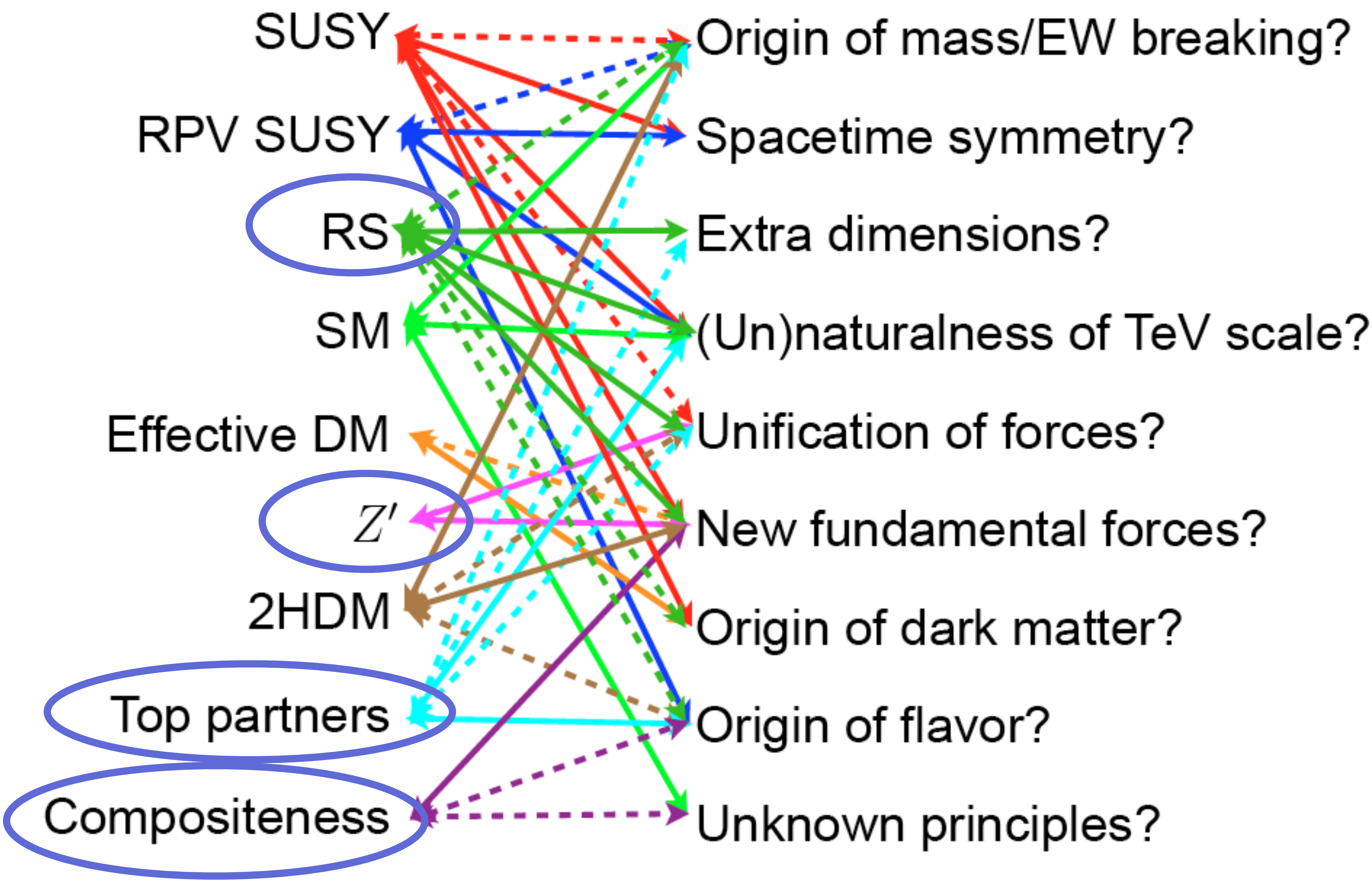
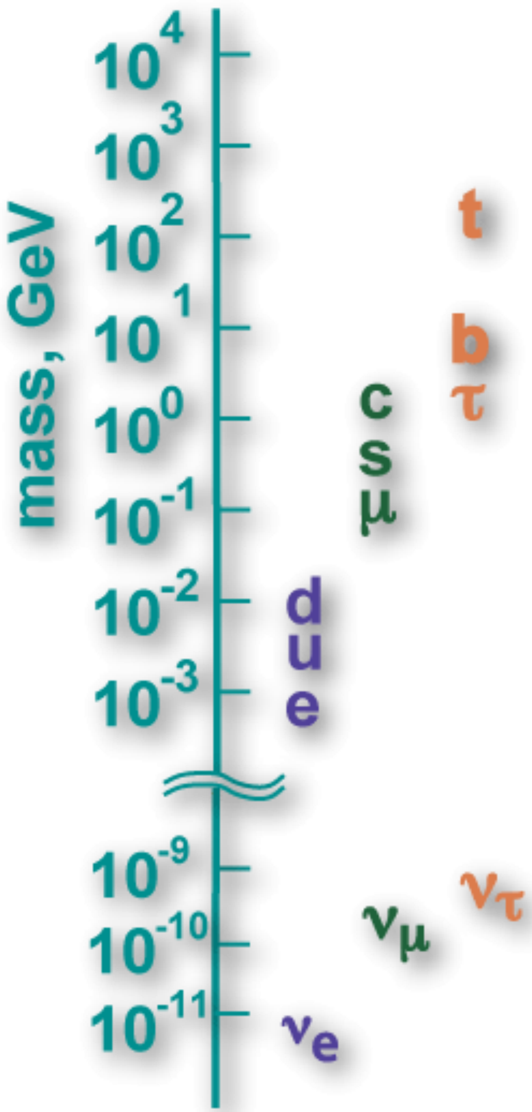
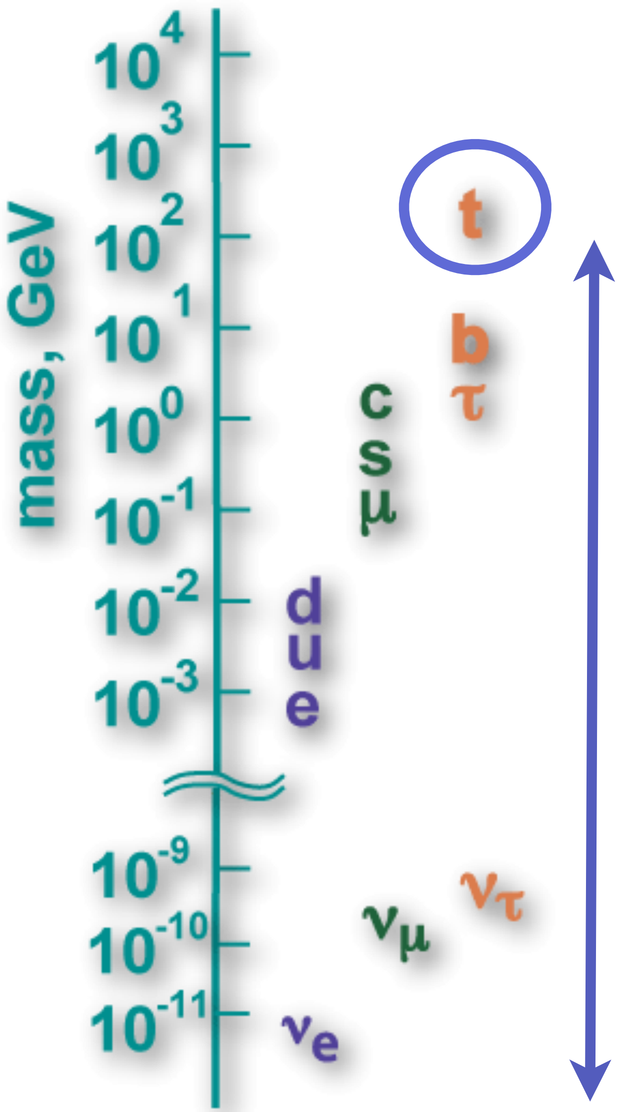


M. Luty, Snowmass BNL energy frontier workshop 2013

Searches with Top

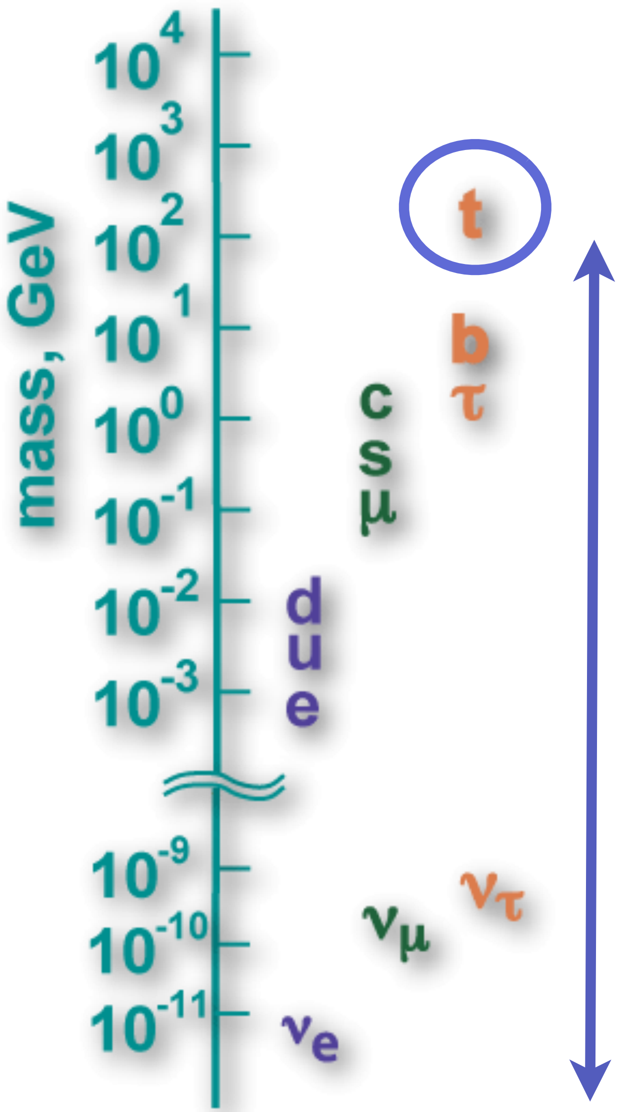


Searches with Top



~5 orders of magnitude!

Searches with Top



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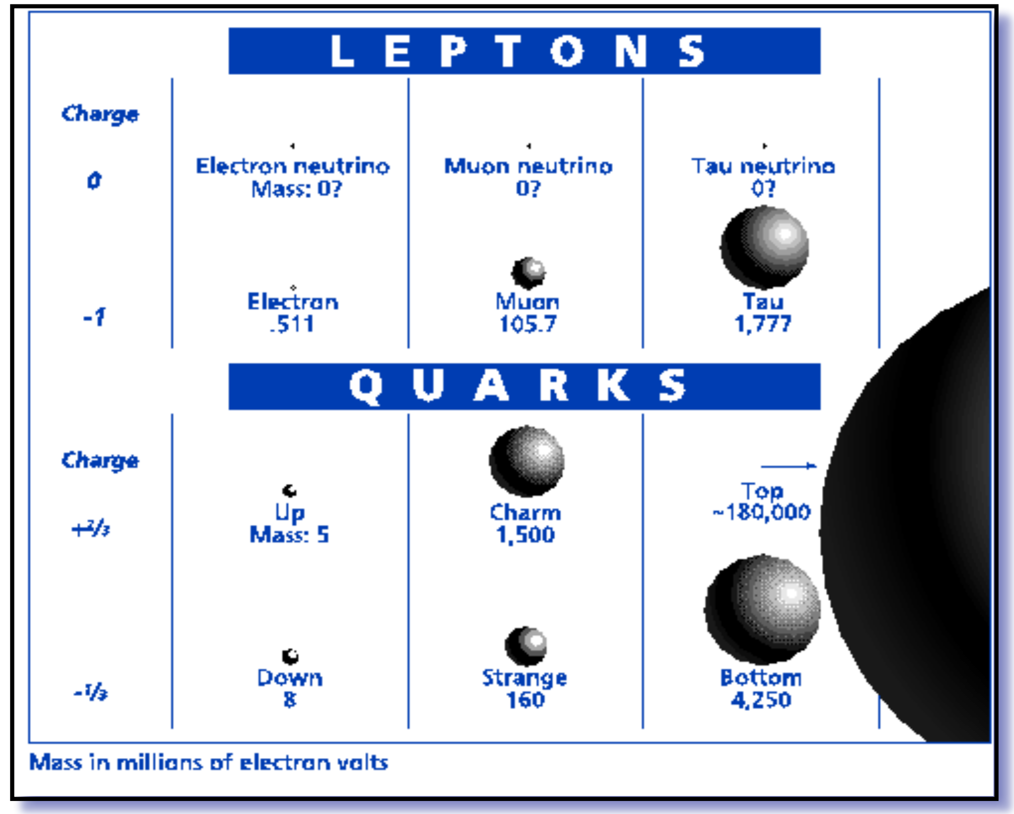
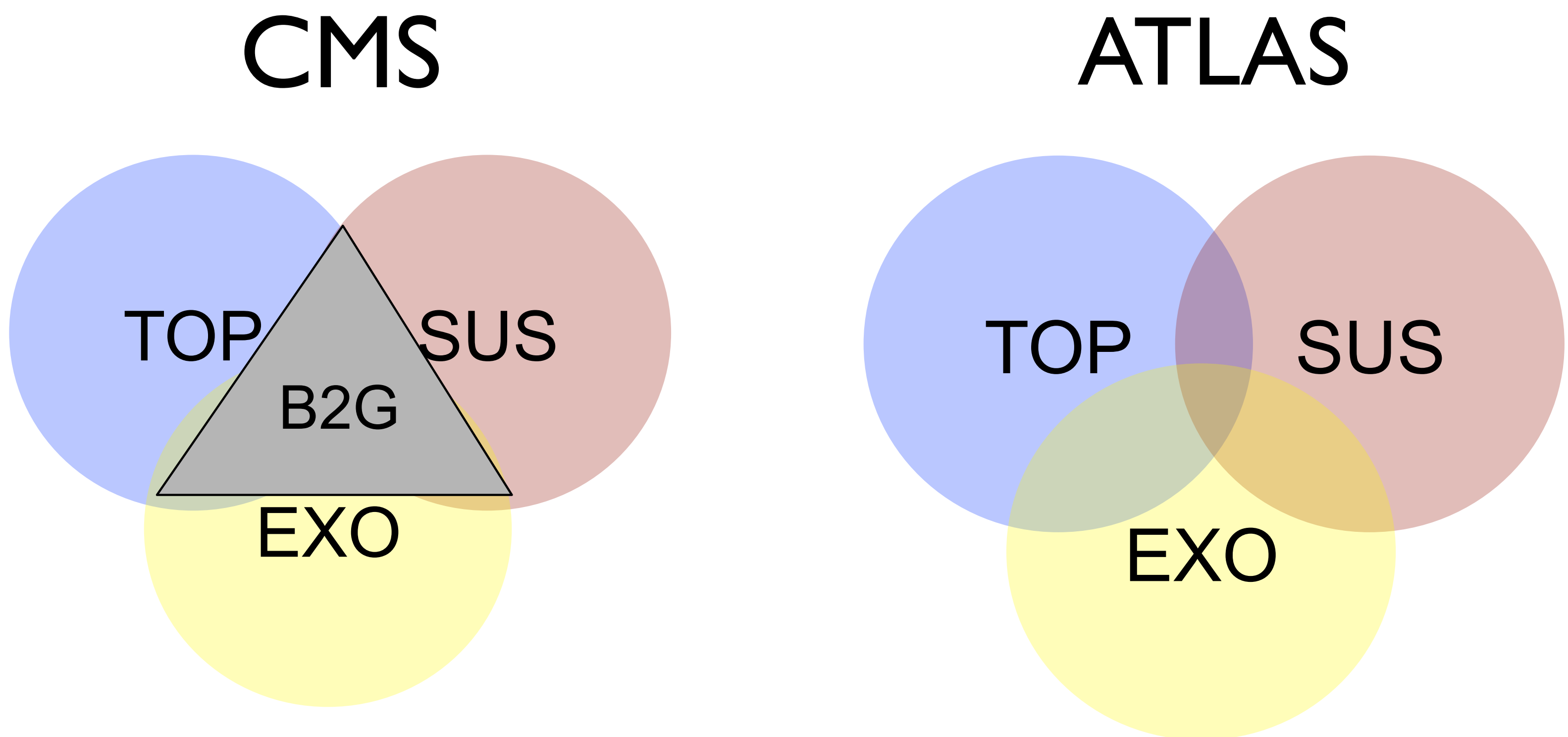


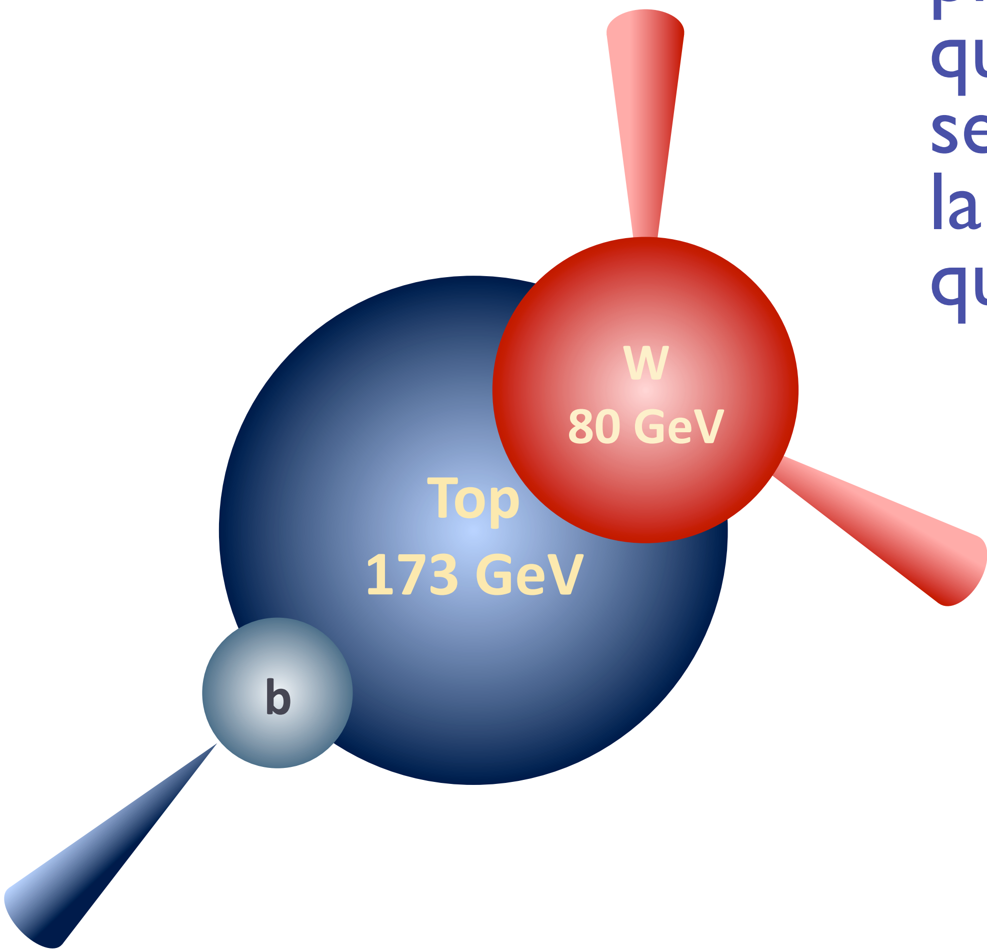
- Top quark is only fermion with a mass of order the EWK scale.
- Large mass suggests it may couple to physics beyond the SM.

