Top Precision and Searches for New Physics

Christian Schwanenberger

DESY

SFB 676 Lectures

Particles, Strings, and the Early Universe

25 November, 2016

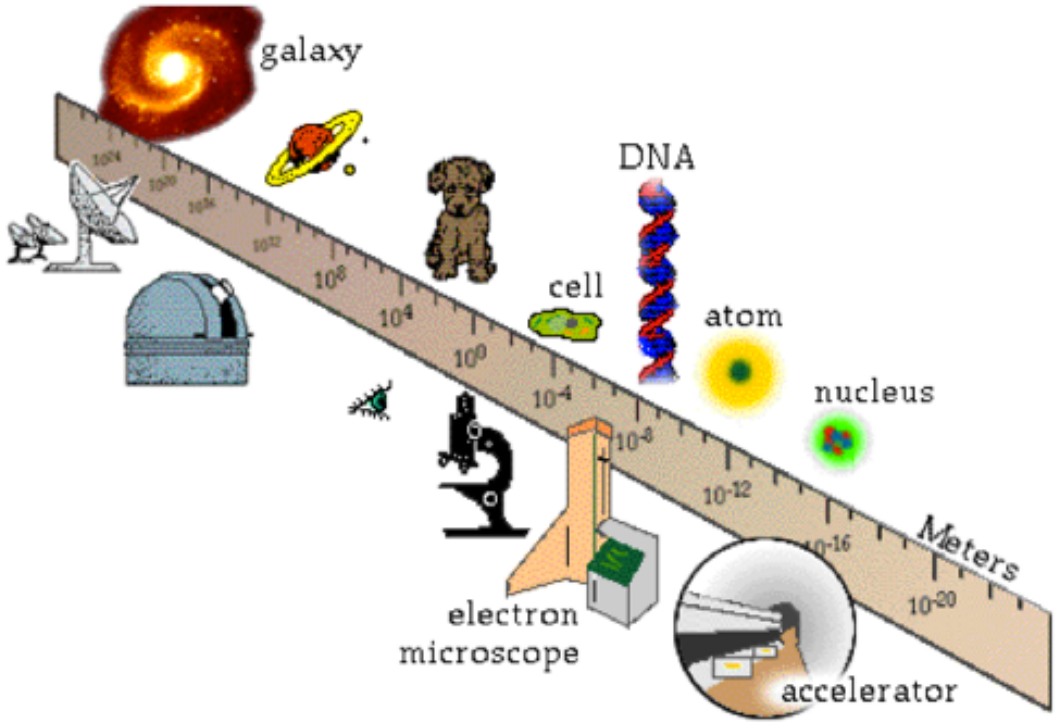
HELMHOLTZ ASSOCIATION

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY

Objective of Elementary Particle

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

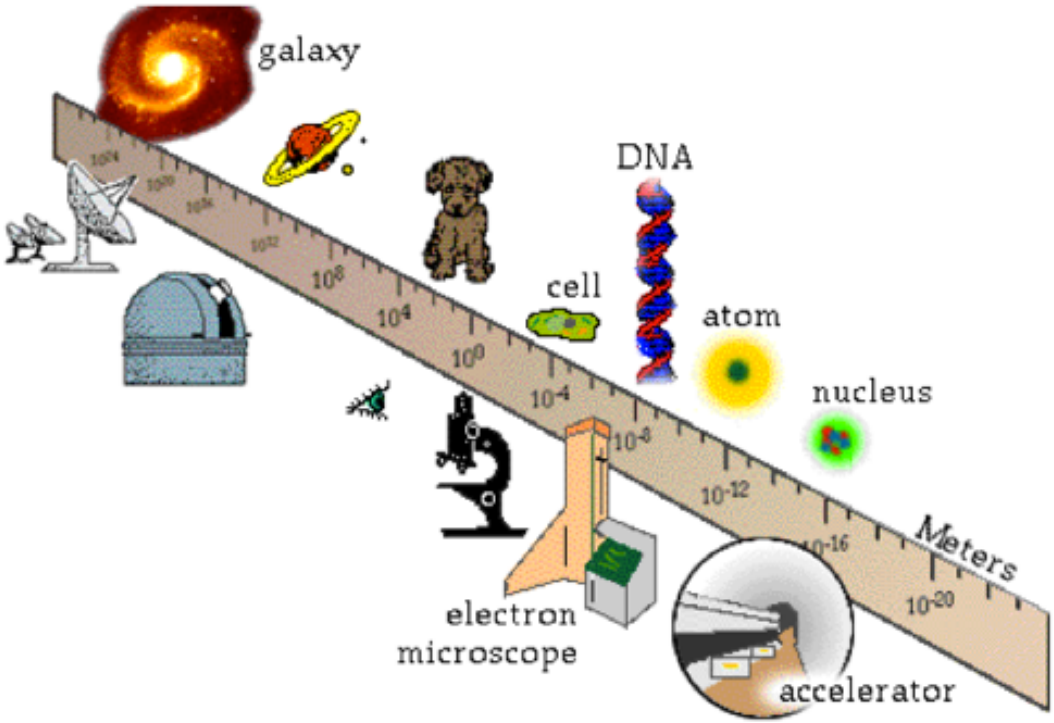


➔ **from the smallest dimensions in microcosm to the largest dimensions in the Universe**

Objective of Elementary Particle

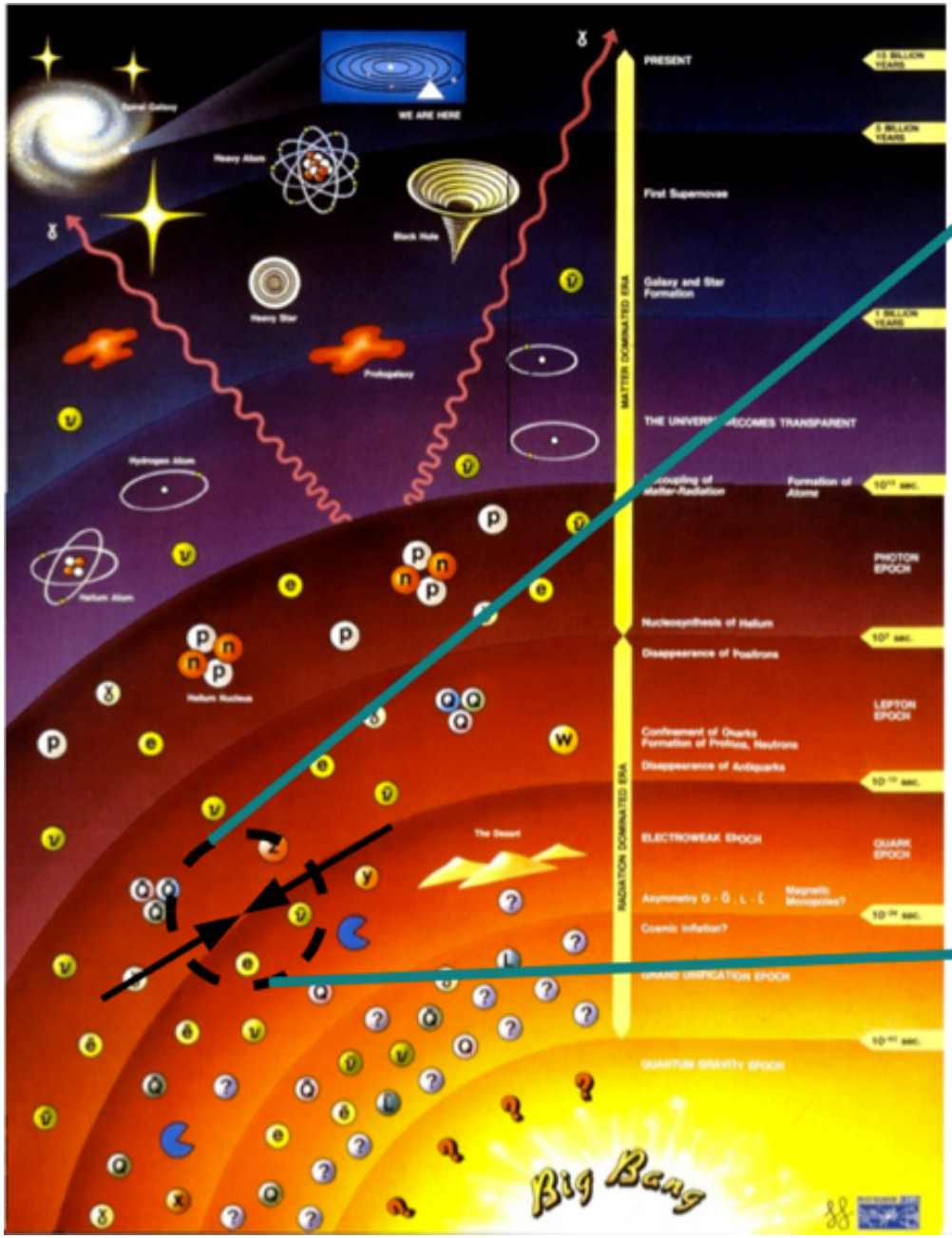
**"Dass ich erkenne, was die Welt
im Innersten zusammenhält."**

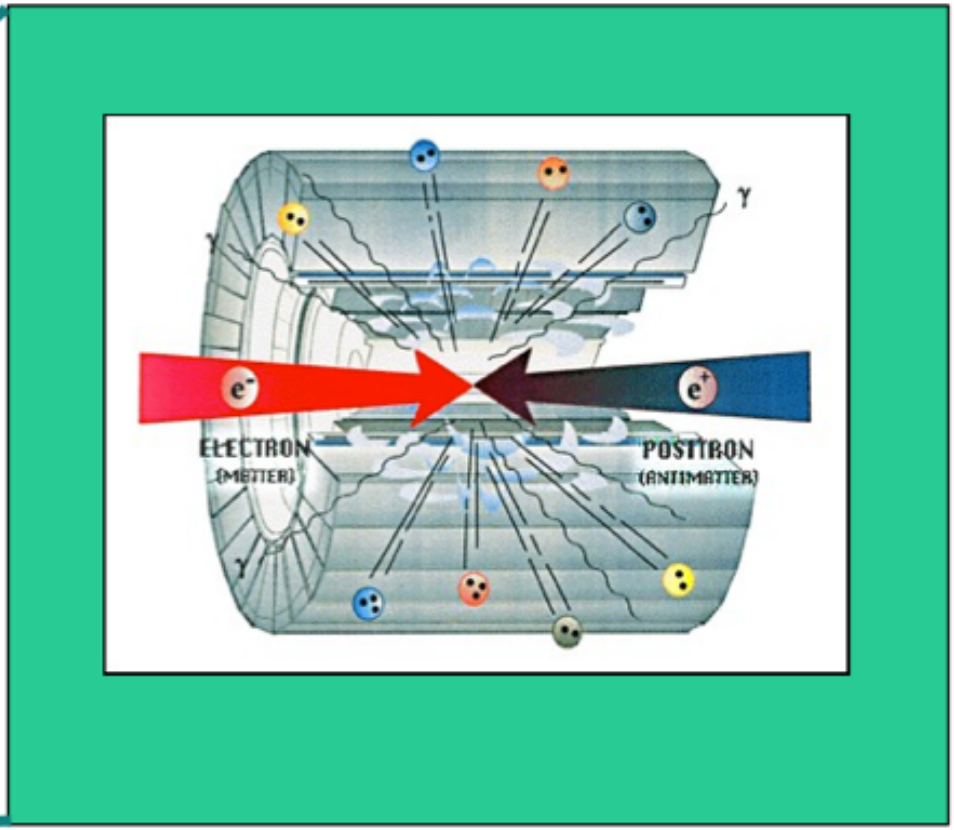
Goethe, Faust



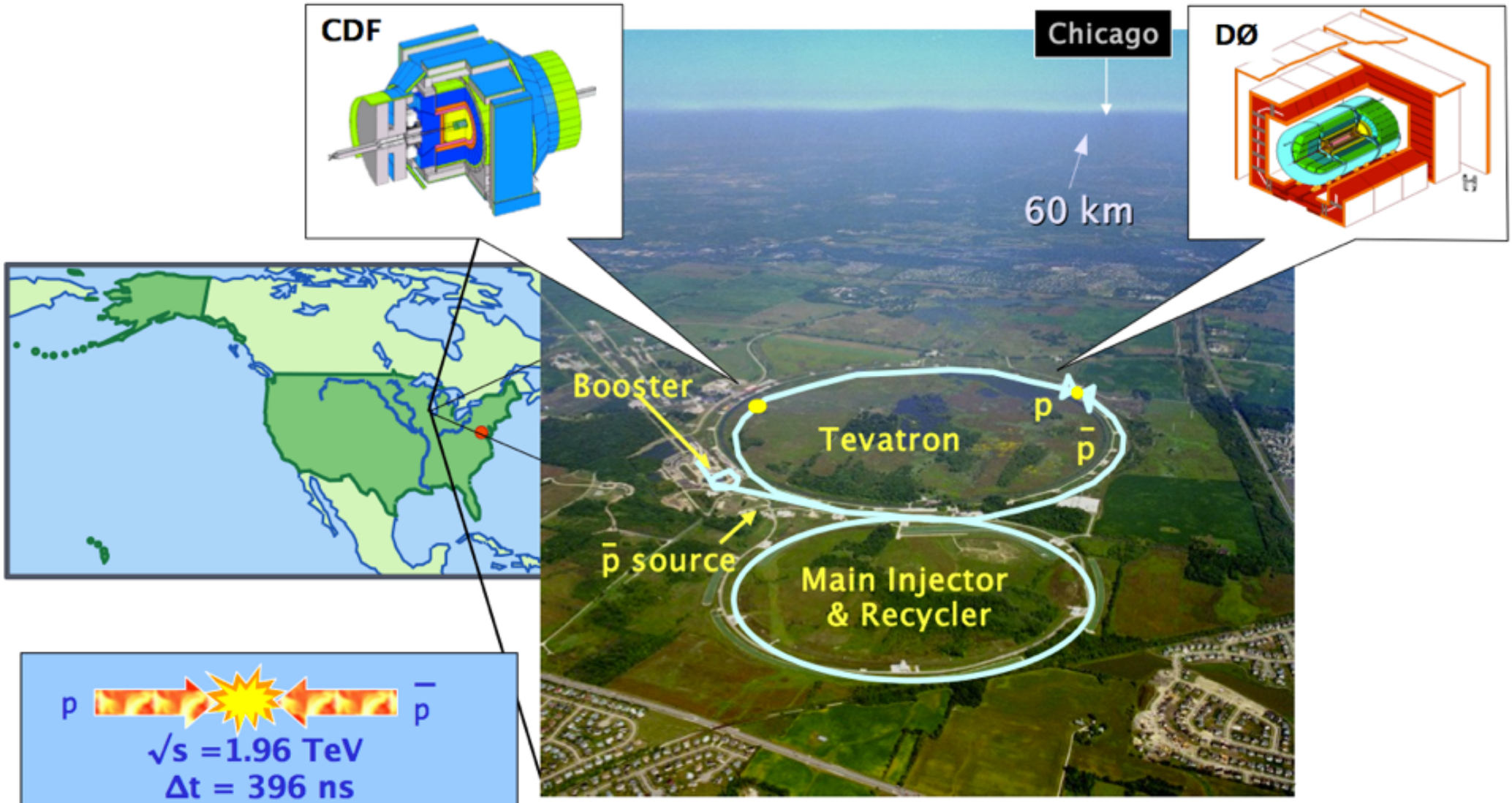
➔ **from the smallest dimensions in microcosm to the largest dimensions in the Universe**

Big Bang in the Lab?





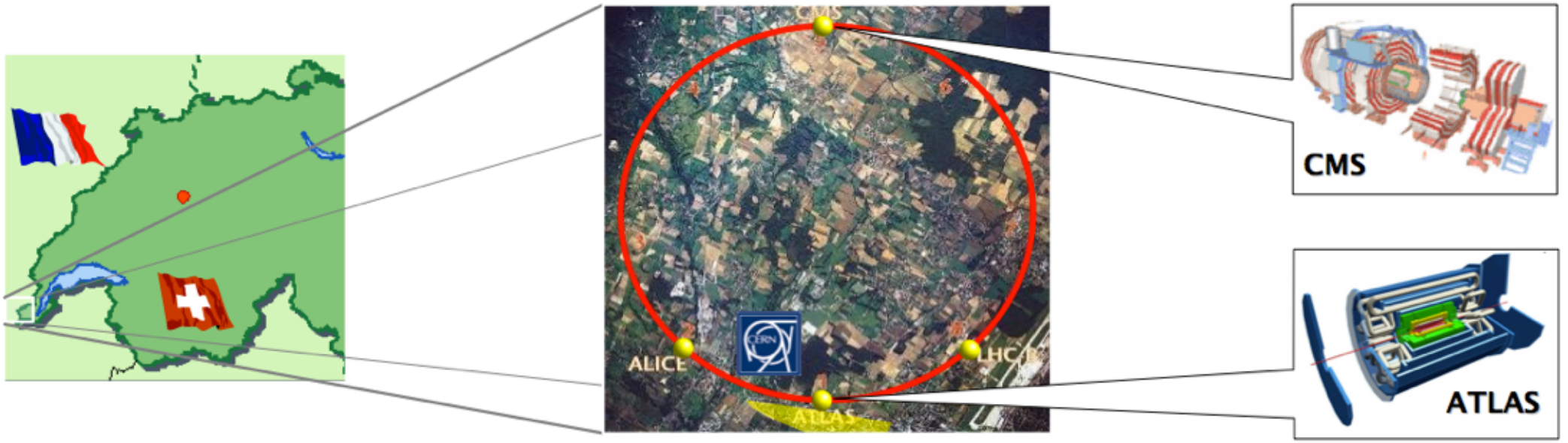
The Tevatron $p\bar{p}$ Collider at Fermilab



$\sqrt{s}$ = 1.96 TeV
Δt = 396 ns

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

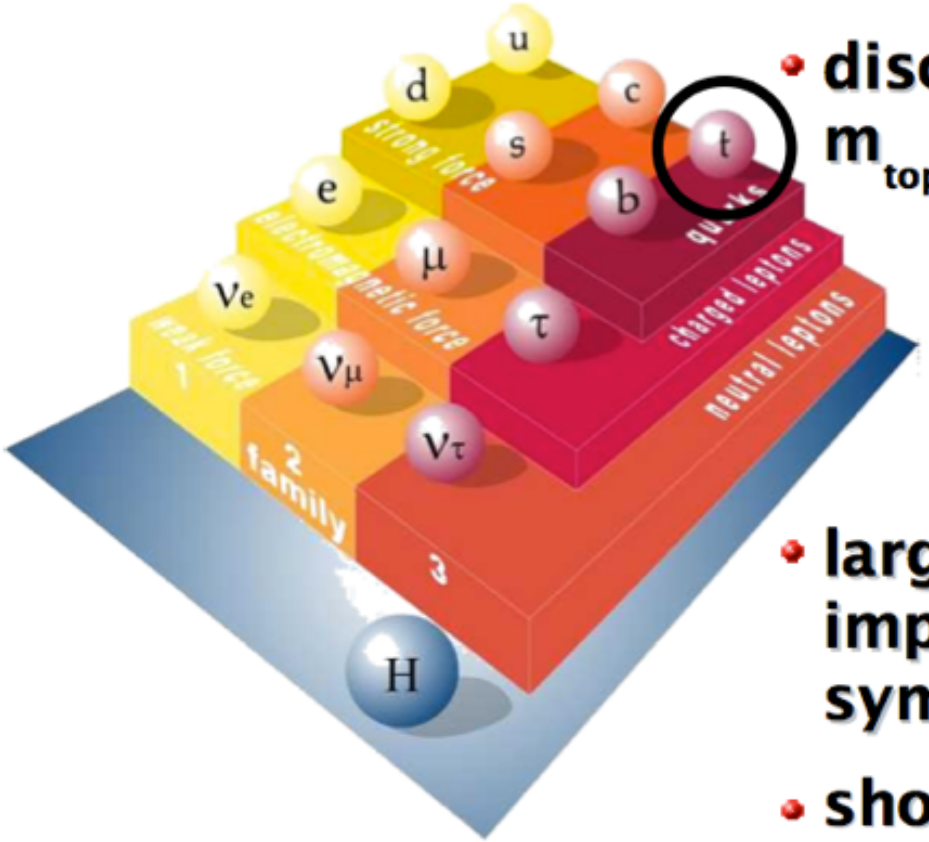
The LHC pp Collider at CERN



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

June 3rd, 2015: First Collisions @ 13 TeV

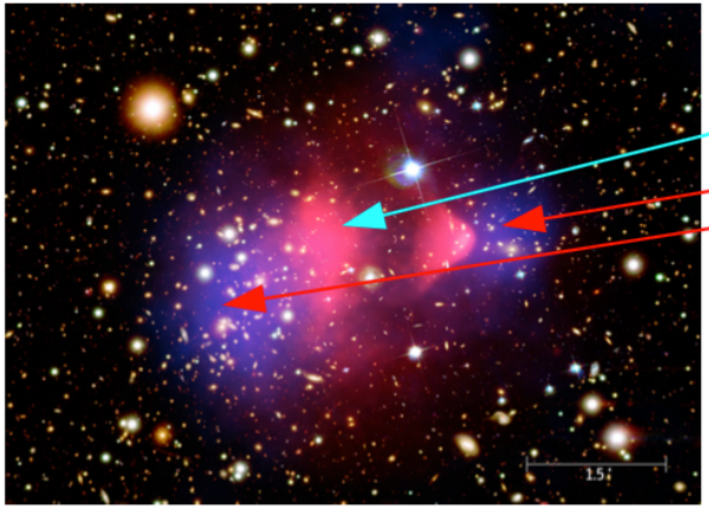
The Top Quark

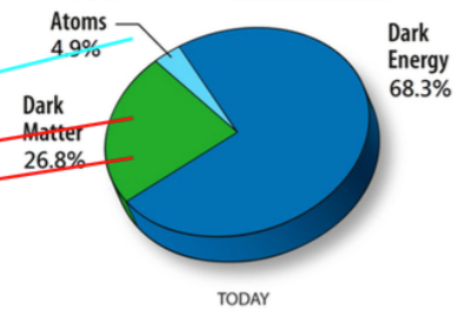


- needed as isospin partner of bottom quark
- discovered in 1995 by CDF and DØ: m_{top} ~ gold nucleus
- large coupling to Higgs boson ~ 1: important role in electroweak symmetry breaking?
- short lifetime: $\tau \sim 5 \cdot 10^{-25}$s $\ll \Lambda^{-1}_{QCD}$: decays before fragmenting → observe "naked"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

Is the top quark the particle as predicted by the SM?

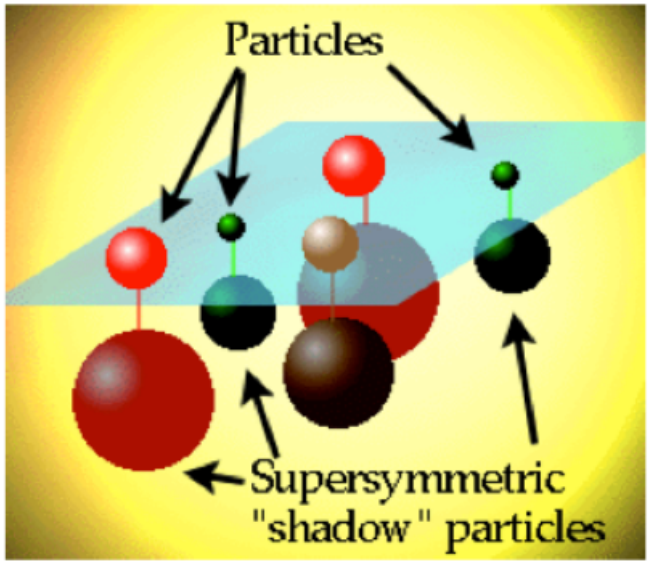
Search for New Phenomena





Dark matter inferred from star motion and gravitational lensing

Supersymmetry:

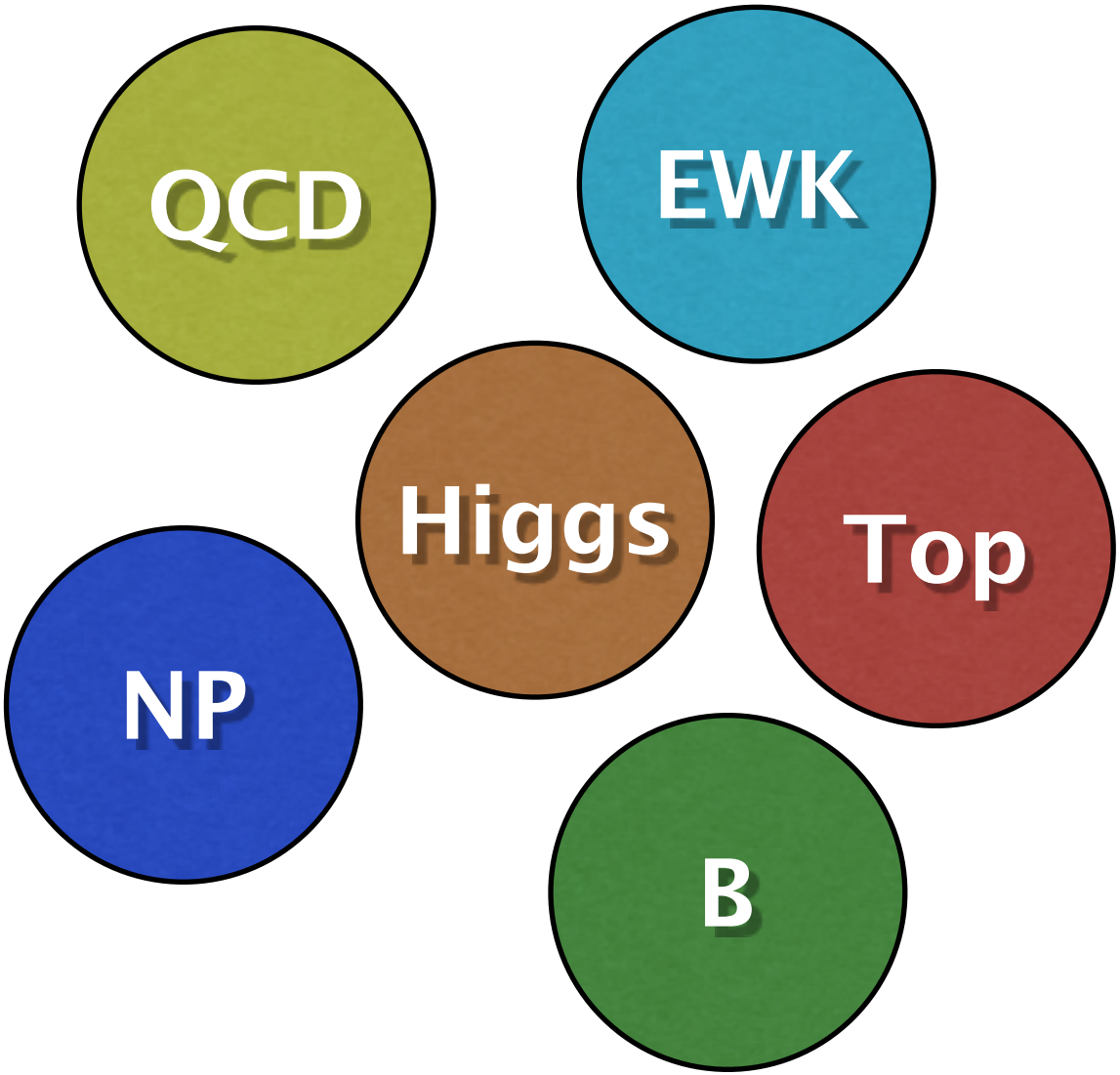


Name	Spin	Superpartner	Spin
Electron	1/2	Selectron	0
Muon	1/2	Smuon	0
Tau	1/2	Stau	0
Neutrino	1/2	Sneutrino	0
Quark	1/2	Squark	0

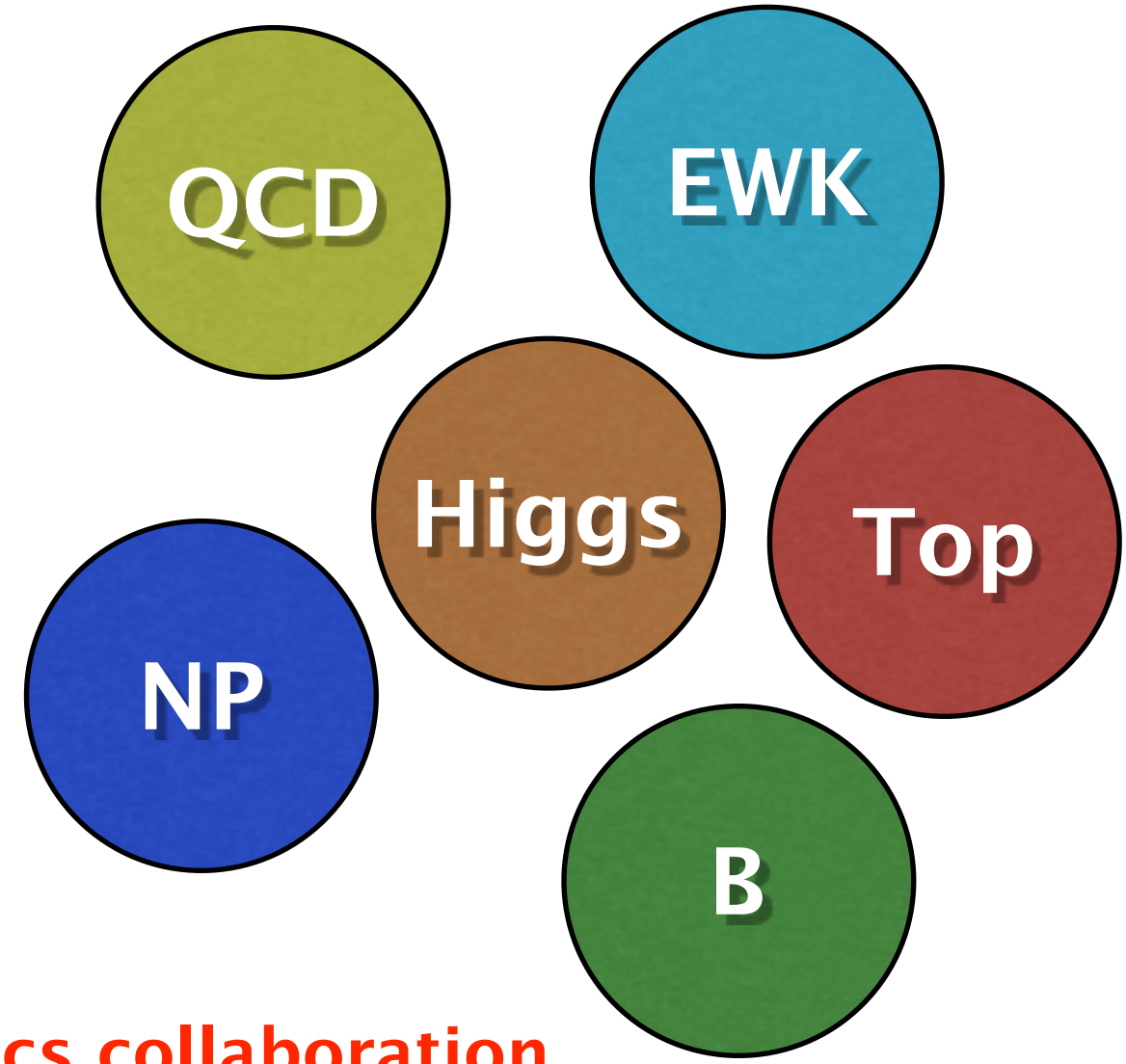
Name	Spin	Superpartner	Spin
Graviton	2	Gravitino	3/2
Photon	1	Photino	1/2
Gluon	1	Gluino	1/2
$W^{+,-}$	1	$Wino^{+,-}$	1/2
Z^0	1	Zino	1/2
Higgs	0	Higgsino	1/2

remedies shortcomings of SM: e.g. dark matter candidate

Physics Groups: DØ Collaboration

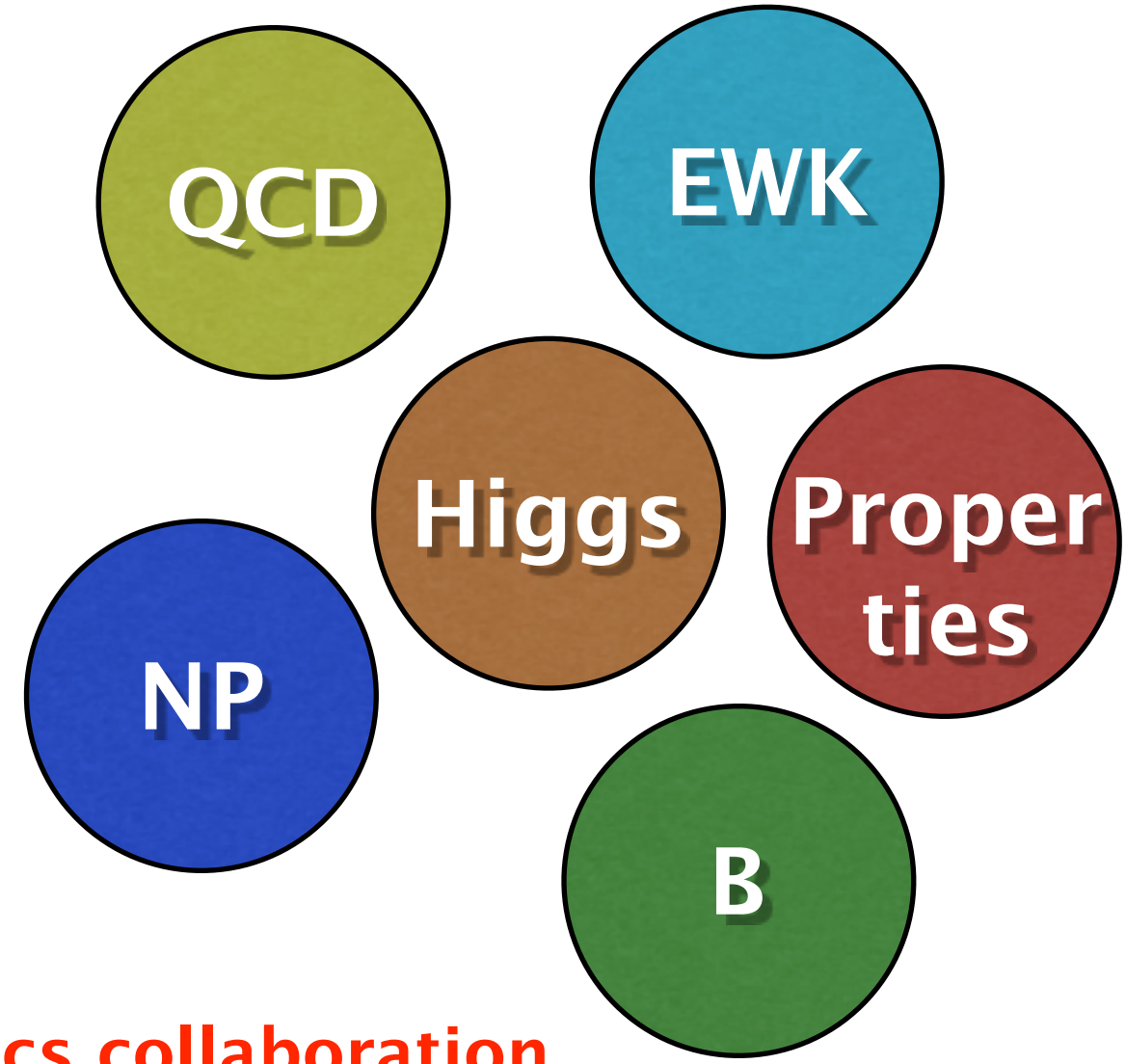


Top Quark Physics Topics



→ top physics collaboration

Top Quark Physics Topics



→ top physics collaboration

Top Quark Physics Topics

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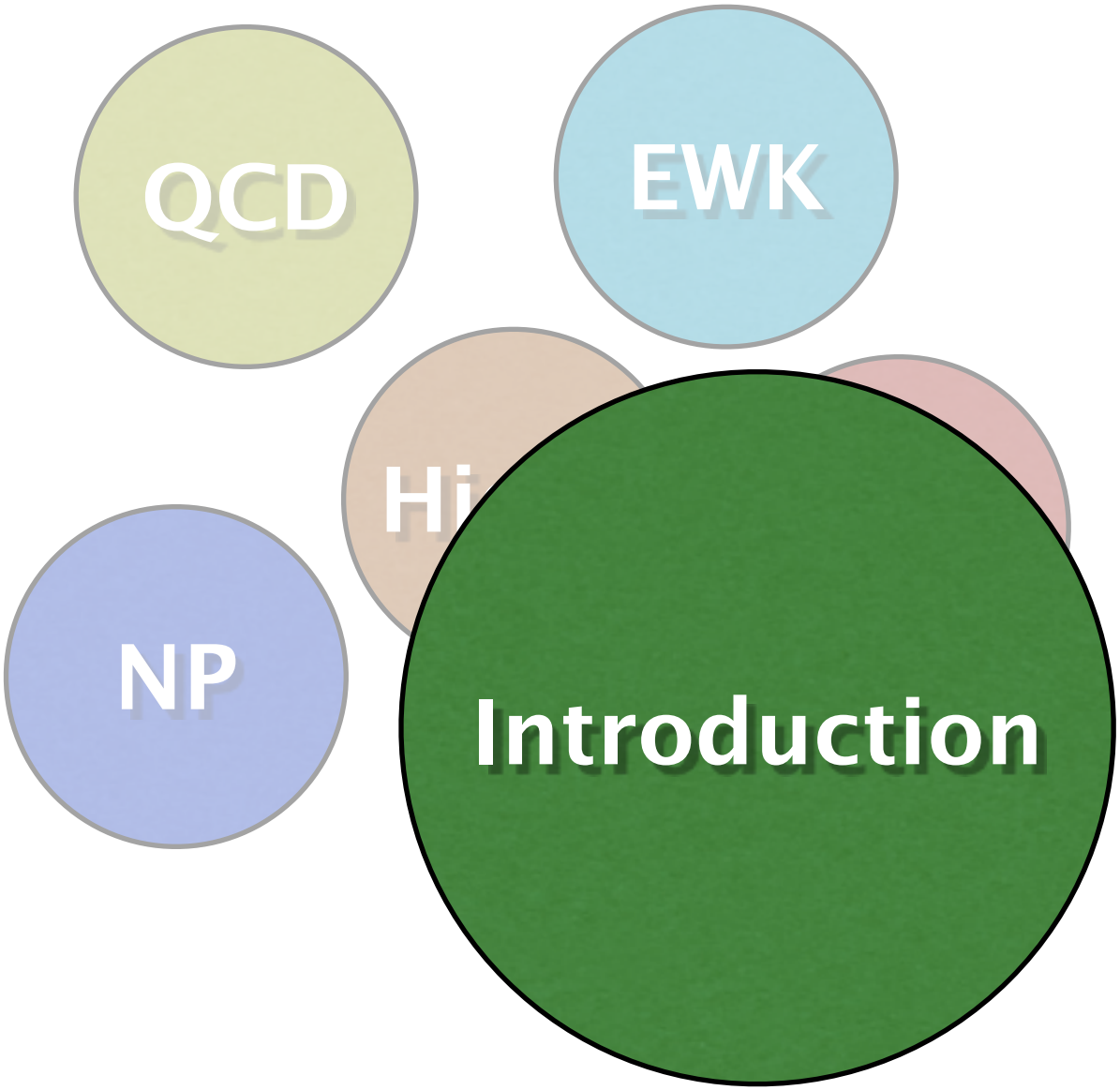
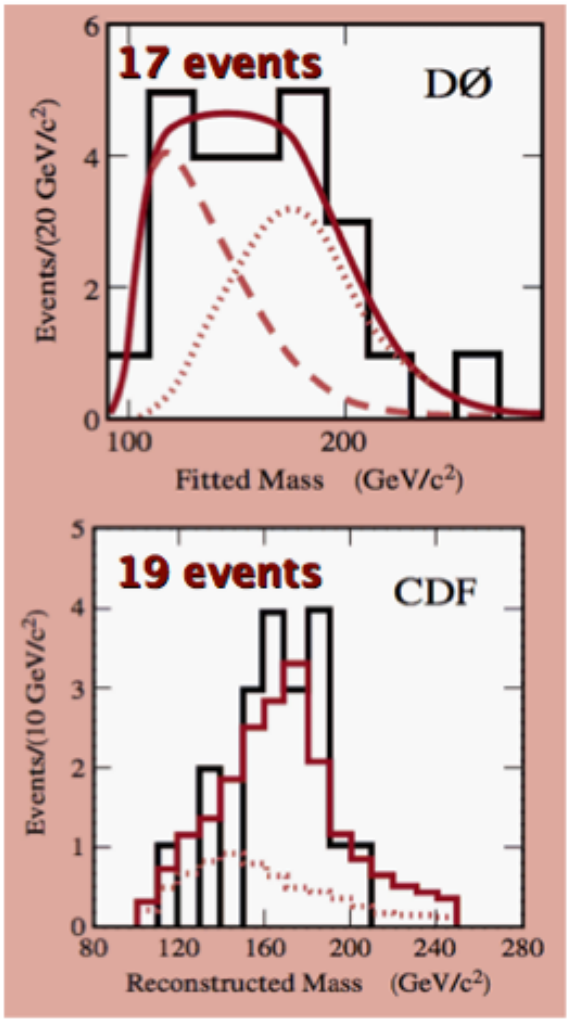
Top Quark Physics Topics



The Top Quark

discovery

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



1995, CDF and DØ experiments, Fermilab

March 2nd, 1995:

