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From Discoveries to Precision Physics:
20 Years of Top Quark Physics

MPP Colloquium
Max-Planck-Institut für Physik, München, March 17, 2015

Ulrich Husemann
Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology

Discovery

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Physicist = Treasure Hunter

How good is “good enough”?

Discovery

Precision

Physicist = Horologist
Every detail matters.

[R. Baumgarten]

Physicist = Treasure Hunter
How good is “good enough”?

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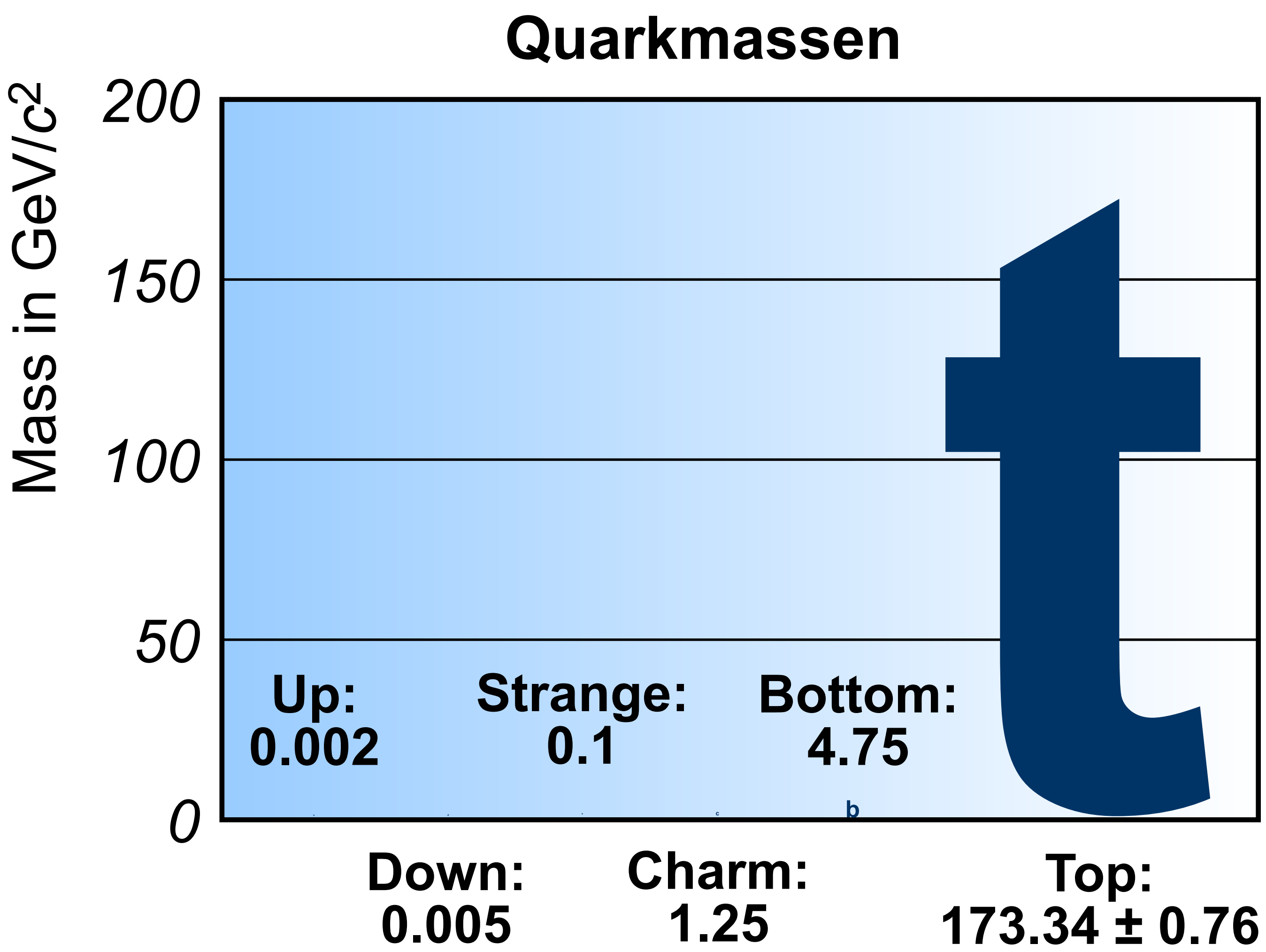
Masses of Elementary Particles



- Fermion masses via **Yukawa coupling** to Higgs field
- Six quarks of the standard model: **vastly different masses**, individual mass values unexplained
- Top quark sticks out: about **40 times heavier** than bottom quark

Top Quark Properties?
Role in Electroweak Symmetry Breaking?

Top – The Special One

The Special One?
[Pick n stick Ltd]

The Special One!

- Large mass: $m_t \approx 173$ GeV
  - Close to scale of **electroweak symmetry breaking**
  - Lagrangian for top Yukawa coupling
    (v ≈ 246 GeV: Higgs vacuum expectation value)

$$\mathcal{L}_{Y,t} = y_t \frac{v}{\sqrt{2}} \bar{t}_L t_R \equiv m_t \bar{t}_L t_R$$

→ $y_t \approx 1$: the only **“normal quark”**?

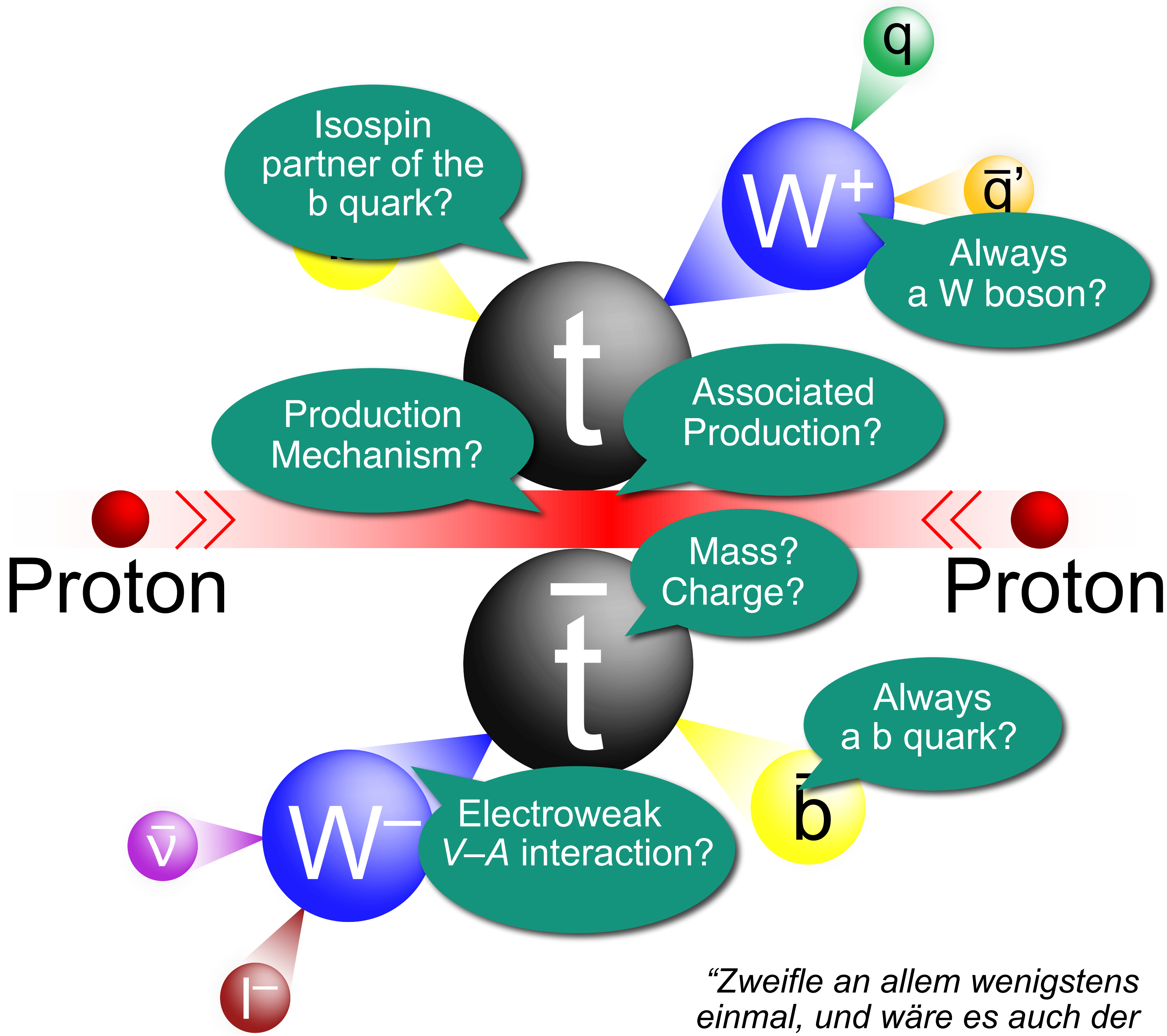
- Top – the only **“free” quark**:
  life time much smaller than hadronization time

$$\tau = \frac{1}{\Gamma} \approx (1.5\,\text{GeV})^{-1} < \frac{1}{\Lambda_{\text{QCD}}} \approx (0.2\,\text{GeV})^{-1}$$

→ (almost) no bound states
→ spin transferred to decay products

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Questions in Top Quarks Physics



"Zweifle an allem wenigstens einmal, und wäre es auch der Satz: zwei mal zwei ist vier"
(G. F. Lichtenberg)

Outline

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The Road to the Top

Top Quark Production

Top + "Something Else"

Top Properties & New Physics

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Outline

Karlsruher Institut für Technologie

The Road to the Top: A Brief History of Top Quark Physics

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

The Road to the Top

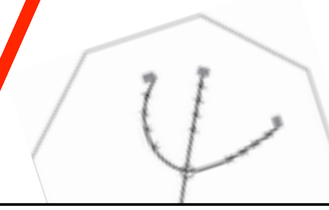
GIM mechanism: a fourth quark is required

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

J/ψ discovery: the fourth quark is found



CKM matrix: CP violation only with three generations

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

CP-Violation in the Renormalizable Theory of Weak Interaction

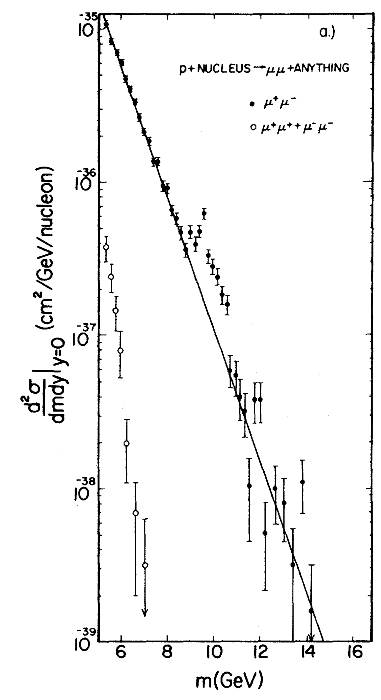
Makoto Kobayashi and Toshihide Maskawa
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

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

Υ discovery: the first quark of the third generation

LETTERS 1 August 1977

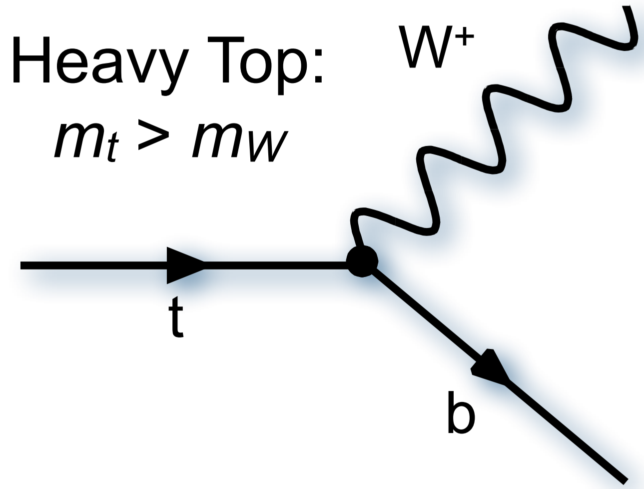


1970 — 1973 — 1974 — 1977

The Road to the Top

PETRA (DESY): e^+e^-, $\sqrt{s} \leq 45$ GeV
$m_t > 23$ GeV/c^2

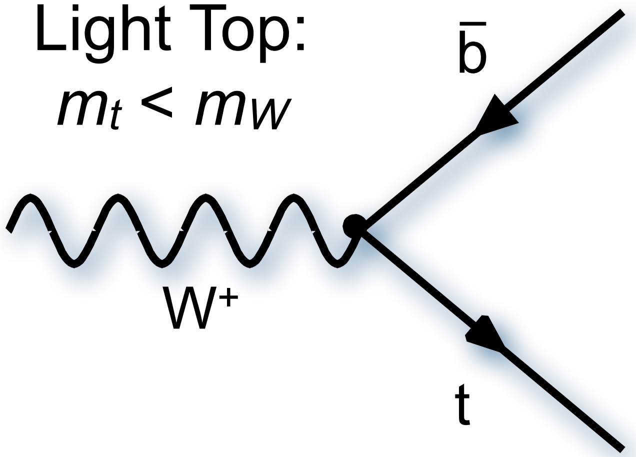
Heavy Top:
$m_t > m_W$



Sp$\bar{\text{p}}$S (CERN): p$\bar{\text{p}}$, $\sqrt{s} \leq 630$ GeV
$m_t > 70$ GeV/c^2

CDF Run 0 (FNAL)
$m_t > 70$ GeV/c^2

Light Top:
$m_t < m_W$



LEP I (CERN): e^+e^-, $\sqrt{s} = 90$ GeV
$m_t = 173$ GeV/c^2 (EW fit)

Tevatron Run I:
Discovery

Lepton Colliders | Hadron Colliders

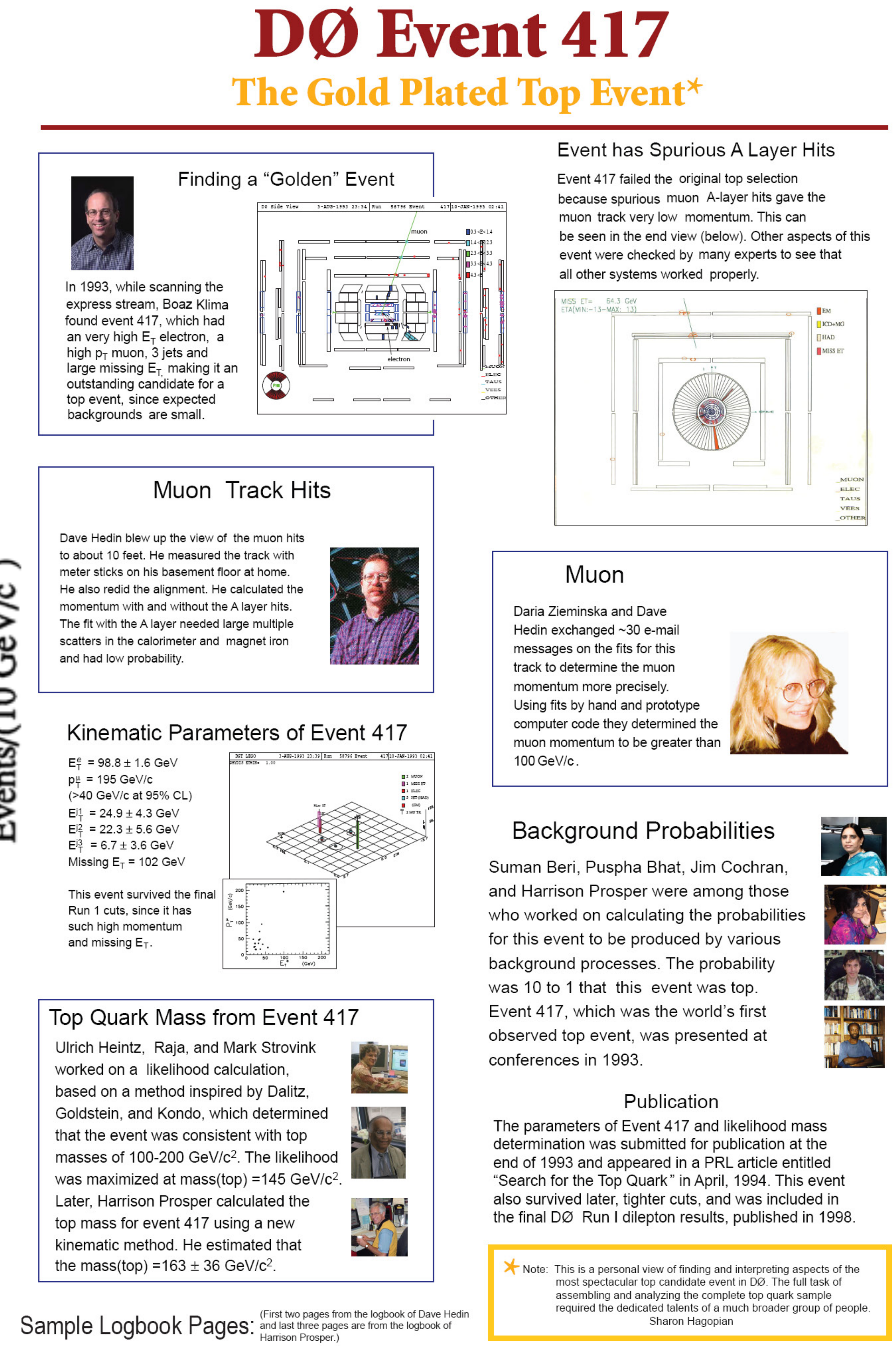
1979 — 1985 — 1990 — 1992 — 1995

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

The Last Mile

- 1992: **Tevatron Run I** starts
- January 1993: "Event 417" (DØ)
- August 1993: **Evidence** for top (CDF, published September 1994)
- March 2, 1995: **Discovery** officially announced (CDF, DØ)

