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Top-quark physics at the LHC

Kevin Kröninger – TU Dortmund

Introduction to the Terascale – DESY Hamburg (22.04.2015)

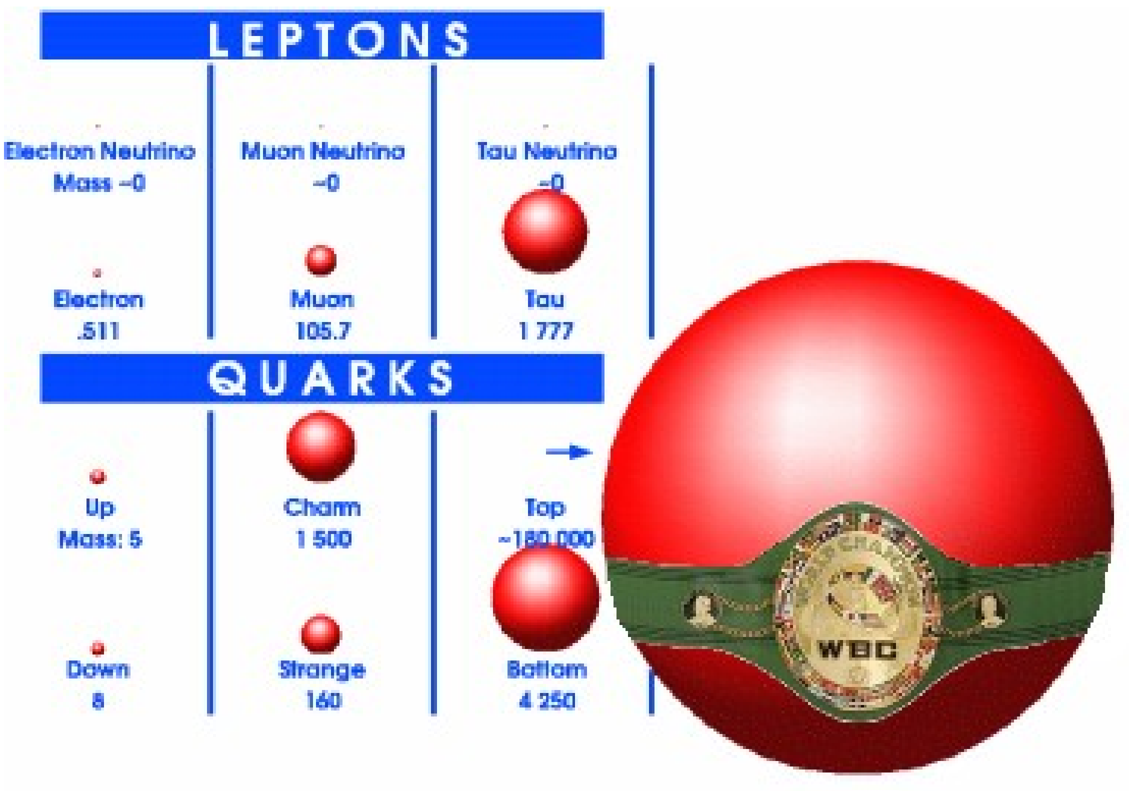
Outline

- Top-quark(s)
  - … in the SM
  - … history
  - … at the LHC
  - … production
  - … signatures
- Measurements
  - Measurement program
  - Example 1: top-quark mass
  - Example 2: *W*-boson polarization
- Conclusions

Question for you

What do you know about the top quark?

Top quarks in the SM



Properties:

- Mass m ~170 GeV/c^2
- Lifetime τ ~ $4 \cdot 10^{-25}$ s
- Spin s = ½
- Isospin T_3 = +½
- Charge Q =+2/3 e

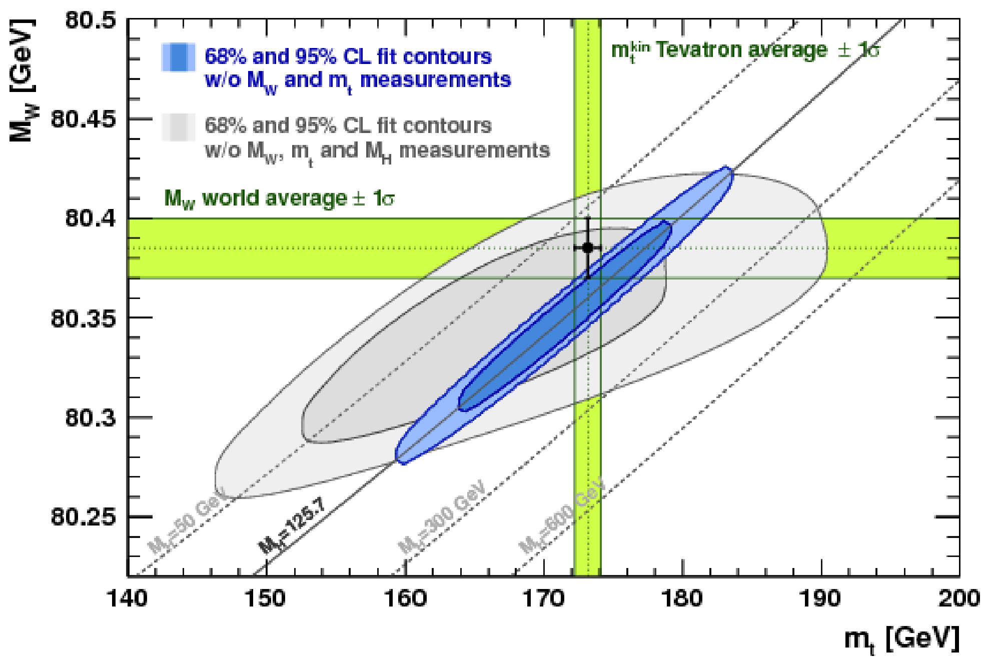
Top quarks in the SM

Role of the top quark in the SM

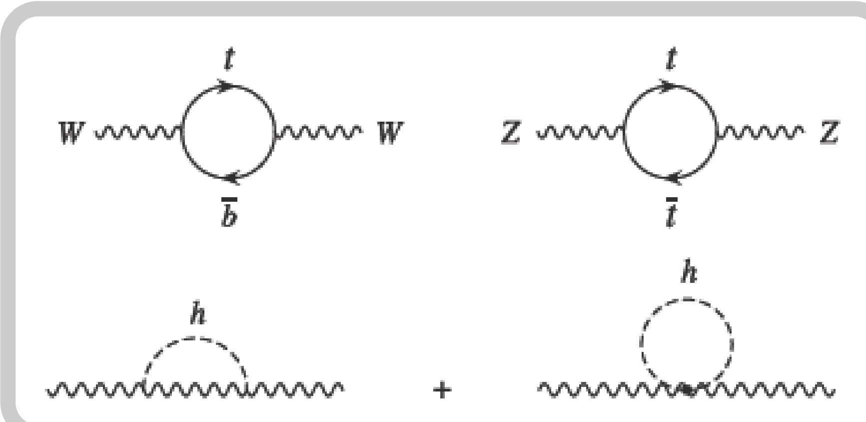
- Four top-quark related parameters:
  - CKM matrix elements
  - Yukawa coupling (top-quark mass)
- Large mass means large Yukawa (Higgs) coupling of roughly unity

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

$$L_{Yukawa}(\phi, \psi) = -g \bar{\psi} \phi \psi$$
$$g = \sqrt{2} m_{top} / v \approx 1$$



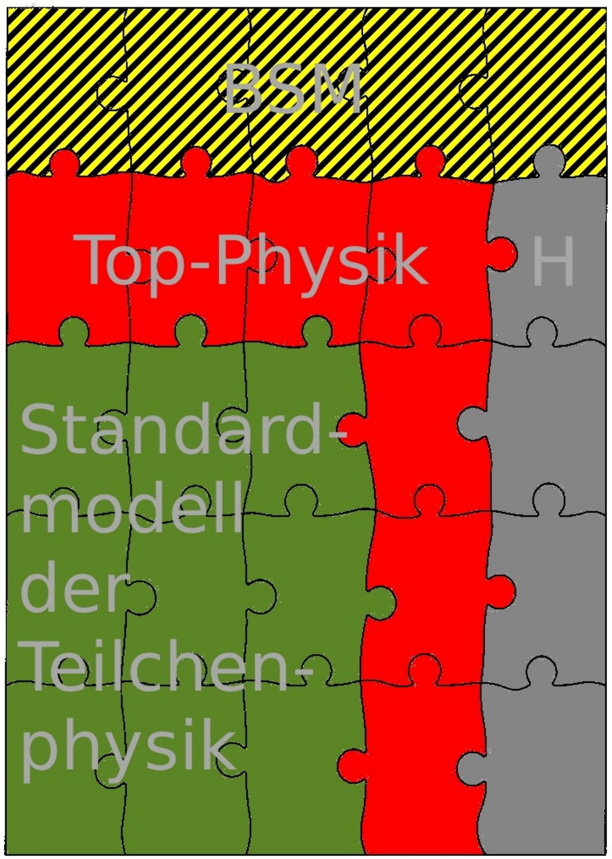
SM predicts connection between top quark, *W* and Higgs boson



Top quarks in the SM

Why study the top quark?

- Plays a 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
  - Precision measurements require 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

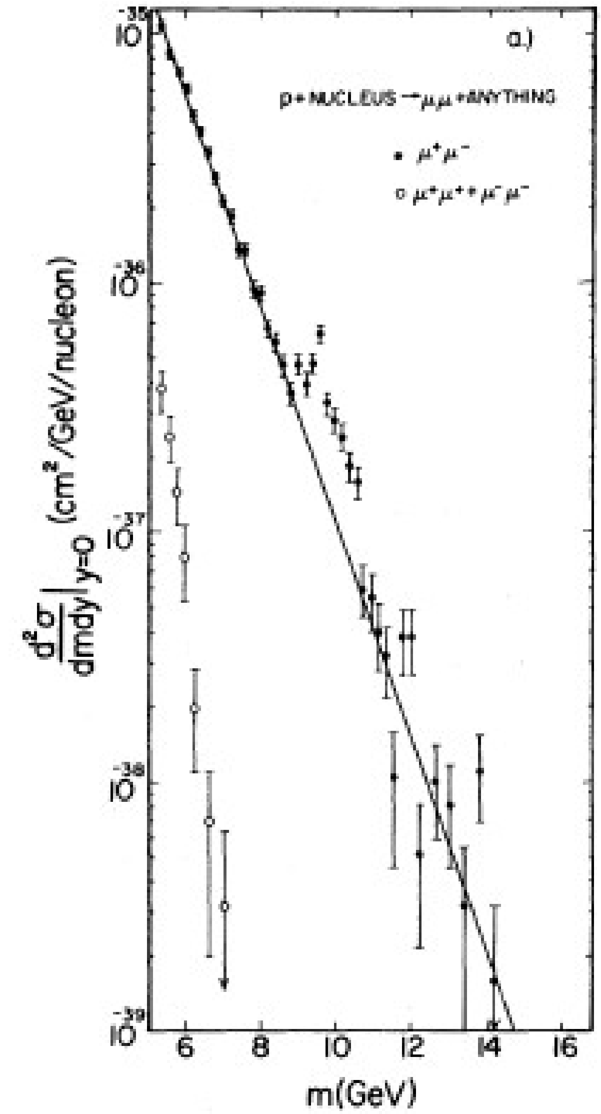
Makoto KOBAYASHI and Toshihide MASKAWA

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.

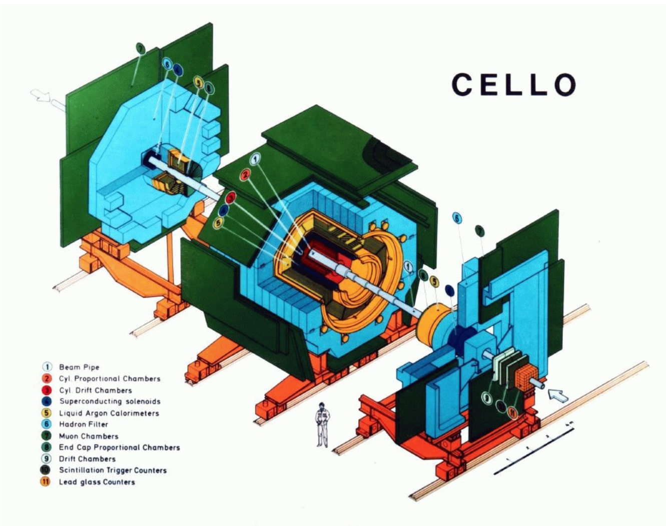
- 1973: CP violation requires three generations (Kobayashi and Maskawa)
- 1975: Discovery of the tau lepton (Perl *et al.*, SLAC)
- 1977: Discovery of the bottom quark (Lederman *et al.*, Fermilab)



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

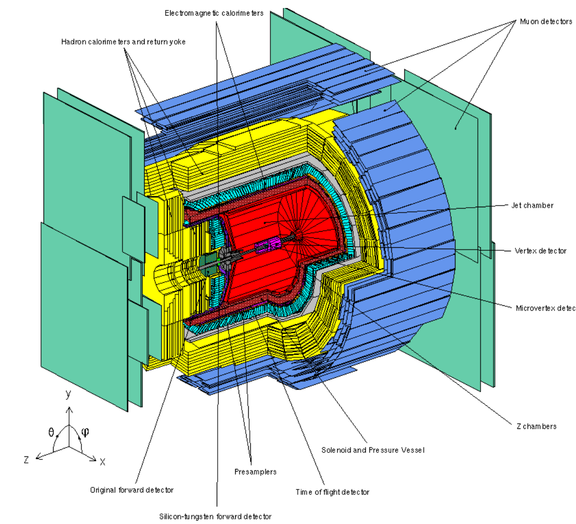
Top-quark history

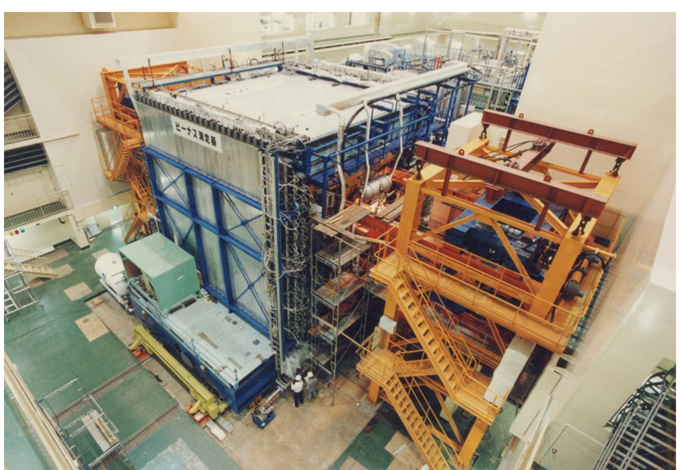
Direct searches (80s and early 90s)



CELLO (e^+e^- PETRA, DESY)
m_{top}>23.3 GeV (95% CL)
[Phys. Lett. B **144** (1984) 297]

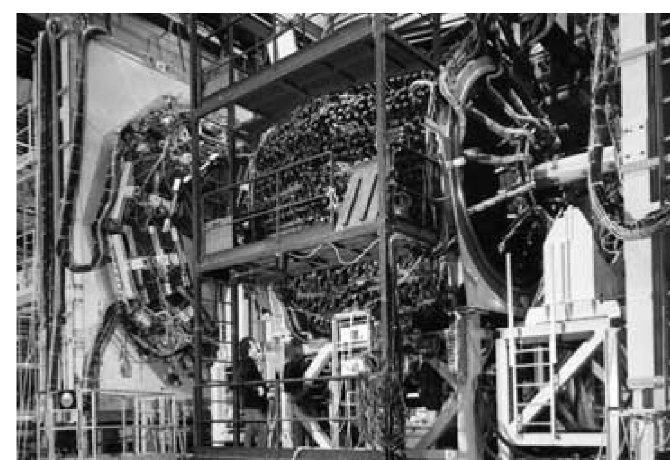
VENUS (e^+e^- TRISTAN, KEK)
m_{top}>30.2 GeV (95% CL)
[Phys. Lett. B **234** (1990) 382]





OPAL (e^+e^- LEP, CERN)
m_{top}>44.5 (95% CL)
[Phys. Lett. B **236** (1990) 364]

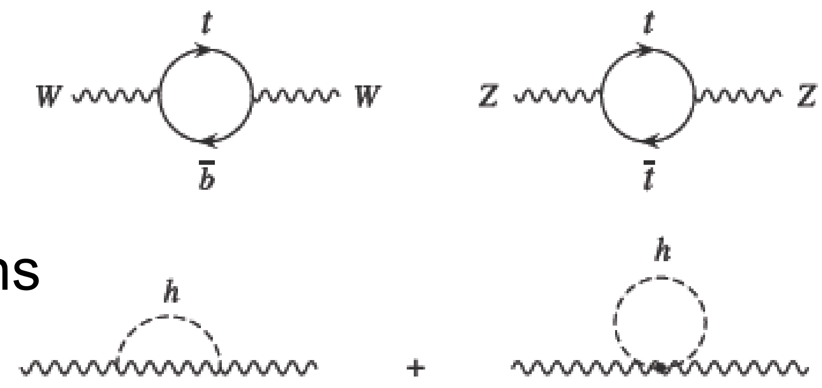
UA2 (ppbar SppS, CERN)
m_{top}>69 GeV (95% CL)
[Z. Phys. C **46** (1990) 179]

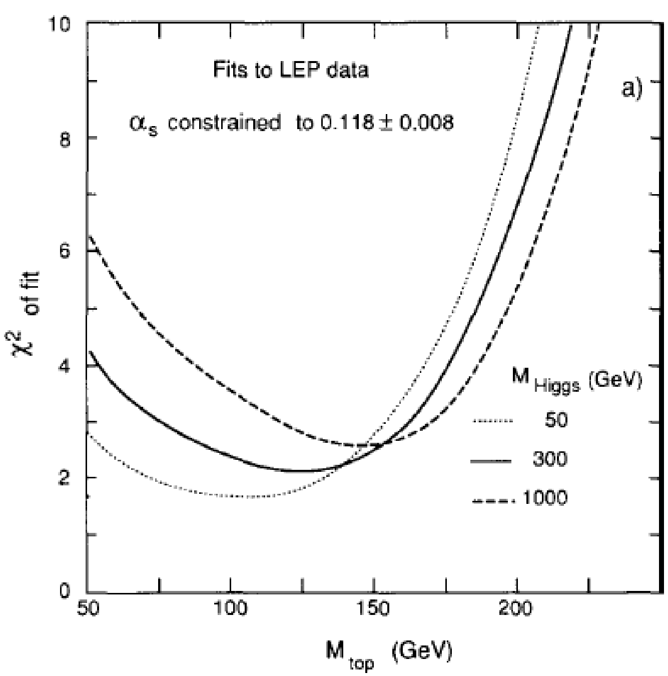


Top-quark history

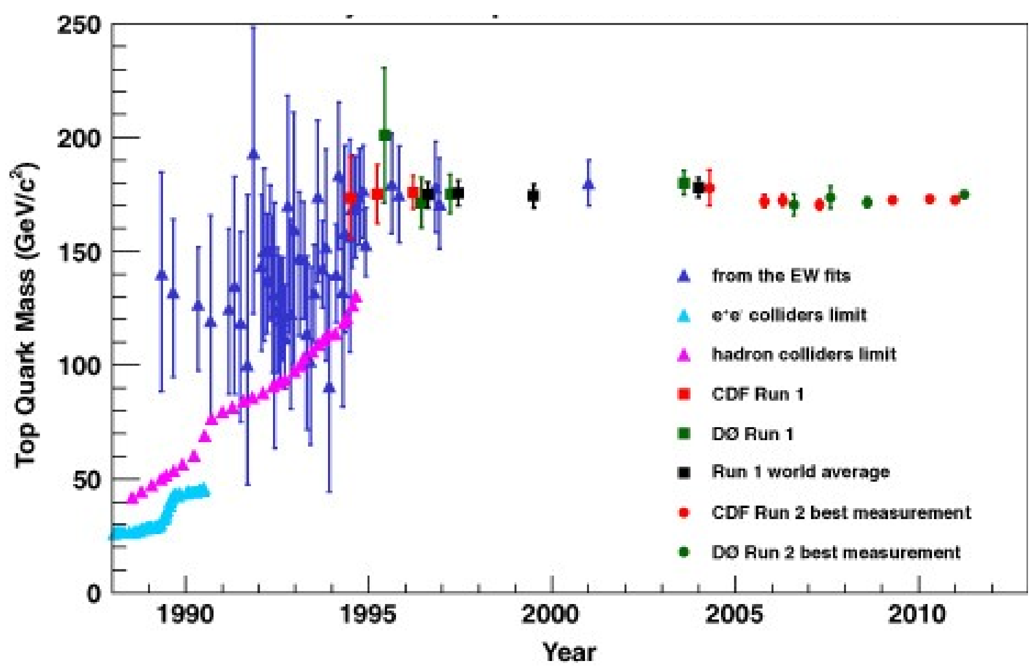
Indirect searches (90s)