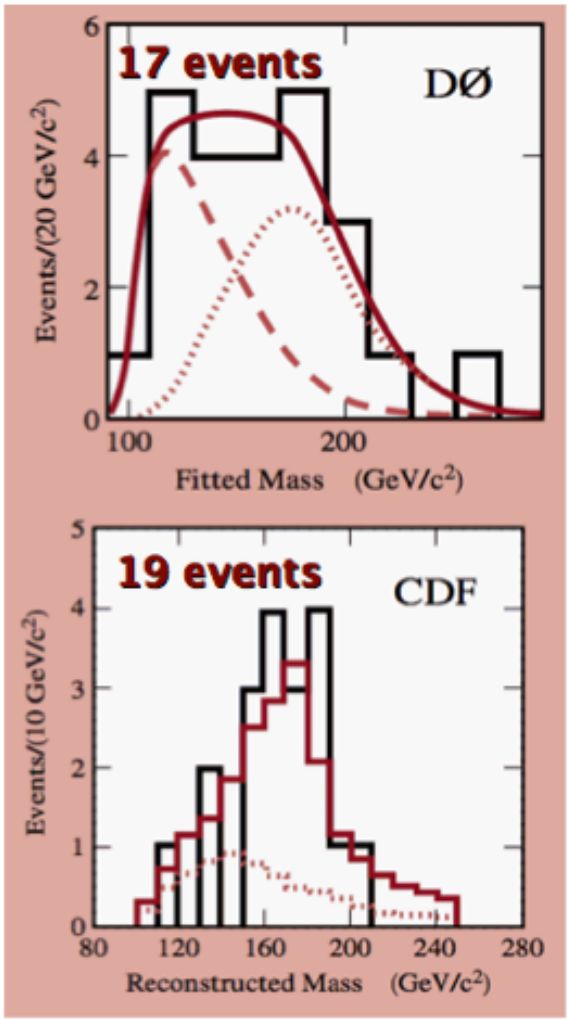
First announcement of Top Discovery

in public seminar at Fermilab

The Top Quark

discovery

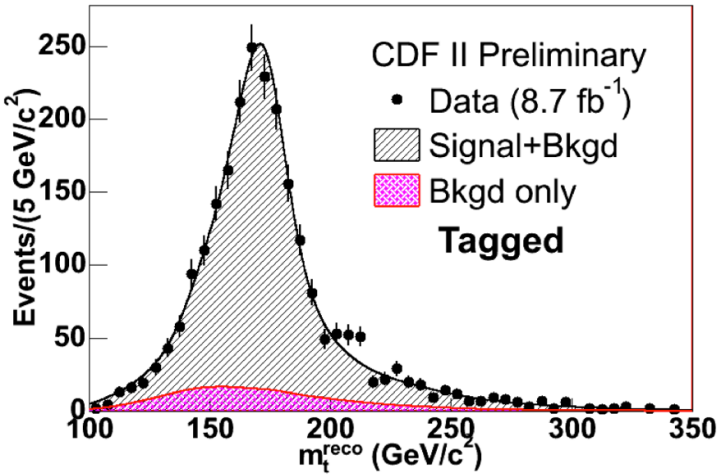
PRL 74, 2632 (1995)
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

today

1000s of events



The Top Quark

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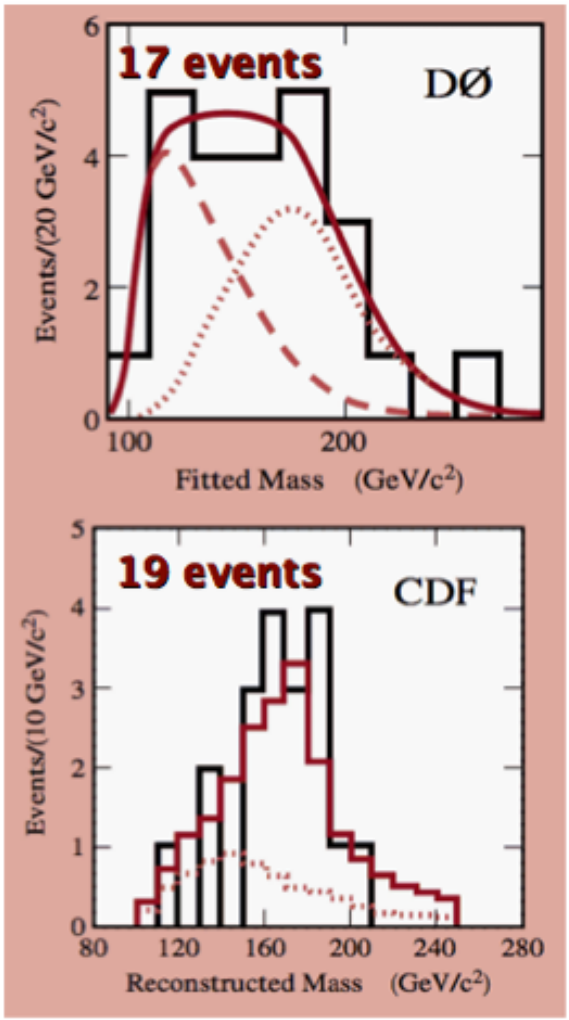

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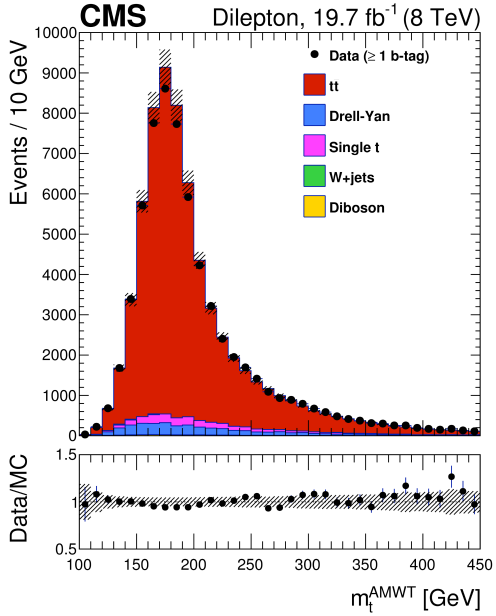
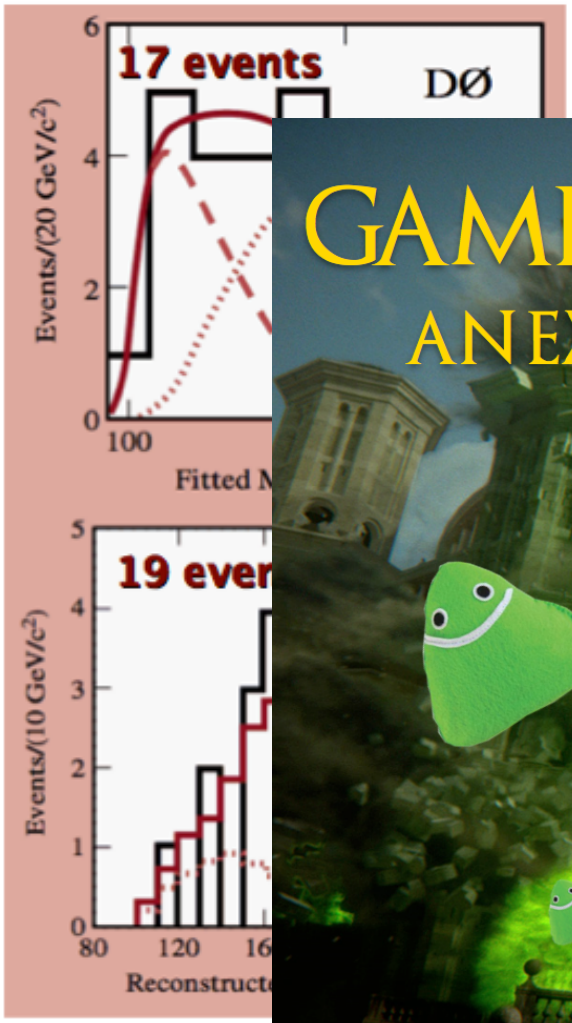


LHC: top quark factory

The Top Quark

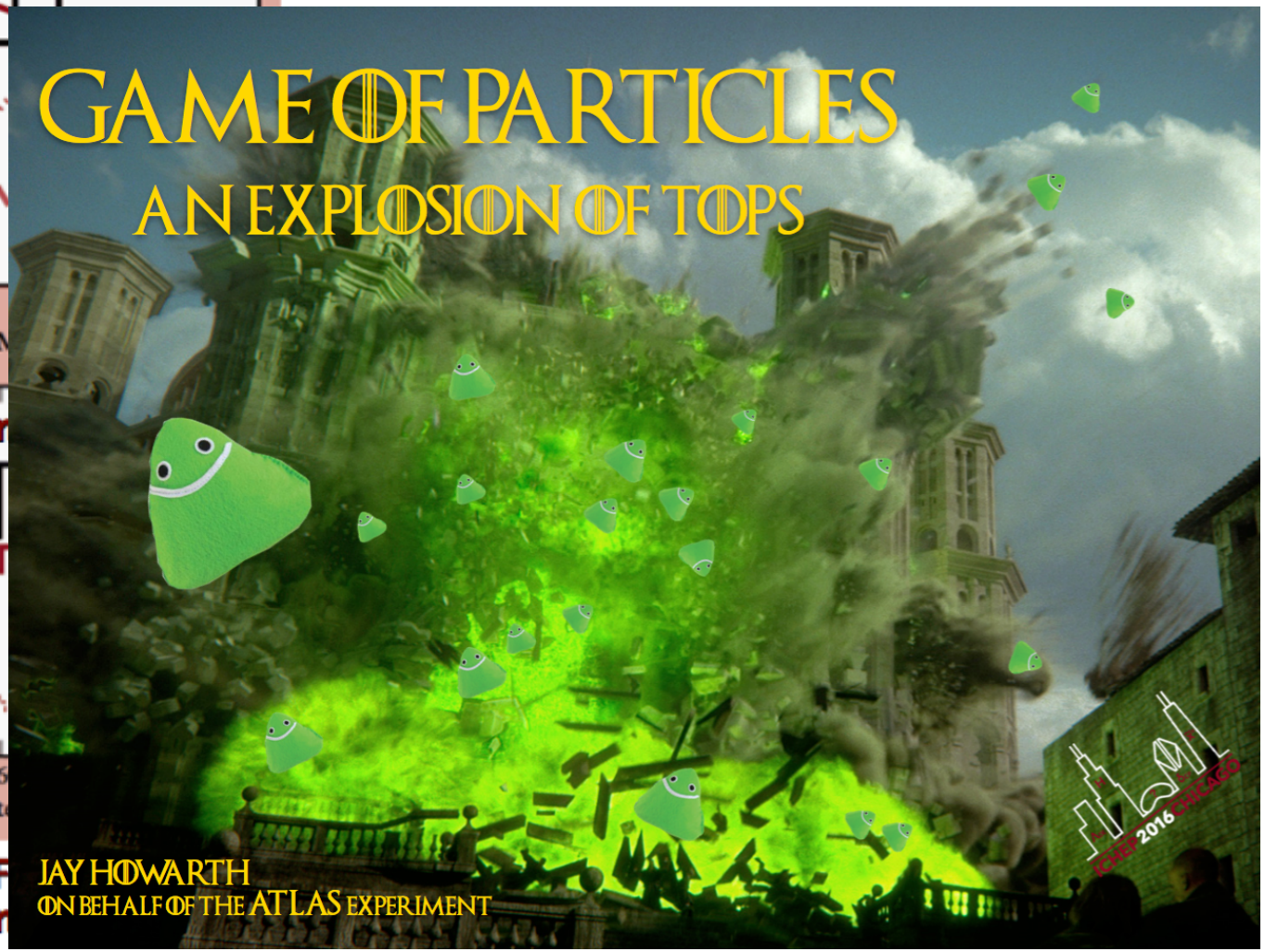
discovery

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



1995, CDF
experimen

today



The Top Quark

discovery

PRL 74, 2632 (1995)
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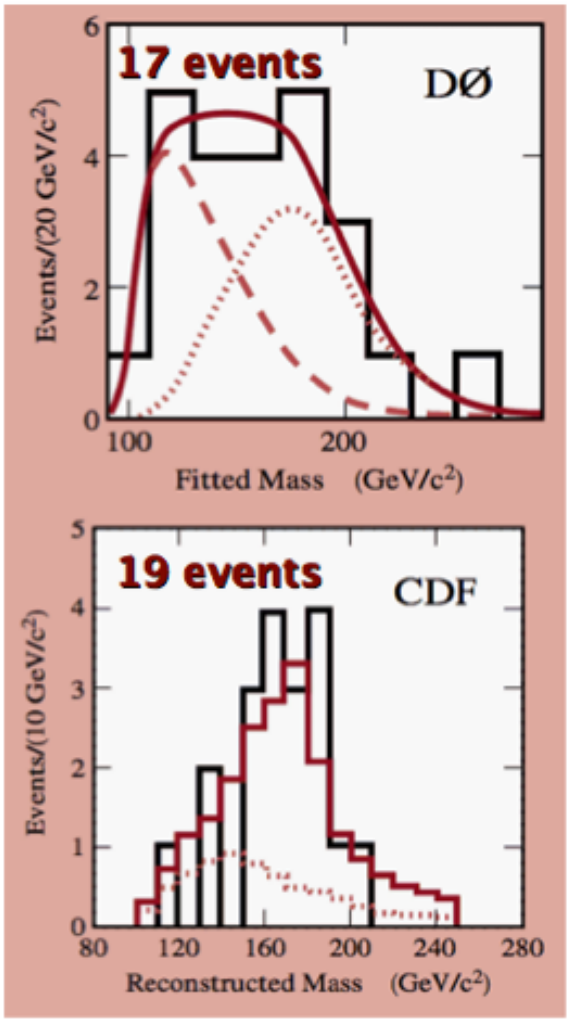

1995, CDF and DØ experiments, Fermilab

today

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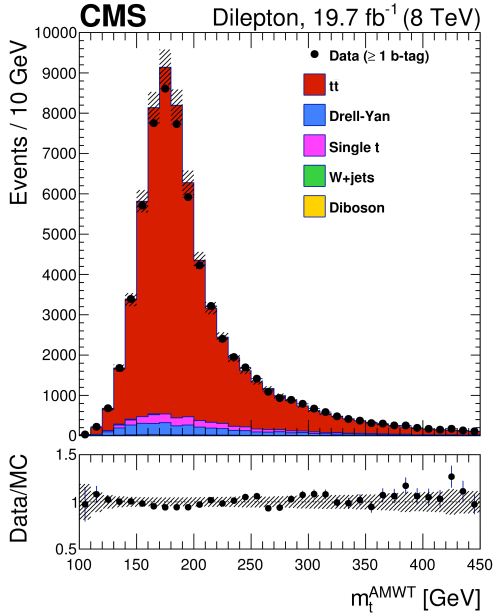
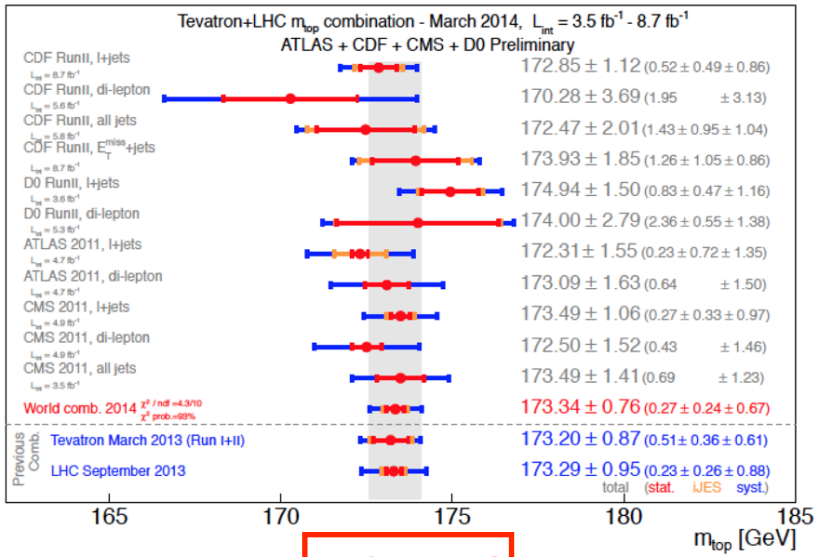


LHC: top quark factory

precision



±0.44%

The Top Quark

discovery

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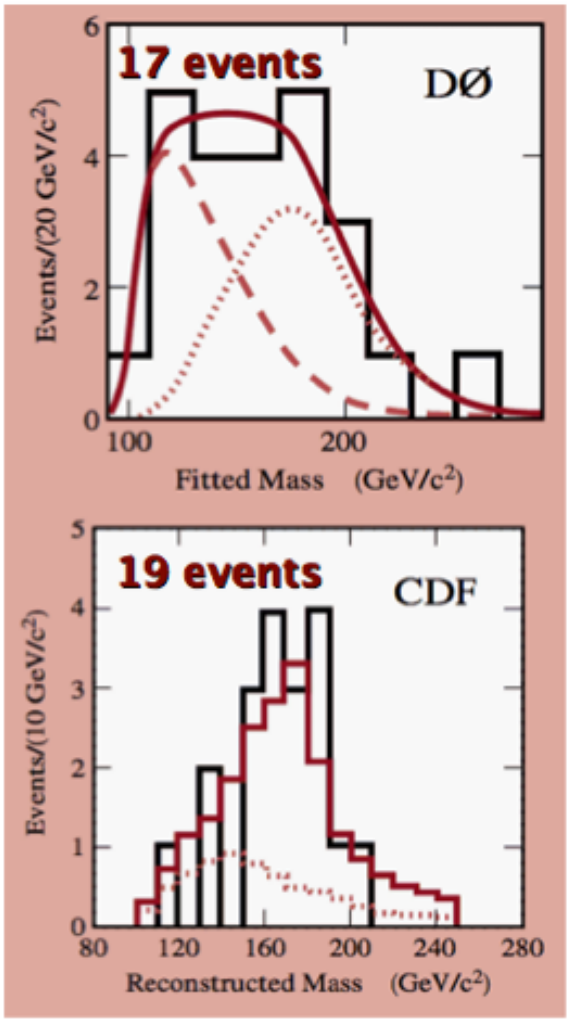
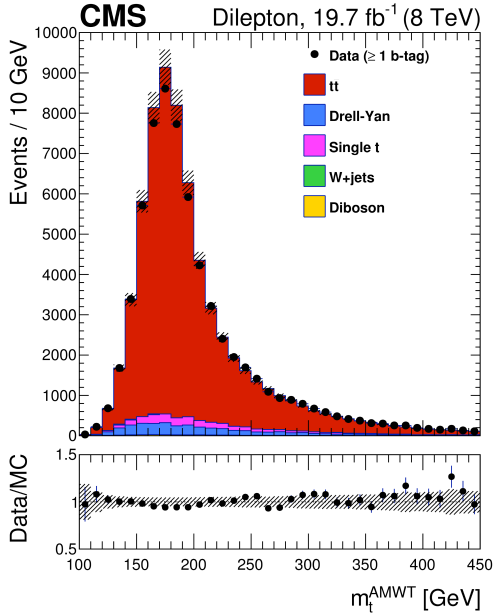
PRL 74, 2626 (1995)



1995, CDF and DØ experiments, Fermilab

today

100000s of events



LHC: top quark factory

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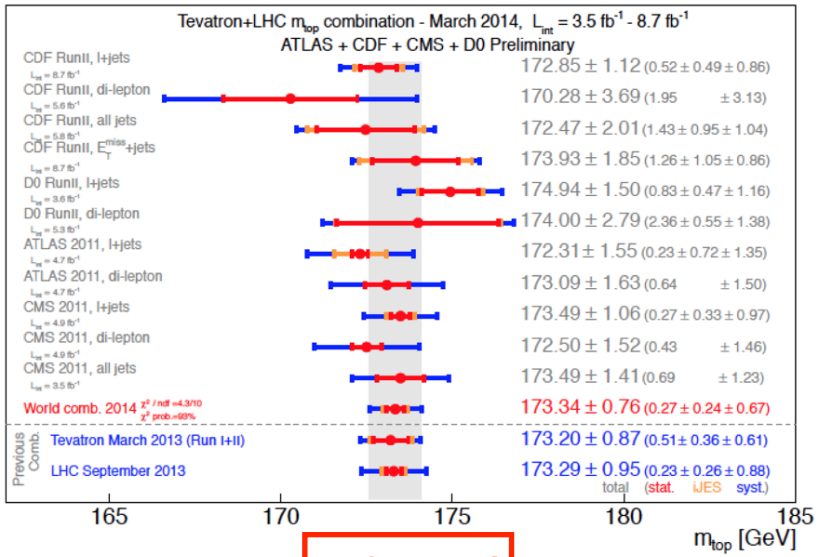
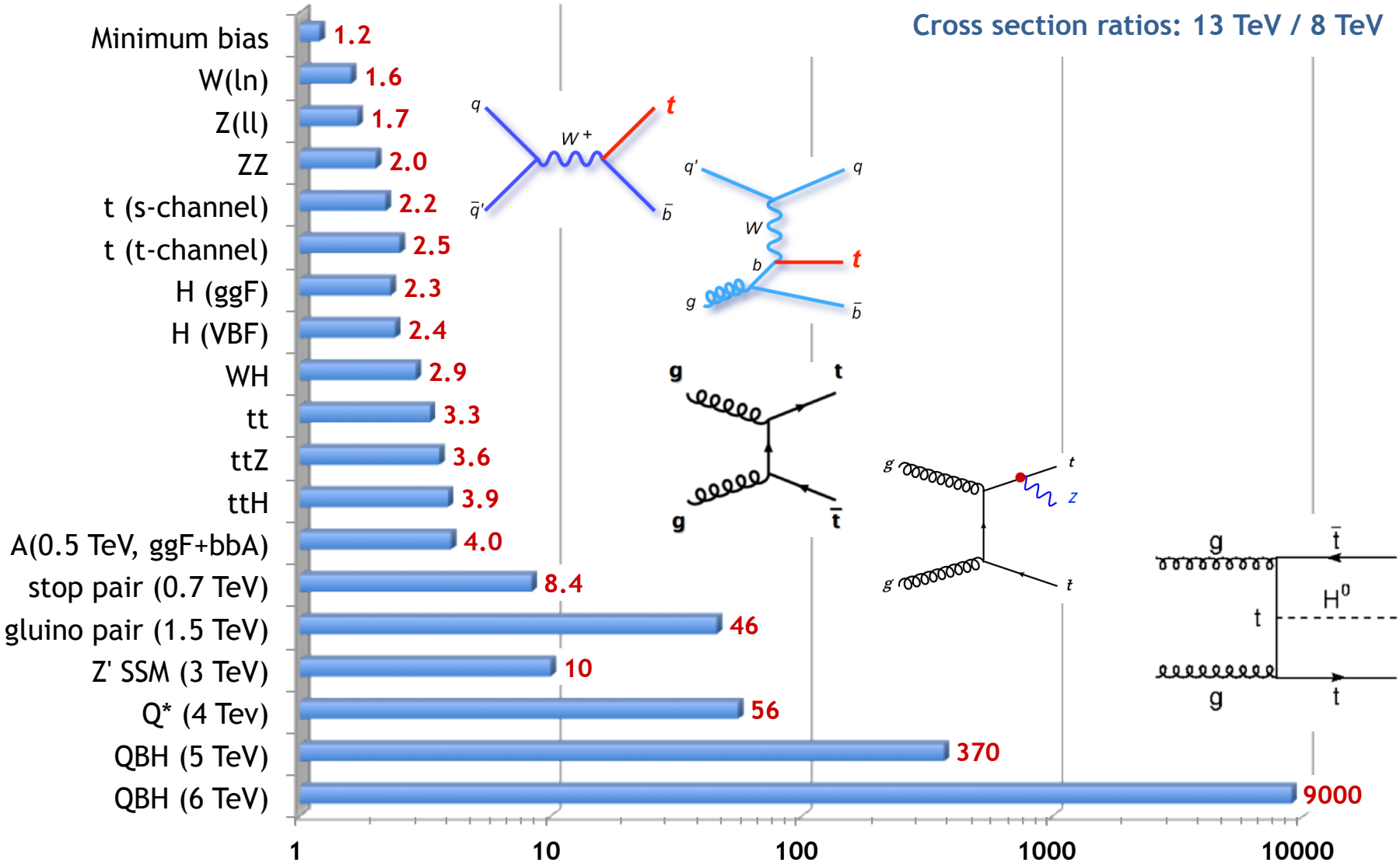


±0.44%

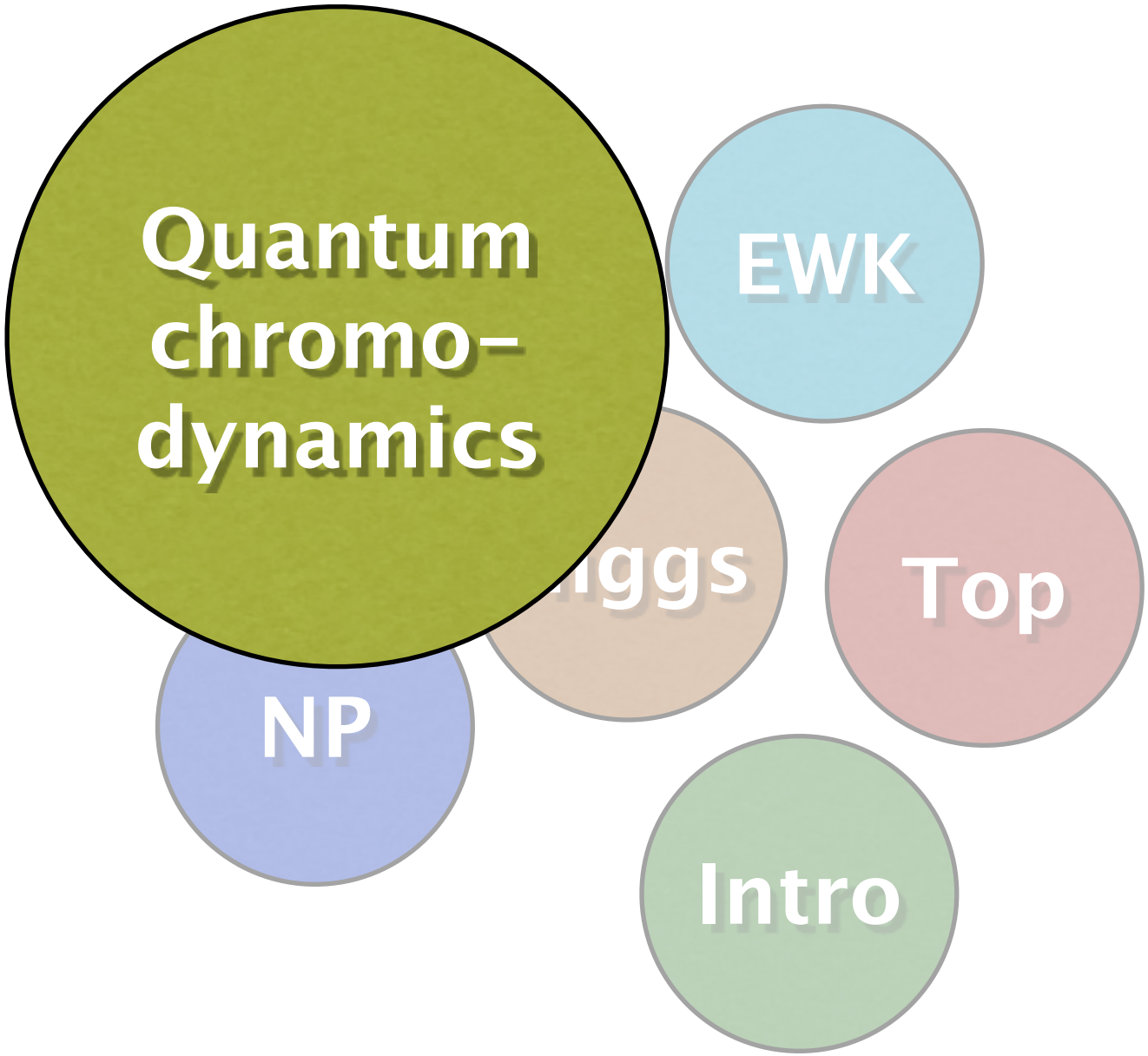
searches

Cross Sections: 13 TeV/8 TeV

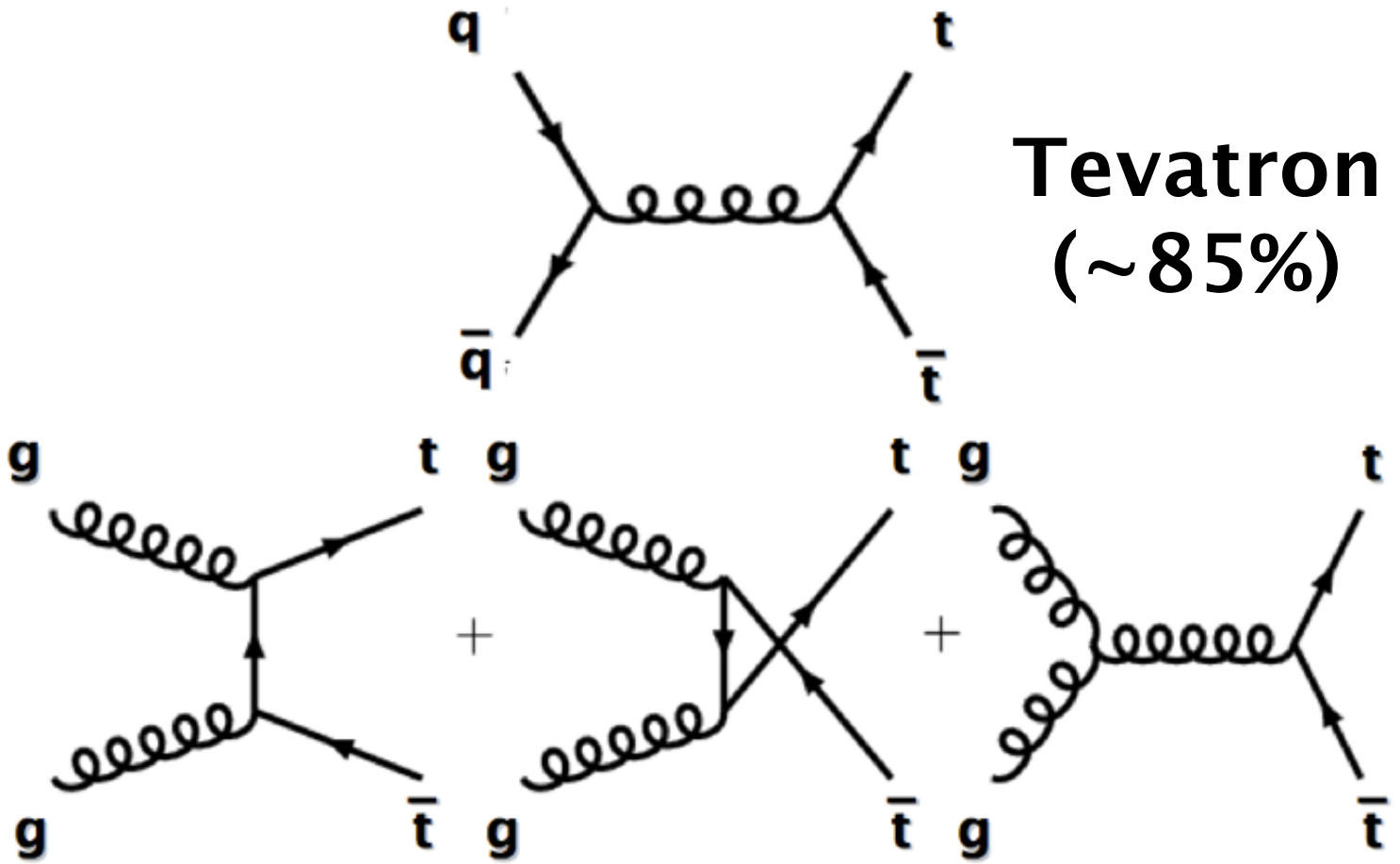


→ excellent prospects for top physics

Top Quark Physics Topics



Top Quark Pair Production

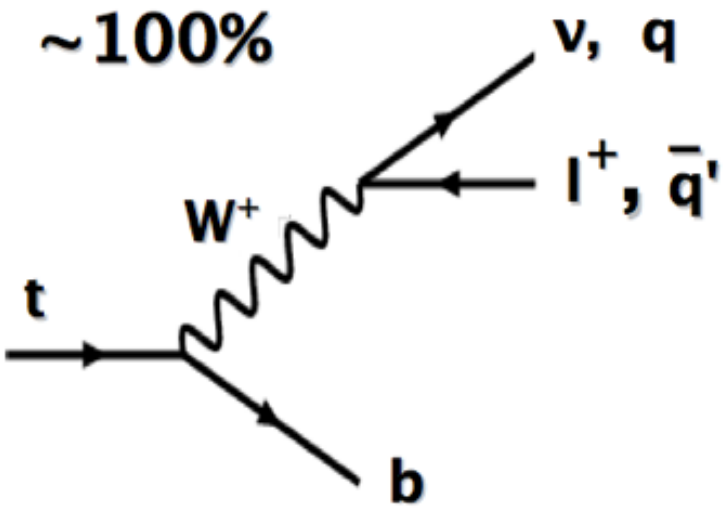


Tevatron (~85%)

LHC (~87%)
(8 TeV)

Top Quark Pair Signatures

top decay:



τ's 14%

alljets 46%

Top Pair Decay Channels

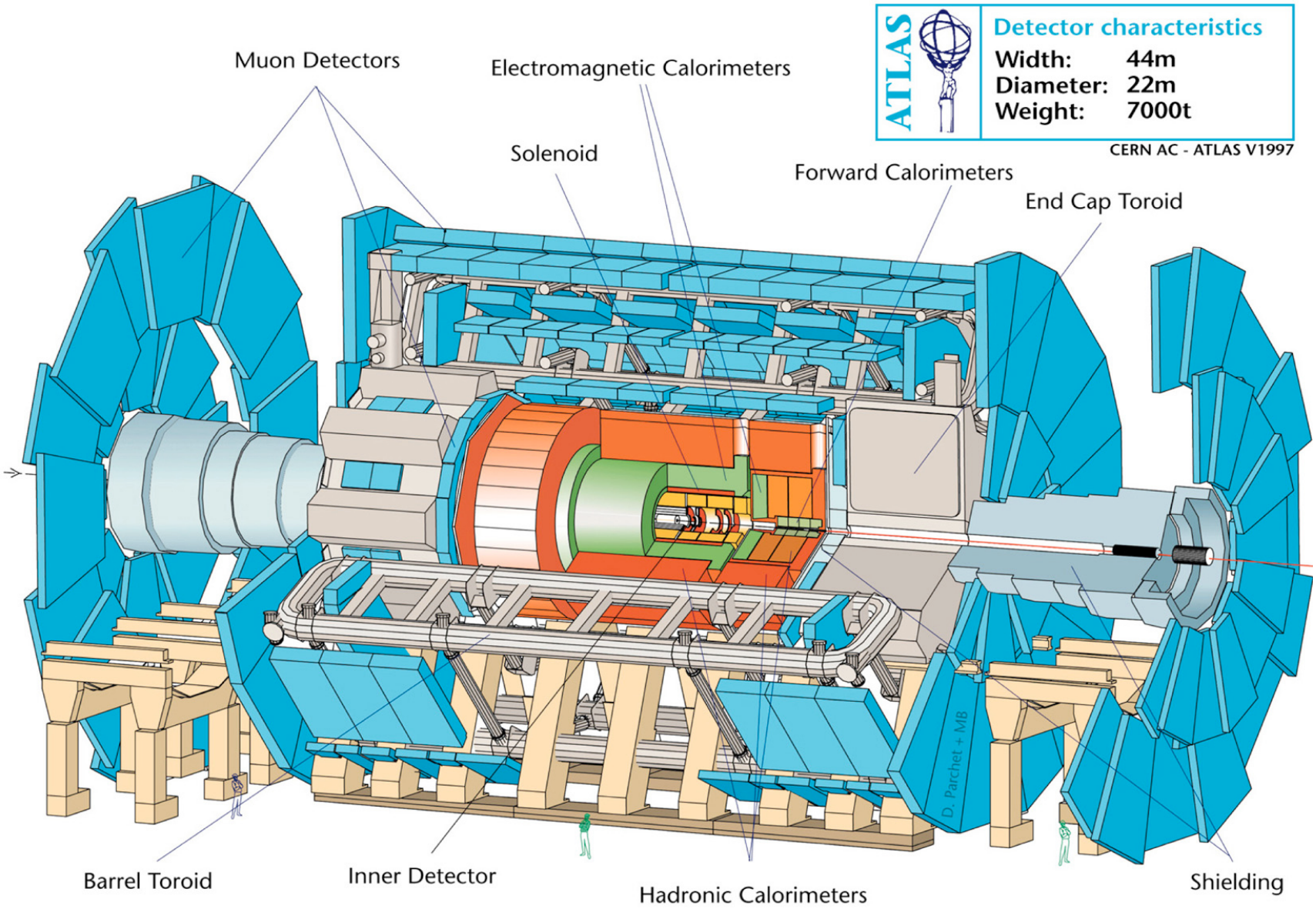
W decay	e^+	μ^+	τ^+	$u\bar{d}$	$c\bar{s}$
e^-	ee	$e\mu$	$e\tau$	electron+jets	
μ^-	$e\mu$	$\mu\mu$	$\mu\tau$	muon+jets	
τ^-	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets	
$\bar{u}d$	electron+jets	muon+jets	tau+jets	all-hadronic	
$\bar{c}s$					