Events/(10 GeV/c^2)



[http://home.fnal.gov/~klima]

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Institut für Experimentelle Kernphysik (IEKP)

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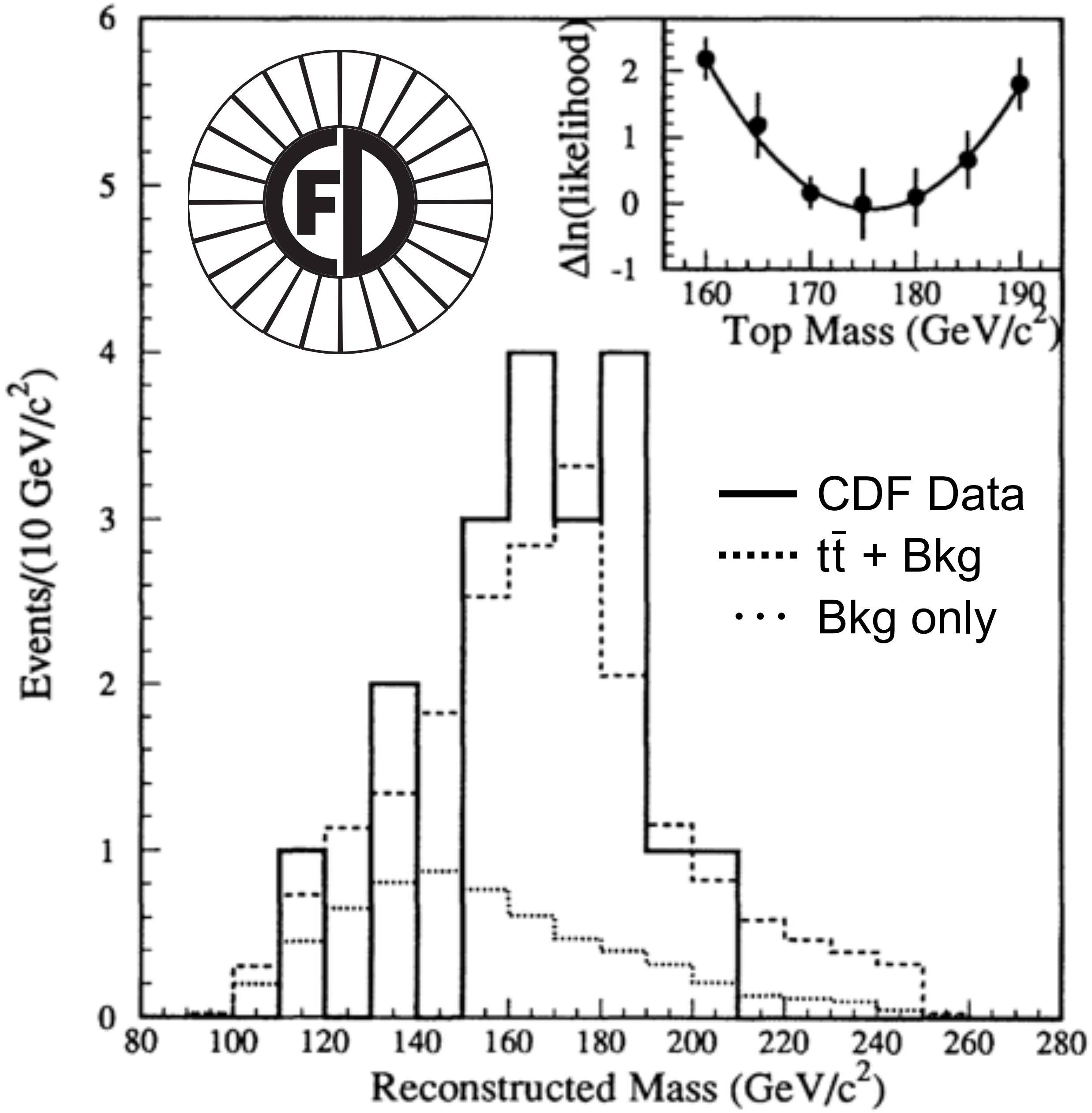
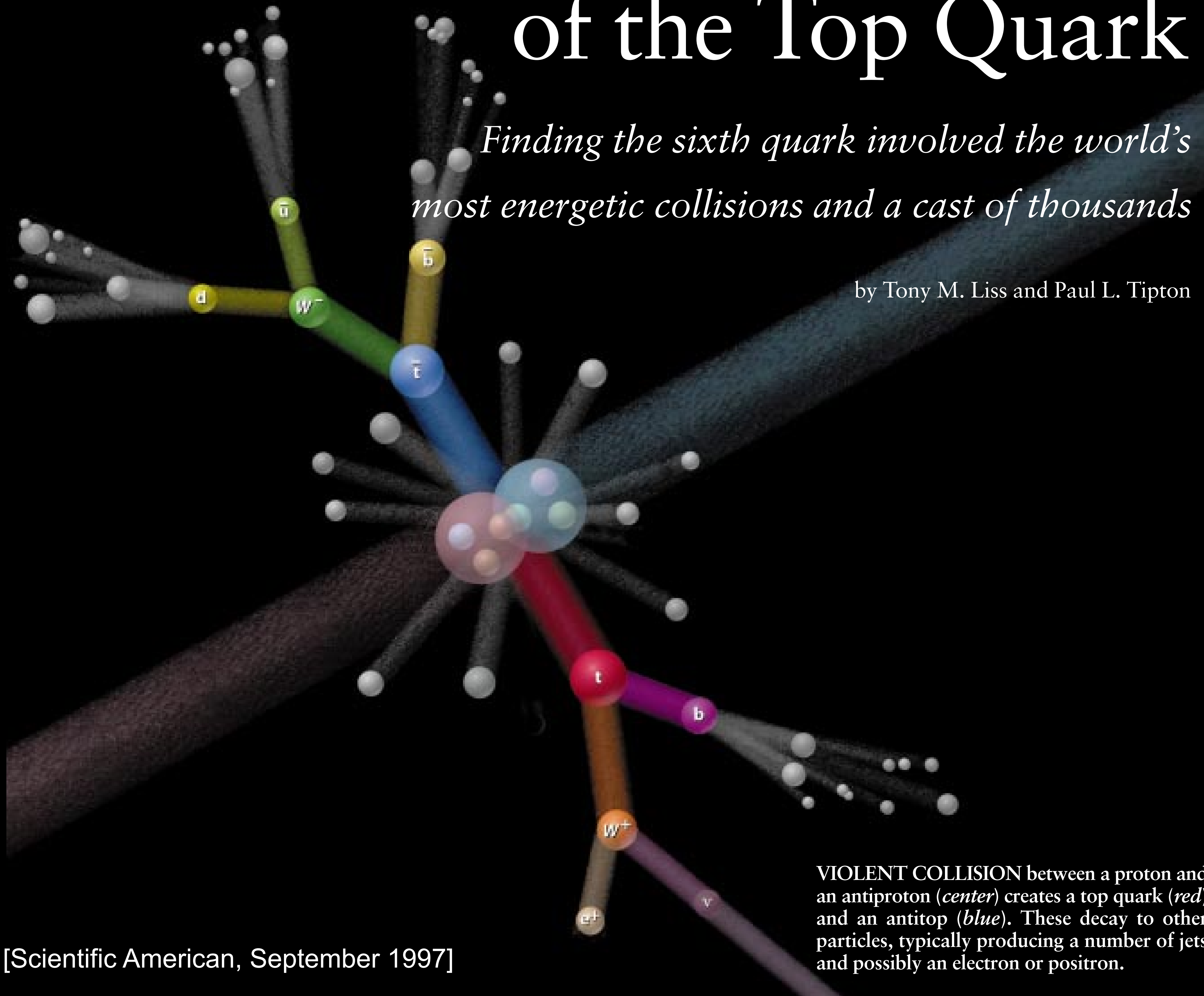


[PRL 74 (1995) 2626]

The Discovery of the Top Quark

Finding the sixth quark involved the world's most energetic collisions and a cast of thousands

by Tony M. Liss and Paul L. Tipton



VIOLENT COLLISION between a proton and an antiproton (*center*) creates a top quark (*red*) and an antitop (*blue*). These decay to other particles, typically producing a number of jets and possibly an electron or positron.

[Scientific American, September 1997]

Top Turns Ten

- 2001: **Tevatron Run II** starts
  → improved detectors, new ideas
- 2008: top mass known to **better than 1% precision**
- 2009: first observation of **single top quark** production
- 2010: **LHC Run I** starts → first top quarks in Europe (ATLAS, CMS)

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Institut für Experimentelle Kernphysik (IEKP)

Top Turns ~~Ten~~ Twenty!

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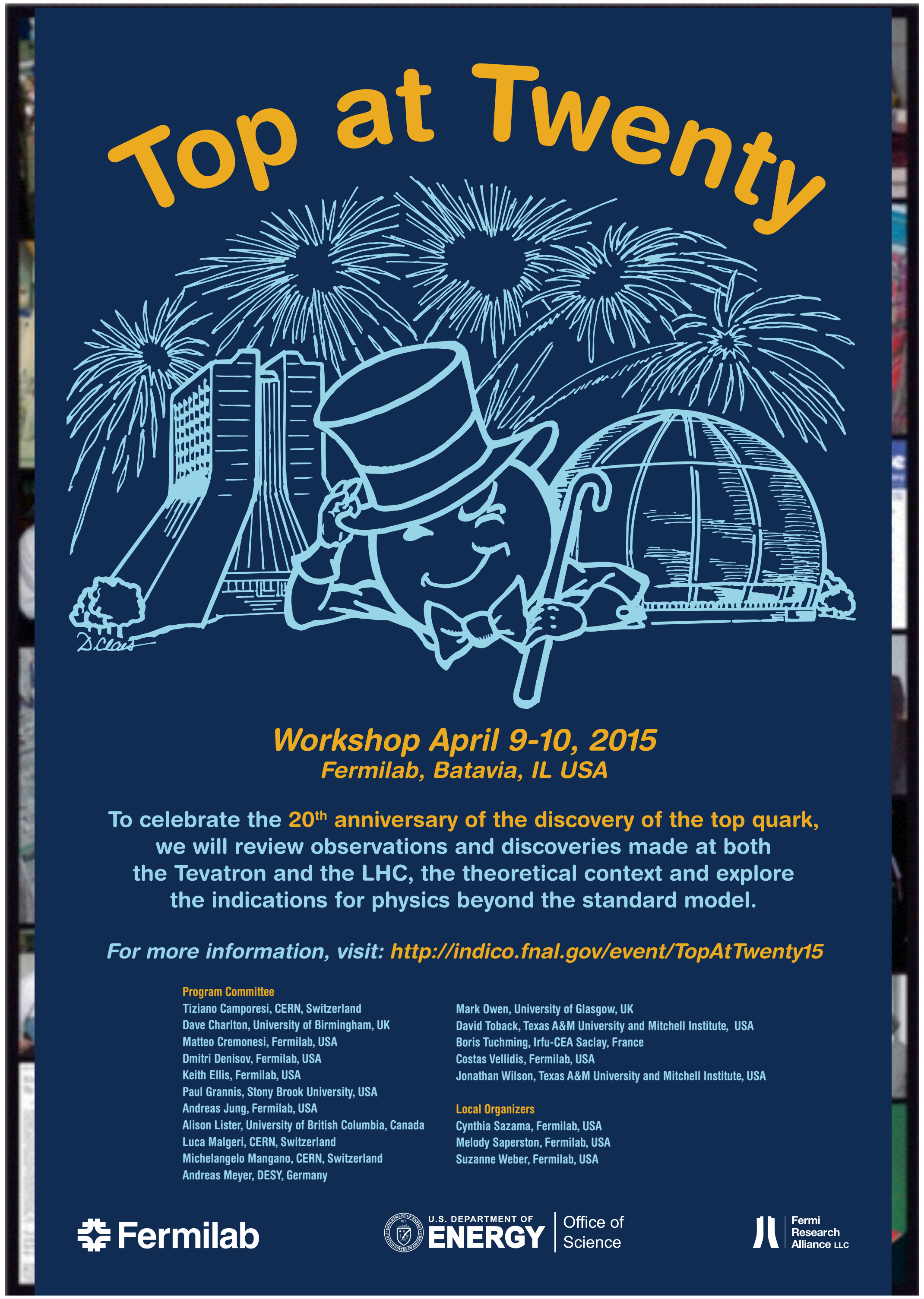

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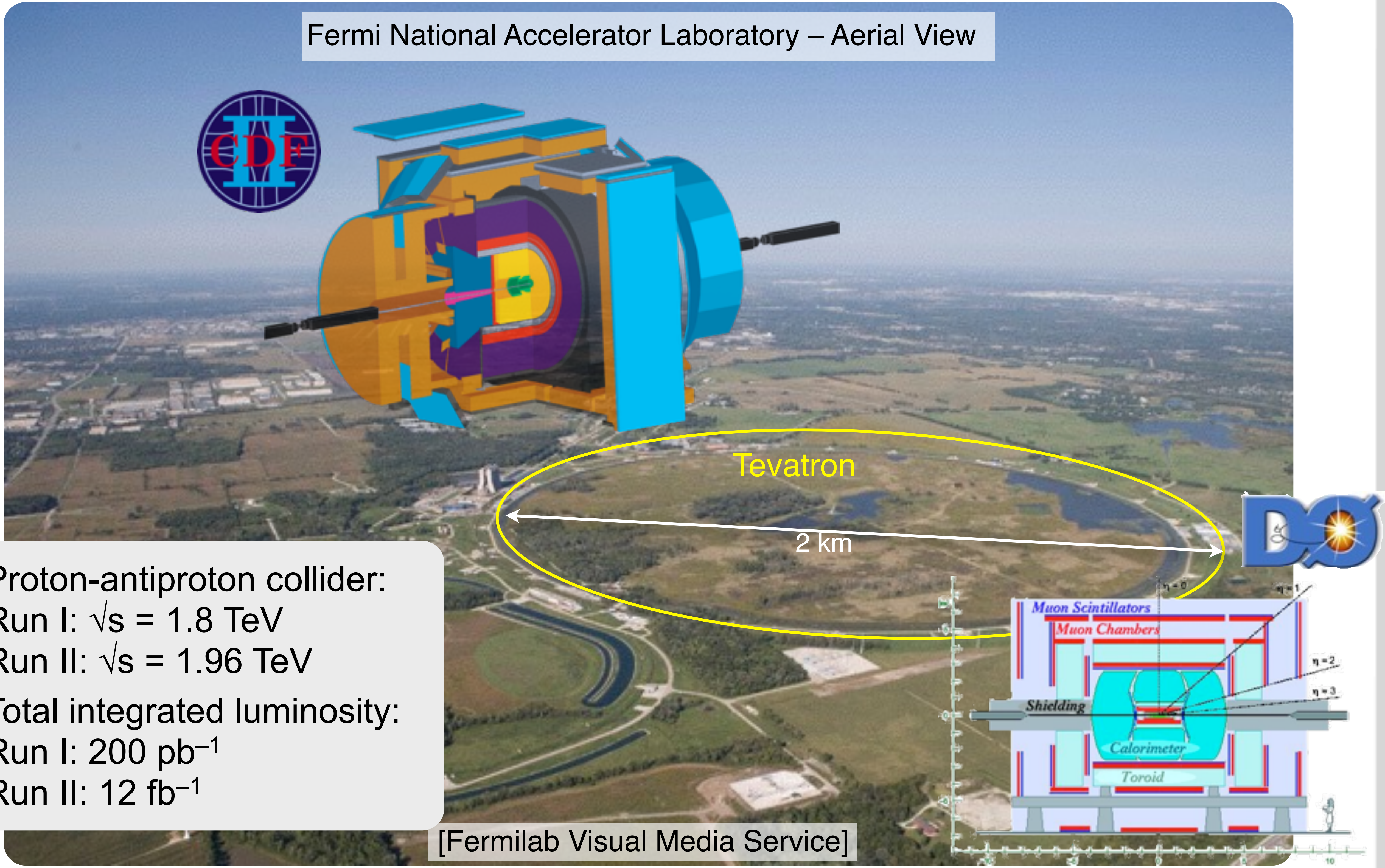
Fermilab Tevatron: 1985–2011



- Proton-antiproton collider:
  Run I: $\sqrt{s}$ = 1.8 TeV
  Run II: $\sqrt{s}$ = 1.96 TeV
- Total integrated luminosity:
  Run I: 200 pb^{-1}
  Run II: 12 fb^{-1}

[Fermilab Visual Media Service]

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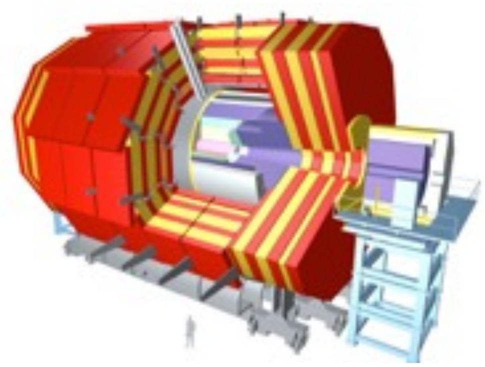
Institut für Experimentelle Kernphysik (IEKP)