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





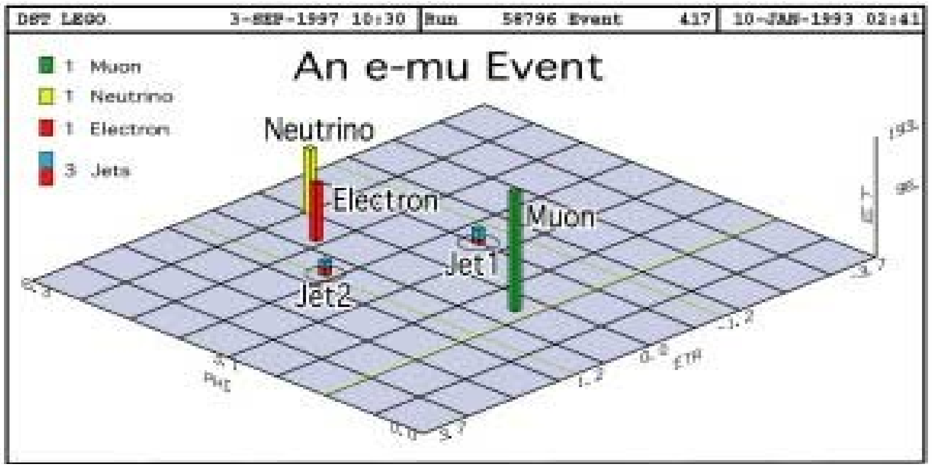
[Phys. Lett. B **276** (1992) 247]

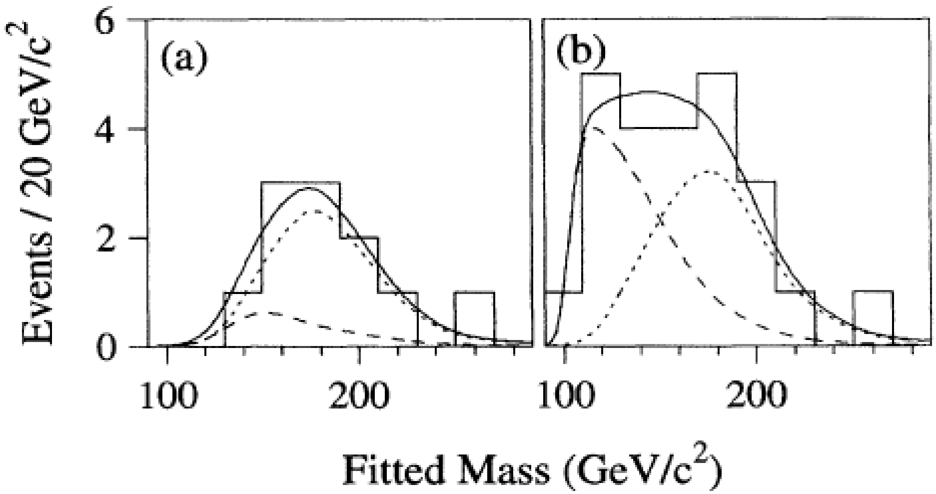


[Ann. Rev. Nucl. Part. Sci. **59** (2009) 505]

Top-quark history

Discovery (1995)





[Phys. Rev. Lett. **74** (1995) 2632]

FERMILAB NEWS RELEASE
A Department of Energy National Laboratory

News Release - March 2, 1995

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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.

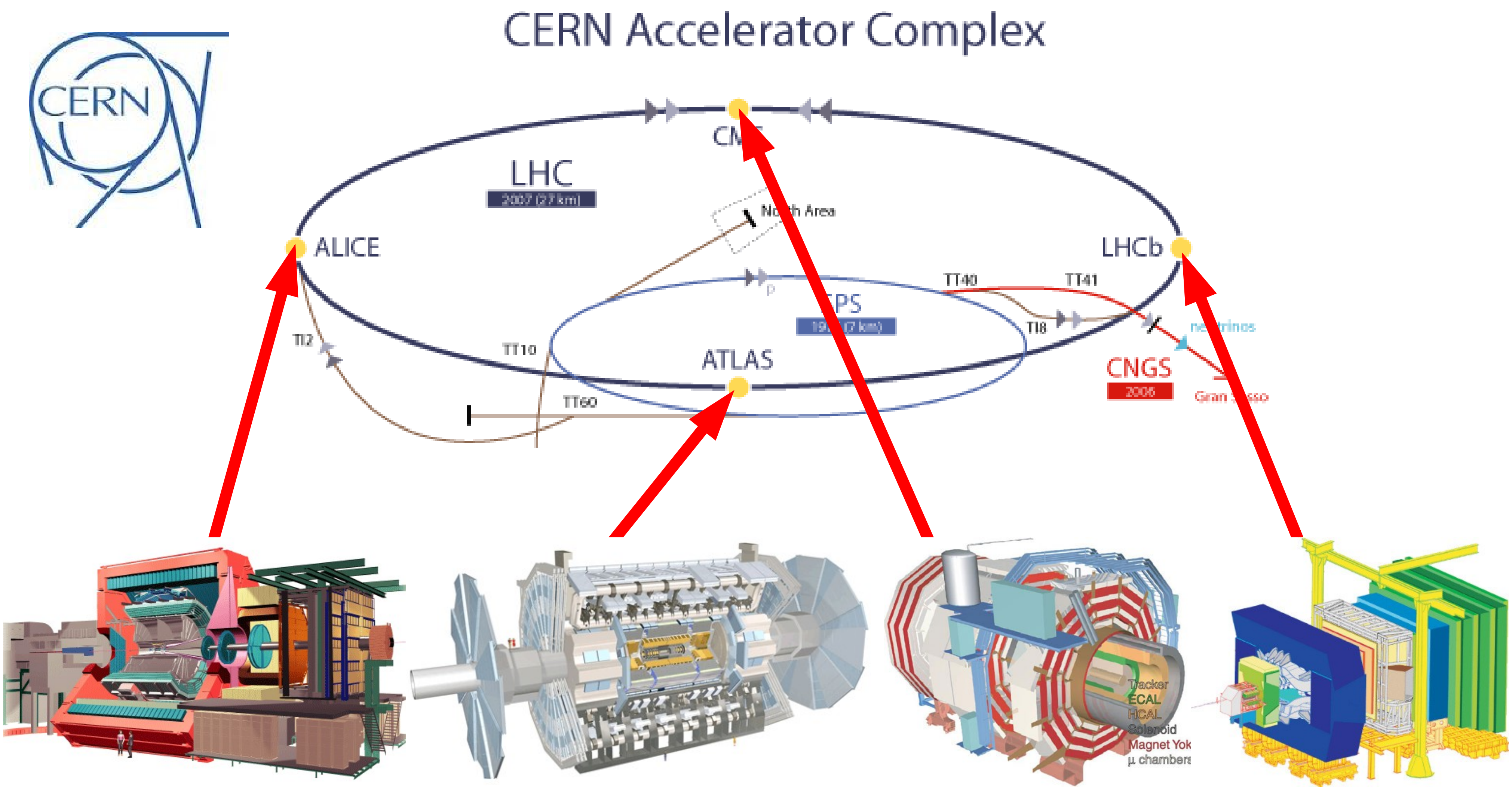
"This discovery serves as a powerful validation of federal support for science," said Secretary of Energy Hazel R. O'Leary. "Using one of the world's most powerful research tools, scientists at Fermilab have made yet another major contribution to human understanding of the fundamentals of the universe."

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



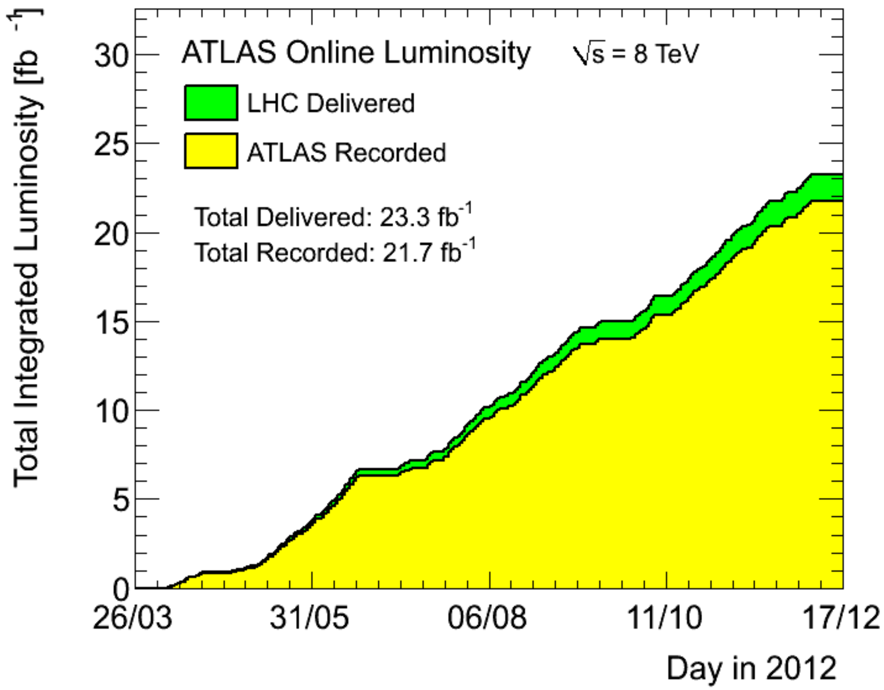
ALICE

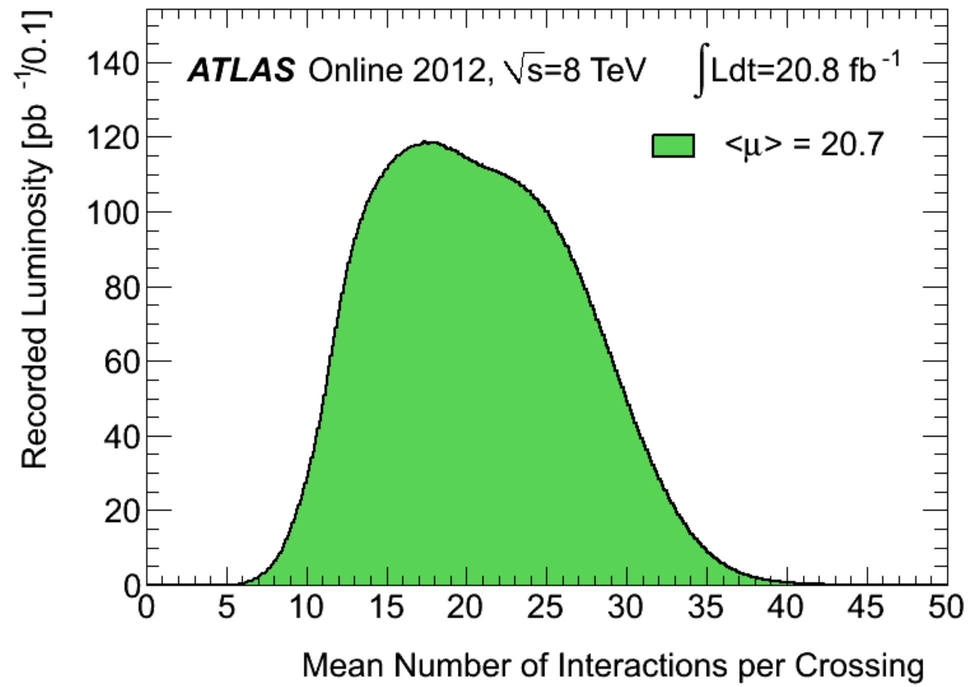
ATLAS EXPERIMENT

CMS

LHCb

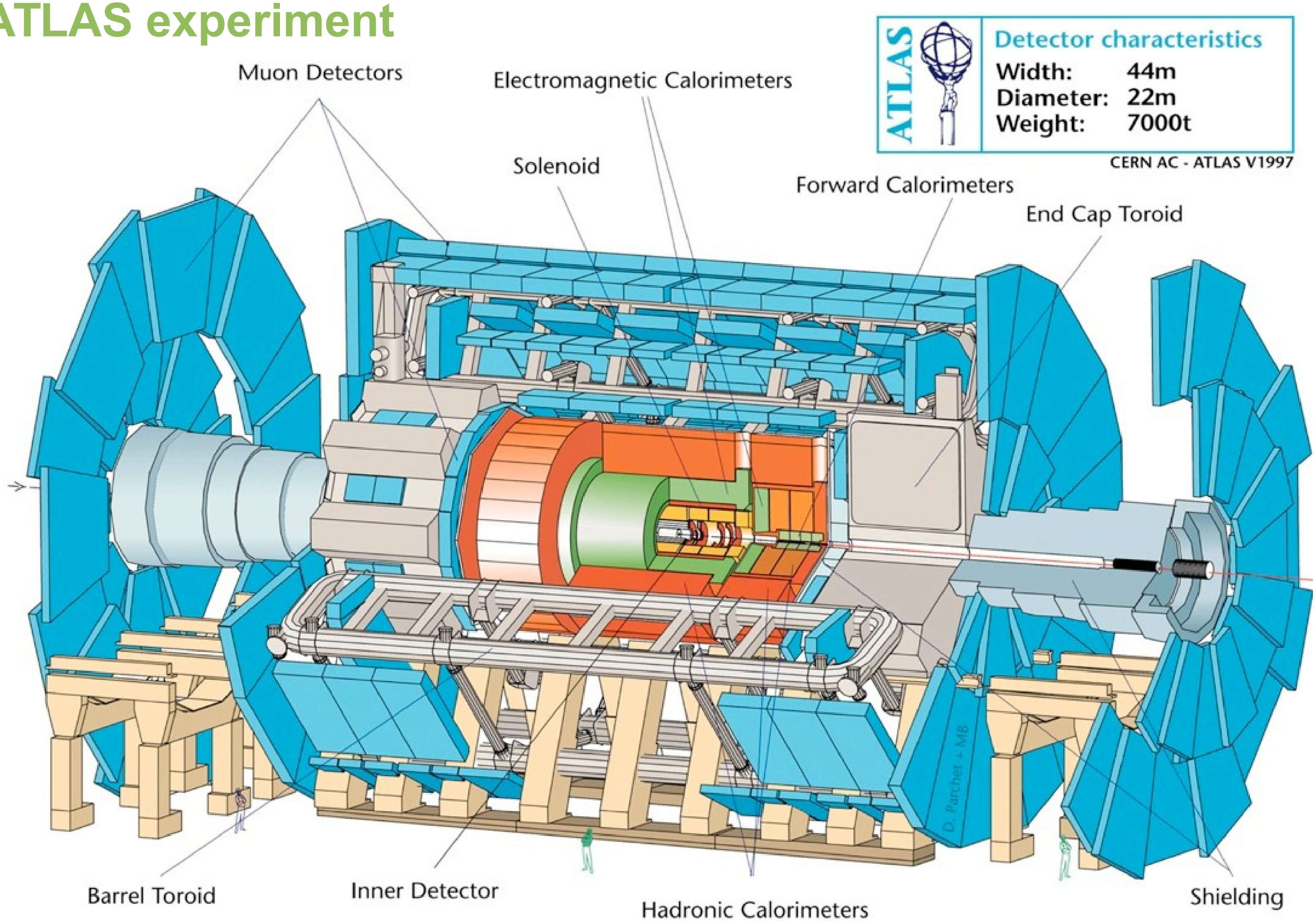
LHC Data





	7 TeV:	**8 TeV:**
Peak luminosity	$3.7\cdot10^{33}$ cm^{-2}s^{-1}	$7.73\cdot10^{33}$ cm^{-2}s^{-1}
Integrated luminosity	5.61 (5.25) fb^{-1}	23.3 (21.7) fb^{-1}
Efficiency (ATLAS)	94%	94%

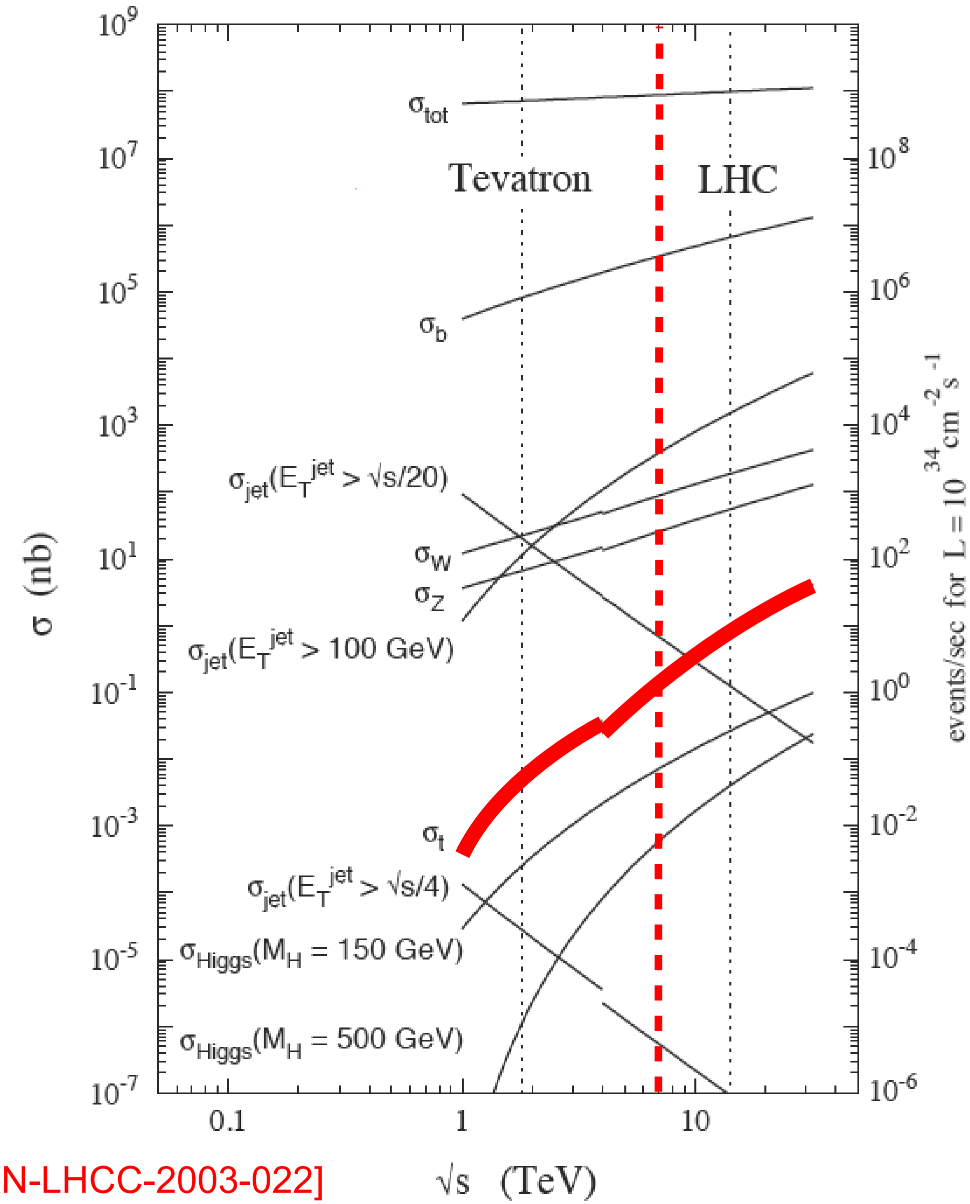
The ATLAS experiment



Top-quark production

Processes at hadron colliders (at 7 TeV)