dileptons

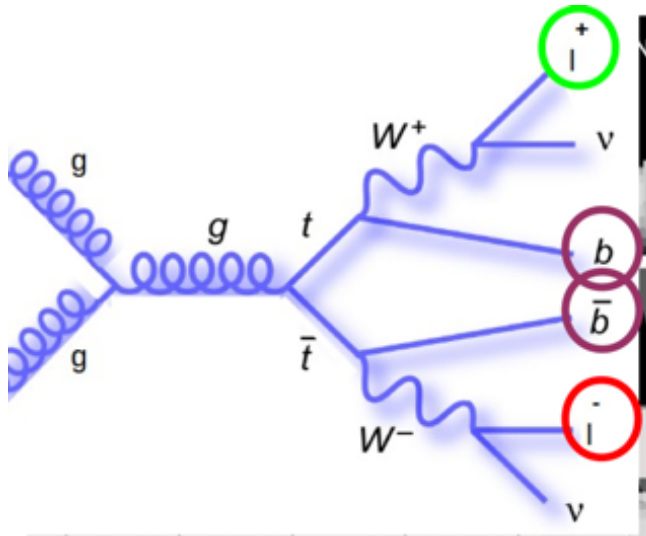
dilepton (e/μ) 6%

e/μ+jets 34%

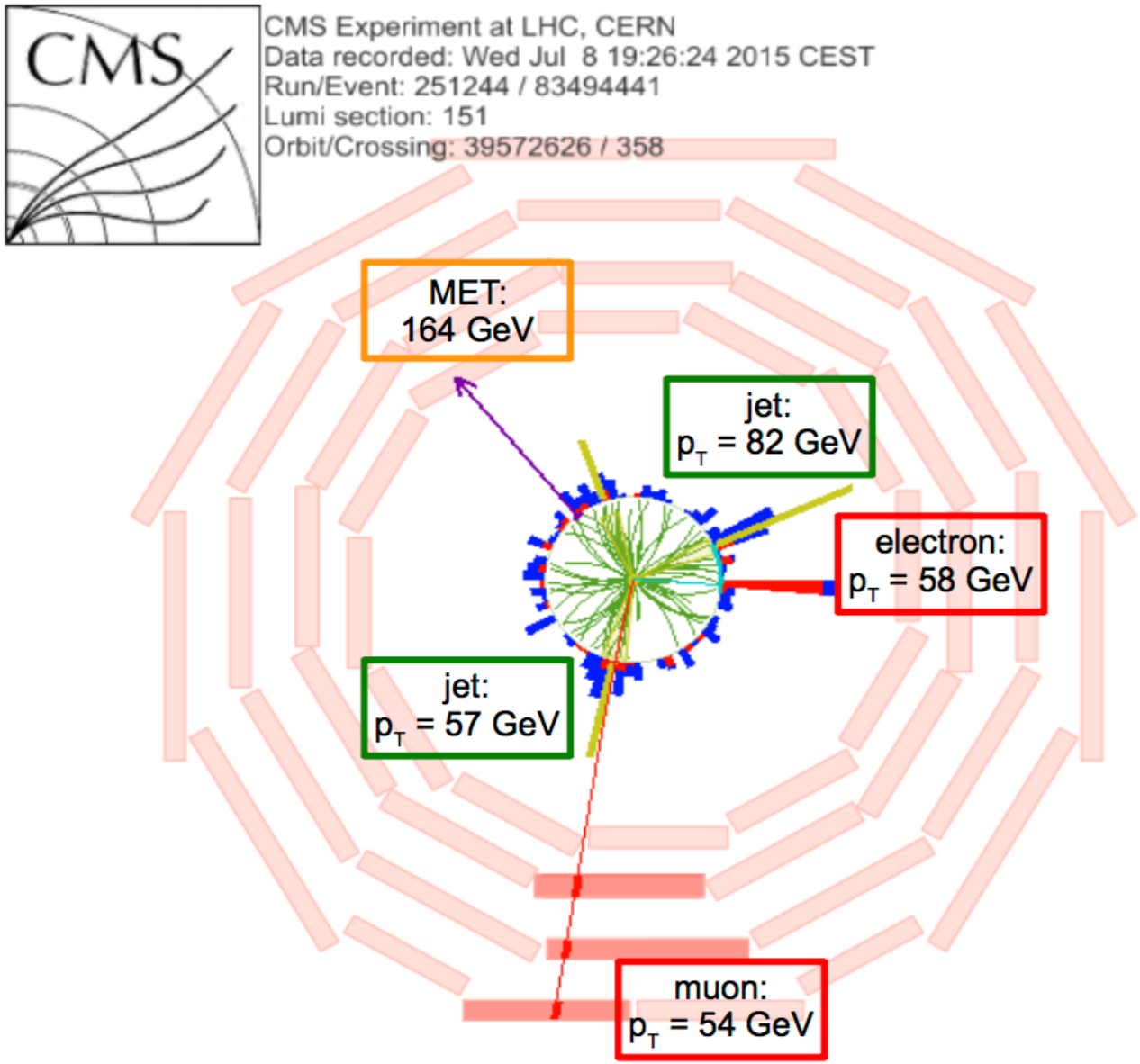
ATLAS Detector

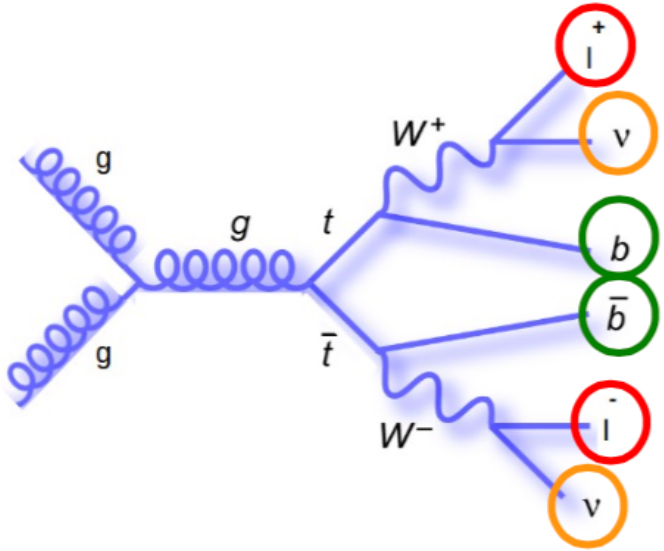


Dilepton Event

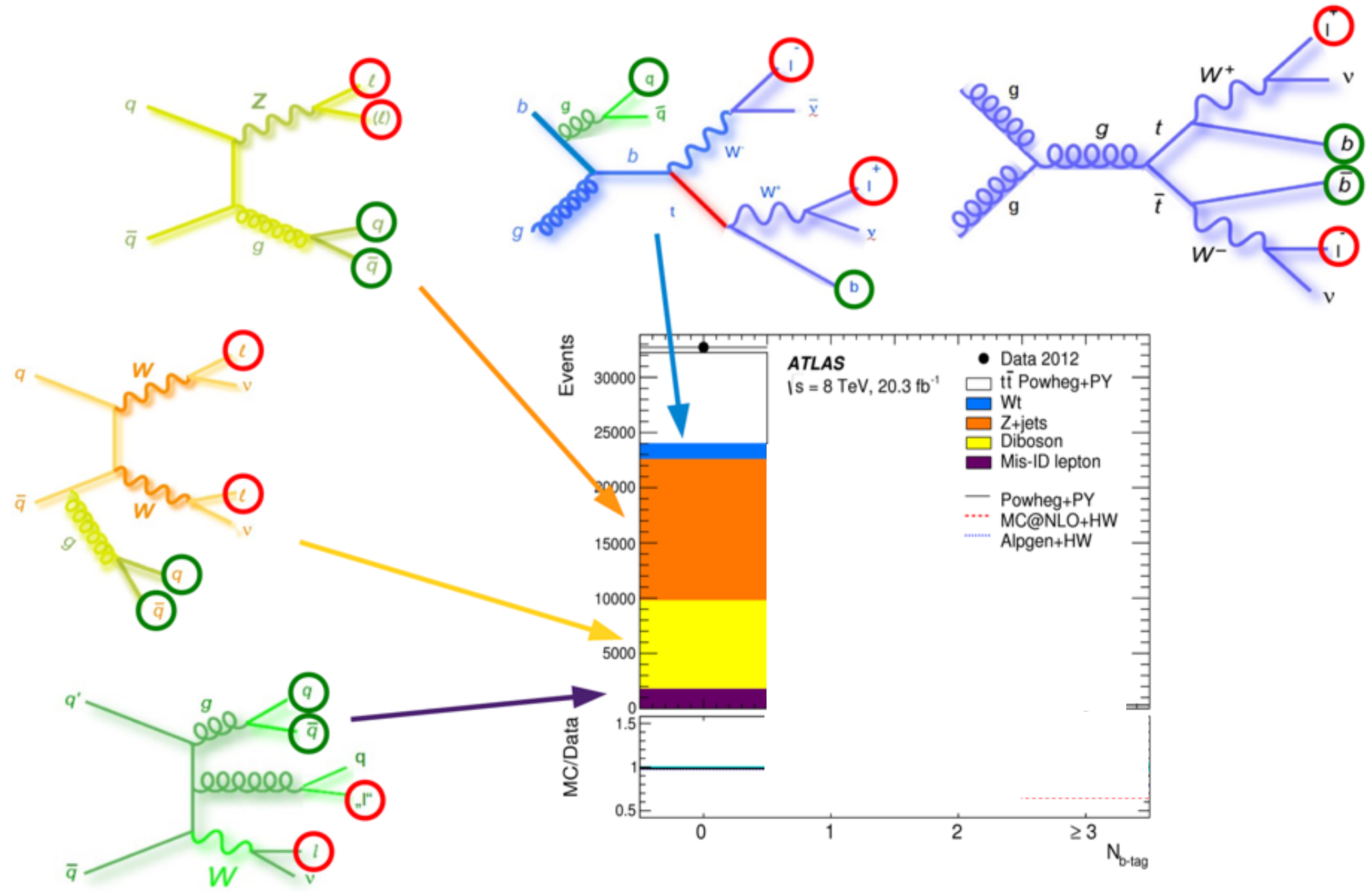


Dilepton Signature





Dilepton Signatures



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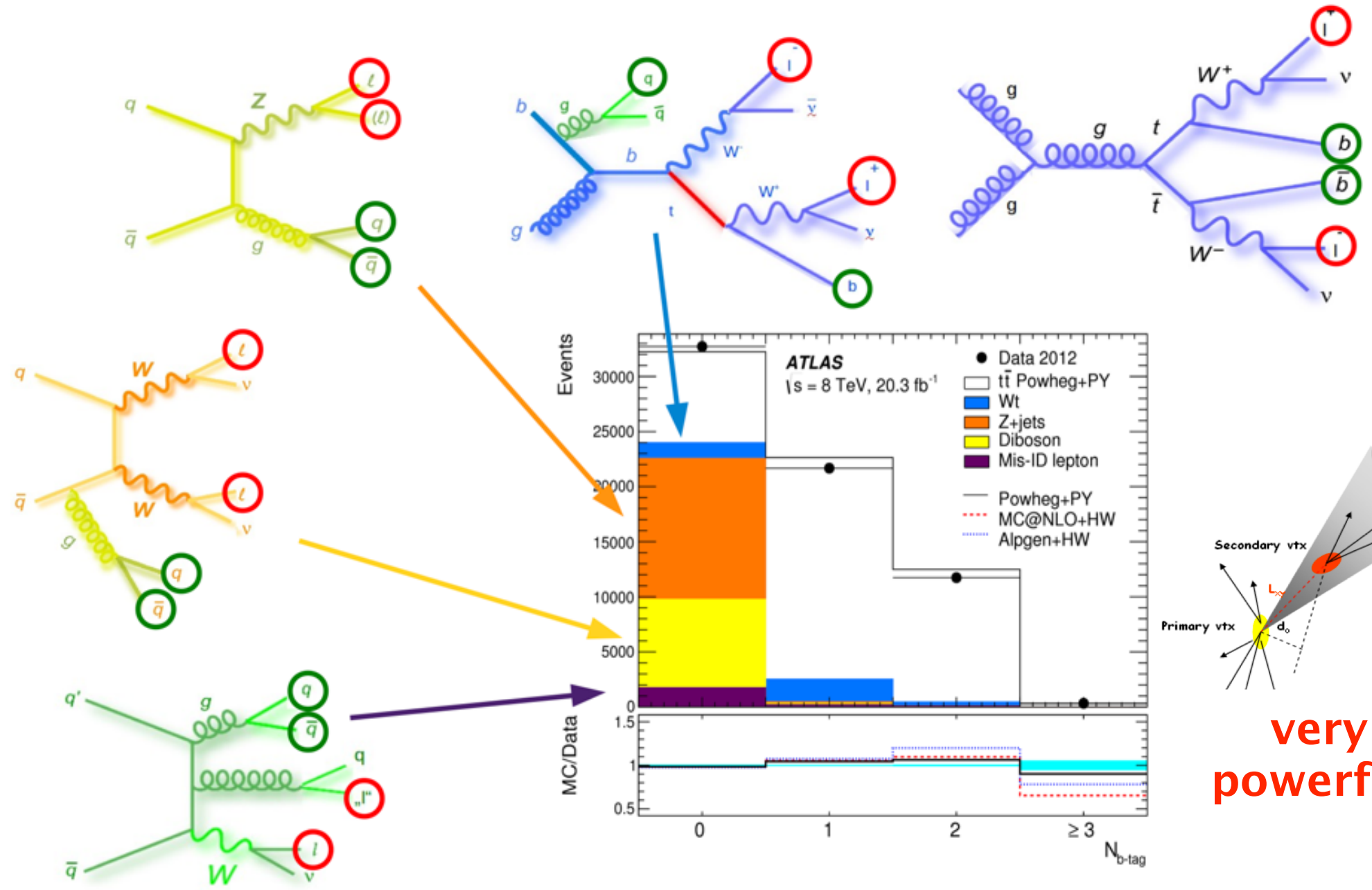
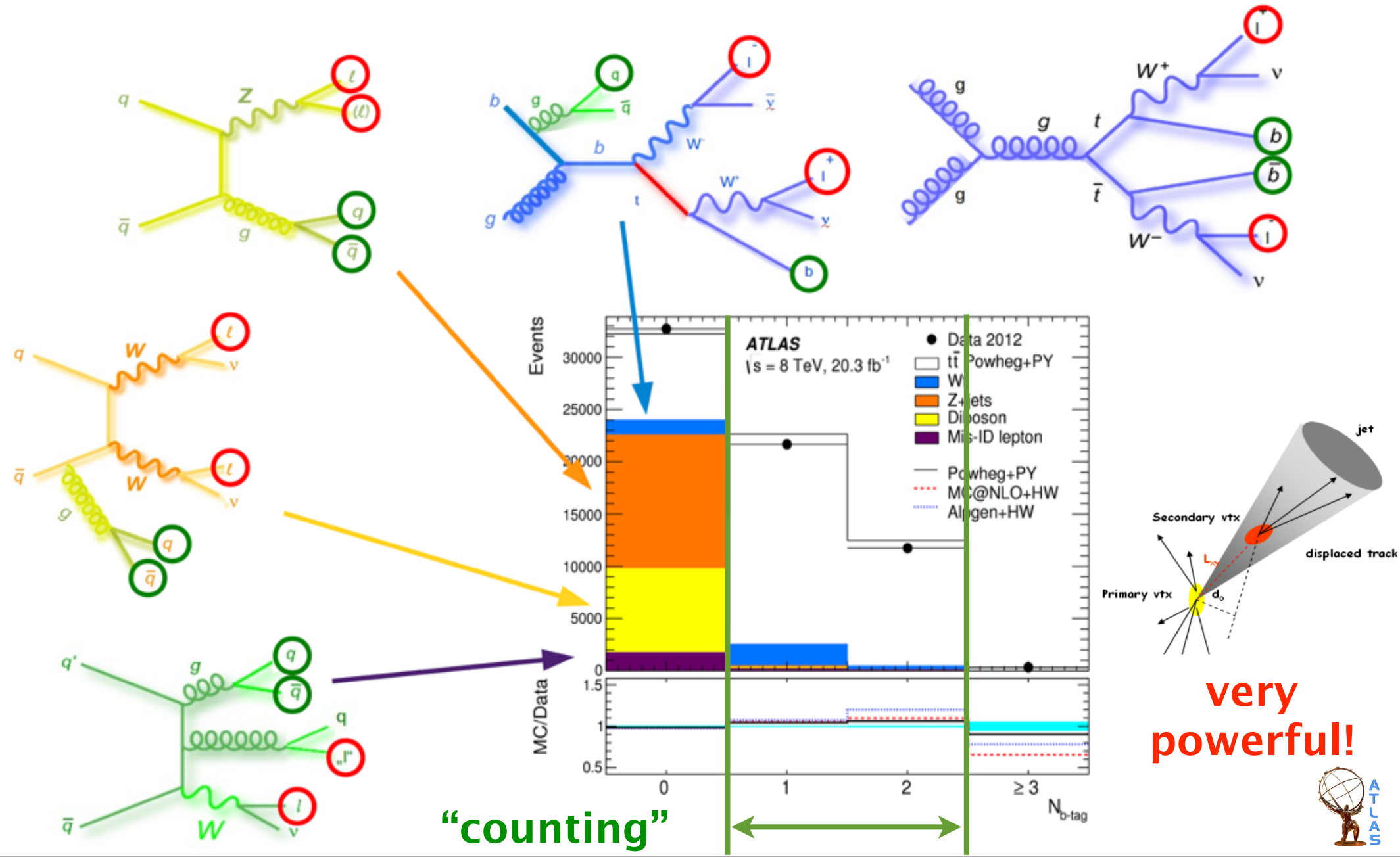
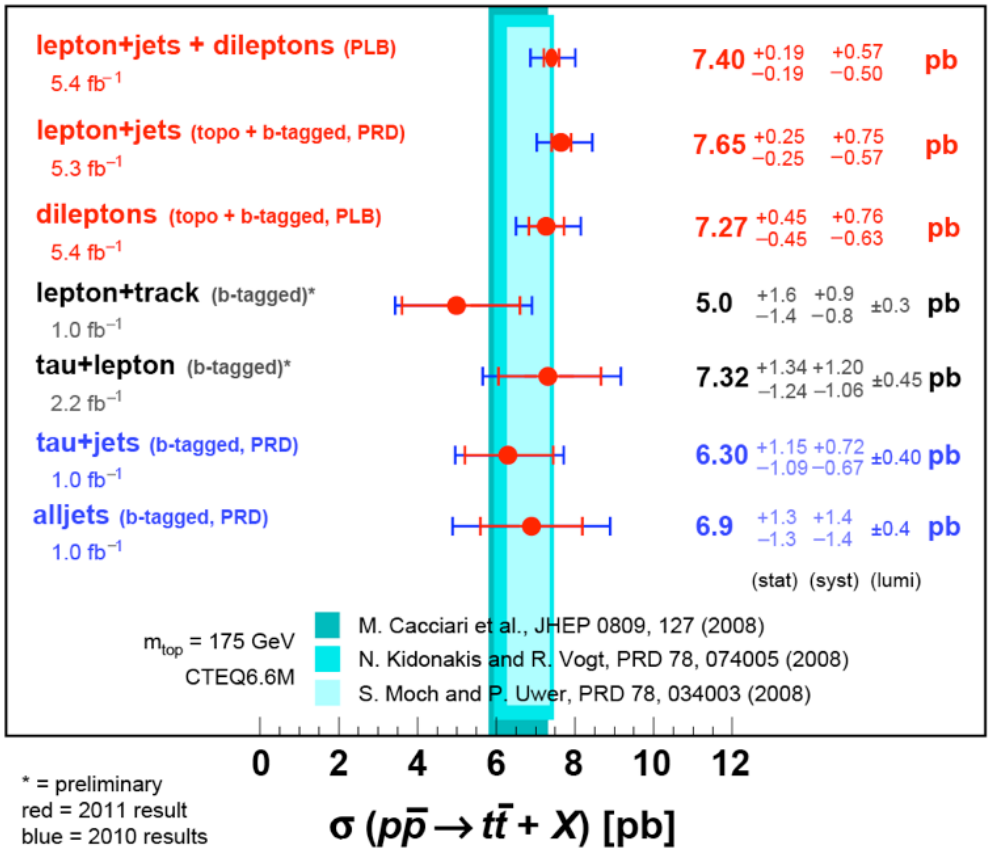
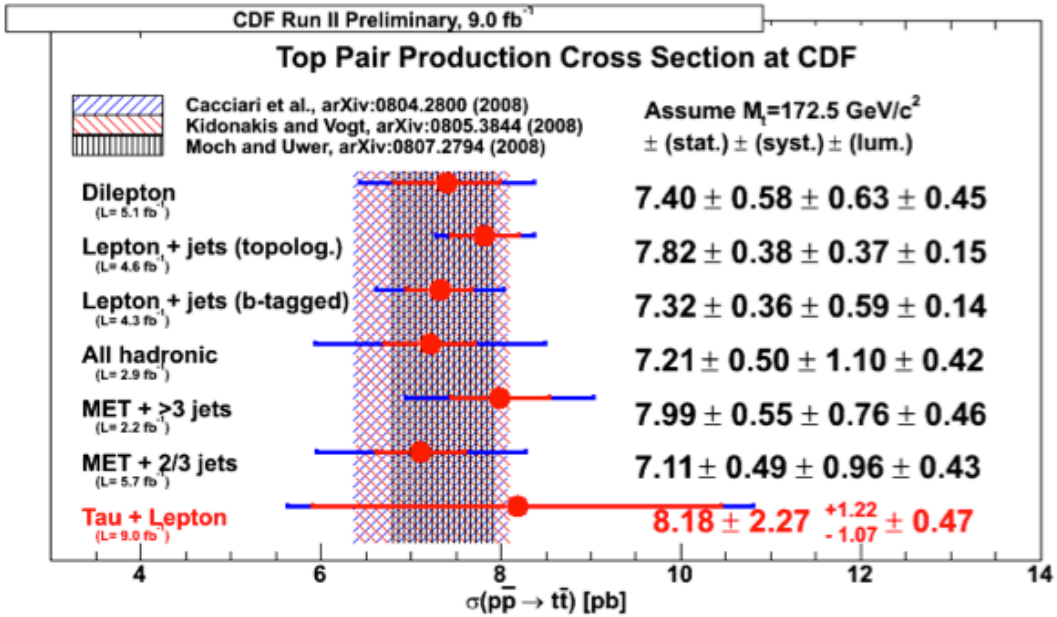


Dilepton Signatures with b-tagging



Top Pair Production Cross Section

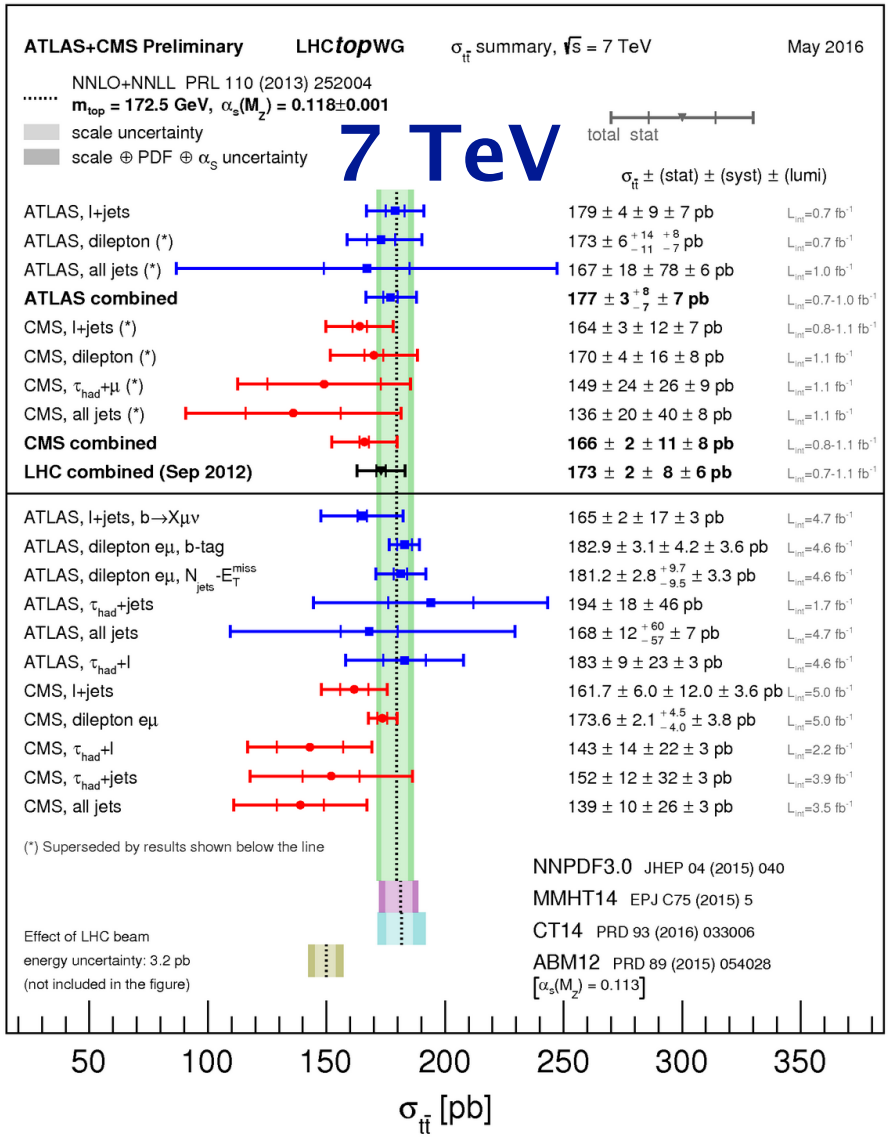


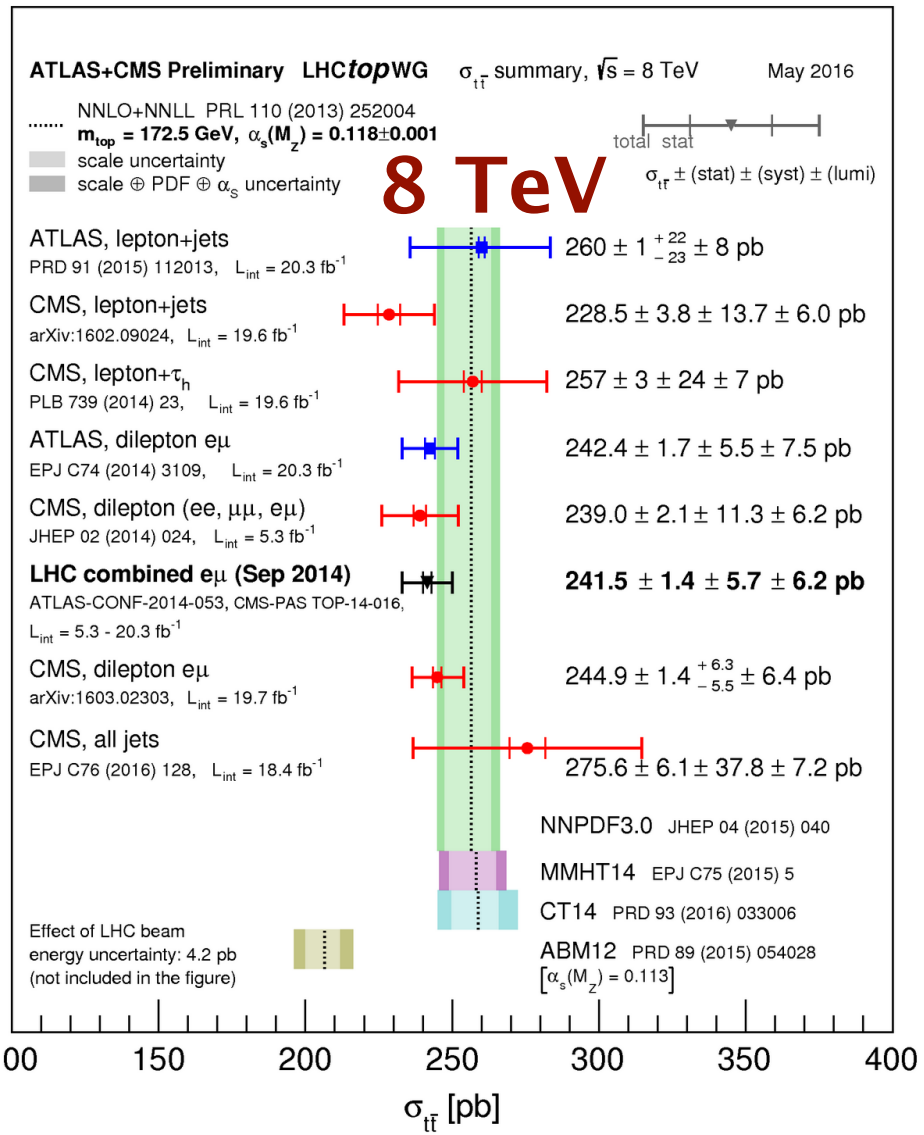


all channels measured except for $\tau_{had}\,\tau_{had}$

→ **good agreement with each other**

Top pair production cross section

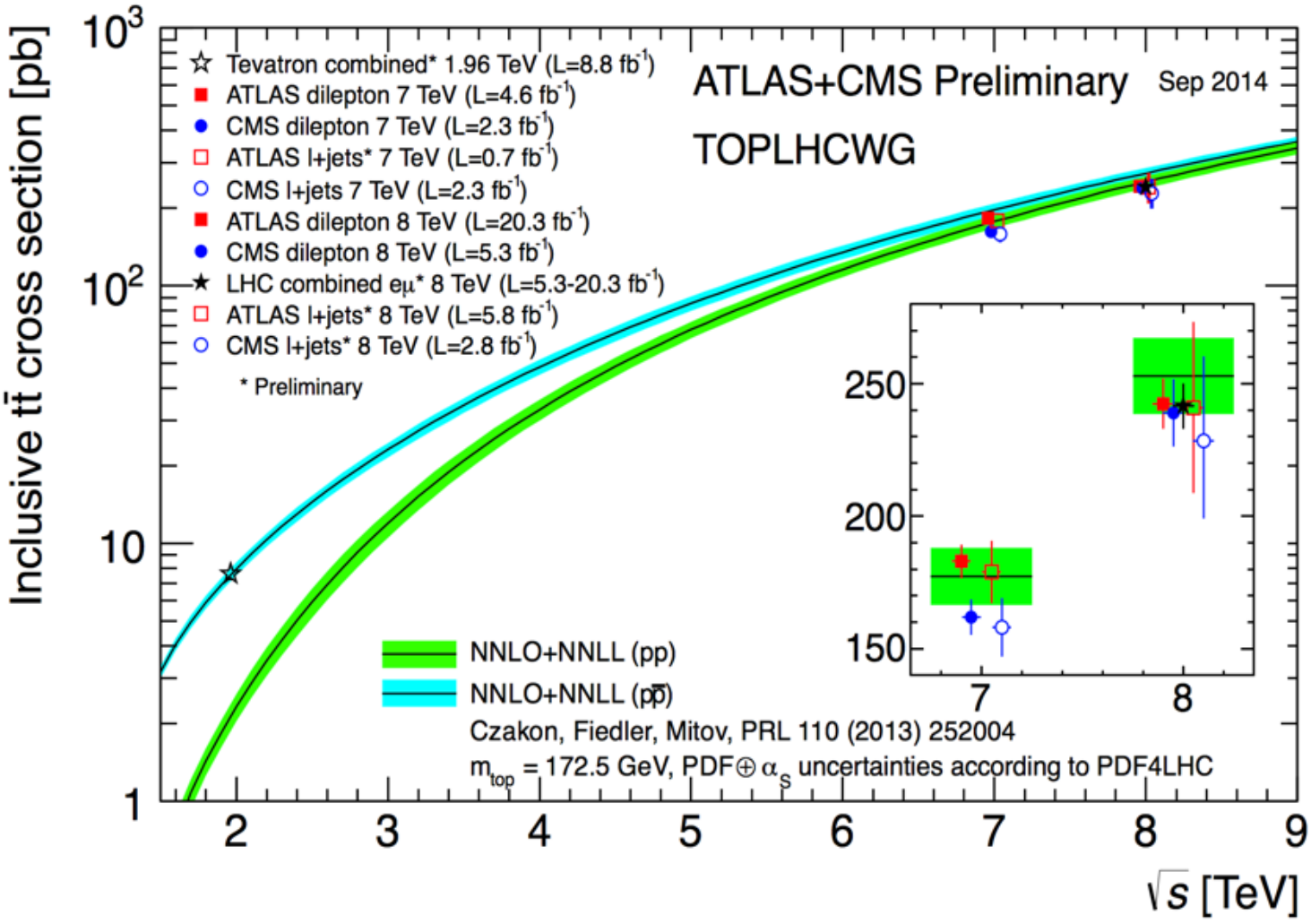




→ (all) channels measured to look for the unexpected

→ no new physics

Top pair production at hadron colliders

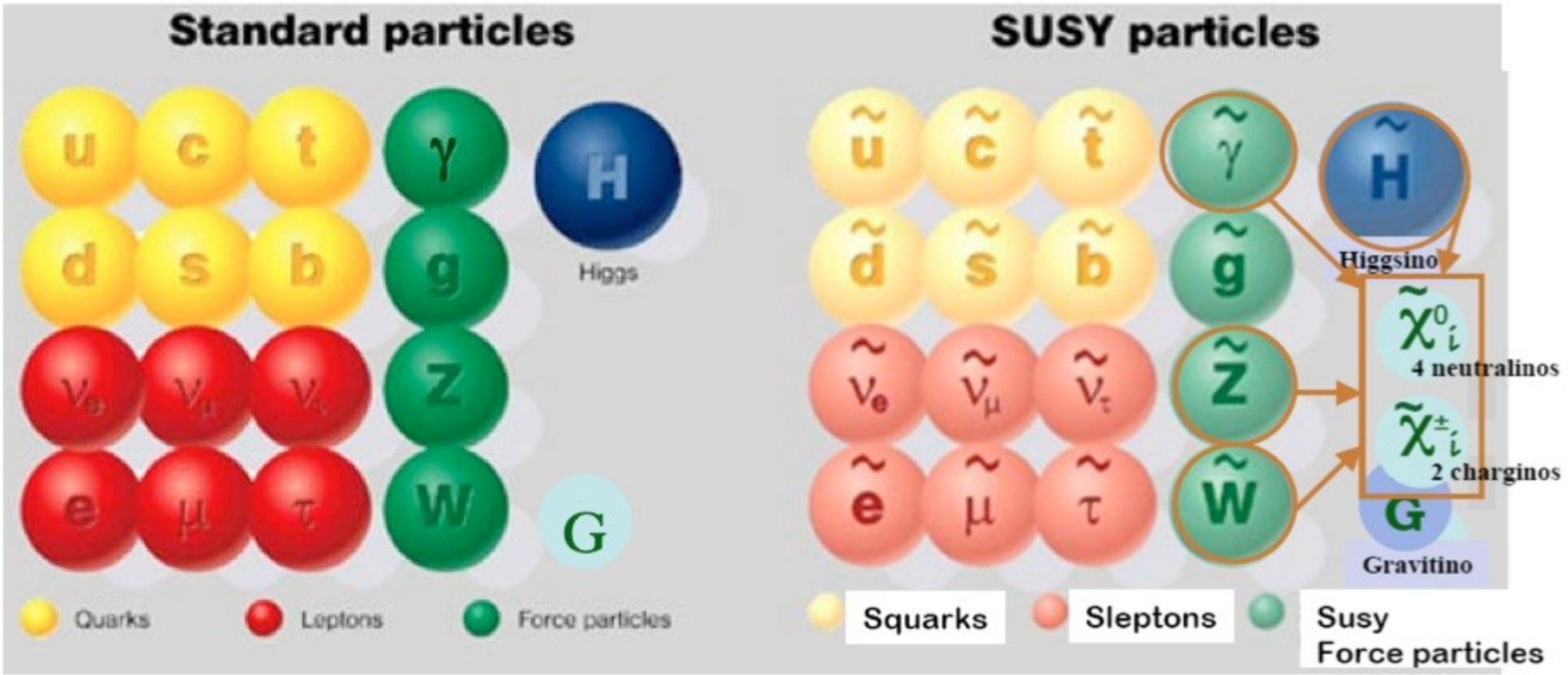


±5.7% (theo)

±3.9% (eμ)

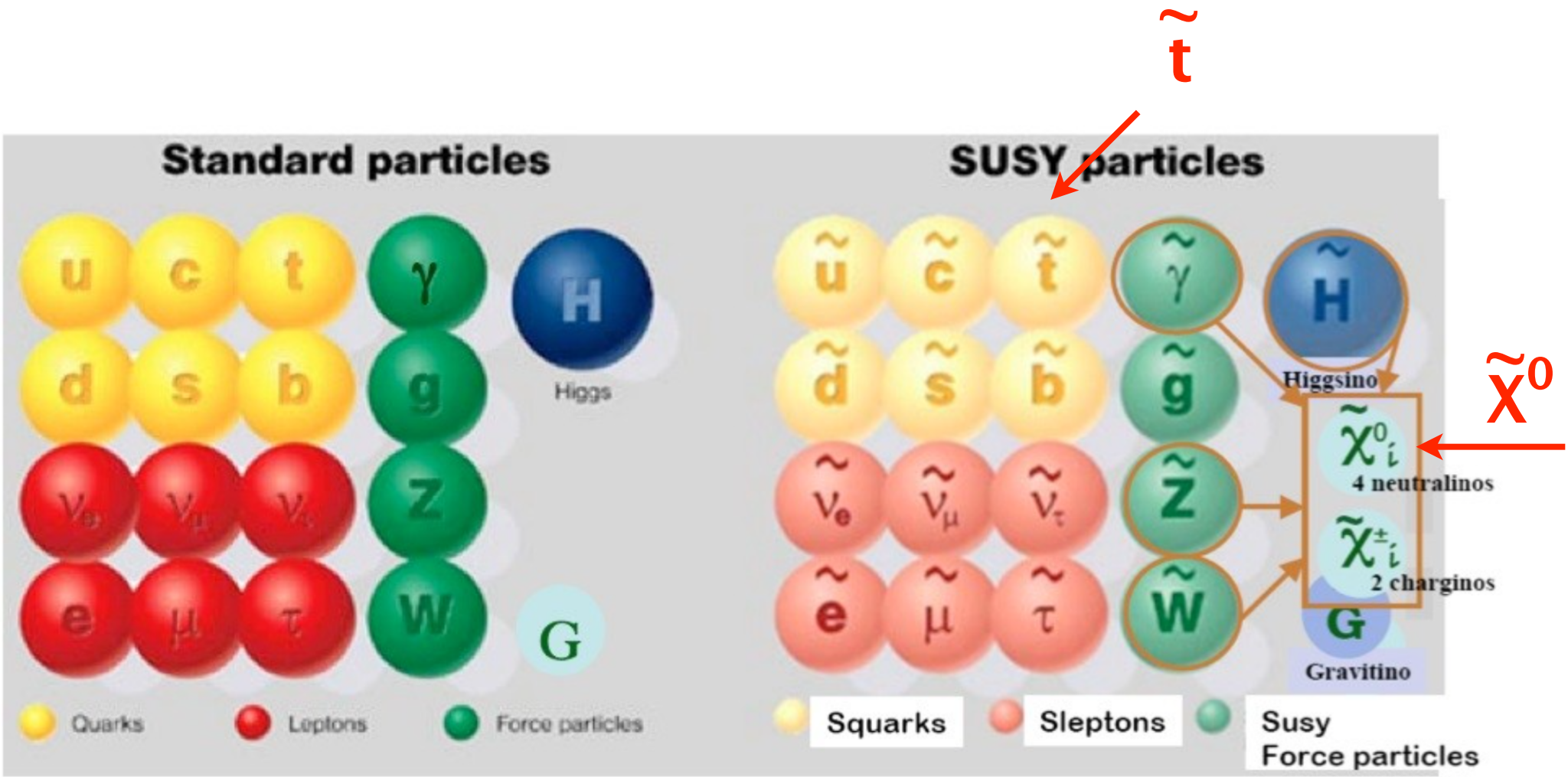
→ **experiments challenge theory again**

Supersymmetry



remedies shortcomings of SM:
e.g. dark matter candidate

Supersymmetry



remedies shortcomings of SM:
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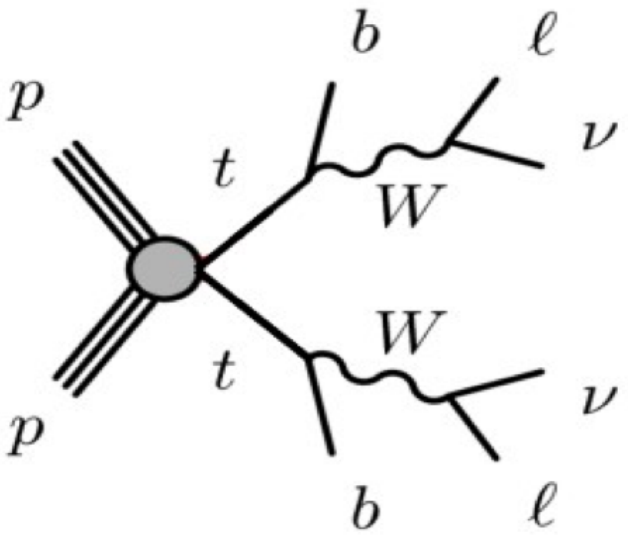
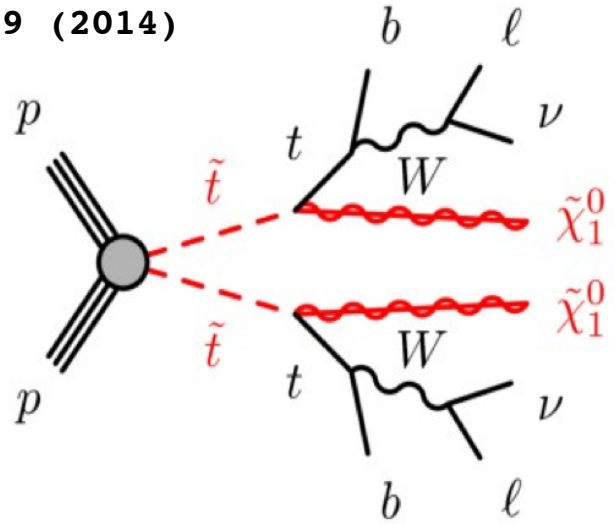
Stop Quark Pair Production

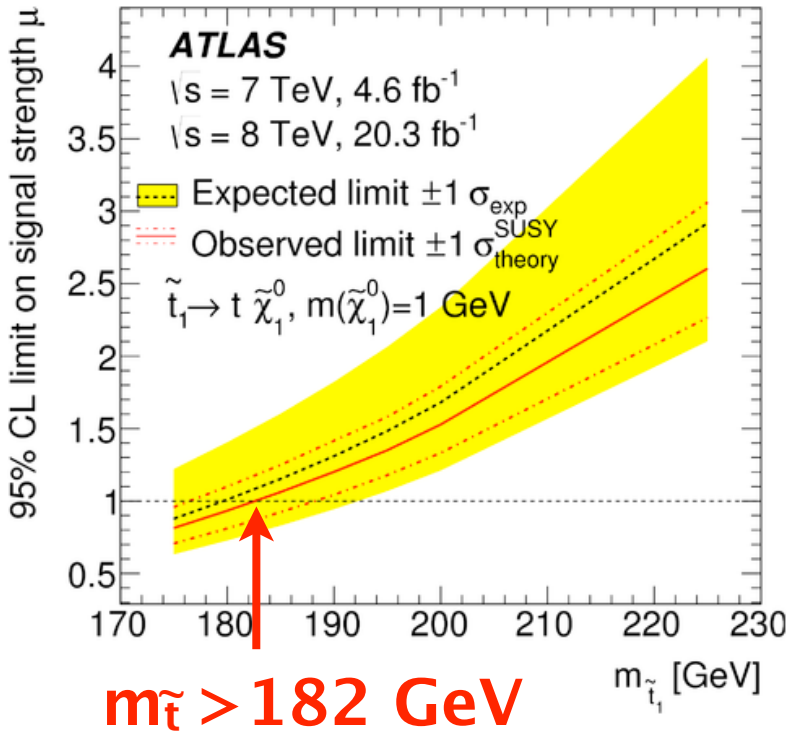


Eur. Phys. J. C74 3109 (2014)

do we see left or right?