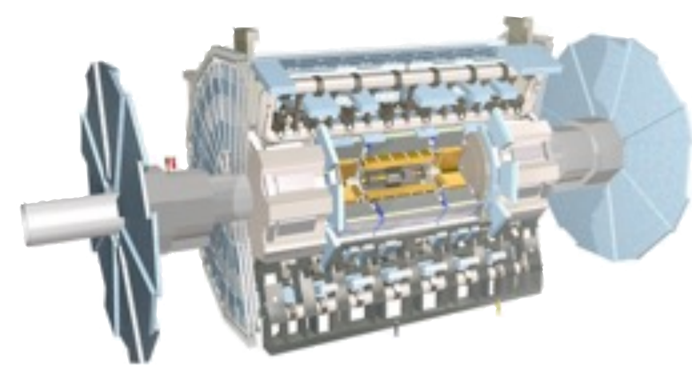
LHC – the Large Hadron Collider

CMS Experiment



- Proton-proton collider
- LHC Run I: 2010–2013
  - 2010/2011: approx. 5 fb^{-1} at $\sqrt{s}$ = 7 TeV
  - 2012: approx. 20 fb^{-1} at $\sqrt{s}$ = 8 TeV
- LHC Run II: from 2015, $\sqrt{s}$ = 13-14 TeV

ATLAS Experiment



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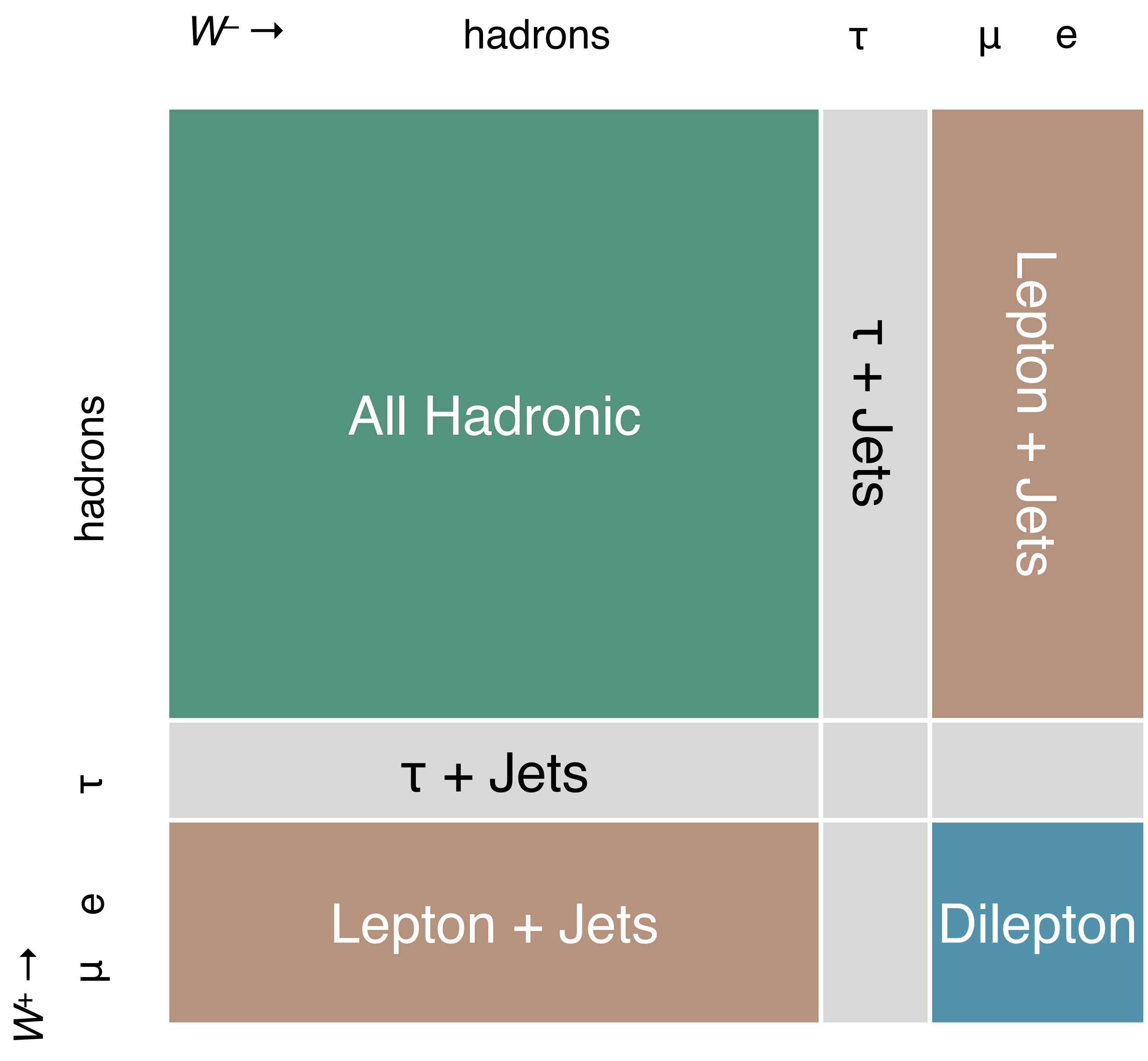
Analyzing Top Quark Events



- Top decay in the standard model: **B(t → Wb) ≈ 100%**
- $t\bar{t}$ decay signatures characterized by **W decays**:
  - **All-Hadronic**: 45% of all decays, large QCD background
  - **Lepton+Jets**: 30% of all decays, moderate backgrounds
  - **Dilepton**: 5% of all decays, very clean, but small branching fraction
- **Challenging** signature: multiple leptons & (b-)jets, missing transverse energy

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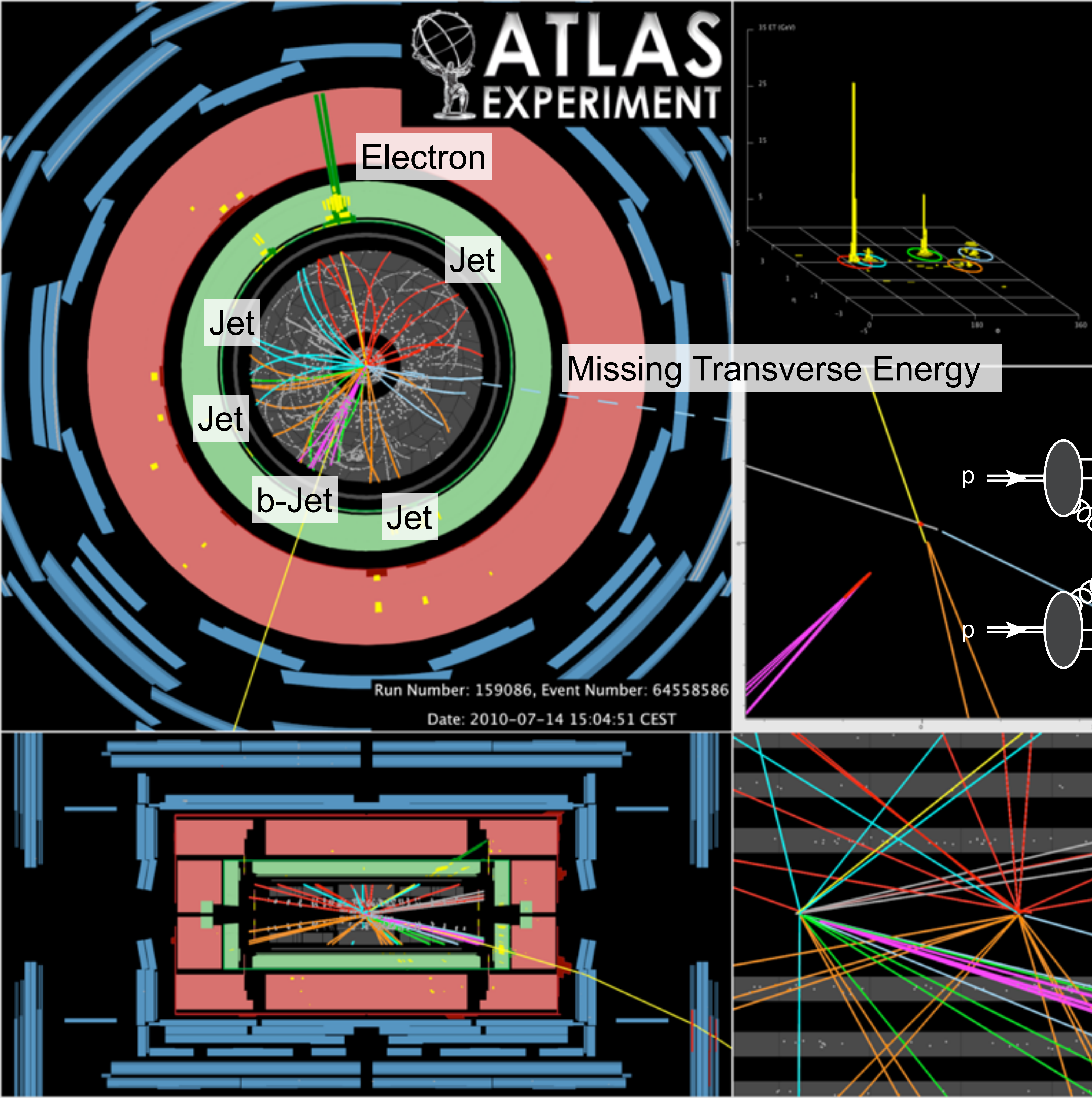

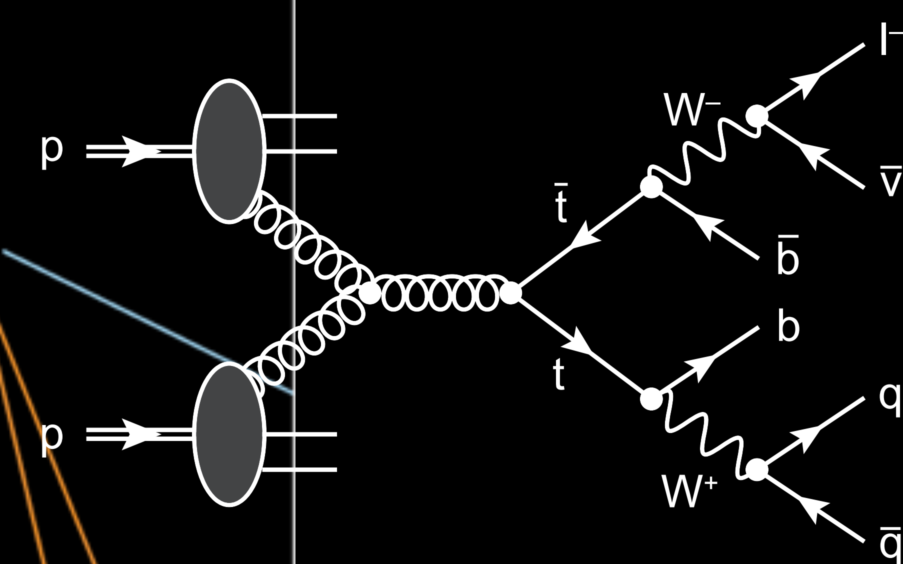

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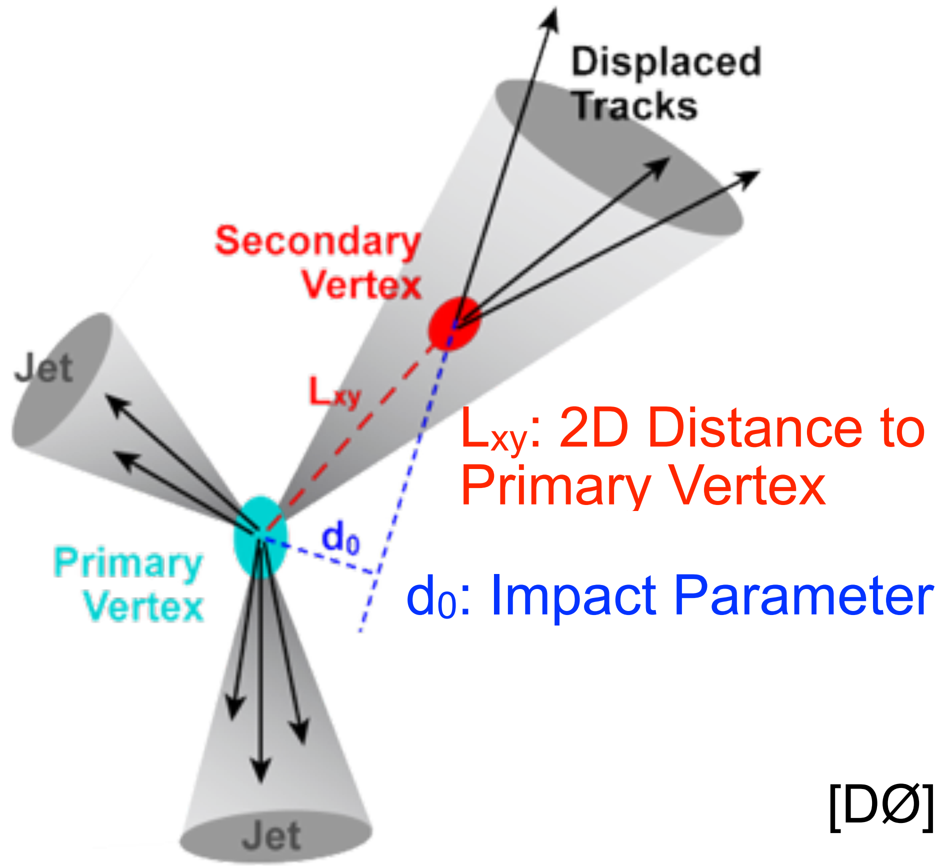
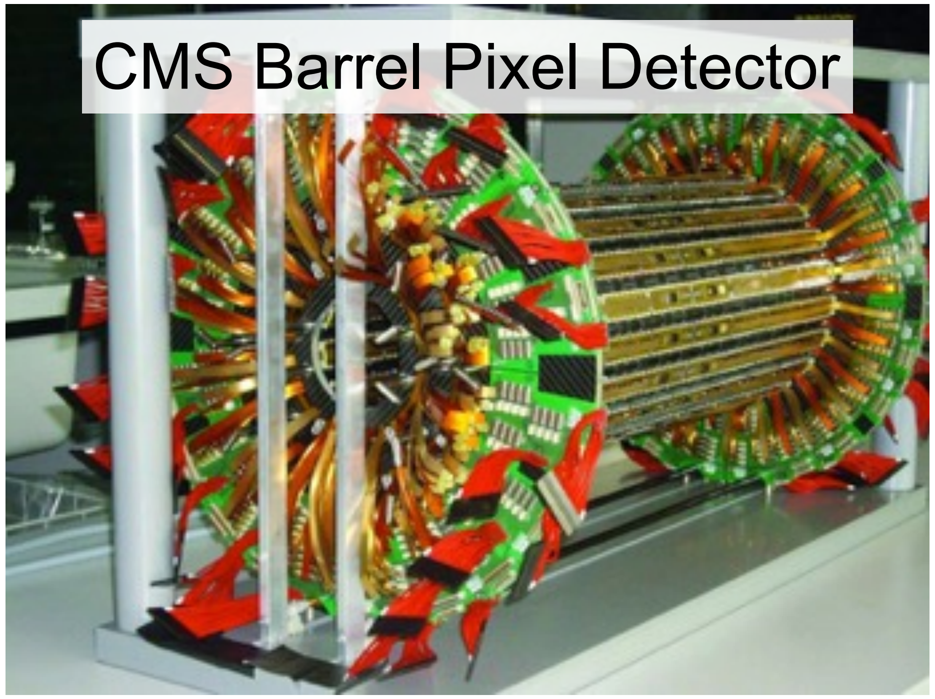
Key Technology: Vertex Detectors

- Reconstruction of top quark signatures requires **entire detector**
- Important experimental technique: identification of **jets with B-hadrons**, (mainly) based on long B-hadron lifetimes → **b-tagging**
- Most important detector technology for b-tagging: **vertex detectors**
  - UA2 experiment (Sp$\bar{p}$S): silicon pad detector on beam pipe
  - Tevatron experiments: silicon **microstrip vertex detectors**
  - LHC experiments: silicon **pixel** and **strip** detectors





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From the Tevatron to the LHC

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	Authors	Silicon Detectors	Tops Produced (per Experiment)	Tops Reconstructed (Lepton+Jets, 1 b-Tag)
Tevatron Run I	400	0.7 m^2 46k Channels	1200	25 Discovery
Tevatron Run II	600	6 m^2 720k Channels	70.000	2000
LHC Run I	2500	200 m^2 75M Channels	6 million	150.000
LHC Run II			*50–100 million/ year*	

LHC: Top Factory
Excellent Detectors – Unprecedented Statistics

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Top Quark Production: The Race for Ultimate Precision

Top Production Cross Section

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- **Master formula** for cross section measurements:

$$\sigma = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{\epsilon \int L \mathrm{d}t}$$

- Challenges for **experiment**
  - N_{bkg}: best possible determination of **background** rate
  - $\int L\mathrm{d}t$: most precise measurement of integrated **luminosity**
  - ε: best possible **modeling of detector geometry**, excellent **calibration**
- Challenges for **theory**
  - σ: most accurate cross section calculation to compare with measurement
  - ε: best possible **modeling of signal efficiency**