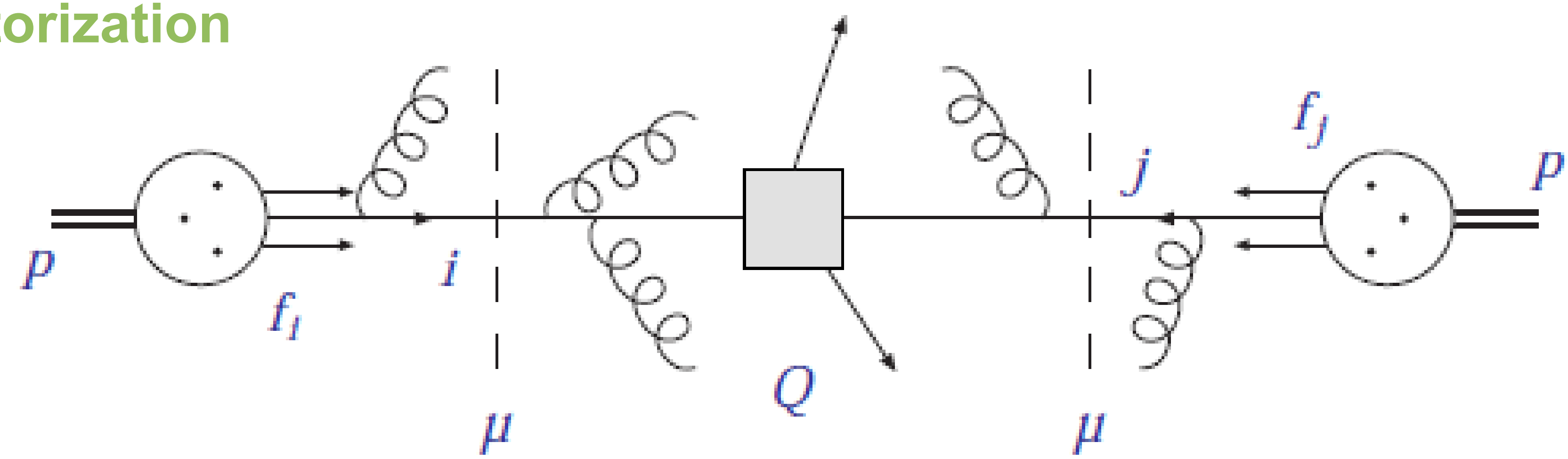
- Total cross section ~110 mb
  - Inelastic ~60 mb
  - Diffractive ~12 mb
  - Elastic ~40 mb
- Inclusive b production ~0,3 mb
- Jet production ~O(μb)
- Inclusive W production ~90 nb
- Top production ~165 pb
- Higgs production <10 pb
- New physics ???



[CERN-LHCC-2003-022]

Top-quark production

Factorization



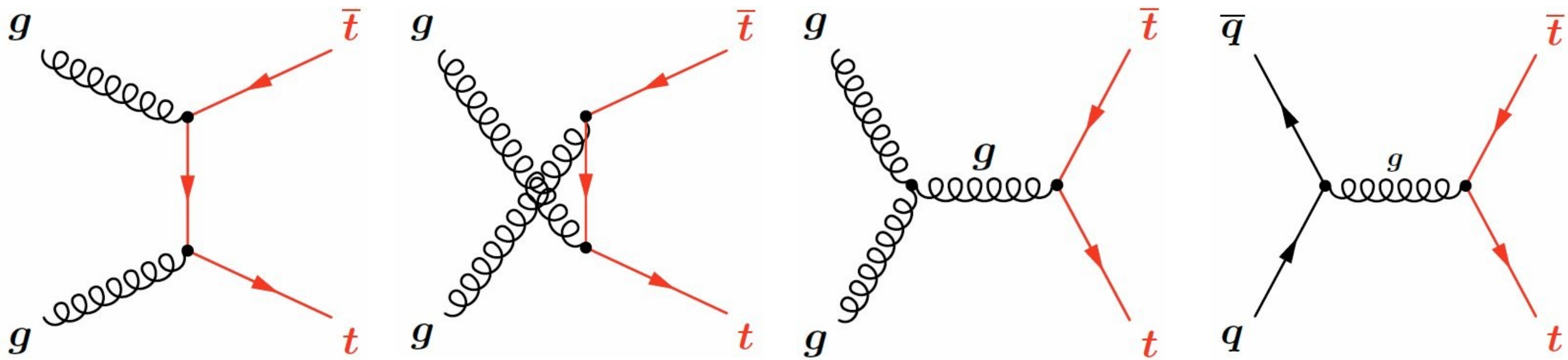
$$\sigma_{pp\to t\bar{t}+X} = \sum_{ij} \iint dx_i\, dx_j\, f_i(x_i,\mu_F)\, f_j(x_j,\mu_F) \cdot \hat{\sigma}_{ij\to t\bar{t}+X}(\alpha_S(\mu_R), Q^2, \mu_F, \mu_R)$$

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

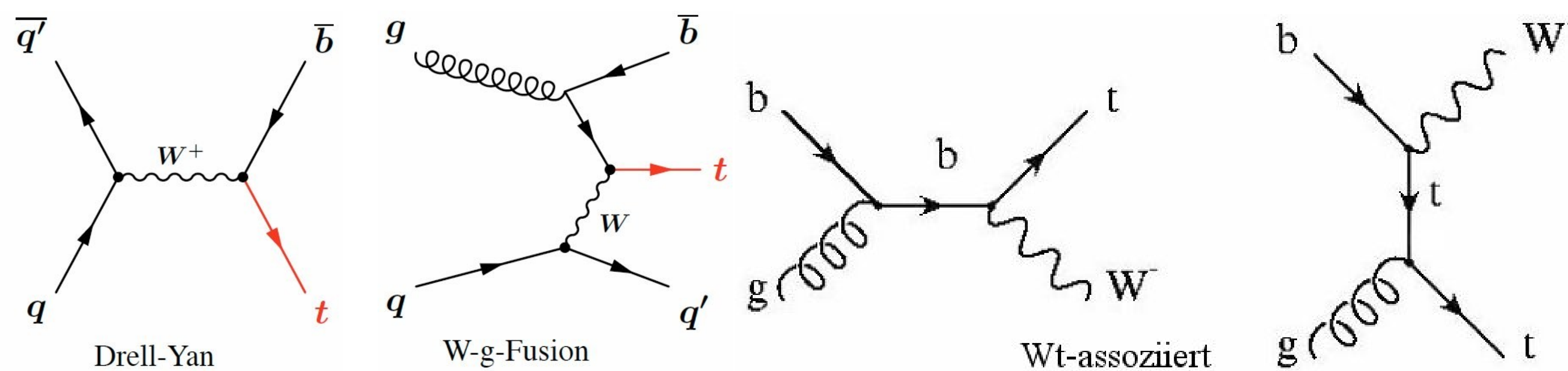
Top-quark production

Partonic reactions

- Top-quark pair production



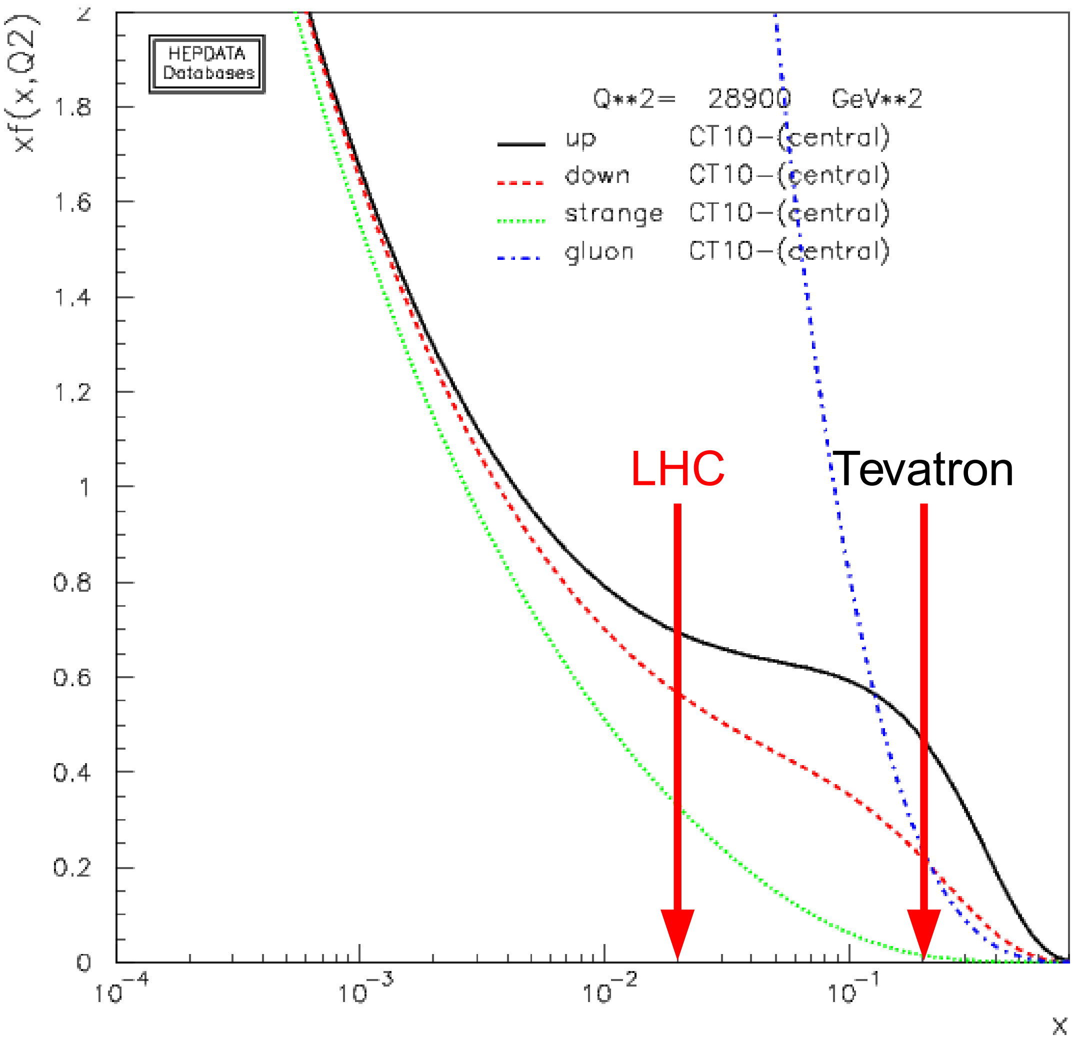
- Single-top production

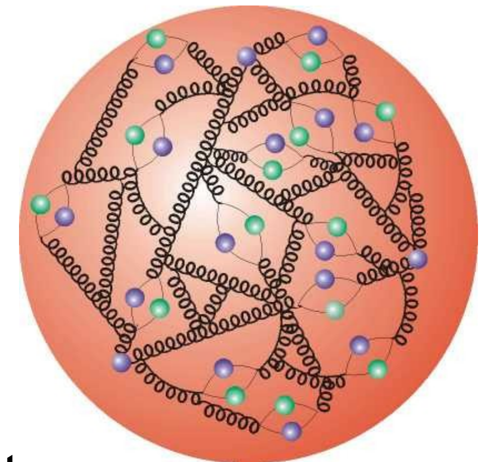


Drell-Yan W-g-Fusion Wt-assoziiert

Top-quark production

Parton luminosities



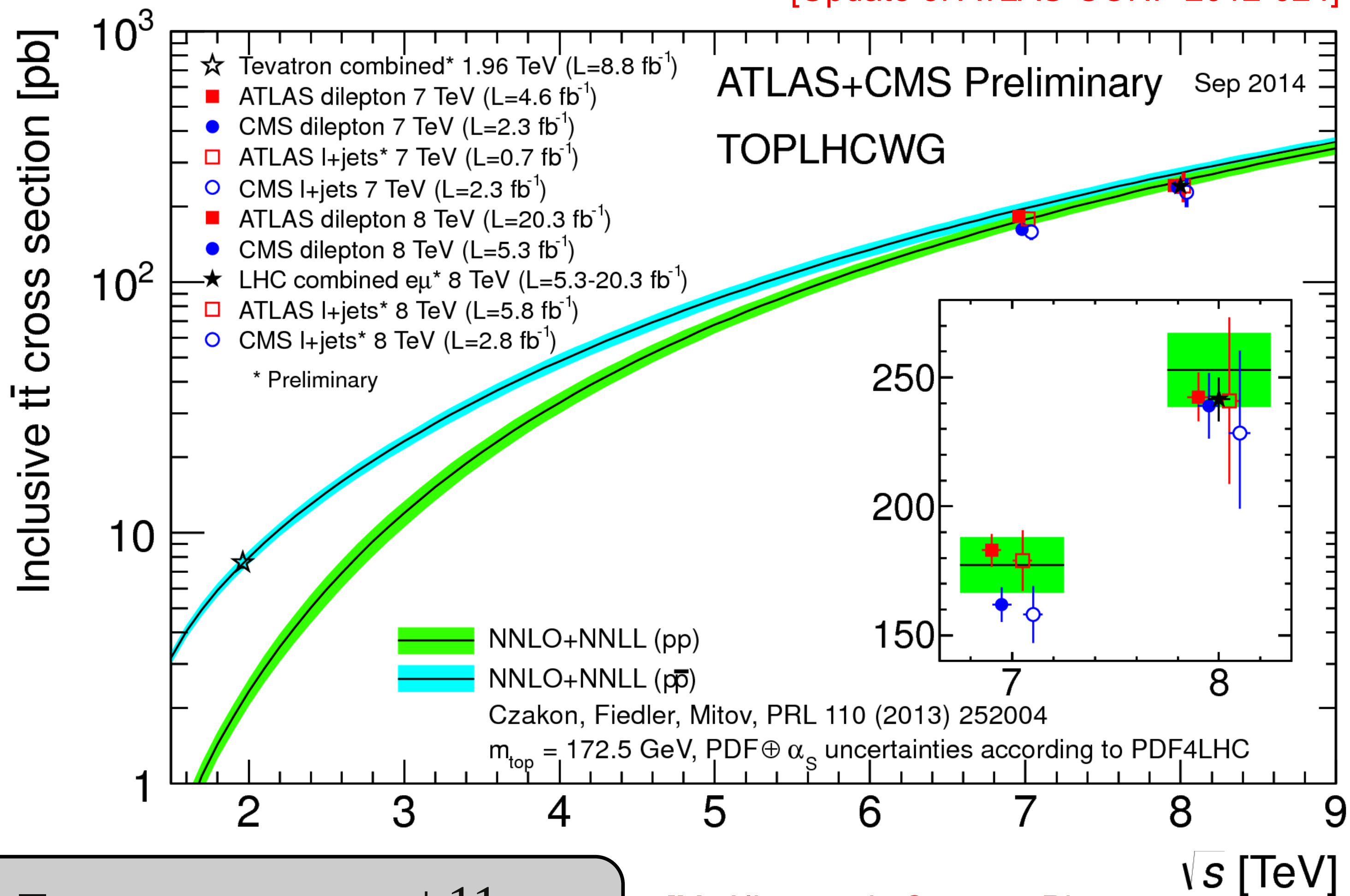


- Proton structure:
  - Gluons dominate for small x
  - Valence quarks dominate compared to sea quarks
- Typical x in top-quark physics:
  - Tevatron: <x> ~ 0.2
  - LHC: <x> ~ 0.02

Top-quark production

Predictions and measurements

[Update of ATLAS-CONF-2012-024]



$$\sigma_{t\bar{t}}(\sqrt{s}=7\ \mathrm{TeV}) = (165\,{}^{+11}_{-16})\ \mathrm{pb}$$

[M. Aliev *et al.*, Comput. Phys. Commun. 182 (2011) 1034]

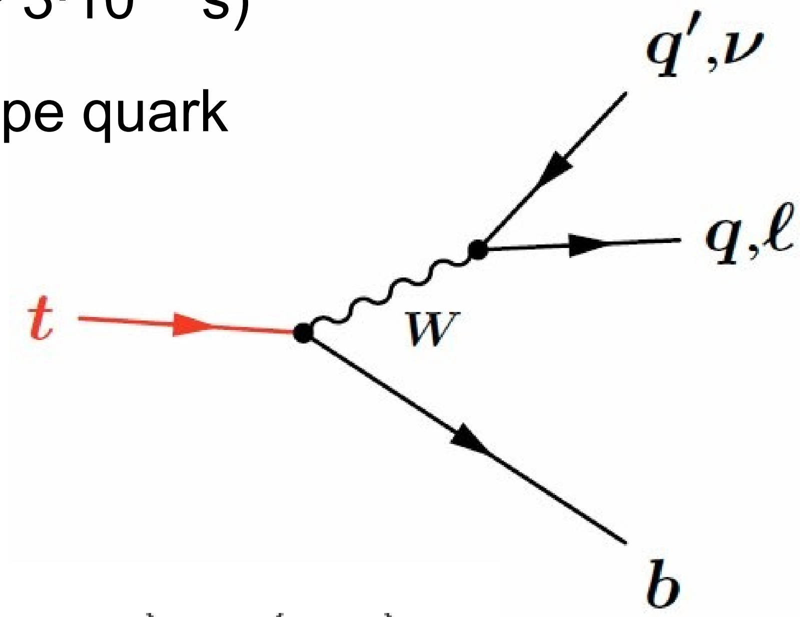
Question for you

How do top quarks decay?

