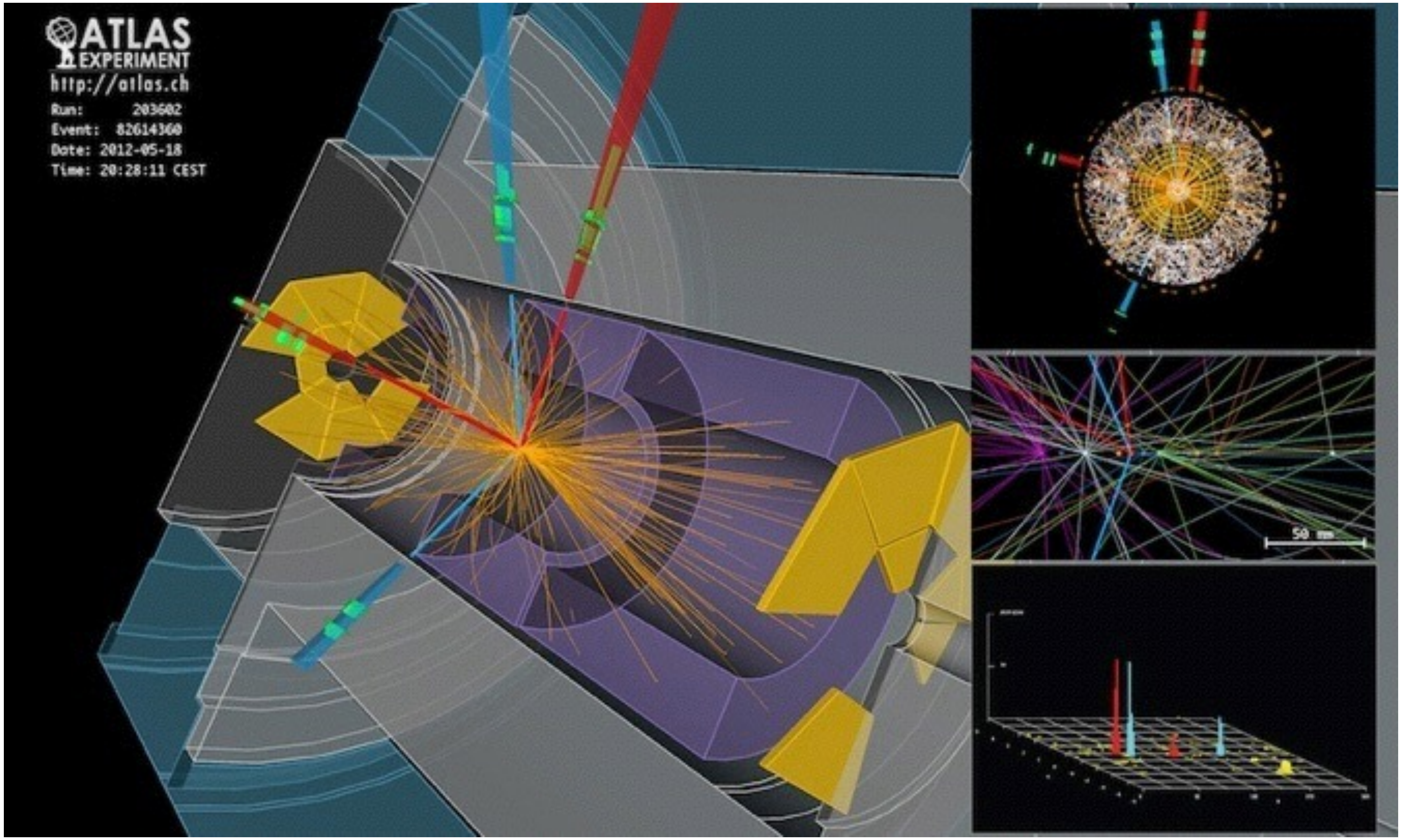
Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)



11. Top Physics

15.12.2013

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

Prof. Dr. Siegfried Bethke
Dr. Frank Simon

Important: Registration for Exams

If you want to take an exam in this course remember to register!

The time & date for the exam is flexible
(the one given in TUMOnline is a dummy date) - Send me an email to fix one!

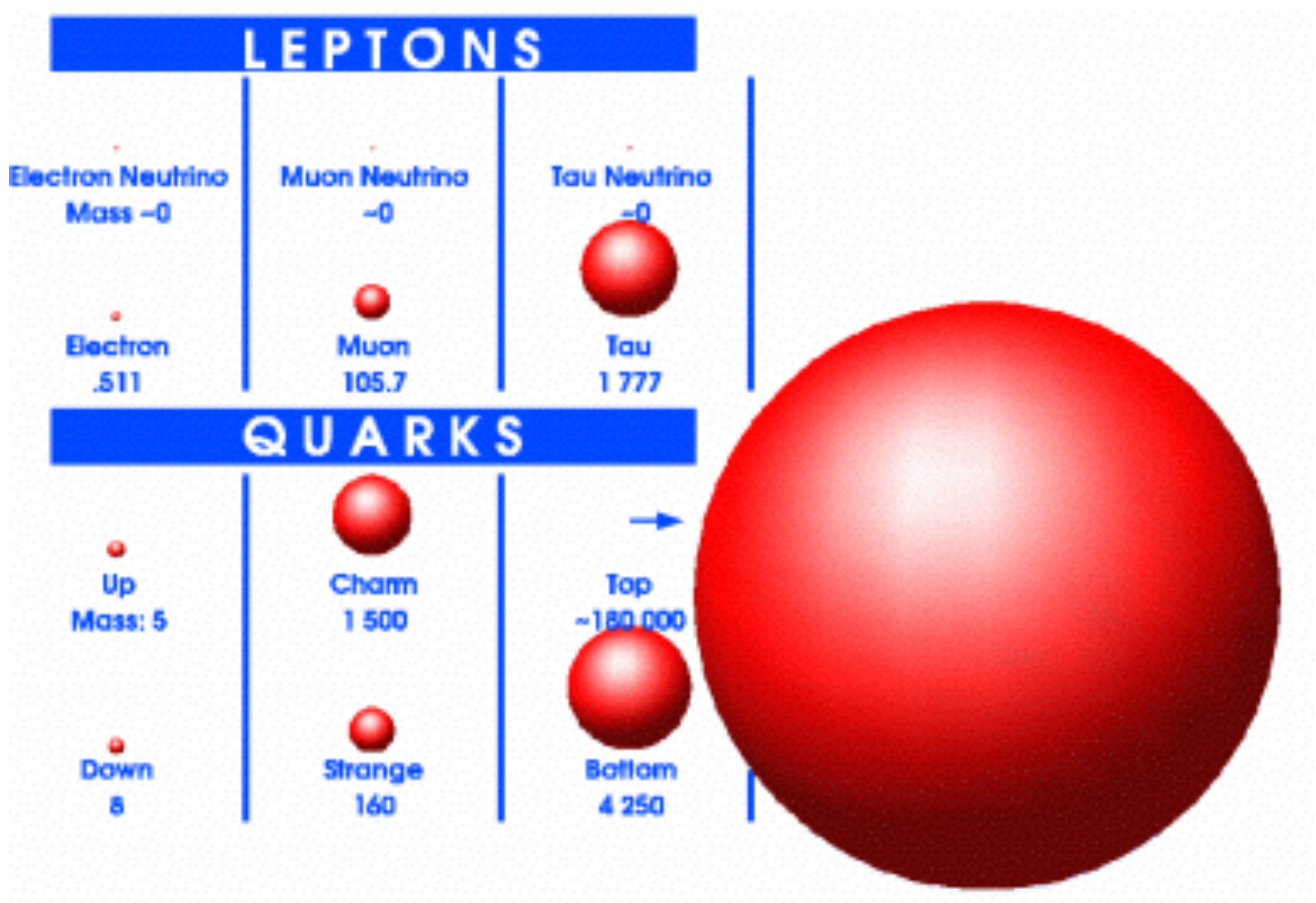
Overview

- 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

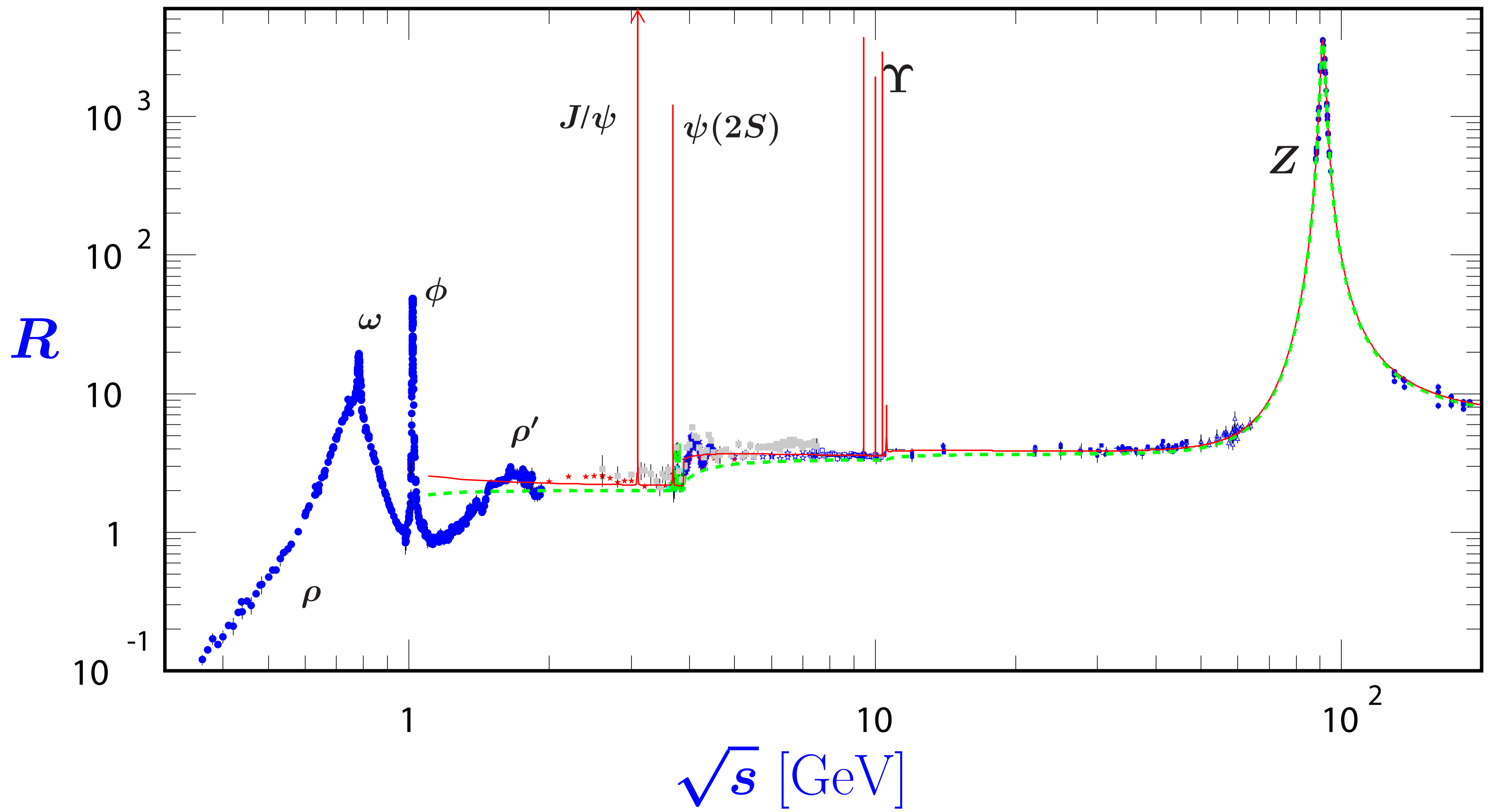
- The Top quark has a special role in the Standard Model
  - It is the heaviest particle, and by far the heaviest Fermion
  - Its mass is comparable to the electroweak scale - The top quark could be a window to new physics!
  - Its life time is shorter than the hadronization time - it does not form bound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



The Questions:

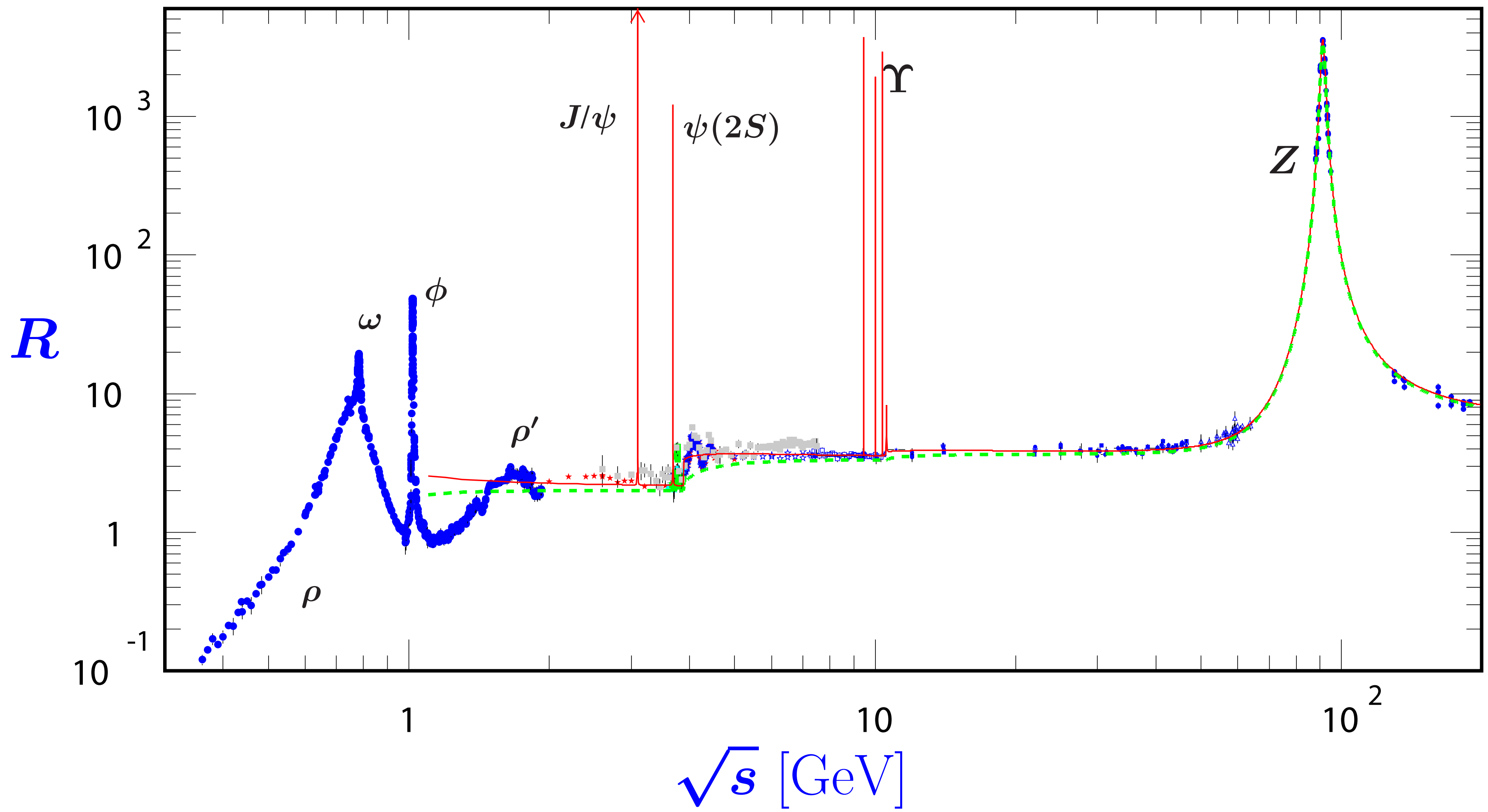
- How are top quarks produced?
- How do they decay?
  - both compared to the SM expectation
- What is the mass of the top quark?

Historical Perspective: Prediction of the Top



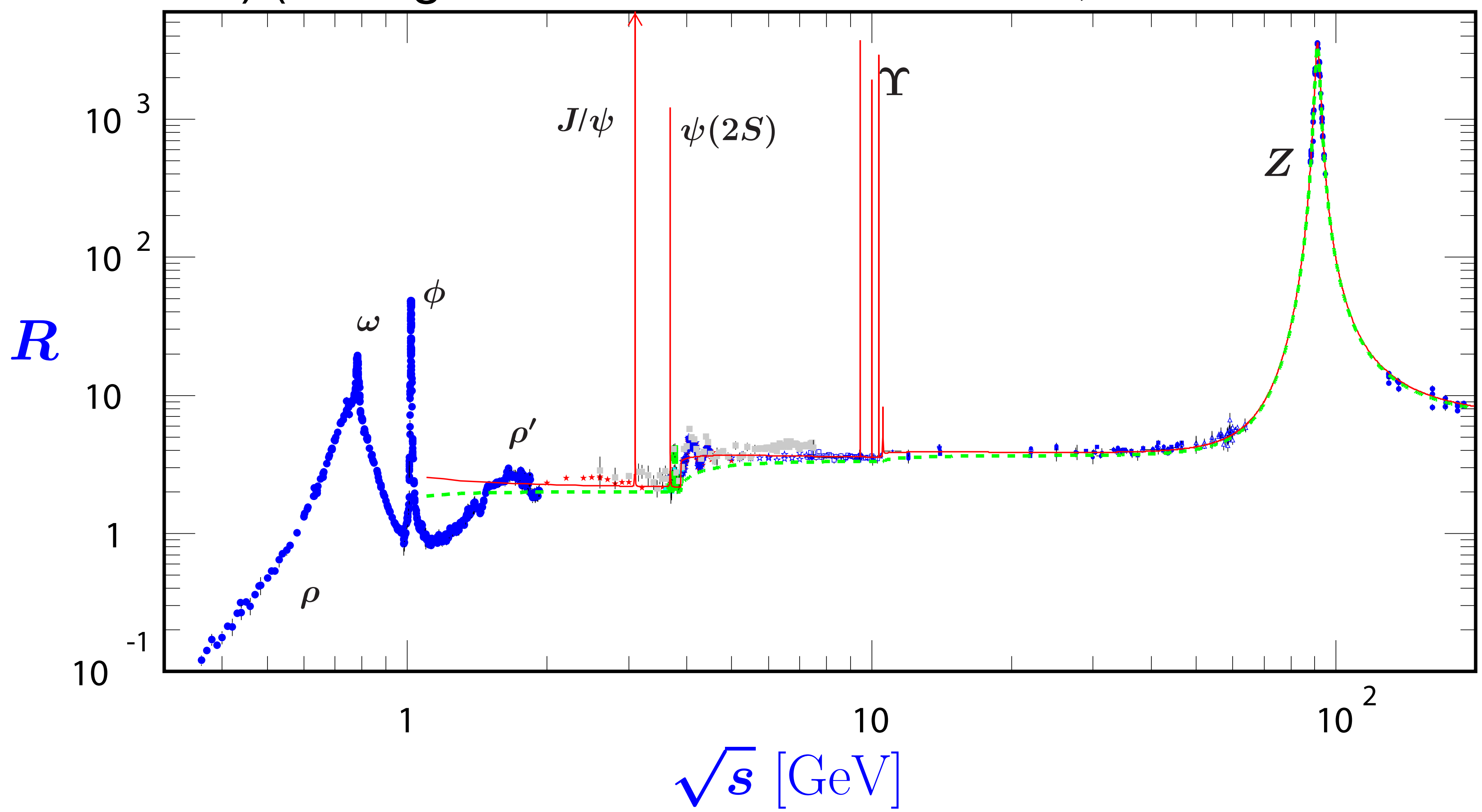
Historical Perspective: Prediction of the Top

- After the discovery of the τ 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



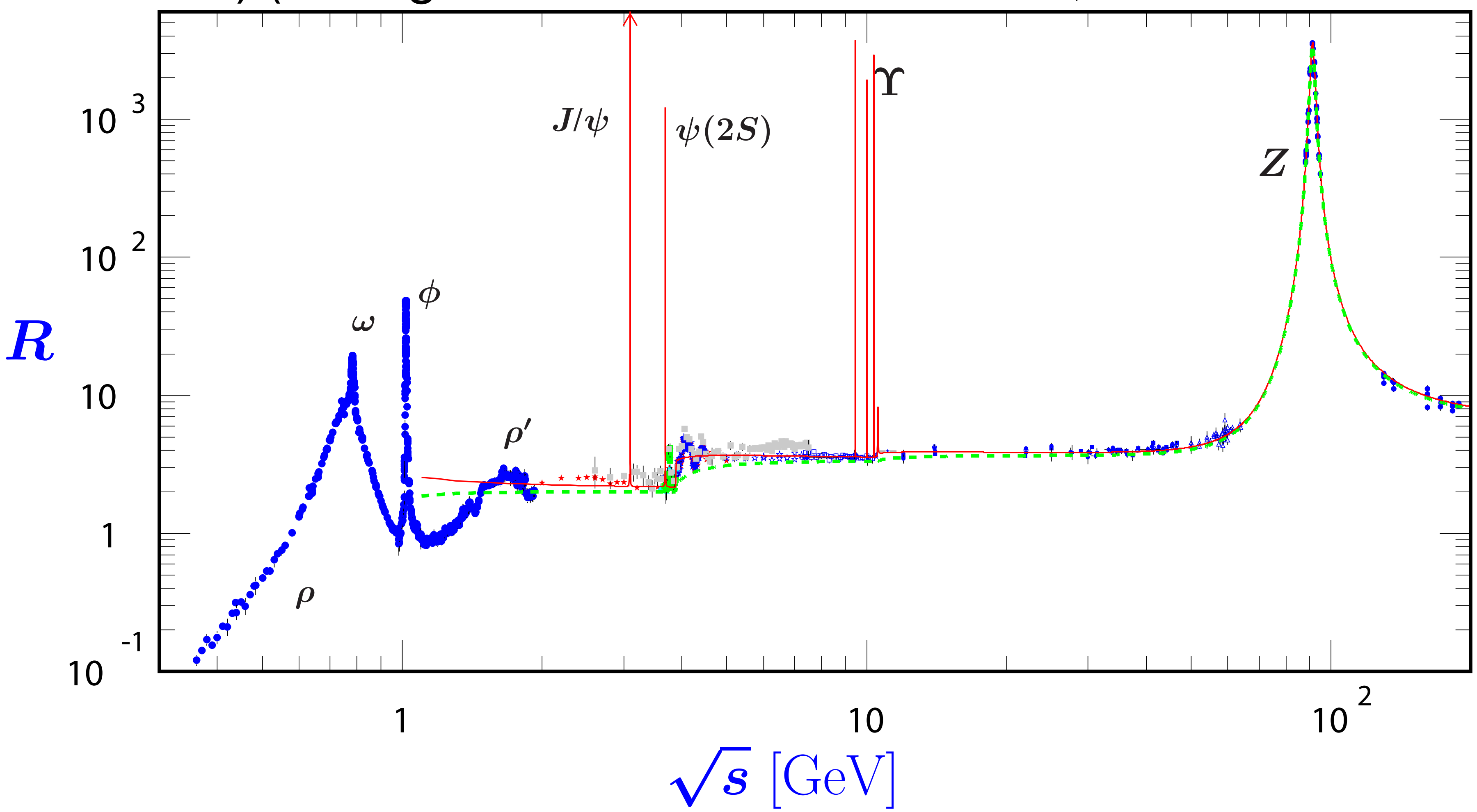
Historical Perspective: Prediction of the Top

- After the discovery of the τ 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
- The discovery of the b quark in 1977 directly implied the existence of the t quark since no flavor-changing neutral currents were observed (in the SM: Due to cancellations of t and b contributions) (analogous to the GIM mechanism, which predicted the c quark)



Historical Perspective: Prediction of the Top

- After the discovery of the τ 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
- The discovery of the b quark in 1977 directly implied the existence of the t quark since no flavor-changing neutral currents were observed (in the SM: Due to cancellations of t and b contributions) (analogous to the GIM mechanism, which predicted the c quark)
- 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)

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)

In the Standard Model (see lecture 03):

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

with

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

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)

In the Standard Model (see lecture 03):

