technische universität dortmund

Department of Physics

Top-quark physics at the LHC

Kevin Kröninger – TU Dortmund

BCD Summer School, Cargese, 30.03.2023

Google

best quark in the world

Alle · Bilder · Shopping · Videos · News · Mehr · Suchfilter

Ungefähr 9.650.000 Ergebnisse (0,48 Sekunden)

Wikipedia
https://en.wikipedia.org › wiki · Diese Seite übersetzen

Top quark

The **top quark**, sometimes also referred to as the truth **quark**, (symbol: t) is the most massive of all observed elementary particles.

Topness: 1
Mass: 172.76±0.3 GeV/c2
Decays into: bottom quark (99.8%); strange…
Electric charge: +2/3 e

History · Production · Decay · Mass and coupling to the...

Ähnliche Fragen

Which quark is most powerful?

Outline

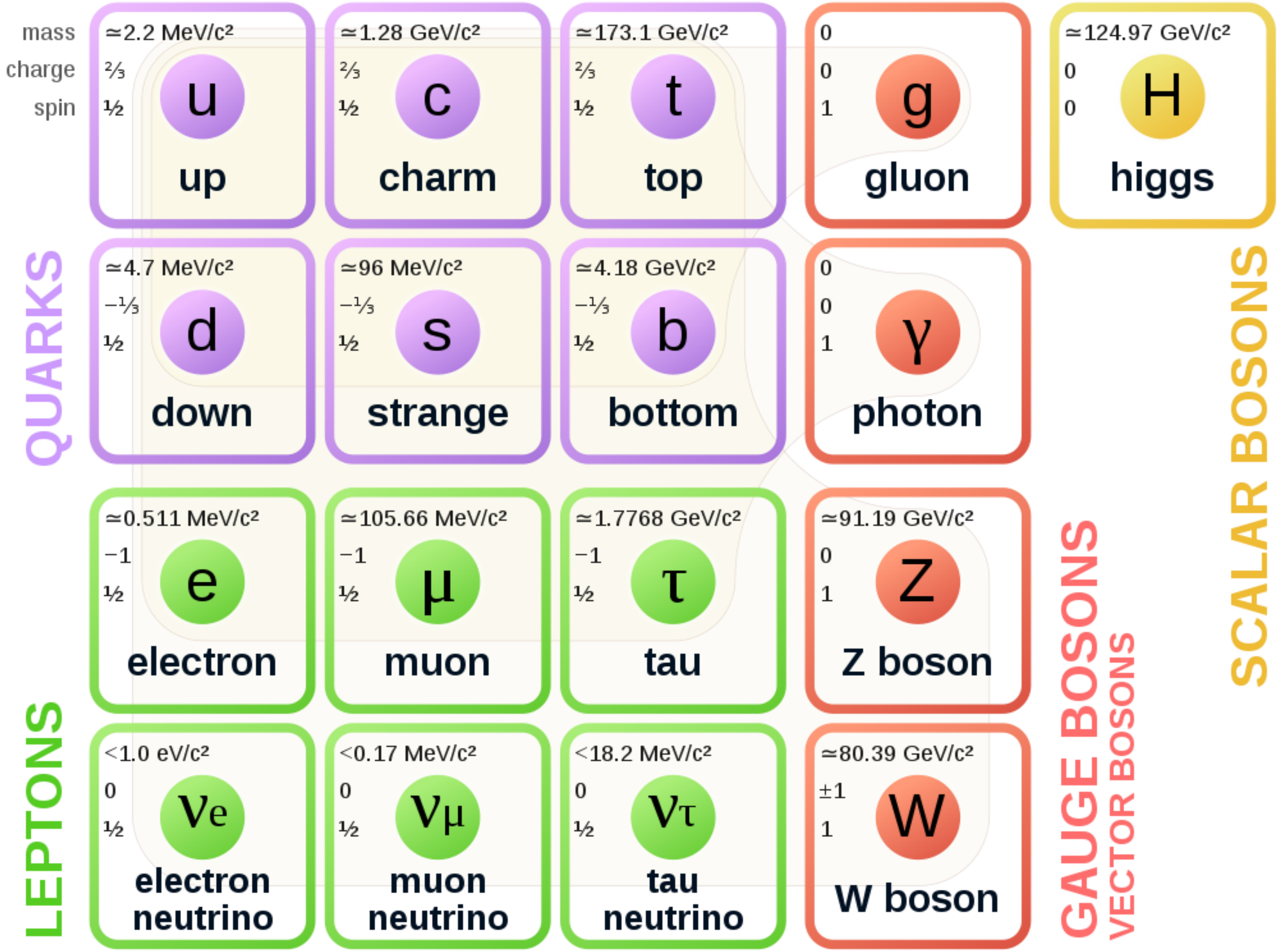
Topics

- The top quark in the SM
- Top quarks at the LHC
- Measurements
- Interpretations in EFTs

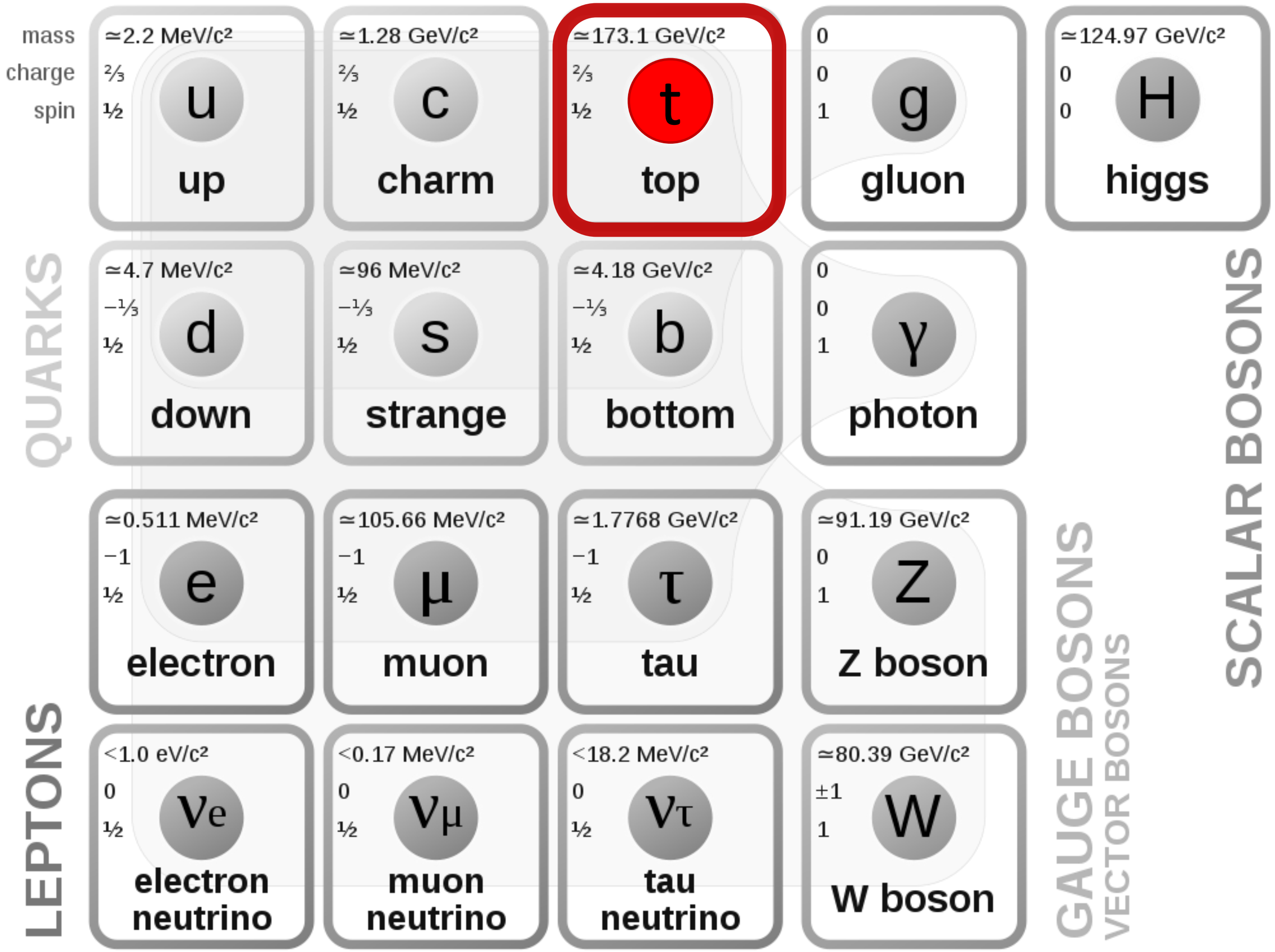
The top quark in the Standard Model

… and why it is important

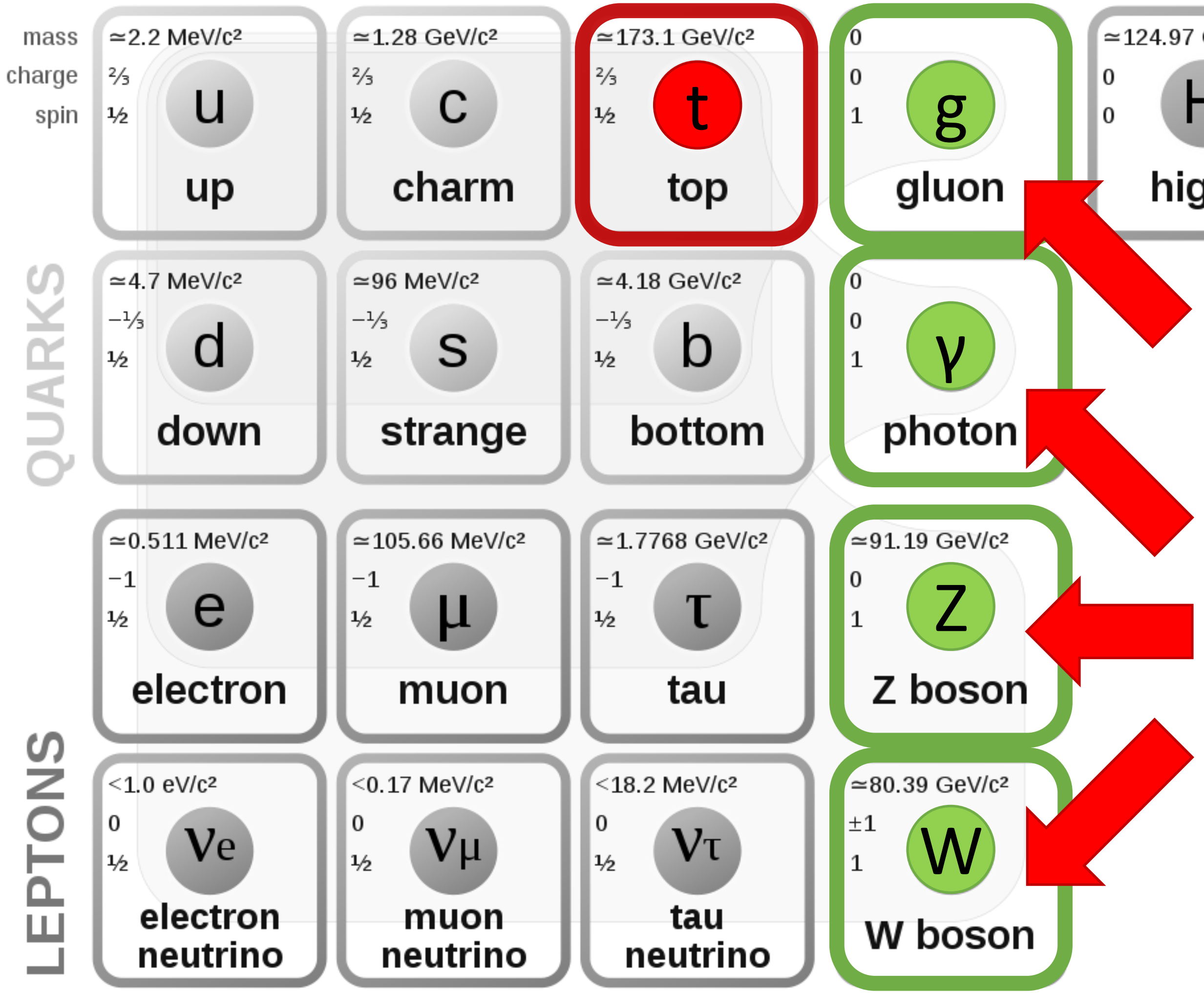
Particles in the SM



The top quark



Fixed SM parameters

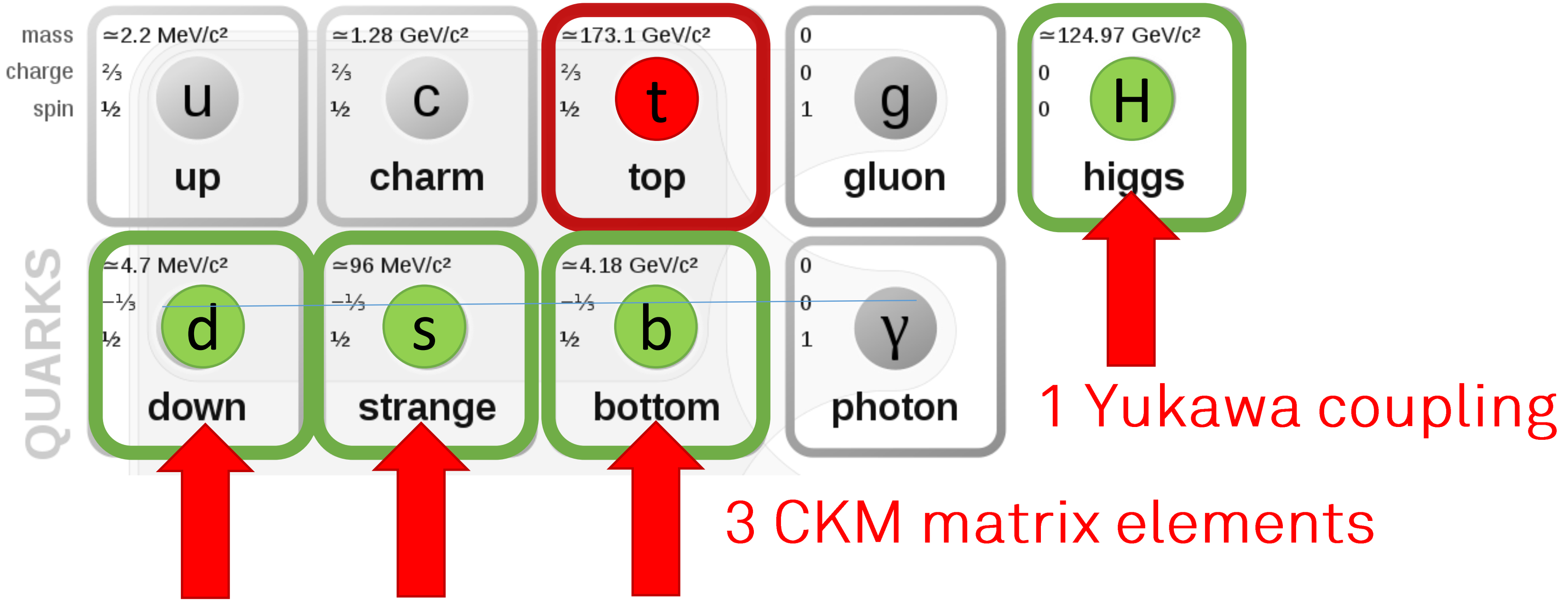


Fixed by strong interaction

Fixed by electroweak interaction

The top quark in the SM

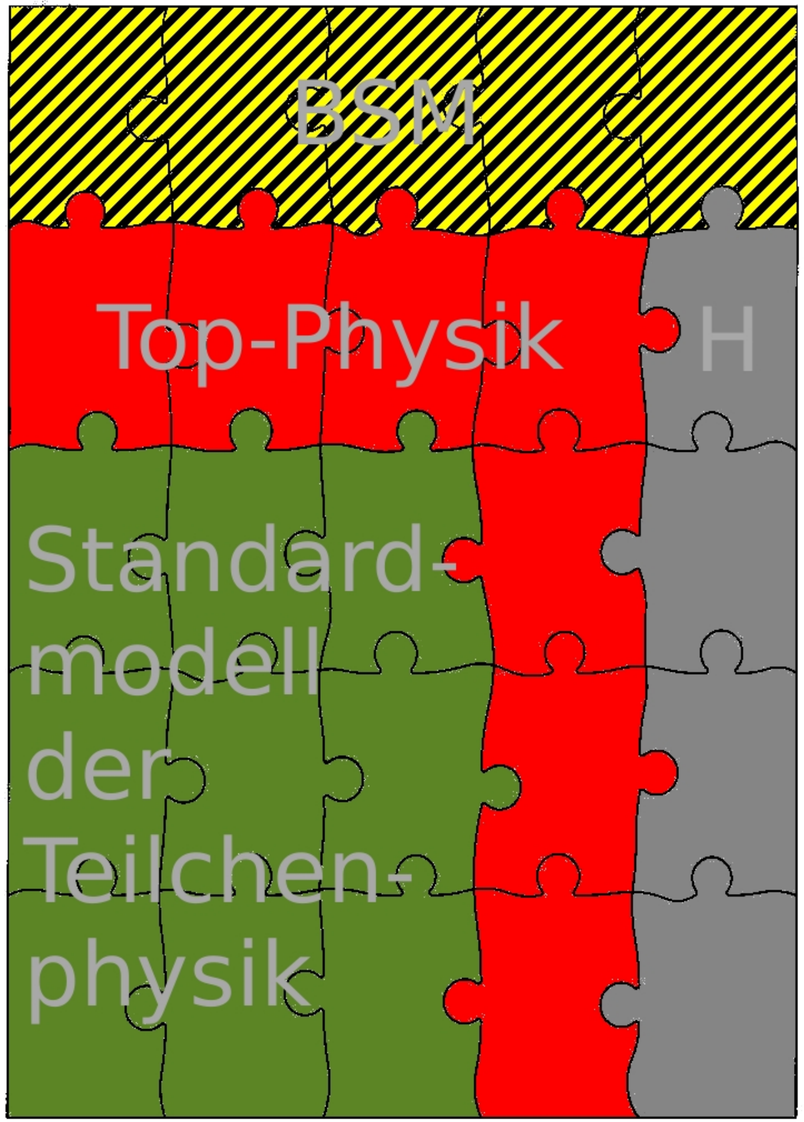
Fixed SM parameters



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

Why study the top quark?