Top Quark-Antiquark Production

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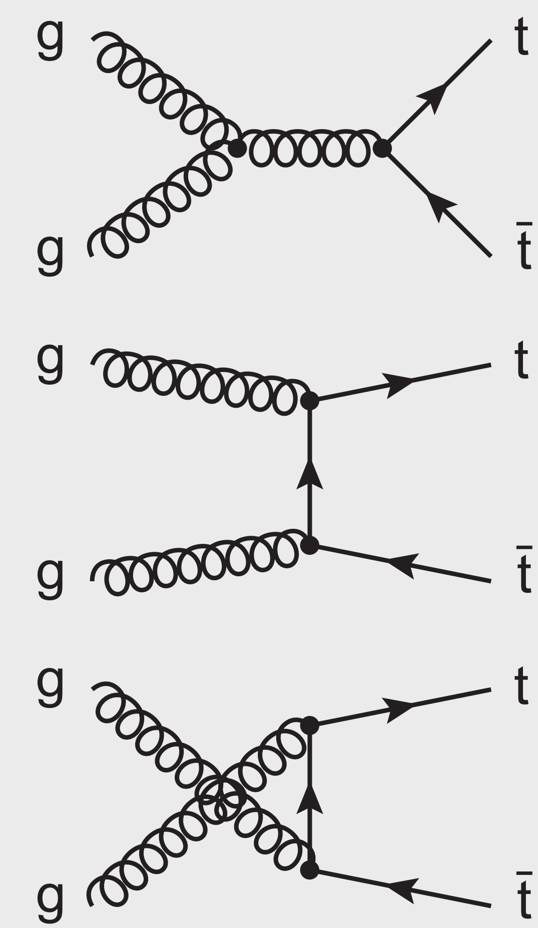
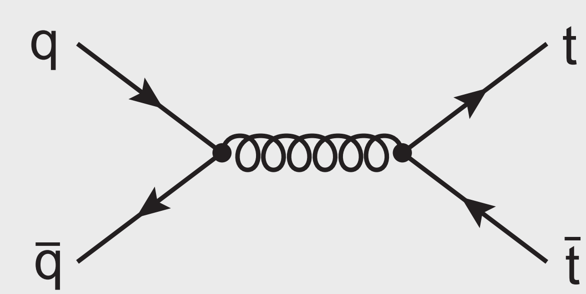
- Typical **heavy quark production** process
  - Quantum chromodynamics (QCD)
  - Gluon fusion and $q\bar{q}$ annihilation
- Theoretical calculations
  - Leading order QCD by far not sufficient, **large corrections**
  - Types of corrections: **higher orders** in α_S, **resummation** of large logarithms
  - State of the art (Czakon, Fiedler, Mitov, 2013): **NNLO + NNLL** (next-to-next-to-leading order and next-to-next-to-leading logarithms)

Gluon-Gluon-Fusion (LHC: 80–90%)



Quark-Antiquark-Annihilation (LHC: 20–10%)



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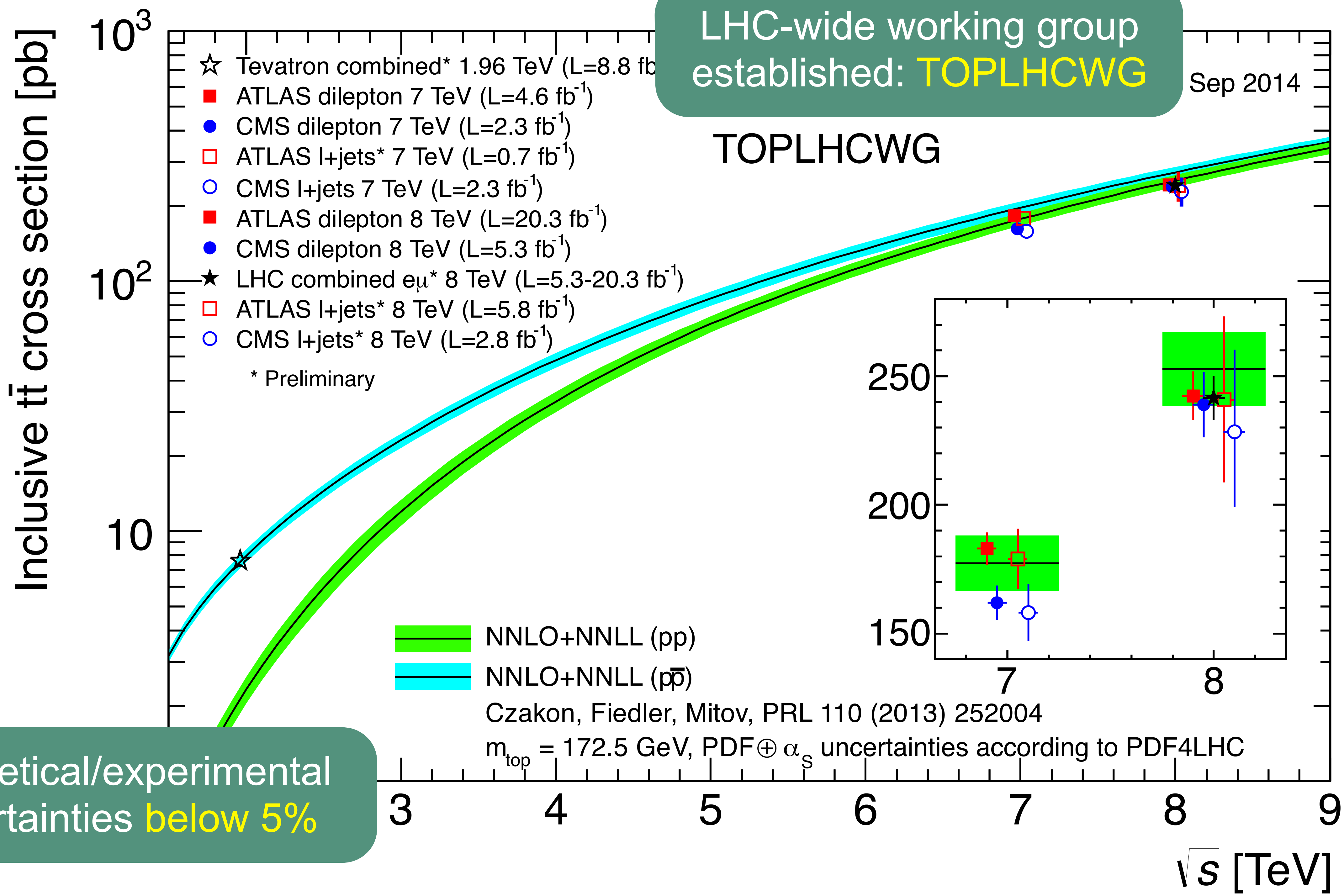
Top Pair Production: Summary

LHC-wide working group established: TOPLHCWG



Theoretical/experimental uncertainties below 5%

[https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures]

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Electroweak Single Top Production

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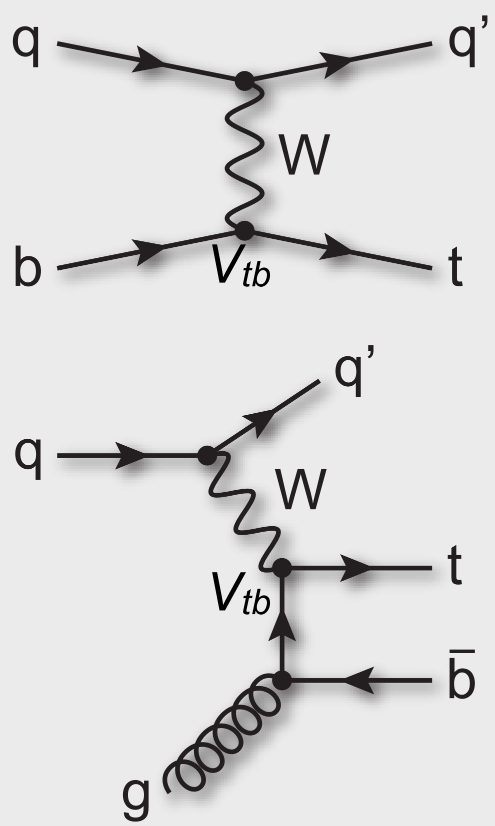
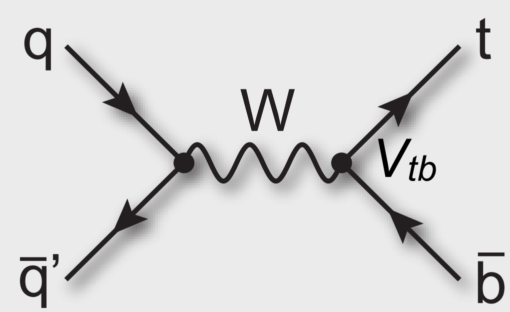
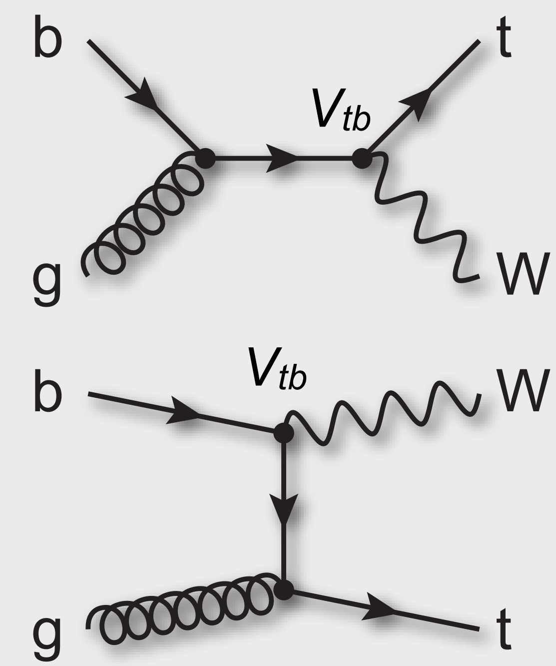
t channel



s channel



associated Wt production



- **Direct** measurement of CKM matrix element $|V_{tb}|$
- Production via W boson exchange: **100% polarized** top quarks
- **PDF constraints** via $t/\bar{t}$ charge ratio
- Access to **BSM physics** (e.g. anomalous couplings)

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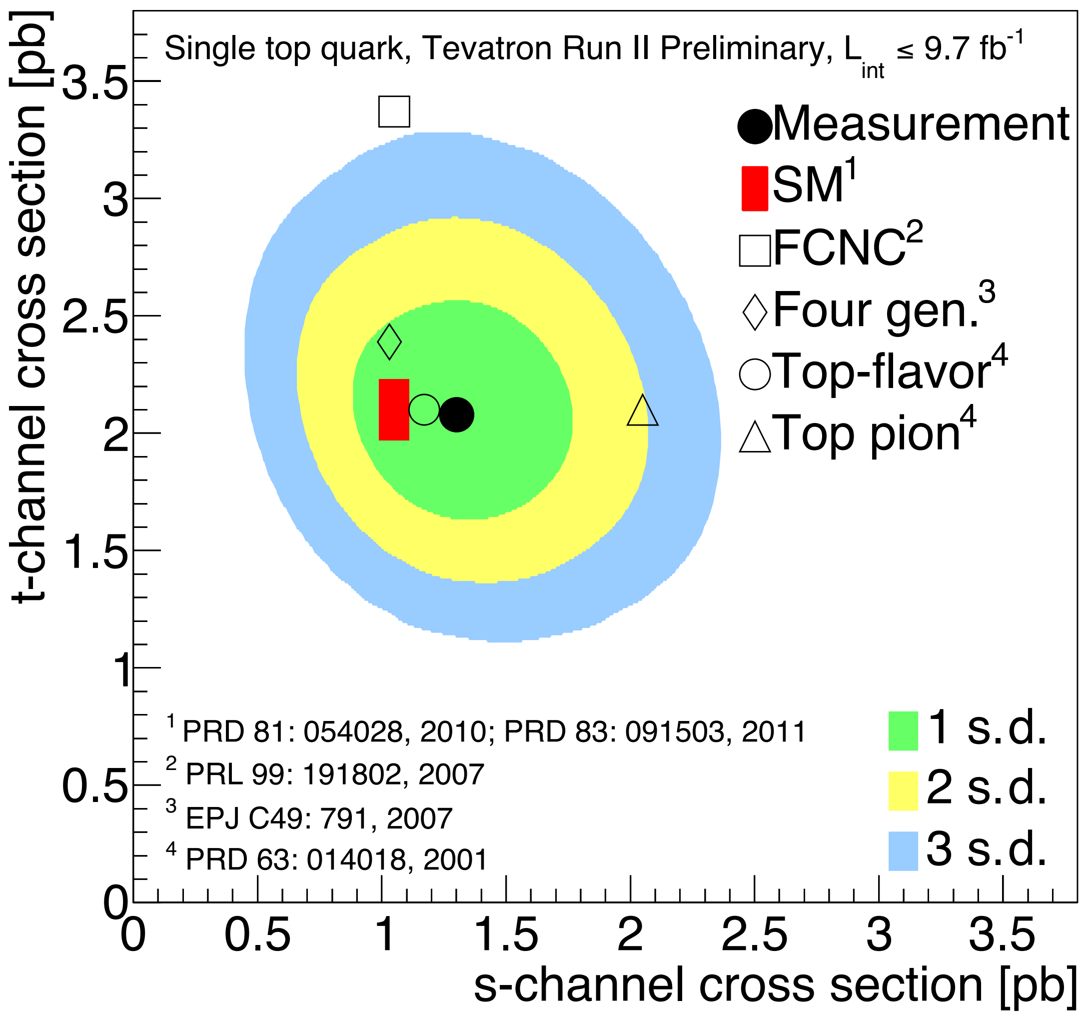
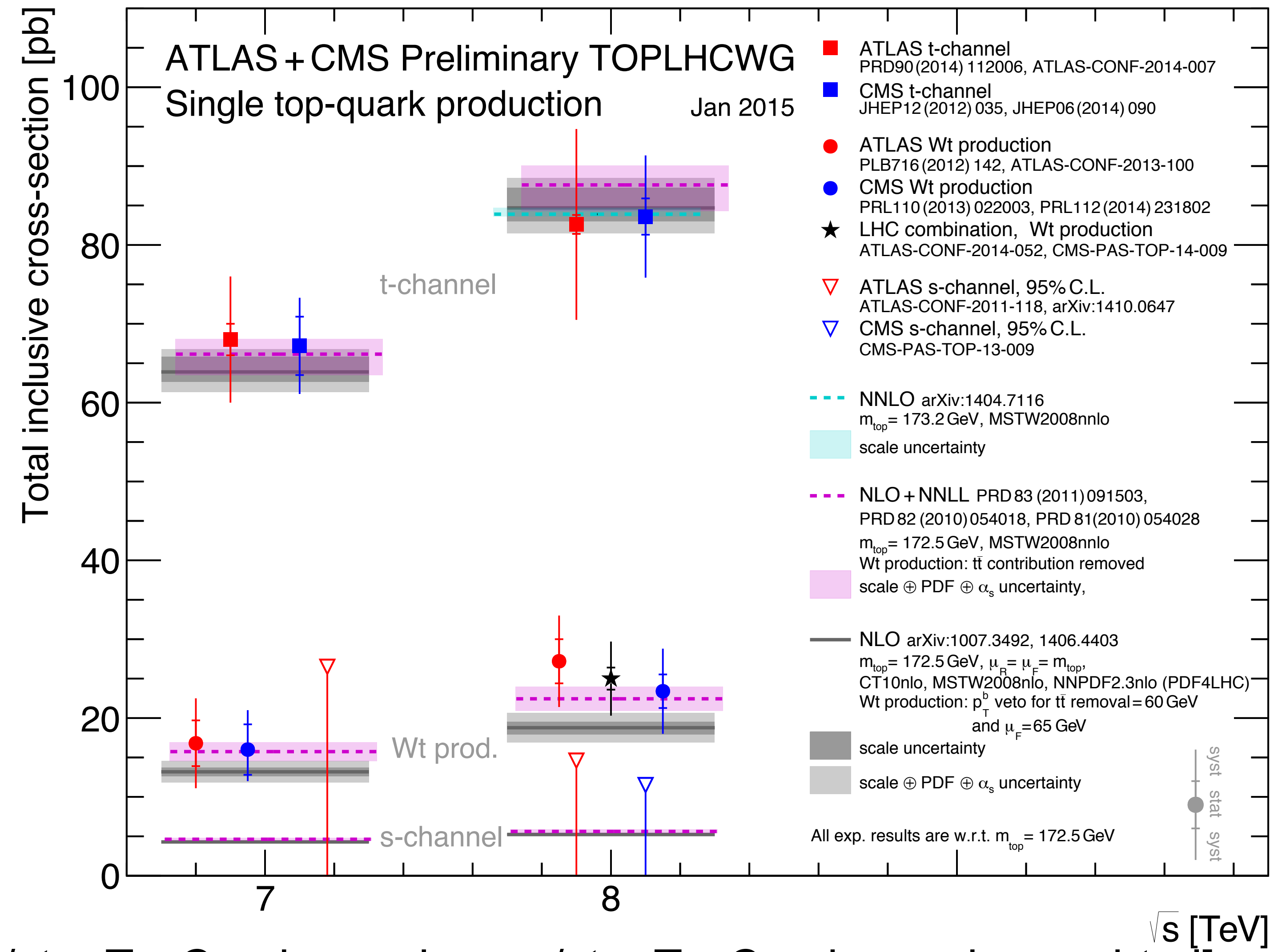
Single Top Production: Summary

- First measurements: **very small** signals → first extensive use of **multivariate analysis techniques** (neural networks etc.) at the Tevatron