New Physics in Top: Popular!



- Top BSM searches span many groups and categories.
- [B2G = Beyond 2nd Generation (Physics Analysis Group)]

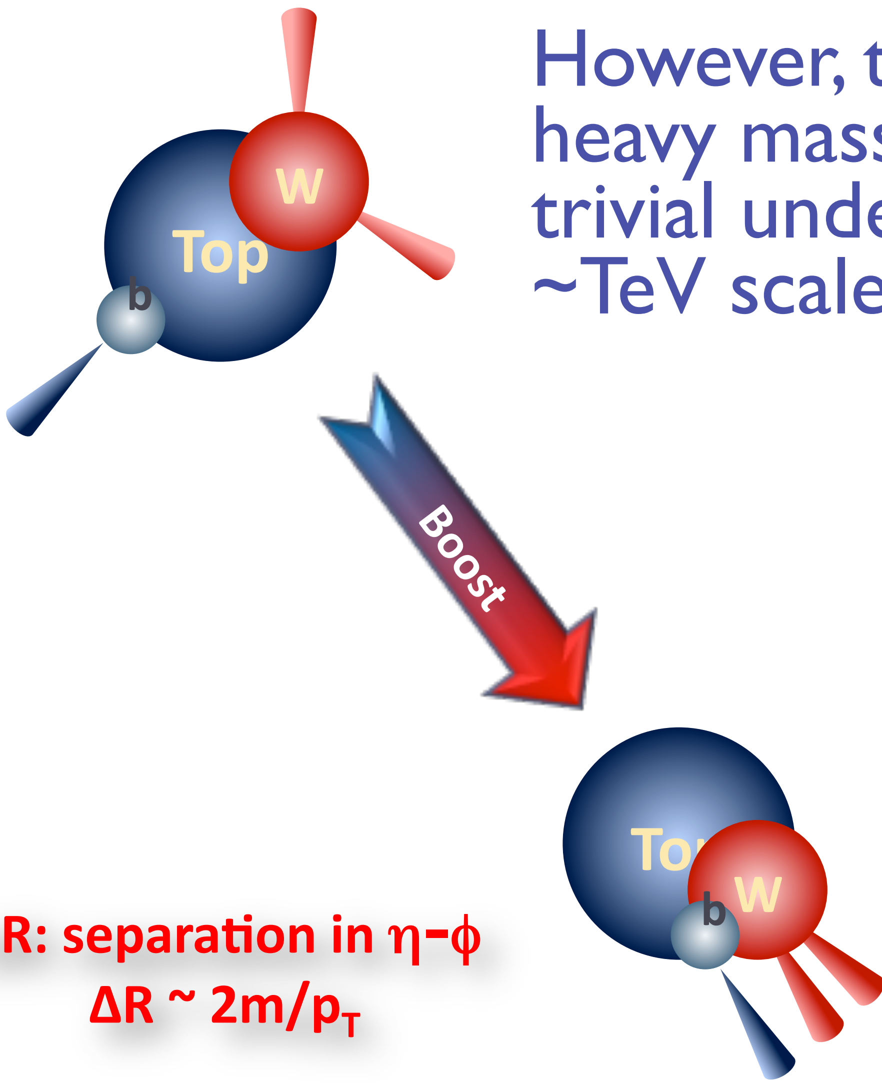
Top Quark Reconstruction



Traditionally, decay products from the top quark are clearly separated due to the large mass of the top quark and W boson...

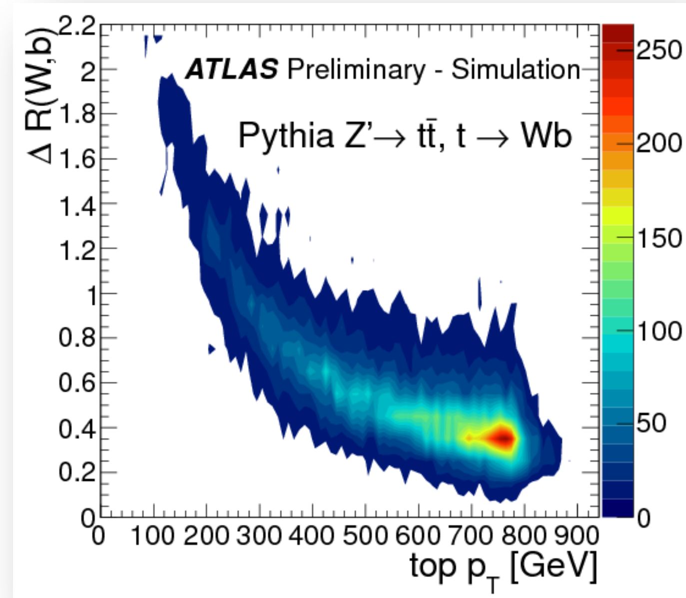
Challenge of Boosted Tops

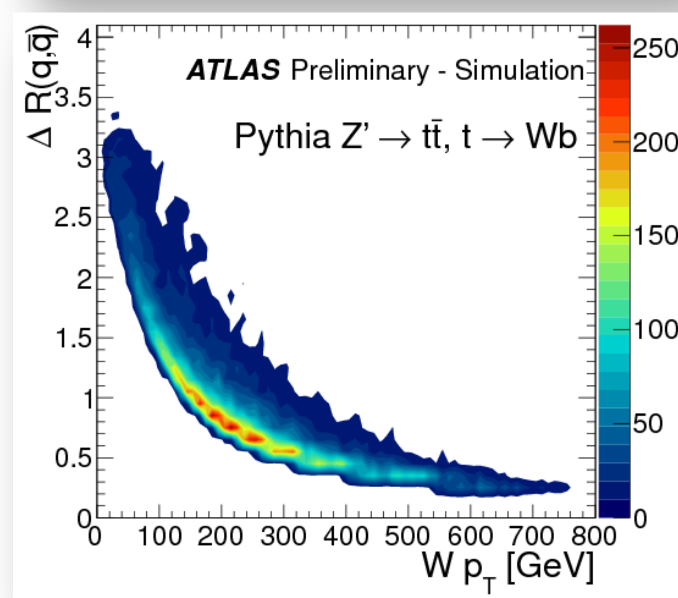
However, these heavy masses are trivial under ~TeV scale boost



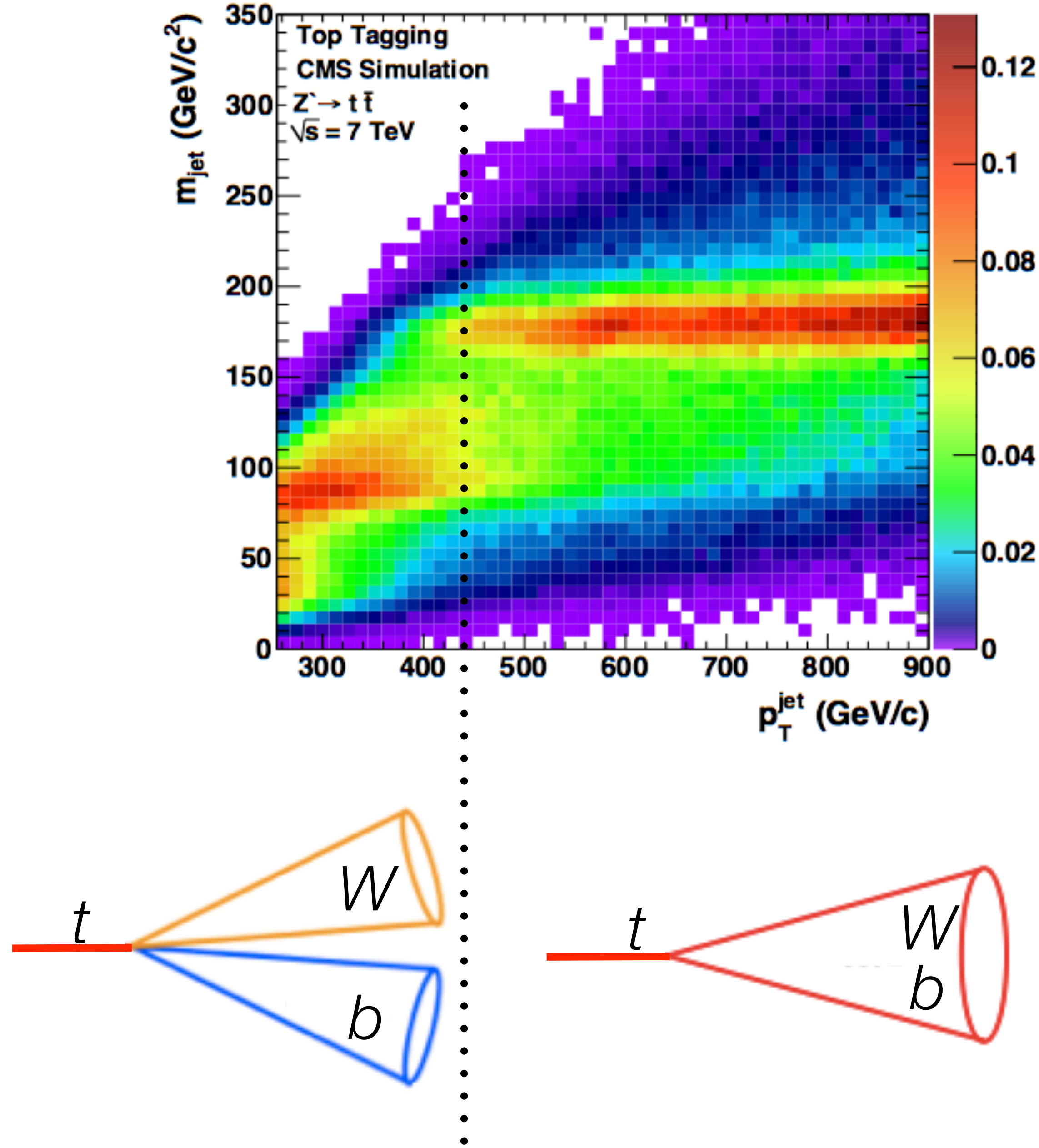
ΔR: separation in η-ϕ

$\Delta R \sim 2m/p_T$





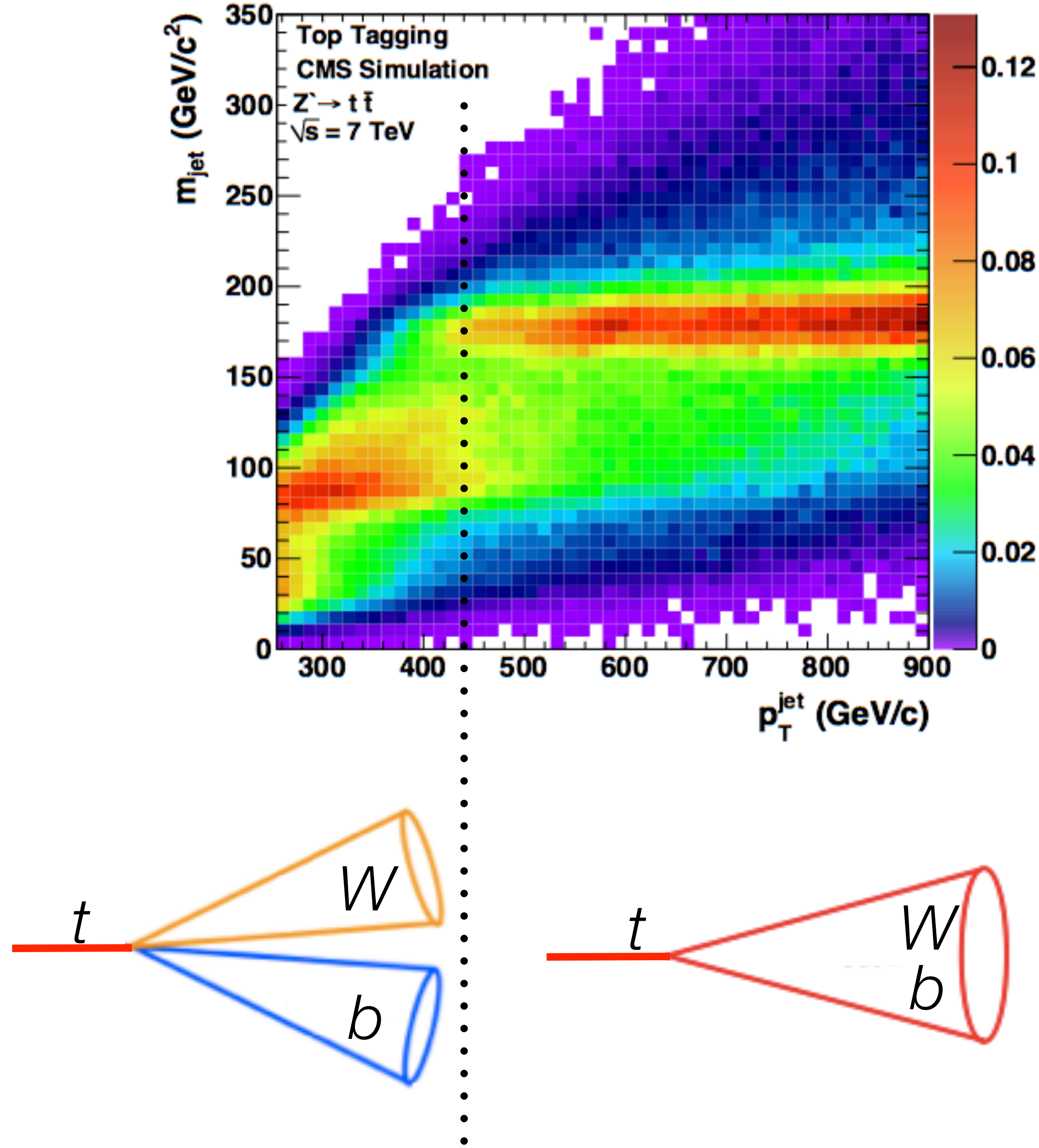
Kinematic Regimes



CMS-PAS-JME-10-013

Kinematic Regimes

- Searches at different mass ranges need different strategies (eg: X→ttbar)



CMS-PAS-JME-10-013

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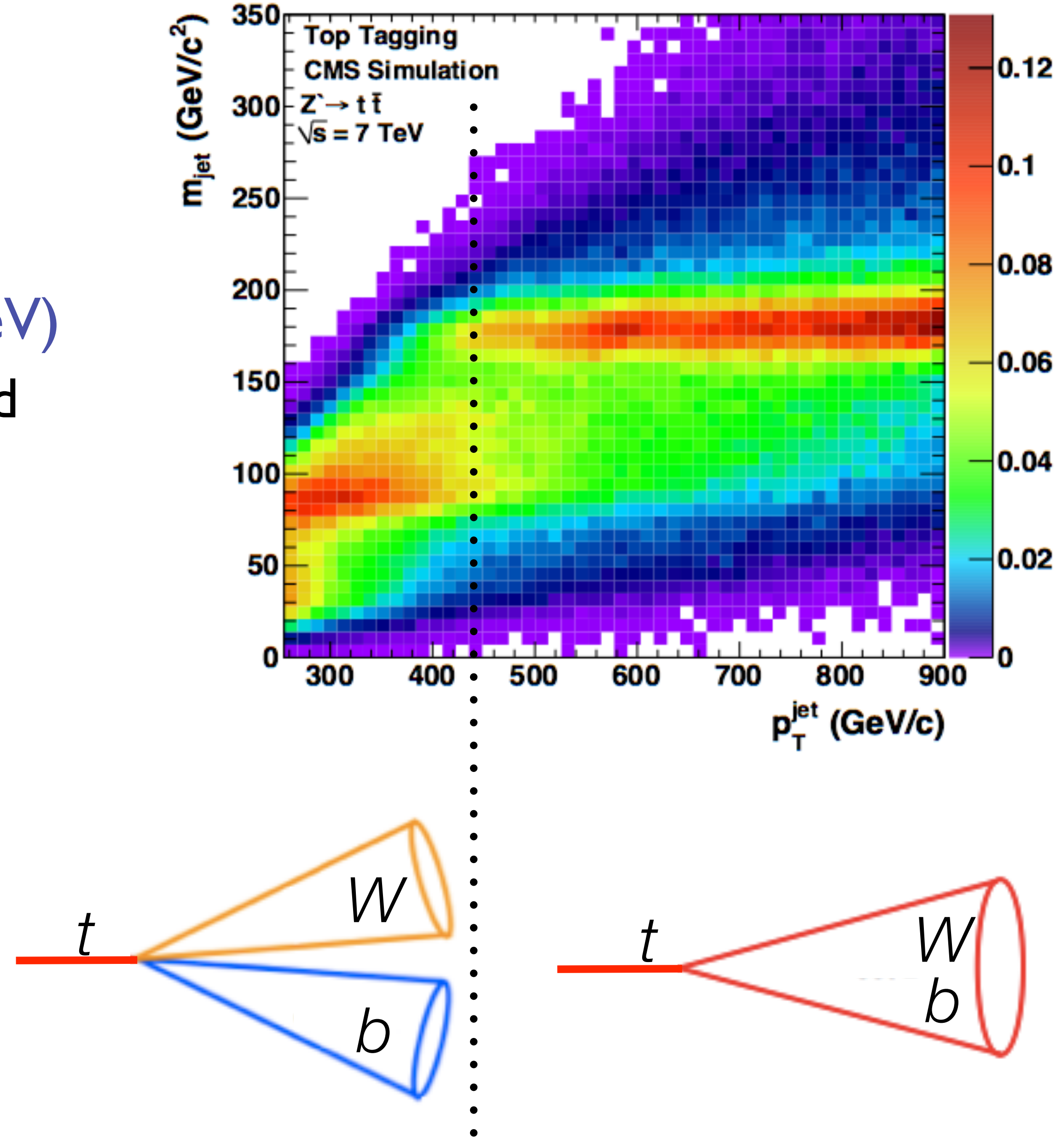
  - Decay products well-separated