Signatures of top quarks

Top-quark decay

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

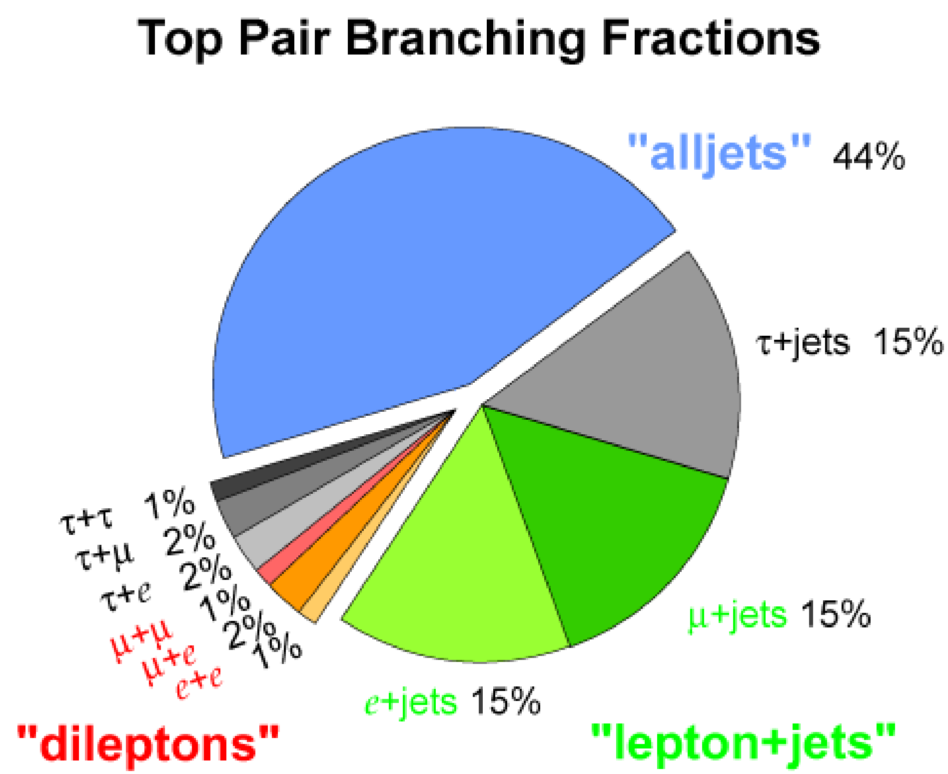


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

Signatures of top quarks

Signatures of top-quark pairs

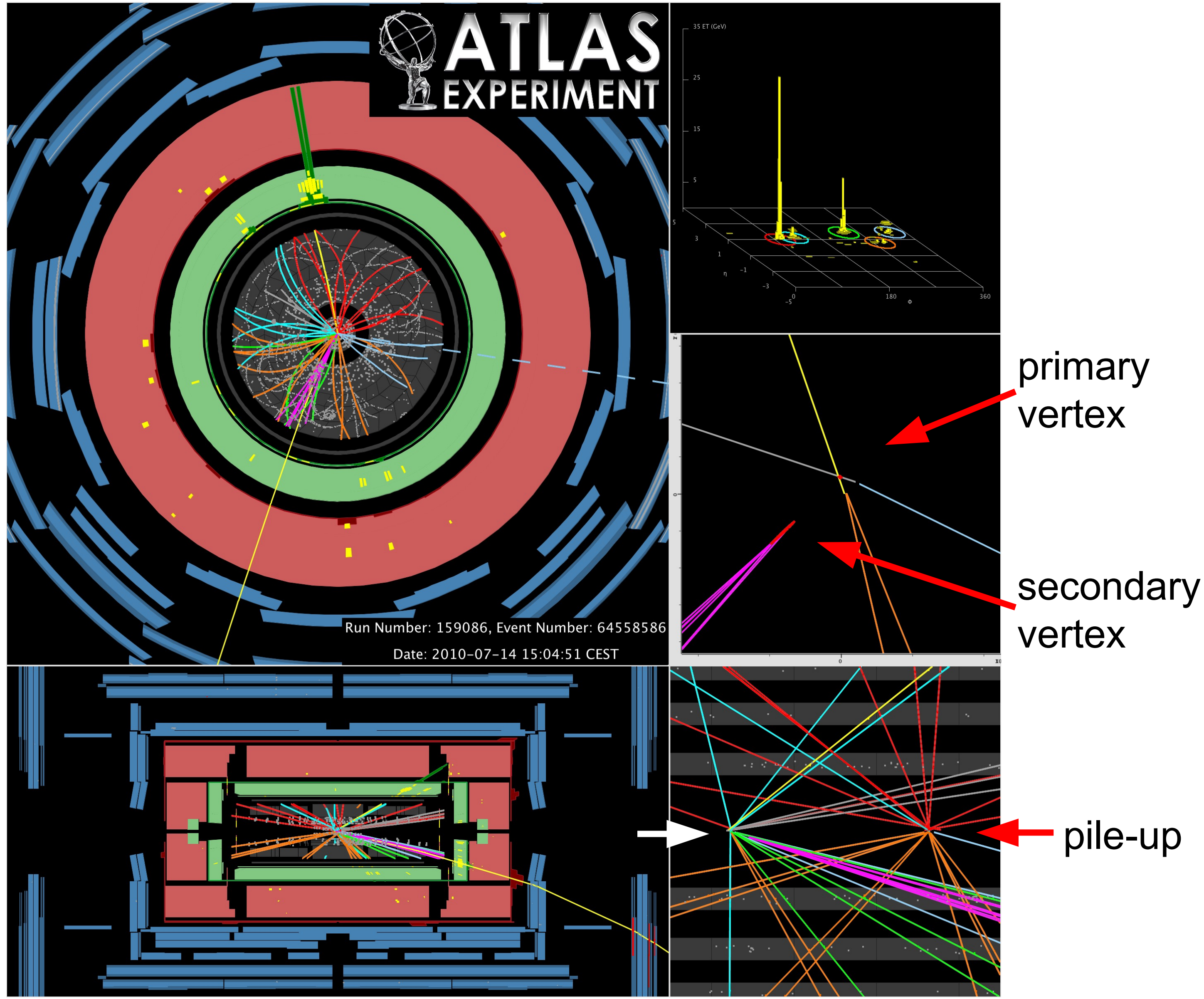
- Decay channels of W boson:
  - Leptonic: B(W→lν) ~ 0.32
  - Hadronic: B(W→qq') ~ 0.68
- Signatures of top-quark pairs:
  - Dilepton channel
  - Full-hadronic channel
  - Single-lepton channel:
    - Large statistics
    - Moderate background
    - Full reconstruction possible
      - Optimal for studies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



Signatures of top quarks

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



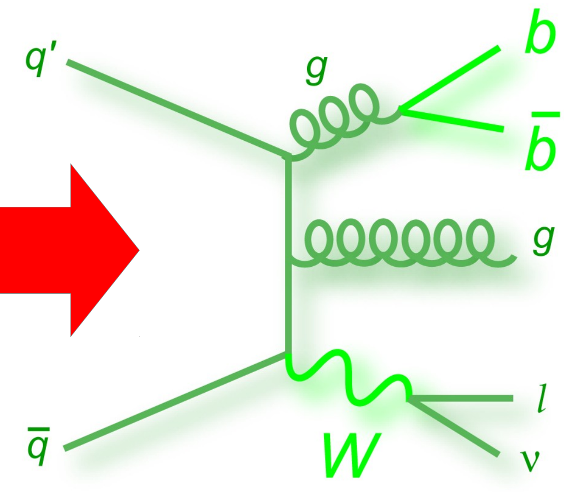
Question for you

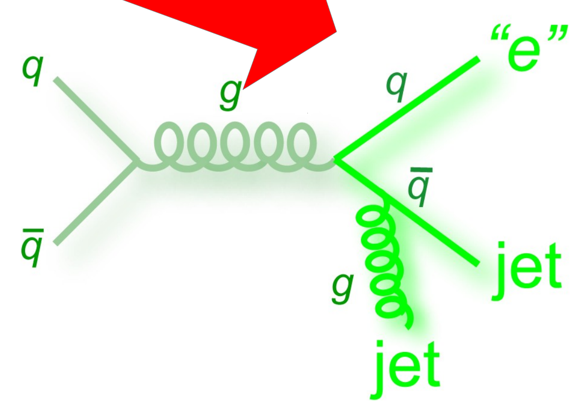
Which processes look like top-quark pair production?

Signatures of top quarks

Background processes

- 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





1.04 fb^{-1} (7 TeV)	**μ+jets**	**e+jets**
Top-quark pairs	6.300 ± 500	4.260 ± 350
Background	2.400 ± 600	1.500 ± 320
Observed	9.124	5.829

W-boson polarization

Results:

- Best fit and uncertainties:

3D:

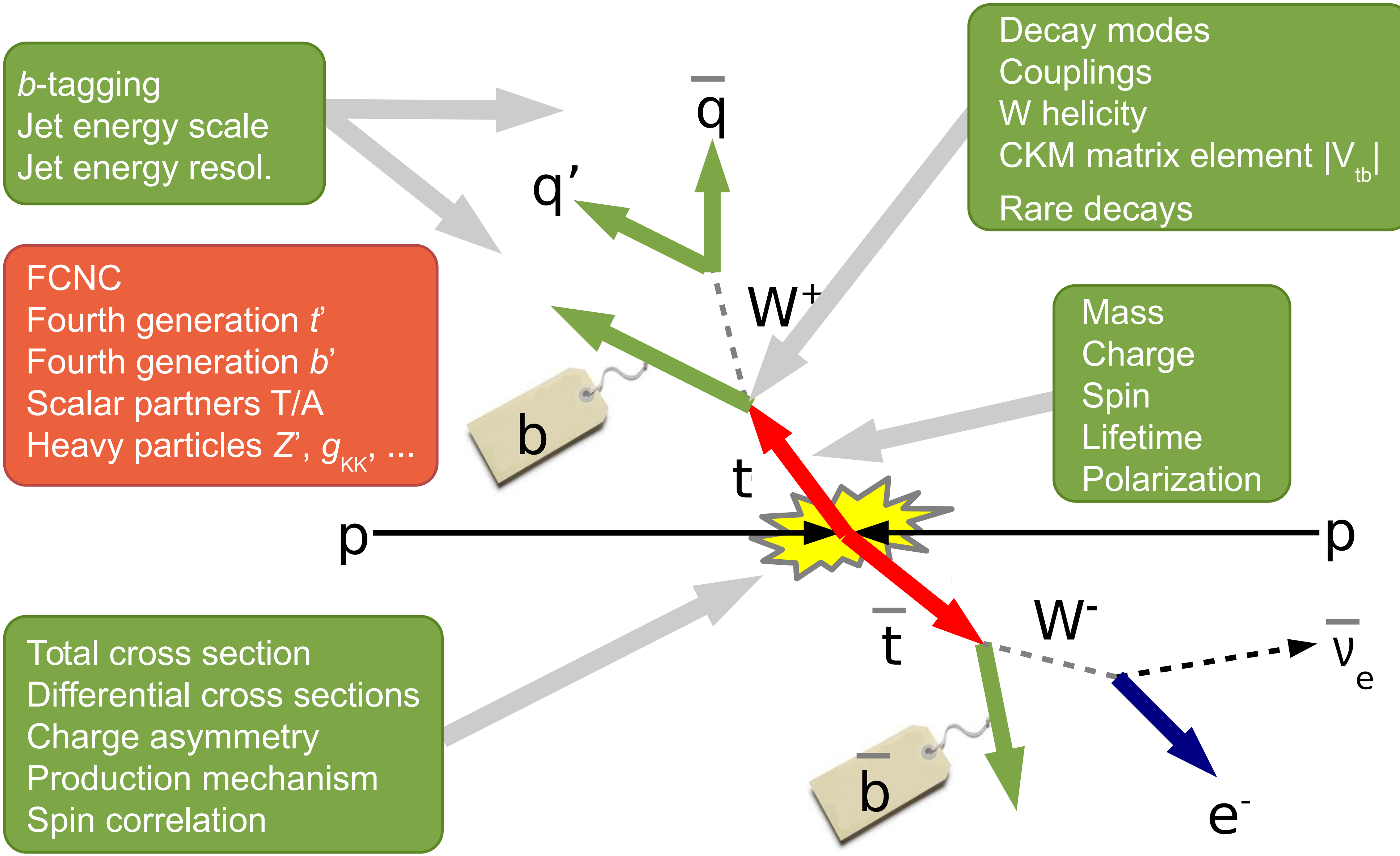
$$F_0 = 0.682 \pm 0.030\ (\text{stat}) \pm 0.033\ (\text{syst})$$
$$F_L = 0.310 \pm 0.022\ (\text{stat}) \pm 0.022\ (\text{syst})$$
$$F_R = 0.008 \pm 0.012\ (\text{stat}) \pm 0.014\ (\text{syst})$$
$$\rho_{0L} = -0.95$$

2D:

$$F_0 = 0.685 \pm 0.017\ (\text{stat}) \pm 0.021\ (\text{syst})$$
$$F_L = 0.315 \pm 0.017\ (\text{stat}) \pm 0.021\ (\text{syst})$$

- Important sources of syst. uncertainty for F_0 (F_L):
  - MC statistics ~ 0.016 (0.012)
  - Top-quark mass~ 0.016 (0.011)
  - Signal modeling~ 0.014 (0.013)

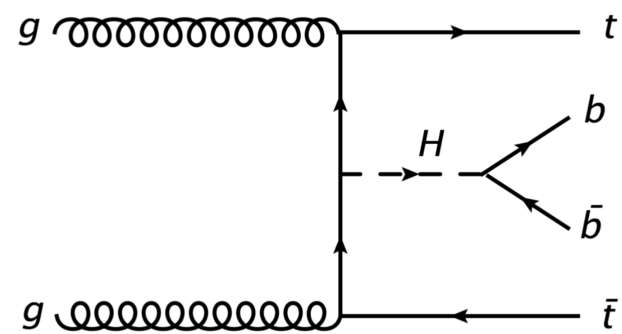
Measurement program

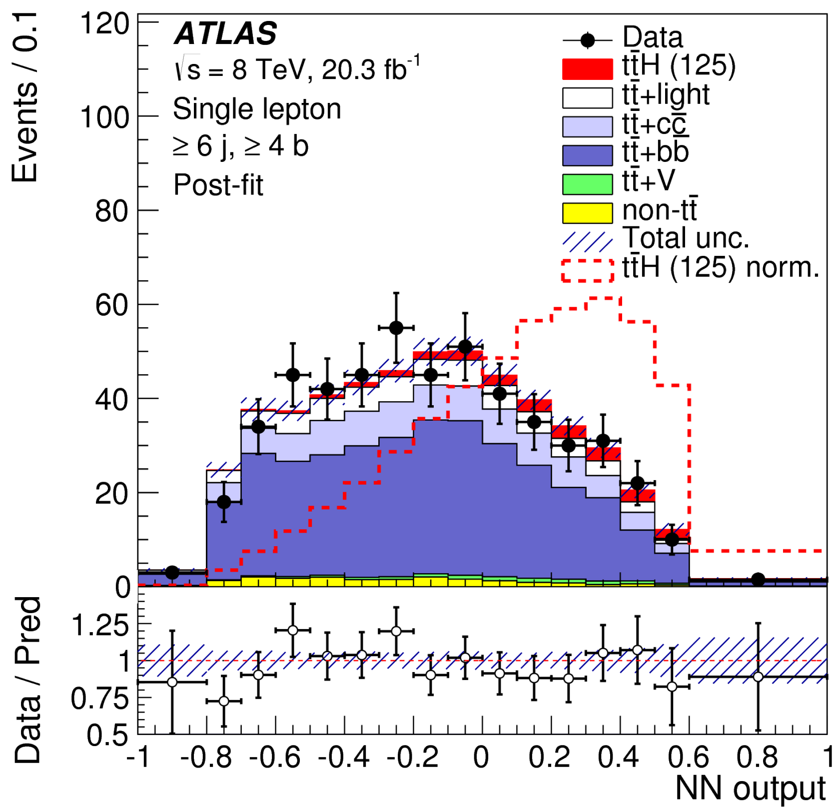


Measurement program

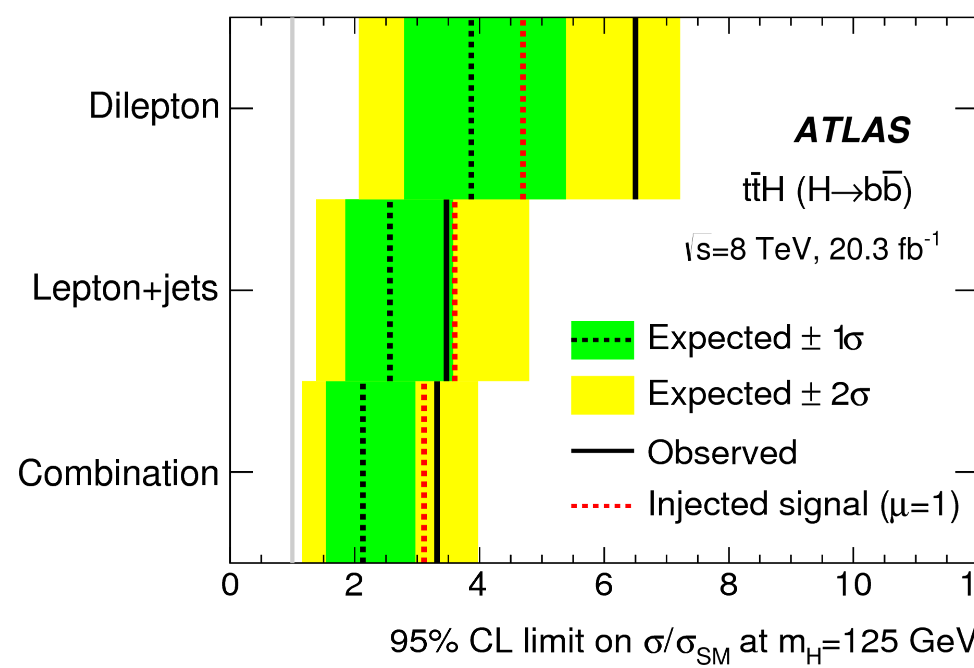
Intrinsic properties

- Mass
- Higgs couplings (ttH)
- CKM-matrix element V_{tb}





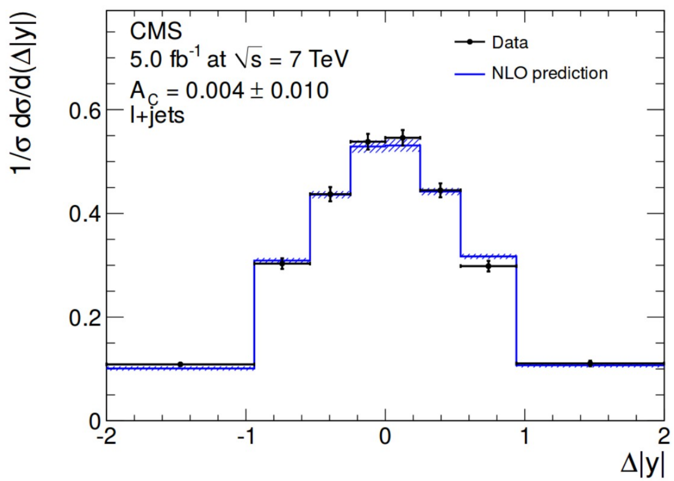
[arXiv:1503.05066]



