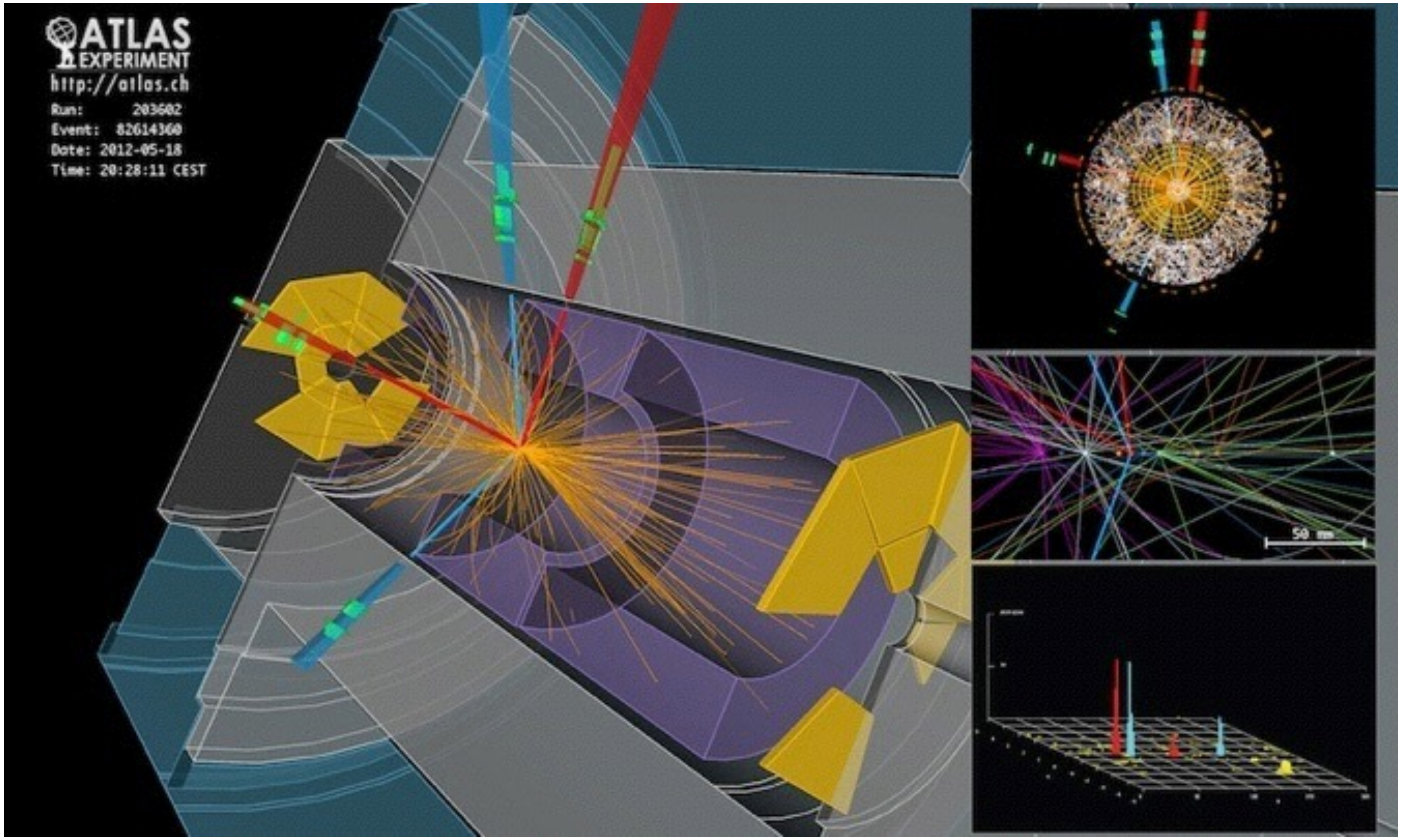
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



11. Top Physics

18.01.2016

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Dr. Frank Simon

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Important: Registration for Exams

The time & date for the exam is flexible
(the one given in TUMOnline is a dummy date) - Directly ask me after the lecture or send me an email to fix one!

Possibility to participate in E18 CERN Excursion

CERN Exkursion 2016

- Zeitraum: Mittwoch 9. März, 7 Uhr bis Freitag 11. März, 22 Uhr
- Kosten: nur Verpflegung
  Reise und Unterbringung werden von der TUM übernommen
- Teilnehmer: max. 50 Plätze (Losverfahren, evtl. Warteliste)
- Anmeldung, Kontakt und weitere Information unter:
  http://www.universe-cluster.de/CERN-Exkursion-2016
- Anmeldeschluss: 15. Februar 2016

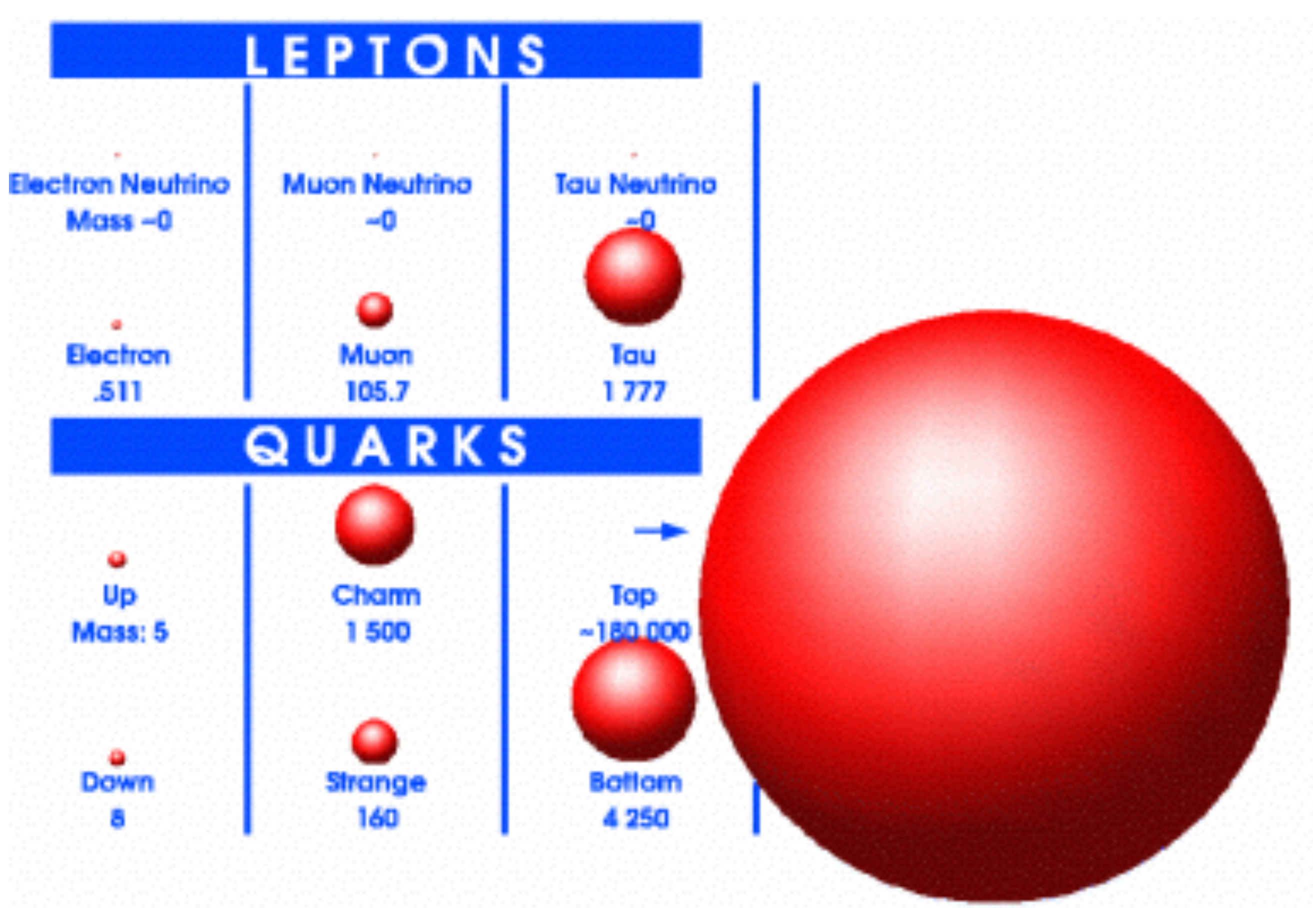
Overview

- 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

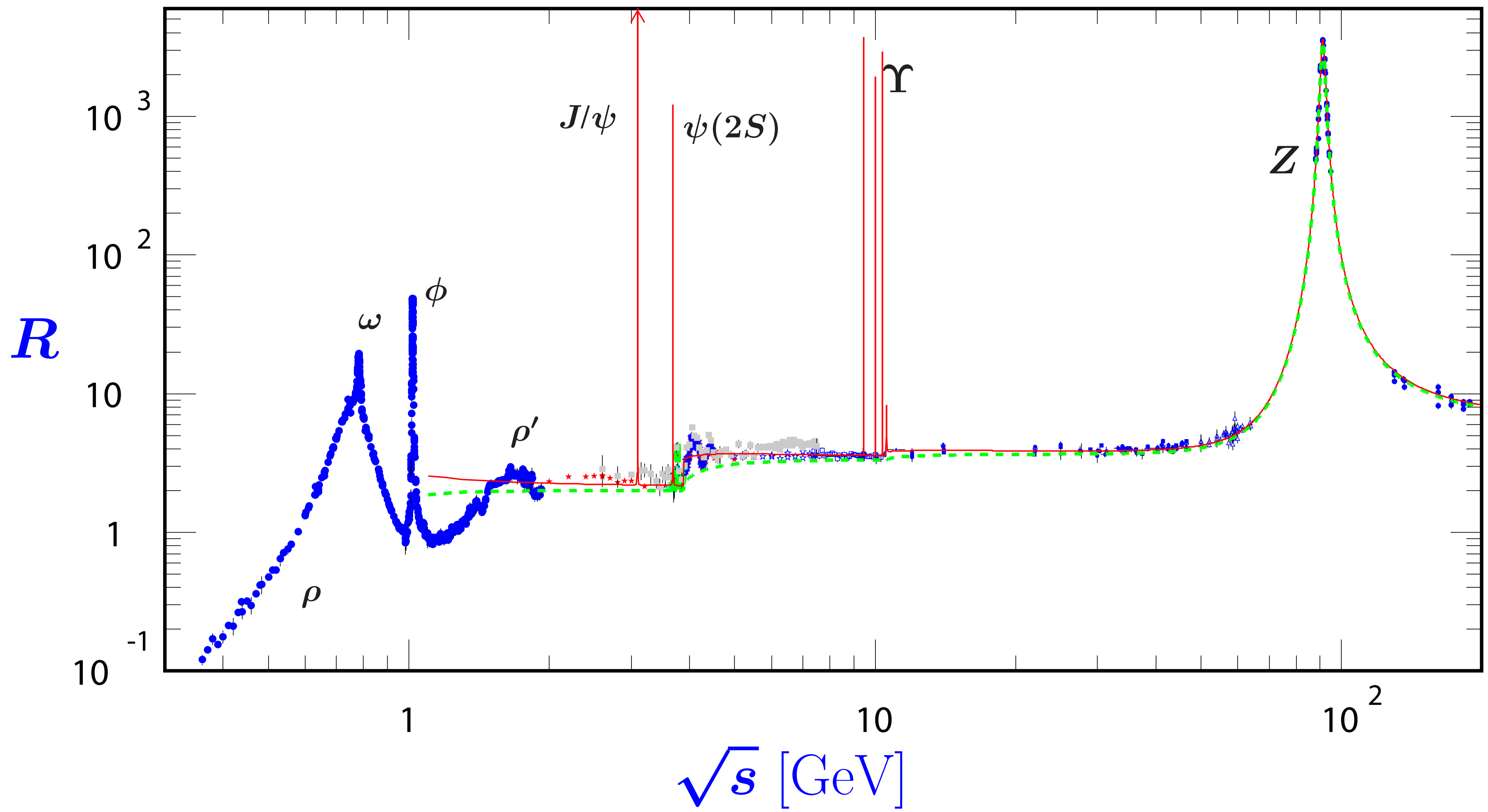
- The Top quark has a special role in the Standard Model
  - It is the heaviest particle, and by far the heaviest Fermion
  - Its mass is comparable to the electroweak scale - The top quark could be a window to new physics!
  - Its life time is shorter than the hadronization time - it does not form bound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



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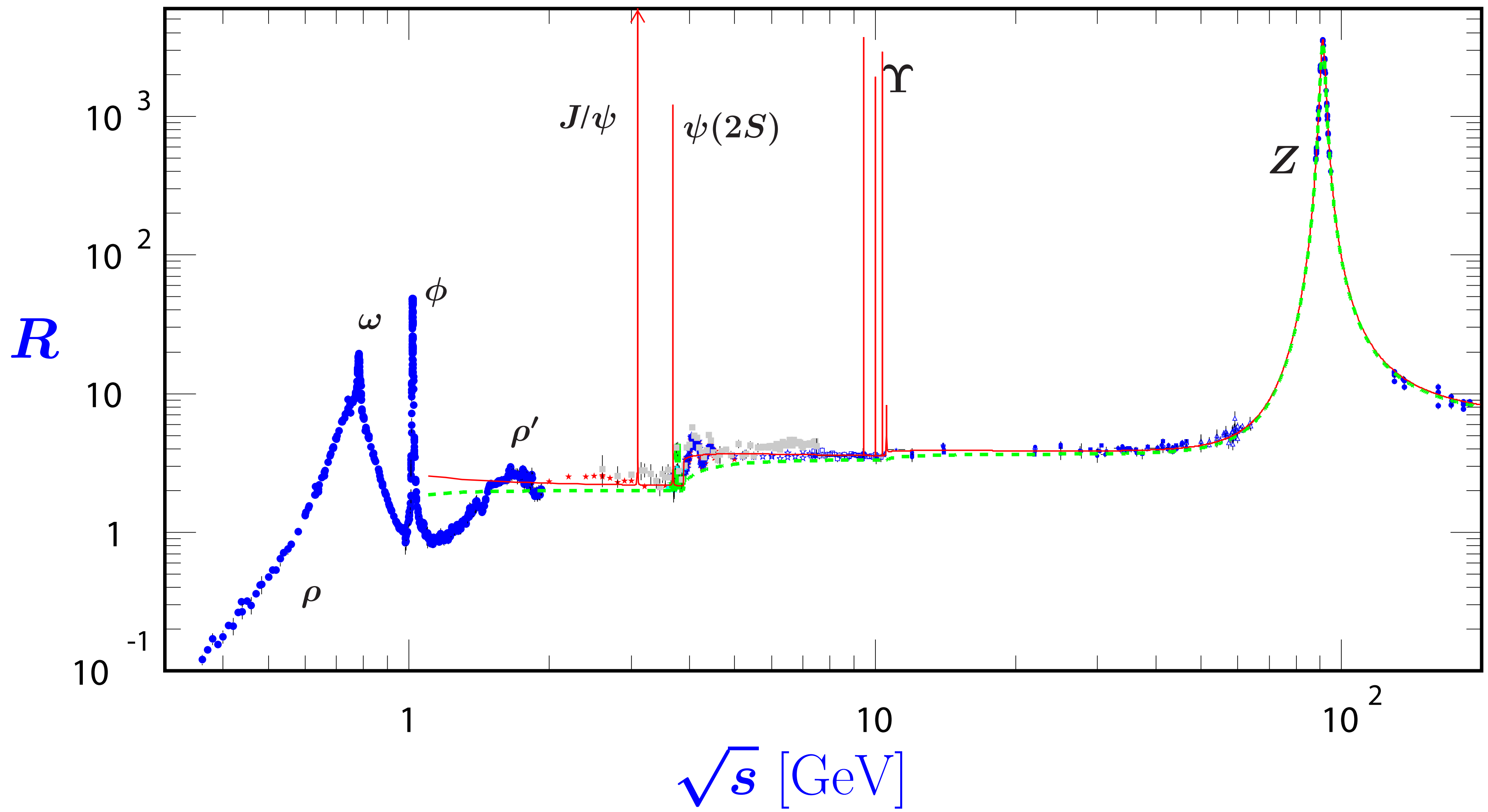
  - Renormalizability of the SM requires equal number of lepton and quark families



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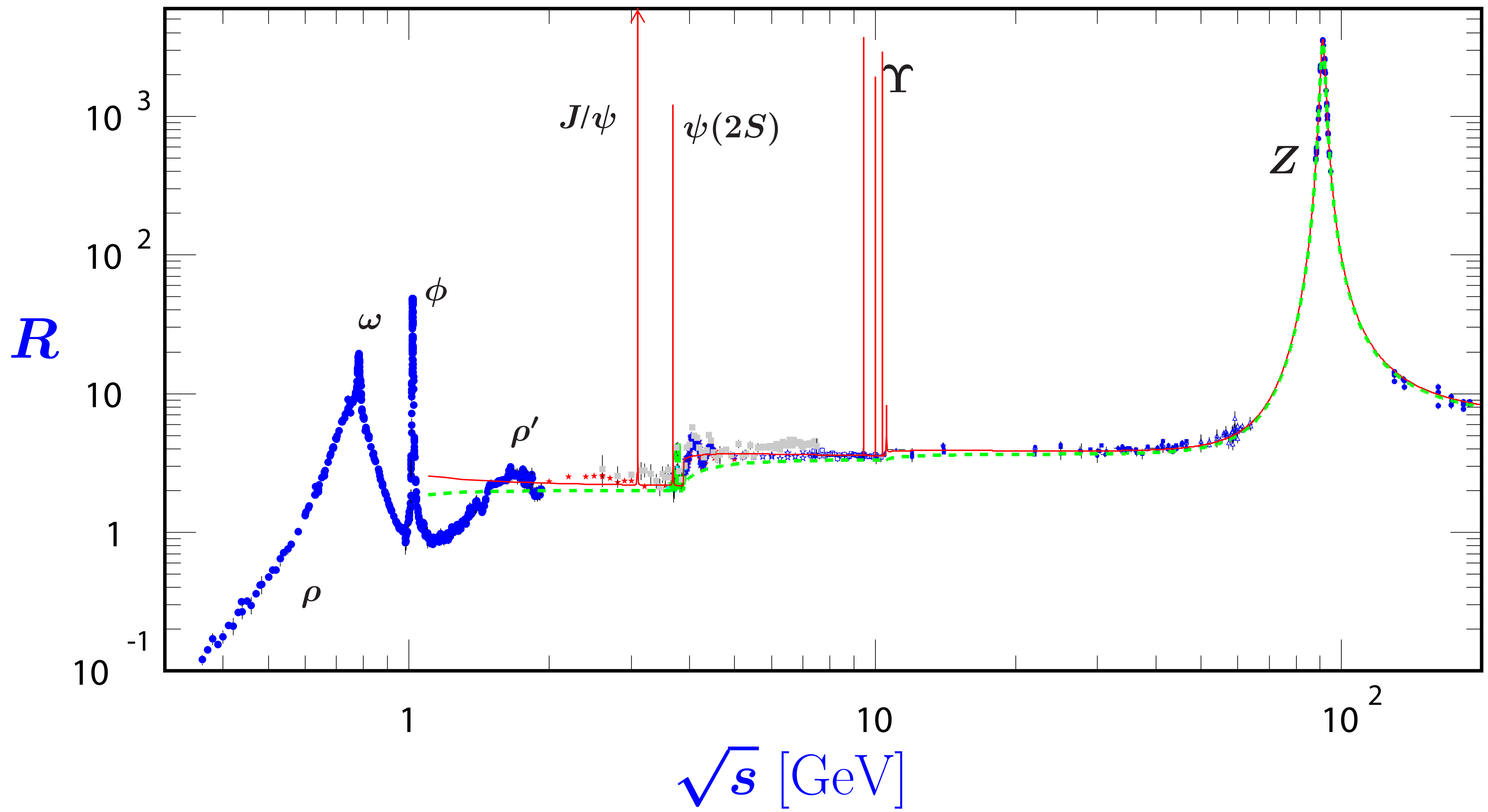

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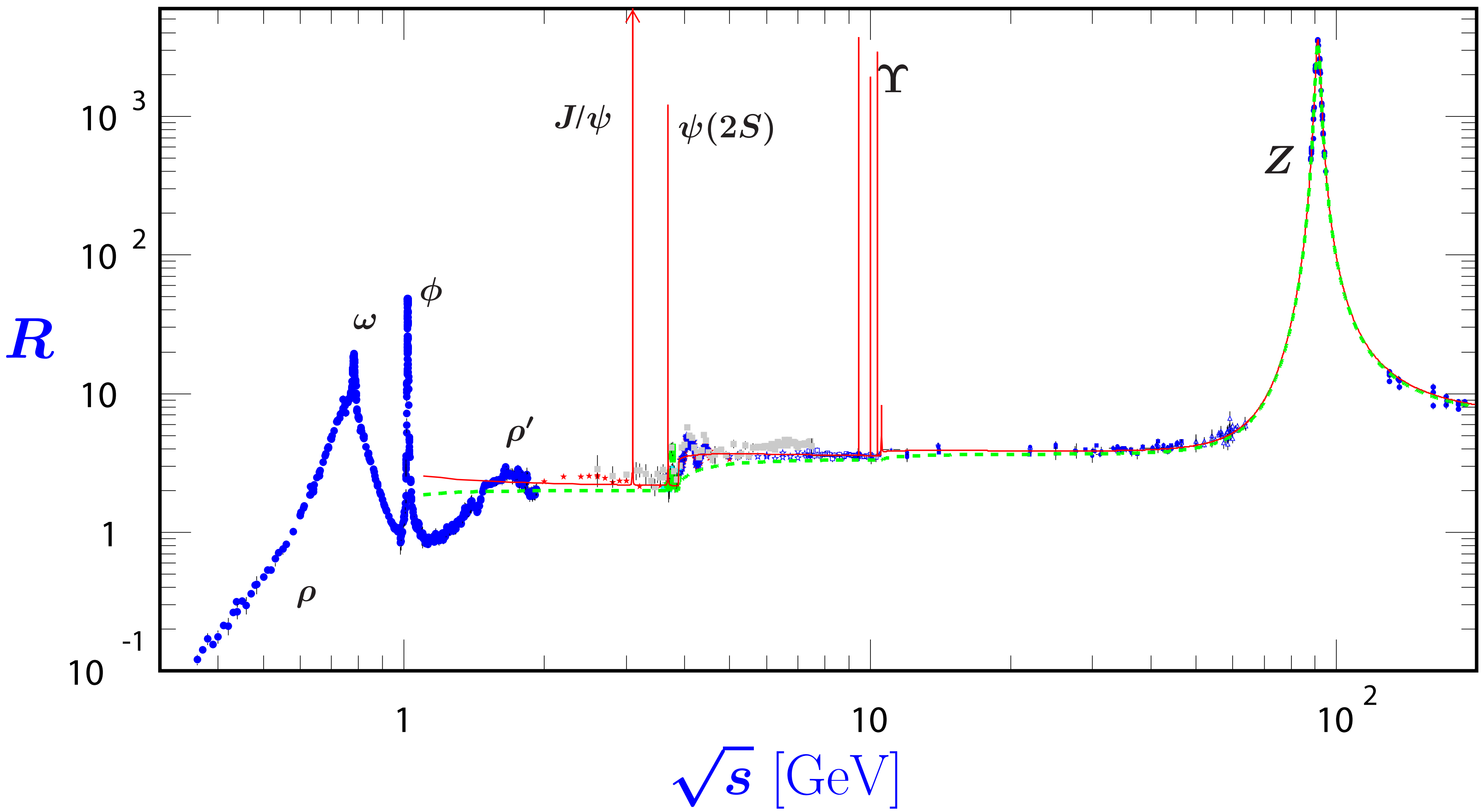
- The precise measurement of the cross-section in e^+e^- - Kollisionen above the b threshold gives the charge of the b: -1/3 => The top has to be + 2/3



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 07):

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

with

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

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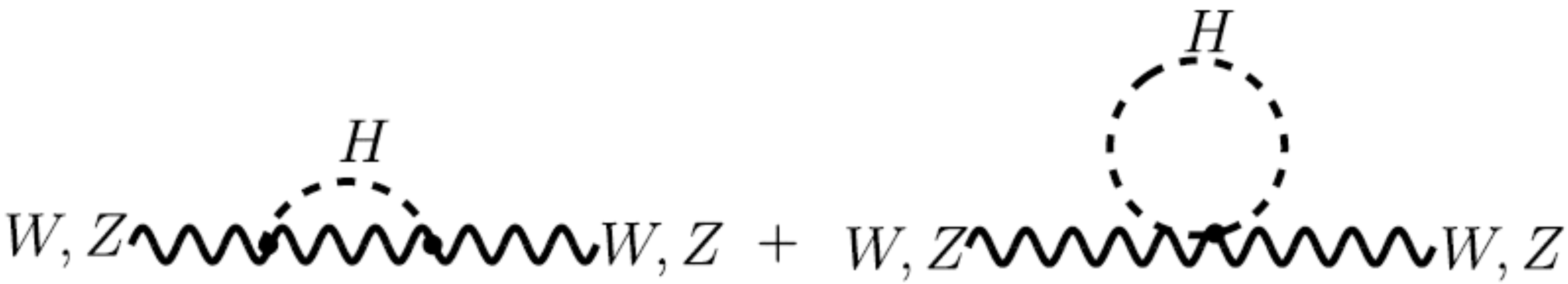
The influence of single top loops:

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

Connections to the Higgs Mass

- Loop corrections also depend on the Higgs:



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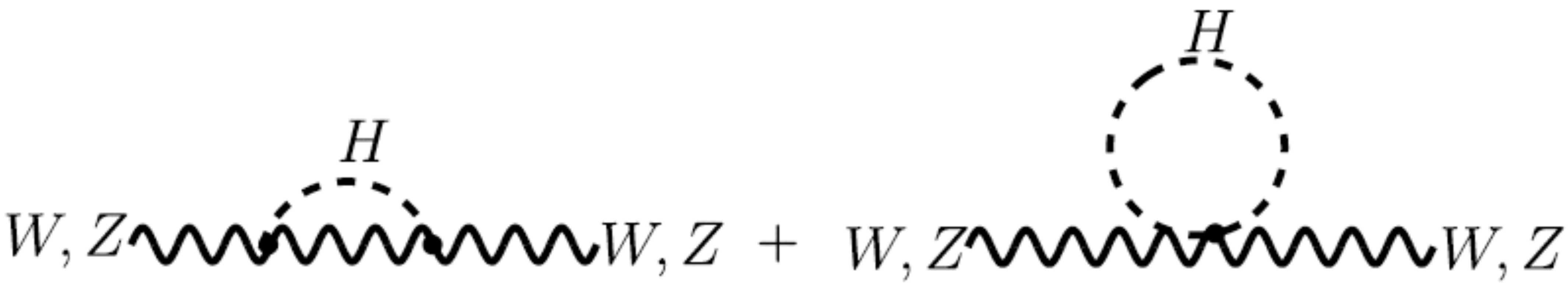

- analogous to the corrections induced by the top there are also corrections originating from the Higgs

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

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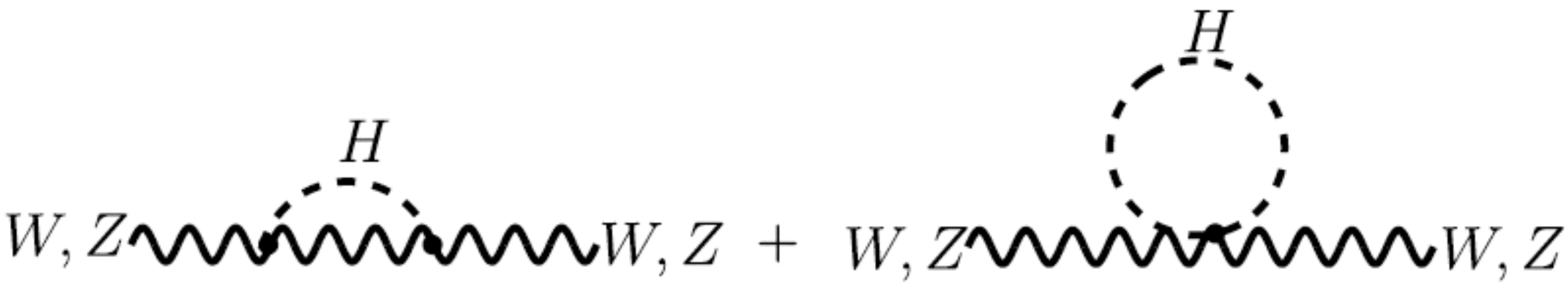

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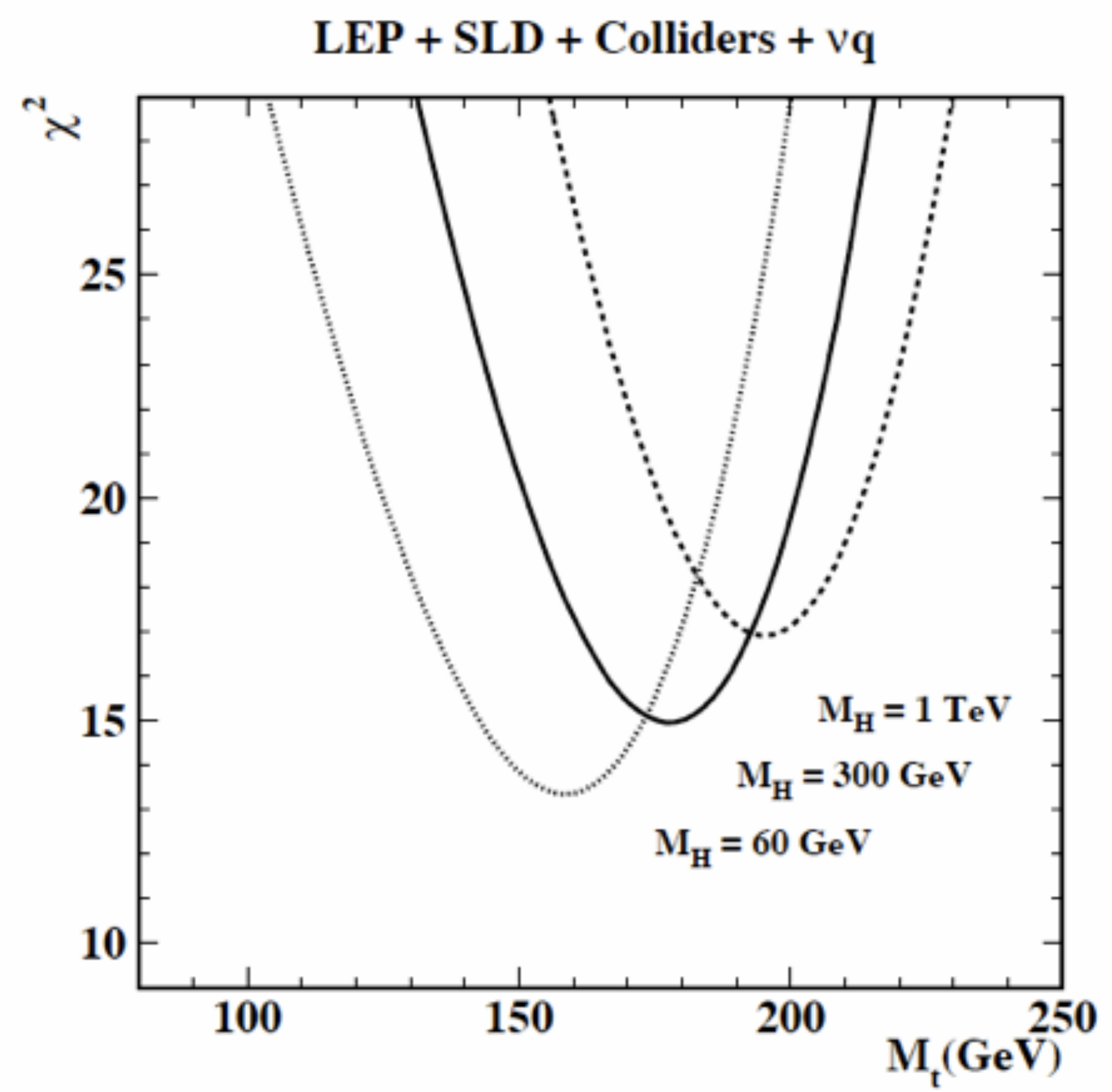
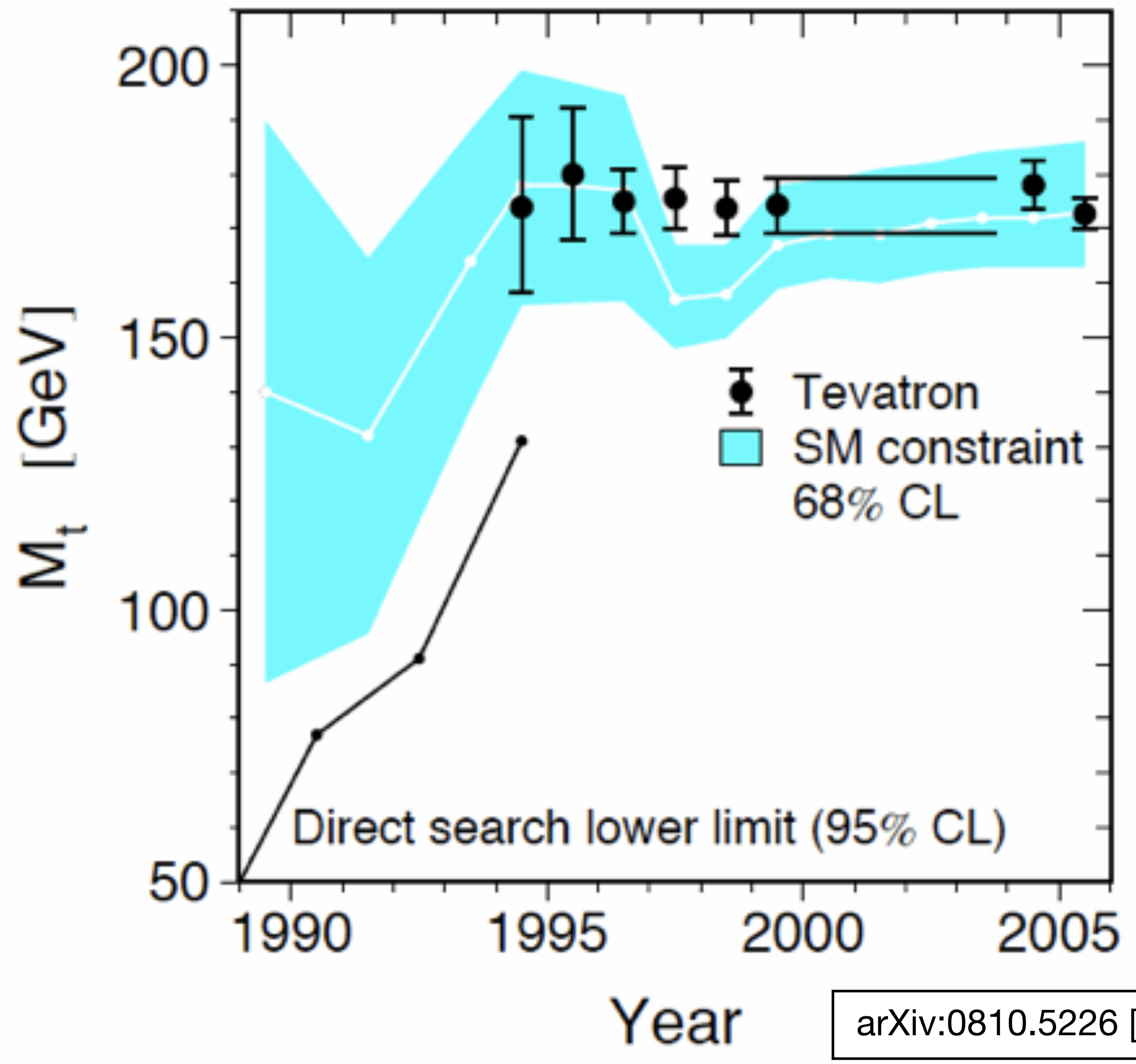
▸ With a precise knowledge of the top mass the Higgs mass can be constrained

- But: only logarithmic dependence on m_H (quadratic in m_T)

Predicting the Top Quark Mass

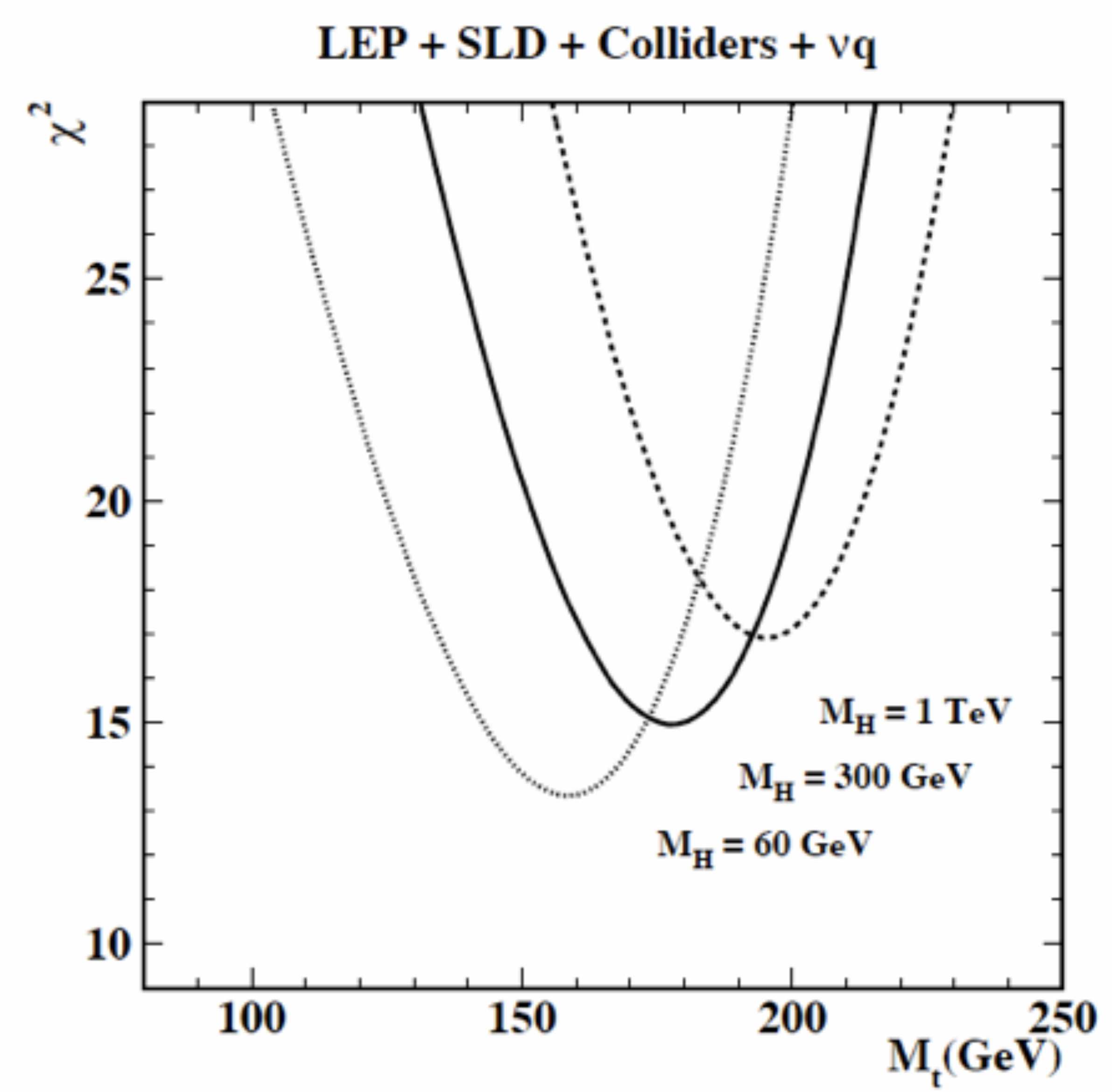


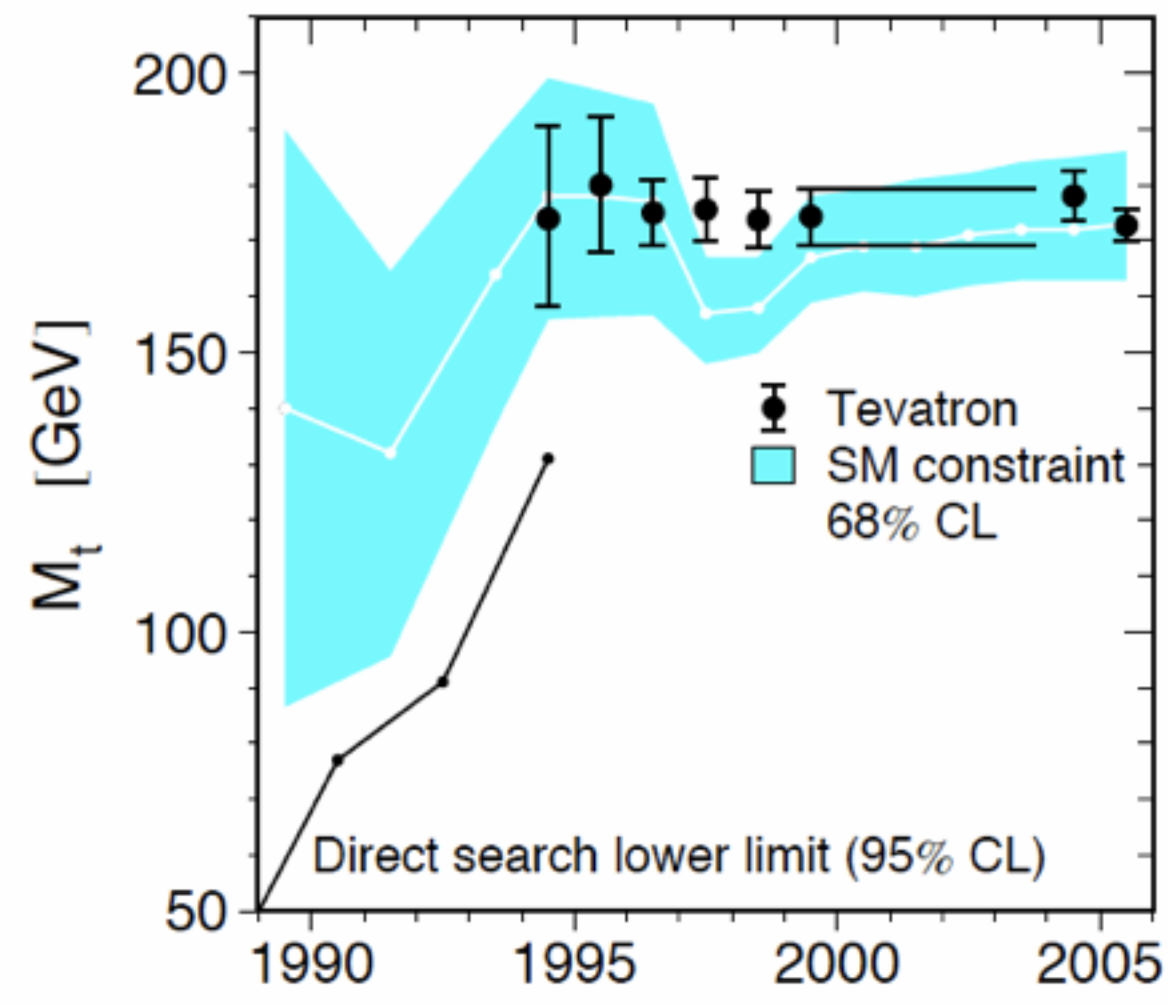


arXiv:0810.5226 [hep-ex]

- Improvement of electroweak precision measurements led to a constant improvement of the prediction of the top quark mass -> early on it was clear the top is heavy!

Predicting the Top Quark Mass





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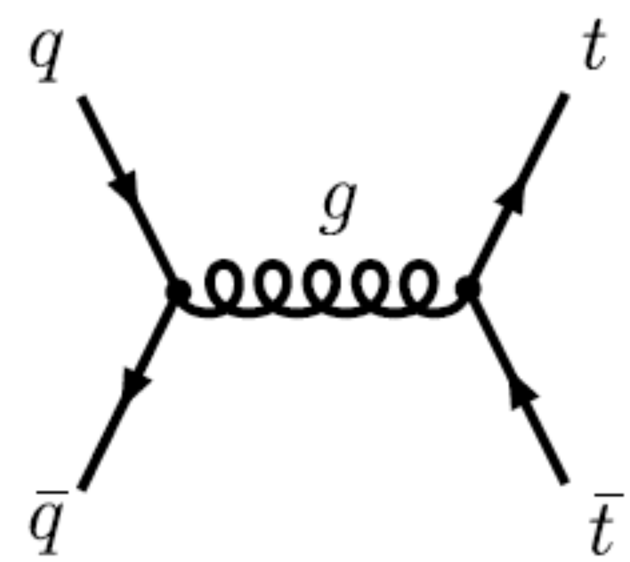
➯ Discovery of the top quark in 1995 at the Tevatron, 18 years after the b

Production and Decay

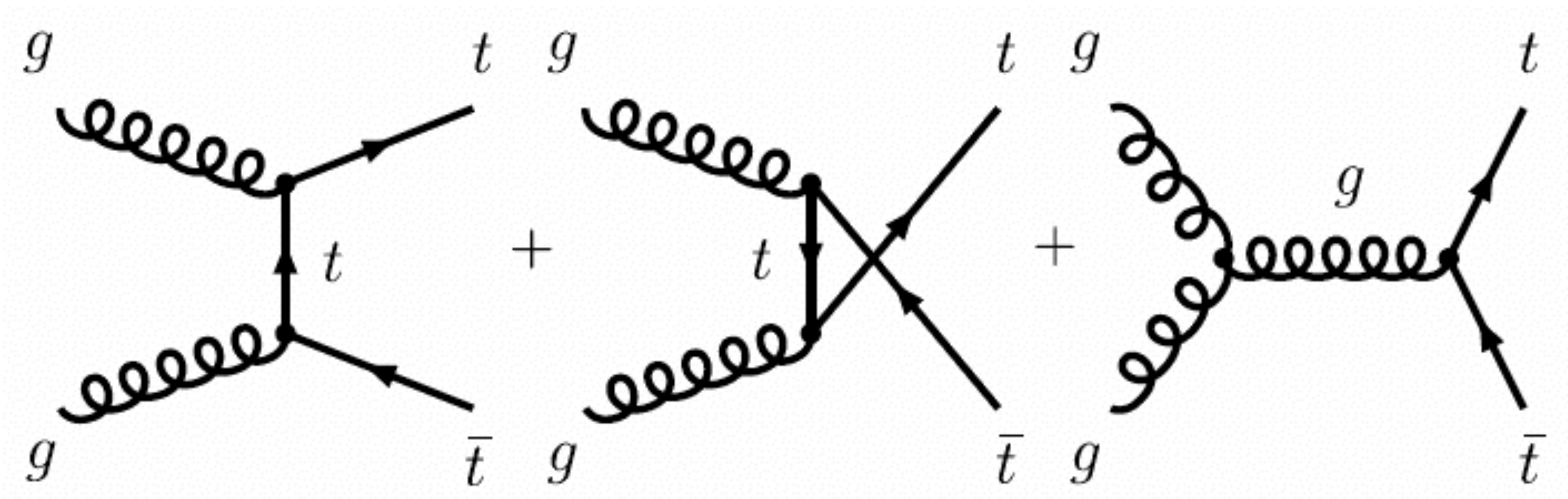
Top Pair Production

- Two important production mechanisms via the strong interaction

Quark-AntiQuark annihilation:



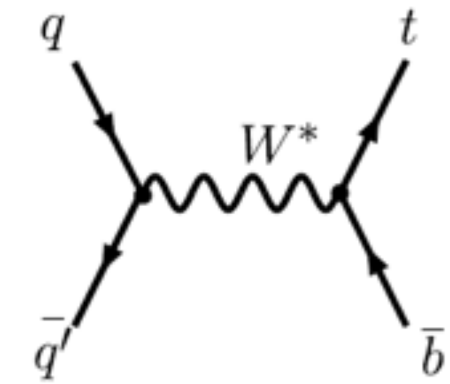
Gluon-Gluon fusion:



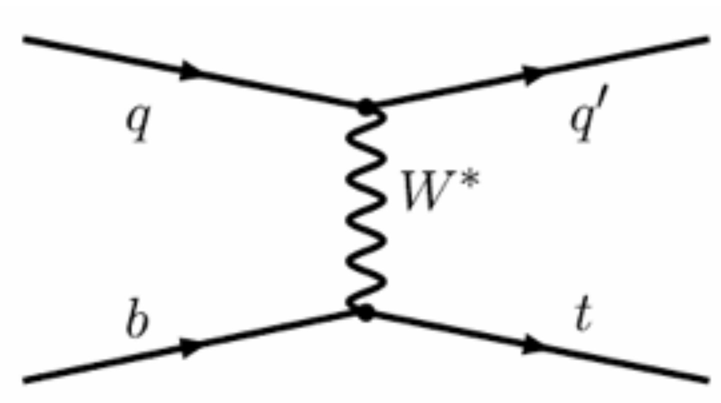
Production of Single Top Quarks

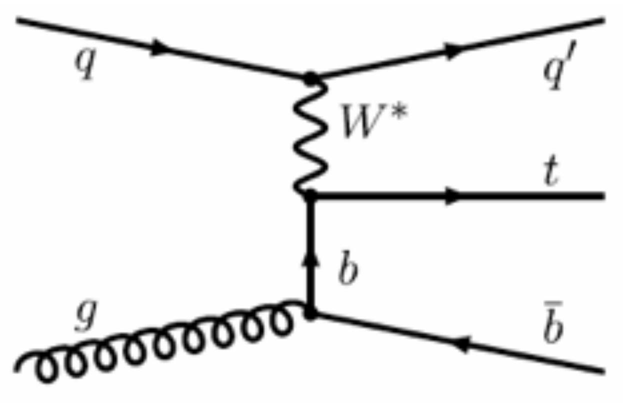
- Production of single top quarks via the weak interaction:

s-channel production via W exchange

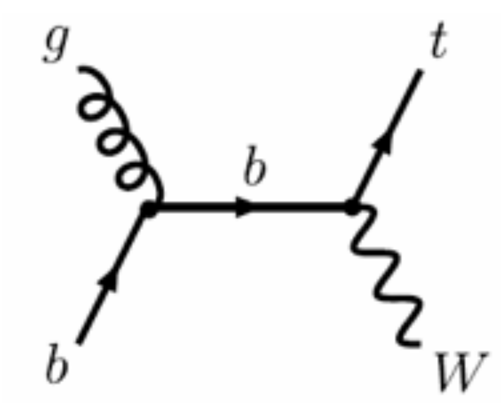


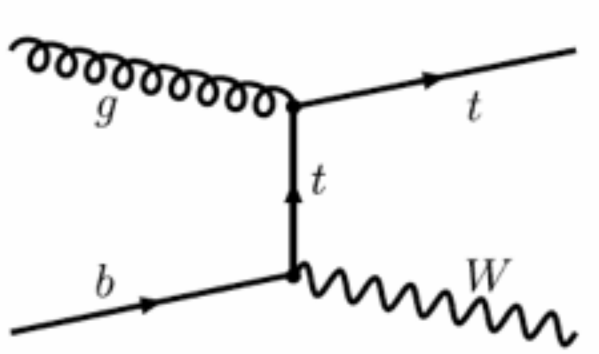
t-channel production





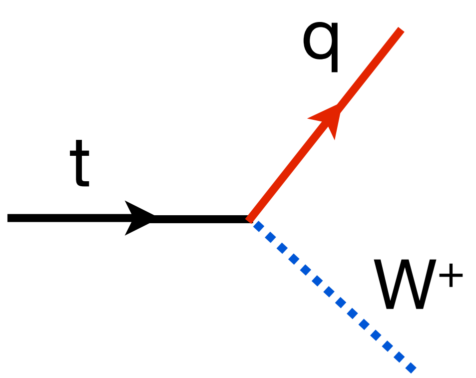
associated production of W and t quark





Top Quark Decay

- Decay via the weak interaction:



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

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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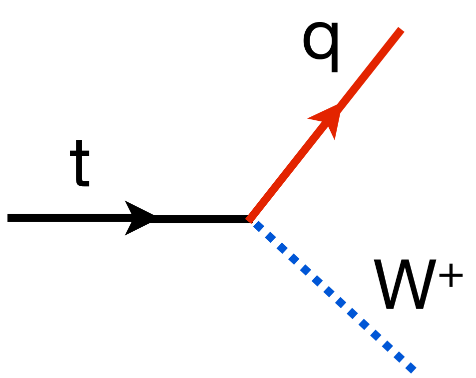

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➫ Top quarks decay almost exclusively into a W boson and a b quark

Top Quark: Width / Lifetime

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

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

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

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

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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, ...)