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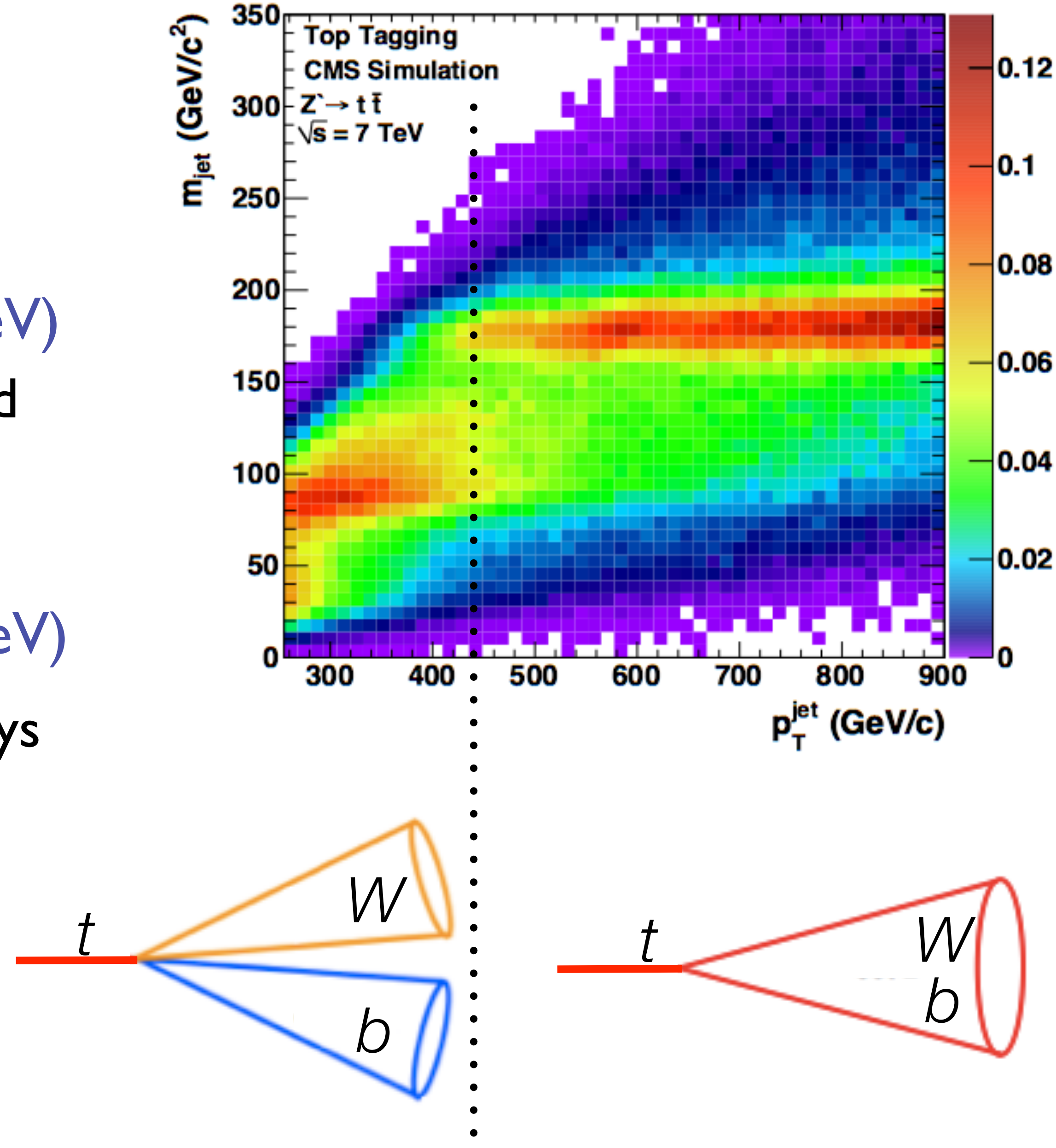
- High-mass searches (>~2TeV)
  - Boosted tops, collimated decays



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Kinematic Regimes

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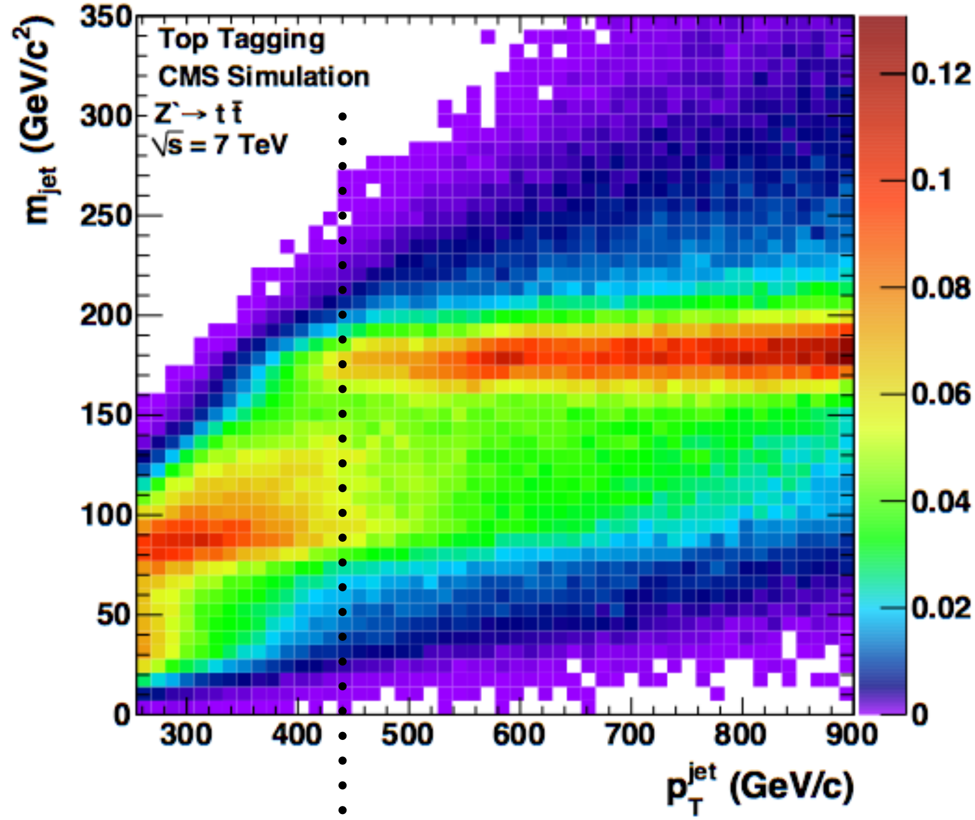
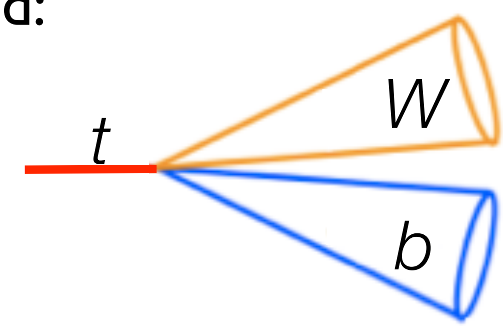
- Low-mass searches (<~1TeV)
  - Decay products well-separated
  - Standard top reco used

- High-mass searches (>~2TeV)
  - Boosted tops, collimated decays
  - Special reco algorithms needed:
  - Jet substructure!

- Intermediate mass range
  - Partially merged, mix of techniques



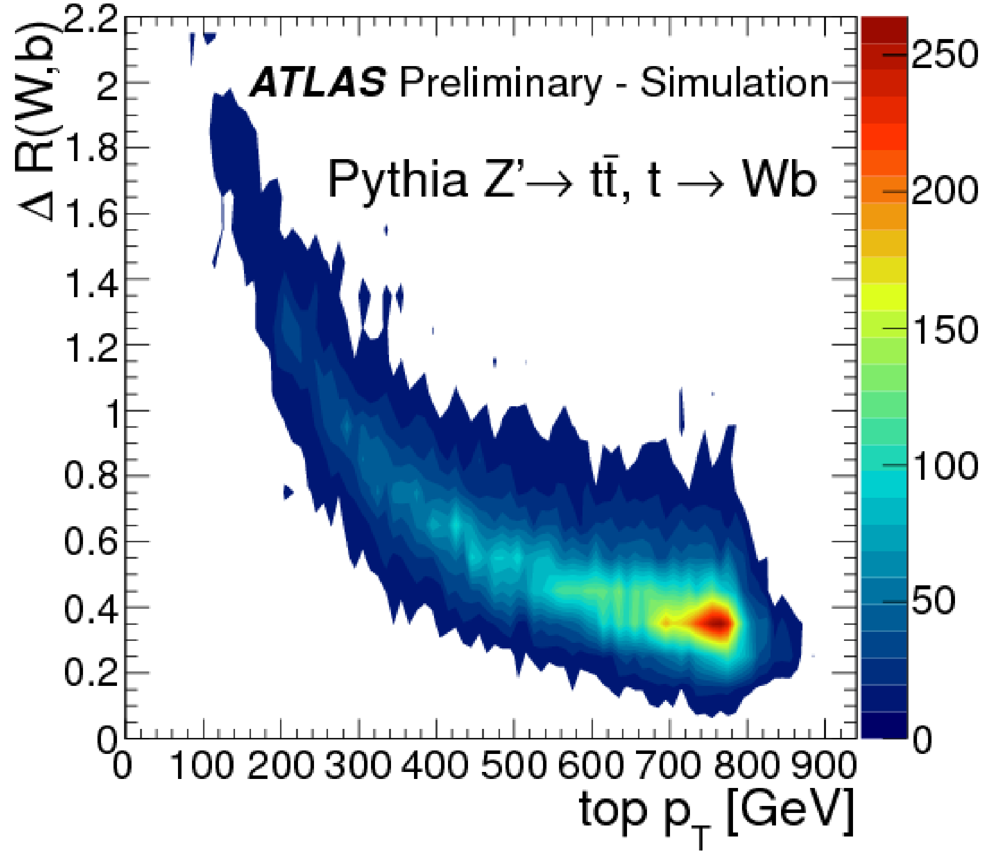


CMS-PAS-JME-10-013

"Fat" Jets

- Choose large jet size for reconstruction to catch all decay products.
- ATLAS & CMS have studied R=0.8,1.0,1.2,1.5.
- Use specific algorithms to identify the collimated decay products within this large-R jet. (C-A jets)

ATLAS-CONF-2012-065



CMS-PAS-JME-15-002

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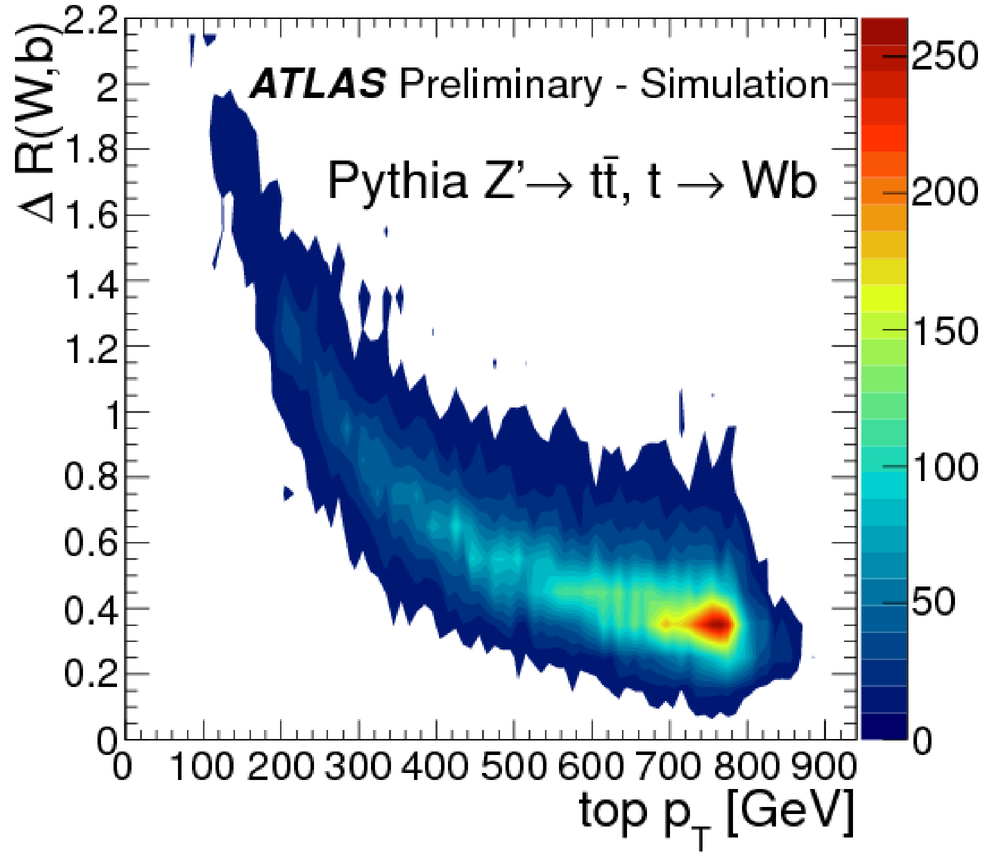
ATLAS-CONF-2012-065



A large amount of work is ongoing in ATLAS and CMS on "tagging" boosted tops, W/Z ("V-tags"), boosted Higgs. Stay tuned....

CMS-PAS-JME-15-002

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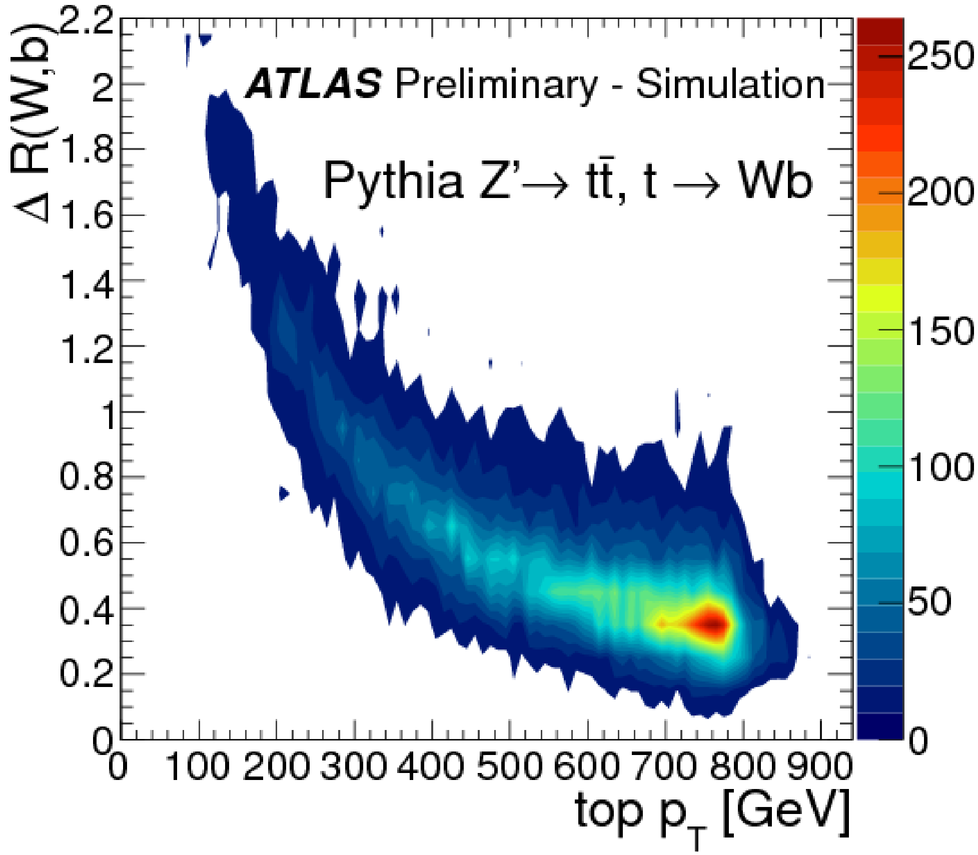

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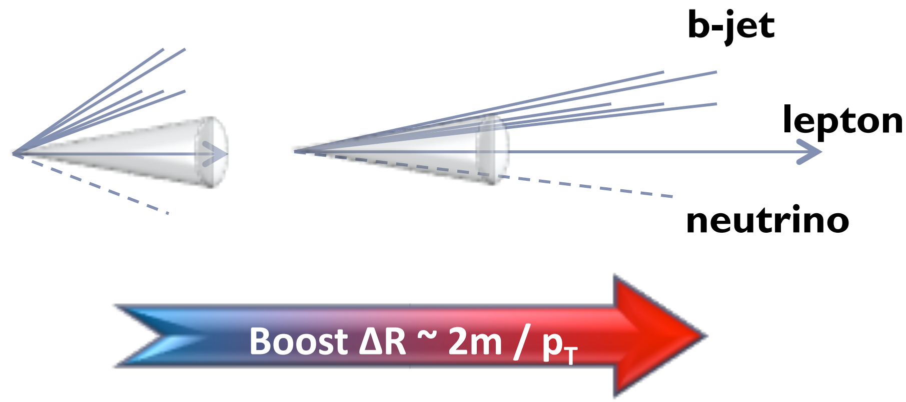
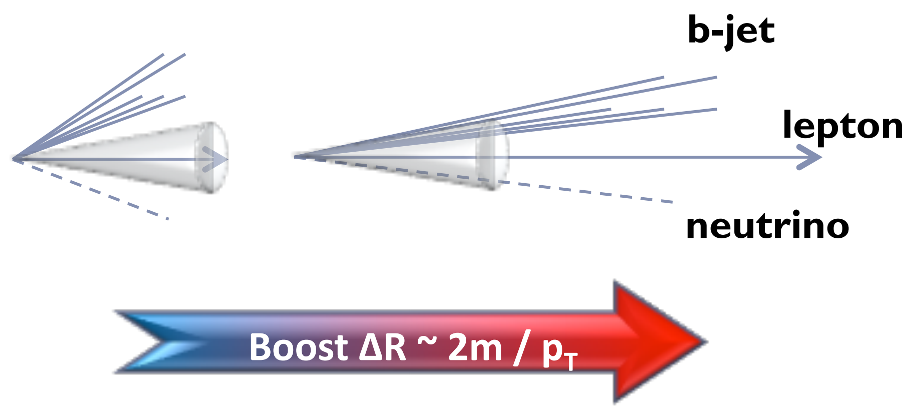
Boosted top references: ATLAS-CONF-2012-065, ATLAS-CONF-2013-084, CMS-PAS-JME-10-013, CMS-PAS-JME-13-007, CMS-PAS-JME-15-002

Lepton Isolation



Lepton Isolation

- lepton and b-jet from boosted top highly collimated: lose isolation efficiency.