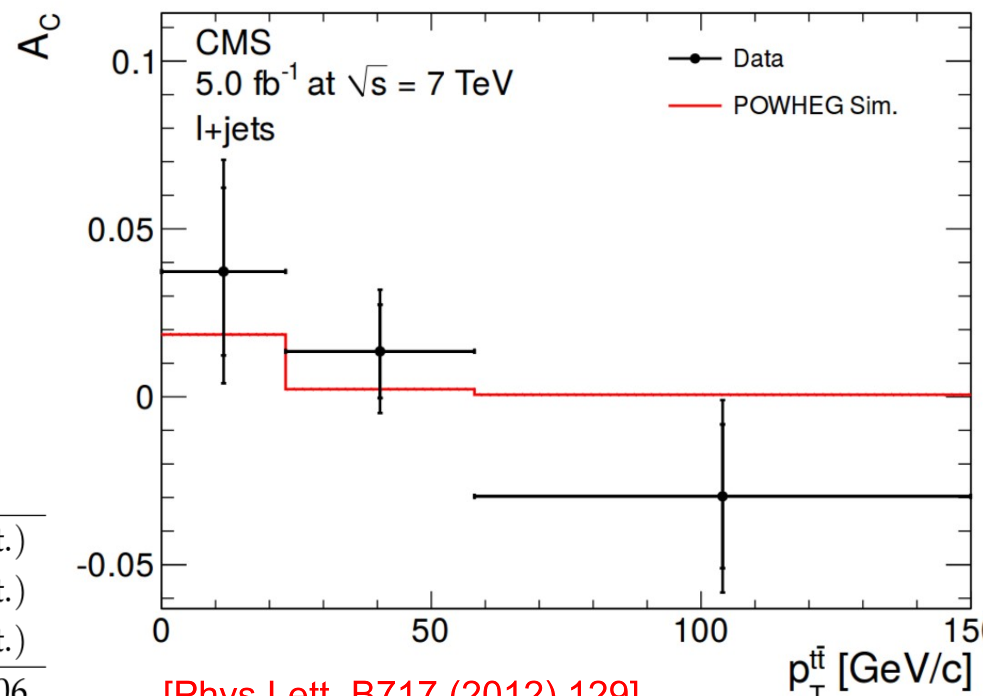
Measurement program

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

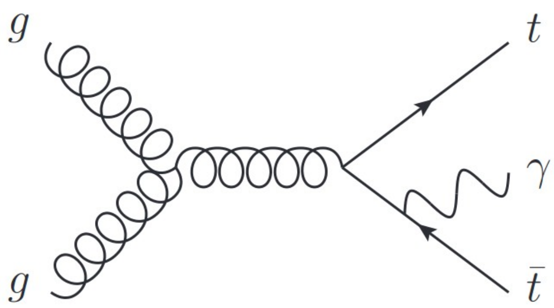


[Phys.Lett. B717 (2012) 129]

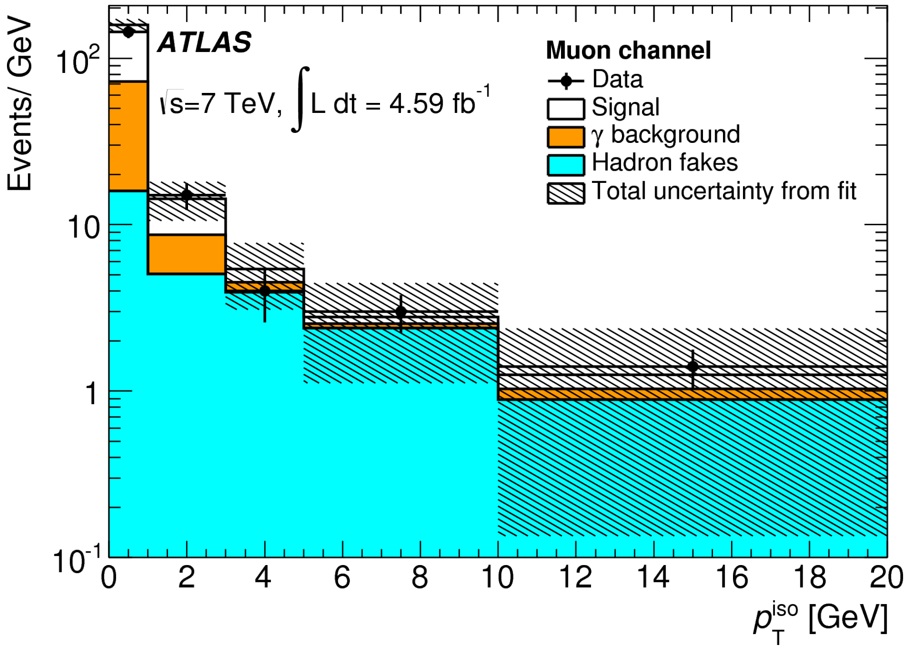
Measurement program

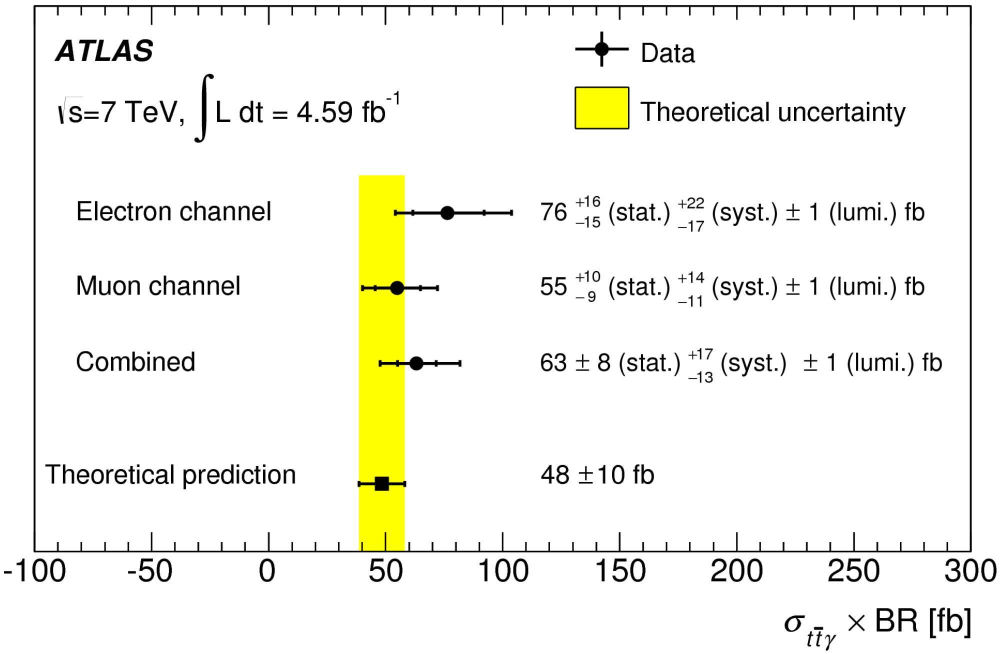
Tests of electroweak predictions

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



[arXiv:1502.00586]

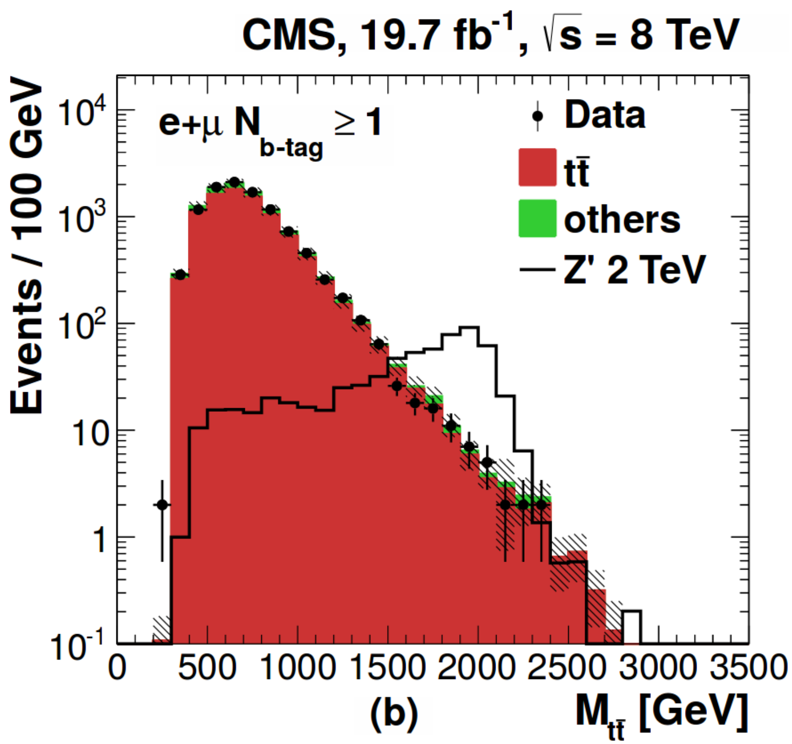




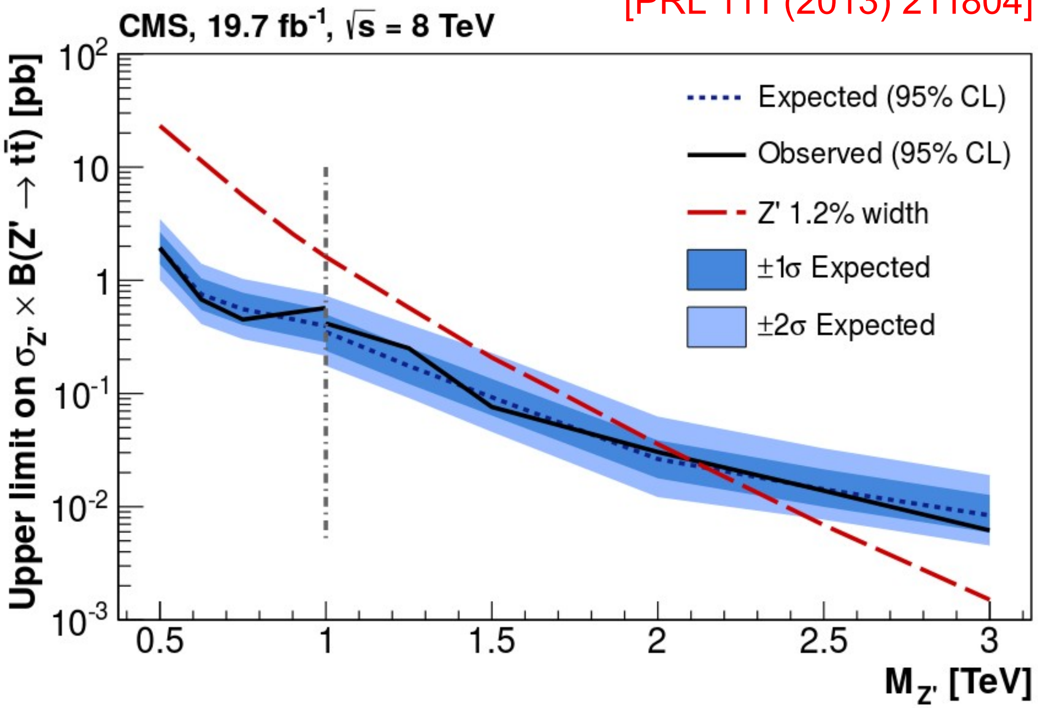
Measurement program

New-physics models including top quarks

- Top-quark pair resonances, e.g. Z', gKK, …
- Top-quark + jet resonances, e.g. color tripletts
- Fourth generation quarks decaying into top quarks
- Supersymmetric top-quark partner (stop)

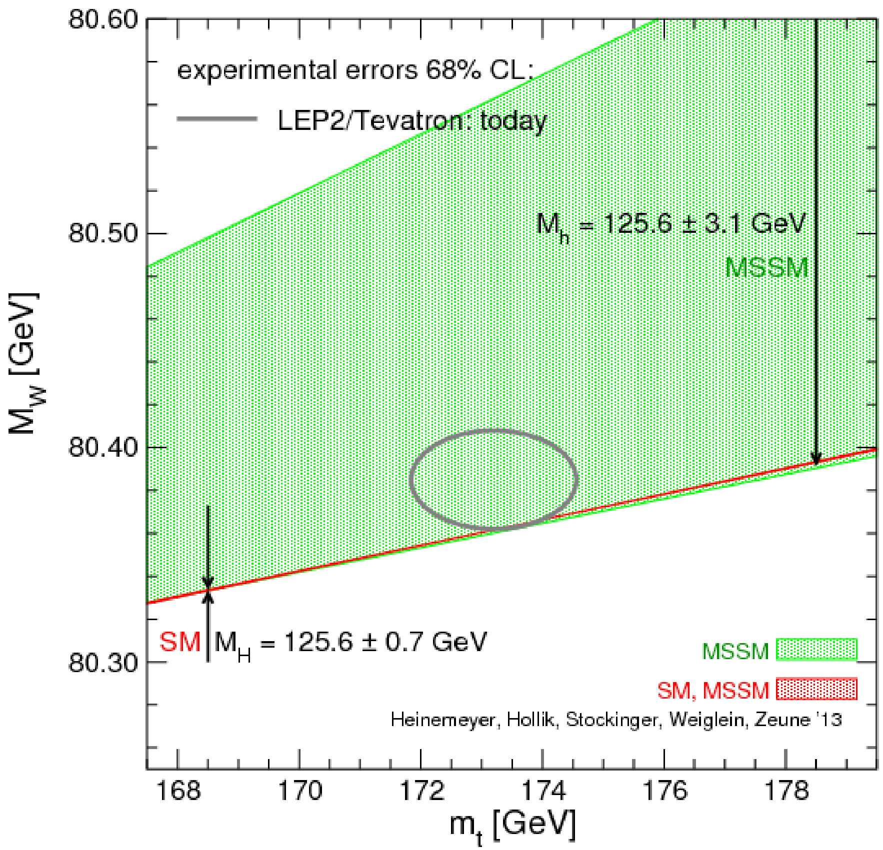


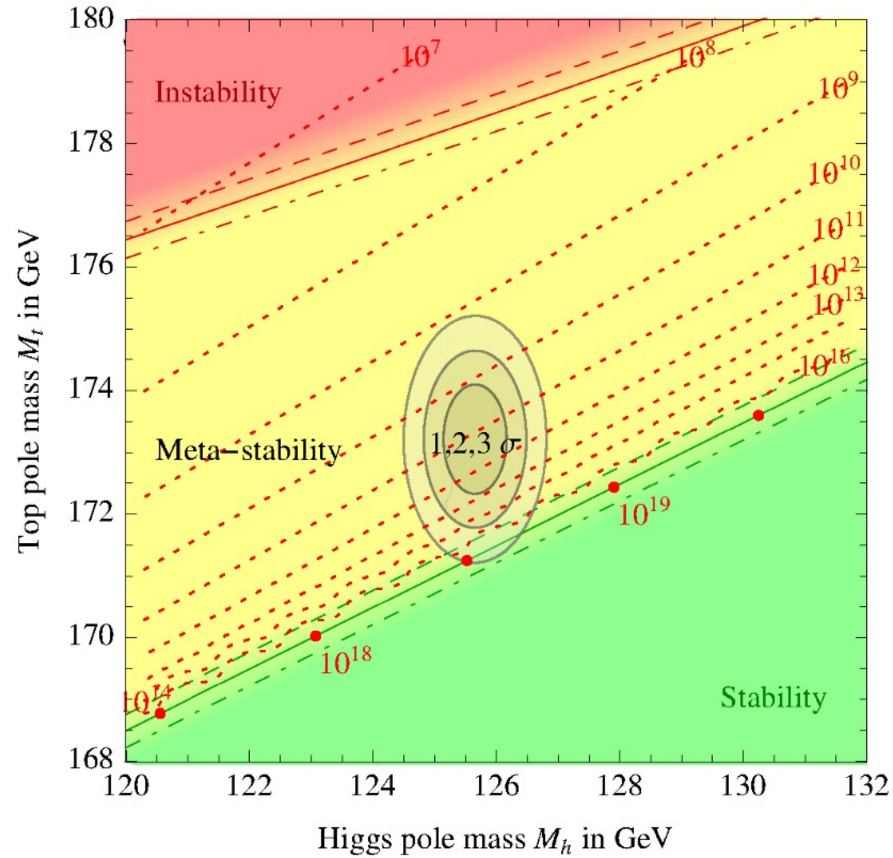
[PRL 111 (2013) 211804]



Top-quark mass

Motivation





Top-quark mass

Strategies

- Build an observable which is sensitive to the top-quark mass
- Statistical analysis, e.g.
  - Template method, compare templates with data
  - Unbinned likelihood fits
  - Matrix-element method
- Estimate impact of systematic uncertainties
  - Change observable if impact too large...
- Channels and selections
  - Single-lepton and dilepton channel
  - All-hadronic
  - Single-top enriched samples
  - From cross-section

Question for you

What limits the precision of a top-quark mass measurement?

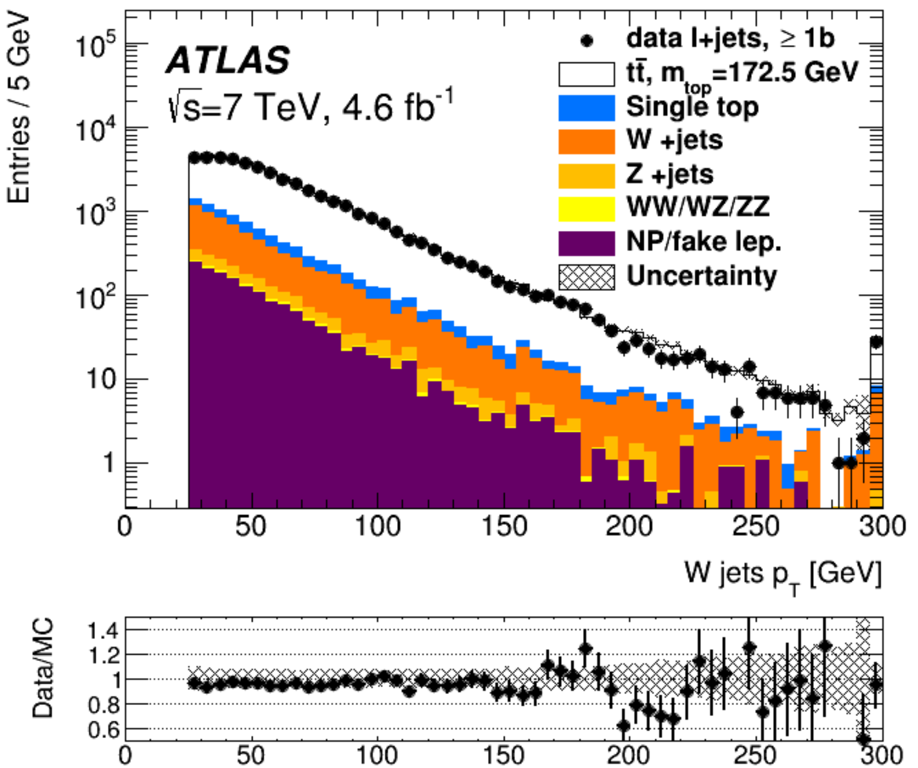
Top-quark mass

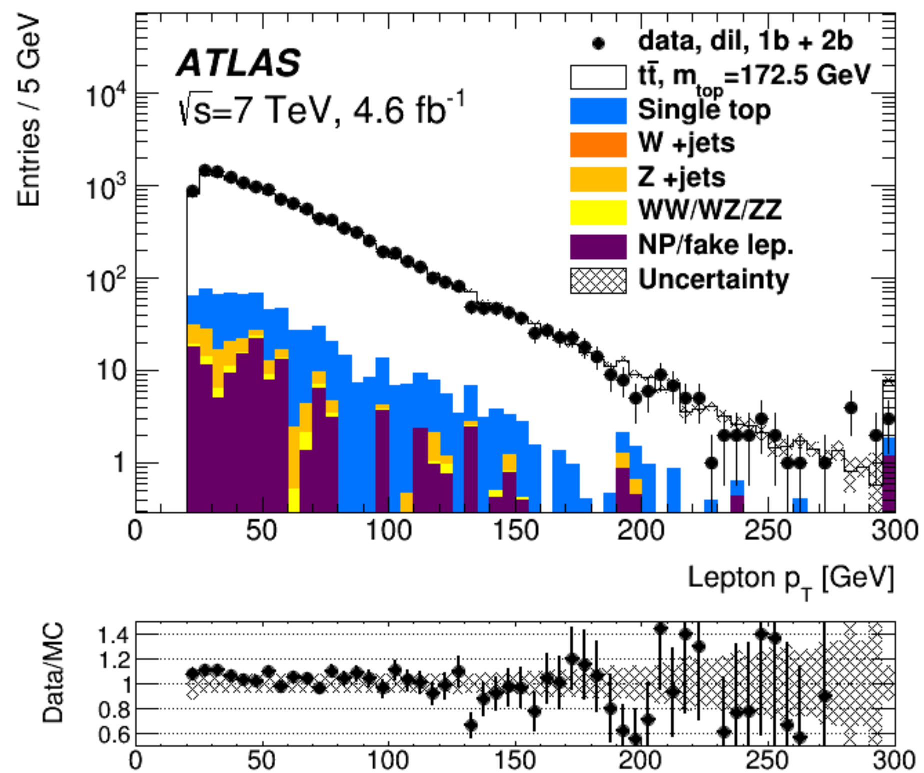
Strategy

- Prime example for a precision measurement
- Select single lepton and dilepton events
- From past: limited by JES and bJES
- Parameters:
  - Top-quark mass
  - JSF
  - b-to-light JSF
- Define three observables:
  - Invariant three-jet (top quark) mass
  - Invariant di-jet (W boson) mass
  - Ratio of b-jet to light-jet transverse momenta
- Combine measurements