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Top Decay: The Decay of the Ws

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  “Universality” of the weak interaction, maximal parity violation

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- W decay via the weak interaction:
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  - couples to left-handed fermions, right-handed anti-fermions, always with the same strength
    - Quarks have a three-fold weight: 3 colors!
    - Example W^+:

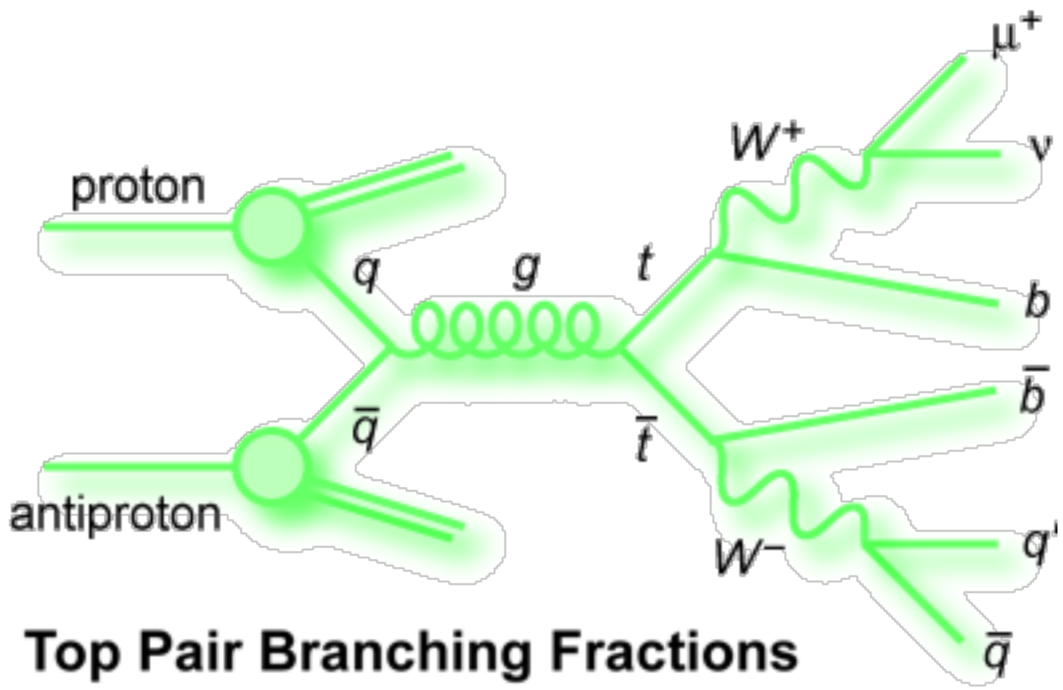
$$W^+ \rightarrow e^+\nu_e : \mu^+\nu_\mu : \tau^+\nu_\tau : u\bar{d}' : c\bar{s}'$$

$$1 \quad : \quad 1 \quad : \quad 1 \quad : \quad 3 \quad : \quad 3$$

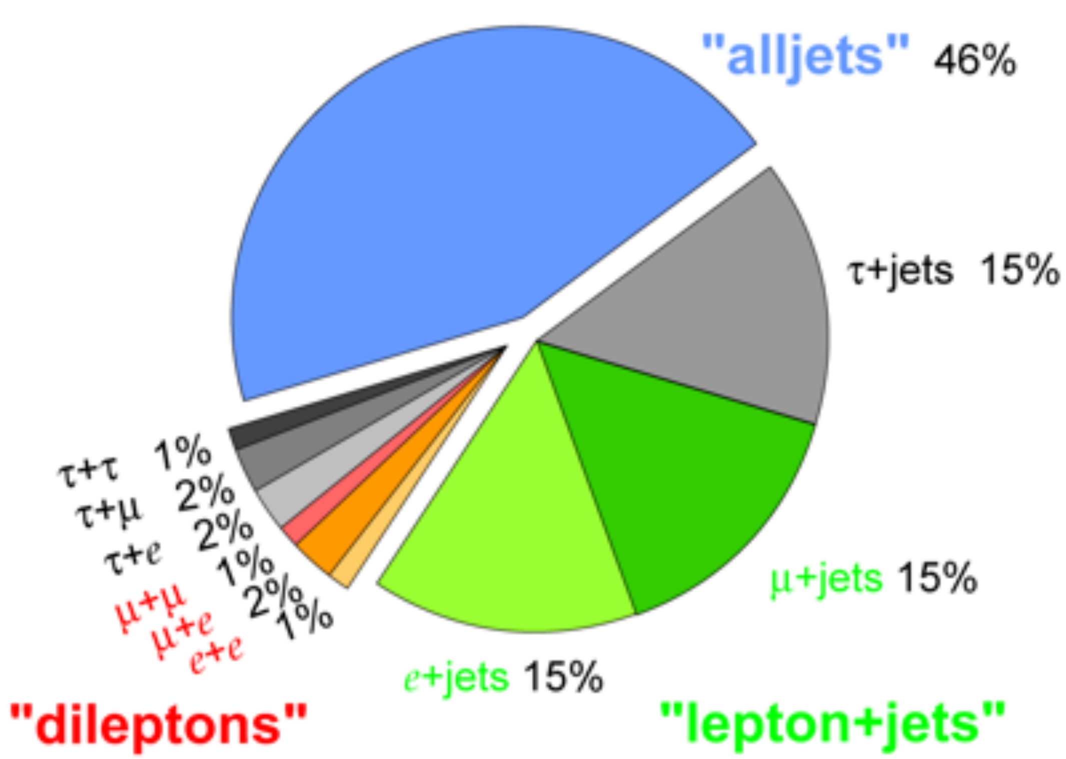
- The types of the W decay determine the different top decay signatures

Top Quark Pair Decays - Classification

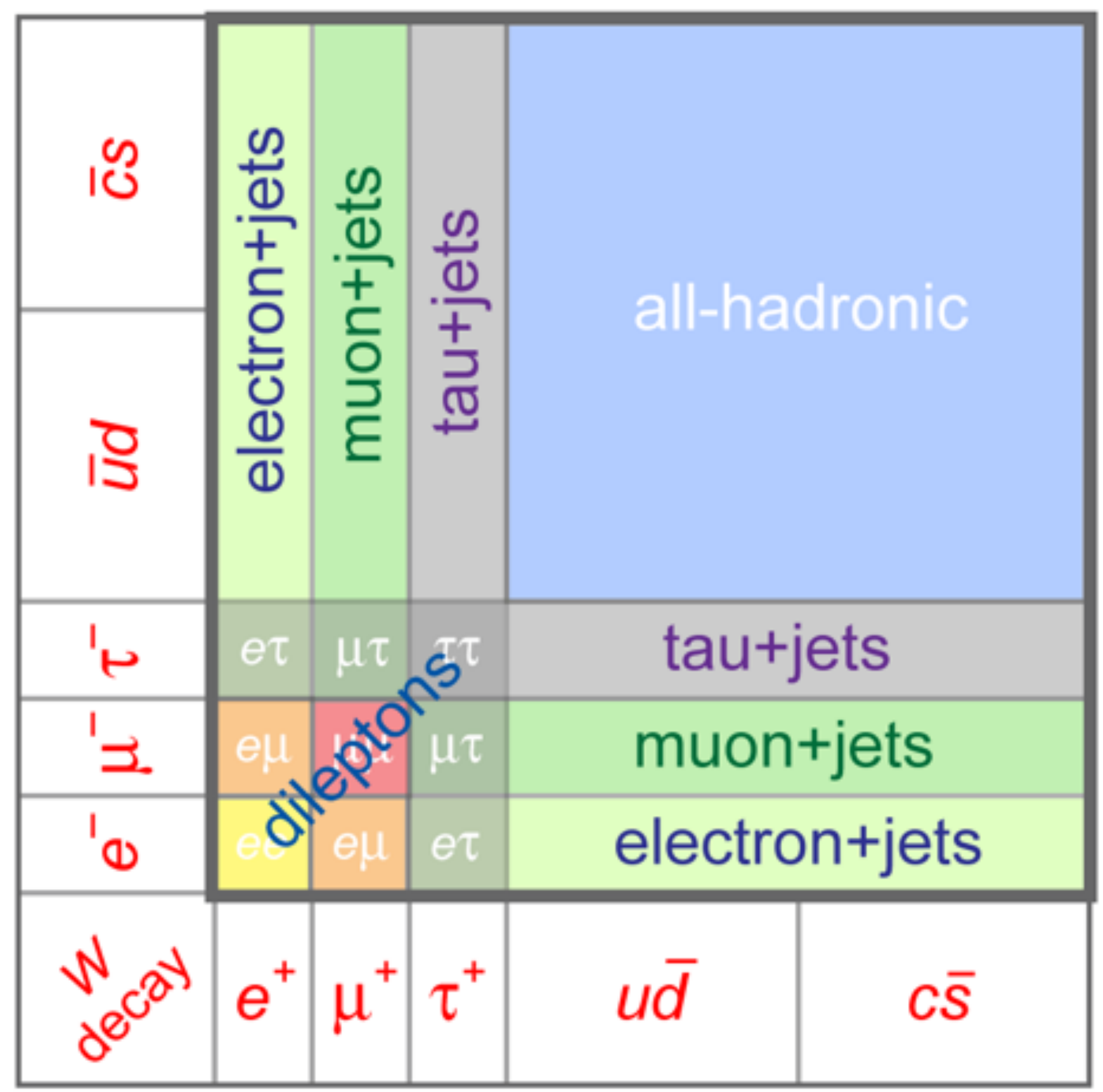
- Classified according to W decay (since basically 100% $t \to bW$)



Top Pair Branching Fractions

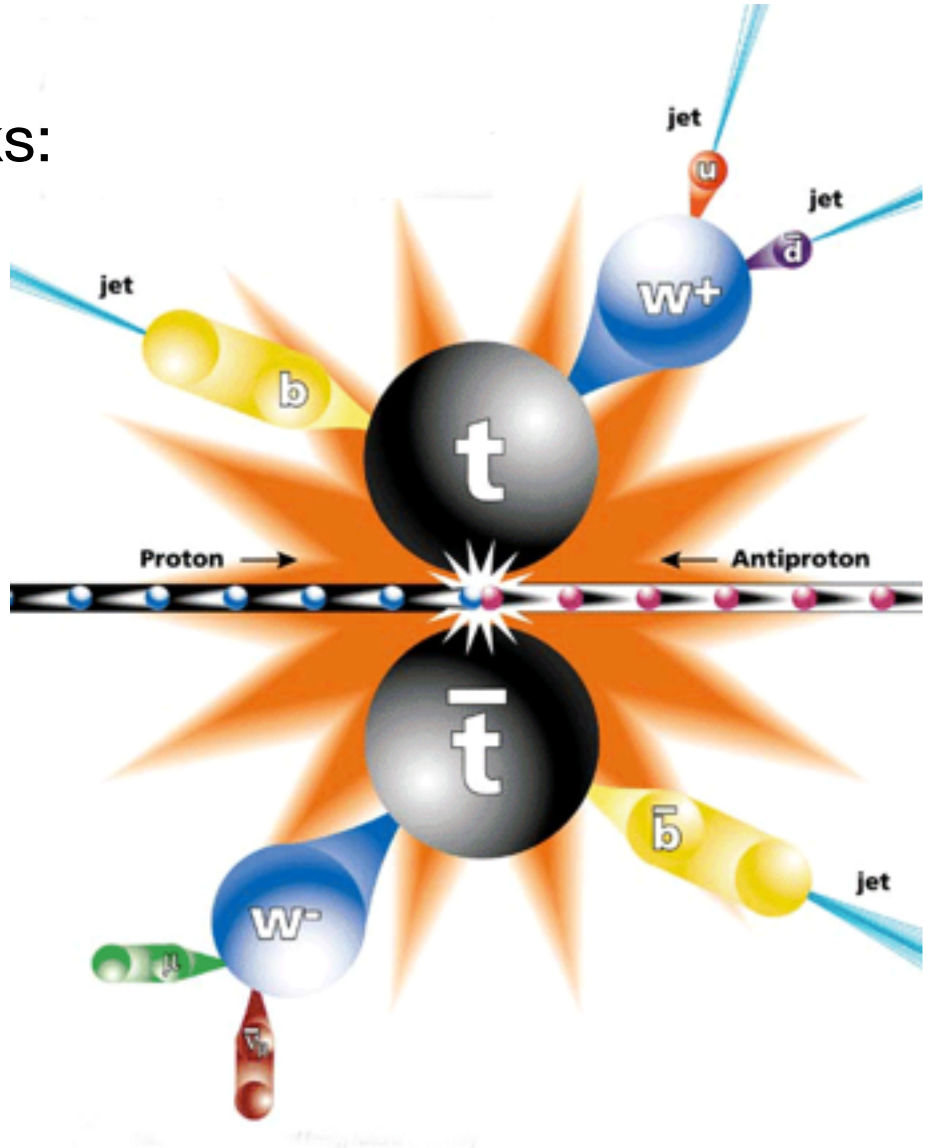


Top Pair Decay Channels



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, μ) from W decay
  - Lepton + Jets: One isolated lepton (e, μ) from W decay, jets from W decay and from b quarks
  - All-Hadronic: Jets from both Ws, jets from b quarks: Tagging crucial - quite difficult at hadron colliders



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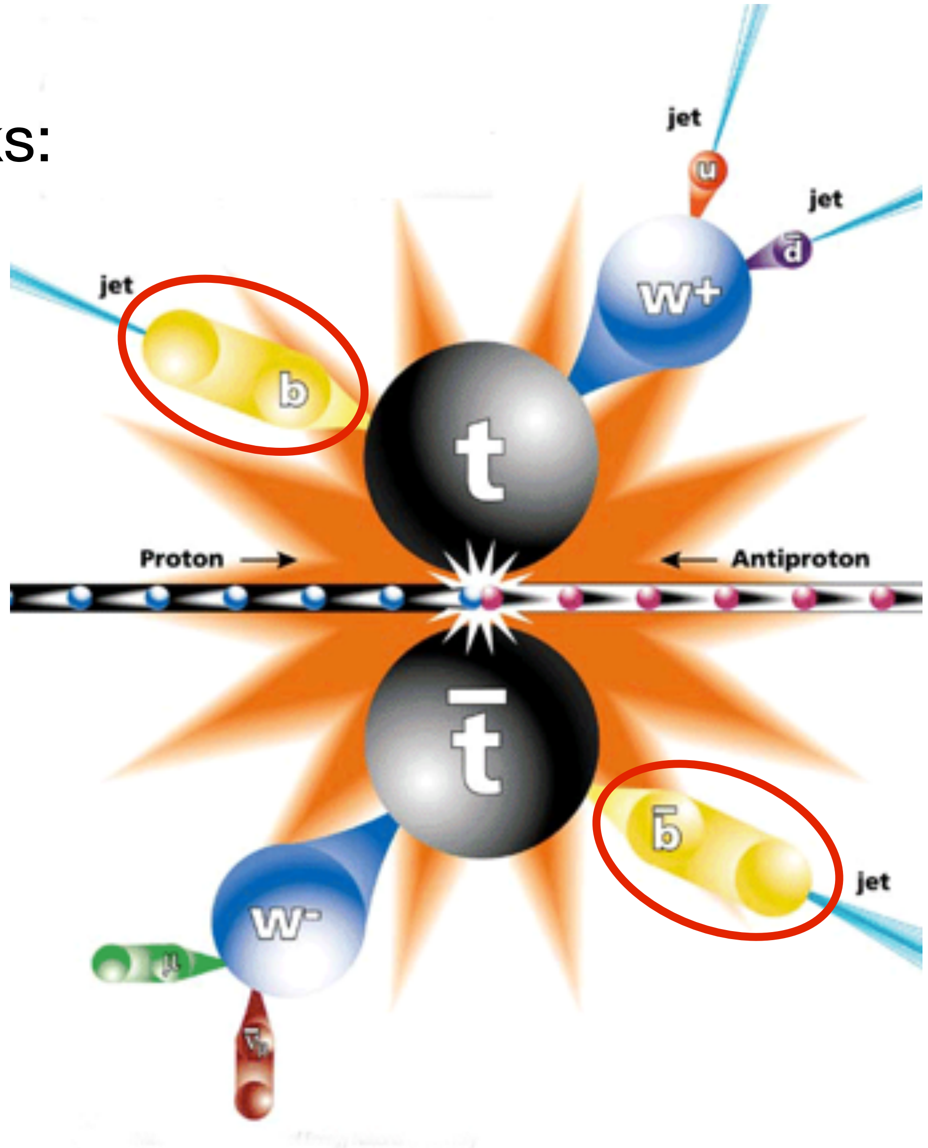
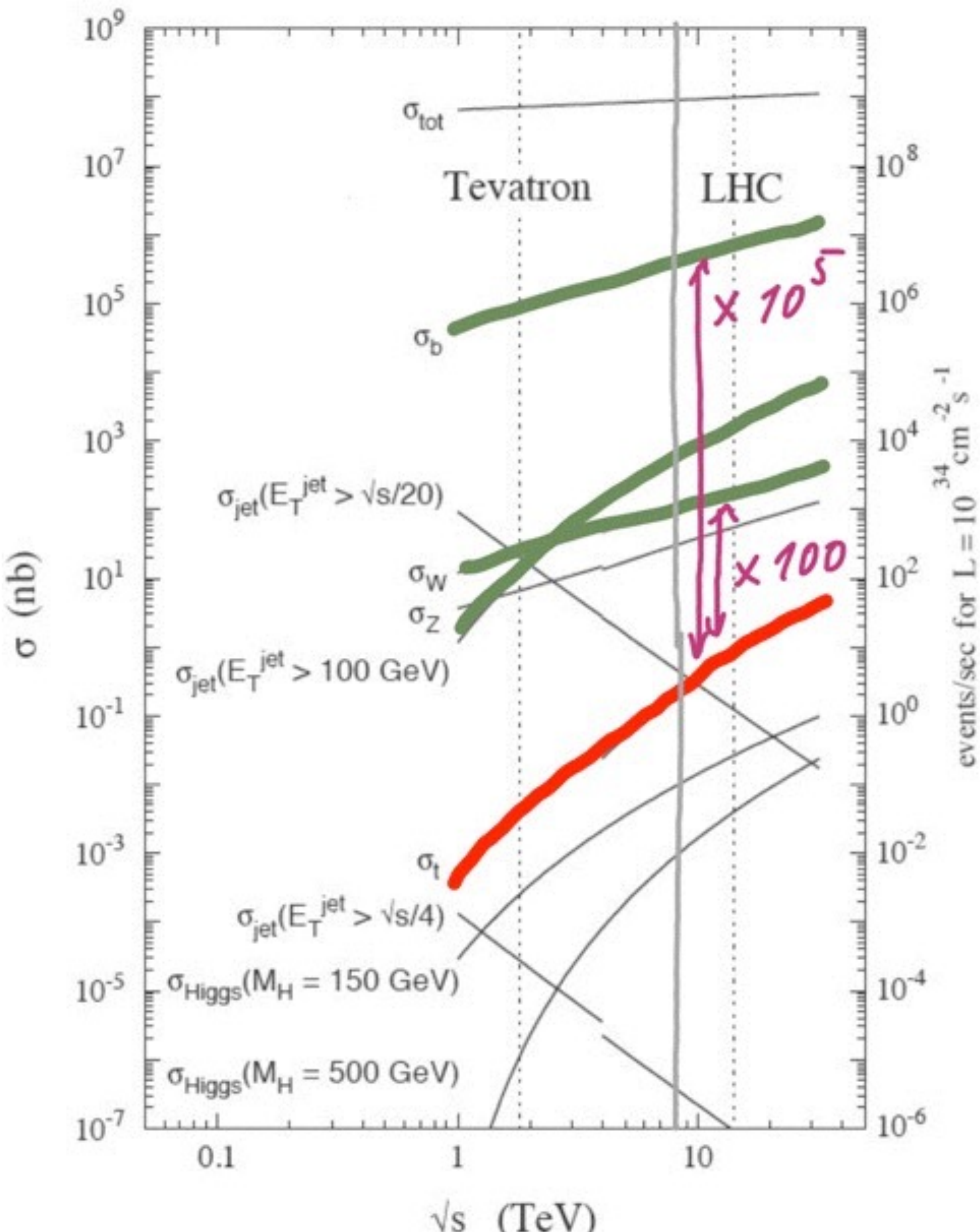


Reminder: b quark identification

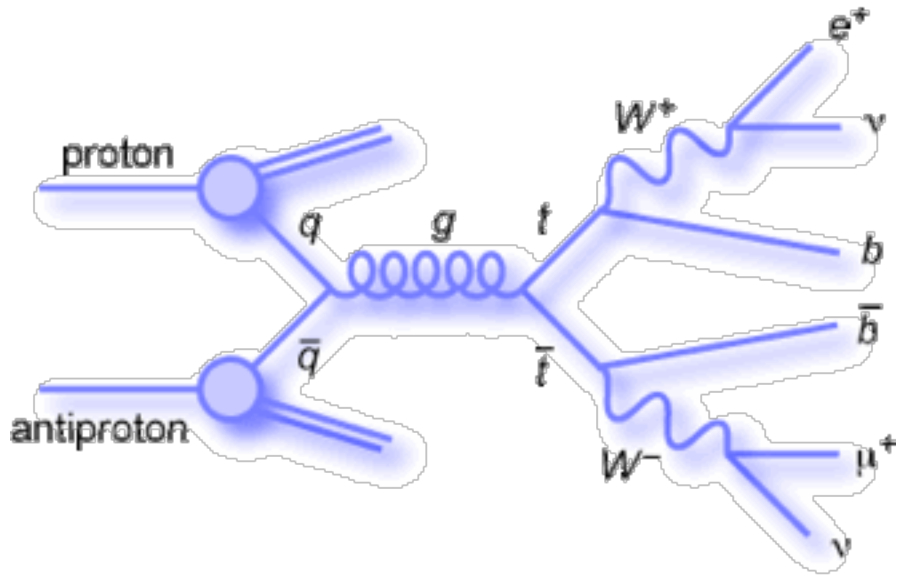
- Relatively long life time of mesons containing b quarks ($c\tau$ (B^0) ~ 460 μm, $c\tau$ ($B^\pm$) ~ 490 μm)
- Identification of a displaced secondary vertex in a jet
  - Jet is "tagged" as a b jet

