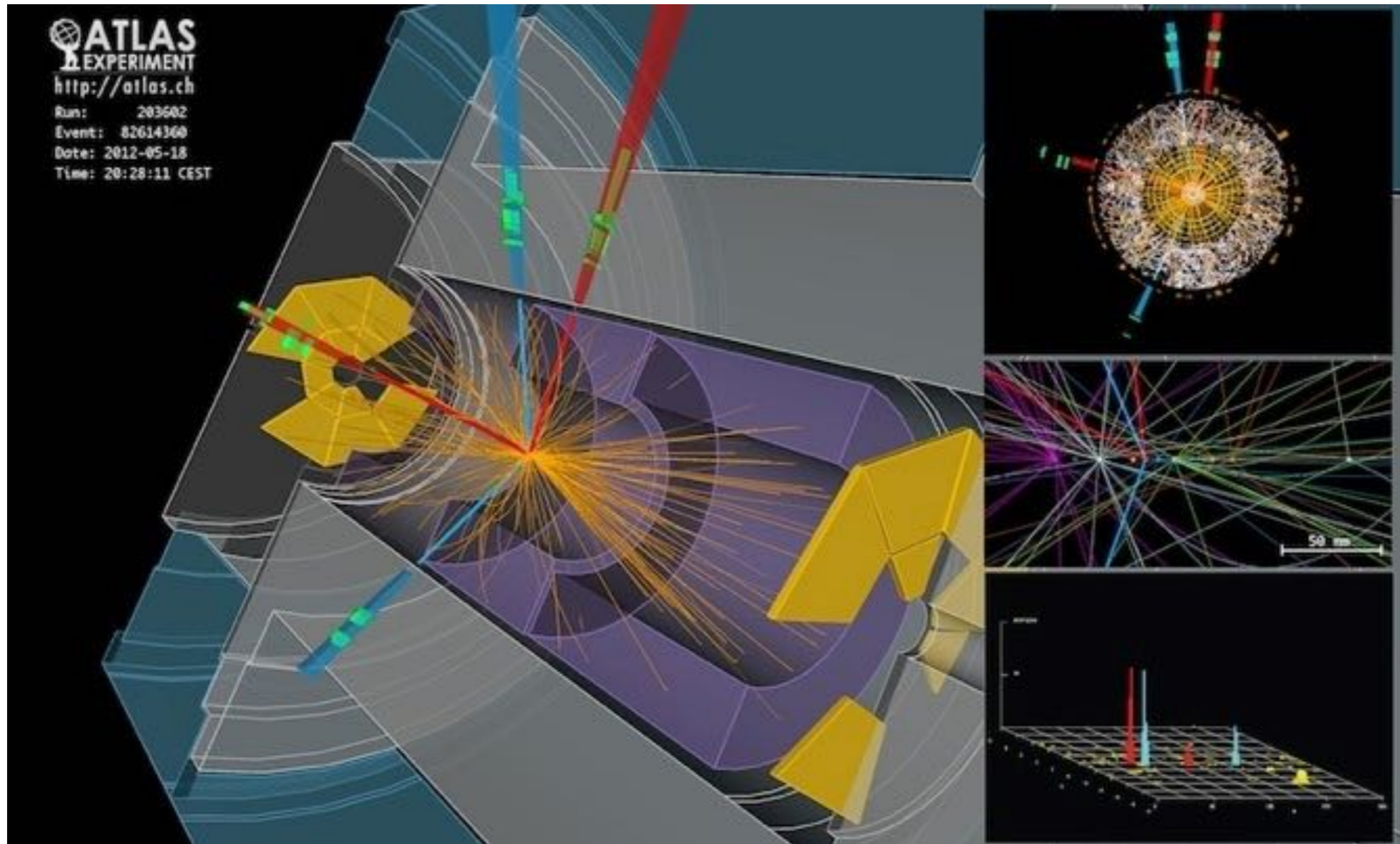


# Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



## 09. Top Physics

19.12.2016



# Overview

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- Introduction: The Top quark in the Standard Model
- Production and decay
  - Pair production and single top production
  - Classification of decay modes
  - Experimental signatures
- Top production
  - Measurement of the pair production cross section
  - First measurements of single top at LHC
- Top properties: Mass

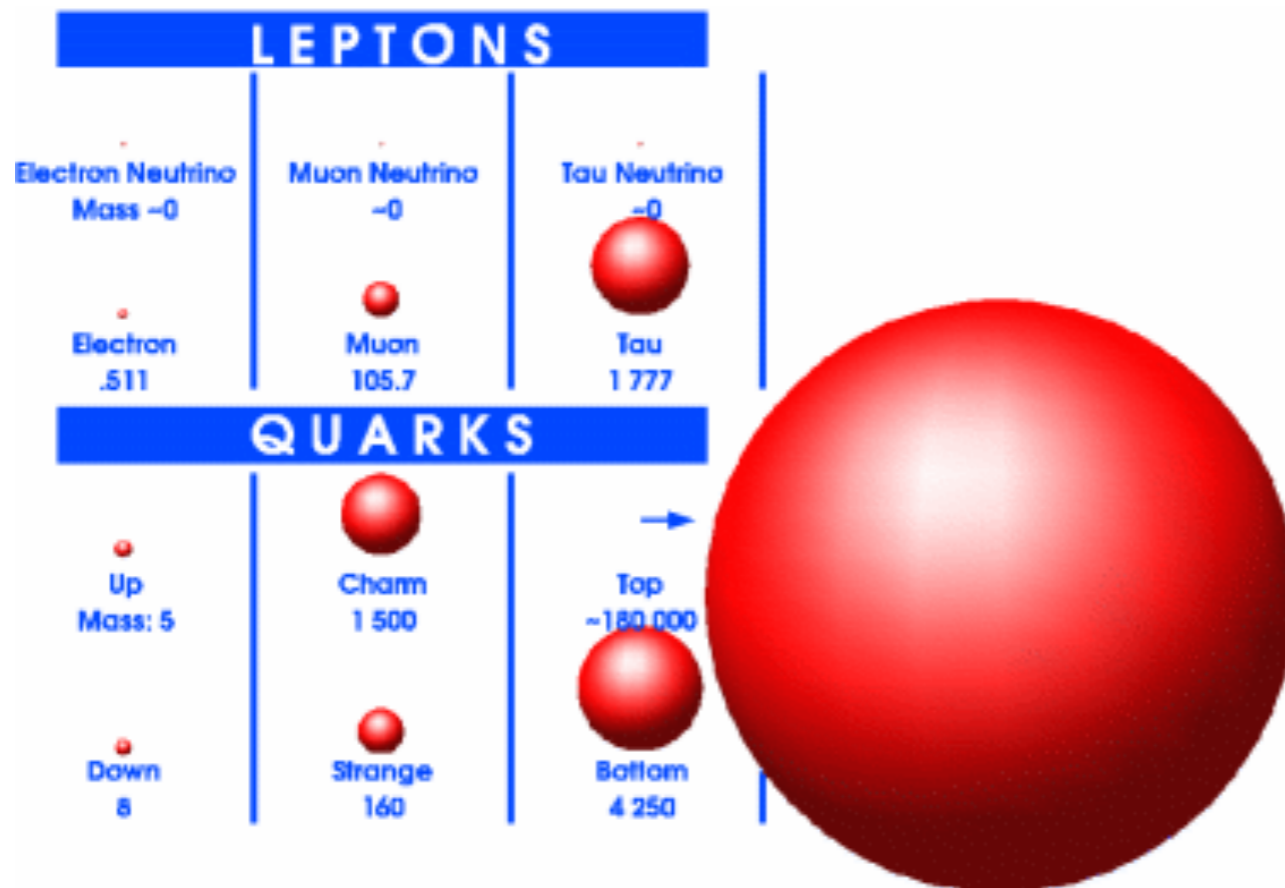
# Introduction:

## The Top Quark in the Standard Model



# Top: A Special Case in the Standard Model

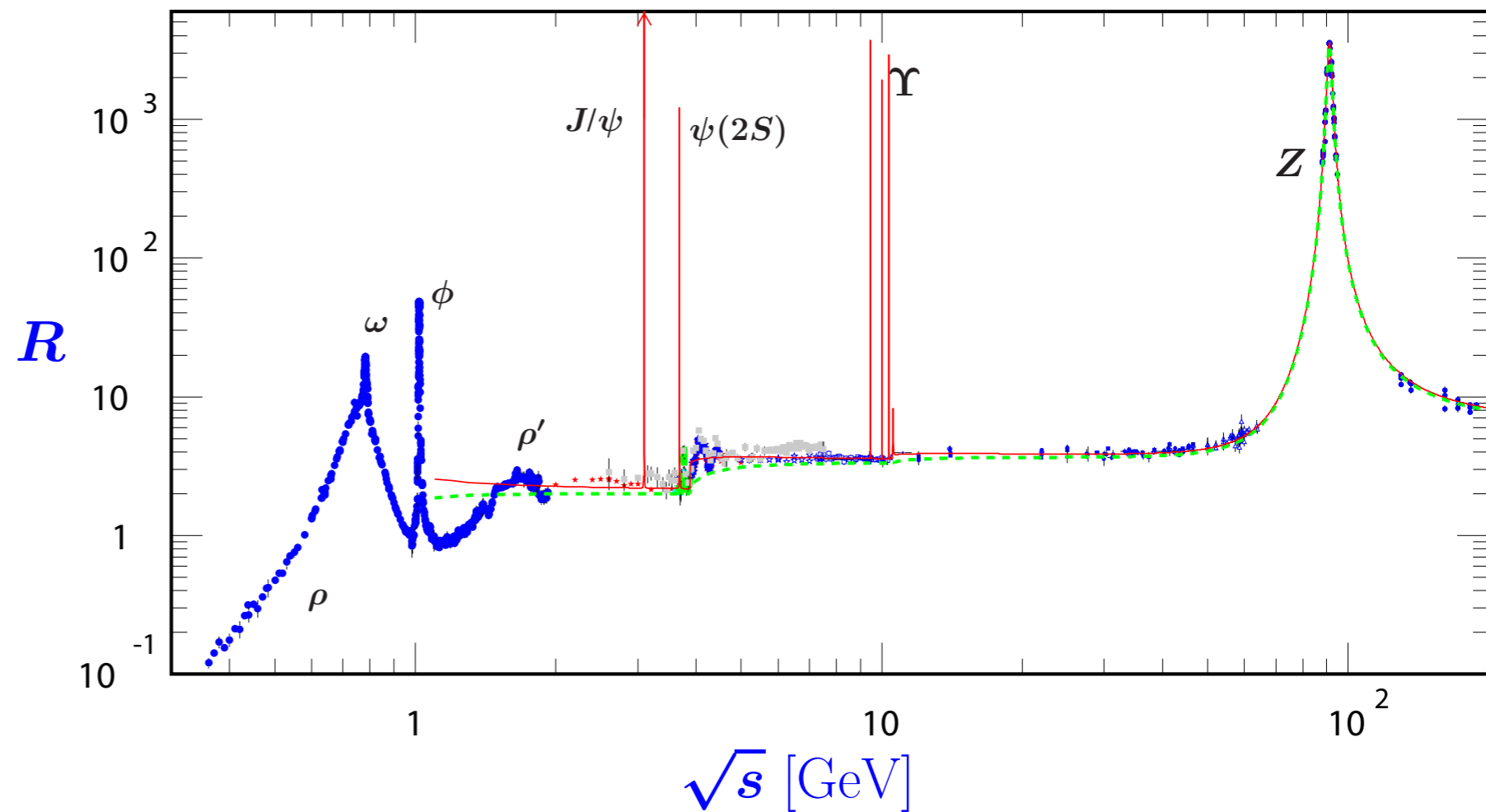
- The Top quark has a special role in the Standard Model
  - It is the heaviest particle, and by far the heaviest Fermion
  - Its mass is comparable to the electroweak scale - The top quark could be a window to new physics!
  - Its life time is shorter than the hadronization time - it does not form bound states



## The Questions:

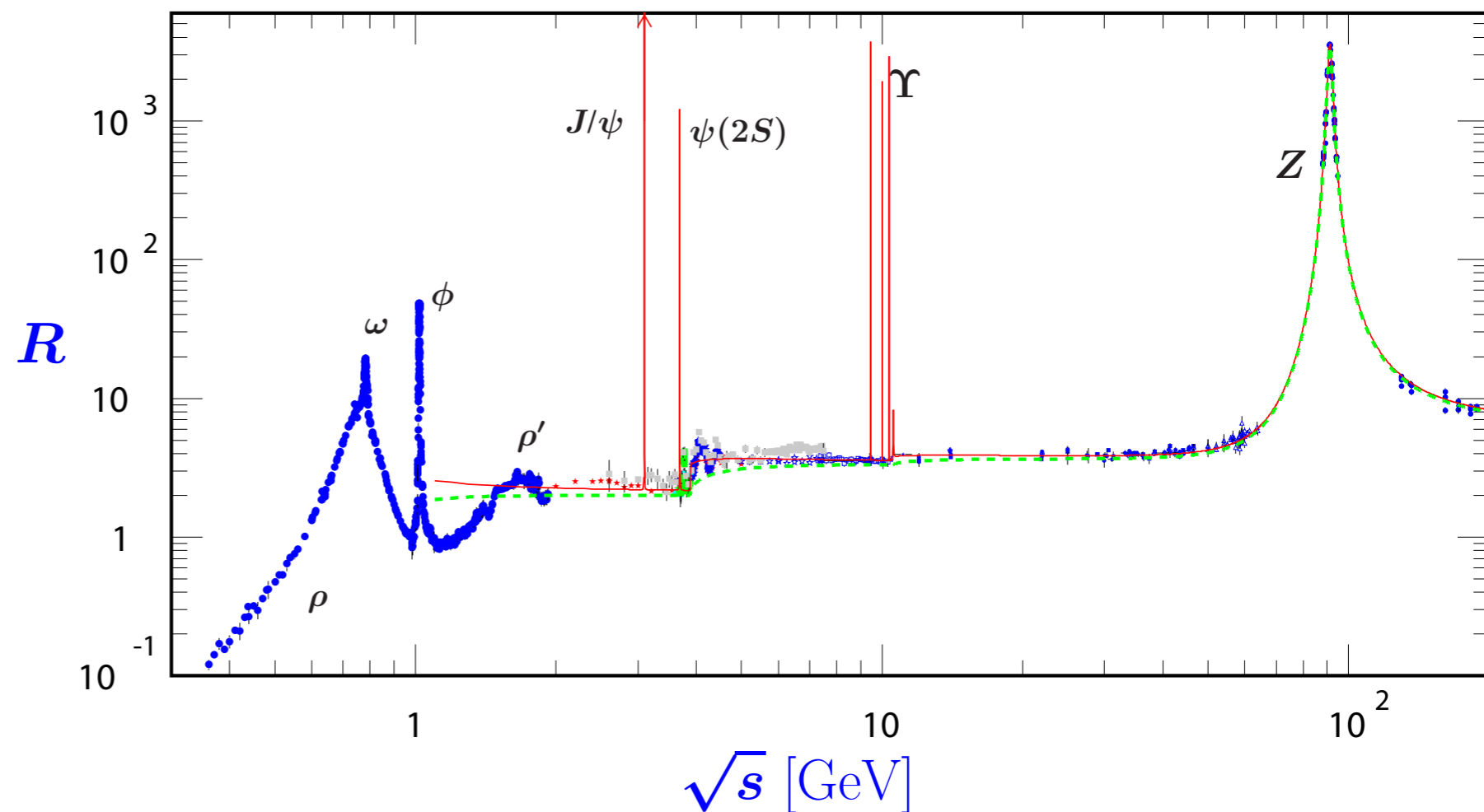
- How are top quarks produced?
- How do they decay?
  - both compared to the SM expectation
- What is the mass of the top quark?

# Historical Perspective: Prediction of the Top



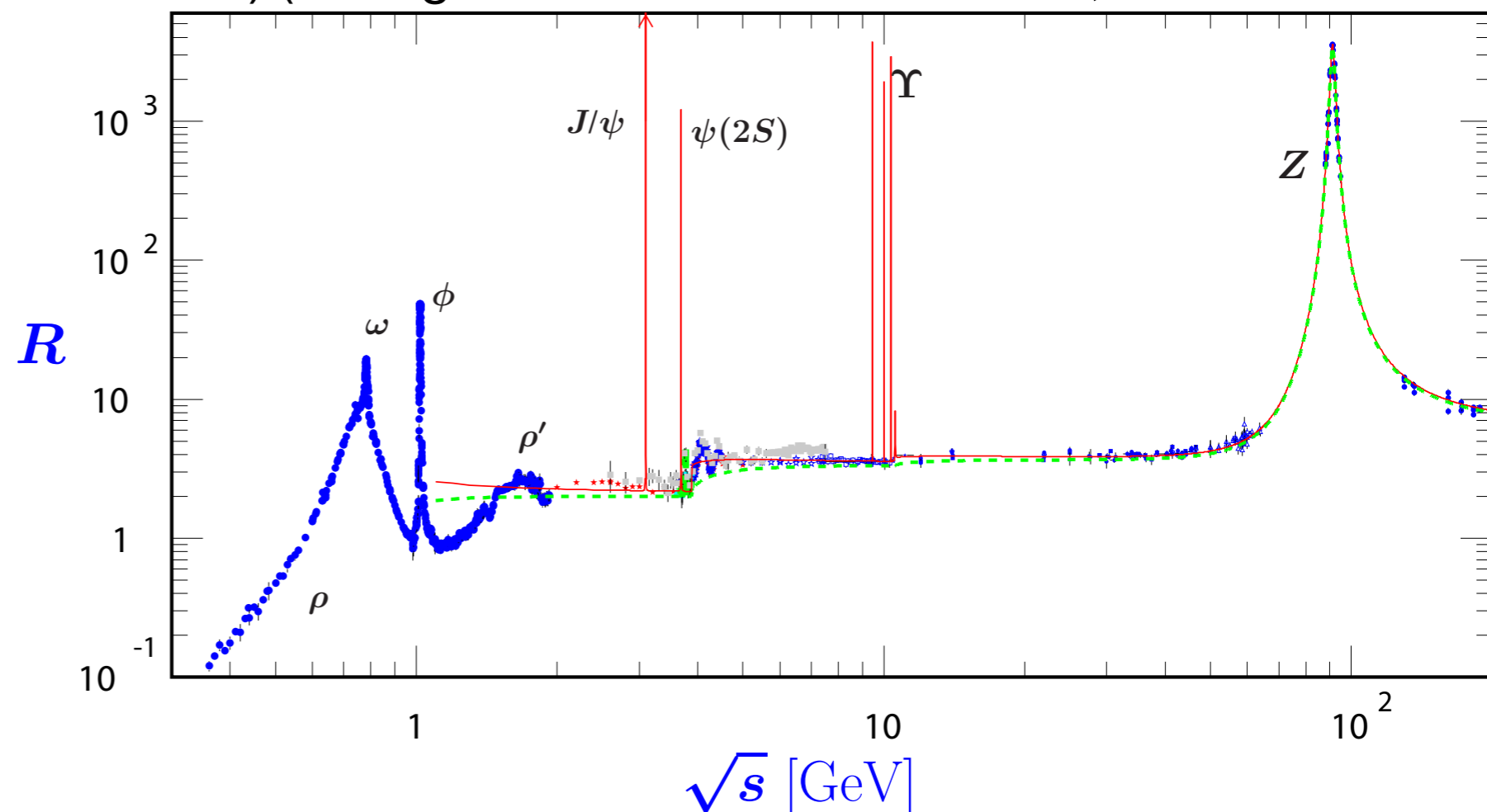
# Historical Perspective: Prediction of the Top

- After the discovery of the  $\tau$  a third quark family was basically obvious (it was already predicted based on the observation of CP violation at a time when only three quarks were known):
  - Renormalizability of the SM requires equal number of lepton and quark families



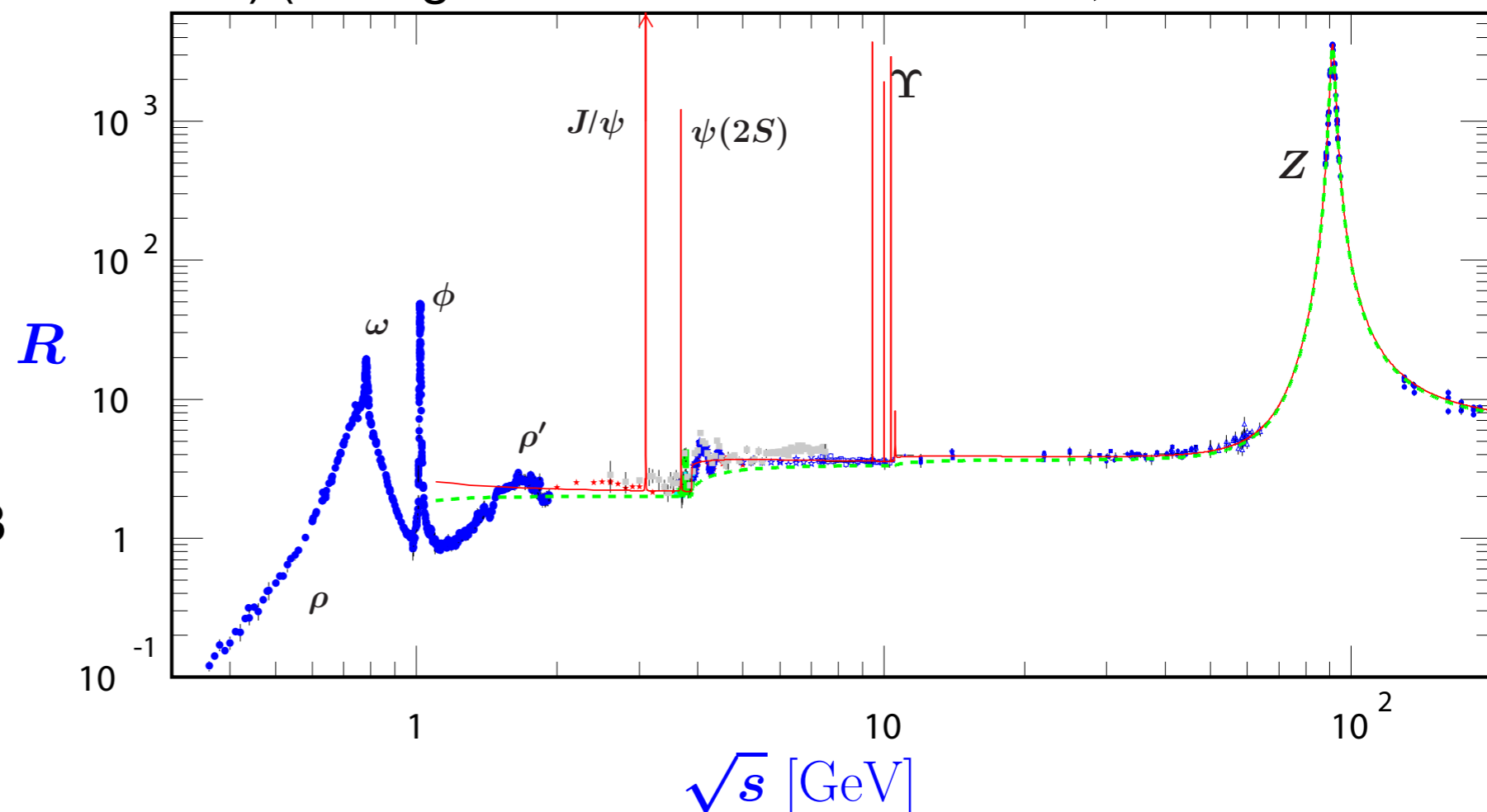
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- The precise measurement of the cross-section in  $e^+e^-$  - Kollisionen above the b threshold gives the charge of the b:  $-1/3$   
 $\Rightarrow$  The top has to be  $+2/3$





# Prediction of the Top Mass

- Quarks have an influence on the mass of the gauge bosons via loops
  - Corrections typically increase with the mass of the particle in the loop
  - ▶ Precise measurements of  $W$  and  $Z$  masses provide information on the top mass (precision depends on the number of orders in the calculation)



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In the Standard Model (see lecture 08):

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F} \frac{1}{\sin^2\theta_W(1 - \Delta r)}$$

with  $\frac{m_W^2}{m_Z^2} = 1 - \sin^2\theta_W$

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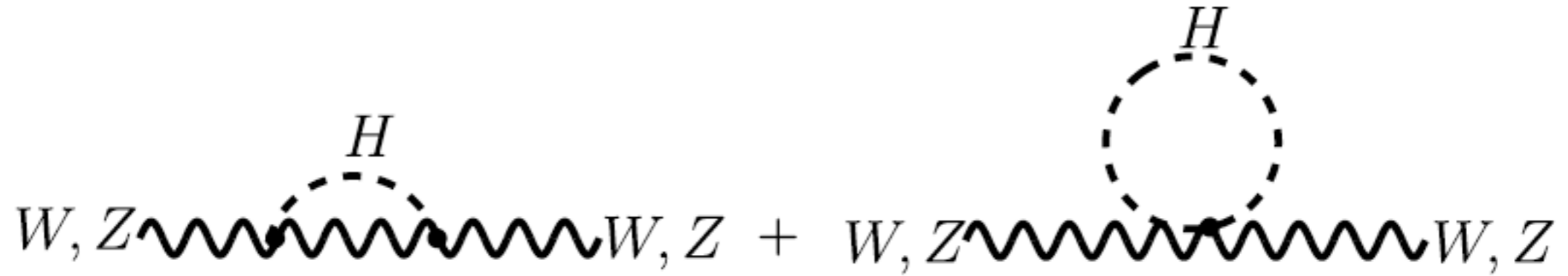
The influence of single top loops:

$$\Delta r^{top} = -\frac{3\sqrt{2}G_F \cot^2\theta_W}{16\pi^2} m_t^2$$

for  $m_t \gg m_b$

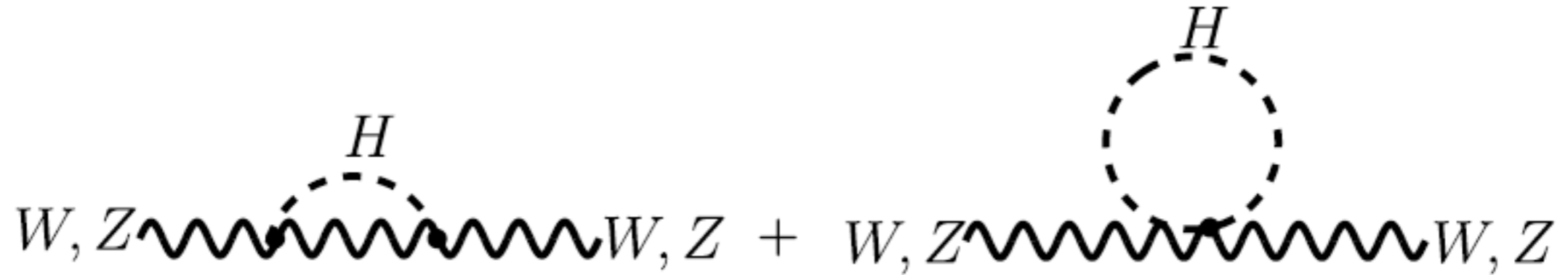
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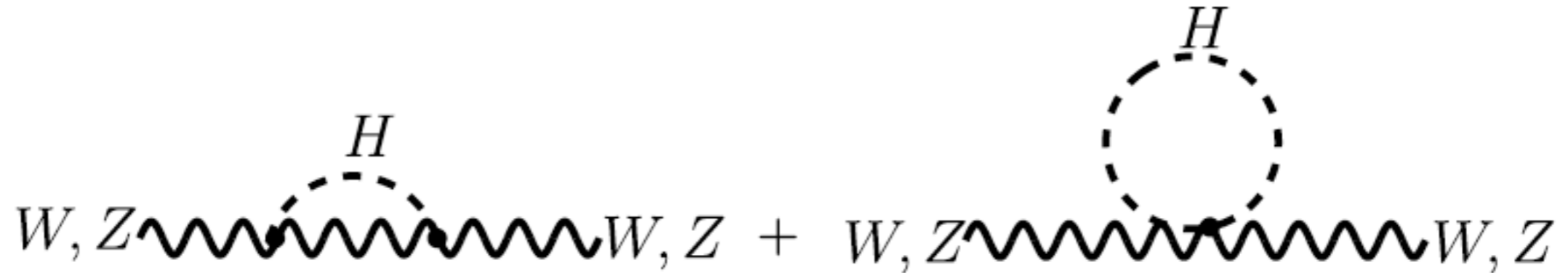