$$\frac{\sigma_{limit}}{\sigma_{SUSY}}$$

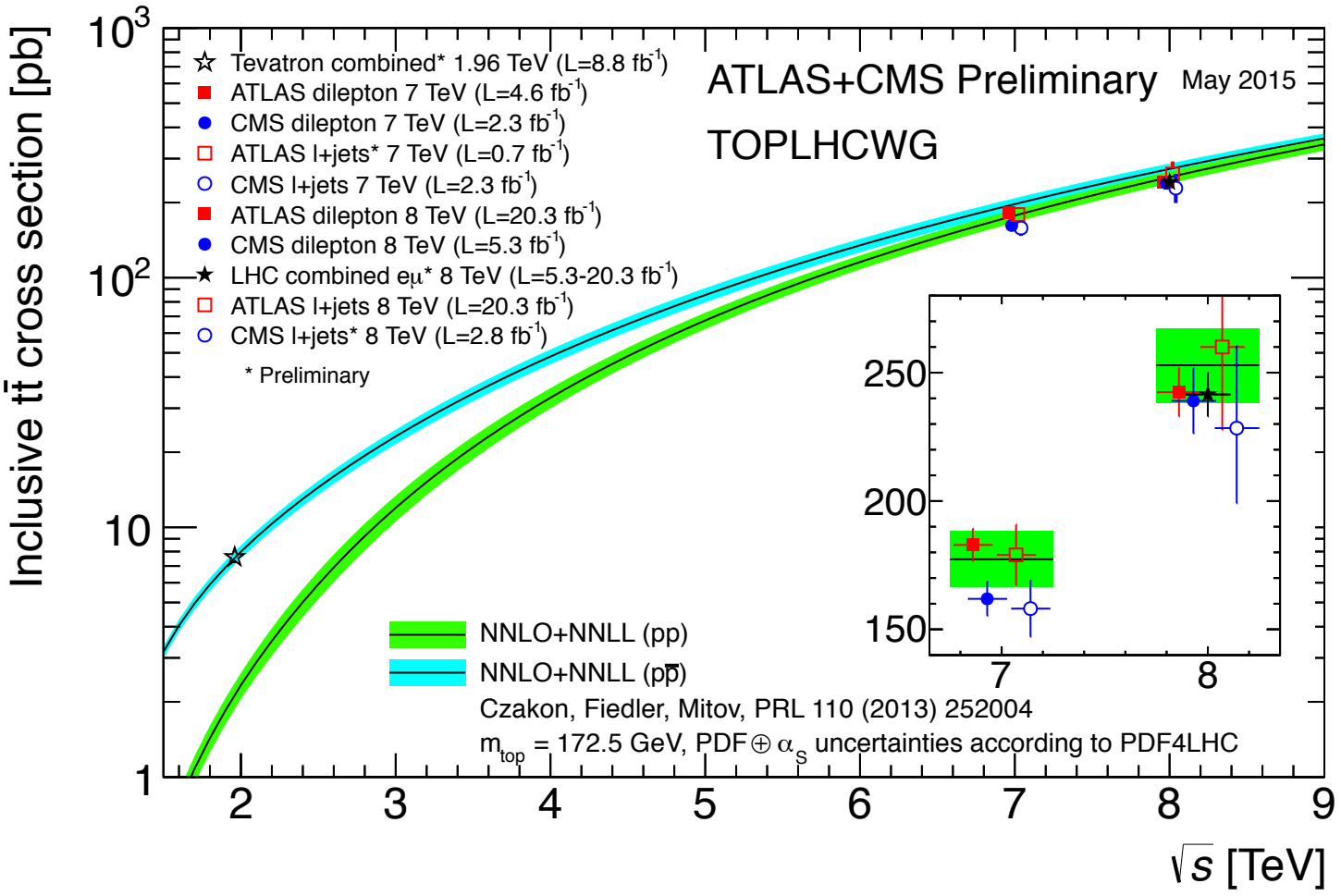


$m_{\tilde{t}} > 182$ GeV

"stealth" scenario:
– small sneutrino mass
– stop mass close to top mass

Top pair production at hadron colliders

eager to put points here



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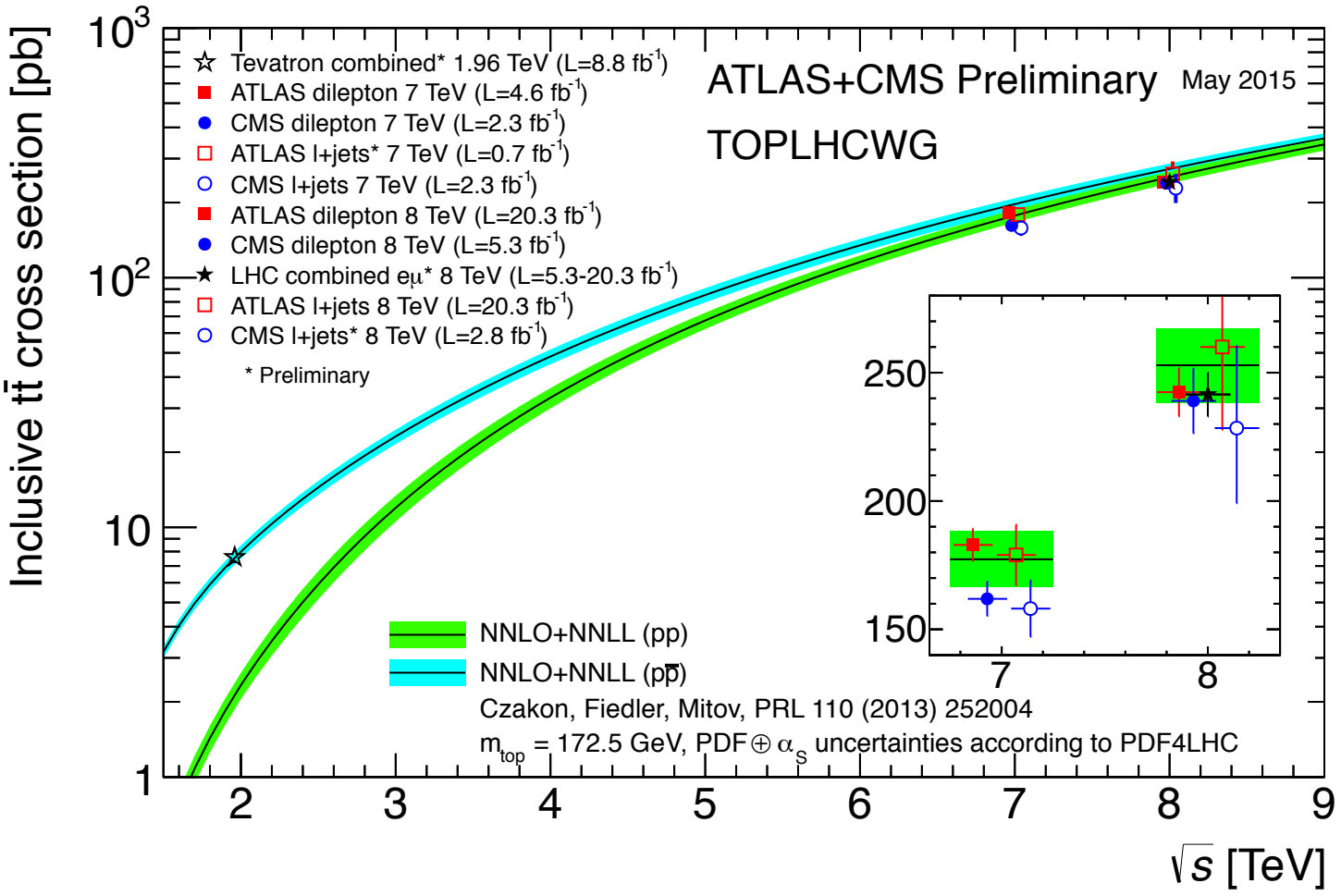
→ experiments challenge theory again

Top pair production at hadron colliders

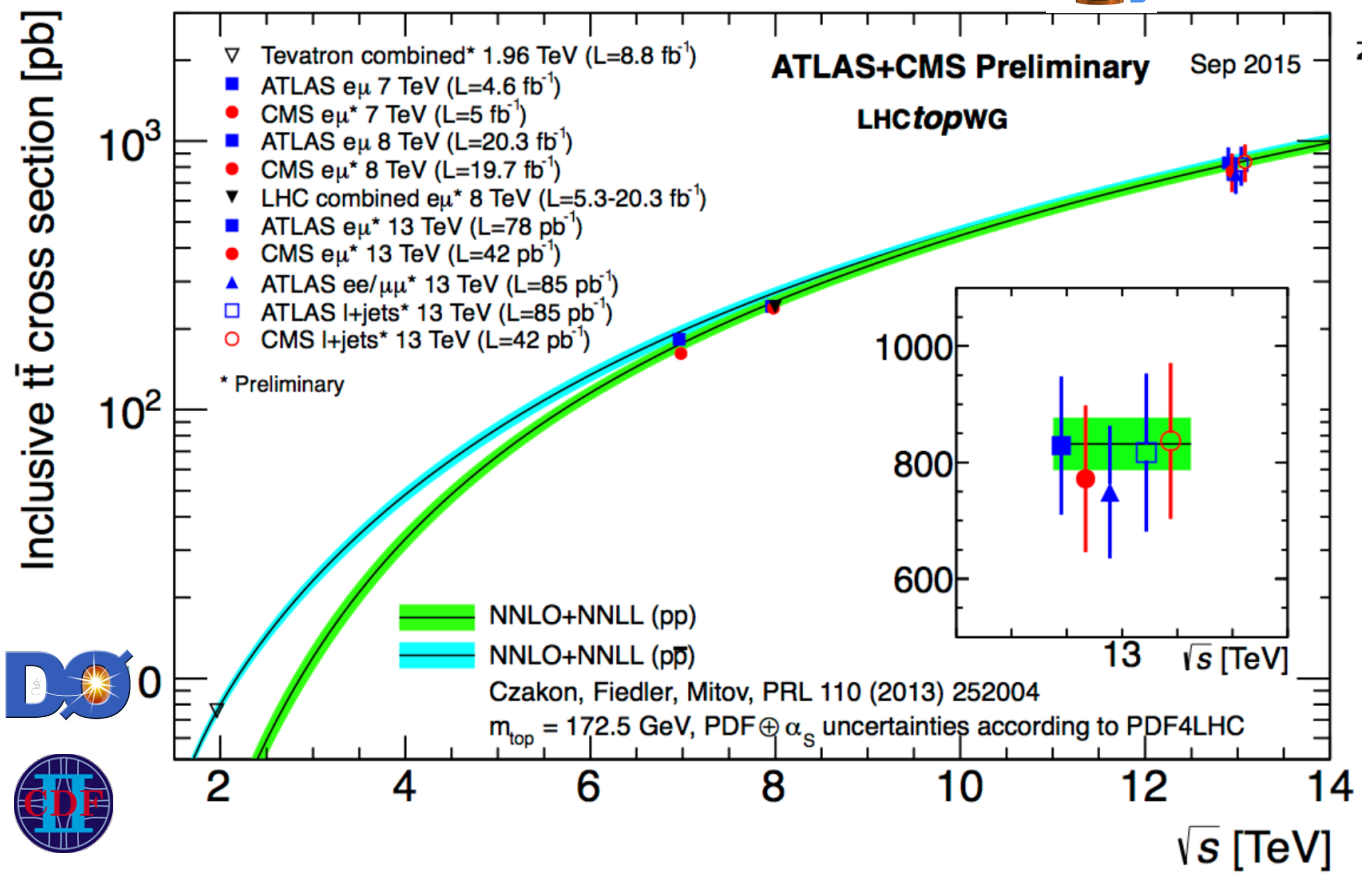


boldly go where no man has gone before

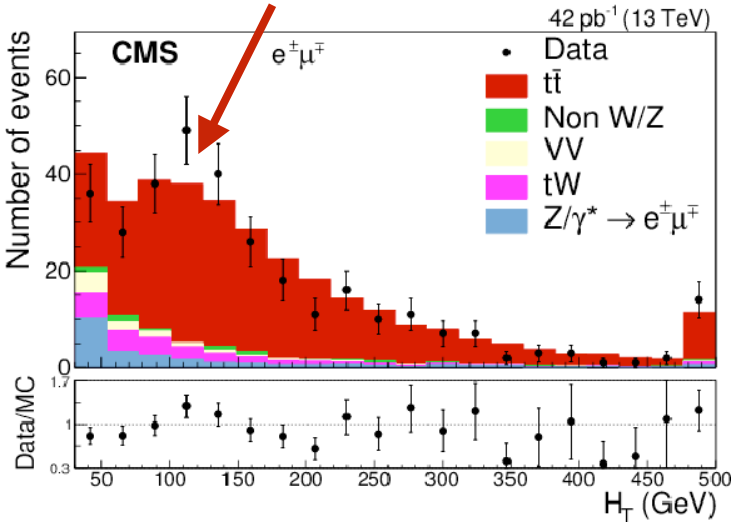
→ **experiments challenge theory again**

Top pair production at 13 TeV

first look at the new world energy frontier



“top quark peak” July 2015

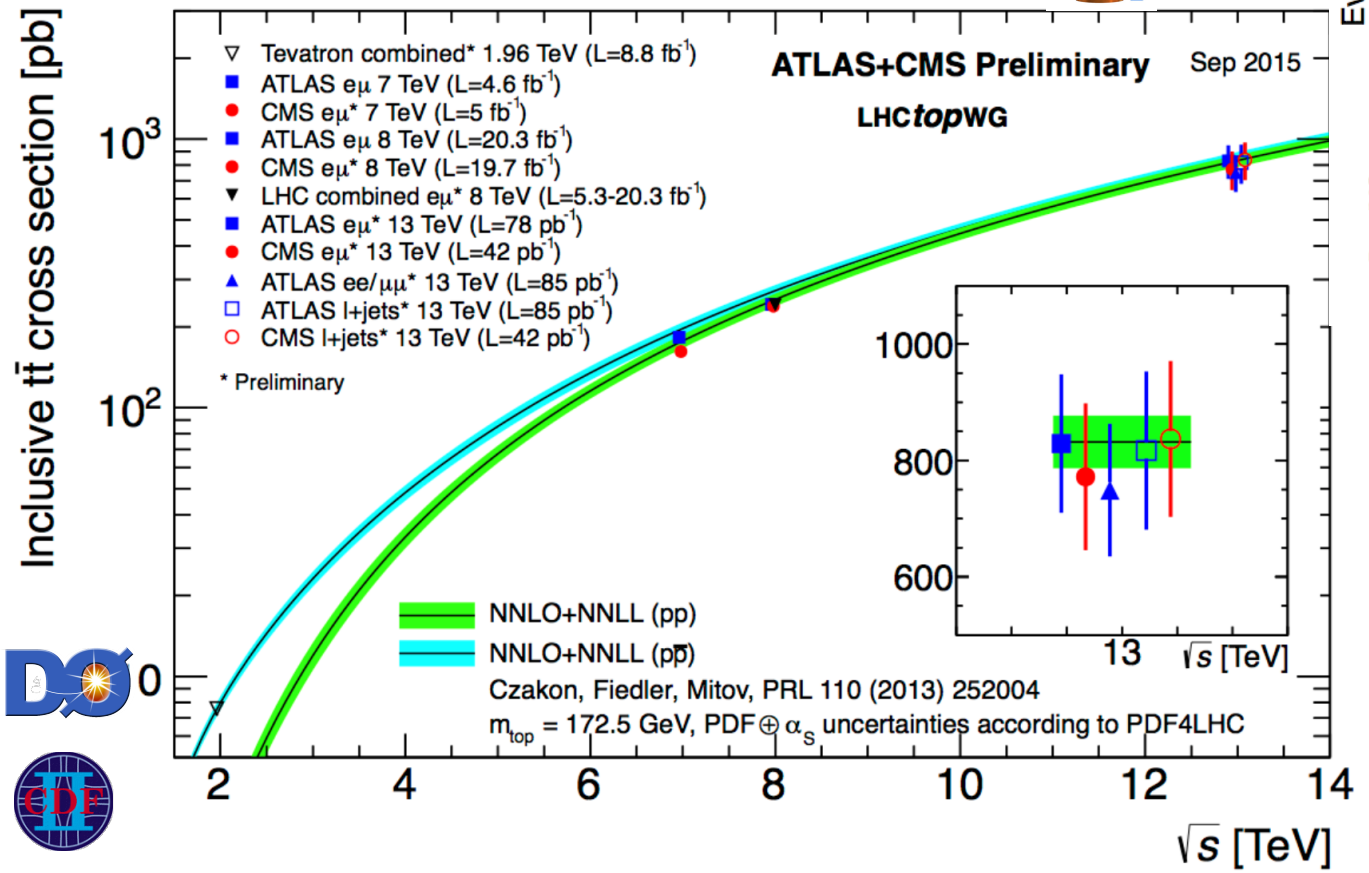


sum of scalar p_T of all jets

→ agreement with SM prediction

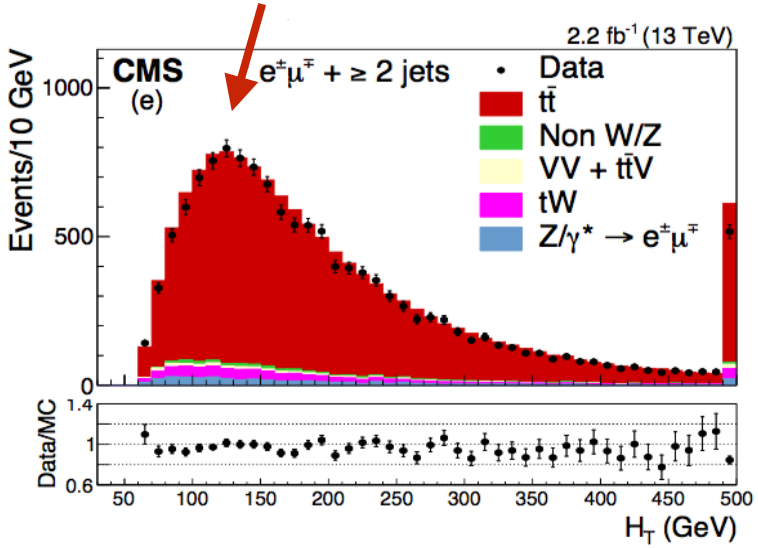
Top pair production at 13 TeV

first look at the new world energy frontier



"top quark peak"

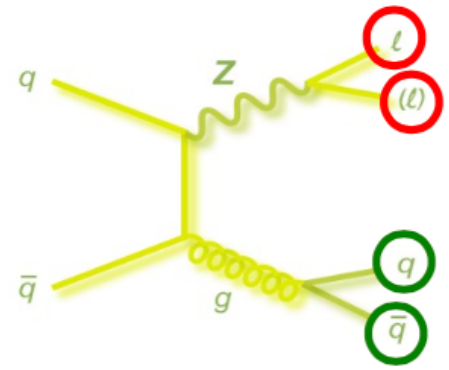
Nov 2016

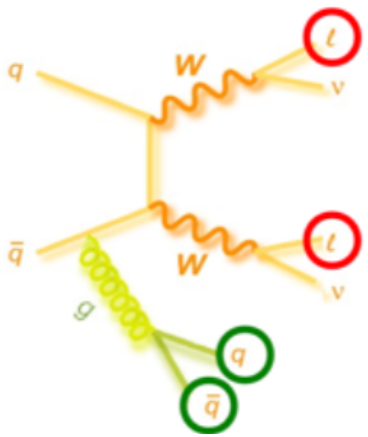


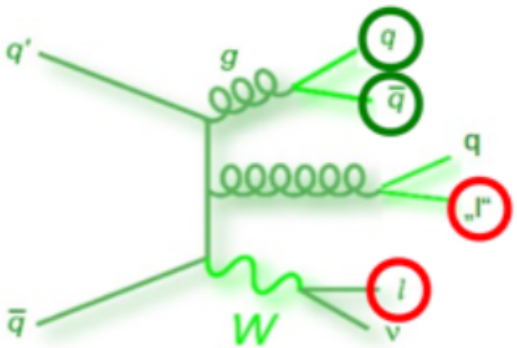
sum of scalar p_T of all jets

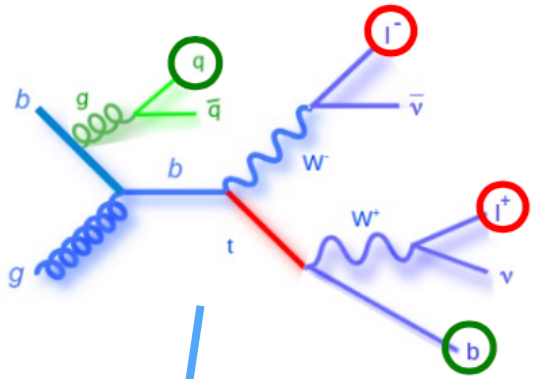
→ agreement with SM prediction

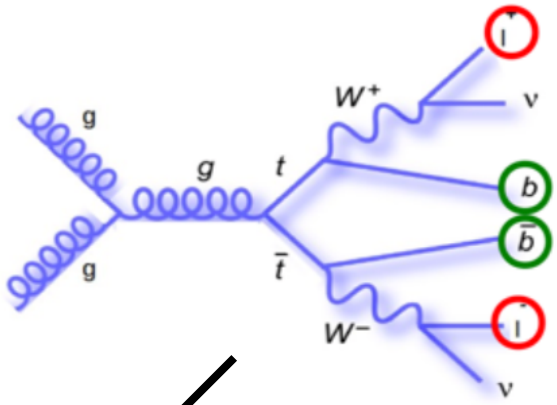
Dilepton Events at 13 TeV

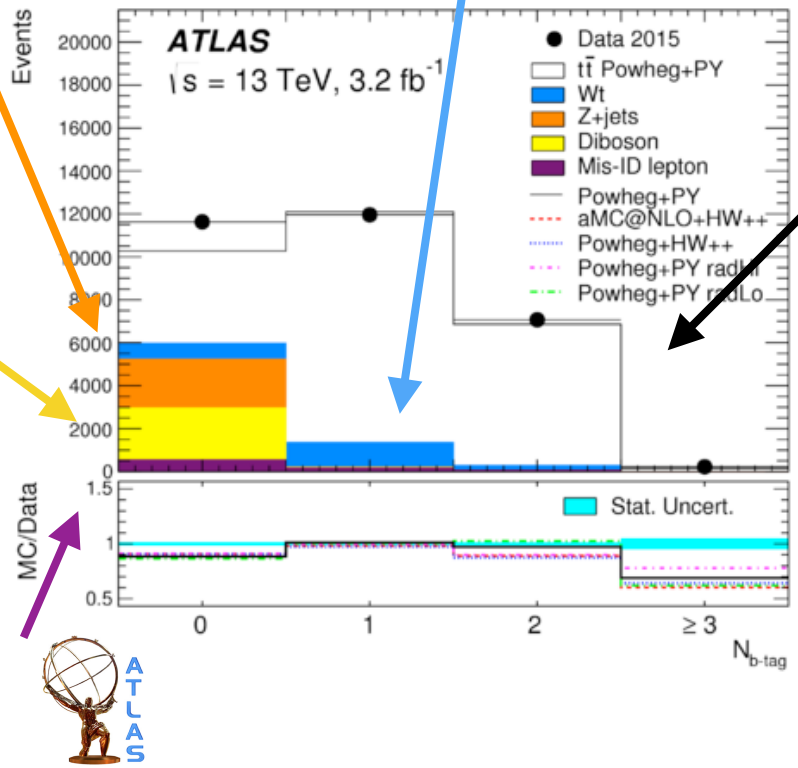


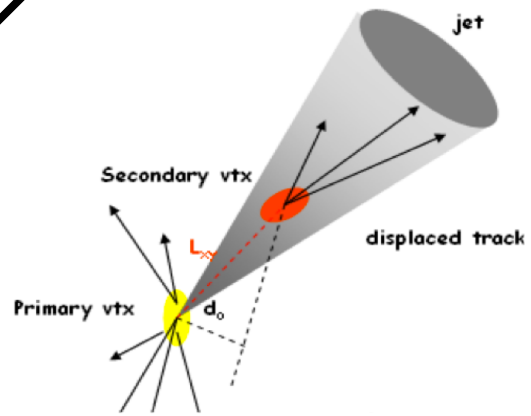






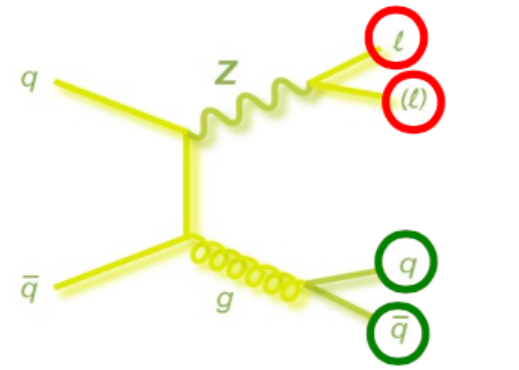


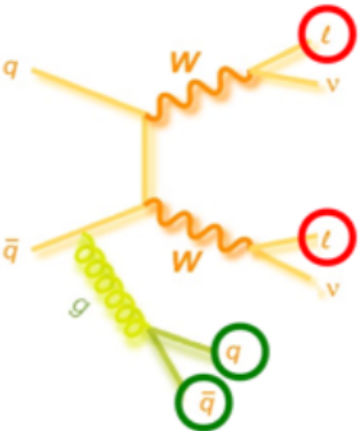


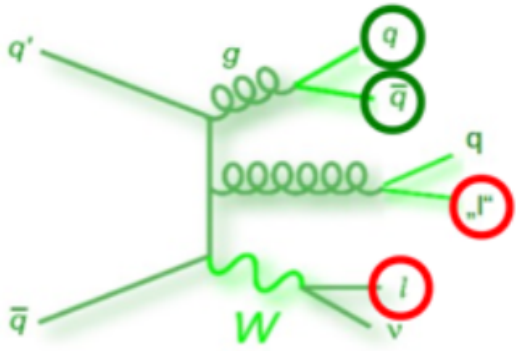


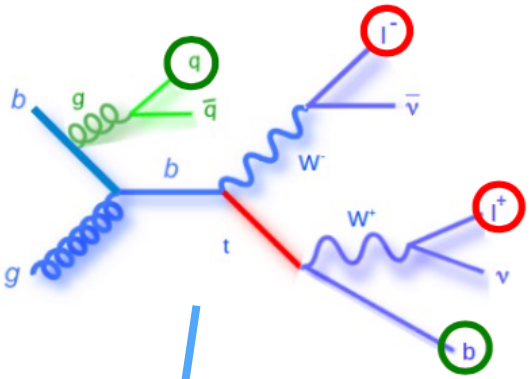
very powerful!

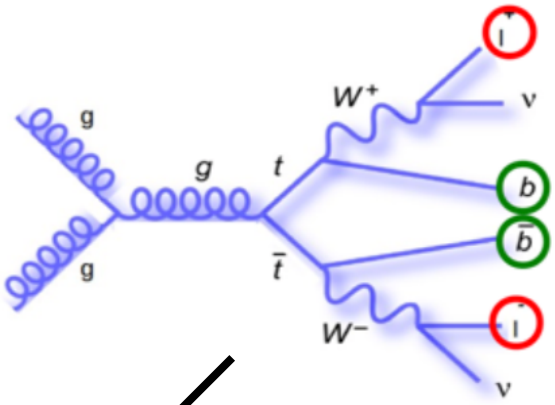
Dilepton Events at 13 TeV

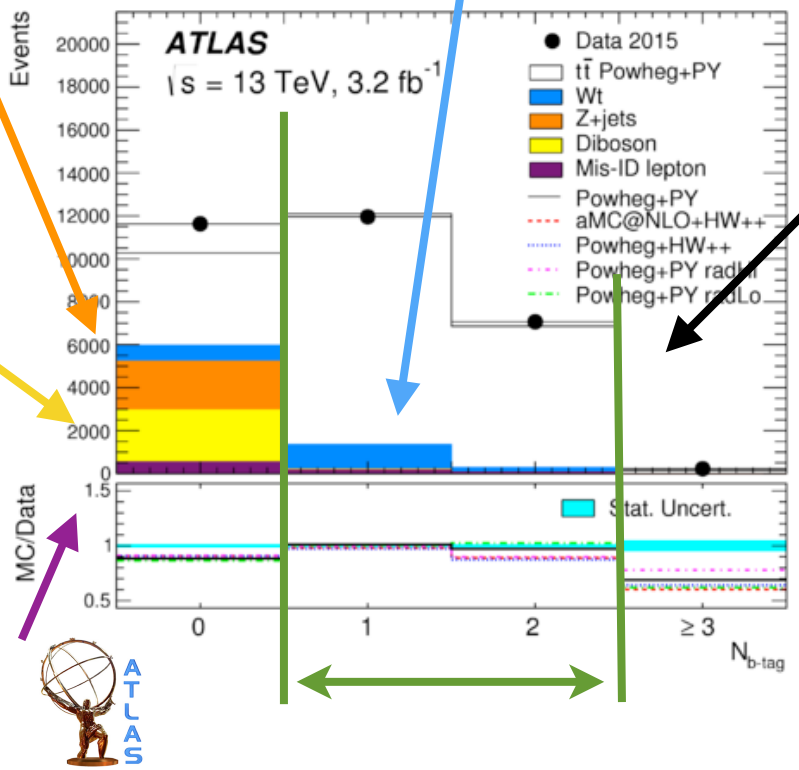








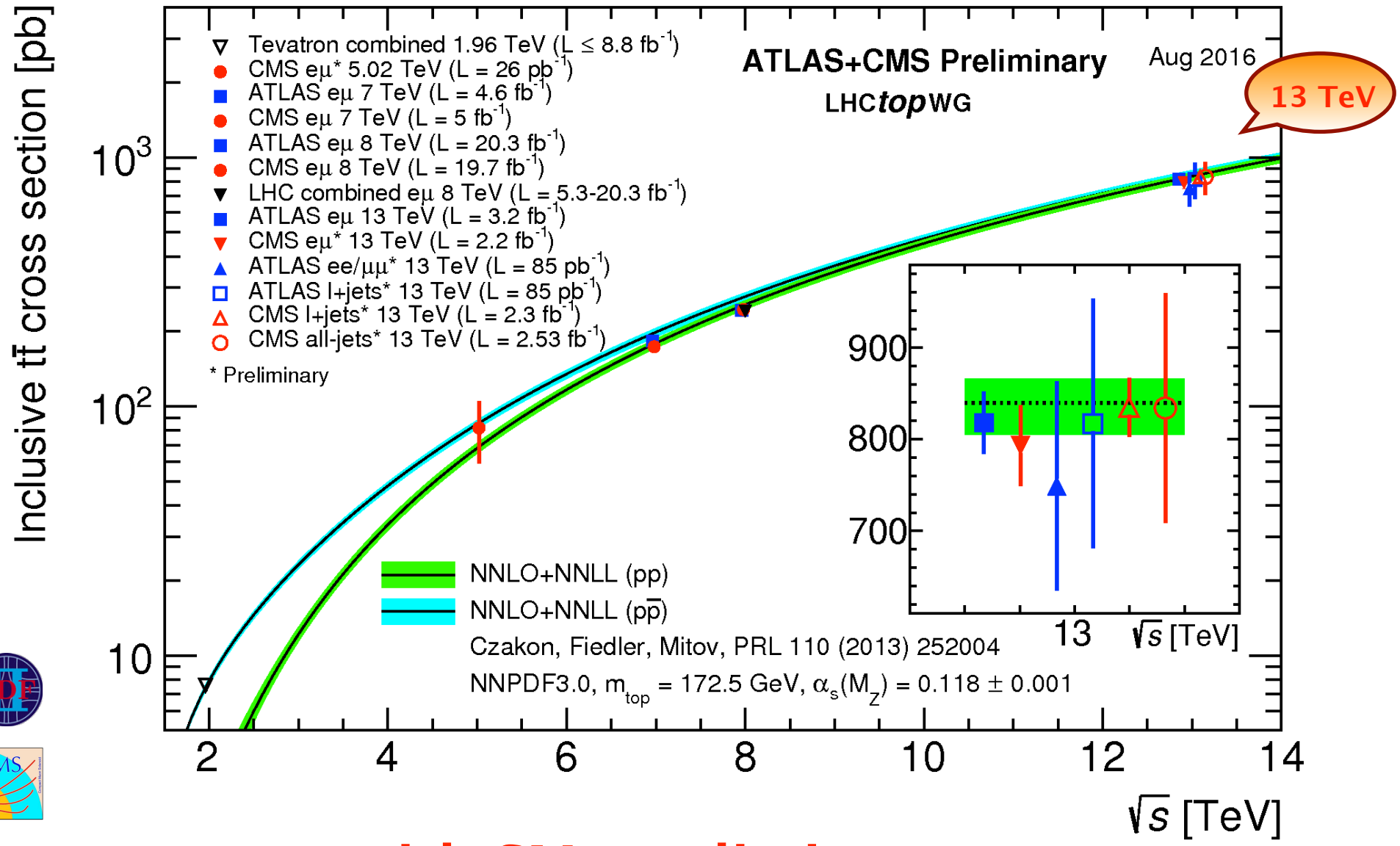




solve equation for tt̄ cross section and fraction of b-jets found (ε_b)

$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\text{bkg}}$$
$$N_2 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} C_b\epsilon_b{}^2 + N_2^{\text{bkg}}$$

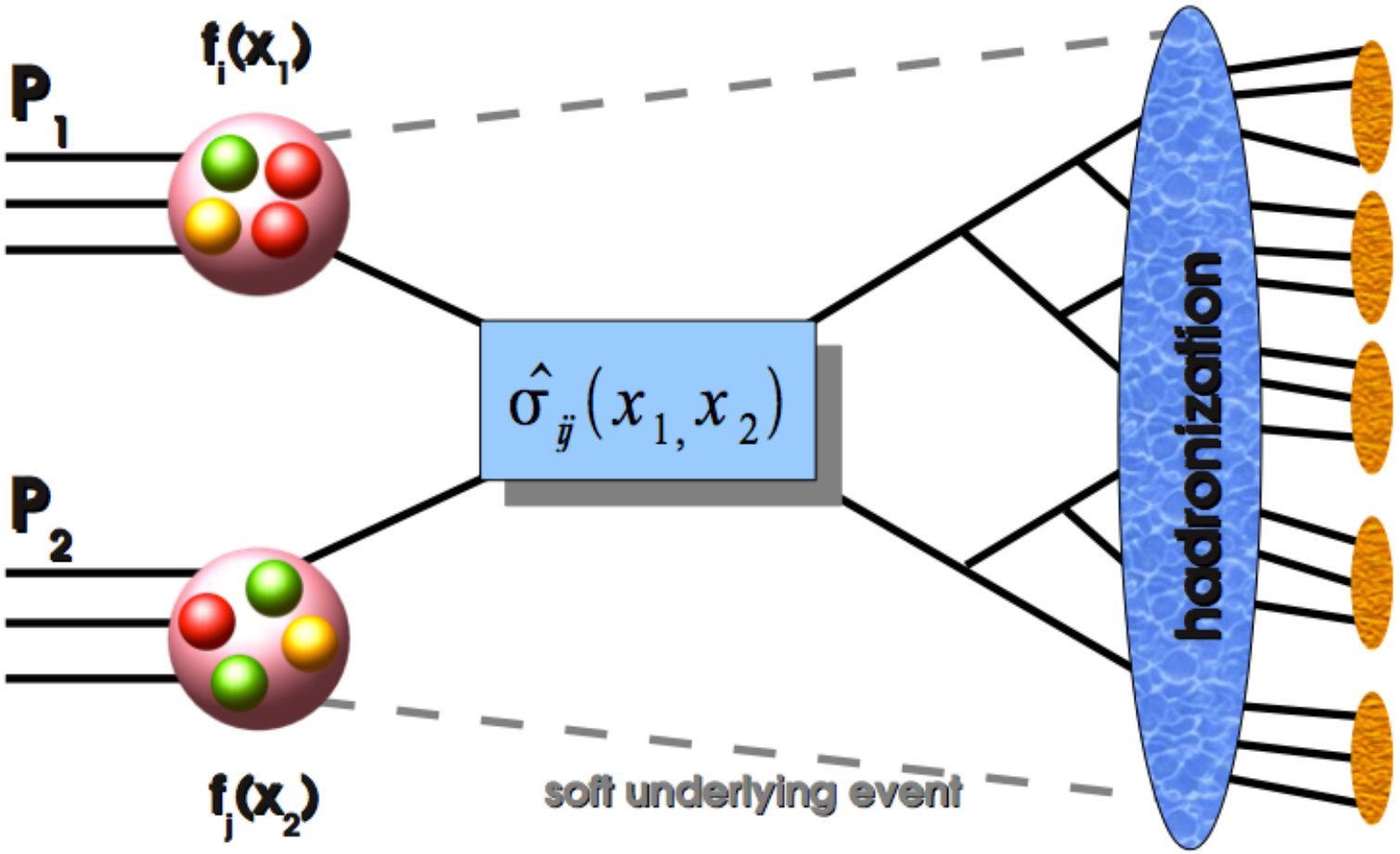
Top pair production at 13 TeV



→ agreement with SM prediction

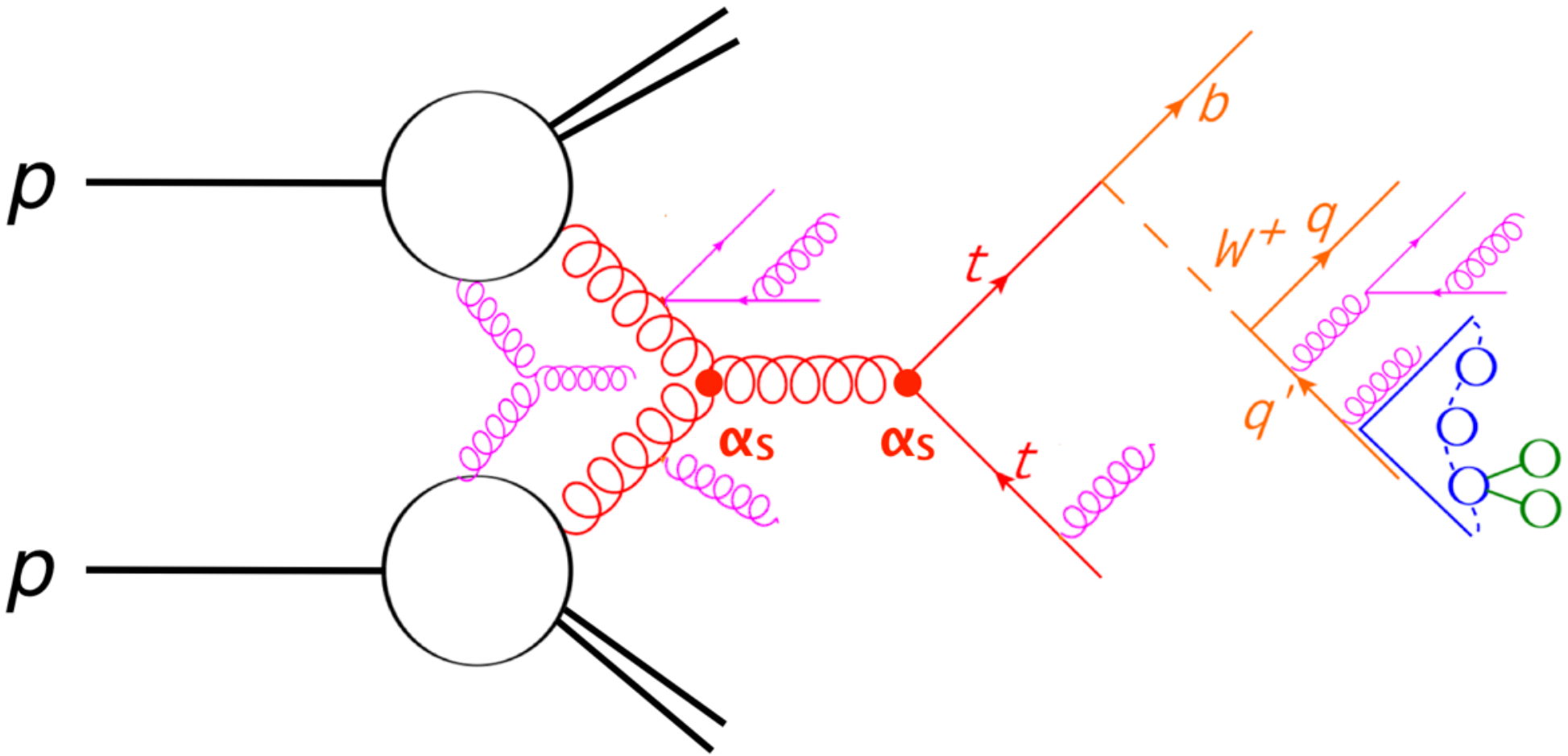
Differential Cross Sections

important tests of higher order QCD calculations:
requires "unfolding" to particle level



“Revolution” in Phenomenology

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



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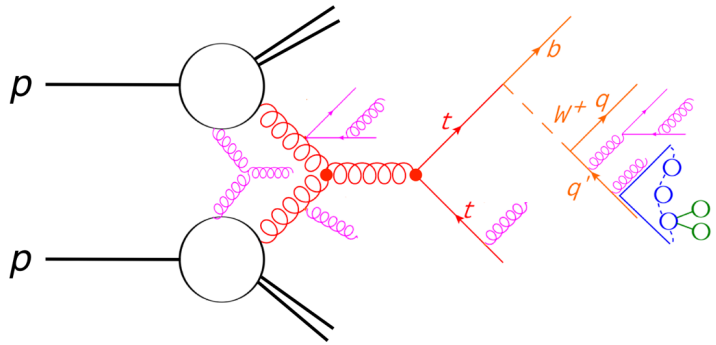
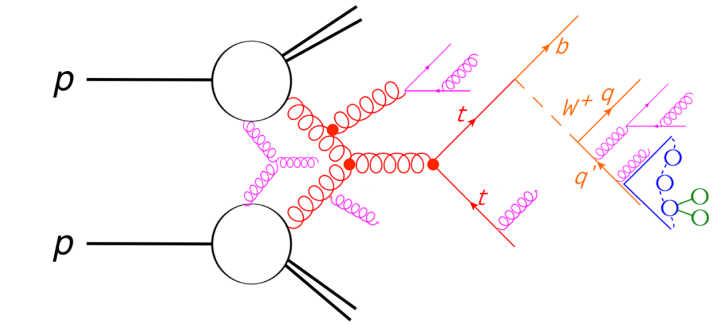
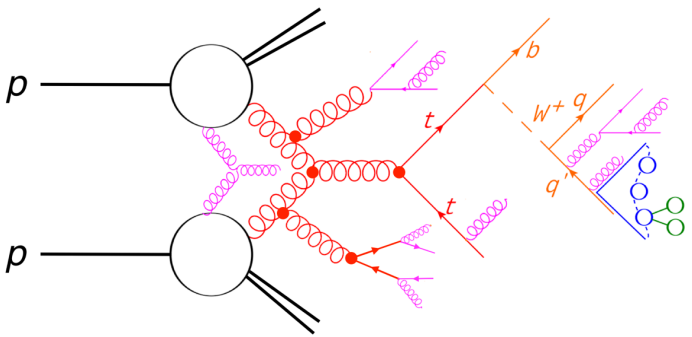
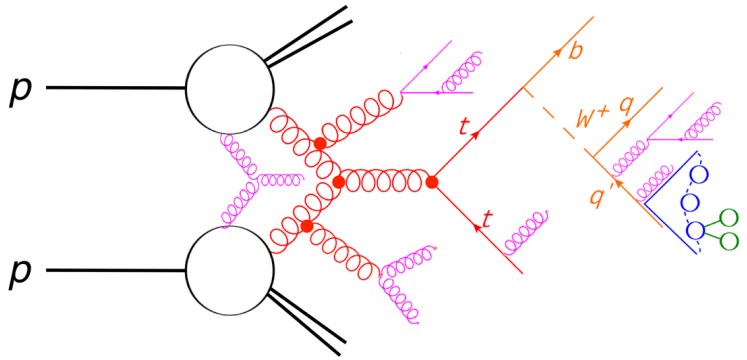


- **LO multileg generators matched with parton shower**
  Alpgen+Pythia, Alpgen+Herwig, ...







...