The Challenge: Background

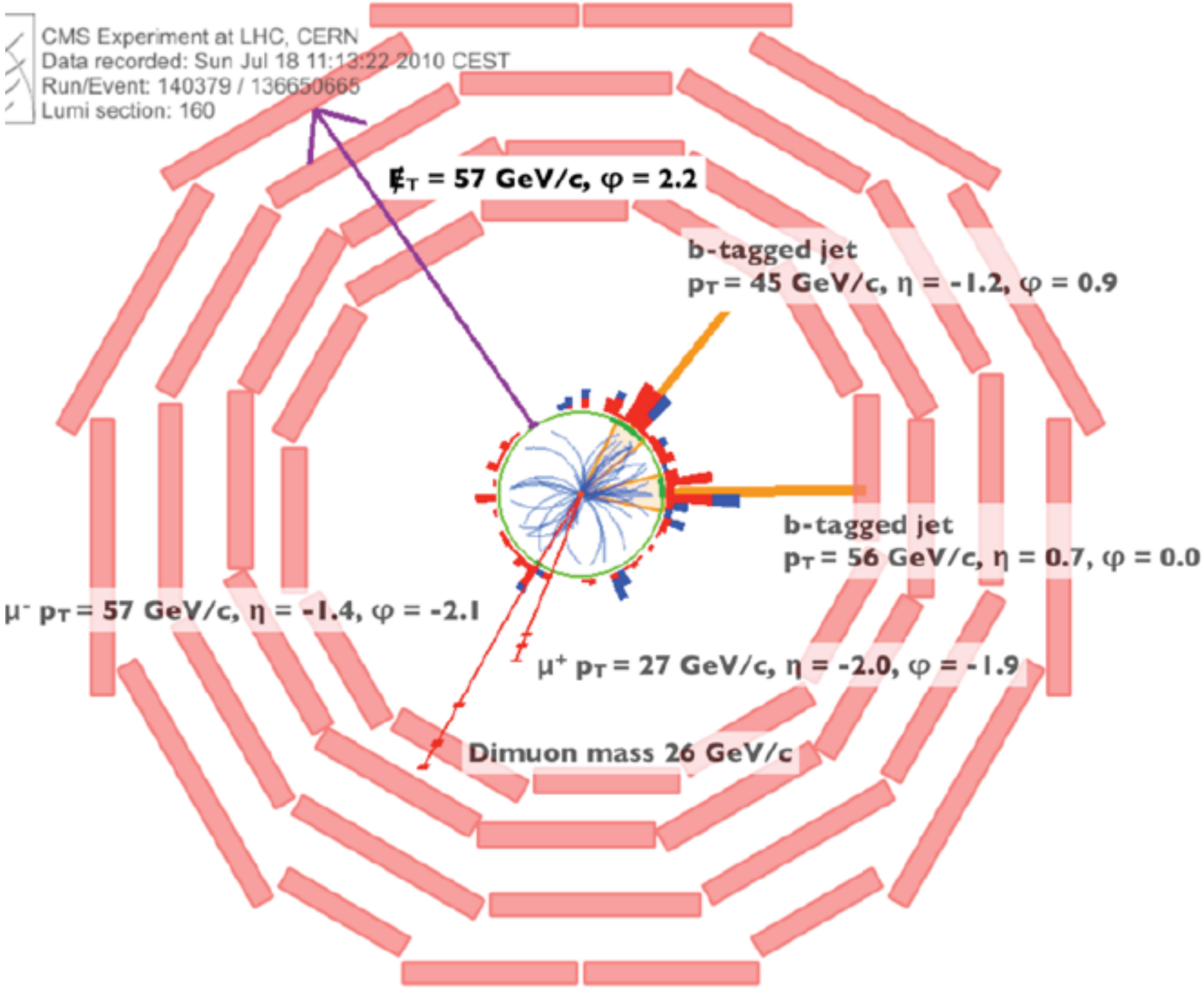
- Top production is only a very small part of the total pp cross section
    - High background, in particular for hadronic decays of the W
        - all-hadronic: QCD multi-jet background (very high!)
        - lepton+jets: W + jets and QCD multi-jet background (ok)
        - di-lepton: Z + jets and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



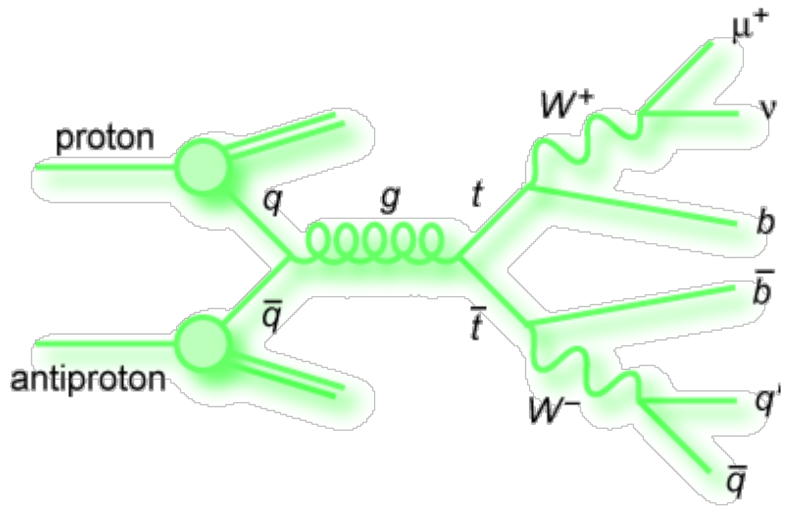
Experimental Detection: Di-Lepton Events



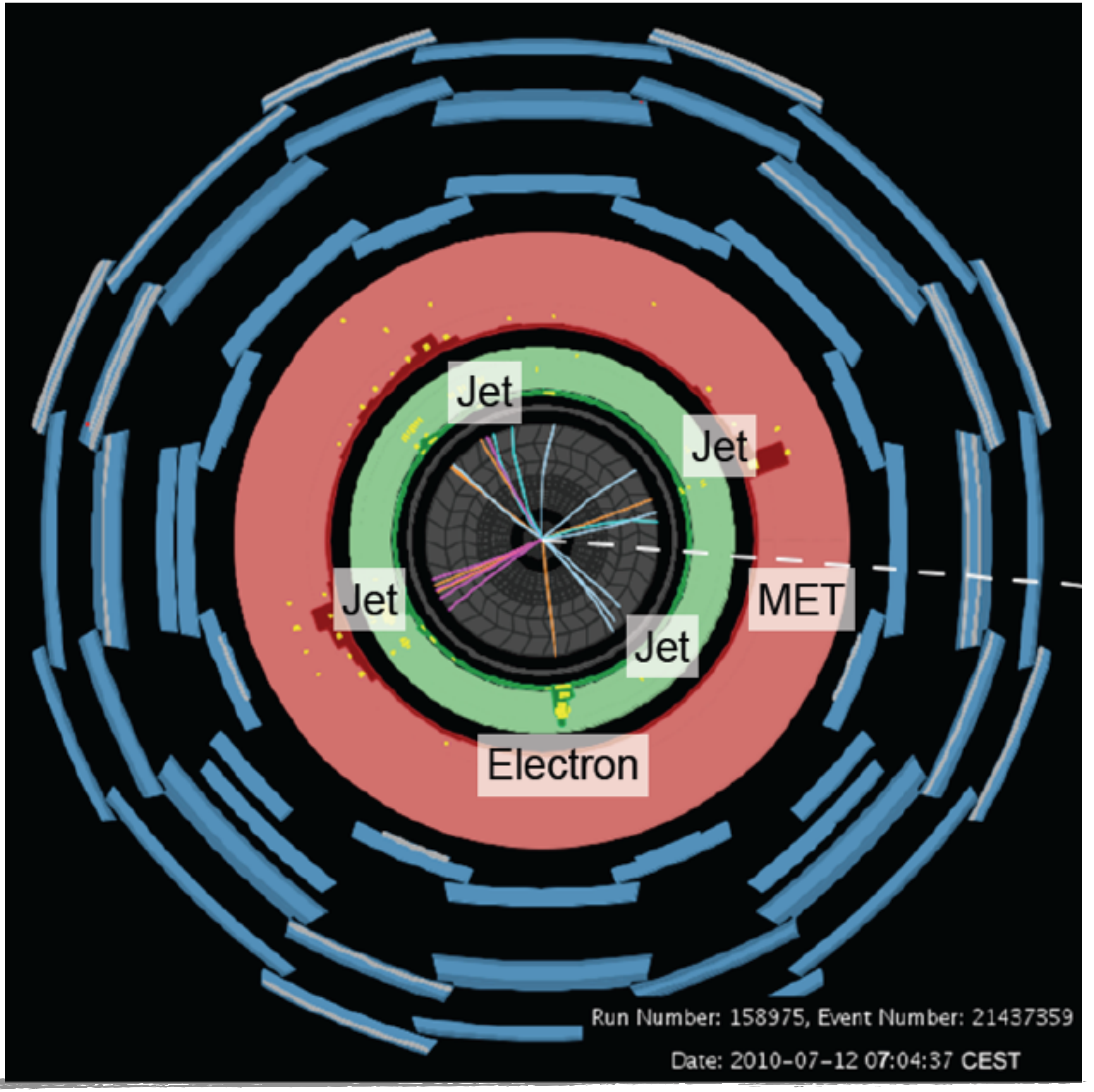
- Clear, clean signature
- missing information from two (undetected) neutrinos
- small branching ratio, low statistics
- Background: mainly W + X



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 + 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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- Optimal: $x_a \sim x_b$, which gives the required parton x:

$$\langle x \rangle = \sqrt{\frac{\hat{s}}{s}} = \frac{2m_t}{\sqrt{s}}$$

~ 0.192 Tevatron Run I (1.8 TeV)

~ 0.176 Tevatron Run II (1.96 TeV)

~ 0.025 LHC (14 TeV)

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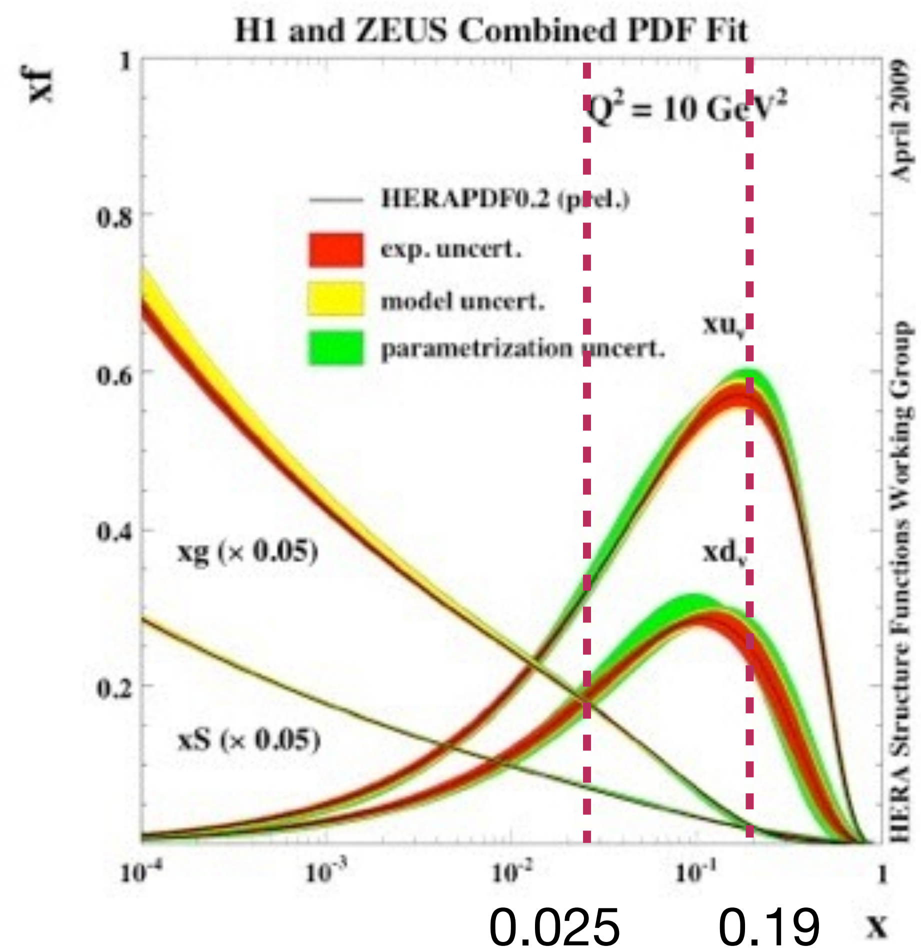
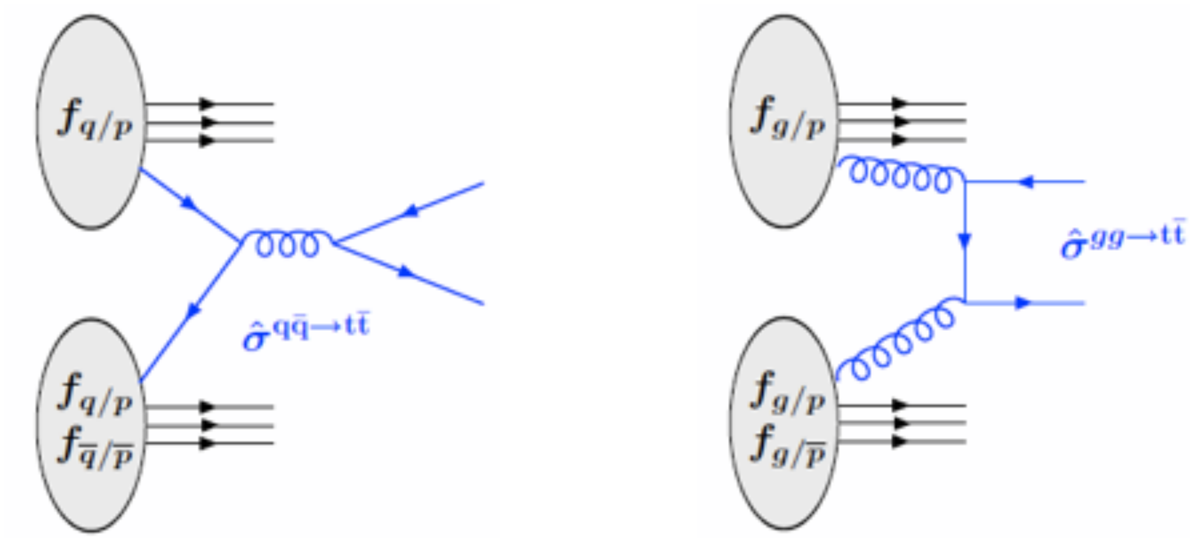
- Mix of the production processes is energy dependence:
  - Tevatron: high x, dominated by valence quarks: Big advantage of proton - anti-proton collisions
  - LHC: lower x, dominated by gluons



Top Quark Pair Production at Hadron Colliders II

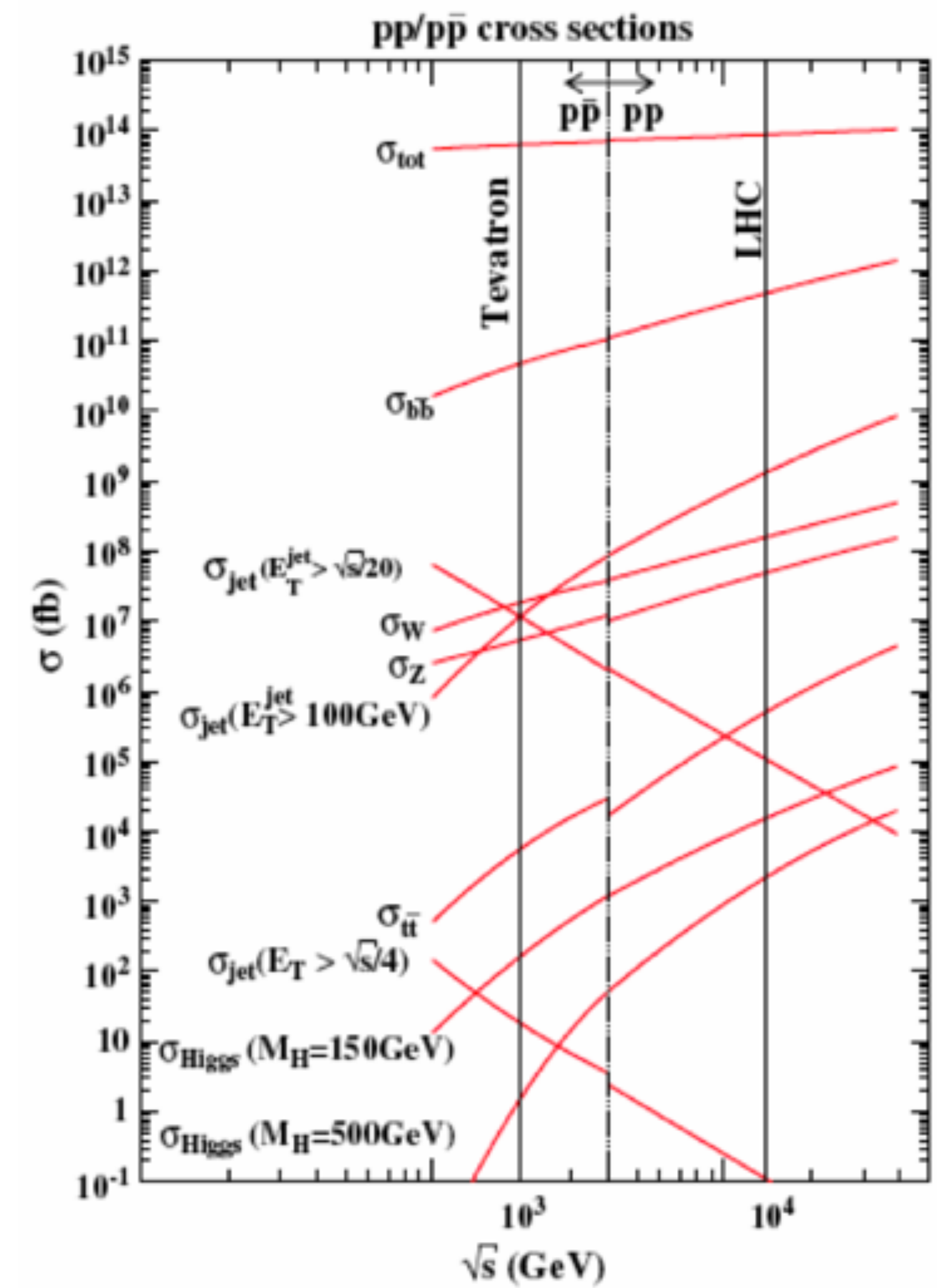
- Production mechanisms: Quark - anti-quark vs gluon-gluon



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

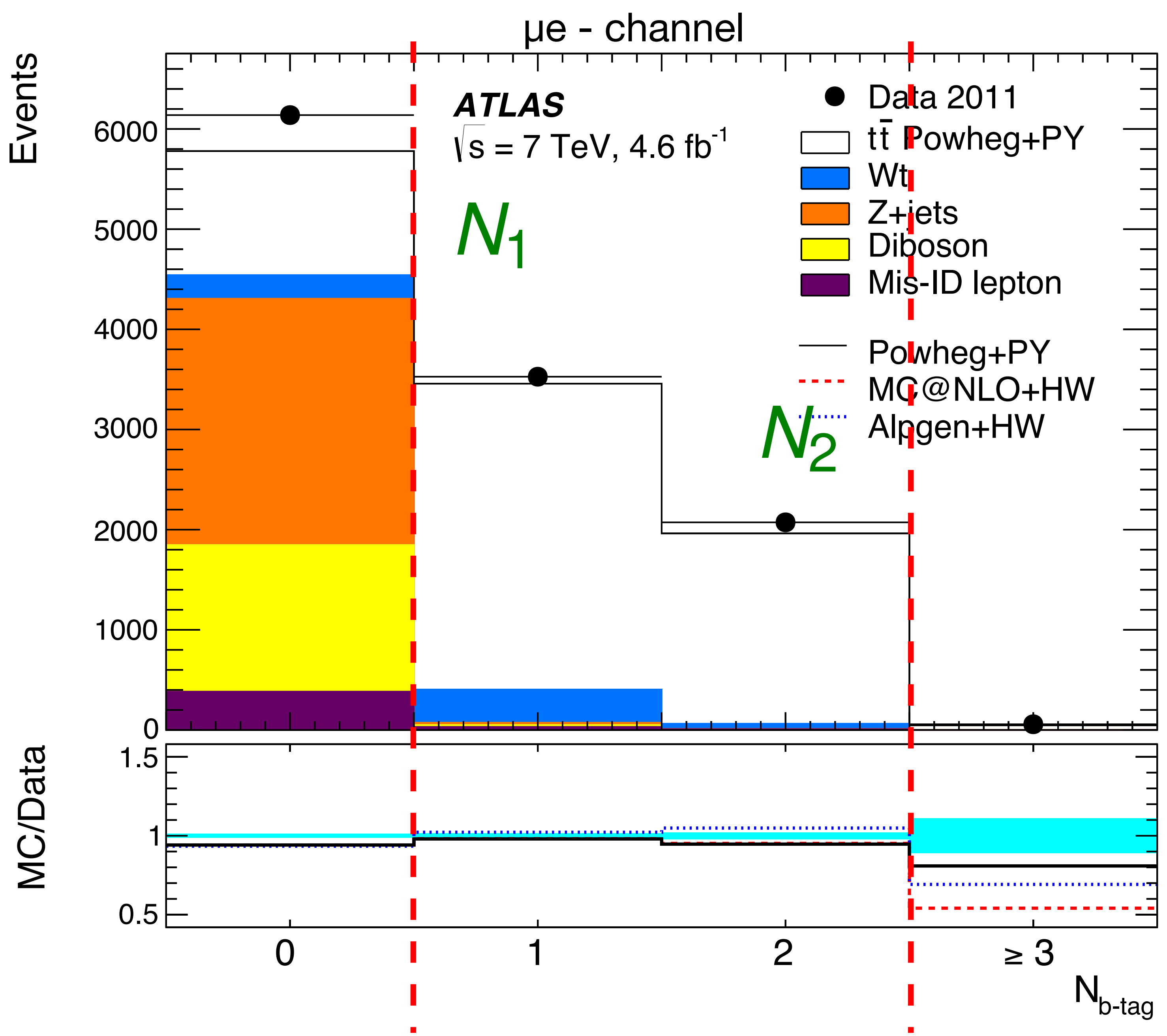
$$\sigma(p\bar{p} \rightarrow t\bar{t}) = \frac{N - B}{A\epsilon \int \mathcal{L} dt}$$

N: Number of selected events
B: Estimation of background events

A: acceptance correction: kinematic and geometric acceptance of the detector
ε: event selection efficiency

Example: ATLAS Di-Leptons

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



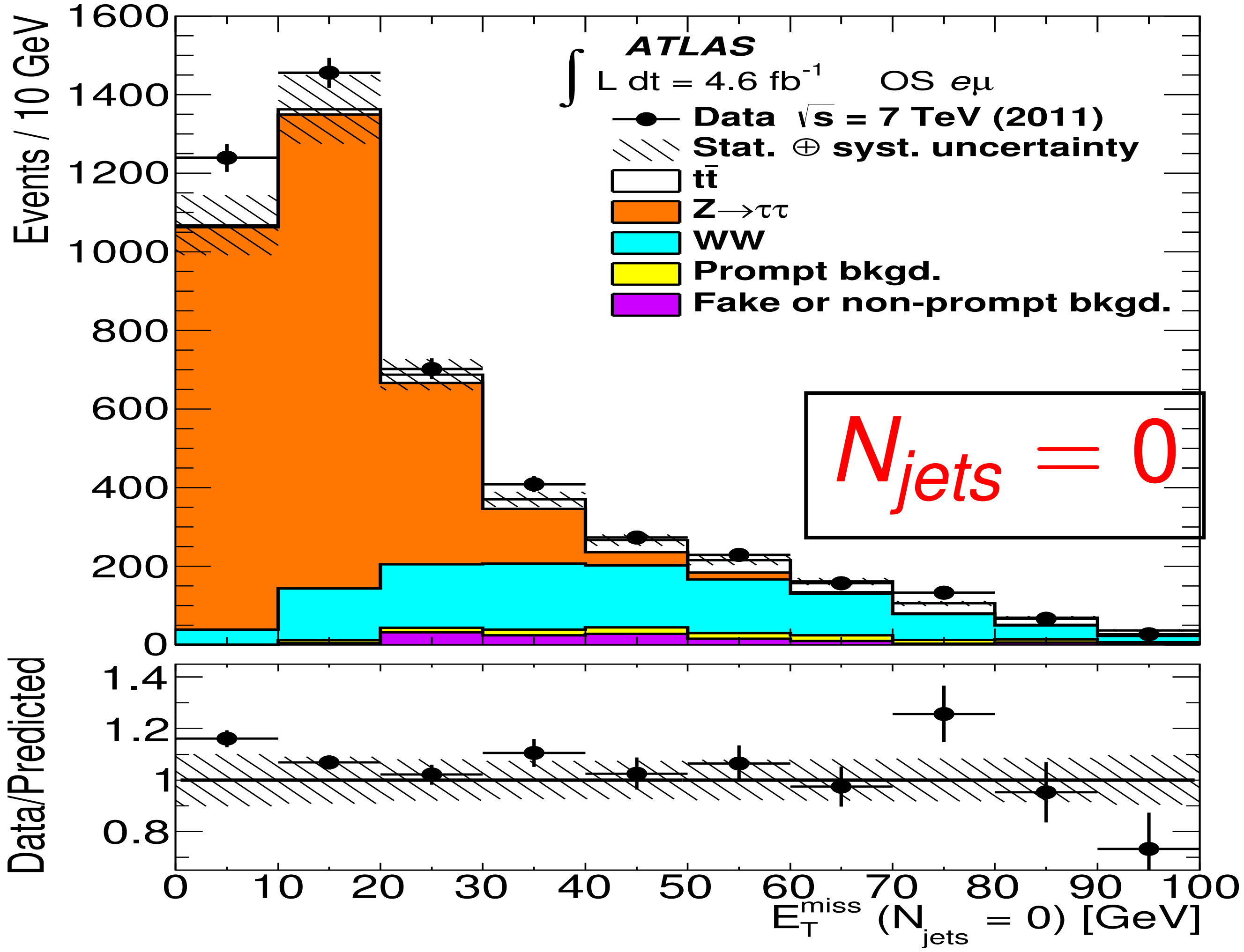
Most important sources of uncertainties:

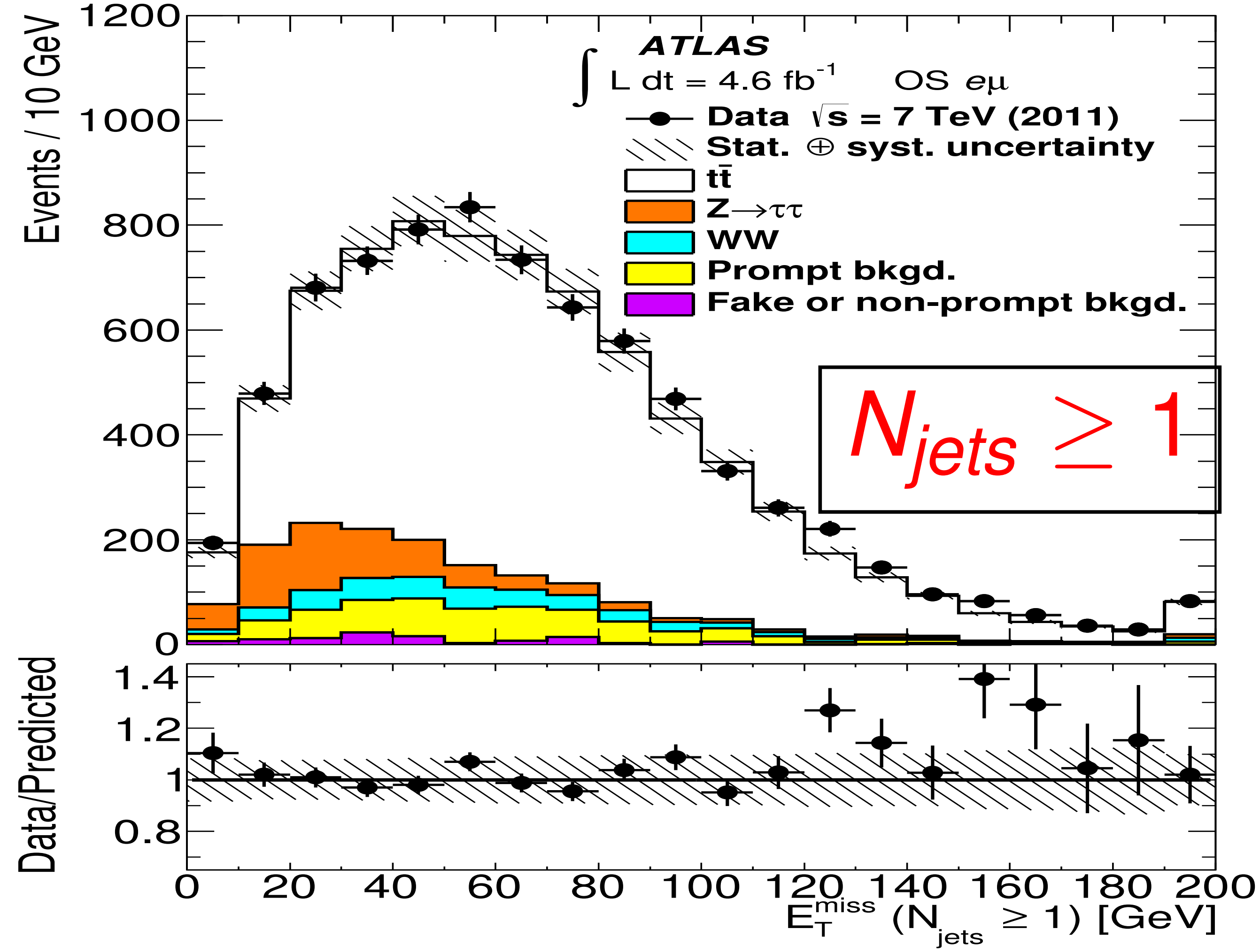
B tagging - How well is it understood?