- analogous to the corrections induced by the top there are also corrections originating from the Higgs

$$\Delta r^{Higgs} = \frac{3\sqrt{2}G_F m_W^2}{16\pi^2} \left( \ln \frac{m_H^2}{m_W^2} - \frac{5}{6} \right) \quad \text{for } m_H \gg m_W$$

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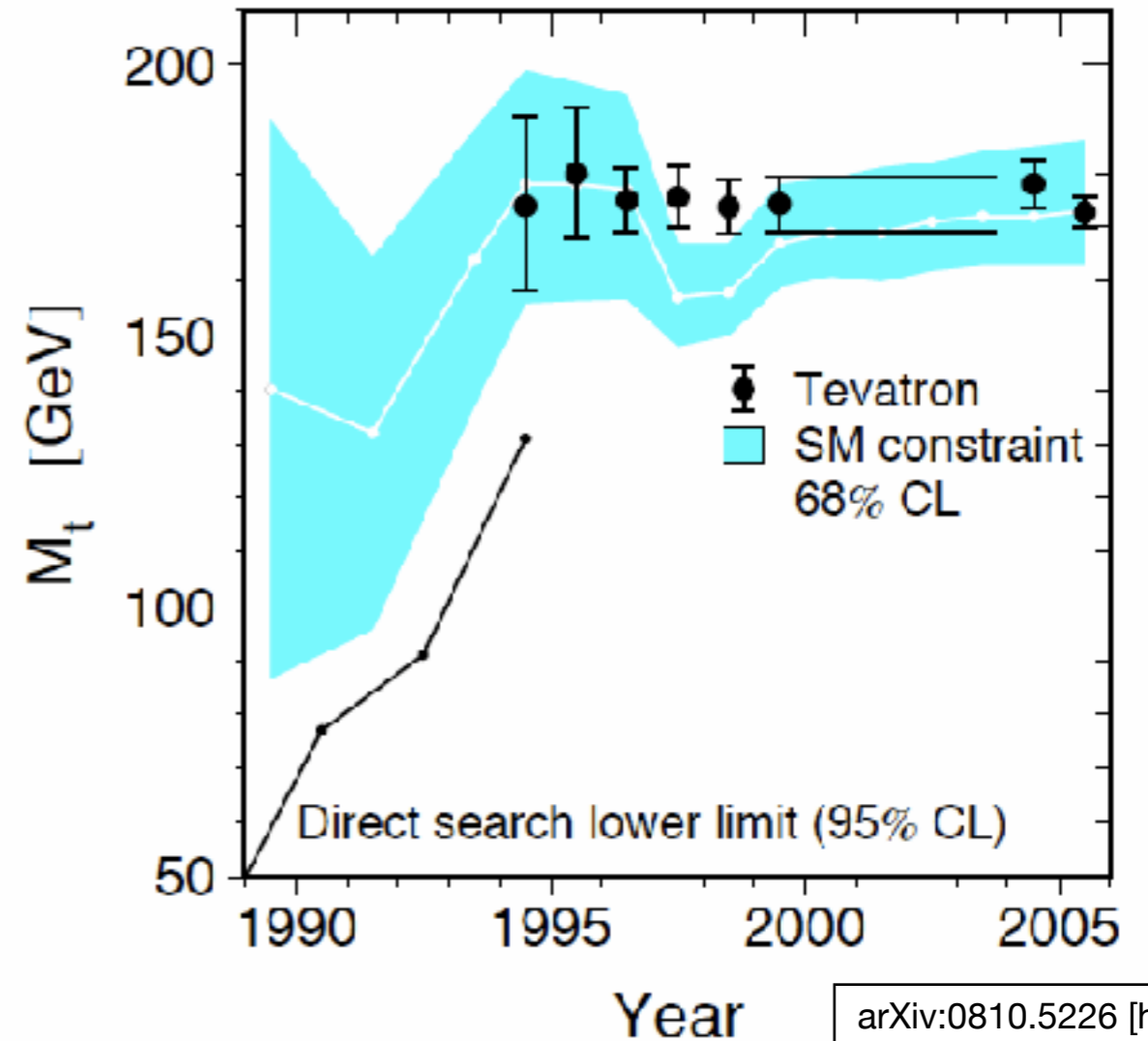
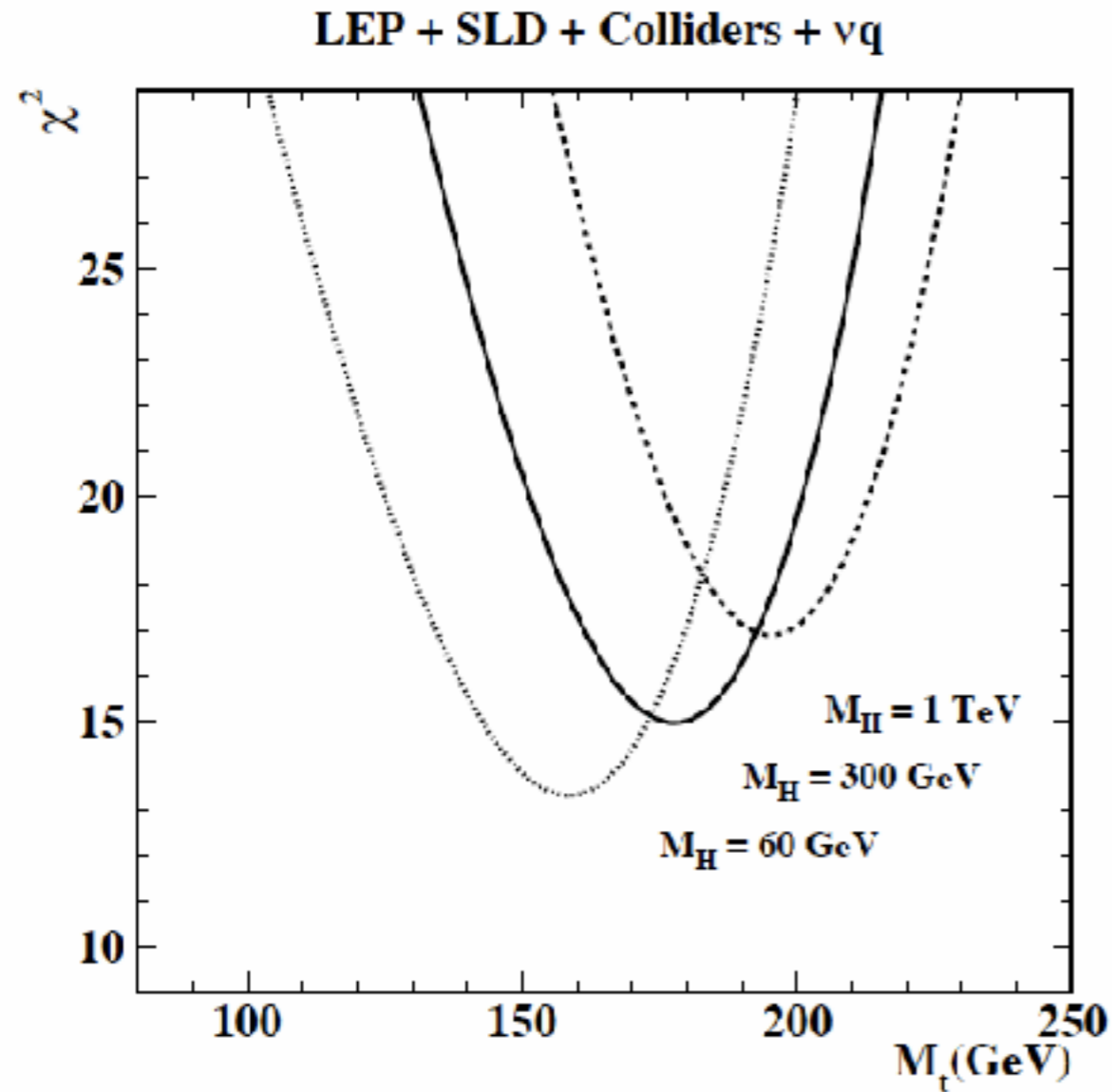


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- ▶ With a precise knowledge of the top mass the Higgs mass can be constrained
  - But: only logarithmic dependence on  $m_H$  (quadratic in  $m_T$ )

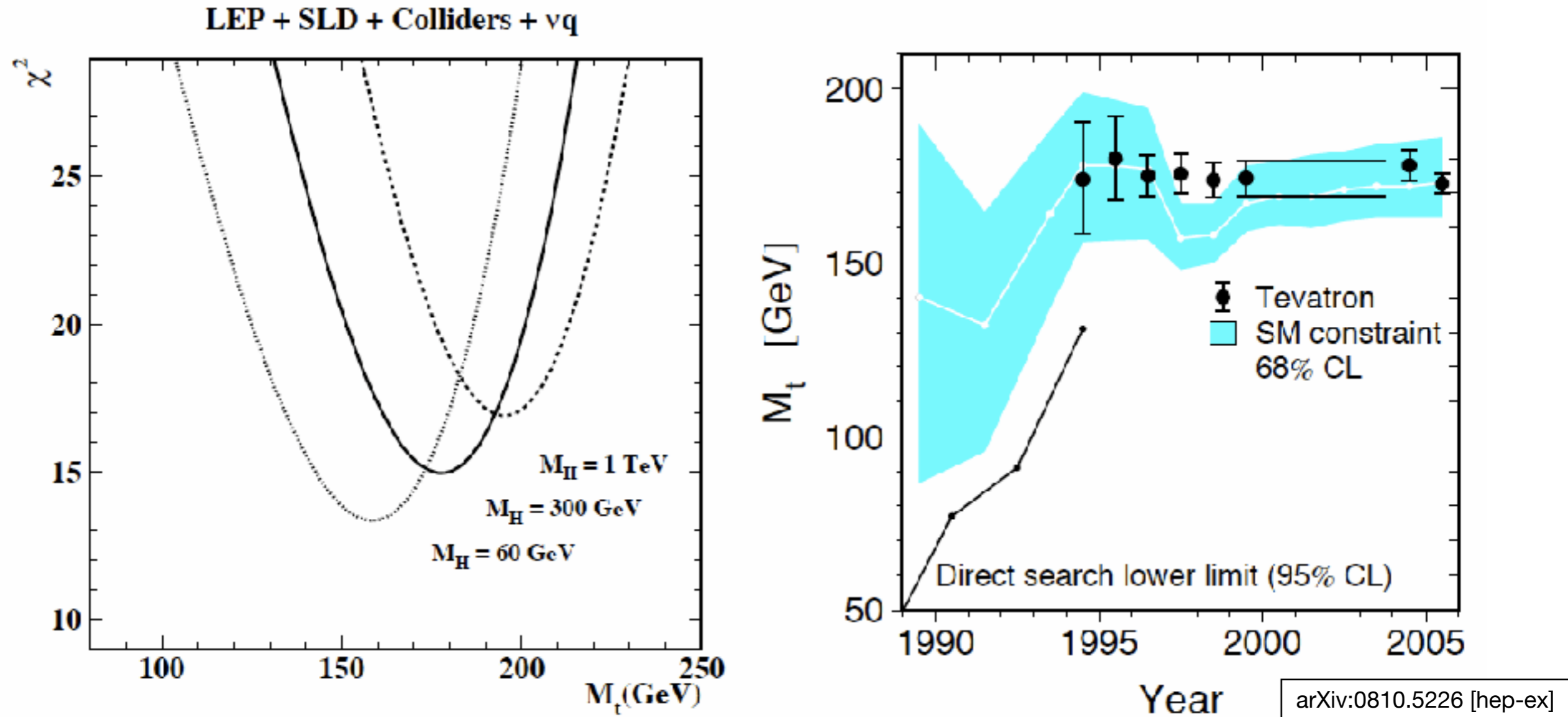
# Predicting the Top Quark Mass



arXiv:0810.5226 [hep-ex]

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⇒ Discovery of the top quark in 1995 at the Tevatron, 18 years after the b



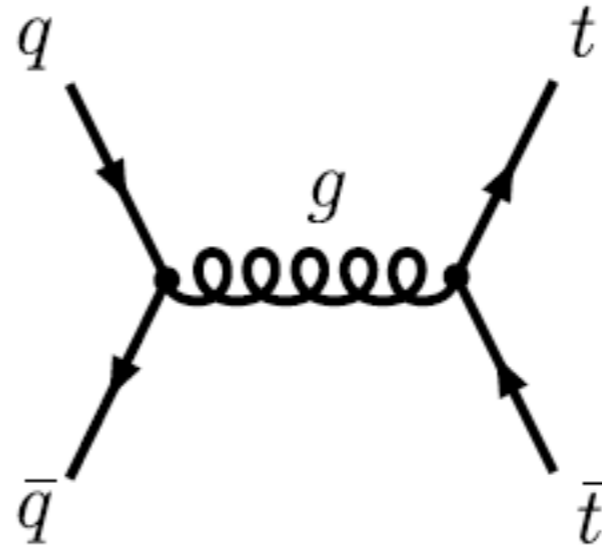
# Production and Decay



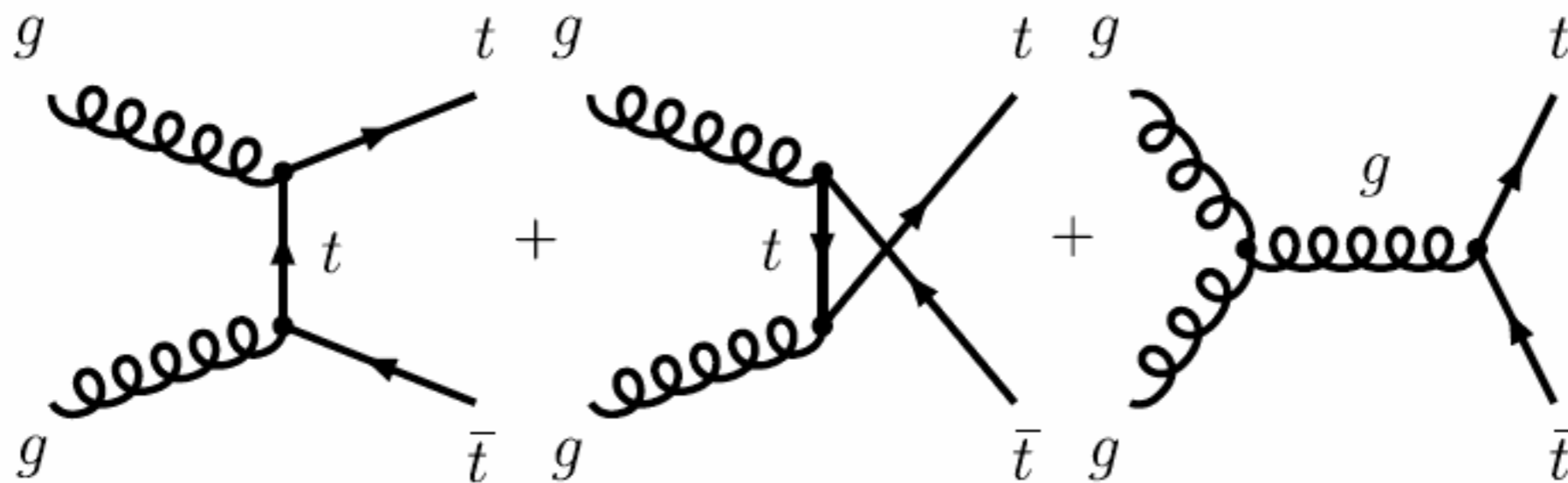
# Top Pair Production

- Two important production mechanisms via the strong interaction

Quark-AntiQuark annihilation:



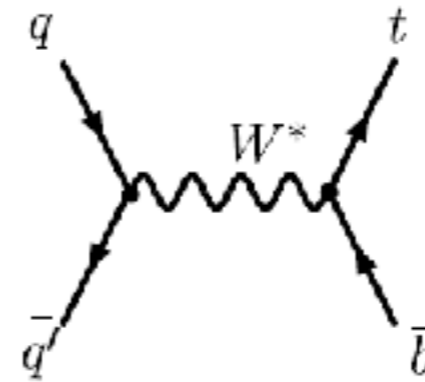
Gluon-Gluon fusion:



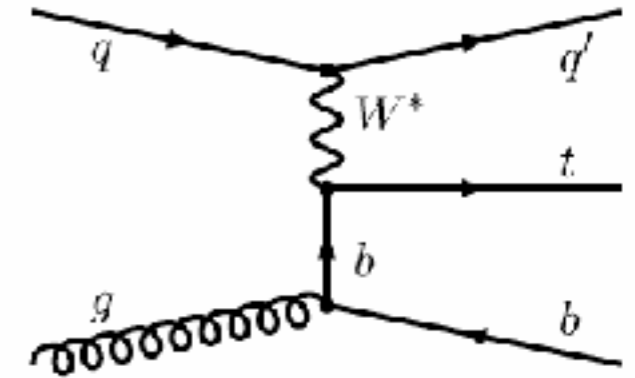
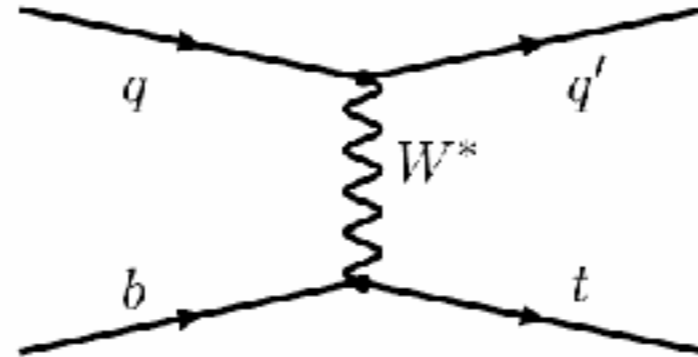
# Production of Single Top Quarks

- Production of single top quarks via the weak interaction:

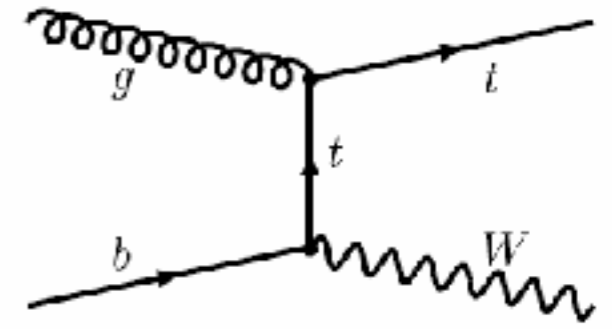
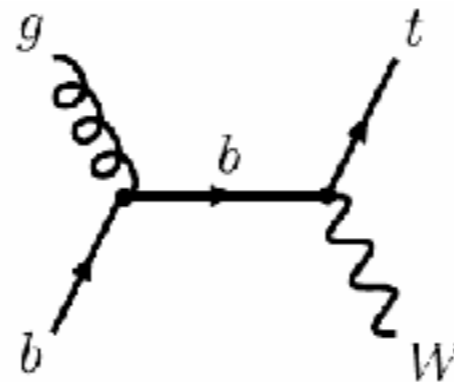
s-channel production via W exchange



t-channel production

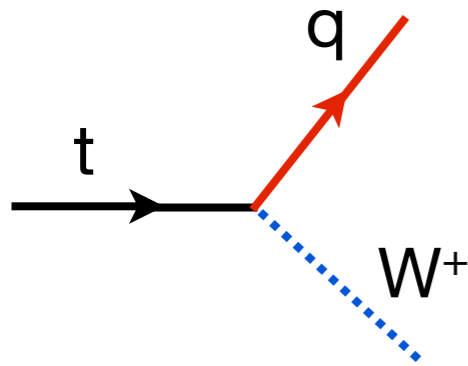


associated production of W and t quark



# Top Quark Decay

- Decay via the weak interaction:



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

Currently (assuming 3 generations and unitarity):

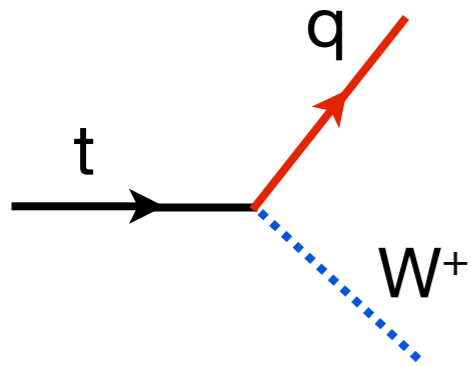
$$|V_{td}| = 0.00874^{+0.00026}_{-0.00037}$$

$$|V_{ts}| = 0.00407 \pm 0.0010$$

$$|V_{tb}| = 0.999133^{+0.000044}_{-0.000043}$$

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⇒ Top quarks decay almost exclusively into a W boson and a b quark

# Top Quark: Width / Lifetime

- In the Standard Modell the width of the top is given by:

$$\Gamma_t = |V_{tb}|^2 \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{m_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi} \left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$$

arXiv:0810.5226 [hep-ex]



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- For a mass of  $\sim 170$  GeV this gives a width of  $\sim 1.3$  GeV
  - ▶ Corresponds to a lifetime of  $\sim 5 \times 10^{-25}$  s
  - ▶ Much shorter than the hadronization time:

$$\tau_{had} = \Lambda_{QCD}^{-1} \approx (0.2 \text{ GeV})^{-1} \approx 3 \times 10^{-24} \text{ s}$$

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⇒ Top quarks do not form bound states, they decay as free quarks

(Still there are influences from the strong interaction, for example via the interaction of the t quarks with the proton remnants in hadron collisions (effects increase with energy), interactions of the decay products from the two quarks in pair production, ...)

arXiv:0810.5226 [hep-ex]





# Top Decay: The Decay of the $W$ s

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“Universality” of the weak interaction, maximal parity violation

# Top Decay: The Decay of the Ws

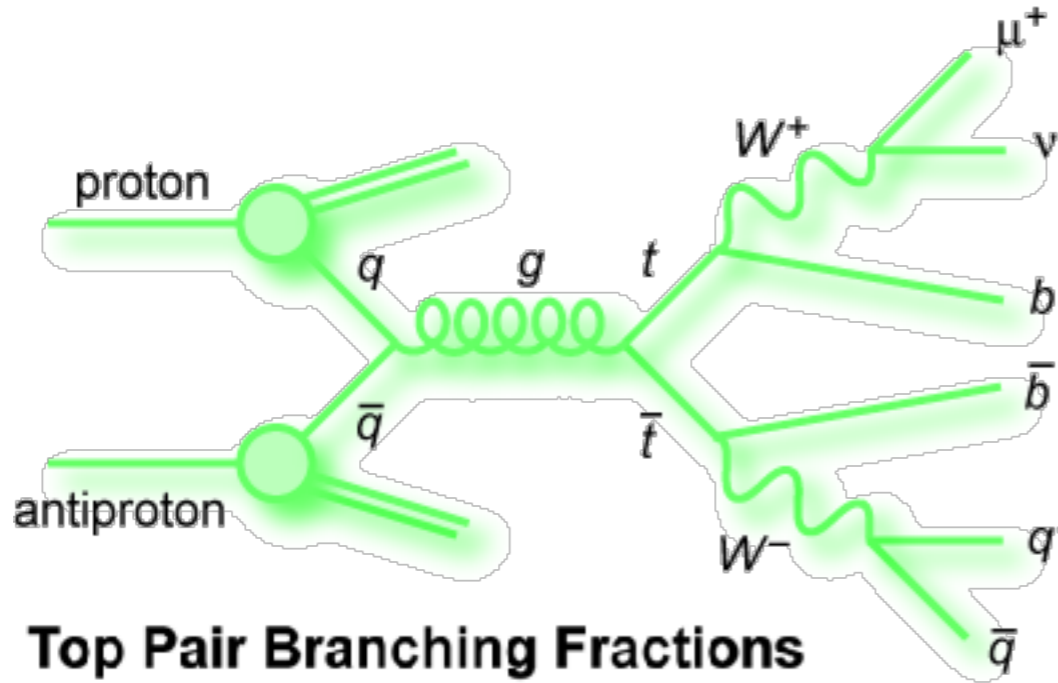
- W decay via the weak interaction:  
“Universality” of the weak interaction, maximal parity violation
- ▶ couples to left-handed fermions, right-handed anti-fermions, always with the same strength
  - ▶ Quarks have a three-fold weight: 3 colors!
  - ▶ Example  $W^+$ :

$$W^+ \rightarrow e^+ \nu_e : \mu^+ \nu_\mu : \tau^+ \nu_\tau : u \bar{d}' : c \bar{s}'$$
$$1 : 1 : 1 : 3 : 3$$

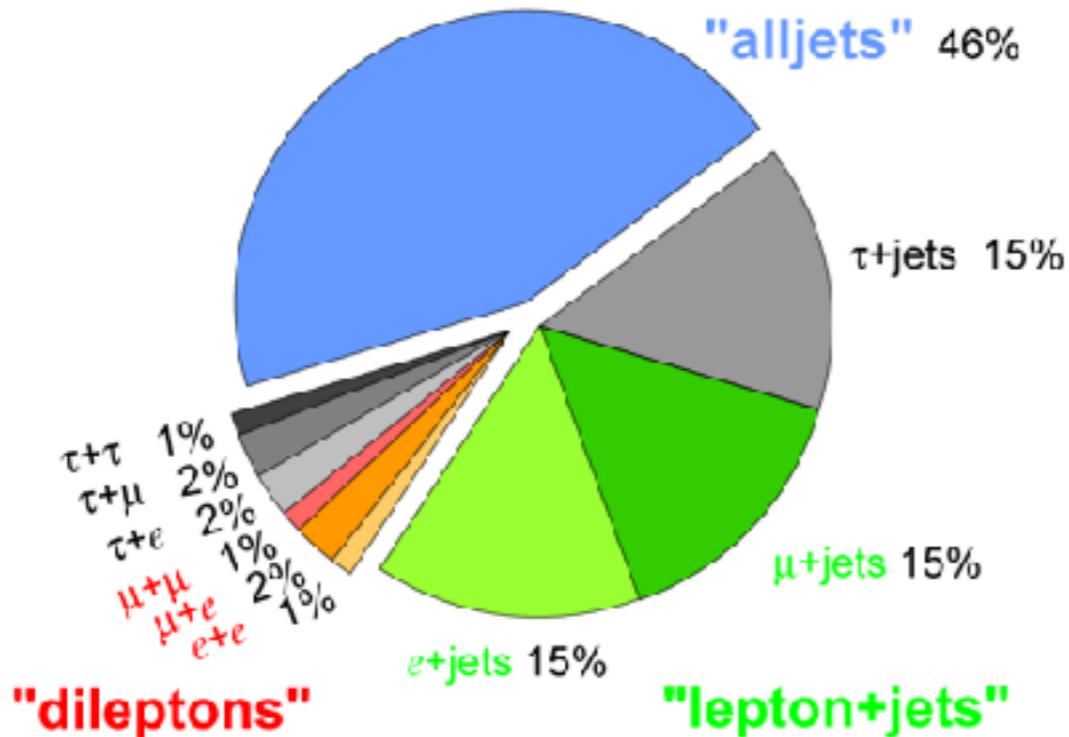
- The types of the W decay determine the different top decay signatures

# Top Quark Pair Decays - Classification

- Classified according to W decay (since basically 100%  $t \rightarrow bW$ )