Tevatron: s and t channel established



LHC: t channel and Wt established, s channel limits



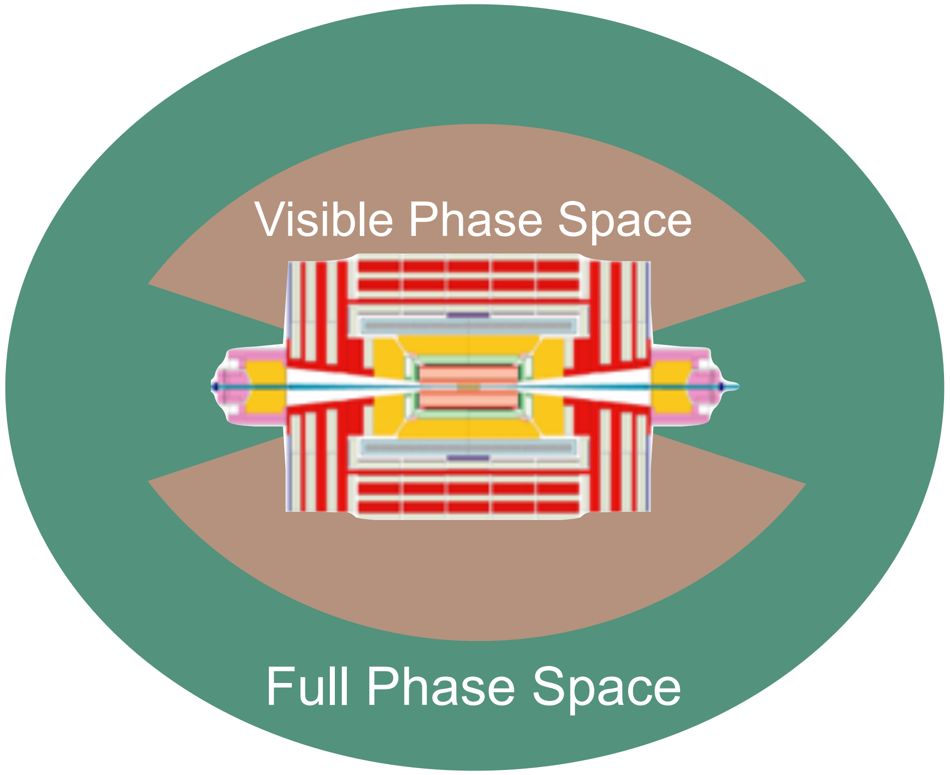
[http://www-cdf.fnal.gov/physics/new/top/2014/stopTevCombo_webpage/stopTevCombo_webpage.html]

[https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures]

Towards Higher Precision

- Various **changes and improvements** over the last 20 years
  - **Changing roles** of decay channels: **dilepton** as the new gold-plated channel in LHC era → large data samples, almost background-free
  - **Technical** improvements, e.g. **in-situ constraints** of systematic uncertainties (profile likelihood ratio)
  - **Conceptual** progress, e. g. clearer **separation of sources of uncertainty**: detector vs. signal vs. background modeling

- Current limitation for inclusive cross section measurements: extrapolation to **full phase space** with theory/simulation tools
  - Cross sections measured in **visible phase space** (aka. fiducial cross sections) → reduced dependence of measurement on signal/background modeling
  - **Differential** cross sections: closer look at decay kinematics



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Differential Cross Sections

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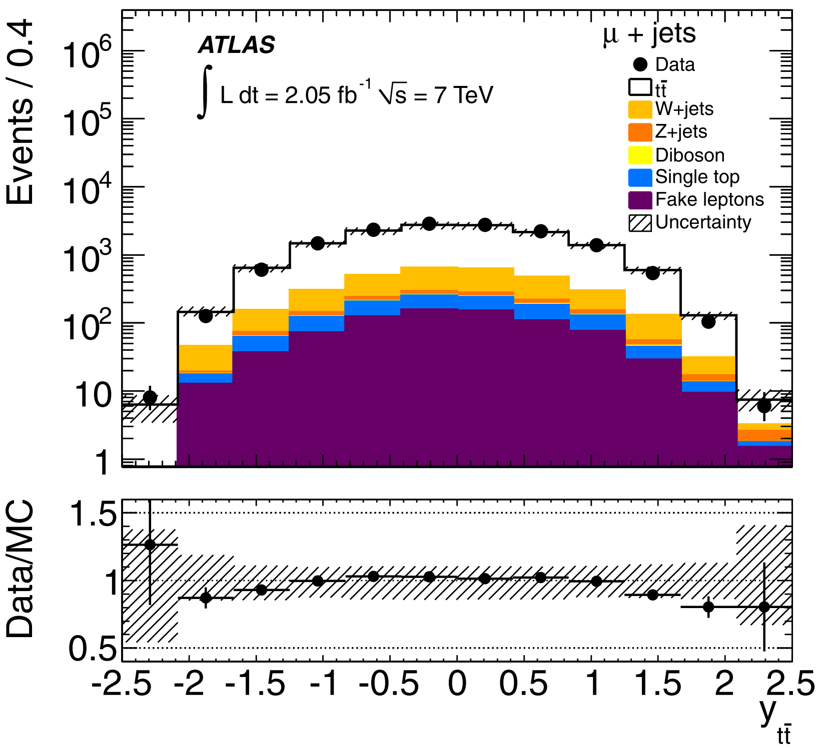
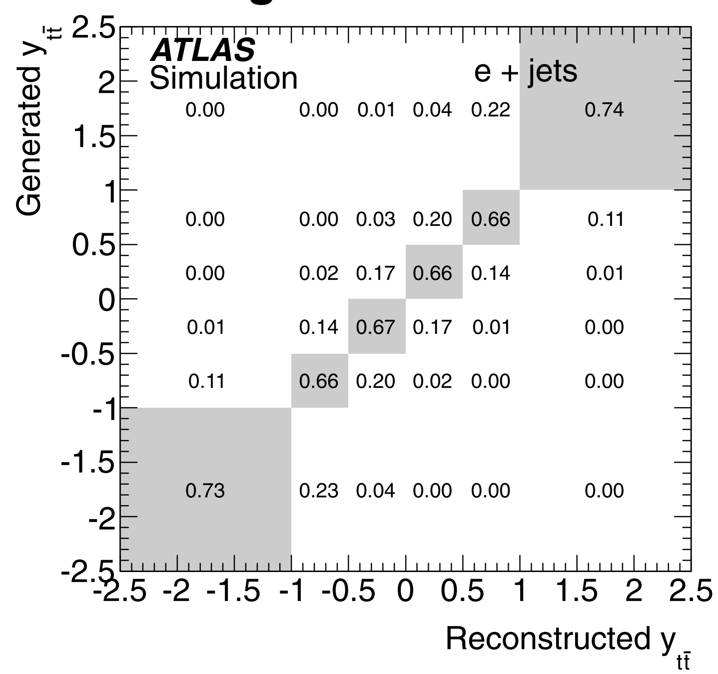
Reconstruction

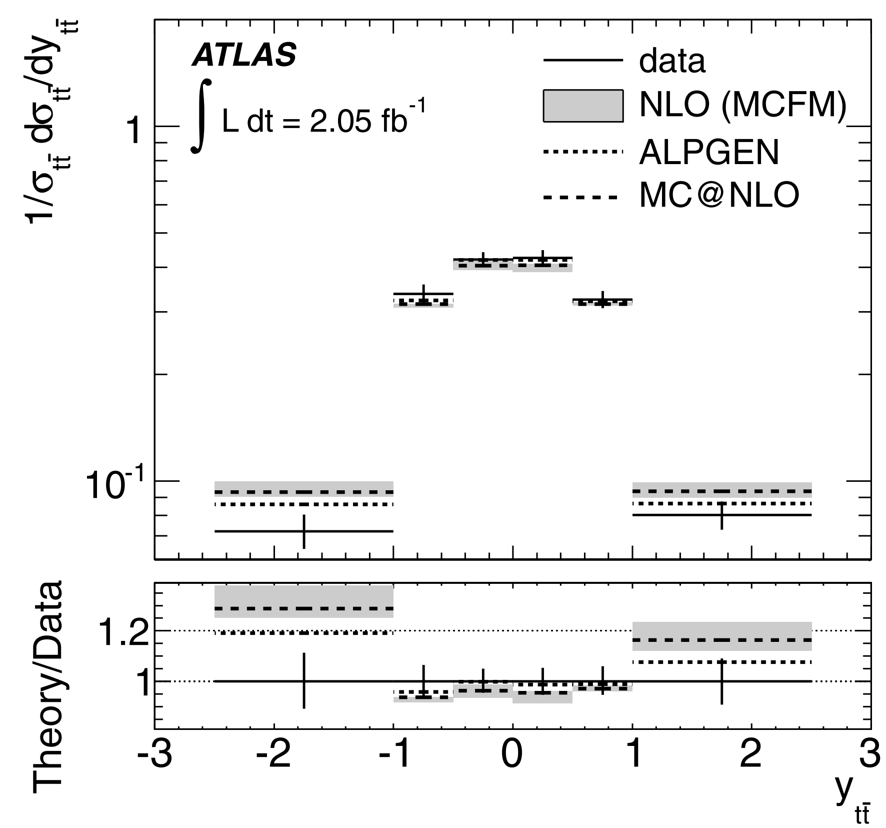


Rapidity: $y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$

Migration Matrix



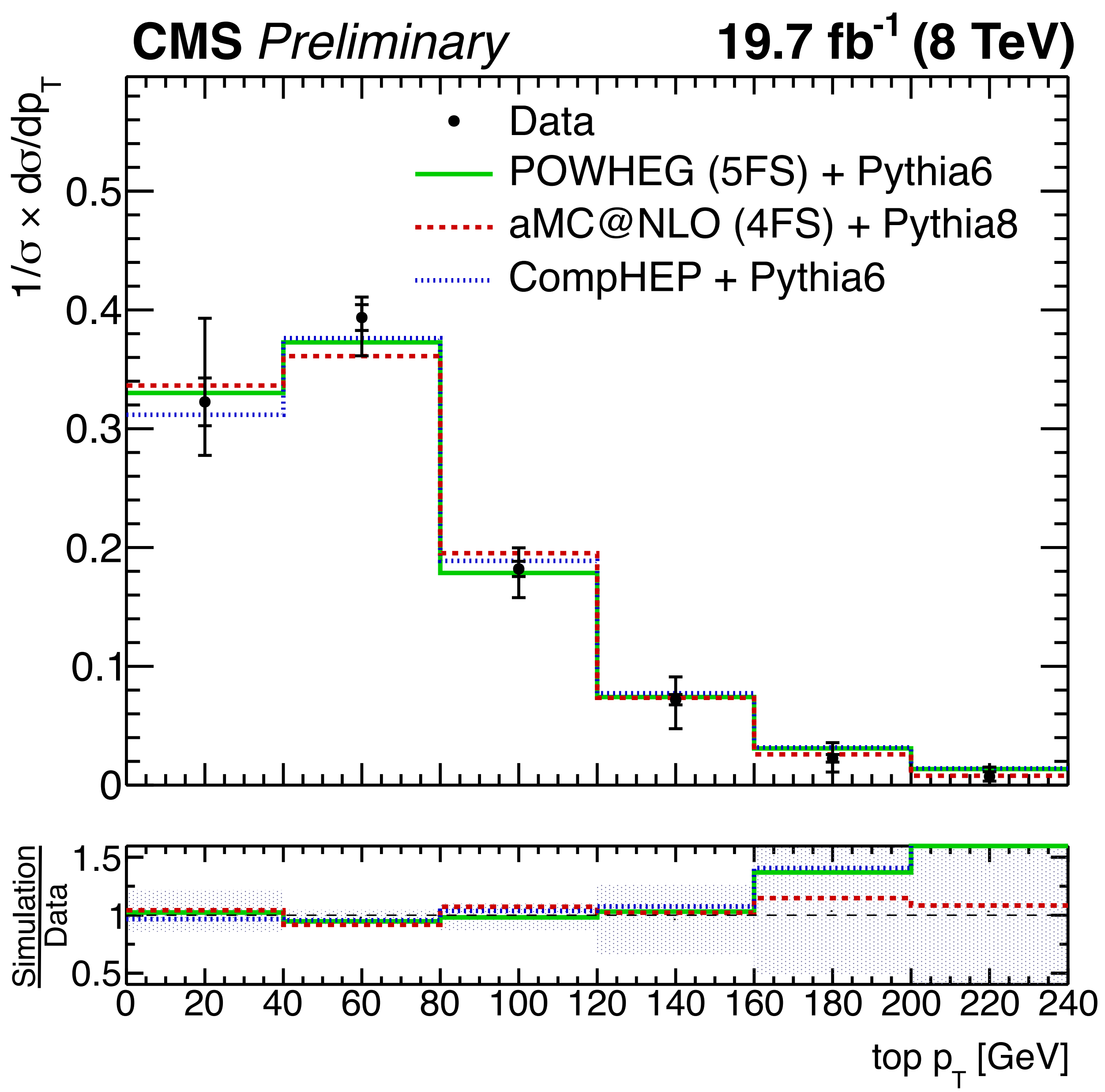
Unfolded Distribution

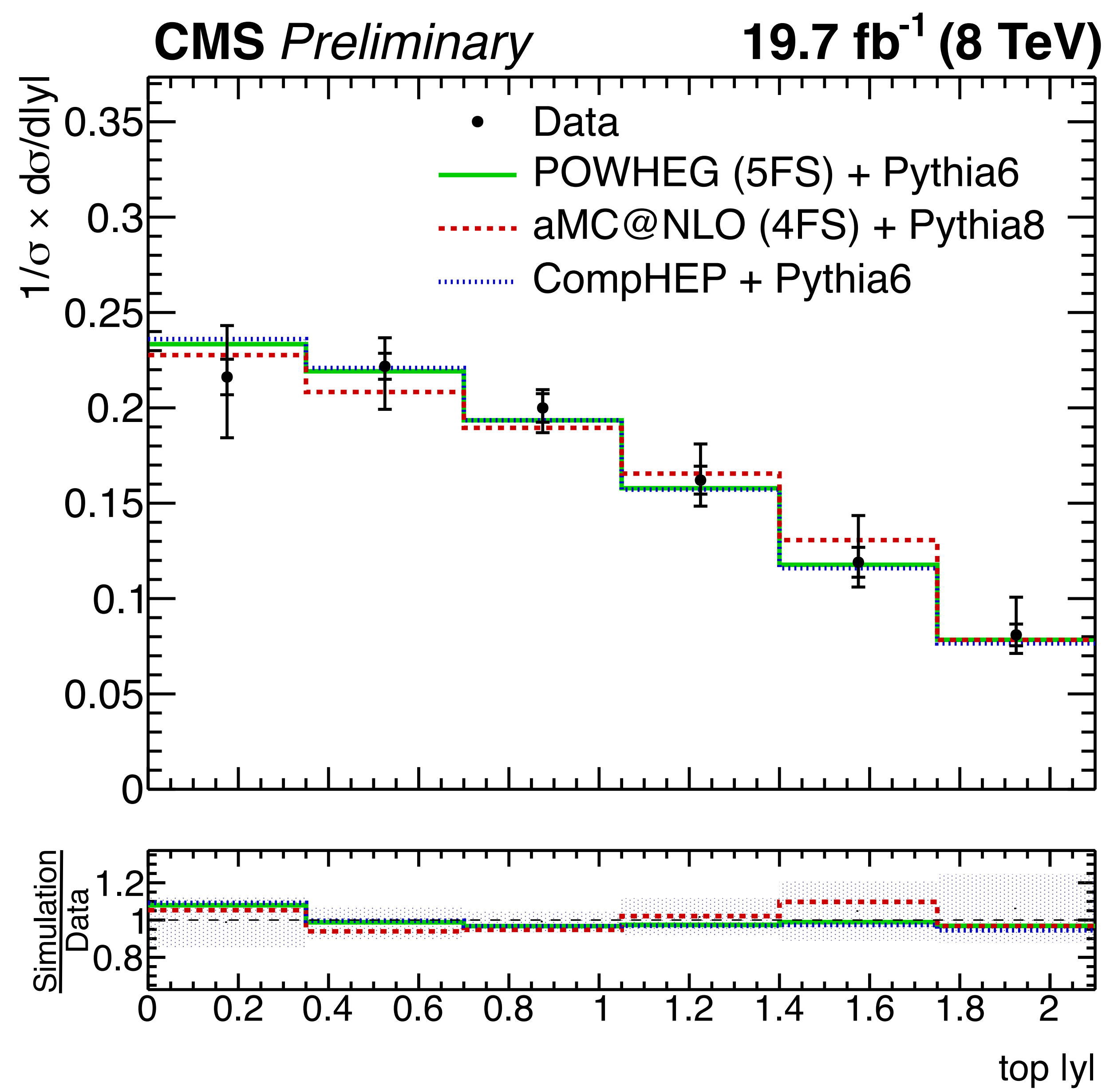


- **Unfolding** of reconstructed quantities to parton or particle level (often in fiducial volume) → **comparison** with other experiments & theory
- **Conceptual** question: Top partons = oversimplified leading-order picture? Connection to observables?