“Revolution” in Phenomenology

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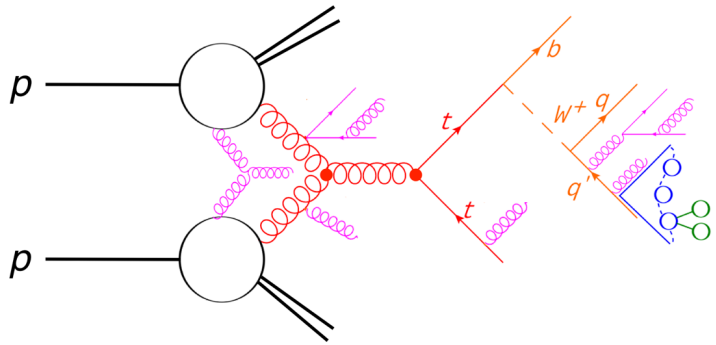
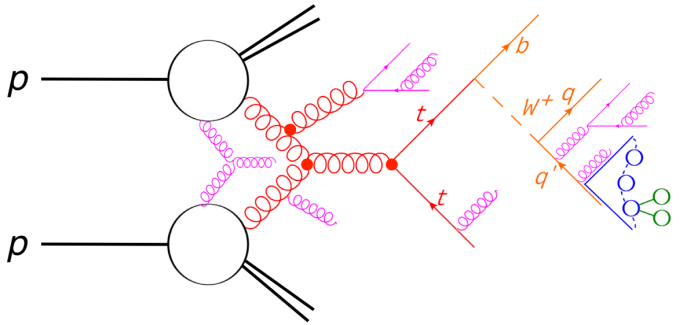
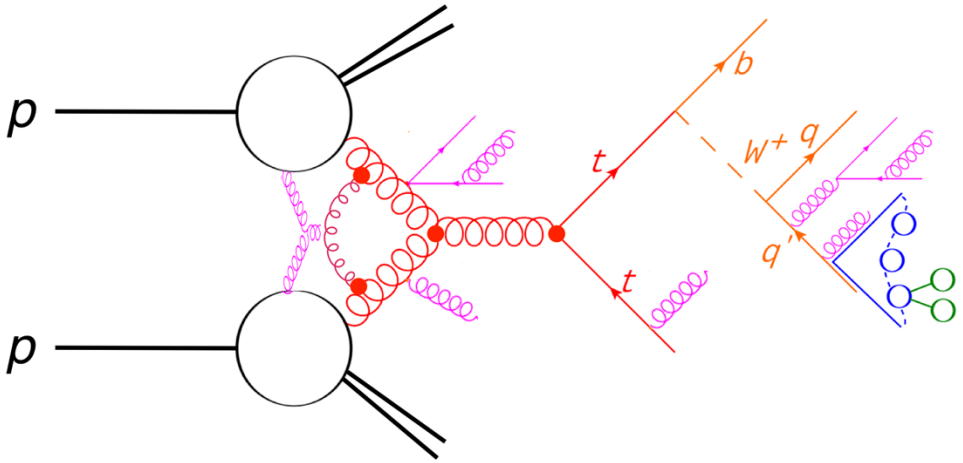
  Alpgen+Pythia, Alpgen+Herwig, ...

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







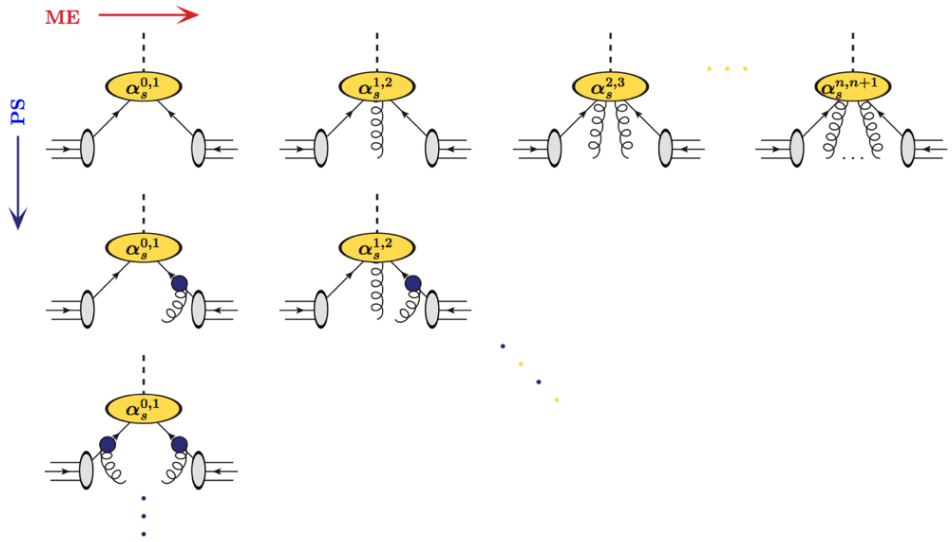
“Revolution” in Phenomenology

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

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

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

- NLO+LO multileg generators matched with parton showers



“Revolution” in Phenomenology

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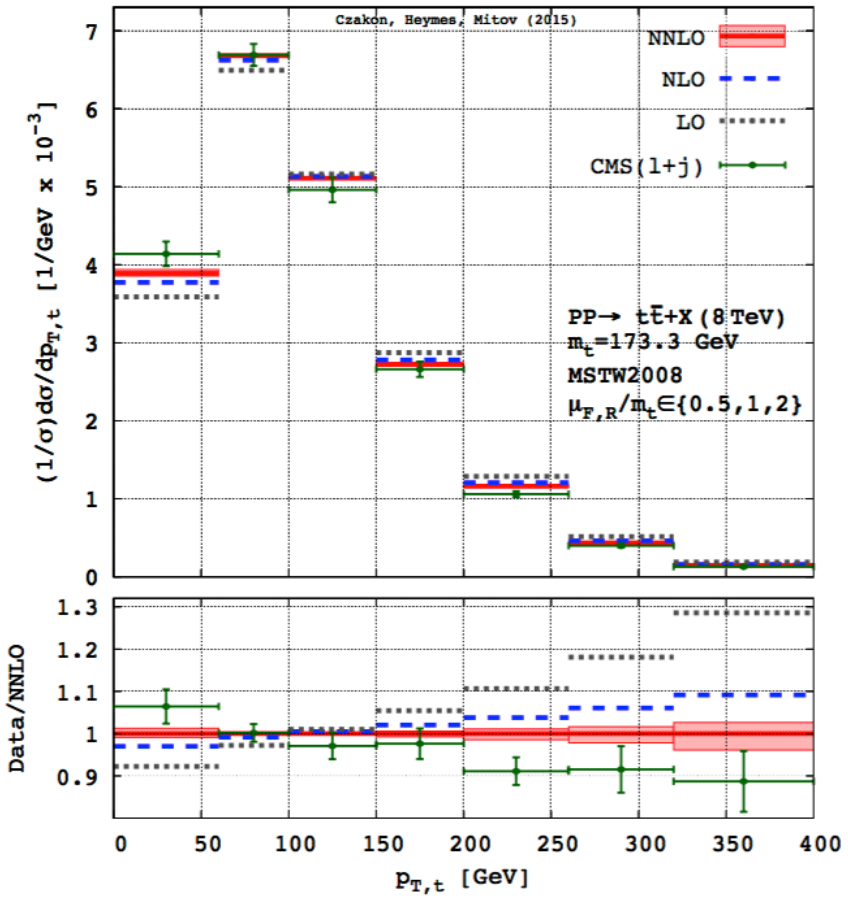
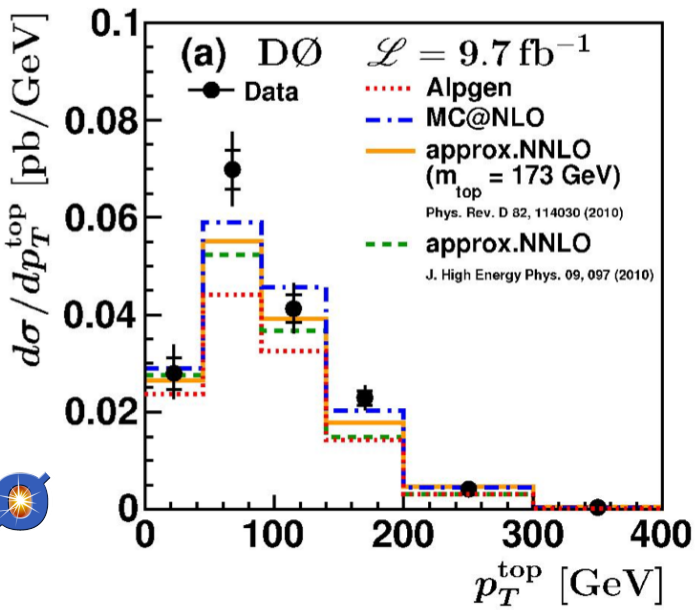
  Pythia, Herwig, ...
- LO multileg generators matched with parton shower
  Alpgen+Pythia, Alpgen+Herwig, ...
- NLO+parton shower generators
  Powheg+Pythia, MC@NLO+Herwig, ...
- NLO+LO multileg generators matched with parton showers
- NNLO QCD calculations

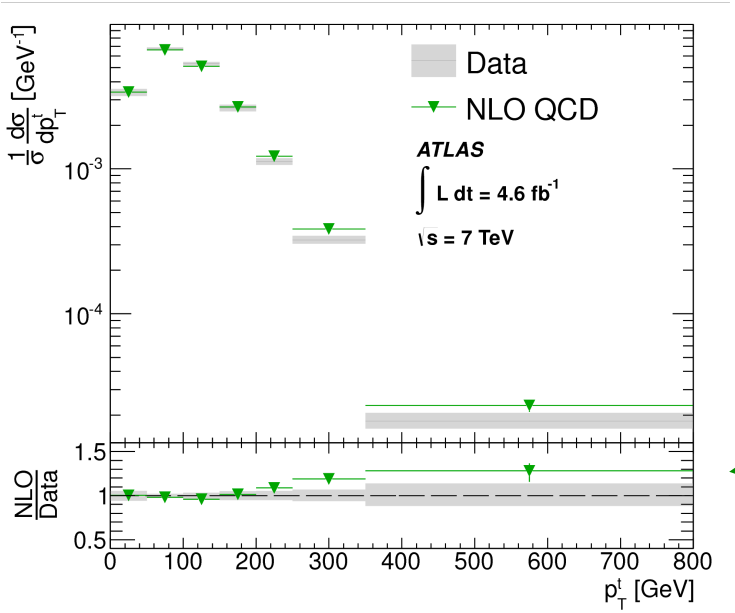
$t\bar{t}$ production in full NNLO:



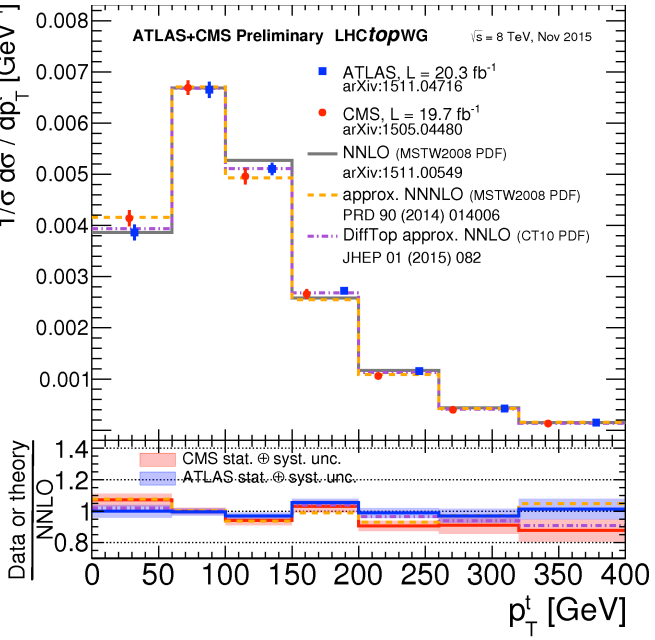
Differential, unfolded: top p_T



2 TeV

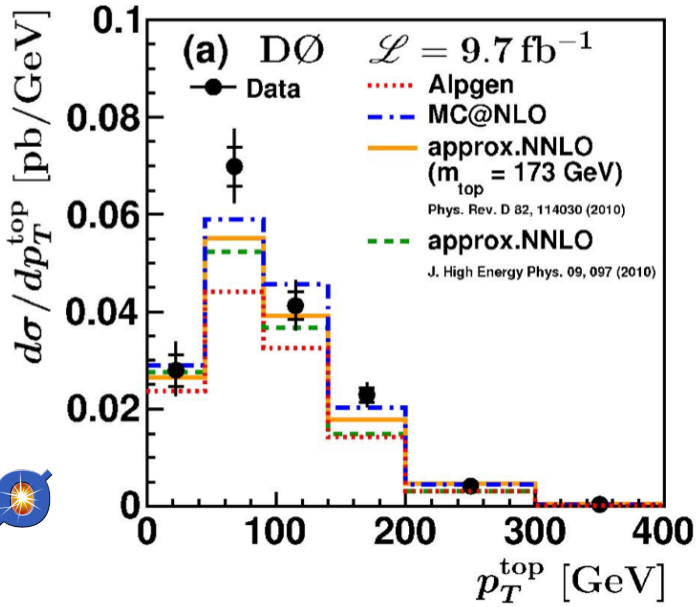


7 TeV

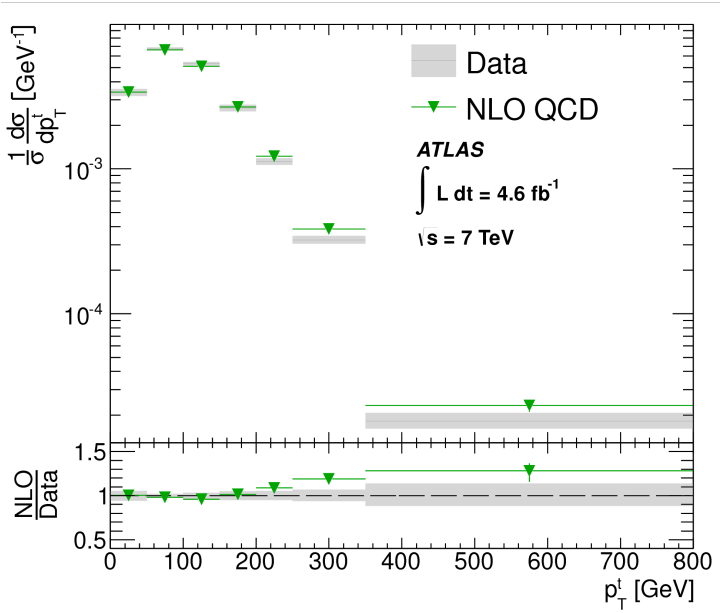


8 TeV

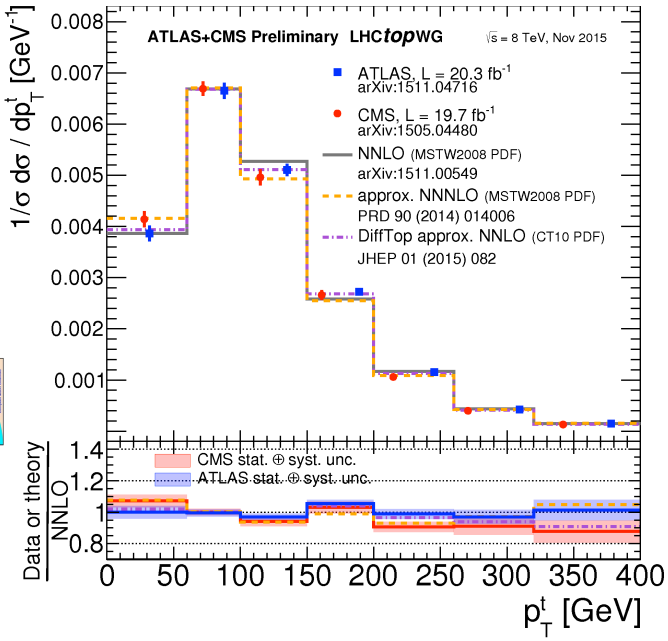
Differential, unfolded: top p_T



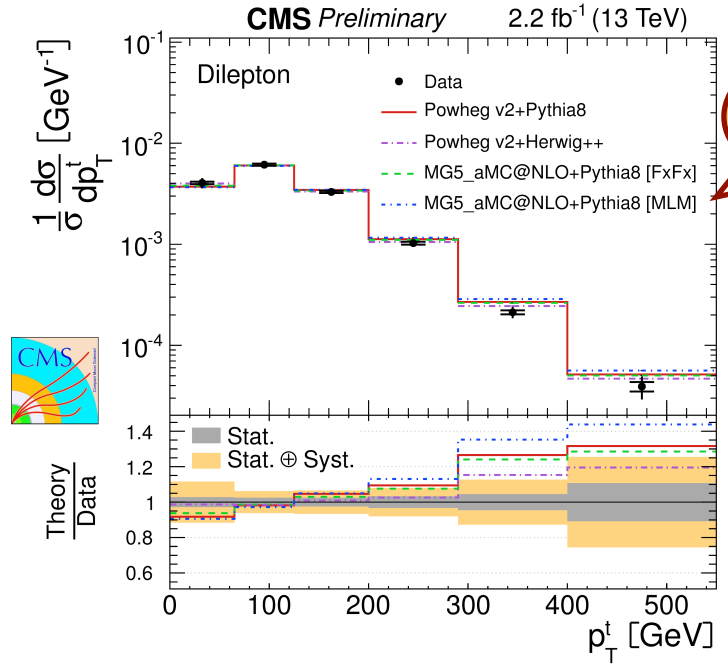
2 TeV



7 TeV



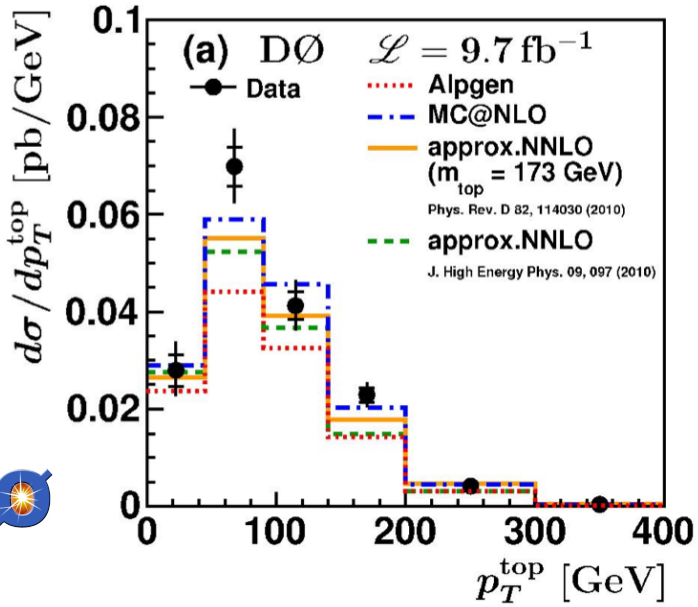
8 TeV



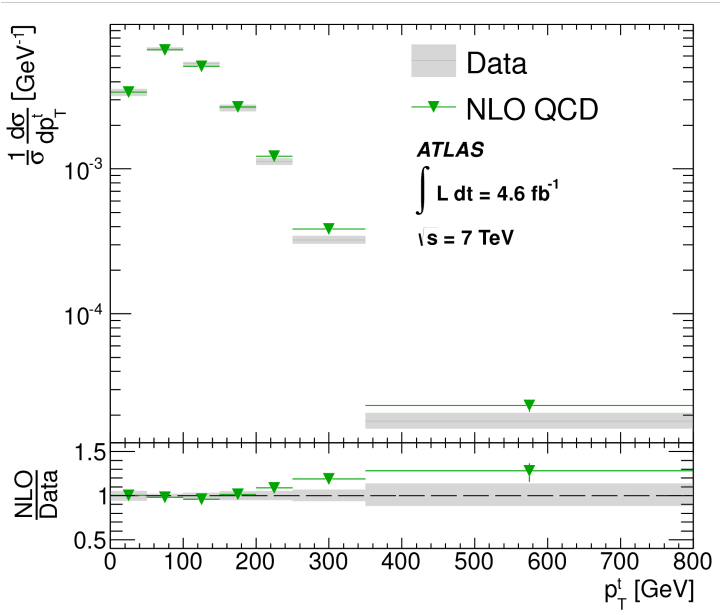
13 TeV

NLO+PS simulations

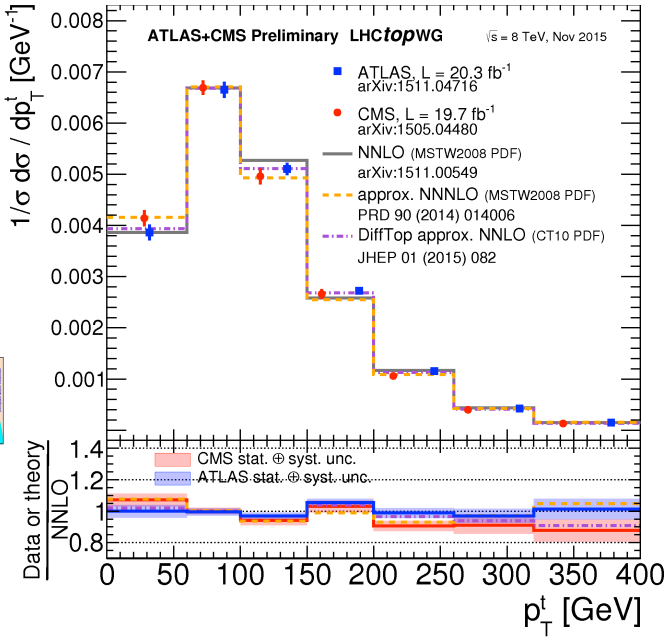
Differential, unfolded: top p_T



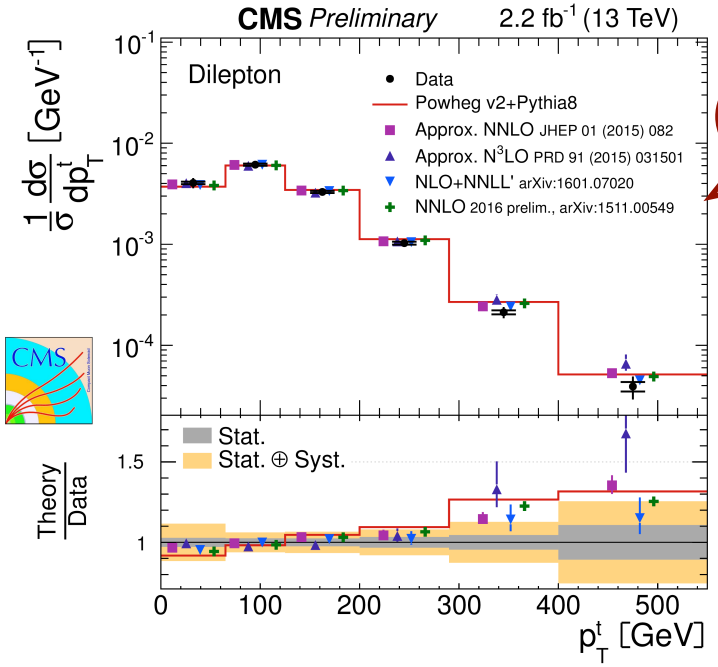
2 TeV



7 TeV



8 TeV

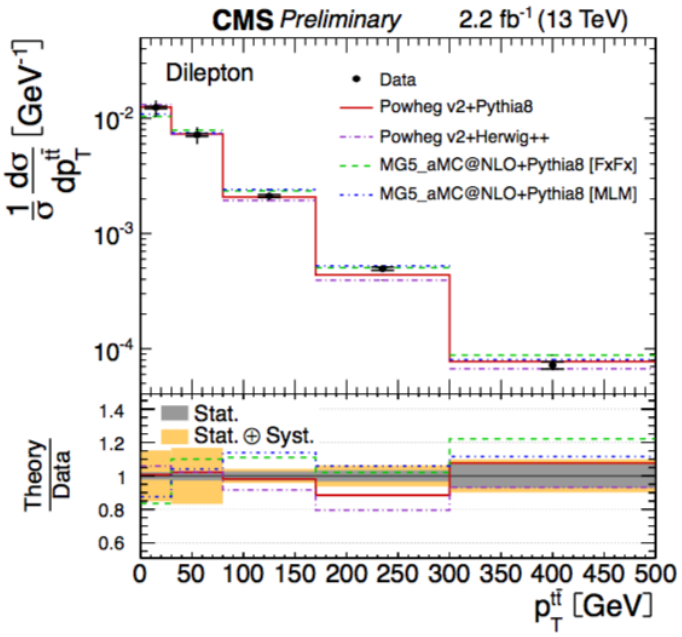


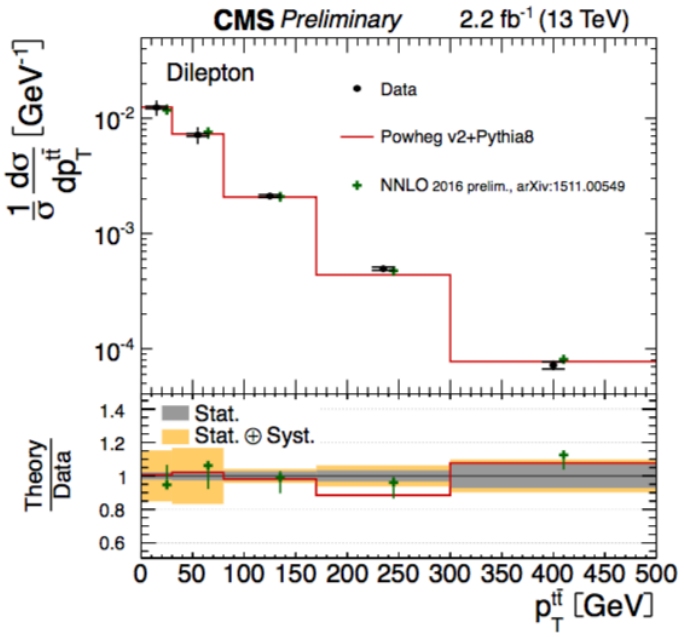
13 TeV

NNLO

Differential, unfolded: $m_{t\bar{t}}$ & $t\bar{t}$ p_T

NLO+PS simulations



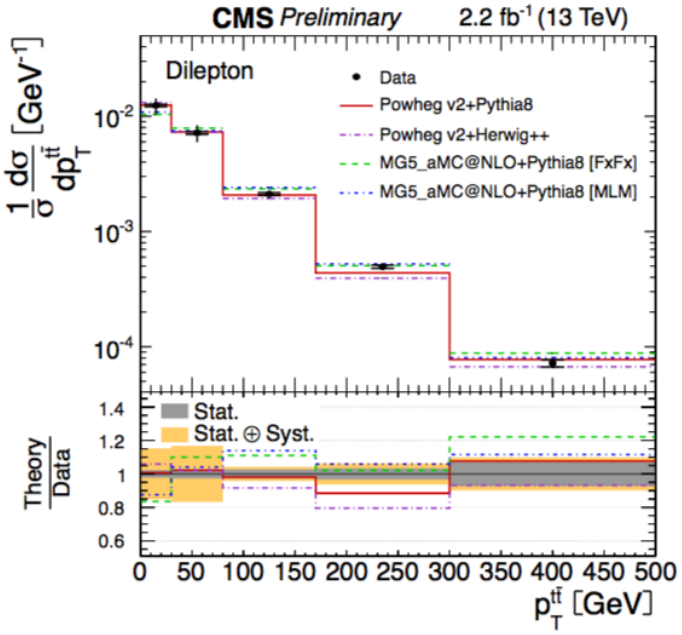


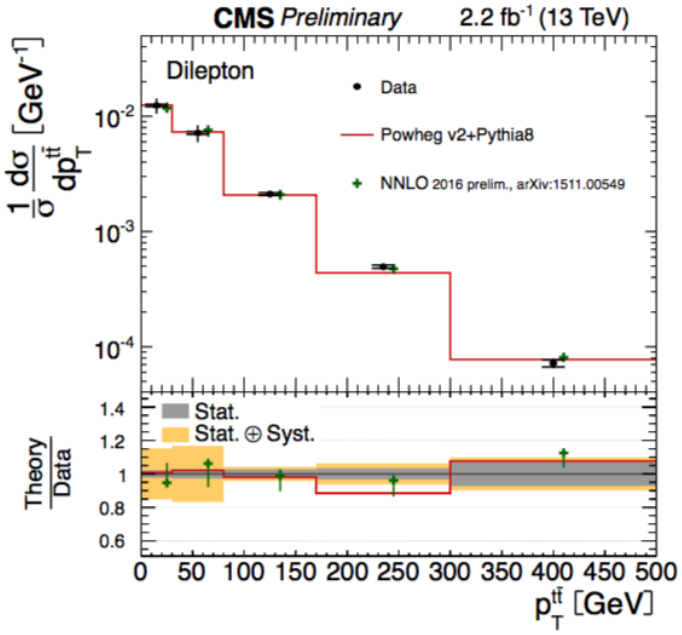
NNLO

13 TeV

Differential, unfolded: $m_{t\bar{t}}$ & $t\bar{t}$ p_T

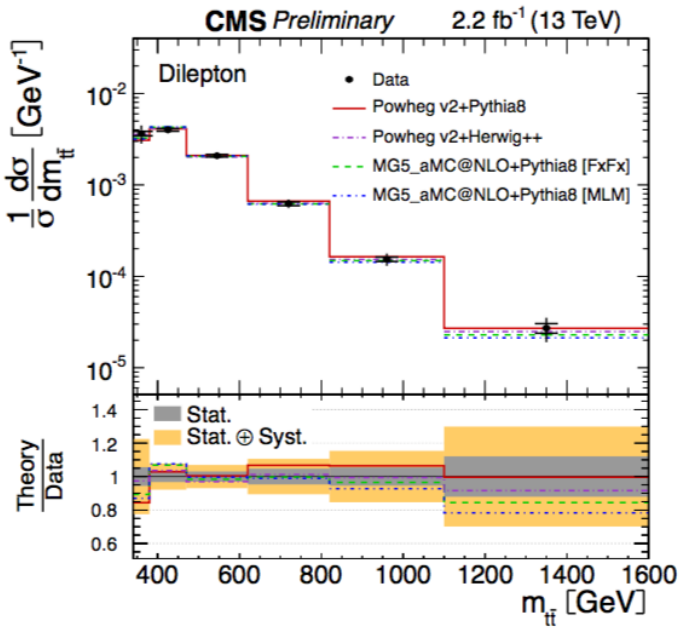
NLO+PS simulations

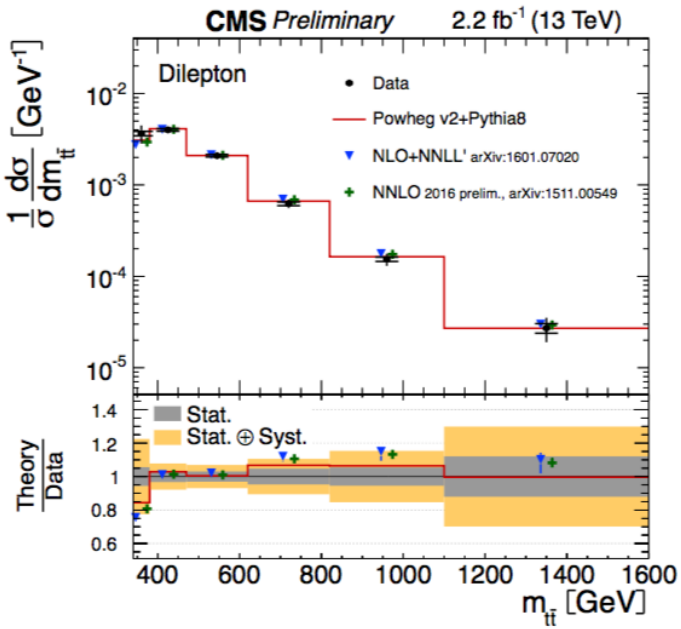


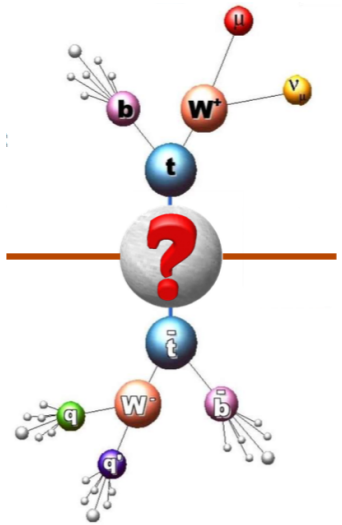


NNLO

13 TeV

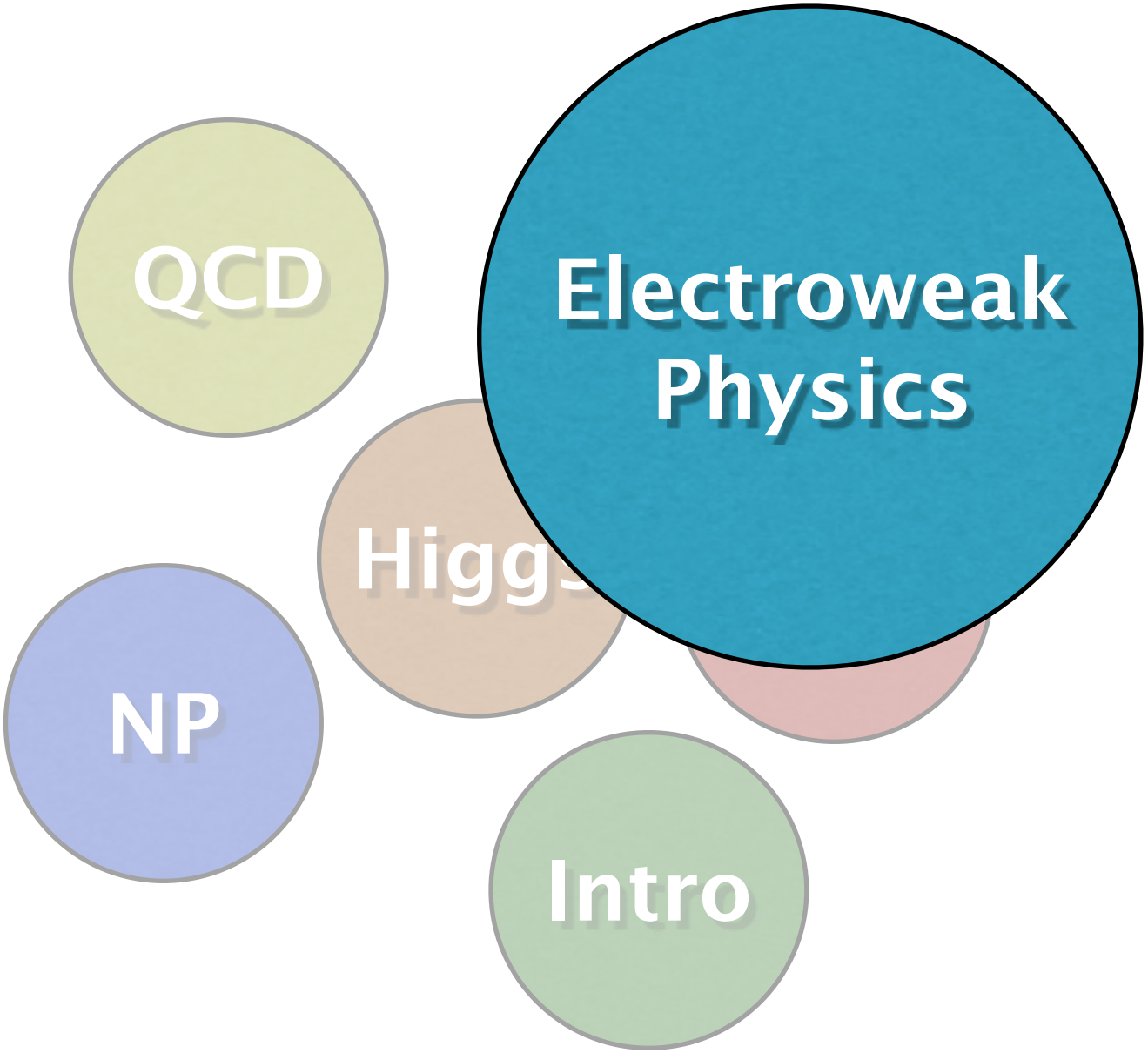






⇒ no new resonances

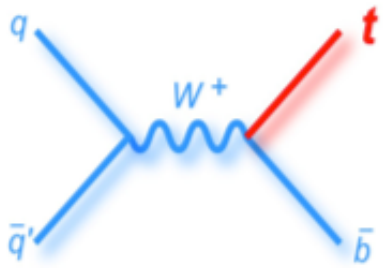
Top Quark Physics Topics

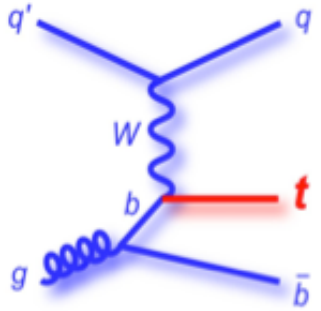


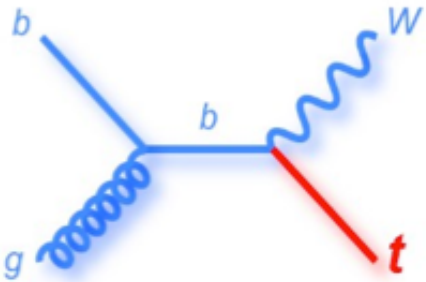
Single Top Quark Production

direct measurement of $|V_{tb}|$

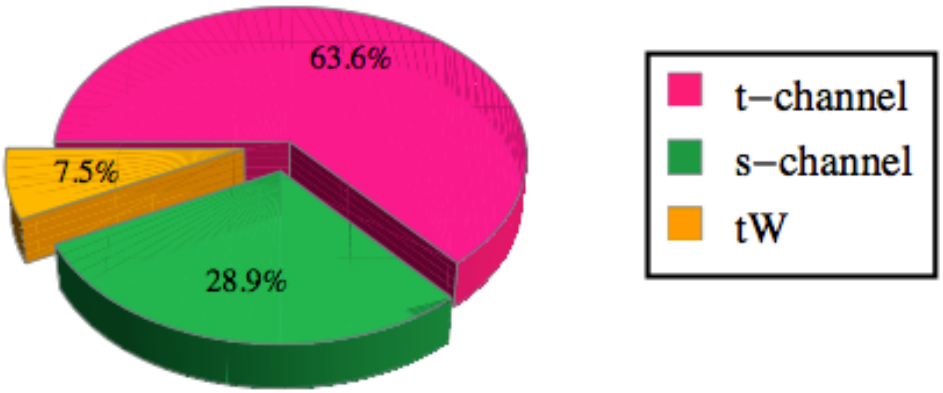
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



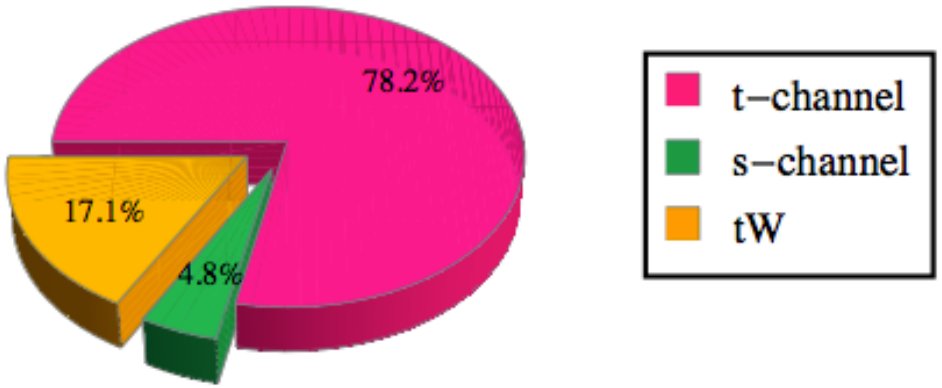




Tevatron



LHC (7 TeV)



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

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

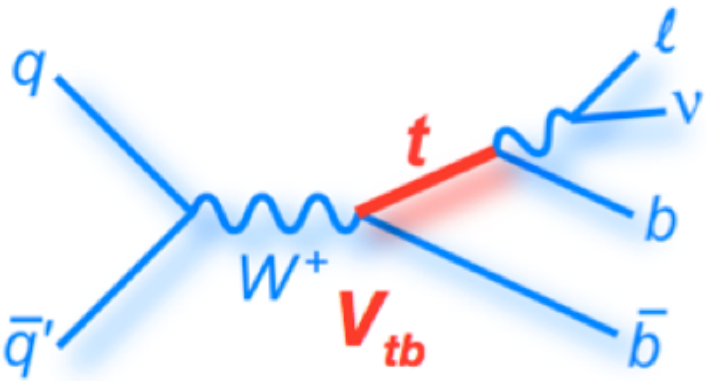
Single Top Quark Selection

s-channel:

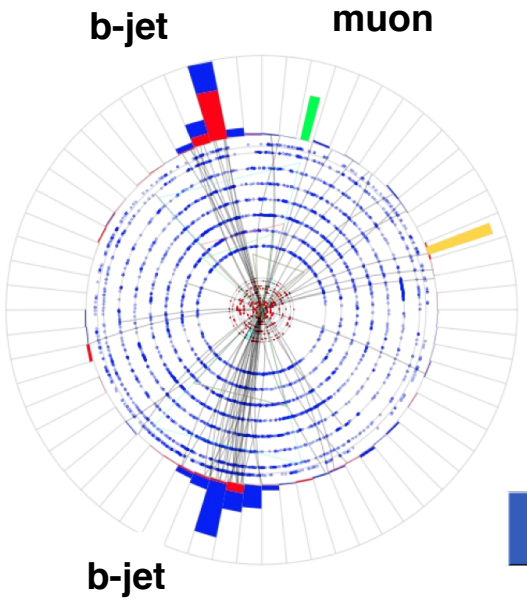
$\sigma_s = 1.05 \pm 0.06$ pb

NLO+NNLL, $m_t = 172.5$ GeV

Kidonakis, PRD 81, 054028 (2010)



- lepton
- missing E_T
- b-jets

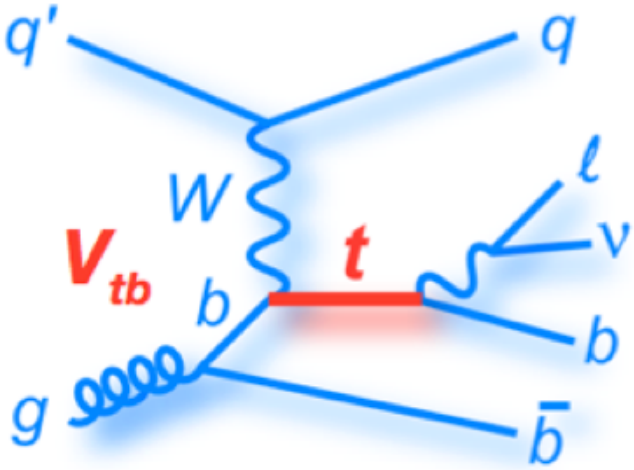


t-channel:

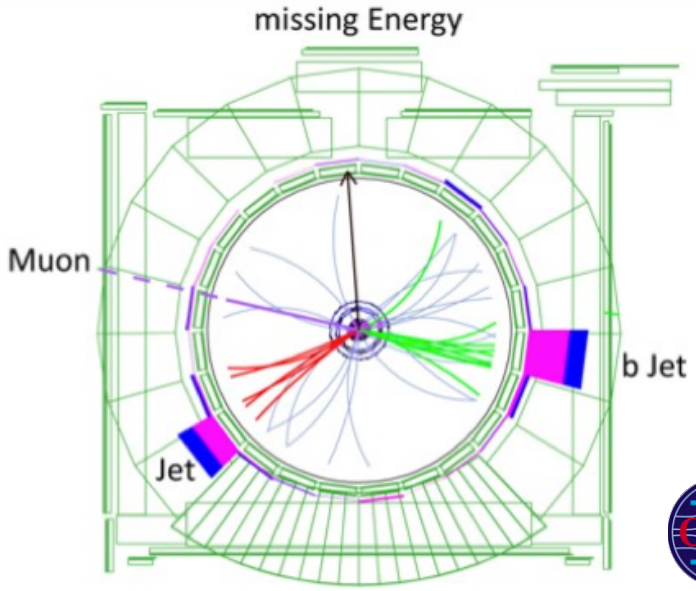
$\sigma_t = 2.12 \pm 0.16$ pb

NLO+NNLL, $m_t = 172.5$ GeV

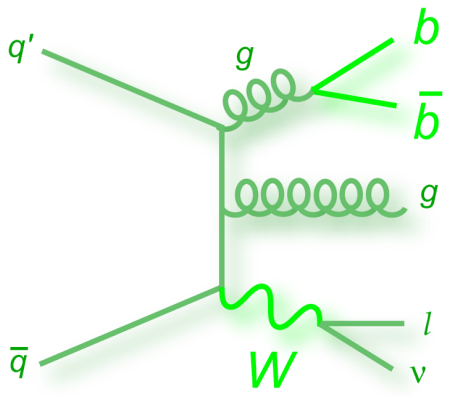
Kidonakis, PRD 83, 091503 (2011)

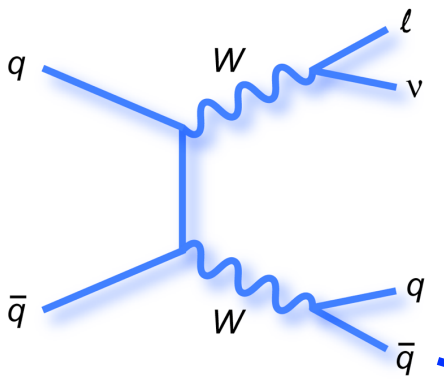


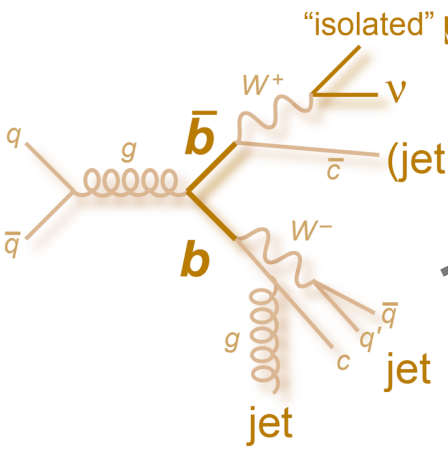
- jets
- lepton
- missing E_T
- b-jets

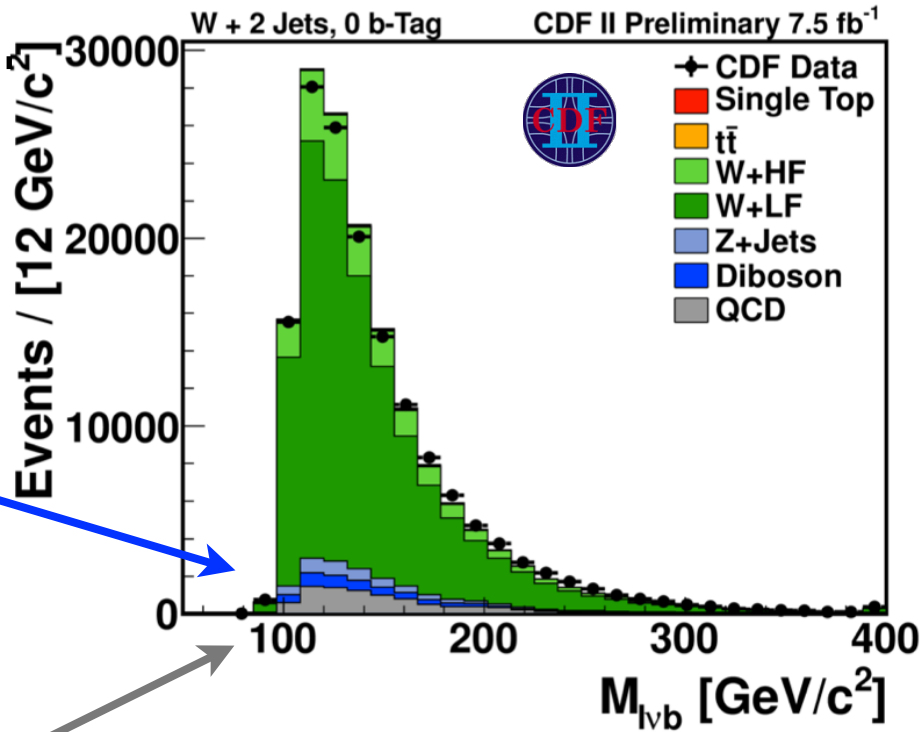


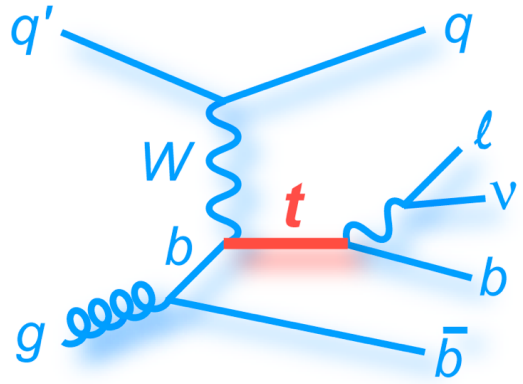
Single Top Quark Yields: pretag

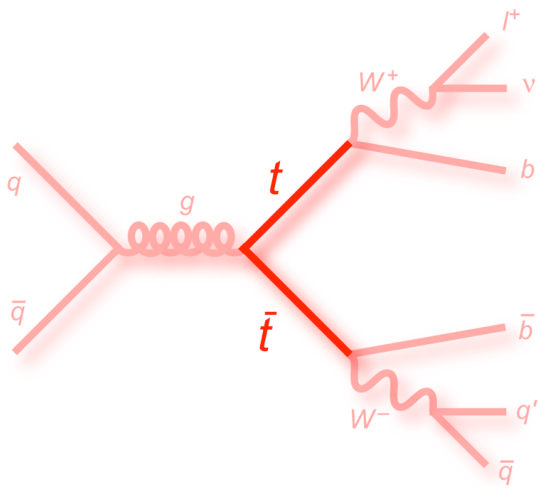






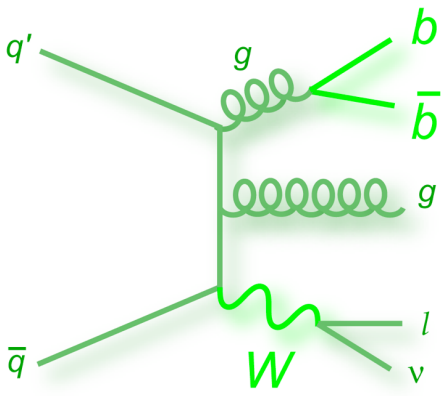


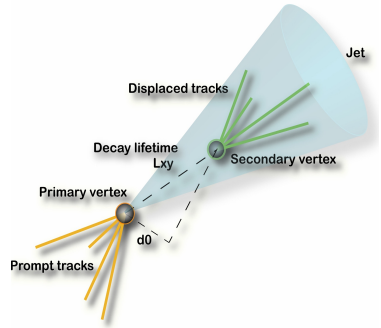


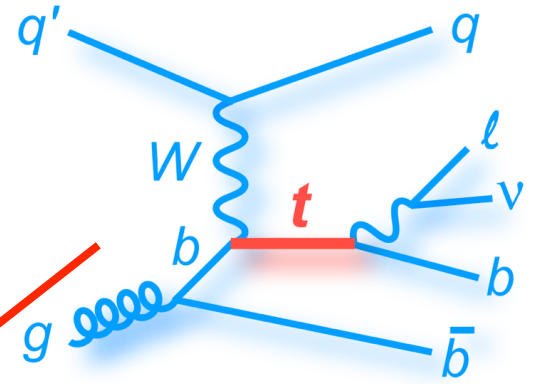


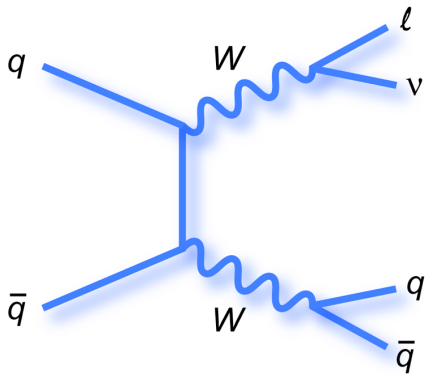
- **best s/b: ~1/200 before b-tagging**

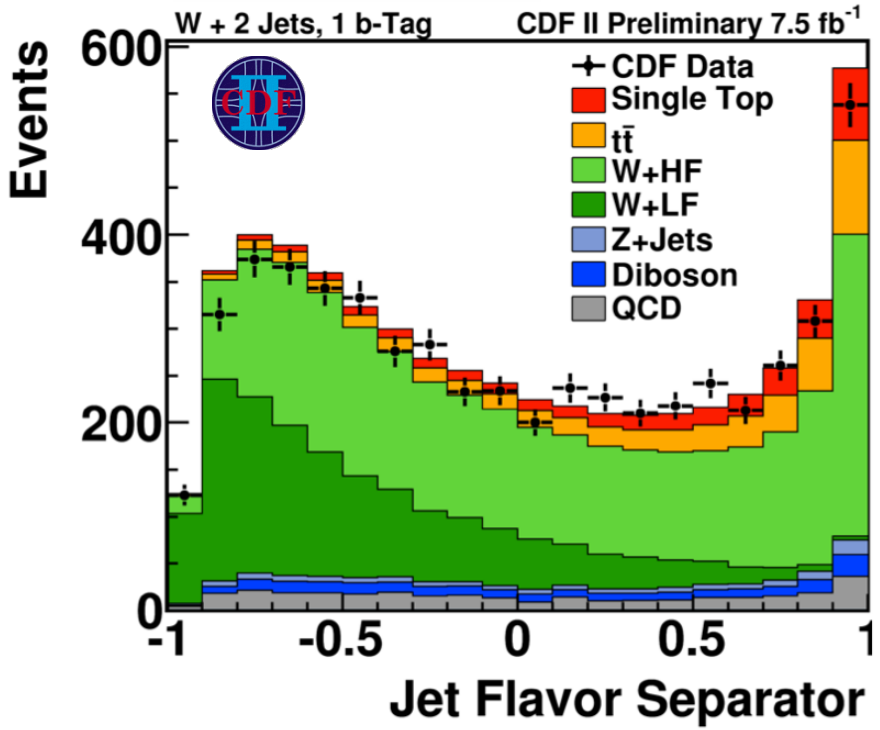
Single Top Quark Yields: b-tagged

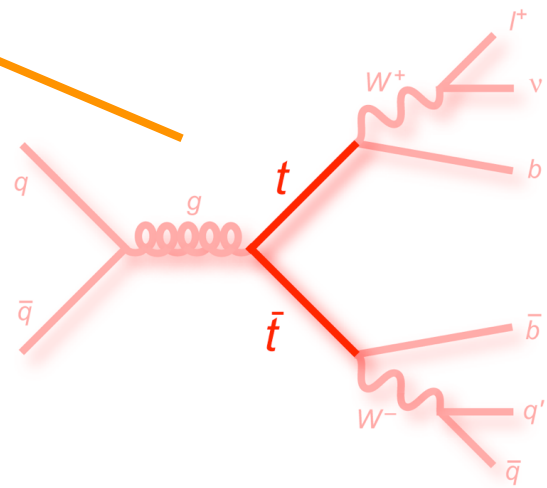


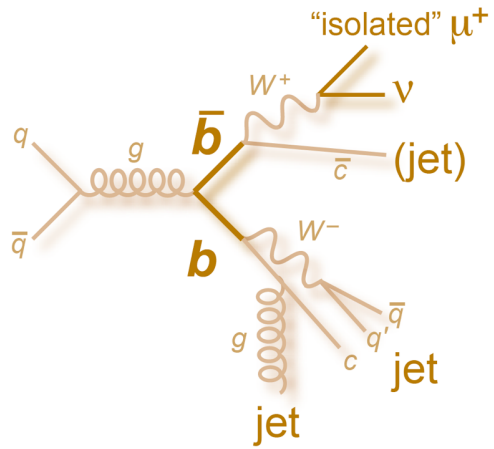






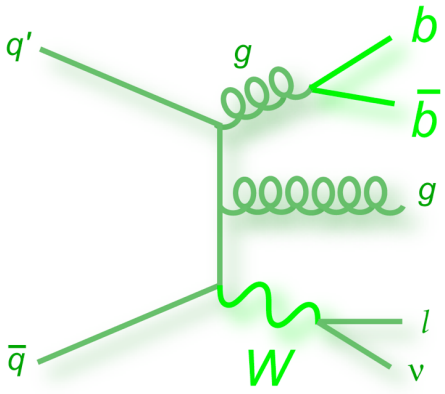


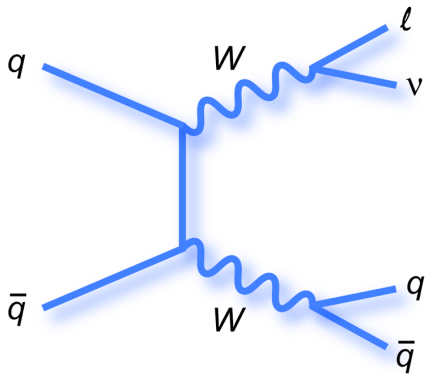


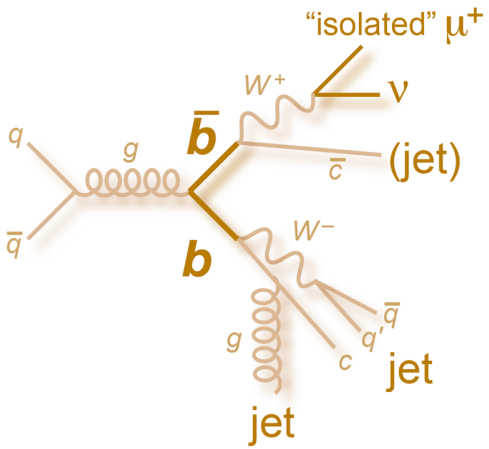


- best s/b: ~1/200 before b-tagging
- best s/b: ~1/10 after b-tagging

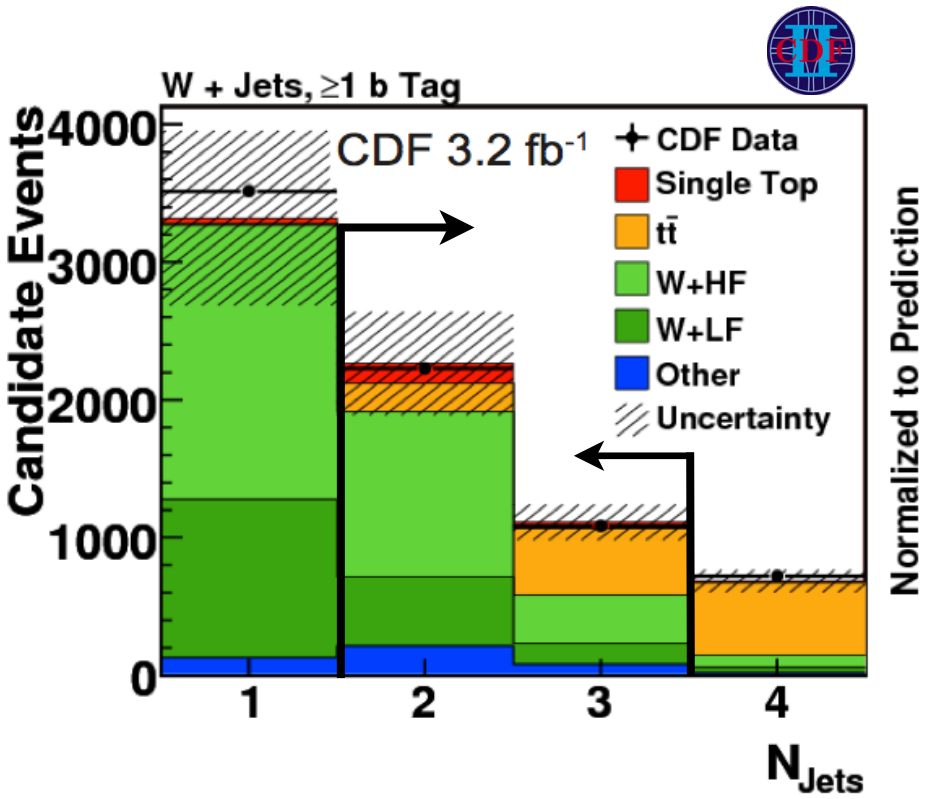
Single Top Quark Yields: b-

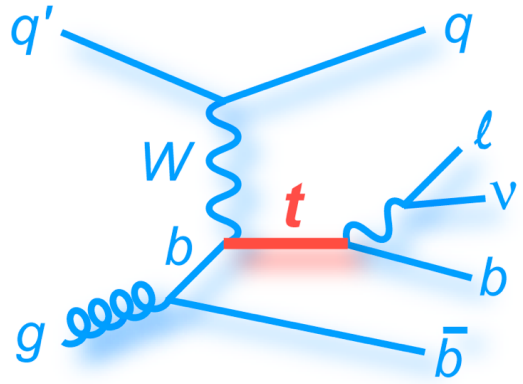


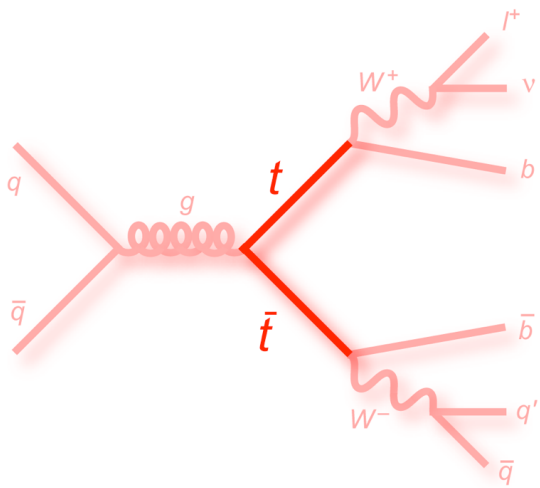




- number of jets and number of b tags to define samples

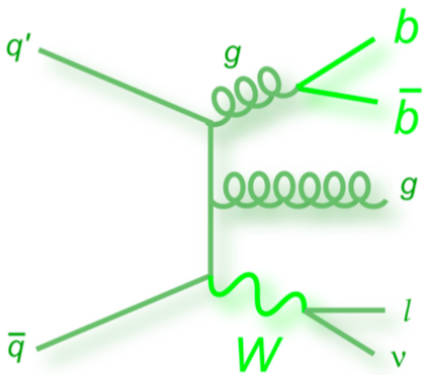


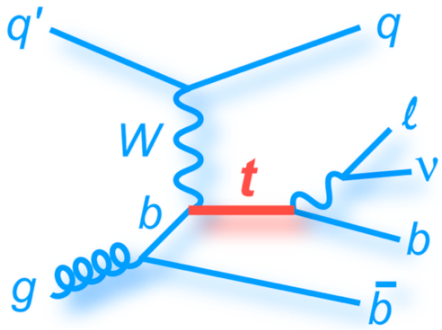


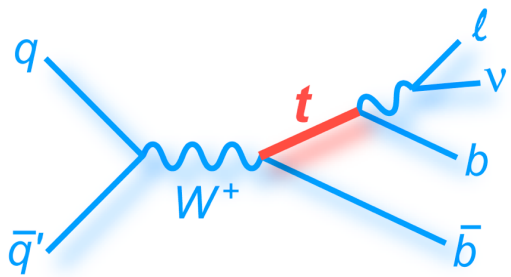


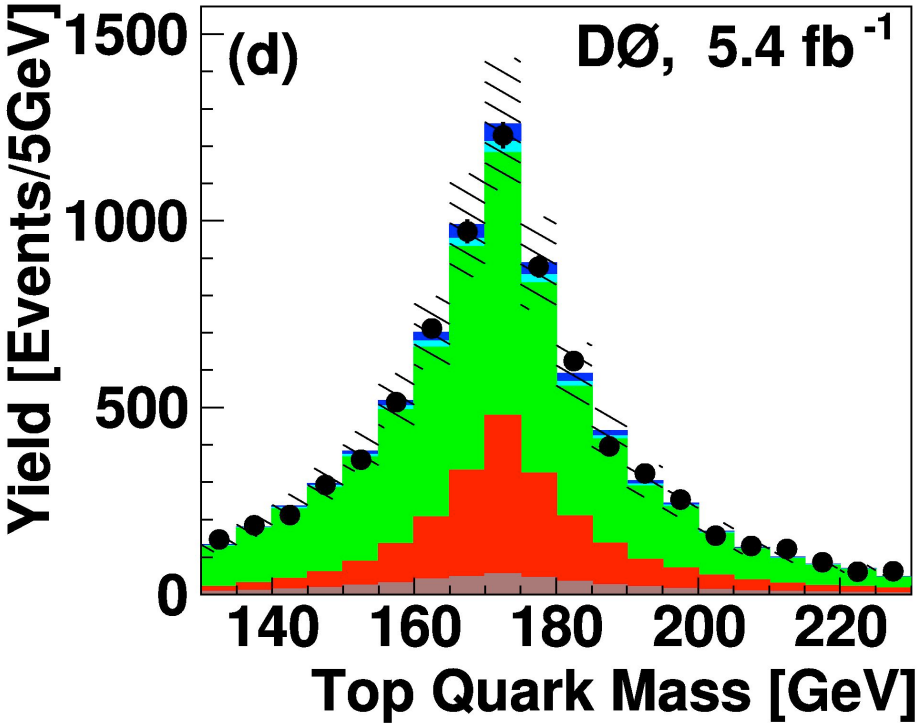
- best s/b: ~1/200 before b-tagging
- best s/b: ~1/10 after b-tagging

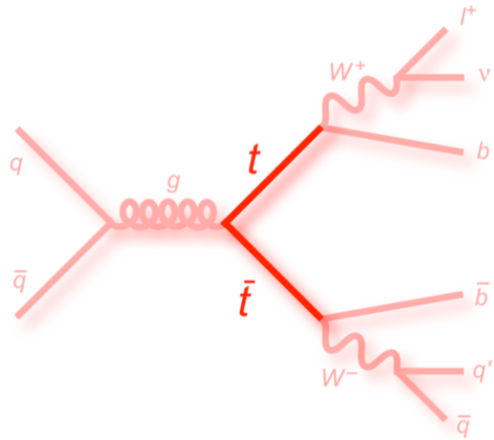
Recontructed Top Mass

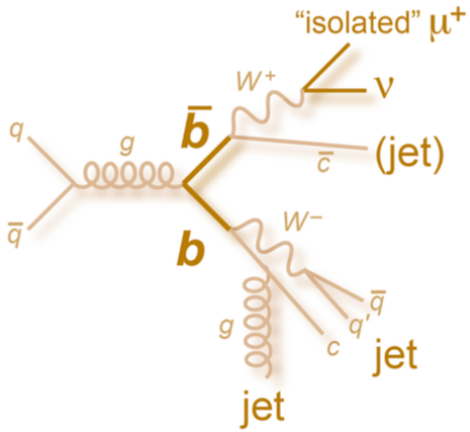










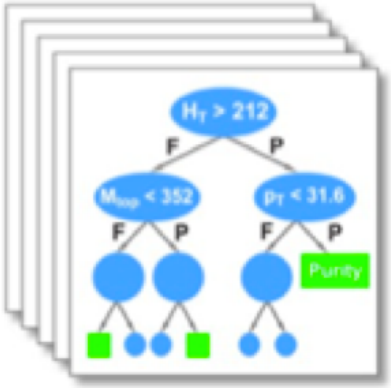


→ signal and background look similar

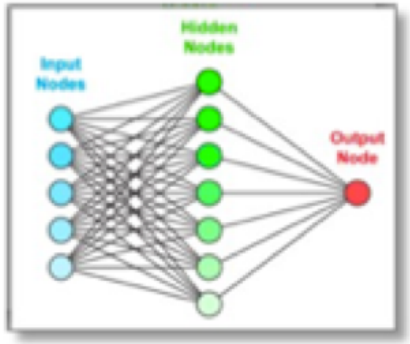
→ errors larger than signal contribution

Multivariate Analyses

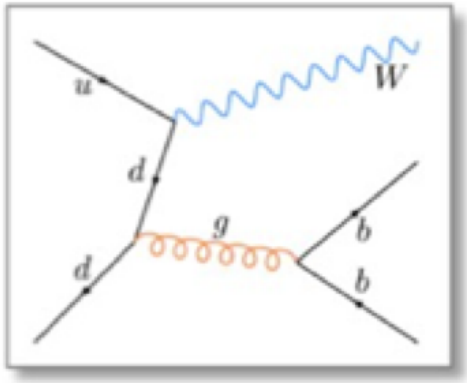
Boosted Decision Trees



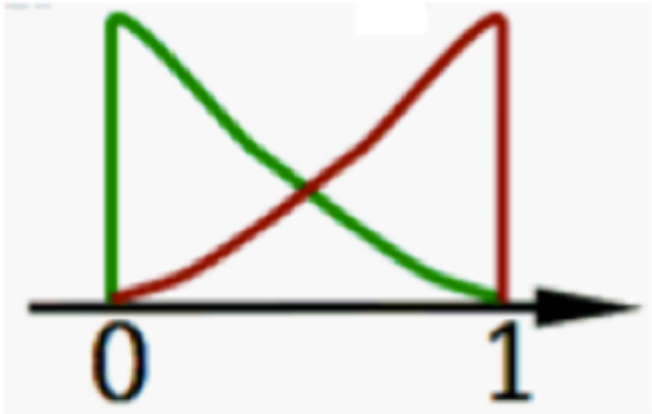
Neural Networks



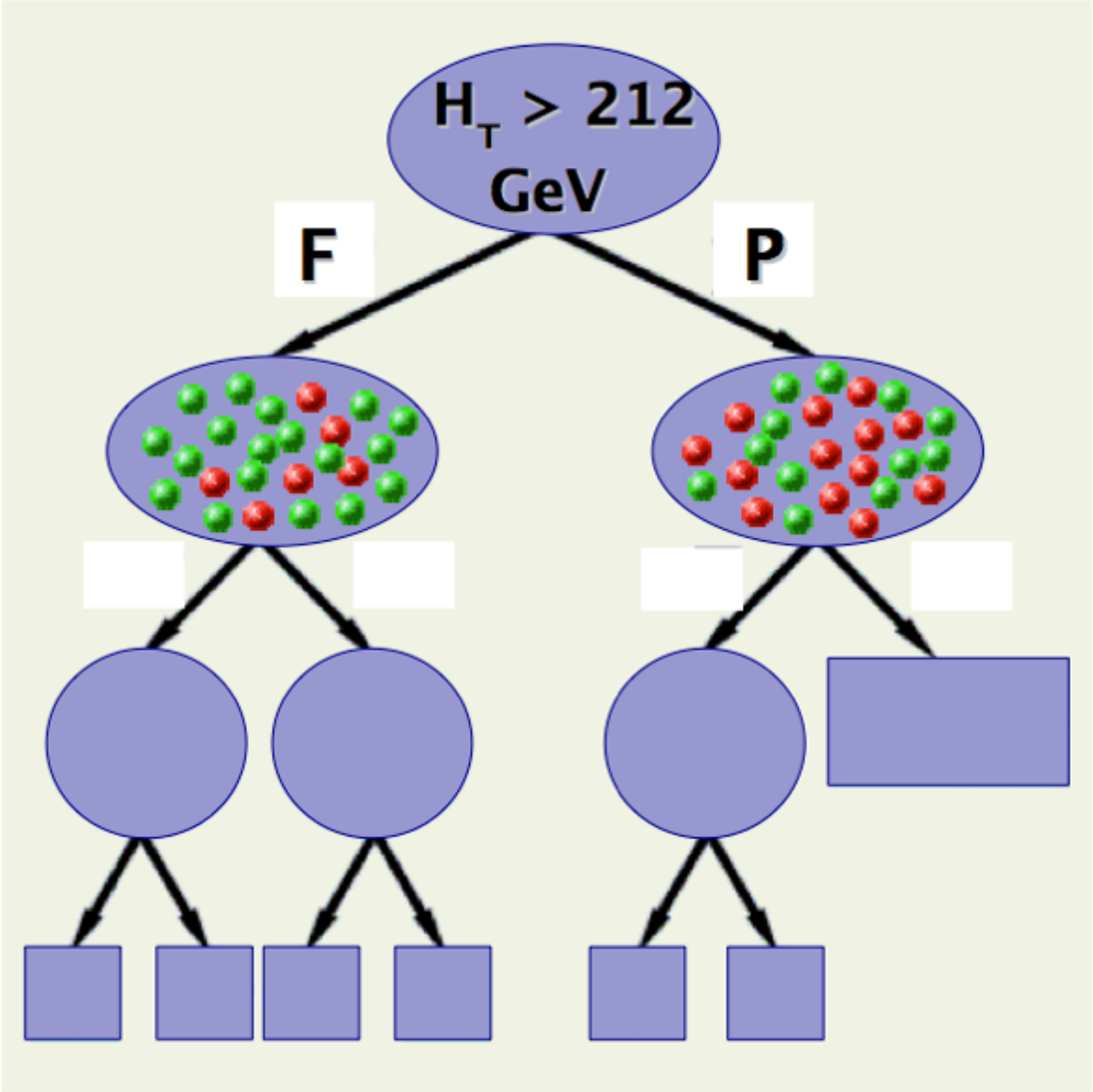
Matrix Elements



background **signal**

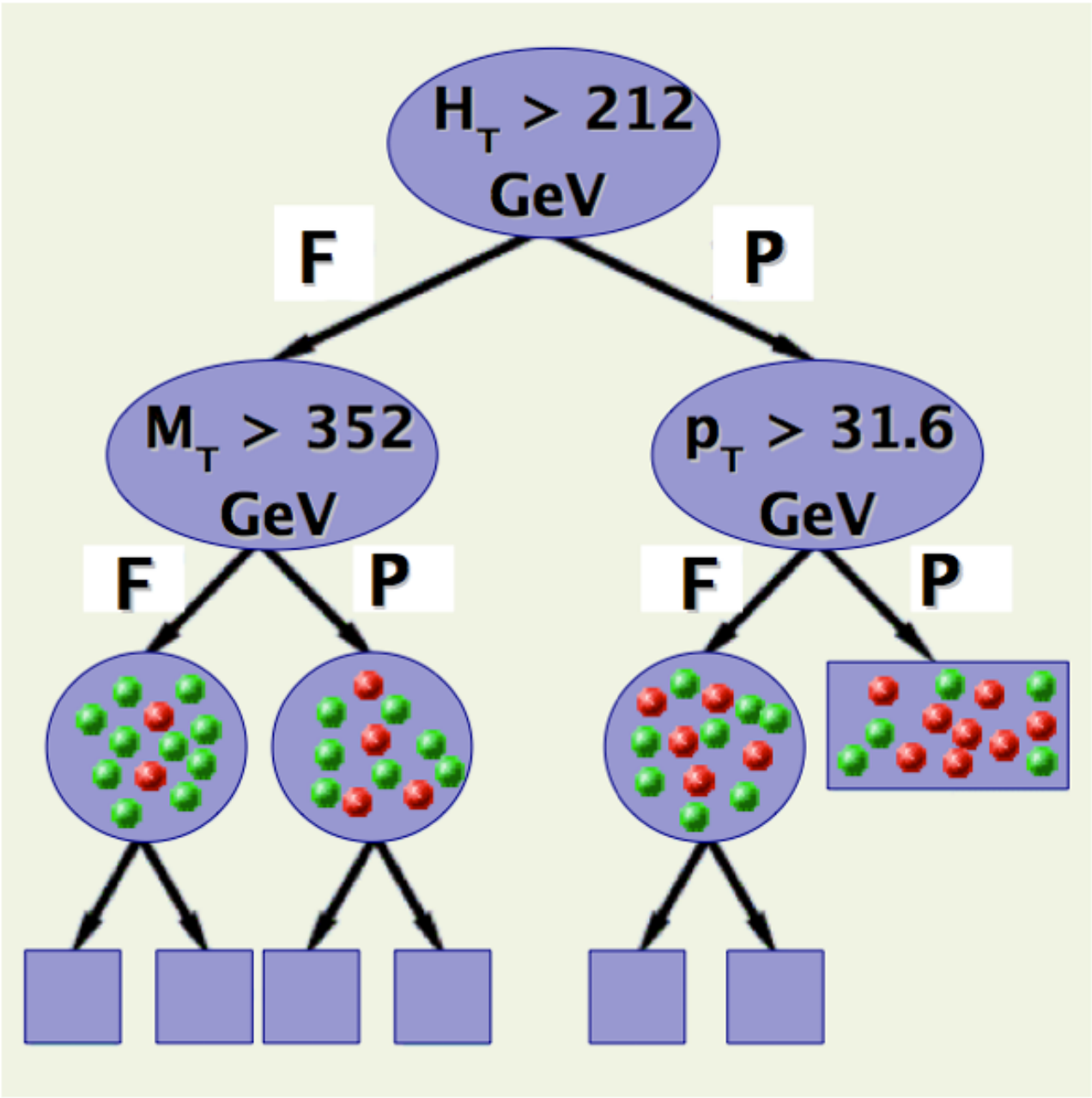


Boosted Decision Trees



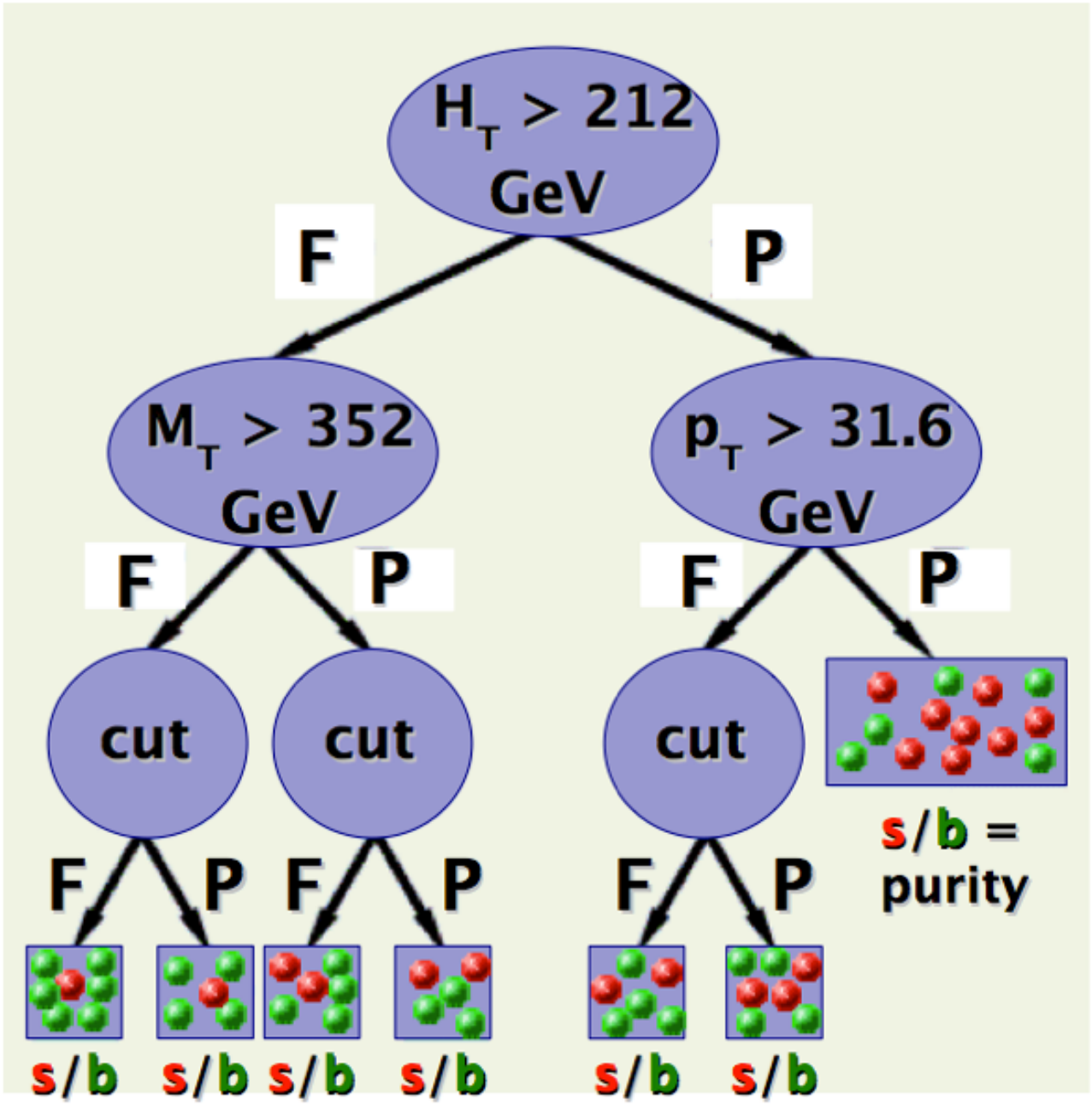
- **IDEA: recover events that fail criteria in cut-based analyses**

Boosted Decision Trees



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

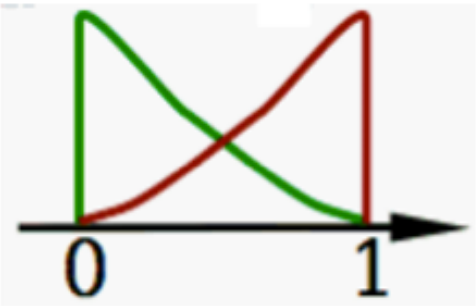
Boosted Decision Trees



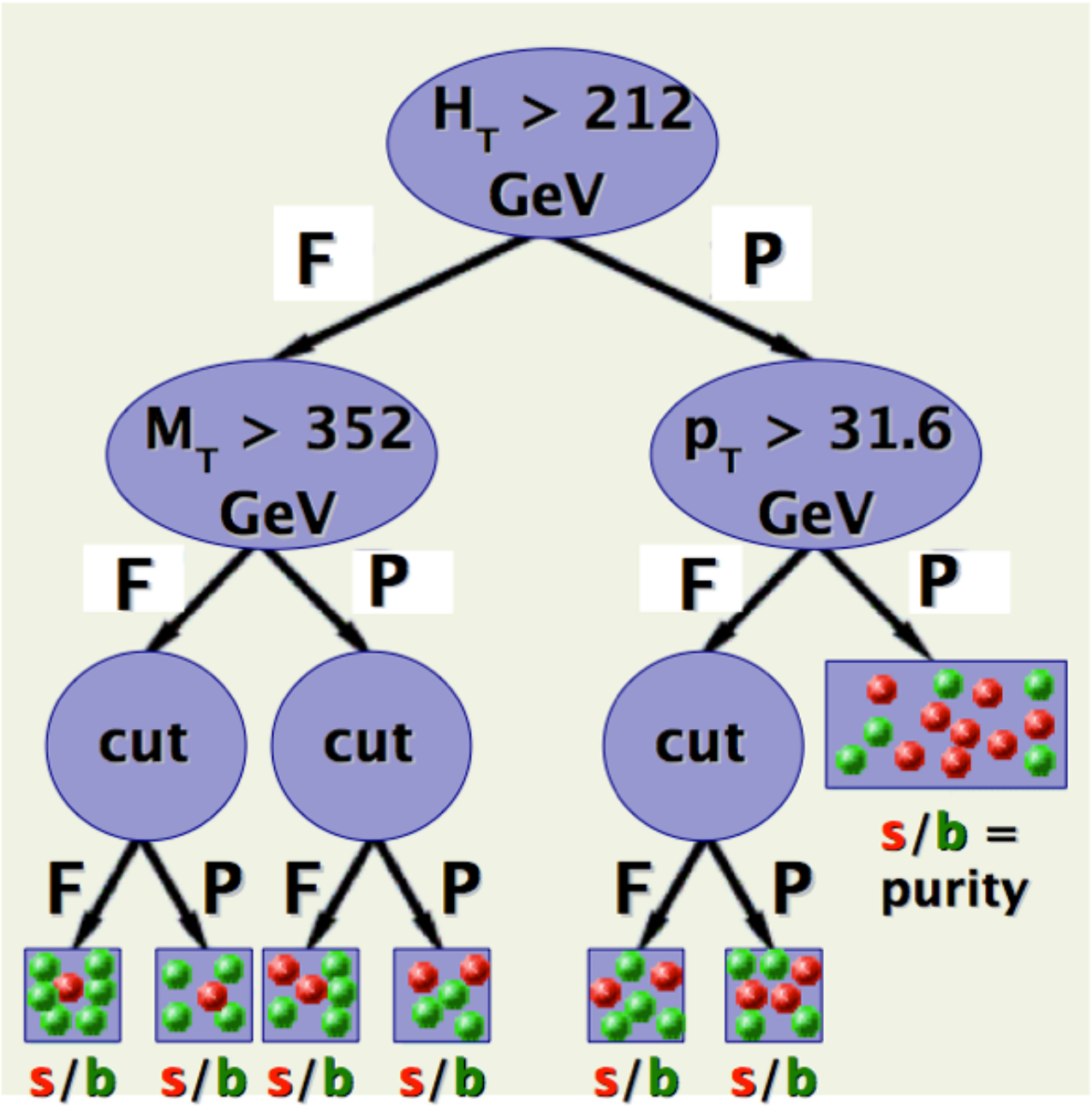
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background signal