Jet energy scale: influences energy cuts

ATLAS Di-Leptons: Missing Energy

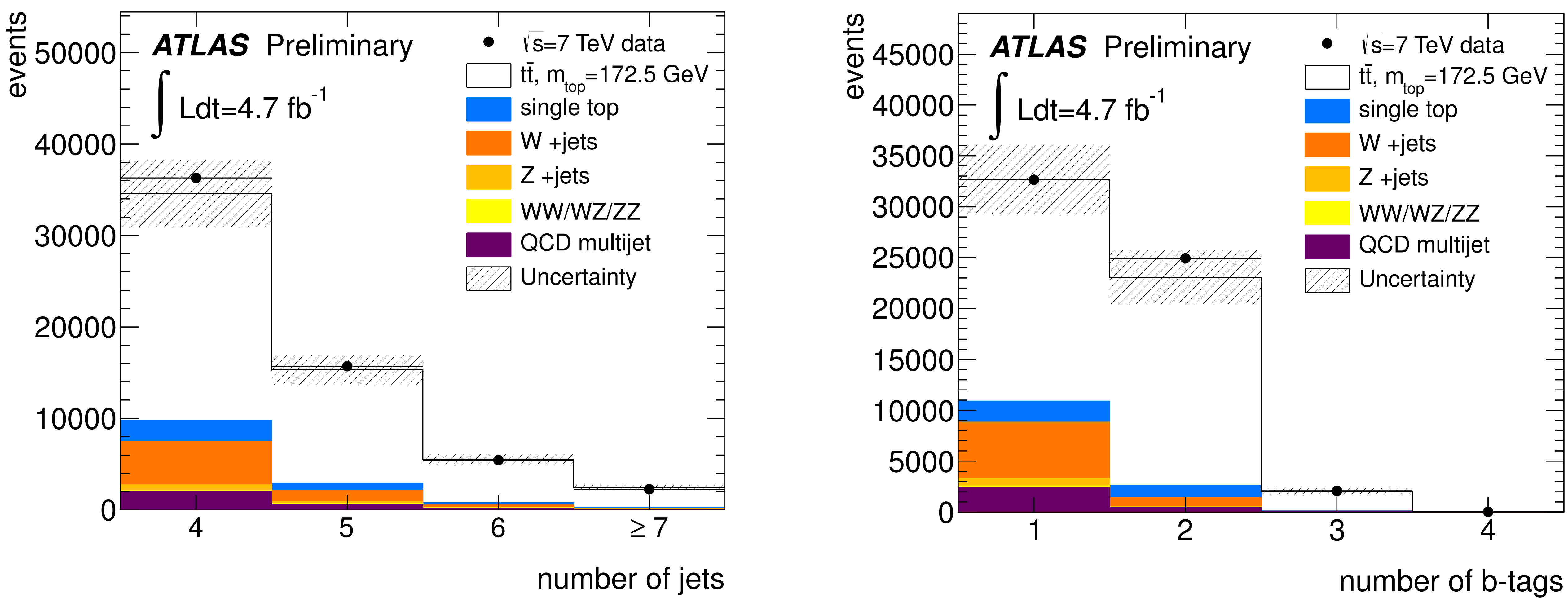
- Missing energy and jets in addition to leptons





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 ttbar), b tagging and missing energy (neutrino!)



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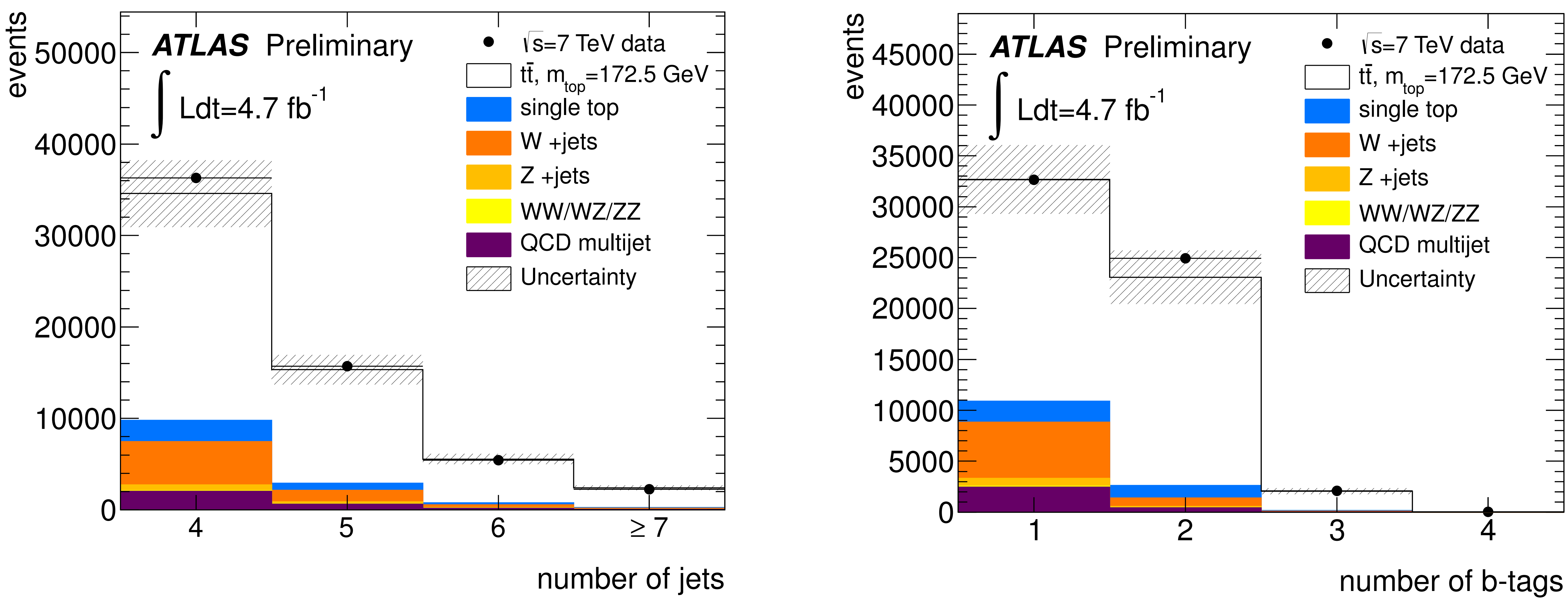
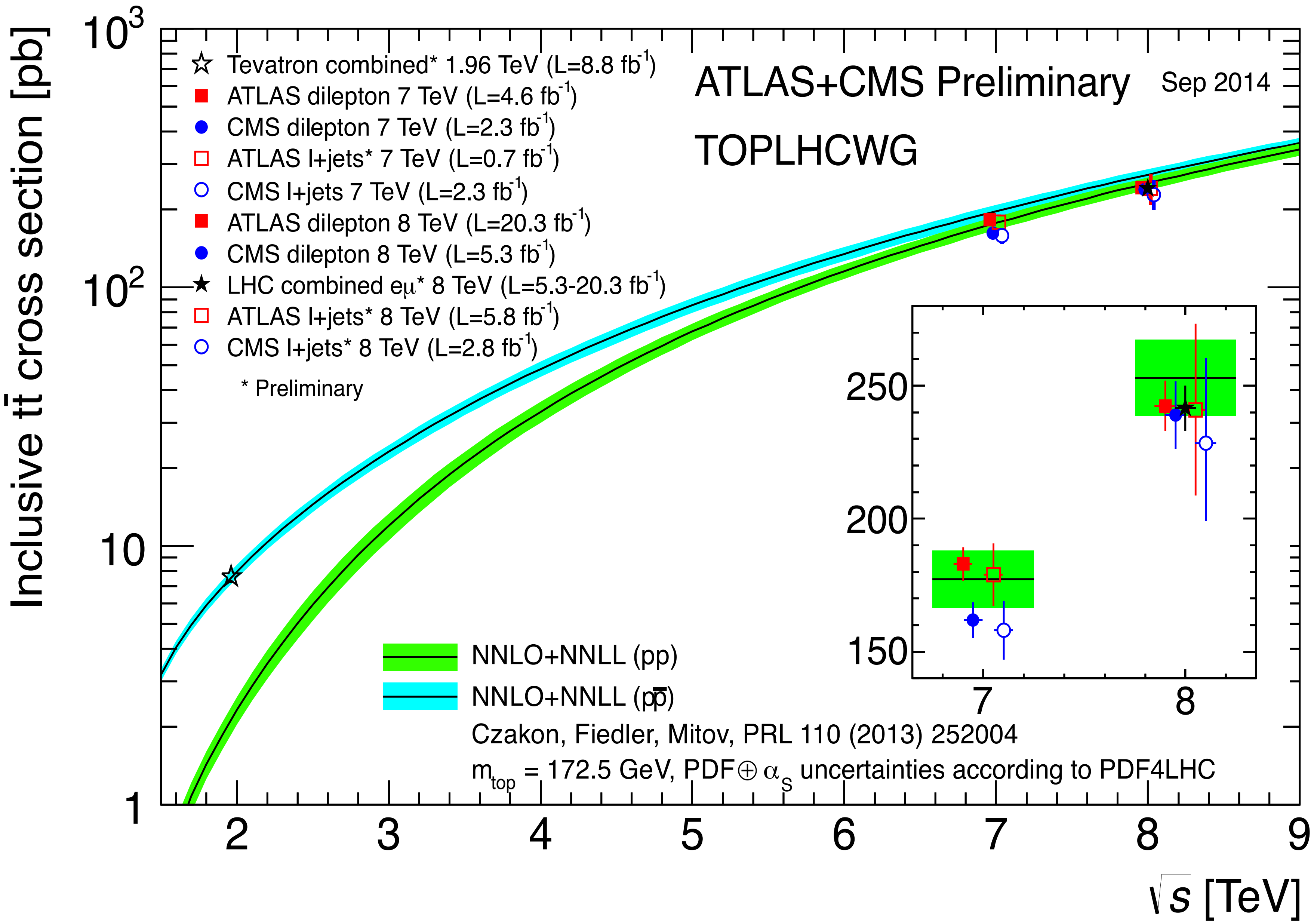


ATLAS-CONF-2013-046

Top Cross Section at LHC



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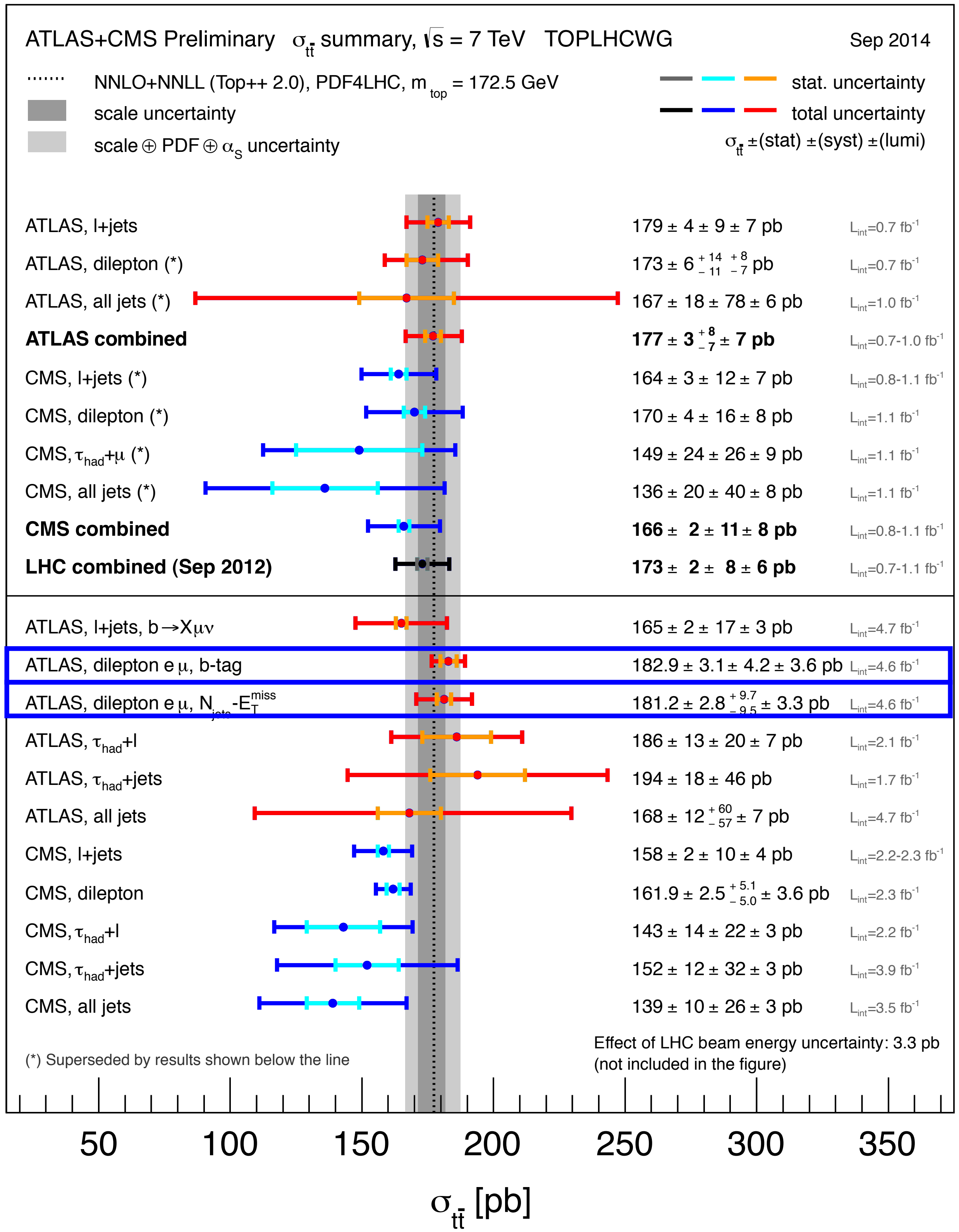
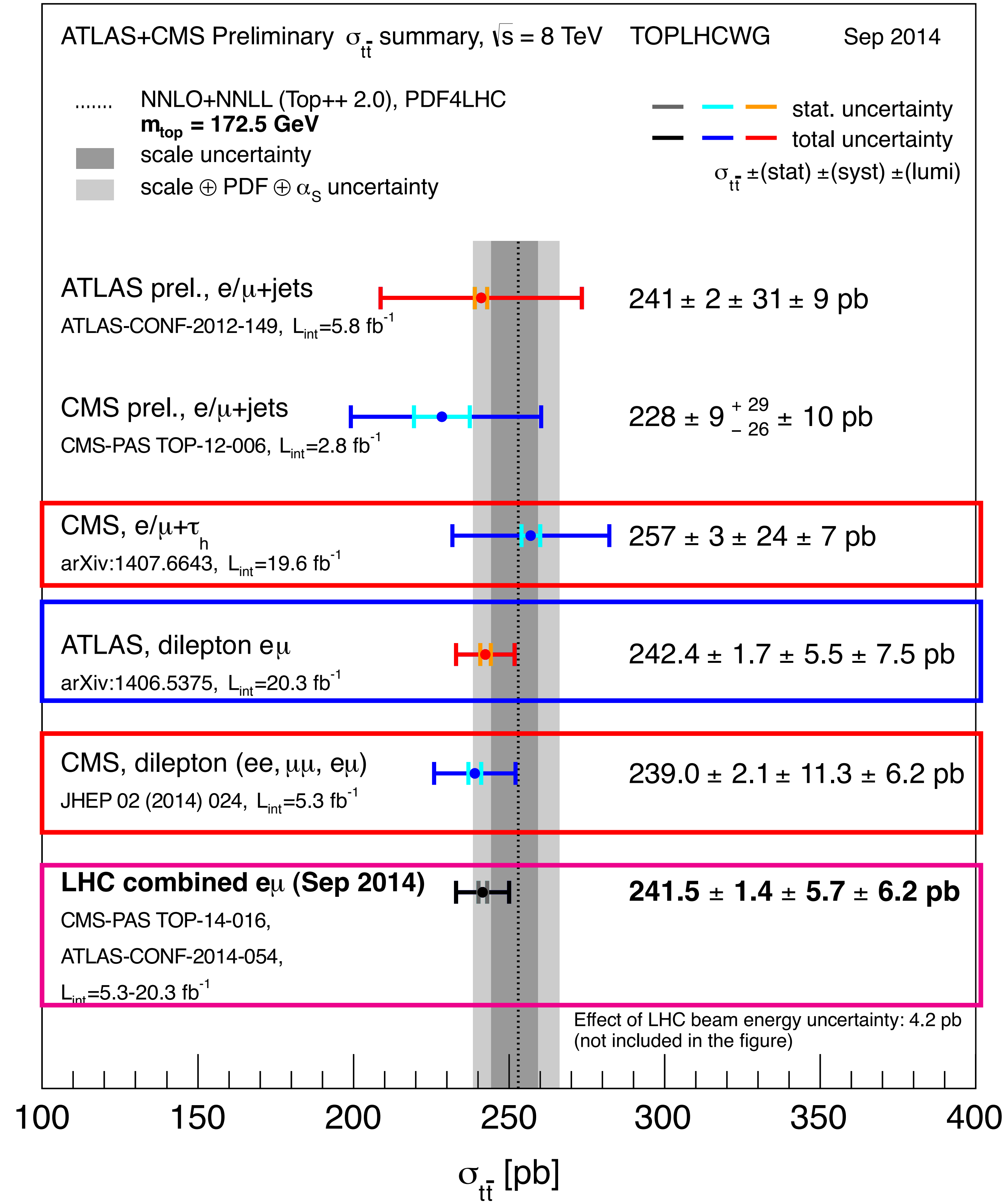
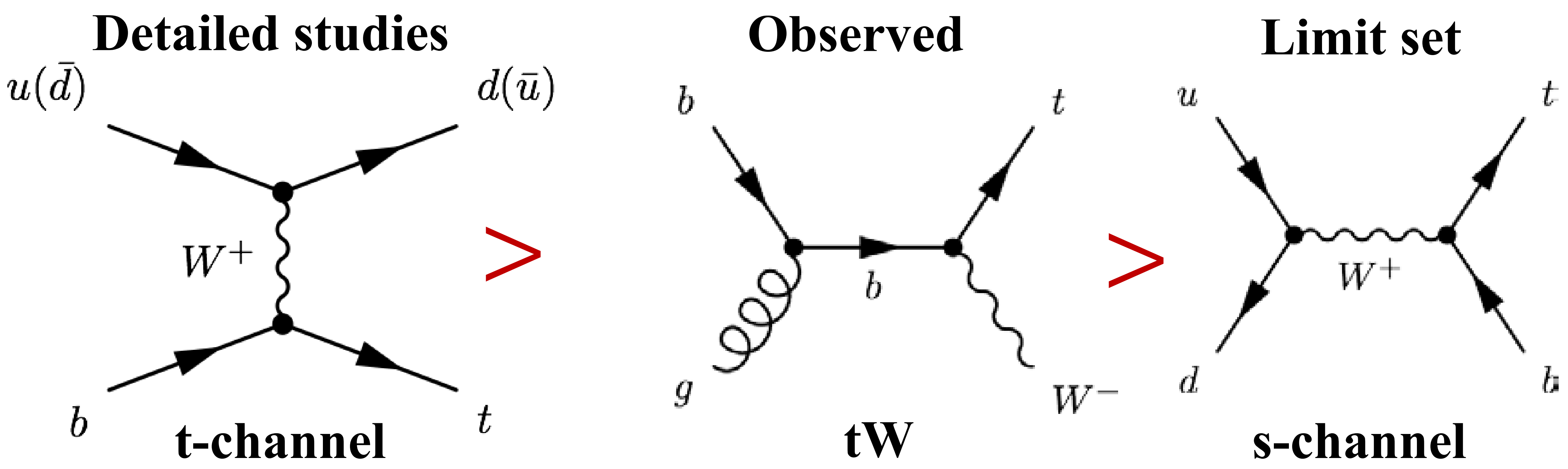




Single Top Production

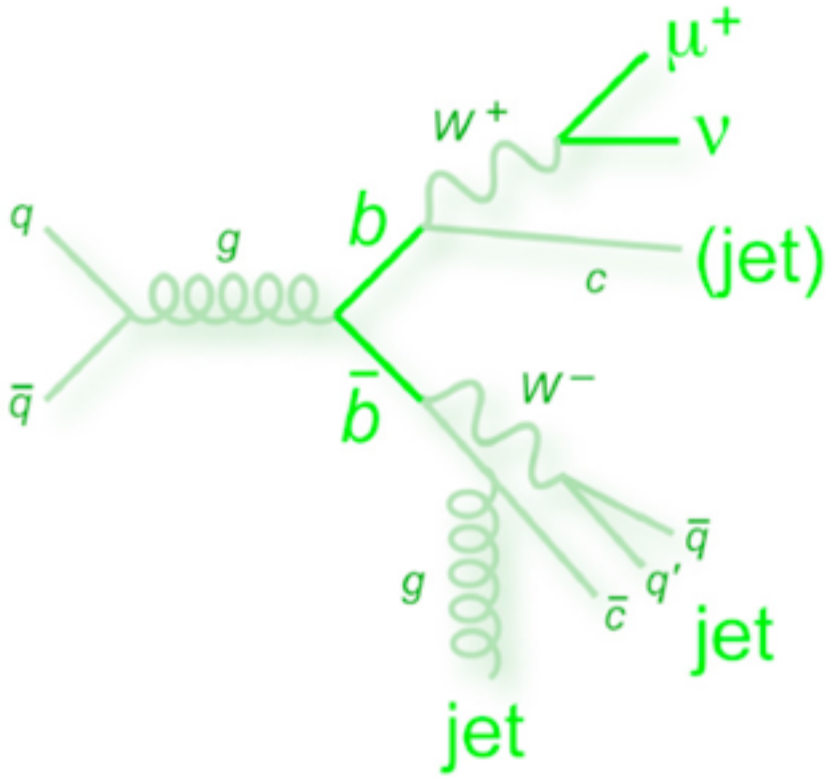
- Production of single top quarks via weak interaction - expectation: σ(single top) ~ 0.4 x σ(top pair)
  - Direct access to Wtb - vertex of the weak interaction!