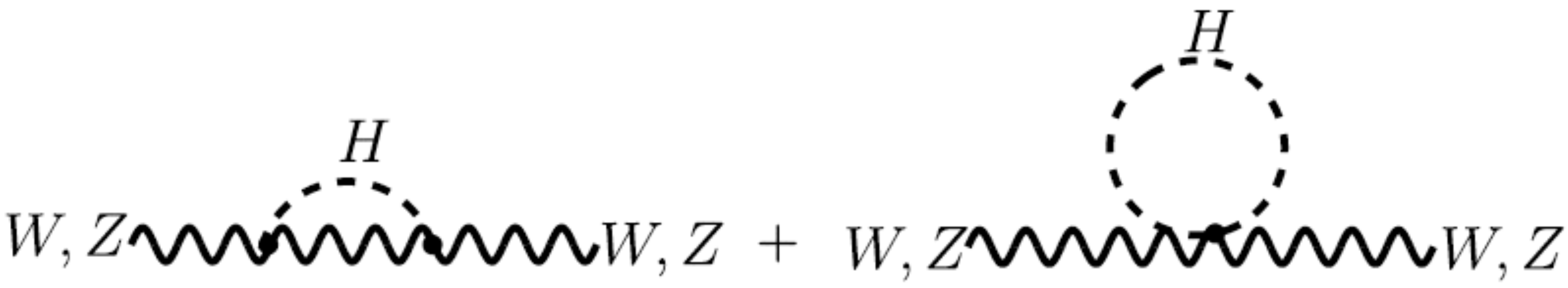
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F}\frac{1}{sin^2\theta_W(1-\Delta r)}$$ with $$\frac{m_W^2}{m_Z^2} = 1 - sin^2\theta_W$$

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 $m_t \gg m_b$

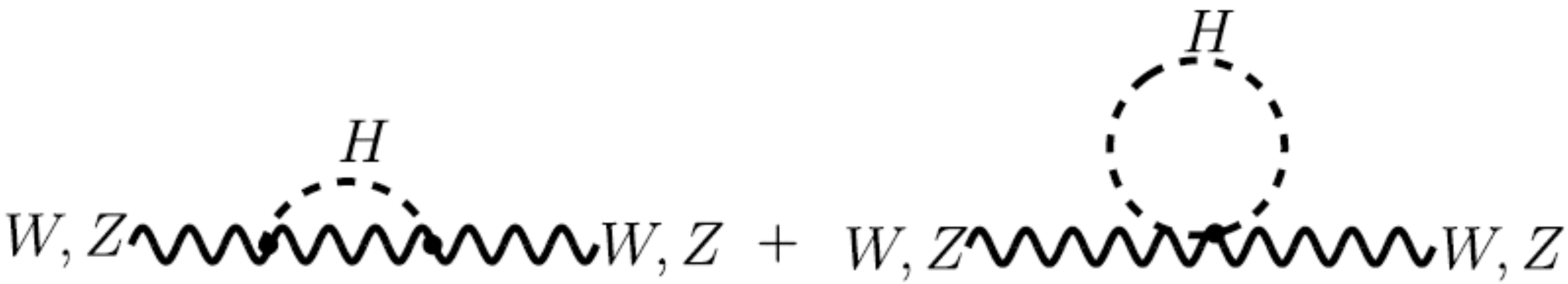
Connections to the Higgs Mass

- Loop corrections also depend on the Higgs:



Connections to the Higgs Mass

- Loop corrections also depend on the Higgs:

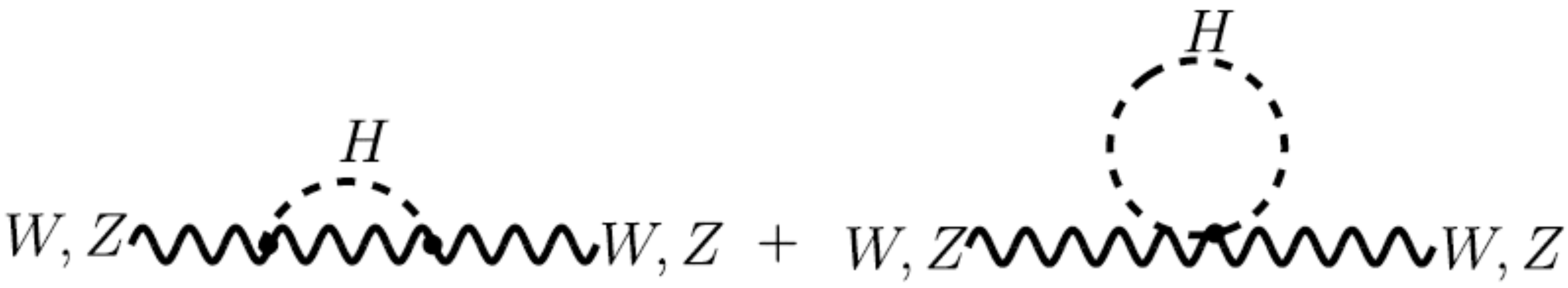


- analogous to the corrections induced by the top there are also corrections originating from the Higgs

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

Connections to the Higgs Mass

- Loop corrections also depend on the Higgs:



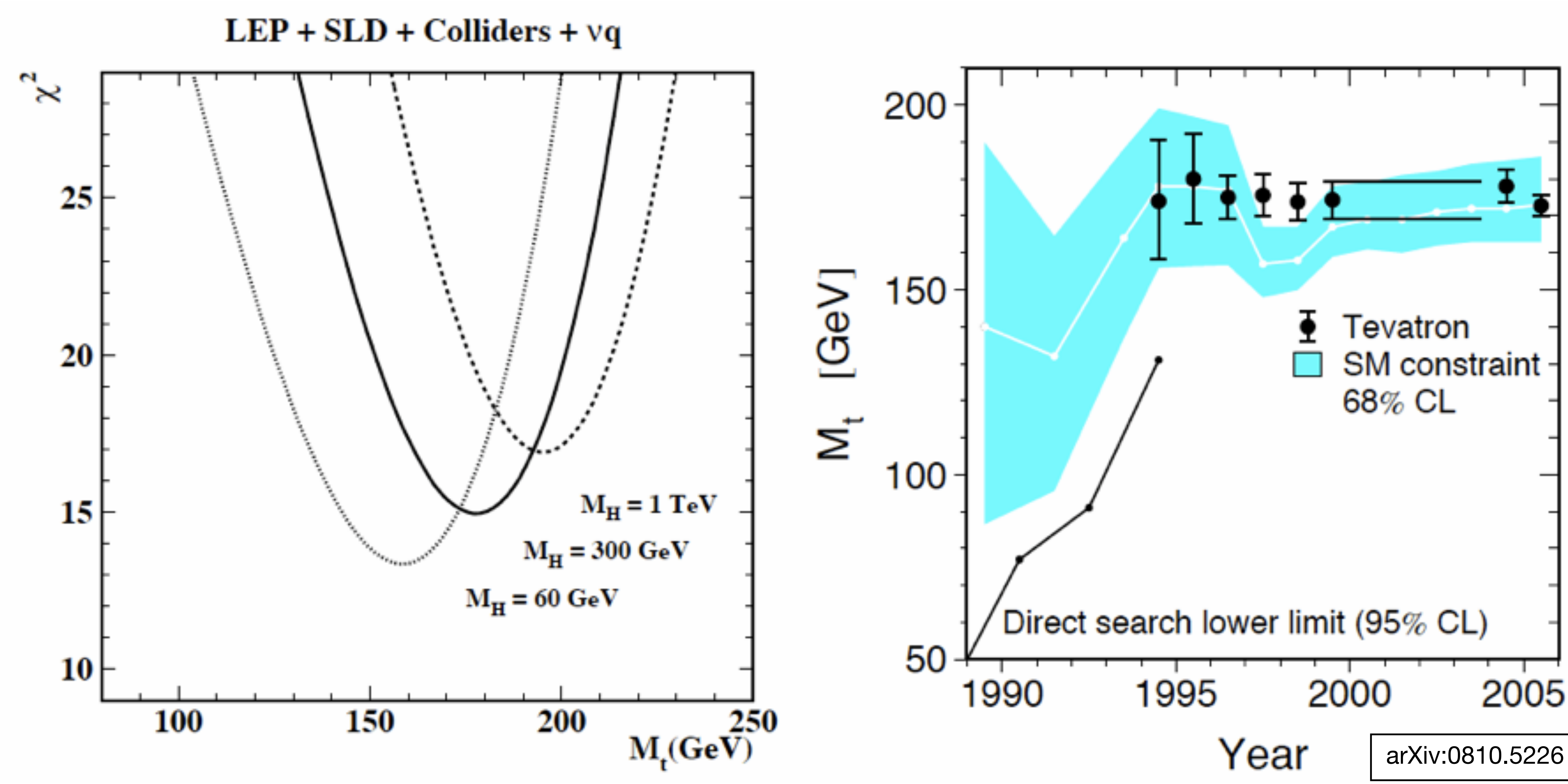
- analogous to the corrections induced by the top there are also corrections originating from the Higgs

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

‣ 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)

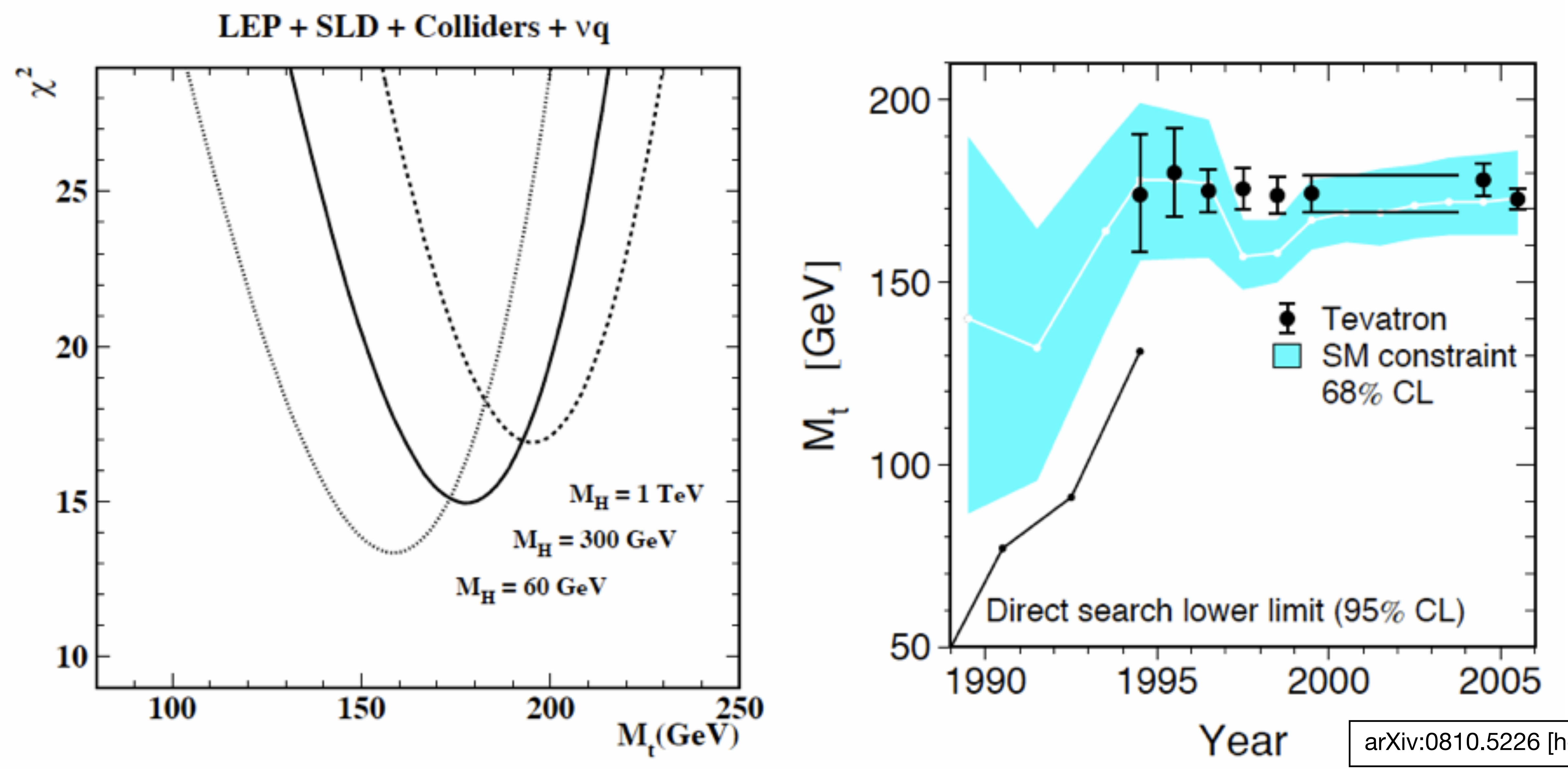
Predicting the Top Quark Mass



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



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!

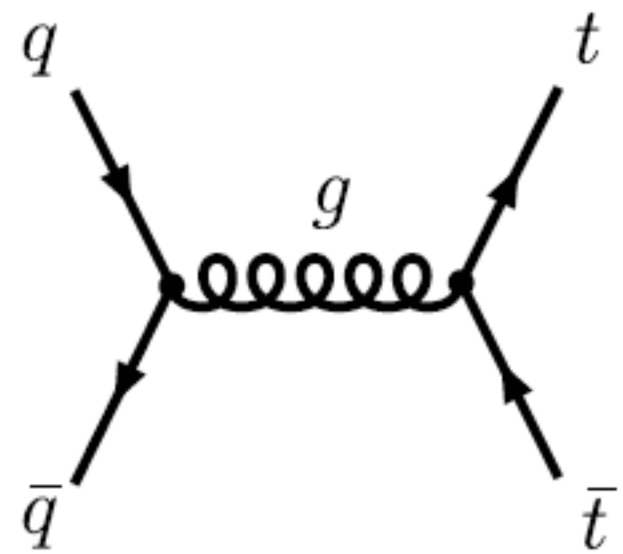
➾ Discovery of the top quark in 1995 at the Tevatron, 18 years after the b

Production and Decay

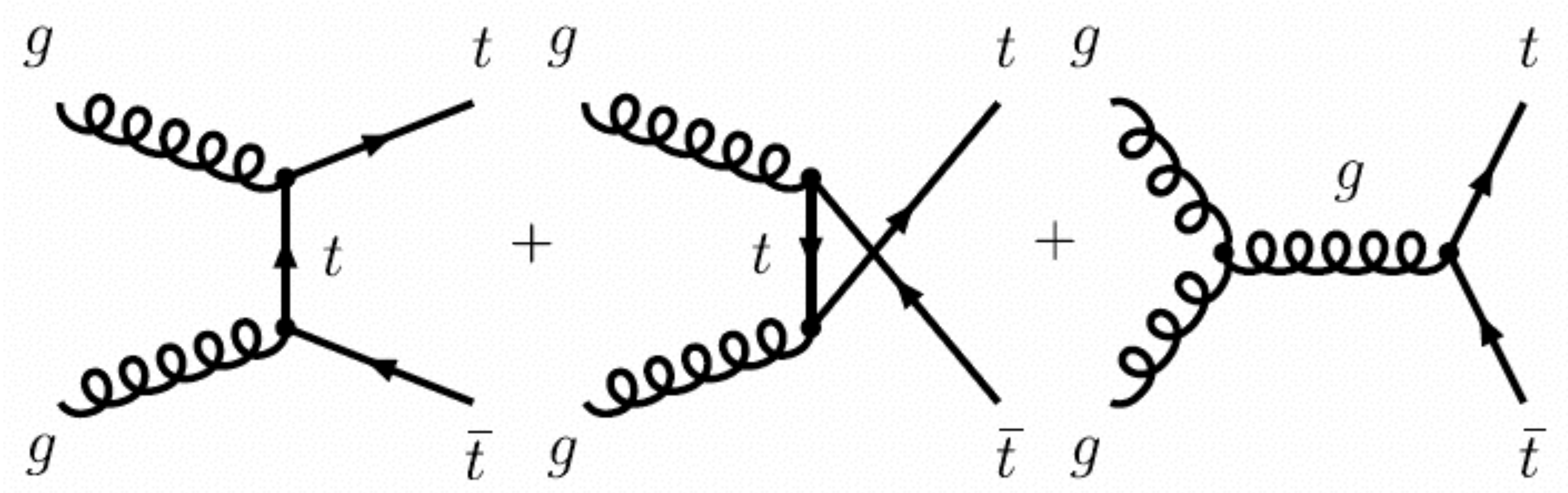
Top Pair Production

- Two important production mechanisms via the strong interaction

Quark-AntiQuark annihilation:



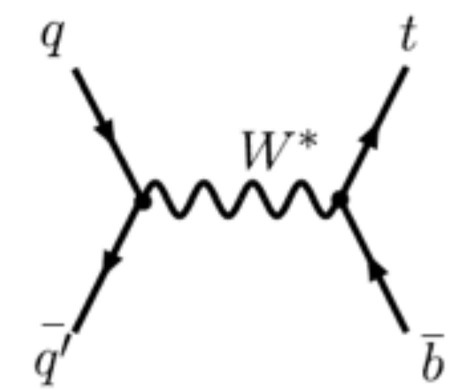
Gluon-Gluon fusion:



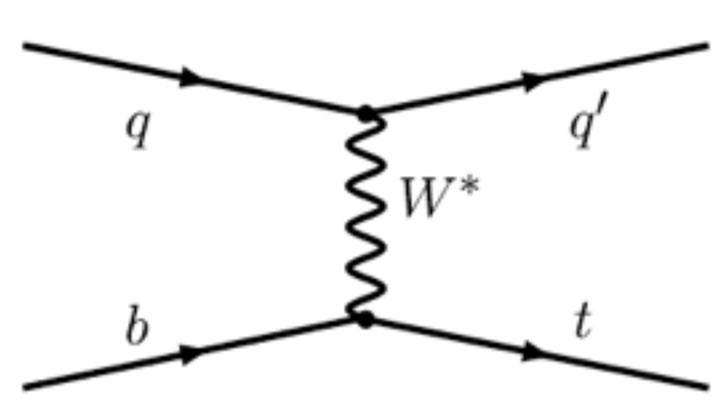
Production of Single Top Quarks

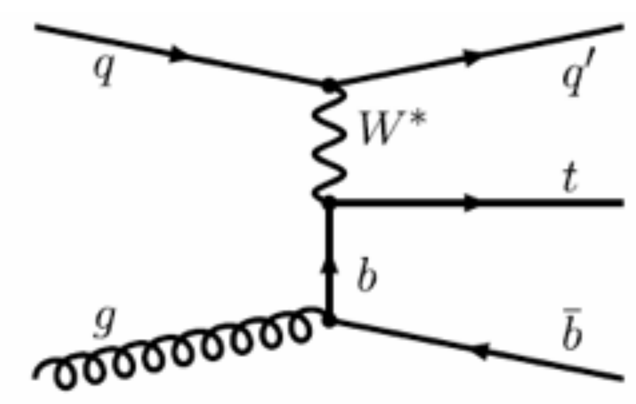
- Production of single top quarks via the weak interaction:

s-channel production via W exchange

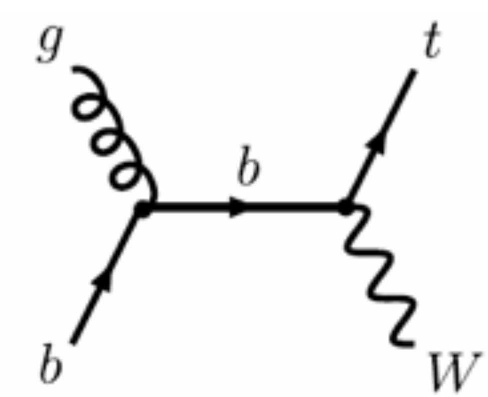


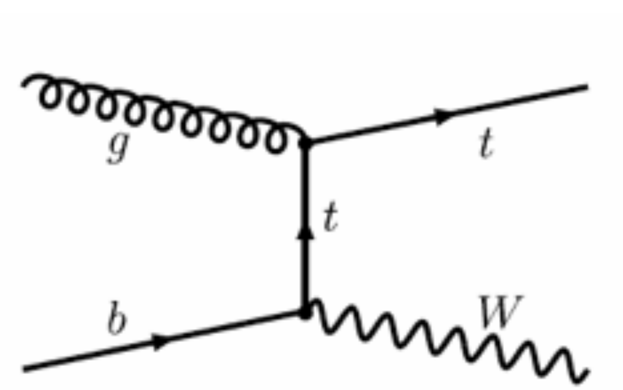
t-channel production





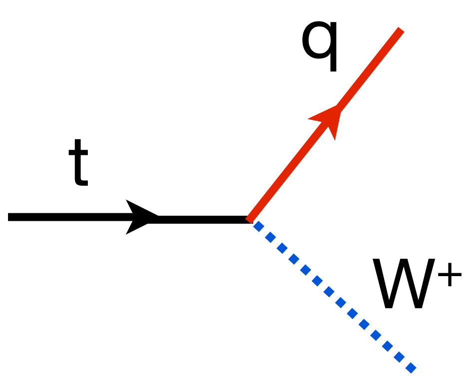
associated production of
W and t quark





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):

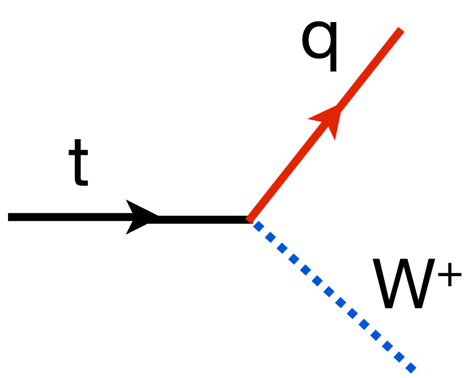
$$|V_{td}| = 0.00874^{+0.00026}_{-0.00037}$$

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

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

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):

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

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

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

➩ 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]

Top Quark: Width / Lifetime

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

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

- 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:

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

arXiv:0810.5226 [hep-ex]

Top Quark: Width / Lifetime

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

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

- 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:

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

⇨ 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 Ws

- W decay via the weak interaction:
  "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^+:

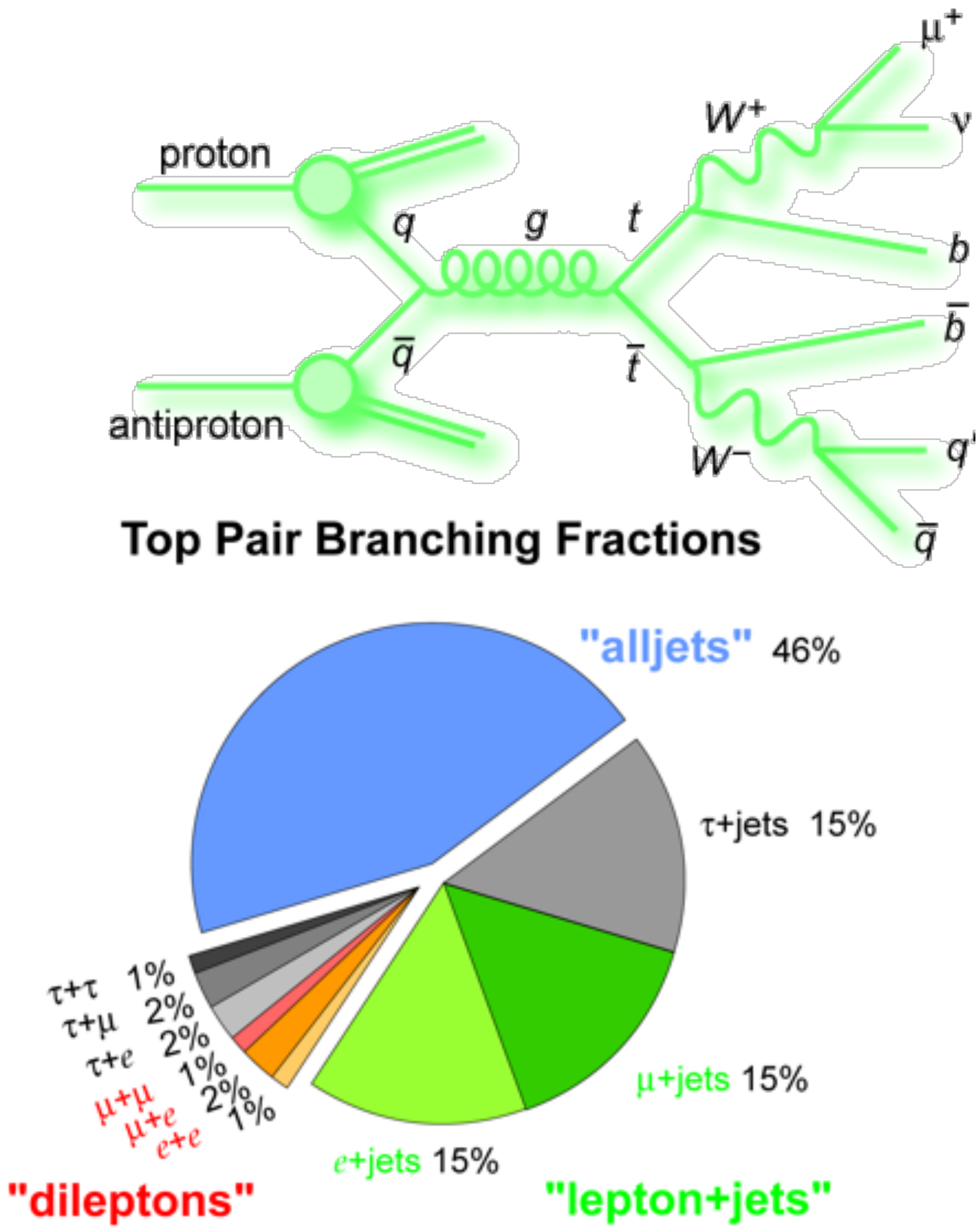
$$W^+ \rightarrow e^+\nu_e : \mu^+\nu_\mu : \tau^+\nu_\tau : u\bar{d}' : c\bar{s}'$$