Boosted Decision Trees

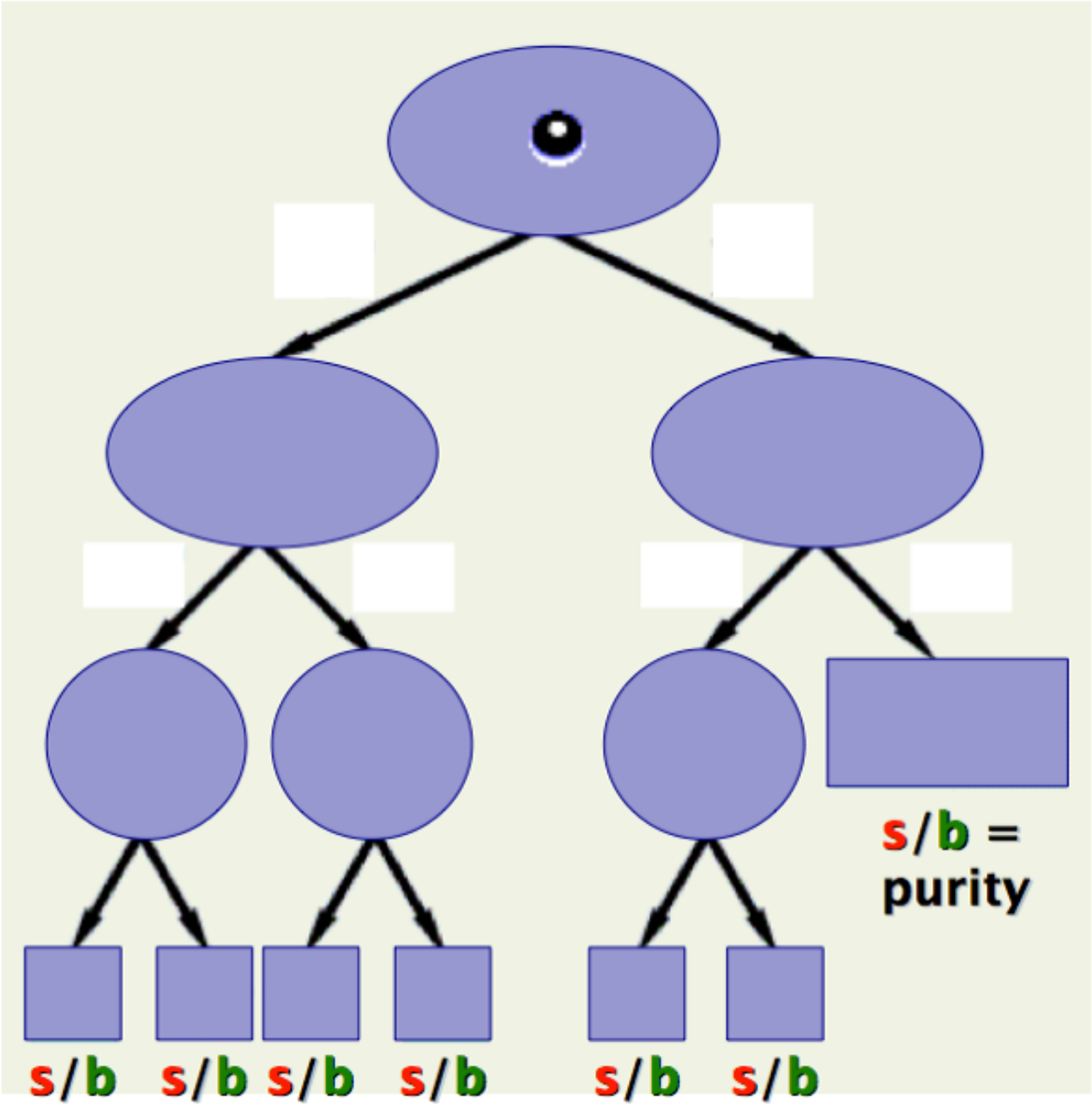


- **IDEA: recover events that fail criteria in cut-based analyses**

boosting:

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

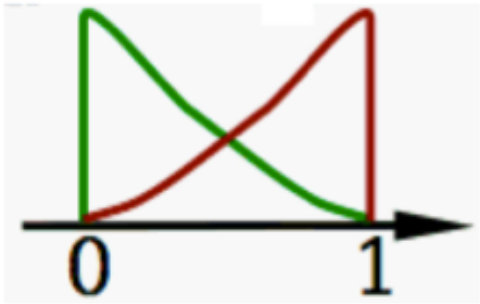
Boosted Decision Trees



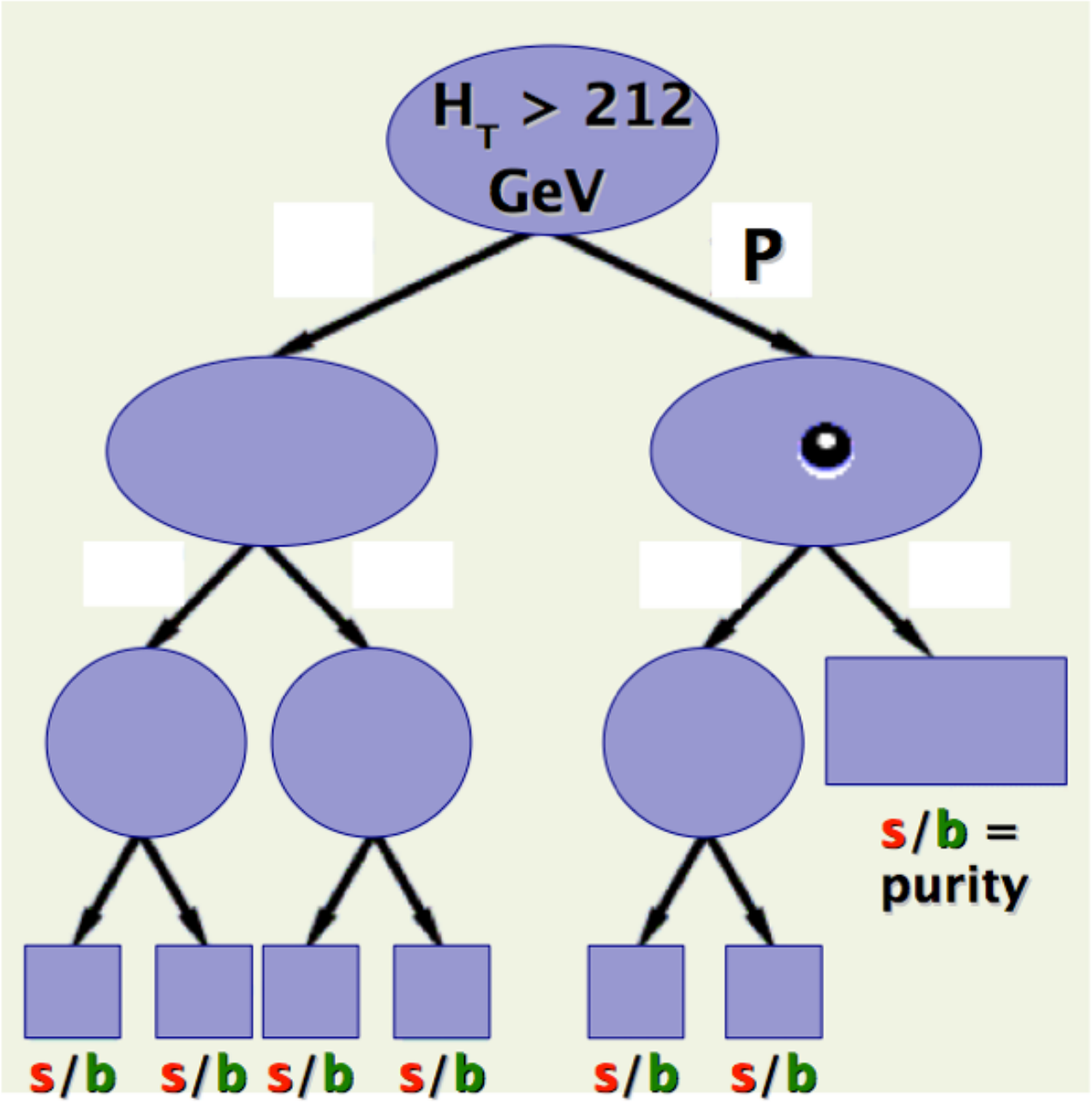
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background signal



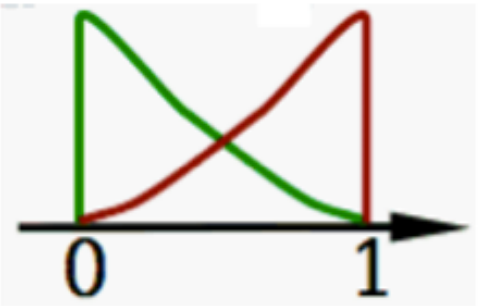
Boosted Decision Trees



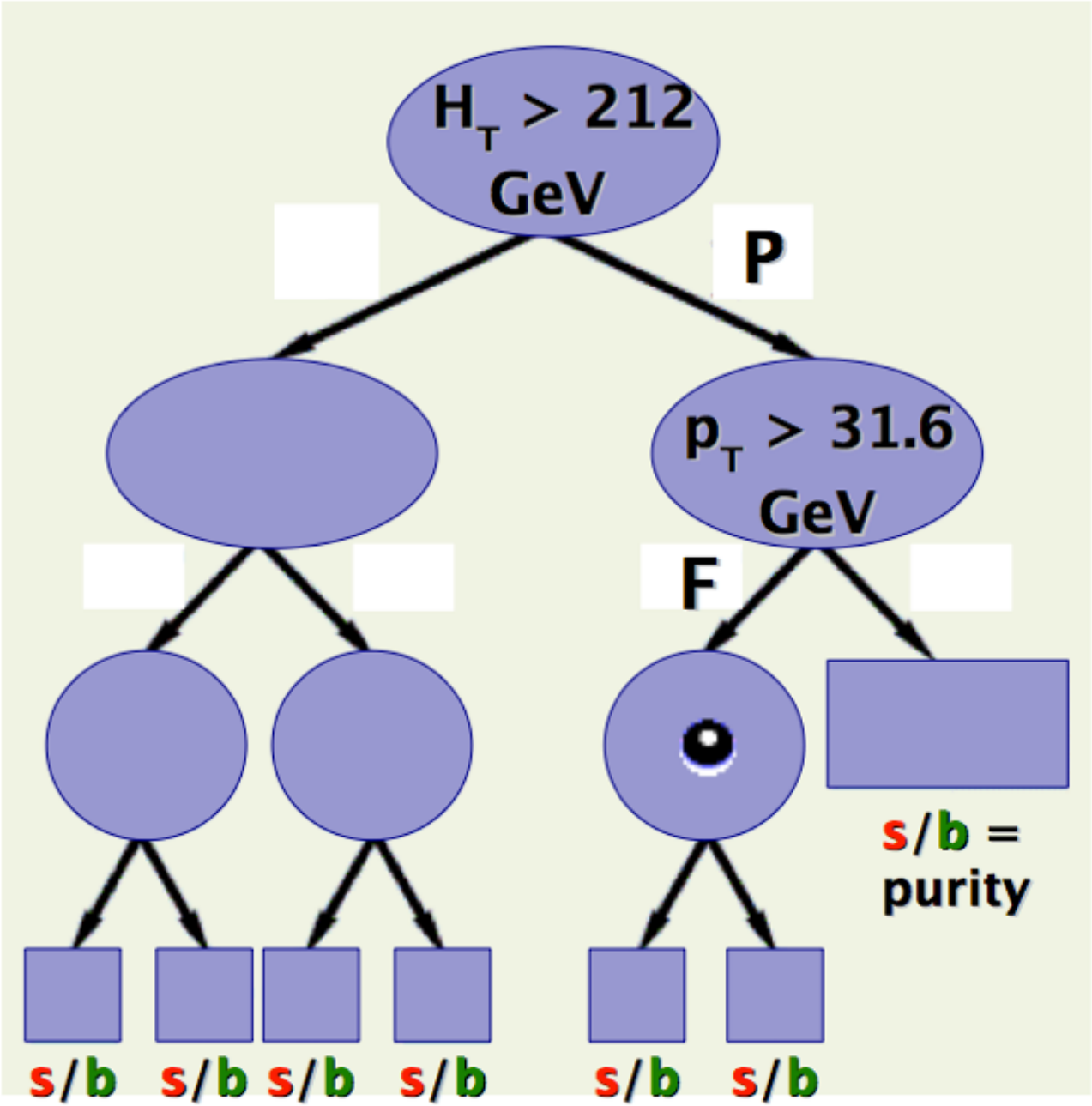
- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

background signal

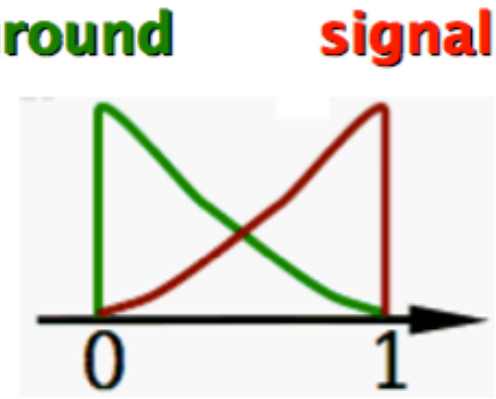


Boosted Decision Trees

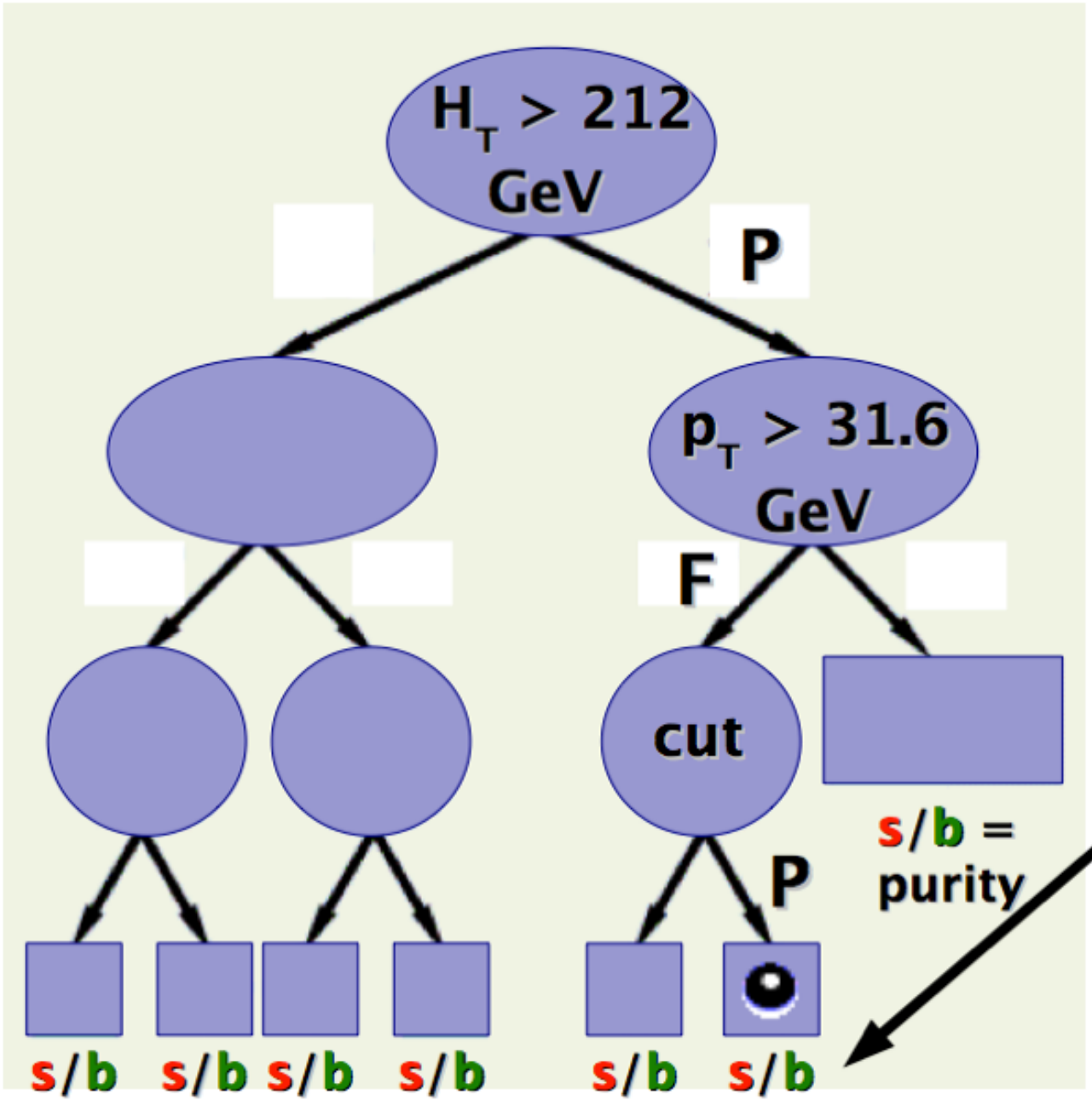


- **IDEA: recover events that fail criteria in cut-based analyses**

- **result: weight for every event**

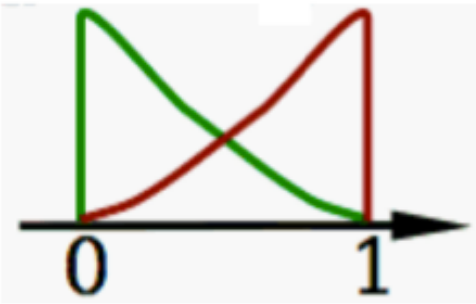


Boosted Decision Trees

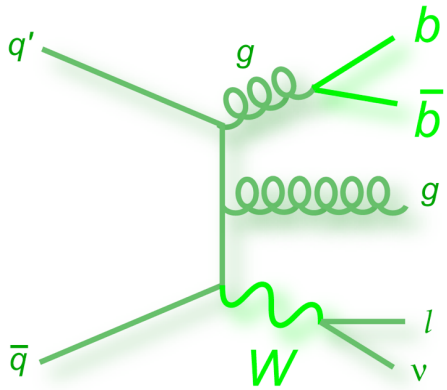


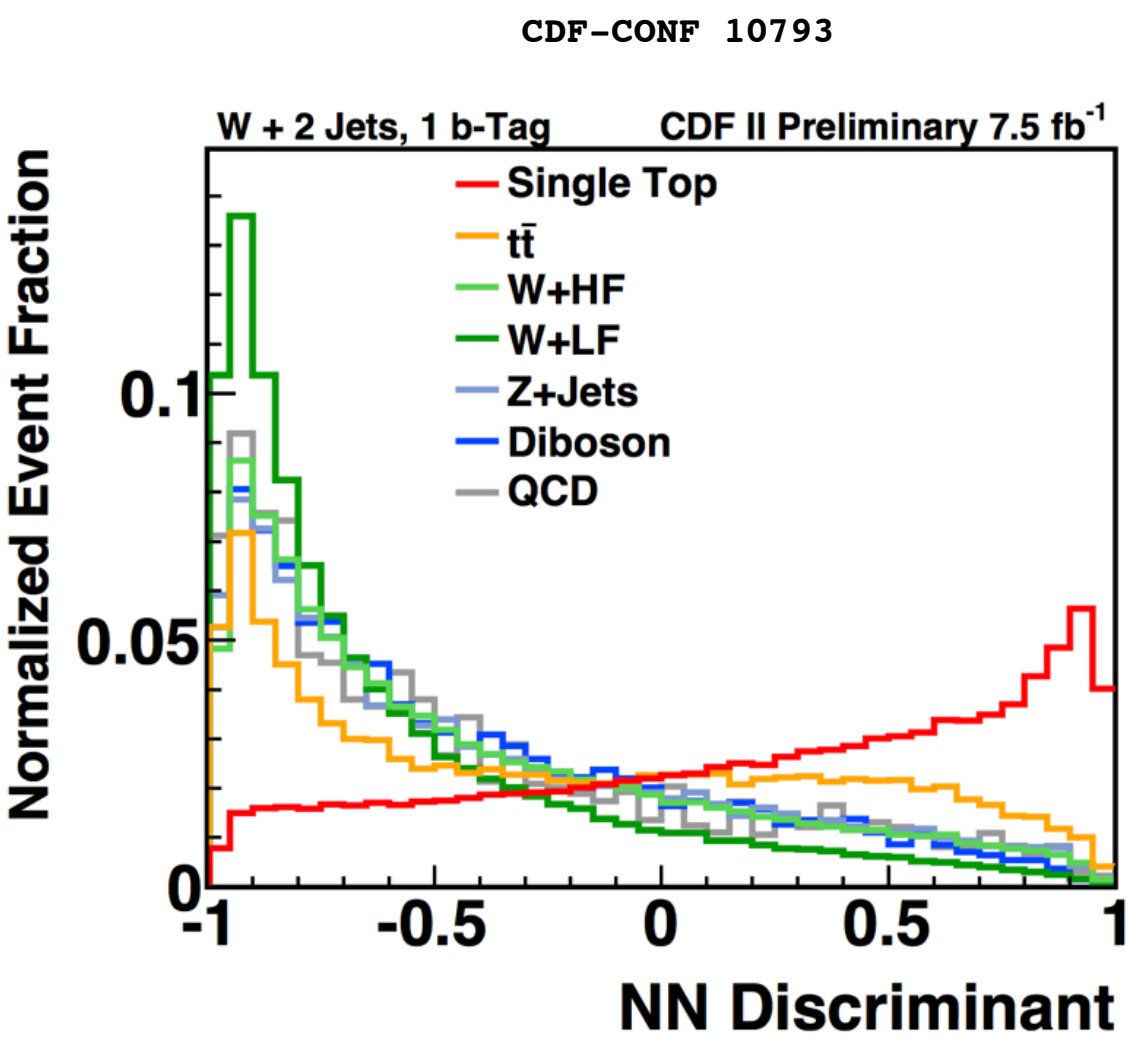
- **IDEA: recover events that fail criteria in cut-based analyses**
- **result: weight for every event**

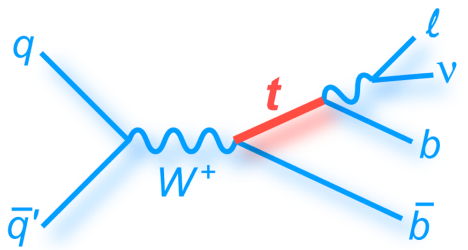
background signal

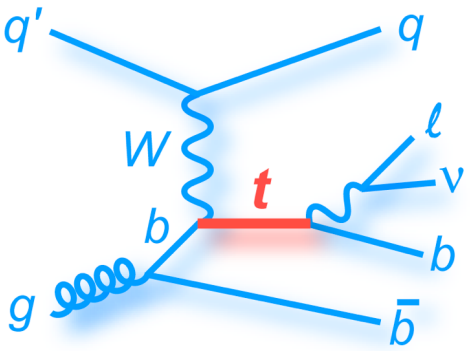


Output Discriminant for s+t

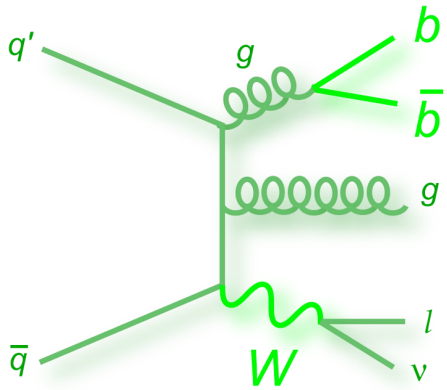




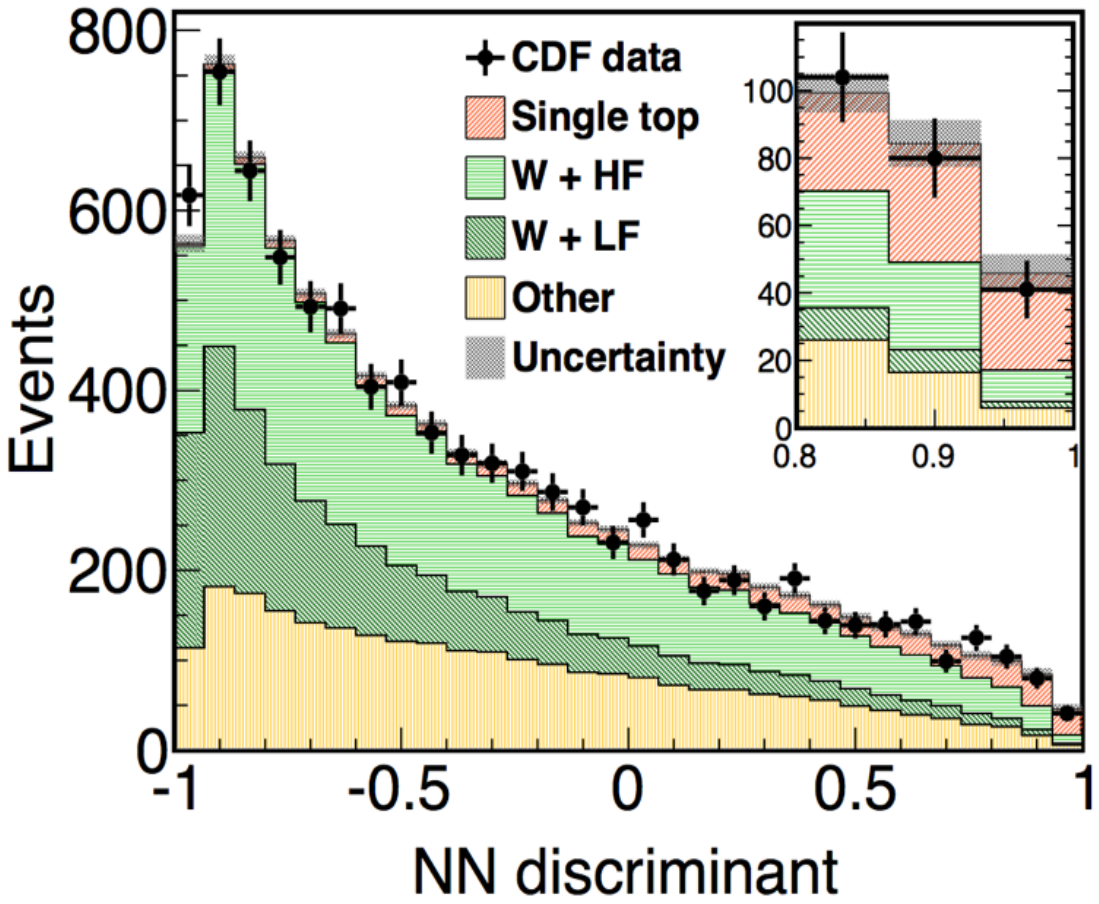


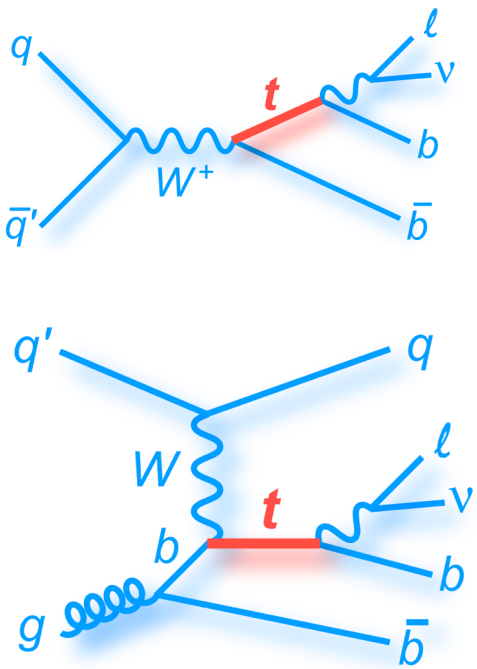


Output Discriminant for s+t channel



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

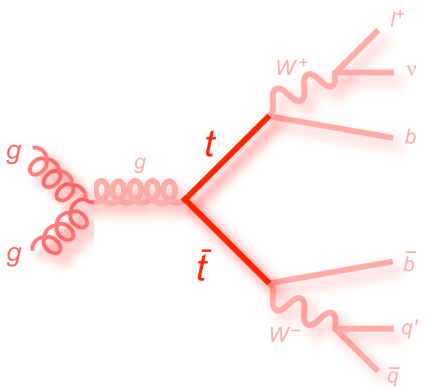


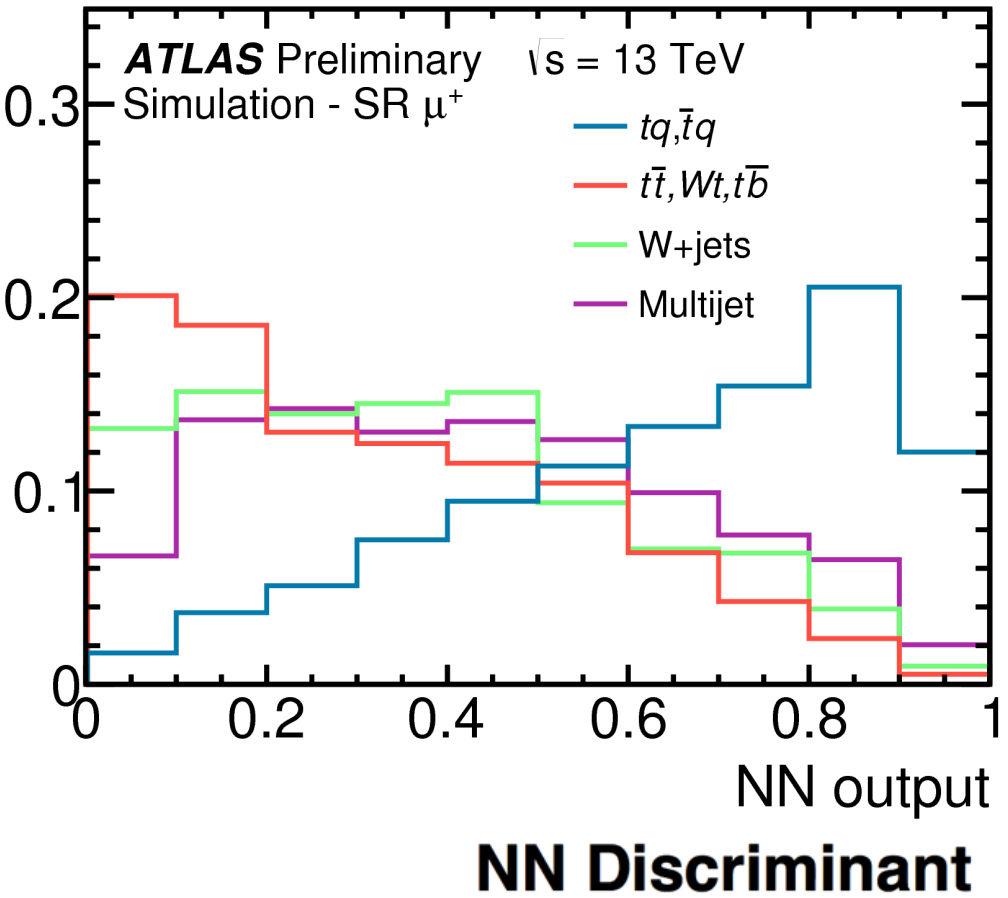


→ **s+t channel observed by CDF and D0 in 2009**

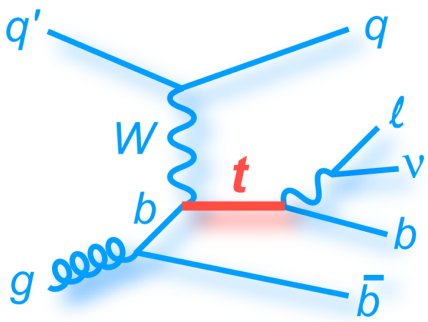
Output Discriminant t-channel

13 TeV



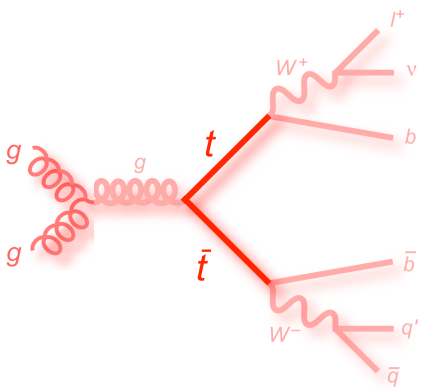


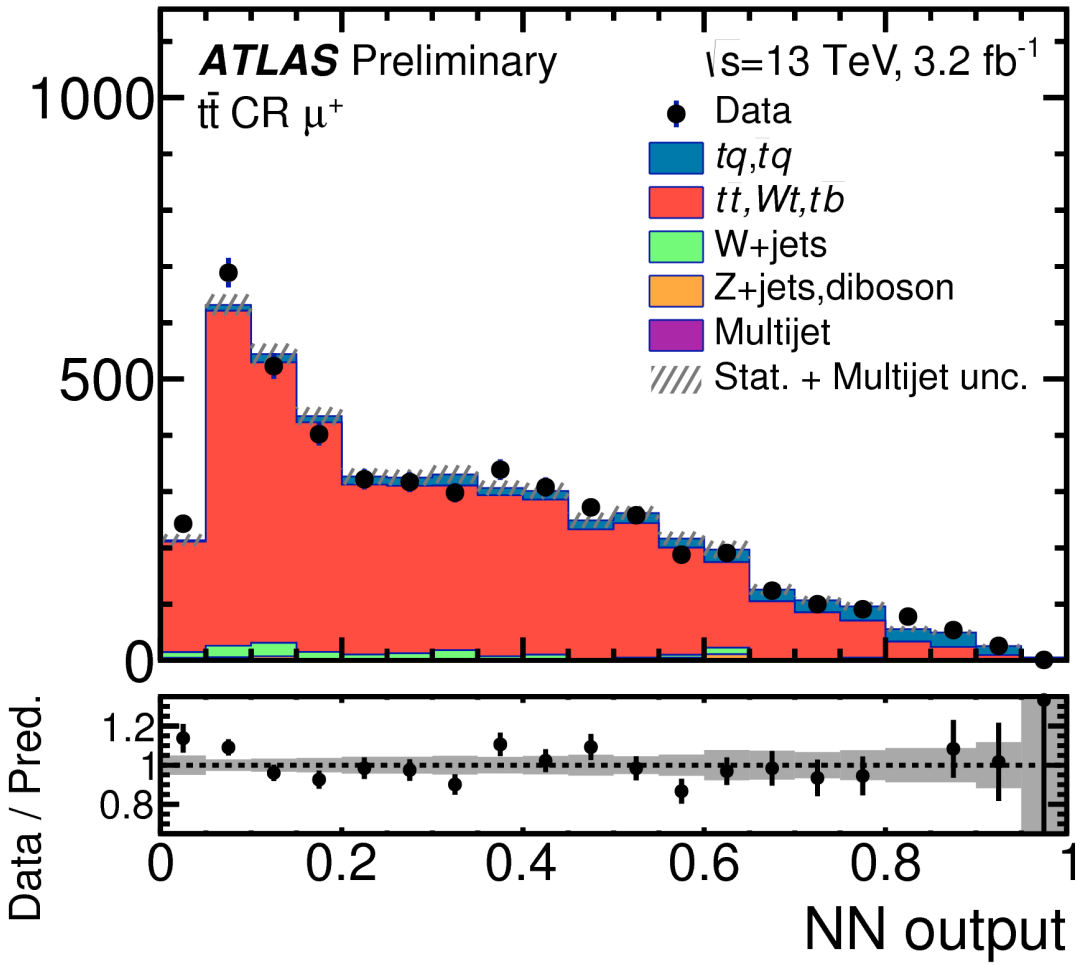
NN Discriminant

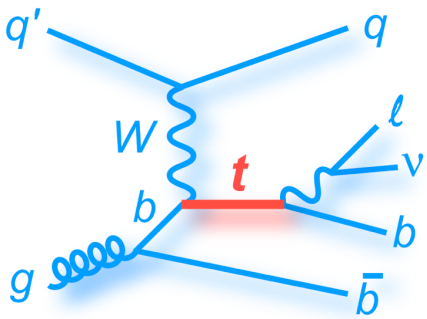


Output Discriminant t-channel

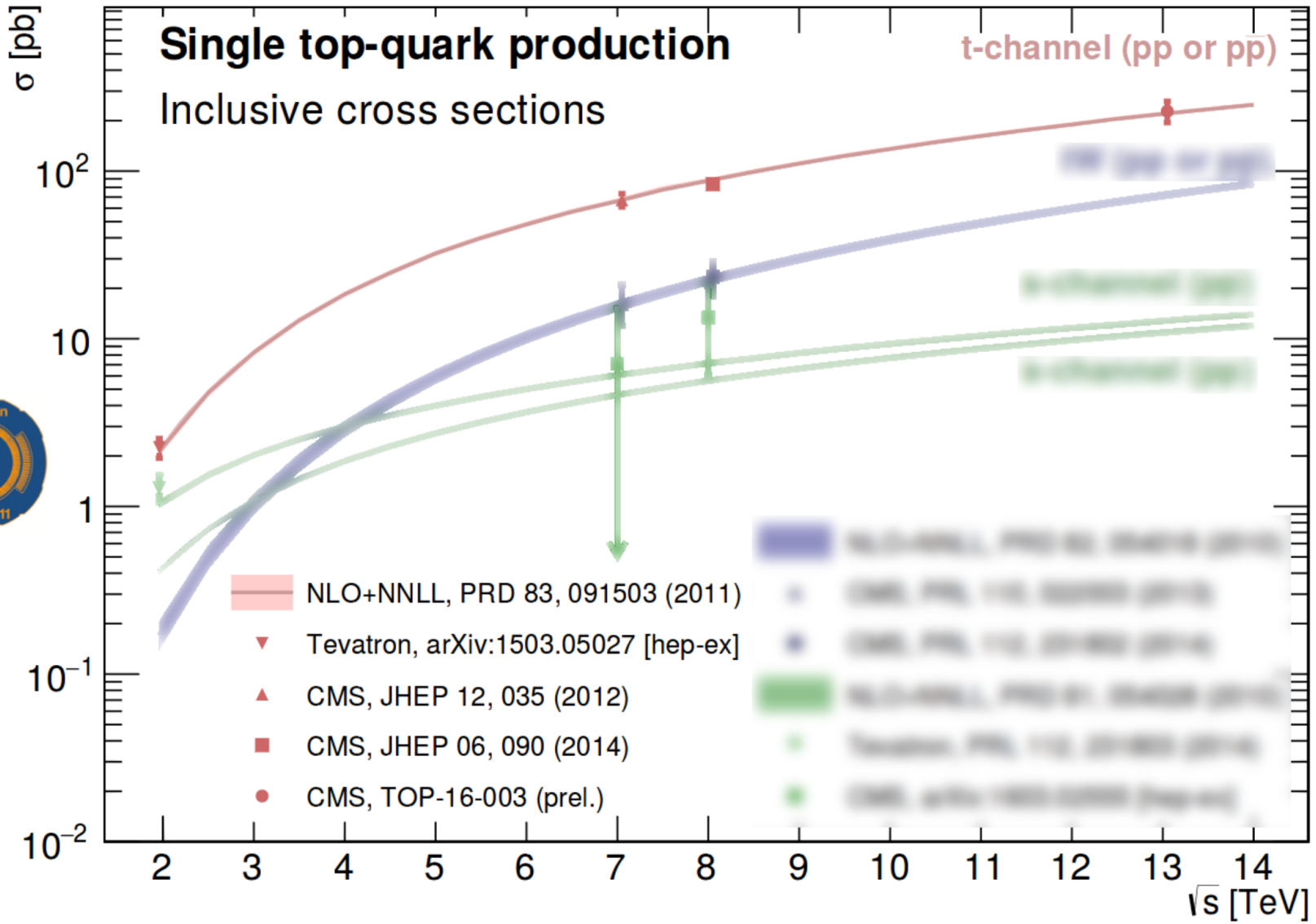
13 TeV

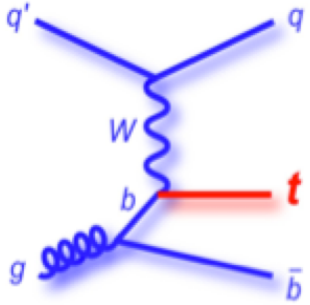






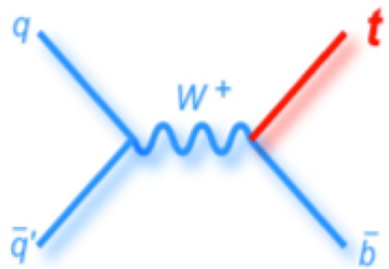
Single top t-channel cross section

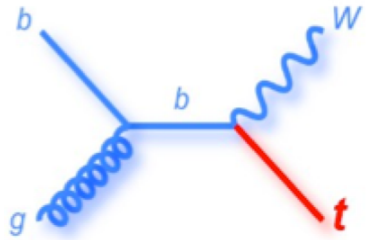


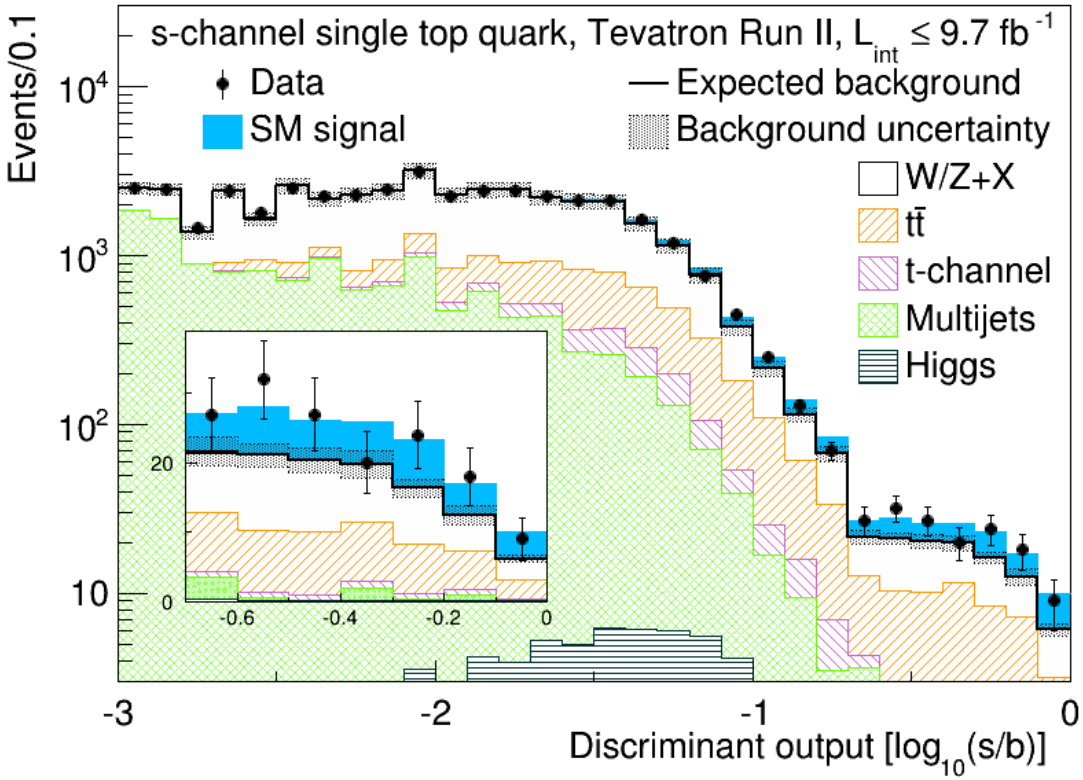


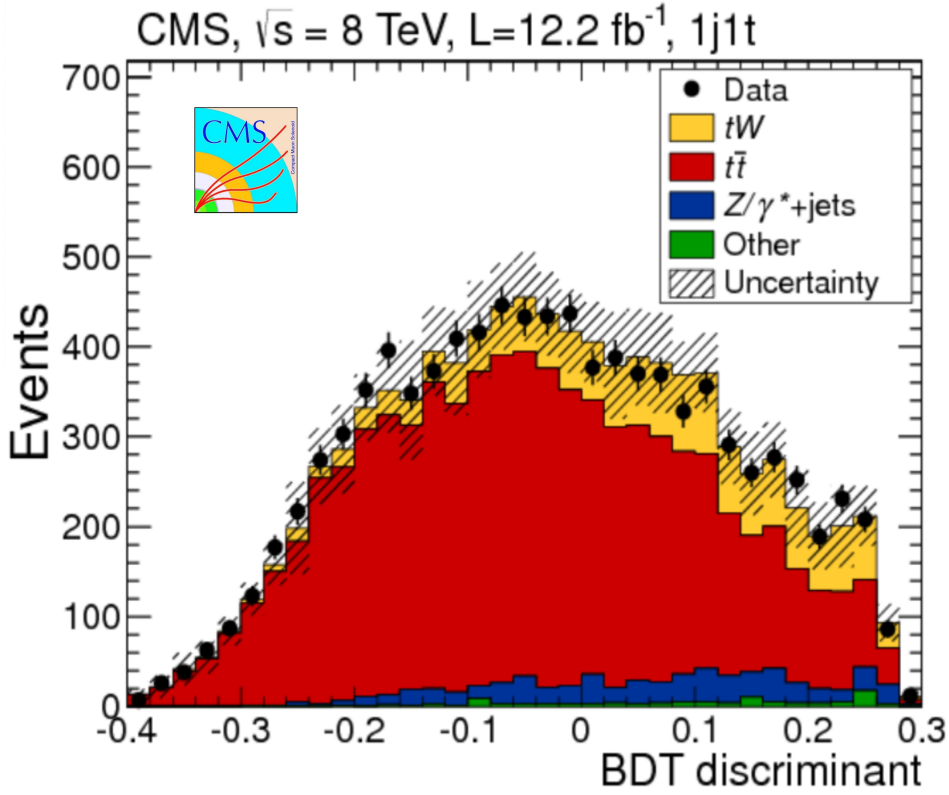
→ agreement with SM predictions!