[Eur. J. Phys. C73 (2013) 2261]

Example: Single Top p_T and y





[CMS-PAS-TOP-14-004]

Transverse Momentum: $p_T = \sqrt{p_x^2 + p_y^2}$

Rapidity: $y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$

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Producing Top Quarks + “Something Else”

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Institut für Experimentelle Kernphysik (IEKP)

Top + "Something Else": Overview

Signature	Impact
$t\bar{t}$ + (heavy flavor) jets	QCD test Background to Higgs and BSM searches
$t\bar{t}$ + missing transverse energy	Heavy BSM particles decaying into top
$t\bar{t}$ + vector bosons (γ, W, Z)	Electroweak top couplings Background to Higgs and BSM searches
$t\bar{t}$ + Higgs	Direct measurement of Yukawa couplings
Single top + Higgs	Sign of top Yukawa coupling

Top + “Something Else”: Overview

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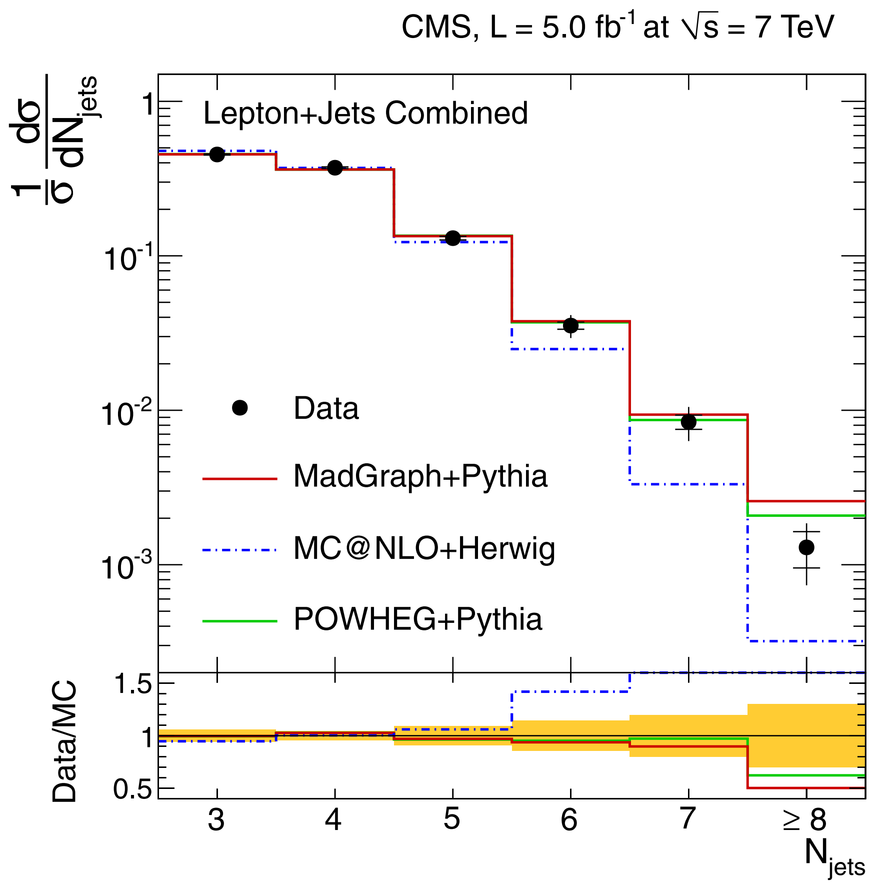
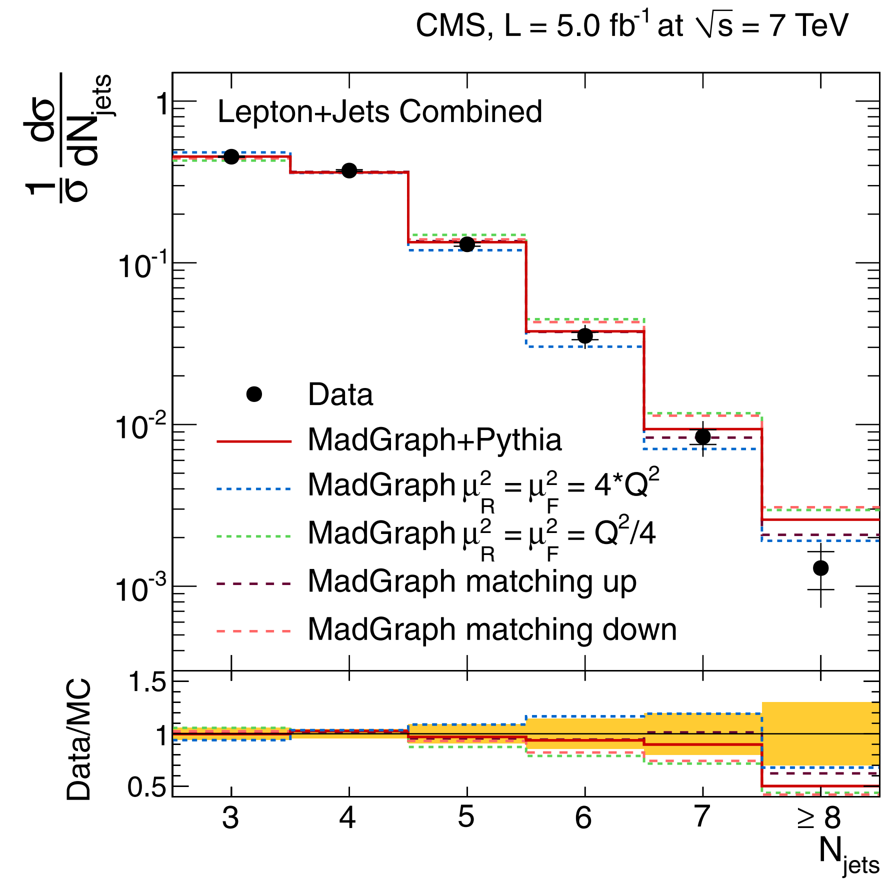
Top + Jets

- Jet multiplicity in $t\bar{t}$ events: **Test** of perturbative QCD and “engineering” measurement of important **background** to many searches





[EPJ C74 (2014) 3014]

- Main results so far:
  - Generally **good agreement** with standard Monte Carlo generators
  - Renormalization/factorization scale uncertainties seem **too conservative**
  - Now exploring **new next-to-leading order** multi-jet MC codes

Associated Top+Higgs Production

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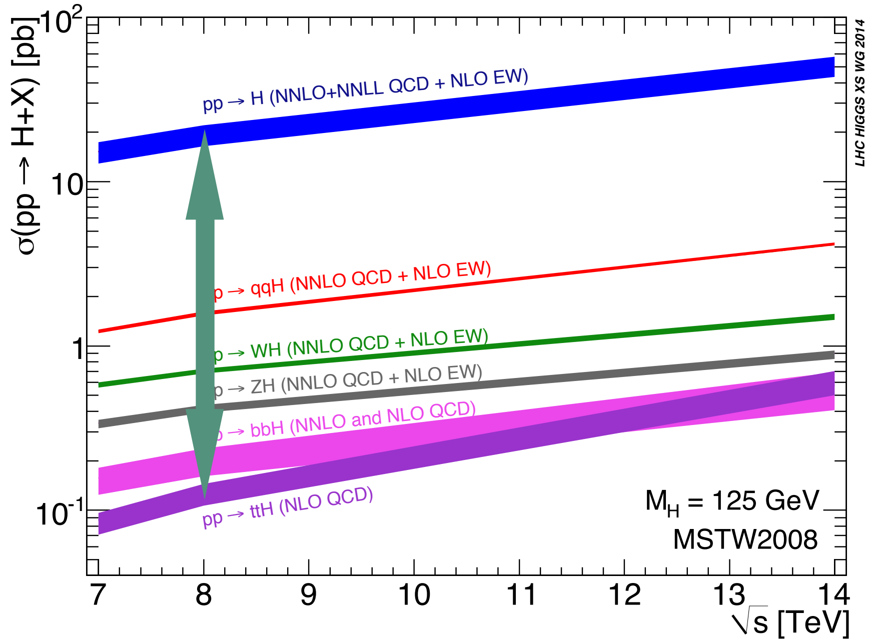
- Top = heaviest SM particle → **largest Yukawa coupling y_t** to the Higgs

Production Cross Section



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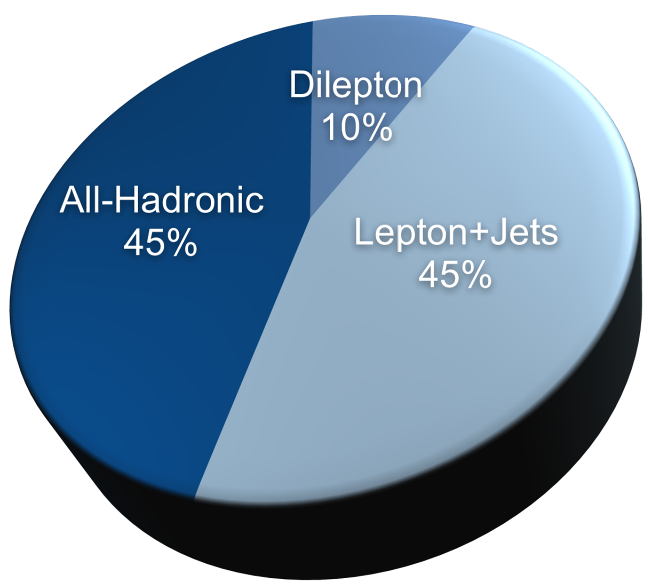
$t\bar{t}$ Branching Fractions



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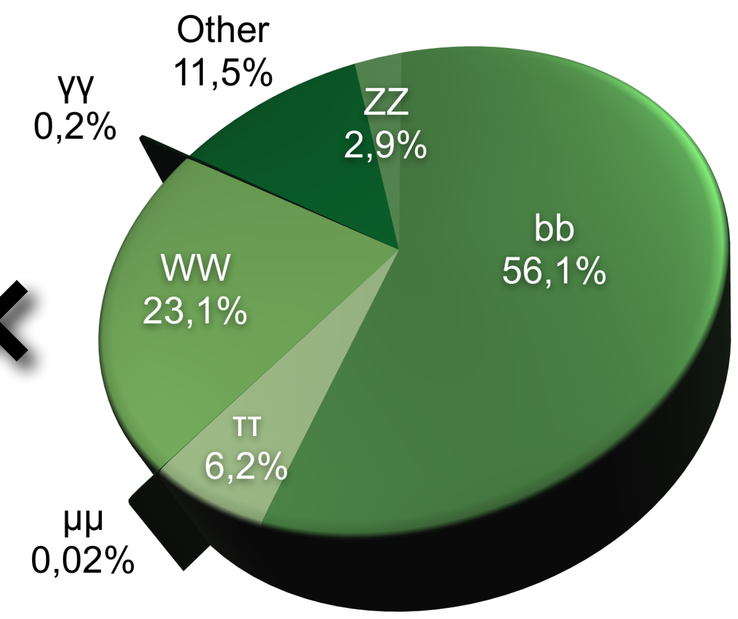
Higgs Branching Fractions

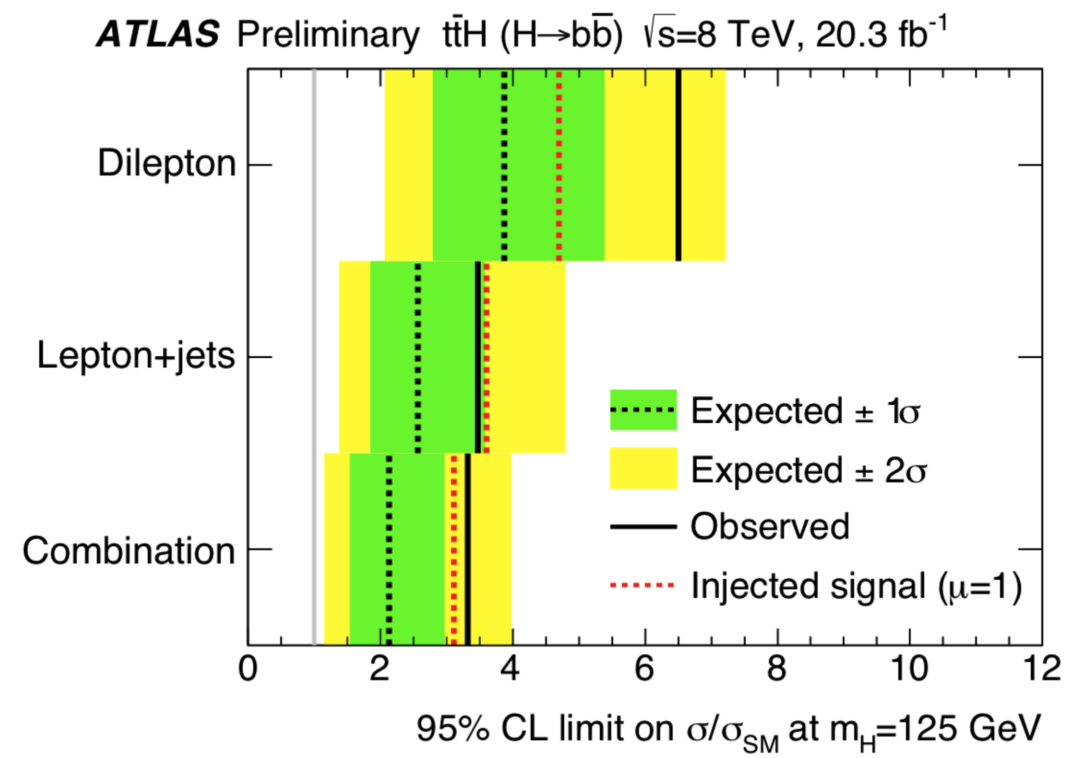


- Very small expected signal and large irreducible backgrounds
  → extensive use of **multivariate** techniques

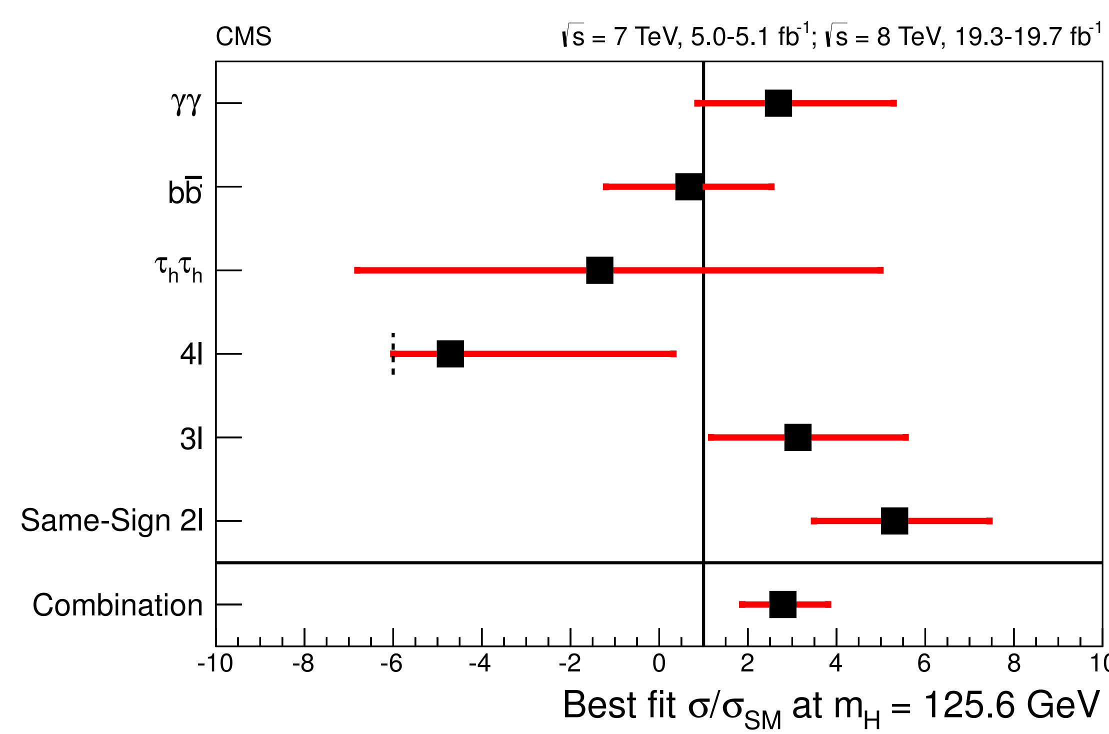
Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

$t\bar{t}H$ Status at the LHC

- Single most sensitive channel **matrix element method** in $H \to b\bar{b}$
  - ATLAS: production cross section smaller than **3.4 times SM** (2.2 expected)
  - CMS: **3.3 times SM** (2.9 expected)
- Many decay channels **combined**: (prior to matrix element results) 2 standard deviations excess over SM (driven by same-sign dileptons)
- Looking forward to **LHC Run II**: 3–4 times larger $t\bar{t}H$ production cross section



[J. Montejo, La Thuile 2015]



[JHEP 09 (2014) 087]

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Top Properties & New Physics

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Top Properties: Then and Now

Karlsruher Institut für Technologie

- Guiding question at the Tevatron: is the top quark really the **6th quark of the SM**?