Top Pair Branching Fractions

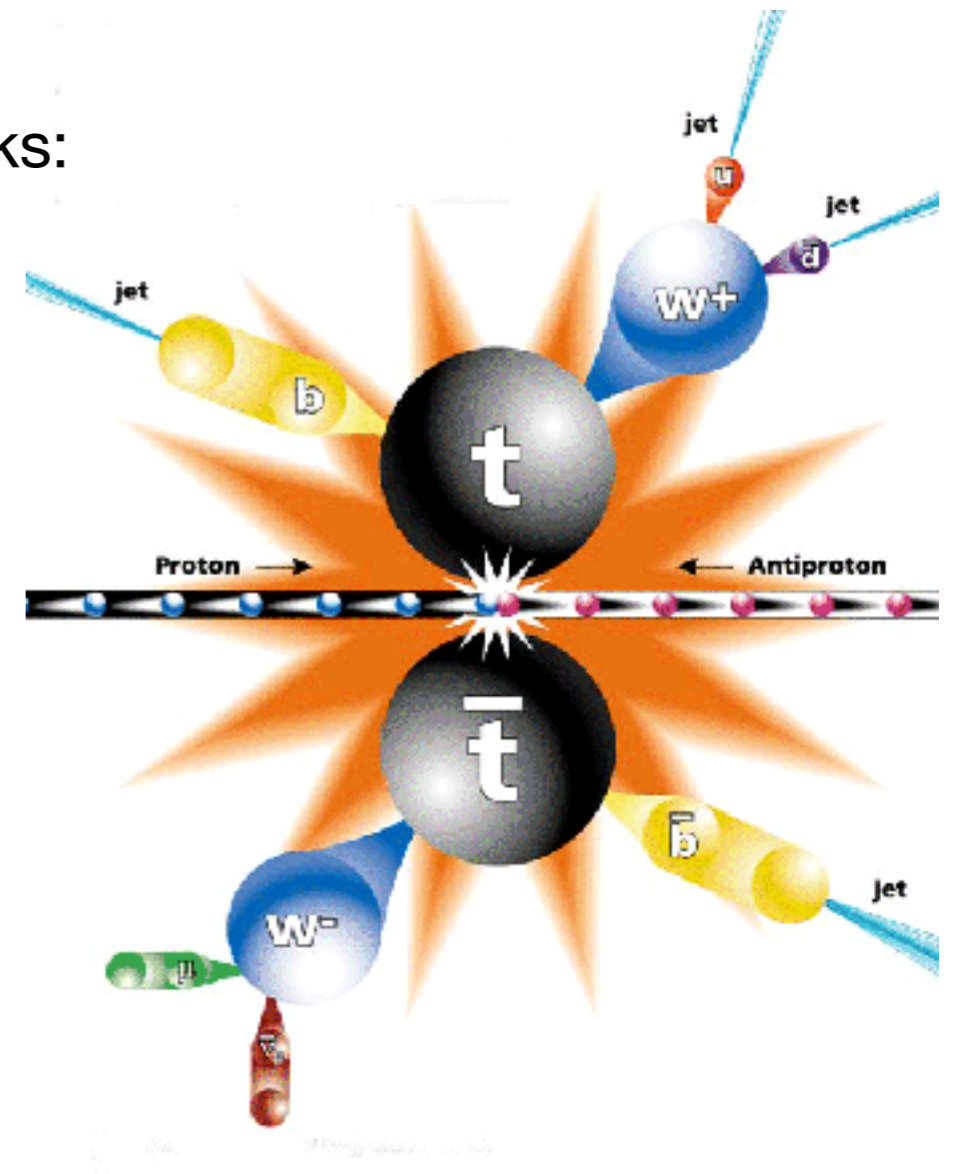


## Top Pair Decay Channels

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

# Detection of Top Events

- Classification of the events based on their characteristic signatures, then a specialized analysis for each decay mode
  - Di-Lepton Events: Two isolated, highly energetic leptons ( $e, \mu$ ) from  $W$  decay
  - Lepton + Jets: One isolated lepton ( $e, \mu$ ) from  $W$  decay, jets from  $W$  decay and from  $b$  quarks
  - All-Hadronic: Jets from both  $W$ s, jets from  $b$  quarks:  
Tagging crucial - quite difficult at hadron colliders

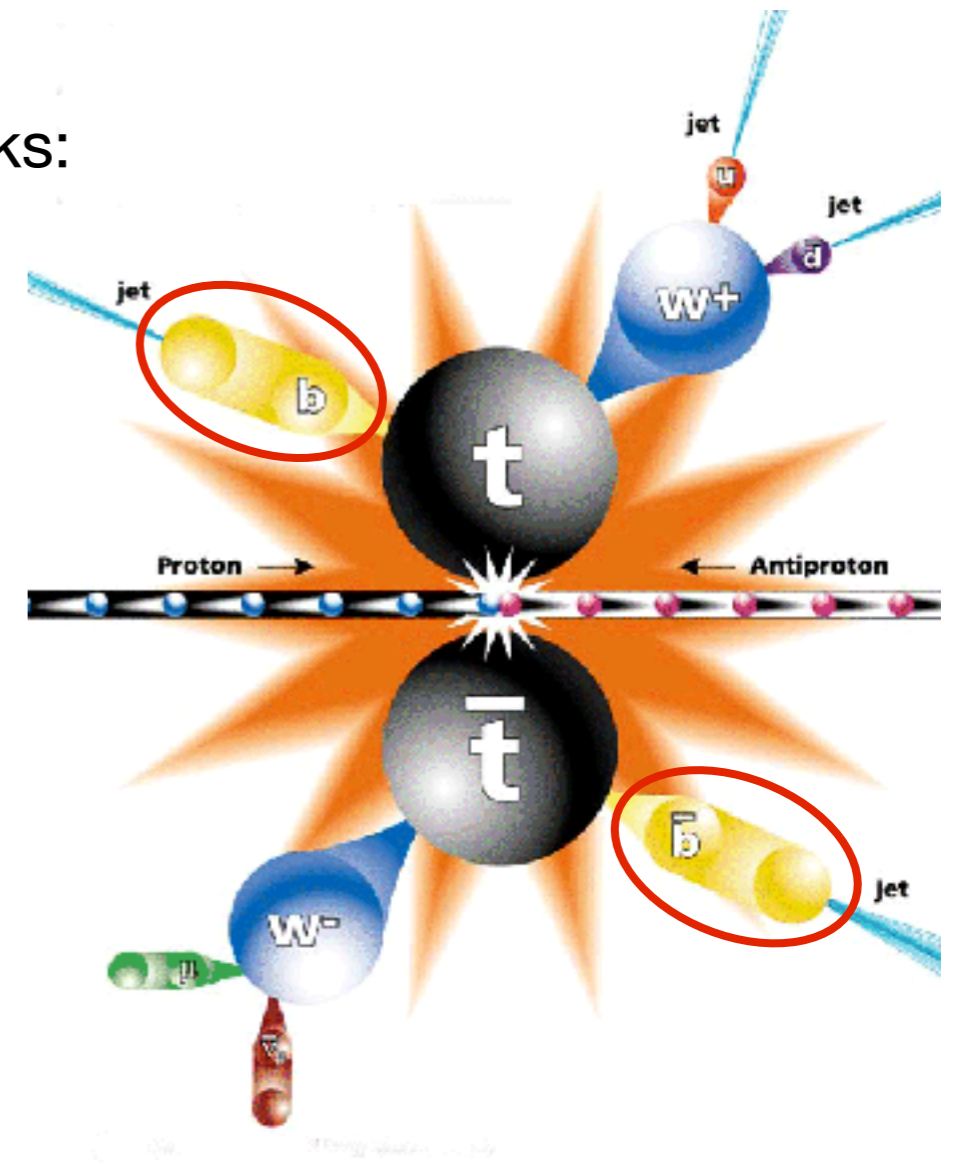


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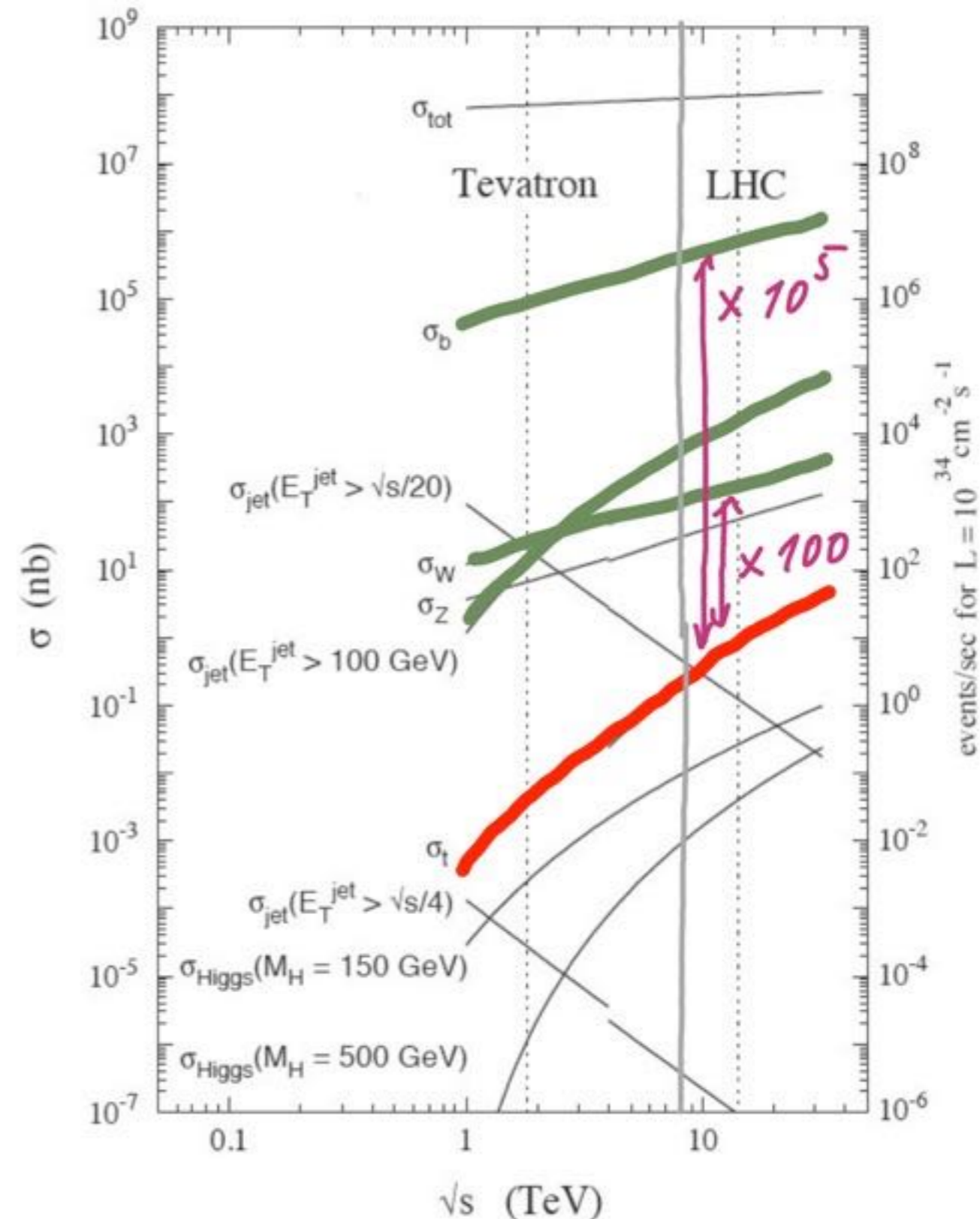
## Reminder: b quark identification

- Relatively long life time of mesons containing b quarks ( $c\tau$  ( $B^0$ )  $\sim 460 \mu\text{m}$ ,  $c\tau$  ( $B^\pm$ )  $\sim 490 \mu\text{m}$ )
  - ▶ Identification of a displaced secondary vertex in a jet
  - ▶ Jet is “tagged” as a b jet

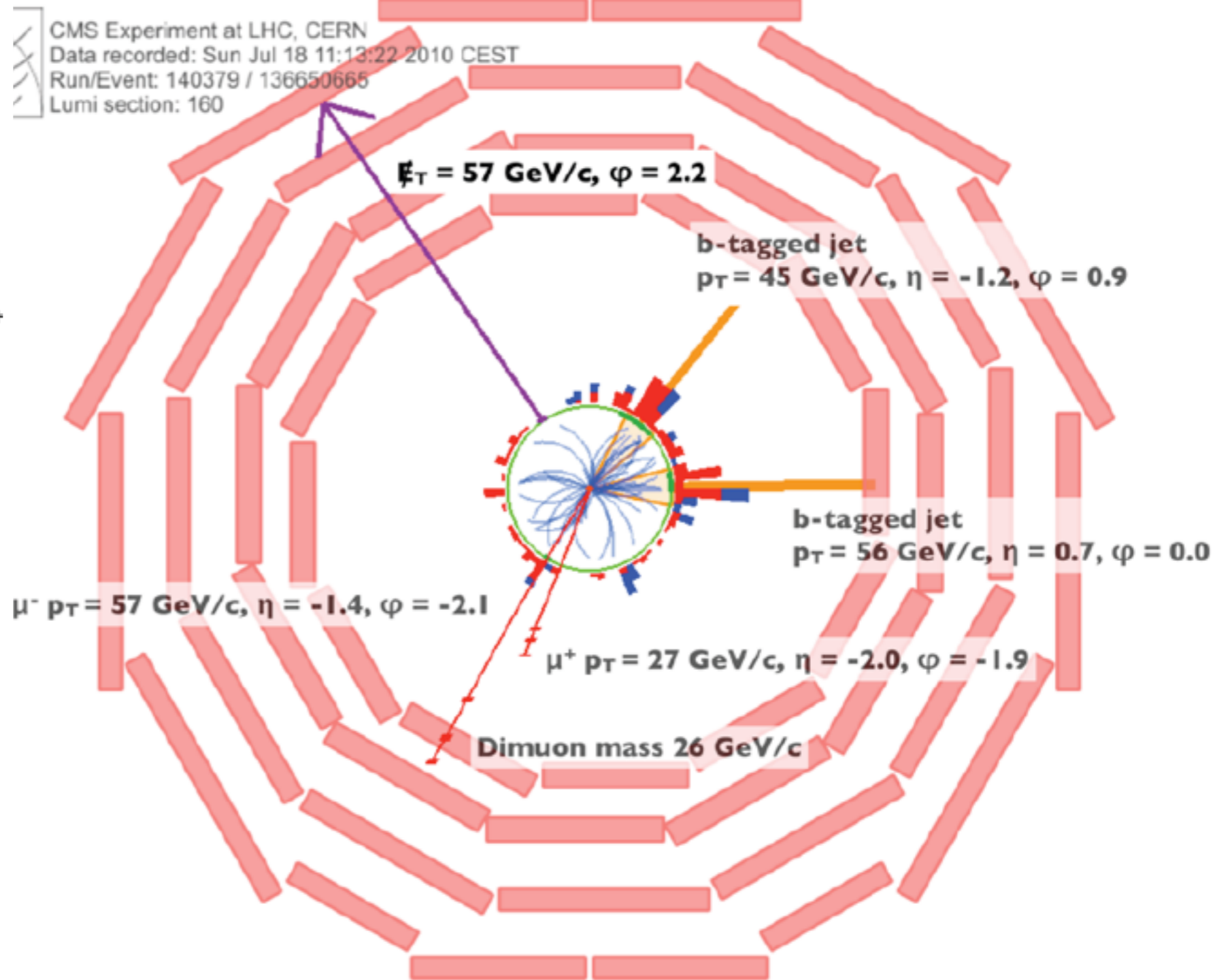
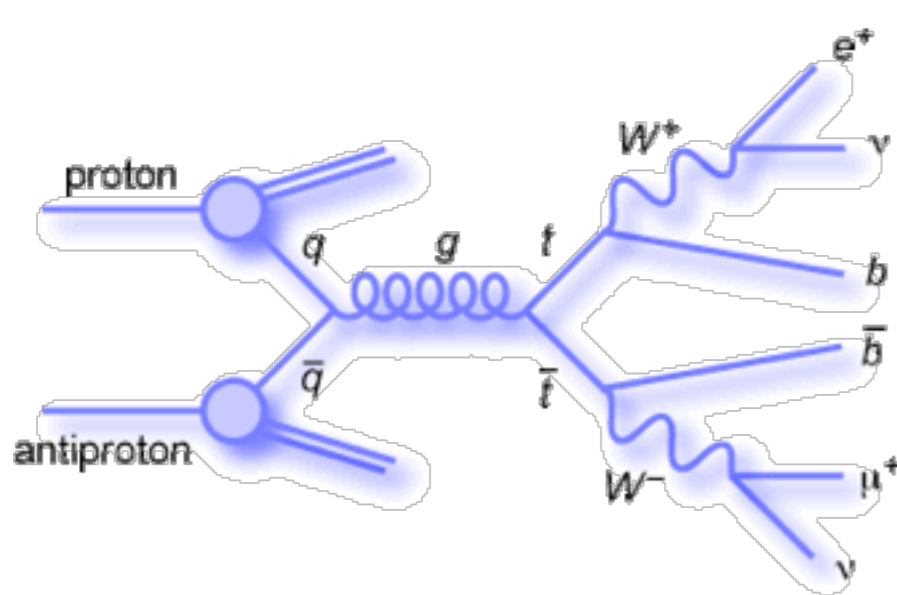


# The Challenge: Background

- Top production is only a very small part of the total pp cross section
- ▶ High background, in particular for hadronic decays of the W
  - ▶ all-hadronic: QCD multi-jet background (very high!)
  - ▶ lepton+jets: W + jets and QCD multi-jet background (ok)
  - ▶ di-lepton: Z + jets and di-boson background (low)

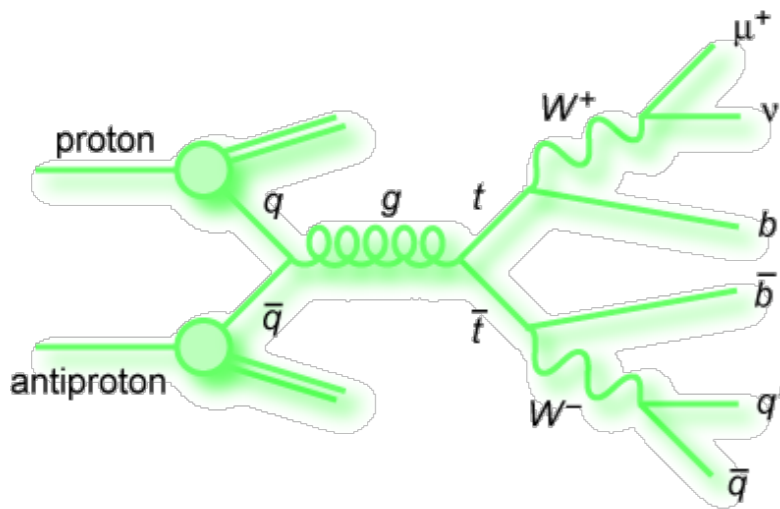


# Experimental Detection: Di-Lepton Events

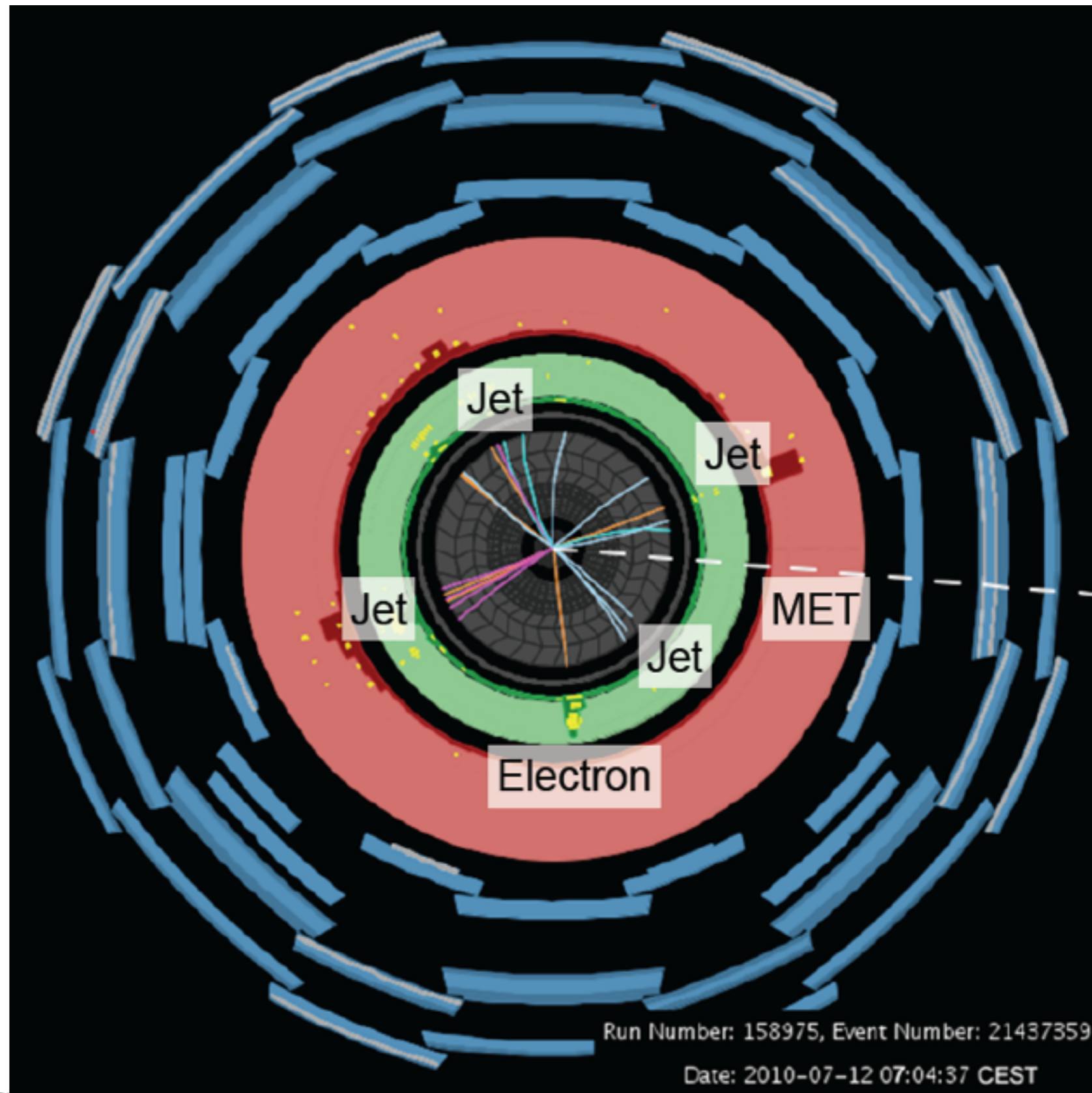


- Clear, clean signature
- missing information from two (undetected) neutrinos
- small branching ratio, low statistics
- Background: mainly  $W + X$

# Experimental Detection: Lepton + Jets



- Relatively clean due to the leptonic decay of one  $W$ 
  - Signature: Isolated lepton, highly energetic jets and missing energy
- missing information from neutrino
- high statistics (BR 30%)
- Background: Mainly  $W + \text{jets}$





# Top Pairs and Single Top: Cross Section

# Top Quark Pair Production at Hadron Colliders

---

- In the parton-parton frame the center-of-mass energy has to be at least  $2 m_t$

$$\hat{s} = x_a x_b s \geq (2 m_t)^2$$

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~ 0.025 LHC (14 TeV)

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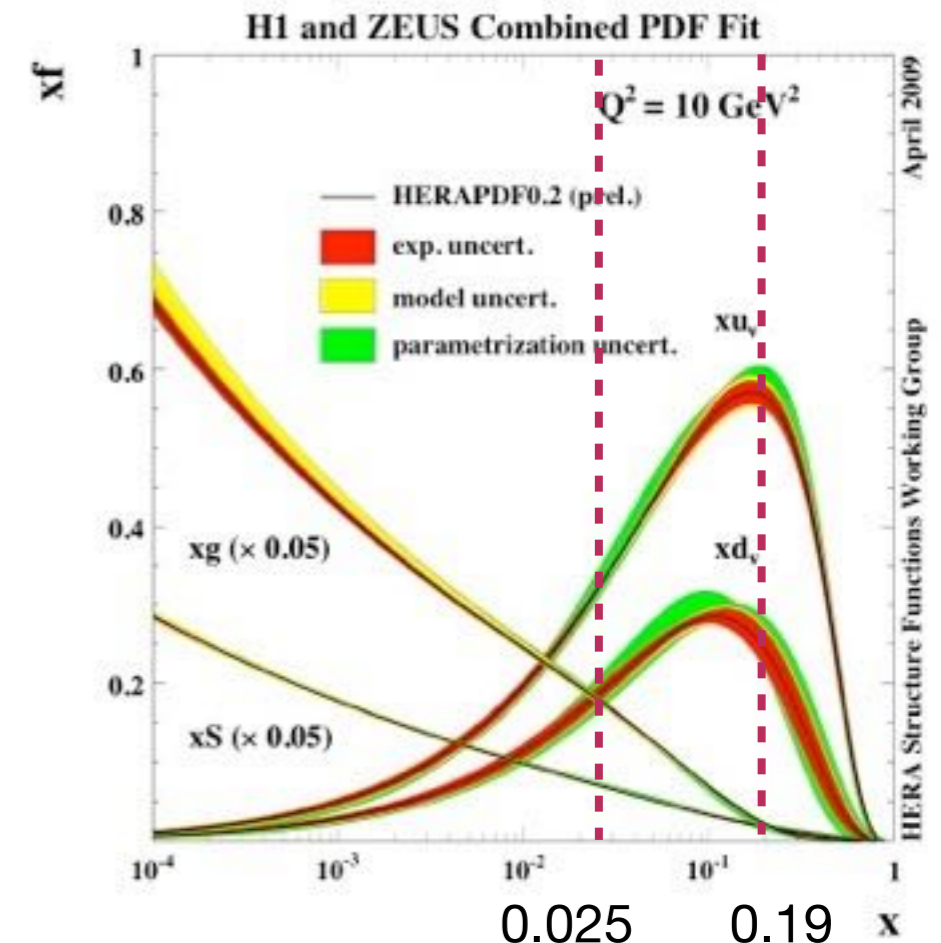
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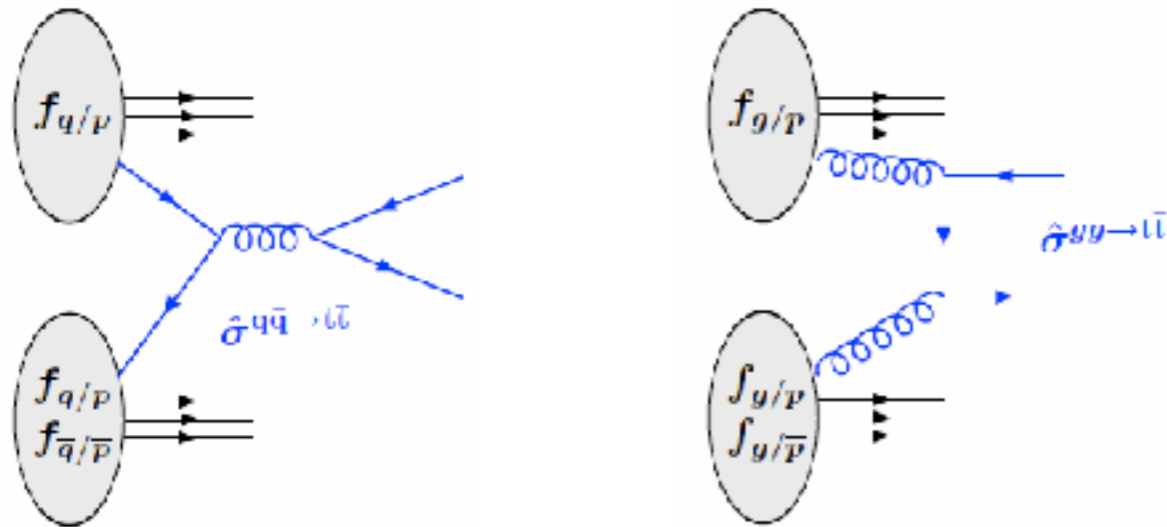
- ▶ Mix of the production processes is energy dependence:

- ▶ Tevatron: high  $x$ , dominated by valence quarks:  
Big advantage of proton - anti-proton collisions
- ▶ LHC: lower  $x$ , dominated by gluons



# Top Quark Pair Production at Hadron Colliders II

- Production mechanisms: Quark - anti-quark vs gluon-gluon

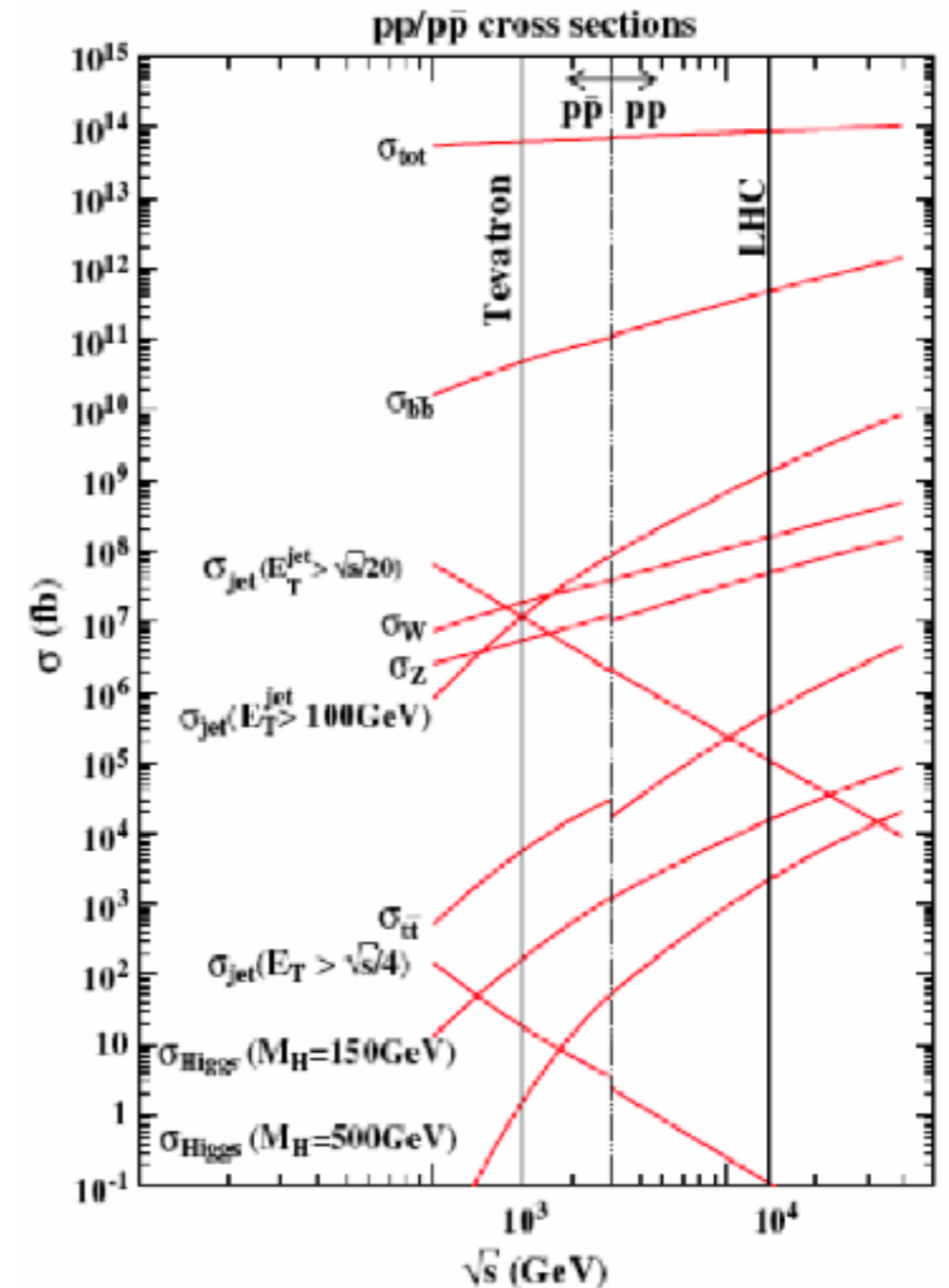


Hadron Collider	Processes	$\sigma_{tt}$ [pb]	Group
Tevatron Run I ( $p\bar{p}$ , $\sqrt{s} = 1.8$ TeV)	90% $q\bar{q} \rightarrow t\bar{t}$	$5.19^{+0.52}_{-0.68}$	Cacciari et al. [117]
	10% $gg \rightarrow t\bar{t}$	$5.24 \pm 0.31$	Kidonakis et al. [119]
Tevatron Run II ( $p\bar{p}$ , $\sqrt{s} = 1.96$ TeV)	85% $q\bar{q} \rightarrow t\bar{t}$	$6.70^{+0.71}_{-0.88}$	Cacciari et al. [117]
	15% $gg \rightarrow t\bar{t}$	$6.77 \pm 0.42$	Kidonakis et al. [119]
LHC ( $pp$ , $\sqrt{s} = 14$ TeV)	10% $q\bar{q} \rightarrow t\bar{t}$	$833^{+52}_{-39}$	Bonciani et al. [118]
	90% $gg \rightarrow t\bar{t}$	$873^{+2}_{-28}$	Kidonakis et al. [120]

arXiv:0810.5226 [hep-ex]

NLO QCD calculations

LHC: Gluon dominated, Tevatron: quark dominated



G. Weiglein et al.  
Physics Reports 426 (2006) 47–358

# Measuring Cross-Sections

- Important for the measurement: event selection, understanding of background
- Choose decay channels that can be selected with high purity  
Initially: Leptonic decays of W bosons (downside: small BR)  
Meanwhile also Lepton + Jets and all-hadronic decays: large BRs
- Event selection: High-energy leptons, jets from b quarks, missing energy (neutrino!)
- Determining the cross section based on:

$$\sigma(p\bar{p} \rightarrow t\bar{t}) = \frac{N - B}{A\epsilon \int \mathcal{L} dt}$$

N: Number of selected events

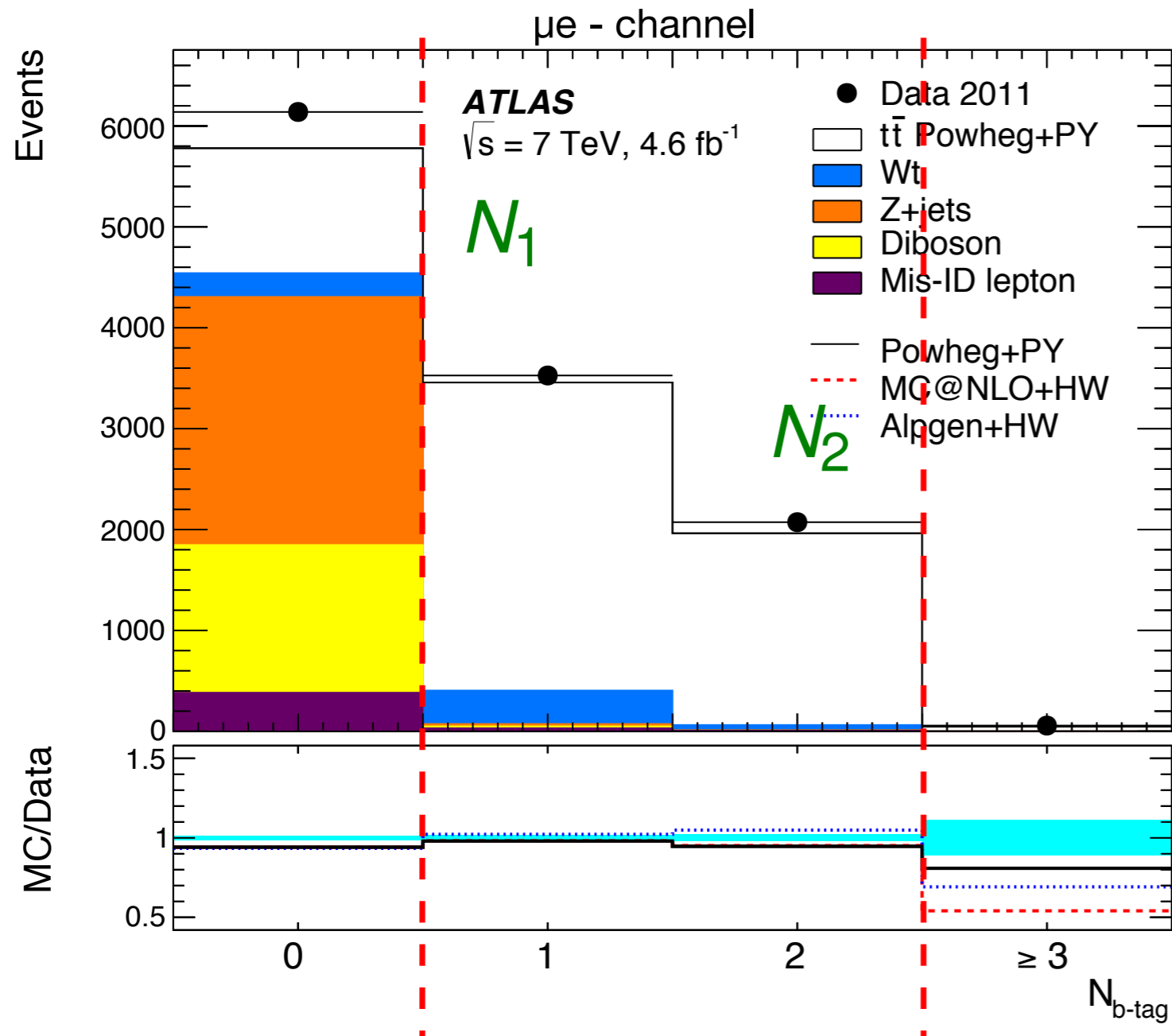
B: Estimation of background events

A: acceptance correction: kinematic and geometric acceptance of the detector

$\epsilon$ : event selection efficiency

# Example: ATLAS Di-Leptons

- B-Tagging important: A real top pair event contains two b quarks



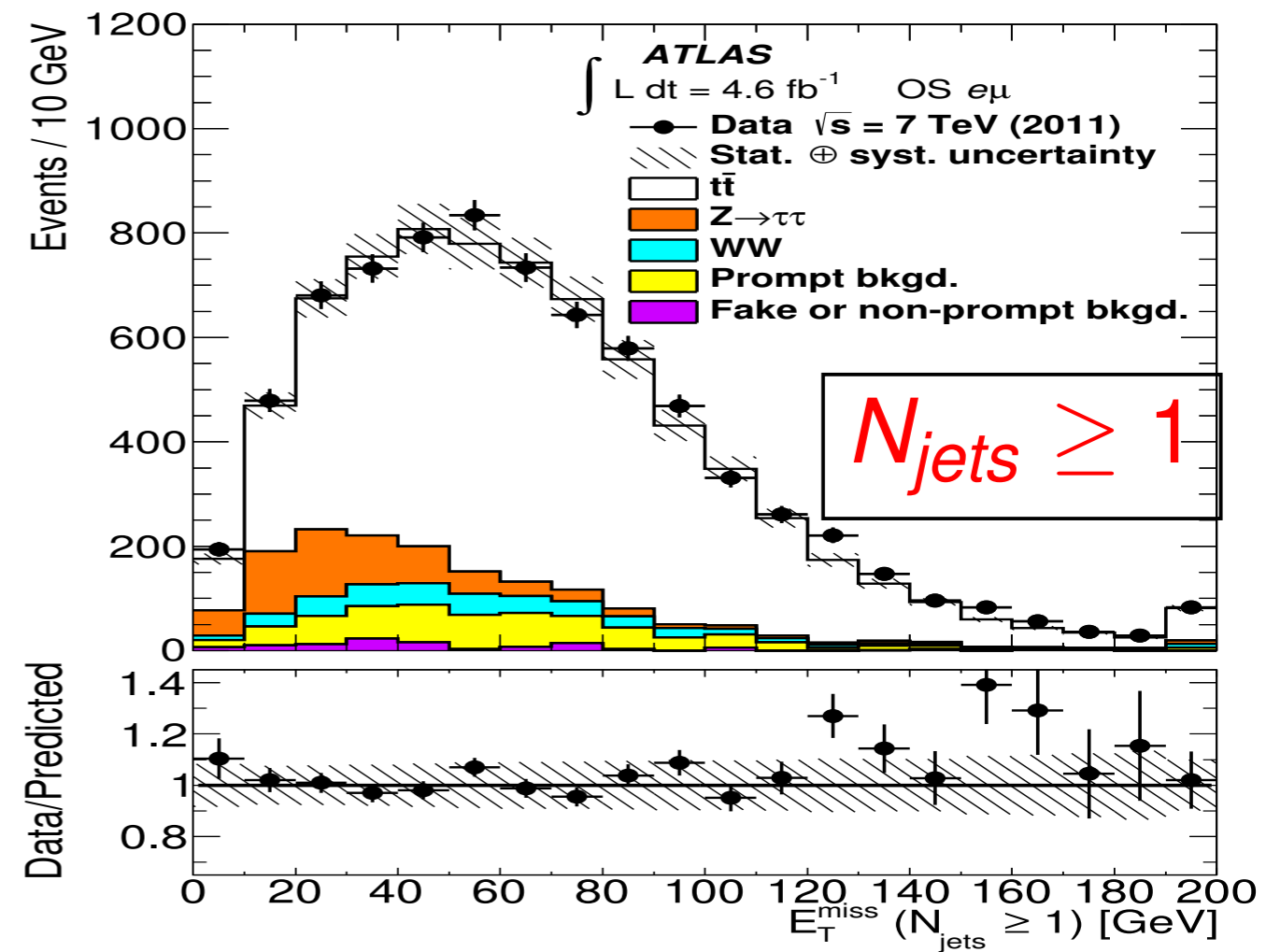
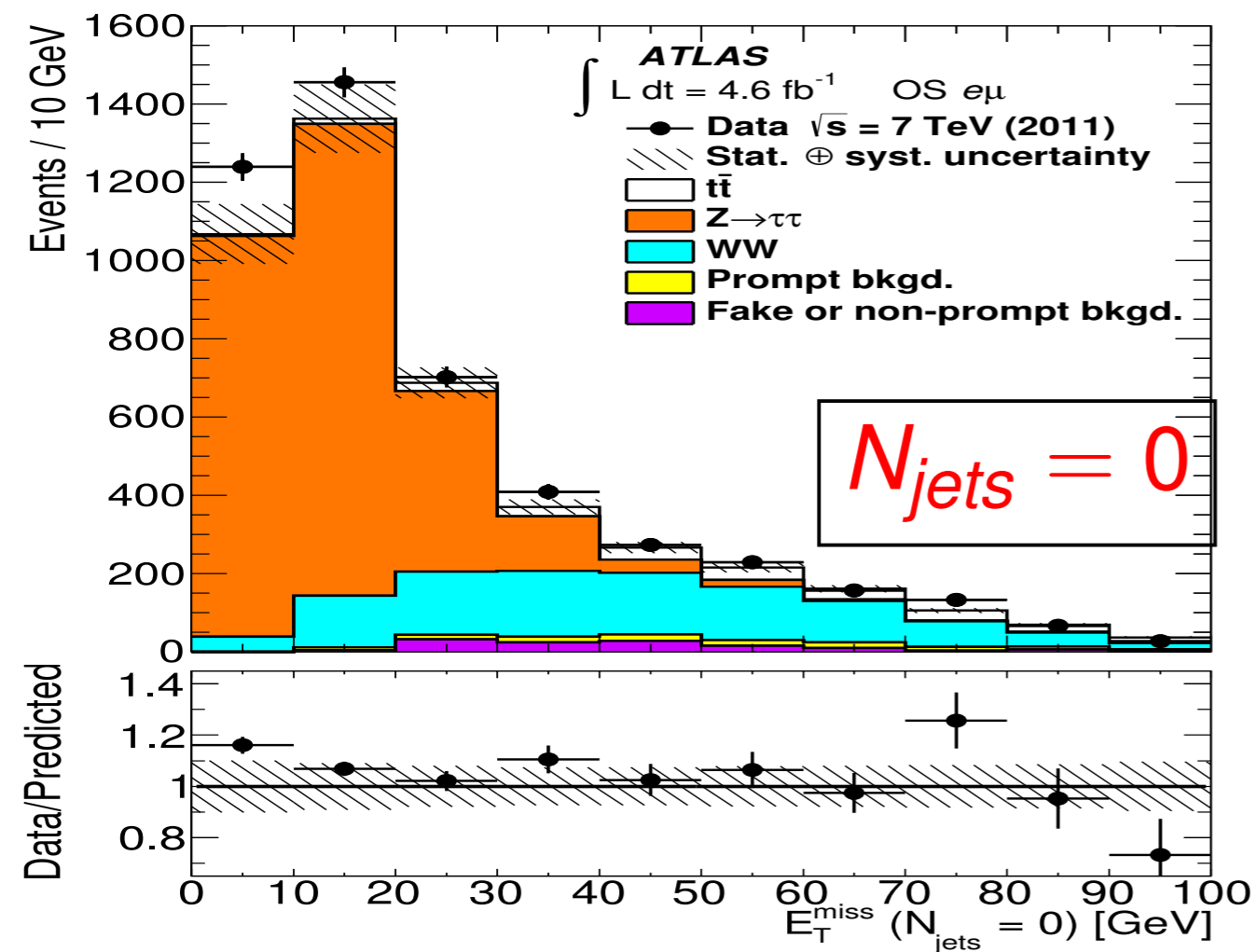
Most important sources of uncertainties:

B tagging - How well is it understood?

Jet energy scale: influences energy cuts

# ATLAS Di-Leptons: Missing Energy

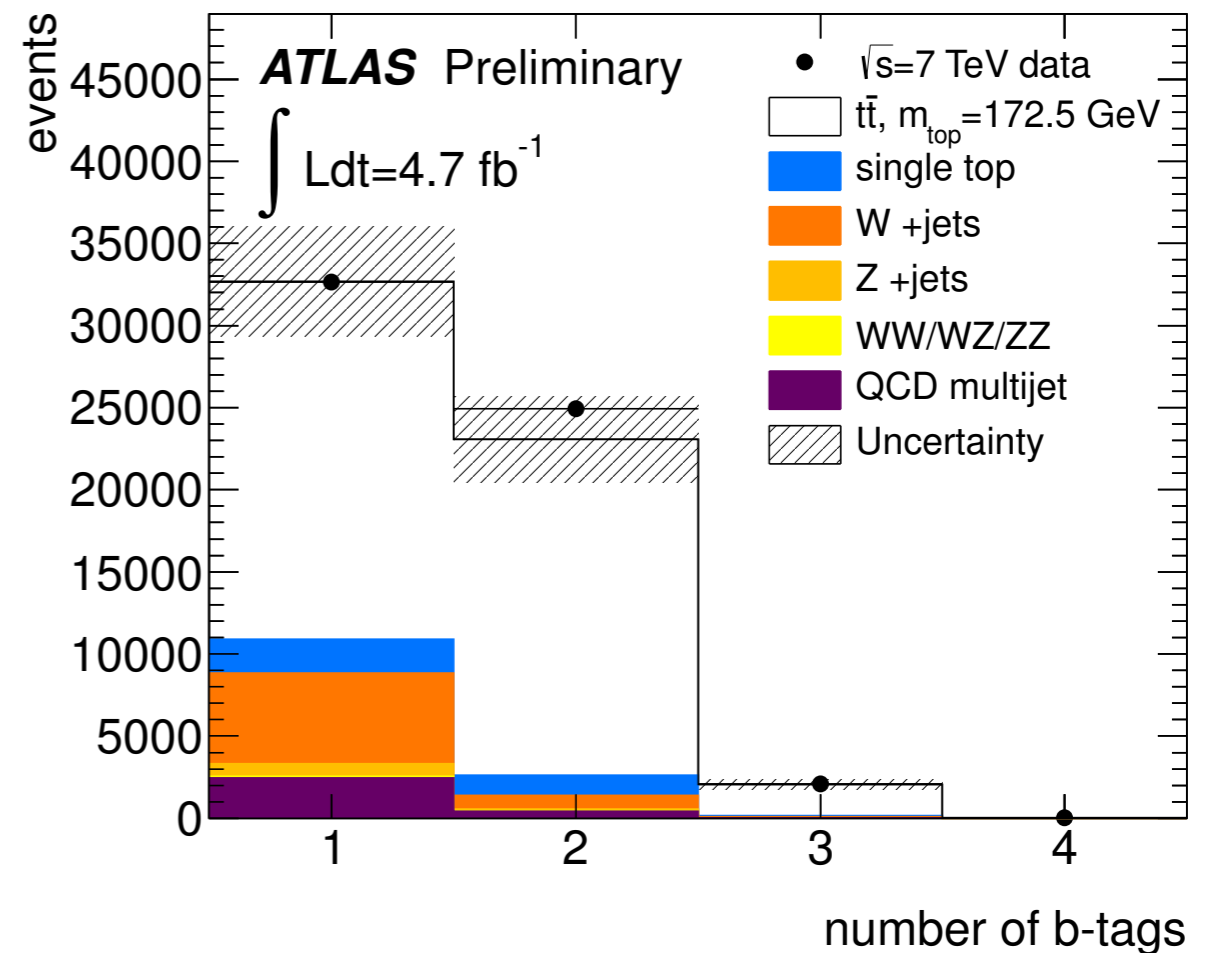
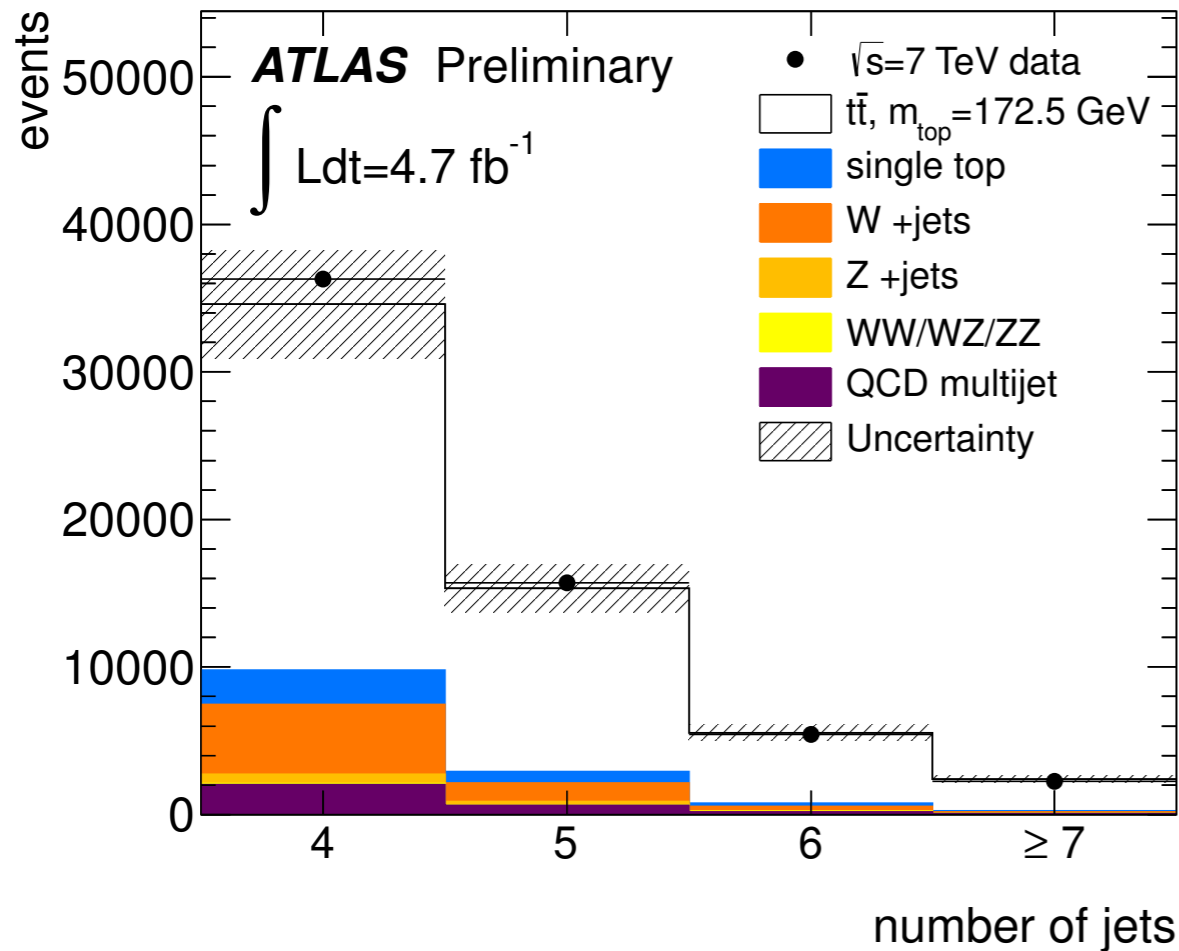
- Missing energy and jets in addition to leptons