s- and Wt-channel Production





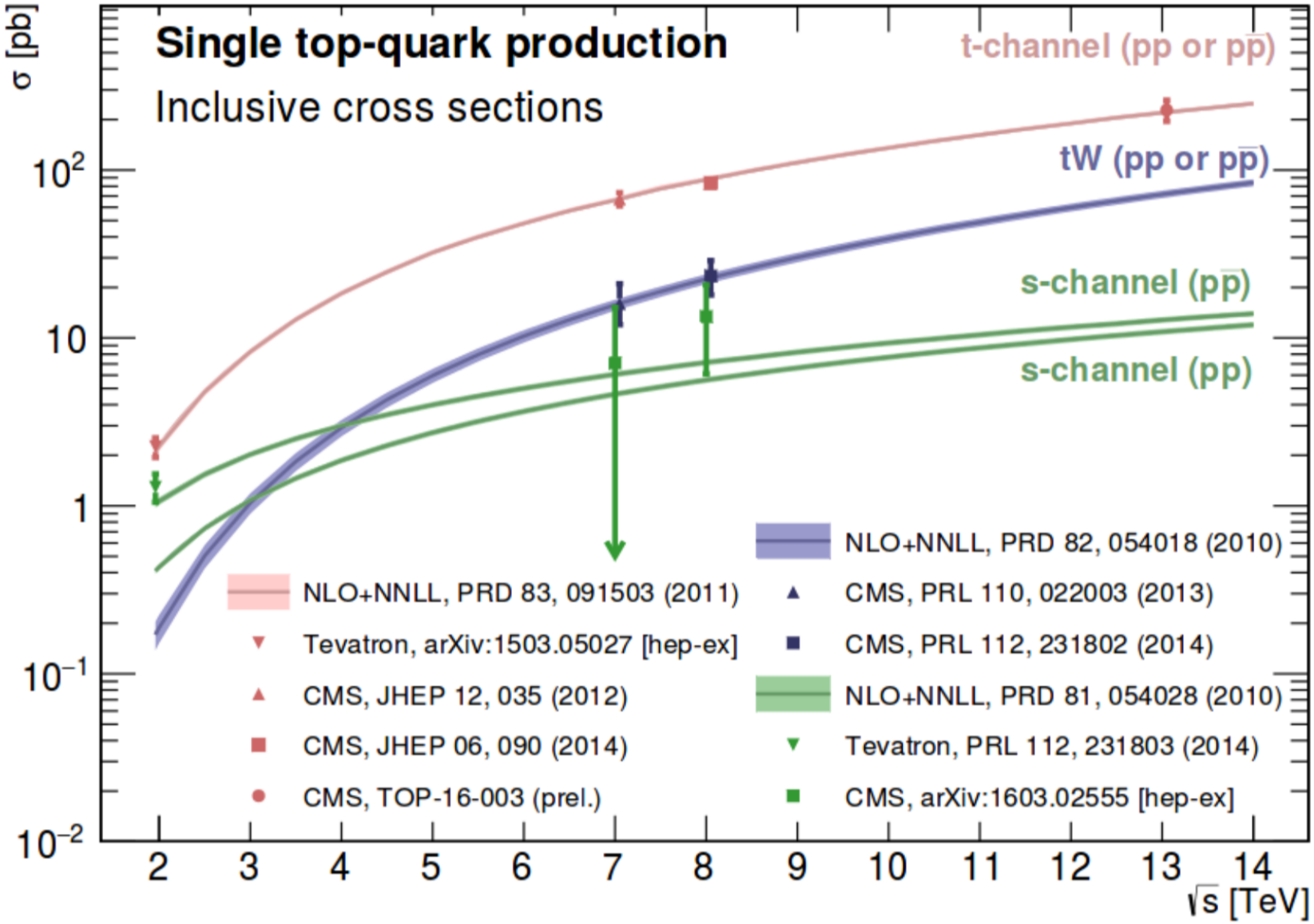


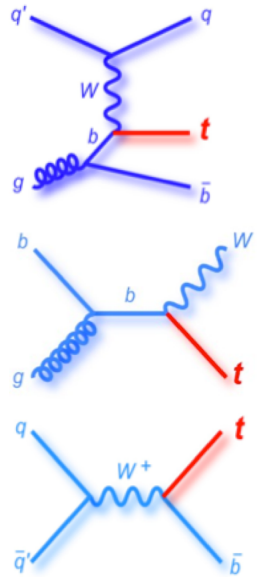


→ observation: 6.3 s.d.

→ observation: 6.1 s.d.

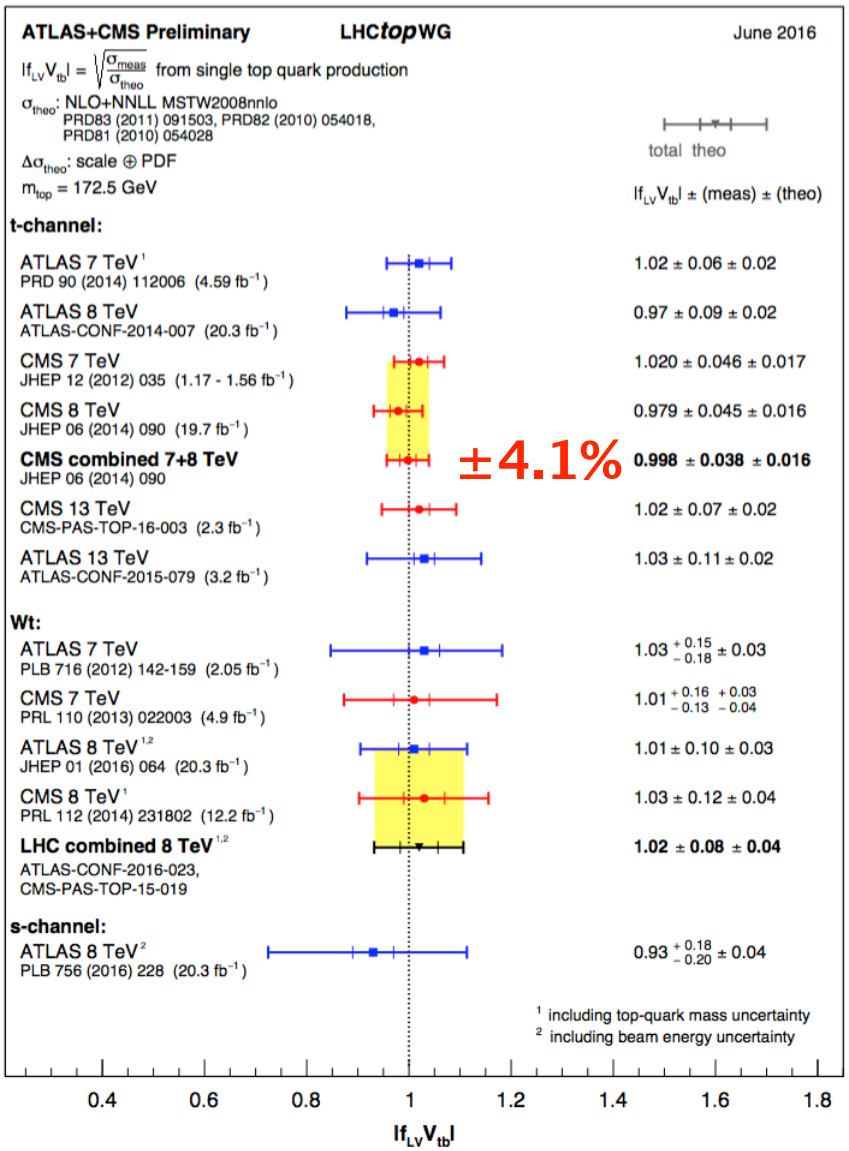
Single channel cross sections



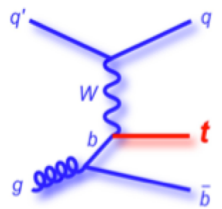


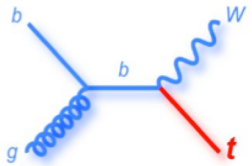
→ **all production modes observed!**

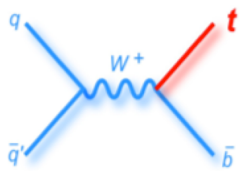
Direct measurement of $|V_{tb}|$



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

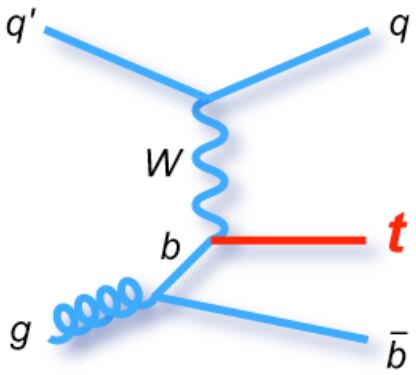




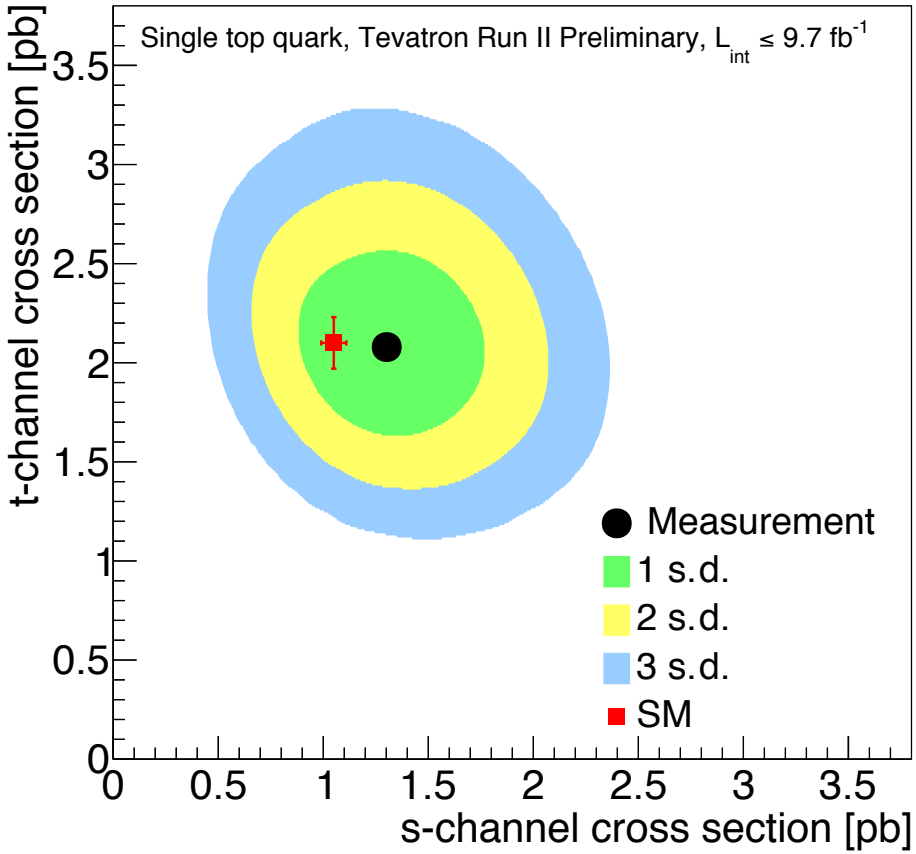


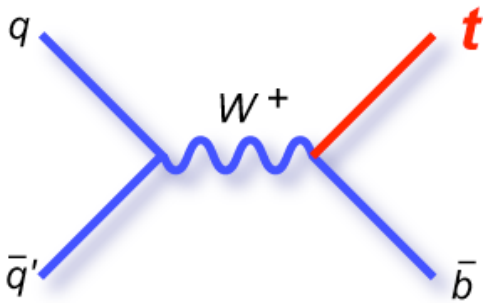
→ no hint for anomalous contribution

Single Top s- vs. t-channel

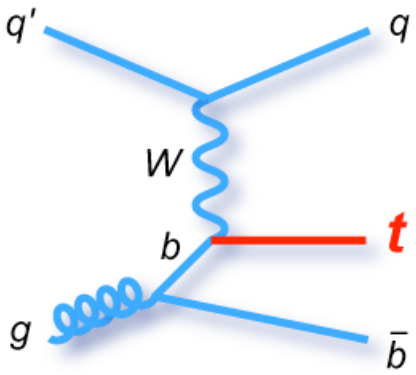


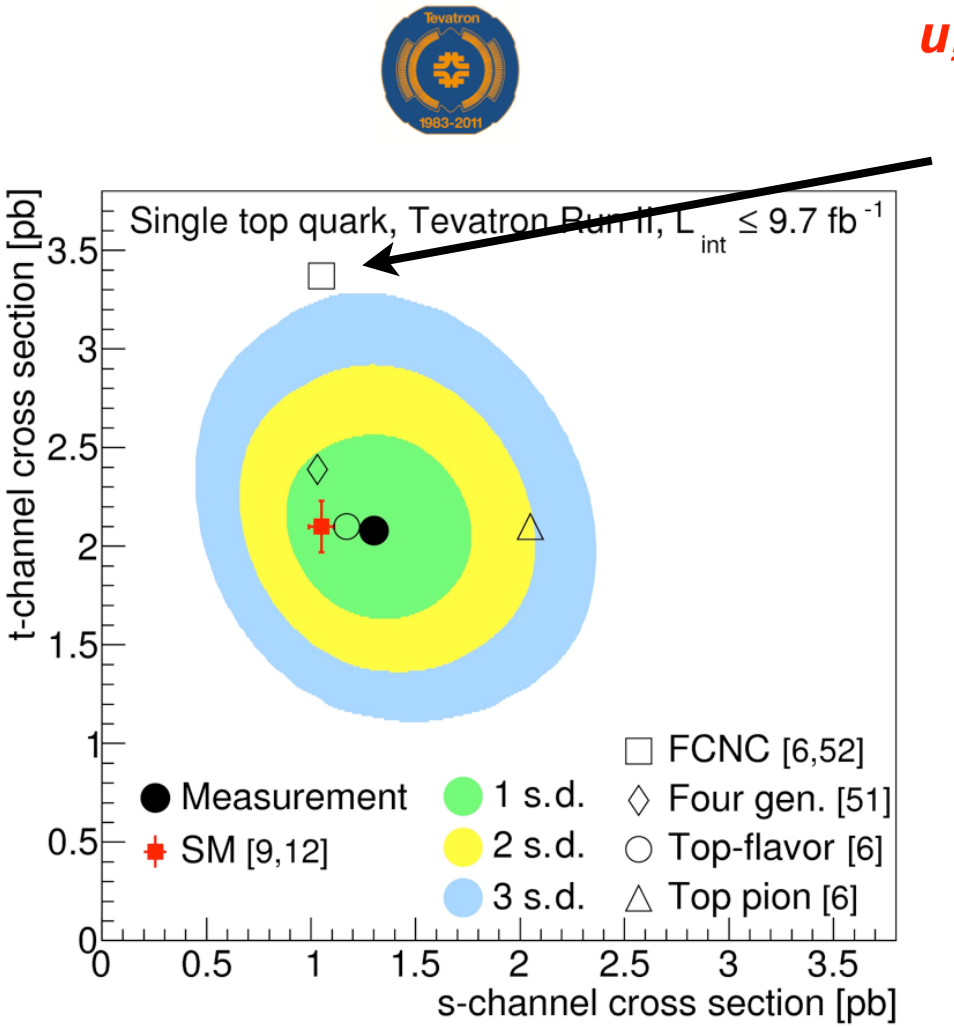
arXiv:1503.05027 [hep-ex]

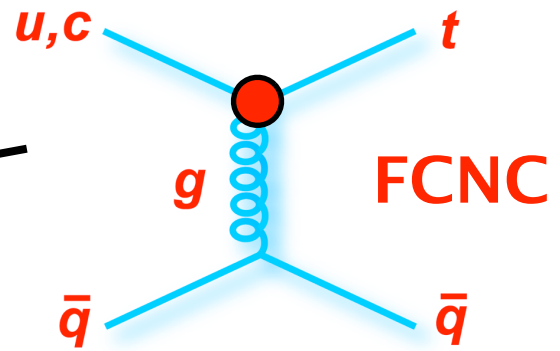


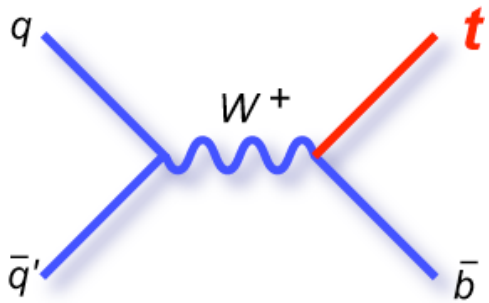


Single Top s- vs. t-channel

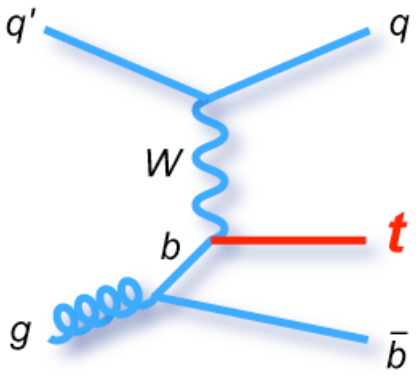


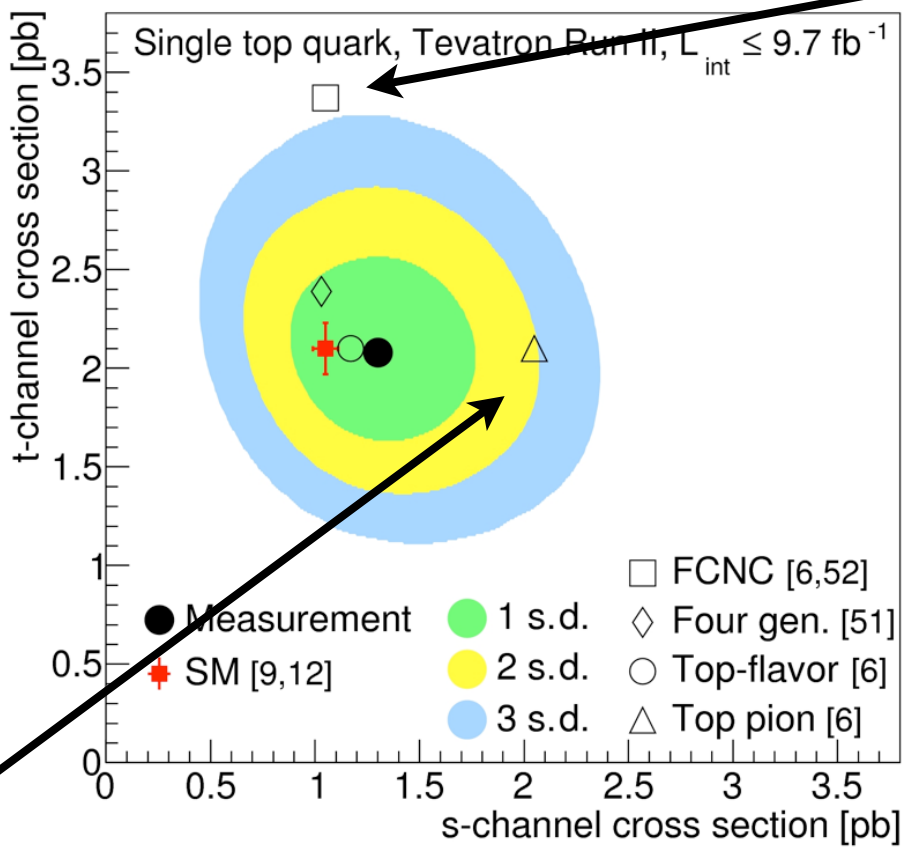


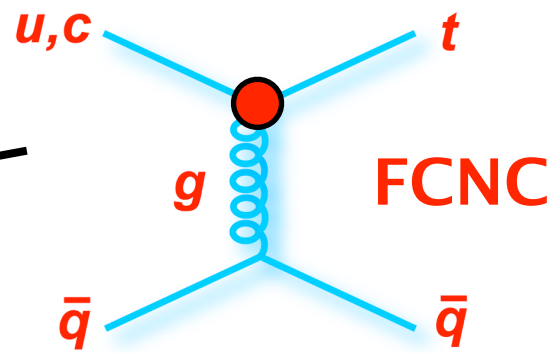


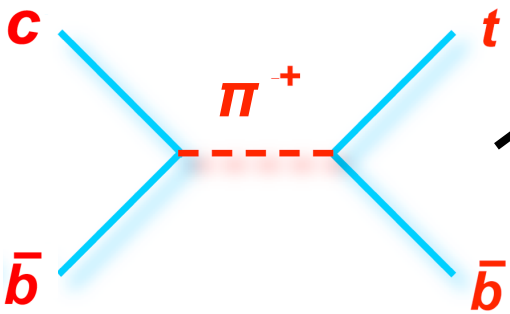


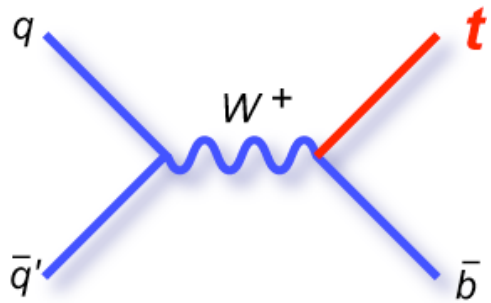
Single Top s- vs. t-channel





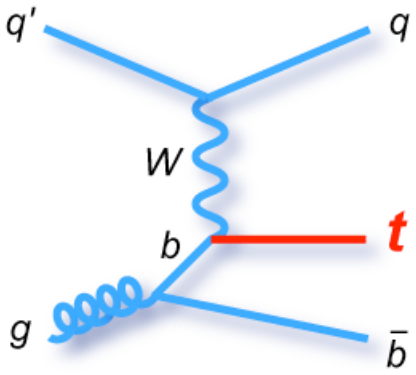


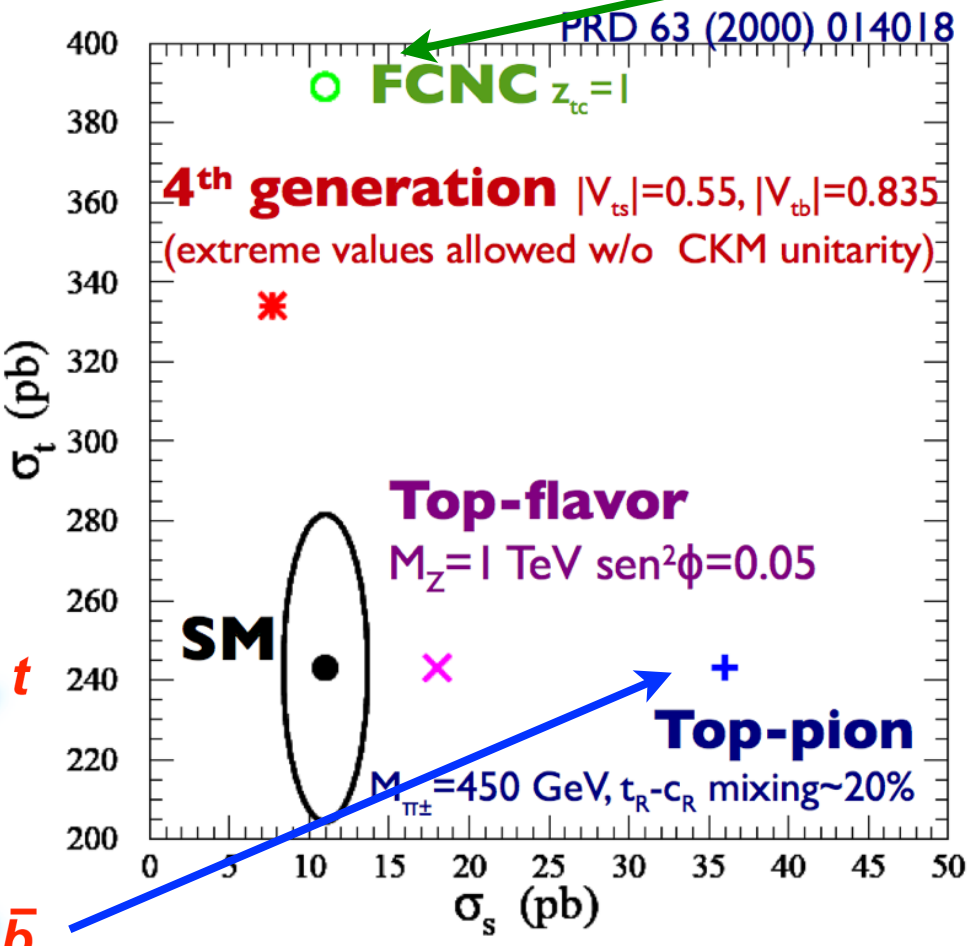


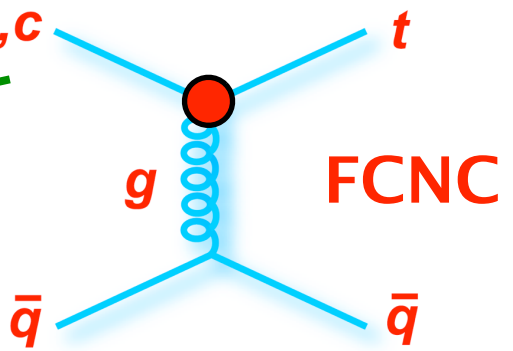


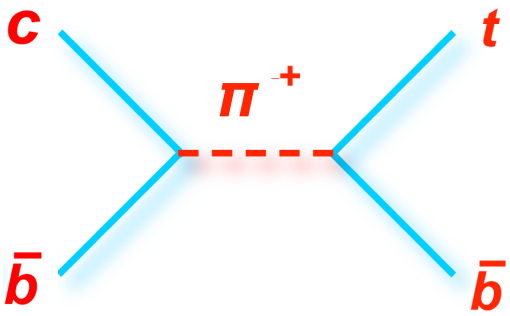
⇒ important to study production channels separately

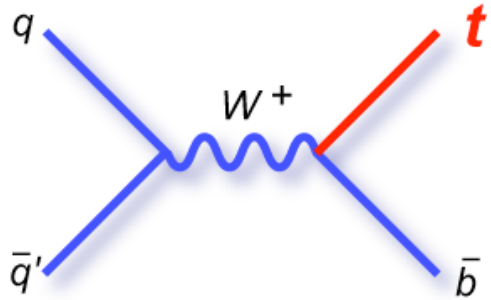
Single Top s- vs. t-channel: Run-II







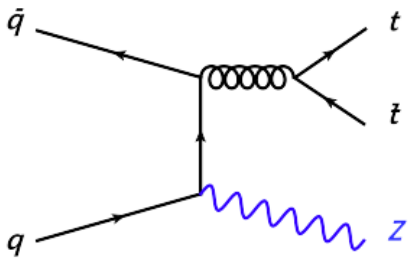


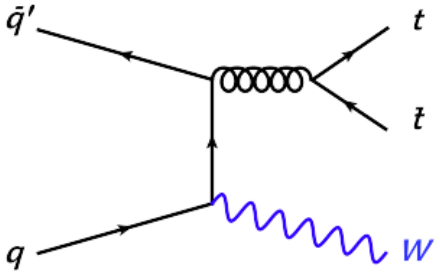


⇒ important to study production channels separately

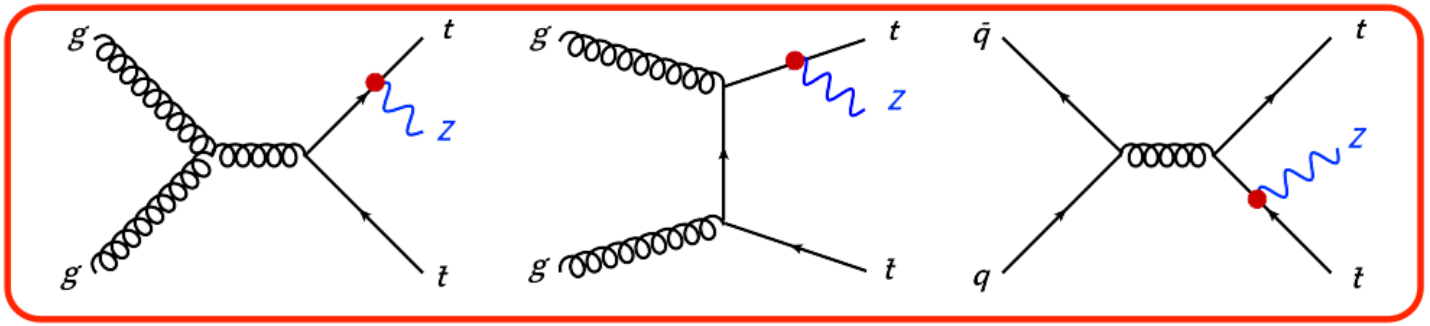
$t\bar{t}Z$ and $t\bar{t}W$ Production

ISR





FSR

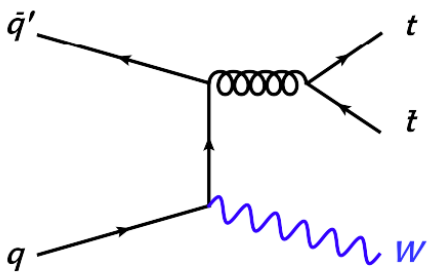


$$-i\frac{e}{\sin\vartheta_W \cos\vartheta_W}(T_3 - \sin^2\vartheta_W Q_t)\gamma^\mu$$

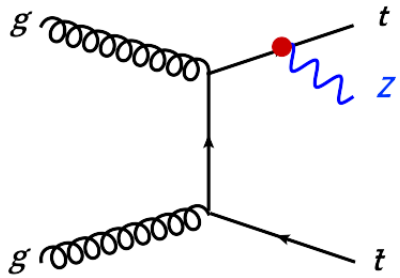
- measure 3rd component of weak isospin
- search for anomalous couplings in $t\bar{t}Z$ vertex

→ it is very interesting to measure rare processes never explored before since new physics could show up!

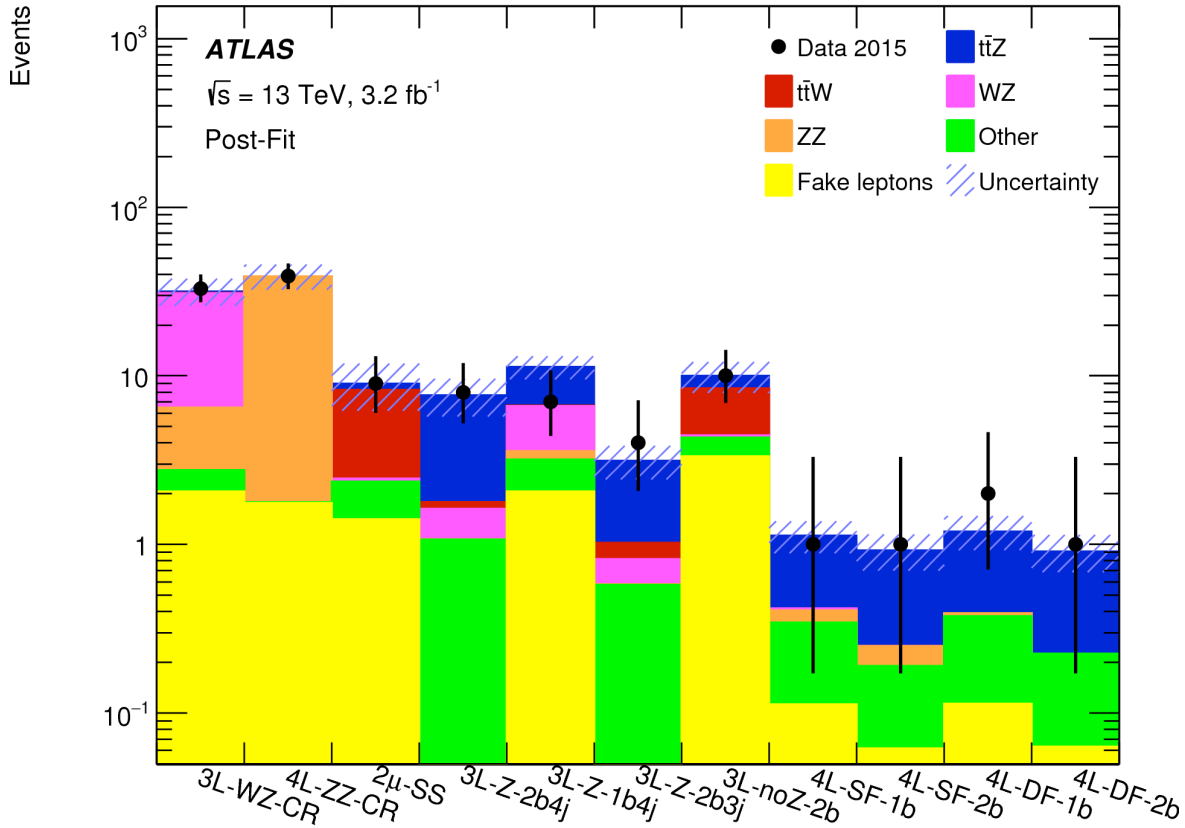
Search for ttZ and ttW



ISR



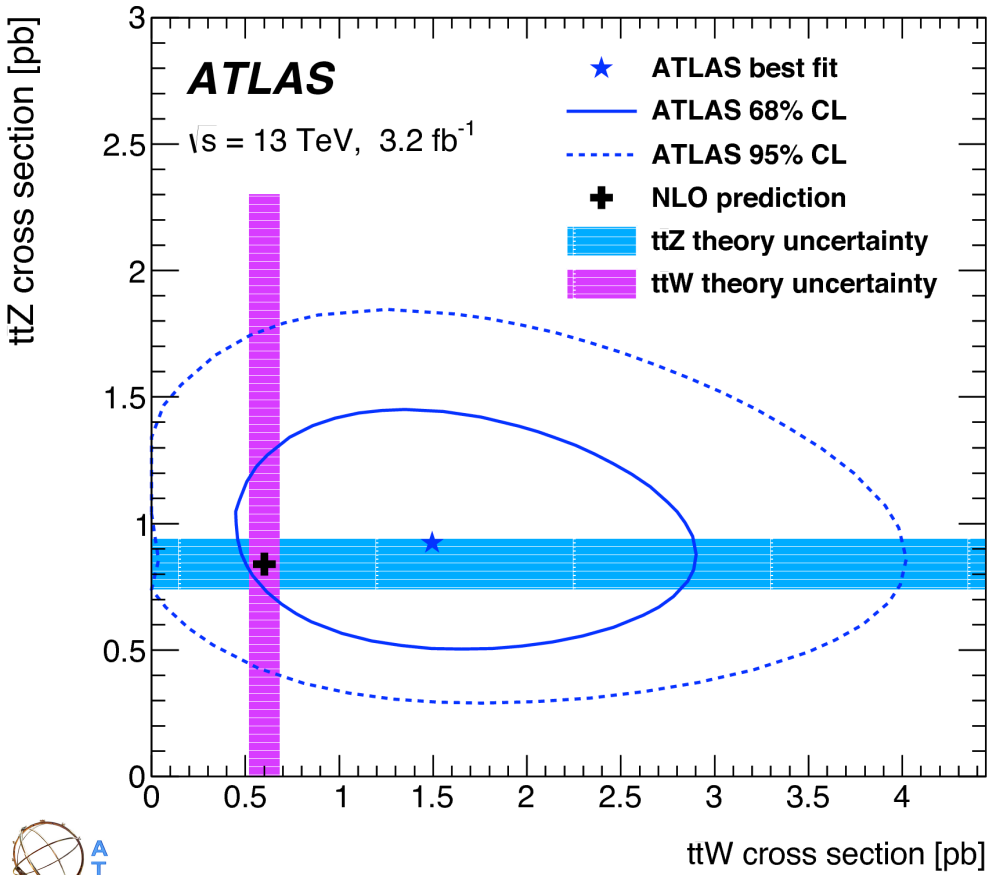
FSR



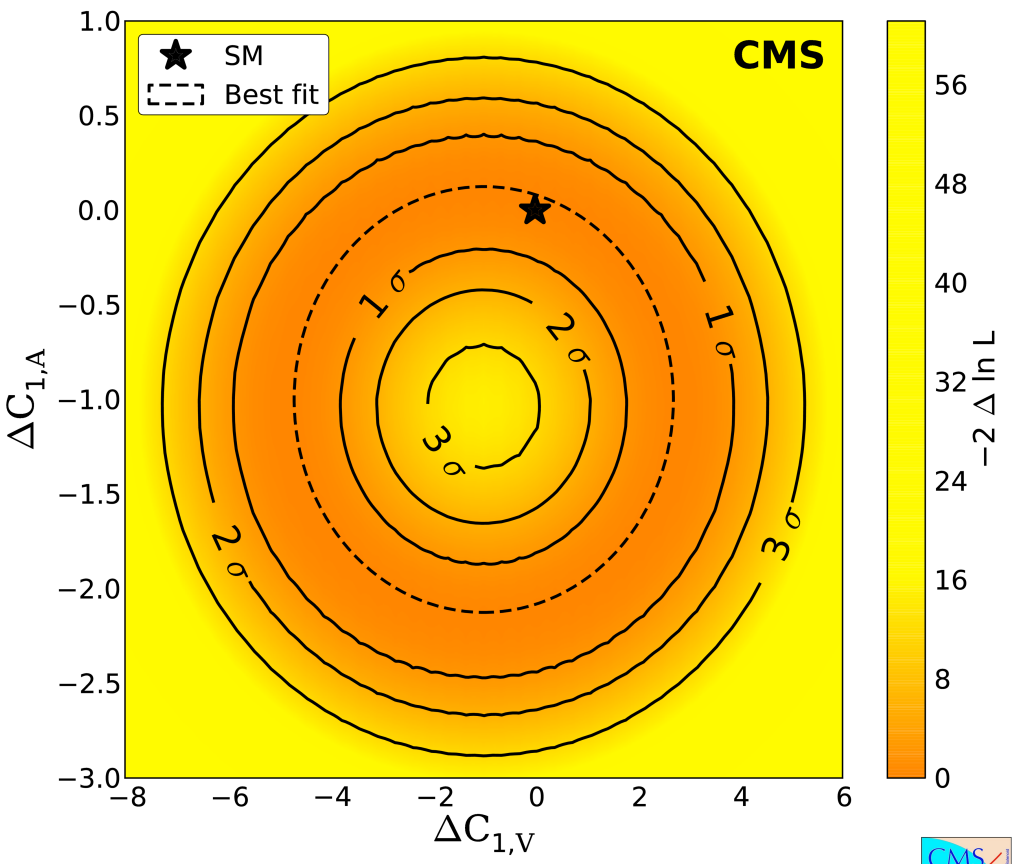
ttW ← → ttZ

Observation of ttV production

ttZ vs. ttW cross sections:



anomalous V or A ttZ couplings:



→ **in agreement with the SM prediction**

→ **no hint for anomalous contribution**

(ttγ also in agreement with SM prediction)