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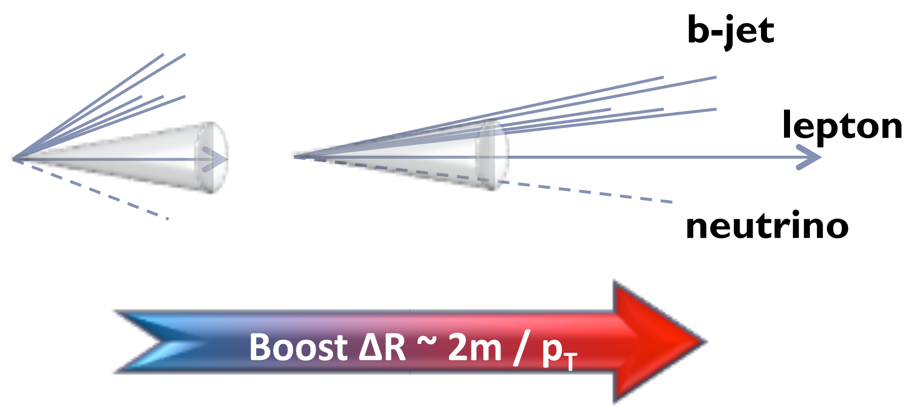

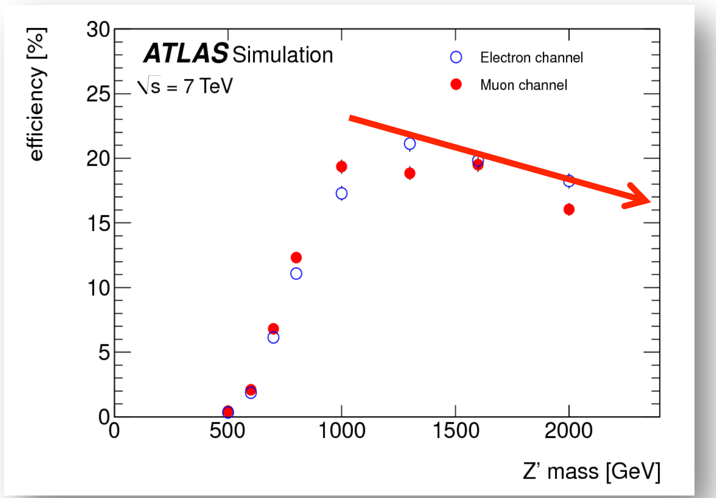

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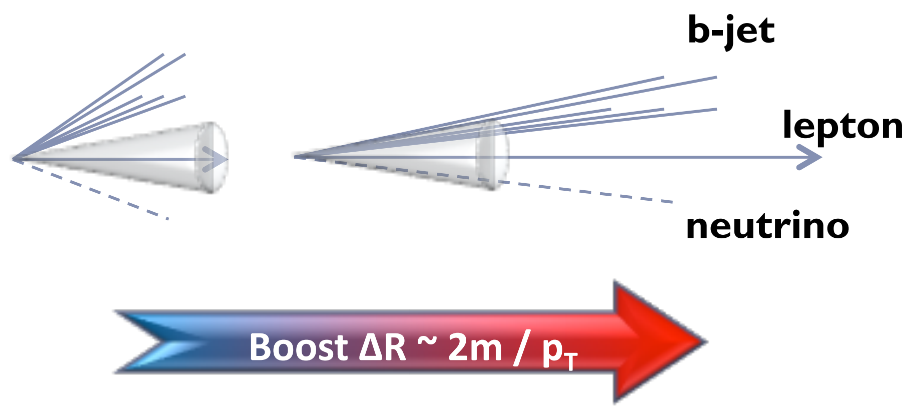
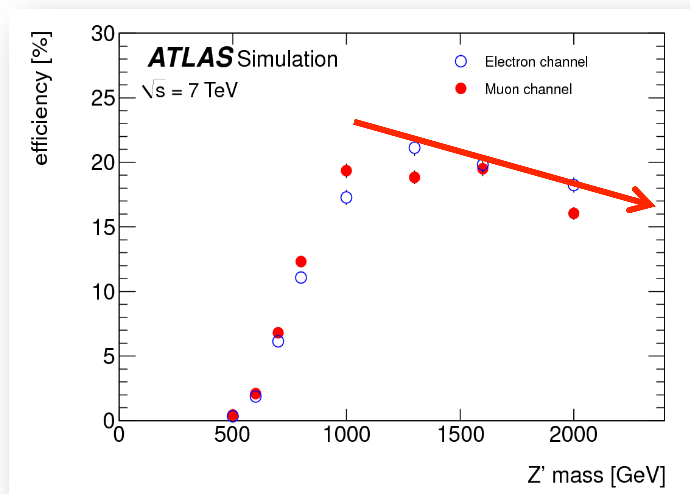
- But even boosted, leptons from tops have larger separation than those from light quark jets.





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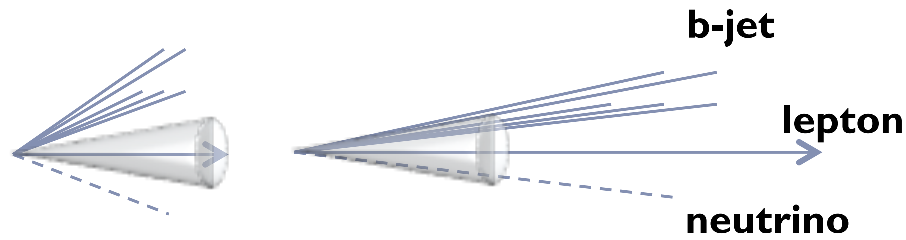
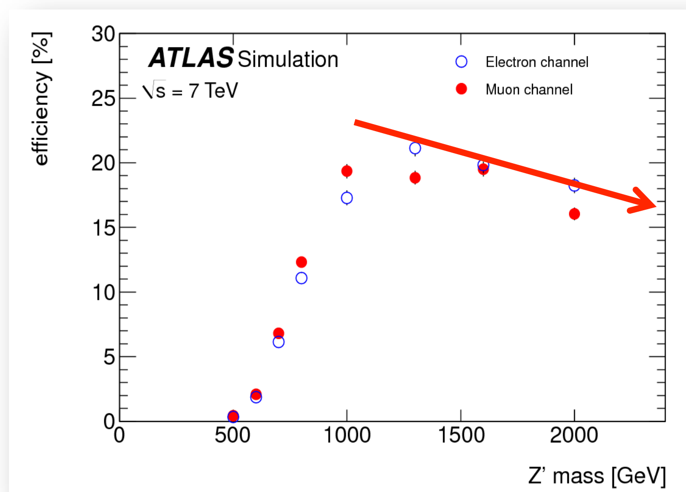
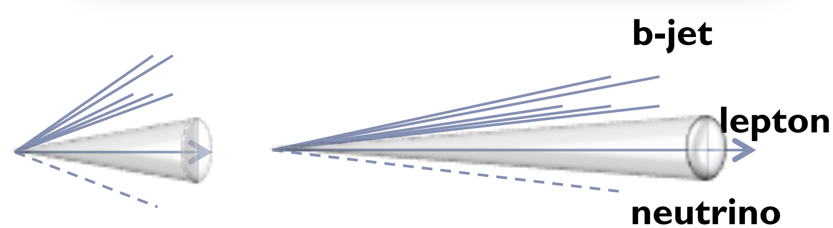


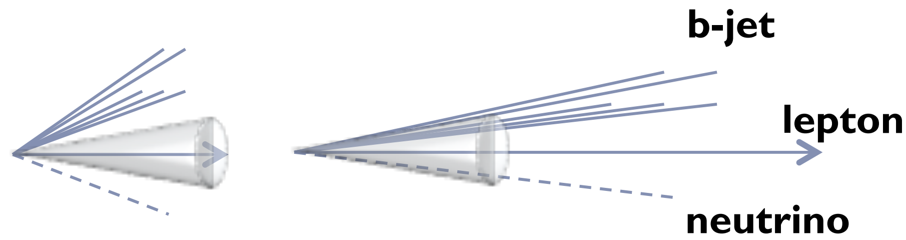


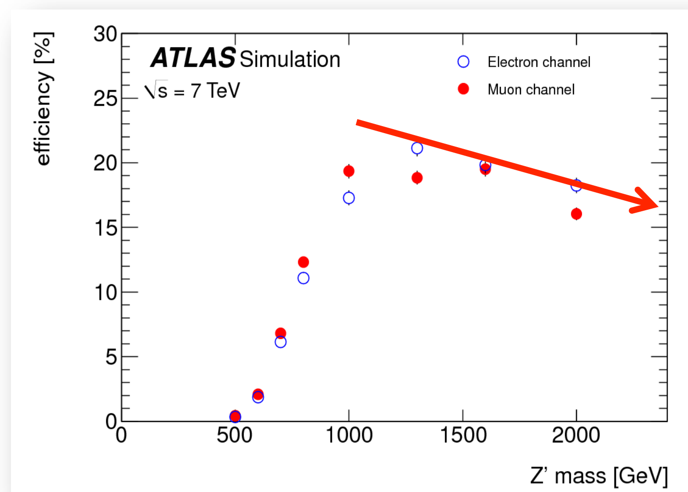


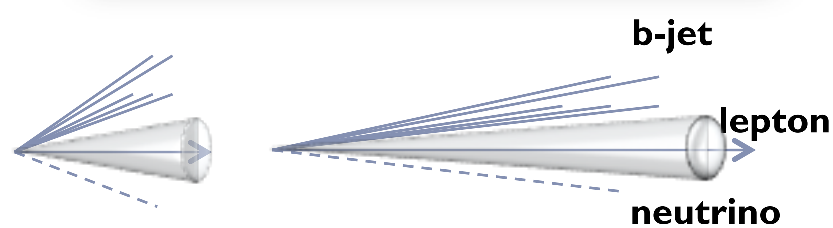
Lepton Isolation

- lepton and b-jet from boosted top highly collimated: lose isolation efficiency.
- But even boosted, leptons from tops have larger separation than those from light quark jets.
- Loss in efficiency can be recovered in part: variable p_T-dependent cone size, “mini isolation”, ...

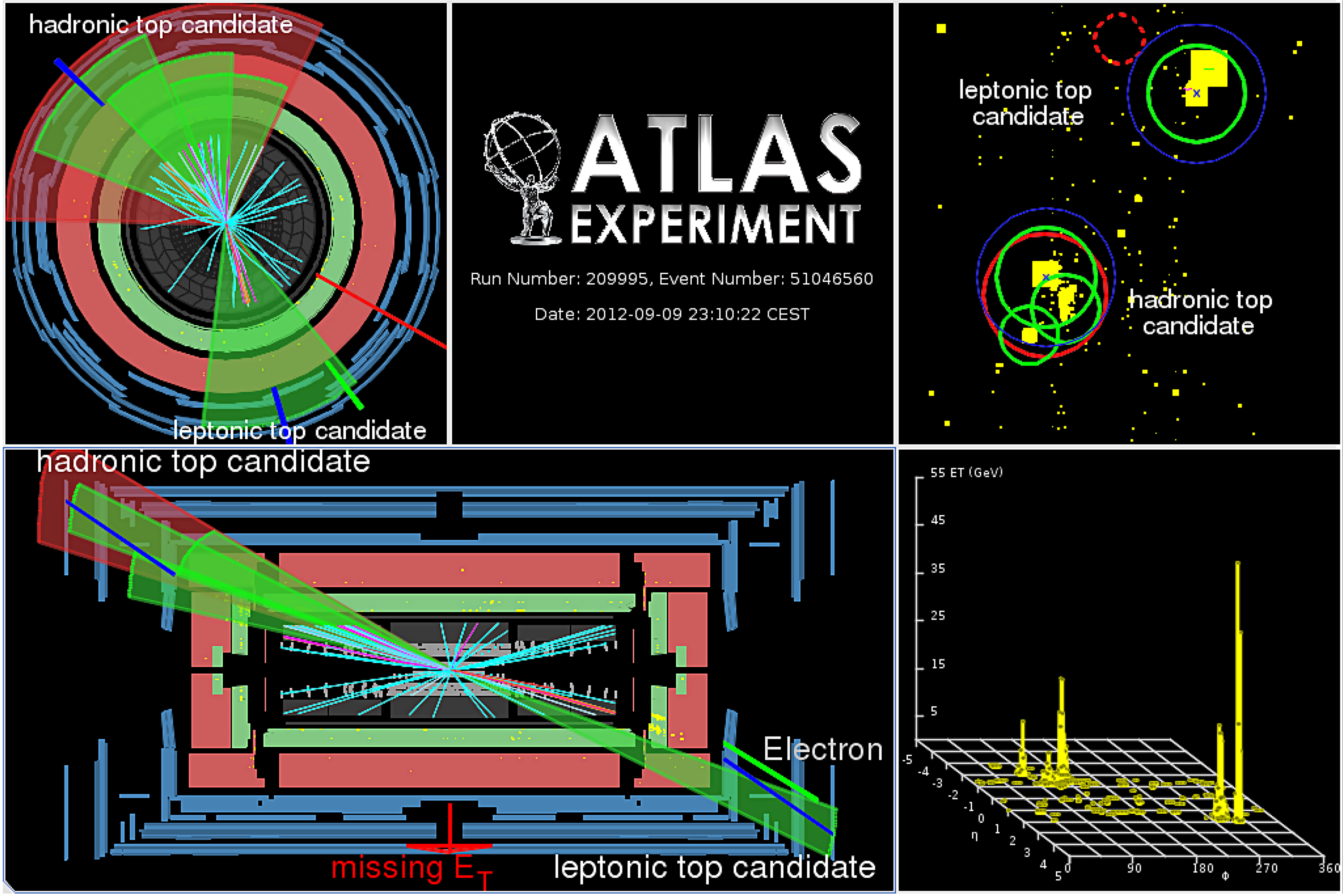
JHEP 1103:059 (2011)
Rehermann, Tweedie







Candidate Top Quark Jets



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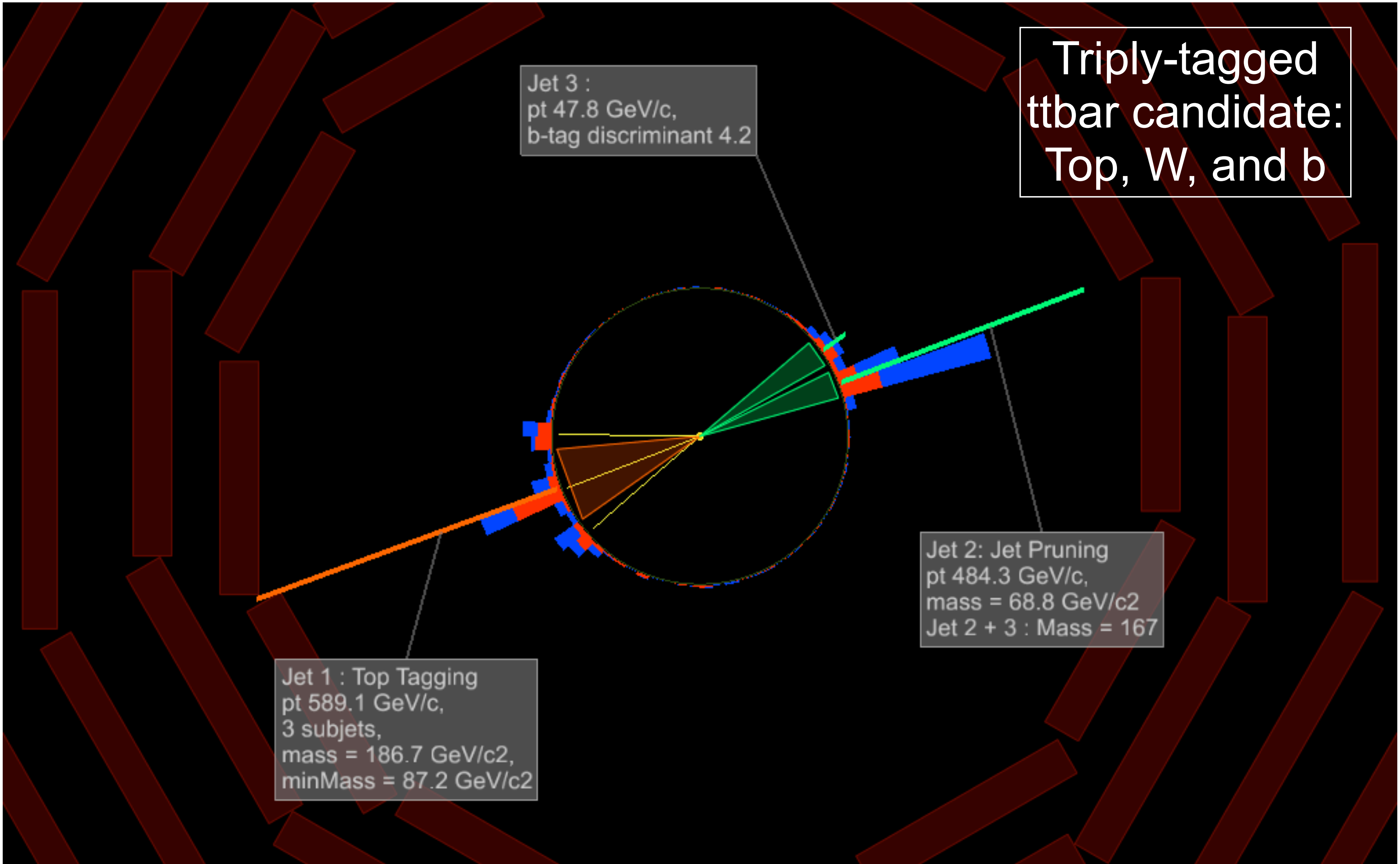
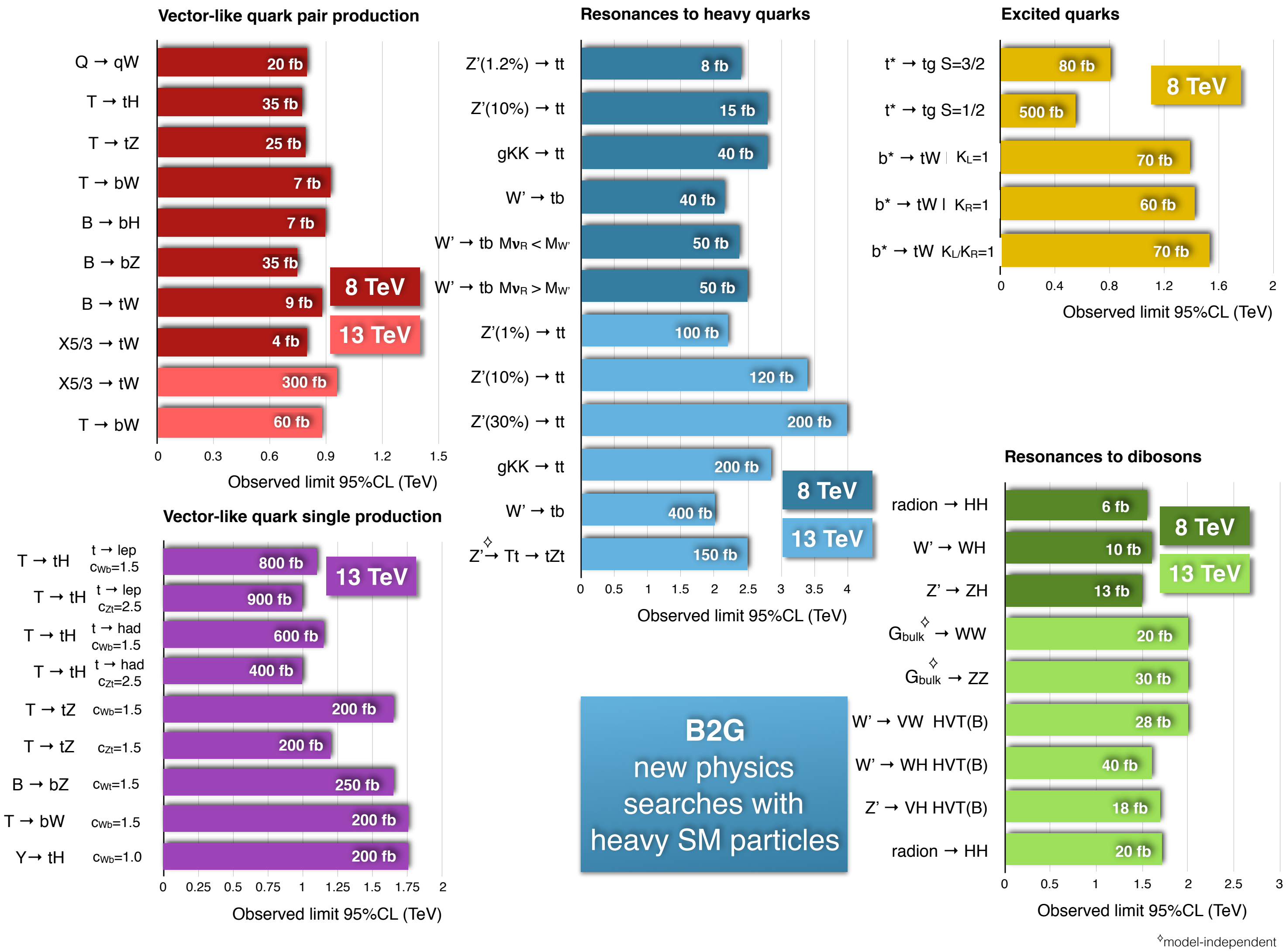