Control plots

[arXiv:1503.05427]





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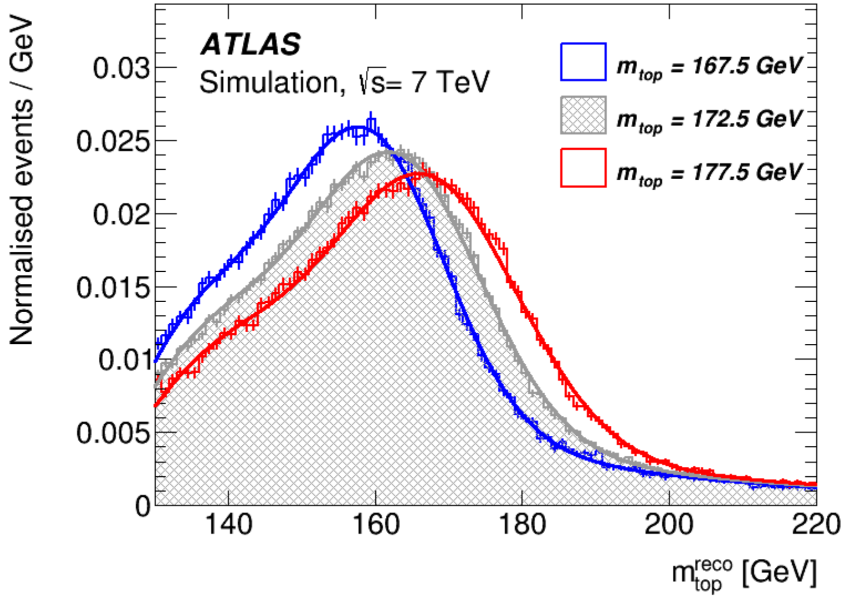
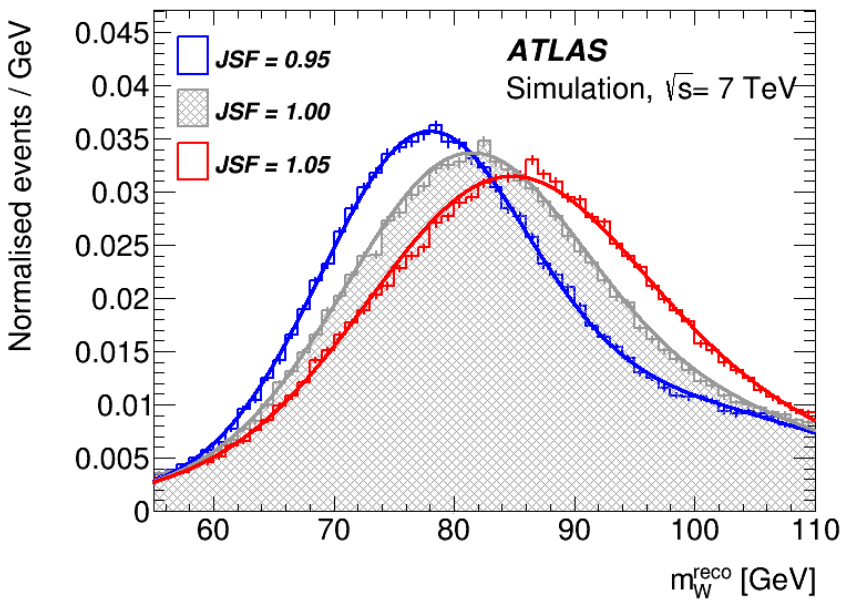
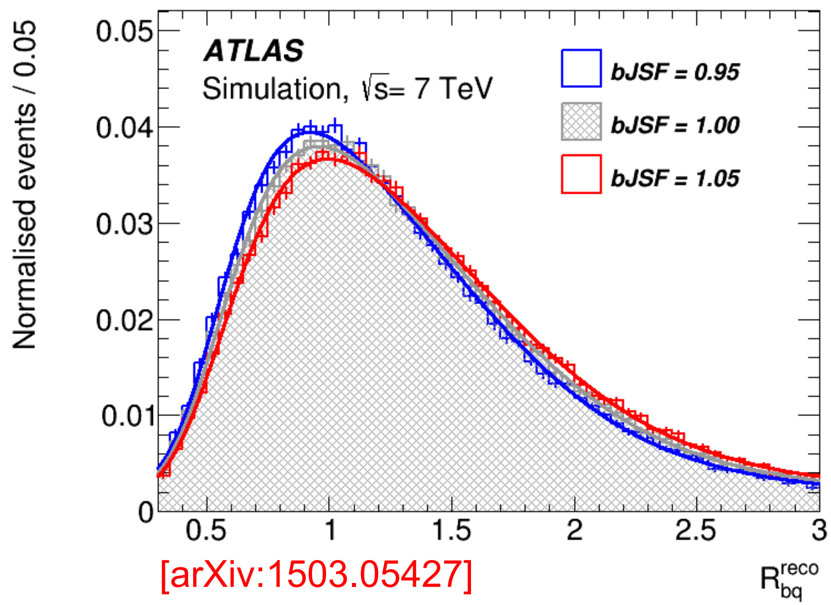
Top-quark mass

Parameterization

- Observables change shape with varying parameters
- Parameterize distributions using templates
- Fit simultaneously to data





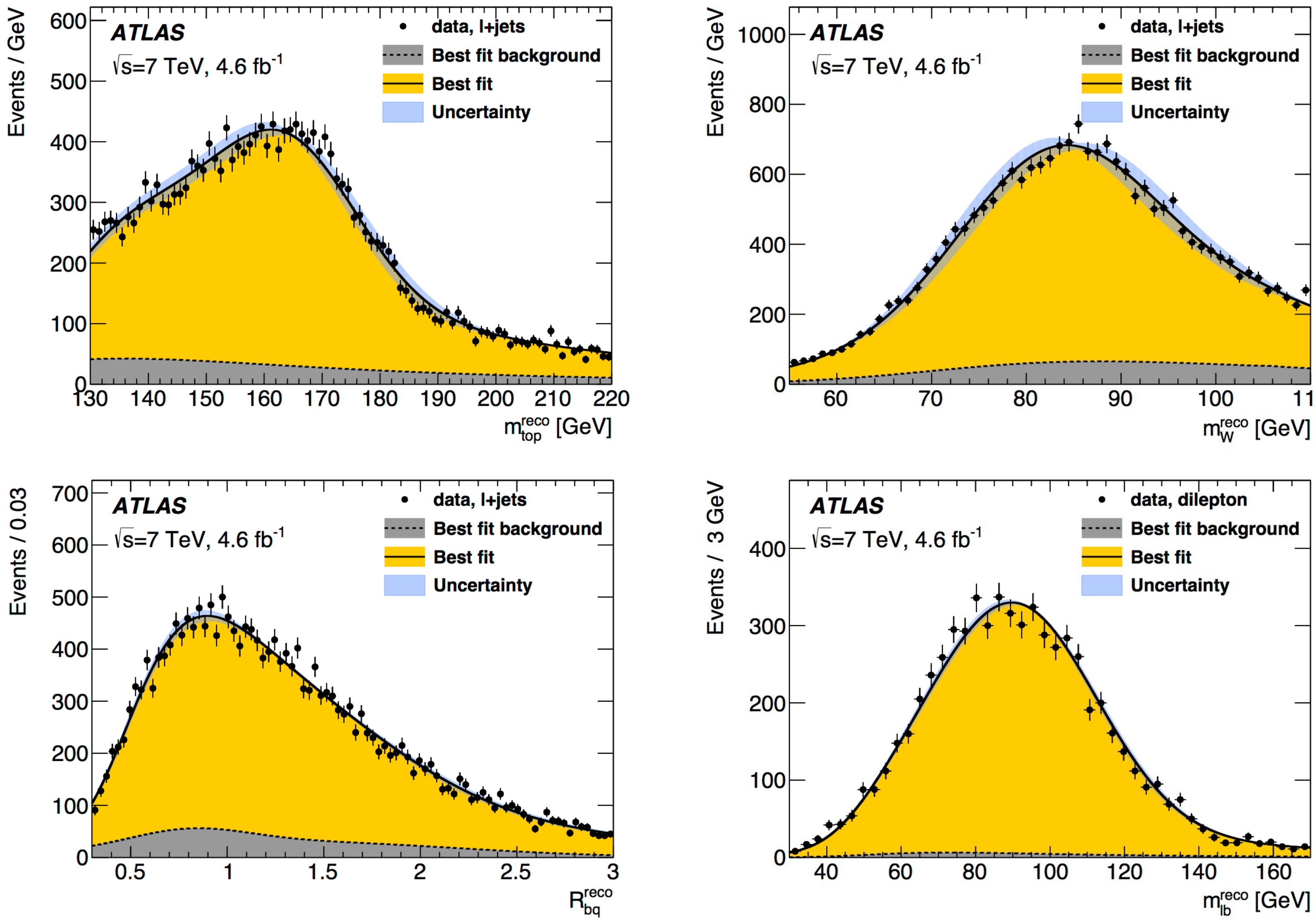


[arXiv:1503.05427]

Top-quark mass

Fit to data

[arXiv:1503.05427]



Top-quark mass

Systematic uncertainties

[arXiv:1503.05427]

	$t\bar{t} \to$ lepton+jets			$t\bar{t} \to$ dilepton	Combination	
	$m_{top}^{\ell+jets}$ [GeV]	JSF	bJSF	m_{top}^{dil} [GeV]	m_{top}^{comb} [GeV]	ρ
Results	172.33	1.019	1.003	173.79	172.99	
Statistics	0.75	0.003	0.008	0.54	0.48	0
– Stat. comp. (m_{top})	*0.23*	*n/a*	*n/a*	*0.54*		
– Stat. comp. (JSF)	*0.25*	*0.003*	*n/a*	*n/a*		
– Stat. comp. (bJSF)	*0.67*	*0.000*	*0.008*	*n/a*		
Method	0.11 ± 0.10	0.001	0.001	0.09 ± 0.07	0.07	0
Signal MC	0.22 ± 0.21	0.004	0.002	0.26 ± 0.16	0.24	+1.00
Hadronisation	0.18 ± 0.12	0.007	0.013	0.53 ± 0.09	0.34	+1.00
ISR/FSR	0.32 ± 0.06	0.017	0.007	0.47 ± 0.05	0.04	−1.00
Underlying event	0.15 ± 0.07	0.001	0.003	0.05 ± 0.05	0.06	−1.00
Colour reconnection	0.11 ± 0.07	0.001	0.002	0.14 ± 0.05	0.01	−1.00
PDF	0.25 ± 0.00	0.001	0.002	0.11 ± 0.00	0.17	+0.57
W/Z+jets norm	0.02 ± 0.00	0.000	0.000	0.01 ± 0.00	0.02	+1.00
W/Z+jets shape	0.29 ± 0.00	0.000	0.004	0.00 ± 0.00	0.16	0
NP/fake-lepton norm.	0.10 ± 0.00	0.000	0.001	0.04 ± 0.00	0.07	+1.00
NP/fake-lepton shape	0.05 ± 0.00	0.000	0.001	0.01 ± 0.00	0.03	+0.23
Jet energy scale	0.58 ± 0.11	0.018	0.009	0.75 ± 0.08	0.41	−0.23
b-Jet energy scale	0.06 ± 0.03	0.000	0.010	0.68 ± 0.02	0.34	+1.00
Jet resolution	0.22 ± 0.11	0.007	0.001	0.19 ± 0.04	0.03	−1.00
Jet efficiency	0.12 ± 0.00	0.000	0.002	0.07 ± 0.00	0.10	+1.00
Jet vertex fraction	0.01 ± 0.00	0.000	0.000	0.00 ± 0.00	0.00	−1.00
b-Tagging	0.50 ± 0.00	0.001	0.007	0.07 ± 0.00	0.25	−0.77
E_T^{miss}	0.15 ± 0.04	0.000	0.001	0.04 ± 0.03	0.08	−0.15
Leptons	0.04 ± 0.00	0.001	0.001	0.13 ± 0.00	0.05	−0.34
Pile-up	0.02 ± 0.01	0.000	0.000	0.01 ± 0.00	0.01	0
Total	1.27 ± 0.33	0.027	0.024	1.41 ± 0.24	0.91	−0.07

Top-quark mass

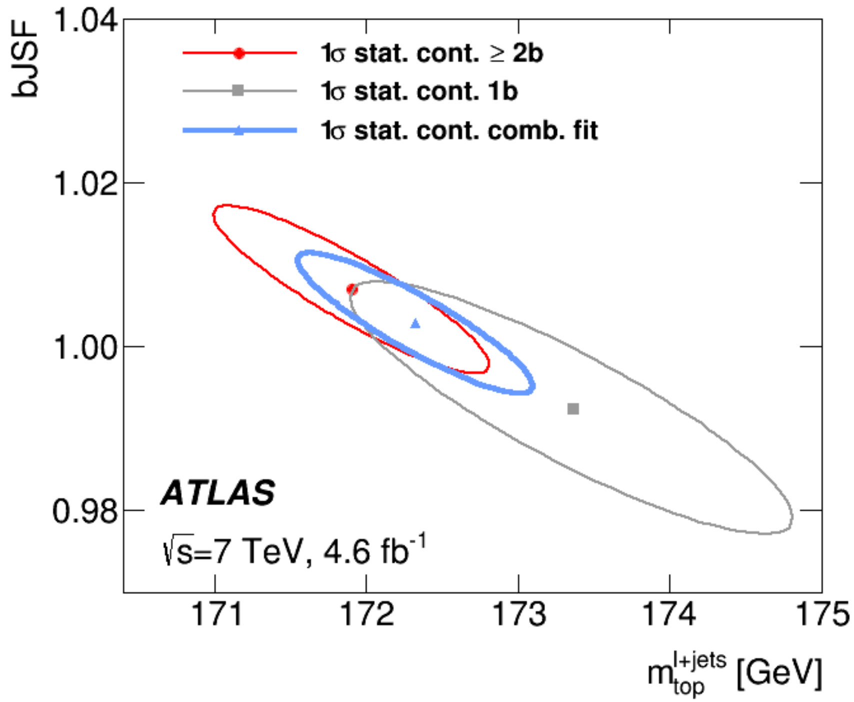
Systematic uncertainties (JES)

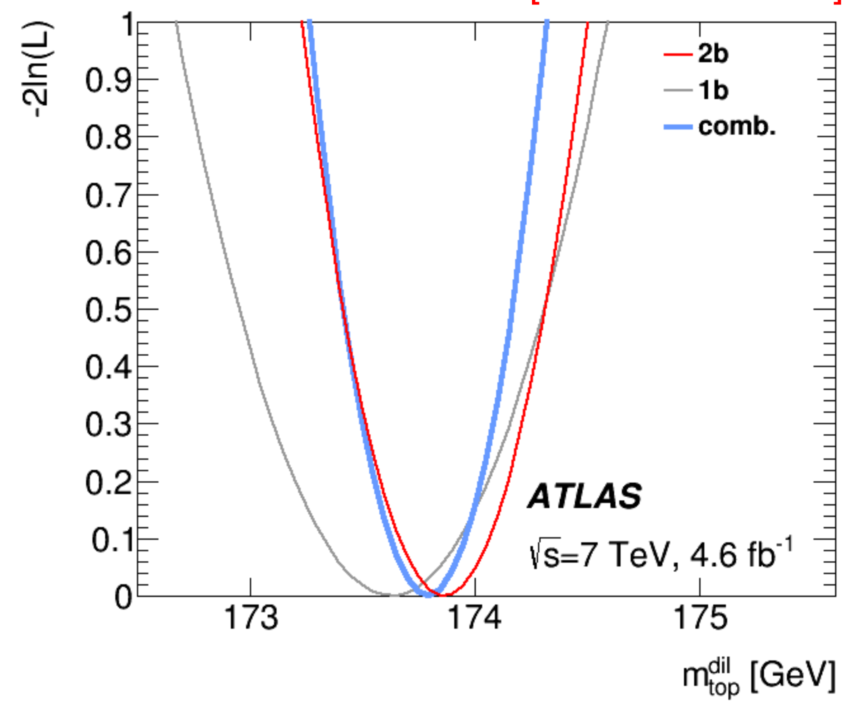
[arXiv:1503.05427]

	$t\bar{t} \to$ lepton+jets			$t\bar{t} \to$ dilepton	Combination	
	$\Delta m_{top}^{\ell+jets}$ [GeV]	ΔJSF	ΔbJSF	Δm_{top}^{dil} [GeV]	Δm_{top}^{comb} [GeV]	ρ
Statistical (total)	0.18 ± 0.04	0.003	0.001	0.16 ± 0.03	0.11	−0.25
– Statistical NP1	−0.17 ± 0.02	+0.002	+0.001	+0.01 ± 0.02	0.09	−1.00
– Statistical NP2	+0.02 ± 0.00	+0.001	−0.000	+0.05 ± 0.00	0.03	+1.00
– Statistical NP3	−0.01 ± 0.02	+0.001	+0.001	+0.12 ± 0.02	0.05	−1.00
– η inter-calibration (stat.)	−0.07 ± 0.02	+0.001	+0.001	+0.10 ± 0.02	0.01	−1.00
Modelling (total)	0.31 ± 0.06	0.009	0.002	0.52 ± 0.04	0.26	−0.18
– Modelling NP1	−0.30 ± 0.03	+0.006	+0.001	+0.22 ± 0.02	0.07	−1.00
– Modelling NP2	+0.03 ± 0.02	+0.002	−0.000	+0.14 ± 0.02	0.08	+1.00
– Modelling NP3	−0.01 ± 0.02	−0.002	−0.000	−0.15 ± 0.02	0.07	+1.00
– Modelling NP4	−0.01 ± 0.00	+0.000	+0.000	+0.02 ± 0.00	0.00	−1.00
– η inter-calibration (model)	+0.07 ± 0.04	+0.007	−0.001	+0.43 ± 0.03	0.23	+1.00
Detector (total)	0.05 ± 0.03	0.007	0.001	0.45 ± 0.04	0.20	−0.19
– Detector NP1	−0.01 ± 0.03	+0.007	+0.001	+0.45 ± 0.02	0.20	−1.00
– Detector NP2	−0.05 ± 0.00	+0.000	+0.001	+0.03 ± 0.00	0.02	−1.00
Mixed (total)	0.02 ± 0.02	0.001	0.001	+0.03 ± 0.02	0.01	−0.80
– Mixed NP1	−0.02 ± 0.00	+0.000	+0.001	+0.02 ± 0.00	0.00	−1.00
– Mixed NP2	+0.00 ± 0.02	+0.001	−0.000	+0.02 ± 0.02	0.01	+1.00
Single particle high-p_T	+0.00 ± 0.00	+0.000	−0.000	+0.00 ± 0.00	0.00	+1.00
Relative non-closure MC	+0.00 ± 0.02	+0.001	−0.000	+0.03 ± 0.02	0.02	+1.00
Pile-up (total)	0.15 ± 0.04	0.001	0.002	0.04 ± 0.03	0.09	+0.03
– Pile-up: Offset(μ)	−0.11 ± 0.02	−0.001	+0.001	−0.02 ± 0.02	0.07	+1.00
– Pile-up: Offset(n_{vtx})	−0.10 ± 0.04	−0.000	+0.001	+0.03 ± 0.03	0.04	−1.00
Flavour (total)	0.36 ± 0.04	0.012	0.008	0.03 ± 0.03	0.20	−0.17
– Flavour Composition	−0.24 ± 0.02	+0.006	−0.002	−0.02 ± 0.02	0.14	+1.00
– Flavour Response	−0.28 ± 0.03	+0.011	−0.008	+0.03 ± 0.02	0.14	−1.00
Close-by jets	−0.22 ± 0.04	+0.005	+0.002	+0.25 ± 0.03	0.01	−1.00
b-Jet energy scale	+0.06 ± 0.03	+0.000	+0.010	+0.68 ± 0.02	0.34	+1.00
Total (without bJES)	0.58 ± 0.11	0.018	0.009	0.75 ± 0.08	0.41	−0.23