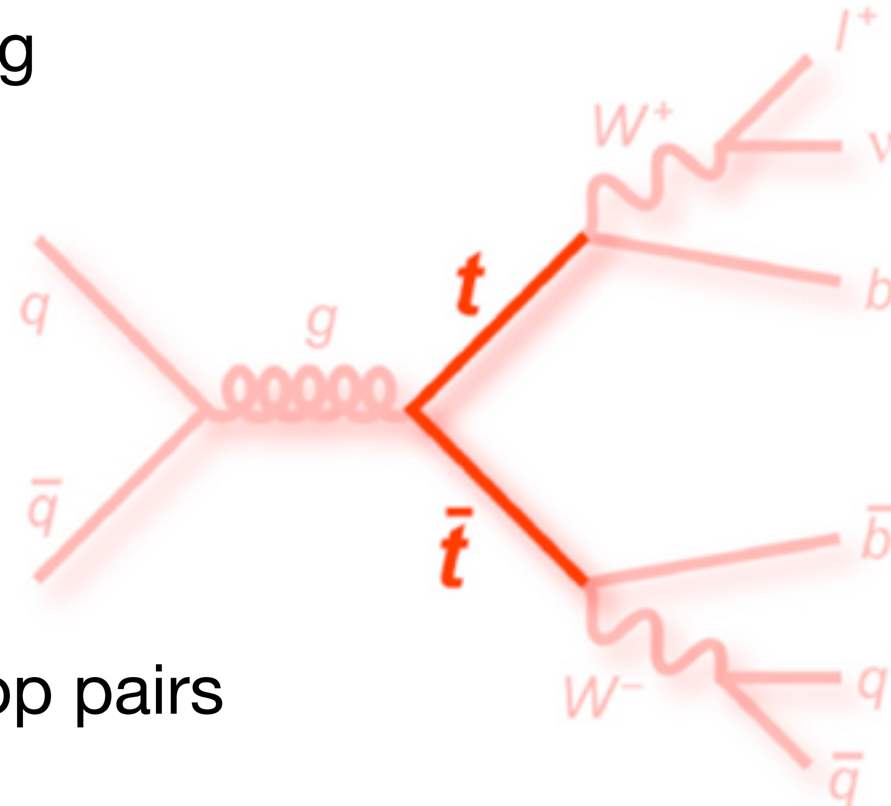
Only one t quark in the final state: Less "spectacular" events than top pair production: Separation from background more difficult!

Background in Single Top Measurements

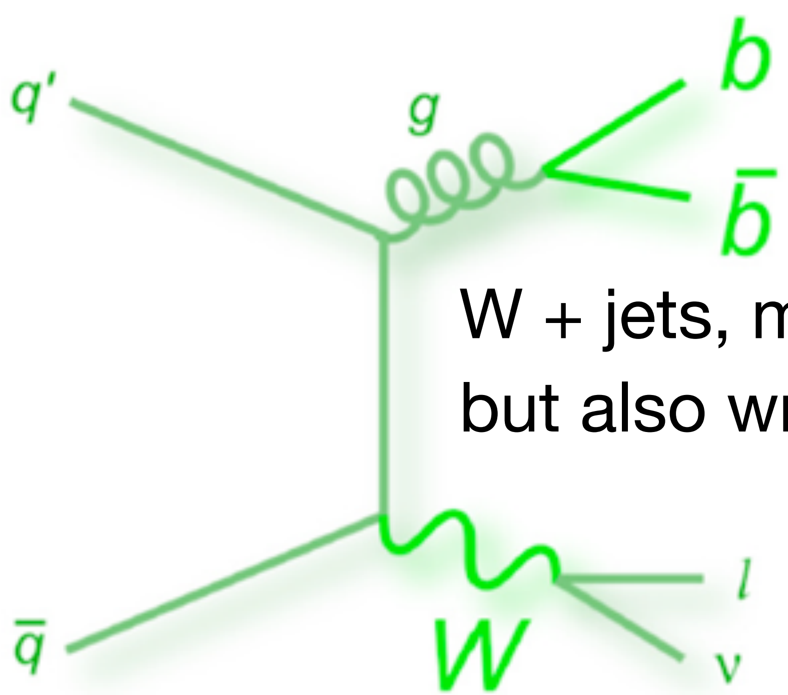
- Events with a W and one or more jets with a b-tag



multi-jet production



mis-identified top pairs



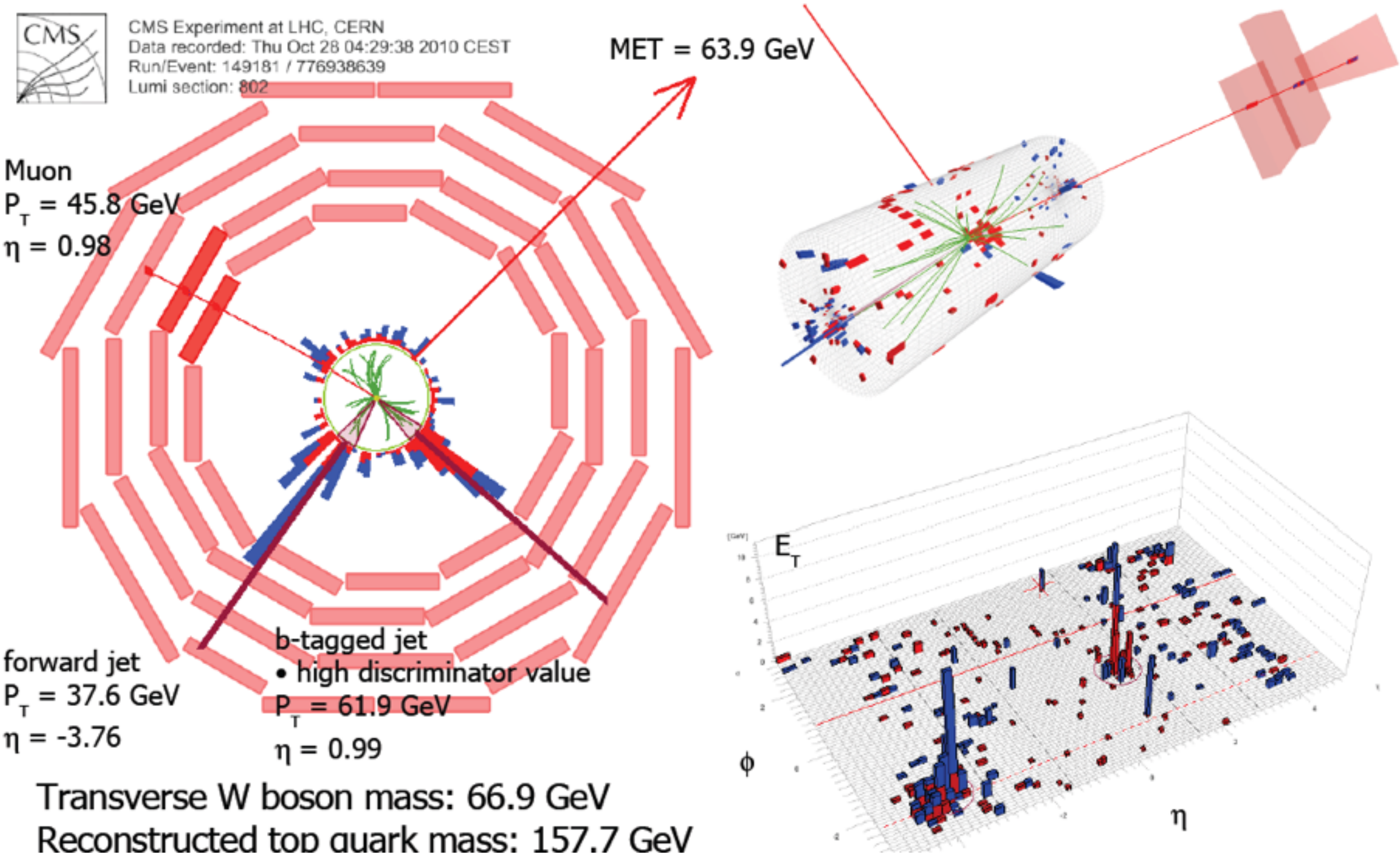
W + jets, mainly b-jets but also wrong tagging

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

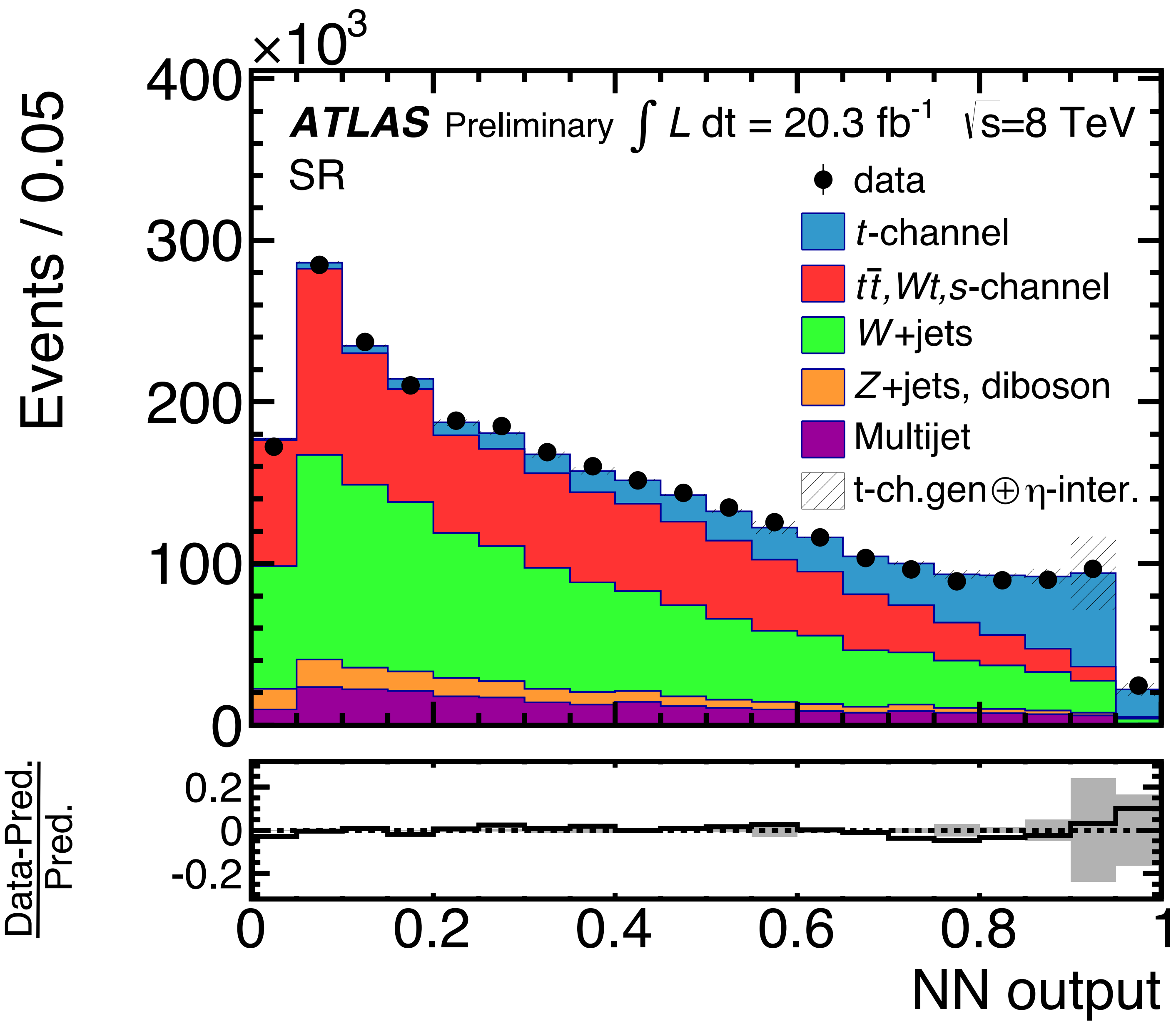
- Neural networks
- Boosted decision trees
- ...

Single Top at the LHC

- A candidate from CMS

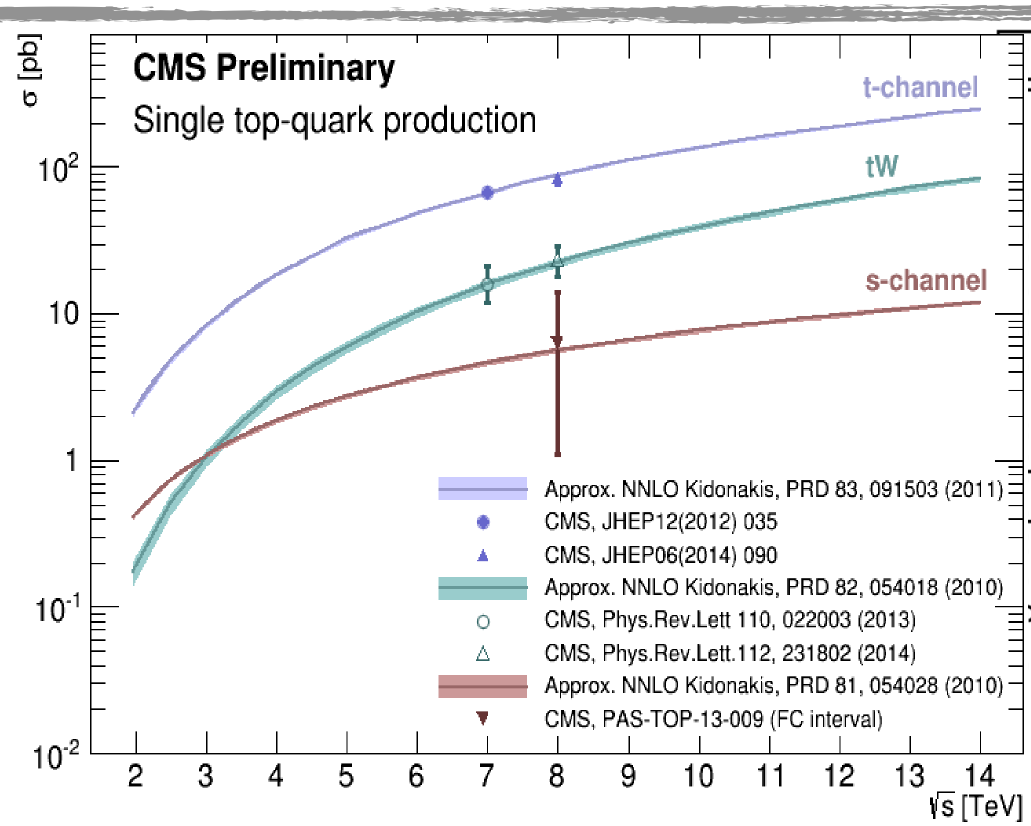


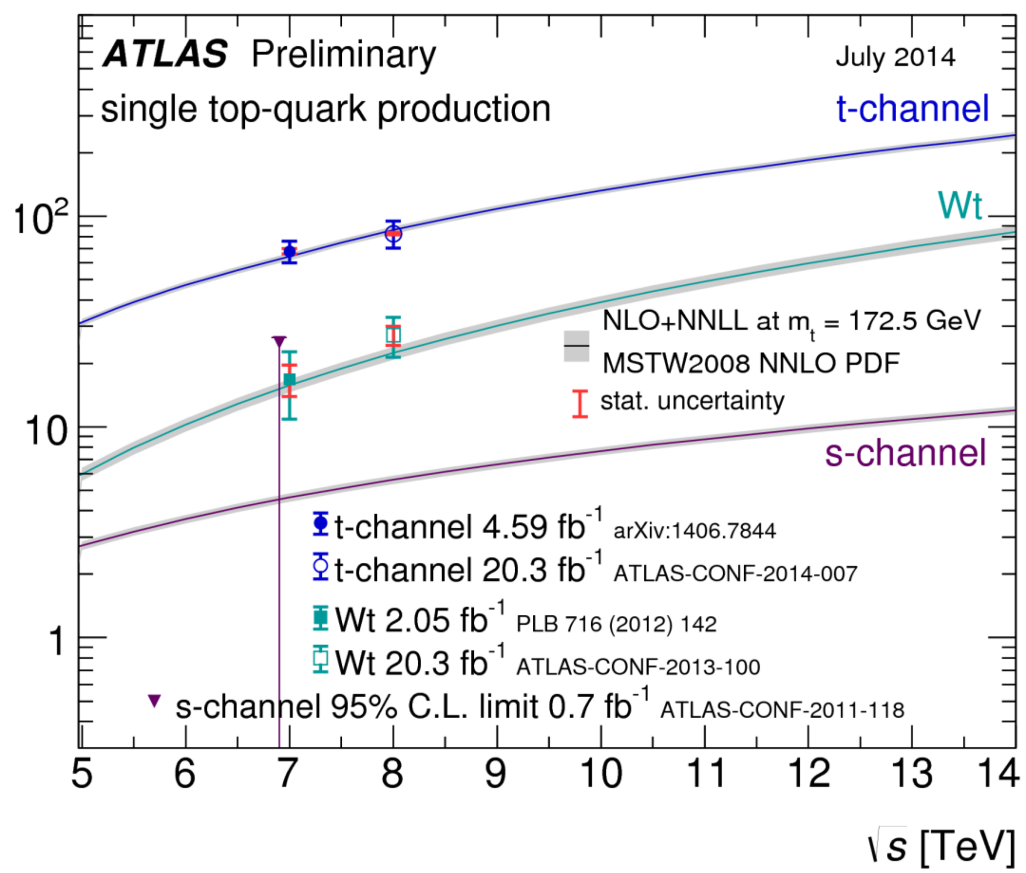
Single Top at the LHC



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

Single Top at the LHC





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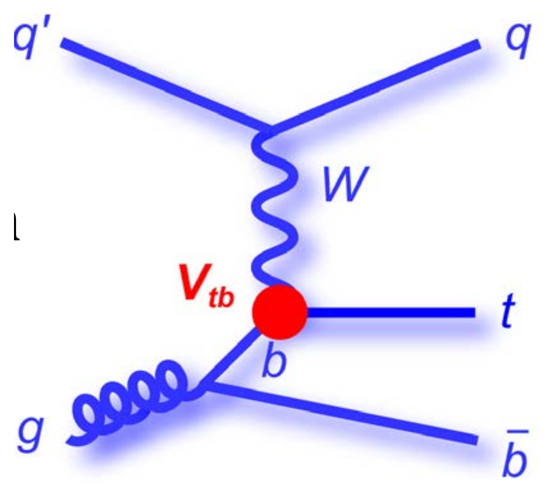
Single Top at the LHC



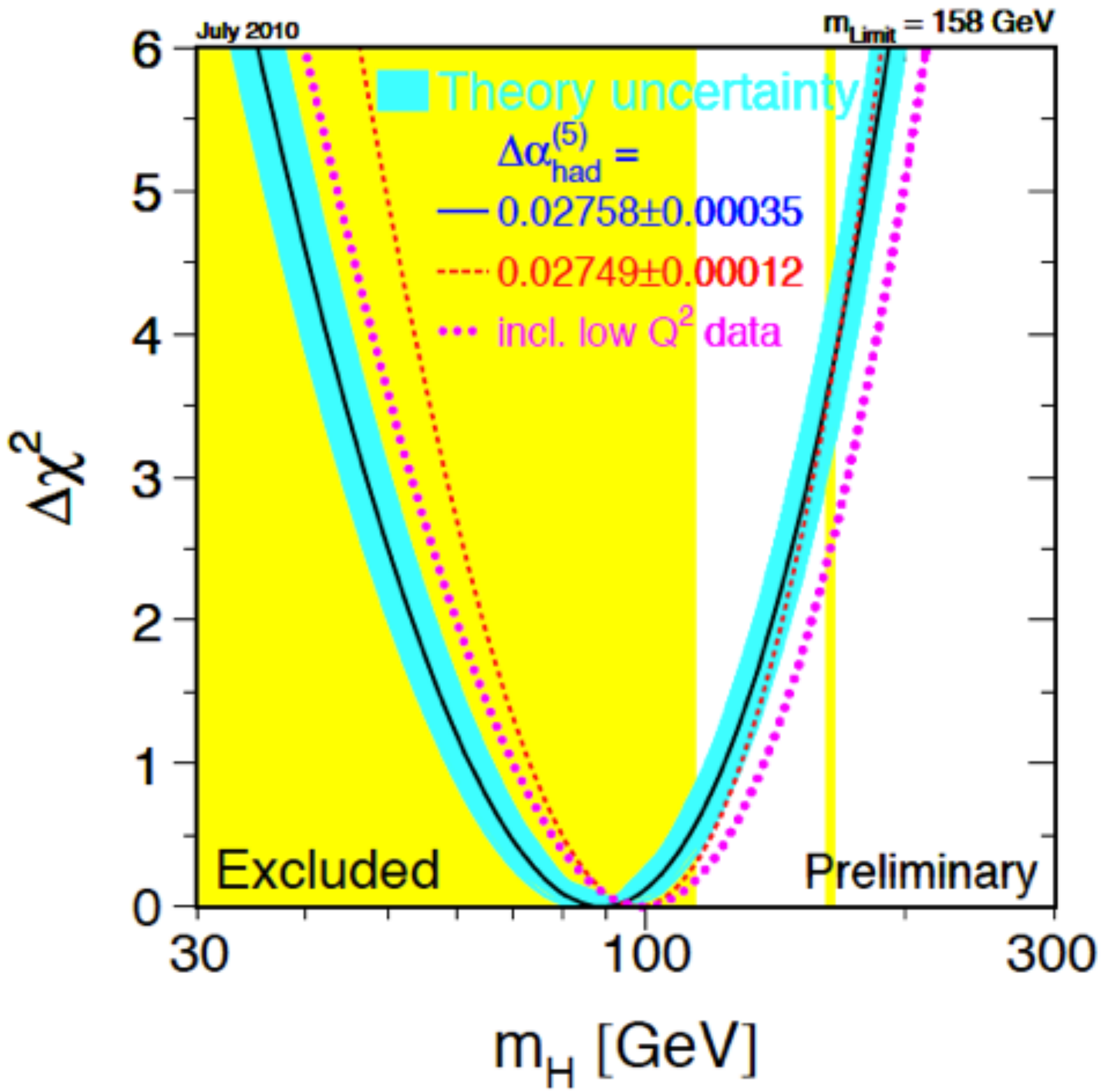
ATLAS: $|V_{tb}| = 1.02 \pm 0.07$
$|V_{tb}| < 1$ ➡ $0.88 < |V_{tb}| <= 1$ @ 95% C.L.

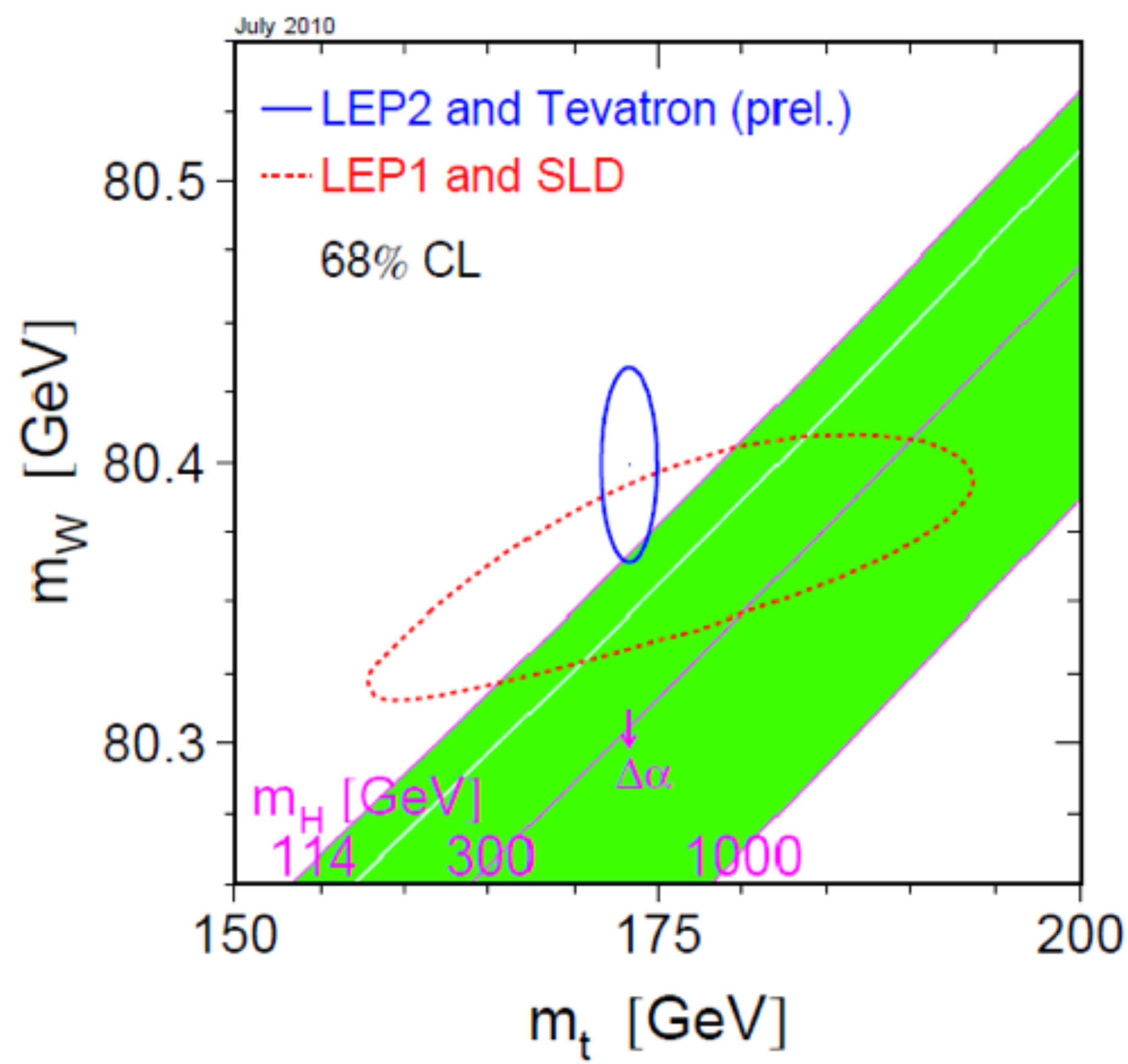
CMS: $|V_{tb}| = 1.020 \pm 0.049$
$|V_{tb}| < 1$ ➡ $0.92 < |V_{tb}| <= 1$ @ 95% C.L.