Substructure is everywhere



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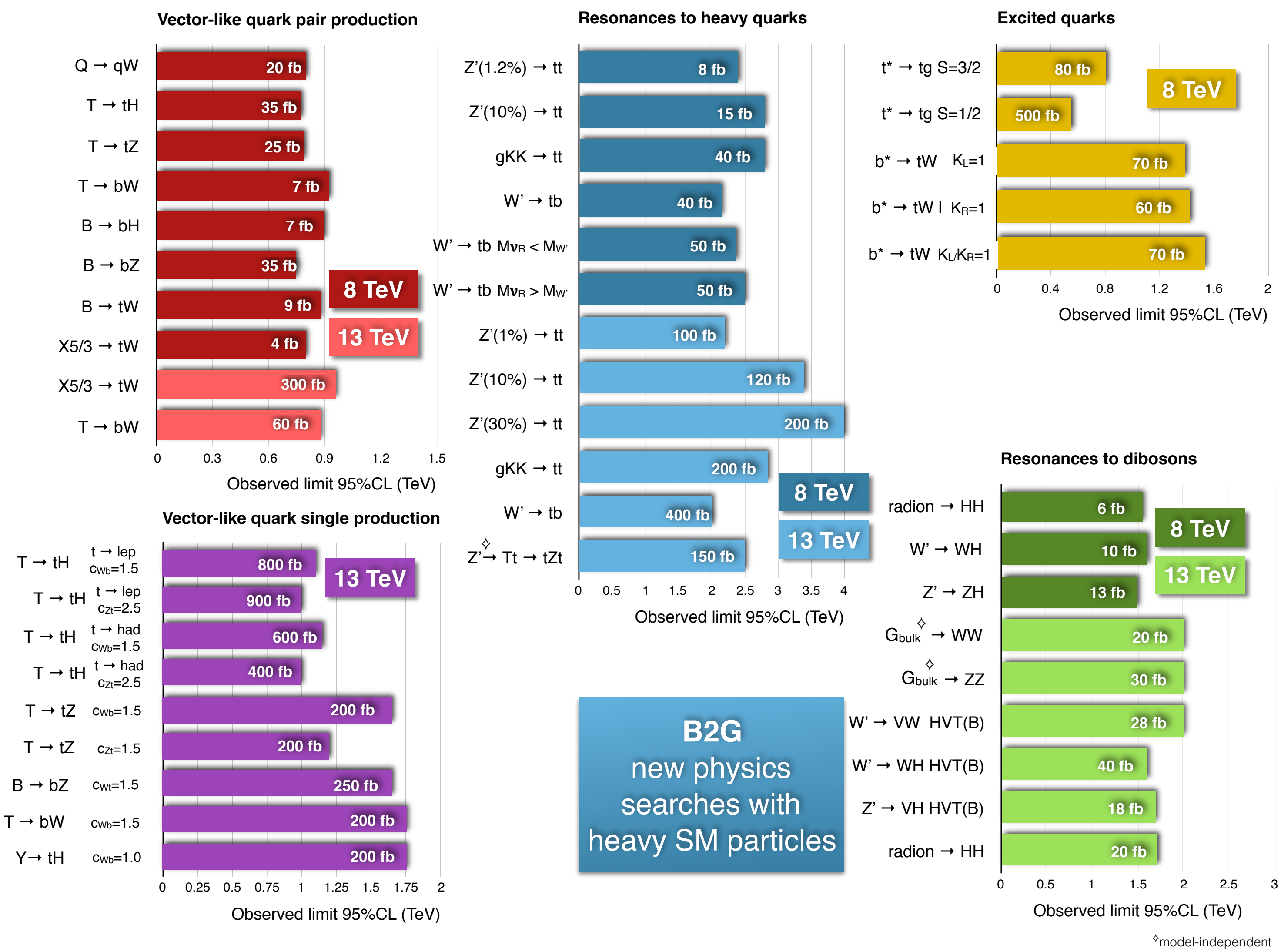


Almost all CMS B2G searches utilizing substructure tools

Boosted Object Reconstruction

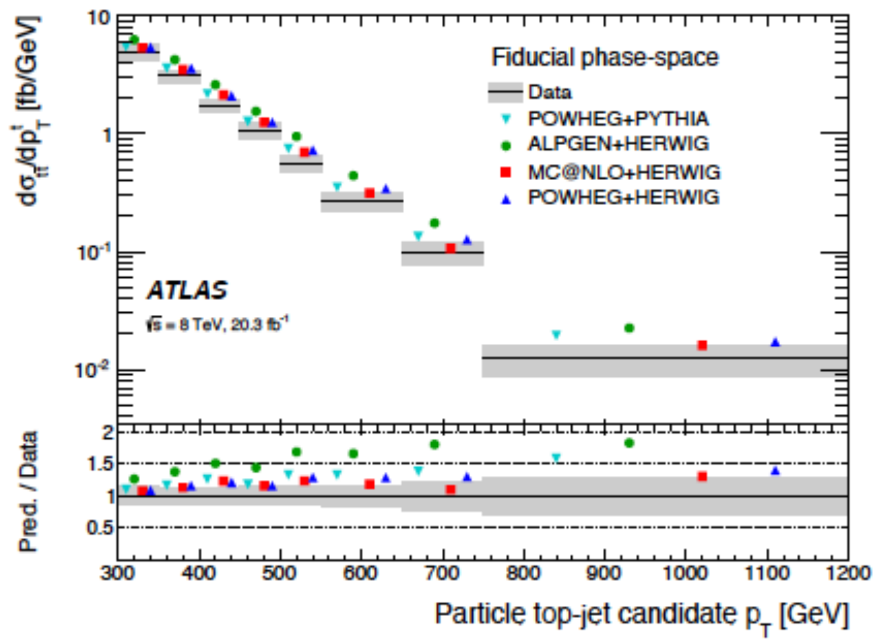
Many new pieces have been added to our boost and substructure chest, and we are beginning to really see bigger solutions.

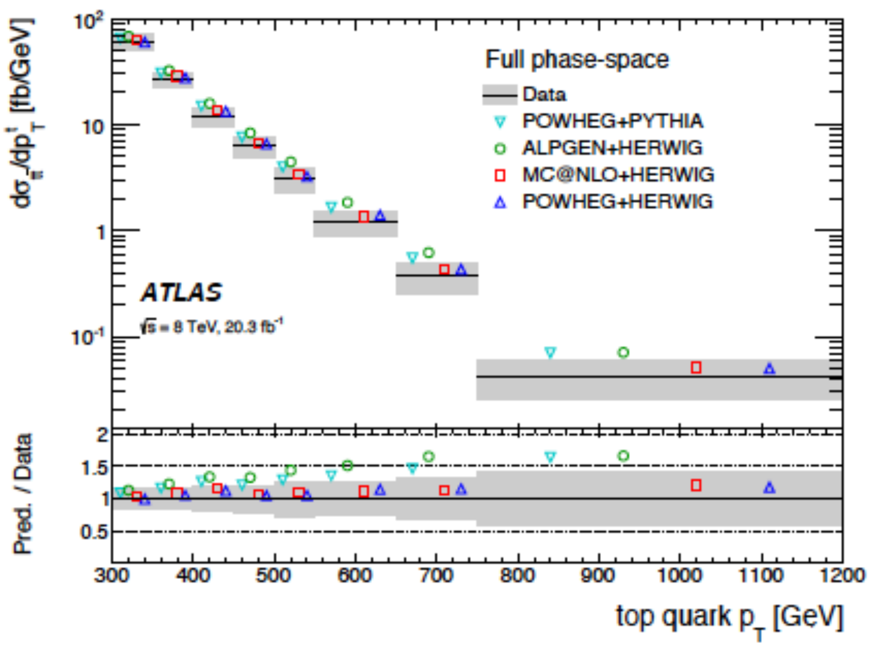
Boosted differential top pair xs

Anything different at high pT?

- p_T>300, trimmed large-R (1.0) jets
- m_{jet} > 100 GeV, substructure selection
- largest jet is hadronic top candidate

see talks: M. Nagrini, L. Skinnari





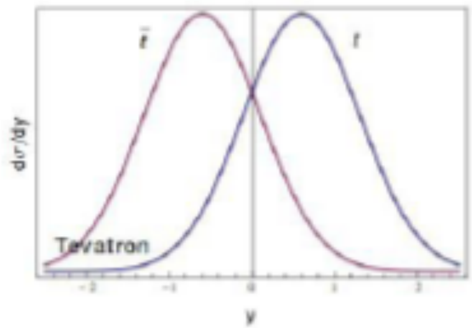
- 13-29% uncertainty, large-R JES dominates
- parton-level result relies on MC: larger systematics
- same trend as resolved analysis:

ATLAS: Phys. Rev. D 93, 032009 (2016)

CMS: arXiv:1605.00116

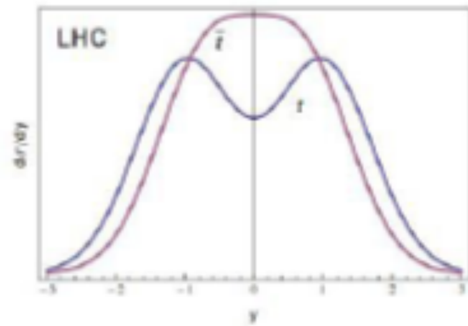
ATLAS-CONF-2015-065

Boosted top pair charge asymmetry



$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$$

$$\Delta y_{t\bar{t}} = y_t - y_{\bar{t}}$$

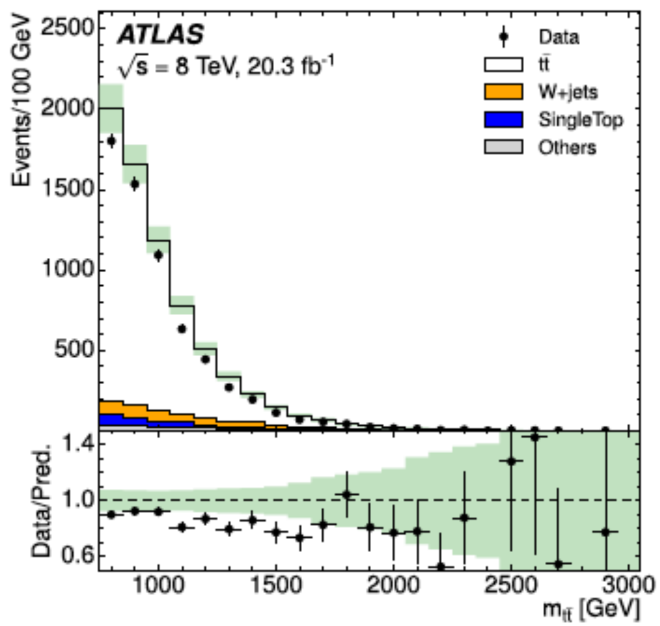


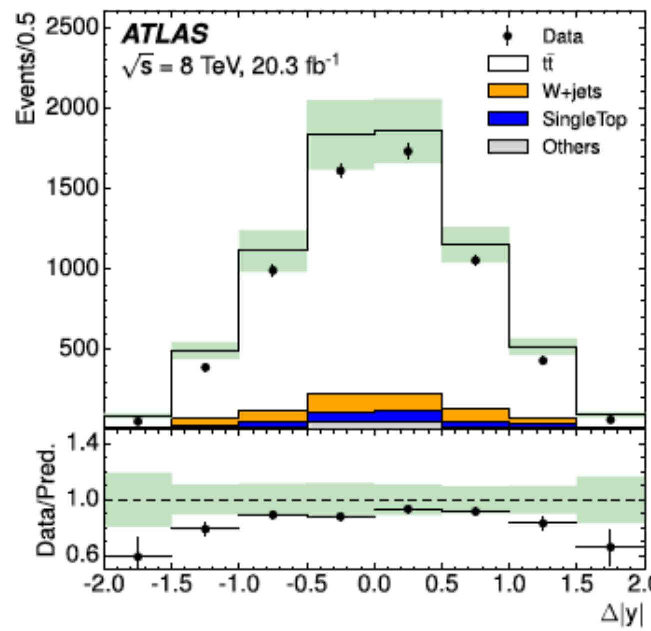
$$A_C = \frac{N(\Delta|y|>0)-N(\Delta|y|<0)}{N(\Delta|y|>0)+N(\Delta|y|<0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

- tt production gives charge asymmetry at NLO due to interference: qq v. gg
- LHC - Tevatron: complementary for searches for new physics

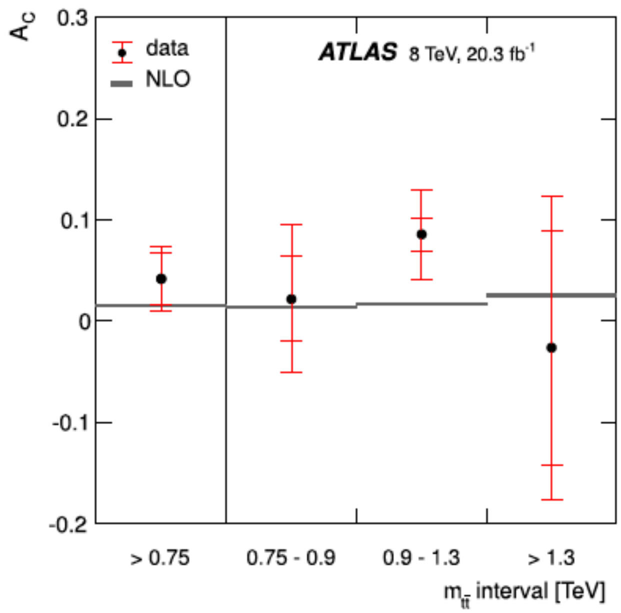
detector-level distributions

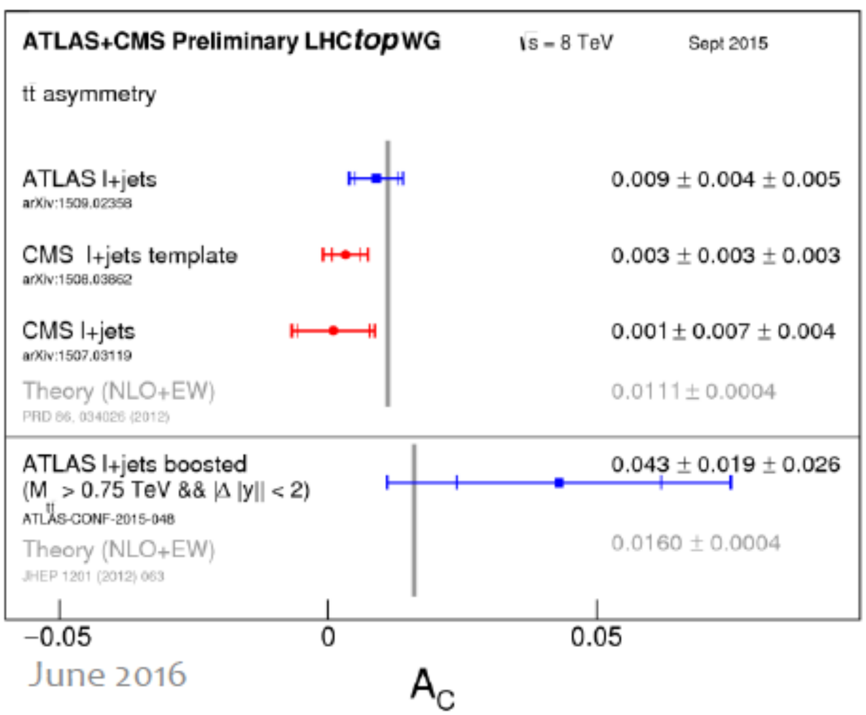




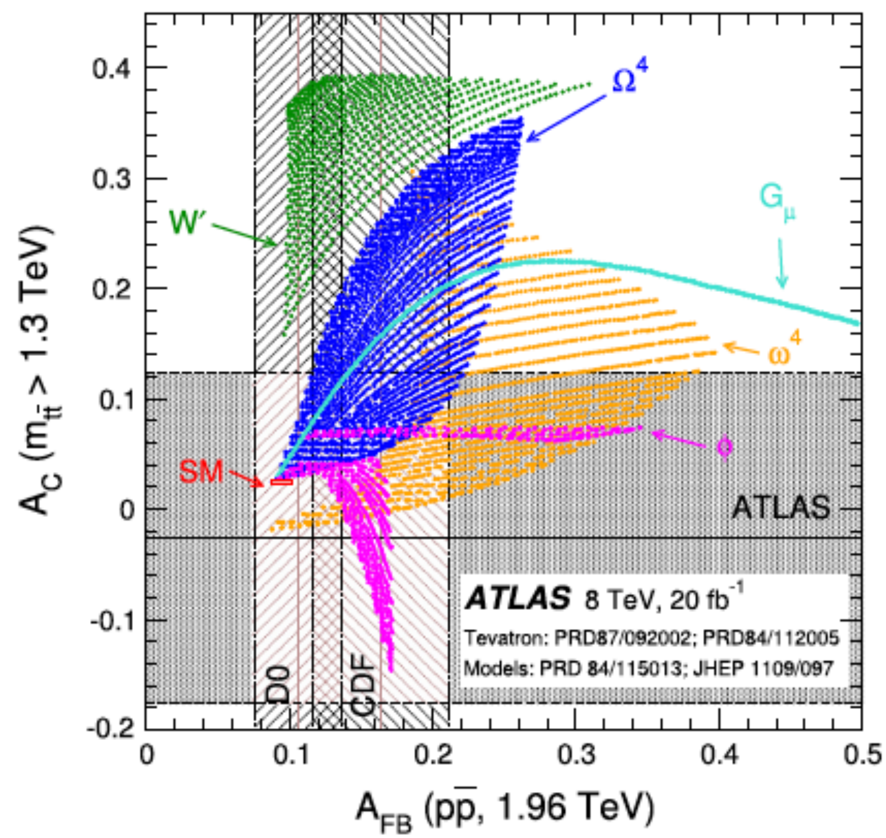
Physics Letters B (2016), Vol. 756, pp. 52-71