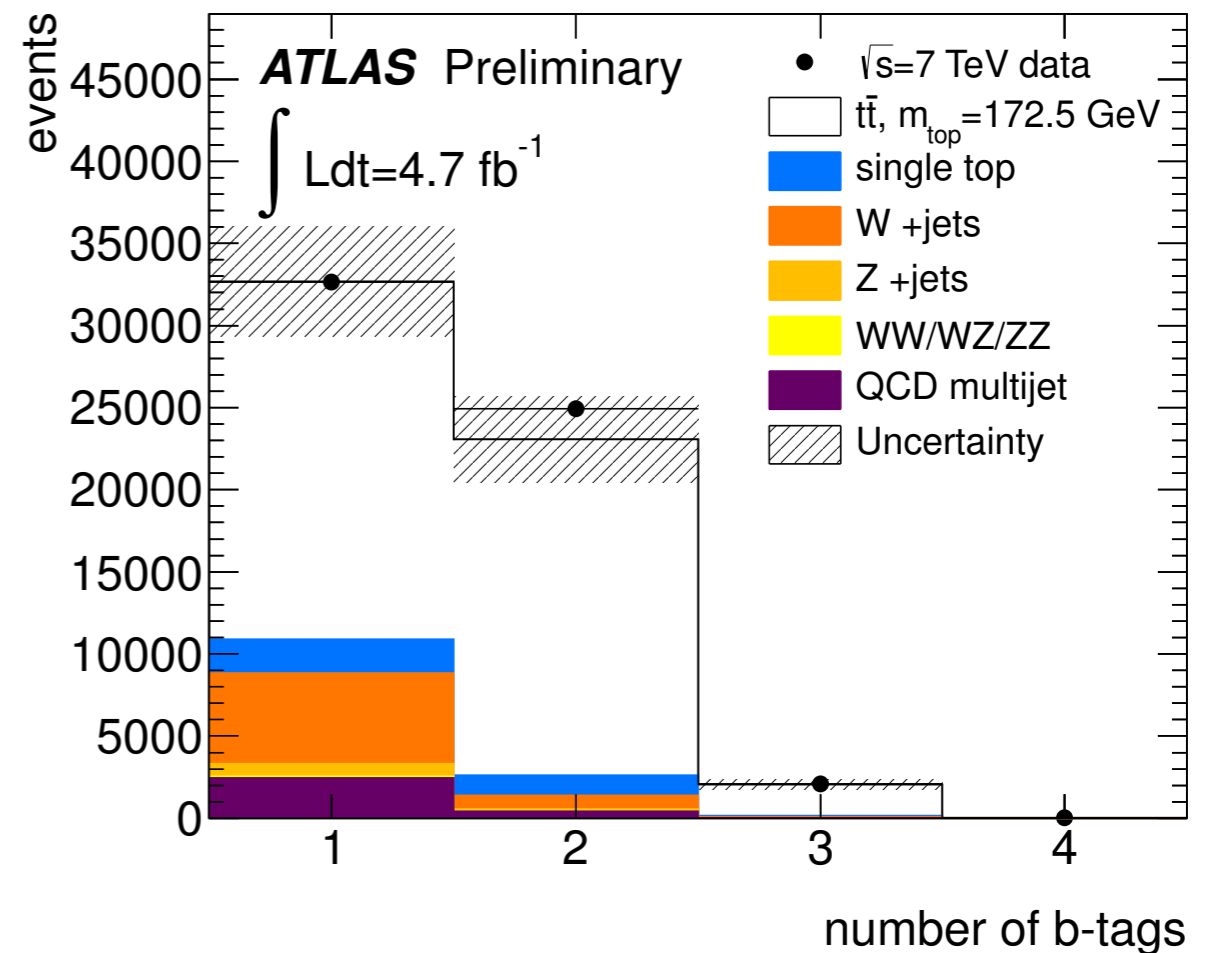
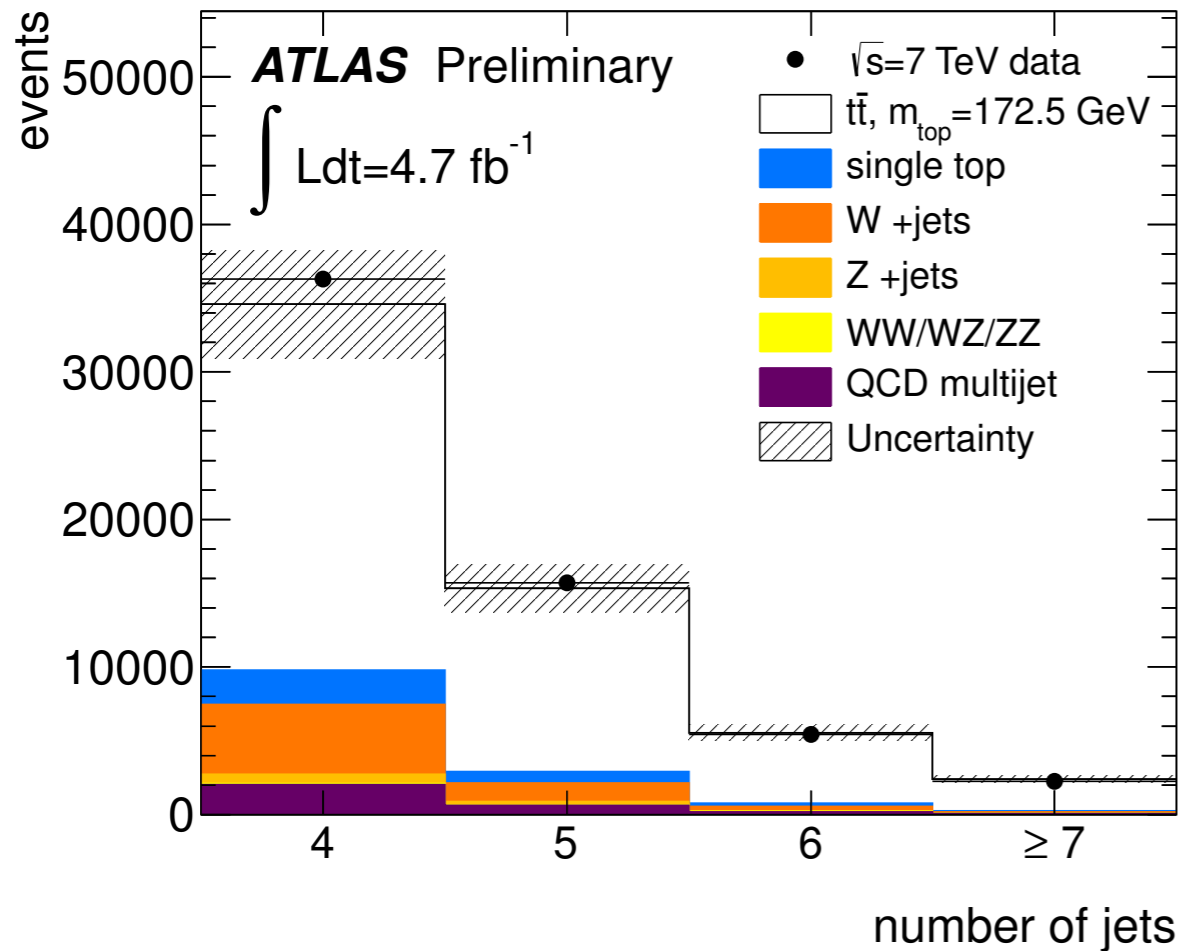
# Leptons + Jets

- More events, but also much more background: Jets from QCD processes and associated production of bosons
- Event selection via high-energy leptons, jet multiplicity (4 jets from  $t\bar{t}$ ), b tagging and missing energy (neutrino!)



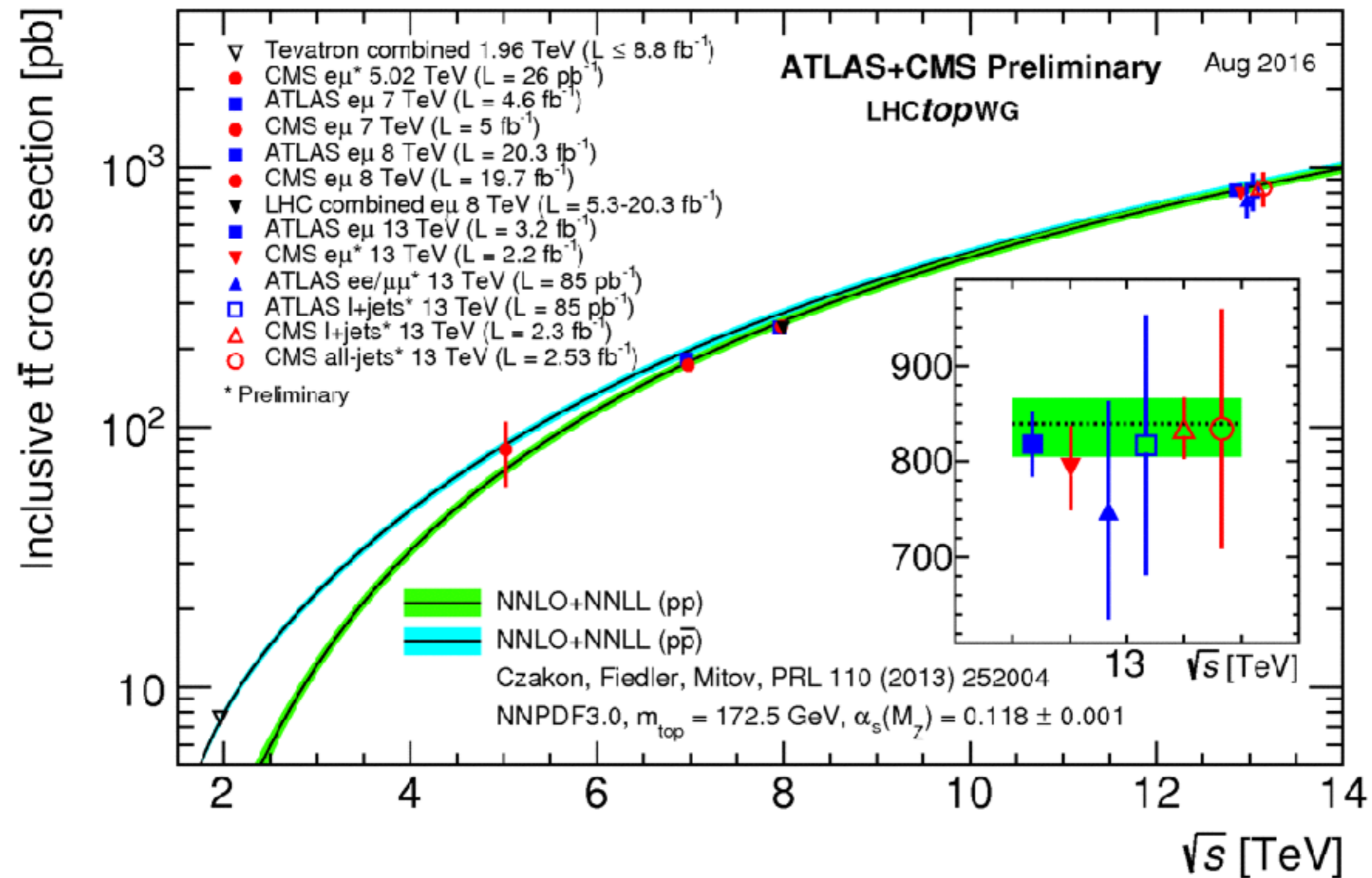
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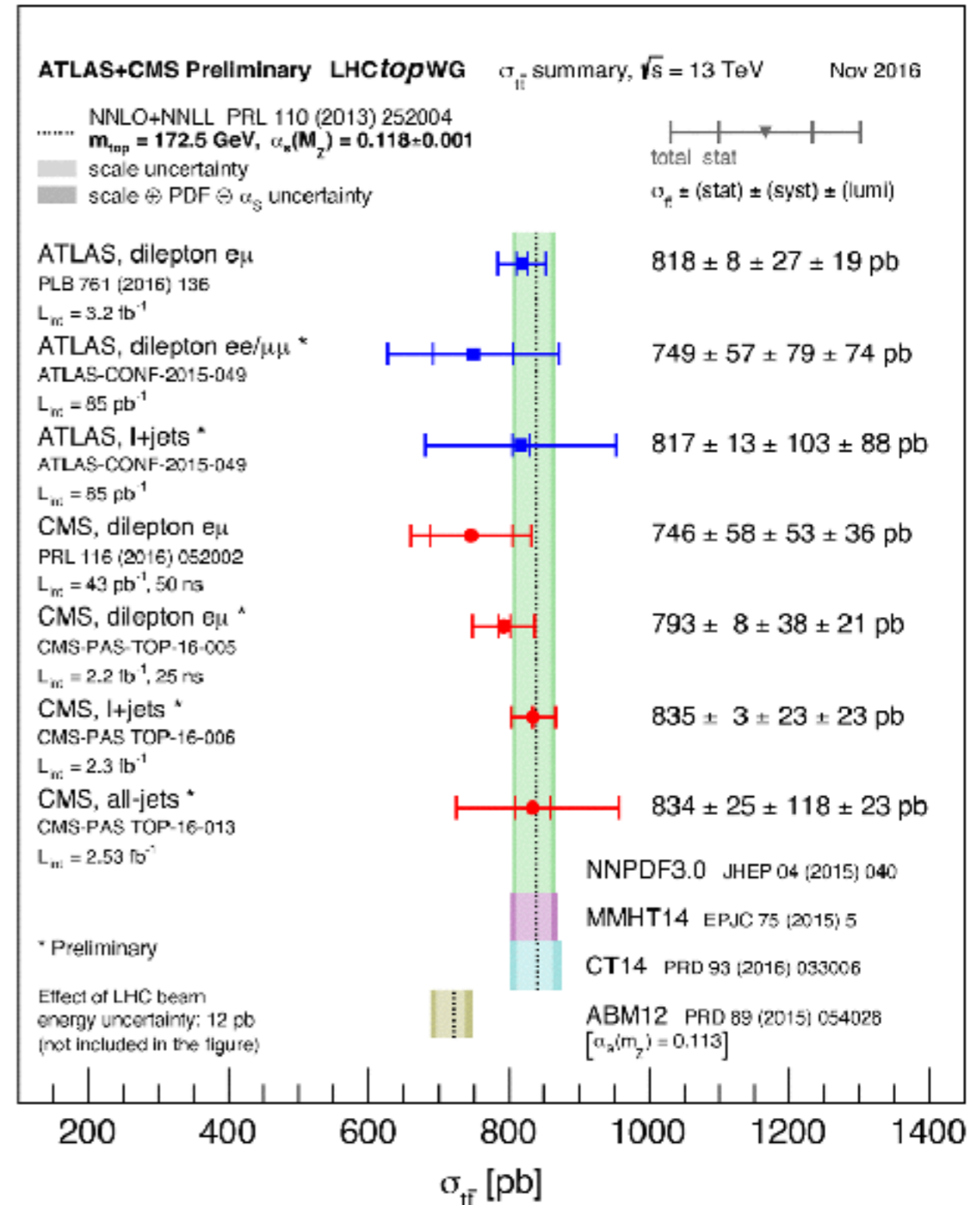
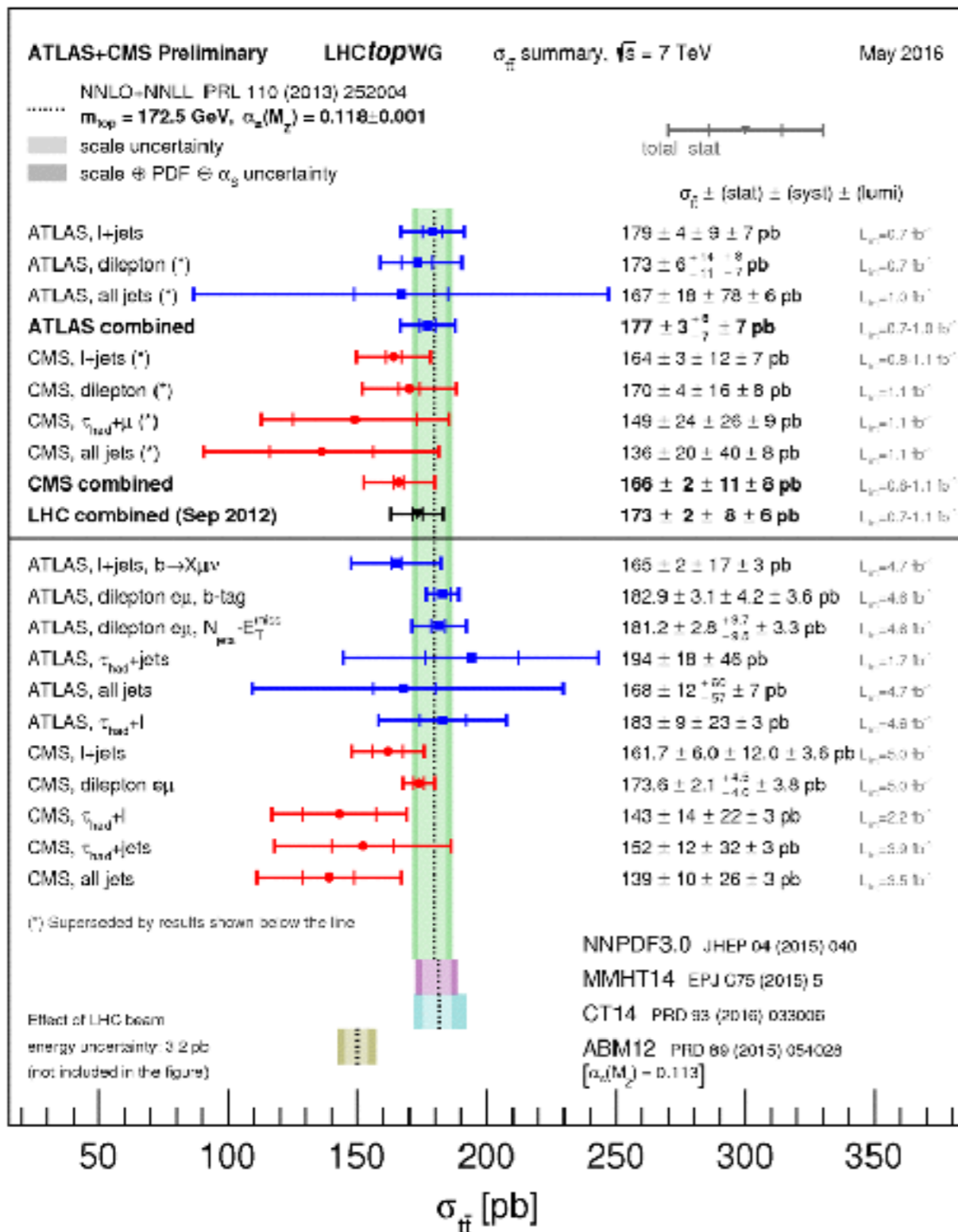


ATLAS-CONF-2013-046

# Top Cross Section at LHC

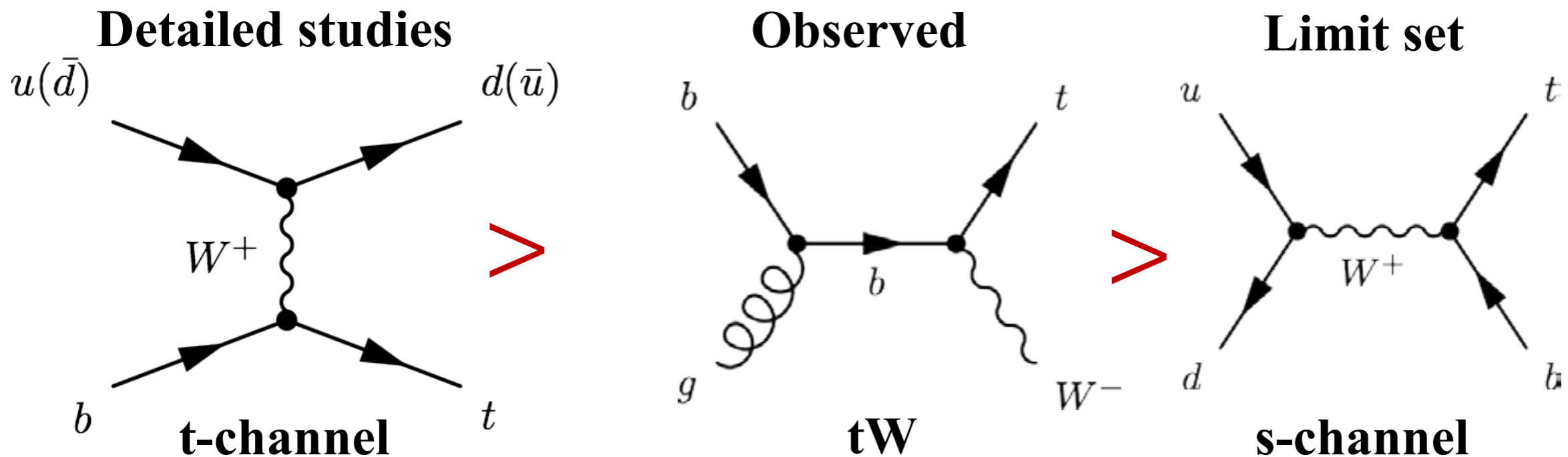


# Top Cross Section at LHC



# Single Top Production

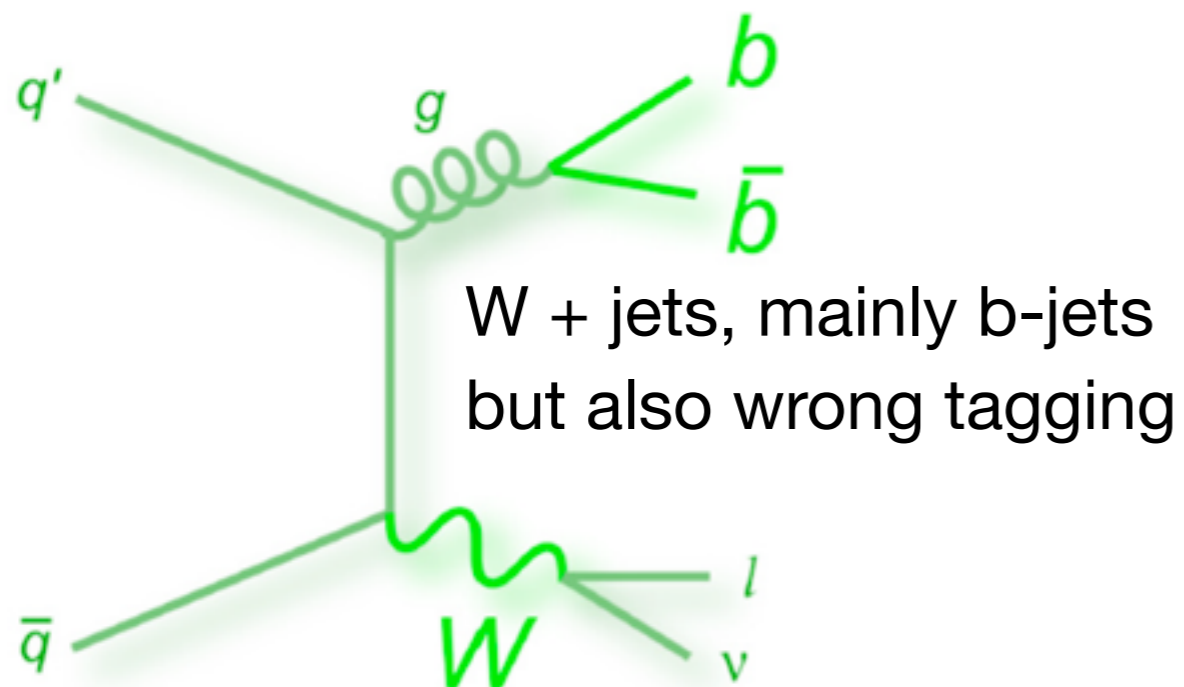
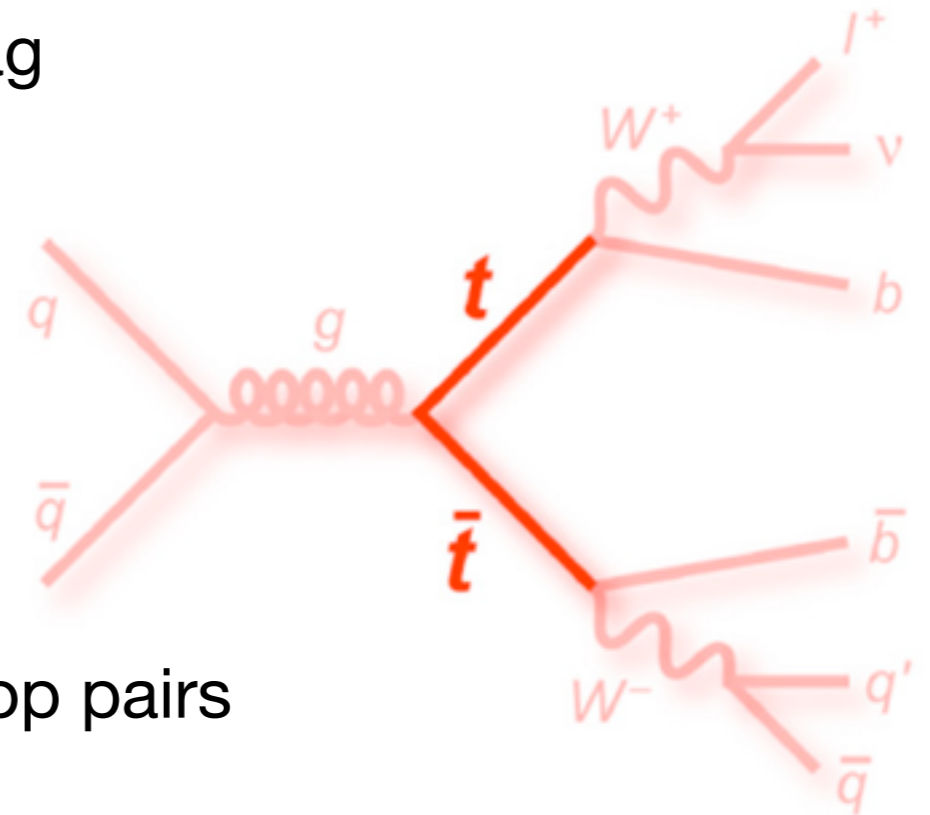
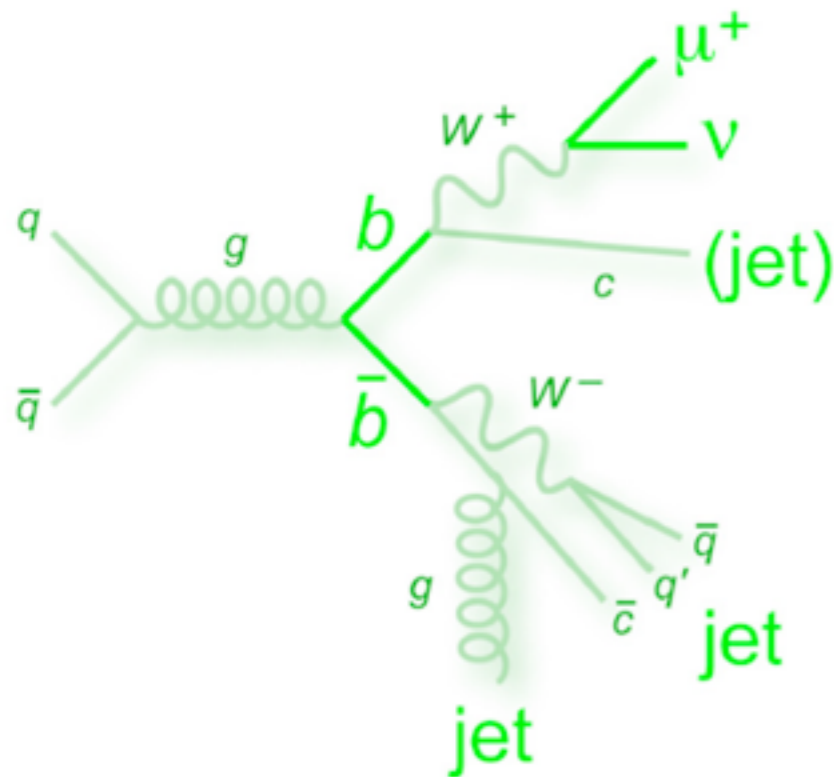
- Production of single top quarks via weak interaction - expectation:  
 $\sigma(\text{single top}) \sim 0.4 \times \sigma(\text{top pair})$
- ▶ Direct access to  $Wtb$  - vertex of the weak interaction!



Only one t quark in the final state: Less “spectacular” events than top pair production: Separation from background more difficult!