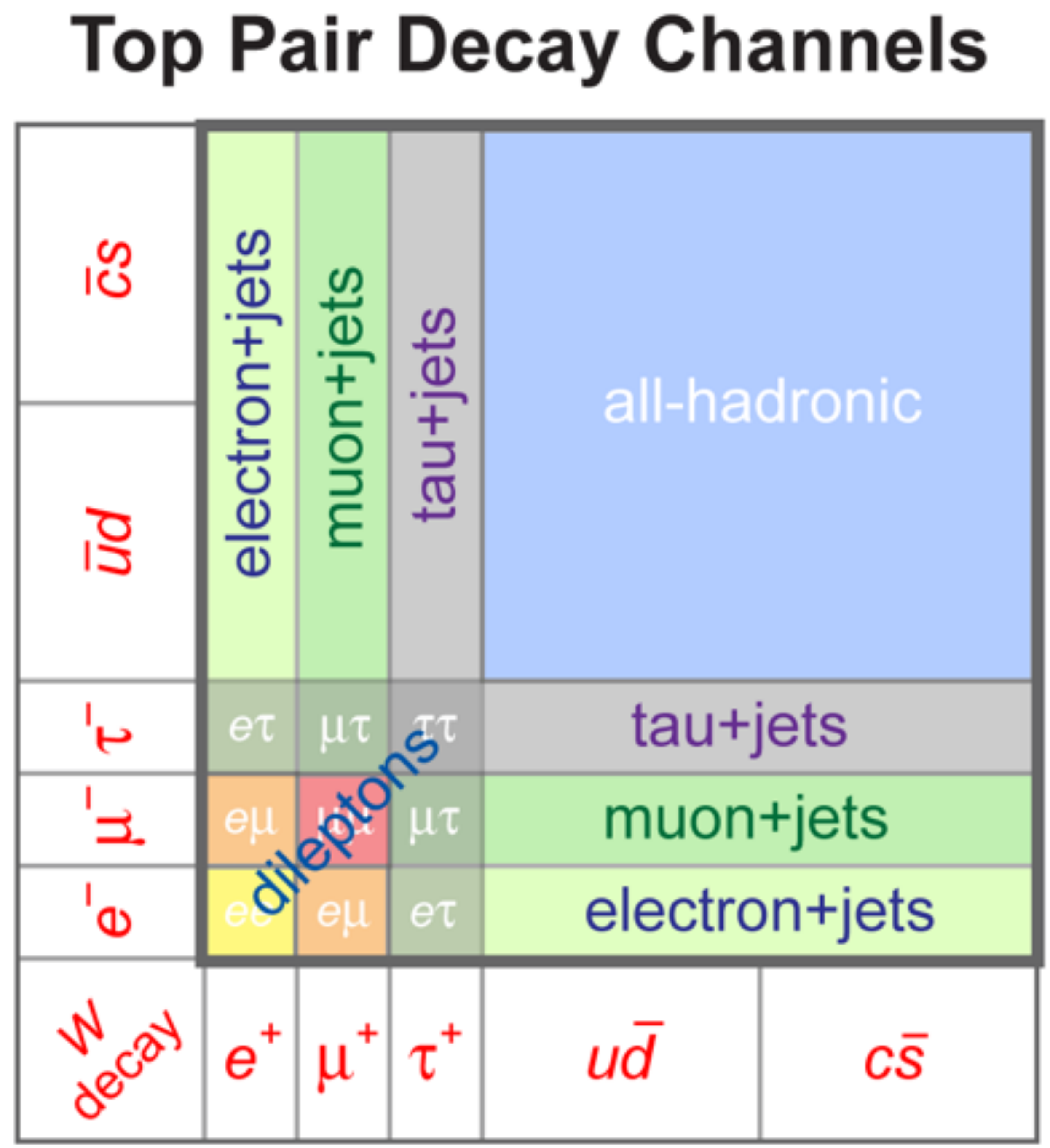
1 : 1 : 1 : 3 : 3

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

Top Quark Pair Decays - Classification

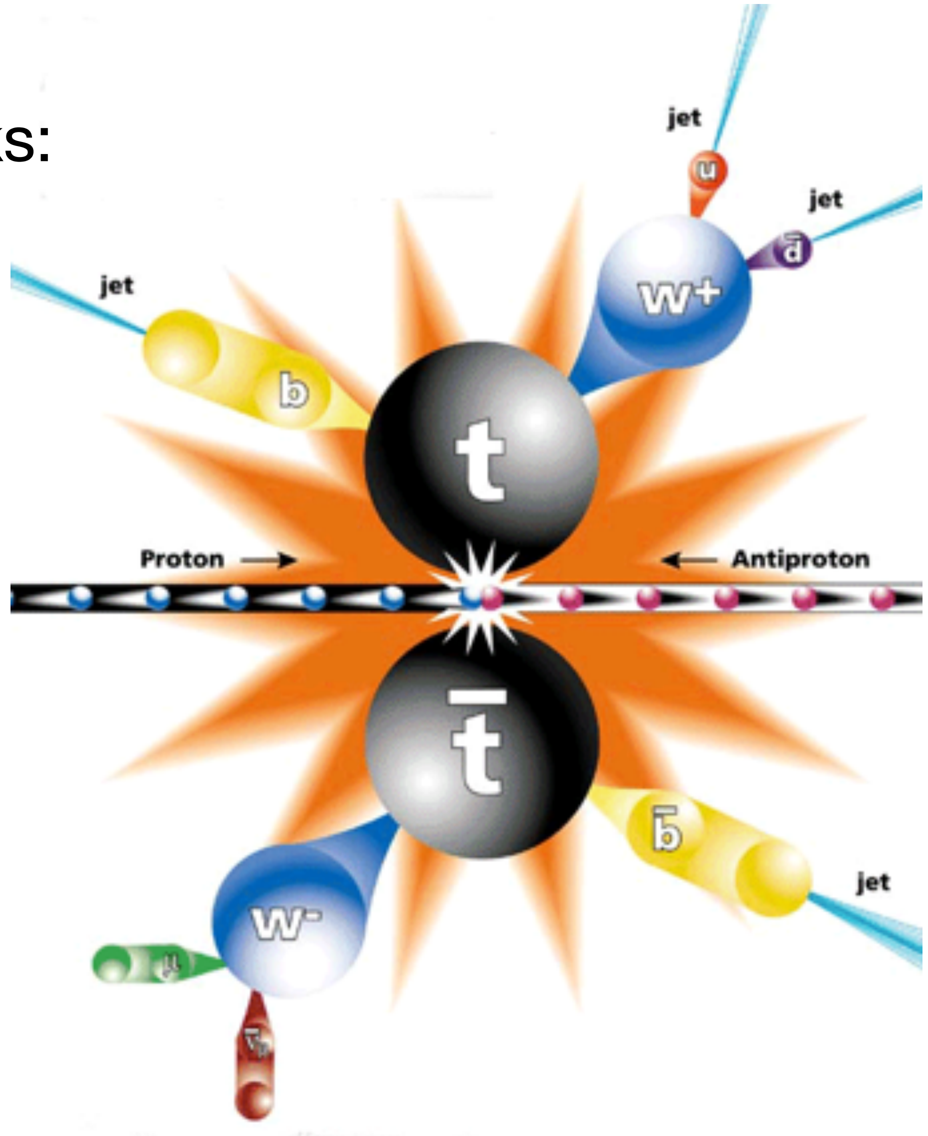
- Classified according to W decay (since basically 100% t → bW)





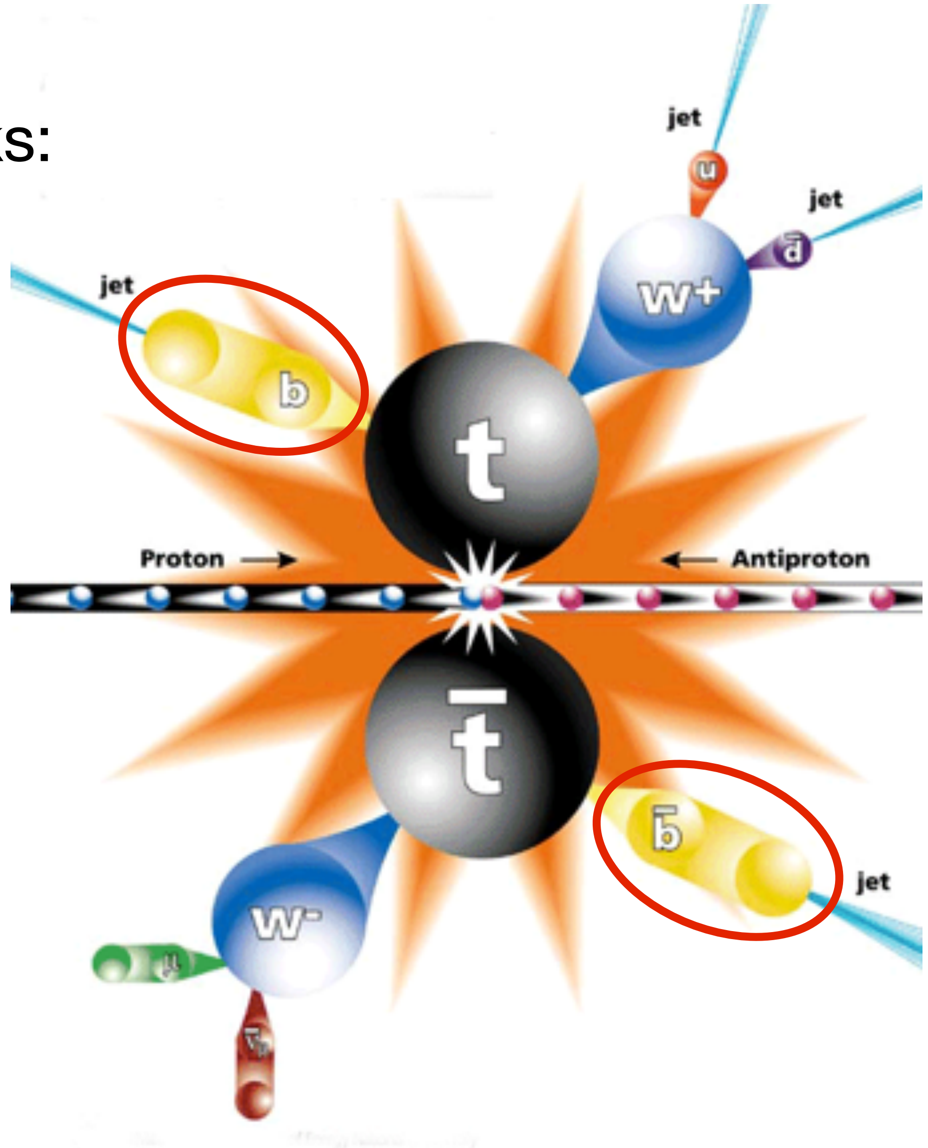
Detection of Top Events

- 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



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

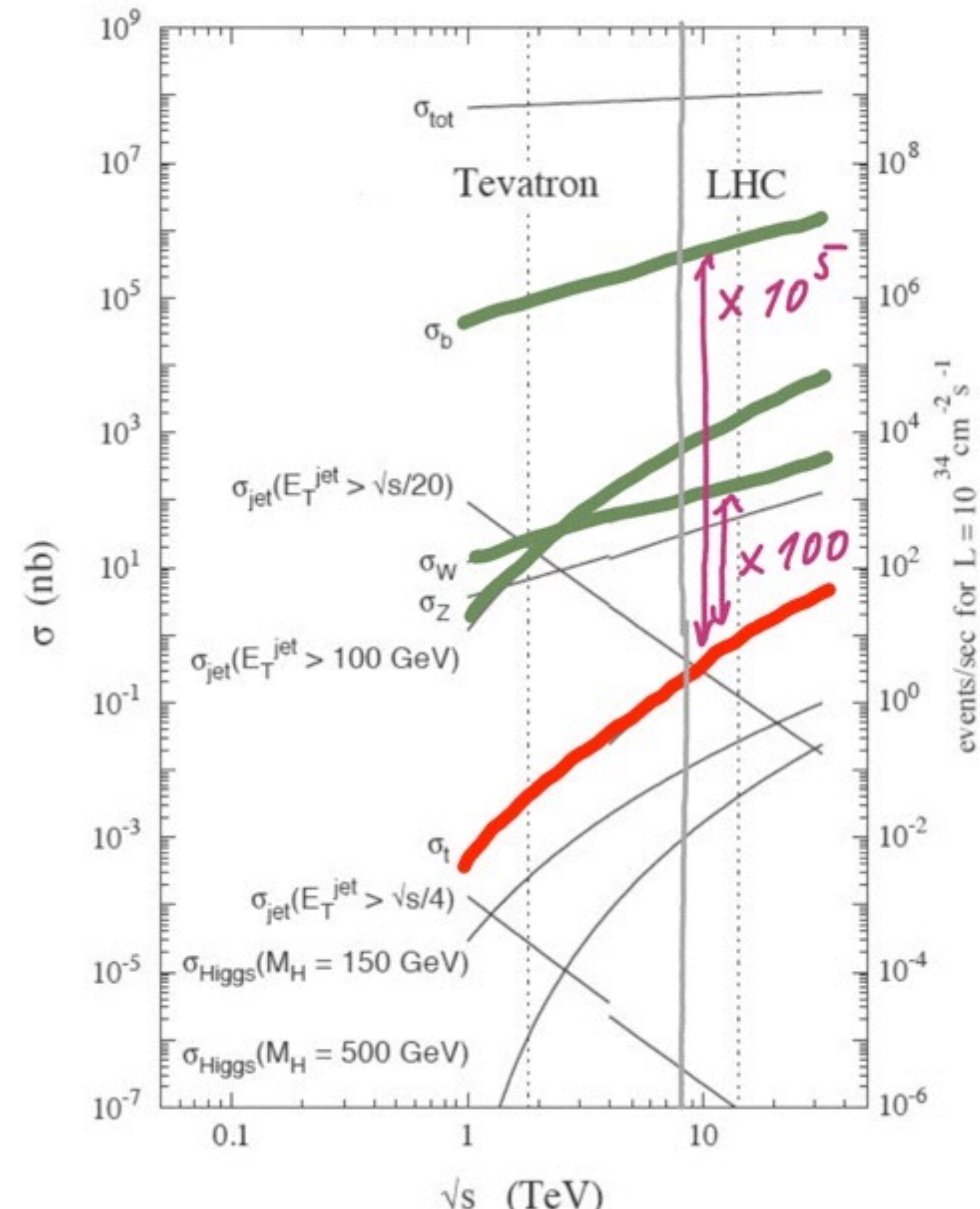


Reminder: b quark identification

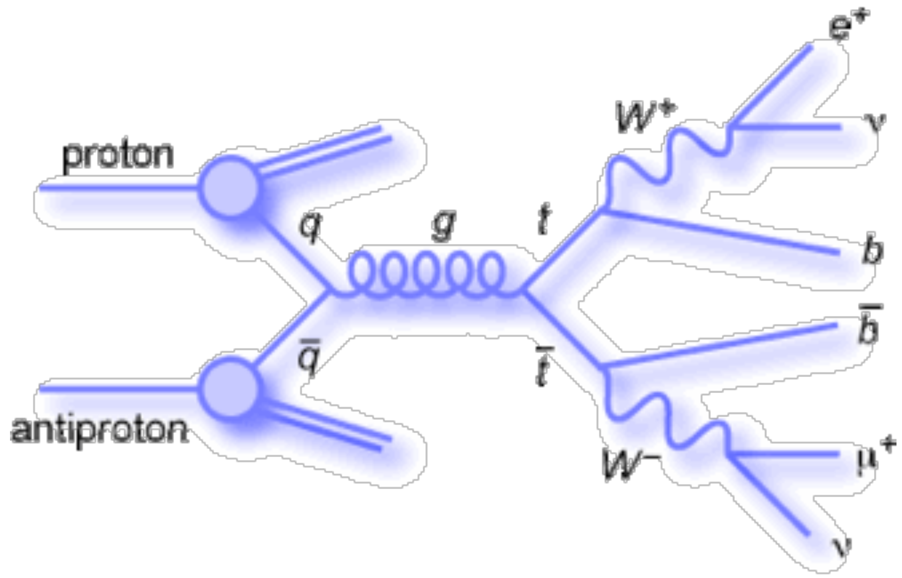
- Relatively long life time of mesons containing b quarks ($c\tau$ (B^0) ~ 460 μm, $c\tau$ ($B^{\pm}$) ~ 490 μm)
- ▸ Identification of a displaced secondary vertex in a jet
  - ▸ Jet is “tagged” as a b jet

The Challenge: Background

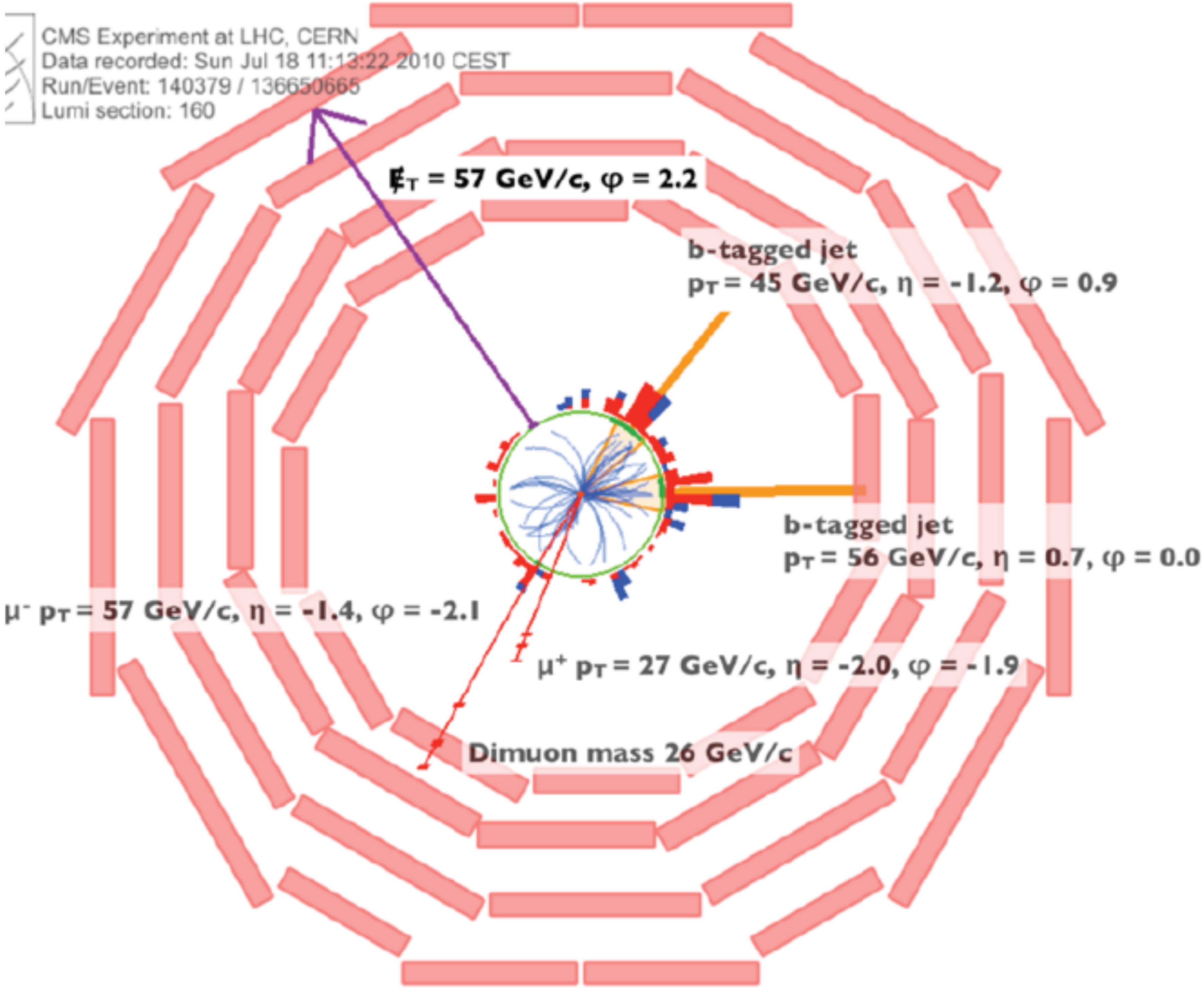
- Top production is only a very small part of the total pp cross section
    - High background, in particular for hadronic decays of the W
        - all-hadronic: QCD multi-jet background (very high!)
        - lepton+jets: W + jets and QCD multi-jet background (ok)
        - di-lepton: Z + jets and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



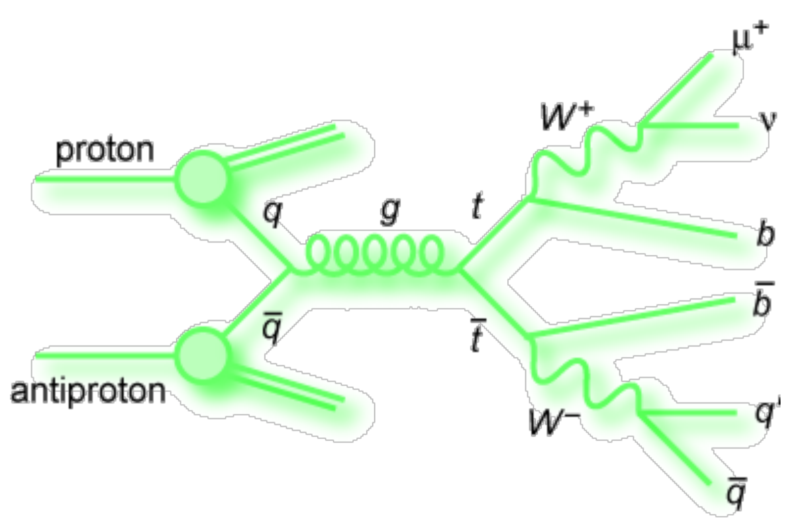
Experimental Detection: Di-Lepton Events