Results

[arXiv:1503.05427]





$$
\begin{aligned}
m_{\mathrm{top}}^{\ell+\mathrm{jets}} &= 172.33 \pm 0.75\,(\mathrm{stat} + \mathrm{JSF} + \mathrm{bJSF}) \pm 1.02\,(\mathrm{syst})\ \ \mathrm{GeV} \\
\mathrm{JSF} &= 1.019\ \pm 0.003\,(\mathrm{stat})\ \pm 0.027\,(\mathrm{syst}), \\
\mathrm{bJSF} &= 1.003\ \pm 0.008\,(\mathrm{stat})\ \pm 0.023\,(\mathrm{syst}), \\
m_{\mathrm{top}}^{\mathrm{dil}} &= 173.79 \pm 0.54\,(\mathrm{stat}) \pm 1.30\,(\mathrm{syst})\ \ \mathrm{GeV}.
\end{aligned}
$$

Combination of channels

- Using BLUE method
- Need to estimate correlations

	$m_{\text{top}}^{\ell+\text{jets}}$	JSF	bJSF	$f_{\text{bkg}}^{\ell+\text{jets},1b}$	$f_{\text{bkg}}^{\ell+\text{jets},2b}$
$m_{\text{top}}^{\ell+\text{jets}}$	1.00				
JSF	–0.36	1.00			
bJSF	–0.89	0.03	1.00		
$f_{\text{bkg}}^{\ell+\text{jets},1b}$	–0.03	–0.01	0.06	1.00	
$f_{\text{bkg}}^{\ell+\text{jets},2b}$	–0.06	–0.09	0.09	0.01	1.00

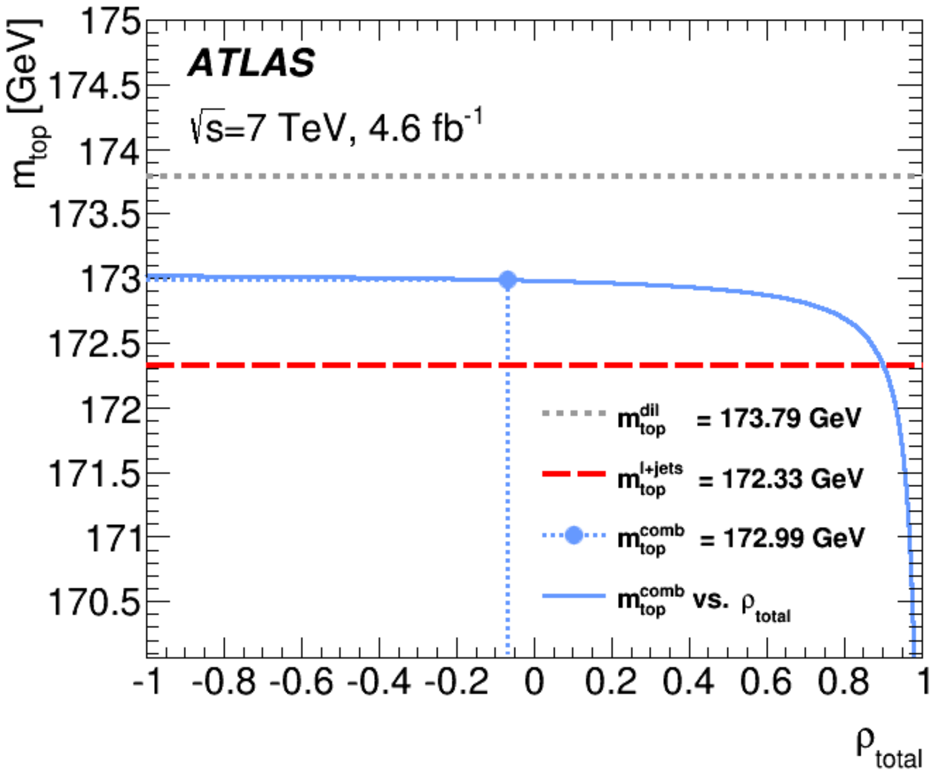
	$m_{\text{top}}^{\text{dil}}$	$f_{\text{bkg}}^{\text{dil},1b}$	$f_{\text{bkg}}^{\text{dil},2b}$
$m_{\text{top}}^{\text{dil}}$	1.00		
$f_{\text{bkg}}^{\text{dil},1b}$	0.07	1.00	
$f_{\text{bkg}}^{\text{dil},2b}$	–0.14	–0.01	1.00

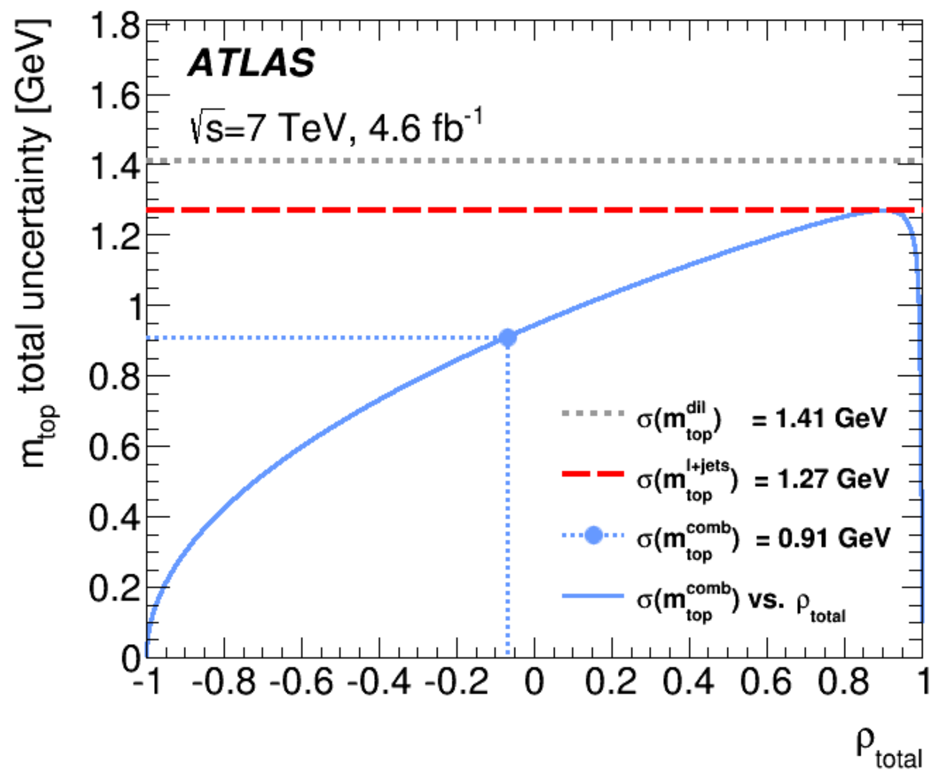
[arXiv:1503.05427]

$$m_{\text{top}}^{\text{comb}} = 172.99 \pm 0.48\,(\text{stat}) \pm 0.78\,(\text{syst})\ \text{GeV} = 172.99 \pm 0.91\ \text{GeV}$$

Study of the correlation assumption

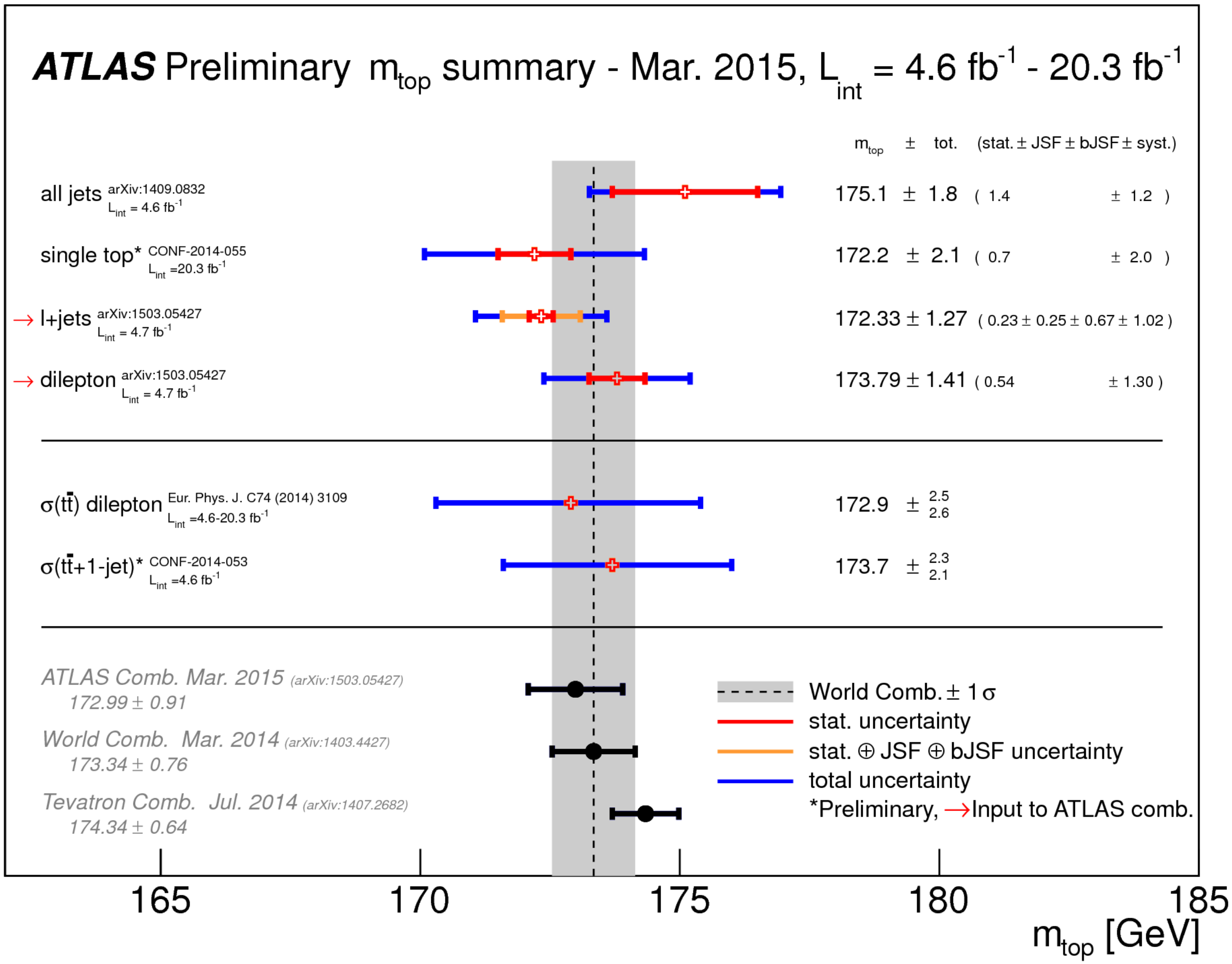
[arXiv:1503.05427]





Top-quark mass

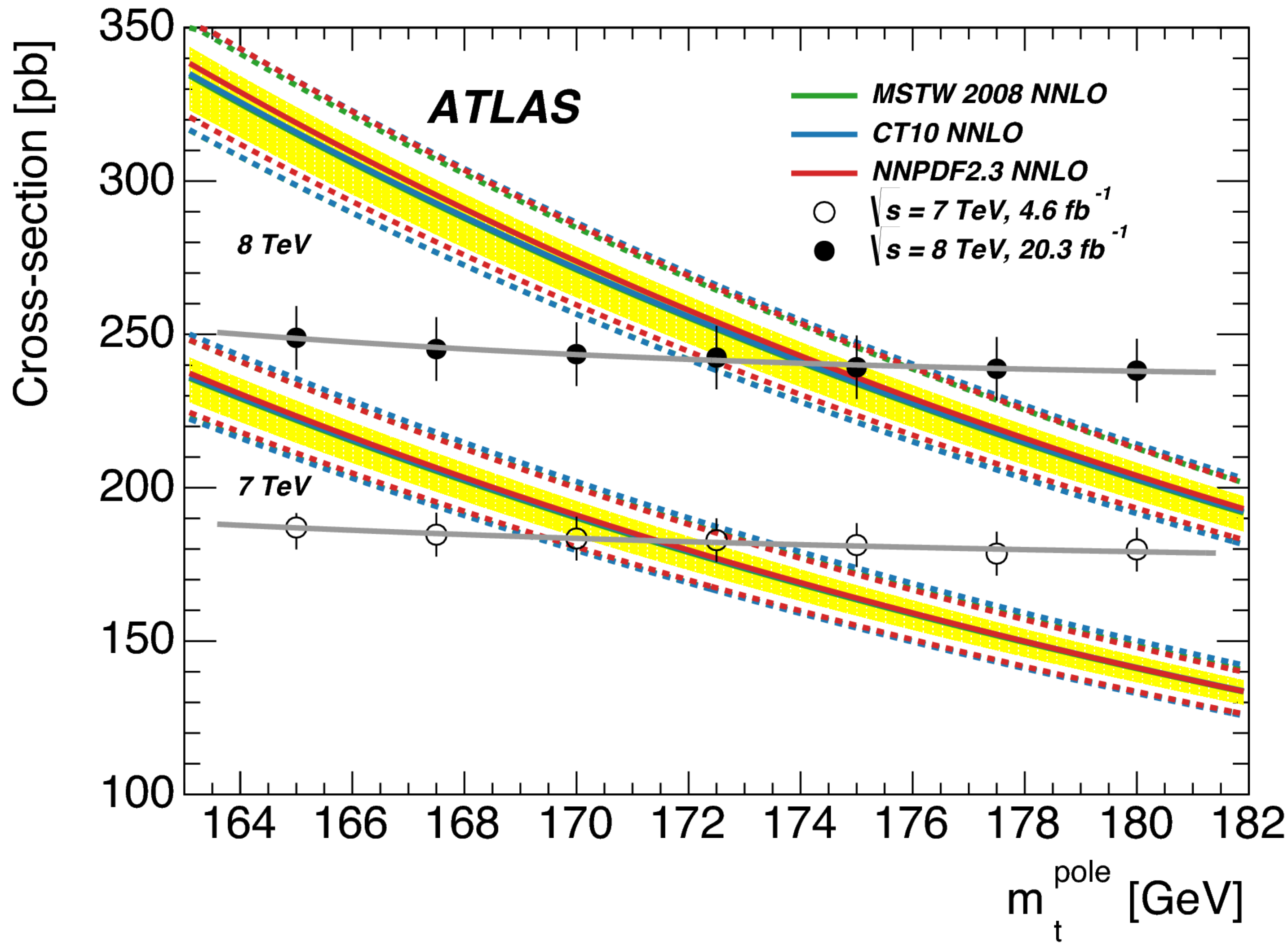
ATLAS summary



Top-quark mass

Measurement from cross section

[arXiv:1406.5375]



W-boson polarization

Physics case

- 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*:

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

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

$$F_R = 0^* \quad \text{(LO)} \rightarrow 0.0017 \pm 0.0001 \quad \text{(NNLO)}$$

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

* assuming m_b=0 GeV

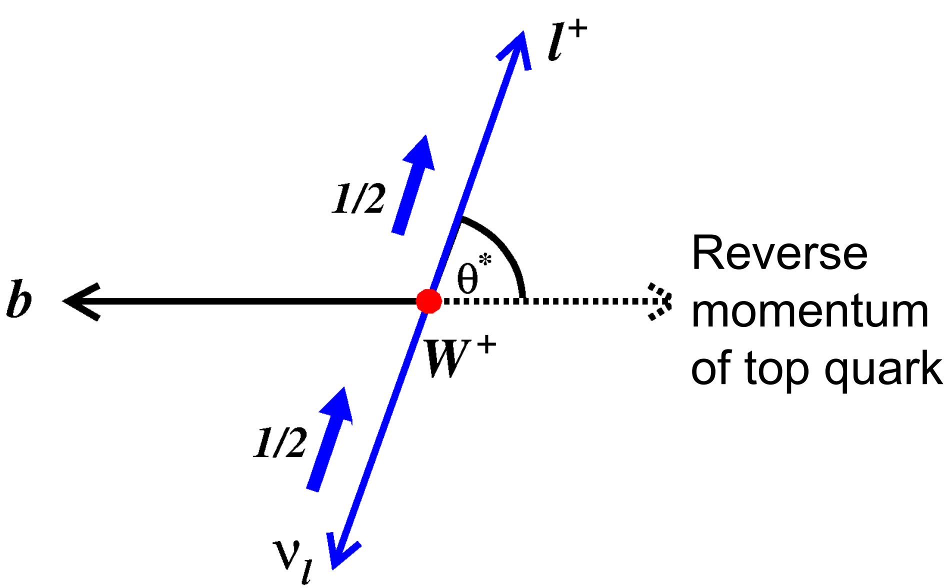
- Helicity fractions are defined by *Wtb* vertex
- Sensitive to BSM effects, e.g. anomalous couplings and additional particles