- Measure the free SM parameters
- Plays special role in the EW sector:
  - Connects to Higgs boson
  - Important for EW precision measurements
- Opens the door to BSM physics:
  - Heaviest known particle
  - Important to understand its properties
  - Every signal is a potential background
- Challenging signature:
  - Use most of the detector subsystems
  - Requires well-understood detector



Hints for a third generation

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

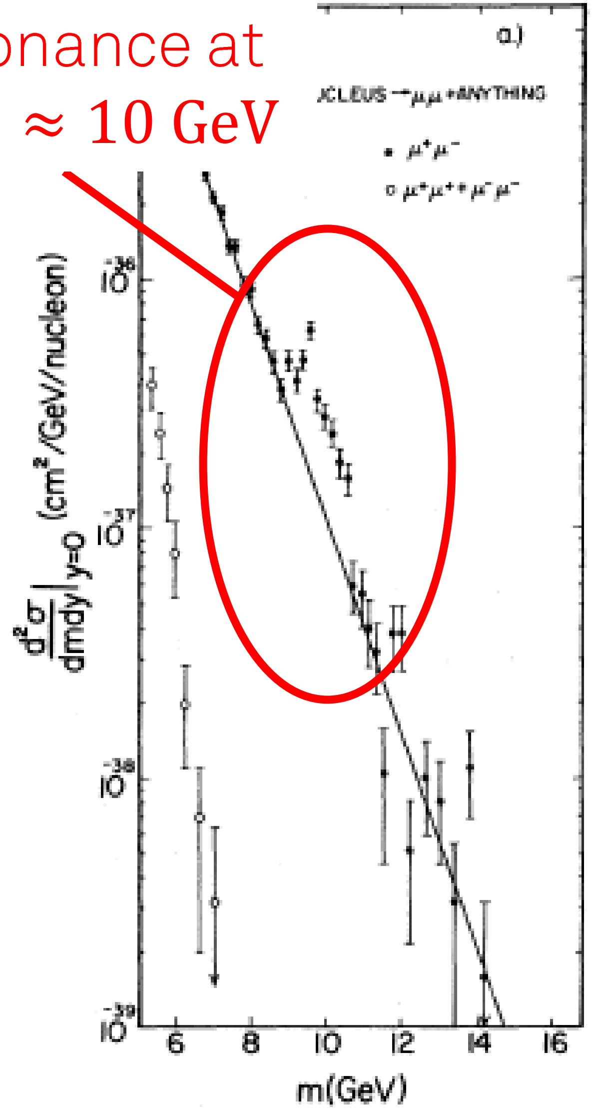
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

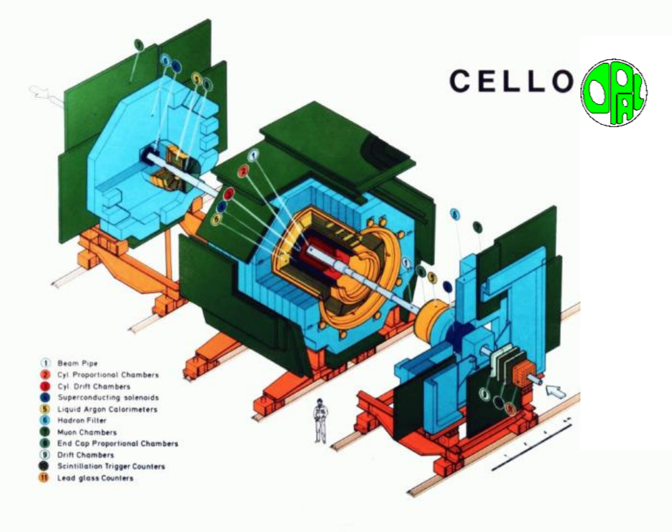
- 1973: CP violation requires three generations (Kobayashi and Maskawa)
- 1975: Discovery of the tau lepton (Perl *et al.*, SLAC)
- 1977: Discovery of the bottom quark (Lederman *et al.*, Fermilab)

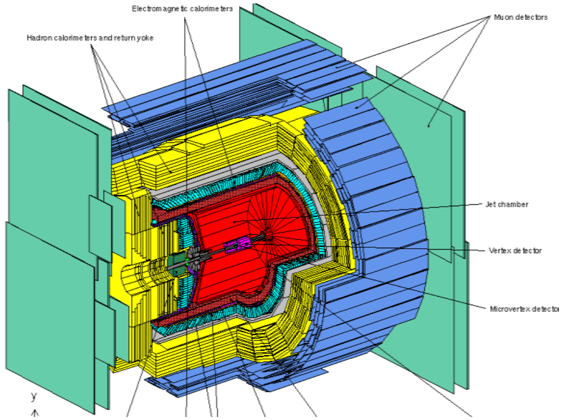
A resonance at
$2 \cdot m_b \approx 10$ GeV

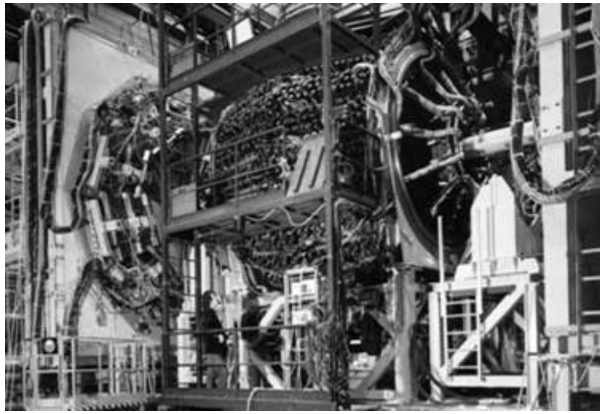


[Phys. Rev. Lett. **39** (1977) 252]

Direct searches (1980ies)



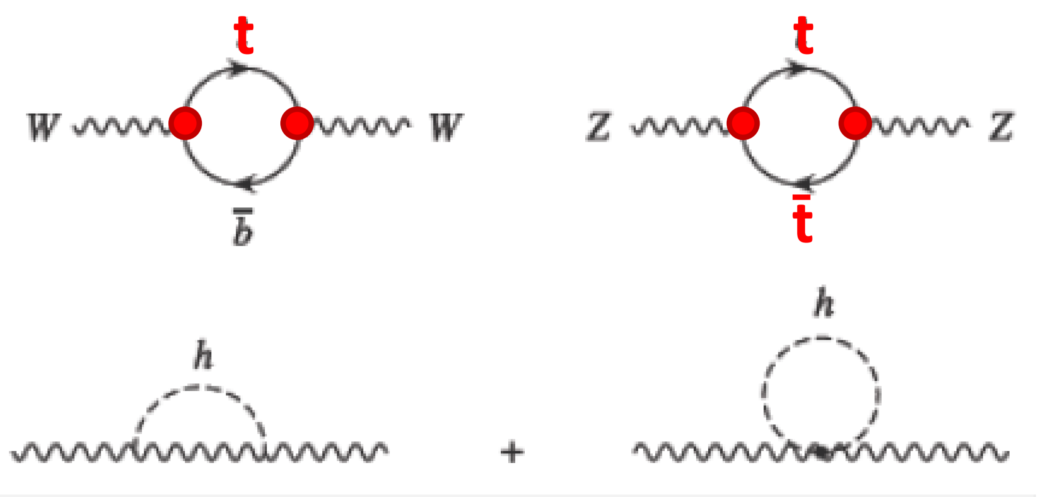


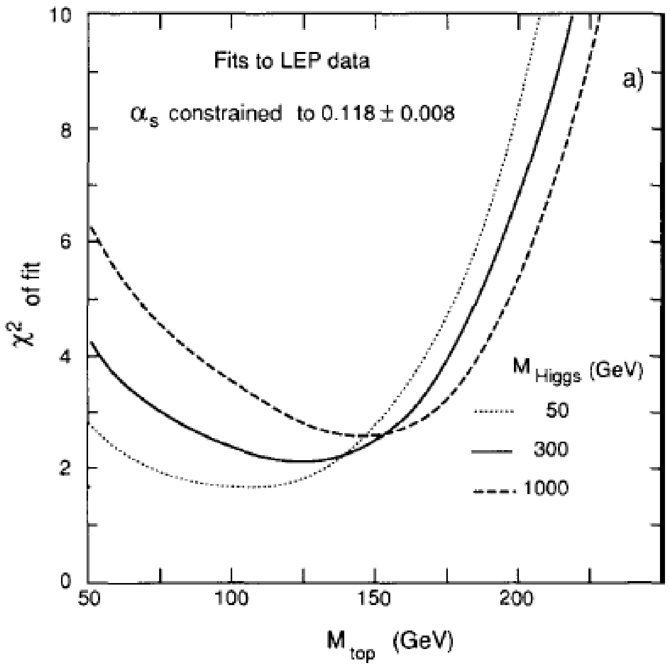


- CELLO (e+e- PETRA, DESY): m_t > 23.3 GeV (95% CL)
  [Phys. Lett. B **144** (1984) 297]
- VENUS (e+e- TRISTAN, KEK): m_t > 30.2 GeV (95% CL)
  [Phys. Lett. B **234** (1990) 382]
- OPAL (e+e- LEP, CERN): m_t > 44.5 (95% CL)
  [Phys. Lett. B **236** (1990) 364]
- UA2 (ppbar SppS, CERN): m_t > 69 GeV (95% CL)
  [Z. Phys. C **46** (1990) 179]

Indirect searches (1990ies)

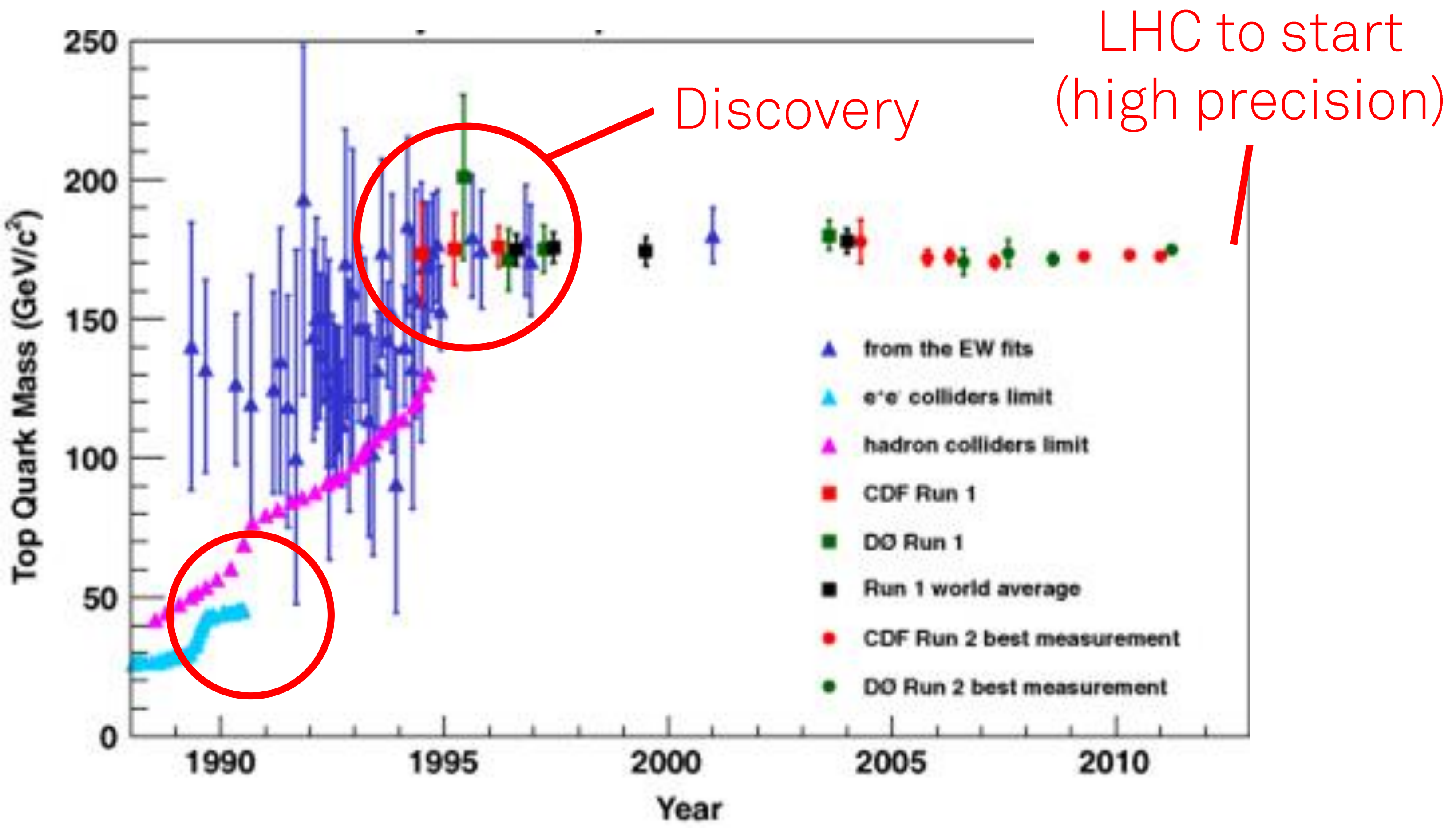
- Top quark, W boson and Higgs boson masses are connected via loop corrections
- Fit of electroweak observables constrains top-quark mass





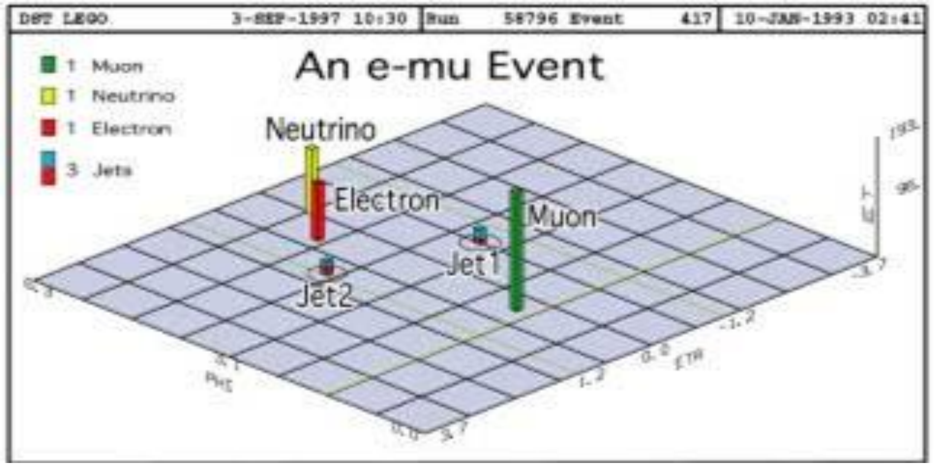
[Phys. Lett. B **276** (1992) 247]

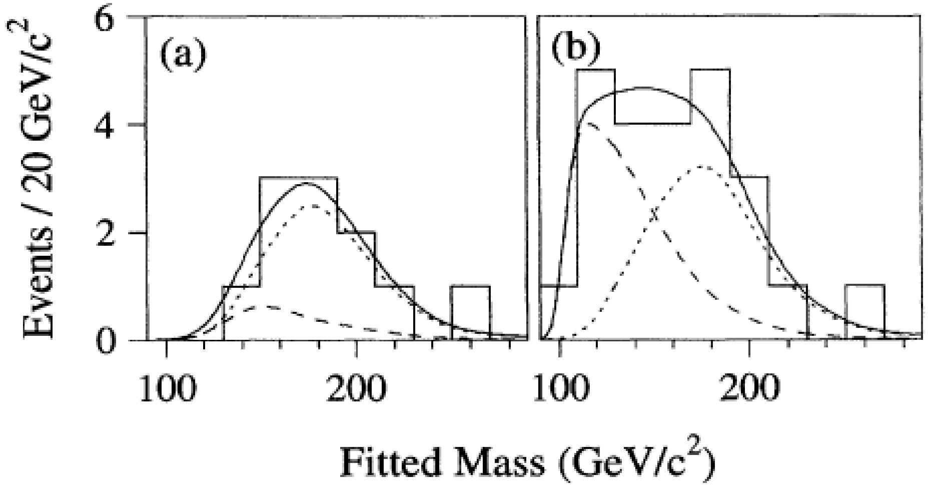
Top-quark mass history



[Ann. Rev. Nucl. Part. Sci. **59** (2009) 505]

Discovery of the top quark (1995)





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NEWS RELEASE

News Release - March 2, 1995

Office of Public Affairs
P.O. Box 500
Batavia, IL 60510
630-840-3351
Fax 630-840-8780
E-Mail TOPQUARK@FNAL.GOV

NEWS MEDIA CONTACTS:
Judy Jackson, 708/840-4112 (Fermilab)
Gary Pitchford, 708/252-2013 (Department of Energy)
Jeff Sherwood, 202/586-5806 (Department of Energy)

PHYSICISTS DISCOVER TOP QUARK

Batavia, IL--Physicists at the Department of Energy's Fermi National Accelerator Laboratory today (March 2) announced the discovery of the subatomic particle called the top quark, the last undiscovered quark of the six predicted by current scientific theory. Scientists worldwide had sought the top quark since the discovery of the bottom quark at Fermilab in 1977. The discovery provides strong support for the quark theory of the structure of matter.

Two research papers, submitted on Friday, February 24, to Physical Review Letters by the CDF and DZero experiment collaborations respectively, describe the observation of top quarks produced in high-energy collisions between protons and antiprotons, their antimatter counterparts. The two experiments operate simultaneously using particle beams from Fermilab's Tevatron, world's highest energy particle accelerator. The collaborations, each with about 450 members, presented their results at seminars held at Fermilab on March 2.

"Last April, CDF announced the first direct experimental evidence for the top quark," said William Carithers, Jr., cospokesman, with Giorgio Bellettini, for the CDF experiment, "but at that time we stopped short of claiming a discovery. Now, the analysis of about three times as much data confirms our previous evidence and establishes the discovery of the top quark."

The DZero collaboration has discovered the top quark in an independent investigation. "The DZero observation of the top quark depends primarily on the number of events we have seen, but also on their characteristics," said Paul Grannis, who serves, with Hugh Montgomery, as DZero cospokesman. "Last year, we just did not have enough events to make a statement about the top quark's existence, but now, with a larger data sample, the signal is clear."

Physicists identify top quarks by the characteristic electronic signals they produce. However, other phenomena can sometimes mimic top quark signals. To claim a discovery, experimenters must observe enough top quark events to rule out any other source of the signals.

"This discovery serves as a powerful validation of federal support for science," said Secretary of Energy Hazel R. O'Leary. "Using one of the world's most powerful research tools, scientists at Fermilab have made yet another major contribution to human understanding of the fundamentals of the universe."

The Department of Energy, the primary steward of U.S. high-energy physics, provided the majority of funding for the research. The Italian Institute for Nuclear Physics and the Japanese Ministry of Education, Science and Culture made major contributions to CDF. Support for DZero came from Russia, France, India, and Brazil. The National Science Foundation contributed to both collaborations. Collaborators include scientists from Brazil, Canada, Colombia, France, India, Italy, Japan, Korea, Mexico, Poland, Russia, Taiwan, and the U.S.