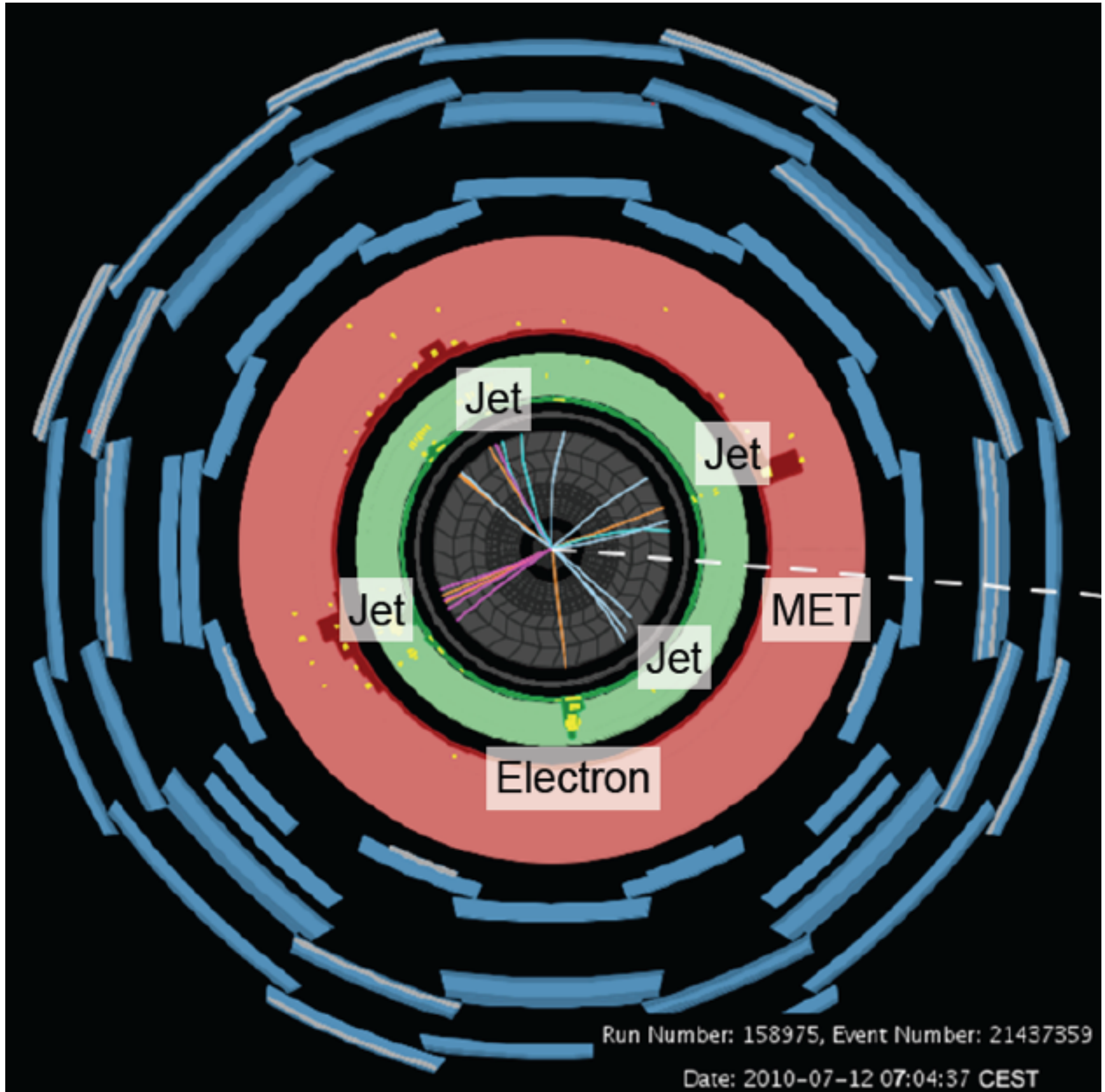
- Clear, clean signature
- missing information from two (undetected) neutrinos
- small branching ratio, low statistics
- Background: mainly W + X



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

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

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

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

- 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)

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

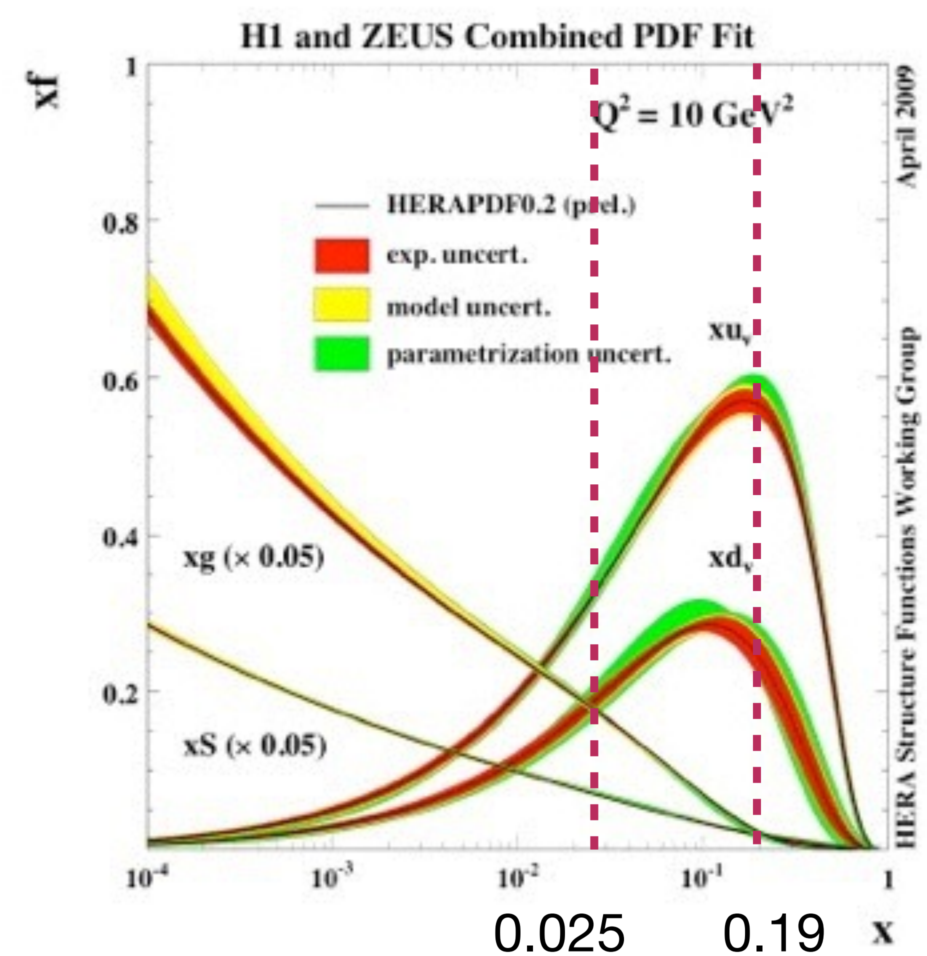
$$\hat{s} = x_a x_b s \geq (2\, m_t)^2$$

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

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

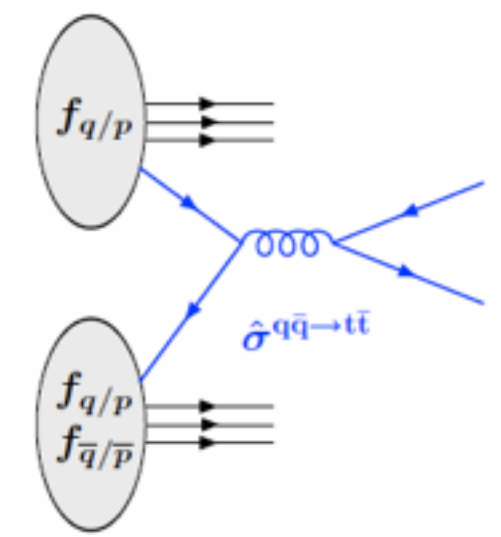
~ 0.192 Tevatron Run I (1.8 TeV)
~ 0.176 Tevatron Run II (1.96 TeV)
~ 0.025 LHC (14 TeV)

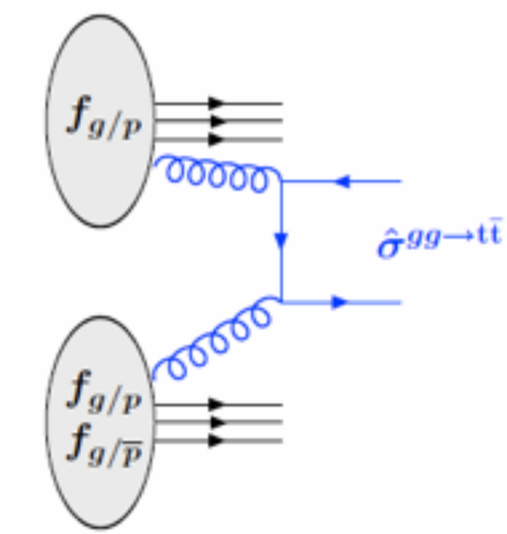
- Mix of the production processes is energy dependence:
  - Tevatron: high x, dominated by valence quarks: Big advantage of proton - anti-proton collisions
  - LHC: lower x, dominated by gluons

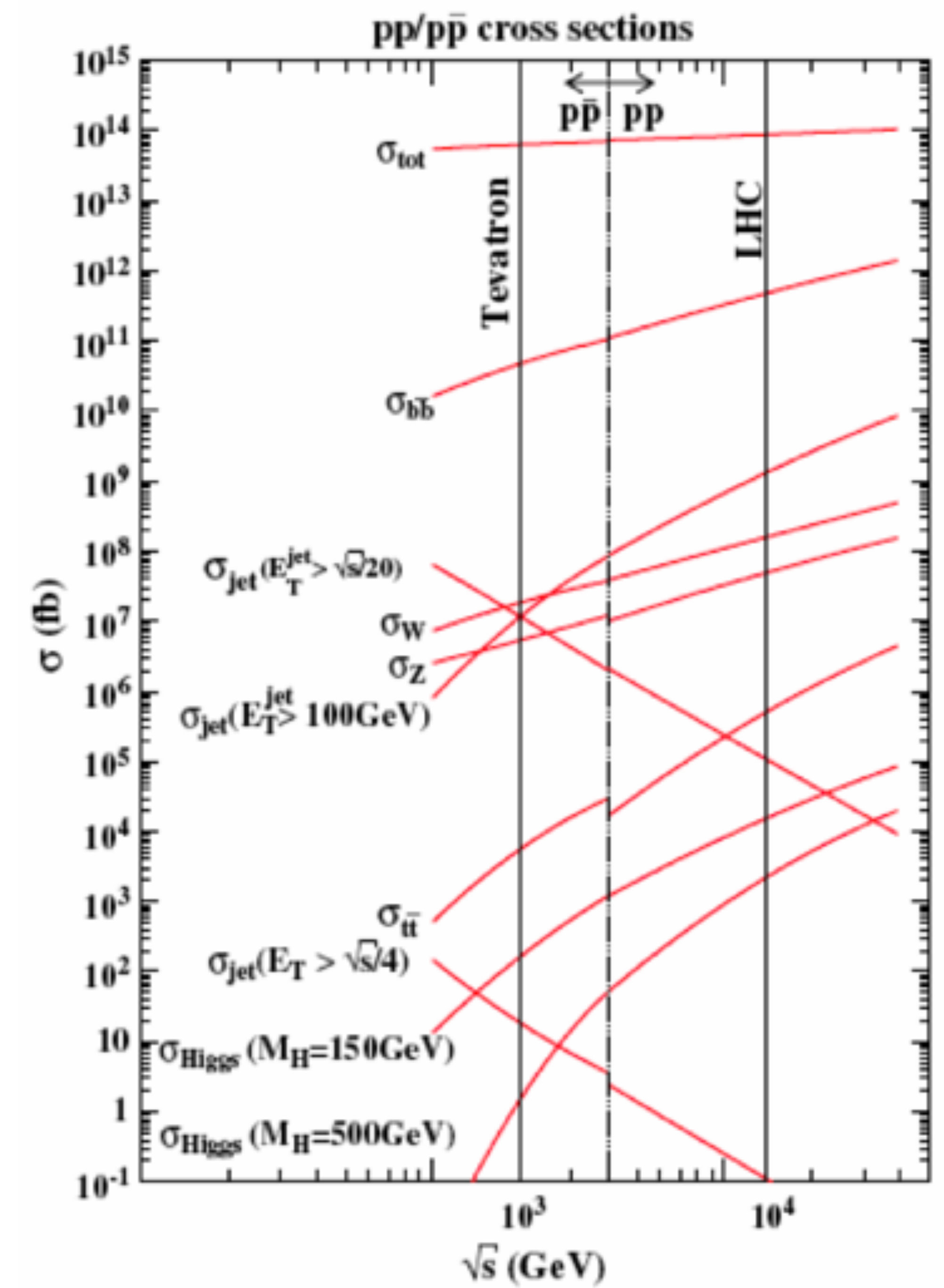


Top Quark Pair Production at Hadron Colliders II

- 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:

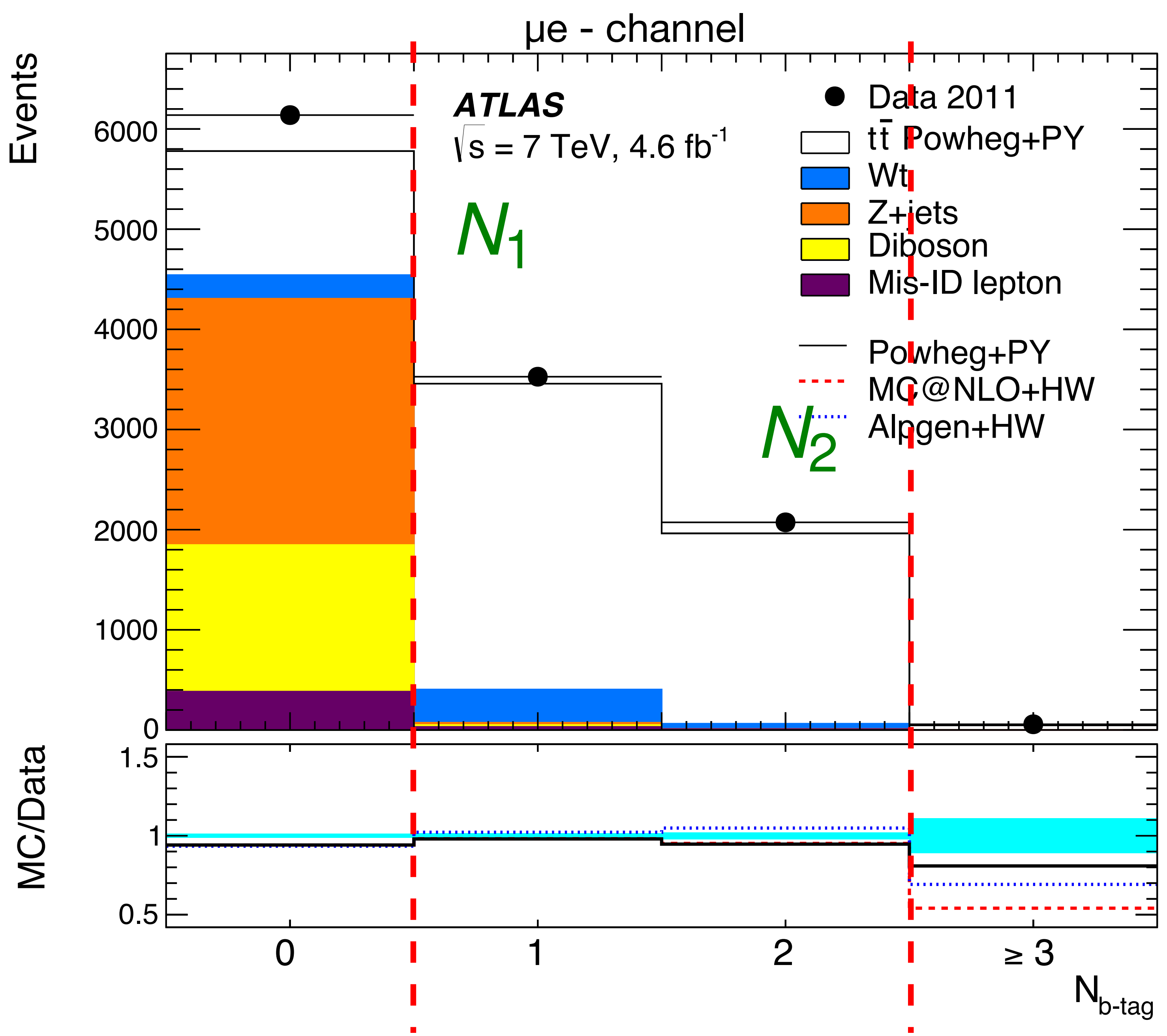
$$\sigma(p\bar{p} \to t\bar{t}) = \frac{N - B}{A\epsilon \int \mathcal{L} dt}$$

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



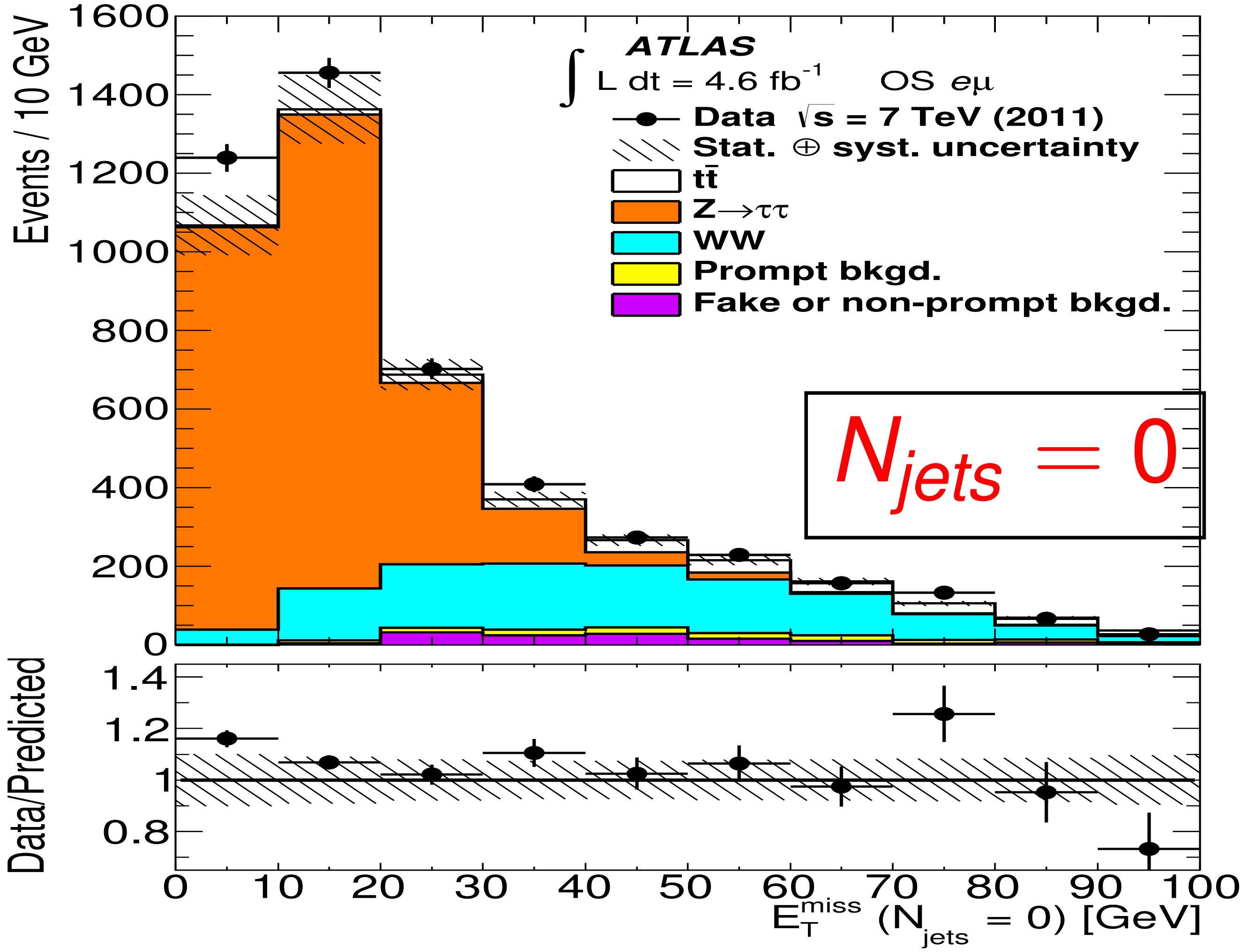
Most important sources of uncertainties:

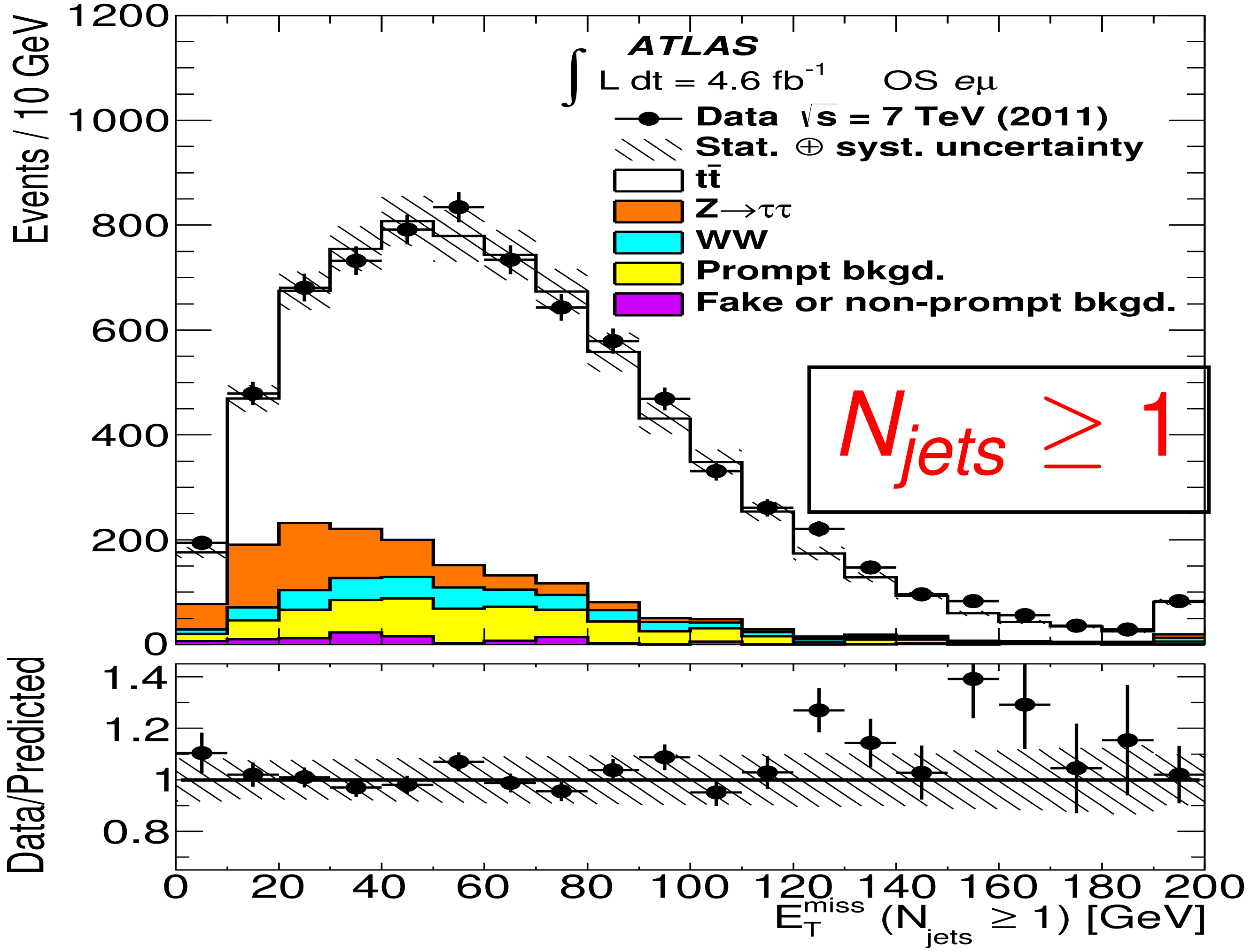
B tagging - How well is it understood?