# Background in Single Top Measurements

- Events with a W and one or more jets with a b-tag

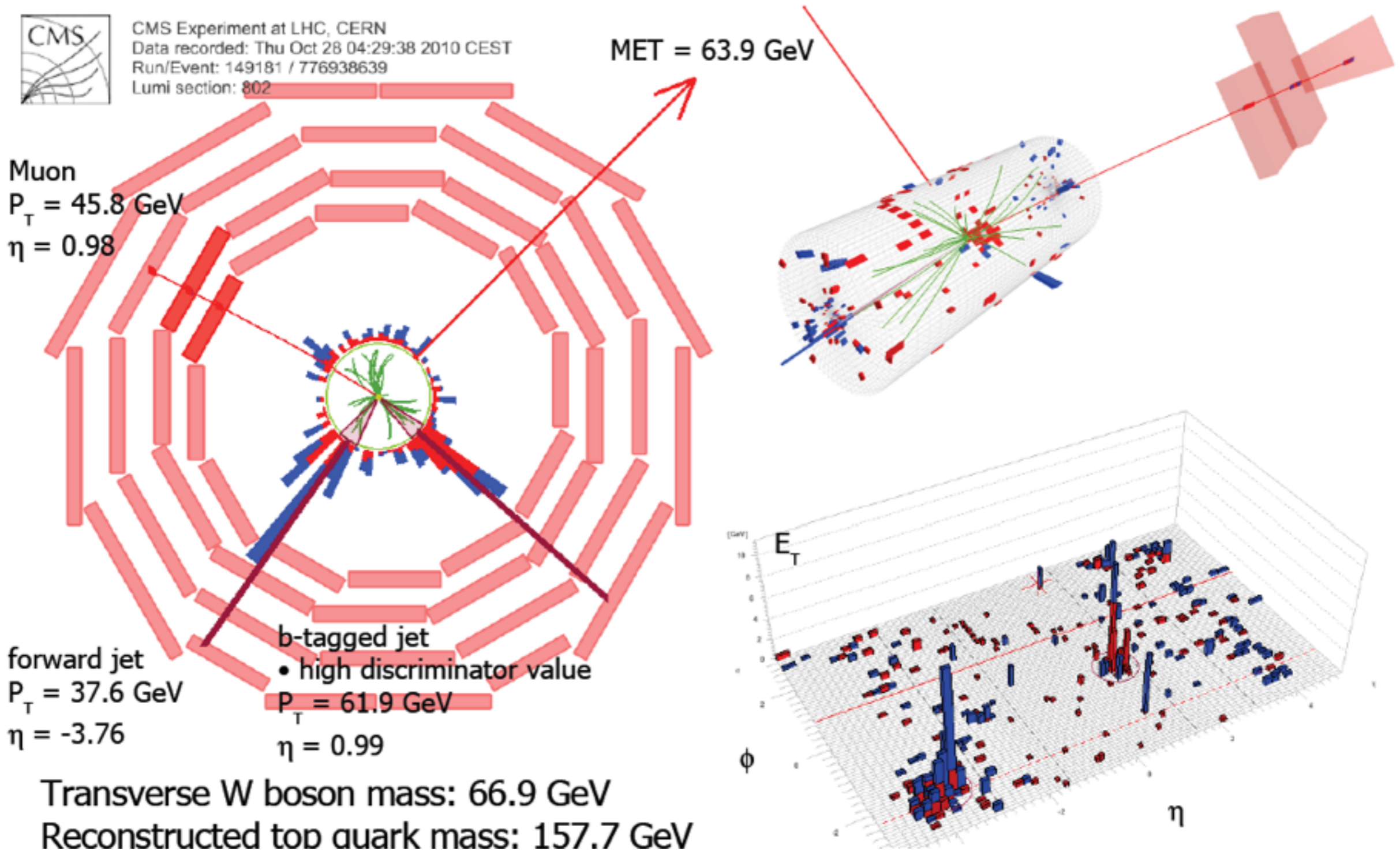


All in all: Modern analysis techniques are needed to reduce the background:

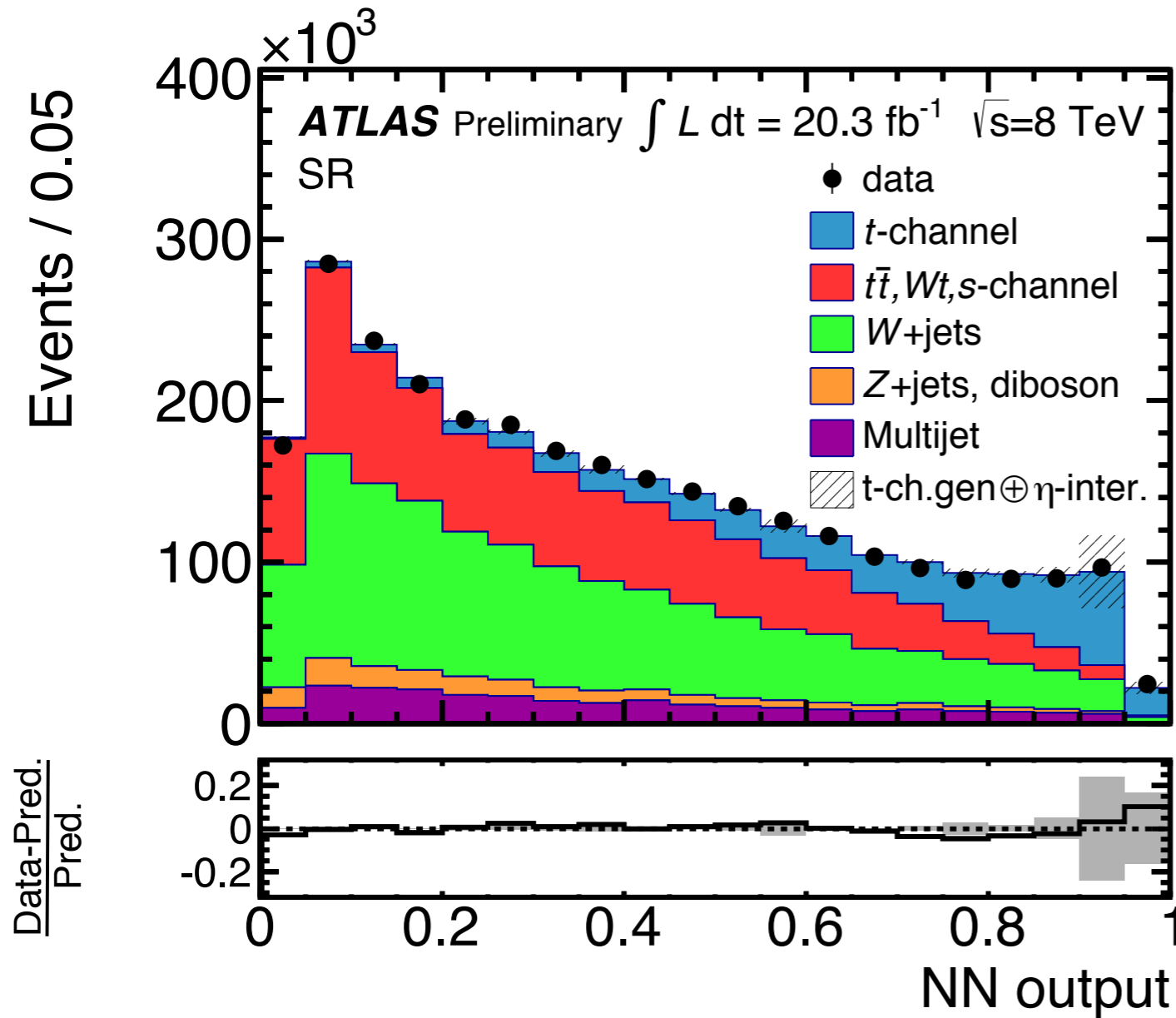
- Neural networks
- Boosted decision trees
- ...

# Single Top at the LHC

- A candidate from CMS



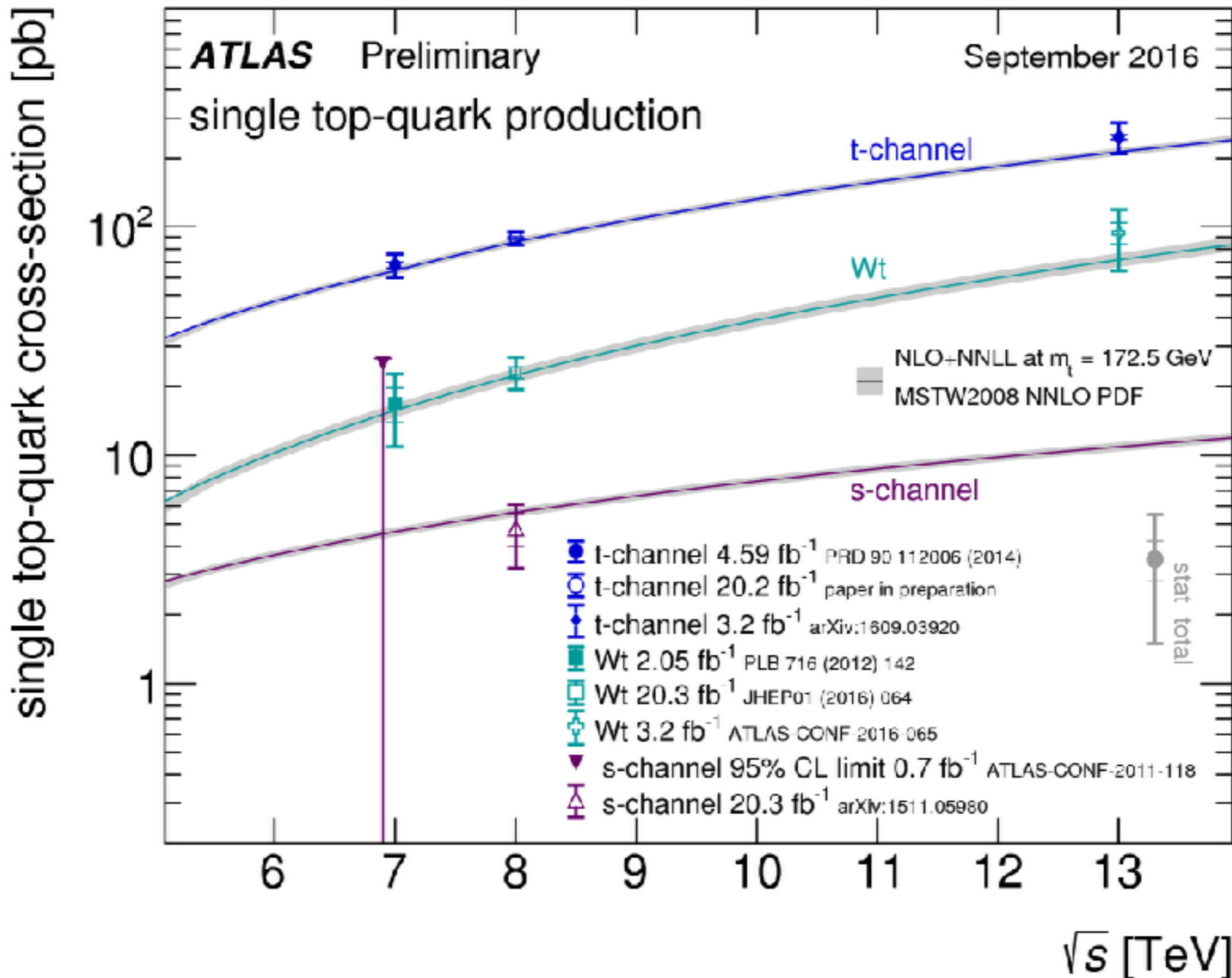
# Single Top at the LHC



- One example - After all selections in particular in the  $t$  channel a strong signal



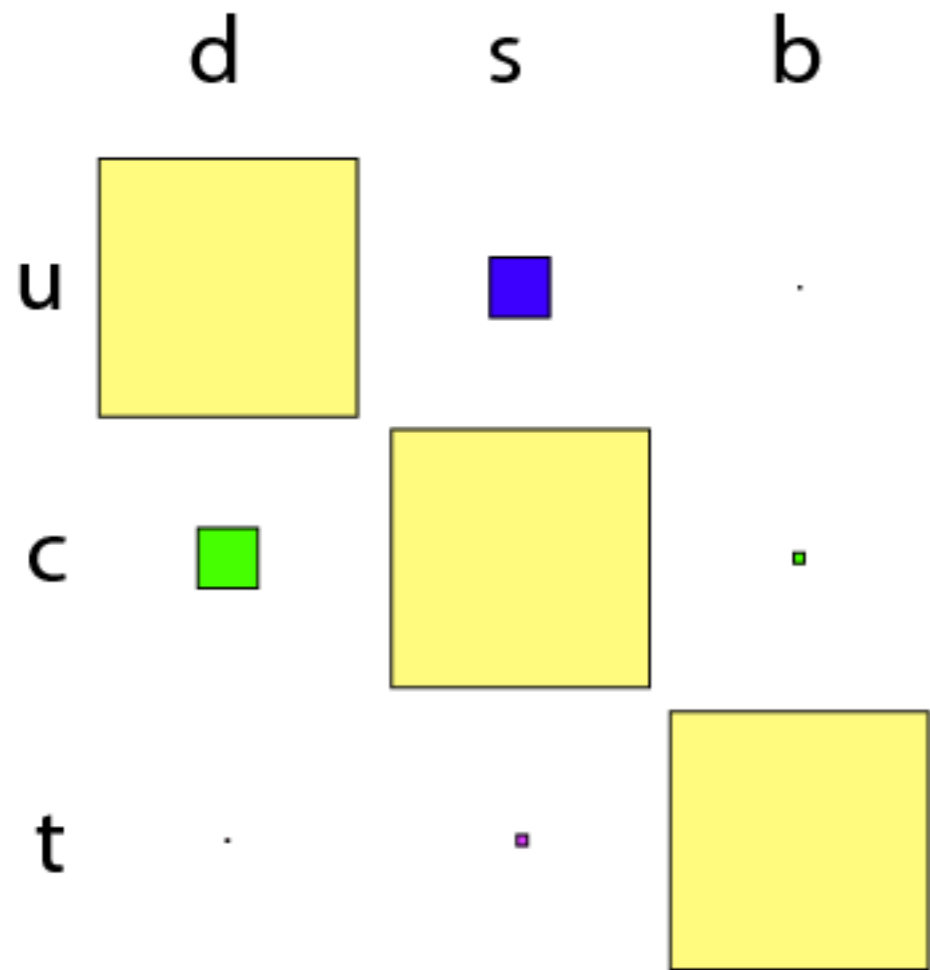
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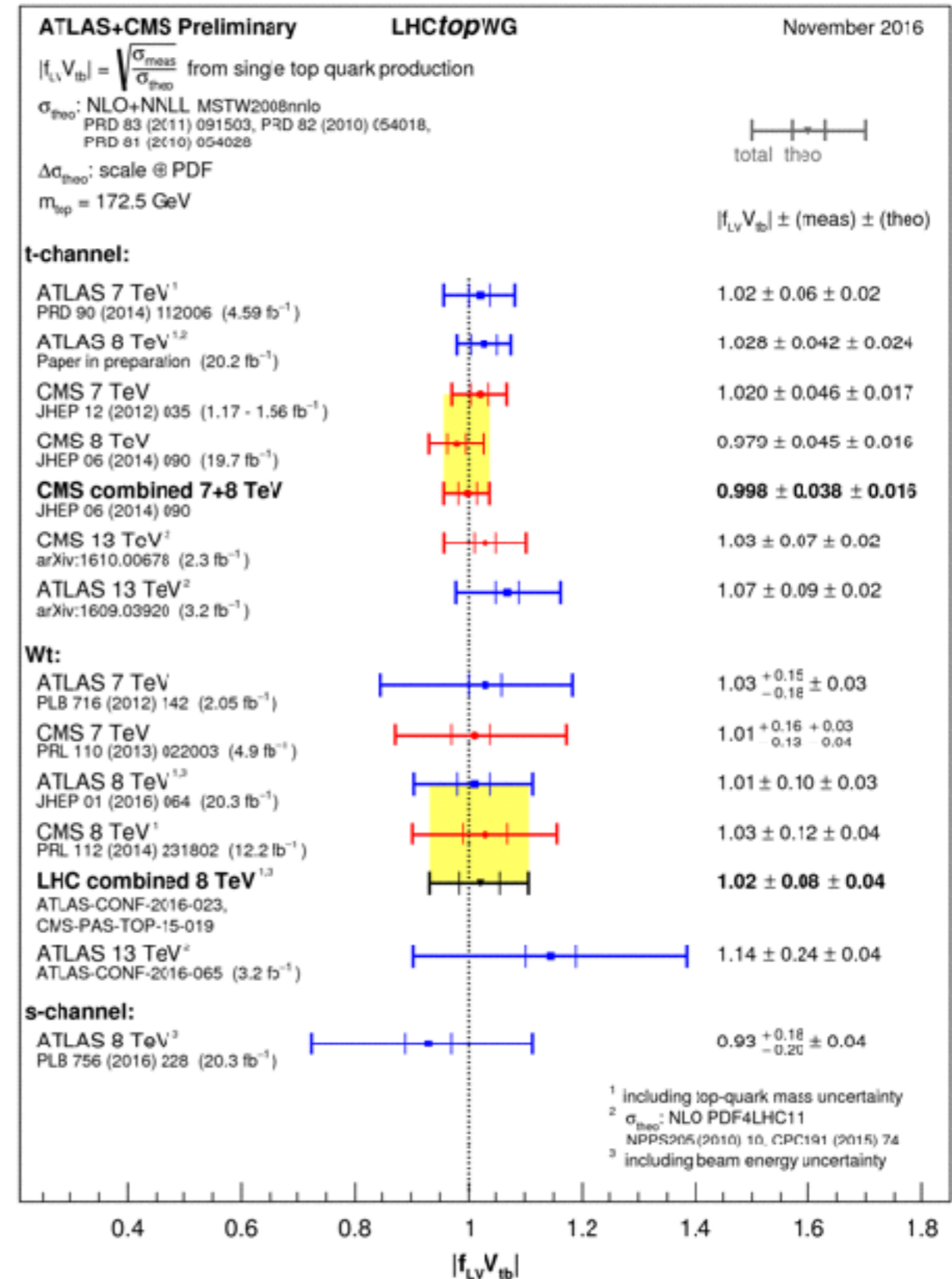
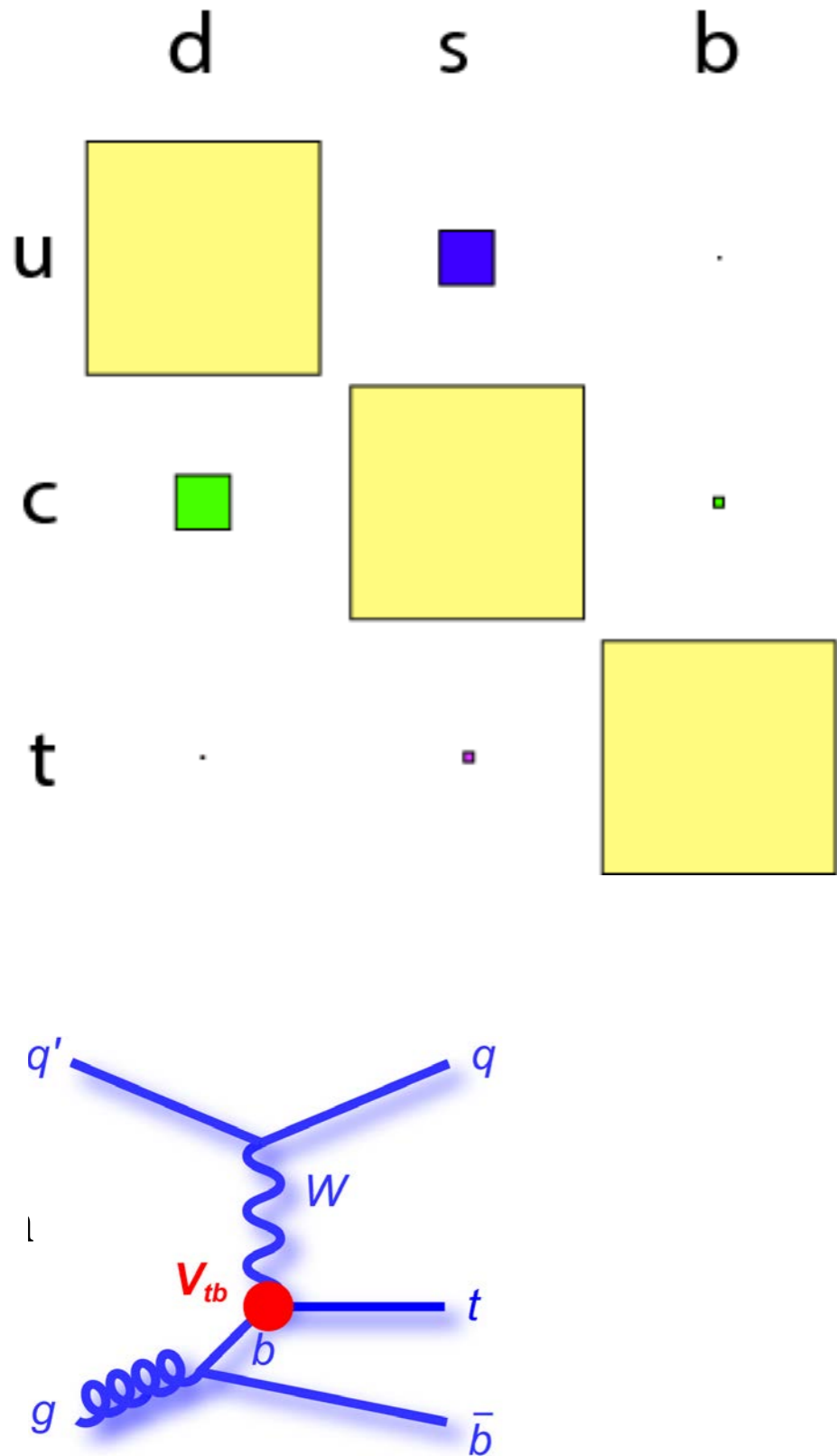
- The cross section is according to the expectation for all channels

# Single Top at the LHC - Measuring CKM Elements



$$V_{\text{CKM}} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$

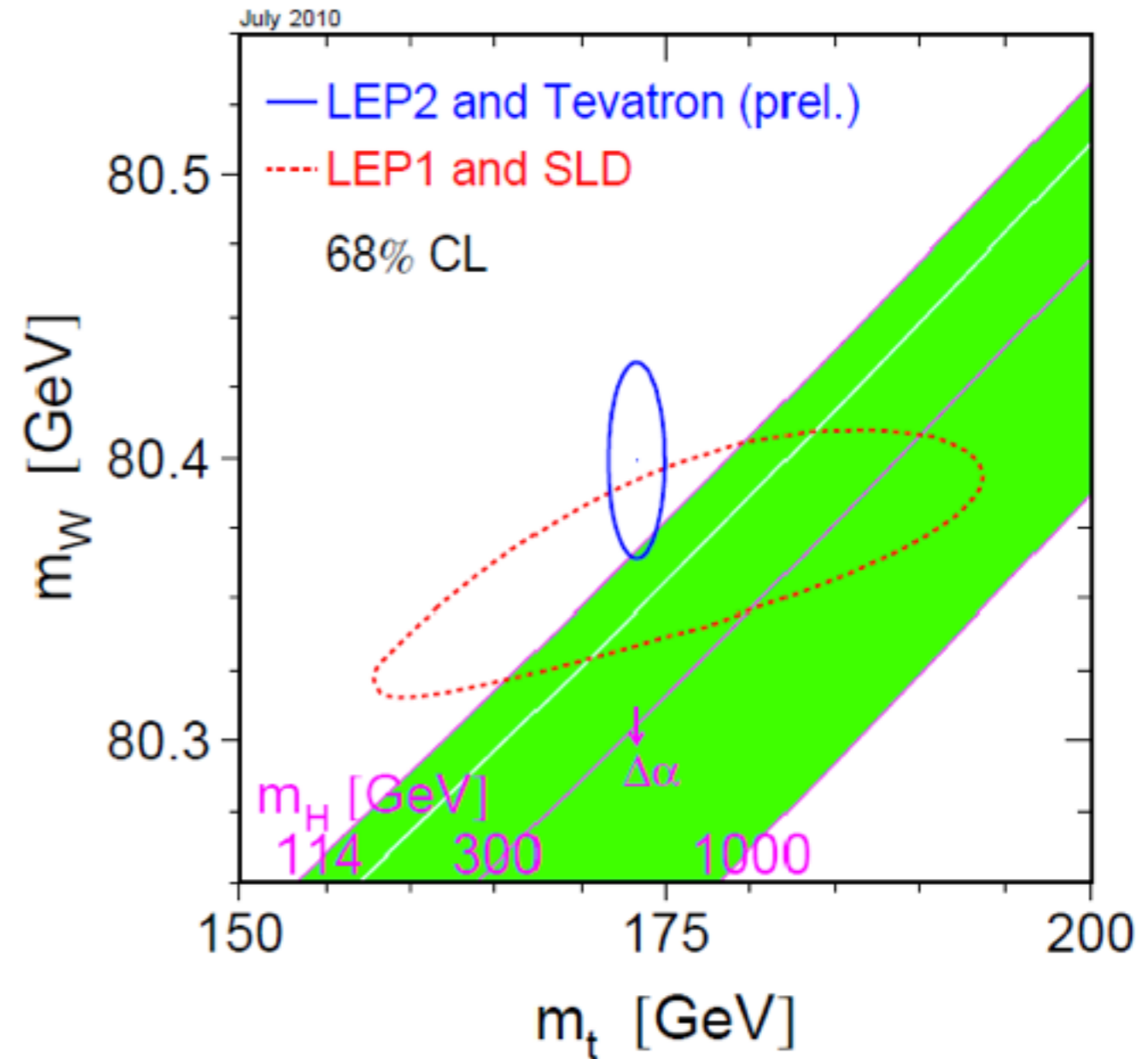
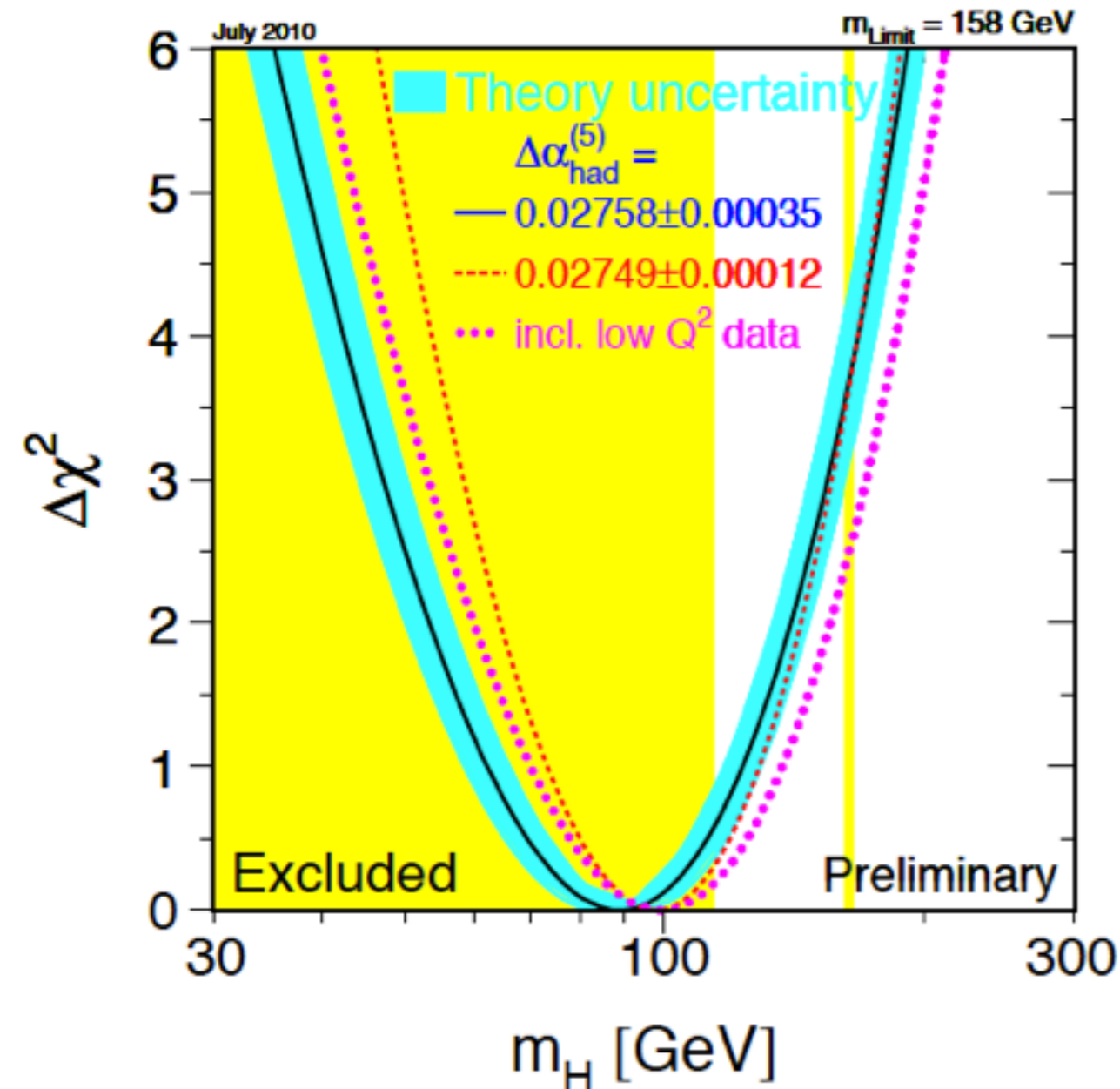
# Single Top at the LHC - Measuring CKM Elements