Boosted top pair charge asymmetry





- differential distributions sensitive to new physics, such as axi-gluons, especially at high m_{tt}
- boosted: m_{tt} >0.75 TeV



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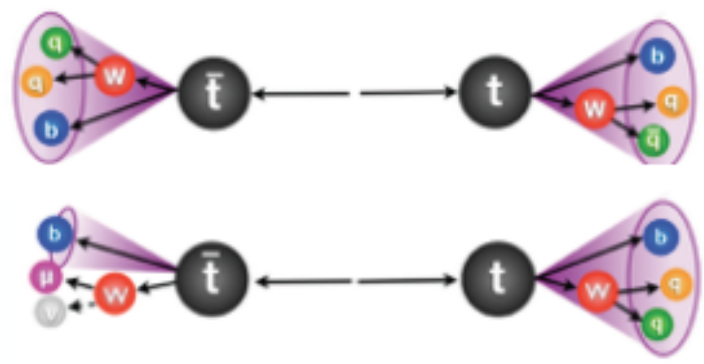
Massive resonances decaying to boosted top pairs

Resonances decaying to boosted top



top-tagged jet

- soft drop jet mass [110, 210] GeV
- Nsubjettiness $\tau_{32} < 0.69$

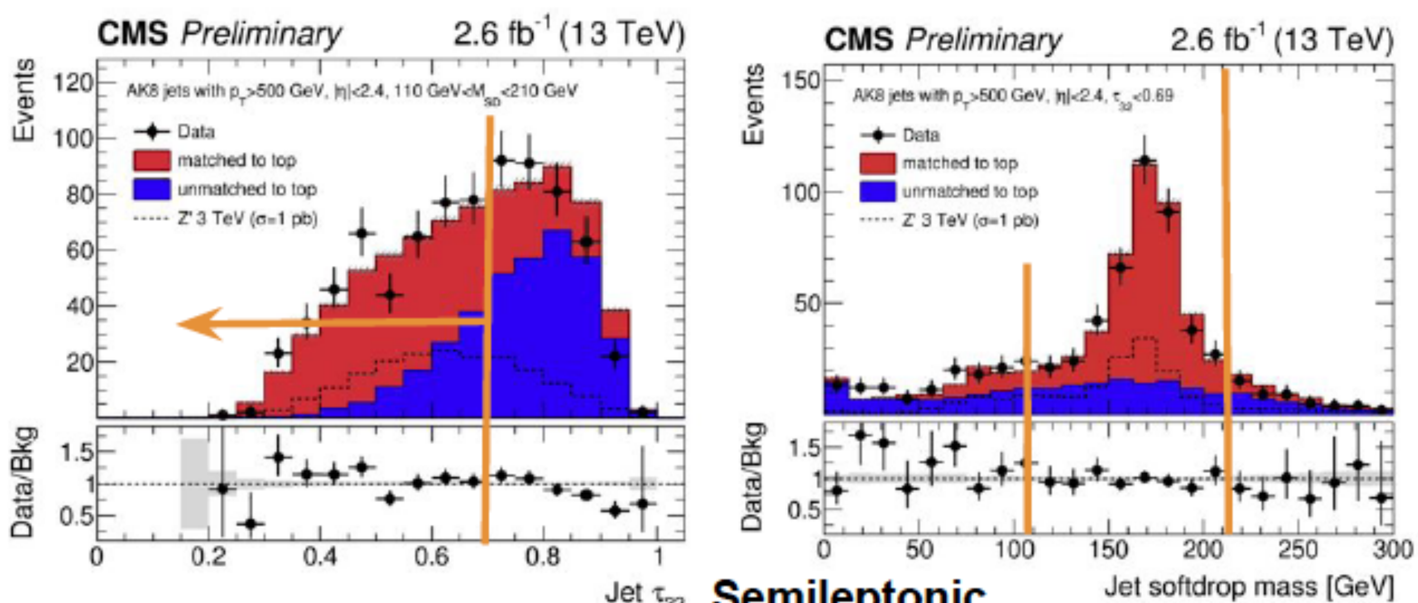
Event categories

- All-hadronic:

2 top-tags ⊗ Δy < 1.0, Δy > 1.0 ⊗ 0 b-tags, 1 b-tag, 2 b-tags

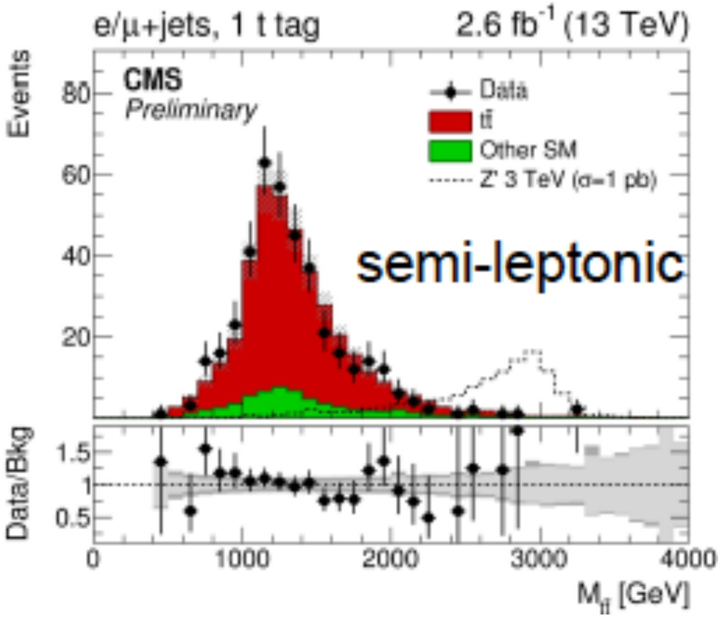
- Semileptonic:

μ/e + jets ⊗ 1 top-tag, 0 top-tags, 1 b-tag, 0 top-tags, 0 b-tags



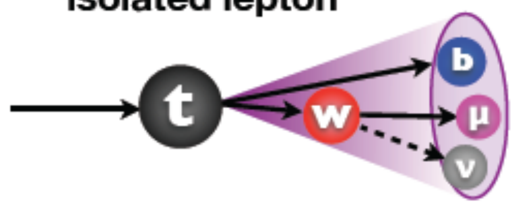
Semileptonic

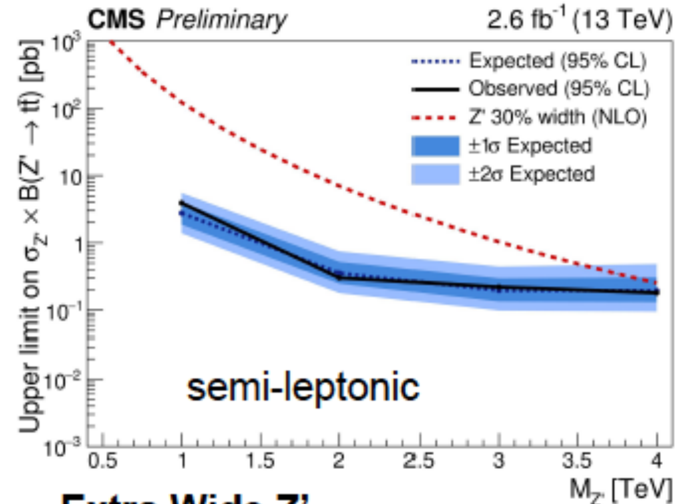
Resonances decaying to boosted top



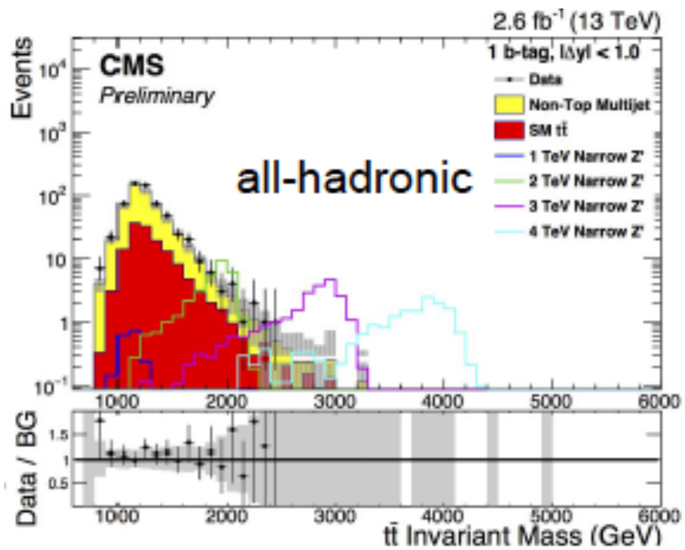
$\Delta R_{min}(l,j) > 0.4 \mid\mid p_{T,rel}(l,j) > 20$ GeV
$X^2 < 30$

Leptonic top with non-isolated lepton

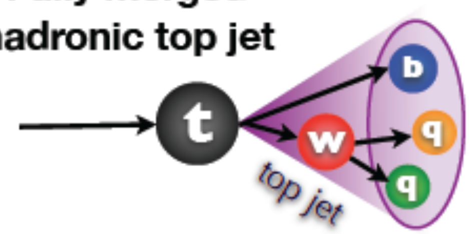




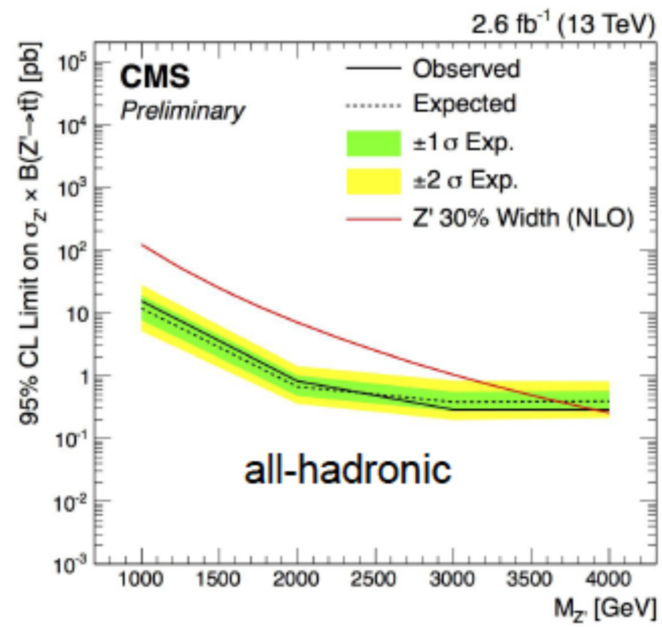
Extra Wide Z'



Fully merged hadronic top jet

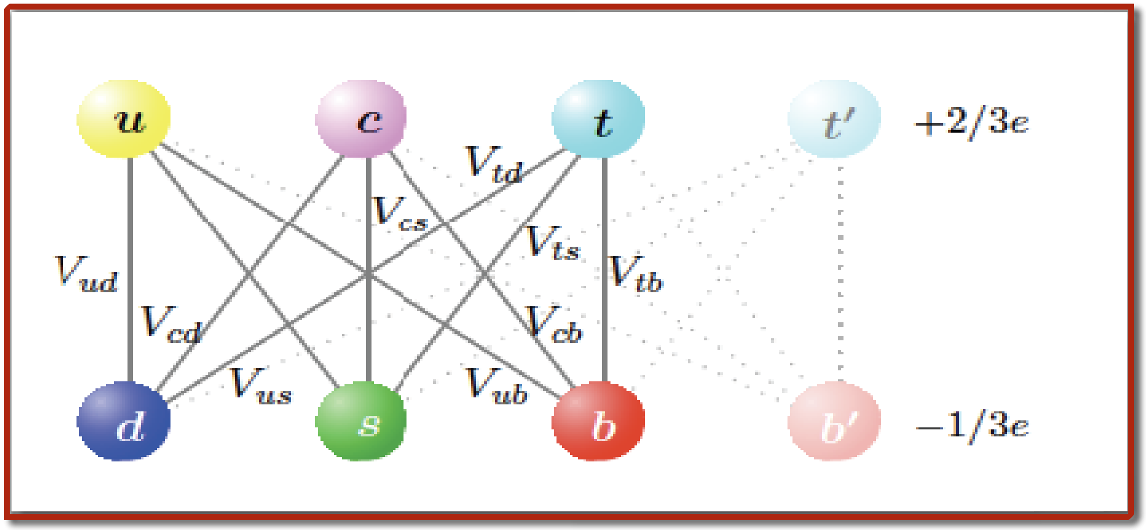


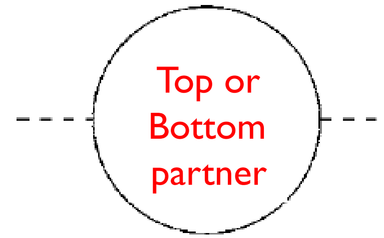
QCD background from data



vector-like quarks

Is there a 4th Generation?





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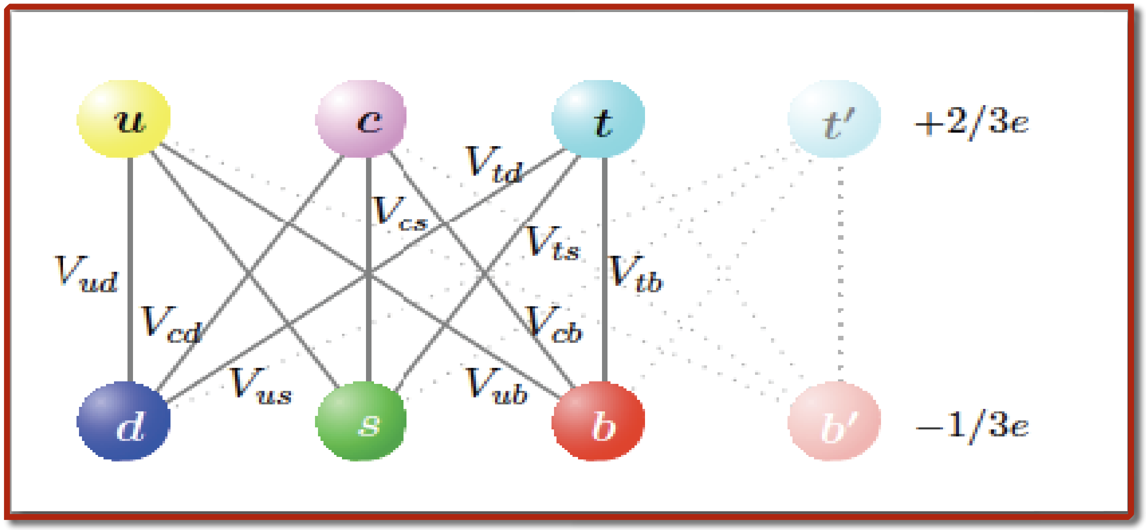

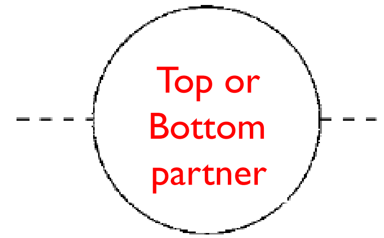

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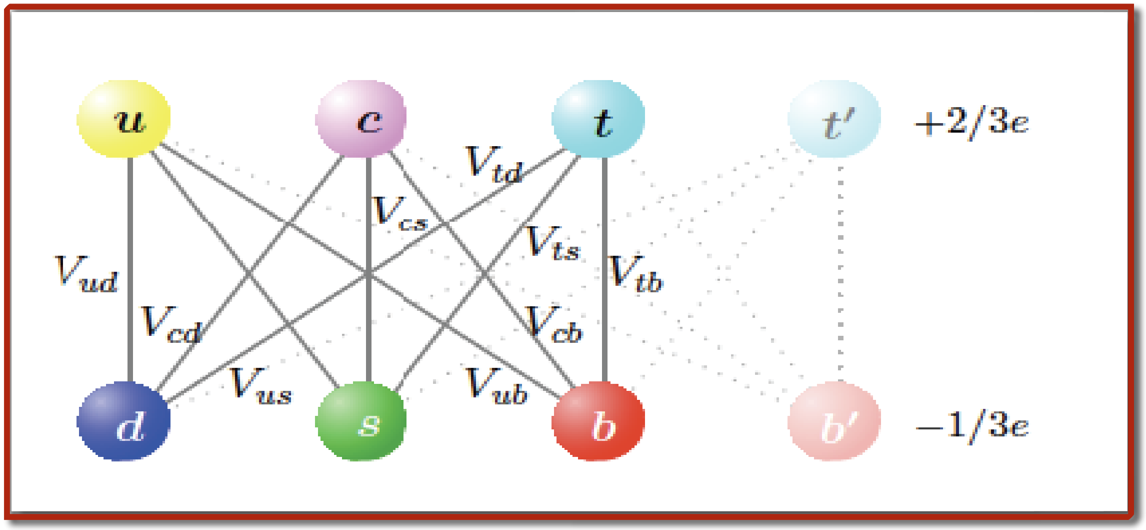