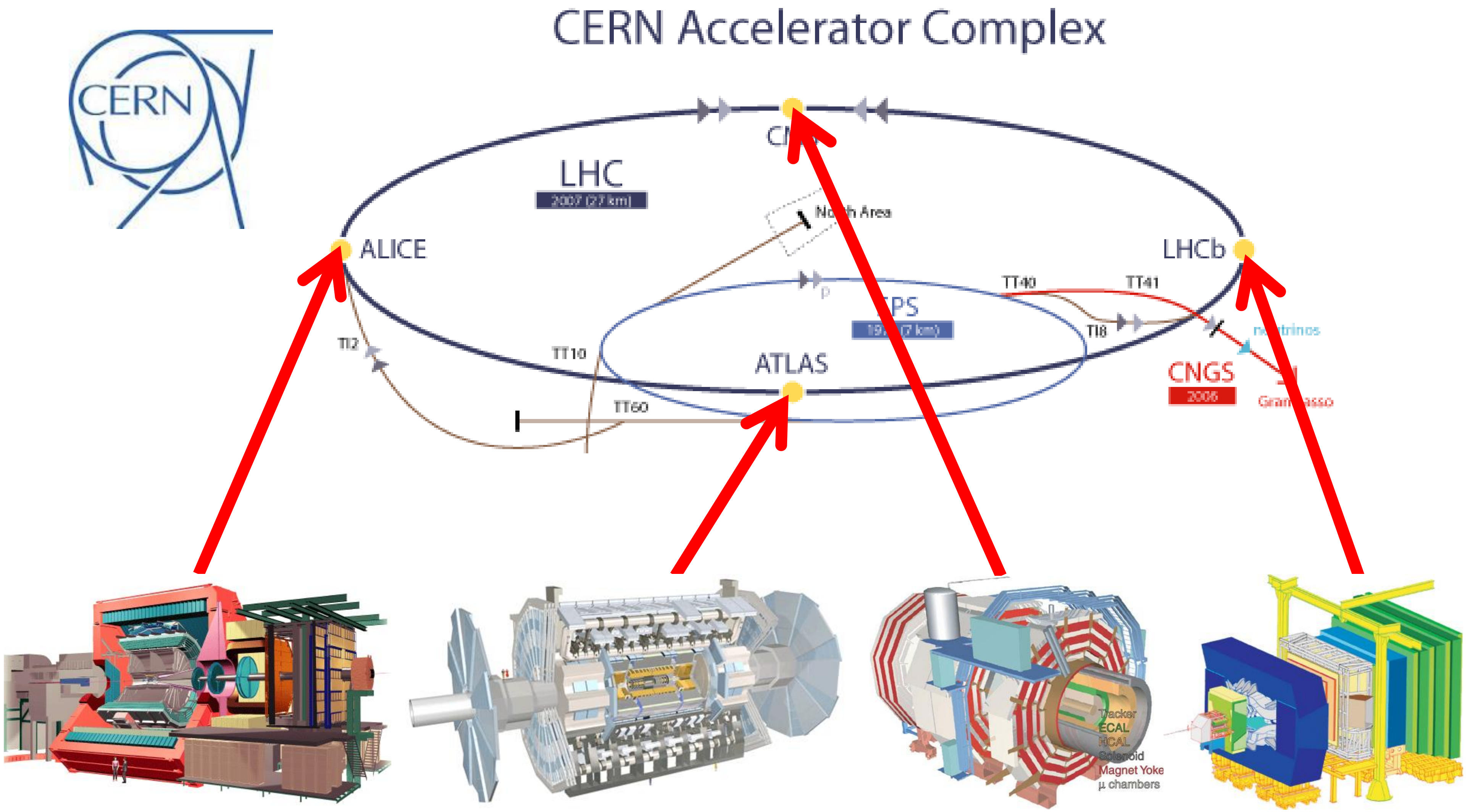
"The discovery of the top quark is a great achievement for the collaborations," said Fermilab Director John Peoples, "and also for the men and women of Fermilab who imagined, then built, and now operate the Tevatron accelerator. We have much to learn about the top quark, and more of nature's best-kept secrets to explore. We look forward to beginning a new era of research with the Tevatron, making the best use of the world's highest-energy collider."

Fermilab, 30 miles west of Chicago, is a high-energy physics laboratory operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.

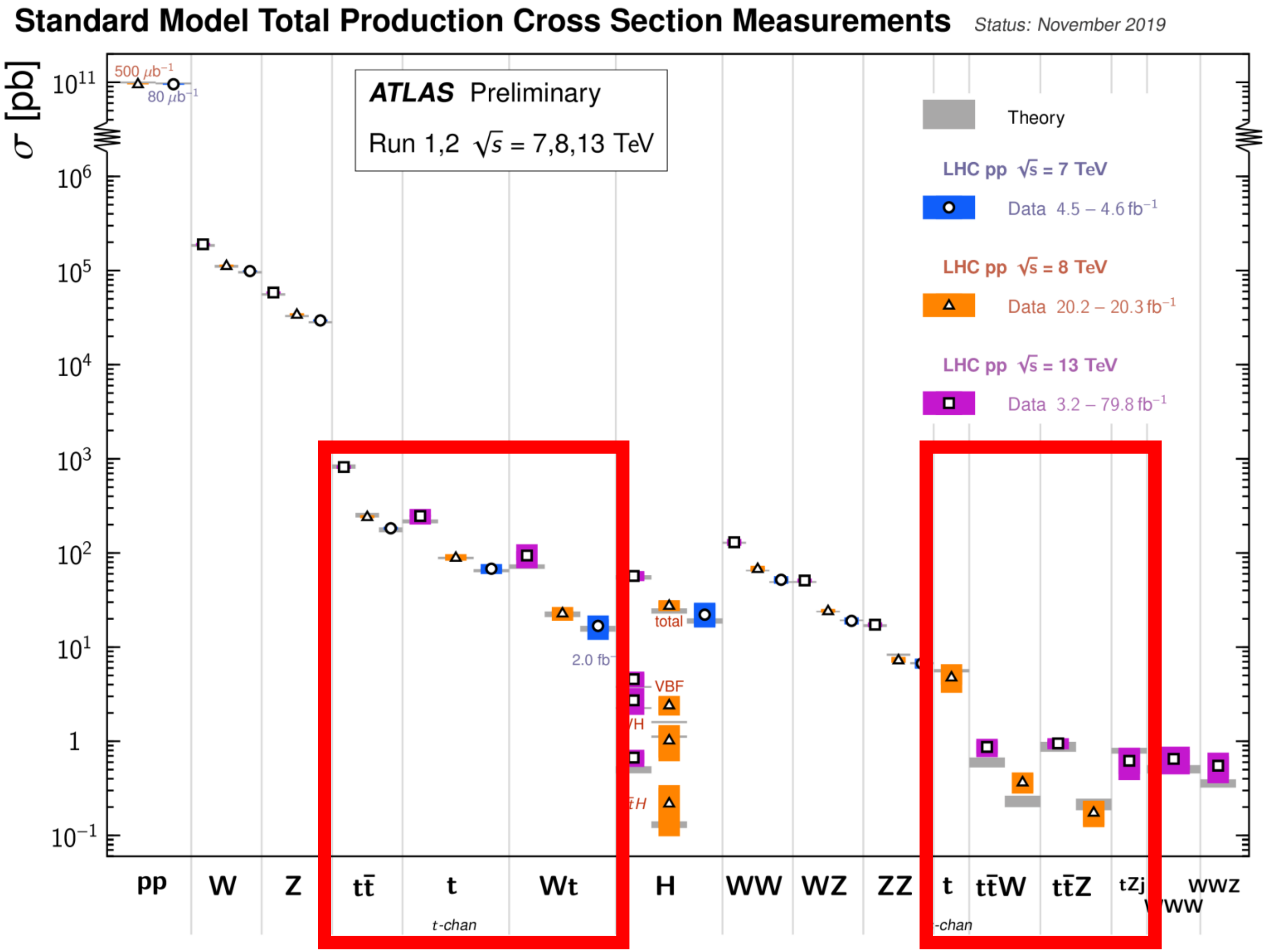
Top quarks at the LHC

A factory

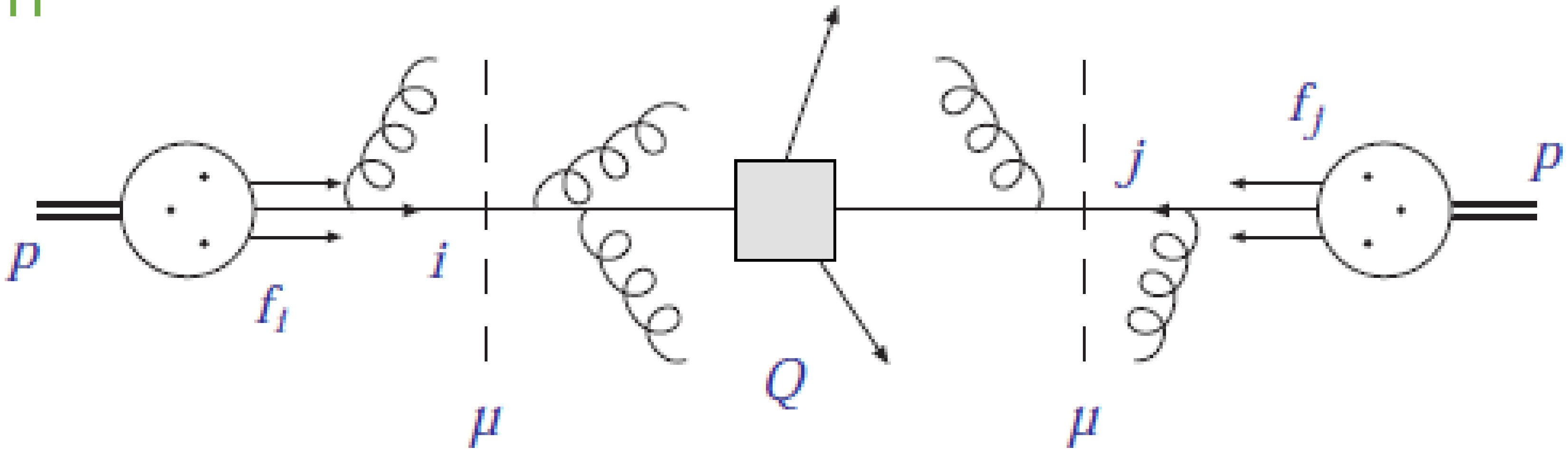
The LHC and its four main experiments



Production cross sections



Factorization



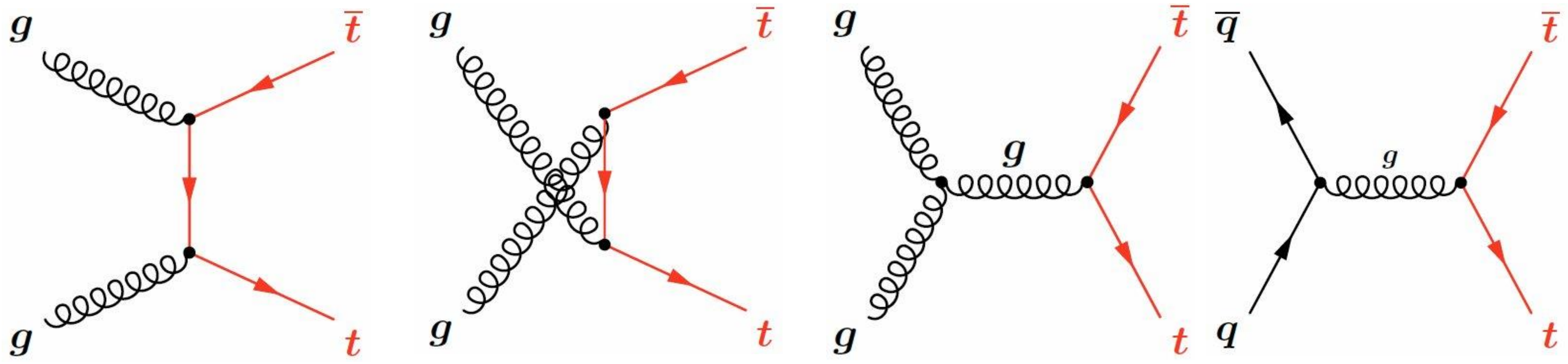
$$\sigma_{pp\rightarrow X} = \sum_{ij} \iint dx_i\, dx_j f_i(x_i, \mu_F) f_j(x_j, \mu_F) \cdot \hat{\sigma}_{ij\rightarrow X}(\alpha_S(\mu_R), Q^2, \mu_F, \mu_R)$$

- Necessary for the calculation:
  - Partonic cross section: NLO known, NNLO also known, diff. distributions, top+X)
  - Parton luminosities: parton distribution functions, measured from data
  - Choice of scales

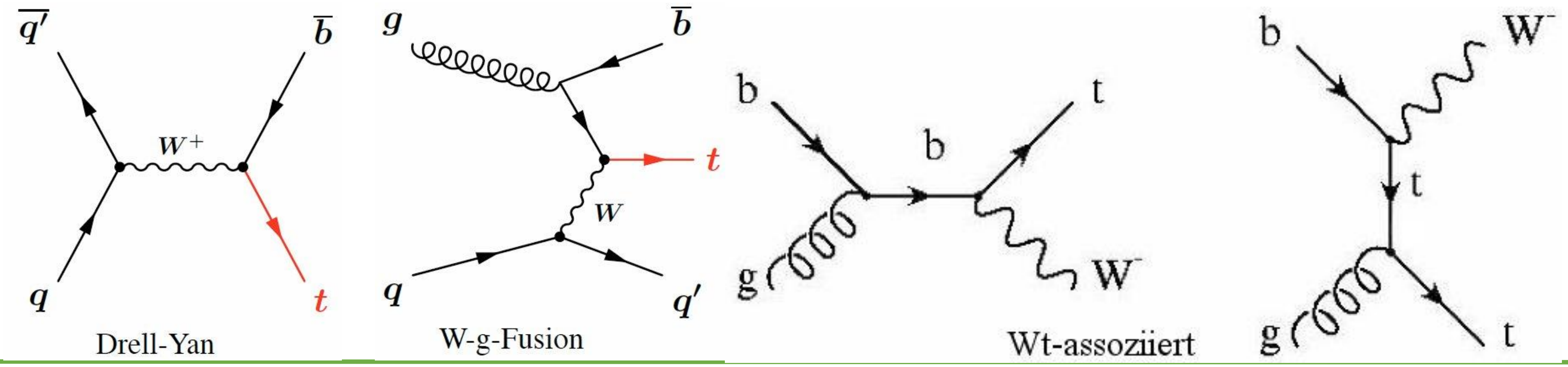
Top-quark production

Partonic reactions

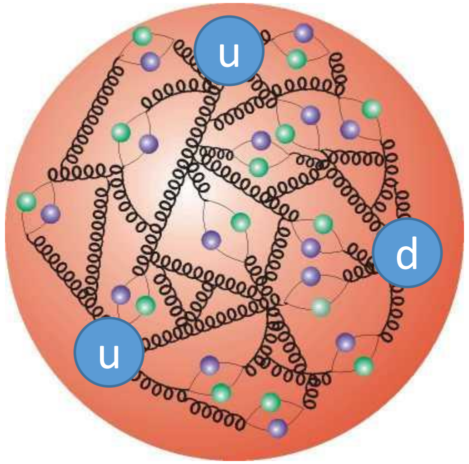
- Top-quark pair production (LO)



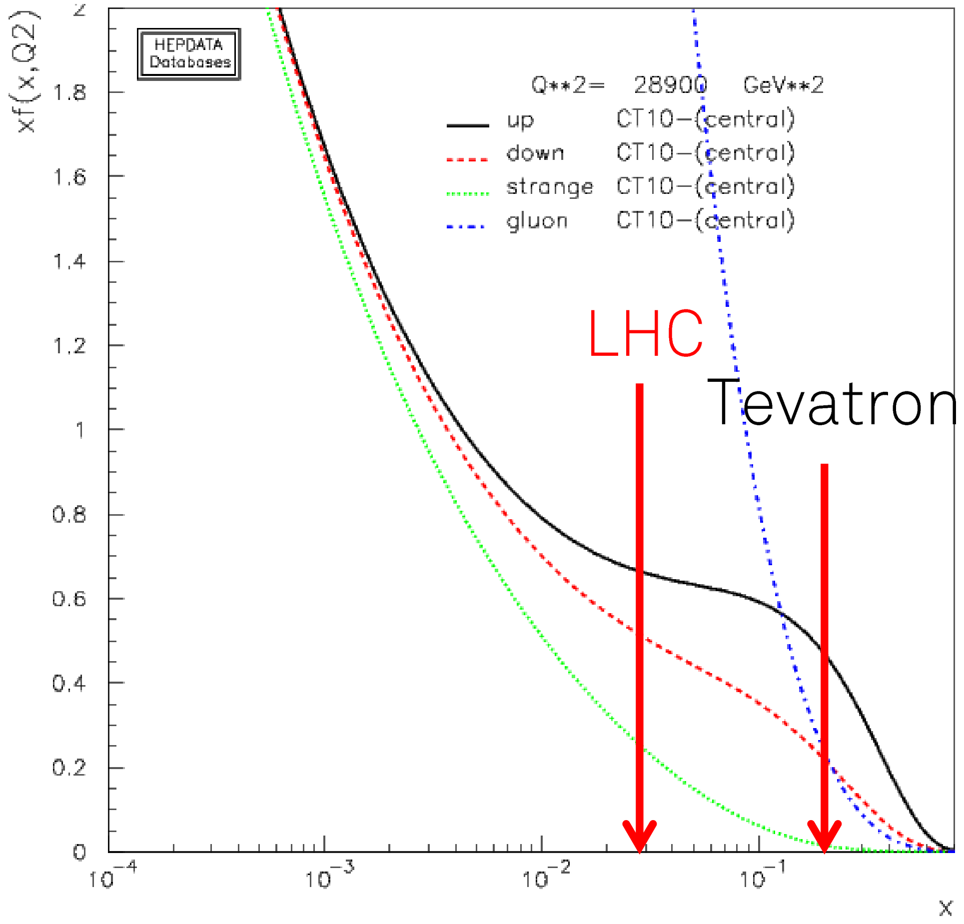
- Singe top-quark production (LO)



Parton luminosities

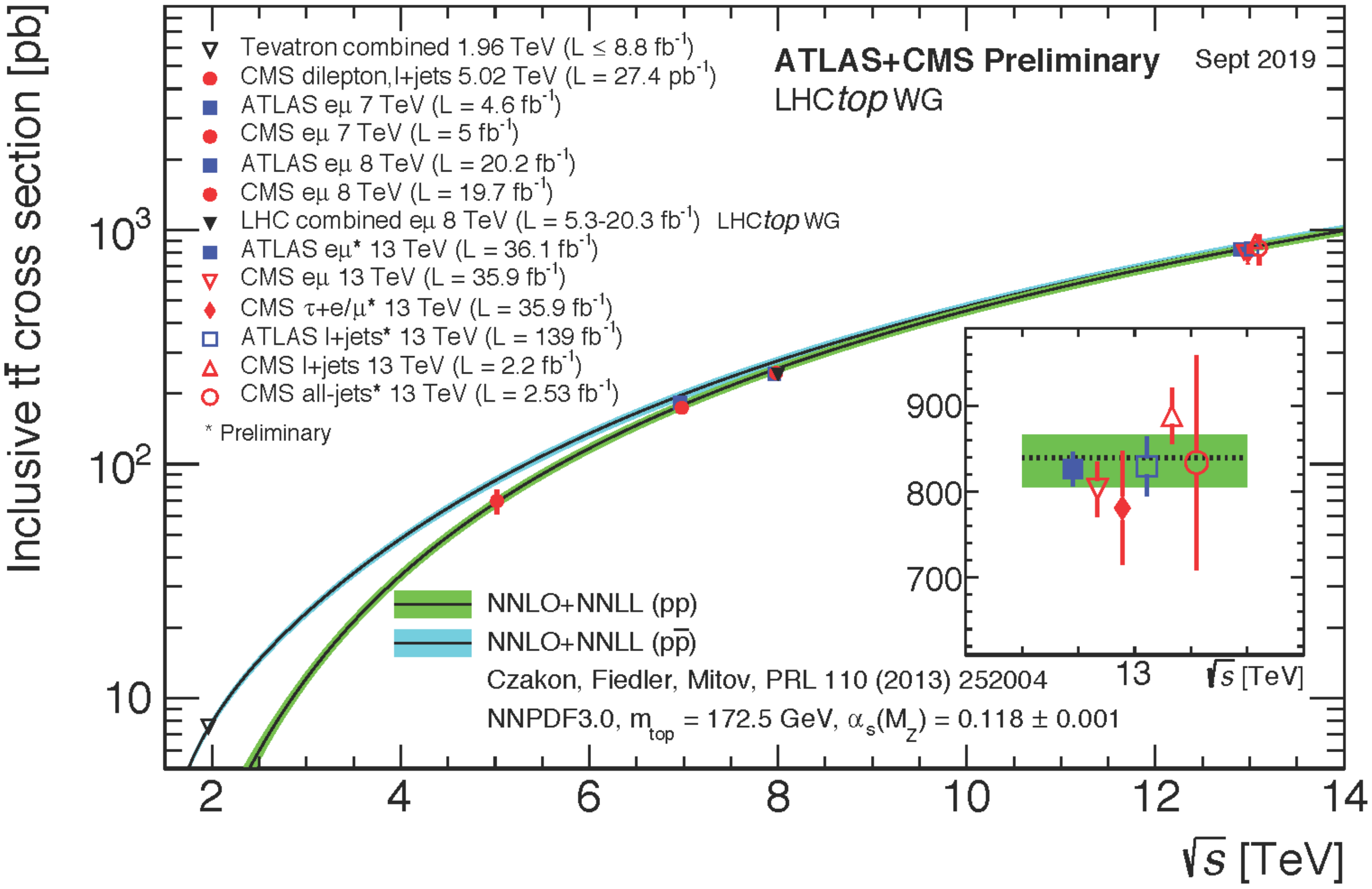


- Proton structure:
  - Gluons dominate for small x
  - Valence quarks dominate for large x
- Typical x in top-quark physics:
  - Assume x ~ 2 m / sqrt(s)
  - Tevatron: ⟨x⟩ ~ 0,2
  - LHC : ⟨x⟩ ~ 0,03