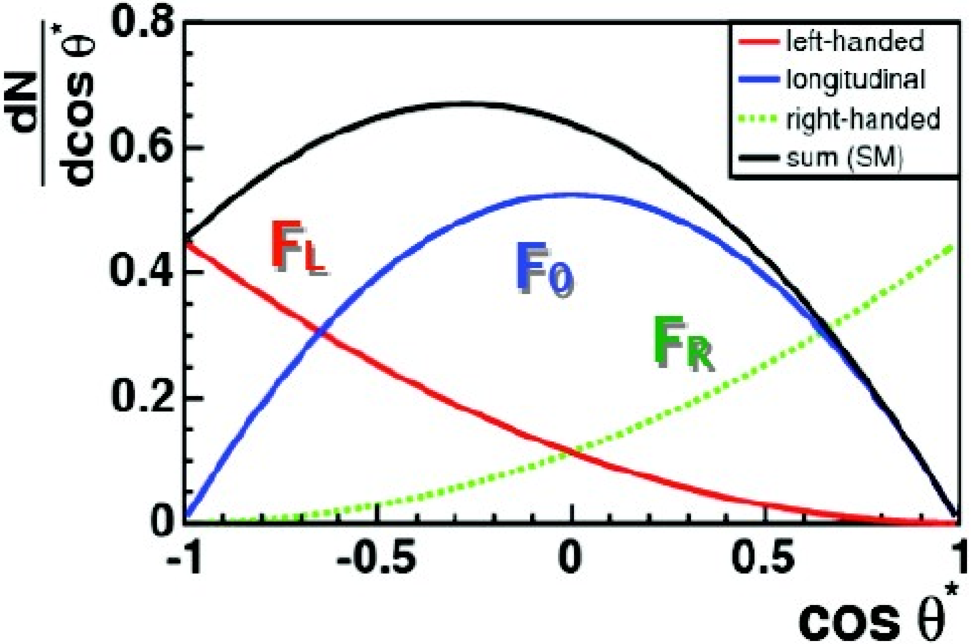
Observables

- 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)





W-boson polarization

CMS measurement

JHEP 10 [(2013) 167]

- Single lepton selection with at least two *b*-tags (5.0 fb^{-1} at 7 TeV)
- Data-driven estimate of W/Z+jets and DY+jets, other sources estimated using simulation
- Signal simulated using MadGraph with PYTHIA, background with MadGraph, POWHEG and PYTHIA
- Reconstruction of final state using a χ^2-based kinematic fit
- Calculation of angle θ* for the lept. and hadr. decaying top quark
- Fit strategy: reweighting events on parton level based on helicity fractions

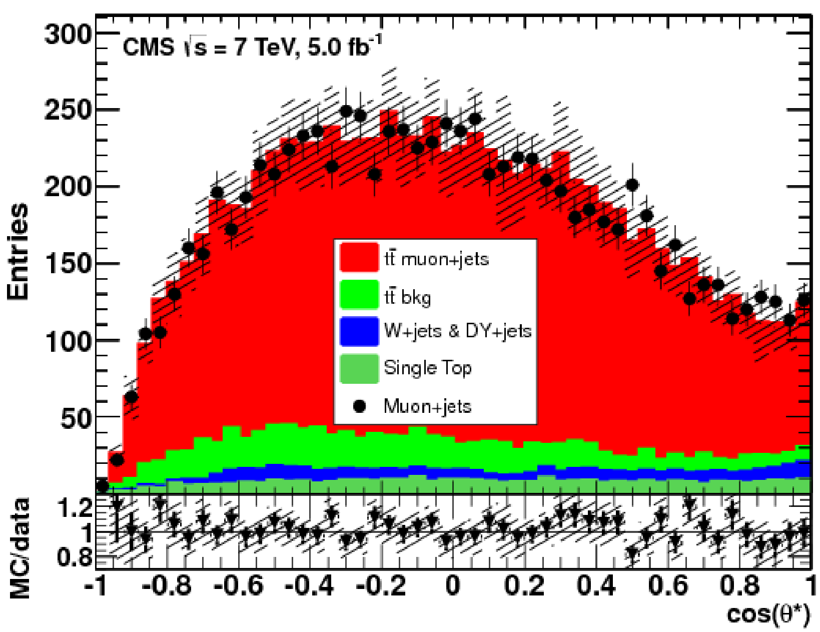
$$W(\cos(\theta^*);F_R,F_L,F_0)=\frac{\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma(F_R,F_L,F_0)}{\mathrm{d}\cos(\theta^*)}}{\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma(F_R^{\mathrm{SM}},F_L^{\mathrm{SM}},F_0^{\mathrm{SM}})}{\mathrm{d}\cos(\theta^*)}}$$

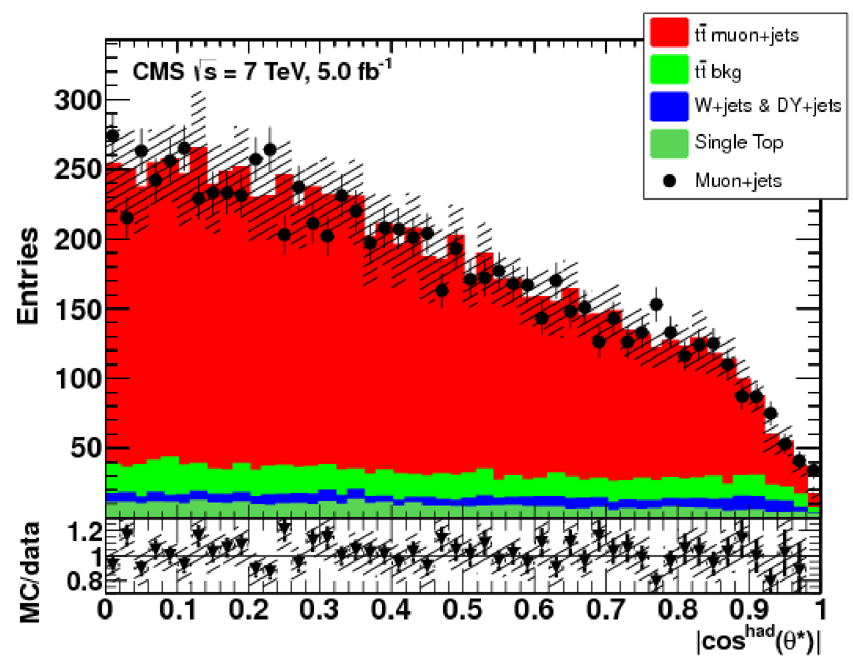
W-boson polarization

CMS measurement

JHEP 10 [(2013) 167]

- Binned likelihood fit to the data:
  - "3D" fit: Signal normalization F_{tt}, F_0 and F_L
  - "2D" fit: Signal normalization F_{tt} and F_0 (assume F_R = 0, include hadr. side)





W-boson polarization

JHEP 10 [(2013) 167]

Results:

- Best fit and uncertainties:

3D:

$$F_0 = 0.682 \pm 0.030\,(\text{stat}) \pm 0.033\,(\text{syst})$$
$$F_L = 0.310 \pm 0.022\,(\text{stat}) \pm 0.022\,(\text{syst})$$
$$F_R = 0.008 \pm 0.012\,(\text{stat}) \pm 0.014\,(\text{syst})$$
$$\rho_{0L} = -0.95$$

2D:

$$F_0 = 0.685 \pm 0.017\,(\text{stat}) \pm 0.021\,(\text{syst})$$
$$F_L = 0.315 \pm 0.017\,(\text{stat}) \pm 0.021\,(\text{syst})$$

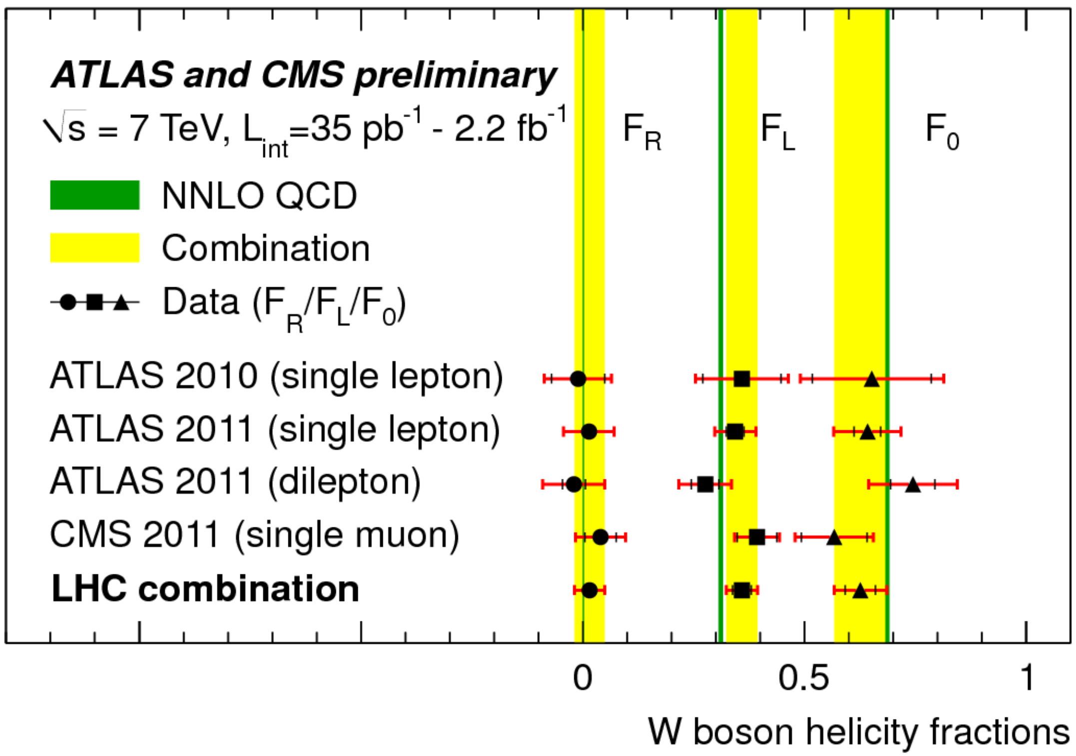
- Important sources of syst. uncertainty for F_0 (F_L):
  - MC statistics ~ 0.016 (0.012)
  - Top-quark mass~ 0.016 (0.011)
  - Signal modeling~ 0.014 (0.013)

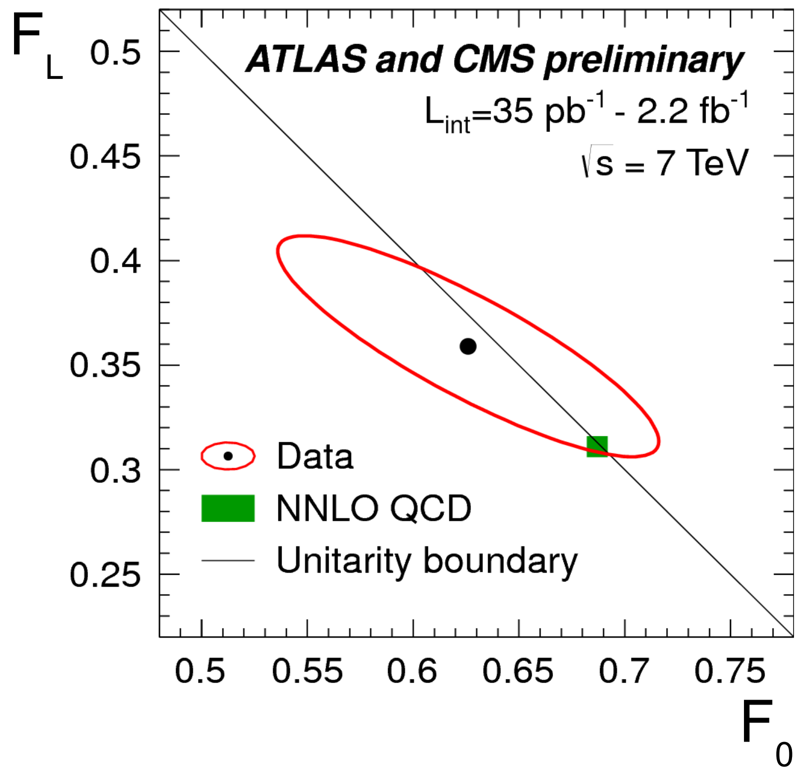
W-boson polarization

Combination

- ATLAS and CMS combination

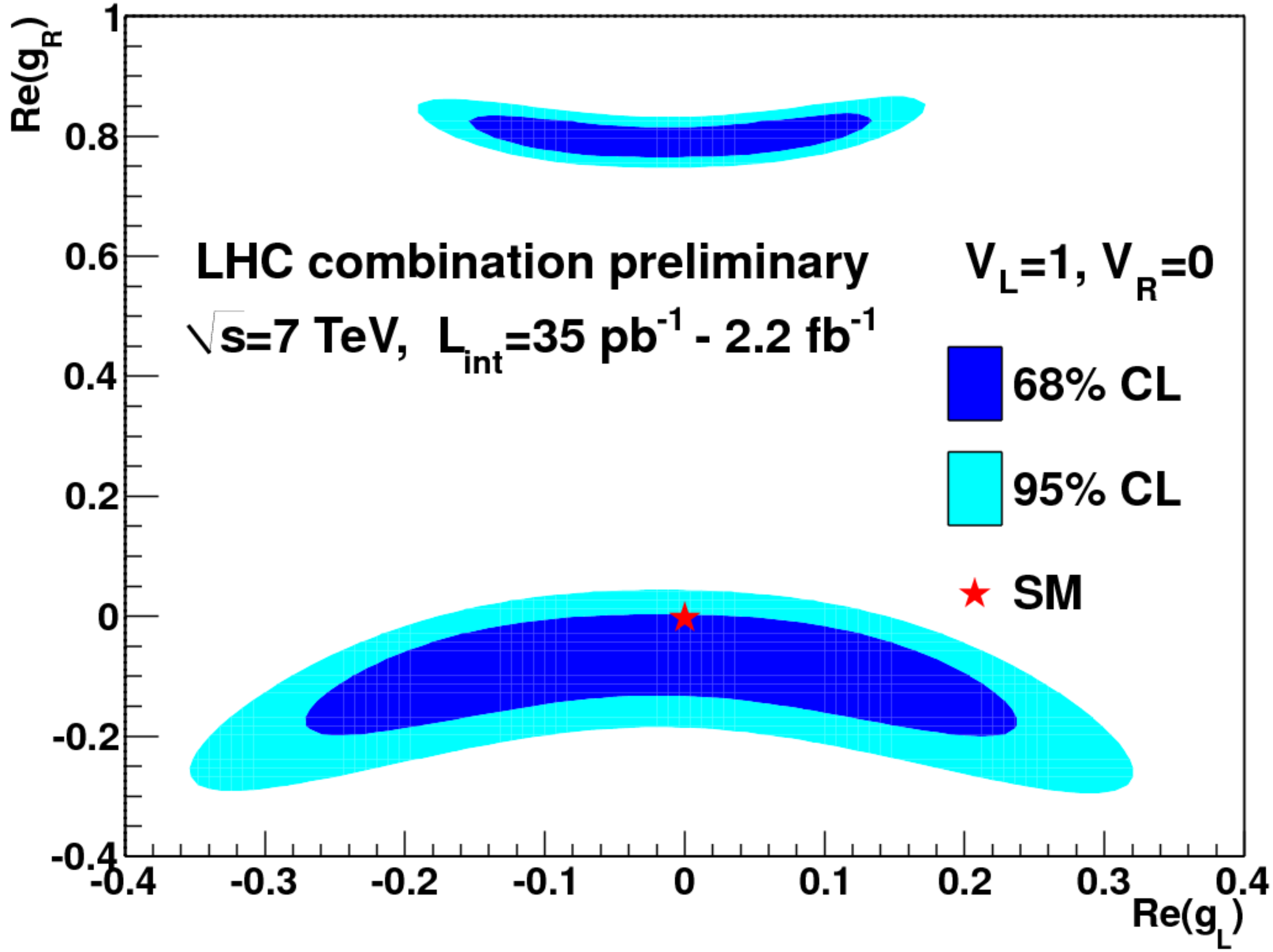
[ATLAS-CONF-2013-033, CMS PAS TOP-12-025]





Interpretation

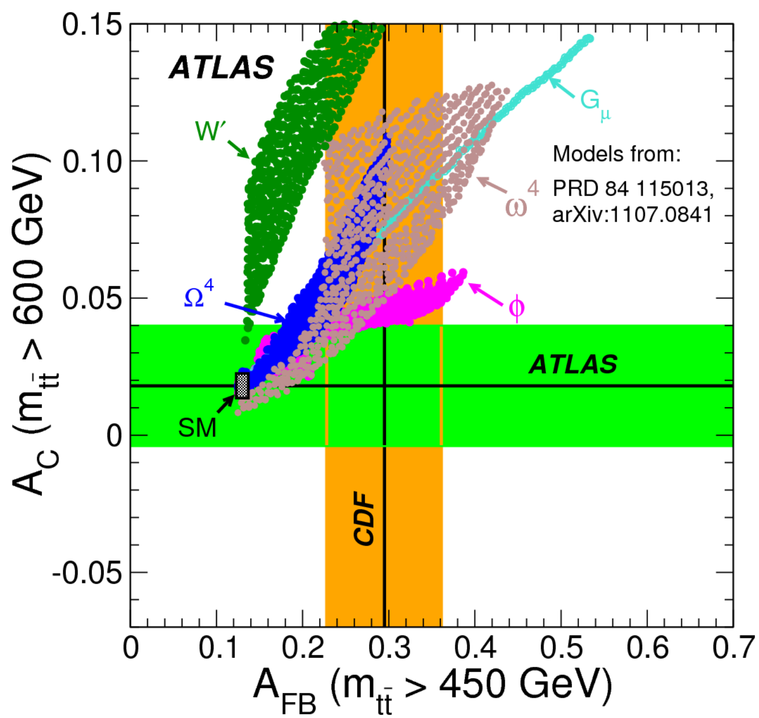
[ATLAS-CONF-2013-033, CMS PAS TOP-12-025]

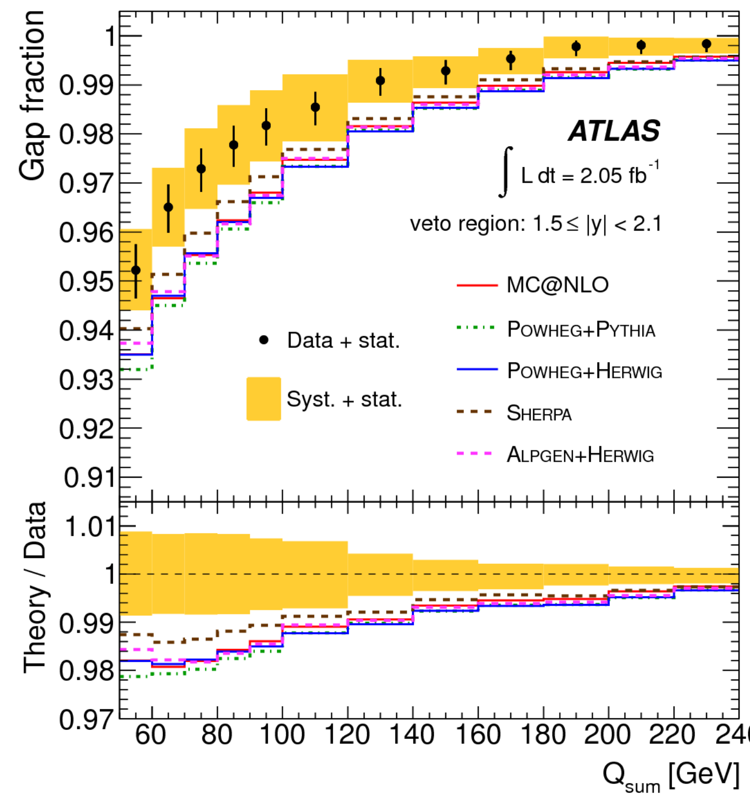


Issues for discussion

Things that are being discussed

- Top-quark pair modeling, e.g. gap fraction, pT of top quark
- Top-quark definition, e.g. stable particle, unfolding
- Top-mass definition, e.g. scheme dependence, MC mass
- Charge asymmetry CDF vs. LHC





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
- LHC: top-quark factory, ATLAS and CMS: paper factories (more than 70 publications (ATLAS+CMS), even more notes)
- Current focus: finish 8 TeV analyses and prepare for 13 TeV run