Jet energy scale: influences energy cuts

ATLAS Di-Leptons: Missing Energy

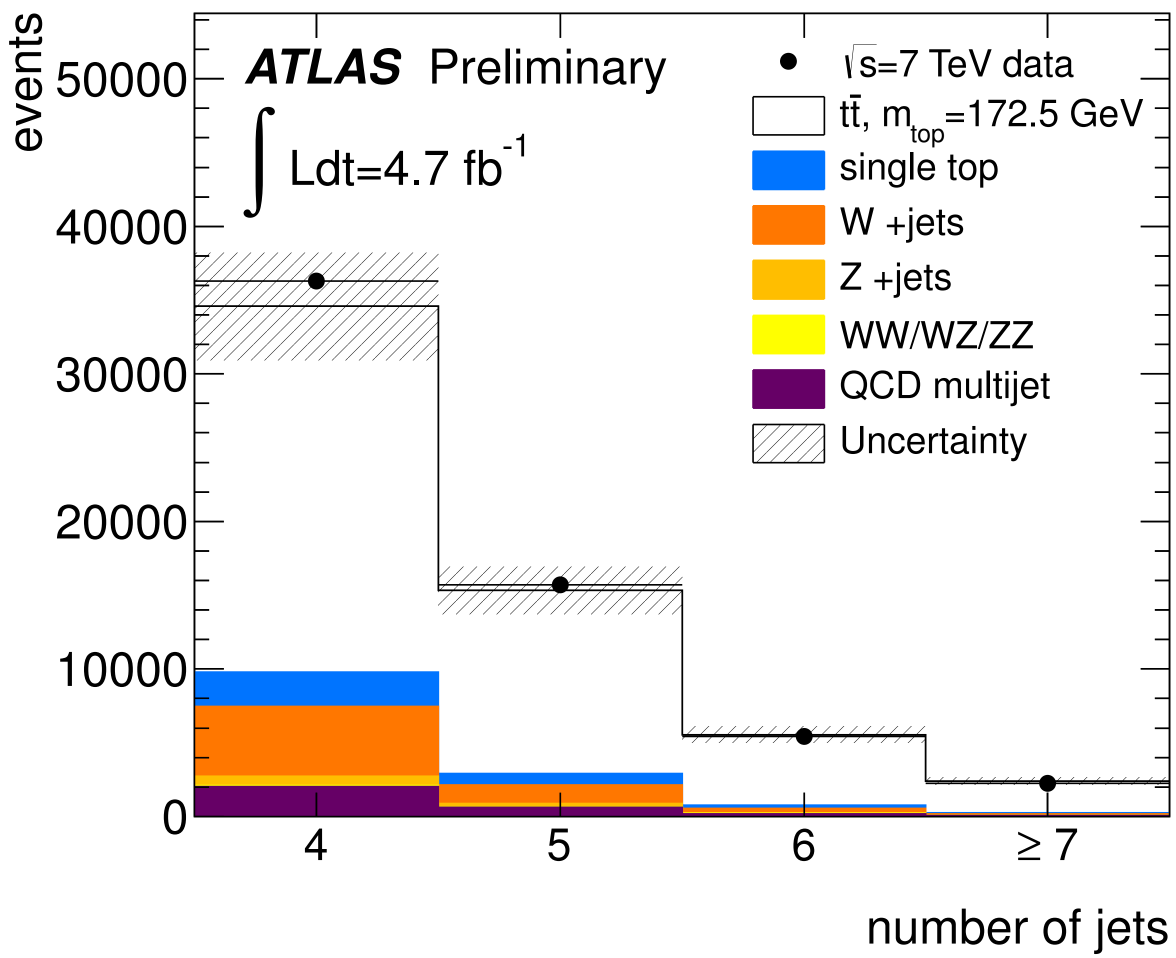
- Missing energy and jets in addition to leptons

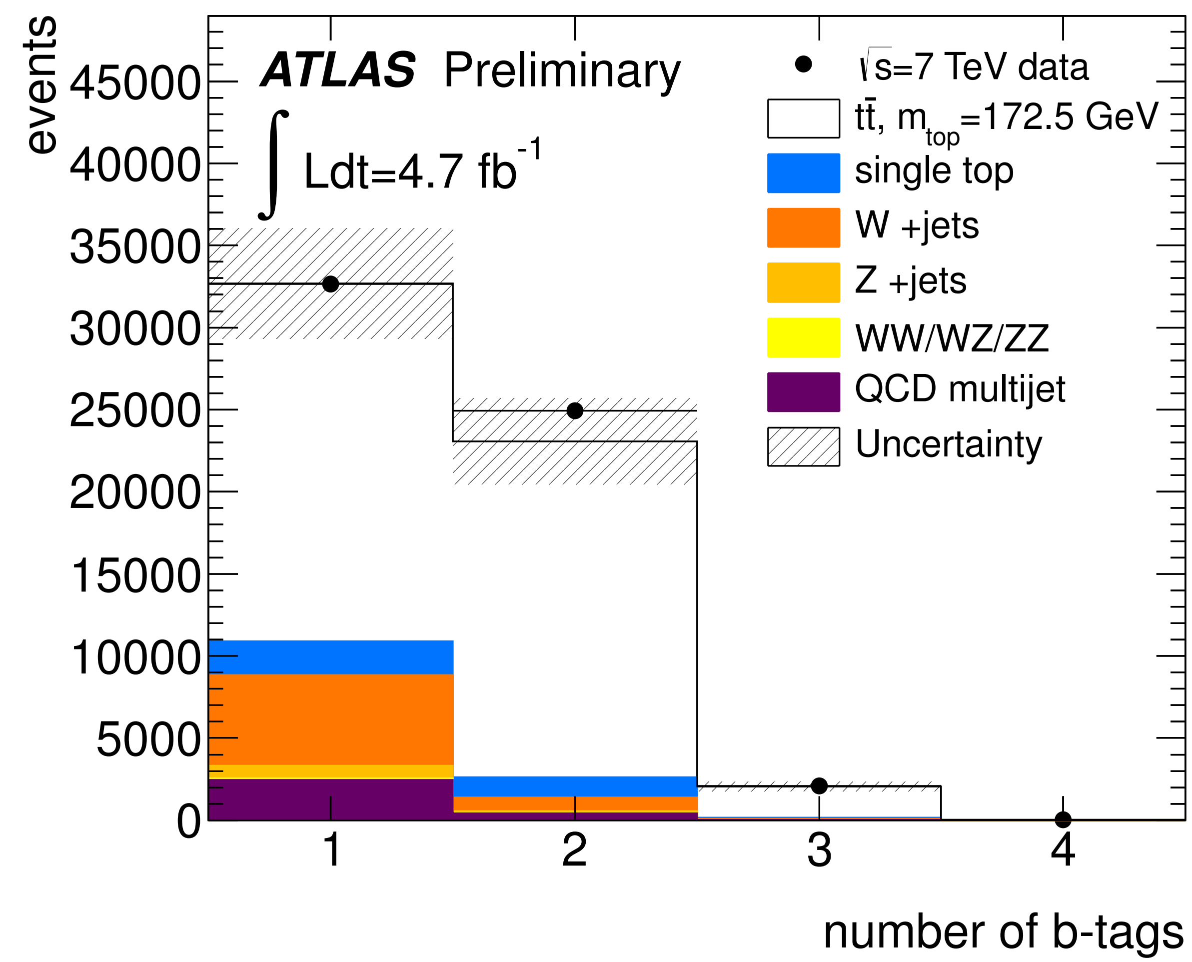




Leptons + Jets

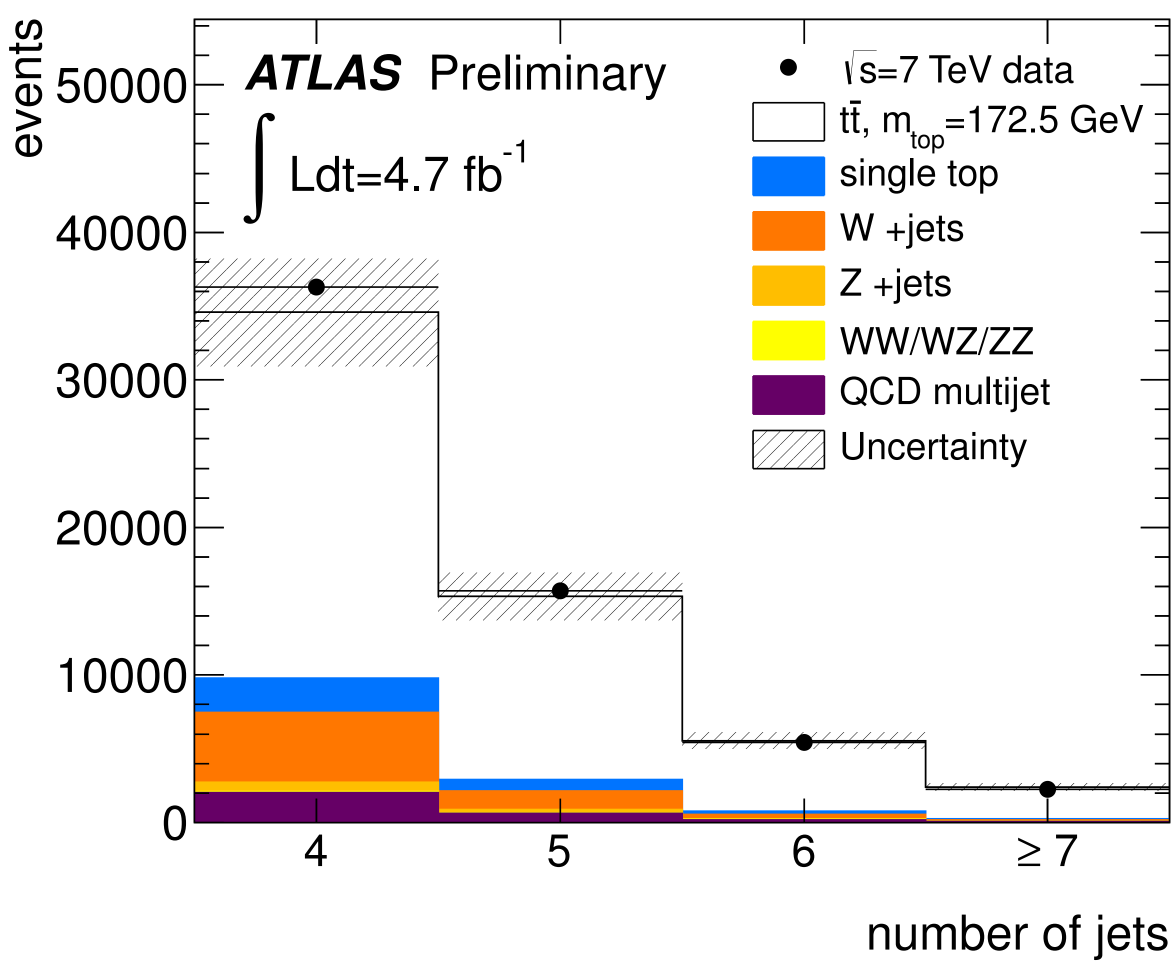
- More events, but also much more background: Jets from QCD processes and associated production of bosons
- Event selection via high-energy leptons, jet multiplicity (4 jets from ttbar), b tagging and missing energy (neutrino!)

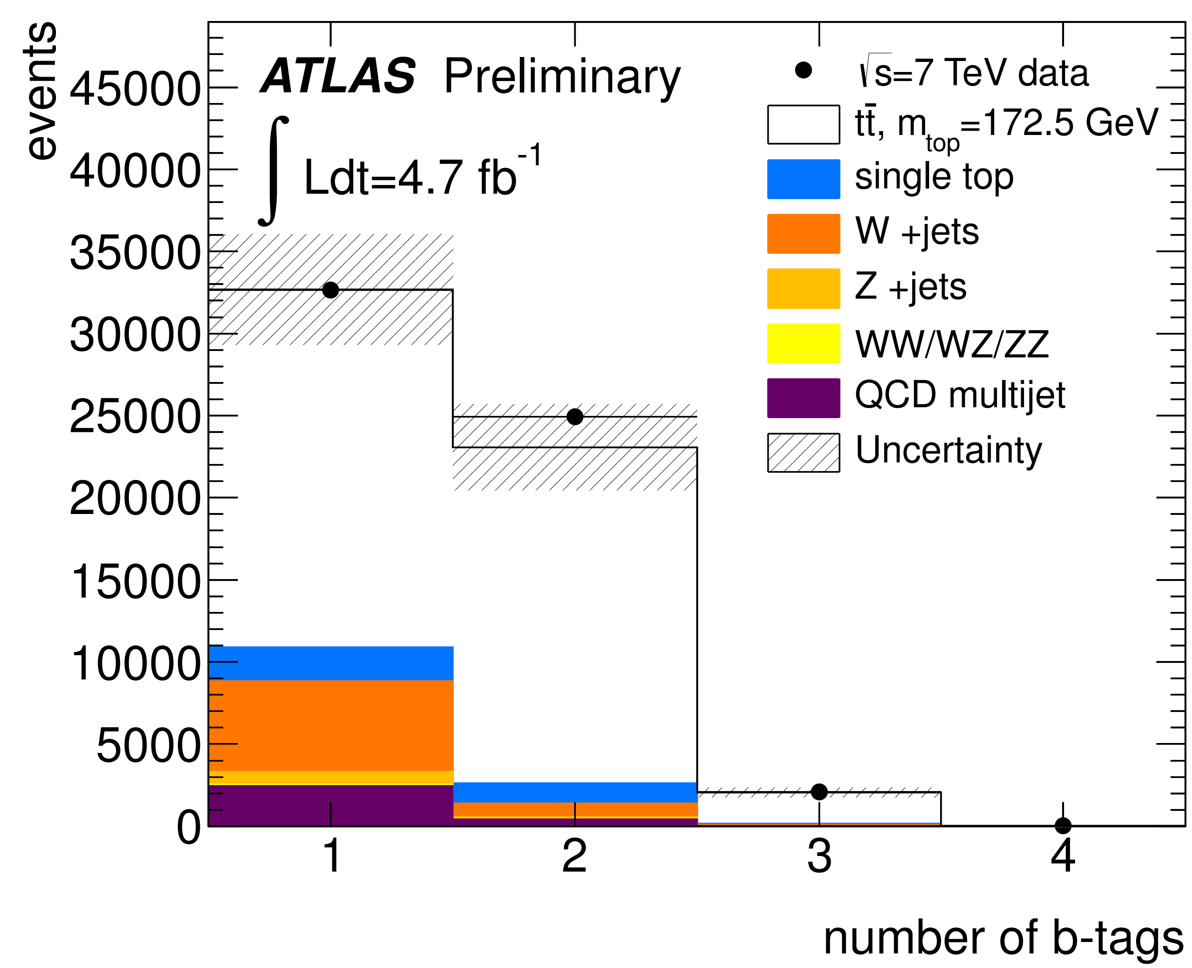




Leptons + Jets

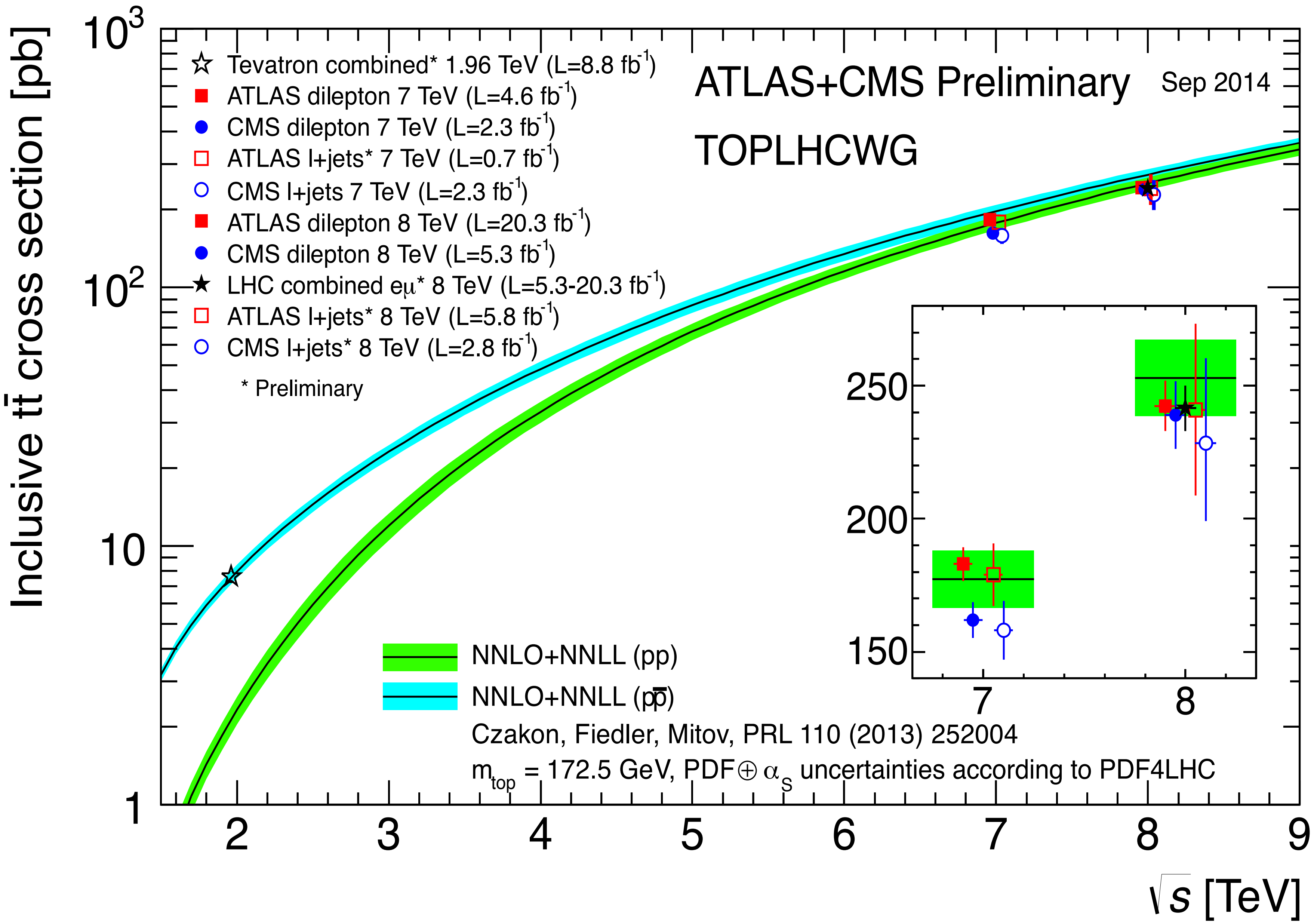
- More events, but also much more background: Jets from QCD processes and associated production of bosons
- Event selection via high-energy leptons, jet multiplicity (4 jets from ttbar), b tagging and missing energy (neutrino!)