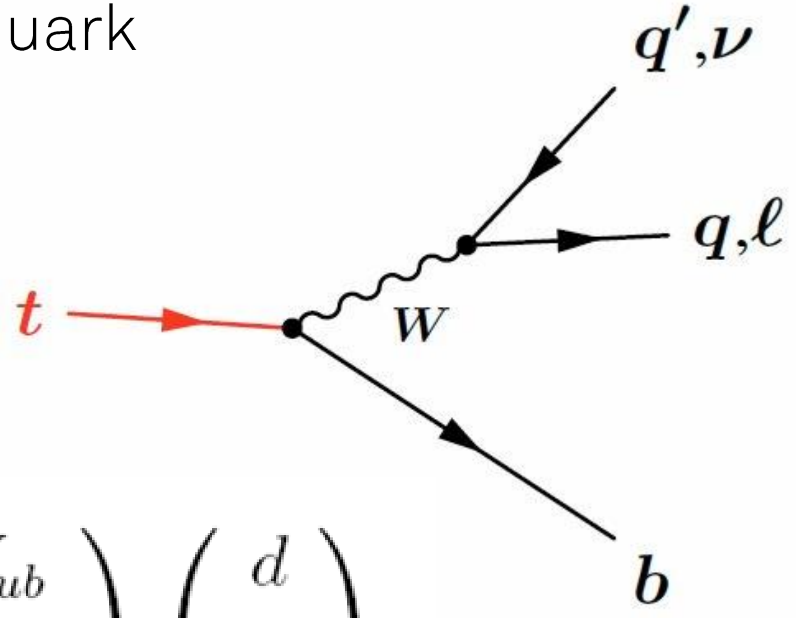
Predictions and measurements

[LHCTopWG]



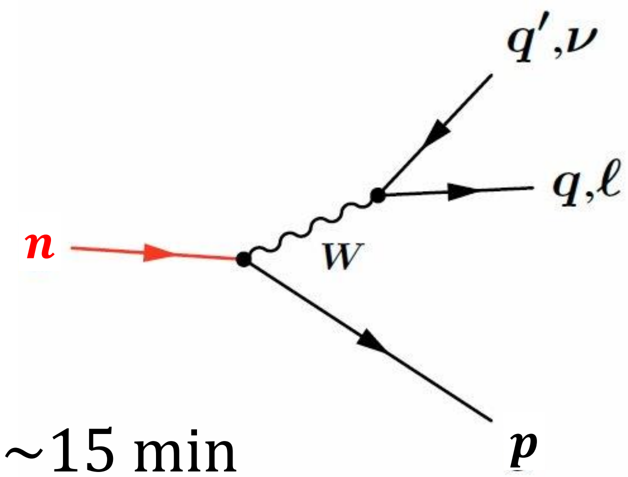
Top-quark decay

- Lifetime of the top quark $\tau \sim 4 \cdot 10^{-25}$ s
- No bound states with top quarks ($\tau < 1/\Lambda_{QCD} \sim 3 \cdot 10^{-24}$ s)
- Weak decay into W boson and down-type quark
- Branching ratios: BR(t → W+q) = $|V_{tq}|^2$
  - BR(t → W+b) ~ 0.998
  - BR(t → W+s) ~ $2 \cdot 10^{-3}$
  - BR(t → W+d) ~ 10^{-4}
- CKM matrix

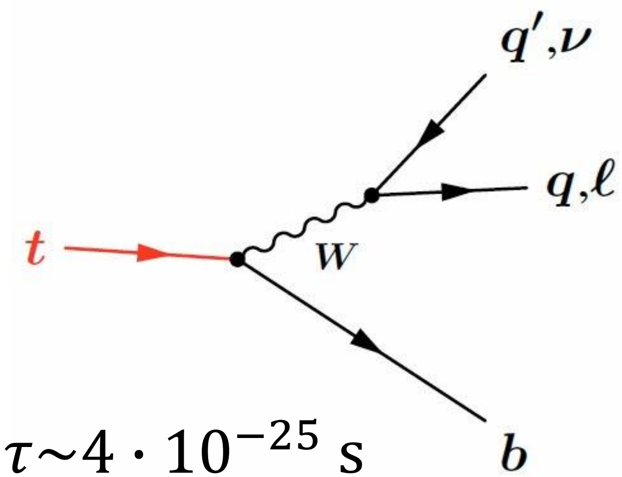


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

Why is the decay of the top quark so much quicker than that of the neutron?

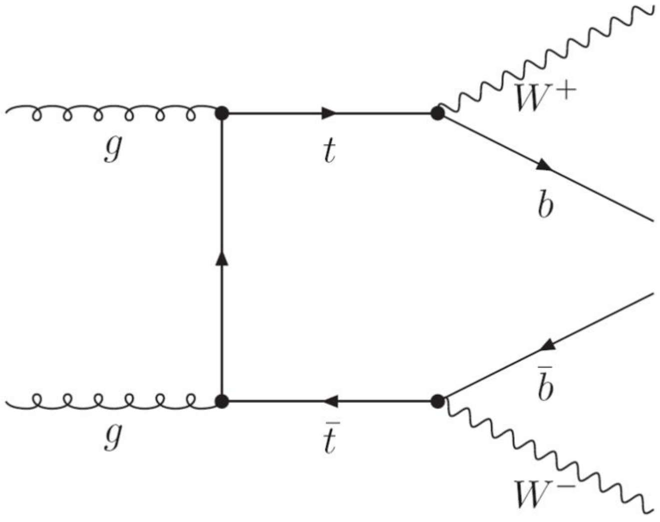


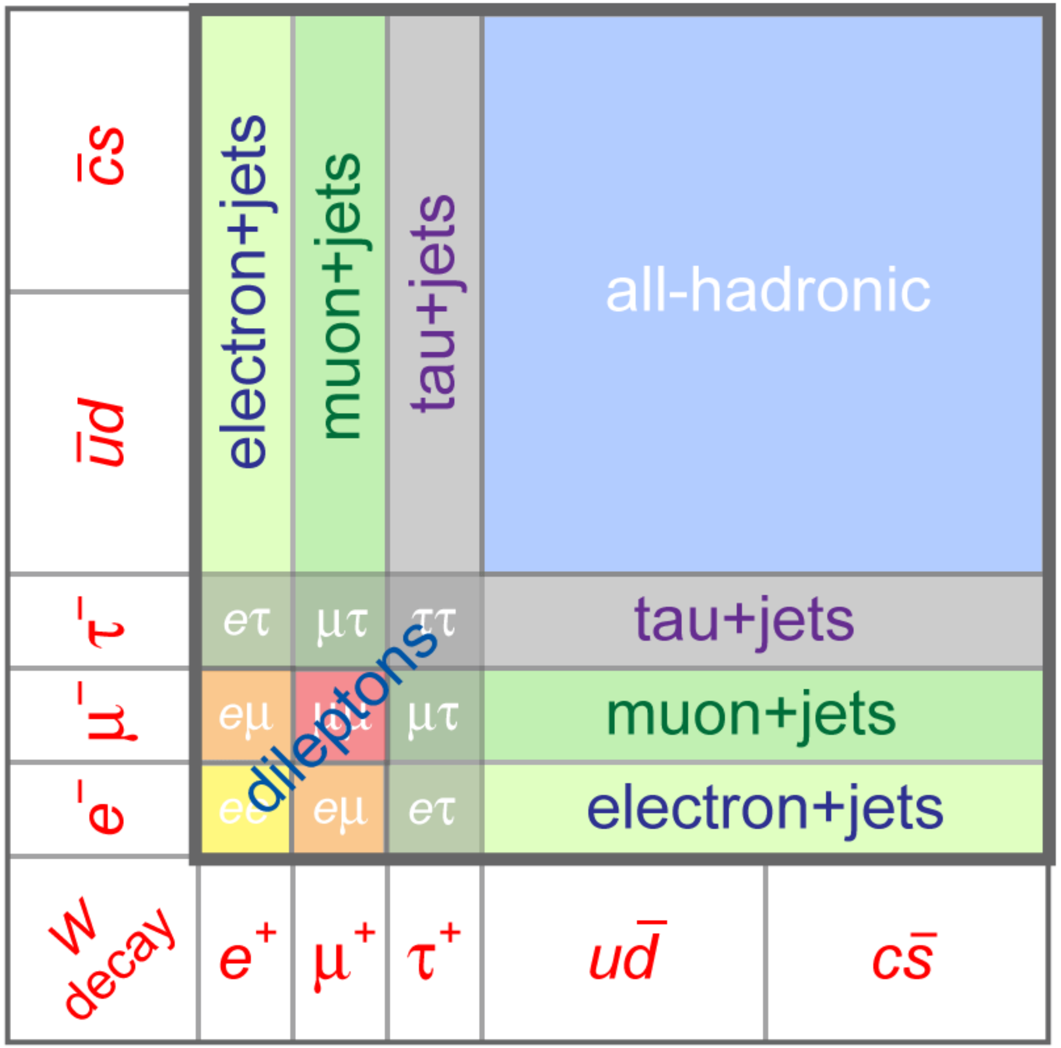
$\tau \sim 15\ \mathrm{min}$



$\tau \sim 4 \cdot 10^{-25}\ \mathrm{s}$

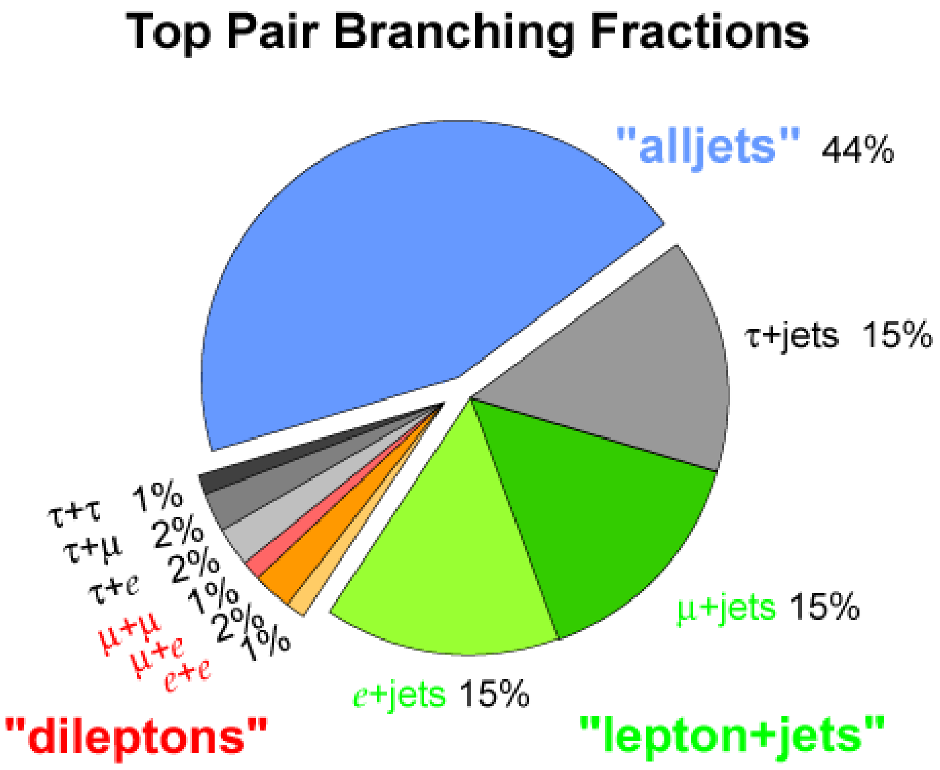
Top-quark pairs





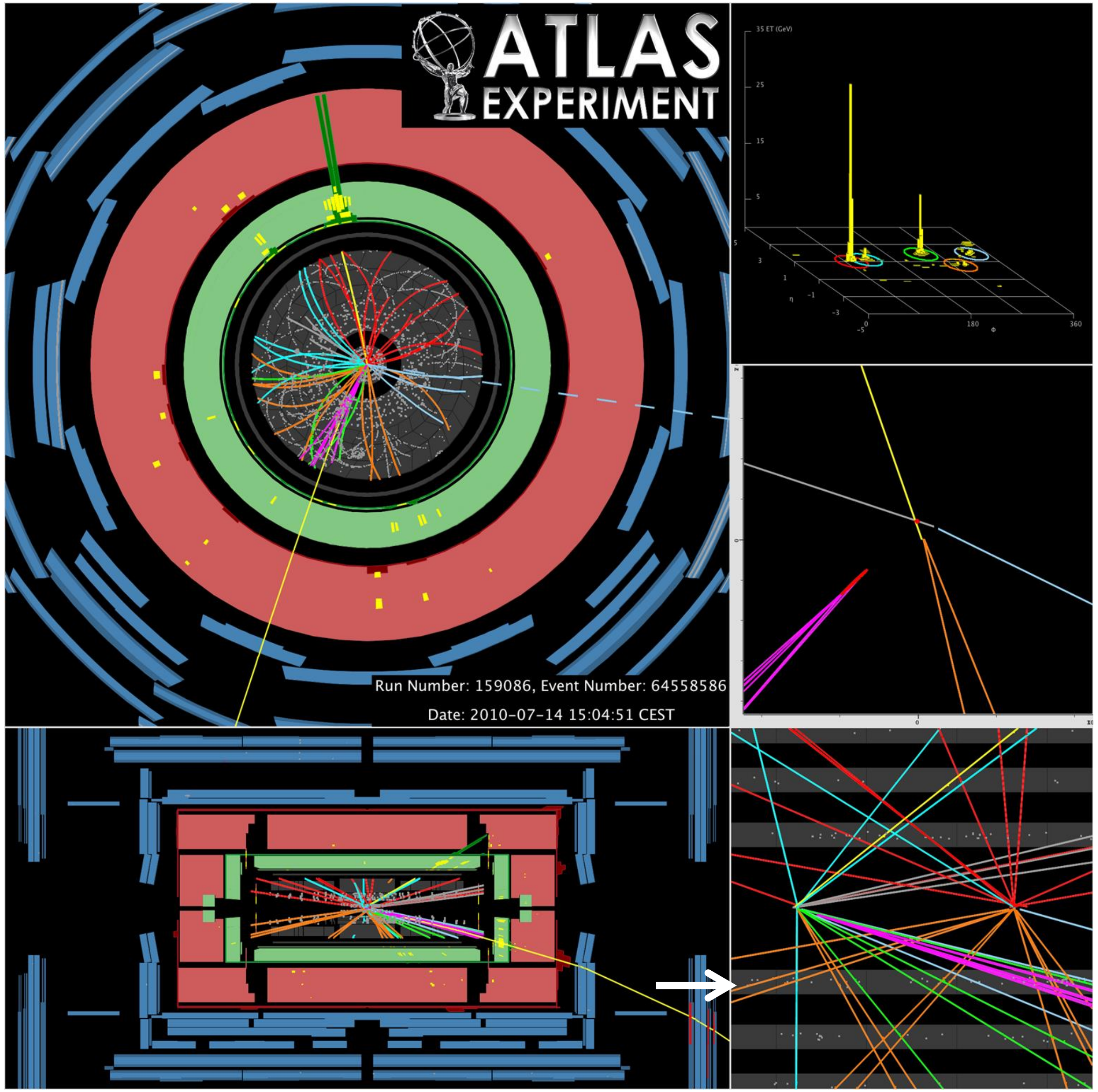
Signatures of top-quark pairs

- Decay channels of W boson:
  - Leptonic: B(W→lν) ~ 0.32
  - Hadronic: B(W→qq') ~ 0.68
- Signatures of top-quark pairs:
  - Dilepton channel
  - Full-hadronic channel
  - Single-lepton channel
- Single-lepton channel:
  - Large statistics
  - Moderate background
  - Full reconstruction possible
  - Optimal for studies of top-quark properties
  - Golden channel for quite some time



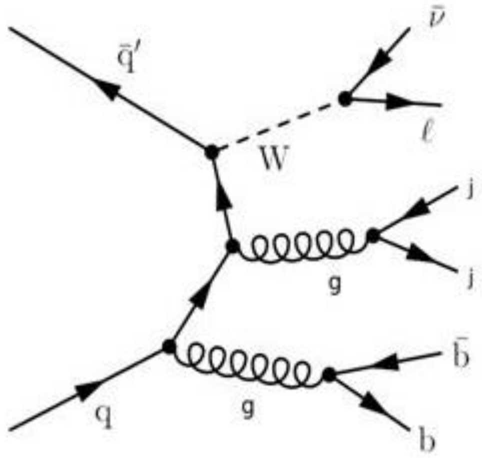
Candidate event

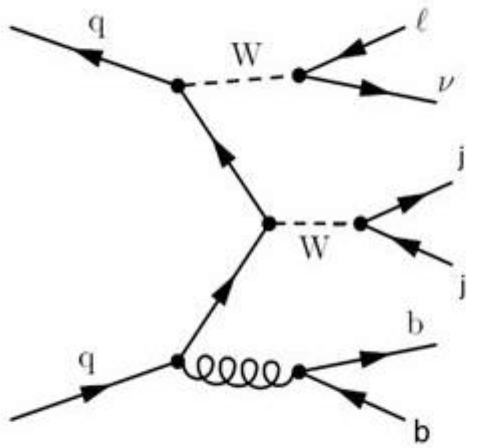
- $p_T(e)$ = 79 GeV
- E_T^{miss} = 43 GeV
- $m_T(W)$ = 87 GeV
- m_{jjj} = 122 GeV
- 4 jets, 1 b-tag