# Top Quark Properties: Mass

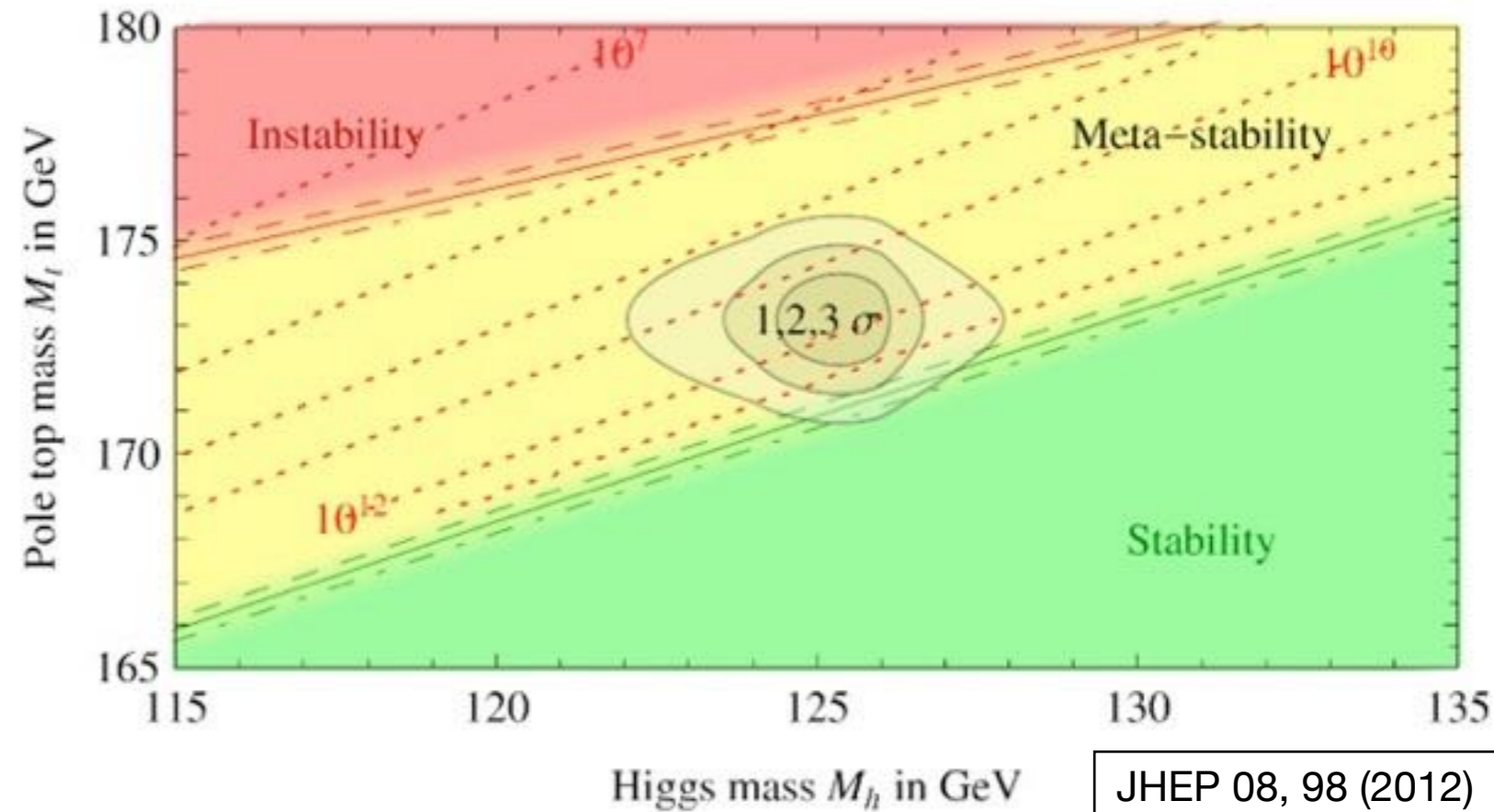
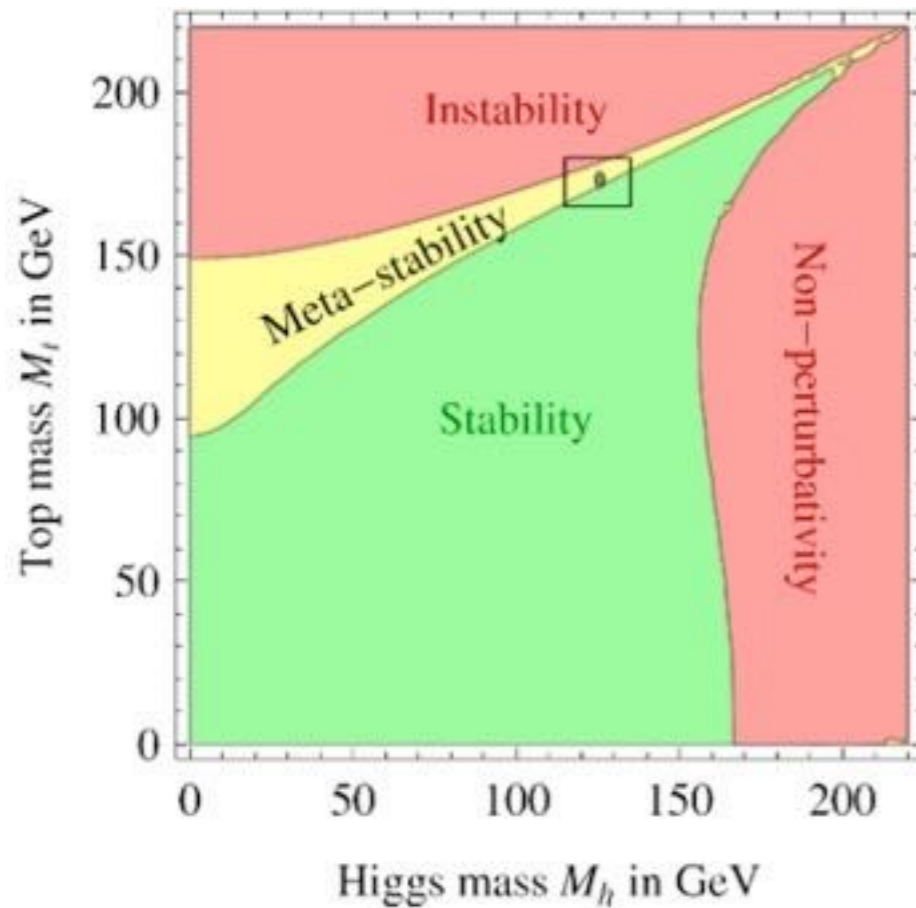


# Reminder: Top Mass in the Standard Model



- Precise determination of the top mass provides information on the Higgs!
- ▶ Already before the discovery in 2012 it was known that the (SM) Higgs has to be light ( $< \sim 160 \text{ GeV}$ )

# The Top Quark and the Fate of the Universe



JHEP 08, 98 (2012)

- Top mass, together with Higgs mass and strong coupling, provides key information on the stability of the SM vacuum at higher scales
  - Possible validity of the SM up to the Planck scale?
  - Impact on evolution of the early universe (Higgs inflation models, ...) & physics beyond the SM

Leading uncertainty: Top Mass!

# Measurement of the Mass: General Issues

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- The mass of the top quark is an important parameter of the standard model - and as such very interesting

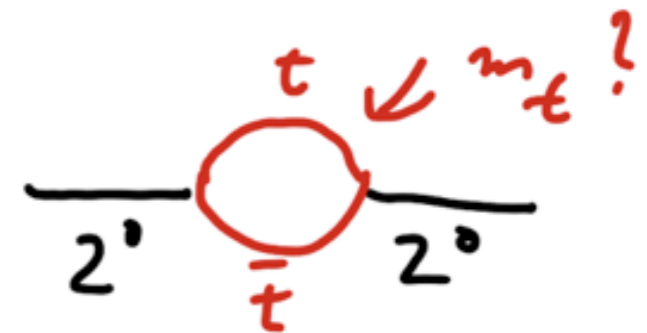
The problem: What is a quark mass? - Here the “standard” definitions of theorists and experimentalists are not the same

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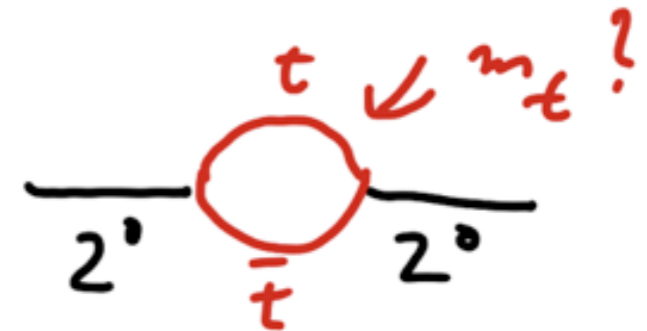


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Defining the mass of the top is not trivial - it is influenced by QCD corrections at higher orders

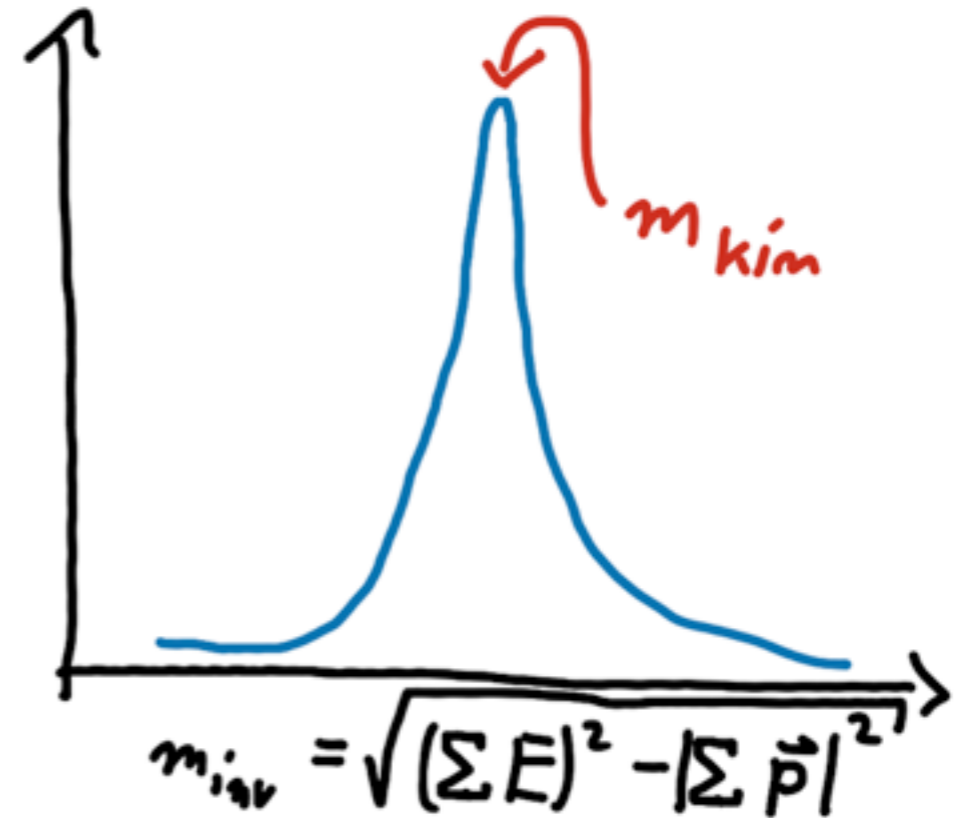
$$\begin{array}{c} t \\ \longrightarrow \\ m_t^{\text{pole}} \end{array} + \begin{array}{c} \text{Σ}_i \\ \text{---} \\ \delta m_t \end{array} + \dots$$

Several definitions exist in theory, depending on the need of the calculations - They can typically be converted with high precision with higher order calculations - Uncertainties on the **100 MeV** level

# Measurement of the Mass: General Issues

For **experiment**:

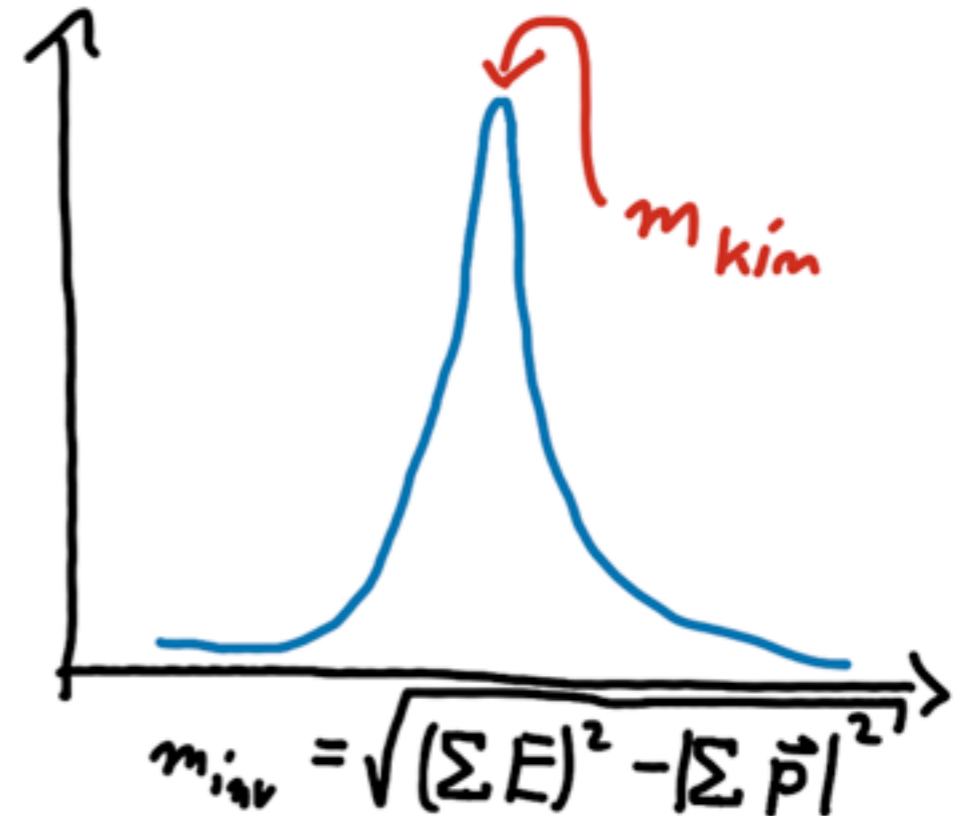
The standard technique to measure a mass is to reconstruct the “invariant mass” of the decay products



# Measurement of the Mass: General Issues

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The challenge: The connection between the experimentally measured “kinetic mass” and the theoretical definitions is unclear - non-perturbative corrections from the strong interaction

Uncertainties on the **GeV** level - comparable to experimental precision of current experiments, will become critical for future top mass measurements!

# Measurement of the Top Mass at LHC

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# Measurement of the Top Mass at LHC

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Di-Lepton, Lepton+Jets, All Hadronic

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- Different methods are used - (almost) all based on kinematic reconstruction:
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  - Matrix-Element-Method: For each event, a probability distribution of the true top mass is calculated based on the reconstructed final state object, probability based on LO matrix elements
    - Combination with Templates: Ideogram - Method
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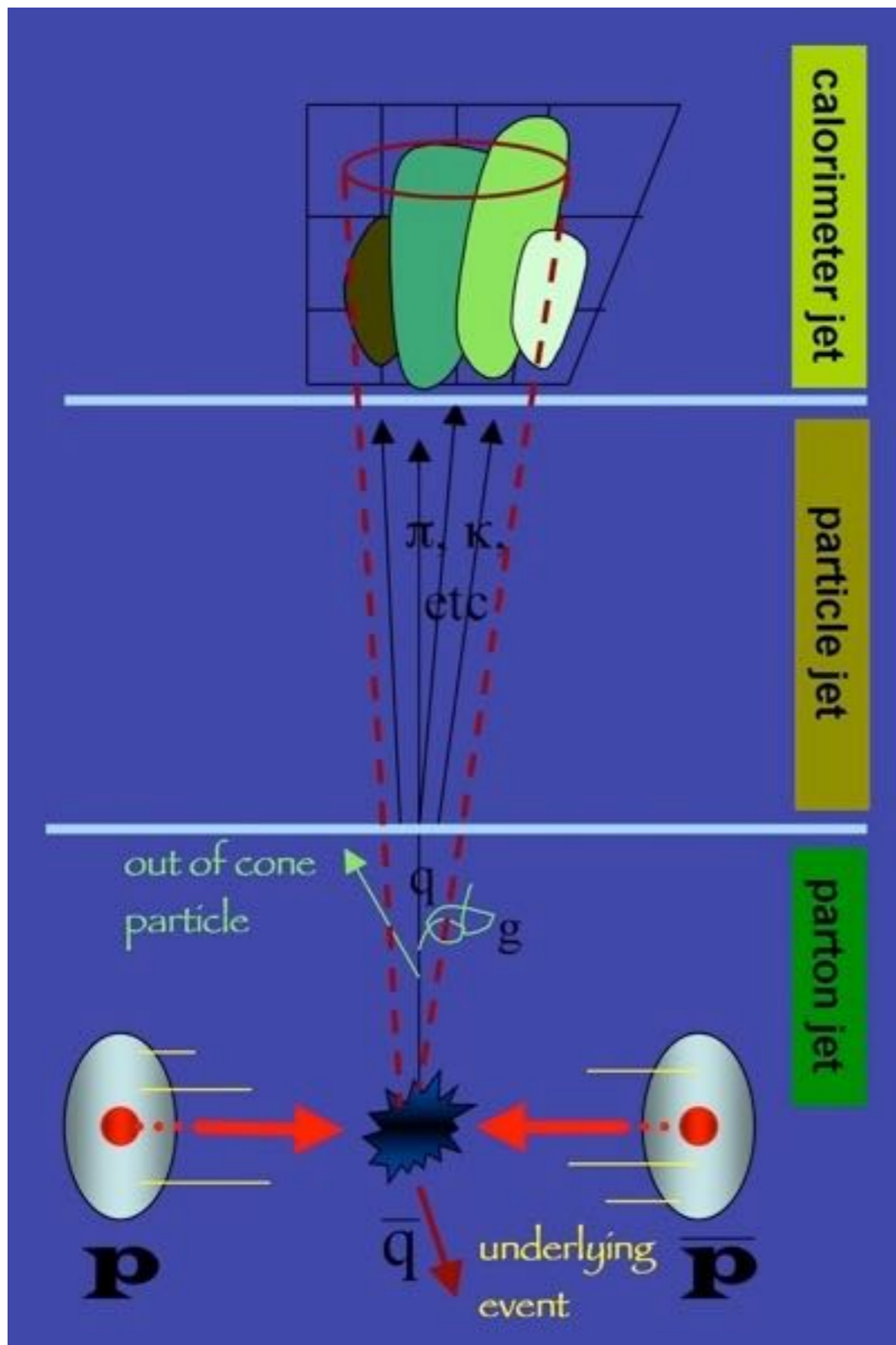


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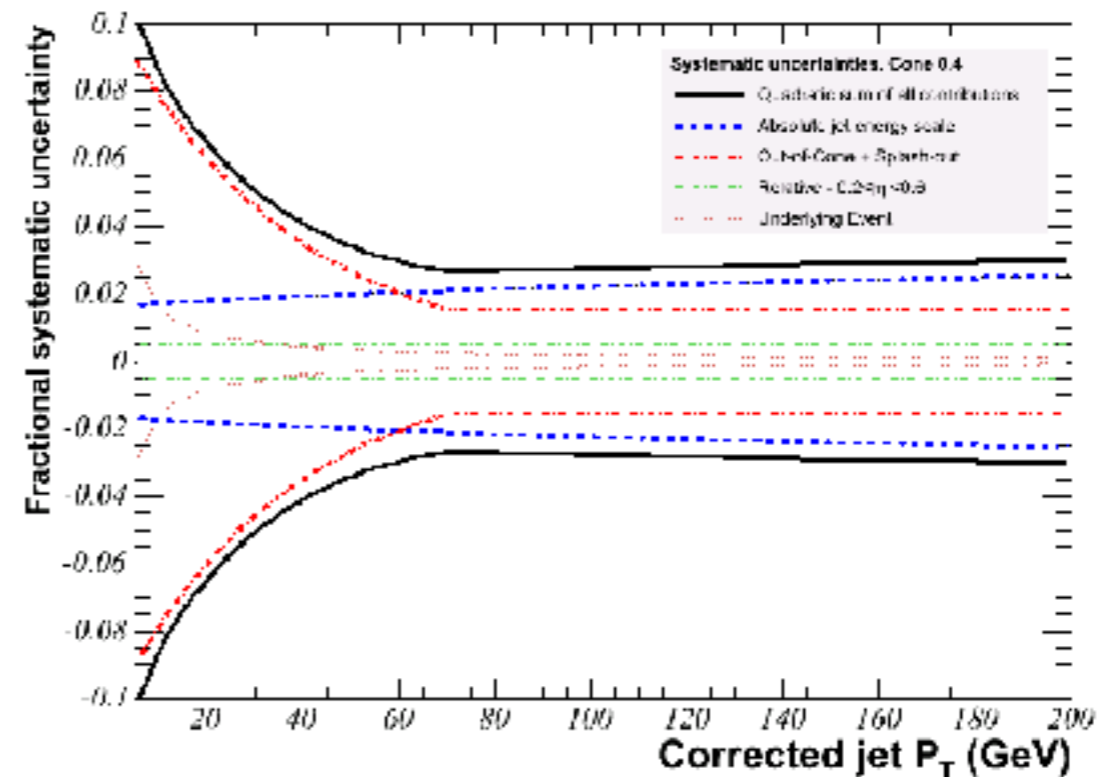
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- ▶ Best accuracy achieved by multi-dimensional fits to reduce systematics
- Most measurements are already limited by systematic uncertainties
  - Important contribution: Jet Energy Scale

# Jet Energy Scale JES



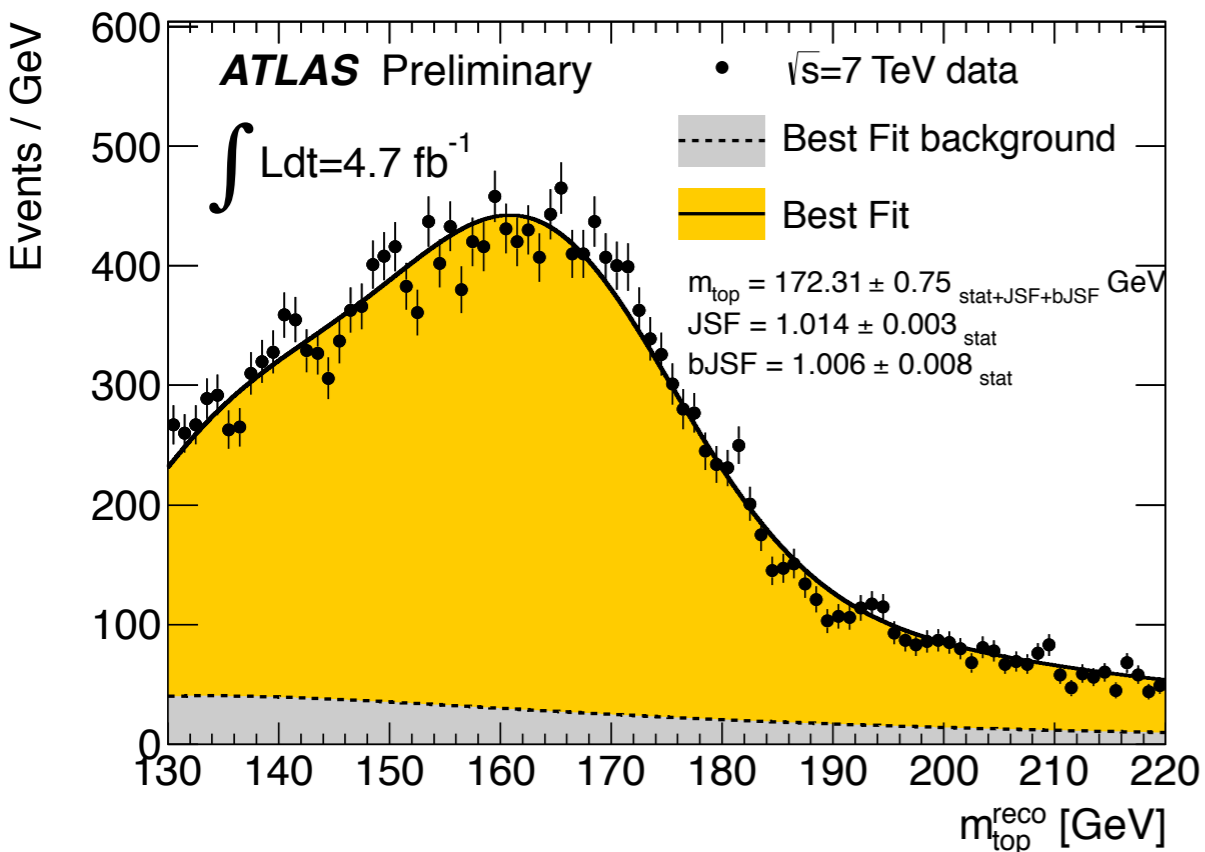
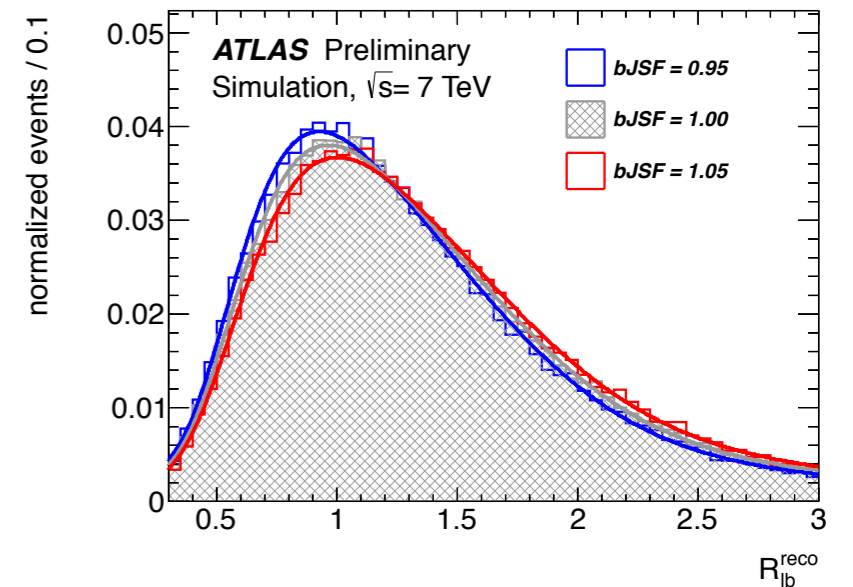
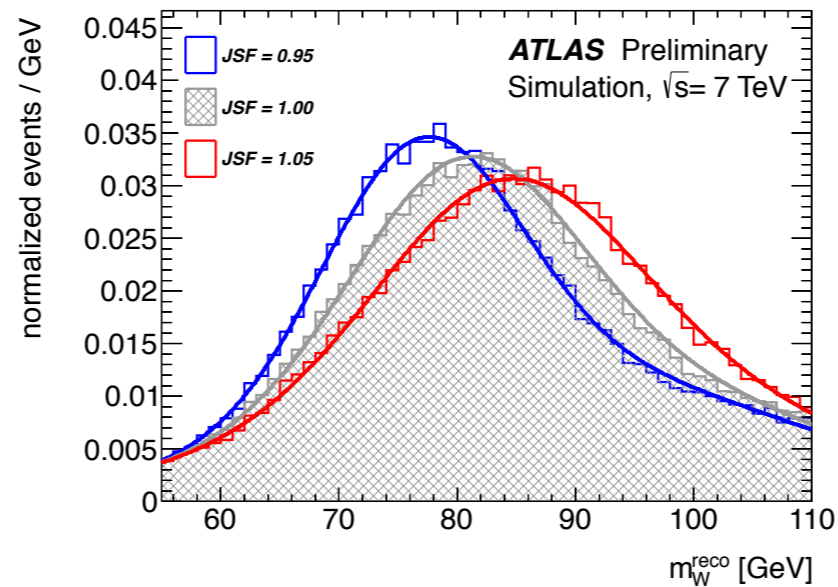
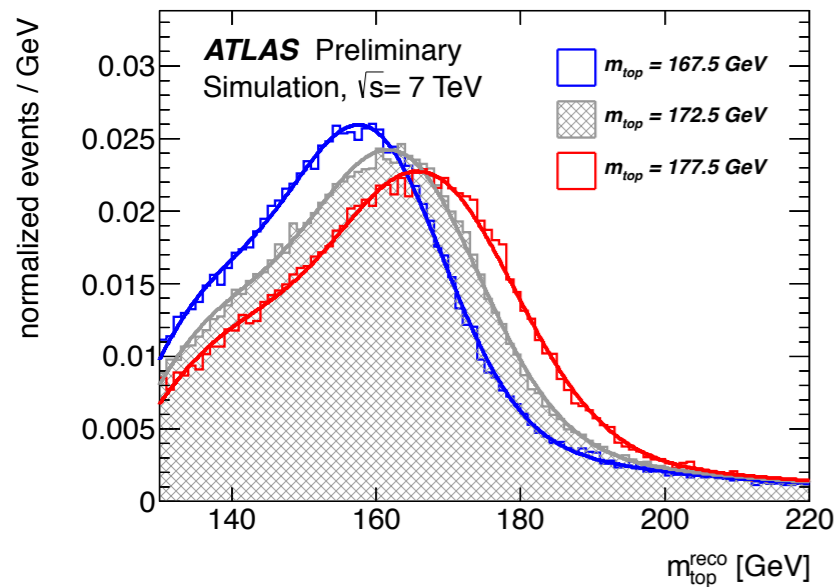
- The measurement of a jet:
  - Energy in a cone with a certain radius (various definitions in use) typically in the calorimeters (more sophisticated approaches also use tracks)
- The physics observable:
  - Energy of the original parton
- ▶ The energy scale corrects from the measured jet energy to the energy of the parton
- ▶ Uncertainties from energy calibration, jet structure, ...