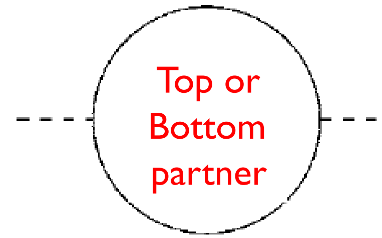

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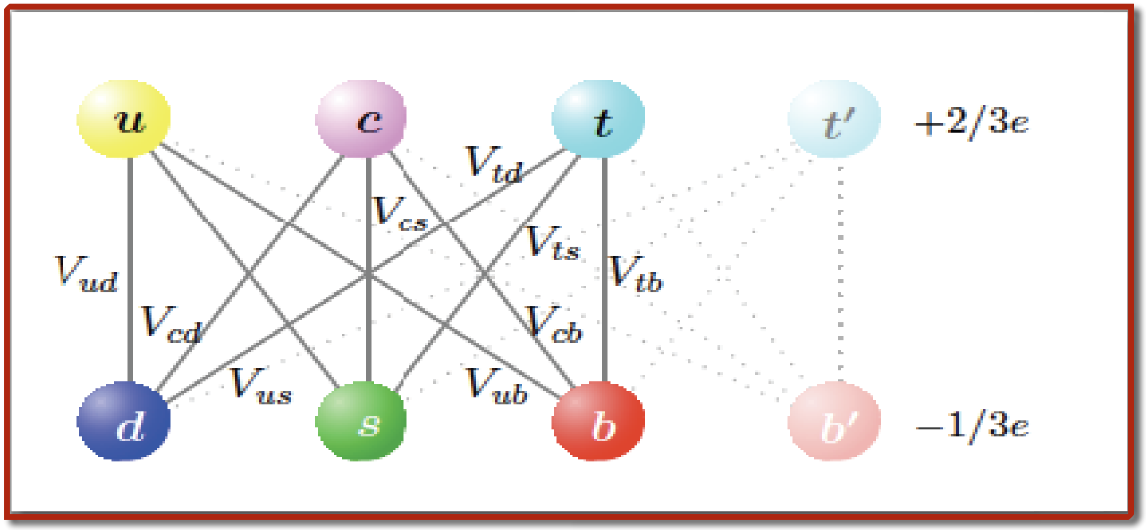

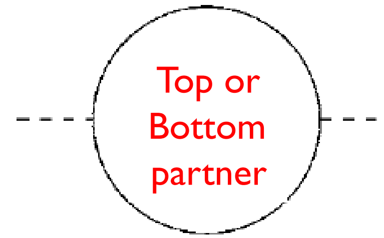

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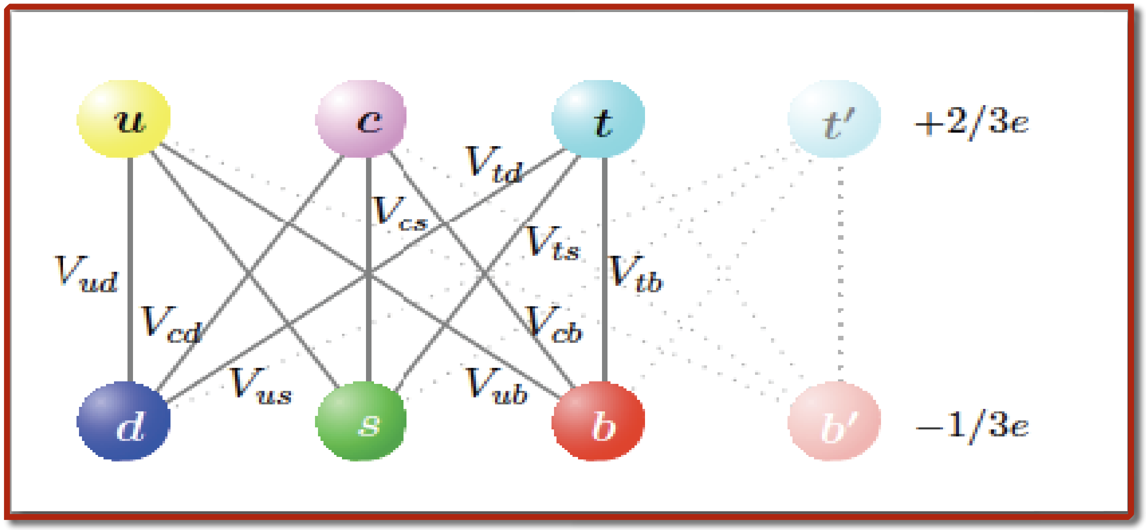

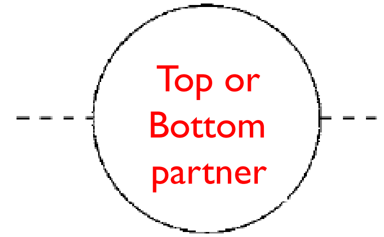

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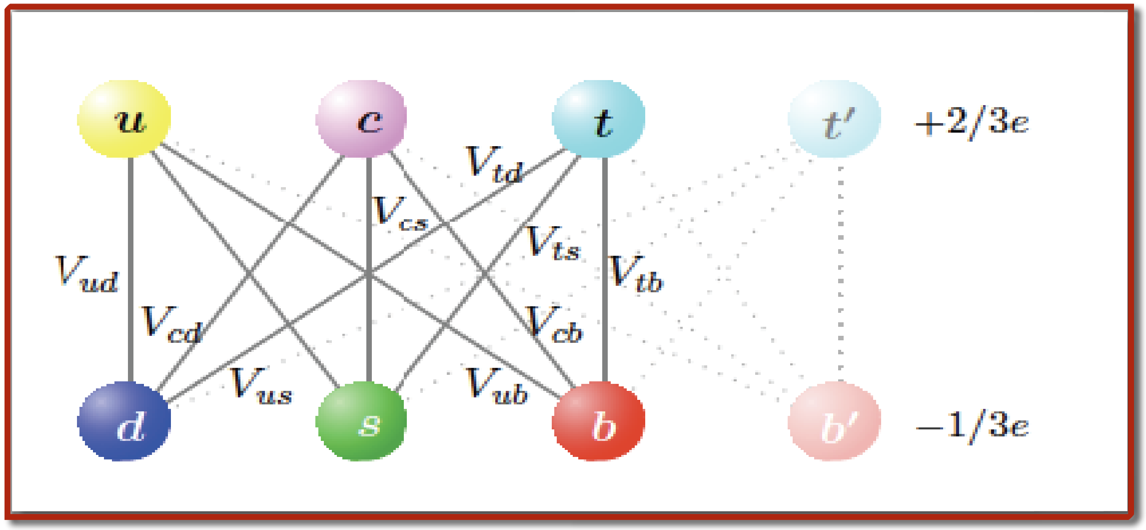

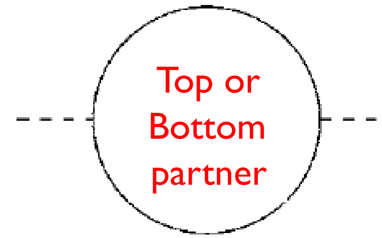

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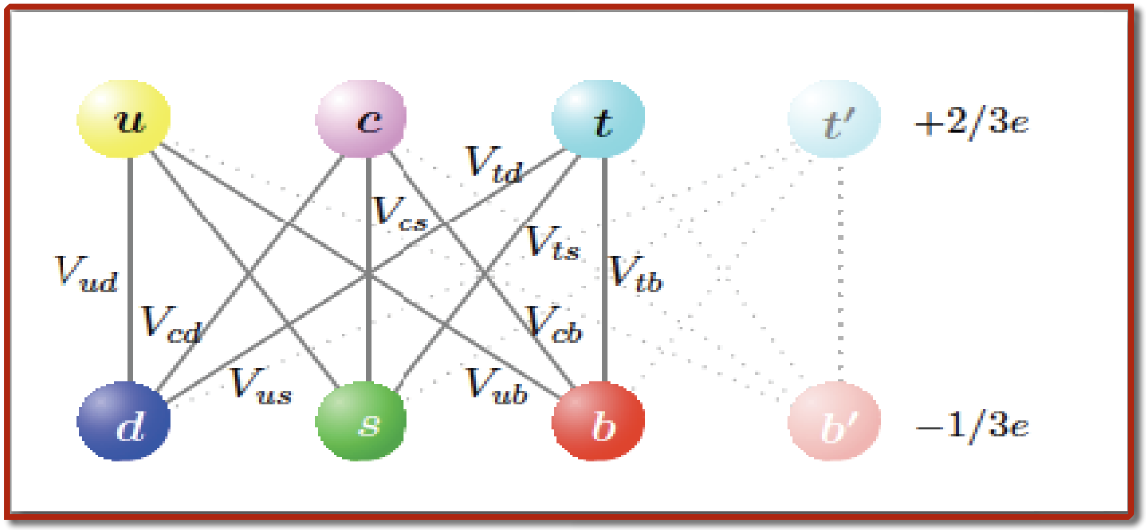

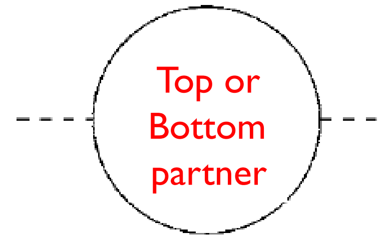

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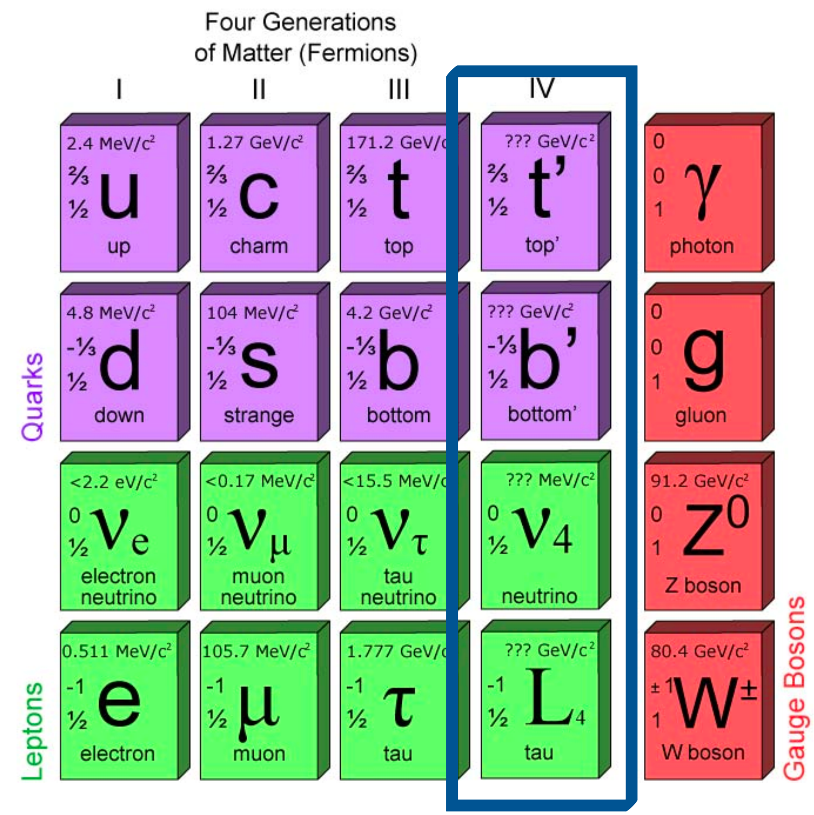
- non-SM 4th gen can enhance CP violation, and heavy ν is DM candidate
- if CKM is diagonal, t′→Wb and b′→tW due to GIM mechanism

Vector-like Quarks

- Not your uncle's 4th generation! L- and R-handed components transform identically under SU(2) weak isospin gauge symmetry
  - don't enhance Higgs prod, unlike 4th gen.
  - appear in Little Higgs & Extra Dimensions
  - cancel quadratic divergences from loops



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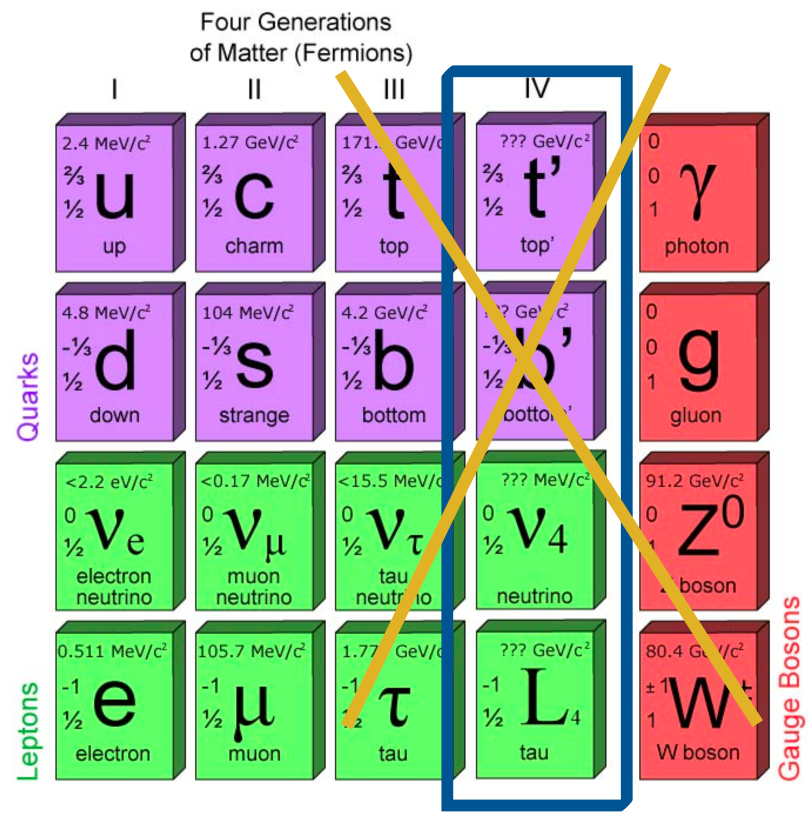

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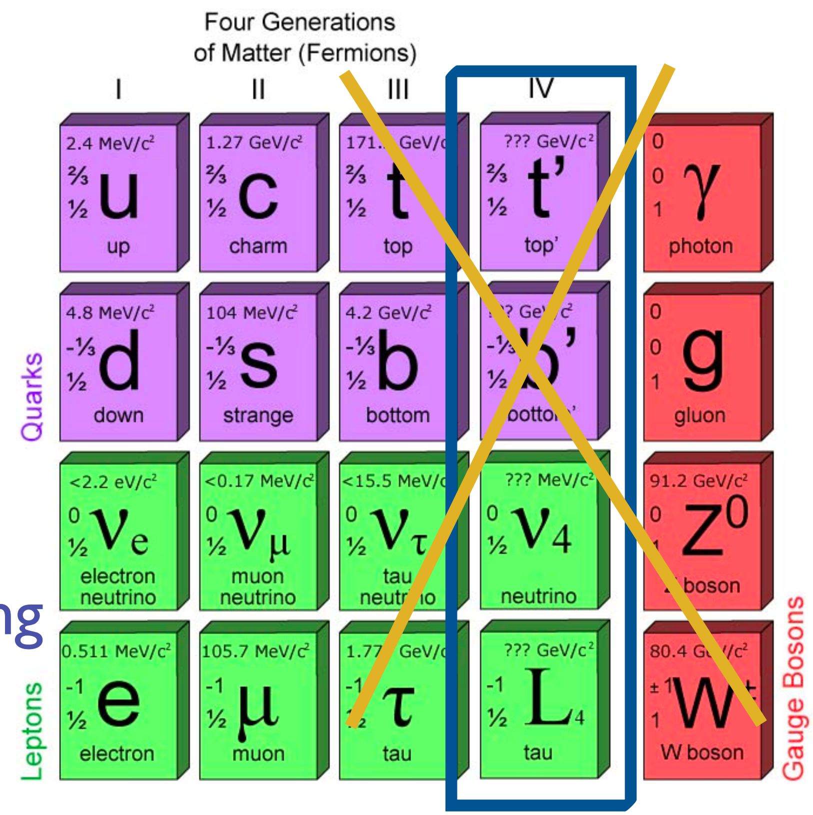

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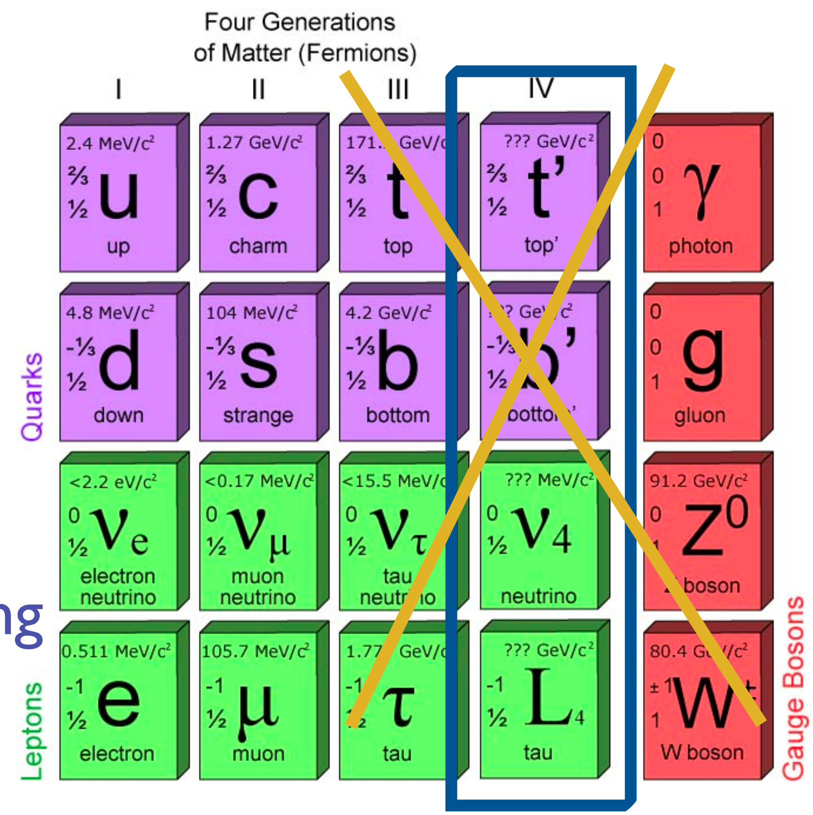