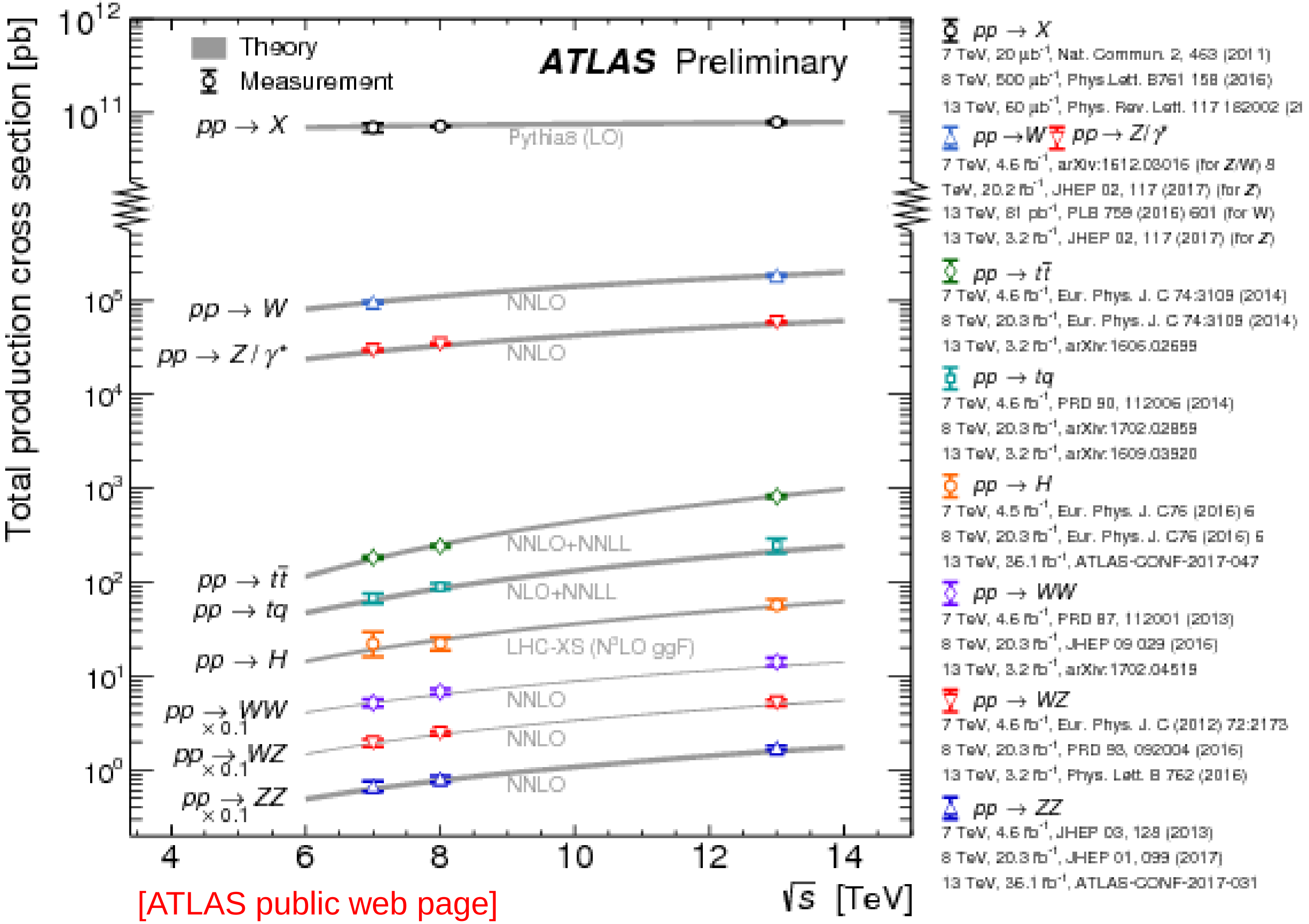
Background (for the single-lepton channel)

- Production of W bosons with additional jets
  - Same final-state objects
  - Irreducible
- (QCD) jet production with misidentified leptons
  - Misidentified electrons (e.g., from pions, jets)
  - Misidentified isolation for muons (non-prompt muons)
- Single top, di-boson production, Z+jets
  - Small contributions





Signal and background



[ATLAS public web page]

Measurements

Again, a biased selection to explain the concepts

Measurement program

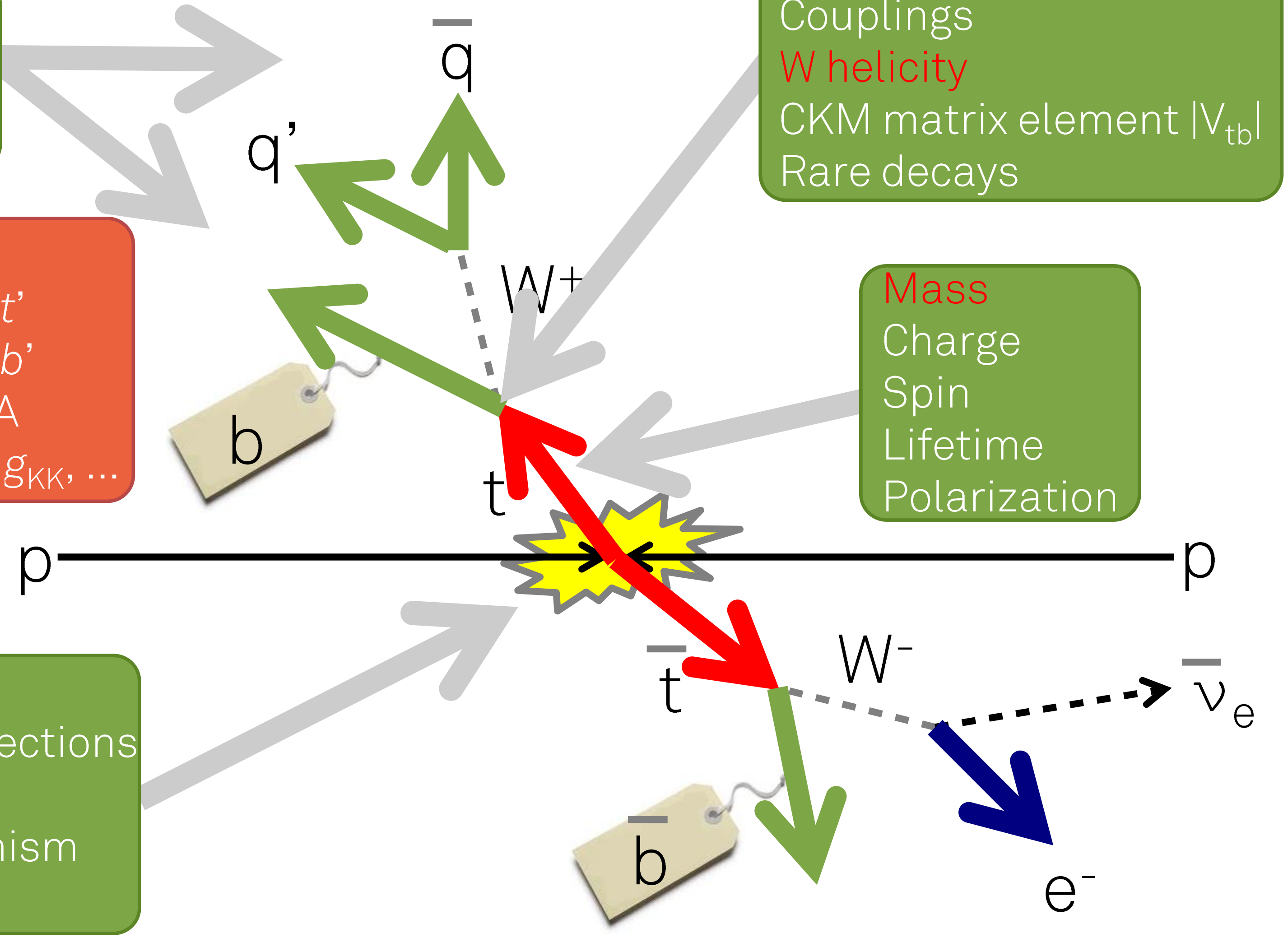
- *b*-tagging
- Jet energy scale
- Jet energy resol.

- FCNC
- Fourth generation *t'*
- Fourth generation *b'*
- Scalar partners T/A
- Heavy particles *Z'*, g_{KK}, ...

- Total cross section
- Differential cross sections
- Charge asymmetry
- Production mechanism
- Spin correlation

- Decay modes
- Couplings
- W helicity
- CKM matrix element $|V_{tb}|$
- Rare decays

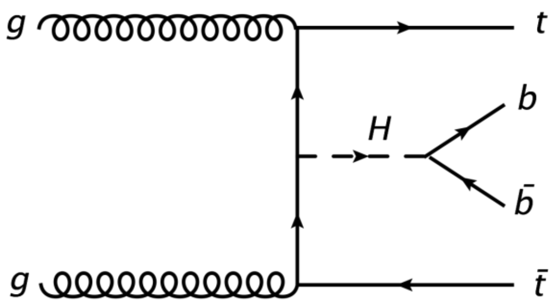
- Mass
- Charge
- Spin
- Lifetime
- Polarization

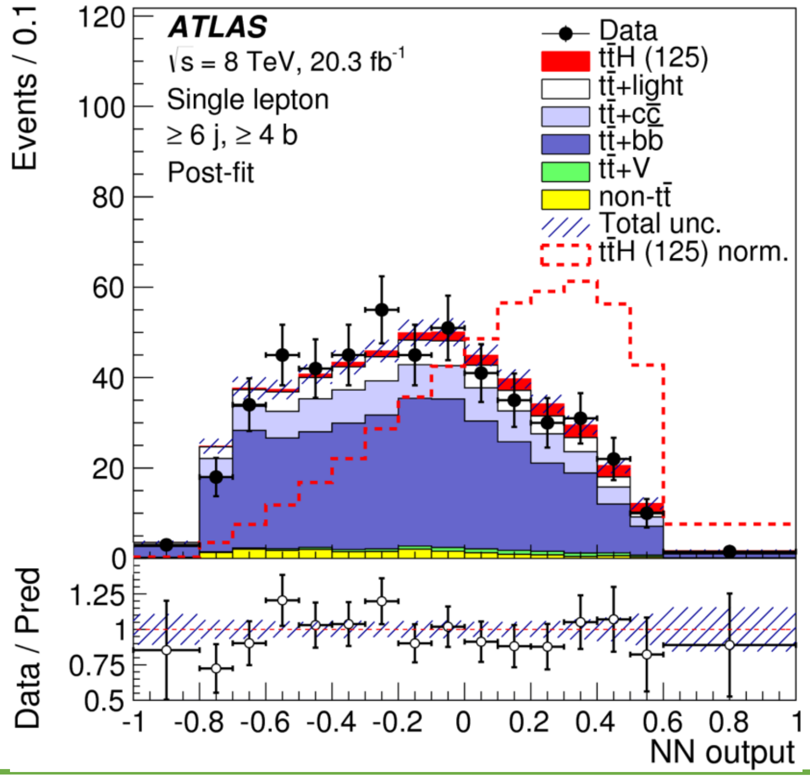


Measurements

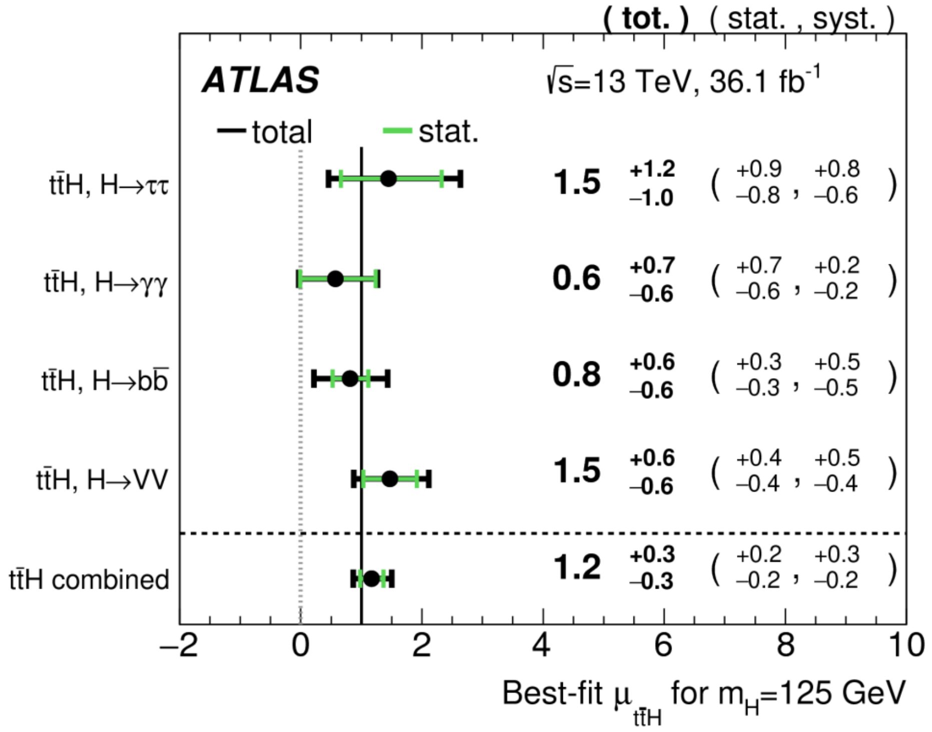
Intrinsic properties

- Mass
- Higgs couplings (ttH)
- CKM-matrix elements





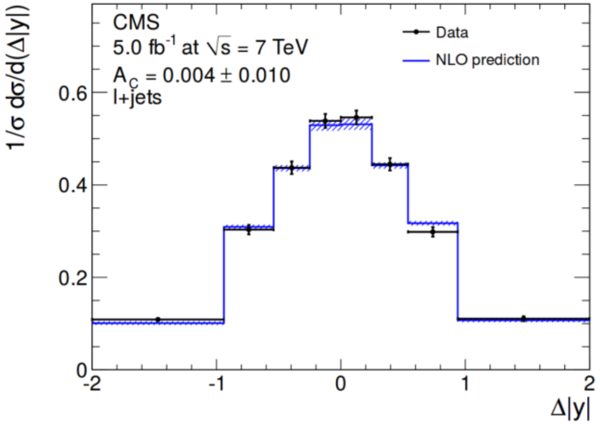
[arXiv:1503.05066]



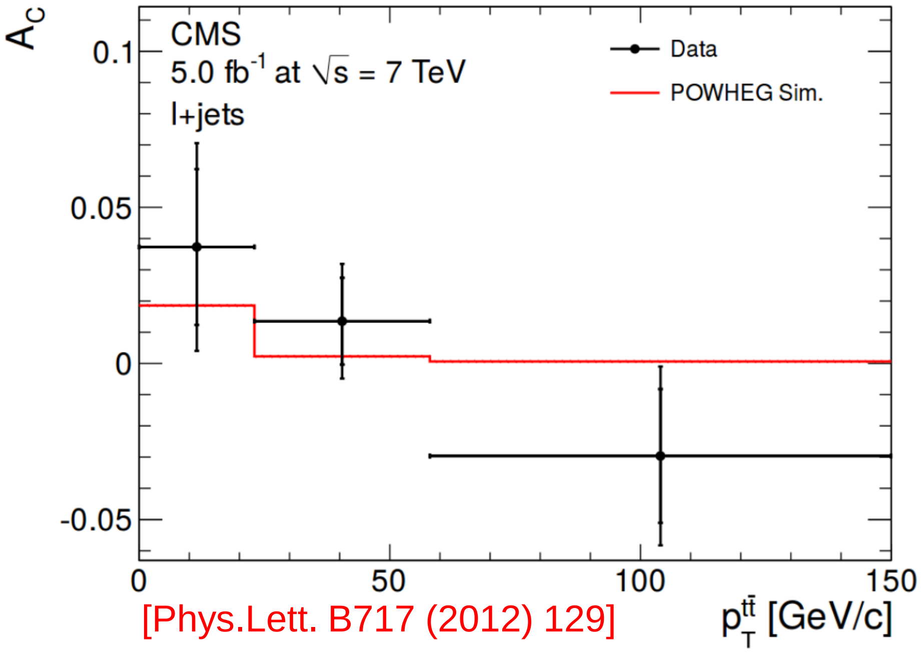
[Phys. Rev. D 97 (2018) 072003]

Tests of QCD predictions

- Total and differential cross-sections for top-quark pair production
- Production of top-quark pairs and additional jets (tt+X)
- Charge asymmetry
- Top-quark polarization in top-quark pairs and spin correlation



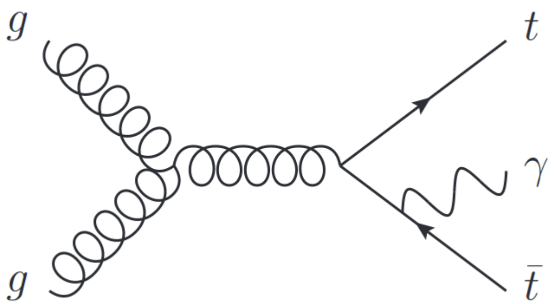
Uncorrected	0.003 ± 0.004 (stat.)
BG-subtracted	0.002 ± 0.005 (stat.) ± 0.003 (syst.)
Final corrected	0.004 ± 0.010 (stat.) ± 0.011 (syst.)
Theoretical prediction (SM)	0.0115 ± 0.0006



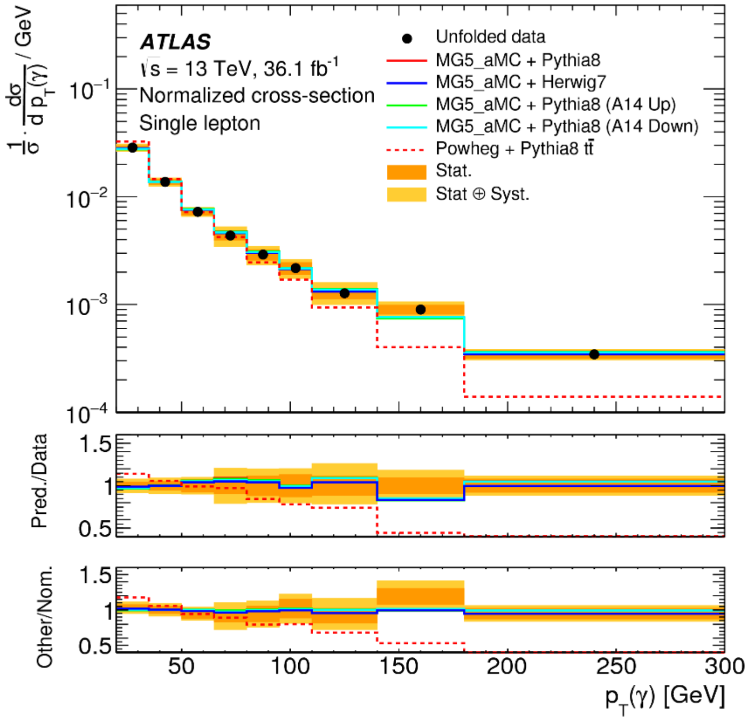
[Phys.Lett. B717 (2012) 129]

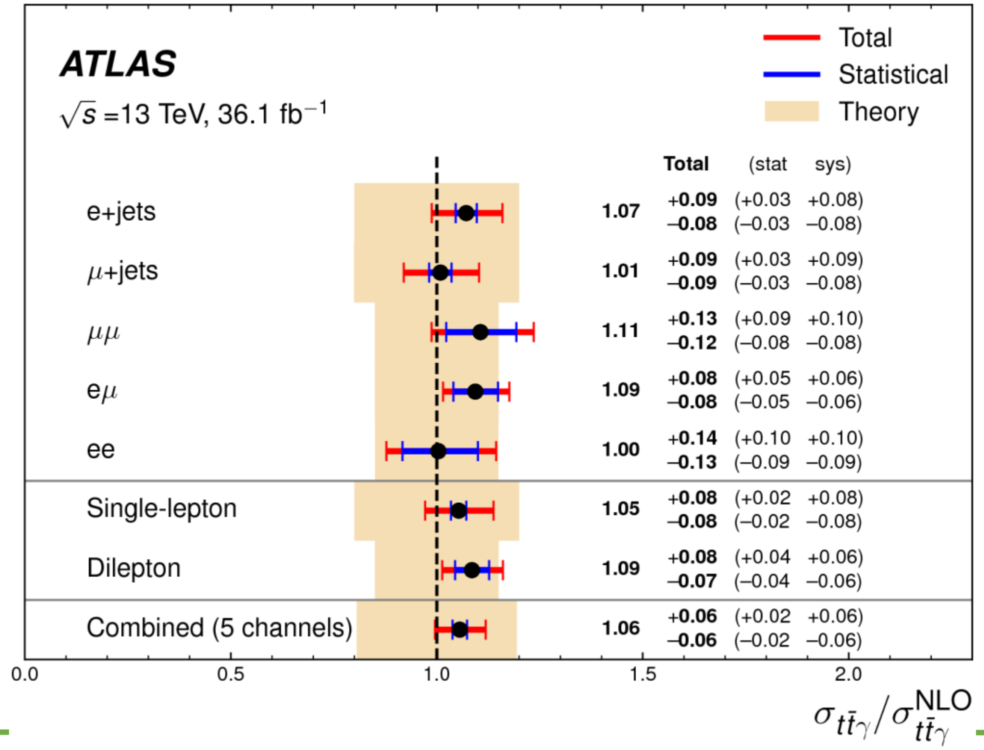
Tests of electroweak predictions

- Single-top quark production
- W-boson polarization
- Couplings to W/Z bosons (tt+V)
- Couplings to photons (tt+photon)