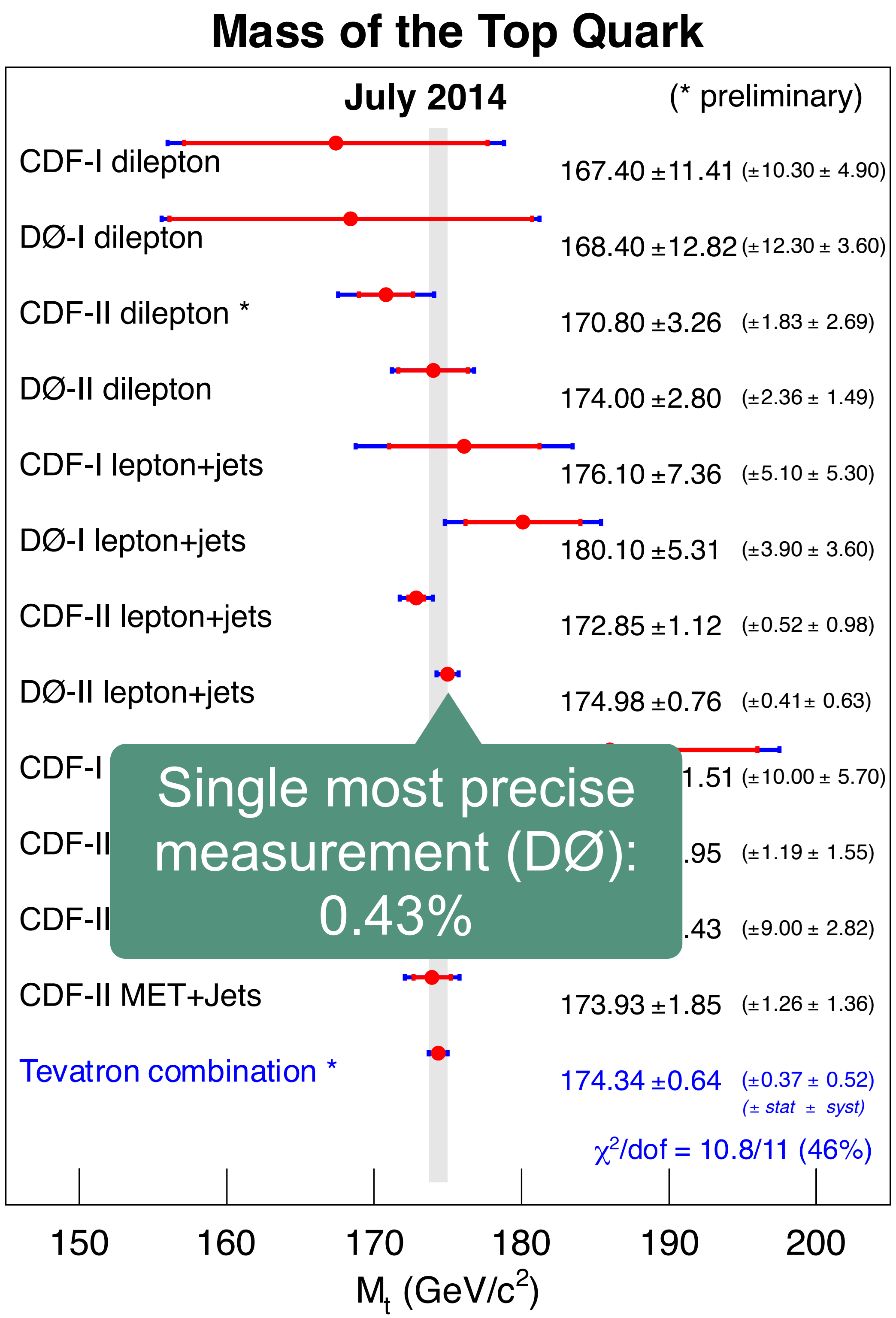
  → Yes, within the uncertainties.

- Next step: **more precision**
  - High-precision top quark **mass**
  - Lots of physics information in **polarization** observables
  - Searches for **new physics**

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Top Mass: Tevatron

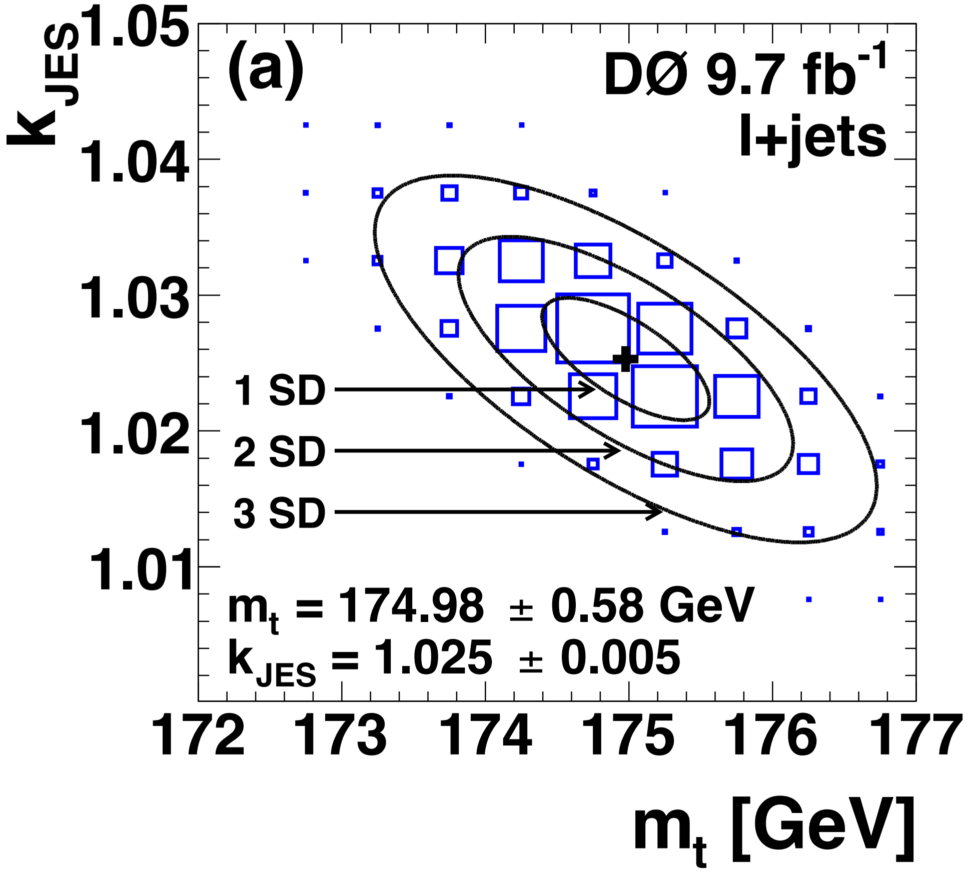
- **Combination** of Tevatron results on top quark mass
  - Data from Tevatron Run I and Run II
  - All top quark decay channels, various techniques
- Results:
  - All results **consistent** within uncertainties
  - Detailed understanding of all **uncertainties** and their **correlations**
  - Combined uncertainty (2014): **0.4%**



Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Top Mass: Technology

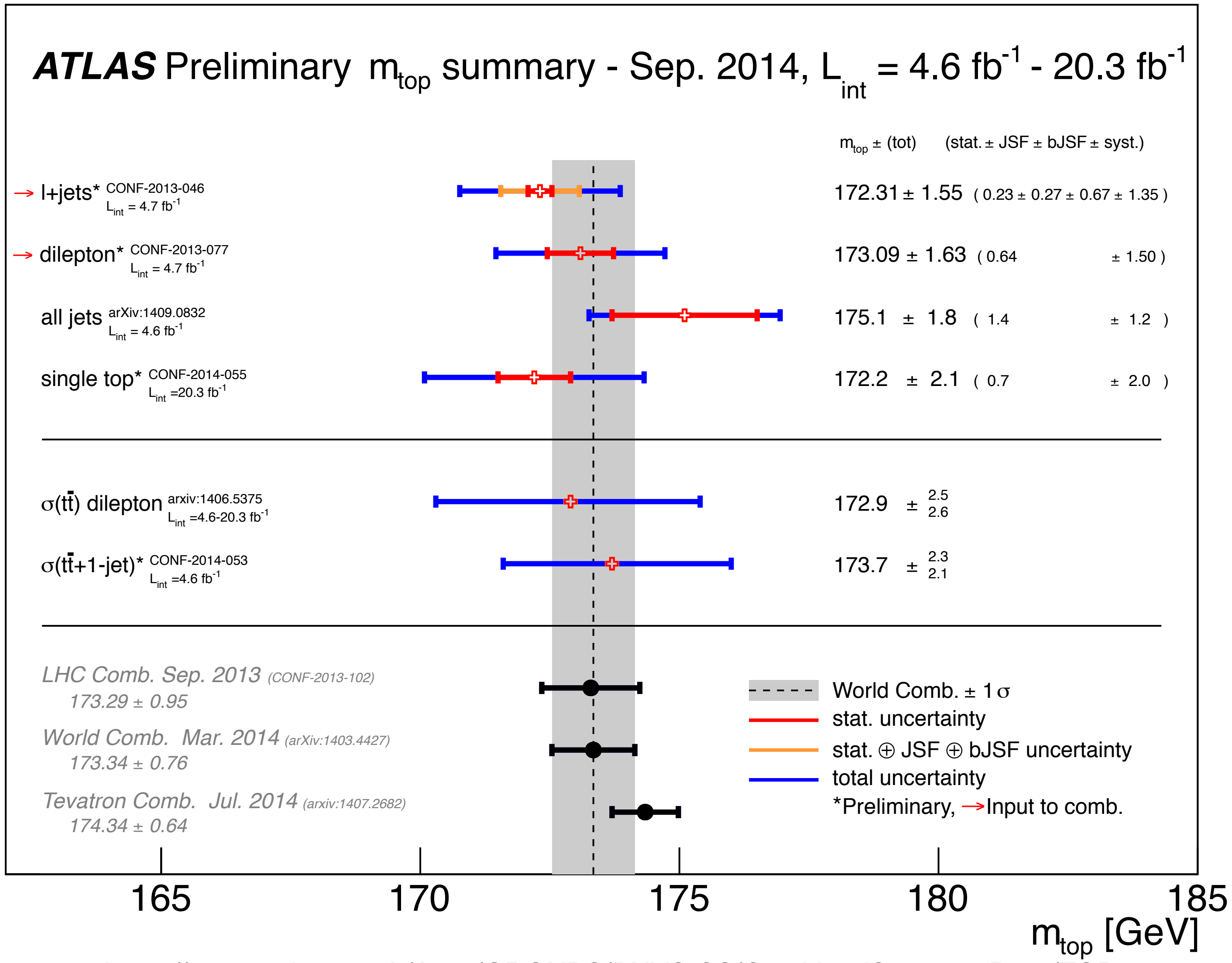
- Many of today's analysis methods **spear-headed at the Tevatron**
- **Matrix-element method** (2003/4):
  - Classification of events with likelihood ratio using **(leading order) matrix element**
  - Exploit full (LO) event information
  - Computationally **expensive**
- **In-situ JES** (2006/7):
  - **W boson mass known** with high precision
  - Lepton+jets (all-hadronic) top decays: 1 (2) hadronic W decays
  - Calibration of jet energy scale (JES) factor k_{JES} with hadronic W decays



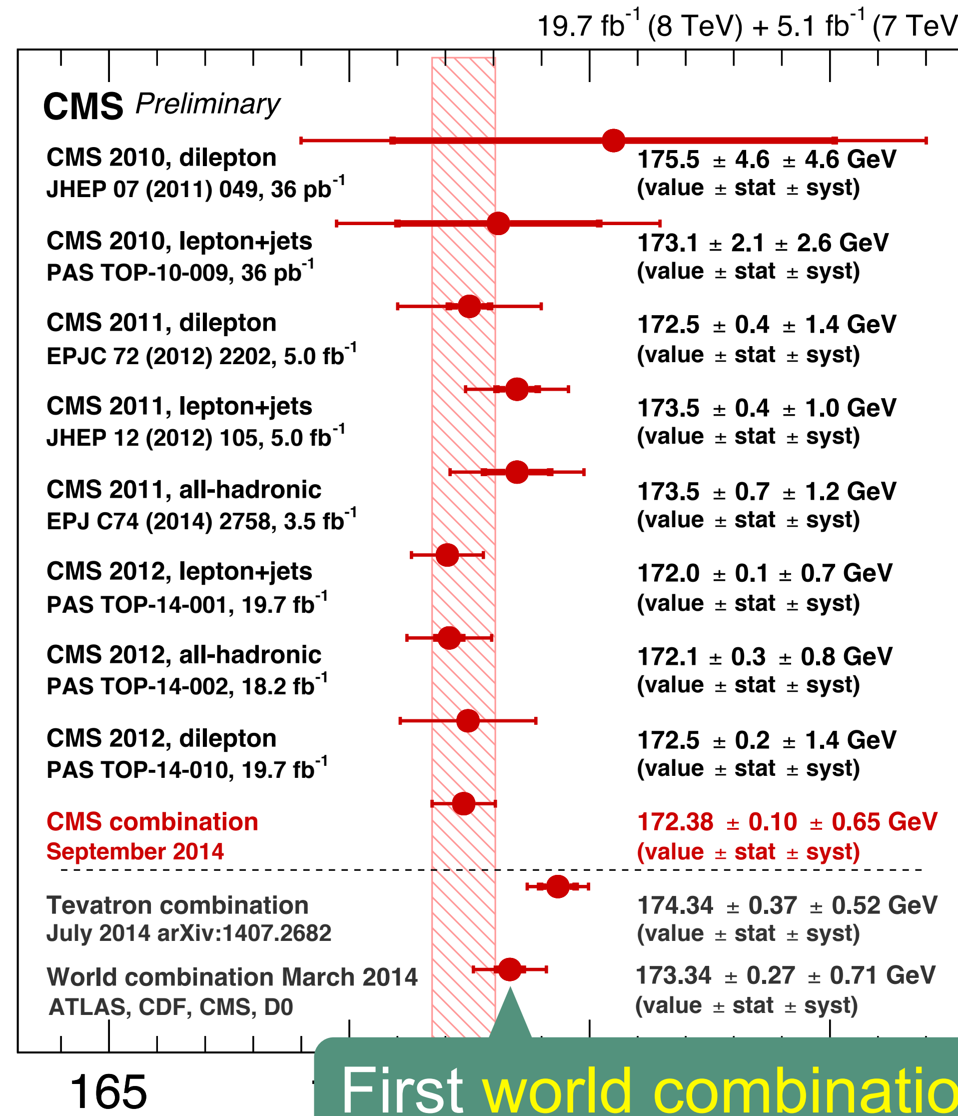
[Phys. Rev. Lett. 113 (2014) 032002]

Top Mass: LHC

Karlsruher Institut für Technologie



https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP



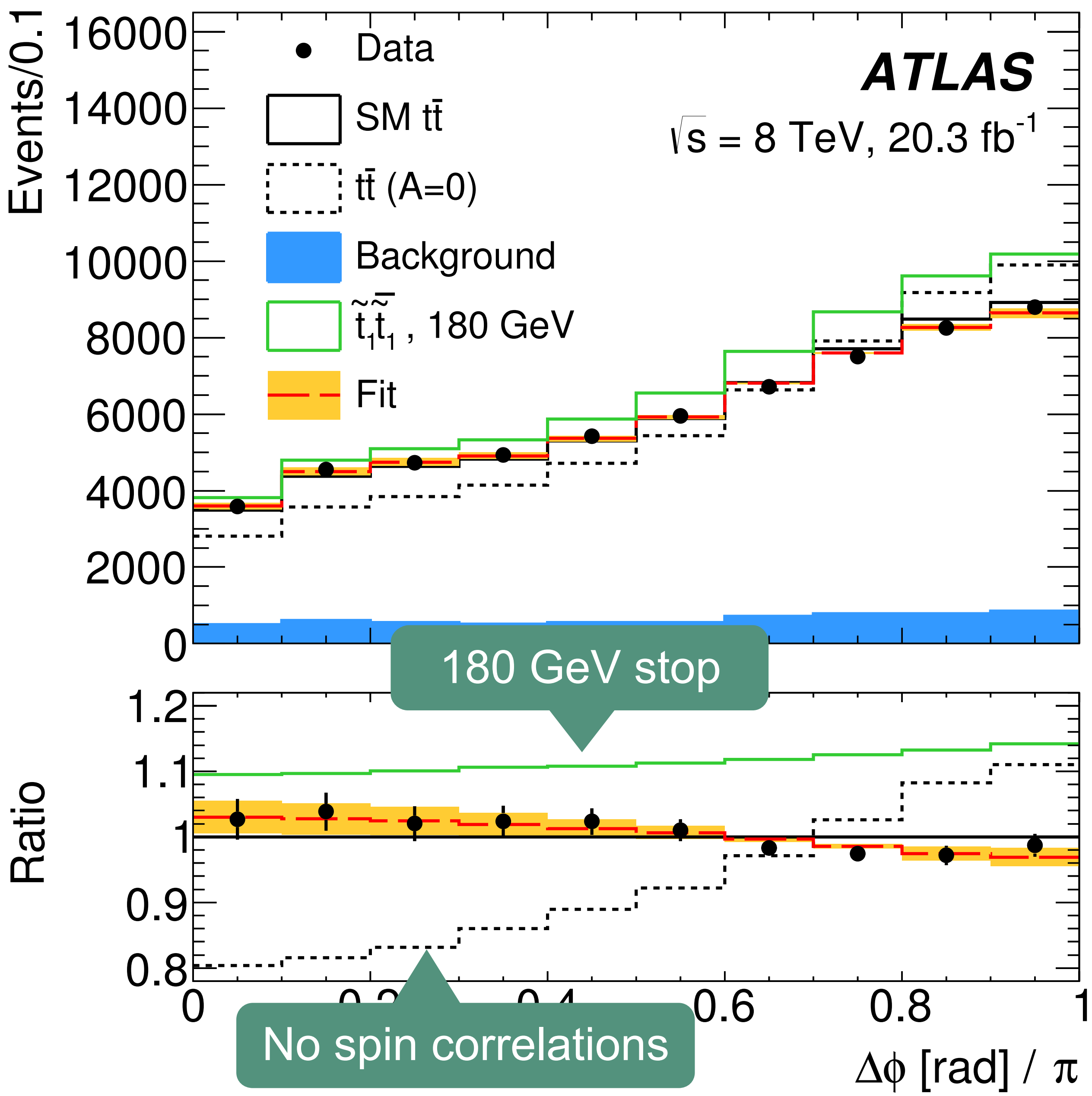
First world combination (March 2014)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures

- LHC has **caught up quickly**: central top mass value and uncertainty comparable to Tevatron → around 0.4% uncertainty
- Long and difficult discussion: pole mass vs. mass in MC simulation? → **alternative** mass measurements, e.g. based on cross section

Polarization Observables

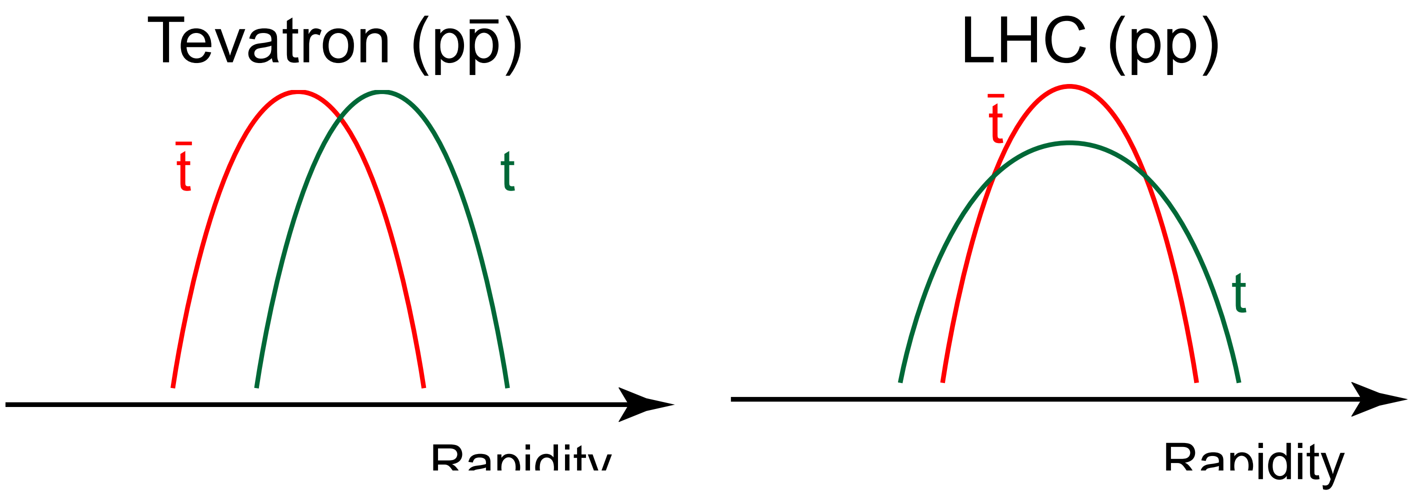
- Relevance:
  - **No hadronization** → top quark spin "easily" accessible
  - Standard model: $t\bar{t}$ spins correlated
  - Expect **imprint of BSM physics**, e.g. supersymmetric top partners ("stops")
- Example: **spin correlations**
  - Observable **leptonic asymmetry**: difference of lepton polar angles $\Delta\phi$
  - Limit on production of **stops** with masses **close to the top mass** (difficult to obtain in other searches)

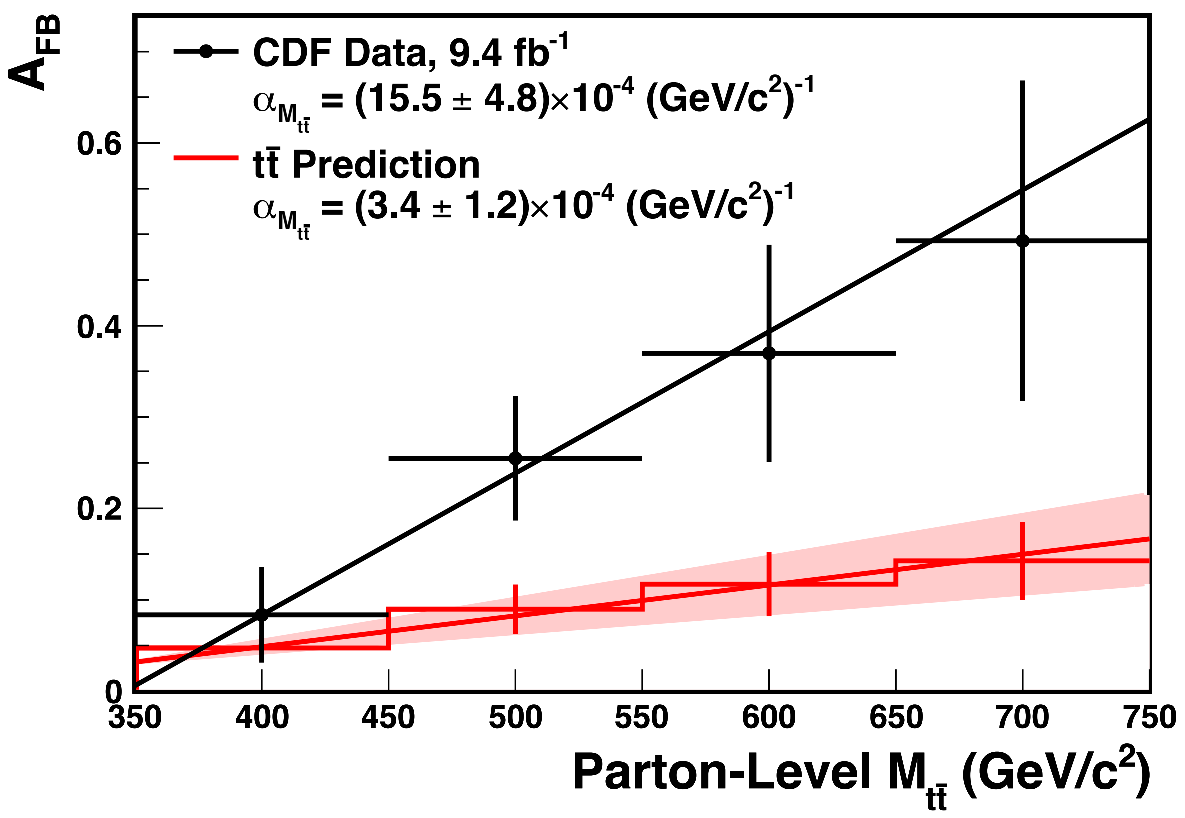


[arXiv:1412.4742, submitted to PRL]

Charge Asymmetry

- $t\bar{t}$ production asymmetries:
  - SM: small effect, contributes first at **NLO** (Kühn, Rodrigo)
  - Tevatron ($p\bar{p}$): tops like to move forward (= in proton direction)
  - LHC (pp): t rapidity distribution wider than $\bar{t}$
- **Excitement** at the Tevatron:
  - Asymmetries **significantly larger** than predicted in SM
  - Many possible explanations, e.g. axigluons



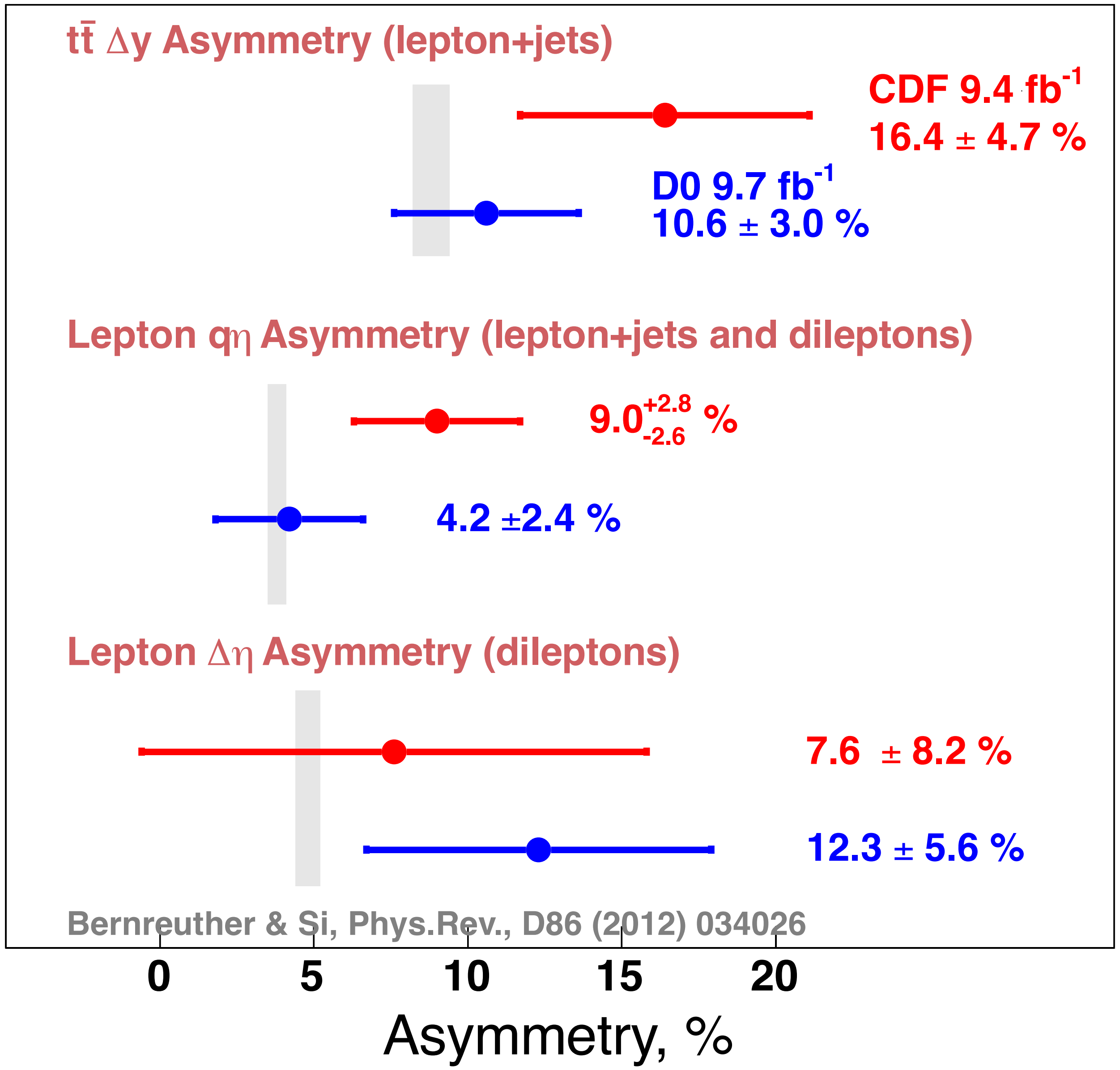


[PRD 87 (2013) 092002]

$$A_{FB} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

Charge Asymmetry

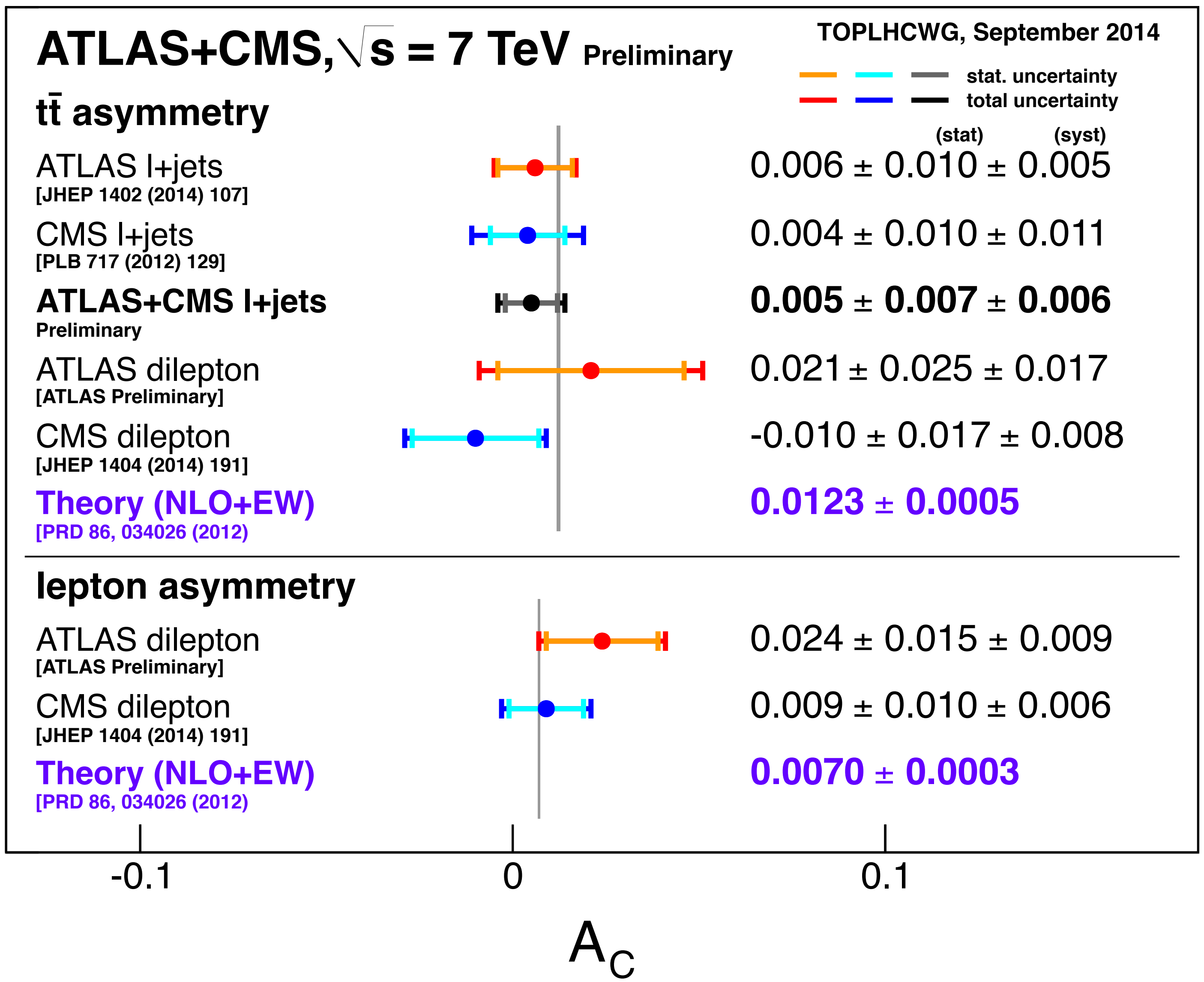
- Recent developments:
  - Improved theory predictions
  - Full Tevatron dataset analyzed
- **Leptonic** asymmetries (Bernreuther, Si): **cleaner** both theoretically and experimentally
- Larger asymmetries predicted at **NNLO** (Czakon, Fiedler, Mitov)



http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

Ulrich Husemann
Institut für Experimentelle Kernphysik (IEKP)

Charge Asymmetry



https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures

- LHC: all asymmetry measurements **compatible** with SM predictions (and zero)
- Difficult to find models that explain deviation at the Tevatron and agreement with SM at the LHC

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To summarize …

There is Much More…

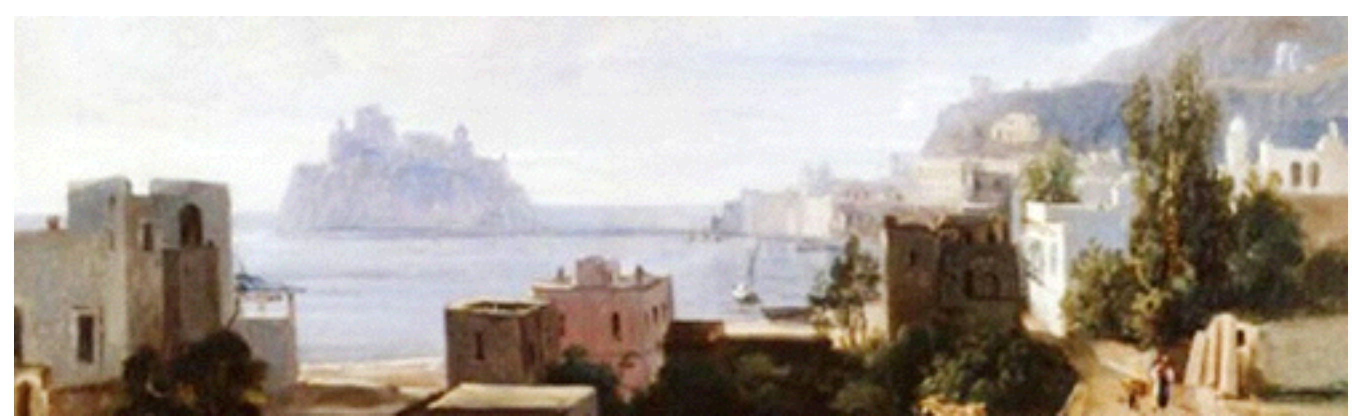
- … than I could present in a one-hour talk
  - Many more top properties measurements
  - Searches for heavy top quark partners
  - New techniques, e.g. reconstruction of “boosted tops”
  - Top physics at future e^+e^- colliders
  - …
- Check out the LHC and Tevatron experiments’ public material
  - CDF: http://www-cdf.fnal.gov/physics/new/top/top.html
  - DØ: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html
  - ATLAS:
    - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults
    - https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/TOP/
  - CMS:
    - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP
    - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOPSummaryFigures
  - TOPLHCWG: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TopLHCWG

TOP 2015

8th International Workshop
on Top Quark Physics

Ischia, Italy, 14-18 September 2015

Contact: top2015@infn.it



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Institut für Experimentelle Kernphysik (IEKP)

Conclusions

- Tevatron: top legacy measurements being finalized
- LHC Run I: 6 million tops on tape
  - Mass and cross sections: towards precision top physics
  - Top properties: exploring connection to Higgs and BSM physics
- LHC Run II: 100M tops per year → the best is yet to come