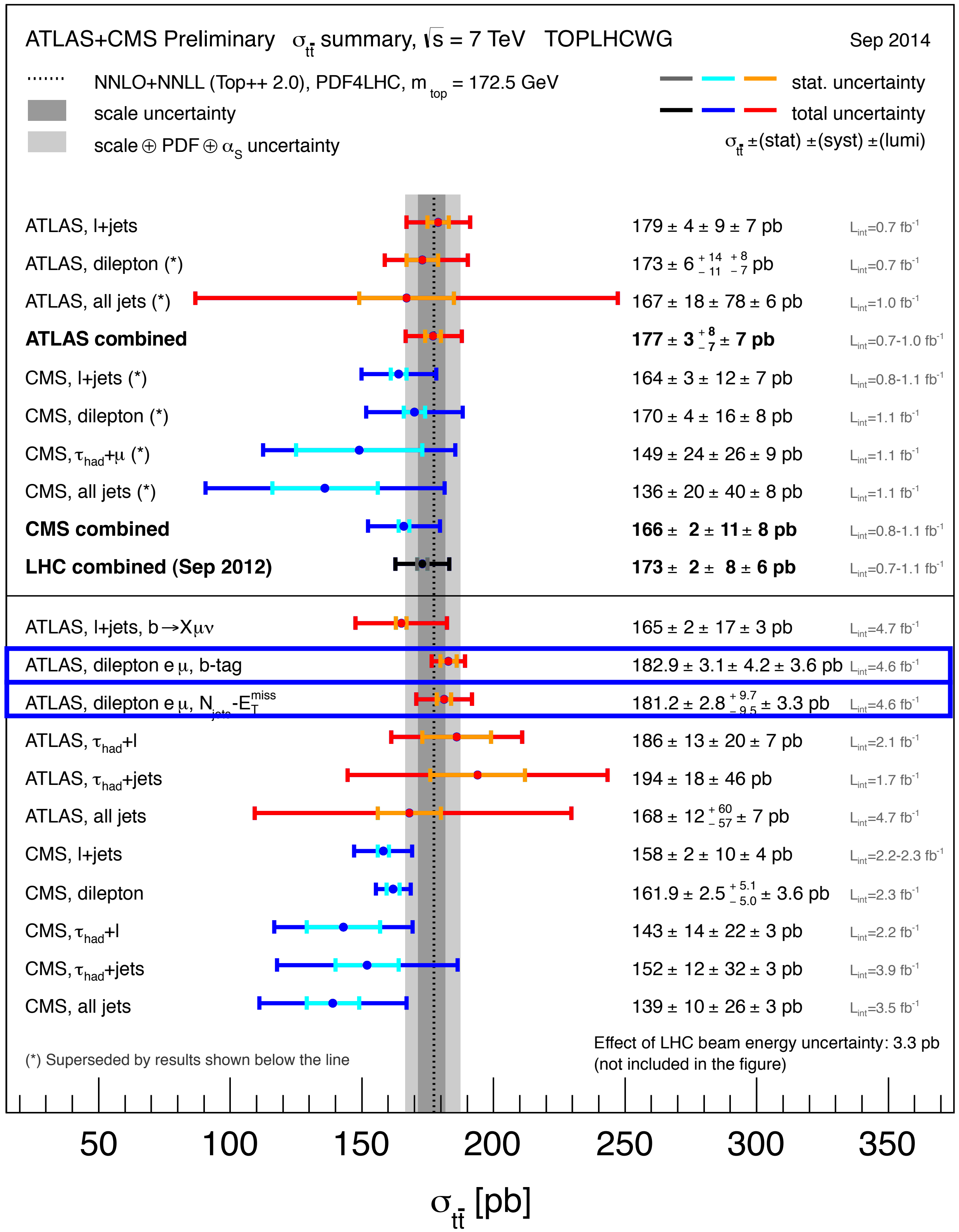


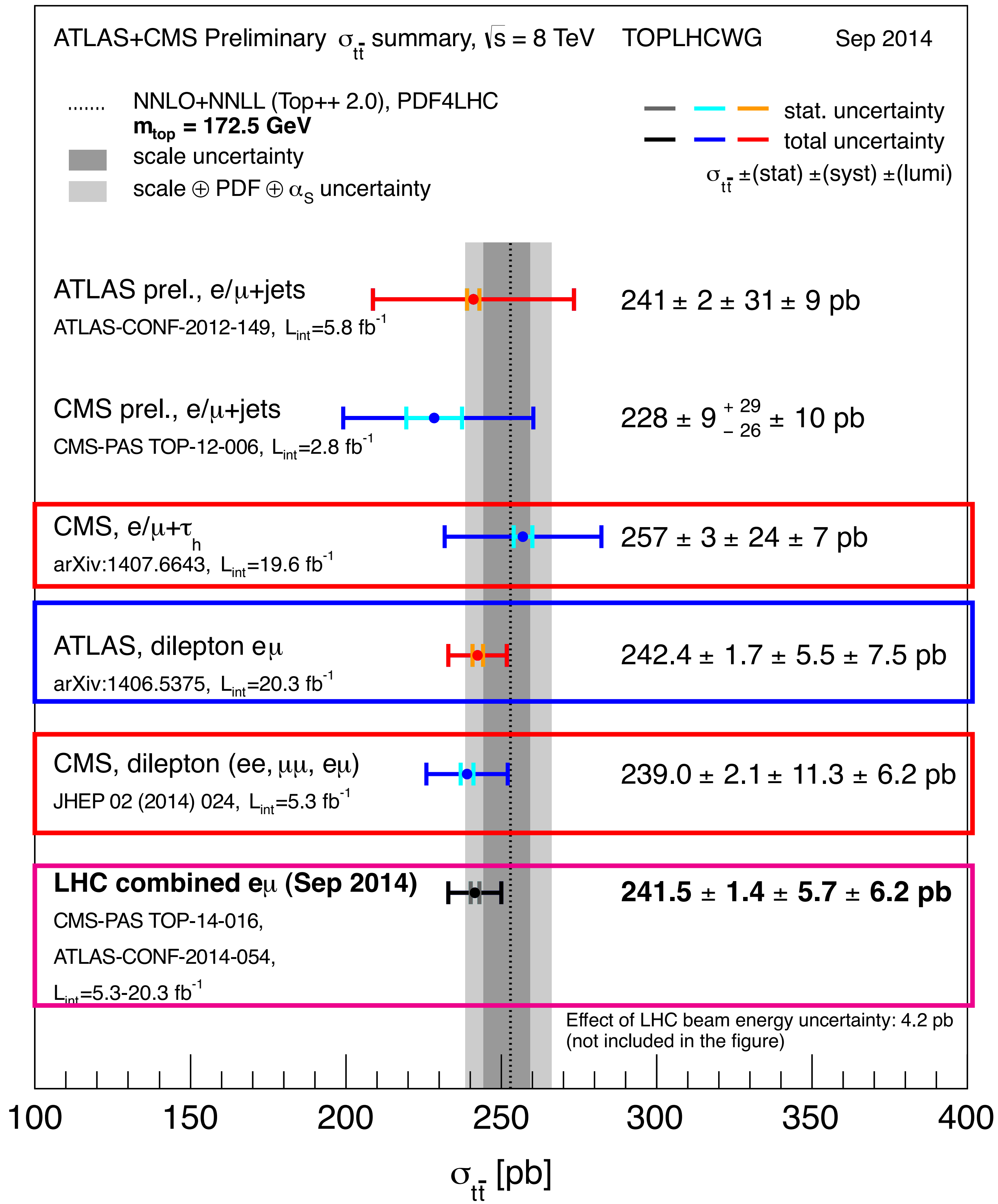
ATLAS-CONF-2013-046

Top Cross Section at LHC



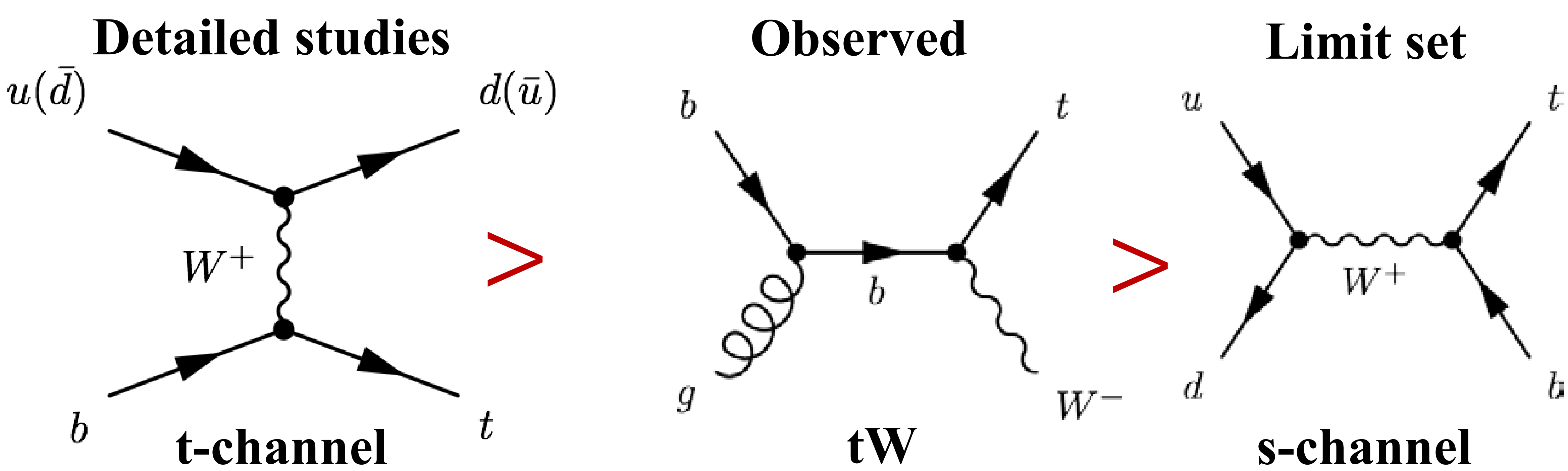
Top Cross Section at LHC





Single Top Production

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

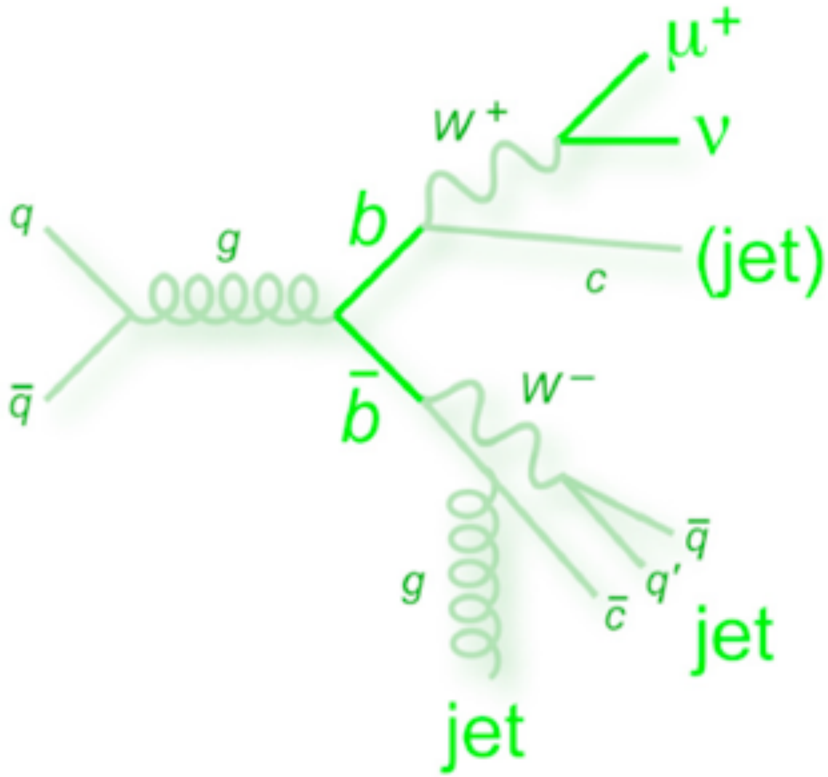


Only one t quark in the final state: Less "spectacular" events than top pair production: Separation from background more difficult!

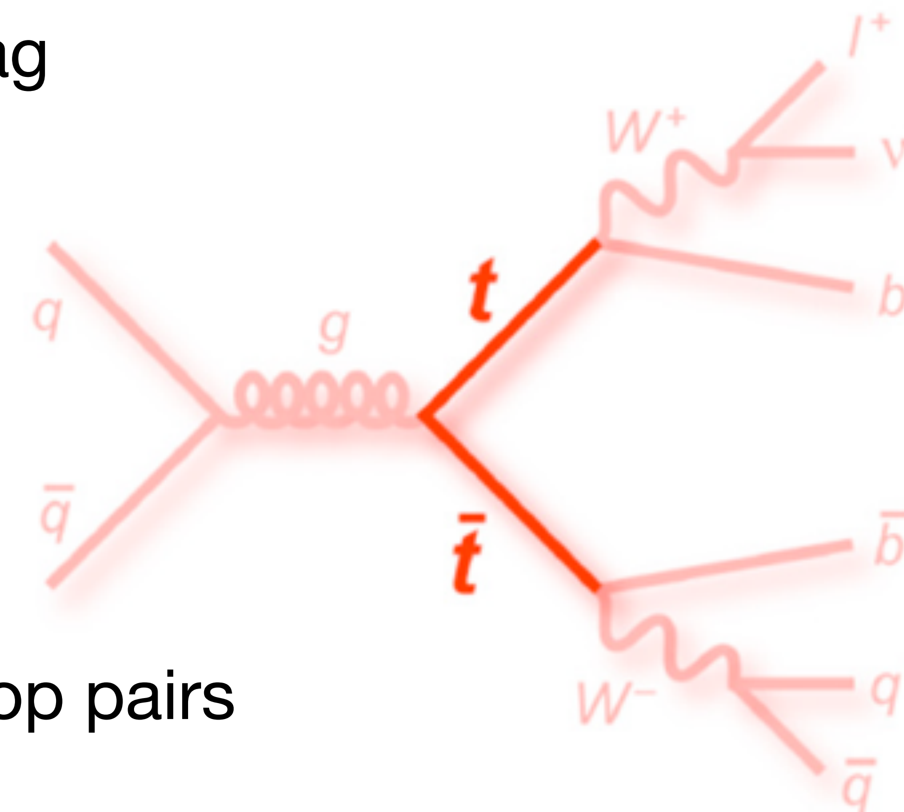
Frank Simon (fsimon@mpp.mpg.de)

Background in Single Top Measurements

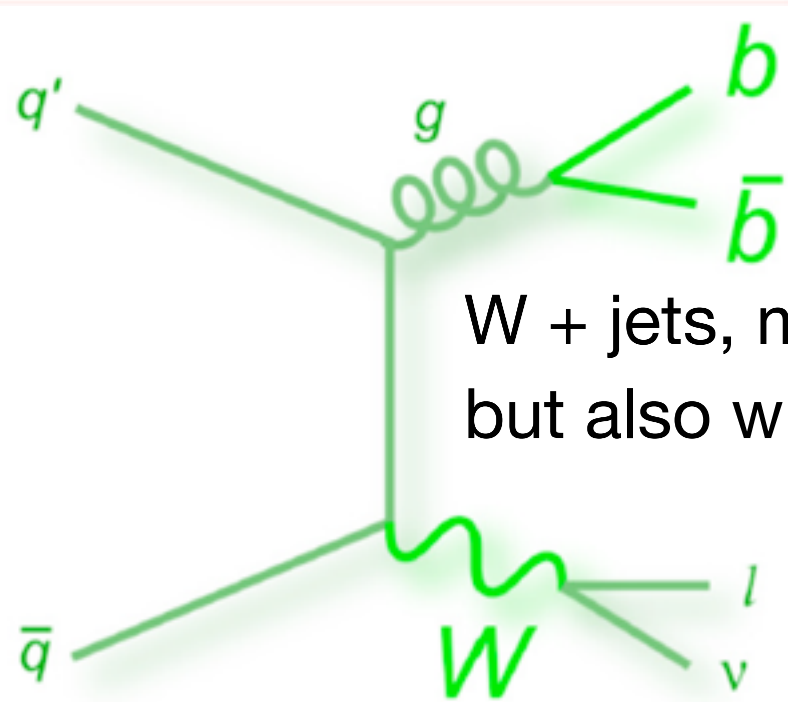
- Events with a W and one or more jets with a b-tag



multi-jet production



mis-identified top pairs



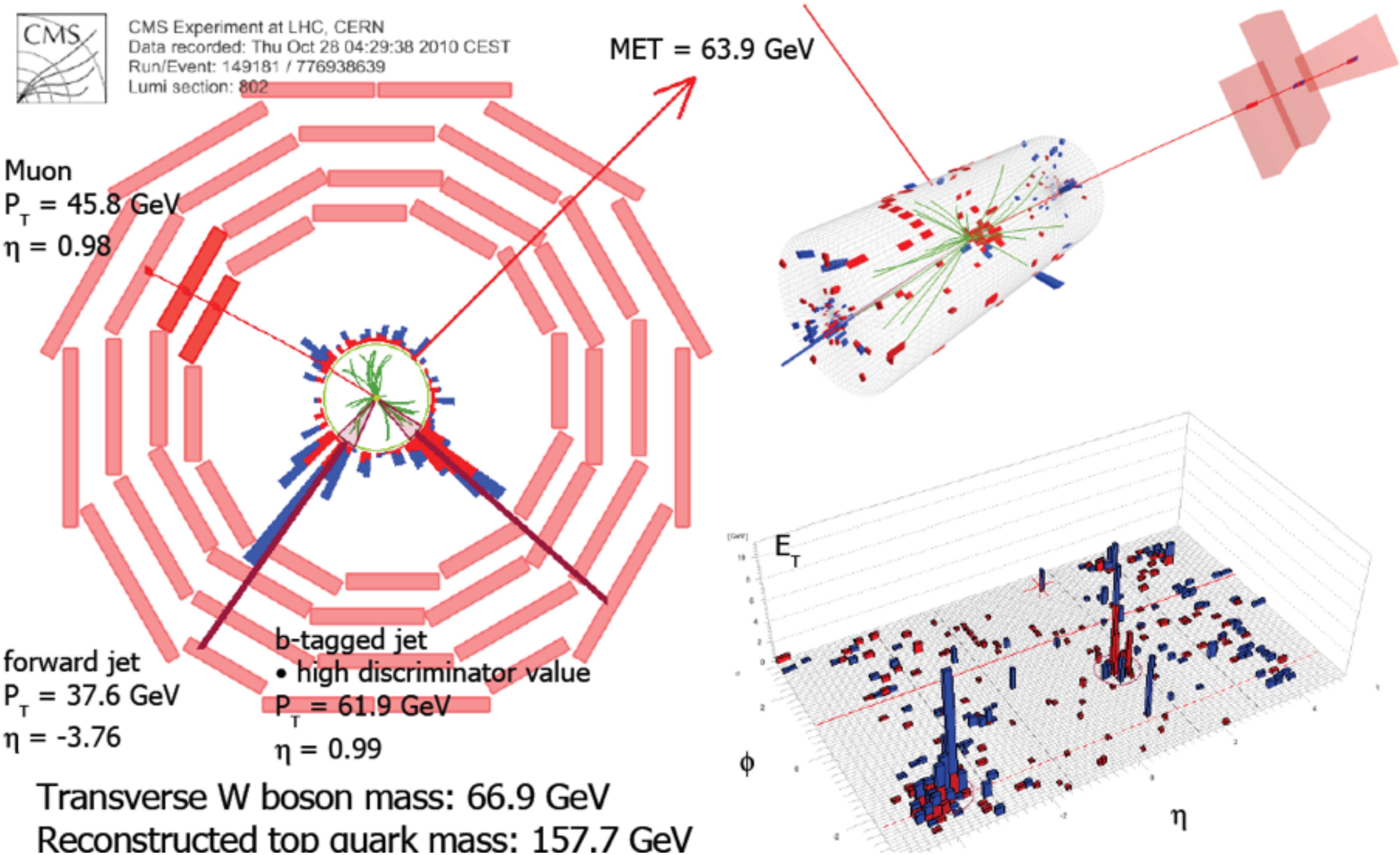
W + jets, mainly b-jets but also wrong tagging

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

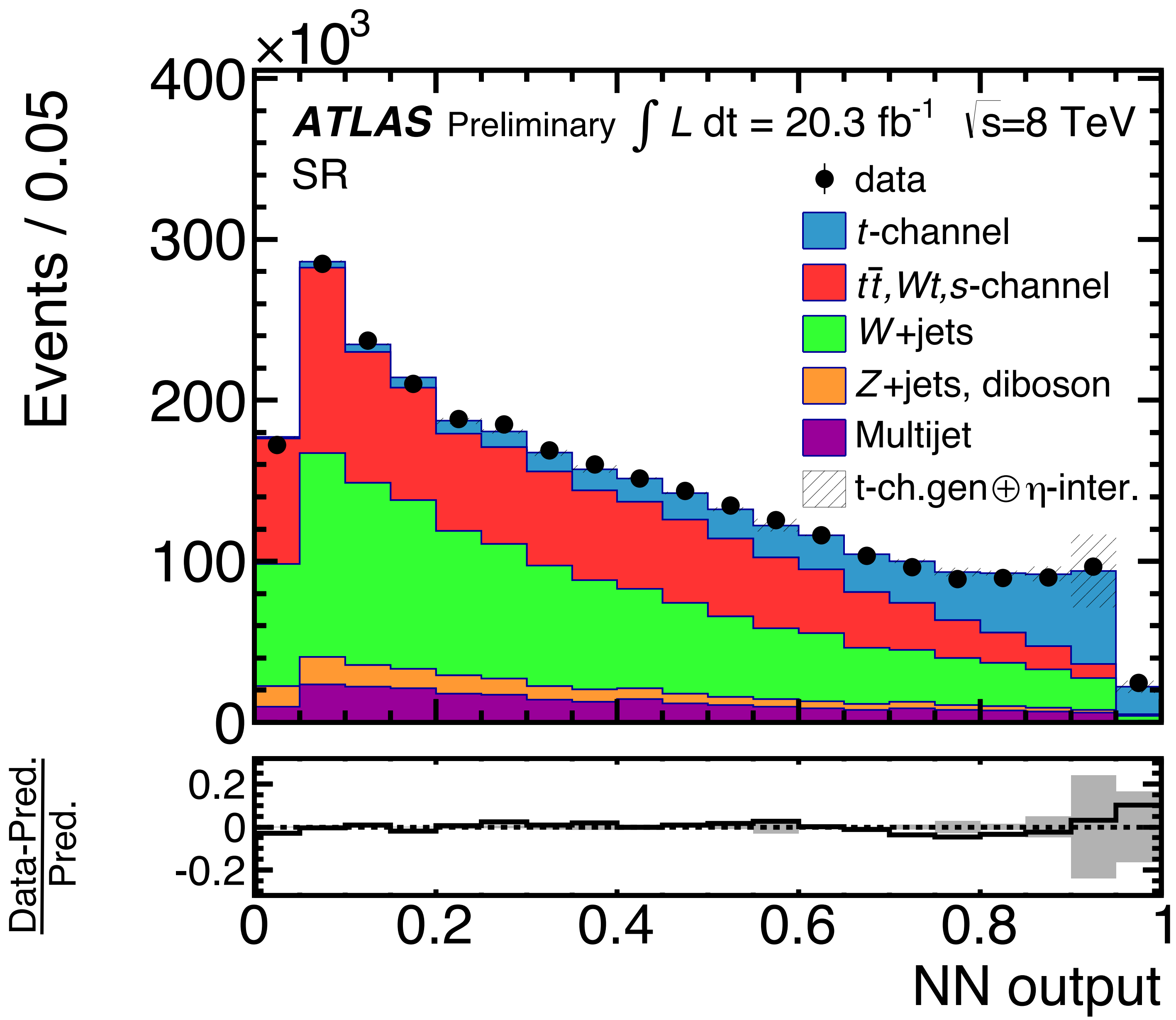
- Neural networks
- Boosted decision trees
- ...

Single Top at the LHC

- A candidate from CMS

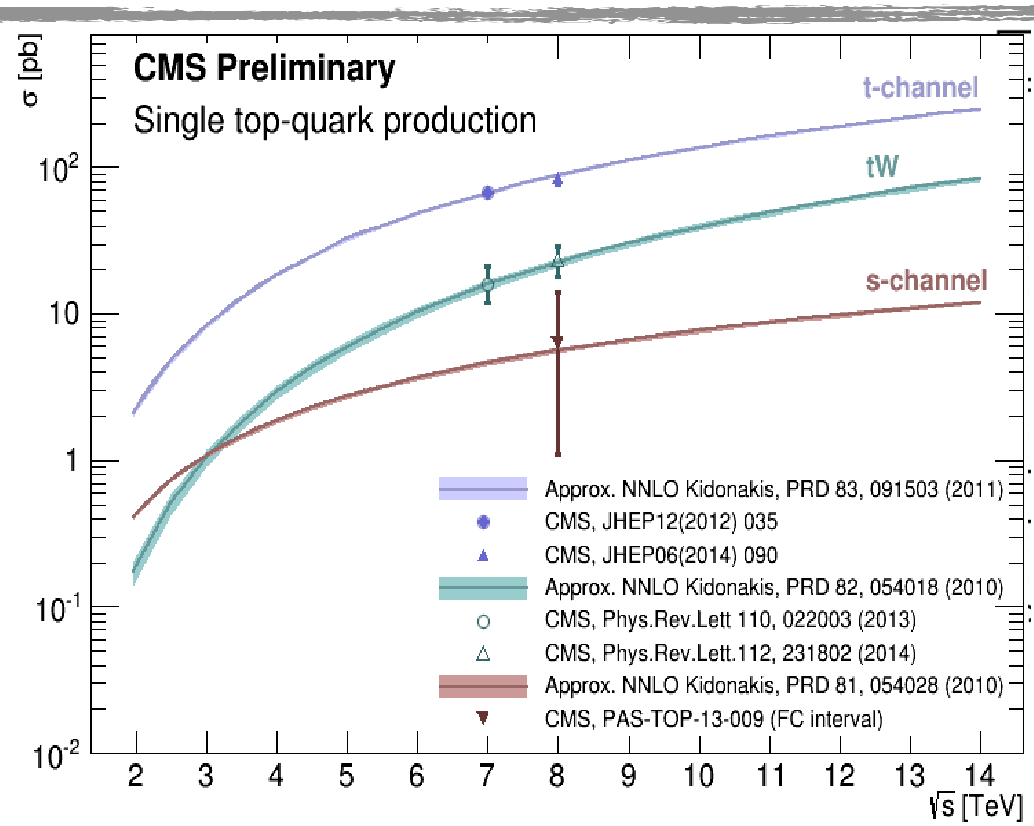


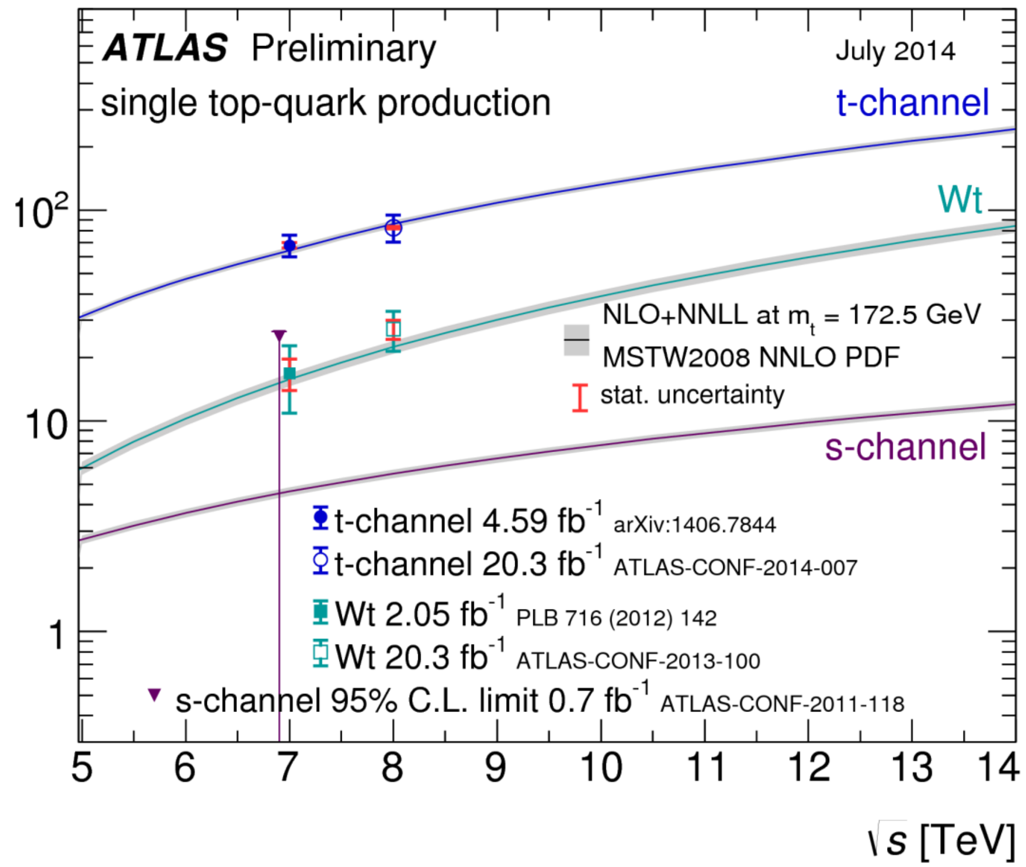
Single Top at the LHC



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

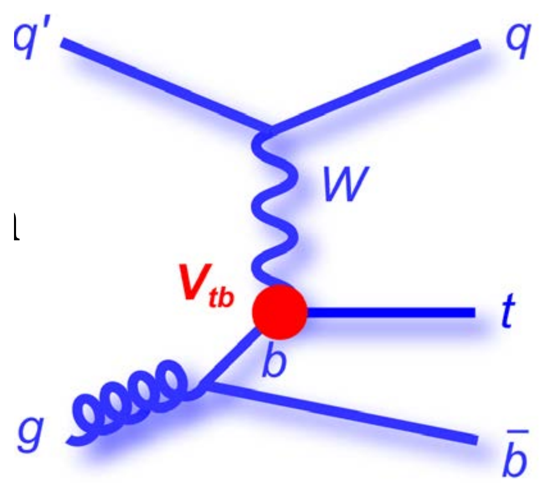
Single Top at the LHC





- One example - After all selections in particular in the t channel a strong signal
  - The cross section is according to the expectation

Single Top at the LHC



- 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

ATLAS: $|V_{tb}| = 1.02 \pm 0.07$

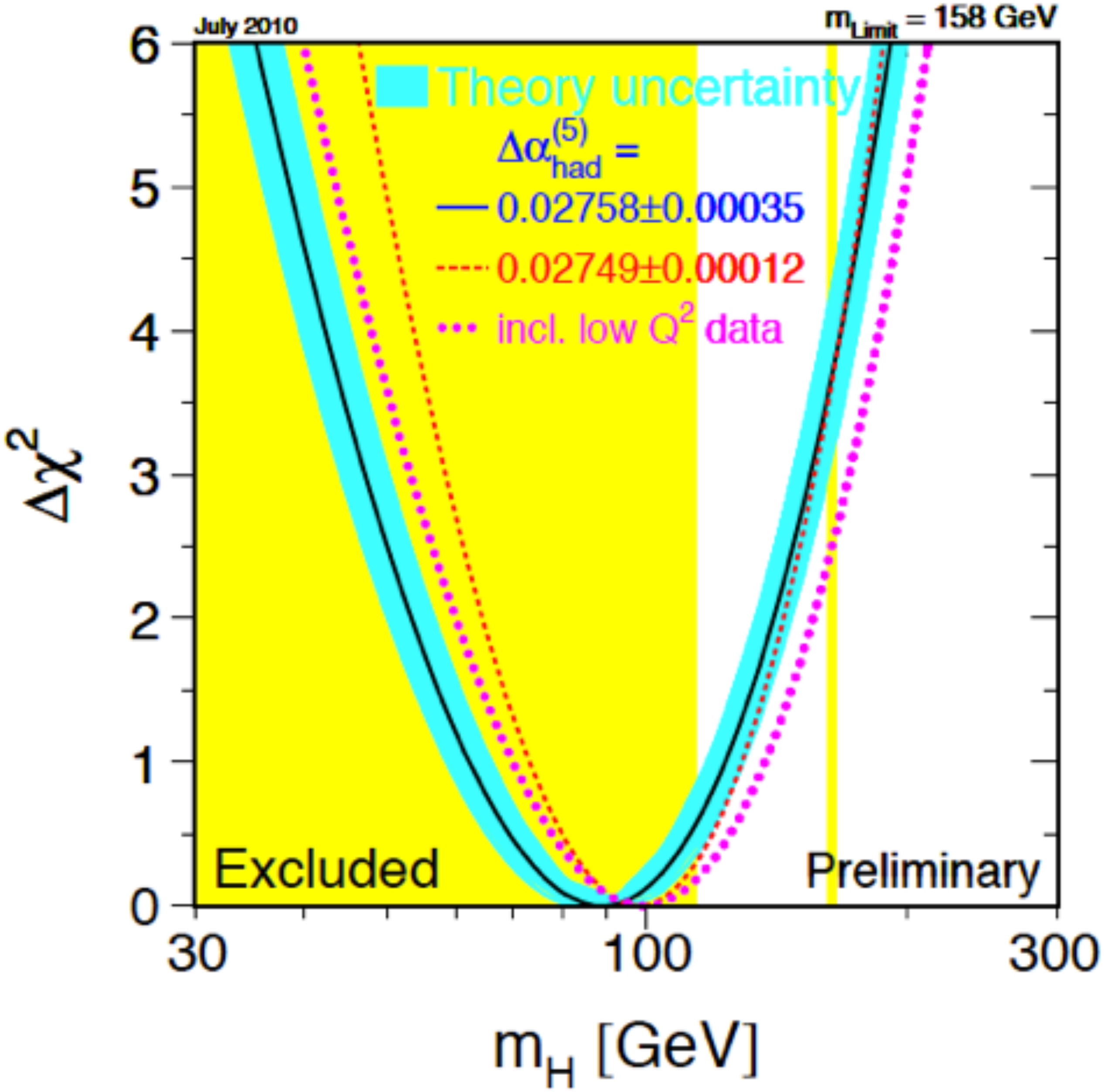
$|V_{tb}| < 1$ ➡ $0.88 < |V_{tb}| <= 1$ @ 95% C.L.