CDF

# One Example: Lepton + Jets in ATLAS

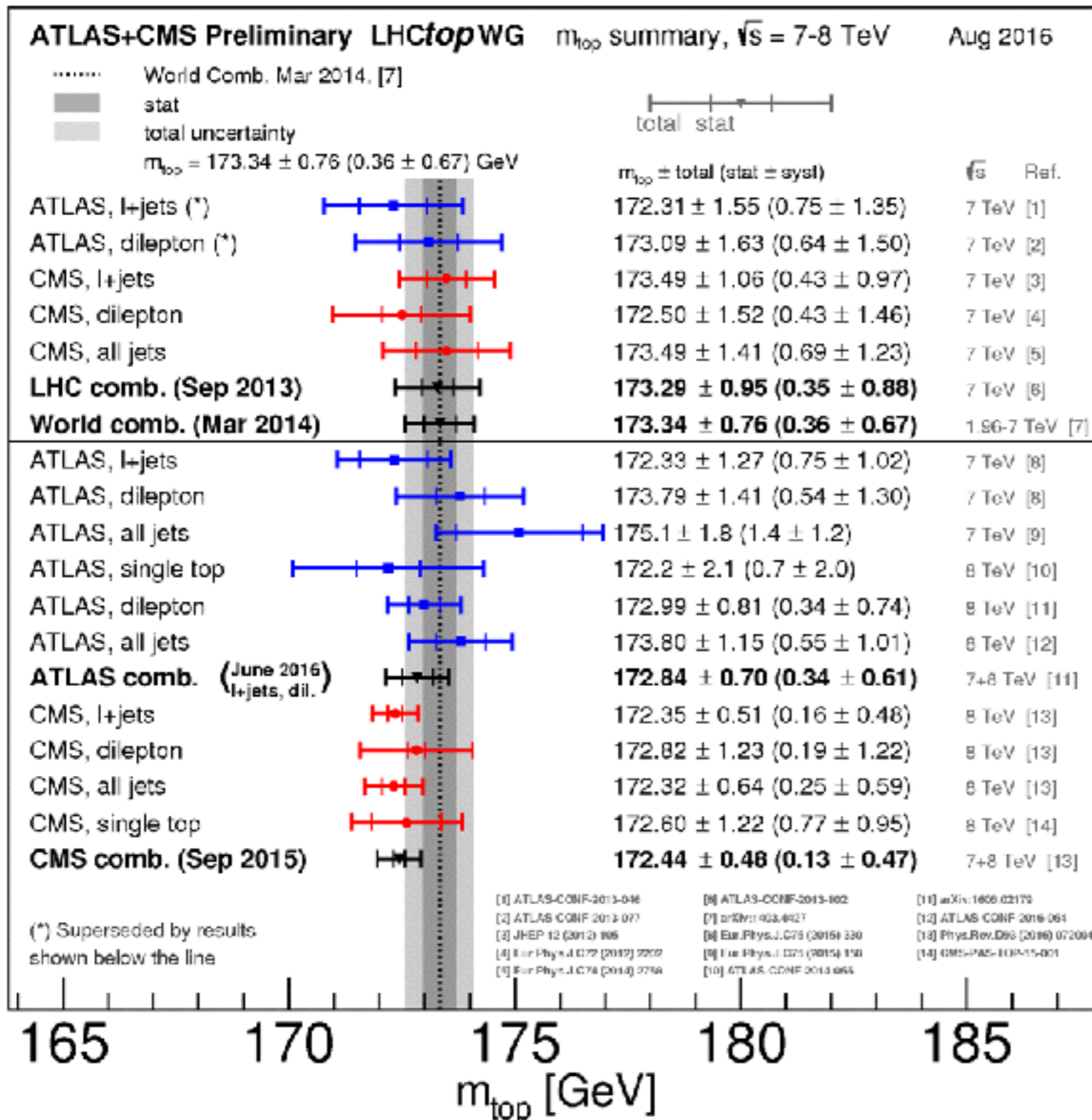
- 3D Template fit to extract mass, JES and specific b-Jet energy scale



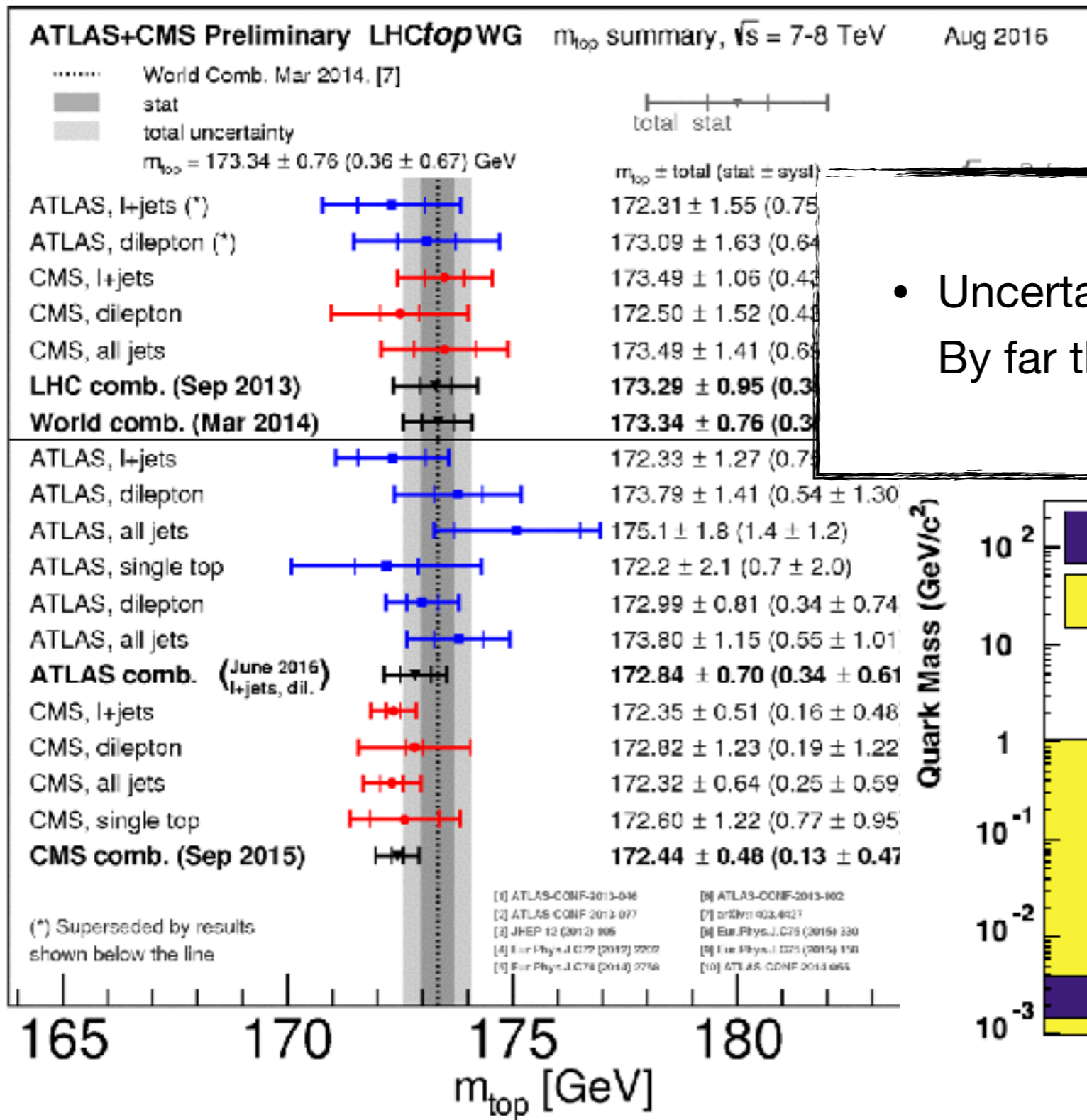
3D fitting substantially reduces systematics (-40% compared to previous technique!)

$$m_{top} = 172.31 \pm 0.23(\text{stat}) \pm 0.27(\text{JSF}) \pm 0.67(\text{bJSF}) \pm 1.35(\text{syst}) \text{ GeV}$$

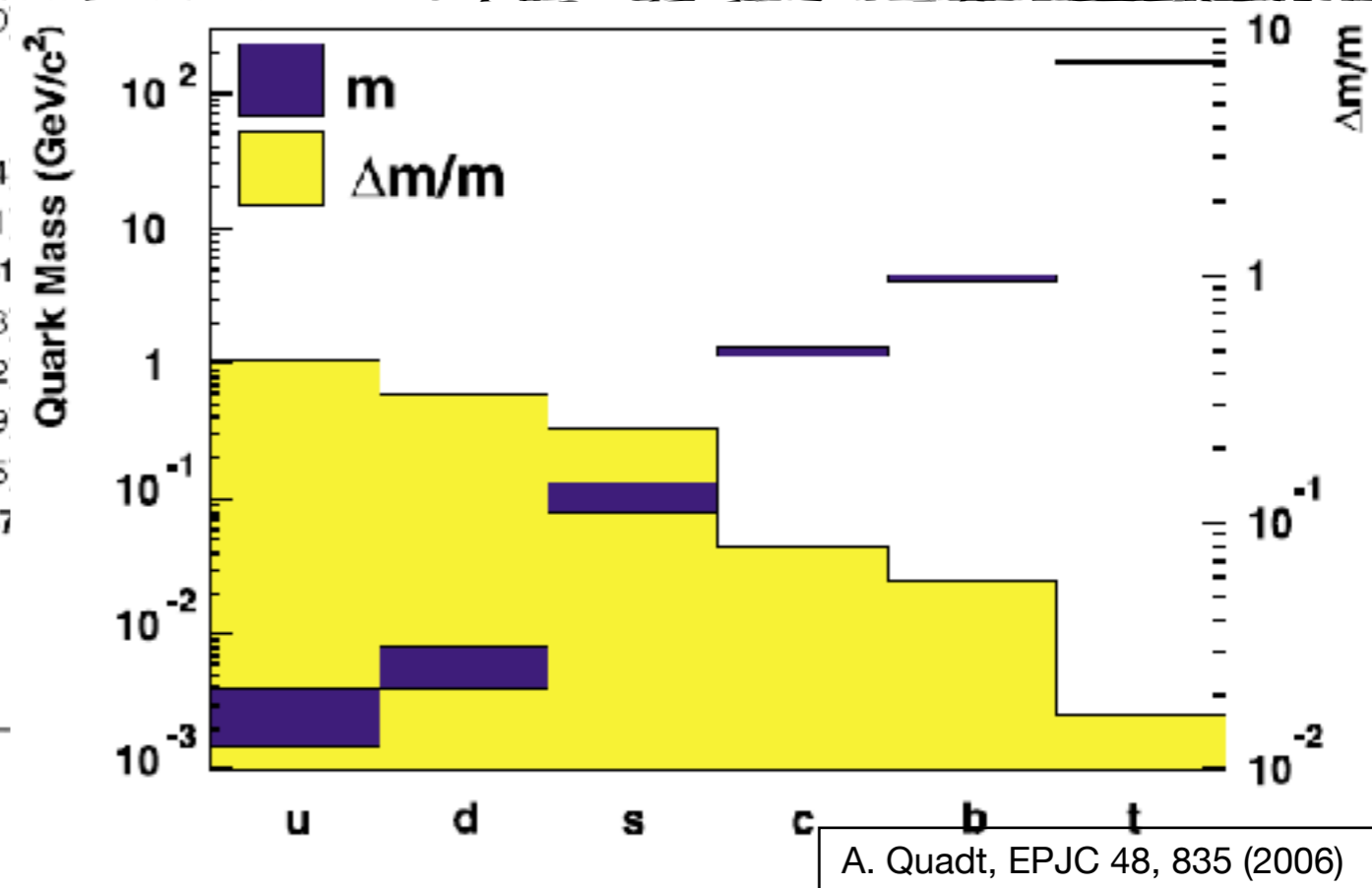
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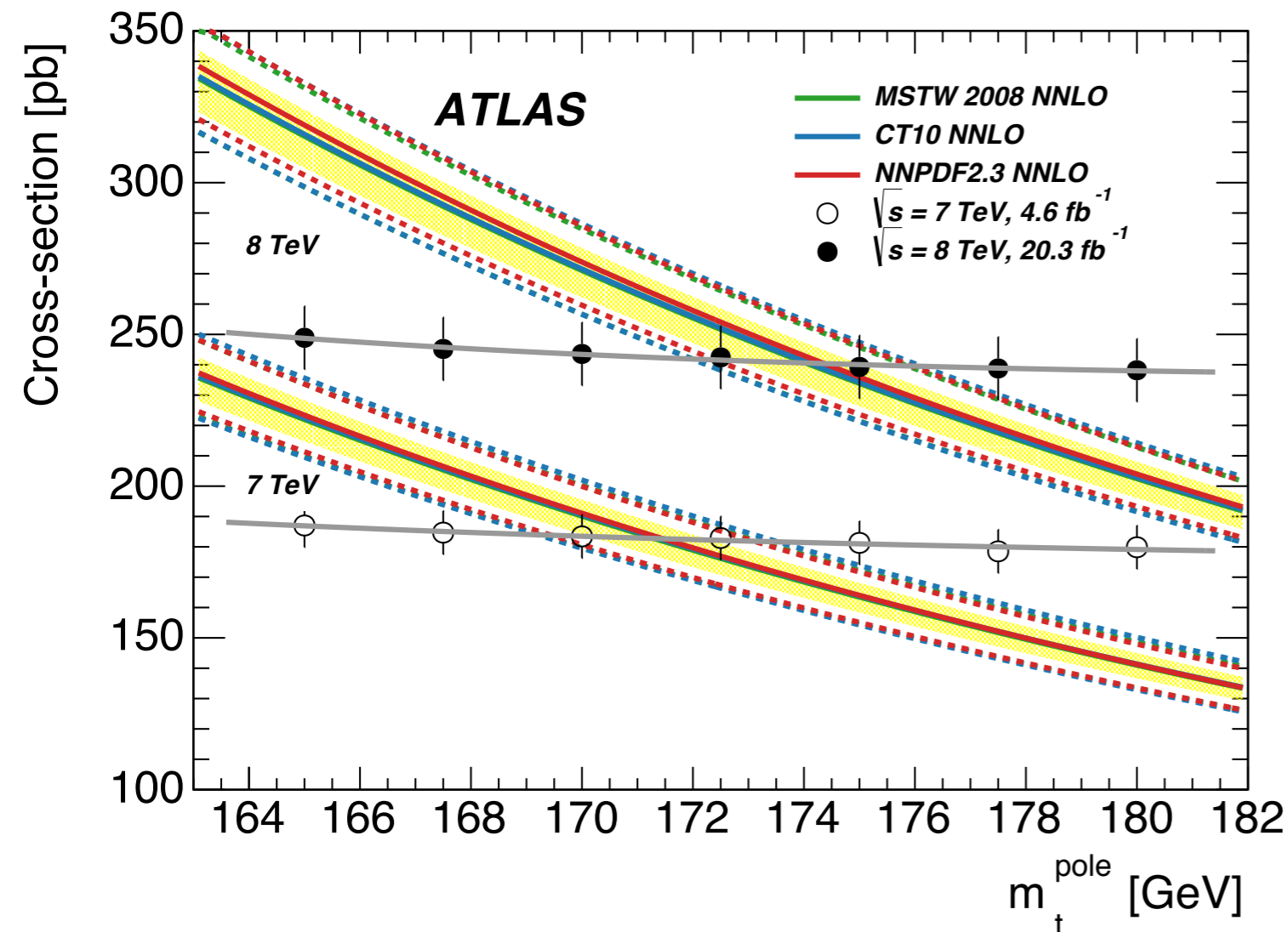


- Uncertainty on the top quark mass < 1%:  
By far the best-known quark mass!



# Connection to Theory

- First attempts to measure theoretically well understood mass parameters:  
Pole mass via the  $t\bar{t}$  cross section



Large Uncertainties:  
Additional uncertainties from pdf  
uncertainties

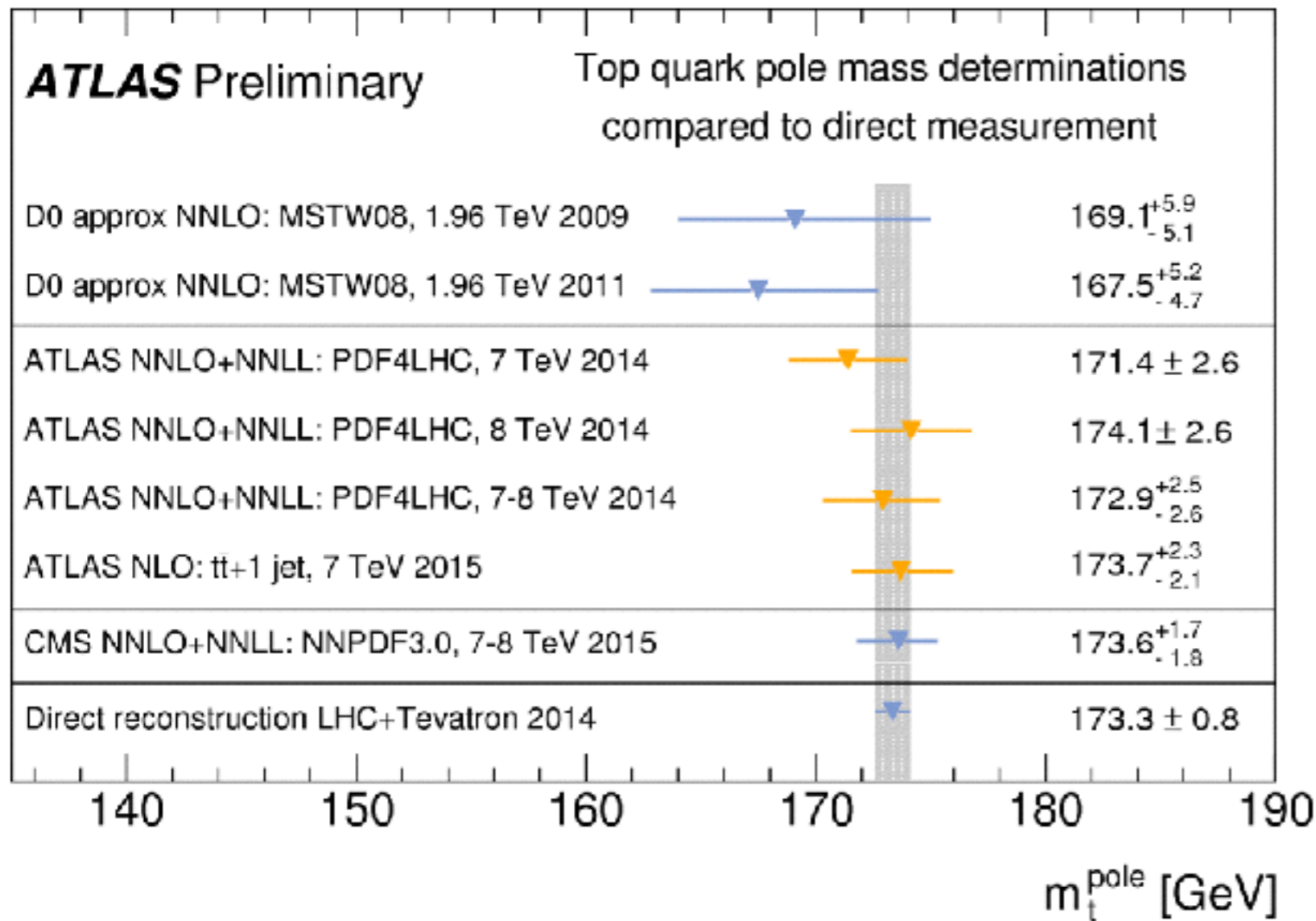
Results:

CMS:  $m^{\text{pole}} = 173.6^{+1.7}_{-1.8} \text{ GeV}$

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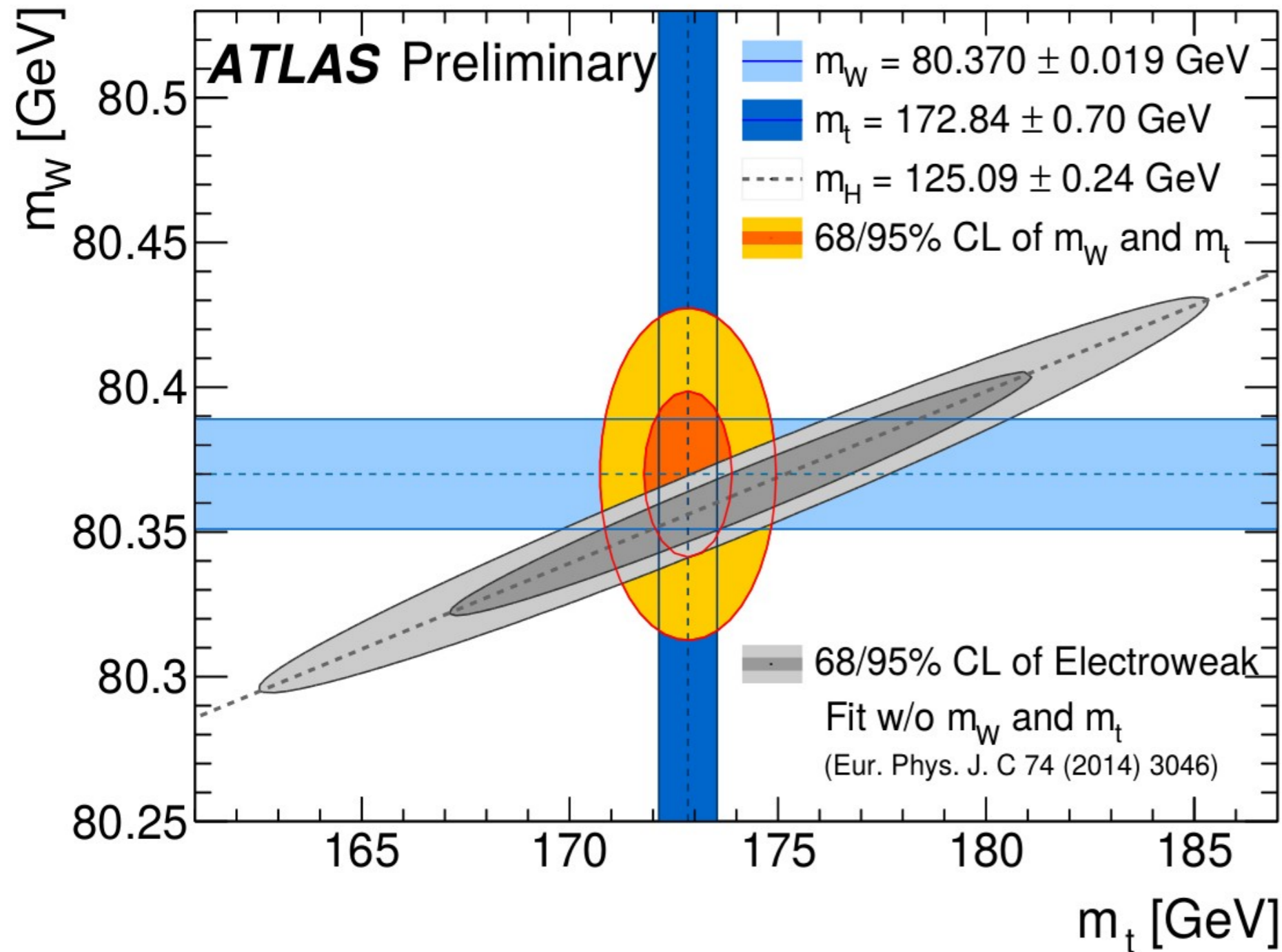
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Important contributions to the understanding of the connection between theory and experiment - will never be competitive in total uncertainty at the LHC

# SM Closure Test: Now Possible with LHC alone



- Using ATLAS results in an electroweak fit:
  - Top mass
  - Higgs mass
  - W mass (result just 6 days old)



# Summary

---

- The Top quark was discovered in 1995, 20 years after the discovery of the b quark
- As the heaviest fermion (and the heaviest particle) in the Standard Model it takes a special role :
  - Provides sensitivity to the Higgs mass and (possibly) to physics beyond the SM
  - Short life time: decays as a free quark
- New Results from LHC: Cross section 20 x - 100 x larger than at Tevatron
  - ⇒ “Top-Factory”:  
Already now the mass measurements from LHC are competitive (~ 3 years at LHC vs 16 years at Tevatron) - and much more is to come:
    - Higher precision on properties
    - Direct measurement of the coupling to the Higgs
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Next Lecture: Higgs I, S. Bethke 09.01.2017



# Schedule

1.	Introduction	17.10.
2.	Accelerators	24.10.
	<b>----- no lecture -----</b>	<b>31.10.</b>
3.	Particle Detectors I	07.11.
4.	Particle Detectors II	14.11.
5.	Trigger, Data Acquisition, Computing	21.11.
6.	Monte Carlo Generators and Detector Simulation	28.11.
7.	QCD, Jets, Proton Structure	05.12.
8.	Tests of the Standard Model	12.12.
9.	Top Physics	19.12.
	<b>----- Christmas -----</b>	
10.	Higgs Physics I	09.01.
11.	Higgs Physics II	16.01.
12.	Physics beyond the SM	23.01.
13.	LHC Outlook & Future Collider Projects	30.01.
	<b>----- no lecture -----</b>	<b>06.02.</b>