- One example - After all selections in particular in the t channel a strong signal
  - The cross section is according to the expectation
  - The CKM-Element Vtb is consistent with 1, uncertainties on the 5-7% level

Top Quark Properties:
Mass

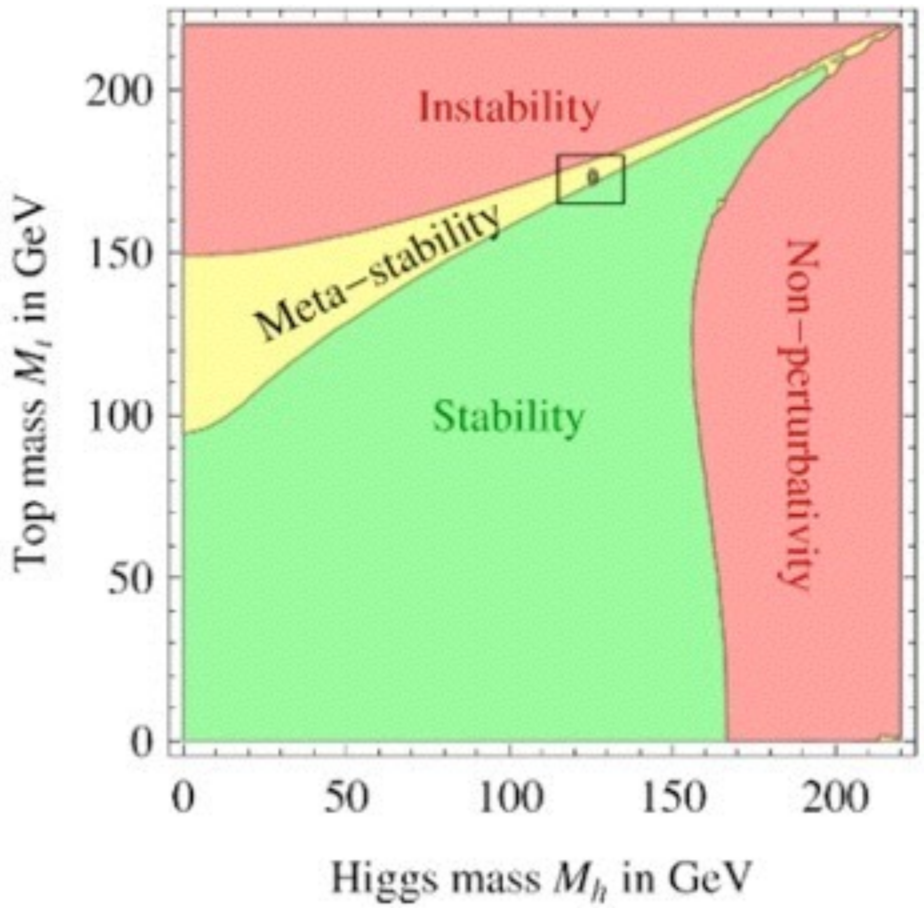
Reminder: Top Mass in the Standard Model

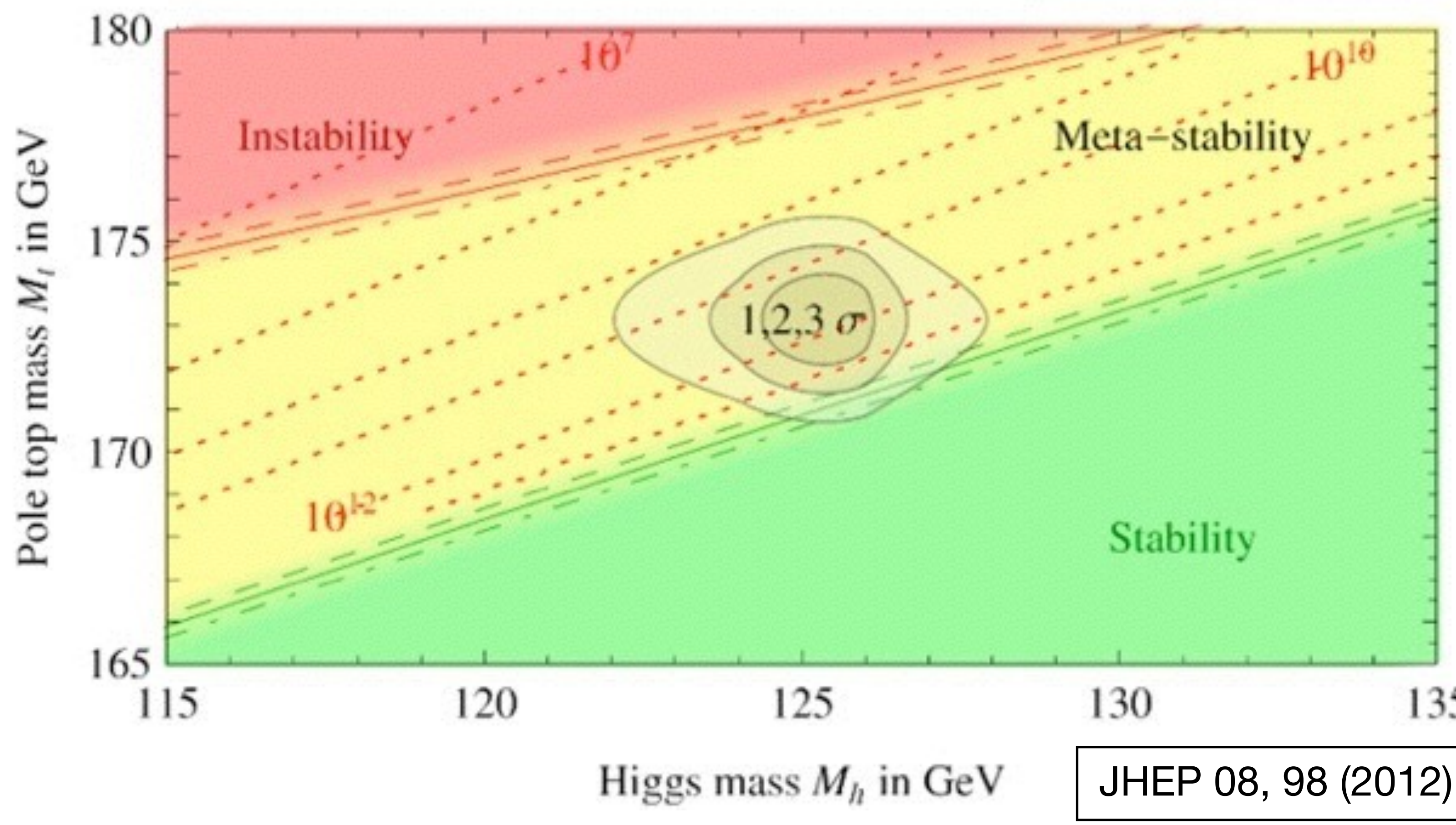




- Precise determination of the top mass provides information on the Higgs!
  - Already before the discovery in 2012 it was known that the (SM) Higgs has to be light (< ~ 160 GeV)

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

- 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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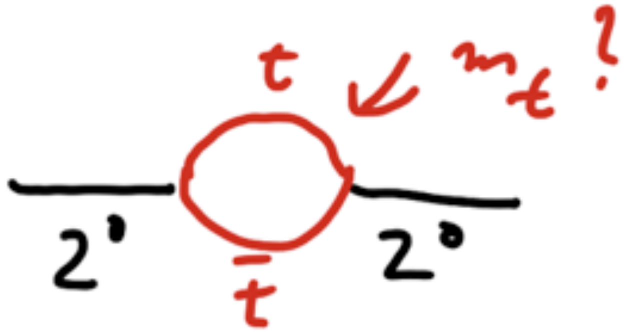
For **theory**: The mass has to be relevant for precision calculations



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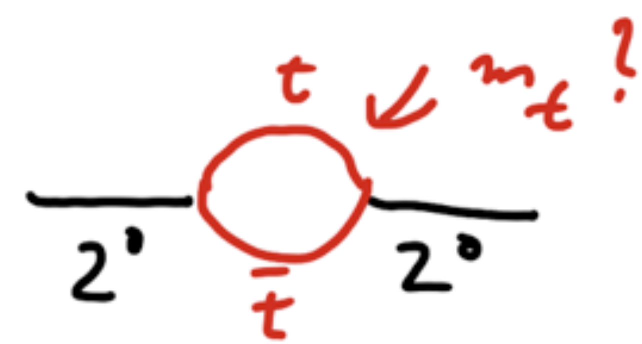
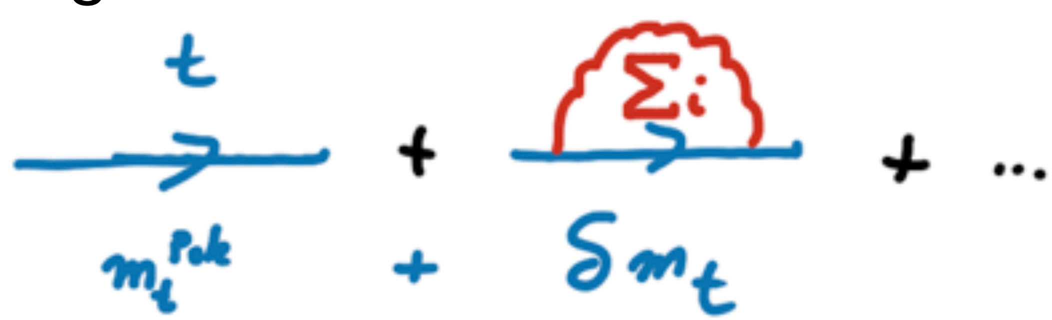


Defining the mass of the top is not trivial - it is influenced by QCD corrections at higher orders

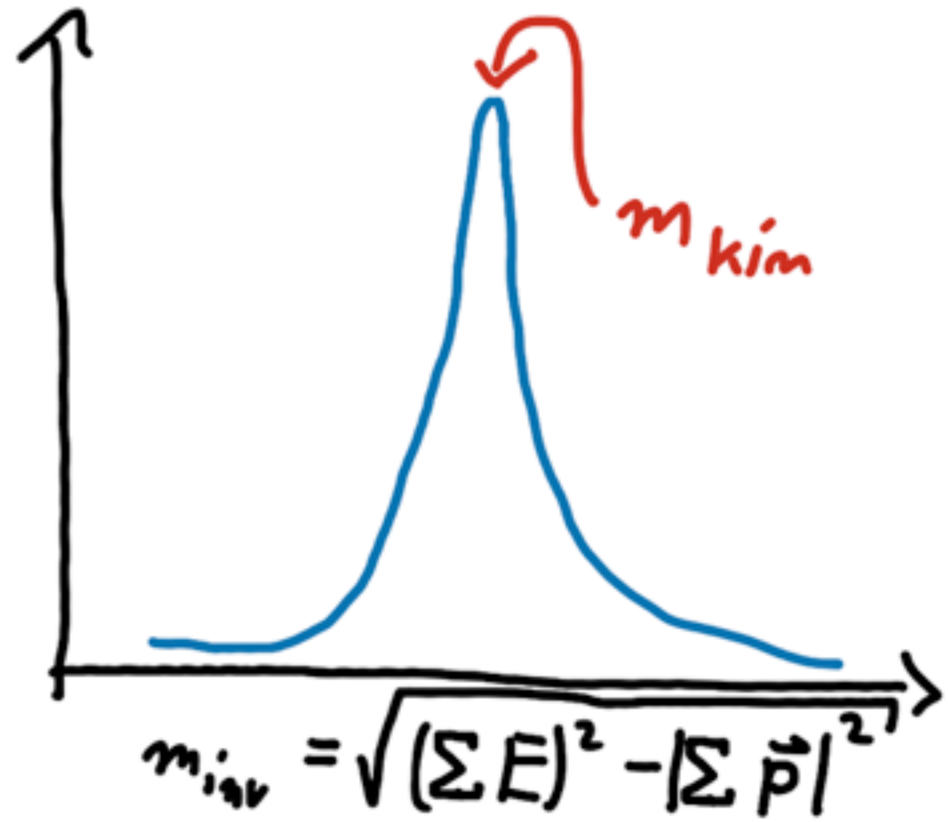


Several definitions exist in theory, depending on the need of the calculations - They can typically be converted with high precision with higher order calculations - Uncertainties on the **100 MeV** level

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



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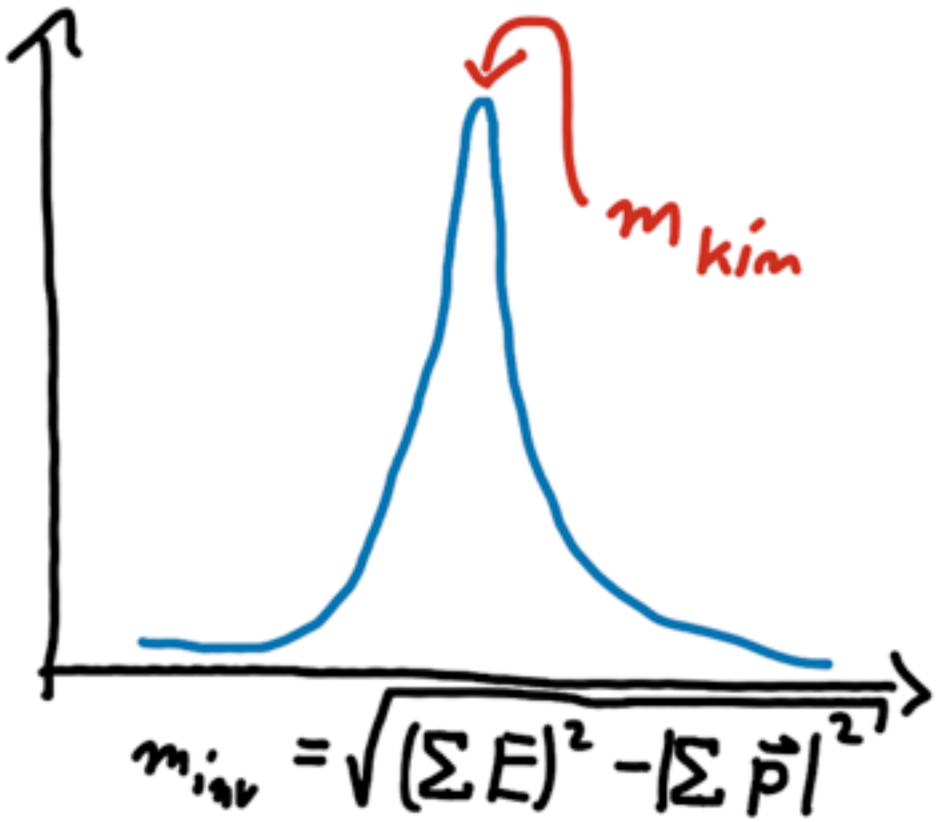

The challenge: The connection between the experimentally measured “kinetic mass” and the theoretical definitions is unclear - non-perturbative corrections from the strong interaction
Uncertainties on the **GeV** level - comparable to experimental precision of current experiments, will become critical for future top mass measurements!

Measurement of the Top Mass at LHC

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- Measurement in all final states of top pair events:
  Di-Lepton, Lepton+Jets, All Hadronic

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- Different methods are used - (almost) all based on kinematic reconstruction:
  - Template-Method: The measured distribution is compared with simulated distributions using different generator top masses as input
  - 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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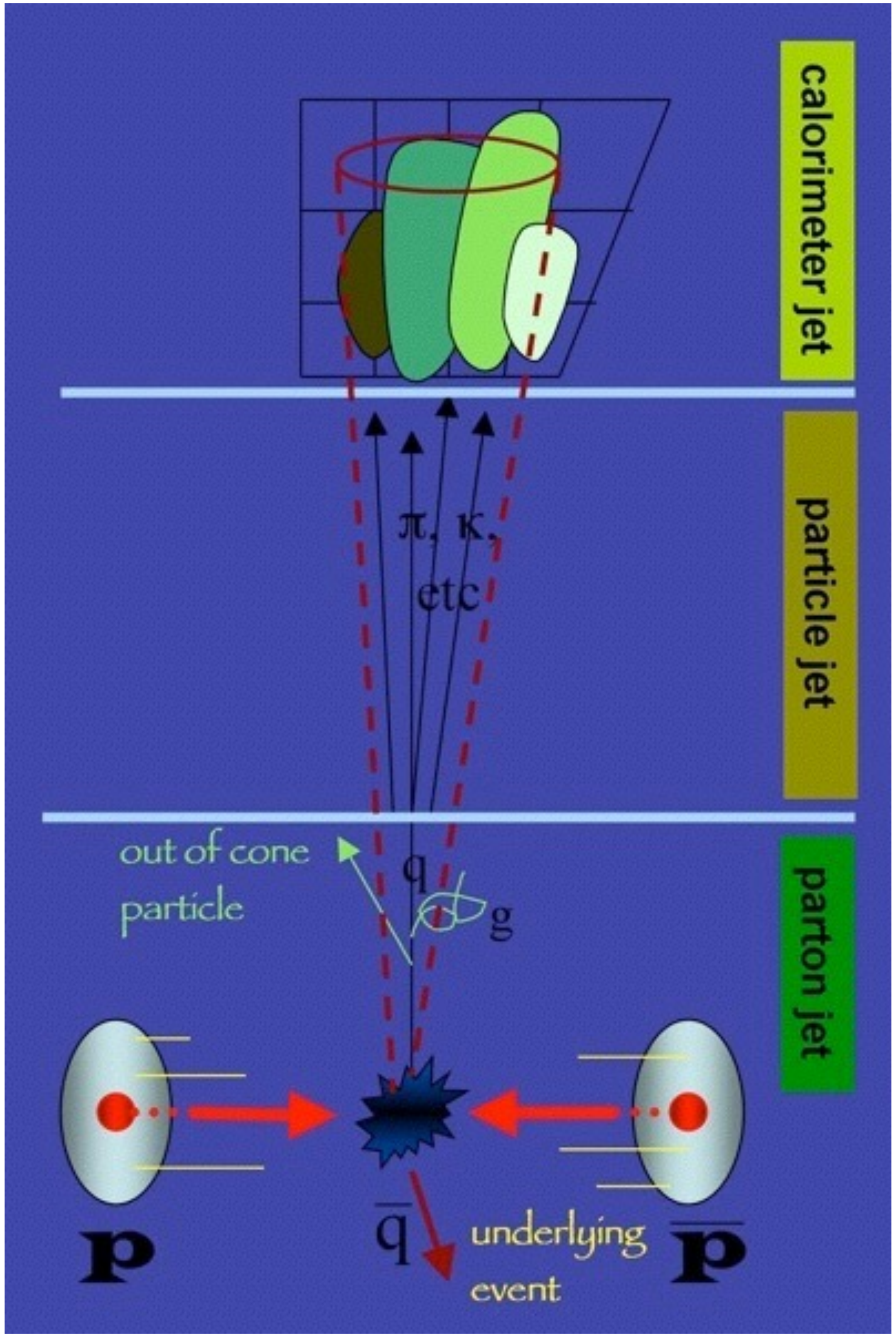
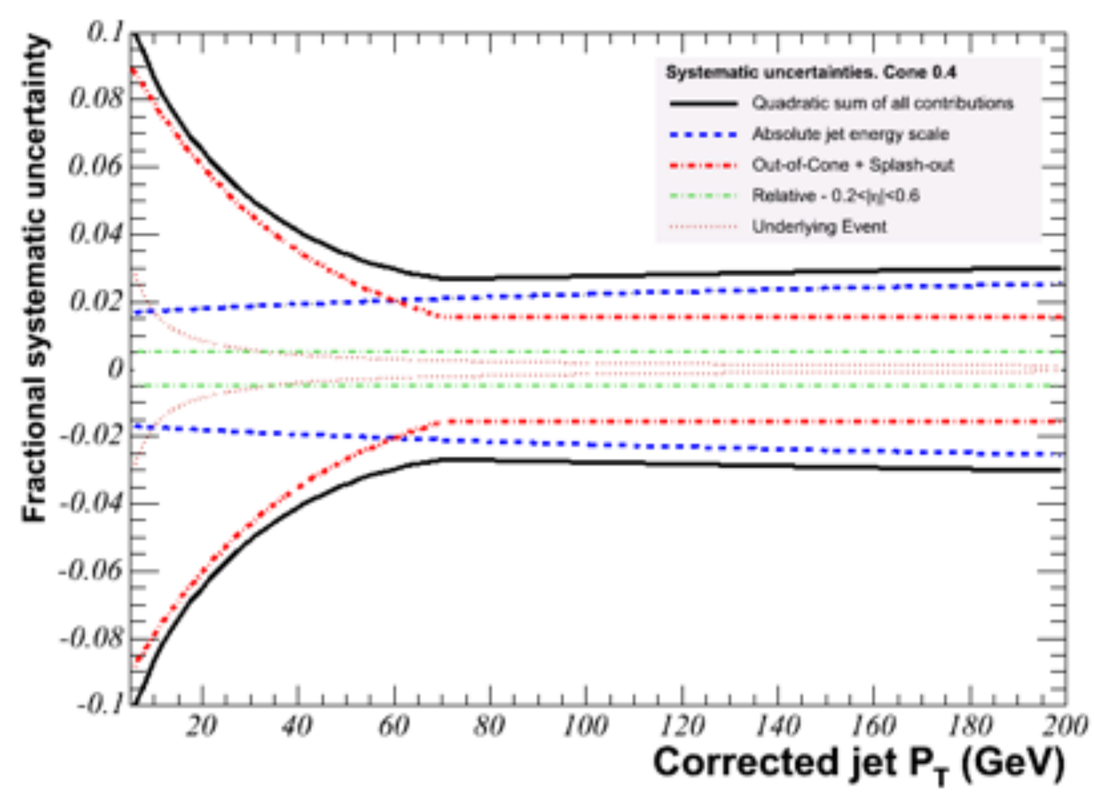
▸ Best accuracy achieved by multi-dimensional fits to reduce systematics

- Most measurements are already limited by systematic uncertainties
  - Important contribution: Jet Energy Scale

Jet Energy Scale JES



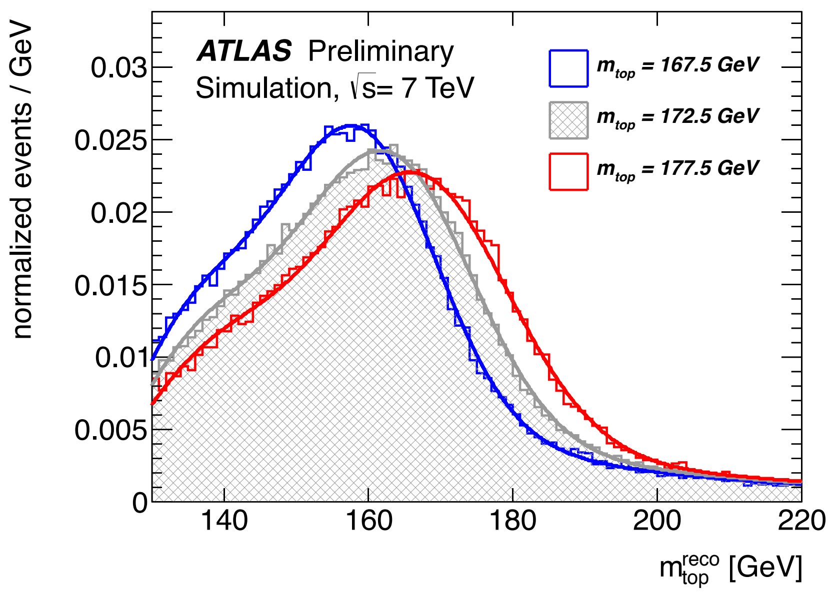
- The measurement of a jet:
  - Energy in a cone with a certain radius (various definitions in use) typically in the calorimeters (more sophisticated approaches also use tracks)
- The physics observable:
  - Energy of the original parton
- The energy scale corrects from the measured jet energy to the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