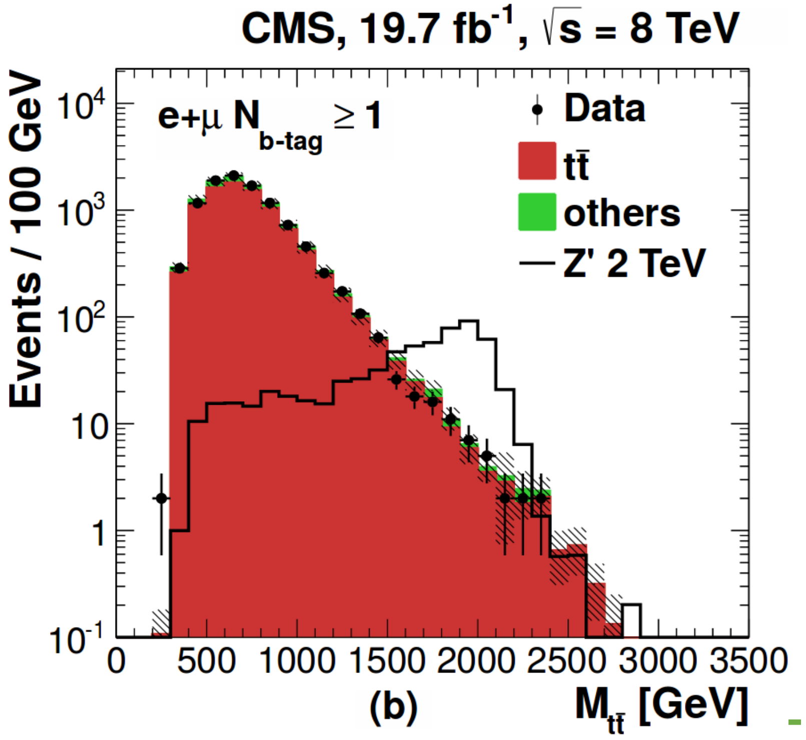
[Eur. Phys. J. C 79 (2019) 382]



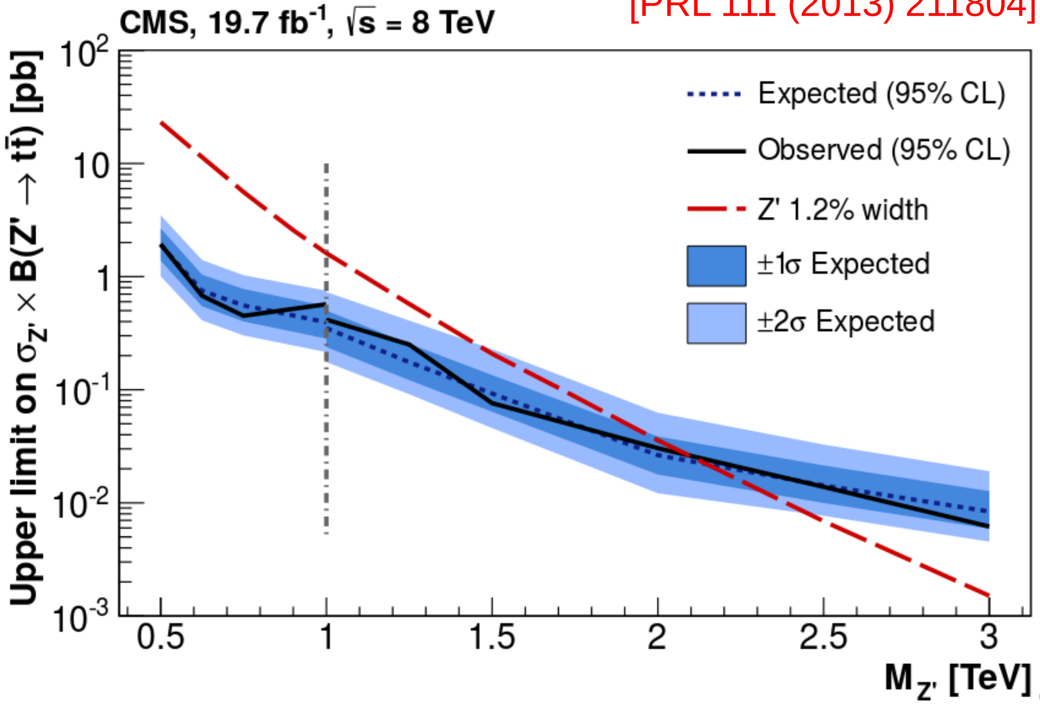


New-physics models including top quarks

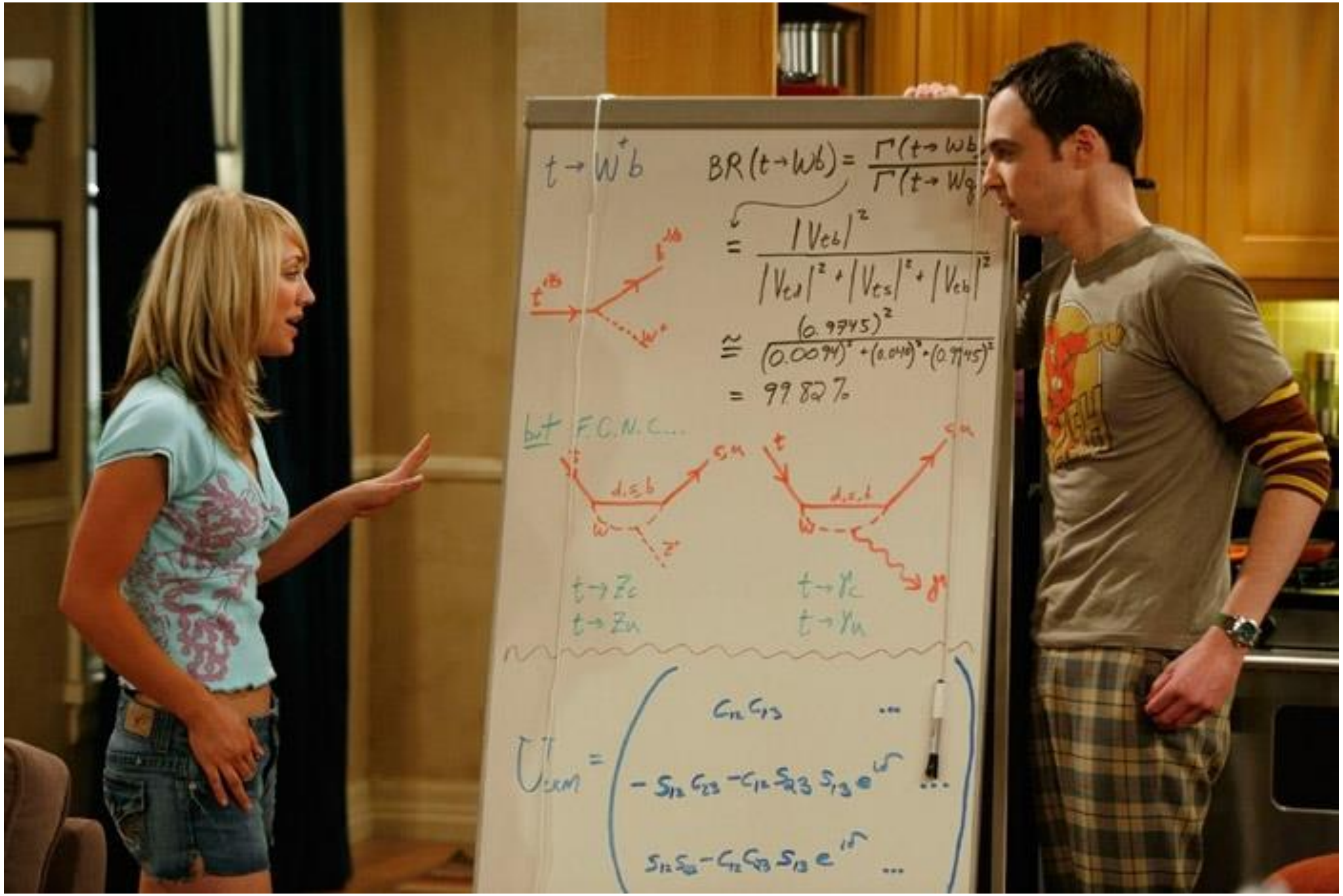
- Top-quark pair resonances, e.g. Z', g_{KK}, ...
- Top-quark + jet resonances, e.g. color tripletts
- (Non-standard) fourth gen. quarks decaying into top quarks
- Supersymmetric top-quark partner (stop)



[PRL 111 (2013) 211804]



Example 1: Search for FCNC



Example 2: W-boson polarization

- Top quark (mostly) decays into bottom quark and real W boson
- Massive spin-1 W boson has three polarization (helicity) states
- SM predictions of helicity fractions:

$$F_0 = \frac{m_{top}^2}{m_{top}^2 + 2m_W^2} \approx 0.70\,(LO) \to 0.687 \pm 0.005\,(NNLO)$$

$$F_L = \frac{2m_W^2}{m_{top}^2 + 2m_W^2} \approx 0.30\,(LO) \to 0.311 \pm 0.005\,(NNLO)$$

$$F_R = 0^*\,(LO) \to 0.0017 \pm 0.0001\,(NNLO)$$

[Phys. Rev. D 81 (2010) 111503]

* assuming m_b=0 GeV

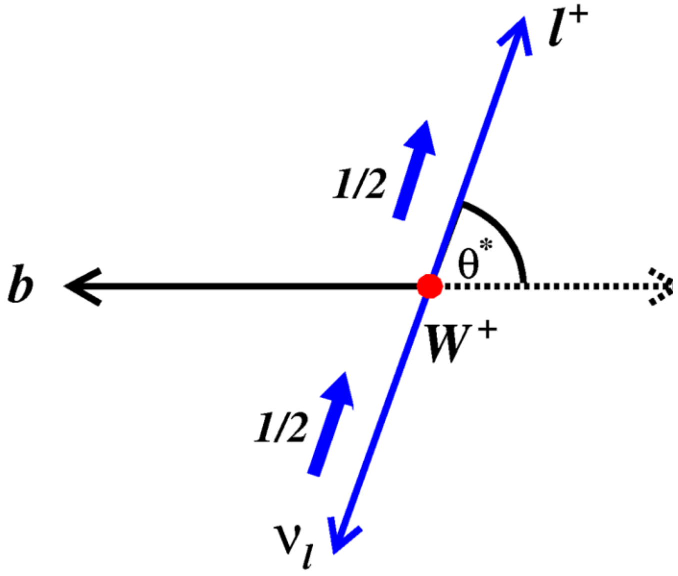
- Helicity fractions are defined by the Wtb vertex
- Sensitive to BSM effects, e.g. anomalous couplings and additional particles

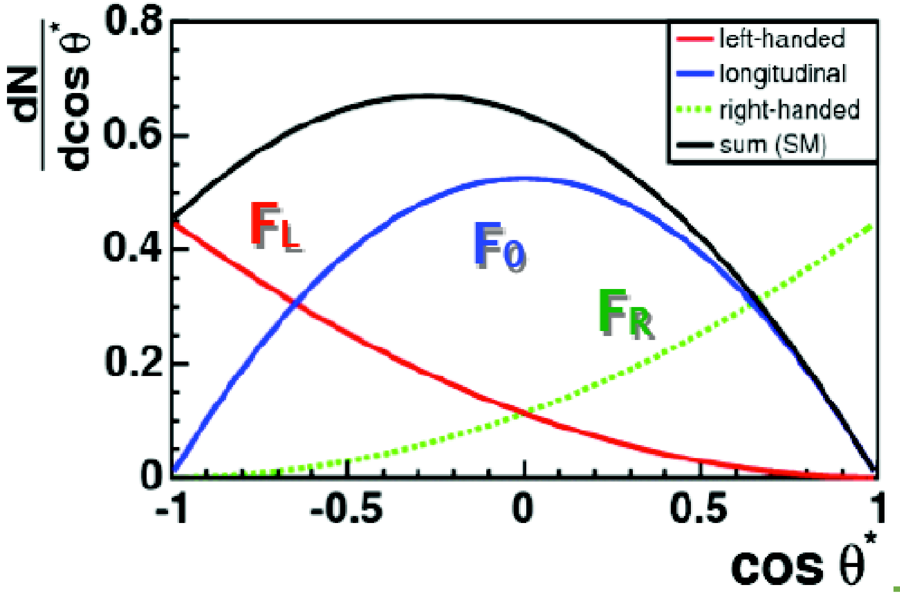
Example 2: W-boson polarization

- Information about *W*-boson polarization from angular distributions of its decay products

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos(\theta^*)} = \frac{3}{8}\left(1+\cos(\theta^*)\right)^2 F_R + \frac{3}{8}\left(1-\cos(\theta^*)\right)^2 F_L + \frac{3}{4}\sin(\theta^*)^2 F_0$$

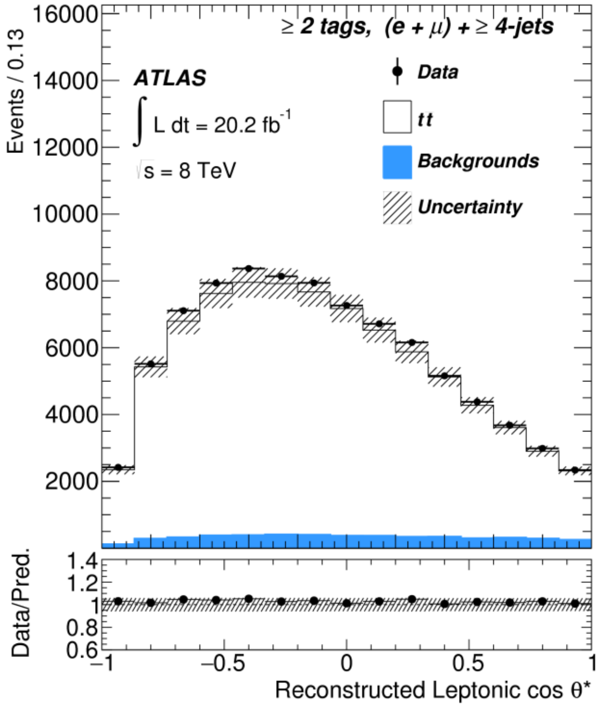
SM prediction: ~0% (F_R), ~31% (F_L), ~69% (F_0)

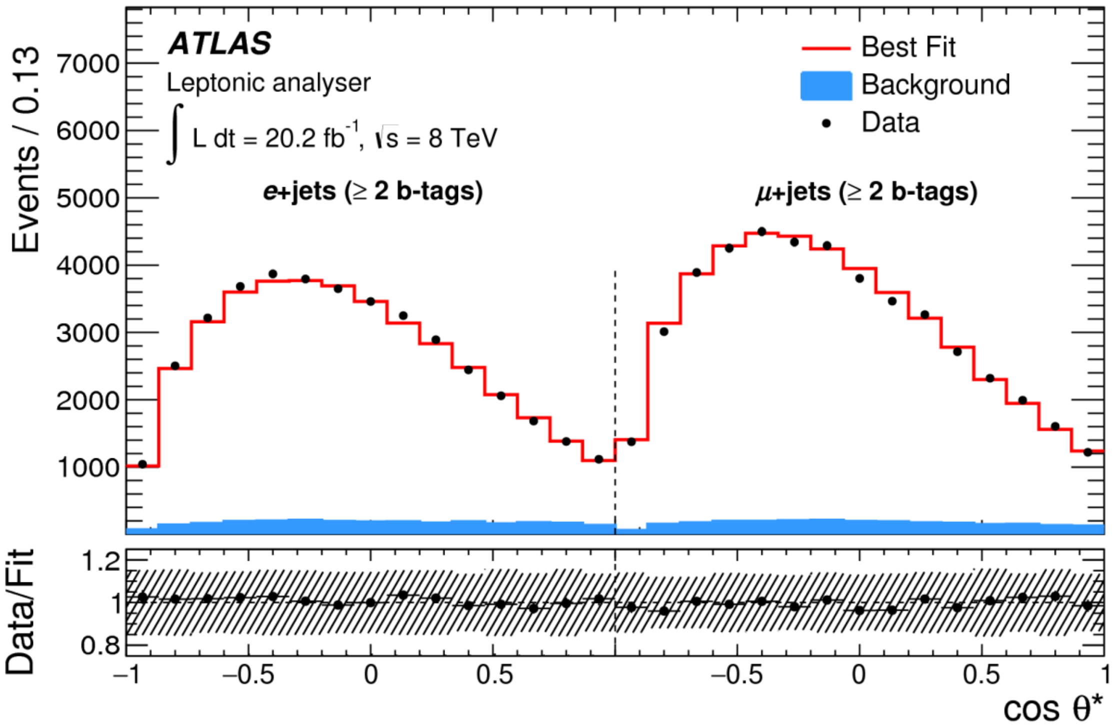




Example 2: W-boson polarization

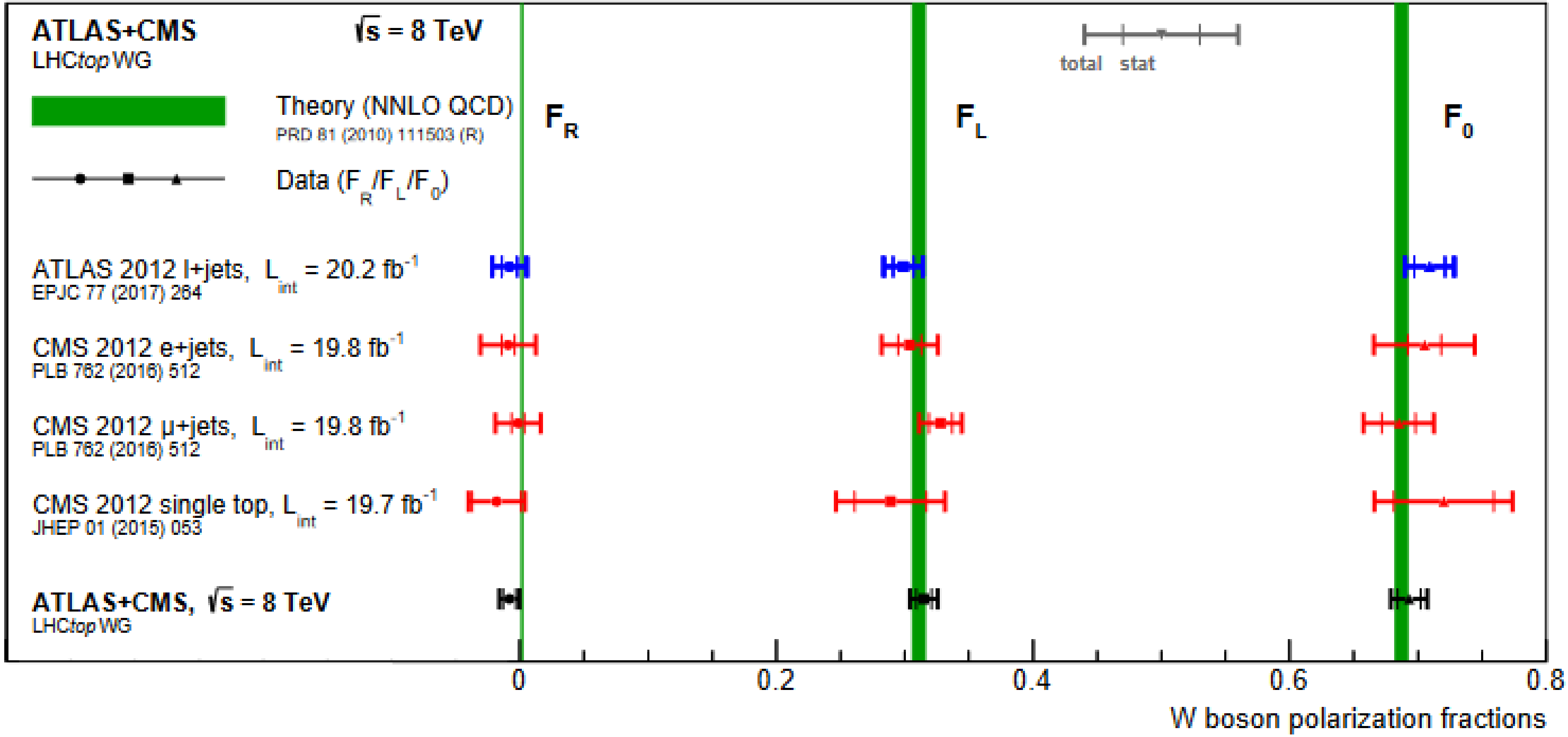
[Eur. Phys. J. C (2017) 77]