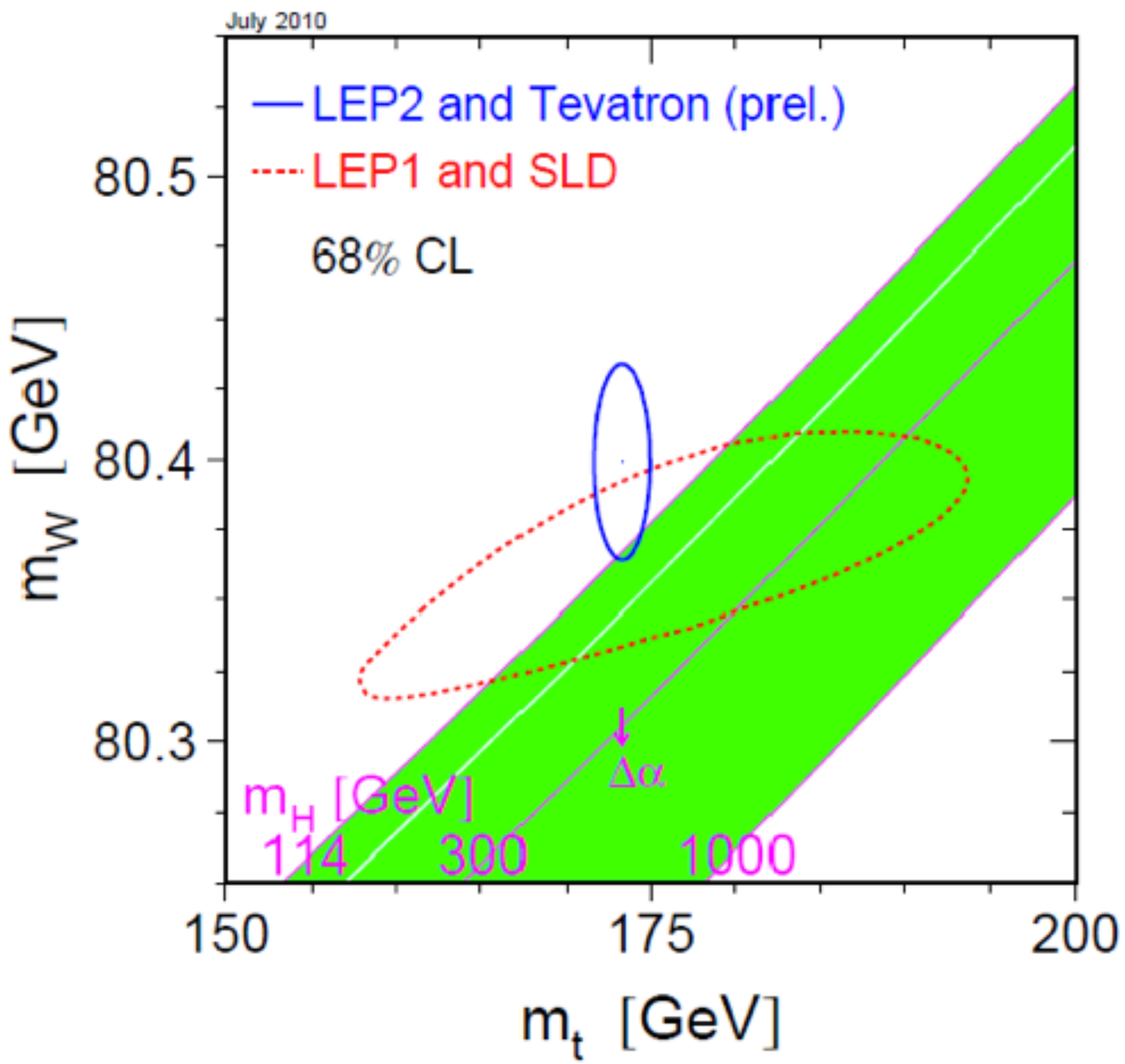
CMS: $|V_{tb}| = 1.020 \pm 0.049$

$|V_{tb}| < 1$ ➡ $0.92 < |V_{tb}| <= 1$ @ 95% C.L.

Top Quark Properties:
Mass

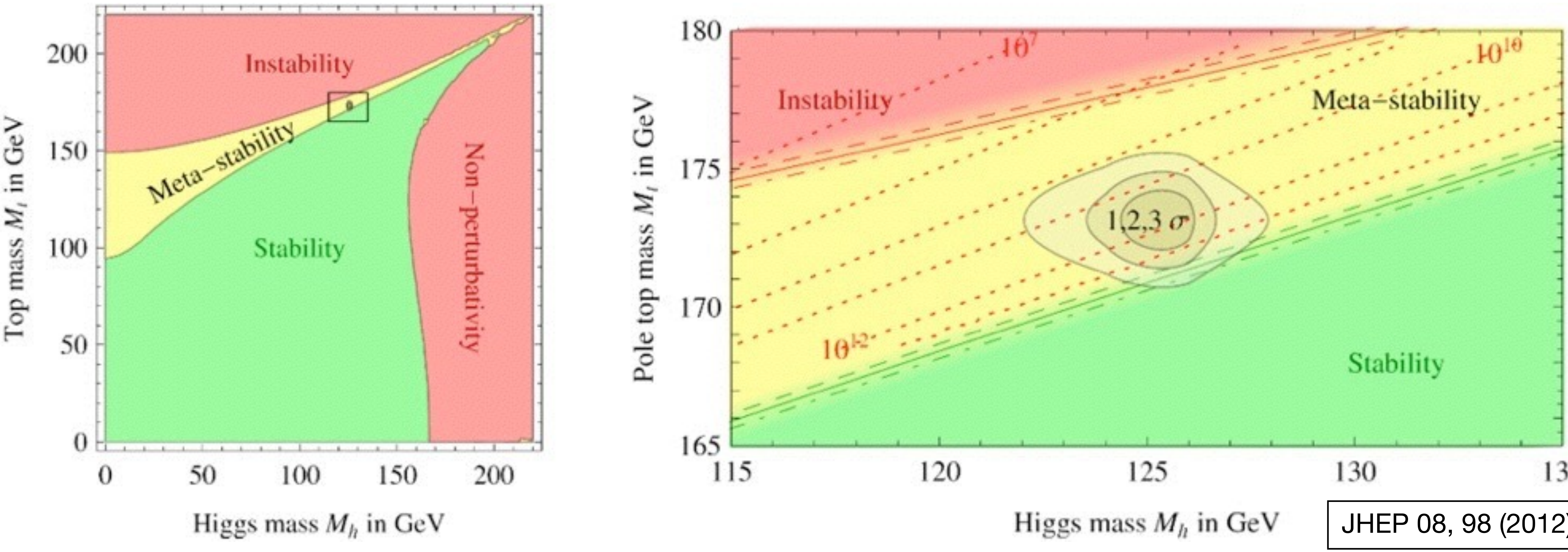
Reminder: Top Mass in the Standard Model





- 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

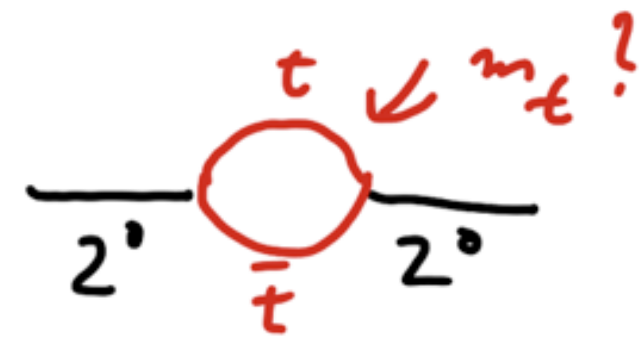
The problem: What is a quark mass? - Here the “standard” definitions of theorists and experimentalists are not the same

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

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

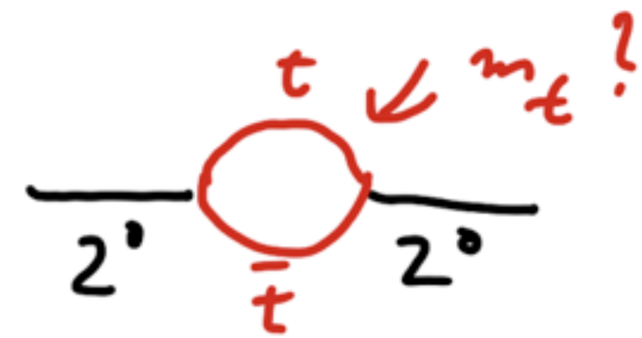


Measurement of the Mass: General Issues

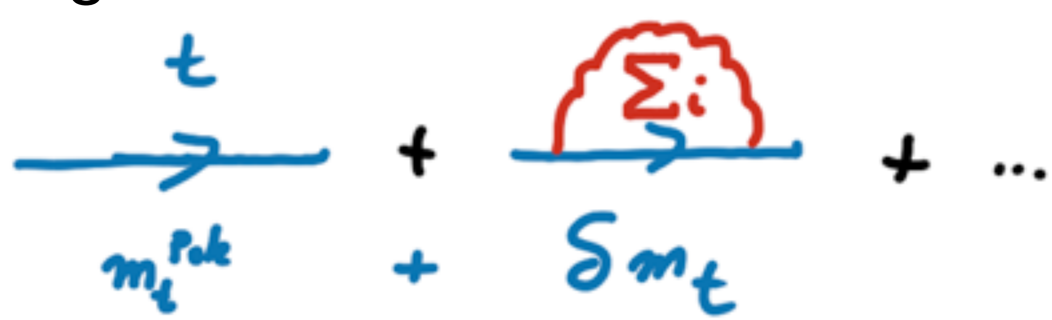
- The mass of the top quark is an important parameter of the standard model - and as such very interesting

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

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



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

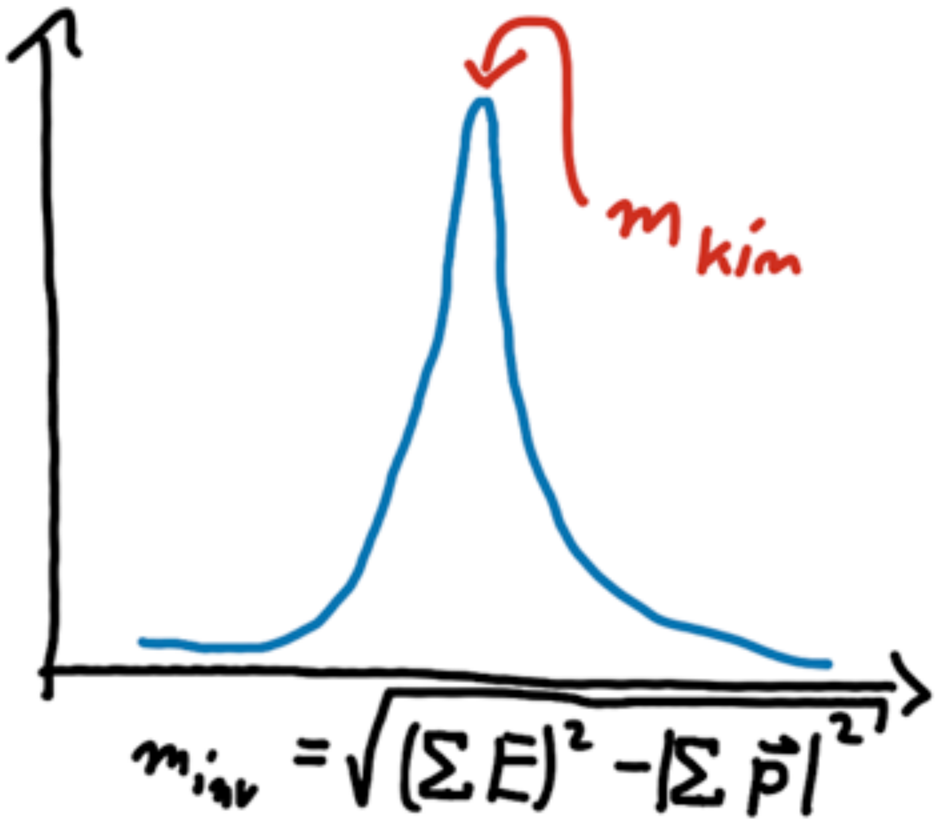


Several definitions exist in theory, depending on the need of the calculations - They can typically be converted with high precision with higher order calculations - Uncertainties on the **100 MeV** level

Measurement of the Mass: General Issues

For **experiment:**

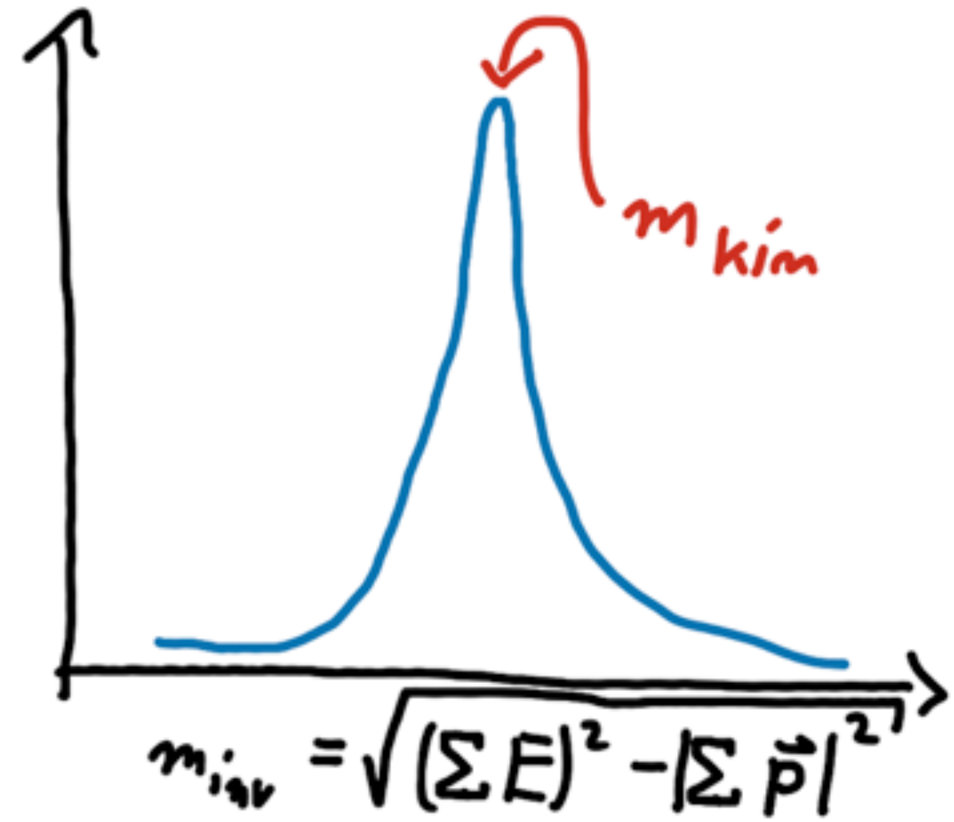
The standard technique to measure a mass is to reconstruct the “invariant mass” of the decay products



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



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

Measurement of the Top Mass at LHC

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

Measurement of the Top Mass at LHC

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

Measurement of the Top Mass at LHC

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

‣ Best accuracy achieved by multi-dimensional fits to reduce systematics

Measurement of the Top Mass at LHC

- Measurement in all final states of top pair events:
  Di-Lepton, Lepton+Jets, All Hadronic
- 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
  - ...
- ▸ Best accuracy achieved by multi-dimensional fits to reduce systematics

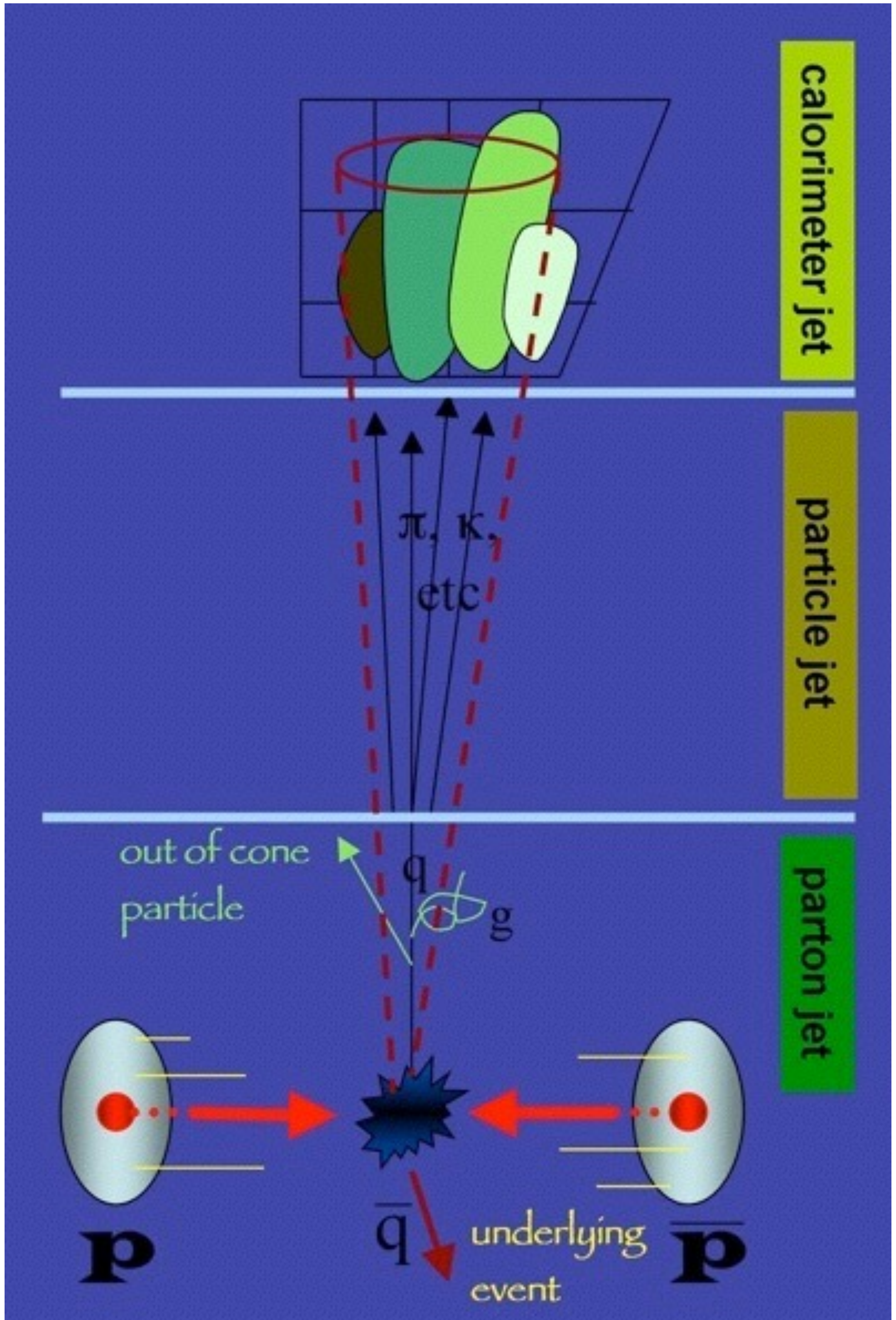
Measurement of the Top Mass at LHC

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

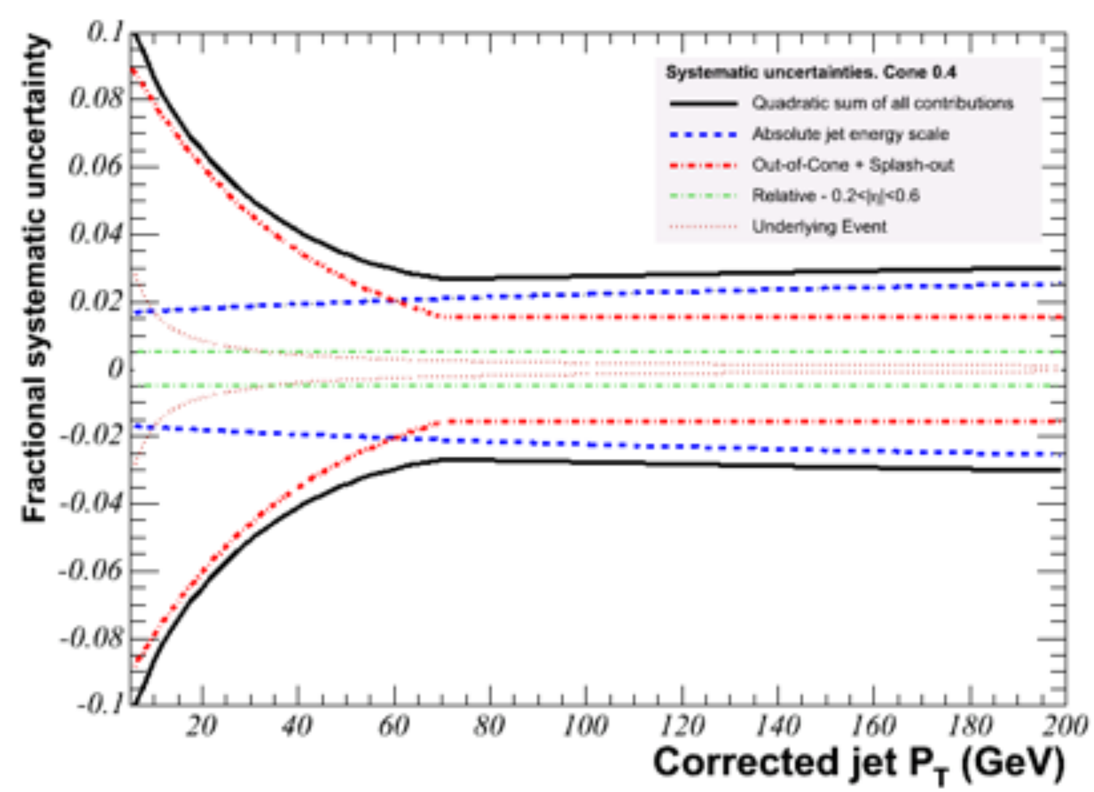
▸ Best accuracy achieved by multi-dimensional fits to reduce systematics