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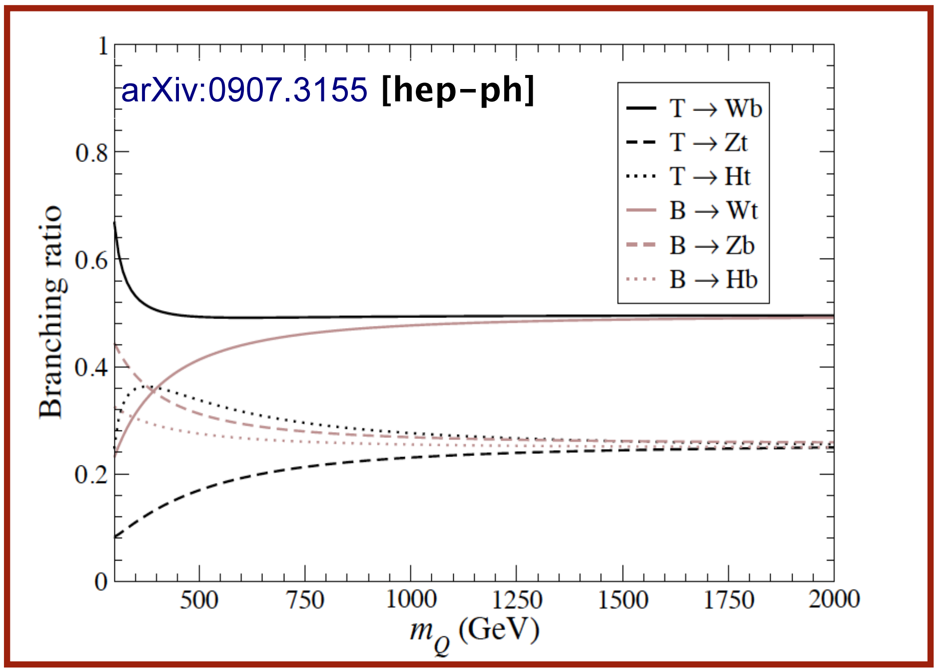
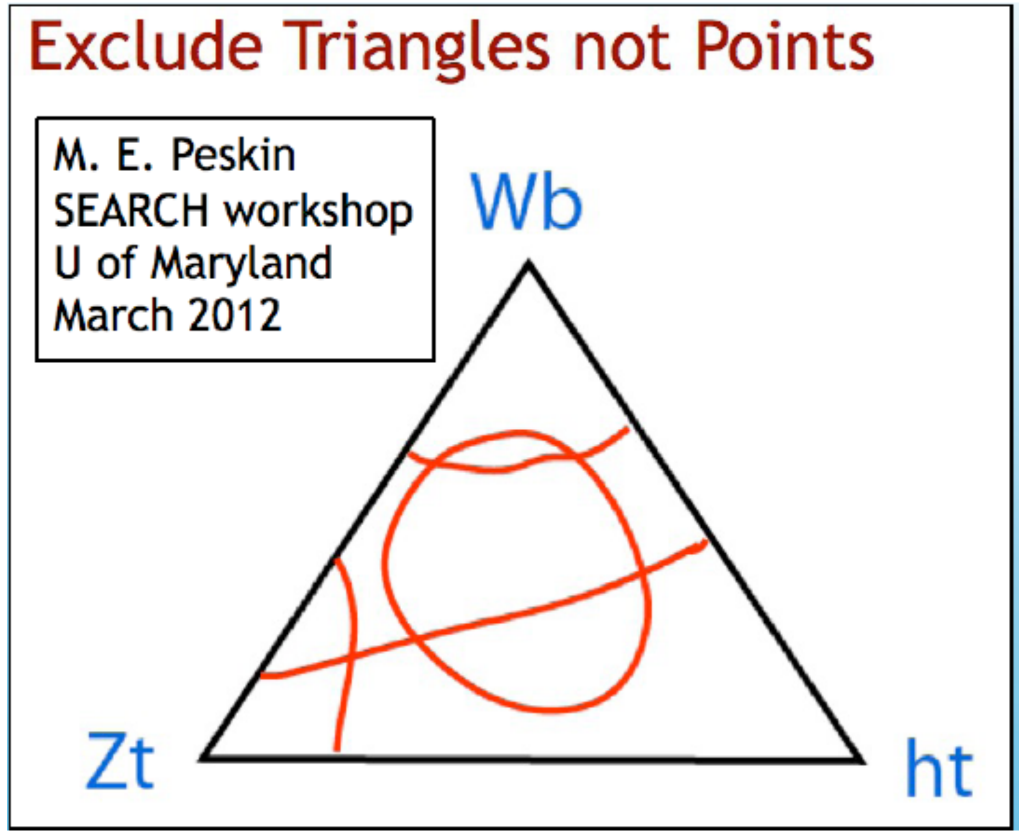
- Can be isospin singlet, doublet, triplet
- Interact with 3rd gen (naturalness): mixing proportional to SM quark mass. Light quark coupling sometimes enhanced.
- Charged and neutral decay, branching depends on mass and model.
- Pair production is mediated by the strong interaction
- Single production can be more pronounced at high masses

Vector-like Quarks

VLQs can have CC and NC decays: the branching ratios are constrained by the relation:

BR(Wb)+BR(tZ)+BR(tH)=1





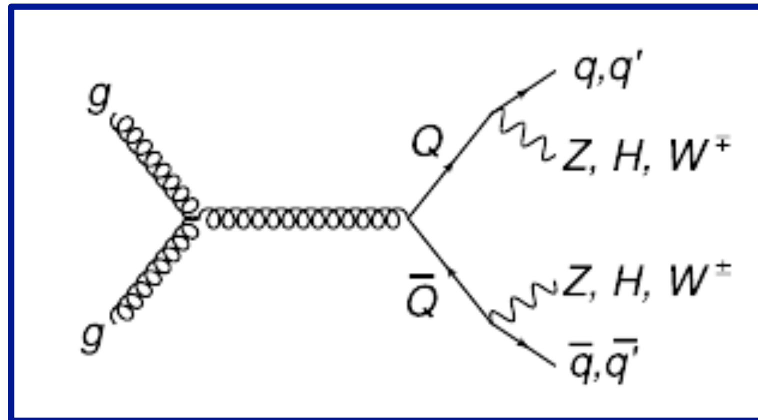
3 varying branching ratios describe the triangle

Partner Quark Topologies

Many distinct event topologies to consider:

$B' \rightarrow tW, bZ, bH$

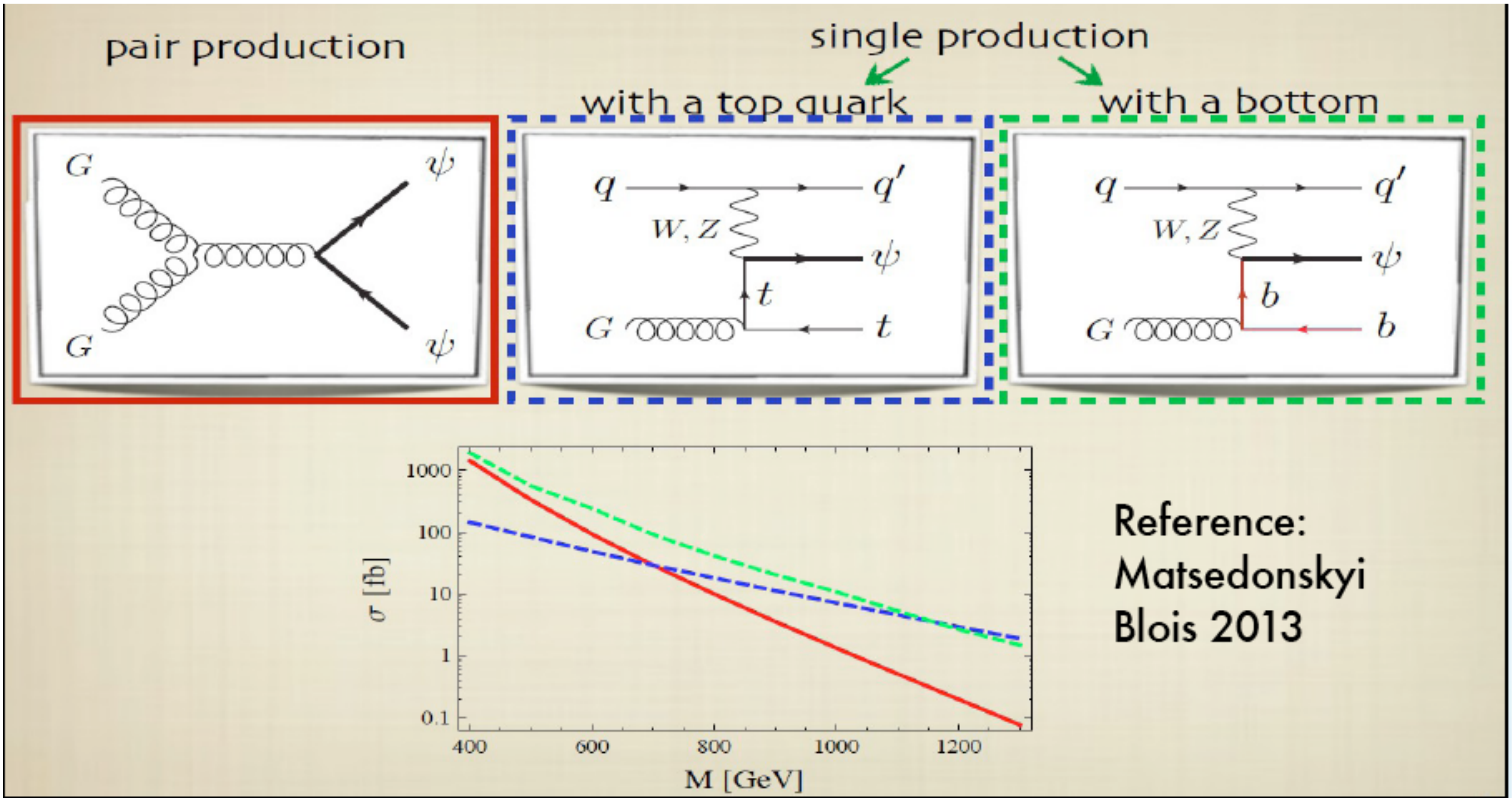
$T' \rightarrow bW, tZ, tH$



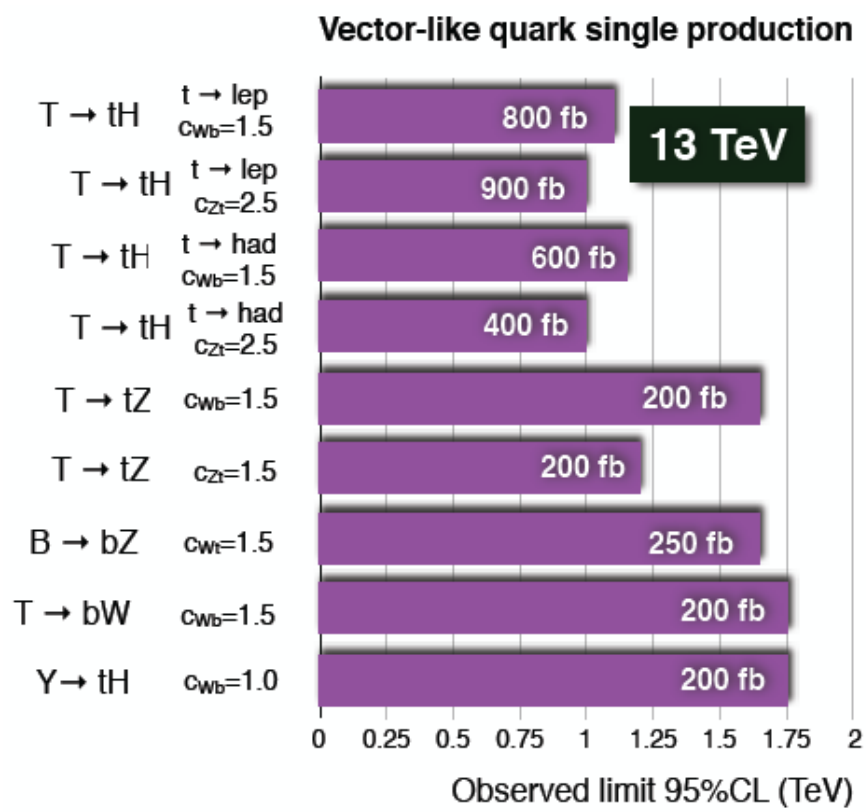
- Leptons, b-jets, (boosted) top, (boosted) W/Z, boosted H are all possible final states.
- Use standard (threshold) identification, and use boosted b-tag and V-tag algorithms as well.
- Set limits at 100% BR and also scan over all possible fractions.

Vector-like Quarks

VLQ example: Partial compositeness



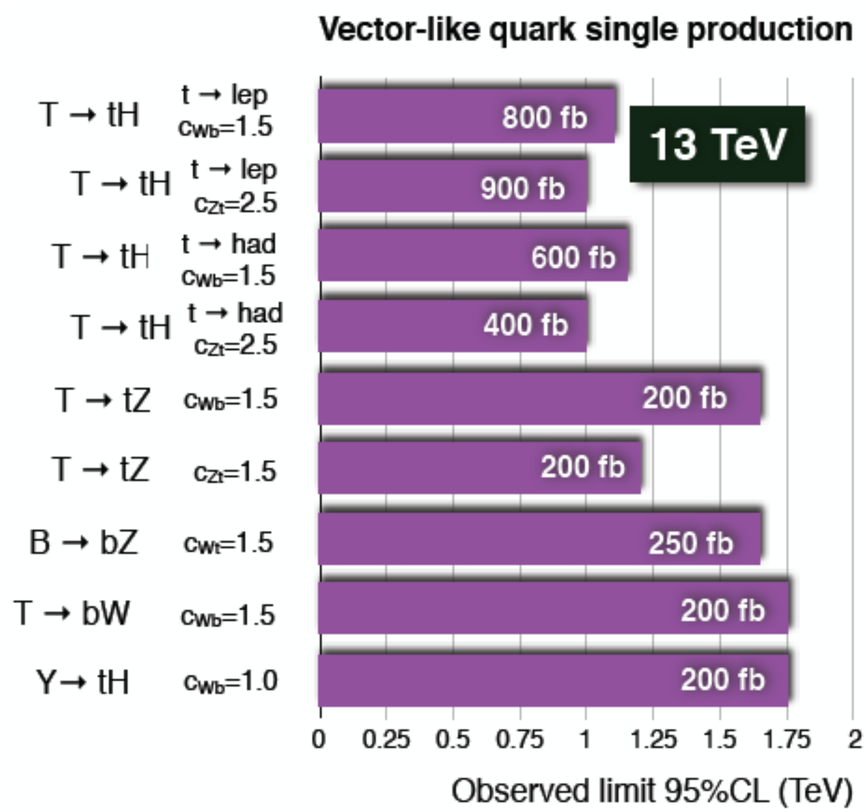
single VLQ Searches (CMS)



…with more coming soon

single VLQ Searches (CMS)

CMS is searching for single production of VLQs for the first time in Run 2 in many channels…



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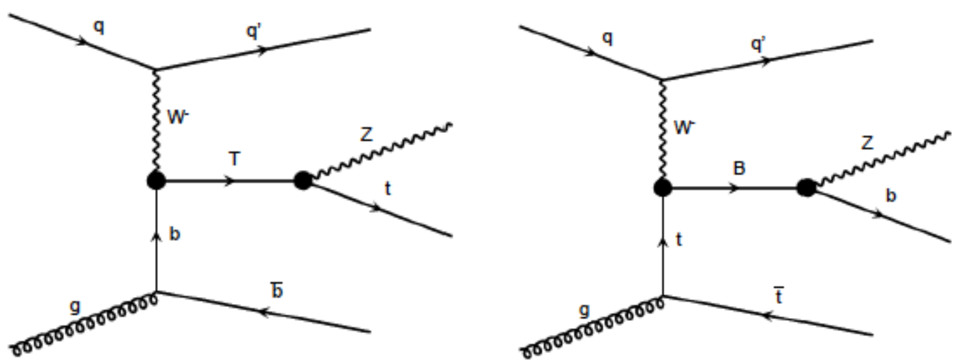
single VLQ Searches (CMS)

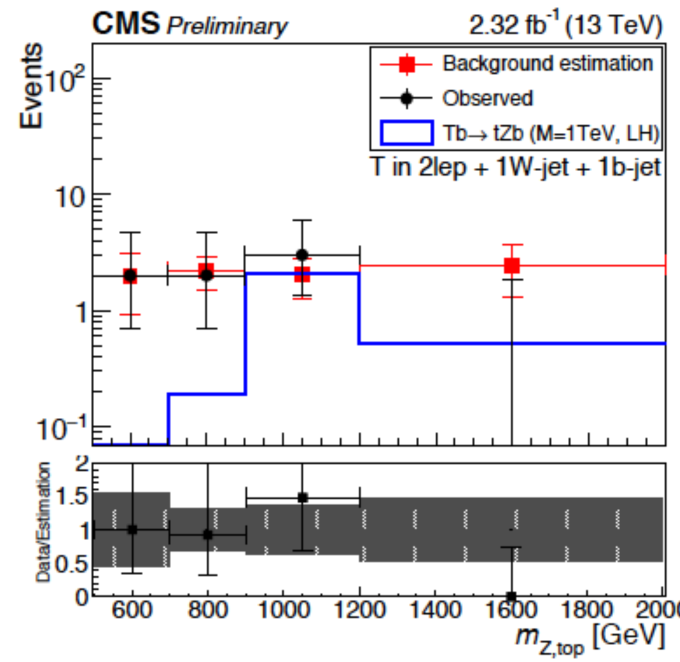
New: Search for T, B in final states with Z boson

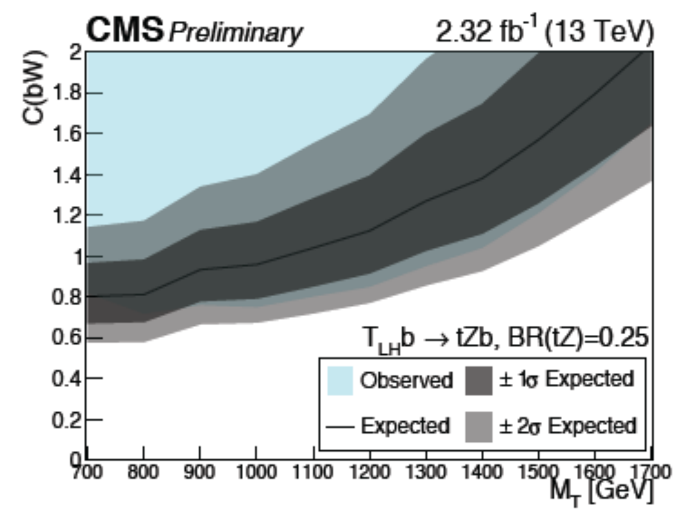
CMS PAS B2G-16-001



6 categories for resolved and boosted final states:

- T → 2ℓ + 1 top-jet
- T → 2ℓ + 1 W-jet + 1b-jet
- T → 2μ + 1b-jet + 2 jets
- T → 2e + 1b-jet + 2 jets
- B → 2μ + 1b-jet
- B → 2e + 1b-jet





interpretations: singlet T, doublet T, singlet B, Z′→tT production

Summary

- I didn't have time to do justice to the many and varied topics in top physics. Many "Top"-ics not covered!
- Measurements of top properties are becoming precise: top spin correlations, W helicity, t-tbar mass difference.
- If there is no new physics found at 13 TeV, top quark studies will be one of the ways to access new physics at higher scales: FCNC, precision top and EWK measurements, top mass.
- Boosted top tagging will be increasingly important in new physics searches and top quark measurements as well as we are moving to higher mass scales.

Welcome to the top!