Example 2: W-boson polarization

- Measurements at ATLAS and CMS
- Combination within the LHCTopWG

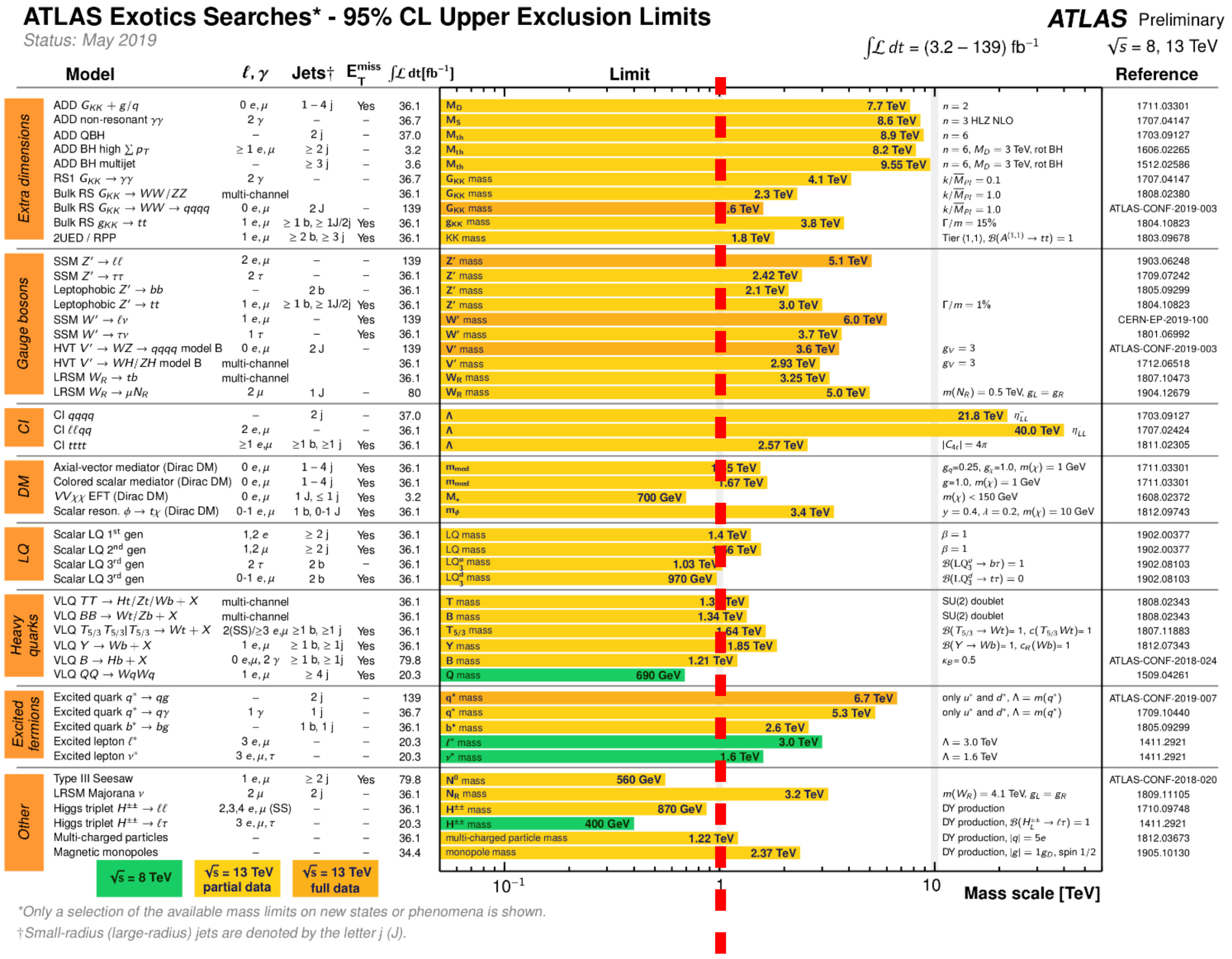


Interpretations in EFTs

Building bridges to the world of flavor

Motivation

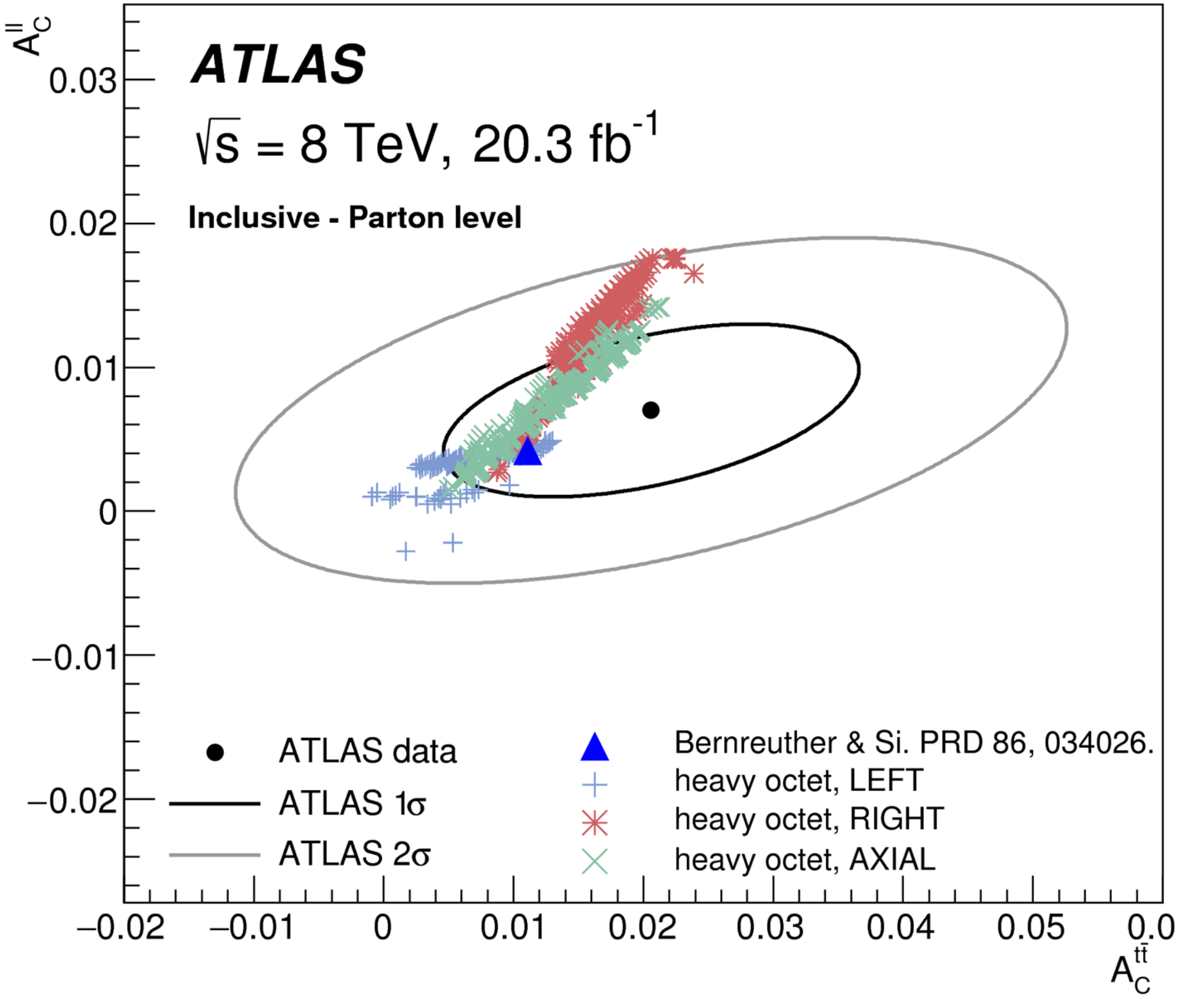
- About 1/3 of all ATLAS papers are direct searches for supersymmetry or exotic physics. Nothing found yet.
- Limited by sqrt(s)
- Go and test more models?



1 TeV

Indirect searches

- Alternative: precision measurements, but what do deviations from the SM mean?
- Need interpretation for indirect searches.
- Top-quark sector is interesting to look at and „easy“ to interpret.
- Limited by sqrt(N) or syst. uncertainties
- Bridge between theory and experiment



Measurements, tests and searches

SM - free parameters:

- Mass
- Charge
- Spin
- Coupling to photons
- Coupling to gluons
- Coupling to *W*/*Z* bosons
- Coupling to Higgs

SM - predictions:

- Cross-sections
- Charge asymmetry
- Decay width
- *W*-boson polarization
- Top polarization
- Spin correlation
- Decay modes

BSM - searches:

- Top-pair resonan.
- Top+jet resonances
- FCNC
- 4th gen. quarks
- Scalar partners
- New gauge bosons

Combined approach:

Measurement of anomalous couplings / EFT

Building an effective model

[Suggestion: arXiv:1401.0470]

- Start with SM Lagrangian $\mathcal{L}_{SM}$ and Ignore concrete larger models
- Add all possible contributions, i.e. operators $O_i^{(d)}$ of dimension d
- Require all SM symmetries, thus $d > 4$ for anomalous contributions
- Resonant scale of new physics is Λ (and large)
- Effective Lagrangian:

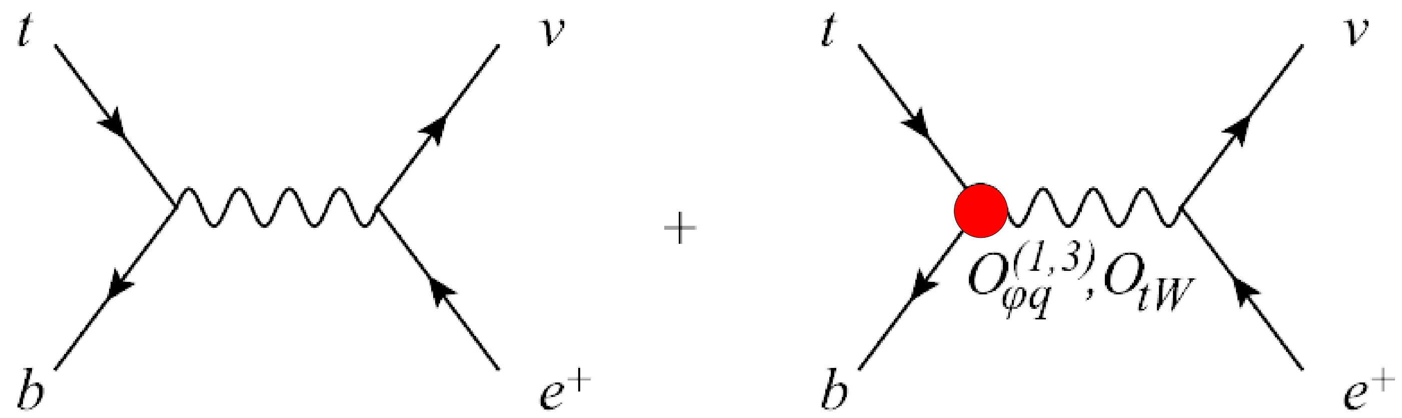
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d>4,i} \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)} + h.c.$$

- Complex coefficients $C_i^{(d)}$ measure the strength of each operator
- Leading order contribution: operators of dimension $d = 6$
- Effects come from interference terms of SM and BSM parts

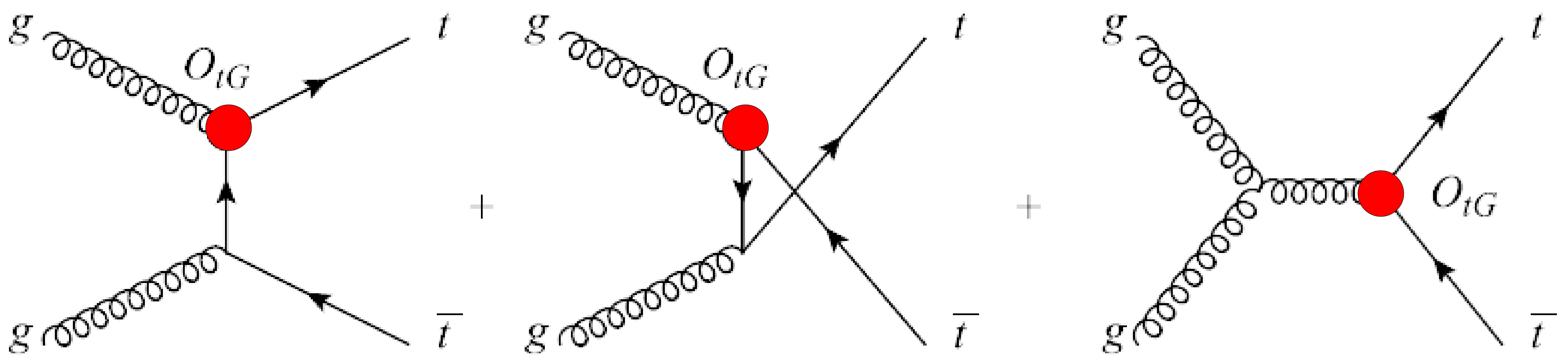
Modified vertices

[Suggestion: arXiv:1401.0470]

- Examples for corrections to the Wtb-vertex (decay)



- Example for corrections to the ttg-vertex (production)



Example: Top and bottom quarks

Eur. Phys. J. C (2020) 80:136
https://doi.org/10.1140/epjc/s10052-020-7680-9

THE EUROPEAN PHYSICAL JOURNAL C

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Regular Article - Theoretical Physics

Constraining top-quark couplings combining top-quark and *B* decay observables

Stefan Bißmann[a], Johannes Erdmann[b], Cornelius Grunwald[c], Gudrun Hiller[d], Kevin Kröninger[e]

Fakultät Physik, TU Dortmund, Otto-Hahn-Str. 4, 44221 Dortmund, Germany

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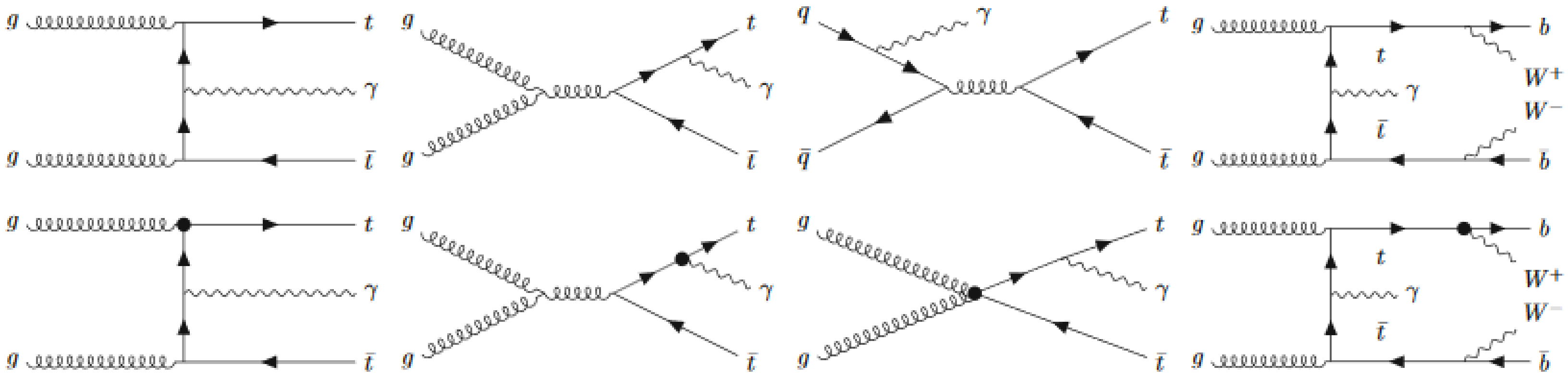
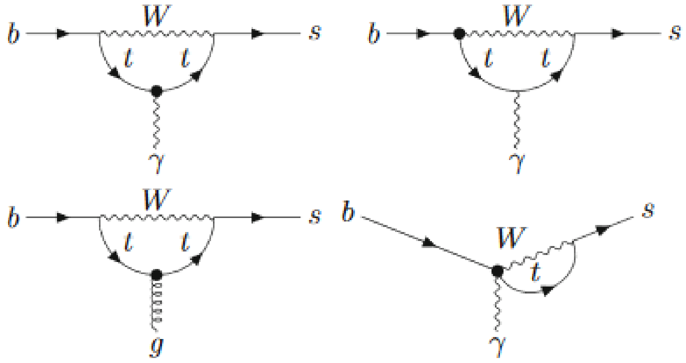
Operators and modified vertices

- Dedicated study of top-quark coupling to the photon
- Subset of operators: O_{uB}, O_{uW}, O_{uG}
- Impact in the top-quark sector:

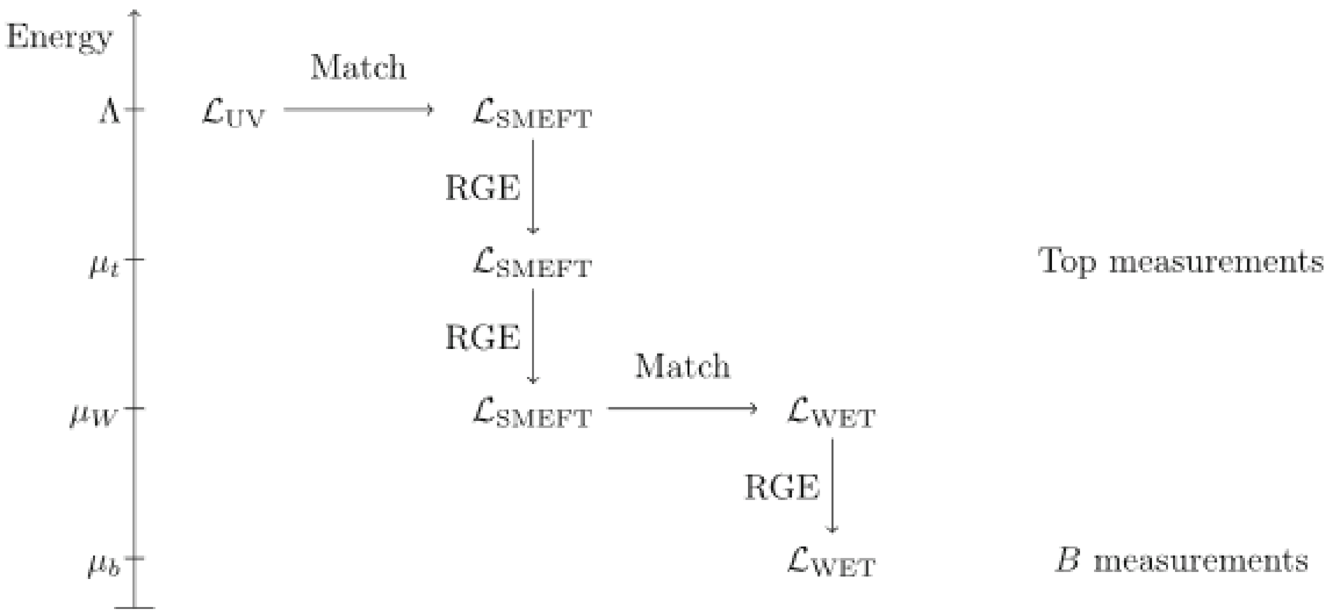


- Impact in the flavor sector:



Operators and energy scales

- Operators can have a simultaneous impact on both sectors
- In general: operators depend on the energy scale
- Here: the (energy) scales in both sectors are different because $m_\mathrm{b} \ll m_\mathrm{top}$
- Need to match the operators



Measurements and predictions

- Production of top-quark pairs + photon

$$\sigma^{\text{fid}}_{\text{ATLAS}}(t\bar{t}\gamma, 1\ell) = 521 \pm 9\,(\text{stat.}) \pm 41\,(\text{syst.})\,\text{fb},$$
$$\sigma^{\text{fid}}_{\text{ATLAS}}(t\bar{t}\gamma, 2\ell) = 69 \pm 3\,(\text{stat.}) \pm 4\,(\text{syst.})\,\text{fb}\,.$$

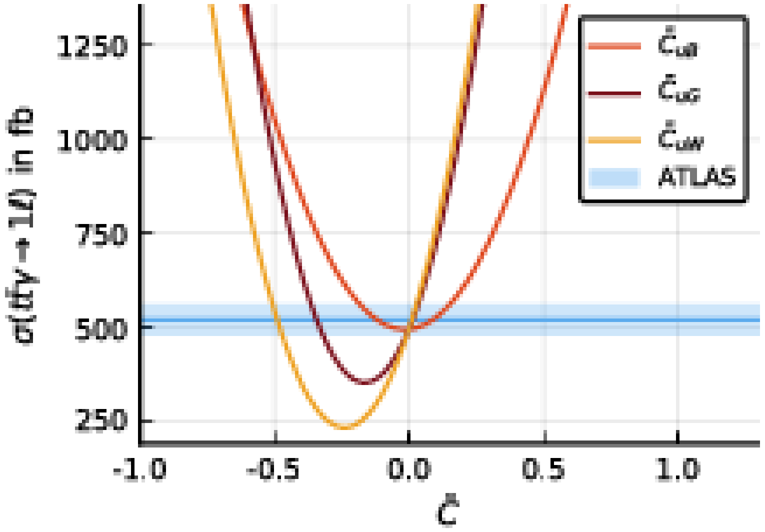
$$\sigma^{\text{fid}}_{\text{SM,NLO}}(t\bar{t}\gamma, 1\ell) = 495 \pm 99\ \text{fb},$$
$$\sigma^{\text{fid}}_{\text{SM,NLO}}(t\bar{t}\gamma, 2\ell) = 63 \pm 9\ \text{fb}\,.$$

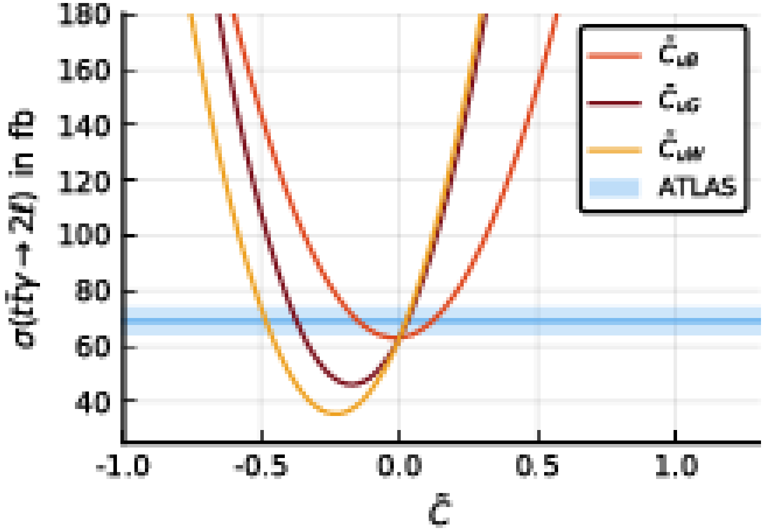
- Rare decay of the B-meson

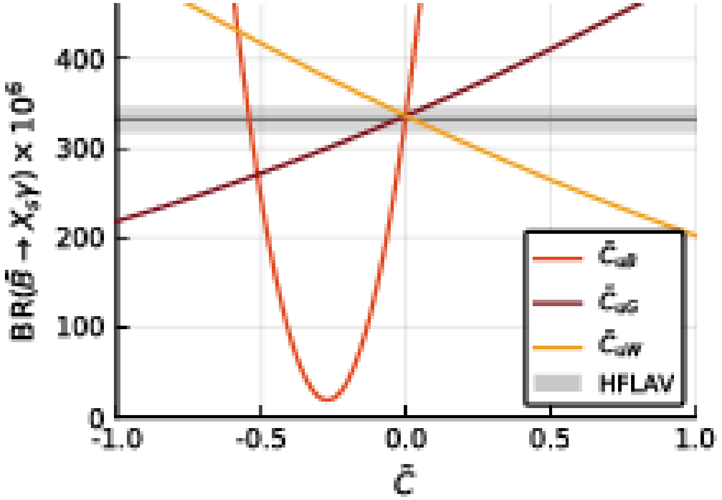
$$\text{BR}(\bar{B} \to X_s\gamma) = (332 \pm 15) \times 10^{-6},$$

$$\text{BR}_{\text{SM}}(\bar{B} \to X_s\gamma) = (336 \pm 23) \times 10^{-6}\,.$$

Impact of the operators



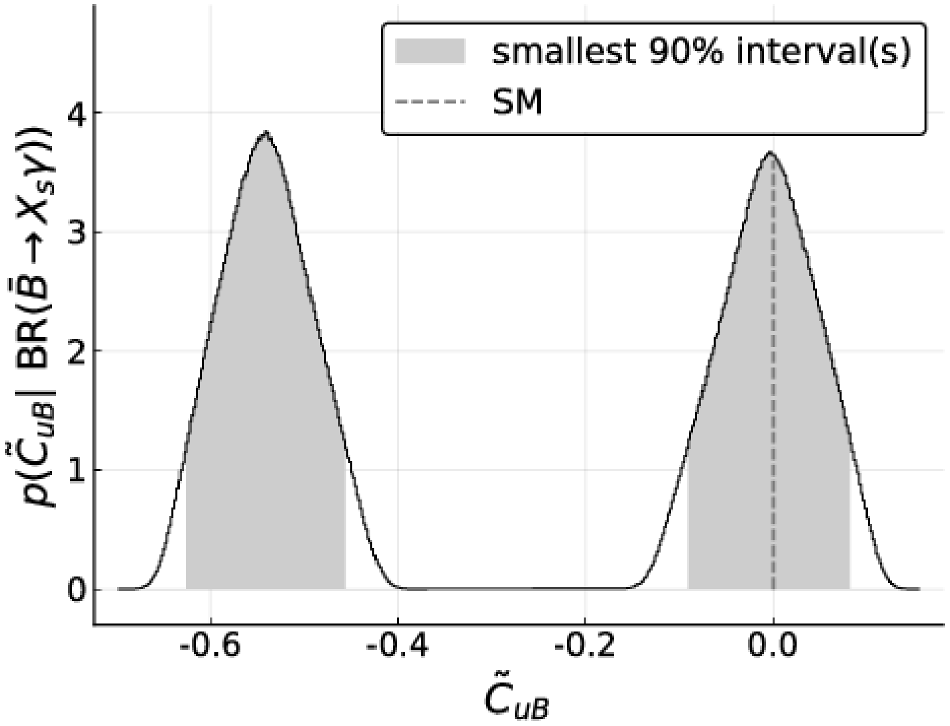




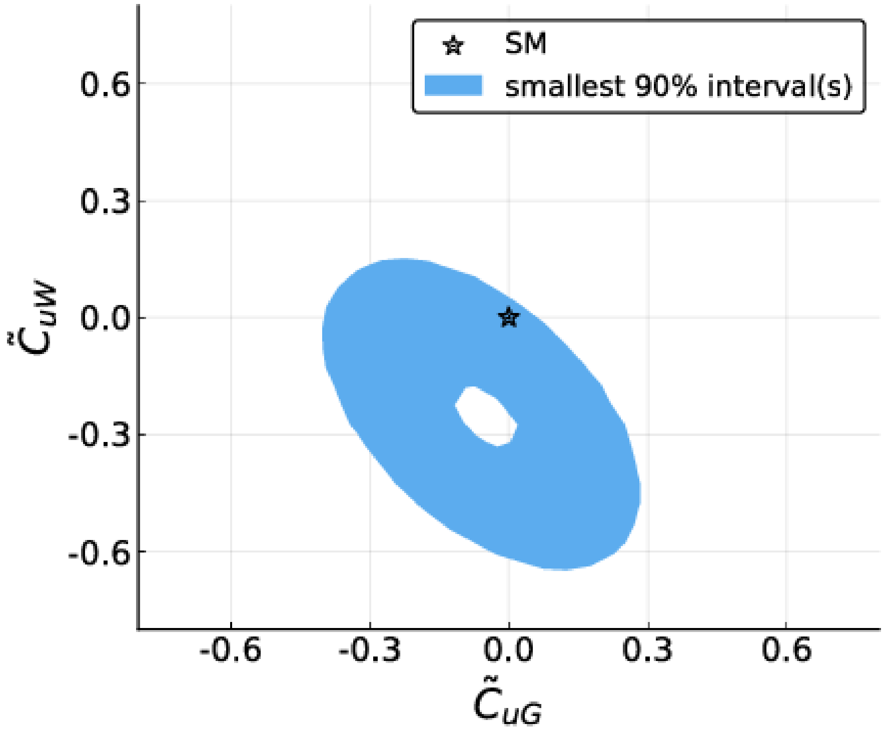
$$\sigma = \sigma^{\mathrm{SM}} + \sum_i \tilde{C}_i \sigma_i^{\mathrm{interf.}} + \sum_{i \leq j} \tilde{C}_i \tilde{C}_j \sigma_{ij}^{\mathrm{BSM}},$$

$$\mathrm{BR}(\bar{B} \to X_s \gamma) = \mathrm{BR}(\bar{B} \to X_c e \bar{\nu})_{\mathrm{exp}} \times \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 \frac{6\alpha_e}{\pi C} (P(E_0) + N(E_0)),$$

Constraints

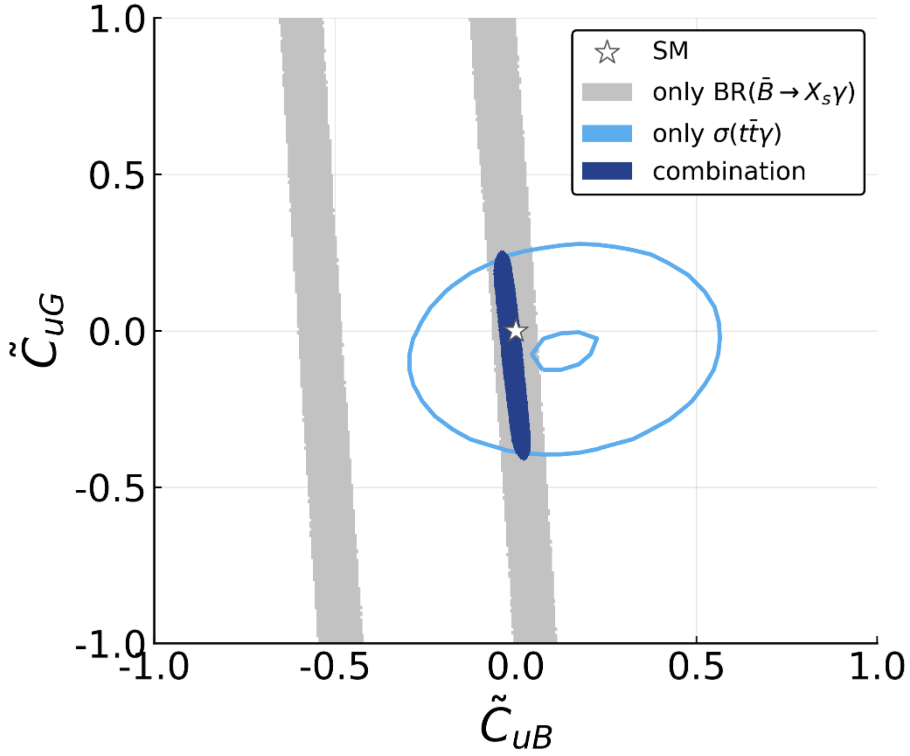


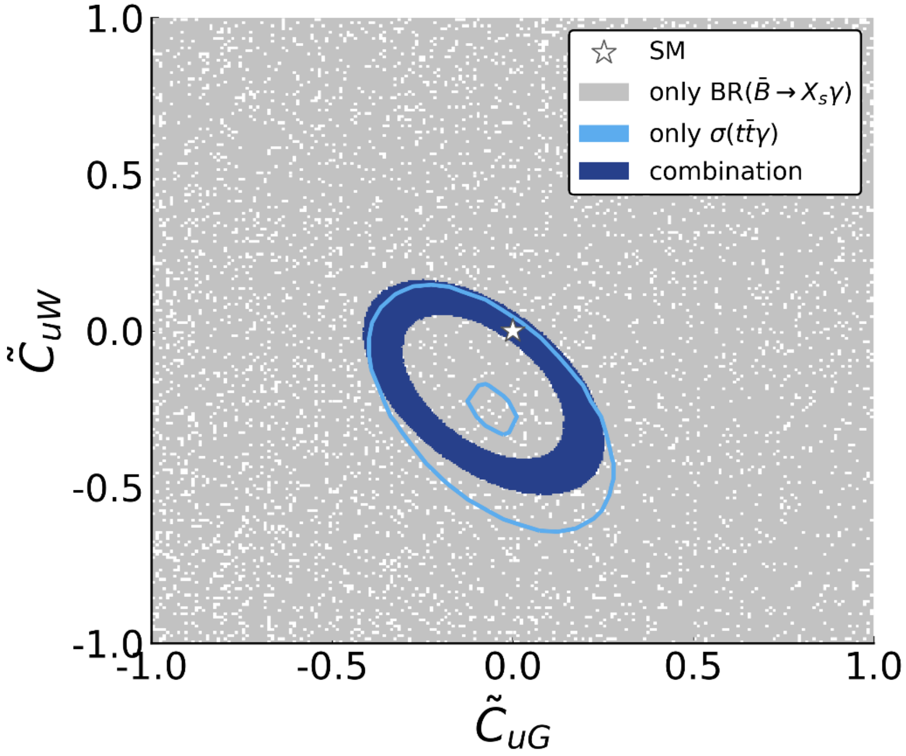
Only flavor physics



Only top-quark physics

Constraints



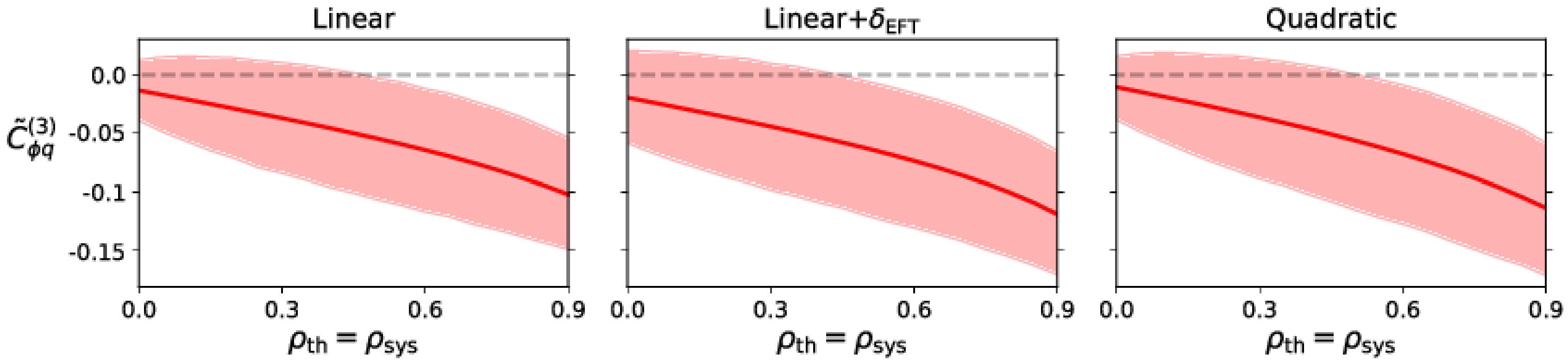


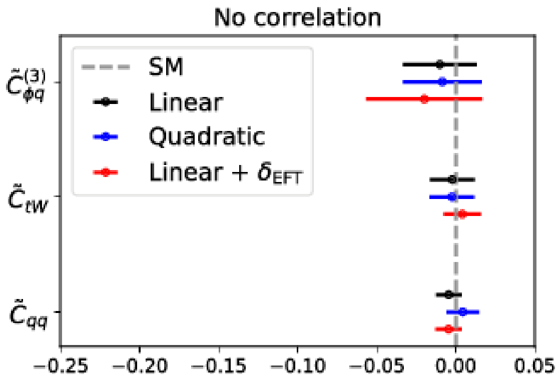
- Large potential for the combination of flavor and top-quark physics observables

Discussion

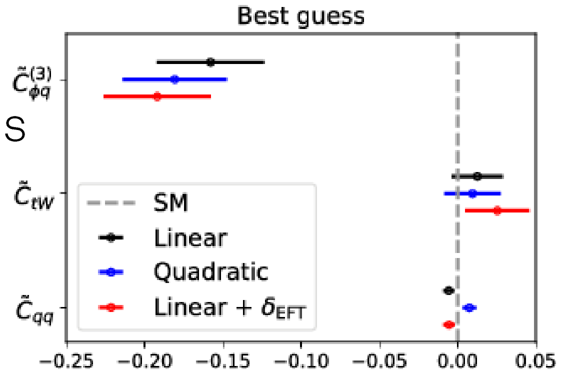
- Correlations among measurements need to be specified, but often only known to experiments
- Can have an impact on the interpretation

[arXiv:1912.06090]





Change in correlations can lead to a (false?) discovery



Conclusions

Conclusions

- The top quark is an interesting study object ...
  - ... on it's own
  - ... for direct searches for BSM physics
  - ... for indirect searches
- Top-quark physics is an active field of research – now more than ever...
  - ... at different experiments
  - ... at different laboratories
  - ... for the theory community
- The LHC is a top-quark factory
- Connection between EFTs, top quarks and flavor physics