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

Jet Energy Scale JES



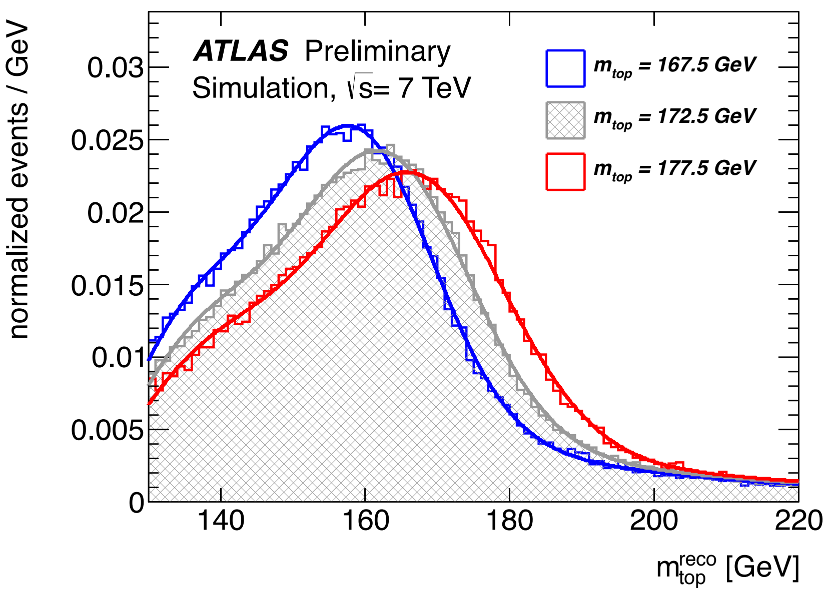
- The measurement of a jet:
  - Energy in a cone with a certain radius (various definitions in use) typically in the calorimeters (more sophisticated approaches also use tracks)
- The physics observable:
  - Energy of the original parton
- The energy scale corrects from the measured jet energy to the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

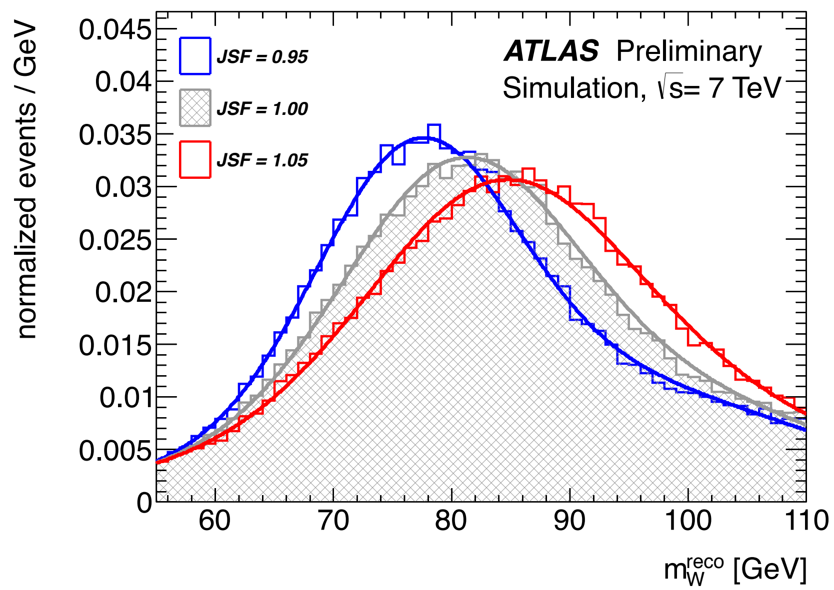


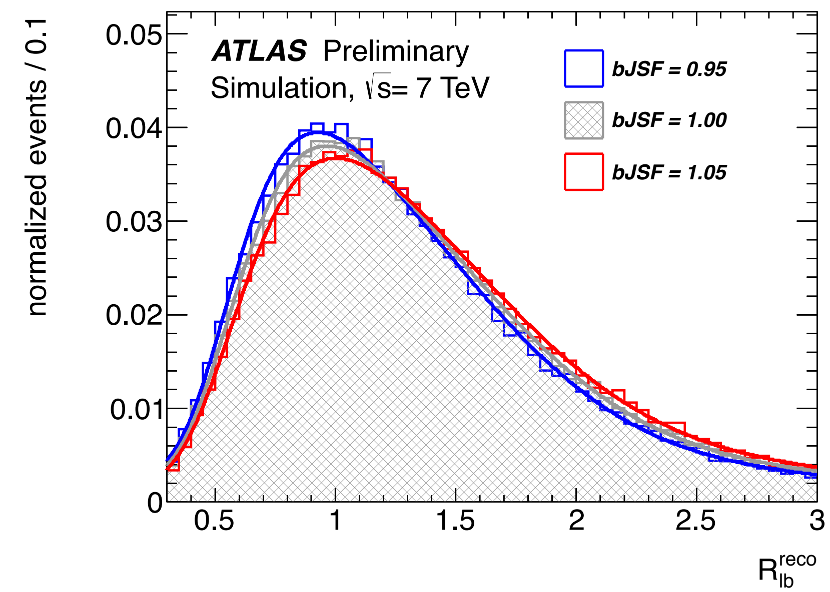
CDF

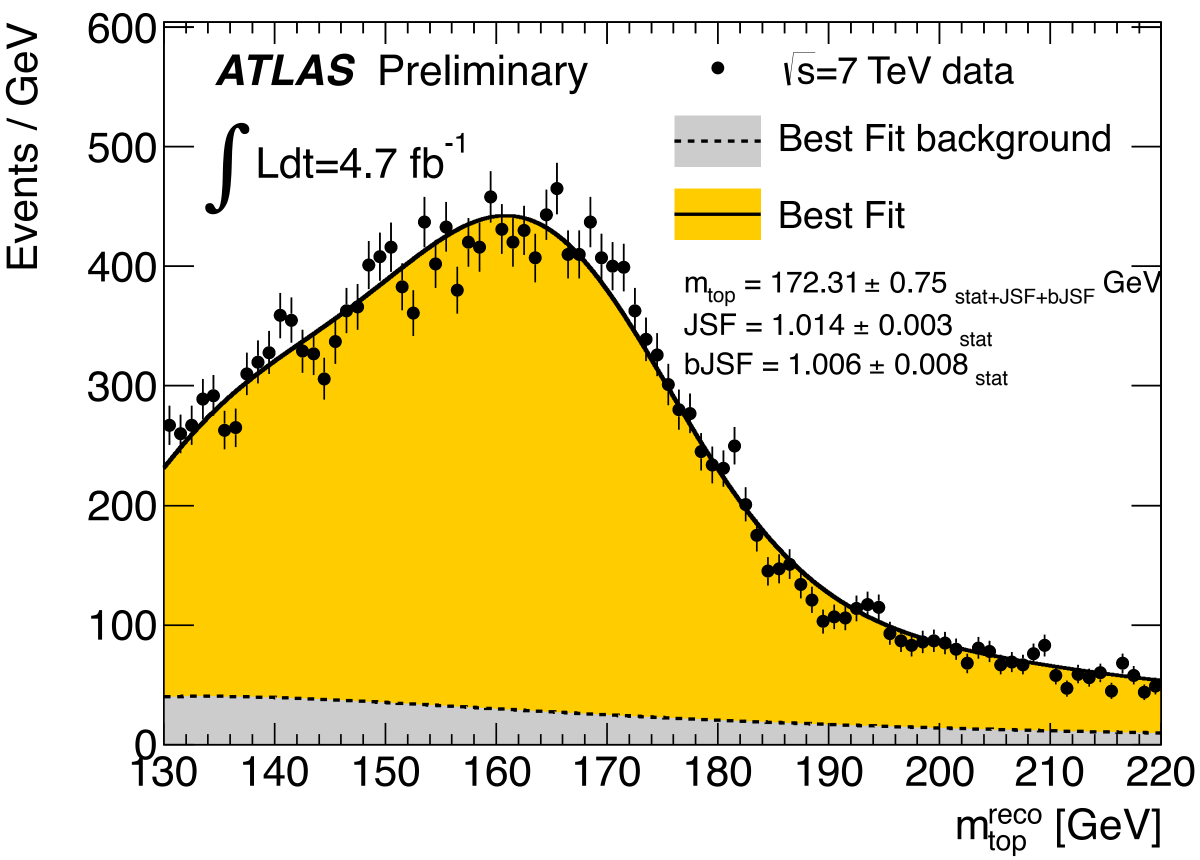
One Example: Lepton + Jets in ATLAS

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





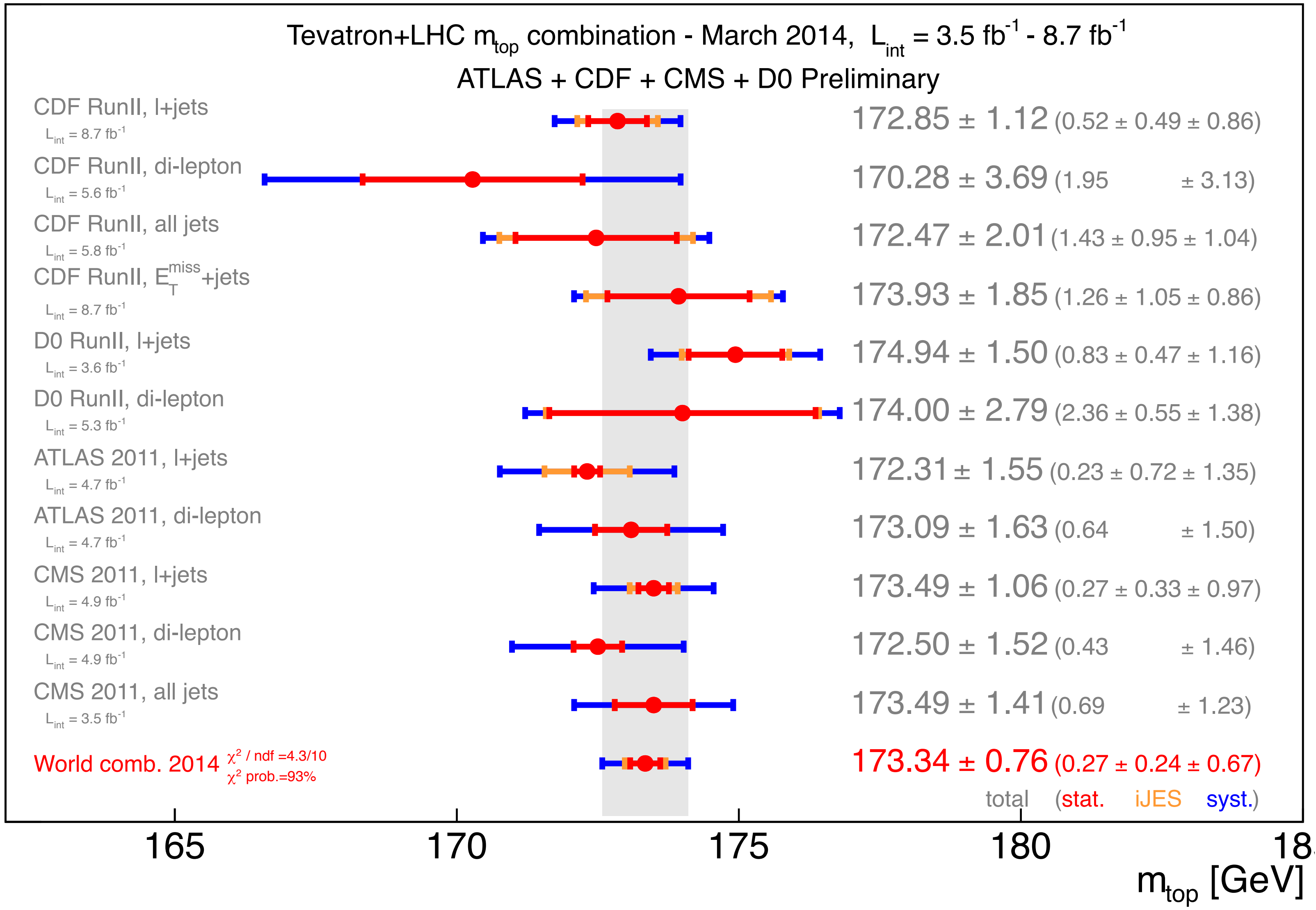




3D fitting substantially reduces systematics (-40% compared to previous technique!)

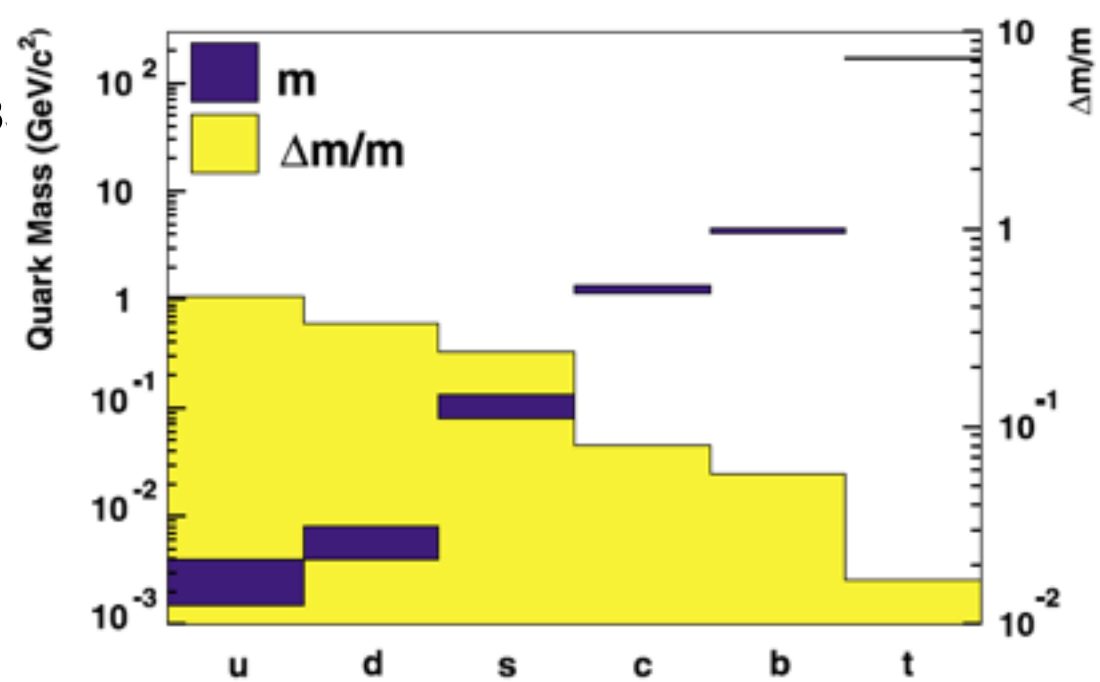
m_{top} = 172.31 ± 0.23(stat) ± 0.27(JSF) ± 0.67(bJSF) ± 1.35(syst) GeV

Top-Mass: Current Status (March 2014)



first-ever LHC - Tevatron combination

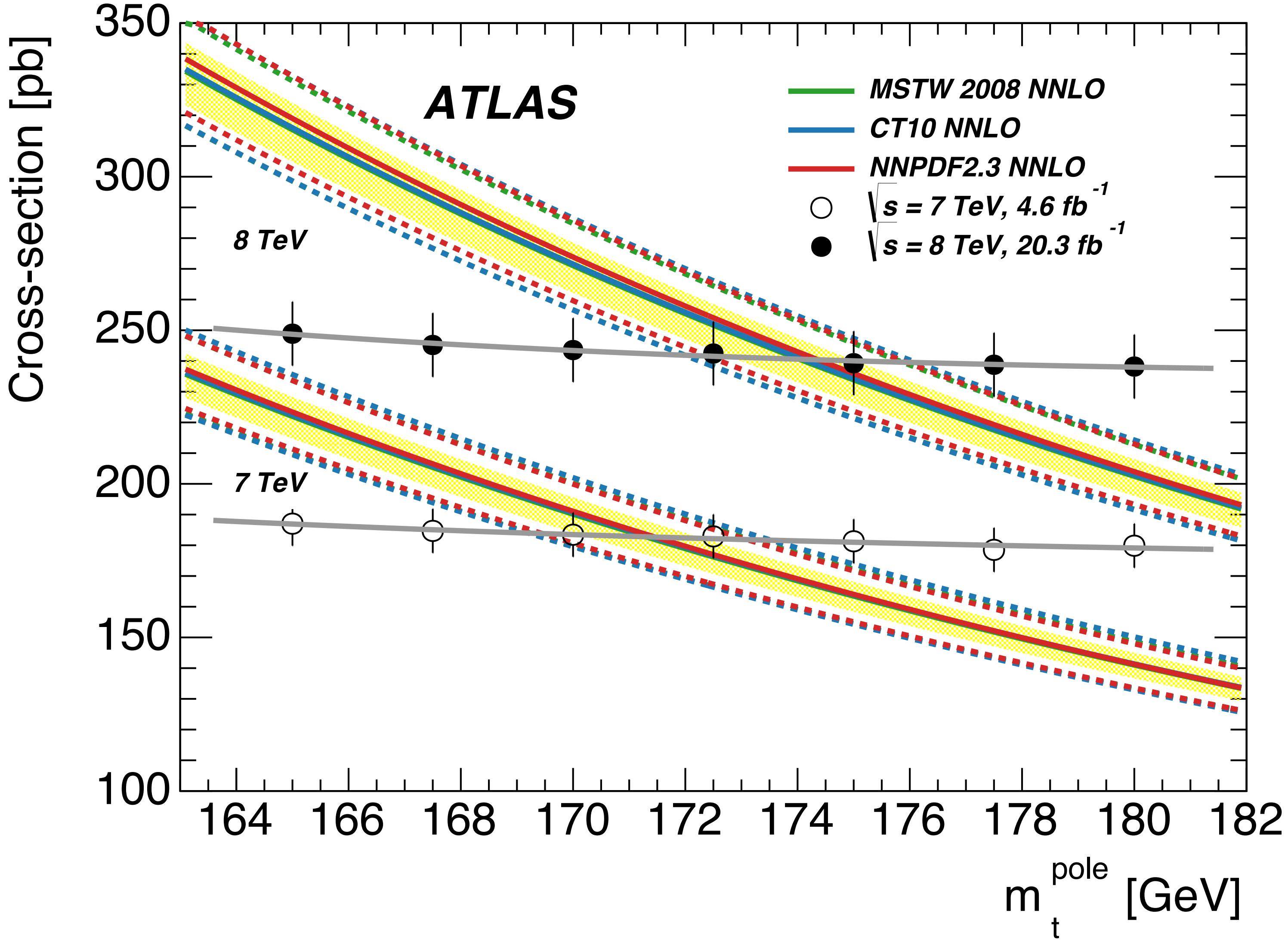
- Both LHC and Tevatron have measurements in all channels
  - Everything is consistent!
- Uncertainty on the top quark mass < **1%**:
  By far the best-known quark mass!



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

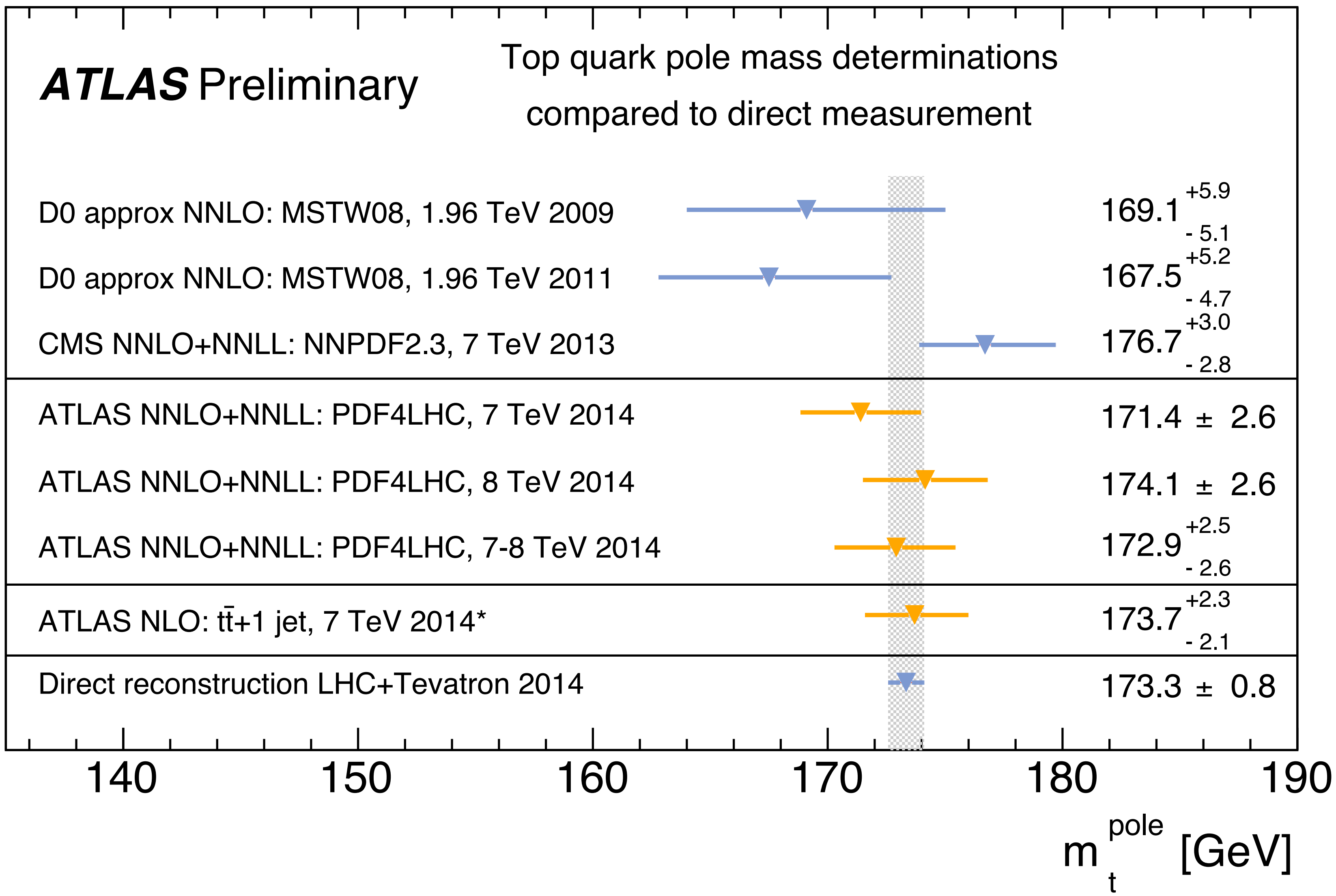
Results:

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

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

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

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 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 (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
  - Maybe, with a bit of luck: New Physics

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 (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
  - Maybe, with a bit of luck: New Physics

Next Lecture: Supersymmetry, S. Bethke 12.01.2015

Zeitplan

1.	Einführung; Stand der Teilchenphysik	06.10.
2.	Teilchendetektoren an Tevatron und LHC (I)	13.10.
3.	Teilchendetektoren an Tevatron und LHC (II)	20.10.
4.	Hadronenbeschleuniger: Tevatron und LHC	27.10.
5.	Monte Carlo Generatoren und Detektor Simulation	03.11.
6.	Trigger, Datennahme und Computing	10.11.
7.	Standard-Modell Tests	17.11.
8.	QCD, Jets, Strukturfunktionen	24.11.
9.	Higgs I	01.12.
10.	Higgs II	08.12.
11.	Top Physics	15.12.
	----------- No Lecture -------------	**22.12.**
	-----------Christmas — — — — — — — — — —	
12.	Supersymmetry	12.01.
13.	Exotica / LHC Pläne	19.01.
14.	Future Collider Projects	26.01.