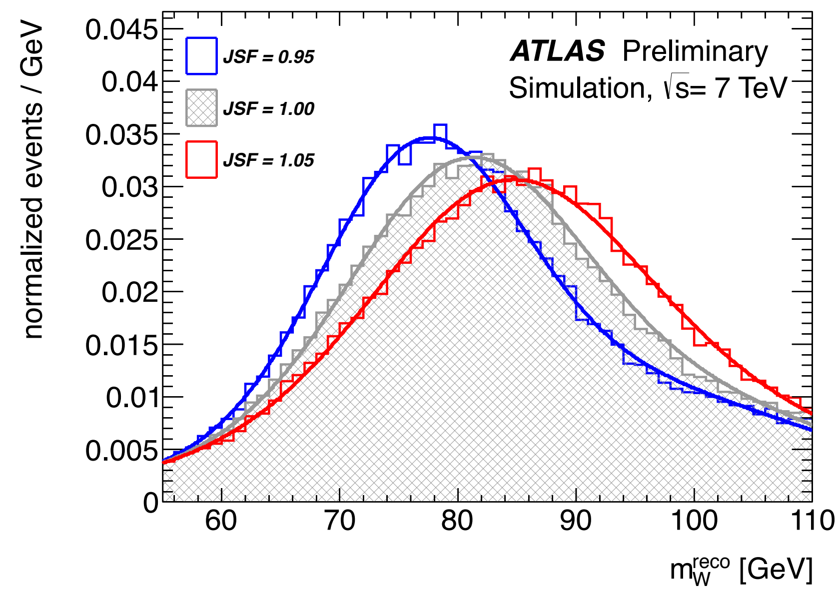


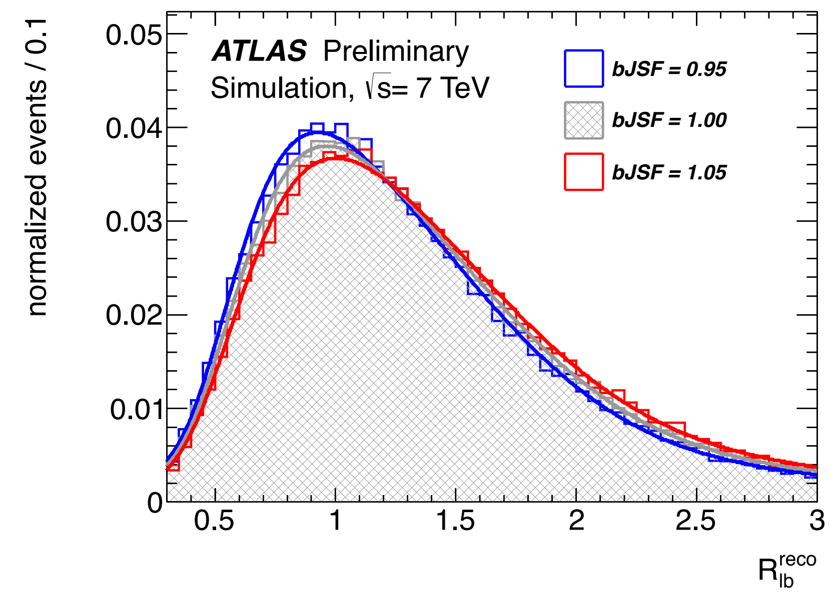
CDF

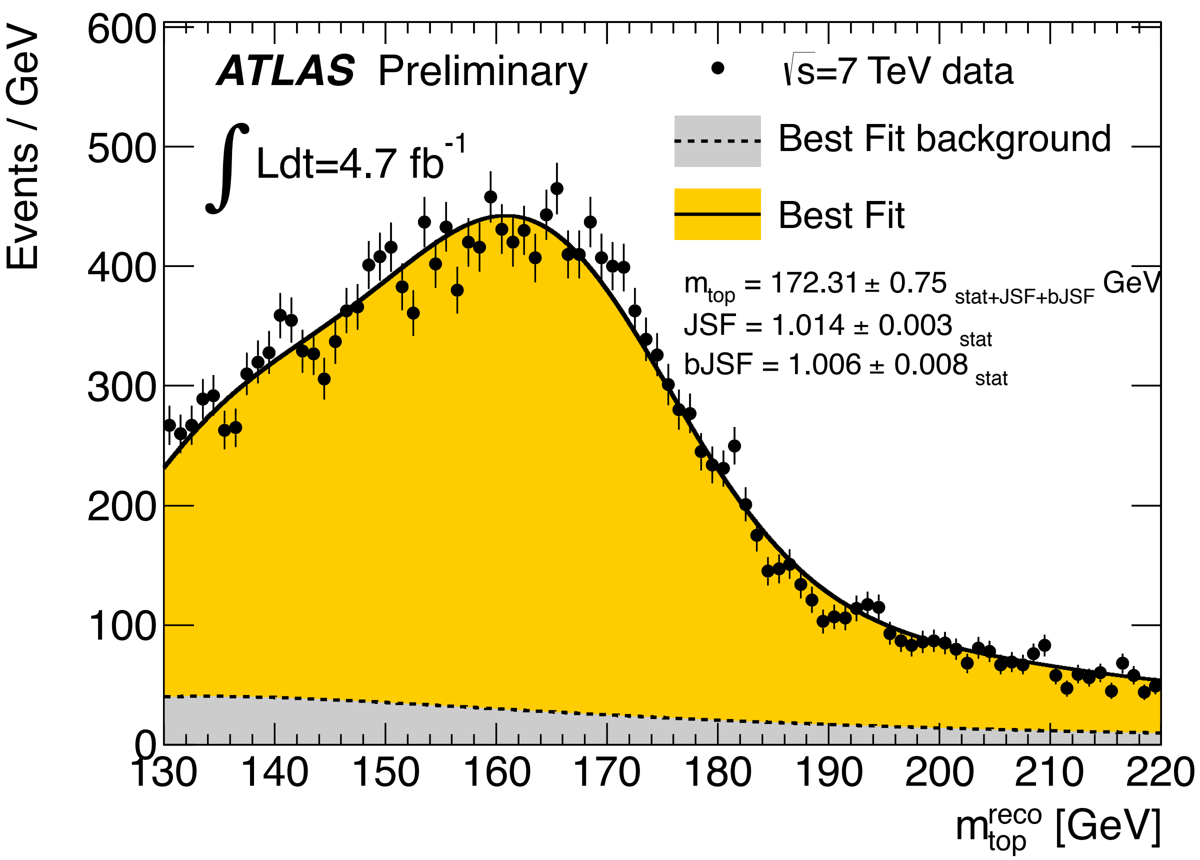
One Example: Lepton + Jets in ATLAS

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





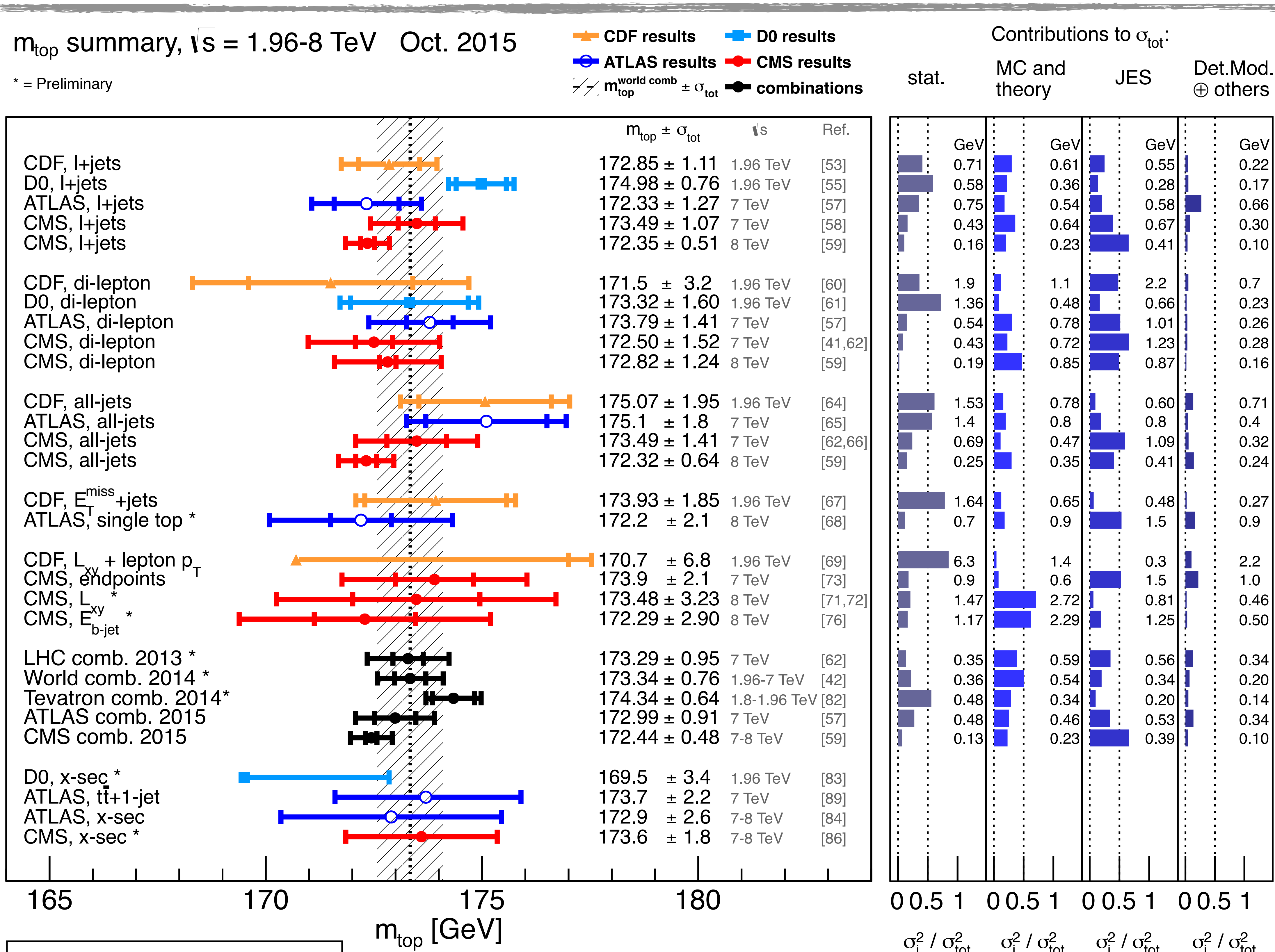




3D fitting substantially reduces systematics (-40% compared to previous technique!)

m_{top} = 172.31 ± 0.23(stat) ± 0.27(JSF) ± 0.67(bJSF) ± 1.35(syst) GeV

Top-Mass: Current Status (March 2014)



G. Cortiana, arXiv:1510.04483

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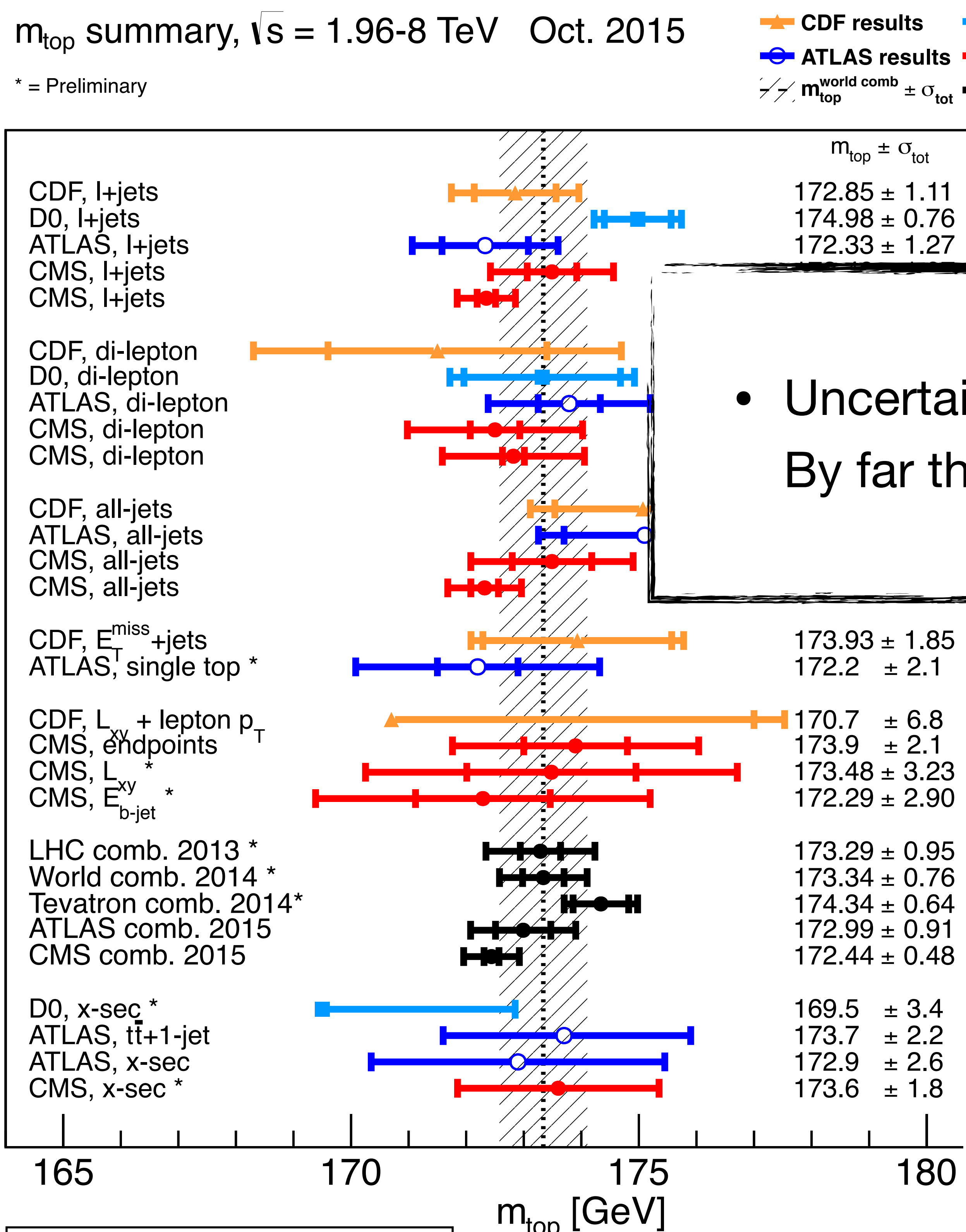
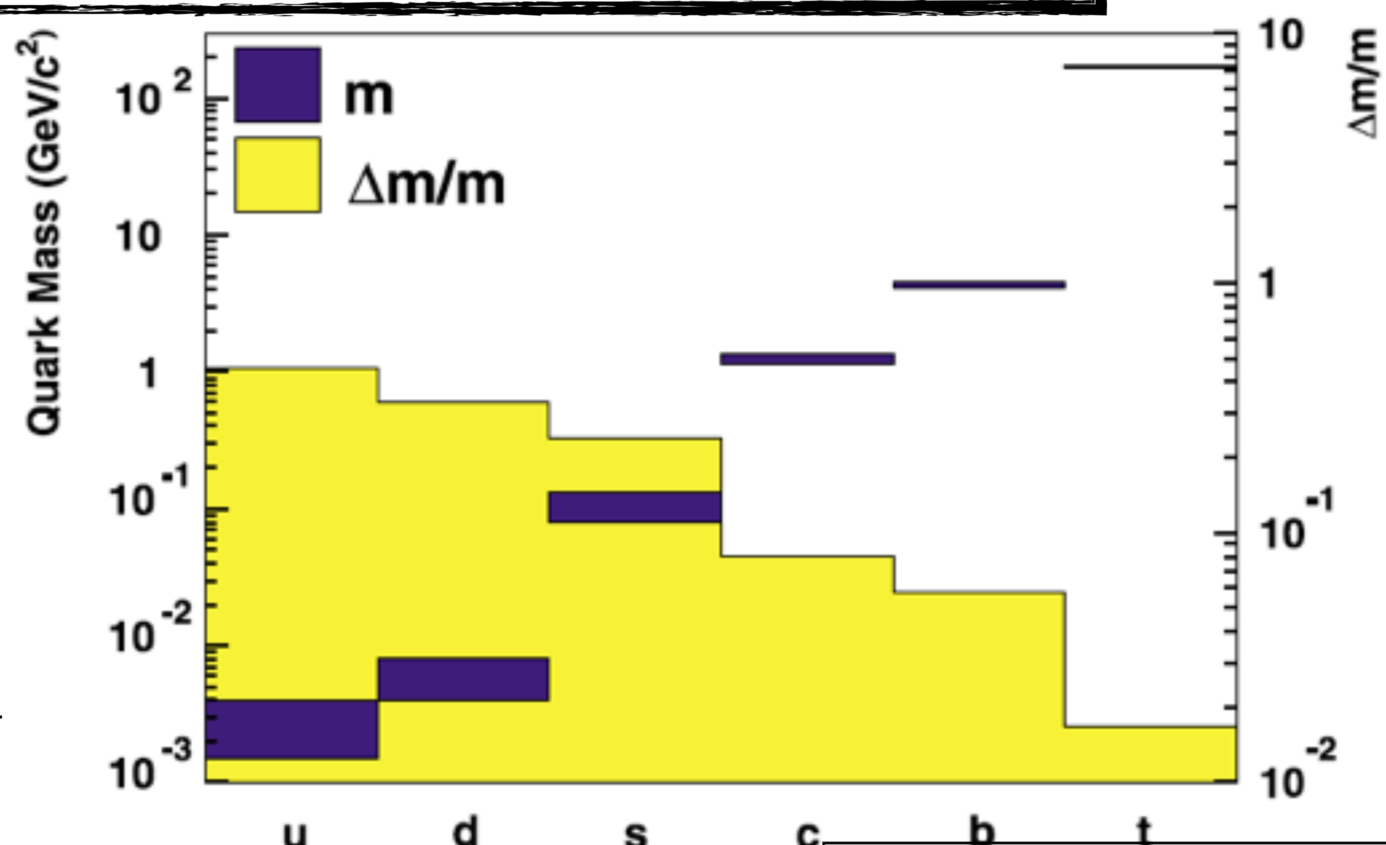


G. Cortiana, arXiv:1510.04483

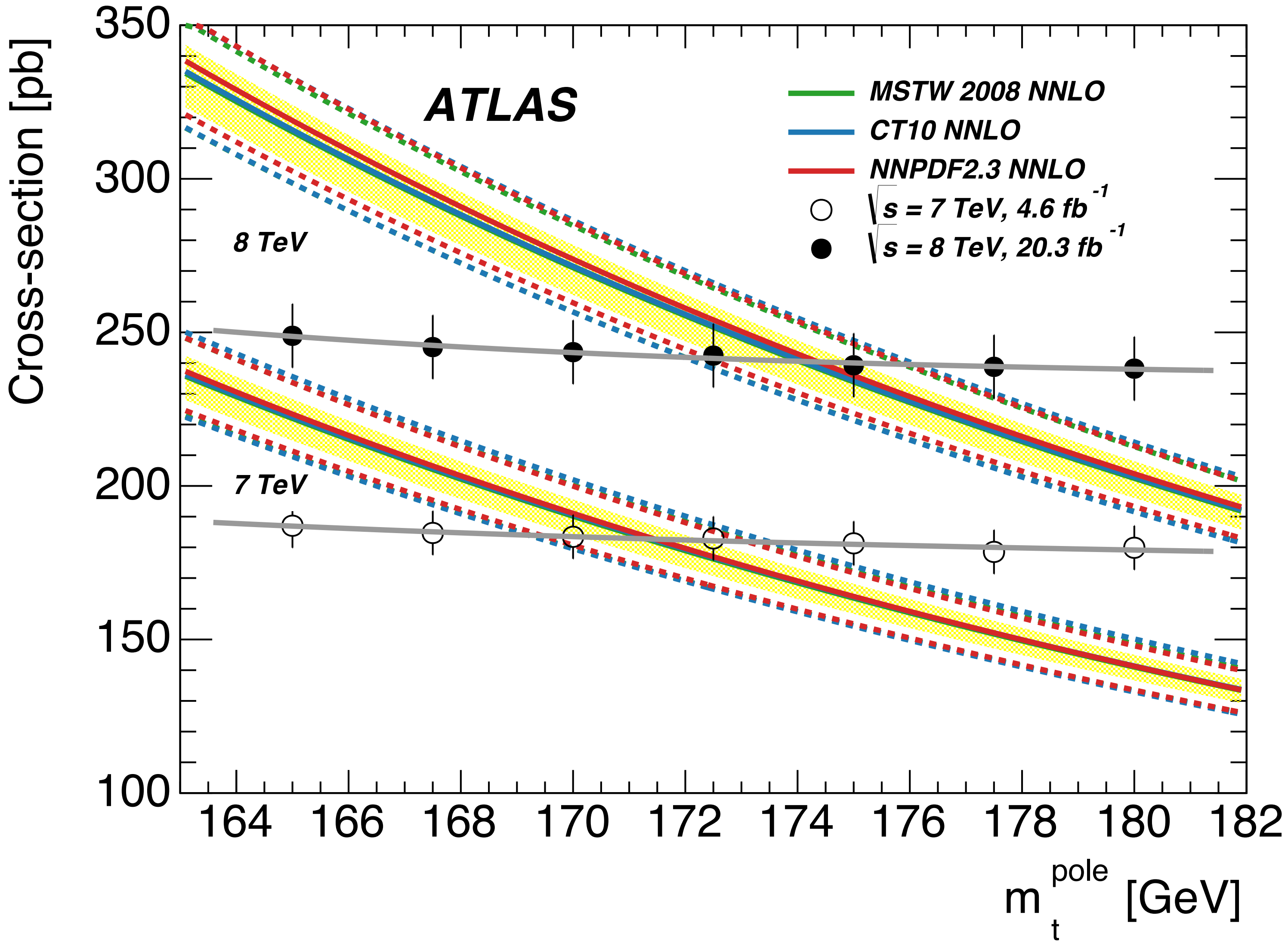
- Uncertainty on the top quark mass **< 1%**:
  By far the best-known quark mass!



A. Quadt, EPJC 48, 835 (2006)

Connection to Theory

- First attempts to measure theoretically well understood mass parameters: Pole mass via the ttbar cross section



Large Uncertainties:
Additional uncertainties from pdf uncertainties

Results:

CMS: $m^{pole} = 176.7^{+3.0}_{-2.8}$ GeV

ATLAS: $m^{pole} = 172.9^{+2.5}_{-2.6}$ GeV

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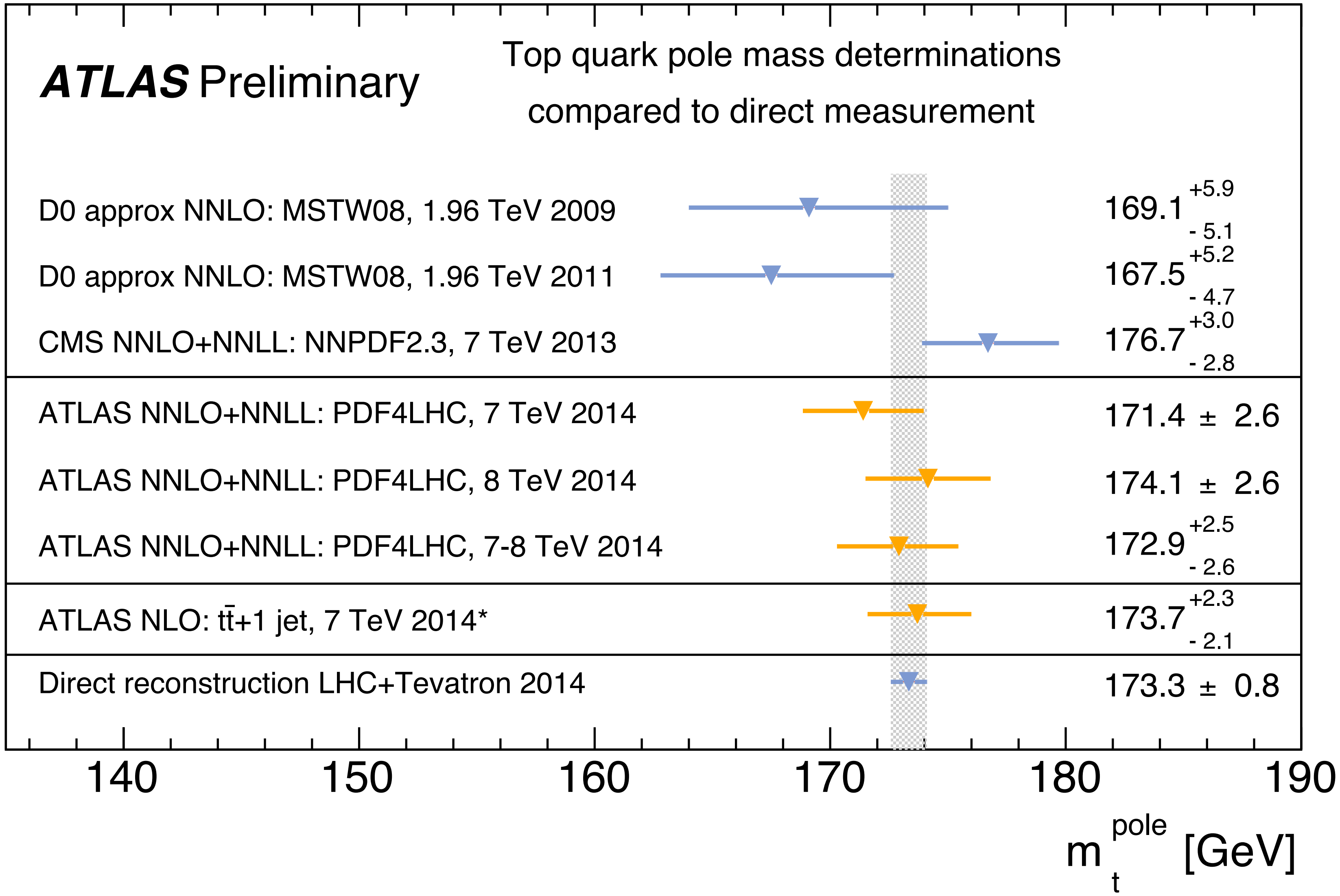

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Important contributions to the understanding of the connection between theory and experiment - will never be competitive in total uncertainty at the LHC

Summary

- The Top quark was discovered in 1995, 20 years after the discovery of the b quark
- As the heavest 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 (2 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: Future Colliders, F. Simon 25.01.2016

Zeitplan

1.	Introduction	12.10.
2.	Particle Detectors I	19.10.
3.	Particle Detectors II	26.10.
4.	Accelerators	02.11.
5.	Trigger, Data Acquisition, Computing	09.11.
6.	Monte Carlo Generators and Detector Simulation	16.11.
7.	Tests of the Standard Model	23.11.
8.	QCD, Jets, Proton Structure	30.12.
9.	Higgs Physics I	07.12.
10.	Higgs Physics II	14.12.
	----------- no lecture -------------	21.12.
	----------- Christmas ---------------------	
11.	Supersymmetry	11.01.
12.	Top Physics	18.01.
13.	Future Collider Projects	25.01
14.	Other models beyond the SM, LHC Outlook	01.02